AFB as a discovery tool for Z' bosons at the LHC

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- **New heavy vector resonances:** Drell-Yan processes at the LHC
- **Beyond commonly used approximations:** Interference and FW effects
- **Interpretation of exp. results:** Mass bounds on Z'-bosons
- **A newly proposed observable:** Forward-Backward Asymmetry as a Z' hunter

based on papers by:

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

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New Heavy vector resonances

- **Most common scenarios predict a single Z' or W':**
  An extra heavy neutral vector boson, Z' or W' can come from weakly interacting theories with at least a light elementary higgs boson:

  Z': E_6, Left-Right, SSM

  W': Left-Right, SSM

- **More complicated models can predict multi-resonances:**
  A tower of extra heavy vector bosons, Z'_n and W'_n, can come from extended gauge groups and strongly interacting theories:

  Z's and W's: Composite Higgs, (N)MWT, ED

The Drell-Yan channel is the favoured process for ALL models.

We focus on the single Z' search in DY within weakly interacting theories with a light elementary Higgs.

Z'-boson at the LHC in DY
Narrow width Benchmark models

[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

Z' searches at the LHC in DY: 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]

NLO EW via HORACE [Carloni Calame et al. '05]

At LO, great ferment on Interference and Finite Width (FW) effects in theoretical studies:

Higgs [E.A. '08, Campbell, Ellis et al. '11, Kauer, Passarino '12, Denner et al. '14]

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

First attempts to deal with Interference and FW effects in experimental analyses at the LHC. They are model-dependent and CPU consuming, so different strategies are adopted:

W' [CMS '14]

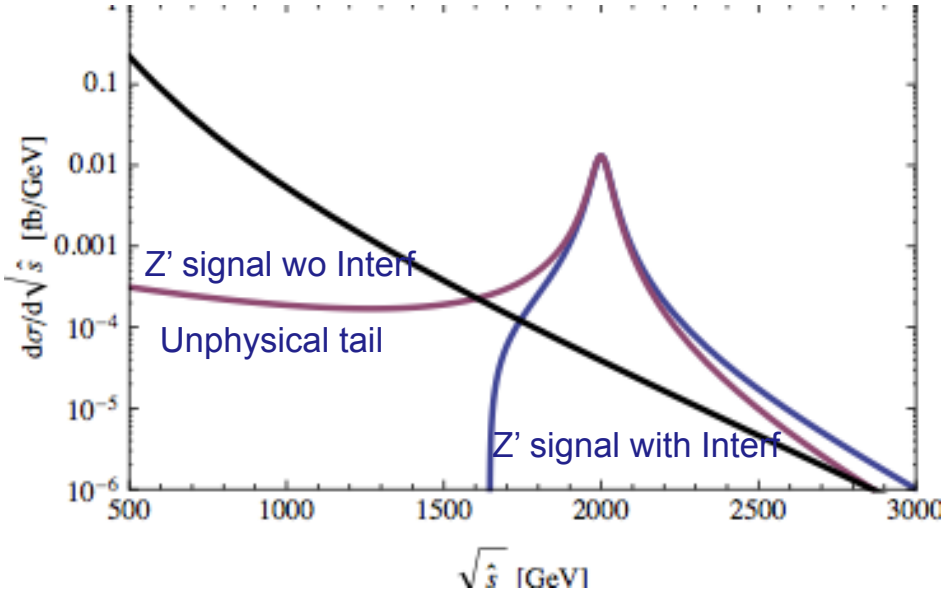
Z' [ATLAS '15, CMS '15]

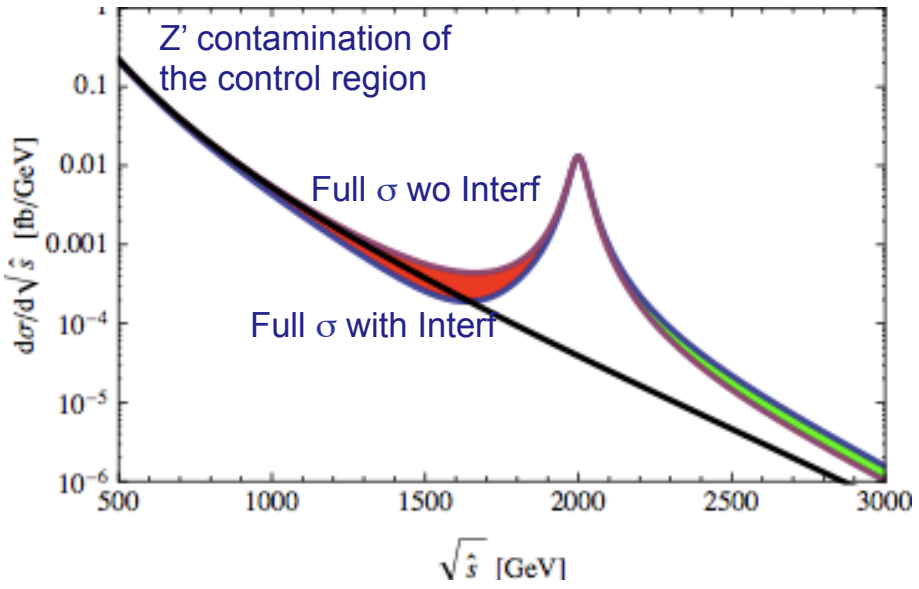
Focus on Z' searches at LO: where do we stand?

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





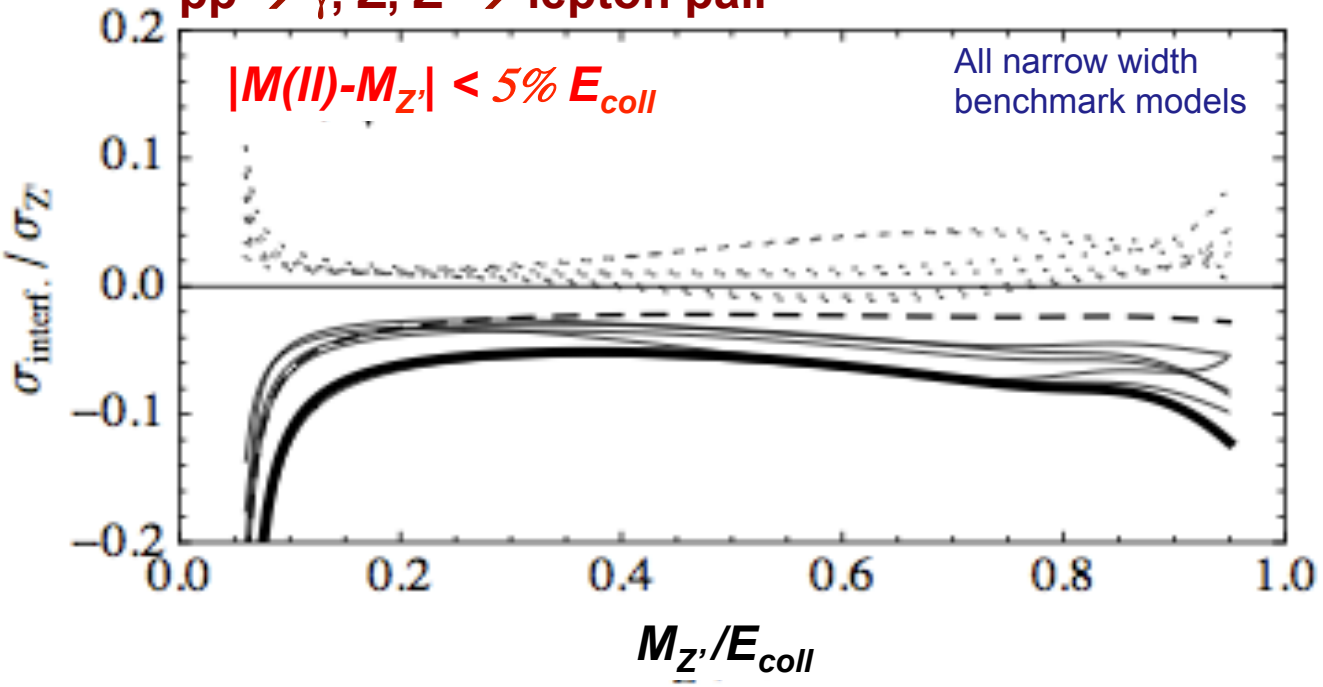
Interference effects are sizeable and model-dependent:

up to O(200%) in the SSM

The impact of Interference and Finite Width effects on presentation of exp. results, data interpretation and mass bound extraction can be important for Z' searches.

