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

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Overview

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

Modelling

Parametrization of the interaction

Low Energy Lagrangian:

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

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

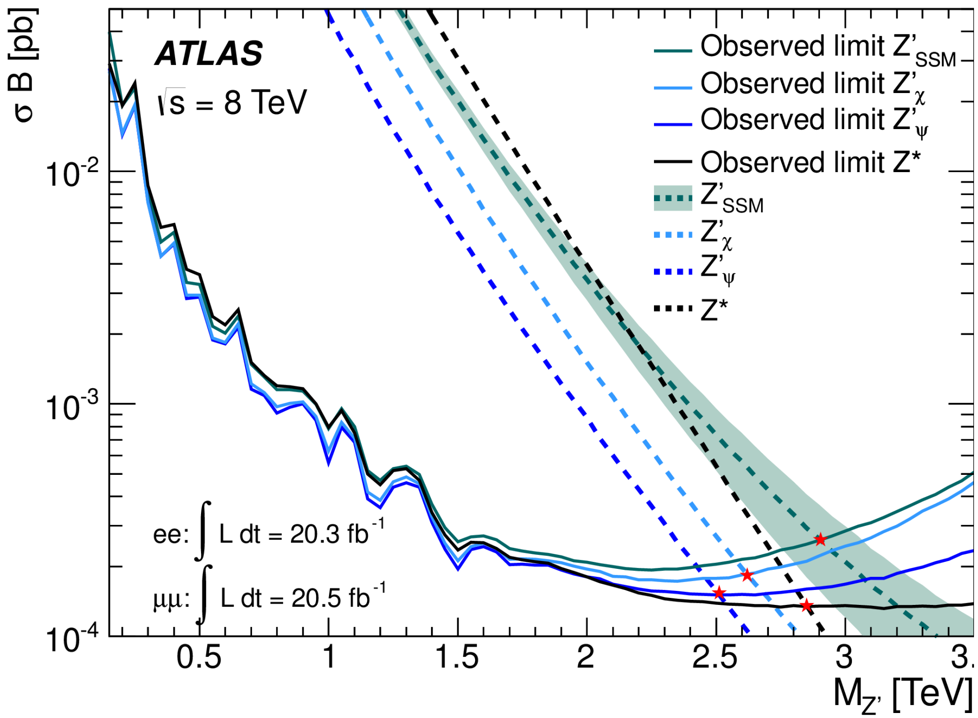
As the structure of the interaction is fixed, the free parameters are:

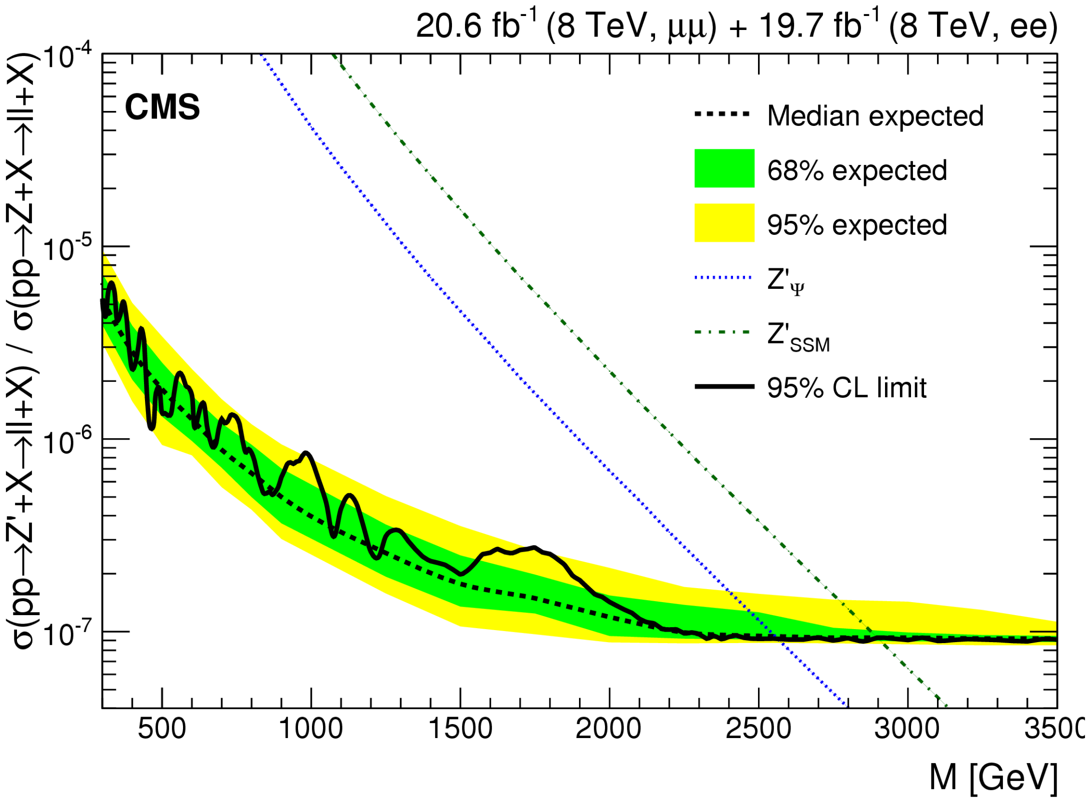
- <u>Fermions' chiral couplings</u>
  (gauge couplings can be absorbed into their definition)

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

Z' search @ LHC

LHC most recent results at 8 TeV





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

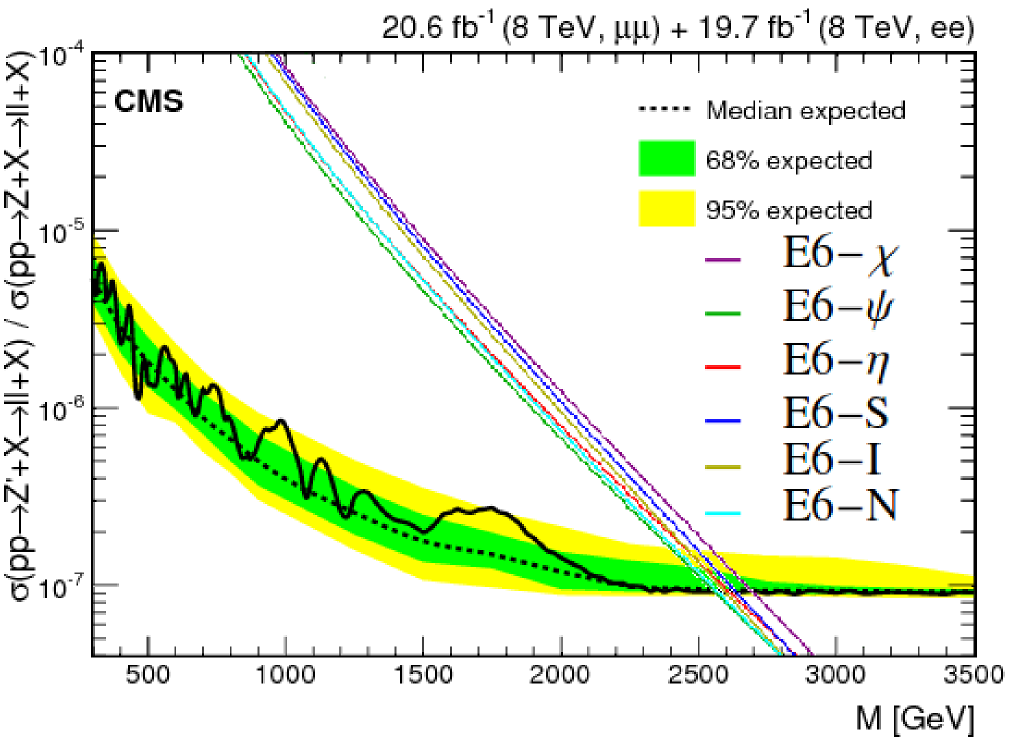
CMS : CMS-EXO-12-061

Typical limits for Z' mass:

$M_{Z'}$ ~ 2.8 TeV

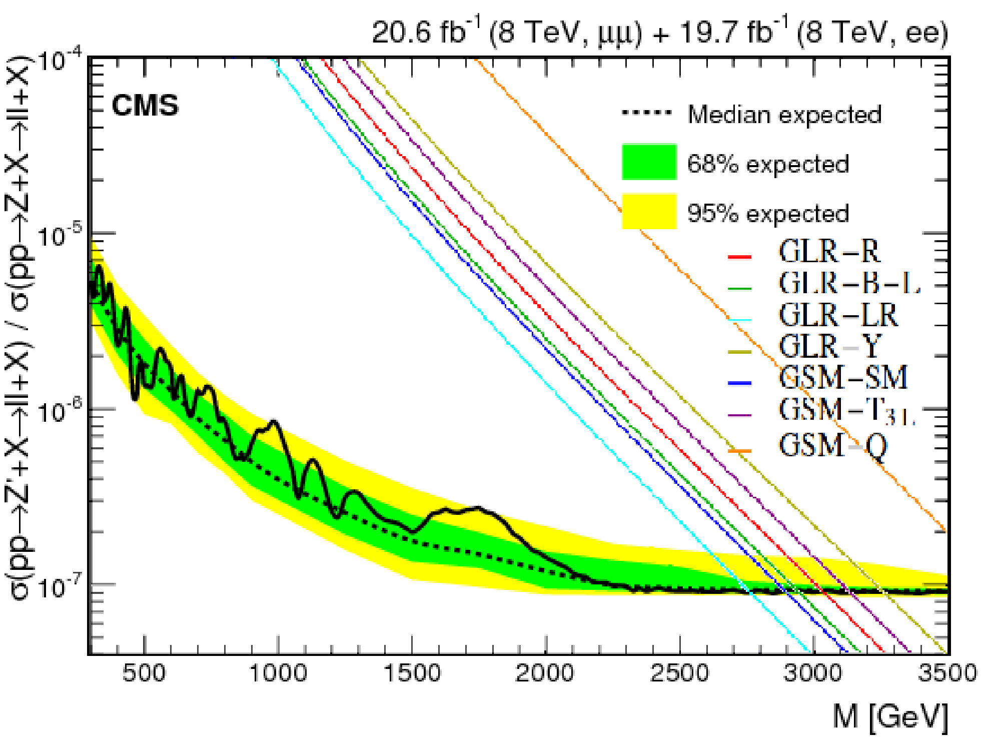
CMS systematically accounted <u>finite width</u> and <u>interference</u> effects as suggested in:
http://arxiv.org/pdf/1304.6700.pdf
JHEP 10 (2013) 153

