Recent progress in theoretical predictions for LHC physics

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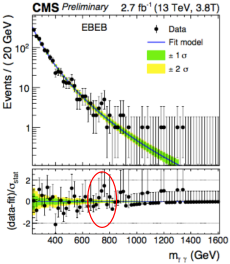
two strategies of looking for new physics

- bump hunting, if possible new particles are in the investigated energy domain
  - analysis data driven
- if new BSM threshold is higher than the available energy
  - look for deviations from SM predictions in the tails of distributions
  - measure the SM couplings and parameters with the highest possible precision in order to discover internal inconsistencies
  - **both above cases require the most possible precision in theoretical predictions**

Most exciting New Physics hint disappeared (∼350 th-papers)

2015 data

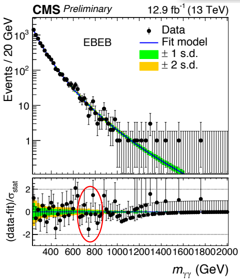
Phys. Rev. Lett. **117**

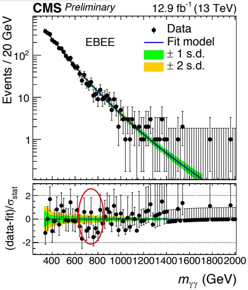


Clarification: the small excess at 750 GeV remained there after reprocessing and final calibration (CMS choice to reprocess prior to publishing).

2016 analysis: straight reload of 2015 analysis

CMS PAS EXO-16-027



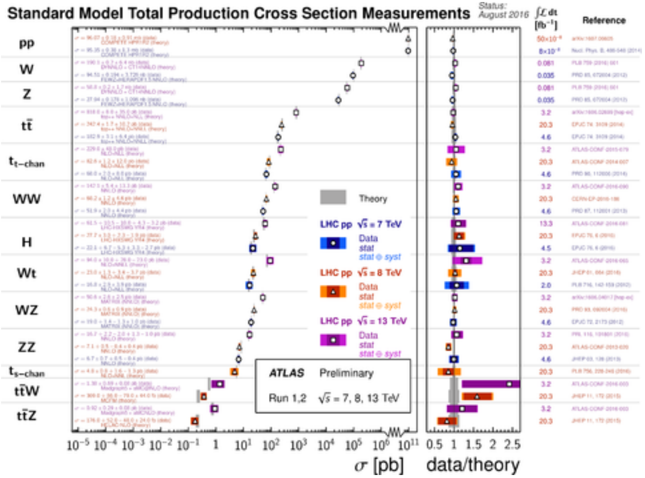


2016 data: no evidence of strengthening of this bump

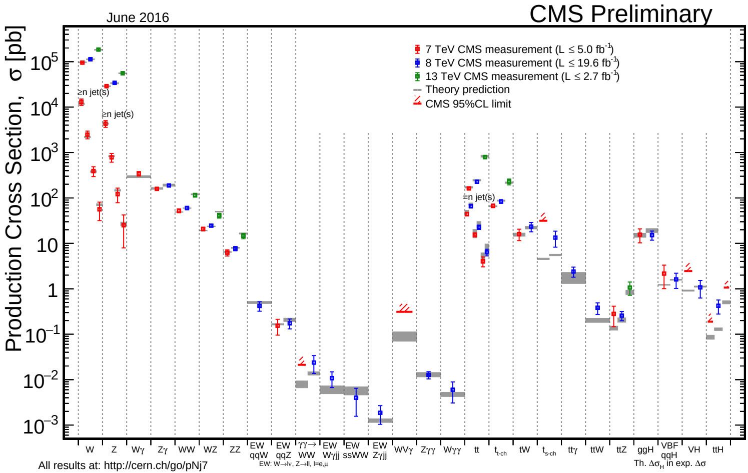
from T. Camporesi, ICHEP 2016

Most impressive results of LHC Run 1

- **measured cross sections in agreement with SM predictions over 6 orders of magnitude**

