Photon-Initiated processes in the di-lepton channel at the LHC

E. Accomando, J. Fiaschi, F. Hautmann,
S. Moretti, C.H. Shepherd-Themistocleous

Based on:
Phys. Rev. D95, 035014 (2017)
&
arXiv:1612.08168

Particle Physics
Rutherford Appleton Laboratory

UNIVERSITY OF Southampton
School of Physics and Astronomy

Overview

- **Introduction: photon collisions at the LHC**
  - Elastic and Inelastic processes for di-lepton production
- **Inelastic PDF sets**
  - Double-Dissociative (DD)
  - Equivalent Photon Approximation (EPA)
  - Single-Dissociative (SD)
- **Inclusive PDF sets**
- **PI effects on the di-lepton spectrum**
  - Impact on *Z'* searches
- **Conclusions**

Photon collisions at the LHC

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Photon collisions at the LHC

Protons are charged objects, surrounded by a **cloud** of virtual photons.

We also have a component of photons **inside the proton** that do contribute to the overall proton energy, same as quarks and gluons.

In the Run-II era, *SM precision measurements* and *BSM searches* in the high-invariant mass region. Here photons interactions represent one of the sources of **systematics uncertainties:**

- Photon Initiated (**PI**) contribution.
- Photon PDFs determination.
- Assumed model for elastic production.

2 leptons – final state

Harland-Lang, Khoze, Ryskin,
Phys. Rev. D94 (2016) no.7, 074008

Bourilkov, arXiv:1606.00523 & arXiv:1609.08994

Accomando, Fiaschi, Hautmann, Moretti, Shepherd-Themistocleous,
Phys. Rev. D95 (2017), 035014,
arXiv:1609.07788 (ICHEP Proceeding),
arXiv:1612.08168

CMS Collaboration,
CMS-PAS-EXO-16-031

4 leptons – final state

Dyndal, Schoeffel,
Acta Phys. Polon. B47 (2016) 1645

tt – final state

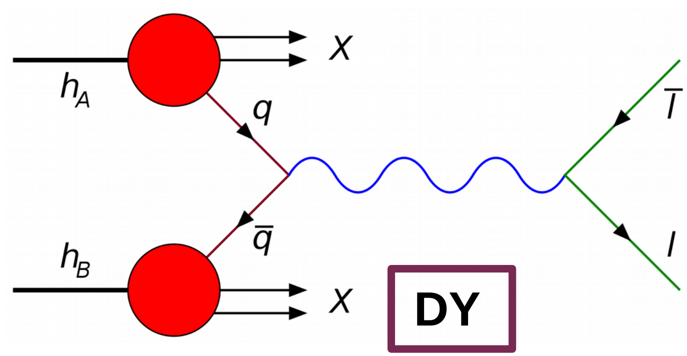
Pagani, Tsinikos, Zaro,
Eur. Phys. J. C76 (2016) no.9, 479

The di-lepton channel

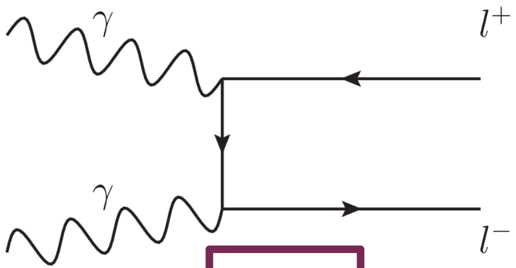
This is to be added to the usual Drell-Yan (DY) process

$$q\bar{q} \longrightarrow \gamma, Z, Z' \longrightarrow \ell^+\ell^-$$

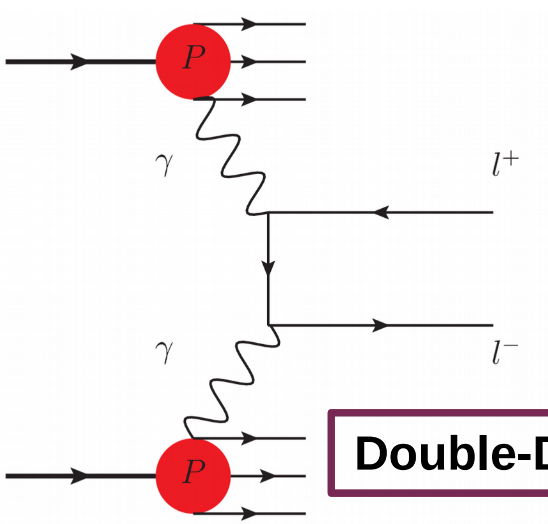
$$pp \longrightarrow \gamma\gamma \longrightarrow \ell^+\ell^-$$



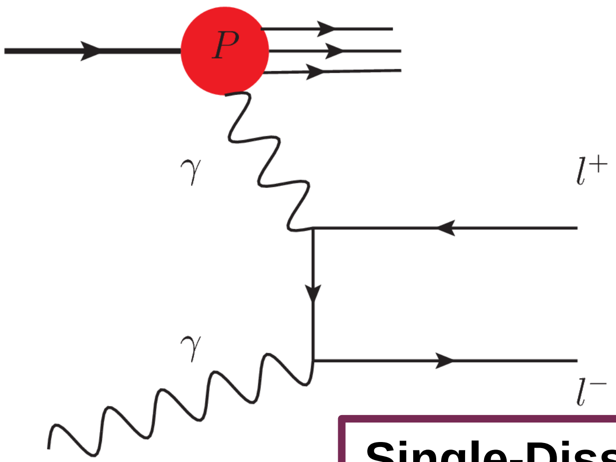
DY



EPA



Double-Dissociative



Single-Dissociative

QED PDF sets for LHC

Inelastic PDF sets:

MRST2004QED
- First QED set with QED corrections to DGLAP evolution equation (lead to isospin violation).
- Includes HERA data.
- No update available – PDF uncertainties not available, LHC data not included.

Martin, Roberts, Stirling, Thorne
Eur. Phys. J. C39, 155 (2005)

CT14QED
- Includes HERA and ZEUS (with isolated photons) data to fit the 'inelastic' photon PDF.
- Do not include LHC data.
- The fraction of momentum carried by the photon satisfying the momentum sum rule, is constrained through fitting procedure.

Schmidt, Pumplin, Stump, Yuan
Phys. Rev. D93, 114015 (2016)

Inclusive PDF sets:

NNPDF3.0QED
- Includes HERA, ATLAS, CMS, LHCb data.
- Global fit using Neural network approach validated through a closure test.
- QED constrains on photon PDF are included through re-weighting procedure (small violation of momentum sum rule).
- Incorporates the 2.3QED photon contribution to the 3.0 global analysis using the APFEL code for the QED correct DGLAP equations.

Ball, Bertone, Carrazza, Deans, Del Debbio, Forte, Guffanti, Hartland, Latorre, Rojo, Ubiali,
JHEP 1504 (2015) 040

CT14QED_inc
- Same as CT14.
- The elastic component is included through EPA calculations.

LUXqed
- Includes DIS data
- Do not include LHC data.
- Use a relation that connects proton structure functions to photon densities (DIS data directly constrains photon PDF).

Manohar, Nason, Salam, Zanderighi
Phys. Rev. Lett. 117, 242002 (2016)

Inelastic PDF sets

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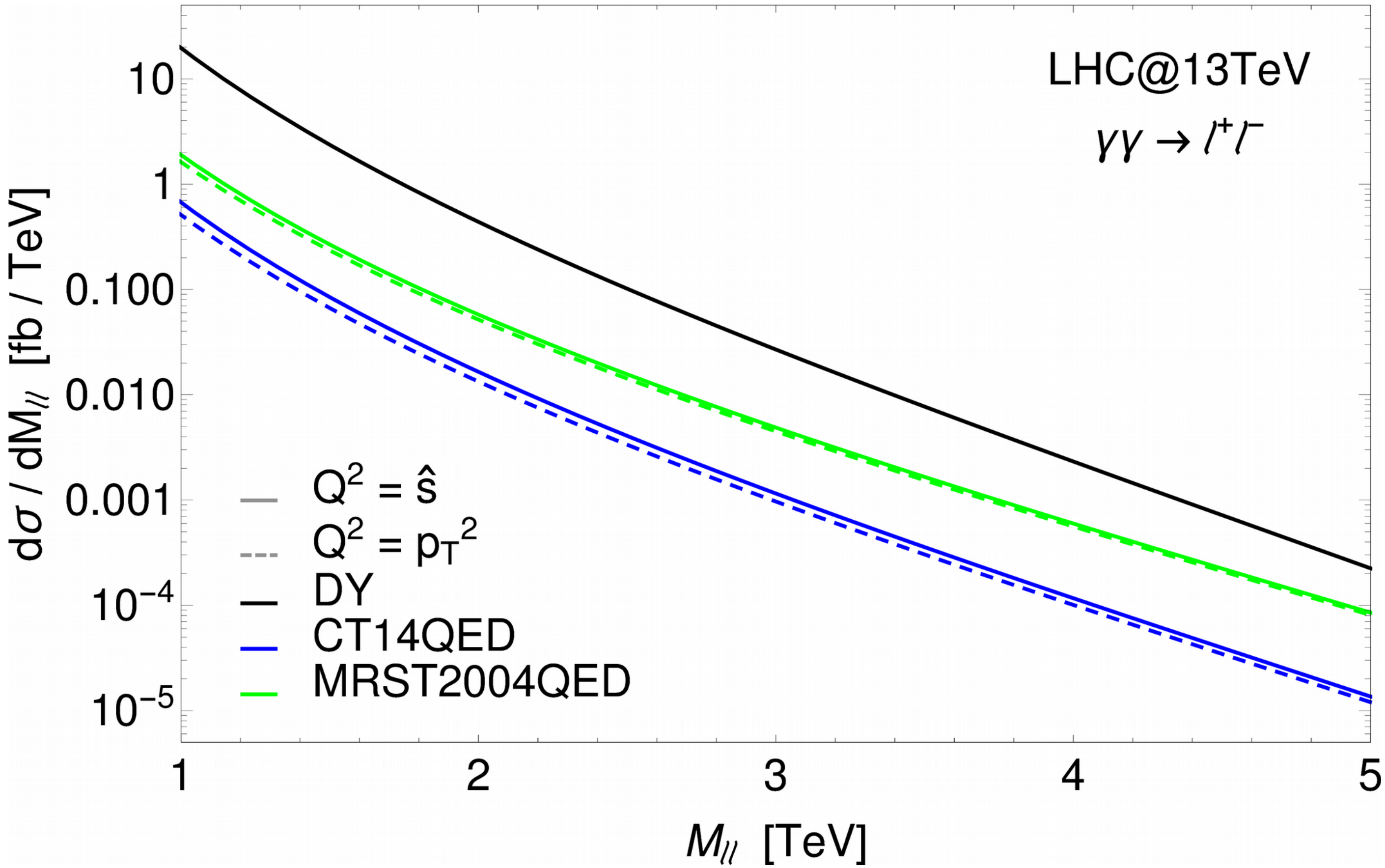
Double-Dissociative

$$\frac{d\sigma_{DD}}{dM_{\ell\ell}} = \iint dx_1 dx_2 \frac{1}{32\pi M_{\ell\ell}} \left|\mathcal{M}(\gamma\gamma \to l^+l^-)\right|^2 f_\gamma(x_1, Q) f_\gamma(x_2, Q)$$

We start considering the **Double-Dissociative (DD)** process, with **both** interacting photons from QED PDFs.