Validating our code



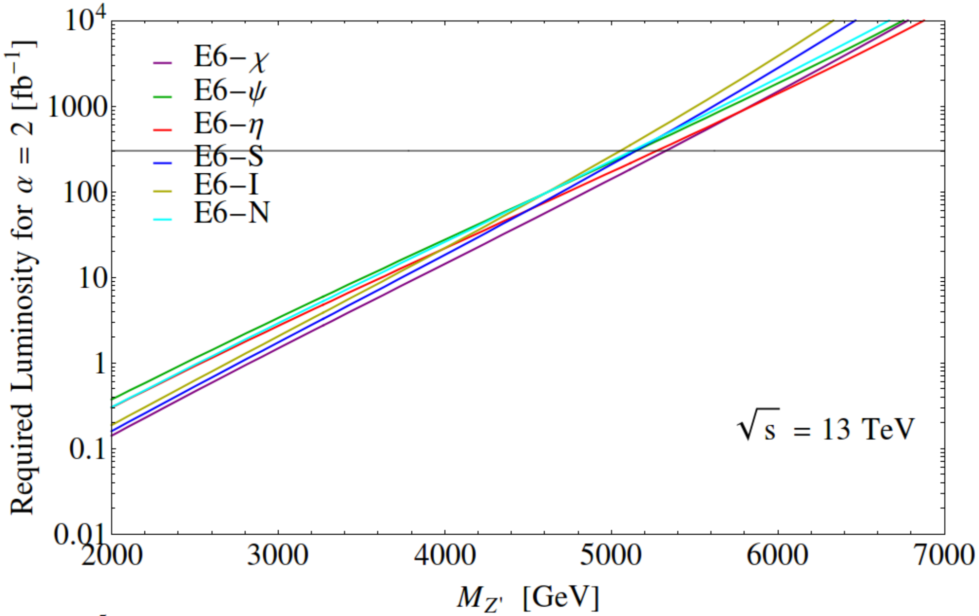
The code has been validated against the latest CMS results on ***Z'*** searches in the dilepton channel

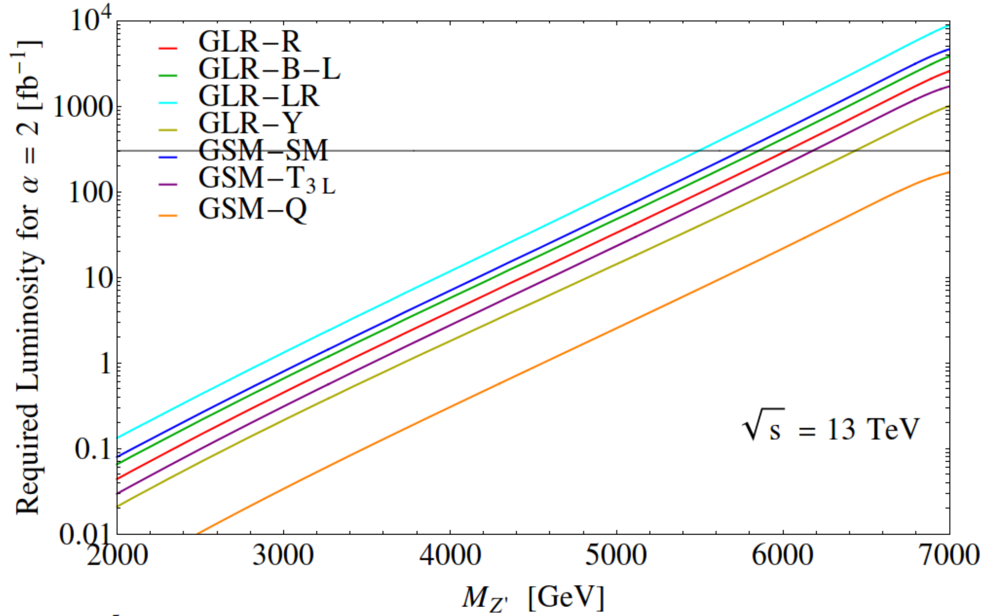
The exclusion limits we found match the experimental results

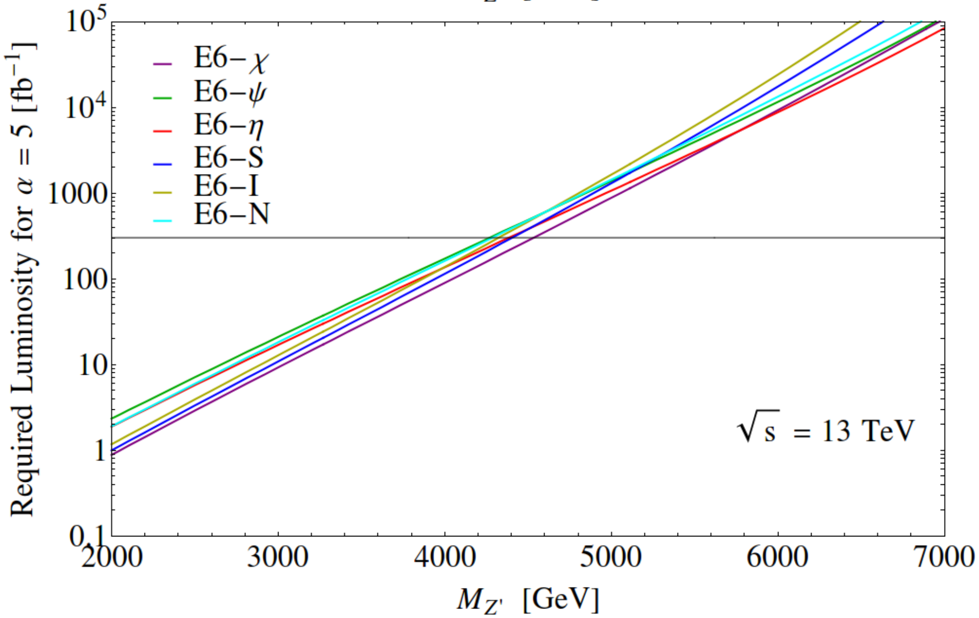


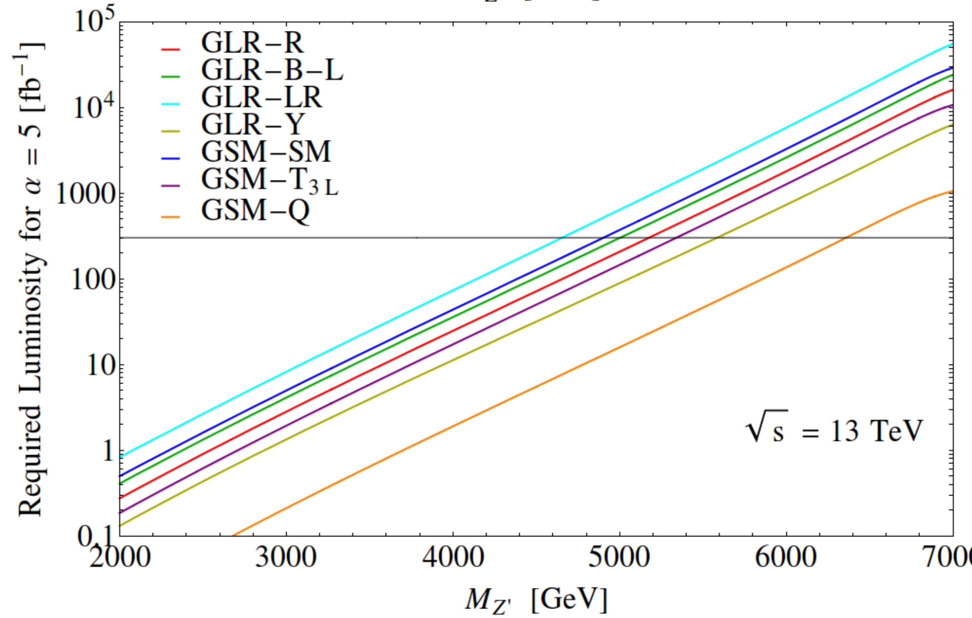
Limits for LHC@13TeV

Exclusion (Significance = 2) and Discovery (Significance = 5) limits









Forward – Backward Asymmetry

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

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

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

Keeping a fixed angle ***θ***, we have the simplest definition for the AFB.

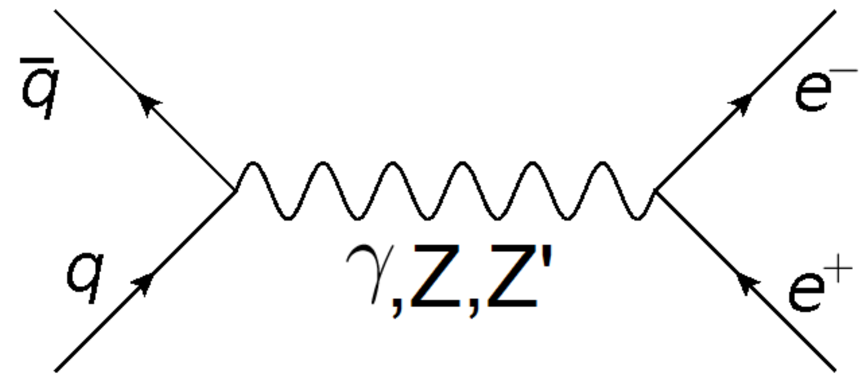
But, in order to correctly define the Forward/Backward direction, we shall use instead ***θ**** that is the angle between incoming quark and the outgoing leptons <u>in the $q\bar{q}$ centre of mass frame</u>

In a Drell-Yan process, how to guess which proton carries the quark and which the antiquark?

The <u>boost of the dilepton system</u> can be used to discriminate the direction of the <u>incoming quark</u>, as we expect the latter to be much more energetic then the antiquark, which comes from the sea.

Following this prescription we can define the <u>reconstructed AFB</u> or **AFB***

Matrix element



With this kind of interaction we end with the usual form for the matrix element and cross section as well

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

The two coefficients are defined by different combination of the couplings

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

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

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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Rizzo : JHEP 0908 082 (2009)

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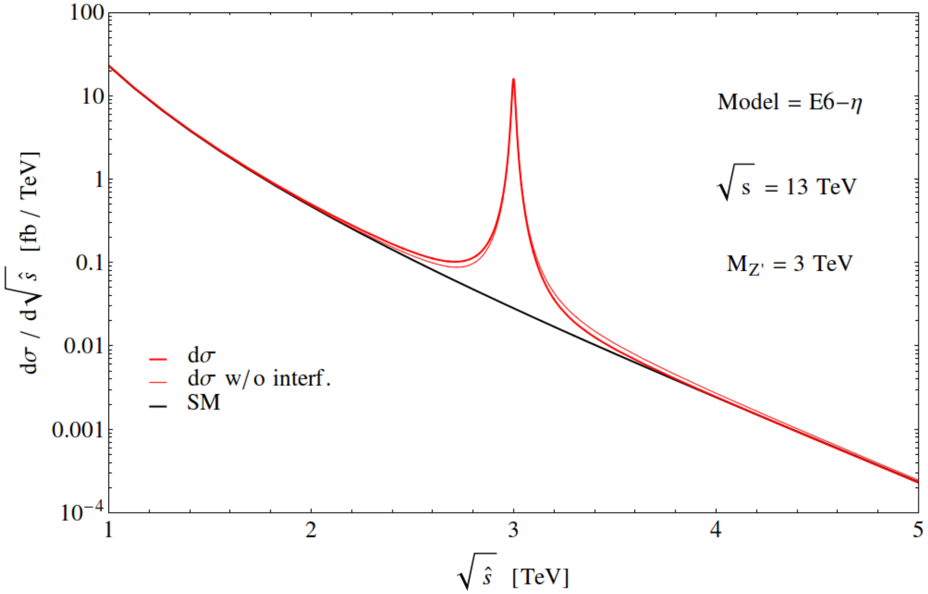
AFB as search tool

