The Discovery of the Higgs Boson

A 30 year-long experimental enterprise

GGI for Theoretical Physics

“Happy birthday Higgs Boson”

Marumi Kado

Sapienza (Roma), CERN and LAL (Orsay)

A Packed Week!

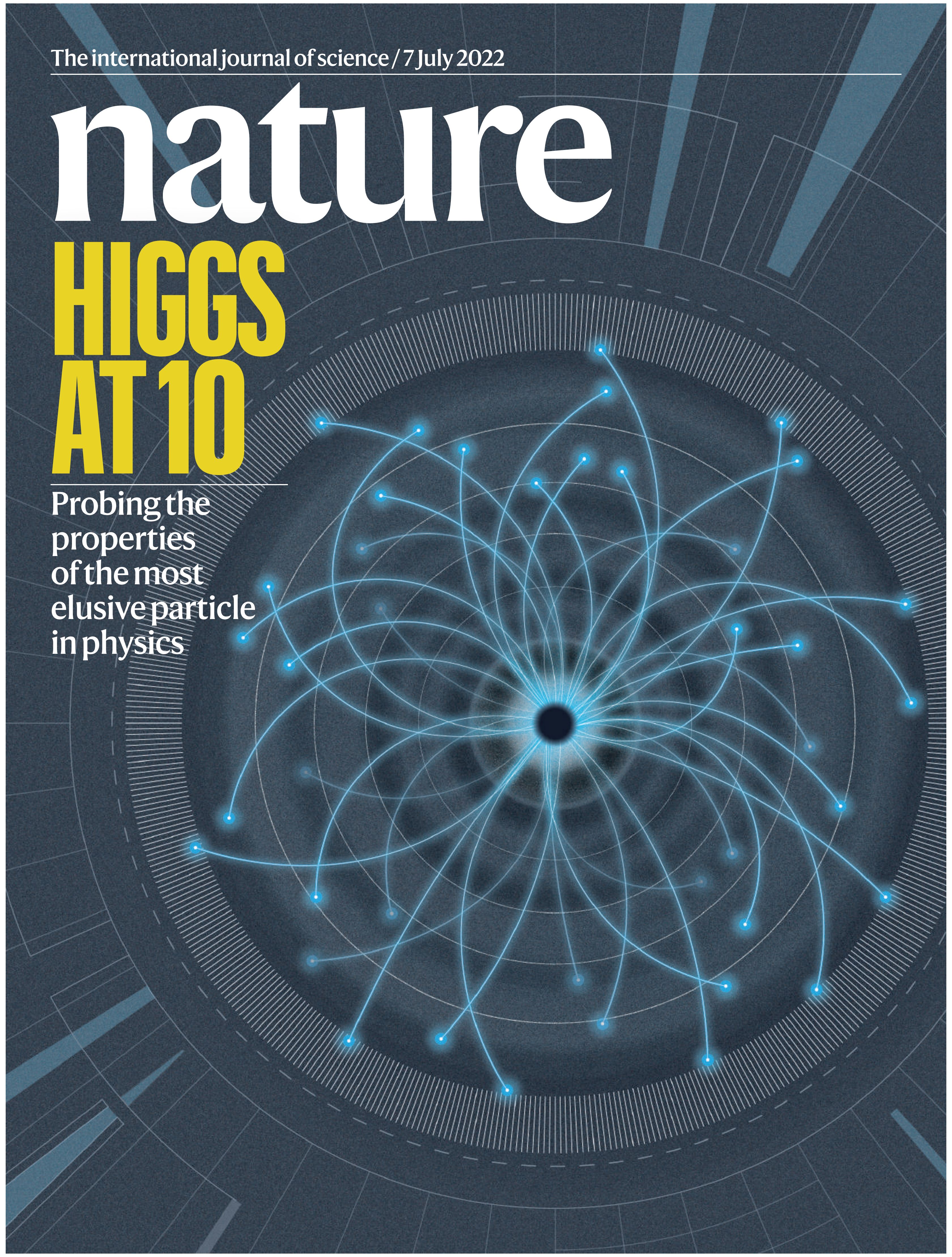
Run 3 started at 13.6 TeV !!

News and pictures from yesterday at CERN

The third run of the Large Hadron Collider has successfully started

A round of applause broke out in the CERN Control Centre on 5 July at 4.47 p.m. CEST when the Large Hadron Collider (LHC) detectors started recording high-energy collisions at the unprecedented energy of 13.6 TeV

A Packed Week!



Join CERN in a historic week for particle physics

Tune in to celebrate ten years of Higgs research at the LHC with CERN on 3 and 4 July. If your hunger for physics hasn't been satiated, stay to witness the start of Run 3 at the LHC on 5 July

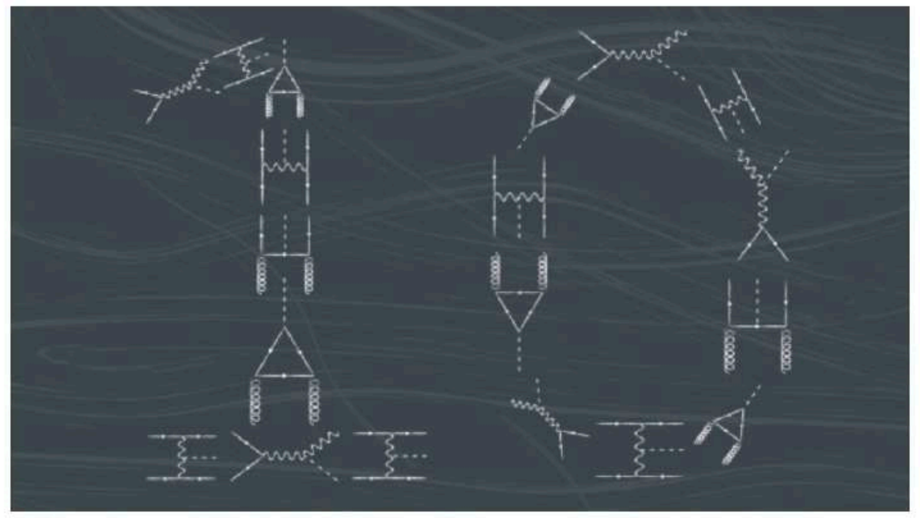
nature portfolio

nature > collection

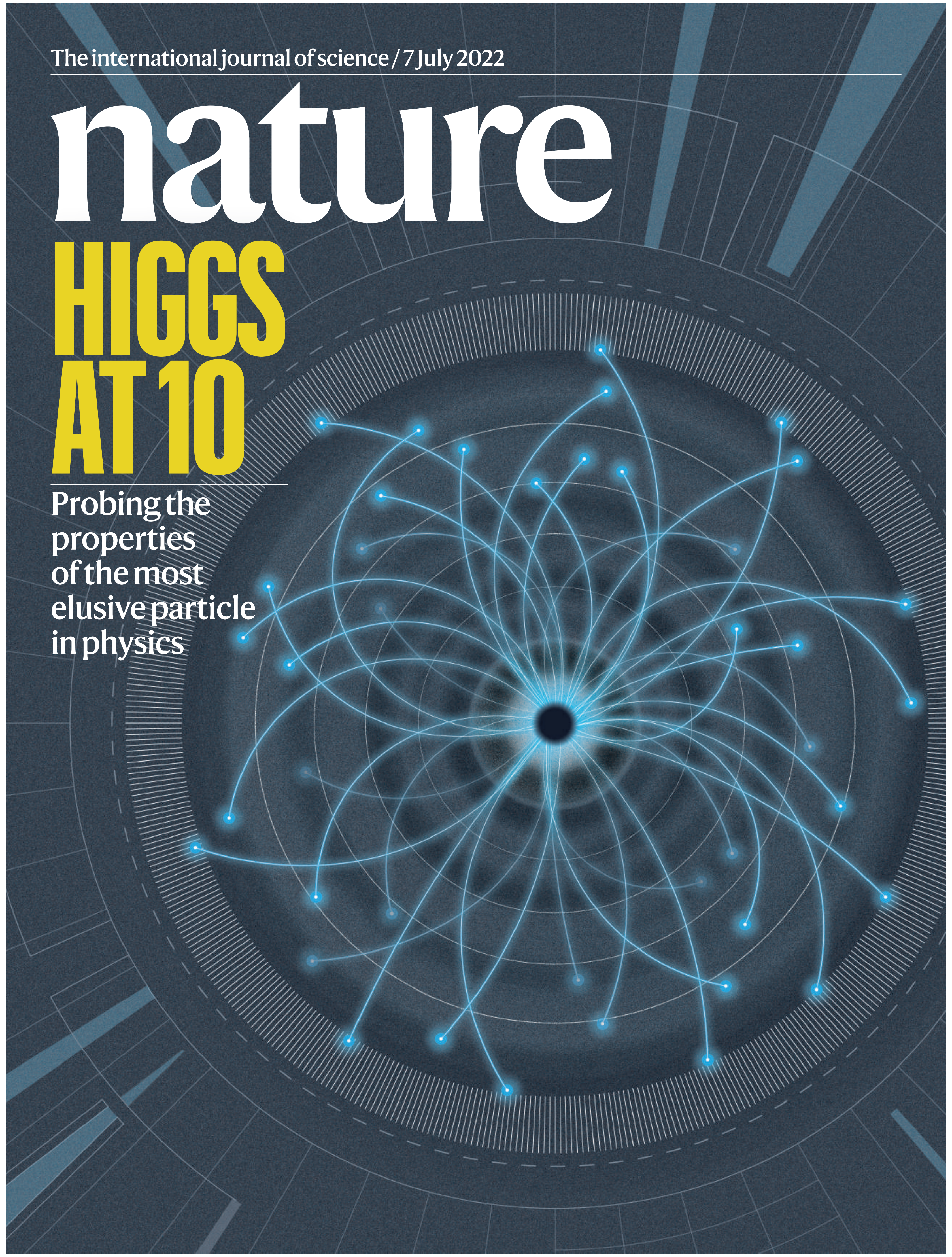
Collection | **04 July 2022**

The Higgs boson discovery turns ten

The discovery of the Higgs boson was announced ten years ago on the 4th of July 2012 — an event that substantially advanced our understanding of the origin of elementary particles' masses. In this collection of articles from *Nature, Nature Physics* and *Nature Reviews Physics* we celebrate this groundbreaking discovery and reflect on what we have learned about the Higgs boson over the intervening years.



Outline



1.- Preamble

2.- A Marvel of Technology

3.- Performing well beyond expectations

4.- The Higgs discovery

5.- Status of Higgs Physics at LHC

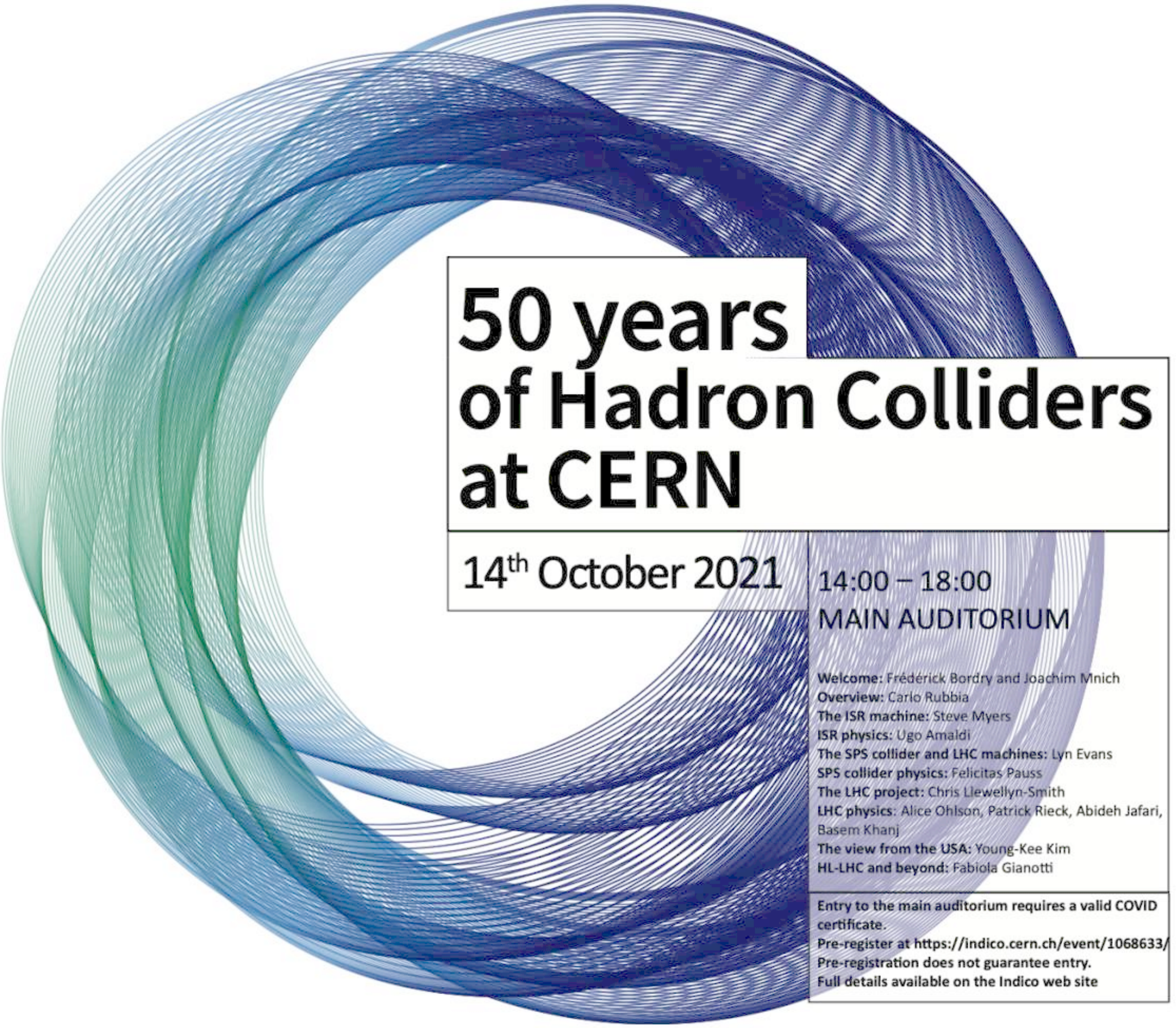
6.- The Essential Role of TH Predictions

7.- Early evidences for Rare processes

8.- Making the Impossible Possible

Important References

50 years of hadron colliders at CERN symposium



Higgs 10 symposium at CERN

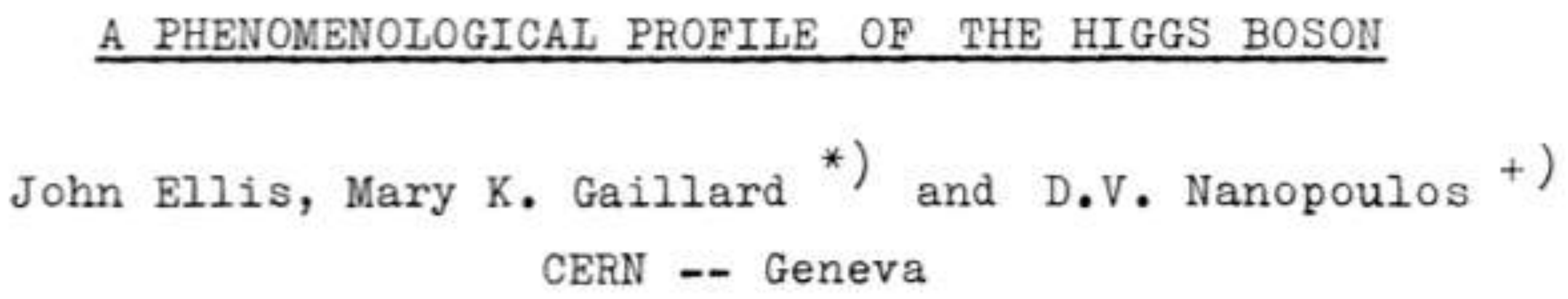
CERN 10 years HIGGS boson discovery

1.- Preamble

Four decades of Higgs Searches

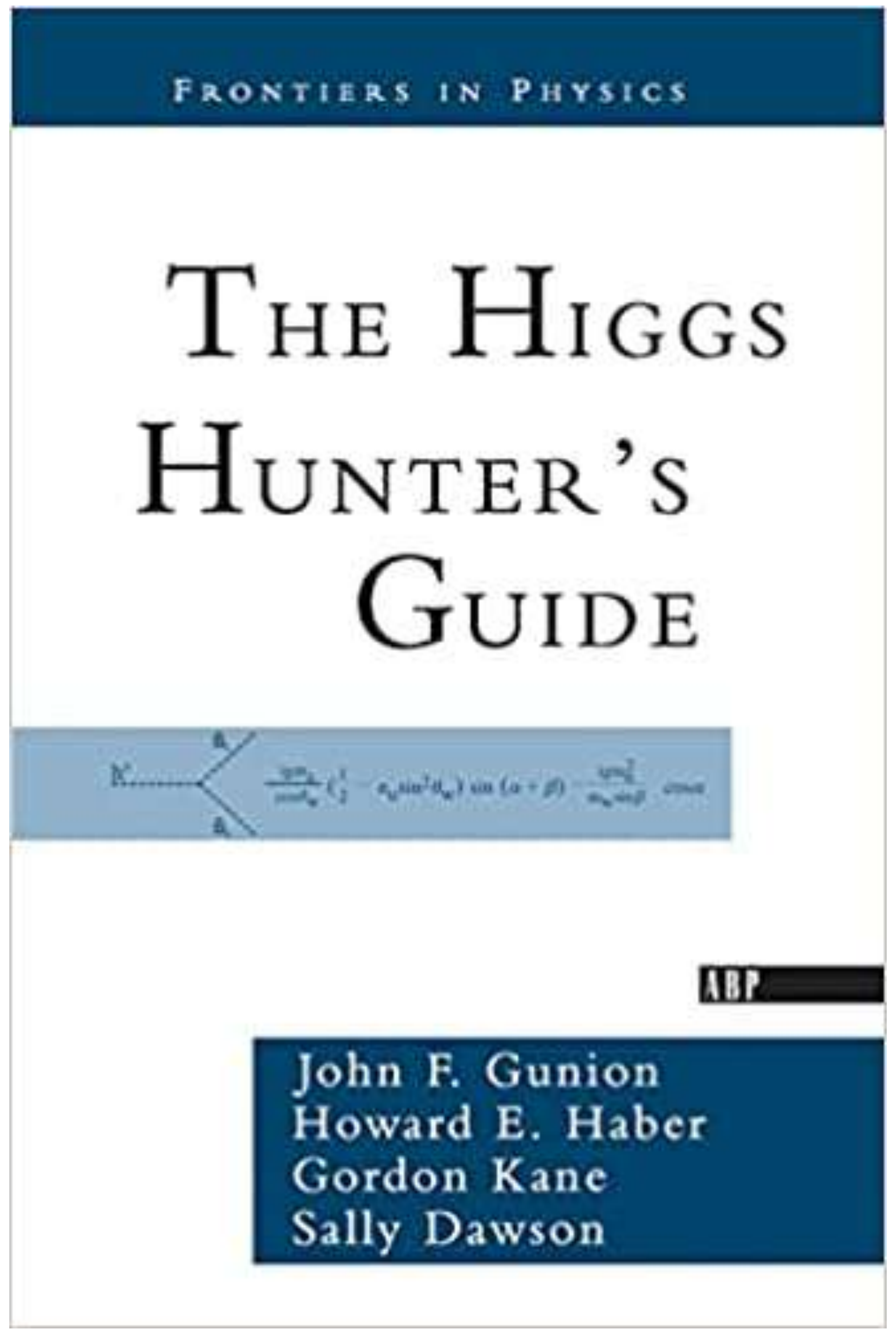
No idea what the mass of the Higgs Boson should be except for VV scattering unitarity and triviality <1 TeV

- $0^+ - 0^+$ transition in ^{16}O or ^{214}Po where $A^* \to A\phi_{\to e^+e^-}$, Kaon decays $K^+ \to \pi^+\phi_{\to \mu^+\mu^-}$ and pion decays $\pi^+ \to \mu^+\nu\phi$
- $(g-2)_\mu$ and muonic atom transitions
- Neutron-Nucleus scattering (nPb) exclusion
- Pion-proton and photon-proton scattering
- Kaon decays $K \to \pi\phi$ … also B and Υ decays
- Cosmological Constant considerations from the minimum of the potential after breaking
- Microwave background observations
- Early pp colisions (ISR) then of course SpS, SppS, and the Tevatron…
- e^+e^- (low direct cross section) ACO, SPEAR, DORIS, PETRA and of course LEP1,2 (up to 209 GeV)…


A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva



Four decades of Higgs Searches

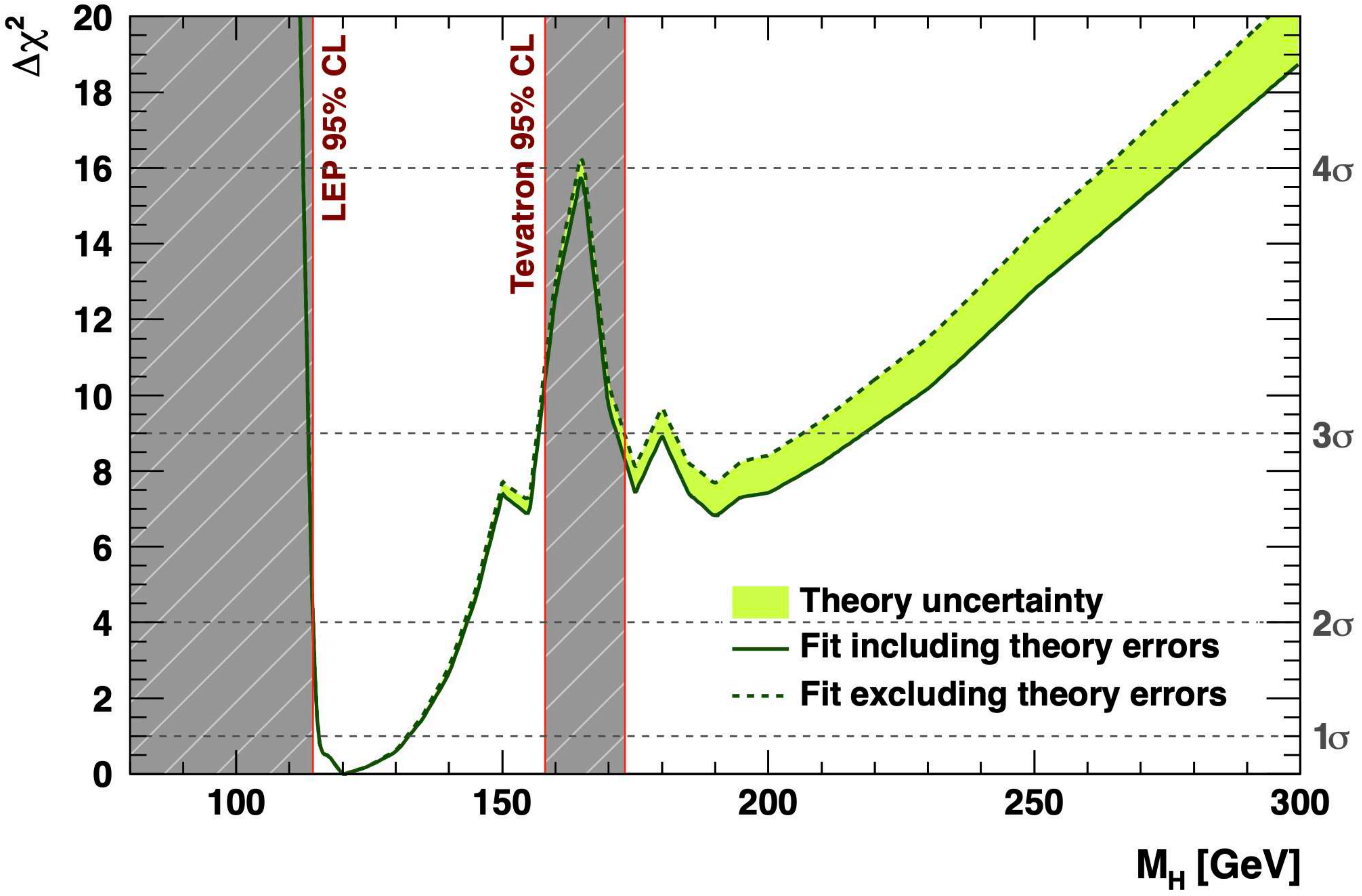
LEP2 provided an absolute lower limit at 114.4 GeV!

The Tevatron had a good sensitivity in the mas region around 160 GeV!

After 30-40 years of searches, in 2008 the tension was culminating!

The low mass region (115-150 GeV) was clearly one not to be missed…

GFitter 2011



… and of course there was the “no-lose” theorem!

2.- A Marvel of Technology

The LHC a « Marvel of Technology »

27 km tunnel originally built for the LEP collider (at an average depth of 100m - lowest point 175m)

LHC facts sheet see:

http://cds.cern.ch/record/2255762

The LHC a « Marvel of Technology »

First mention of the LHC in 1977 by sir John Adams (former CERN director) as an option of a superconducting hadron collider to be hosted in the LEP tunnel (requesting that the LEP be made large enough to host a proton collider of at least 3 TeV beam energy). That was a period very busy with extremely important physics results.

- 1984-88: CERN and ECFA workshop in Lausanne, LEP tunnel completed (Europe's largest civil engineering project prior to the channel tunnel).
- 1990-92: workshop in Aachen (definition of the main discovery channels), ATLAS and CMS letters of intent.
- 1993-94 Cancellation of 40 TeV SSC, 10m prototype magnet reached 8.73 T and approval of the LHC
- 1997-98: ATLAS, CMS, LHCb and ALICE experiments approved.
- 2003-05: Caverns completed installation started.
- 2007-08: LHC dipoles installed in LHC (after having been stocked in parking lots, individually checked at SM18), experiments installed…

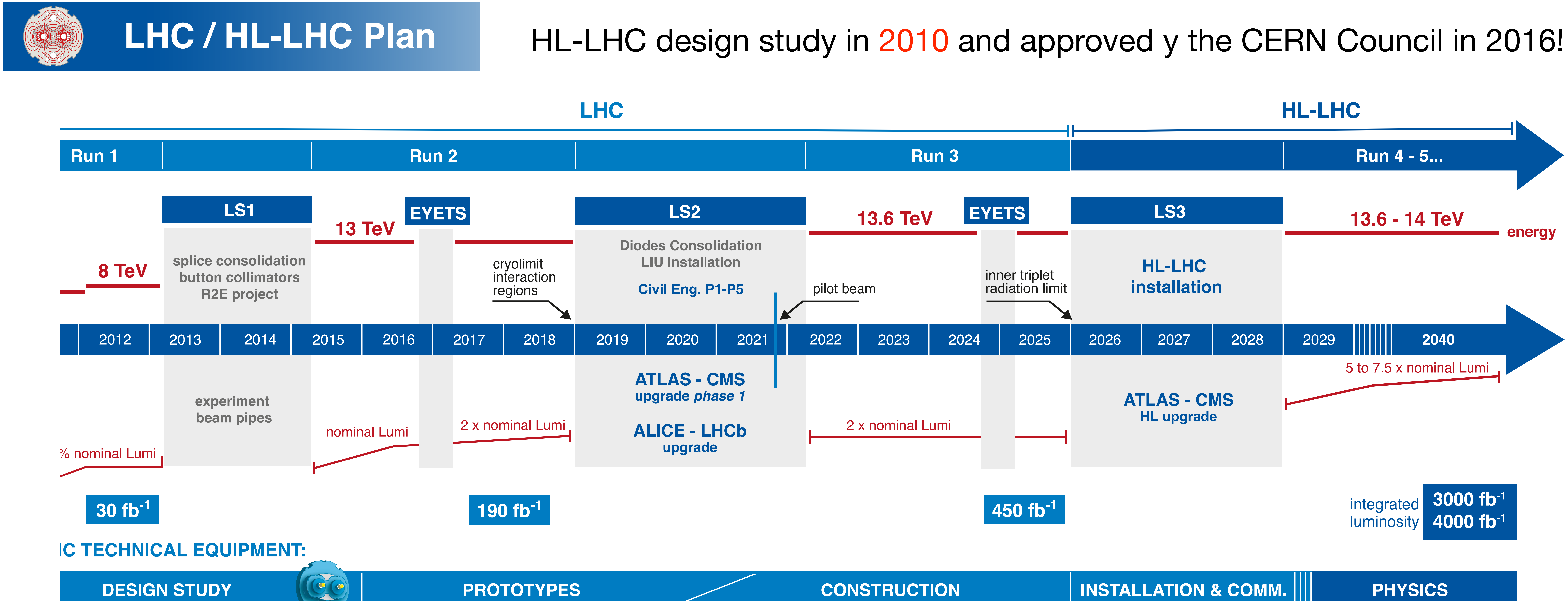
'it all started with the CERN – ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel' **Peter Jenni**

10 September 2008 Start of the LHC

Since 2009: 12 years of successful operations and landmark results!

Immediately on to the next project: HL-LHC

HL-LHC design study in 2010 and approved y the CERN Council in 2016!



Major machine and detector upgrades have already started in preparation of the high luminosity phase!

« The most ambitious scientific experiment in history »

Unrivalled at the Energy Frontier

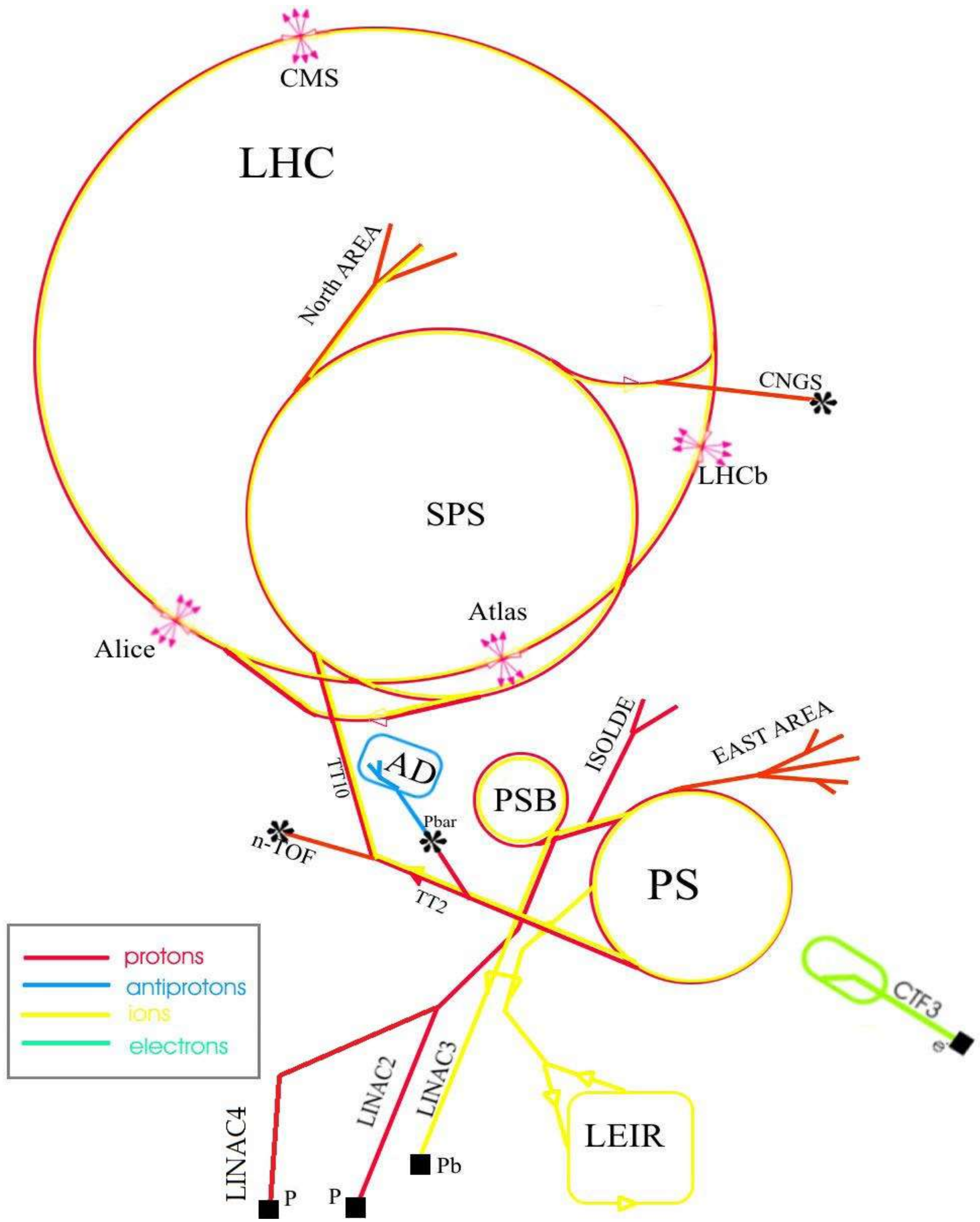
13 TeV (centre-of-mass energy)

Outstanding at Intensity Frontier

Record Luminosity* of $2.14 \times 10^{34}\ cm^2 s^{-1}$

The LHC is « the most ambitious scientific experiment in history »

An Zeptospace Odyssey G. Giudice



*Surpassed in June 2020 by SuperKEKB at $2.2 \times 10^{34}\ cm^2 s^{-1}$

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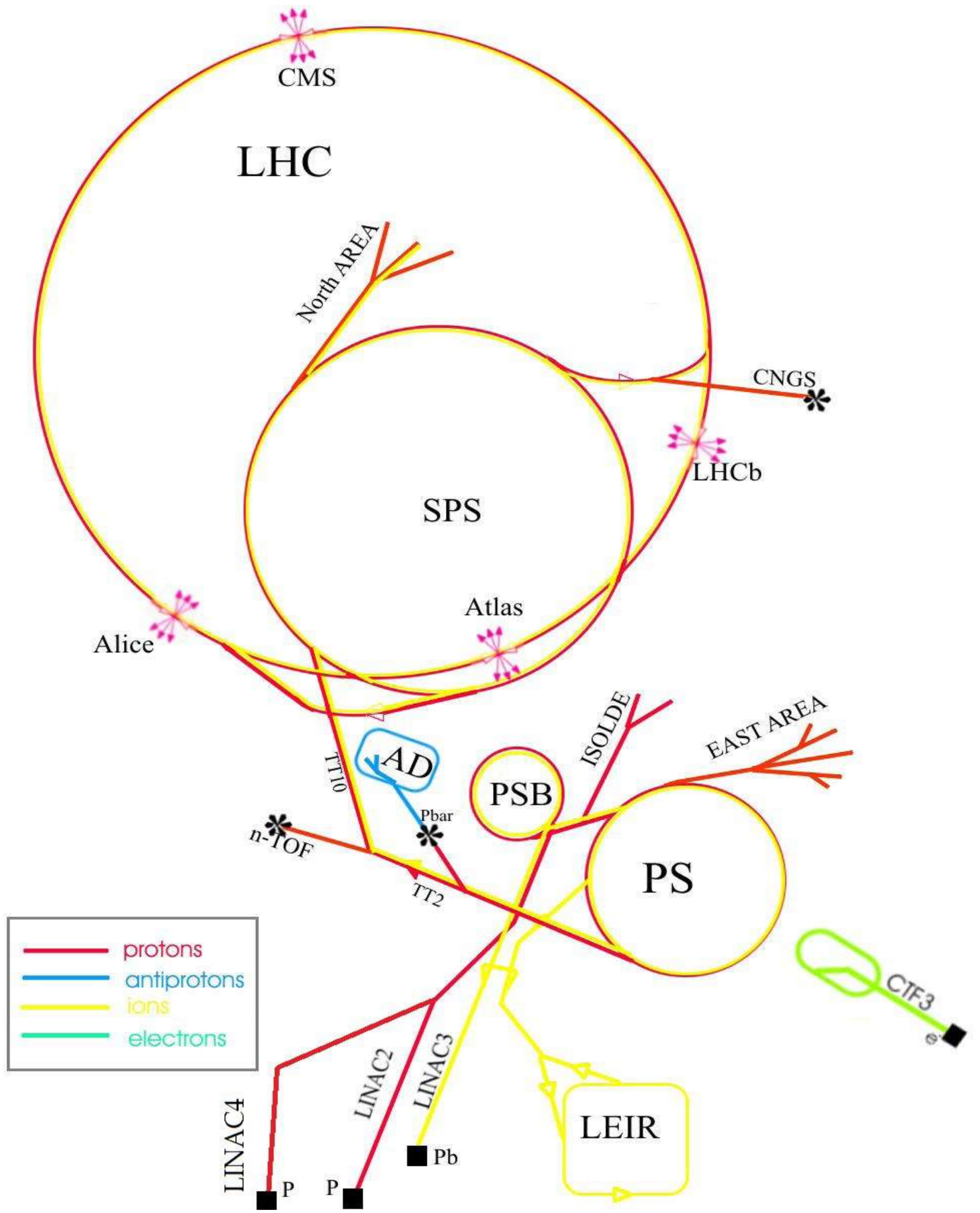
LHC nano fact sheet

- Circumference of 27 km;
- 9300 Magnets (1232 bending dipoles) reaching 8.3T with current of 11,400 A;
- Beams are made of trains of 2808 bunches containing approximately 100 Billion protons each; Bunches are separated within trains by 25ns (approximately 7m).

Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.

*Surpassed in June 2020 by SuperKEKB at $2.2 \times 10^{34}\ cm^2 s^{-1}$



Construction and Commissioning of the LHC

LHC Operation challenge:

Unprecedented beam energy and luminosities (for a hadron machine)

- Main challenge : Stored beam energy 2 orders of magnitude higher than previous machines… **350 MJ**
- Total stored energy in the magnets (11 GJ, enough to melt 15 tons of copper)

Experiments: Vision of the Founders!

A very simplified summary:

detector signature	accessible physics process
$\mu^\pm$	$H \to ZZ \to 4\mu^\pm$ $Z' \to \mu^+\mu^-$ (σ_m ?)
$\mu^\pm$, jets, $p\!\!\!/_T$	add: $H \to ZZ \to \mu^+\mu^-\nu\bar{\nu}$ $W' \to \mu^\pm\nu$ compositeness $\tilde{q}, \tilde{g}$ (direct decays) jet spectroscopy
e, $\mu^\pm$, jets, $p\!\!\!/_T$ (non-)magnetic central part (reduced tracking)	add: 4× rate $H \to ZZ \to 4e^\pm$ 2× rate $H \to ZZ \to e^+e^-\nu\bar{\nu}$ 2× rate Z', W' $\tilde{q}, \tilde{g}$ (also cascade decays) mass resolution $e\mu$ heavy Q, L $H \to \gamma\gamma$
$e^\pm$, $\mu^\pm$, $\tau^\pm$, jets, $p\!\!\!/_T$ full momentum and tracking	add: more redundancy and cross-checks on above, H^+, SUSY-H, heavy flavour tags

Lepton detection at LHC is crucial. Small rates are expected for many potential signals

⇒ detection of e and μ

Muons are relatively easy to identify but hard to measure well

(precise μ measurements may mean hundreds of MCHF)

Electrons are relatively easy to measure but hard to identify at 10^{34}

(radiation-hard inner detector)

Lepton isolation criteria are also important to reject back-grounds from heavy flavour decays

Higgs, SUSY and more scenarios provided a wide breadth of possibilities…

… to design detectors with broad capabilities!

It is thanks to the vision of the founders in the mid-80's that the LHC physics program is be so broad!

P. Jenni, Higgs10 symposium

15 Years of Design

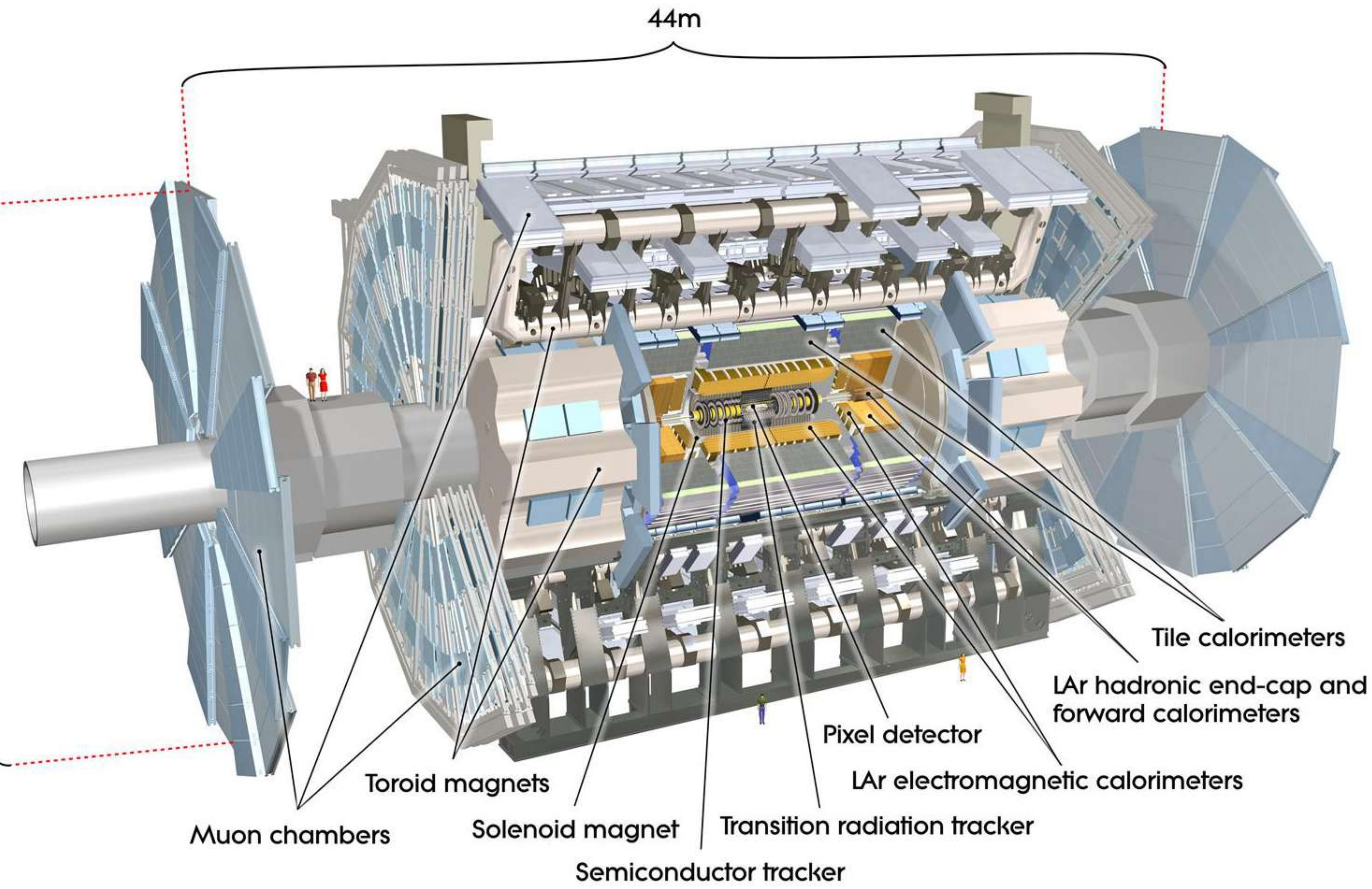
General Purpose Detectors: ATLAS

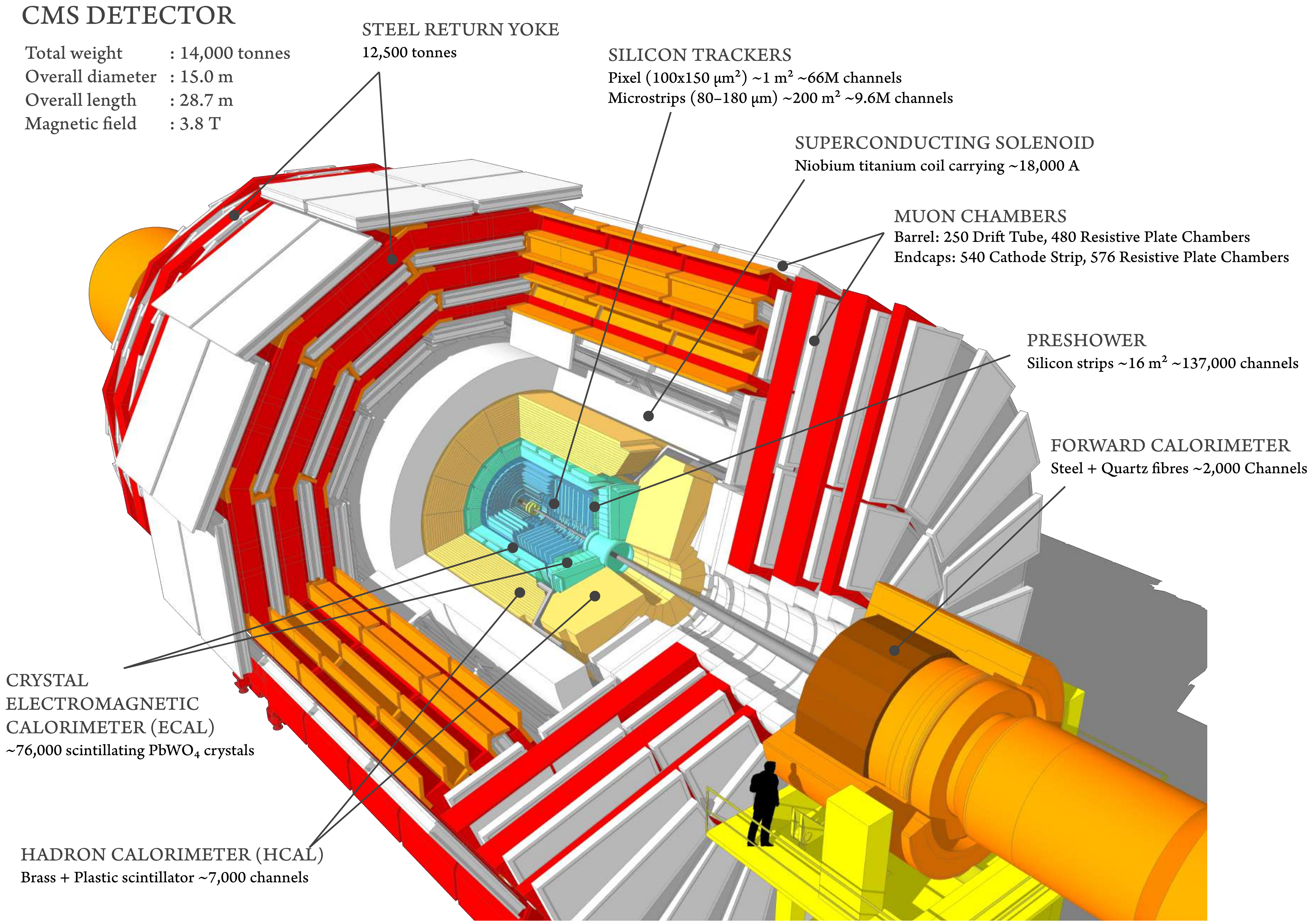
ATLAS nano fact sheet

- 25m Diameter and 44m length
- Over 7000 tons
- O(100) Million readout channels

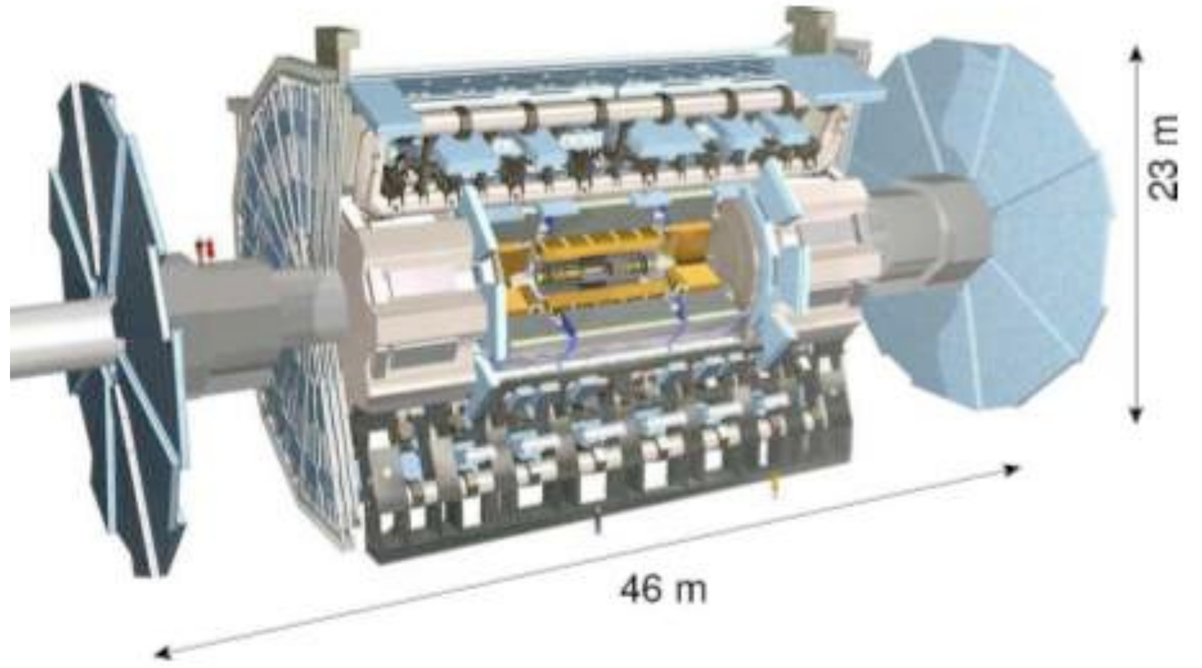
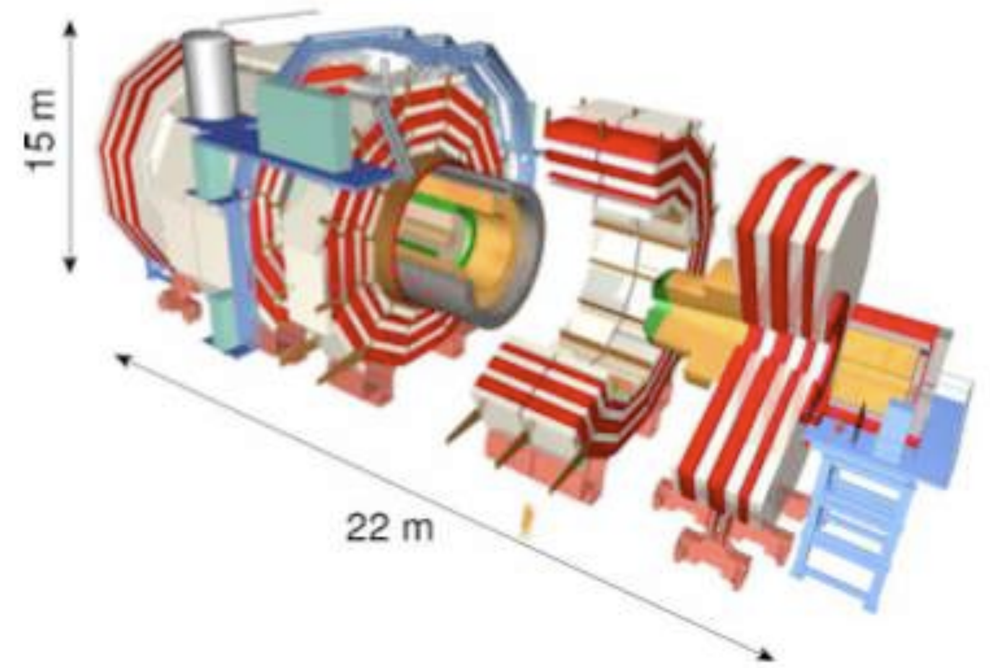
CMS nano fact sheet

