

Theory aspects: low- p_T^V and W -mass extraction

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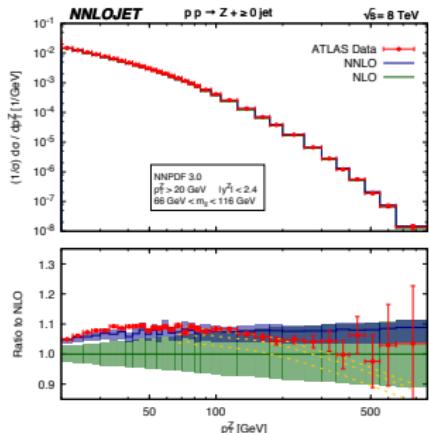
outline

- recent development in the description of Z/W production
- some debated issues about th. uncertainties on p_\perp^W
- difference between W and Z : the case of initial state b quarks
- status on polarization coefficients A_i for Z production
- relevant higher order effects for M_W extraction

lepton pair p_\perp : two regimes

- large p_\perp ($\gtrsim 20$ GeV), where pert. th. is reliable
 - ▶ state of the art is NNLO QCD
- small p_\perp ($\lesssim 20$ GeV): $\sim 90\%$ of the cross section
 - ▶ resummation of $\log \left(\frac{M_V}{q_\perp} \right)$ is needed
 - ▶ sensitivity to the non-perturbative model of the MC Evt Gen

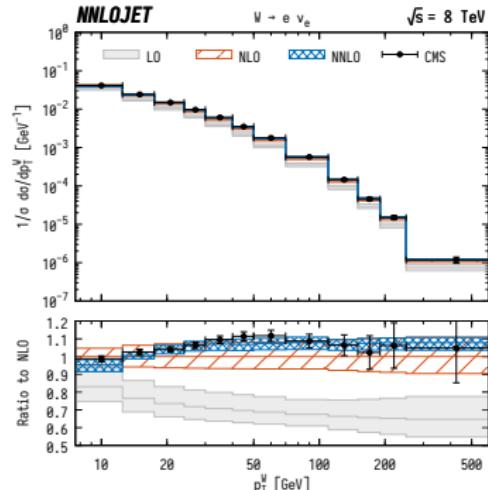
Large p_T region



A. Gehrmann-De Ridder et al., arXiv:1605.04295

A. Huss, p_T^Z and p_T^W theory meeting, CERN 2018

R. Boughezal et al., 1512.01291, 1602.05612, 1602.08140



A. Gehrmann-De Ridder et al., arXiv:1712.07543

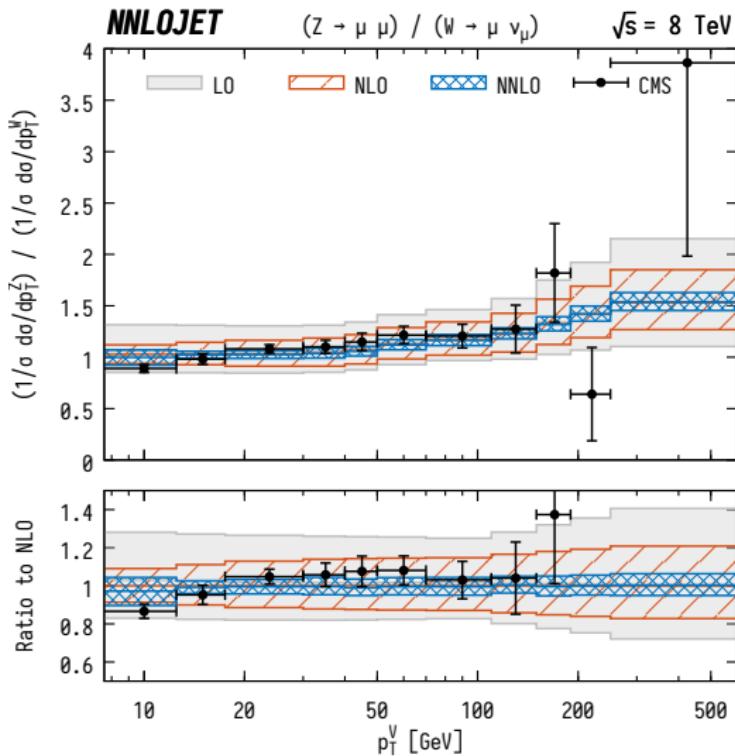
A. Huss at p_T^Z and p_T^W theory meeting, CERN 2018

