Workshop on Forward Physics and QCD with LHC, EIC, and Cosmic Rays

To be submitted to PRD

Non-elastic contributions for the production of high-mass pairs

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Outline

- Overview on photon collisions at the LHC
  - Elastic dilepton production
  - Non-elastic events at high masses
- Photon luminosities for elastic and non-elastic interactions
  - Effect of photon fluxes and QED PDFs
- High-mass pair production
  - Production cross sections for dimuons and WW
- Fudge factor predictions as a ratio of photon luminosities
  - Addressing uncertainties from different emissions

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Photon collisions at the LHC

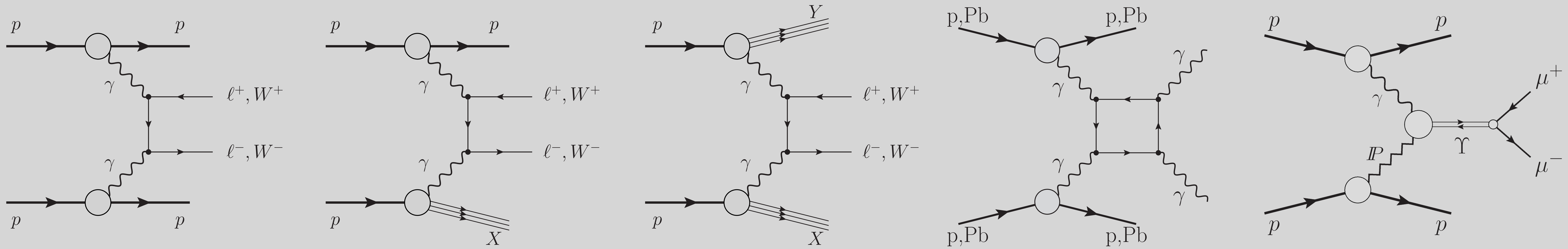
- The kinematic region accessed by the LHC has raised the interest on the **electromagnetic production** of resonances and pairs during the past years;

    1. Exclusive **dilepton** production
    [CMS-FWD-10-005, CMS-FWD-11-004, CMS-FSQ-12-010, ATLAS-2015, ATLAS-2017, ATLAS-2019]

    2. **Vector meson** photoproduction
    [CMS-FSQ-13-009, CMS-FSQ-16-007, ALICE-2014, ALICE-2019, LHCb-2012-044, LHCb-2015-011, LHCb-2018-011]

    3. Exclusive **diboson** production [CMS-FSQ-12-010, CMS-FSQ-13-008, ATLAS-2016, ATLAS-2020]

- This opens the possibility to investigate the **photon content** of the proton at higher energies;



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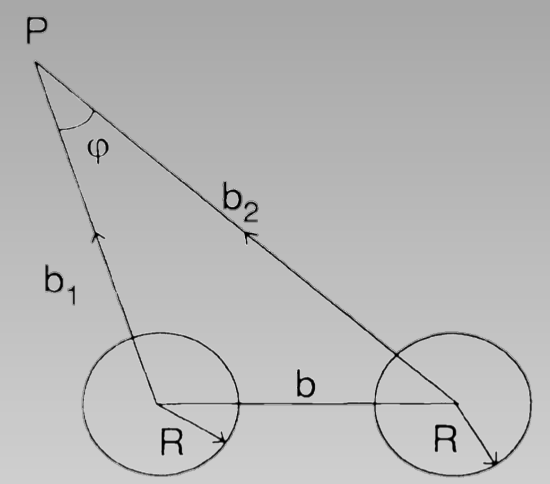
Dileptons in elastic collisions

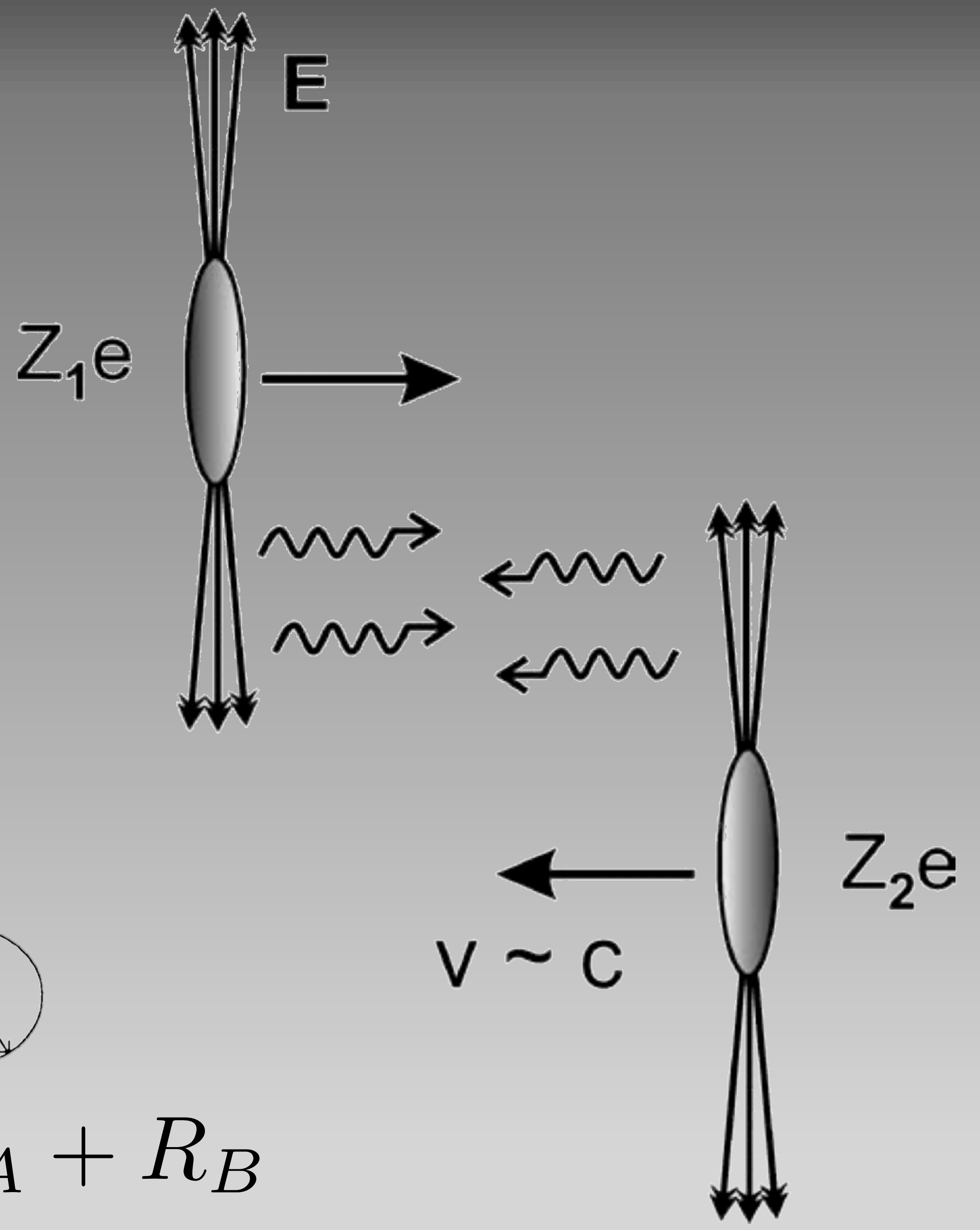
- Given the high energy beams with charged particles, protons and Lead nuclei can be taken as **photon sources** for particle scattering;

- The total cross section for the 2-photon fusion mechanism is factorized using the **Weizsäcker-Williams or Equivalent Photon Approximation (EPA)**: Budnev *et al*, PhysRept 15 (1975) 181

$$\sigma_{\rm tot}(s) = \int\int dx_1\, dx_2\, f^{\gamma}_{h_1}(x_1) f^{\gamma}_{h_2}(x_2) \hat{\sigma}_{\gamma\gamma\to X}(x_1 x_2 s)$$