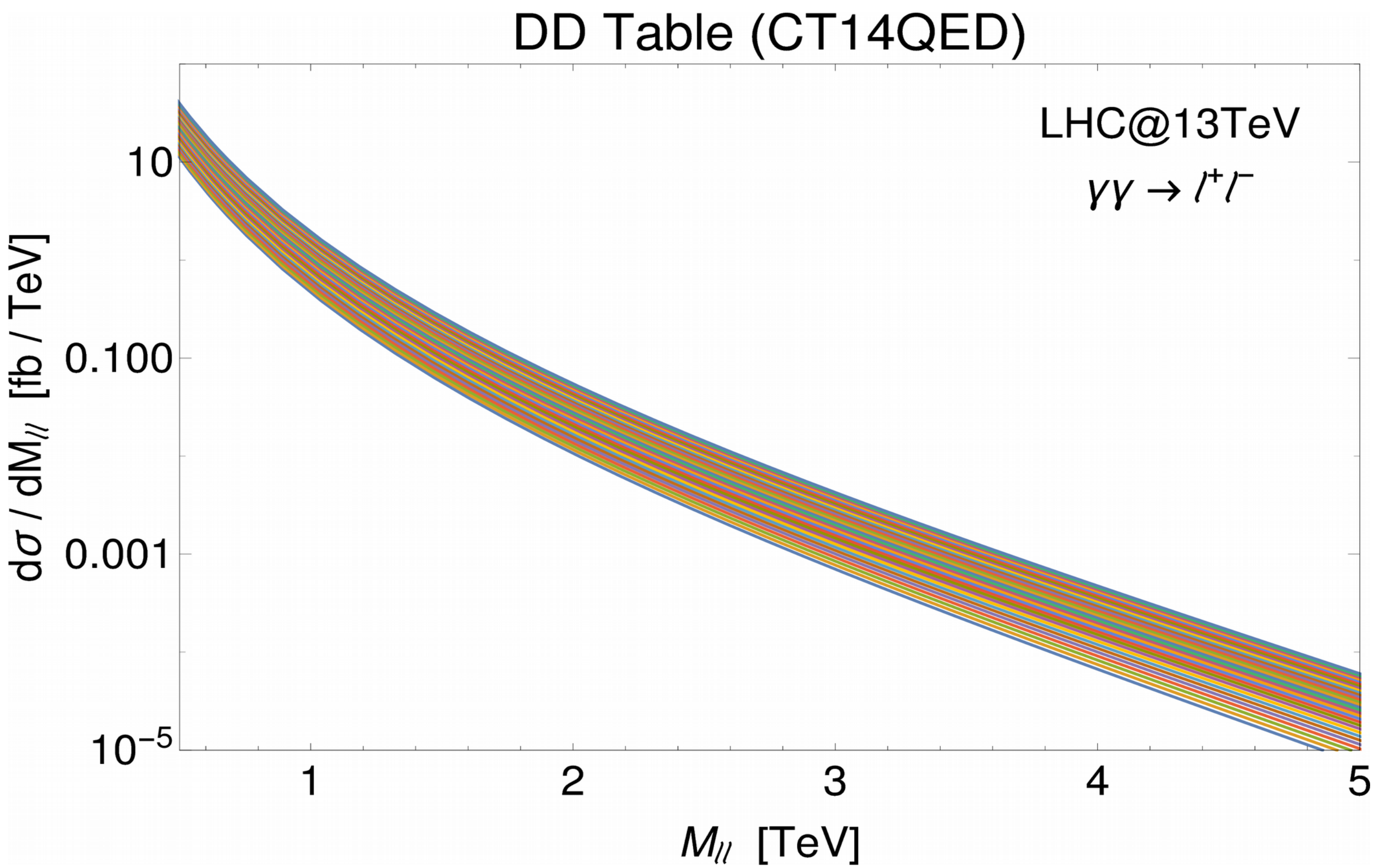
The photons extracted from the QED PDFs are **resolved**, i.e. they are **real** ***($Q^2 = 0$)***



Double-Dissociative

CT14QED → table of 31 PDF fitted imposing a progressive constrain on the relative momentum carried by the photon *(p_γ = 0.00% - 0.30%)*

Their analysis provides the bound:
$p_\gamma \leq$ 0.11% at *68% C.L.*
We have considered the average of the first 12 tables as central value, and the relative 1σ error band consistently.



Equivalent Photon Approximation

Virtual photons spectrum is included through the **"Equivalent Photon Approximation" (EPA)**

Budnev, Ginzburg, Meledin, Serbo, Phys. Rept. 15, 181 (1975)

$$dN(x,Q^2) = \frac{\alpha}{\pi}\frac{dx}{x}\frac{dQ^2}{Q^2}\left[(1-x)\left(1-\frac{Q^2_{min}}{Q^2}\right)F_E + \frac{x^2}{2}F_M\right]$$

Virtual photons ($Q^2 \neq 0$)

$$Q^2_{min} = \frac{m_p^2 x^2}{1-x}, \qquad F_E = \frac{4m_p^2 G_E^2 + Q^2 G_M^2}{4m_p^2 + Q^2},$$

$$G_E^2 = \frac{G_M^2}{\mu_p^2} = \left(1+\frac{Q^2}{Q_0^2}\right)^{-4}, \quad F_M = G_M^2$$

Piotrzkowski, Phys. Rev. D63, (2001) 071502

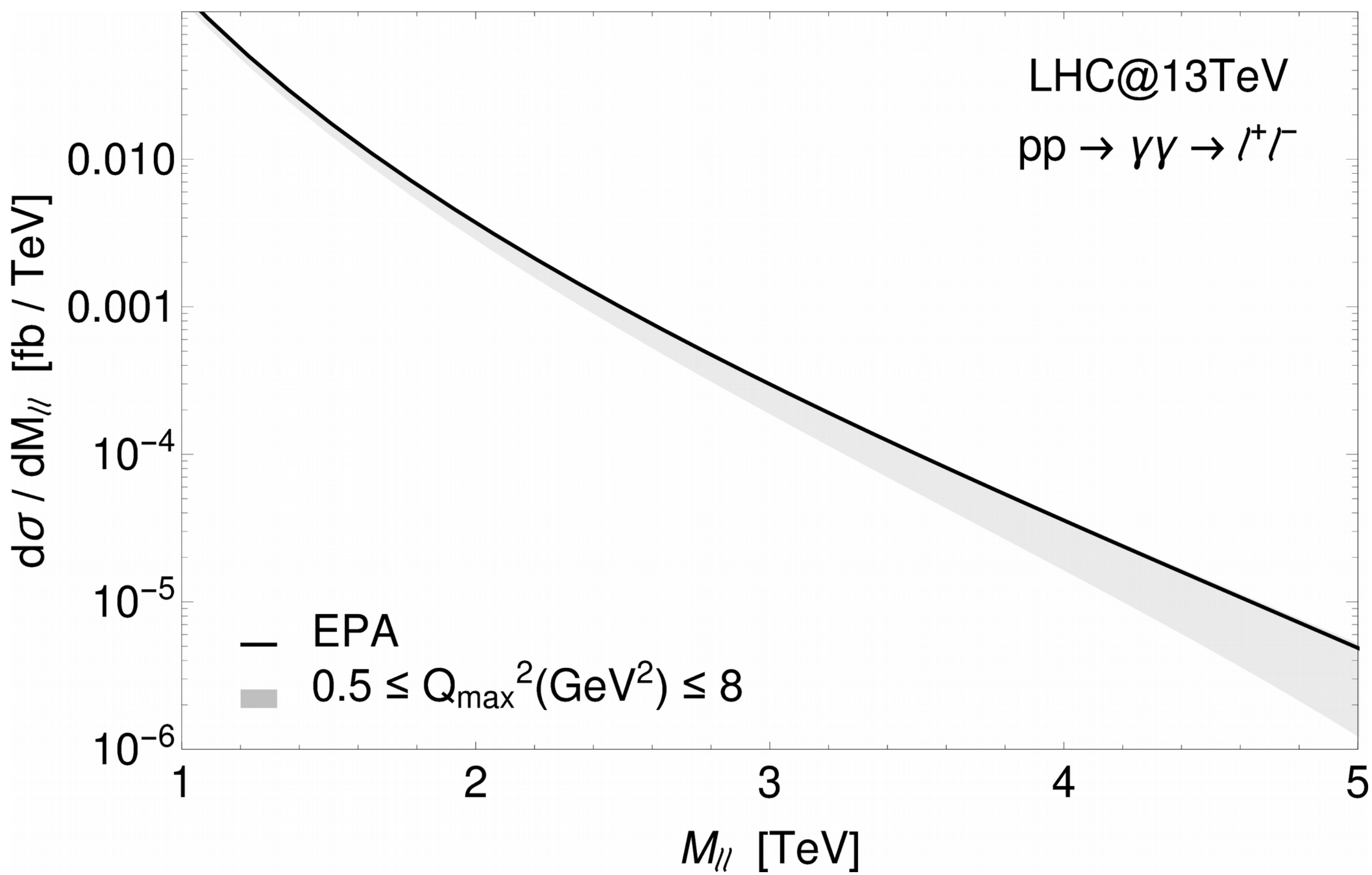
$$\begin{aligned} \mu_p^2 &= 7.78 \\ Q_0^2 &= 0.71\ GeV^2 \\ Q^2_{max} &= 2\ GeV^2 \end{aligned}$$

- Experimentally measured with great precision
- Value from data best fit
- We will vary this parameter to estimate the systematics

Equivalent Photon Approximation

Virtual-virtual photon interaction → **EPA**

$$\frac{d\sigma_{EPA}}{dM_{\ell\ell}} = \frac{dL_{\gamma\gamma}}{dM_{\ell\ell}}\sigma_{\gamma\gamma} = \int_{Q^2_{1,min}}^{Q^2_{1,max}} dQ_1^2 \int_{Q^2_{2,min}}^{Q^2_{2,max}} dQ_2^2 \iint dx_1 dx_2 \frac{|\mathcal{M}(\gamma\gamma \to l^+l^-)|^2}{32\pi M_{ll}} N(x_1, Q_1^2) N(x_2, Q_2^2)$$



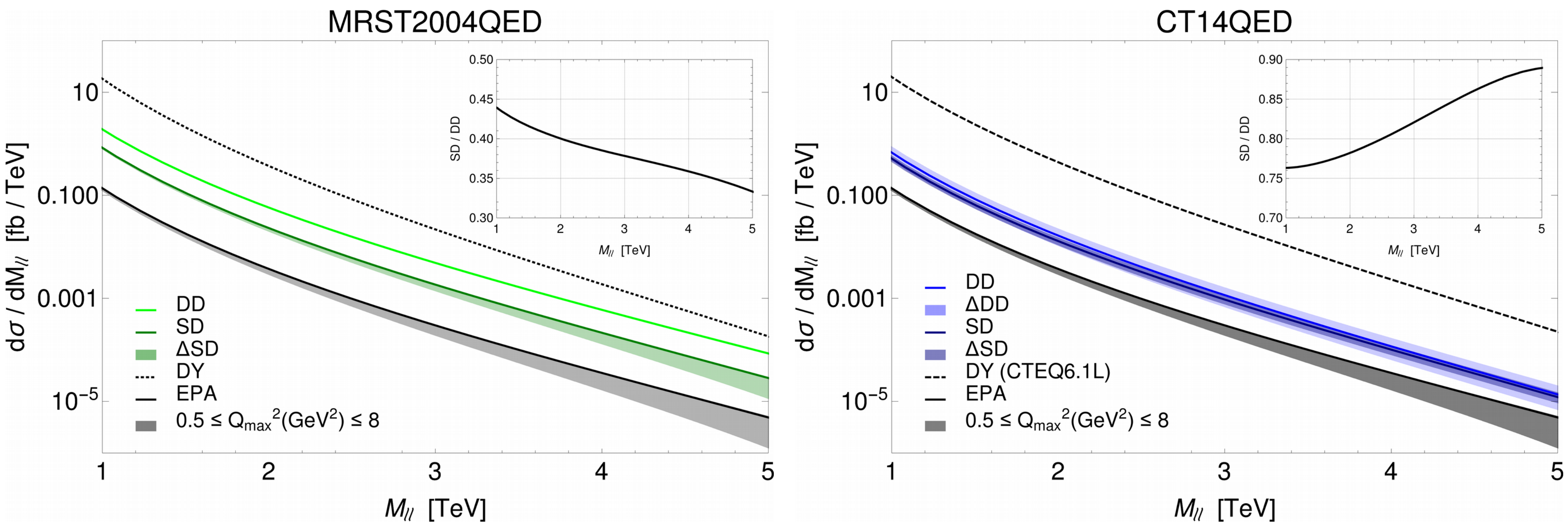
We varied the Q^2_{max} parameter to estimate the **theoretical error**

All the results have been calculated in the CMS acceptance region
[CMS Collaboration, JHEP 1504, 025 (2015)]

Single-Dissociative

Real-virtual photon interaction → **Single-Dissociative (SD)**

$$\frac{d\sigma_{SD}}{dM_{\ell\ell}} = \int_{Q^2_{1,min}}^{Q^2_{1,max}} dQ_1^2 \iint dx_1 dx_2 \frac{|\mathcal{M}(\gamma\gamma \to l^+l^-)|^2}{32\pi M_{ll}} N(x_1, Q_1^2) f_\gamma(x_2, Q) + (x_1 \leftrightarrow x_2)$$

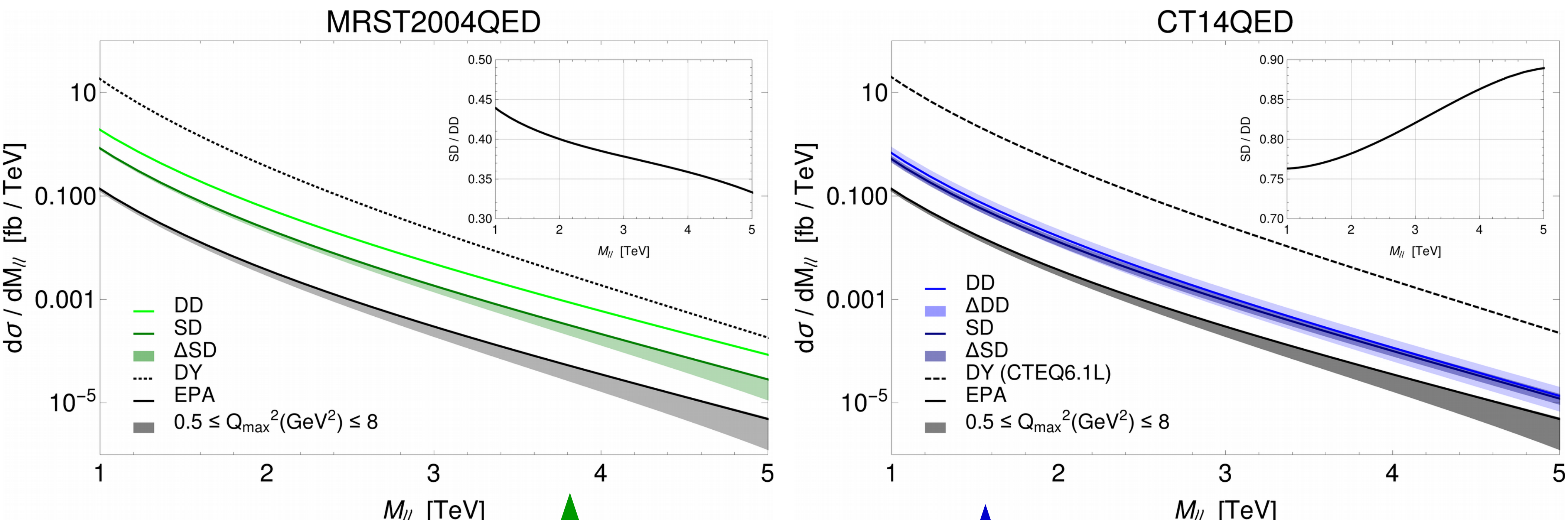


*The error bands include **both** the PDF error and the systematics on the photon spectrum*

