Electroweak Theory at the LHC

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Large Hadron Collider Physics Conference (LHCP2015)

St. Petersburg, 2 September 2015

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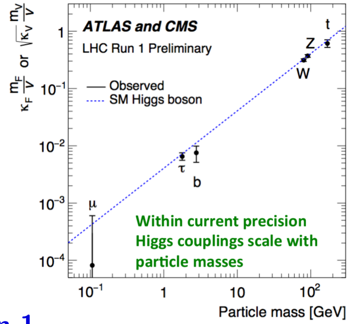
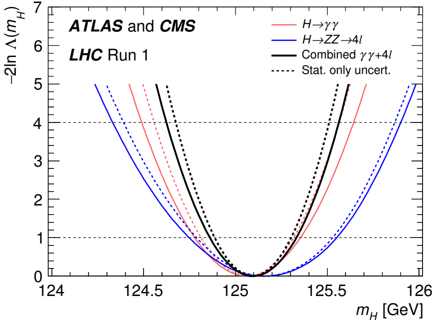
Success of the Standard Model at Run1





Run 1

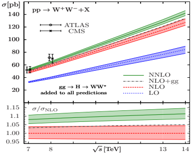
- SM promoted to realistic description of EW symmetry breaking (at present precision level and energy scales)
- M_H measurement $\Rightarrow$ instead of disproving the SM, Run1 has turned it into a fully predictive theory – at the quantum level!

Run2

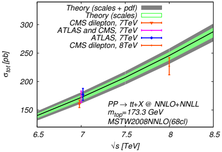
- can falsify or verify the SM with more stringent tests at higher energy and higher precision

Huge advances in theoretical precision I

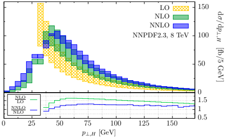
WW@NNLO



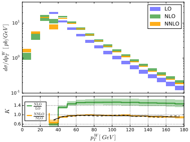
$t\bar{t}$@NNLO



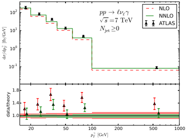
$H + j$@NNLO



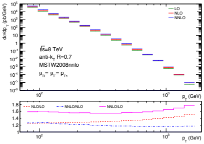
$W + j$@NNLO



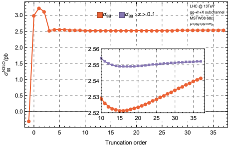
$W\gamma$@NNLO



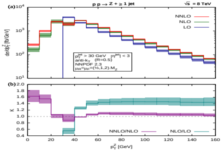
dijets@NNLO



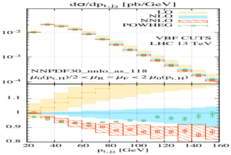
H@N^{3}LO



Zj@NNLO



VBF@NNLO



Huge advances in theoretical precision II

Vast progress in different areas

- NLO QCD multi-leg revolution (now also NLO EW)
- NNLO QCD $2 \to 2$ and N^{3}LO $2 \to 1$
- analytic N...LL resummations
- (N)NLO+PS matching, NLO multi-jet merging
- PDFs ...

Qualitative/methodological changes

- powerful new techniques (reduction, master integrals, subtraction methods, ...)
- emphasis on flexible/automated approaches and close link to Monte Carlo

Exploitation of state-of-the-art theory precision at LHC

- wide potential benefits for sensitivity of LHC measurements
- systematic exploitation in complex analyses will take a few years

Challenging the SM in the EW sector (DY, VV, VVV,. . .)

Cleanest and most precise measurements

- tests of EW theory up to TeV scale
- laboratory to validate theory precision

Backgrounds

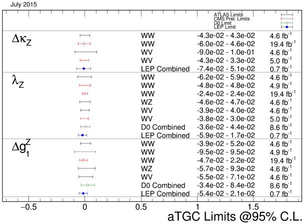
- to BSM and Higgs (including interference effects)

Interesting anomalies at Run1

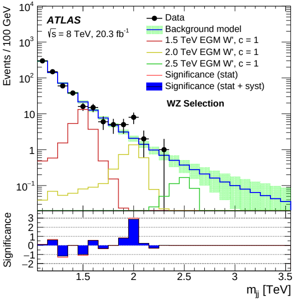
- excesses in σ_{WW} (partially resolved)
- diboson anomalies at 2 TeV (still open)

Theory precision crucial for direct/indirect BSM sensitivity

LEP vs LHC aGCs (ZWW)



2.5σ anomaly $M_{VV} \sim 2$ TeV



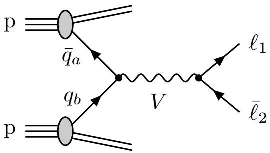
This talk

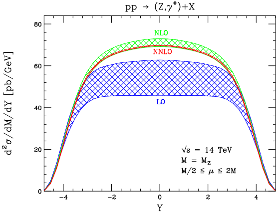
Some recent advances in theory precision for vector-boson production processes

1. Precision for Drell–Yan
2. Diboson production at NNLO
3. NLO EW corrections (and their automation)
4. $V+$ multijets at NLO EW

Apologies for many important omissions!

Precision in Drell–Yan





[Anastasiou et al. '04]

High-precision EW measurements

- $M_W, \sin^2(\theta_W)$
- requires NNLO+NNLL QCD + NLO EW → talks by Ferrera/Forte
- NLO+PS still widely used

NNLO+PS matching: MINLO [Karlberg et al. '14], UN²LOPS [Höche et al. '14], GENEVA [Alioli et al. '15]

⇒ state-of-the art NNLO precision

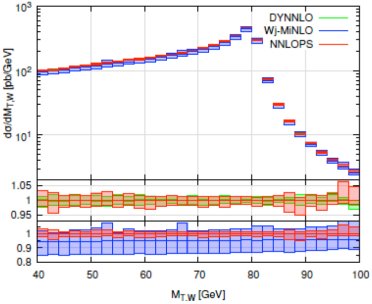
⇒ LL resummation of multiple QCD emissions (regime of small $p_{T,V}$)

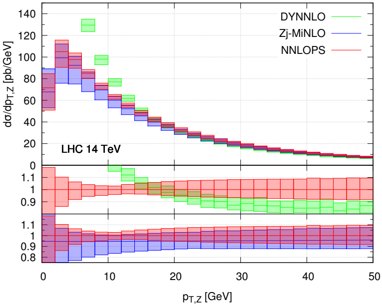
⇒ realistic description at particle level (hadronisation, UE,...)