$$|\vec{b}_1 - \vec{b}_2| > R_A + R_B$$



Bertulani, Klein, Nystrand, *Ann. Rev. Nucl. Part. Sci.* **55** (2005) 271

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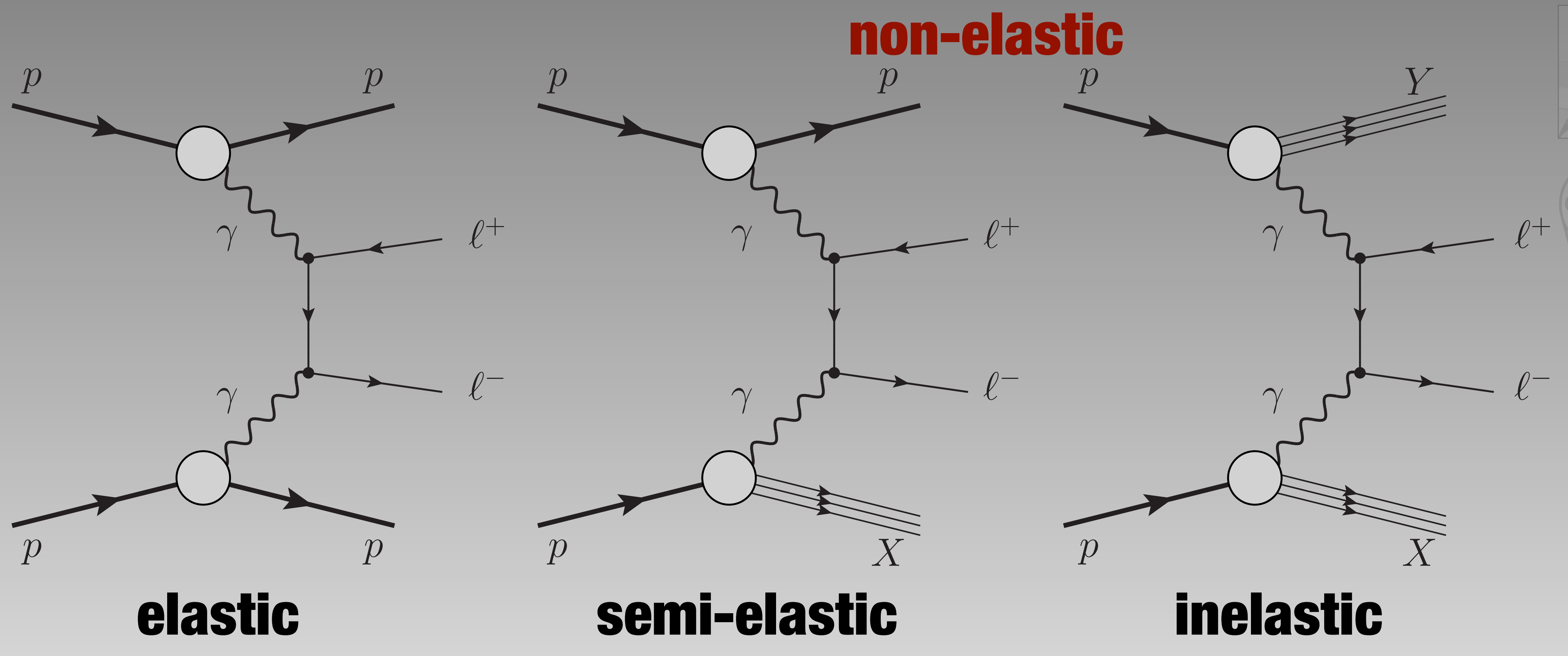
- First results by CMS for the production of dielectrons and dimuons show **good agreement** with event generators for elastic and non-elastic contributions. CMS-FWD-10-005 CMS-FWD-11-004

  - Latest results covering a larger invariant mass window have shown that the predictions are **overshooting** the data (possibly for re-scattering effects as a survival factor). GGS *et al*, JHEP 02 (2015) 159

- ATLAS results have shown **good** agreement with other event generators. ATLAS-2015 ATLAS-2020

Constraints on the ratio to elastic events

- Dimuon events can be used to quantify the **non-elastic to elastic** contribution;
- Events with proton dissociation have very distinct kinematical distribution compared to elastic events;
- CMS has been studying this aspect at higher invariant masses given the **lack of MC generators** with non-elastic contribution:



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F factor

$$F_{2011} = \left.\frac{N_{\mu\mu(\text{data})} - N_{\text{DY}}}{N_{\text{elastic}}}\right|_{M(\mu^+\mu^-)>160\text{ GeV}} = 3.52 \pm 0.1,$$ **CMS-FSQ-12-010**

$$F_{2012} = \left.\frac{N_{\mu\mu(\text{data})} - N_{\text{DY}}}{N_{\text{elastic}}}\right|_{M(\mu^+\mu^-)>160\text{ GeV}} = 4.85 \pm 0.2,$$ **CMS-FSQ-13-008**

- The ratio of non-elastic to elastic contributions is relevant to **constraint** photon PDFs at all ranges in Bjorken *x* and Q^2.

VP Gonçalves, GGS
PRD 91 (2015) 054013

GGS, VP Gonçalves,
PRD 92 (2015) 014013

Production of photon pairs

- The contribution of W loops in the light by light scattering starts to dominate above invariant masses of **~200 GeV**;

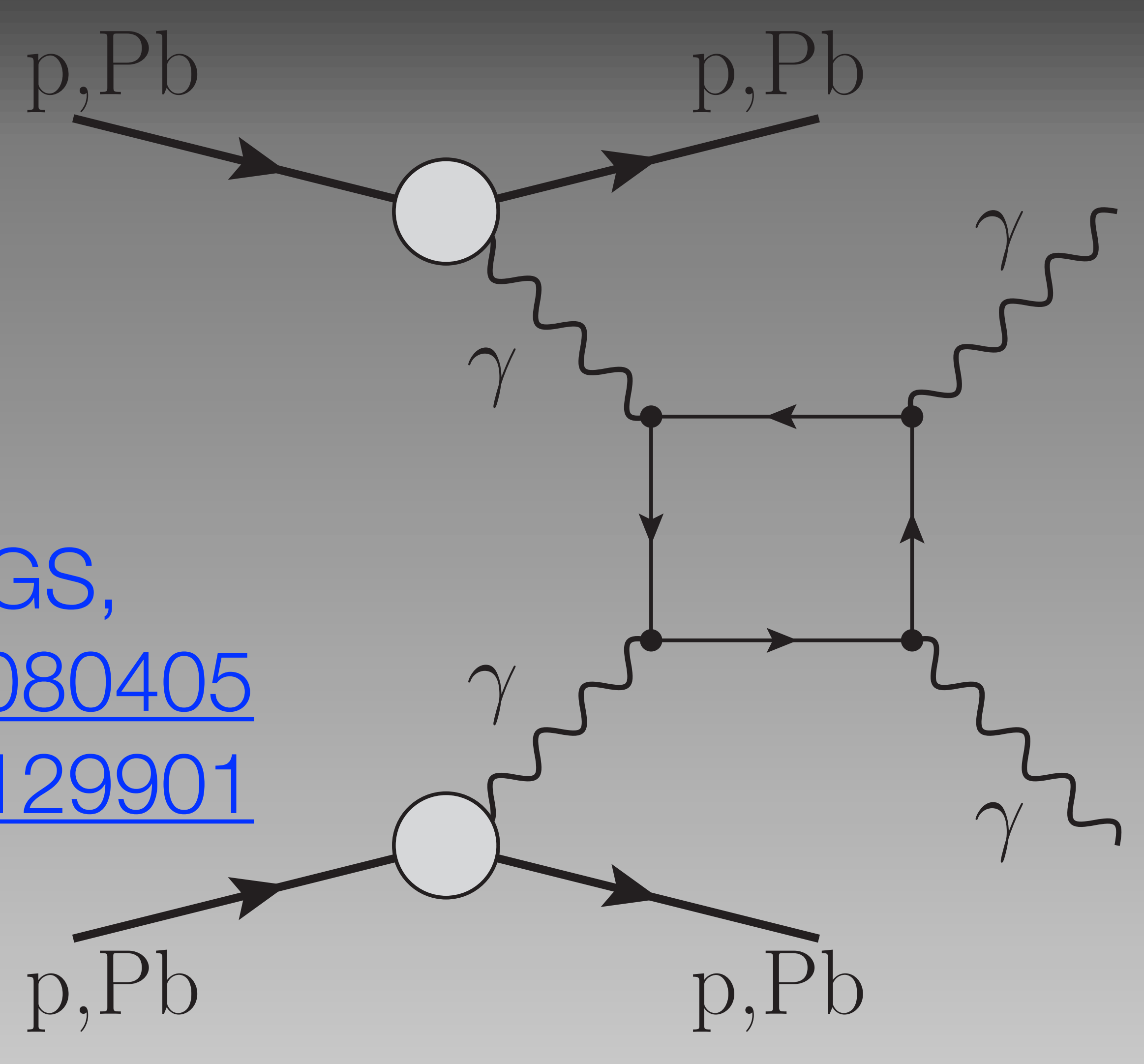
  Goncalves *et al*, PRD 102 (2020) 074014

  Fichet *et al*, JHEP 02 (2015) 165

  - Pb-Pb collisions favours the search for **SM** light by light scattering;

  - *p-p* collisions reach higher γγ c.m. energies to produce high-mass pairs.