- 15m Diameter and 21m length
- 14000 tons
- O(75) Million readout channels

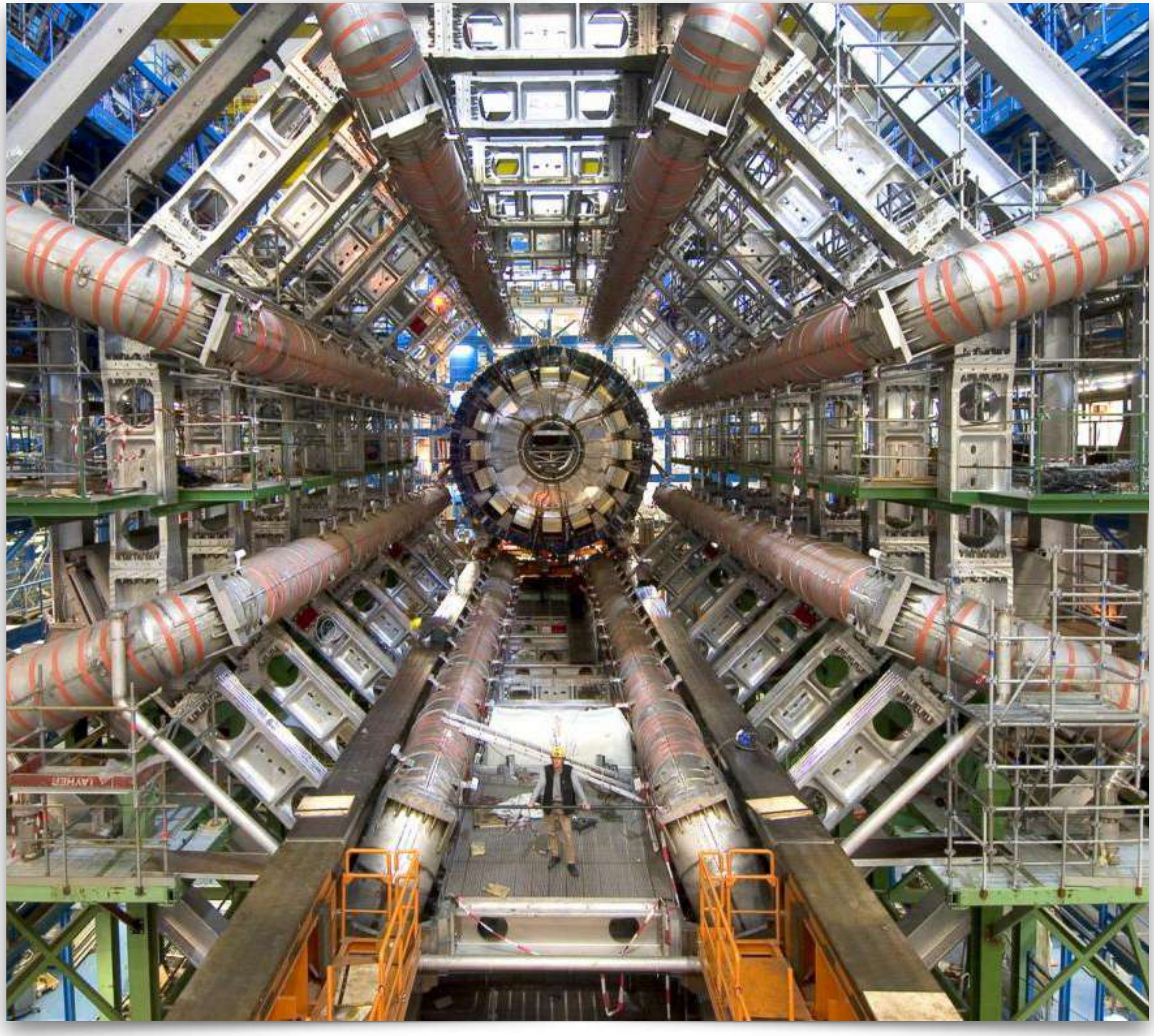


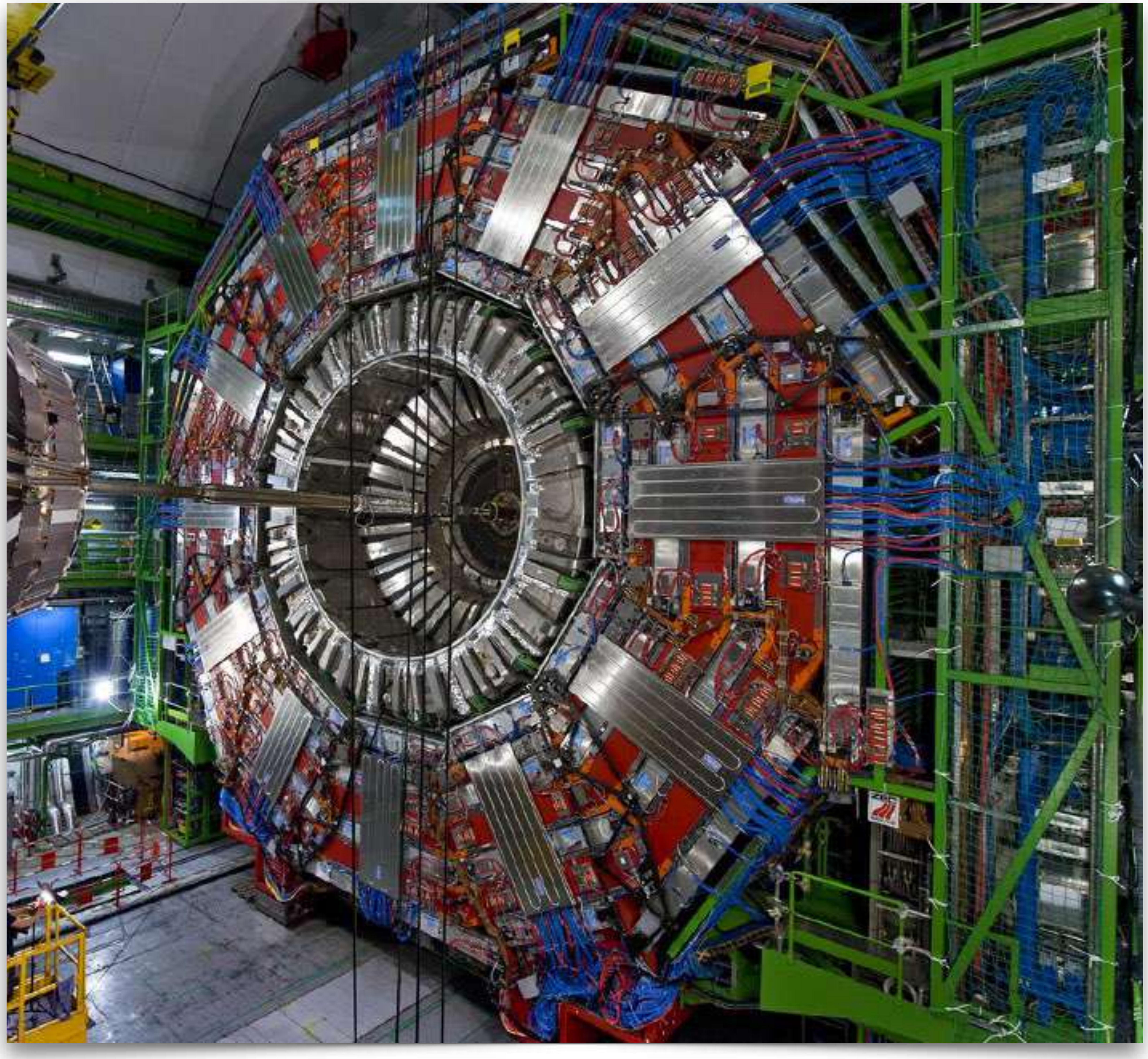


General Purpose Detectors: ATLAS

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ & Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\%$ (at 50 GeV) $\sim 11\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

10 Years of Construction





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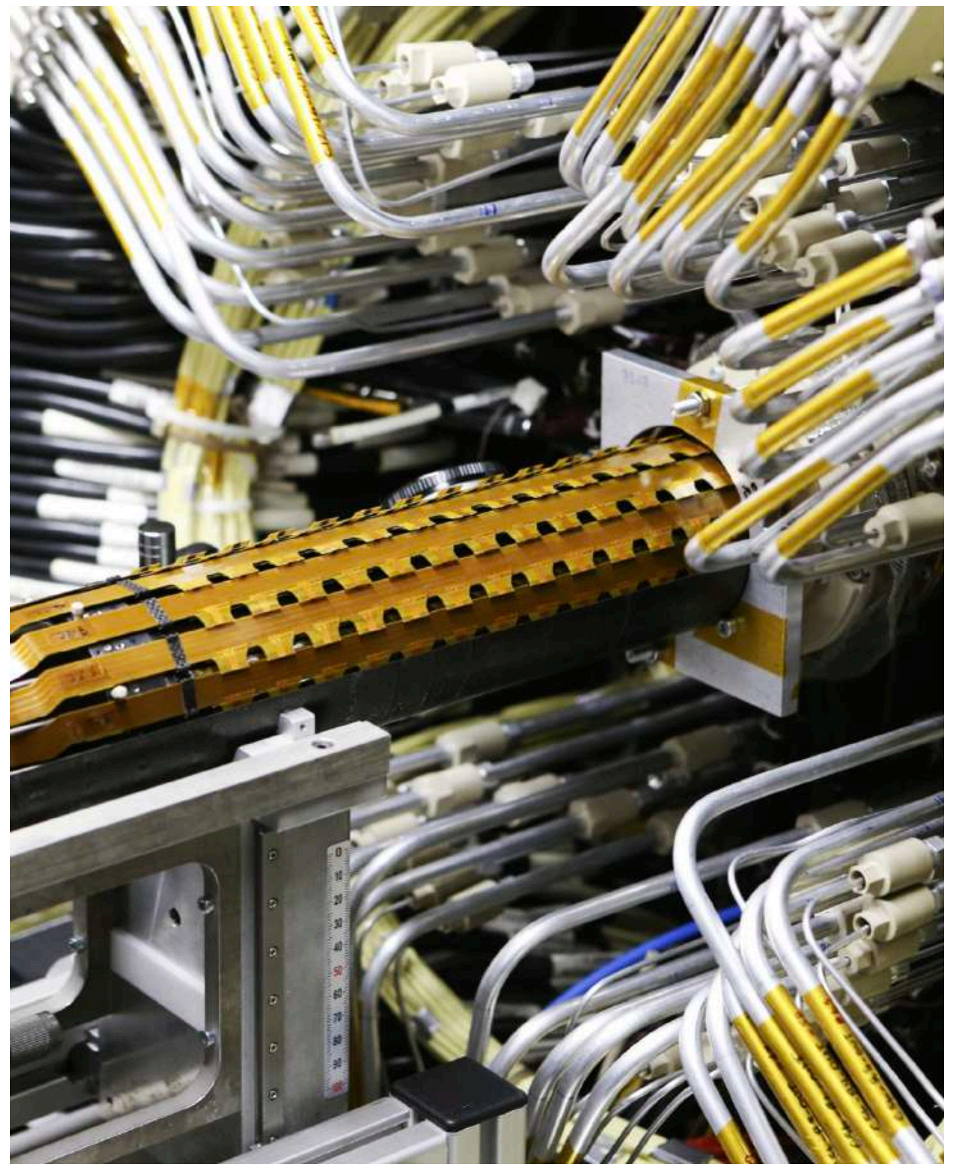
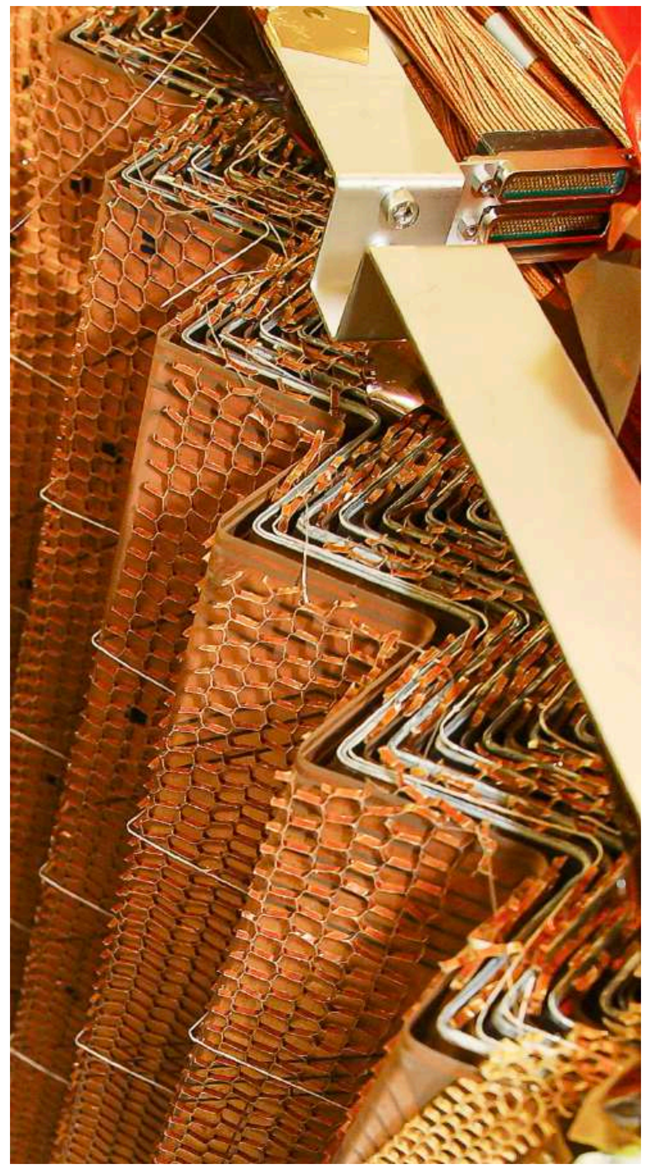
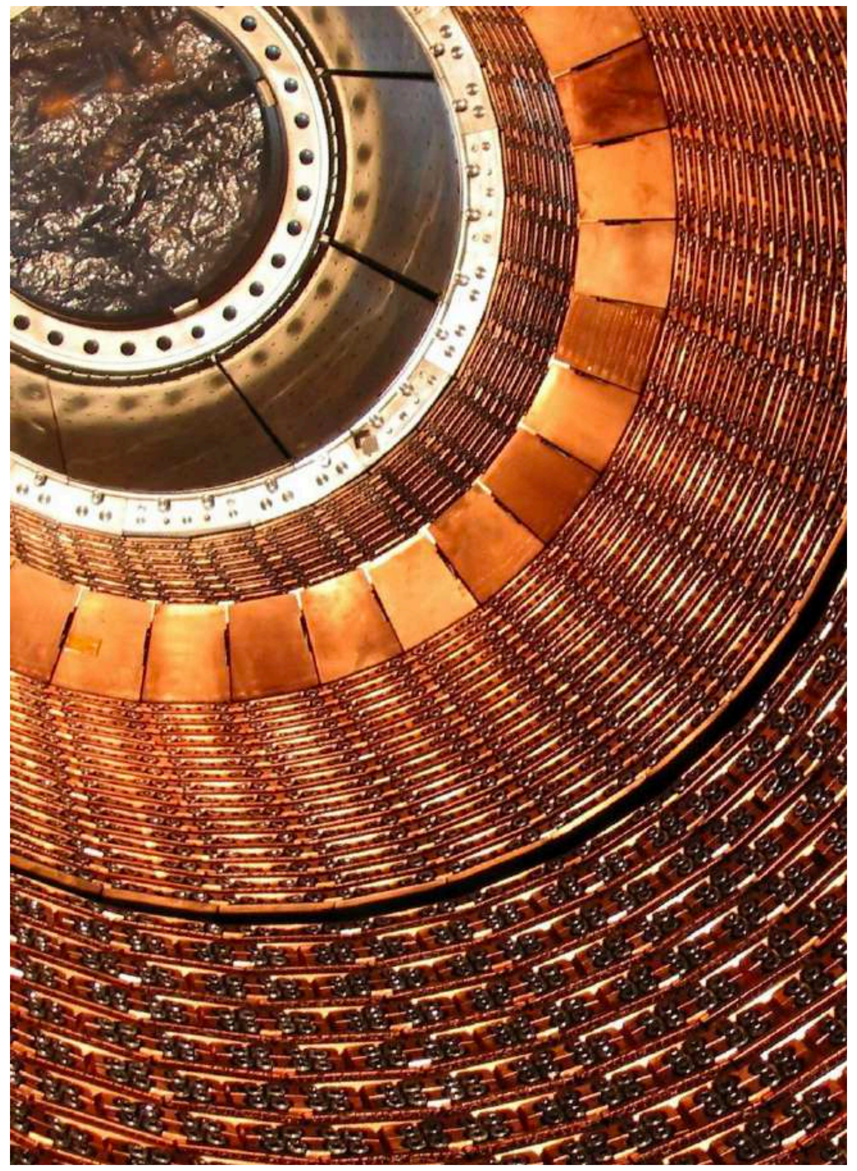
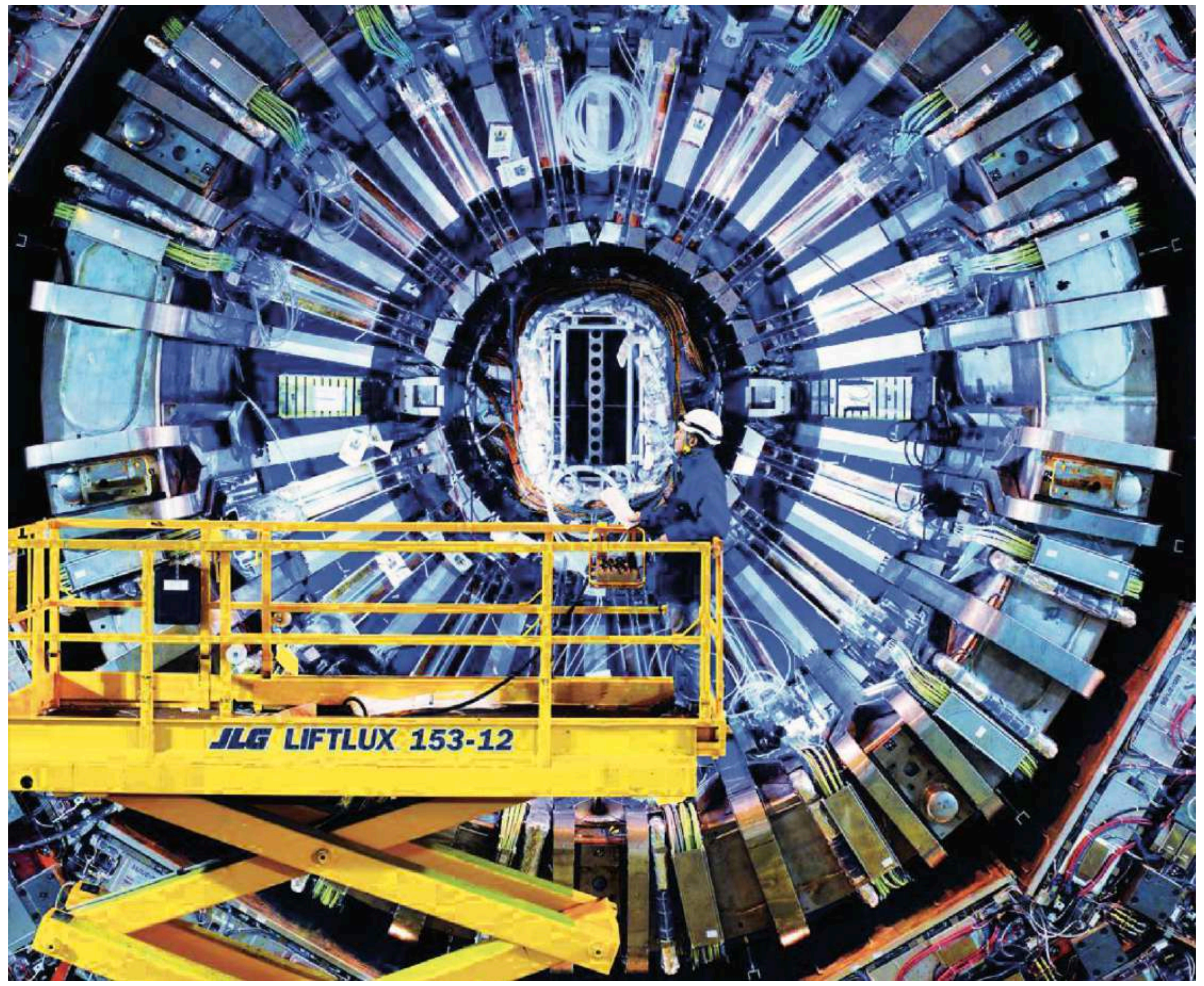
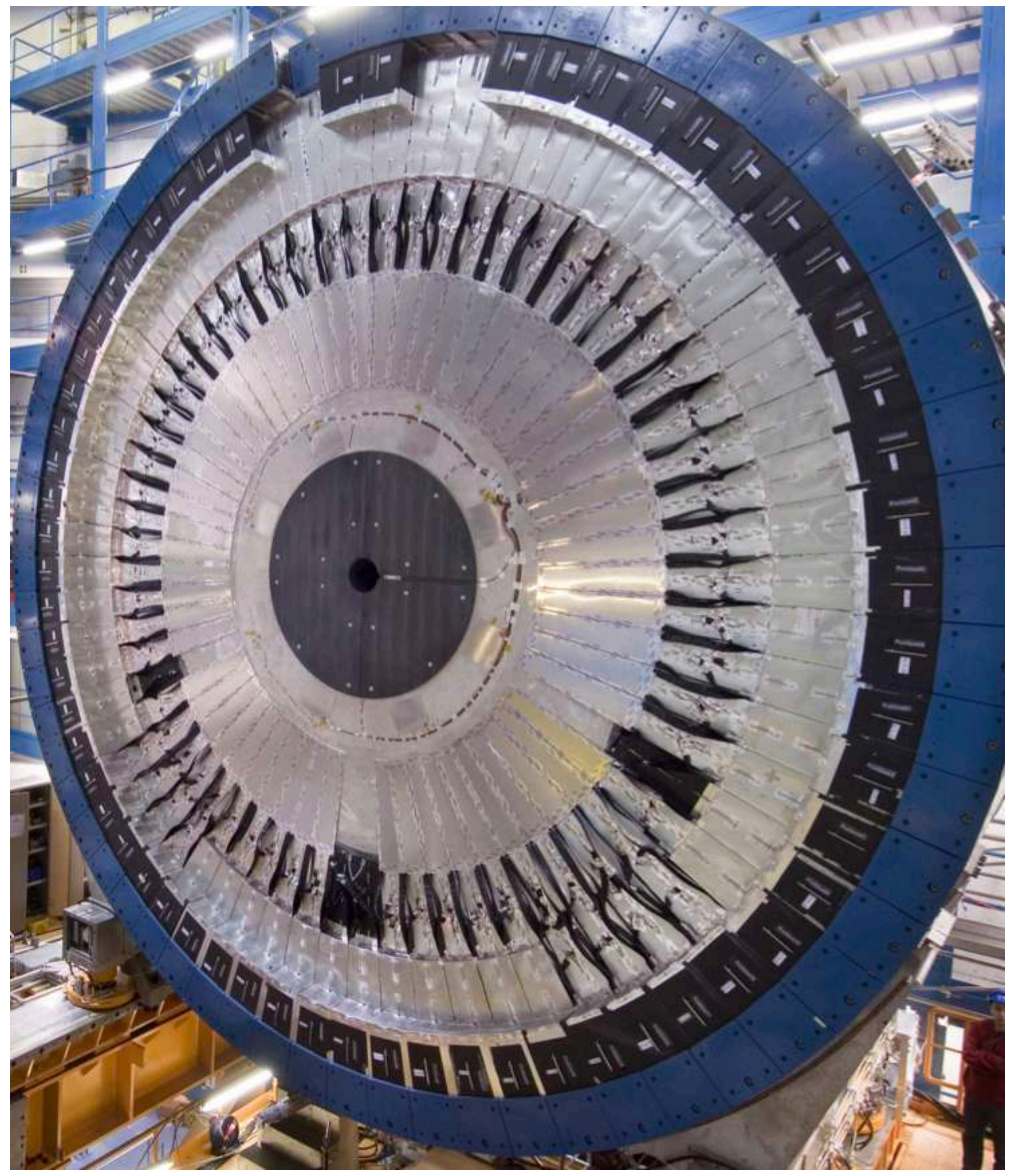
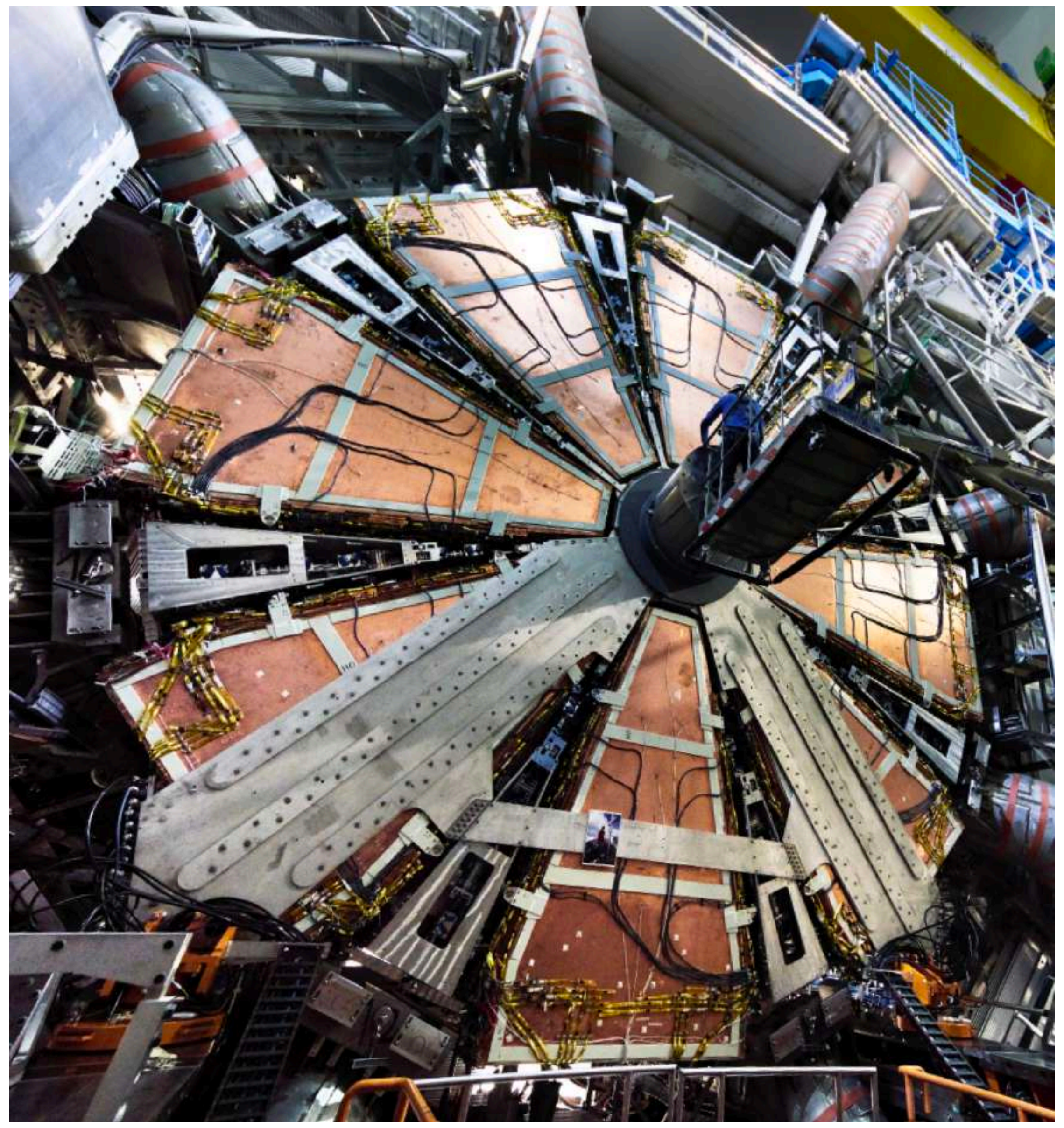
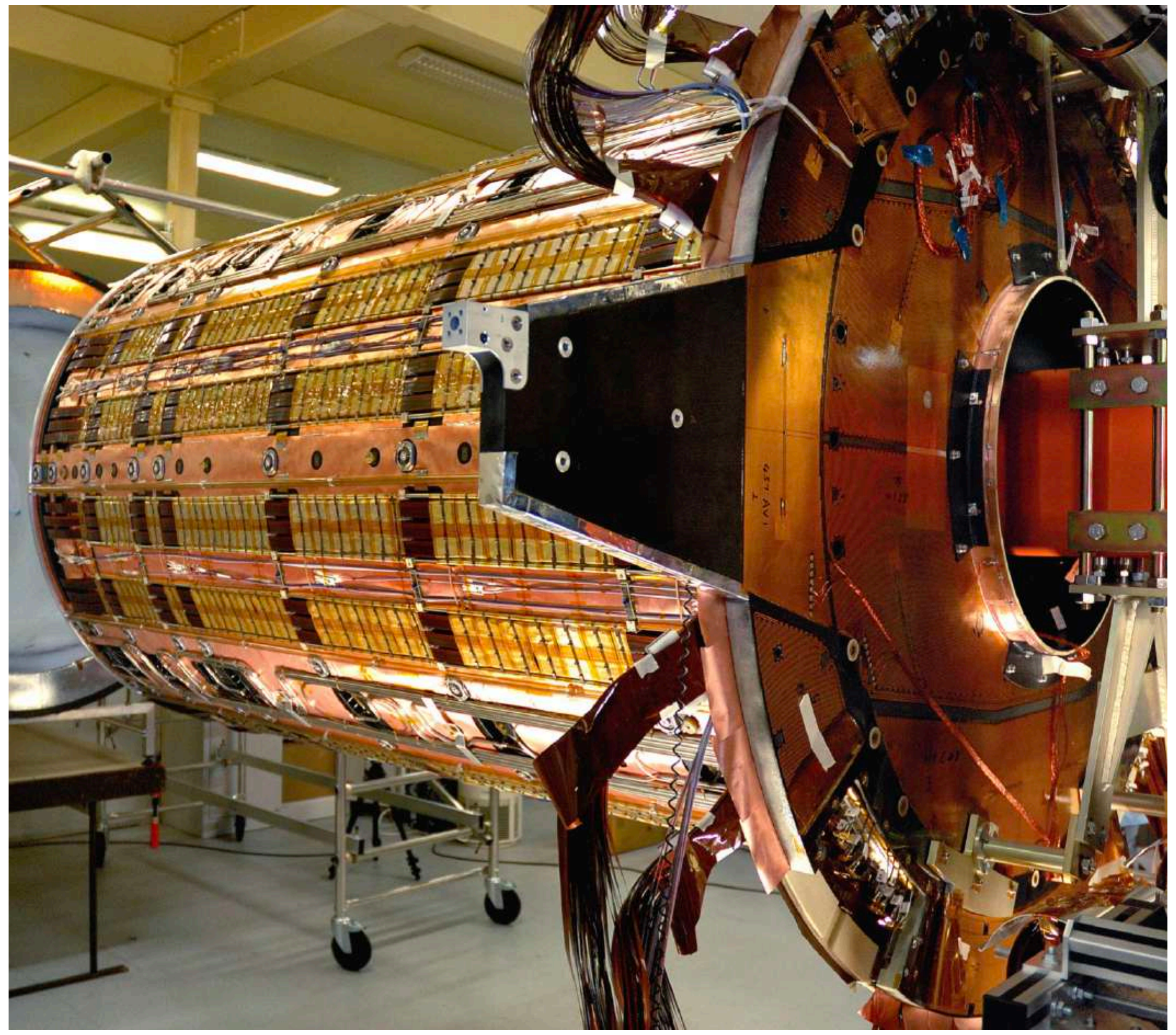
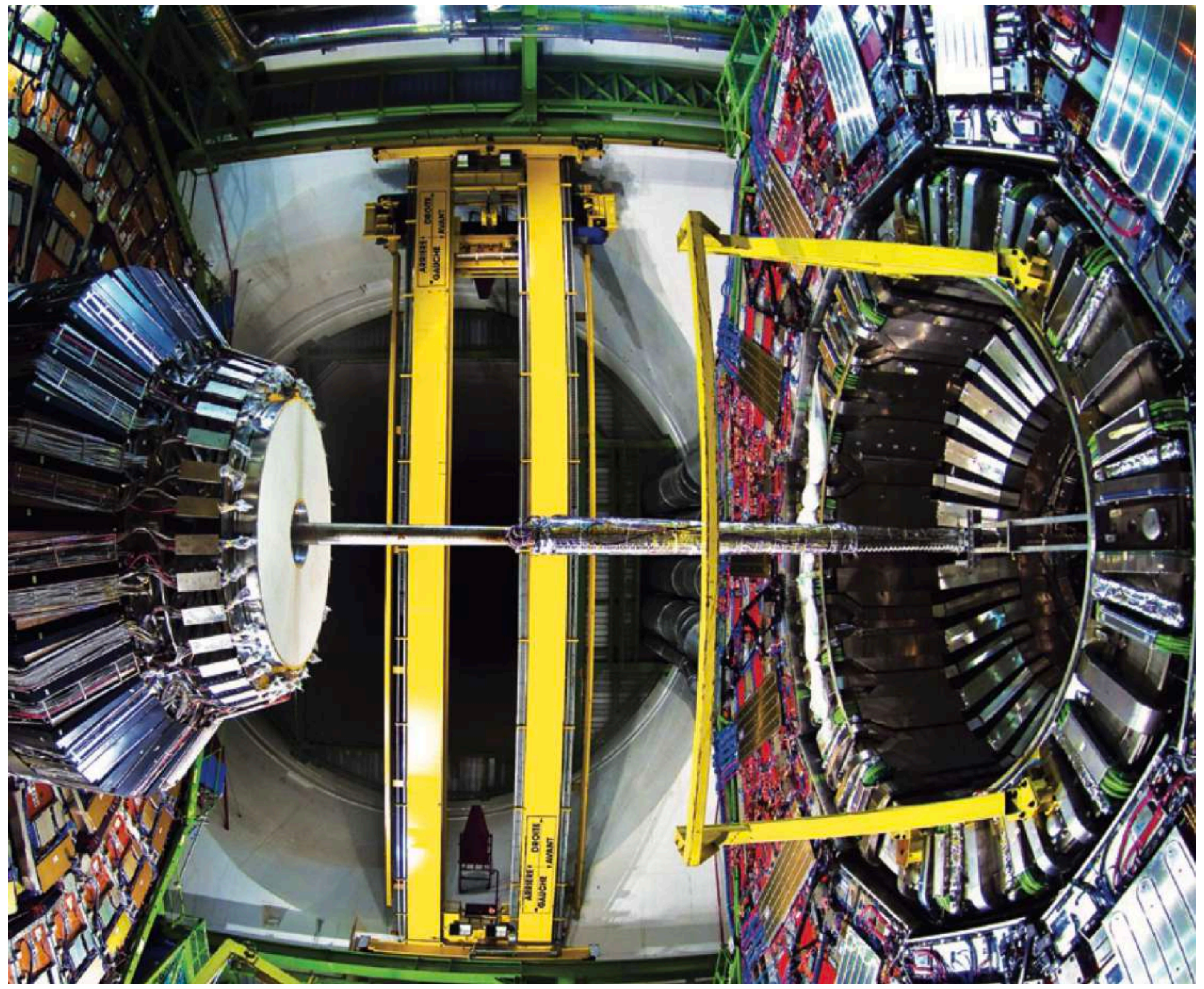






Conditions for Approval

C. Llewllyn Smith CERN Director General 1994-1998

50 years of hadron colliders at CERN symposium

- **Approval of the LHC depended on**
  - Robust scientific case (exploration of large new domain*, with good reasons to expect discoveries)
  - Uniqueness
  - Unanimous support of world particle physics community
  - Technical success of CERN
  - No budget bump (imposed)

***The breadth and diversity of the scientific program of the LHC not only in Higgs physics and well beyond (require a series of seminars) is worth emphasising!**

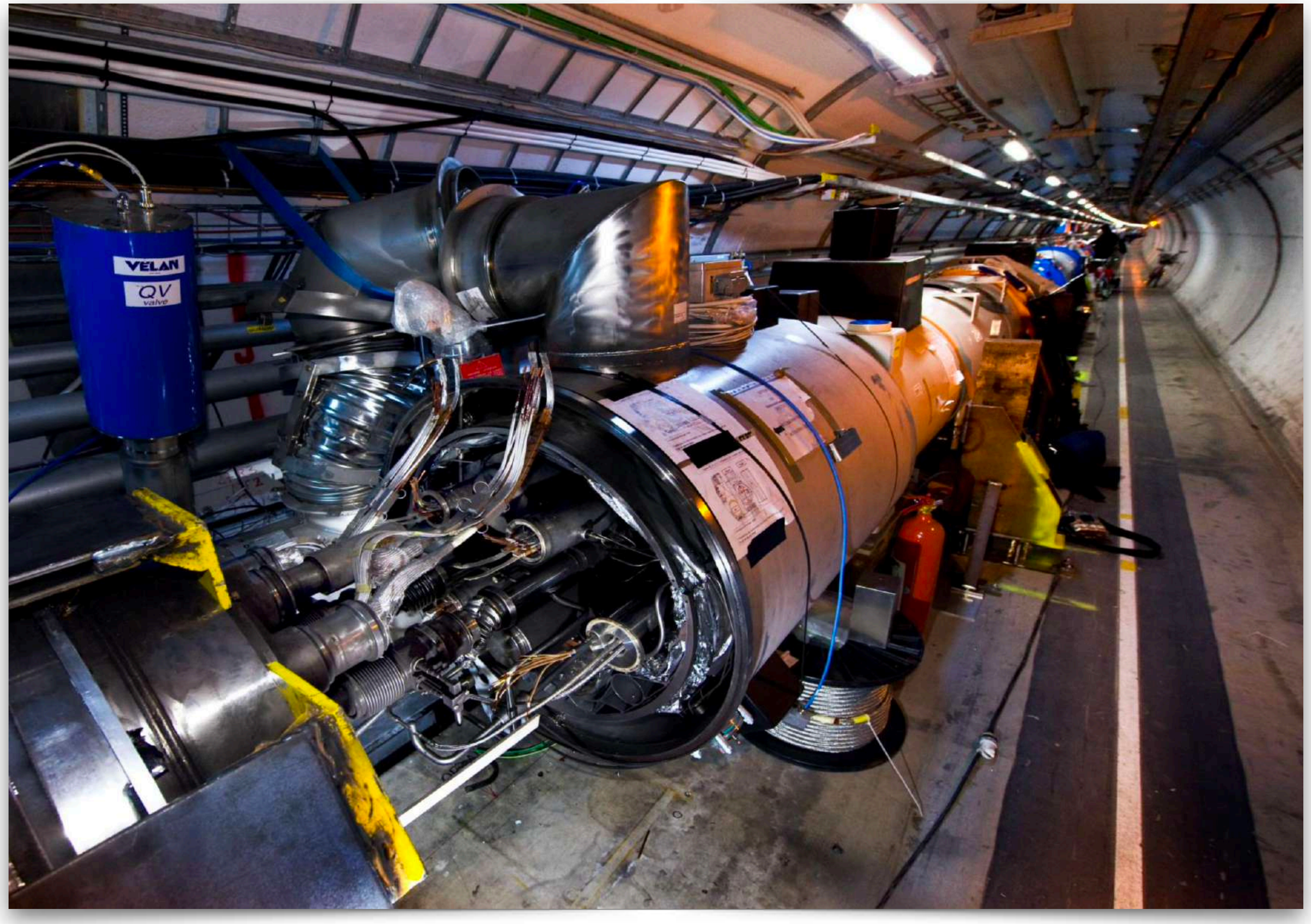
3.- Performing well beyond expectations

Not precisely the expected start…

THE Sun

1 September 2008

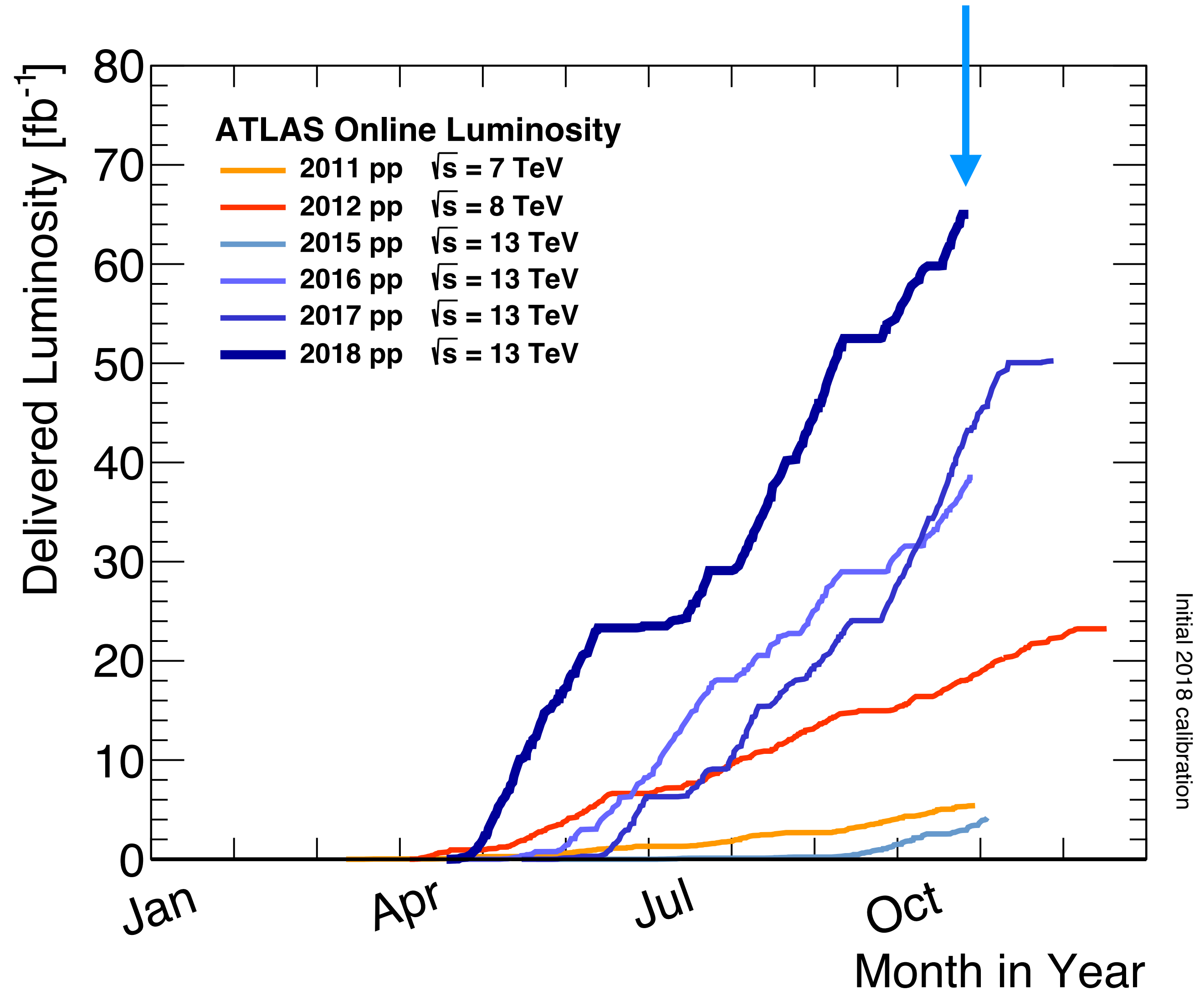
19 September 2008

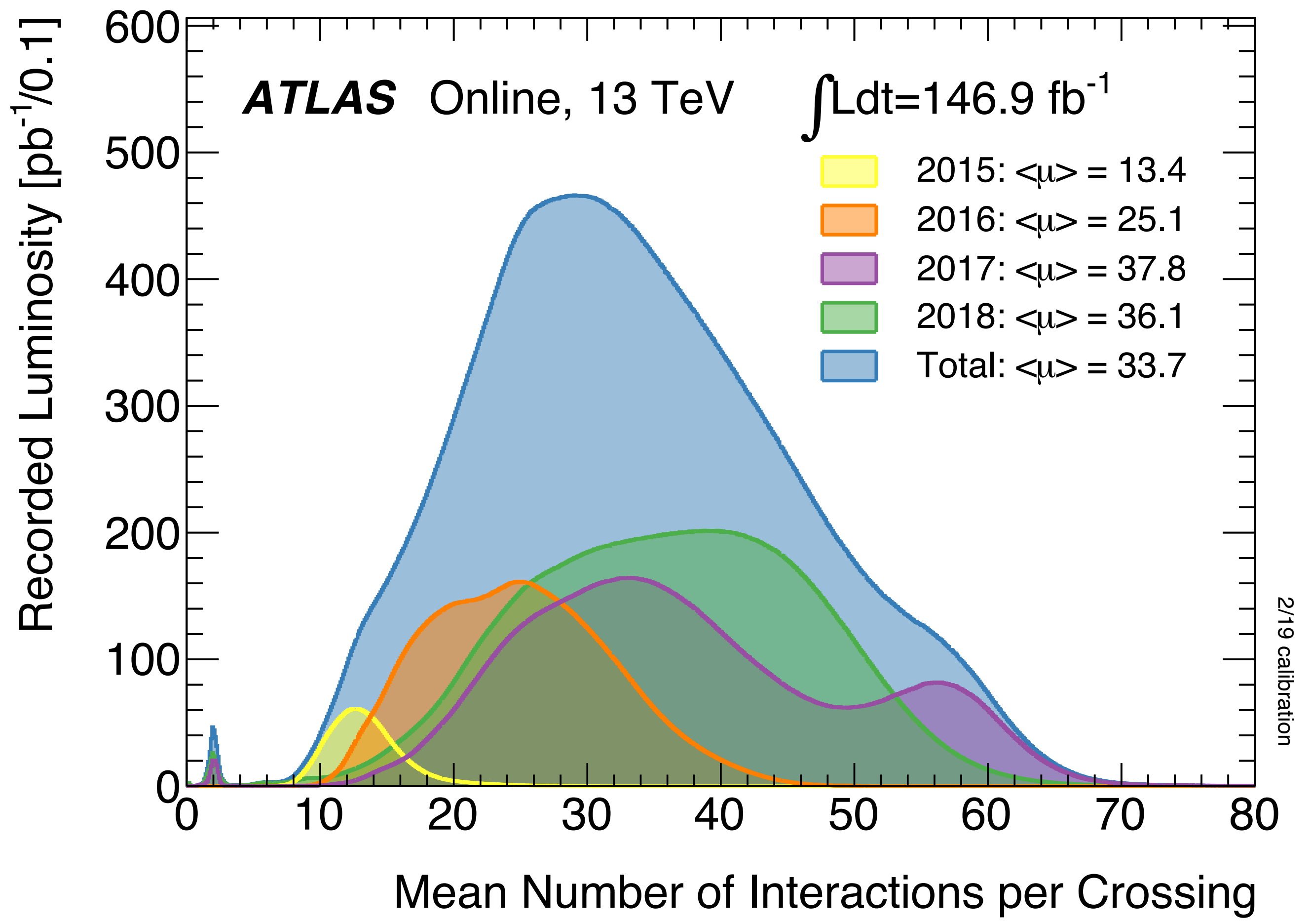


… not the end of the world, but 700 m damaged area with 39 dipoles and 14 quadrupoles and beam vacuum affected over 2.7 km, 1 year repair and LS1 to consolidate interconnections!

