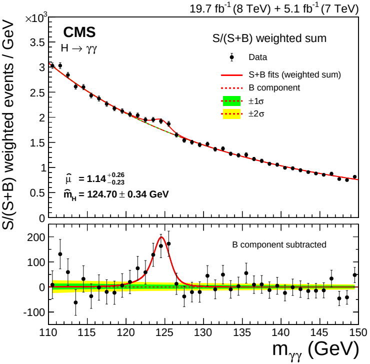
(Aspects of) Standard Model Theory at the LHC

Fulvio Piccinini

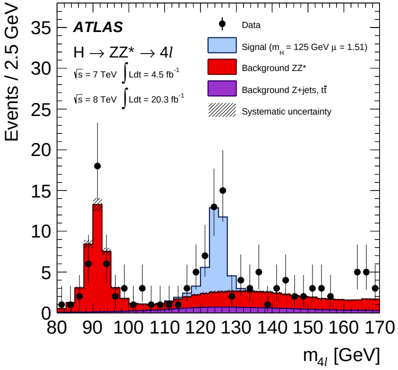
INFN Sezione di Pavia

XI ATLAS Italia Workshop, 4-6 November 2015, Cosenza

Most famous result of LHC Run 1: Higgs boson discovery

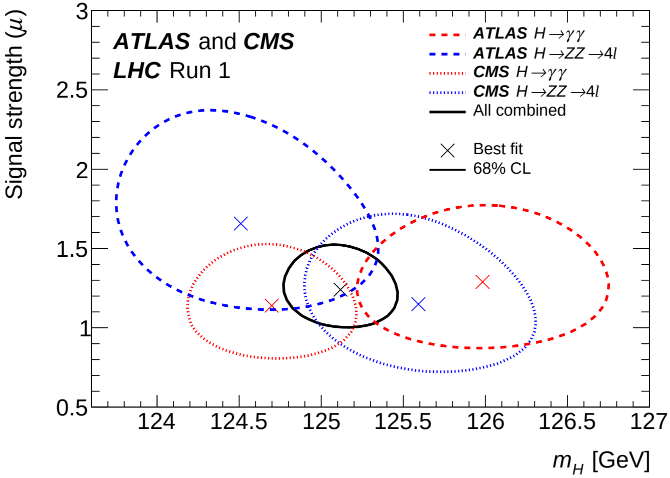


arXiv:1407.0558



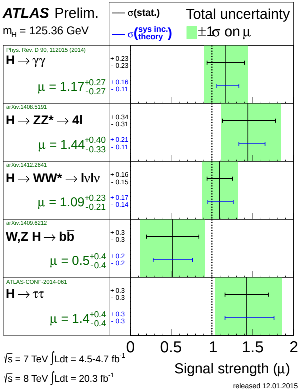
arXiv:1408.5191

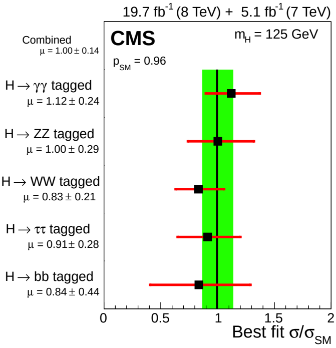
Higgs mass measurement:
$m_H = 125.09 \pm 0.21(\mathrm{stat},) \pm 0.11 \mathrm{syst.}$ GeV



