Precise determination of W/Z transverse-momentum spectrum including higher-order QCD-EW corrections.

German F. R. SBORLINI

Departamento de Física Fundamental
Universidad de Salamanca (USAL)

10.05.2023

7th RED LHC Workshop
(IFT - Madrid, Spain)

This project has received funding from the European Union´s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No.101034371

Outline

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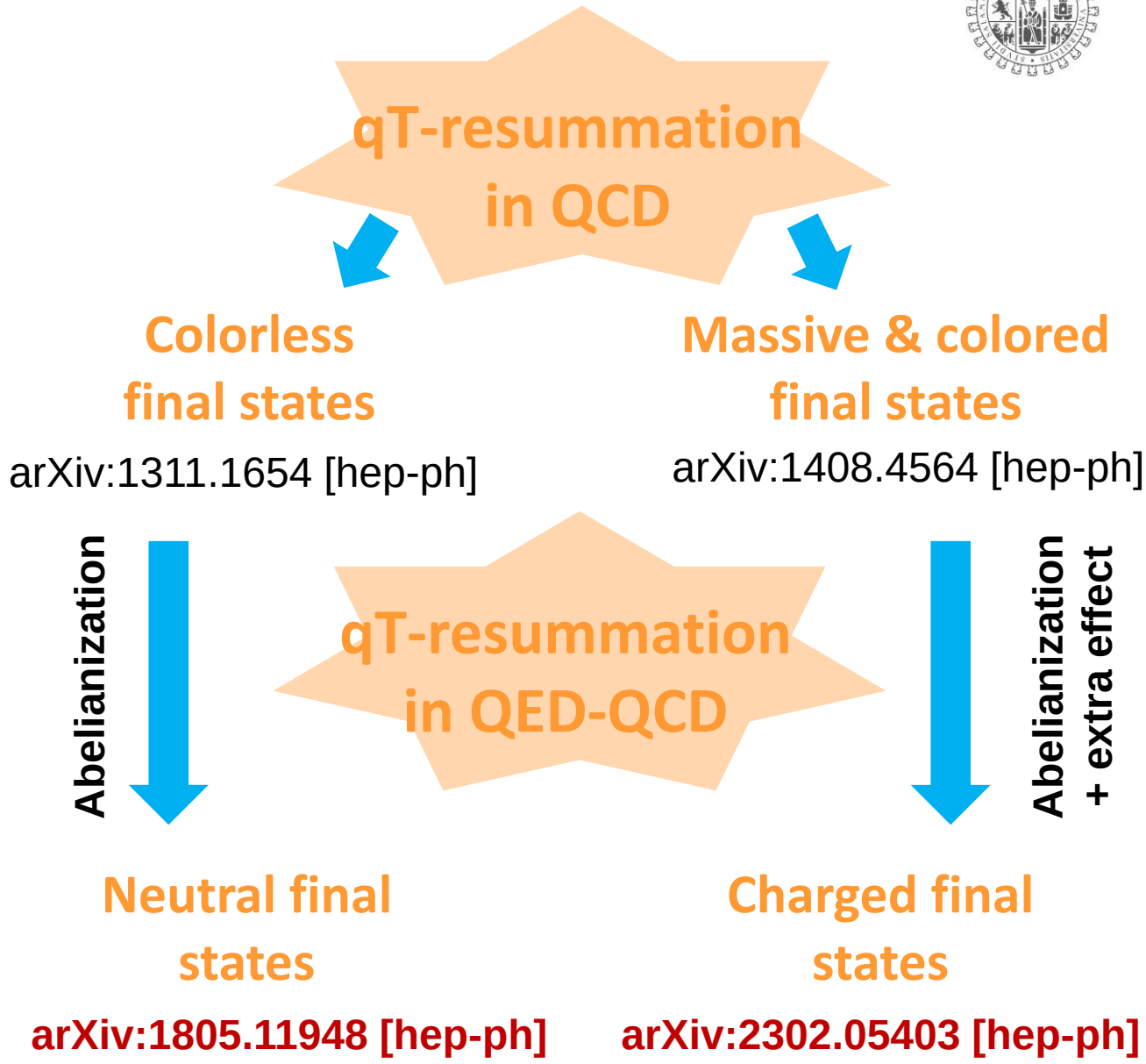
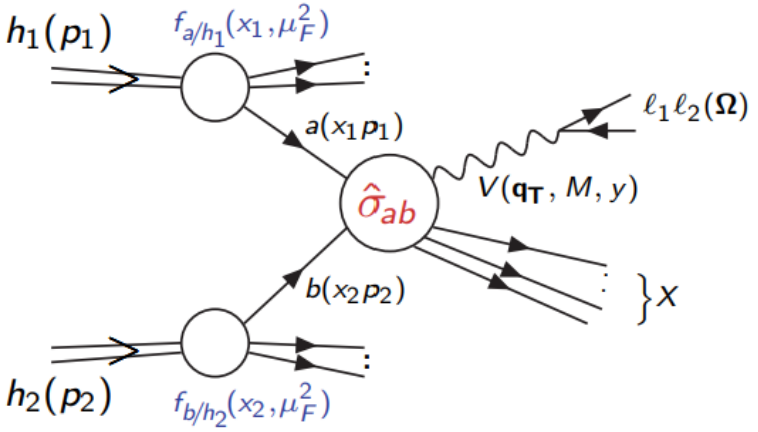
   - B. **qT-resummation in QED-QCD (neutral final state)**
   - C. **qT-resummation in QED-QCD (charged final state)**
2. Phenomenological results
   - A. **QED-QCD corrections to Z/W production**
   - B. **Impact on W/Z ratio**
3. Conclusions