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

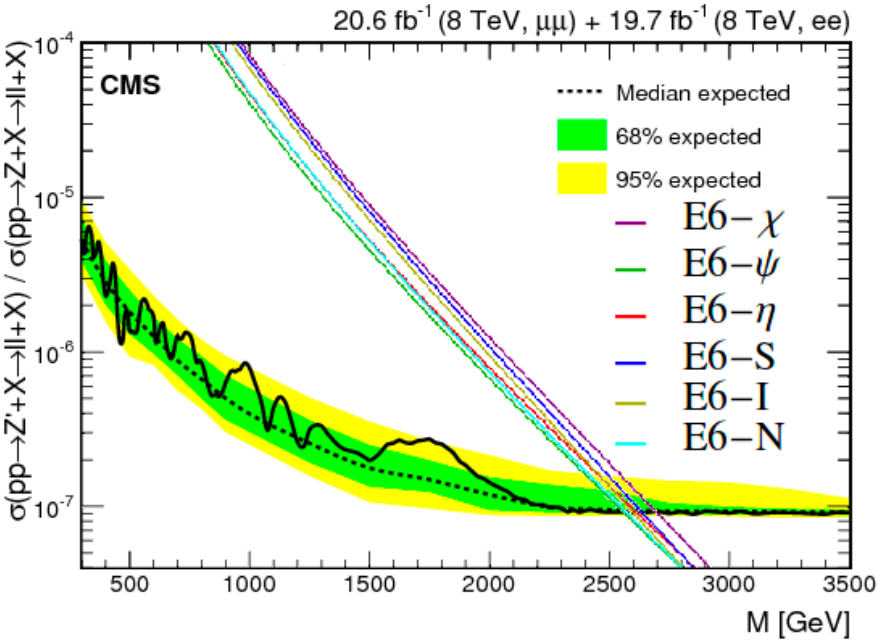
Impose the cut $|M(ll)-M_{Z'}| < 5\% E_{coll}$ to be as much as possible model-independent. Interference effects are in fact below O(10%), i.e. comparable with NLO EW+QCD uncertainties. **[E.A., Becciolini, Belyaev, Fiaschi, Moretti, Shepherd-Themistocleous, 2013]**

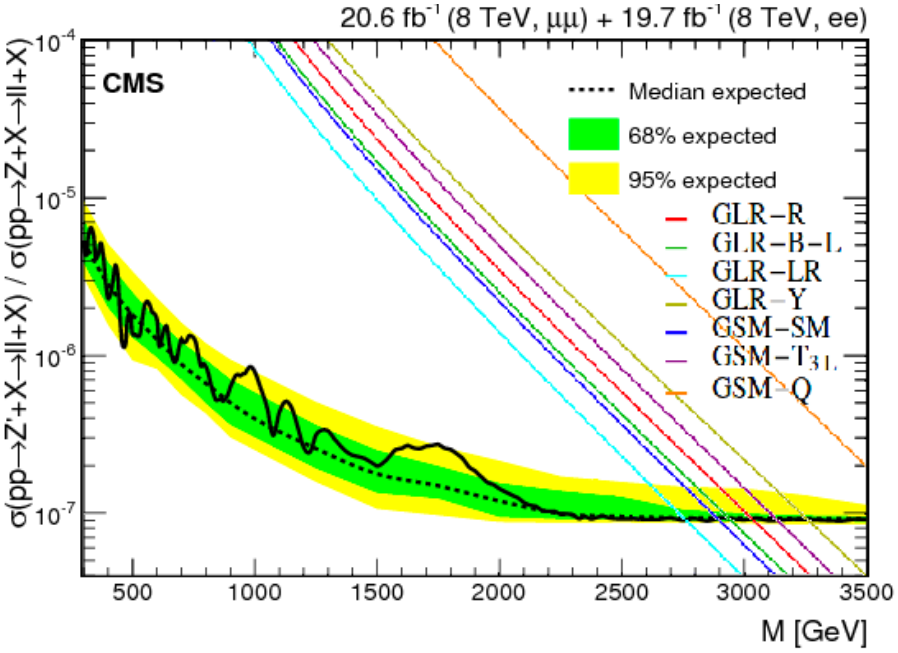
Implemented in the last CMS analysis on dilepton states, arXiv:1412.6302

Limits on Narrow width Z' from CMS

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

pp → γ, Z, Z' → ee, μμ with $|M(ll)-M_{Z'}| < 5\%\ E_{coll}$





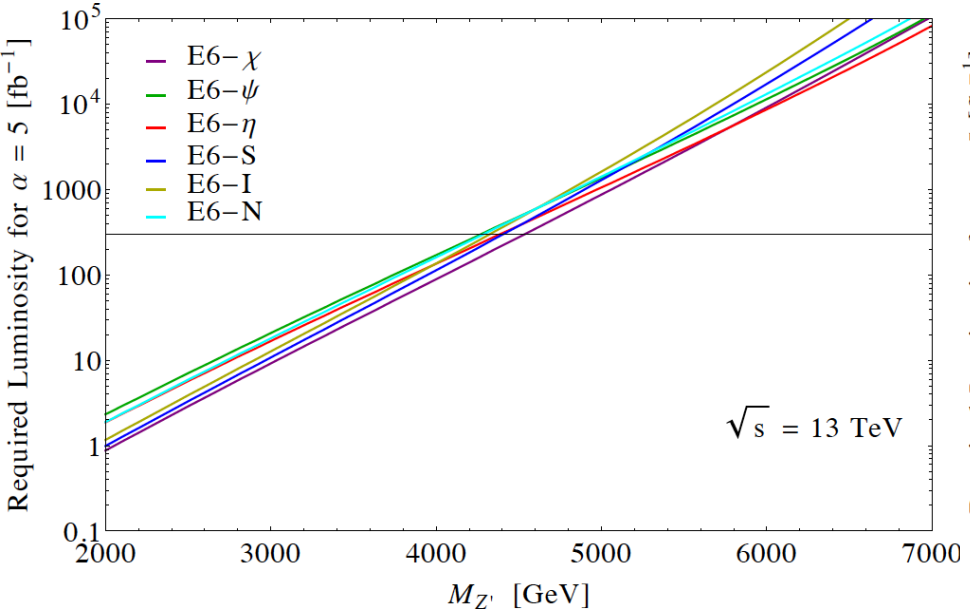
Class	E_6						GLR				GSM		
$U'(1)$ Models	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM	T_{3L}	Q
$M_{Z'}$ [GeV]	2700	2560	2620	2640	2600	2570	3040	2950	2765	3260	2900	3135	3720

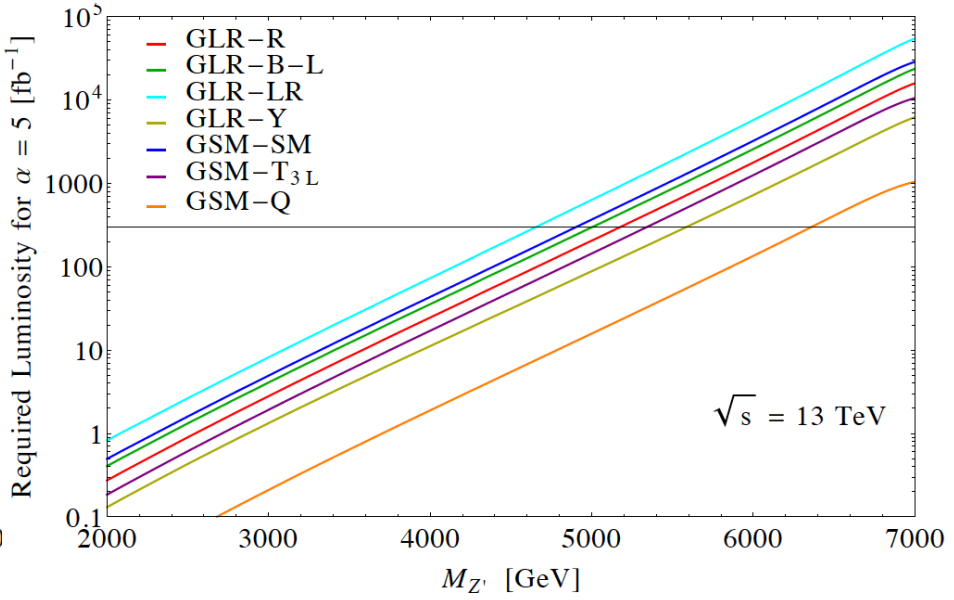
Search window for Run II

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

Projection on Narrow width Z' @ 13 TeV

pp → γ, Z, Z' → ee, μμ with $|M(ll)-M_{Z'}| < 5\%\ E_{coll}$

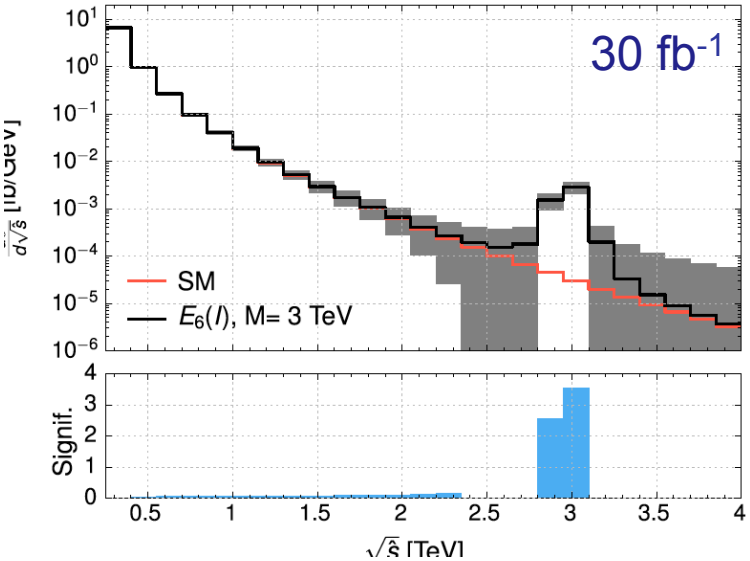


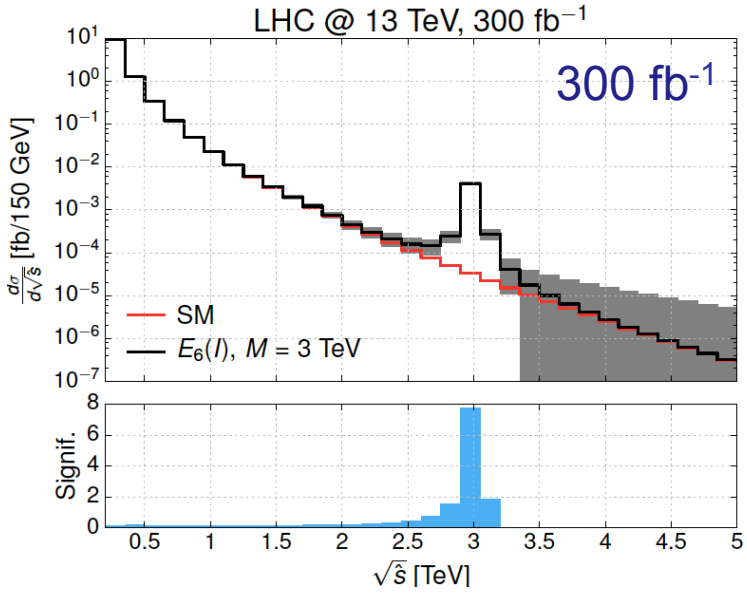


Class	E_6						GLR				GSM		
$U'(1)$ Models	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM	T_{3L}	Q
$M_{Z'}$ [GeV]	4535	4270	4385	4405	4325	4290	5175	5005	4655	5585	4905	5340	6360
$M_{Z'}$ [GeV]	5330	5150	5275	5150	5055	5125	6020	5855	5495	6435	5750	6180	8835

