ELECTROWEAK CORRECTIONS FOR HADRON COLLIDERS

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particleface

PARTICLEFACE 2020

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Outline

- 1- Motivation and introduction
  - q_T-resummation formalism
- 2- Mixed H.O. QCD-QED effects
  - Mixed QCD-QED resummation formalism
  - Study of H.O. resummed effects on Z production
- **3- Mixed H.O. corrections within LTD approach**
  - **Application: corrections to Higgs decays**
- Conclusions

Standard methods

New fully-local and 4-dimensional method

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Introduction and motivation

Why HEP people should care about this?

- HEP community should be aware of the importance of higher-orders (*and properly deal with them*)
- **We have a framework, the *Standard Model*, and we need to test it!**
- **SO…**

WE MUST BE ABLE TO PROPERLY DESCRIBE SM PHENOMENOLOGY!!!

- Properly describing SM implies focusing on **precise** theoretical calculations
- If **theoretical errors** (and their **definition**) are not under control, we won't be able to **distinguish** these scenarios:

Data-theory discrepancies are due to:

- ***Improper SM computations*** *(we don't know how to solve SM…)*
- ***Improper theoretical model*** *(SM is not suitable…)*

Introduction and motivation

Why we need EW corrections?

- More precise experimental data is available!! We need to include (**previously neglected**) small theoretical effects!!
- NLO QCD is the entry-level; **NNLO QCD is the "standard"**

- **Inclusion of EW/QED beyond LO could lead to novel effects:**
  - Quark-gluon interacting with leptons and photons
  - Charge separation
  - **Dependence on the photon content of the proton!**

Manohar, Nason, Salam, Zanderighi, '17

  - Enhanced contributions at high-energies (due to the running EM coupling)
  - Enhanced QED radiation effects at low-energies (resummation needed)

Interesting interplay with QCD effects!

Introduction and motivation

Our (starting) playground: Drell-Yan process

- To perform the computation, factorization theorem is used:

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

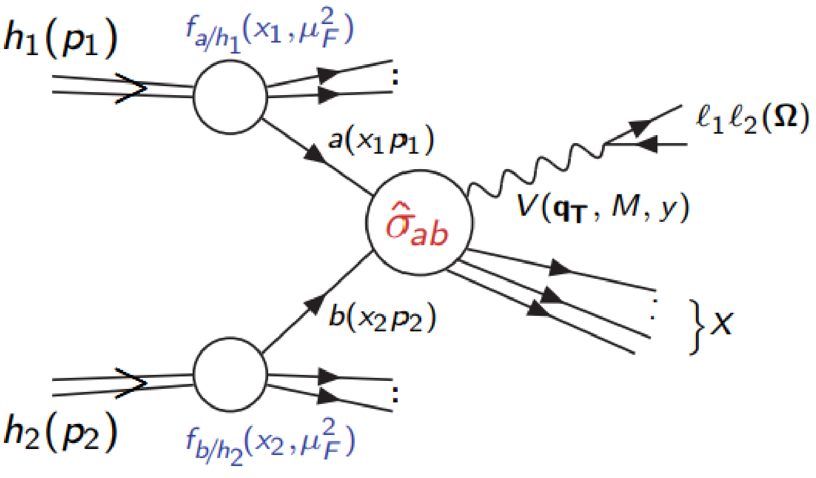
PDFs
(non-perturbative)

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:

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

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



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

Computational framework

- Soft gluon/photon radiation could provide non-negligible effects in the low q_T region → **Extend qt-resummation to deal with QCD-QED radiation!**
- Some formulae to introduce qt-resummation in QCD:
  - The singular (i.e. divergent) part has an universal structure:

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

$$\times\sum_{a_1,a_2}\int_{x_1}^{1}\frac{dz_1}{z_1}\int_{x_2}^{1}\frac{dz_2}{z_2}\left[H^F C_1 C_2\right]_{c\bar{c};a_1a_2} f_{a_1/h_1}(x_1/z_1,b_0^2/b^2)\,f_{a_2/h_2}(x_2/z_2,b_0^2/b^2)$$

  - 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

Computational framework

- **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]

Including 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 non-trivial mixing)***

Based on standard methods:
DREG regulated amplitudes and
pole subtraction

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…

  SOLVED!