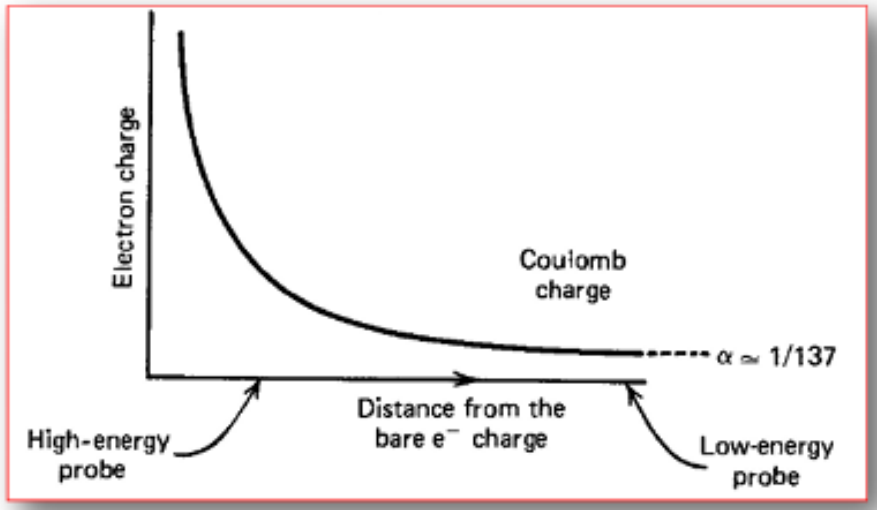


Why do we need QED-QCD and resummation for DY?

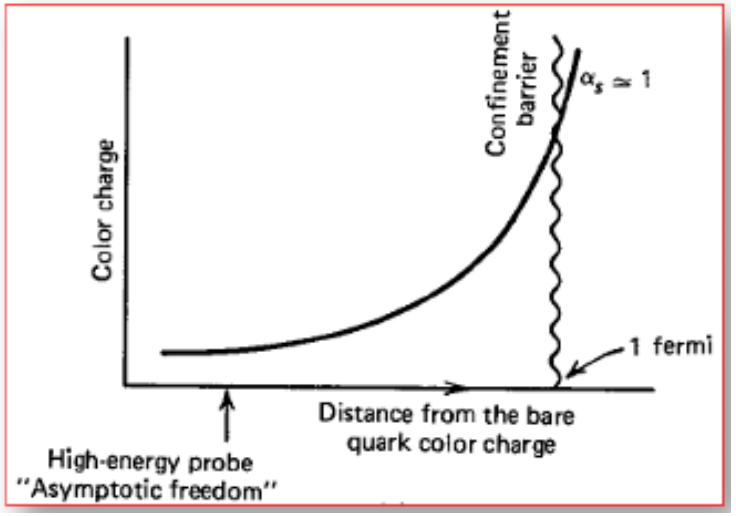
- Drell-Yan (DY) is a paramount at hadron colliders: it is used for SM and BSM physics, calibration, SM parameter extraction, …
- DY is measured with an astonishing precision **(per-thousand level!)**



- **Inclusion of EW/QED beyond LO could lead to novel effects:**
  - Quark-gluon interacting with leptons and photons
  - **Dependence on the photon content of the proton!**
  - Enhanced contributions at high-energies (due to the running EM coupling)



QED vs. QCD



Michiel Botje, "Lectures on Particle Physics II"