MINLO–POWHEG [Hamilton, Nason, Re, Zanderighi '13; Karlberg, Re, Zanderighi '14]

Method

- MINLO merging for $V + 0, 1$ jet (without merging scale)
- NNLO reweighting of 3 inclusive observables ($d\sigma/$y,$\ldots$)

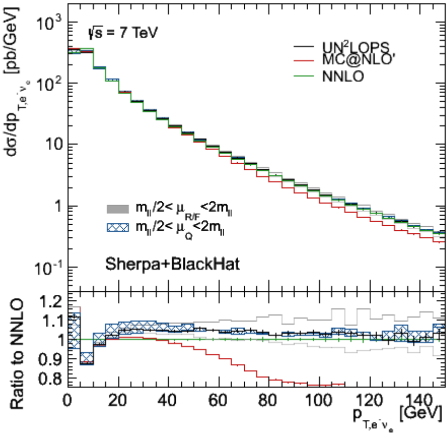




Benefits

- uncertainties more realistic (wrt parton shower) and reduced (wrt NLO)
- regularisation of fixed-order divergence at small p_T

UN^{2}LOPS–SHERPA [Höche, Li, Prestel '14]



Method

- UNLOPS merging for $V + 0, 1$ jets
- 2-loop correction in 0-jet bin (not showered, no reweighting)

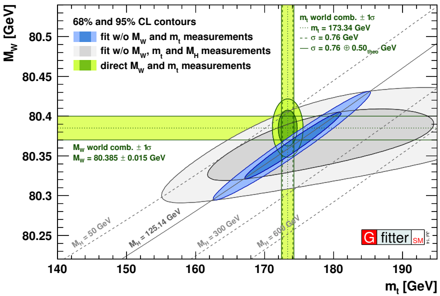
Benefits

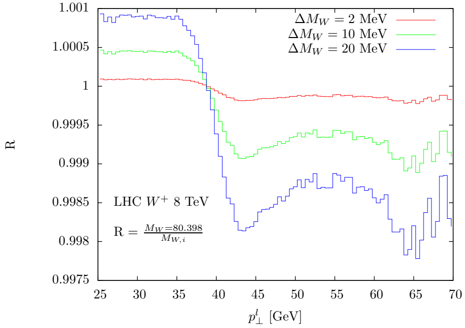
- sizable improvement wrt NLO+PS for $p_{T,V}$ and $p_{T,\ell}$
- more realistic and reduced scale uncertainties

MINLO, UN^{2}LOPS, GENEVA define new standard of ME+PS precision

$\Rightarrow$ crucial to investigate merits, caveats and precision for critical observables

M_W measurement in $pp \to \ell\nu$





Status of M_W (at $M_H = 125\,\text{GeV}$)

- SM theory fully predictive
  $\Rightarrow (\Delta M_W)_{\text{indirect}} = 8\,\text{MeV}$
- experimental world average
  $\Rightarrow (\Delta M_W)_{\text{direct}} = 15\,\text{MeV}$

LHC target $\Delta M_W < 10\,\text{MeV}$

$\Rightarrow$ powerful SM test, significant sensitivity to BSM parameter space

$\Rightarrow$ calls for sub-permille level precision in the modelling of the Jacobian peaks of $p_{T,\ell}$ and $M_{T,W}$ distributions

PDF and perturbative uncertainties

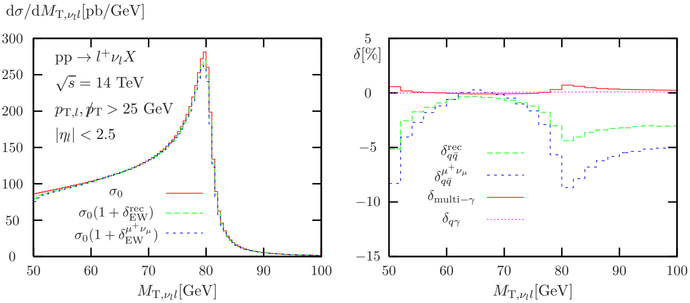
Expected PDF uncertainties at LHC

- $\Delta M_W \sim 10\,\text{MeV}$ with individual PDF sets [Bozzi et al. '15; Quackenbush/Sullivan '15]
- but global PDF spread $\Delta M_W \sim 20\,\text{MeV}$ needs to be reduced
- possible significant improvement from LHCb measurement [Bozzi et al. '15]

Perturbative effects beyond NNLO QCD

- NLO EW corrections [Dittmaier, Krämer '01; Baur et al. '01; . . .]

