Z' physics: new bounds, searches and the role of AFB as discovery tool at the LHC

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arXiv:1503.02672 [hep-ph]

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Overview

- **Introduction**
  - Model independent Drell – Yan neutral channel searches
  - LHC bounds at 8 TeV and predictions for Run II at 13 TeV
  - Introducing the AFB observable
  - Finite width and interference effects
- **The role of AFB as a search tool**
  - AFB in narrow and wide Z' scenarios
  - Sources of uncertainties
- **Conclusions**

Modelling

Parametrization of the interaction

Low Energy Lagrangian:

$$SU(3)_c \otimes SU(2)_V \otimes U(1)_{em} \otimes \boxed{U(1)_{Z'}}$$

$$\mathcal{L} \supset g' Z'_\mu \bar{\psi} \gamma^\mu (a_V - a_A \gamma_5) \psi$$

As the structure of the interaction is fixed, the free parameters are:

- <u>Fermions' chiral couplings</u>
  (gauge couplings can be absorbed into their definition)

- <u>Mass</u> and <u>Width</u> of the Z' boson
  (Including the latter enable us to explore finite width and interference effects)

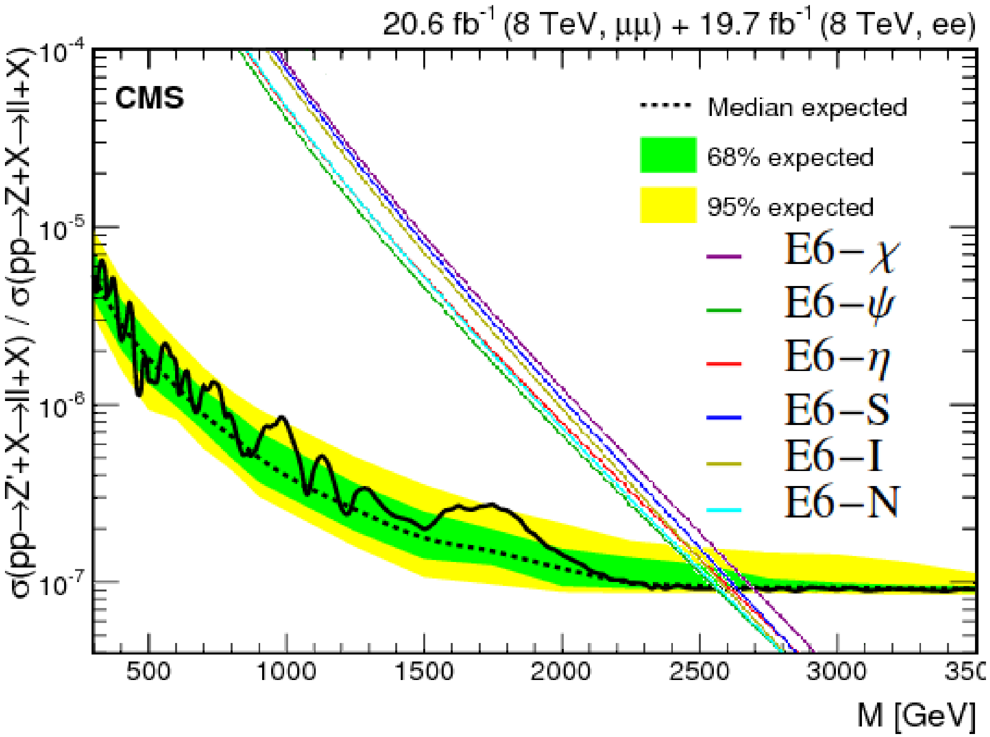
Parameters

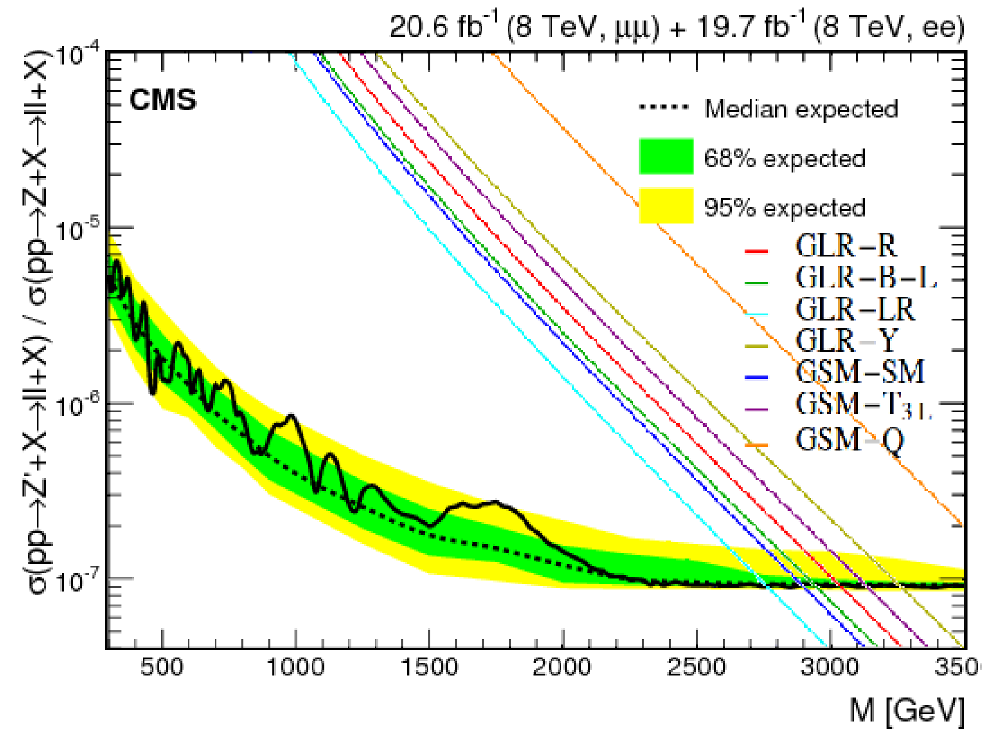
Table of couplings for narrow models:

$U(1)'$	$Parameter$	a_V^u	a_A^u	a_V^d	a_A^d	a_V^e	a_A^e	a_V^ν	a_A^ν
$E6(g' = 0.462)$	θ								
χ	0	0	-0.316	-0.632	0.316	0.632	0.316	0.474	0.474
ψ	0.5π	0	0.408	0	0.408	0	0.408	0.204	0.204
η	-0.29π	0	-0.516	-0.388	-0.129	0.388	-0.129	0.129	0.129
S	0.129π	0	-0.130	-0.581	0.452	0.581	0.452	0.516	0.516
I	0.21π	0	0	-0.5	0.5	0.5	0.5	0.5	0.5
N	0.42π	0	0.317	-0.157	0.474	0.157	0.474	0.316	0.316
$GLR(g' = 0.592)$	ϕ								
R	0	0.5	-0.5	-0.5	0.5	-0.5	0.5	0	0
$B-L$	0.5π	0.333	0	0.333	0	-1	0	-0.5	-0.5
LR	-0.130π	0.326	-0.459	-0.591	0.459	-0.06	0.459	0.199	0.199
Y	0.25π	0.589	-0.354	-0.118	0.354	-1.061	0.354	-0.354	-0.354
$GSM(g' = 0.762)$	α								
SM	-0.072π	0.186	0.487	-0.336	-0.487	-0.035	-0.487	0.487	0.487
$T3L$	0	0.5	0.5	-0.5	-0.5	-0.5	-0.5	0.5	0.5
Q	0.5π	1.333	0	-0.667	0	-2	0	0	0

8 TeV bounds

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





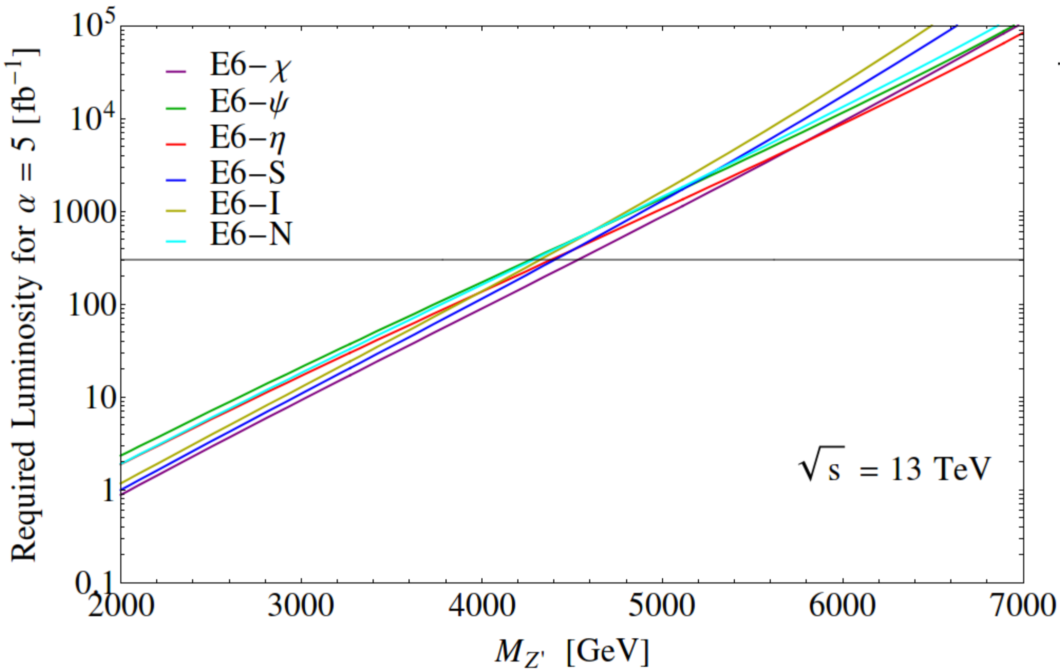
The exclusion limits we found <u>match</u> the experimental results

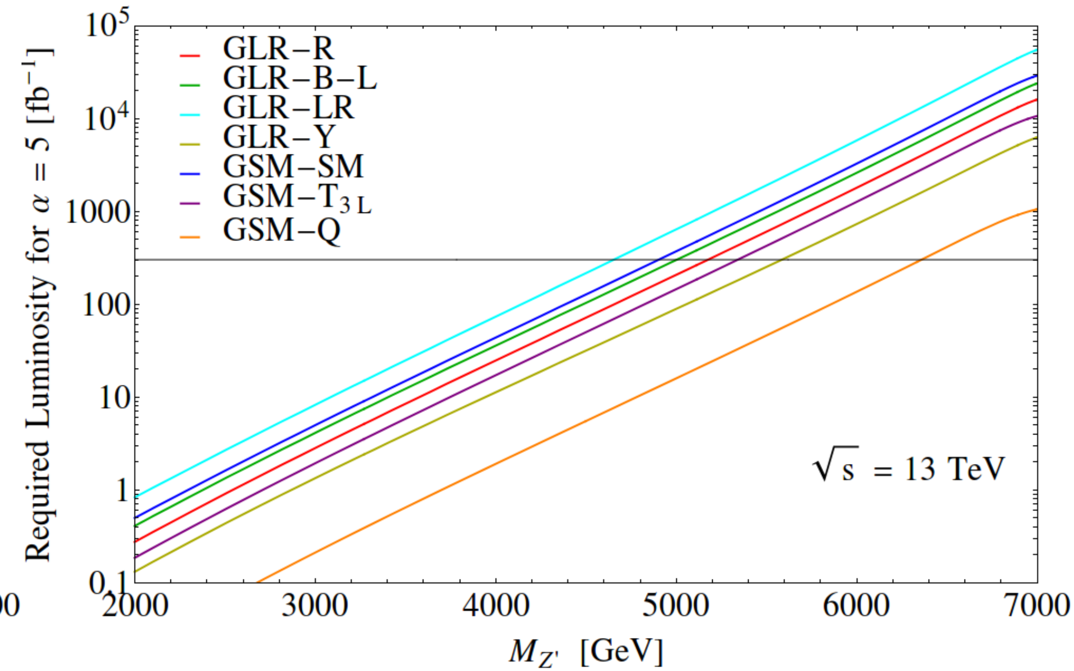
Class	E_6						GLR				GSM		
$U'(1)$ Models	χ	ψ	η	S	I	N	R	$B-L$	LR	Y	SM	T_{3L}	Q
$M_{Z'}$ [GeV]	2700	2560	2620	2640	2600	2570	3040	2950	2765	3260	2900	3135	3720

Begin of the search window for Run II

Projection on Narrow Z' @ 13 TeV

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





Discovery (1st line) and Exclusion (2nd line) limits

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 Run II : 2.5 TeV < Mz' < 6.5 TeV

Forward – Backward Asymmetry

$$A^*_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sigma_F = \int_0^1 \frac{d\sigma}{d\cos\theta^*} d\cos\theta^*$$

$$\sigma_B = \int_{-1}^0 \frac{d\sigma}{d\cos\theta^*} d\cos\theta^*$$

θ* is the angle between incoming quark and the outgoing leptons in the $q\bar{q}$ centre of mass frame

$$\sum_{spin,col} \left| \sum_i \mathcal{M}_i \right|^2 = \frac{\hat{s}^2}{3} \sum_{i,j} |P_i^* P_j| \left[(1+\cos^2\theta) C_S^{i,j} + 2\cos\theta C_A^{i,j} \right]$$

Cross section term: $(1+\cos^2\theta) C_S^{i,j}$

AFB term: $2\cos\theta C_A^{i,j}$

$$C_S^{i,j} = (a_{V_i} a_{V_j} + a_{A_i} a_{A_j})_L (a_{V_i} a_{V_j} + a_{A_i} a_{A_j})_Q$$

$$C_A^{i,j} = (a_{V_i} a_{A_j} + a_{A_i} a_{V_j})_L (a_{V_i} a_{A_j} + a_{A_i} a_{V_j})_Q$$