ATLAS and CMS, arXiv:1503.07589

Higgs properties





CMS, arXiv:1412.8662

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/

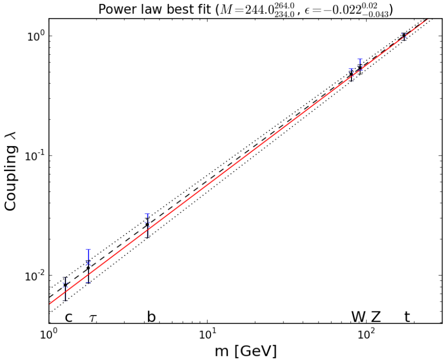
Higgs boson properties

- $Hf\bar{f}$ parameterized as

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}$$

- HVV parameterized as

$$g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

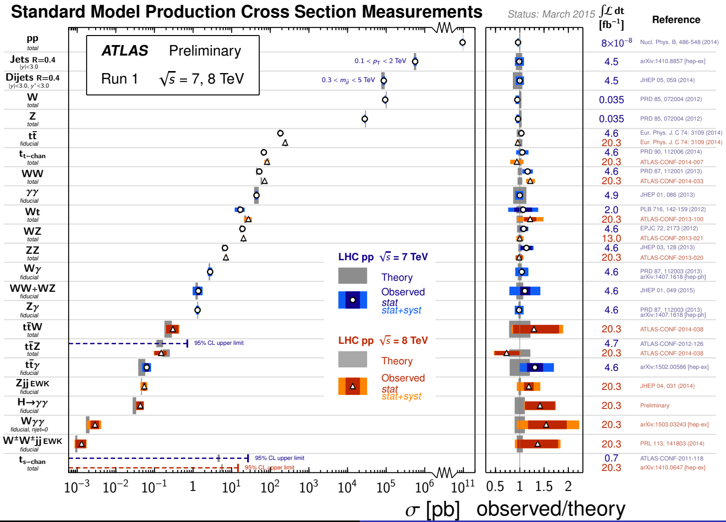


J. Ellis and T. You, arXiv:1303.3879

SM recovered with $\epsilon \to 0$ & $M \to 246$ GeV

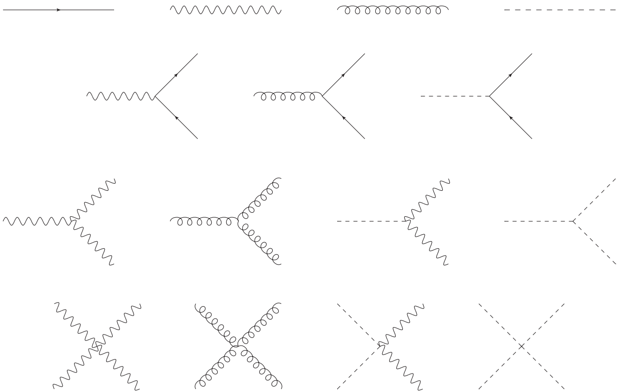
Most impressive results of LHC Run 1

- **measured cross sections in agreement with SM predictions over 9 orders of magnitude**



What is behind all this? The SM Lagrangian

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

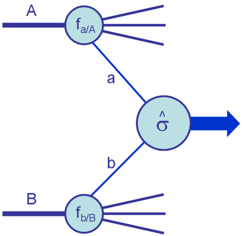


From SM Lagrangian to collider phenomenology

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

$$\sigma^{\text{theory}} \equiv \sum_{a,b} \int_0^1 dx_1\, dx_2 f_{a,H_1}(x_1, \mu_F^2, \mu_R^2) f_{b,H_2}(x_2, \mu_F^2, \mu_R^2) \times$$

$$\times \int_\Phi d\hat{\sigma}_{a,b}(x_1, x_2, Q^2/\mu_F^2, Q^2/\mu_R^2) + \mathcal{O}\left(\frac{\Lambda_{QCD}^n}{Q^n}\right)$$



Campbell, Huston, Stirling, hep-ph/0611148

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

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

Theoretical predictions

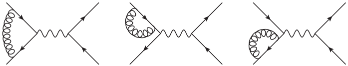
- Four main classes of computer programs
  - fixed order parton-level Monte Carlo programs, where the hard scattering is calculated with the highest feasible perturbative accuracy (NLO, NNLO, N3LO)
    - inclusive w.r.t. additional QCD/QED radiation, without transition from partons to hadrons
    - NO event generation
  - programs which give predictions with resummation of potentially large logarithms, limited to specific observables
  - general purpose Monte Carlo (parton shower) event generators, which can simulate in a completely exclusive way (even if with some approximations) the complete evolution of a hadron-hadron collision
  - matched fixed-order with parton shower event generators , which merge positive features of both approaches

NLO (QCD and/or EW) corrections

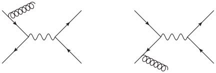
$$\sigma_{\rm NLO} = \int d\sigma_0 + \int d\sigma_V + \int d\sigma_R$$

example of QCD NLO corrections to DY

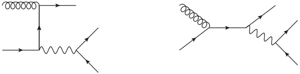
- virtual corrections



- real corrections
  - initial state radiation



  - new process: gluon in initial state



- for EW corr., W, Z, H, γ in the loops and γ in the real contribution R
- γ can come also from initial state $\Longrightarrow$ PDF should provide also the photon content of the proton (at present only NNPDF2.3 with large uncertainties)

The NLO "revolution"

- MCFM has been (and still is) the reference code for NLO numerical calculations (cross sections and distributions)
- Several breakthrough in the computational techniques of virtual amplitutes during last ten years

Britto, Cachazo, Feng, 2004

Ossola, Papadopoulos, Pittau, 2007

Ellis, Giele, Kunszt, 2007

- $\Longrightarrow$ development of automatic codes for NLO calculations. E.g.:
  - Blackhat+Sherpa
  - GoSam+Sherpa
  - Helac-NLO
  - MadGraph5_aMC@NLO
  - NLOjet++
  - Njet
  - OpenLoops+Sherpa
  - Recola

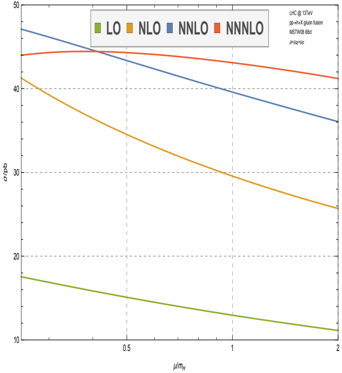
From NLO to NNLO accuracy

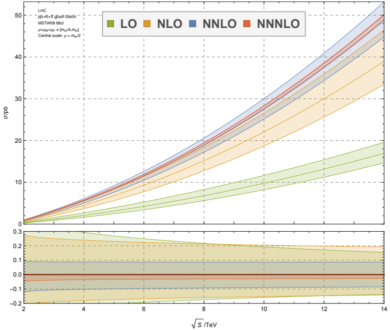
Recent developments allowed to build up fully differential QCD NNLO codes for several processes

- Higgs production in gluon fusion (N3LO for inclusive cross section)
- neutral and charged Drell-Yan
- Higgs $+$jet
- $W/Z+$jet
- diboson production
  - $\gamma\gamma$
  - $W\gamma$, $Z\gamma$, with lepton decays and off-shell effects
  - ZZ including lepton decays and off-shell effects
  - WW
  - WZ
  - HH