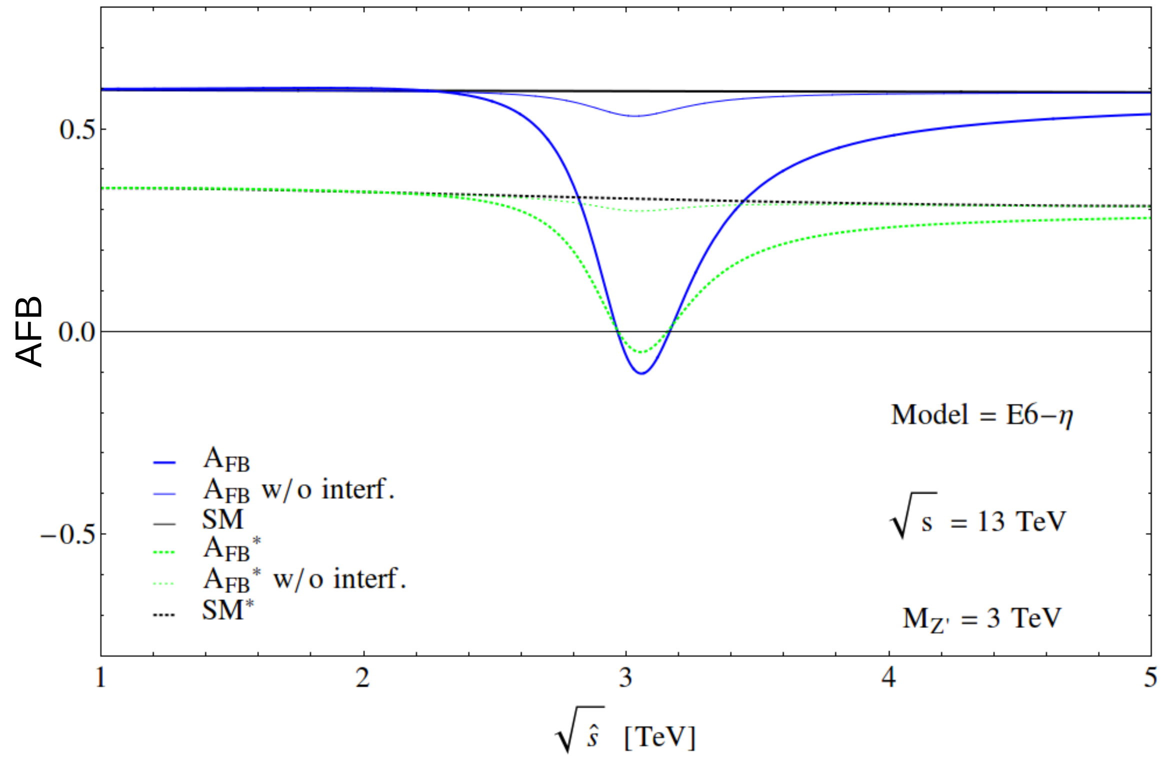
- It comes from the ratio of cross sections → Systematic uncertainties cancel (PDFs, luminosity, etc.)

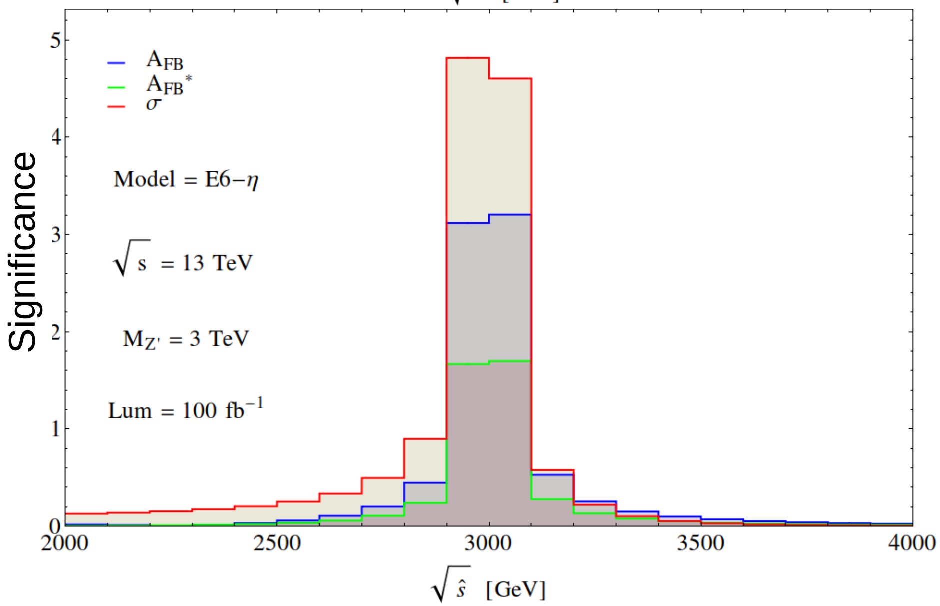
- For both narrow & wide resonances AFB can be used together with the bump search → Off-peak effects due to interference are sizeable and can be observed

Narrow resonance: E6-η case

Interference Effects



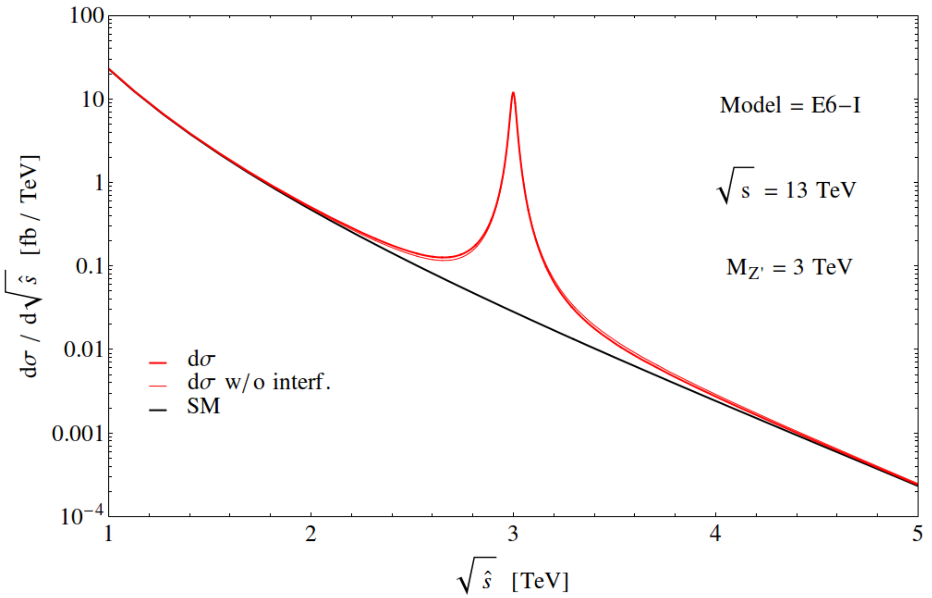


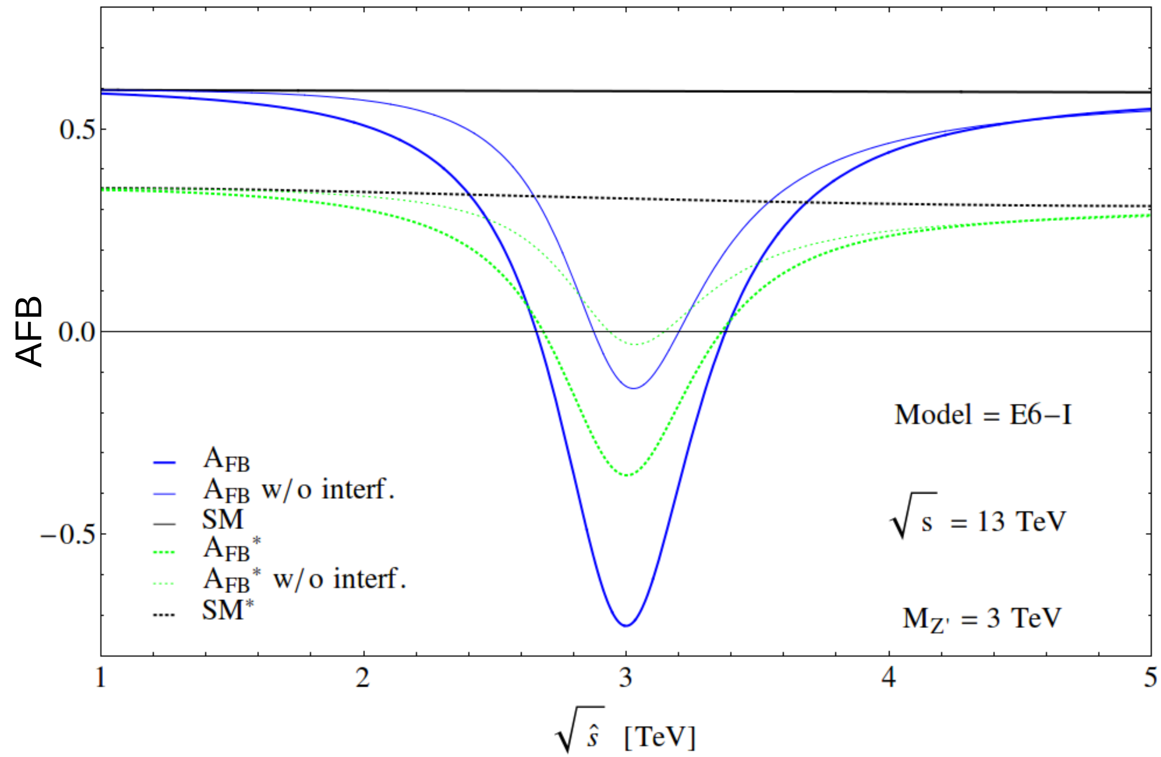


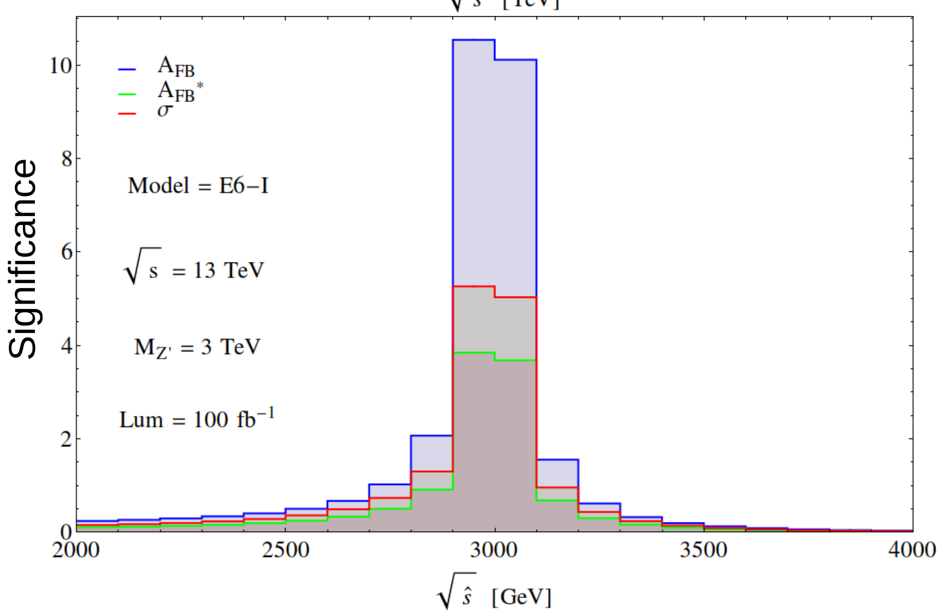
<u>Interference</u> plays an essential role in determining the shape of the AFB

Narrow resonance: E6-I case

Interference Effects







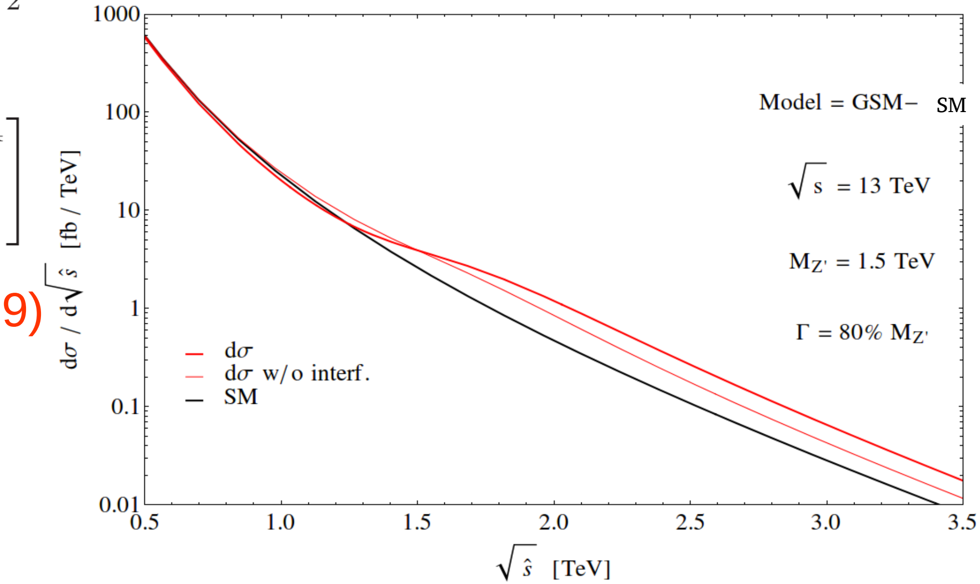
<u>Interference</u> can accentuate the peak in the AFB.
A <u>high significance peak</u> can occur for the AFB as well.