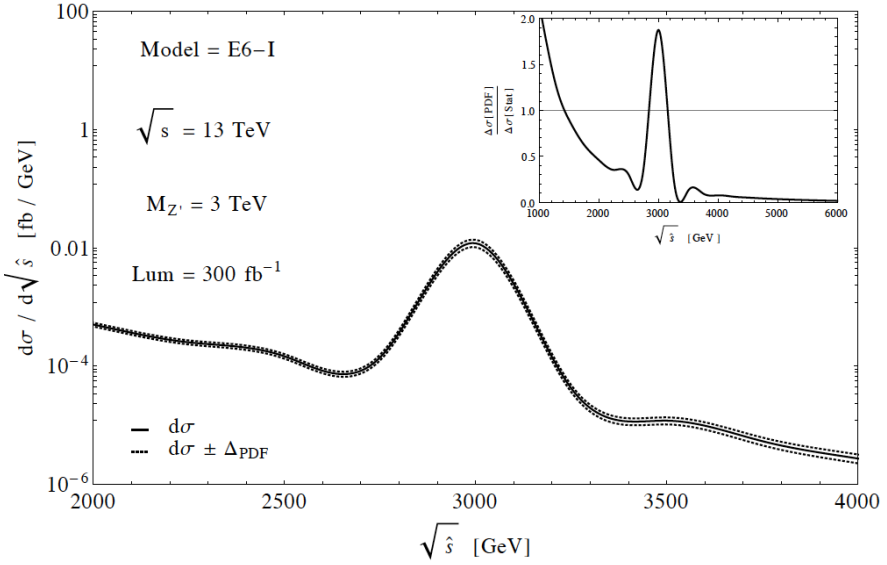
Search window in the next Run II: 2.5 TeV < $M_{Z'}$ < 6.5 TeV

Realistic prospects for Z' @ 13 TeV

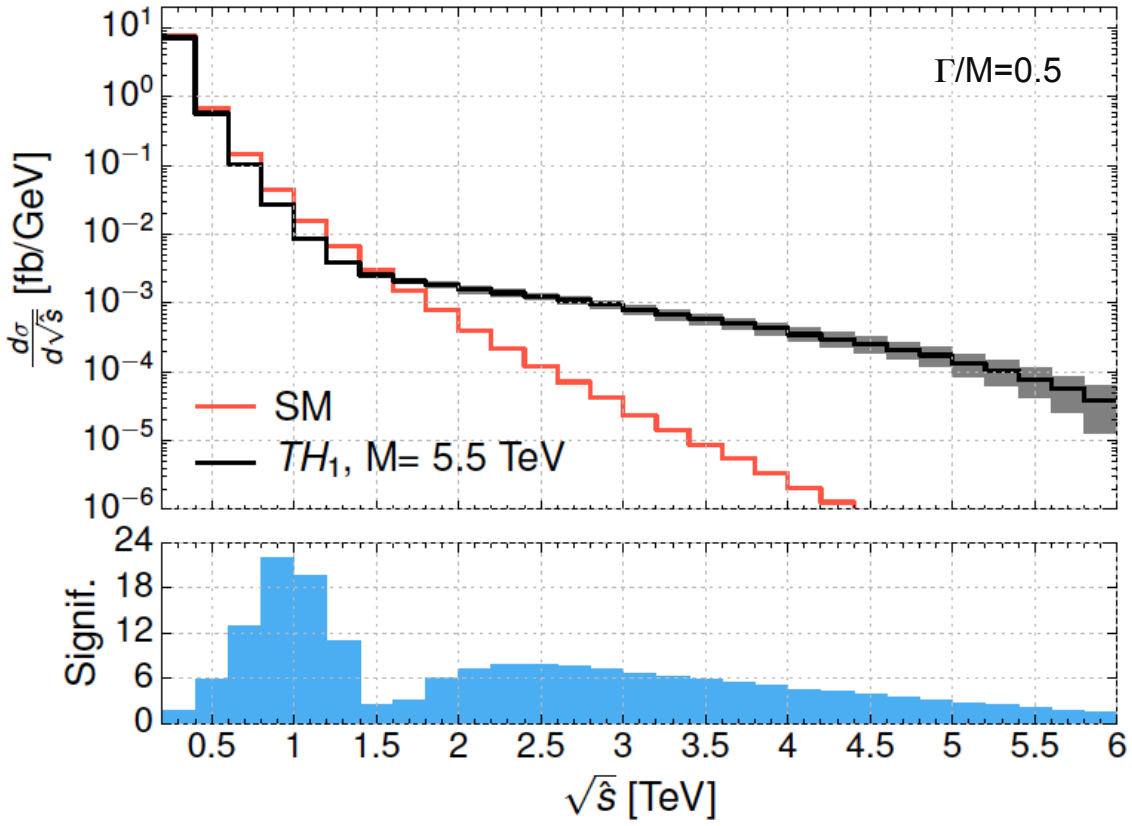




- At low luminosity a Z' evidence could not be that convincing
- At high luminosity the PDF error could spoil the significance



Realistic prospects for Z' @ 13 TeV
A wide Z'-boson



Z' bosons could be wide and appear as broad resonances spread over the SM background leading to a difficult interpretation of the excess of events.

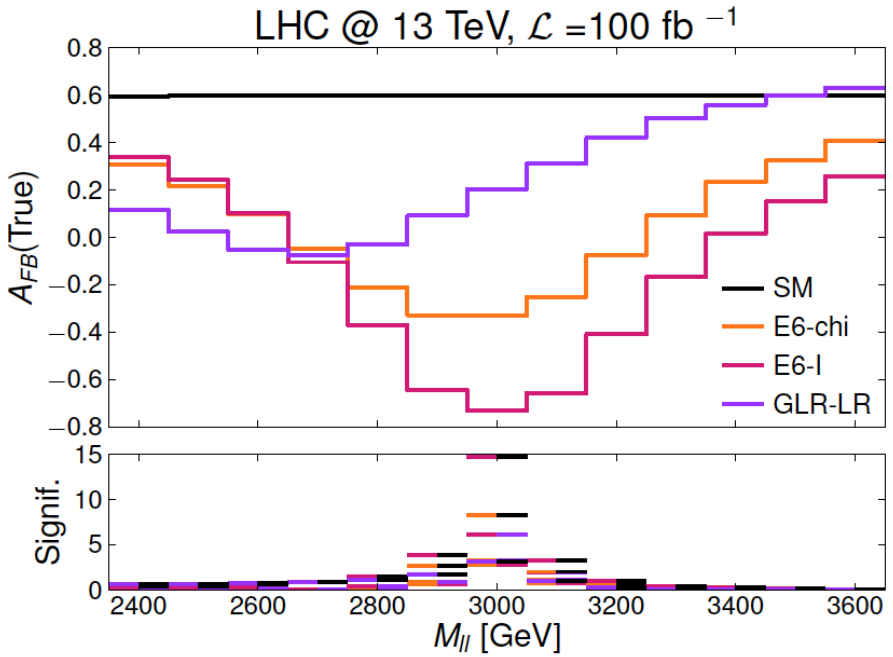
Benchmark models:

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

These reasons motivate the introduction of the Forward Backward Asymmetry (AFB) as a new observable for the Z' boson search

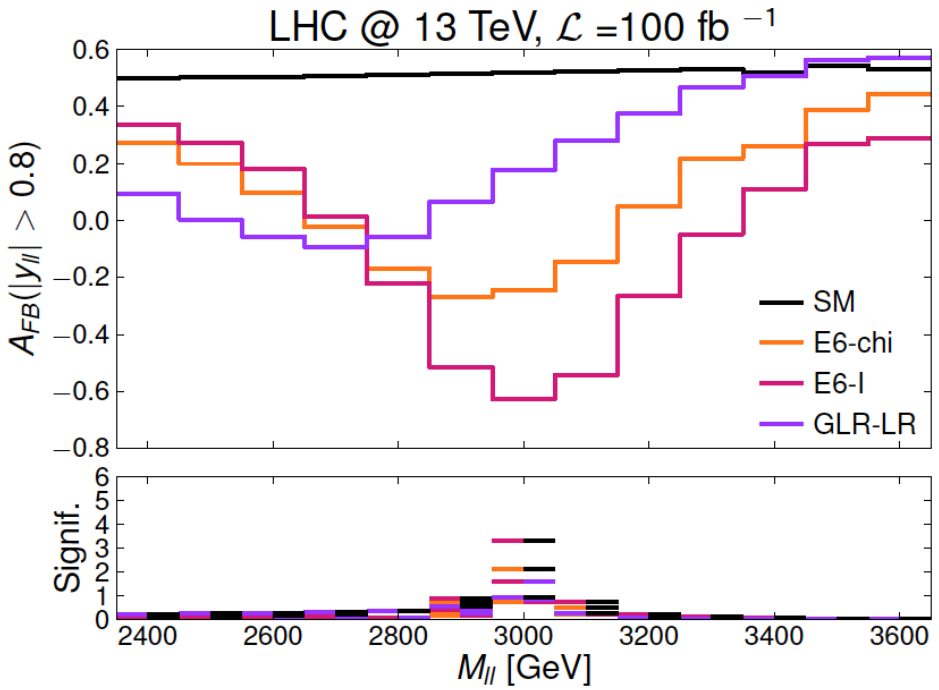
Forward-Backward Asymmetry (AFB)

(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.

