Impact of the photon PDFs on di-lepton final states at the LHC

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Southampton University and RAL

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based on arXiv:1606.06646

E. A., Fiaschi, Moretti, Hautmann, Shepherd-Themistocleous (NExT)

A Southampton – RAL collaboration
in the spirit of the NExT Institute

Overview

- **Z' physics at the LHC**
  Single narrow resonances
  Wide resonances

- **Z' searches in the Drell-Yan channel**
  Strategies and current limits

- **The photon induced correction**
  Impact on Z' searches at high di-lepton invariant masses
  Error analysis and theoretical uncertainties

- **Conclusion**

Benchmark models for a Narrow Width Z'-boson

[E.A., Belyaev, King, Fedeli, Shepherd-Themistocleous, arXiv:1010.6058]

$U(1)'$	Parameter	g_V^u	g_A^u	g_V^d	g_A^d	g_V^e	g_A^e	g_V^ν	g_A^ν
E_6 ($g' = 0.462$)	θ								
$U(1)_\chi$	0	0	-0.316	-0.632	0.316	0.632	0.316	0.474	0.474
$U(1)_\psi$	0.5π	0	0.408	0	0.408	0	0.408	0.204	0.204
$U(1)_\eta$	-0.29π	0	-0.516	-0.387	-0.129	0.387	-0.129	0.129	0.129
$U(1)_S$	0.129π	0	-0.129	-0.581	0.452	0.581	0.452	0.516	0.516
$U(1)_I$	0.21π	0	0	0.5	-0.5	-0.5	-0.5	-0.5	-0.5
$U(1)_N$	0.42π	0	0.316	-0.158	0.474	0.158	0.474	0.316	0.316
GLR ($g' = 0.595$)	ϕ								
$U(1)_R$	0	0.5	-0.5	-0.5	0.5	-0.5	0.5	0	0
$U(1)_{B-L}$	0.5π	0.333	0	0.333	0	-1	0	-0.5	-0.5
$U(1)_{LR}$	-0.128π	0.329	-0.46	-0.591	0.46	0.068	0.46	0.196	0.196
$U(1)_Y$	0.25π	0.833	-0.5	-0.167	0.5	-1.5	0.5	-0.5	-0.5
GSM ($g' = 0.760$)	α								
$U(1)_{SM}$	-0.072π	0.193	0.5	-0.347	-0.5	-0.0387	-0.5	0.5	0.5
$U(1)_{T_{3L}}$	0	0.5	0.5	-0.5	-0.5	-0.5	-0.5	0.5	0.5
$U(1)_Q$	0.5π	1.333	0	-0.666	0	-2.0	0	0	0

The Soton group is the theory reference for the CMS Z' Physics in di-lepton final states. We analyzed systematically all benchmark models for data interpretation.

Z' physics at the LHC in Drell-Yan tools and methods

- Great accuracy at QCD and/or EW NLO and beyond, mass scale dependent K-factors are implemented in several tools:

  > NLO QCD via MC@NLO [Frixione et al.] and POWEG [Alioli et al.]
  > NLO+NLL [Jezo, Lyonnet et al. '14]
  > Fully exclusive QCD and EW corrections via FEWZ [Ye Li '12]
  > NLO EW via HORACE [Carloni Calame et al. '05]

- At LO, great ferment on Interference and Finite Width (FW) effects:

  > Z' and W' Physics [E.A. et al. '12, Bella et al., Jeso et al. '14]

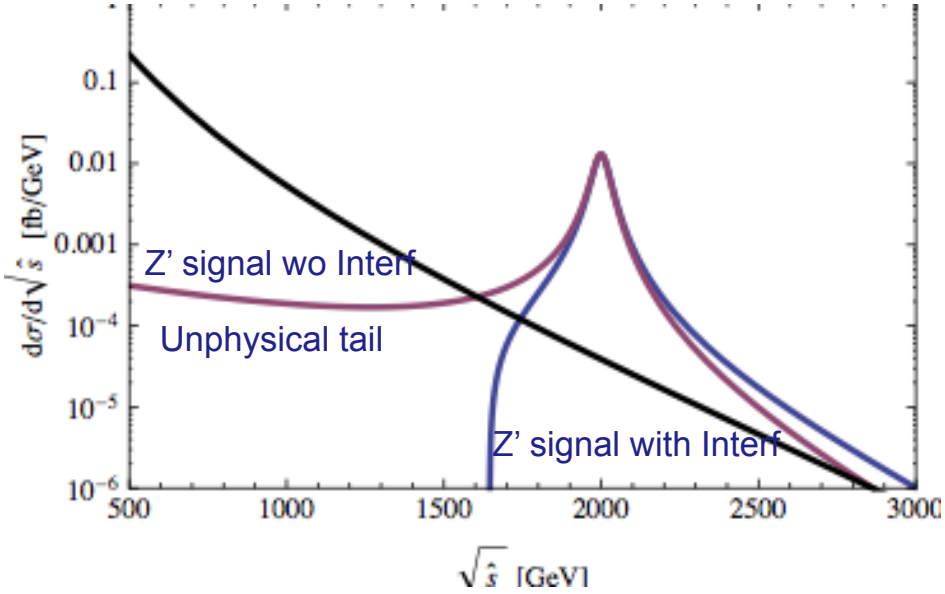
- Interference and FW effects are model-dependent and CPU time consuming. Different strategies are adopted by ATLAS and CMS from 2014 on.

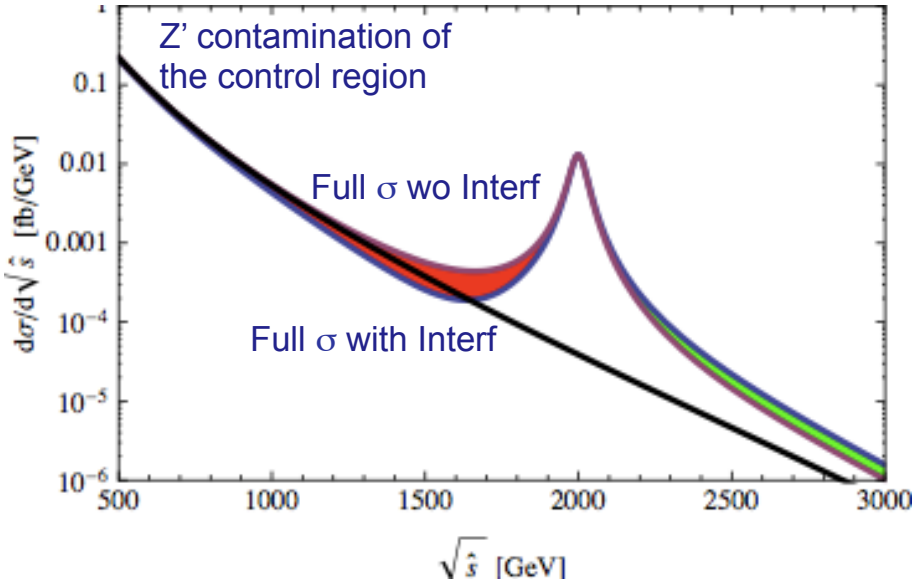
Focus on Z' searches at LO: where do we stand?

SSM Z' Drell-Yan production @ the LHC
Non-interferred model vs complete SSM

[E.A., Becciolini, Belyaev, Fiaschi, Moretti, Shepherd-Themistocleous, arXiv:1304.6700]

pp → γ, Z, Z' → lepton pair





Interference effects are sizeable and model-dependent:

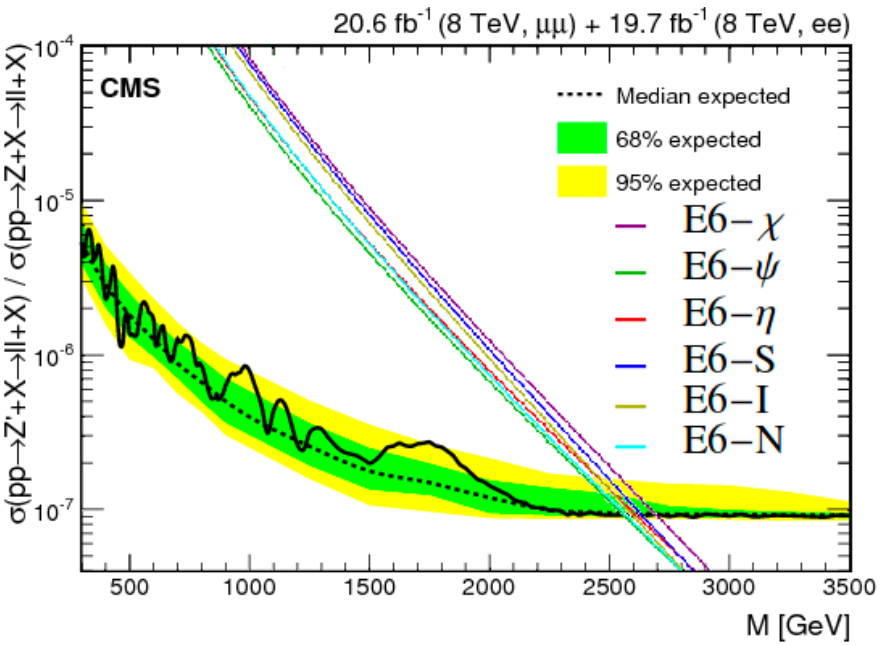
up to O(200%) in the SSM

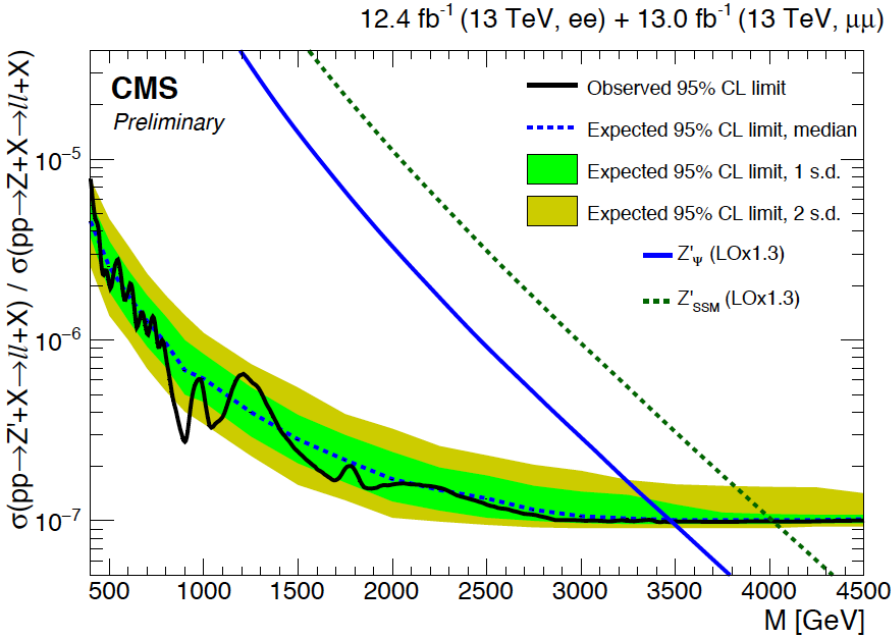
Impose **IM(ll)-$M_{Z'}$I < 5% E_{coll}** for a model independent approach up to O(10%) acc. for all Z'-boson masses and all NW Z' models. Applied in the CMS analyses for data interpretation from arXiv:1412.6302 on.

