Towards Electroweak Precision at the LHC

Stefan Dittmaier

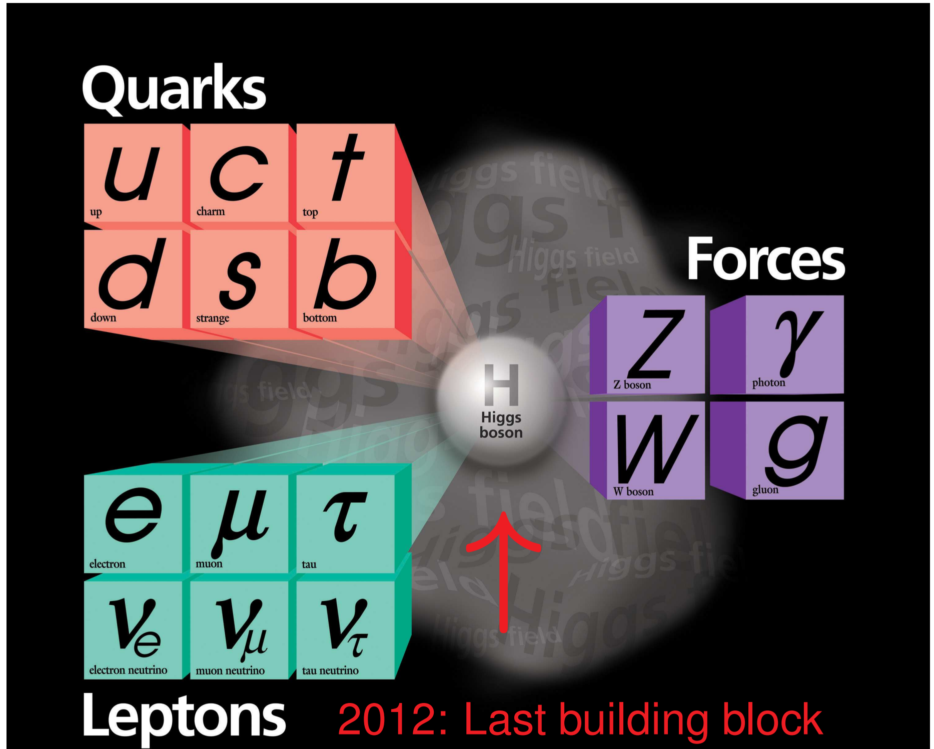
Albert-Ludwigs-Universität Freiburg

Status quo of particle phenomenology

Francois Englert

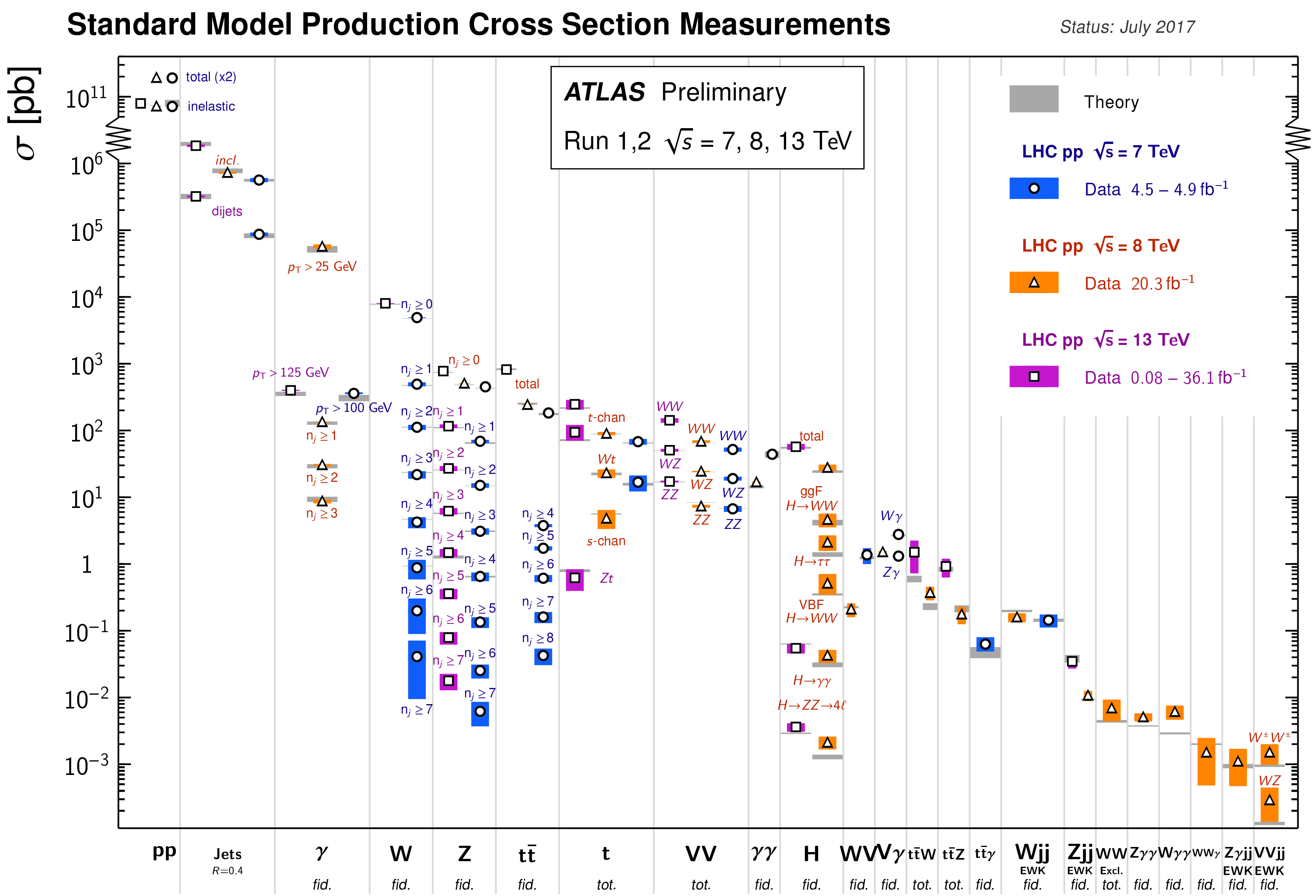
2013

Peter Higgs



2012: Last building block of the Standard Model found

Standard Model carved in stone ??



Good overall agreement between theory & experiment !

(+similar results from CMS)

LHC physics – where do we stand ?

- many analyses of SM particles
- Higgs precision physics
- new channels investigated, e.g. $\mathrm{W^+W^+} \to \mathrm{W^+W^+}$, $\mathrm{B} \to \mu\mu$
- searches for new particles (SUSY + more) generically pushed to $M \gtrsim 1\,\mathrm{TeV}$

$\Rightarrow$ SM in better shape than ever

New physics (if in reach) hides in small and subtle effects !

LHC run 2 and beyond – mission and prospects

- centre-of mass energy $13{-}14\,\mathrm{TeV}$
  $\hookrightarrow$ energy reach extends deeper into TeV range
- integrated LHC luminosity will reach $\sim 100\,\mathrm{fb}^{-1}$ per exp. at run 2
  $\hookrightarrow$ many measurements at several-% level
- some $1000\,\mathrm{fb}^{-1}$ at high-luminosity LHC ?

$\Rightarrow$ High precision needed from theory

This talk: *(topical+incomplete!)* review of recent developments at the precision frontier

Contents

Structure of precision calculations

Illustration of "‘hard"’ and "‘soft"’ parts in an event simulation

(designed by Sherpa)

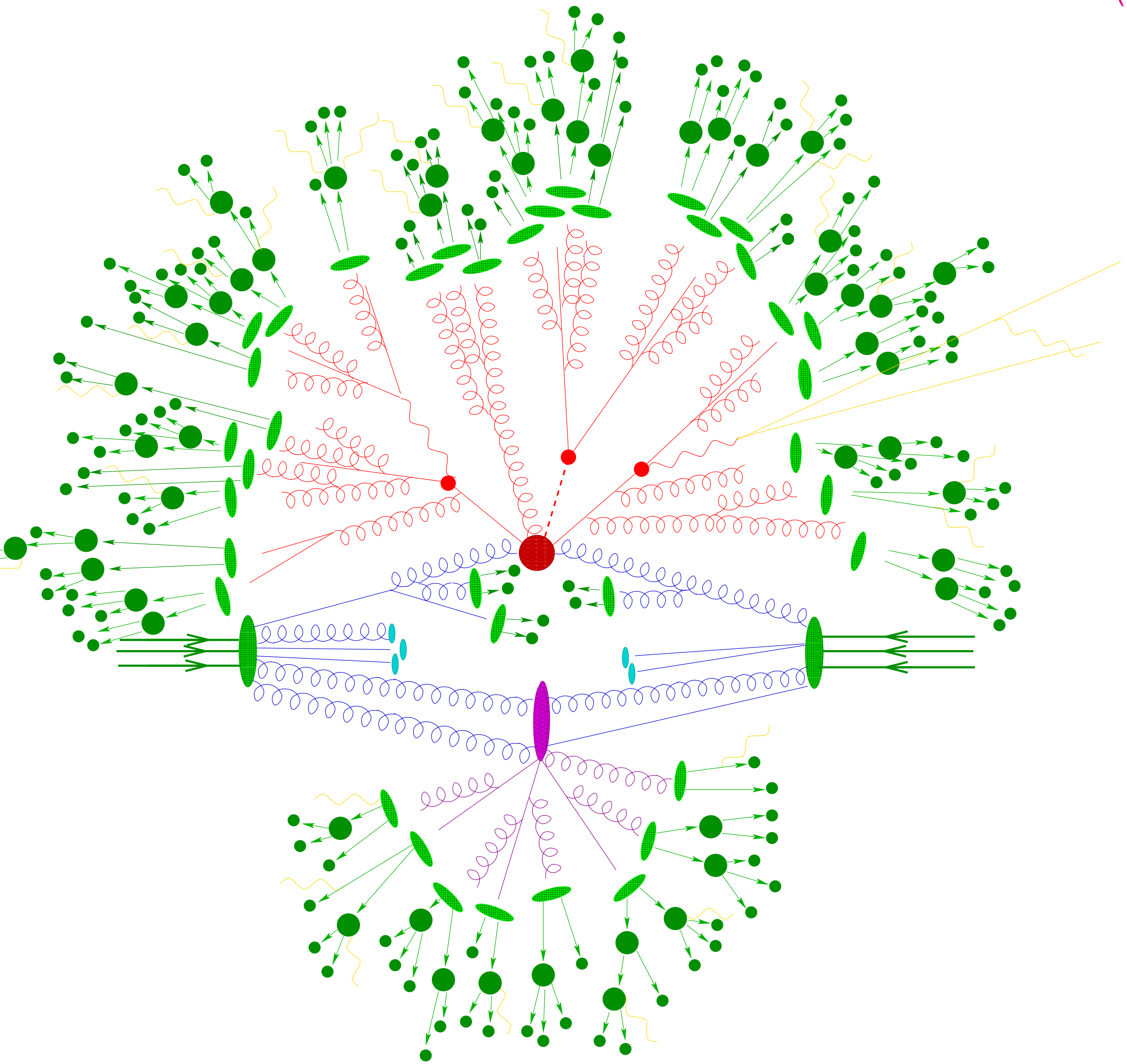


Illustration of "‘hard"’ and "‘soft"’ parts in an event simulation

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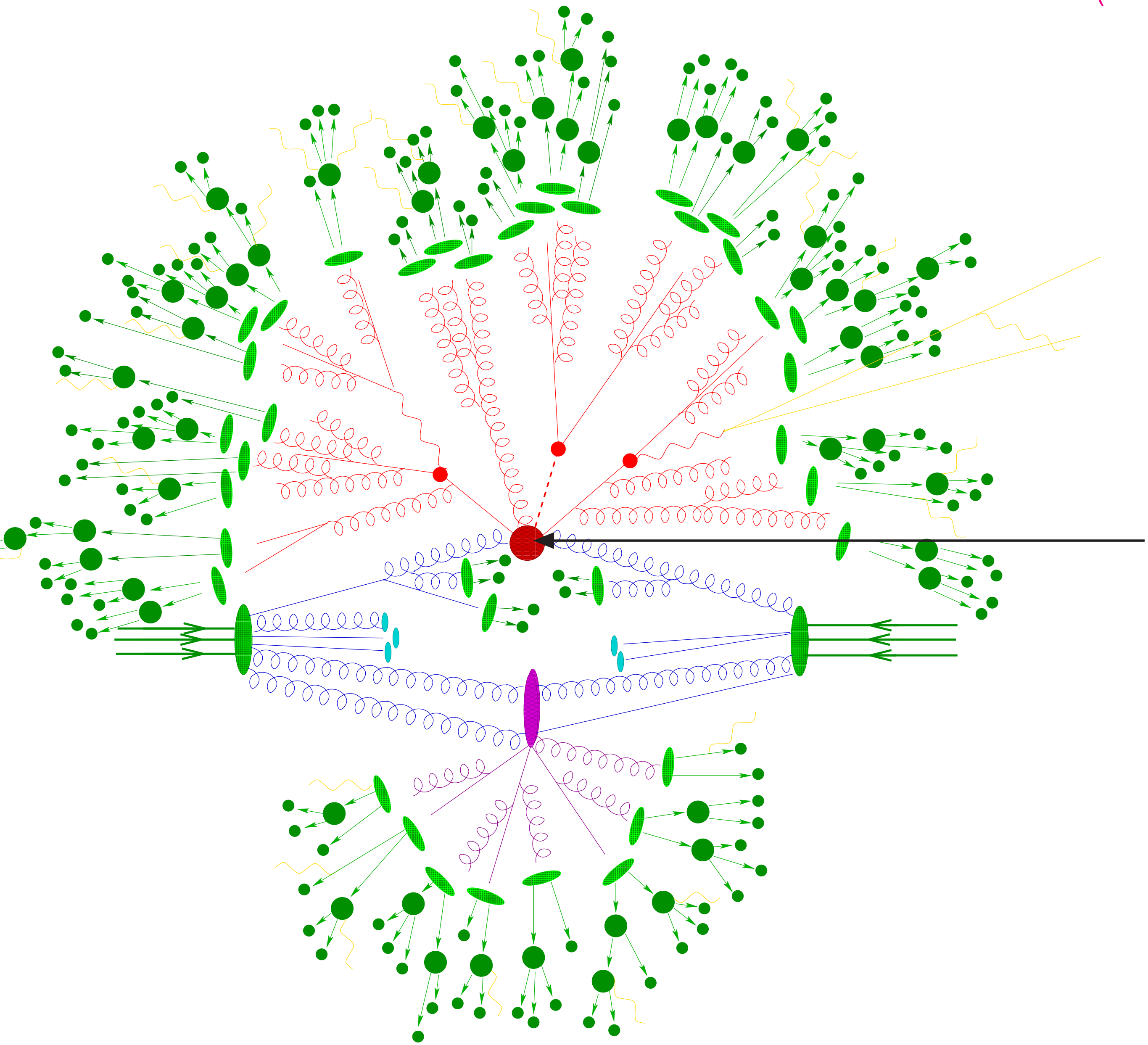


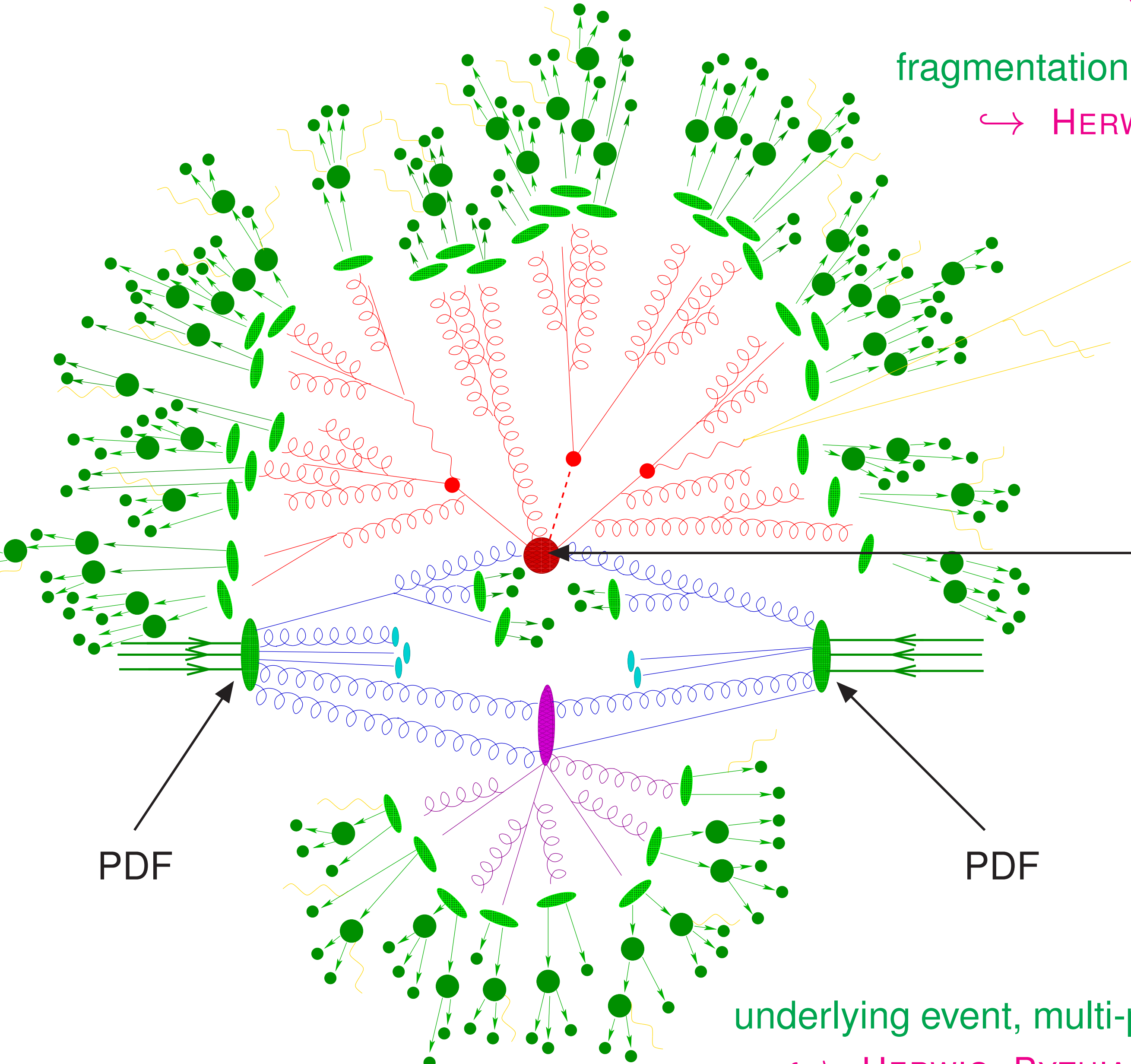
Hard partonic scattering
↪ perturbative part
= subject of this talk

Illustration of "‘hard"’ and "‘soft"’ parts in an event simulation

(designed by Sherpa)

fragmentation after parton shower

↪ HERWIG, PYTHIA, SHERPA



Hard partonic scattering
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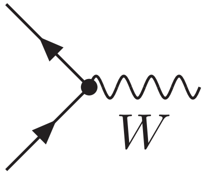
underlying event, multi-parton interactions

↪ HERWIG, PYTHIA, SHERPA

Perturbative predictions for particle processes

LO cross sections

– stable particles
– partonic final states



Perturbative predictions for particle processes

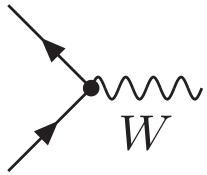
LO cross sections

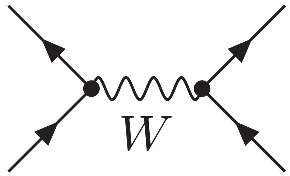
– stable particles
– partonic final states

↓

LO improvements

– particle decays
– off-shell contributions
– universal corrections





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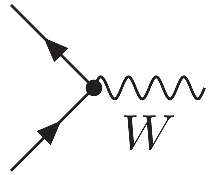

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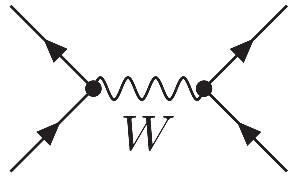

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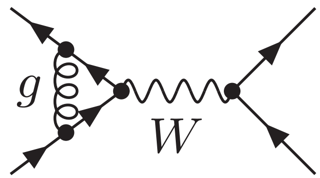
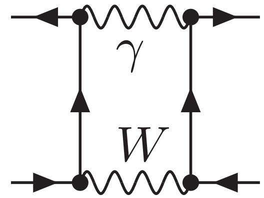
NLO cross sections

– QCD+EW corrections
– hard jets / LO Jet structure
– γ radiation





Perturbative predictions for particle processes

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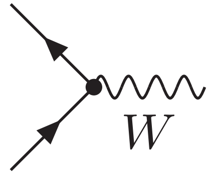

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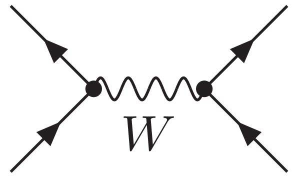

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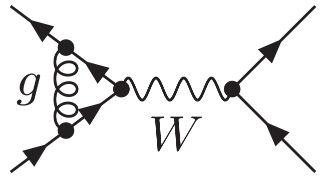
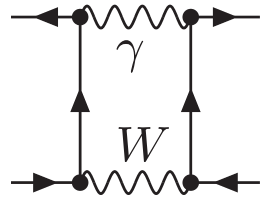
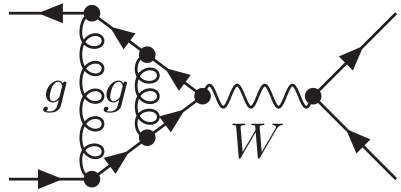
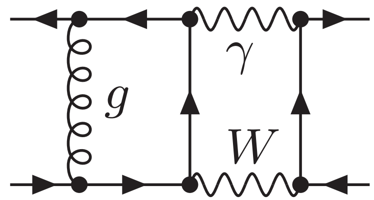




NNLO cross sections
– QCD (+EW?) corrections
– QCD$\times$EW corrections
– more hard jets / NLO jet structure





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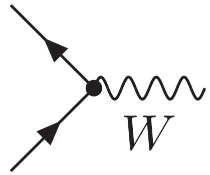

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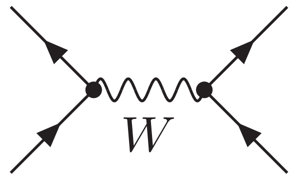

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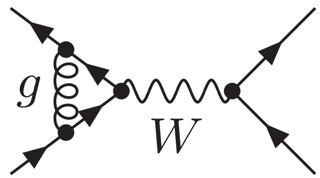

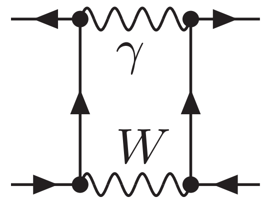

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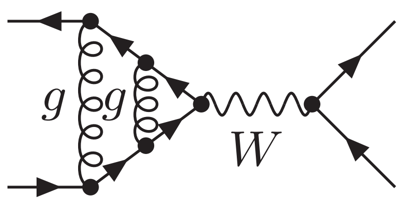

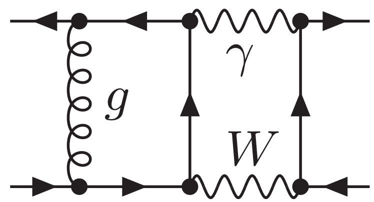

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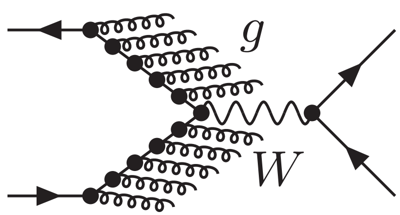
Analyt. QCD resummations
– reduced scale dependence
– elimination of perturb. artifacts
– for special observables



Perturbative predictions for particle processes

LO cross sections
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Analyt. QCD resummations
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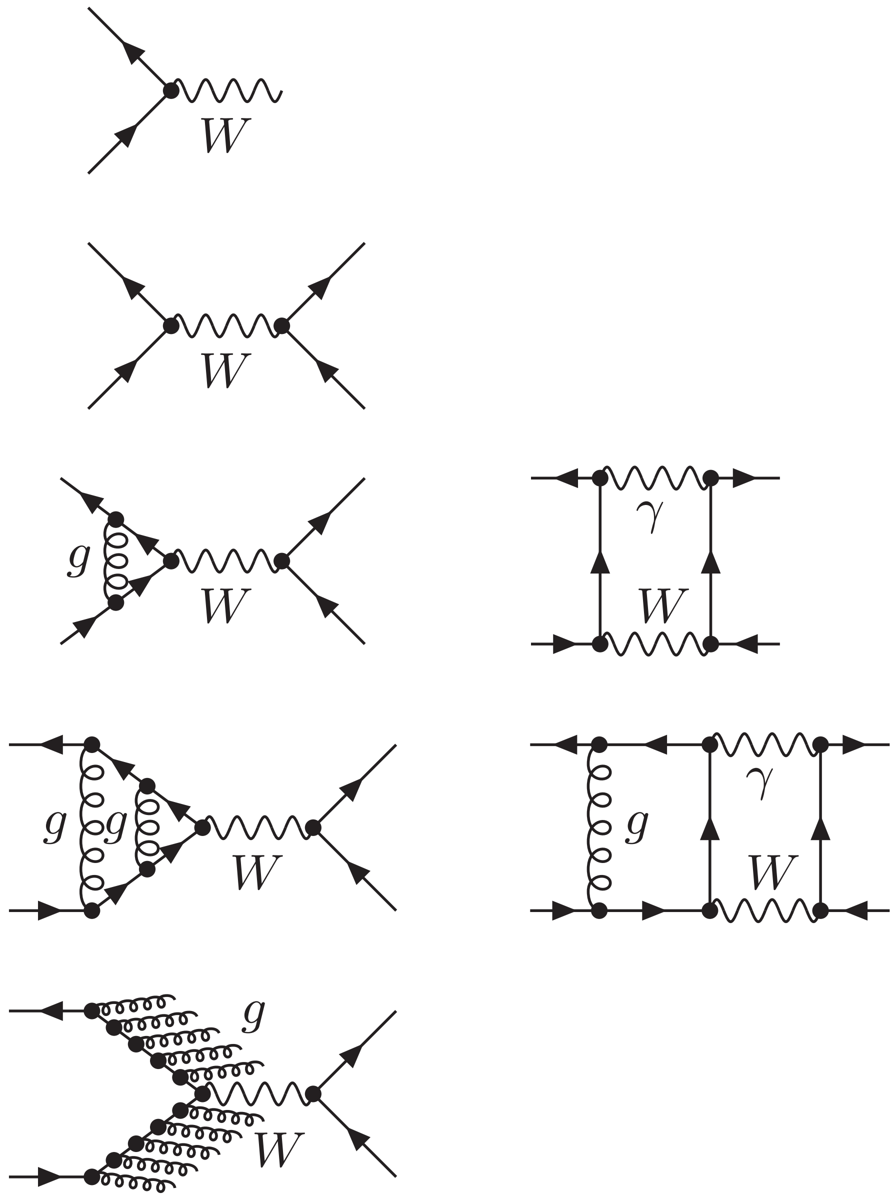
Precise pseudo-observables
σ, $\mathrm{d}\sigma/\mathrm{d}X$, M, Γ, A_{FB}, etc.