R. Boughezal et al., arXiv:1602.06965

- yellow dash: ew corrections

A. Denner et al., arXiv:1103.0914

and on the ratio W/Z



A. Gehrmann-De Ridder et al., arXiv:1712.07543

Small p_\perp region: resummation techniques

- recent progress by different groups on resummation
 - ▶ q_\perp resummation in impact parameter space, up to NNLL matched to NNLO fully differential on leptons (DYRES)

S. Catani et al., arXiv:1507.06937

- ▶ SCET base resummation, up to NNLL' (GENEVA)
 - ▶ resummation in direct space (RadISH)

S. Alioli et al., arXiv:1211.7049, arXiv:1508.01475

• recent progress in Monte Carlo generators

- ▶ inclusion of NLO splitting kernels (DIRE)

S. Höche, F. Krauss, S. Prestel, 1705.00982

S. Höche, S. Prestel, arXiv:1705.00742

- ▶ development of GENEVA Monte Carlo
- ▶ DY at NNLOPS accuracy, in POWHEG+MiNLO and SHERPA

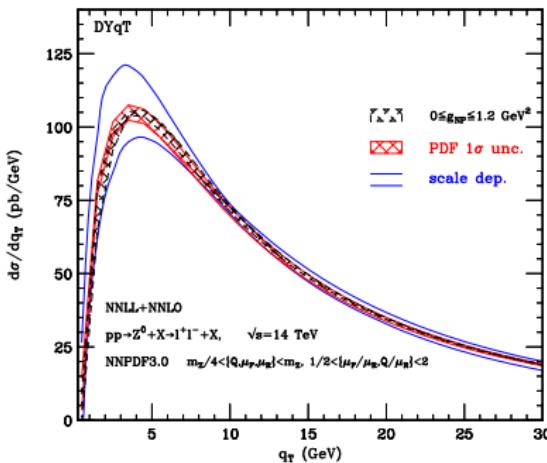
S. Alioli et al., arXiv:1605.07192

Karlberg, Re, Zanderighi, arXiv:1407.2940

Höche, Li, Prestel, arXiv:1405.3607

LHC Electroweak WG, Precision measurements in DY processes subgroup

PDF uncertainties and NP effects

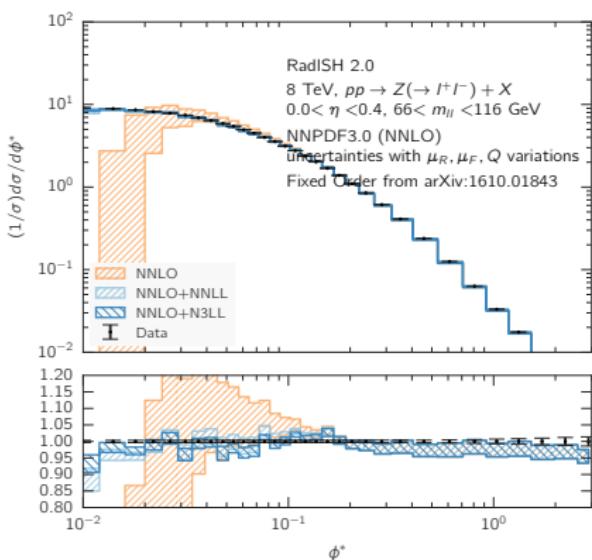
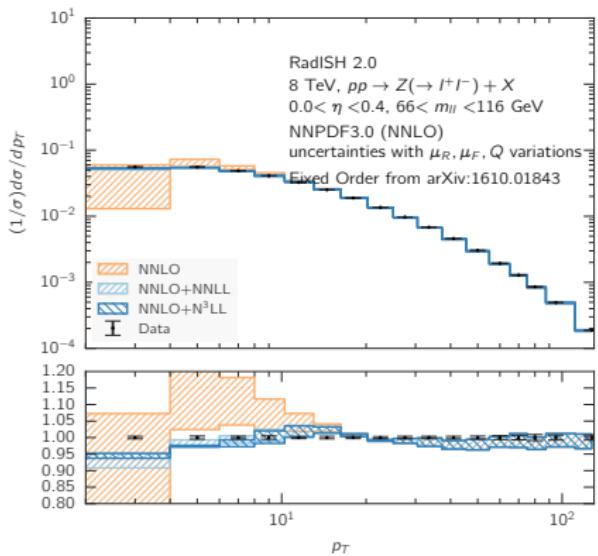