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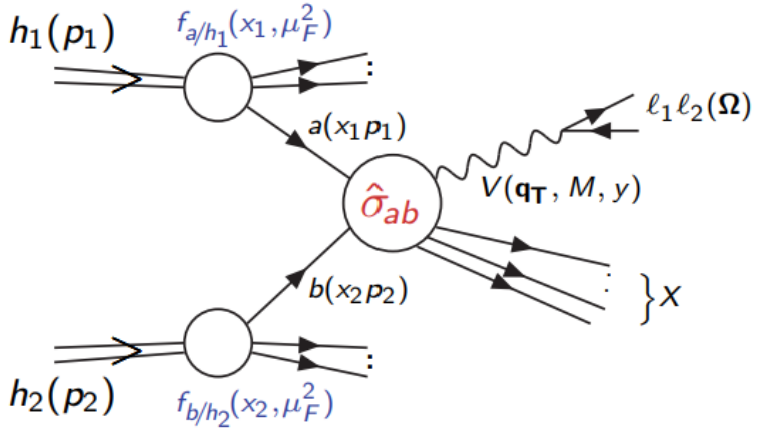
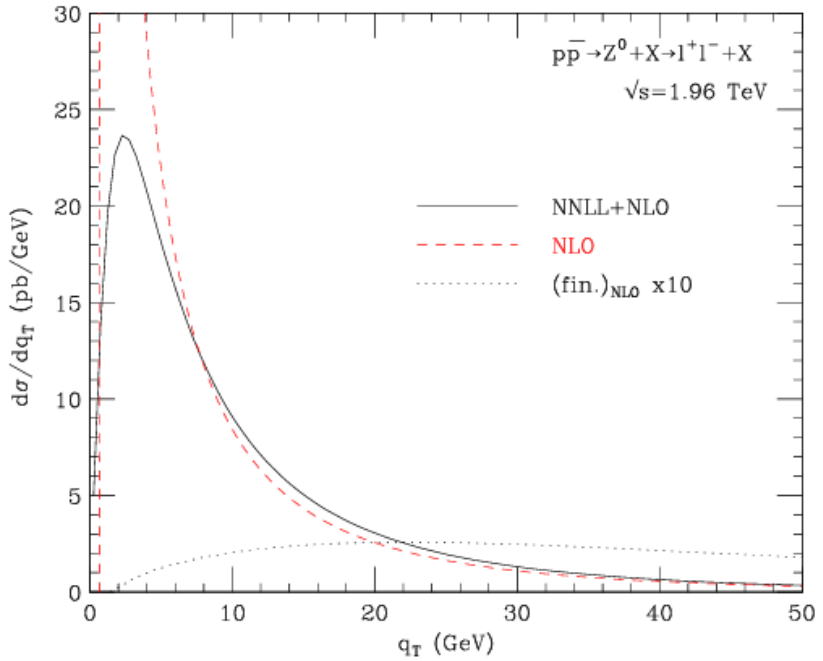
- **Particular interest in the low qT-region:**
  - Fixed-order calculations are no longer reliable
  - **Presence of logarithmically enhanced contributions!**
  - qT spectrum is phenomenologically relevant





arXiv:1007.2351 [hep-ph]

qT-resummation in QCD

- Soft gluon radiation leads to a modification of the spectrum in the low-qT region
- **Perturbative fixed-order expansion not reliable** ➡ **Re-arrange or resum:**

$$\int_0^{q_T^2} dq'^2_T \frac{d\hat{\sigma}}{dq'^2_T} \approx 1 + \alpha_S \left[c_{12} L^2 + c_{11} L + \ldots\right] + \alpha_S^2 \left[c_{24} L^4 + c_{23} L^3 + \ldots\right] + \ldots$$

- **<u>Master formulae for qT-resummation in QCD:</u>**
  - The singular (i.e. divergent) part has an universal structure:

$$\frac{d\sigma_F^{(\mathrm{sing})}(p_1, p_2; \mathbf{q_T}, M, y, \mathbf{\Omega})}{d^2\mathbf{q_T}\, dM^2\, dy\, d\mathbf{\Omega}} = \frac{M^2}{s} \sum_{c=q,\bar{q},g} \left[d\sigma^{(0)}_{c\bar{c},F}\right] \int \frac{d^2\mathbf{b}}{(2\pi)^2}\, e^{i\mathbf{b}\cdot\mathbf{q_T}}\, S_c(M, b)$$

$$\times \sum_{a_1,a_2} \int_{x_1}^1 \frac{dz_1}{z_1} \int_{x_2}^1 \frac{dz_2}{z_2} \left[H^F C_1 C_2\right]_{c\bar{c};a_1 a_2} f_{a_1/h_1}(x_1/z_1, b_0^2/b^2)\, f_{a_2/h_2}(x_2/z_2, b_0^2/b^2)$$

  - The **Sudakov factor** resums all the soft/collinear-emissions from the incoming legs; it is process independent
  - The **"hard-collinear"** coefficients **H** and **C** are related with the hard-virtual and collinear parts, and also contain the process dependence.