D'Enterria, GGS,
PRL 111 (2013) 080405
PRL 116 (2016) 129901



Fichet *et al*, JHEP 02 (2015) 165

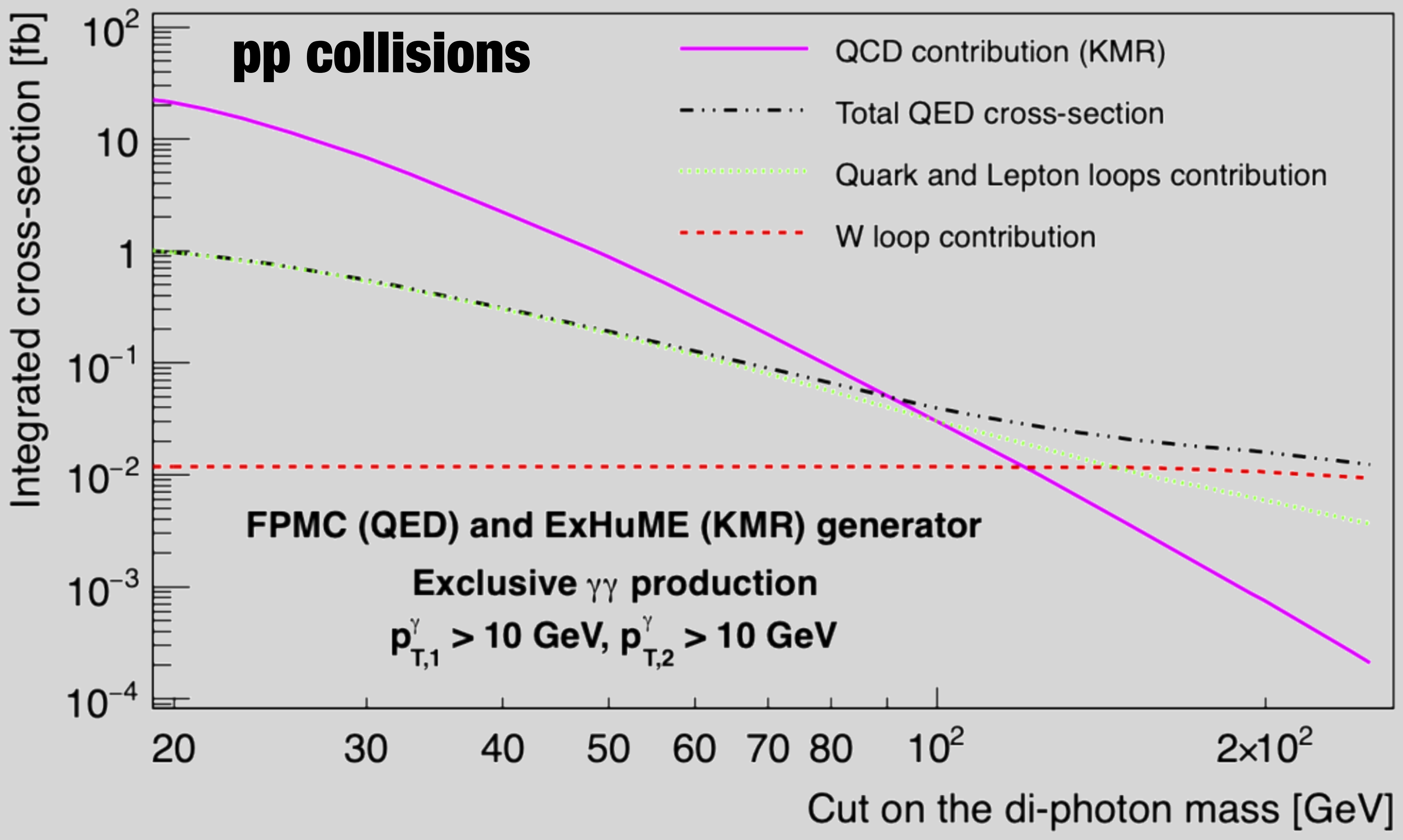
- The high-mass region is the main focus for searches of New Physics;

Goncalves, Moreira
2101.03798

CMS Collaboration
CMS-EXO-18-014

Goncalves, Moreira
PLB 808 (2020) 135635

Baldenegro *et al*
2010.07855



Fichet *et al*, JHEP **02** (2015) 165

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Motivation

Snowmass 2021 LoI

- Clarify the **luminosities** for non-elastic interactions on the production of high-mass pairs; 2009.03838
  - Parton distribution function with QED contributions should be addressed in order to test the relation between elastic and non-elastic predictions.
- Quantify the contributions to be tested at the LHC kinematic regime, especially with the current **forward detectors** of CMS and ATLAS experiments;

GGS, VP Gonçalves, PRD 91 (2015) 054013

- Extract a **global** *F* factor to provide the non-elastic contribution in the production of high-mass pairs;

$$F = \frac{\sigma^{\text{el}} + \sigma^{\text{semi}} + \sigma^{\text{inel}}}{\sigma^{\text{el}}}, \quad F = \frac{\sigma^{\text{el}} + \sigma^{\text{semi}}}{\sigma^{\text{el}}}$$

  - Signal processes are exclusive $\mu^+\mu^-$ and W^+W^- productions given their well-known production cross sections;

$$\sigma(pp \to (\gamma\gamma) \to x^+x^-) = S^2_\gamma \int_0^1 \int_{\frac{4m^2}{x_1 s}}^1 f_{\gamma,1}(x_1, Q^2) f_{\gamma;2}(x_2; Q^2) \hat{\sigma}(\gamma\gamma \to x^+x^-) dx_1 dx_2$$

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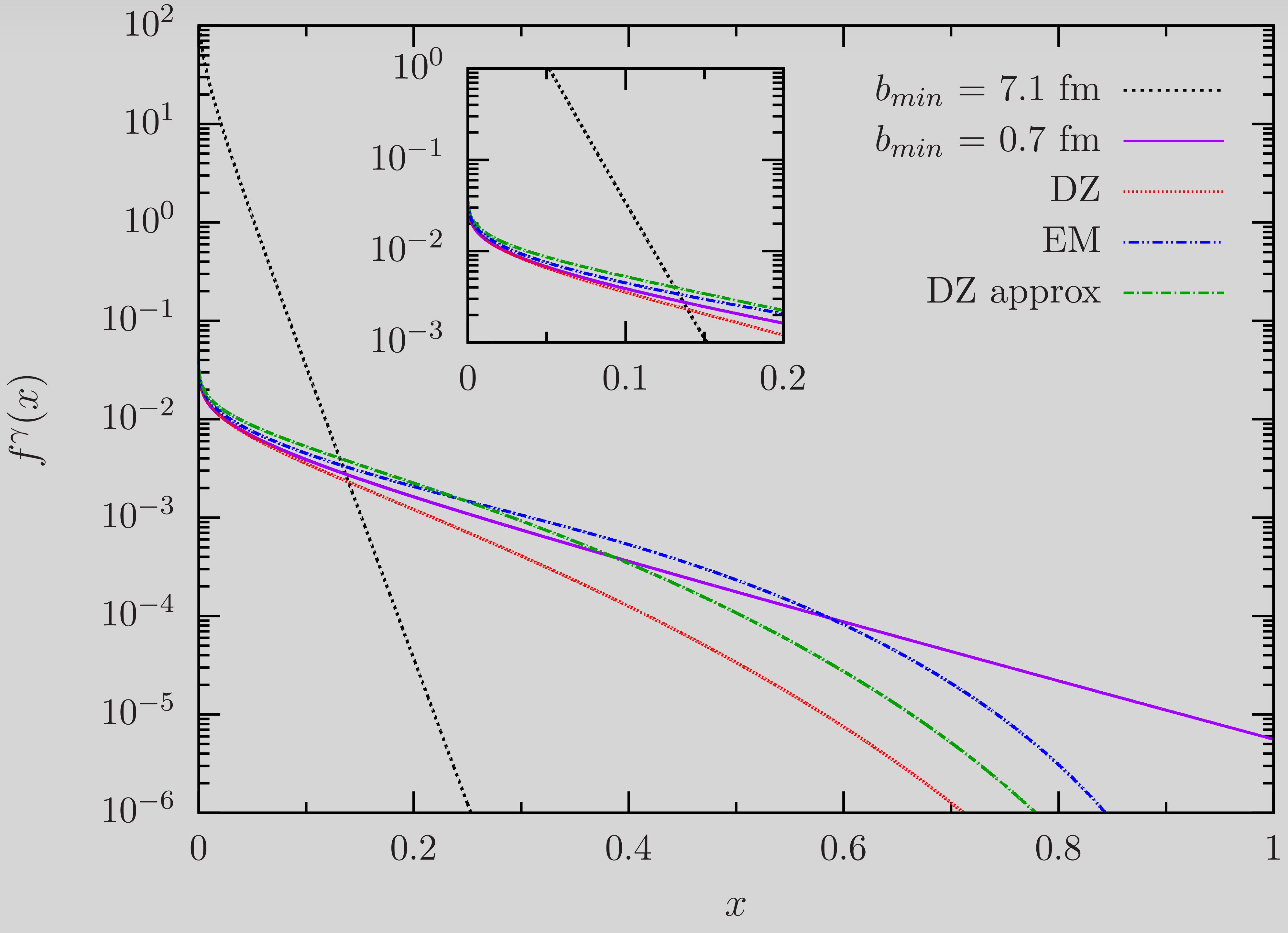
Elastic photon fluxes

- The photon emission based on the EPA are written based on approaches for both **electric** and **magnetic** modes of the proton electromagnetic form factors:
  - Drees-Zeppenfeld (electric mode only): PRD 39 (1989) 2536
    $$f_\gamma^{\rm el}(x) = \left(\frac{\alpha}{\pi}\frac{1-x+0.5x^2}{x}\right)\left(\ln A - \frac{11}{6} - \frac{3}{A} + \frac{3}{2A^2} + \frac{1}{3A^3}\right)$$
  - Approximate DZ: $\frac{Q^2 - Q^2_{\rm min}}{Q^4} \approx \frac{1}{Q^2}$
    $$f_\gamma^{\rm el}(x) = \left(\frac{\alpha}{\pi}\frac{1-x+0.5x^2}{x}\right)\left(\frac{A+3}{A-1}\ln A - \frac{17}{6} - \frac{4}{3A} + \frac{1}{6A^2}\right)$$
  - Kniehl (electric and magnetic modes): PLB 254 (1991) 267
    $$f_\gamma^{\rm el}(x) = \frac{\alpha}{2\pi}\int_{Q^2_{\rm min}}^{\infty}\frac{dQ^2}{Q^2}\left\{2\left[\frac{1}{x}\left(\frac{1}{x}-1\right)+\frac{m_p^2}{Q^2}\right]H_1(Q^2) + H_2(Q^2)\right\}$$
    $$H_1(Q^2) = \frac{G_E^2(Q^2) + \frac{Q^2}{4m_p}G_M^2(Q^2)}{1+\frac{Q^2}{4m_p}}, \qquad H_2(Q^2) = G_M^2(Q^2).$$
  - Comparison with ion source case:
    $$f_\gamma^{\rm el}(x) = \frac{Z^2\alpha}{\pi x}\left\{2\xi K_0(\xi)K_1(\xi) - \xi^2\left[K_1^2(\xi) - K_0^2(\xi)\right]\right\}$$



Cahn, Jackson, PRD 42 (1990) 3690 Muller, Schramm, PRD 42 (1990) 3699

Photon luminosities

- The photon fluxes play a central role in this investigation given that the partonic cross section **cancel out** in the *F* factor ratio;