Motivations

Features: | **Consequence:**

AFB as diagnostic tool

- AFB depends on different combination of the couplings, with respect to the cross section → Complementary information about the chiral couplings, with respect to the cross section

  Rizzo : JHEP 0908 082 (2009)

- The shape of the AFB is affected by strong interference effects → The model dependent shape of the AFB can help in distinguish between different models

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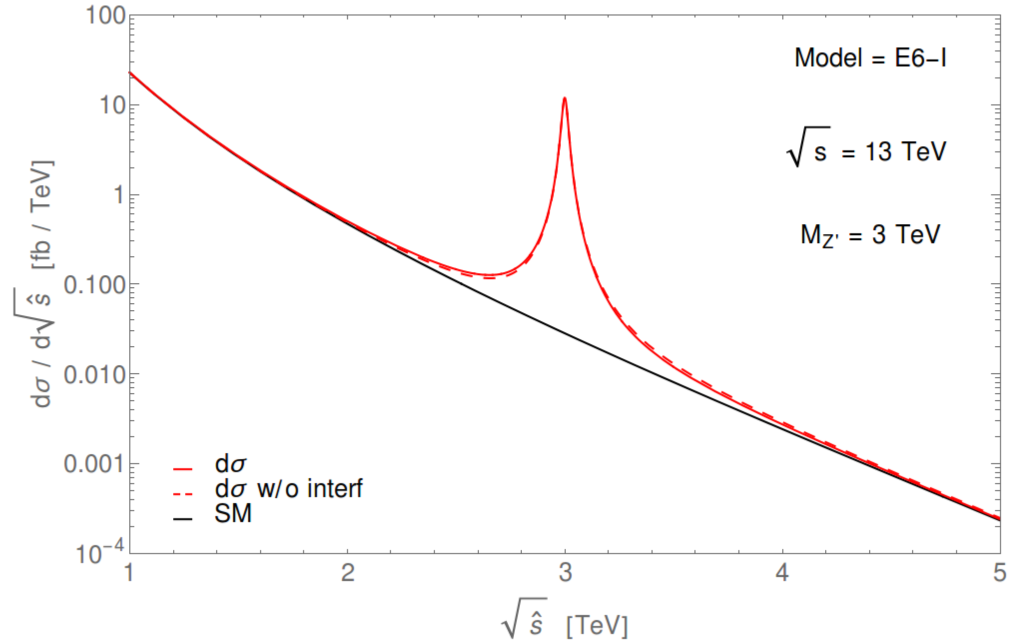
AFB as search tool

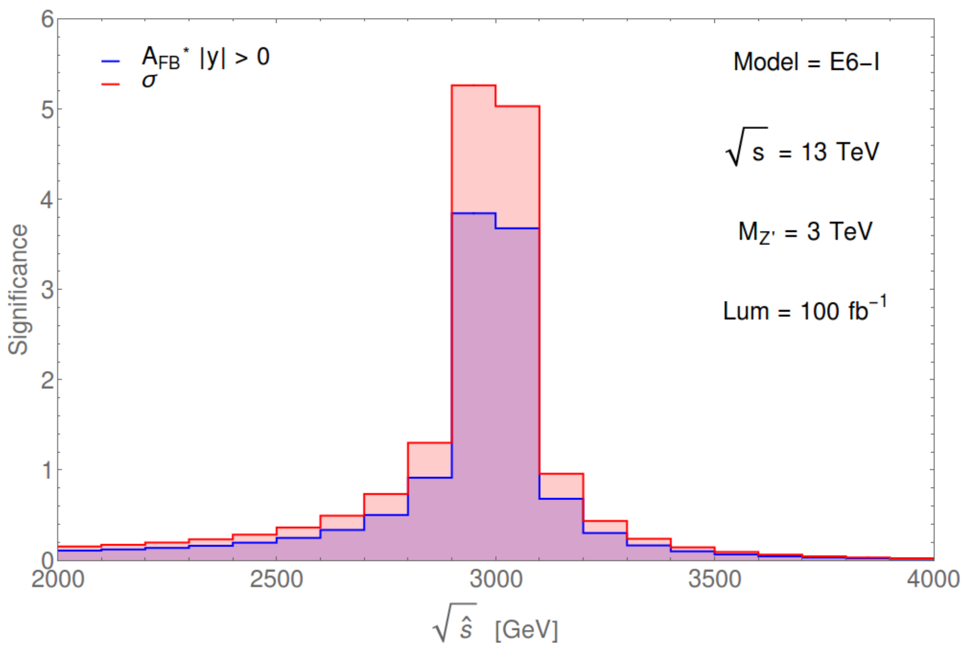
- It comes from the ratio of cross sections → Systematic uncertainties cancel (PDFs, luminosity, etc.)

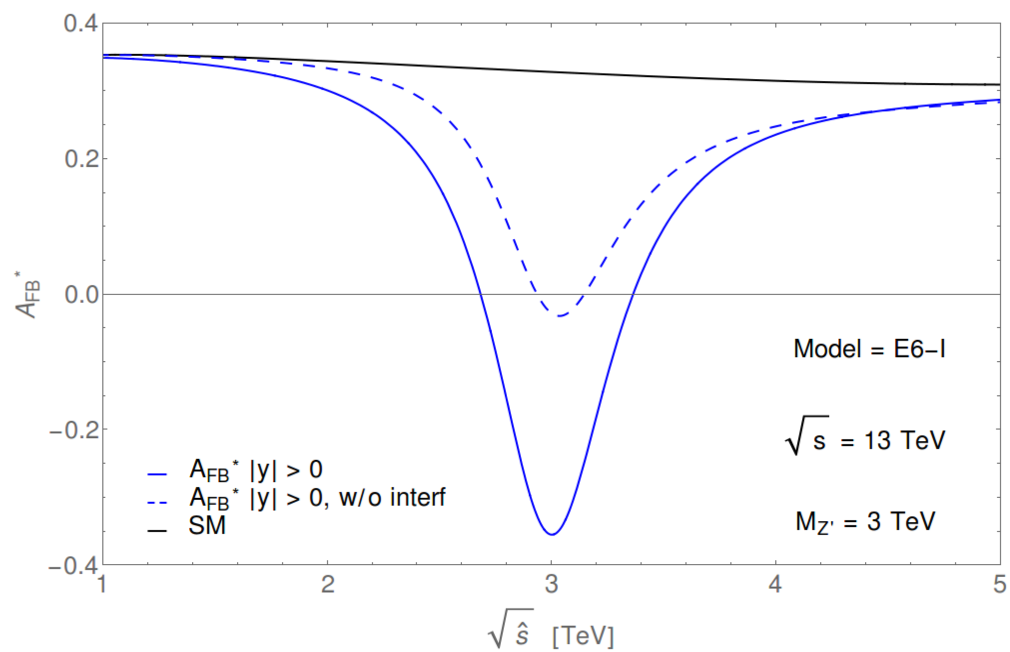
- For both narrow & wide resonances AFB can be used together with the bump search → Off-peak effects due to interference are sizeable and can be observed

Narrow case [E6 – I]

Interference can accentuate the peak in the AFB.
A high significance peak can occur for the AFB as well.





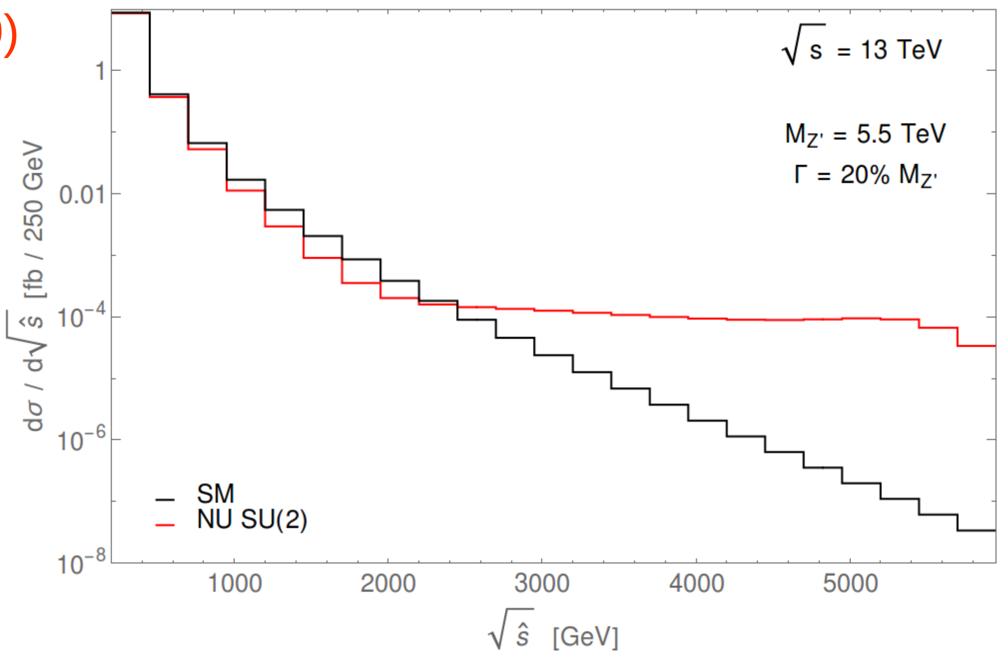


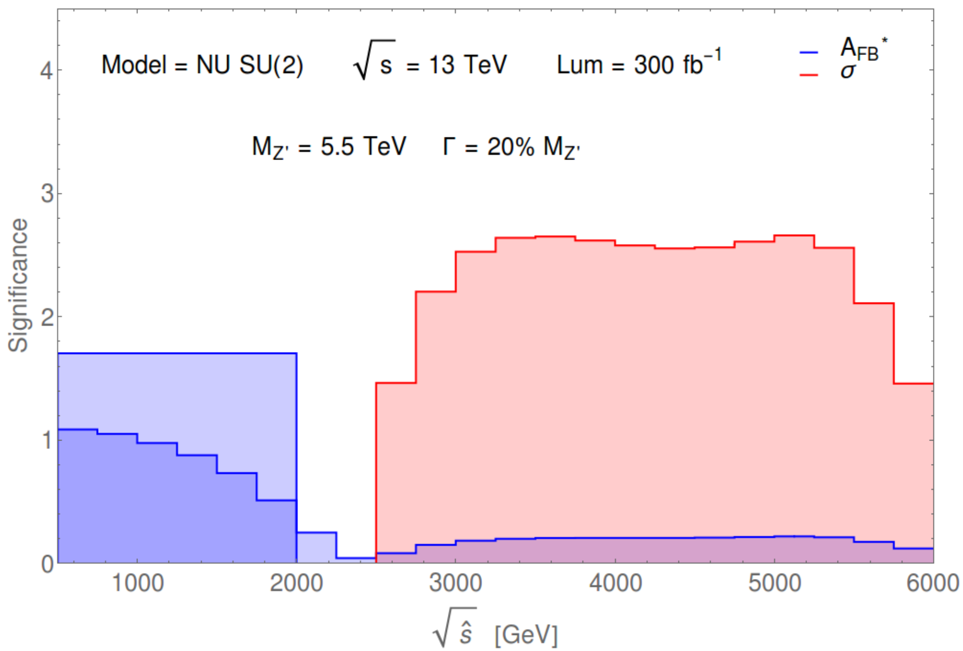
Wide case [Non Universal SU(2)]

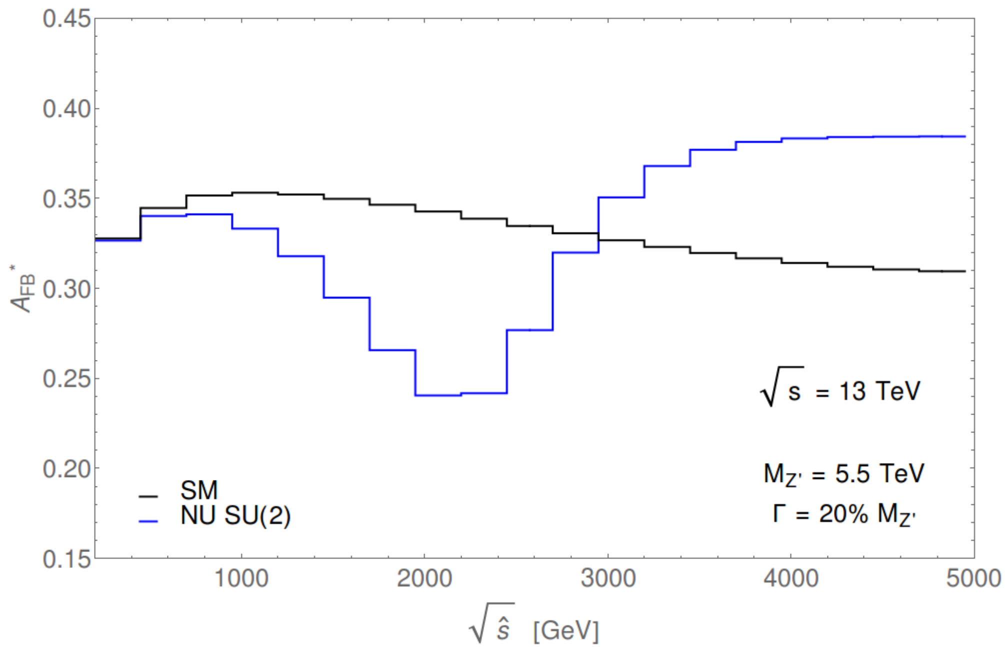
Malkawi, Yuan : Phys.Rev. D61 015007 (2000)

Interference effects can shift the AFB peak to a lower invariant mass value.

We can combine the information from the two observables, in order to achieve a better significance.





