INCREASING THE PRECISION FOR Z PRODUCTION AT COLLIDERS: MIXED QCD-QED EFFECTS

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VNIVERSITAT DE VALÈNCIA

EUROPEAN PHYSICAL SOCIETY HEP2019

EPS-HEP Conference

Ghent (Belgium) – July 12th, 2019

Outline

- 1- QCD corrections to Drell-Yan
  - q_T-resummation formalism
  - Study of H.O. corrections
- 2- Mixed H.O. QCD-QED effects
  - **Mixed QCD-QED resummation formalism**
  - **Study of H.O. resummed effects on Z production**
- Conclusions

CENTRAL PART OF THE TALK!

Supported by cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

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Part 1: QCD corrections for DY

- **I)- Brief introduction and q_T-resummation formalism**

- **III)- Analysis of H.O. QCD corrections**

Introduction and motivation

Drell-Yan process

- To perform the computation, factorization theorem is used:

$$\frac{d\sigma}{d^2\vec{q}_T\, dM^2 d\Omega dy} = \sum_{a,b}\int dx_1 dx_2\, f_a^{h_1}(x_1)\, f_b^{h_2}(x_2)\, \frac{d\hat{\sigma}_{ab\to V+X}}{d^2\vec{q}_T\, dM^2 d\Omega dy}$$

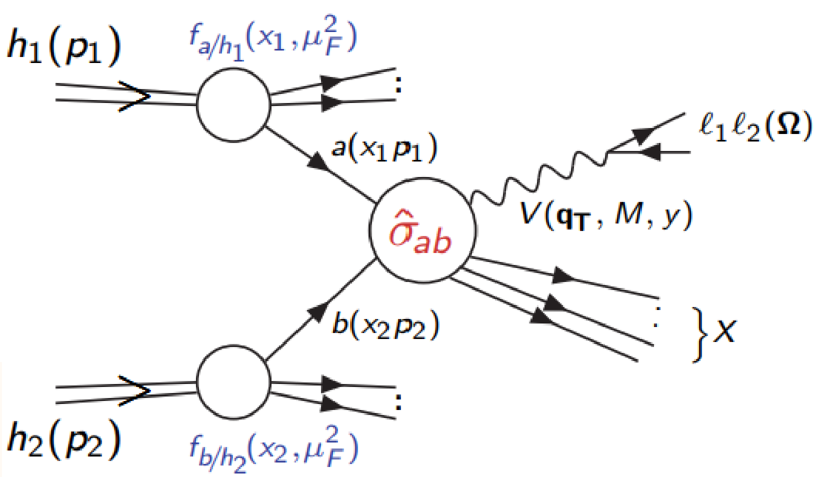
PDFs (non-perturbative)

Partonic cross-section (perturbative)

- Fixed-order corrections fail to describe the low q_T region ➡ Presence of enhanced logarithmic contributions
- **SOLUTION:** Resumming the perturbative expansion:

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

$$L = \log\left(M^2/q_T^2\right) \quad \text{and} \quad \alpha_S\, L >> 1$$



Extracted from the talk "NNLO QCD predictions and q_T resummation for V production", by G. Ferrera, (LHCP 2017, May 18th 2017, Shanghai)

q_T-resummation formalism

- Soft gluon/photon radiation could provide non-negligible effects in the low q_T region → **Extend qt-resummation to deal with QCD-QED radiation!**

PURPOSE OF THIS TALK!

- Some formulae to introduce qt-resummation in QCD:
  - 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]

q_T-resummation formalism

- **More details about the resummation formula:**
  - The Sudakov factor contains the logarithmically enhanced contributions. It can be resumed to all orders within perturbation theory!