Performing well beyond expectations!

Record 2018
More than 60 fb^{-1} collected by experiments





Run 1 : 7 and 8 TeV and of ~20 fb-1 Pile-Up ~30

Run 2 : 13 TeV ~**140 fb^{-1}** Pile Up of ~30-40

However impressive, to get to 3000 fb^{-1} would require
50 full years of running the LHC!

$$\mathcal{L} = \frac{N_p^2 f k_b \gamma}{4\pi\beta^* \varepsilon_N} F$$

Parameter	Run 1		Run 2		Nominal	HL-LHC
	2010	2012	2016	2018		
CoM Energy	7 TeV	8 TeV	13 TeV	13 TeV	14 TeV	14 TeV
N_p	$1.1\ 10^{11}$	$1.6\ 10^{11}$	$1.2\ 10^{11}$	$1.2\ 10^{11}$	$1.15\ 10^{11}$	$2.2\ 10^{11}$
Bunches k	368	1380	2300	2500	2808	2760
Spacing	150 ns	50 ns	25 ns	25 ns	25 ns	25ns
ε (mm rad)	2.4-4	2.5	2.6	2.6	3.75	2.5
β* (m)	3.5	0.6	0.4	0.4	0.55	0.15
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$\sim 7x10^{33}$	$1.5x10^{33}$	$2x10^{34}$	10^{34}	$8x10^{34}$
PU	~2	~30	~30	~50	~25	~130

LHC performed well beyond expectations!

Trigger, DAQ and Software Challenges

- **Trigger Challenge** : select ~400-1000 out of 20M events per second while keeping the interesting (including unknown) physics

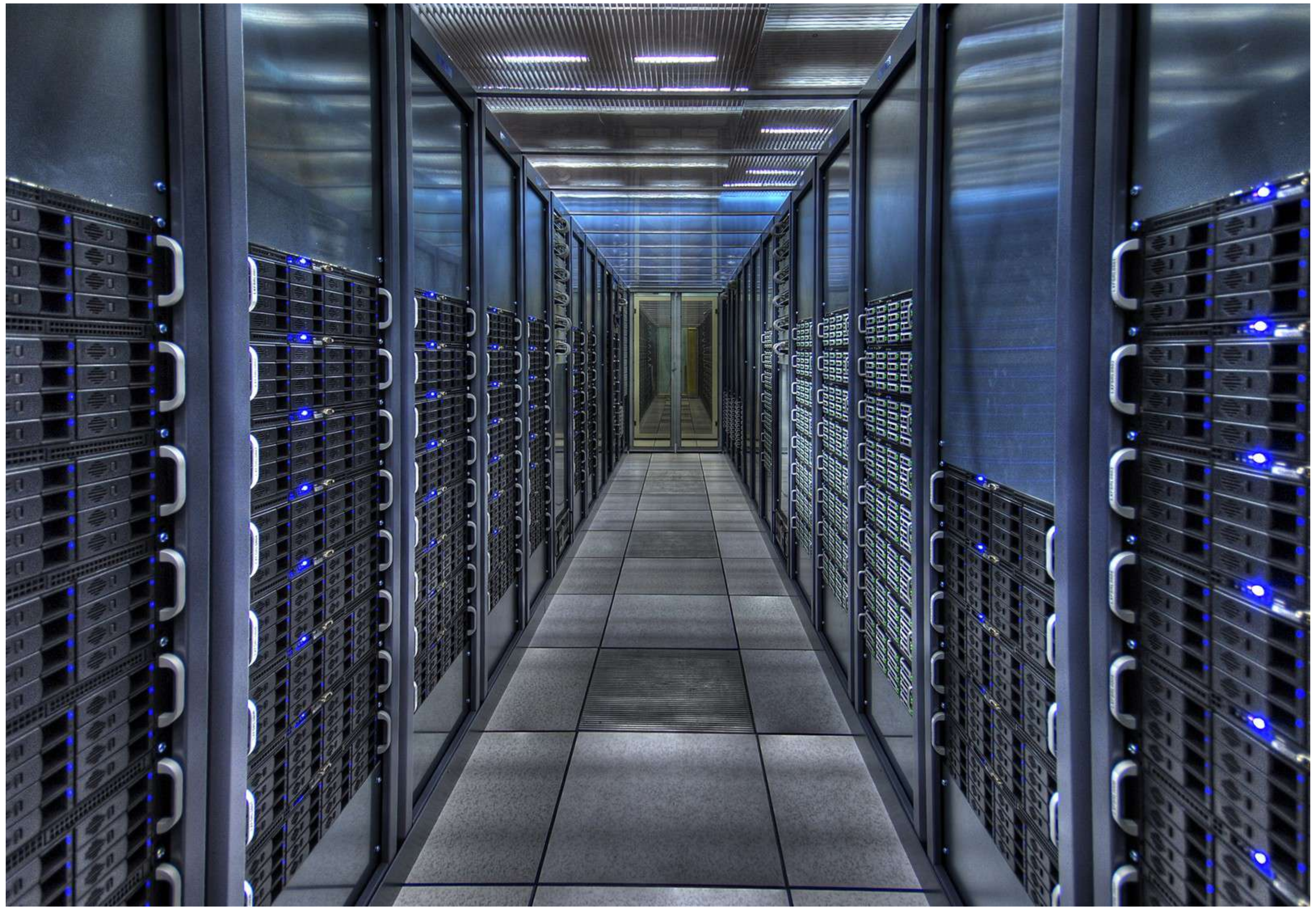
- **Read out and reconstruct** approximately **O(100M)** electronics channels at ~1-2 kHz. *Raw event size ~1.5 MB*

- **Computing Challenge** : reconstruct, store and distribute 1000 complex events per second and the very large amount of simulation (over 750 PB disk and 1200 PB tape - Grid of 1M Cores).

- **Analysis Challenge** : Maintain high (and as much as possible stable) reconstruction and identification efficiency.

- **Deep Learning** : Ideal environment to develop Machine Learning techniques: in particular in areas such as trigger, reconstruction, object identification, calibration and Pile up Mitigation.

CERN Computing Center



Computing grid and computing resources management performed well beyond expectations!

Performance Achievements: Trigger

- Run 1 and Run 2: So far excellent trigger and object reconstruction performance in **increasing levels of PU**. Trigger Thresholds kept relatively stable throughout.

- The gain in acceptance and in performance with new detectors (to improve PU mitigation), new algorithms and new computing capabilities is expected to at least match current experimental performance.
    - Keeping Trigger thresholds at similar levels
    - Object reconstruction performance (efficiency vs rejection and energy scale and resolution) at stable levels.
    - Challenge to come: improve calibrations not only with more data to come but also improved strategies.

Menus at LHC and for HL-LHC

Signature	Run 1	Run 2	HL-LHC
Single e (isolated)	25	27	22 / 27
Single photon	120	140	120*
HT	700	700	375 / 350
MET	150	200	200

From A. Sfyrla LHCP 2018

- Increase readout rate 750-1000 kHz (currently 100 kHz).
- Increased latency and higher granularity.
- Enhanced data processing capabilities, storage rate up to 10 kHz (currently 1-2 kHz).

Performance Achievements: Object Reconstruction

Electrons, photons and muons

- Multivariate methods used for identification (at many levels) and calibration
- In-situ calibration using Z, W, J/Psi and Upsilons

Jets/MET

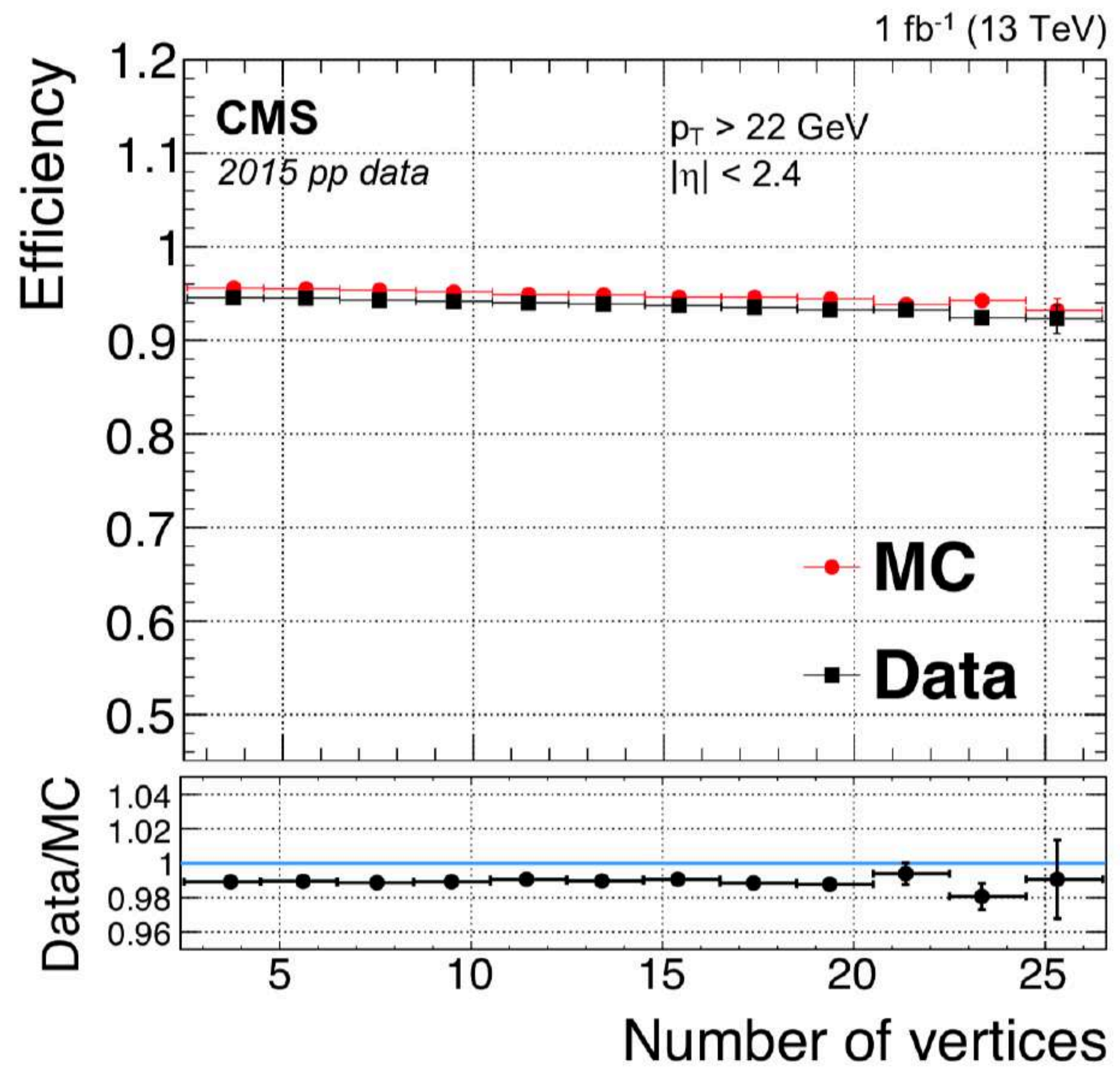
- JES *in situ* uncertainty reach ~1% level already (central and intermediate pT range) – using Z, γ and multi-jets.
- PU mitigation using associated tracks (jets and soft term in MET)

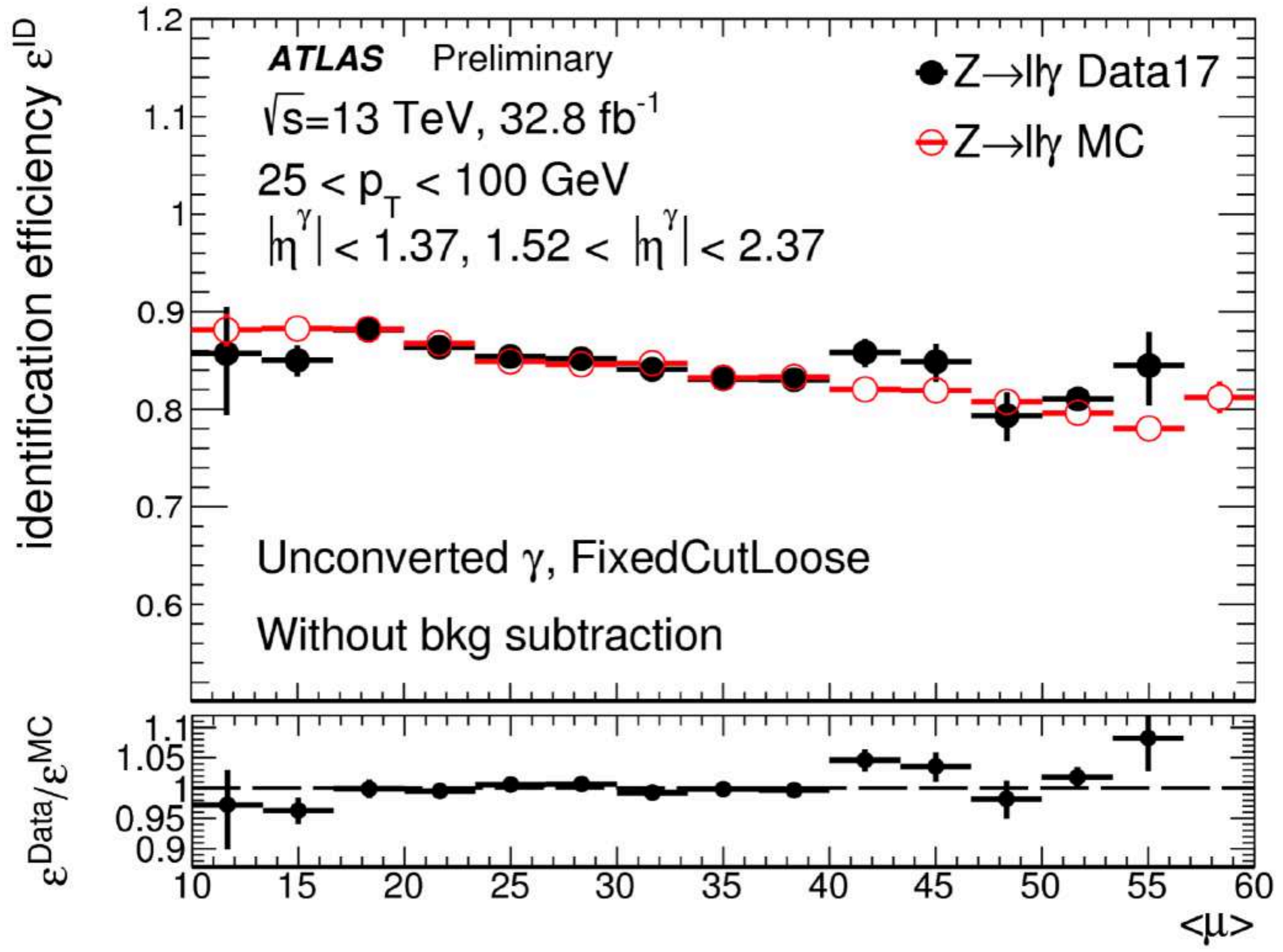
Taus

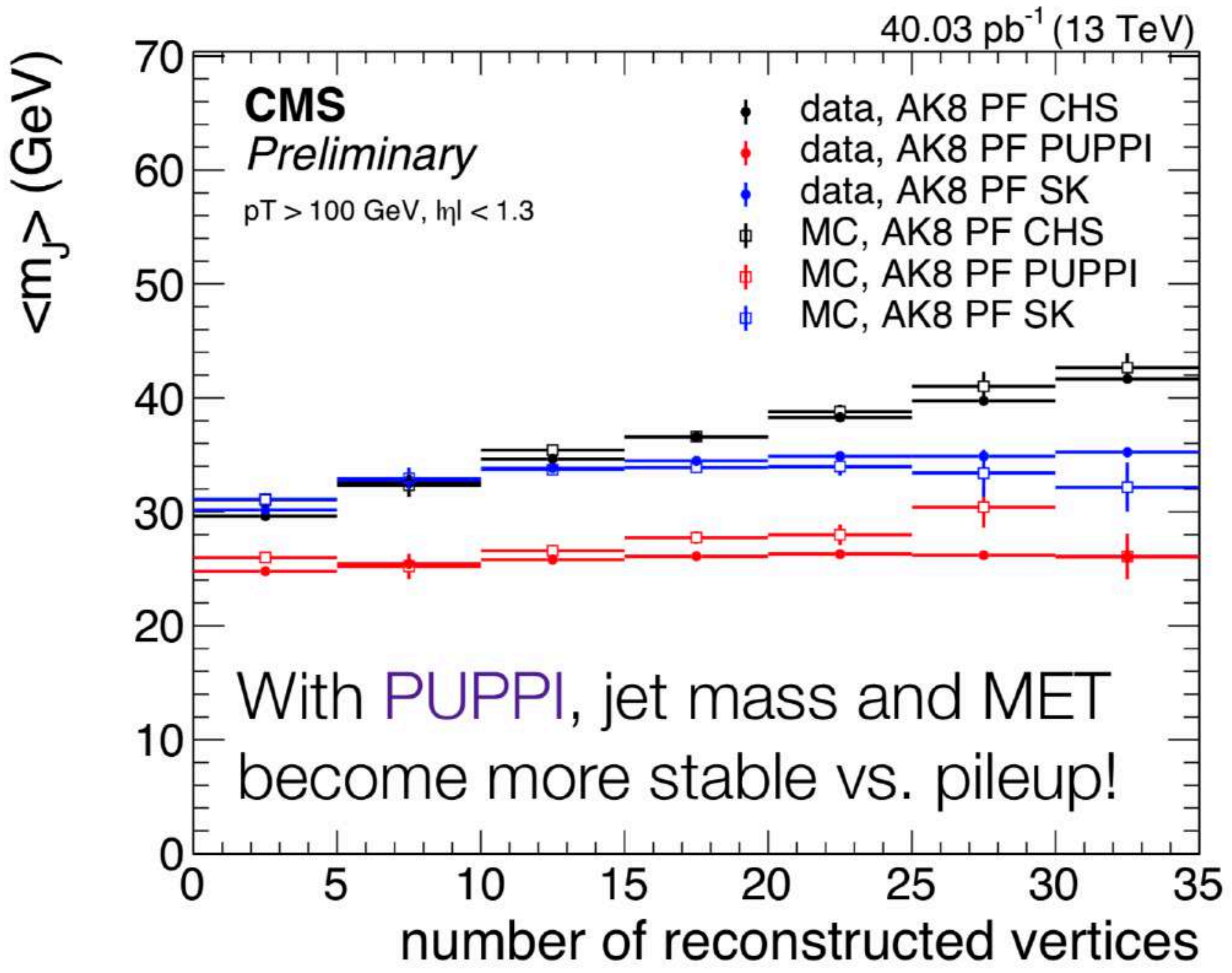
- BDT and RNN based identification (70% eff. and ~50 rej.)
- In-situ calibration based on Z events

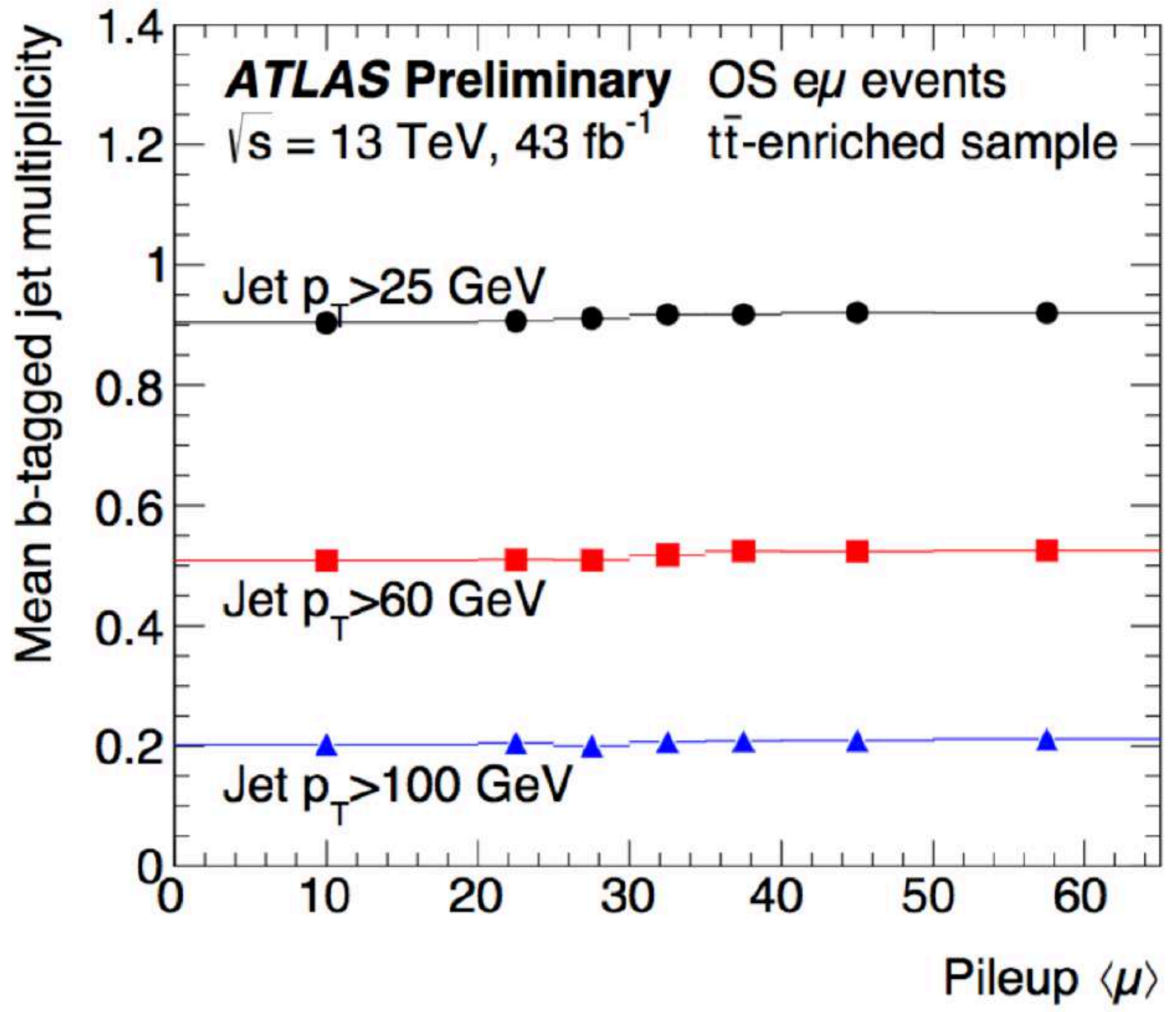
B- and C-jets

- In-situ calibration of b-tag efficiency (using top events and/ or diet events)
- DL techniques from low level variables bring significant improvements









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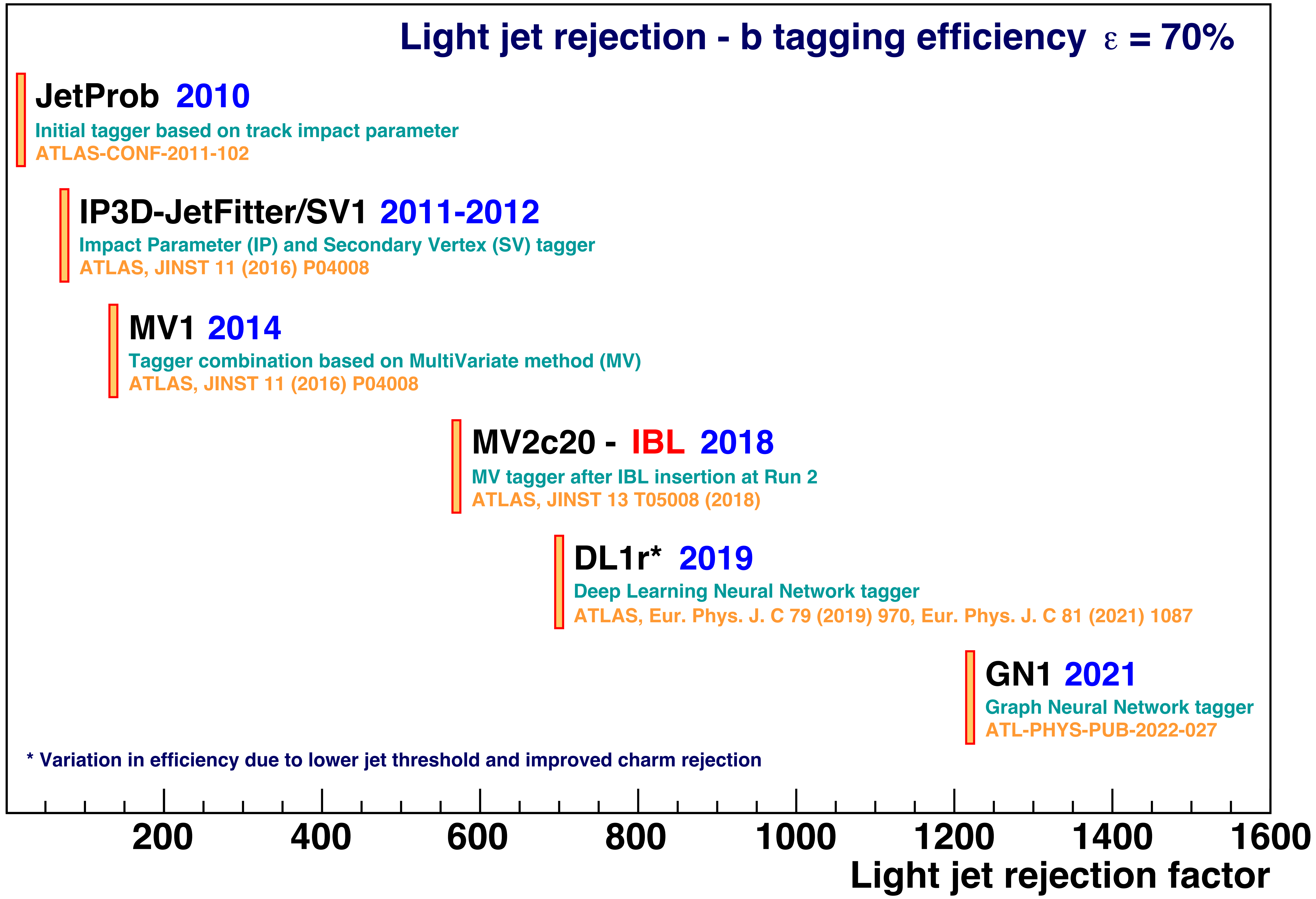
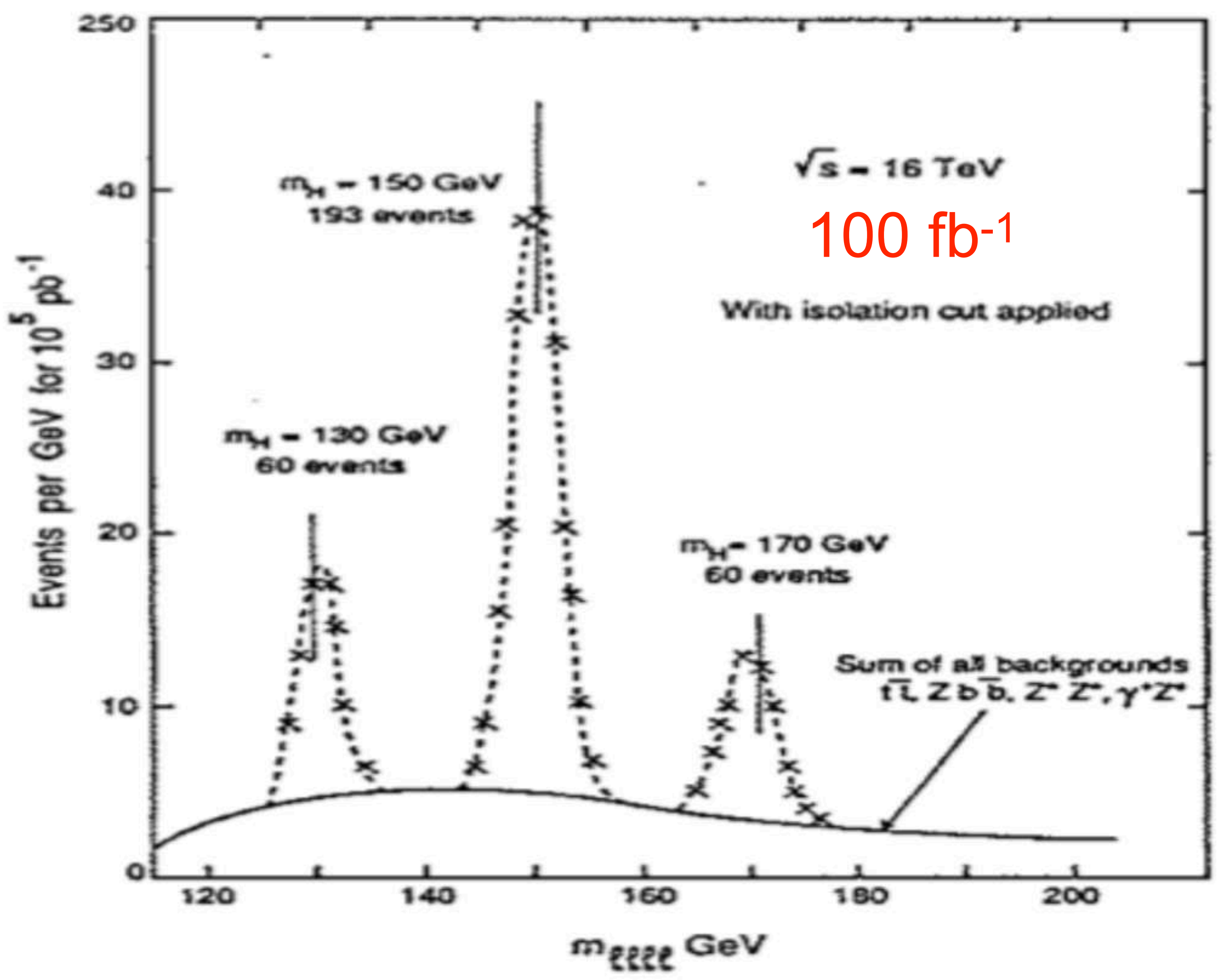


Reconstruction performance: Well calibrated, robust to PU and… well exceeding expectations!