$\Rightarrow$ $\mathcal{O}(10\%)$ shape corrections dominated by FS γ-emission $\Rightarrow$ $\Delta M_W = \mathcal{O}(100\,\text{MeV})$



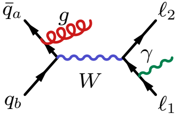
Relevant higher-order EW effects

Approximate treatment in POWHEG [Barzè et al. '12/'13]

- NLO QCD+EW matched to QCD$\otimes$QED parton shower

$\Rightarrow$ LL resummation for **multi-γ emissions** $\Rightarrow \Delta M_W = \mathcal{O}\,(10\,\mathrm{MeV})$

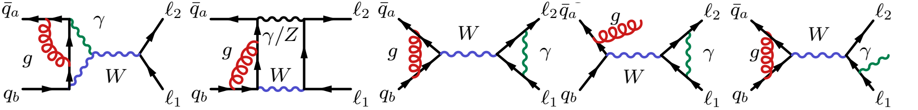
$\Rightarrow$ LL resummation for **QCD$\otimes\gamma$ emissions** $\Rightarrow \Delta M_W = \mathcal{O}\,(10\,\mathrm{MeV})$



Alternative approximations of mixed QCD–EW effects

- ad-hoc (N)NLO QCD $\times$ NLO EW multiplications [Cao et al. '04; Balossini et al. '09; Richardson et al. '10; Li/Petriello '12]

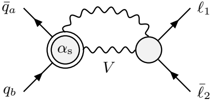
Calculation of $\mathcal{O}\,(\alpha\alpha_S)$ NNLO corrections [Dittmaier, Huss, Schwinn] (ongoing)



- expansion around W-resonance works well at $\mathcal{O}\,(\alpha)$ and renders $\mathcal{O}\,(\alpha\alpha_S)$ tractable

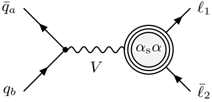
Mixed EW–QCD corrections (pole expansion)

Non-factorisable



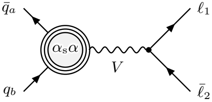
- soft-photon initial–final exchange
- most involved but done [Dittmaier, Huss, Schwinn ’14]
- numerically negligible

Final–Final



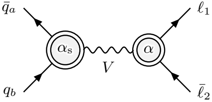
- simple, constant shift
- irrelevant for M_W

Initial–Initial



- partial results [Kotikov et al. ’07; Bonciani et al. ’11; Kilgore et al. 12; Kara ’13]
- expected impact on M_W negligible

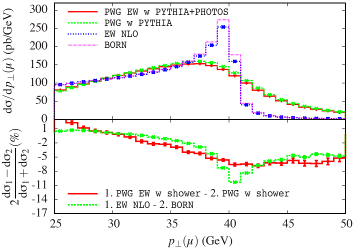
Initial QCD–Final EW

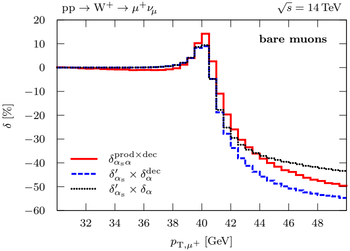


- dominant contribution
- preliminary results [Dittmaier, Huss, Schwinn ’14]

$\rightarrow$ talk by C. Schwinn

Mixed EW–QCD preliminary results





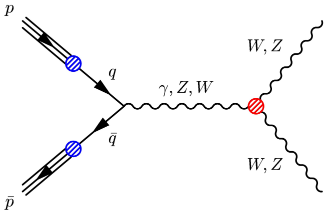
Nontrivial $\mathcal{O}(\alpha\alpha_S)$ effects

- naive factorisation OK for $M_{T,W}$ but off by $\gg 1\%$ for $p_{T,\ell}$
- related to large QCD corrections from jet recoil!

$\Rightarrow$ $\mathcal{O}(\alpha\alpha_S)$ calculation very valuable to validate POWHEG approximation

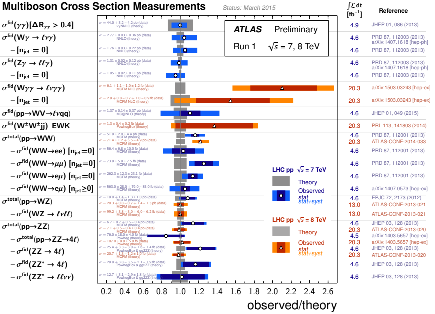
Outline

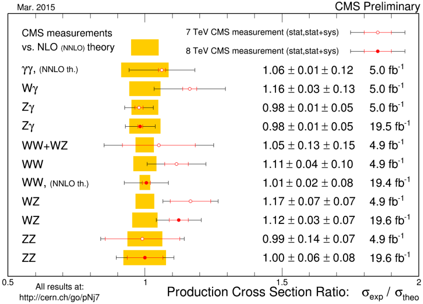
Diboson production at LHC



- test SU(2)×U(1) gauge structure
- interplay with $H \to VV$
- BSM searches, . . .

NLO QCD insufficient to match current experimental precision

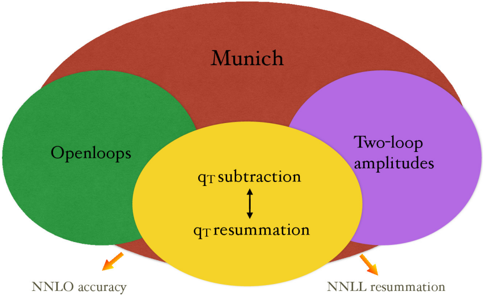




Diboson production at NNLO QCD

Kallweit

Cascioli
Maierhöfer
Lindert
S.P.



Gehrmann, Tancredi
von Manteuffel, Weihs;
Caola, Henn, Melnikov
Smirnov, Smirnov

Grazzini, Kallweit, Rathlev, Wiesemann

Flexible NNLO+NNLL framework based on q_T-subtraction [Catani, Grazzini '06]

⇒ $Z\gamma$ and $W\gamma$ at NNLO [Grazzini et al. '13–'15]

⇒ ZZ at NNLO [Cascioli et al. '14; Grazzini et al. '15] +NNLL [Grazzini et al. '15]

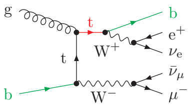
⇒ W^+W^- at NNLO [Gehrmann et al. '14] +NNLL [Grazzini et al. '15]

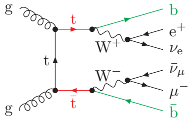
→ talk by S. Kallweit

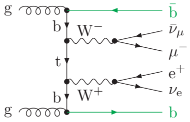
Theoretical definition(s) of top-free W^+W^- production

Huge Wt and $t\bar{t}$ contamination from $\overbrace{W^+W^-b}^{+40\%\ \text{NLO}}$ and $\overbrace{W^+W^-b\bar{b}}^{+400\%\ \text{NNLO}}$

- intimately connected with W^+W^- through $g \to b\bar{b}$ singularities
- top subtraction tricky and not unique $\Rightarrow$ theoretical ambiguity in $\sigma_{WW}^{\text{(N)NLO}}$!