NNLL+NNLO result for Z q_T spectrum at the LHC. Perturbative scale dependence, PDF uncertainties and impact of NP effects.

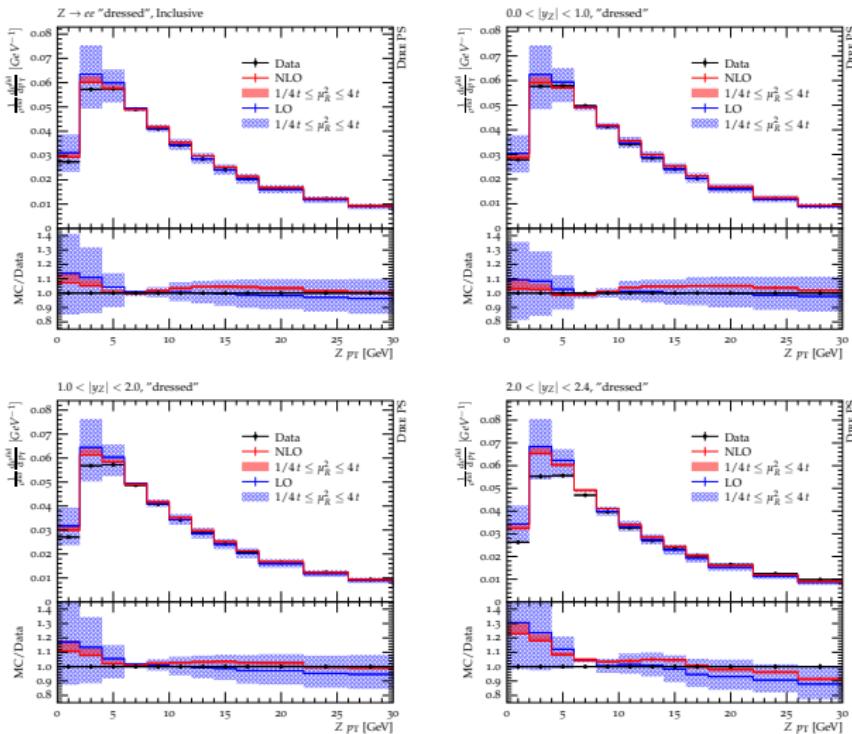
- PDF uncertainty is smaller than the scale uncertainty and it is approximately independent on q_T (around the 3% level).
- Non perturbative *intrinsic* k_T effects parametrized by a NP form factor $S_{NP} = \exp\{-g_{NP}b^2\}$ with $0 < g_{NP} < 1.2 \text{ GeV}^2$:
$$\exp\{\mathcal{G}_N(\alpha_S, \tilde{L})\} \rightarrow \exp\{\mathcal{G}_N(\alpha_S, \tilde{L})\} S_{NP}$$
- NP effects increase the hardness of the q_T spectrum at small values of q_T .
- NNLL+NNLO result with NP effects very close to perturbative result except for $q_T < 3 \text{ GeV}$ (i.e. below the peak).

Work in progress towards N3LL+NNLO in direct space

W. Bizon, P. Monni, E. Re, L. Rottoli and P. Torrielli, arXiv:1705.09127, arXiv:1604.02191, work in progress



- reduction of scale uncertainty for MC with NLO splitting kernels



S. Höche, F. Krauss, S. Prestel, 1705.00982

S. Höche, S. Prestel, arXiv:1705.00742

Extrapolating from Z to W .

