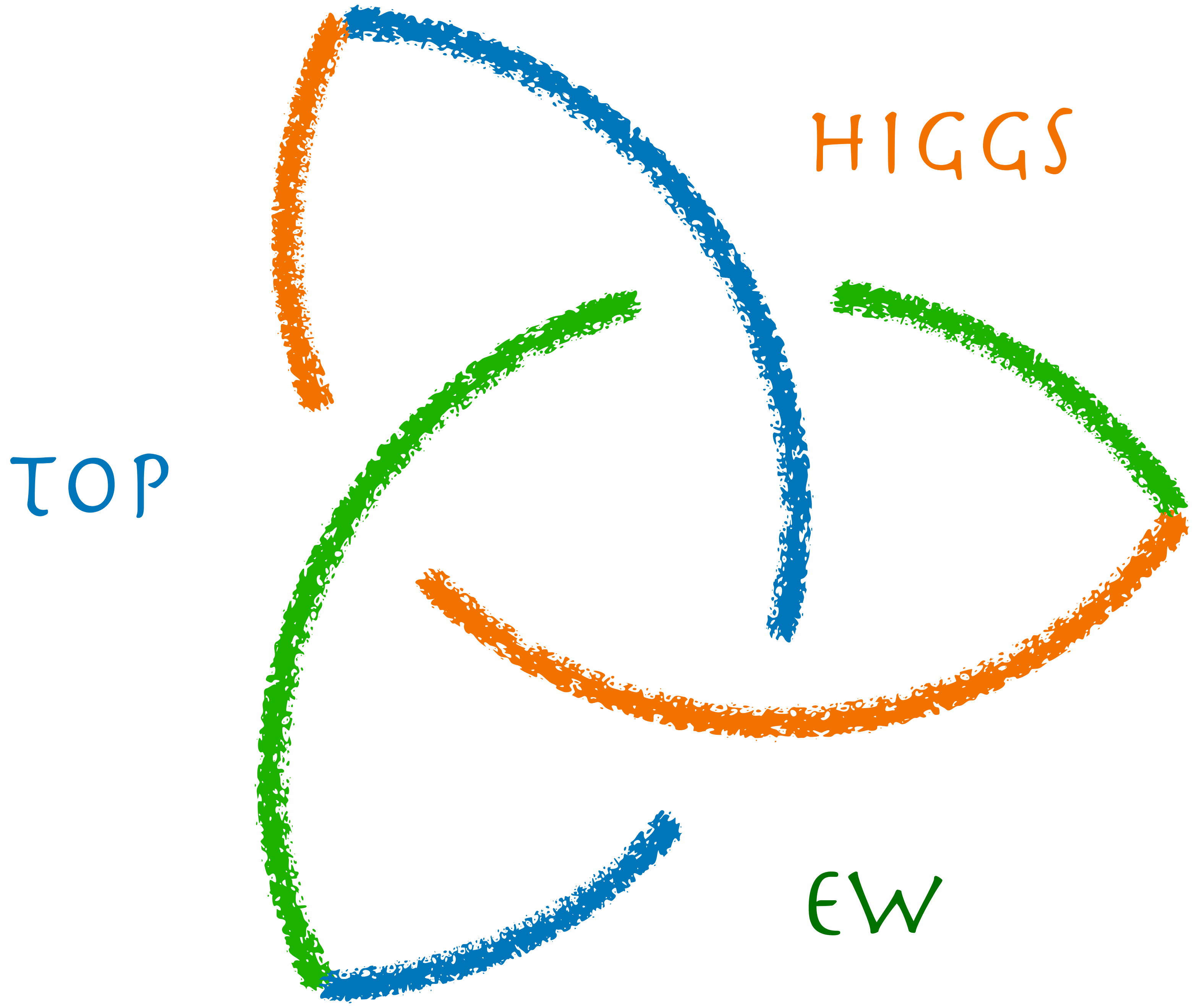
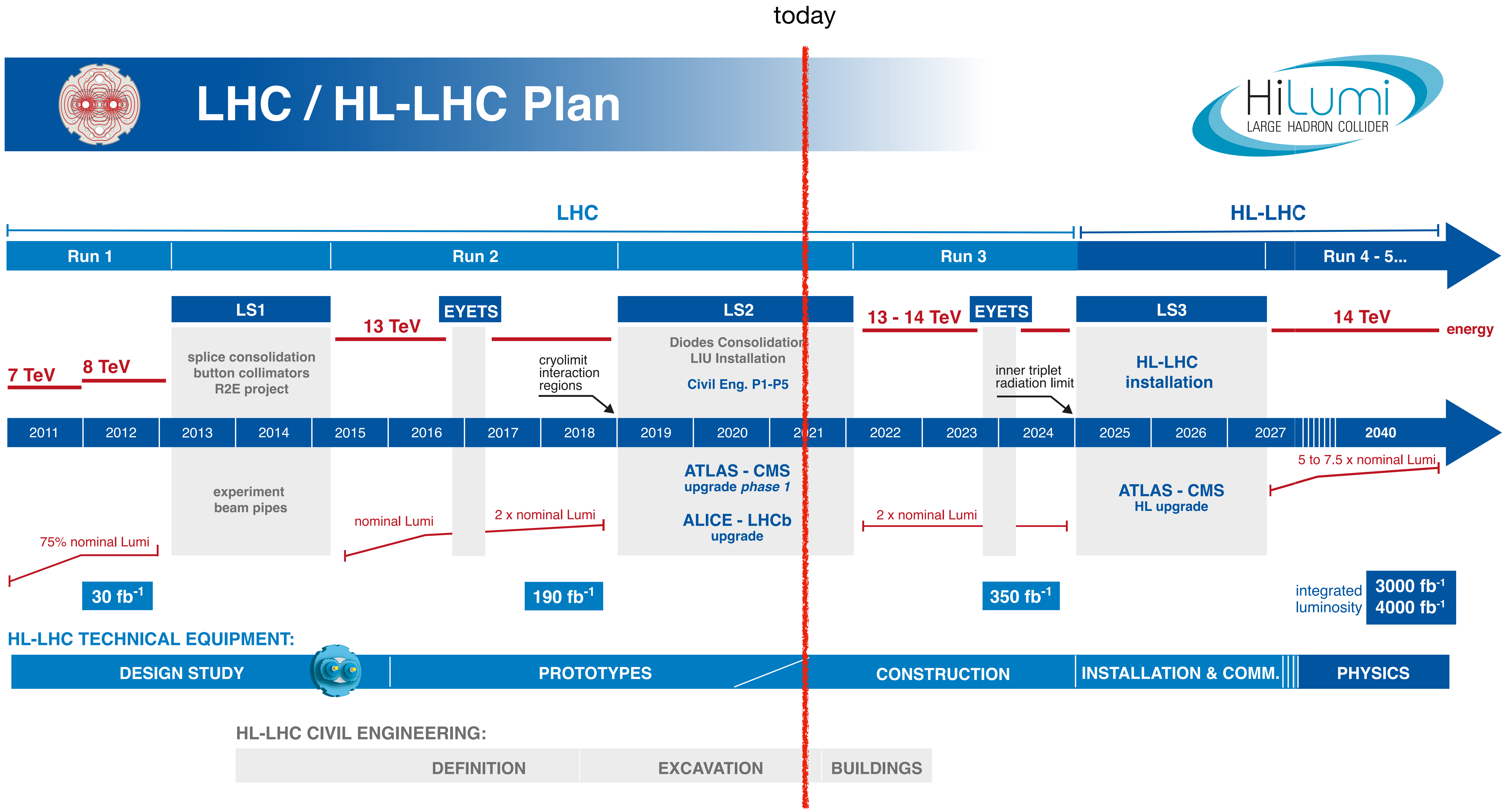
The precision potential of the LHC



Fabio Maltoni
Università di Bologna
Université catholique de Louvain

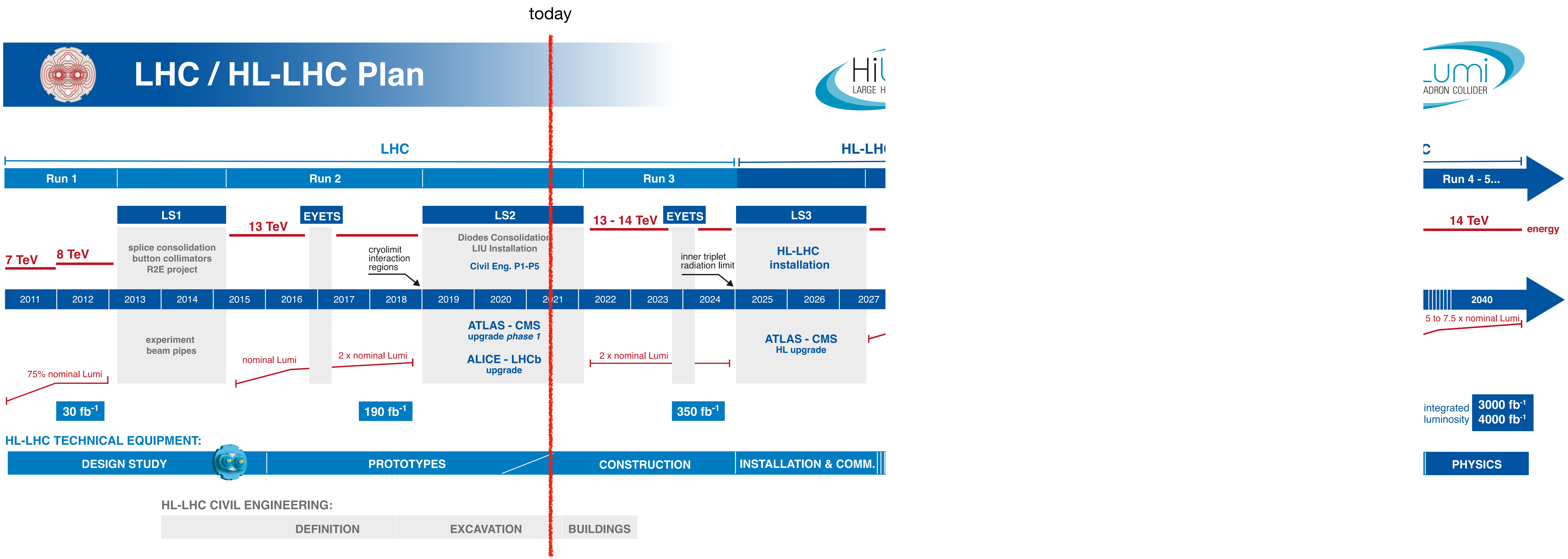
Where do we stand?

The LHC reference frame and unit of time



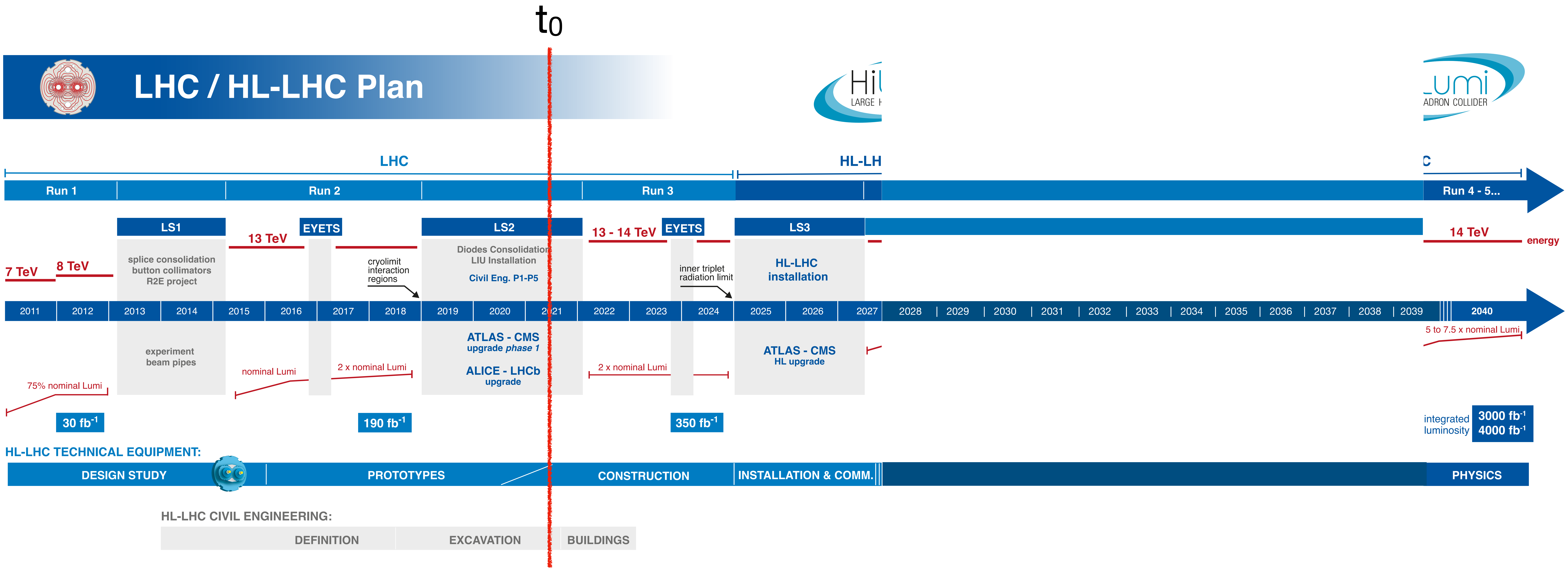
Where do we stand?

The LHC reference frame and unit of time



Where do we stand?

The LHC reference frame and unit of time



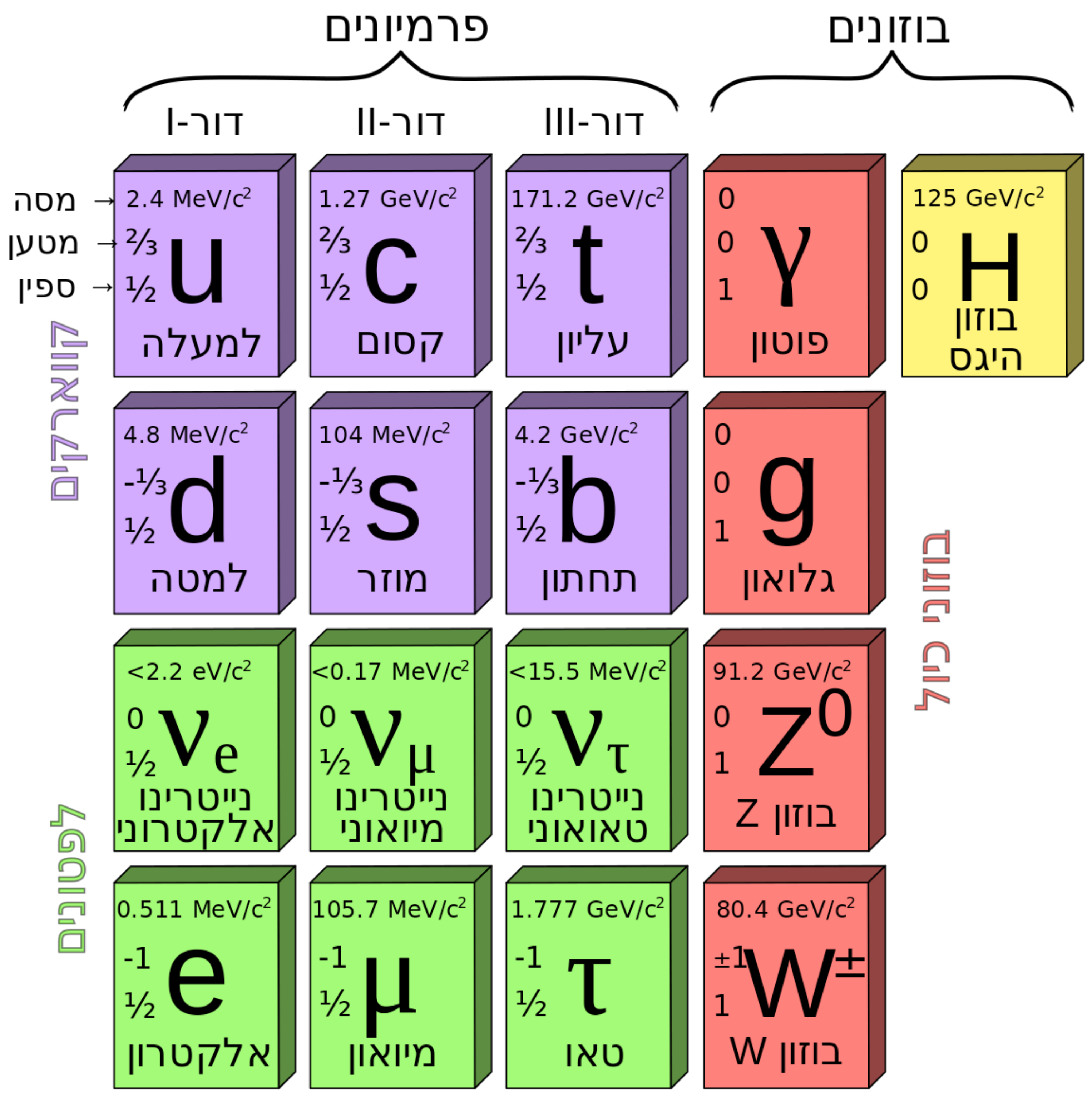
We are at 1/3 of our adventure with 1/20 of the expected data

Where do we stand?

The LHC reference frame and unit of time

Where do we stand?

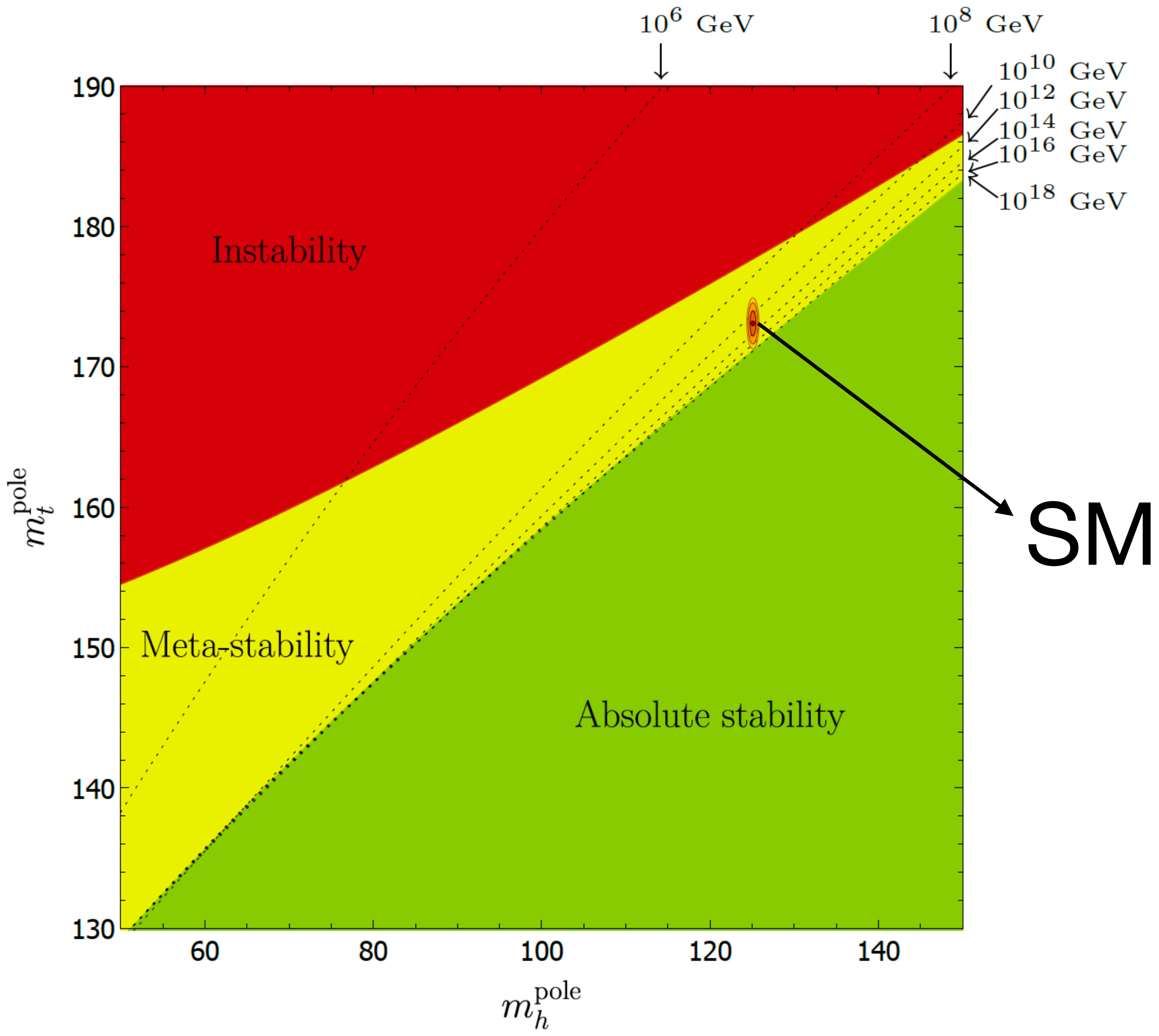
$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}i\not{D}\psi + (y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \mathrm{h.c.}) + |D_\mu\phi|^2 - V(\phi)$$



- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fund. representation.
- The $SU(2) \times U(1)$ symmetry is spontaneously broken to $U(1)_{EM}$.
- Yukawa interactions lead to fermion masses, mixing and CP violation.
- Matter+gauge group => Anomaly free
- Renormalisable = valid to “arbitrary” high scales.
- A number of accidental symmetries seen in Nature.
- Neutrino masses can be accommodated in two distinct ways.

Where do we stand?

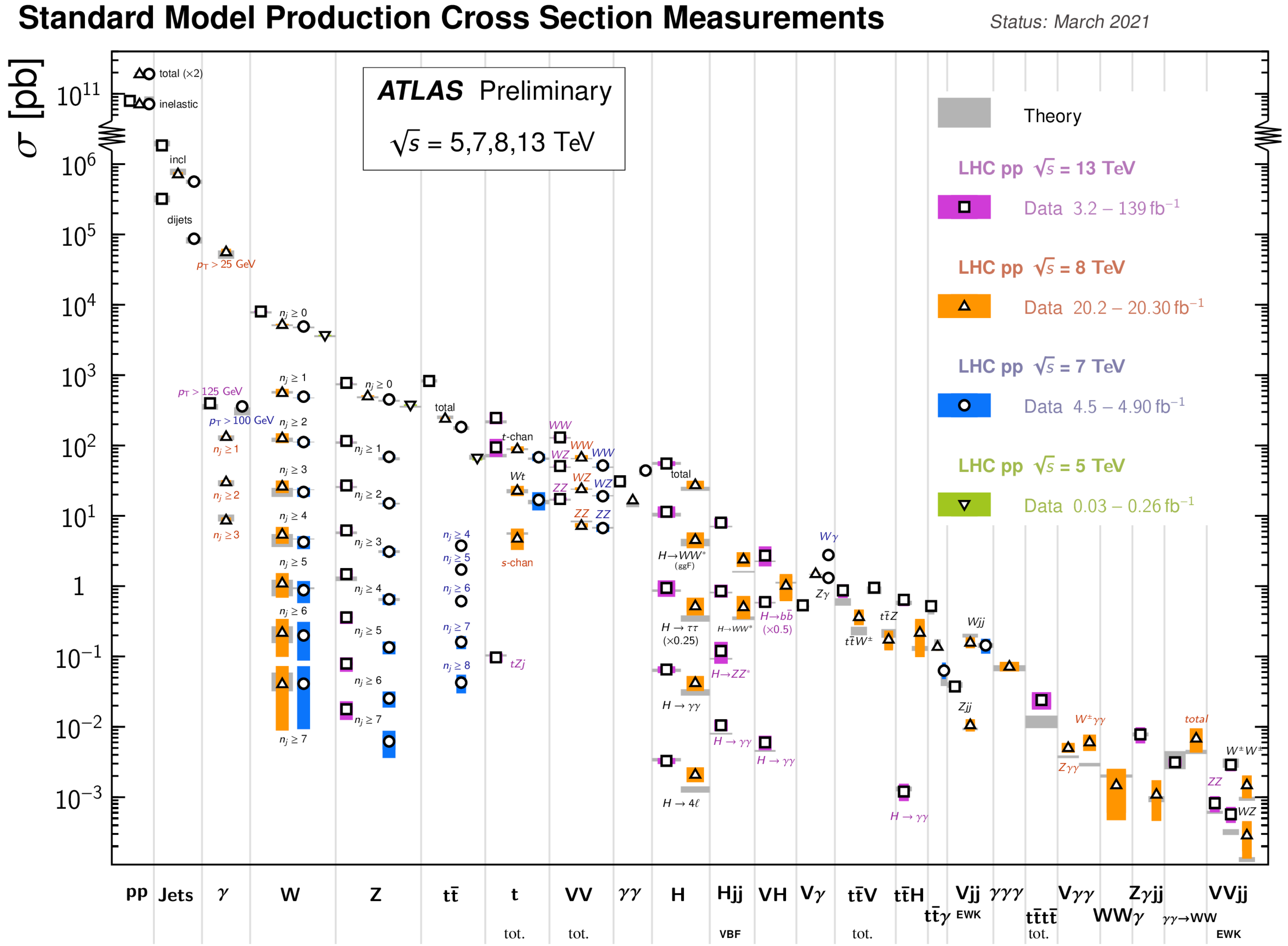
$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}i\not{D}\psi + (y_{ij}\bar{\psi}_L^i\phi\psi_R^j + \mathrm{h.c.}) + |D_\mu\phi|^2 - V(\phi)$$



[Andreassen et al. 1707.08124]

- $SU(3)_c$ x $SU(2)_L$ x $U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fund. representation.
- The SU(2) x U(1) symmetry is spontaneously broken to $U(1)_{EM}$.
- Yukawa interactions lead to fermion masses, mixing and CP violation.
- Matter+gauge group => Anomaly free
- Renormalisable = valid to “arbitrary” high scales.
- A number of accidental symmetries seen in Nature.
- Neutrino masses can be accommodated in two distinct ways.

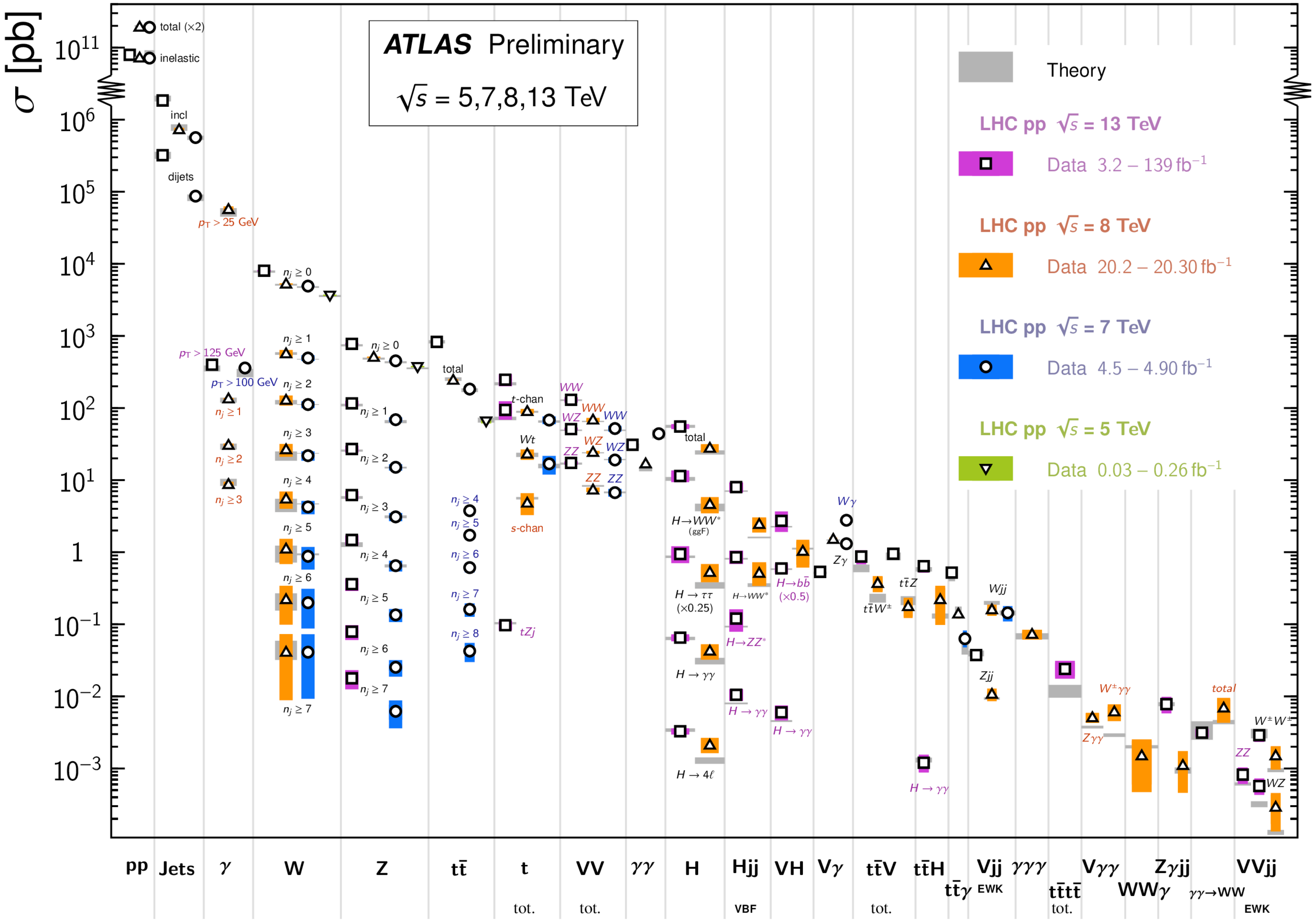
Where do we stand?



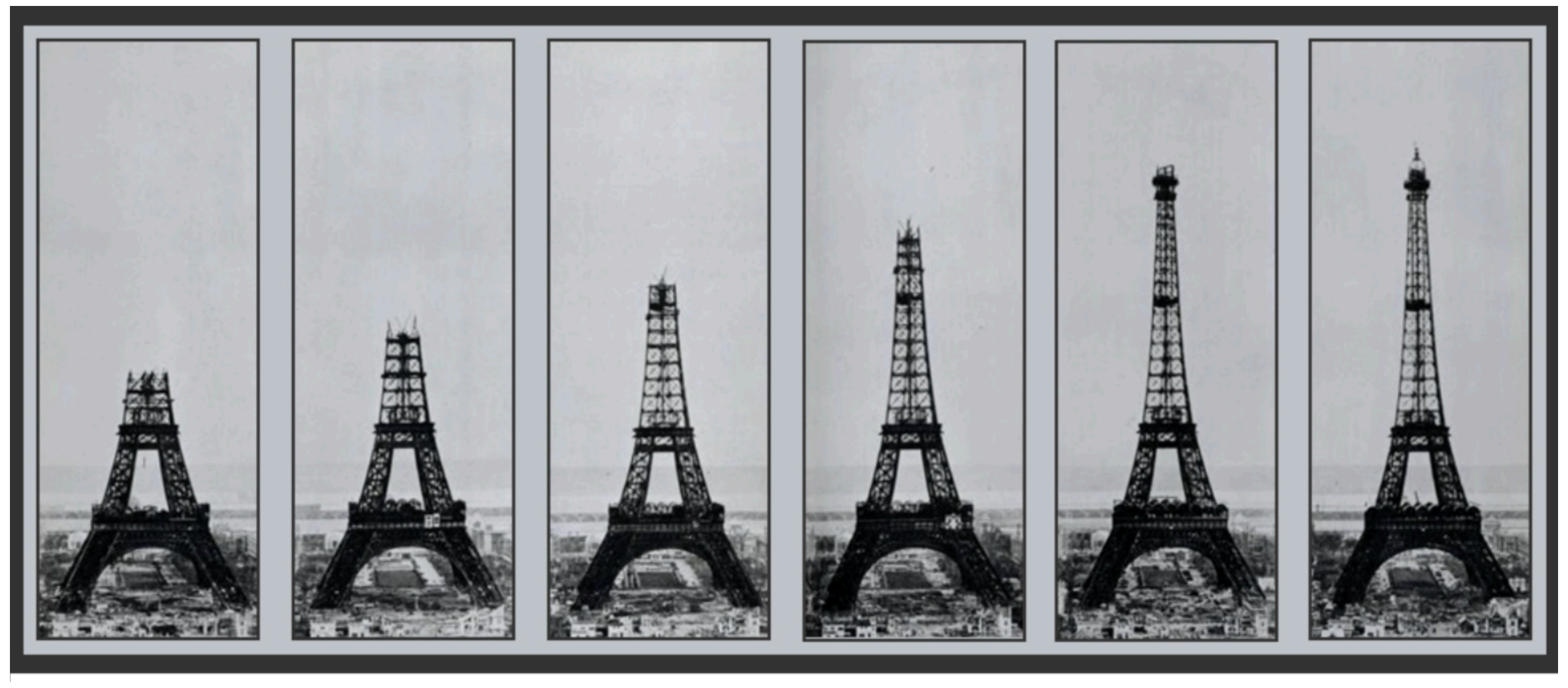
- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).

Where do we stand?

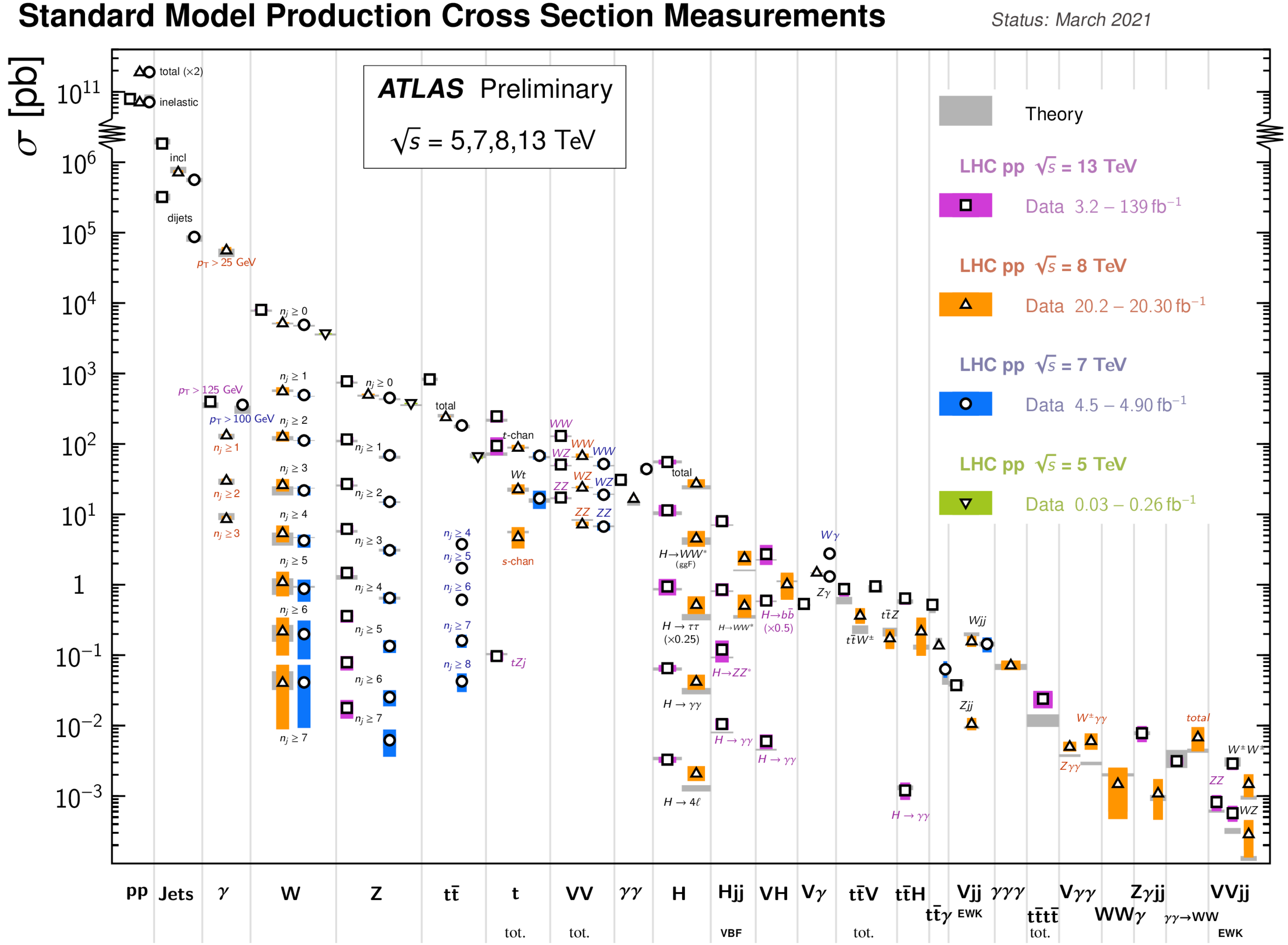
Standard Model Production Cross Section Measurements *Status: March 2021*



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).
- Comparison with SM predictions shows that we have the necessary theoretical and experimental control to move onto the next phase.



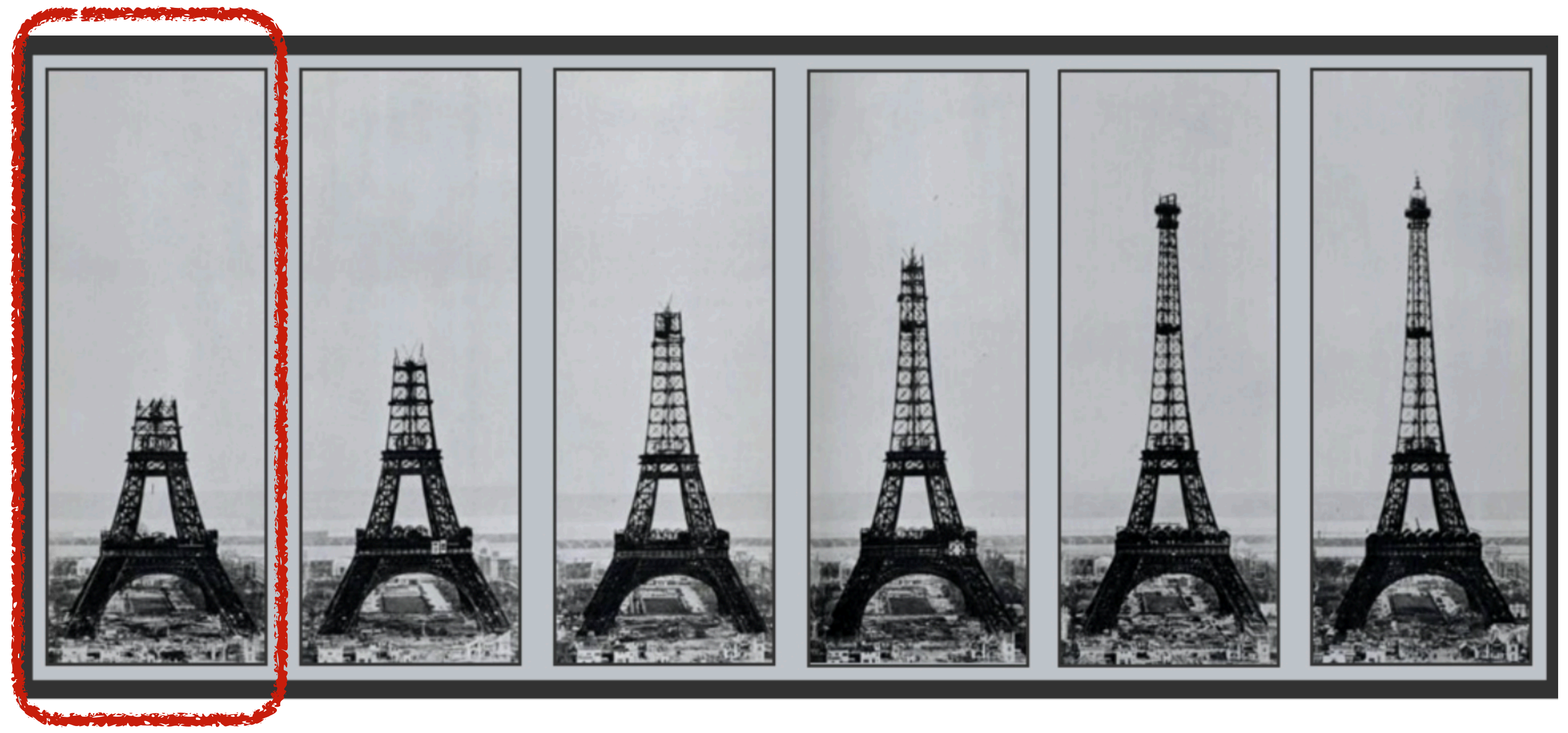
Where do we stand?



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.

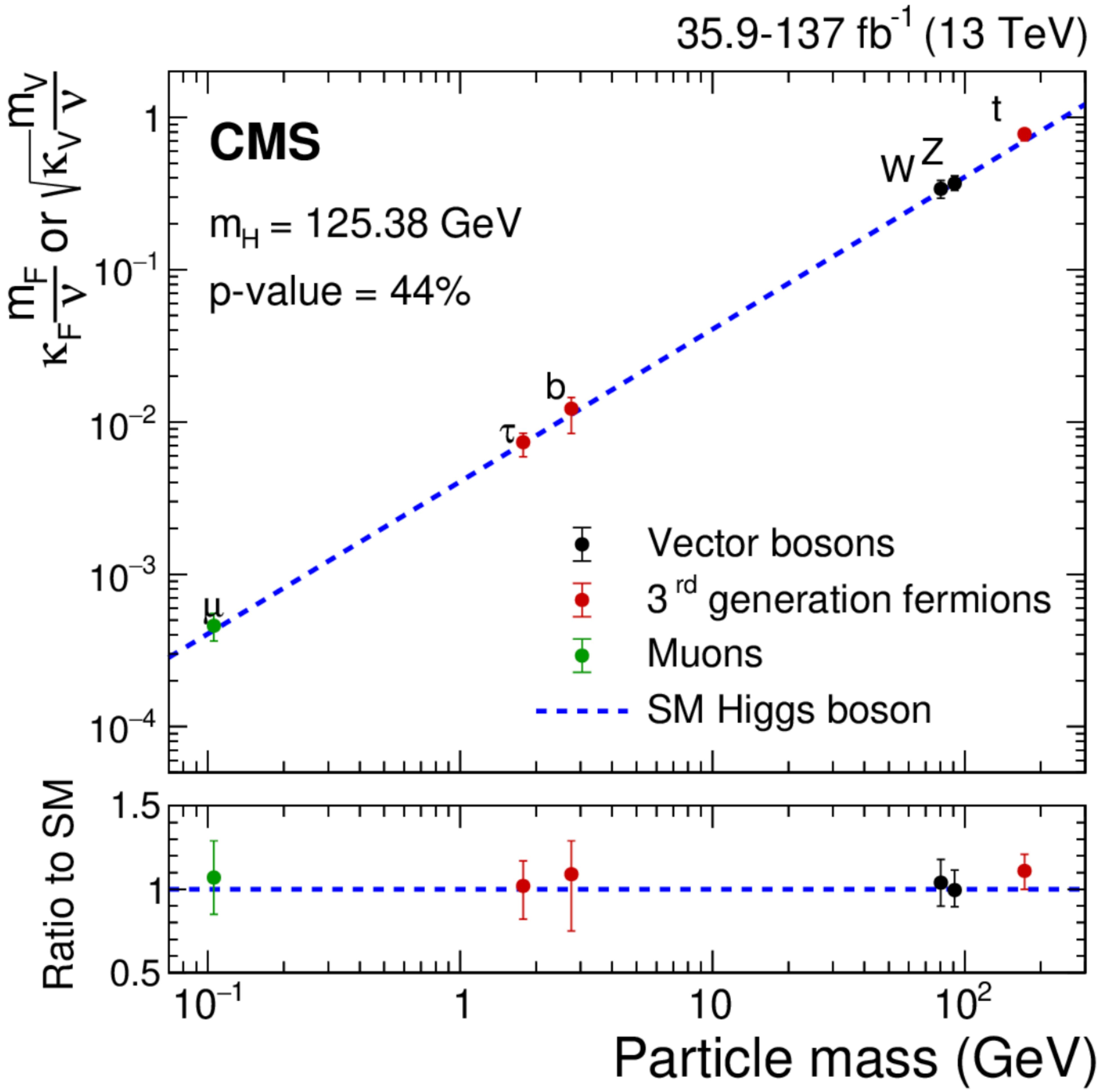
- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).

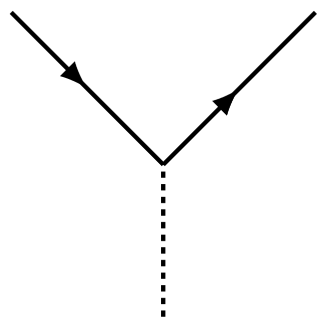
- Comparison with SM predictions shows that we have the necessary theoretical and experimental control to move onto the next phase.



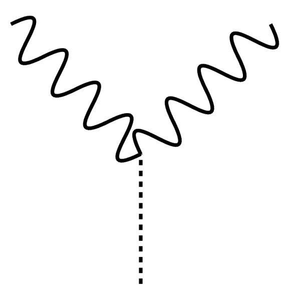
Where do we stand?

Higgs





$$i\, m_f/v$$



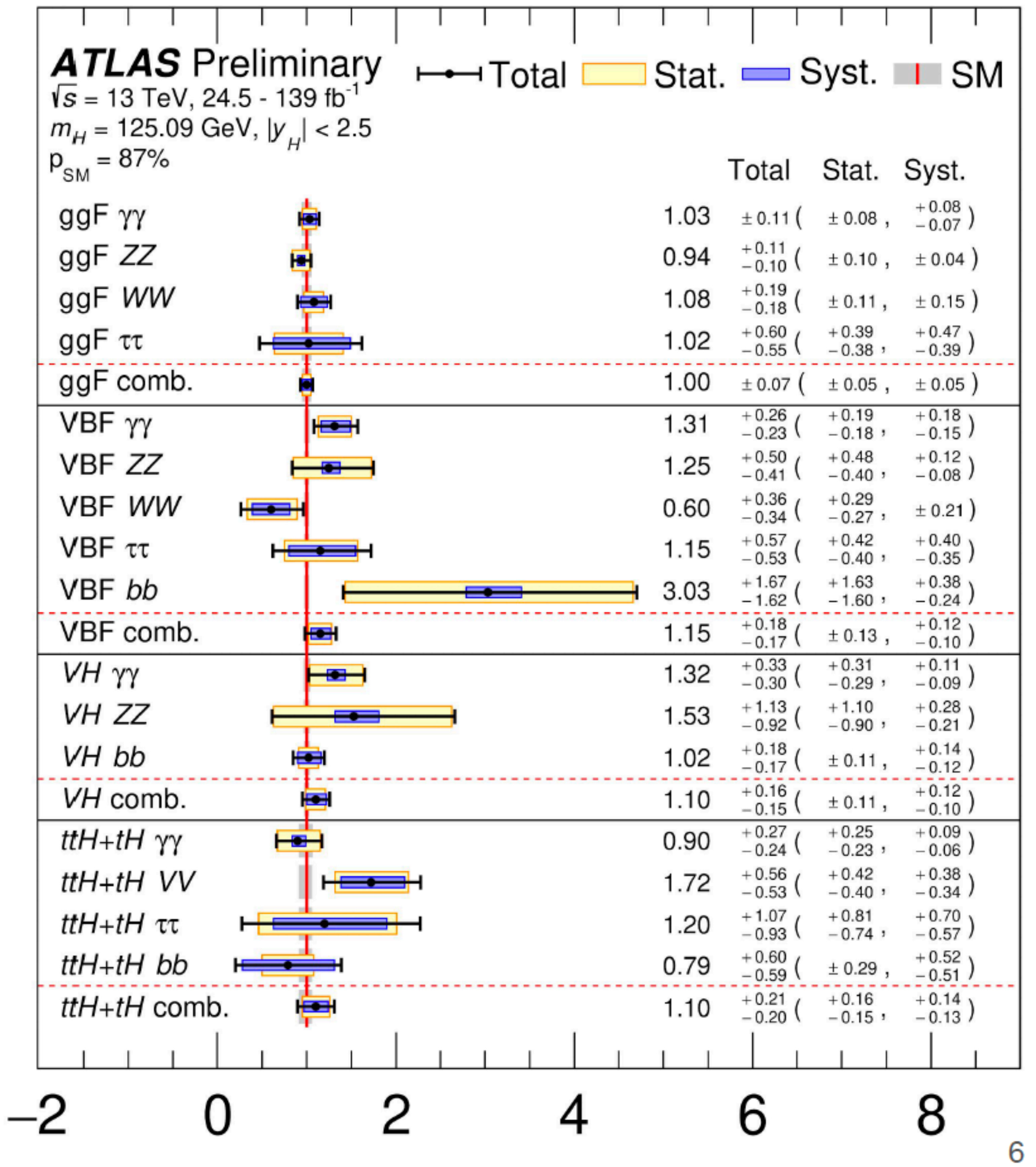
$$igm_W g_{\mu\nu} = 2iv g_{\mu\nu} \cdot m_W^2/v^2$$

$$ig\frac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2iv g_{\mu\nu} \cdot m_Z^2/v^2$$

Unique mass generation mechanism for fermions and vectors.

Constrained system.

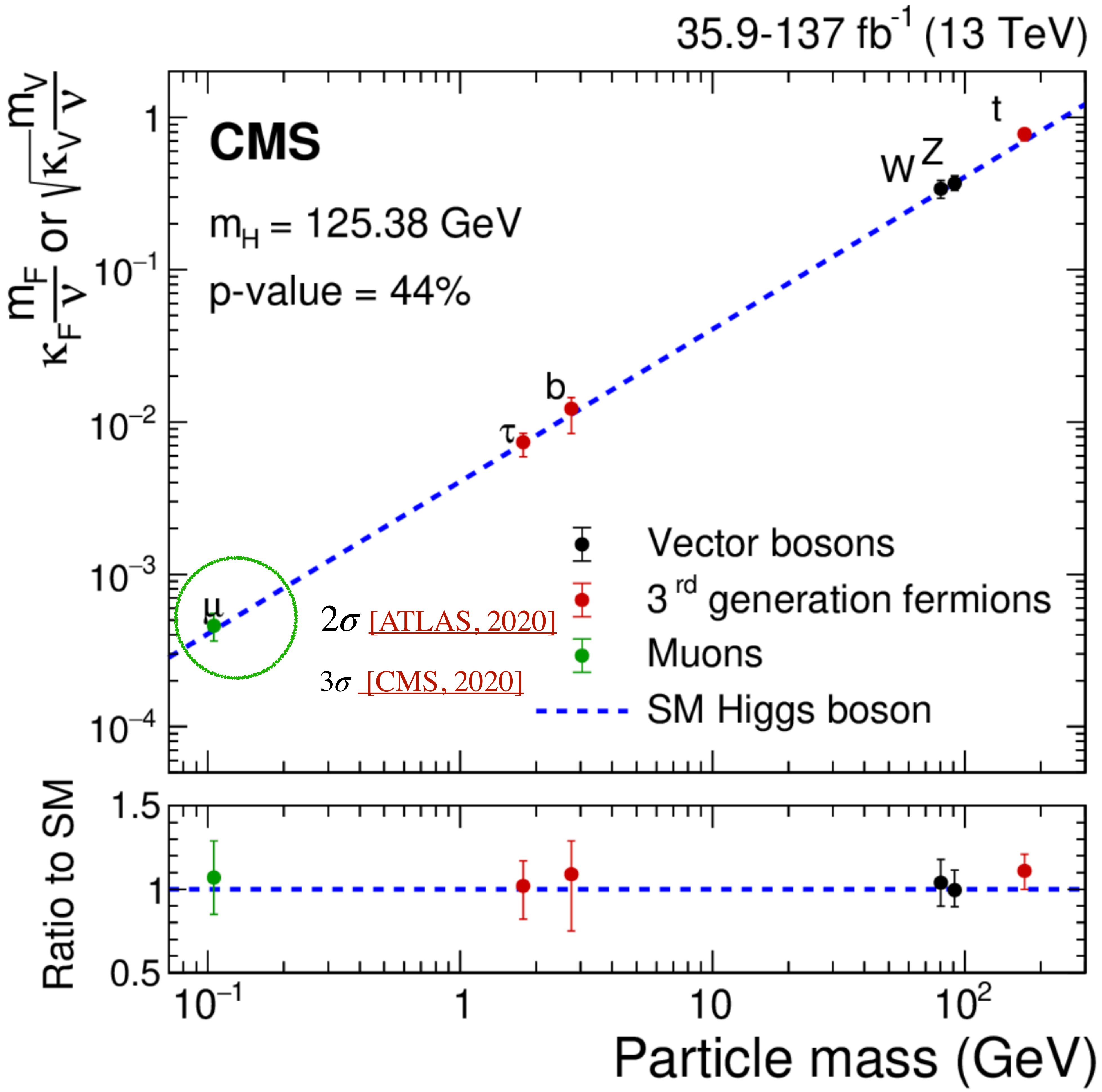
[ATLAS 2020]

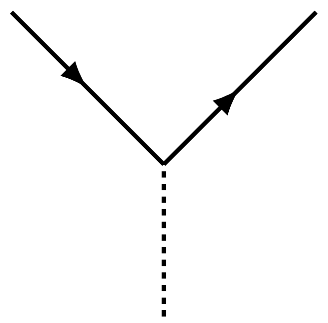


6

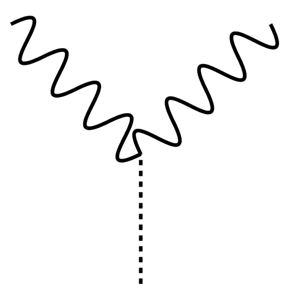
Where do we stand?

Higgs





$i\, m_f/v$



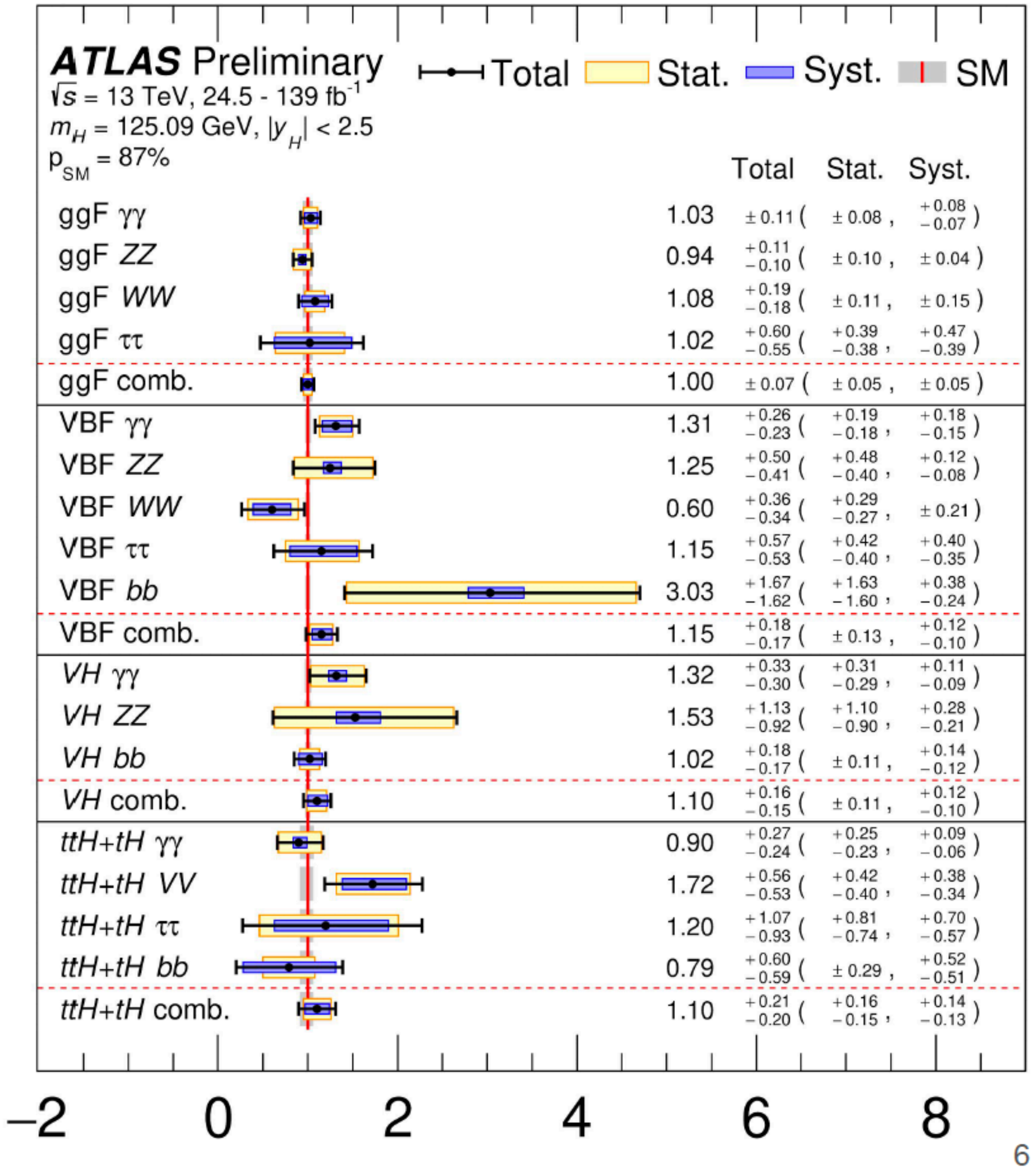
$igm_W g_{\mu\nu} = 2i\,v g_{\mu\nu} \cdot m_W^2/v^2$

$ig\dfrac{m_Z}{\cos\theta_W} g_{\mu\nu} = 2ivg_{\mu\nu} \cdot m_Z^2/v^2$

Unique mass generation mechanism for fermions and vectors.

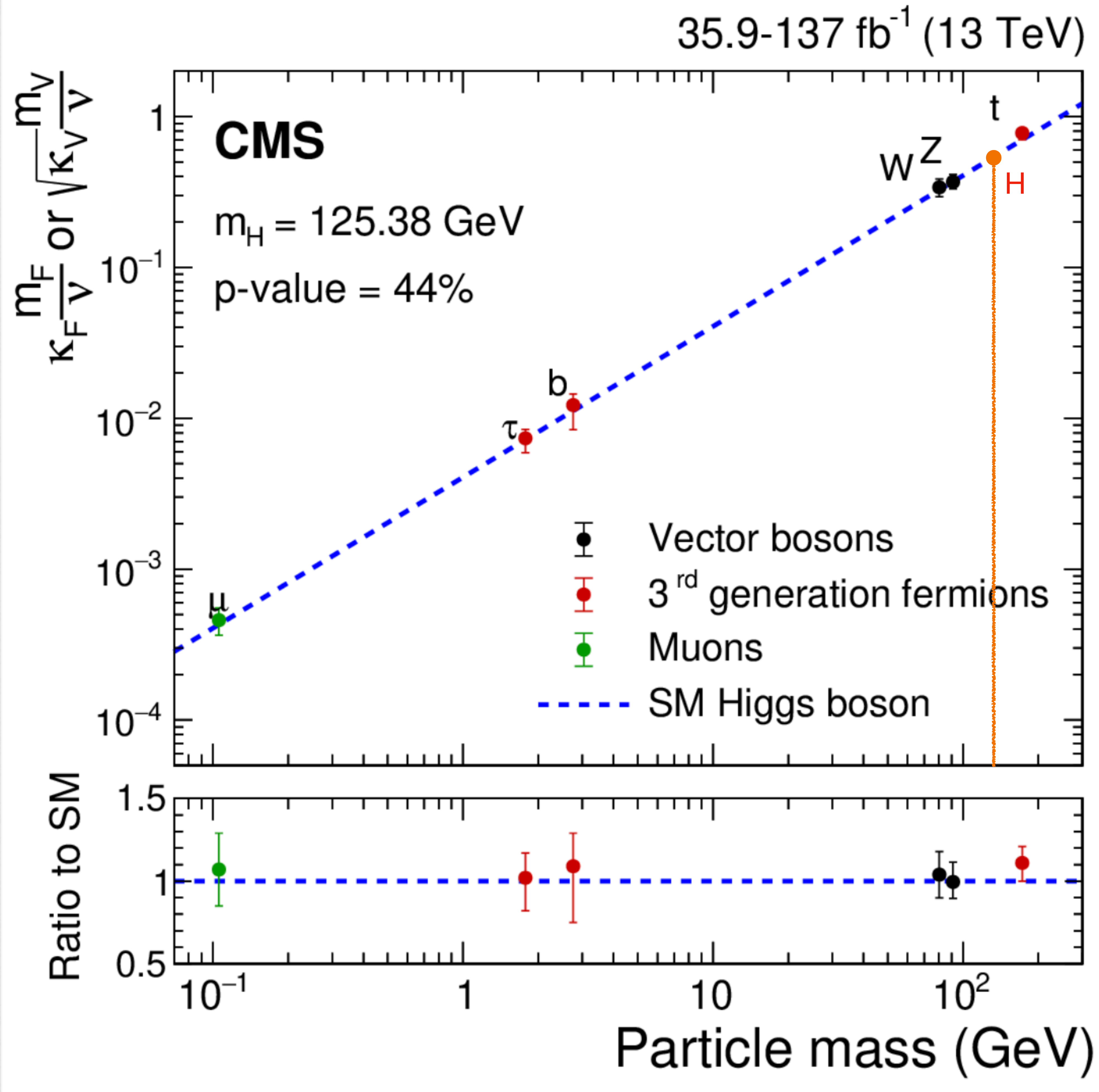
Constrained system.

[ATLAS 2020]



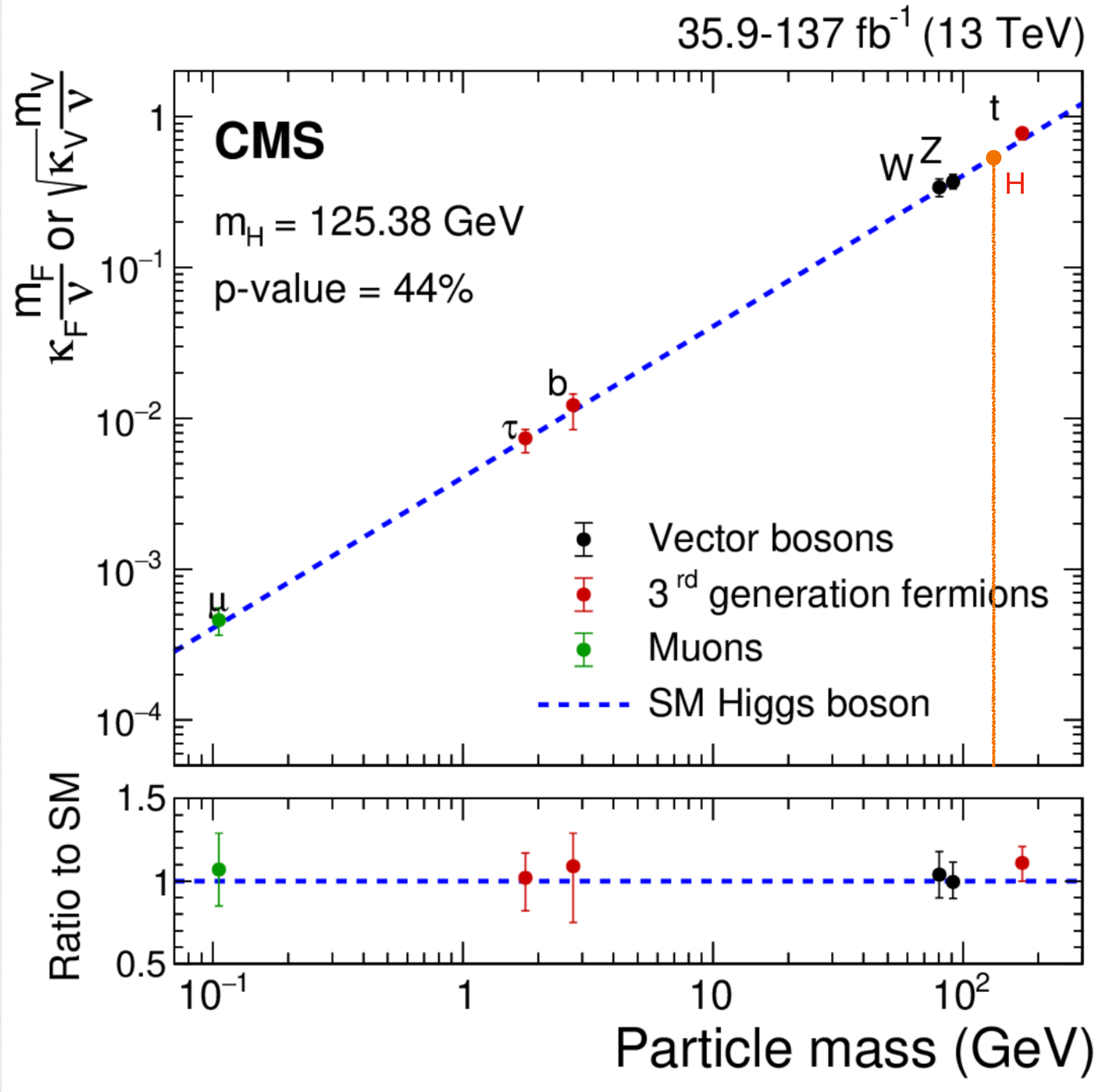
Where do we stand?