Limits on Narrow width Z' from CMS

[E.A., Belyaev, Fiaschi, Moretti, Shepherd-Themistocleous, arXiv:1503.02672]

pp → γ, Z, Z' → ee, mm with IM(ll)-$M_{Z'}$l < 5% E_{coll}



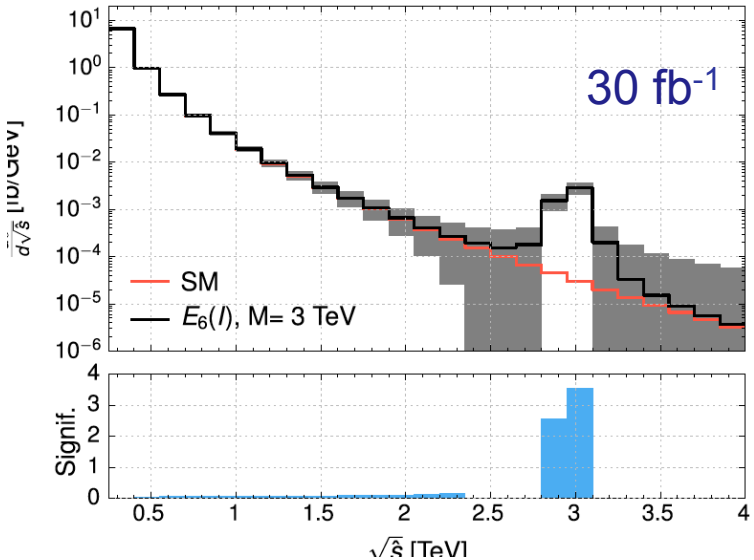


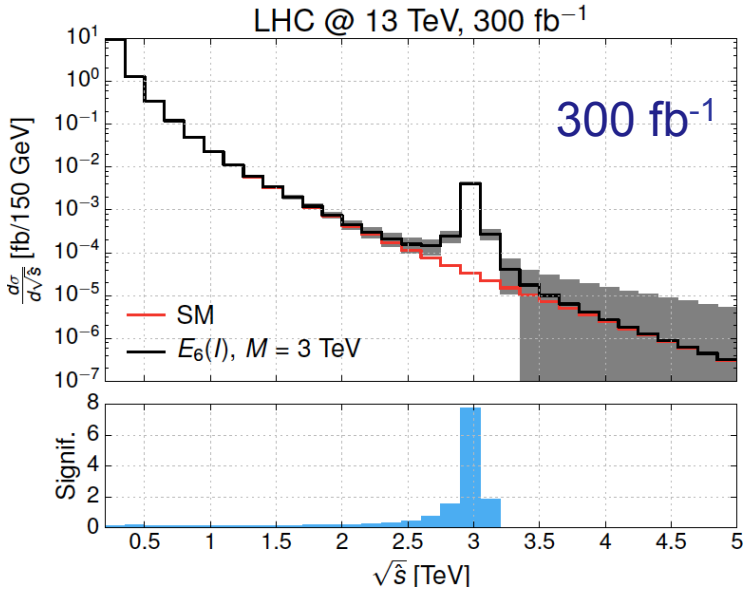
Class	E_6						GLR				GSM		
$U'(1)$ Models	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM	T_{3L}	Q
$M_{Z'}$ [GeV]	2700	2560	2620	2640	2600	2570	3040	2950	2765	3260	2900	3135	3720

Search window for Run II

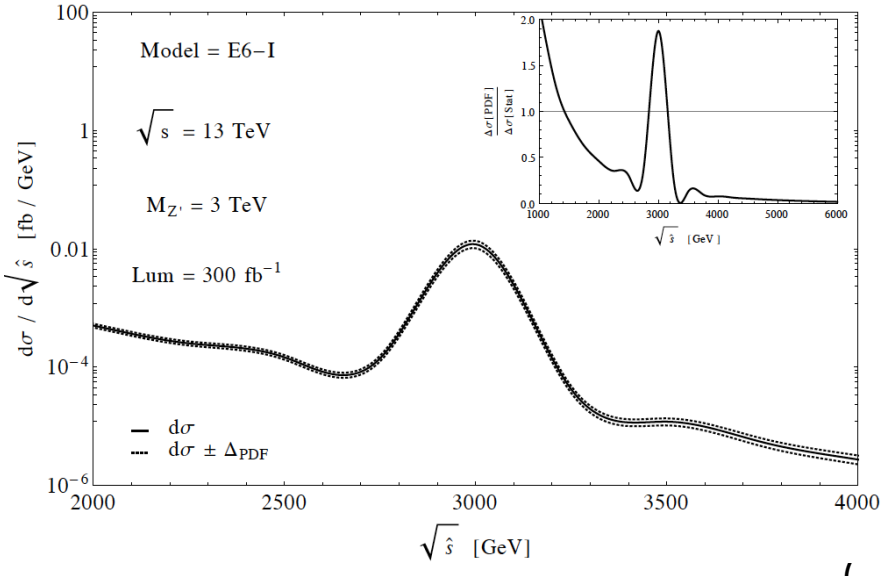
Similar limits have been obtained by Jezo et al., arXiv:1410.4692

Realistic prospects for a narrow Z' @ 13 TeV





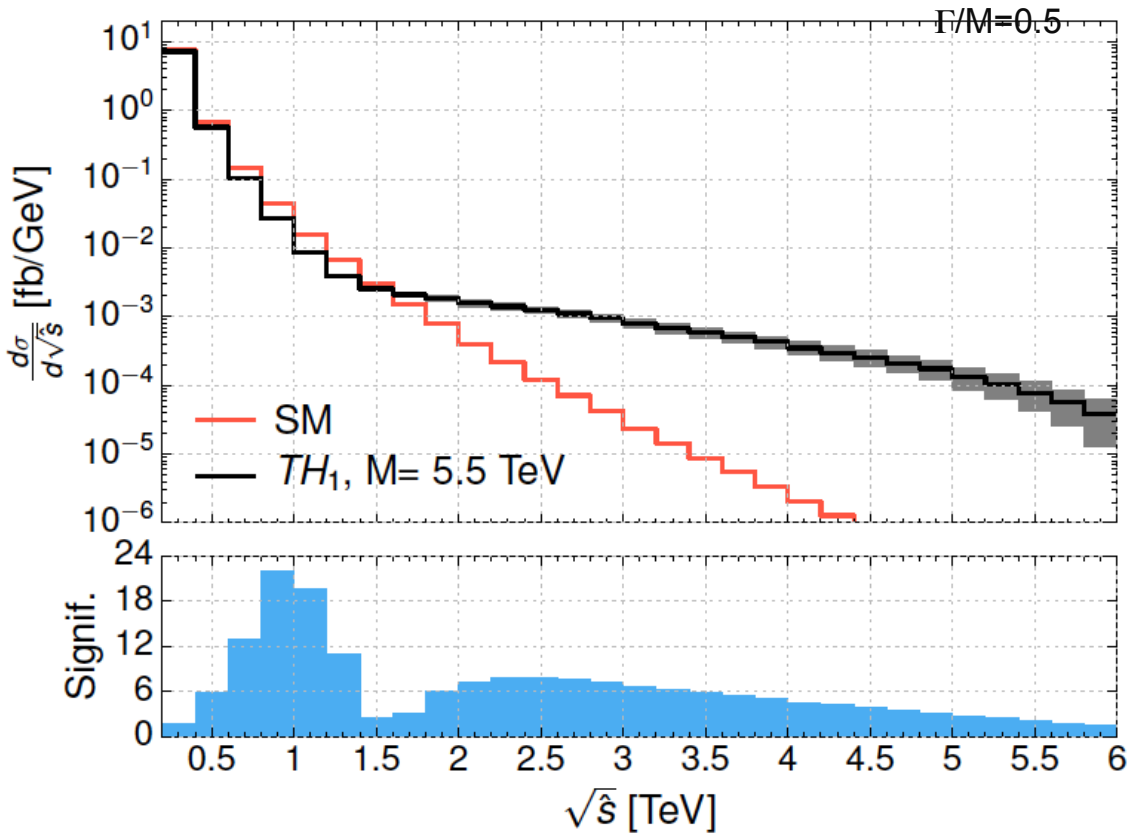
- On the PDF's, see review by Accardi et al. 1602.03154 and 1603.08096
- At low luminosity, the Photon Induced (PI) background could affect the fitting procedure.
- At high luminosity, both PI and PDF error at large-x could have an impact on data interpretation.



Realistic prospects for a wide Z' @ 13 TeV

Benchmark models:

- wide SSM [Altarelli et al., Z. Phys. C45, 109 (1989)]
- Non-Universal SM [Malkawi etal., hep-ph/9906215; Kim et al., arXiv:1405.7762]
- Contact interactions



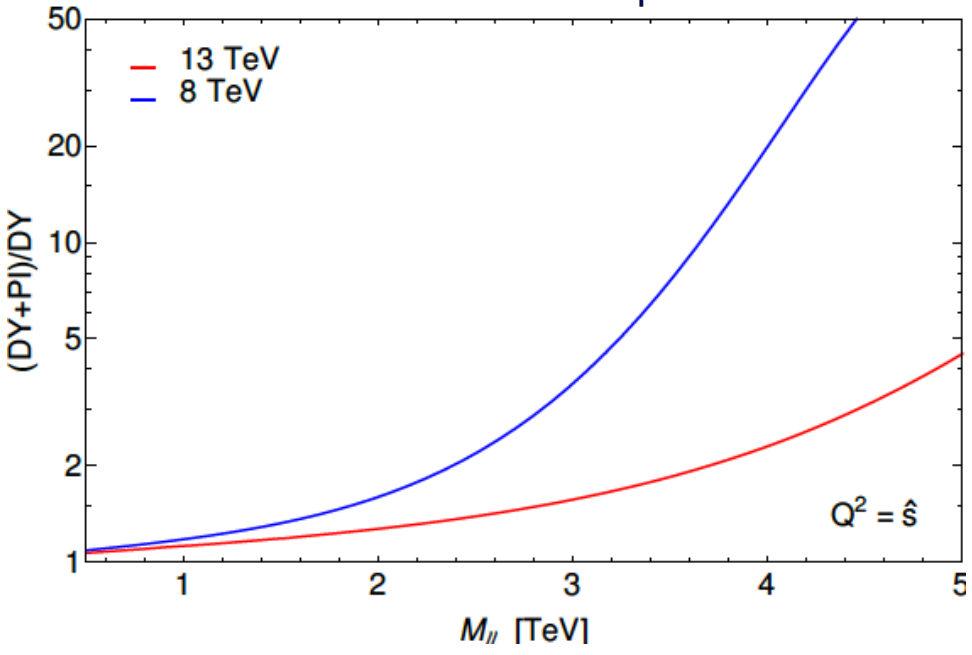
Z' bosons could be wide and appear as non-shaped signals evenly spread over the SM backg. leading to a difficult interpretation of any excess of events in the counting strategy.