N3LO predictions for inclusive Higgs cross section

C. Anastasiou et al., arXiv:1503.06056

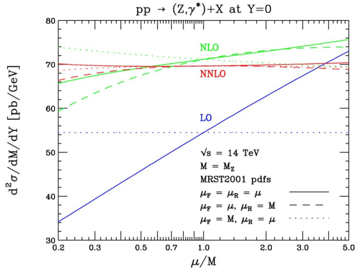


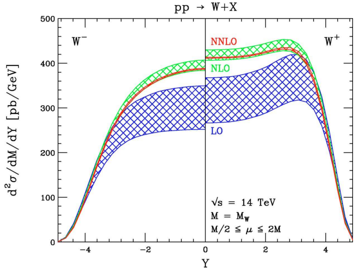


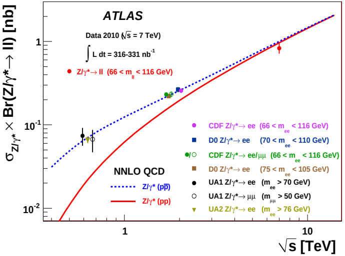
- reduced scale dependence
- N3LO correction $\sim 2\%$ w.r.t NNLO

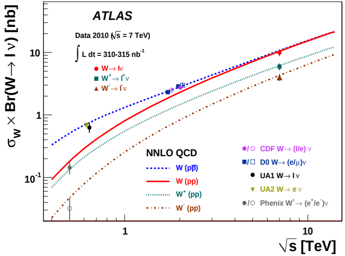
fully differential NNLO QCD corrections to DY

DYNNLO, FEWZ



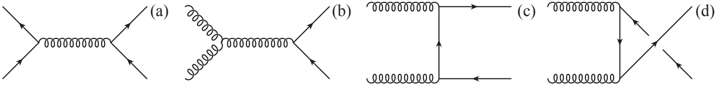






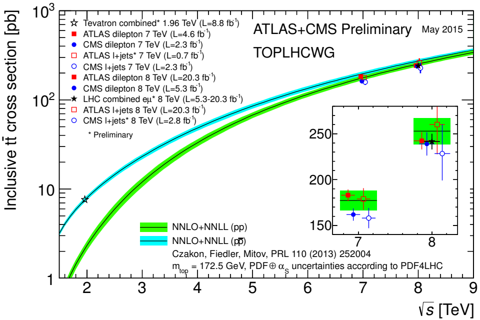
Top quark physics@NNLO

- $t\bar{t}$ production



- fixed order NNLO+NNLL resummation (Top++)

M. Czakon, P. Fiedler and A. Mitov, arXiv:1303.6254

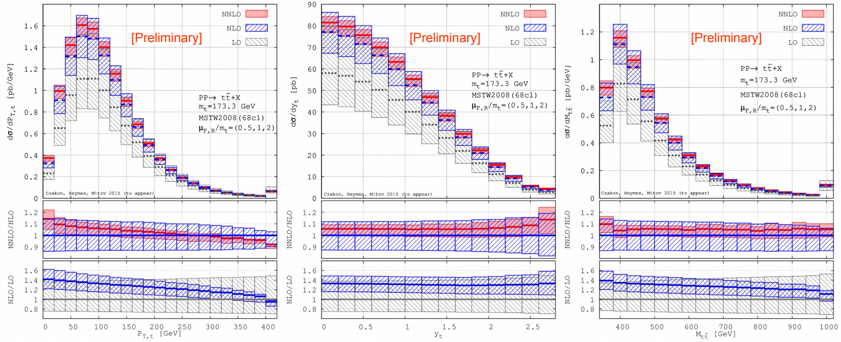


$t\bar{t}$ differential distributions @NNLO

LHC 8TeV (preliminary)

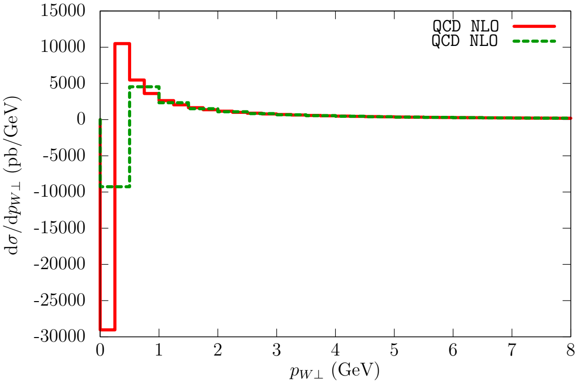
[Czakon, Fiedler, DH, Mitov.; in preperation]

P_T of t　　Rapidity of t　　Invariant mass



D. Heymes, talk at TOP2015, Ischia, September 2015

When NLO not reliable, e.g. W/Z transverse momentum



- NLO calculation totally unpredictive in the region of small $p_\perp^V$
- actually the tree-level prediction is zero $\Longrightarrow$
  - in the large $p_\perp$ region predictions are LO
  - extremely sensitive to extra radiation, in particular to multigluon radiation

Resummation: basic idea

- perturbative calculation

$$\int_0^{Q_\perp^2} dq_\perp^2 \frac{d\sigma}{dq_\perp^2} \sim 1 + \alpha_s \left[c_{12} \log^2 \frac{M^2}{Q_\perp^2} + c_{11} \log \frac{M^2}{Q_\perp^2} + c_{10} \right]$$

$$+ \alpha_s^2 \left[c_{24} \log^4 \frac{M^2}{Q_\perp^2} + \ldots + c_{21} \log \frac{M^2}{Q_\perp^2} + c_{20} \right] + \mathcal{O}(\alpha_s^3)$$

