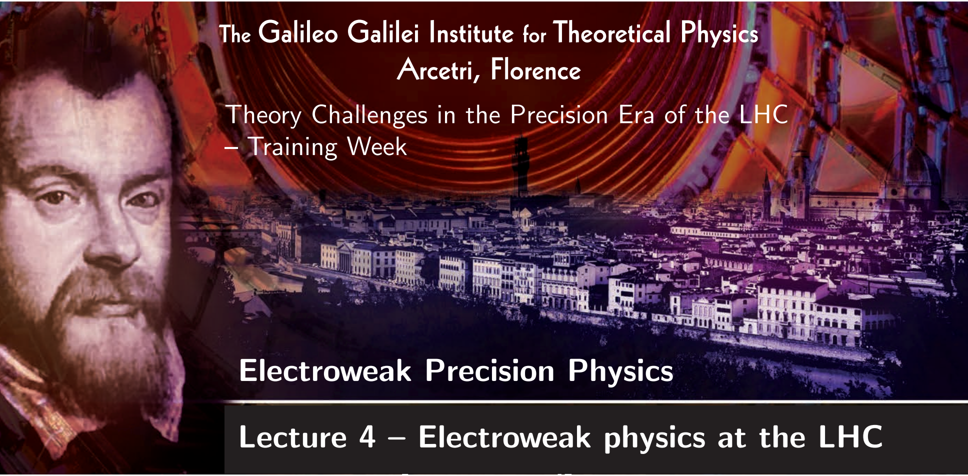

The Galileo Galilei Institute for Theoretical Physics
Arcetri, Florence

Theory Challenges in the Precision Era of the LHC
– Training Week

Electroweak Precision Physics

Lecture 4 – Electroweak physics at the LHC

Stefan Dittmaier
universität freiburg

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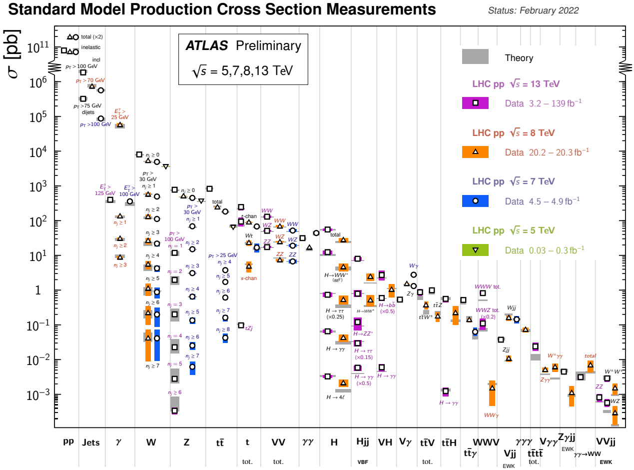
Precision physics at the LHC – preliminaries



- excellent agreement between SM predictions and LHC data,
  $\hookrightarrow$ SM can only be challenged with highest possible precision!
- NNLO QCD $\oplus$ NLO EW corrections meanwhile standard in most $2 \to 2$ key processes

Precision ingredients in predictions:

- fixed-order QCD (multi-loop amplitudes/integrals, NNLO IR subtraction, etc.)
- beyond fixed-order (resummation, parton showers, multi-jet merging, etc.)
- NLO EW corrections (multi-leg multi-scale amplitudes/integrals, etc.)
  - salient features discussed in the following
  - technicalities beyond this lecture (automation via MadGraph5_aMC@NLO, OpenLoops, Recola/Collier, etc.)

Plan for this lecture:

- review some EW key processes/measurements
  ↪ V, VV, VVV production, $VV \to VV$ scattering, Higgs physics
- highlight significance of EW corrections
- highlight specific features of EW corrections
  ↪ off-shell effects
- touch upon some more subtle EW/photonic effects
  ↪ photon/jet separation

Note: Selection of topics by far not exhaustive (and personally biased)

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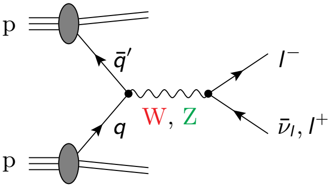
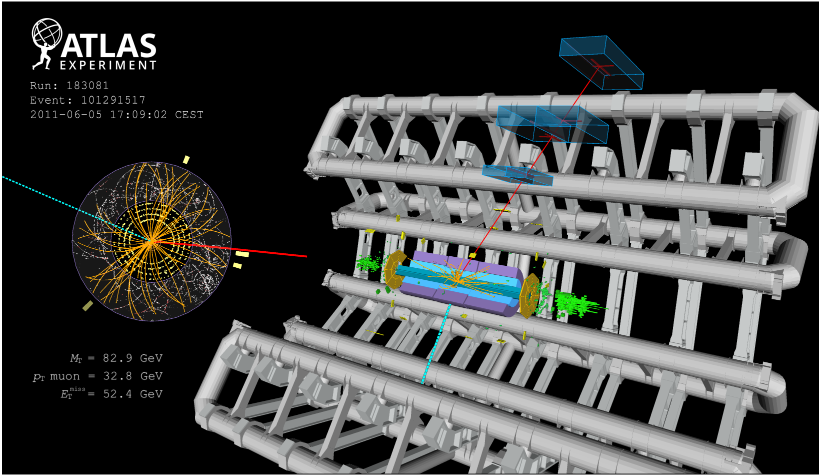
Single-W/Z production



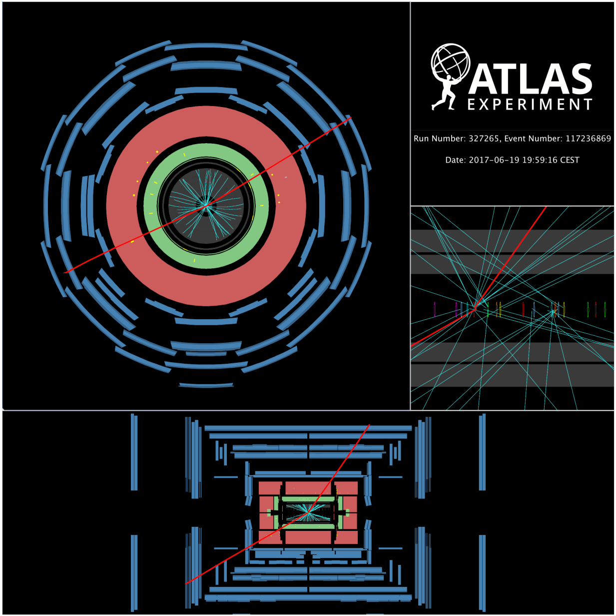
Physics goals:

- M_Z $\rightarrow$ detector calibration by comparing with LEP1 result
- $\sin^2\theta_{\rm eff}^{\rm lept}$ $\rightarrow$ comparable precision with LEP1 and SLC
- M_W $\rightarrow$ exceeds LEP2 precision by factor of 2–3,
  most recent $\Delta M_W^{\rm ATLAS} = 16\,{\rm MeV}$
  (tension with $\Delta M_W^{\rm CDF} = 9\,{\rm MeV}$)
- σ, $d\sigma$ $\rightarrow$ precision SM studies
- decay widths Γ_Z and Γ_W from M_{ll} or $M_{T,l\nu_l}$ tails
- search for Z' and W' at high M_{ll} or $M_{T,l\nu_l}$
- information on PDFs

A $\mathrm{W} \to \mu\nu_\mu$ event from ATLAS



A $Z \to \mu^+\mu^-$ event from ATLAS



Comments on the theory status

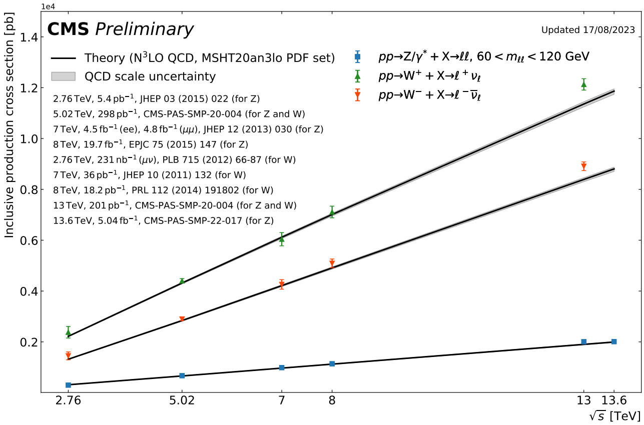
- fixed-order QCD corrections known to N^3LO for cross sections, Duhr et al. '20
  to NNLO for differential distributions
  Hamberg et al '90; ... Melnikov et al. '06; Catani et al. '09, ...
- EW corrections known to NLO Baur et al. '97; Zykunov '01; S.D. et al. '01; ...
  + higher-order improvements (universal corrections, multi-γ)
- fixed-order mixed $\mathcal{O}(\alpha_s \alpha)$ corrections
  (pole approximation for $\mathrm{W/Z}$, for Z even fully off-shell)
  S.D. et al. '14;'15;'20; Behring et al. '20; Bonciani et al. '21;
  Armadillo et al. '22; Buccioni et al. '22; ...
- QCD resummations (q_T resummation, SCET, etc.),
  QCD/QED parton showers, etc.
  $\hookrightarrow$ essential to describe p_T spectra of $\mathrm{W/Z}$ bosons

Note:

Differential high-precision measurements very challenging due to

- QCD/top background for W bosons
- detector effects (Z production also used as standard candle)
- $\not{E}_\mathrm{T}$ measurements relies on calorimeter

W/Z cross-section measurements at the LHC:

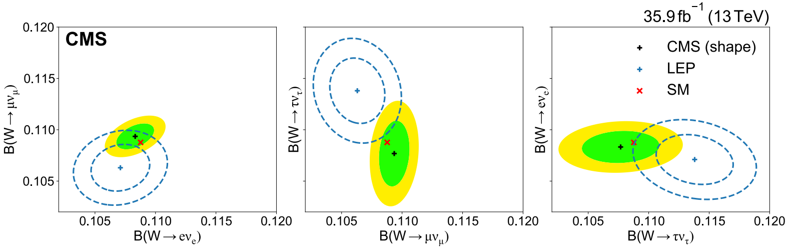


Good agreement between LHC data and N^{3}LO QCD + NLO EW predictions

(tension for 13 TeV W-boson cross sections to be clarified, PDFs?)