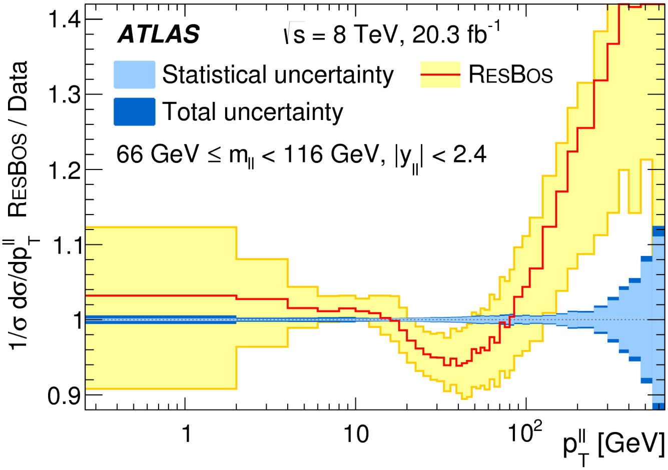


the same from CMS



- **for several final states the theory uncertainty is (and will be even further) the limiting factor**

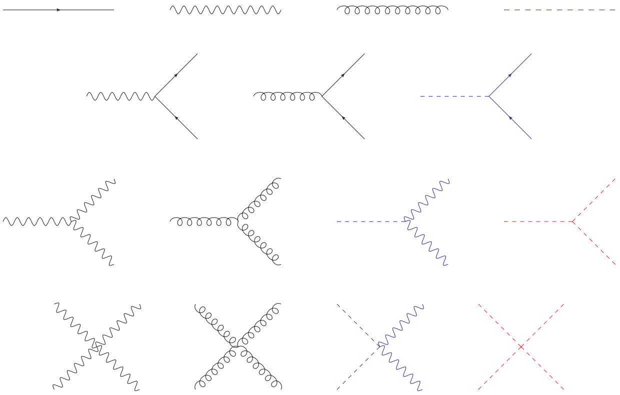
precision also on distributions: e.g. $p_T^{l^+l^-}$



- exp uncertainty at the % level over a wide range of p_T values

Starting point: the SM Lagrangian

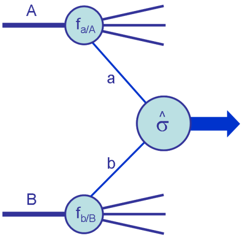
$$\mathcal{L}_{\rm matter} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm gauge-int.} + \mathcal{L}_{\rm Yukawa-inter.} + \mathcal{L}_{\rm Higgs\,self-int.}$$



From SM Lagrangian to collider phenomenology

$$\sigma^{\text{exp}} \equiv \frac{1}{\int \mathcal{L} dt} \frac{N^{obs}}{A\ \epsilon} = \sigma^{\text{theory}}$$

$$\sigma^{\text{theory}} = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a,H_1}(x_1, \mu_F^2, \mu_R^2) f_{b,H_2}(x_2, \mu_F^2, \mu_R^2) \times$$
$$\times \int_\Phi d\hat{\sigma}_{a,b}(x_1, x_2, Q^2/\mu_F^2, Q^2/\mu_R^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}^n}{Q^n}\right)$$



Campbell, Huston, Stirling, hep-ph/0611148

- PDF's fitted from data
- $\hat{\sigma}$ calculated perturbatively

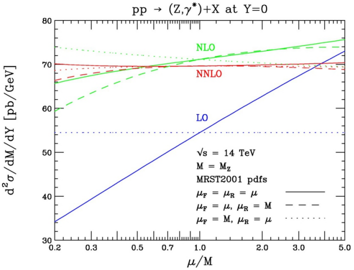
$$\sigma = \sigma_0 (1 + \alpha_s \delta_1^{\text{QCD}} + \alpha_s^2 \delta_2^{\text{QCD}} + \alpha \delta_1^{\text{EWK}} + \ldots)$$