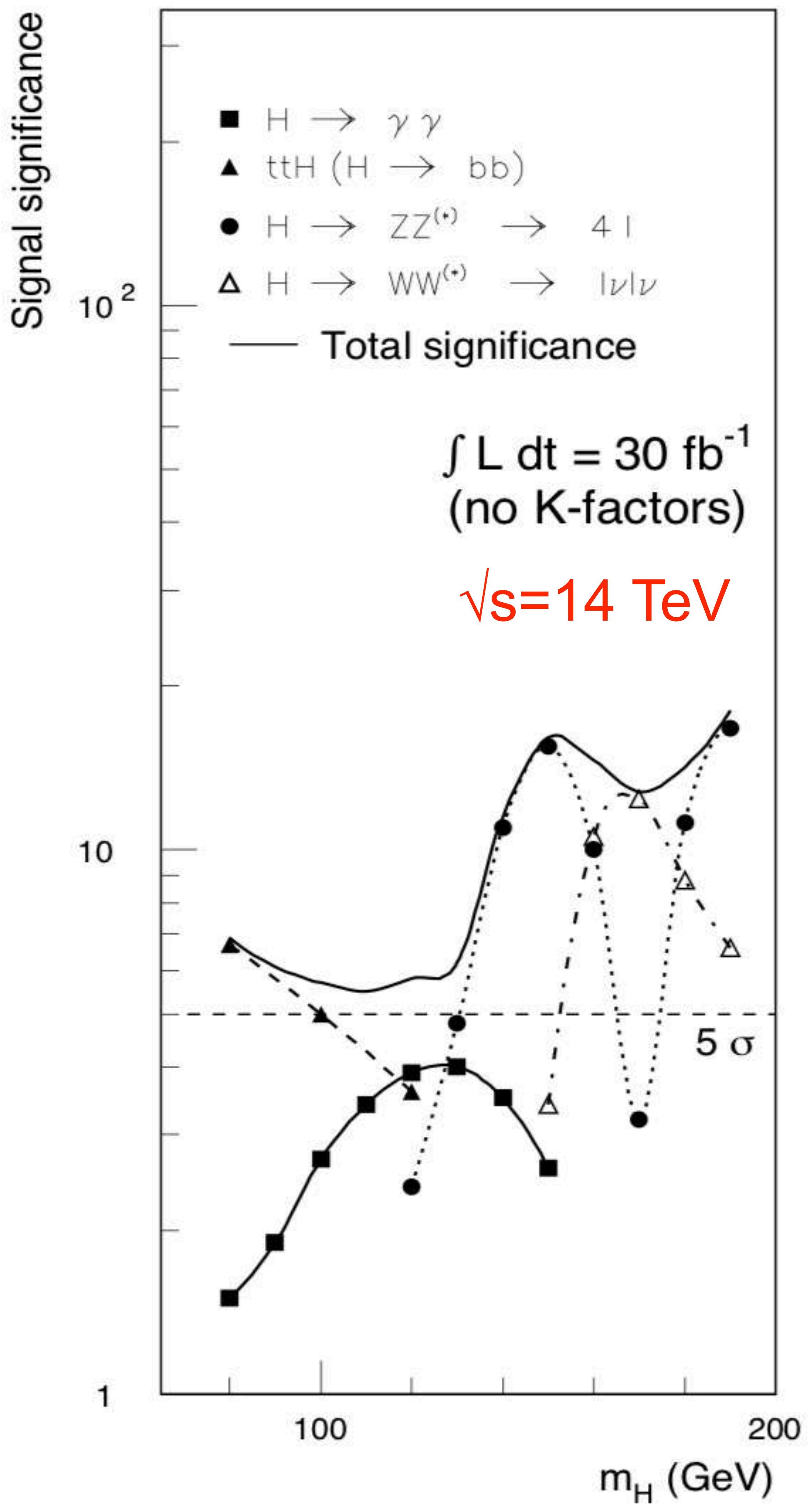
4.- The Higgs discovery

Evolution of Sensitivity

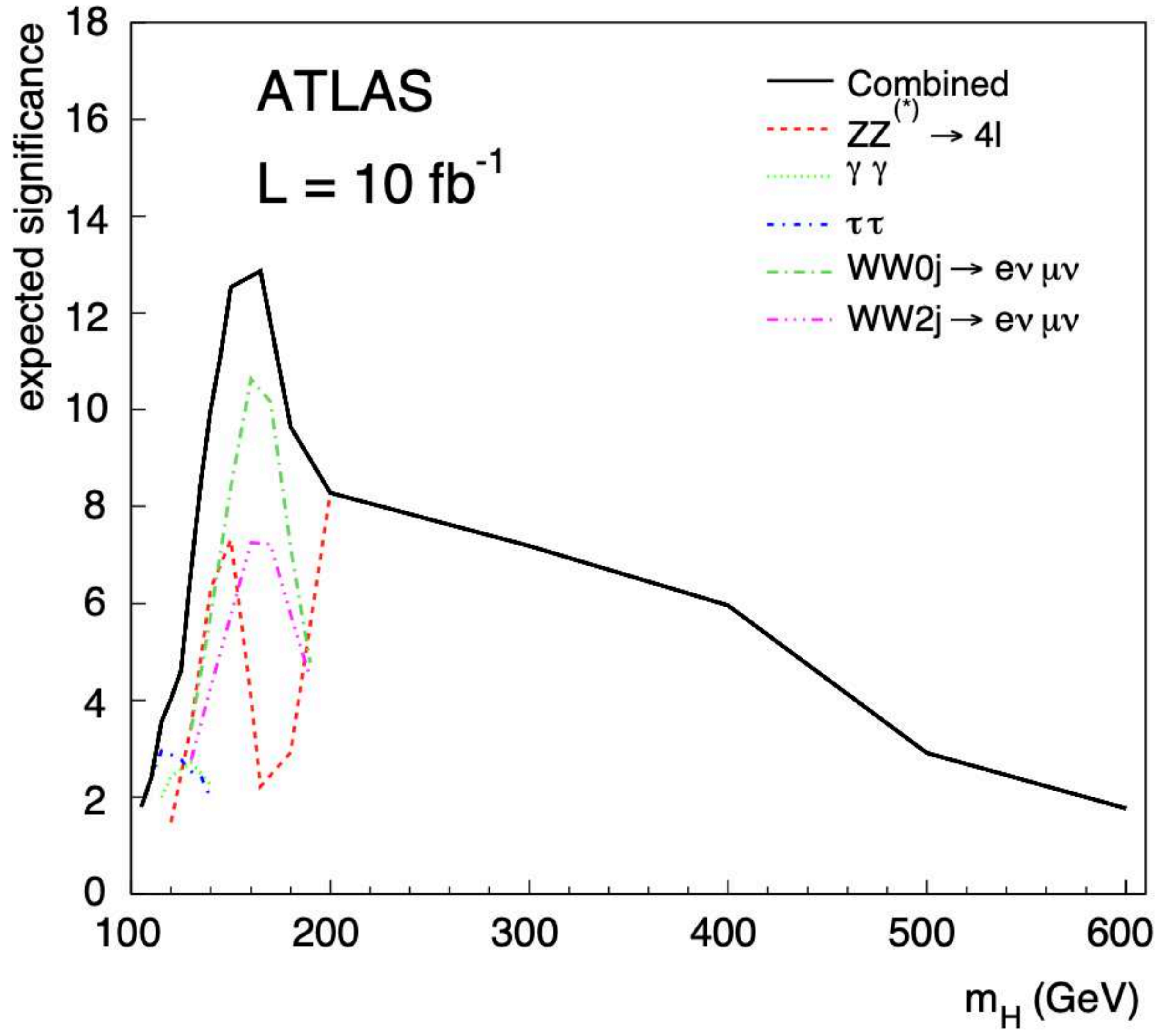
LHC Workshop, Aachen, October 1990

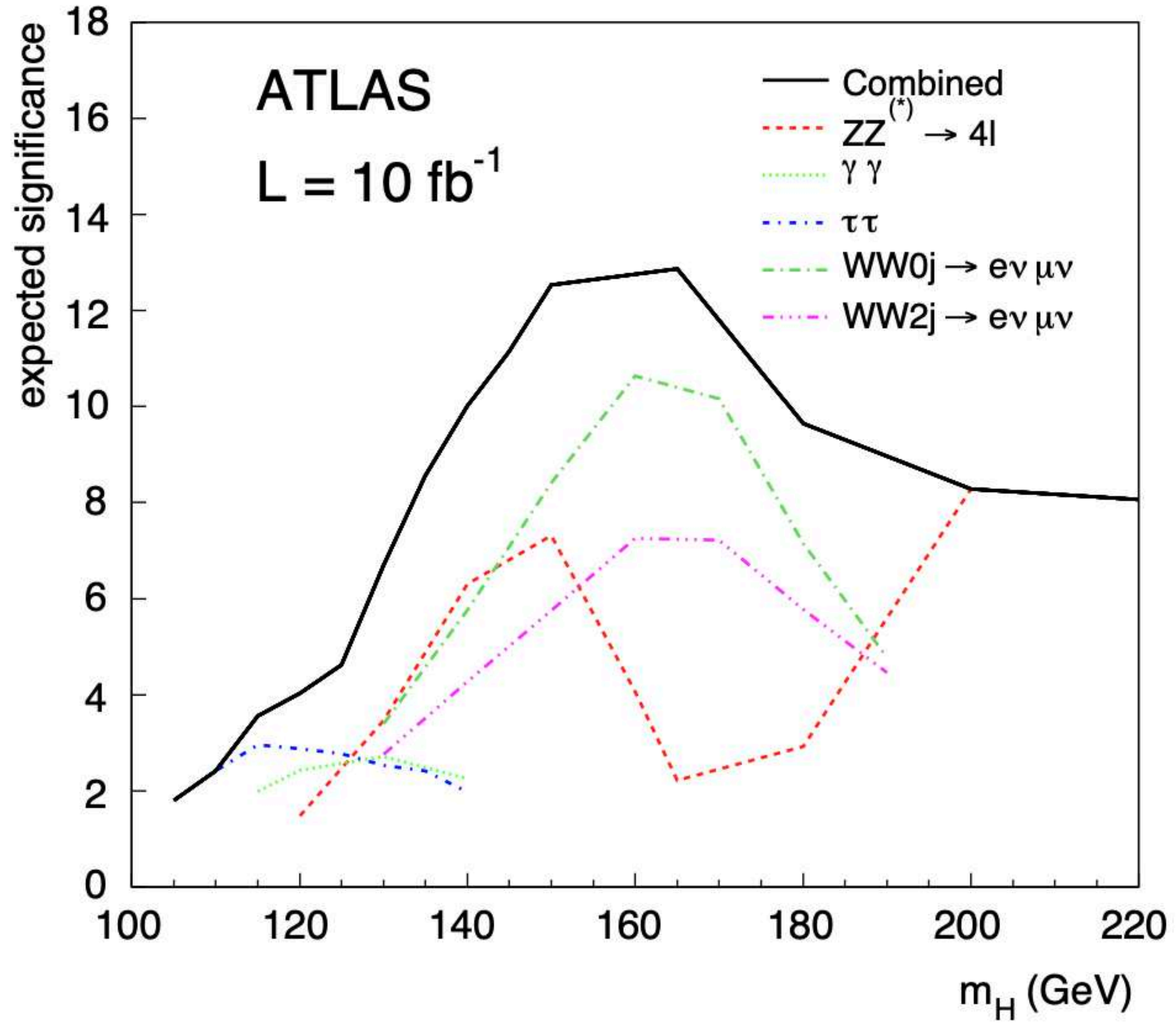


ATLAS TDR 1999

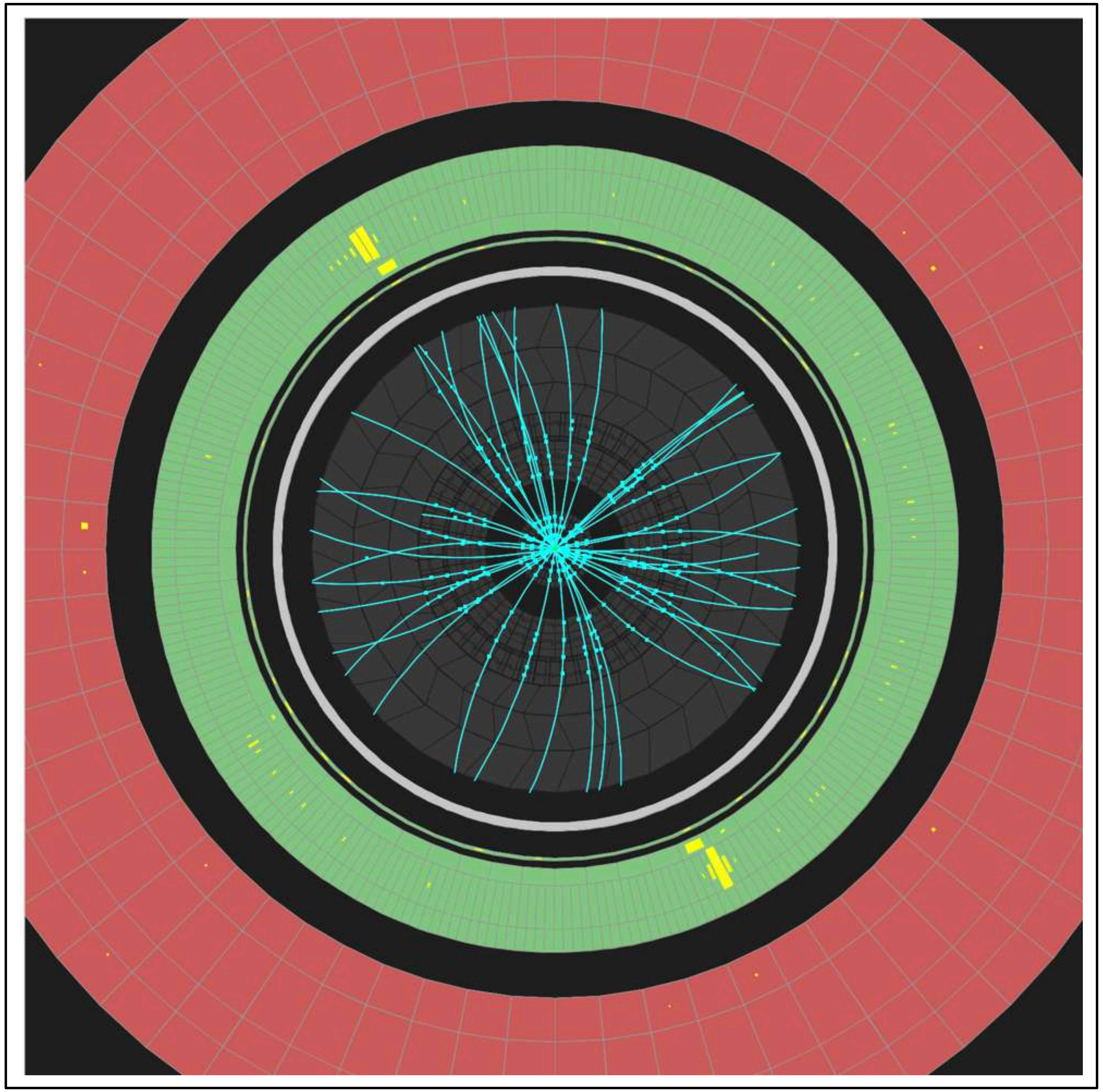


ATLAS CSC 2008



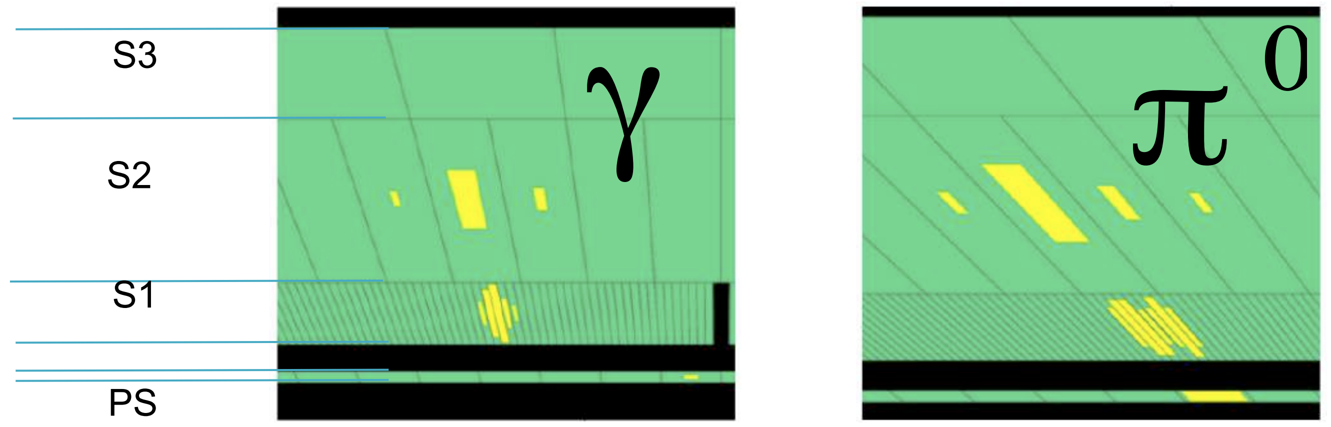


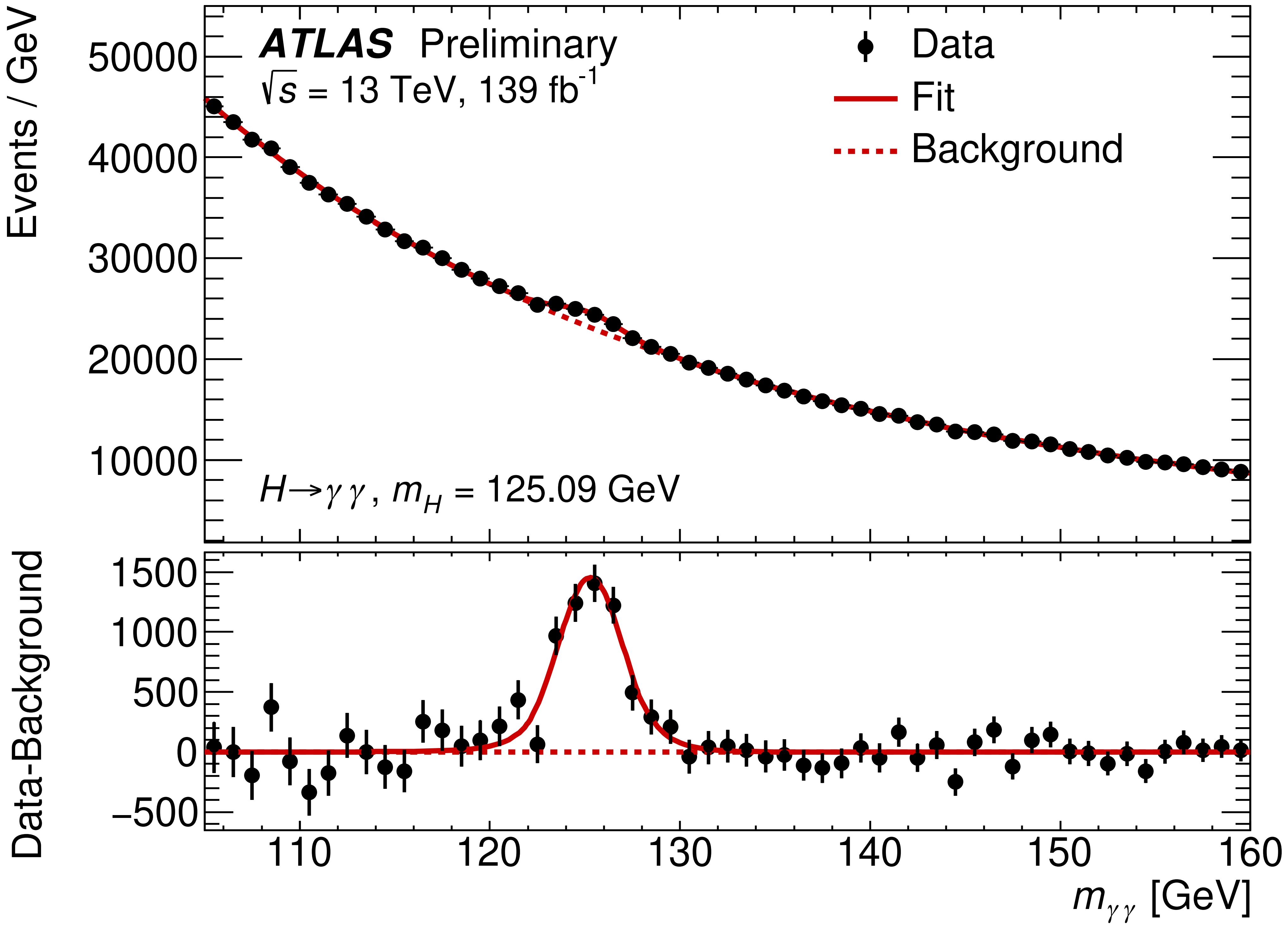
Bread and Butter Discovery Channels



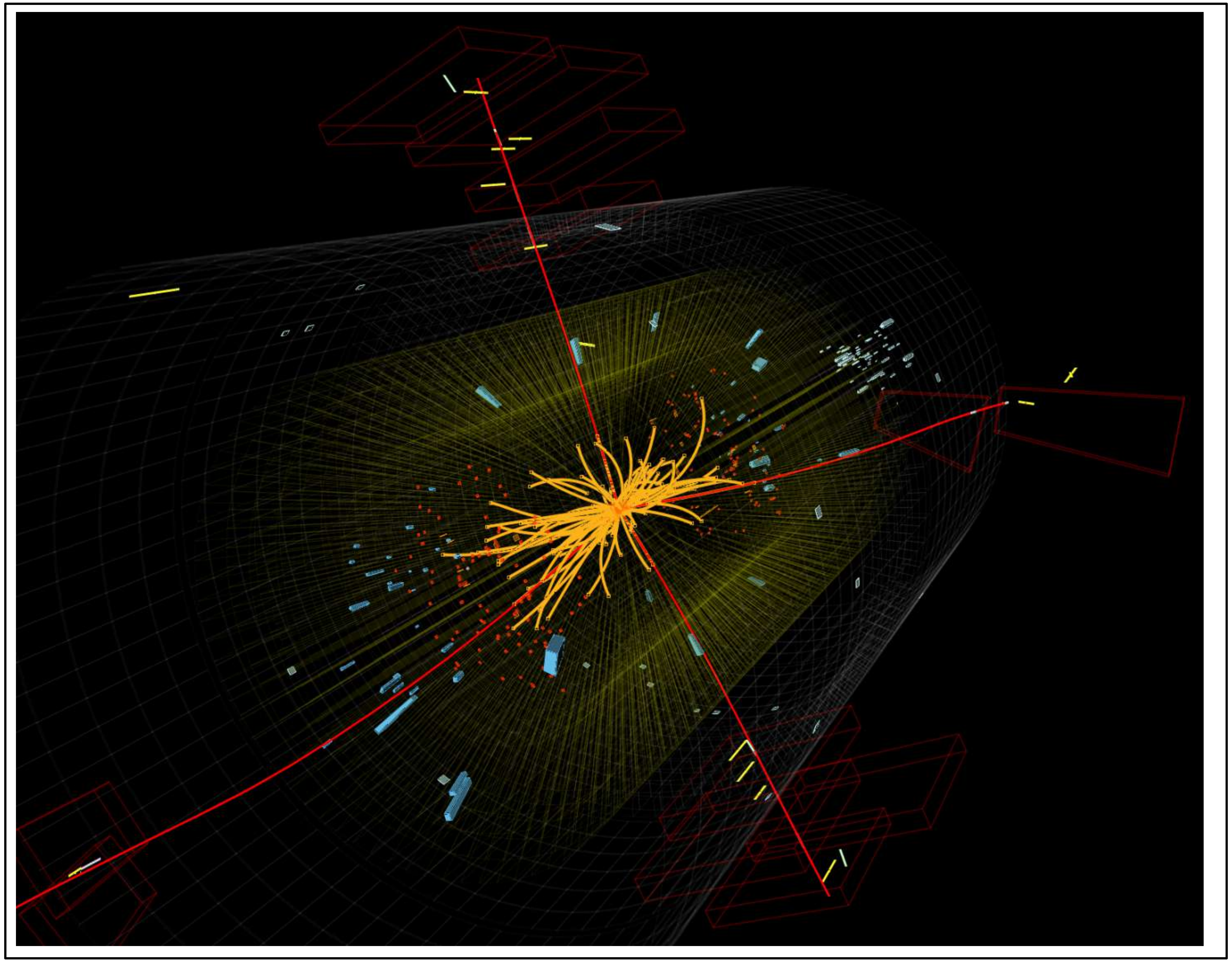
Highlight features

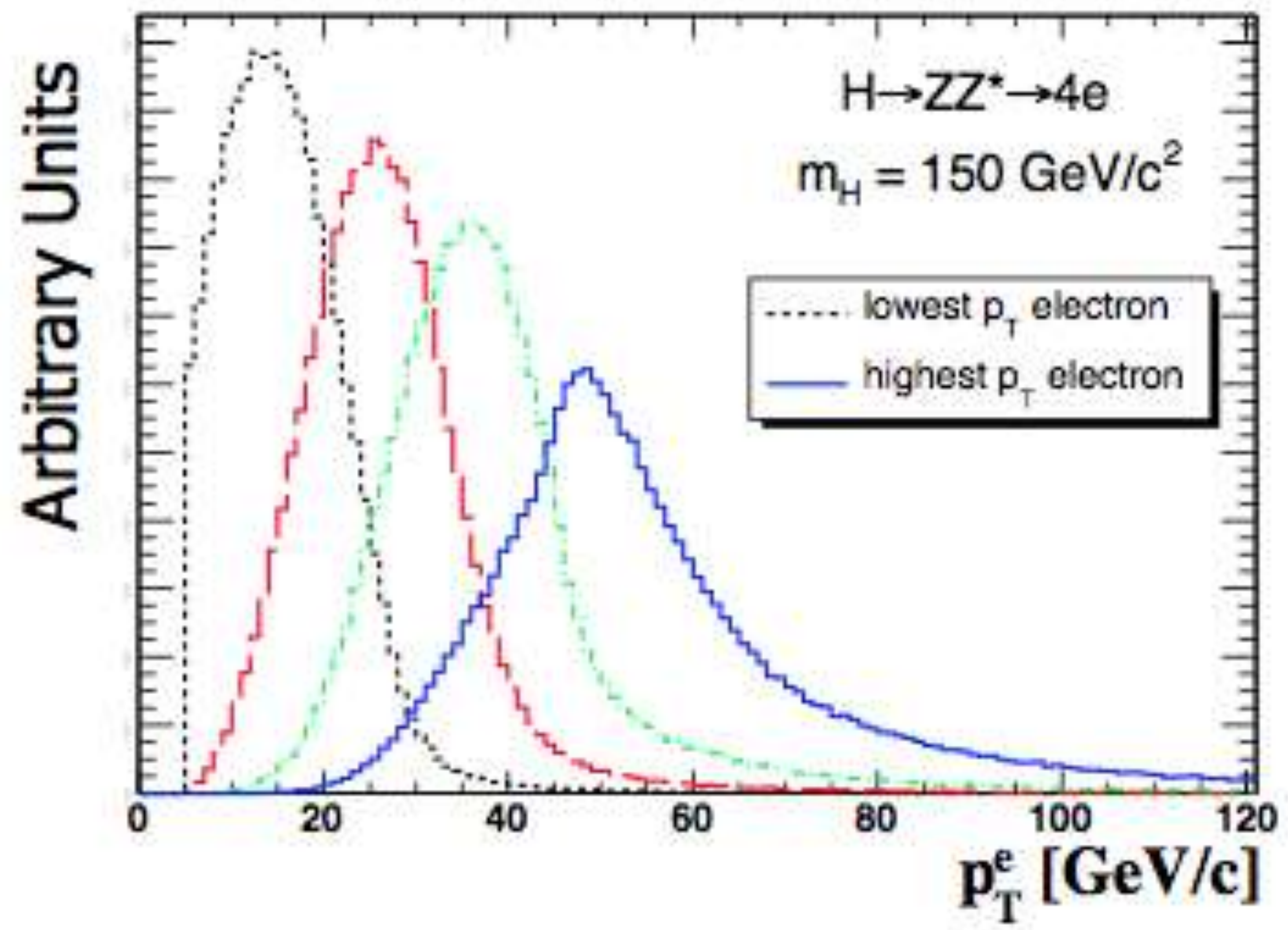
- Excellent calibration and resolution
- π^0-γ Rejection, requires a rejection of jets of $\sim 10{,}000$

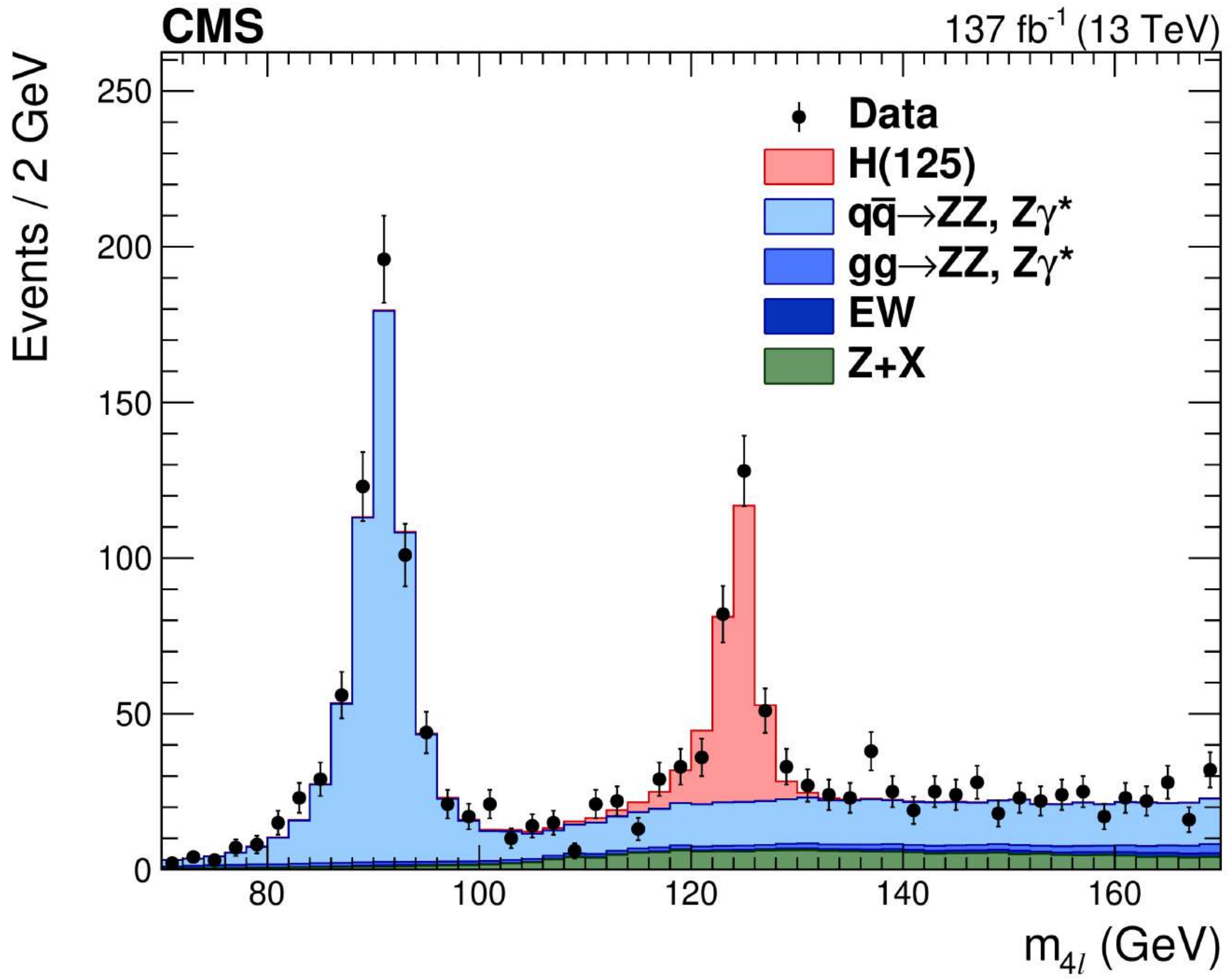




Bread and Butter Discovery Channels





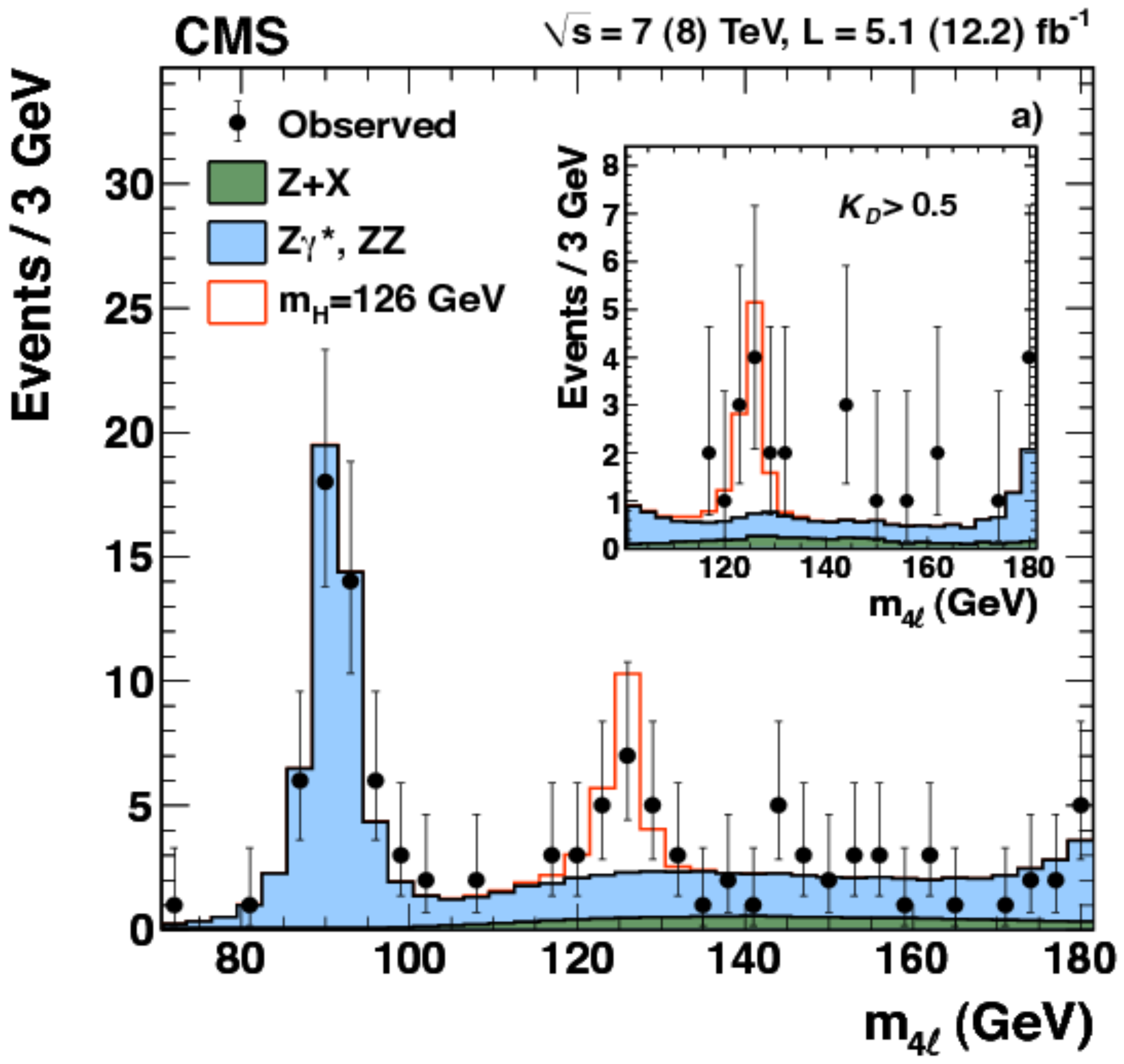


Golden channel

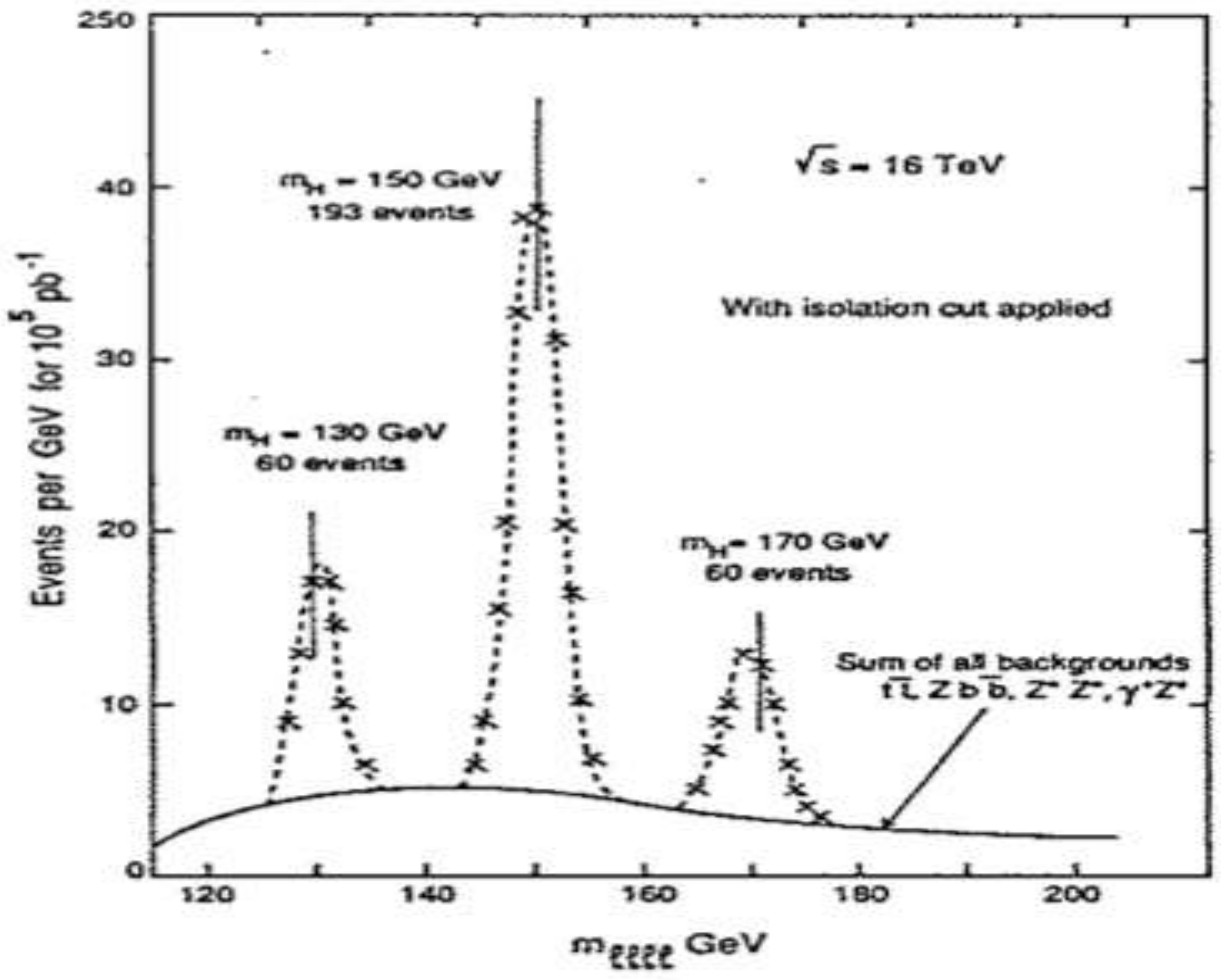
Highlight feature: Very low rate! Efficiency is key, lowering pT threshold on trailing lepton!

The ZZ Channel Historical Perspective

2012



1990

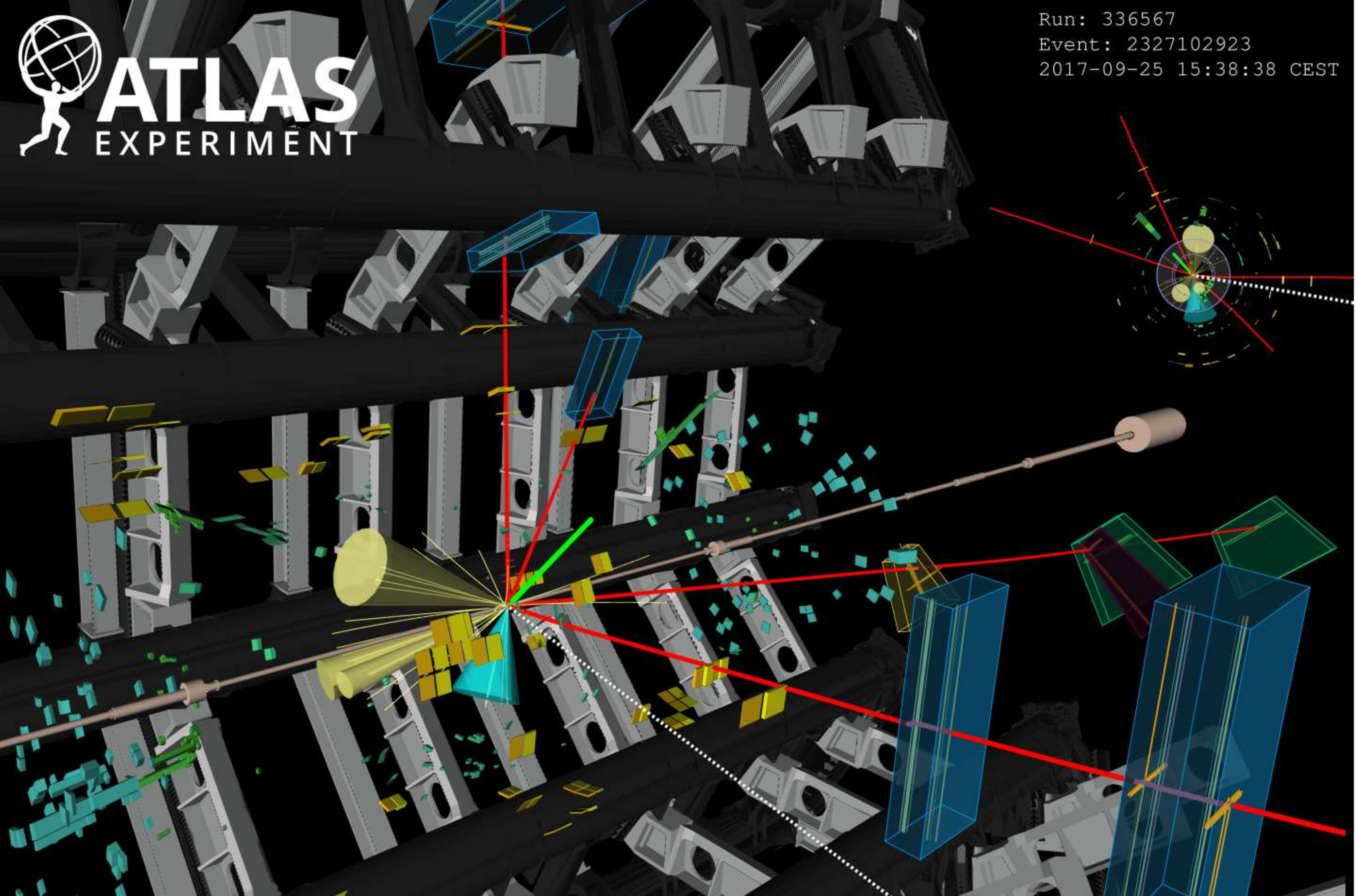


7 - 8 TeV, ~25 fb^{-1}

Significance ~7 σ

16 TeV, 100 fb^{-1}

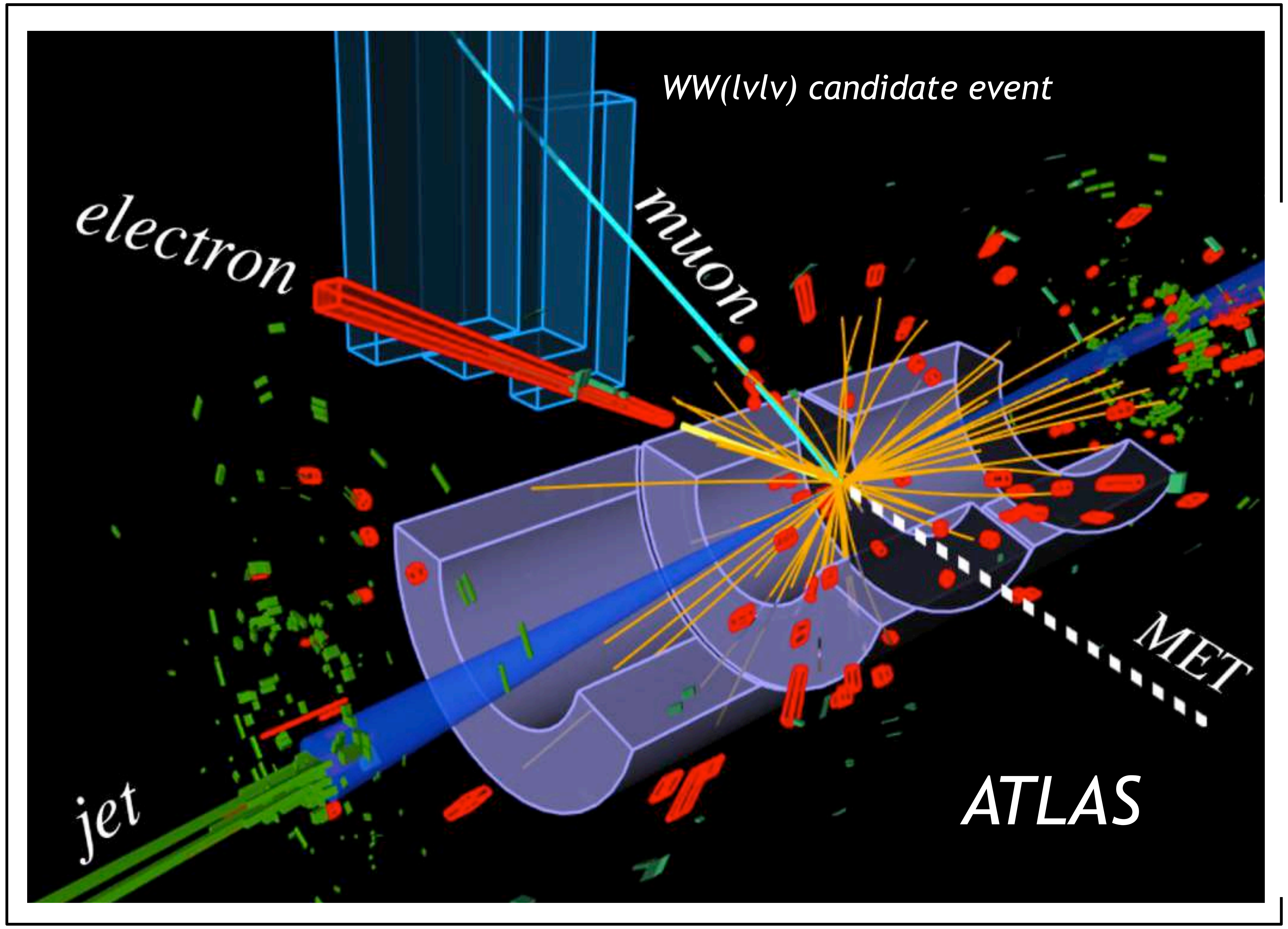
Significance ~6 σ

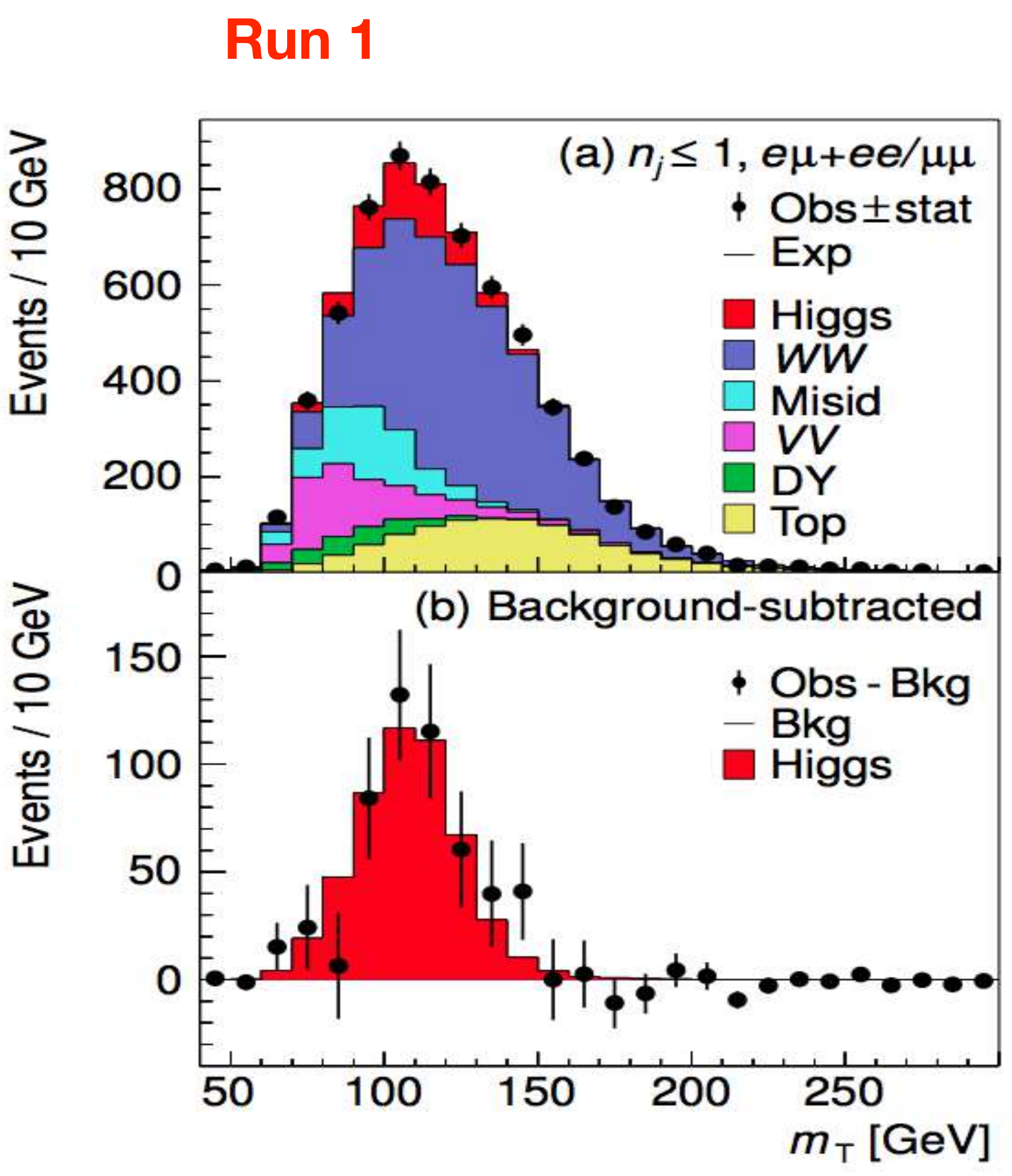


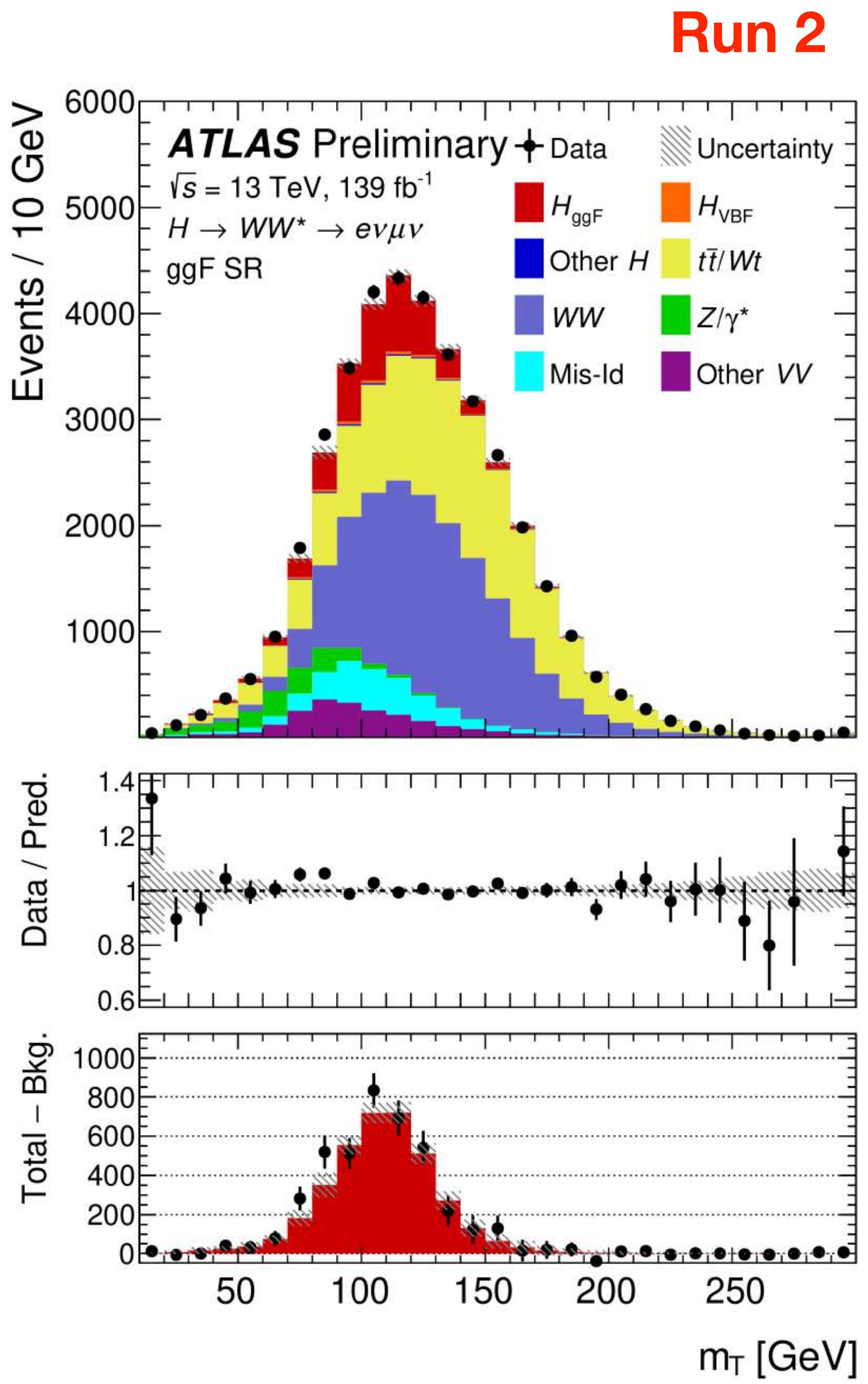
4 muon event with mass 124.4 GeV, one Z mass of 89,3 GeV and the lower mass of 33 GeV, one electron, four jets, lowest pT has tight b-tagging.

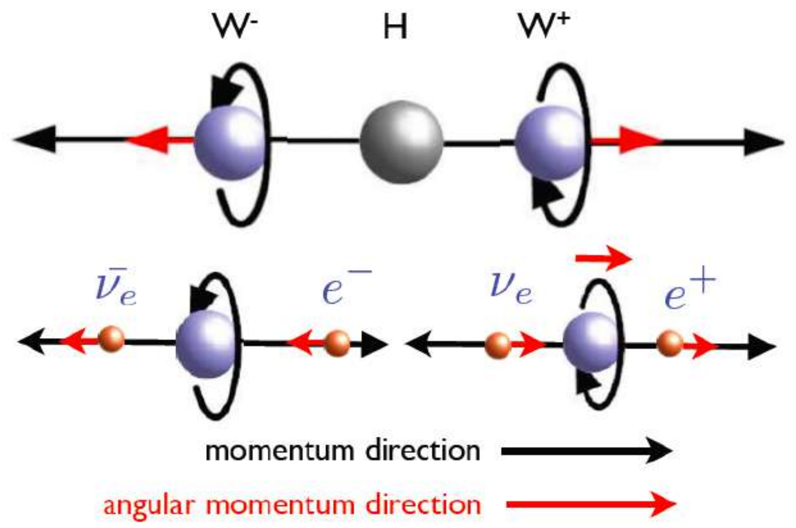
$$s/b \sim 30$$

Discovery Channels









Highlight feature:
Uses the Higgs scalar nature and V-A nature of the W coupling that

(WW but not only) Background modelling is key in this channel, huge progress made to improve modelling and properly define jet bin uncertainties!