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

Mixed QCD-QED resummation

Required ingredients: 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:**

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

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

QCD and QED couplings are not independent! Important to develop a consistent framework

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

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

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

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

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

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 QED part

Pure QCD

Mixed QCD-QED

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

Mixed QCD-QED resummation

Abelianization of the qt-formalism

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

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

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

Pure QED

Pure QCD

(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!!!

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

$$g'^{(2)}_N(\alpha L) = \frac{\widetilde{B}'^{(1)}_{q,N}}{\beta'_0}\ln(1-\lambda') - \frac{A'^{(2)}_q}{\beta'^2_0}\left(\frac{\lambda'}{1-\lambda'} + \ln(1-\lambda')\right)$$
$$+\,\frac{A'^{(1)}_q\beta'_1}{\beta'^3_0}\left(\frac{1}{2}\ln^2(1-\lambda') + \frac{\ln(1-\lambda')}{1-\lambda'} + \frac{\lambda'}{1-\lambda'}\right)$$

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

Mixed QCD-QED resummation

Abelianization of the qt-formalism

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

$$\boxed{g'^{(1,1)}(\alpha_S L, \alpha L) = \frac{A_q^{(1)}\,\beta_{0,1}}{\beta_0^2\,\beta'_0}\,h(\lambda,\lambda') + \frac{A_q'^{(1)}\,\beta'_{0,1}}{\beta_0'^2\,\beta_0}\,h(\lambda',\lambda)}$$

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

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

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

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

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

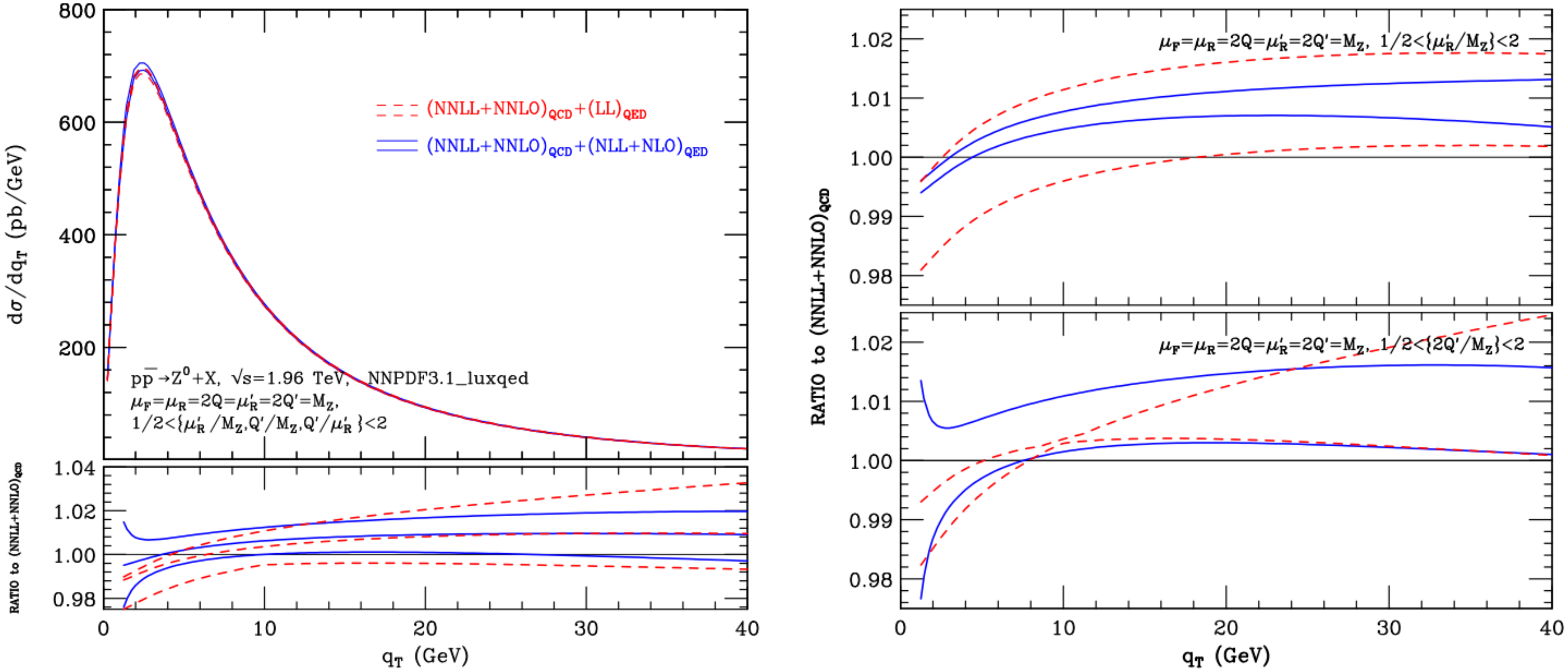
$$\mathcal{H}_{q\bar{q}\leftarrow q\bar{q},N}'^{F\,(1)} = \frac{e_q^2}{2}\left(\frac{2}{N(N+1)} - 8 + \pi^2\right)$$
$$\mathcal{H}_{q\bar{q}\leftarrow \gamma q,N}'^{F\,(1)} = \mathcal{H}_{q\bar{q}\leftarrow q\gamma,N}'^{F\,(1)} = \frac{3\,e_q^2}{(N+1)(N+2)}$$
$$\mathcal{H}_{q\bar{q}\leftarrow \gamma\gamma,N}'^{F\,(1)} = \mathcal{H}_{q\bar{q}\leftarrow qq,N}'^{F\,(1)} = \mathcal{H}_{q\bar{q}\leftarrow \bar{q}\bar{q},N}'^{F\,(1)} = 0$$