Higgs



Where do we stand?

Higgs

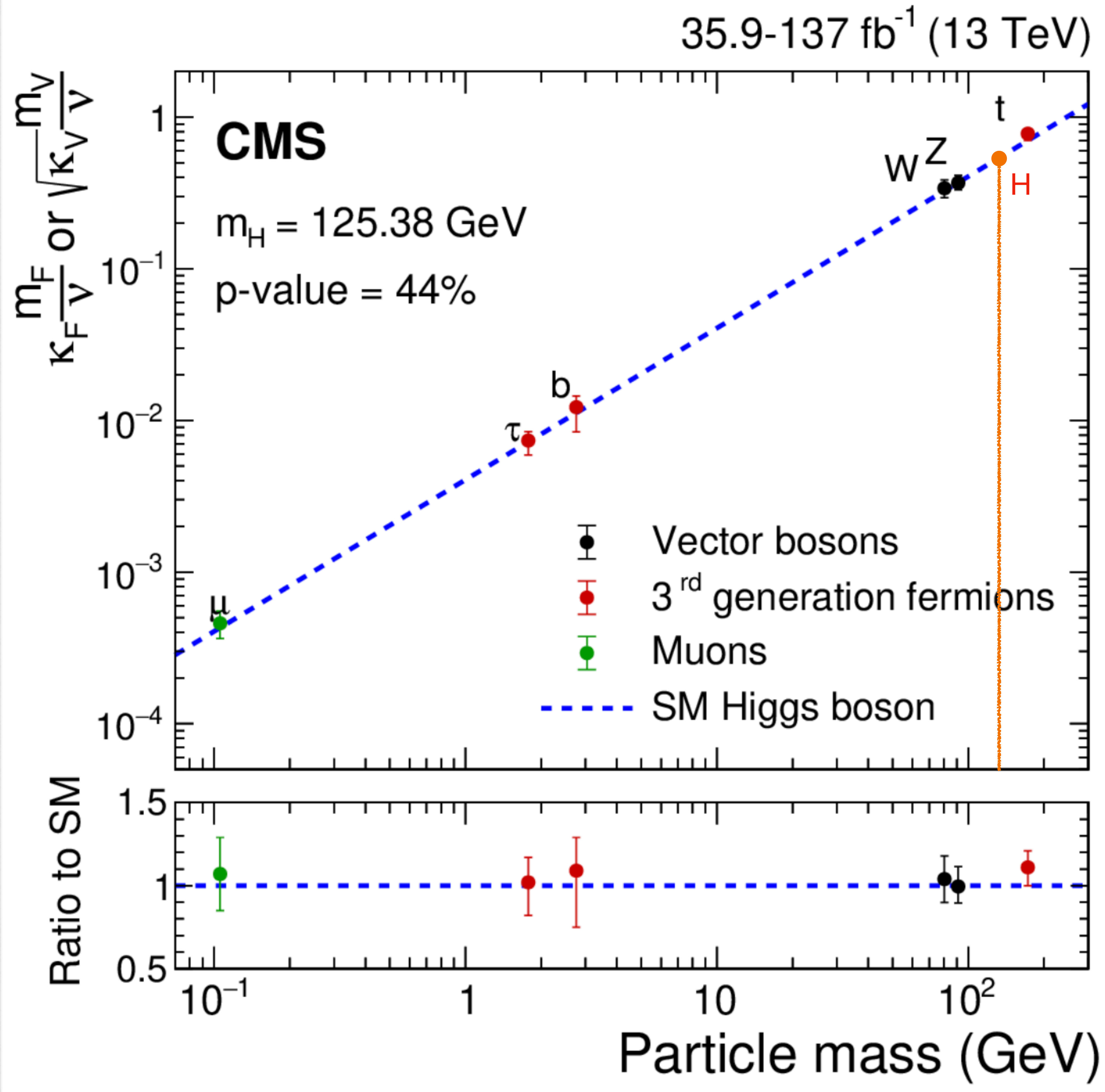


$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots$$

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \implies \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \qquad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

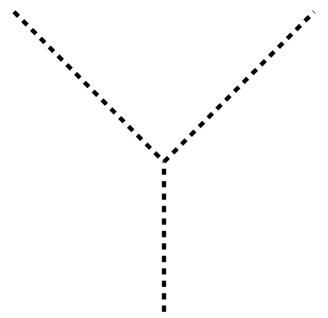
Where do we stand?

Higgs



$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \dots$$

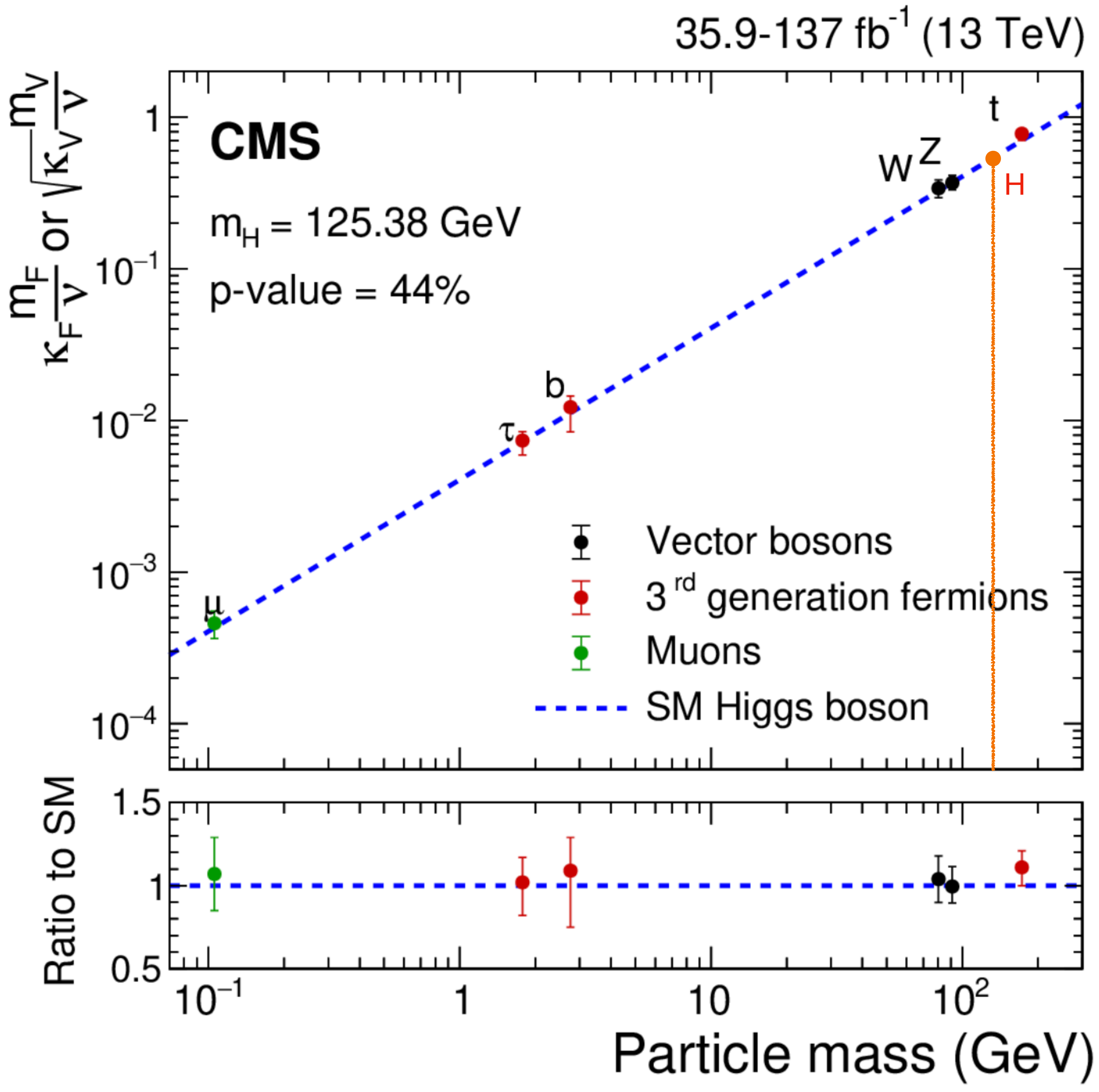
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \implies \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \qquad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$



$$-3\, iv \cdot m_h^2/v^2$$

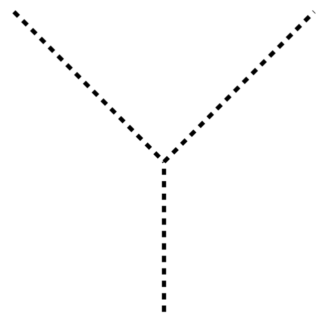
Where do we stand?

Higgs

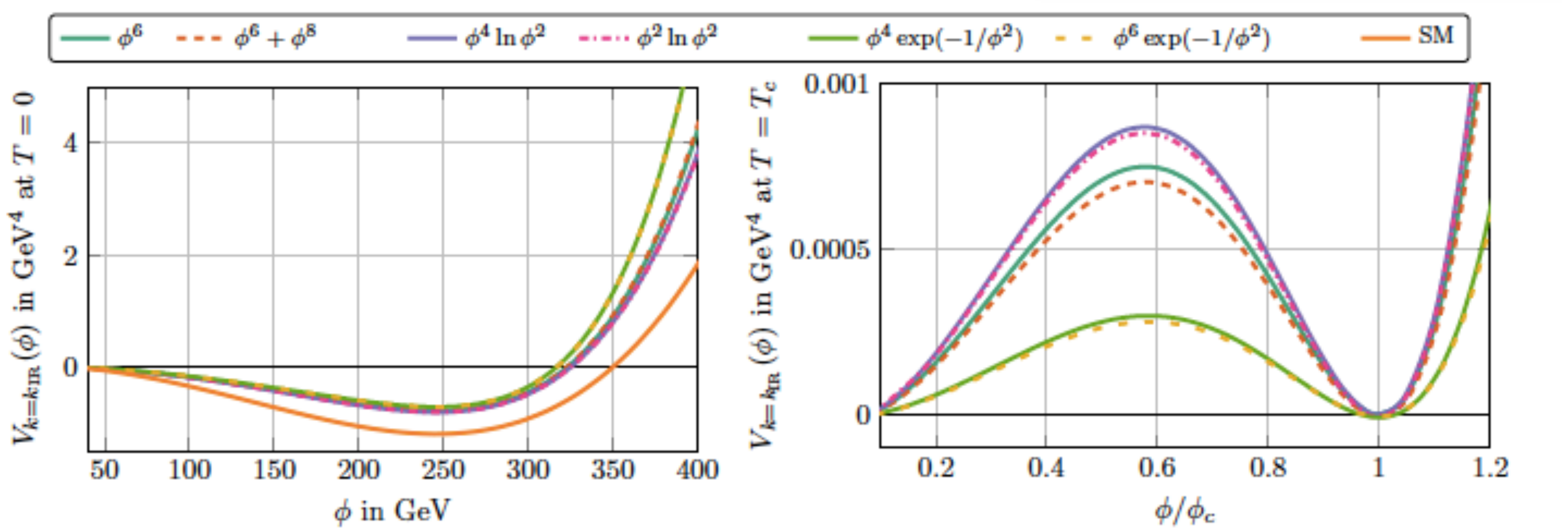


$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \dots$$

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \;\Rightarrow\; \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \qquad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$



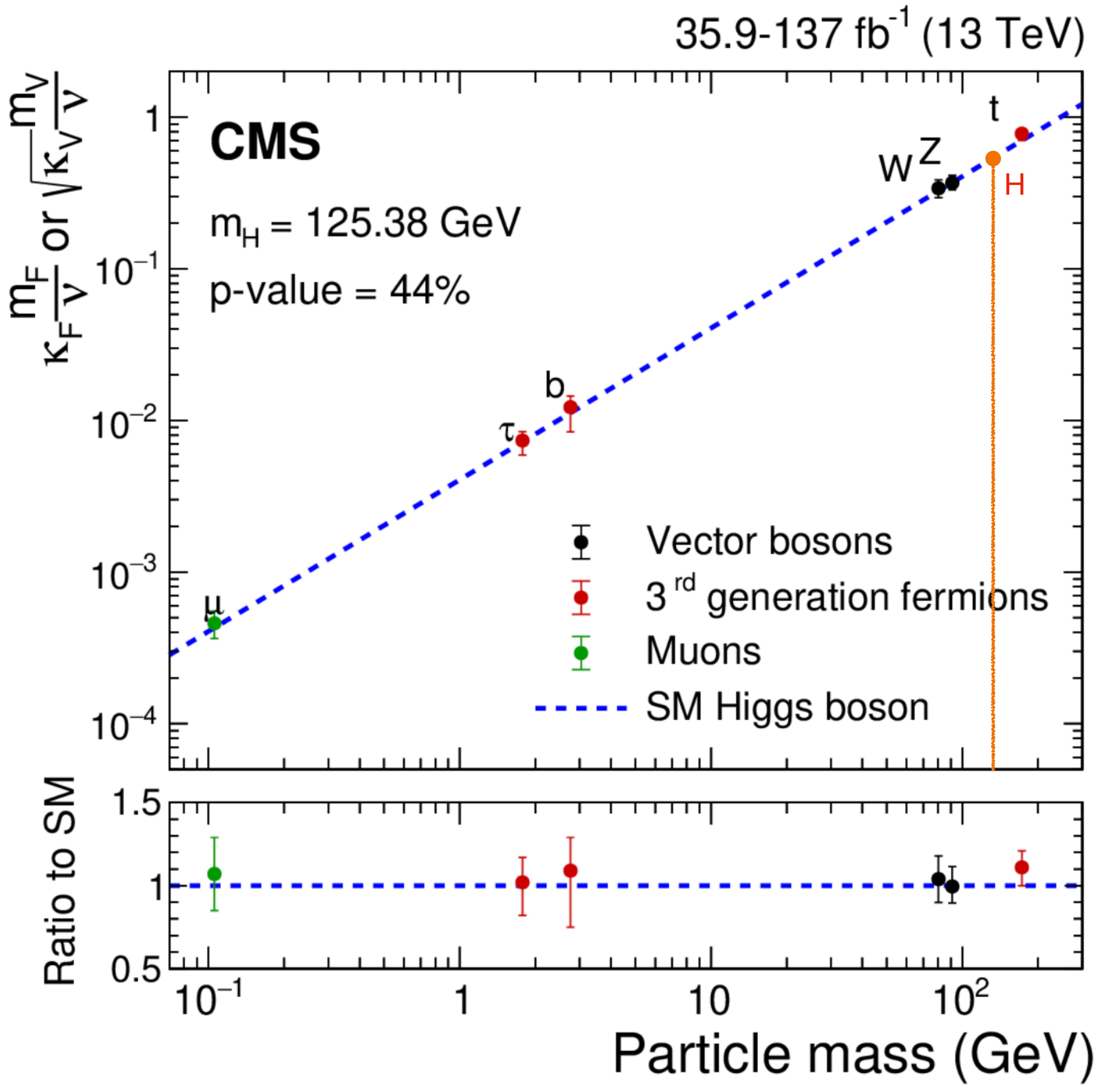
$$-3\, i v \cdot m_h^2/v^2$$



Reichert et al. 1711.00019

Where do we stand?

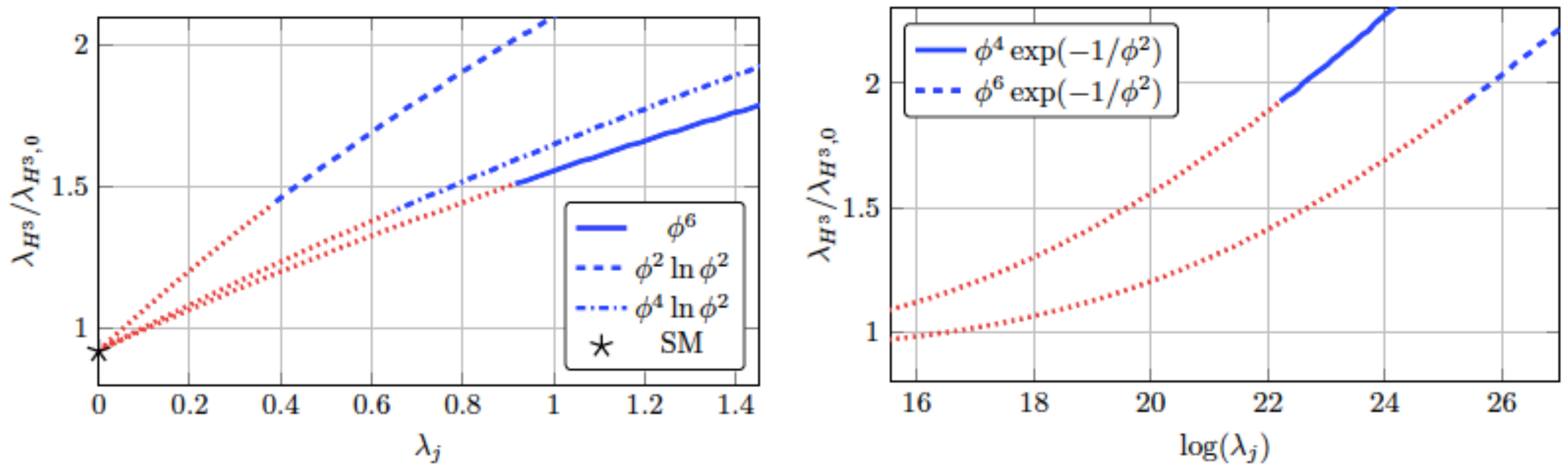
Higgs



$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots$$

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \qquad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

$$-3\,iv \cdot m_h^2/v^2$$



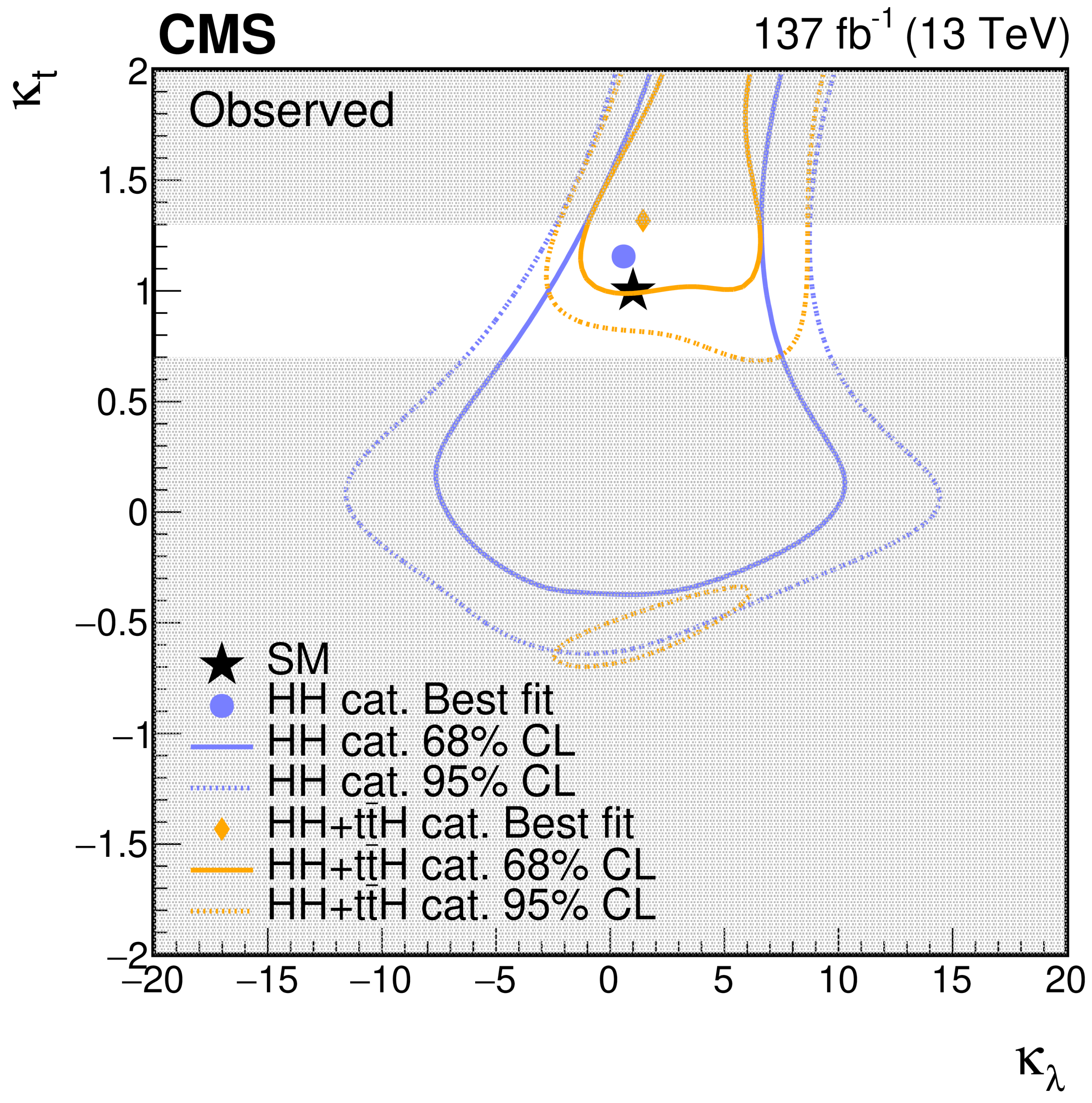
Reichert et al. 1711.00019

$k_\lambda > 1.5 \Rightarrow$ 1st ord ($T = 0$ and $T = T_c$ connected)

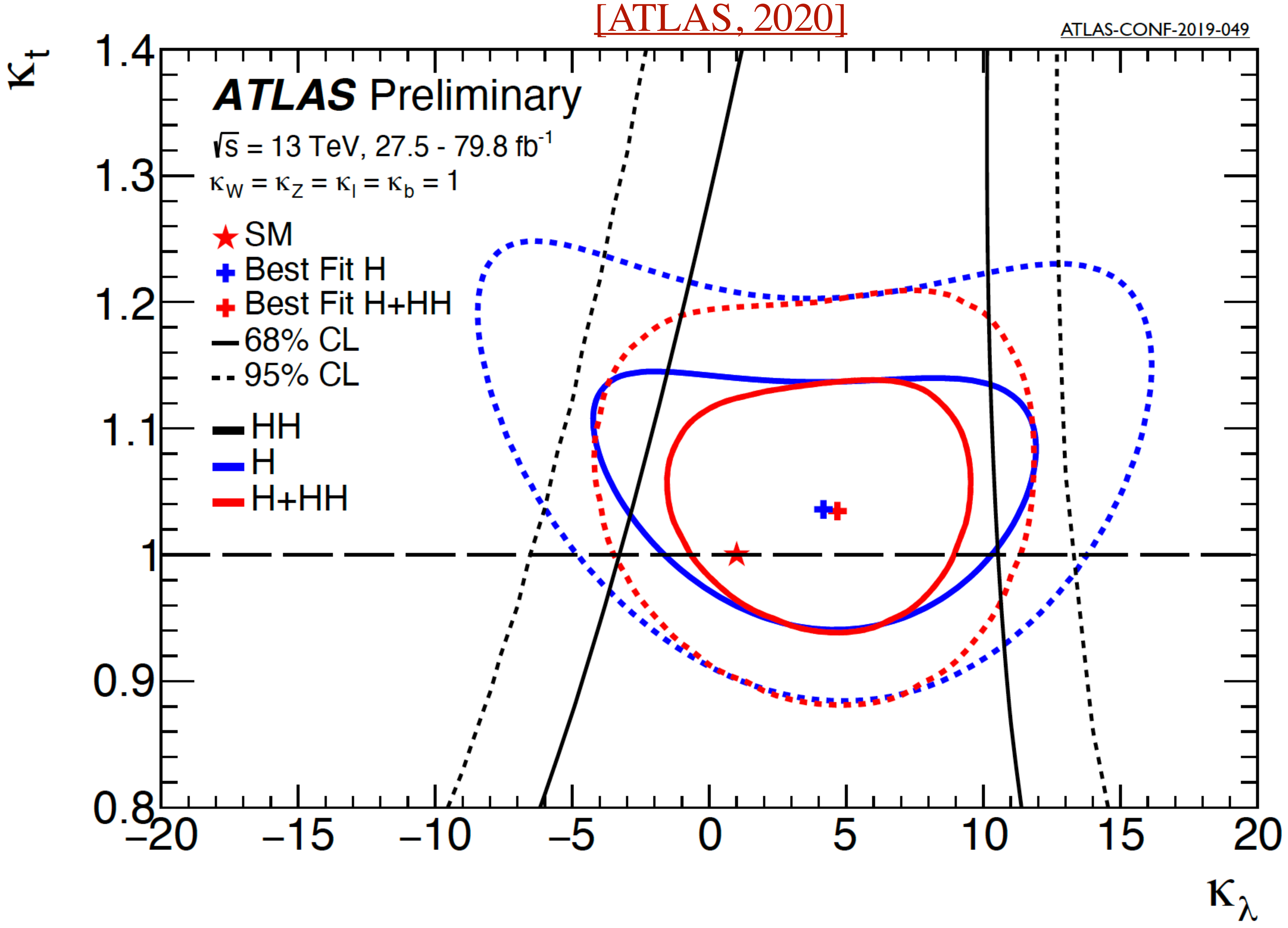
$\delta k_\lambda \sim 5\,\% \Rightarrow$ 1st ord ($T = 0$ and $T = T_c$ not connected)

Where do we stand?

Higgs self coupling



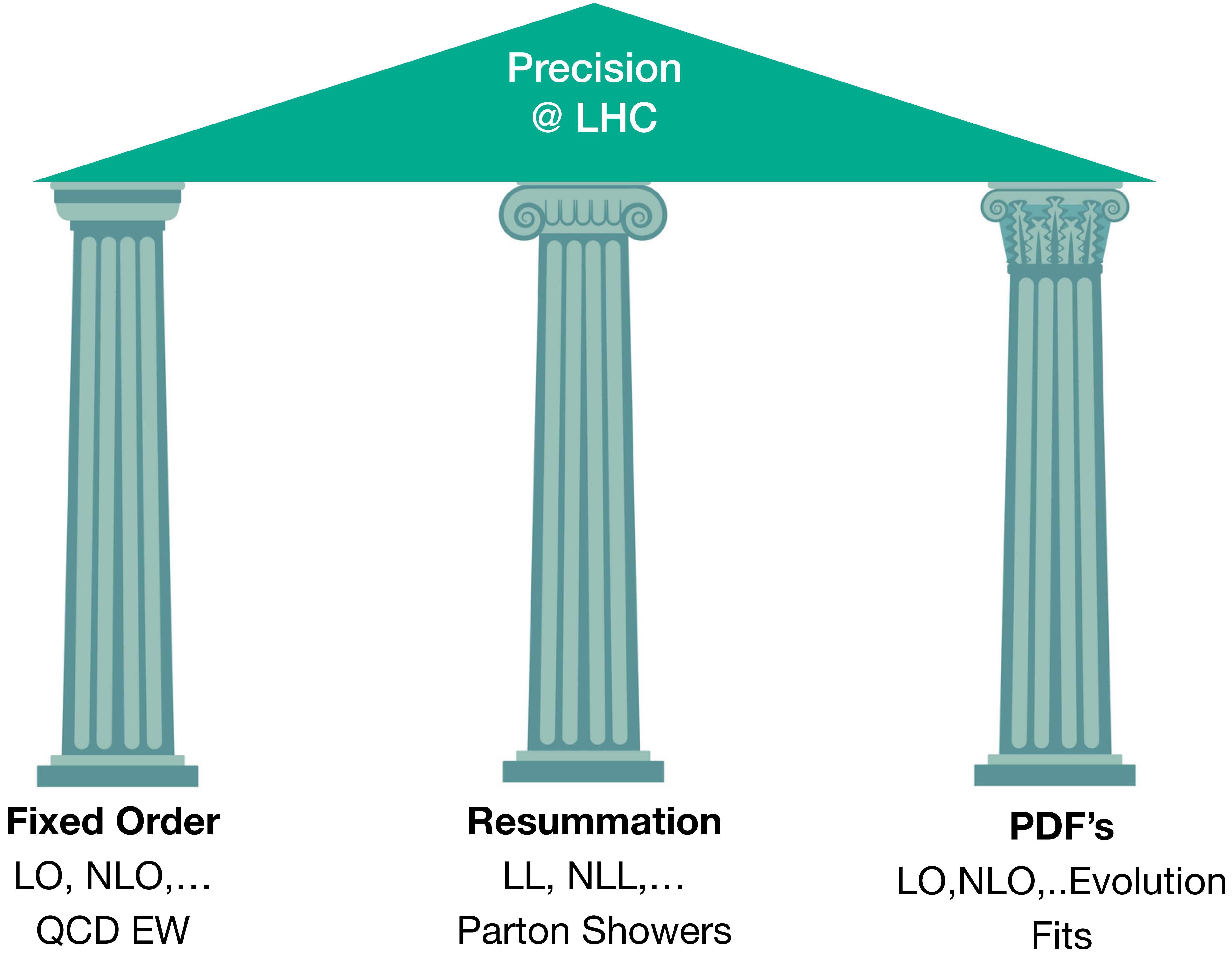
[ATLAS, 2020]



One of the flagship measurements foreseen for the HL-LHC. [Di Micco et al., 1910.00012]

Precision calculations for the LHC

Status

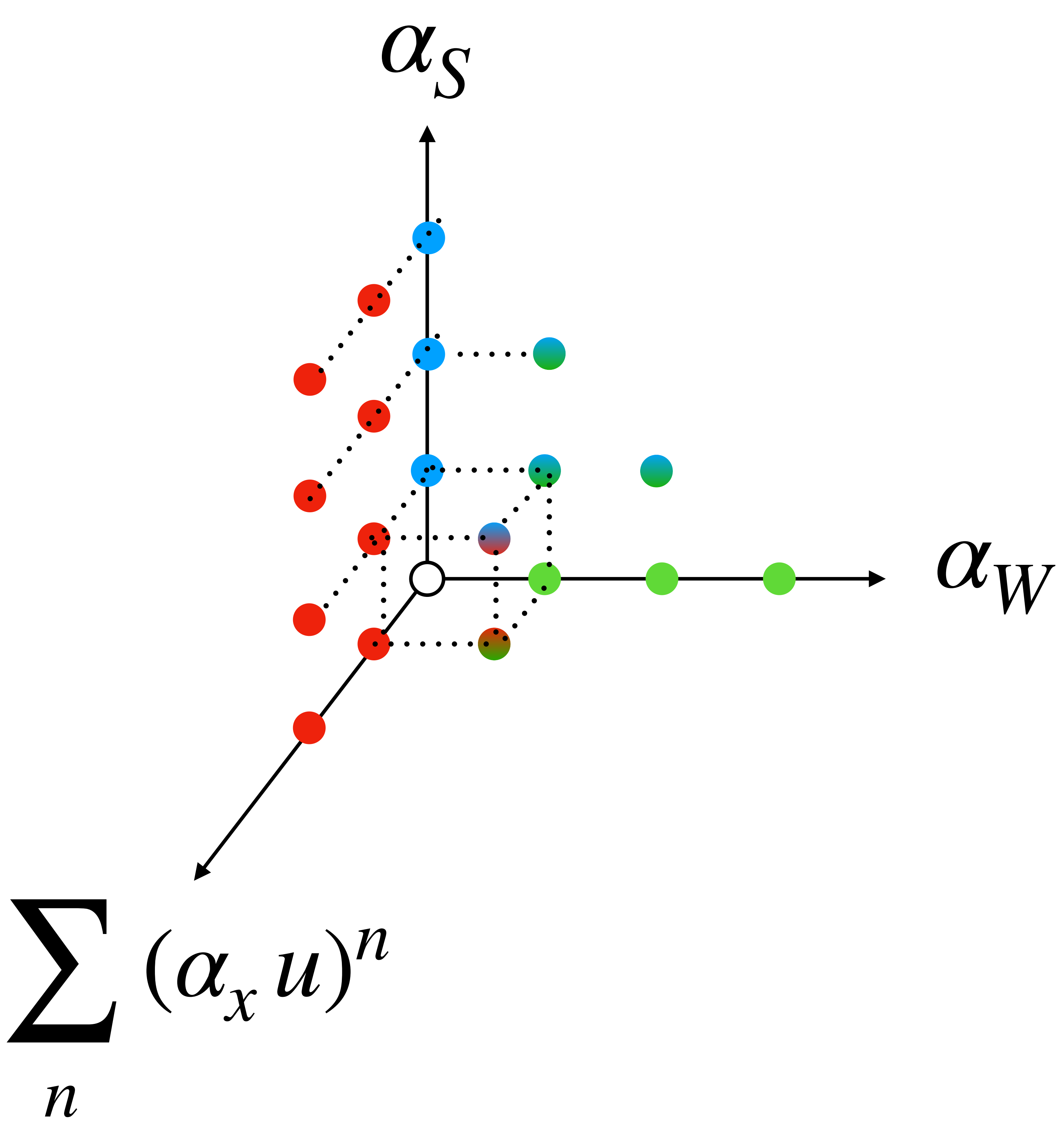


Precision calculations for the LHC

The path

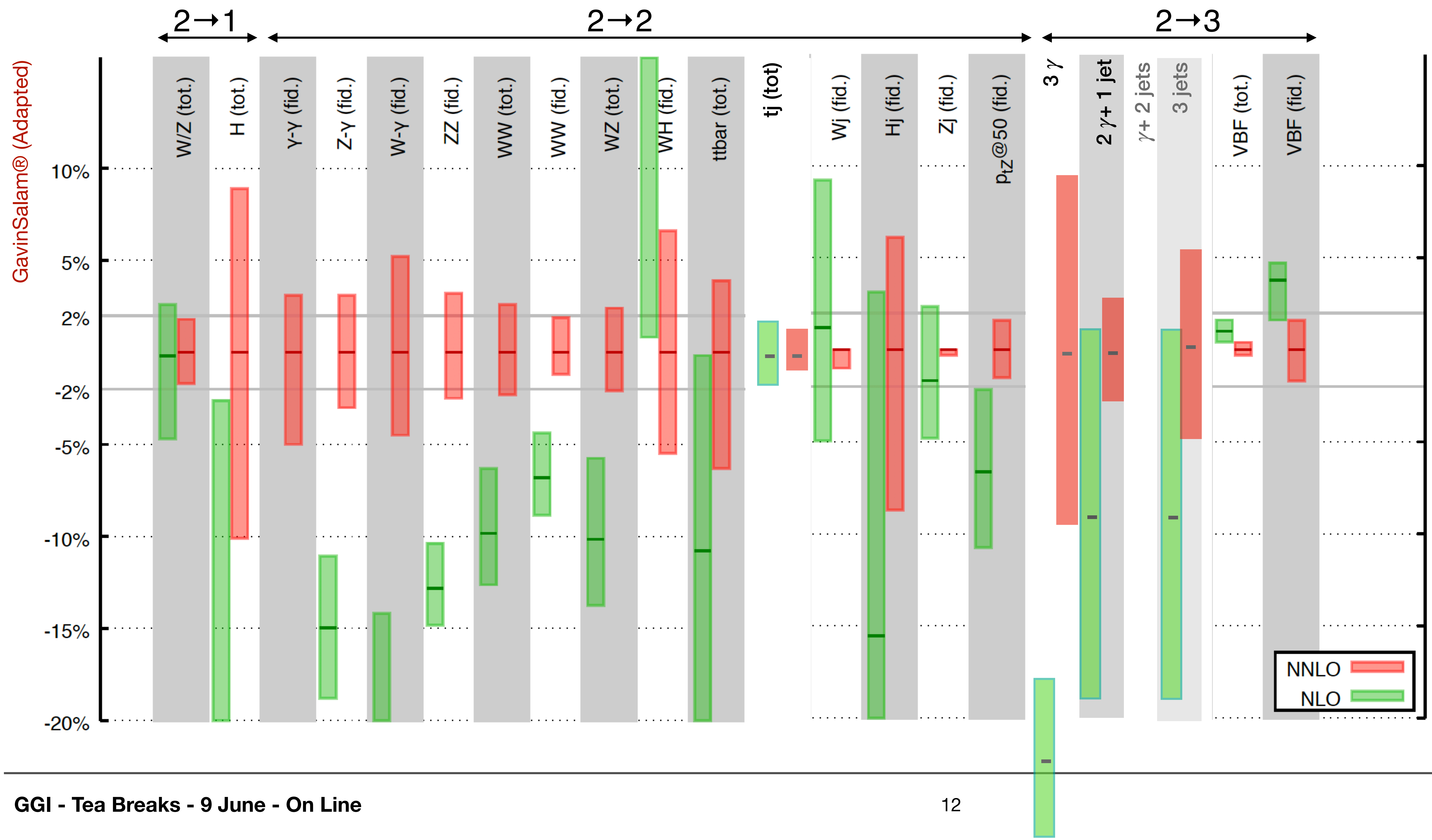
"Rules of thumb at the LHC":

- Predictions must be calculated at least to **NLO QCD** to control the central value at 10-20%.
- **N2LO QCD** provides control at 5% level and on the uncertainties stabilizing the perturbative expansion.
- **N2LO QCD** is expected to be of the **same order** as **NLO EW** $\alpha_S^2 \sim \alpha_W$, **yet EW** corrections grow large and negative at high energies (Sudakov logs).
- **N3LO QCD** is the frontier of precision aiming ~1% of MHO uncertainties.
- **Resummation** Universal, all-order terms that are potentially large for some observables (logs or 1PI loops for propagators) need to be resummed. They might refer to global or non-global observables. Resummation leads to mprovements in precision and accuracy.



Precision calculations for the LHC

Status: Fixed Order



- NNLO brings us in the few percent arena
- Several NNLO computations move the central value out of the NLO uncertainties
- The 2→3 wall broken

Precision calculations for the LHC

N3LO revolution

Soft triple-real radiation for Higgs production at N3LO

Charalampos Anastasiou (Zurich, ETH), Claude Duhr (Durham U., IPPP and Zurich, ETH), Falko Dulat (Zurich, ETH), Bernhard Mistlberger (Zurich, ETH) (Feb 18, 2013)

Published in: *JHEP* 07 (2013) 003 • e-Print: 1302.4379 [hep-ph]

High precision determination of the gluon fusion Higgs boson cross-section at the LHC

Charalampos Anastasiou (Zurich, ETH), Claude Duhr (CERN and Louvain U., CP3), Falko Dulat (Zurich, ETH), Elisabetta Furlan (Zurich, ETH), Thomas Gehrmann (Zurich U.) et al. (Feb 1, 2016)

Published in: *JHEP* 05 (2016) 058 • e-Print: 1602.00695 [hep-ph]

Differential Higgs production at N^{3}LO beyond threshold

Falko Dulat (SLAC), Bernhard Mistlberger (CERN), Andrea Pelloni (Zurich, ETH) (Oct 9, 2017)

Published in: *JHEP* 01 (2018) 145 • e-Print: 1710.03016 [hep-ph]

Higgs Boson Gluon-Fusion Production in QCD at Three Loops #29

Charalampos Anastasiou (Zurich, ETH), Claude Duhr (CERN and Louvain U., CP3), Falko Dulat (Zurich, ETH), Franz Herzog (NIKHEF, Amsterdam), Bernhard Mistlberger (Zurich, ETH) (Mar 20, 2015)

Published in: *Phys.Rev.Lett.* 114 (2015) 212001 • e-Print: 1503.06056 [hep-ph]

8 years

Higgs boson production at hadron colliders at N^{3}LO in QCD

Bernhard Mistlberger (CERN) (Feb 2, 2018)

Published in: *JHEP* 05 (2018) 028 • e-Print: 1802.00833 [hep-ph]

Differential Higgs production at N^{3}LO beyond threshold #21

Falko Dulat (SLAC), Bernhard Mistlberger (CERN), Andrea Pelloni (Zurich, ETH) (Oct 9, 2017)

Published in: *JHEP* 01 (2018) 145 • e-Print: 1710.03016 [hep-ph]

Fully Differential Higgs Boson Production to Third Order in QCD #1

X. Chen (Zurich U. and KIT, Karlsruhe, TP and KIT, Karlsruhe), X. Chen (Zurich U. and KIT, Karlsruhe, TP and KIT, Karlsruhe), T. Gehrmann (Zurich U.), E.W.N. Glover (Durham U., IPPP), A. Huss (CERN) et al. (Feb 15, 2021)

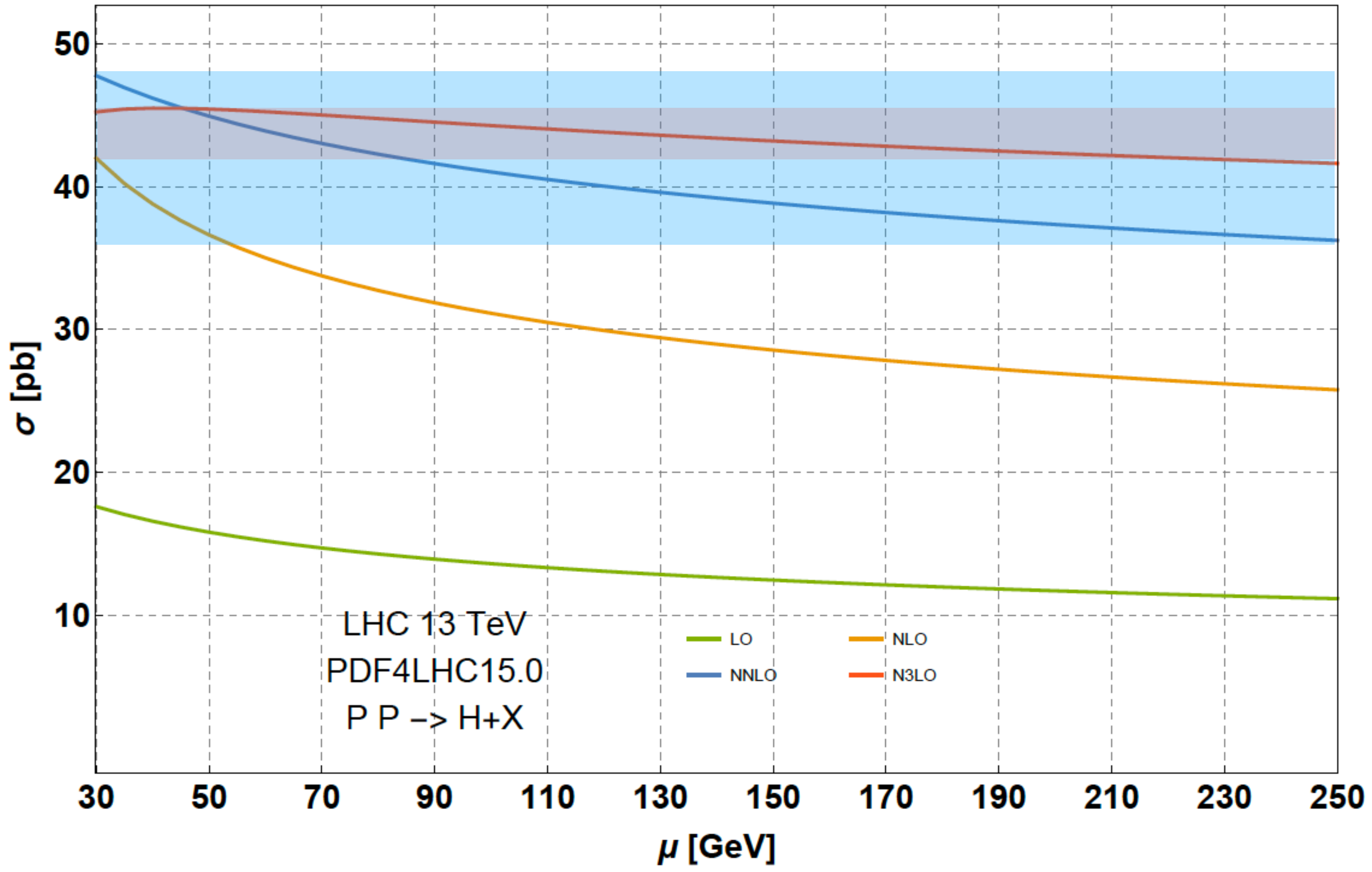
e-Print: 2102.07607 [hep-ph]

Major tour de force

Milestone of the precision program of the theoretical community

Precision calculations for the LHC

N3LO revolution



- Very significant reduction of MHO uncertainties.
- Differential distributions are available.
- Uncertainty budget points to PDF as the main source of error.

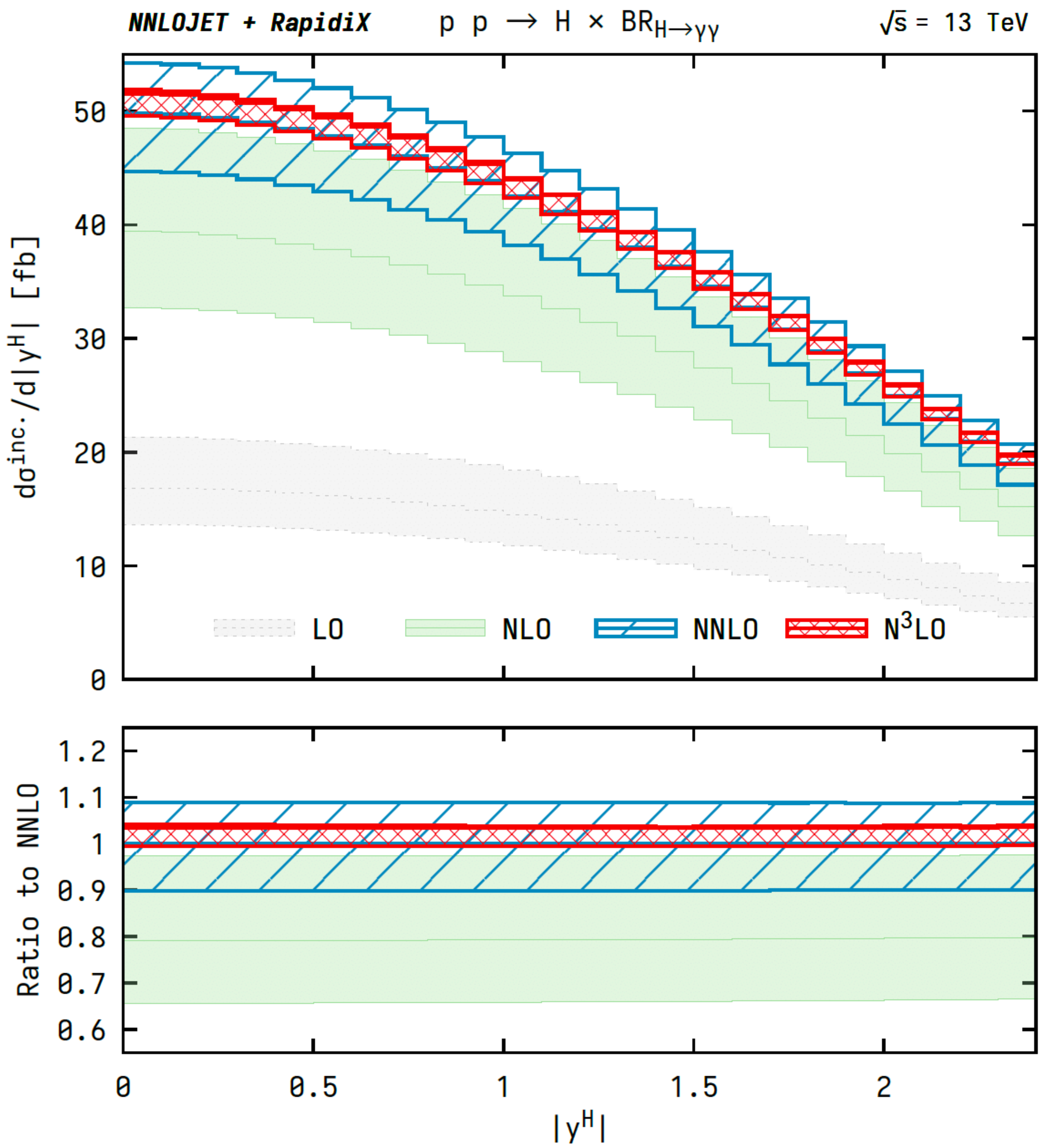
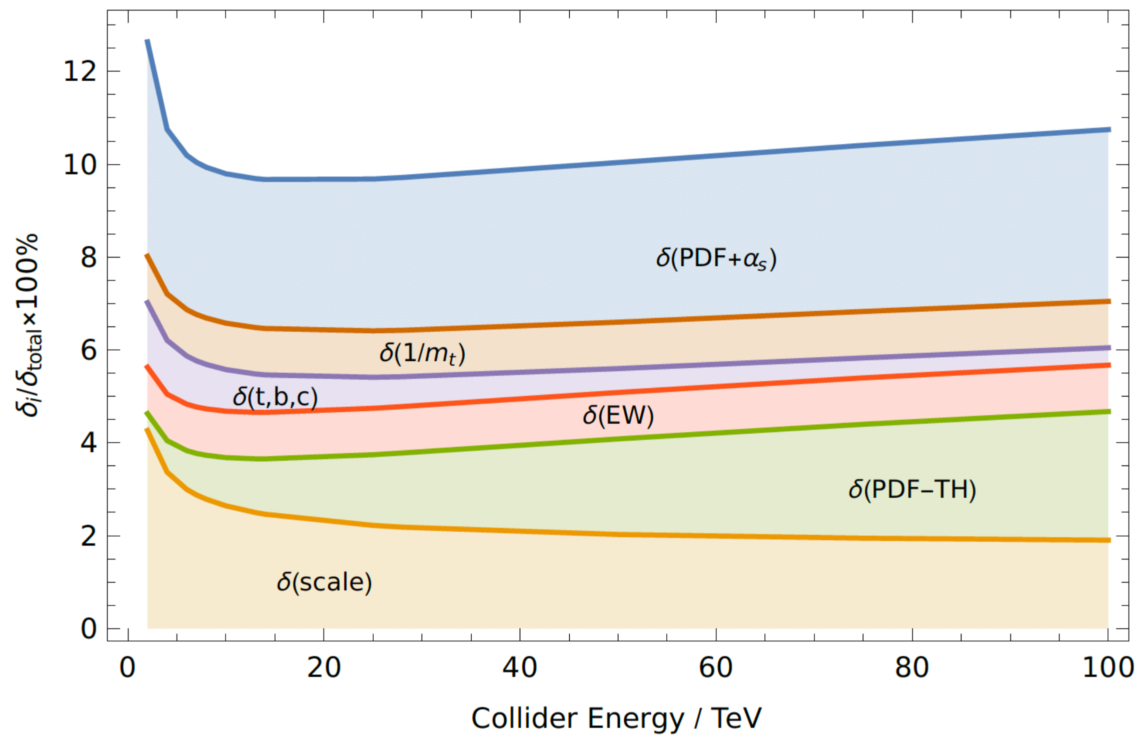


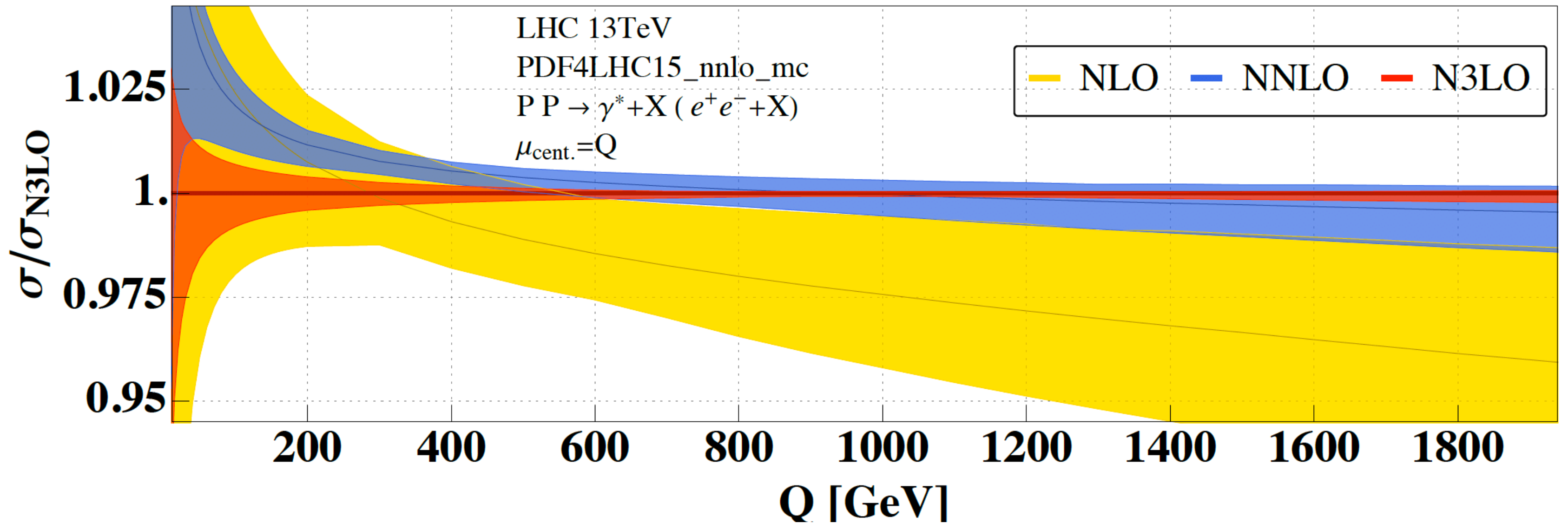
Table 2: Gluon fusion Higgs boson production cross sections and uncertainties as a function of the pp collider energy.

$\sqrt{s}$	σ	δ(theory)		δ(PDF)	$\delta(\alpha_s)$	
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$	$\binom{+4.27\%}{-6.49\%}$	± 0.89 pb $(\pm 1.85\%)$	$^{+1.24\text{pb}}_{-1.26\text{pb}}$	$\binom{+2.59\%}{-2.62\%}$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}$	$\binom{+4.28\%}{-6.46\%}$	± 1.00 pb $(\pm 1.85\%)$	$^{+1.40\text{pb}}_{-1.41\text{pb}}$	$\binom{+2.60\%}{-2.62\%}$
27 TeV	146.65 pb	$^{+6.65\text{pb}}_{-9.44\text{pb}}$	$\binom{+4.53\%}{-6.43\%}$	± 2.81 pb $(\pm 1.95\%)$	$^{+3.88\text{pb}}_{-3.82\text{pb}}$	$\binom{+2.69\%}{-2.64\%}$



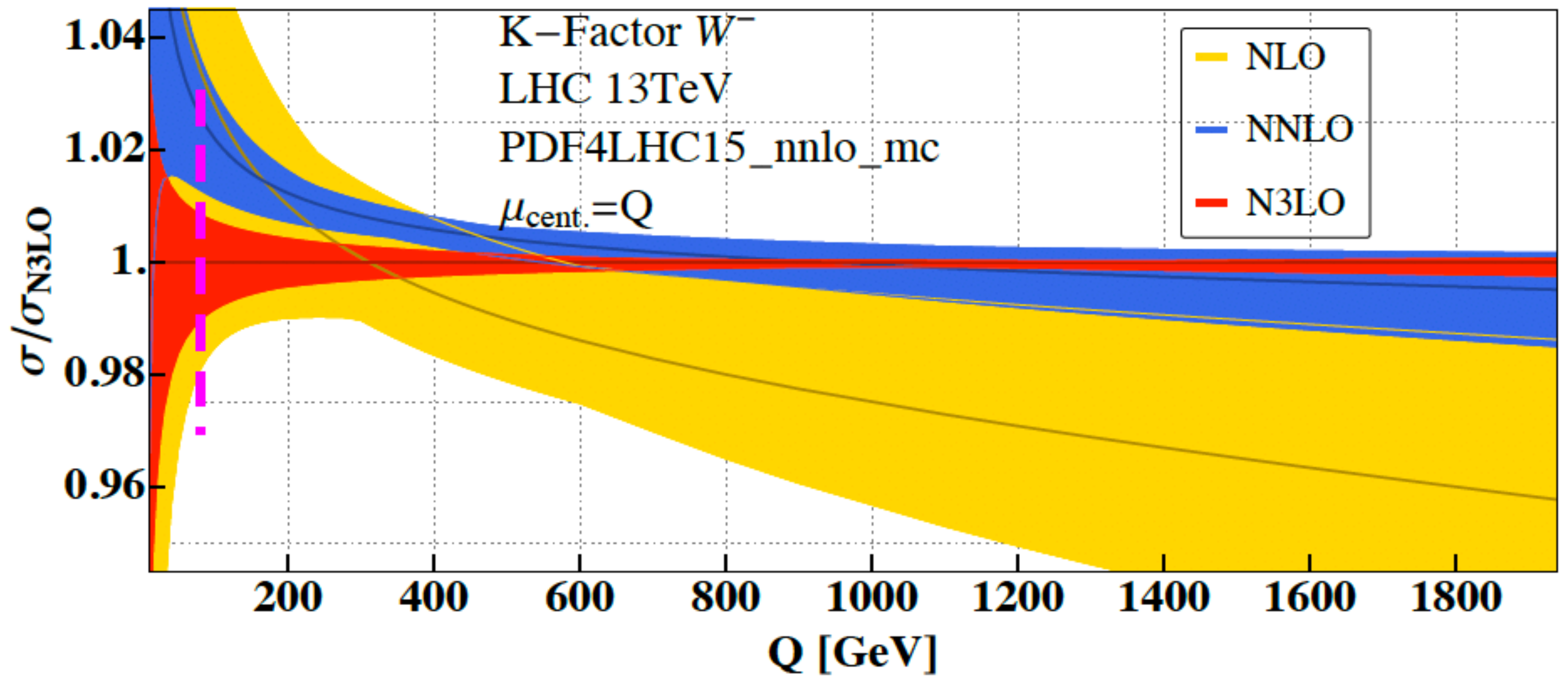
Precision calculations for the LHC

N3LO revolution

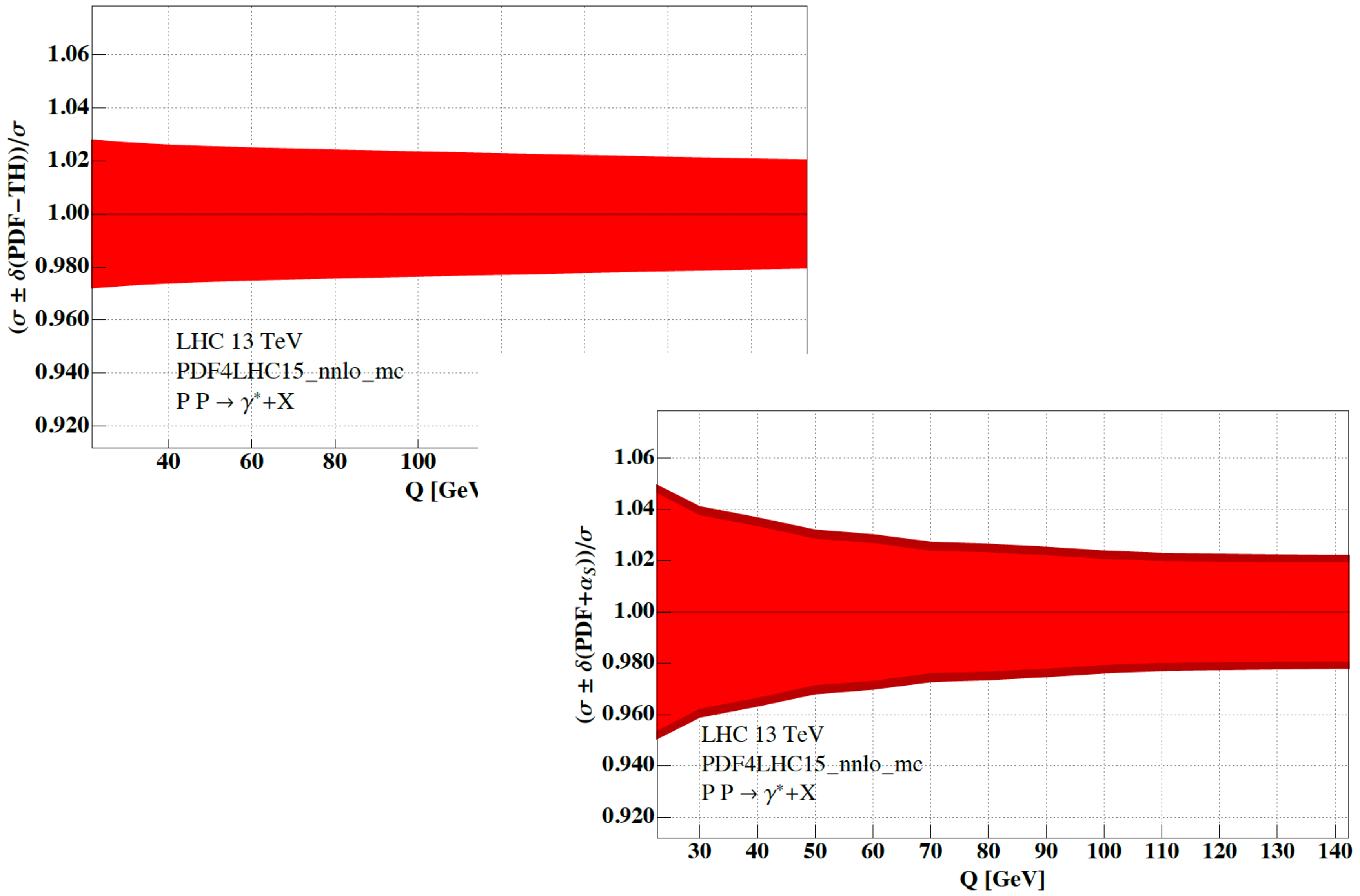


[Duhr, Dulat and Mistelberger, 2001.07717]

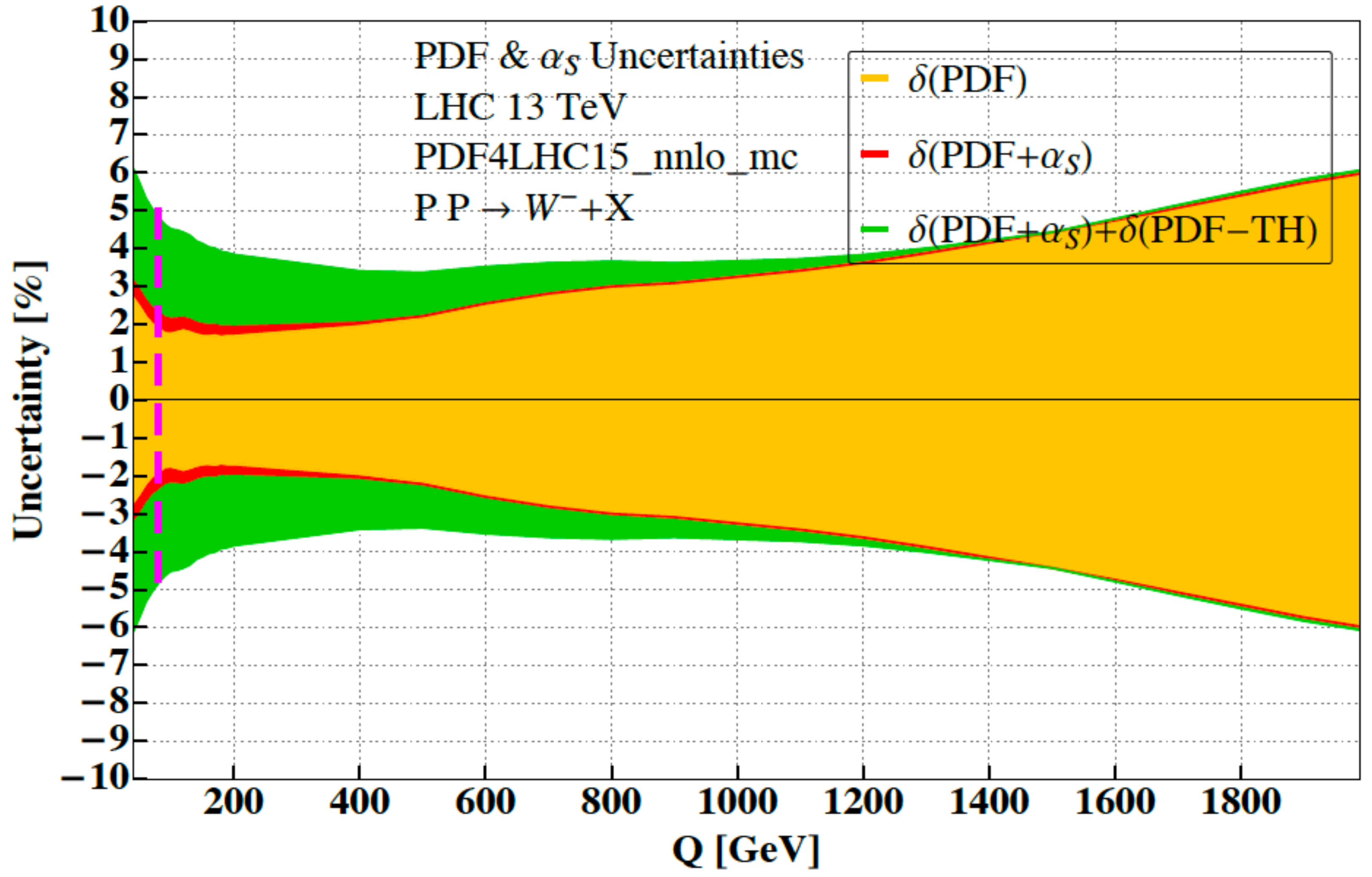
- Non-overlapping uncertainty bands.
- Z/γ^* to come.
- Uncertainty budget points to PDFs as the main source of error.