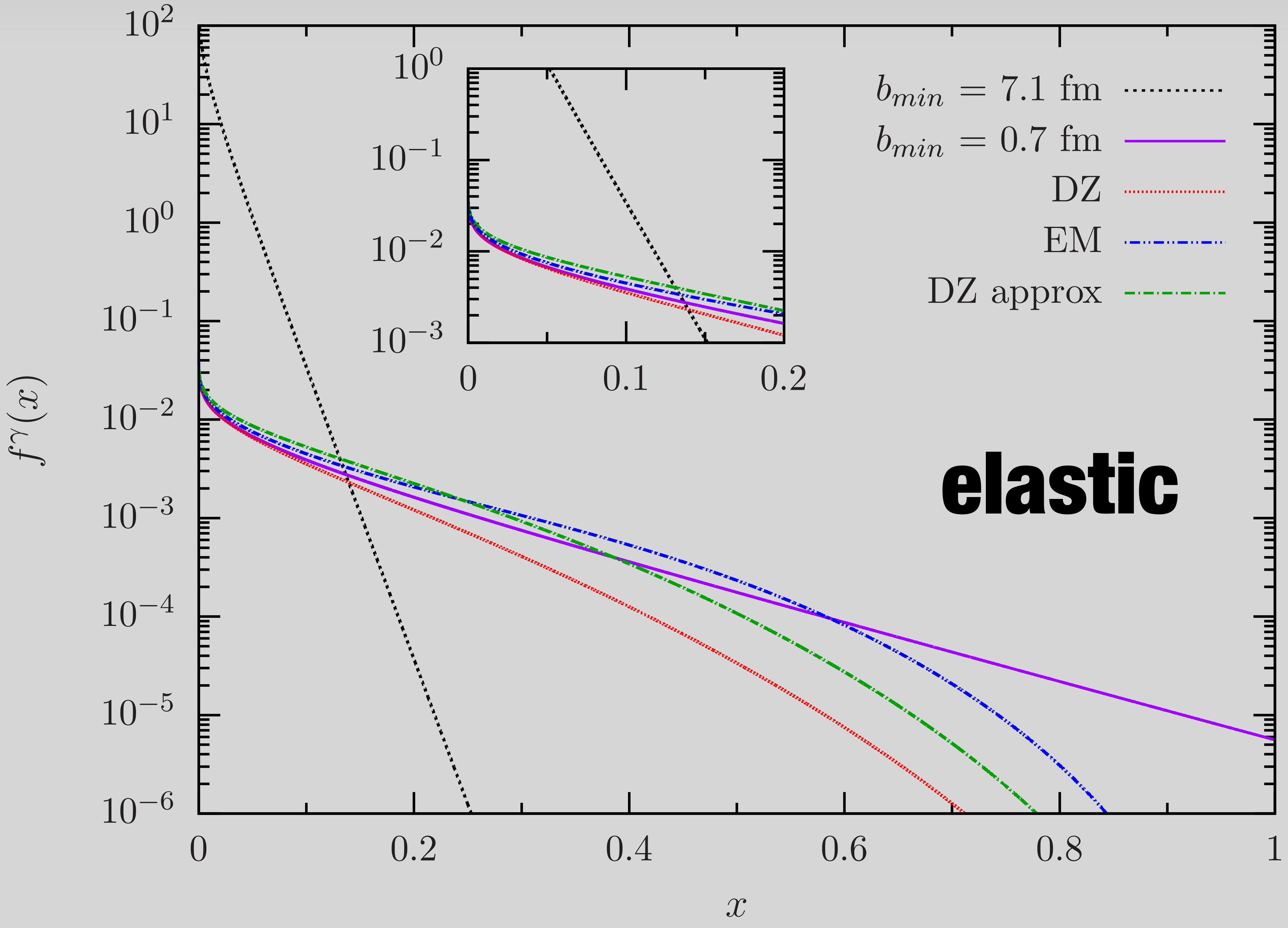
$$\mathcal{L}^{\rm el} \sim x_1 f^{\rm el}_{\gamma,1}(x_1;Q^2) x_2 f^{\rm el}_{\gamma,2}(x_2;Q^2),$$

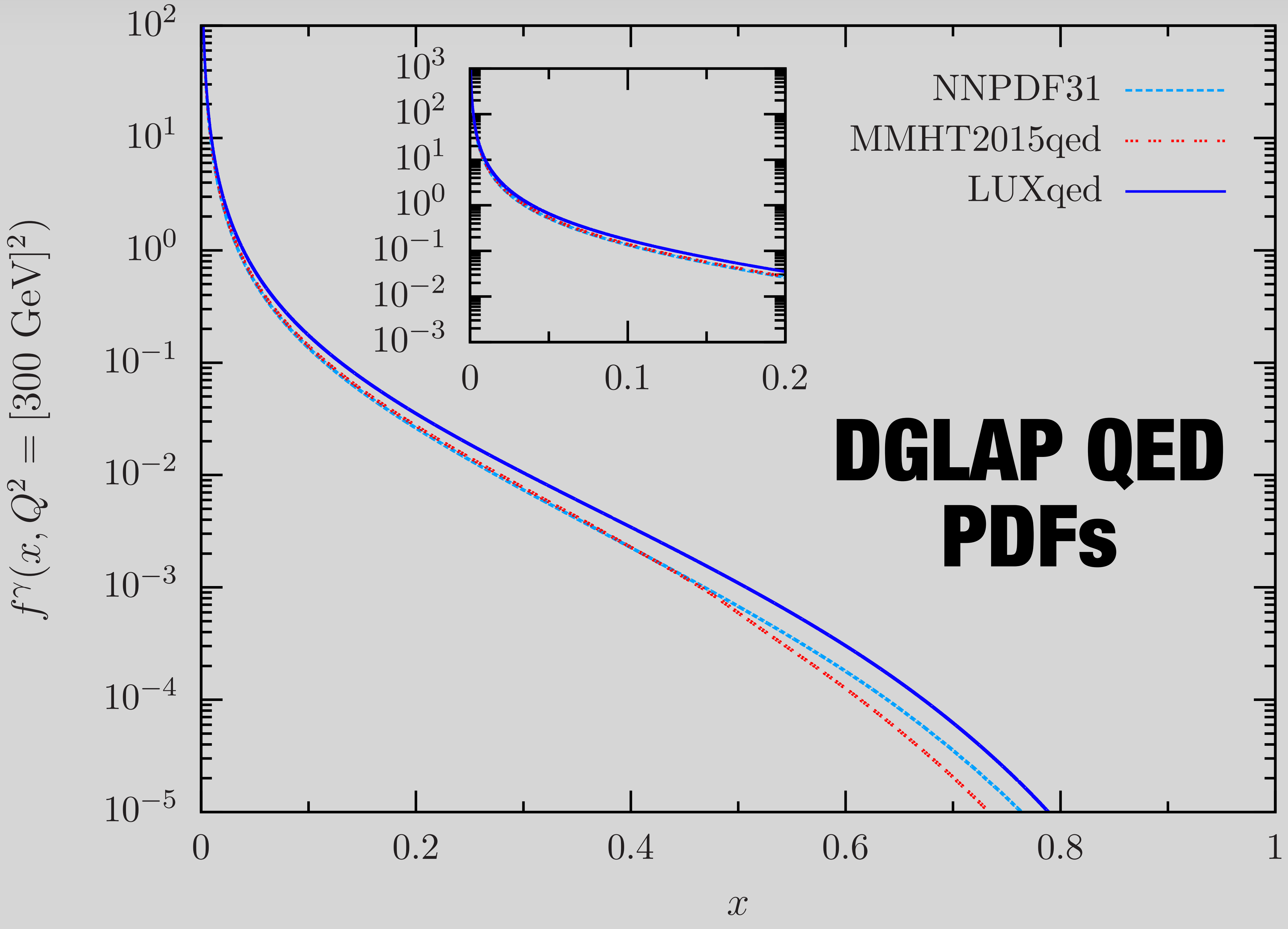
$$\mathcal{L}^{\rm semi} \sim x_1 f^{\rm PDF}_{\gamma,1}(x_1;Q^2) x_2 f^{\rm el}_{\gamma,2}(x_2;Q^2) + x_1 f^{\rm el}_{\gamma,1}(x_1;Q^2) x_2 f^{\rm PDF}_{\gamma,2}(x_2;Q^2),$$

$$\mathcal{L}^{\rm inel} \sim x_1 f^{\rm PDF}_{\gamma,1}(x_1;Q^2) x_2 f^{\rm PDF}_{\gamma,2}(x_2;Q^2),$$