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. NNPDF3.1QED (uses LUX's method)

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

Z production with *mixed NLL QED*

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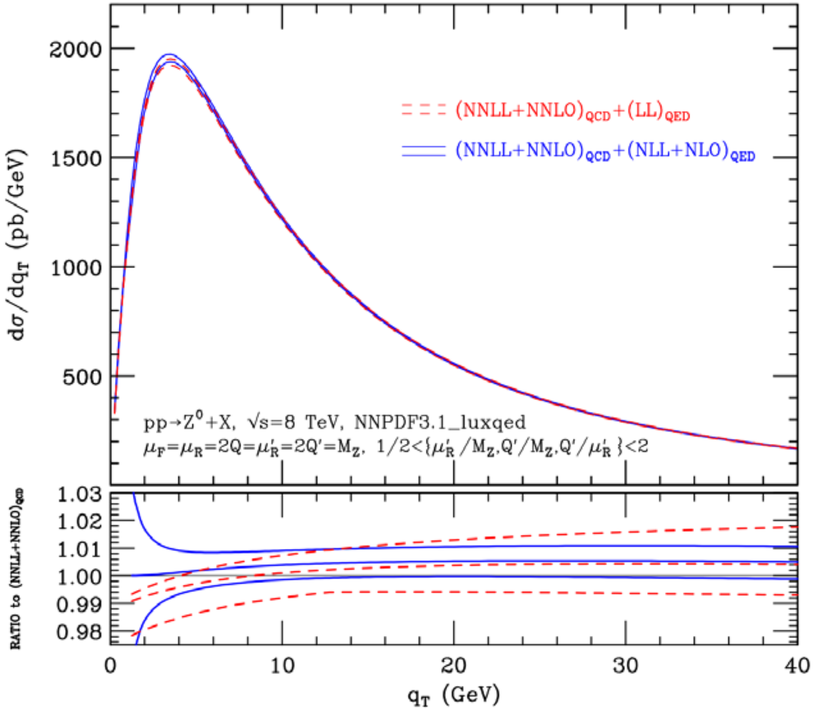