Catani et al, Nucl. Phys. B881 (2014) [arXiv:1311.1654]

- **Components of the resummation master formula:**
  - The Sudakov factor contains the logarithmically enhanced contributions.

$$S_c(M,b) = \exp\left\{ -\int_{b_0^2/b^2}^{M^2} \frac{dq^2}{q^2} \left[A_c(\alpha_S(q^2)) \ln\frac{M^2}{q^2} + B_c(\alpha_S(q^2)) \right] \right\}$$

with

$$A_c(\alpha_S) = \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n A_c^{(n)}$$

$$B_c(\alpha_S) = \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n B_c^{(n)}$$

  - $\mathbf{A_c}$ and $\mathbf{B_c}$ depend on the leg responsible for the emission. **They are related to the splitting functions!**
  - Also, **C** and **H** are calculable within perturbation theory. **C** is process independent (**H** contains the virtuals):

$$H_q^F(x_1p_1, x_2p_2; \mathbf{\Omega}; \alpha_S) = 1 + \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n H_q^{F\,(n)}(x_1p_1, x_2p_2; \mathbf{\Omega})$$

$$C_{q\,a}(z; \alpha_S) = \delta_{q\,a}\ \delta(1-z) + \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{\pi}\right)^n C_{q\,a}^{(n)}(z)$$

Loop information (finite parts)

Radiation from incoming legs (transitions)

  - **The resumed component can be alternatively expressed as:**

$$\frac{d\hat{\sigma}^{(\mathrm{res.})}_{a_1a_2\to F}}{dq_T^2}(q_T, M, \hat{s}; \mu_F) = \frac{M^2}{\hat{s}} \int_0^{\infty} db \frac{b}{2} J_0(b\,q_T)\, \mathcal{W}^F_{a_1a_2}(b, M, \hat{s}; \mu_F)$$

with

$$\mathcal{W}_N^F(b, M; \mu_F) = \hat{\sigma}_F^{(0)}(M)\, \mathcal{H}_N^F(\alpha_S; M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2) \times \exp\left\{\mathcal{G}_N(\alpha_S, L; M^2/\mu_R^2, M^2/Q^2)\right\}$$

Hard collinear part

Logarithmically-enhanced contributions

Catani et al, Nucl. Phys. B881 (2014) [arXiv:1311.1654]

- **Photon radiation introduced by "Abelianization" of gluon emission:** transforms color factors into charges by defining suitable replacements

More details in arXiv's: 1512.00612, 1606.02887, 1805.11948, 1805.12214, 2005.10705

- **Our master formulae for simultaneous QED-QCD resummation with neutral final states:**
  - We extend the *colorless QCD formalism* starting from:

$$\mathcal{W}'^{F}_{N}(b,M;\mu_F)=\hat{\sigma}^{(0)}_{F}(M)\,\mathcal{H}'^{F}_{N}(\alpha_S,\alpha;M^2/\mu_R^2,M^2/\mu_F^2,M^2/Q^2)\times\exp\left\{\mathcal{G}'_{N}(\alpha_S,\alpha,L;M^2/\mu_R^2,M^2/Q^2)\right\}$$

  - The hard-collinear part is expanded in a power series:

$$\mathcal{H}'^{F}_{N}(\alpha_S,\alpha)=\mathcal{H}^{F}_{N}(\alpha_S)+\frac{\alpha}{\pi}\mathcal{H}'^{F\,(1)}_{N}+\sum_{n=2}^{\infty}\left(\frac{\alpha}{\pi}\right)^{n}\mathcal{H}'^{F\,(n)}_{N}+\sum_{n,m=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^{n}\left(\frac{\alpha}{\pi}\right)^{m}\mathcal{H}'^{F\,(n,m)}_{N}$$

Pure QCD | Pure QED part | Mixed QCD-QED

  - The Sudakov is also expanded in the same fashion:

$$\mathcal{G}'_{N}(\alpha_S,\alpha,L)=\mathcal{G}_{N}(\alpha_S,L)+L\,g'^{(1)}(\alpha L)+g'^{(2)}_{N}(\alpha L)+\sum_{n=3}^{\infty}\left(\frac{\alpha}{\pi}\right)^{n-2}g'^{(n)}_{N}(\alpha L)$$
$$+g'^{(1,1)}(\alpha_S L,\alpha L)+\sum_{\substack{n,m=1\\ n+m\neq 2}}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^{n-1}\left(\frac{\alpha}{\pi}\right)^{m-1}g'^{(n,m)}_{N}(\alpha_S L,\alpha L)$$

with $\lambda=\frac{1}{\pi}\beta_0\,\alpha_S\,L$, $\lambda'=\frac{1}{\pi}\beta'_0\,\alpha\,L$ — Large log!!!