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

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

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

  - **A_c** and **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, i.e. loops):

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

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

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

H.O. resummed QCD corrections

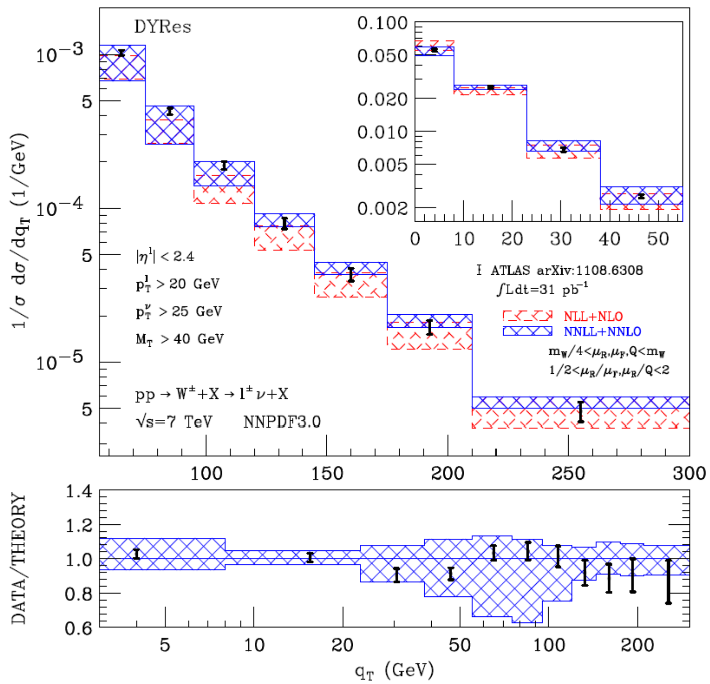
Drell-Yan process: path to refined predictions

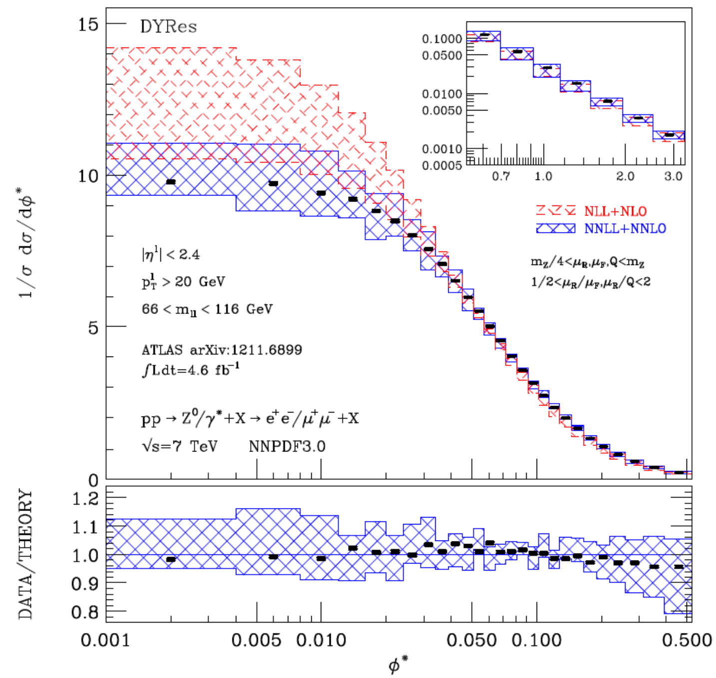
- Fixed-order description of QCD corrections
  - **NLO** Drell and Yan, ‘70
  - **NNLO** Hamberg et al, 91’; Anastasiou et al, ‘03; Melnikov and Petrielo, ‘06; Catani et al, ’09-’10; Boughezal et al, ‘15, …
- Excellent agreement in the high q_T region! Inclusion of *QED and EW* higher-orders (F.O. approach) to increase precision!!
- Resummed corrections computed up to NNLL+NNLO with q_T-resummation formalism:
  - **DYqT:** inclusive qT spectrum
    [Bozzi,Catani,de Florian,G.F.,Grazzini(’09,’11)]
    http://pcteserver.mi.infn.it/~ferrera/dyqt.html
  - **DYRes:** fully exclusive resumed corrections (plus decay into leptons)
    [Catani,de Florian,G.F.,Grazzini(’15)]
    http://pcteserver.mi.infn.it/~ferrera/dyres.html
- Recent progress to include higher logarithmic terms (N^3LL)
  Catani et al ’14; Bizon et al ’18-’19;

H.O. resummed QCD corrections

Drell-Yan process: H.O. corrections in QCD

DYRes results: q_T spectrum of W and ϕ^* spectrum of Z boson at the LHC





NLL+NLO and NNLL+NNLO bands for $W^\pm$ q_T spectrum compared with ATLAS data.
Lower panel: ratio with respect to the NNLL+NNLO central value.