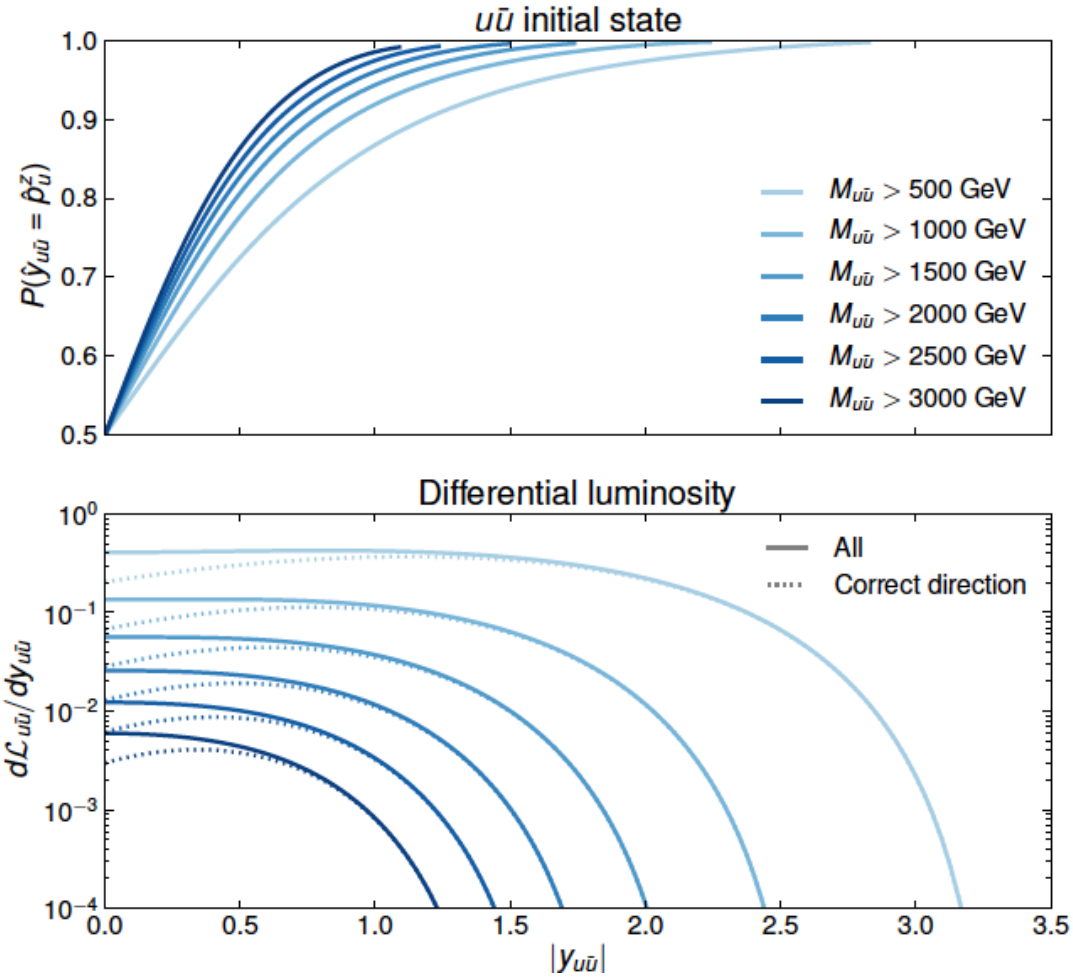
A_{FB} can be reconstructed at the LHC via the boost variable i.e. the rapidity of the dilepton system: $Y_{ll}=0.5\ \log[(E_{ll}+P_{ll})/(E_{ll}-P_{ll})]$



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.

Reconstructed AFB and Y_{ll} cut



The probability of guessing the correct direction of the initial quark depends on both the Y_{ll} cut and the Z' boson mass (or energy scale).

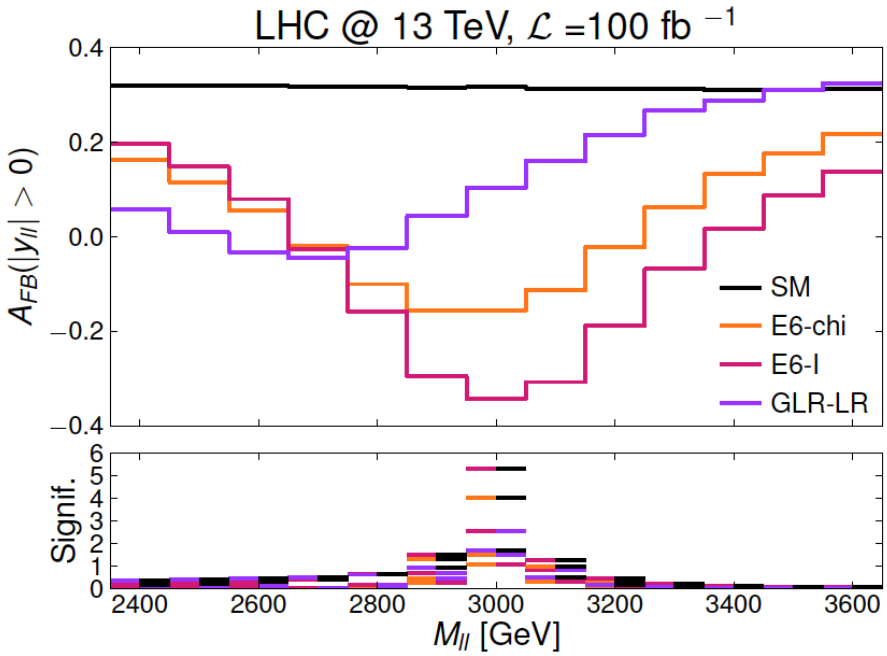
At Run II, the Y_{ll} cut can be relaxed

The qq luminosity rapidly decreases with the Y_{ll} cut for $M_{Z'} > 2500$ GeV.

The acceptance rapidly decreases with increasing Y_{ll} cut and $M_{Z'}$

Forward-Backward Asymmetry (AFB)

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



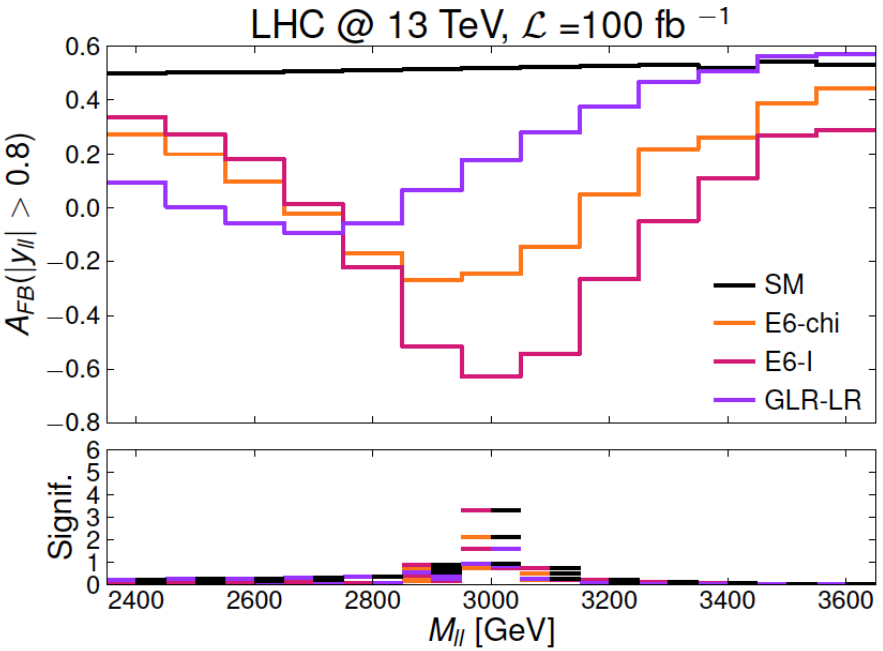
$$A_{FB}=(\sigma_F-\sigma_B)/(\sigma_F+\sigma_B)$$

The statistical error is:

$$\delta A_{FB}=[(1-A^2_{FB})/Nevt]^{1/2}$$

Delicate balance between aiming to reconstruct the true shape of AFB via the Y_{ll} cut and preserving high acceptance i.e. high statistics (Nevt).