- Elastic and non-elastic contributions are accounted in a set of luminosities for:

$$\sigma = \mathcal{L}(M^2, Y; Q^2)\hat{\sigma}(M^2_{\gamma\gamma})$$





Elastic QED PDF removed if present

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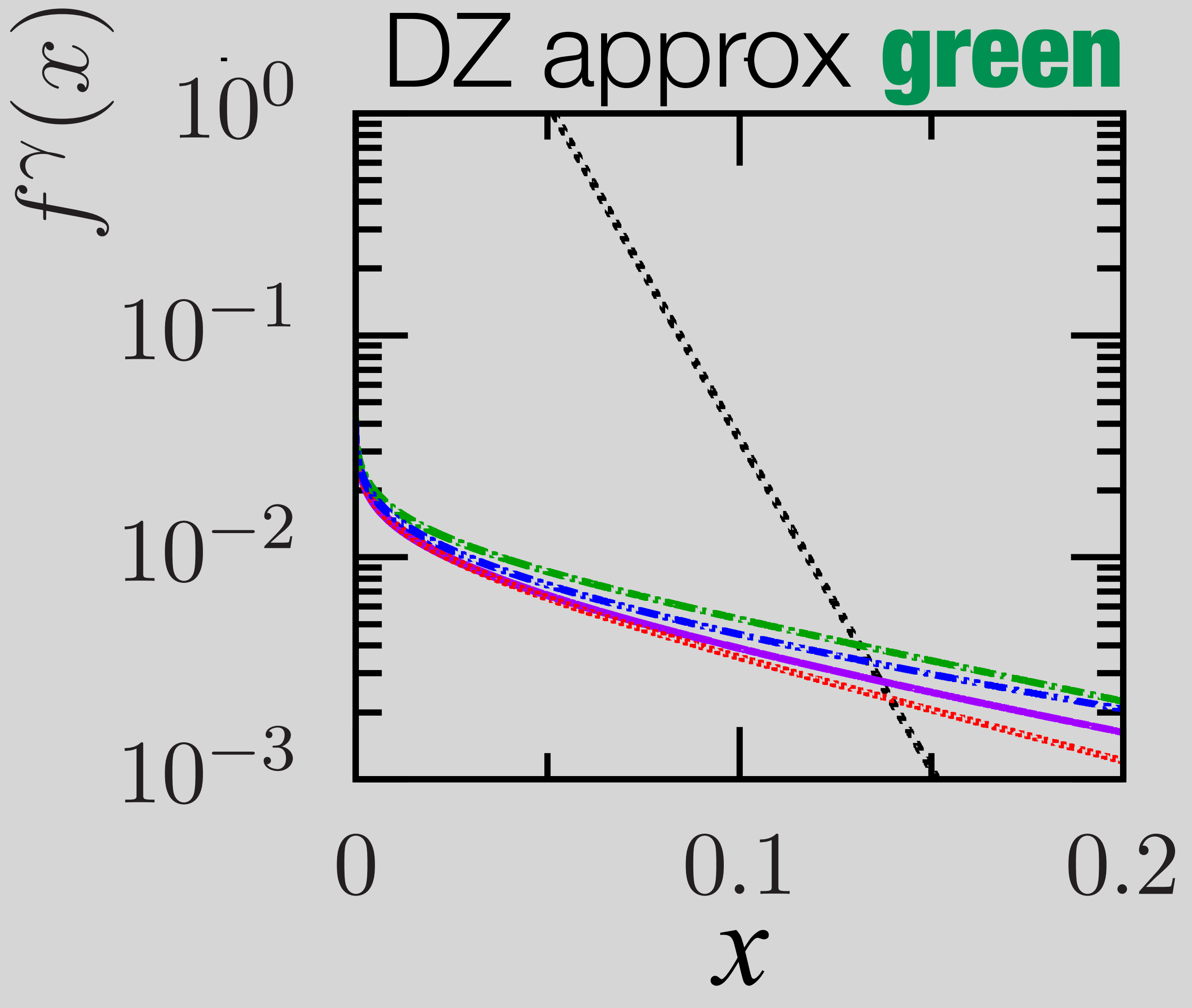
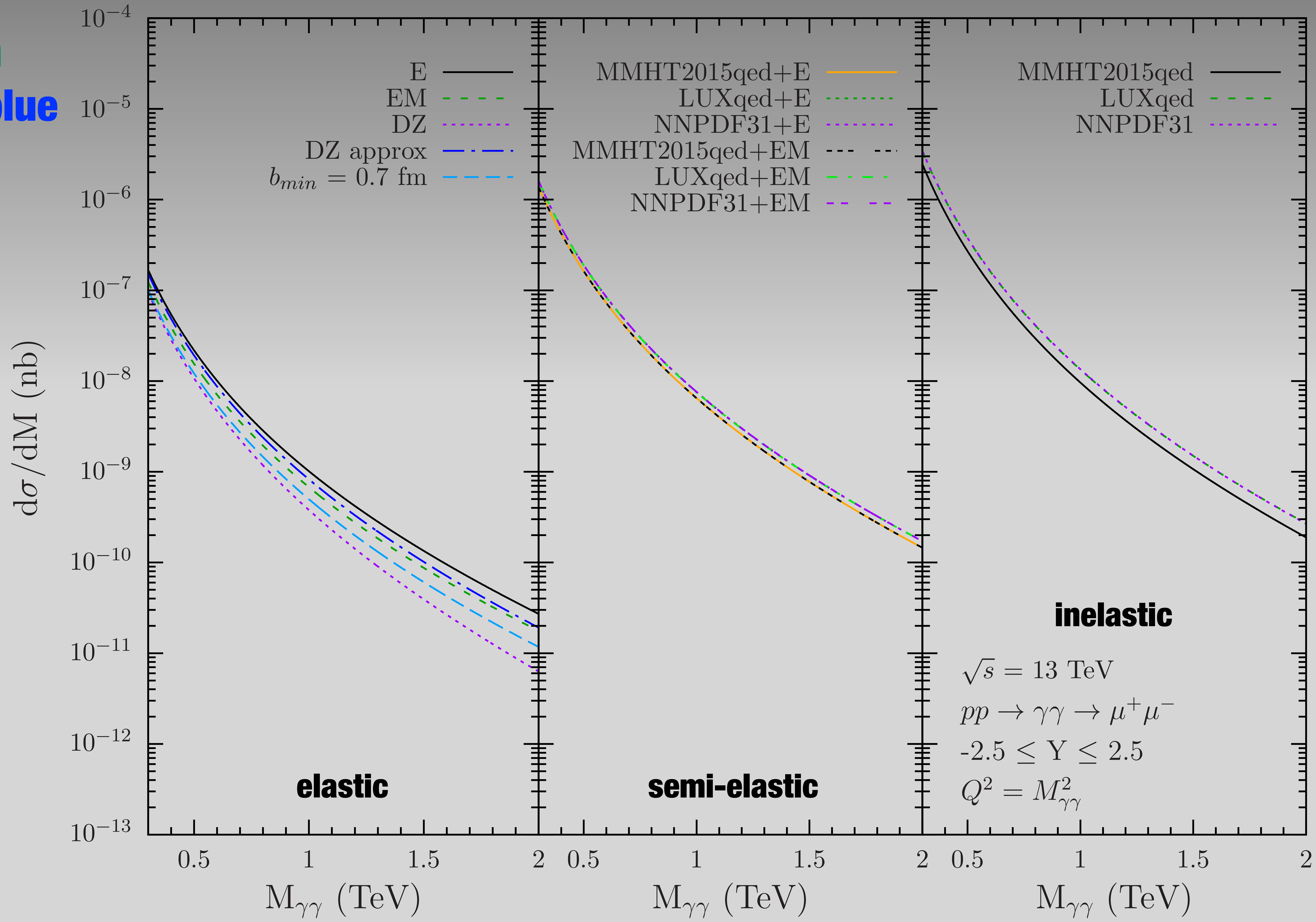
Production cross sections at the LHC