Single-Dissociative

Real-virtual photon interaction → **Single-Dissociative (SD)**

$$\frac{d\sigma_{SD}}{dM_{\ell\ell}} = \int_{Q^2_{1,min}}^{Q^2_{1,max}} dQ_1^2 \iint dx_1 dx_2 \frac{|\mathcal{M}(\gamma\gamma \to l^+l^-)|^2}{32\pi M_{ll}} N(x_1, Q_1^2) f_\gamma(x_2, Q) + (x_1 \leftrightarrow x_2)$$



SD / DD of the order

35 – 40 %

75 – 90 %

The **SD** contribution appears to be non-negligible

*The error bands include **both** the PDF error and the systematics on the photon spectrum*

Inclusive PDF sets

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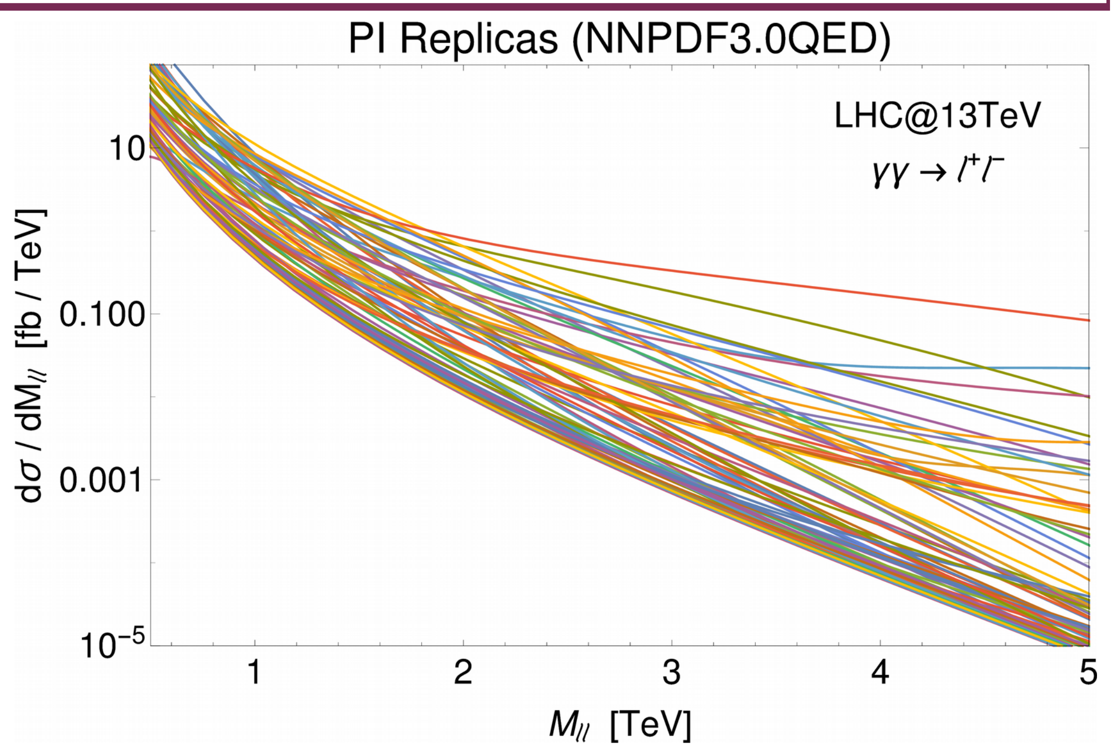
Inclusive PDF sets

NNPDF3.0QED → 100 PDF Replicas

$$\sigma_0 = \langle \sigma \rangle = \frac{1}{N} \sum_{k=1}^{N} \sigma_k$$

$$(\Delta\sigma)^2 = \frac{1}{N} \sum_{k=1}^{N} (\sigma_k - \sigma_0)^2$$



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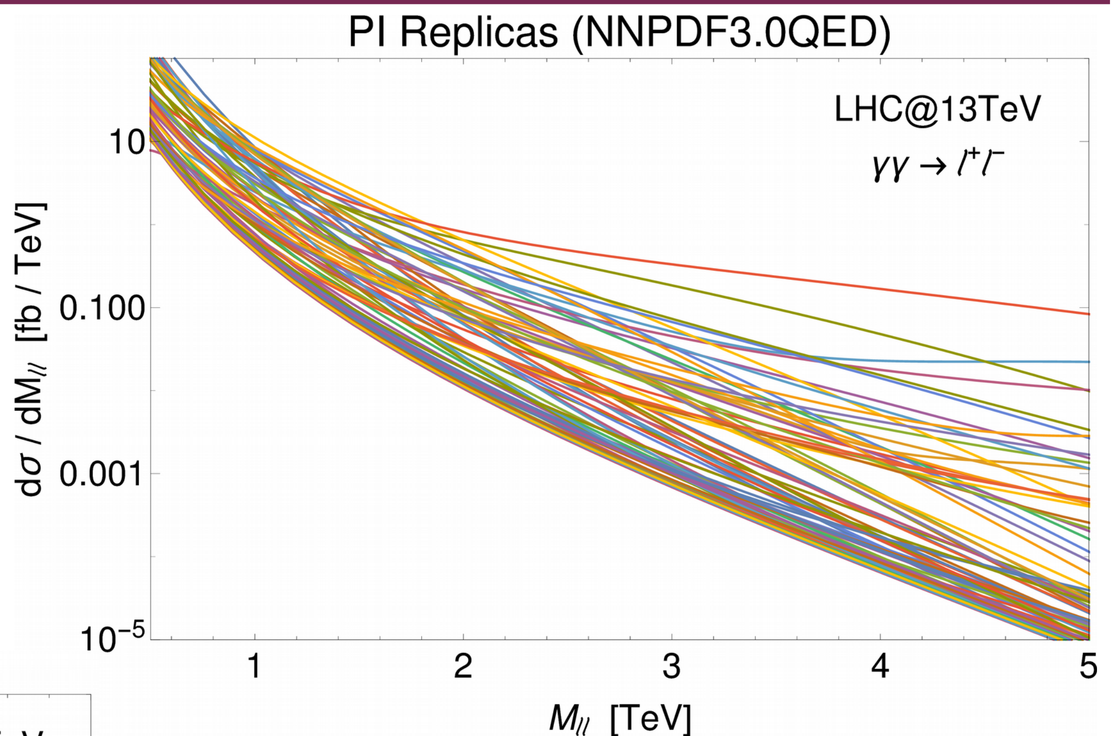
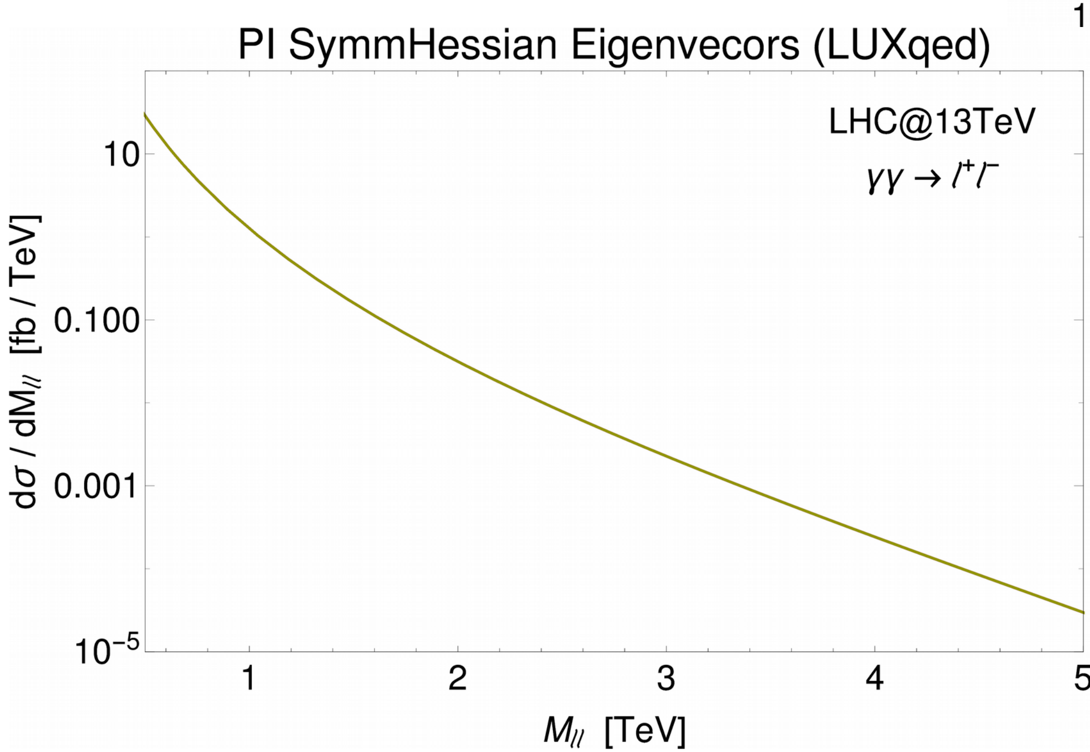




LUXqed → 100 Symmetric Hessian eigenvectors (PDF4LHC delivery)

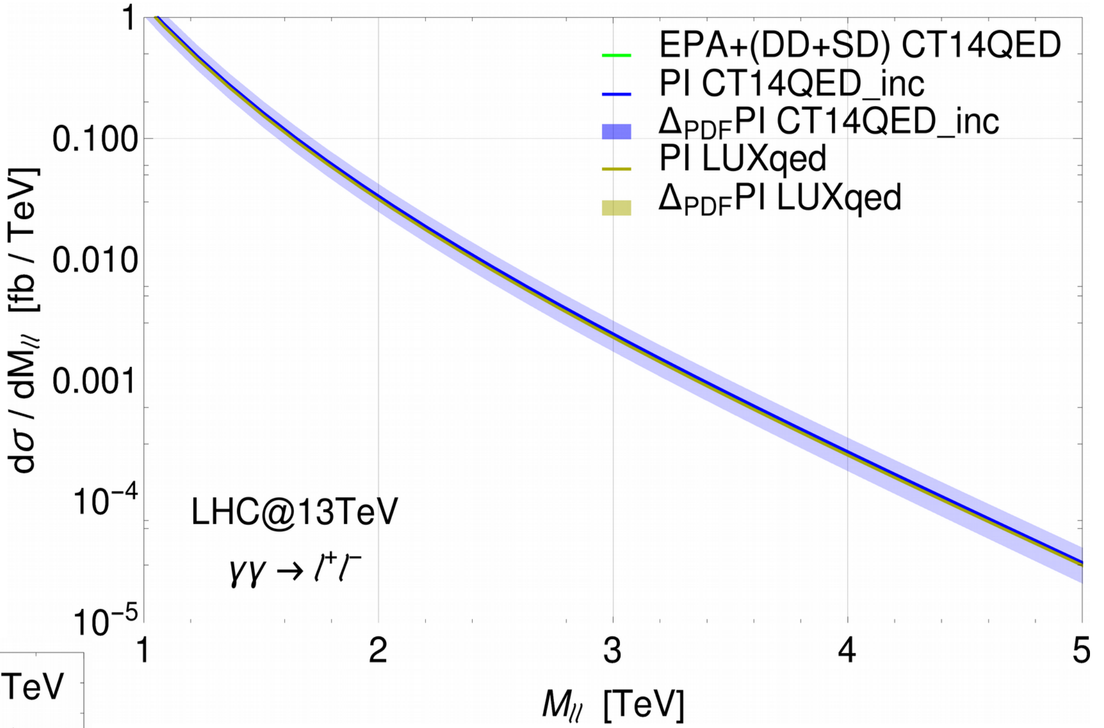
$$(\Delta\sigma)^2 = \sum_{k=1}^{N} (\sigma_k - \sigma_0)^2$$

PDF4LHC recommendations for LHC Run II, Butterworth et al., J. Phys. G: Nucl. Part. Phys. 43 023001 (2016)