A Textbook and Timely Discovery

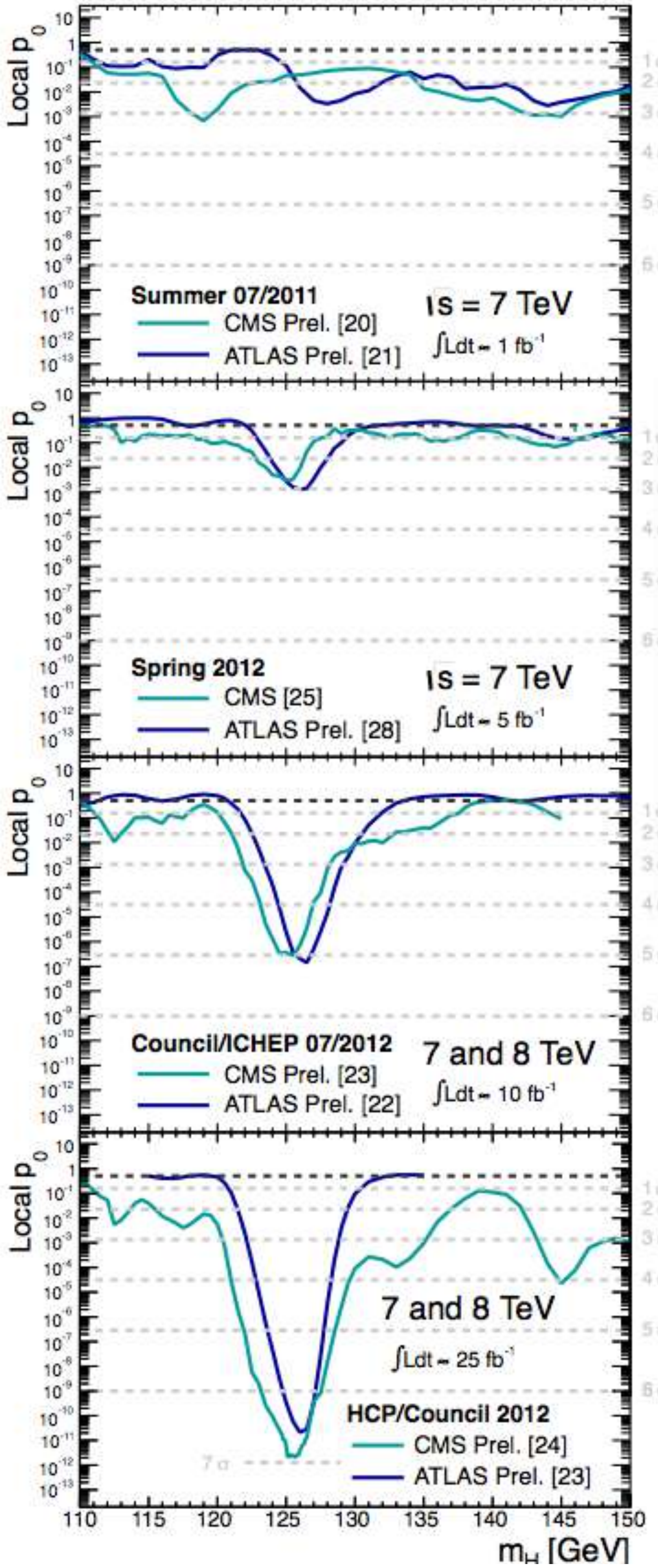
- Summer 2011 EPS and Lepton-Photon: **Still focused on limits.**
- December 2011 CERN Council: **First hints.**
- Summer 2012 CERN Council and ICHEP: **Discovery!**
- December 2012 CERN Council: **Beginning of a new era!**

✓ Strongly Motivated

✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels



Higgs Discovery announcement July 4, 2012

2013

“Understanding the mass of subatomic particles” [full]

Francois Englert and Peter Higgs

Review see latest PDG review

5.- Status of Higgs Physics at LHC

HL-LHC is a Higgs Factory

Outcome of the 2013 European Strategy: HL-LHC!

European Strategy 2012-2013 Recommendations

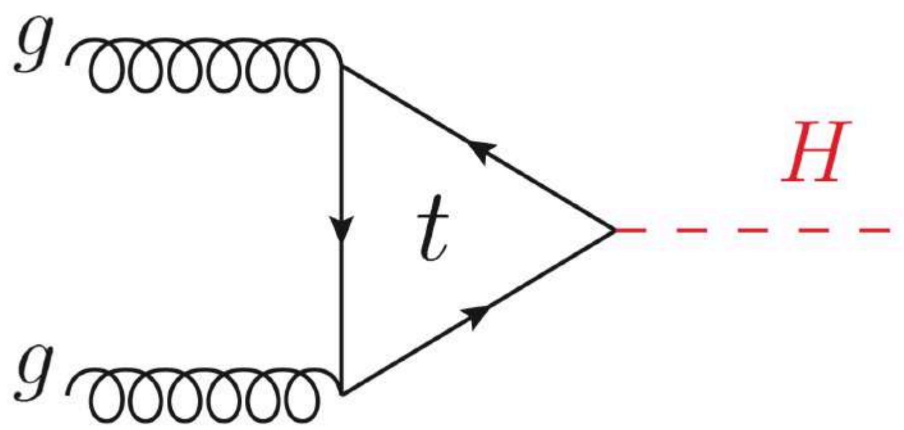
HL-LHC is a **Higgs factory** ~160 M Higgs events

In comparison Future ee up to ~1.3 M Higgs Events, but much cleaner and « usable » events

Process	ggF	HH	ttH
13 TeV / 8 TeV	**2.3**	**2.4**	**3.9**
13.6 TeV / 13 TeV	**7%**	**11%**	**13%**
14 TeV / 13.6 TeV	6%	7%	7%

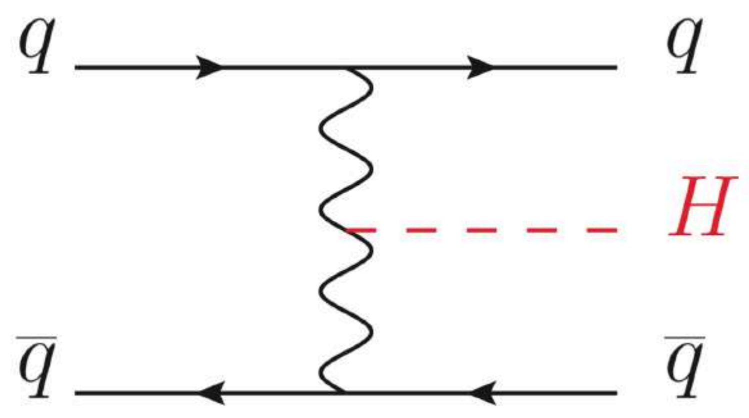
Higgs boson (main) Production Modes

Production rates at Run 2 (13 TeV) for ~150 fb^{-1}



Gluon fusion process

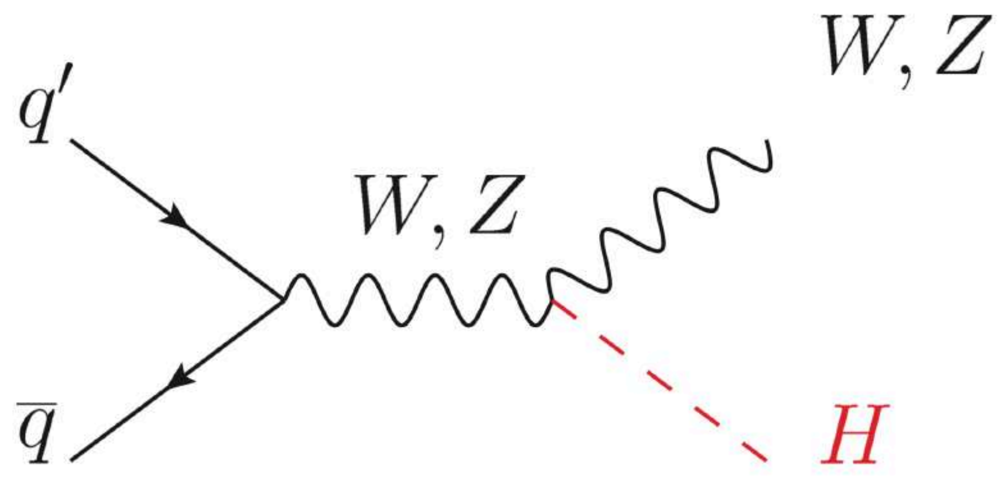
~8 M events produced



Vector Boson Fusion

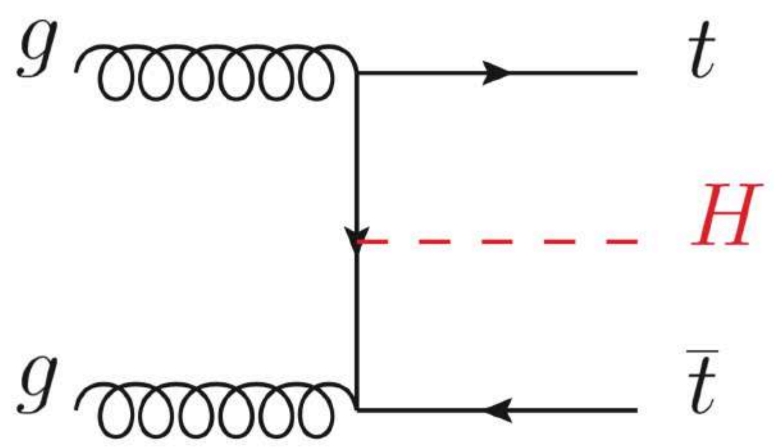
Two forward jets and a large rapidity gap

~600 k events produced



W and Z Associated Production

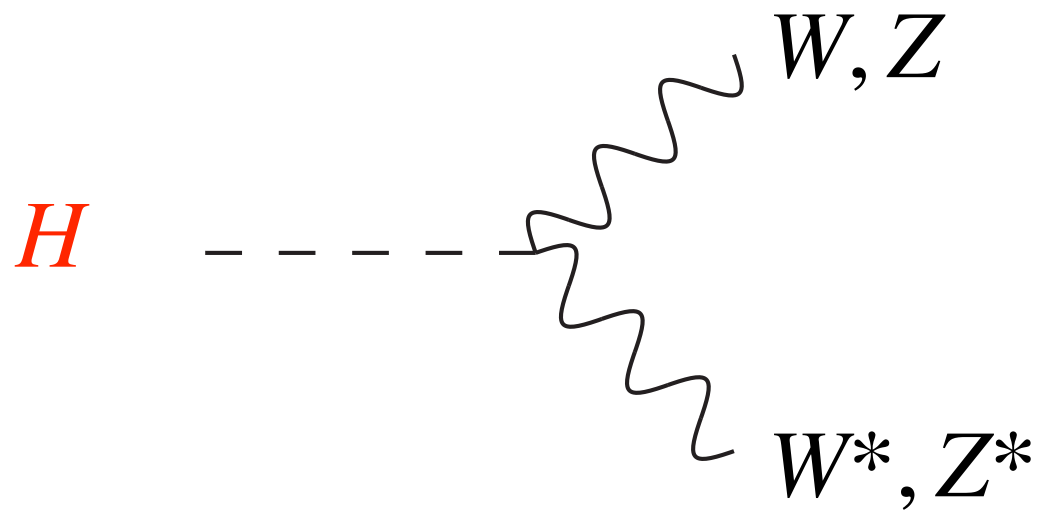
~400 k events produced



Top Assoc. Prod.

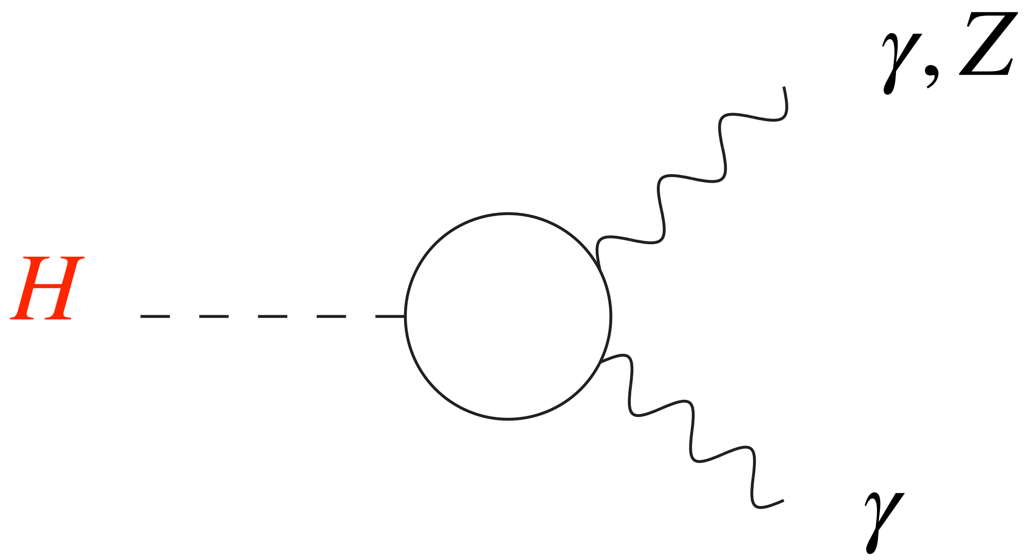
~80 k evts produced

Decay branching fractions



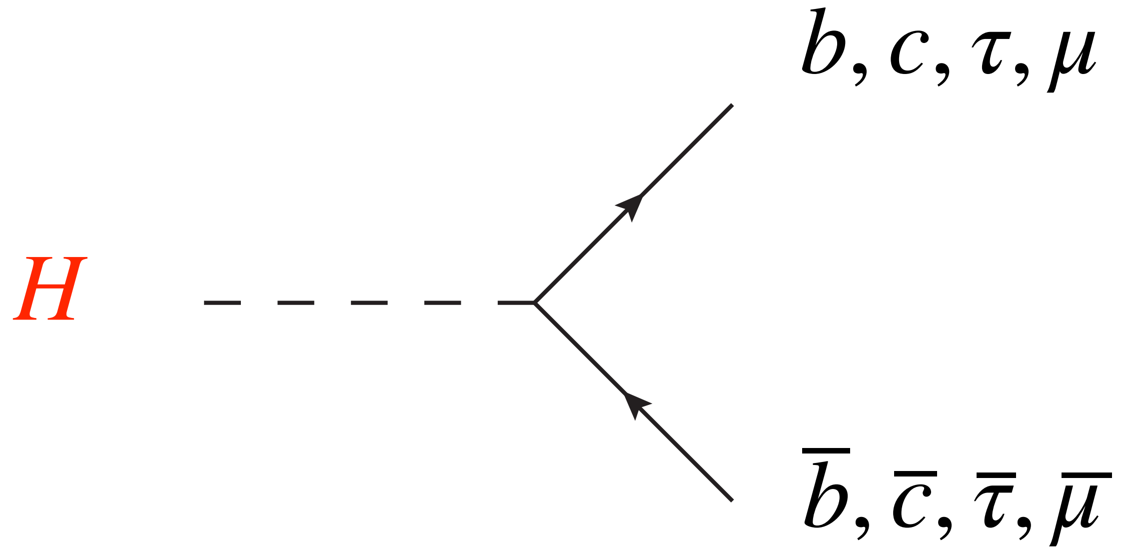
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

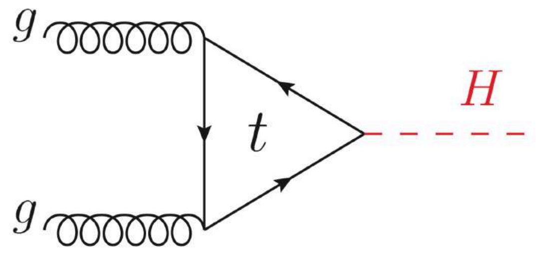
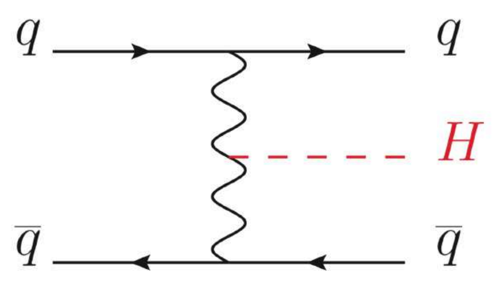
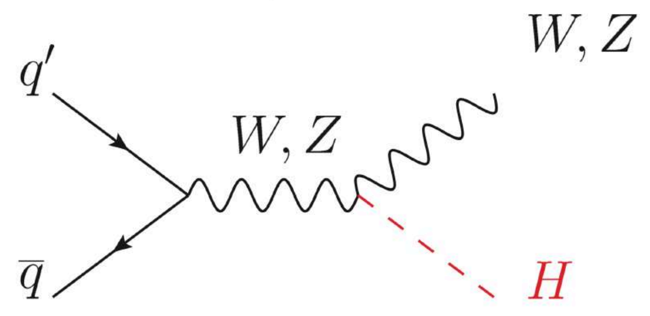
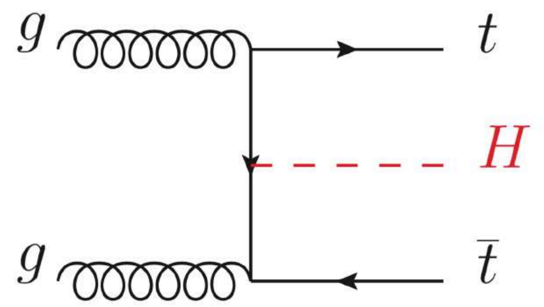
$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 5% (~150 fb-1) of full HL-LHC dataset!

	Channel categories	Br	ggF	VBF	VH	ttH
			 ~8 M vets produced	 ~600 k vets produced	 ~400 k vets produced	 ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

*N3LO

Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%
B_{inv}		$< 11\,\%$	$< 16\,\%$	
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)	

How elementary is the Higgs Boson?

Minimal Composite Higgs scenarios

$$g_{HVV} = \frac{2m_V^2}{v}\sqrt{1 - v^2/f^2}$$

$$4\pi f \gtrsim 9\,\mathrm{TeV}$$

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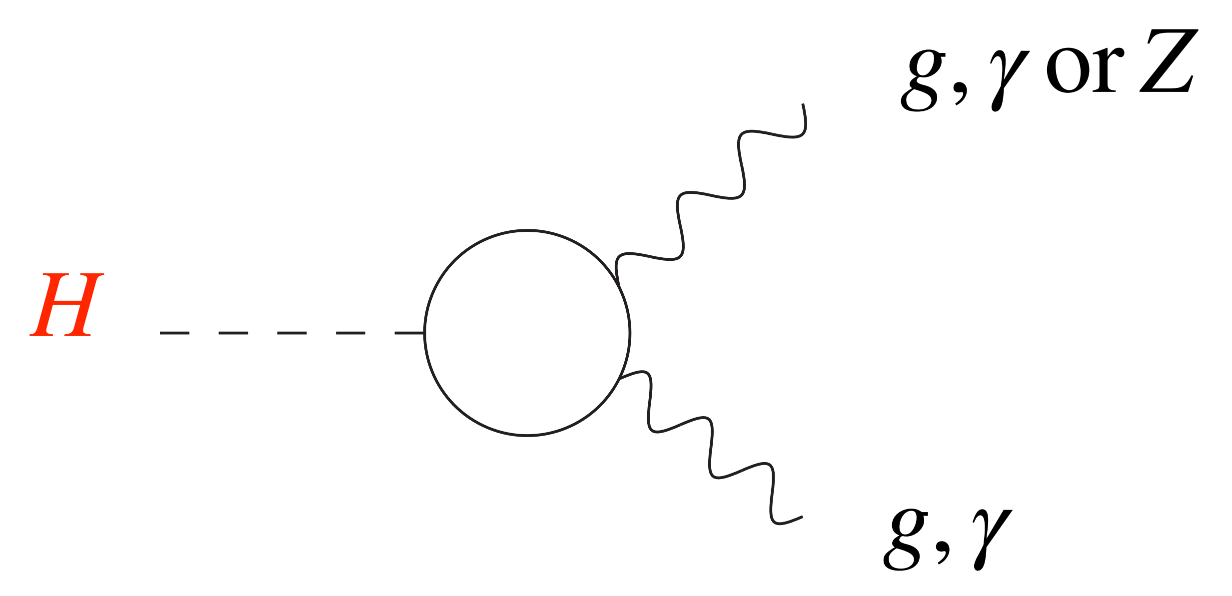
Probing new particles through loops



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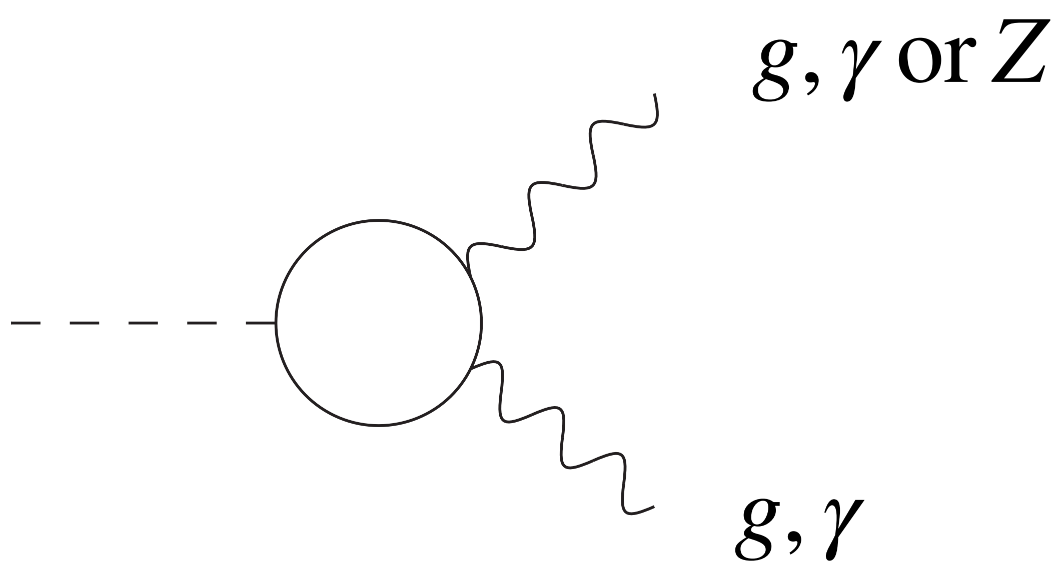
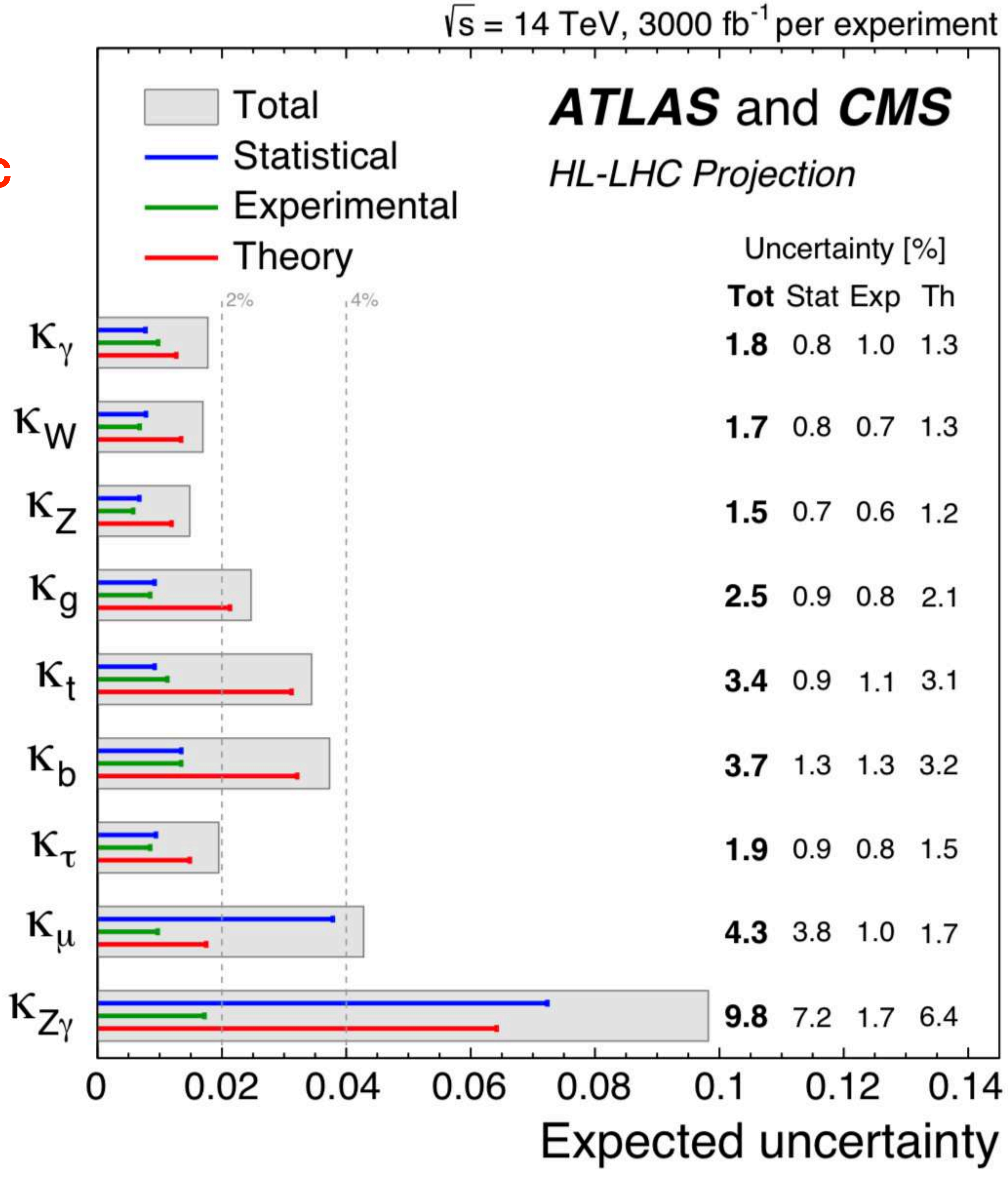


Probing the **Flavour Hierarchy** through the Yukawa couplings!

Precision Higgs Couplings Measurements

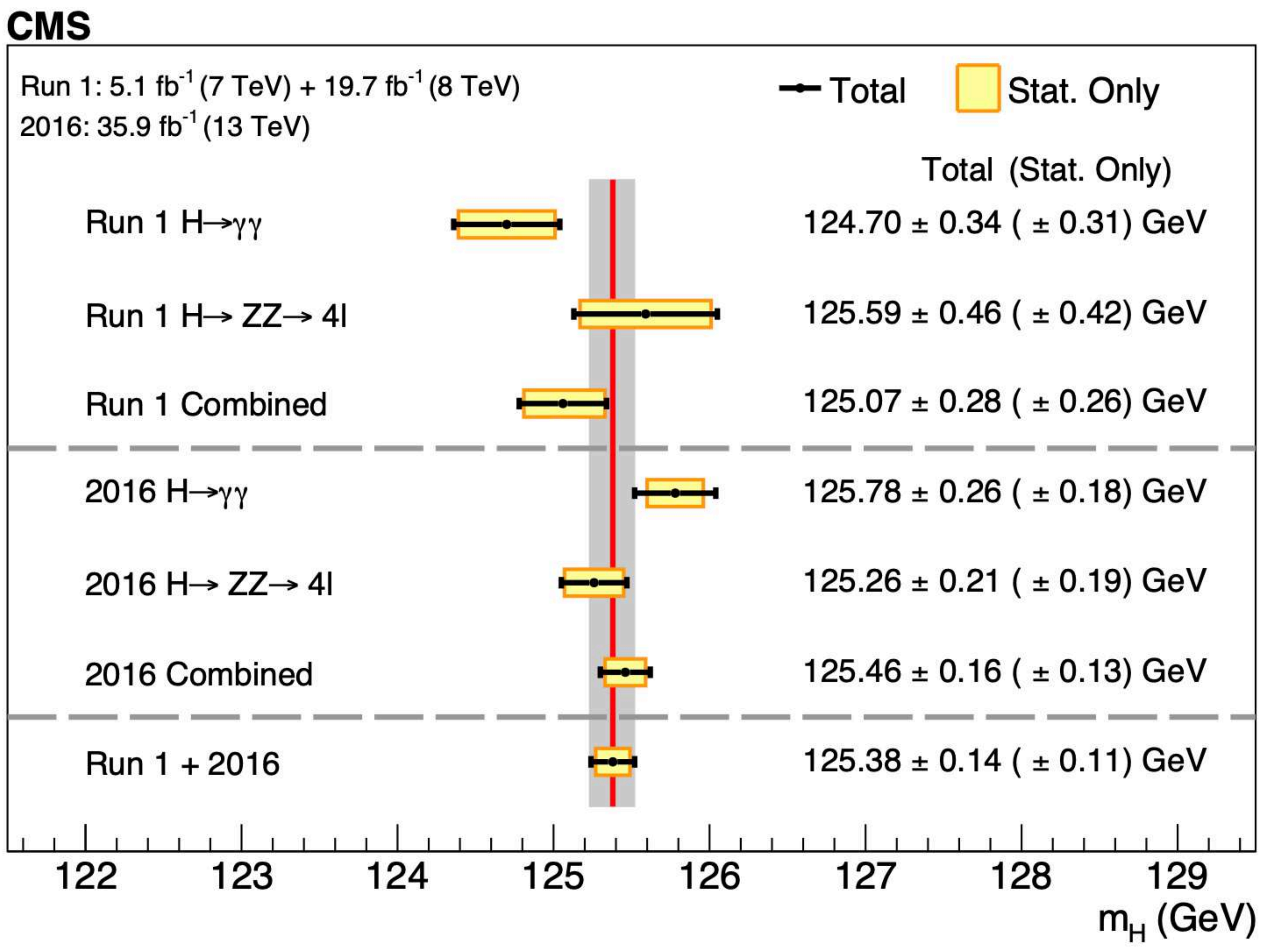
	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



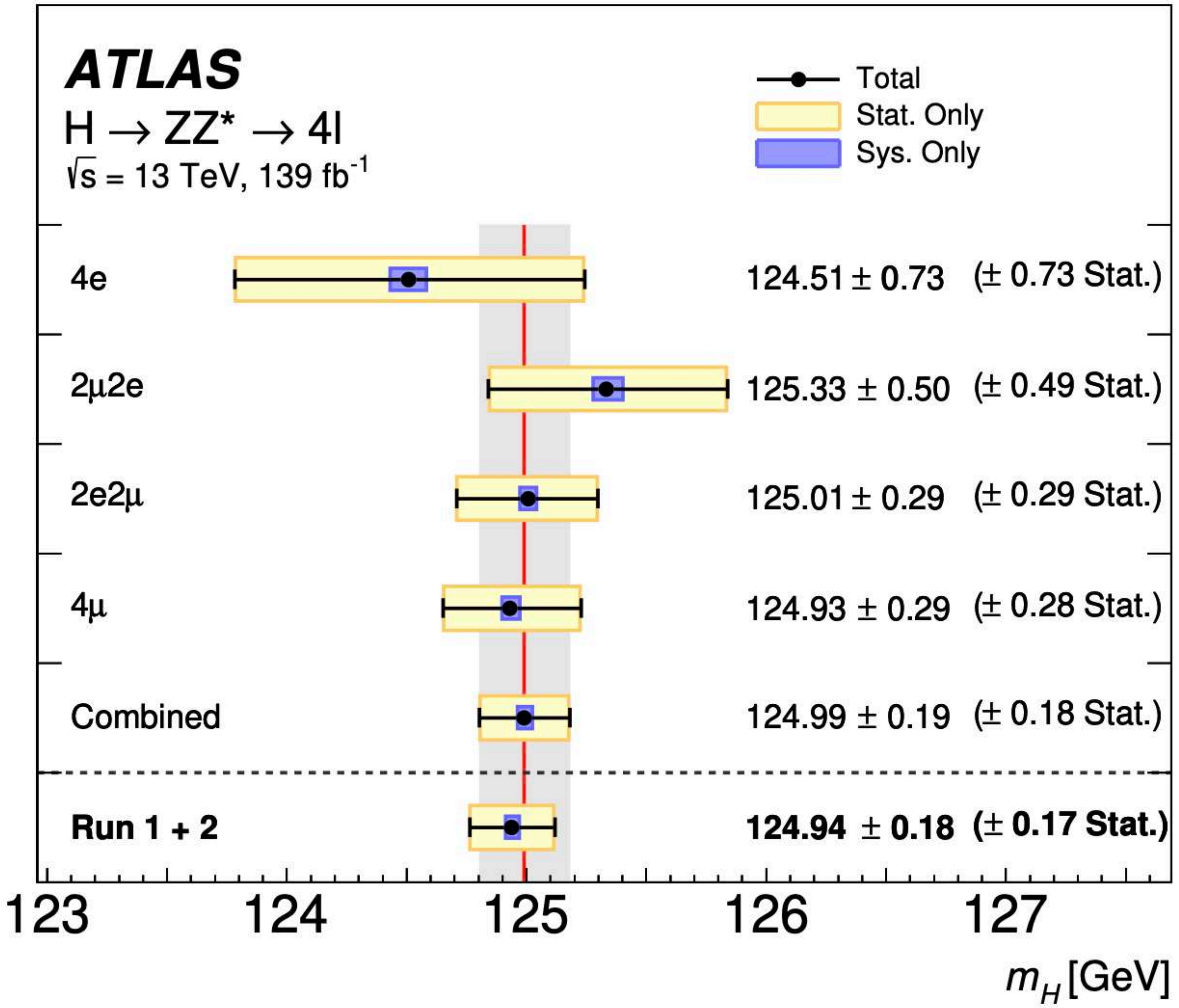
TH Uncertainties dominant (assumed to be 1/2 of Run 2)

Measurement of the Higgs Boson Mass

Most precise measurement from CMS:



Latest measurement from ATLAS:

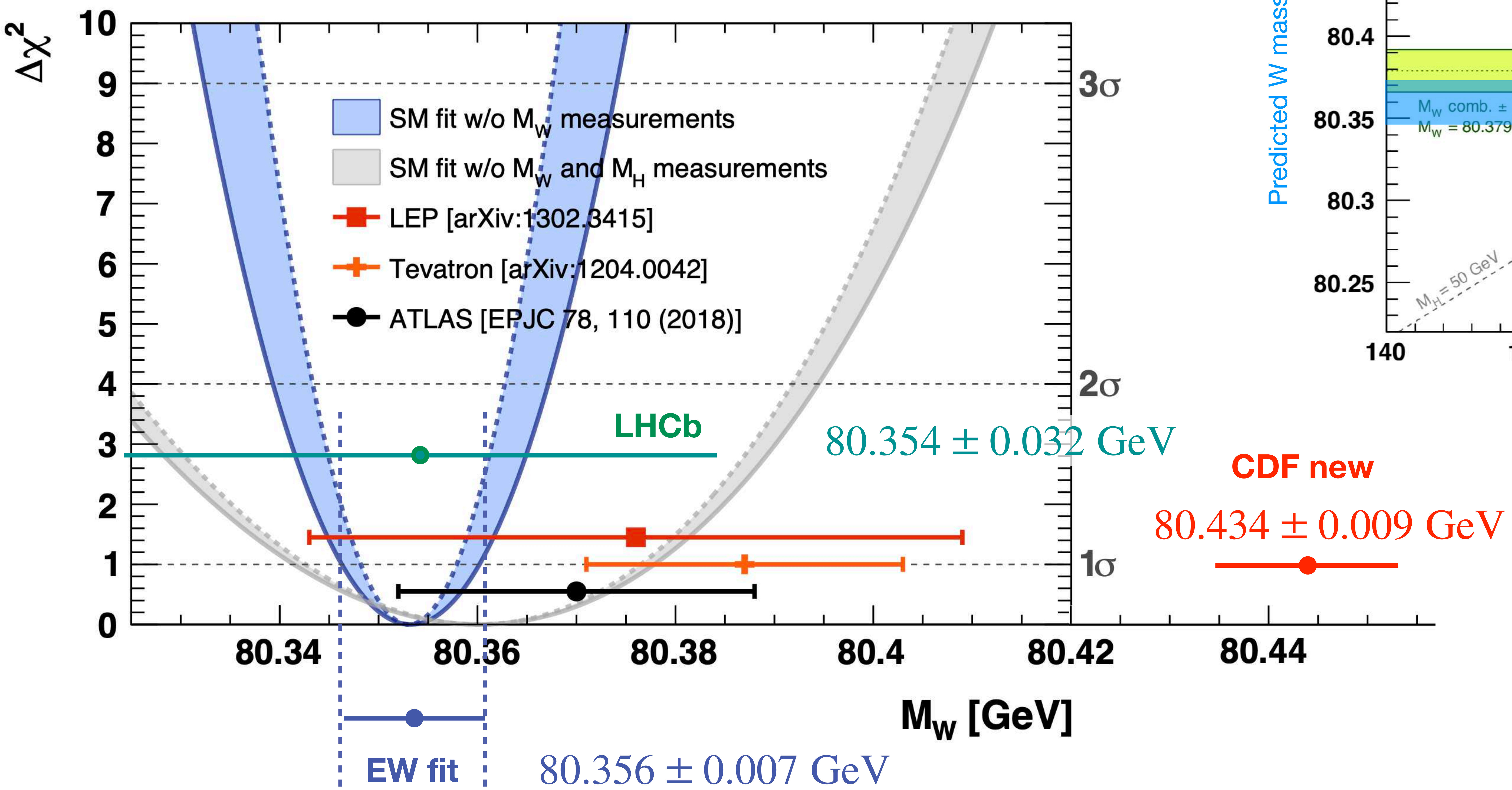


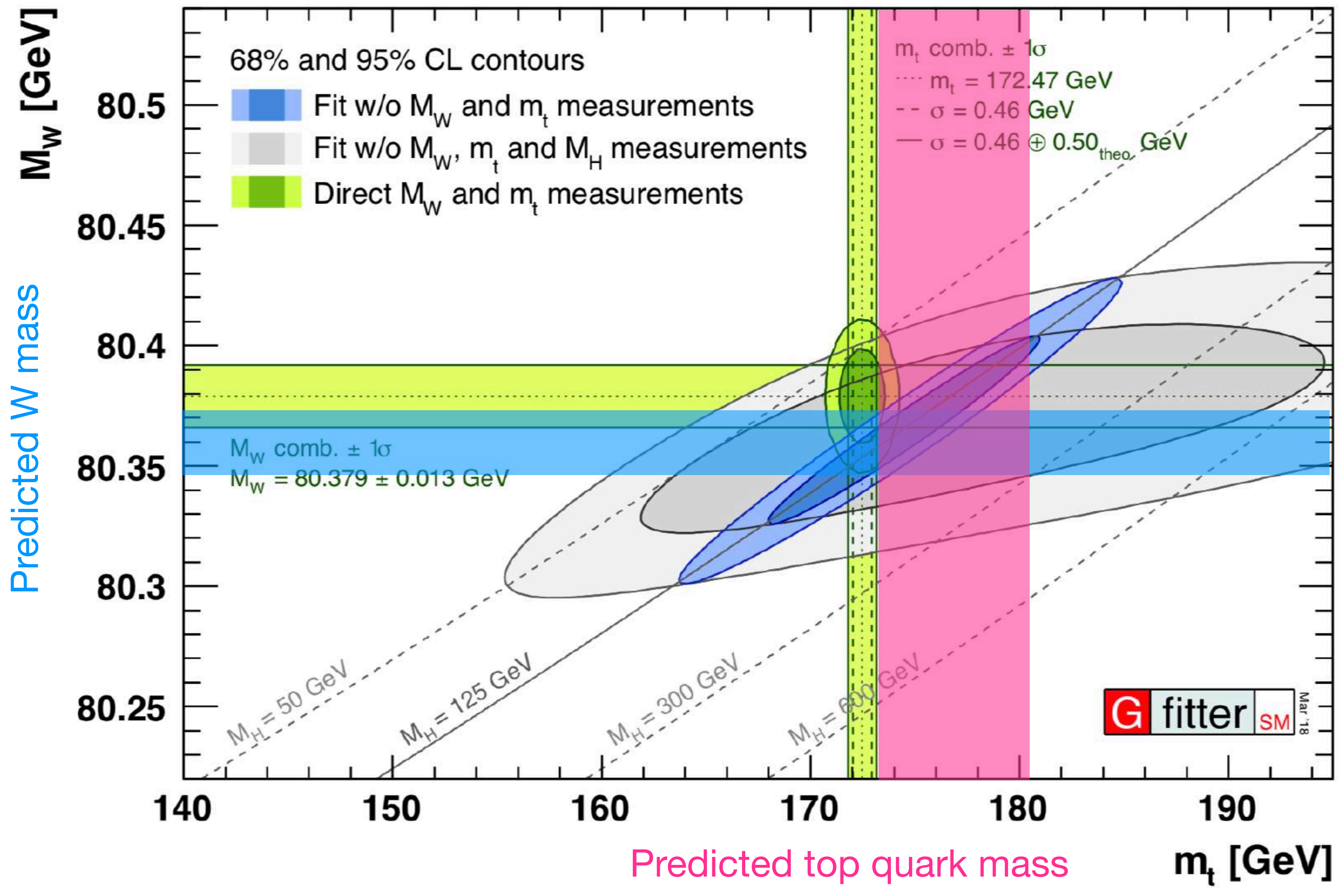
Systematic uncertainty (dominated by muon momentum calibration) of 30 MeV!

What have we Learned from Knowing its Mass?

Precision measurements allow to make predictions!!

Assuming the SM, the top quark mass and Higgs boson mass were (approximately) known before being discovered!





The knowledge of the Higgs mass has large impact on the precision of indirect measurements!

The current level of precision on the Higgs mass has little impact on this.

6.- The Essential Role of TH Predictions

Modelling and predictions - an overarching question!

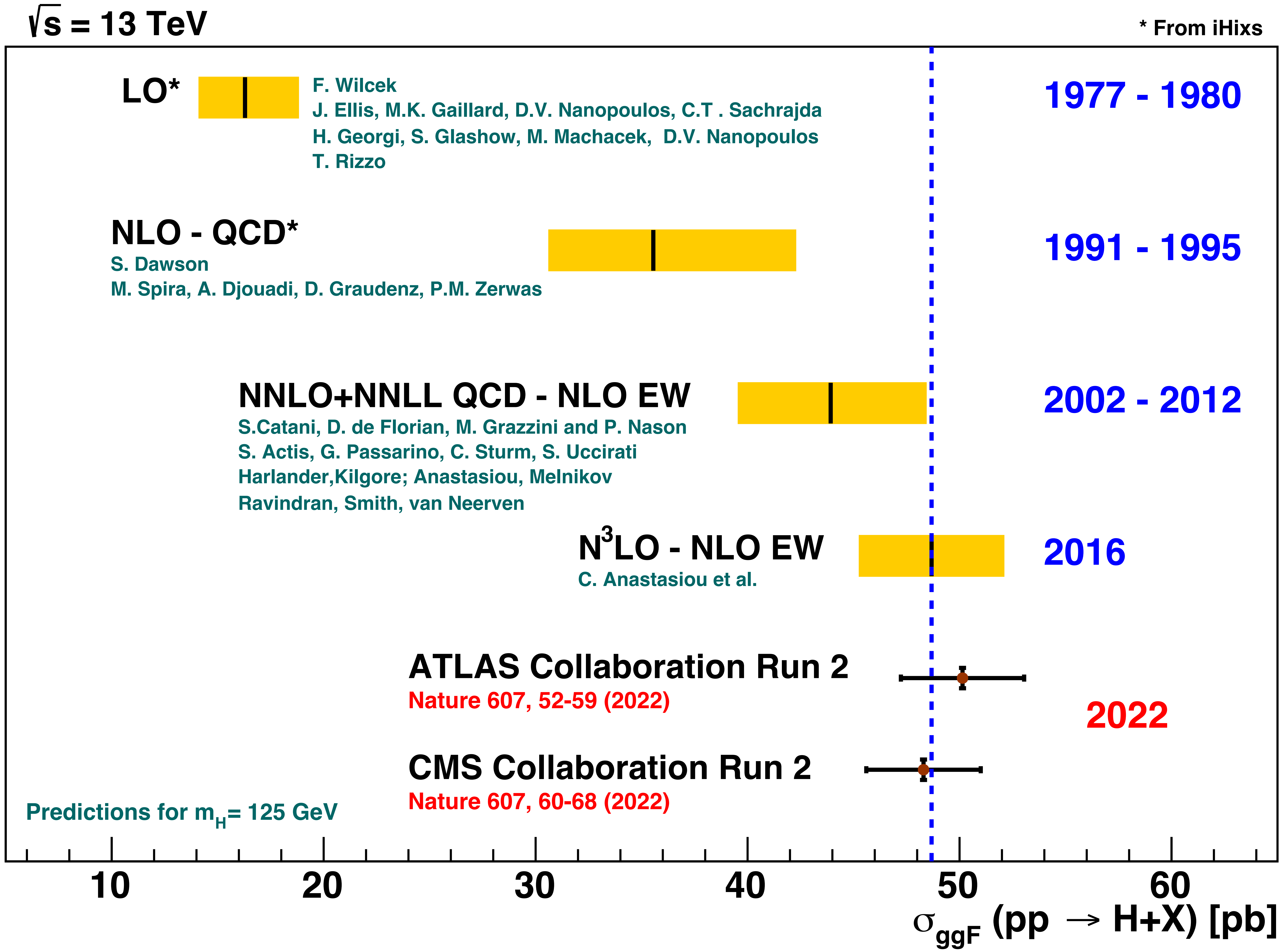
The dominant systematic uncertainties in a very large number of analysis: modelling and TH systematic uncertainties.

The level of precision reached so far **relies** on a number of **TH breakthroughs**

- The « Next-to… » revolutions, and novel tools for automated calculations at higher orders
- Reaching N3LO-QCD precision (ggF, VBF and VBF-HH)
- NNLO Monte Carlos (requiring NNLO-PS matching!)
- Up to N3LL resummation matched to fixed order
- IR and Colinear safe fast Jet reconstruction algorithms

These are one of the most important **pillars of precision at the LHC**, and Higgs physics in particular.