… and G-functions in terms of A and B coefficients (perturbative)

Cieri, Ferrera and GS, JHEP 08 (2018) 165 [arXiv:1805.11948]

qT-resummation in QED-QCD (charged final state)

- **When final state is electrically charged, we "Abelianize" the QCD result for colorful final states.**
- **We start from the master formula for QCD resummation in ttbar production** Catani et al [arXiv:1408.4564]

$$W_N^V(b,M) = \sum_{c a_1 a_2} \sigma^{(0)}_{c\bar{c},V}(\alpha_S(M^2)) f_{a_1/h_1,N}(b_0^2/b^2) f_{a_2/h_2,N}(b_0^2/b^2) \times S_c(M,b) \times [(\mathbf{H}^V \boldsymbol{\Delta} C_1 C_2)]_{c\bar{c},a_1,a_2;N}(M^2, b_0^2/b^2)]$$

- The soft factor $\boldsymbol{\Delta}$ accounts for soft (non-collinear) wide-angle radiation from final state and from initial-final state interferences
- Full EW loop-effects can be included within **H**

- **Master formulae for simultaneous QED-QCD resummation with charged final states:**
  - The soft factor part is expanded in a power series, exploiting the fact that EM charge is Abelian:

$$\Delta(\alpha;Q,b) = \exp\left\{ -\int_{b_0^2/b^2}^{Q^2} \frac{dq^2}{q^2} D'(\alpha(q^2)) \right\} \quad \text{with} \quad D'(\alpha) = \frac{\alpha}{\pi} D'^{(1)} + \sum_{n=2}^{+\infty} \left(\frac{\alpha}{\pi}\right)^n D'^{(n)}$$

For W-boson production:

$$D'^{(1)} = -\frac{e_V^2}{2}$$

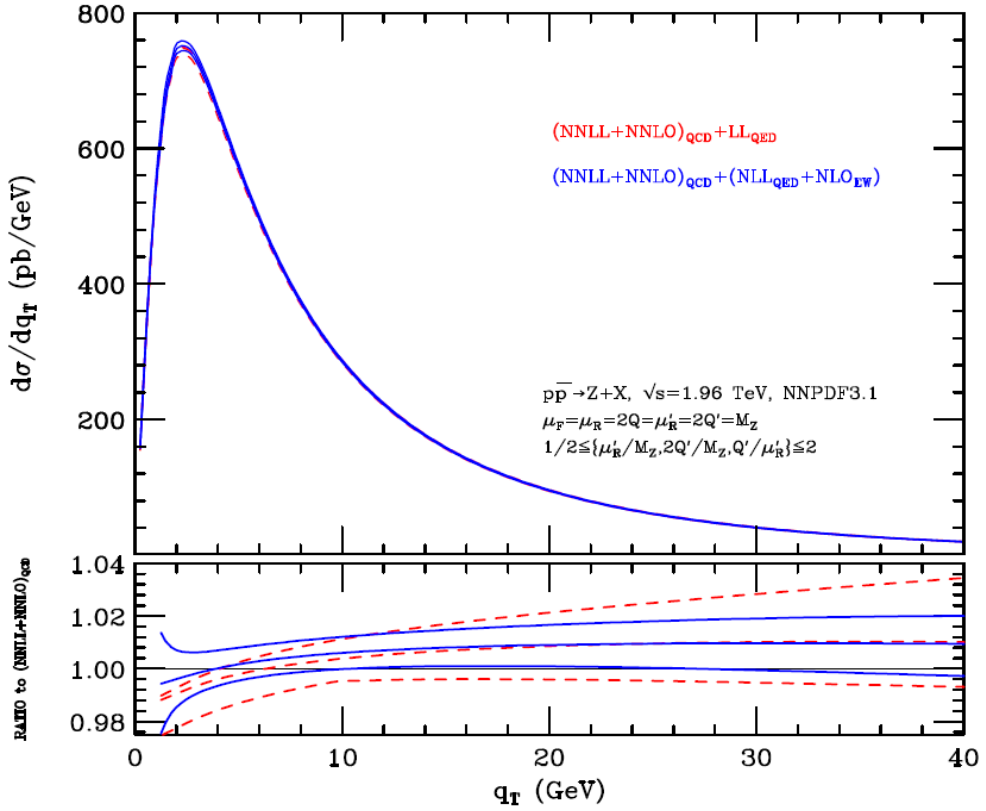
  - The Sudakov factor also includes an additional term; in the exponential G-function we have:

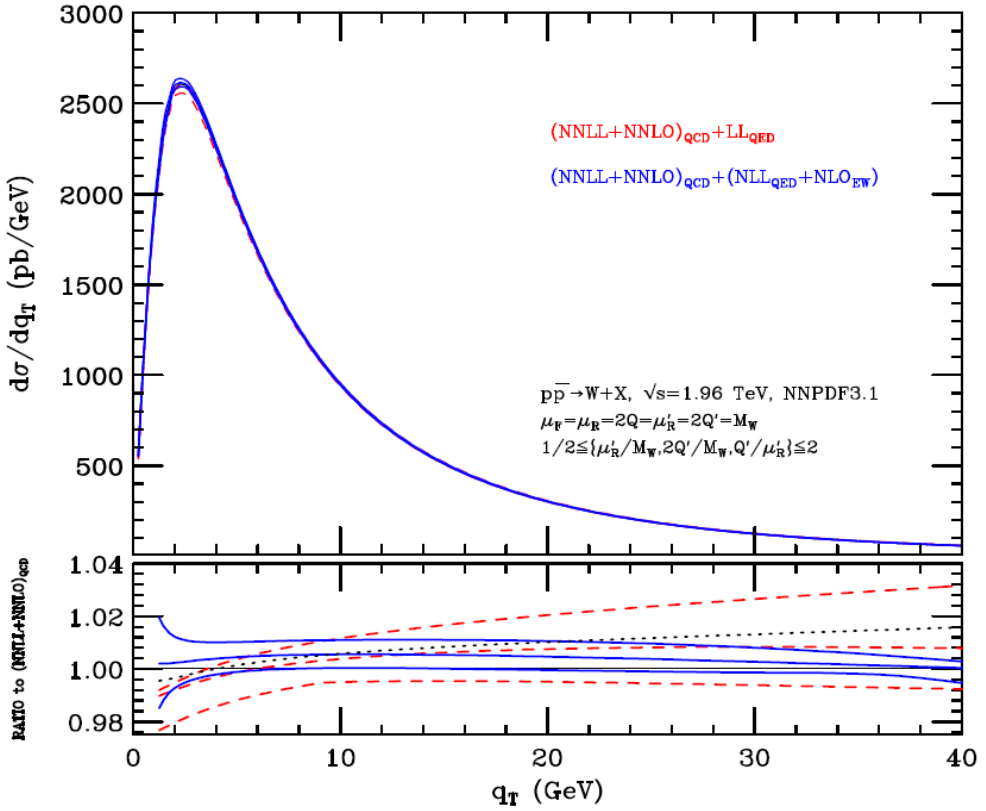
$$\mathcal{G}'_N(\alpha,L) = -\int_{b_0^2/b^2}^{Q^2} \frac{dq^2}{q^2} \left(A'(\alpha(q^2)) \log\left(\frac{M^2}{q^2}\right) + \widetilde{B}'_N(\alpha(q^2)) + D'(\alpha(q^2)) \right)$$

Autieri, Cieri, Ferrera and GS [arXiv:2302.05403]