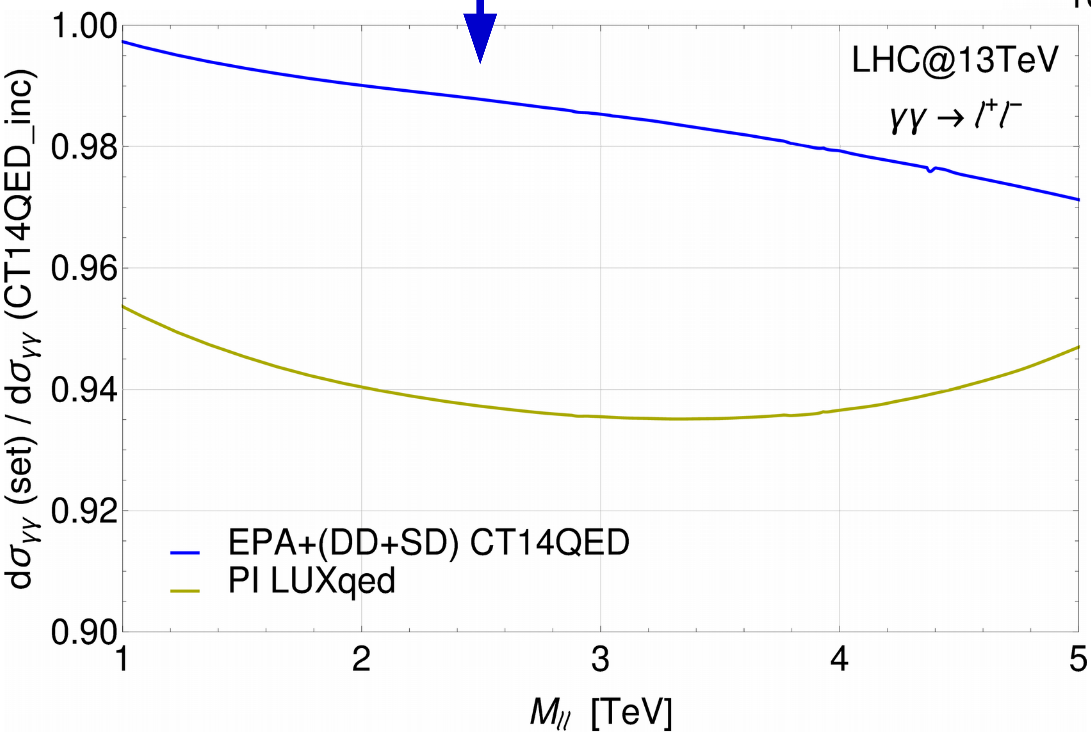
CT14QED_inc → same table of 31 PDFs as **CT14QED**

Inclusive PDF sets

As cross check we find good agreement between the three separate components **EPA+(DD+SD)** with **CT14QED** and the PI prediction obtained with **CT14QED_inc**



Double-counting below **~3%**



We find good agreement between the **LUXqed** and the **CT14QED_inc** predictions, consistent with the uncertainty of the latter (**~20%**)

PI effects on the di-lepton spectrum

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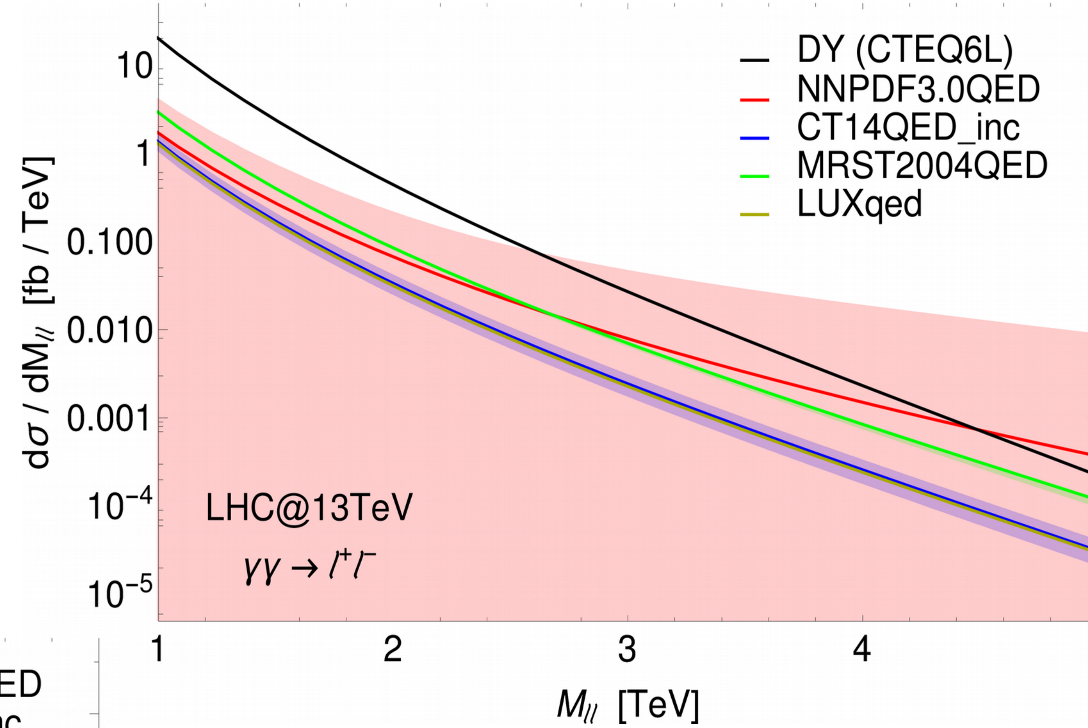
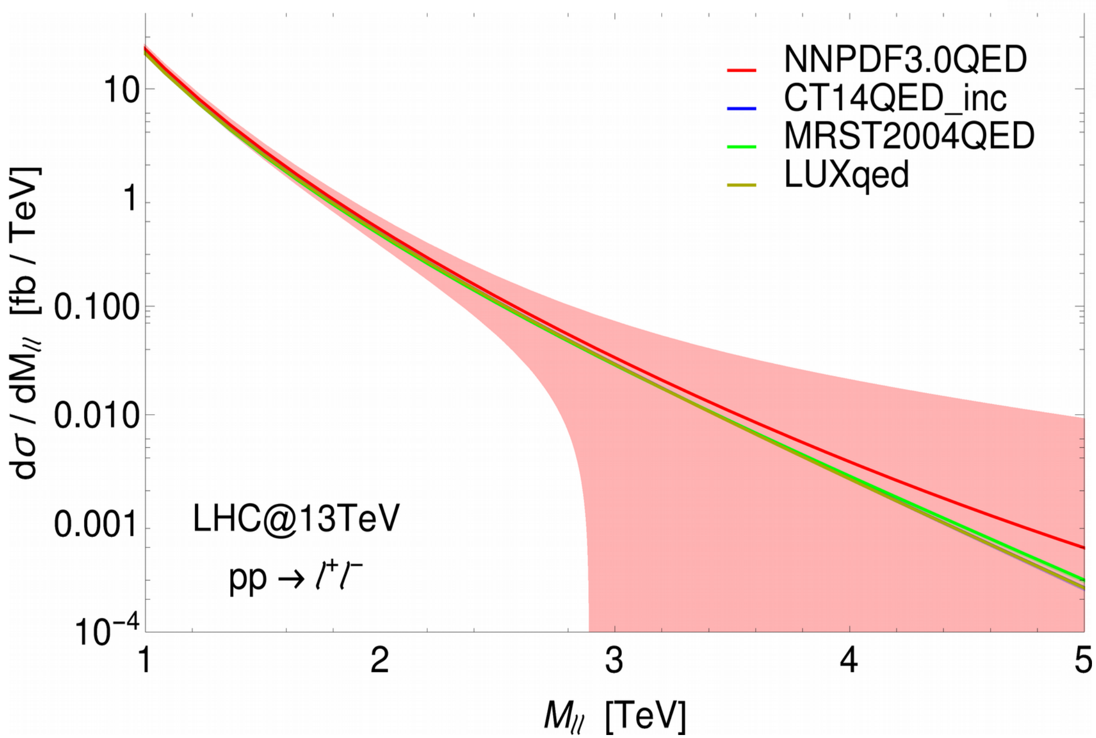
PI effects on the di-lepton spectrum

Complete (elastic+inelastic) result for the PI contribution to the di-lepton channel and its PDF error



Sizeable differences, up to <u>one order of magnitude</u>, between the different QED PDF sets predictions.

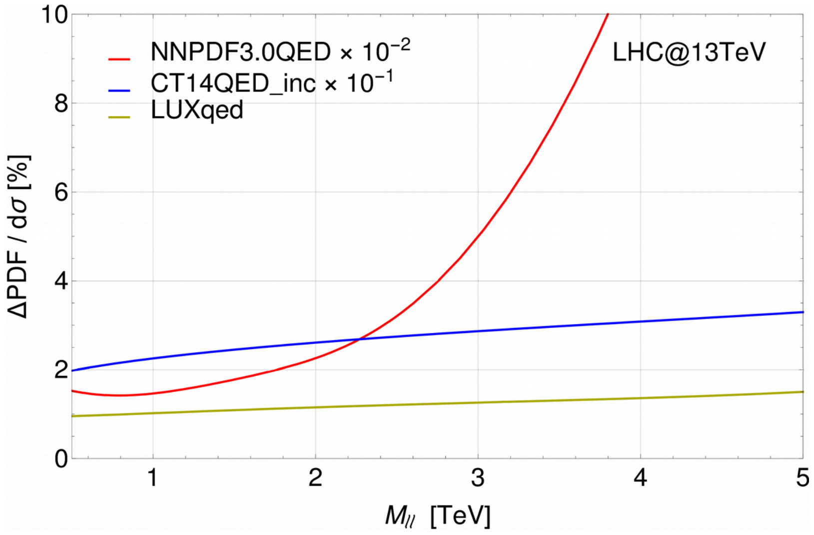


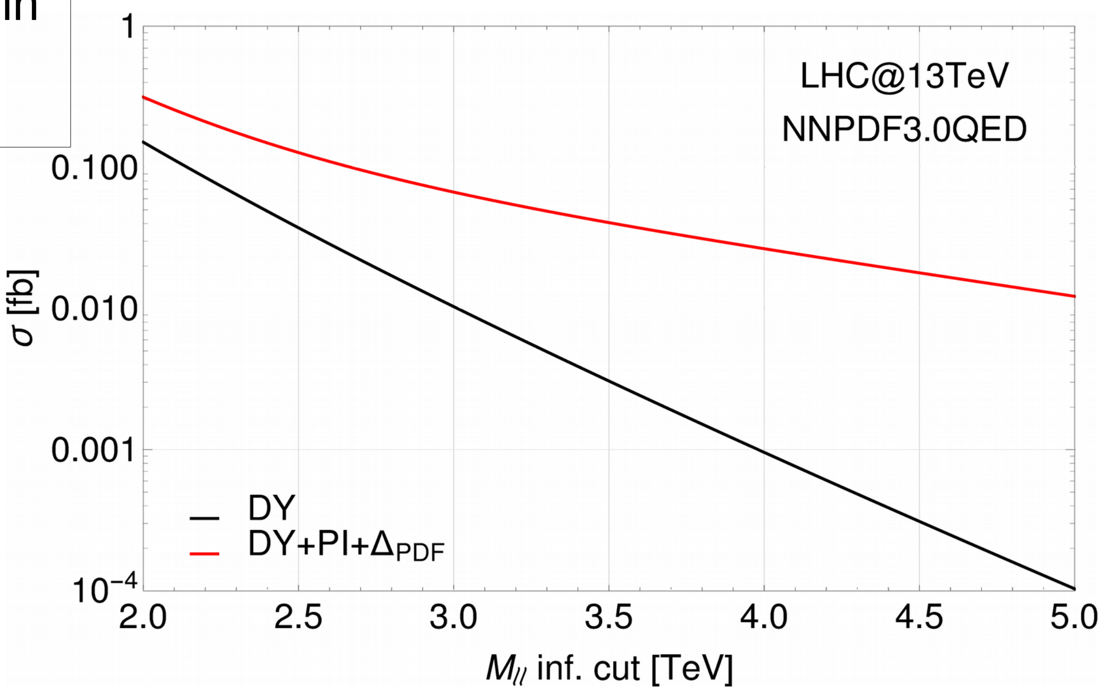
Full di-lepton spectrum and its PDF error as predicted by different PDF sets

Most conservative scenario (**NNPDF3.0QED**) → Invariant mass distribution of di-lepton pairs **dominated by systematics** around *3 TeV*

PI systematics

Large differences between PDF uncertainties in different sets. From now on we will consider most conservative scenario (**NNPDF3.0QED**)