NLL+NLO and NNLL+NNLO bands for Z/γ^* ϕ^* spectrum compared with ATLAS data.
Lower panel: ratio with respect to the NNLL+NNLO central value.

Extracted from the talk "NNLO QCD predictions and q_T resummation for V production", by G. Ferrera, (LHCP 2017)

Part 2: QCD-QED corrections

- **I)- Development of a formalism to deal with mixed QCD-QED computations**

- **II)- Application to Z production**

(NNLL+NNLO QCD plus NLL+NLO QED plus NEW non-trivial mixing)

Mixed QCD-QED resummation

Abelianization of the qt-formalism

- **Path to QCD-QED resummation:**
- **Step I:** Transform all the QCD coefficients into the QED ones with the Abelianization algorithm (done!). Obtain QED resummation formula (done!).
  - *Subtlety I:* Charge separation effects due to up and down sectors.
  - *Subtlety II:* Photons and leptons must be included (closed loops), as well as the photon PDF → *Non trivial dependence!*

    SOLVED!
- **Step II:** Deal with QCD-QED radiation simultaneously. We need to Abelianizate all the coefficients, and perform the perturbative expansions with two couplings!
  - *Subtlety I:* Check of factorization formulae and its functional structure
  - *Subtlety II:* Compute *all* the coefficients, including the **mixed** ones!
  - *Subtlety III:* Applicable for **color-less neutral** final states…

Cieri, Ferrera and GS, JHEP 08 (2018) 165

Mixed QCD-QED resummation

Required ingredient: mixed RGE equations!

- **Coupled differential equations:** Crucial to recover non-trivial mixed terms in *g-functions*

$$\frac{d\ln\alpha_S(\mu^2)}{d\ln\mu^2} = \beta(\alpha_S(\mu^2),\alpha(\mu^2)) = -\sum_{n=0}^{\infty}\beta_n\left(\frac{\alpha_S}{\pi}\right)^{n+1} - \sum_{n,m+1=0}^{\infty}\beta_{n,m}\left(\frac{\alpha_S}{\pi}\right)^{n+1}\left(\frac{\alpha}{\pi}\right)^{m}$$

$$\frac{d\ln\alpha(\mu^2)}{d\ln\mu^2} = \beta'(\alpha(\mu^2),\alpha_S(\mu^2)) = -\sum_{n=0}^{\infty}\beta'_n\left(\frac{\alpha}{\pi}\right)^{n+1} - \sum_{n,m+1=0}^{\infty}\beta'_{n,m}\left(\frac{\alpha}{\pi}\right)^{n+1}\left(\frac{\alpha_S}{\pi}\right)^{m}$$

- **Mixed beta function coefficients:**

$$\beta_0 = \frac{1}{12}(11\,C_A - 2\,n_f)\,, \qquad \beta_{0,1} = -\frac{N_q^{(2)}}{8}\,,$$

$$\beta'_0 = -\frac{N^{(2)}}{3}\,, \qquad \beta'_1 = -\frac{N^{(4)}}{4}\,, \qquad \beta'_{0,1} = -\frac{C_F C_A N_q^{(2)}}{4},$$

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Mixed QCD-QED resummation

Abelianization of the qt-formalism

- **Our (explicit) formulae (in b-space)**
  - Originally, in the QCD formalism, the resumed component is given by

$$\frac{d\hat{\sigma}^{(\text{res.})}_{a_1 a_2 \to F}}{dq_T^2}(q_T, M, \hat{s}; \mu_F) = \frac{M^2}{\hat{s}} \int_0^\infty db \frac{b}{2} J_0(b\, q_T)\, \mathcal{W}^F_{a_1 a_2}(b, M, \hat{s}; \mu_F)$$

and we extend it by "exponentiating" photon/gluon radiation:

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

Hard collinear part

Logarithmically-enhanced contributions

  - 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

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Mixed QCD-QED resummation

Abelianization of the qt-formalism

- **Our (explicit) formulae (in b-space)**
  - The Sudakov factor is also expanded:

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

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

Pure QCD

Pure QED

(New) mixed QCD-QED!!