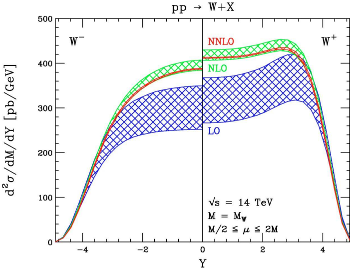
Higher order SM corrections

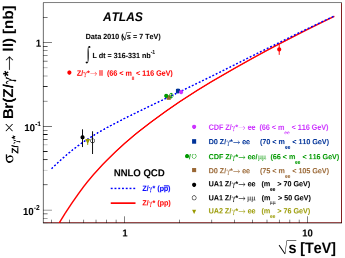
- **a powerful per cent level comparison between theoretical predictions and measurements requires the inclusion of perturbative higher order corrections**
- in particular, for observables inclusive on additional radiation, fixed order calculations are reliable
- for $2 \to 1$ and $2 \to 2$ scattering processes the QCD NNLO corrections have been recently calculated, with the help of new subtraction schemes
  - for colourless final states
    - Higgs production
    - C.C. and N.C. Drell Yan
    - $pp \to HW$, $pp \to HZ$
    - $pp \to VV'$, $V, V' = Z, W, \gamma$
  - for final states involving coloured particles
    - $pp \to t\bar{t}$, single-top production
    - Wj, Zj and Hj production
    - $pp \to Hjj$ in VBF

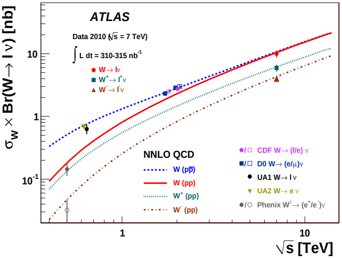
fully differential NNLO QCD corrections to DY

DYNNLO, FEWZ

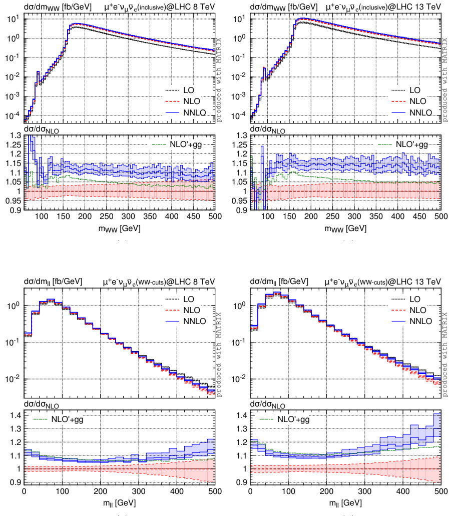








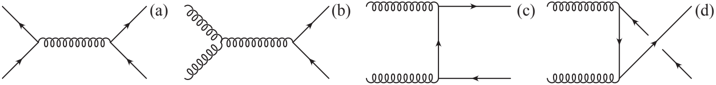
NNLO QCD corr's to $pp \to W^+W^- \to 4$ leptons