EM **green**
DZ approx **blue**

EM **blue**
DZ approx **green**





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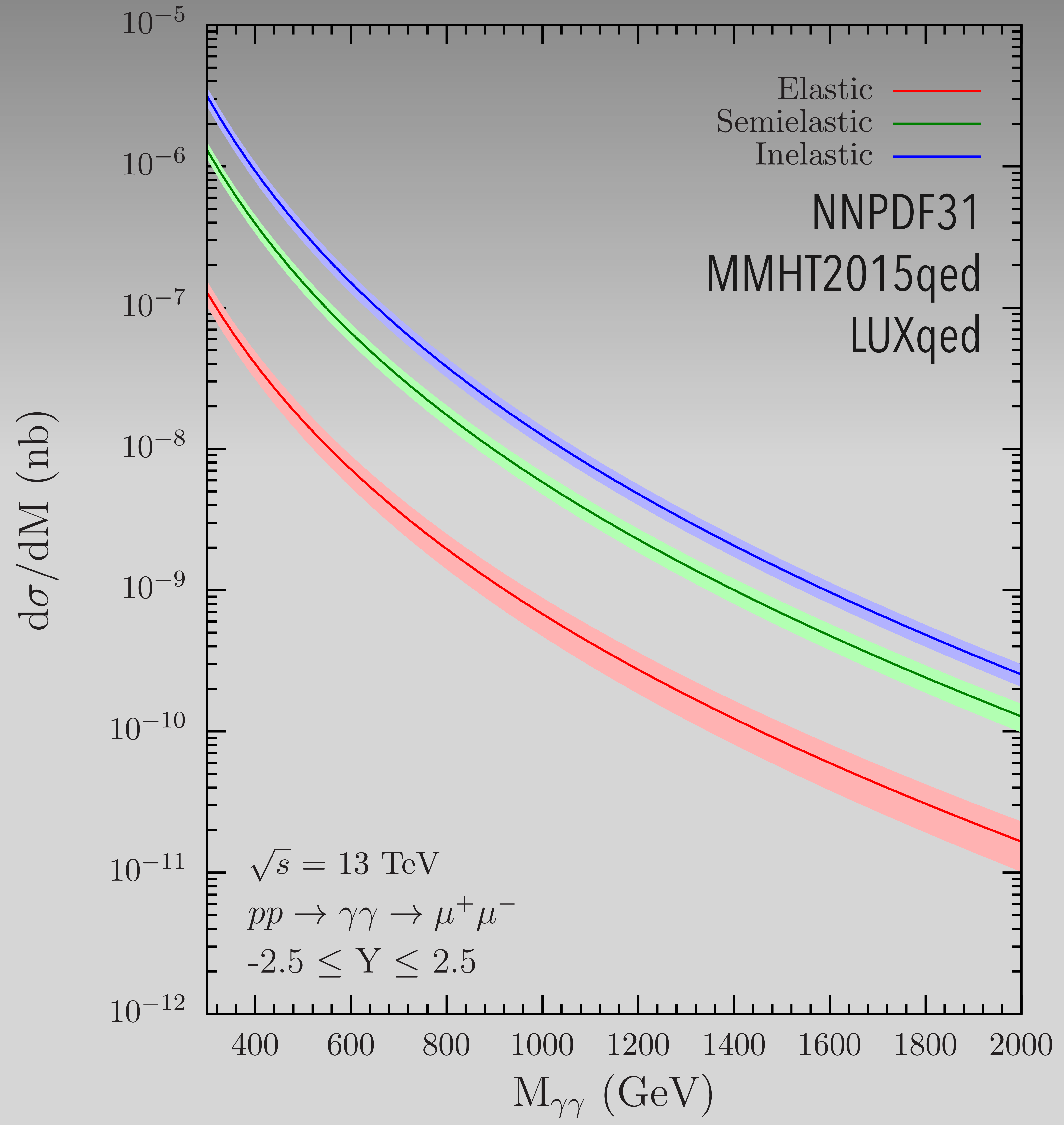
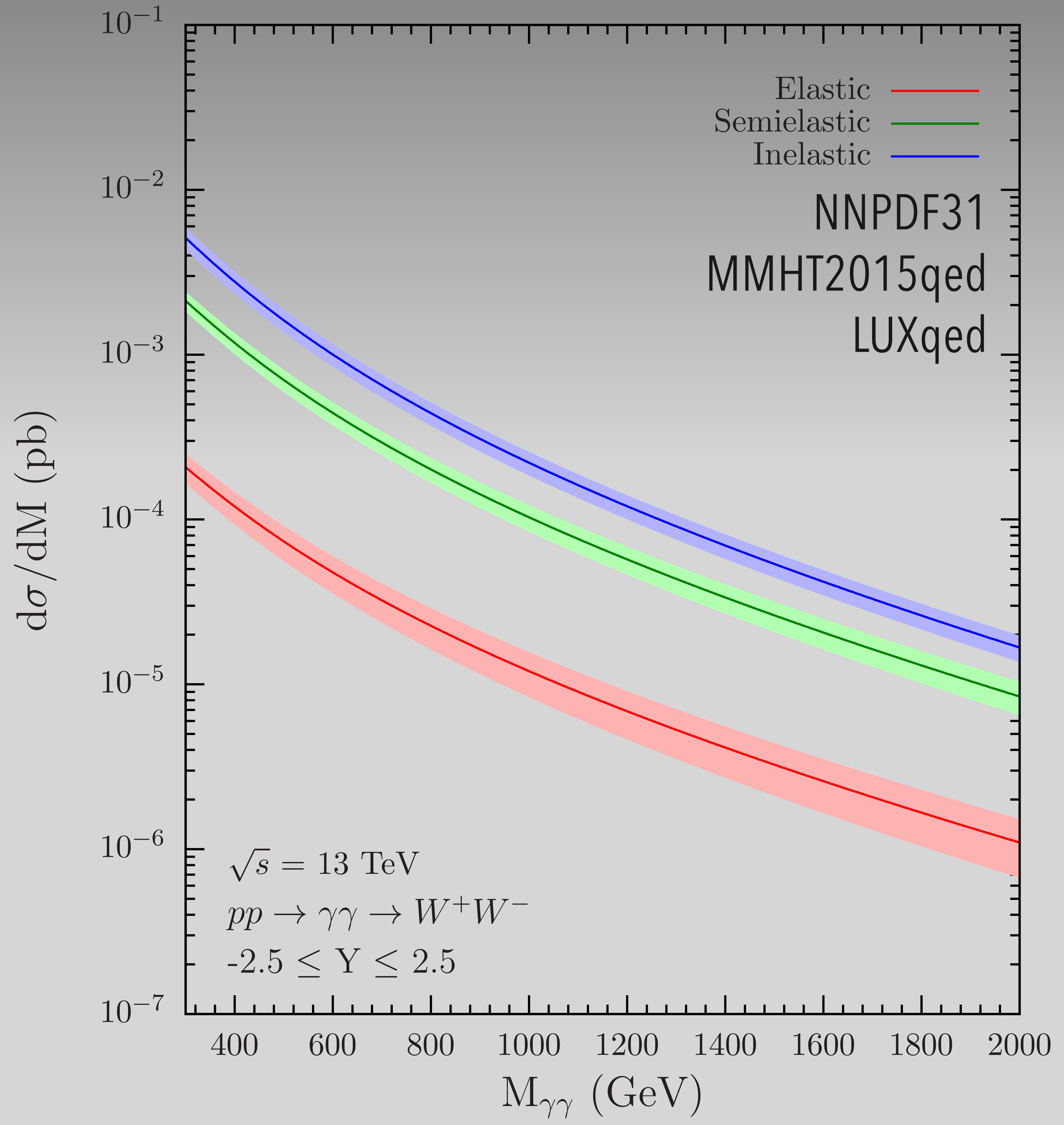
Size of non-elastic contributions





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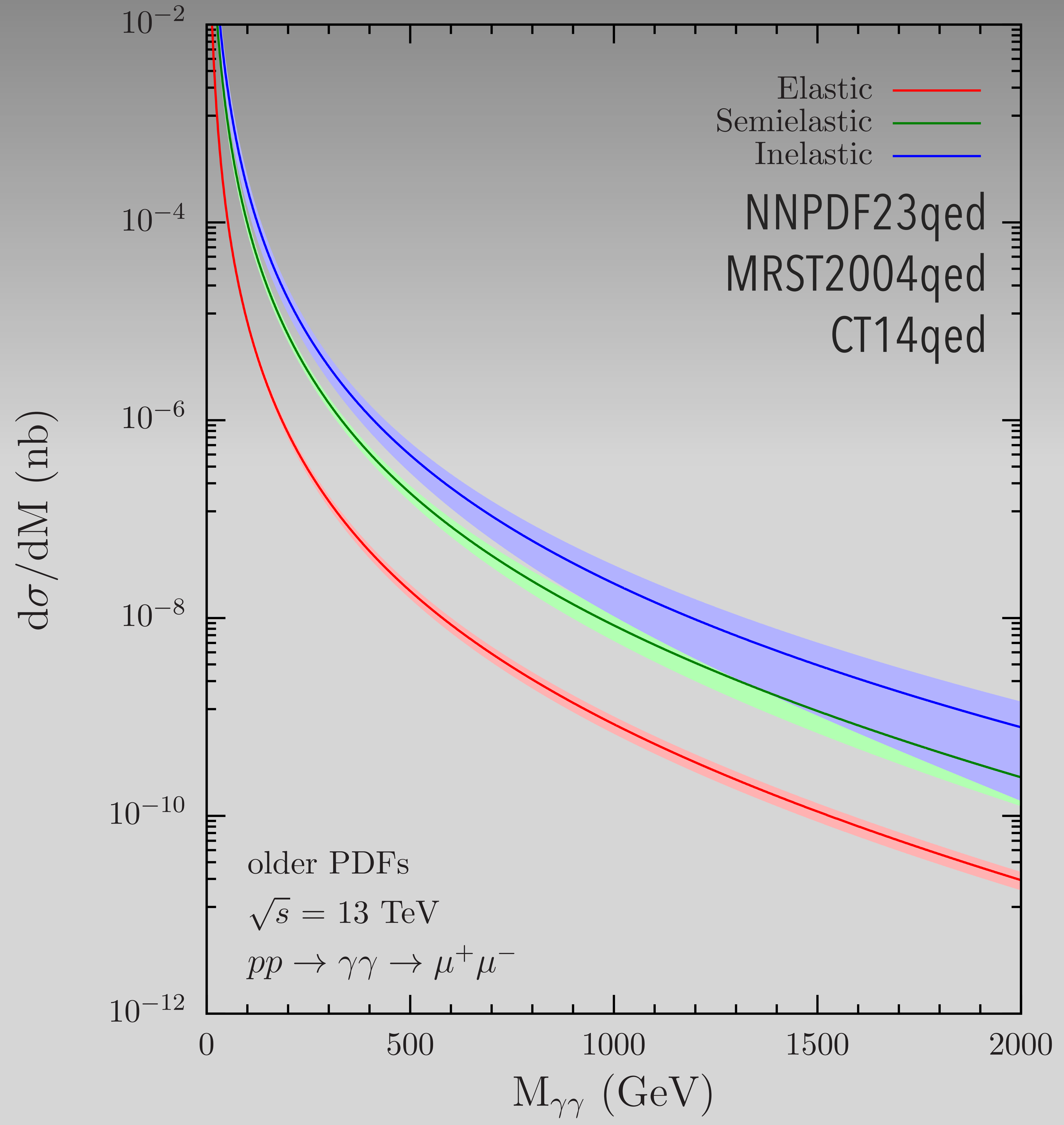
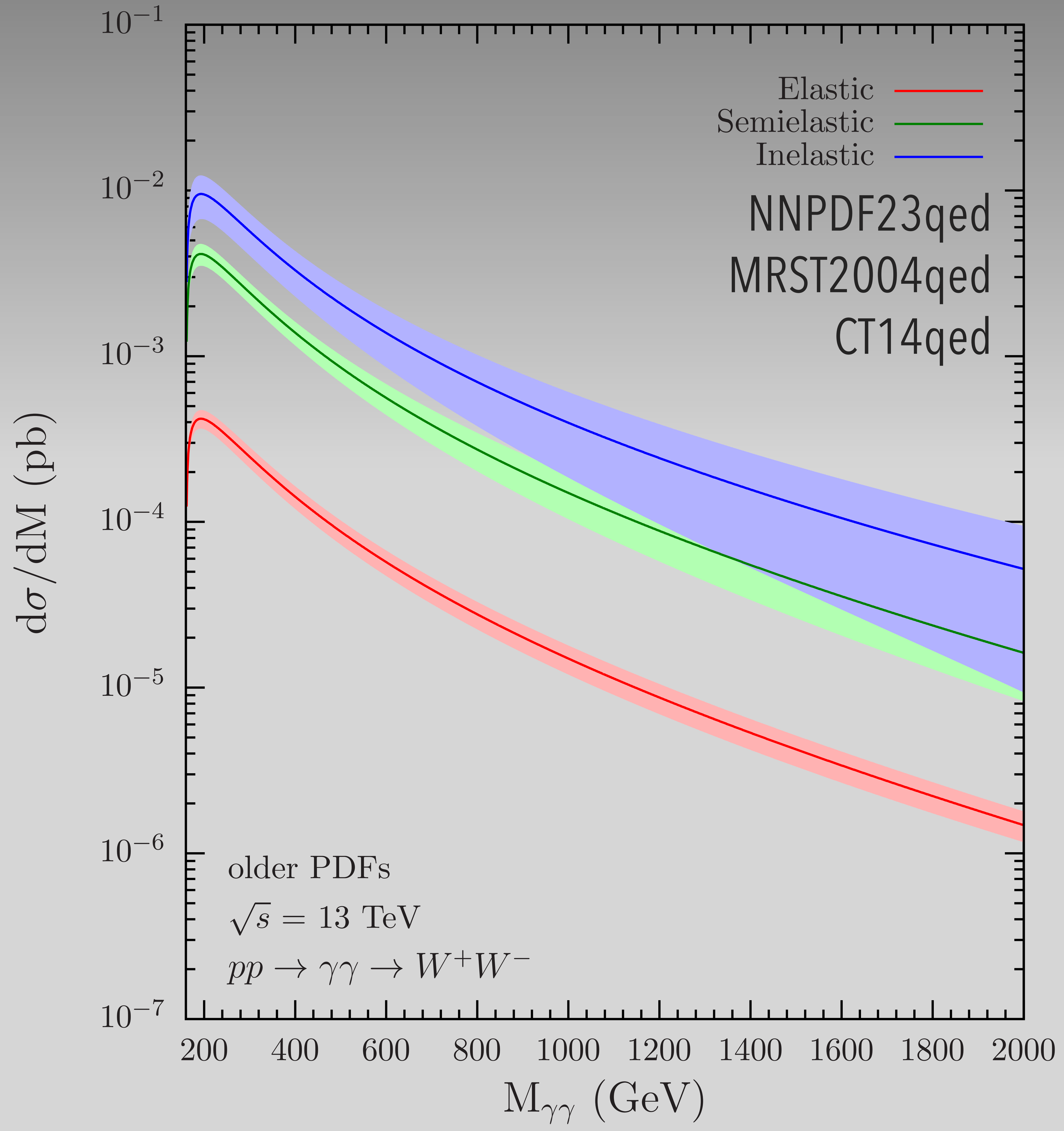
Size of non-elastic contributions (older PDFs)