G. Ferrera, talk at M_W meeting, GGI Florence, 20 October 2014

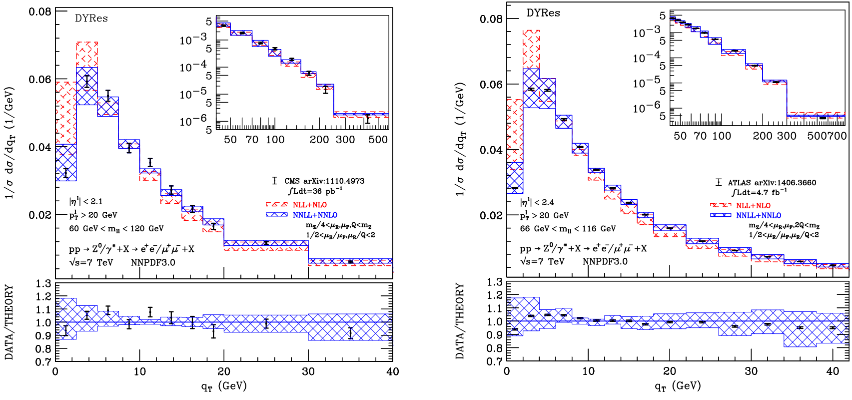
- for $Q_\perp \to 0 \qquad \alpha_s^m \log^n \gg 1$

$\alpha_S L^2$	$\alpha_S L$	$\cdots$	$\cdots$	$\cdots$	$\mathcal{O}(\alpha_S)$
$\alpha_S^2 L^4$	$\alpha_S^2 L^3$	$\alpha_S^2 L^2$	$\alpha_S^2 L$	$\cdots$	$\mathcal{O}(\alpha_S^2)$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\alpha_S^n L^{2n}$	$\alpha_S^n L^{2n-1}$	$\alpha_S^n L^{2n-2}$	$\cdots$	$\cdots$	$\mathcal{O}(\alpha_S^n)$
dominant logs	next-to-dominant logs	$\cdots$	$\cdots$	$\cdots$	$\cdots$

- same problem for every process, when large differences between energy scales appear
- solution: resummation, $\alpha_s^n \log^{2n}$ (LL), $\alpha_s^n \log^{2n-1}$ (NLL), ...

DYRES, comparison with LHC data

- NNLL resummation with NNLO normalization



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

another way to resummation: parton shower

material from P. Nason, in arXiv:0902.0293; P.Nason and B. Webber, arXiv:1202.1251

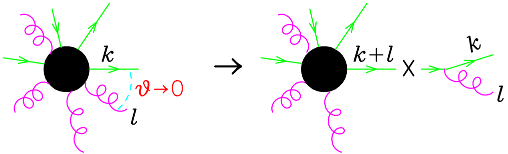
- basic example: $\gamma^* \to q\bar{q}g$ in the soft limit

$$|\mathcal{M}_{q\bar{q}g}|^2 = |\mathcal{M}_{q\bar{q}}|^2 4\pi\alpha_s C_F \frac{2q_1 \cdot q_2}{(q_1 \cdot k)(q_2 \cdot k)}$$

$$|\mathcal{M}_{q\bar{q}g}|^2 d\Phi_{q\bar{q}g} \simeq |\mathcal{M}_{q\bar{q}}|^2 d\Phi_{q\bar{q}} d\mathcal{S}$$

$$d\mathcal{S} = \frac{2\alpha_s C_F}{\pi} \frac{dE_g}{E_g} \frac{d\vartheta}{\sin\vartheta} \frac{d\phi}{2\pi}$$

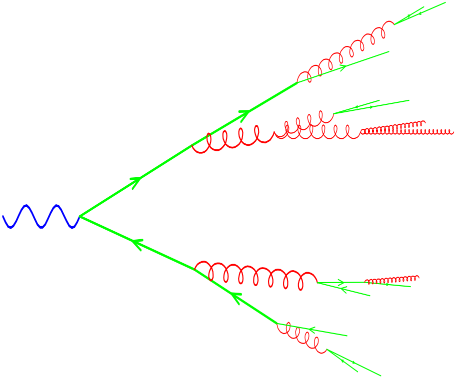
- in general



$$|M_{n+1}|^2 d\Phi_{n+1} \Rightarrow |M_n|^2 d\Phi_n \quad \frac{\alpha_s(t)}{2\pi} \frac{dt}{t} P_{q,qg}(z)\, dz \, \frac{d\phi}{2\pi}$$

how the $q\bar{q}$ final state appears after showering

- After application of the algorithm, for the case of $\gamma^* \to q\bar{q}$, the final states appears as a shower of partons



P. Nason, arXiv:0902.0293[hep-ph]

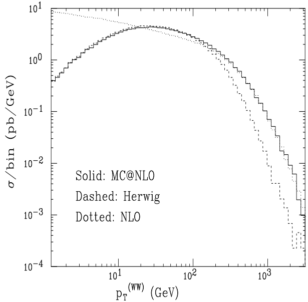
- for all generated partons the kinematics is known, i.e. we have full exclusive information on the final state partons

parton shower event generators

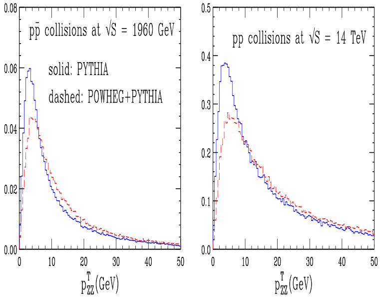
- positive features
  - complementarity with fixed order calculations
  - soft/collinear regions are automatically treated with Leading Log resummation
  - they include a model for the description of the underlying event and the hadronization
  - completely exclusive event generation, very useful for interface to detector simulation software
- 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