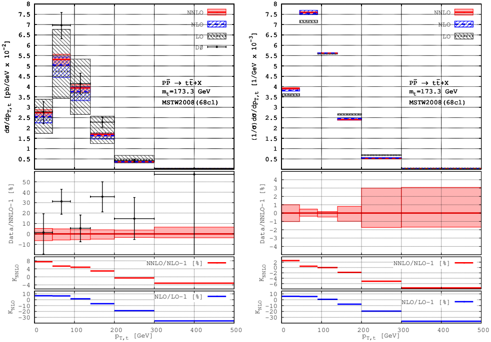


M. Grazzini et al., arXiv:1605.02716

$t\bar{t}$ @NNLO QCD

- $t\bar{t}$ production

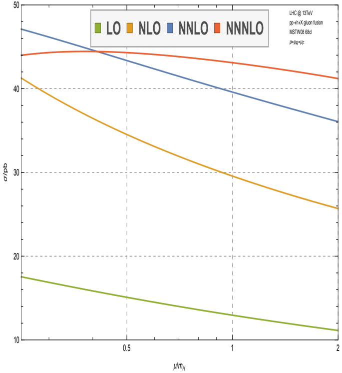


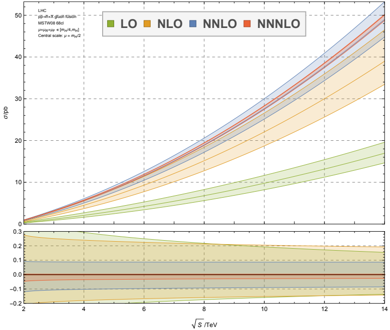


M. Czakon, P. Fiedler D. Heymes and A. Mitov, arXiv:1601.05375

N3LO predictions for inclusive Higgs cross section

C. Anastasiou et al., arXiv:1503.06056; arXiv:1602.00695





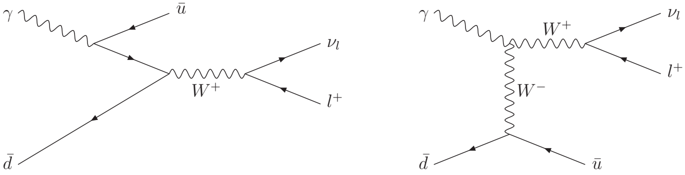
- reduced scale dependence
- N3LO correction $\sim 2\%$ w.r.t NNLO

also electroweak corrections enter the game, in two ways

- ($\alpha_{e.m.} \sim \alpha_s^2 \Longrightarrow$ NLO EWK $\sim$ NNLO QCD)
  - usually largest effects from QED radiation from external legs $\sim \alpha \log\left(\frac{Q^2}{m^2}\right)$
  - EWK effects particularly relevant for observables (partially) insensitive to QCD corrections, e.g.
    - Higgs decays to four leptons
    - transverse mass in the charged DY process
- on the NLO side, EW radiative corrections to $2 \to 2$, $2 \to 3$ and few $2 \to 4$ processes are already known
- LHC run2 is exploring (with enough statistics) regions of phase space with scales $Q^2 >> M_W^2 \Longrightarrow$ dominance of Sudakov logarithms $\alpha \log^2\left(\frac{|Q^2|}{M^2}\right)$

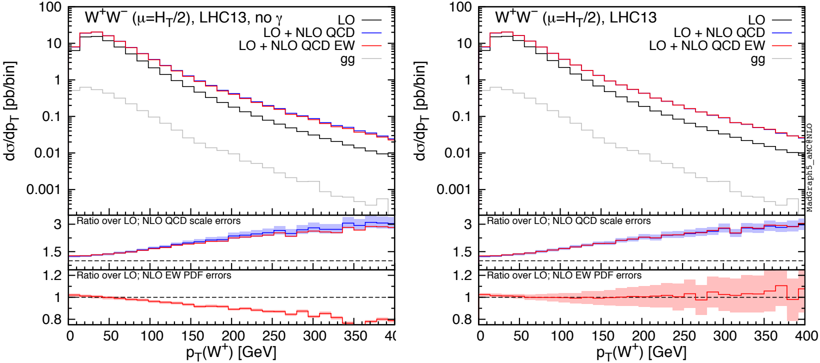
Photon induced processes

- at the same perturbative order of real NLO EW (QED) corrections contribute diagrams with γ in the initial state



- for neutral systems of charged F.S. particles also contributions at tree level (e.g. $\gamma\gamma \to \mu^+\mu^-$ or $\gamma\gamma \to W^+W^-$)
- typically they become relevant for large invariant mass of the system and forward kinematics, when $t-$channel enhancements are possible
- Necessary PDF sets which provide the γ PDF
- existing sets
  - MRST2004QED
  - NNPDF2.3QED, NNPDF3.0QED
  - CT14QED

Large uncertainties due to photon PDF's

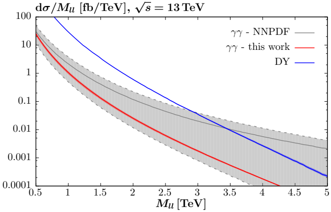


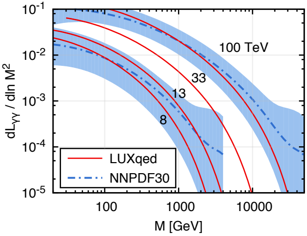
D. Pagani, talk at MBI2015, DESY Hamburg, 3 September 2015

The problem of the γ PDF uncertainty

- Very recently it has been realized that the available parameterizations do not include the information from coherent emission $p \to p\gamma$ at low Q^2, which is well measured experimentally through the electric and magnetic proton form factors
  - the coherent emission is crucial for the input PDF at low Q^2 scale