Our finding: no Y_{ll} cut maximizes the significance for $M_{Z'} > 2500$ GeV

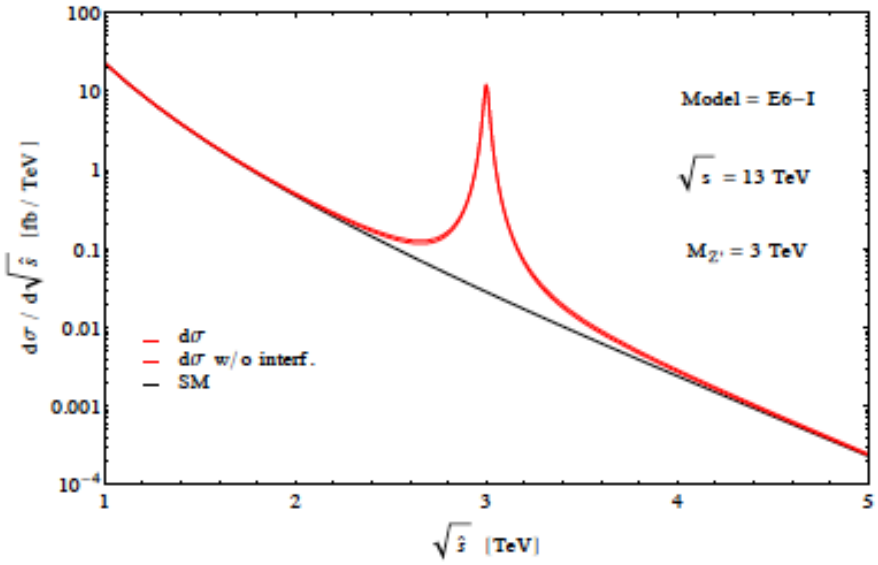


AFB as a Z' search tool in DY

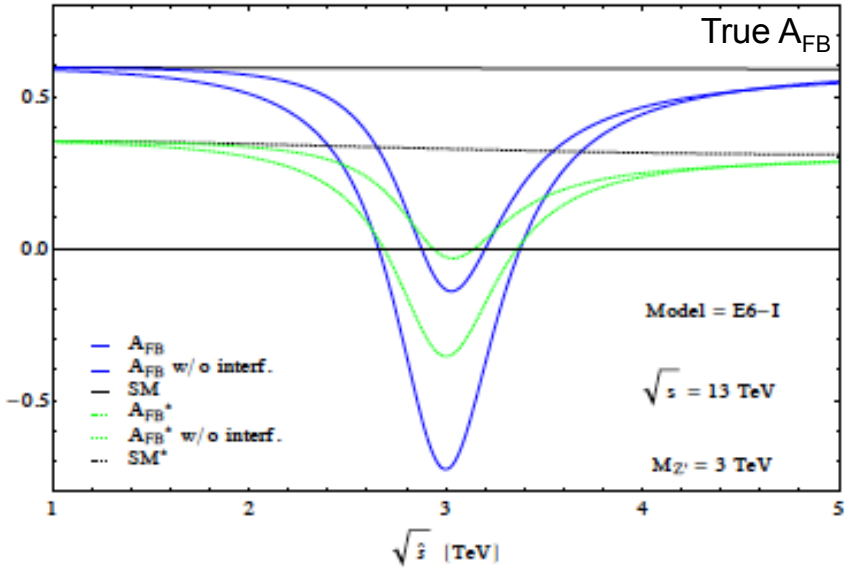
pp → γ, Z, Z' → ee, μμ

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

Bump search



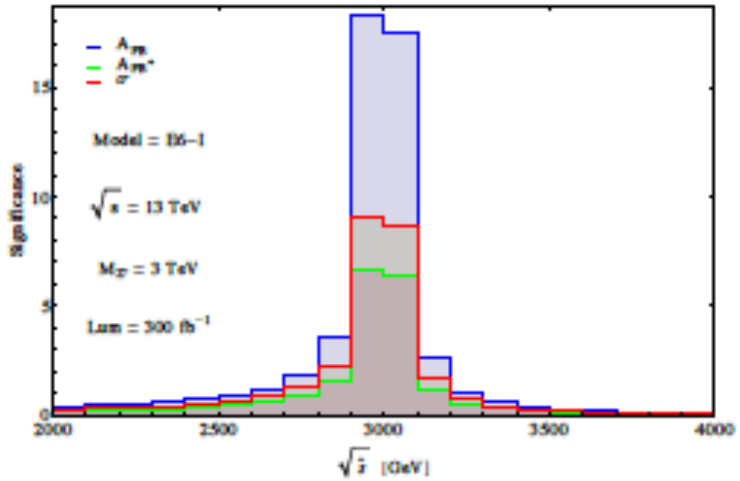
A_{FB} search



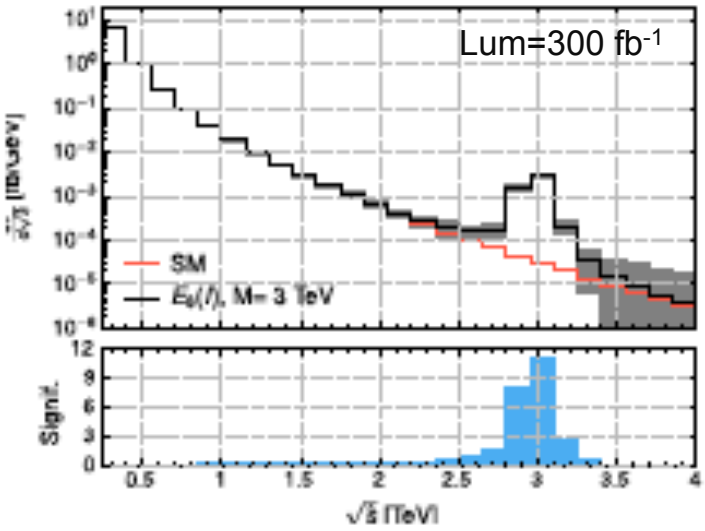
The interference Z' – SM is an intrinsic ingredient of A_{FB}

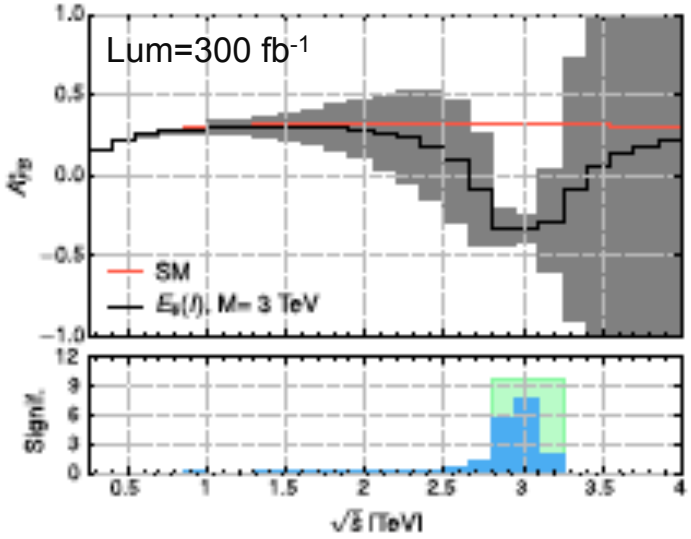
AFB as a Z' search tool in DY

pp → γ, Z, Z' → ee, μμ



- The true A_{FB} can give rise to a significance much bigger than the bump.
- The reconstruction of the A_{FB} depletes it, but still the significance remains sizeable.