Further recent results from the LHC

Test of lepton universality in W decays: (mostly from $\mathrm{t\bar{t}}$ events)



$\hookrightarrow$ tension in LEP results not confirmed

Limits on lepton-flavour violation in Z decays:

ATLAS results: $\mathrm{BR(Z \to e\tau)} < 5 \cdot 10^{-6}$ $(\mathrm{OPAL}: < 9.8 \cdot 10^{-6})$

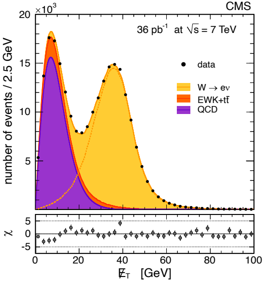
$\mathrm{BR(Z \to \mu\tau)} < 6.5 \cdot 10^{-6}$ $(\mathrm{DELPHI}: 12 \cdot 10^{-6})$

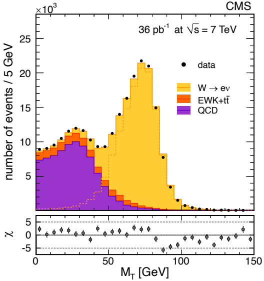
$\hookrightarrow$ LHC supersedes LEP limits

Differential W/Z cross sections

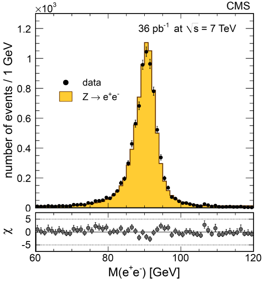
$\hookrightarrow$ information on M_W, $\sin^2\theta_\mathrm{eff}^\mathrm{lept}$, etc.

W bosons:





Z bosons:

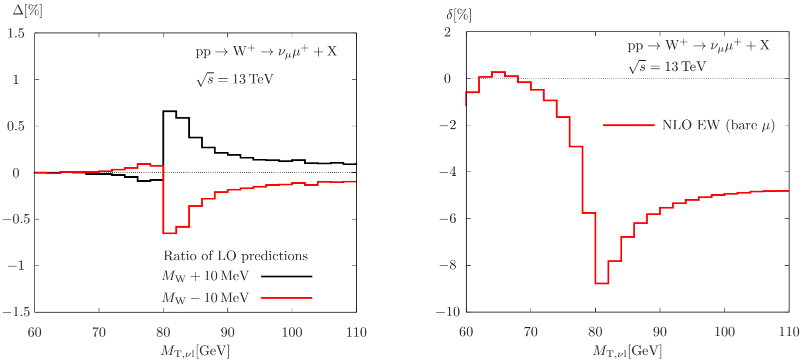


Note locations of Jacobian peaks / resonance at

$$\not{E}_\mathrm{T} \sim M_\mathrm{W}/2,$$
$$M_\mathrm{T} \sim M_\mathrm{W},$$
$$M_{\mathrm{e}^+\mathrm{e}^-} \sim M_\mathrm{Z}$$

Sensitivity of distributions to M_{W} versus NLO EW corrections:

(based on S.D., Krämer '01)



Shape prediction at the level of few 0.1% required!

↪ Proper inclusion of EW corrections at NLO + beyond crucial!

↪ In particular, check resonance treatment!

Exercise: Compare two different resonance treatments!

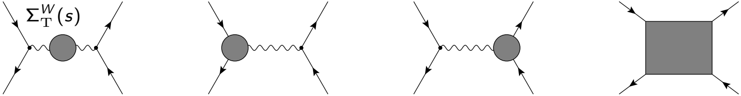
Complex-mass scheme (CMS)

$\hookrightarrow$ see lecture 3!

Treatment of W productionv ia some “factorization scheme (FS)”:

SD, Krämer ’01

Virtual corrections:



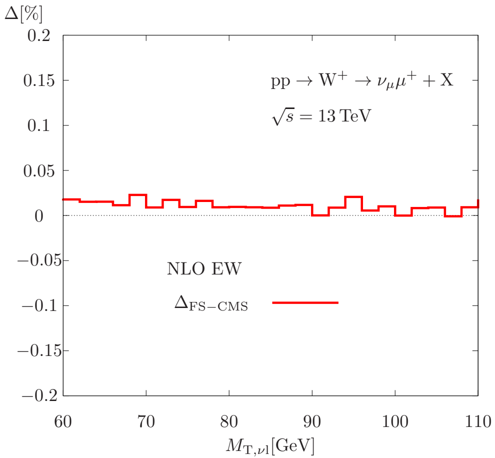
W self-energy | $Wq\bar{q}'$ and $W\nu_l l$ vertex corrections | box diagrams

$$\mathrm{d}\sigma_{\mathrm{virt}}^{\mathrm{FS}}(\hat{s},\hat{t}) = \underbrace{\mathrm{d}\sigma_{\mathrm{LO}}}_{\propto \frac{1}{|\hat{s}-M_{\mathrm{W}}^2+\mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}}|^2}} \times \underbrace{\Big[\delta_{WW}(\hat{s})+\delta_{Wdu}(\hat{s})+\delta_{W\nu_l l}(\hat{s})+\delta_{\mathrm{box}}(\hat{s},\hat{t})\Big]}_{\Gamma_{\mathrm{W}}\neq 0 \text{ only in } \log(\hat{s}-M_{\mathrm{W}}^2+\mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}})}$$

Real photonic corrections:

- amplitude gauge invariant for complex W-boson mass μ_{W} and real s_{W}
- IR divergences exactly match between $\mathrm{d}\sigma_{\mathrm{virt}}^{\mathrm{FS}}$ and $\mathrm{d}\sigma_{\mathrm{real}}^{\mathrm{FS}}$

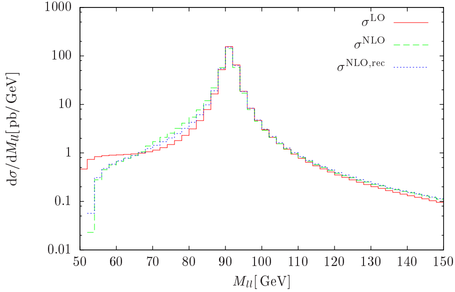
Comparison of width schemes for W production at NLO EW

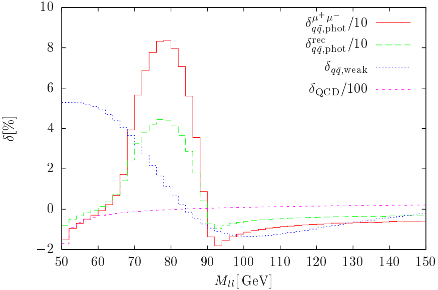


Consistency between the FS and CMS at the level of
$\Delta_{\mathrm{FS-CMS}} = \frac{\mathrm{d}\sigma_{\mathrm{FS}}}{\mathrm{d}\sigma_{\mathrm{CMS}}} - 1 \sim 0.02\%$!