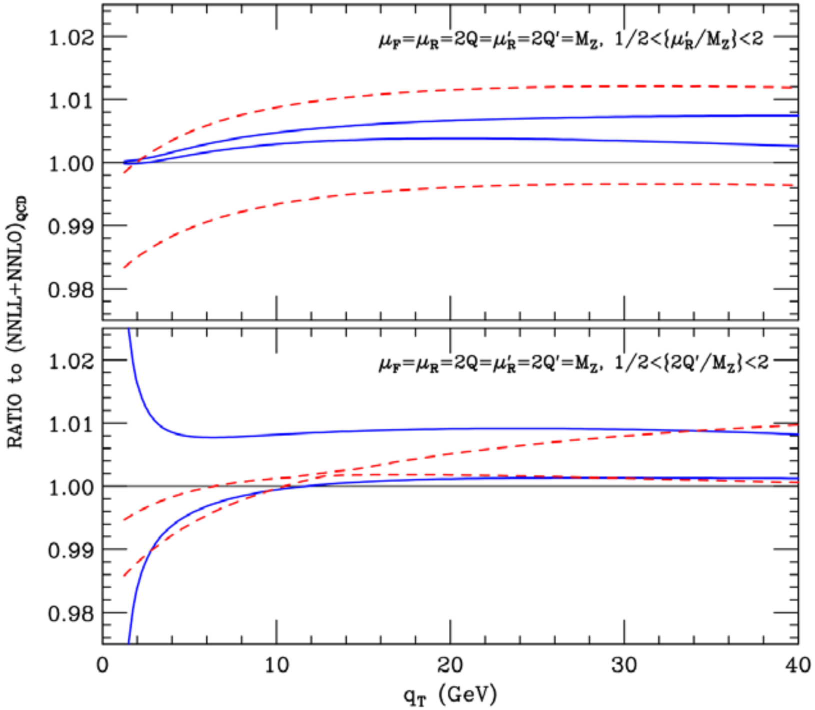

  - Collider: LHC at 8 TeV
  - Z production, using the narrow with approximation, with NNLL + NNLO QCD as reference to compare the QED effects. NNPDF3.1QED (uses LUX's method)

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

Z production with *mixed NLL QED*

Some plots

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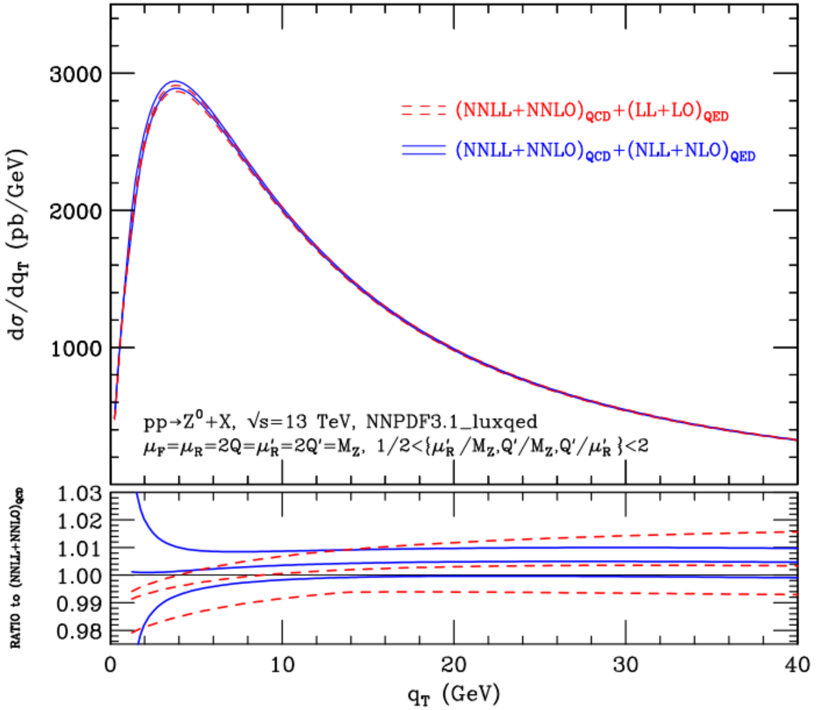
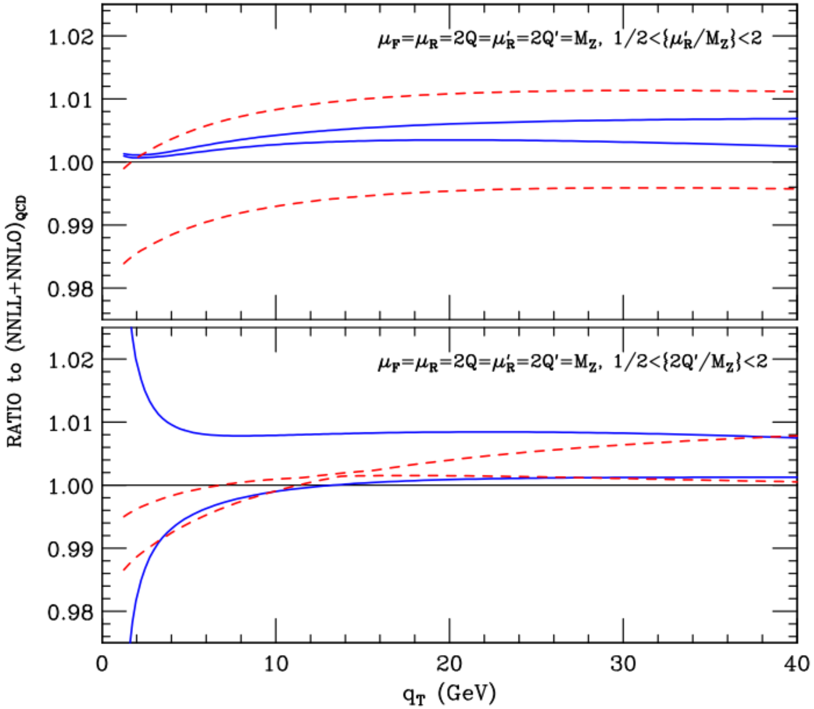