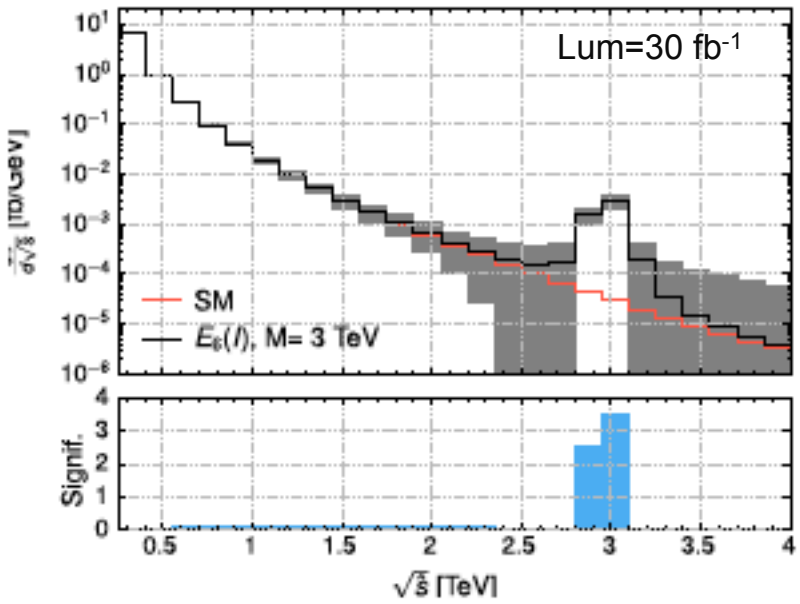


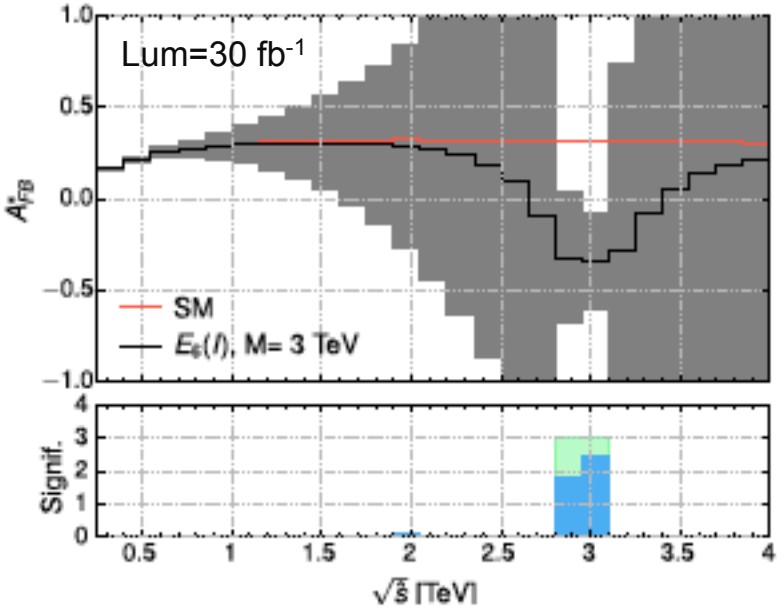


AFB as a Z' search tool in DY

pp → γ, Z, Z' → ee, μμ

First 2 years of Run II: collected Lum = 30 fb^{-1}

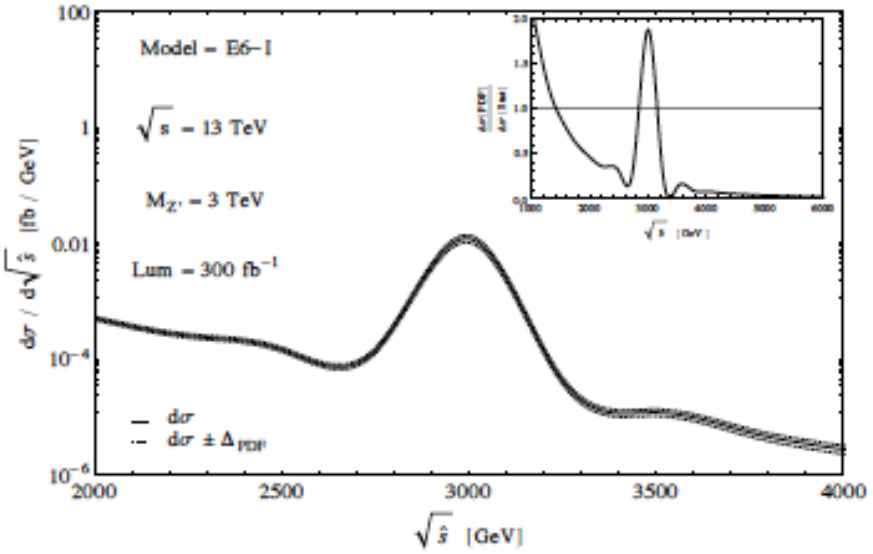




An evidence in the bump search can be reinforced by a further evidence in an independent and differently shaped observable, i.e. the off-peak A_{FB}

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

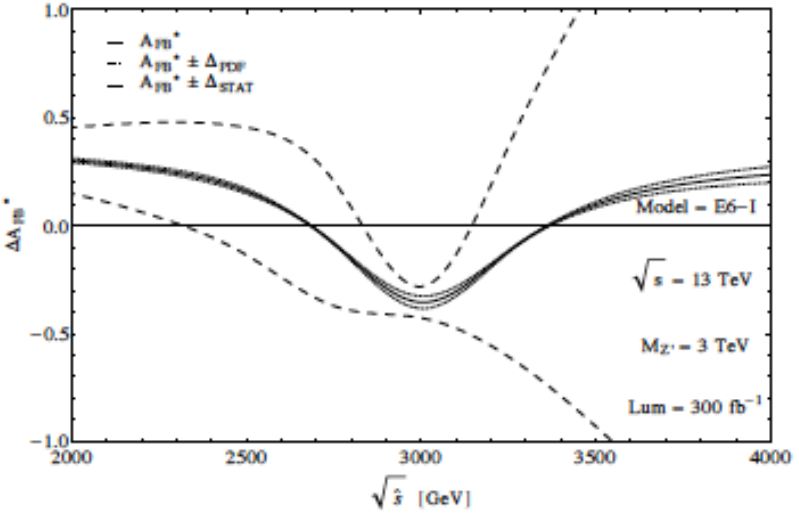
$$\Delta A_{FB}=0.5\,(1-A^2_{FB})\,|\Delta(d\sigma_F/dm_{ll})-\Delta(d\sigma_B/dm_{ll})|$$

Hessian PDF uncertainty

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

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

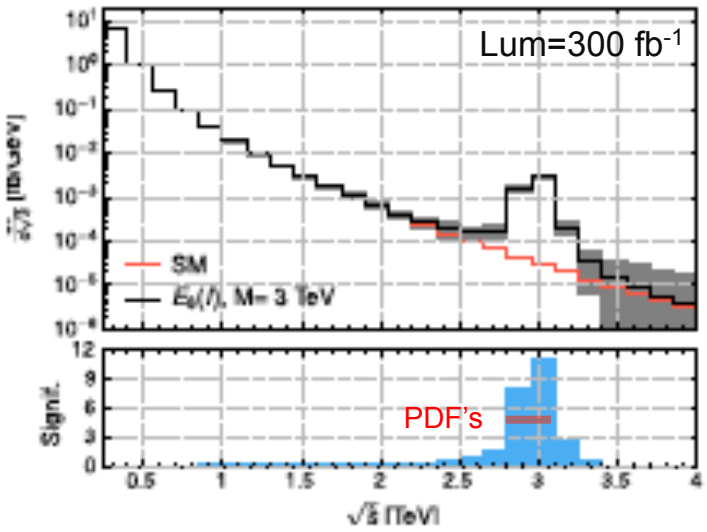
$(d\sigma/dm_{ll})^{+}_{i}$ is the value of the observable using the PDF error set corresponding to the + direction of the eigenvalue i.



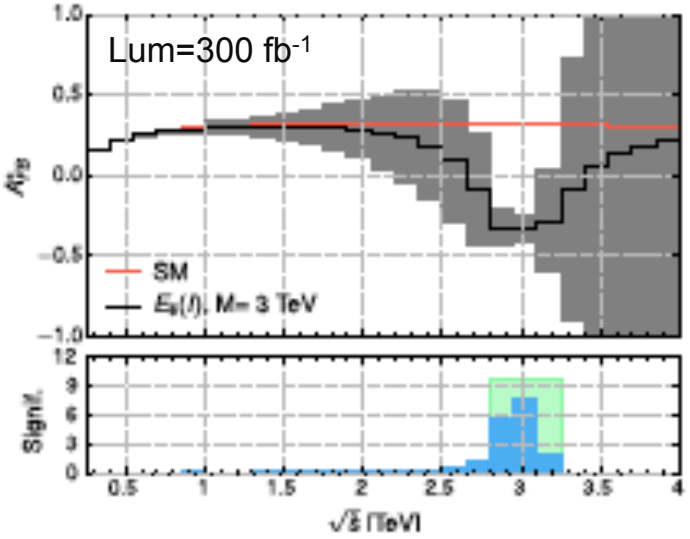
AFB as a Z' search tool in DY

pp → γ, Z, Z' → ee, μμ

Dilepton invariant mass distribution



Reconstructed A_{FB}

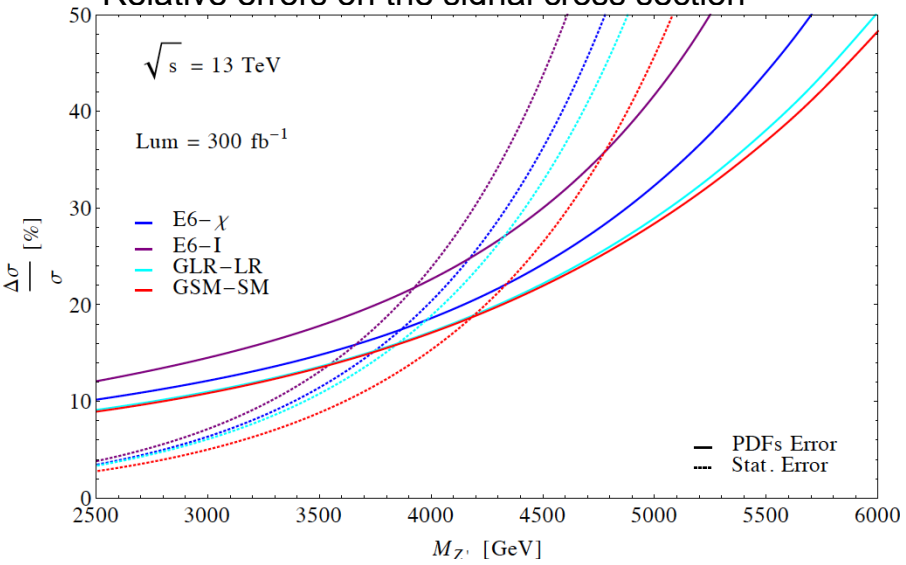


If statistical and PDF errors are combined linearly, the significance in the bump search rapidly drops, making the AFB quite competitive.