The Importance of the Higgs Boson HO corrections



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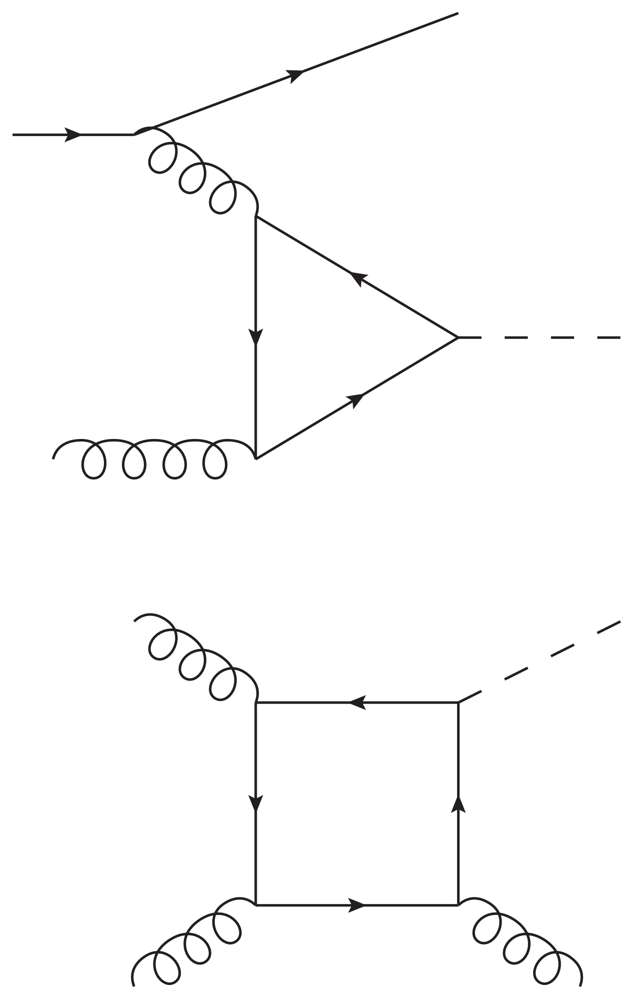
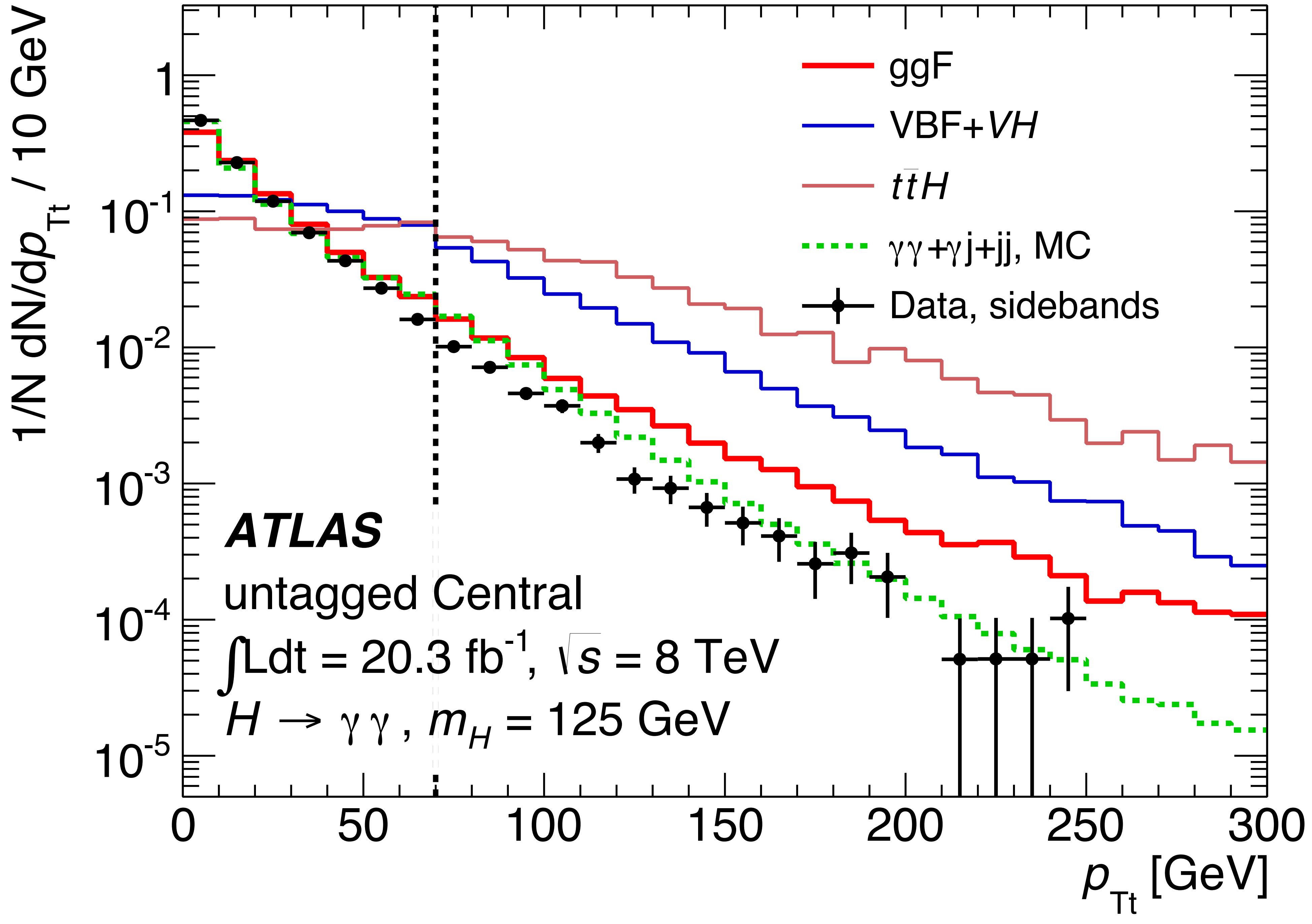
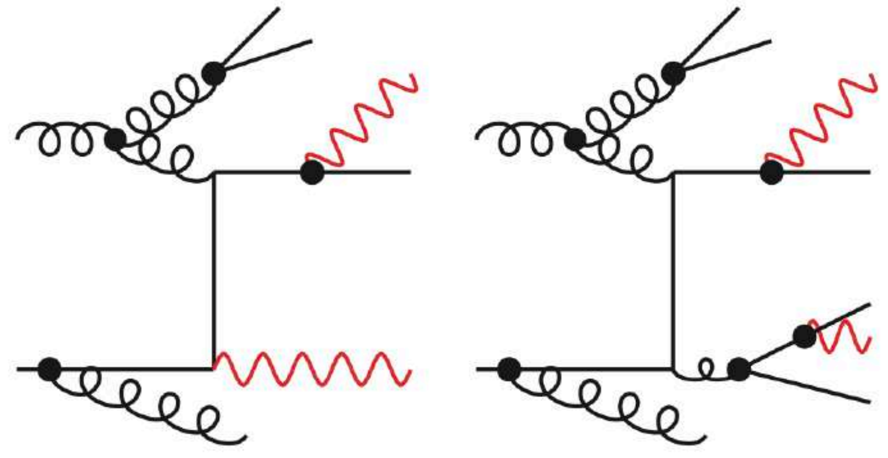
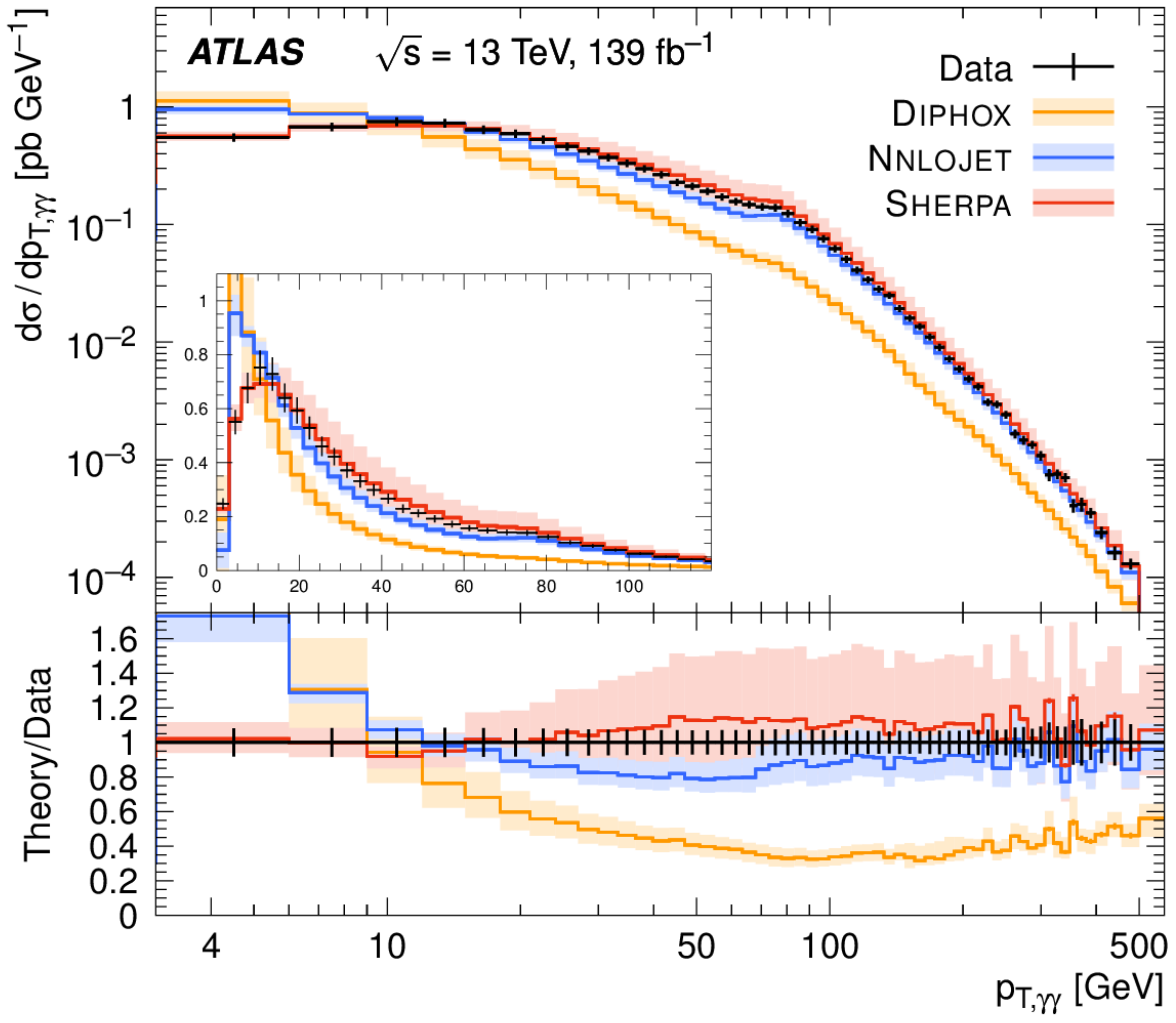




Differential di-photon Measurements!

Not only an electromagnetic process also non trivial strong dynamics!

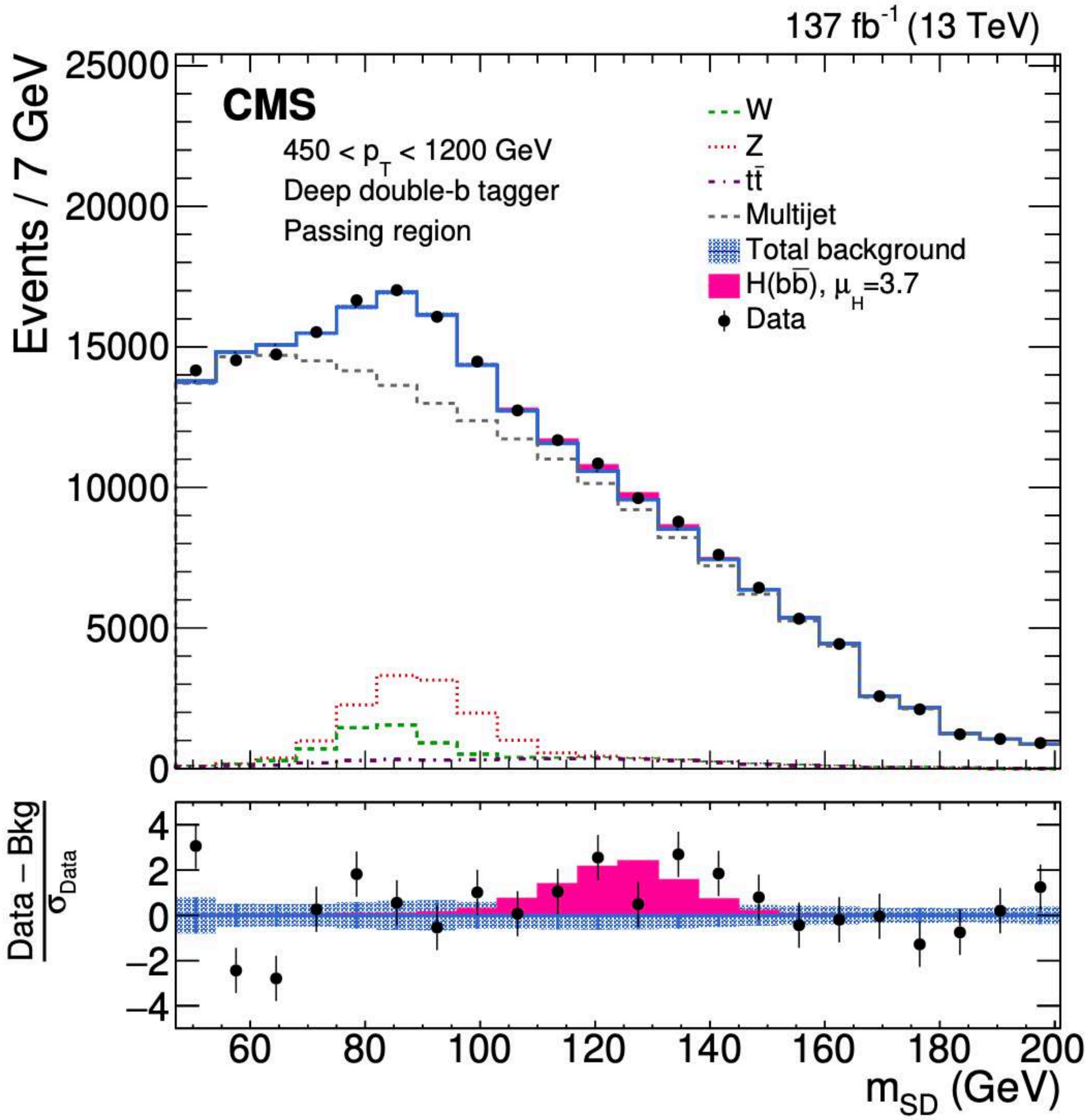




- Inclusive Higgs production has large higher order corrections
- Transverse momentum and/or additional jets bring invaluable additional signal-background discrimination (played an important role in the discovery)

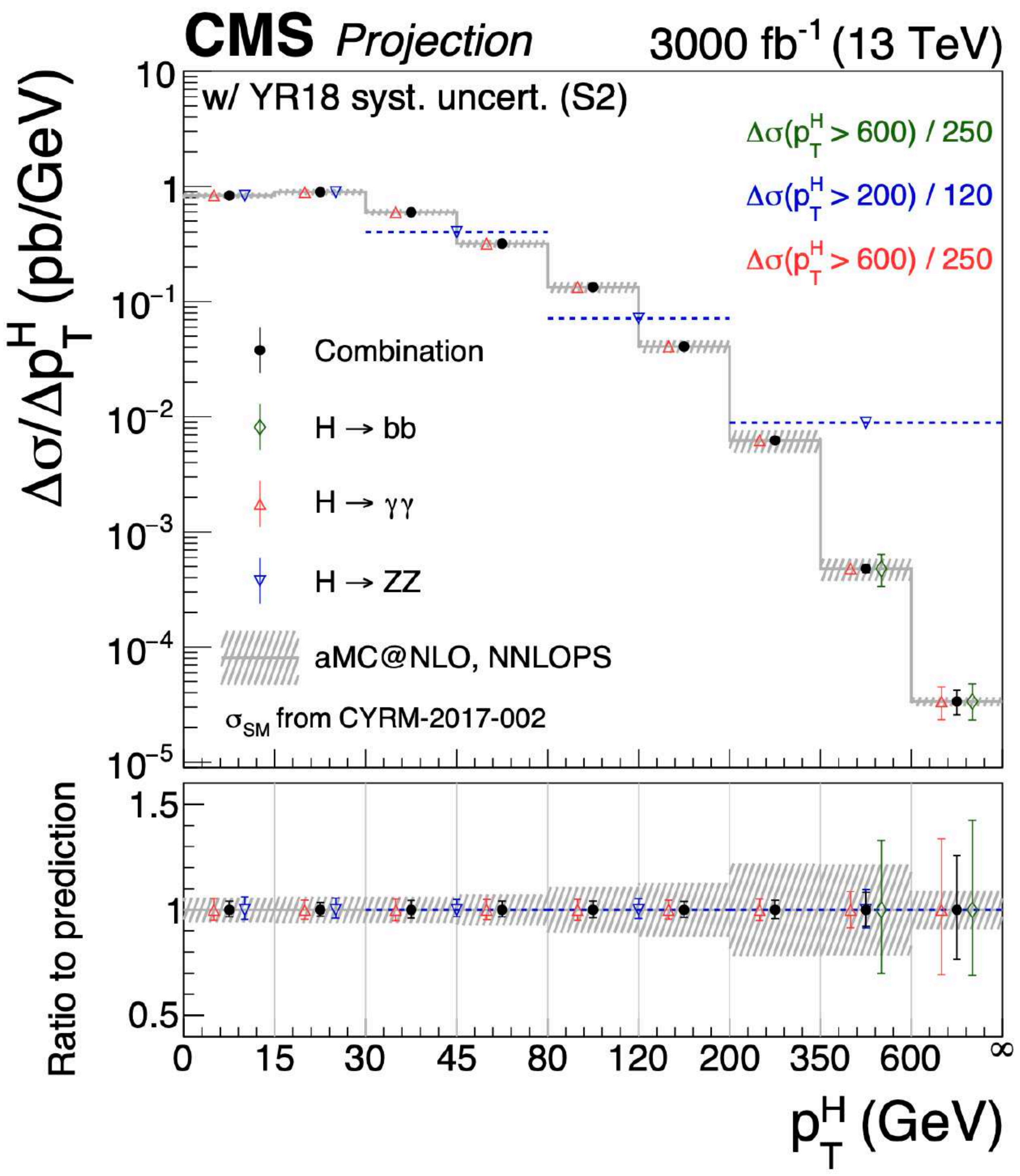
Importance of ancillary measurements!

Boosting the Higgs Boson!



Thought to be completely impossible!

Expected H significance ($\mu_H = 1$)	$0.7\,\sigma$
Observed H significance	$2.5\,\sigma$

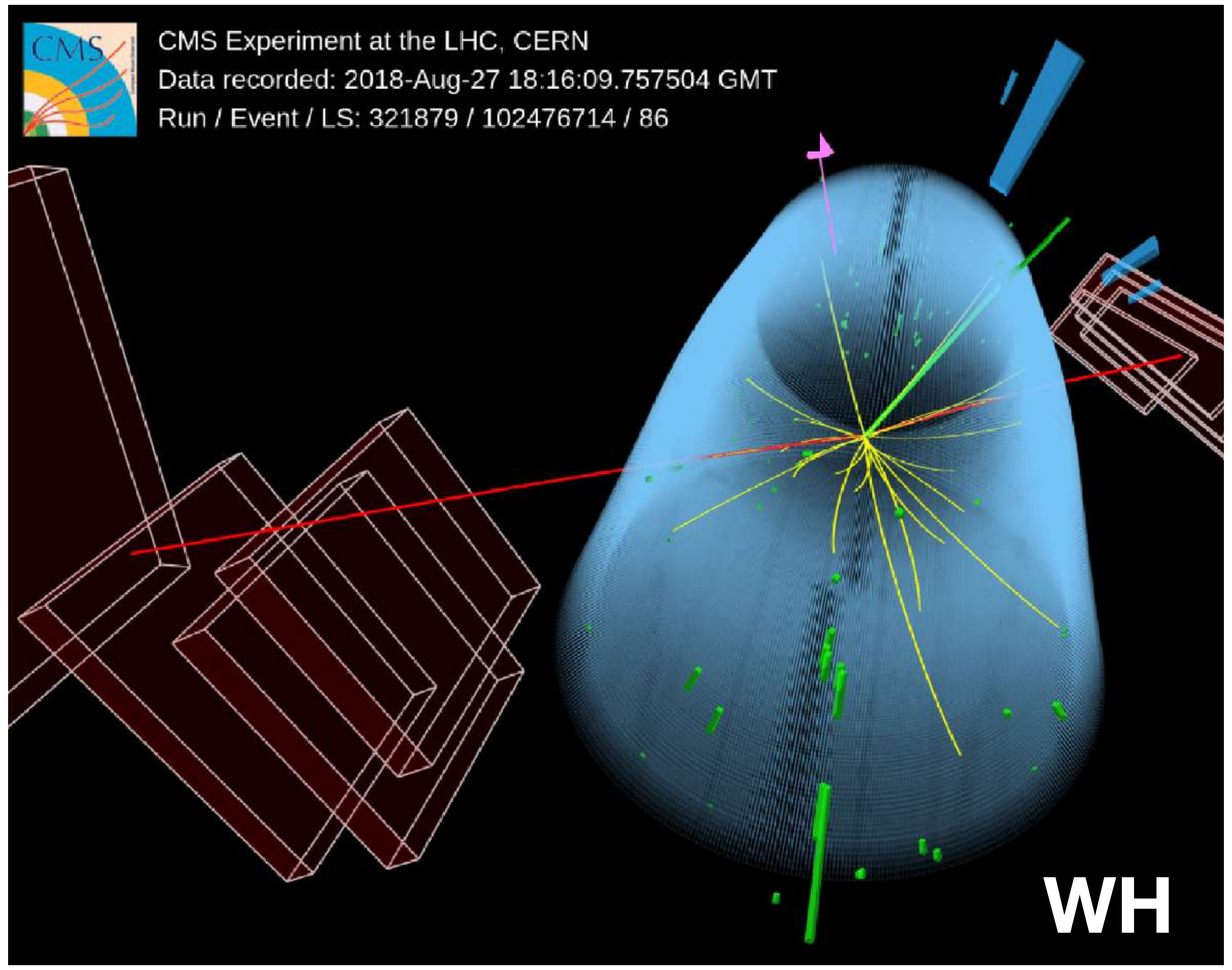


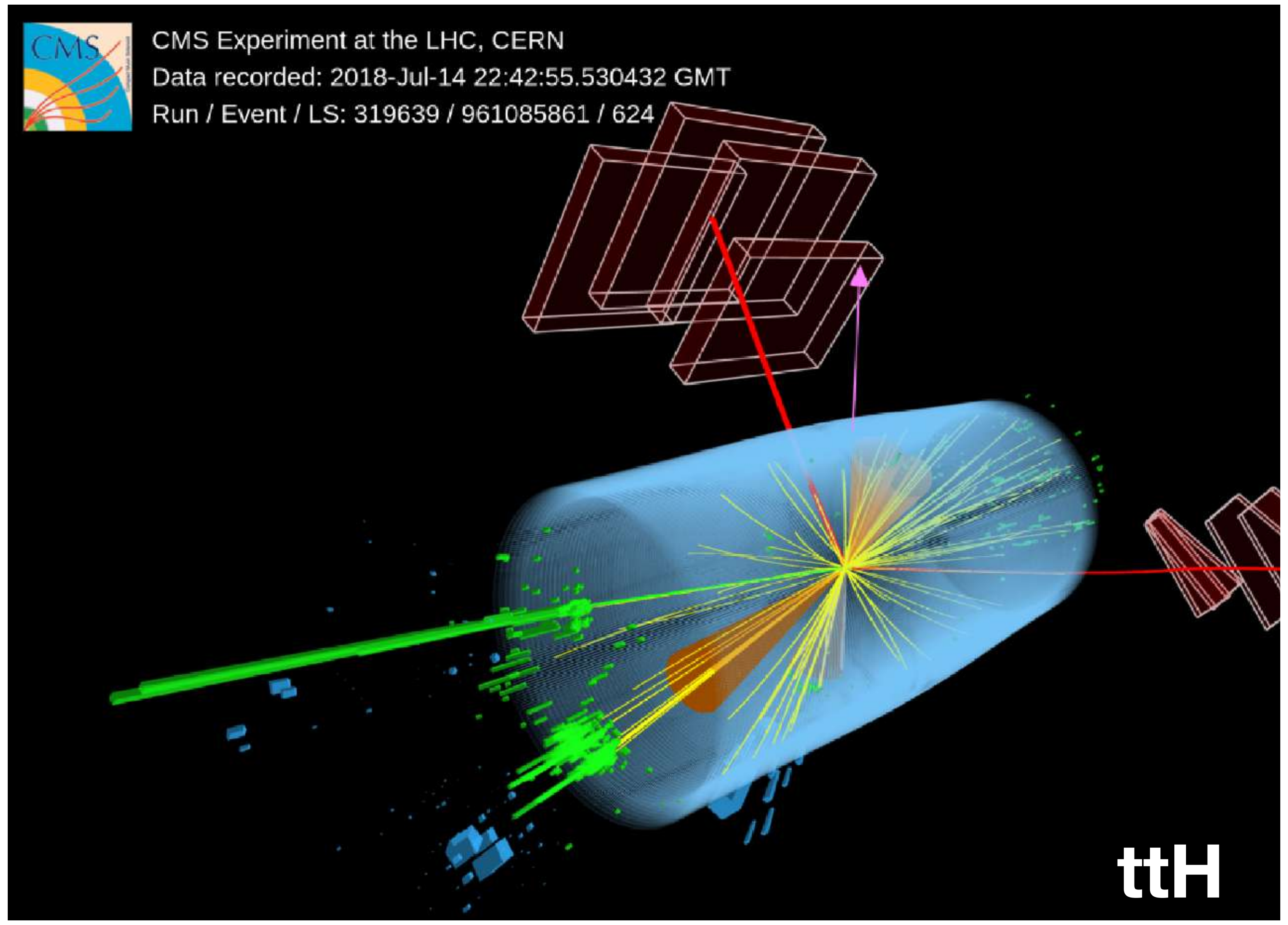
Yet can play an important role in the measurements of the inclusive production at high transverse momentum!

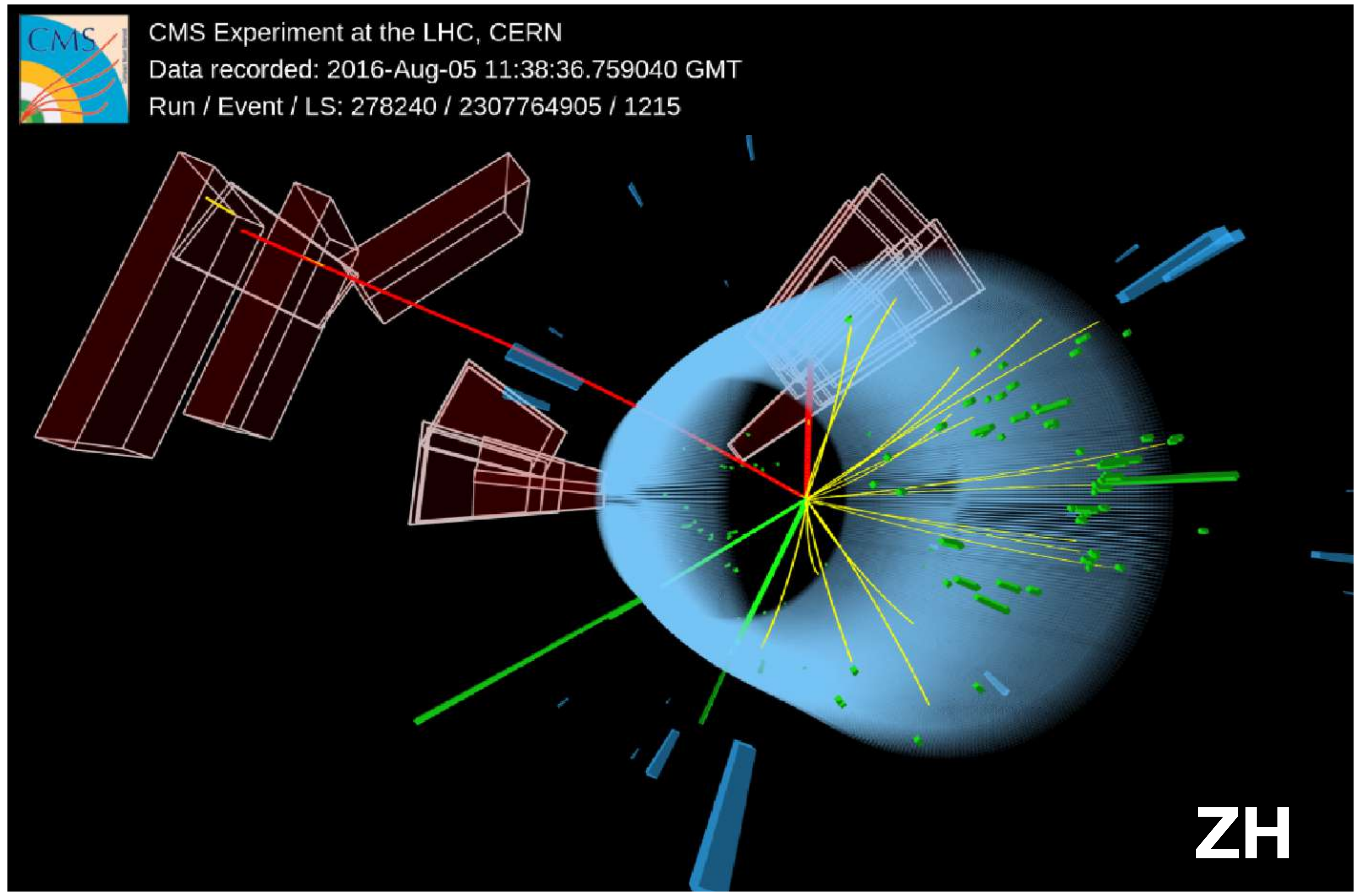
Extremely interesting to for indirect NP constraints!

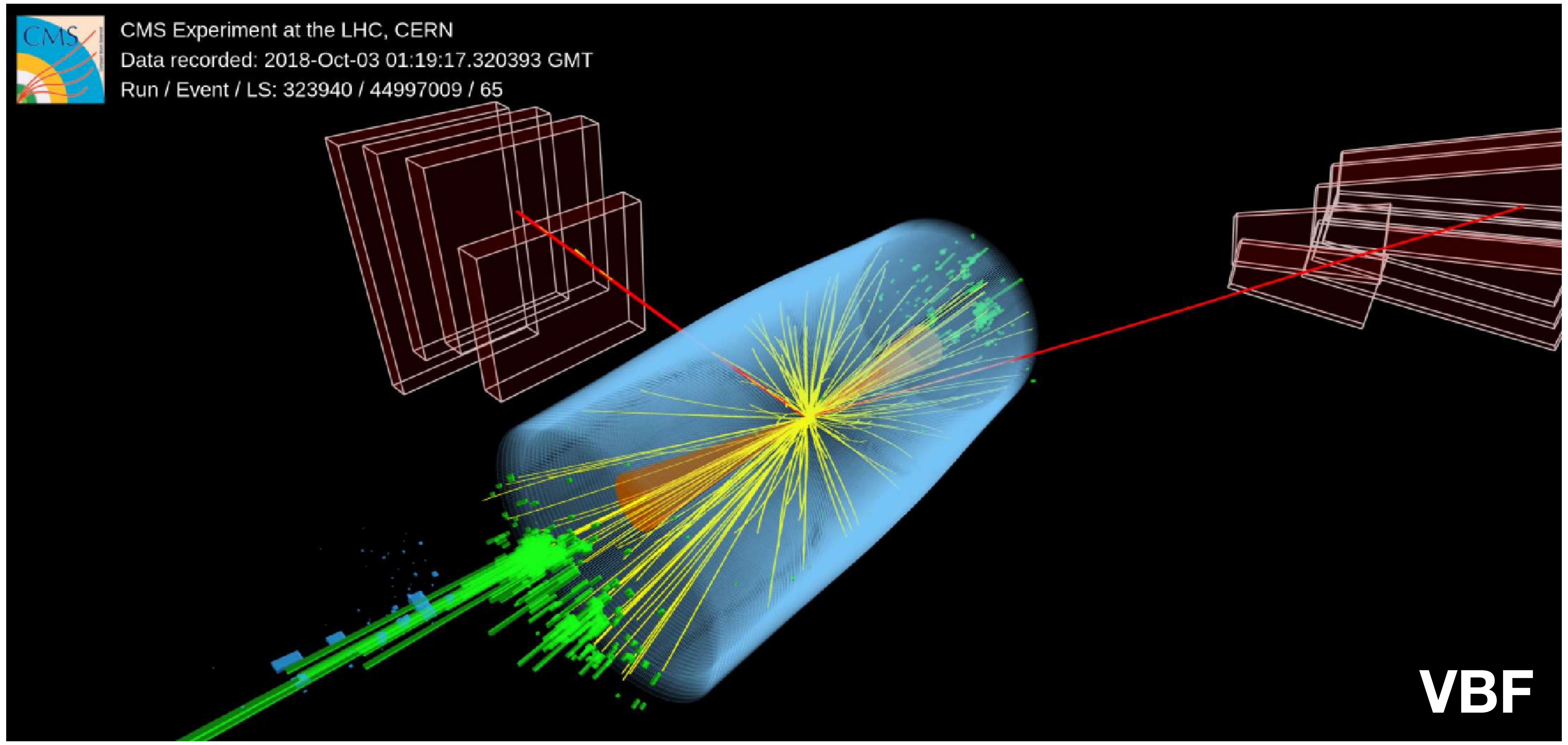
7.- Early evidences for Rare processes

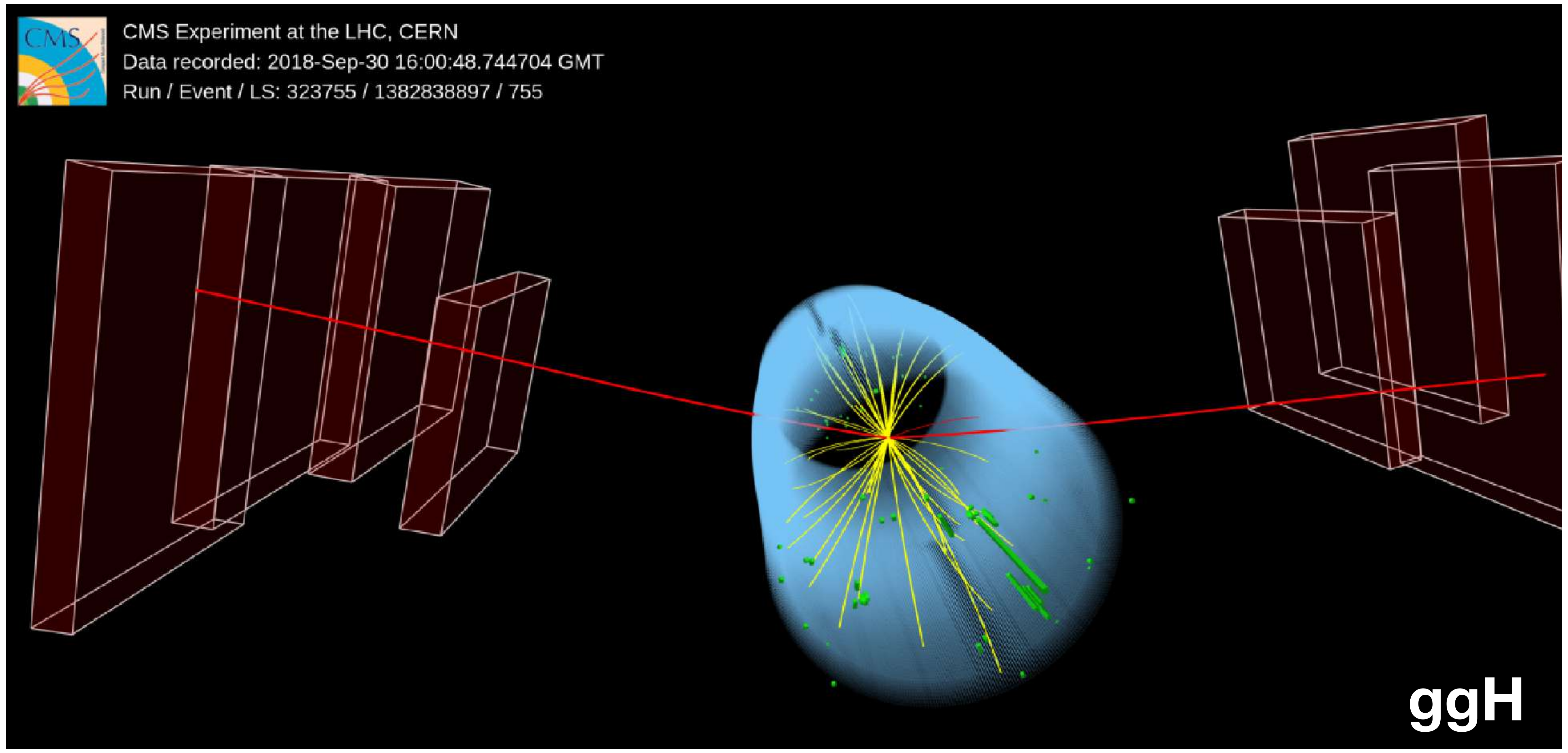
Evidence for $H \to \mu^+\mu^-$









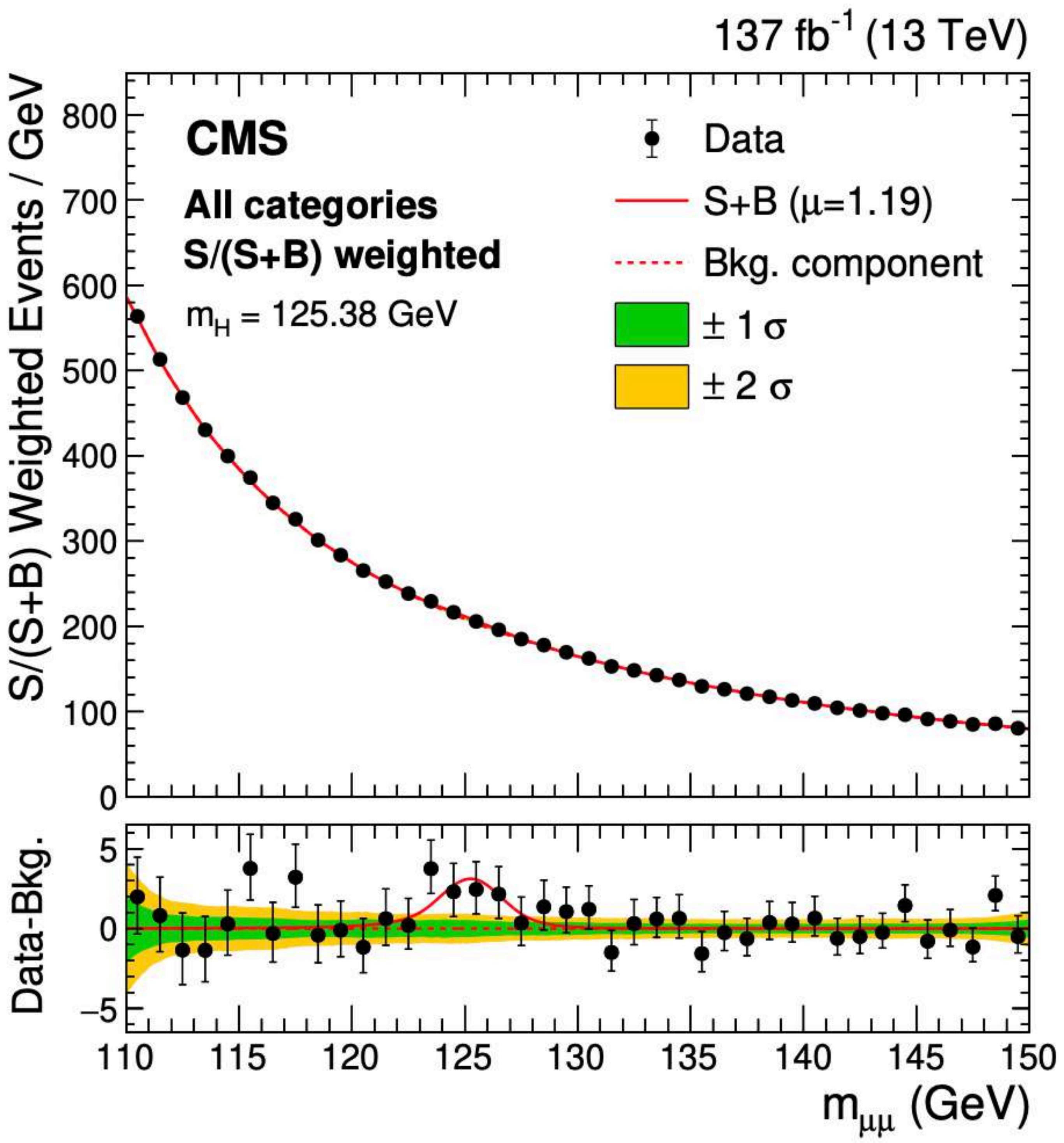


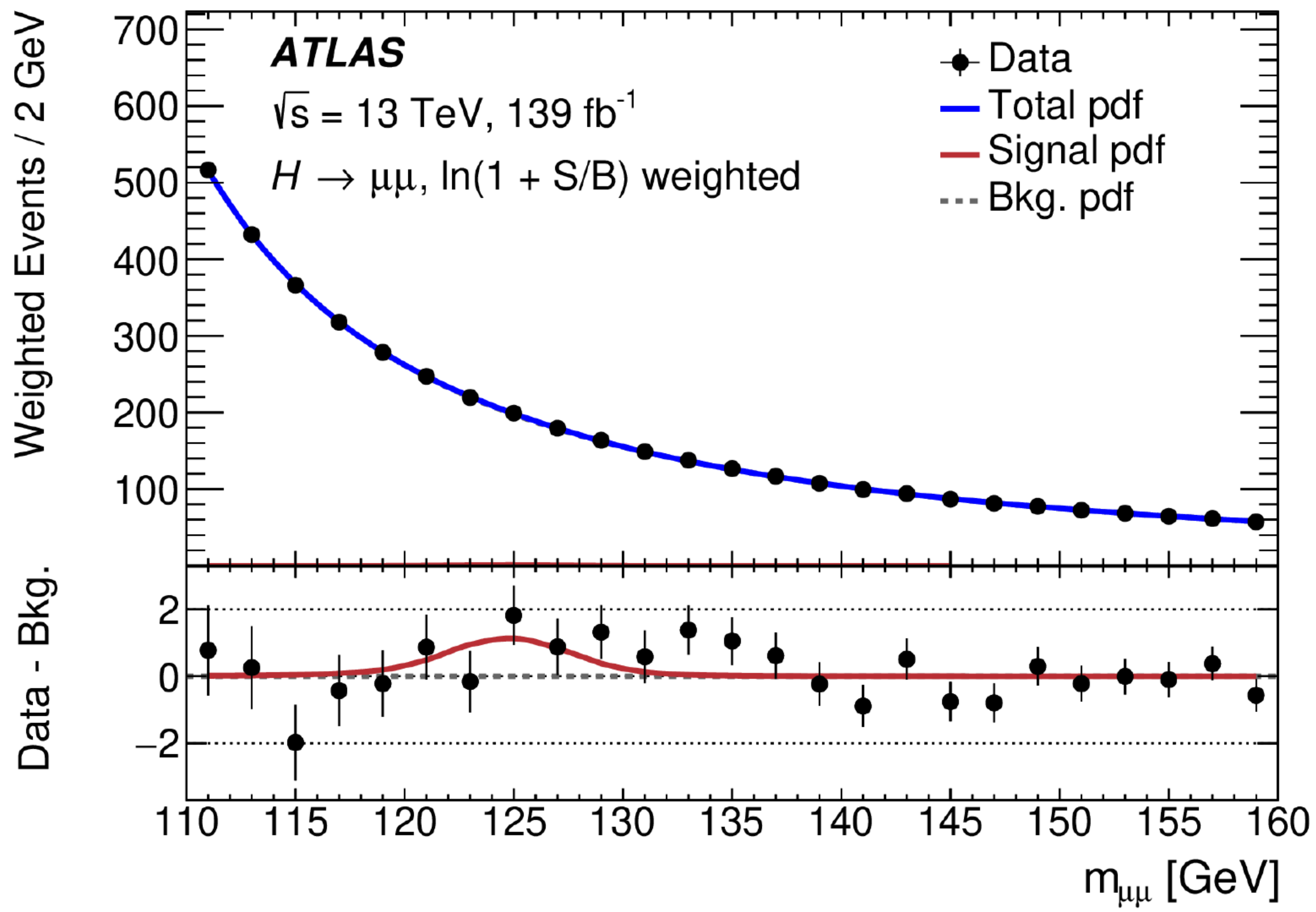
Evidence for Second Generation Yukawa Coupling

Very challenging channel!

- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity: ggF, VBF, VH, ttH; mass resolution through Brem recovery!

Summary of all categories Estimate the background parameters through a fit of an analytical form!





Evidence for Second Generation Yukawa Coupling

Very challenging channel!

- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity: ggF, VBF, VH, ttH; mass resolution through Brem recovery!

Summary of all categories Estimate the background parameters through a fit of an analytical form!