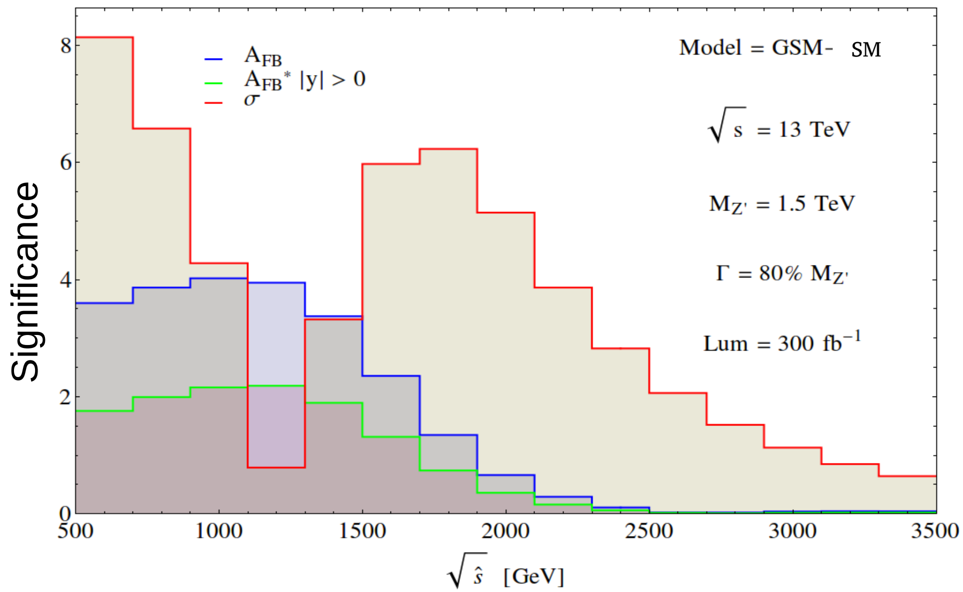
Wide resonance

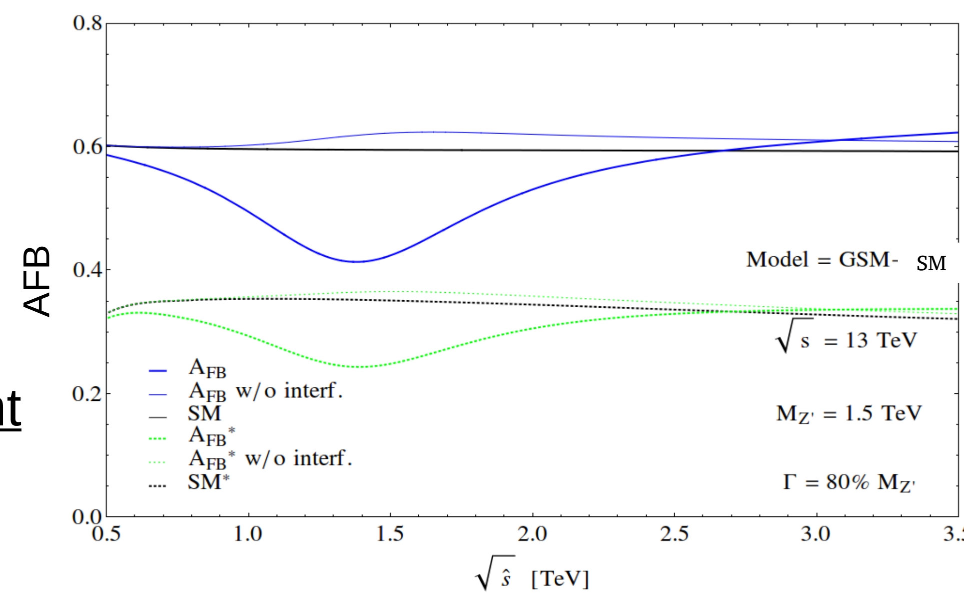
Wide GSM-SM benchmark

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

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

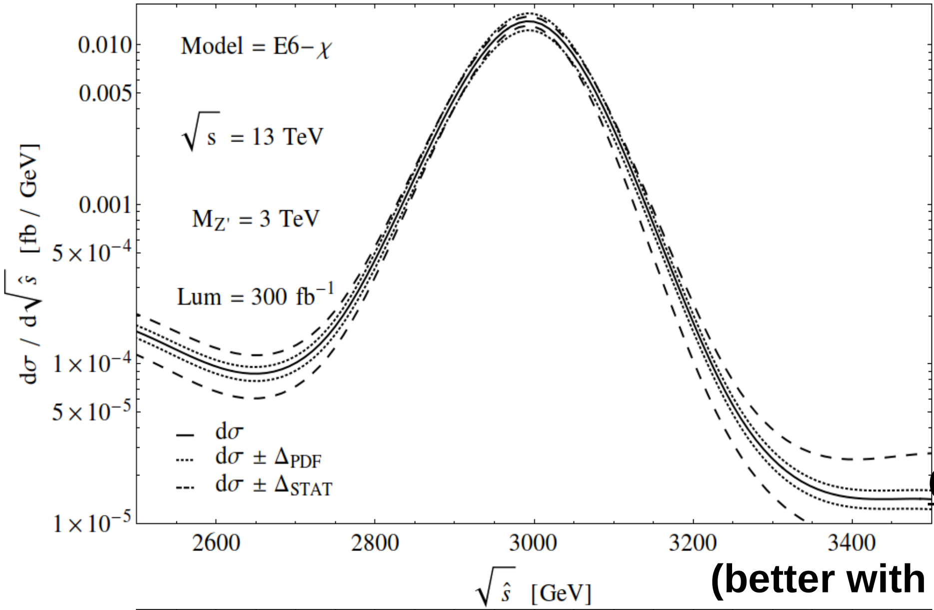


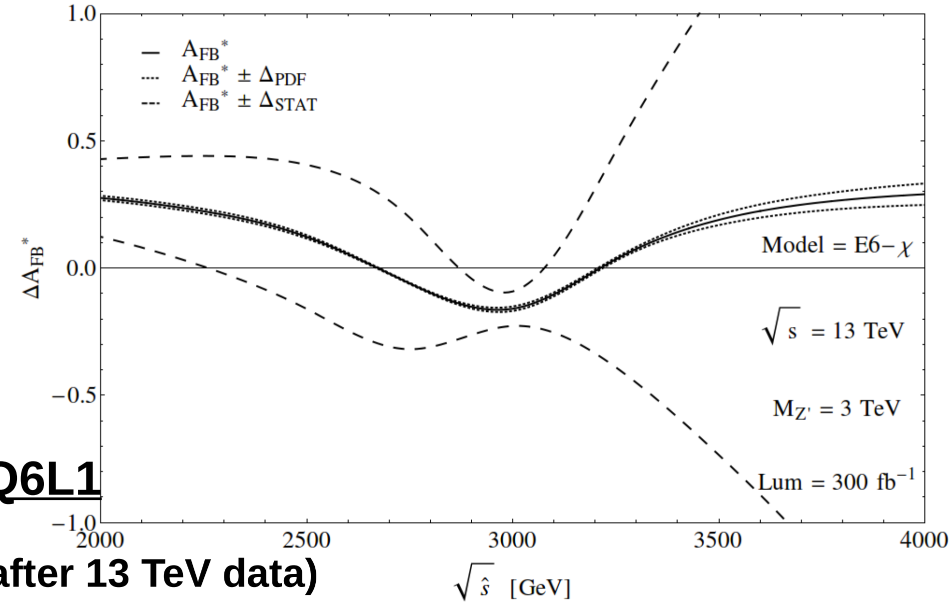




In the case of wide resonances when an event counting strategy is usually adopted, AFB maintain a peaking shape and can be used to identify a neutral resonance

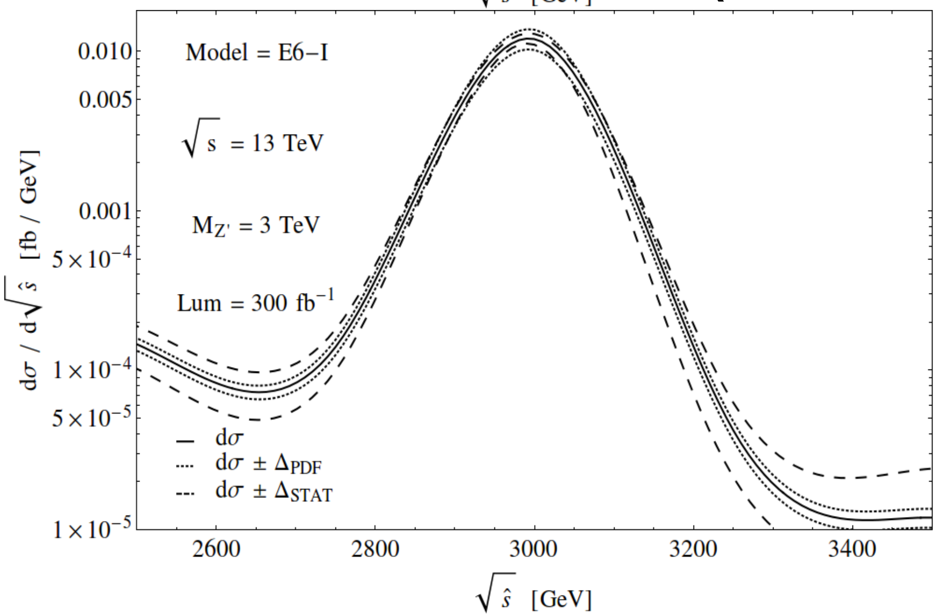
PDFs vs Statistic Uncertainties

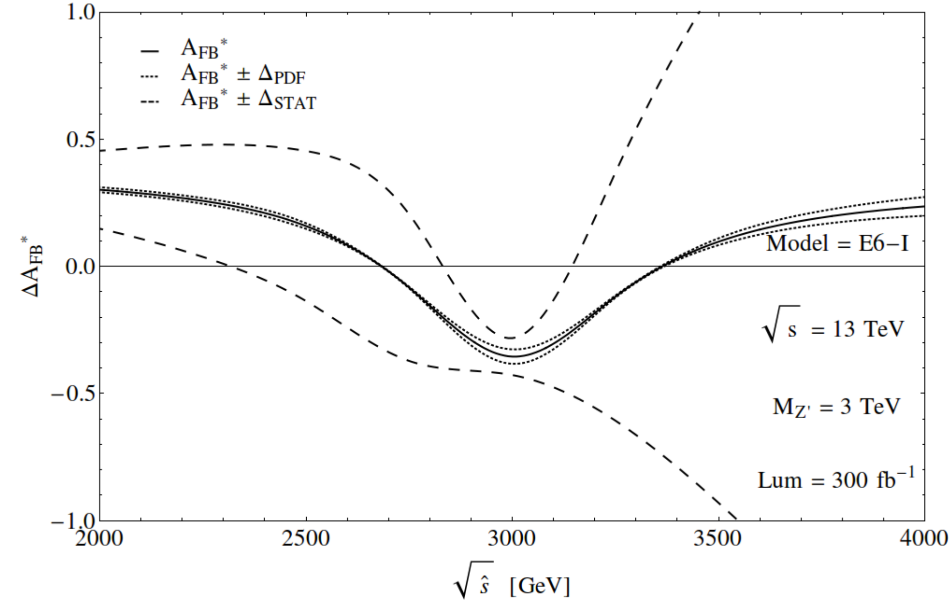




CTEQ6L1

(better with sets after 13 TeV data)