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
  - Sherpa + OpenLoops
  - Herwig++Matchbox + OpenLoops/Gosam
  - Madgraph4 + POWHEG

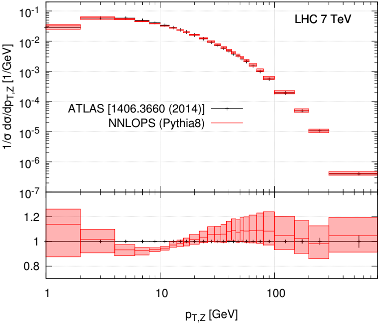
matching Parton Shower with higher orders

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

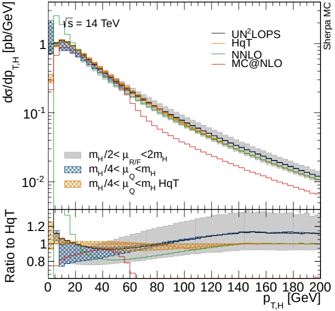
Hamilton, Nason, Oleari, Zanderighi, arXiv:1212.4504; Hamilton, Nason, Re, Zanderighi, arXiv:1309.0017

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

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



1407.2940



1407.3773

directions in $t\bar{t}$

- untile recently the top quark has been treated as stable in NLOPS generators
- in view of the precise measurement of the top quark mass, the NLO QCD corrections to top decay have been aloready included in the narrow width approximation, retaining all spin correlations

Frixione, Laenen, Motylinksi, Webber

- Also in POWHEG the NLO corrections to the decay have been included

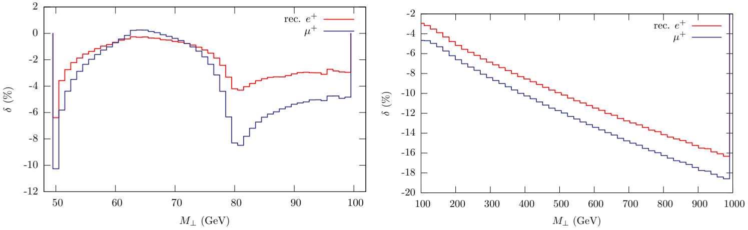
Campbell, Ellis, Nason, Re, 2014

- ongoing activity to include also finitie width effects and interferences, i.e. to calculate $W^+W^-b\bar{b}$ at NLOPS accuracy

talk given by E. Re at TOP2015, 15 September 2015, Ischia

Electroweak corrections

- $\alpha_s^2 \simeq \alpha \Longrightarrow$ electroweak corrections are important as well
- two regimes where they become particularly relevant:
  - precision measurements involving leptons in the final state
  - particularly relevant for M_W direct determination and angular variables measurements in $H \to 4$ leptons
  - regions of the phase space where the energy scales $\gg M_W$ (Sudakov region, where terms $\sim \alpha \log^2\left(\frac{Q^2}{M_W^2}\right)$ become large)
- example of charged Drell-Yan



Carloni Calame, Montagna, Nicrosini, Vicini, hep-ph/0609170

fixed order EW and matching with QEDPS

- During last decade, in particular within the context of precision W mass measurement at Tevatron, several fixed order Monte Carlo codes have been developed, including LO QCD and NLO EW corrections
  - HORACE
  - W/ZGRAD
  - WINHAC
  - SANC
- two event generators match consistently the NLO EW corrections with the QEDPS
  - HORACE, for charged and neutral Drell-Yan (LO in QCD)

    Carloni Calame, Montagna, Nicrosini, Vicini, hep-ph/0609170; arXiv:0710.1722

  - Hto4l, for Higgs decay to 4 leptons

    Boselli, Carloni Calame, Montagna, Nicrosini, F.P., arXiv:1503.07394

QCD and electroweak NLOPS for Drell-Yan

- within POWHEG, for DY, a fully consistent merging of NLO QCD and EW corrections and matching with QCD parton shower and QED higher orders (with PHOTOS or with the shower itself)

  Barzè, Montagna, Nason, Nicrosini, F.P., arXiv:1202.0465

  Barzè, Montagna, Nason, Nicrosini, F.P., Vicini, arXiv:1302.4606

- in this approach, also the bulk of $\mathcal{O}(\alpha\alpha_s)$ corrections should be accounted for
- Perturbatively the QCD - EW interference is a two-loop effect

$$d\sigma = d\sigma_0 + d\sigma_{\alpha_s} + d\sigma_{\alpha} + d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \ldots$$

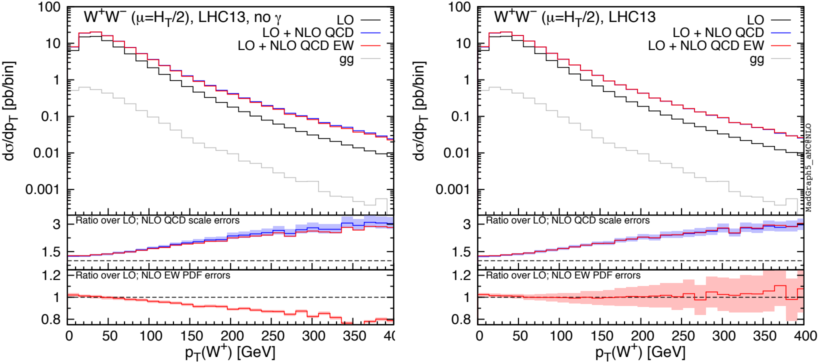
$\mathcal{O}(\alpha_s \alpha)$ corrections around M_W