Survey of EW corrections to Z production

SD, Huber '09

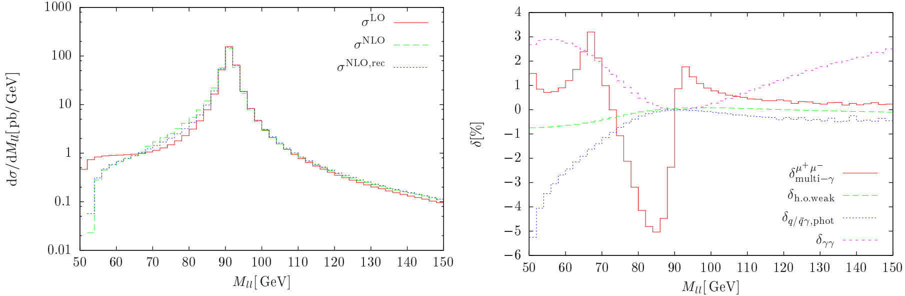




- NLO QED corrections (mostly FSR) several 10%
  [maximally $\sim$ 40%(80%) for dressed leptons (bare muons)]
- Mulit-γ effects still at the few-% level
- Weak NLO corrections at the few-% level
  $\hookrightarrow$ most sensitive to width scheme

Survey of EW corrections to Z production

SD, Huber '09



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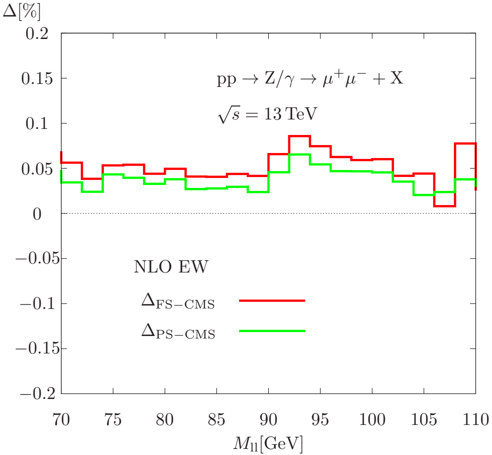
Comparison of width schemes for Z production at NLO EW

(based on S.D., Huber '09)



Resonance schemes:

(see lecture 3!)

CMS = complex-mass scheme

PS = pole scheme

FS = factorization scheme
(less solid, more tricky due to γ/Z interference)

Consistency between the PS, FS, and CMS at the level of

$\Delta_{\mathrm{FS/PS-CMS}} = \frac{\mathrm{d}\sigma_{\mathrm{FS/PS}}}{\mathrm{d}\sigma_{\mathrm{CMS}}} - 1 \lesssim 0.1\%!$

Forward–backward asymmetry $A_{\rm FB}(M_{\ell\ell})$ in neutral-current Drell–Yan production

Issue: symmetric pp initial state at the LHC, i.e. no preferred forward direction!

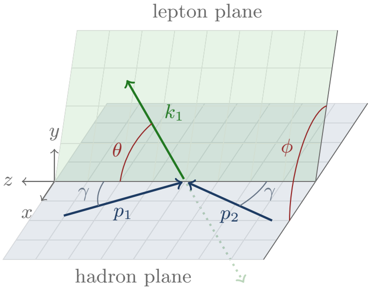
Solution: exploit PDF difference between (valence) q and (sea) $\bar{q}$

$\hookrightarrow$ on average, q carries more momentum than $\bar{q}$!

$\hookrightarrow$ on average, CM($q\bar{q}$) $\approx$ CM(Z) $\approx$ CM($\ell^+\ell^-$) $\to$ q direction!

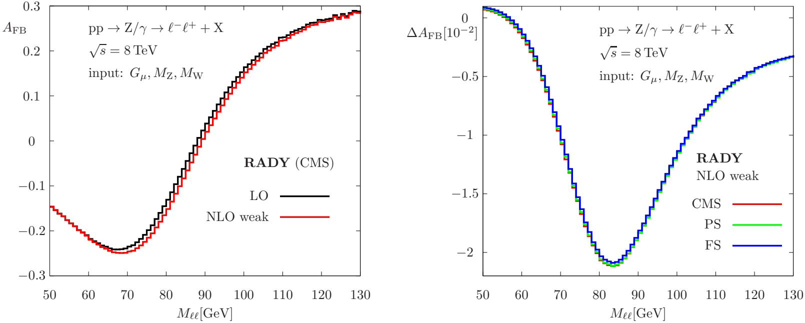
$\Rightarrow$ Collins–Soper angle θ, ϕ:

- go into centre-of-mass frame CM(Z) of the Z boson
- z axis = line of intersection of leptonic and hadronic planes
- $+z$ direction inherited from Z direction in LAB frame
- $+x$ direction from beams
- $+y$ direction completes right-handed coordinate system
- θ, ϕ = polar angles of ℓ^- momentum $\vec{k}_1$



FB asymmetry A_{FB} in Z production – weak corrections and width schemes

A_{FB} defined via Collins–Soper angles $\quad\rightarrow\quad$ sensitivity to $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$



Experimental uncertainties and precision targets:

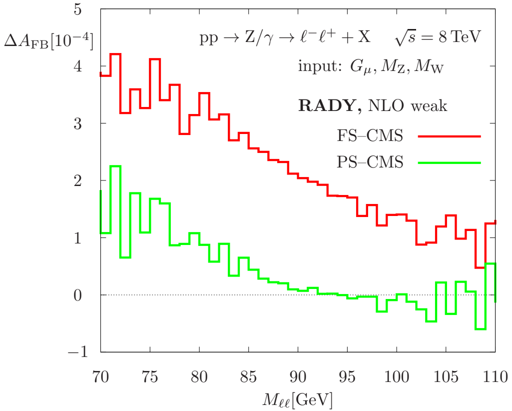
- Z resonance at LEP: $\quad \Delta A_{\mathrm{FB}}^{\mathrm{b}} = 0.0016, \quad \Delta A_{\mathrm{FB}}^{\ell} = 0.0010$

  $\hookrightarrow\ \Delta\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.00029$ from $\Delta A_{\mathrm{FB}}^{\mathrm{b}}$

- LHC precision target for predictions: $\quad \Delta A_{\mathrm{FB}}(M_{\ell\ell}) \lesssim 10^{-4}$

  $\hookrightarrow$ great challenge (not yet completely reached)

FB asymmetry A_{FB} – differences of width schemes differentially

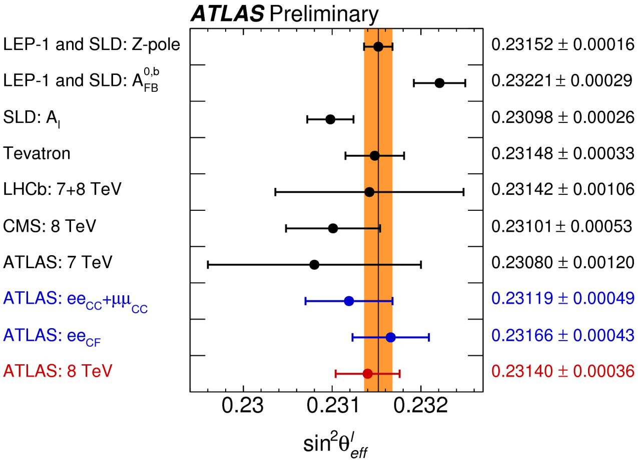


$\hookrightarrow$ |PS-CMS| $\lesssim 10^{-4}$

FS less accurate (theoretically not as solid as PS/CMS)

$\hookrightarrow$ theoretical improvements beyond NLO EW very desirable!

Measurements of the effective weak mixing angle – current status



↪ LHC closes in on LEP precision!

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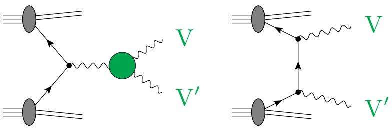
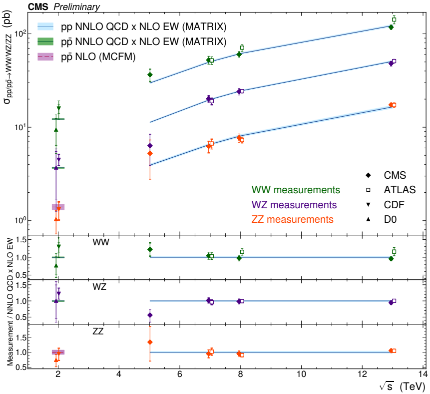
Massive di-boson production

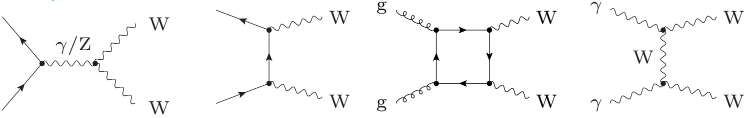




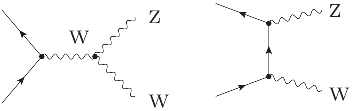
- overall good agreement between data and SM
- NNLO QCD corrections essential for proper descritpion of data
- NLO EW corrections important in differential distributions
- data constrain anomalous *VVV* couplings

Complementarity in WW / WZ / ZZ production

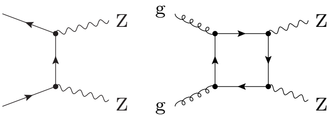
WW production:



WZ production:

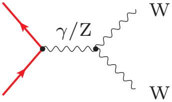


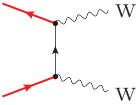
ZZ production:

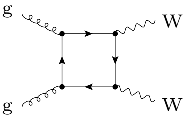


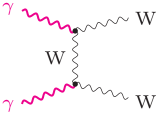
Complementarity in WW / WZ / ZZ production

WW production:

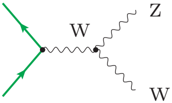


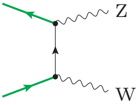




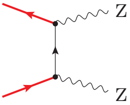


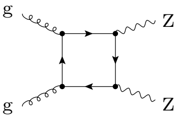
WZ production:





ZZ production:



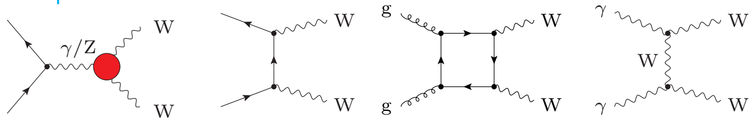


Sensitivity to different PDF combinations:

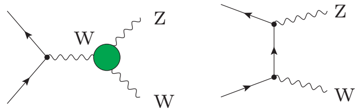
- $q\bar{q}$ in $\mathrm{WW/ZZ}$
- $u\bar{d}/d\bar{u}$ in $\mathrm{W^+Z/W^-Z}$
- $\gamma\gamma$ in WW

Complementarity in WW / WZ / ZZ production

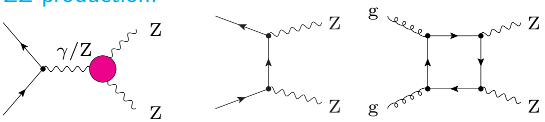
WW production:



WZ production:



ZZ production:

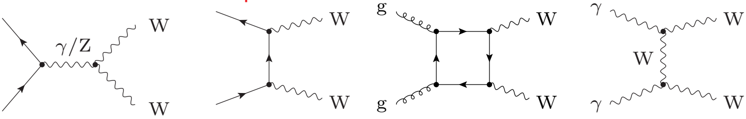


Sensitivity to different anomalous TGCs:

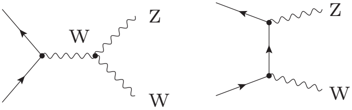
- overlay of $\gamma\mathrm{WW}/\mathrm{ZWW}$ in WW
- only ZWW in WZ
- $\gamma\mathrm{ZZ}/\mathrm{ZZZ}$ in ZZ

Complementarity in WW / WZ / ZZ production

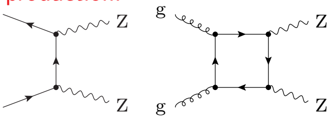
WW production:



WZ production:

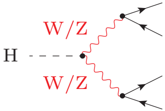


ZZ production:

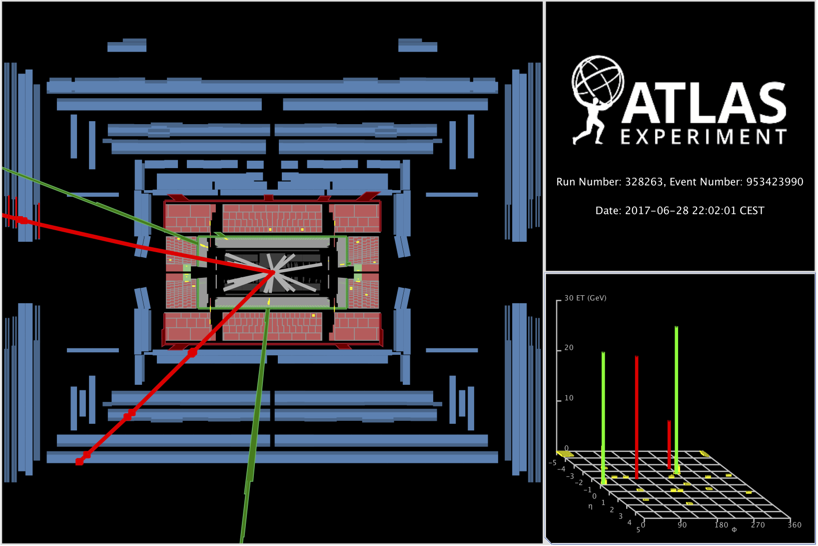


Background to Higgs production
in channel $\mathrm{H} \to \mathrm{WW}^*/\mathrm{ZZ}^* \to 4f$

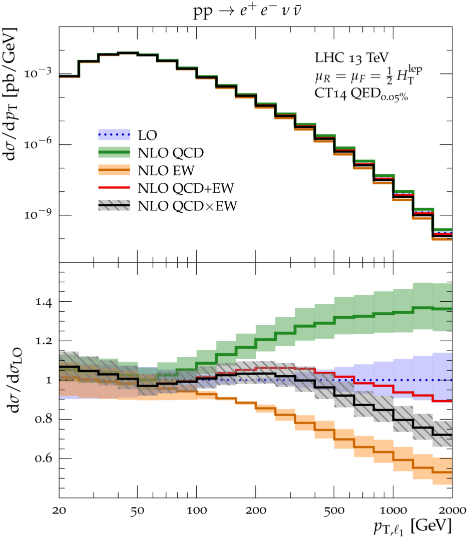
$\hookrightarrow$ off-shell calculation
particularly important for WW/ZZ!



A $\mu^+\mu^-e^+e^-$ event from ATLAS



$\mathrm{pp} \to \mathrm{WW/ZZ} \to \mathrm{e^+e^-}\nu\bar\nu + X$: survey of different NLO contributions



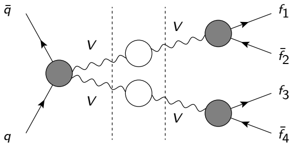
Kallweit et al. '17

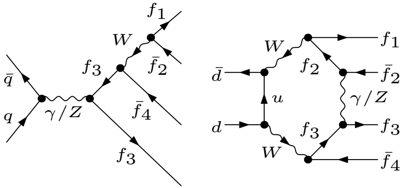
- XS contributions:
  $\mathrm{WW} + \mathrm{ZZ} +$ interferences
- Jet veto:
  $H_\mathrm{T}^\mathrm{jet} = \sum_{i\in\mathrm{jets}} p_{\mathrm{T},i} \; > \; H_\mathrm{T}^\mathrm{lep}$
  $\hookrightarrow \; K_\mathrm{QCD}$ moderate
- EW corrections
  $\sim -40\%$ in TeV range
  (EW Sudakov logarithms)
- Combination of QCD and EW corrections:
  $|\,$QCD+EW $-$ QCD$\times$EW$\,|$
  $\sim \; \delta_\mathrm{QCD} \times \delta_\mathrm{EW}$
  $\sim$ 10–20% for $p_{\mathrm{T},\ell_1} \gtrsim 1\,\mathrm{TeV}$

Note: product better motivated!

EW corrections – full NLO versus pole approximation

Double-pole approximation (DPA) calculation vs. Full off-shell $q\bar{q} \to 4f$





DPA:

- ▶ expansion about resonance poles
  ↪ factorizable & non-fact. corrs.
- ▶ not many diagrams (2→2 production)
- \+ numerically fast
- – validity only for $\sqrt{\hat{s}} > 2M_V + \mathcal{O}(\Gamma_V)$

Full off-shell:

- ▶ off-shell calculation with complex-mass scheme
- ▶ many off-shell diagrams ($\sim 10^3$/channel)
- – CPU intensive
- \+ NLO accuracy everywhere

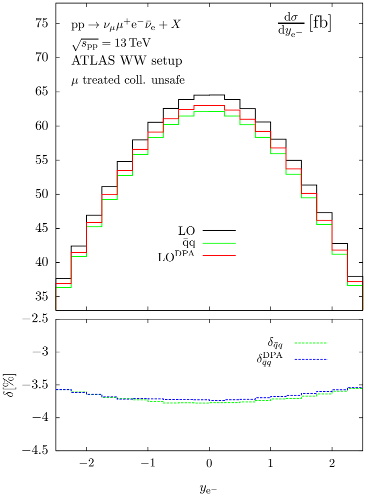
Approaches compared for $\mathrm{e^+e^-/pp \to WW} \to 4f$, etc.

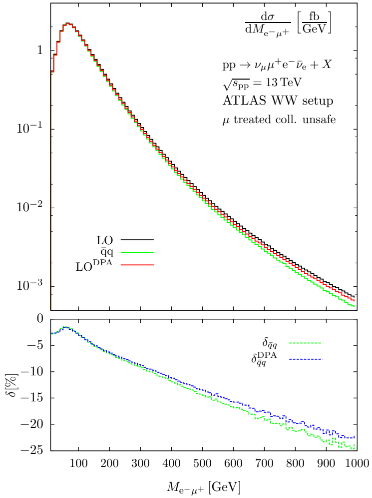
(similarly for $\mathrm{pp \to WWW} \to 6\ell$, $\mathrm{pp(WW \to WW)} \to 4\ell 2\mathrm{j}$, etc.)