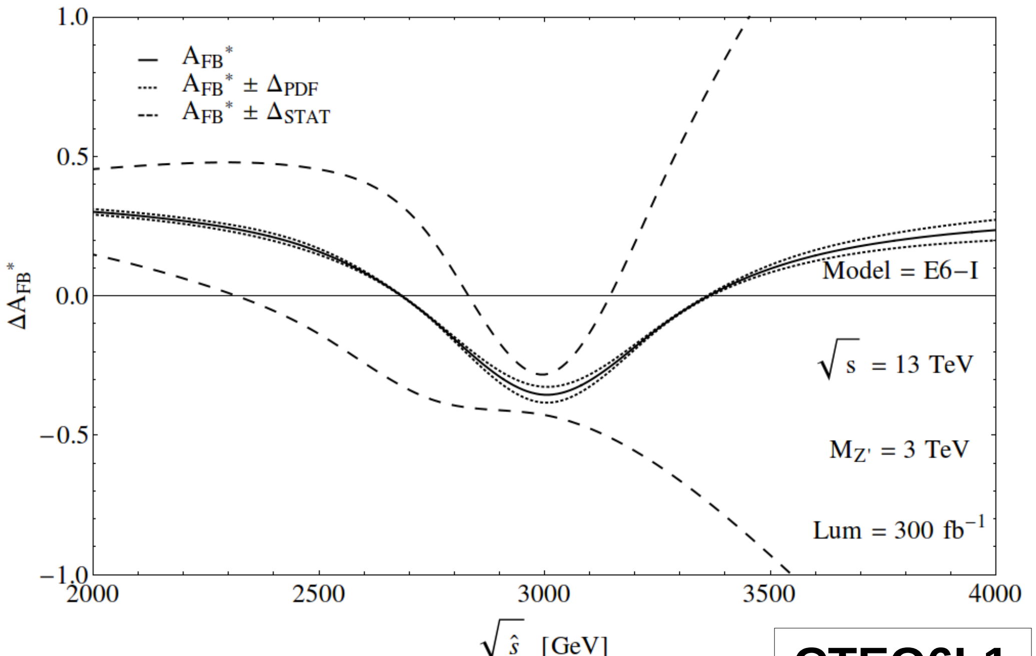


PDFs vs Statistic Uncertainties

PDF uncertainties obtained through the Hessian method

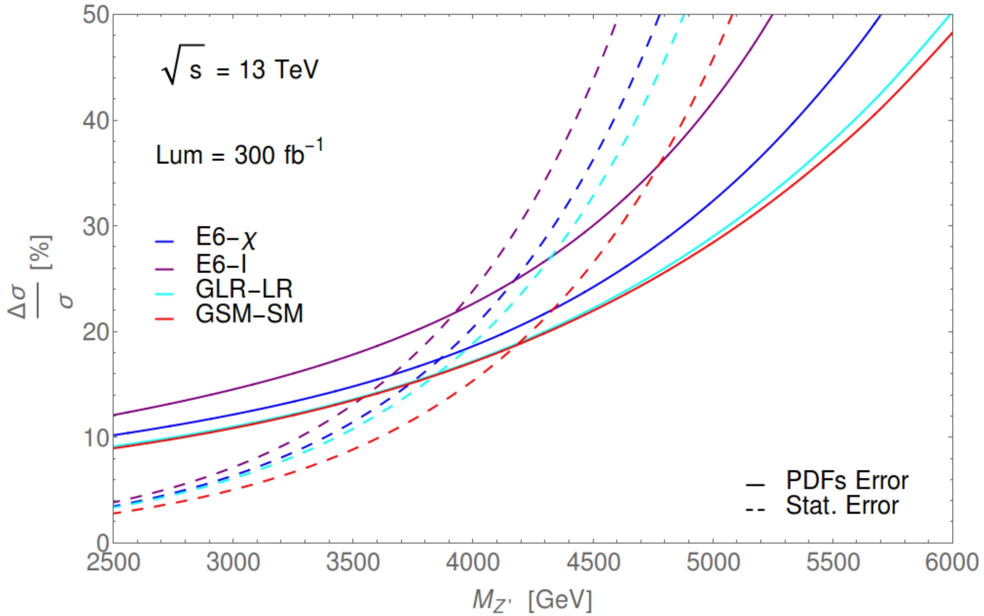
The PDF's error on AFB is always <u>smaller</u> than the statistical one over the full range of Z' boson masses that will be covered during Run II

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

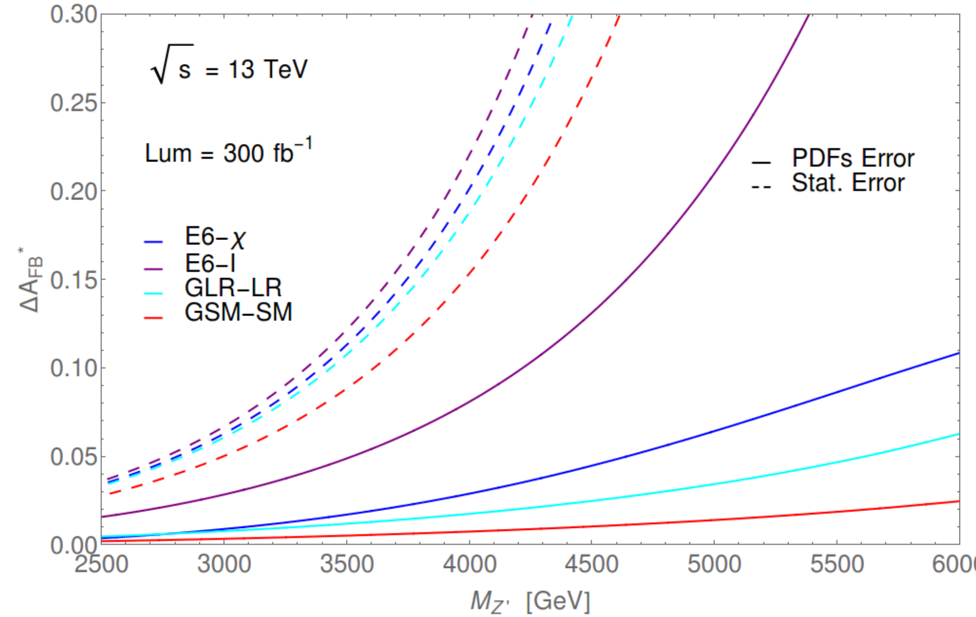


CTEQ6L1

Relative errors on the cross section



Absolute errors on the AFB



Conclusions

- In the context of searching for a heavy neutral resonance (***Z'***), we choose to study the dilepton decay channel, as it is clean and we can perform precise measurements on both the final state leptons.

- From the angular distribution of the final state leptons we can determine the Forward-Backward Asymmetry. This observable presents key features:

  - Complementary information with respect to the cross section distribution about the chirality of the couplings between the ***Z'*** and the initial and final state fermions.

  - The shape of the AFB is model dependent and can be used to distinguish which theoretical model predicts a specific ***Z'***.

  - In the case of narrow resonances AFB can be a valid alternative to the cross section observable since it is less sensitive to systematic uncertainties and in some cases still has a large significance.

  - In the case of wide resonances the information coming from the cross section distribution can be lost in the background, or can only be interpreted in terms of counting strategy, while the AFB maintain a definite shape and can be used to identify a neutral resonance.

  - PDFs uncertainties are comparable with the statistic error in the cross section, while in the AFB, due to cancellations, the PDFs uncertainties are sub dominant

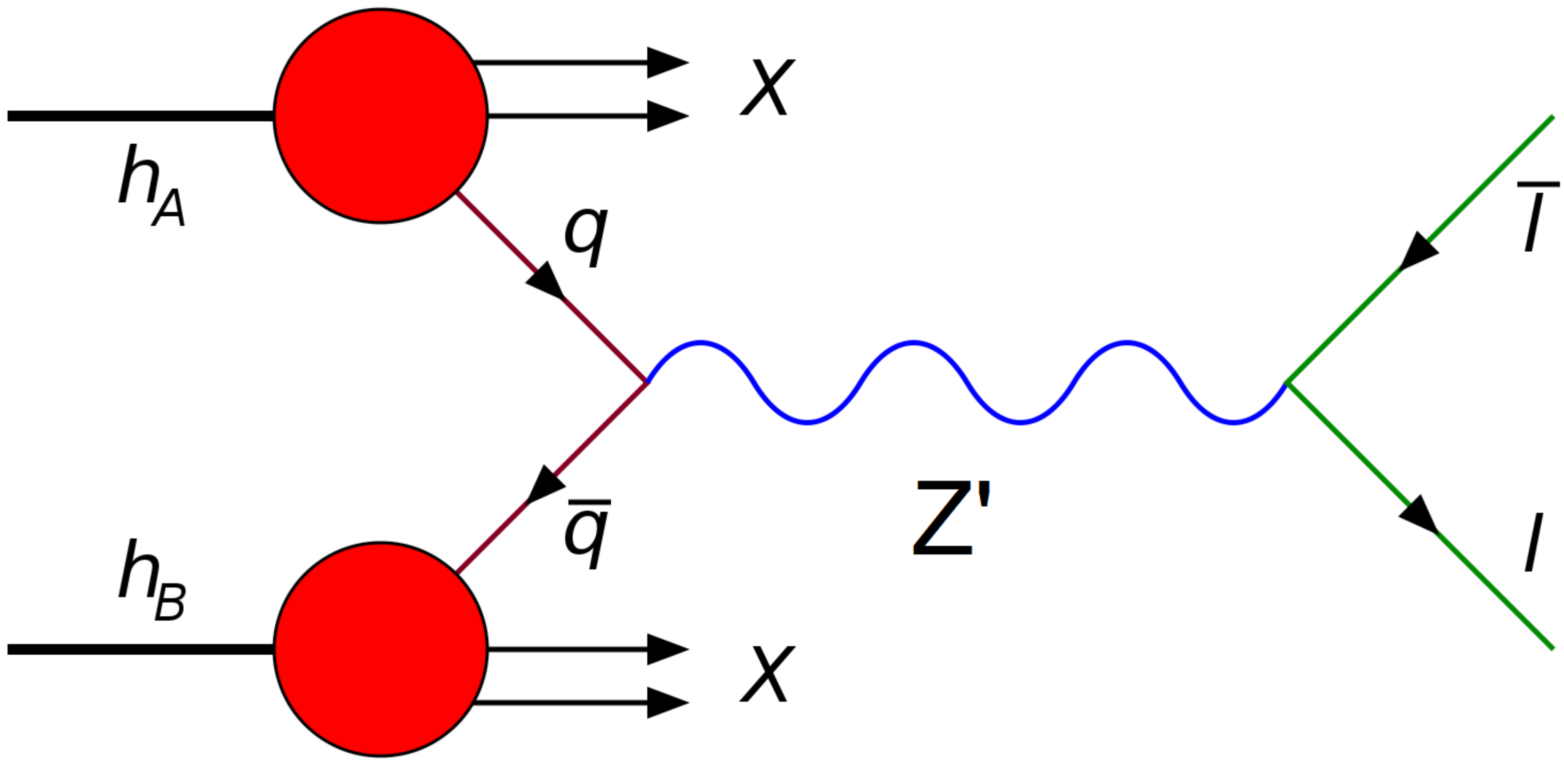
- We have developed and validated our code against the latest experimental bounds and then we have been able to derive discovery/exclusion limits for the **LHC-Run II**

- We have demonstrated the role of AFB not only as a **Z'** post-discovery analysis tool, but also as a **Z'** search tool itself.

Thank you!

Drell-Yan

Neutral Channel Drell-Yan Z' search



Motivations:

Leptons in the final state are:

- Easy to detect
- Precise to measure
- Almost background-free

$$pp \to Z' \to e^+e^-$$

CTEQ6L1 PDFs were used

Significance

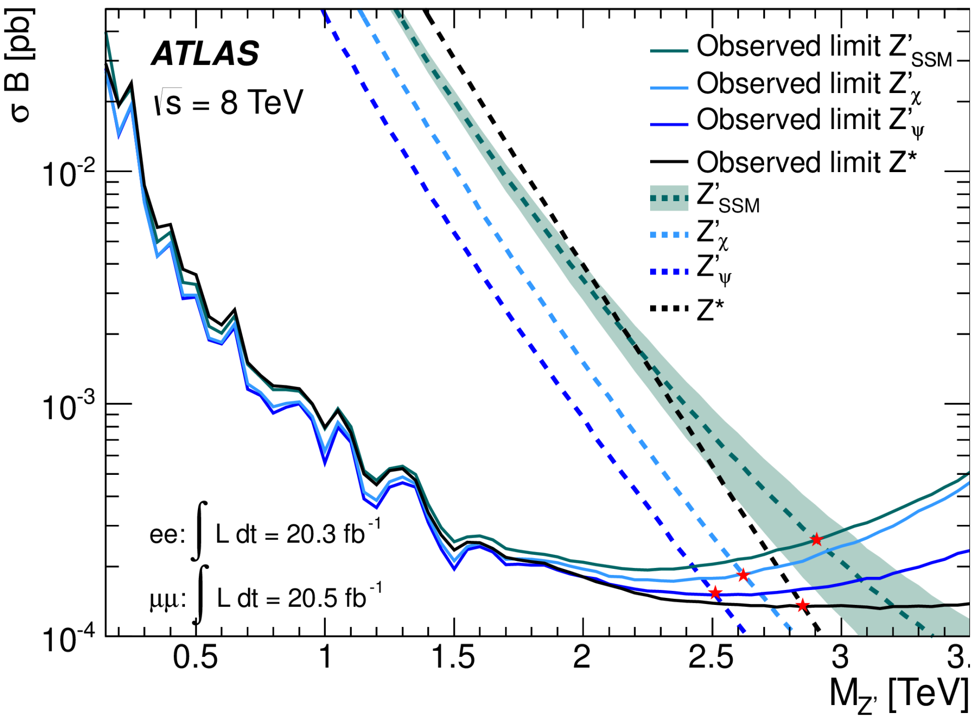
Definition of uncertainties and significance