  - The *g-functions* for QED are:

$$\lambda = \tfrac{1}{\pi}\beta_0\,\alpha_S\,L$$

$$\lambda' = \tfrac{1}{\pi}\beta'_0\,\alpha\,L$$

Large log!!!

$$g'^{(1)}(\alpha L) = \frac{A_q'^{(1)}}{\beta'_0}\,\frac{\lambda' + \ln(1-\lambda')}{\lambda'}$$

$$g_N'^{(2)}(\alpha L) = \frac{\widetilde{B}_{q,N}'^{(1)}}{\beta'_0}\ln(1-\lambda') - \frac{A_q'^{(2)}}{\beta_0'^2}\left(\frac{\lambda'}{1-\lambda'} + \ln(1-\lambda')\right)$$

$$+ \frac{A_q'^{(1)}\beta'_1}{\beta_0'^3}\left(\frac{1}{2}\ln^2(1-\lambda') + \frac{\ln(1-\lambda')}{1-\lambda'} + \frac{\lambda'}{1-\lambda'}\right)$$

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Mixed QCD-QED resummation

Abelianization of the qt-formalism

- **Our (explicit) formulae (in b-space)**
  - The new mixed first-order *g-function*:

$$g'^{(1,1)}(\alpha_S L, \alpha L) = \frac{A_q^{(1)}\beta_{0,1}}{\beta_0^2\beta_0'} h(\lambda,\lambda') + \frac{A_q'^{(1)}\beta'_{0,1}}{\beta_0'^2\beta_0} h(\lambda',\lambda)$$

$$h(\lambda,\lambda') = -\frac{\lambda'}{\lambda-\lambda'}\ln(1-\lambda) + \ln(1-\lambda')\left[\frac{\lambda(1-\lambda')}{(1-\lambda)(\lambda-\lambda')} + \ln\left(\frac{-\lambda'(1-\lambda)}{\lambda-\lambda'}\right)\right] - \mathrm{Li}_2\left(\frac{\lambda}{\lambda-\lambda'}\right) + \mathrm{Li}_2\left(\frac{\lambda(1-\lambda')}{\lambda-\lambda'}\right),$$

  - New **A, B** and **H** coefficients:

$$A_q'^{(1)} = e_q^2 \qquad A_q'^{(2)} = -\frac{5}{9}e_q^2 N^{(2)}$$

$$\widetilde{B}_{q,N}'^{(1)} = B_q'^{(1)} + 2\gamma_{qq,N}'^{(1)}$$

$$B_q'^{(1)} = -\frac{3}{2}e_q^2$$

$$\gamma_{qq,N}'^{(1)} = e_q^2\left(\frac{3}{4} + \frac{1}{2N(N+1)} - \gamma_E - \psi_0(N+1)\right)$$

$$\gamma_{q\gamma,N}'^{(1)} = \frac{3}{2}e_q^2\frac{N^2+N+2}{N(N+1)(N+2)}$$

$$\mathcal{H}'^{F\,(1)}_{q\bar{q}\leftarrow q\bar{q},N} = \frac{e_q^2}{2}\left(\frac{2}{N(N+1)} - 8 + \pi^2\right)$$

$$\mathcal{H}'^{F\,(1)}_{q\bar{q}\leftarrow \gamma q,N} = \mathcal{H}'^{F\,(1)}_{q\bar{q}\leftarrow q\gamma,N} = \frac{3\,e_q^2}{(N+1)(N+2)}$$