The Photon Induced (PI) background can become an issue for data interpretation

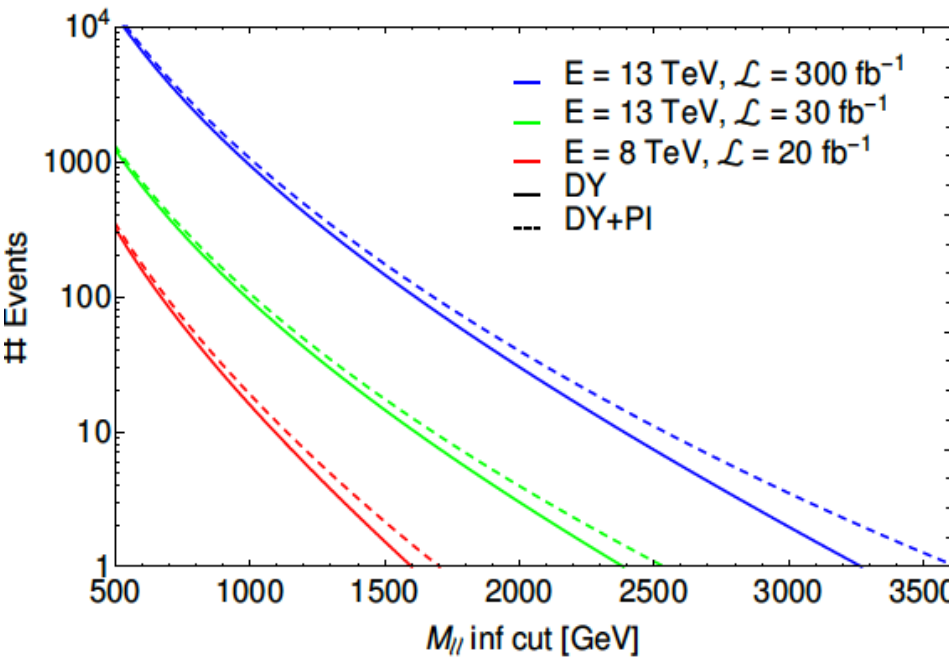
PI impact on Z' searches in DY @ 13 TeV

[E.A., Fiaschi, Hautmann, Moretti, Shepherd-Themistocleous, arXiv:1606.06646]

PI contribution to the e+ e- spectrum



Cumulative e+ e- events



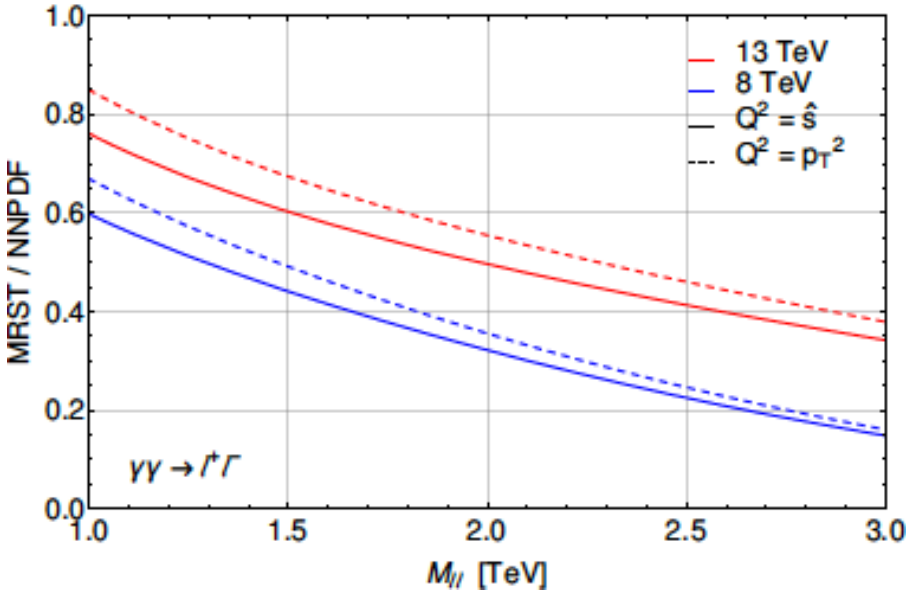
The PI contribution can be sizeable @ 13 TeV

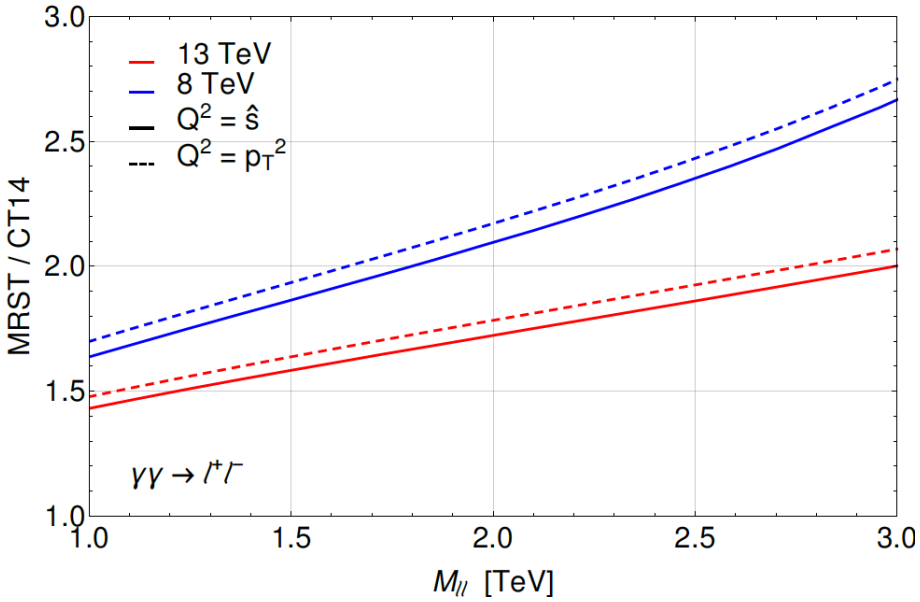
PI = 50% DY at 2.5 TeV with NNPDF
PI = 100% DY at 3.5 TeV with NNPDF

The PI can also affect the shape of SM the background.

PI impact on Z' searches in DY @ 13 TeV

Comparison between different QED PDFs





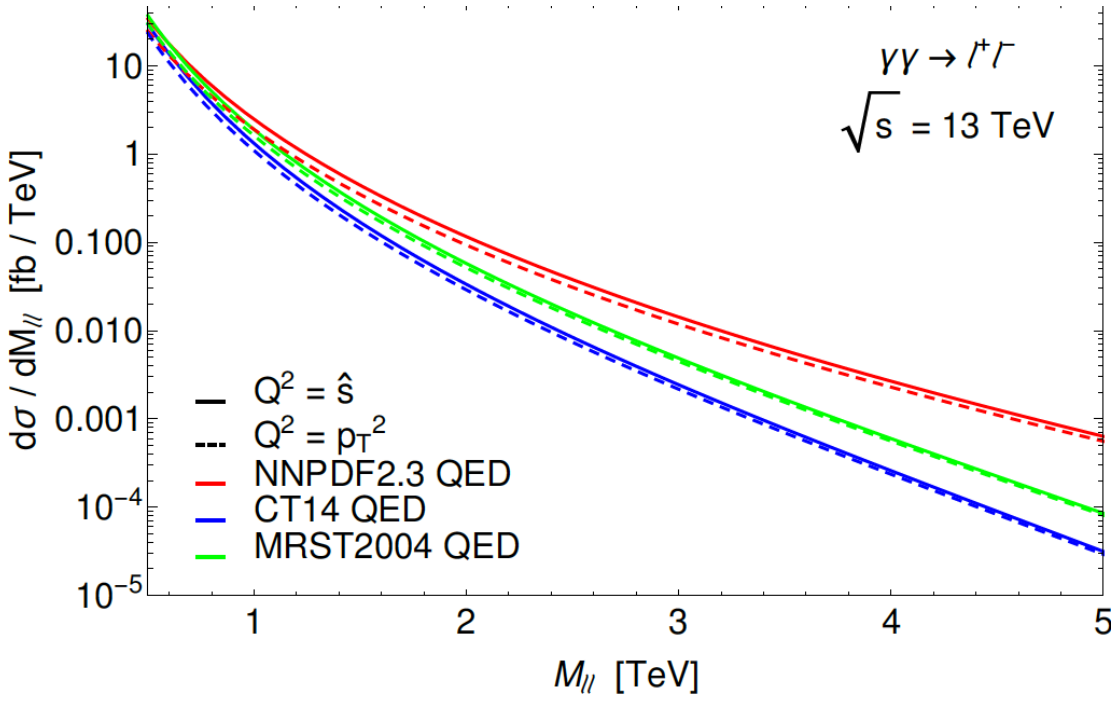
Very different central values

MRST2004QED = **40%** NNPDF2.3QED at 2.5 TeV
CT14QED = **20%** NNPDF2.3QED at 2.5 TeV

PI = 50 - 100% DY with NNPDF2.3QED (2.5 – 3.5 TeV)
PI = 20 - 40% DY with MRST2004QED (2.5 – 3.5 TeV)
PI = 10 - 20% DY with CT14QED (2.5 – 3.5 TeV)

PI impact on Z' searches in DY @ 13 TeV

Comparison between different QED PDFs

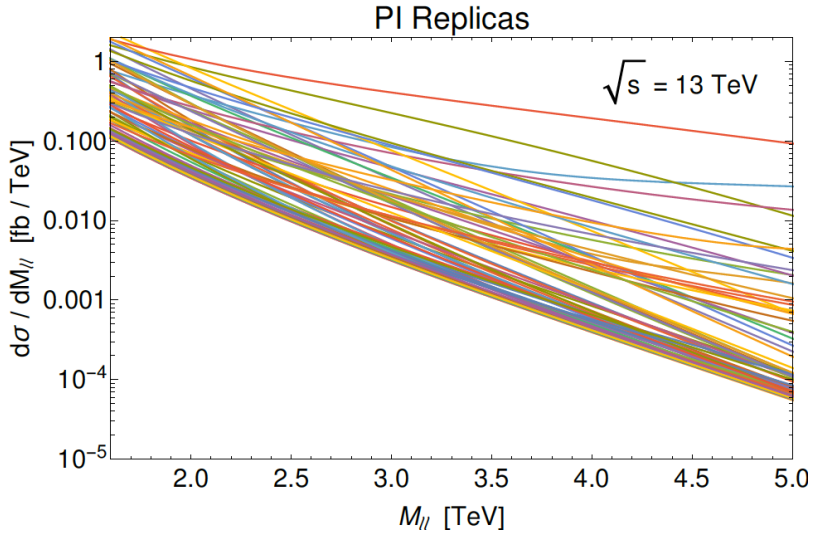


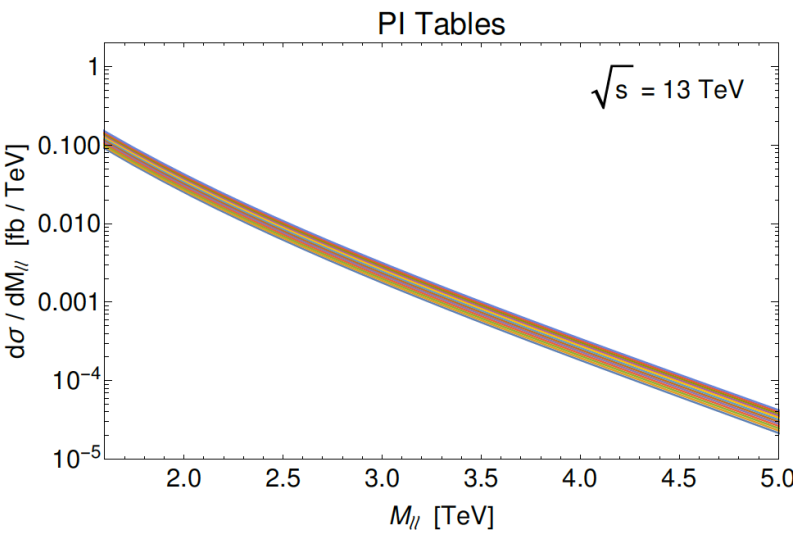
Differences between the predictions (central value) from each QED PDF set are substantial.