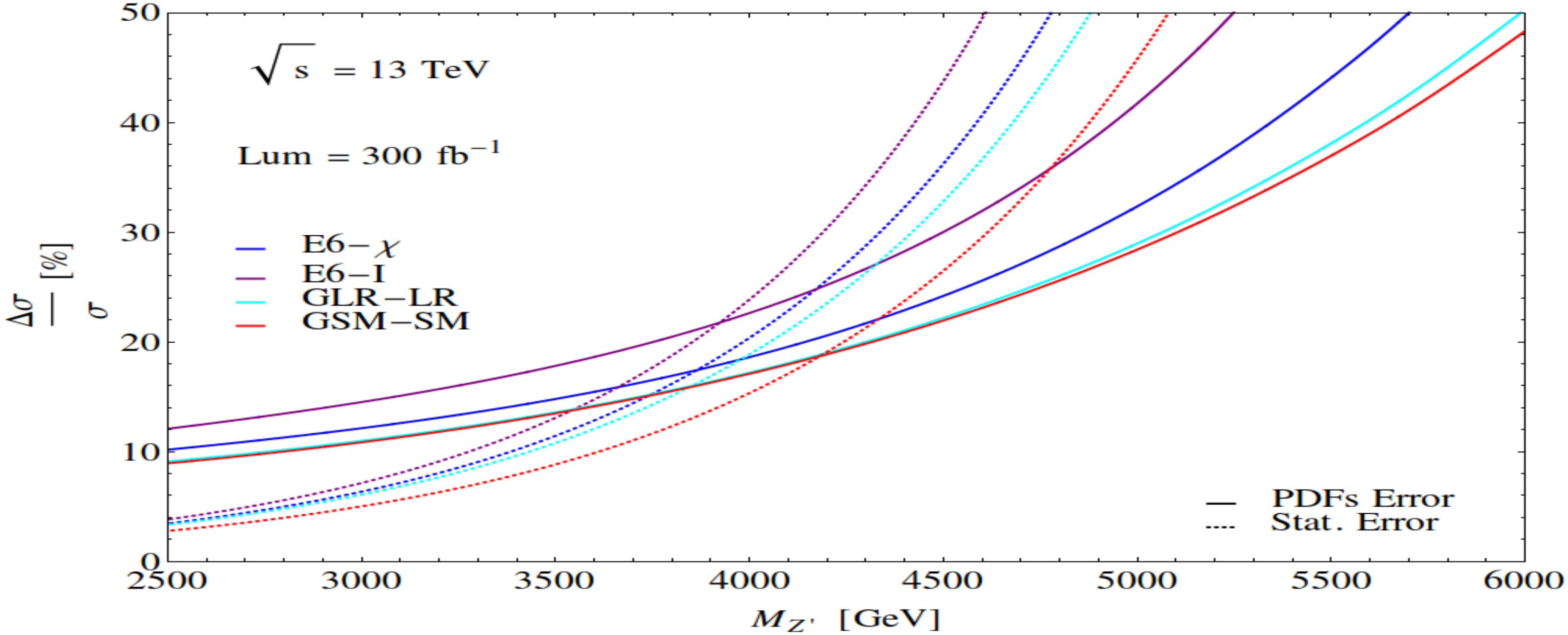


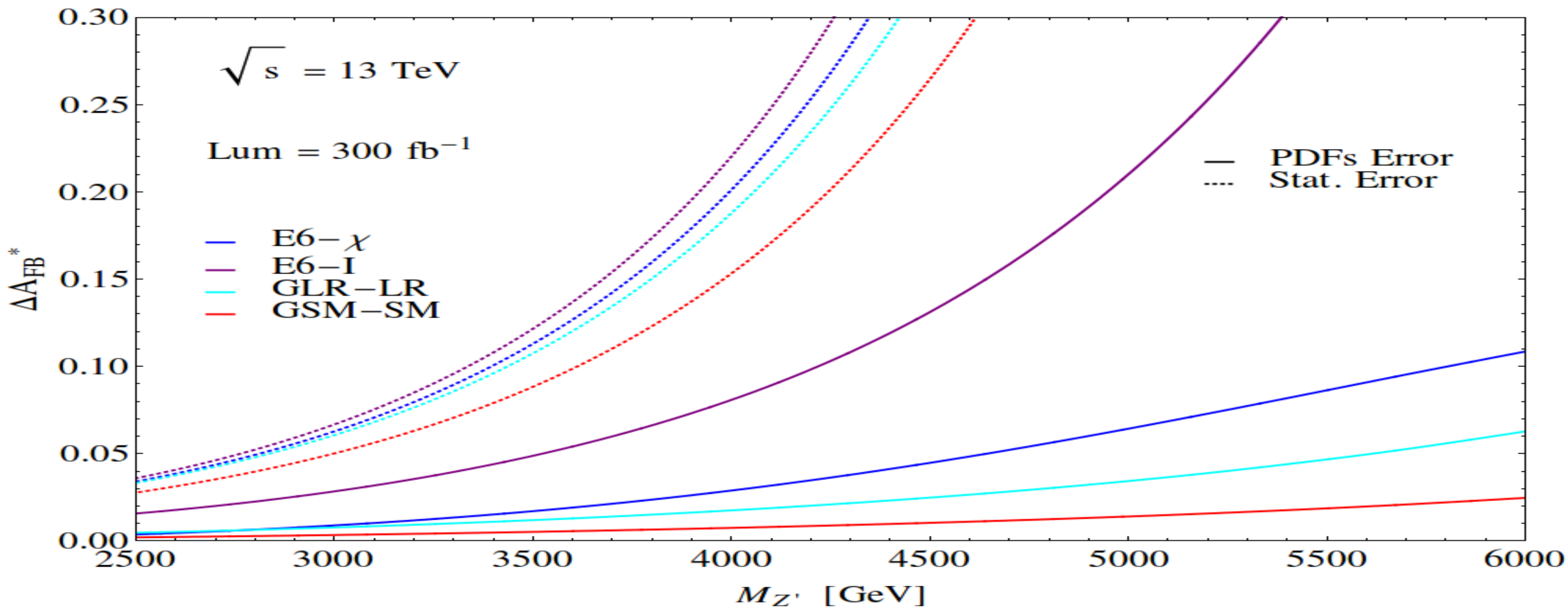


In the cross section, PDFs and statistic uncertainties are comparable.

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

PDFs vs Statistic Uncertainties





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 combined with the cross section to achieve discovery (or improve exclusion)

  - 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.

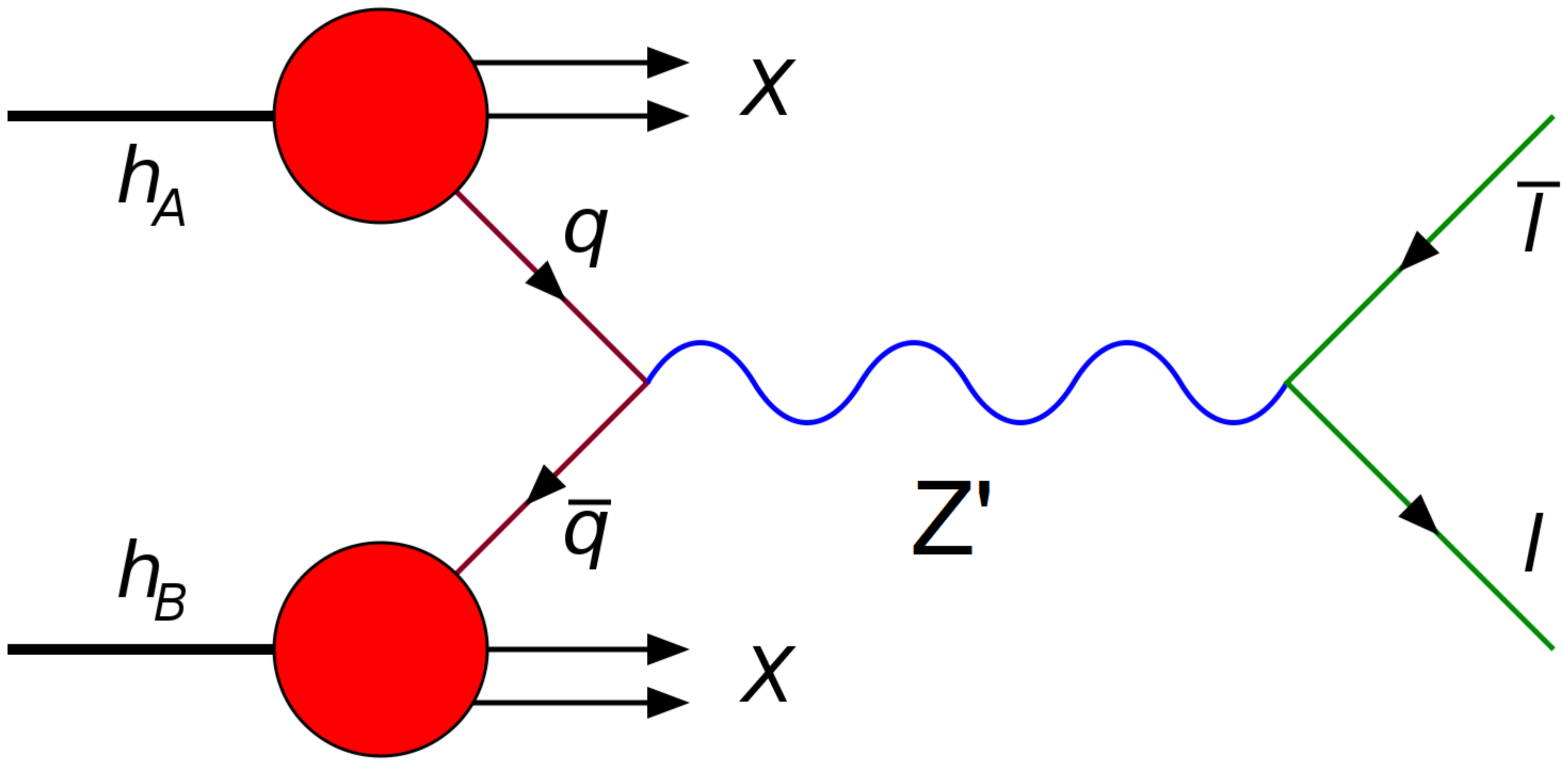
  - PDFs uncertainties are comparable with the statistic error in the cross section, while in the AFB, due to cancellations, the PDFs uncertainties are sub dominant

- We have developed and validated our code, derived discovery/exclusion limits for the **LHC-Run II** and demonstrated the role of AFB not only as a **Z'** post-discovery analysis tool, but also as a **Z'** search tool.