[Duhr, Dulat and Mistelberger, 2007.13313]



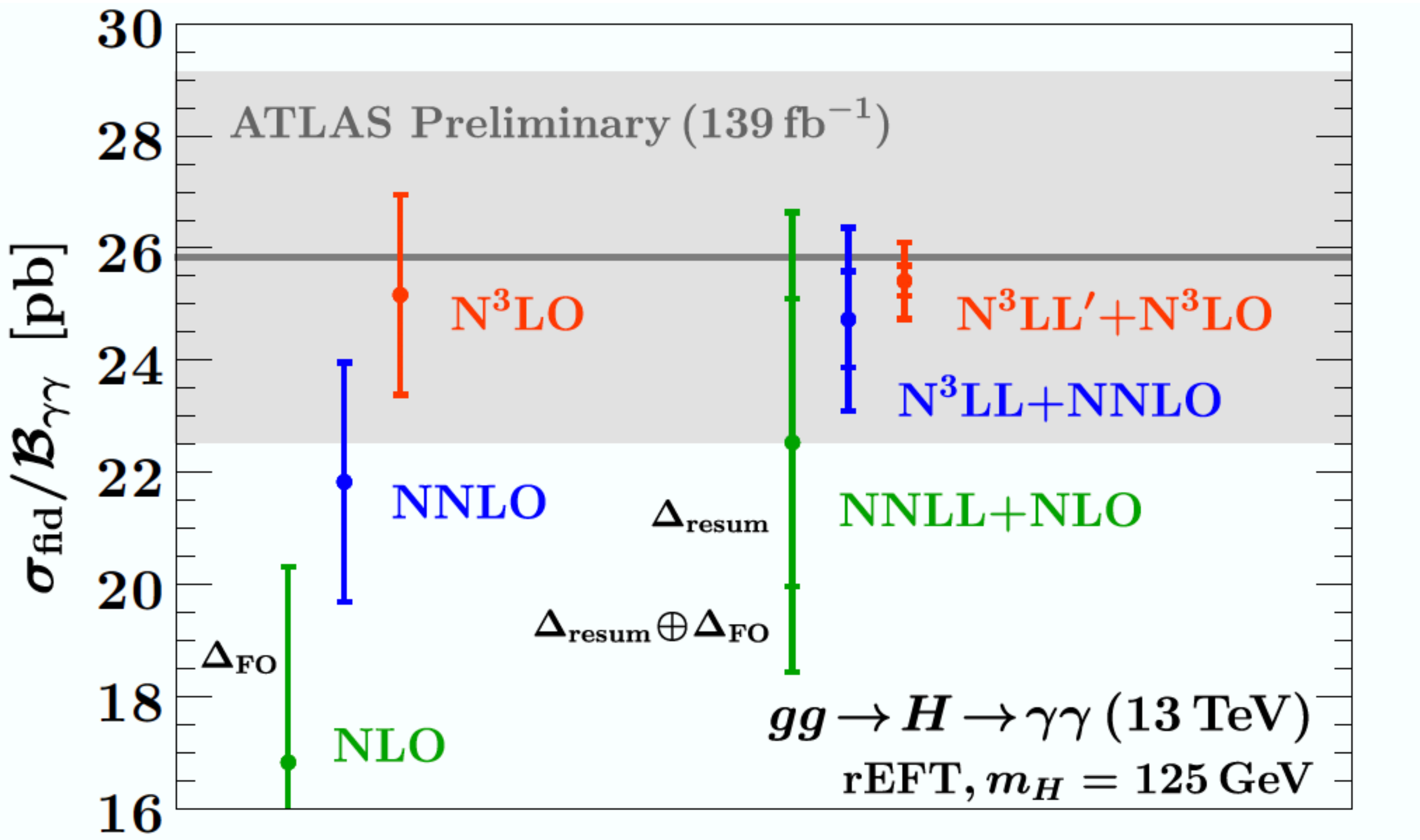
$$\delta(PDF-TH) = \frac{1}{2}\left|\frac{\sigma^{(2)}_{\text{NNLO}-\text{PDFs}} - \sigma^{(2)}_{\text{NLO}-\text{PDFs}}}{\sigma^{(2)}_{\text{NNLO}-\text{PDFs}}}\right|$$

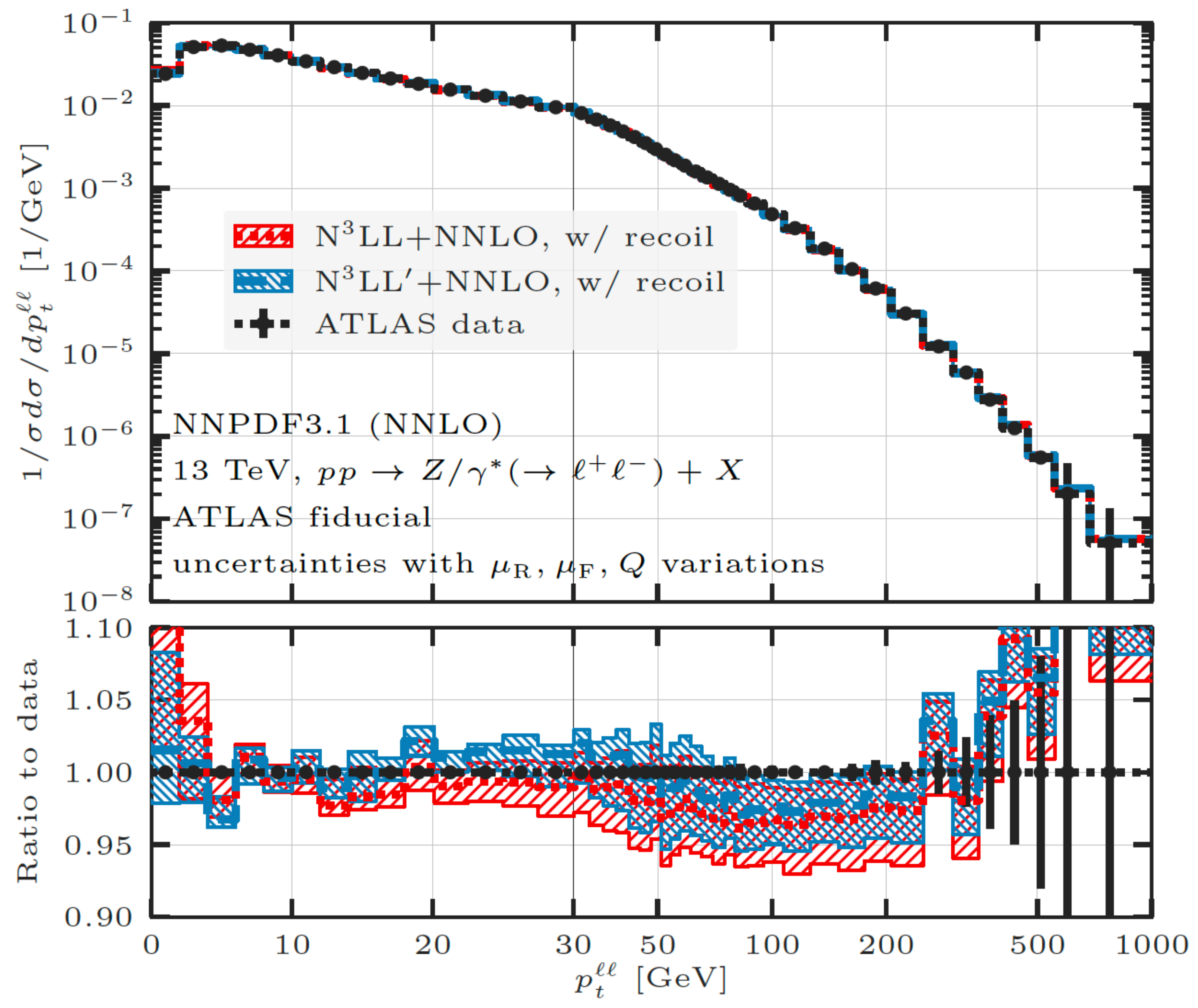


Precision calculations for the LHC

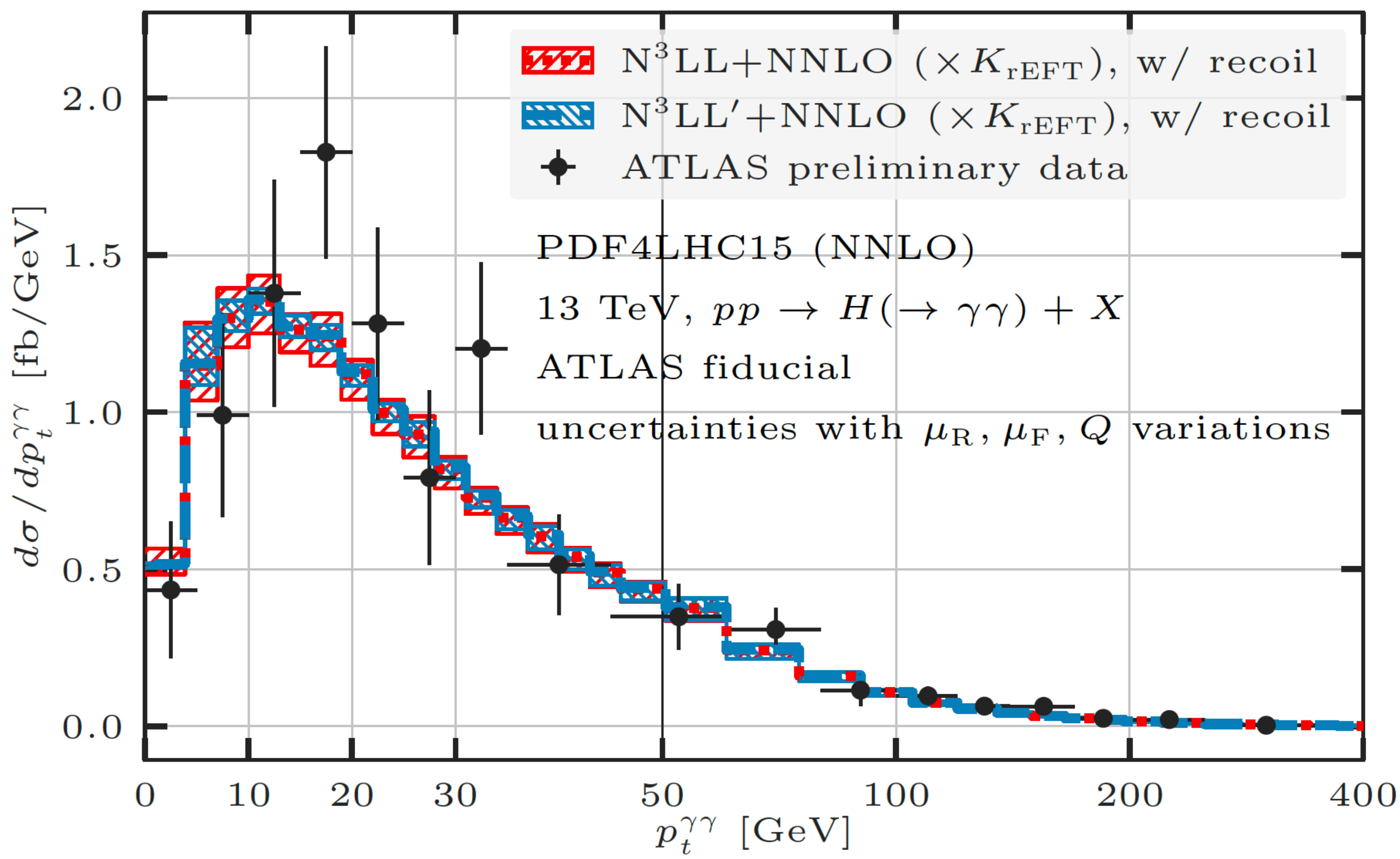
Status: Resummation

[Billis et al. et al, 2102.08039]





[E. Re, L. Rottoli and P. Torrielli et al, 2104.07509]

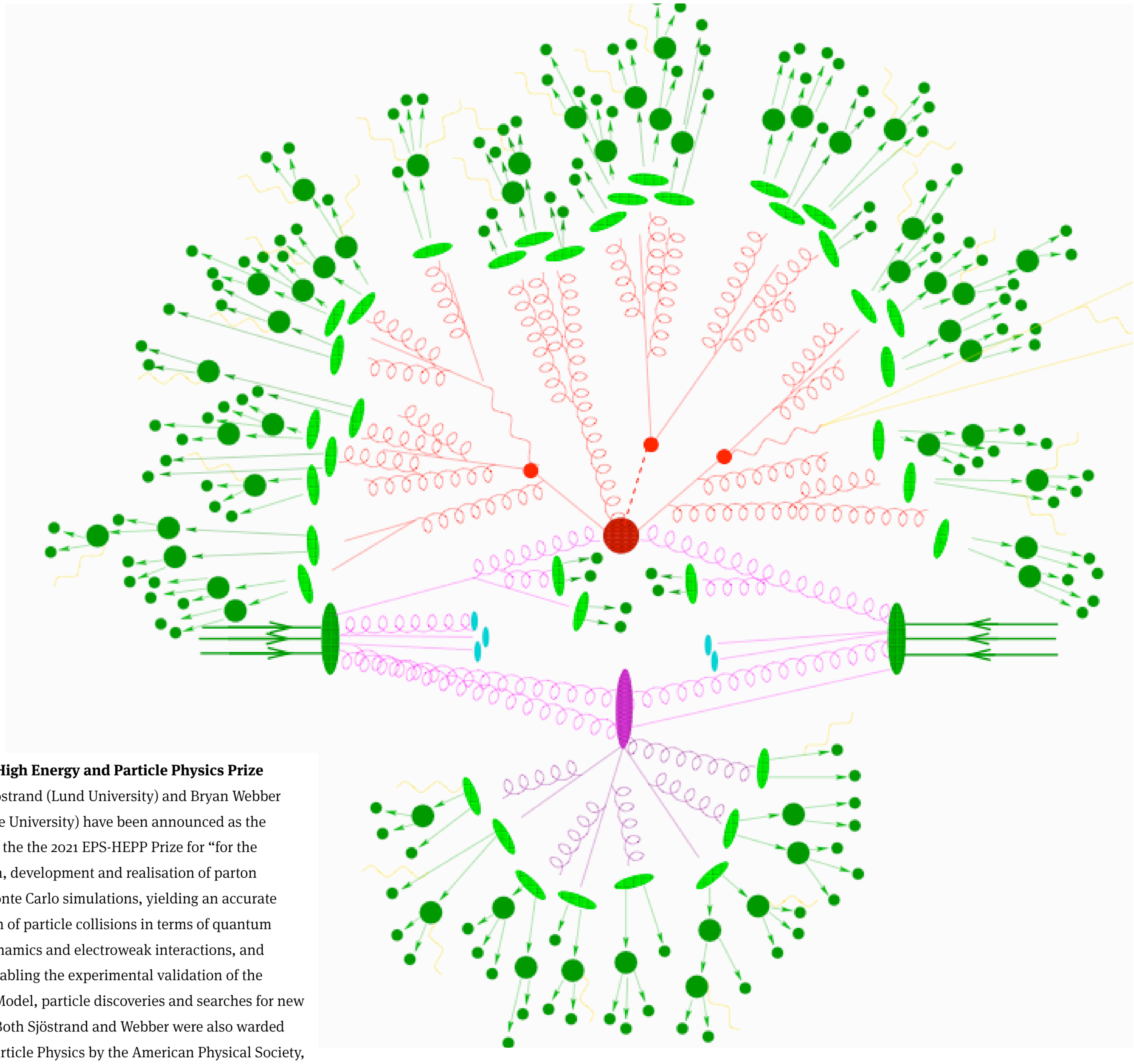


Resummation improves the stability of the cross section predictions even in presence of cut-induced log effects.

The calculation is fully exclusive with respect to the Born kinematics, which allows the application of arbitrary fiducial selection cuts on the decay products of the resonance. With a transverse-recoil prescription, the dominant classes of subleading-power corrections in a fiducial setup are accounted for. The resummed predictions are matched with fixed-order differential spectra at next-to-next-to-leading order (NNLO) accuracy.

Precision calculations for the LHC

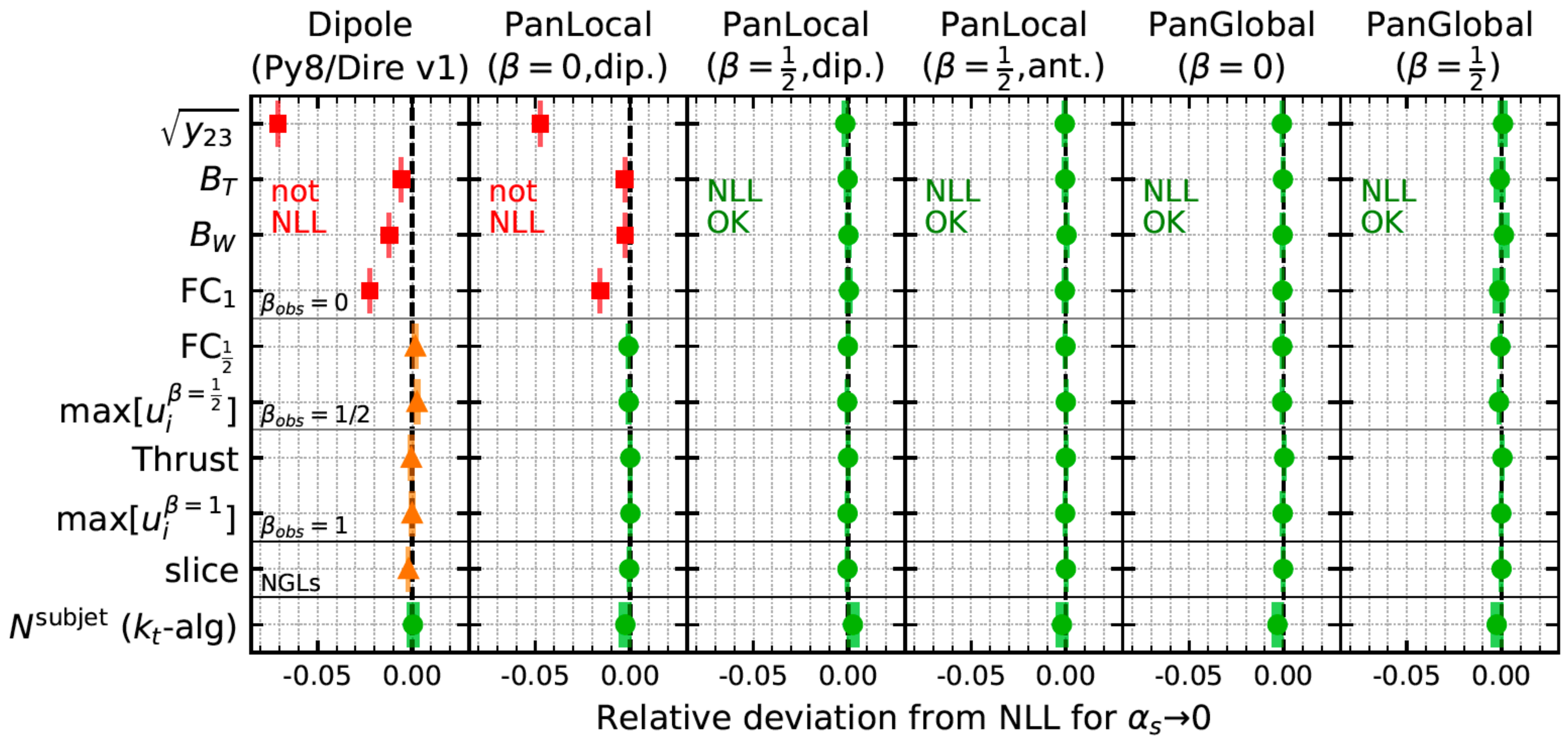
Fully exclusive simulations



Bryan Webber (left) and Torbjörn Sjöstrand (right). Credit: Lund University, T Sjöstrand

2021 EPS High Energy and Particle Physics Prize
Torbjrn Sjöstrand (Lund University) and Bryan Webber (Cambridge University) have been announced as the winners of the the 2021 EPS-HEPP Prize for "for the conception, development and realisation of parton shower Monte Carlo simulations, yielding an accurate description of particle collisions in terms of quantum chromodynamics and electroweak interactions, and thereby enabling the experimental validation of the Standard Model, particle discoveries and searches for new physics." Both Sjöstrand and Webber were also warded the 2012 Sakurai Prize for Theoretical Particle Physics by the American Physical Society, along with the late Guido Altarelli.

All current PS implementations are formally at LL accuracy (with several improvements towards NLL). Moving them to NLL has been proven a formidable challenge. Needs to account subheading effects in the logs and in color.



[M. Dasgupta et al. 2002.11114] [K. Hamilton et al. 2011.10054]

Systematic explorations are on-going and very promising.

[Nagy and Soper 2011.04773, 2011.04777]

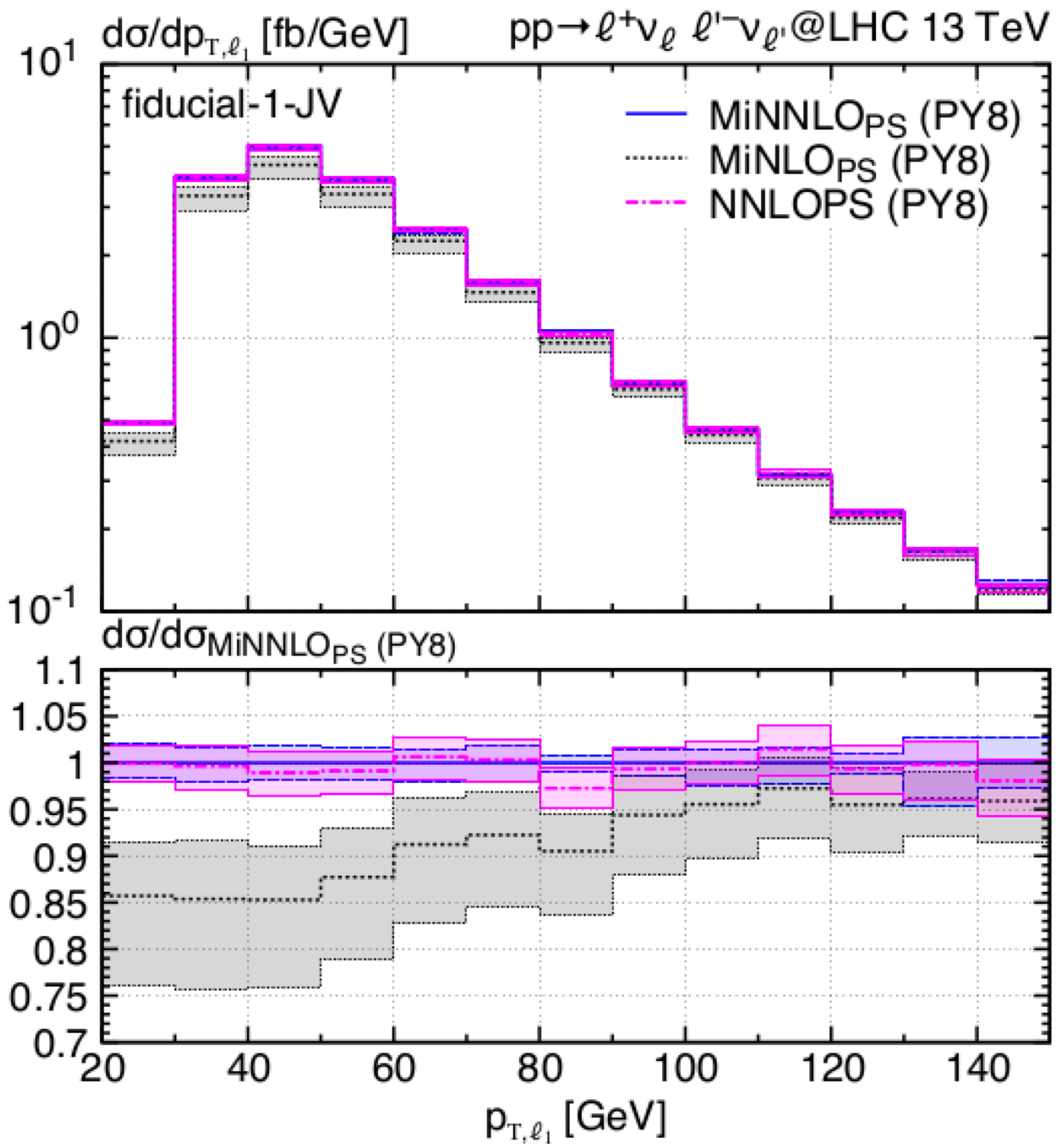
[Forshaw et al. 2003.06400]

Precision calculations for the LHC

Example: NNLO+Parton Shower

- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\mathrm{veto}})]$
- preserve the PS accuracy (leading log - LL)
- possibly, no merging scale required.

$$\frac{\mathrm{d}\bar{B}(\Phi_{\mathrm{FJ}})}{\mathrm{d}\Phi_{\mathrm{FJ}}} = \exp[-\tilde{S}(p_{\mathrm{T}})]\left\{\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{FJ}}}\right]^{(1)}\left(1+\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}[\tilde{S}(p_{\mathrm{T}})]^{(1)}\right)\right.$$
$$\left.+\left(\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{FJ}}}\right]^{(2)}+\left(\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\right)^3[D(p_{\mathrm{T}})]^{(3)}F_\ell^{\mathrm{corr}}(\Phi_{\mathrm{FJ}})\right\}$$



Precision calculations for the LHC

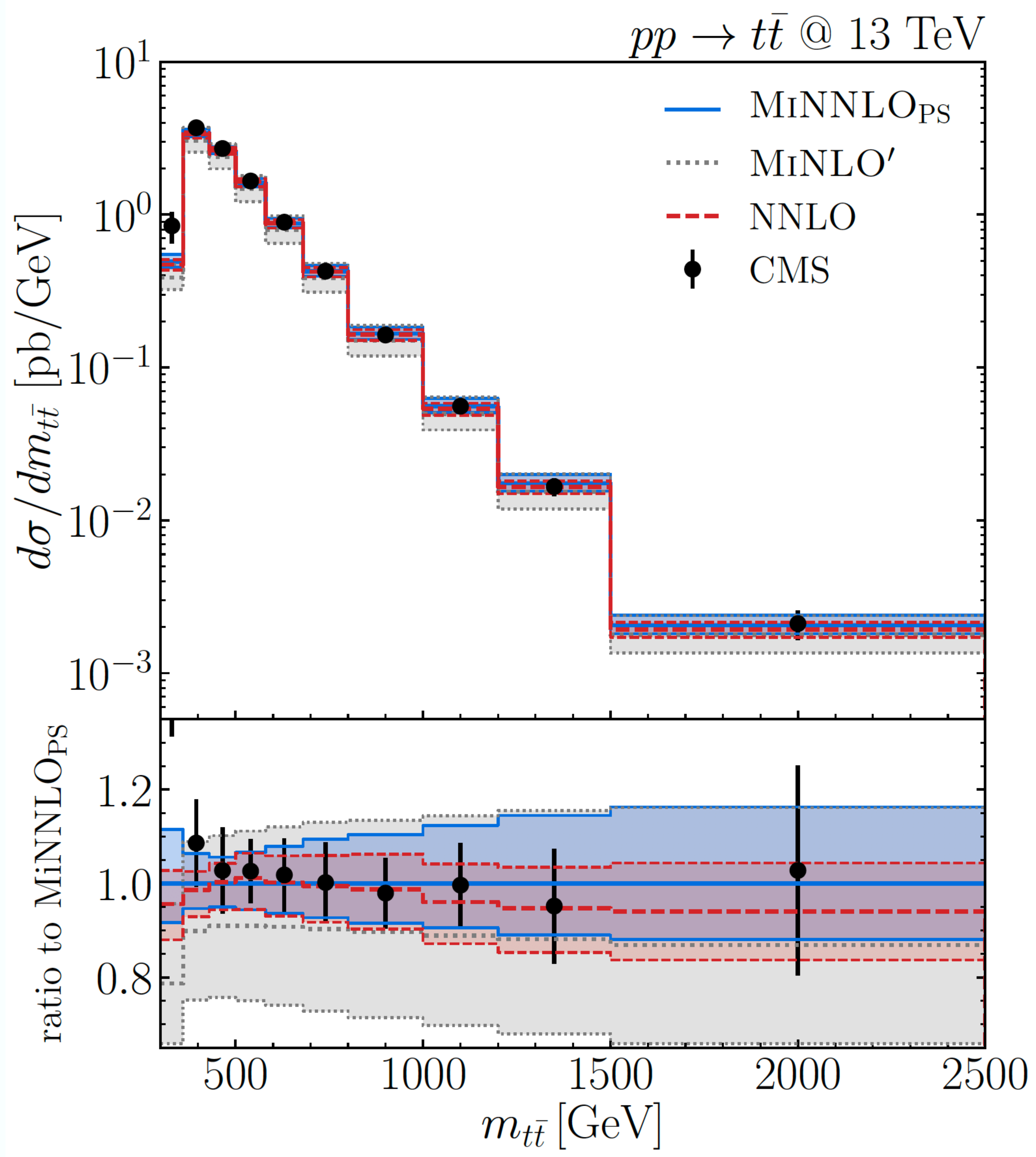
Example: NNLO+Parton Shower

- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\text{veto}})]$
- preserve the PS accuracy (leading log - LL)
- possibly, no merging scale required.

$$\frac{\mathrm{d}\bar{B}(\Phi_{\mathrm{FJ}})}{\mathrm{d}\Phi_{\mathrm{FJ}}} = \exp[-\tilde{S}(p_{\mathrm{T}})]\left\{\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{FJ}}}\right]^{(1)}\left(1+\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}[\tilde{S}(p_{\mathrm{T}})]^{(1)}\right)\right.$$
$$\left.+\left(\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{FJ}}}\right]^{(2)}+\left(\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\right)^3[D(p_{\mathrm{T}})]^{(3)}F_\ell^{\mathrm{corr}}(\Phi_{\mathrm{FJ}})\right\}$$

colour singlet: $$\mathrm{d}\sigma_{\mathrm{res}}^F \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\ H\ (C\otimes f)(C\otimes f)\right\}$$ COLOR

heavy quark pair: $$\mathrm{d}\sigma_{\mathrm{res}}^F \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H\Delta})\,(C\otimes f)(C\otimes f)\right\}$$



Precision calculations for the LHC

Example: NNLO+Parton Shower

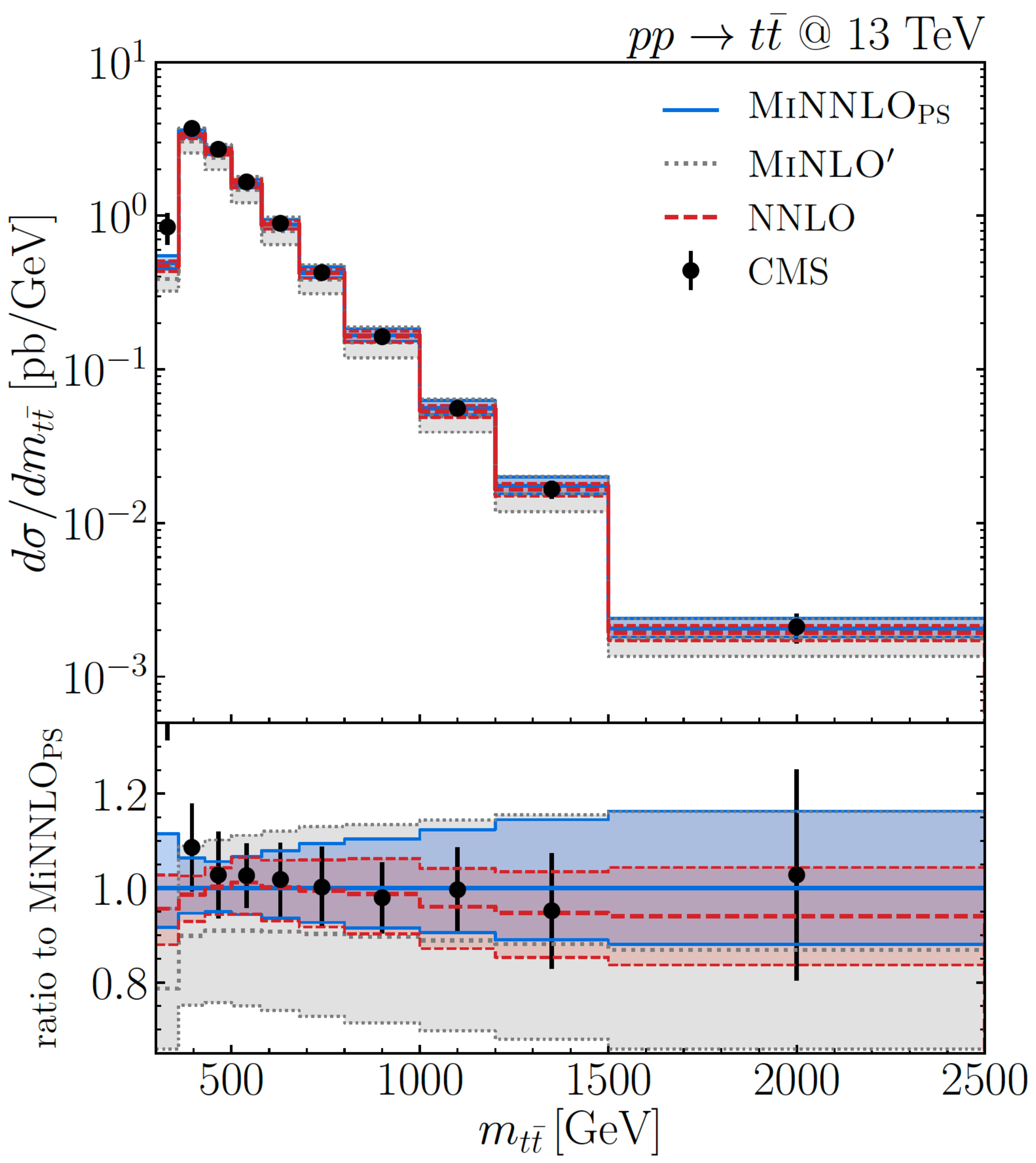
- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\mathrm{veto}})]$
- preserve the PS accuracy (leading log - LL)
- possibly, no merging scale required.

$$\frac{\mathrm{d}\bar{B}(\Phi_{\mathrm{FJ}})}{\mathrm{d}\Phi_{\mathrm{FJ}}} = \exp[-\tilde{S}(p_{\mathrm{T}})]\left\{\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{FJ}}}\right]^{(1)}\left(1+\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}[\tilde{S}(p_{\mathrm{T}})]^{(1)}\right)\right.$$
$$\left.+\left(\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\right)^2\left[\frac{\mathrm{d}\sigma_{\mathrm{FJ}}}{\mathrm{d}\Phi_{\mathrm{FJ}}}\right]^{(2)}+\left(\frac{\alpha_{\mathrm{S}}(p_{\mathrm{T}})}{2\pi}\right)^3[D(p_{\mathrm{T}})]^{(3)}F_\ell^{\mathrm{corr}}(\Phi_{\mathrm{FJ}})\right\}$$

colour singlet: $$d\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\; H \; (C\otimes f)(C\otimes f)\right\}$$

COLOR

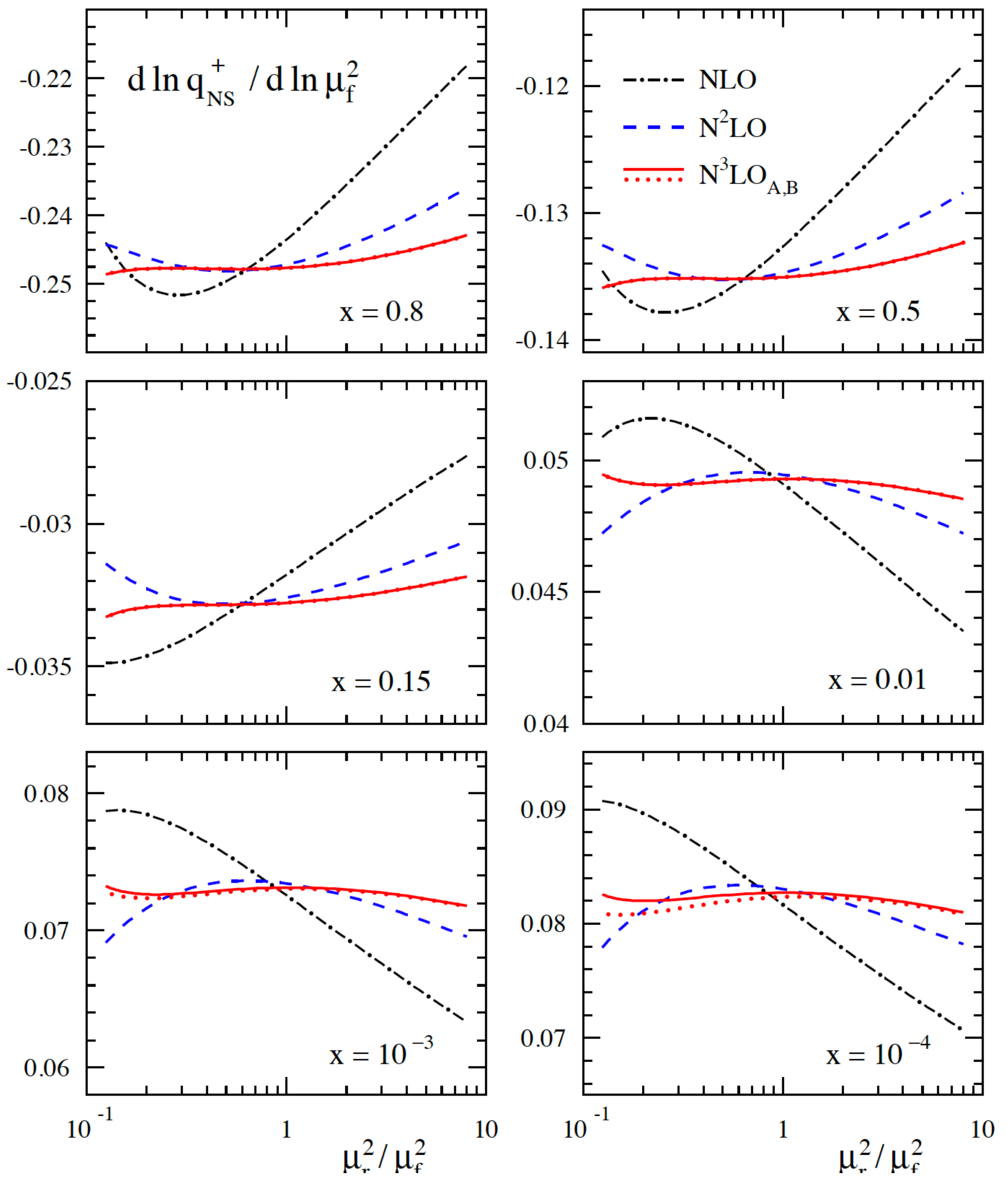
heavy quark pair: $$d\sigma^F_{\mathrm{res}} \sim \frac{\mathrm{d}}{\mathrm{d}p_T}\left\{e^{-S}\,\mathrm{Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)(C\otimes f)\right\}$$



A MILESTONE IN ACCURATE LHC SIMULATIONS!

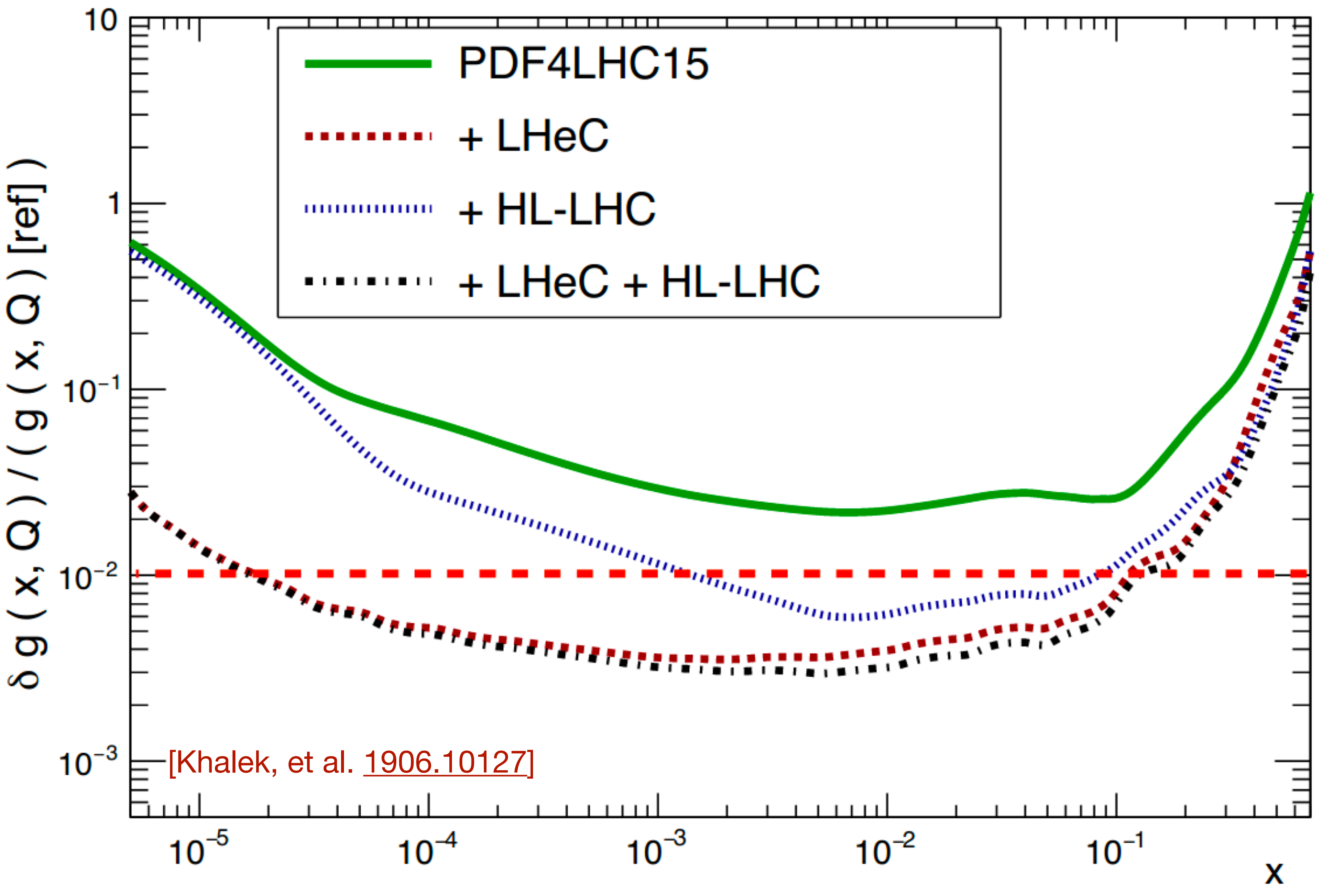
Precision calculations for the LHC

Status: PDF's



[Moch et al. , 1707.08315]

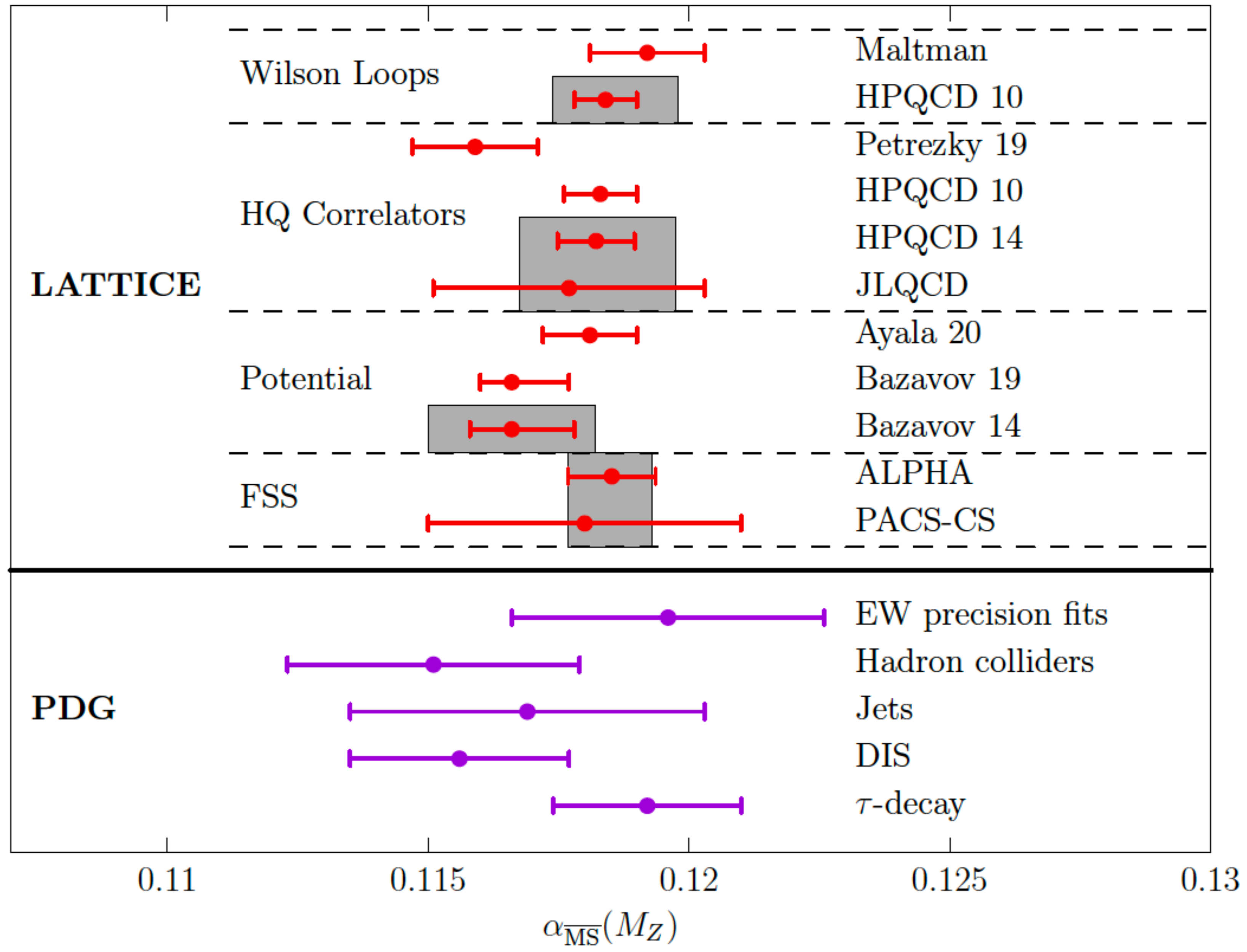
- Complete N3LO PDF's evolution not available yet. Non-singlet evolution available at 4 loops already.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice?



The lattice frontier

α_S and PDF's

Lattice determinations of the strong coupling [Del Debbio and A. Ramos e-Print: 2101.04762]



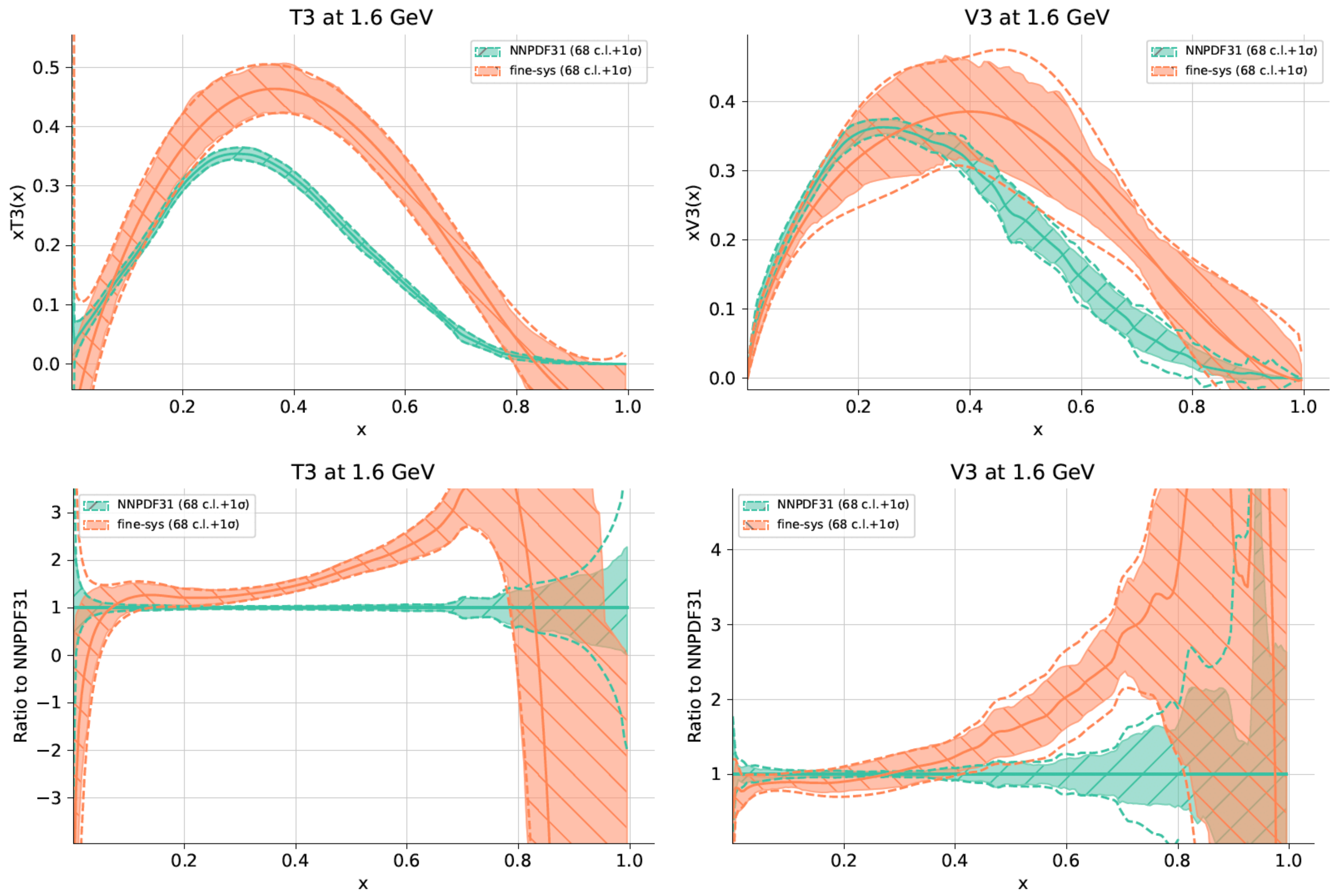
$$P(Q) = \sum_{k=0}^{n} c_k(s)\alpha^k_{\overline{\rm MS}}(\mu) + \mathcal{O}(\alpha^{n+1}_{\overline{\rm MS}}(\mu)) + \mathcal{O}\left(\frac{\Lambda^p}{Q^p}\right), \qquad (s = \mu/Q)\,.$$

MHO PC

Using Lattice QCD, one can combine input from well-measured QCD quantities -- like for example the proton mass, or a meson decay constant -- with the perturbative expansion of a short distance observable that does not need to be directly observable (like the quark anti-quark force). The advantage of this approach is that the experimental input comes from the hadron spectrum with a negligible uncertainty.

Parton Distribution Functions from Ioffe Time Pseudodistributions from Lattice Calculations: Approaching the Physical Point [Bálint Joó et al. : 2004.01687]

Neural-network analysis of Parton Distribution Functions from Ioffe-time pseudodistributions [L. Del Debbio et al. 2010.03996]



$V_3(x) = u(x) - \bar{u}(x) - [d(x) - \bar{d}(x)]$

$T_3(x) = u(x) + \bar{u}(x) - [d(x) + \bar{d}(x)]$

$$\mathfrak{M}(\nu, z_3^2) = \int_{-1}^{1} dx\, C(x\nu, \mu^2 z_3^2)\, f(x, \mu^2) + \mathcal{O}(z_3^2\Lambda^2)$$

$$C(\xi, \mu^2 z_3^2) = e^{i\xi} - \frac{\alpha_s}{2\pi} C_F \int_0^1 dw \left[\frac{1+w^2}{1-w}\log\left(z_3^2\mu^2\frac{e^{2\gamma_E+1}}{4}\right) + 4\frac{\log(1-w)}{1-w} - 2(1-w)\right]_+ e^{i\xi w} + \mathcal{O}(\alpha_s^2)$$

This formula allows to relate collinear PDFs to quantities which are computable in lattice QCD simulations, through a factorized expression similar to those relating collinear PDFs to physical cross sections.It can be used in a fitting framework, to extract PDFs from lattice data, performing the same kind of analysis which is usually done when considering experimental data.

Precision physics at the HL-LHC
Three questions

1. Given the statistics increase of a factor ~20 with respect to what we currently have what is the expected experimental precision on key EW/top/Higgs measurements and a reasonable goal for TH predictions?

2. How will we achieve it? What is it needed? What are the challenges and the current avenues?

3. How to frame and interpret our results?

Precision physics at the HL-LHC

Three questions

1. Given the statistics increase of a factor ~20 with respect to what we currently have what is the expected experimental precision on key EW/top/Higgs measurements and a reasonable goal for TH predictions?

2. How will we achieve it? What is it needed? What are the challenges and the current avenues?

3. How to frame and interpret our results?

Imagining to win all the amazing challenges ahead of us in the next 20 years, **how we will maximally exploit the data** having in mind to address the open questions in our field (and in particular about New Physics beyond the EW scale)?

Precision physics at the HL-LHC

Three questions

1. Given the statistics increase of a factor ~20 with respect to what we currently have what is the expected experimental precision on key EW/top/Higgs measurements and a reasonable goal for TH predictions?

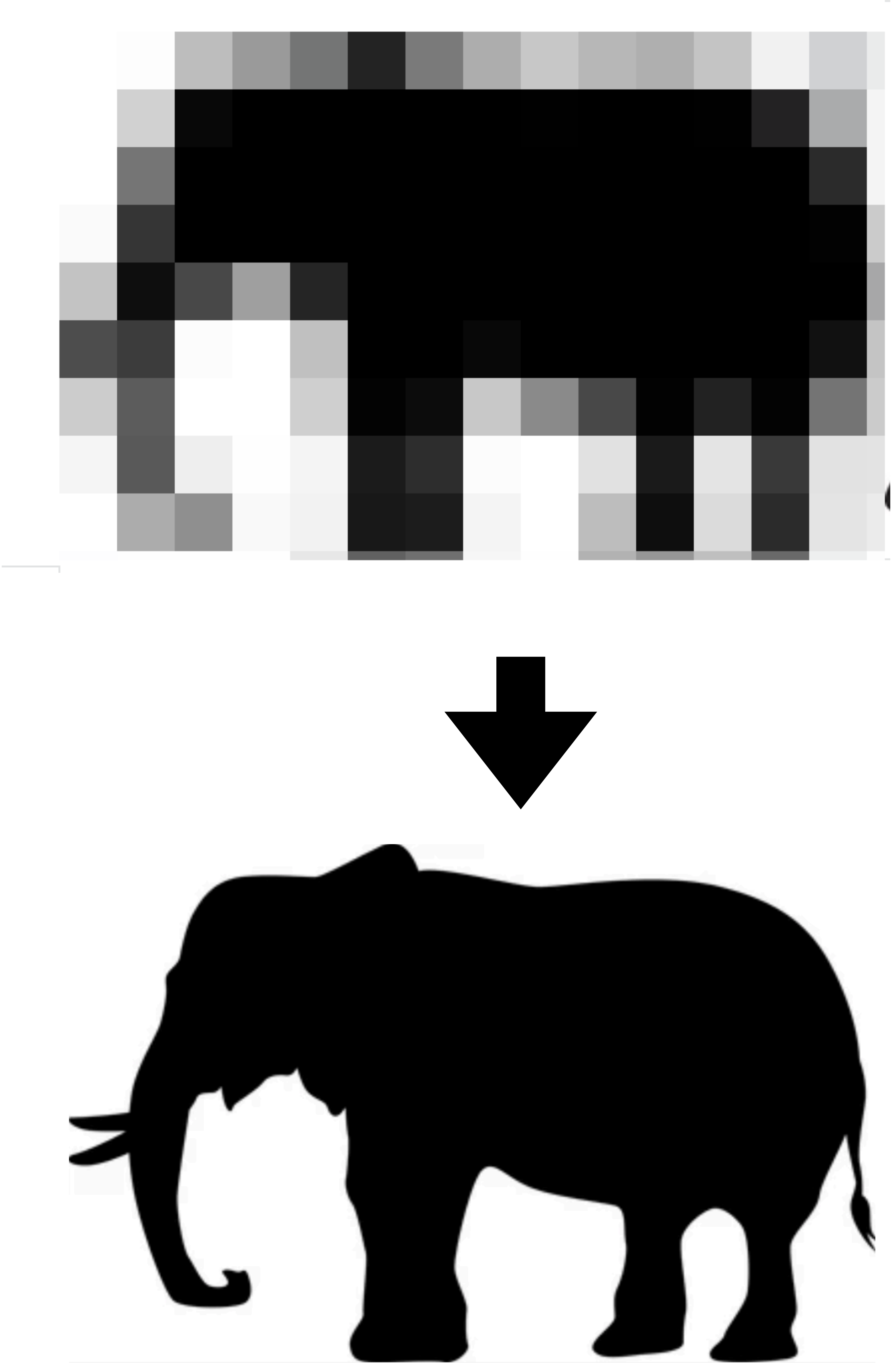
2. How will we achieve it? What is it needed? What are the challenges and the current avenues?

3. How to frame and interpret our results?

Imagining to win all the amazing challenges ahead of us in the next 20 years, **how we will maximally exploit the data** having in mind to address the open questions in our field (and in particular about New Physics beyond the EW scale)?