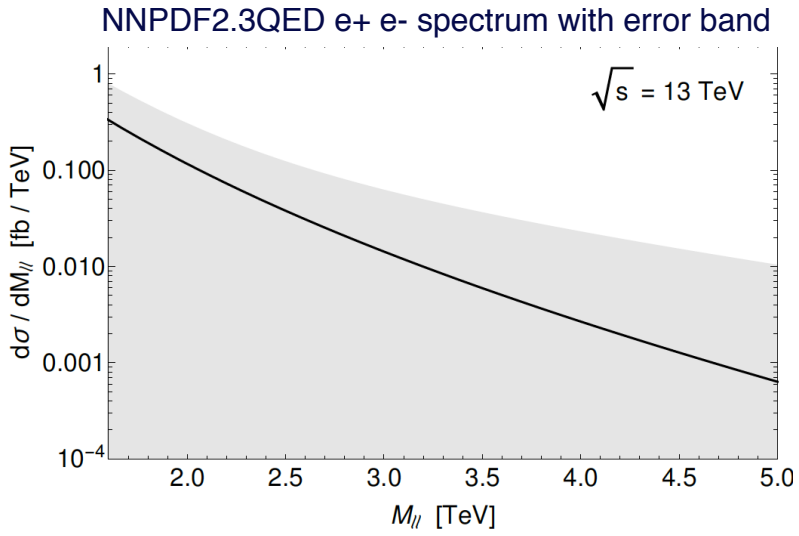
That is already a measure of the PI uncertainty.

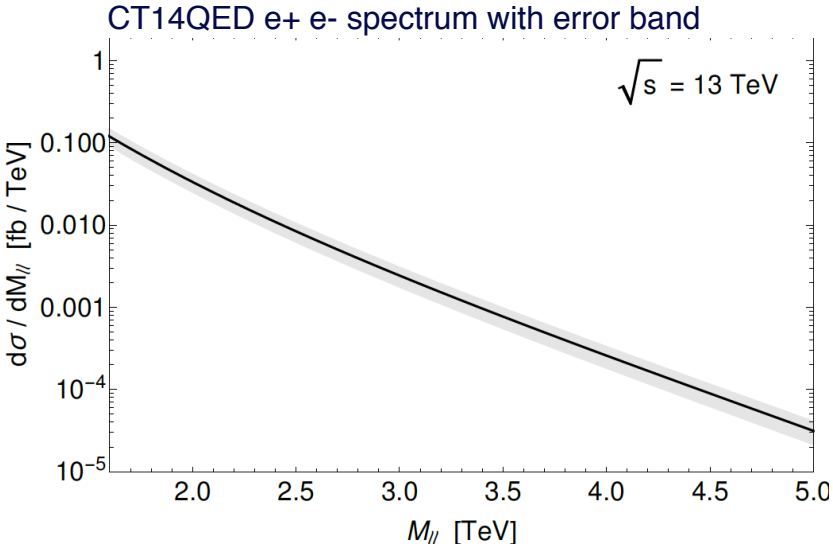
QED PDF uncertainty on the PI @ 13 TeV

See also: Manohar et al. 1607.040266 and Harland-Lang et al: 1607.04635





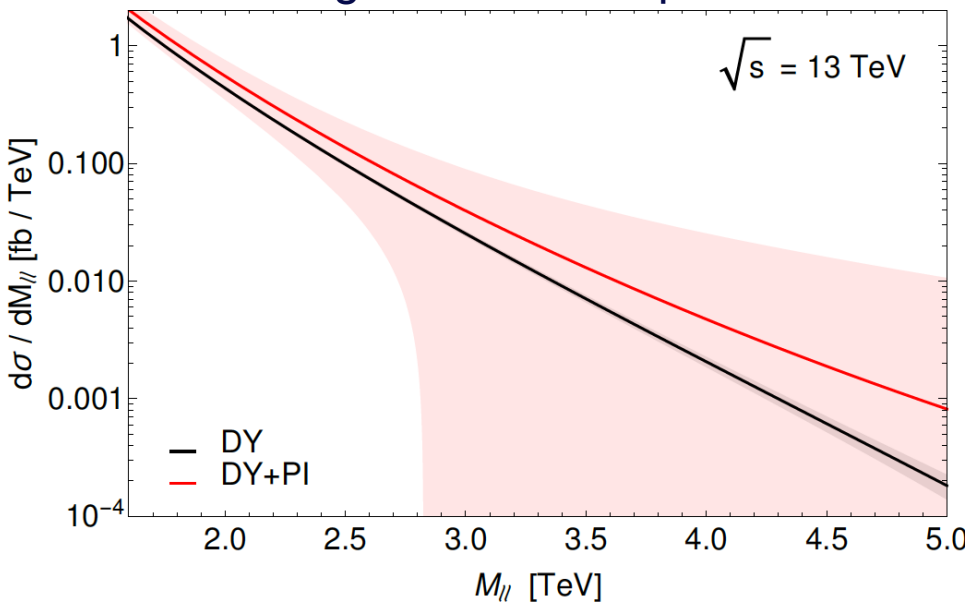


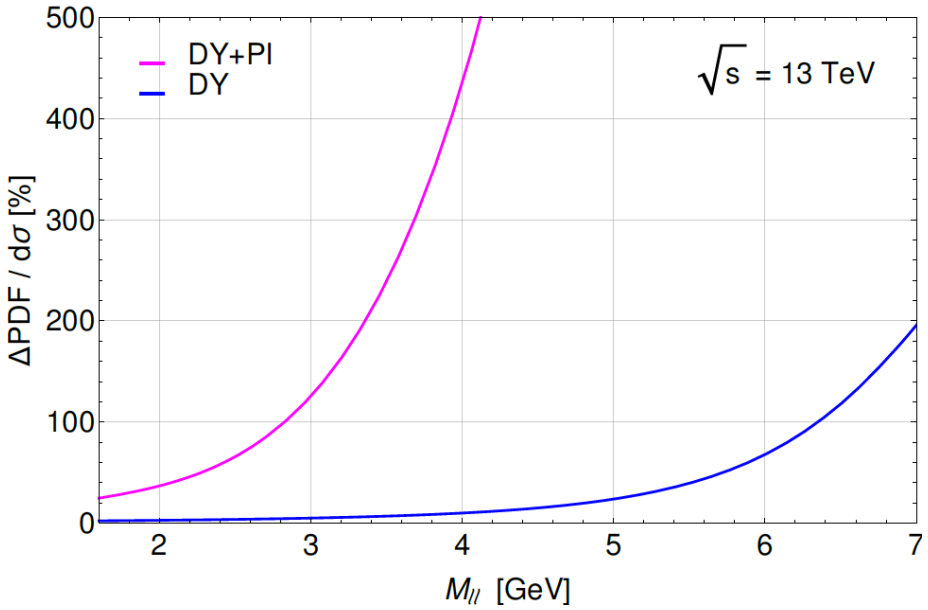


QED PDF uncertainty in DY @ 13 TeV

with the NNPDF replica method

SM background: e+ e- spectrum





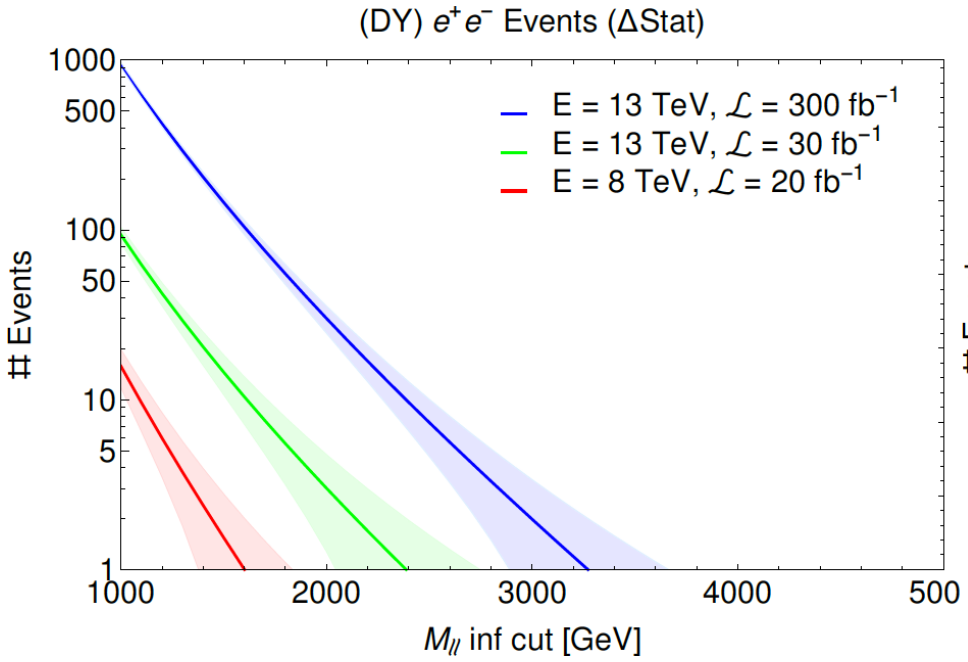
Very large systematic error on DY

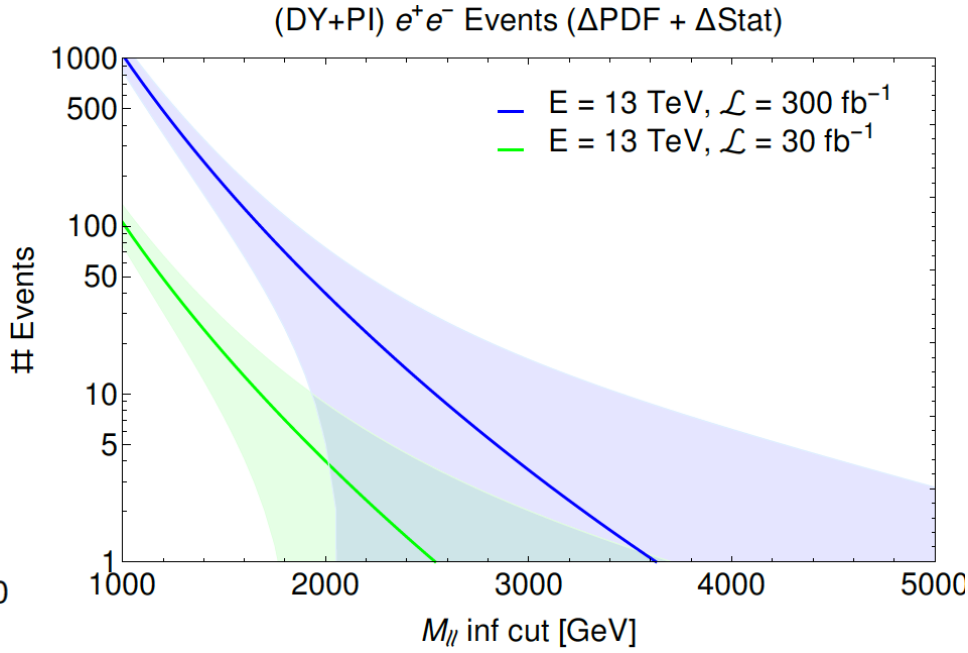
(PI + DY) PDF error = 60% (2.5 TeV)
PI central value = 50% DY central value