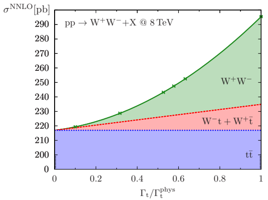
Definition A: **veto b-quark emissions in 4F scheme** $(m_b > 0)$

- $\Rightarrow \ln(m_b/M_W)$ terms might jeopardize NNLO accuracy!

Definition B: **top-resonance fit in 5F-scheme** $(m_b = 0)$

$$\lim_{\xi_t \to 0} \sigma_{\text{full}}^{5F}(\xi_t \Gamma_t) = \xi_t^{-2} \left[\sigma_{t\bar{t}}^{5F} + \xi_t\, \sigma_{Wt}^{5F} + \xi_t^2\, \sigma_{W^+W^-}^{5F} \right]$$

$\Rightarrow$ for inclusive $\sigma_{WW}^{\text{NNLO}}$ only 1–2% ambiguity (A vs B)



Relevant issue for percent-precision tests of W^+W^- physics! . . . Relation to σ_{WW}^{EXP}?

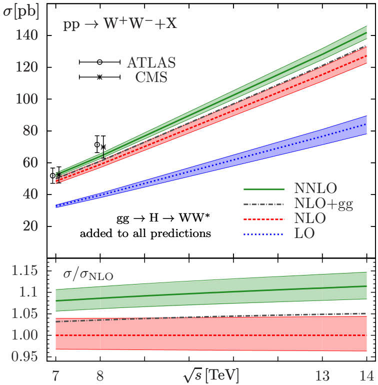
NNLO predictions for $pp \to W^+W^-$ [Gehrmann et al. '14]

Unexpectedly large QCD corrections

- $+58\%$ NLO and $+12\%$ NNLO at 14 TeV
- well beyond expected size from scale uncertainties and $gg \to W^+W^-$ $(+4\%)$

Residual scale uncertainty

- 3% NNLO scale variation

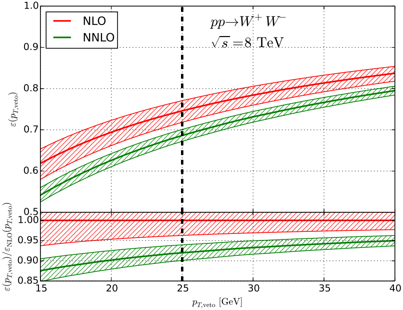


Comparison with ATLAS and CMS data

- NNLO reduces significance of excess in 8 TeV ATLAS measurement and agrees well with published 8 TeV result by CMS

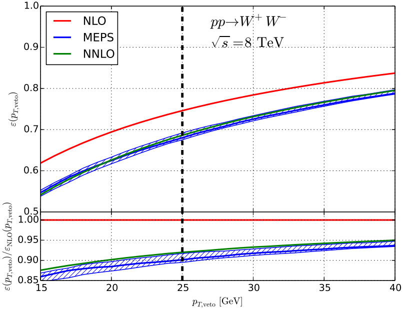
Jet-veto efficiency for $pp \to W^+W^-$ [Grazzini et al. (preliminary)]

NNLO vs NLO



- fiducial region of ATLAS (CMS) measurement involves jet veto at $p_T = 25(30)$ GeV
- NNLO correction of -8% wrt NLO
- NNLO seems consistent with Powheg

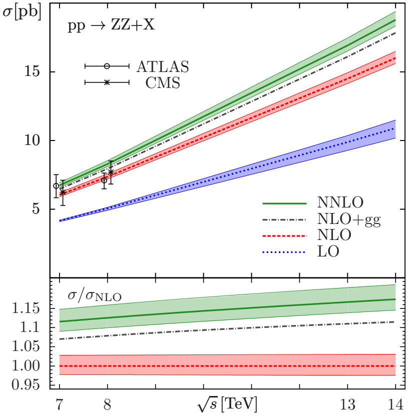
NNLO vs MEPS@NLO (Sherpa)

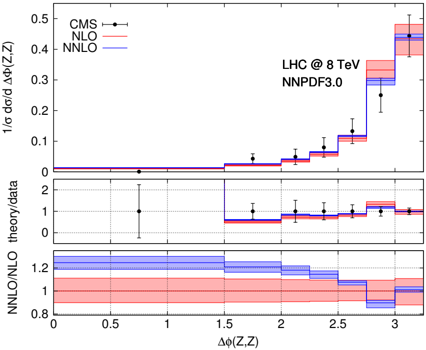


- MEPS@NLO $\Rightarrow$ 1st emission at NLO + LLs + particle level
- quite stable wrt scale variations
- consistent with NNLO

resummation $\rightarrow$ talk by S. Forte

$pp \to ZZ \to 4\ell$ at NNLO [Cascioli et al. '14; Grazzini et al. '15]



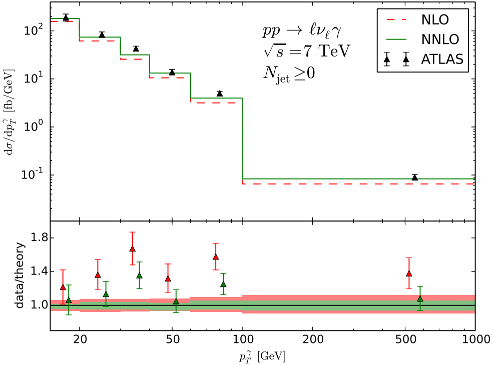


- $+17\%$ NNLO for σ_{ZZ} at 14 TeV
- dominated by $gg \to ZZ$ $(+10\%)$
- non-overlapping scale variation bands

- Off-shell $Z/\gamma^* \to 4\ell$ decays and fully differential predictions $\Rightarrow$ comparison to fiducial/differential measurements
- some moderate shape corrections and consistency with ATLAS/CMS data

$pp \to W\gamma \to \ell\nu\gamma$ at NNLO QCD [Grazzini et al. '15]

Very large NNLO correction to $\sigma_{W\gamma}$ at 7 TeV: +19% (w.o. gg channel!)