Towards the HL-LHC

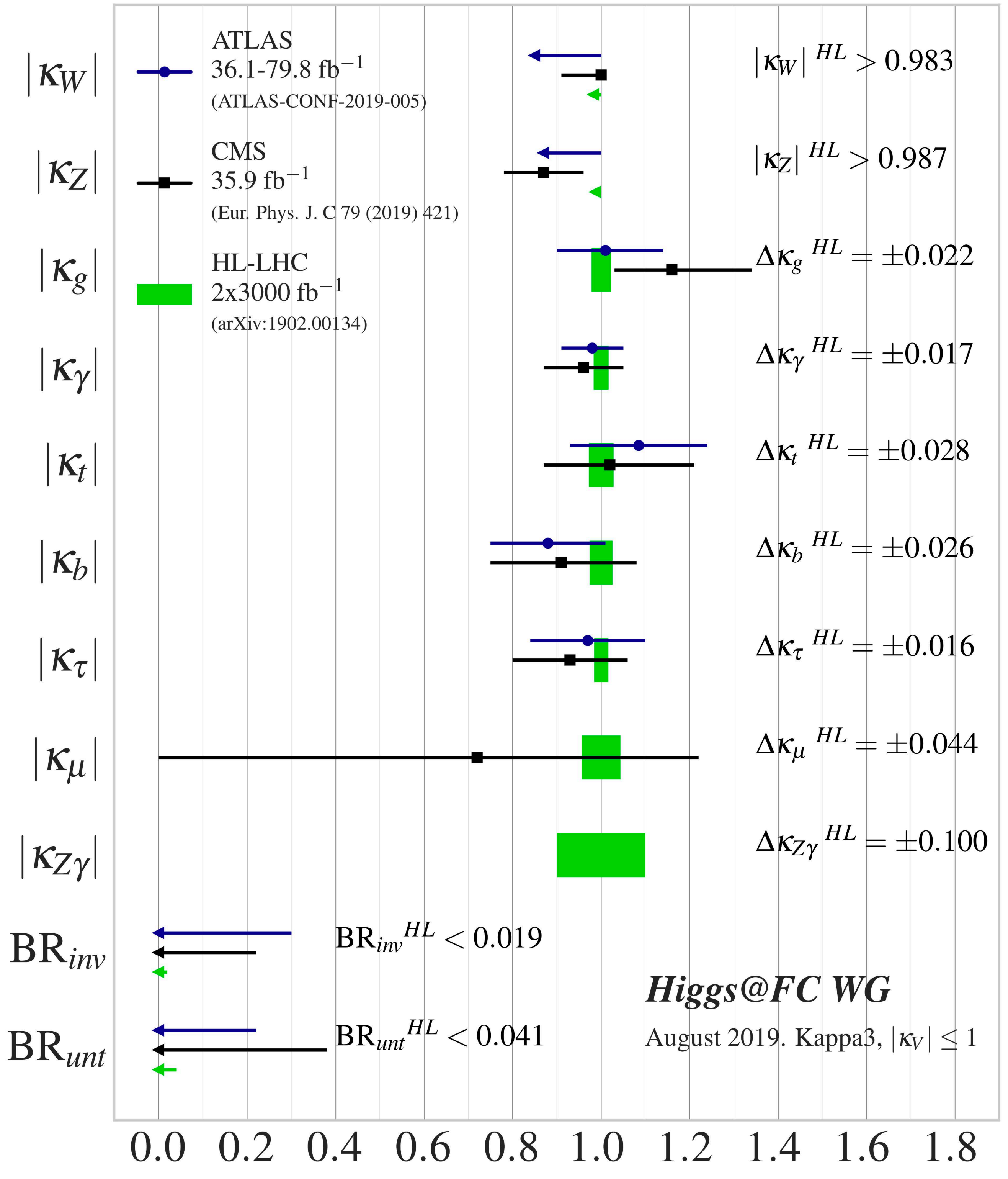
- 20-fold data sample
- 1/5 statistical uncertainties
- Comparable reduction of systematic uncertainties?
- Definition of tails and access to rare processes



HL-LHC projections

Higgs couplings

[De Blas et al., 2020]



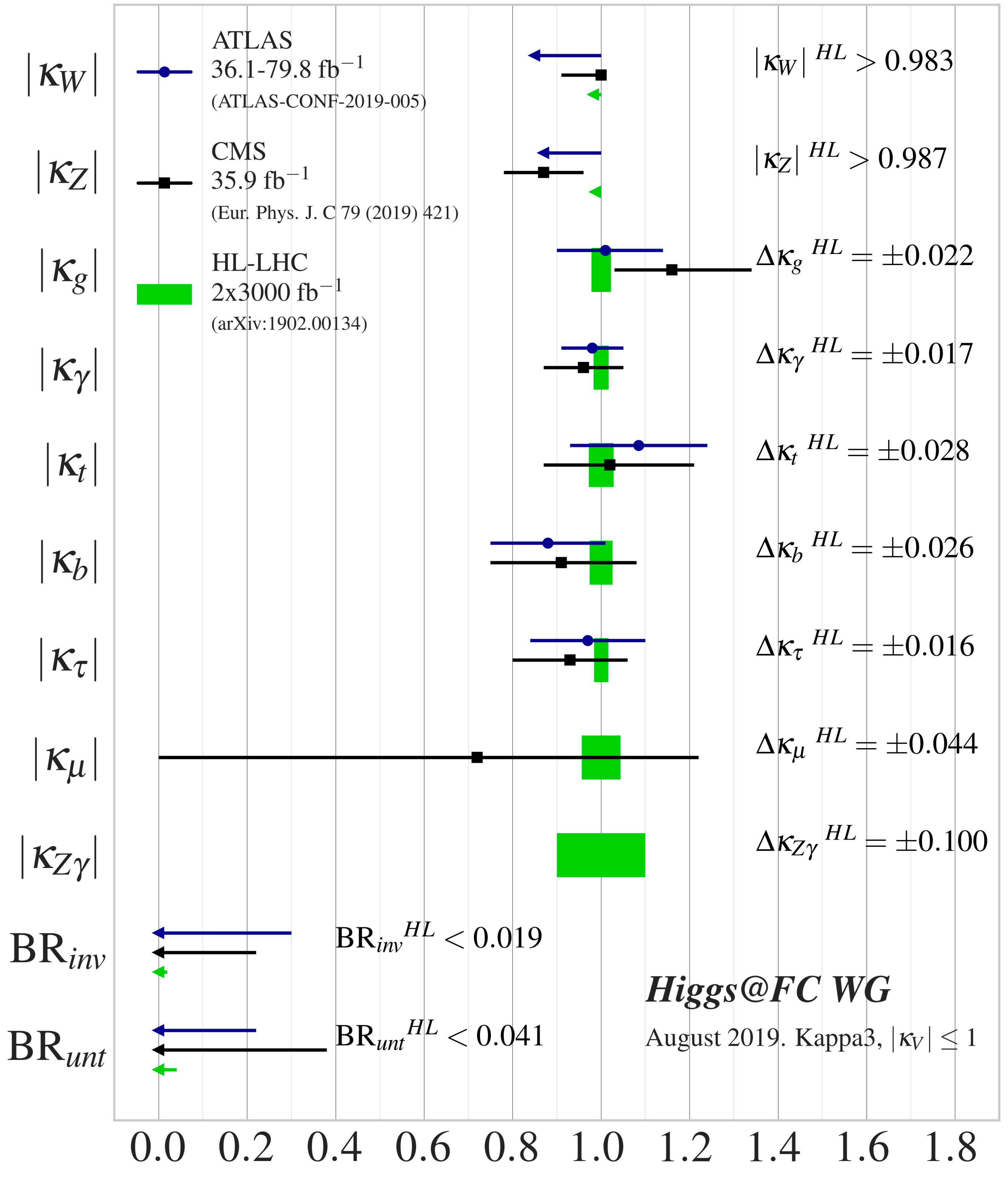
10-20%

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

HL-LHC projections

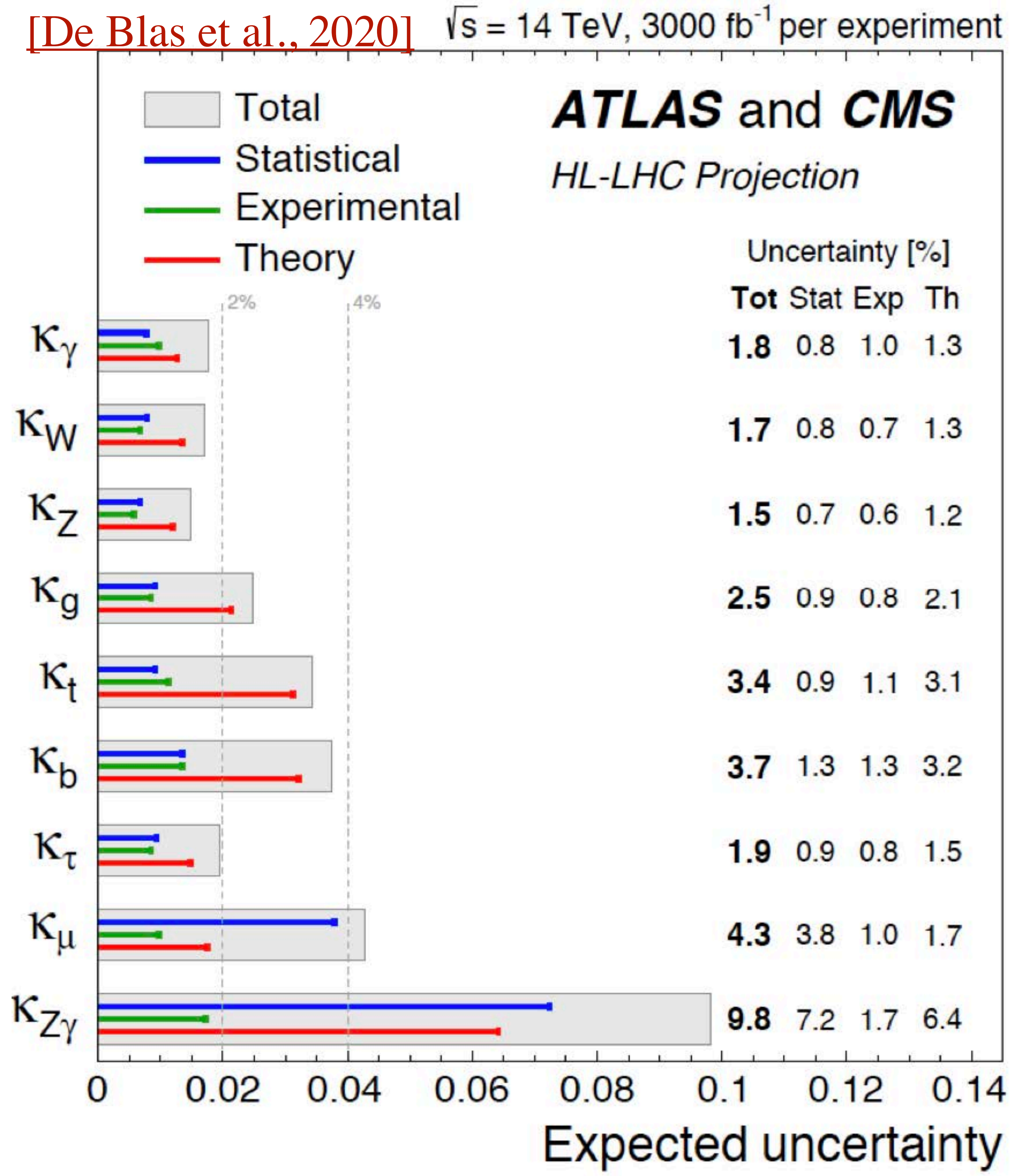
Higgs couplings

[De Blas et al., 2020]



10-20% → 2-4%

[De Blas et al., 2020]



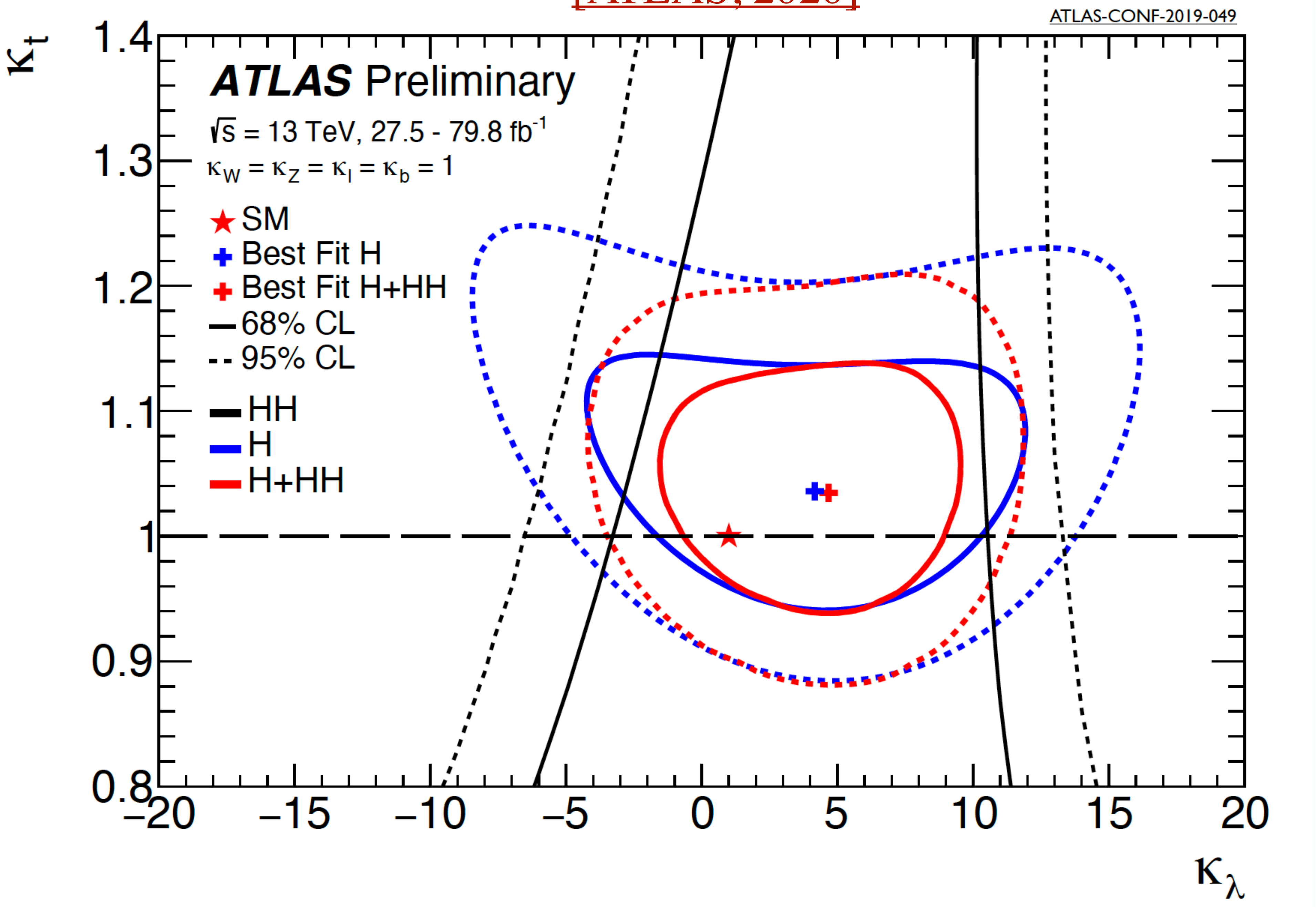
$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

HL-LHC projections

Higgs couplings

Now

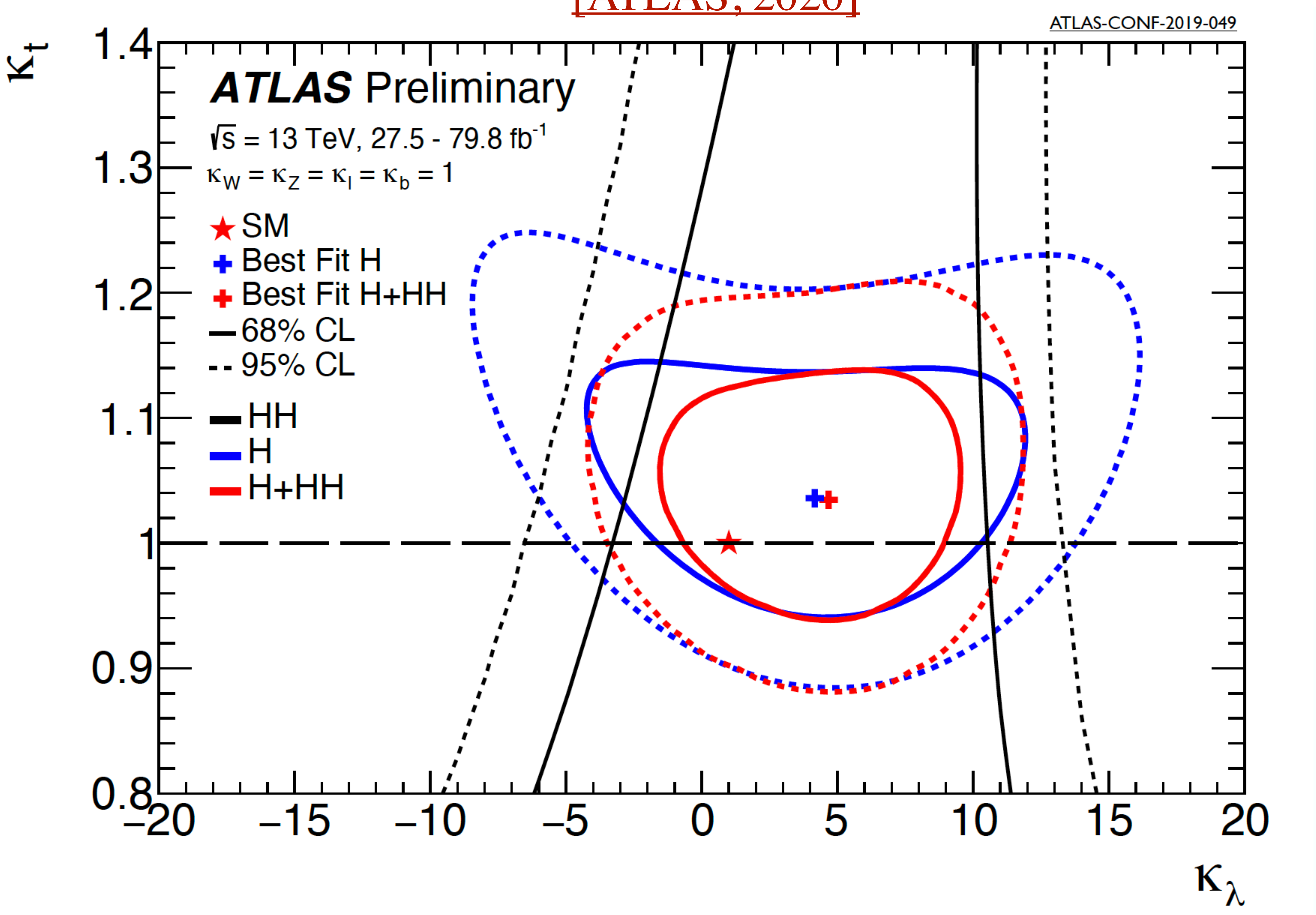
[ATLAS, 2020]



HL-LHC projections
Higgs couplings

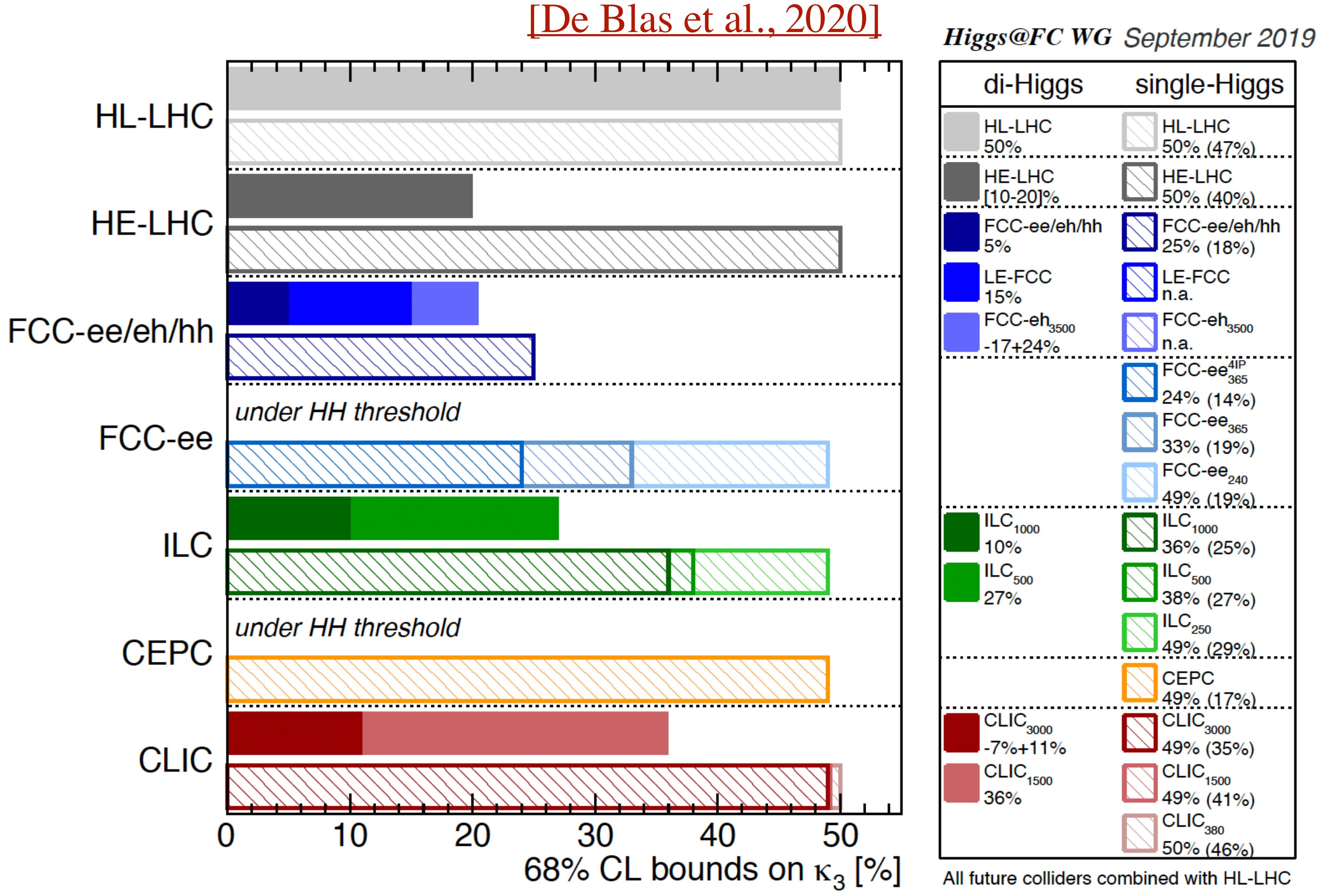
Now

[ATLAS, 2020]



Future

[De Blas et al., 2020]



Currently limits on k_λ from H and HH are comparable and will stay so at the HL-LHC.
Borderline sensitivity to say something about EW baryogenesis…

Towards the HL-LHC

- 20-fold data sample
- 1/5 statistical uncertainties
- Comparable reduction of systematic uncertainties?
- Definition of tails and access to rare processes

- Are we ready?
- Is everything understood and clear just need to do it?
- Are we sure there are no roadblocks?
- Are we sure we will make a discovery?

Towards the HL-LHC

- 20-fold data sample
- 1/5 statistical uncertainties
- Comparable reduction of systematic uncertainties?
- Definition of tails and access to rare processes

- Are we ready?
- Is everything understood and clear just need to do it?
- Are we sure there are no roadblocks?
- Are we sure we will make a discovery?

NO!

Towards the HL-LHC

- 20-fold data sample
- 1/5 statistical uncertainties
- Comparable reduction of systematic uncertainties?
- Definition of tails and access to rare processes

•Are we ready?
•Is everything understood and clear just need to do it?
•Are we sure there are no roadblocks?
•Are we sure we will make a discovery?

NO!

Explore = travel through (an unfamiliar area) in order to learn about it.

Towards the HL-LHC

- 20-fold data sample
- 1/5 statistical uncertainties
- Comparable reduction of systematic uncertainties?
- Definition of tails and access to rare processes

•Are we ready?
•Is everything understood and clear just need to do it?
•Are we sure there are no roadblocks?
•Are we sure we will make a discovery?

NO!

Explore = travel through (an unfamiliar area) in order to learn about it.

•Are we ready to start the adventure?
•Do we have a plan and/or strategy?
•Are the clear challenges to attack?
•Can we invent/use new tools?
•Will anything new understood/found/invented/devised along the way that will stay on a longer time scale?

Towards the HL-LHC

- 20-fold data sample
- 1/5 statistical uncertainties
- Comparable reduction of systematic uncertainties?
- Definition of tails and access to rare processes

•Are we ready?
•Is everything understood and clear just need to do it?
•Are we sure there are no roadblocks?
•Are we sure we will make a discovery?

NO!

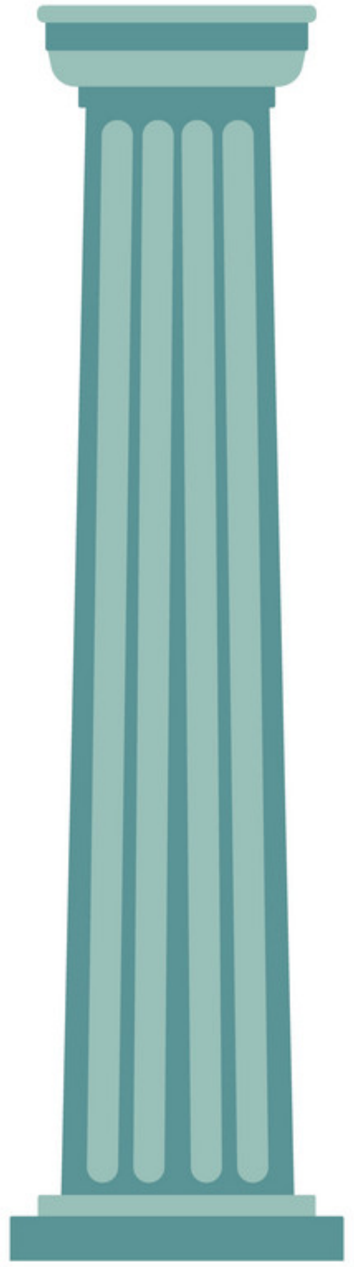
Explore = travel through (an unfamiliar area) in order to learn about it.

•Are we ready to start the adventure?
•Do we have a plan and/or strategy?
•Are the clear challenges to attack?
•Can we invent/use new tools?
•Will anything new understood/found/invented/devised along the way that will stay on a longer time scale?

YES!

Precision calculations for the LHC

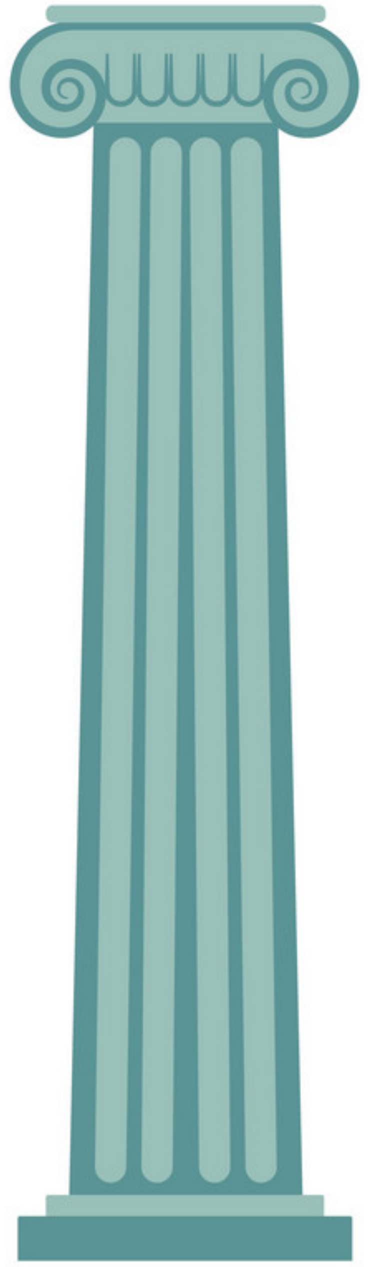
The challenges towards the "1% goal"



Fixed Order

LO, NLO,…

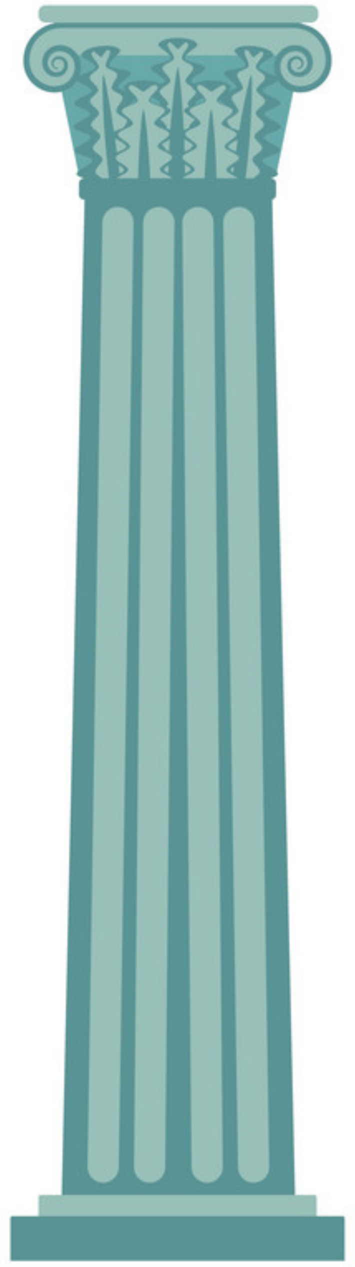
QCD/EW



Resum

LL, NLL,…

PS



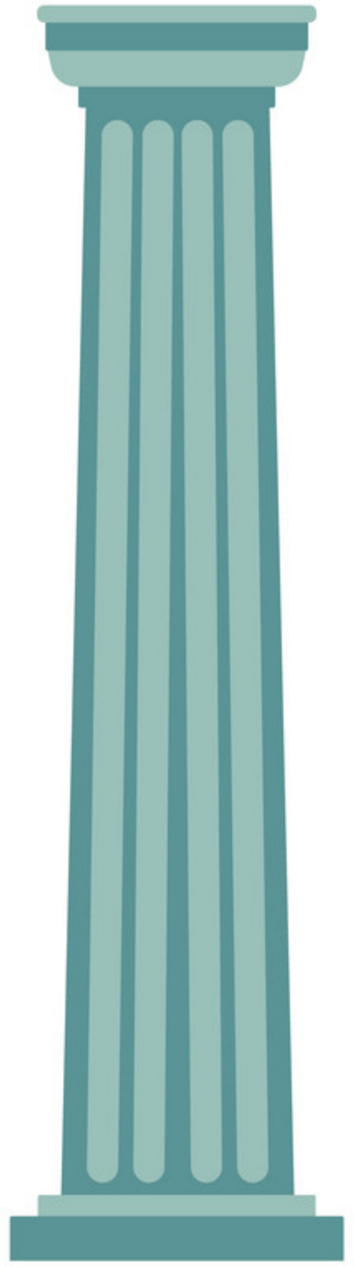
PDF's

LO,NLO,..

Fits

Precision calculations for the LHC

The challenges towards the "1% goal"

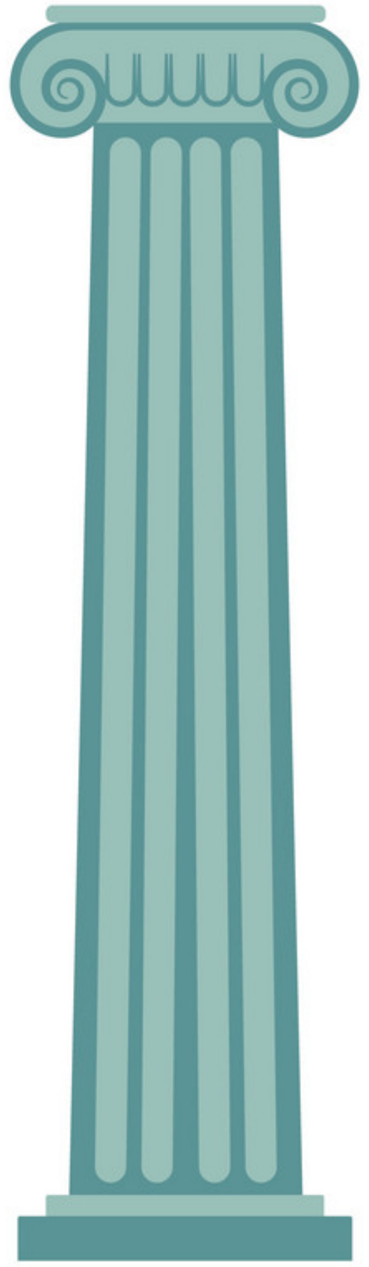


Fixed Order

LO, NLO,…

QCD/EW

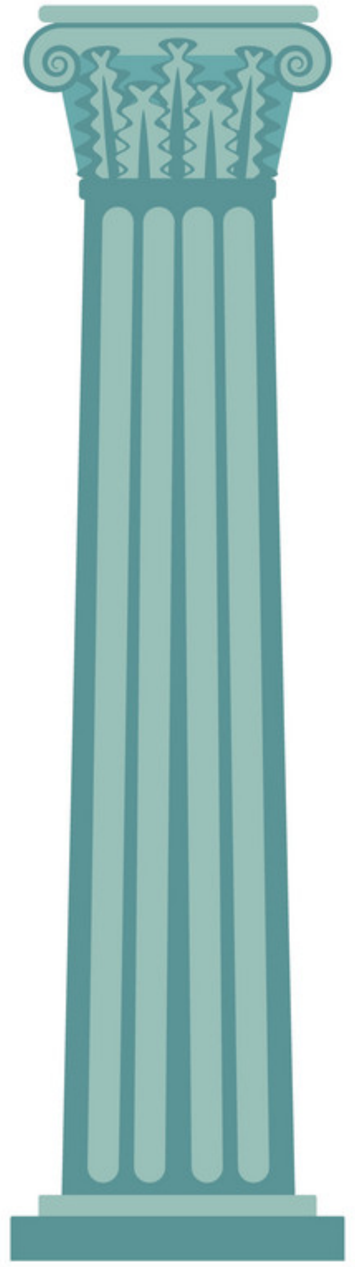
- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.



Resum

LL, NLL,…

PS



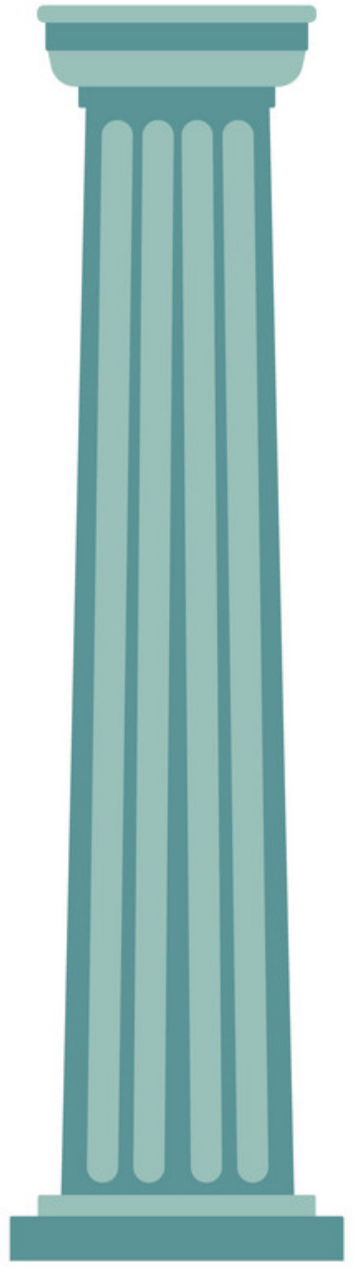
PDF's

LO,NLO,..

Fits

Precision calculations for the LHC

The challenges towards the “1% goal”

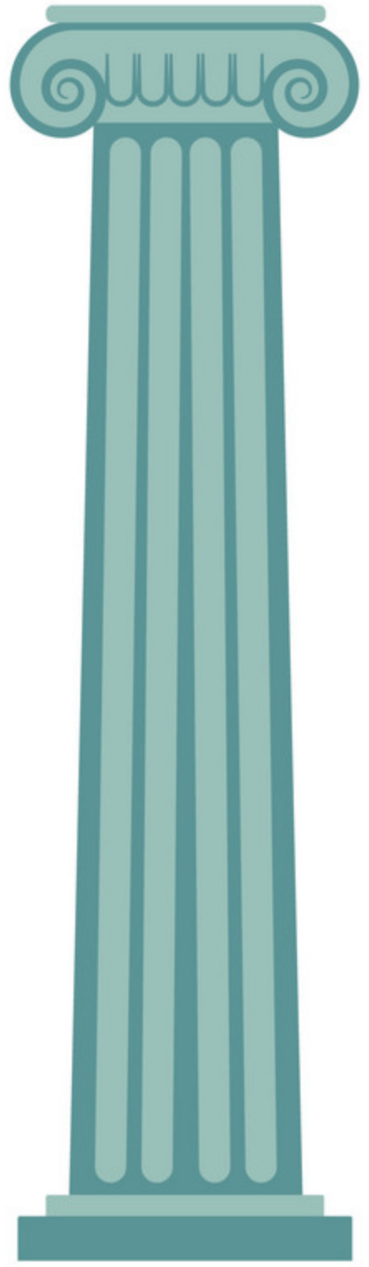


Fixed Order

LO, NLO,…

QCD/EW

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

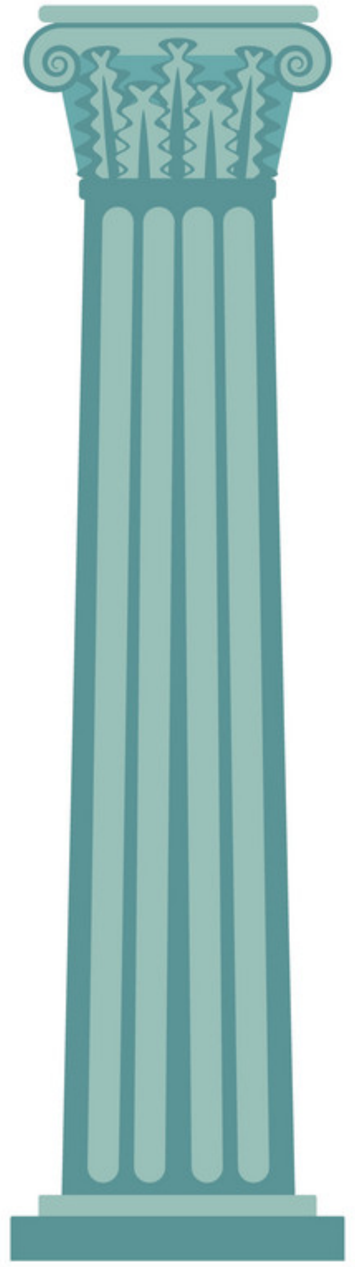


Resum

LL, NLL,…

PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



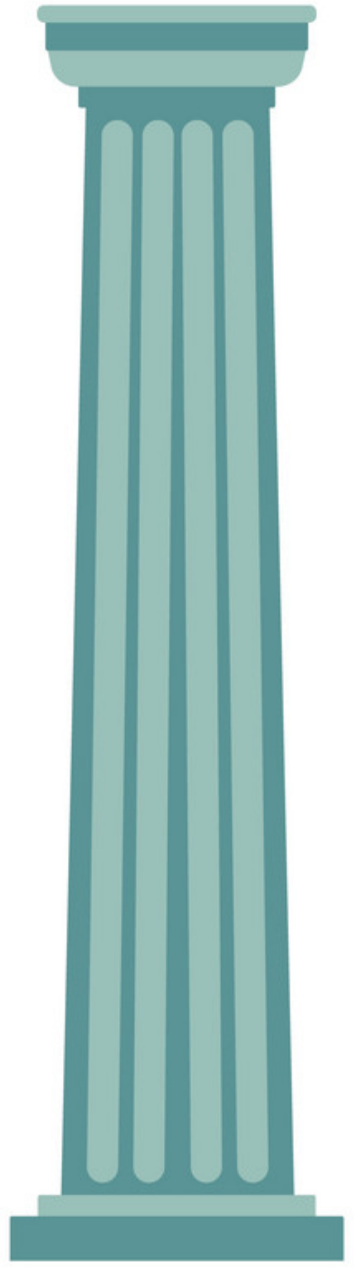
PDF’s

LO,NLO,..

Fits

Precision calculations for the LHC

The challenges towards the "1% goal"

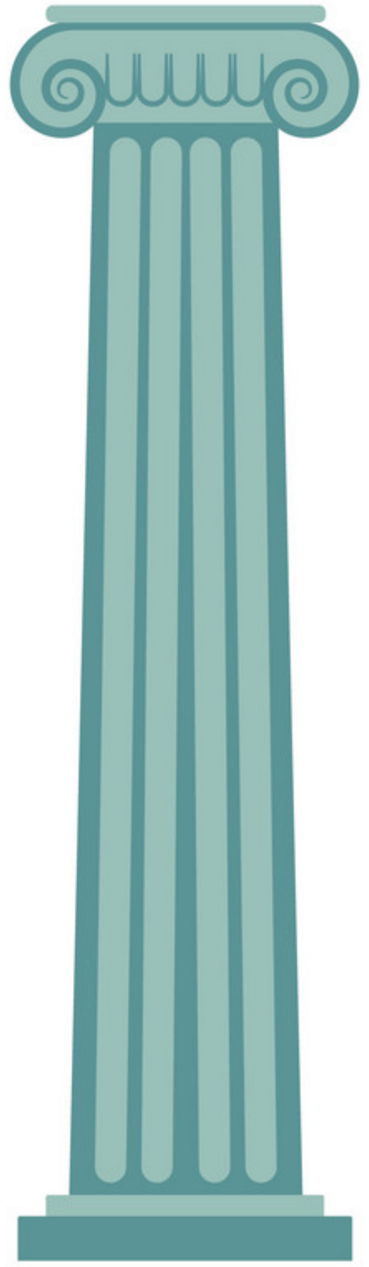


Fixed Order

LO, NLO,…

QCD/EW

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

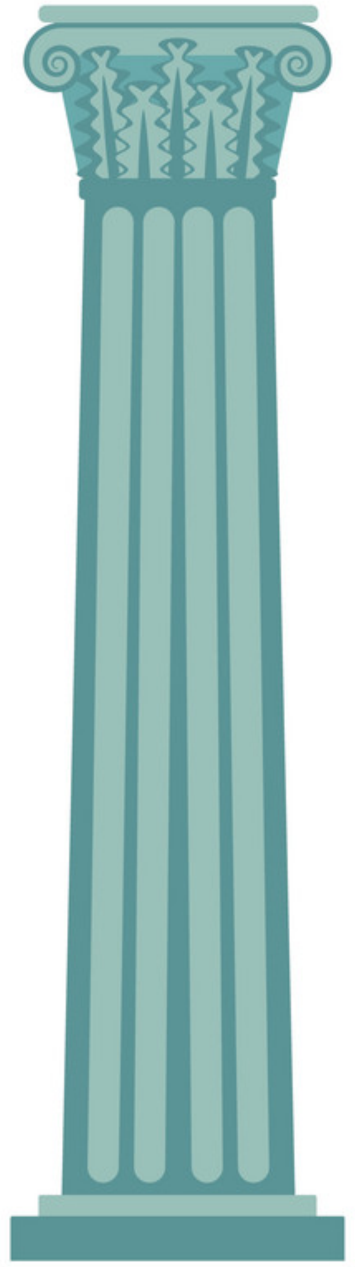


Resum

LL, NLL,…

PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



PDF's

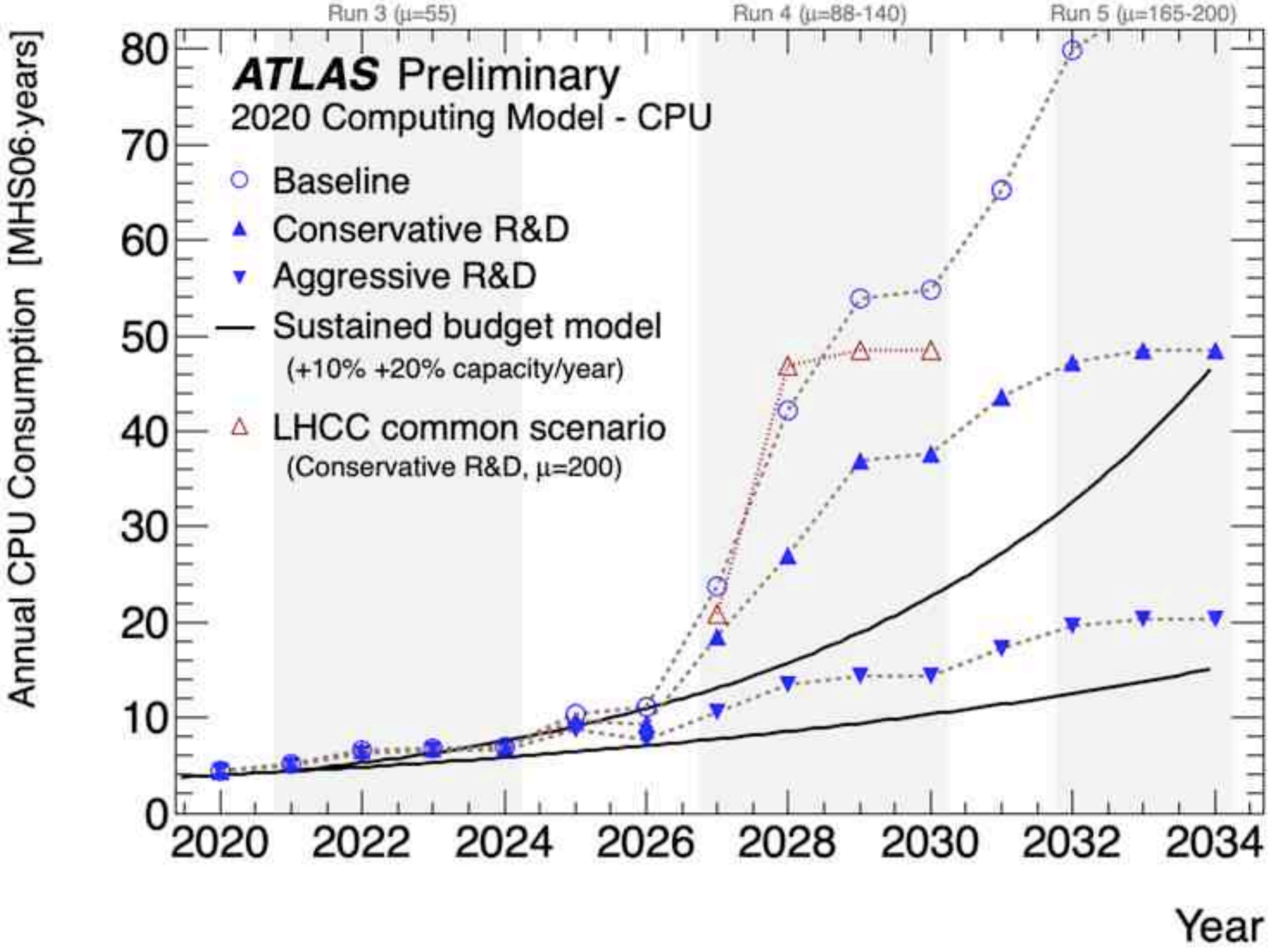
LO,NLO,..

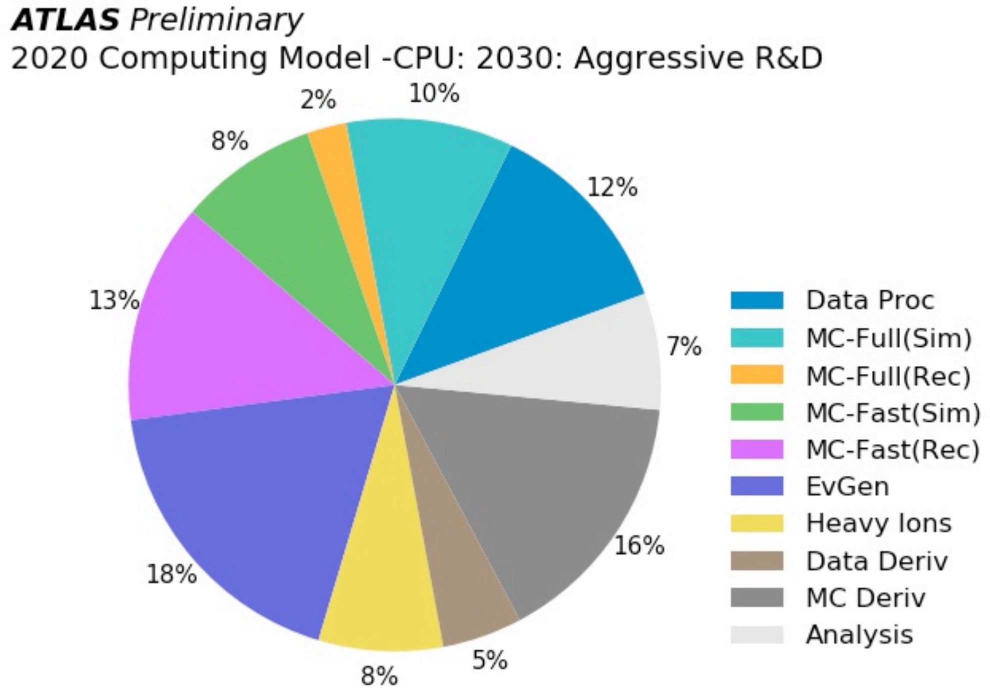
Fits

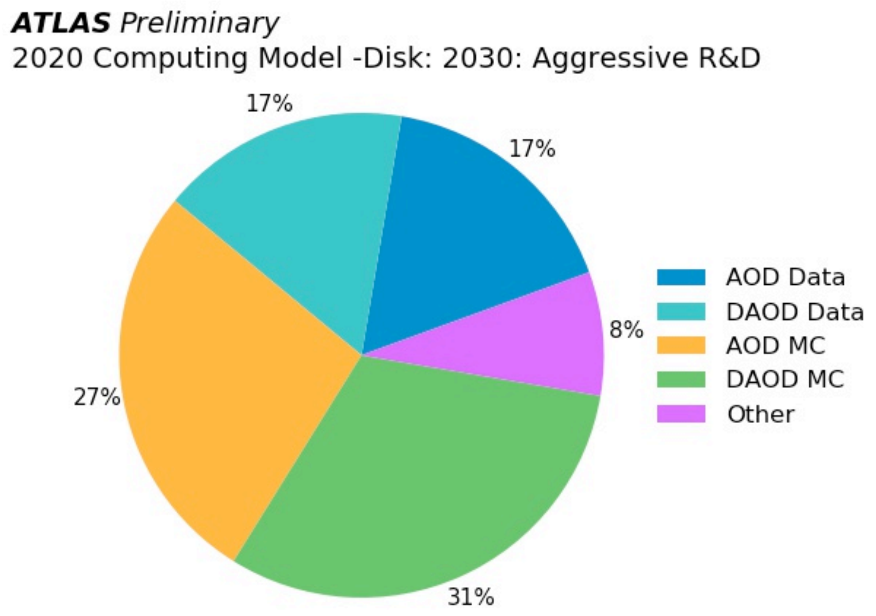
- Complete N3LO PDF's evolution not available yet.
- PDF determination from fitting large set of data. Final quality depends on measurements.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice.

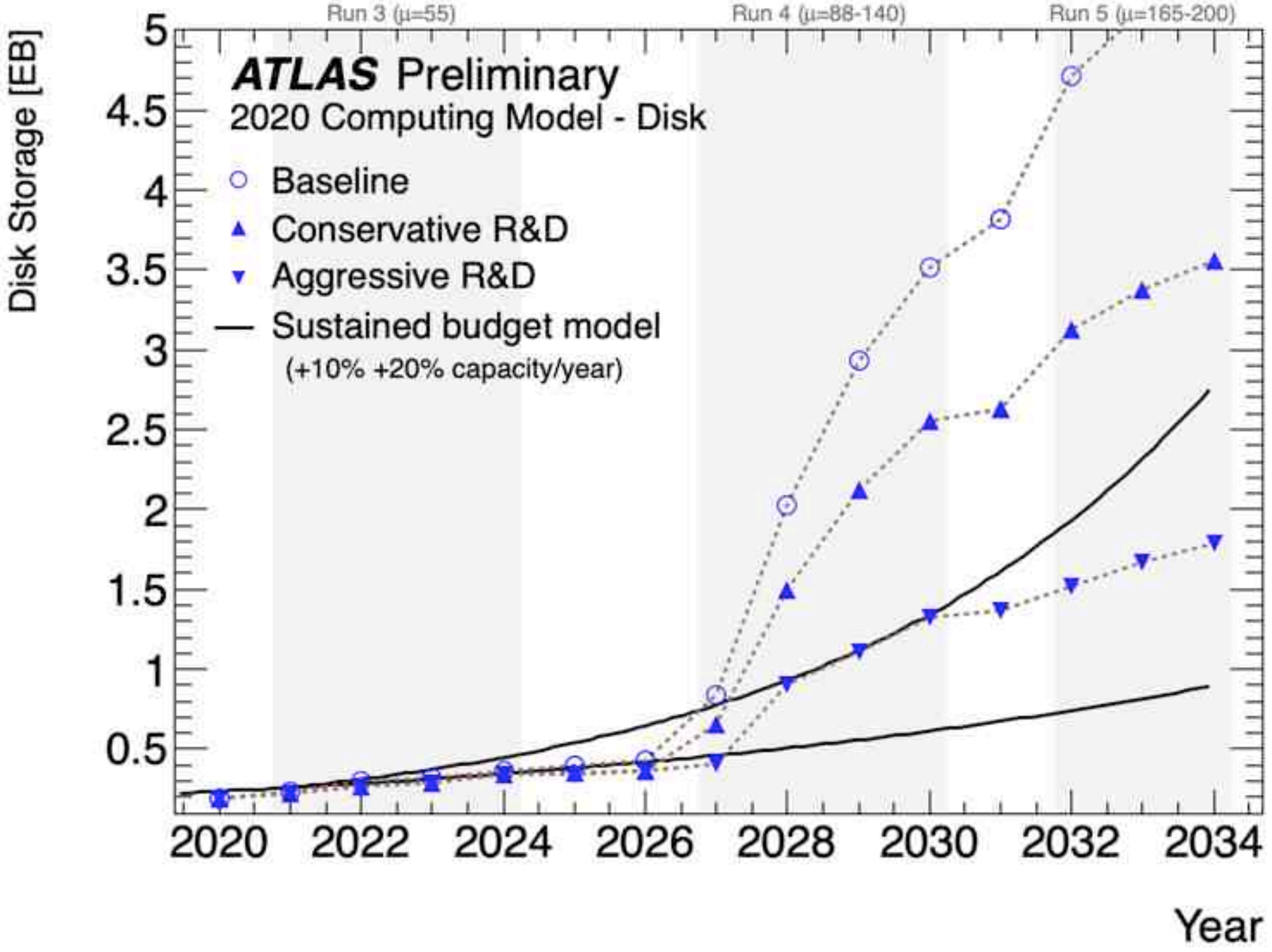
Precision calculations for the LHC

Computing needs





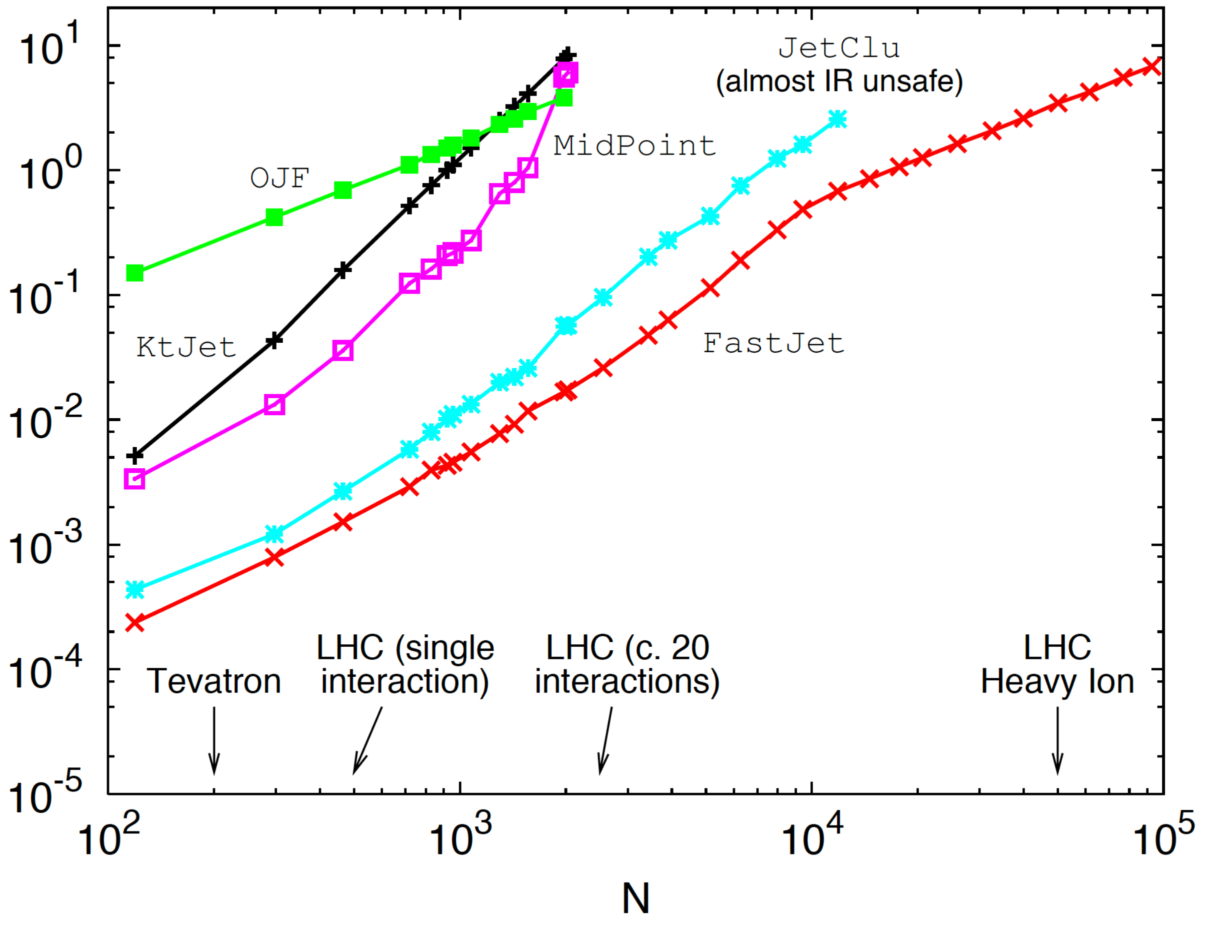


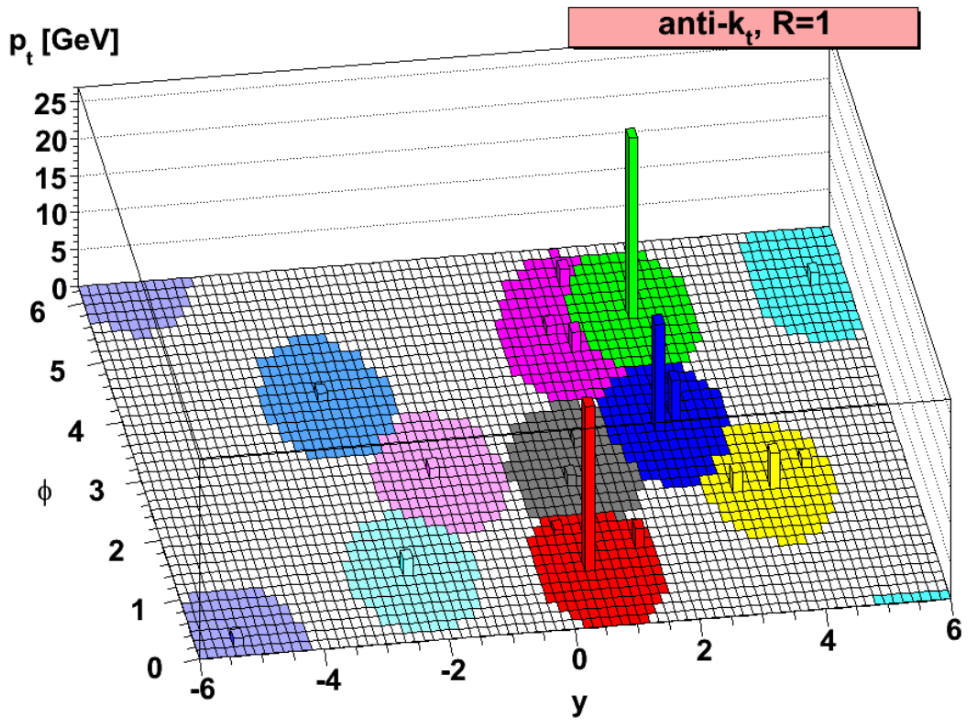


Wide set of needs. MC simulations significantly contribute to the budget [2004.13687, 2008.13636]. More so, if TH improvements (NNLO,…) which are very expensive will be folded in. Change in paradigm for MC generation seems to be needed.