PI + ΔPI = 80 – 350 % DY @ 2.5 – 3.5 TeV

QED PDF uncertainty in DY @ 13 TeV

with the NNPDF replica method



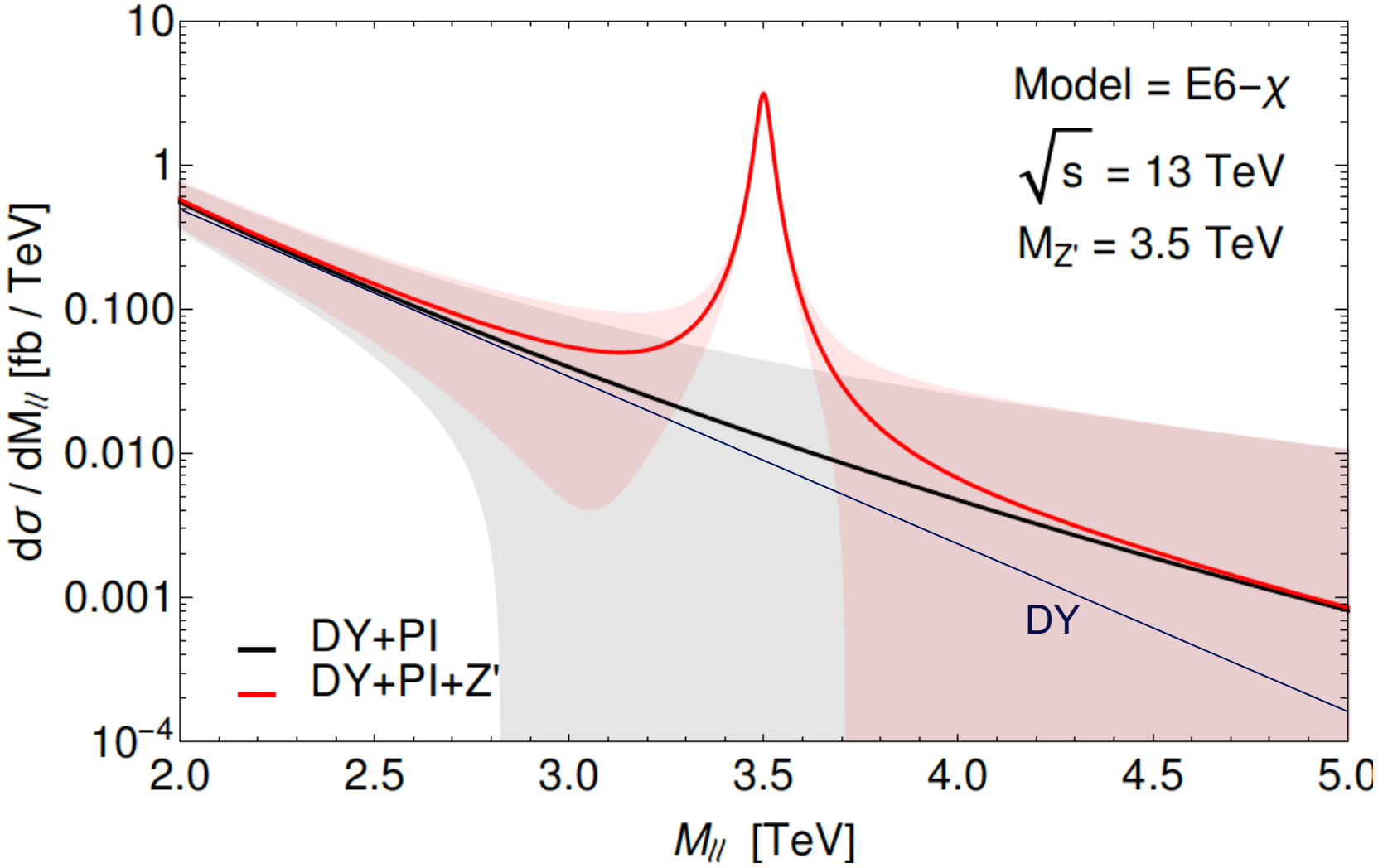


The number of SM background events is very poorly determined.

What is background free via pure DY might NOT be anymore with DY + PI plus PDF error.

Resonant Z' search in DY @ 13 TeV

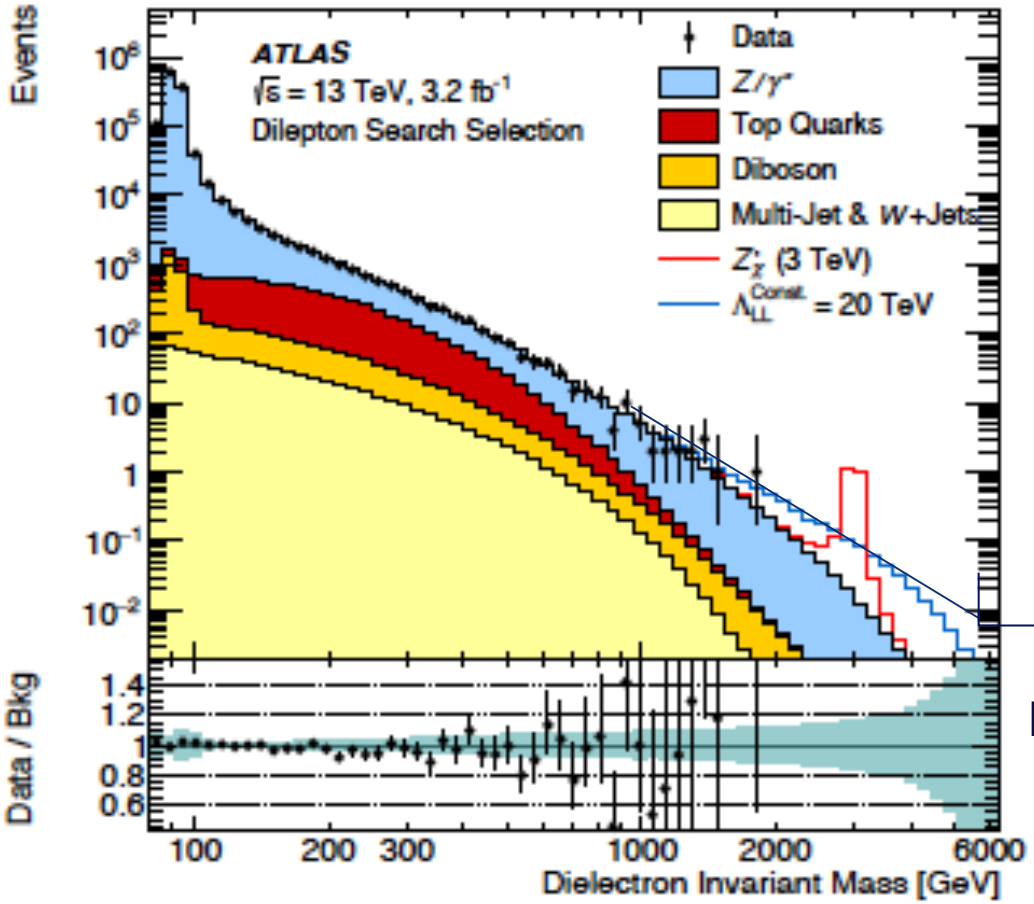
with the NNPDF replica method



Non-resonant Z' searches in DY @ 13 TeV

with the NNPDF replica method

arXiv:1607.03669v



Pi and PDF error might blurry any non-resonant excess

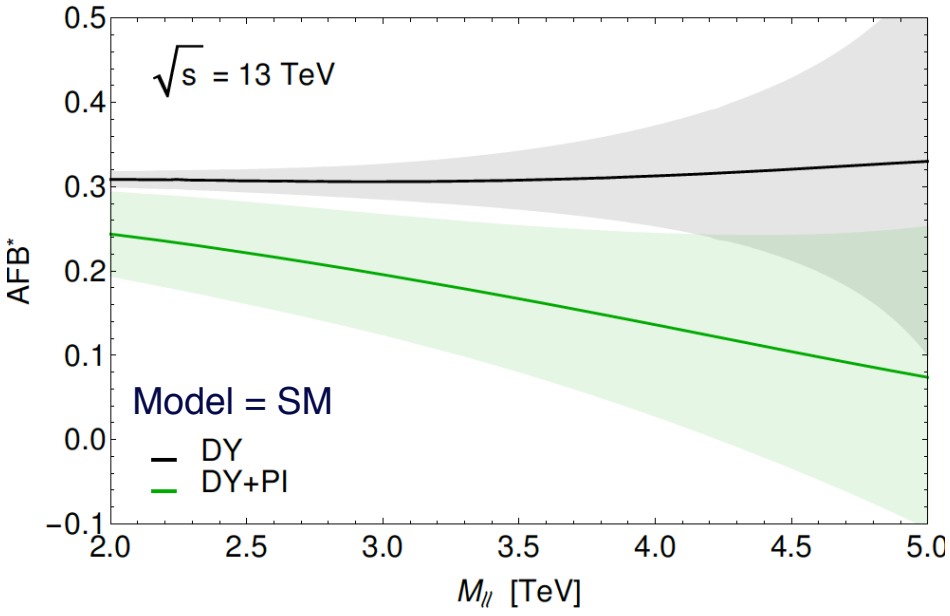
DY + Pi with PDF error rescaling

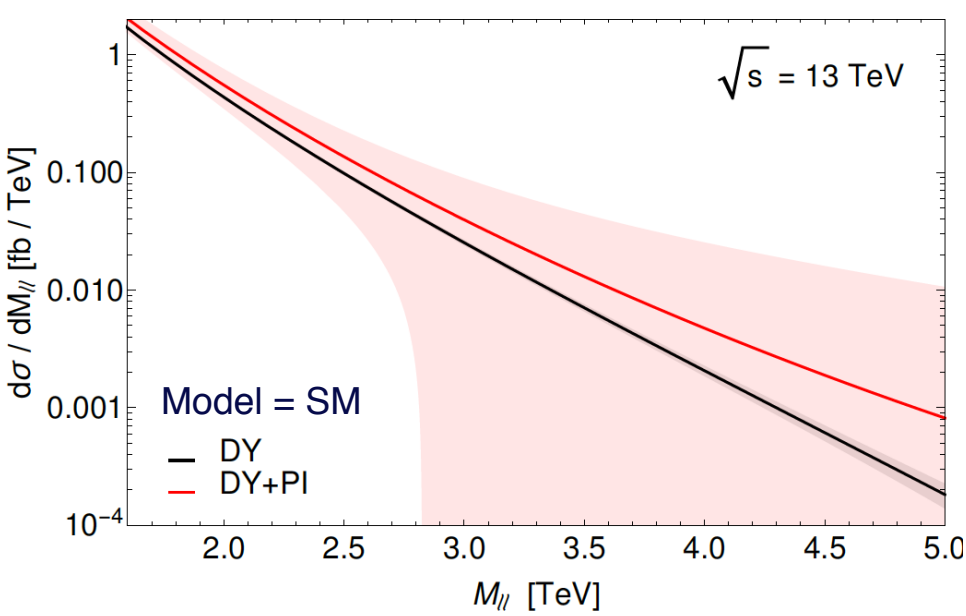
Forward-Backward Asymmetry @ 13 TeV

to reduce systematic errors

$A_{FB}=(\sigma_F-\sigma_B)/(\sigma_F+\sigma_B)$
is defined in the CM of the hard-scattering where the Forward and Backward directions are taken with respect to the incoming quark.