CMS Result

Expected 2.5σ

Observed 3.0σ

$$\mu = 1.19 \pm 0.43$$

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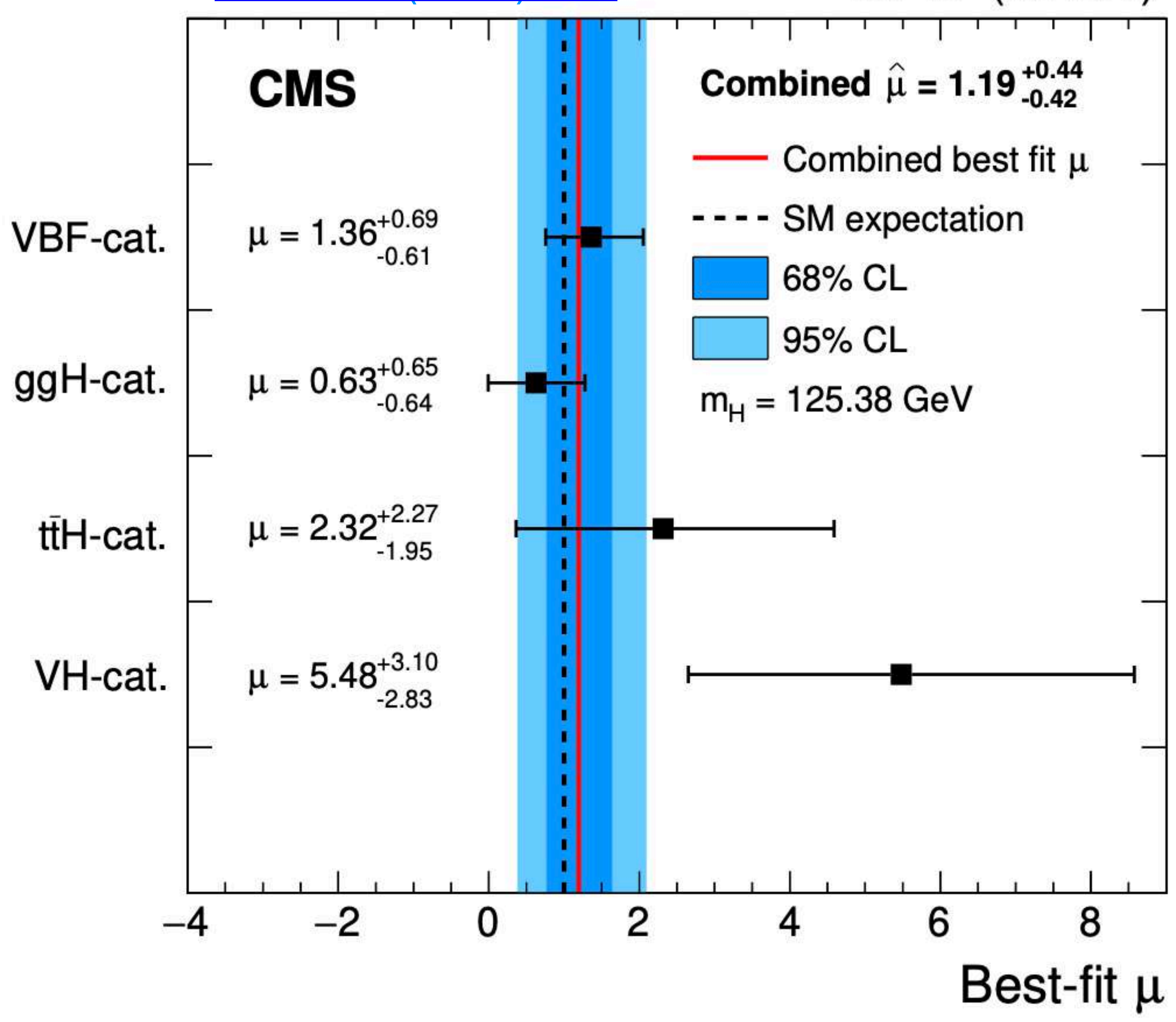
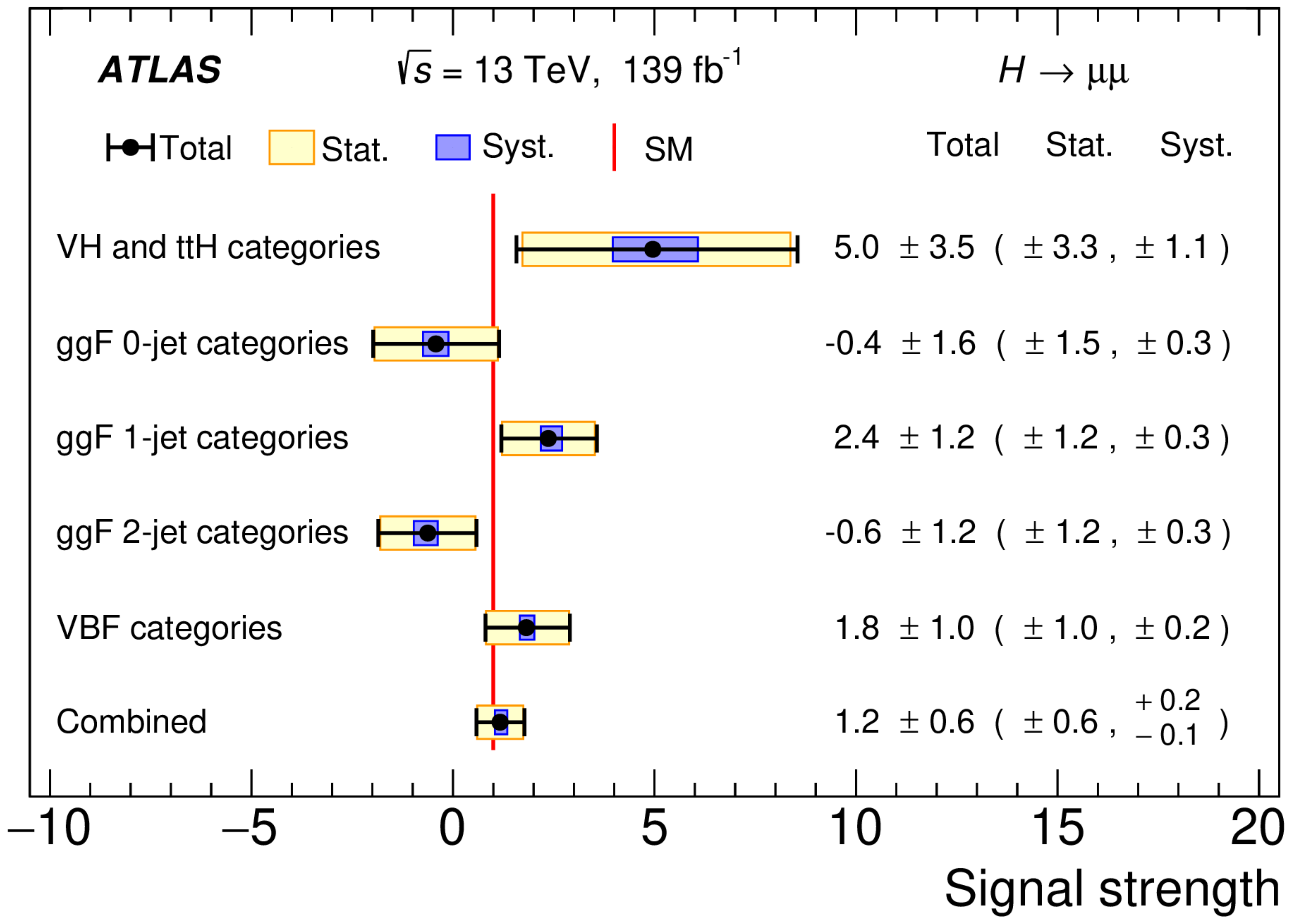


PLB 812



ATLAS Result

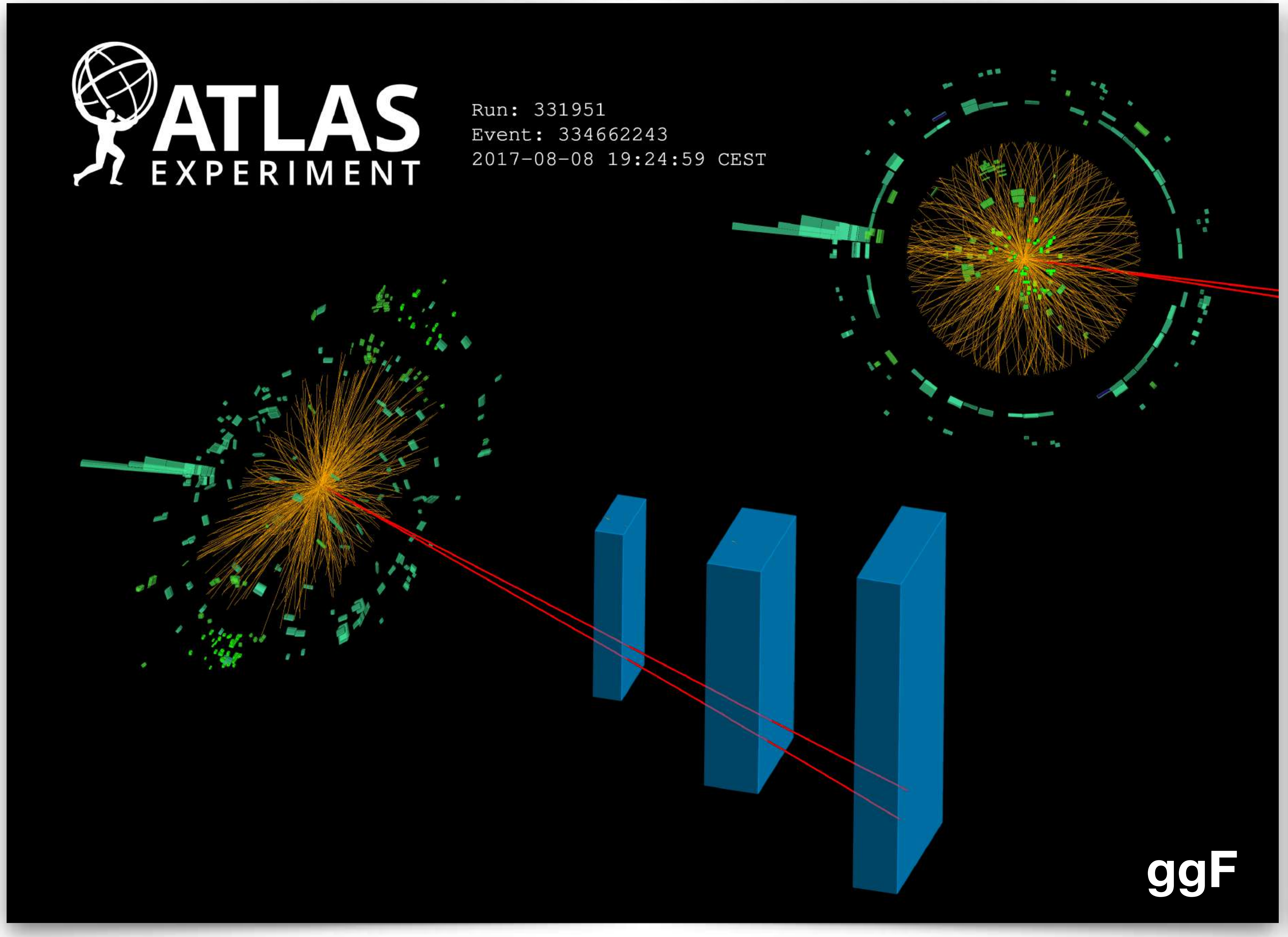
Expected 1.7σ

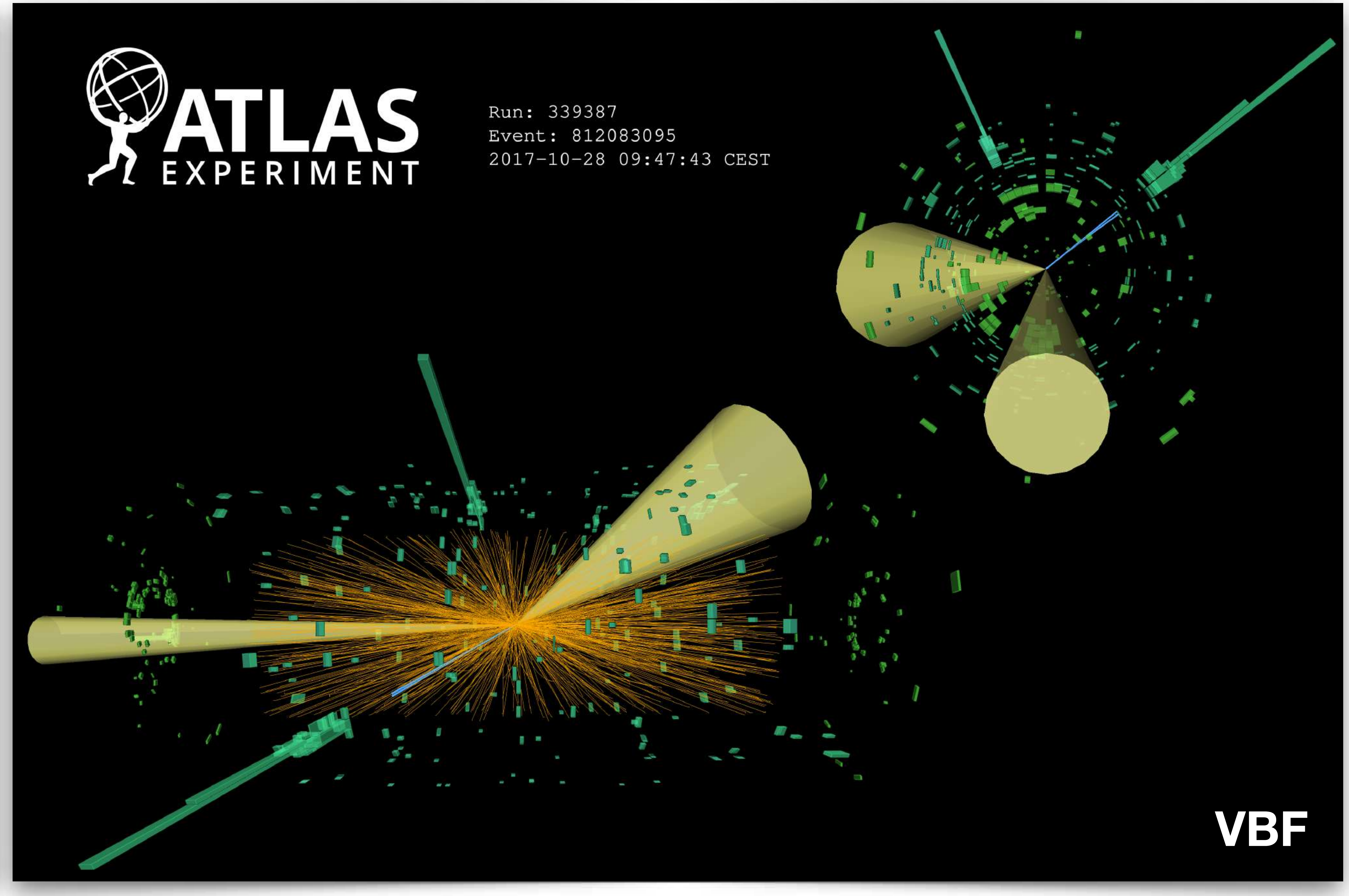
Observed 2.0σ

$$\mu = 1.2 \pm 0.6$$

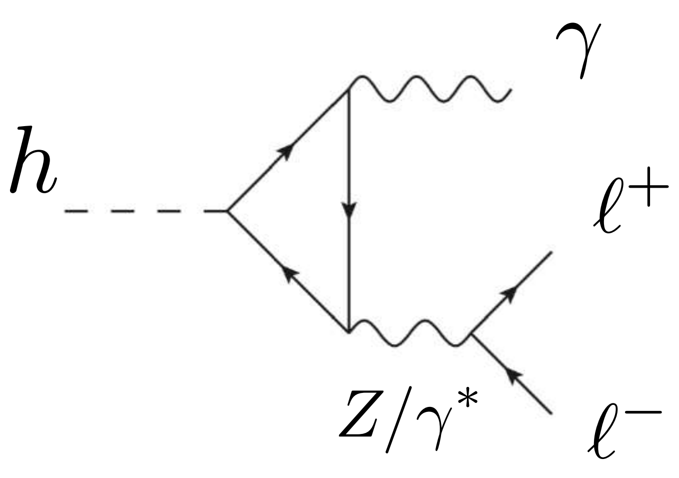
Result dominated by statistical uncertainty, but watch systematics!

Evidence for $H \rightarrow \gamma\ell^+\ell^-$





Evidence for $H \to \gamma\ell^+\ell^-$



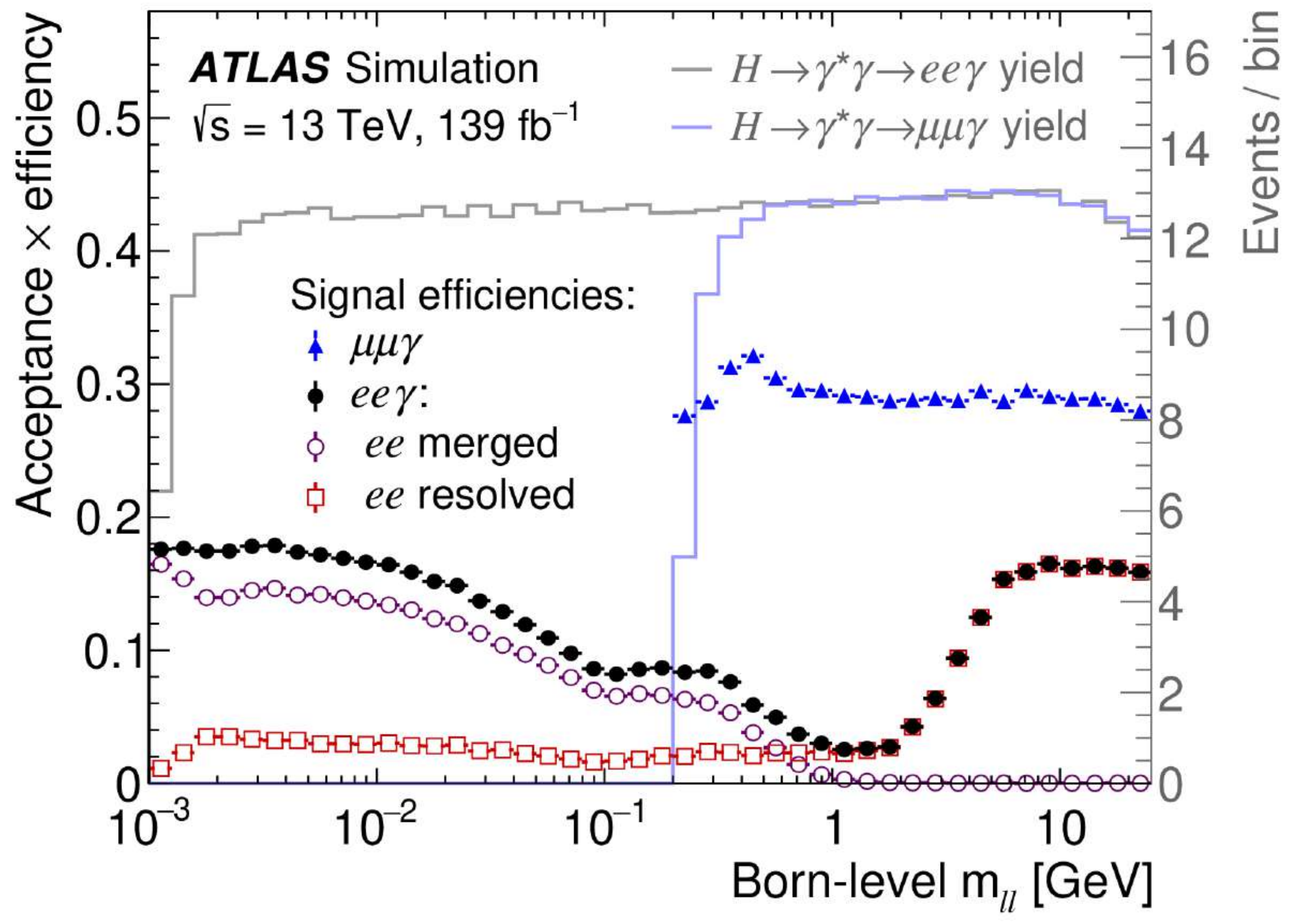
Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

~ 1.7% of $Br(\gamma\gamma)$

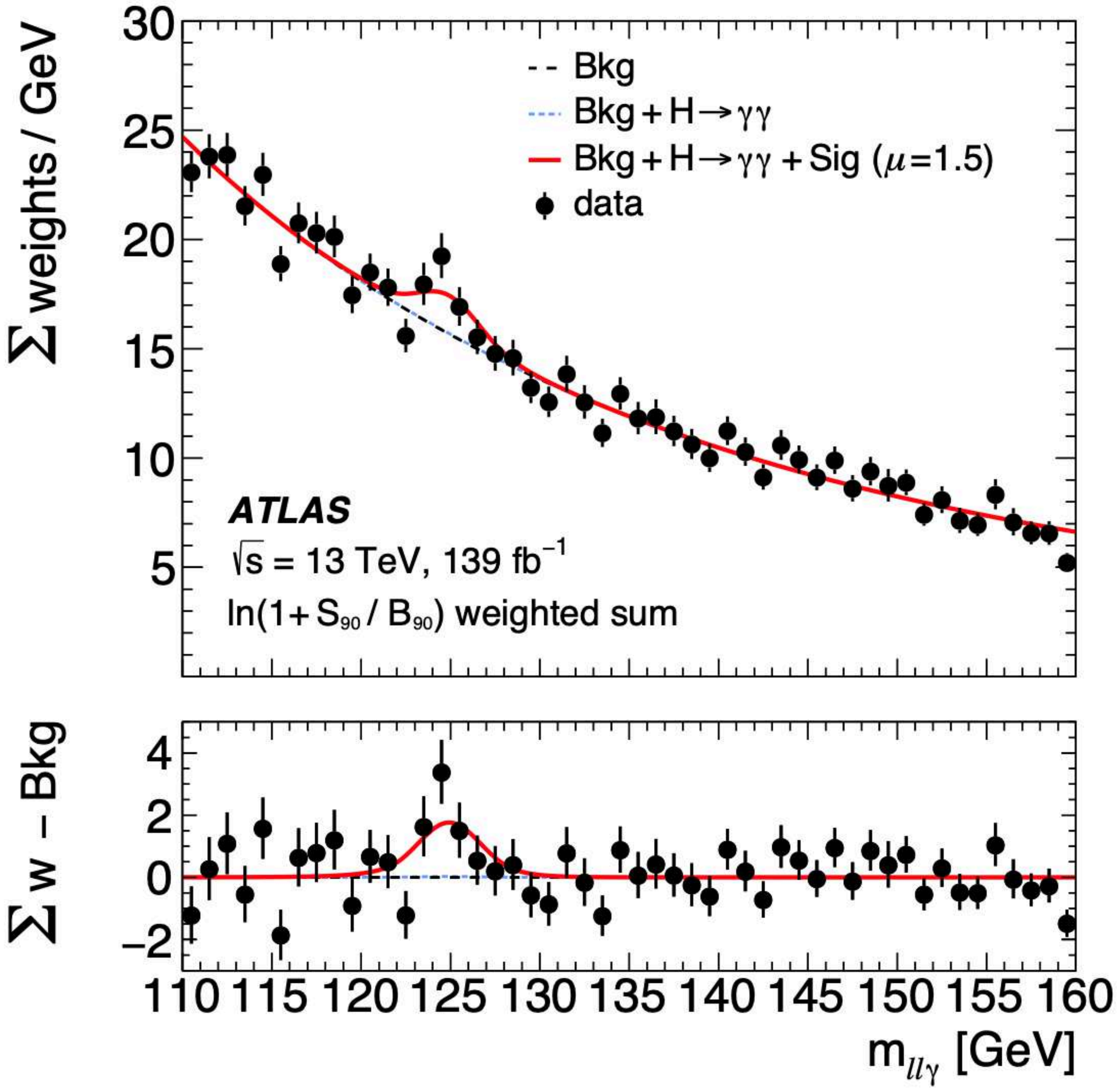
$$m_{\ell^+\ell^-} < 50 \text{ GeV}$$

Key experimental challenge is to go to low dilepton mass this required a **new reconstruction technique**:

Merged electron reconstruction where a calorimeter (electron-like) cluster is associated to two tracks and conversions are carefully rejected!



[Phys. Lett. B 819 (2021) 136412]



- 3 x 3 categories (VBF, high pT ggF, low pT ggF) ⊗ (ee resolved, ee merged, $\mu\mu$)
- Contributions from J/ψ are removed with a mass cut

$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5 \text{ (stat.) } ^{+0.2}_{-0.1} \text{ (syst.)}$$

$$\mu_{\text{exp}} = 1.0 \pm 0.5 = 1.0 \pm 0.5 \text{ (stat.) } ^{+0.2}_{-0.1} \text{ (syst.)}$$

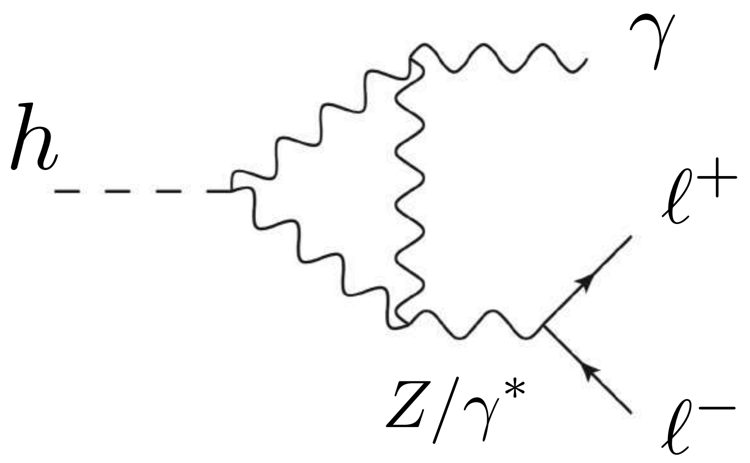
Expected 2.1σ

Observed 3.2σ

Searches for the $H \to Z\gamma$ Decay Mode

Z-photon $|H^2|W^a_{\mu\nu}W^{\mu\nu a}$

Field tensor coupling not measured yet!



~ 2.3% of $Br(\gamma\gamma)$

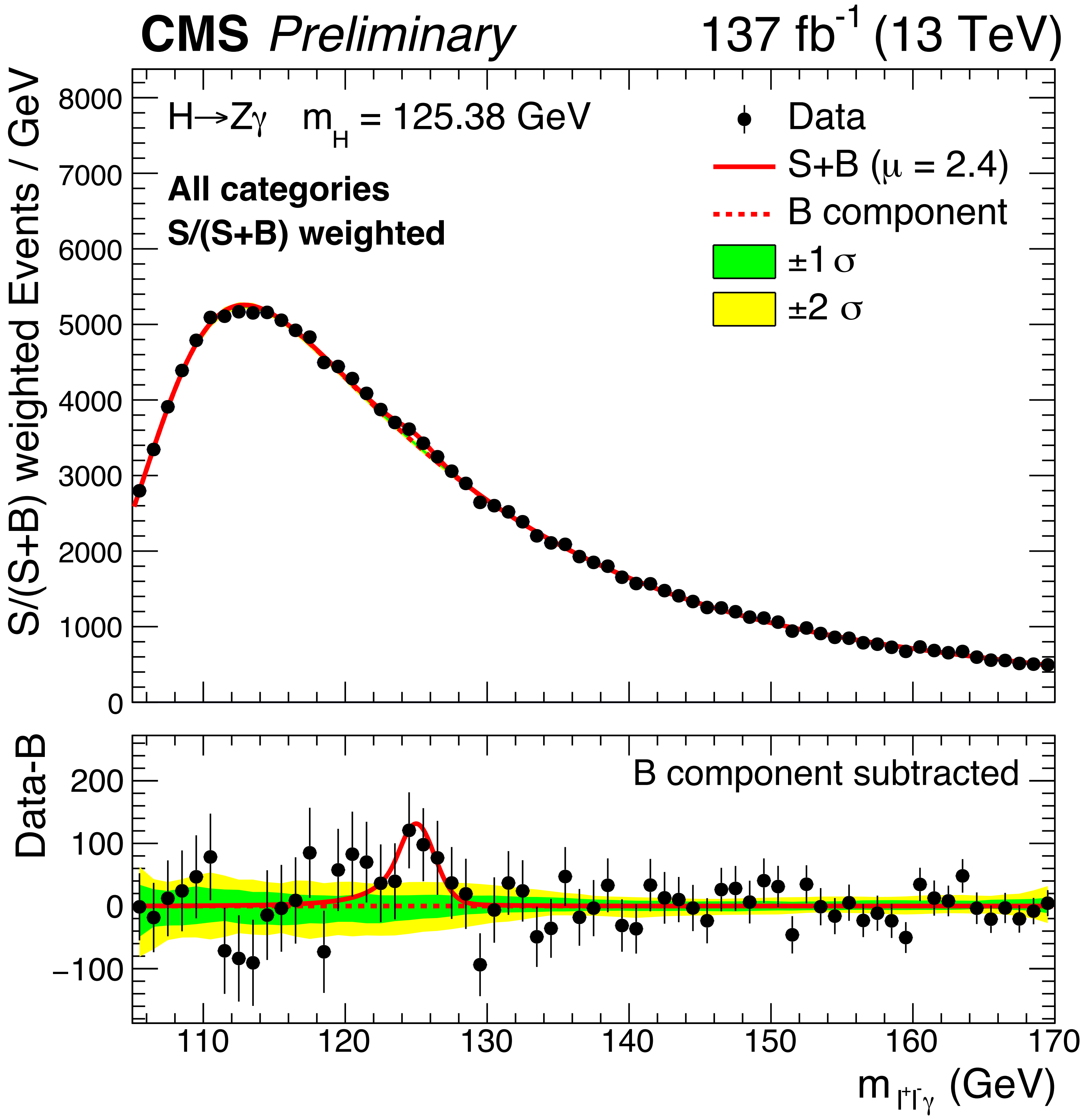
CMS Result

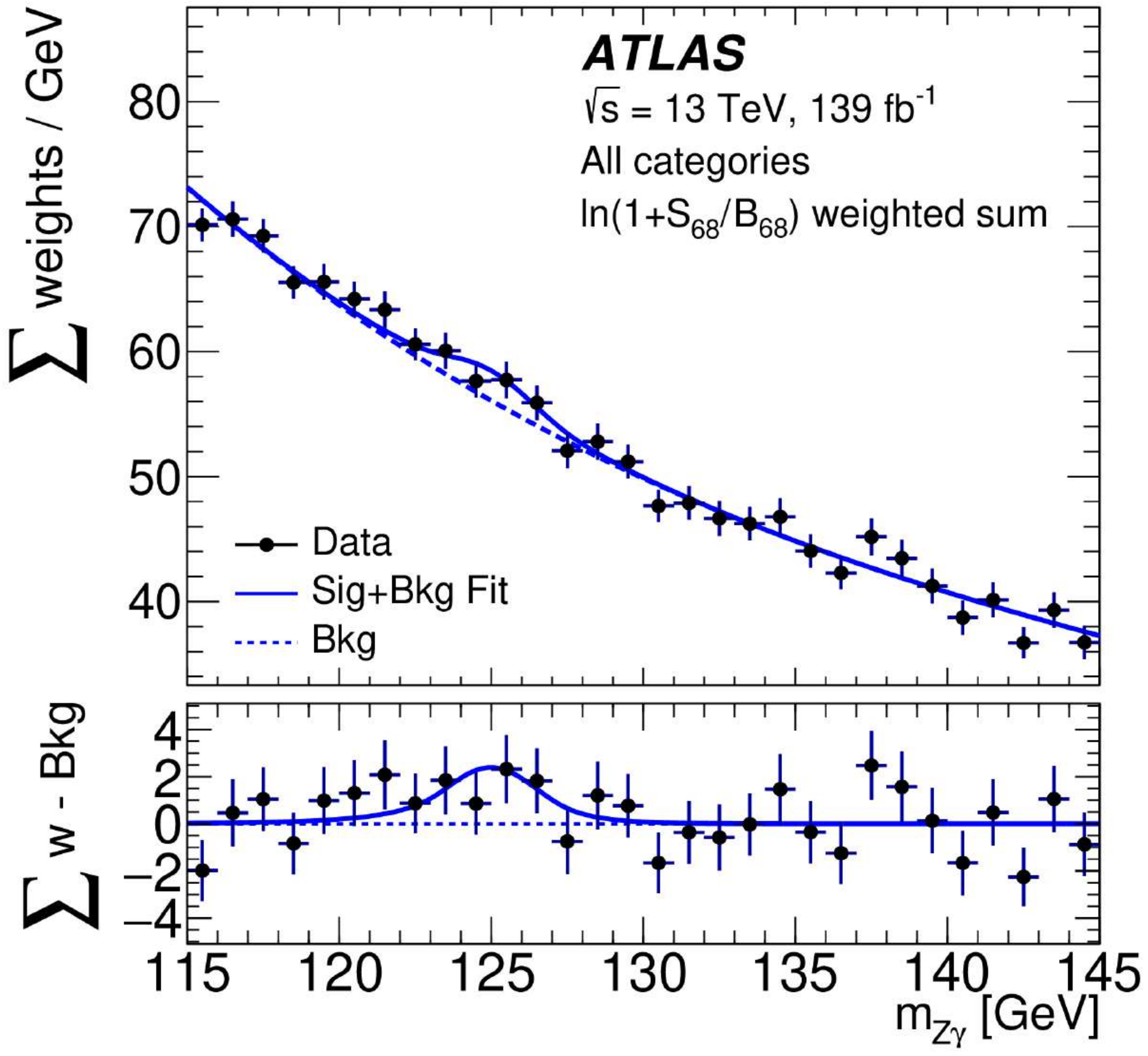
ggF, VBF, VH and ttH enriched channels

$\mu_{Z\gamma} = 2.4 \pm 0.9$

Expected 1.2σ

Observed 2.7σ





ATLAS Result

ggF and VBF enriched channels

$\mu_{Z\gamma} = 2.0 \pm 0.9$

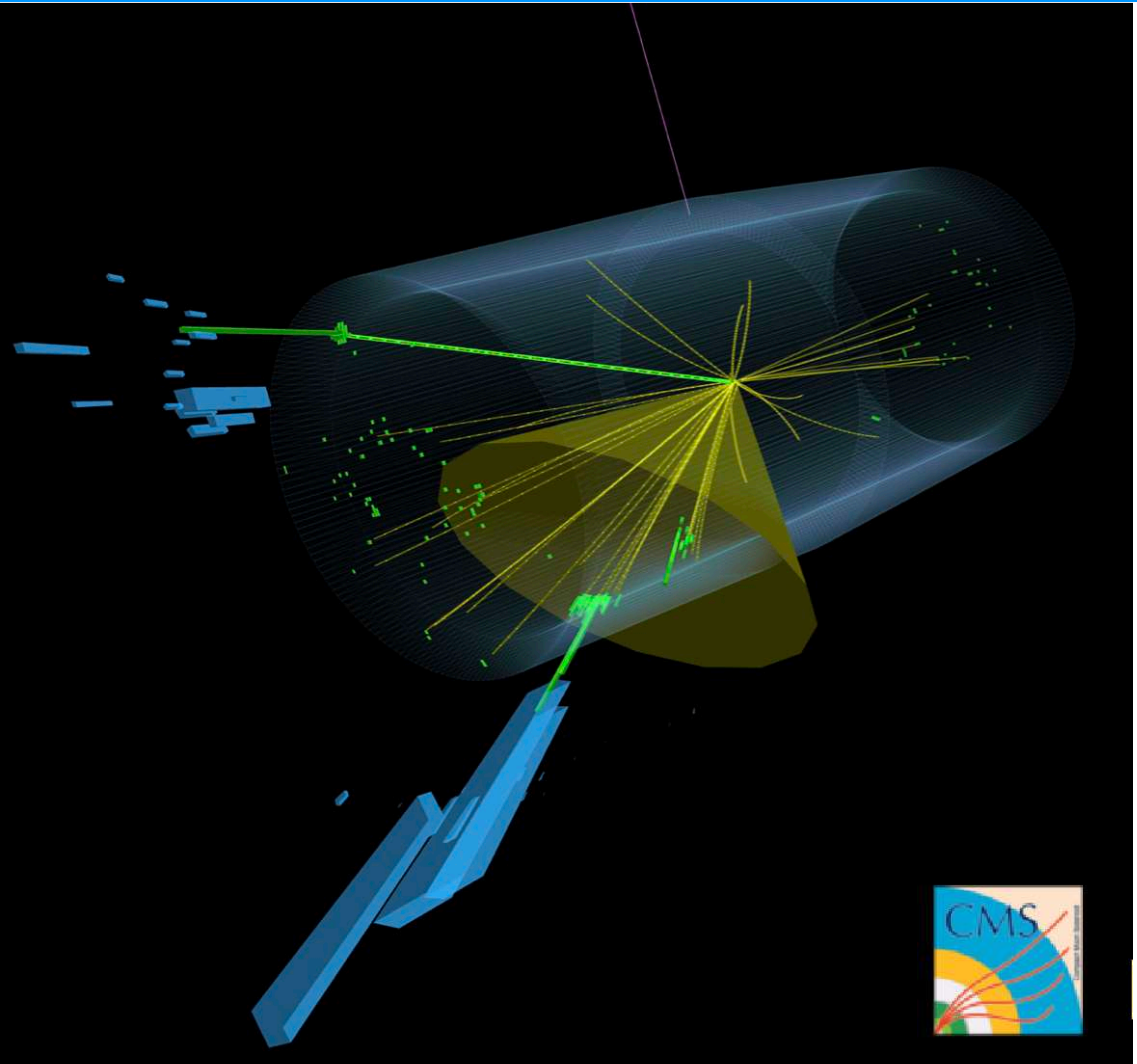
Expected 1.2σ

Observed 2.2σ

To follow closely at Run 3 for first evidence!

8.- Making the Impossible Possible

The Yukawa coupling to charm



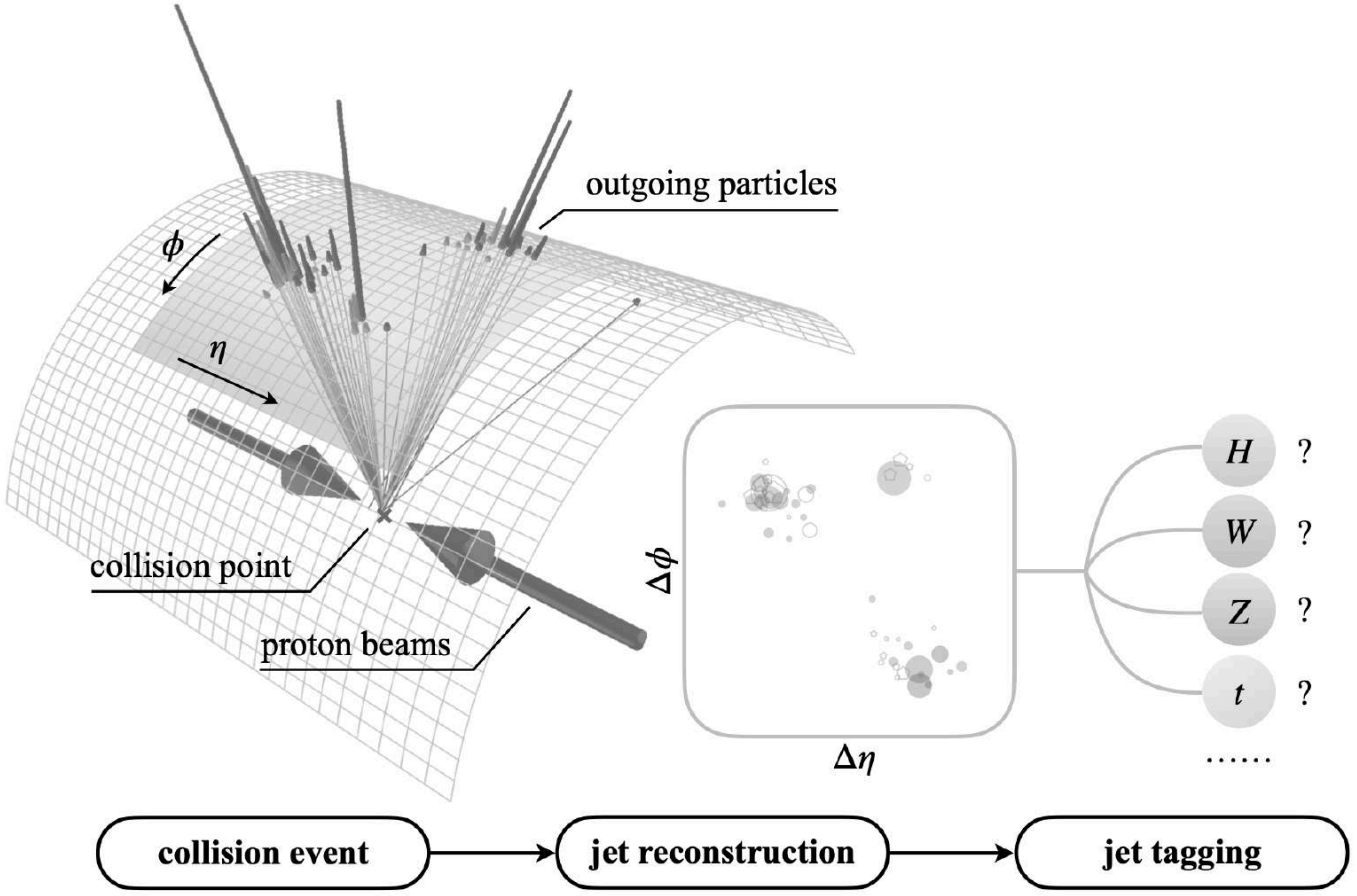


Illustration from [Particle Transformer]

Use of state-of-the-art ML techniques

Use "particle clouds" (with more info than only 3D coordinates - 2D eta-phi, pT, charge, particle

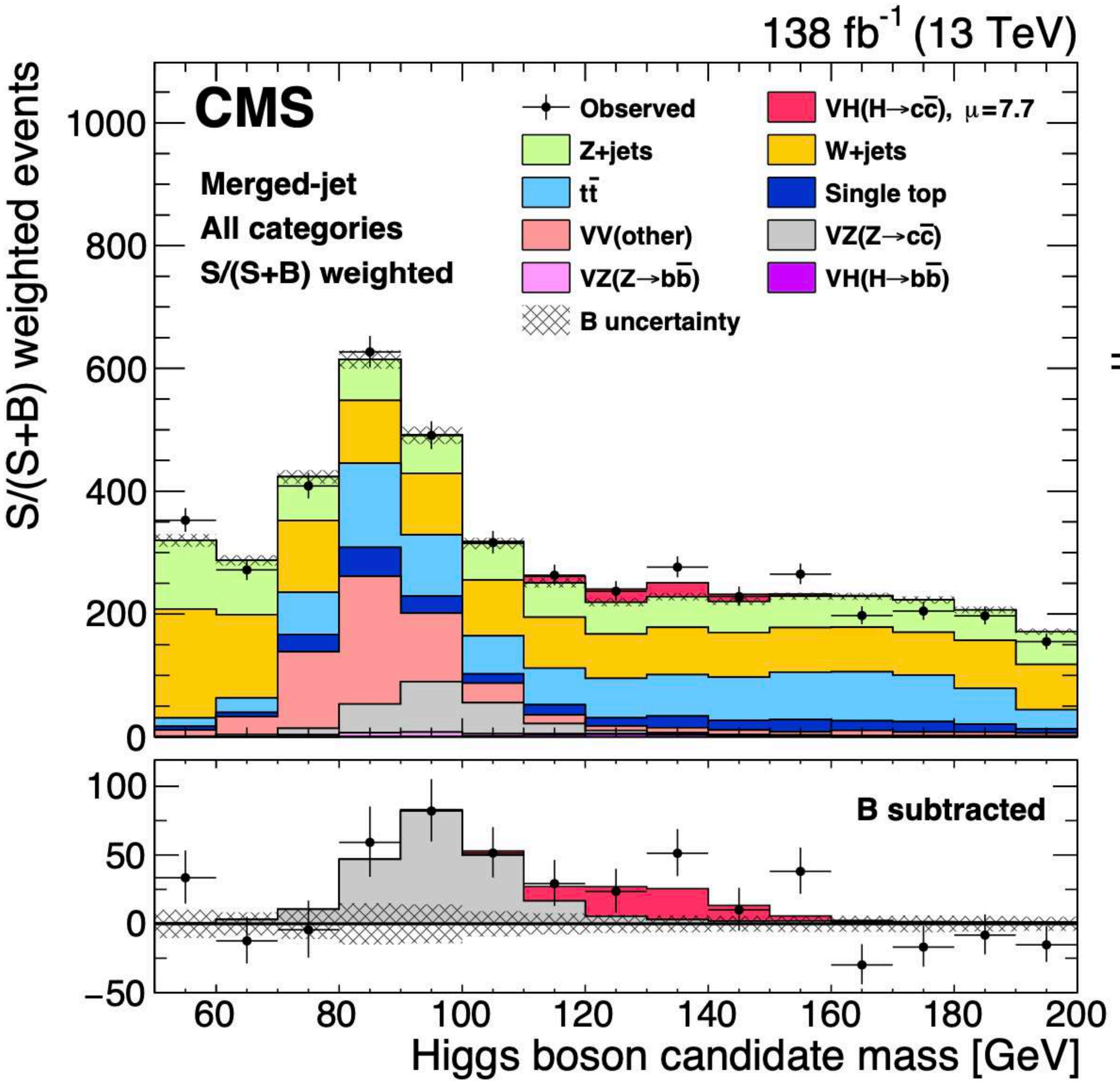
[Particle Net] uses Dynamic Graph CNN

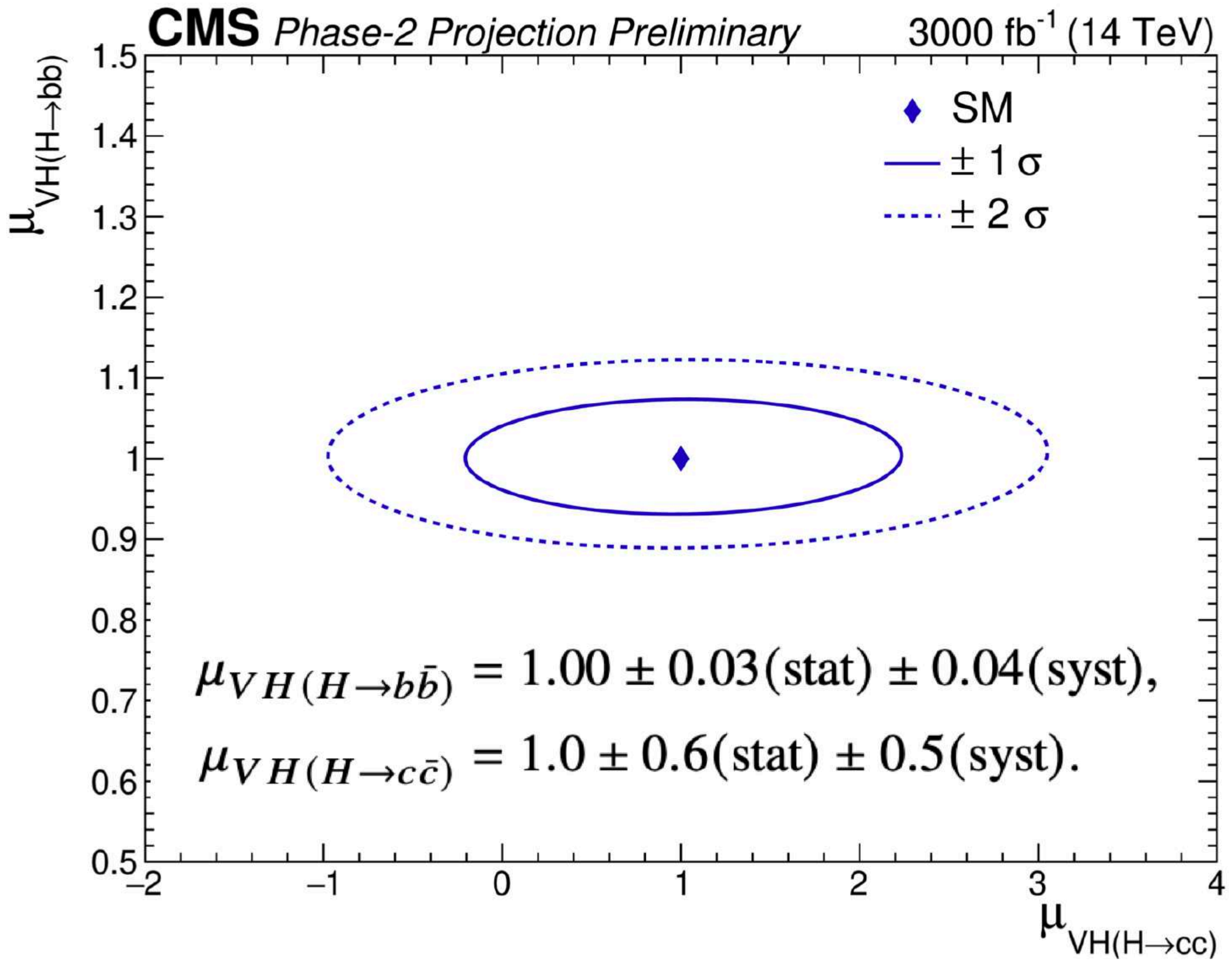
The challenging Yukawa coupling to charm

Signal strength:
μ < 14.4

Impact of boosted
Resolved: 19.0 (exp)
Boosted: 8.8 (exp)
Combined: 7.6 (exp)

Constraints on charm Yukawa
$1.1 < \kappa_c < 5.5$

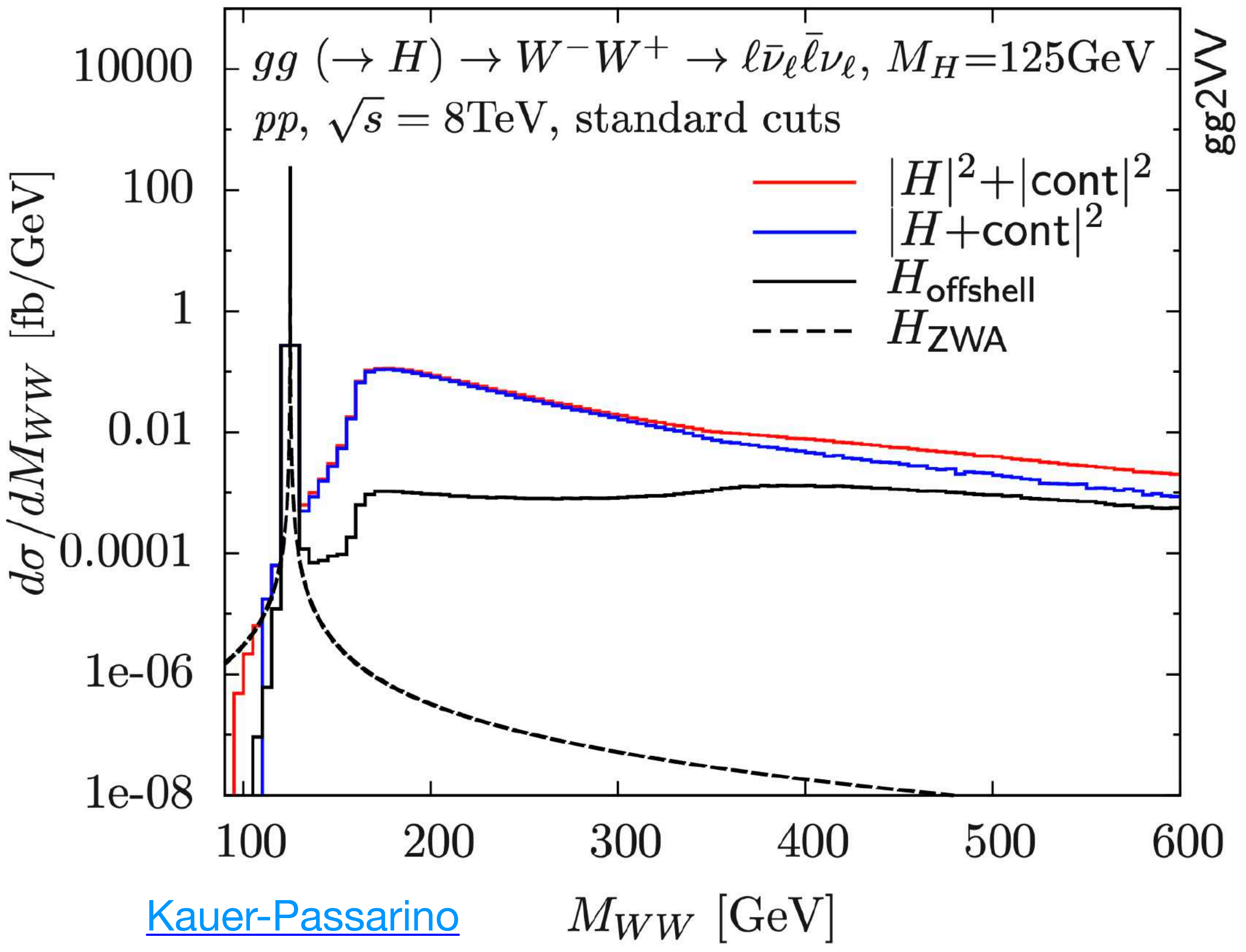




This result is very encouraging on the possibility of being sensitivity to this process at the LHC

Off Shell HVV Couplings and Width

Off Shell couplings



Kauer-Passarino

Higgs Boson width

Assumption of Standard Model and comparison to on shell allows for a measurement of the width of the Higgs boson!