The fast-jet revolution (2005)

$N^3 \rightarrow N \log N$

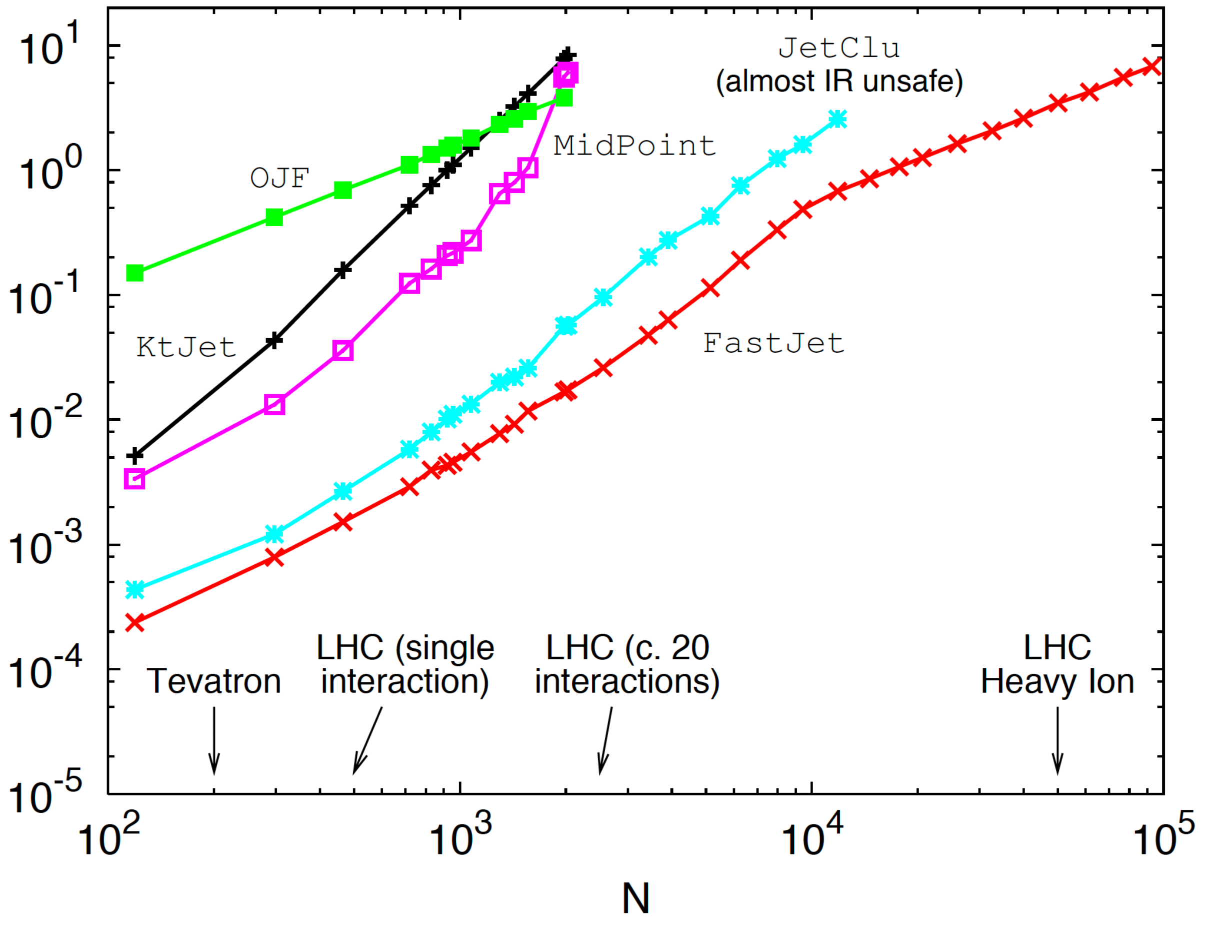


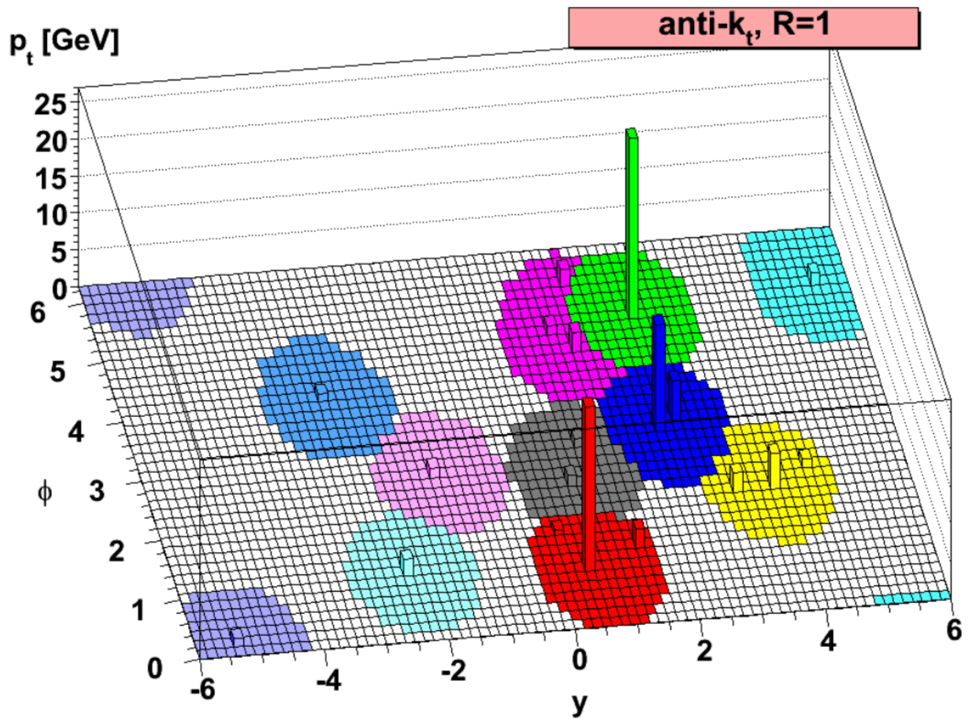


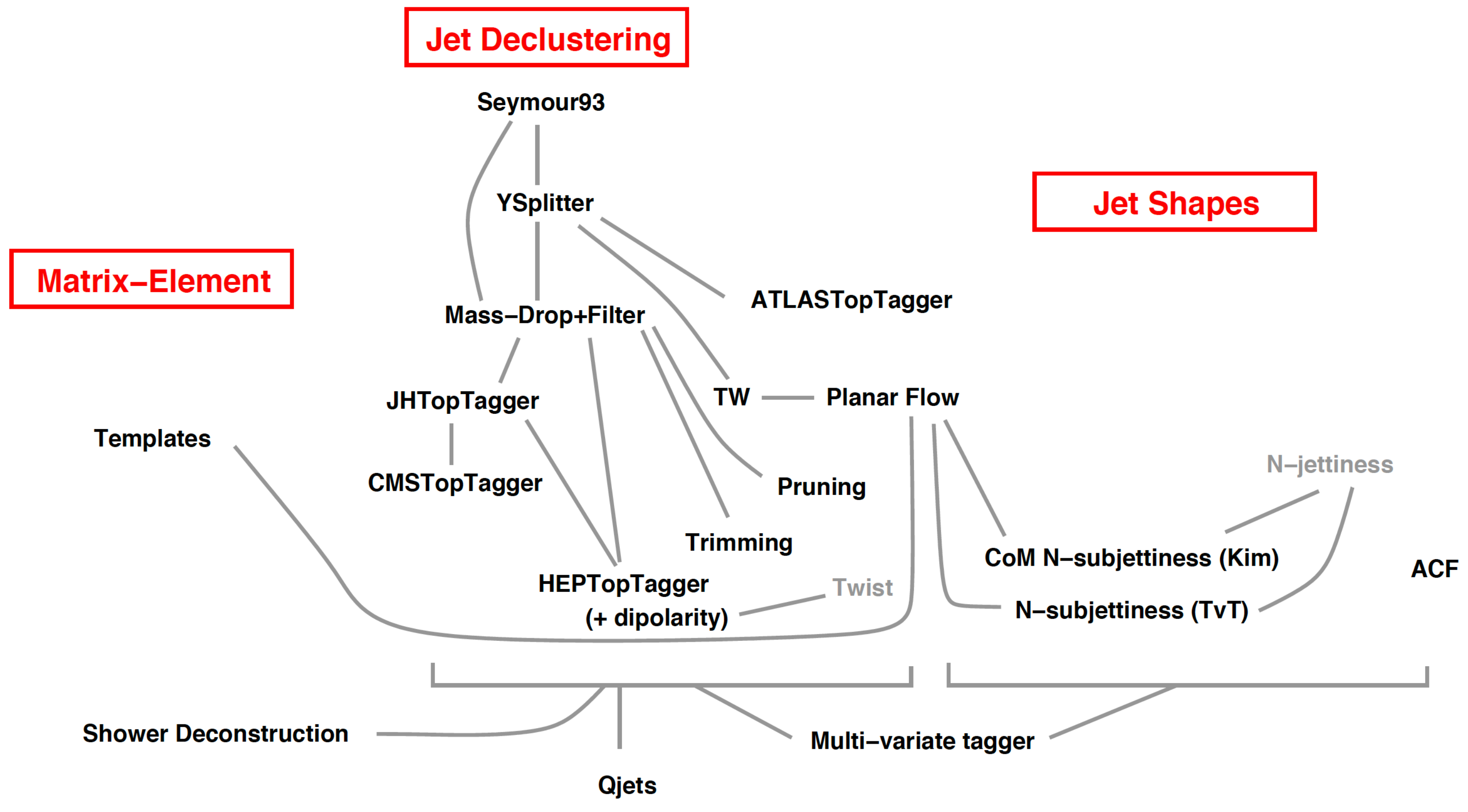
[2005] [Cacciari, Salam, Soyez] [2008]

The fast-jet revolution (2005)

$N^3 \rightarrow N \log N$



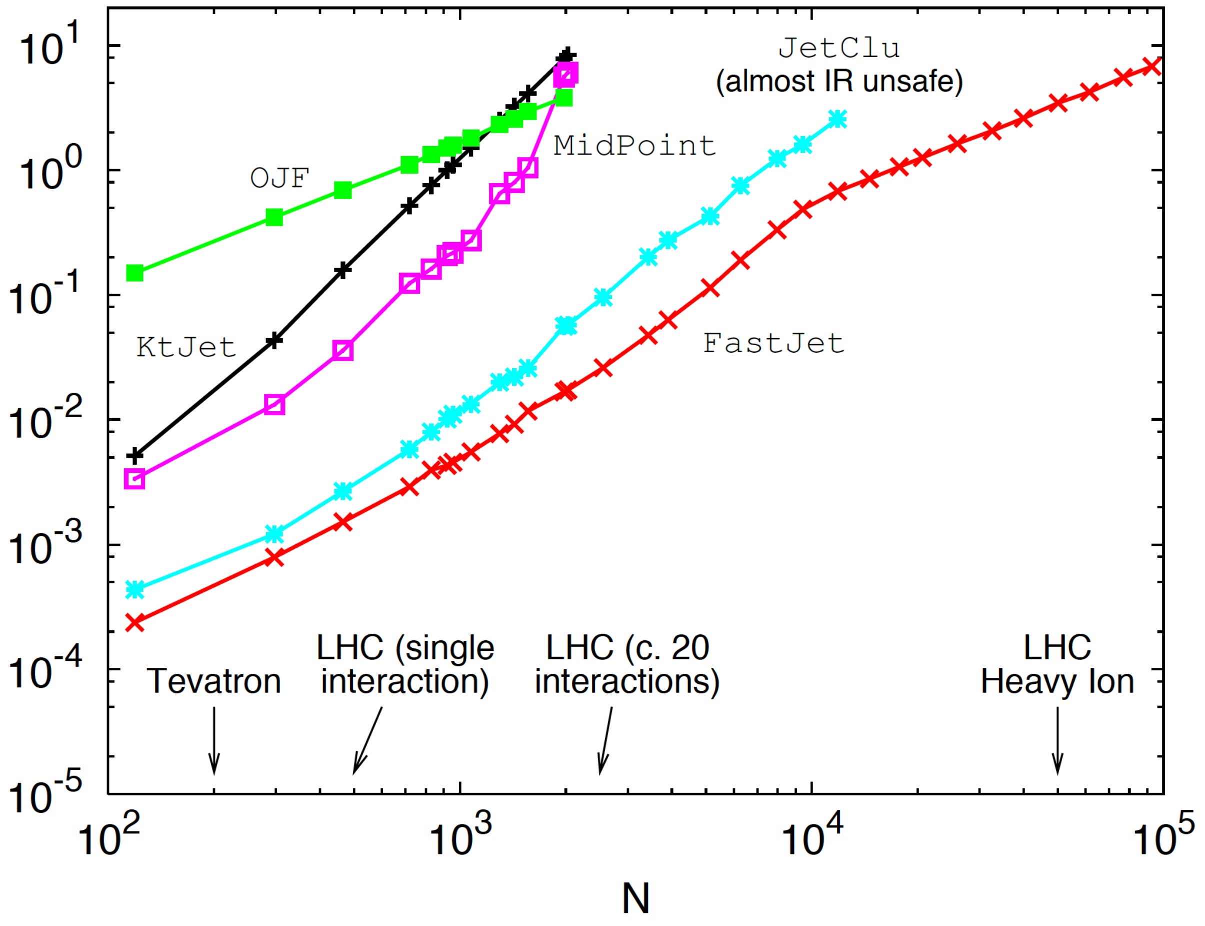


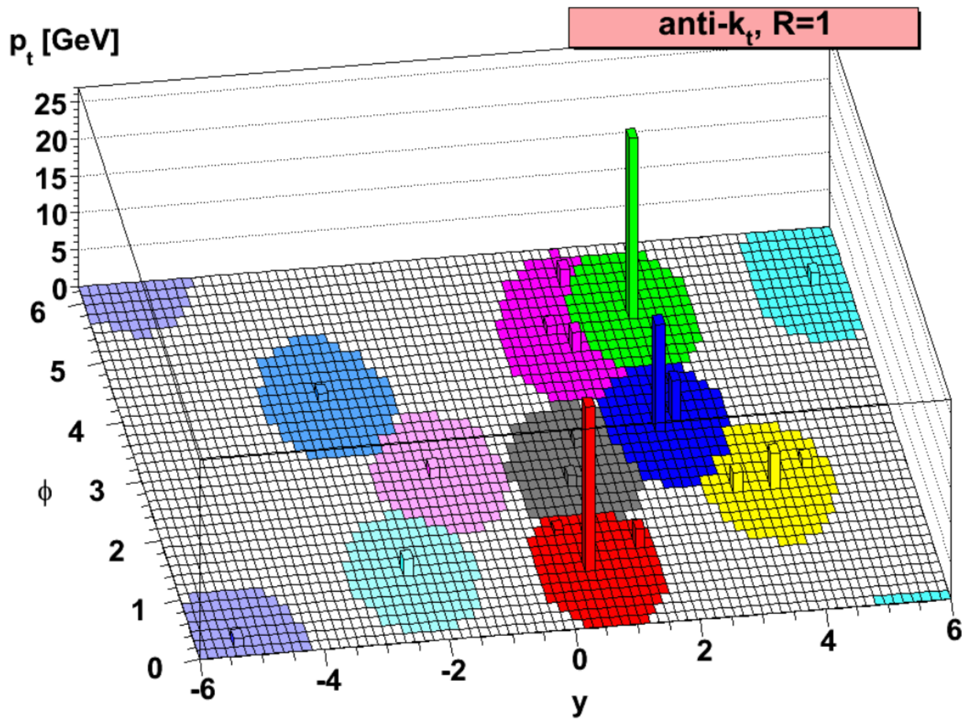


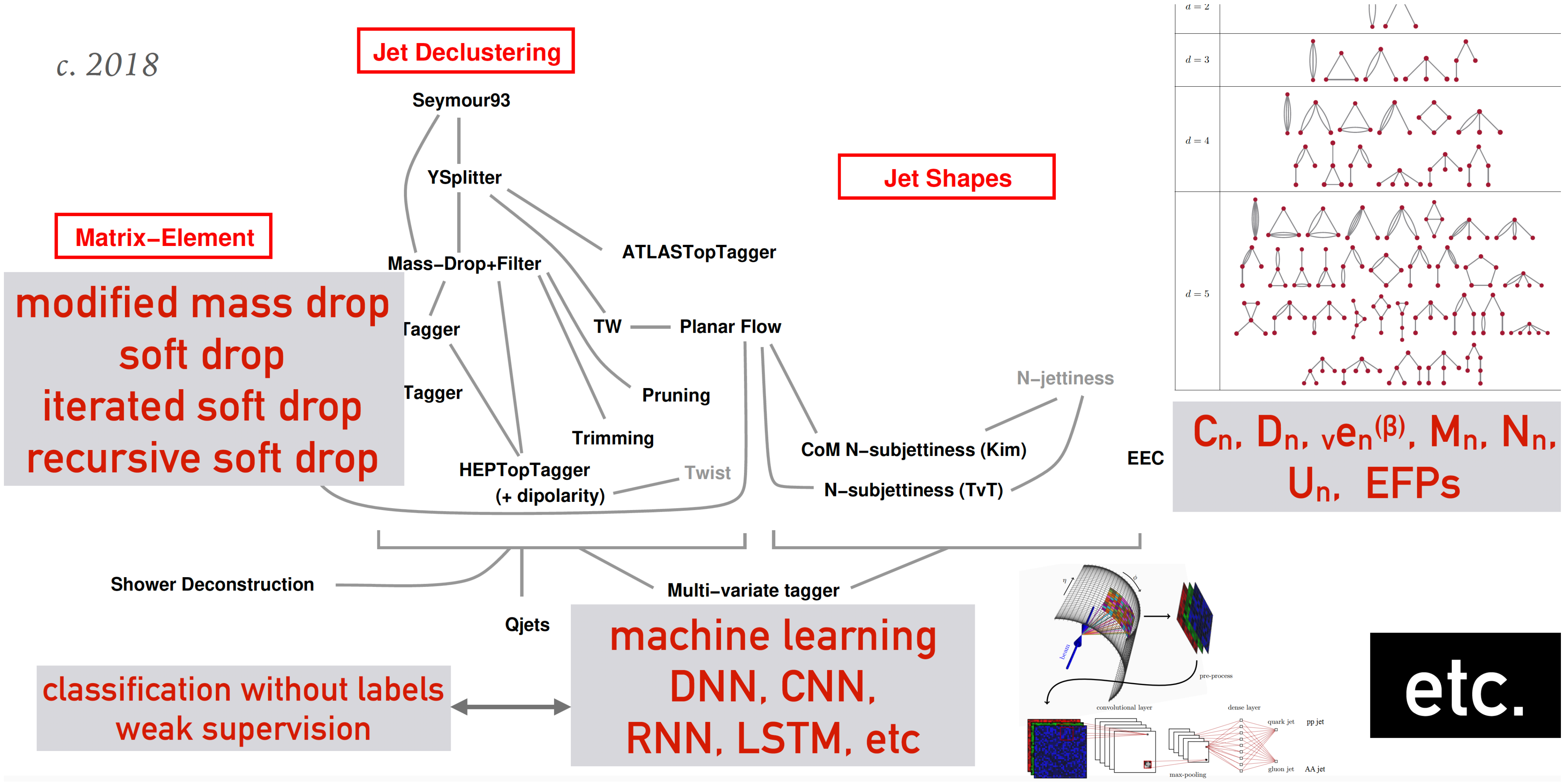
[2005] [Cacciari, Salam, Soyez] [2008]

The fast-jet revolution (2005)

$N^3 \rightarrow N \log N$





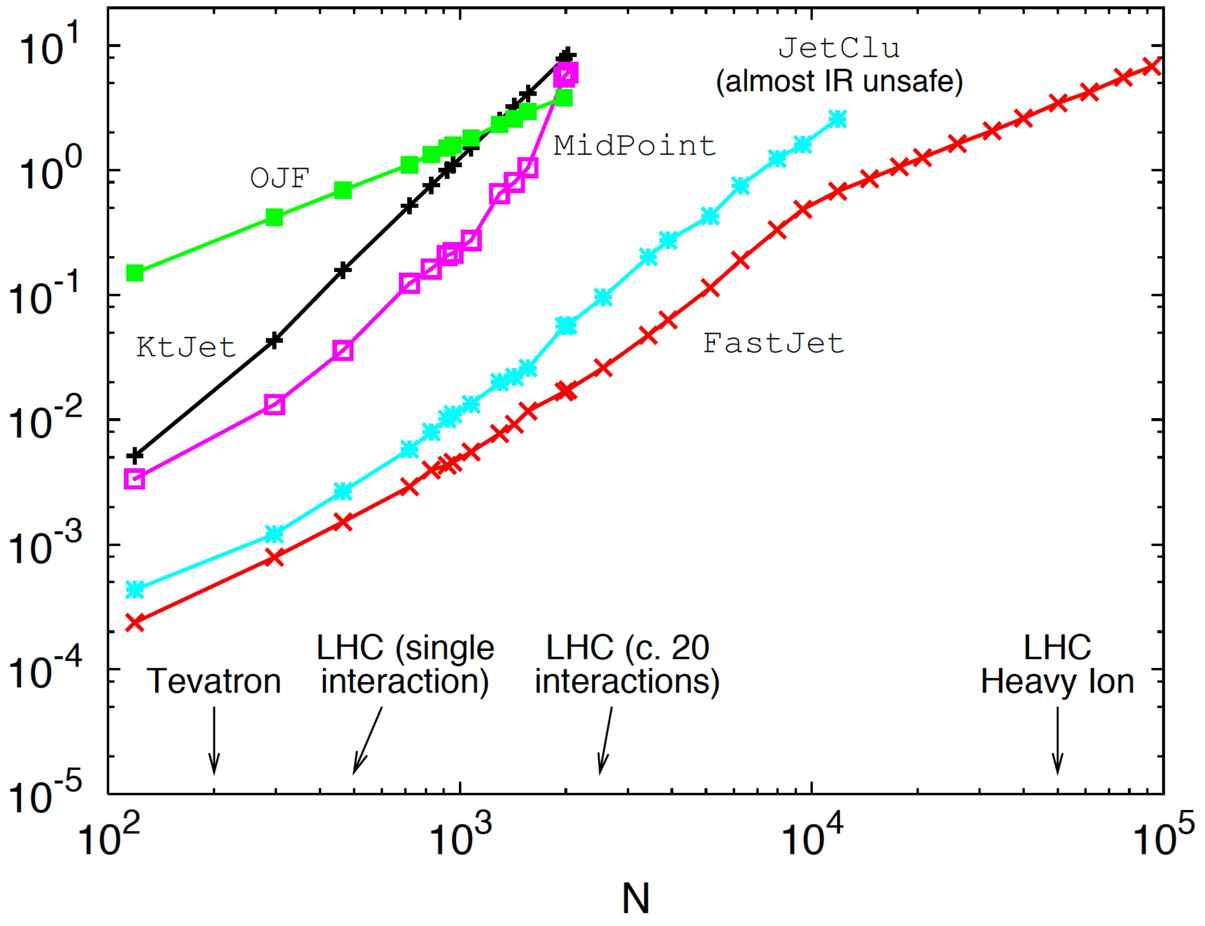


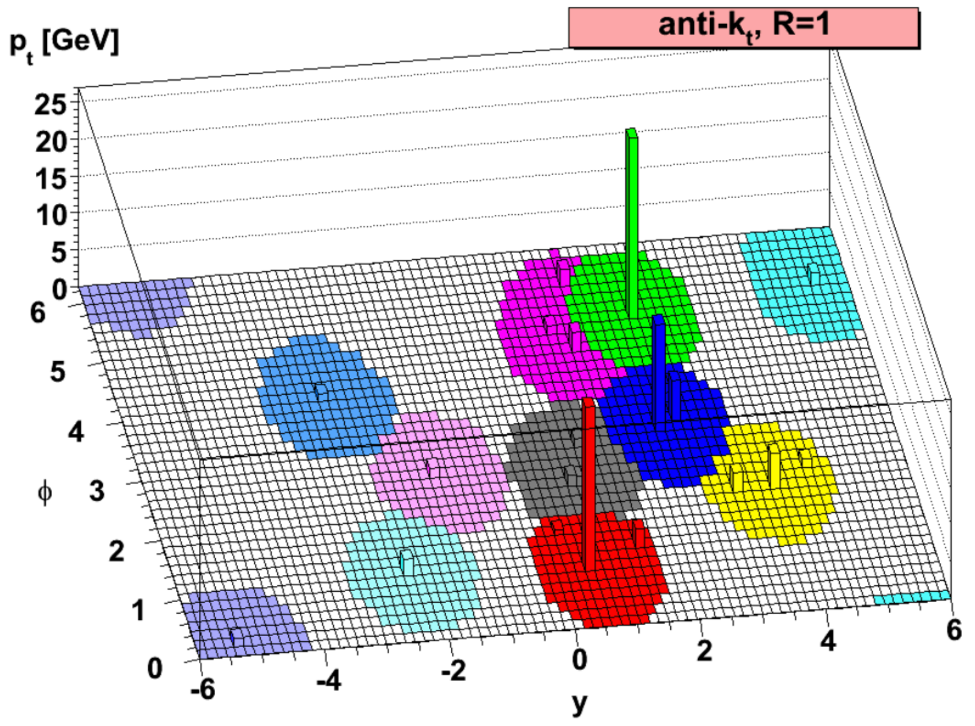
[2005] [Cacciari, Salam, Soyez] [2008]

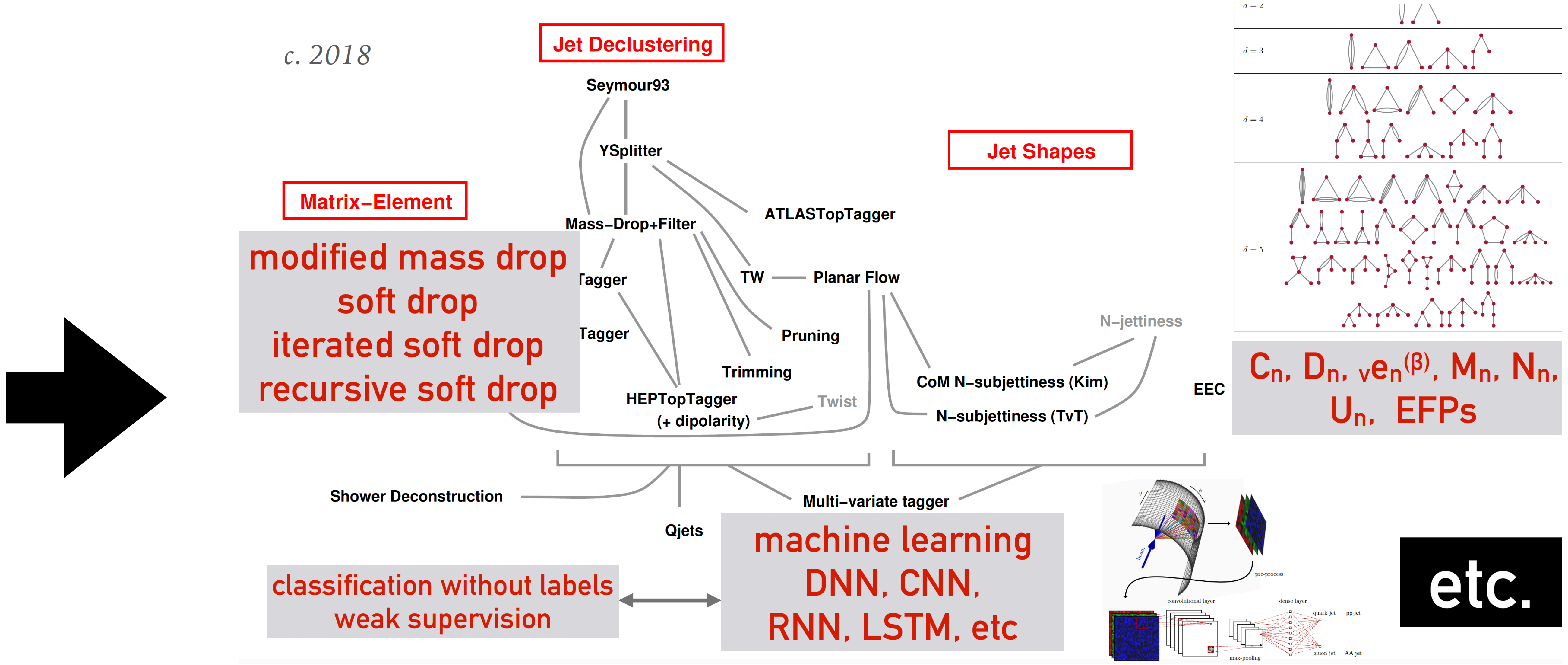
[Gavin Salam @ Boost 2018]

The fast-jet revolution (2005)

$N^3 \to N \log N$







[2005] [Cacciari, Salam, Soyez] [2008]

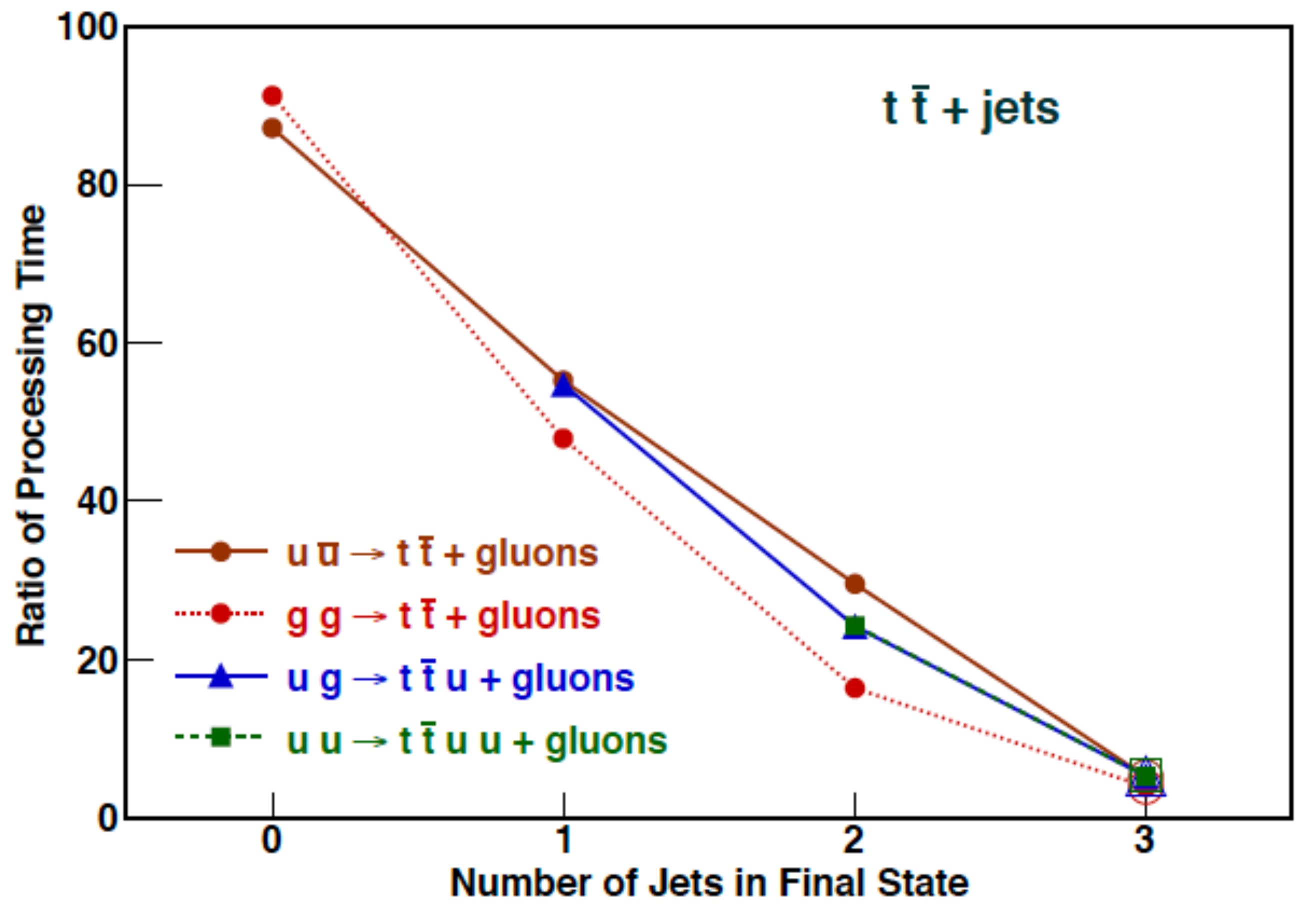
[Gavin Salam @ Boost 2018]

Algorithmic improvement triggered a new field of study in jet sub-structure, tagging, boosted objects, NP searches as well as testing ground for new theoretical ideas, computations and technologies.

Algorithmic challenges

New architectures

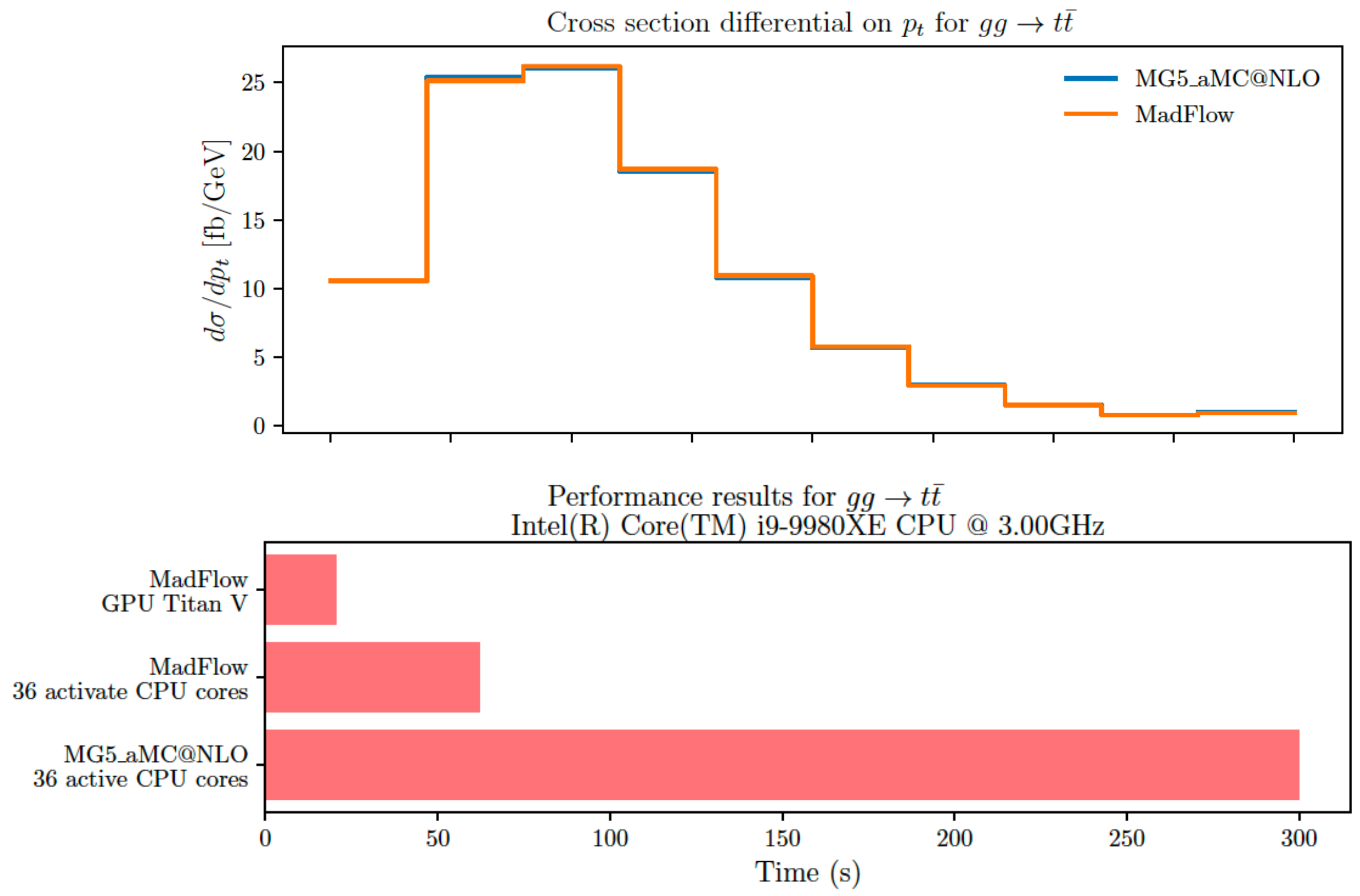
MadGraph on GPUs 2013



[Hagiwara et al. , 1305.0708]

Proof of principle implementation based on CUDA and first GPUs. Memory constraints, large color matrices → huge gains but scaling with # extra partons bad…

MadGraph on GPUs - on going



[S. Carrazza et al. , 2105.10529]

Completely different approach, based on TensorFlow primitives, Vegas and PDF implementations, and of matrix elements using dedicated ALOHA routines.

Algorithmic challenges
Machine Learning techniques

A survey of machine learning-based physics event generation

[Y. Alanazi, et al. 2106.00643]

Understanding Event-Generation Networks via Uncertainties

[M. Bellagente et al 2104.04543]

Phase Space Sampling and Inference from Weighted Events with Autoregressive Flows

[B. Stienen et al. , 2011.13445]

i-flow: High-dimensional Integration and Sampling with Normalizing Flows

[Christina Gao et al. 2001.05486]

How to GAN Event Unweighting

[M. Backes et al. : 2012.07873]

Generative Networks for LHC events

[Anja Butter and Plehn 2008.08558]

Invertible Networks or Partons to Detector and Back Again

[M. Bellagente et al. e-Print: 2006.06685]

How to GAN away Detector Effects

[M. Bellagente et al, 1912.00477]

How to GAN LHC Events

Anja Butter et al. 1907.03764 [hep-ph]

MLEGs	Data Source	Detector Effect	Reaction/Experiment	ML Model
[Hashemi *et al.*, 2019]	Pythia8	DELPHES + pile-up effects	$Z \to \mu^+\mu^-$	regular GAN
[Otten *et al.*, 2019]	MadGraph5 aMC@NLO	DELPHES3	$e^+e^- \to Z \to l^+l^-$, $pp \to t\bar{t}$	VAE
[Butter *et al.*, 2019]	MadGraph5 aMC@NLO		$pp \to t\bar{t} \to (bq\bar{q}')(\bar{b}\bar{q}q')$	MMD-GAN
[Di Sipio *et al.*, 2019]	MadGraph5, Pythia8	DELPHES + FAST-JET	$2 \to 2$ parton scattering	GAN+CNN
[Ahdida *et al.*, 2019]	Pythia8 + GEANT4		Search for Hidden Particles (SHiP) experiment	regular GAN
[Alanazi *et al.*, 2020b] [Velasco *et al.*, 2020]	Pythia8		electron-proton scattering	MMD-WGAN-GP, cGAN
[Martínez *et al.*, 2020]	Pythia8	DELPHES particle-flow	proton collision	GAN, cGAN
[Gao *et al.*, 2020]	Sherpa		$pp \to W/Z + n$ jets	NF
[Howard *et al.*, 2021]	MadGraph5 + Pythia8	DELPHES	$Z \to e^+e^-$	SWAE
[Choi and Lim, 2021]	MadGraph5 + Pythia8	DELPHES	$pp \to bb\gamma\gamma$	WGAN-GP

Impressive progress in the exploration of different methods and in identifying the most relevant questions in last couple of years!

- Can the ML-MC go beyond the statistical precision of the training event samples?
- Can they faithfully reproduce the physics?
- Can they provide new physics insights?

Algorithmic challenges

Machine Learning techniques

A survey of machine learning-based physics event generation

[Y. Alanazi, et al. 2106.00643]

Understanding Event-Generation Networks via Uncertainties

[M. Bellagente et al 2104.04543]

Phase Space Sampling and Inference from Weighted Events with Autoregressive Flows

[B. Stienen et al. , 2011.13445]

i-flow: High-dimensional Integration and Sampling with Normalizing Flows

[Christina Gao et al. 2001.05486]

How to GAN Event Unweighting

[M. Backes et al. : 2012.07873]

Generative Networks for LHC events

[Anja Butter and Plehn 2008.08558]

Invertible Networks or Partons to Detector and Back Again

[M. Bellagente et al. e-Print: 2006.06685]

How to GAN away Detector Effects

[M. Bellagente et al, 1912.00477]

How to GAN LHC Events

Anja Butter et al. 1907.03764 [hep-ph]

Impressive progress in the exploration of different methods and in identifying the most relevant questions in last couple of years!

- Can the ML-MC go beyond the statistical precision of the training event samples?
- Can they faithfully reproduce the physics?
- Can they provide new physics insights?

Algorithmic challenges

Machine Learning techniques

[A survey of machine learning-based physics event generation](#)

[Y. Alanazi, et al. 2106.00643]

[Understanding Event-Generation Networks via Uncertainties](#)

[M. Bellagente et al 2104.04543]

[Phase Space Sampling and Inference from Weighted Events with Autoregressive Flows](#)

[B. Stienen et al. , 2011.13445]

[i-flow: High-dimensional Integration and Sampling with Normalizing Flows](#)

[Christina Gao et al. 2001.05486]

[How to GAN Event Unweighting](#)

[M. Backes et al. : 2012.07873]

[Generative Networks for LHC events](#)

[Anja Butter and Plehn 2008.08558]

[Invertible Networks or Partons to Detector and Back Again](#)

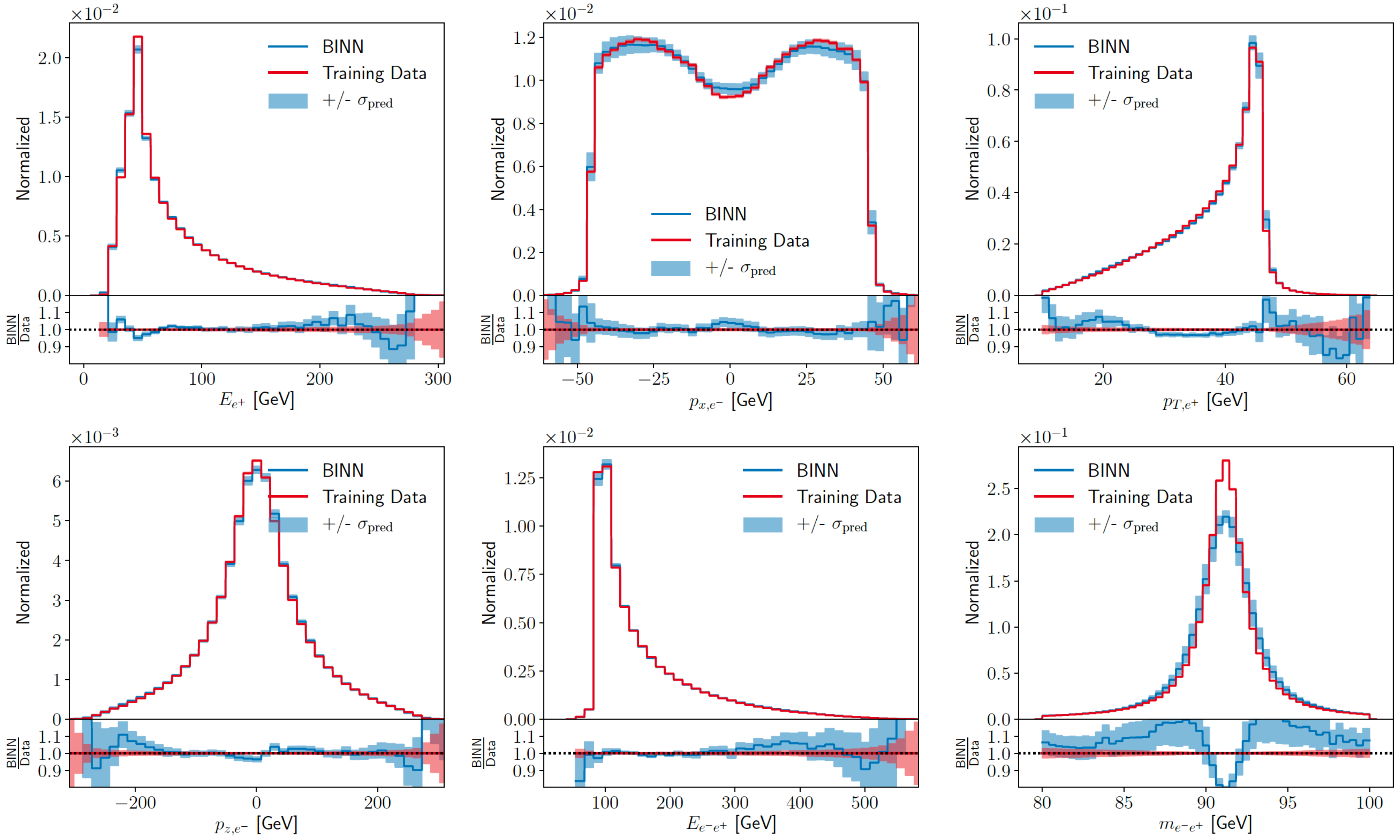
[M. Bellagente et al. e-Print: 2006.06685]

[How to GAN away Detector Effects](#)

[M. Bellagente et al, 1912.00477]

[How to GAN LHC Events](#)

Anja Butter et al. 1907.03764 [hep-ph]



Impressive progress in the exploration of different methods and in identifying the most relevant questions in last couple of years!

- Can the ML-MC go beyond the statistical precision of the training event samples?
- Can they faithfully reproduce the physics?
- Can they provide new physics insights?

Algorithmic challenges

Quantum Computing

Growing interest in quantum computations for HEP:

Quantum Algorithm for High Energy Physics Simulations
[C. W. Bauer et al. 1904.03196]

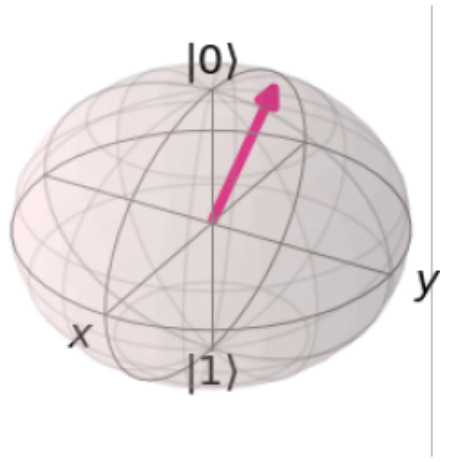
Quantum Algorithms for Jet Clustering
Annie Y. Wei et al. 1908.08949 [hep-ph]

Towards a quantum computing algorithm for helicity amplitudes and parton showers
Khadeejah Bepari et al. 2010.00046 [hep-ph]

Determining the proton content with a quantum computer
Adrián Pérez-Salinas et al. 2011.13934

Simulating collider physics on quantum computers using effective field theories
C. W. Bauer et al. 2102.05044 [hep-ph]

Quantum algorithm for Feynman loop integrals
Selomit Ramírez-Uribe et al. 2105.08703

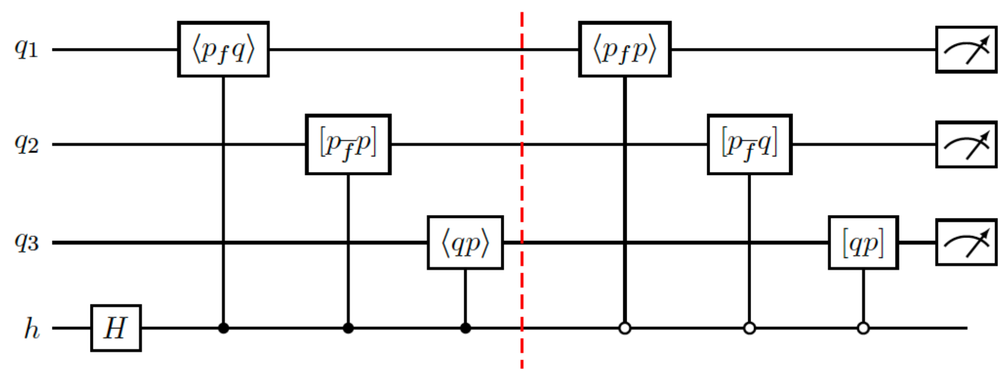


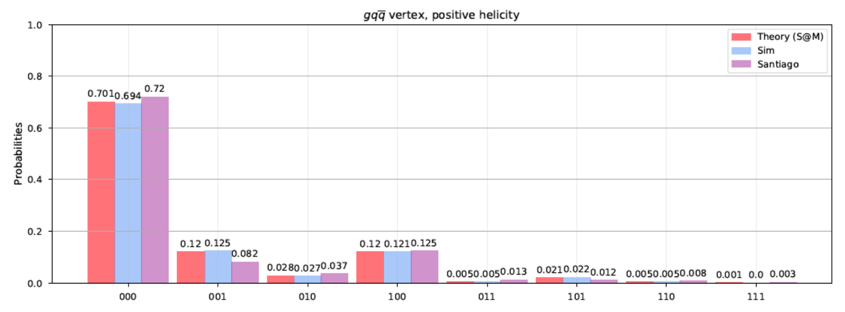
$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle = \begin{pmatrix} \cos\frac{\theta}{2} \\ \sin\frac{\theta}{2}e^{i\phi} \end{pmatrix},$$

(a) $|p\rangle^{\dot{a}}$

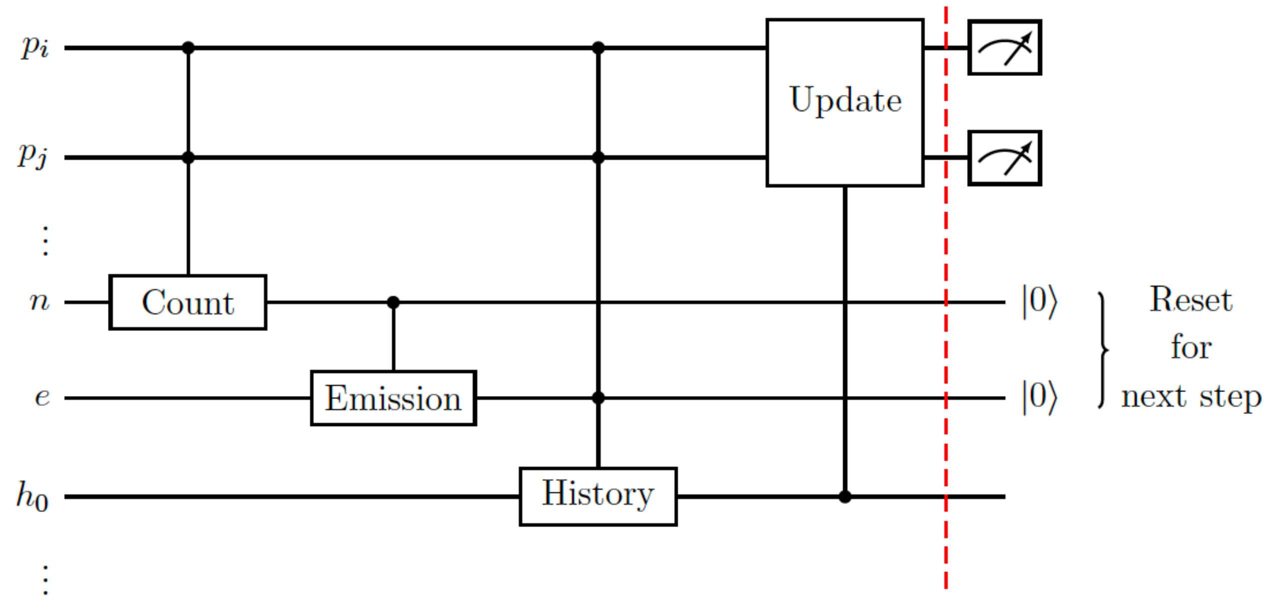
sum over helicities

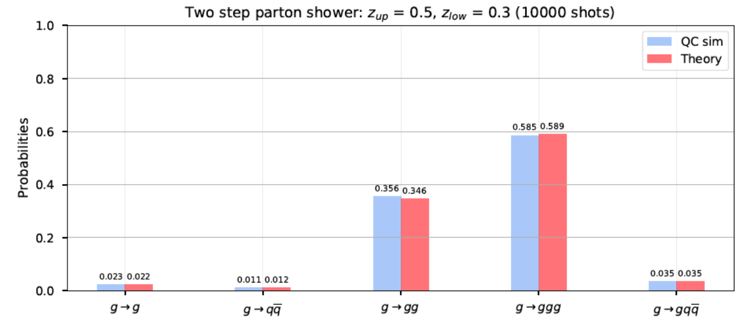
$$\mathcal{M}_{+} = -\sqrt{2}\frac{\langle p_f q\rangle[p_{\bar{f}}p]}{\langle qp\rangle}, \qquad \mathcal{M}_{-} = -\sqrt{2}\frac{\langle p_f p\rangle[p_{\bar{f}}q]}{[qp]}.$$





sum over PS histories





Many initiatives (see e.g. https://quanthep.eu/)

Precision physics at the HL-LHC

The main questions

1. Given the statistics increase of a factor ~20 with respect to what we currently have what is the expected experimental precision on key EW/top/Higgs measurements and a reasonable goal for TH predictions?

2. How will we achieve it? What is it needed? What are the challenges and the current avenues?

3. How to frame and interpret our results?

Searching for new interactions with an EFT

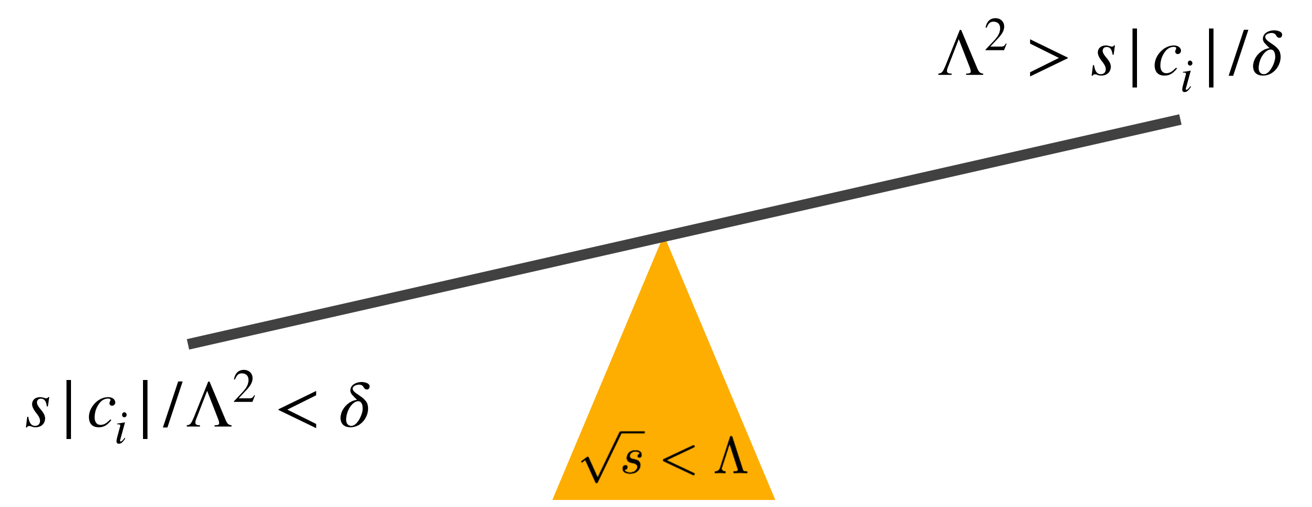
A simple approach

One can satisfy all the previous requirements, by building an EFT on top of the SM that respects the gauge symmetries:

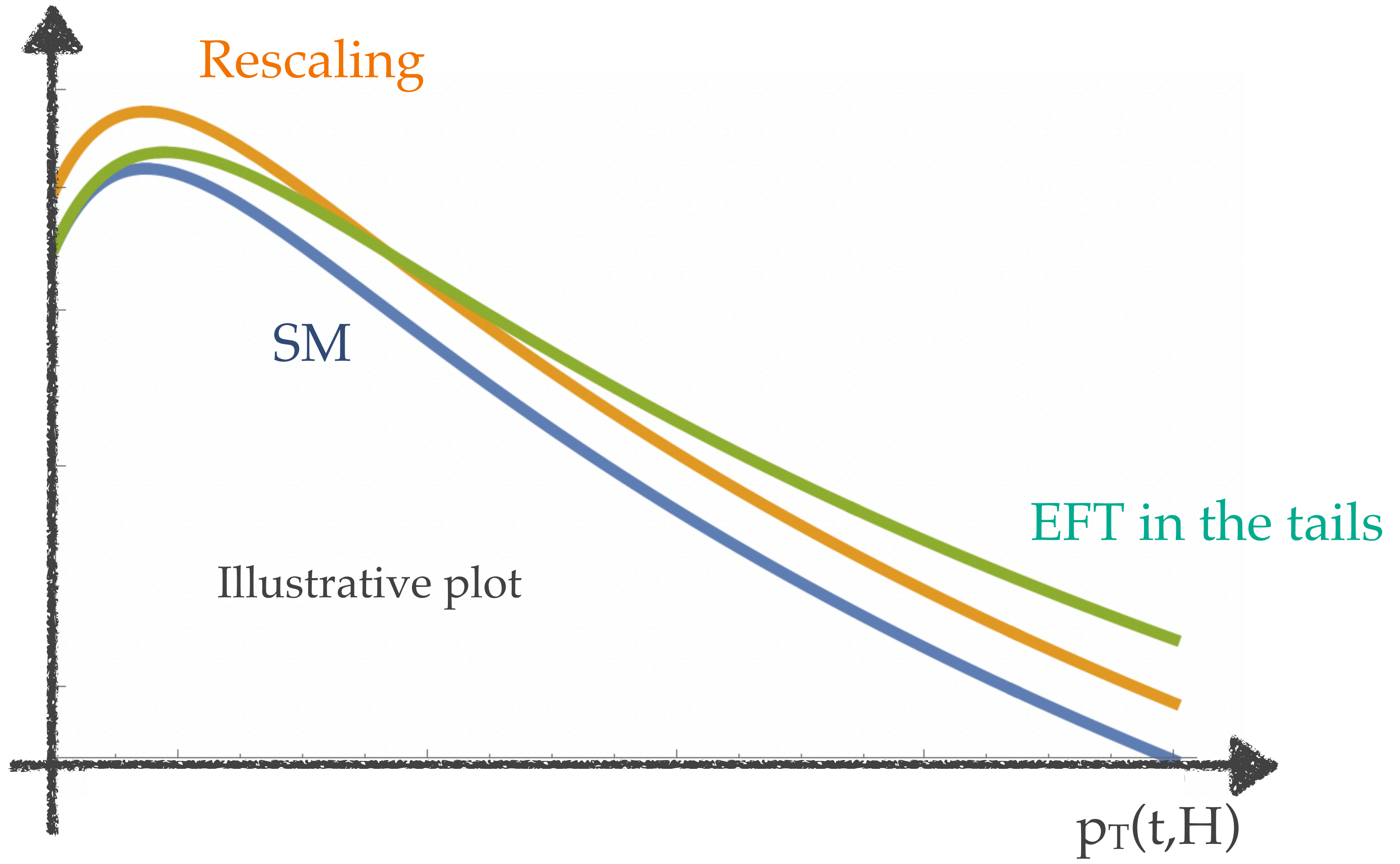
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots$$

With the "only" assumption that all new states are heavier than energy probed by the experiment $\sqrt{s} < \Lambda$.

The theory is renormalizable order by order in $1/\Lambda$, perturbative computations can be consistently performed at any order, and the theory is predictive, i.e., well defined patterns of deviations are allowed, that can be further limited by adding assumptions from the UV. Operators can lead to larger effects at high energy (for different reasons).



Energy helps precision



* Sufficiently weakly interacting states may also exist without spoiling the EFT.

A powerful approach

Searching for new interactions with an EFT

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2}\sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

A powerful approach

Searching for new interactions with an EFT

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Most precise/accurate experimental measurements with uncertainties and correlations

A powerful approach

Searching for new interactions with an EFT

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Most precise SM predictions for observables:
NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations

A powerful approach

Searching for new interactions with an EFT

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Most precise EFT predictions

Most precise SM predictions for observables:
NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations

A powerful approach

Searching for new interactions with an EFT

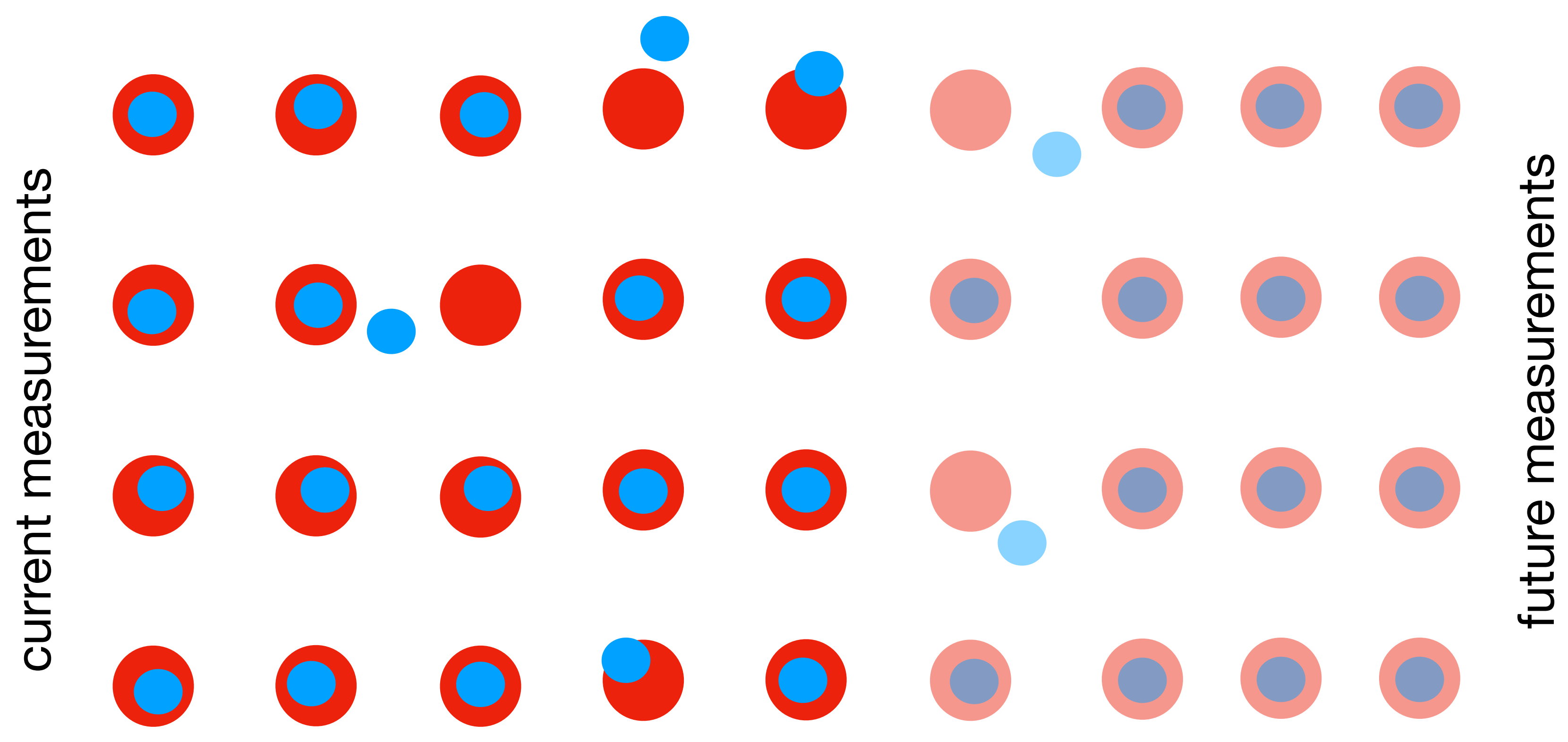
The master equation of an EFT approach has three key elements:

$$\Delta\mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2}\sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Most precise EFT predictions

Most precise SM predictions for observables:
NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations



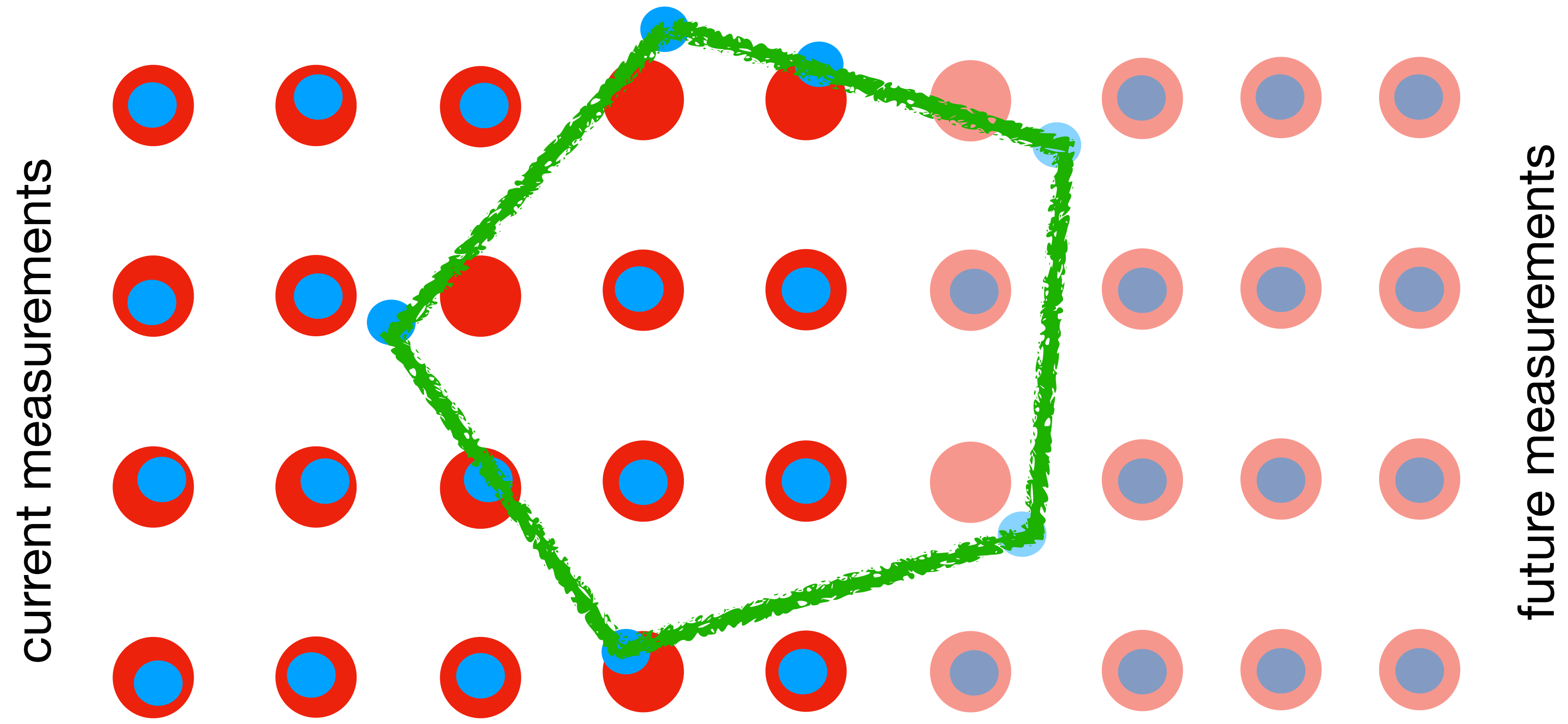
$\Rightarrow$ increased NP Sensitivity

A powerful approach

Searching for new interactions with an EFT

The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2}\sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



$\Rightarrow$ increased NP Sensitivity

Most precise EFT predictions

Most precise SM predictions for observables:
NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations

A powerful approach

Searching for new interactions with an EFT

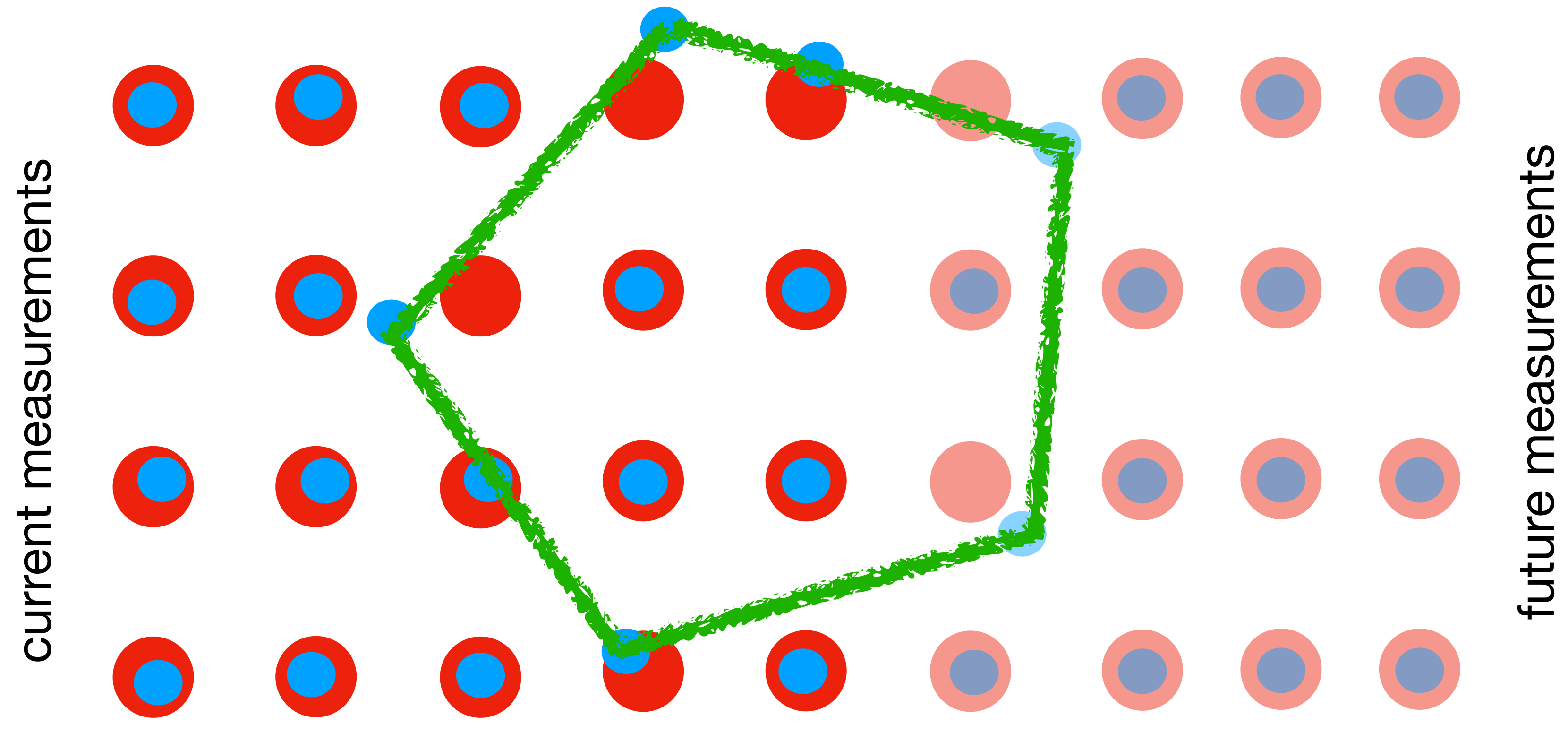
The master equation of an EFT approach has three key elements:

$$\Delta \mathrm{Obs}_n = \mathrm{Obs}_n^{\mathrm{EXP}} - \mathrm{Obs}_n^{\mathrm{SM}} = \frac{1}{\Lambda^2} \sum_i a_{n,i}^{(6)}(\mu)\, c_i^{(6)}(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Most precise EFT predictions

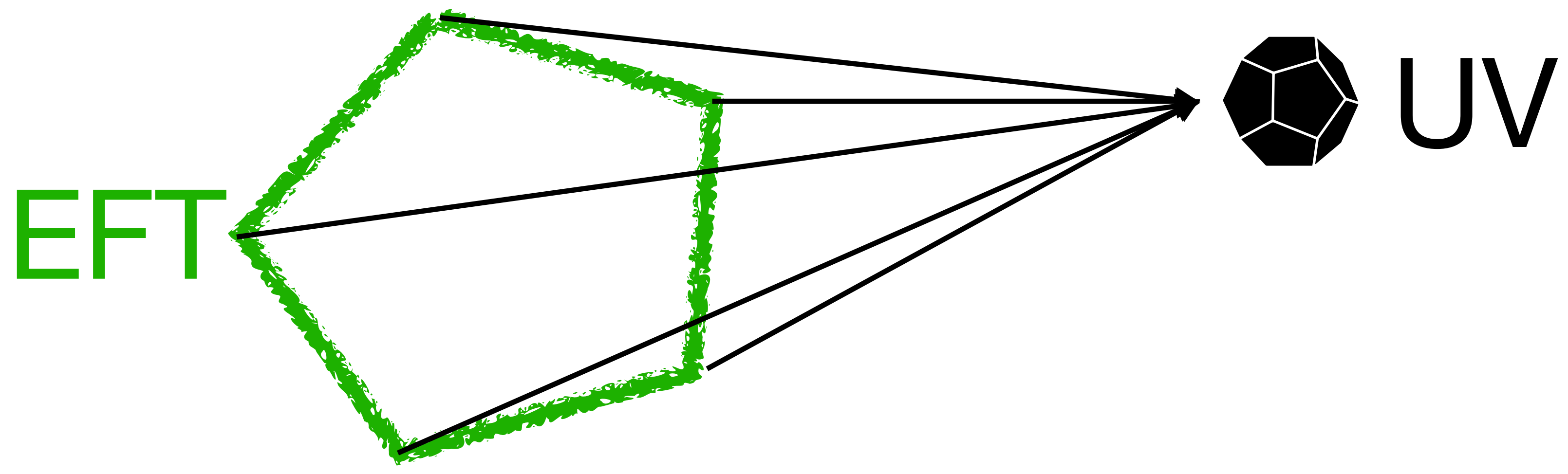
Most precise SM predictions for observables:
NLO, NNLO, N3LO…

Most precise/accurate experimental measurements with uncertainties and correlations



⇒ increased NP Sensitivity

⇒ increased UV identification power



Precision Physics
First round of considerations

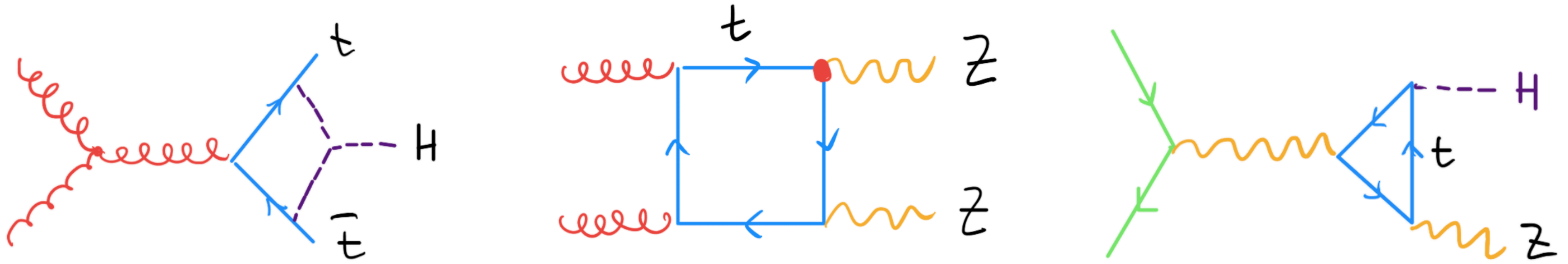
- Running and exploiting the (HL)-LHC is a major challenge from both the TH/EXP p.o.v's.
- Several breakthroughs are expected to occur along the way.
- The TH "1% goal" gives an idea of the advancements in the precision that will be needed to meet the exp precision.
- The EFT approach provides a universal, consistent and systematically improvable language to interpret the exp data and combine/communicate with other exps. Huge potential.
- Just moving now the first steps into global EFT interpretations, steep learning curve. Major changes in the way exp measurements are performed and value is perceived will occur.