A_{FB} can be reconstructed at the LHC via the boost variable i.e. the rapidity of the dilepton system: $Y_{ll}=0.5\ \log[(E_{ll} + P_{ll})/(E_{ll} - P_{ll})]$

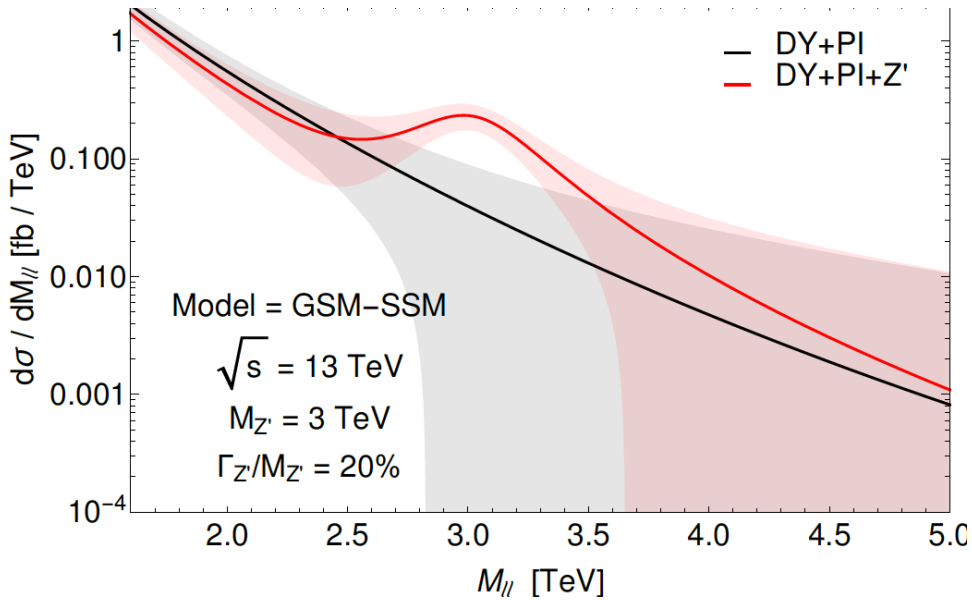


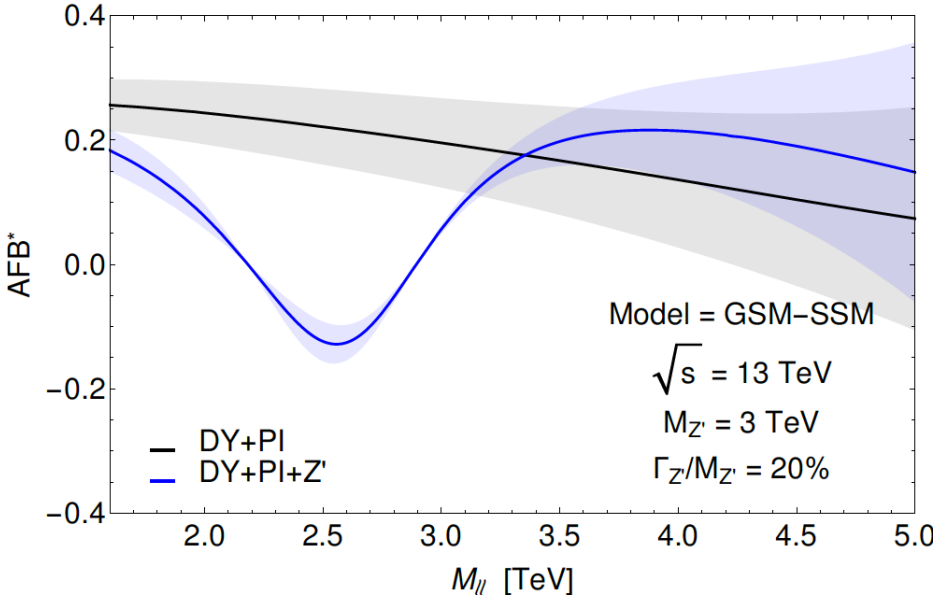


AFB is less affected by QED effects

Forward-Backward Asymmetry @ 13 TeV

for data interpretation in wide Z‘ searches





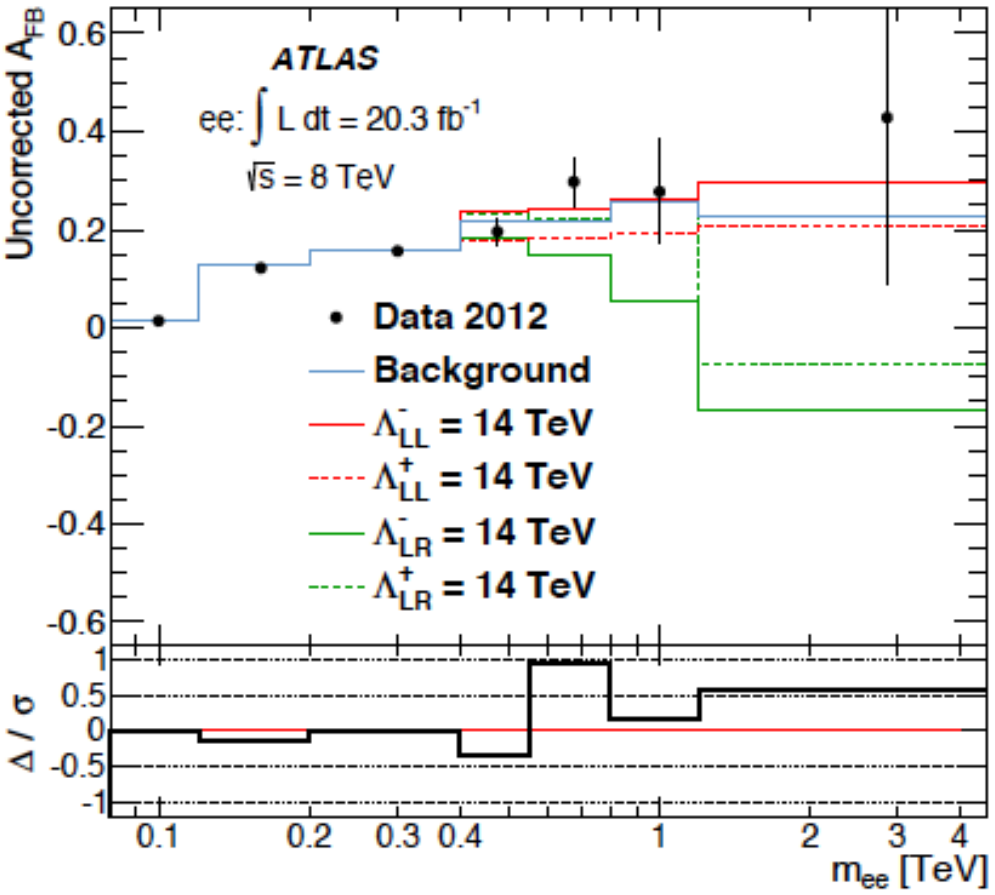
The off-peak AFB is more robust against QED effects.

This independent and differently shaped observable could be then used as a post-discovery variable to help validate any possible excess of events observed in the di-lepton spectrum.

Forward-Backward Asymmetry @ 13 TeV

for data interpretation in wide Z‘ searches

arXiv:1407.2410



An excellent measurement hopefully to be continued.

Conclusions

- For the Z'-boson search at the LHC in di-lepton final states, there are two dominant irreducible SM backgrounds:
  i) DY production via Z* and γ
  ii) photon-induced production (PI)

- For the latter, three PDF sets have been used: CT14, MRST and NNPDF.

- For assessing theory systematics, while the DY is generally under control this is no longer the case for the PI process, irrespectively of which PDF set is used:

  i) large differences occur between the three packages in the central value predictions
  ii) CT14QED has no systematic procedure for the PDF error extraction, yet.
  iii) MRST2004QED offers no error analysis.
  iv) NNPDF2.3QED uses the replica method that yields a large uncertainty, O(100%).

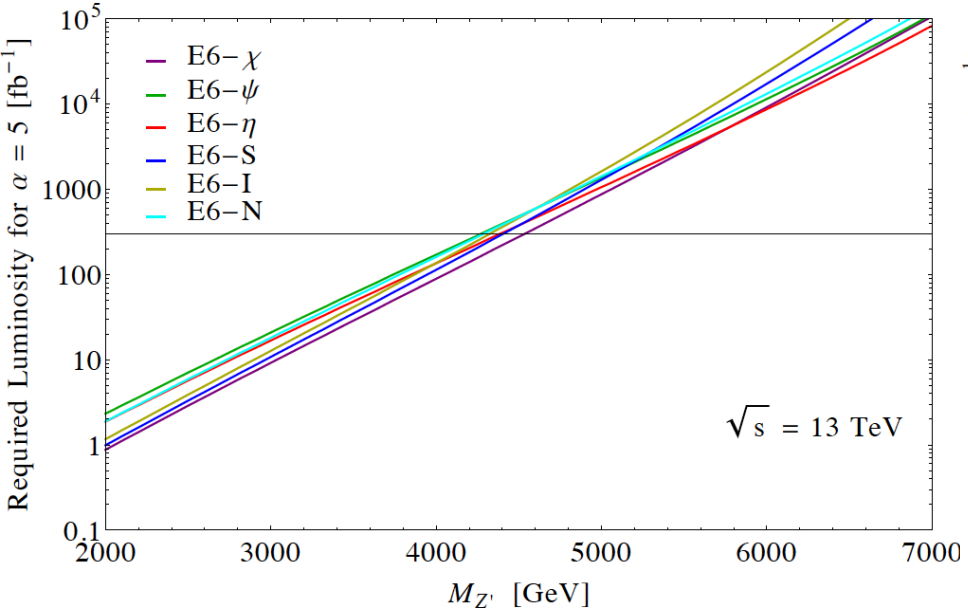
- This QED theoretical uncertainty is well visible in the di-lepton spectrum at high invariant masses and has impact on resonant and non-resonant data interpretation.

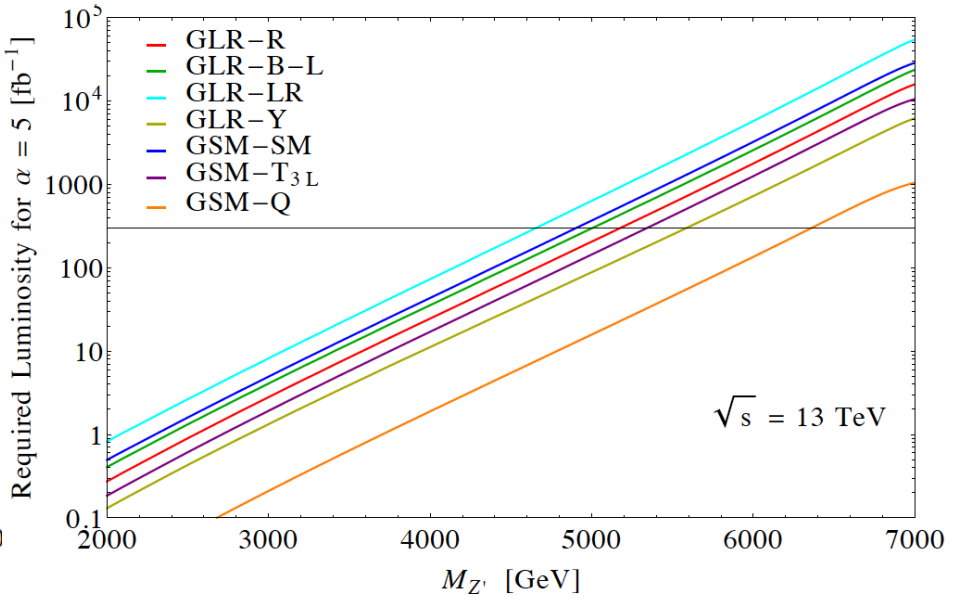
- Until clarity is made, we suggest the use of AFB to reduce the theoretical systematics.