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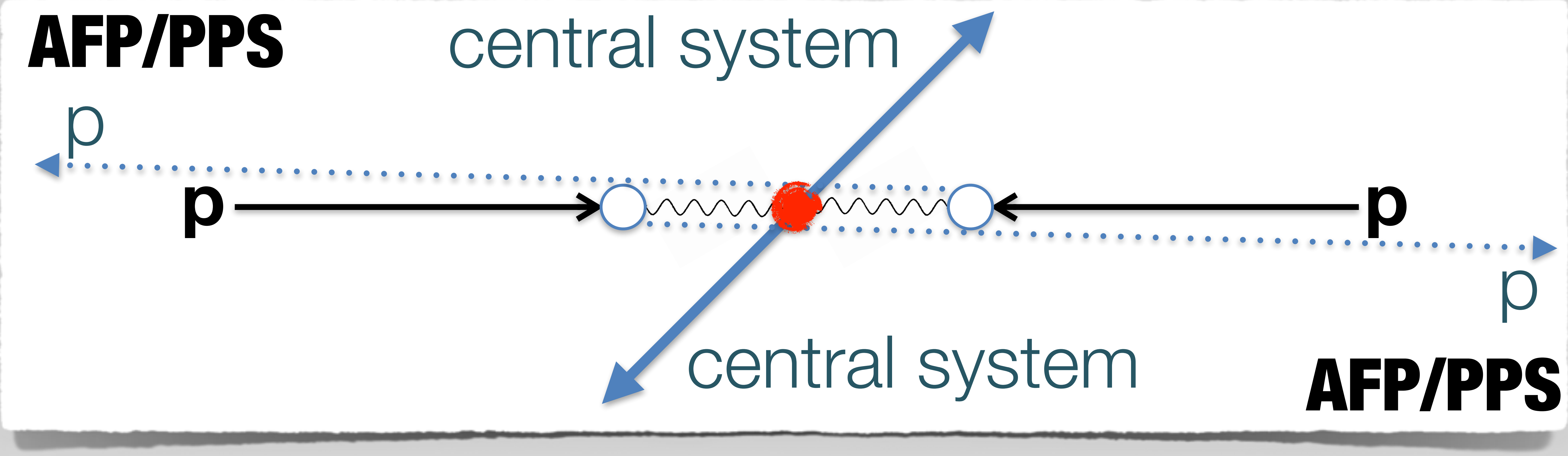
Tagging protons

- First data reports from CMS and ATLAS focused in the signal events collected by the **central detectors** only: two opposite-charge, isolated leptons;
- Intact protons emerge from the IP after an electromagnetic interaction in a trajectory **very close** to the beam pipe (a deviation of a few **milliradians** from the beam);
- Newly installed forward detectors (ATLAS-AFP and CMS-PPS) are able to measure these intact protons, suitable for the **high-luminosity** regime of the HL-LHC;
  - Sensitivity lies from ~**400 GeV** to **2 TeV** based on the proton loss of momentum: $\xi = \frac{\Delta p}{p}$



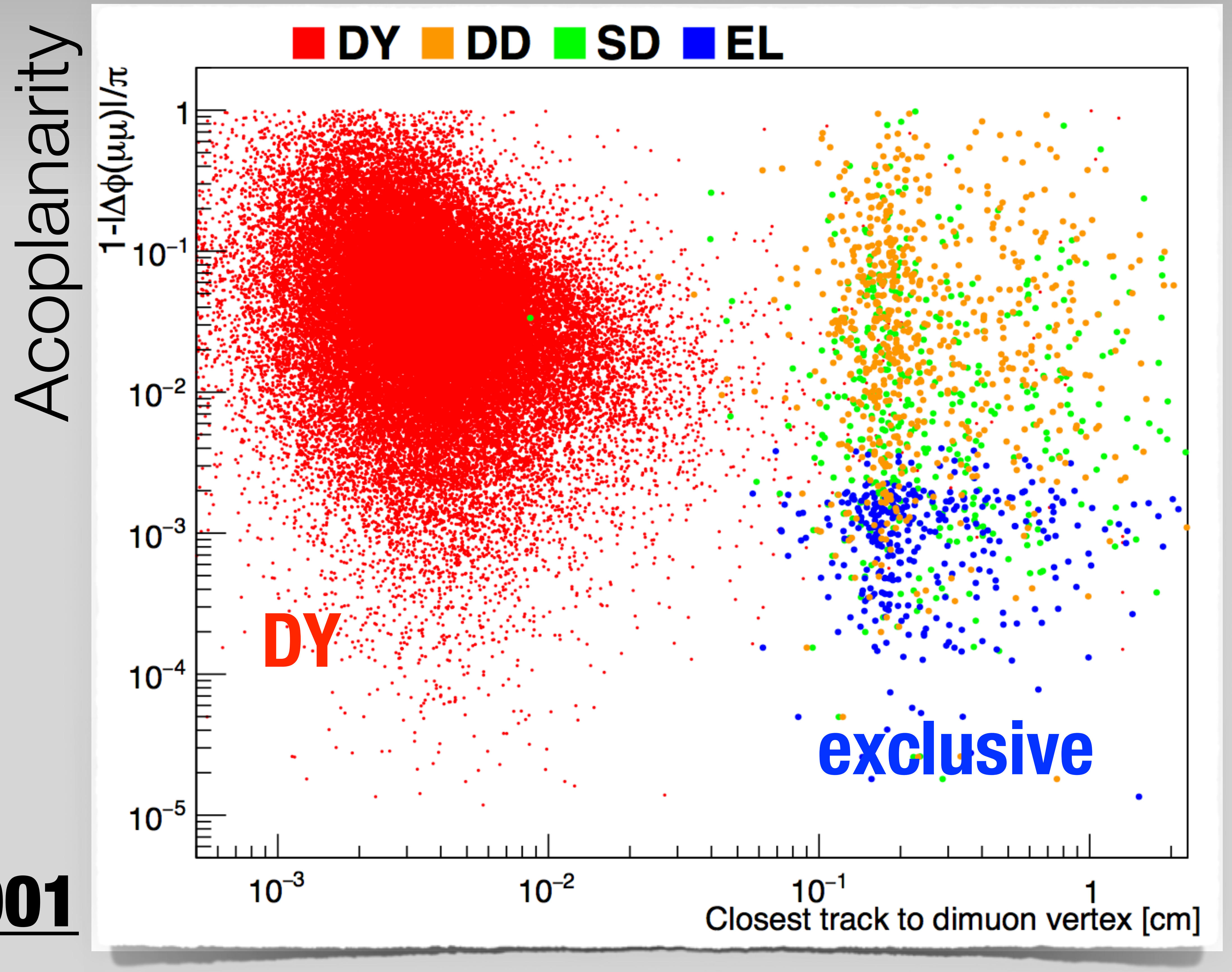
Observations at PPS

- First measurement performed was the exclusive 2-photon production of **high-mass muon pairs** at 13 TeV in events with intact protons;

- A total of <u>20 observed events</u> within the expectation for a **single arm** measurement considering the LHC optics and the Roman Pots positions;

- A large portion of the kinematic region sensitive to the exclusive production of dileptons include non-elastic events (**orange** + **green** points);

- Such events are well modelled with a few event generators, but the search for W boson or high-mass New Physics **lacks** the contribution of the proton dissociation.