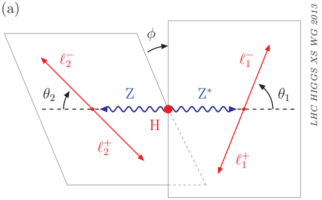
Manohar, Nason, Salam, Zanderighi, arXiv:1607.04266; Harland-Lang, Khoze and Ryskin, arXiv:1607.04635

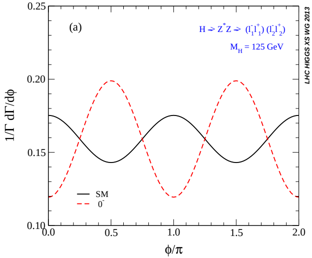




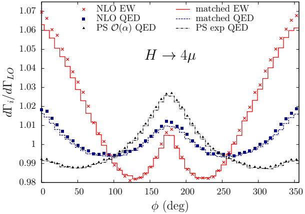
- uncertainty already well below 10% and central value close to the minimum predicted by NNPDF

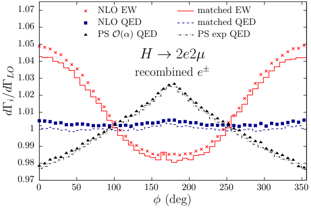
not always dominance of QED. Example: $H \to 4l$





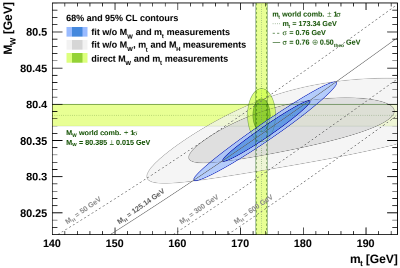
LHC Higgs Cross Section WG, arXiv:1307.1347



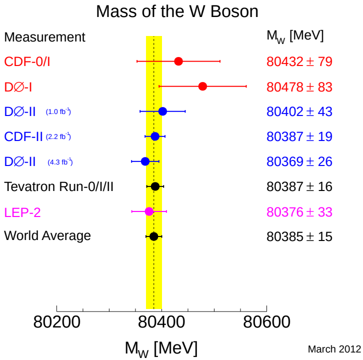


S. Boselli et al, arXiv:1503.07394

M_W direct measurement: crucial for a SM stress-test



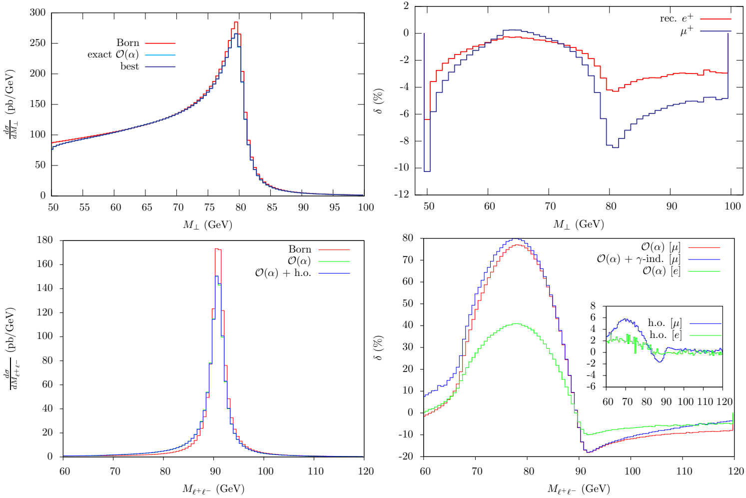
Gfitter, EPJC 74 (2014) 3046



TeVatron EWWG, arXiv:1204.0042

- A precise ($\delta M_W < 10$ MeV) M_W measurement at LHC Run2 and beyond will be an important goal of the LHC precision physics pogramme

Effects of EW corrections: W and Z production



- EW $\mathcal{O}(\alpha)$ change the shape $\rightarrow \delta M_W \simeq 100$ MeV