extra slides

Projection on Narrow width Z' @ 13 TeV

pp → g, Z, Z' → ee, mm with IM(ll)-$M_{Z'}$I < 5% E_{coll}



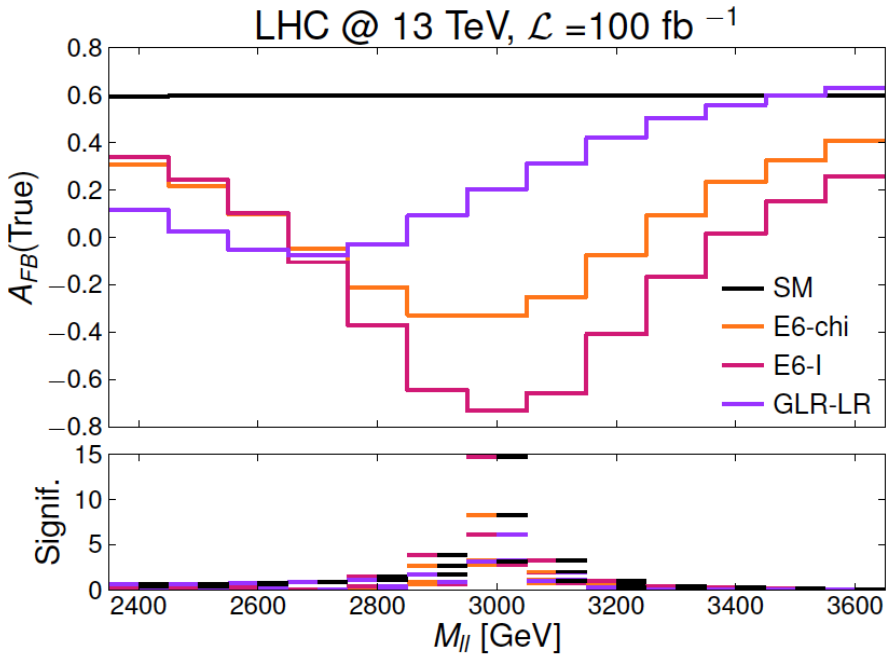


Class	E_6						GLR				GSM		
$U'(1)$ Models	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM	T_{3L}	Q
$M_{Z'}$ [GeV]	4535	4270	4385	4405	4325	4290	5175	5005	4655	5585	4905	5340	6360
$M_{Z'}$ [GeV]	5330	5150	5275	5150	5055	5125	6020	5855	5495	6435	5750	6180	8835

Search window at Run II: 2.5 TeV < $M_{Z'}$ < 6.5 TeV

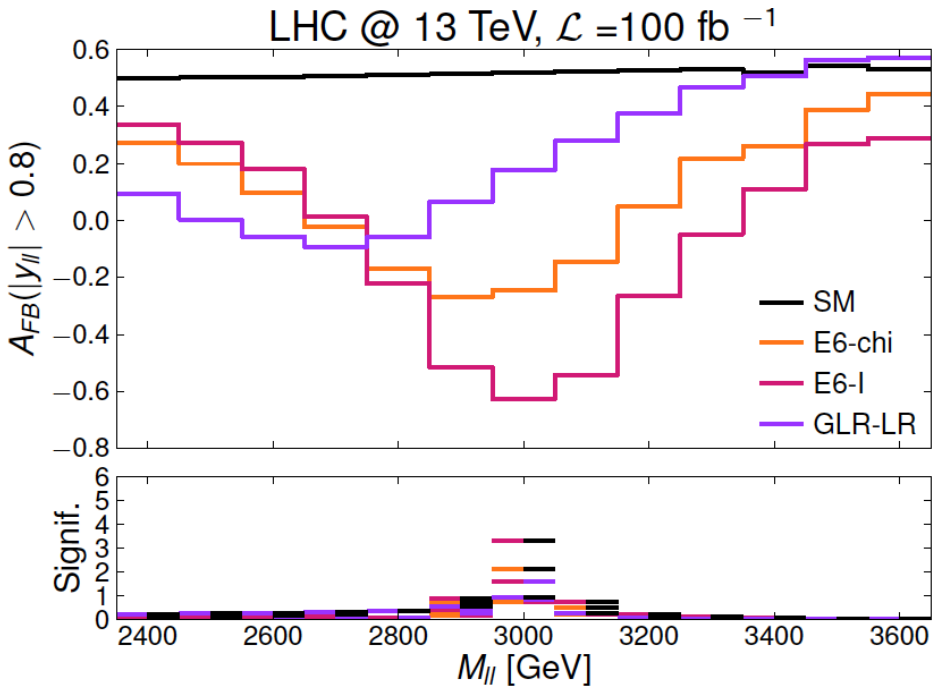
Forward-Backward Asymmetry (AFB)

(Dittmar,Nicollerat,Djouadi 03; Petriello,Quackenbush 08)



$A_{FB}=(\sigma_F-\sigma_B)/(\sigma_F+\sigma_B)$ is defined in the CM of the hard-scattering where the Forward and Backward directions are taken with respect to the incoming quark.

A_{FB} can be reconstructed at the LHC via the boost variable i.e. the rapidity of the dilepton system: $Y_{ll}=0.5\ \log[(E_{ll}+P_{ll})/(E_{ll}-P_{ll})]$

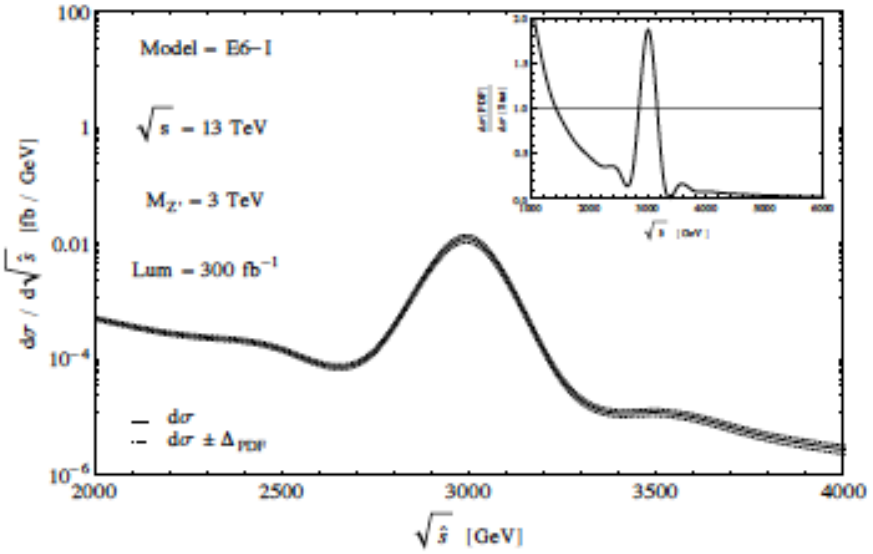


Usually adopted for distinguishing between different Z' models **[Dittmar, Nicollerat, Djouadi 03; Petriello, Quackenbush 08, Rizzo]**

It is here proposed as a primary search observable.

AFB and PDF's error in DY at high scales

pp → γ, Z, Z' → ee, μμ



- The error on the dilepton invariant mass distribution is dominated by the PDF's uncertainty on peak.
- The error on the off-resonance A_{FB} is dominated by the statistics over the full invariant mass range as the PDF's uncertainty is largely cancelled in the ratio

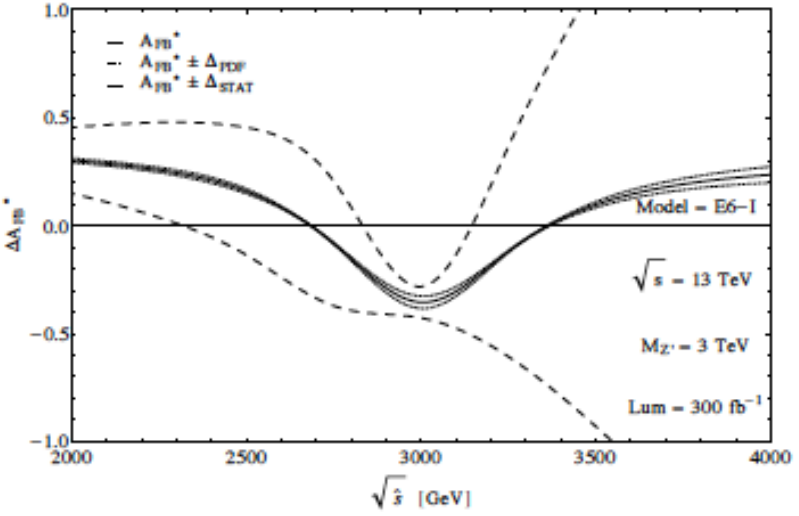
$$\Delta A_{FB}=0.5\,(1-A^2_{FB})\,|\Delta(d\sigma_F/dm_{ll})-\Delta(d\sigma_B/dm_{ll})|$$

Hessian PDF uncertainty

Cteq6.6 gives a central value and 40 error sets. The symmetric error on the dilepton invariant mass distribution is:

$$\Delta(d\sigma/dm_{ll})=[\,\Sigma|(d\sigma/dm_{ll})^{+}_{i}-(d\sigma/dm_{ll})^{-}_{i}\,]^{1/2}$$

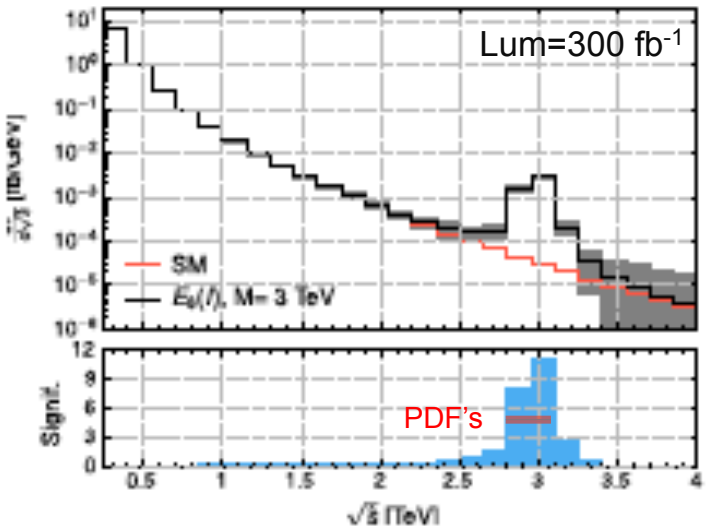
$(d\sigma/dm_{ll})^{+}_{i}$ is the value of the observable using the PDF error set corresponding to the + direction of the eigenvalue i.