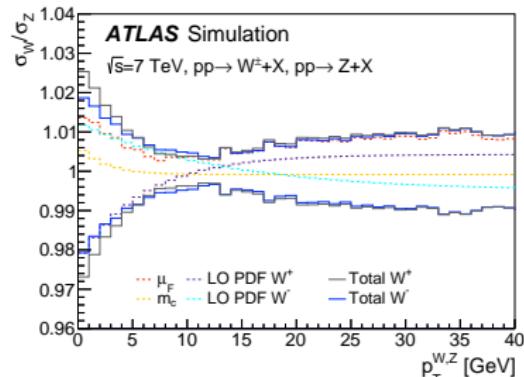
Focus on low $p_T^W \lesssim 30$ GeV relevant for m_W

- $\simeq 2\%$ uncertainties in p_T^W translate into $\simeq 10$ MeV uncertainty in m_W
- ⇒ Use precise Z measurement to get best possible prediction for W

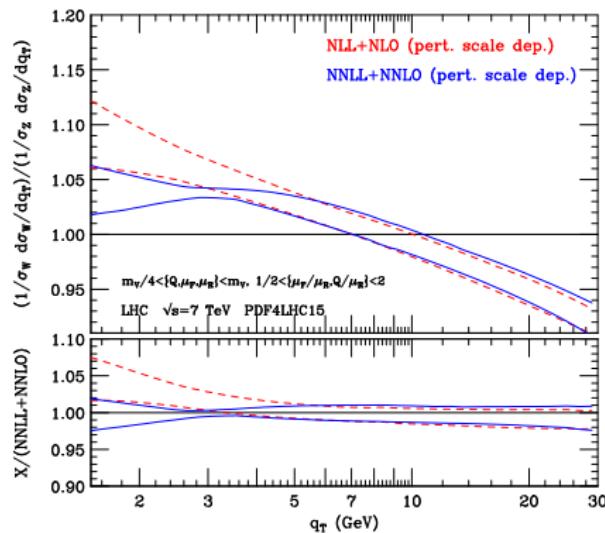
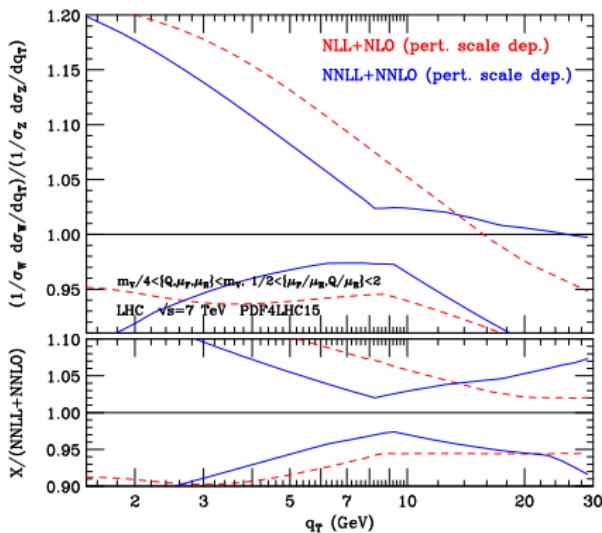
- One way to think about it

$$\frac{d\sigma(W)}{dp_T} = \left[\frac{d\sigma(W)/dp_T}{d\sigma(Z)/dp_T} \right]_{\text{theory}} \times \left[\frac{d\sigma(Z)}{dp_T} \right]_{\text{measured}}$$

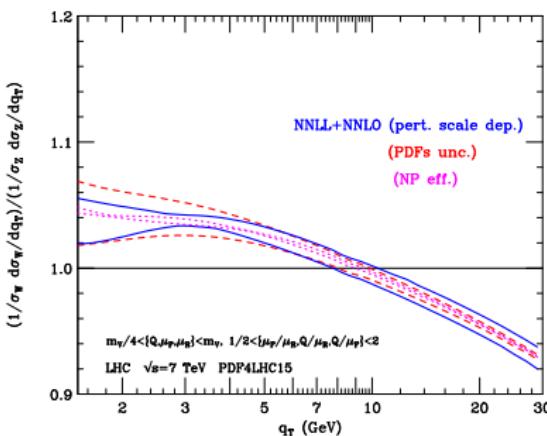
- There is no direct resummation for ratio, it is always a derived quantity
- Relies on ratio being more precise than individual processes, which relies on theory uncertainties being strongly correlated between processes
- More general: Use common theory framework and fit to Z data
 - Not restricted to a specific combination (like ratio)
 - Tuning Pythia on Z data is one example of this
 - Requires explicit information on correlations between processes