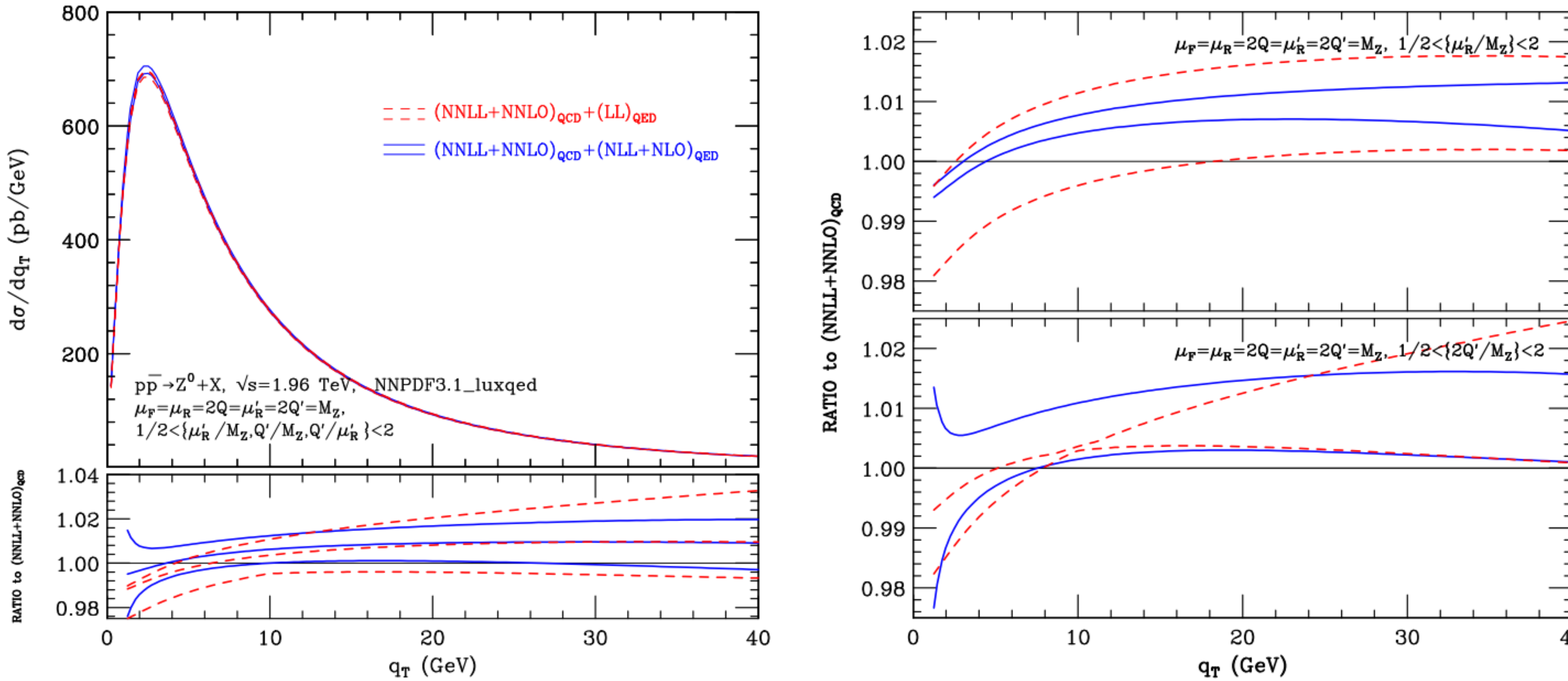
$$\mathcal{H}'^{F\,(1)}_{q\bar{q}\leftarrow \gamma\gamma,N} = \mathcal{H}'^{F\,(1)}_{q\bar{q}\leftarrow qq,N} = \mathcal{H}'^{F\,(1)}_{q\bar{q}\leftarrow \bar{q}\bar{q},N} = 0$$

Cieri, Ferrera and GS, JHEP 08 (2018) 165

Z production with *mixed NLL QED*

Some plots

- **Case of study:** Z production (implemented in DYqt)



- Collider: Tevatron at 1.96 TeV
- Z production, using the narrow with approximation, with NNLL + NNLO QCD as reference to compare the QED effects. NEW NNPDF3.1QED (uses LUX's method)