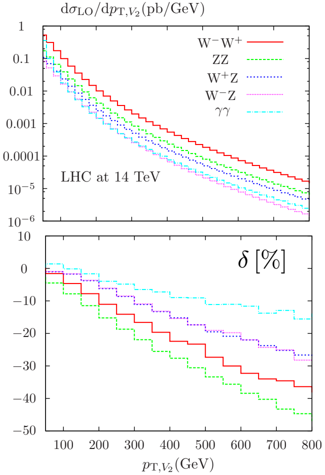


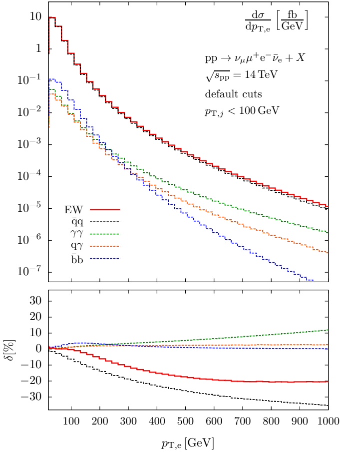
NNLO QCD corrections to dibosons in general

- can be unexpectedly large
- behave differently depending on channel
- already relevant to explain Run1 data

NLO EW corrections to $pp \to WW, WZ, ZZ$

[Bierweiler et al. '12–'13; Baglio et al. '13; Billoni et al. '13]





From $\mathcal{O}(1\%)$ to $\mathcal{O}(50\%)$ in the TeV region

⇒ NLO EW mandatory for SM tests and BSM searches at high energy

Outline

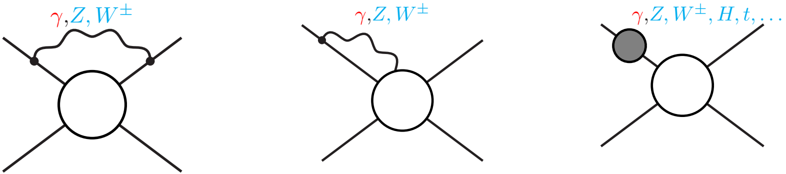
1 Precision for Drell–Yan

2 Diboson production at NNLO

3 NLO EW corrections (and their automation)

4 $V+$ multijets at NLO EW

EW Sudakov logarithms at TeV scale



Virtual **EW bosons coupling to on-shell legs at** $Q^2 \gg M_W^2$

$\Rightarrow$ large $\alpha \ln^2(Q^2/M_W^2)$ corrections of soft/collinear origin

Universality and factorisation [Denner,S.P. '01] similarly as in QCD

$$\delta\mathcal{M}^{\rm 1-loop}_{\rm LL+NLL} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k)I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\rm ew}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

- depend on external EW charges (anomalous dimensions) and kinematic details
- large negative corrections to any process at high $p_T, E_{T,\rm miss}, H_T, M_{\rm inv}, \ldots$

EW Sudakov effects at 1 TeV

Typical size at 1-loop

$$\left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{LL}} \simeq -\frac{4\alpha}{\pi s_{\mathrm{w}}^2}\ln^2\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq -26.4\% \qquad \left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{NLL}} \simeq +\frac{6\alpha}{\pi s_{\mathrm{w}}^2}\ln\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq +15.6\%$$

Typical size at 2-loops [Bauer, Becher, Ciafaloni, Comelli, Denner, Fadin, Jantzen, Kühn, Lipatov, Manohar Martin, Melles, Penin, S.P., Smirnov, ...]

$$\left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{LL}} \simeq +\frac{8\alpha^2}{\pi^2 s_{\mathrm{w}}^4}\ln^4\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq 3.5\% \qquad \left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{NLL}} \simeq -\frac{24\alpha^2}{\pi^2 s_{\mathrm{w}}^4}\ln^3\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq -4.1\%$$

Bottom line

$\Rightarrow$ EW corrections exceed NLO QCD uncertainties at $Q^2 \gg M_W^2$

$\Rightarrow$ systematic inclusion of EW effects important for any search at the TeV scale

Automation of NLO EW corrections

NLO EW calculations 2001–2015 (most $2 \to 2$ and some $2 \to 3$ processes)

- DY [Dittmaier et al. '01–'09; Wackeroth et al. '99–'12; Arbuzov et al. '05, Carloni Calame et al. '06; Li et al. '12; Barzè et al. '12–'13;], $V+$jet [Maina et al. '04; Kühn et al.'05–'08; Hollik et al. '07, Denner et al. '09–'12; Becher et al. '13; Hollik et al. '15], single top [Beccaria et al. '06–'08; Bardin et al. '10], $t\bar{t}$ [Beenakker et al. '94; Kühn et al. '05–'06; Bernreuter et al. '06–'08; Hollik et al. '07–'11], di-jets [Moretti et al. '05–'06; Dittmaier et al. '12], VH [Ciccolini et al. '03; Denner et al. '12–'15], $H+2$ jets (VBF) [Dittmaier et al. '07–'15], dibosons [Accomando et al. '02; Bierweiler et al. '12–'13; Billoni et al. '13; Gieseke et al. '14; Baglio et al. '13], $V\gamma$ [Accomando et al. '02–'05; Hollik et al. '04, Denner et al. 14], WWj [Wei–Hua et al. '15], WZZ [Nhung et al. '13], WWZ [Yong–Bai et al. '15], $H \to 4f$ [Bredenstein et al. '06; Boselli et al. '15]