W/Z ratio q_T spectrum: perturbative scale uncertainty



W/Z ratio: the q_T spectrum



- Ratio of W/Z observables substantially reduces both the experimental and theoretical systematic uncertainties [Giele,Keller('97)].
- Correlated ($\mu^W/M_W = \mu^Z/M_Z$) scale variations by factor 2 (avoiding ratios larger than 2) gives reasonable estimate of pert. uncertainty (nice overlap of scale variation bands for $q_T > 3$ GeV).
- PDF uncertainty dominates at very small ($q_T \lesssim 5$ GeV).
- Non trivial interplay of perturbative and NP effects.

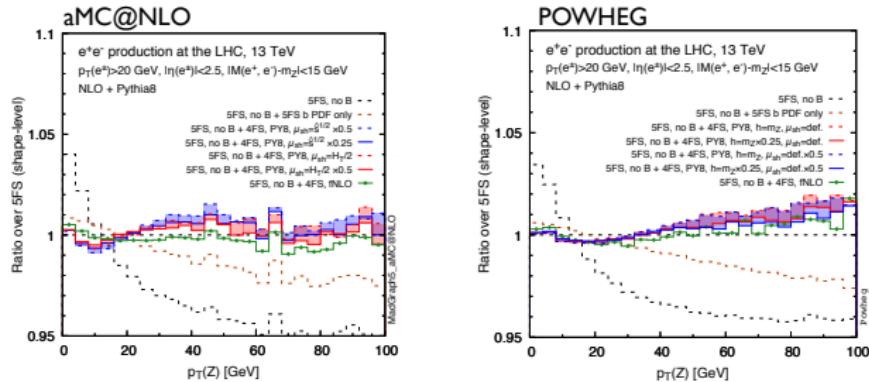
Ratio of NNLL+NNLO results for W/Z q_T spectra at the LHC. Perturbative scale dependence, PDF uncertainties and impact of NP effects.

$b\bar{b}$ contribution to p_\perp^Z

E. Bagnaschi, F. Maltoni, A. Vicini and M. Zaro, arXiv:1803.04336

- two schemes
 - ▶ 5 flavour scheme (massless b , resummation of $\log(p_\perp^b/m_b)$)
 - ▶ 4 flavour scheme (finite m_b with exact kinematics of $\ell^+\ell^- b\bar{b}$)
- improvement from a combination of the two schemes
 - ▶ p_\perp^Z distribution split into 2 contributions: with and without B hadrons in final state

$$\frac{d\sigma^{best}}{dp_\perp^{\ell^+\ell^-}} = \frac{d\sigma^{5FS-Bveto}}{dp_\perp^{\ell^+\ell^-}} + \frac{d\sigma^{4FS}}{dp_\perp^{\ell^+\ell^-}}$$



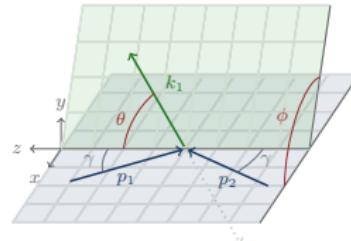
- ▶ $\Delta M_W < 5$ MeV from $p_\perp^{\ell^-}$ (with sensitivity to the fit window)