AFB and PDF's error in DY at high scales

pp → γ, Z, Z' → ee, μμ

Relative errors on the signal cross section



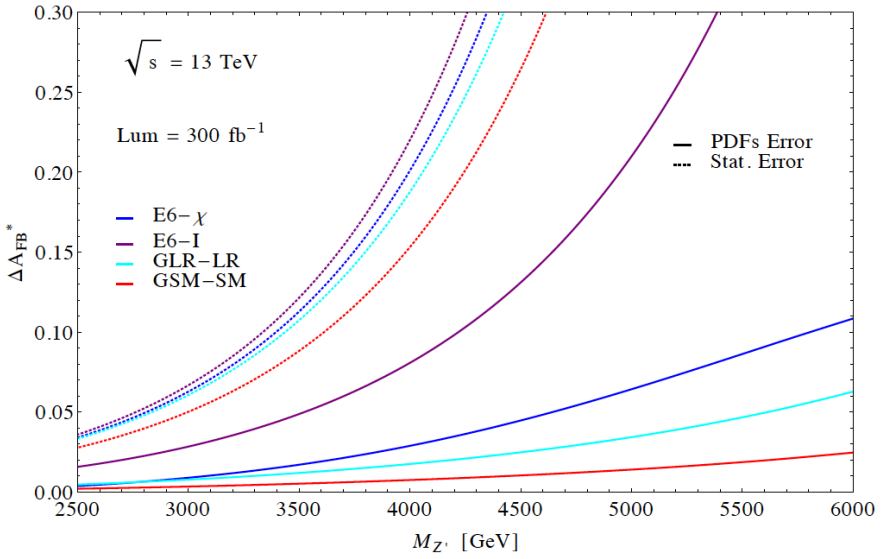
A PDF's refitting procedure could in principle reduce the error on the cross section. The procedure could be however scale and New Physics dependent.

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

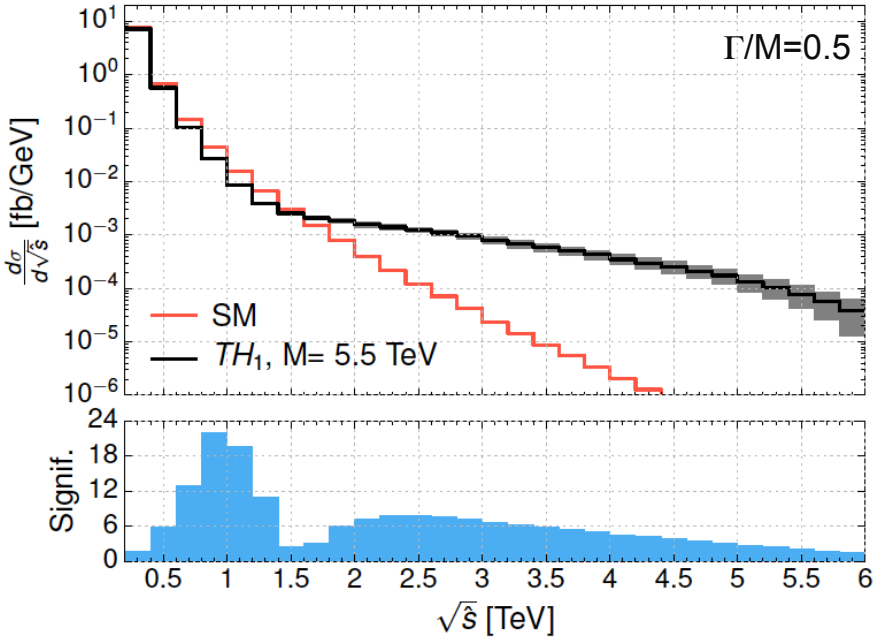
The PDF's error on A_{FB} is always smaller than the statistical one over the full range of Z' boson masses can be searched for during Run II.

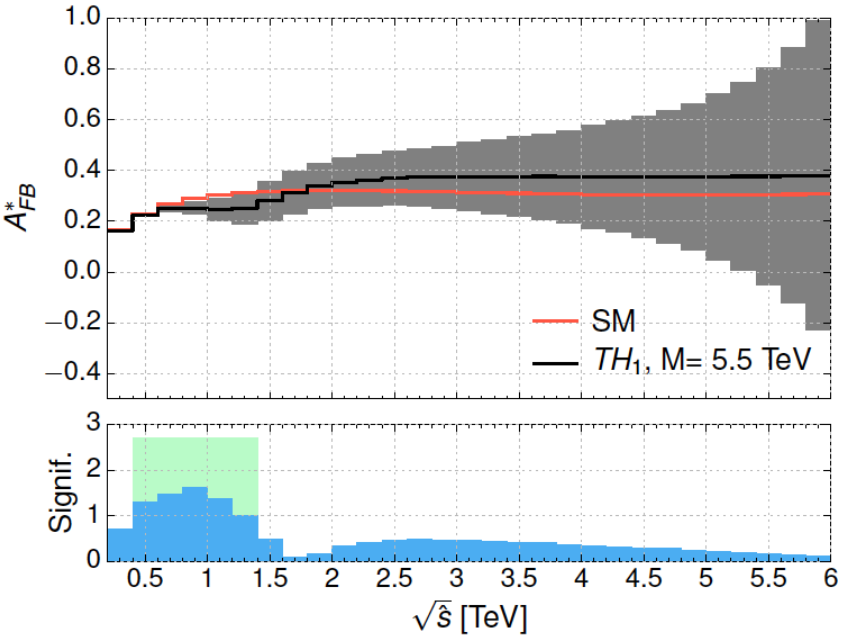
A_{FB} is much more robust than the total cross section as to PDF's.

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

Conclusions

- **We have discussed the importance of interference effects in searches for extra heavy Z' bosons.**
  The impact of Interference and Finite Width effects on presentation of experimental results, data interpretation and mass bound extraction can be important for Z' searches.
  Last analyses by ATLAS and CMS have imported these findings and account for such effects even if with different strategies.

- **Interferences are intrinsic to the Forward-Backward Asymmetry. In order to maximize the LHC potential in searching for new Z's, our proposal is to promote the A_{FB} to be a primary observable.**

- **The A_{FB} can in fact give rise to a significance comparable to or even bigger than that one expected from the default bump search.**

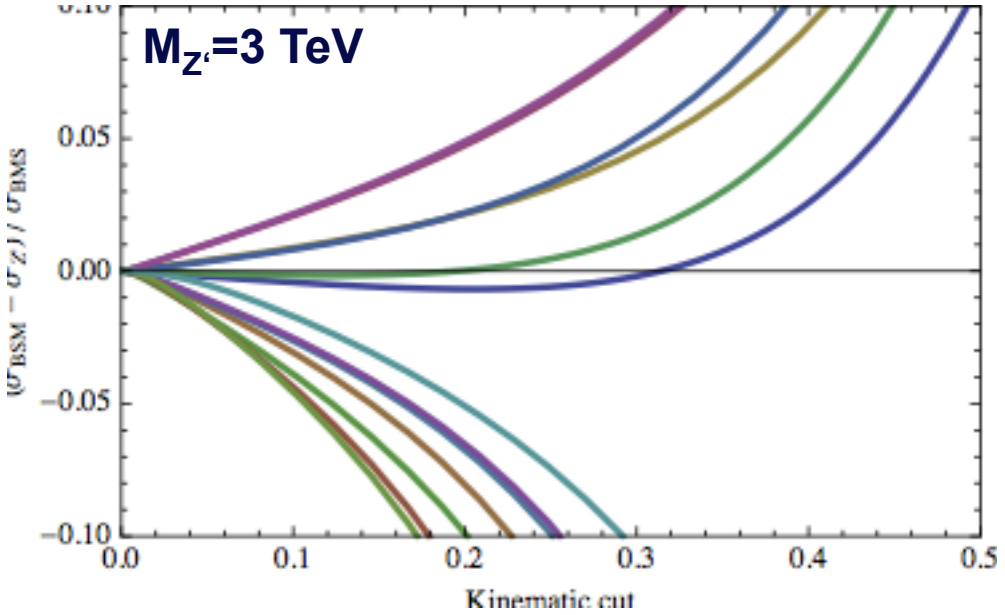
- **The A_{FB} is moreover much more robust against PDF's uncertainties.**

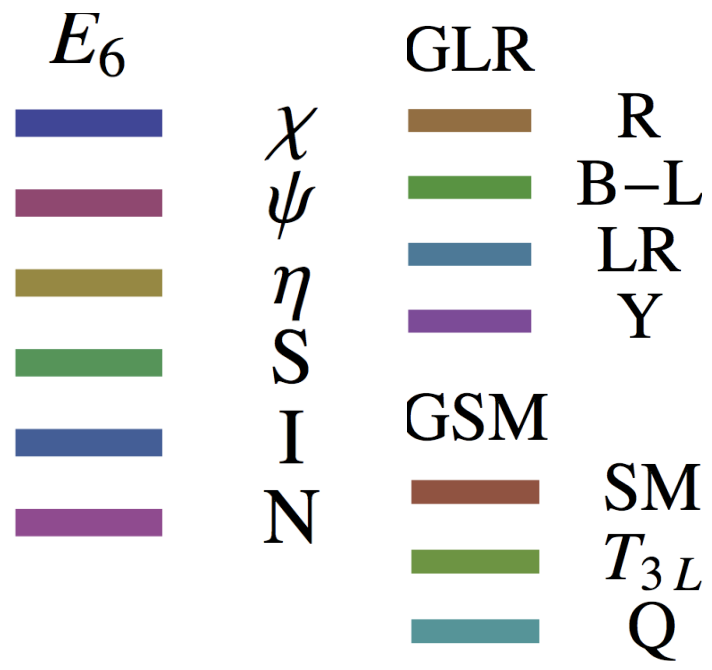
Improving large-x PDF's uncertainties is mandatory for high energy DY.