Carloni Calame et al., PRD 69 (2004) 037301, JHEP 0710 (2007) 109

mixed QCD - EW corrections

- Perturbatively the QCD - EW interference is a two-loop effect

$$\begin{aligned} d\sigma &= d\sigma_0 \\ &+ d\sigma_{\alpha_s} + d\sigma_{\alpha} \\ &+ d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \dots \end{aligned}$$

- the $\mathcal{O}(\alpha\alpha_s)$ calculation involves as building blocks
  - NNLO virtual corrections at $\mathcal{O}(\alpha\alpha_s)$ (not yet available)
    - necessary two-loop master integrals (with $m = 0$ external particles and $M_W = M_Z$) just appeared
      R. Bonciani et al., arXiv:1604.08581
  - NLO EW corrections to $l\bar{l}^{(')}+$ jet
  - NLO QCD corrections to $l\bar{l}^{(')}+\gamma$
  - double real contributions $l\bar{l}^{(')}+\gamma+$ jet
  - PDF's with NNLO accuracy at $\mathcal{O}(\alpha\alpha_s)$

    (not yet available)
- recently calculated:
  - dominant $\mathcal{O}(\alpha_s\alpha)$ corrections to DY in pole approximation
    Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216

effects on M_W

	bare muons		dressed leptons	
	$M_{\mathrm{W}}^{\mathrm{fit}}$ [GeV]	ΔM_{W}	$M_{\mathrm{W}}^{\mathrm{fit}}$ [GeV]	ΔM_{W}
LO	80.385	− 90 MeV	80.385	− 40 MeV
$\mathrm{NLO_{ew}}$	80.295		80.345	
$\mathrm{NLO_{s\oplus ew}}$	80.374	− 14 MeV	80.417	− 4 MeV
NNLO	80.360		80.413	

Dittmaier, Huss, Schwinn, NPB 904 (2016) 216

Fixed order calculations not always reliable

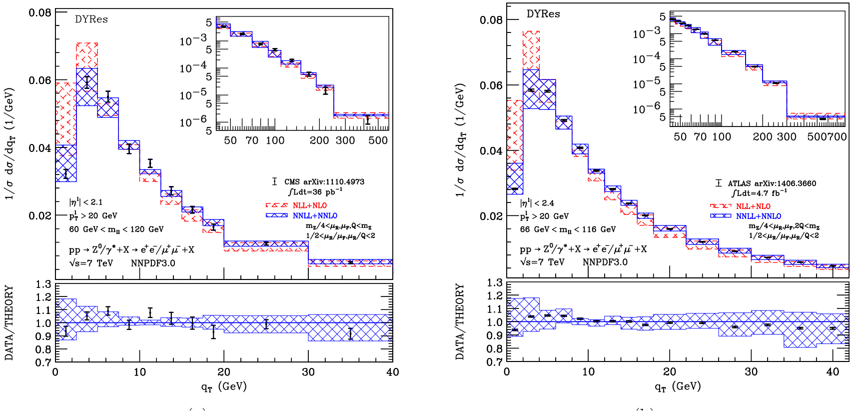
- in regions of phase space where large scale differences appear, e.g.
  - $p_T \ll M_V$ in DY
  - small x, $Q^2/s \ll 1$
  - in regions of phase space where the radiation is tightly constrained, e.g.
    - large x, $Q^2/s \to 1$

  large logs appear which spoil perturbation theory
- solution: resummation, $\alpha_s^n \log^{2n}$ (LL), $\alpha_s^n \log^{2n-1}$ (NLL), ...
- an alternative approach is given by SCET formalism
  - also EWK Sudakov Logs can be automatically resummed in the SCET formalism

Bauer, Becher, Manohar, ...

q_T resummation with DYRES, comparison with LHC data

- NNLL resummation with NNLO normalization



Catani, De Florian, Ferrera, Grazzini, arXiv:1507.06937

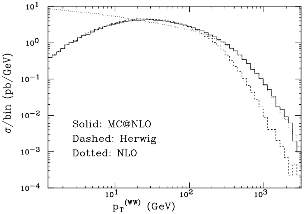
another way for resummation: parton shower