QED-QCD corrections to W/Z production

- **Vector boson production at Tevatron (E_{CM} = 1.96 Tev)**



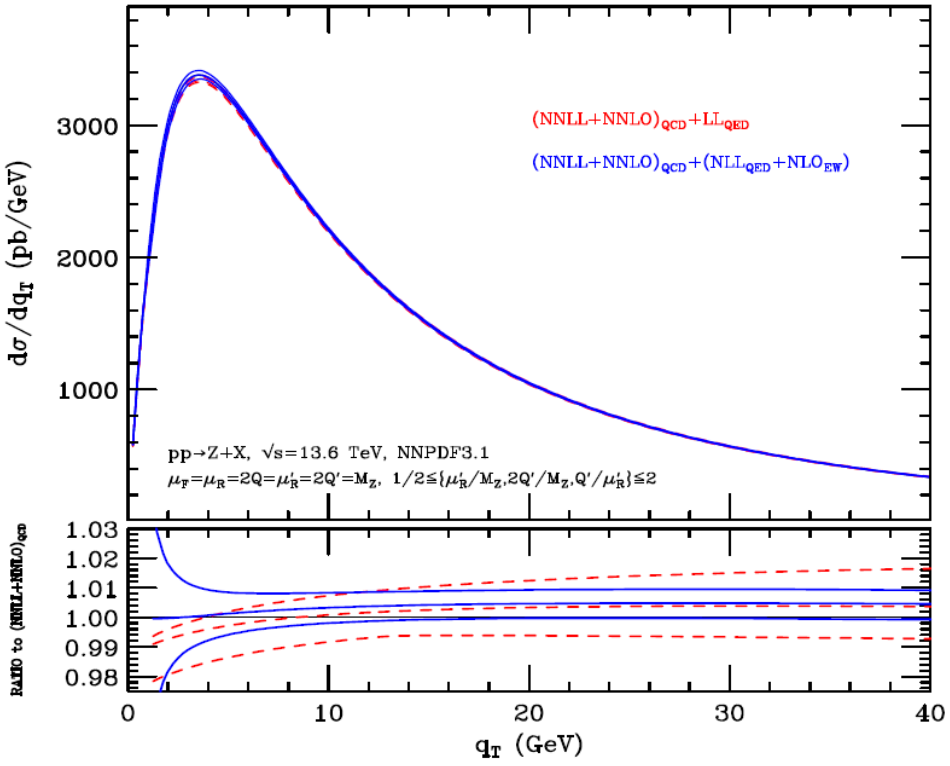


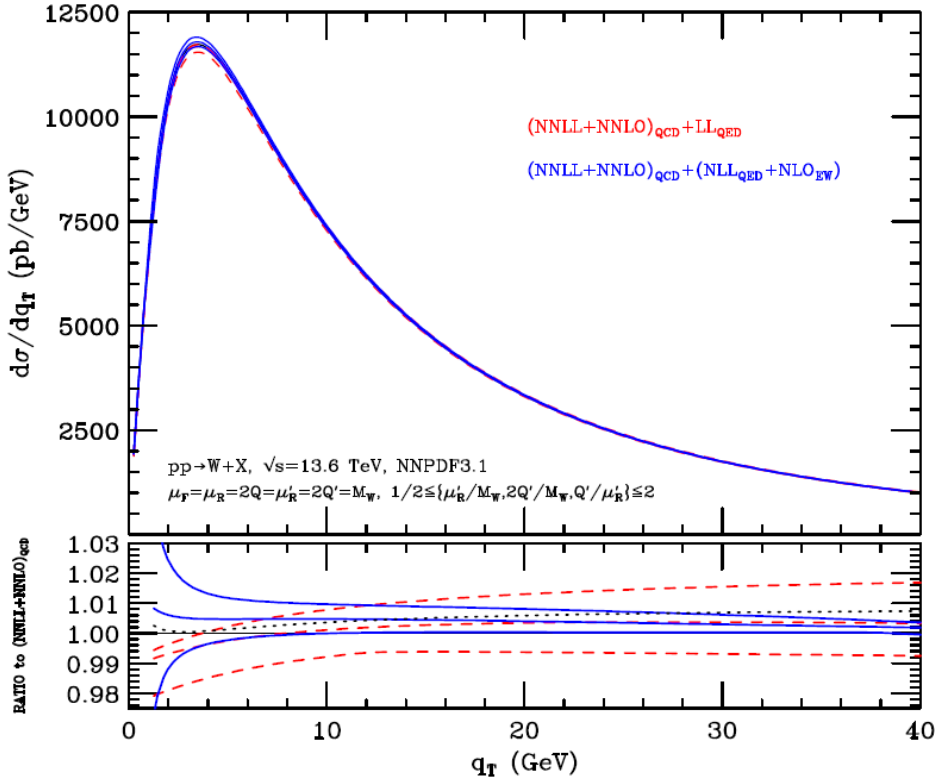
- **LL_{QED}:** spectrum slightly harder (O(1%) correction), and scale variation O(2-4%)
- **NLL_{QED}+NLO_{EW}:** effects of O(0.5%) but scale variation band reduced by a factor 2

- **LL_{QED}:** spectrum slightly harder (O(<1%) correction), and scale variation O(2-3%)
- **NLL_{QED}+NLO_{EW}:** effects of O(1%), scale variation band reduced by a factor 1.5-2. D_1 makes the spectrum softer (enhances B_1 term)

QED-QCD corrections to W/Z production

- **Vector boson production at LHC (E_{CM} = 13.6 Tev)**
  - *Impact of QED effects reduced w.r.t. Tevatron (enhanced gluon contribution)*





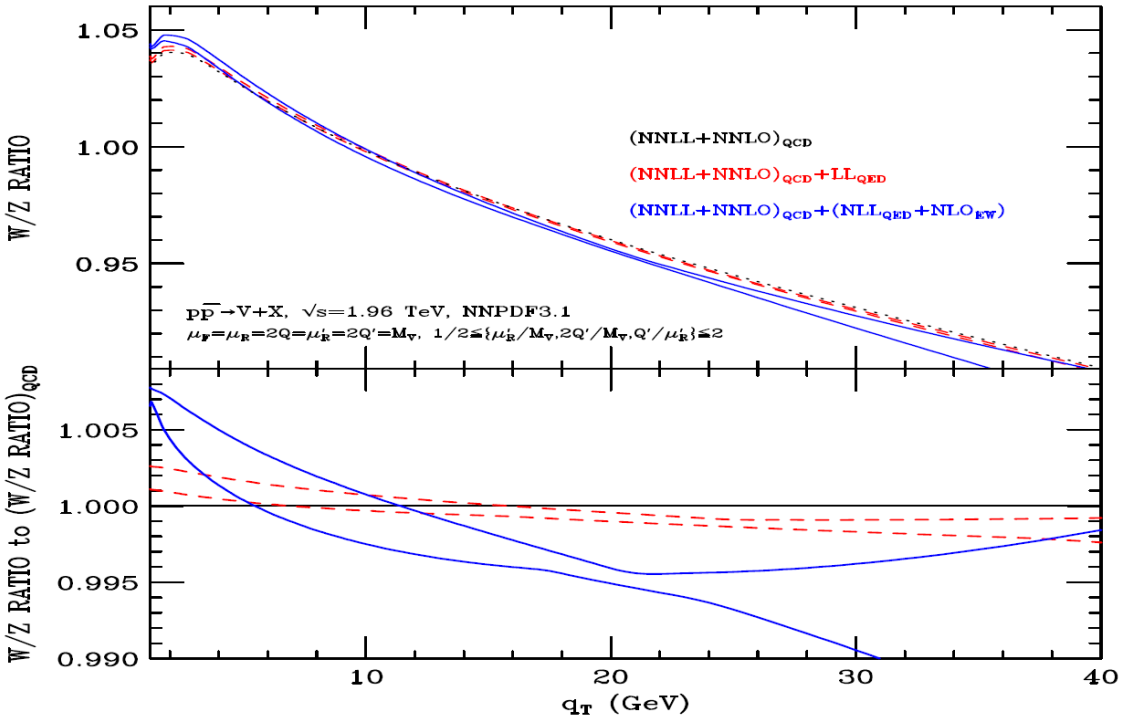
- **LL_{QED}:** spectrum slightly modified (-1% to 0.5%) correction), and scale variation O(2%)
- **NLL_{QED}+NLO_{EW}:** effects of O(+0.5%) but scale variation band reduced by a factor 1.5-2