Extra information

A powerful approach
Progress in SMEFT at 1-loop level

1-loop accuracy allows:

- Unveil the SMEFT structure (mixing)
- K-factors (accuracy)
- Scale uncertainties (precision)
- Exploit loop sensitivity:

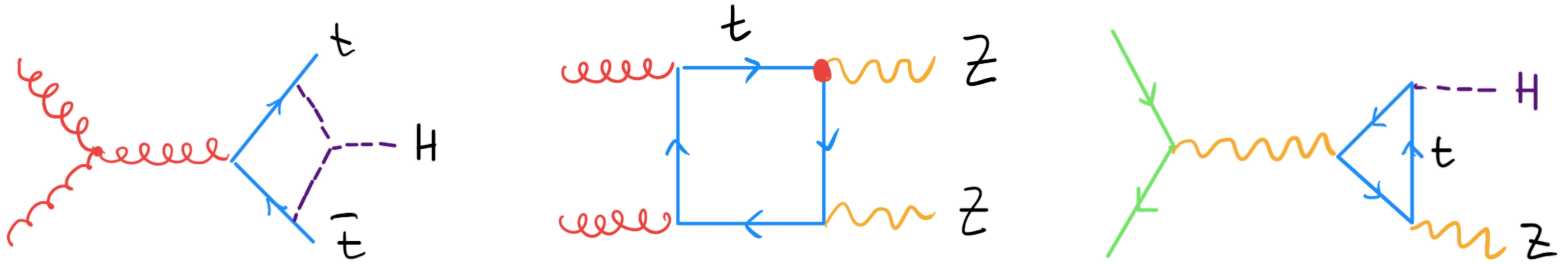


"same strategy" as in SM@dim4

A powerful approach
Progress in SMEFT at 1-loop level

1-loop accuracy allows:

- Unveil the SMEFT structure (mixing)
- K-factors (accuracy)
- Scale uncertainties (precision)
- Exploit loop sensitivity:



"same strategy" as in SM@dim4

RGE

· Anomalous dimension matrix [Jenkins, Manohar and Trott, 2013,2014,2014]

Production

· pp→jj (4F) [Gao, Li, Wang, Zhu, Yuan, 2011]
· pp→tt (4F) [Shao, Li, Wang, Gao, Zhang, Zhu, 2011]
· pp →VV [Dixon, Kunszt, Signer ,1999] [Melia, Nason, Röntsch, Zanderighi ,2011] [Baglio, Dawson, Lewis ,2017,2018,2019][Chiesa et al., 2018]
· top FCNCs [Degrande, FM, Wang, Zhang ,2014] [Durieux, FM, Zhang ,2014]
· pp →tt (chromo) [Franzosi, Zhang ,2015]
· pp →tj [Zhang ,2016] [de Beurs, Laenen, Vreeswijk, Vryonidou ,2018]
· pp → ttZ [Rontsch and Schulze,2015] [Bylund, FM, Tsinikos, Vryonidou, Zhang ,2016]
· pp → ttH [FM, Vryonidou, Zhang ,2016]
· pp →HV,Hjj [Greljo, Isidori, Lindert, Marzocca, 2015][Degrande, Fuks, Mawatari, Mimasu, Sanz ,2016], [Alioli, Dekens, Girard, Mereghetti ,2018]
· pp→H [Grazzini, Ilnicka, Spira, Wiesemann ,2016] [Deutschmann, Duhr, FM, Vryonidou ,2017]
· pp → tZj,tHj [Degrande, FM, Mimasu, Vryonidou, Zhang ,2018]
· pp → jets [Hirschi, FM, Tsinikos, Vryonidou ,2018]
· pp → VVV [Degrande, Durieux, FM, Mimasu, Vryonidou, Zhang, 20xx]
· gg → ZH,Hj,HH [Bylund, FM, Tsinikos, Vryonidou, Zhang ,2016]
· Higgs self-couplings [McCullough, 2014][Degrassi, Giardino, FM, Pagani, Shivaji, Zhao, 2016-2018][Borowka et al. 2019][FM,Pagani, Zhao, 2019]
· EW loops in tt [Kuhn et al.,1305.5773], [Martini 1911.11244]
· EW top loops in Higgs & EW [Vryonidou, Zhang ,2018][Durieux, Gu, Vryonidou, Zhang ,2018] [Boselli et al. 2019]
· Drell-Yan (EW corrections) [Dawson and Giardino, 2021]

Decay

· Top [Zhang ,2014] [Boughezal, Chen, Petriello, Wiegand ,2019]
· h → VV [Hartmann, Trott ,2015] [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati ,2015, 2015] [Dawson, Giardino ,2018,2018][Dedes, et al. ,2018] [Dedes, Suxho, Trifyllis ,2019]
· h → ff [Gauld, Pecjak, Scott ,2016] [Cullen, Pecjak, Scott ,2019][Cullen, Pecjak, ,2020]
· Z,W [Hartmann, Shepherd, Trott ,2016] [Dawson, Ismail, Giardino ,2018,2018,2019]

EWPO

· EWPO [Zhang, Greiner, Willenbrock '12] [Dawson, Giardino ,2020]

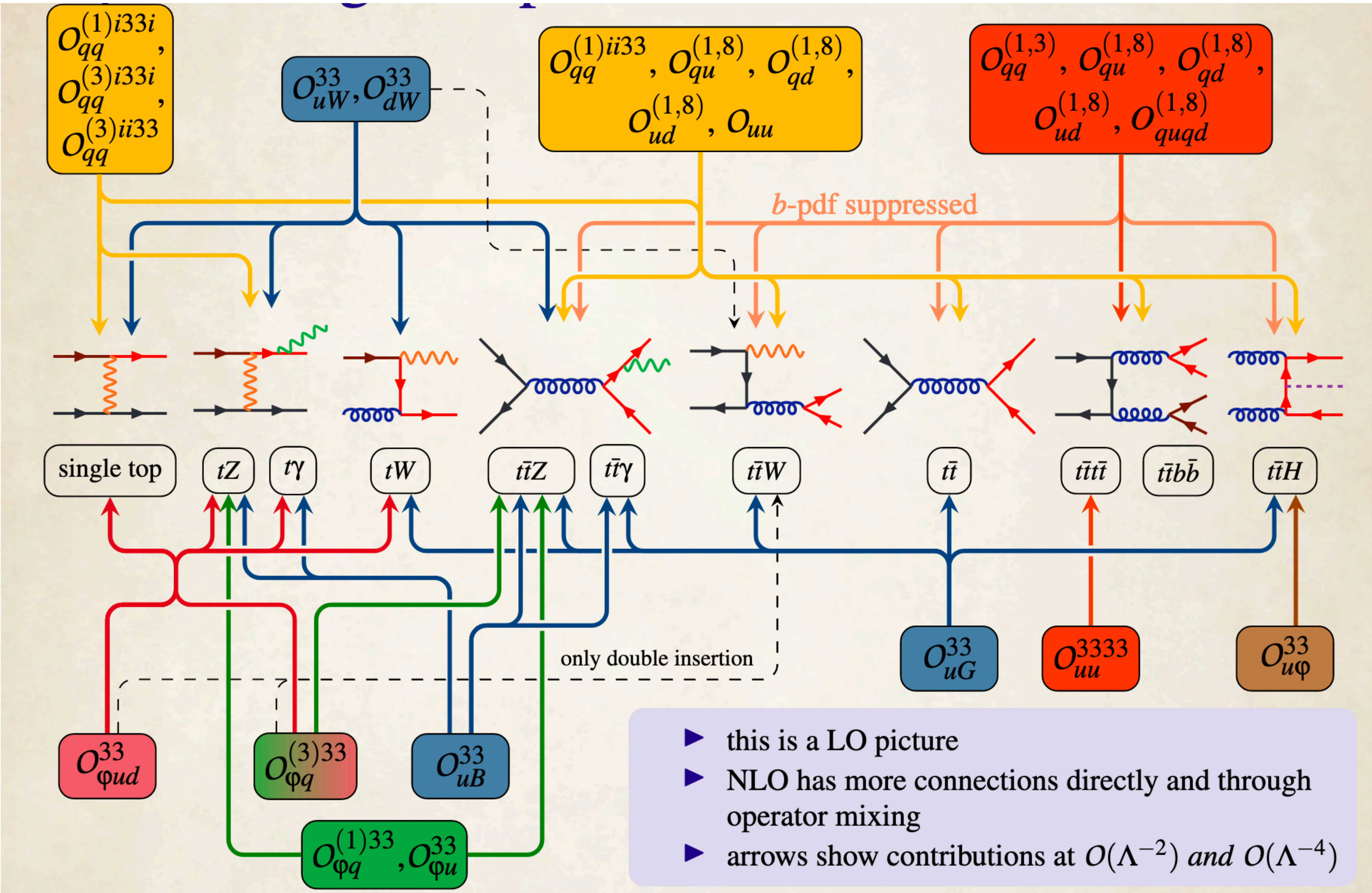
A powerful approach

Is this easy?

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

[Galler, ICHEP2020]



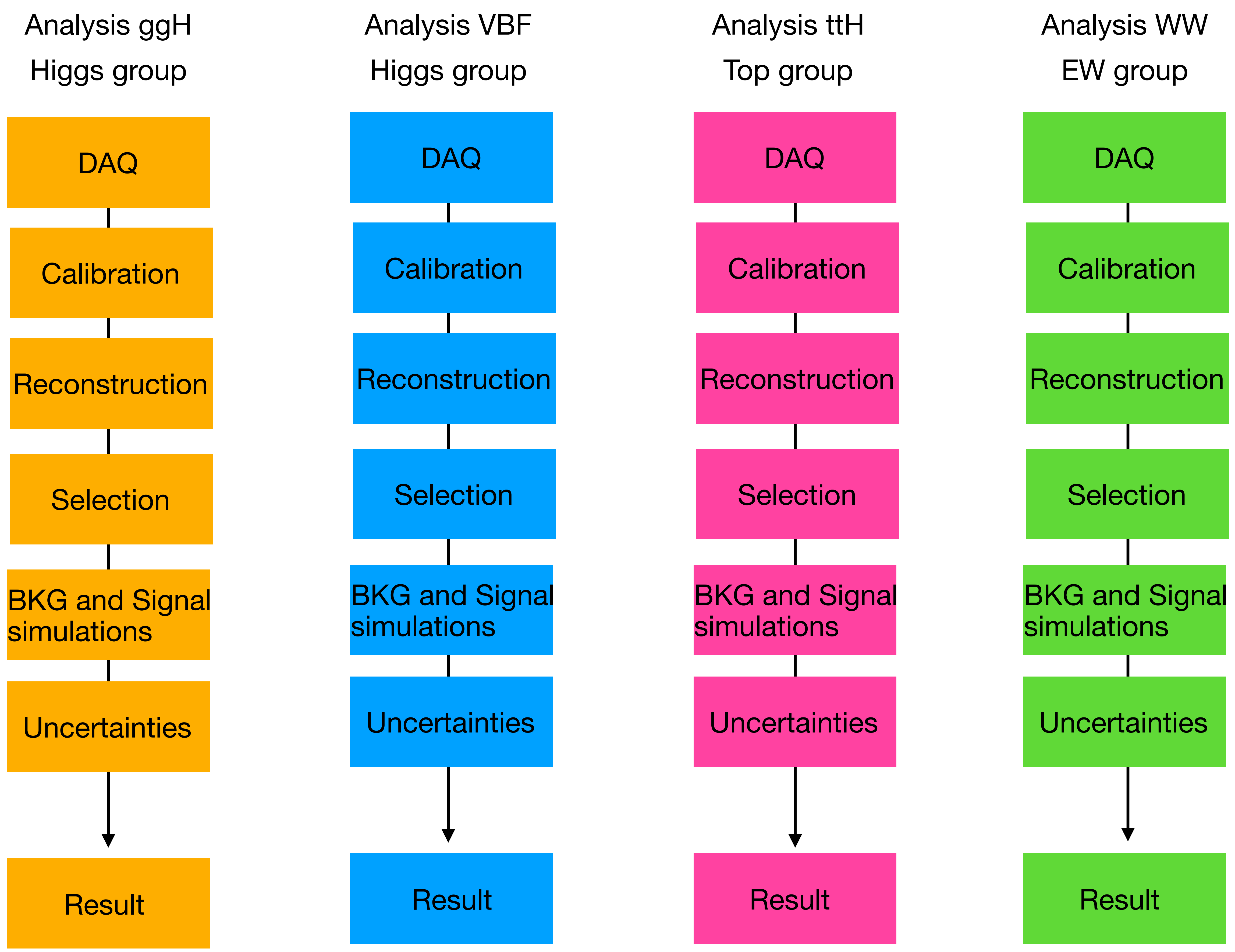
A powerful approach

Is this easy?

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)



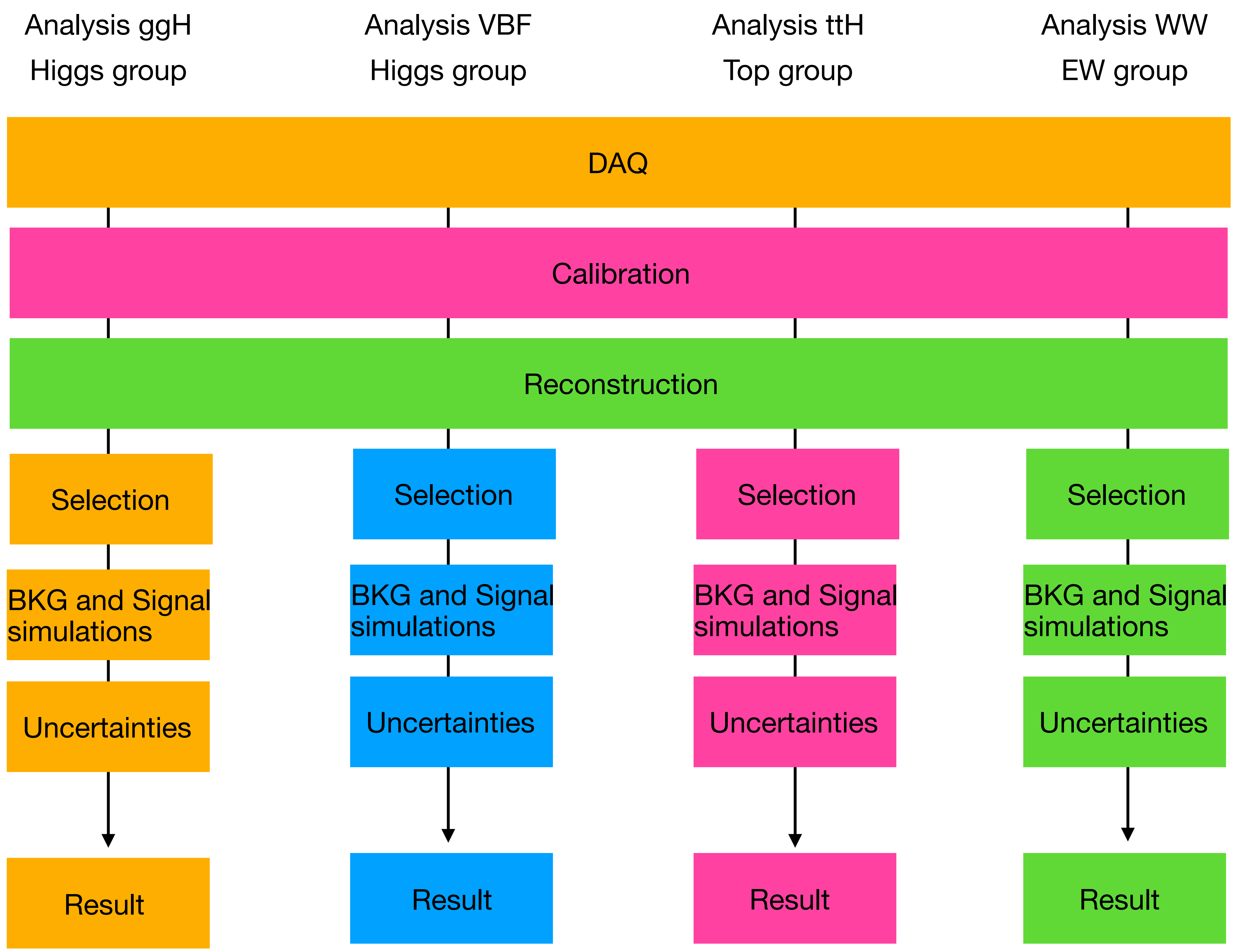
A powerful approach

Is this easy?

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)



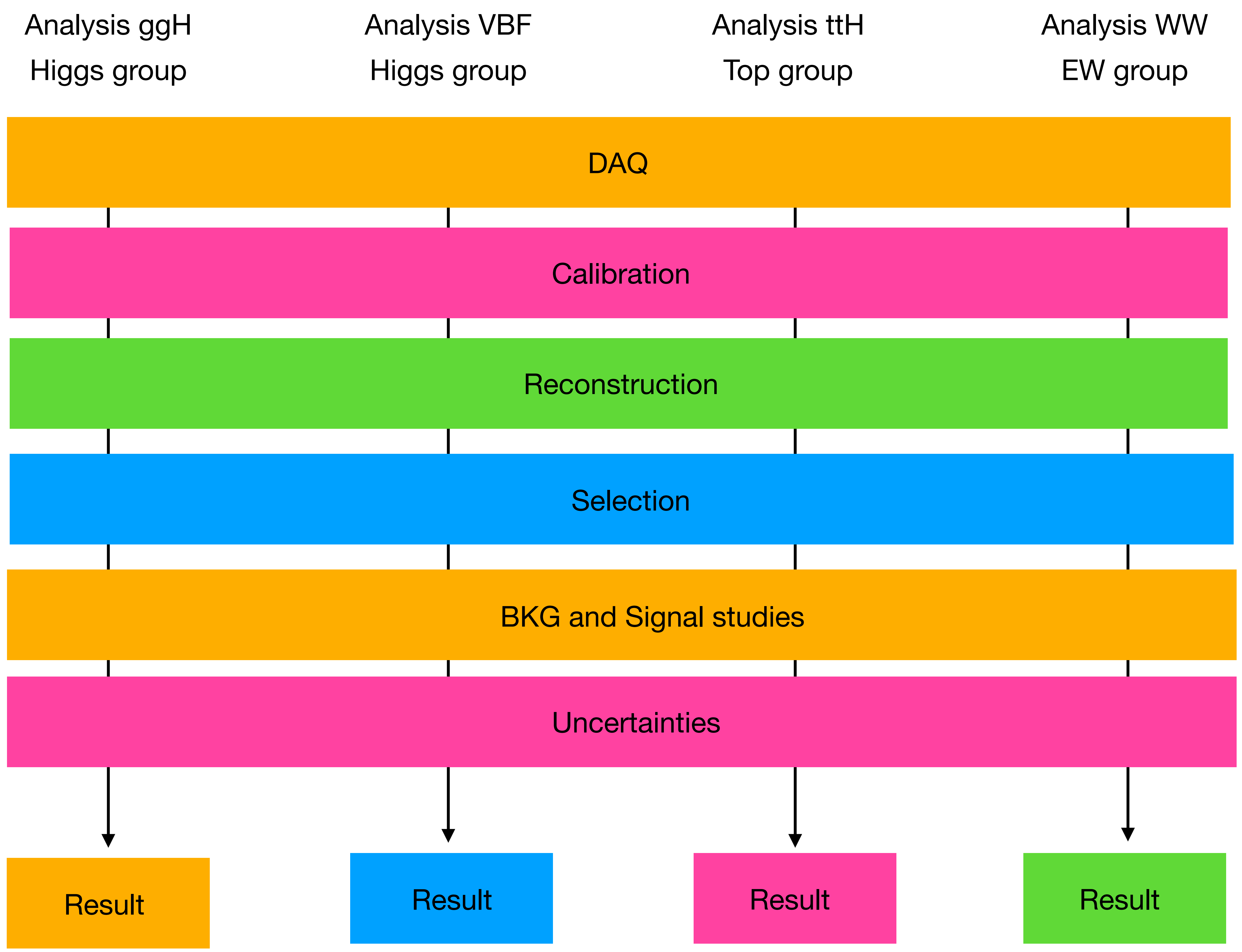
A powerful approach

Is this easy?

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)



A powerful approach
Is this easy?

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)

Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

A LHC EFT WG has been set up to move things forward.

A powerful approach

Is this easy?

It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)

Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

A LHC EFT WG has been set up to move things forward.

Top-down

A powerful approach

Is this easy?

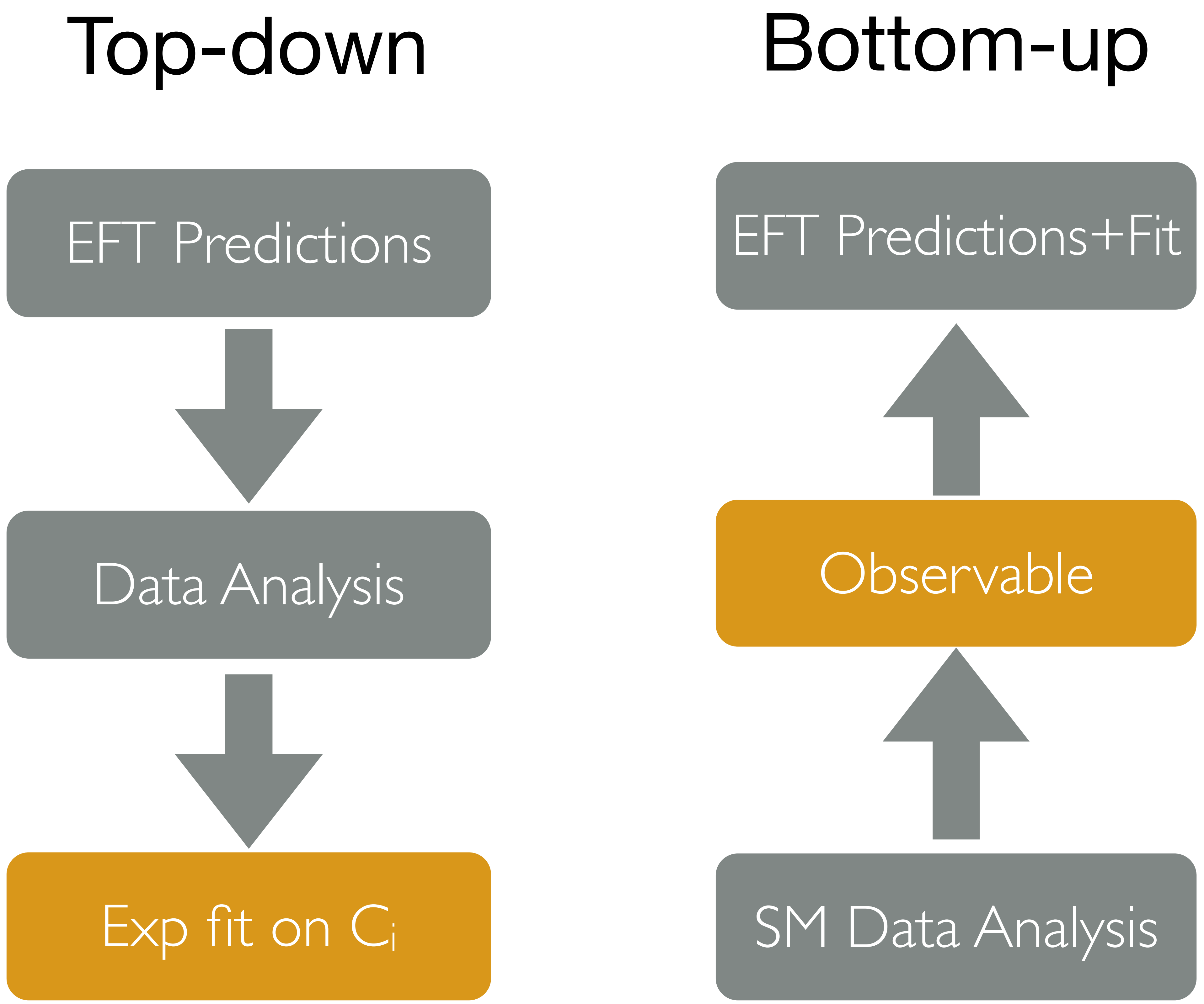
It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)

Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

A LHC EFT WG has been set up to move things forward.



A powerful approach

Is this easy?

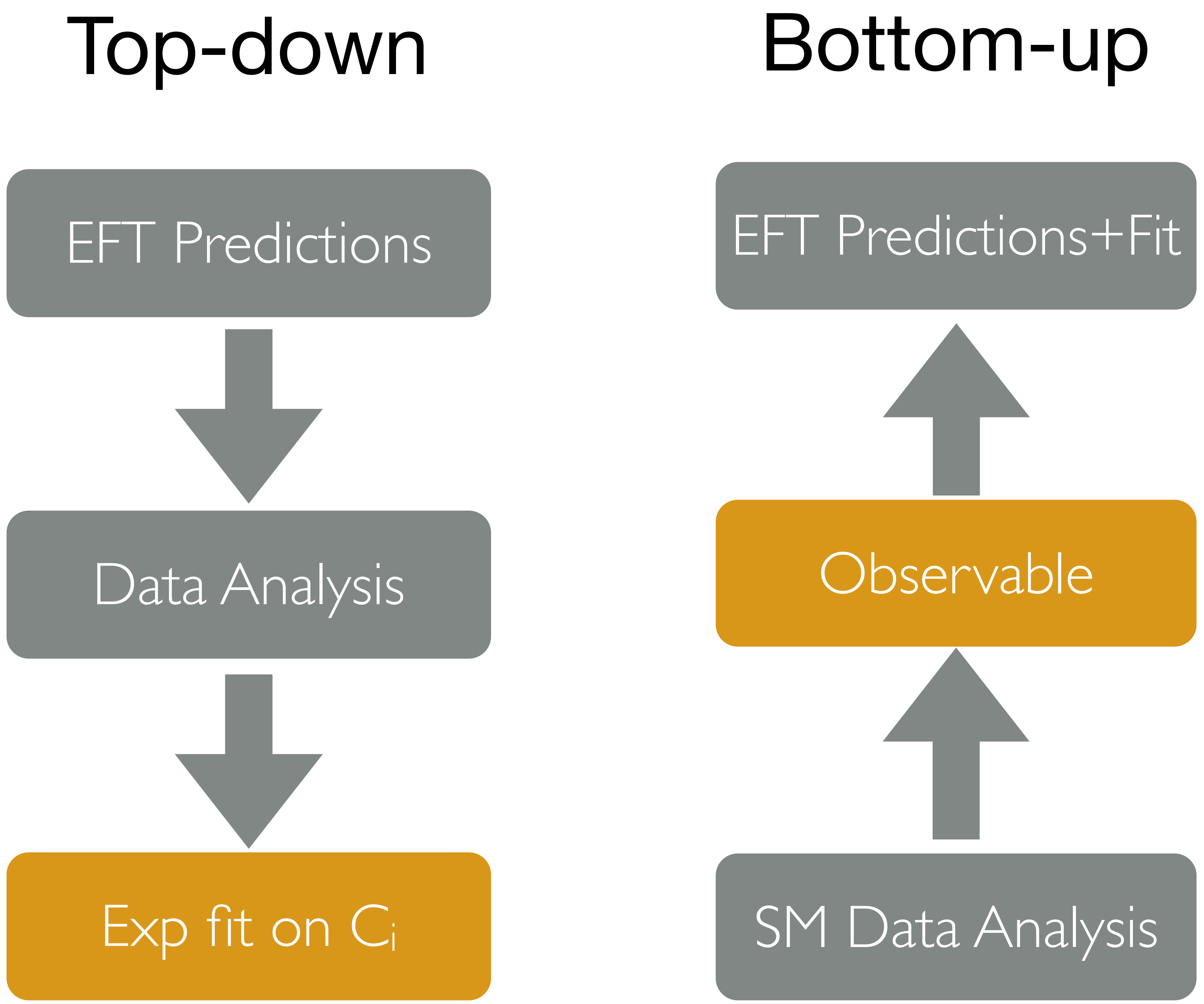
It's as exciting as challenging. Pattern of deformations enter many observables in a correlated way.

Needs to manage complexity, uncertainties and correlations.

Needs coordinated work among analysis groups in collaborations traditionally working separately (top, Higgs, EW,…)

Needs coordinated work between theorists and experimentalists (model dependence, validity, interpretations, matching to the UV).

A LHC EFT WG has been set up to move things forward.



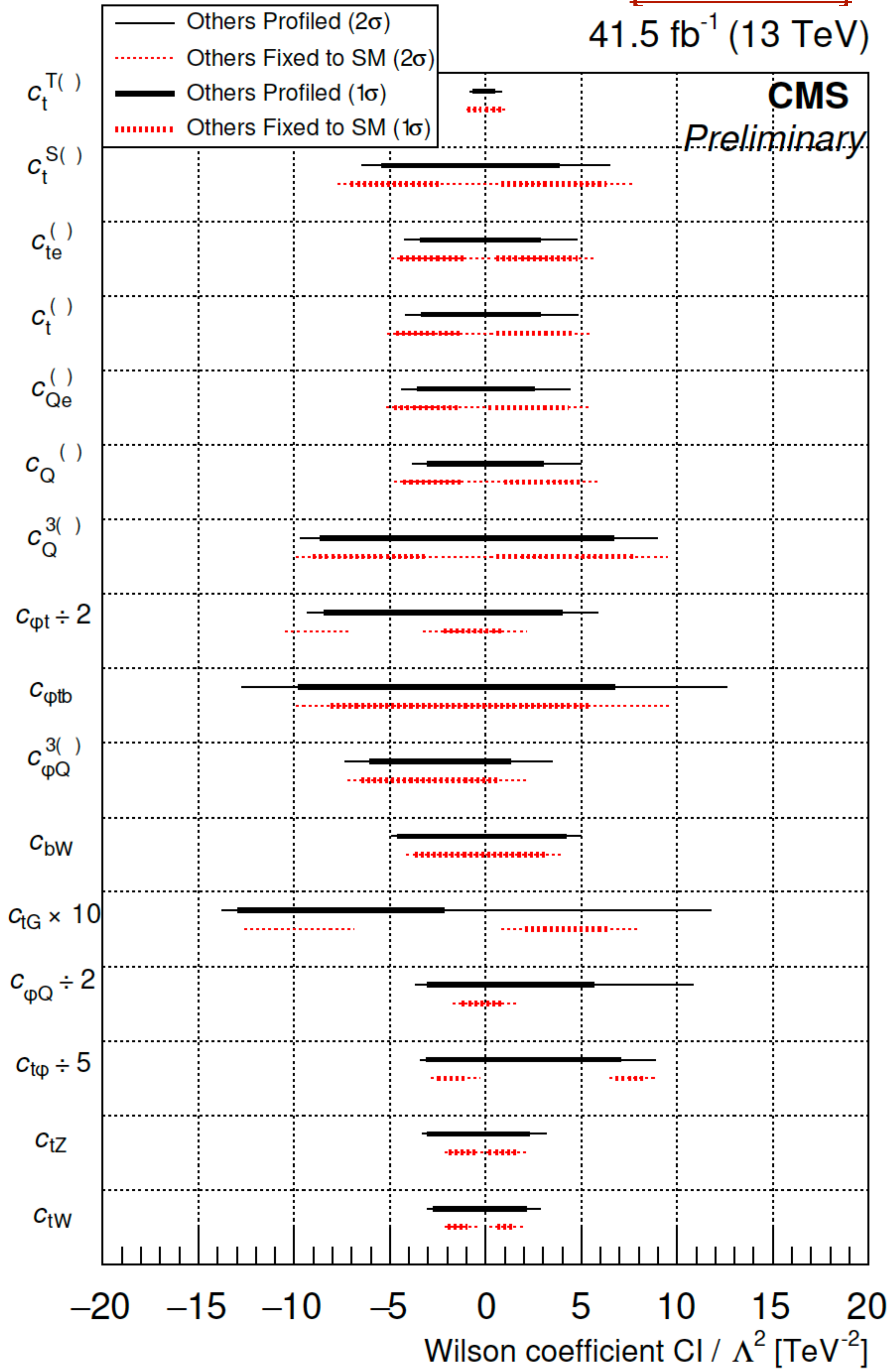
Complementary!

Top-down EXP fits

CMS top fit

- 35 signal regions, 16 operators, including ttll ones.
- Limits for operators only appearing here comparable with global TH fits, see, e.g., top fitter:
- First example of top-down EFT analysis in the top quark context.

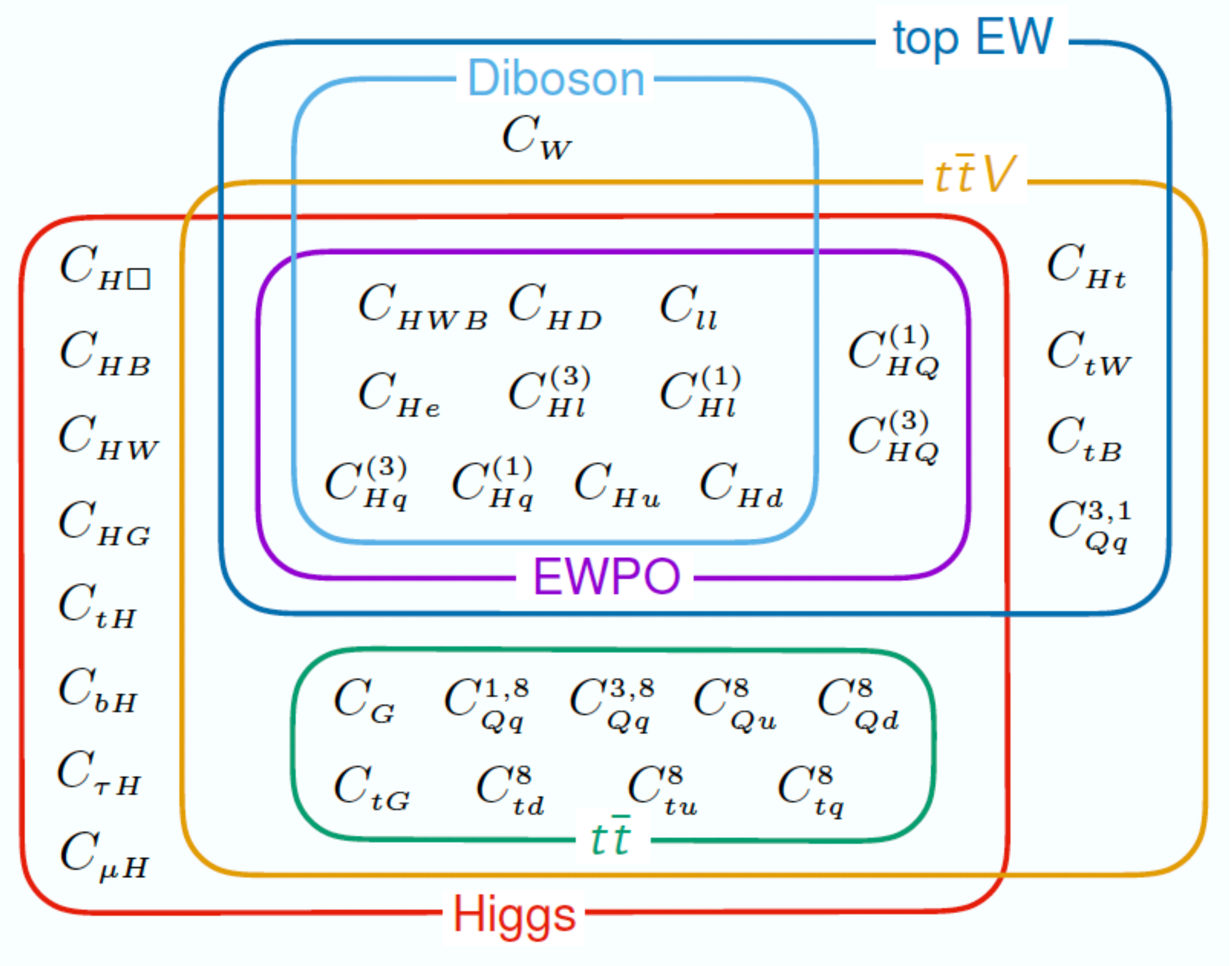
[CMS 2020]



Global fits

Global fits: EWPO+H+EW+Top

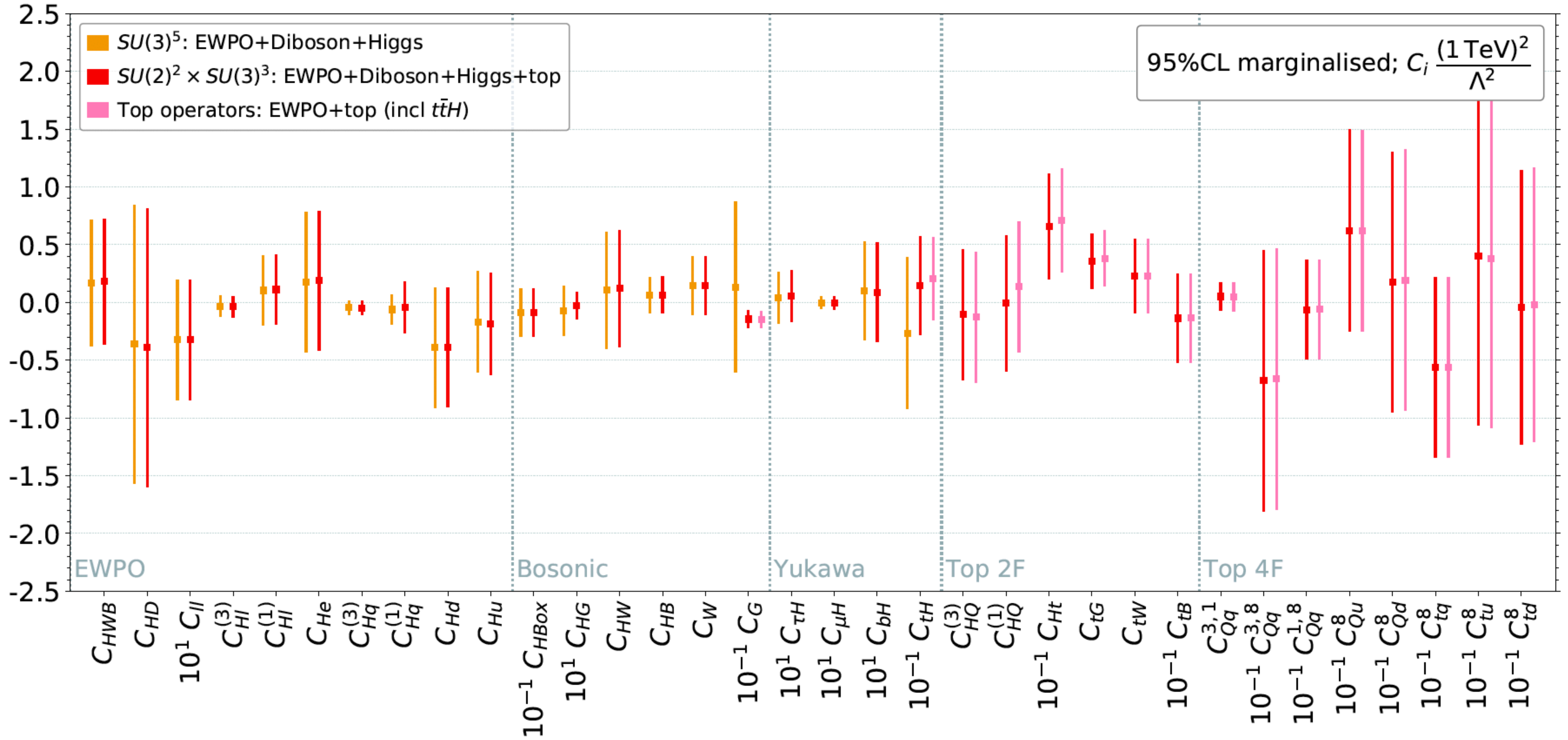
- Already now and without a dedicated experimental effort there is considerable information that can be used to set limits:
  - Fitmaker [Ellis et al. 2012.02779]
  - SMEFiT [Either et al. 2105.00006]
  - SFitter [Biekötter, Corbett, Plehn, 2018] + [Brivio et al., 1910.03606] (separated)
  - HEPfit [de Blas, et al. 2019]
- 30+ operators, linear and/or quadratic fits, Higgs/Top/EW at LHC, WW at LEP and EWPO.



Global fits

Global fits: EWPO+H+EW+Top

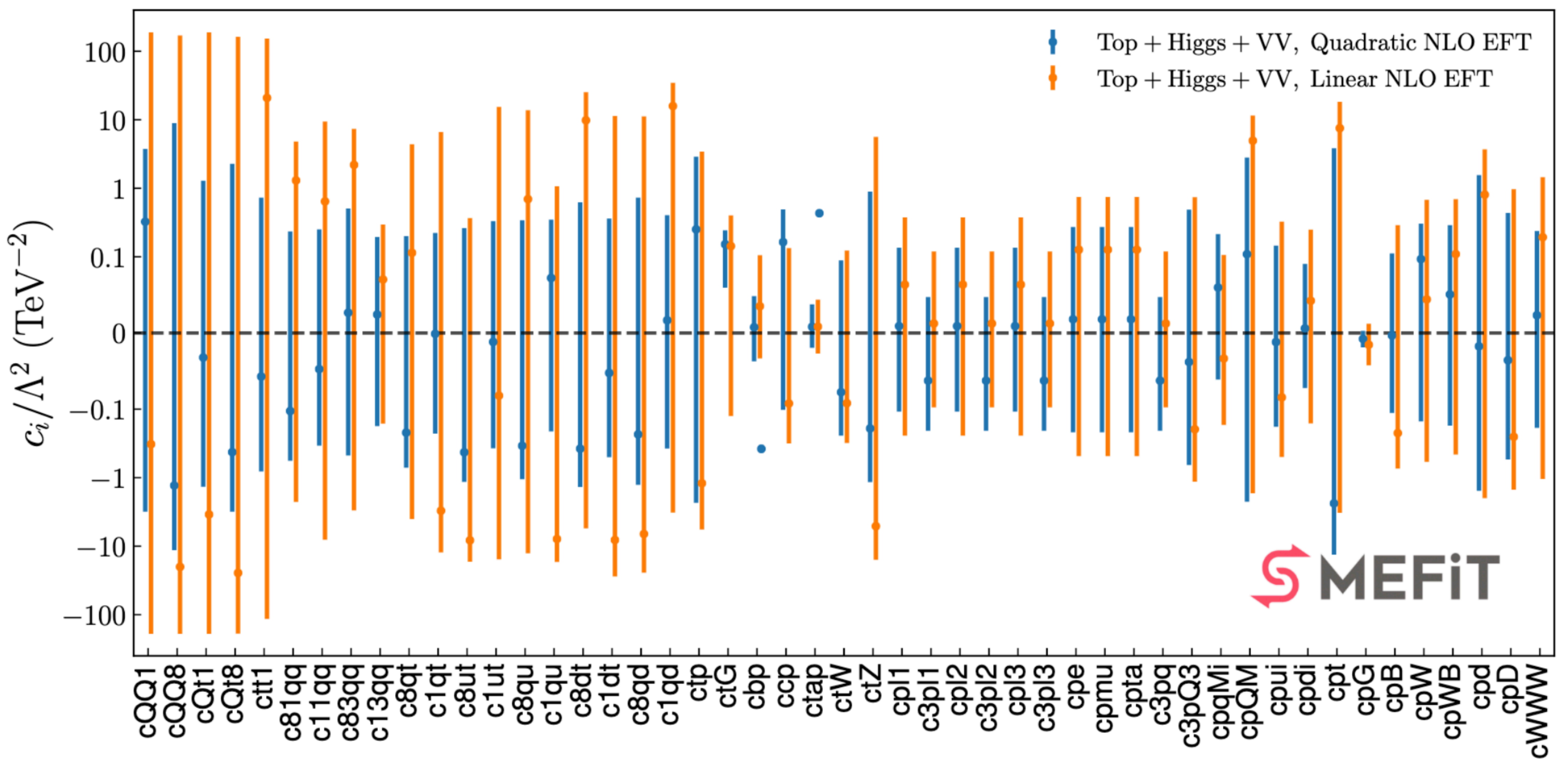
[Ellis et al. 2012.02779]



34 operators, $SU(2)^2 \times SU(3)^3$

EWPO fitted, 341 data points

[Either et al. 2105.00006]



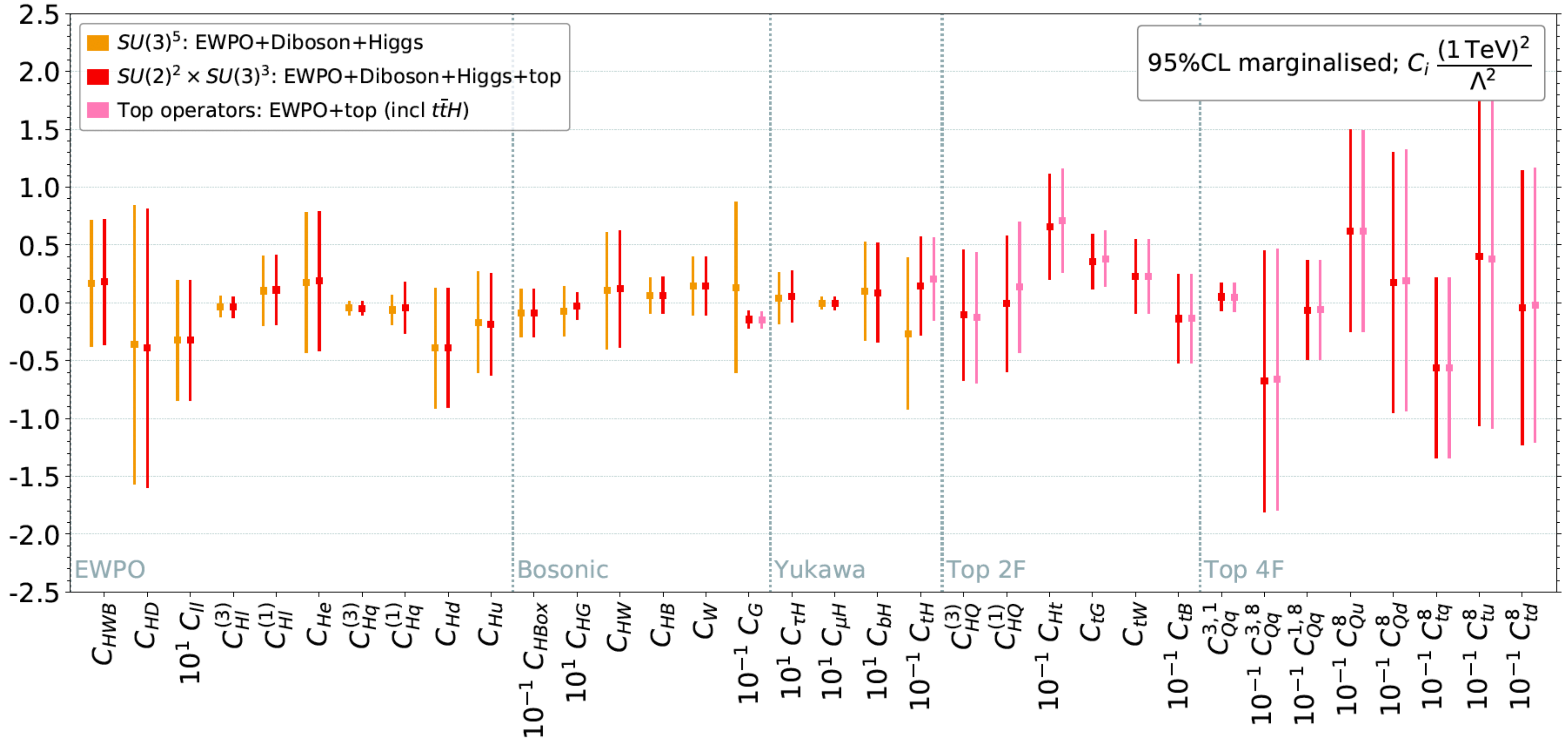
36 operators, $SU(2)^2 \times SU(3)^3$

EWPO fixed, 317 data points

Global fits

Global fits: EWPO+H+EW+Top

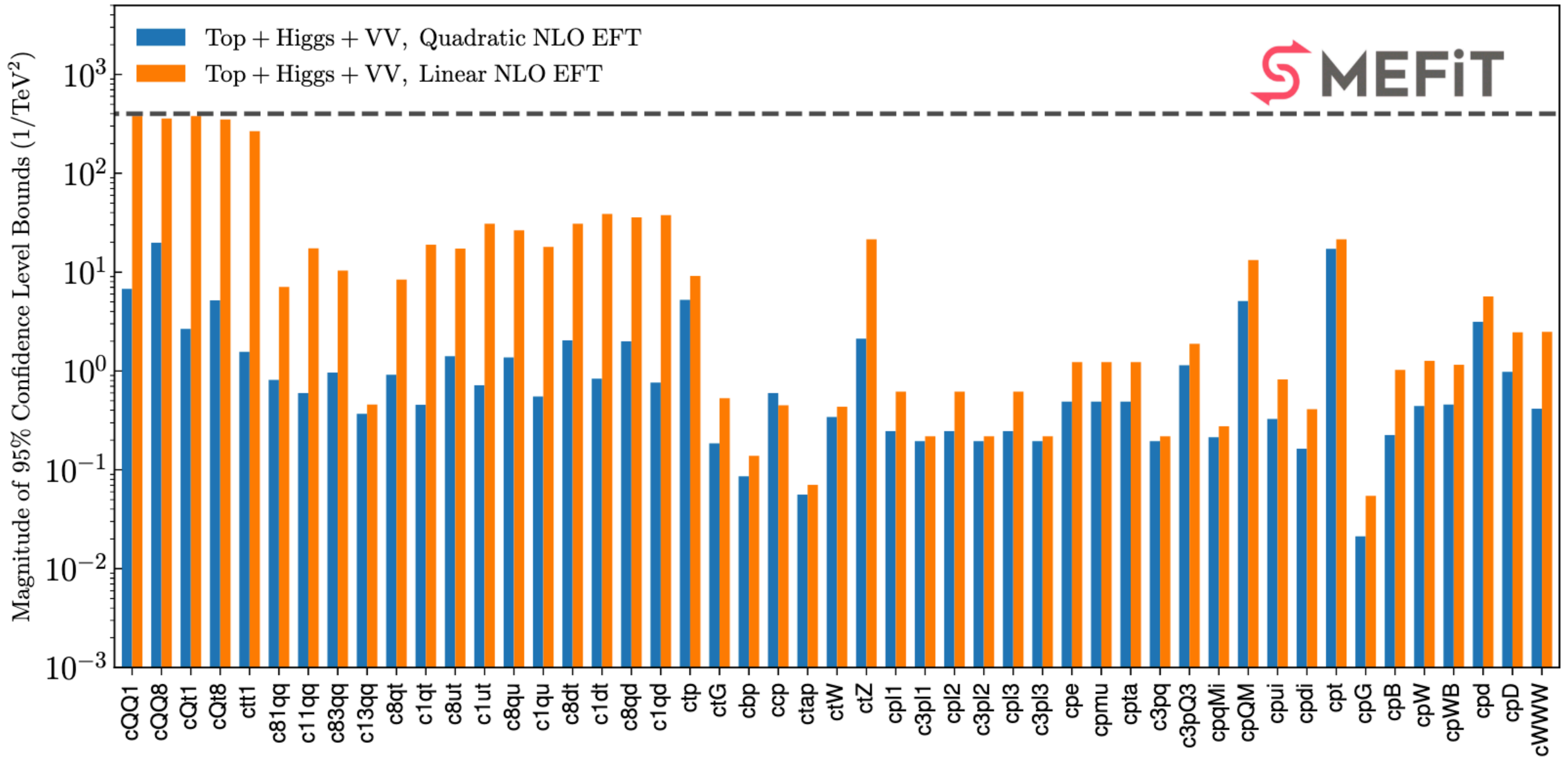
[Ellis et al. 2012.02779]



34 operators, $SU(2)^2 \times SU(3)^3$

EWPO fitted, 341 data points

[Either et al. 2105.00006]



36 operators, $SU(2)^2 \times SU(3)^3$

EWPO fixed, 317 data points

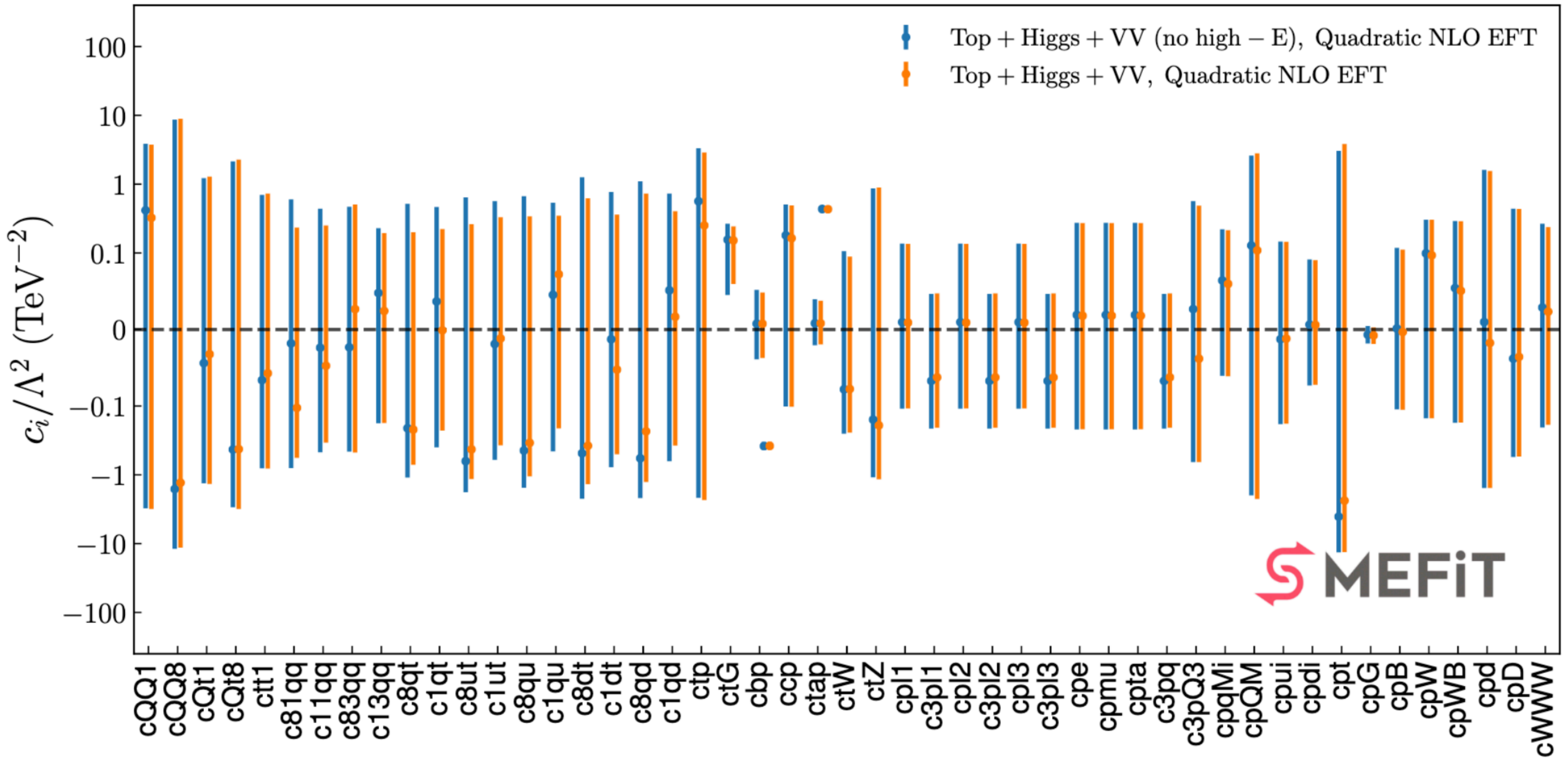
Global fits

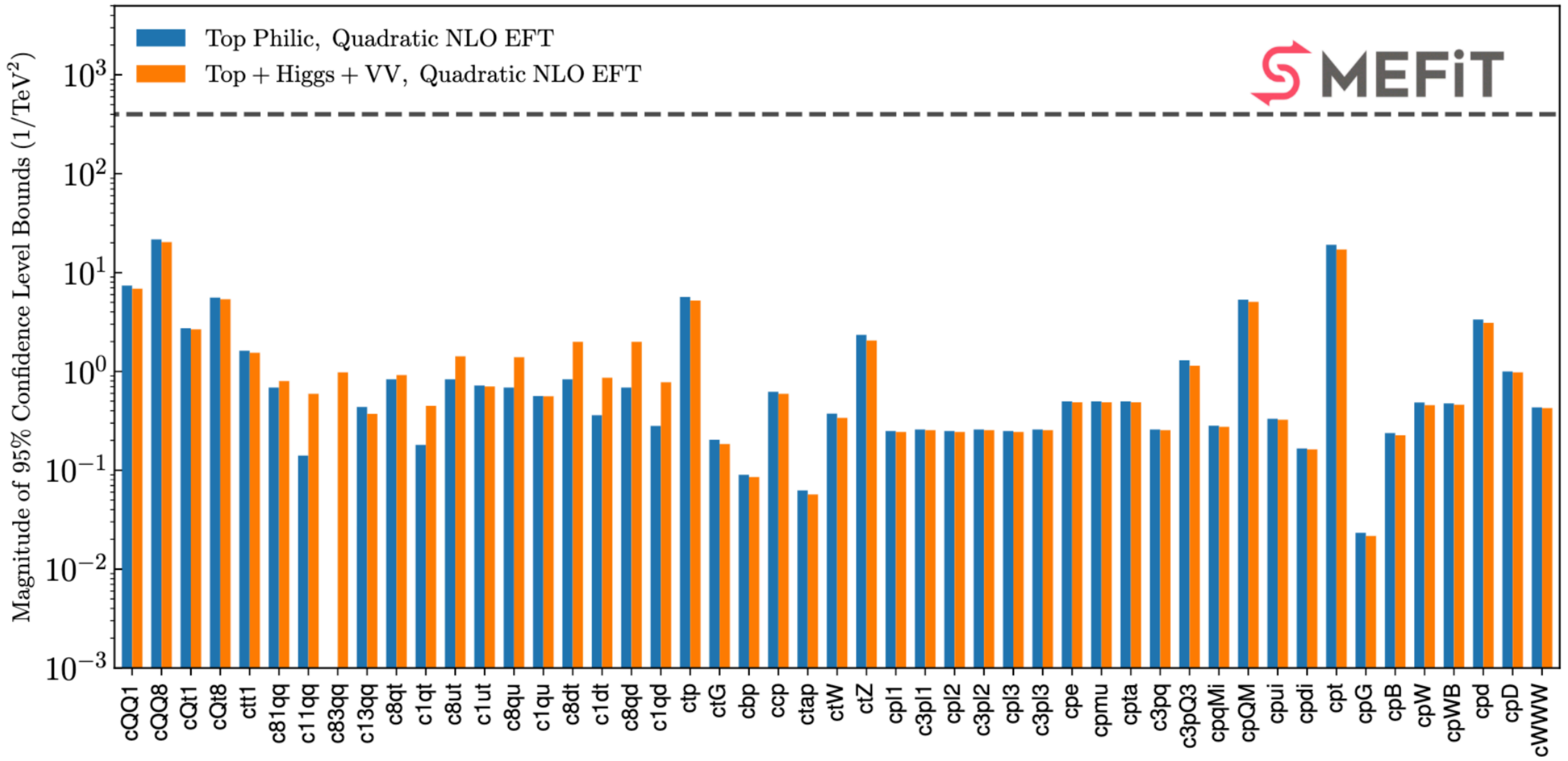
Global fits: EWPO+H+EW+Top

Data restriction

[Either et al. 2105.00006]

Theory restriction





The limited role of the high energy tails (so far)

Top-Philic scenario (14 → 5 dof in the 2Q2q)