Advent of NLO EW automation 2014–15

Tools	first results	
RECOLA+COLLIER	$pp \to \ell^+\ell^- jj$	[arXiv:1411.0916]
OPENLOOPS+ MUNICH/SHERPA	$pp \to W + 1, 2, 3$ jets	[arXiv:1412.5156]
MADGRAPH5_AMC@NLO	$pp \to t\bar{t} + V$	[arXiv:1504.03446]
GOSAM+ MADDIPOLE	$pp \to W + 2$ jets	[arXiv:1507.08579]

Benefits

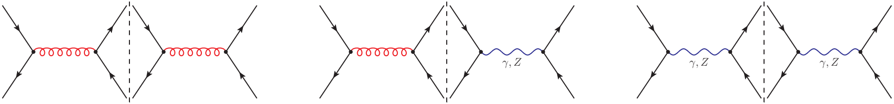
⇒ **NLO QCD+EW for any $2 \to 2, 3, 4$ SM process** (just started)

⇒ matching to parton showers (and merging) at NLO QCD+EW (in progress)

⇒ very simple I/O as for NLO QCD but different physics. . .

Nontrivial QCD-EW interferences for $q\bar{q} \rightarrow q\bar{q} + \ldots$

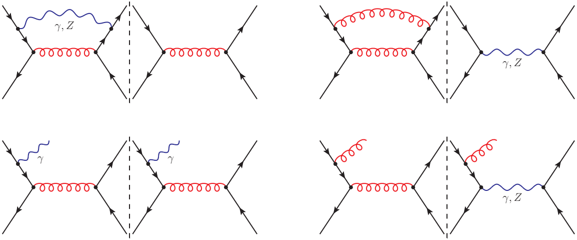
LO contributions of order α^m, α^{m+1},..., α^{m+k}



QCD — interference — EW

NLO EW corrections of order α^{m+1}, ..., α^{m+k+1} (nontrivial bookkeeping)

$\mathcal{O}\left(\alpha^{m+1}\right)$ "standard' — $\mathcal{O}\left(\alpha^{m+1}\right)$ "interference"

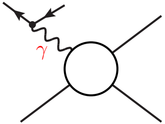


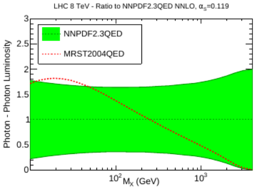
and so on ...

$\Rightarrow$ EW corrections can involve emissions of photons and QCD-partons

Photons in the initial state

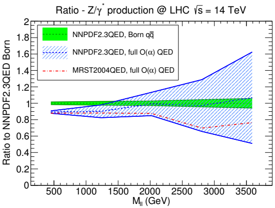
Factorisation of $q \to q\gamma$ singularities $\Rightarrow$ QED PDFs with photon

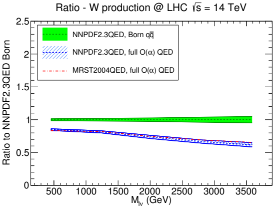


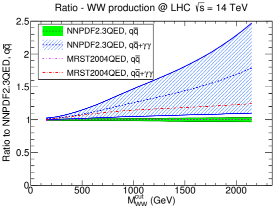


- LO QED evolution
- γ-fit to DIS+DY data (NNPDF)
- $\mathcal{O}\,(50\%)$ γ-uncertainty

Very large γ-induced effects with $\mathcal{O}\,(100\%)$ uncertainty in TeV region







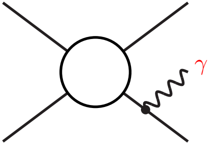
Wanted: - NLO QED PDFs

- new fit of γ-PDF with accurate high-energy data & theory [Boughezal et al.'14]

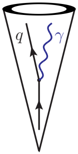
Photons (and jets) in the final state

Cancellation of FS photon singularities

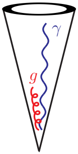
- requires IR subtraction method [Catani,Dittmaier,Seymour, Trocsanyi; Frixione, Kunszt, Signer]
- photon emission off quarks renders IR safe jet definition nontrivial at NLO EW



Option A: Democratic jet-algorithm approach (jets $\equiv$ photons)



collinear $q \to q\gamma$ singularities cancelled clustering q, g, γ on same footing



soft gluon singularities $\leftrightarrow$ hard photons inside jets: cancelled in jet-production (NLO EW) + γ-production (NLO QCD)

Option B: Separation of jets from photons ($E_\gamma / E_{\mathrm{jet}} < z_{\mathrm{thr}}$ inside jets)

- $q \to q\gamma$ singularity must be absorbed into fragmentation function

$\Rightarrow$ requires careful theoretical *and experimental* treatment of photon–jet interplay

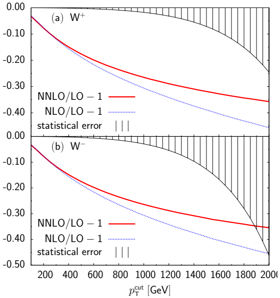
Outline

1. Precision for Drell–Yan
2. Diboson production at NNLO
3. NLO EW corrections (and their automation)
4. $V+$ multijets at NLO EW

V+1 jet vs V+ multijets

Very large EW corrections to $pp \to Z/W + 1$ jet

- NLO (electro)weak [Maina, Ross, Moretti '04;Kühn, Kulesza, S.P.,Schulze '04–'07]
- EW Sudakov logs beyond NLO [Kühn, Kulesza, S.P.,Schulze '04–'07; Becher, Garcia i Tormo '13]
- NLO QCD+EW with off-shell Z/W decays [Denner,Dittmaier,Kasprzik,Muck '09–'11]



V+multijets

- dominates inclusive V+ jet production at high H_T
- crucial for BSM searches
- large EW corrections in Sudakov app. (untested in multijet regime) [Chiesa et al. '13]

⇒ first exact NLO EW calculations...