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

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

CTEQ6L1 PDFs were used

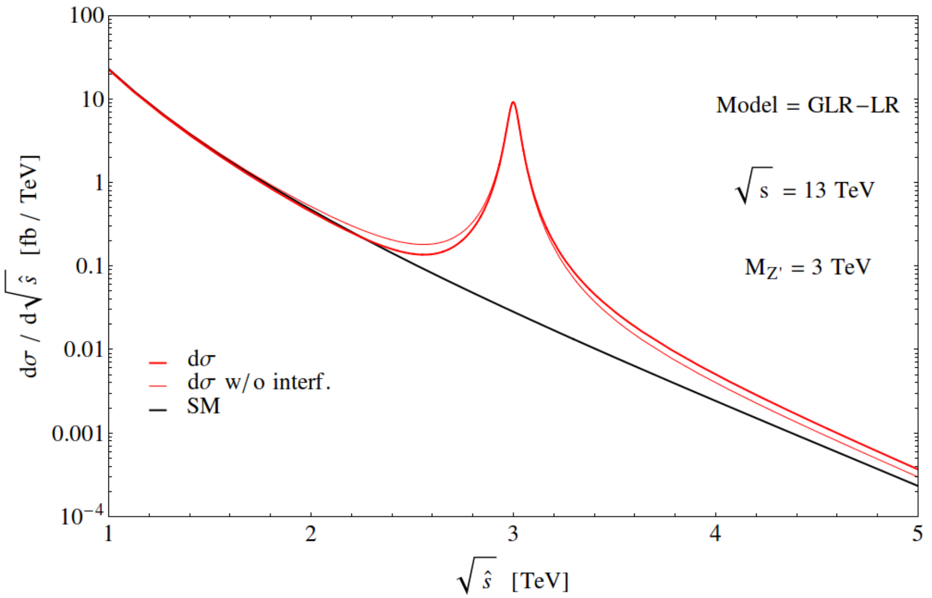
Parameters

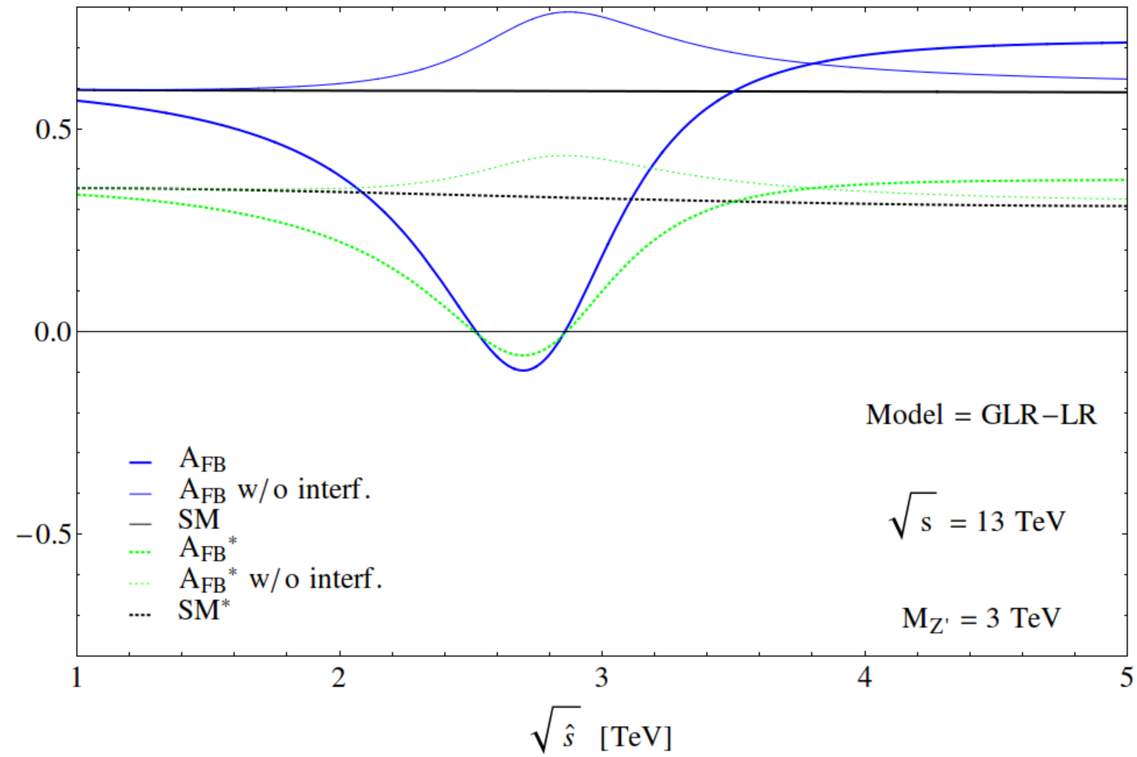
Table of couplings for narrow models:

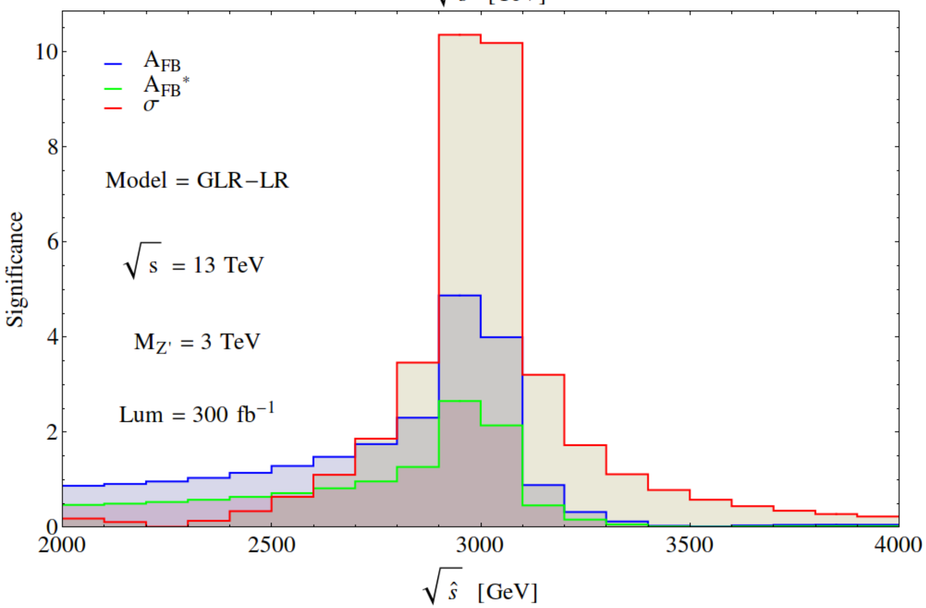
$U(1)'$	$Parameter$	a_V^u	a_A^u	a_V^d	a_A^d	a_V^e	a_A^e	a_V^ν	a_A^ν
$E6(g' = 0.462)$	θ								
χ	0	0	-0.316	-0.632	0.316	0.632	0.316	0.474	0.474
ψ	0.5π	0	0.408	0	0.408	0	0.408	0.204	0.204
η	-0.29π	0	-0.516	-0.388	-0.129	0.388	-0.129	0.129	0.129
S	0.129π	0	-0.130	-0.581	0.452	0.581	0.452	0.516	0.516
I	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