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$

Biedermann et al. '16

Rapidity and invariant-mass distributions





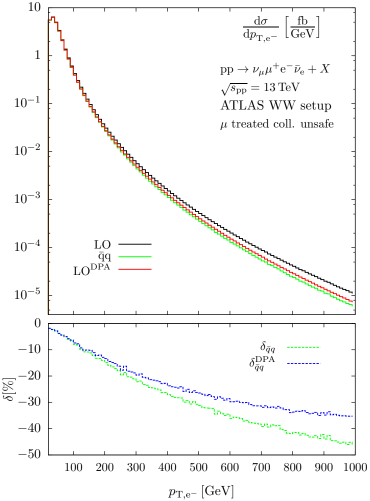
Level of agreement as expected (dominance of doubly-resonant diagrams)

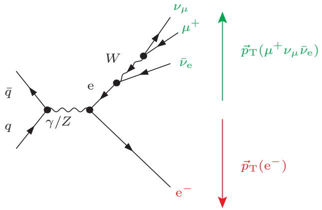
$\hookrightarrow$ difference $\lesssim 0.5\%$ whenever cross section sizable

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$

Biedermann et al. '16

Transverse-momentum distribution of a single lepton



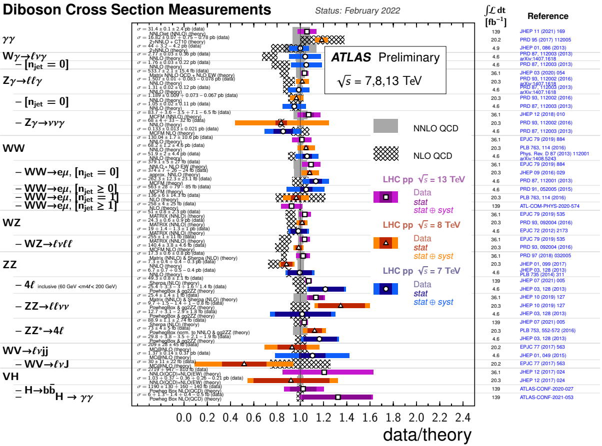


Impact of singly-resonant diagrams where e^- takes recoil from $(\mu^+ \nu_\mu \bar{\nu}_\mathrm{e})$

(W bremsstrahlung to Drell–Yan production of $\mathrm{e}^+\mathrm{e}^-$)

Agreement degrades for $p_\mathrm{T} \gtrsim 300\,\mathrm{GeV}$, since off-shell diagrams get enhanced

Diboson results – overview

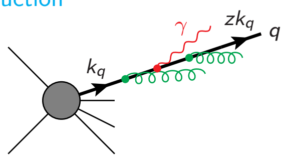


A subtlety: photon–jet separation for $W\gamma/Z\gamma$ production

$\hookrightarrow$ quark-to-photon fragmentation function

Glover, Morgan '94

or Frixione isolation Frixione '98

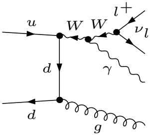


Excursion: photon–jet separation via photon fragmentation function $D_{q\to\gamma}$

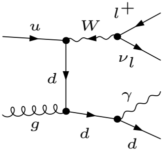
Glover, Morgan '94

Why?

- QCD radiation cannot be suppressed by cuts
  $\hookrightarrow$ treat at least soft/collinear jets inclusively

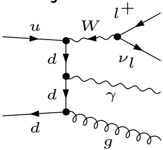


- separation of collinear quarks and photons leads to IR-unstable corrections $\propto \ln(m_q^2/Q^2)$
  $\hookrightarrow$ recombine collinear quarks and photons



- quark and gluon jets cannot be distinguished event by event
  $\hookrightarrow$ common recombination required for quarks/gluons with photons

$\Rightarrow$ $\underbrace{(g_{\rm hard} + \gamma_{\rm soft})}_{\text{EW corr. to X+jet}}$ and $\underbrace{(g_{\rm soft} + \gamma_{\rm hard})}_{\text{QCD corr. to X}+\gamma}$ both appear as 1 jet



Problem: signatures of X+jet and X+γ overlap !

Excursion: photon–jet separation via photon fragmentation function $D_{q\to\gamma}$ (continued)

Glover, Morgan '94

Solution:

- idea: declare γ–jet systems as γ or jet according to energy share
- determine photon energy fraction $z_\gamma = \dfrac{E_\gamma}{E_{\rm jet}+E_\gamma}$ of photon/jet system

  $\hookrightarrow$ event selection: $z_\gamma > z_0$: photon

  $z_\gamma < z_0$: jet (typical value $z_0 = 0.7$)

- but: cut on z_γ destroys inclusiveness needed for KLN theorem

  $\hookrightarrow$ collinear singularity $\propto \alpha \ln m_q$ remains (but are universal!)

- absorb universal collinear singularity in "fragmentation function" $D_{q\to\gamma}(z_\gamma)$

  $\hookrightarrow$ subtract convolution of LO cross section with

$$D^{\overline{\rm MS}}_{q\to\gamma}(z_\gamma,\mu_{\rm fact})\Big|_{\rm mass.reg.} = \frac{\alpha Q_q^2}{2\pi} P_{q\to\gamma}(z_\gamma)\left[\ln\frac{m_q^2}{\mu_{\rm fact}^2} + 2\ln z_\gamma + 1\right]$$

$\to$ cancels coll. singularities

$$+\; D^{\rm ALEPH}_{q\to\gamma}(z_\gamma,\mu_{\rm fact})$$

$\leftarrow$ non-pert. part fitted to ALEPH data

where $P_{q\to\gamma}(z_\gamma) = \frac{1+(1-z_\gamma)^2}{z_\gamma}$ = quark-to-photon splitting function

Excursion: photon–jet separation via Frixione isolation

Frixione '98

Idea: suppress jets inside collinear cone around photons:

$$p_{\mathrm{T,jet}} < \varepsilon\, p_{\mathrm{T},\gamma} \left(\frac{1-\cos R_{\gamma\mathrm{jet}}}{1-\cos R_0} \right) \qquad (R_0 = \text{fixed cone size})$$

- photon and jet collinear ($R_{\gamma\mathrm{jet}} \to 0$) $\to$ event discarded
- photon soft or collinear to beams ($p_{\mathrm{T},\gamma} \to 0$) $\to$ event discarded
- jet soft or collinear beams ($p_{\mathrm{T,jet}} \to 0$) $\to$ event kept $\Rightarrow$ IR safety

Comments:

- Frixione isolation simple to implement theoretically, but problematic experimentally
- cleaner isolation of non-perturbative effects by fragmentation function
- approximate relation between the two methods:

$$z_\gamma \sim \frac{p_{\mathrm{T},\gamma}}{p_{\mathrm{T},\gamma}+p_{\mathrm{T,jet}}} > \frac{1}{1+\varepsilon \frac{1-\cos R_{\gamma\mathrm{jet}}}{1-\cos R_0}} \sim \frac{1}{1+\varepsilon} \quad \text{for} \quad R_{\gamma\mathrm{jet}} \sim R_0$$

$\hookrightarrow$ methods yield quite similar results for $z_0 \sim \frac{1}{1+\varepsilon}$

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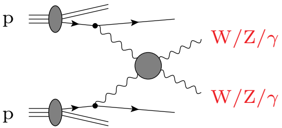
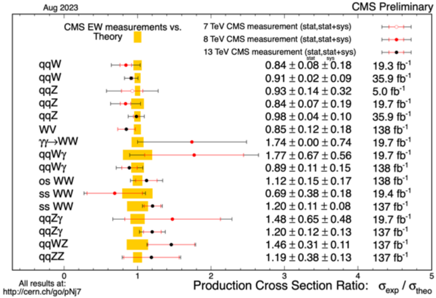
Electroweak gauge-boson scattering





Physics interest:

- strong sensitivity to EW gauge-boson self-interaction
- window to EW symmetry breaking (EWSB) via off-shell Higgs exchange, complementary to direct analyses of (on-shell) Higgs bosons

Analysis framework:

- "SM Effective Theory (SMEFT)" based on SM particle content

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\,\mathcal{L}_i^{({\rm dim}-6)},$$

effective dim-6 operators
Buchmüller, Wyler '85; Grzadkowski et al. '10

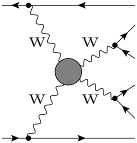
- Specific SM extensions (extended Higgs sectors, modified EWSB, etc.)

All channels measured by ATLAS & CMS $\rightarrow$ compatibility with SM

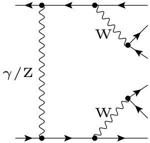
$\Rightarrow$ BSM effects (if accessible) subtle and small $\rightarrow$ highest precision required !

Classification of LO diagrams for $\mathrm{pp} \to \mathrm{VV}' + 2\,\mathrm{jets}$

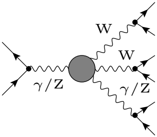
EW channels



VBS channels



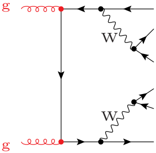
bkg diags

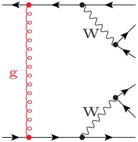


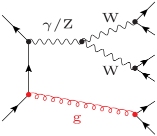
VVV channels

$|\mathcal{M}_{\mathrm{EW}}|^2 \propto \alpha^6$

QCD channels







$|\mathcal{M}_{\mathrm{QCD}}|^2 \propto \alpha_{\mathrm{s}}^2 \alpha^4$

EW–QCD interference $\to$ colour-suppressed $=$ small $\propto \alpha_{\mathrm{s}} \alpha^5$