Perturbative predictions for particle processes

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Precise pseudo-observables
σ, $\mathrm{d}\sigma/\mathrm{d}X$, M, Γ, A_{FB}, etc.

LHC = "Long and Hard Calculations" (T.Binoth)

QCD corrections – issues and state of the art

- NLO:

  widely automated (2 → 4 standard, 2 → 5, 6 for selected processes)

  ↪ BlackHat, GoSam, HELAC-NLO, MadGraph5_aMC@NLO, NJet, OpenLoops, Recola, Sherpa, ...

- NLO PS merging and ME matching:

  widely automated → (a)MC@NLO, FxFx, MiNLO, POWHEG, Sherpa, ...

- NNLO:

  more & more differential results for 2 → 2 processes:

  $$\gamma\gamma,\ \mathrm{t\bar{t}},\ \mathrm{W}\gamma,\ \mathrm{Z}\gamma,\ \mathrm{WW},\ \mathrm{WZ},\ \mathrm{ZZ},\ \mathrm{W+jet},\ \mathrm{Z+jet},\ \mathrm{H+jet},\ \mathrm{2jets},\ \ldots$$

  Boughezal et al., Catani et al., Czakon et al., Cascioli et al., Gehrmann et al., Glover et al., Grazzini et al., Melnikov et al. ...'11–

- NNLO PS:

  first results in Drell–Yan, $\mathrm{gg} \to \mathrm{H}$, Higgs-strahlung

  ↪ Geneva, MiNLO, NNLOPS, UNNLOPS

- NNNLO:

  total $\mathrm{gg} \to \mathrm{H}$ cross section Anastasiou et al. '13–'16

- analytical resummations:

  a whole industry, different methods for dedicated limits, results for many procs.

Features of EW corrections

Relevance and size of EW corrections

generic size $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$ suggests NLO EW $\sim$ NNLO QCD
but systematic enhancements possible, e.g.

- by photon emission
  $\hookrightarrow$ kinematical effects, mass-singular log's $\propto \alpha \ln(m_\mu/Q)$ for bare muons, etc.
- at high energies
  $\hookrightarrow$ EW Sudakov log's $\propto (\alpha/s_W^2)\ln^2(M_W/Q)$ and subleading log's

EW corrections to PDFs at hadron colliders

induced by factorization of collinear initial-state singularities, new: photon PDF

Instability of W and Z bosons

- realistic observables have to be defined via decay products (leptons, γ's, jets)
- off-shell effects $\sim \mathcal{O}(\Gamma/M) \sim \mathcal{O}(\alpha)$ are part of the NLO EW corrections

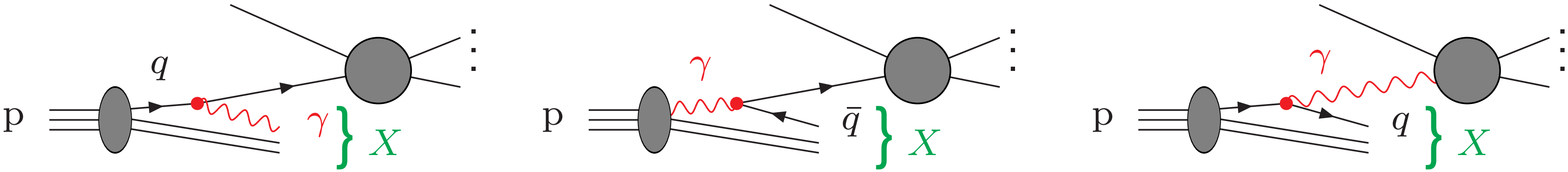
Combining QCD and EW corrections in predictions

- how to merge QCD and EW results with a proper error estimate
- reweighting procedures in MC's

More precision in

... parton distribution functions

Electroweak effects in PDFs



Collinear splittings $q \to q\gamma$, $\gamma \to q\bar{q}$ lead to quark mass singularities

- absorption of $\alpha \ln m_q$ singularities via factorization into redefined PDFs
  $\hookrightarrow$ $\mathcal{O}(\alpha)$ corrections in DGLAP evolution (evaluate, e.g., with APFEL, Bertone et al. '13)

- $\mathcal{O}(\alpha)$ corrections to all PDFs
  $\hookrightarrow$ typical impact: $\Delta(\mathrm{PDF}) \lesssim 0.3\%\ (1\%)$ for $x \lesssim 0.1\ (0.4)$, $\mu_{\mathrm{fact}} \sim M_{\mathrm{W}}$

- photon PDF $\sim \dfrac{Q_q^2 \alpha}{\alpha_{\mathrm{s}}} \times$ gluon PDF $\sim 10^{-2} \times$ gluon PDF
  $\hookrightarrow$ inelastic (p breaks up) + elastic (p remains intact) contributions

PDF sets with $\mathcal{O}(\alpha)$ effects and γPDF:

- MRSTQED04 Martin et al. [MRST collaboration] '04

  $\hookrightarrow$ only inelastic γPDF from model, $\Delta_\gamma \sim 20\%$ $(x \sim 0.01{-}0.1)$

- NNPDF2.3/3.0QED Ball et al. [NNPDF collaboration] '13,'14

  $\hookrightarrow$ inelastic+elastic fitted to high-mass Drell–Yan data, $\Delta_\gamma \sim 20{-}100\%$

- CT14QEDinc Schmidt et al. [CTEQ collaboration] '15

  $\hookrightarrow$ inelastic from model + fit to DIS data, elastic from Weizsäcker–Williams

  $\Delta_\gamma \sim 5{-}10\%$

- LUXqed Manohar et al. '16,'17

  $\hookrightarrow$ inelastic+elastic derived from proton structure functions and formfactors

  $\Delta_\gamma \sim 1{-}2\%$ Breakthrough!

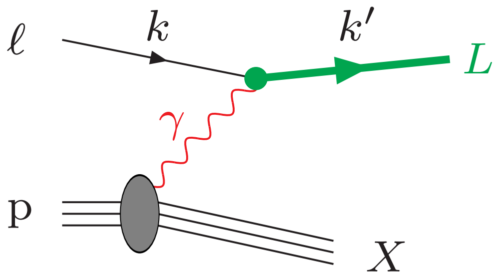
- γPDF determinations not available via LHAPDF by

  Harland-Lang et al. '16; xFitter (Giuli et al.) '17

  $\hookrightarrow$ model for inelastic+elastic fitted to high-mass Drell–Yan data, $\Delta_\gamma^{\mathrm{xFit}} \sim 30\%$

LUXqed photon PDF from DIS structure functions

Manohar et al. '16



Heavy, neutral toy lepton L with mass $M \gg M_\mathrm{p}$

$$\mathcal{L}_\mathrm{int} = g\overline{L}\sigma^{\mu\nu}F_{\mu\nu}\ell$$

Parton model cross section: $\quad xs = M^2,\ Q^2 = -(k-k')^2$

$$\sigma = g^2\left\{xf_\gamma(x,\mu_\mathrm{F}^2) + \sum_q \frac{Q_q^2\alpha}{2\pi}\int_x^1 \frac{\mathrm{d}z}{z}\,\frac{x}{z}\,f_q(x,\mu_\mathrm{F}^2)\left[zp_{\gamma q}(z)\ln\left(\frac{xs}{\mu_\mathrm{F}^2}\right) + \dots\right]\right\}$$

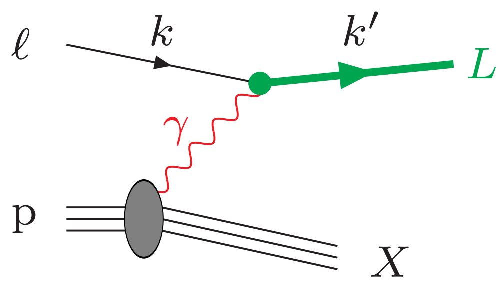
$\stackrel{!}{=}$ inclusive hadronic cross section parametrized by hadronic tensor $W^{\mu\nu}$:

$$\sigma_{\ell\mathrm{p}\to LX} \propto g^2\int\frac{\mathrm{d}^4k'}{Q^4}\,L_{\mu\nu}(k,k')\,\underbrace{W^{\mu\nu}(p,p_\gamma)}\,\delta(k'^2-M^2)$$

$$= -g_\mathrm{T}^{\mu\nu}F_1(x,Q^2) + \frac{p_\mathrm{T}^\mu p_\mathrm{T}^\nu}{pp_\gamma}F_2(x,Q^2)$$

LUXqed photon PDF from DIS structure functions

Manohar et al. '16



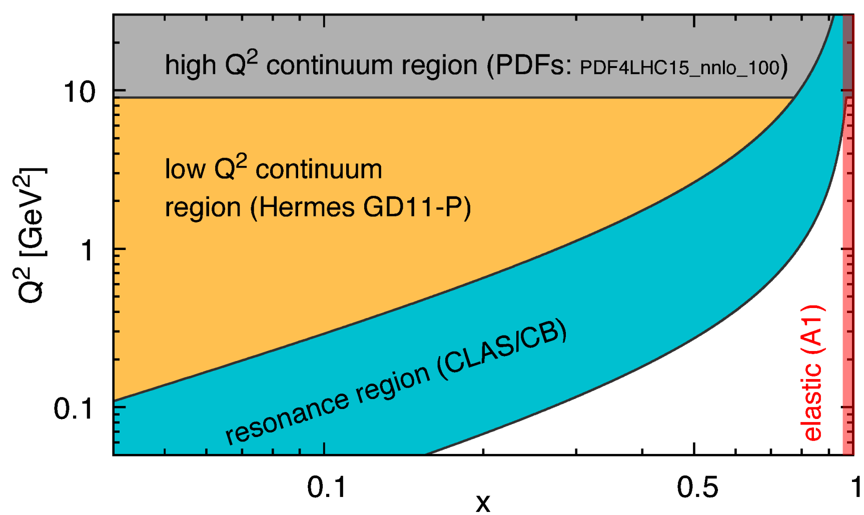
Heavy, neutral toy lepton L with mass $M \gg M_{\mathrm{p}}$

$$\mathcal{L}_{\mathrm{int}} = g\overline{L}\sigma^{\mu\nu}F_{\mu\nu}\ell$$

$\Rightarrow$ f_γ in terms of structure functions F_2 and $F_{\mathrm{L}} = F_2 - 2xF_1$:

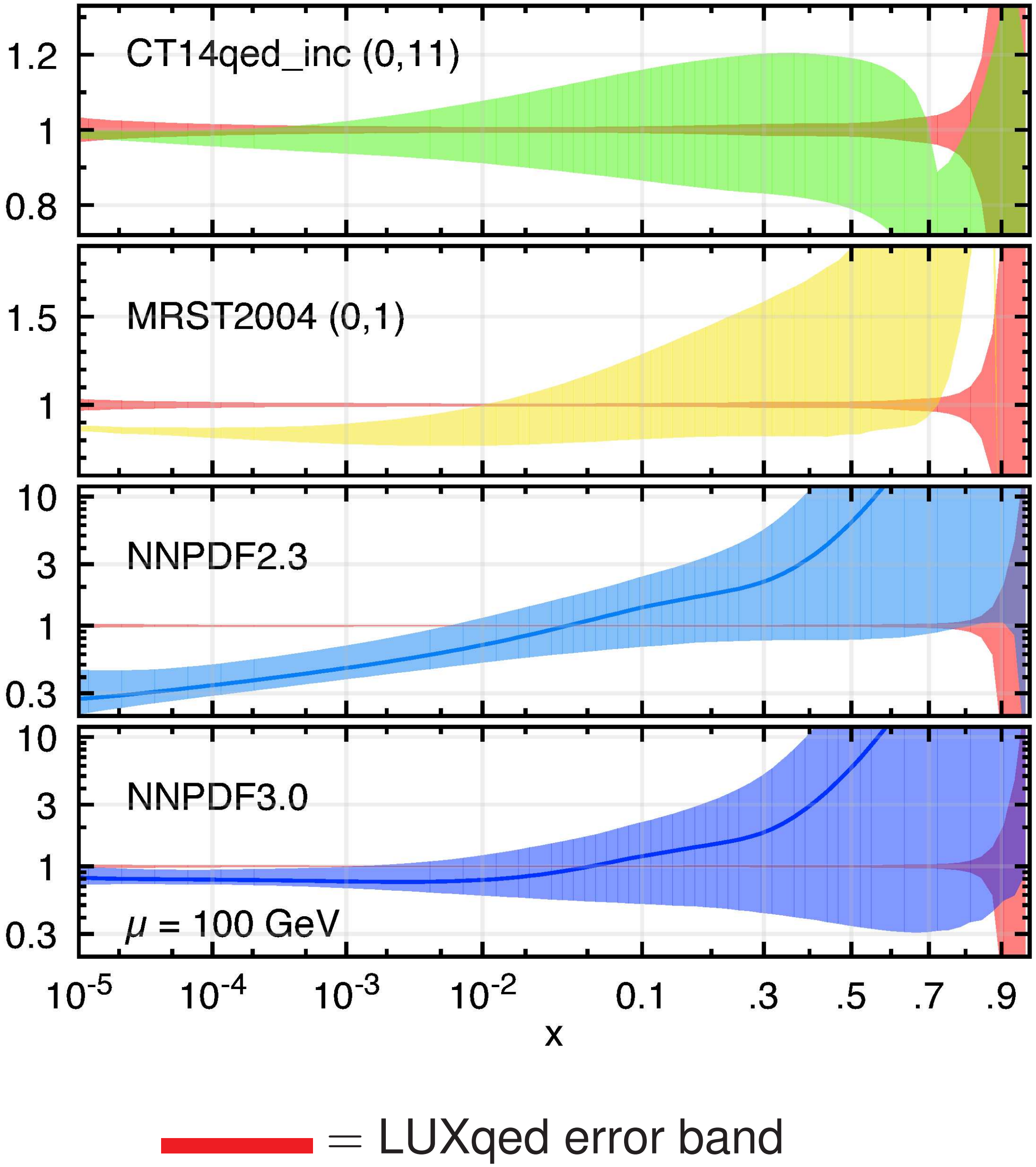
$$x f_\gamma(x,\mu^2) = \frac{1}{2\pi\alpha}\int_x^1 \frac{\mathrm{d}z}{z}\left\{\int^{\mu^2\cdots}\frac{\mathrm{d}Q^2}{Q^2}\,\alpha(Q^2)^2\left[(z p_{\gamma q}(z)+\ldots)F_2\left(\frac{x}{z},Q^2\right) - z^2 F_{\mathrm{L}}\left(\frac{x}{z},Q^2\right)\right]\right.$$
$$\left. - \alpha(\mu^2)^2 z^2 F_2\left(\frac{x}{z},\mu^2\right)\right\}$$

Integral directly evaluated from data!



LUXqed versus other photon PDF variants:

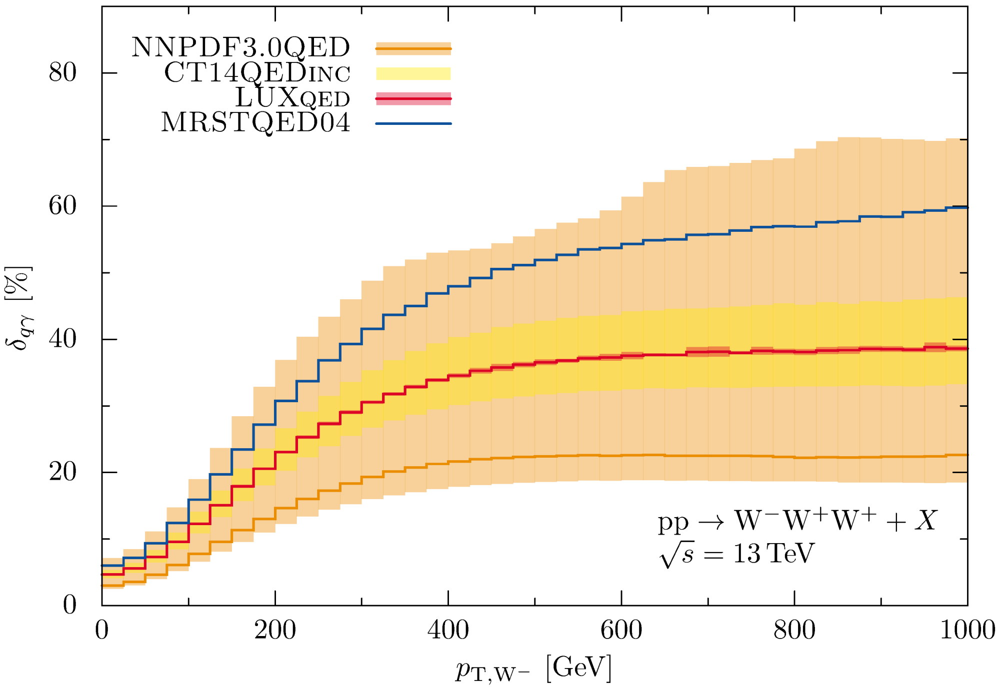
Manohar et al. '16



Photon-induced channels in LHC processes

- Significant in high-mass Drell–Yan production
- Potential impact in all W production processes
- $q\gamma$ contributions typically reduced by jet veto

An extreme example: $\mathrm{pp}(q\gamma) \to \mathrm{WWW} + X$ S.D., Huss, Knippen '17



$\sqrt{s}$[TeV]	σ^{NLO}[pb]	$\delta^{\mathrm{EW}}_{q\gamma}$ [%]
7	0.04469	5.7
8	0.05792	6.6
13	0.1381	10.7
14	0.1565	11.5
100	2.697	40.3

More precision in

... jet production

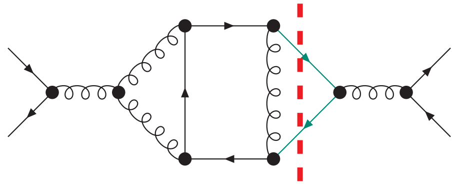
Hadronic jet production at NNLO QCD

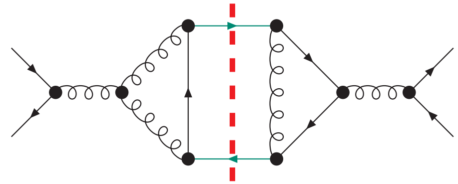
Currie, Glover, Pires '16; Currie et al. '17

First results available! (leading colour approximation)

- NNLO contribution of $q\bar{q}$ channel: $(\mathrm{gg}, q\mathrm{g}, \ldots$ analogously)

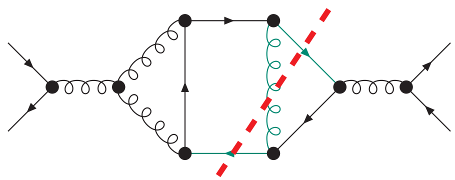
$$\Delta\hat{\sigma}_{\mathrm{NNLO},q\bar{q}} = \int_2 \left[2\,\mathrm{Re}\left\{ \mathcal{M}^{(2\to2)}_{\text{2-loop}}\, \mathcal{M}^{(2\to2)*}_{\text{tree}} \right\} + \left| \mathcal{M}^{(2\to2)}_{\text{1-loop}} \right|^2 \right]$$

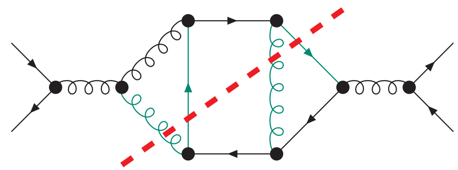




Glover et al. '01–'03; Bern et al. '02–'04

$$+ \int_3 2\,\mathrm{Re}\left\{ \mathcal{M}^{(2\to3)}_{\text{1-loop}}\, \mathcal{M}^{(2\to3)*}_{\text{tree}} \right\} + \int_4 \left| \mathcal{M}^{(2\to4)}_{\text{tree}} \right|^2$$





Bern et al. '93,'95; Kunszt et al. '94

- **Last bottleneck:** consistent cancellation of infrared singularities between 2-loop$(2\to2)$, 1-loop$(2\to2,3)$, tree$(2\to4)$ parts

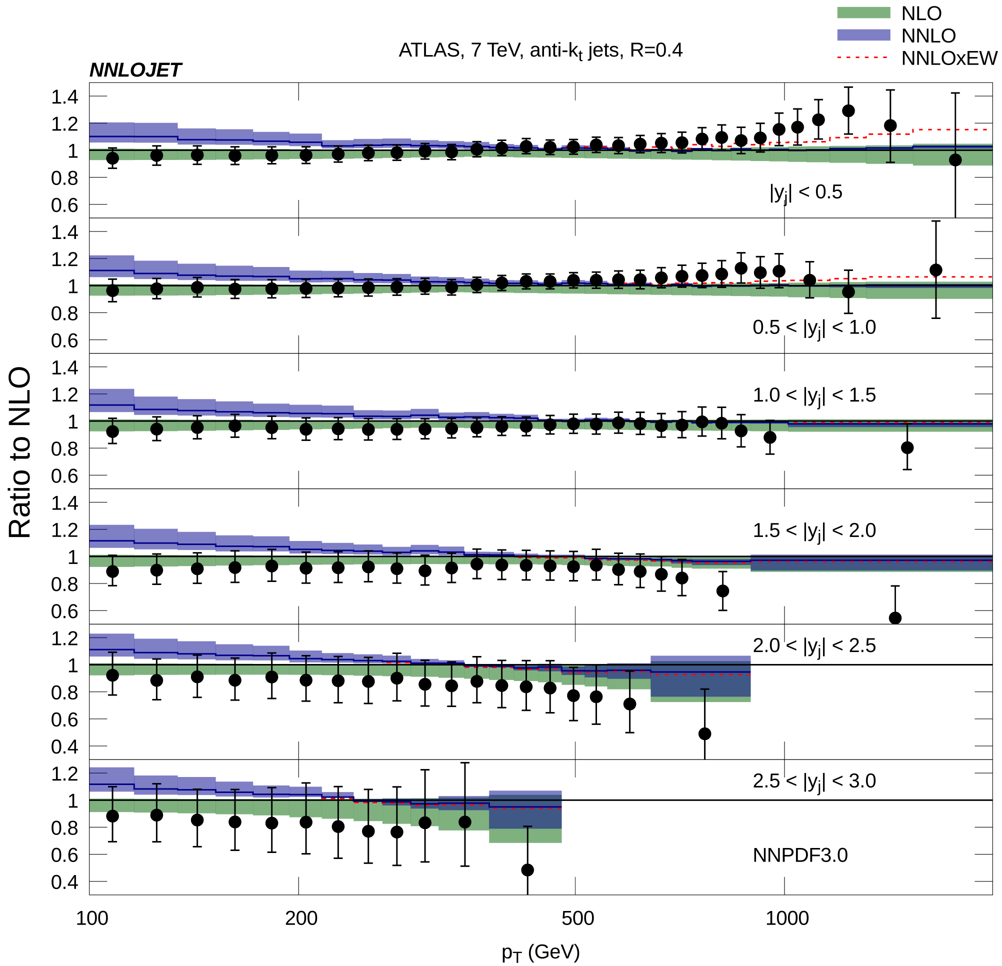
$\hookrightarrow$ "antenna subtraction" successfully applied

Gehrmann-DeRidder / Gehrmann et al. '05–'12; Currie et al. '13

Single-jet inclusive production at NNLO QCD

Currie, Glover, Pires ’16

(N)NLO QCD versus ATLAS data:



Rapidity slices:

central region

forward/backward region

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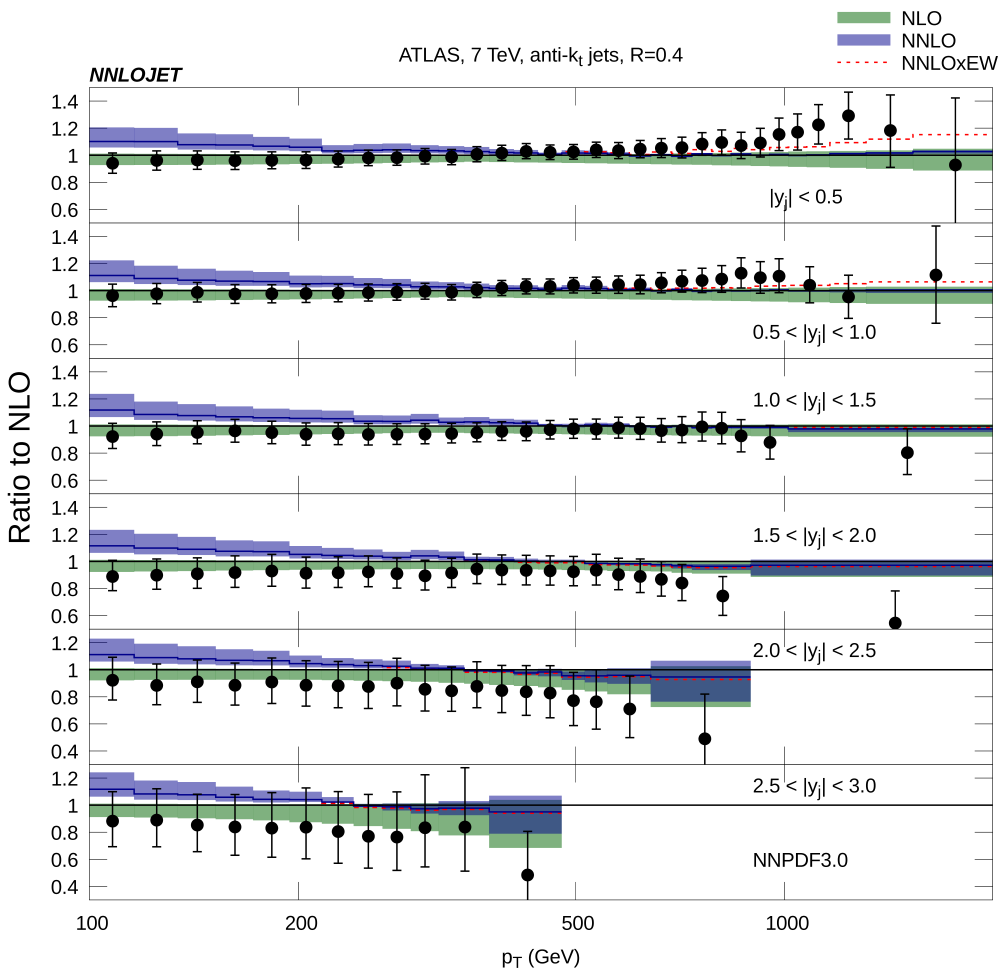

- Reduction of scale uncertainties:

  NLO $\rightarrow$ NNLO QCD

  10–20% some % at large p_{T}

- QCD versus data:
  - ◇ NLO: agreement
  - ◇ NNLO: tension at low p_{T}

  But: LHC/Tevatron inclusive jets enter PDF fit in NNLO$_{\mathrm{approx}}$ QCD

  $\hookrightarrow$ Impact on PDF fits expected!