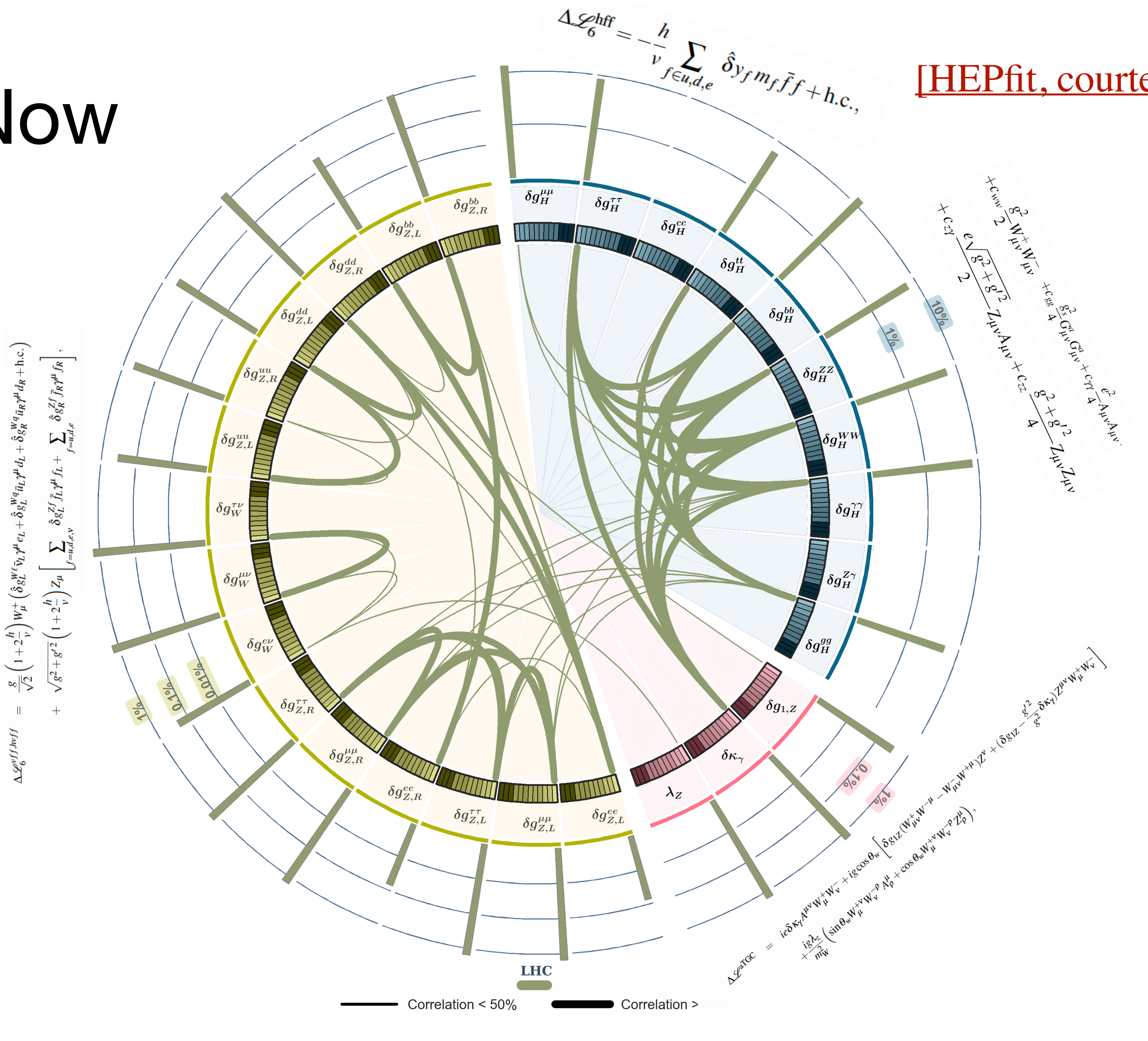
Global fits: now vs future

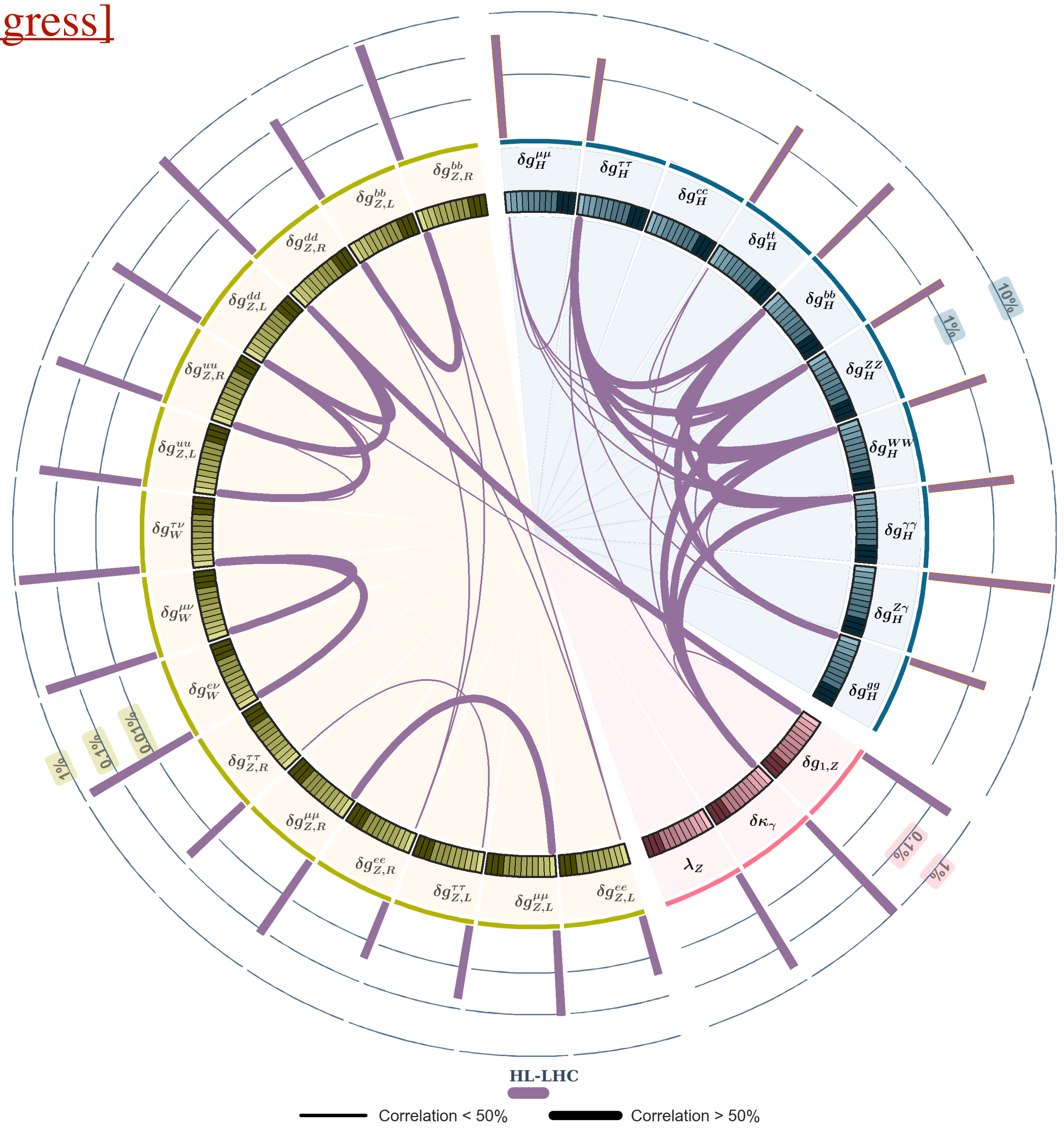
EWPO+EW+Higgs

Now

[HEPfit, courtesy of De Blas et al., work in progress]

HL-LHC





EW known at 0.1%
TGC known at 1%
Higgs known at 10%

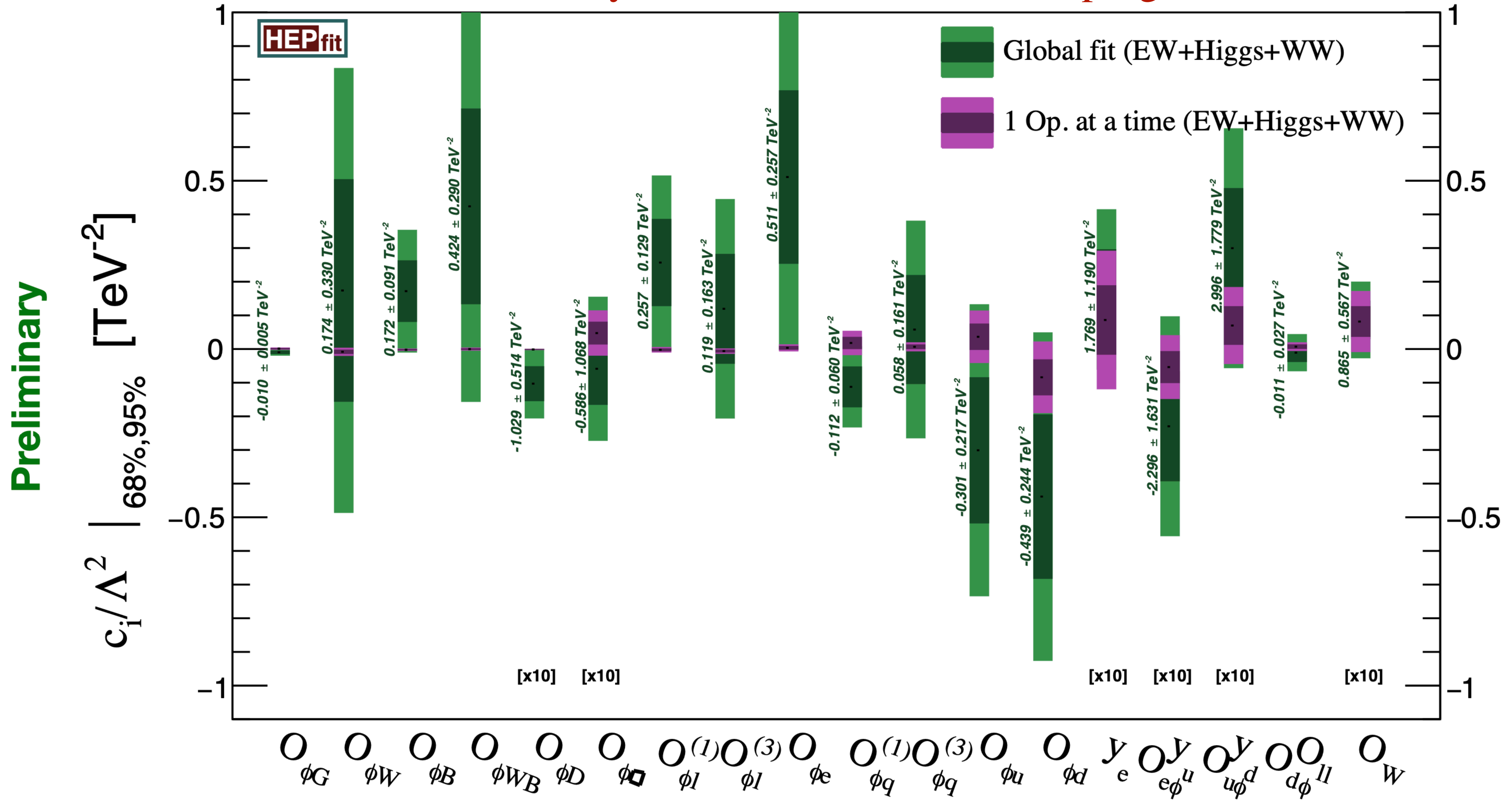
As constraints improve for the TGC and Higgs correlations increase.

Global fits: now vs Future

EW+Higgs+EWPO

Now

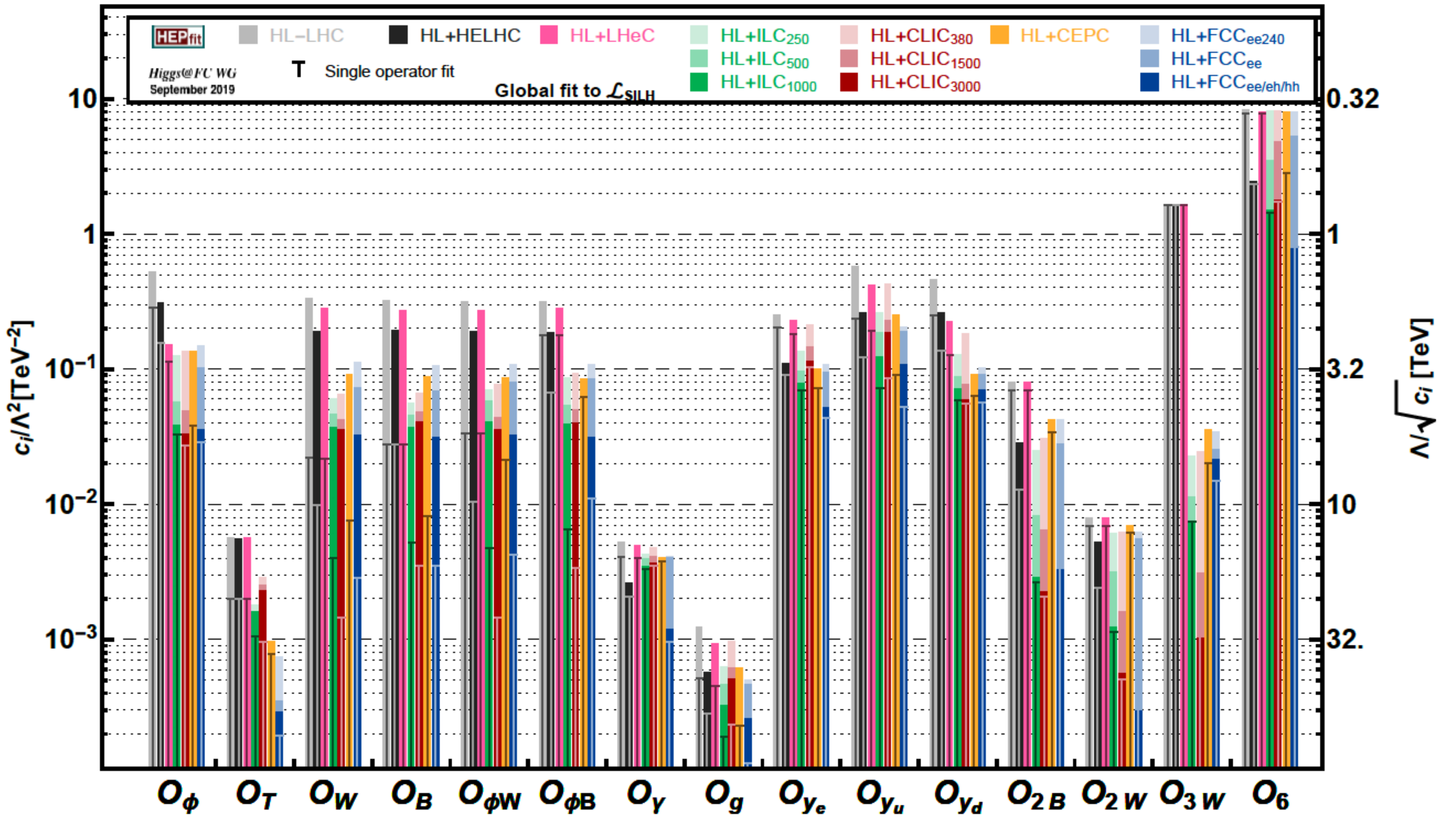
[Courtesy of De Blas et al., work in progress]



New Physics assumptions: CP-even, U(3)[5]

Future

[De Blas et al., 2020]



Expected more than 1 order of magnitude improvements

Global EFT Fits

Theory trends

Many directions of development and improvements in the fits are being pursued in TH:

- [Global] Extension to data sets from other (lower-energy) experiments.
- [NLO] Improvement at NLO (QCD+EW) in the SMEFT on-going. RGE at two loops needed to maintain NLO accuracy at different scales. Inclusion of theory uncertainties.
- [Unlocking] Effects and constraints at dim=8 or HEFT.
- [UV] Constraints from and to UV models, systematic studies of applicability/validity. Mixing.
- [PDF] Evaluation of the theory uncertainties to interplay with the PDF fits.
- [MaxSensitivity] Optimal observables, “energy helps accuracy”, “X without the X”….
- [QFT] General QFT arguments: resummation of higher-order terms, basis independent formulations (e.g. amplitudes), positivity/convexity.

Les Houches wishlist 2019

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ (incl.) $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$ $\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}}$	$\mathrm{N^3LO_{HTL}}$ (partial results available) $\mathrm{NNLO_{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO^{(VBF)}_{QCD}} + \mathrm{NLO^{(VBF)}_{EW}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to H + V$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NLO^{(t,b)}_{gg \to HZ}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$

Table I.1: Precision wish list: Higgs boson final states. $\mathrm{N^xLO^{(VBF^*)}_{QCD}}$ means a calculation usi the structure function approximation.

process	known	desired
$pp \to V$	$\mathrm{N^3LO^{(z\to 0)}_{QCD}}$ (incl.) $\mathrm{N^3LO_{QCD}}$ (incl., γ^*) $\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^2LO_{EW}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $+ \mathrm{NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops)
$pp \to V + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^{\pm}W^+W^-$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to \gamma\gamma + j$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	

Table I.3: Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$. Full leptonic decays are understood if not stated otherwise.

process	known	desired
$pp \to t\bar{t}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects) $\mathrm{NLO_{EW}}$ (w/ decays, off-shell effects)	$\mathrm{NNLO_{QCD}}$ (w/ decays)
$pp \to t\bar{t} + j$	$\mathrm{NLO_{QCD}}$ (w/ decays) $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + 2j$	$\mathrm{NLO_{QCD}}$ (w/ decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + Z$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t} + W$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t/\bar{t}$	$\mathrm{NNLO_{QCD}}$*(w/ decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)

Table I.4: Precision wish list: top quark final states. $\mathrm{NNLO_{QCD}}$ * means a calculation using the structure function approximation.

process	known	desired
$pp \to 2\,\mathrm{jets}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to 3\,\mathrm{jets}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

Table I.2: Precision wish list: jet final states.

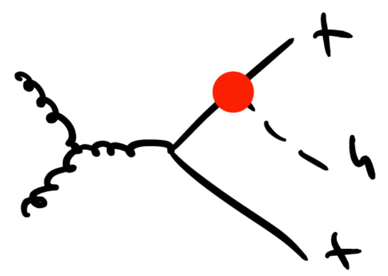
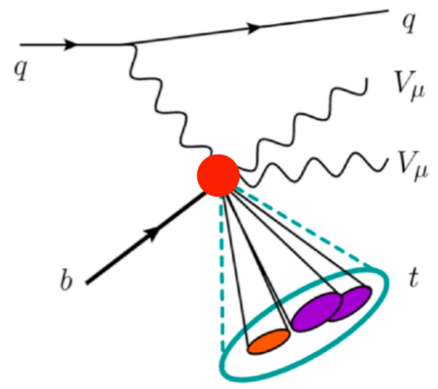
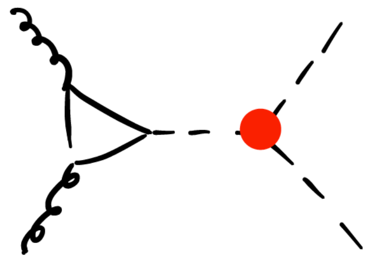
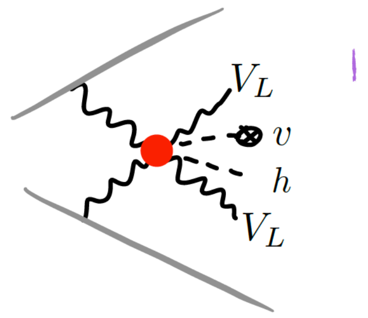
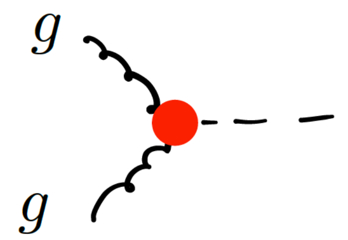
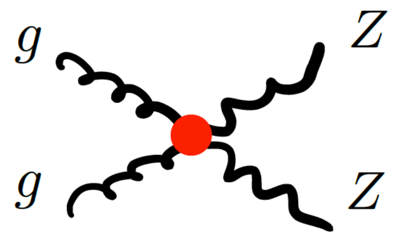
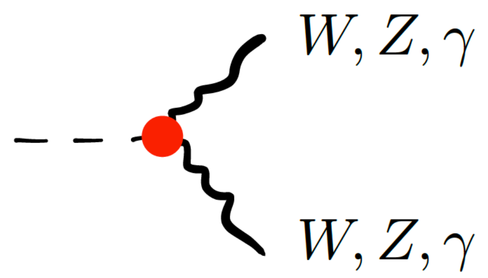
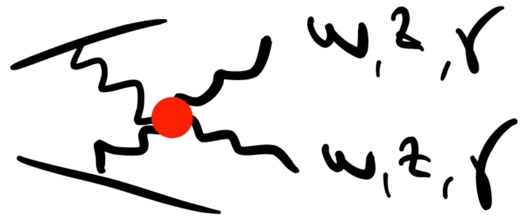
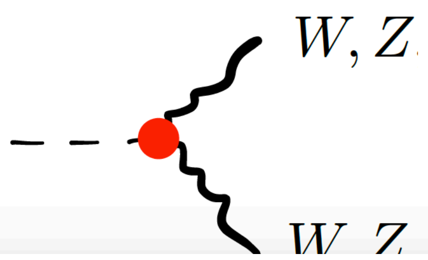
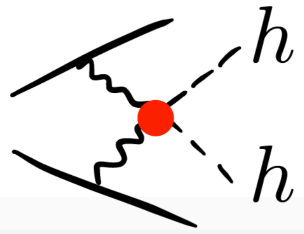

NNLO
GavinSalam® (Adapted)
W/Z total, H total, Harlander, Kilgore
H total, Anastasiou, Melnikov
H total, Ravindran, Smith, van Neerven
WH total, Brein, Djouadi, Harlander
H diff., Anastasiou, Melnikov, Petriello
H diff., Anastasiou, Melnikov, Petriello
W diff., Melnikov, Petriello
W/Z diff., Melnikov, Petriello
H diff., Catani, Grazzini
W/Z diff., Catani et al.
VBF total, Bolzoni, Maltoni, Moch, Zaro
WH diff., Ferrera, Grazzini, Tramontano
γ-γ, Catani et al.
Hj (partial), Boughezal et al.
ttbar total, Czakon, Fiedler, Mitov
Z-γ, Grazzini, Kallweit, Rathlev, Torre
jj (partial), Currie, Gehrmann-De Ridder, Glover, Pires
ZZ, Cascioli it et al.
ZH diff., Ferrera, Grazzini, Tramontano
WW , Gehrmann et al.
ttbar diff., Czakon, Fiedler, Mitov
Z-γ, W-γ, Grazzini, Kallweit, Rathlev
Hj, Boughezal et al.
Wj, Boughezal, Focke, Liu, Petriello
Hj, Boughezal et al.
VBF diff., Cacciari et al.
Zj, Gehrmann-De Ridder et al.
ZZ, Grazzini, Kallweit, Rathlev
Hj, Caola, Melnikov, Schulze
Zj, Boughezal et al.
WH diff., ZH diff., Campbell, Ellis, Williams
γ-γ, Campbell, Ellis, Li, Williams
WZ, Grazzini, Kallweit, Rathlev, Wiesemann
p_{tZ}, Gehrmann-De Ridder et al.
WW , Grazzini et al.
MCFM at NNLO, Boughezal et al.
single top, Berger, Gao, C.-Yuan, Zhu
HH, de Florian et al.
p_{tH}, Chen et al.
p_{tZ}, Gehrmann-De Ridder et al.
jj, Currie, Glover, Pires
γX, Campbell, Ellis, Williams
γj, Campbell, Ellis, Williams
VH, H->bb, Ferrera, Somogyi, Tramontano
single top, Berger, Gao, Zhu
HHZ, Li, Li, Wang
DIS jj, Žlebčík et al.
VH, H->bb, Caola, Luisoni, Melnikov, Roentsch
p_{tW}, Gehrmann-De Ridder et al.
VBF diff., Cruz-Martinez, Gehrmann, Glover, Huss
Wj, Zj, Gehrmann-De Ridder et al.
ttbar total, Catani et al.
γj, Chen et al.
H->bbj, Mondini, Williams
ttbar diff., Catani et al.
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2030
2040
NLO
automation
NLO+PS
NNLO
2-loop revolution
N3LO
N4LO
CKKW
MC@NLO
POWHEG
MENLOPS/FxFx/MiNLO
NNLOPS
MiNNLOPS
H
γ^*
$W^\pm$
N3LOPS

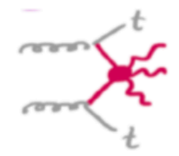
Higgs couplings

Higgs couplings without the Higgs

[Henning et al. 1812.09299]

$$\kappa_t \Longleftrightarrow \frac{|H|^2 Q\tilde{H}t_R}{\Lambda^2}$$

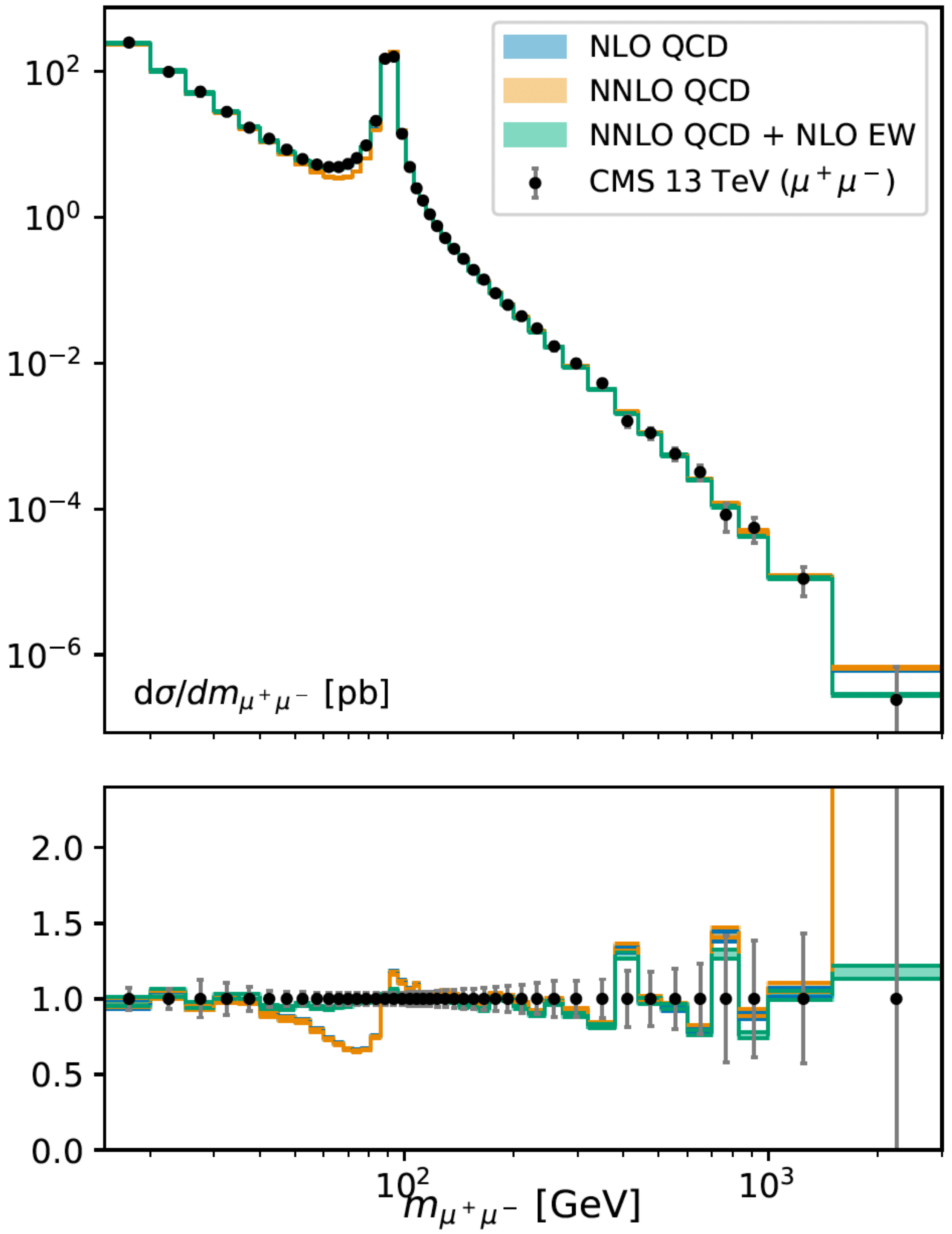
HwH Program		$\sim const$	$\sim E^2$
κ_t	$\lvert H\rvert^2 Q\tilde{H}t_R$		
κ_λ	$\lvert H\rvert^6$		
κ_G	$\lvert H\rvert^2 G^a_{\mu\nu}G^{a\,\mu\nu}$		
κ_γ $\kappa_{Z\gamma}$	$\lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$ $\lvert H\rvert^2 W^a_{\mu\nu}W^{a\,\mu\nu}$		
κ_V	$\lvert H\rvert^2 \partial_\mu H^\dagger \partial^\mu H$		

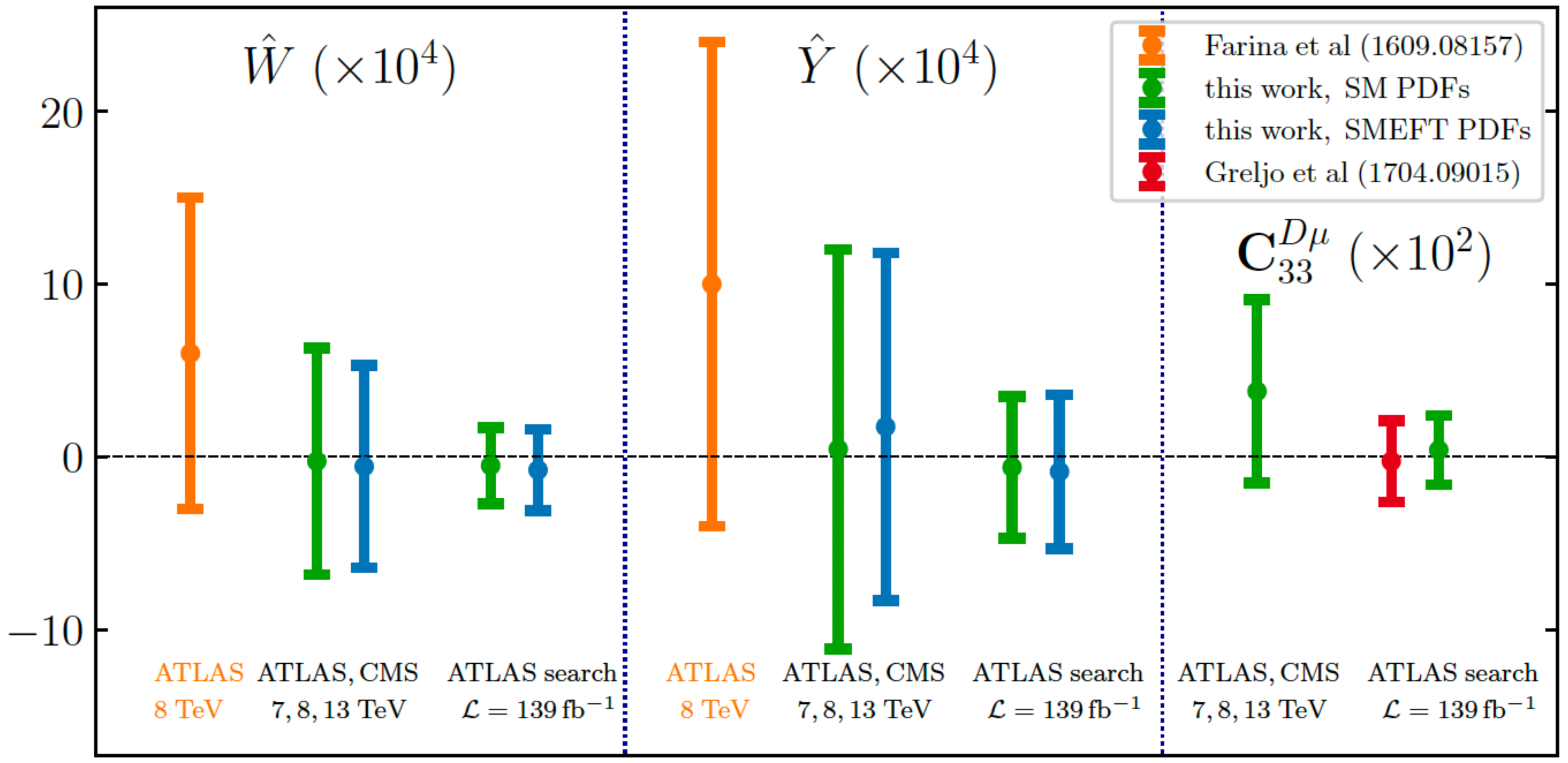
Legs	Order	Diagram	Channels	Xsec[fb]	QCD bgnd	L/T
$1 \to 4$	QCD		$tW^\pm W^\pm W^\mp$	0.7	/	0.03
			$tW^\pm ZZ$	0.4	/	0.03
	EW		$tbW^\pm W^\pm$	3.5	/	0.10
			$tbW^\pm W^\mp$	3.5	/	0.20
			$tbW^\pm Z$	3.8	/	0.11
			$tbZZ$	0.02	0	0.09
$2 \to 3$	QCD^2		$ttZWW$	0.083	/	0.03
			$ttZZZ$	0.008	/	0.04
			$tbWWW$	19	/	0.04
			$tbWZZ$	3.8	/	0.07
	EW^2		ttZ	0.1	/	0.29
			$ttW^\pm$	0.3	/	0.32
			tbZ	0.2	/	0.31
			$tbW^\pm(SS)$	0.9	2	0.29
			$tbW^\pm(OS)$	19	/	0.45
	EW $*$ QCD		$tbW^\pm W^\mp$	75	467	0.15
			$tbW^\pm W^\pm$	75	458	0.13
			$tbW^\pm Z$	26	215	0.15
			$tbZZ$	4	0	0.07
			$tW^\pm W^\mp W^\pm$	0.7	/	0.03
			$tW^\pm ZZ$	0.4	/	0.03
			$tW^\pm W^\mp$	9	7.15	0.09
			$tW^\pm W^\pm$	8	6.44	0.10
			$tW^\pm Z$	9	75.4	0.07
			tZZ	5	2.64	0.07

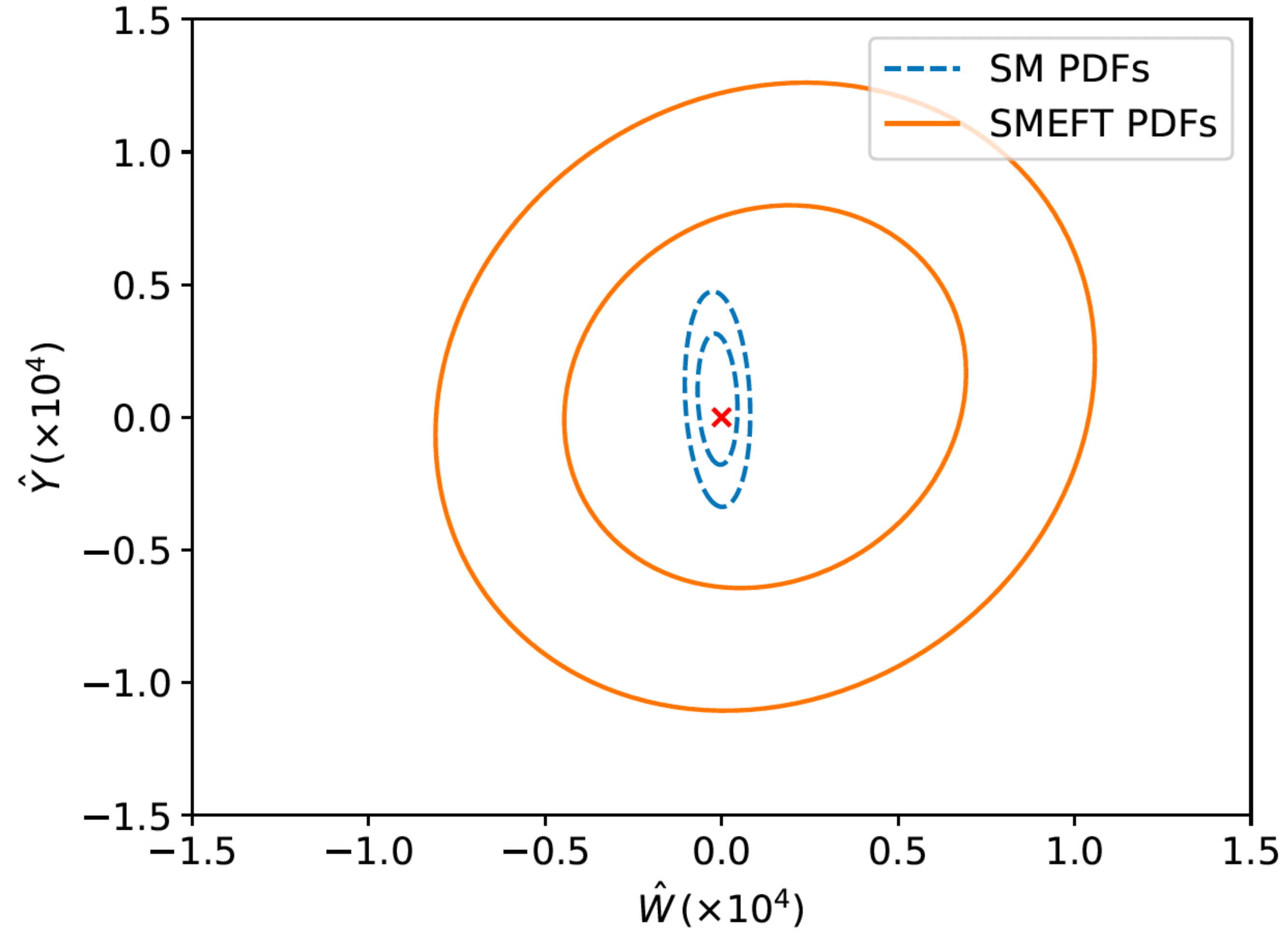
Disentagle SMEFT from HEFT!

Global EFT Fits

EFT and PDF fits







[Greljo et al. 2104.02723]

The EW Precision Potential of the (HL-)LHC

Andrea Wulzer

Università degli Studi di Padova

CERN

École Polytechnique Fédérale de Lausanne

The LHC Precision Program

At the LHC we can do more than searching for bumps !!
Because of **remarkable progresses** in:

- ✦ PDF determination
- ✦ high-order calculations/generators
- ✦ analysis techniques

The LHC Precision Program

At the LHC we can do more than searching for bumps !!
Because of **remarkable progresses** in:

- ✦ PDF determination
- ✦ high-order calculations/generators
- ✦ analysis techniques

A “SM” Precision Program?

- ✦ Within the SM, we can only measure SM parameters ($m_H, m_W, \sin\theta_W$)
- ✦ **Testing** the **SM** entails comparing with **SM extensions** (e.g., EWPT par.)*

*__Testing__ SM **calculations** is interesting and useful, but is not the final goal

The LHC Precision Program

At the LHC we can do more than searching for bumps !!
Because of **remarkable progresses** in:

- ✦ PDF determination
- ✦ high-order calculations/generators
- ✦ analysis techniques

A "SM" Precision Program?

- ✦ Within the SM, we can only measure SM parameters ($m_H, m_W, \sin\theta_W$)
- ✦ **Testing** the **SM** entails comparing with **SM extensions** (e.g., EWPT par.)*

A "BSM" Precision Program

- ✦ Be as **"agnostic"** as possible on BSM models, at the same time **learning** as much as possible on **concrete** BSM scenarios
- ✦ The (linear d=6) SM EFT is the **prime candidate** BSM "model"

*__Testing__ SM **calculations** is interesting and useful, but is not the final goal

High-Energy Probes

EFT

$\mathcal{L}^{d=6}$

Low-energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\mathrm{EW}}^2/\Lambda^2$

High-energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

High-Energy Probes

EFT

$\mathcal{L}^{d=6}$

Low-energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\mathrm{EW}}^2/\Lambda^2$

- ✦ Higgs properties are established success
- ✦ Challenge is systematics unc. reduction
- ✦ “Easy” lunch at HL only for rare dec.s/proc.s

High-energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

High-Energy Probes

EFT

$\mathcal{L}^{d=6}$

Low-energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\rm EW}^2/\Lambda^2$

- ✦ Higgs properties are established success
- ✦ Challenge is systematics unc. reduction
- ✦ “Easy” lunch at HL only for rare dec.s/proc.s

High-energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- ✦ Effects can overcome systematics
- ✦ Fully exploits Energy frontier
- ✦ Steady improvement with luminosity

High-Energy Probes

EFT

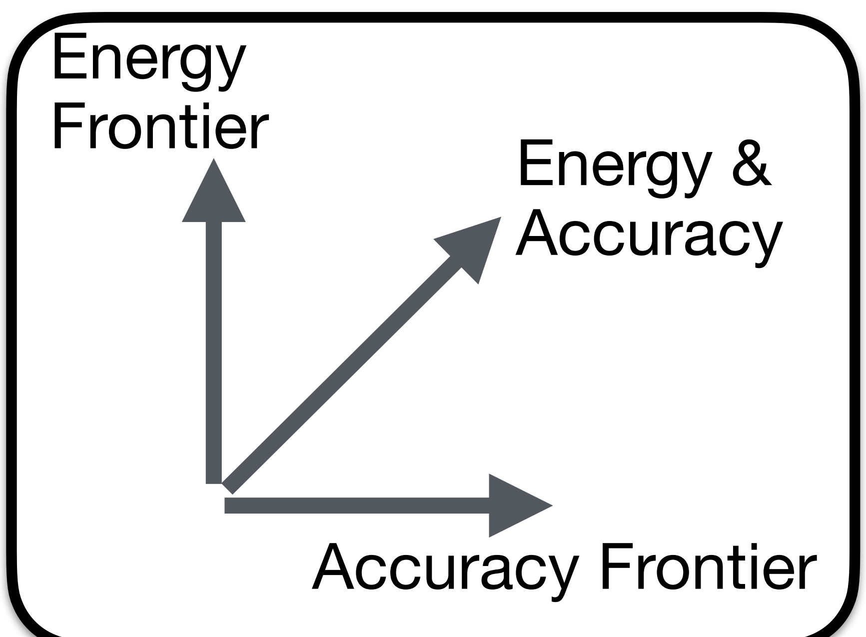
$\mathcal{L}^{d=6}$

Low-energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\rm EW}^2/\Lambda^2$

- ✦ Higgs properties are established success
- ✦ Challenge is systematics unc. reduction
- ✦ "Easy" lunch at HL only for rare dec.s/proc.s

High-energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

- ✦ Effects can overcome systematics
- ✦ Fully exploits Energy frontier
- ✦ Steady improvement with luminosity



High-Energy Probes

The Accuracy and Energy of **LEP** set a **benchmark**

$$1‰ \;@\; 100\,\mathrm{GeV} \;\sim\; 10\% \;@\; 1\,\mathrm{TeV}$$

Beyond that threshold, **hadron colliders win, even in processes well measured by LEP!**

Variety of LHC-accessible proc.s is way superior to LEP one. Much more **complete** (and challenging) **exploration**

High-Energy Probes

The Accuracy and Energy of **LEP** set a **benchmark**

$$1‰ \;@\; 100\,\mathrm{GeV} \;\sim\; 10\% \;@\; 1\,\mathrm{TeV}$$

Example: Neutral Drell—Yan at the 8 TeV LHC:

$m_{\ell\ell}$ [GeV]	$\frac{d\sigma}{dm_{\ell\ell}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]
116–130	2.28×10^{-1}	0.34	0.53	0.63
130–150	1.04×10^{-1}	0.44	0.67	0.80
150–175	4.98×10^{-2}	0.57	0.91	1.08
175–200	2.54×10^{-2}	0.81	1.18	1.43
200–230	1.37×10^{-2}	1.02	1.42	1.75
230–260	7.89×10^{-3}	1.36	1.59	2.09
260–300	4.43×10^{-3}	1.58	1.67	2.30
300–380	1.87×10^{-3}	1.73	1.80	2.50
380–500	6.20×10^{-4}	2.42	1.71	2.96
500–700	1.53×10^{-4}	3.65	1.68	4.02
700–1000	2.66×10^{-5}	6.98	1.85	7.22
1000–1500	2.66×10^{-6}	17.05	2.95	17.31

~ 1 TeV measured at **~ 10%**

Reach comparable with LEP ?

High-Energy Probes

The Accuracy and Energy of **LEP** set a **benchmark**

$$1‰ \ @\ 100\,\mathrm{GeV} \ \sim\ 10\% \ @\ 1\,\mathrm{TeV}$$

Example: Neutral Drell—Yan at the 8 TeV LHC:

$m_{\ell\ell}$ [GeV]	$\frac{d\sigma}{dm_{\ell\ell}}$ [pb/GeV]	δ^{stat} [%]	δ^{sys} [%]	δ^{tot} [%]
116–130	2.28×10^{-1}	0.34	0.53	0.63
130–150	1.04×10^{-1}	0.44	0.67	0.80
150–175	4.98×10^{-2}	0.57	0.91	1.08
175–200	2.54×10^{-2}	0.81	1.18	1.43
200–230	1.37×10^{-2}	1.02	1.42	1.75
230–260	7.89×10^{-3}	1.36	1.59	2.09
260–300	4.43×10^{-3}	1.58	1.67	2.30
300–380	1.87×10^{-3}	1.73	1.80	2.50
380–500	6.20×10^{-4}	2.42	1.71	2.96
500–700	1.53×10^{-4}	3.65	1.68	4.02
700–1000	2.66×10^{-5}	6.98	1.85	7.22
1000–1500	2.66×10^{-6}	17.05	2.95	17.31

~ 1 TeV measured at **~ 10%**

Reach comparable with LEP ?

Statistically dominated error

>> X-sec (at high mass) @ run-2

Run-2 will surpass LEP ?

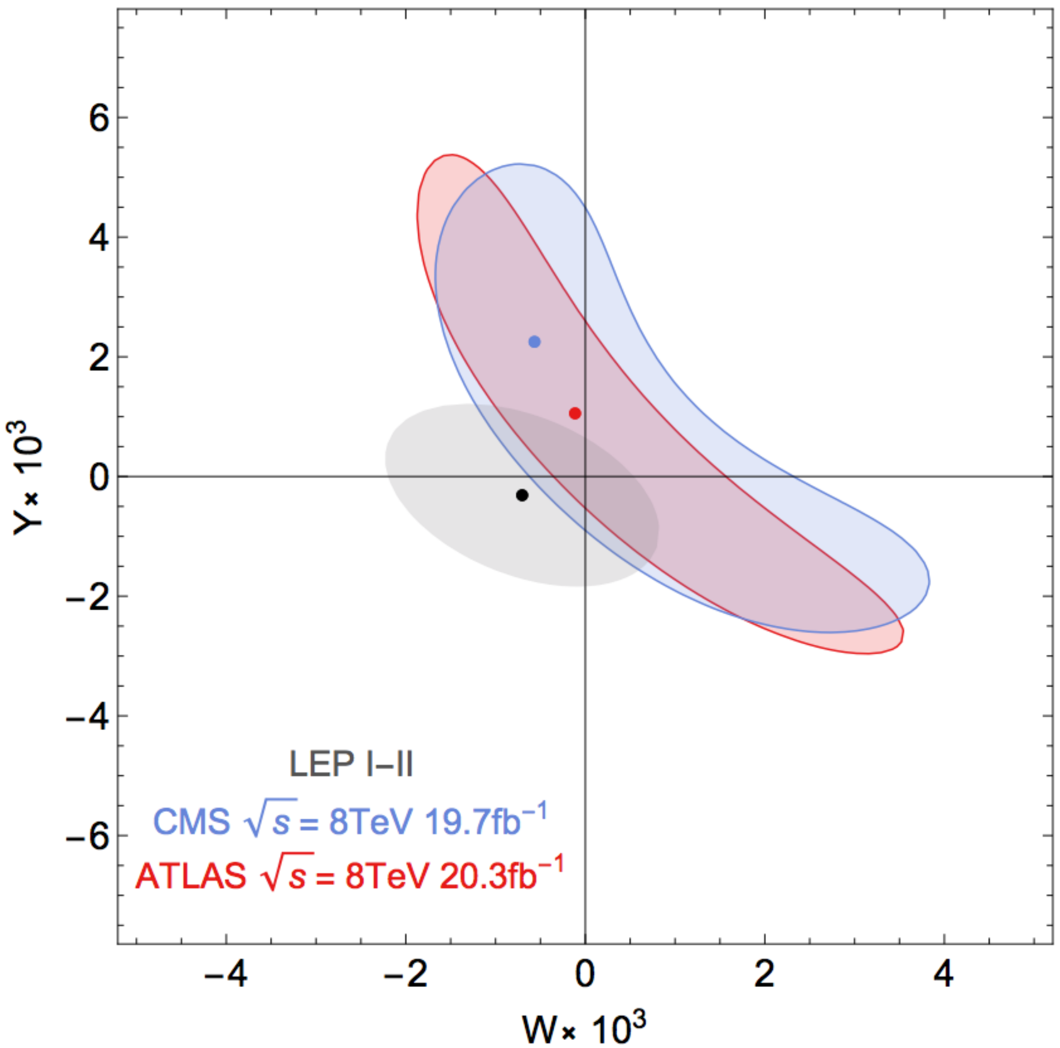
High-Energy Drell—Yan

[Farina, Panico, Pappadopulo, Ruderman, Torre AW, 2016]

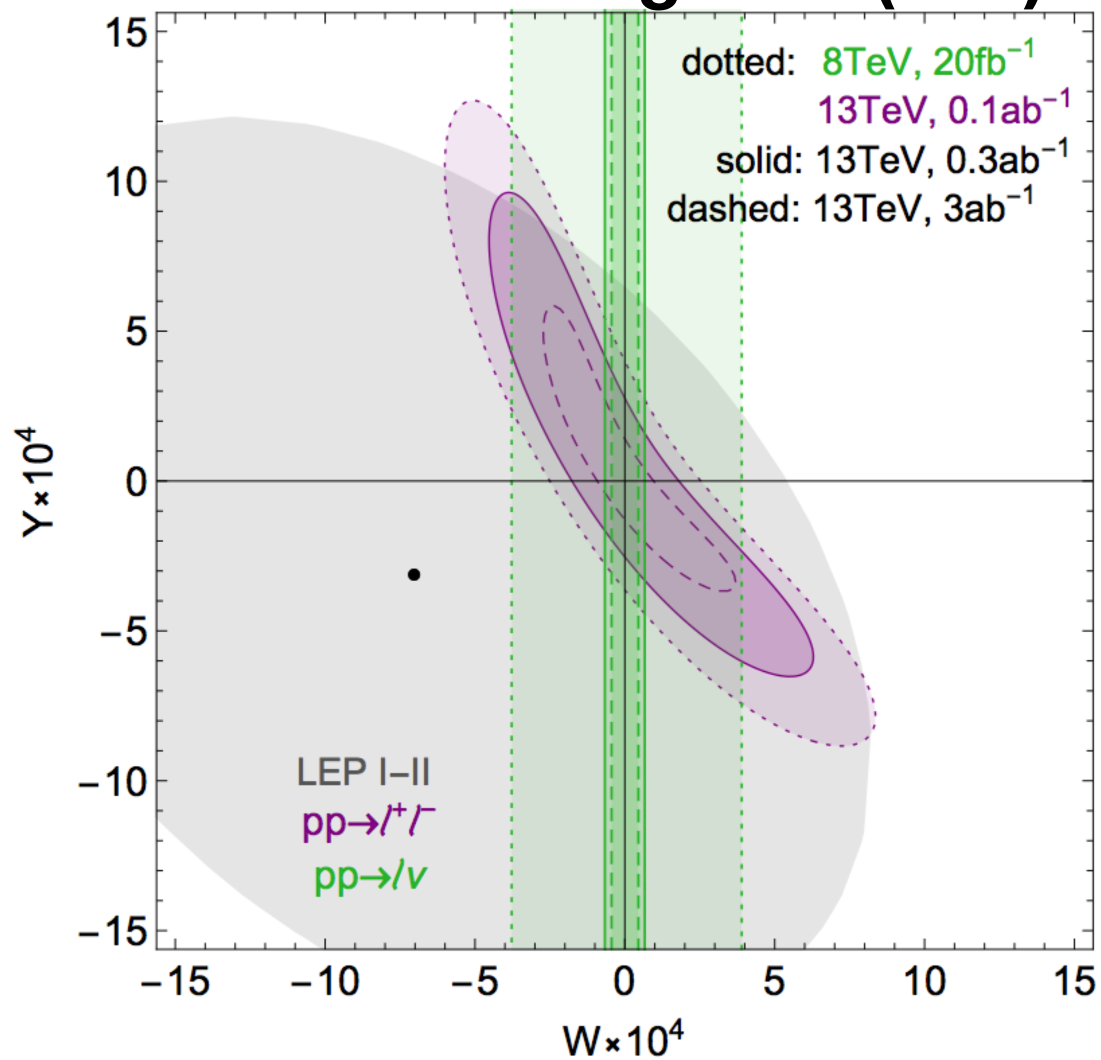
Two-parameters (Universal op.s) sensitivity projection:

$$-\frac{\mathrm{W}}{4\,m_W^2}(D_\mu W_{\nu\rho})^2 \qquad -\frac{\mathrm{Y}}{4\,m_W^2}(D_\mu B_{\nu\rho})^2$$

Neutral DY @ 8TeV



Neutral and Charged @ (HL-)LHC



High-Energy Probes: What is Needed?

Accurate Experimental Measurements:

in the **right** kin. ranges and of **right** observables

- ✦ **Dedicated** experimental analyses, careful systematics reduction
- ✦ **Precision** with **hadronic** objects would be **game-changer**

High-Energy Probes: What is Needed?

Accurate Experimental Measurements:

in the **right** kin. ranges and of **right** observables

- ✦ **Dedicated** experimental analyses, careful systematics reduction
- ✦ **Precision** with **hadronic** objects would be **game-changer**

Accurate Theoretical Predictions:

in the **right** kin. ranges and of **right** observables

- ✦ **NLO** automated, **NNLO**~available, **NLO EW**~available at NLLog at least
- ✦ **PDF** uncertainties reduction
  Without fitting NP away! [Carrazza, Degrande, Iranipour, Rojo, Ubiali, 2019; Greljo, Rojo, Ubiali et.al. 2021]
- ✦ **Fast BSM predictions!** (e.g., by re-weighting)

High-Energy Probes: What is Needed?

Accurate Experimental Measurements:

in the **right** kin. ranges and of **right** observables

- ✦ **Dedicated** experimental analyses, careful systematics reduction
- ✦ **Precision** with **hadronic** objects would be **game-changer**

Accurate Theoretical Predictions:

in the **right** kin. ranges and of **right** observables

- ✦ **NLO** automated, **NNLO**~available, **NLO EW**~available at NLLog at least
- ✦ **PDF** uncertainties reduction
  Without fitting NP away! [Carrazza, Degrande, Iranipour, Rojo, Ubiali, 2019; Greljo, Rojo, Ubiali et.al. 2021]
- ✦ **Fast BSM predictions!** (e.g., by re-weighting)

Growing-with-energy Targets:

- ✦ **Pair up** operators and final states
- ✦ Characterise effects, design **analyses** and **observables**
- ✦ **Assess implications**, Beyond Wilson C. reach tables!

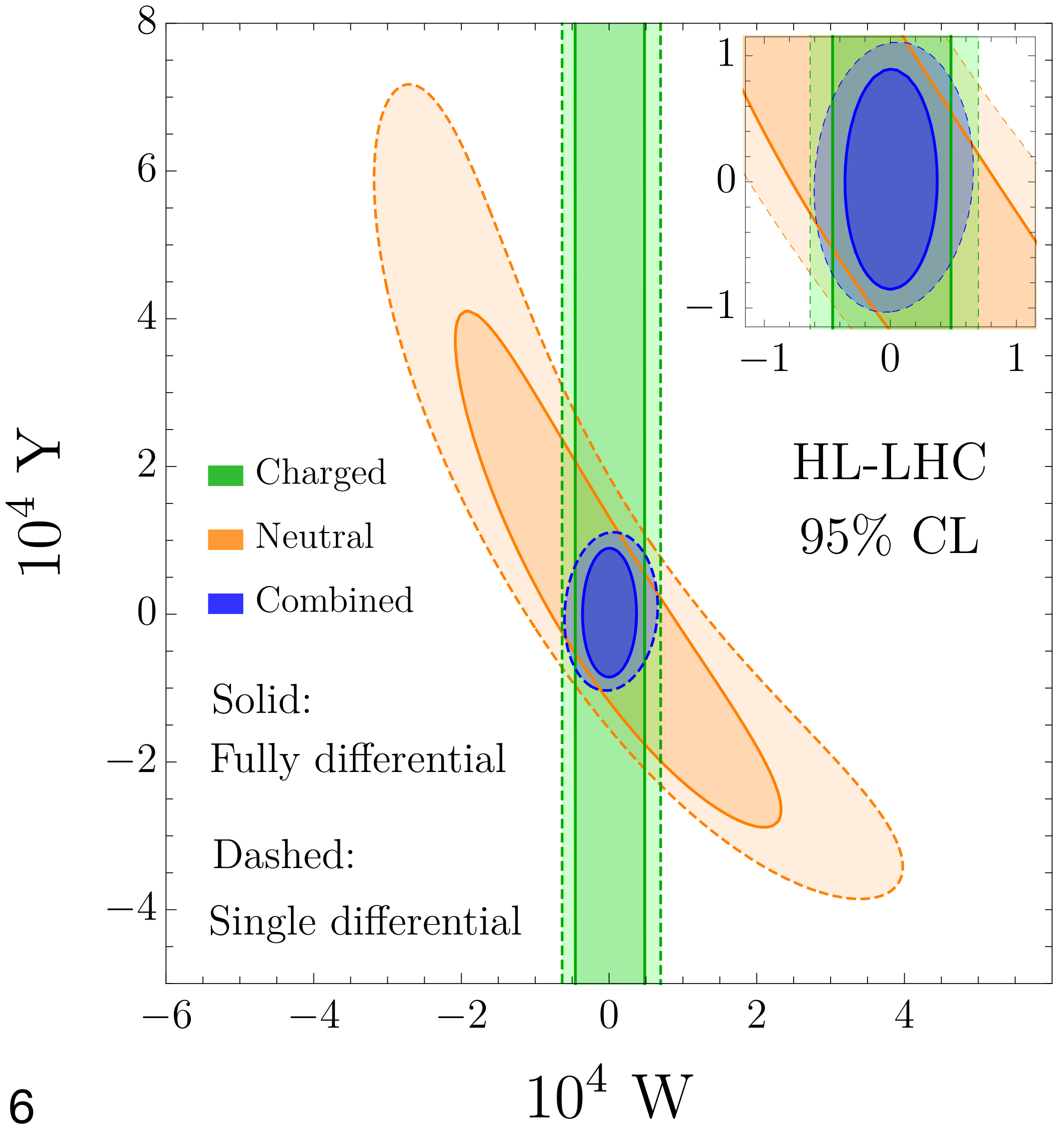
Compare reach, assess EFT validity and assumptions, translate on models, …

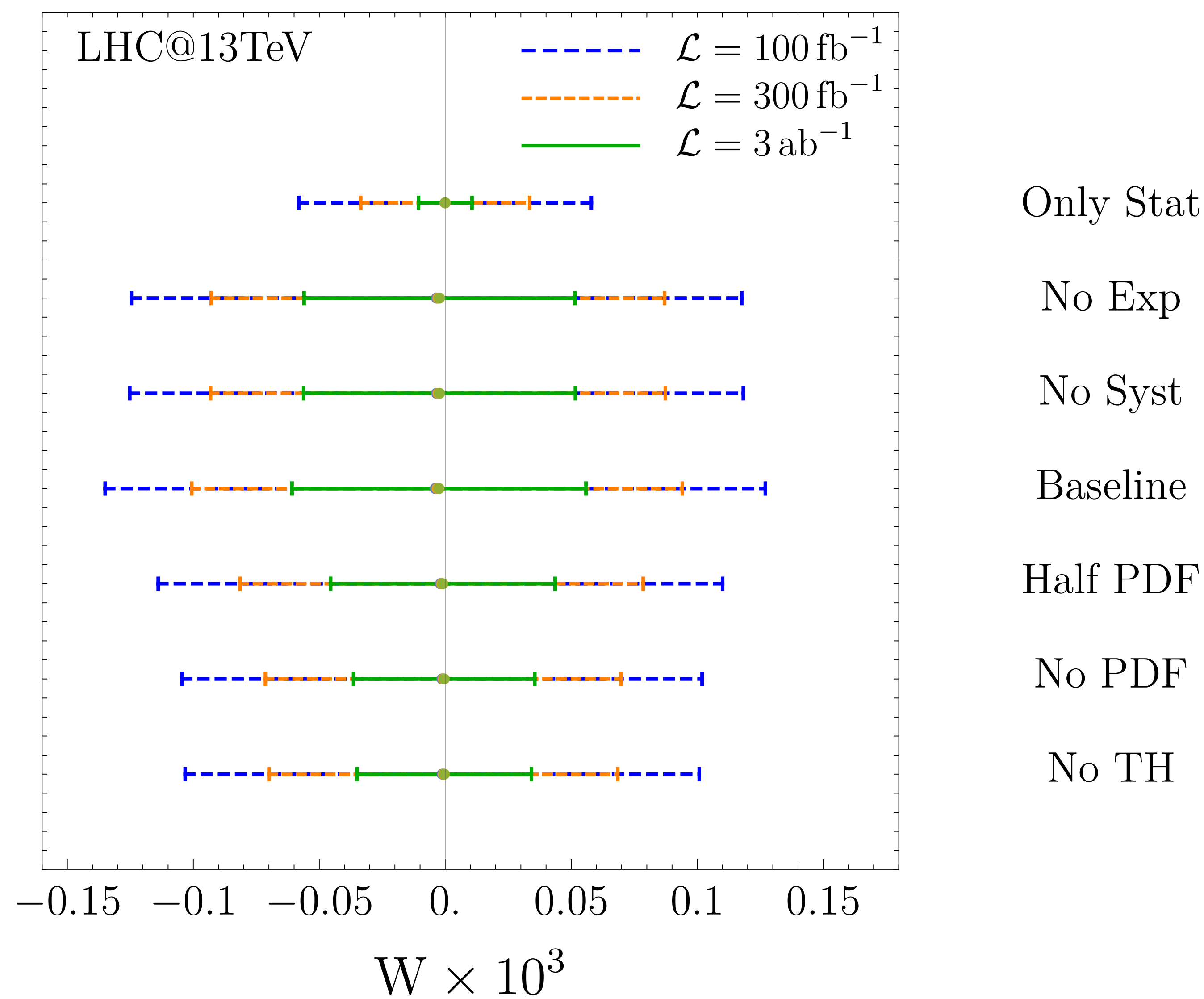
High-Energy Probes: What is Needed?