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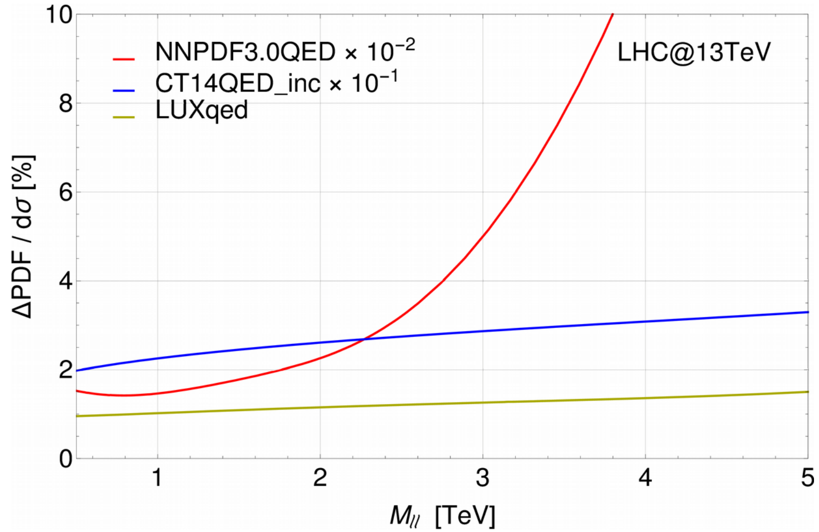
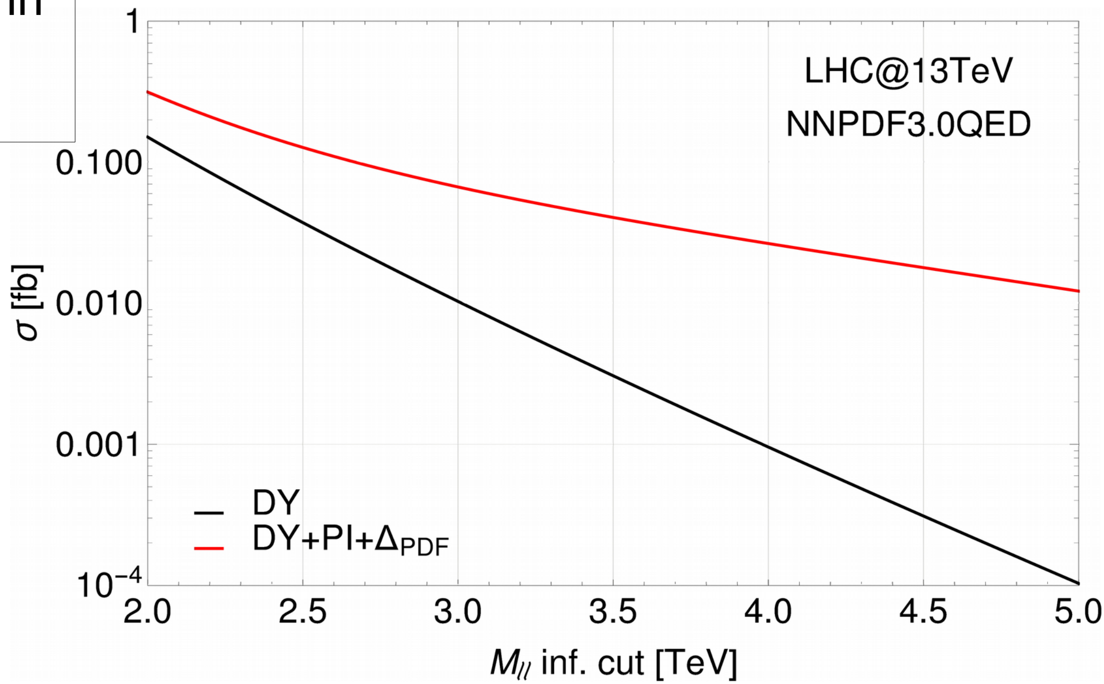
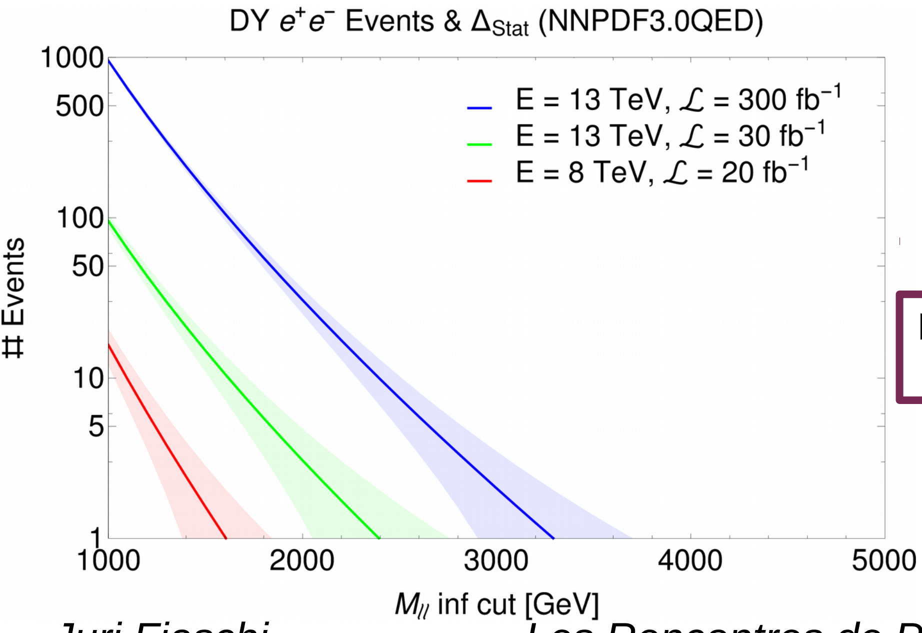
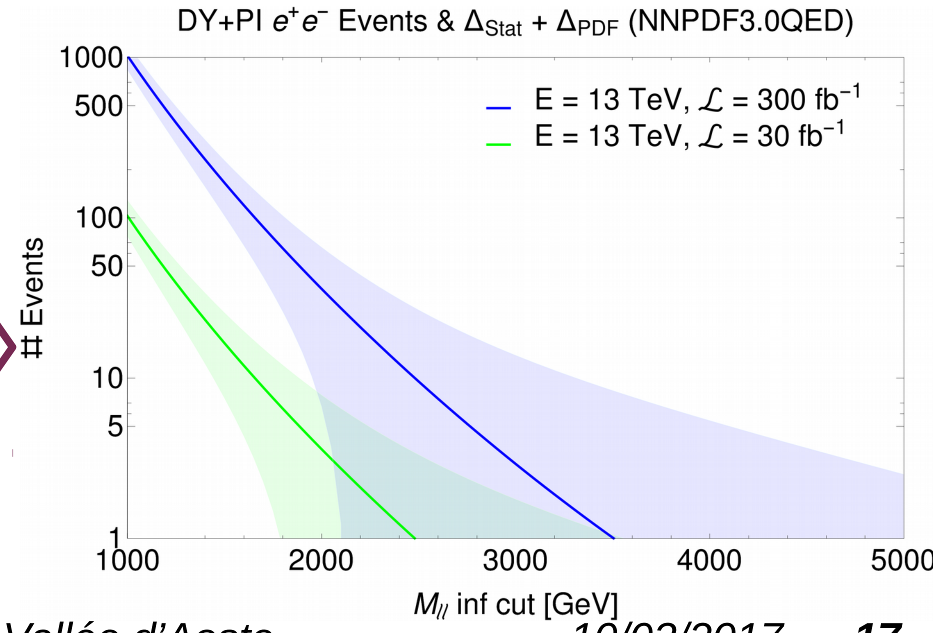


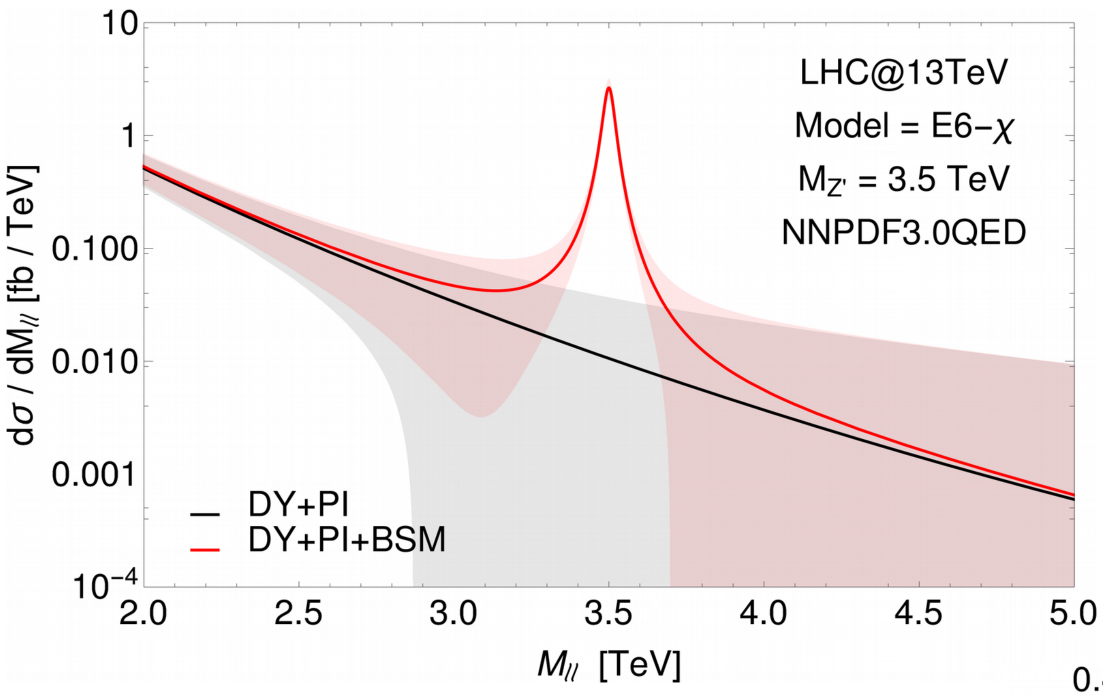




Including PI & PDF error



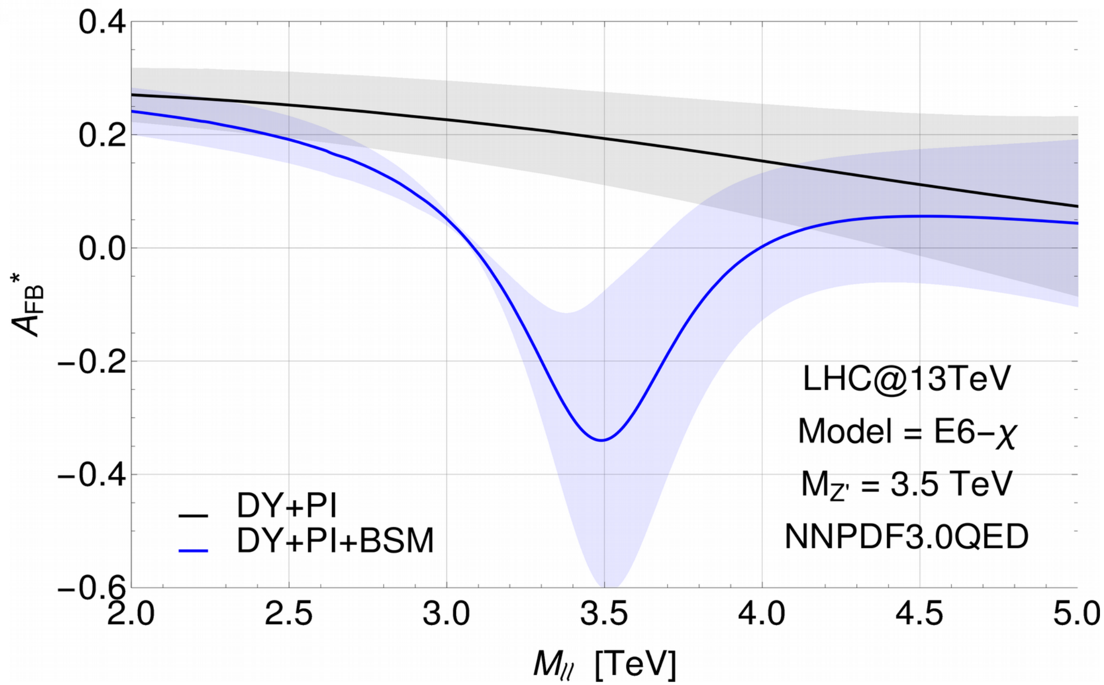
Narrow *Z'* resonances



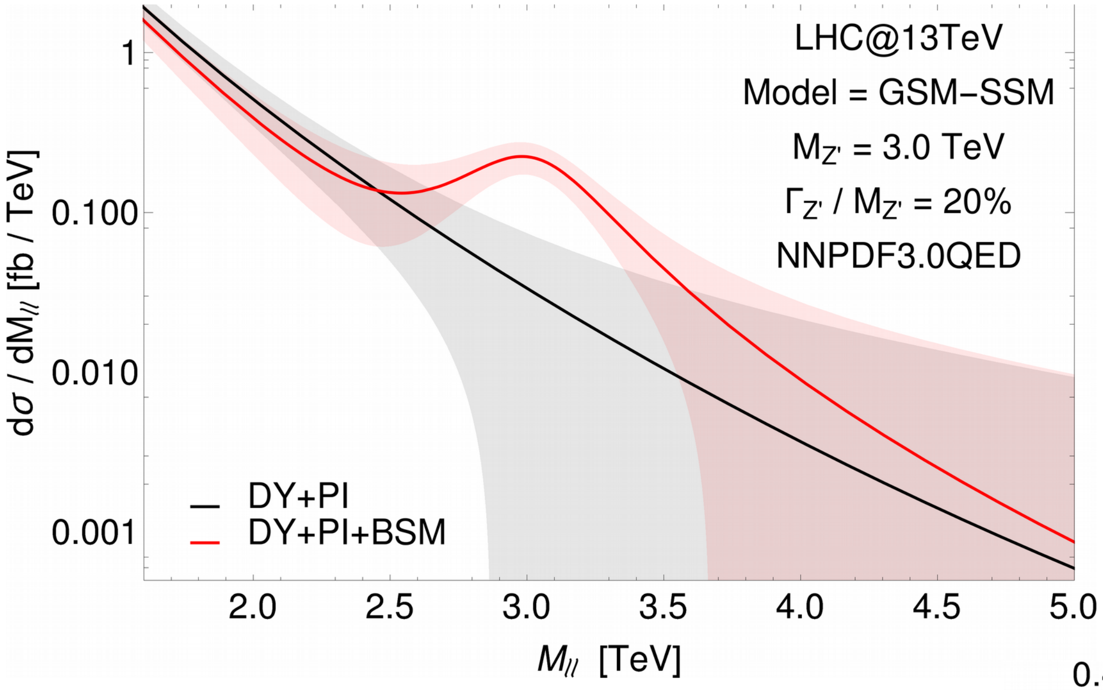
Bump searches for **narrow resonances** are marginally affected by photon interactions.