extra slides

Z' @ the LHC in all models: size and sign of interference effects

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





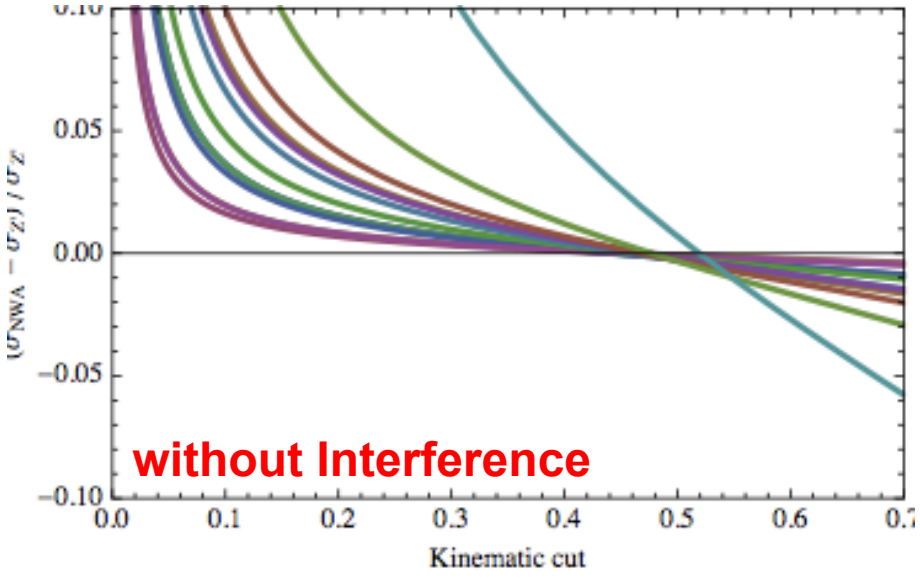
Kinematical cut = $|M_{inv}(ll)-M_{Z'}|/M_{Z'}<\Delta m/M_{Z'}$

Strategy #1: New dedicated analysis to distinguish between Z' models
Strategy #2: interference below theoretical uncertainties via cuts i.e. quasi-model independent analysis as in the current scheme

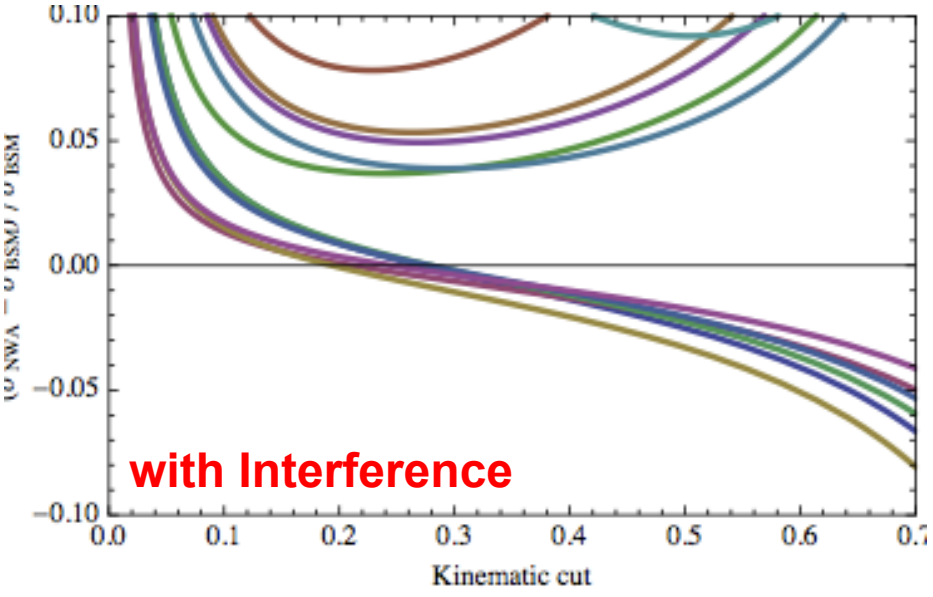
Z' @ the LHC in all models: NWA vs FW

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

$(\sigma_{NWA} - \sigma_{Z'})/\sigma_{Z'}$



$(\sigma_{NWA} - \sigma_{BSM})/\sigma_{BSM}$



Results in NWA cannot be reproduced exactly when interference is included, or the NWA can only be valid up to some accuracy

Strategy #2 : NWA accuracy below theoretical uncertainties via cuts

W' and Z' searches at the LHC in DY

Latest analyses in the Drell-Yan channel

ATLAS:

- **Z' search in the dilepton invariant mass distribution, arXiv:1209.2535**
  interference included only for Kaluza-Klein Z's in ED theories as suggested by [Bella et al, arXiv:1004.2432]

- **W' search in the dilepton transverse mass distribution, arXiv:1209.4446**
  no intereference included

CMS:

- **Z' search in the dilepton invariant mass distribution, arXiv:1212.7165**
  no intereference included

- **W' search in the dilepton transverse mass distribution, arXiv:1204.4764**
  interference included as suggested by [E.A. et al, arXiv:1110.0713]
  see talk by Philipp Millet

$M_{Z'} > 2.22$ TeV and $M_{W'} > 3.10 – 3.35$ TeV

Z' searches at the LHC in DY: approximate vs complete result

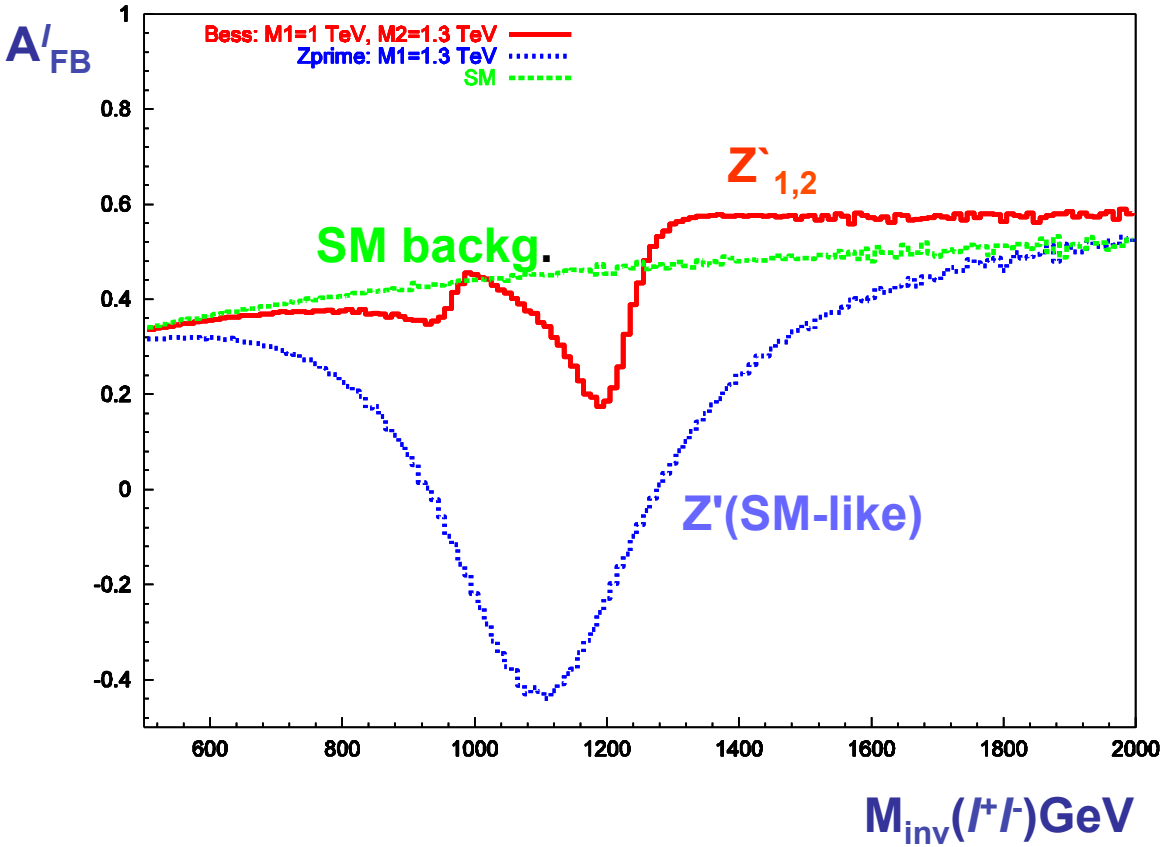
[E. A., Becciolini, Belyaev, Fiaschi, King, Moretti, Shepherd-Themistocleous (NExT) & De Curtis, Dominici, Fedeli (Florence University and INFN: arXiv:1110.0713 on W' and arXiv:1304.6700 on Z'].

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

Our point: the impact of Interference and Finite Width effects on presentation of exp. results, data interpretation and mass bound extraction can be sizeable for Z' searches

Forward-backward asymmetry A_{FB} in $pp \to l^+l^-$

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



$M_{Z`1}$ =1.0TeV
$M_{Z`2}$ =1.3TeV
$M_{Z`(SM\text{-}like)}$ =1.3TeV

$$A_{FB} = \left[\frac{d\sigma^F}{dM_{\rm inv}} - \frac{d\sigma^B}{dM_{\rm inv}}\right] / \left[\frac{d\sigma^F}{dM_{\rm inv}} + \frac{d\sigma^B}{dM_{\rm inv}}\right]$$