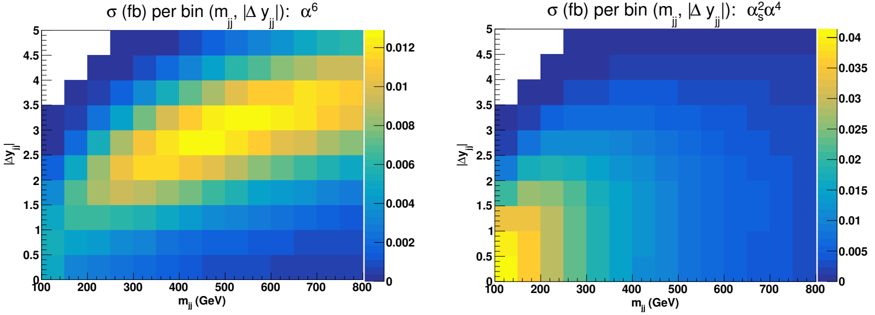
$\hookrightarrow$ Task: enhance VBS contribution via dedicated VBS cuts,
but include all channels/diagrams in predictions (at least in LO)

$\mathrm{pp}(\mathrm{W}^+\mathrm{W}^+ \to \mathrm{W}^+\mathrm{W}^+) \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e} + 2\mathrm{jets} + X$ at the LHC

EW VBS versus QCD contributions:

VBSCAN (Ballestrero et al. '18)

EW VBS contribution: QCD contribution:

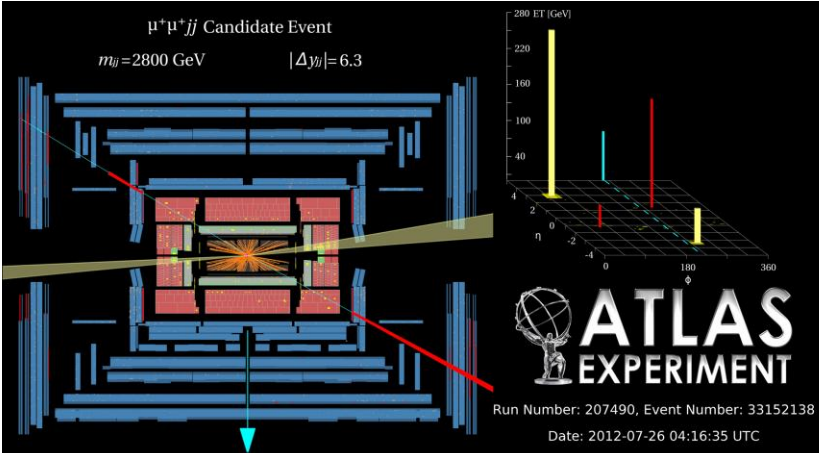


Typical VBS cuts: $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$, $|\Delta y_{\mathrm{jj}}| > 2.5$ $\to$ hard forward/backward jets

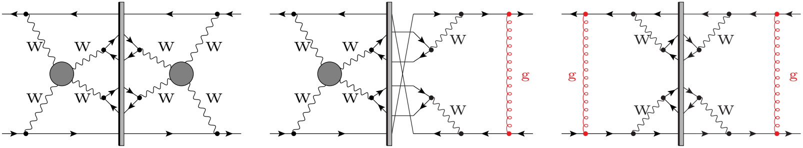
$\hookrightarrow$ Strong suppression ($\lesssim 10\%$) of QCD (and WWW contributions) for $\mathrm{W}^\pm\mathrm{W}^\pm$ VBS!

Note: much lesser suppression for other VBS channels

A typical W^+W^+ scattering event at the LHC



Schematic view of perturbative orders at LO and NLO



$\mathcal{M}^{\mathrm{LO}}_{\mathrm{EW}}\,\mathcal{M}^{\mathrm{LO}*}_{\mathrm{EW}}$ $\quad$ $\mathcal{M}^{\mathrm{LO}}_{\mathrm{EW}}\,\mathcal{M}^{\mathrm{LO}*}_{\mathrm{QCD}} + \mathrm{c.c.}$ $\quad$ $\mathcal{M}^{\mathrm{LO}}_{\mathrm{QCD}}\,\mathcal{M}^{\mathrm{LO}*}_{\mathrm{QCD}}$

LO $\quad \mathcal{O}(\alpha^6) \quad \mathcal{O}(\alpha_s\alpha^5) \quad \mathcal{O}(\alpha_s^2\alpha^4)$

EW $\quad$ QCD $\quad$ EW $\quad$ QCD $\quad$ EW $\quad$ QCD

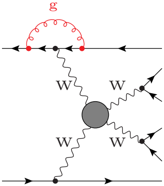
NLO $\quad \mathcal{O}(\alpha^7) \quad \mathcal{O}(\alpha_s\alpha^6) \quad \mathcal{O}(\alpha_s^2\alpha^5) \quad \mathcal{O}(\alpha_s^3\alpha^4)$

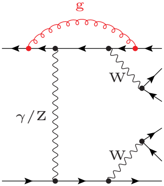
EW $\quad$ mixed EW–QCD $\quad$ QCD

$\Rightarrow$ Tower of mixed EW–QCD corrections at NLO

Survey of NLO contributions of QCD type

QCD corrections to EW channels

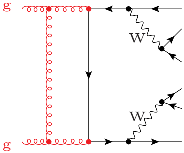


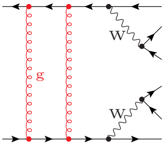


$\times\, \mathcal{M}_{\mathrm{EW}}^{\mathrm{LO}*} \quad \propto \quad \alpha_{\mathrm{s}}\alpha^6$

$\hookrightarrow$ QCD corrections only $\sim 5\%$ (little colour exchange between protons)

QCD corrections to QCD channels



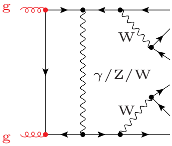


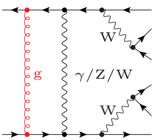
$\times\, \mathcal{M}_{\mathrm{QCD}}^{\mathrm{LO}*} \quad \propto \quad \alpha_{\mathrm{s}}^3\alpha^4$

- no relation to EW VBS subprocess, just QCD $VV + 2$jet production
- contribution damped by VBS cuts, but still quite large
  ($\mathrm{W}^\pm\mathrm{W}^\pm$ is exception with $\sim 10\%$, since gg channel missing)

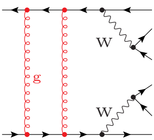
NLO corrections of EW and mixed QCD–EW types

Mixed QCD–EW contributions $\propto\ \alpha_s^2\alpha^5$



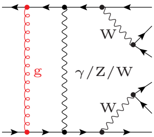


$\times\ \mathcal{M}_{\mathrm{QCD}}^{\mathrm{LO}*}$



$\times\ \mathcal{M}_{\mathrm{EW}}^{\mathrm{LO}*}$

Mixed QCD–EW contributions $\propto\ \alpha_s\alpha^6$

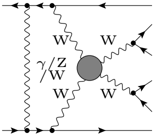


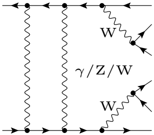
$\times\ \mathcal{M}_{\mathrm{EW}}^{\mathrm{LO}*}$

mixed contributions not VBS enhanced,
partially colour-suppressed

$\hookrightarrow$ very small

Purely EW contributions $\propto\ \alpha^7$





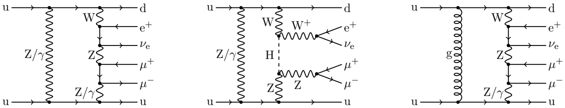
$\times\ \mathcal{M}_{\mathrm{EW}}^{\mathrm{LO}*}$

Sudakov-enhanced VBS corrections,
$\sim -15\%$ (larger in distributions)

$\hookrightarrow$ experimentally relevant!

Comments on NLO calculations:

- genuine QCD corrections available since more than 10 years (several groups)
- NLO predictions for full NLO tower extremely challenging, but available
  $W^\pm W^\pm$: Biedermann et al. '16,'17; S.D. et al. '23; WZ: Denner et al. '19;
  ZZ: Denner et al. '20,'21; $W^\pm W^\mp$: Denner et al. '22
- Main challenges:
  - algebraic complexity (many partonic channels, $\sim$ some 10^5 diagrams)
    $\hookrightarrow$ recursive one-loop amplitude generators RECOLA / OPENLOOPS
  - multi-leg tensor one-loop integrals (8-point functions)
    $\hookrightarrow$ numerically stable evaluation with COLLIER library
    or improved OPENLOOPS reduction

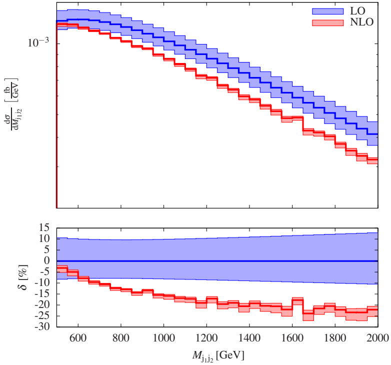


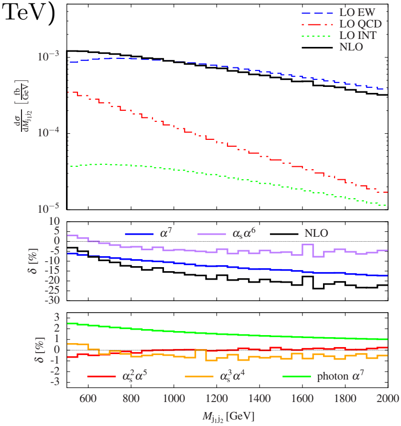
- NLO/MC techniques pushed to the extreme, but work well:
  QCD/QED dipole subtraction formalism, complex-mass scheme, multi-channel Monte Carlo integration, etc.
- new subtlety: integration over low-virtuality $\gamma^* \to q\bar{q}$ splitting
  $\hookrightarrow$ relation to $\Delta\alpha_{\rm had}$ via "conversion function" Denner et al. '19