$pp \rightarrow \ell\bar{\ell}$ as a calibration tool

- the matrix element for the production and decay of a spin one vector boson can be parameterized by an expansion on second order polinomials with nine coefficients (corresponding to nine polarization terms)

$$\begin{aligned}\frac{d\sigma}{dq_T^2 dy d\cos\vartheta d\phi} &= \frac{3}{16\pi} \frac{d\sigma^{\text{unpol.}}}{dq_T^2 dy d\cos\vartheta d\phi} \left\{ 1 + \cos^2 \vartheta \right. \\ &+ \frac{1}{2} A_0 (1 - 3 \cos^2 \vartheta) + A_1 \sin 2\vartheta \cos \phi \\ &+ \frac{1}{2} A_2 \sin^2 \vartheta \cos 2\phi + A_3 \sin \vartheta \cos \phi \\ &+ A_4 \cos \vartheta + A_5 \sin^2 \vartheta \sin 2\phi \\ &\left. + A_6 \sin 2\vartheta \sin \phi + A_7 \sin \vartheta \sin \phi \right\}\end{aligned}$$

- ϑ and ϕ refer to a $\ell\bar{\ell}$ rest frame
- orientation given by the **Collin-Soper** frame



angular coefficients

- can be measured

at low energies: NA10, E615, NuSea

at Tevatron: arXiv 1103.5699; at LHC for Z : arXiv:1606.00689, arXiv:1505.03512

at LHC for W : arXiv:1203.2165, arXiv:1104.3829

- can be predicted theoretically

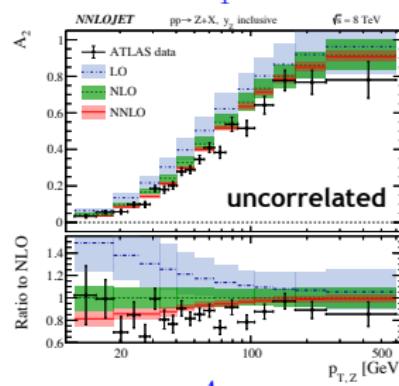
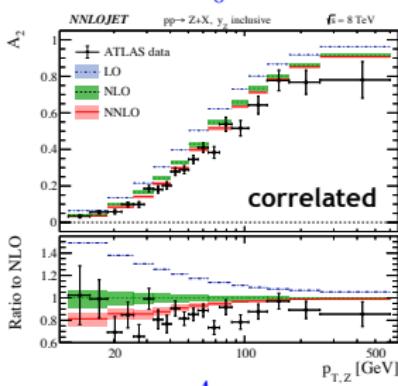
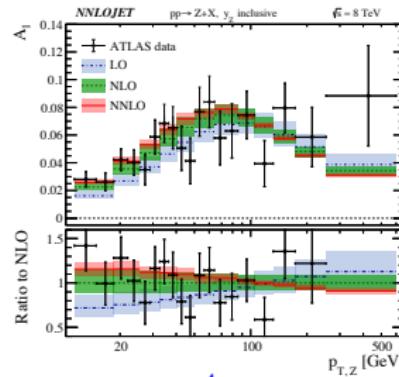
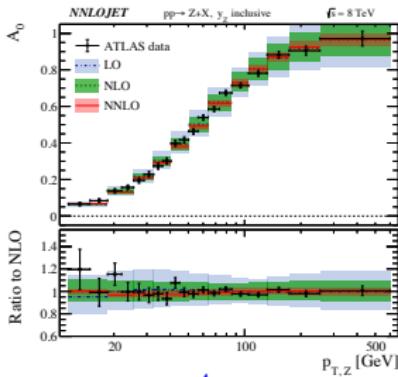
$$\langle f(\vartheta, \phi) \rangle = \frac{\int_1^1 d \cos \vartheta \int_0^{2\pi} d\phi \, d\sigma(\vartheta, \phi) f(\vartheta, \phi)}{\int_1^1 d \cos \vartheta \int_0^{2\pi} d\phi \, d\sigma(\vartheta, \phi)}$$

$$\begin{aligned} A_0 &= 4 - 10 \langle \cos^2 \vartheta \rangle & A_1 &= 5 \langle \sin^2 \vartheta \cos \phi \rangle & A_2 &= 10 \langle \sin^2 \vartheta \cos 2\phi \rangle \\ A_3 &= 4 \langle \sin \vartheta \cos \phi \rangle & A_4 &= 4 \langle \cos \vartheta \rangle & A_5 &= 5 \langle \sin^2 \vartheta \sin 2\phi \rangle \\ A_6 &= 5 \langle \sin 2\vartheta \sin \phi \rangle & A_7 &= 4 \langle \sin \vartheta \sin \phi \rangle \end{aligned}$$