- The two loop $\mathcal{O}(\alpha\alpha_s)$ calculation involves

  Dittmaier, Huss, Schwinn, arXiv:1403.3216; 1405.6897

  - virtual corrections at $\mathcal{O}(\alpha\alpha_s)$
  - EW corrections to $l\bar{l}^{(\prime)}+$ jet
  - QCD corrections to $l\bar{l}^{(\prime)}+\gamma$
  - PDF's with NNLO accuracy at $\mathcal{O}(\alpha\alpha_s)$
- However the bulk of the effects are in the soft/collinear regions where factorization holds
  - in the factorized limit, $\mathcal{O}(\alpha\alpha_s)$ terms given by $\mathcal{O}(\alpha)\otimes\mathcal{O}(\alpha_s)$
  - moreover for the specific case of DY at the $V(=W,Z)$ peak the largest part of EW corrections comes from photon emission from external lepton leg(s)
- Work in progress to
  - crosscheck the results
  - quantitative estimate on the W mass determination at LHC
- Up to now initial state photon induced processes not yet included (see the large uncertainties on the following slide)

Large uncertainties due to photon PDF's



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

- ongoing work to reach the complete automation of the EW corrections, as for QCD
- at present MadGraph5_aMC@NLO includes them for massive final states

When EW forces becomes strong: the Sudakov zone

In the Sudakov limit, i.e.

$$\forall \quad l, k \quad 2 p_k p_l \simeq r \gg M_W^2$$

for virtual one-loop amplitudes, Denner and Pozzorini [1] proved that

$$\begin{aligned} M^{\text{Virt } O(\alpha)} = & \text{Double log. part} \\ & + \text{Single log. part} \\ & + \delta\,(\text{parameter renorm.})\, M^{\text{Born}} \end{aligned}$$

- the corrections depend only on the the kinematics and on the flavour of each external leg (and pairs of external legs)
- the expression for δ^{DL} and δ^{SL} in known (universality)
- factorize on the Born (and $SU2$-correlated) matrix element

The algorithm is suited for a numerical implementation in ALPGEN

Chiesa et al., arXiv:1305.6837

[1] A. Denner and S. Pozzorini Eur.Phys.J. **C18** (2001) 461-480, Eur.Phys.J. **C21** (2001) 63-79

Event selections at ATLAS and CMS

- observable: $m_{\rm eff} = \sum_{jet_i} |p_{T\, jet_i}| + \not{E}_T$ ATLAS: Phys.Rev. **D87** 012008 (2013)
- channels: 2, 3, 4 jets plus missing E_T
- basic experimental cuts:

$$m_{\rm eff} > 1 \text{ TeV} \qquad \not{E}_T / m_{\rm eff} > 0.3$$

$$p_T^{j_1} > 130 \text{ GeV} \qquad p_T^{j_2} > 40 \text{ GeV} \qquad |\eta_j| < 2.8$$

$$\Delta\phi(\vec{p}_T^{\,j}, \vec{\not{p}}_T) > 0.4 \quad \Delta R_{(j_1, j_2)} > 0.4$$

- observables: $\vec{\not{H}}_T = -\sum_i \vec{p}_{t\,i} \qquad H_T = \sum_i p_{T\,i}$

CMS: Phys.Rev.Lett. **109** 171803 (2012)

- channels: at least 3 jets plus missing E_T
- basic experimental cuts:

$$H_T > 500 \text{ GeV} \qquad |\vec{\not{H}}_T| > 200 \text{ GeV}$$

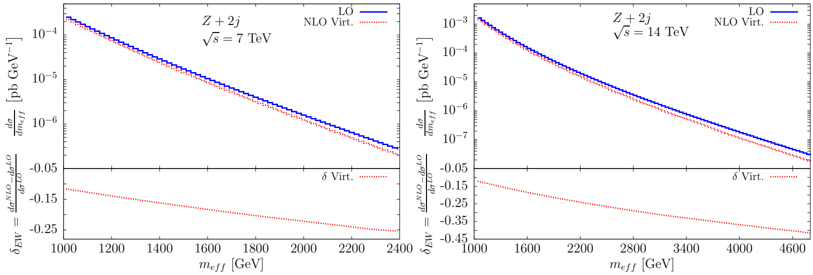
$$p_T^j > 50 \text{ GeV} \qquad |\eta_j| < 2.5 \quad \Delta R_{(j_i, j_k)} > 0.5$$

$$\Delta\phi(\vec{p}_T^{\,j_1, j_2}, \vec{\not{H}}_T) > 0.5 \qquad \Delta\phi(\vec{p}_T^{\,j_3}, \vec{\not{H}}_T) > 0.3$$

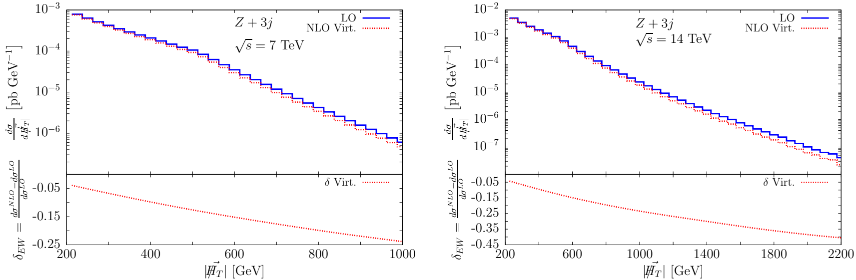
in both analysis:

- large amount of missing E_T plus hard jets
- $Z(\nu\bar{\nu})$+jets irreducible SM background (the most relevant for 2 and 3 jets)
- Denner-Pozzorini algorithm provides a good estimate of the $\mathcal{O}(\alpha)$ corrections to the background processes $Z(\nu\bar{\nu}) + 2/3$jets

Results for $Z + 2$jets at the LHC, ATLAS setup



Results for $Z + 3$jets at the LHC, CMS setup



$Z(\to \nu\bar{\nu}) + n\,$jets: background estimate

expected data MC

$$\frac{d\sigma(Z(\to \nu\bar{\nu}) + n\,\text{jets})}{dX} = \frac{d\sigma(\gamma + n\,\text{jets})}{dX} \times R^n$$

$$R^n = \left[\frac{d\sigma(Z(\to \nu\bar{\nu}) + n\,\text{jets})}{dX}\right] \Big/ \left[\frac{d\sigma(\gamma + n\,\text{jets})}{dX}\right]$$

$Z(\to \nu\bar{\nu}) + n$ jets: background estimate

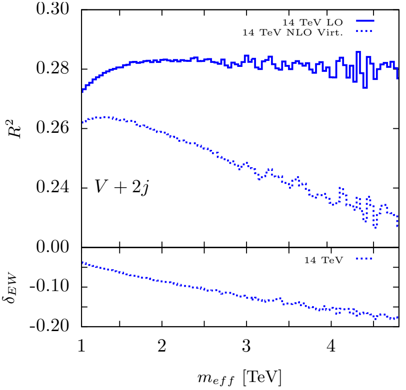
In the R^n ratio

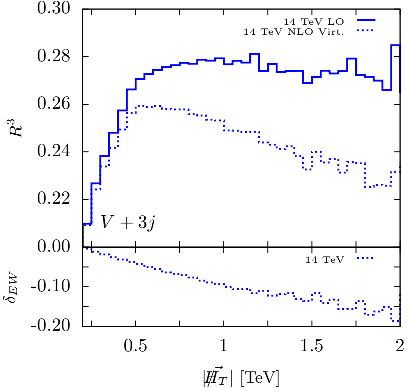
- PDFs and scale choices dependence
- higher order pQCD corrections
- shower and hadronization effects

largely cancel

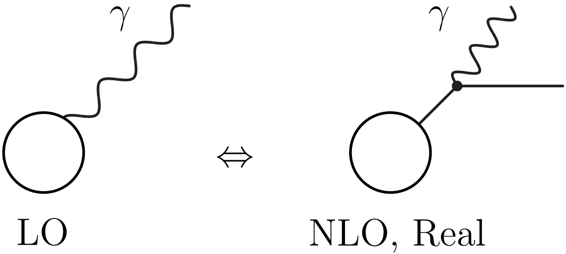
S. Ask et al. JHEP **1110** (2011);
Z. Bern et al. Phys.Rev. **D84** (2011);
Z. Bern et al. Phys.Rev. **D87** (2013)

EW corrections to R^n $(n = 2, 3$ jets$)$ at 14 TeV





Feature of NLO QCD corr's to proc's with isolated γ [2]



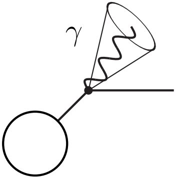
- QED singularities from the integration of real QCD corrections
- no virtual counterpart

[2] Neglecting the secondary photons coming from hadronic decays

Theoretical options

smooth-cone isolation

S. Frixione, Phys. Lett. B **429** (1998) 369



NLO, Real

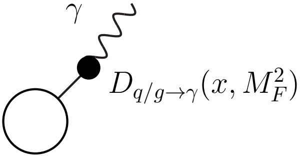
$$\sum_{R_{j,\gamma}<R}^{\forall_{R<R_0}} E_{T,j} < \epsilon_h \, p_{\mathrm{T}}^{\gamma} \left(\frac{1-\cos R}{1-\cos R_0} \right)$$

not directly comparable

to data

fragmentation function

S. Catani et al., JHEP **0205** (2002) 028



NLO, Real

- extracted from data
- **collinear** approximation
- no exclusive parton generation

$$\sigma(p_\gamma) = \sigma_\gamma^D(p_\gamma, M_F) + \sum_a \int_0^1 \frac{dz}{z} D_{a\to\gamma}(z, M_F)\sigma^a(\frac{p_\gamma}{z}, M_F)$$

$W\gamma$ production in POWHEG

L. Barzè, M. Chiesa, G. Montagna, P. Nason, O. Nicrosini and V. Prosperi, arXiv:1408.5766

Target:

- predictions for $pp \to W(l\nu)\gamma$ at QCD NLO+PS accuracy

- fully exclusive generation of radiated particles $(q/g/\gamma)$ in the POWHEG framework without relying on fragmentation functions

three categories of generated events in C-scheme

features of the C-samples, which are natural in the POWHEG framework

- $W\gamma+$ parton, with γ harder than parton
- $Wj+\gamma$, with γ softer than one parton
- $Wjj+\gamma$, with γ generated by the QED parton shower and softer than at least two partons
- it is mandatory a shower with interleaved QCD and QED emissions