- positive features
  - complementarity with fixed order calculations
  - soft/collinear regions are automatically treated with Leading Log resummation
  - they include a model for the description of the underlying event, MPI and the hadronization
  - completely exclusive event generation, very useful for interface to detector simulation software and extrapolation
- problems
- the cross section prediction is pure LO (due to the unitarity of the algorithm)
- improvement: matching between fixed order NLO calculation and parton shower event generators

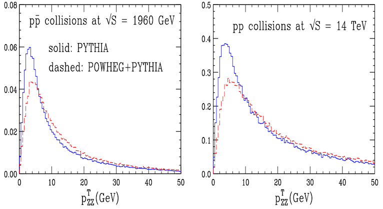
requirements to the matching

- avoid double counting
  - showering the Born events generate events with one additional parton from the shower. Such events are already accounted for in the NLO real radiation contribution
- ensure smooth distributions in the phase space
- since a decade two working algorithm have been developed:
  1. MC@NLO (S. Frixione and B. Webber (2002))
  2. POWHEG (P. Nason (2004))
- comparison MC@NLO - POWHEG
  - both ensure total cross section at NLO accuracy
  - MC@NLO exponentiates only the singular part of the real radiation amplitude
  - POWHEG modifies the Sudakov form factor by exponentiating the complete real radiation amplitude
  - differences between the two codes are beyond NLO accuracy $\Longrightarrow$ this can be used as an handle to guess the theoretical uncertainty due to missing higher orders

examples and the path to automation



S. Frixione and B. Webber, hep-ph/0204244



P. Nason and G. Ridolfi, hep-ph/0606275

- the recent automation on NLO multileg calculations triggered also the development of interfaces between automatic NLO matrix elements and parton showers, according to the MC@NLO or POWHEG methods. E.g.:
  - MadGraph5_aMC@NLO
  - MUNICH + Sherpa + OpenLoops
  - Herwig++Matchbox + OpenLoops/Gosam
  - Madgraph + POWHEG
- QCD@NLOPS acc. in principle automatized for every process
- QCD$\oplus$/$\otimes$EWK@NLOPS acc. under development, available for few selected processes

matching Parton Shower with higher orders

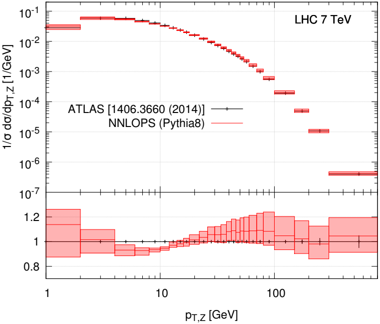
- recent developments on Higgs production, Drell-Yan and HW up to NNLO accuracy

Hamilton, Nason, Oleari, Zanderighi, arXiv:1212.4504; Hamilton, Nason, Re, Zanderighi, arXiv:1309.0017

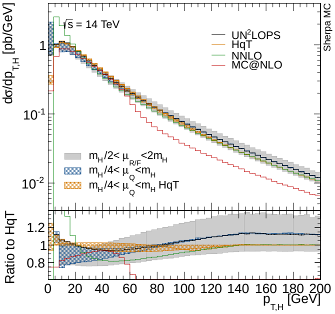
Hamilton, Nason, Zanderighi, arXiv:1501.4637; Karlberg, Re, Zanderighi, arXiv:1407.2940

Höche, Li, Prestel, arXiv:1407.3773; Höche, Li, Prestel, arXiv:1405.3607

Astill, Bizon, Re and Zanderighi, arXiv:1603.01620



1407.2940



1407.3773

Summary and outlook

- run2 of LHC and beyond demand continuous progress in the precision of theoretical calculations/generators
- last few years witnessed very important advancements in
  - fixed order corrections @NNLO QCD accuracy and mixed $\mathcal{O}(\alpha_s \alpha)$ NNLO contributions in a completely differential way
  - automation of NLO QCD/EWK calculations for every parton multiplicity in the final states
  - standardisation of event generators @NLOPS accuracy
  - development of QCD$\oplus$/$\otimes$EWK @NLOPS accuracy, applied to selected processes
  - first studies at NNLOPS QCD accuracy
  - (not discussed here) advancements in the development of the SMEFT, where operators with dim > 4 are included in the Lagrangian for a (almost) model-independent bottom-up approach to the deviations from the SM predictions