Single-jet inclusive production at NNLO QCD

Currie, Glover, Pires '16

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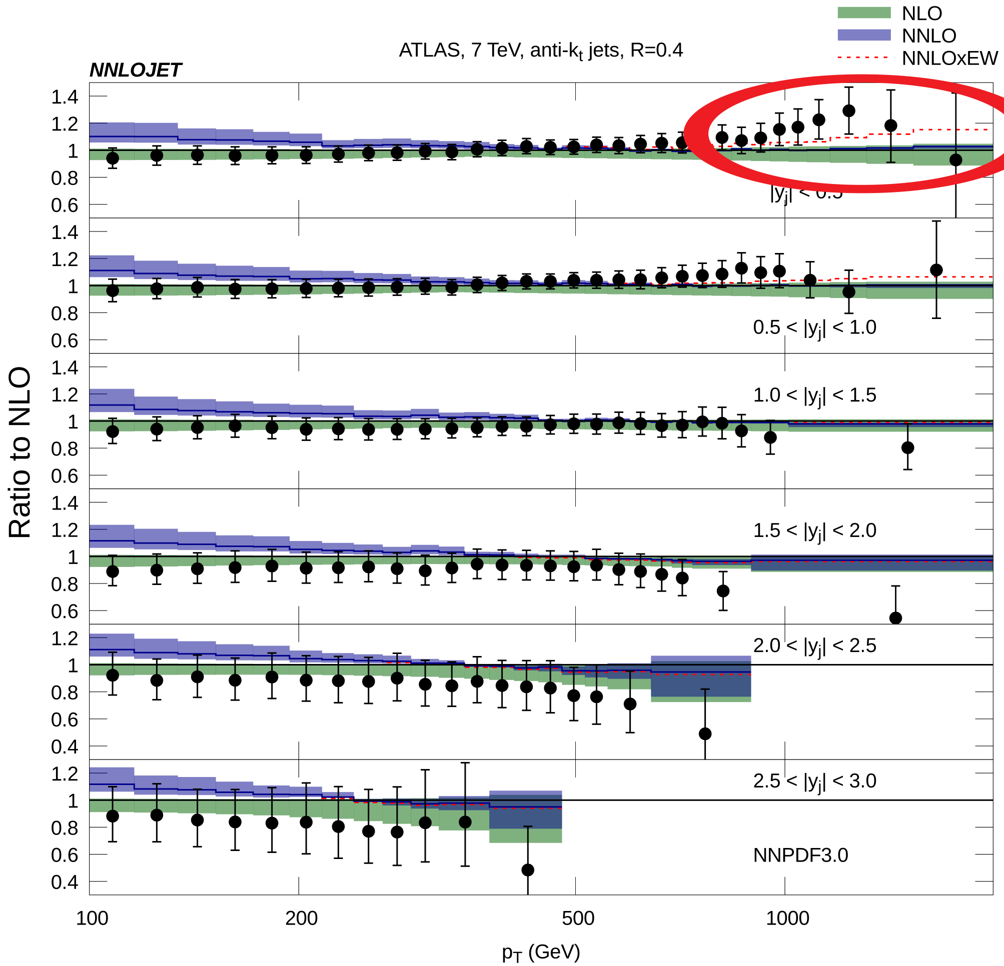


- Upcoming sensitivity to
  EW corrections S.D., Huss, Speckner '12
  Frederix et al. '17

- Reduction of scale uncertainties:
  NLO $\to$ NNLO QCD
  10–20% some % at large p_T

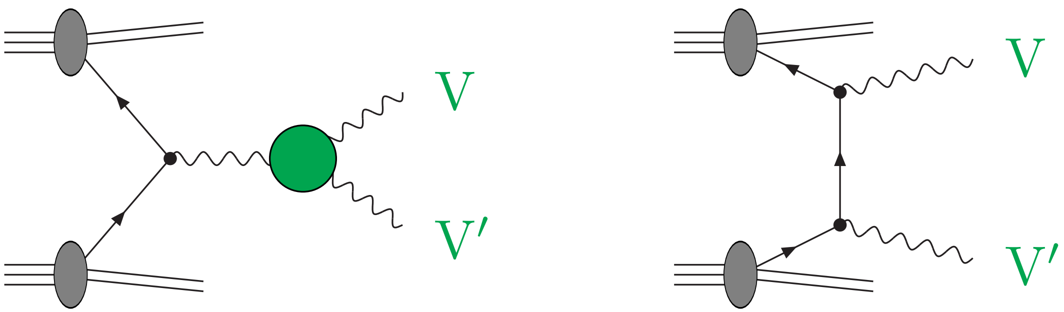
- QCD versus data:
  - NLO: agreement
  - NNLO: tension at low p_T

  But: LHC/Tevatron inclusive jets enter PDF fit in NNLO$_{\text{approx}}$ QCD
  $\hookrightarrow$ Impact on PDF fits expected!

More precision in

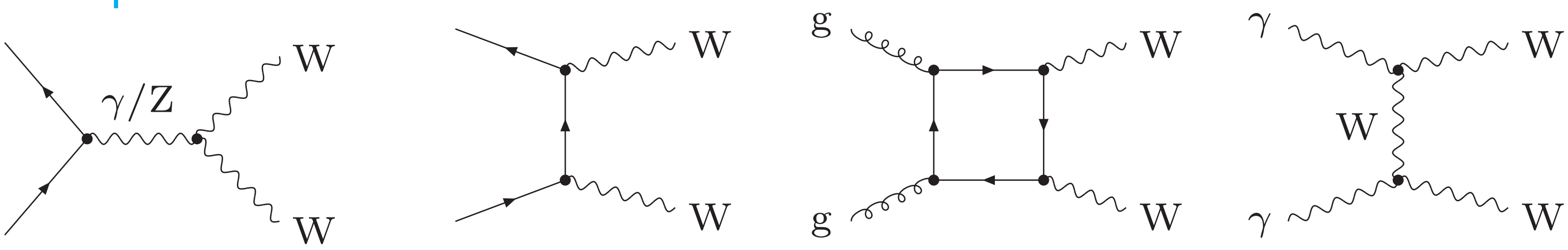
... weak gauge-boson production

Electroweak di-boson production

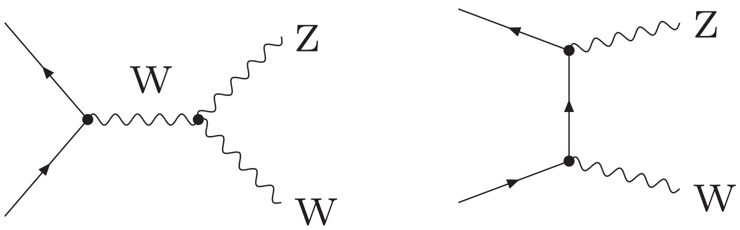


Complementarity in WW / WZ / ZZ production

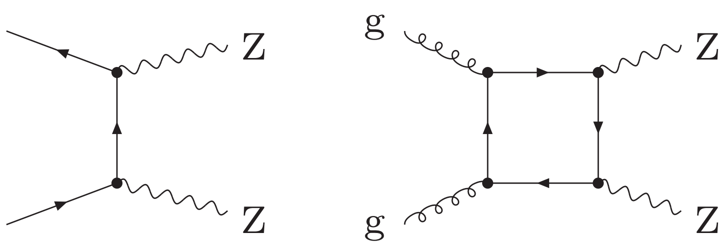
WW production:



WZ production:

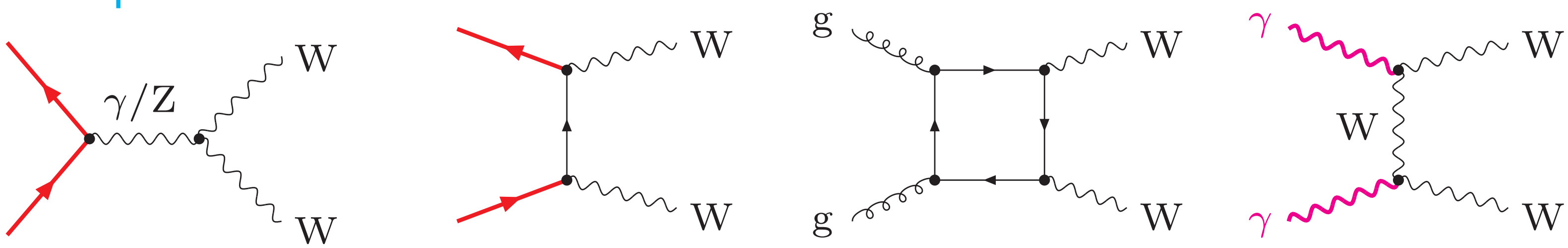


ZZ production:

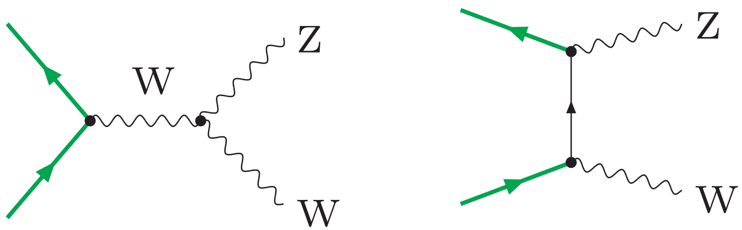


Complementarity in WW / WZ / ZZ production

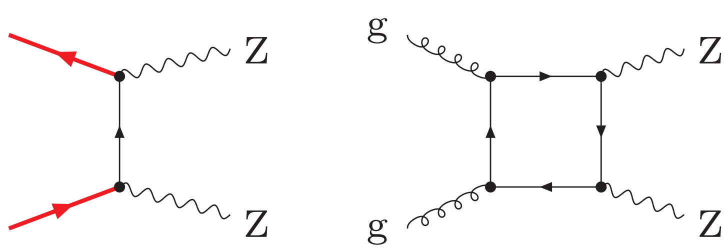
WW production:



WZ production:



ZZ production:

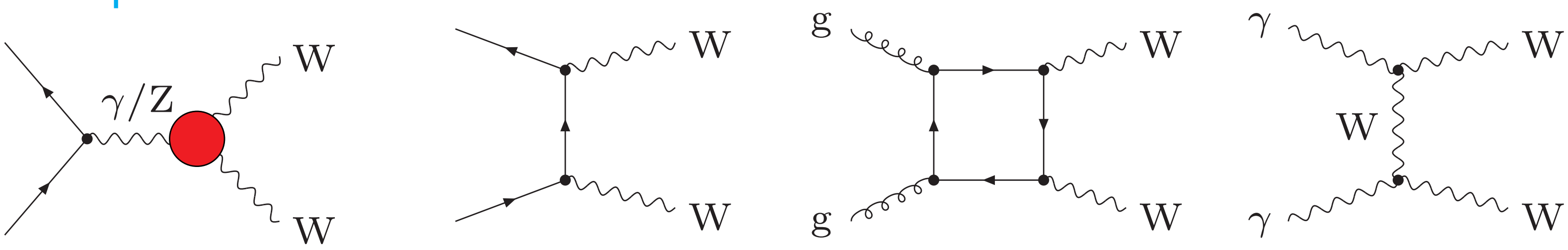


Sensitivity to different PDF combinations:

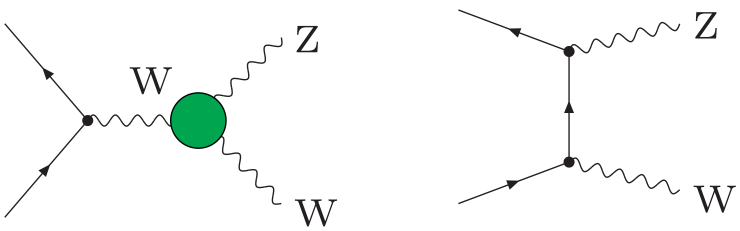
- $q\bar{q}$ in $\mathrm{WW/ZZ}$
- $u\bar{d}/d\bar{u}$ in $\mathrm{W^+Z/W^-Z}$
- $\gamma\gamma$ in WW

Complementarity in WW / WZ / ZZ production

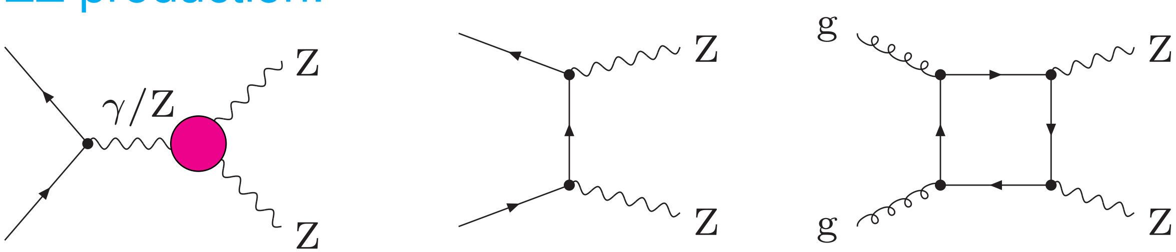
WW production:



WZ production:



ZZ production:

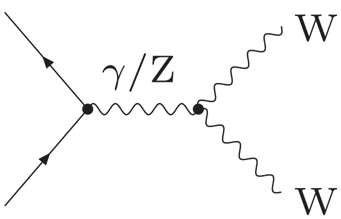


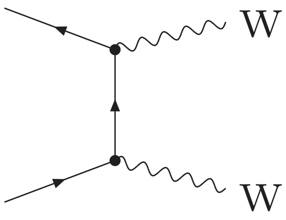
Sensitivity to different anomalous TGCs:

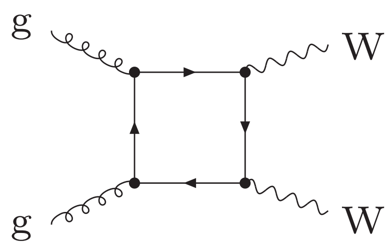
- overlay of $\gamma\mathrm{WW}/\mathrm{ZWW}$ in WW
- only ZWW in WZ
- $\gamma\mathrm{ZZ}/\mathrm{ZZZ}$ in ZZ

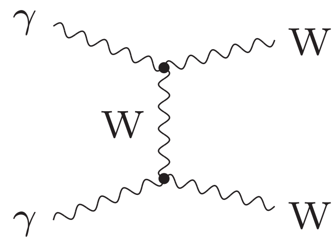
Complementarity in WW / WZ / ZZ production

WW production:

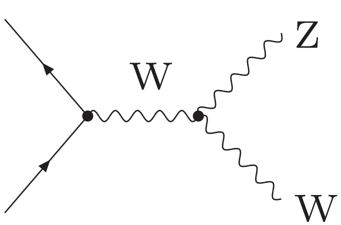


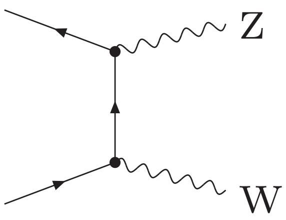




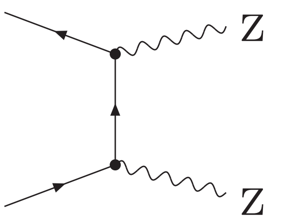


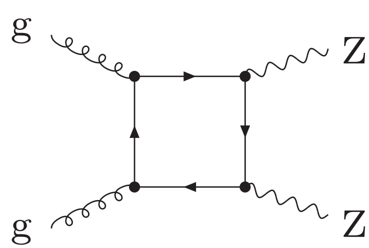
WZ production:





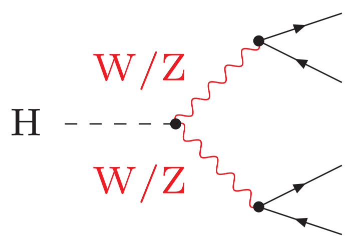
ZZ production:





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

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

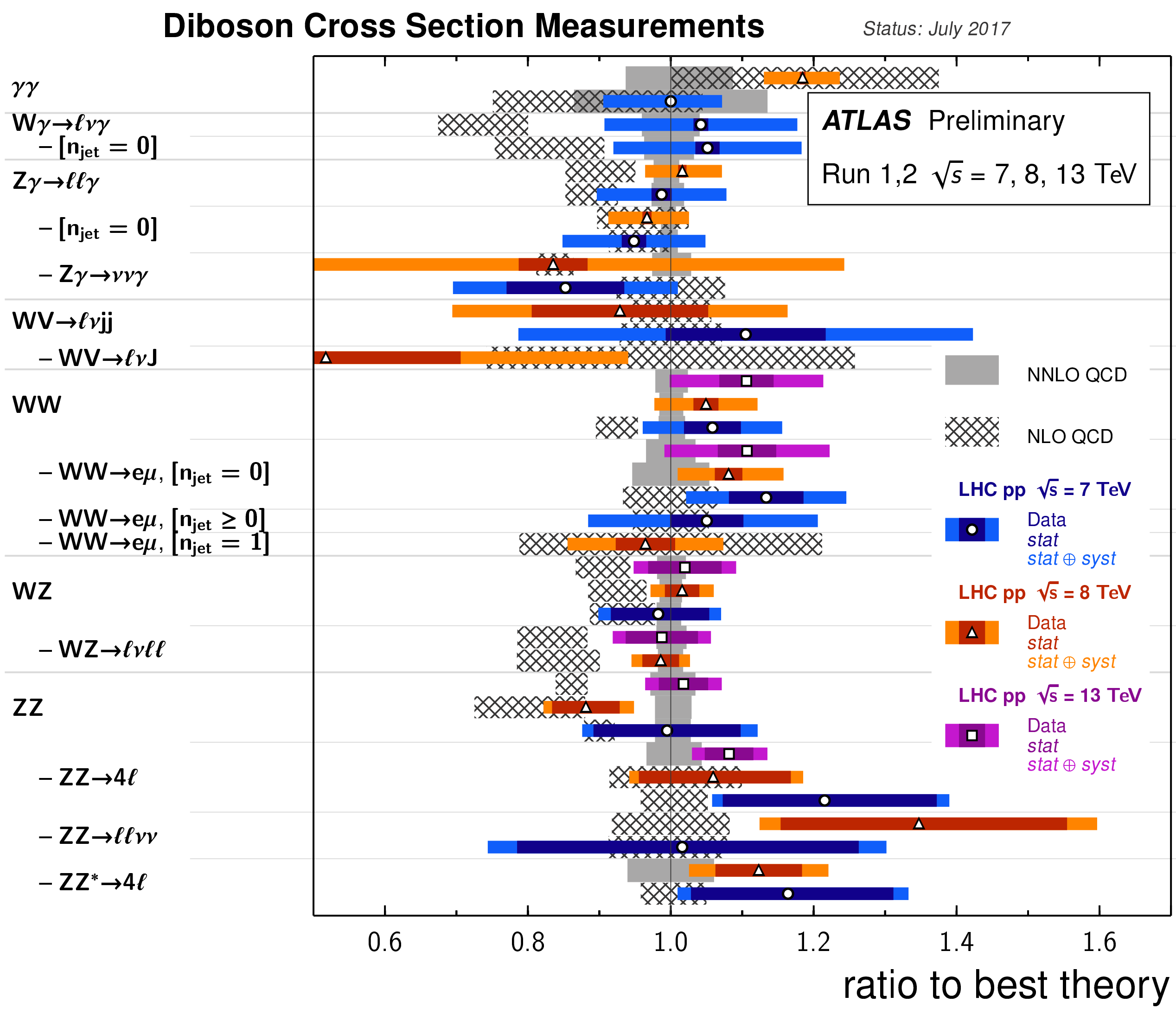


State-of-the-art predictions for $\mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}$ production

- NNLO QCD (off-shell $\mathrm{W/Z}$ with leptonic decays)
  - WW Gehrmann et al. ’14; Grazzini et al. ’16
  - ZZ Cascioli et al. ’14; Grazzini, Kallweit, Rathlev ’15
  - WZ Grazzini et al. ’16
  - $\mathrm{gg} \to \mathrm{WW/ZZ}$ LO Binoth et al. ’05,’06 $+$ NLO QCD Caola et al. ’15,’16

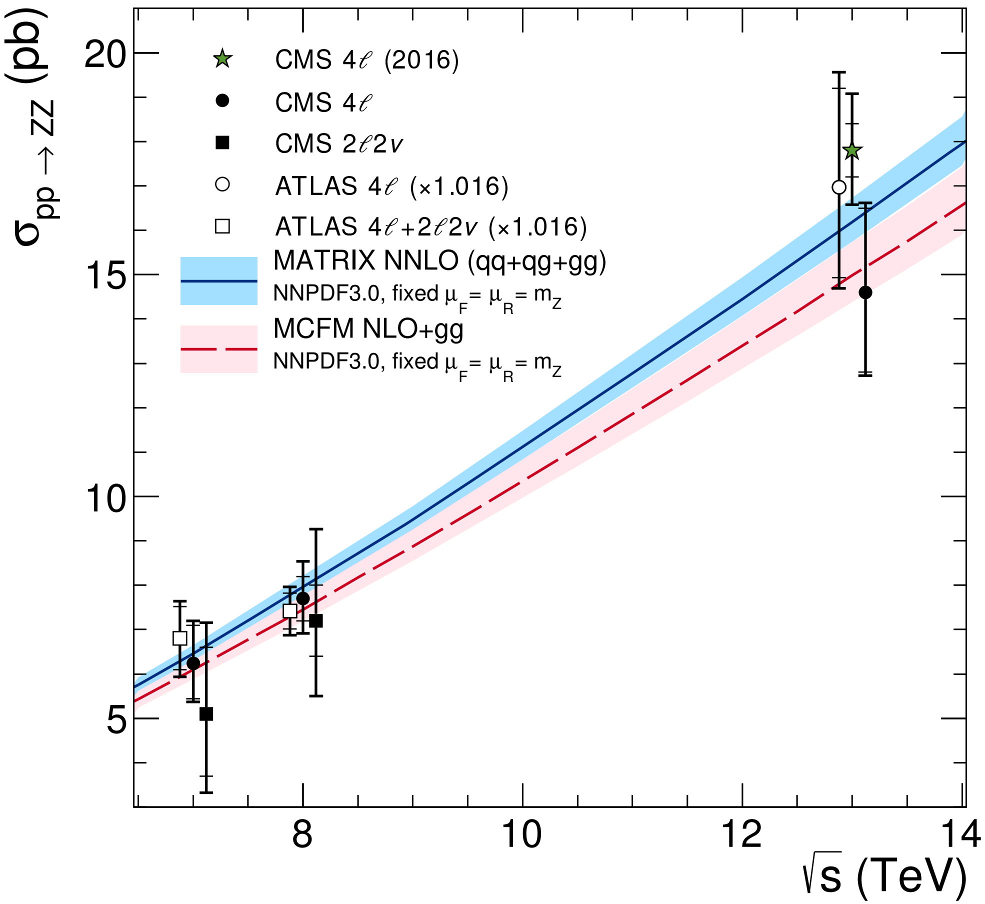
- NLO EW
  - stable $\mathrm{W/Z}$ bosons — Bierweiler, Kasprzik, Kühn ’12/’13; Baglio, Le, Weber ’13
  - $\mathrm{pp} \to \mathrm{WW} \to 4\ell$ in DPA — Billoni et al. ’13
  - approximative inclusion in HERWIG++ — Gieseke, Kasprzik, Kühn ’14
  - $\mathrm{pp} \to \mathrm{ZZ} \to 4\ell$ with off-shell Z’s — Biedermann et al. ’16
  - $\mathrm{pp} \to \mathrm{WW} \to 2\ell 2\nu$ with off-shell W’s — Biedermann et al. ’16; Kallweit et al. ’17
  - $\mathrm{pp} \to \mathrm{WZ} \to 3\ell\nu$ with off-shell $\mathrm{W/Z}$’s — Biedermann et al. ’17

Theory versus experiment for di-boson production



Note: impact of NNLO QCD corrections significant !