Narrow resonance

Interference Effects



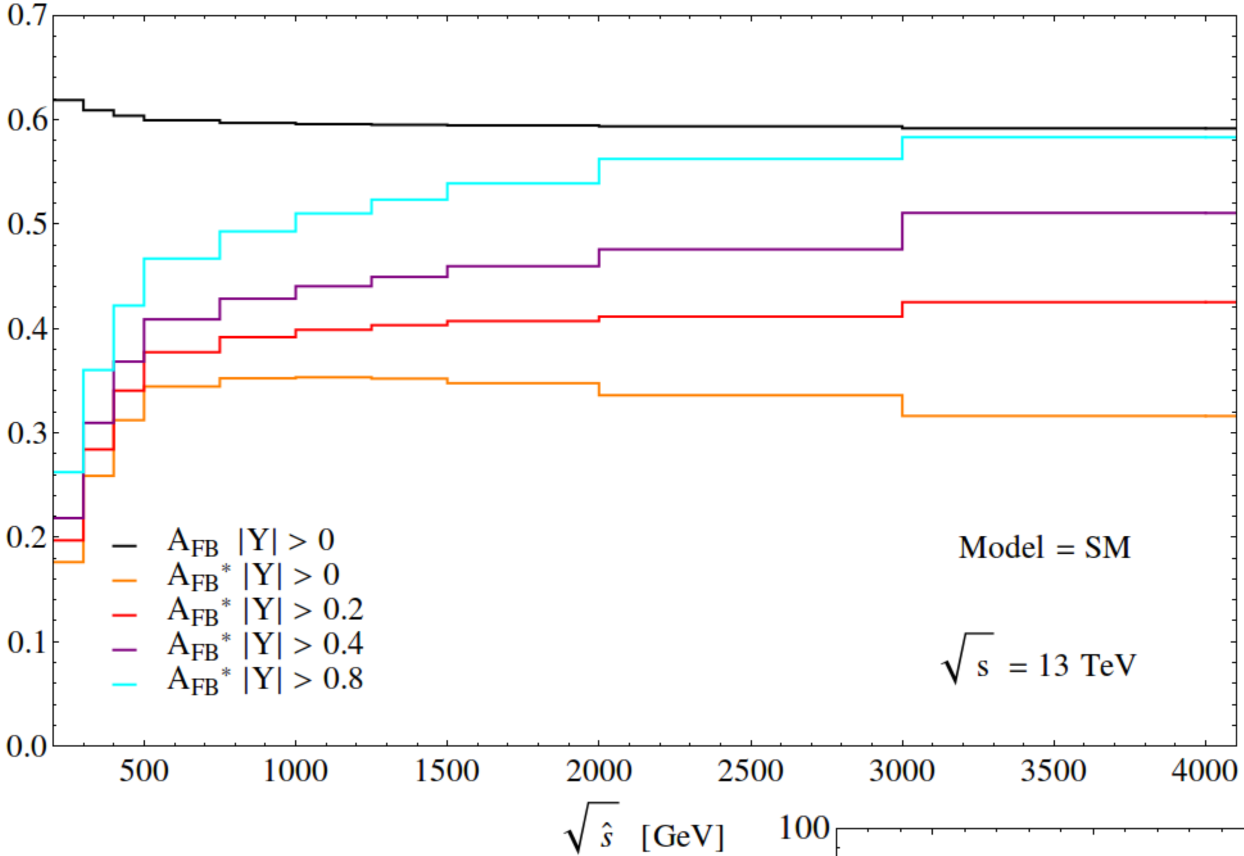


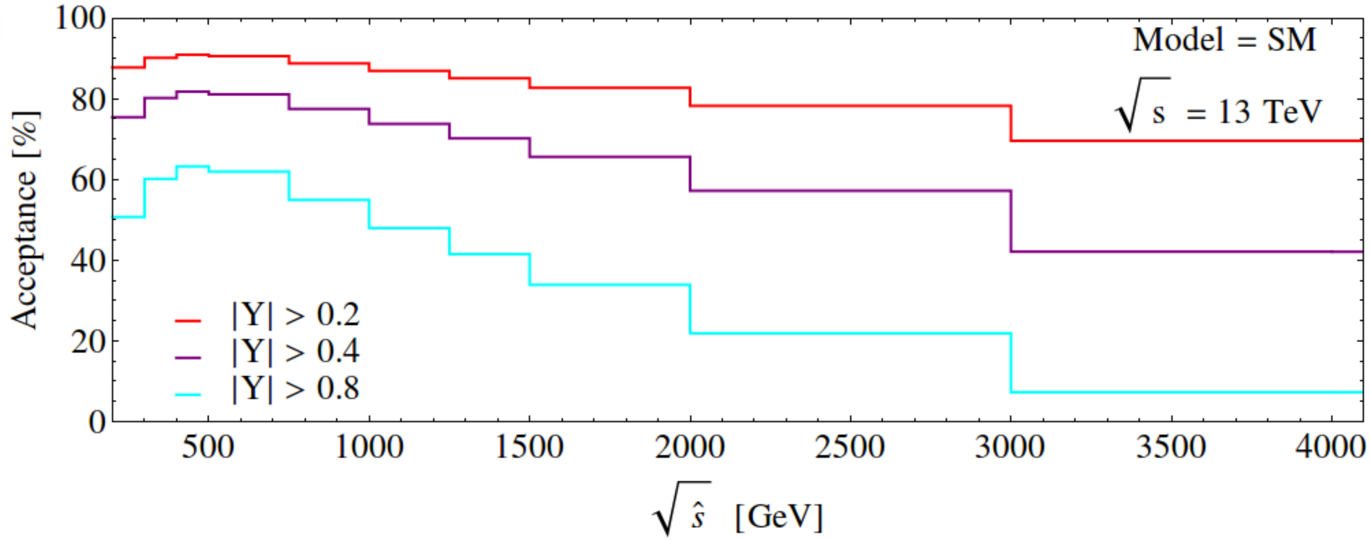


Interference can shift the peak of the AFB.
A tail with appreciable significance can occur.

Backup slide

Rapidity cuts





Backup slide

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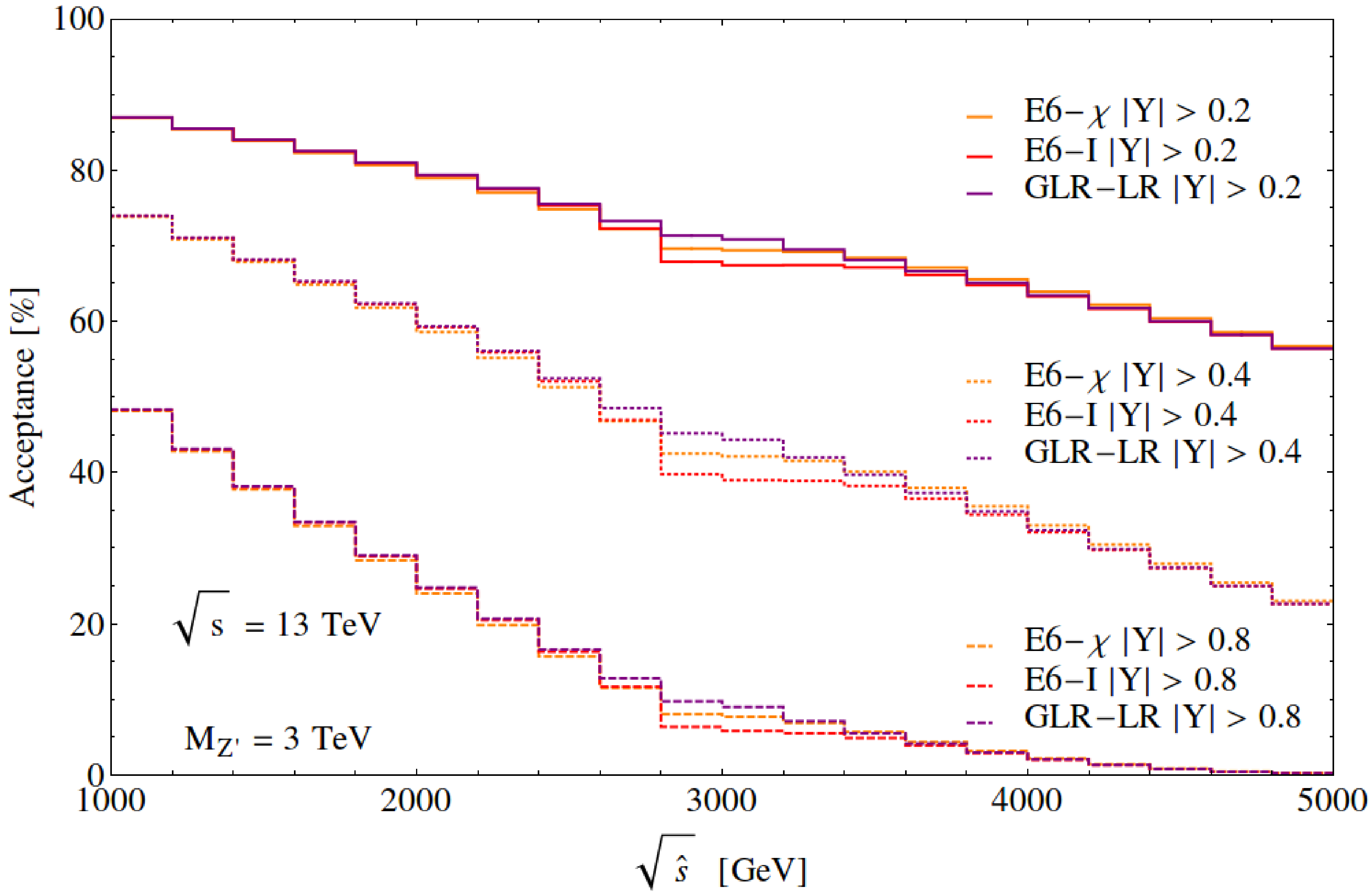


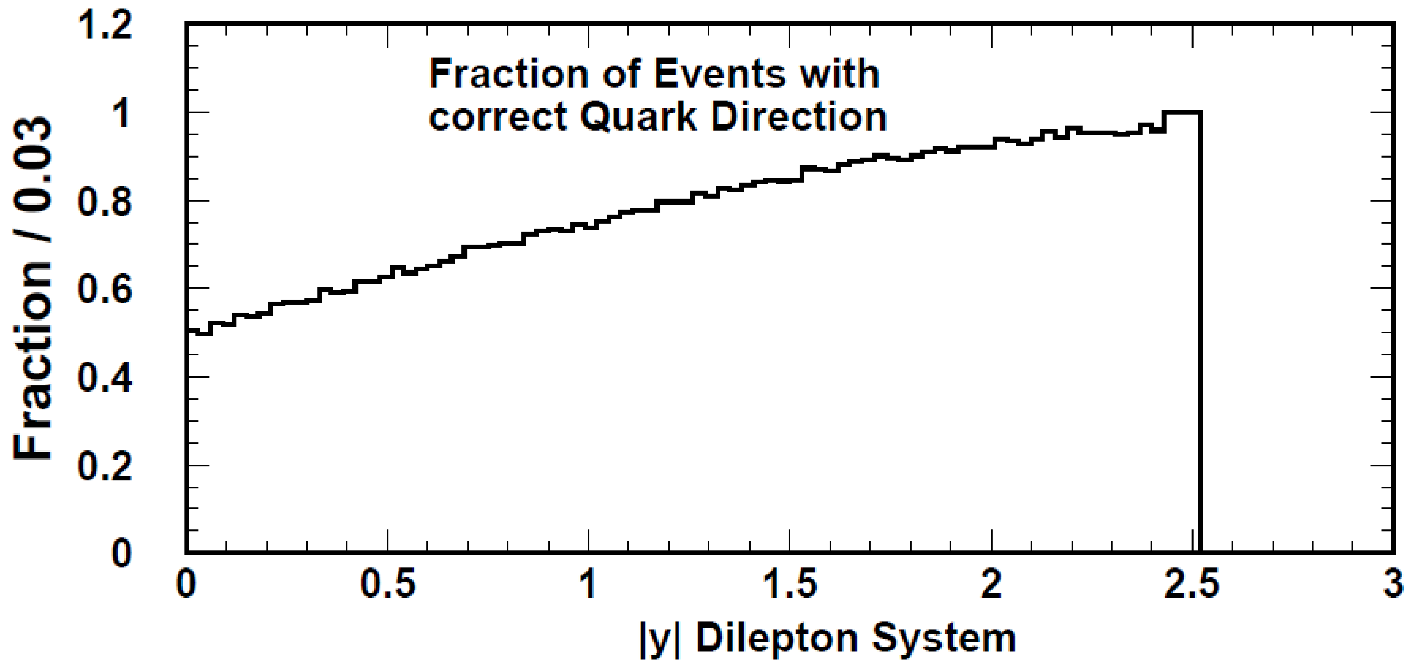
Forward / Backward

Subtlety 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:

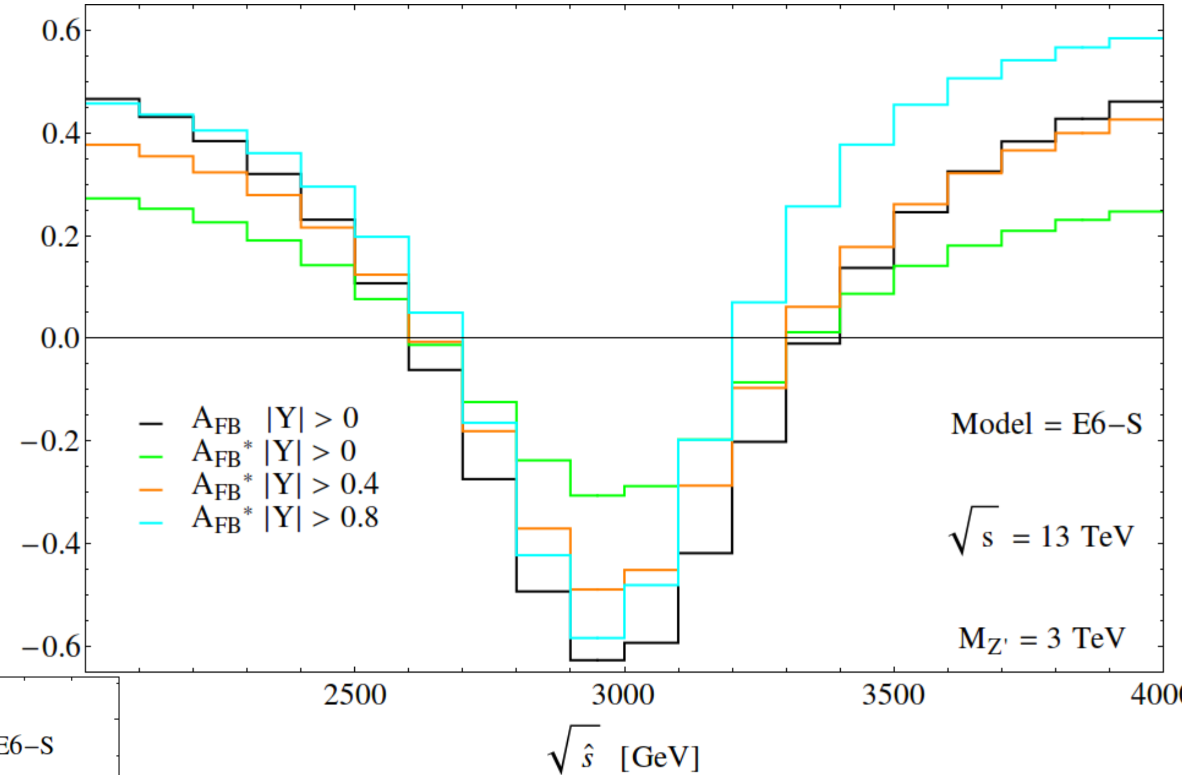
In this case of neutral process, we expect that the dilepton longitudinal momentum marks the direction of the quark, as the latter is supposed to be more energetic than the antiquark (which comes from the sea).