<u>CMS-PPS-17-001</u>

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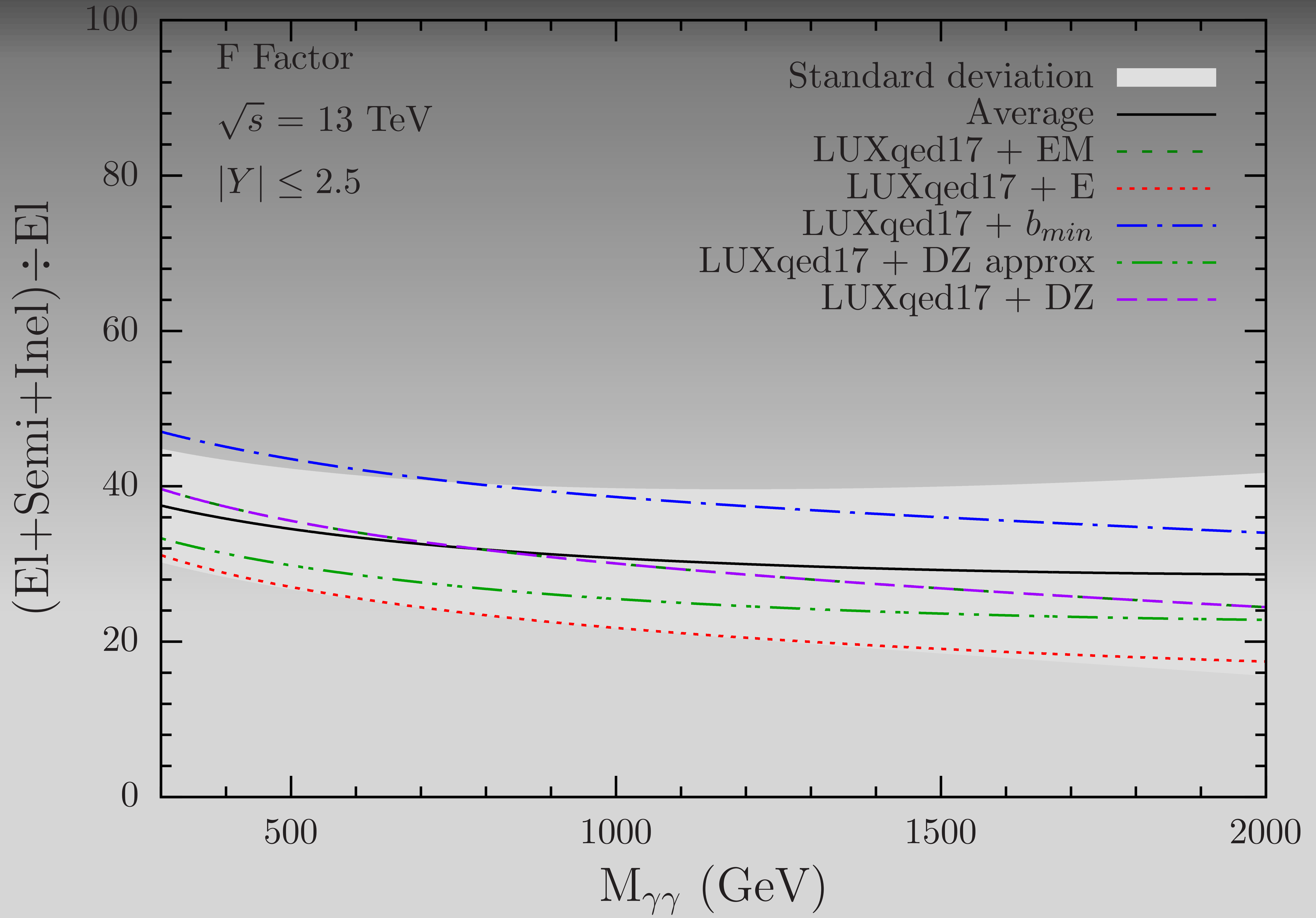
F factor

$$F = \frac{\sigma^{\text{el}} + \sigma^{\text{semi}} + \sigma^{\text{inel}}}{\sigma^{\text{el}}}$$



- The uncertainty around the average is not negligible over the entire invariant mass window;
- Although the particular PDF uncertainties have been reduced from older ones, the fudge factor still shows an overall **~15%** uncertainty at 300 GeV and **~40%** at 2 TeV.

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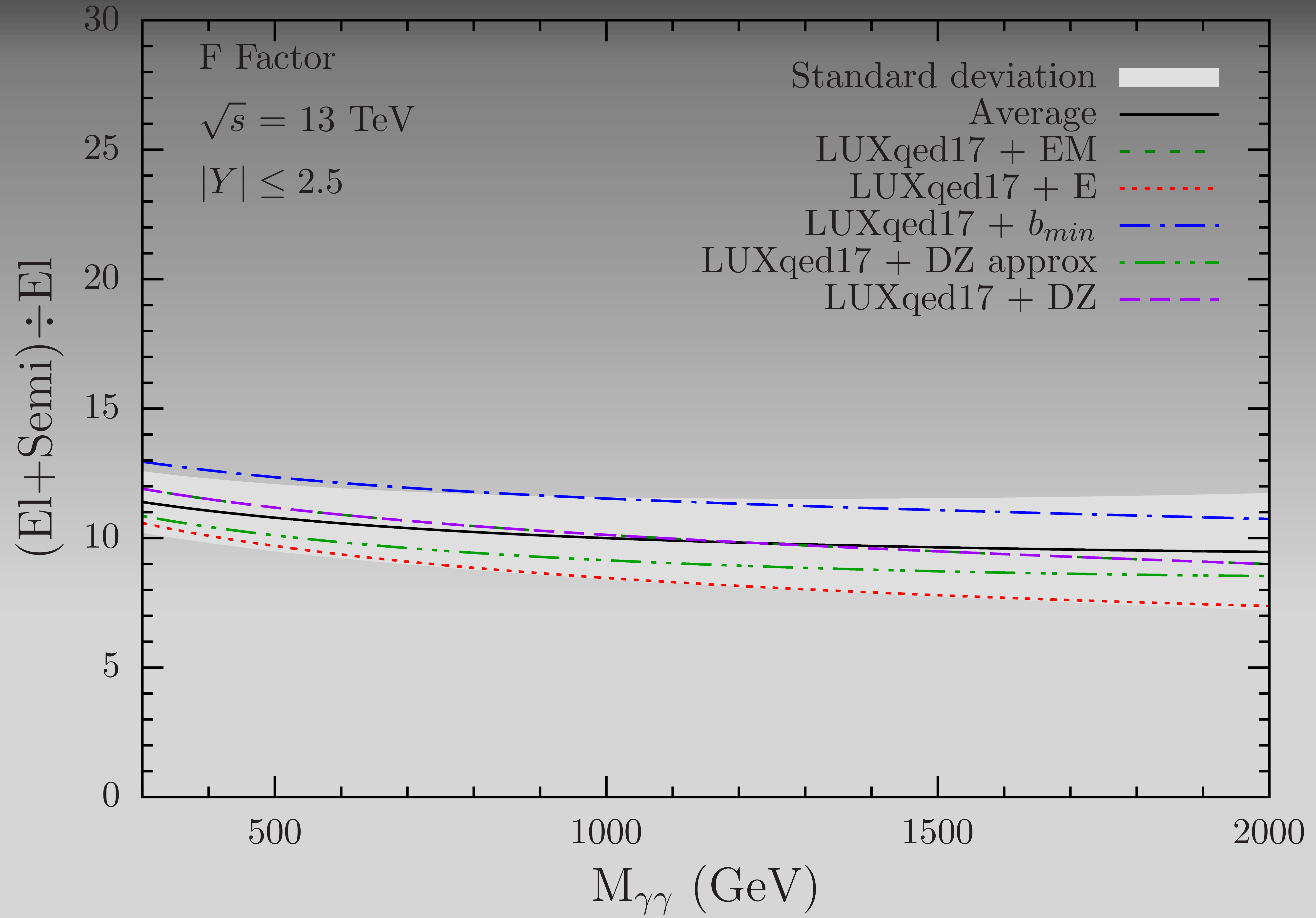
F factor

$$F = \frac{\sigma^{\text{el}} + \sigma^{\text{semi}}}{\sigma^{\text{el}}}$$



- The fudge factor is **nearly** the same for both dimuon and WW final states;
  - This result confirms that the partonic cross sections are indeed **cancelled out**.
- The overall luminosities ratio provides a **global** view of the non-elastic contributions.

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Conclusions

- The LHC data has been providing new insights on the **photon content** of the proton;

- Uncertainties of non-elastic contributions are not negligible, especially at the **high-mass** region;

  - Searches for New Physics in an electromagnetic production mechanism may be **improved** by including the non-elastic contributions together with **proper event selection**.

- An overall fudge factor is possible to be addressed over a **large mass window** in order to predict the size of the **non-elastic contributions** based on the photon luminosities

  - Important constraint for **QED PDF** parametrizations.

- Final MC plots being finished to submit this work to PRD.

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