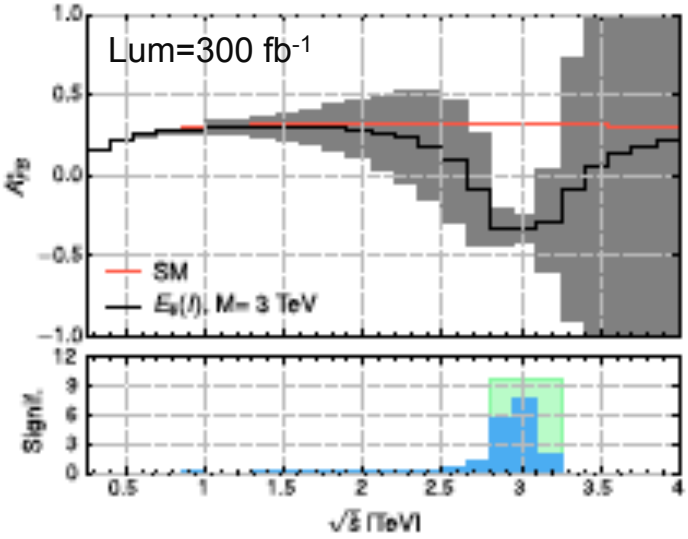
AFB as a Z' search tool in DY

pp → γ, Z, Z' → ee, μμ

Dilepton invariant mass distribution



Reconstructed A_{FB}

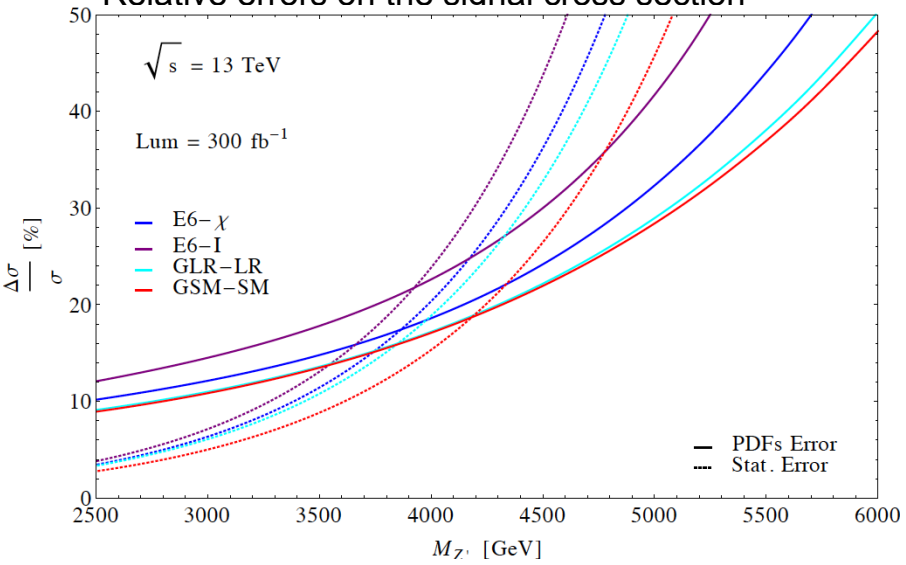


If statistical and PDF errors are combined linearly, the significance in the bump search rapidly drops, making the AFB quite competitive.

AFB and PDF's error in DY at high scales

pp → γ, Z, Z' → ee, μμ

Relative errors on the signal cross section



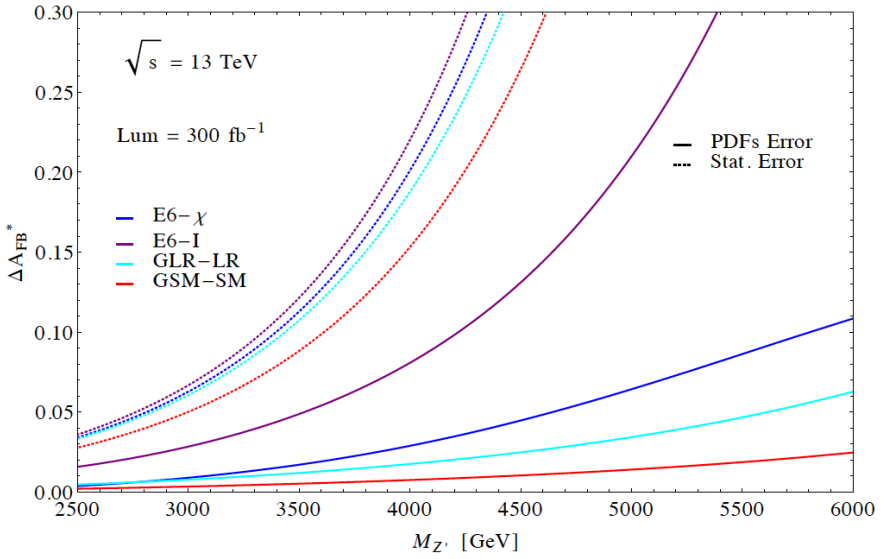
A PDF's refitting procedure could in principle reduce the error on the cross section. The procedure could be however scale and New Physics dependent.

Improving large-x PDF's uncertainties is mandatory for high energy DY.

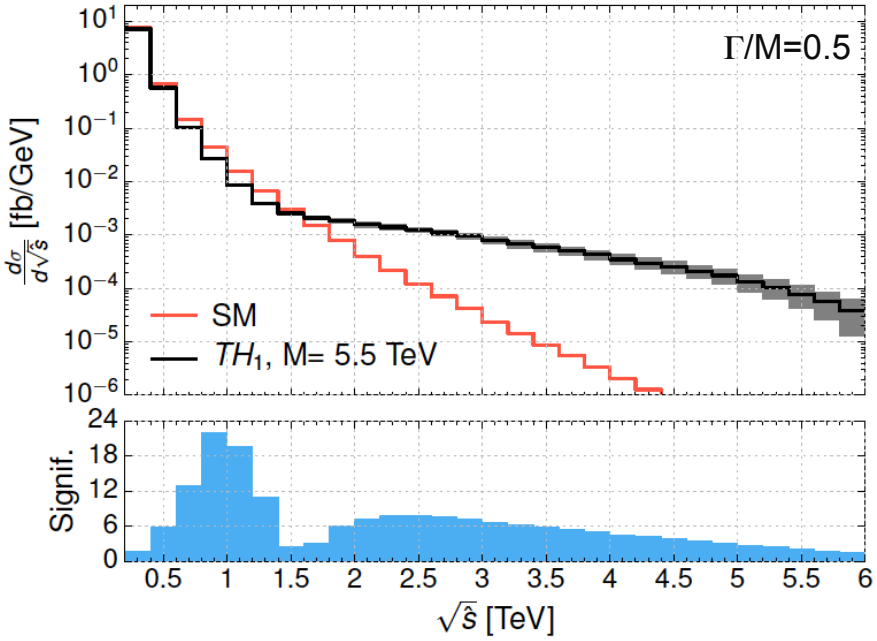
The PDF's error on A_{FB} is always smaller than the statistical one over the full range of Z' boson masses can be searched for during Run II.

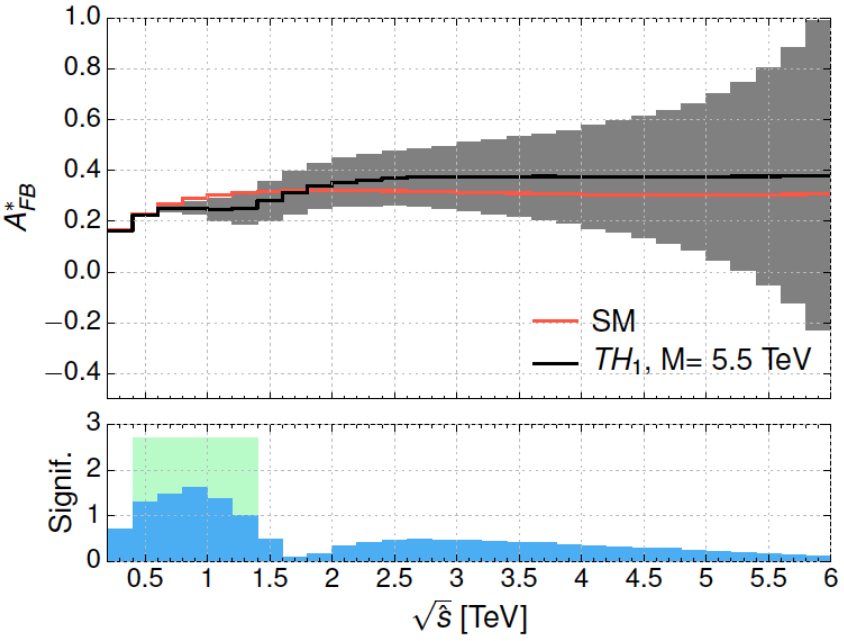
A_{FB} is much more robust than the total cross section as to PDF's.

Errors on the reconstructed A_{FB}



AFB as a Z' search tool in DY
A wide Z'-boson

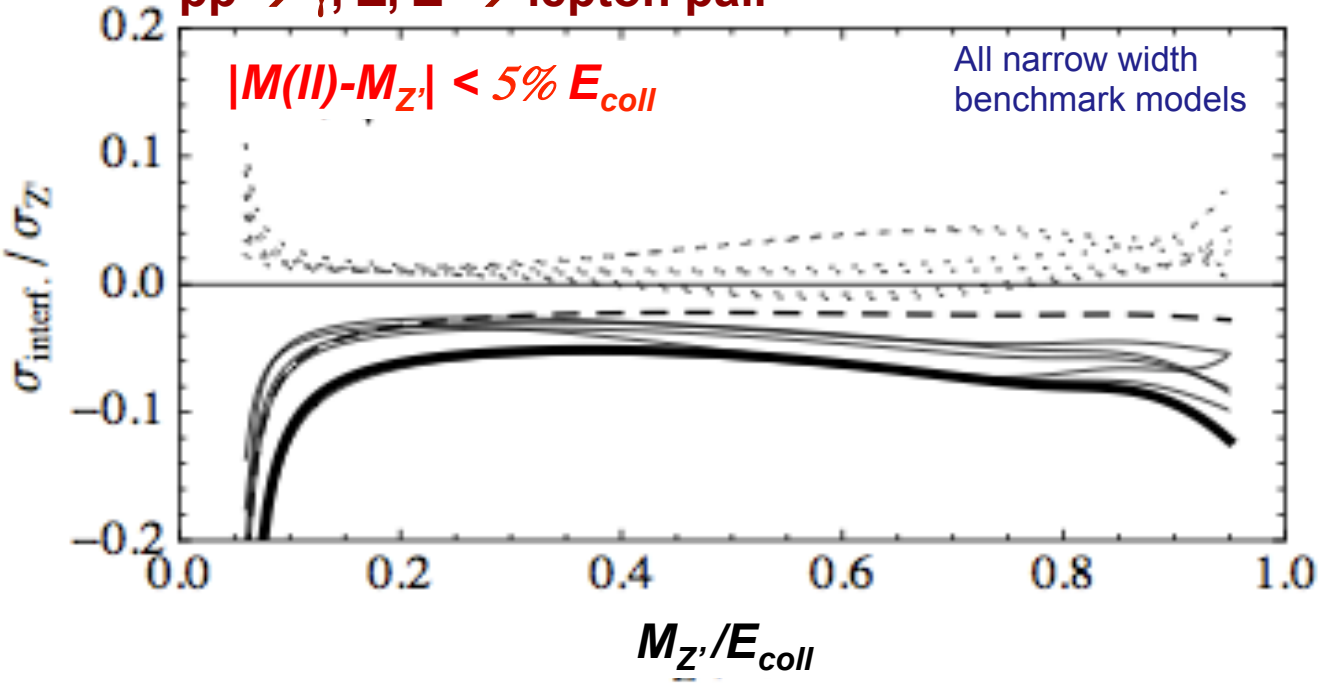




A shape-analysis of the AFB would support the interpretation of any excess of data in the invariant mass distribution

Narrow width Z' @ the LHC in all models: search strategy & theoretical accuracy

pp → γ, Z, Z' → lepton pair



The model independent approach up to O(10%) for all Z'-boson masses

Impose the cut $|M(ll)-M_{Z'}| < 5\%\ E_{coll}$ to be as much as possible model-independent. Interference effects are in fact below O(10%), i.e. comparable with NLO EW+QCD uncertainties. **[E.A., Becciolini, Belyaev, Fiaschi, Moretti, Shepherd-Themistocleous, 2013]**

Implemented in the last CMS analysis on dilepton states, arXiv:1412.6302