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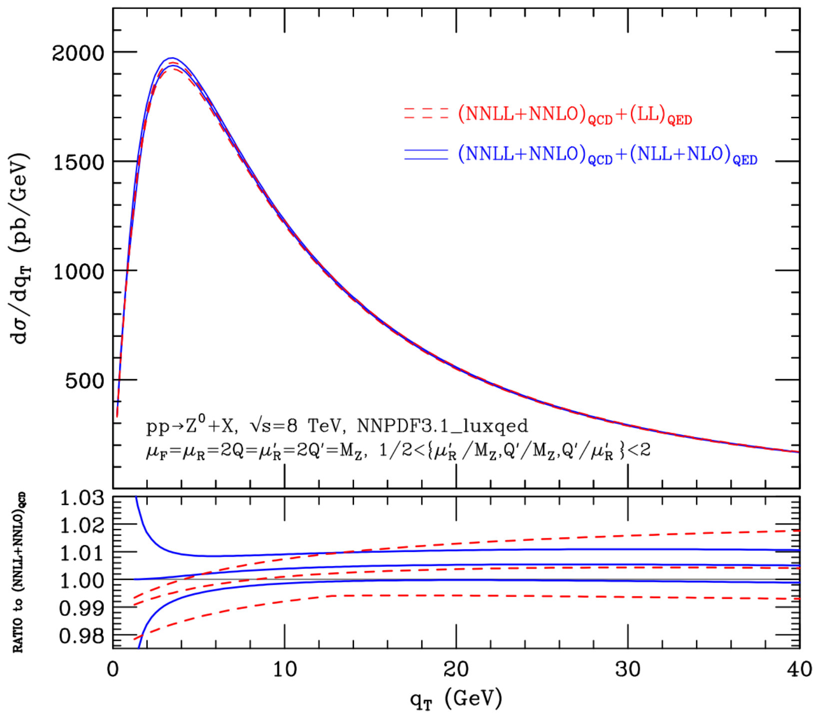

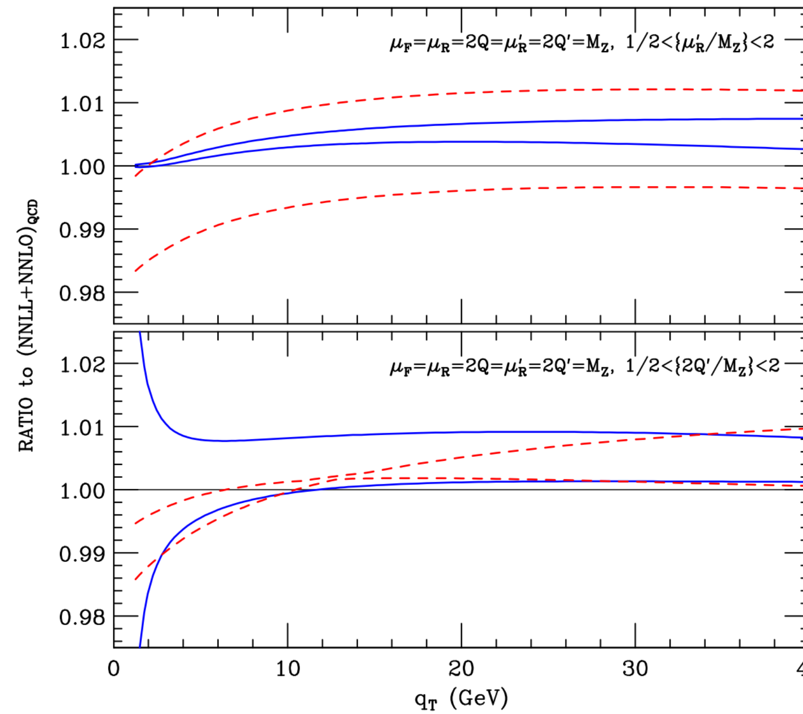

- Collider: LHC at 8 TeV
- Z production, using the narrow with approximation, with NNLL + NNLO QCD as reference to compare the QED effects. NEW NNPDF3.1QED (uses LUX's method)