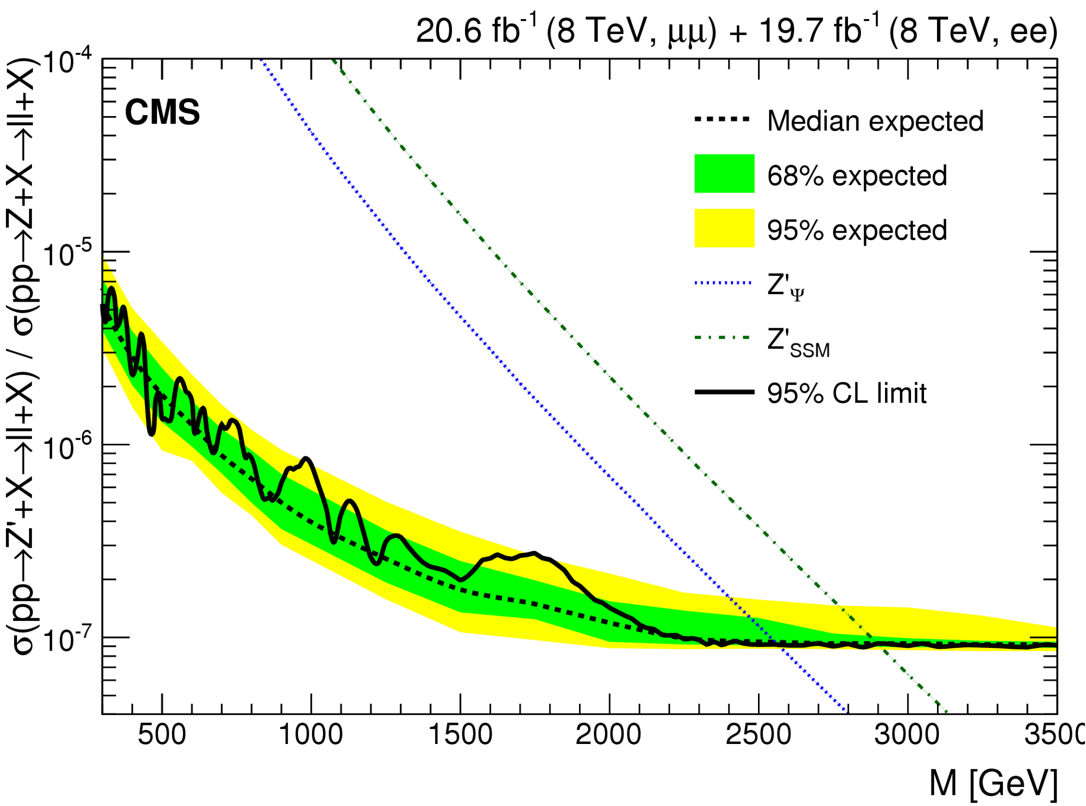
$$\delta\sigma = \sqrt{N_{events}} \longrightarrow \alpha = \frac{|\sigma - \sigma^{SM}|}{\delta\sigma}$$

$$\delta A_{FB} = \sqrt{\frac{1 - A_{FB}^2}{N_{events}}} \longrightarrow \alpha = \frac{|A_{FB} - A_{FB}^{SM}|}{\delta A_{FB}}$$

Z' search @ LHC

LHC most recent results at 8 TeV





ATLAS : Phys. Rev. D 90, 052005 (2014)

CMS : CMS-EXO-12-061

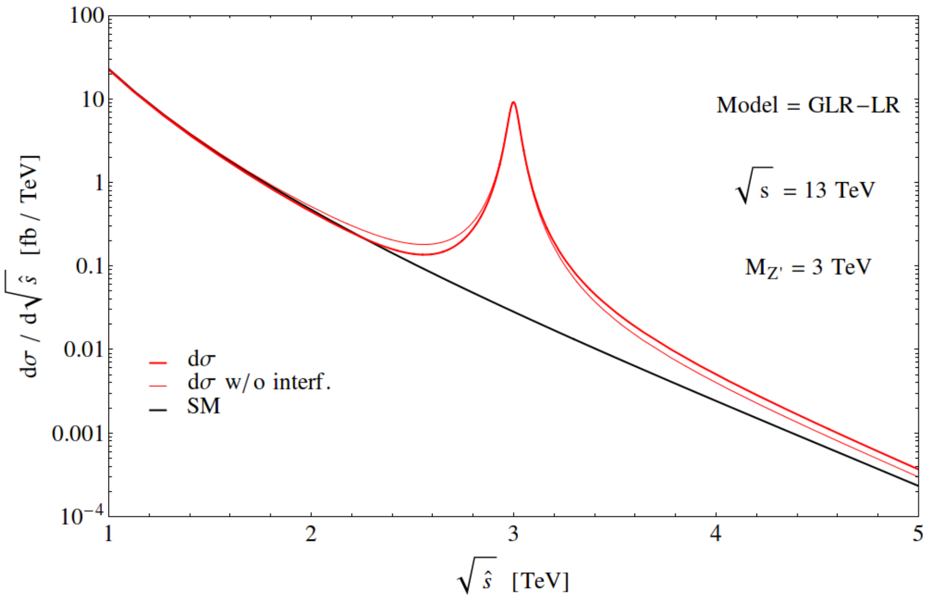
Typical limits for Z' mass:

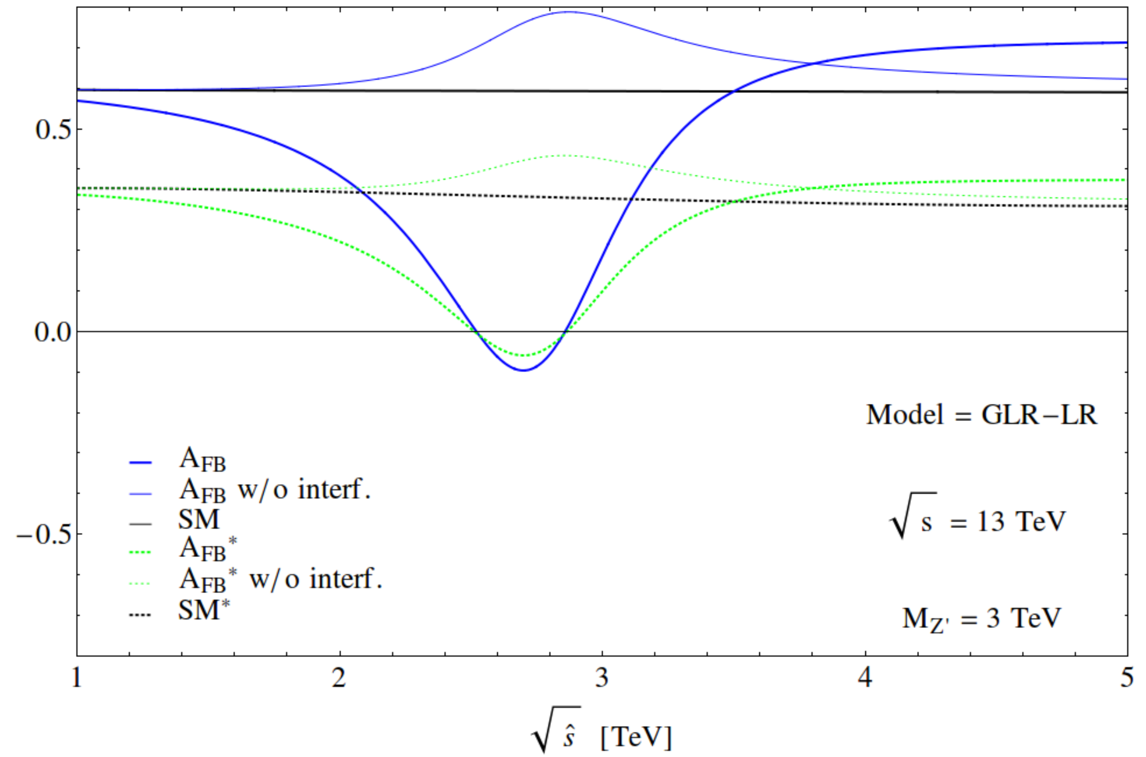
$M_{Z'}$ ~ 2.8 TeV

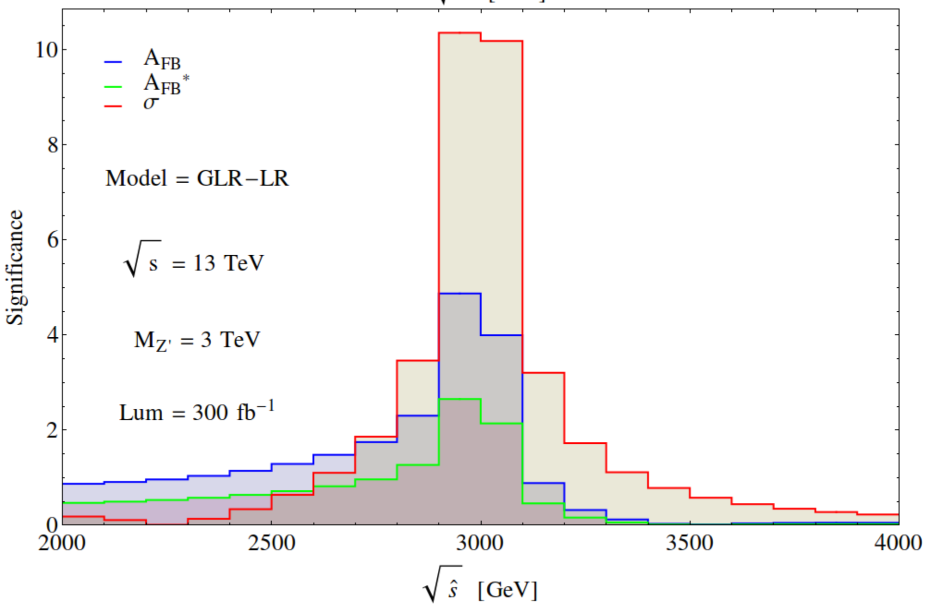
CMS systematically accounted <u>finite width</u> and <u>interference</u> effects as suggested in:
http://arxiv.org/pdf/1304.6700.pdf
JHEP 10 (2013) 153

Narrow case [GLR – LR]

Interference Effects

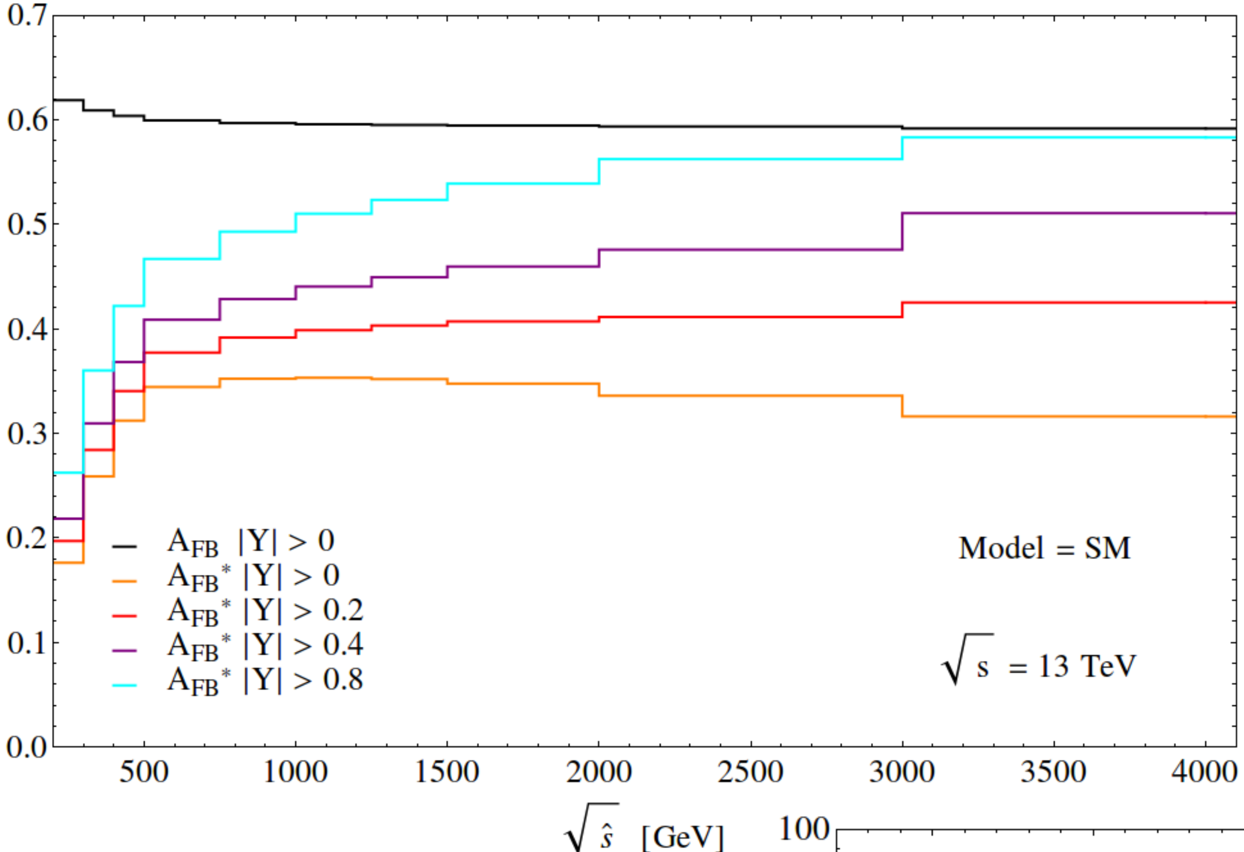




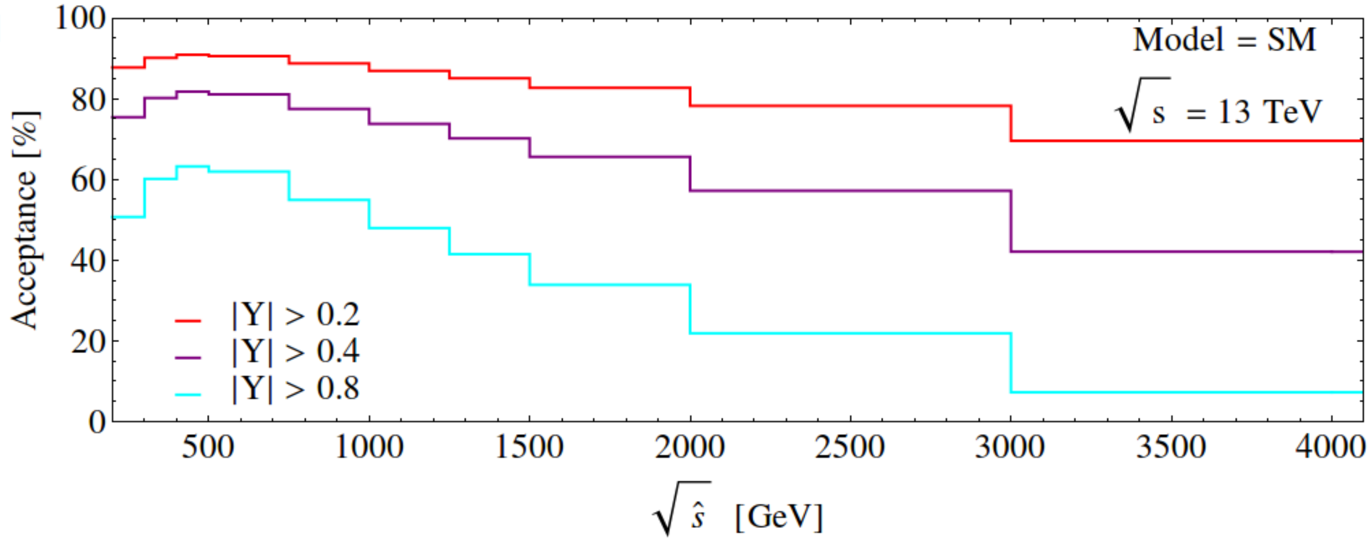


<u>Interference</u> can shift the peak of the AFB.
A <u>tail</u> with appreciable significance can occur.