Tower of NLO corrections to QCD $\mathrm{W^+W^+} + 2\mathrm{j}$ channel

Biedermann et al. '16,'17

Example: $M_{\mathrm{j_1 j_2}}$ distribution $(\sqrt{s} = 13\,\mathrm{TeV})$





EW $\mathcal{O}(\alpha^7)$ contribution is largest NLO correction

$\hookrightarrow$ $\delta_{\alpha^7} = -13\%$ for integrated cross section within VBS cuts

Good description of dominant correction by leading EW high-energy logarithms:

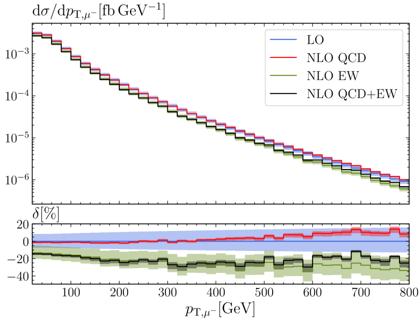
$$\delta_{\alpha^7} \approx -\frac{2\alpha}{s_\mathrm{W}^2\pi} \ln^2\left(\frac{Q^2}{M_\mathrm{W}^2}\right) + \frac{19\alpha}{12 s_\mathrm{W}^2\pi} \ln\left(\frac{Q^2}{M_\mathrm{W}^2}\right), \qquad Q \sim \langle M_{4\ell}\rangle \sim 400\,\mathrm{GeV}$$

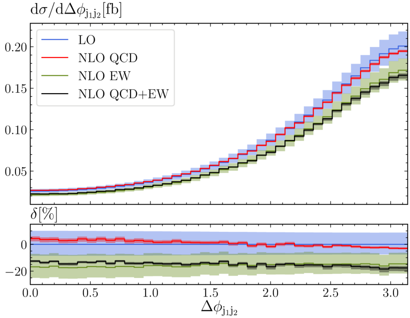
(due to soft/collinear W/Z exchange)

Another example:

LO contributions and corrections to $\mathrm{WZ} + 2\mathrm{j}$ channel

Denner et al. '19





- LO contributions after VBS cuts:

$$\Delta_{\alpha^6} \sim 20\%, \qquad \Delta_{\alpha_s\alpha^5} \sim 0.5\%, \qquad \Delta_{\alpha_s^2\alpha^4} \sim 80\%$$

- Corrections to the EW channel (relative to $\sigma^{\mathrm{LO}}_{\alpha^6}$):

$$\delta_{\alpha^7} = -16\%, \qquad \delta_{\alpha_s\alpha^6} = -2\%$$

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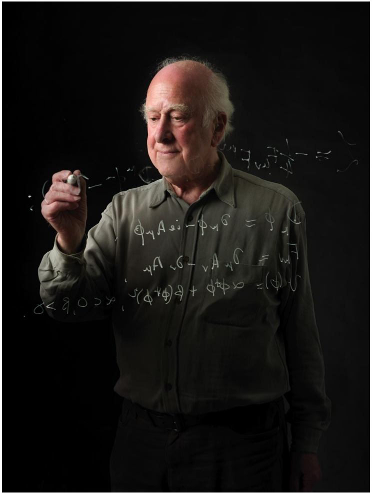
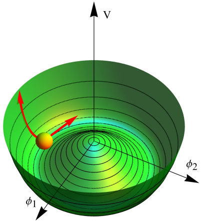
Imprint of the Higgs mechanism



... describing the "Abelian Higgs model"



Splitting the Higgs field ϕ:

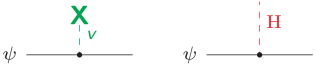
$$\phi(x) = \underbrace{\phi_{\mathrm{min}}}_{=v} + \underbrace{H(x)}$$

vacuum part — Higgs field excitation

$\hookrightarrow$ generates Higgs particle

Coupling of field ψ to ϕ:

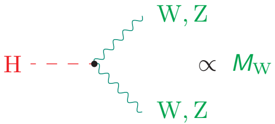
$$g\phi(x)\psi(x)^2 = \underbrace{g\,v}_{=m}\,\psi(x)^2 + g\,H(x)\psi(x)^2 + \ldots$$

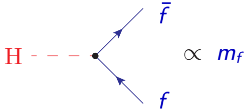


$\hookrightarrow$ Particle ψ receives mass $m = vg$ via interaction with ϕ

Higgs production and decay at the LHC

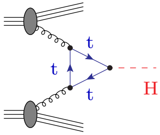
Higgs bosons couple proportional to particle masses:

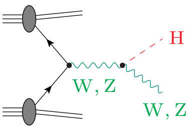


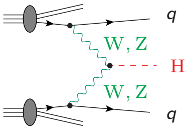


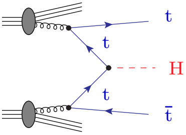
$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders ($p\bar{p}/pp$):

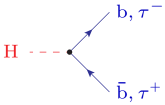


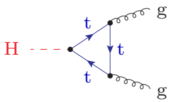


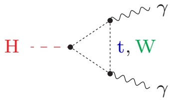


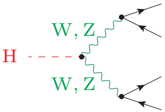


Decay channels for Higgs bosons of moderate mass ($M_H \lesssim 300\,\mathrm{GeV}$):



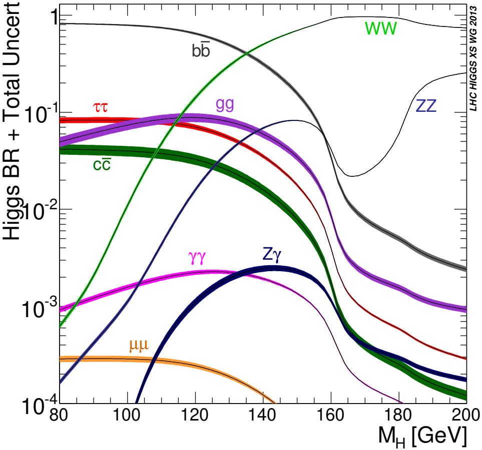






Branching ratios
of the SM Higgs boson

LHC Higgs XS WG '10–'13



$$\mathrm{BR}_{\mathrm{H}\to X} = \frac{\Gamma_{\mathrm{H}\to X}}{\Gamma_{\mathrm{H,tot}}}$$

Many decay channels open
at $M_\mathrm{H} = 126\,\mathrm{GeV}$

$\hookrightarrow$ good for couplings analysis !

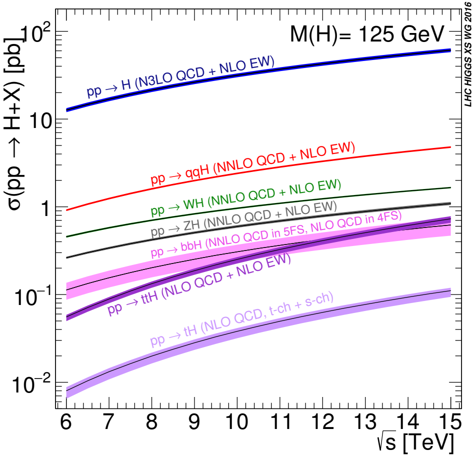
Parametric + theoretical uncertainty:

M_H[GeV]	$\mathrm{H}\to$ $\mathrm{b\bar{b}}$	$\tau^+\tau^-$	$\mathrm{c\bar{c}}$	gg	$\gamma\gamma$	WW	ZZ
120	3%	6%	12%	10%	5%	5%	5%
150	4%	3%	10%	8%	2%	1%	1%
200	5%	3%	10%	8%	2%	$< 0.1\%$	$< 0.1\%$

$\leftarrow$ dominated by $\delta\Gamma_{\mathrm{H}\to\mathrm{b\bar{b}}}$ (row 120)

SM Higgs XS predictions for the LHC

LHC Higgs XS WG '16



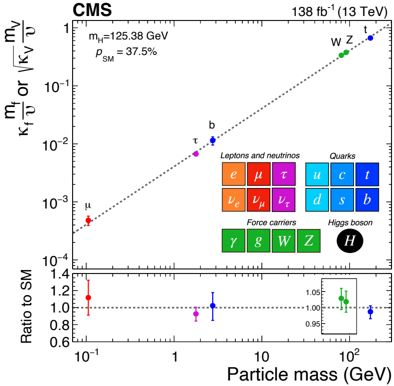
Rough numbers:

$M_{\rm H} = 125\,{\rm GeV}$	Uncertainties		NLO/NNLO/NNNLO	
$\sqrt{s} = 14\,{\rm TeV}$	theory	PDF4LHC	QCD	EW
ggF	6%	3%	>100%	5%
VBF	1%	2%	5%*	5%
WH	1%	2%	20%	7%
ZH	4%	2%	35%	5%
ttH	9%	4%	20%	1–2%