Cieri, Ferrera and GS, JHEP 08 (2018) 165

Z production with *mixed NLL QED*

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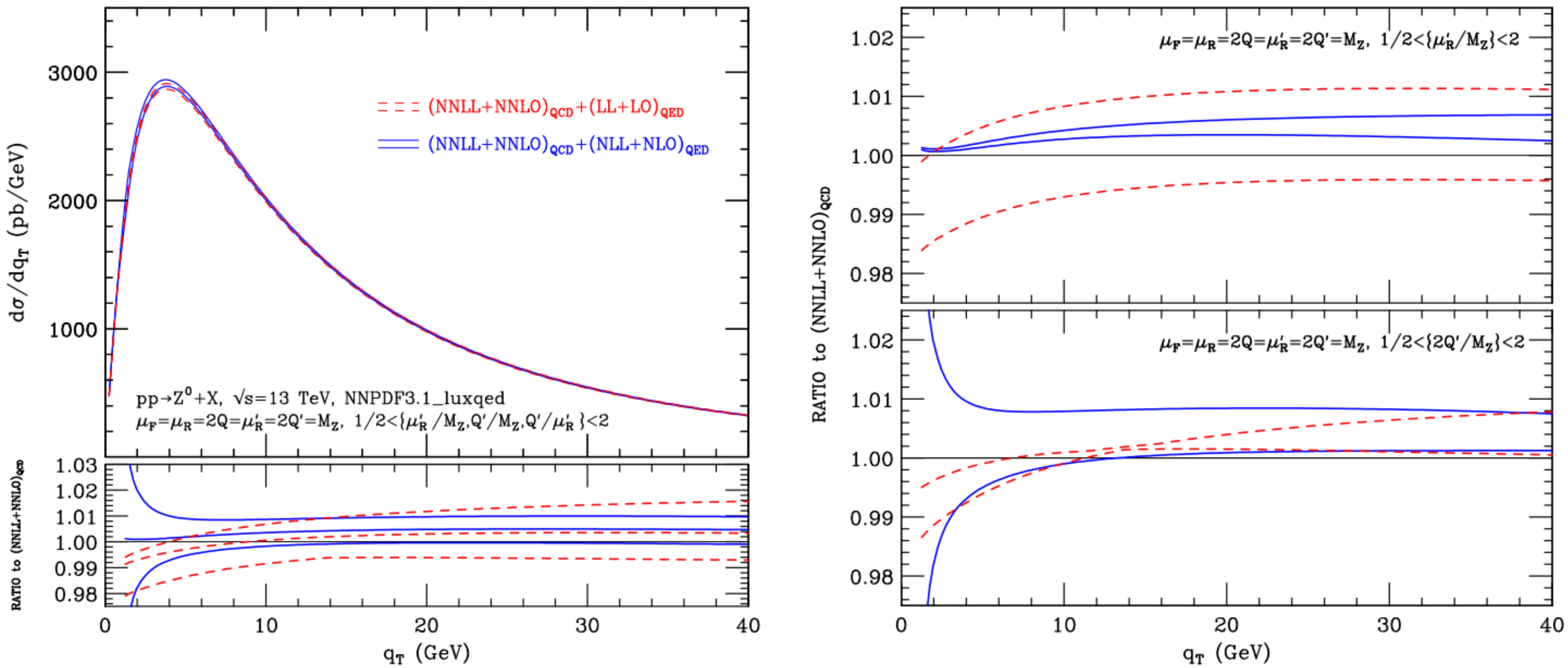

- Collider: LHC at 13 TeV
- Z production, using the narrow with approximation, with NNLL + NNLO QCD as reference to compare the QED effects. NEW NNPDF3.1QED (uses LUX's method)

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Conclusions

- *DY process is a playground to applying/developing new methods.*
- *Relevance from the experimental/phenomenological/theoretical side!!!*
- **Part 1:** Review of QCD corrections
  - q_T-resummation is an efficient method to compute H.O. for DY
  - (Complete) NNLL+NNLO QCD corrections; N^3LL' available
- **Part 2:** Including mixed QCD-QED effects
  - Mixed resummation applied to Z production (uses a **new formalism!**)
  - Results: **Non negligible (few percent) effects at low pt!!!**
  - **Work-in-progress to describe mixed QCD-QED effects for W boson production**

Thanks for the attention!!