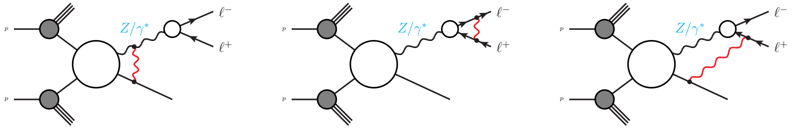
$pp \to \ell^+\ell^- + 2$ jets at NLO EW [Denner, Hofer, Scharf, Uccirati '14]

NLO QCD+EW automation (tools)

- Loop amplitudes: RECOLA [Actis et al. '13] and COLLIER [Denner et al. '14]
- Monte Carlo: in-house

Off-shell $Z/\gamma^* \to \ell^+\ell^-$ decays nontrivial at NLO EW (in contrast to NLO QCD)

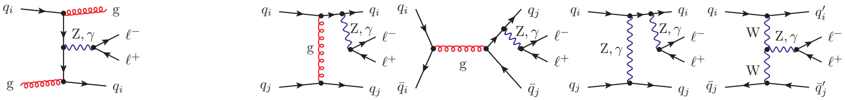
- corrections to production×resonance×decay + non-fact corrections



- exact off-shell treatment requires challenging $2 \to 4$ calculation for $pp \to \ell^+\ell^- jj$
- 11% (1.5%) off-shell effects without (with) $|M_{\ell\ell} - M_Z| < 15$ GeV cut

Ingredients of $pp \to \ell^+\ell^- jj$ at $\mathcal{O}\left(\alpha_S^2\alpha^3\right)$

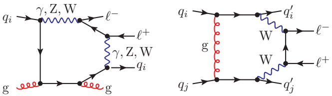
LO QCD and EW contributions: $\mathcal{O}\left(\alpha_S^2\alpha^2\right)$, $\mathcal{O}\left(\alpha_S\alpha^3\right)$, $\mathcal{O}\left(\alpha^4\right)$



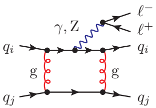
$\Rightarrow$ **VBF+diboson contributions and EW–QCD interferences**

NLO corrections: $\underbrace{\mathcal{O}\left(\alpha_S^3\alpha^2\right), \mathcal{O}\left(\alpha_S^2\alpha^3\right)}_{\text{“Zjj@NLO QCD+EW”}}$, $\underbrace{\mathcal{O}\left(\alpha_S^1\alpha^4\right), \mathcal{O}\left(\alpha_S^0\alpha^5\right)}_{\text{“VBF@NLO QCD+EW”}}$

QCD Born $\times$



EW Born $\times$



$\Rightarrow$ $\mathcal{O}\left(10^3\right)$ 1-loop diagrams with $\mathcal{O}\left(100\right)$ hexagons+pentagons per channel

$\Rightarrow$ feasibility of highly non-trivial NLO EW calculations demonstrated

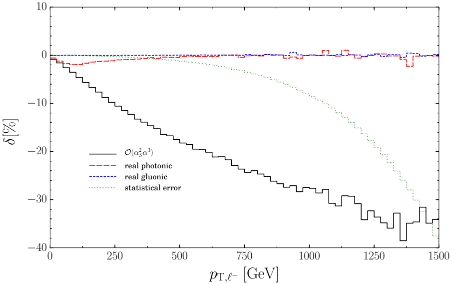
$\mathcal{O}\left(\alpha_S^2\alpha^3\right)$ EW corrections to $pp \to \ell^+\ell^- jj$ at 13 TeV

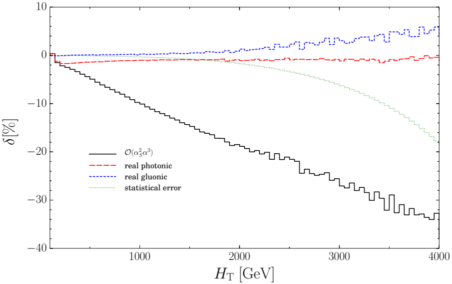
Inclusive quantites $(\sigma, d\sigma/d\eta, \dots)$

- only 2–3%

Large Sudakov effects in tails of p_T and H_T distributions

- -20% to -35% in (multi)TeV region (depending on kinematic variable)
- statistically relevant up to $H_T = 5$ TeV at $L = 300\,\text{fb}^{-1}$





possible implications for CMS excess at $M_{eejj} \sim 2$ TeV?

$pp \to W + 1, 2, 3$ jets at NLO QCD+EW

[Kallweit,Lindert,Maierhöfer,S.P.,Schönherr '14]

NLO QCD+EW automation (tools)

- Loop amplitudes: OpenLoops [Cascioli et al. '13] and Collier [Denner et al. '14]
- Monte Carlo: Munich [Kallweit] or Sherpa [Hoeche et al.]