Rapidity cuts and Acceptances



Rapidity cuts



Rapidity cuts and Acceptances

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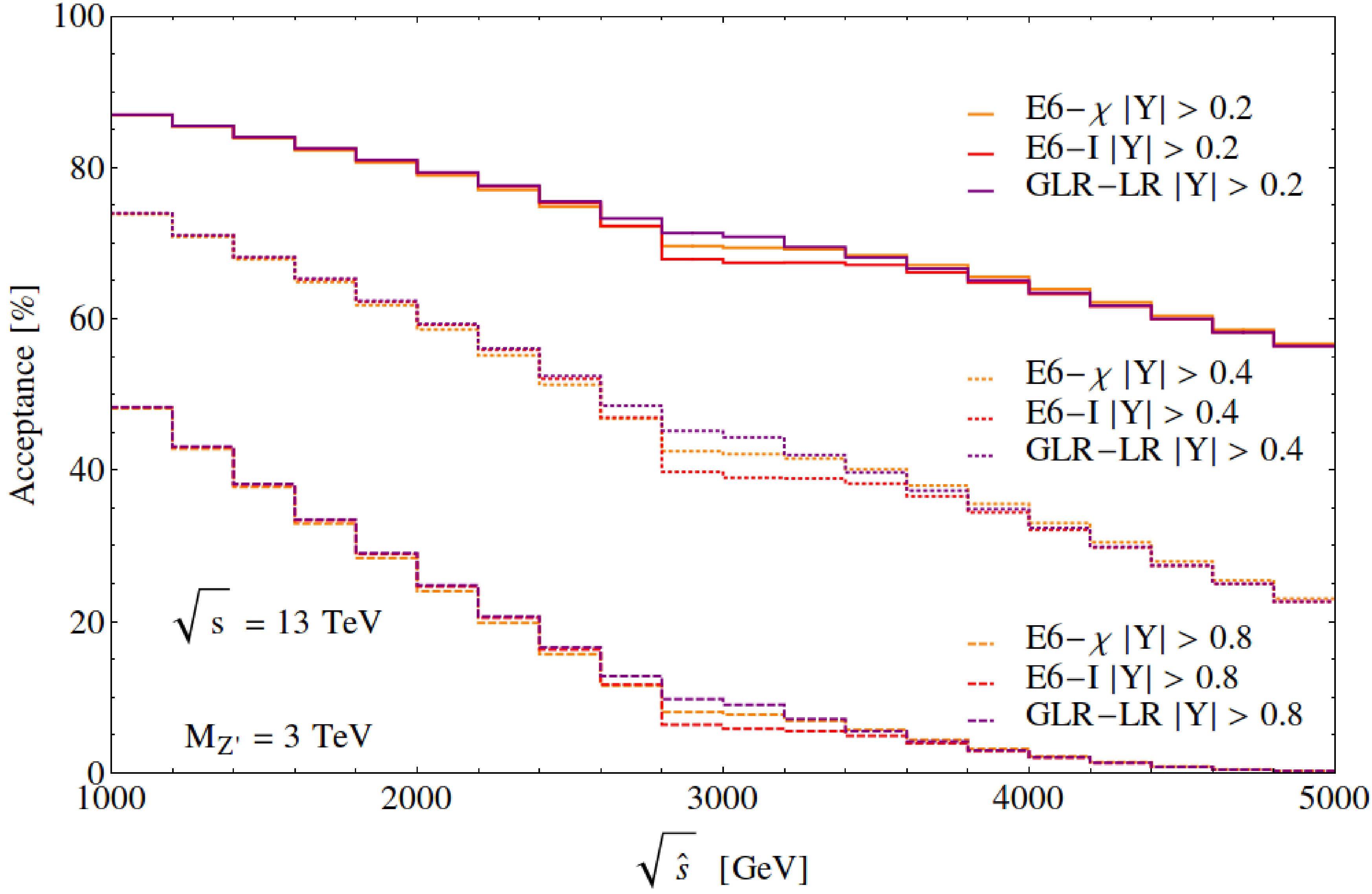


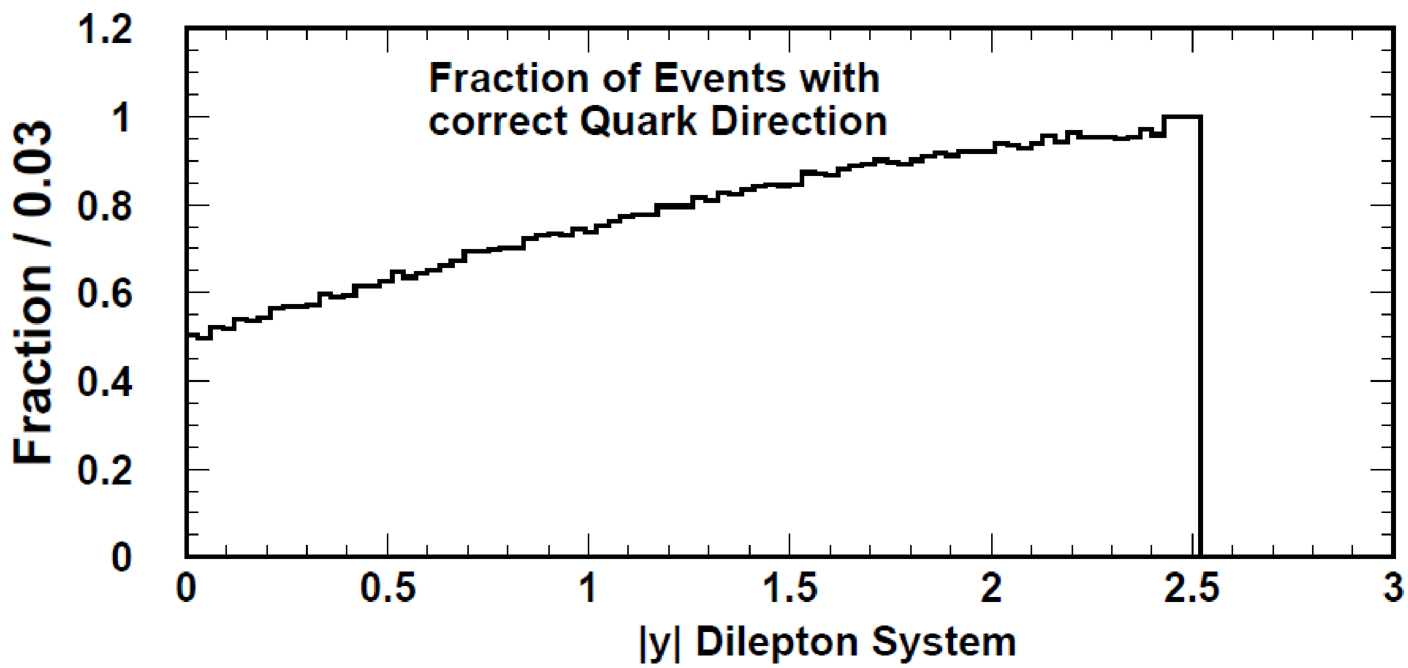
Forward / Backward

Subtletey in the definition of “Forward” and “Backward”:

In order to construct the asymmetry, we need to know which is the forward direction.
But in a Drell-Yan process we don't know from which proton the quark/antiquark comes from.

General rule:

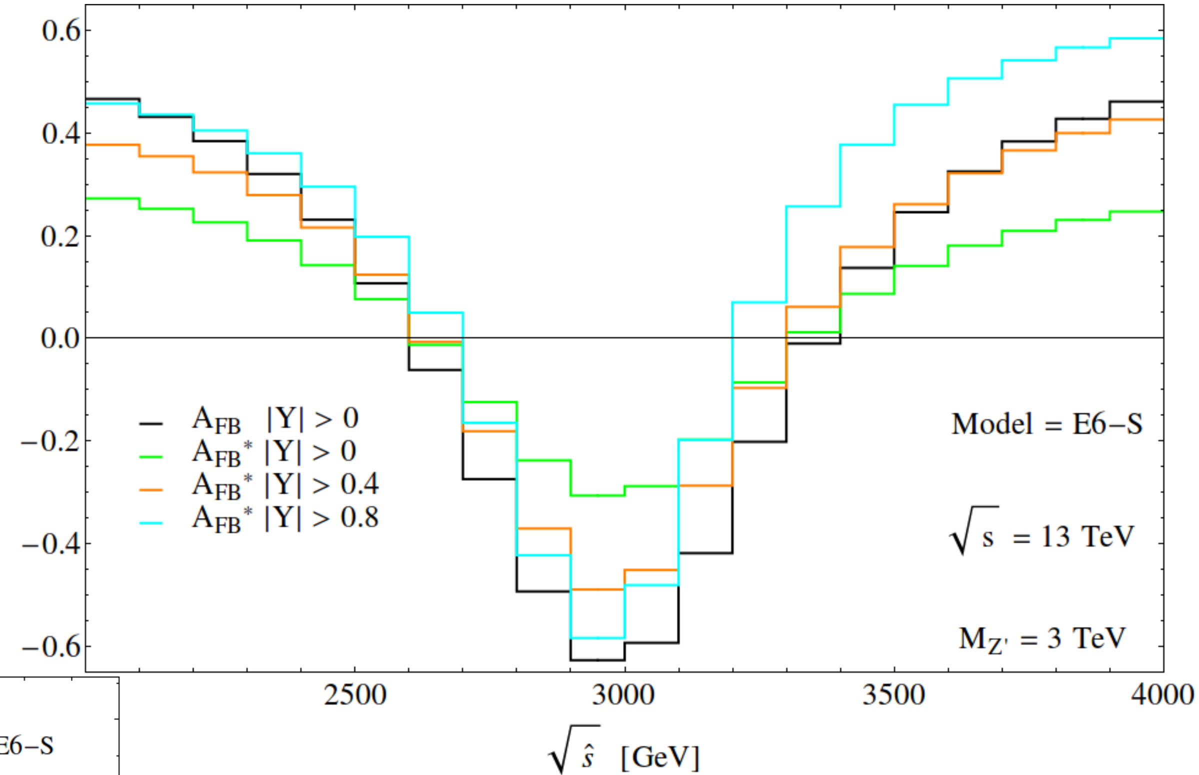
In this case of neutral process, we expect that the dilepton longitudinal momentum marks the direction of the quark, as the latter is supposed to be more energetic than the antiquark (which comes from the sea).

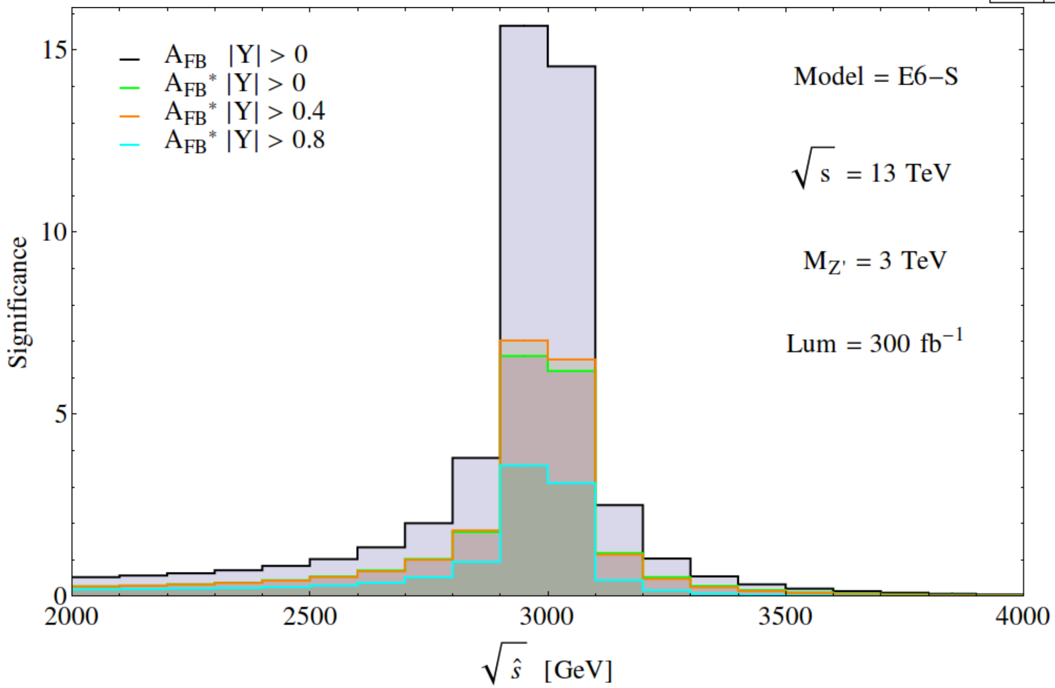


Dittmar : Phys.Rev.D55:161-166 (1997)

Reconstruction

The shape of the reconstructed AFB is smeared, but we can recover a more visible shape by applying rapidity (**Y**) cuts.