ZZ production – NNLO QCD theory versus experiment

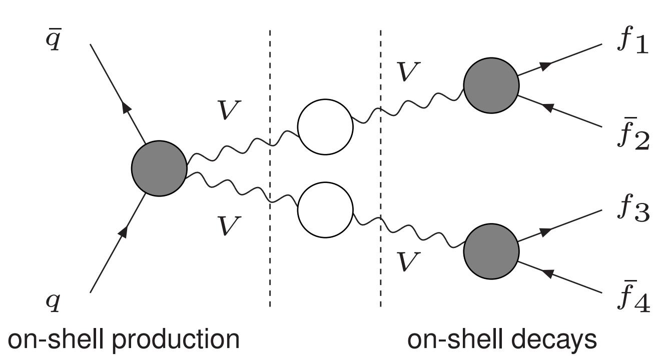


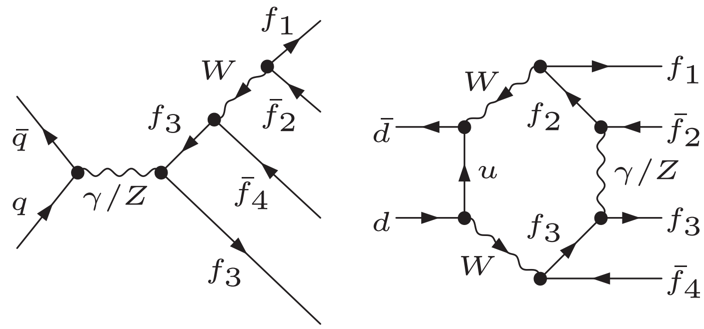
Good agreement between TH and EXP !

- NNLO QCD correction $\sim 7(12)\%$ @ $8(13)$ TeV, scale uncertainty $\lesssim 3\%$
- gg contribution $\sim 7(10)\%$ @ $8(13)$ TeV
- higher energy & higher statistics $\to$ EW corrections important

EW corrections with leptonic W/Z decays

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





- expansion about resonance poles
  $\hookrightarrow$ factorizable & non-factorizable corrs.
- not many diagrams ($2\to2$ production)

\+ numerically fast

– validity only for $\sqrt{\hat{s}} > 2M_V + \mathcal{O}(\Gamma_V)$

- off-shell calculation with complex-mass scheme
- many off-shell diagrams ($\sim 10^3$/channel)

– CPU intensive

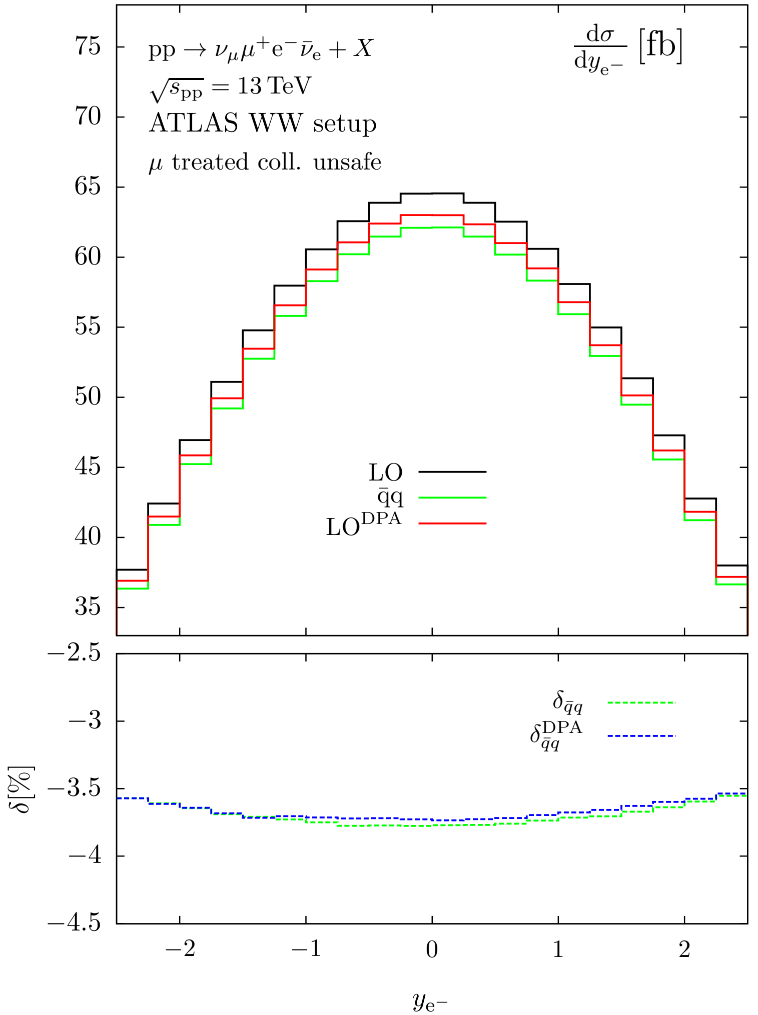
\+ NLO accuracy everywhere

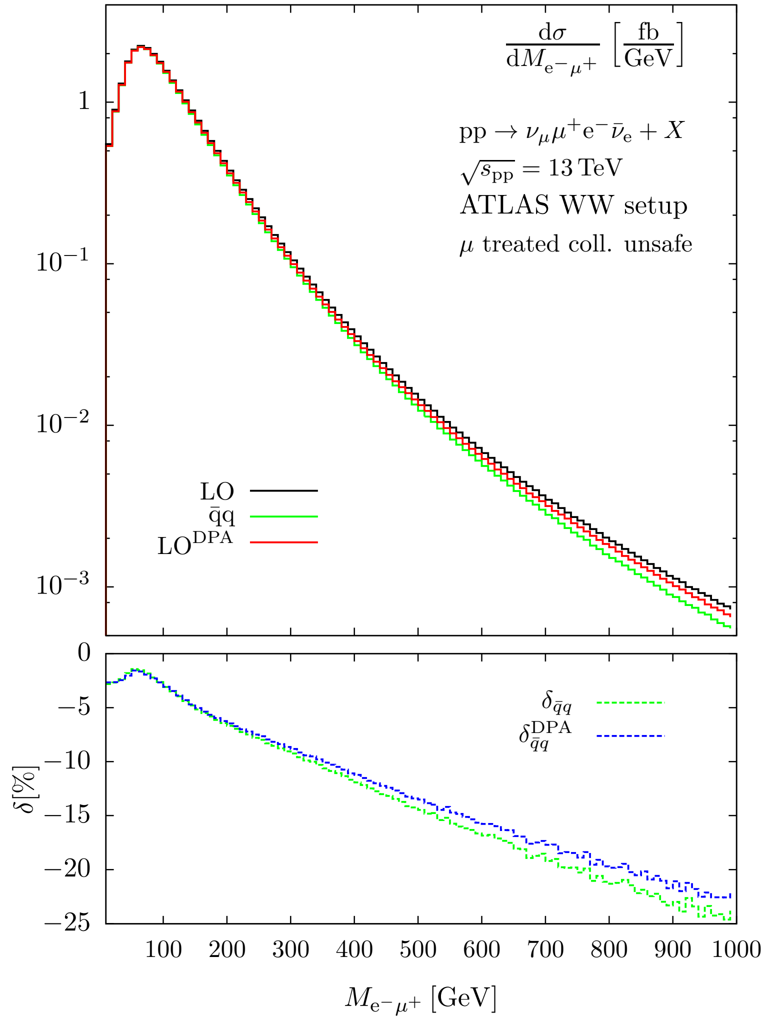
Approaches compared for $\mathrm{e^+e^-} \to \mathrm{WW} \to 4f$ Denner, S.D., Roth, Wieders '05

$\mathrm{pp} \to \mathrm{WW} \to 4f$ Biedermann et al. '16

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

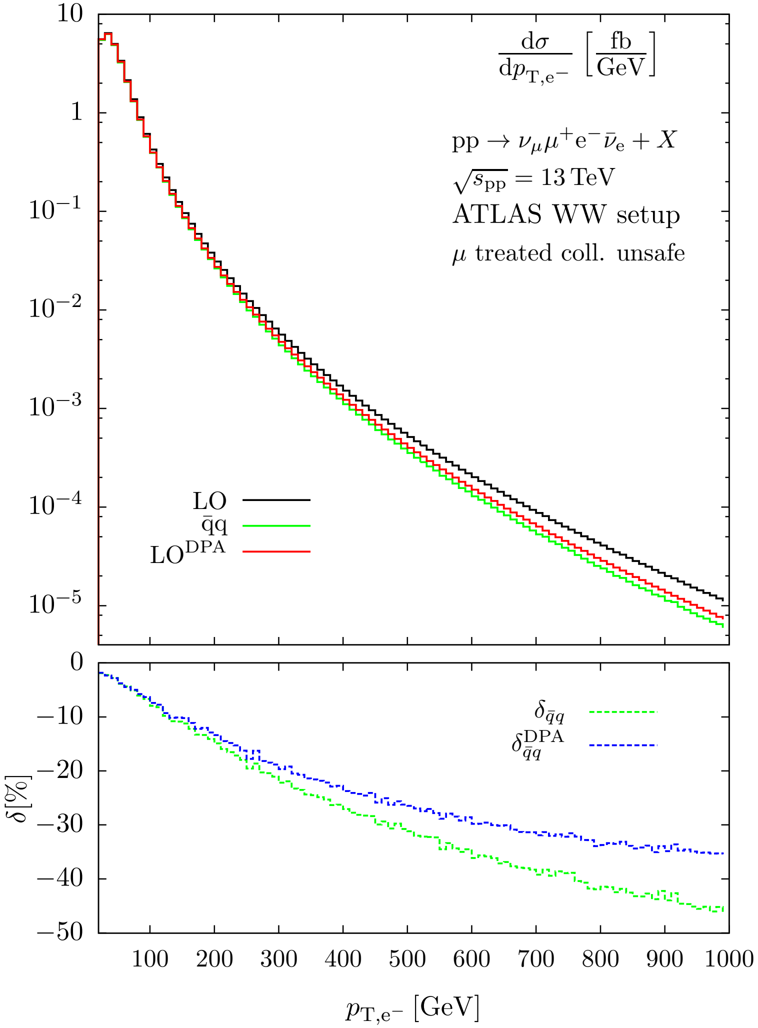


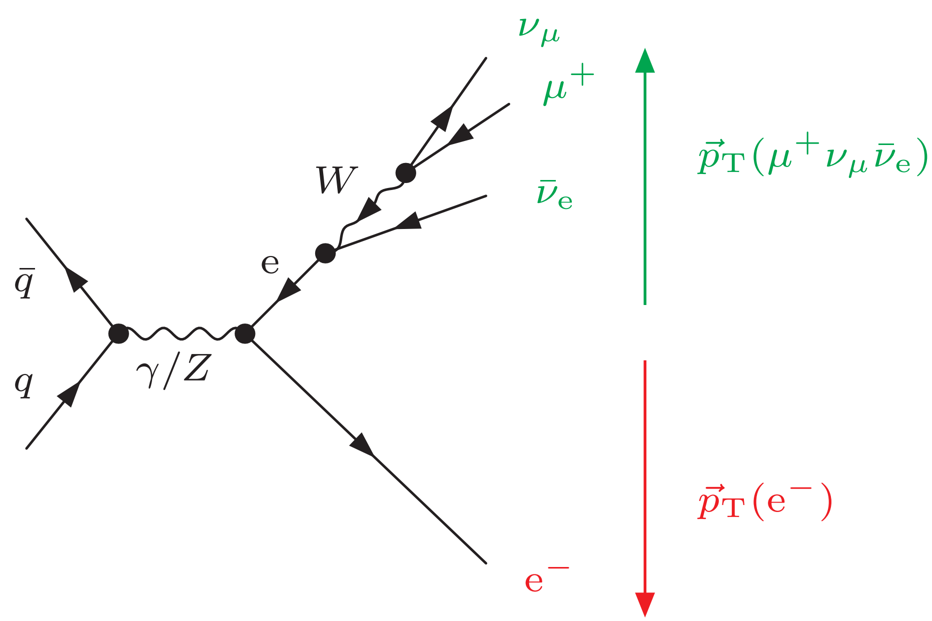


Level of agreement as expected (dominance of doubly-resonant diagrams)

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





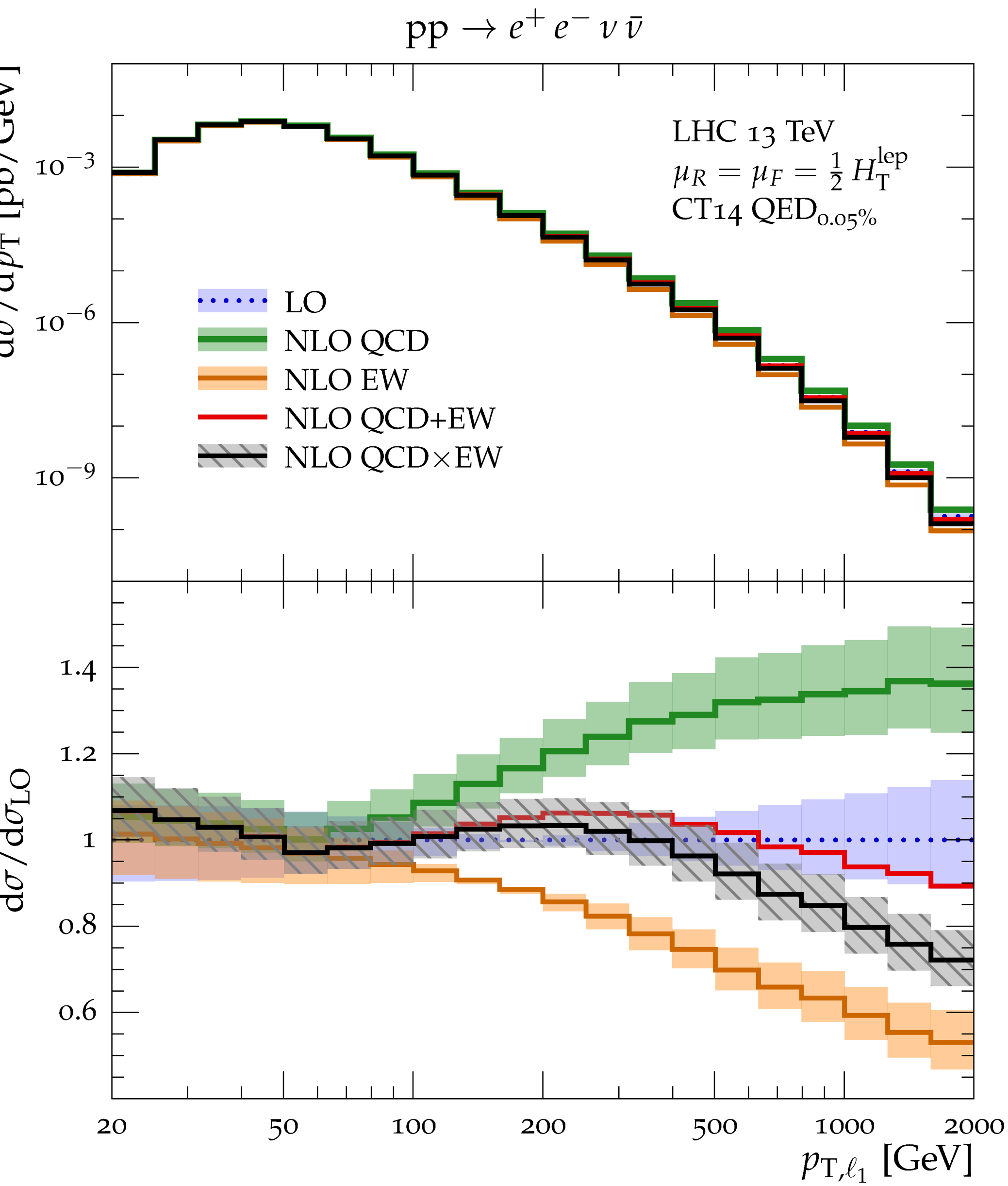
Impact of singly-resonant diagrams
where e^- takes recoil from $(\mu^+\nu_\mu\bar{\nu}_\mathrm{e})$

(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

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

Kallweit et al. '17

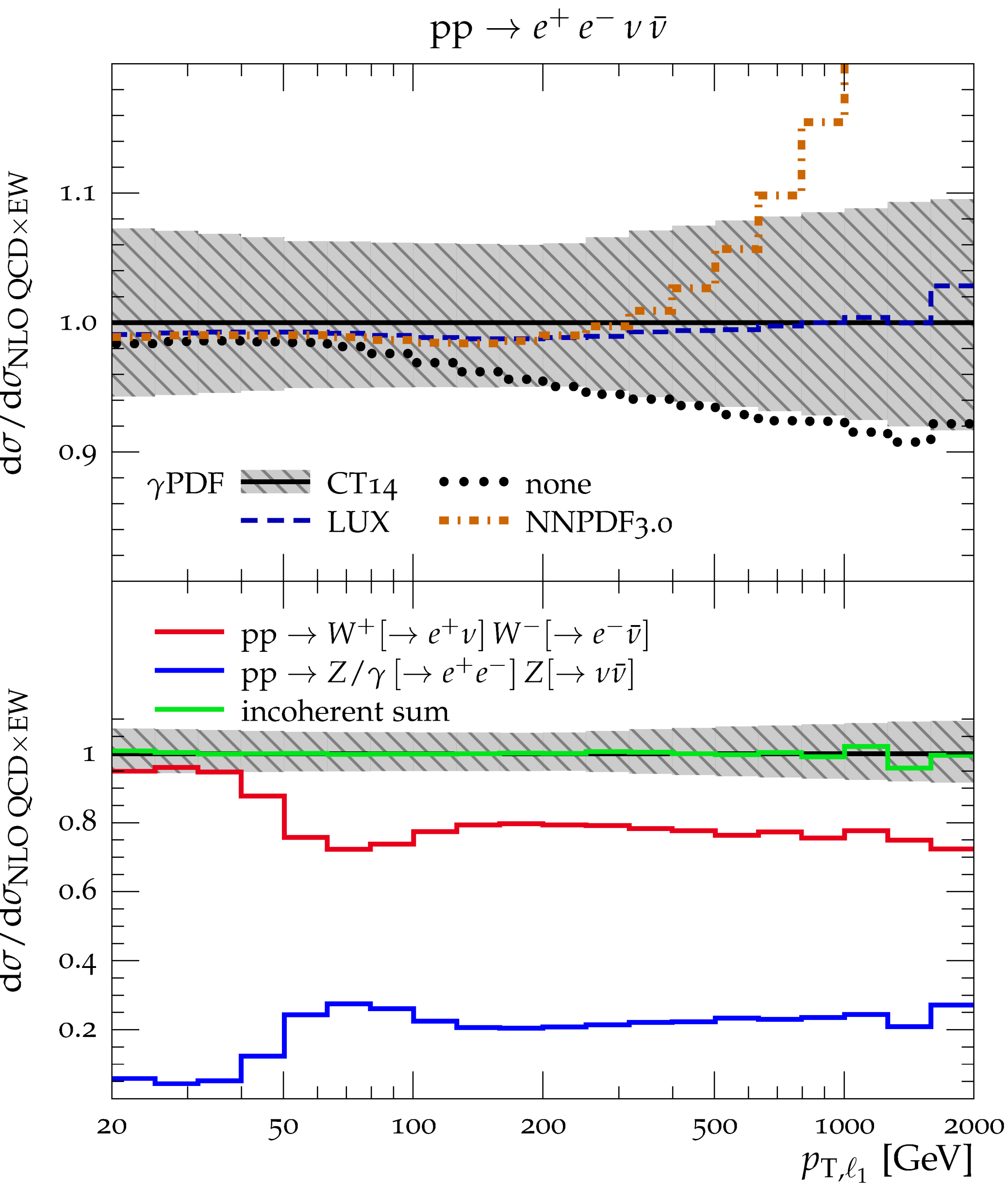


- XS contributions:
  $\mathrm{WW} + \mathrm{ZZ} +$ interferences
- Jet veto:
  $$H_\mathrm{T}^\mathrm{jet} = \sum_{i \in \mathrm{jets}} p_{\mathrm{T},i} \; > \; H_\mathrm{T}^\mathrm{lep}$$
  $\hookrightarrow \; K_\mathrm{QCD}$ moderate
- Combination of QCD and EW corrections:
  | QCD+EW − QCD×EW |
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

  Note: product better motivated!

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

Kallweit et al. '17



- $\gamma\gamma + q\gamma$ contributions:
  $\gtrsim 10\%$ for $p_{\mathrm{T},\ell_1} \gtrsim 1\,\mathrm{TeV}$
  - CT14 $\approx$ LUXQED
  - Δ_{LUXQED} negligible
  - $\Delta_{\mathrm{NNPDF}} \sim 100\%$
    for $p_{\mathrm{T},\ell_1} \gtrsim 1\,\mathrm{TeV}$

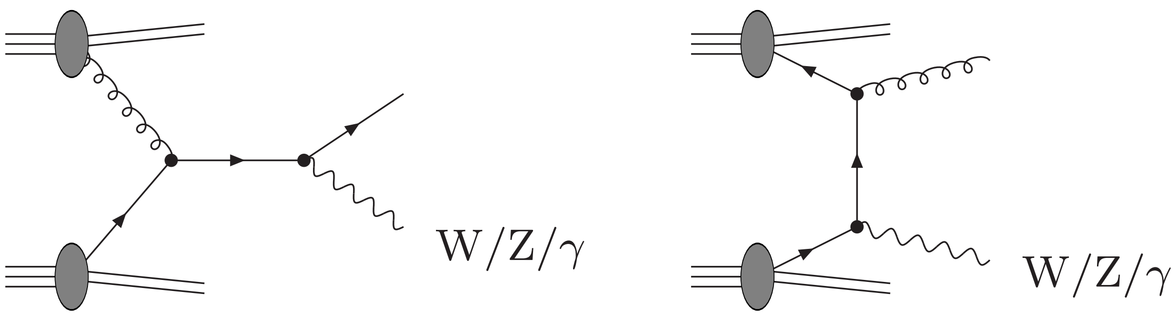
- WW and ZZ contributions:
  - interference negligible
  - ZZ less suppressed
    for larger p_{T,ℓ_1}
    (influence of singly resonant parts)

Combining QCD and EW corrections,

MC reweighting, error assessment, ...

Example:

$\mathrm{W}/\mathrm{Z}/\gamma + \mathrm{jet}$ background predictions for Dark Matter searches



QCD⊗EW corrections via MC reweighting

Lindert et al. '17 (TH+ATLAS+CMS)

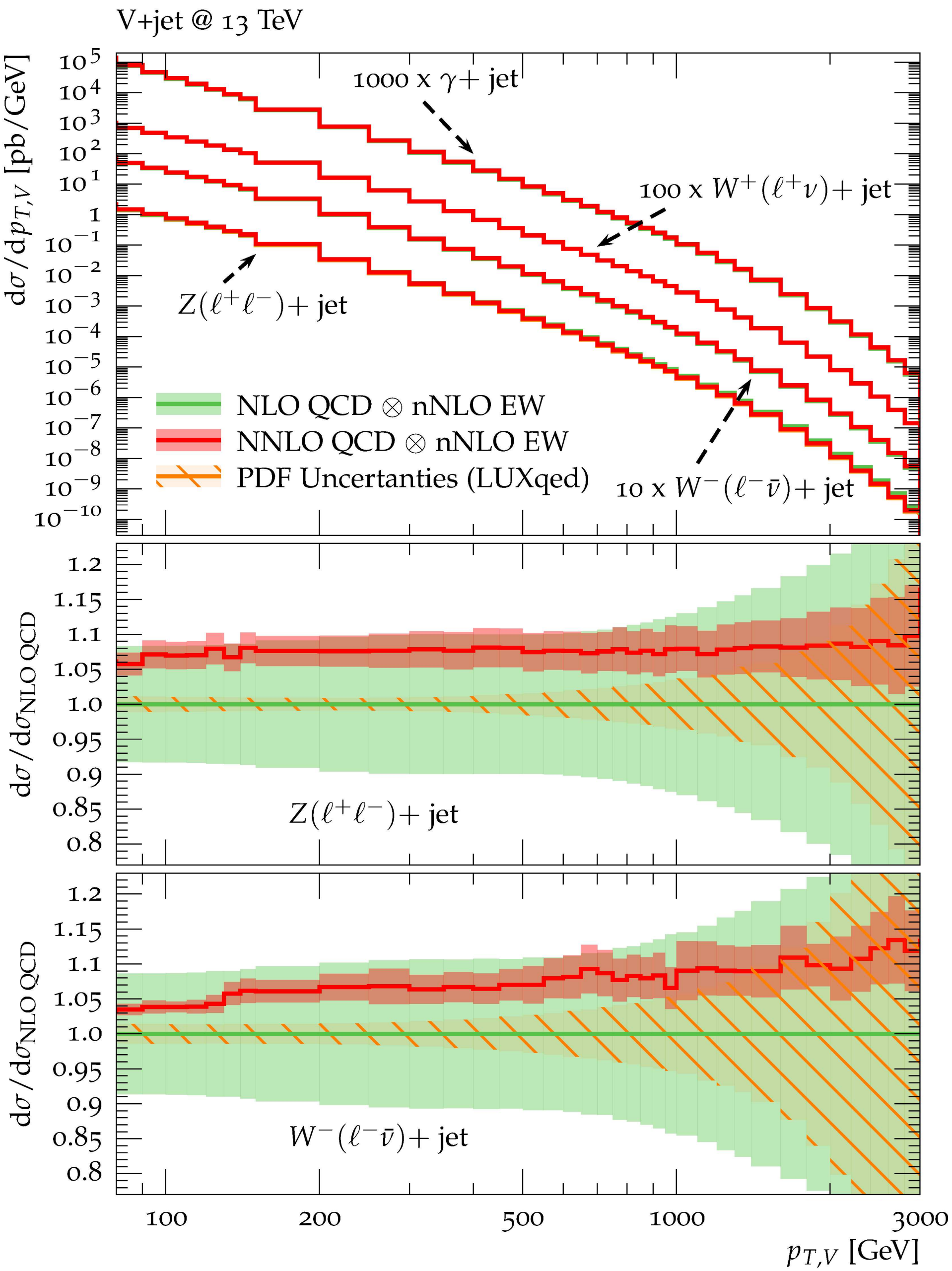
$$\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma(\vec{\varepsilon}_{\mathrm{MC}},\vec{\varepsilon}_{\mathrm{TH}}) = \frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}}) \times \underbrace{\left(\frac{\frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{TH}}(\vec{\varepsilon}_{\mathrm{TH}})}{\frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}})}\right)}_{\text{reweighting factor, } \vec{y} \text{ integrated over}}$$

$x = p_{\mathrm{T},V}$, $\vec{y} =$ remaining phase space

- $\sigma_{\mathrm{MC}} =$ fully differential MC prediction with MC nuisance parameters $\vec{\varepsilon}_{\mathrm{MC}}$
- $\sigma_{\mathrm{TH}} =$ perturbative state-of-the-art theory predictions
  at NNLO QCD, NLO EW (+leading h.o. EW corrections)
  Gehrmann et al., Boughezal et al., Campbell et al., SHERPA/MUNICH/OPENLOOPS, ...
- $\vec{\varepsilon}_{\mathrm{TH}} =$ theory nuisance parameters
  - QCD and EW uncertainties (scales, h.o.)
  - QCD×EW versus QCD+EW
  - PDF uncertainties
  - correlations between different processes and phase-space regions

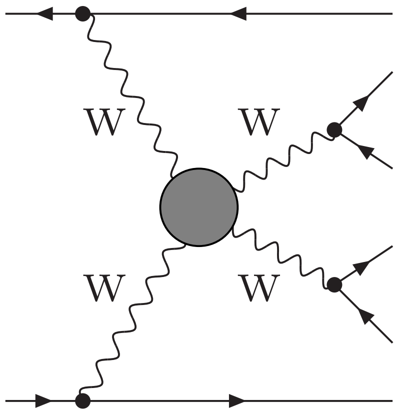
Note: Study includes many process-dependent/independent details, but several features generalize!