- QCD NNLO predictions with NNLOJET

⇒ next slide

A. Gehrmann-De Ridder et al., arXiv:1708.00008



- correlated and uncorrelated refer to μ_F and μ_R variations on numerator and denominator
- at NNLO the two options give very similar results

M_W extraction: theoretical uncertainties

- M_{\perp}^W mainly sensitive to QED FSR
- p_{\perp}^{ℓ} sensitive to both QCD and QED corrections
- several calculations/codes available for NLO EW and QCD corrections, and interface to higher orders
 - ▶ detailed comparisons and benchmarking results published in arXiv:1606.02330

Higher-order corrections (for M_W fit)

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

- multi-photon emission from the final state $\rightarrow \delta M_W \simeq 10$ MeV for $\mu\nu_\mu$ final state

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

- mixed QCD-EWK corrections

Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216

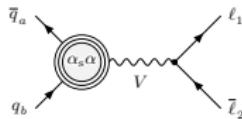
- NNLO EWK effects

C.M. Carloni Calame et al., Phys.Rev. D96 (2017) 093005

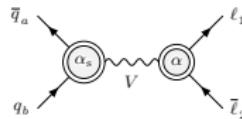
- ▶ EWK input scheme
- ▶ lepton pair emission

fixed order $\mathcal{O}(\alpha_s \alpha)$ in pole approximation

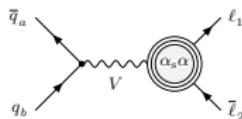
- two main classes of contributions:
 - ▶ factorizable
 - ▶ non-factorizable



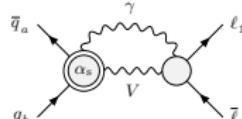
(a) Factorizable initial–initial corrections



(b) Factorizable initial–final corrections



(c) Factorizable final–final corrections



(d) Non-factorizable corrections

S. Dittmaier, A. Huss and C. Schwinn, arXiv:1601.02027

- a) not known but expected to be very small

$(\mathcal{O}(\alpha))$ corrections in PA $\implies M_{\perp}$ and $M(l^+ l^-)$ insensitive to QED ISR
in addition M_{\perp} and $M(l^+ l^-)$ mildly affected by NLO QCD corrections

- b) this gives the bulk of the contribution

- c) no real contributions \implies no impact on shape of M_{\perp} and $M(l^+ l^-)$
d) numerical impact below 0.1%

$\mathcal{O}(\alpha_s \alpha)$ corrections through Monte Carlo

- The POWHEG-BOX includes NLO QCD & EW corrections interfaced to QCD/QED shower, i.e. **NLOPS EW \oplus QCD** accuracy

① POWHEG_W_ew_BMNNP, CC DY

Barzè et al, JHEP 1204 (2012) 037

② POWHEG_W_ew_BW, CC DY

Bernaciak and Wackerlo, PRD 85 (2012) 093003

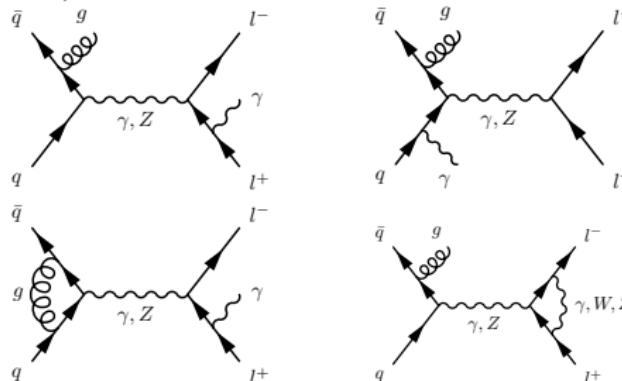
③ POWHEG_Z_ew_BMNNPV, NC DY

Barzè et al, EPJC 73 (2013) 6, 2474

④ independent implementation

Mück and Oymanns, JHEP 1705 (2017) 090

- correctly taken into account the NLO contribution with one additional radiation in the soft/collinear limit