In the **AFB*** observable systematic uncertainties are sensibly reduced.

The inclusion of the PI events in the **AFB*** is important since they reduce its SM prediction.

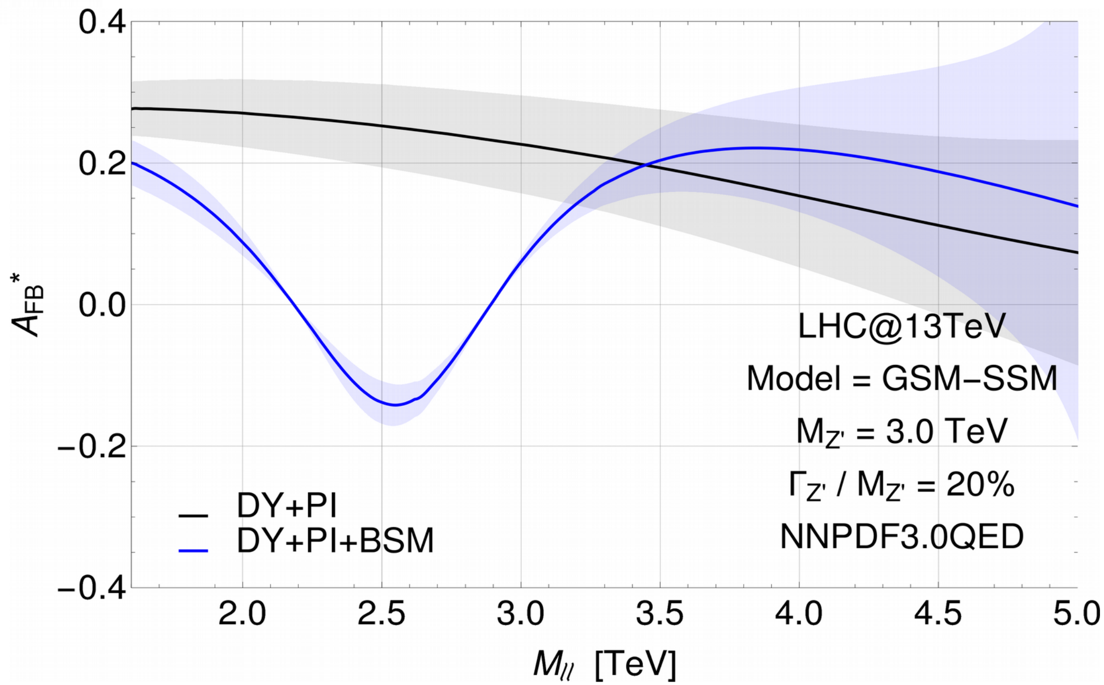


Wide Z' resonances



In **wide resonances** (similar to the **non-resonant** scenario) searches the loss of sensitivity due to the photon PDF uncertainties is visible.

A non resonant signal can still be observed in the **AFB*** distribution.



Conclusions

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Conclusions

- We presented the updated SM prediction for the *di-lepton* spectrum in the LHC Run-II setup where in addiction to the Drell-Yan (DY) we included the **Photon Initiated (PI)** terms, obtained using QED PDF sets.

- Using inelastic sets (**MRST2004QED**, **CT14QED**) we have evaluated the separate contribution coming from **Double-Dissociative (DD), Single-Dissociative (SD)** and pure **EPA**.
  - While the latter results negligible with respect to the others, the SD term has been found important, varying between **~35%** and **~90%** of the DD term along the spectrum, depending on the PDF set.

- The sum of those three terms have been compared with the complete PI predictions obtained using inclusive sets (**CT14QED_inc**, **NNPDF3.0QED**, **LUXqed**).
  - When available we estimated the uncertainties coming from photon PDFs.
  - The large discrepancies we found between different PDF sets central values have been discussed in light of those systematics.

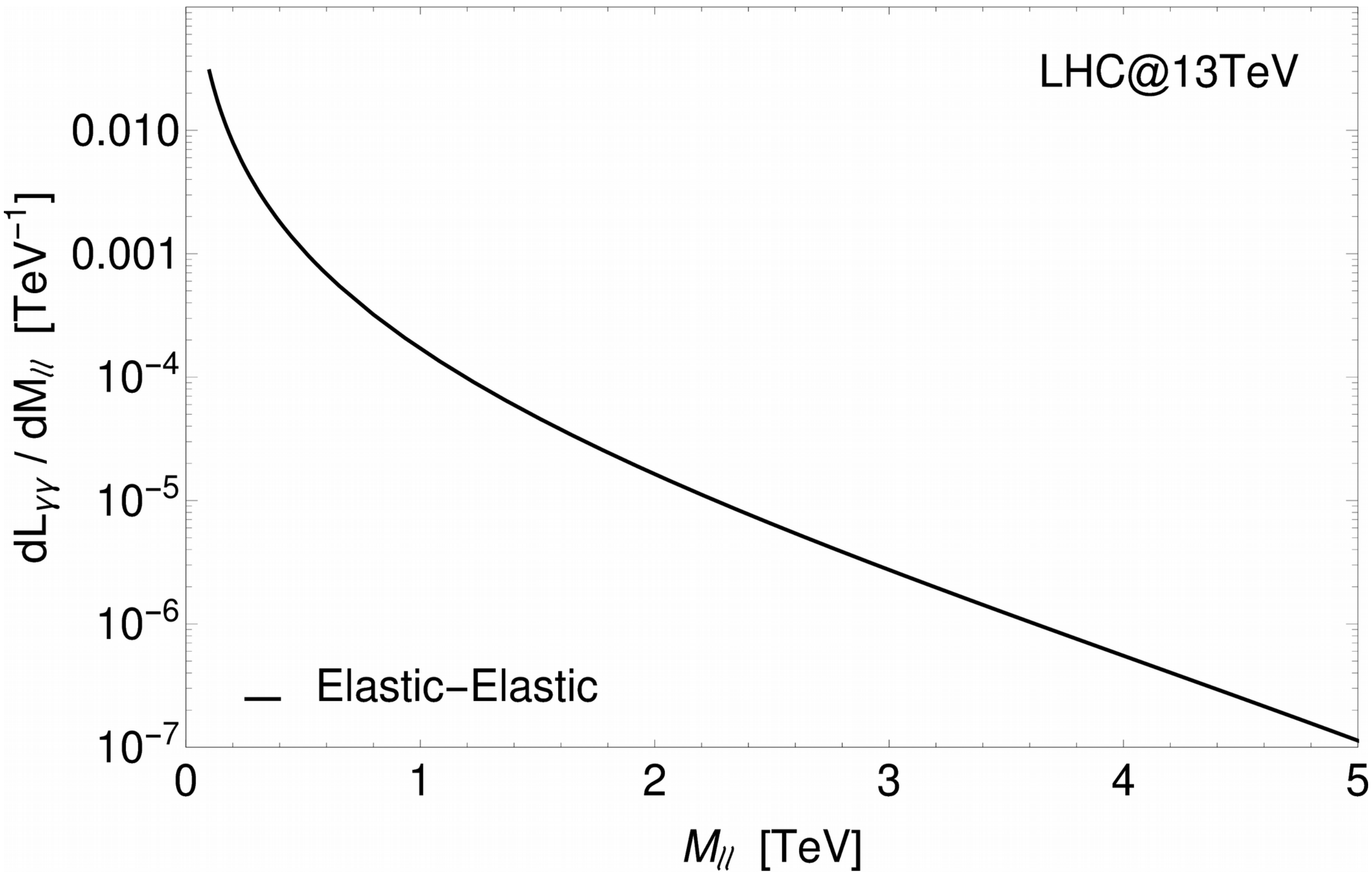
- With the most conservative predictions (**NNPDF3.0QED**) we have analysed the effects of PI contributions in BSM searches for resonant and non-resonant objects in this channel.
  - Bump searches for narrow **Z’** are marginally affected.
  - “Counting events” strategies for non-resonant objects have to consistently include PI effects.
  - Measurements of the **Forward-Backward Asymmetry** (**AFB***) distribution can disentangle BSM signals or they can be used to constrain photon PDFs.

Thank you!

Equivalent Photon Approximation

Integrating **two photon spectra**
we obtain the photon luminosity

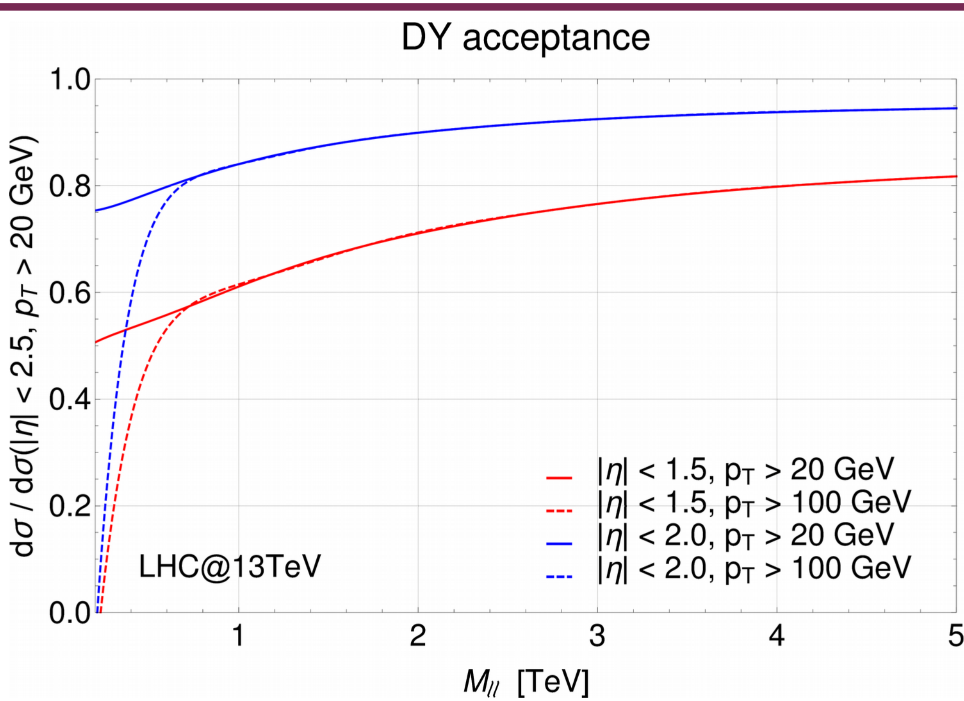
$$\frac{dL_{\gamma\gamma}}{dM_{\ell\ell}} = 2\frac{M_{\ell\ell}}{E_{coll}^2}\int_{Q^2_{1,min}}^{Q^2_{1,max}} dQ_1^2 \int_{Q^2_{2,min}}^{Q^2_{2,max}} dQ_2^2 \int \frac{dx_1}{x_1}\frac{dN}{dx_1 dQ_1^2}(x_1, Q_1^2)\frac{dN}{dx_2 dQ_2^2}(x_2 = \frac{M_{\ell\ell}^2}{x_1 E_{coll}^2}, Q_2^2)$$

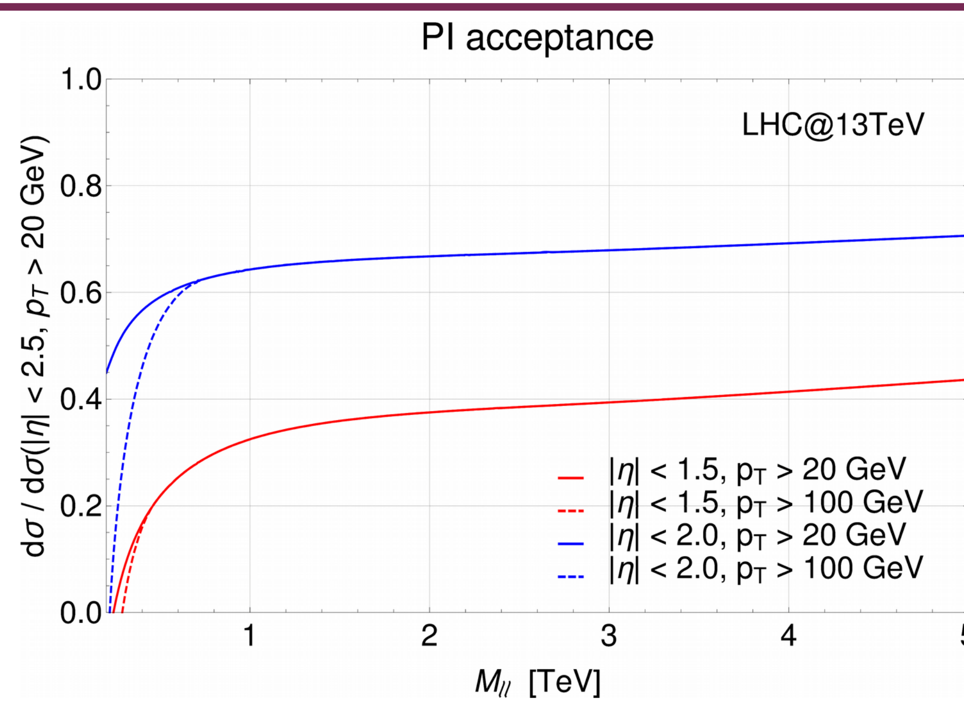


Validated √

[Schul, (2011), *Measurement of two-photons interactions at the LHC*, Louvain U.]