* NNNLO QCD available

... on the current experimental status

- overall good agreement between data and SM preciction
- Higgs couplings measured for 3rd and 2nd fermion generation
  $\hookrightarrow$ results confirm Higgs mechanism
- precision further increases in next years, analyses go more and more differential
  $\hookrightarrow$ towards global EFT analyses
- great future challenge: Higgs self-couplings



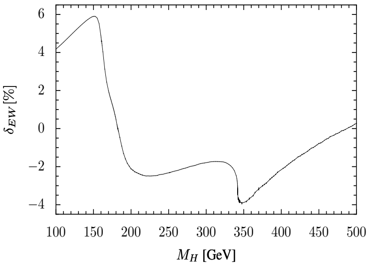
... on theory predictions and this lecture

- SM predictions in very good shape
  (N^{3}LO QCD + NLO EW for ggH/VBF, ..., NLO QCD + EW for $\mathrm{t\bar{t}H}$, ...)
- QCD issues more essential than EW $\rightarrow$ QCD lectures
- EW corrections relevant at $\sim 5\%$ level $\rightarrow$ selected examples in the following
- coupling measurements beyond κ framework $\rightarrow$ (SM)EFT lectures

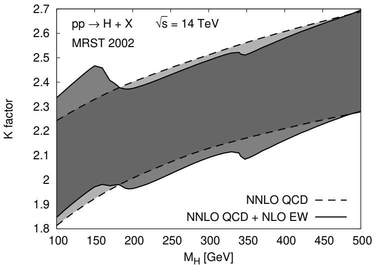
Example: EW corrections to $\mathrm{H} \to \mathrm{gg}$, $\mathrm{H} \to \gamma\gamma$, $\mathrm{pp(gg)} \to \mathrm{H} + X$

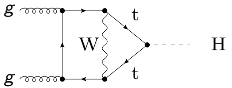
Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:



K factors for pp cross section:
(band: $M_\mathrm{H}/2 < \mu_{\mathrm{R/F}} < 2M_\mathrm{H}$, $\mu_\mathrm{R}/2 < \mu_\mathrm{F} < 2\mu_\mathrm{R}$)



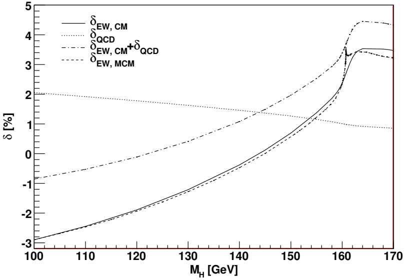


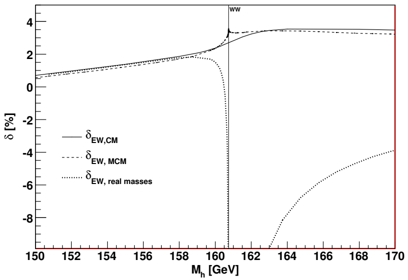
etc.

EW corrections ...

- matter at the 5% accuracy level
- numerical technique for massive 2-loop integrals introduced
  Passarino et al. '04,'08
- show non-trivial structures near WW, ZZ, $\mathrm{t\bar{t}}$ thresholds
  $\hookrightarrow$ careful inclusion of unstable-particle effects (otherwise unphysical peaks)

EW corrections to the $\mathrm{H} \to \gamma\gamma$ decay width: Actis, Passarino, Sturm, Uccirati '08

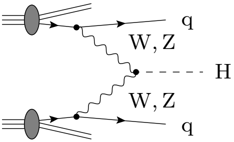




- EW and QCD corrections to $\mathrm{H} \to \gamma\gamma$ equally important!
- real $\mathrm{W}/\mathrm{Z}/\mathrm{t}$ masses lead to singularities (divergences) at $M_{\mathrm{H}} = 2M_{\mathrm{W}}$, etc.
- minimal complex-mass scheme (MCM):
  complex $\mathrm{W}/\mathrm{Z}/\mathrm{t}$ masses only in singular terms $\rightarrow$ not sufficient

  $\Rightarrow$ full complex-mass scheme (CM) required near thresholds

Example: Higgs production via weak vector-boson fusion (VBF)

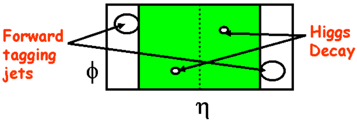


colour exchange between quark lines suppressed

$\Rightarrow$ small QCD corrections

VBF cuts and background suppression:

signature = Higgs + 2jets

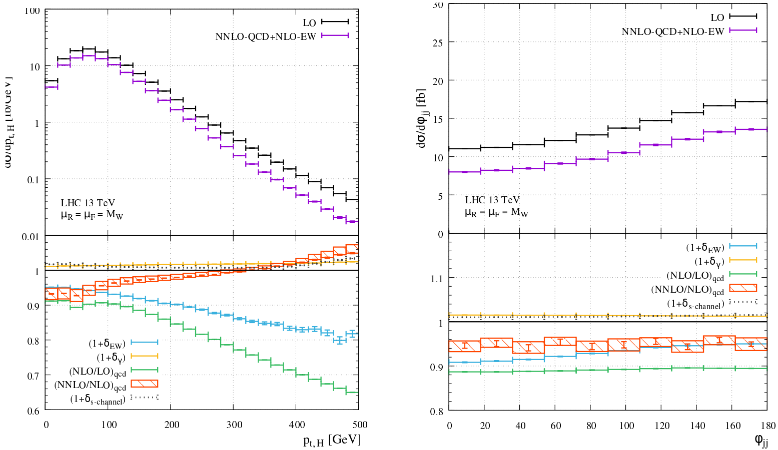


- 2 hard "tagging" jets demanded:
  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$
- tagging jets forward–backward directed:
  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0.$

$\hookrightarrow$ Suppression of background

- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or WW production Zeppenfeld et al. '94–'99
- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

Fiducial VBF cross section @ NNLO QCD + NLO EW LHC Higgs XS WG '16

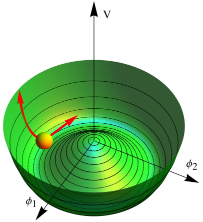


- scale uncertainty $\sim$ 1–2%
- (N)NLO QCD and NLO EW corrections $\sim$ 5–20%
- γ-induced and s-channel contributions $\sim$ 1.5%

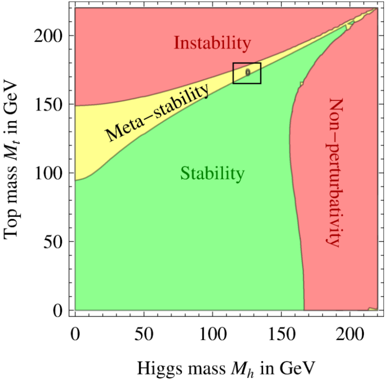
Outlook to the future:

Higgs self-coupling λ
– window to new physics ?

$$V(H) = \frac{1}{2} M_{\rm H}^2 H^2 + \frac{v}{4} \lambda H^3 + \frac{1}{16} \lambda H^4$$



Degrassi et al. '12
(see also Bednyakov et al. '15)



SM prediction: $\lambda(M_{\rm H}^2) \propto M_{\rm H}^2$ with "running" $\lambda(\mu)$ in the range $v < \mu < \Lambda = M_{\rm NP}$

Note: $M_{\rm H} = 126\,{\rm GeV}$ SM escapes problems !

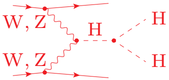
- $\lambda(\mu) < 0$: vacuum instability
- $\lambda(\mu) \to \infty$: triviality, non-perturbativity, ... consistency problem

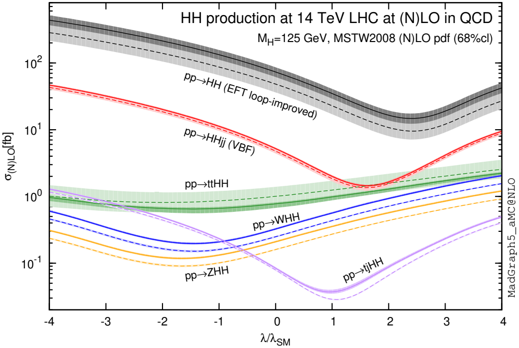
$\Rightarrow$ Exp. challenge: measuring λ in Higgs pair production

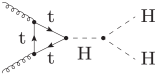
Alternative: constraints via loop effects in single-Higgs production? $\to$ EFTs

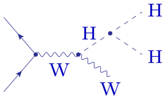
Cross sections for HH production

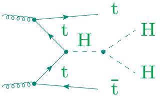
Maltoni et al. '14











Comments:

- cross sections small, additional suppression by BRs, large background
  $\Rightarrow$ great experimental challenge! (most promising $b\bar{b}\gamma\gamma, b\bar{b}\tau^+\tau^-, \ldots$)
- Exp. prospect for high-luminosity LHC: $\Delta\lambda/\lambda \sim 50\%$
- Theory predictions:
  - QCD: NLO under control, resummations
    $\hookrightarrow$ beyond: massive multi-loop calculations, great challenges!
  - EW: corrections exp. less important, but theoretically interesting ...

Literature

$\hookrightarrow$ See Lecture 1 !