MC-reweighted predictions for $V + \text{jet}$ at high $p_{\mathrm{T},V}$ Lindert et al. '17 (TH+ATLAS+CMS)

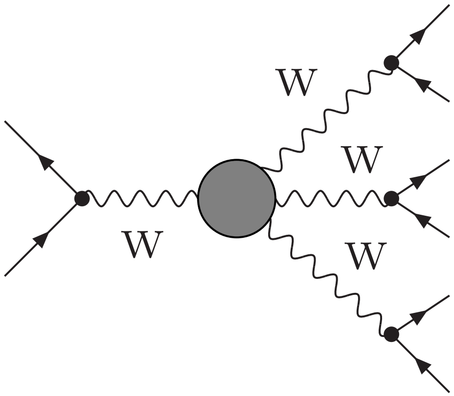


- perturbative XS uncertainties (combined quadratically) $\sim 5\%$ for $p_{\mathrm{T},V} \gtrsim 1{-}2\,\mathrm{TeV}$
- PDF uncertainties (correlated among processes) $\sim 5\%\ (10\%)$ at $p_{\mathrm{T},V} \gtrsim 1(2)\,\mathrm{TeV}$
- W/Z XS ratio uncertainty (not shown) $\sim 1{-}2\%\ (5\%)$ at $p_{\mathrm{T},V} \sim 1(2)\,\mathrm{TeV}$

Rare electroweak processes



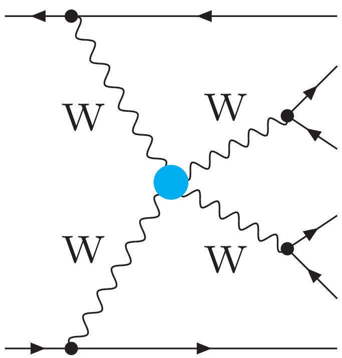
vector-boson scattering



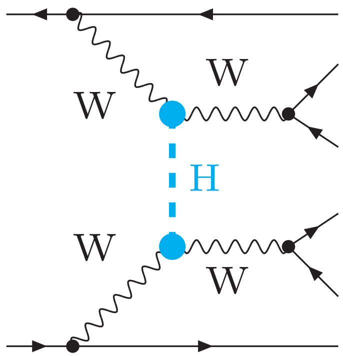
VVV production

Physics goals in VBS and VVV production

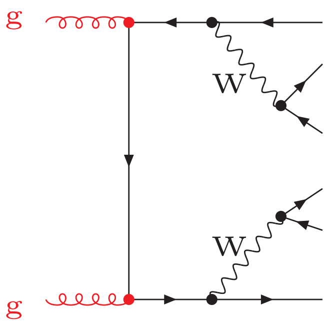
- direct access to quartic EW gauge couplings

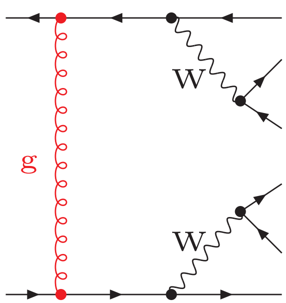


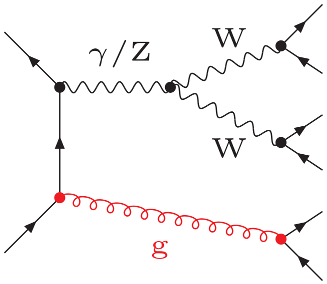
- longitudinal gauge bosons at high energies
  ↪ probe SM unitarization mechanism
- window to electroweak symmetry breaking
  via off-shell Higgs exchange



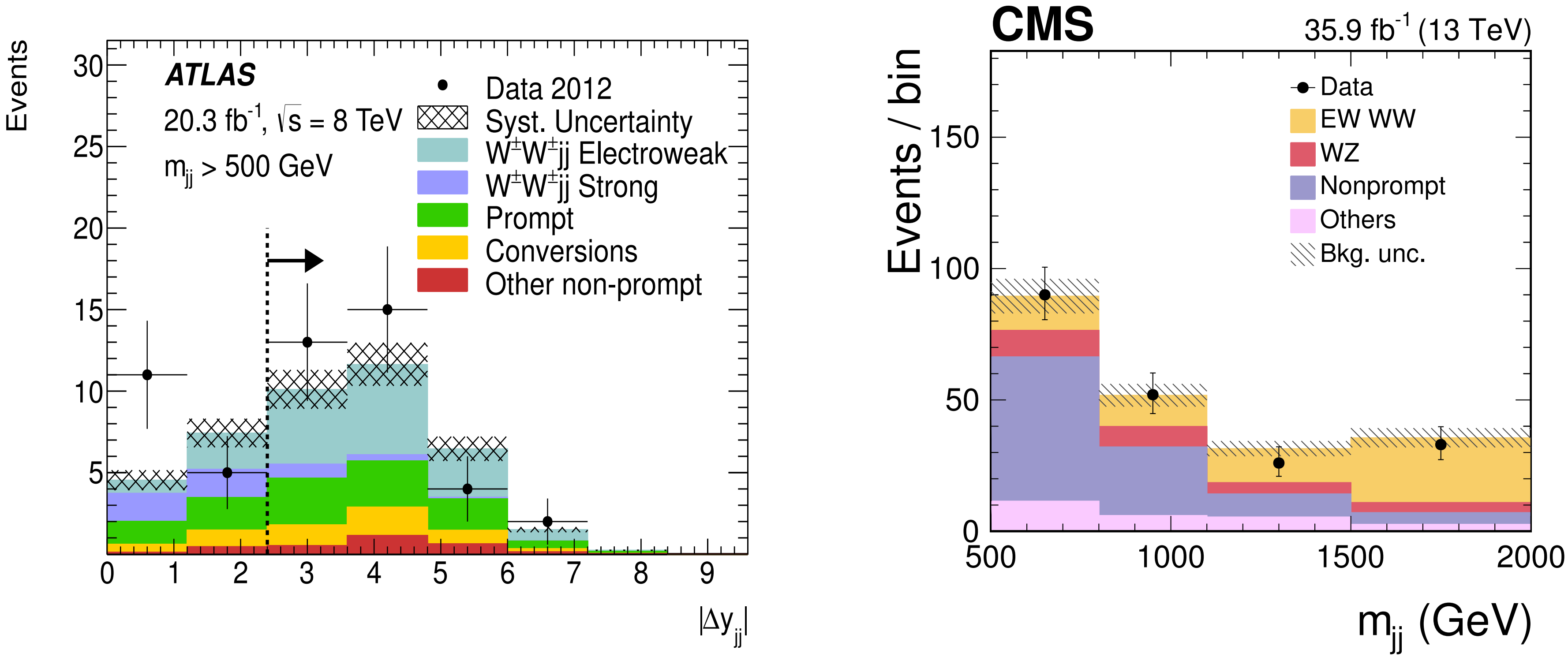
Note: severe QCD background to VBS signatures







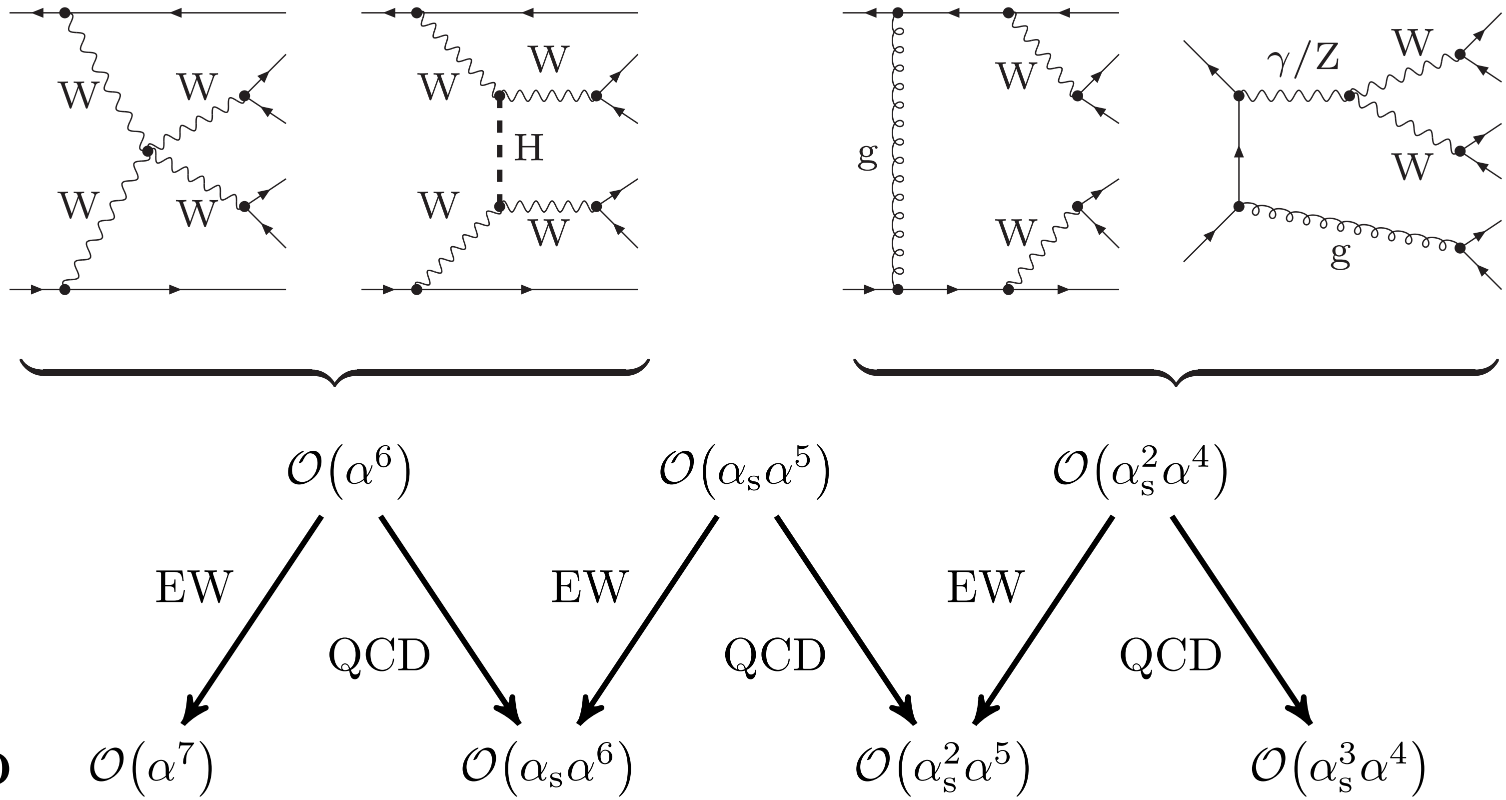
$\mathrm{pp} \to \mathrm{W}^\pm\mathrm{W}^\pm + 2\mathrm{jets}$ measured with $8\,\mathrm{TeV}/20.3\,\mathrm{fb}^{-1}$ LHC data



	Fiducial $\sigma\,[\mathrm{fb}]$: (different acceptances)	$\sigma_{\mathrm{SM}}\,[\mathrm{fb}]$:
ATLAS:	$1.3 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})\,\mathrm{fb}$	$0.95 \pm 0.06\,\mathrm{fb}$ (POWHEGBOX/VBFNLO/SHERPA)
CMS:	$3.83 \pm 0.66(\mathrm{stat}) \pm 0.35(\mathrm{syst})\,\mathrm{fb}$	$4.25 \pm 0.27\,\mathrm{fb}$ (LO FROM MADGRAPH)

$\hookrightarrow$ compatibility with the SM, but still large uncertainties

$\mathrm{pp} \to \mathrm{W^+W^+} + 2\mathrm{jets} \to \mathrm{e^+}\nu_\mathrm{e}\mu^+\nu_\mu + 2\mathrm{jets}$ at NLO



Predictions:

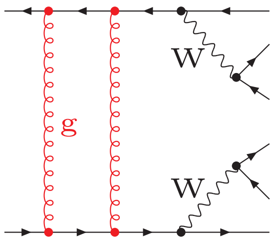
- previously: NLO QCD $(\alpha_\mathrm{s}\alpha^6, \alpha_\mathrm{s}^3\alpha^4)$ Jäger et al. '06–'09; Melia et al. '10,'11; Denner et al. '12; Greiner et al. '12; Campanario et al '13
- new: full tower of NLO corrections Biedermann, Denner, Pellen '16,'17

  1-loop automation with RECOLA + COLLIER (8-point functions!)

  Actis et al. '16 — Denner, S.D., Hofer '16

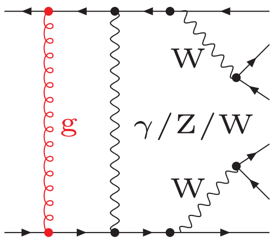
Survey of NLO diagramsn for $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu + 2\mathrm{jets}$

$\alpha_\mathrm{s}^3\alpha^4$:

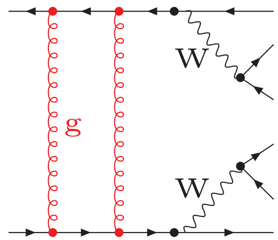


$\times \mathcal{M}^{\mathrm{LO}*}_{\mathrm{QCD}}$

$\alpha_\mathrm{s}^2\alpha^5$:

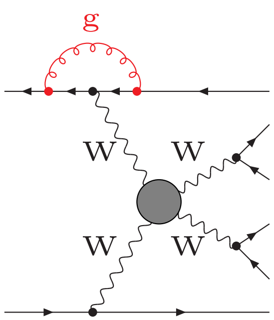


$\times \mathcal{M}^{\mathrm{LO}*}_{\mathrm{QCD}}$

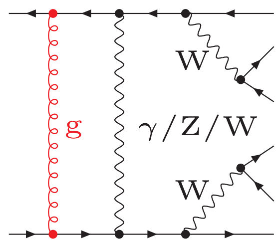


$\times \mathcal{M}^{\mathrm{LO}*}_{\mathrm{EW}}$

$\alpha_\mathrm{s}^1\alpha^5$:

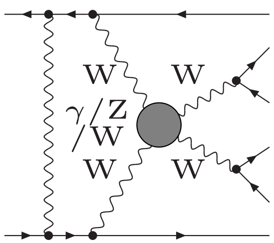


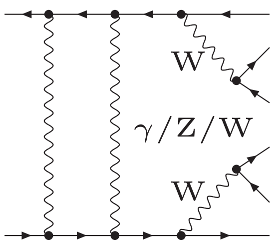
$\times \mathcal{M}^{\mathrm{LO}*}_{\mathrm{EW}}$



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

α^7:



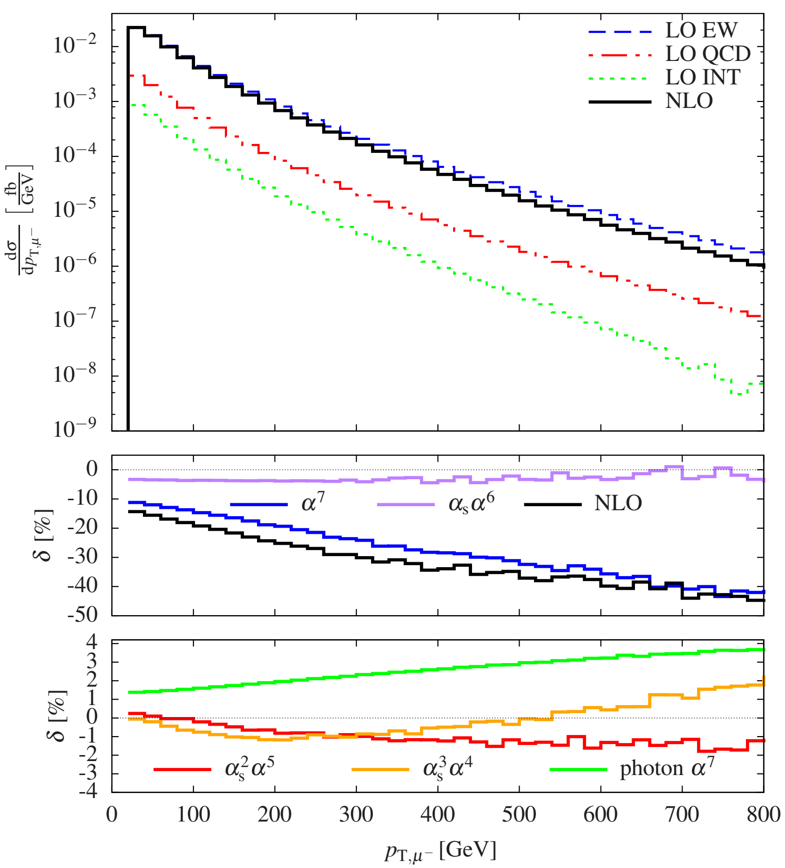


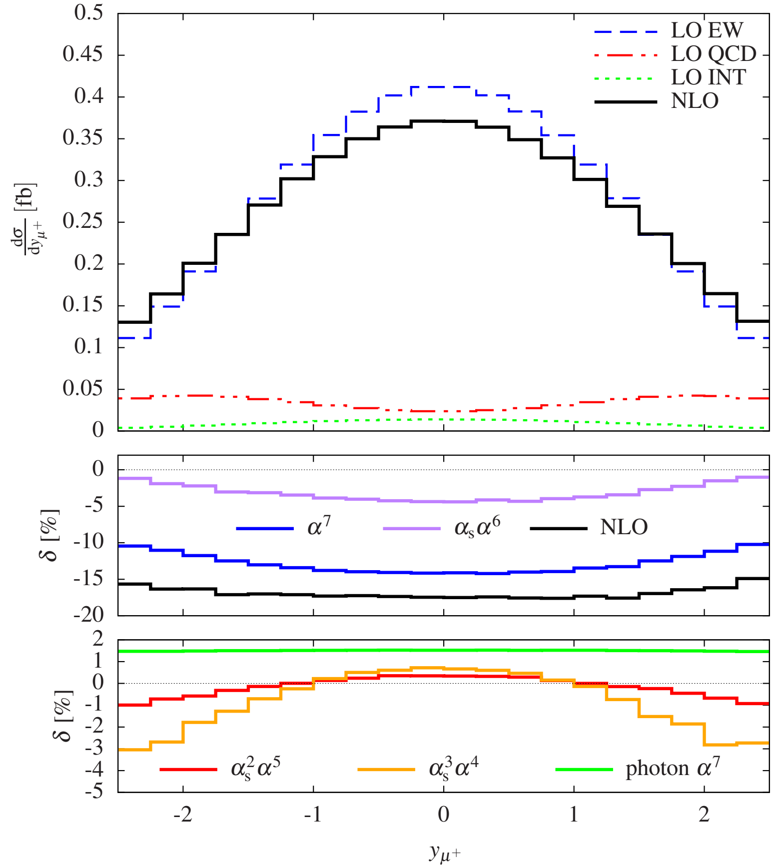
$\times \mathcal{M}^{\mathrm{LO}*}_{\mathrm{EW}}$

+ real corrections

(g/γ bremsstrahlung, $q\mathrm{g}/q\gamma$ collisions)

NLO corrections for $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^+\nu_\mu + 2\mathrm{jets}$ Biedermann, Denner, Pellen '16,'17





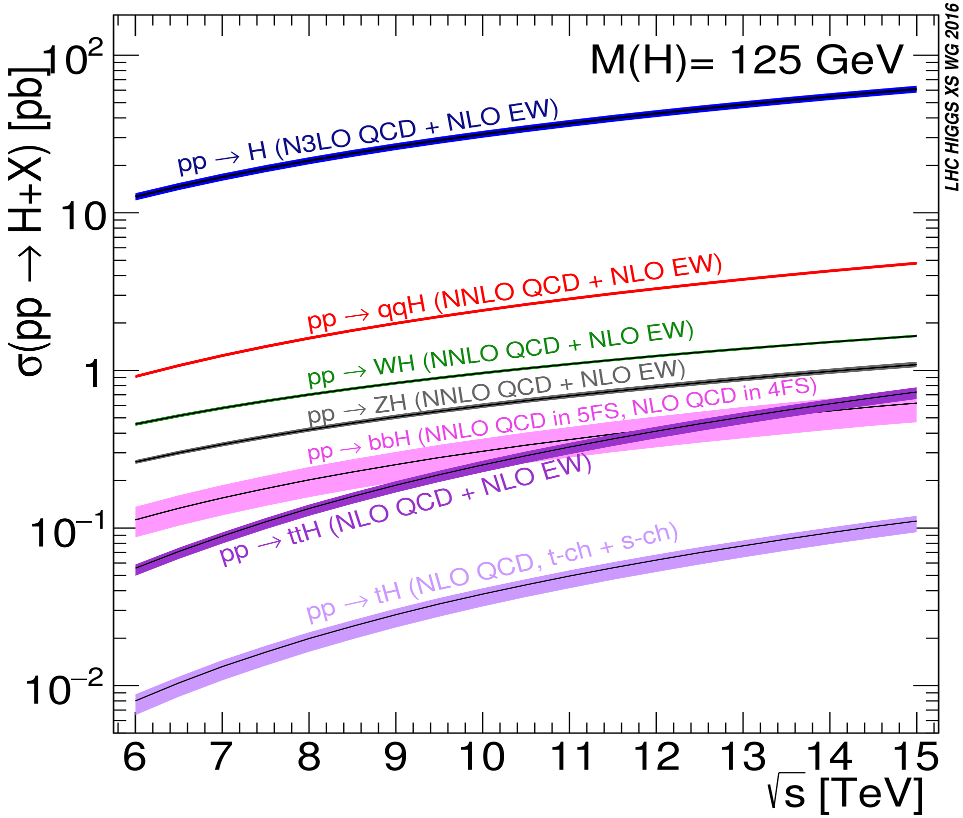
- VBS cuts: $M_{jj} > 500\,\mathrm{GeV},\ p_{T,j} > 30\,\mathrm{GeV},\ p_{T,\ell} > 20\,\mathrm{GeV},$ etc.
- NLO EW corr. to σ_{fid}: -13% $\to$ relevant for upcoming measurements !