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2\kappa_V^2)_{on\ shell} = (\kappa_t^2\kappa_V^2)_{off\ shell}$$

Current measurement (CMS) PRD 99 (2019):

$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

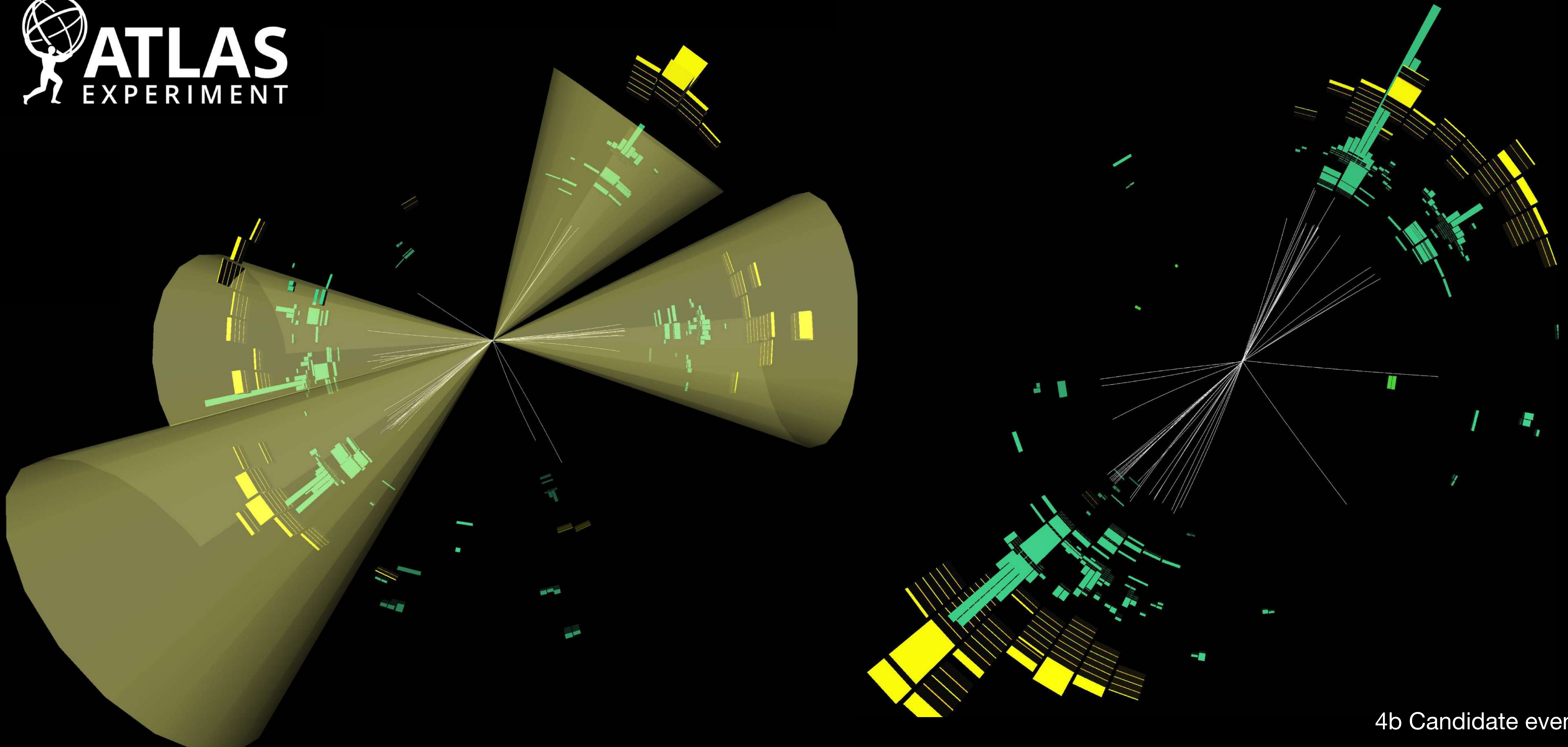
Evidence for Off-Shell production at 3.6σ

at HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}$ Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab^{-1}

Remarkable result to follow closely at Run 3!
How much better can be done at HL-LHC?

Hot off the press! Non resonant $HH \rightarrow b\bar{b}b\bar{b}$

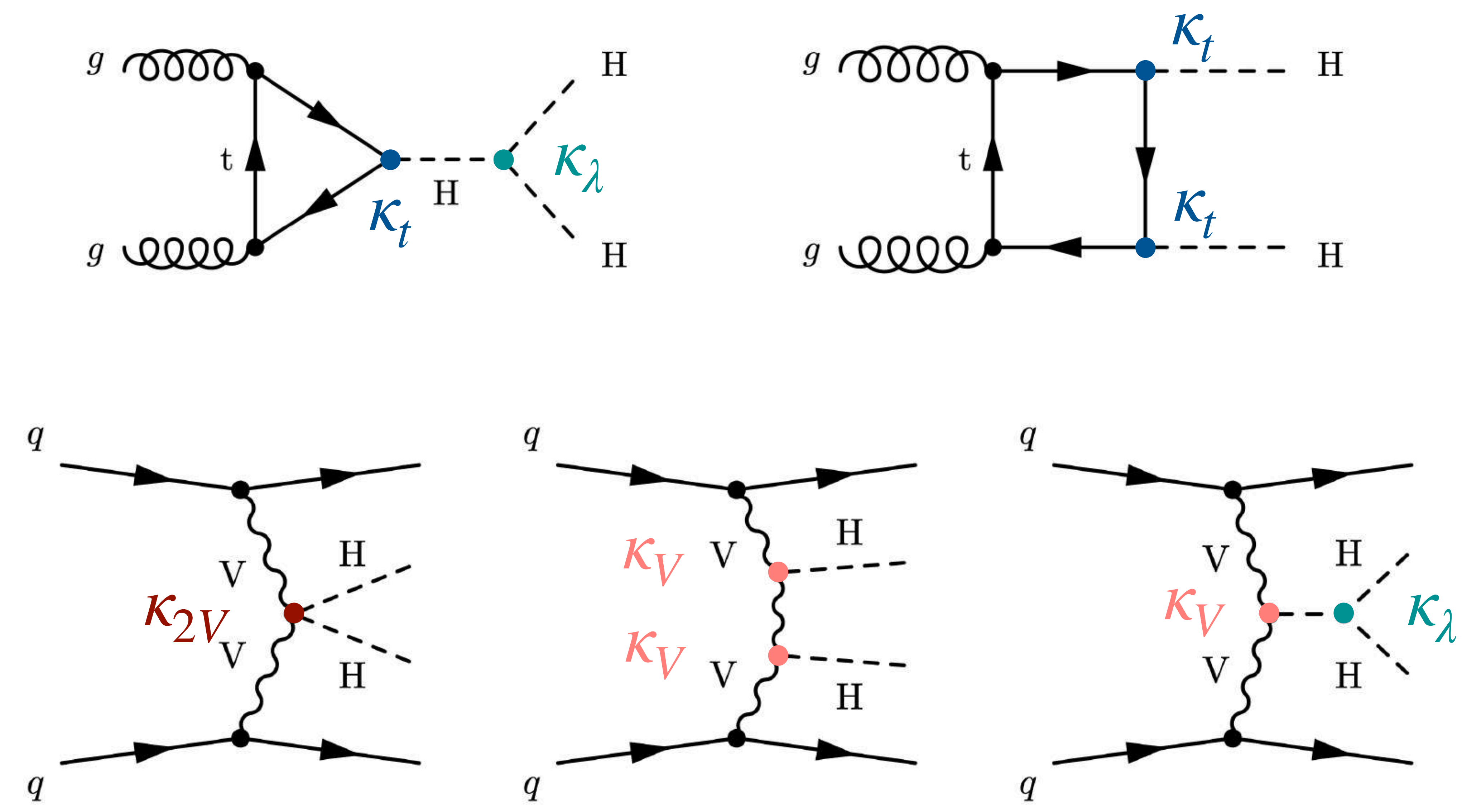
ATLAS EXPERIMENT



4b Candidate event

HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (and VBF)



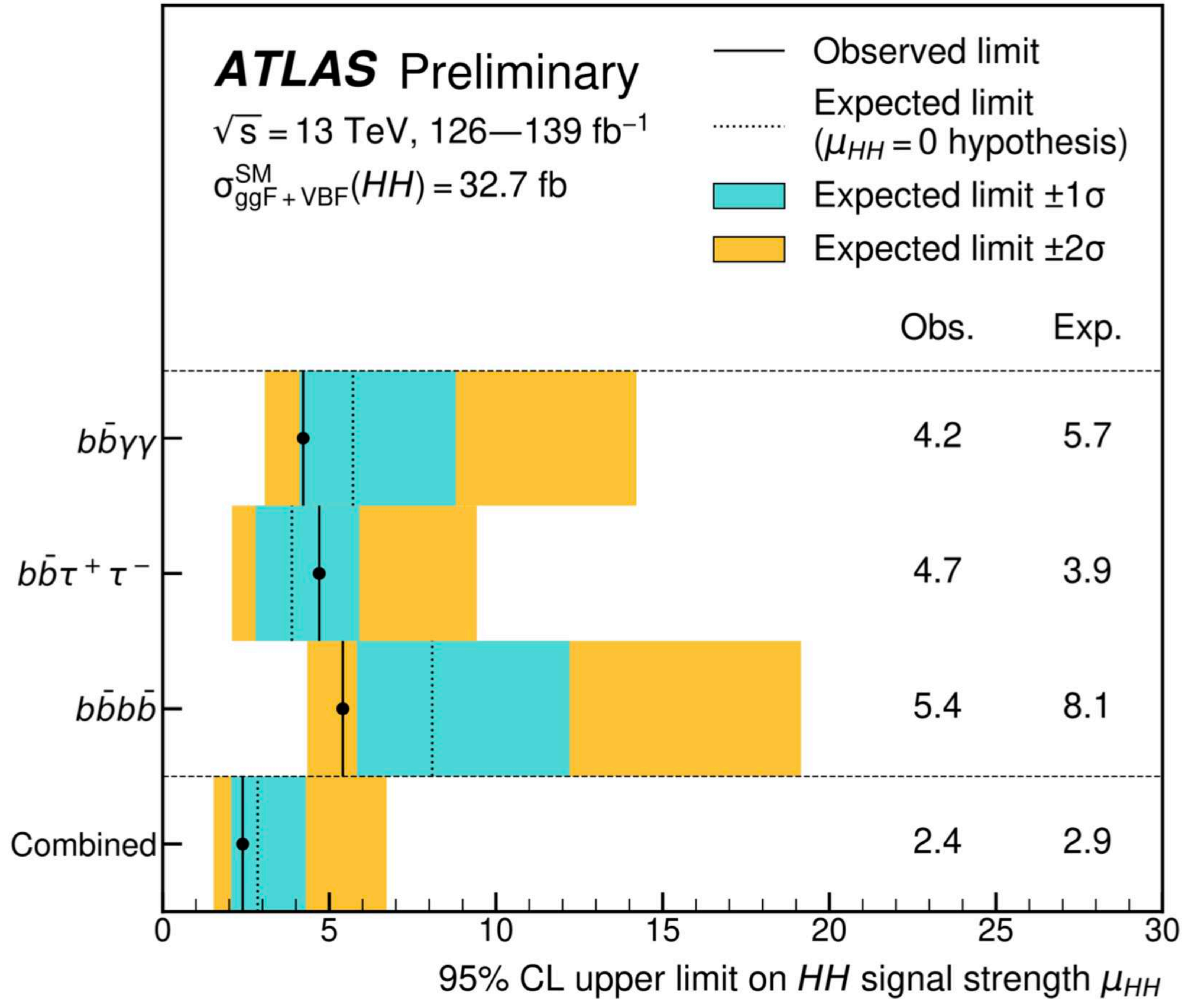
With the VBF production mode not only limits on κ_λ also on κ_{2V}

Bishara, Contino, Rojo

Very similar analysis as the Off-shell Higgs couplings!

Incredibly small cross section ~1000 times smaller than Higgs production! but still more than 100k event will be produced at HL-LHC!

Multiple channels investigated: depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!



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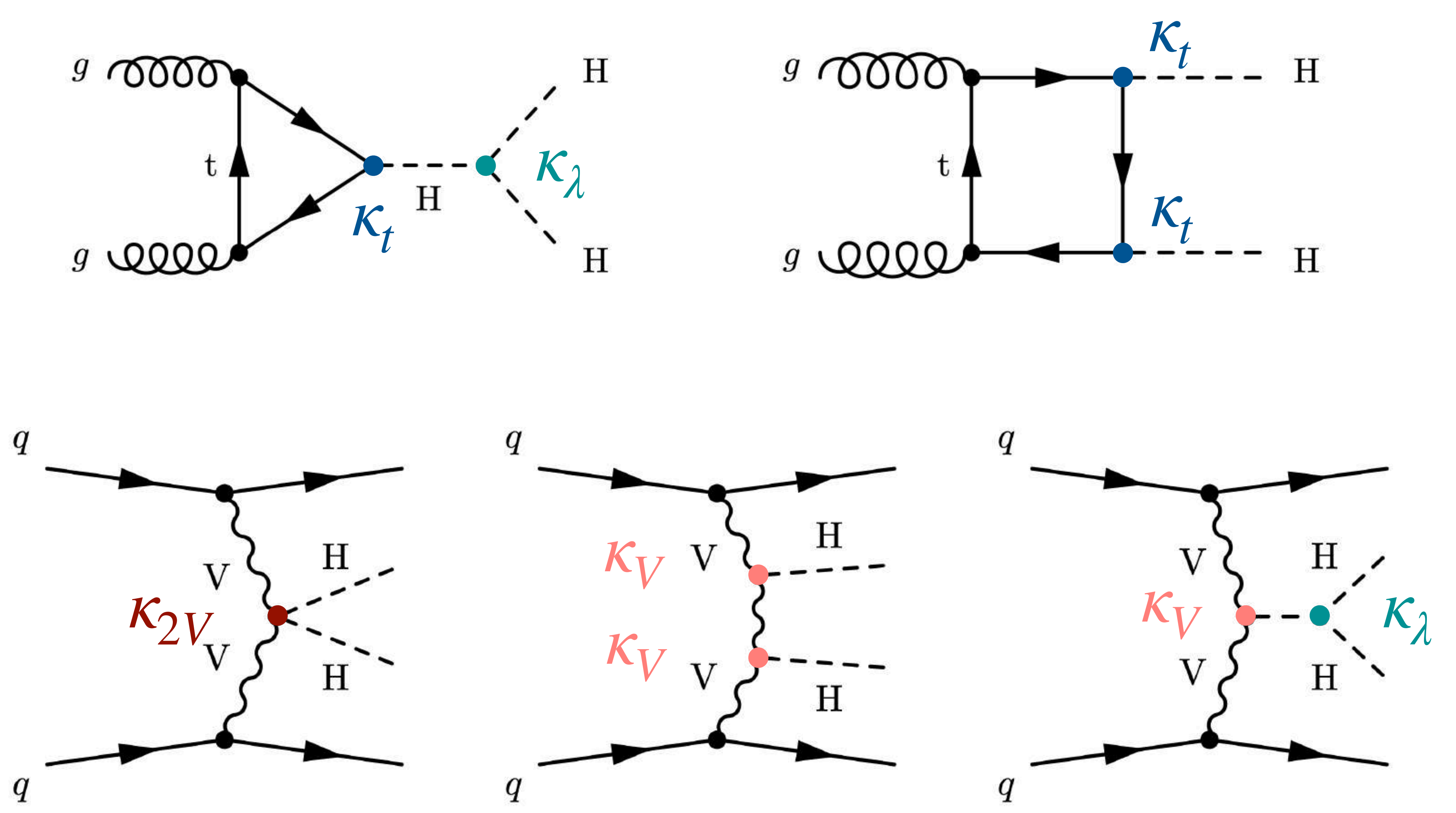

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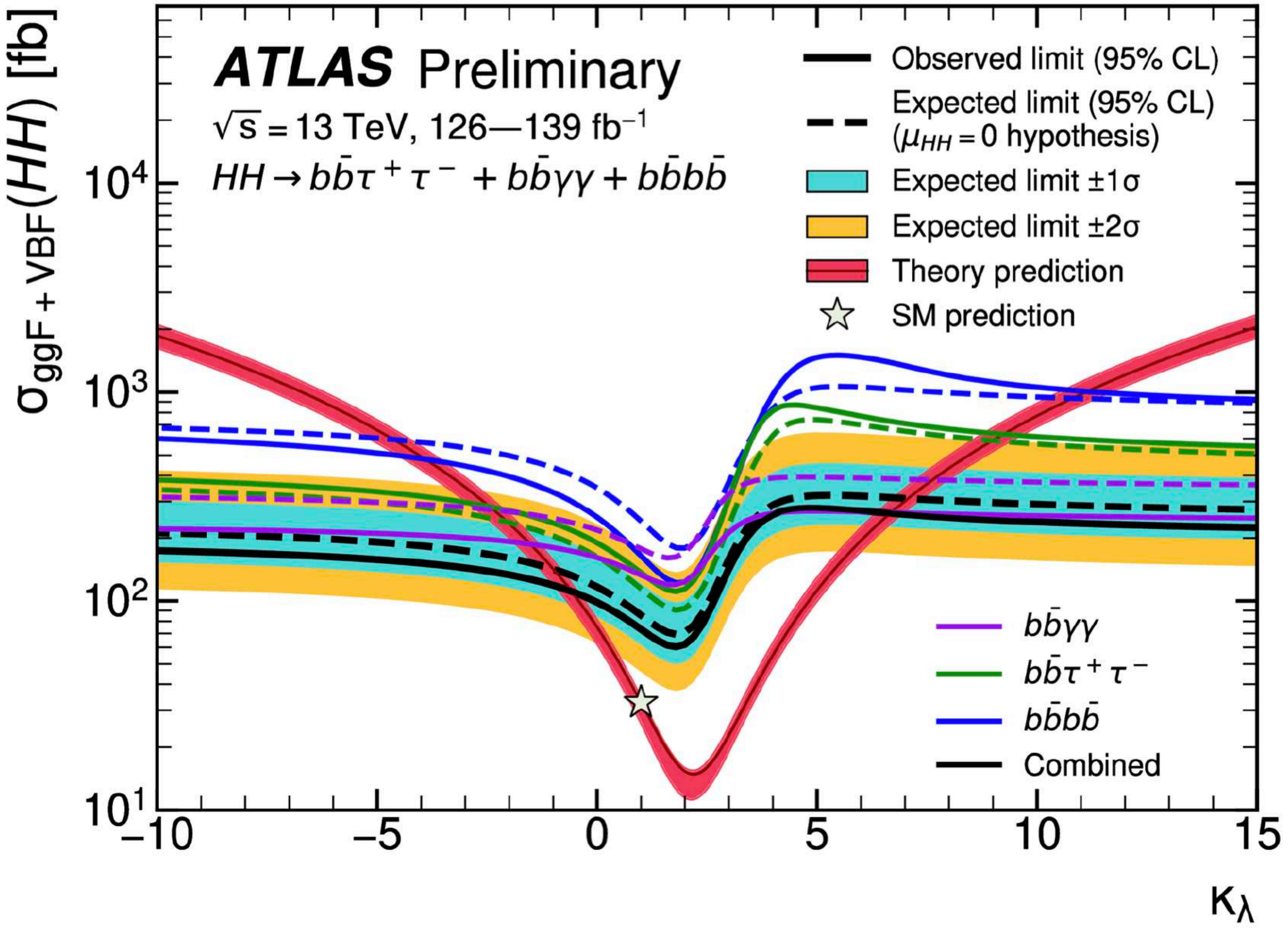


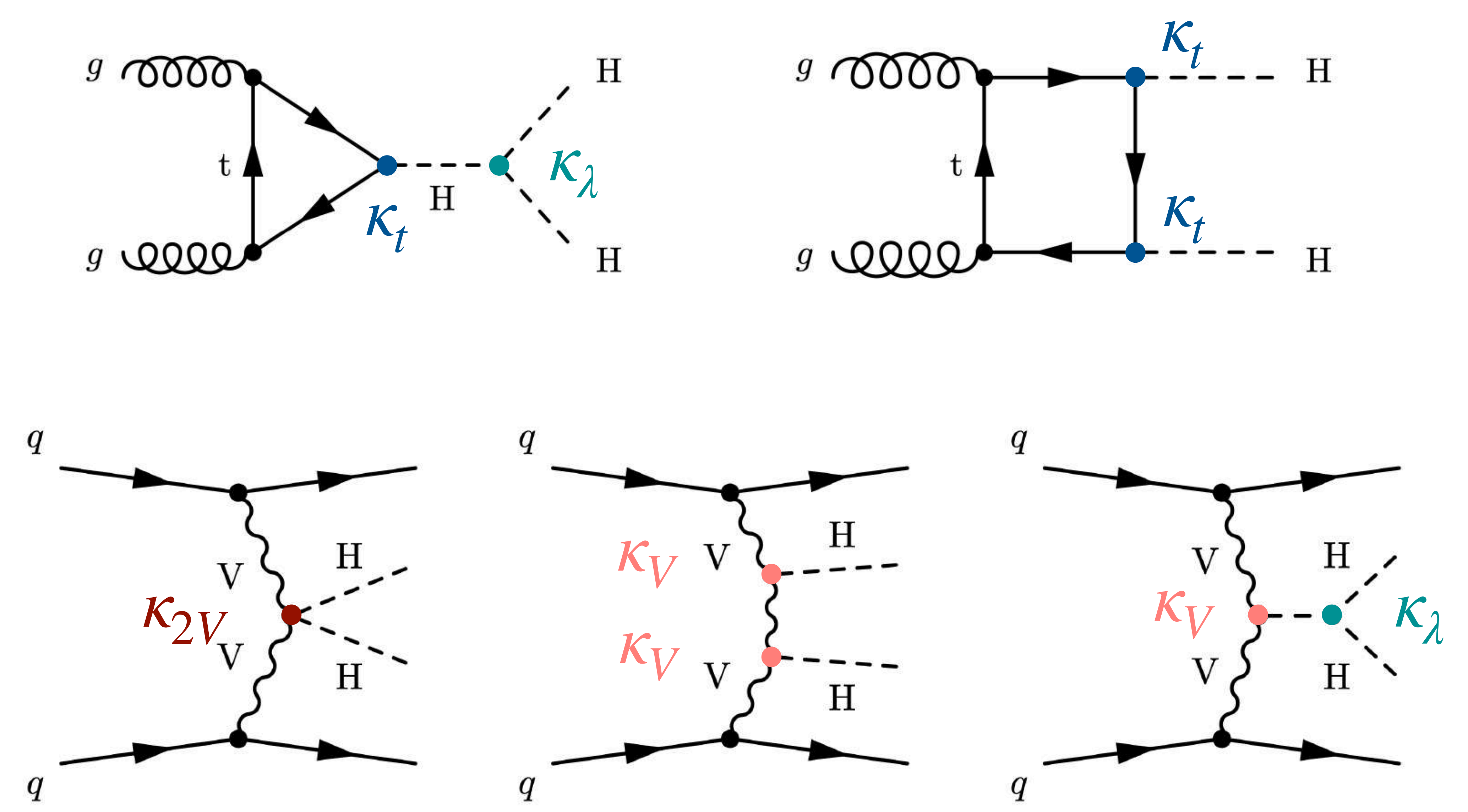
ATLAS

Observed $-0.4 < \kappa_\lambda < 6.3$

Expected $-1.9 < \kappa_\lambda < 7.5$

HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (and VBF)



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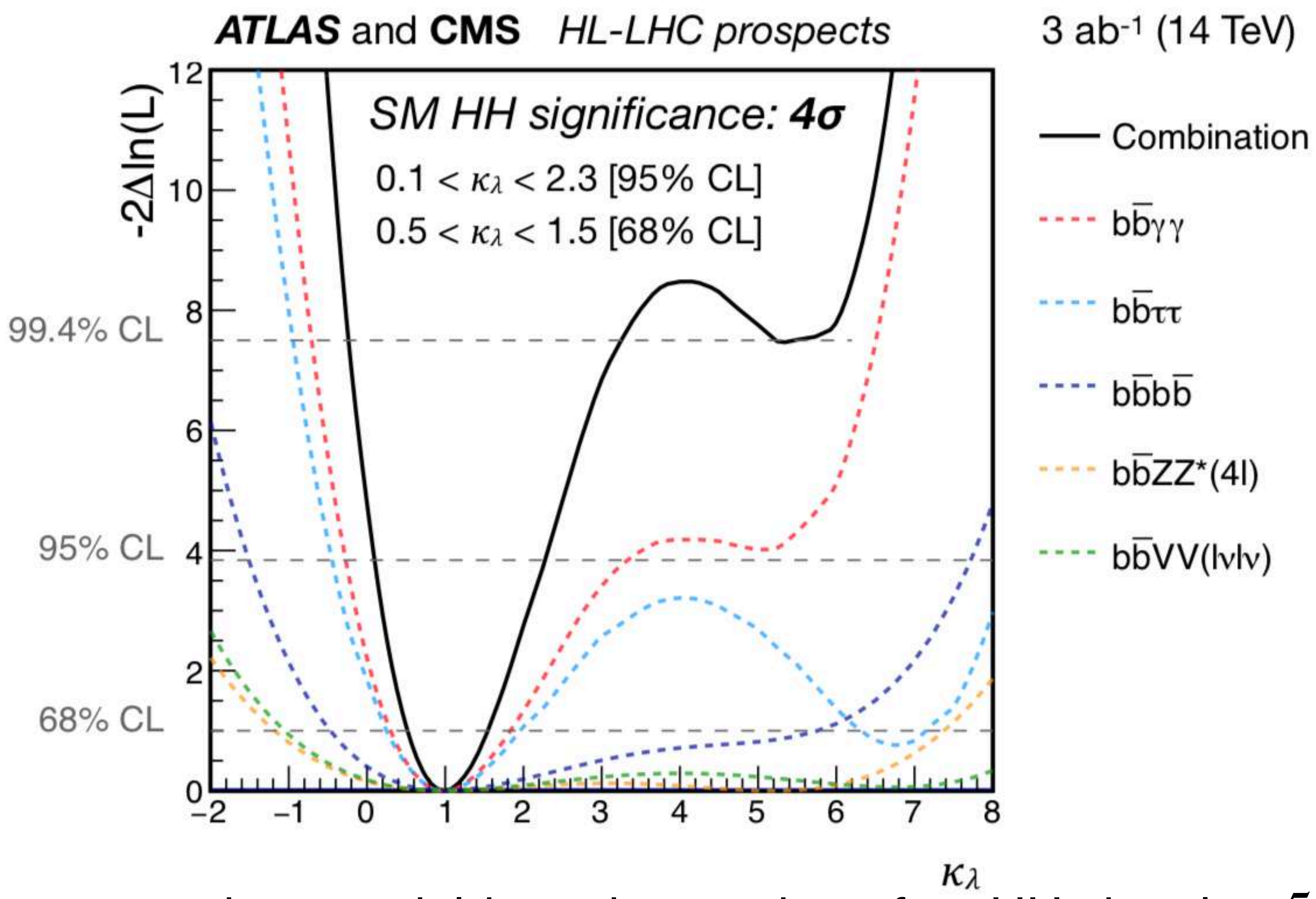
At HL-LHC



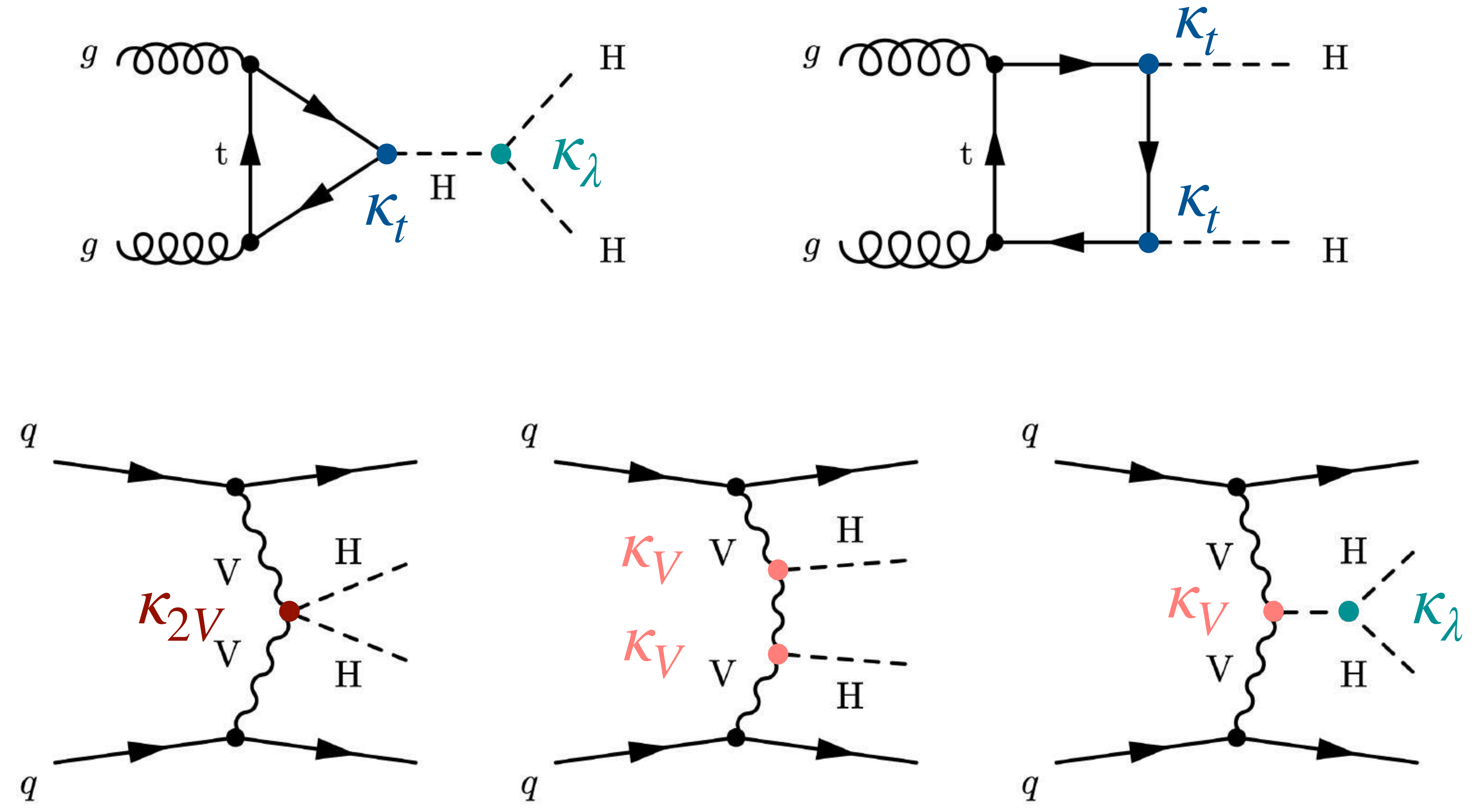
Current estimates yield an observation of an HH signal at 5σ

50% level constraints on the Higgs boson self coupling!

$$0.5 < \kappa_\lambda < 1.5$$

HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (and VBF)



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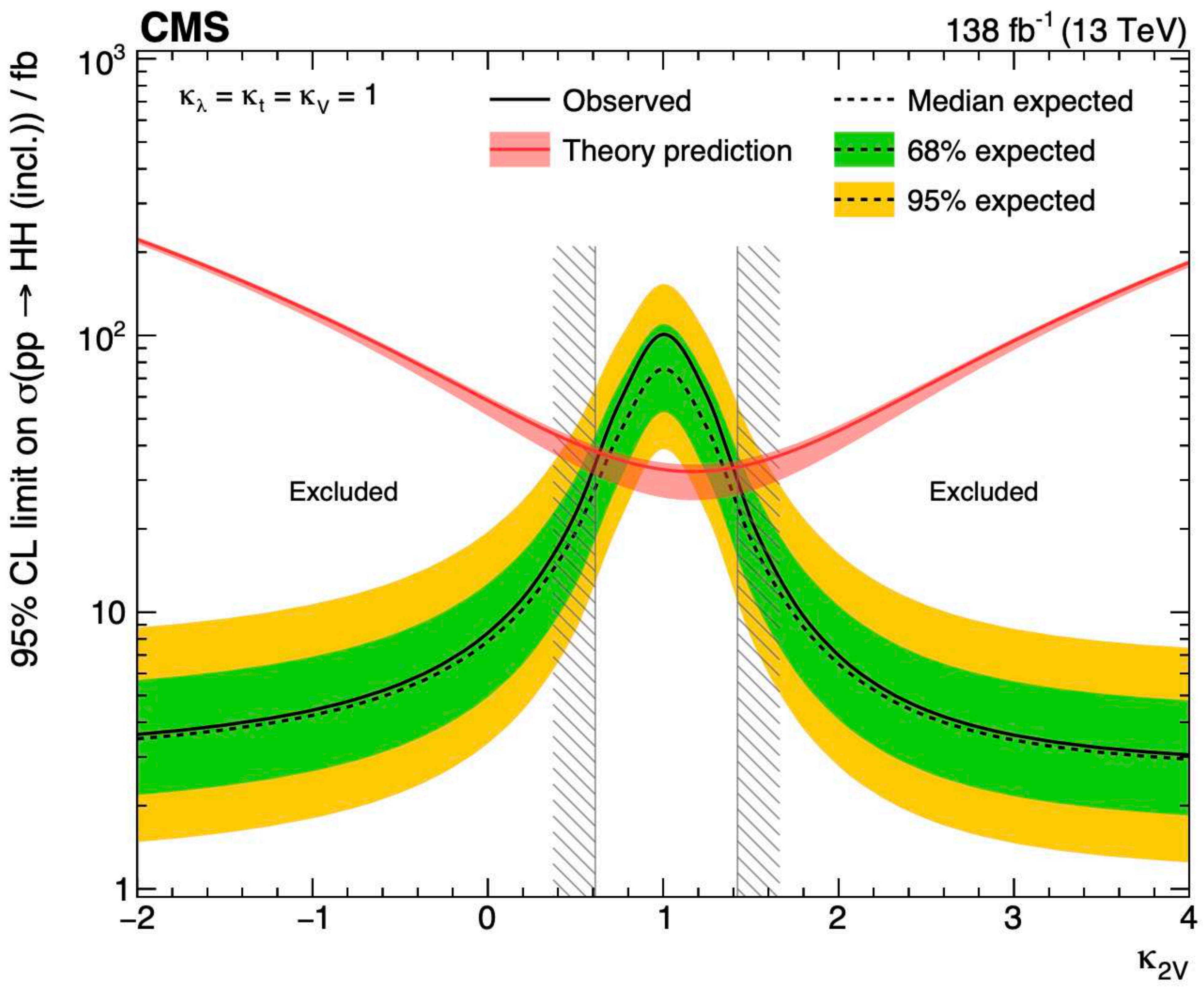


CMS

$$0.67 < \kappa_{2V} < 1.38 \qquad g_{HHVV} = \frac{2m_V^2}{v^2}(1 - 2v^2/f^2)$$

Excludes $\kappa_{2V} = 0$ at 6.6 standard deviations!!

Conclusions

- Beyond the celebrations, the 10th anniversary of the Higgs discovery is a good moment to reflect on what has been achieved since and where we are going…

- How have we achieved?

  The machine, experiment designs, their construction, their commissioning, their calibration, the object reconstruction, the software, the computing grid, the analyses as well as the theoretical predictions and Monte Carlo simulations have performed well beyond expectations!

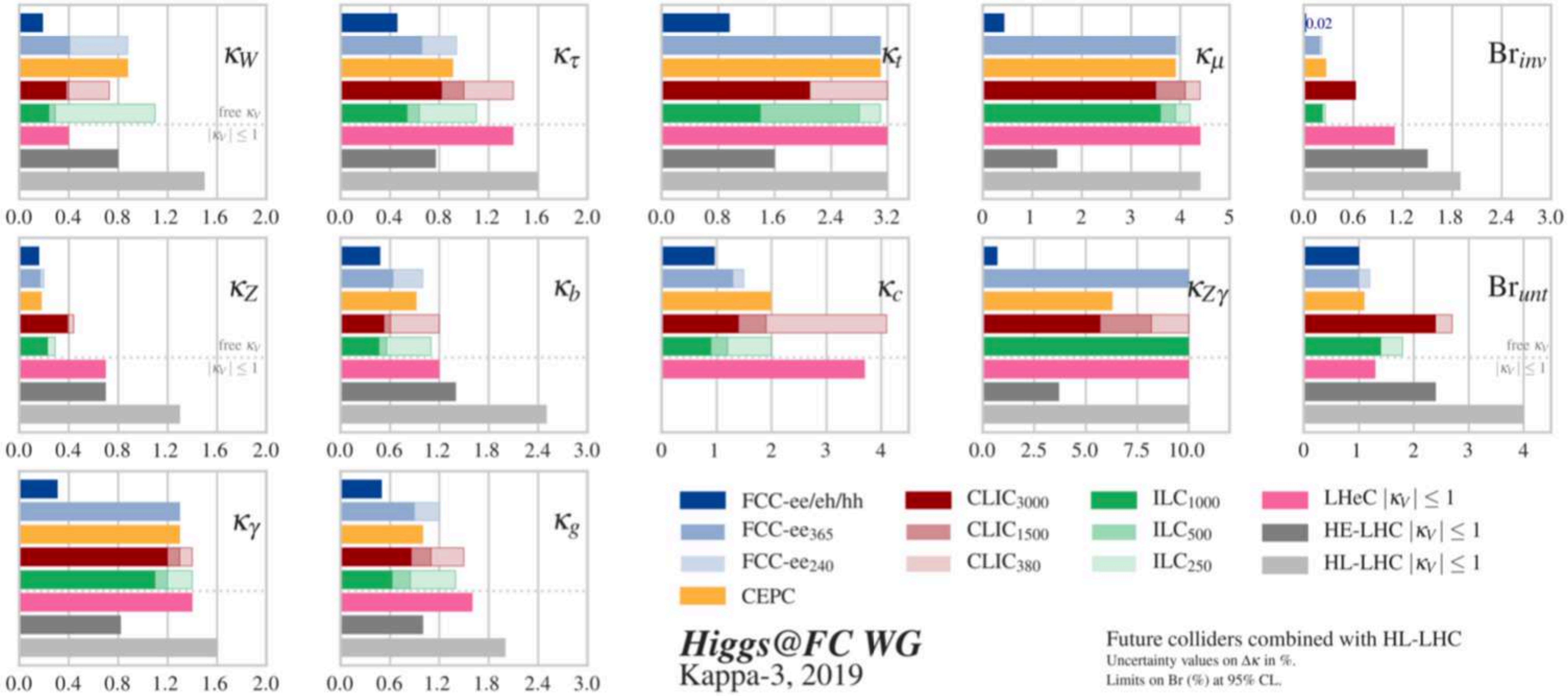
- Progress fuelled with new ideas and allows us to dream beyond what was thought to be impossible!

- The HL-LHC has a superb Higgs physics (and beyond) program, the Run 3 will provide exceptional intermediate goals to push further the possible at HL-LHC!

- Beyond HL-LHC…

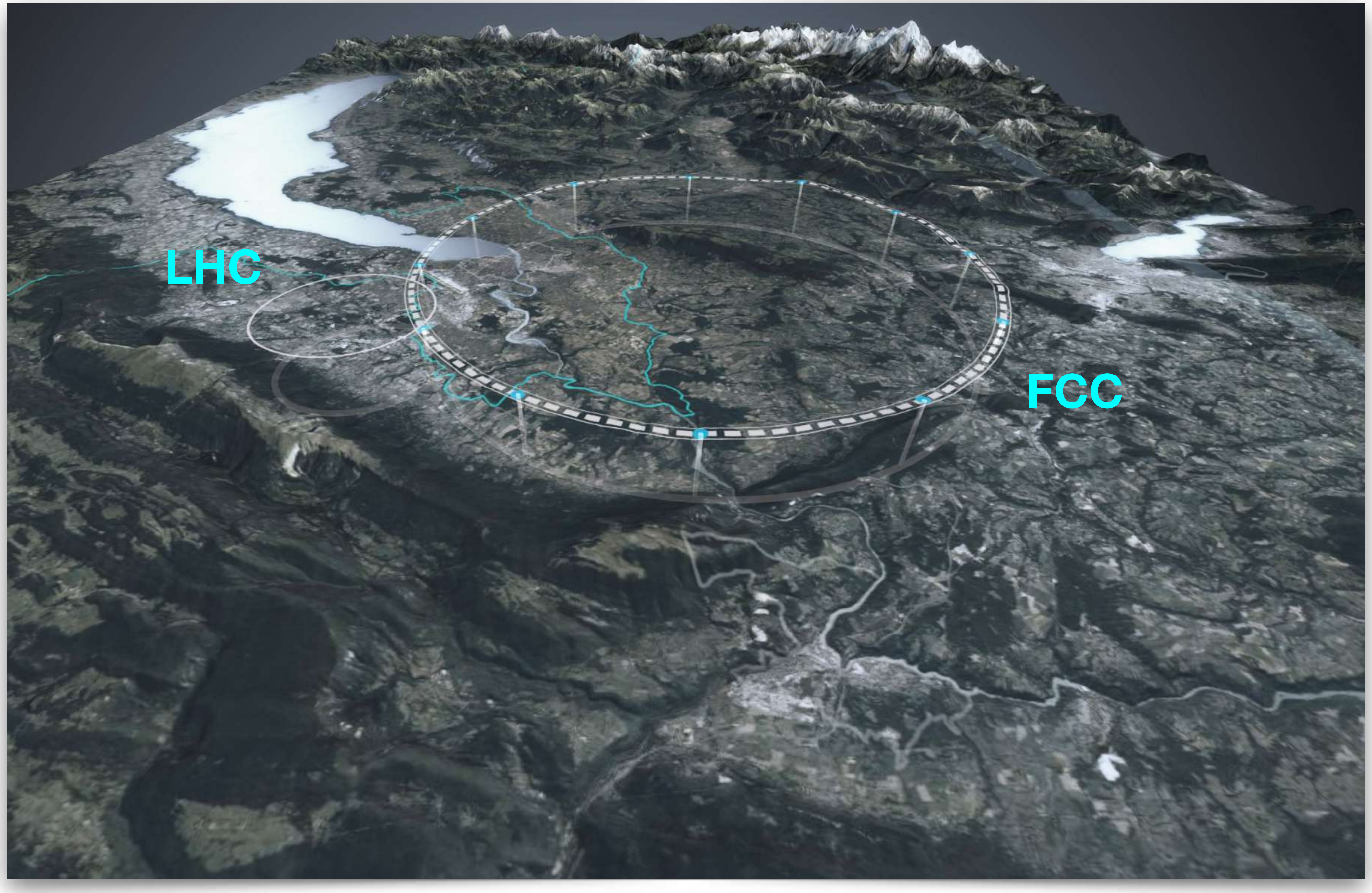
Outlook

What is the best machine that could be built after the LHC?



FCC-ee/eh/hh also offers opportunity to few percent level measurement of trilinear coupling.

Outlook



Approval of future major projects will require

✓ - Robust scientific case

✓ - Major discoveries at the LHC (The Higgs discovery qualifies!)

- Unanimous support of world particle physics community

✓ - Continued technical success

✓ - 'Reasonable' budget envelope

✓ - Public support

C. Llewllyn Smith CERN Director General 1994-1998

50 years of hadron colliders at CERN symposium