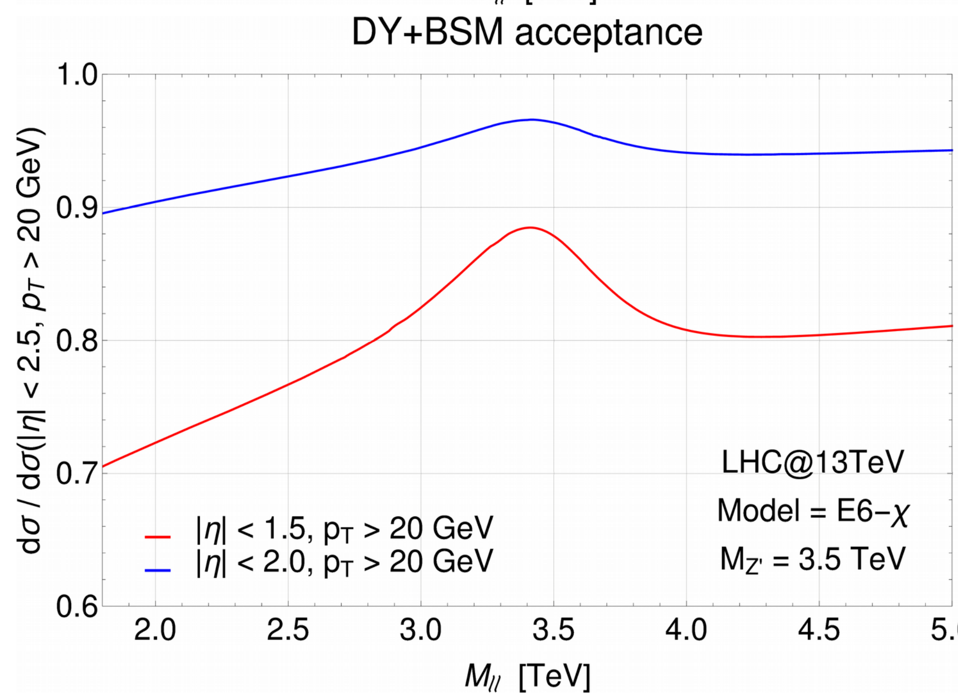
Backup slides



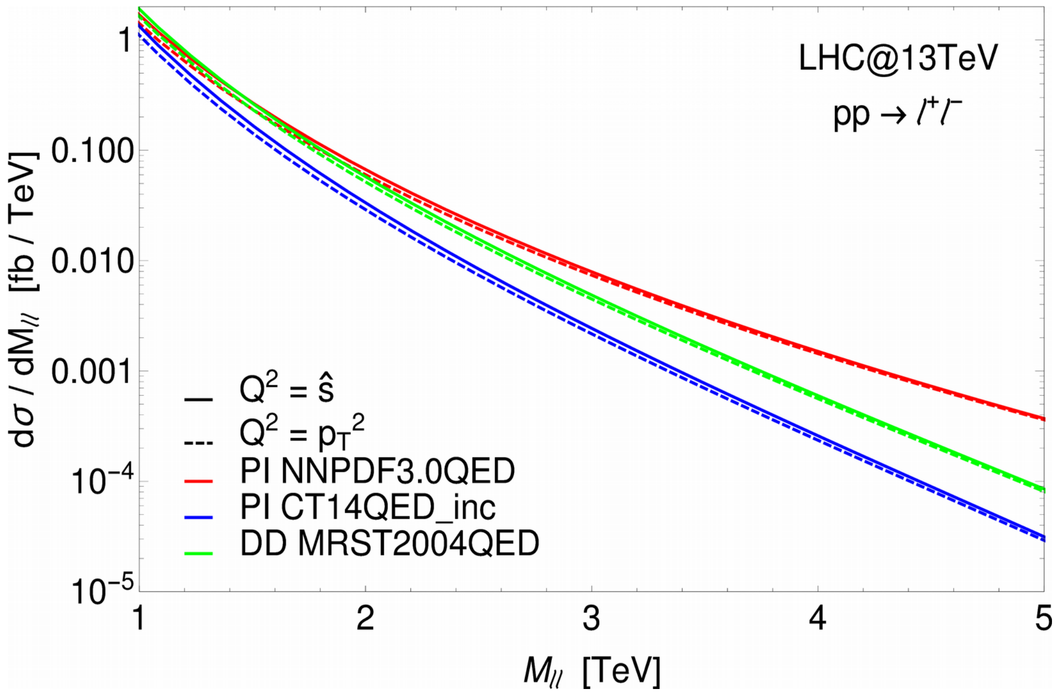


Stronger **η** cuts can in principle reduce the **PI** contribution, at the price of a loss of statistic.

Nevertheless a resonant signal can survive

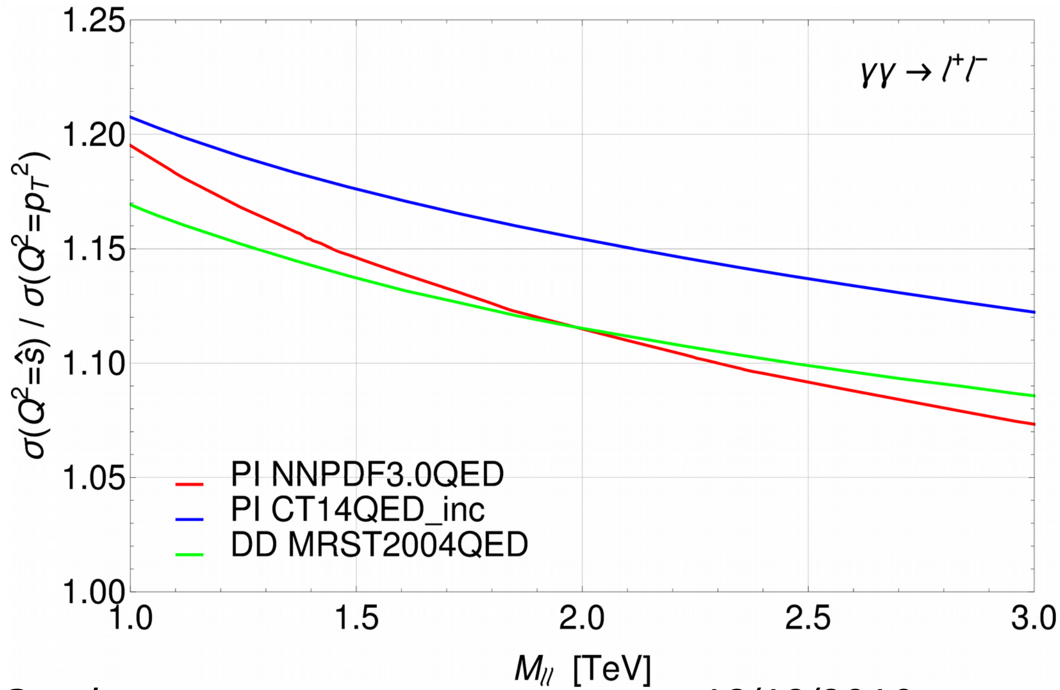


Backup slides



The choice of the factorization scale **can affect** the predictions

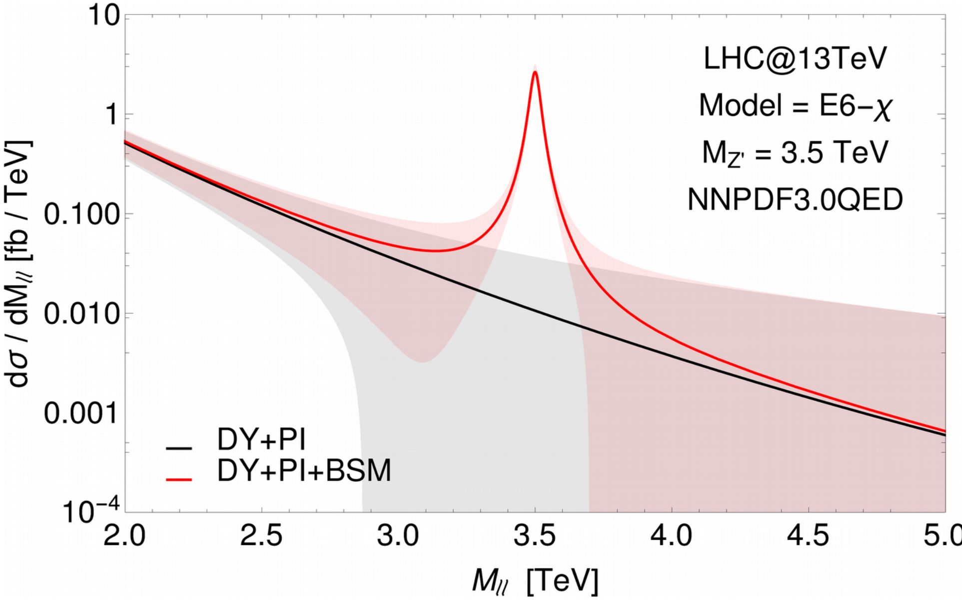
In the **CT14QED_inc** set the difference is of the same order of PDF uncertainties

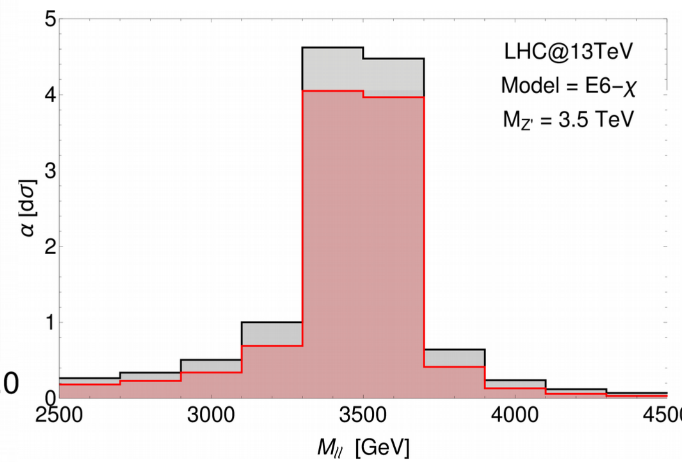


Impact on *Z'* searches

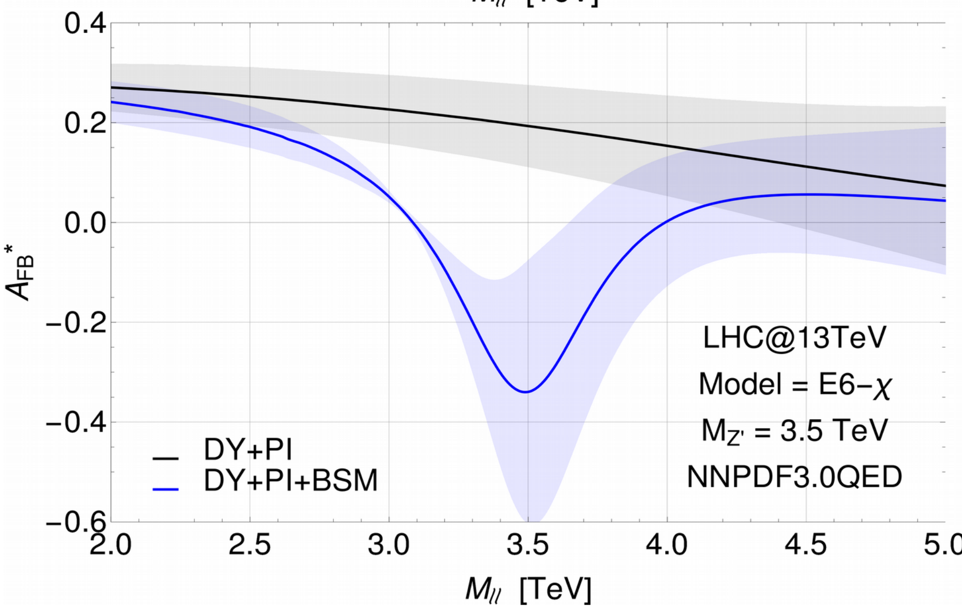
We want to test the sensitivity of the LHC in light of the results we have found.