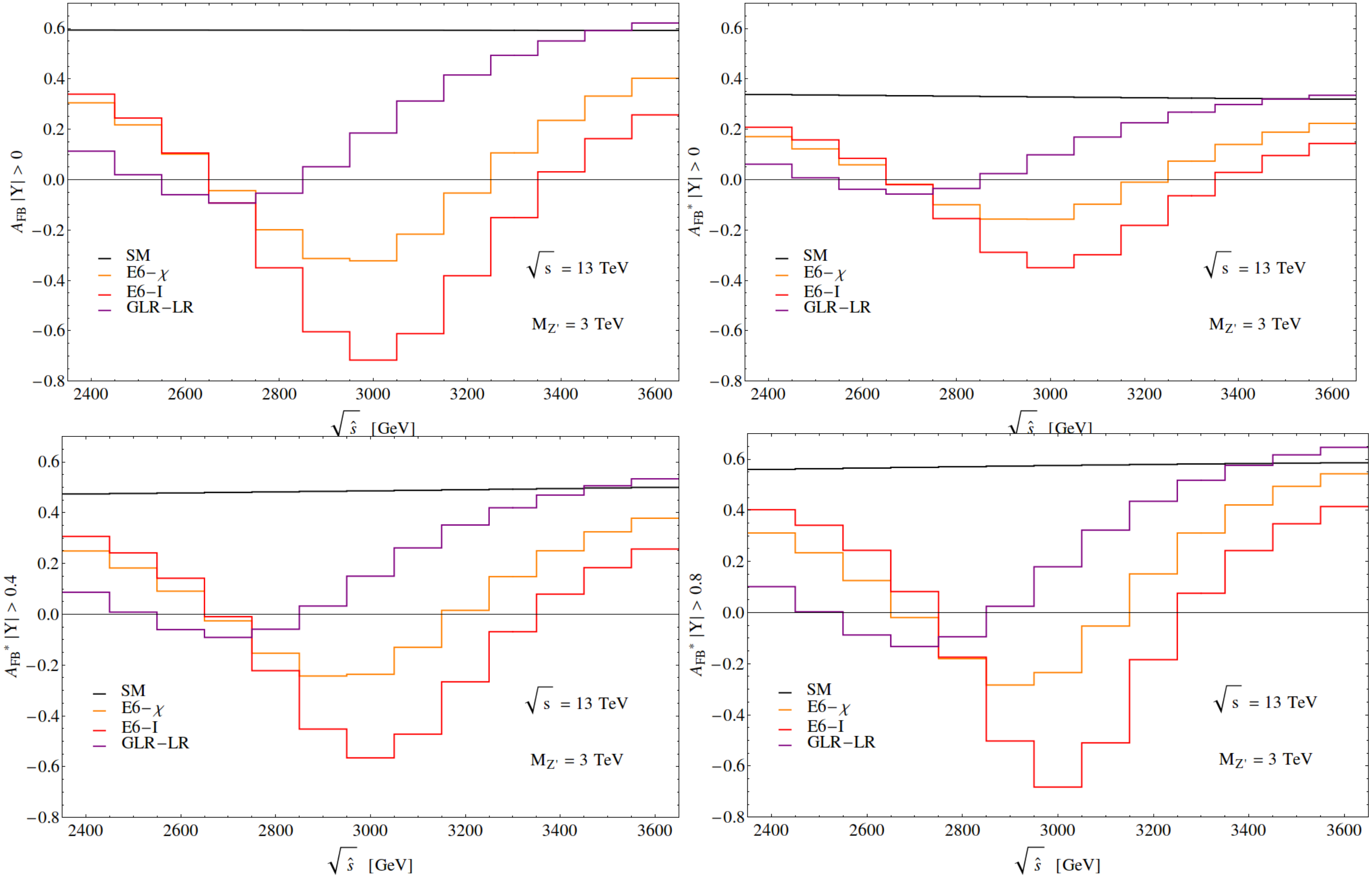




Nevertheless the cuts reduce the statistic of the events.
The observable is more reliable without the rapidity cuts.

Reconstruction

The rapidity cuts alter <u>model dependence!</u>



With the convention adopted in the reconstruction procedure, the probability of choosing the right direction for the incoming quark is <u>flavour dependent</u>.

Reconstruction

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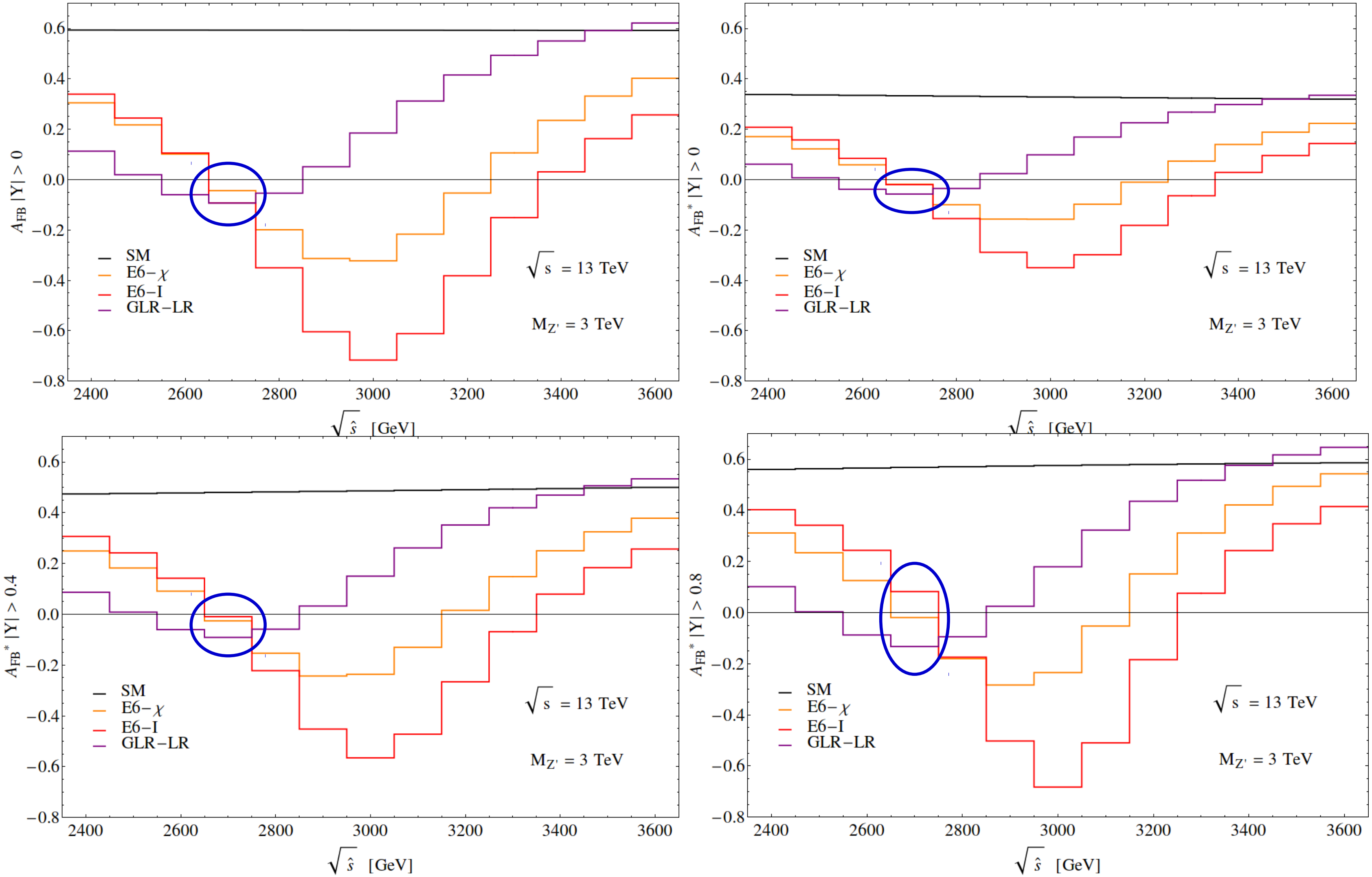
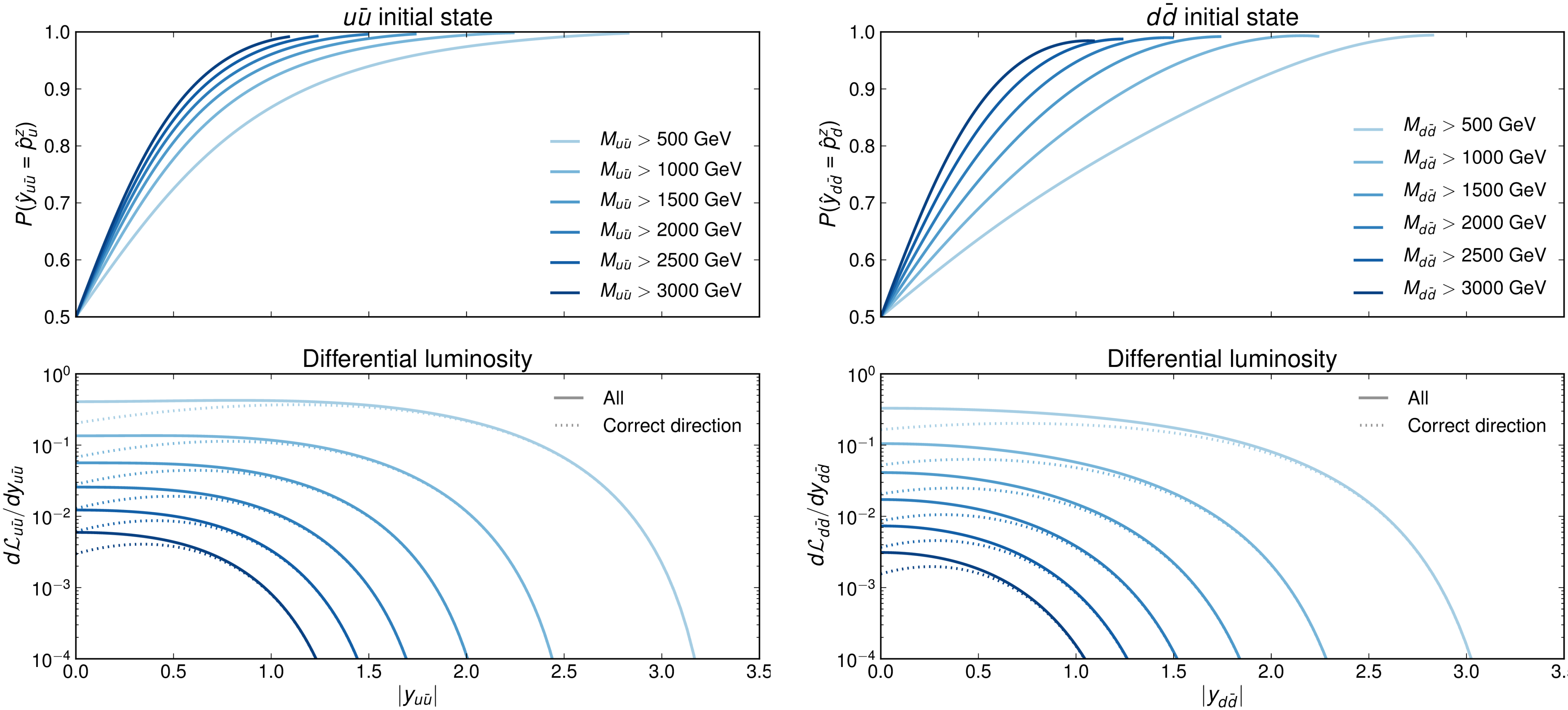


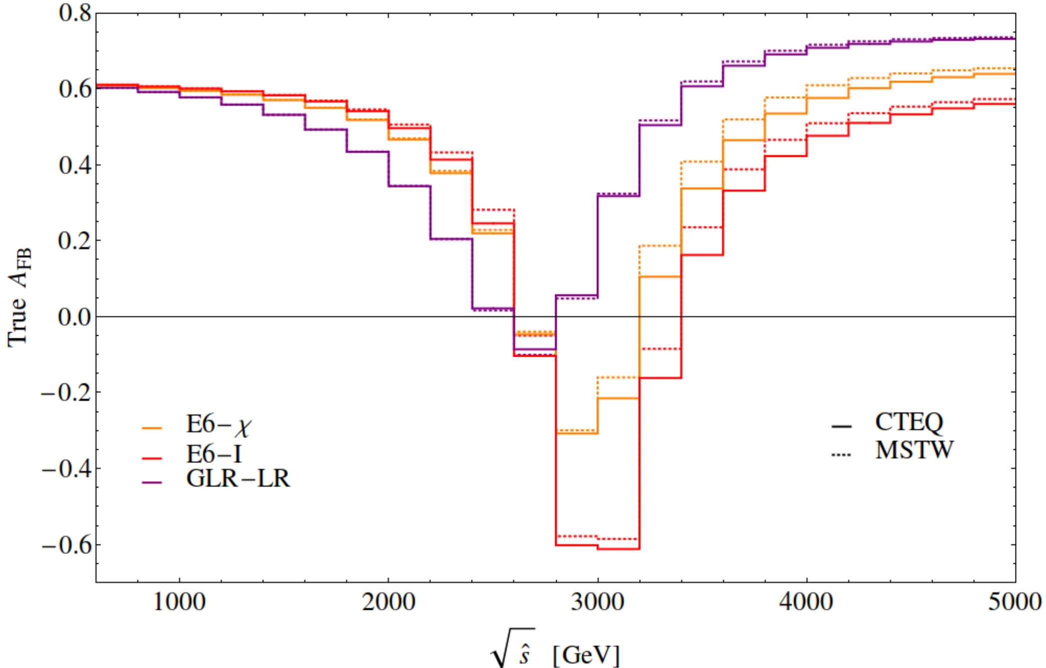
Models with <u>different couplings</u> to ***u*** and ***d*** quarks have a <u>different behaviour</u> under the application of rapidity cuts