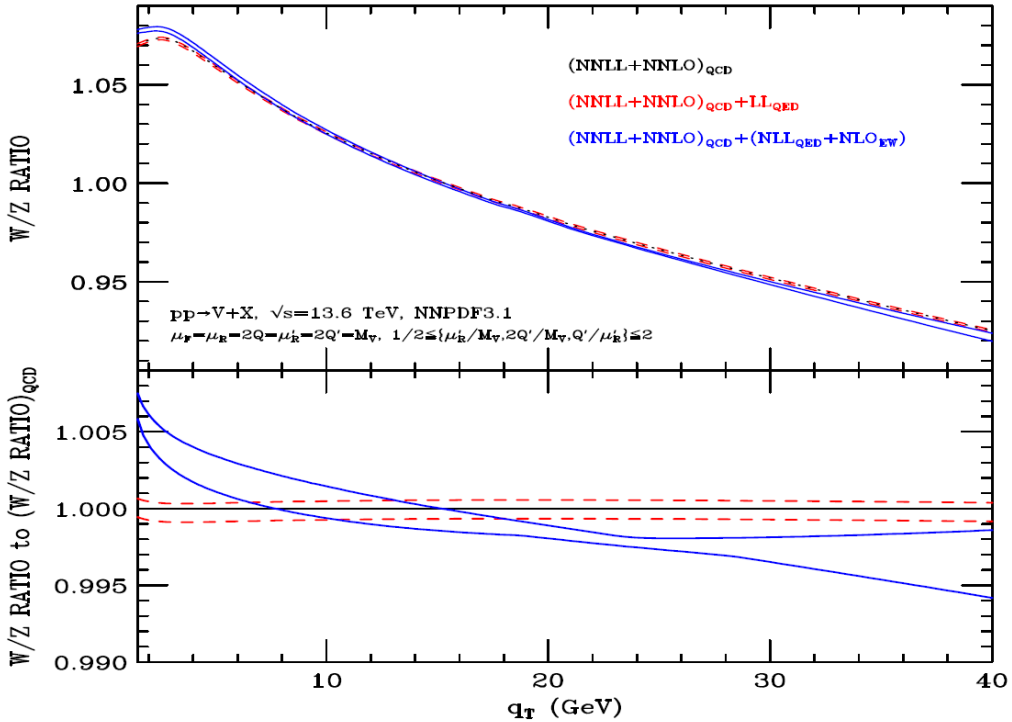
- **LL_{QED}:** spectrum slightly harder (O(<1%) correction), and scale variation O(2%)
- **NLL_{QED}+NLO_{EW}:** effects of O(1%), scale variation band reduced by factor 1.5-2 (up to 4). D_1 makes the spectrum softer.

Impact on W/Z qT-spectrum ratio

$$R(q_T) = \frac{\frac{1}{\sigma_W}\frac{d\sigma_W}{dq_T}}{\frac{1}{\sigma_Z}\frac{d\sigma_Z}{dq_T}}$$

- **R-ratio for Tevatron (left) and LHC (right)**
  - This ratio is useful for m_W determination
  - QED-EW effects at LHC reduced w.r.t. Tevatron due to enhanced gluon luminosity





- LL_{QED} effects are per-mille level, as well as the scale variation.
- $NLL_{QED}+NLO_{EW}$ effects are larger than at the lowest order (larger error bands w.r.t. LL calculation!!).
- This is due to new QED-EW effects that do not cancel in the ratio. *Further investigation required!*

Conclusions

- **We introduced mixed QCD-QED/EW effects in the qT-resummation formalism**
- The formalism was applied to Z/W boson production (EW one-loop included!)
- **Implemented in DYqT; ongoing efforts to migrate to DYTurbo**

arXiv:1910.07049 [hep-ph]

- **Results for Z production are in agreement with the previous findings**; EW one-loop effects are very small w.r.t. QED ones.
- Corrections to **W boson production range from per-mille to percent level**, with a **reduction of the error band when considering NLL_{QED}+NLO_{EW} effects**
- LL_{QED} corrections induced to R(qT) are very small (per-mille level), but they are **slightly enhanced when considering the NLL_{QED}+NLO_{EW} effects**. **The error bands become wider!**

THANKS!