More precision in

... Higgs-boson production

SM Higgs XS predictions for the LHC

LHC Higgs XS WG 2016
(CERN-2017-002-M, arXiv:1610.07922)

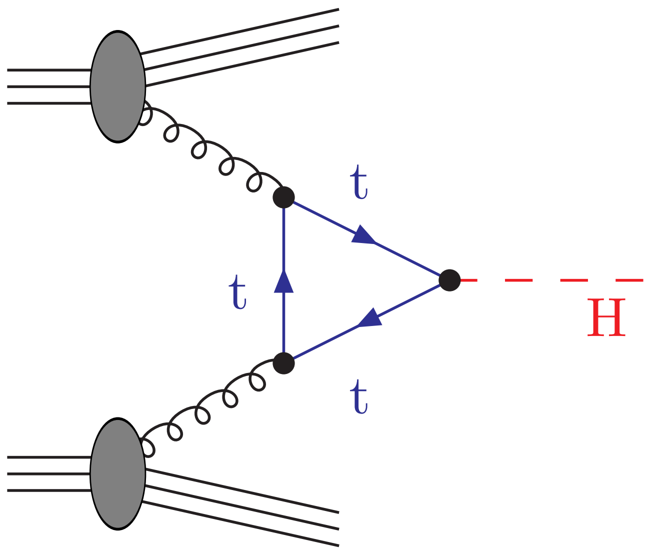


Rough numbers:

$M_{\mathrm{H}} = 125\,\mathrm{GeV}$, $\sqrt{s} = 14\,\mathrm{TeV}$	Uncertainties: theory	Uncertainties: PDF4LHC	NLO/NNLO/NNNLO: QCD	NLO/NNLO/NNNLO: 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

Higgs production via gluon fusion



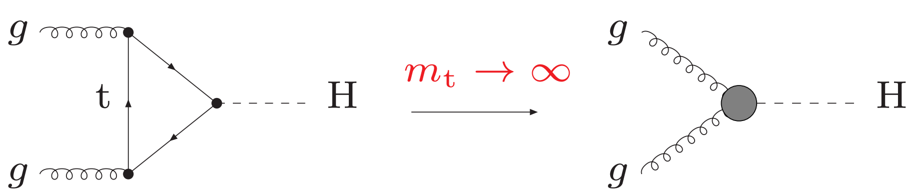
Corrections to Higgs-boson production via gluon fusion

- QCD corrections:
  - full NLO, NNLO via expansions

$$K = \frac{\sigma_{\mathrm{NNLO}}}{\sigma_{\mathrm{LO}}} \sim 2.0$$

Graudenz, Spira, Zerwas ’93
Djouadi, Graudenz, Spira, Zerwas ’95
...
Marzani et al. ’08
Pak, Rogal, Steinhauser ’09
Harlander, Ozeren ’09

  - NNNLO in limit $m_{\mathrm{t}} \to \infty$



Chetyrkin et al. ’98,’06; Moch/Vogt ’05;
Schröder/Steinhauser ’06; Baikov et al. ’09;
Gehrmann et al. ’10,’12; Duhr/Gehrmann ’13;
Li/Zhu ’13; Kilgore ’13; Hoeschele et al.’13;
Buehler/Lazopoulos ’13;
Anastasiou et al. ’13–’16

  - resummations up to N^{3}LL

Catani et al. ’03,’14; Moch et al. ’05;
Laenen, Magnea ’05; Idilbi et al. ’05;
Ravindran ’05,’06; Ravindran et al. ’06;
Ahrens et al. ’08,’11; Berger et al. ’10;
Stewart, Tackmann ’11; Banfi et al. ’12;
Becher, Neubert ’12; deFlorian et al. ’12,’14;
Bonvini et al. ’14; Schmidt, Spira ’15

- EW corrections
  - complete NLO correction known $\sim \mathcal{O}(5\%)$

Aglietti, Bonciani, Degrassi, Vicini ’04,’06
Degrassi, Maltoni ’04
Actis, Passarino, Sturm, Uccirati ’08

  - mixed $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections for small M_{H}

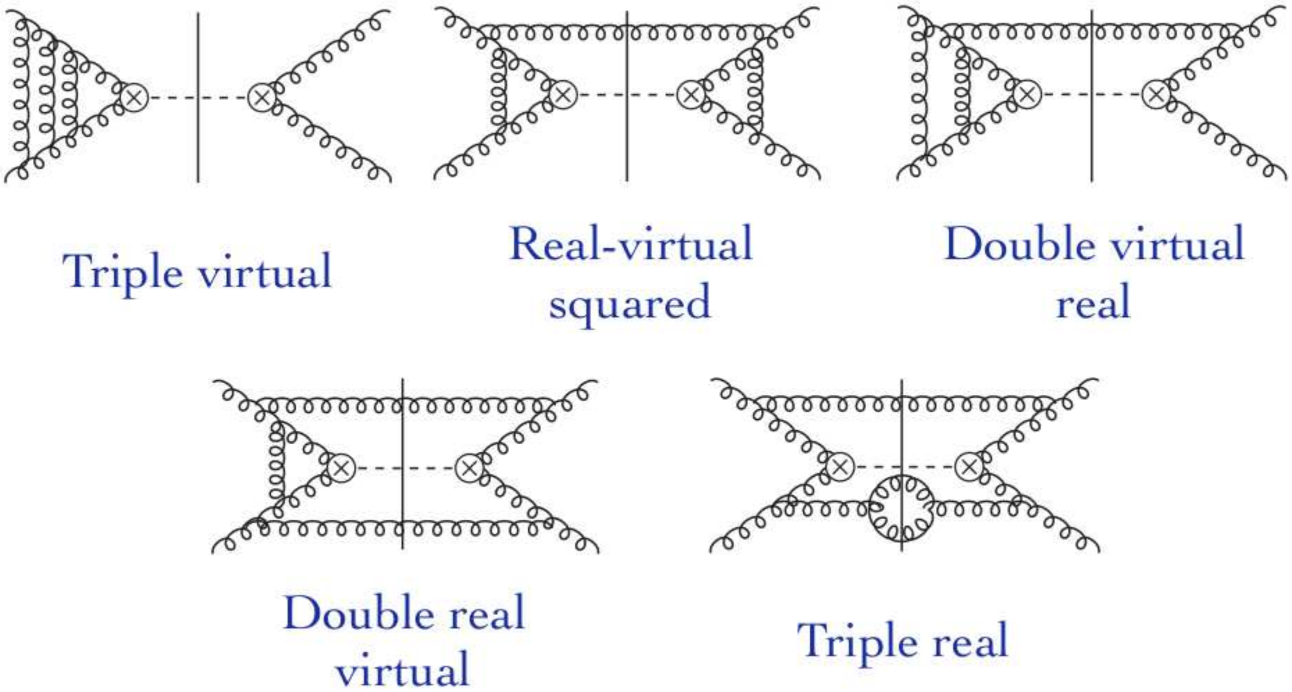
Anastasiou, Boughezal, Petriello ’08

gg → H @ NNNLO QCD

- great theory effort, many ingredients
  (Wilson coefficients, 3-loop amplitudes,
  hard emission contributions, etc.)

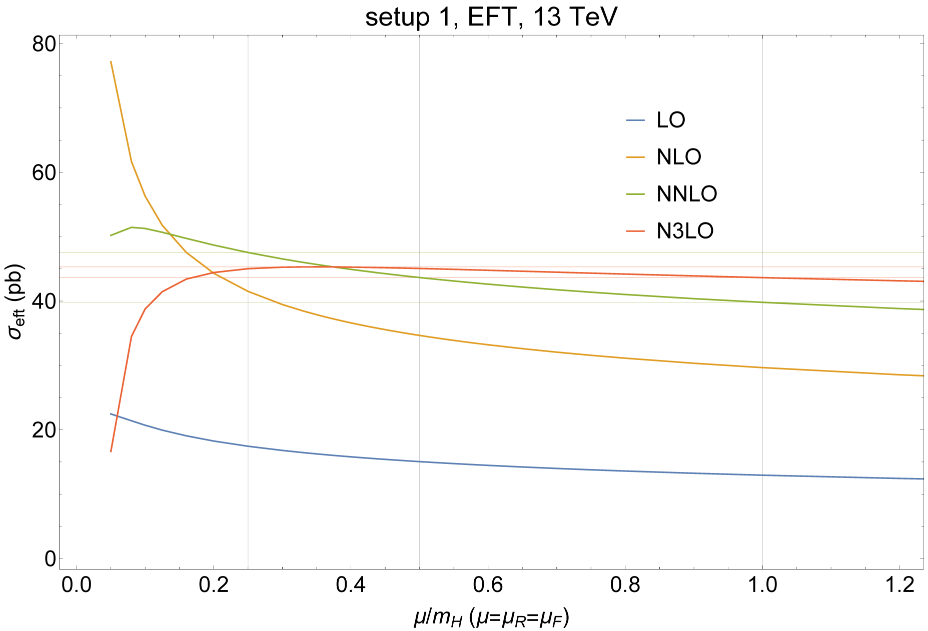
Chetyrkin et al. ’98,’06; Moch/Vogt ’05; Schröder/Steinhauser ’06; Baikov et al. ’09; Gehrmann et al. ’10,’12; Anastasiou et al. ’13,’14; Duhr/Gehrmann ’13; Li/Zhu ’13; Kilgore ’13; Hoeschele et al.’13; Buehler/Lazopoulos ’13; ...

- full NNNLO cross section Anastasiou et al. ’15,’16



$gg \to H$ @ NNNLO QCD + resummations + NLO EW

Anastasiou et al. '16



- correction:
  $\frac{\Delta\sigma_{\rm NNNLO}}{\sigma_{\rm NNLO}} \sim 3\%$ @ $\mu = M_{\rm H}/2$
- scale uncertainty:
  9% @ NNLO $\to$ $\sim 2\%$ @ NNNLO
- full TH uncertainty: $\sim 6\%$
- PDF$\oplus\alpha_{\rm s}$ uncertainty: $\sim 3\%$

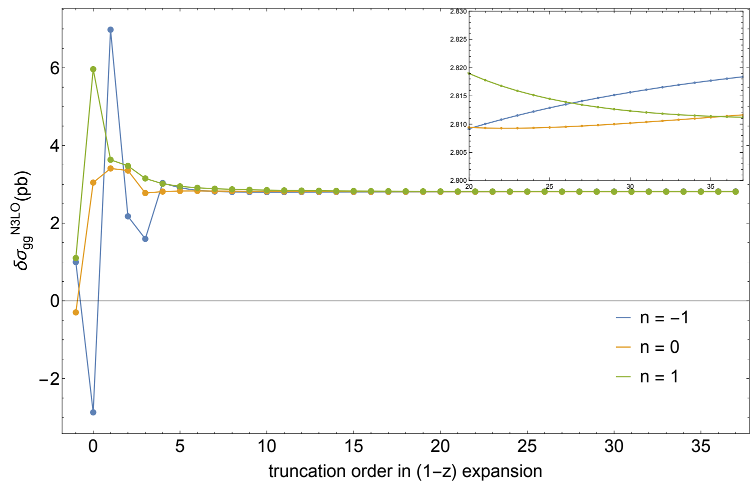
Details / comments:

- total XS obtained from expansion in $z = \frac{M_{\rm H}^2}{\hat{s}}$:

$$\frac{\hat{\sigma}_{ij}^{(3,N)}}{z^{n+1}} = \delta_{ig}\delta_{jg}\frac{\hat{\sigma}^{(3)}_{\rm virt+soft}}{z^{n+1}} + \sum_{k=0}^{N} c_{ij}^{(k)}(1-z)^k$$

  $\hookrightarrow$ convergence depends on N and n

- several uncertainty sources of $\sim 1\%$:
  $1/m_{\rm t}$ expansion, quark mass effects, QCD$\otimes$EW, NNNLO/NNLO PDF mismatch, $(1-z)^k$ expansion



Conclusions

Status quo of LHC physics

SM in better shape than ever – reason for despair?

Status quo of LHC physics

SM in better shape than ever

The (avoidable) disaster:

headlines like this ...

The Crazy Times

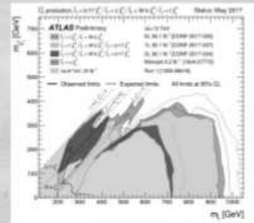
24 JUN 2017

LHC fails to find new particles

By SOME HEADLINE HUNTER

Since years and decades we were told by high-energy physicists that new particles, indicating new fancy mathematical structures like supersymmetry, will be copiously found the Large Hadron Collider. Billions of euros were spent in a wrong line of research. Stop this waste of money ... blabla ...

Instead we are told now that only 5% of matter or energy are visible to us. This means our renowned experts have no idea about 95% of the universe ... more blabla ...



Reuters

International Moose Count Underway

By BOB O'BOBSTON

The UN-sponsored International Moose Census got off to a flying start today with hopes for an increase in the worldwide moose population compared to last year's disapointing figures. Among the traditional early reporters were Egypt, returning figures of six moose, a twenty percent increase on 2011's figures of five, and Uruguay whose moose population remains stable at eleven.

According to Robbie McRobson, head of the UN Moose Preservation Council, worldwide moose numbers are expected to grow markedly on last year due to the traditional moose strongholds of Canada and the United States, with the larger developing moose ecologies also poised to make gains. The largest percentagege increase in moose will likely come from China", says McRobson, The Chinese government has invested heavily in moose infrastructure over the past decade, and their committment to macrofauna is beginning to pay dividends". Since 2004 China has expanded moose pasture from 1.5% of arable land to nearly 3.648% and moose numbers are expected to rise to 60,000 making China a net moose exporter for the first time. This is good news for neighbouring Mongolia, a barren moose-wasteland whose inhabitents nonetheless have an insatiable desire for the creatures. The increase in Beijing-Ulanbataar trade is anticipated to relieve pressure on the relatively strained Russian suppliers, but increase Mongolia's imbalance of trade with its larger neighbour.

Historically the only competitor to China in the far eastern moose markets has been Singapore but the tiny island nation is set to report a net loss, expecting a decrease of more than five percent on last year's 50,000 moose counted. The head of Singapore's Agency for Agriculture, Jing-Feng Lau, explained to an incredulous Singaporean parliament yesterday that bad weather had contributed to this season's poor showing, most notably when a cargo of 150 moose were swept out into the Indian ocean in a monsoon.

Yet again the global demand for moose will be met largely by the US and Canada. The recession-hit States is taking comfort in its moose growth figures with gross production expected to break 700,000 and net exports to grow by 2%. The worldwide dominance of Canada shows no signs of abating though with this year's moose population expected to match last year's record figures of one hundred million billion.

Europe's rise as an international moose power will slow slightly this year as a response to the European Union's move towards standardising the European moose. Stringent quality controls are holding back the development of the eastern european populations compared to last year when they contributed significantly to europe's strong growth figures. Norway, which is not an EU member but has observer status, strengthed in numbers relative to the Euro area with numbers of Norweigian moose, known locally as elk" expected to rise for the tenth consecutive year, particularly thanks to a strong showing in the last quarter.

As moose season reaches its close, researchers world wide are turning to science in an attempt to boost next year's figures. NASA stunned the scientific community today with the announcment of their discovery that the moon is significantly smaller than previously believed. This conclusion, which is the conclusion of a ten-year collaborative project, will have profound implications for the moose community as the gravitational field is now known to be of the right strength to support moose in orbit.

According to John Johnson, head of the NASA Moon Sizing Experiment the first delivery of moose into low moon orbit could be achieved as early as the third quarter of next year. The technology to nurture moose in space is available now", he said, "all that is needed is political will".

Granny wins World Wrestling Championship

By ROY MCROYSTON

Status quo of LHC physics

SM in better shape than ever

The scientific view:

Nature has decided how things are.

Our task is just to create knowledge ...

The Good Times

24 JUN 2017

LHC explores microcosmos deeper and deeper

By COULD B. YOU

The Large Hadron Collider is the world's largest and most powerful particle collider and the most complex experimental facility ever built. Its mission is to explore the microcosmos down to small distances never explored in any laboratory before, and therefore to chart unexplored territory. The common quest of fundamental research unifies experts from all over the world with most diverse cultural background ...

The LHC performance is marvelous and exceed expectations. Its wealth of results confirms predictions from the Standard Model with unprecedented precision - a theory that was suggested in the 196070's as the outcome of experimental and theoretical fundamental research of decades. The question to which extent our present understanding of the fundamental forces of Nature will hold true or has to be modified or revolutionised is as exciting as ever ...

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Status quo of LHC physics

SM in better shape than ever

New physics (if in reach) discoverable only via precision in EXP + TH !

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Precision SM calculations: mature field with continuous progress !

- NLO QCD: successfully automated
- (N)NNLO QCD: more and more results in Higgs, EW, jet, top physics
- NLO EW: especially relevant at high scales, many existing results
- Monte Carlo's: increasing precision by NLO, PS merging, ME matching

$\Rightarrow$ Most precise results should be used ! (... and quoted)

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Future directions

- Precision for BSM models (SMEFT, SUSY, non-SUSY, . . .)
- New theoretical, mathematical, and computational concepts

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"In ~~football as in watchmaking~~ *particle theory*, talent and elegance mean nothing without rigour and precision."
[Lionel Messi]

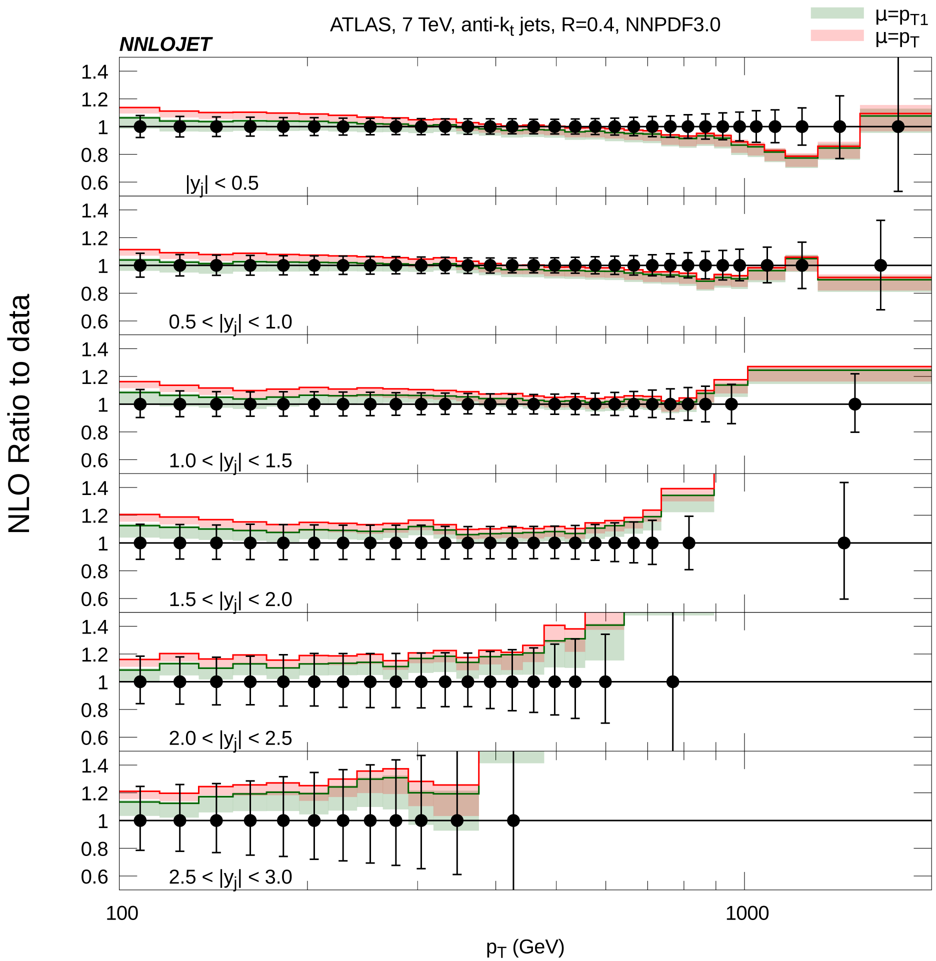
Merry Christmas !

Backup slides

Single-jet inclusive production at (N)NLO QCD

Currie, Glover, Pires ’16; Currie et al. ’17

NLO QCD versus ATLAS data:



Rapidity slices:

central region

forward/backward region

2 different scale choices $\mu = \color{green}{p_{\mathrm{T1}}}$ = leading jet transverse mom.: $\alpha_{\mathrm{s}}(p_{\mathrm{T1}})^n$

$\color{red}{p_{\mathrm{T}}}$ $\to$ multiple scales: $\alpha_{\mathrm{s}}(p_{\mathrm{T1}}) \cdot \alpha_{\mathrm{s}}(p_{\mathrm{T2}}) \cdots$

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Currie, Glover, Pires '16; Currie et al. '17

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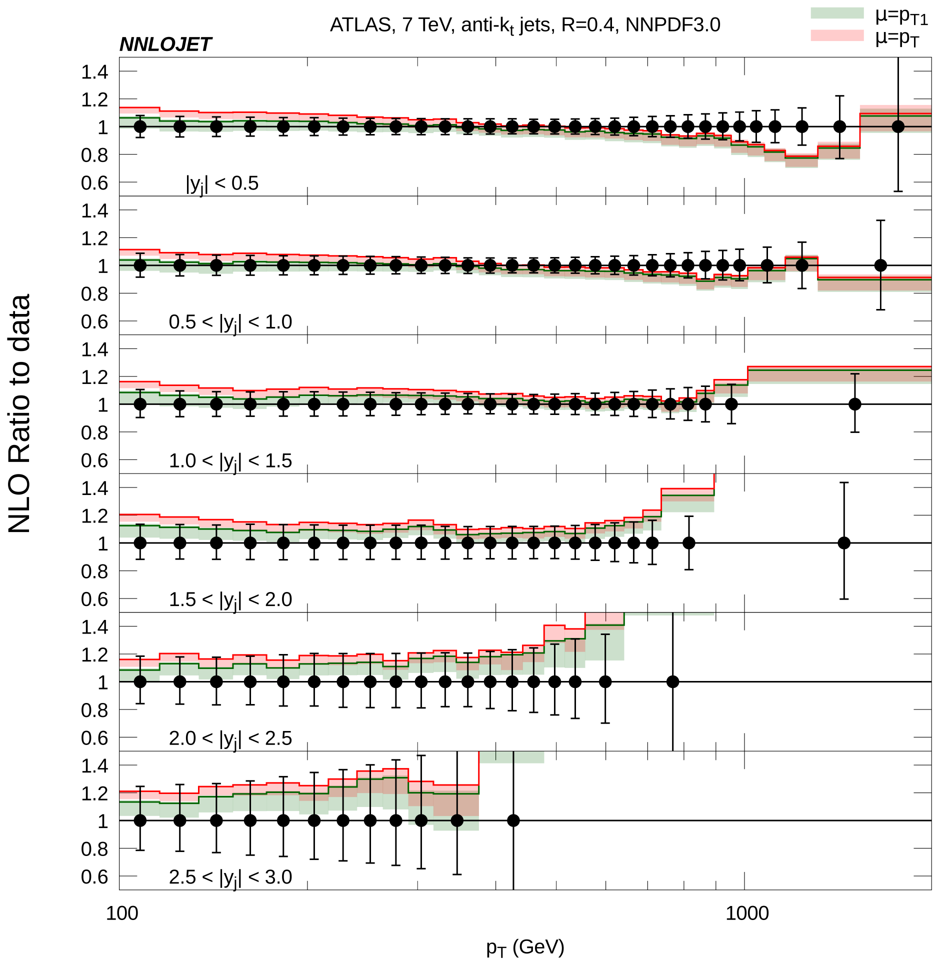

- Good agreement between NLO QCD and data
- NLO scale uncertainties $\sim 20\%(40\%)$ for central (forward) jets
- Note:
  LHC/Tevatron inclusive jets enter PDF fit in $\text{NNLO}_{\text{approx}}$ QCD

Single-jet inclusive production at (N)NLO QCD

Currie, Glover, Pires '16; Currie et al. '17

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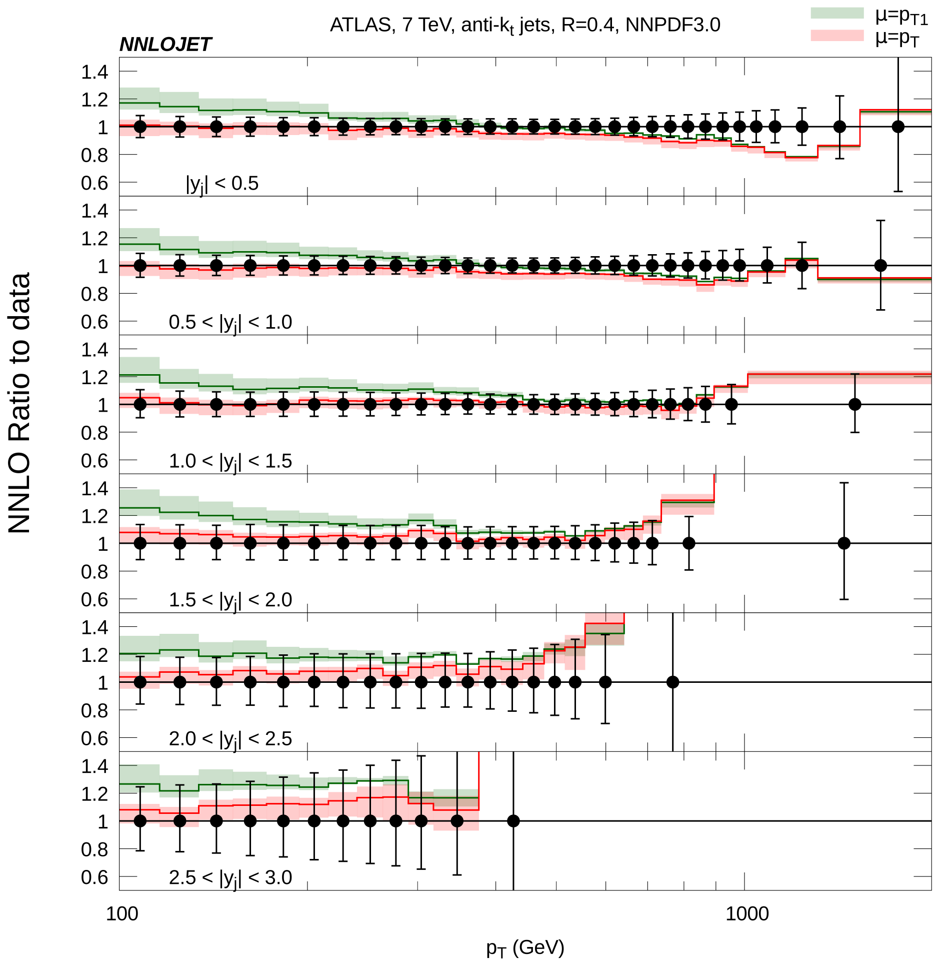


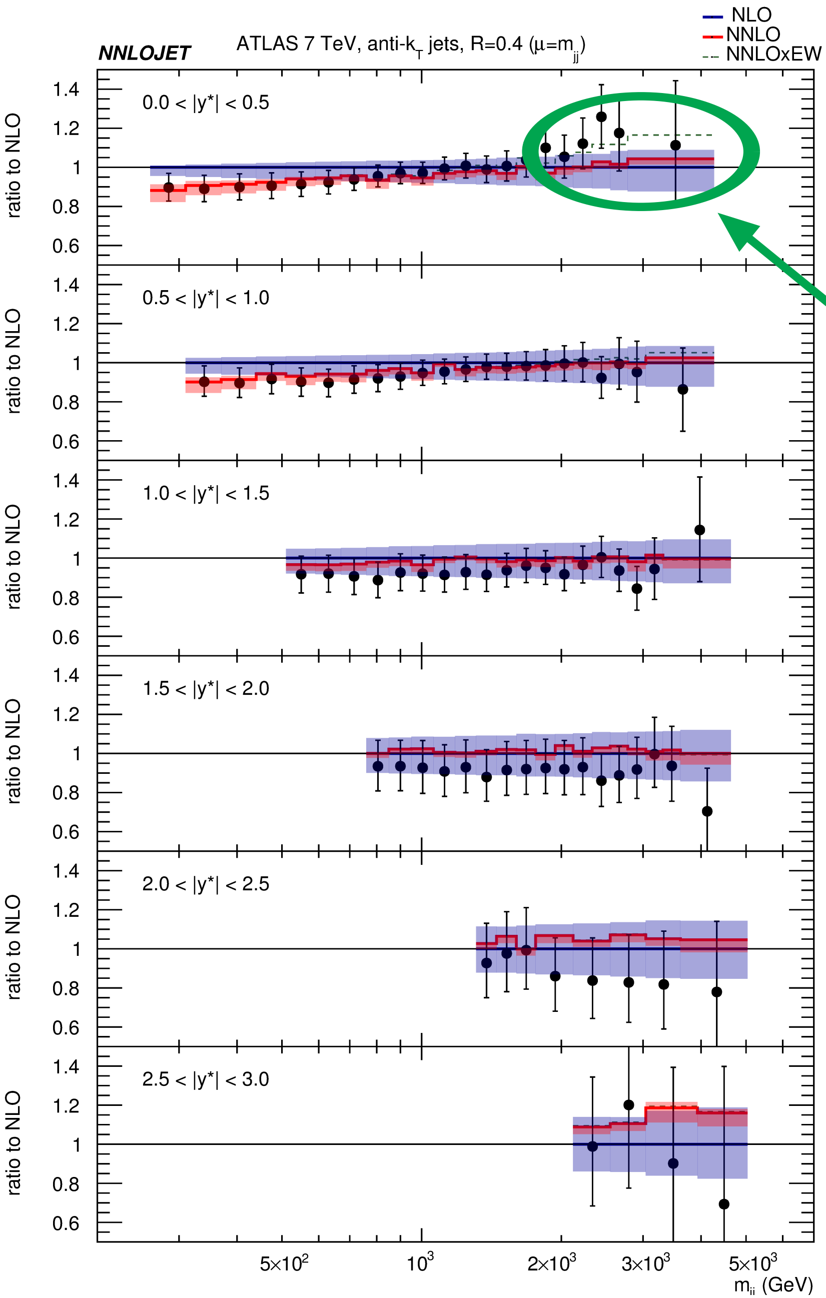
QCD scale uncertainties:

- significant reduction at NNLO
- some $\%$ for high p_{T}
  $\hookrightarrow$ picture consistent
- $\sim 10\%$ for low p_{T},
  but picture not fully consistent
  $\hookrightarrow$ further studies required!