- Collider: LHC at 13 TeV
- Z production, using the narrow with approximation, with NNLL + NNLO QCD as reference to compare the QED effects. NNPDF3.1QED (uses LUX's method)

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

Mixed H.O. corrections within LTD

- **I)- Using LTD to develop a numerical, fully-local and four-dimensional framework for QFT**
- **II)- Application to Higgs decays into photons/gluons (1-loop & 2-loop!)**

Radically new approach:
fully local and four-dimensional framework

About LTD/FDU formalism

What is this? Why we need this?

- **Available techniques are facing several bottlenecks:**
    - **Virtual corrections beyond NNLO (masses, kinematics, thresholds)**
    - Presence of IR/UV singularities, not direct numerical implementation
    - Theoretical issues with DREG at higher-orders
    - Non-local approaches for cancellation of singularities → **Not efficient!**

- Alternatives are starting to pop-up… **LTD is our proposal**
    - **Short description: "Open loops into trees"**
    - **Purpose: "Express loops as Euclidean integrals, and combine them with real terms/local UV counter-terms"**

More details:

→ **Selomit's talk (multiloop computations)**

→ **Jesús's talk (singular structures and thresholds)**

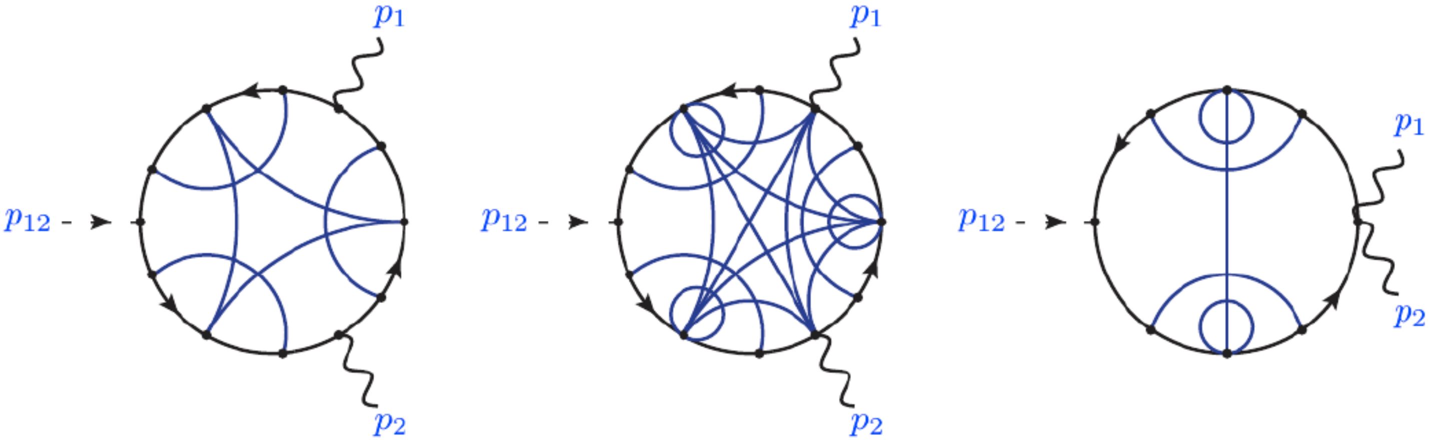
Higgs decays within LTD

Non-mixed QCD/QED corrections

- **Previous results: Higgs decay @ 1-loop within LTD formalism**

Driencourt-Mangin, Rodrigo, GS, EPJ C78 (2018) no.3, 231
Driencourt-Mangin, PhD. Thesis, arXiv:1907.12450 [hep-ph]

- **"Non-mixed QED" corrections at 2-loops**



  - 12 diagrams with internal top-quark; 37 diagrams with internal charged-scalar particles (toy-model)

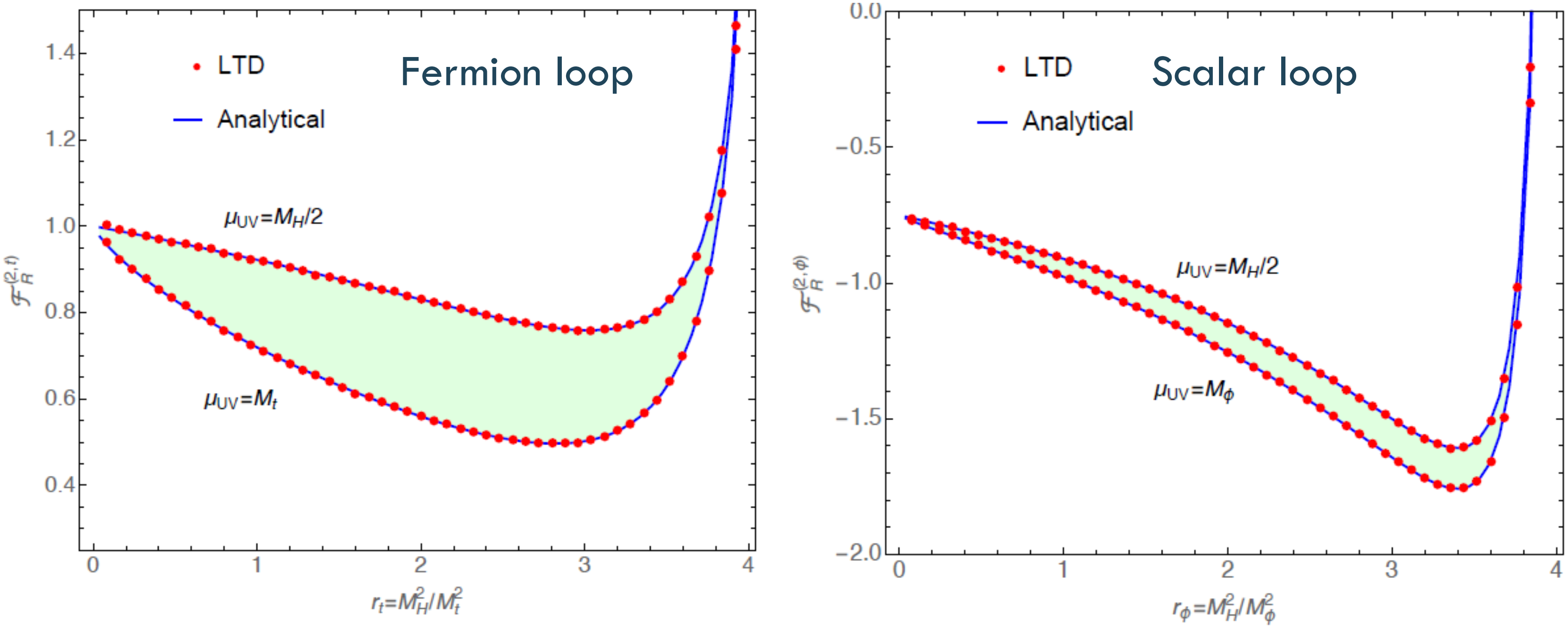
Driencourt-Mangin, Rodrigo, GS, Torres Bobadilla, JHEP 02 (2019) 143