Difference between C-LO and C-NLO: accuracy of the $Wj\gamma$ sample

- LO in C-LO
- NLO in C-NLO

Comparison with ATLAS data @7 TeV[3]

$$p_{\mathrm{T}}^{\gamma} > 15 \text{ GeV}, \, |\eta_\gamma| < 2.37, \, \Delta R_{\ell\gamma} > 0.7,$$

$$R_0 = 0.4, \, \epsilon_h = 0.5, \, \sum_{R_{j,\gamma} < R_0} E_{T,j} < \epsilon_h \, p_{\mathrm{T}}^{\gamma}$$

$$p_{\mathrm{T}}^{\ell} > 25 \text{ GeV}, \, |\eta_\ell| < 2.47, \, p_{\mathrm{T}}^{\text{miss.}} > 35 \text{ GeV}$$

$$E_T^{\text{jet}} > 30 \text{ GeV}, \, |\eta_{\text{jet}}| < 4.4, \, \Delta R(e/\mu/\gamma, \text{jet}) > 0.3$$

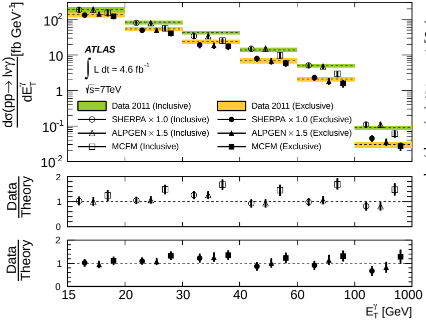
[Pb]	$N_{\text{jet}} = 0$	$N_{\text{jet}} \geq 0$
Exp.	$1.77^{\pm 0.04\,\text{stat}}_{\pm 0.08\,\text{lumi}} \pm 0.24\,\text{syst}$	$2.74^{\pm 0.05\,\text{stat}}_{\pm 0.14\,\text{lumi}} \pm 0.32\,\text{syst}$
MCFM	1.39 ± 0.17	1.96 ± 0.17
C-LO	$1.42^{+0.15}_{-0.15}$	$2.25^{+0.24}_{-0.24}$
C-NLO	$1.69^{+0.11}_{-0.22}$	$2.95^{+0.20}_{-0.38}$
NNLO*	$1.493^{+0.02}_{-0.04}$	$2.453^{+0.10}_{-0.10}$

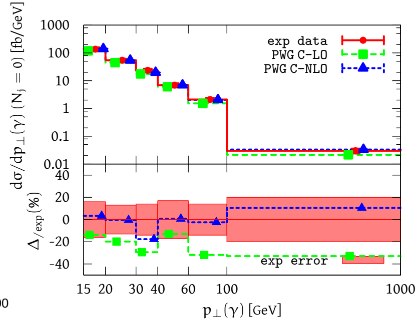
*M. Grazzini, S. Kallweit, D. Rathlev, arXiv:1504.01330; PLB731 (2014), arXiv:1202.0465

[3] Phys. Rev. **D87** (2013)

Comparison with ATLAS data: distributions (1)

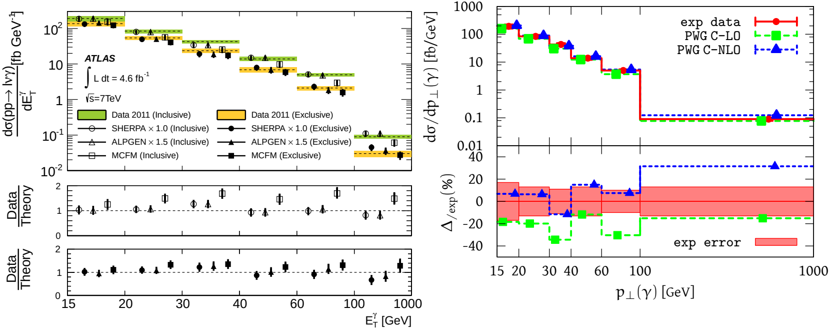
$p_T^\gamma,\ N_{\rm jet} = 0$





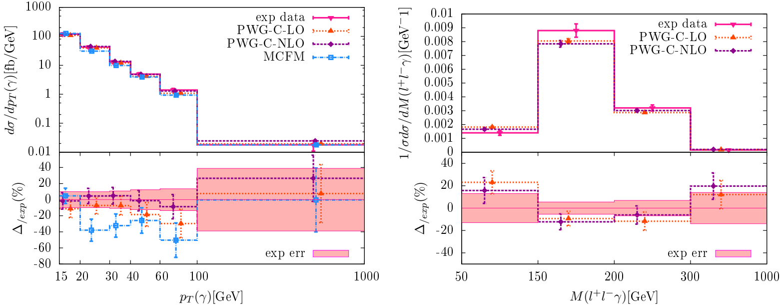
Comparison with ATLAS data: distributions (2)

$p_T^\gamma,\ N_{\rm jet} \geq 0$



$Z\gamma$, in progress (mainly by V. Prosperi)

- both channels $Z \to l^+ l^-$ and $Z \to \nu\bar{\nu}$ implemented
- $gg \to Z\gamma$ included as finite remainder
- preliminary comparisons with ATLAS data



- smaller difference between C-LO and C-NLO w.r.t. $W\gamma$, reflecting the smaller NNLO QCD corrections

M. Grazzini, S. Kallweit, D. Rathlev, arXiv:1504.01330