Impact on PDF fits expected!

Di-jet production at NNLO QCD

Currie et al. '17



- Upcoming sensitivity to
  EW corrections S.D., Huss, Speckner '12 Frederix et al. '17

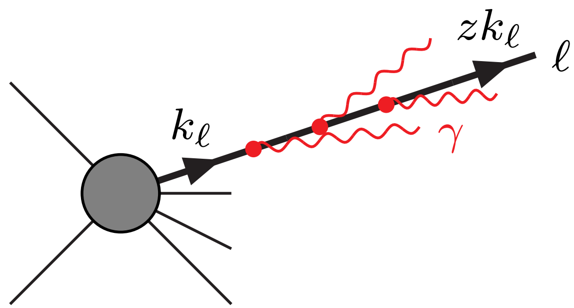
- Good agreement between NNLO QCD and data

- Reduction of scale uncertainties:

  NLO → NNLO QCD

  10–20% some %

Collinear final-state radiation (FSR) off leptons



Leading logarithmic effect is universal:

$$\sigma_{\mathrm{LL,FSR}} = \underbrace{\int \mathrm{d}\sigma^{\mathrm{LO}}(k_l)}_{\text{hard scattering}} \int_0^1 \mathrm{d}z \underbrace{\Gamma^{\mathrm{LL}}_{\ell\ell}(z,Q^2)}_{\text{leading-log structure function, } Q \text{ = typ. scale}} \Theta_{\mathrm{cut}}(zk_l)$$

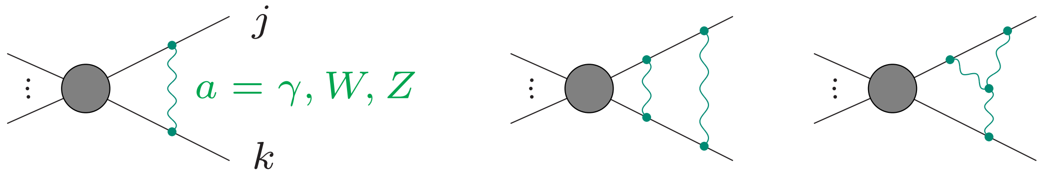
- $\Gamma^{\mathrm{LL}}_{\ell\ell}(z,Q^2)$ known to $\mathcal{O}(\alpha^5)$ + soft exponentiation, equivalent description by QED parton showers
- $\mathcal{O}(\alpha)$ approximation: $\Gamma^{\mathrm{LL},1}_{\ell\ell}(z,Q^2) = \frac{\alpha(0)}{2\pi}\left[\ln\left(\frac{Q^2}{m_\ell^2}\right) - 1\right]\left(\frac{1+z^2}{1-z}\right)_+$
- log-enhanced corrections for “bare” leptons (muons) $\quad\to$ large radiative tails
- KLN theorem: mass-singular FSR effects cancel if $(\ell\gamma)$ system is inclusive (full integration over z)
- full FSR not universal, in general not even separable from other EW corrections

Recommendations for experimentalists:

- no unfolding or subtraction of FSR effects !
  $\hookrightarrow$ would introduce untransparent conventions for non-universal EW corrections
- use concept of “dressed leptons” if reduction of large FSR effects is desirable
  (recombination of collinear $\ell\gamma$ configurations, analogous to QCD jet algorithms)

Electroweak radiative corrections at high energies

Sudakov logarithms induced by soft gauge-boson exchange



etc.

+ sub-leading logarithms from collinear singularities

Typical impact on $2 \to 2$ reactions at $\sqrt{s} \sim 1\,\mathrm{TeV}$:

$$\delta^{1-\mathrm{loop}}_{\mathrm{LL}} \sim -\frac{\alpha}{\pi s_{\mathrm{W}}^2} \ln^2\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -26\%, \qquad \delta^{1-\mathrm{loop}}_{\mathrm{NLL}} \sim +\frac{3\alpha}{\pi s_{\mathrm{W}}^2} \ln\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 16\%$$

$$\delta^{2-\mathrm{loop}}_{\mathrm{LL}} \sim +\frac{\alpha^2}{2\pi^2 s_{\mathrm{W}}^4} \ln^4\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 3.5\%, \qquad \delta^{2-\mathrm{loop}}_{\mathrm{NLL}} \sim -\frac{3\alpha^2}{\pi^2 s_{\mathrm{W}}^4} \ln^3\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -4.2\%$$

$\Rightarrow$ Corrections still relevant at 2-loop level

Note: differences to QED / QCD where Sudakov log's cancel

- massive gauge bosons W, Z can be reconstructed
  $\hookrightarrow$ no need to add "real W, Z radiation"
- non-Abelian charges of W, Z are "open" $\to$ Bloch–Nordsieck theorem not applicable

Extensive theoretical studies at fixed perturbative (1-/2-loop) order and suggested resummations via evolution equations

Beccaria et al.; Beenakker, Werthenbach; Ciafaloni, Comelli; Denner et al.; Fadin et al.; Hori et al.; Melles; Kühn et al.; Manohar et al. '00–

$\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$: integrated cross section in various setups

Biedermann et al. ’16

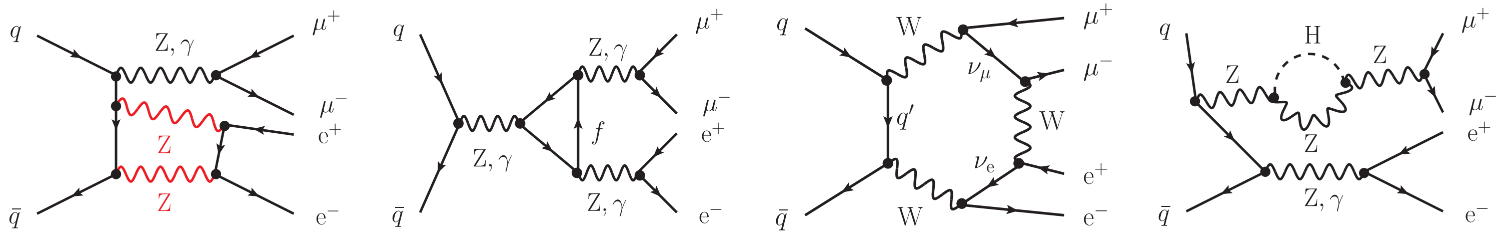
LHC		$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta^{\mathrm{NLO}}_{\bar{q}q}$ [%]	$\delta^{q\neq\mathrm{b}}_{q\gamma}$ [%]	$\delta_{\gamma\gamma}$ [%]	δ_{EW} [%]	$\delta_{\mathrm{b}\gamma}$ [%]
Inclusive	8 TeV	238.65(3)	−3.28	0.44	0.84	−2.01	1.81
	13 TeV	390.59(3)	−3.41	0.49	0.73	−2.20	2.30
ATLAS WW	8 TeV	165.24(1)	−3.56	−0.26	1.01	−2.81	0.18
	13 TeV	271.63(1)	−3.71	−0.27	0.87	−3.11	0.23
Higgs bkg	8 TeV	31.59(2)	−2.52	−0.21	0.60	−2.13	0.15
	13 TeV	49.934(2)	−2.54	−0.22	0.52	−2.25	0.18

- Electroweak corrections moderate
  (due to inclusiveness of the event selection)

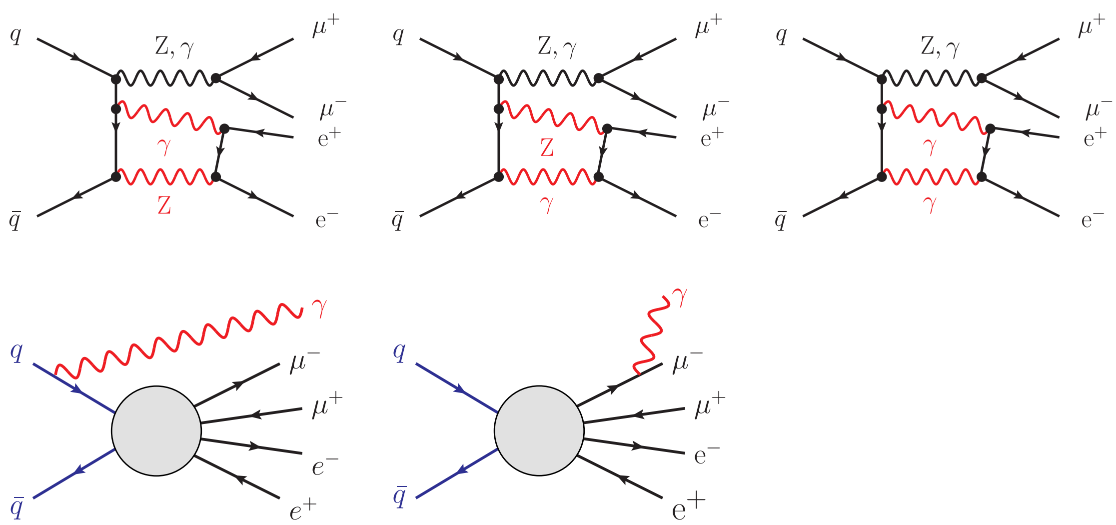
  Note: no gauge-invariant separation of weak and photonic corrections
- Deviation of δ from DPA $\sim 0.1\%$
- Deviation of δ from on-shell WW calculation $\sim 1\%$
  (only rough estimate, depends on cuts)

$\mathrm{pp} \to \mathrm{ZZ} \to 4\ell + X$: separation of weak and photonic corrections

Examples for weak diagrams:



Examples for photonic diagrams:



Note:

Photonic diagrams in SM and $\mathrm{U}(1)_\gamma \times \mathrm{U}(1)_\mathrm{Z}$ theory identical

$\hookrightarrow$ gauge-invariant photonic contributions for each (independent) charge factor

$\mathrm{pp} \to \mathrm{ZZ} \to 4\ell + X$: integrated cross section in various setups

Biedermann et al. '16

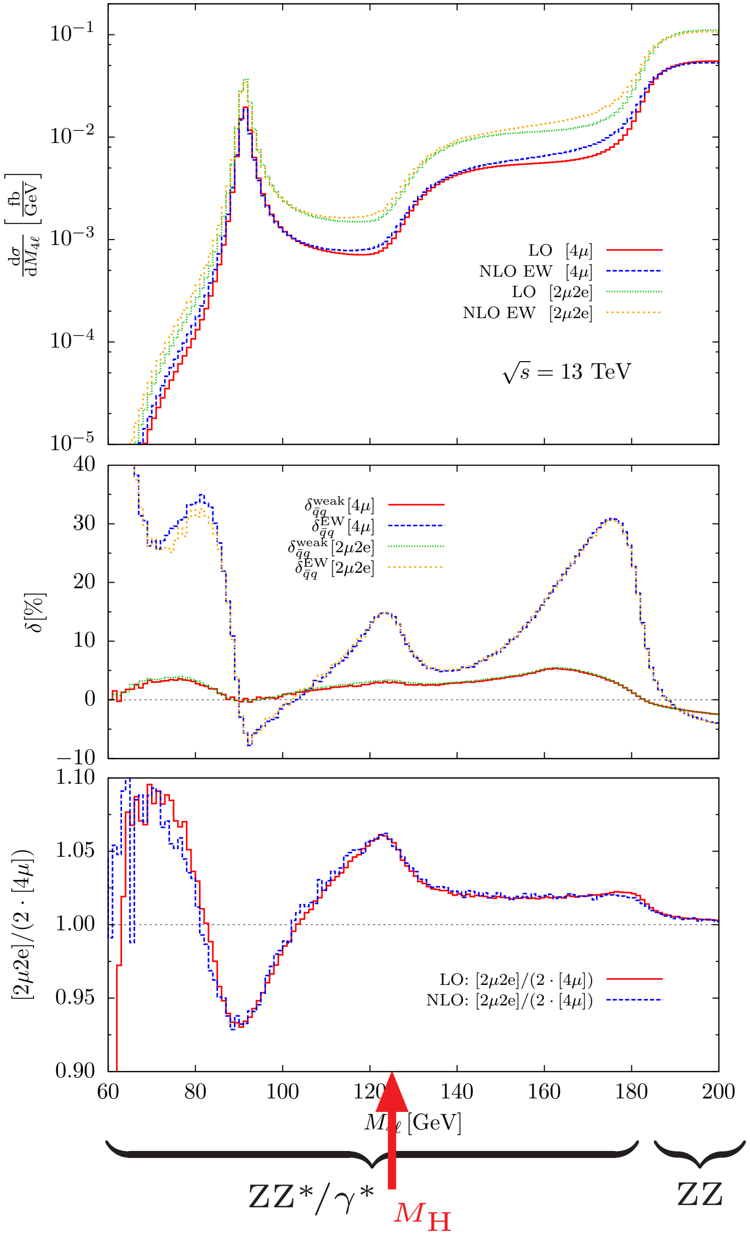
	$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta^{\mathrm{weak}}_{\bar{q}q}$ [%]	$\delta^{\mathrm{phot,safe}}_{\bar{q}q}$ [%]	$\delta^{\mathrm{phot,unsafe}}_{\bar{q}q}$ [%]	$\delta_{\gamma\gamma}$ [%]	$\delta_{q\gamma}$ [%]
incl. [2μ2e]	11.4962(4)	−4.32	−0.93	−1.68	+0.13	+0.02
incl. [4μ]	5.7308(3)	−4.32	−0.94	−2.43	+0.11	+0.02
Higgs [2μ2e]	13.8598(3)	−3.59	−0.04	−0.28	+0.23	−0.09
Higgs [4μ]	7.1229(2)	−3.42	−0.09	−0.66	+0.30	−0.14

- Weak and photonic corrections moderate
- Deviation of δ from on-shell ZZ calculation $\sim 1\%$
- $q\gamma$ and $\gamma\gamma$ negligible (at per-mille level)

Comments on event selection and cuts:

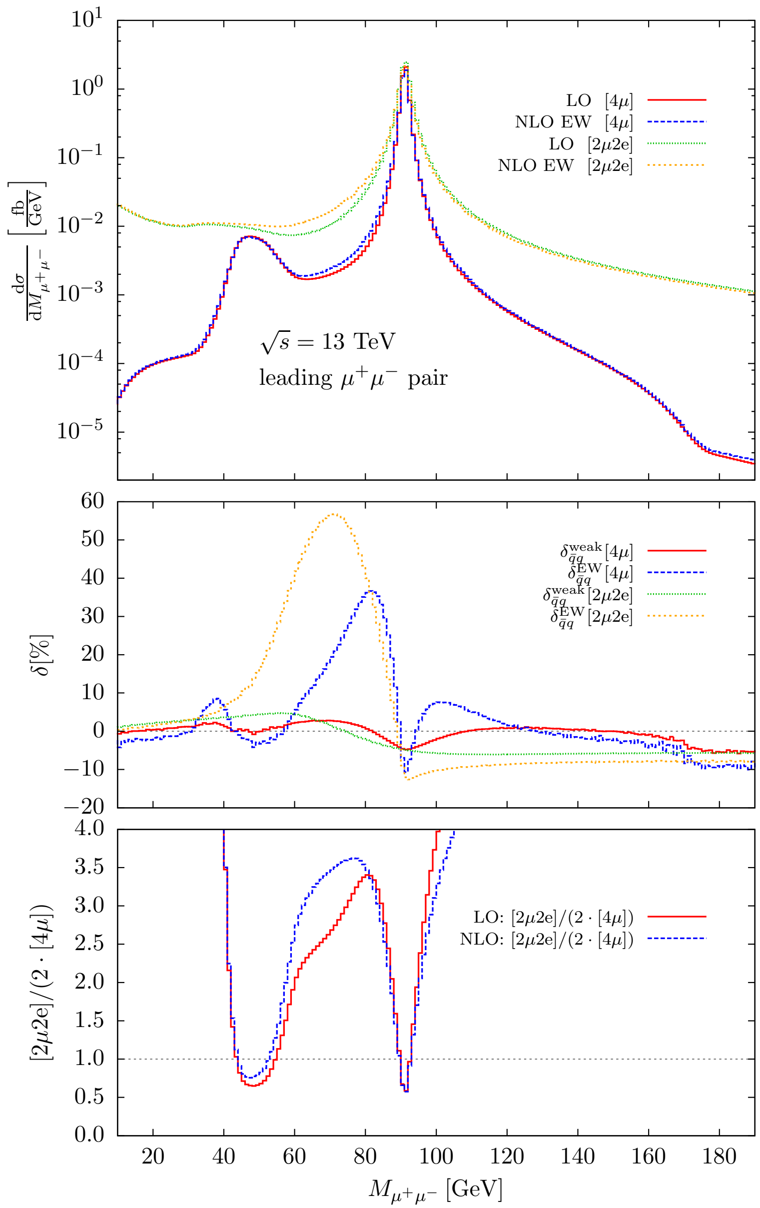
- 4μ states: leading $\mu^+\mu^-$ pair has smaller $|M_{\mu^+\mu^-} - M_Z|$
- Inclusive setup: $p_T(\ell_i) > 15\,\mathrm{GeV}$, etc.
- Higgs-specific setup: $p_T(\ell_i) > 6\,\mathrm{GeV}$, etc.
  in addition: $40\,\mathrm{GeV} < M_{\ell_1^+\ell_1^-} < 120\,\mathrm{GeV}$, $12\,\mathrm{GeV} < M_{\ell_2^+\ell_2^-} < 120\,\mathrm{GeV}$

$M_{4\ell}$ distribution for $\mathrm{pp} \to 4\ell + X$ Biedermann et al. '16



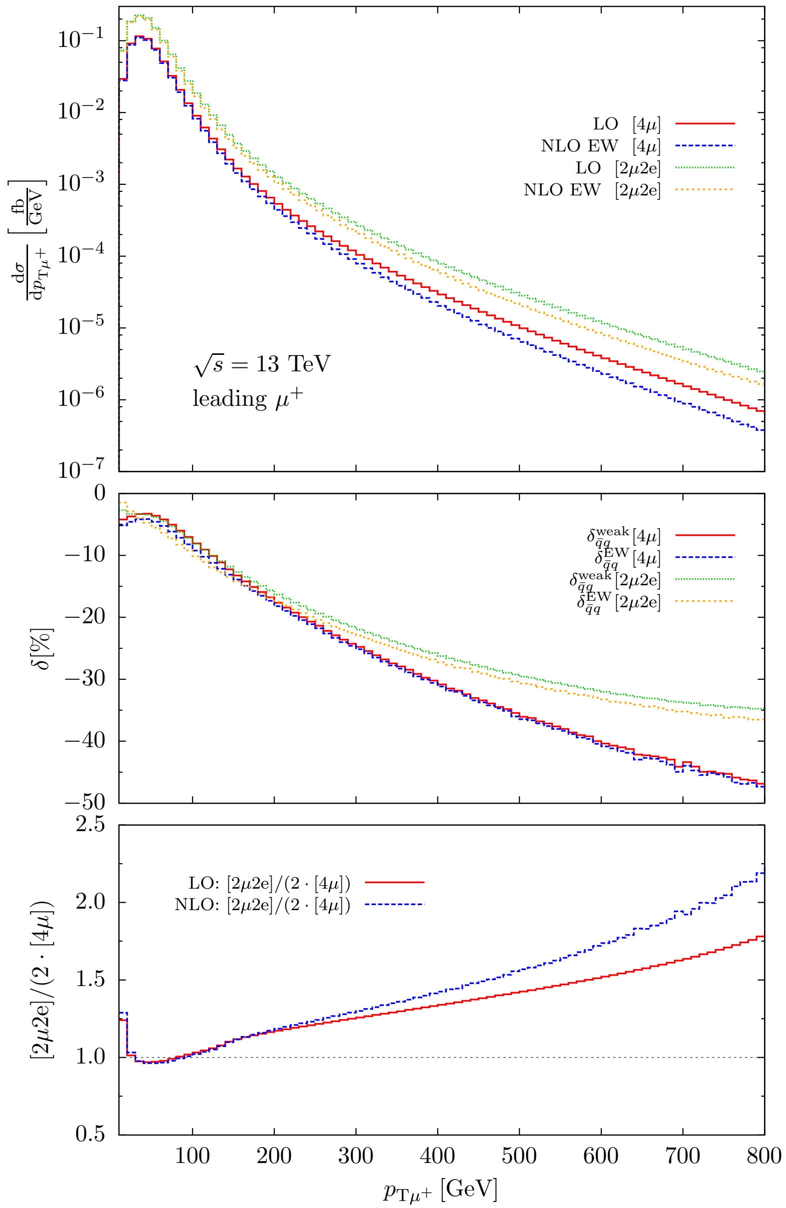
- photonic corrections:
  large, but well-known radiative tails below thresholds and resonances
- weak corrections $\sim 5\%$:
  sign change of at $M_{4\ell} \sim 2M_Z$!
- $\gamma\gamma$ and $q\gamma$ contributions $\lesssim 0.3\%$
  (not shown)
- relative corrections
  insensitive to lepton pairing

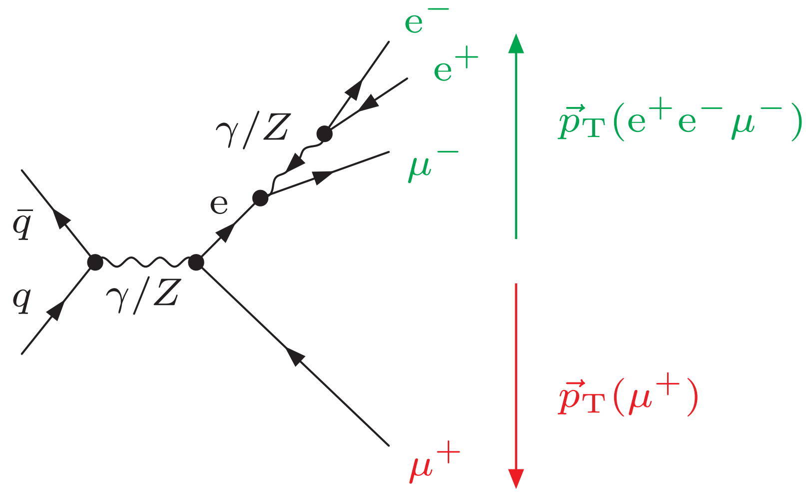
$M_{2\ell}$ distribution for $\mathrm{pp} \to 4\ell + X$ Biedermann et al. '16