$W + n$-jet production at $\mathcal{O}\left(\alpha_S^{n+1}\alpha\right)$ (NLO QCD) and $\mathcal{O}\left(\alpha_S^{n}\alpha^2\right)$ (NLO EW)

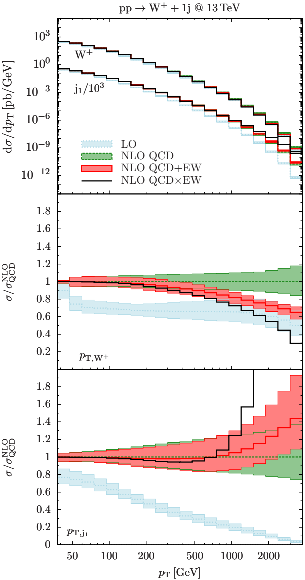
- highest # of jets with on-shell W $\Rightarrow$ study tool performance for $n_{\text{jets}} = 1, 2, 3$

$W + 3$ jets	# QCD trees	# EW trees	# QCD 1-loop	# EW 1-loop
$u_i\bar{d}_i \to W^+ q_j\bar{q}_j g$	12	33	352	1042
$u_i\bar{d}_i \to W^+ q_i\bar{q}_i g$	24	66	704	2084
$u_i\bar{d}_i \to W^+ ggg$	54	-	2043	2616

  - many flavour combinations & crossings $\Rightarrow$ unconceivable w.o. automation
  - NLO EW more complex but less CPU expensive than NLO EW!

- pheno results $\Rightarrow$ insights into NLO QCD–EW interplay and n_{jets} dependence...

NLO QCD+EW corrections to $pp \to W^+ + 1\,\text{jet}$

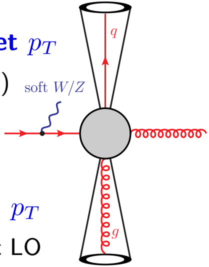


Large NLO corrections at high $p_{T,W}$

- $+100\%$ (QCD) $- 20$–35% (EW)
- large EW$\times$QCD uncertainty!

Giant NLO corrections at high jet p_T

- $+1000\%$ (QCD) $+$ 10–50% (EW)
- huge uncertainties!

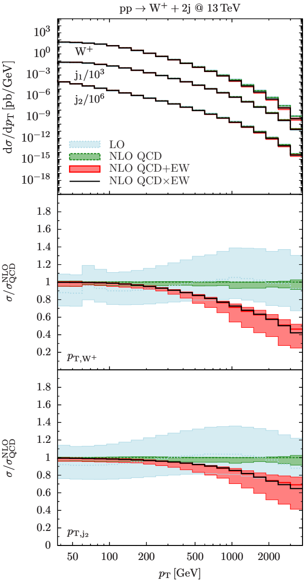


Problem of $pp \to W+$ jet at high p_T

- NLO dominated by $W + 2\,\text{jets}$ at LO

$\Rightarrow W+$**multijets NLO QCD+EW mandatory!!**

NLO QCD+EW corrections to $pp \to W^+ + 2, 3$ jets



Stable NLO QCD behaviour

- small and almost p_T independent
- $\lesssim 10\%$ scale dependence at NLO

Large negative EW effects (resummation desirable)

- -30–60% at $p_{T,W}$ =1–4 TeV
- -15–25% at $p_{T,j}$ =1–4 TeV

Take home message

- NLO QCD+EW for $W + 2, 3$ jets under control
- next: NLO QCD+EW merging of $W + 1, 2, 3$ jets

$\Rightarrow$ reliable prediction for *inclusive* $W+$jet production

Conclusions

Impressive advances of theory precision for EW processes

- NNLO, NNLO+PS, NNLO+NNLL, ...
- NLO EW $\Rightarrow$ important at TeV scale!

(N)NLO theory tools

- increasingly automated, flexible and widely applicable

Outlook

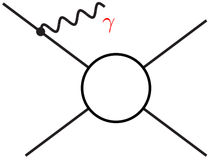
- enhanced opportunities to challenge the SM at Run2
- inherent physics complexity of precision theory will require great care in the application of theory tools (automated or not) to LHC analyses

Backup slides

Electroweak bremsstrahlung

Real photon emission

- mandatory since soft/collinear γ unresolved
- complete cancellation of QED singularities

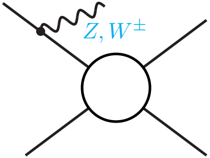


Real Z, W emission [Ciafaloni,Comelli, ...]

- **inclusive emission**: only partial $\ln(\hat{s}/M_W)$ cancellation

$\leftrightarrow$ free SU(2) charges, collinear IS logs, kinematic $M_{Z,W}$ effects

- **typical experimental cuts**: modest $\ln(\hat{s}/M_W)$ cancellation (strongly dependent on process and analysis)

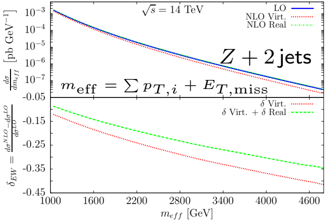


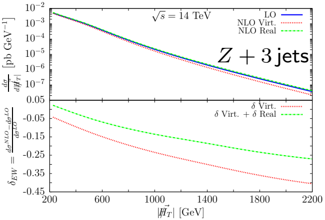
Bookkeeping of $pp \to X$ and $pp \to X + V$ processes

- important to add both contributions to physical observables while keeping them as separate processes (XV production $\ni X$ production)
- otherwise double counting, e.g. overlap of ZW, $Z(+V)$ and $W(+V)$ production
- separation trivial since Z/W emission is tree level and IR finite

EW Sudakov logarithms in $pp \to Z(\nu\bar{\nu}) + 2, 3$ jets [Chiesa, Montagna, Barzé, Moretti, Nicrosini, Piccinini, Tramontano '13]

$Z(\nu\bar{\nu})+$ multijet background to MET $+ 2/3j + 0\ell$ searches in ATLAS/CMS





Virtual Sudakov LL+NLL effects [Denner, S.P. '01]

- process-independent implementation in ALPGEN

$\Rightarrow$ 15–40% negative corrections in (multi)TeV range

Real emission effects from $pp \to ZZ/WW/WZ + n$-jets

- with $Z/W \to jj, \ell^+\ell^-, \ell\nu, \nu\bar{\nu}$ decays and $n = 0, \ldots 2/3$ (not fixed!)

$\Rightarrow$ modest positive correction 5–10%

Strong motivation for $pp \to V+$multijets at NLO EW!