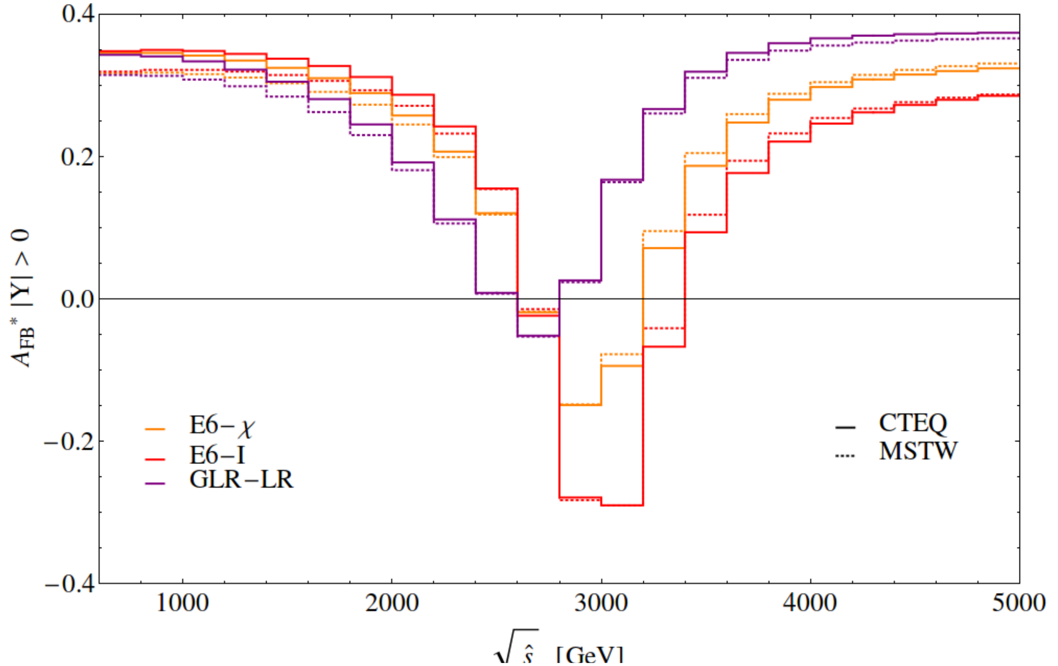
Parton probabilities and luminosities

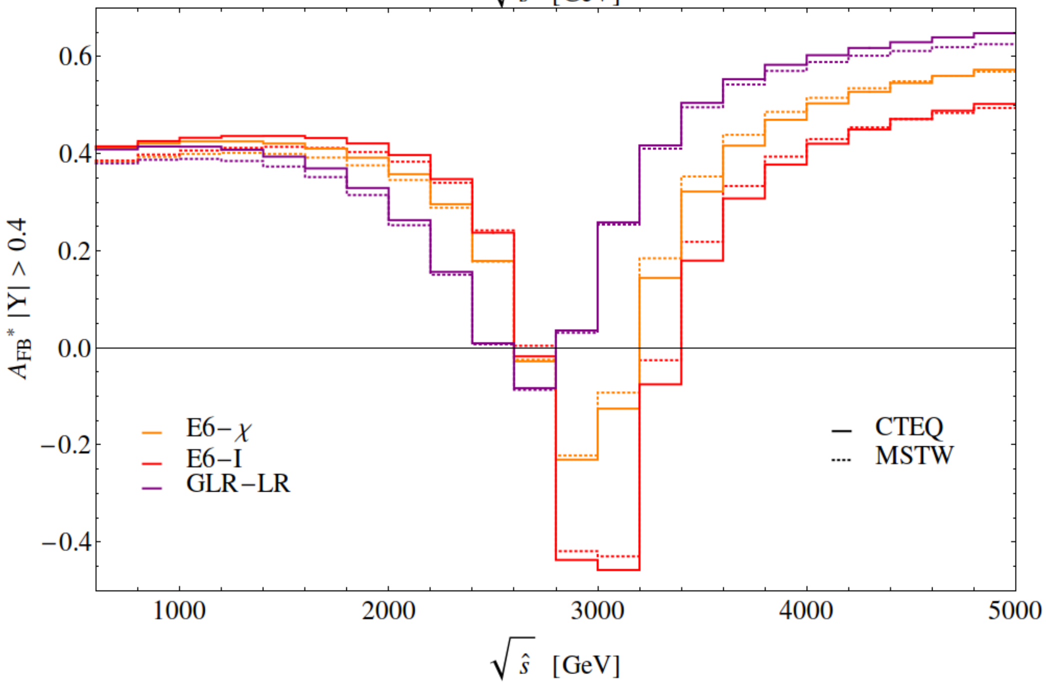
Partonic correct direction and luminosity

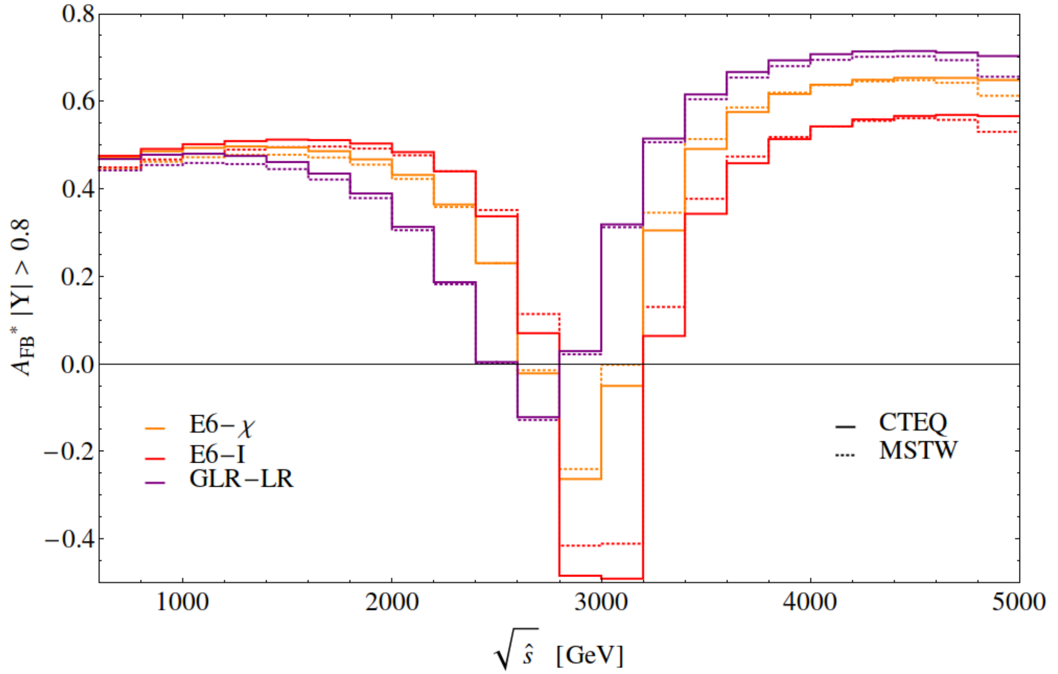


PDFs comparison

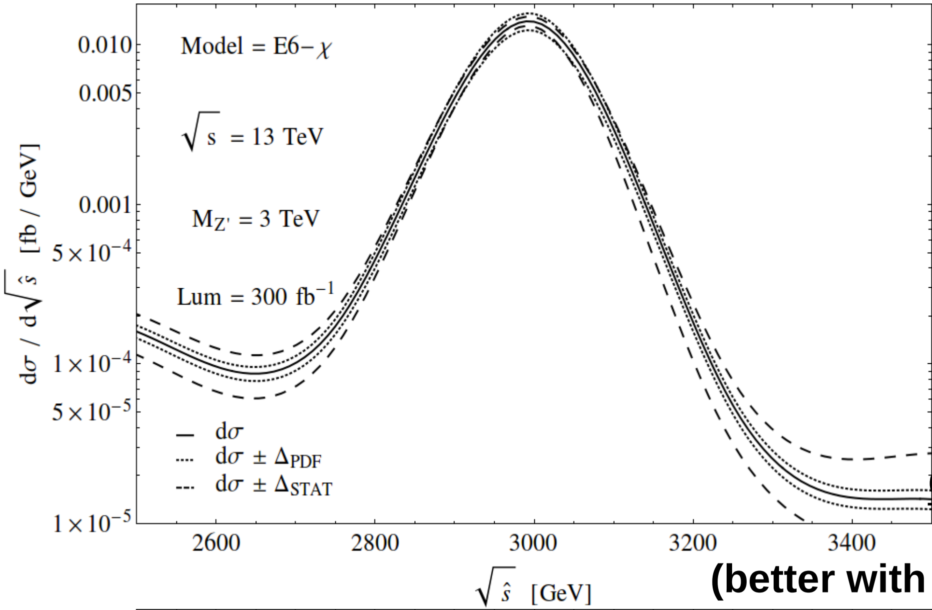


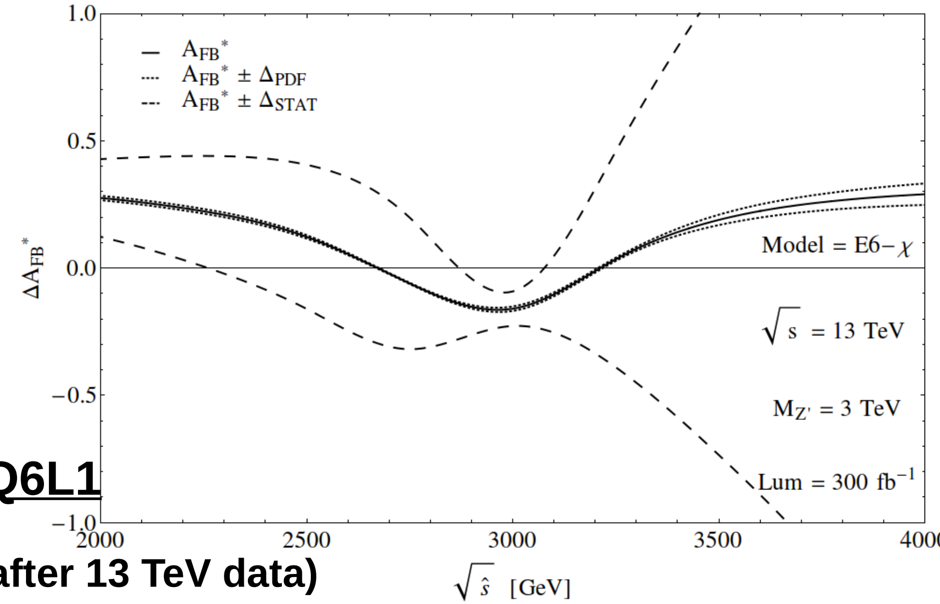






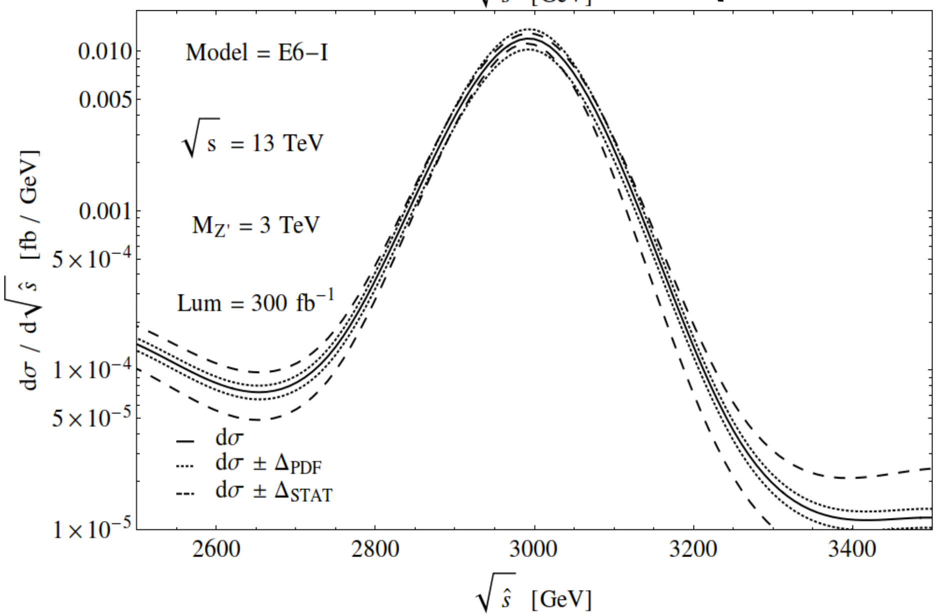
PDFs vs Statistic Uncertainties

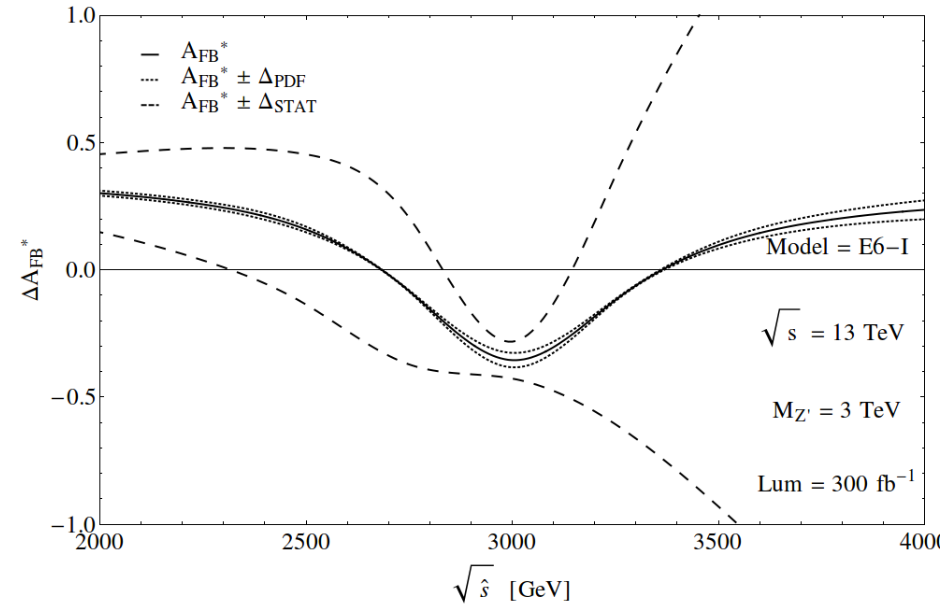




CTEQ6L1

(better with sets after 13 TeV data)