Fully-Differential High-Energy Drell—Yan:

[Ricci, Torre, AW, 2021; Ricci, Panico, AW, 2021]

- ✦ BSM predictions at NLO_{QCD}+PS, plus approx-NLO_{EW}
- ✦ PDF unc. are largest; Sensitivity floor is well below



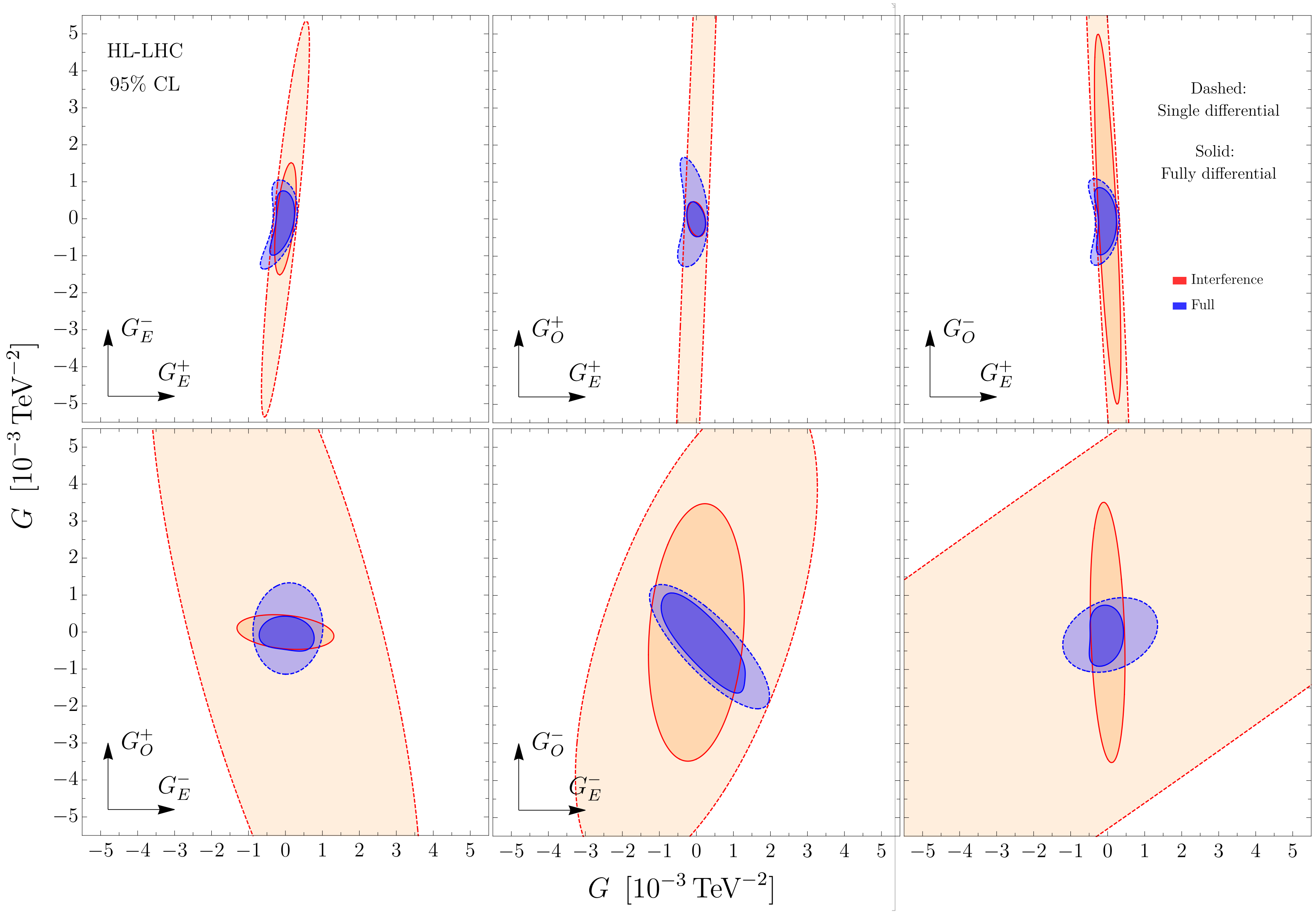


High-Energy Probes: What is Needed?

Fully-Differential High-Energy Drell—Yan:

[Ricci, Torre, AW, 2021; Ricci, Panico, AW, 2021]

- ✦ BSM predictions at NLO_{QCD}+PS, plus approx-NLO_{EW}
- ✦ PDF unc. are largest; Sensitivity floor is well below
- ✦ All 7 growing-with-energy operators included (6 accessible)
- ✦ Feasible only because **BSM** predictions from event **re-weighting**

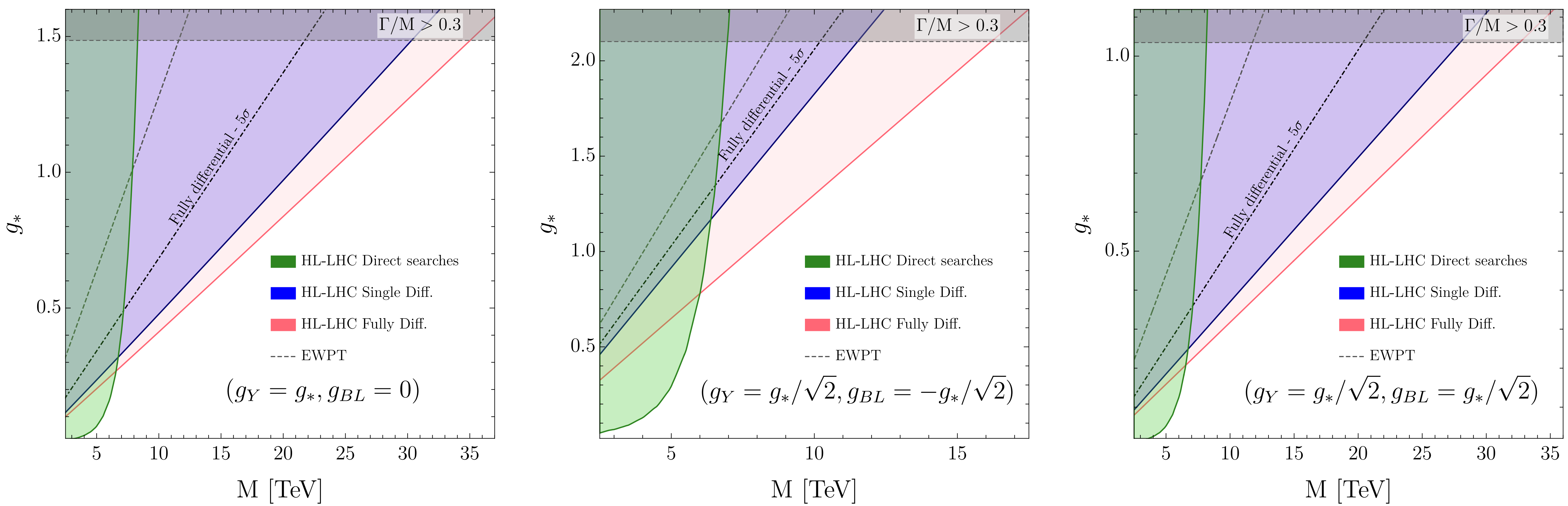


High-Energy Probes: What is Needed?

Fully-Differential High-Energy Drell—Yan:

[Ricci, Torre, AW, 2021; Ricci, Panico, AW, 2021]

- ✦ BSM predictions at NLO_{QCD}+PS, plus approx-NLO_{EW}
- ✦ PDF unc. are largest; Sensitivity floor is well below
- ✦ All 7 growing-with-energy operators included (6 accessible)
- ✦ Feasible only because **BSM** predictions from event **re-weighting**
- ✦ Extended sensitivity, **discovery** and **characterisation** potential for Z'

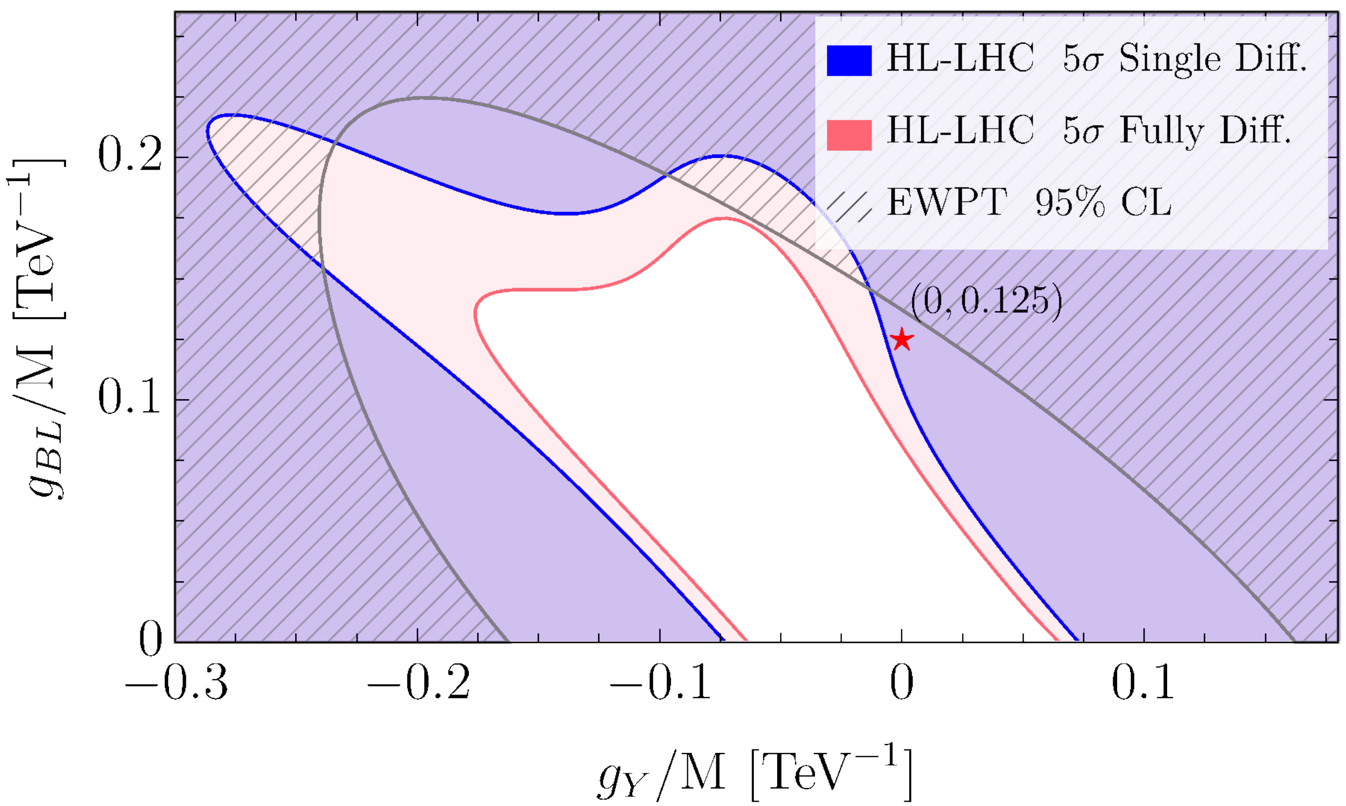


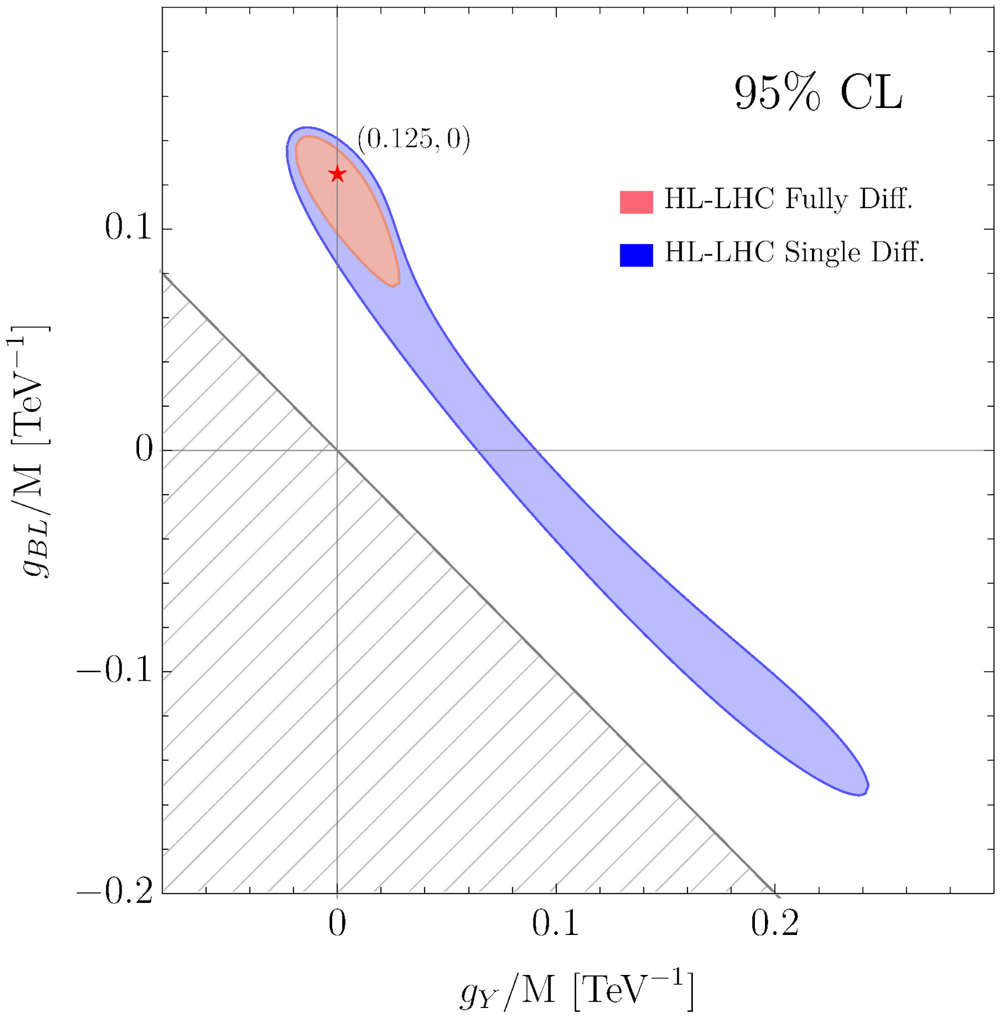
High-Energy Probes: What is Needed?

Fully-Differential High-Energy Drell—Yan:

[Ricci, Torre, AW, 2021; Ricci, Panico, AW, 2021]

- ✦ BSM predictions at NLO_{QCD}+PS, plus approx-NLO_{EW}
- ✦ PDF unc. are largest; Sensitivity floor is well below
- ✦ All 7 growing-with-energy operators included (6 accessible)
- ✦ Feasible only because **BSM** predictions from event **re-weighting**
- ✦ Extended sensitivity, **discovery** and **characterisation** potential for Z'





High-Energy DiBosons

Next-to-Simplest EW process

still, quite some work has been and will be needed …

High-Energy DiBosons

Next-to-Simplest EW process

still, quite some work has been and will be needed …

[Falkowski, Gonzalez-Alonso, Greljo, Marzocca, 2015]

[Green, Meade, Pleier, 2016]

[Butter, Éboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch, 2016]

[Franceschini, Panico, Pomarol, Riva, AW, 2017]

[Panico, Riva, AW, 2017]

[Azatov, Elias-Miro, Reyimuaji, Venturini, 2017]

[Azatov, Barducci, Venturini, 2019]

[Baglio, Dawson and Homiller, 2019]

[Grojean, Montull, Riembau, 2019]

[Chen, Glioti, Panico, AW, 2020]

[Banerjee, Gupta, Ochoa-Valeriano, Spannowsky, Venturini, 2020]

[Huang, Lane, Lewis, Liu, 2020]

[Baglio, Dawson, Homiller, Lane, Lewis, 2020]

[Banerjee, Gupta, Reiness, Seth, Spannowsky, 2020]

[CMS-PAS-SMP-20-014]

[CMS-PAS-SMP-20-005]

[ATLAS 2103.10319]

…

High-Energy DiBosons

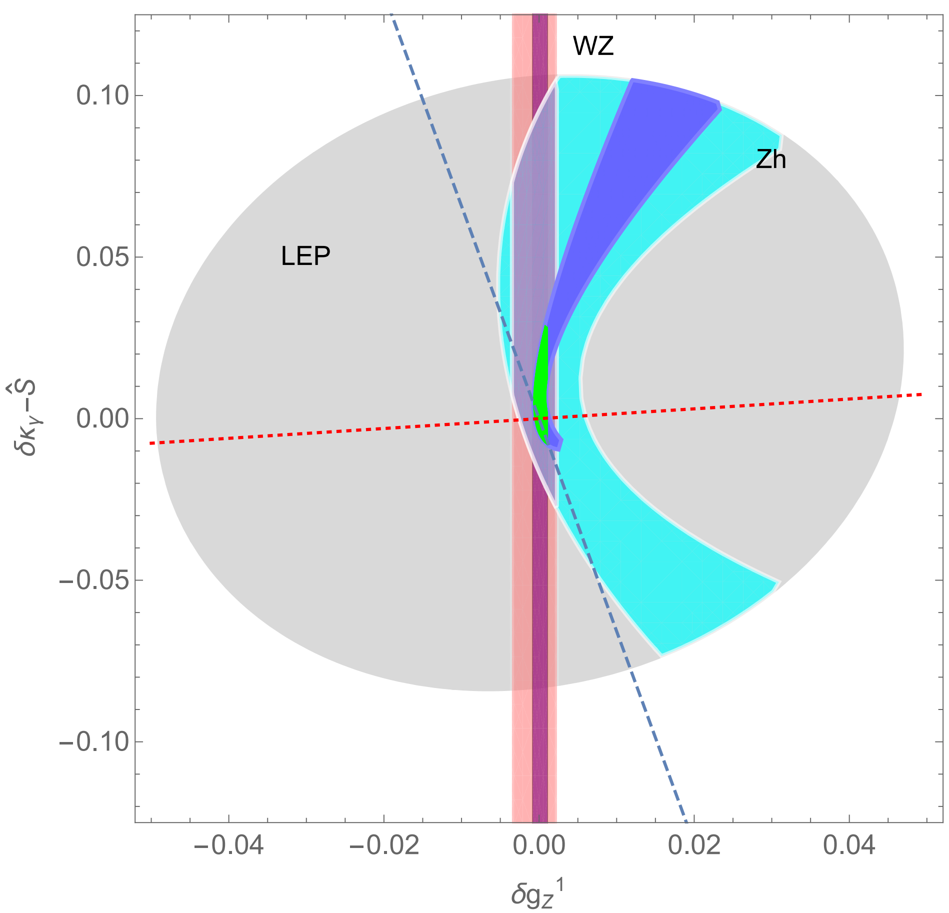
Next-to-Simplest EW process

still, quite some work has been and will be needed …

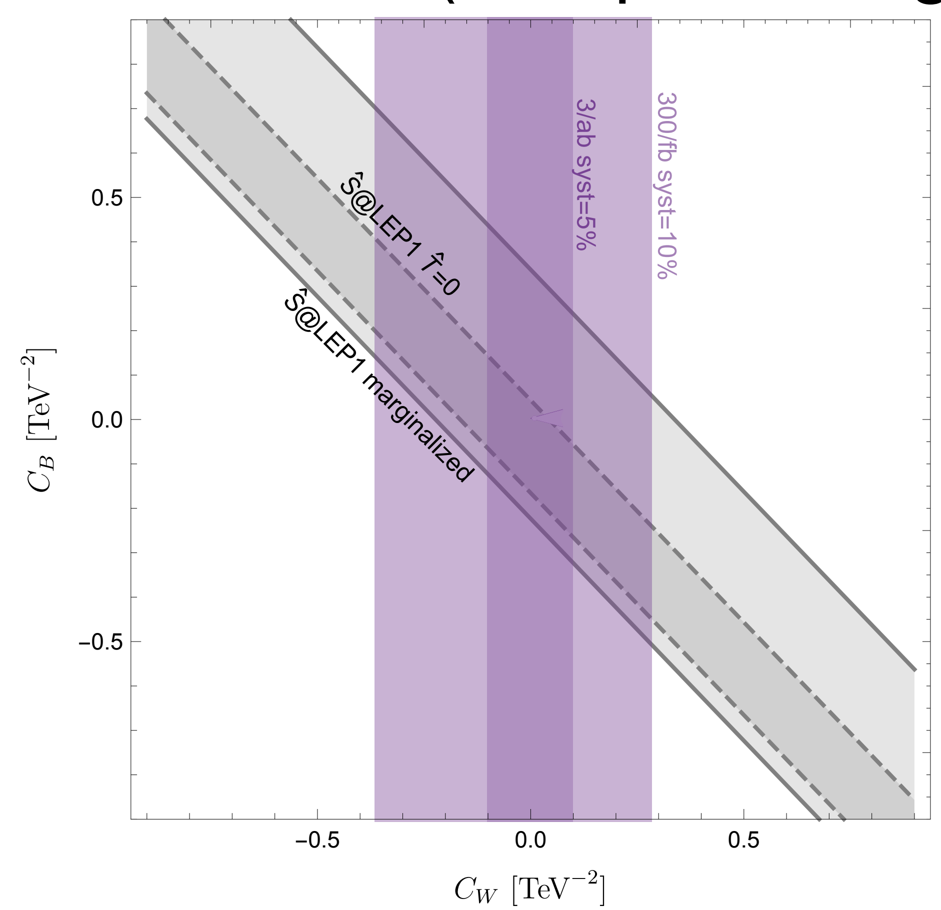
Longitudinal DiBosons:

- ✦ **Four** growing-with-energy operators; Probed by $\mathbf{V_L V_L}$ and $\mathbf{V_L h}$
- ✦ Fully leptonic WZ is the simplest; (Z→ll) (h→bb) studied as well

LHC vs LEP (Univ. Th.)



LHC vs LEP (Composite Higgs)



High-Energy DiBosons

Next-to-Simplest EW process

still, quite some work has been and will be needed …

Longitudinal DiBosons:

- ✦ **Four** growing-with-energy operators; Probed by $\mathbf{V_L V_L}$ and $\mathbf{V_L h}$
- ✦ Fully leptonic WZ is the simplest; ($Z\to ll$) ($h\to bb$) studied as well

Gain with **hadronic decays** could be enormous

High-Energy DiBosons

Next-to-Simplest EW process

still, quite some work has been and will be needed …

Longitudinal DiBosons:

- ✦ **Four** growing-with-energy operators; Probed by $\mathbf{V_L V_L}$ and $\mathbf{V_L h}$
- ✦ Fully leptonic WZ is the simplest; ($Z\rightarrow ll$) ($h\rightarrow bb$) studied as well

  Gain with **hadronic decays** could be enormous
- ✦ No “EFT validity issue”, if accurate enough

EFT Validity

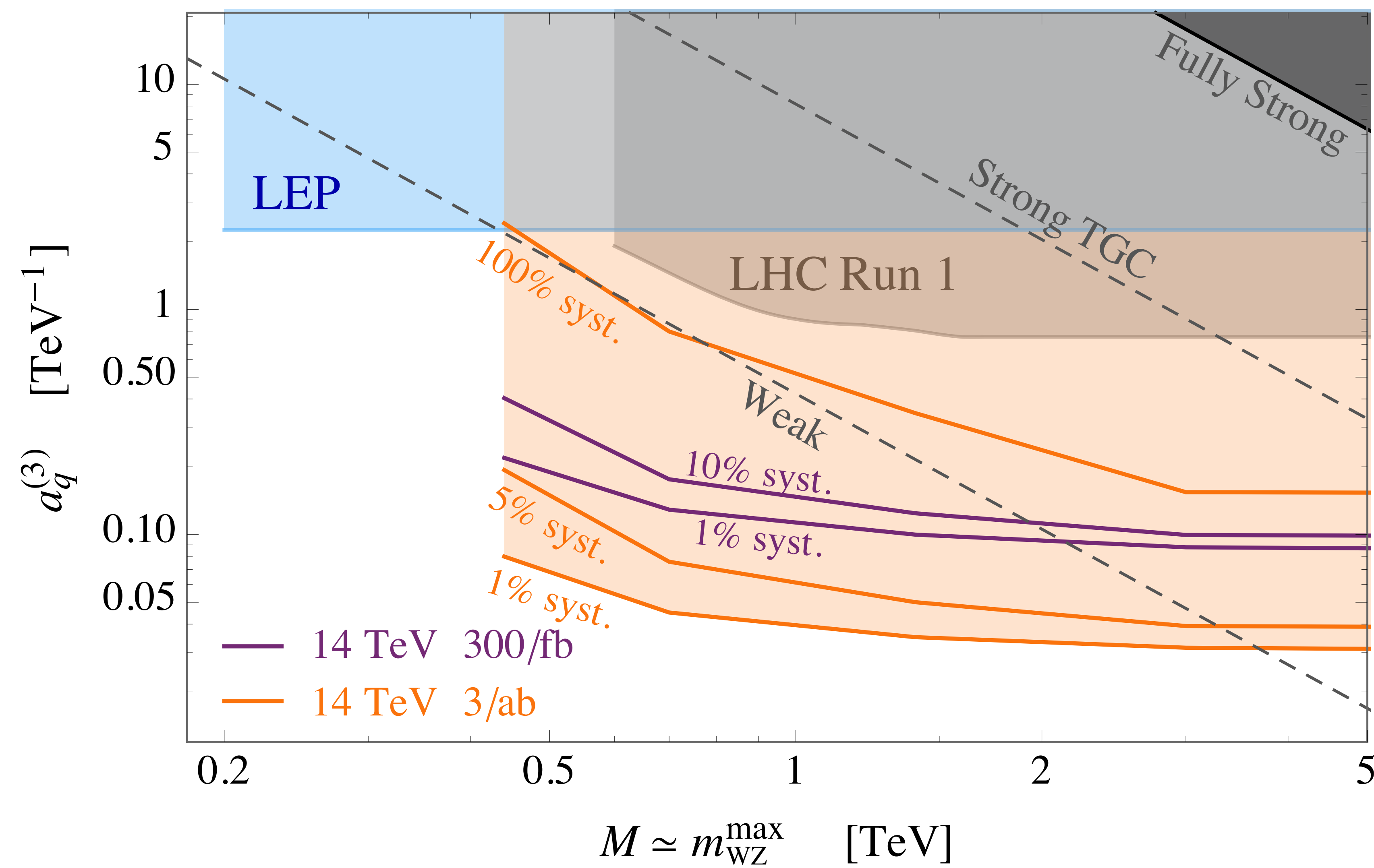
Which UV theories are we probing?

EFTs have finite upper energy cutoff of validity

EFT Validity

Which UV theories are we probing?

EFTs have finite upper energy cutoff of validity



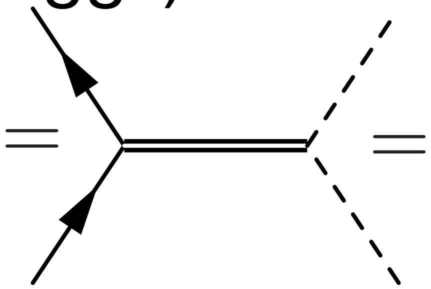
EFT Validity

Which UV theories are we probing?

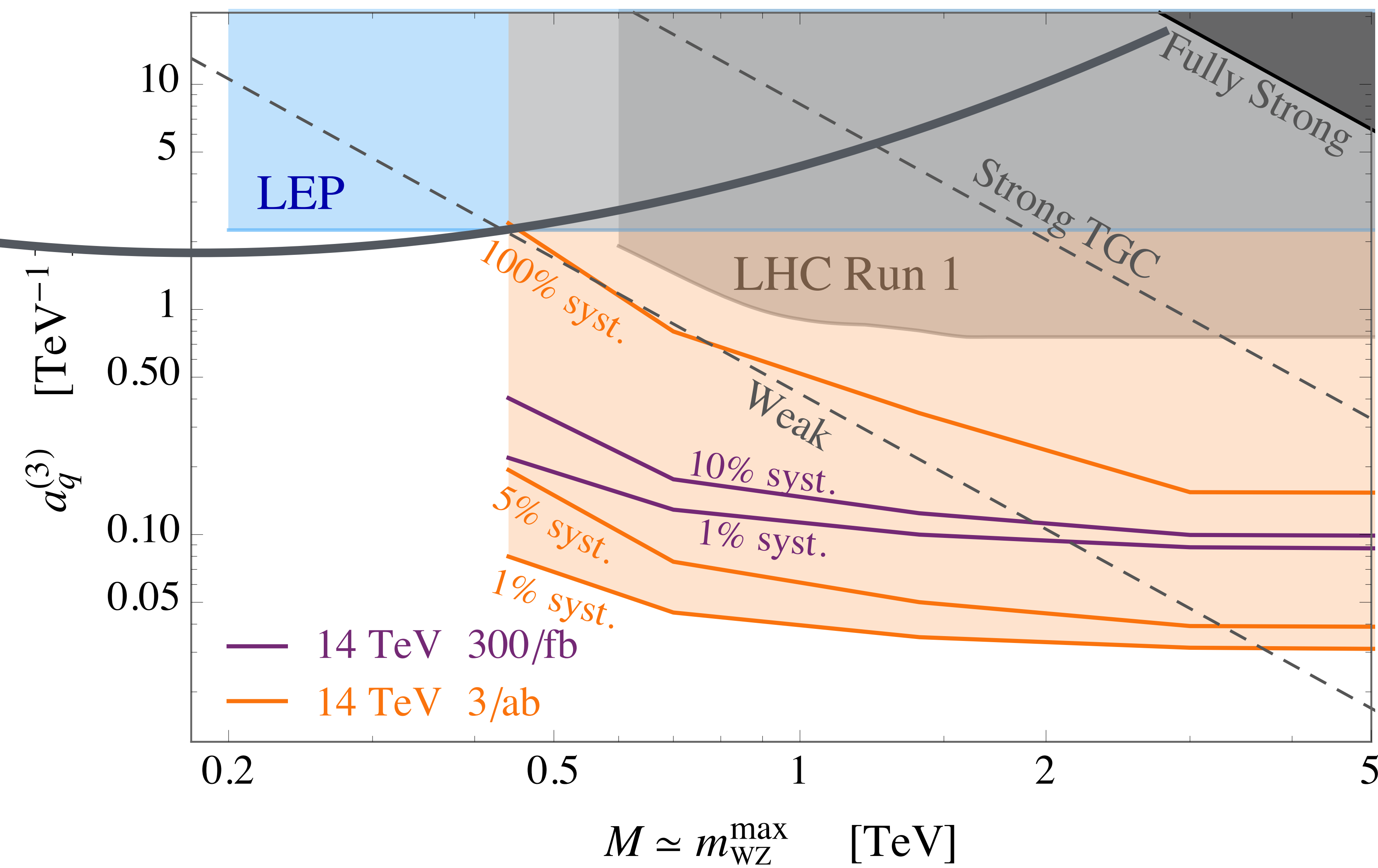
EFTs have finite upper energy cutoff of validity

Strongly-coupled quarks
(and Higgs)

$a_q^{(3)} =$



$= \dfrac{16\pi^2}{M^2}$

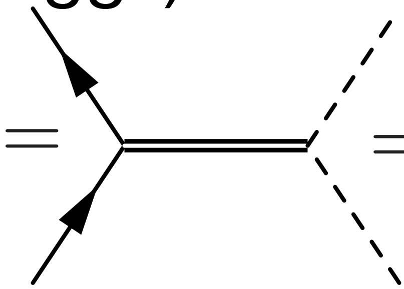


EFT Validity

Which UV theories are we probing?

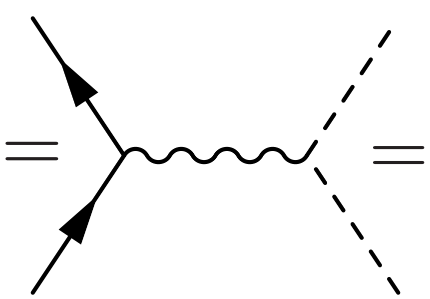
EFTs have finite upper energy cutoff of validity

Strongly-coupled quarks (and Higgs)

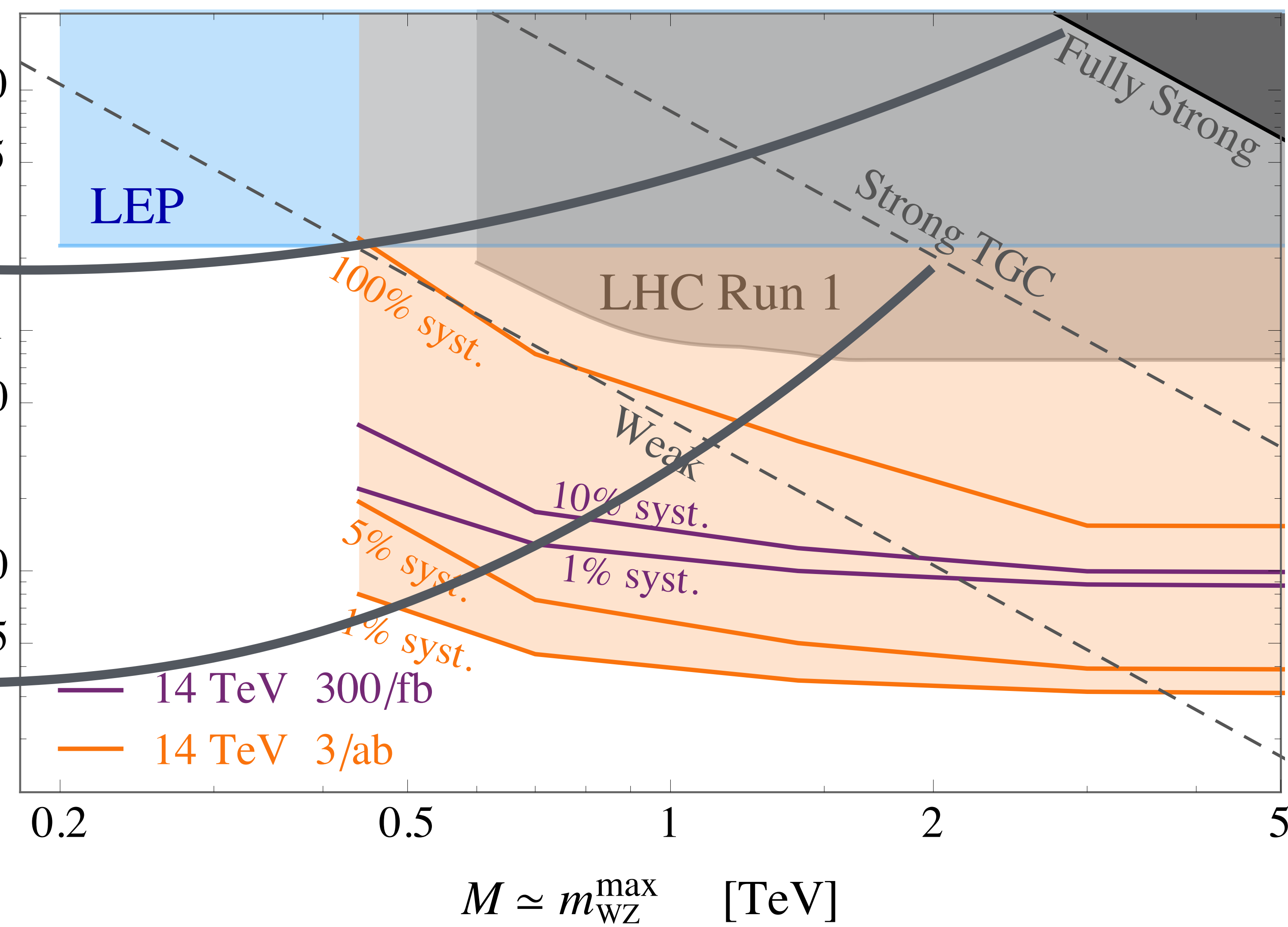


$$a_q^{(3)} = \quad = \frac{16\pi^2}{M^2}$$

Weakly-coupled quarks, **strongly coupled gauge**



$$a_q^{(3)} = \quad = \frac{4\pi\, g_W}{M^2}$$

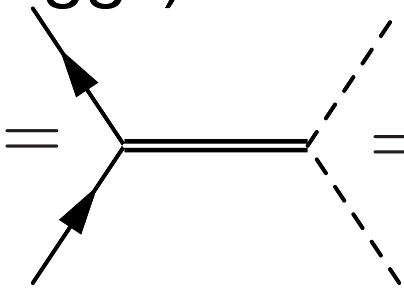


EFT Validity

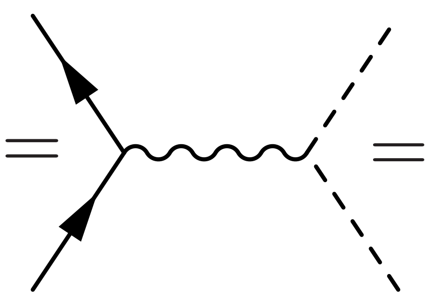
Which UV theories are we probing?

EFTs have finite upper energy cutoff of validity

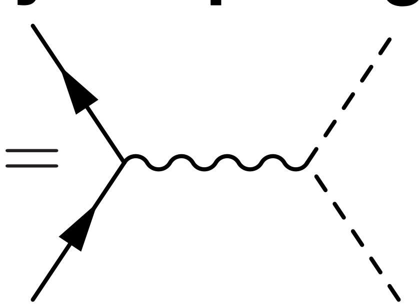
Strongly-coupled quarks (and Higgs)

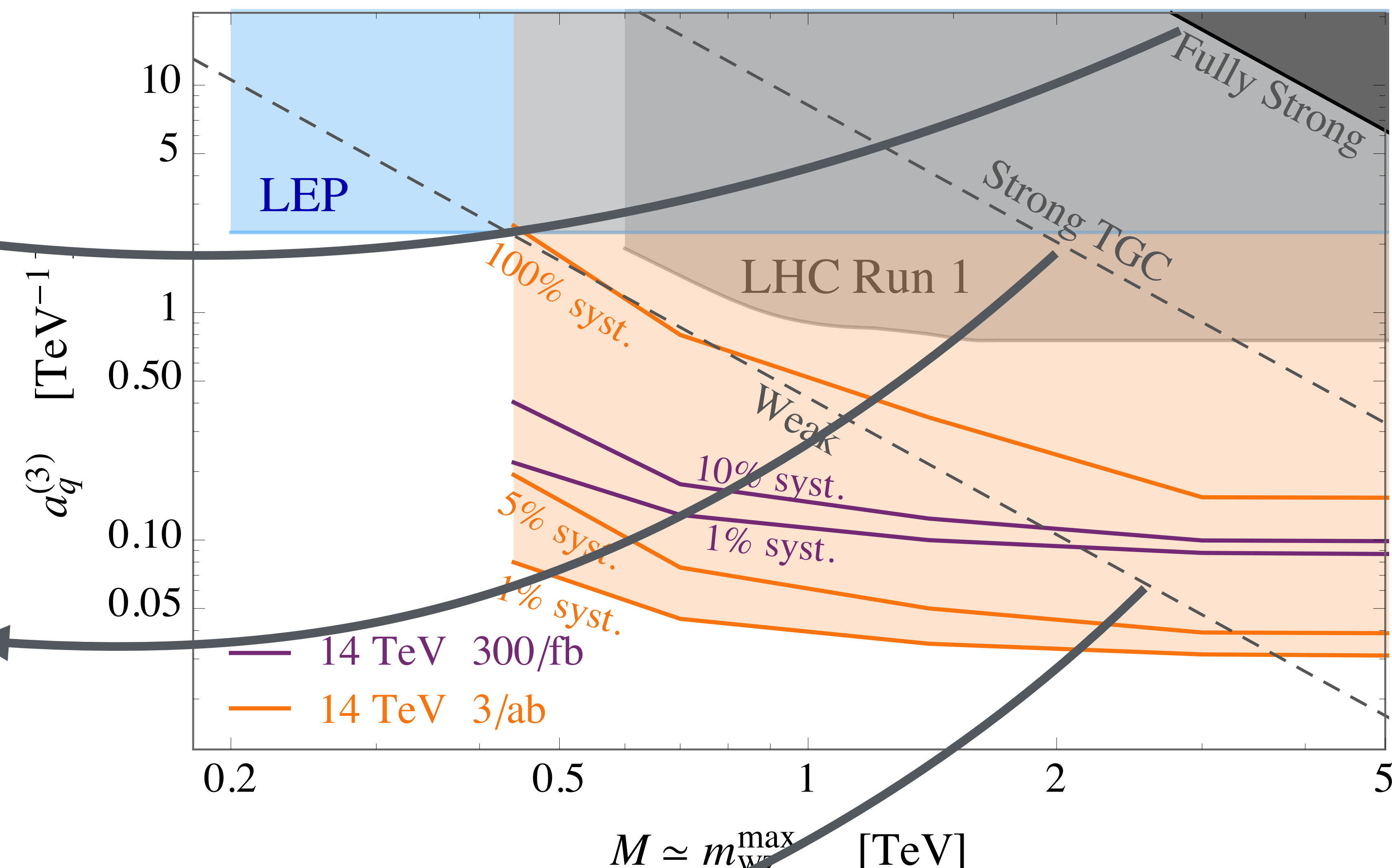
$a_q^{(3)} =$  $= \dfrac{16\pi^2}{M^2}$

Weakly-coupled quarks, **strongly coupled gauge**

$a_q^{(3)} =$  $= \dfrac{4\pi\, g_W}{M^2}$

Weakly-coupled quarks, **weakly coupled gauge**

$a_q^{(3)} =$  $= \dfrac{g_W^2}{M^2}$

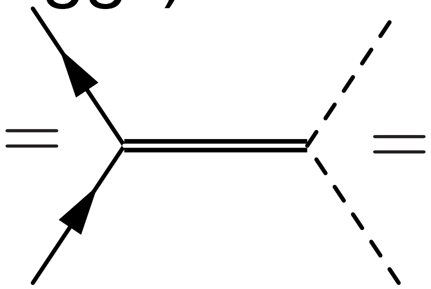


EFT Validity

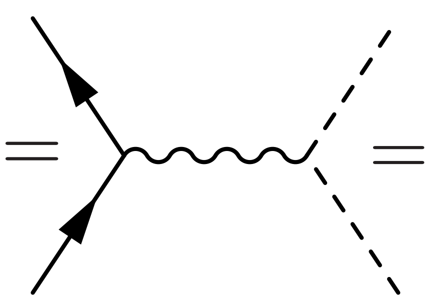
Which UV theories are we probing?

EFTs have finite upper energy cutoff of validity

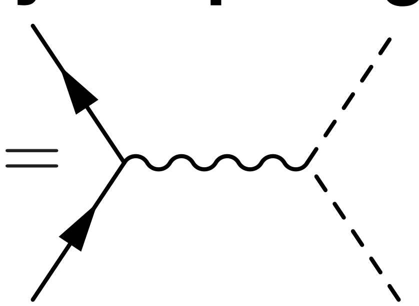
Strongly-coupled quarks
(and Higgs)

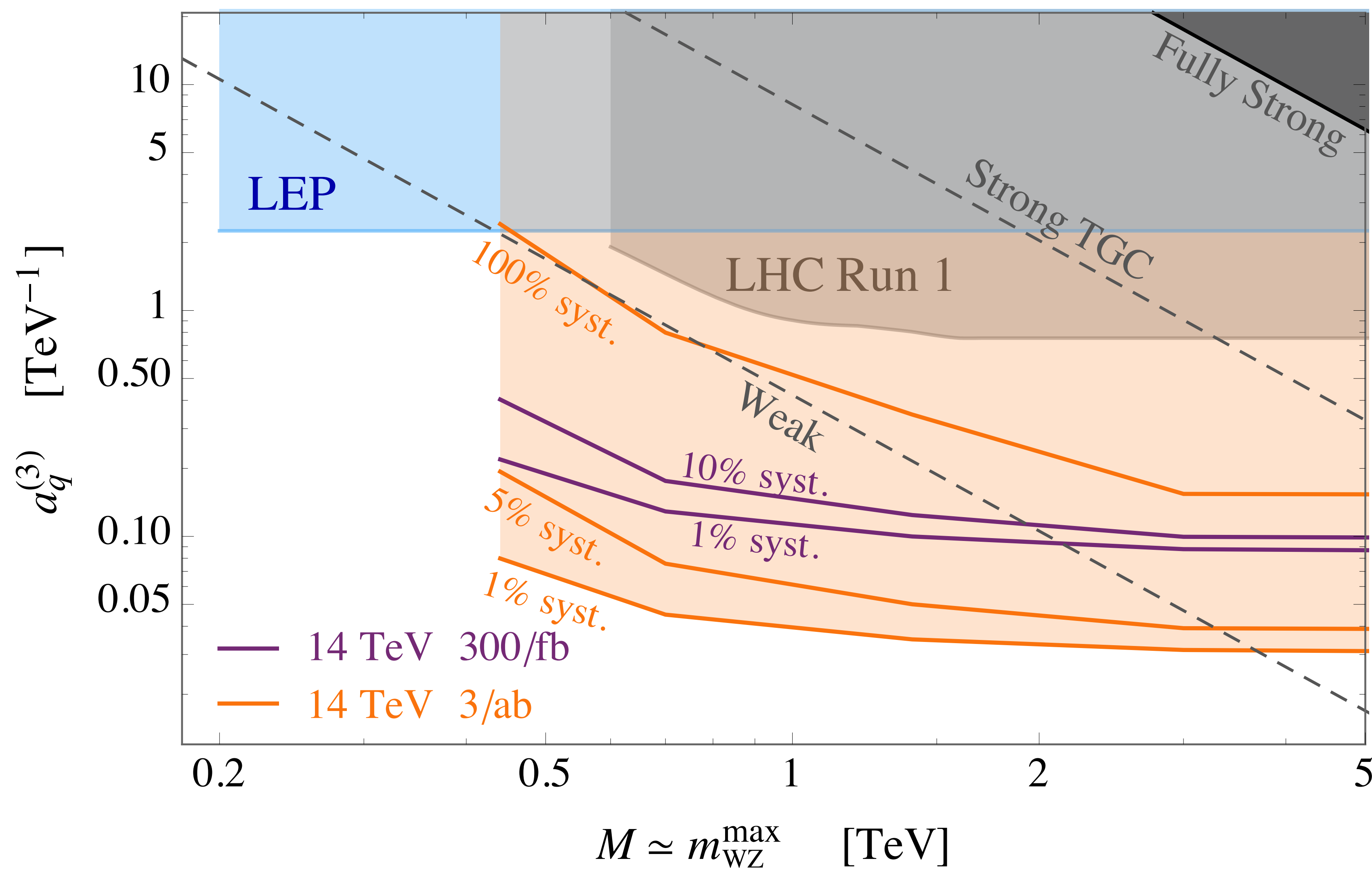
$a_q^{(3)} =$  $= \frac{16\pi^2}{M^2}$

Weakly-coupled quarks,
strongly coupled gauge

$a_q^{(3)} =$  $= \frac{4\pi\, g_W}{M^2}$

Weakly-coupled quarks,
weakly coupled gauge

$a_q^{(3)} =$  $= \frac{g_W^2}{M^2}$

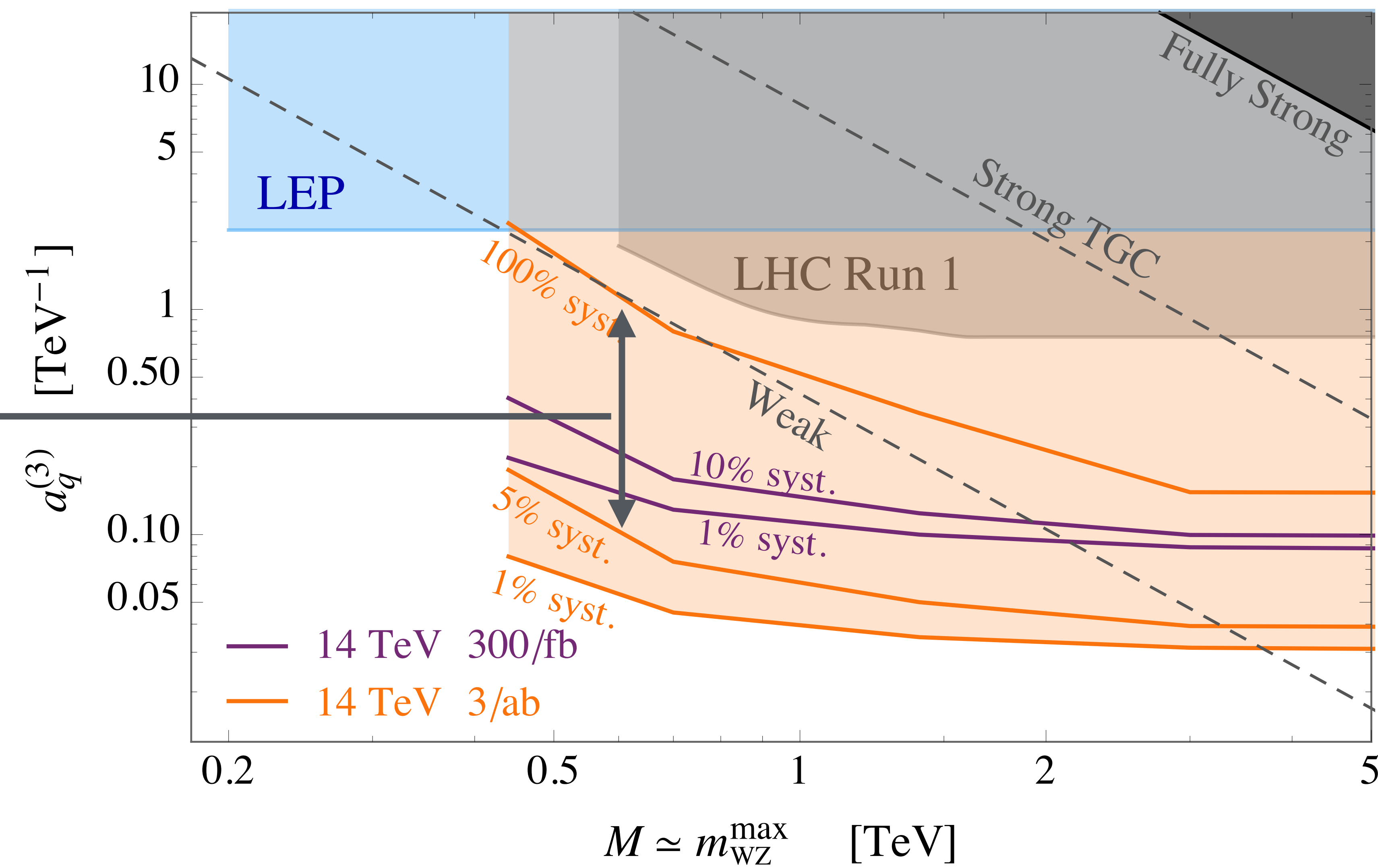


Unlike run-1, we will **surpass LEP** for theories where quarks and gauge fields are elementary! (Higgs can be composite)

EFT Validity

Which UV theories are we probing?

EFTs have finite upper energy cutoff of validity



WE NEED ACCURACY!!
both Exp and Th

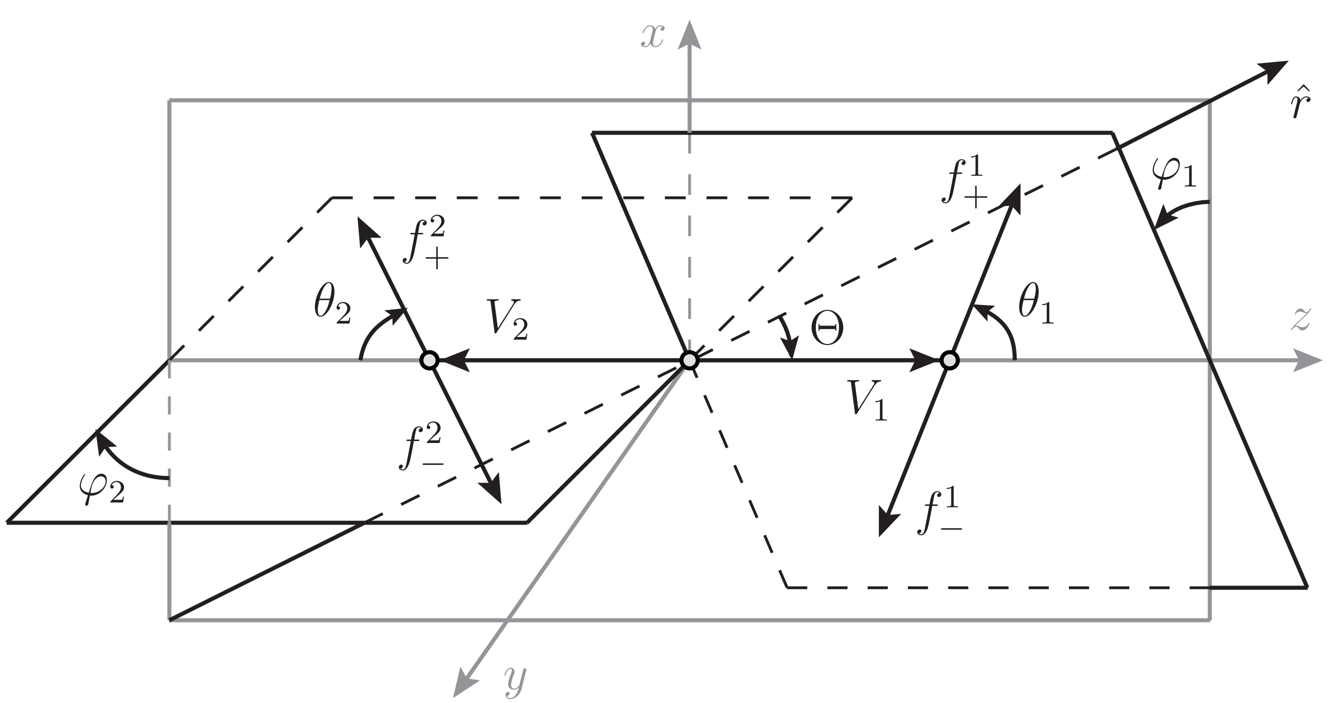
Unlike run-1, we will **surpass LEP** for theories where quarks and gauge fields are elementary! (Higgs can be composite)

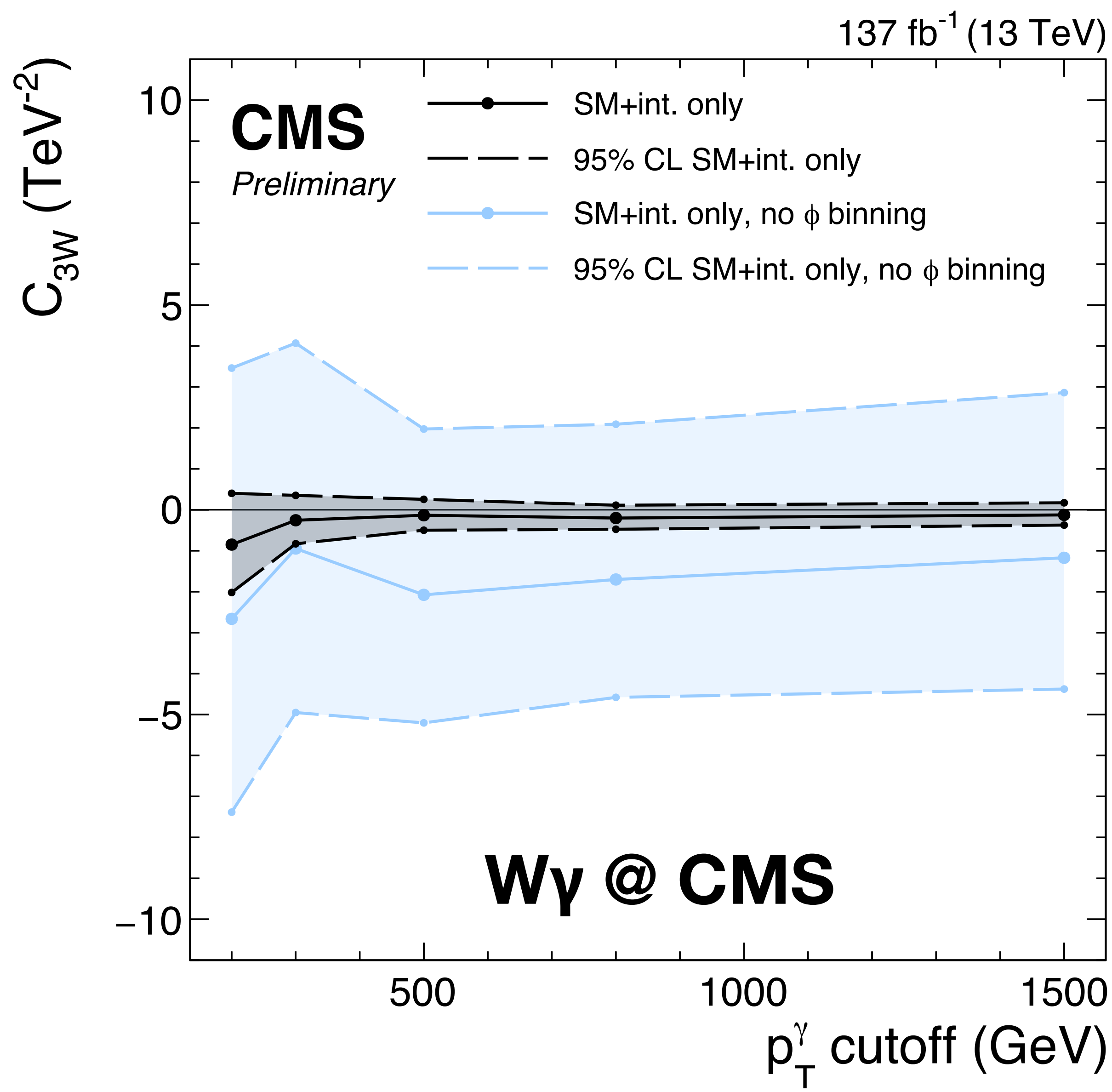
High-Energy DiBosons

Transverse DiBosons:

- ✦ Targets are F^3 operators; issue with **helicity mismatch**
- ✦ Must measure **plane** (rather than circular) polarizations

[Panico, Riva, AW, 2017]





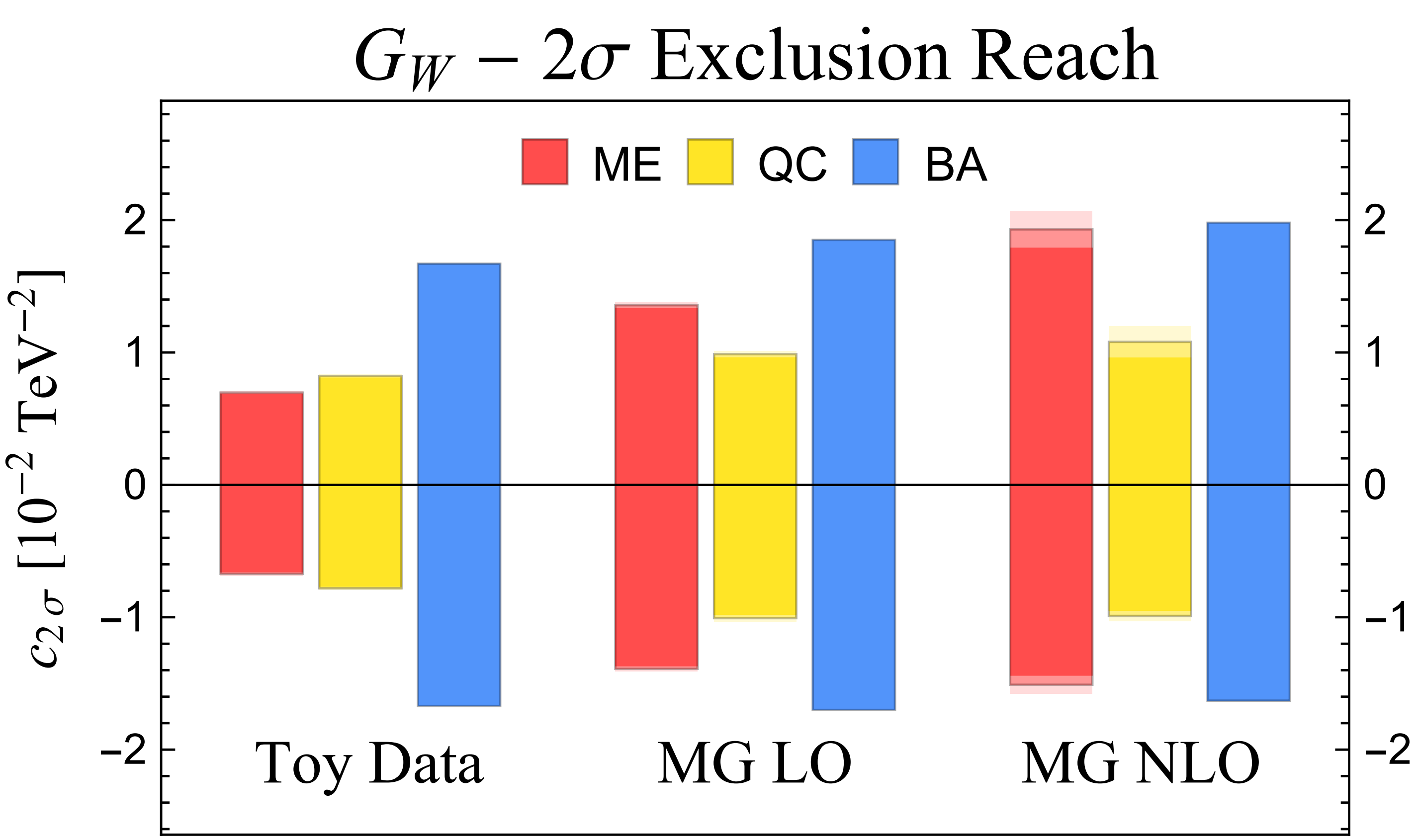
High-Energy DiBosons

Transverse DiBosons:

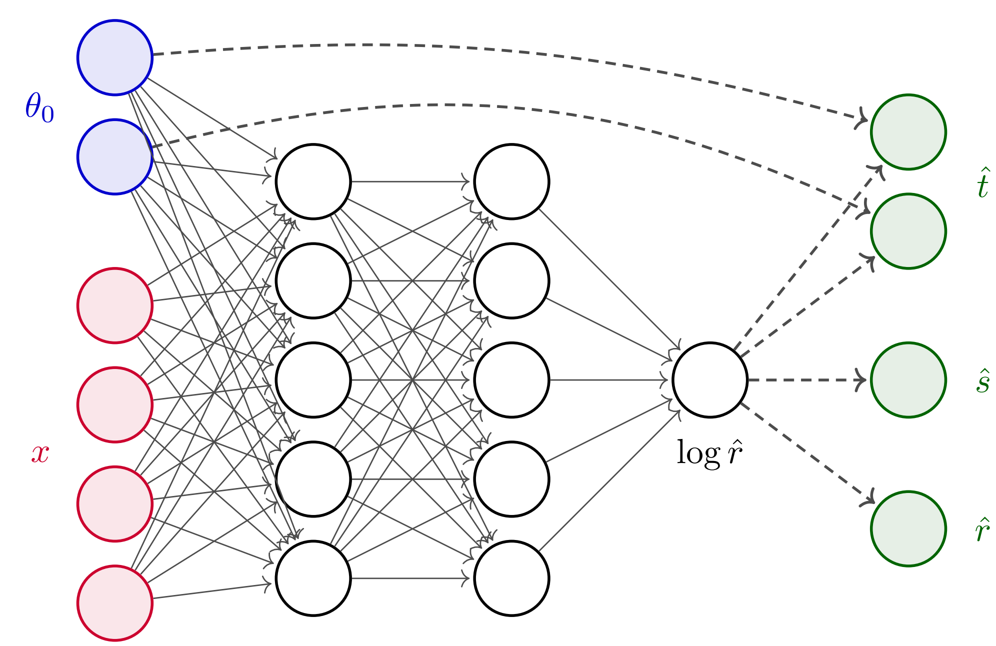
- ✦ Targets are F^3 operators; issue with **helicity mismatch**
- ✦ Must measure **plane** (rather than circular) polarizations

[Panico, Riva, AW, 2017]

- ✦ Great perspectives for multivariate analyses with novel ML techniques



[Chen, Glioti, Panico, AW, 2020]



[Brehmer, Kling, Espejo Cranmer (MadMiner),2019]

…

[Brehmer, Dawson, Homiller, Kling, Plehn, 2019]

…

Conclusions

- **Great physics ahead of us**
  20 years might be **just enough** time
- **The BSM Precision Program**
  Needs dedicated EXP/QCD/PDF/BSM work
  EFT useful models' "container". Connects low with **high-energy probes**
  Inside, there are models waiting to be discovered
- **Work in Progress!**
  We will not be sure of syst. until measurements out (DY is taking 3 yrs!)
  Are existing calculations/PDF really sufficient in relevant kin. regimes?
  Many more channels to be considered (HZ done, had.V?, WW?, **top?**)
  [for a still incomplete list, see Henning, Lombardo, Riembau, Riva, 2018]
- **Going Multivariate?**
  There might be much to gain compared to diff. XS measurements.
  Requires dedicated analyses, refined statistical tools, challenging assessment of systematics, and/or Neural Networks… that's great!

Thank You!

Our questions to the Audience

- The Flavour interplay
  flavour assumptions incorporating bounds and anomalies

- Which EFT?
  Is linear d=6 EFT a good **minimal** target?

- Precision bottlenecks
  PDF@1%?, M.C.@1%?, … and?

- EXP/TH Integration **is** needed
  HowTo?