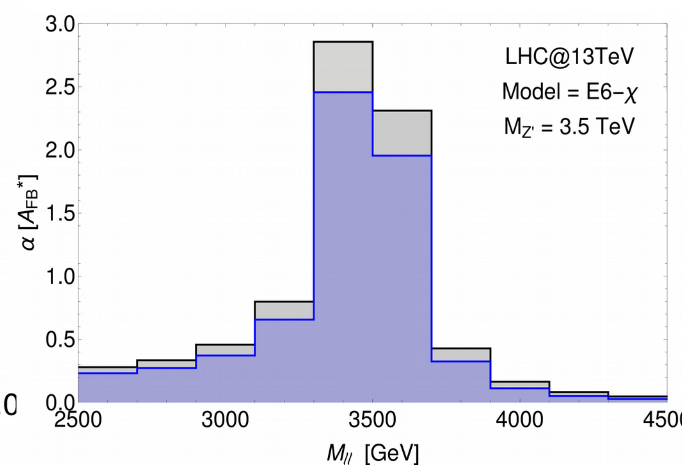
Bump searches for **narrow resonances** are marginally affected by photon interactions.





The invariant mass distribution peaked shape is <u>not much affected</u> by systematics.



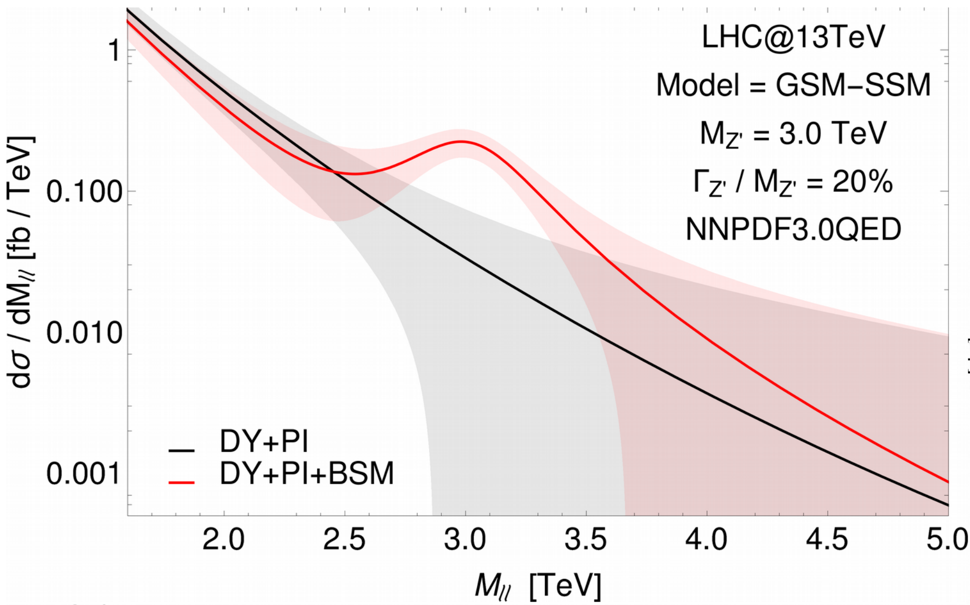


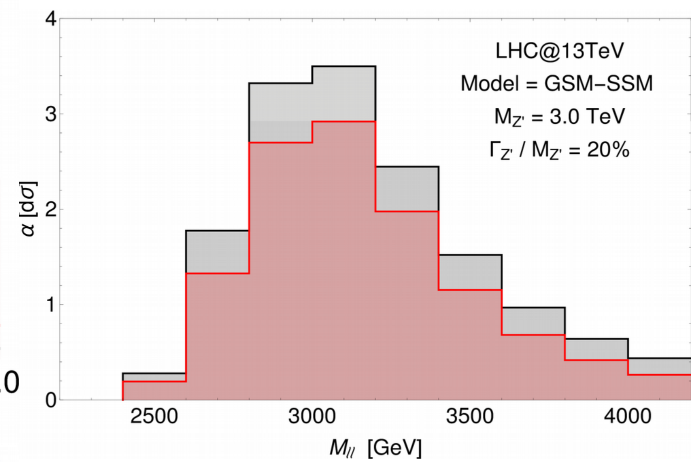
The inclusion of the PI events in the **AFB** is important since they reduce its SM prediction.

Impact on *Z'* searches

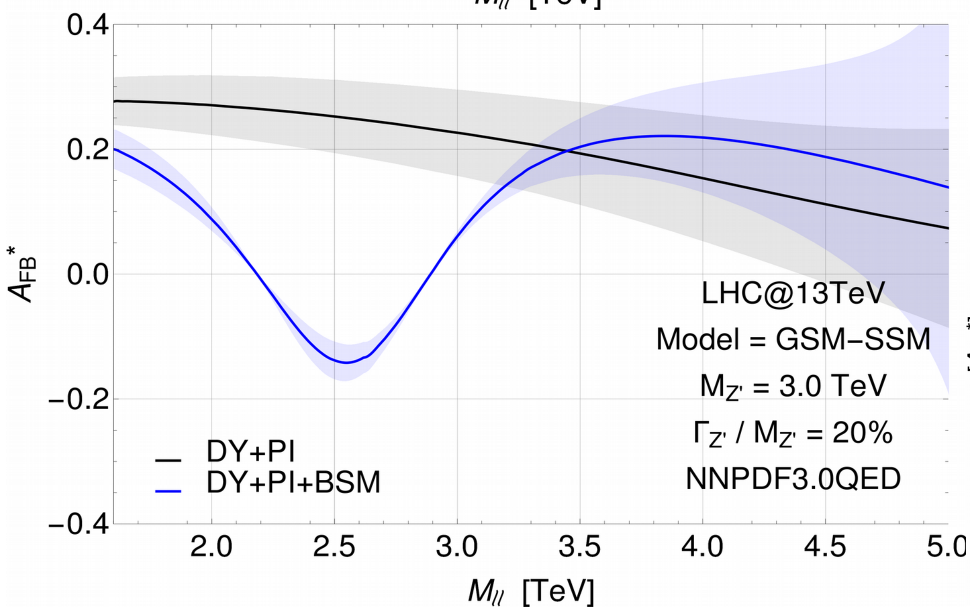
We want to test the sensitivity of the LHC in light of the results we have found.

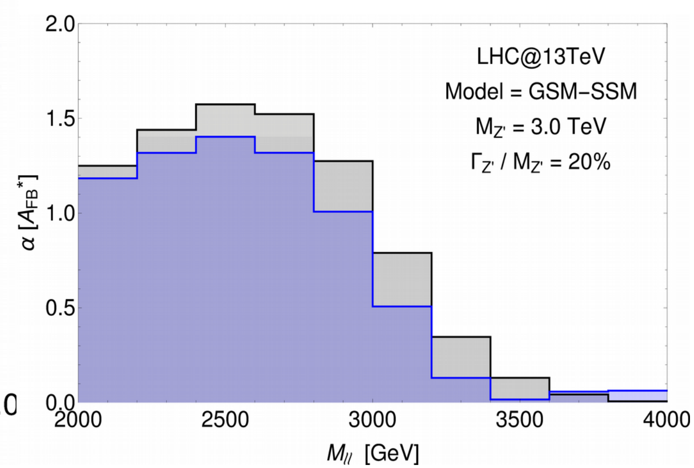
In the case of **wide resonances** (similar to the non-resonant scenario) we can notice the loss of sensitivity due to the photon PDF uncertainties.





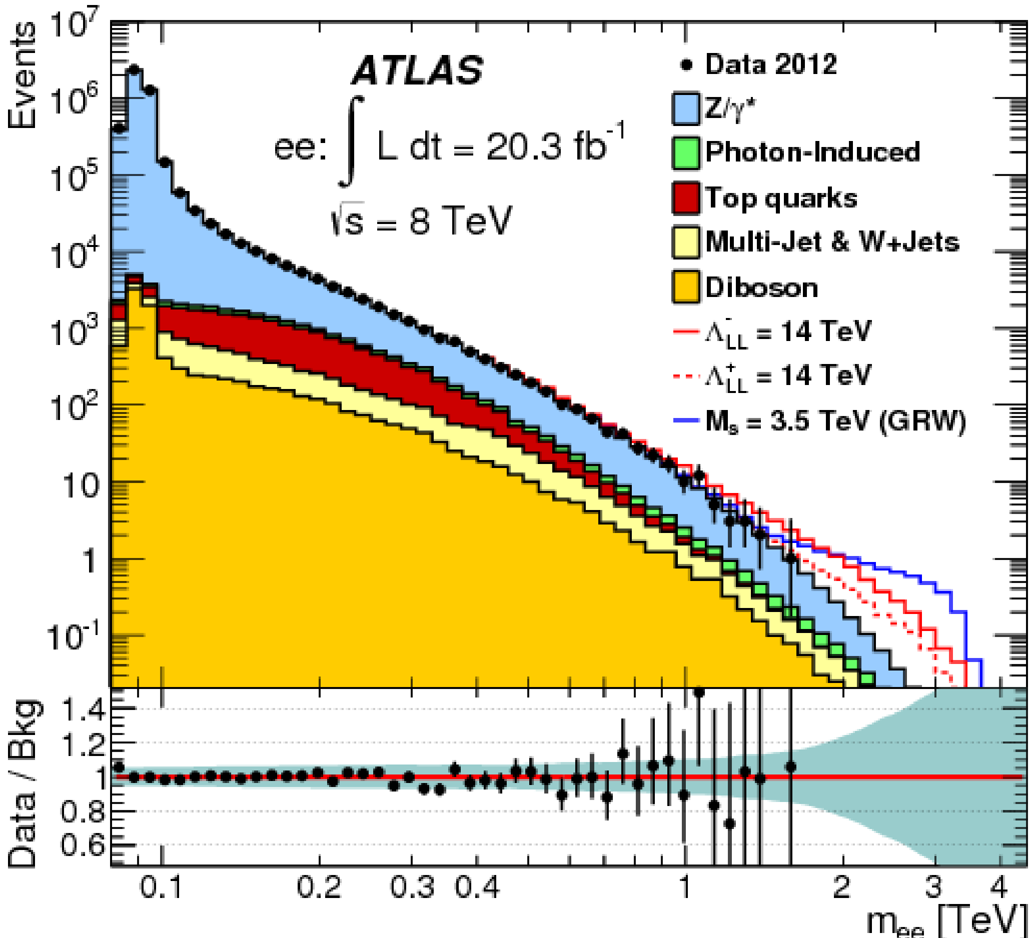
The invariant mass distribution is <u>strongly affected</u> by systematics.

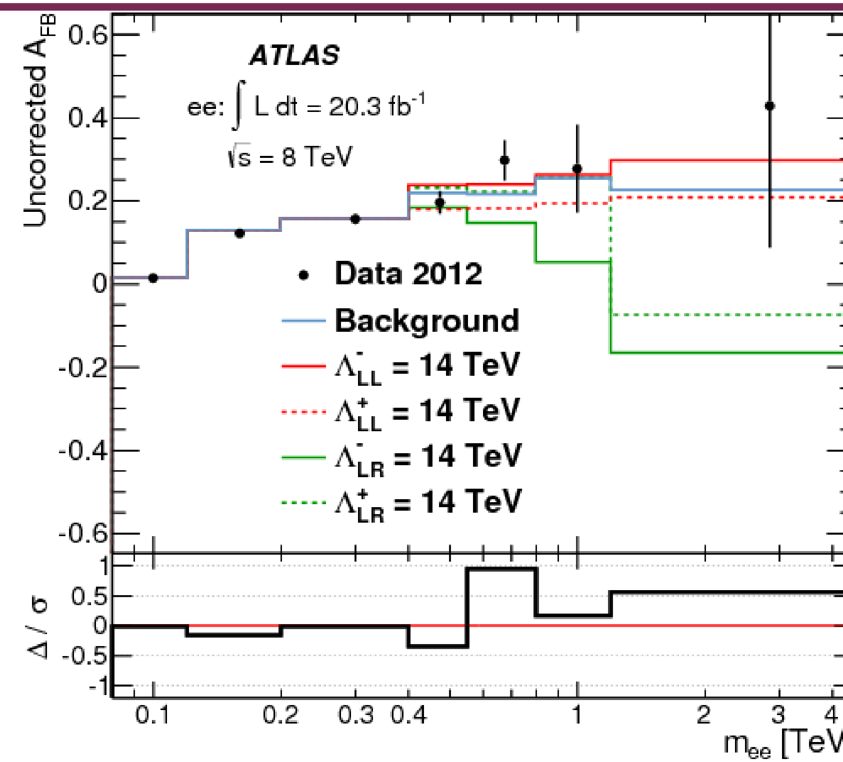




In the **AFB** observable systematic uncertainties are sensibly reduced.

Contact Interactions





[ATLAS Collab.
Eur. Phys. J. C74 (2014) no.12, 3134]()

PI effect <u>can mimic contact interaction</u> signal in both the **invariant mass** and **AFB*** distributions

The correct interpretation of results <u>requires</u> the introduction of PI contribution