- comparison POWHEG-BOX-V2 vs NNLO in pole approx

C.M. Carloni Calame et al., Phys.Rev. D96 (2017) 093005

$$d\sigma_{\text{POWHEG}} = d\sigma_0 \left[1 + \delta_{\alpha_s} + \delta_\alpha + \sum_{m=1, n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n} \right],$$

$$\Delta M_W^{\alpha_s \alpha}(\mu^+ \nu_\mu) = -16.0 \pm 3.0 \text{ MeV} \quad \text{vs} \quad \delta_{\text{NNLO}} = -14 \text{ MeV}$$

Dittmaier, Huss, Schwinn, NPB 885 (2014) 318, NPB 904 (2016) 216

- summary of residual effects present in $(\text{QCD} \oplus \text{EW})_{\text{NLOPS}}$ but missing in $\text{QCD}_{\text{NLOPS}} \otimes \text{QEDPS}$

		ΔM_W (MeV)	
QED FSR model		M_T	p_T^ℓ
Tevatron	PYTHIA	$+5 \pm 2$	$+17 \pm 5$
	PHOTOS	-2 ± 1	-8 ± 5
LHC	PYTHIA	$+6.2 \pm 0.8$	$+29 \pm 4$
	PHOTOS	-0.6 ± 0.8	-2 ± 4

- differences in shifts induced by PYTHIA QEDPS and PHOTOS disappear when used on top of $\text{QCD} \oplus \text{EW}$ NLO

NNLO effect: lepton pair corrections

C.M. Carloni Calame et al., Phys.Rev. D96 (2017) 093005

- emission of a photon converting to a lepton pair
 $\sim \mathcal{O}(\alpha^2 L^2)$ \sim two-photon contribution
- contribution implemented in HORACE v3.1 (now also available in POWHEG_ew, with PYTHIA8 QEDPS) through QED running of $\alpha(Q^2)$ included in the Sudakov form factor

alternative implementation: N. Davidson, T. Przedzinski and Z. Was, CPC 199 (2016) 86, arXiv:1011.0937

- $\Delta M_W(\mu^+ \nu) \sim 5 \pm 1$ MeV (from M_\perp) and $\sim 3 \pm 2$ MeV (from p_\perp^ℓ)

NNLO uncertainty: input parameter scheme

- pert. EW calculations require a coherent set of input param. in the gauge sector, e.g.
 - ▶ $\alpha(0)$, M_W and M_Z
 - ▶ G_μ , M_W and M_Z to be preferred in the CC DY
 - ▶ we can define

$$\begin{aligned}\alpha_\mu^{tree} &\equiv \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2 \vartheta \\ \alpha_\mu^{1l} &\equiv \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \sin^2 \vartheta (1 - \Delta r)\end{aligned}$$

- ▶ three possible different expression for the cross section, starting to differ at $\mathcal{O}(\alpha^2)$

$$\begin{aligned}\alpha_0 &: \quad \sigma = \alpha_0^2 \sigma_0 + \alpha_0^3 (\sigma_{SV} + \sigma_H), \\ G_\mu \text{ I} &: \quad \sigma = (\alpha_\mu^{tree})^2 \sigma_0 + (\alpha_\mu^{tree})^2 \alpha_0 (\sigma_{SV} + \sigma_H) - 2\Delta r (\alpha_\mu^{tree})^2 \sigma_0, \\ G_\mu \text{ II} &: \quad \sigma = (\alpha_\mu^{1l})^2 \sigma_0 + (\alpha_\mu^{1l})^2 \alpha_0 (\sigma_{SV} + \sigma_H)\end{aligned}$$

- differences present at NLO, after matching with higher orders, become much smaller

$$\Delta M_W \sim 2 \text{ MeV} \pm 1 - 2 \text{ MeV}$$

Summary

- several new approaches and results to p_{\perp}^V
- possible improvement in the near future in the th. uncertainty ascribed to p_{\perp}^W
- in the sector of QCD and electroweak corrections to M_{\perp} and p_{\perp}^{ℓ} , th. uncertainties under control for an M_W determination with $\Delta M_W \sim 10$ MeV