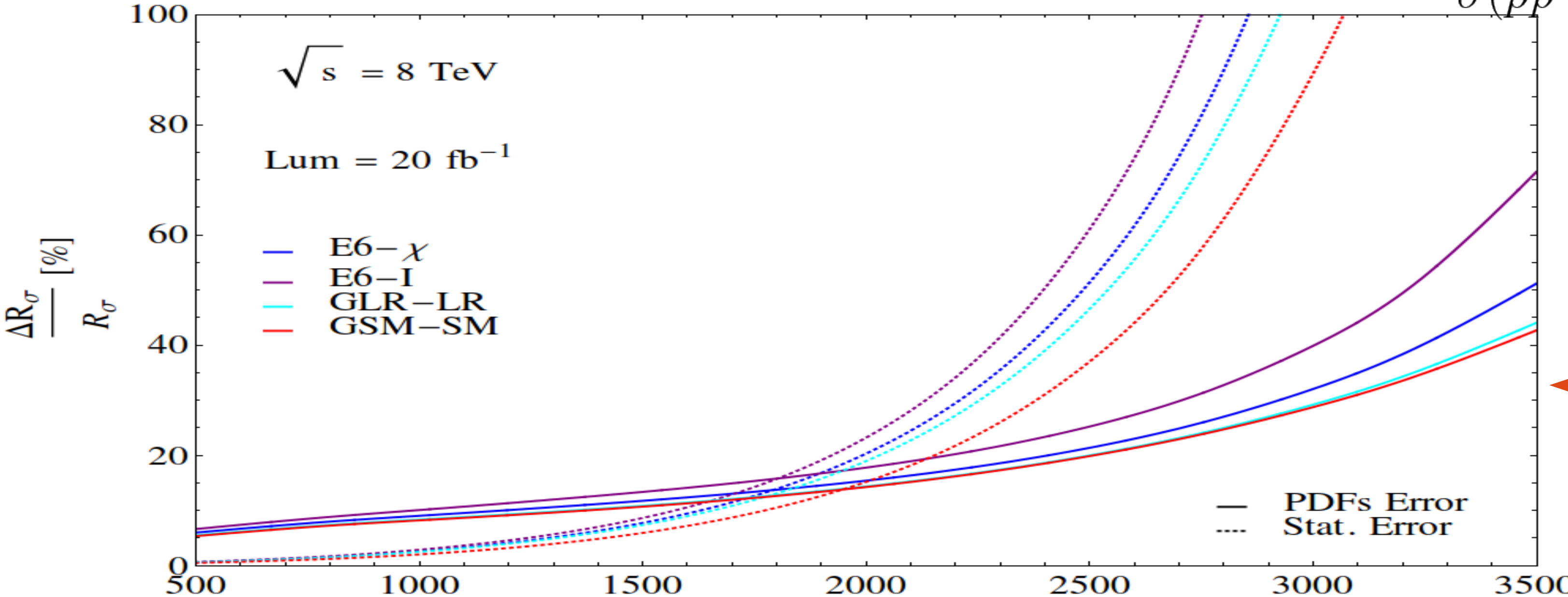


In the cross section, PDFs and statistic uncertainties are comparable.

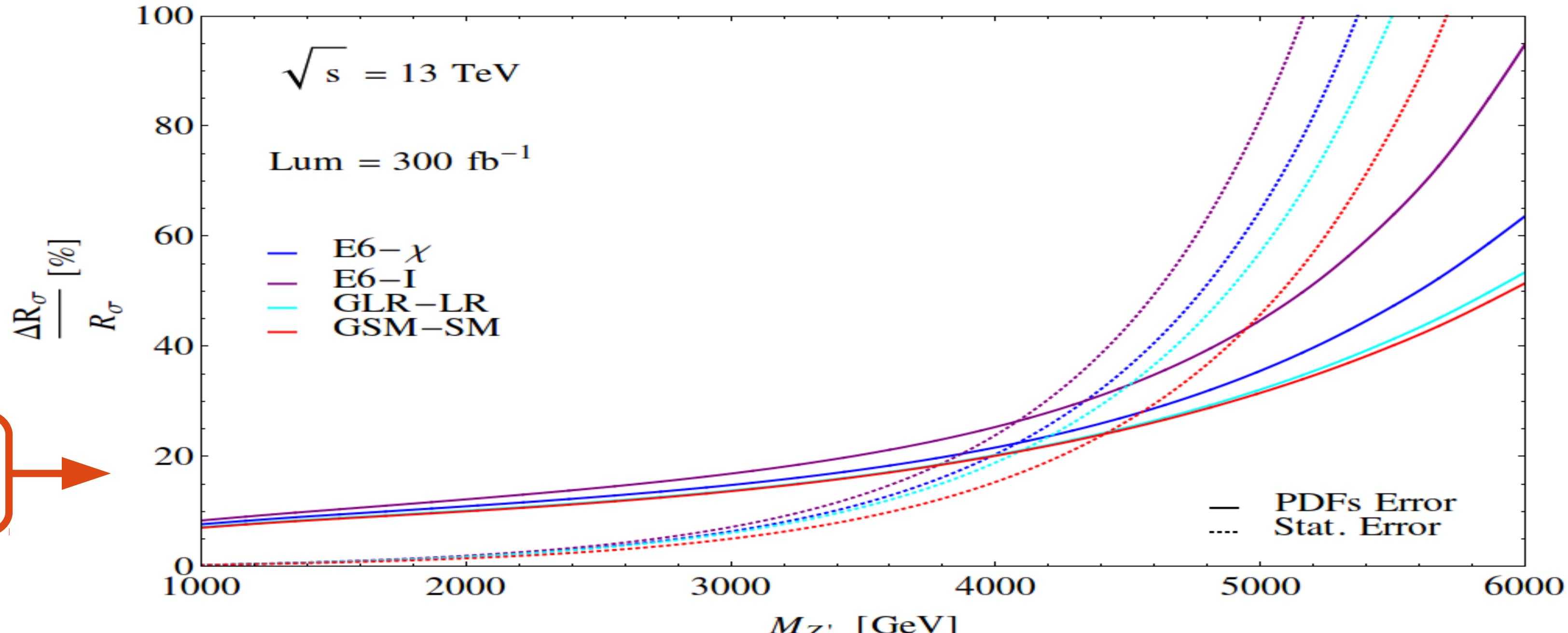
In the AFB, statistic uncertainties are dominant with respect to the PDFs.

R_σ error

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to ll + X)}{\sigma(pp \to Z + X \to ll + X)}$$



8 TeV
20 fb^{-1}



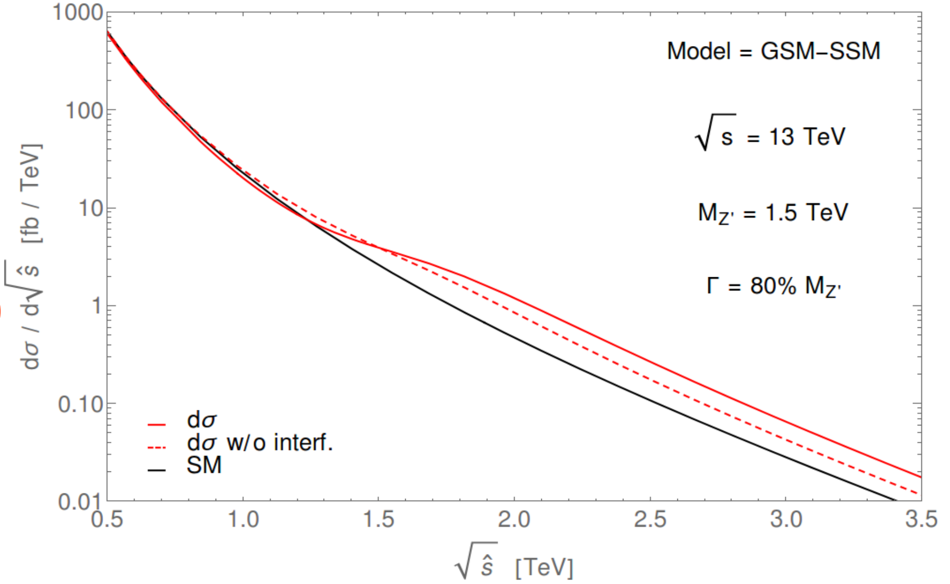
13 TeV
300 fb^{-1}

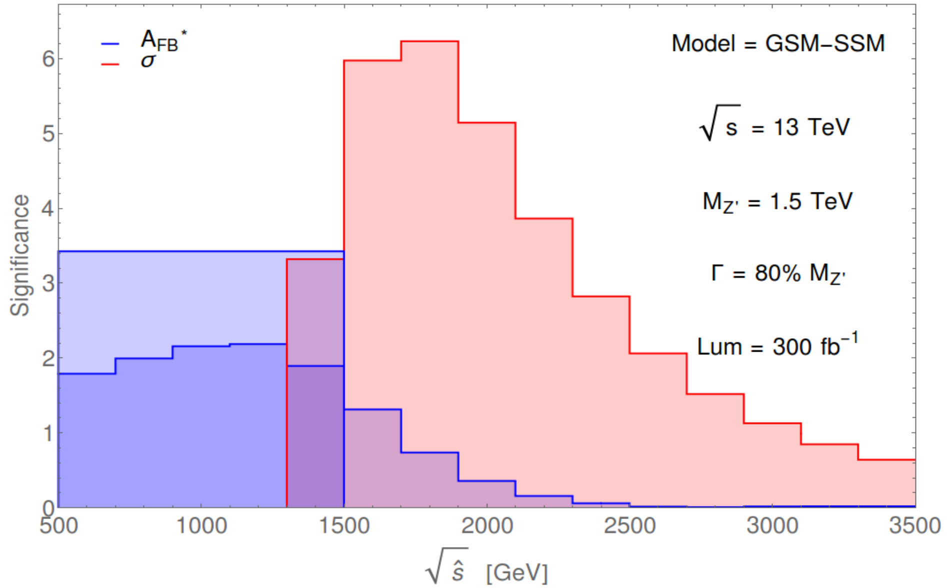
Wide resonance

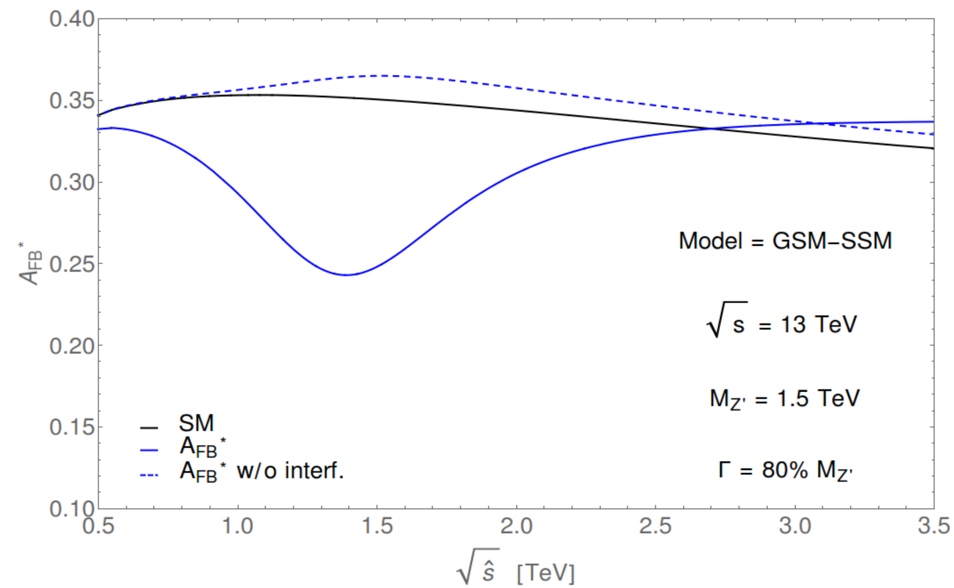
Wide GSM-SM benchmark

$$\Gamma(Z' \to W^+W^-) = \frac{\alpha}{48} cotg\theta_W M_{Z'} \left(\frac{M_{Z'}}{M_W}\right)^4 \left(1 - 4\frac{M_W^2}{M_{Z'}^2}\right)^{3/2} \left[1 + 20\left(\frac{M_W}{M_{Z'}}\right)^2 + 12\left(\frac{M_W}{M_{Z'}}\right)^4\right]$$

Altarelli, Mele, Ruiz-Altaba : Z.Phys. C45 109 (1989)







In the case of wide resonances when an event counting strategy is usually adopted, AFB maintain a peaking shape and can be used to identify a neutral resonance