Higgs decays within LTD

Higgs to diphoton decay @ 2-loops

- **Features of the computation**
  - Amplitude is UV/IR finite, **BUT still requires regularization**
  - LTD provides **fully local** regularization → Direct numerical implementation!
  - Automatized algorithm for local 2-loop renormalization

EXCELLENT AGREEMENT WITH KNOWN RESULTS!



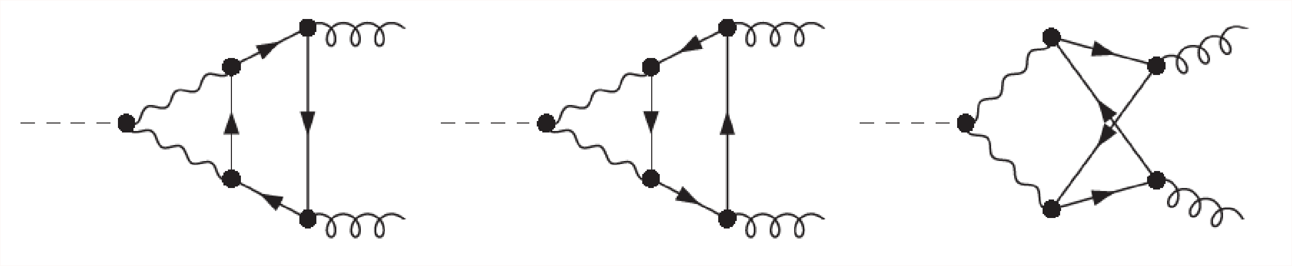
Driencourt-Mangin, Rodrigo, GS, Torres Bobadilla, JHEP 02 (2019) 143

Higgs decays within LTD

Higgs to di-gluon decay @ 2-loops

PRELIMINAR RESULTS, still under investigation!!!

- **Computation of mixed EW-QCD corrections to H->gg at 2-loops**
  - **Three master diagrams**



  - **Application of spin-helicity formalism + LTD**

    Driencourt-Mangin, Rodrigo, GS, Torres Bobadilla, arXiv:1911.11125 [hep-ph]

  - **Need for local renormalization (even if results are IR/UV finite)**

  - ***Partial checks I:*** *fermion mass to zero, we reproduce known results*

    Aglietti, Bonciani, Degrassi, Vicini, Phys.Lett.B 595 (2004) 432

  - ***Partial checks II:*** *massive fermions, below threshold configurations*
  - *Still some (minor) numerical issues*

Driencourt-Mangin, Rodrigo, GS, Torres Bobadilla, in preparation

Conclusions

- ✓ *EW corrections are crucial within the precision program*
- ✓ *Relevance from the experimental/phenomenological/theoretical side!!!*
- ✓ **Part 1:** EW-QCD corrections within qt-subtraction
  - ✓ Efficient method to compute H.O. for DY
  - ✓ Mixed resummation applied to Z production (uses a **new formalism**)
- ✓ **Part 2:** EW-QCD effects through the LTD-based approach
  - ✓ Fully **local cancellation** of IR/UV singularities
  - ✓ Purely **four-dimensional implementation**
  - ✓ DREG results successfully recovered for Higgs decays
  - ✓ **Advantage: improved numerical efficiency**