- weak and photonic corrections to $[2\mu 2\mathrm{e}]$:
  - ◇ shape inherited from Z decay (as in single-Z production)
  - ◇ offset from ZZ production
  - ↪ explains sign change of δ^{weak} in $M_{4\ell}$ distribution
- distribution very sensitive to lepton pairing, but not the relative corrections

$p_{\mathrm{T},\ell}$ distribution for $\mathrm{pp} \to 4\ell + X$ Biedermann et al. ’16



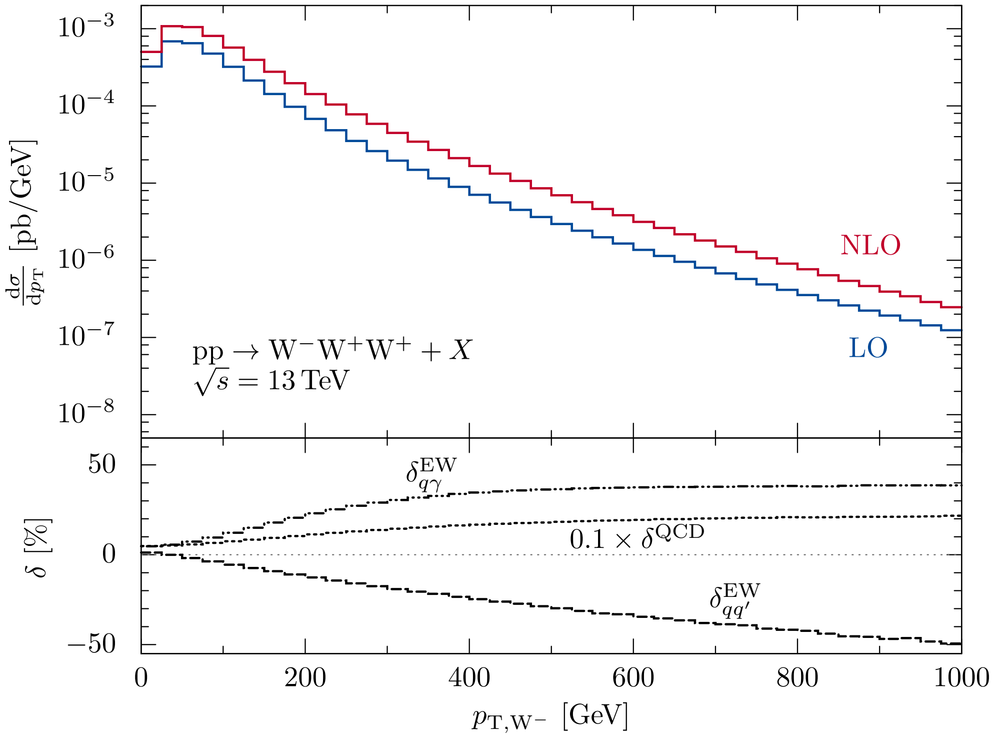


- corrections to $[2\mu 2e]$:
  - ◇ inclusive setup:
    significant influence of singly-resoannt diagrams
  - ◇ Higgs-specific setup:
    singly-resoannt diagrams suppressed
- corrections independent from lepton pairing in Higgs-specific setup

Status of predictions for VVV production:

- NLO QCD — Lazopoulos et al. '07; Hankele et al. '07; Binoth et al. '08; Campanario et al. '08; Nhung et al. '13
- NLO EW — Nhung et al. '13; Shen et al. '15,'16; Wang et al. '16; S.D. et al. '17

$\mathrm{pp} \to \mathrm{W}^-\mathrm{W}^+\mathrm{W}^+ + X$ at NLO:



S.D., Huss, Knippen '17

$\sqrt{s}$[TeV]	σ^{NLO}[pb]	$\delta^{\mathrm{EW}}_{q\bar{q}}$[%]	$\delta^{\mathrm{EW}}_{q\gamma}$[%]	δ^{QCD}[%]
7	0.04469	−3.4	5.7	51.4
8	0.05792	−3.5	6.6	55.0
13	0.1381	−4.1	10.7	70.0
14	0.1565	−4.2	11.5	72.6
100	2.697	−5.4	40.3	148.1

- huge QCD corrections
  ↪ multi-jet merging, resummations necessary
- significant $q\gamma$ contributions

ATLAS ($8\,\mathrm{TeV}/20.3\,\mathrm{fb}^{-1}$) σ^{fid}[fb]:

$\ell\nu\ell\nu\ell\nu$: $0.31^{+0.35}_{-0.33}(\mathrm{stat})^{+0.32}_{-0.35}(\mathrm{syst})$ fb

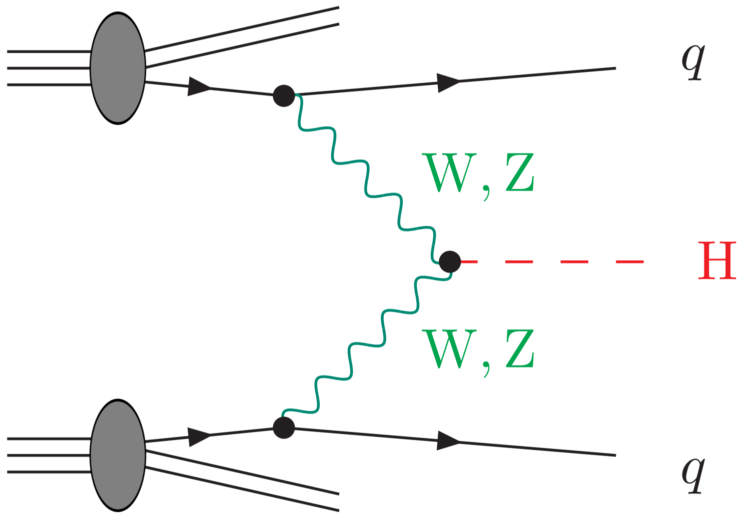
$\ell\nu\ell\nu jj$: $0.24^{+0.39}_{-0.33}(\mathrm{stat}) \pm 0.19(\mathrm{syst})$ fb

σ_{SM}[fb]: (VBFNLO/MadGraph5_aMC@NLO)

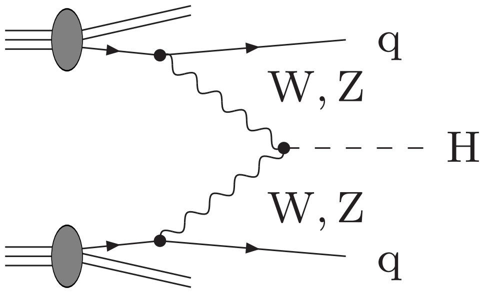
$0.309 \pm 0.007(\mathrm{stat}) \pm 0.015(\mathrm{PDF}) \pm 0.008(\mathrm{scale})$ fb

$0.286 \pm 0.006(\mathrm{stat}) \pm 0.015(\mathrm{PDF}) \pm 0.010(\mathrm{scale})$ fb

Higgs production via vector-boson fusion



Higgs production via weak vector-boson fusion (VBF)



colour exchange between quark lines suppressed

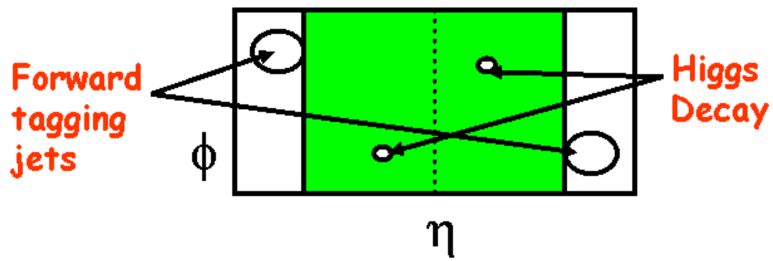
$\Rightarrow$ small QCD corrections

Han, Valencia, Willenbrock '92; Spira '98;
Djouadi, Spira '00; Figy, Oleari, Zeppenfeld '03

$\hookrightarrow$ t-channel approximation (vertex 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

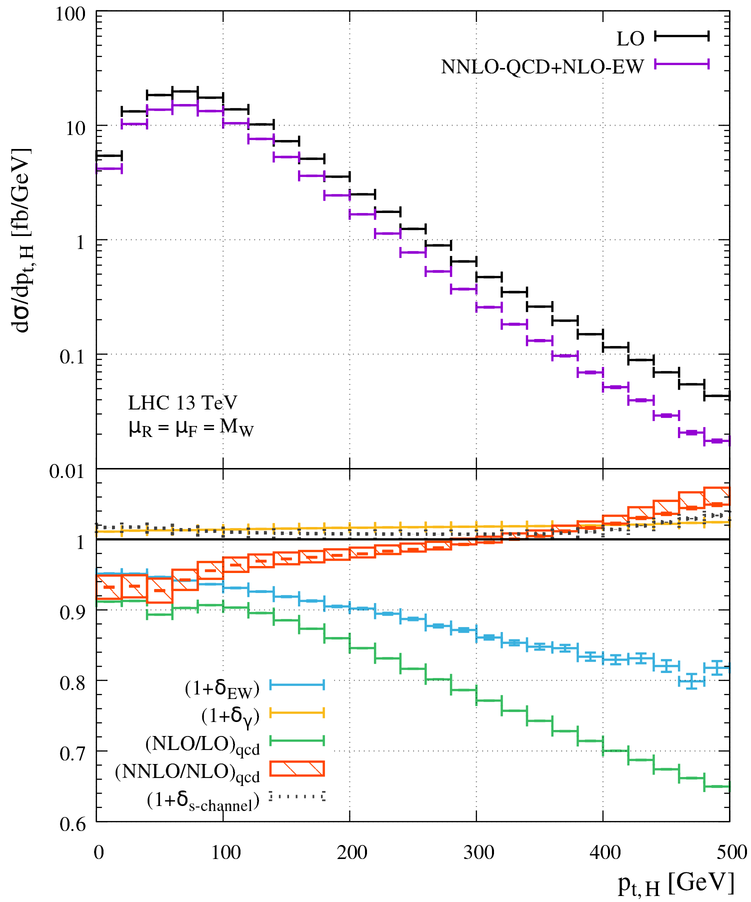
- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

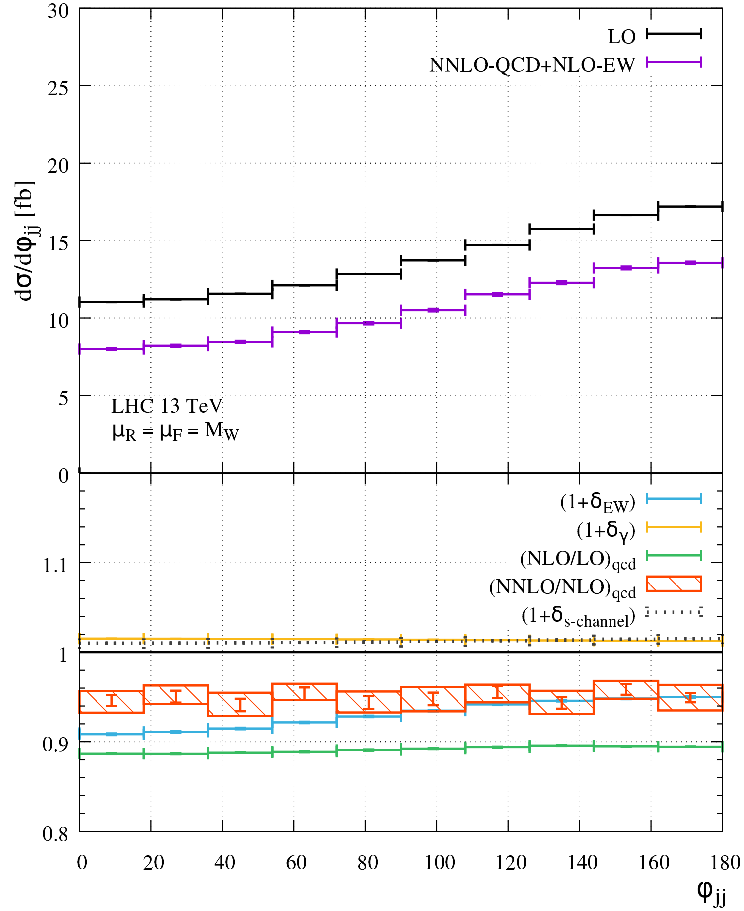
Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in DIS-like approximation
  Han et al. '92; Spira '98; Djouadi, Spira '00; Figy et al. '03; Berger, Campbell '04; Nason, Oleari '09
- (full) NLO QCD+EW corrections to VBF
  ↪ NLO QCD $\sim$ NLO EW $\sim 5{-}10\%$
  Ciccolini, Denner, S.D. '07
  Figy, Palmer, Weiglein '10 (DIS-like EW)
- NNLO QCD corrections to VBF in DIS-like approximation
  ↪ NNLO QCD $\sim 5\%$
  Bolzoni, Maltoni, Moch, Zaro '10; Cacciari et al. '15
- NNNLO QCD corrections to VBF in DIS-like approximation
  ↪ NNNLO QCD $\sim 0.1{-}0.2\%$ Dreyer, Karlberg '16
- NLO QCD corrections to $gg \to Hgg$, etc.
  Campbell, R.K.Ellis, Zanderighi '06
  ↪ contribution to VBF $\sim 5\%$
  Nikitenko, Vazquez '07 (NLO scale uncertainty $\sim 35\%$)
- QCD loop-induced interferences between VBF and Hgg-initiated channels
  ↪ impact $\lesssim 10^{-3}\,\%$ (negligible!)
  Andersen, Binoth, Heinrich, Smillie '07
  Bredenstein, Hagiwara, Jäger '08
- loop-induced VBF in gg scattering
  Harlander, Vollinga, Weber '08
  ↪ impact $\sim 0.1\%$
- SUSY QCD+EW corrections
  Hollik, Plehn, Rauch, Rzehak '08
  ↪ $|\mathrm{MSSM} - \mathrm{SM}| \lesssim 1\%$ for SPS points ($2{-}4\%$ for low SUSY scales)

Fiducial cross sections @ NNLO QCD + NLO EW

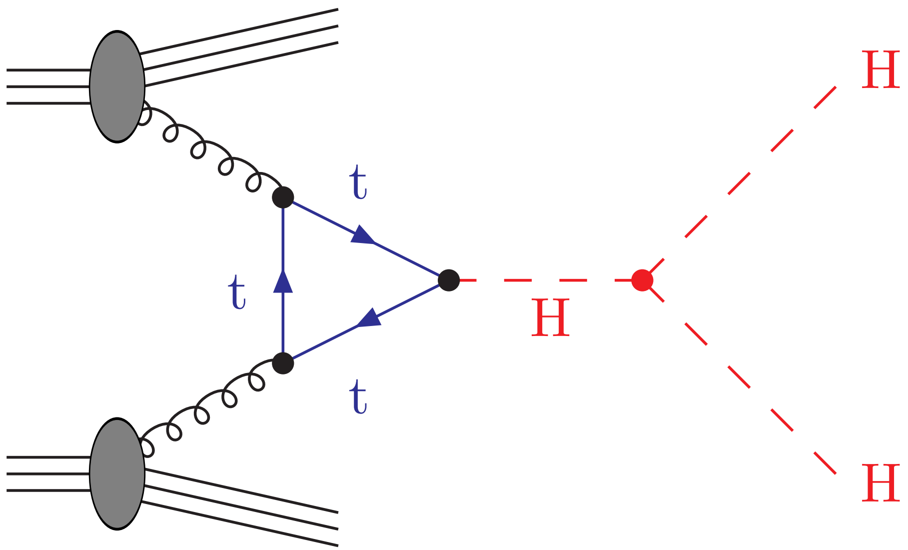
LHC Higgs XS WG '16





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

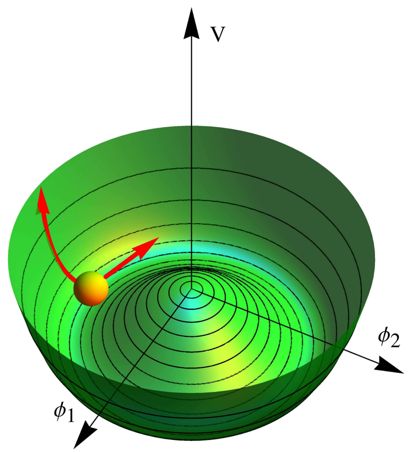
Higgs pair production via gluon fusion

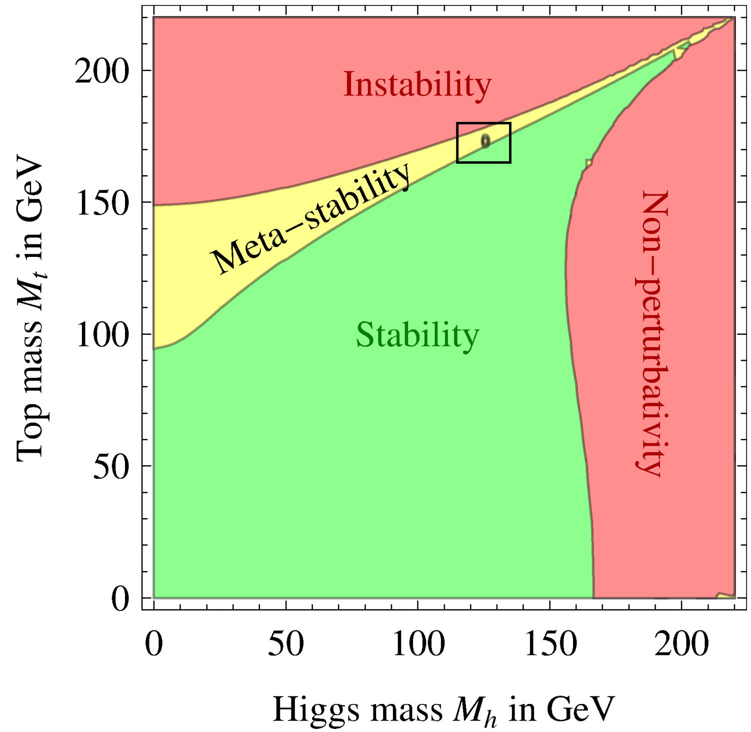


Higgs self-coupling λ – window to new physics ?

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

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





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 !

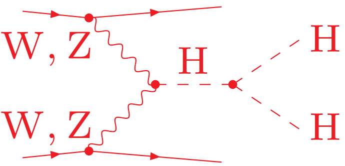
- $\lambda(\mu) < 0$: vacuum instability
- $\lambda(\mu) \to \infty$: triviality, non-perturbativity, ... consistency problem

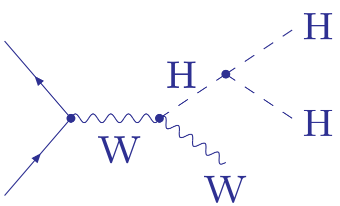
$\Rightarrow$ Exp. challenge: measuring λ in Higgs pair production

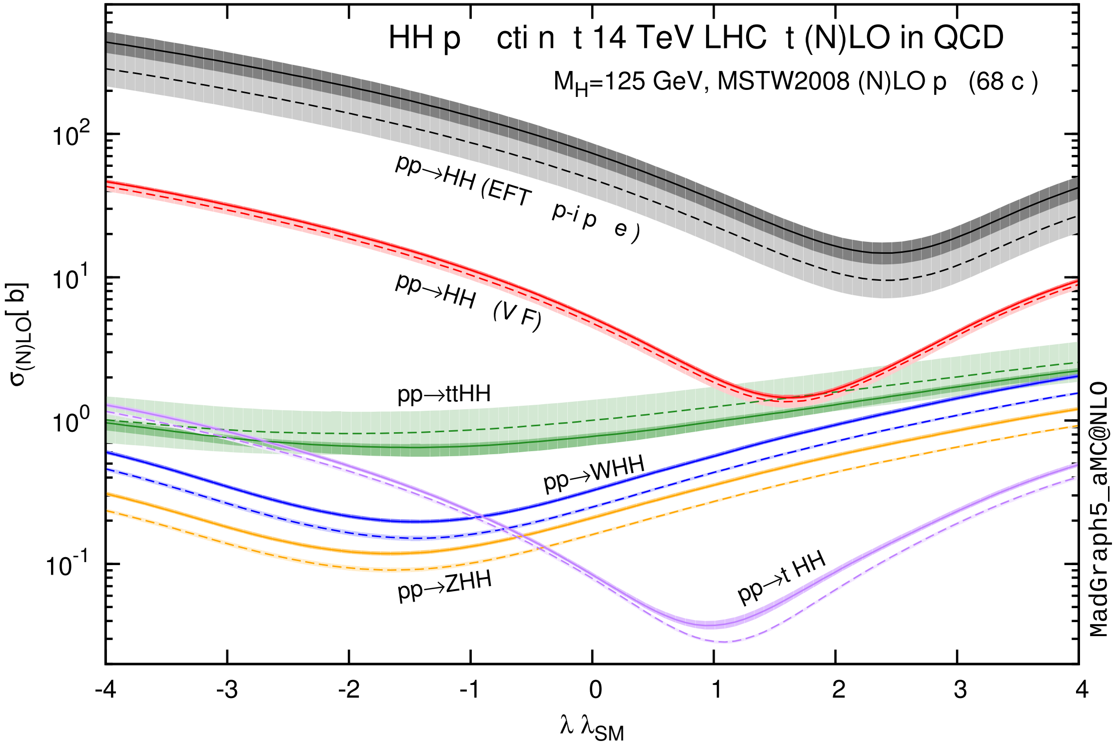
Alternative: constraints via loop effects in single-Higgs production

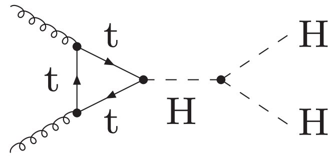
Higgs self-coupling λ – window to new physics ?

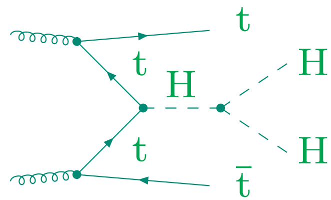
Maltoni et al. '14











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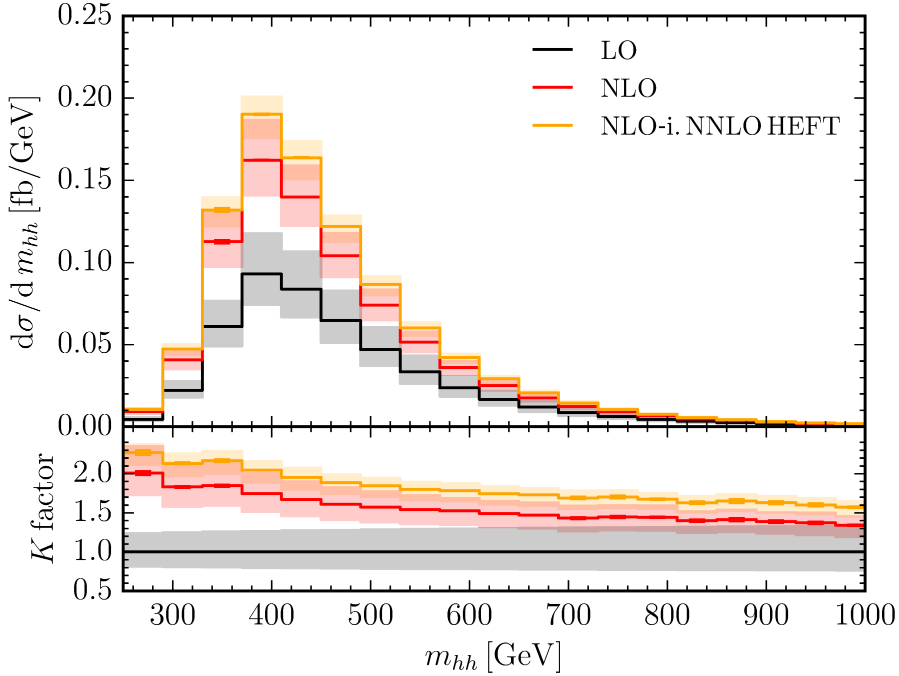
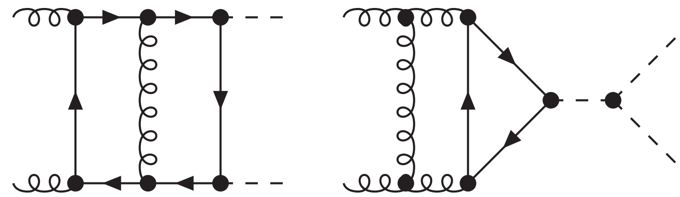
More precision for $\mathrm{pp(gg)} \to \mathrm{HH}$

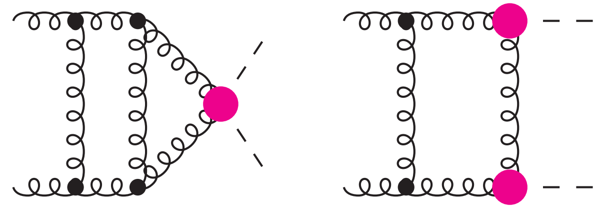
Borowka et al. '16



NLO:



NNLO HEFT:
$(m_t \to \infty)$



- LO Eboli et al. '87; Glover, van der Bij '88 $\sigma_{\mathrm{LO}}(m_t)$
- NLO: $m_t \to \infty$ Dawson, S.D., Spira '98 $+100\%$

  $1/m_t$ expansion Grigo et al. '13,'15; Degrassi et al. '16

  full m_t dependence Maltoni et al. '14; Borowka et al. '16 -14%
- NNLO ($1/m_t$ expansion): $+20\%$

  deFlorian et al. '13,'16; Grigo et al. '14,'15
- QCD parton shower effects / resummations

  Li et al. '13; Maierhöfer et al. '14; Frederix et al. '14 Shao et al. '13; deFlorian et al. '15

TH uncertainty:
(@ 14 TeV)
$\Delta_{\mathrm{scale}} \sim 6\%$
$\Delta_{\mathrm{PDF}+\alpha_s} \sim 3\%$