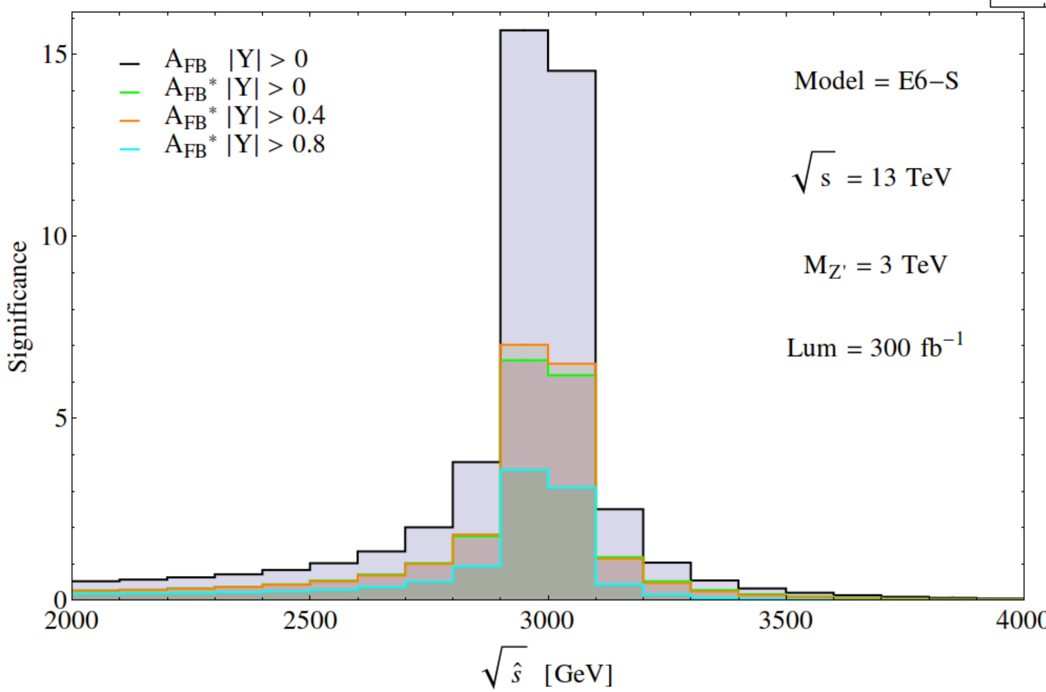


Dittmar : Phys.Rev.D55:161-166 (1997)

Reconstruction

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



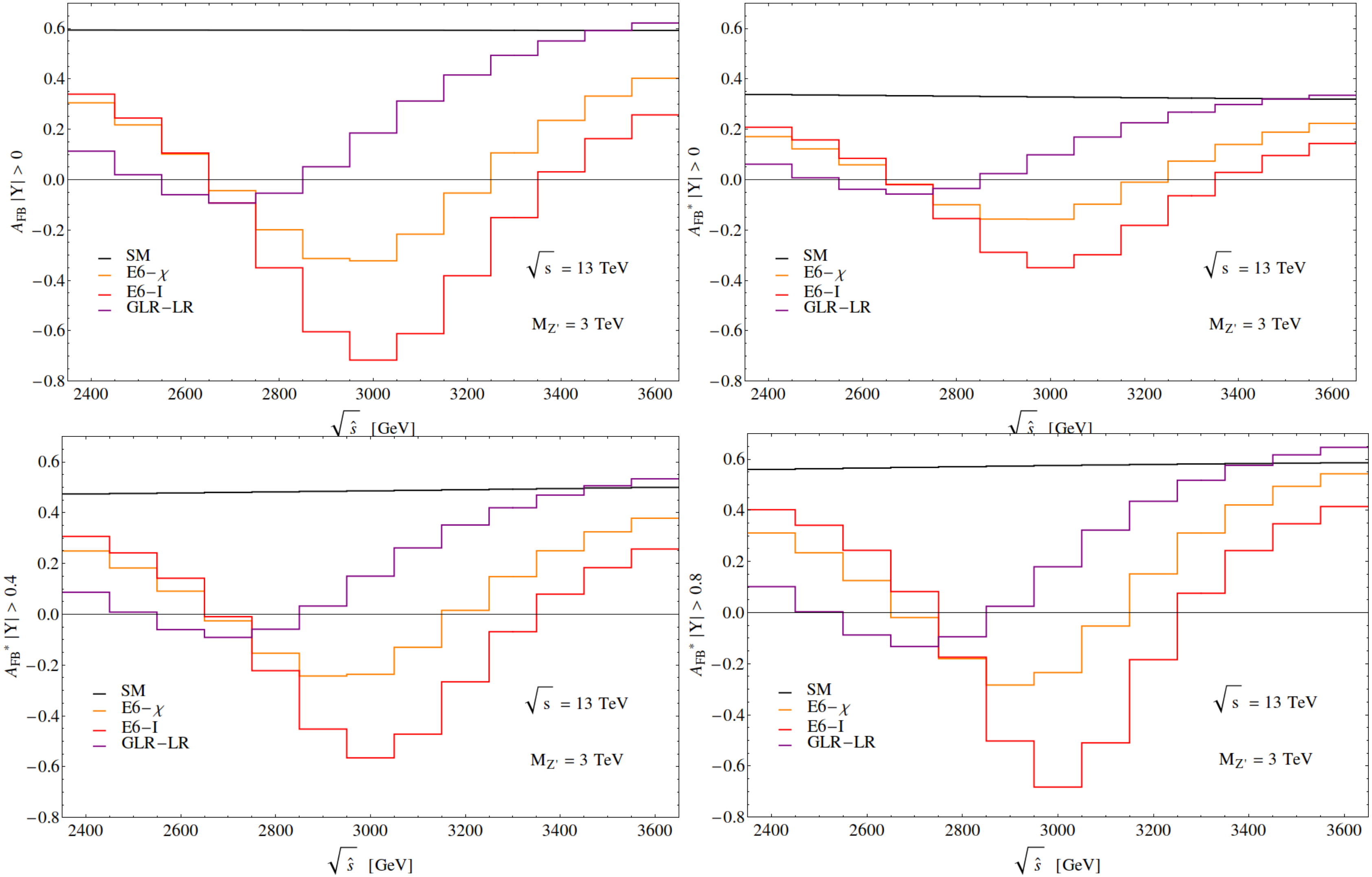


Nevertheless the cuts reduce the statistic of the events.
The observable is more reliable <u>without</u> the rapidity cuts.

Reconstruction

The rapidity cuts alter model dependence!

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



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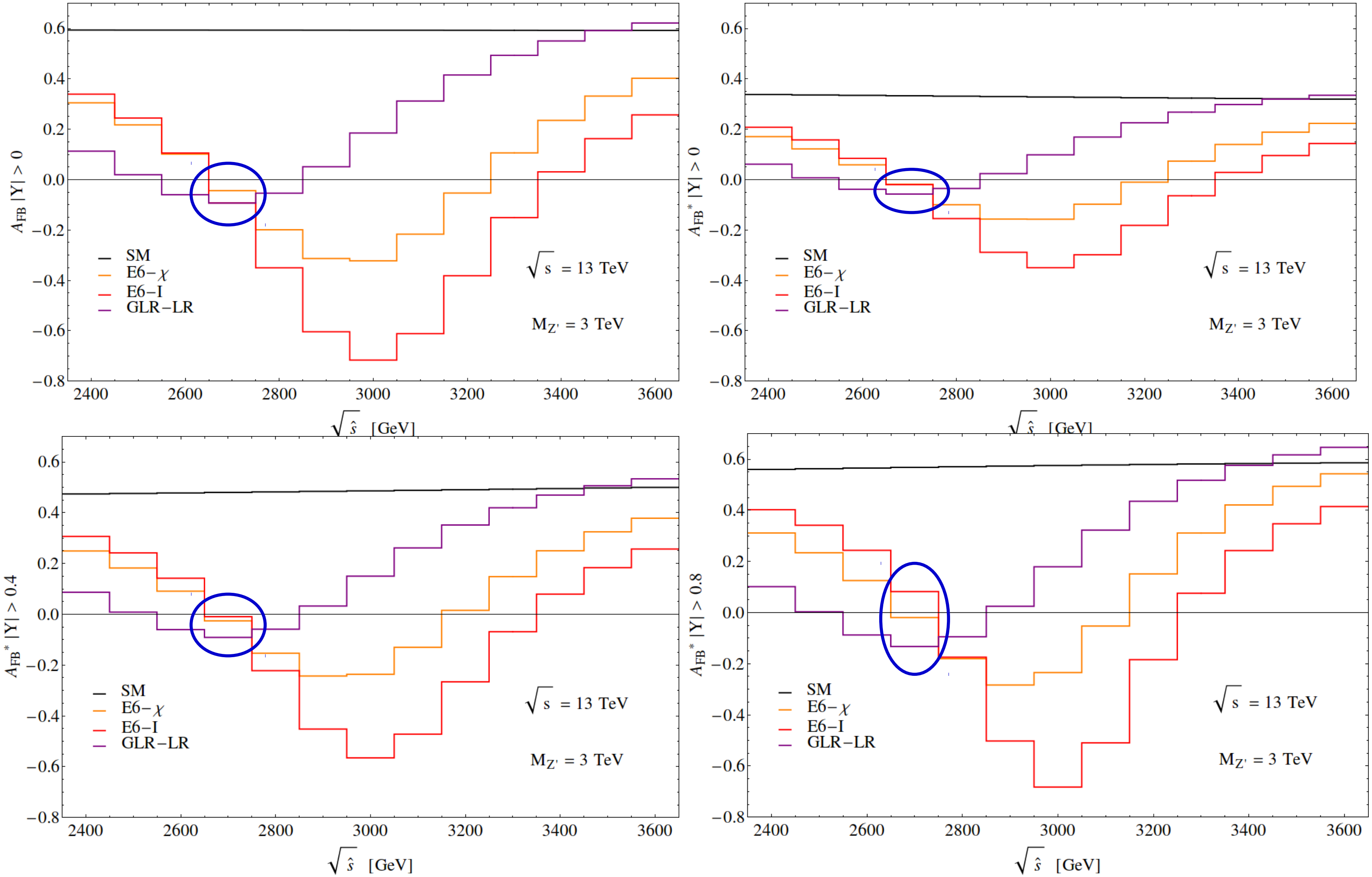
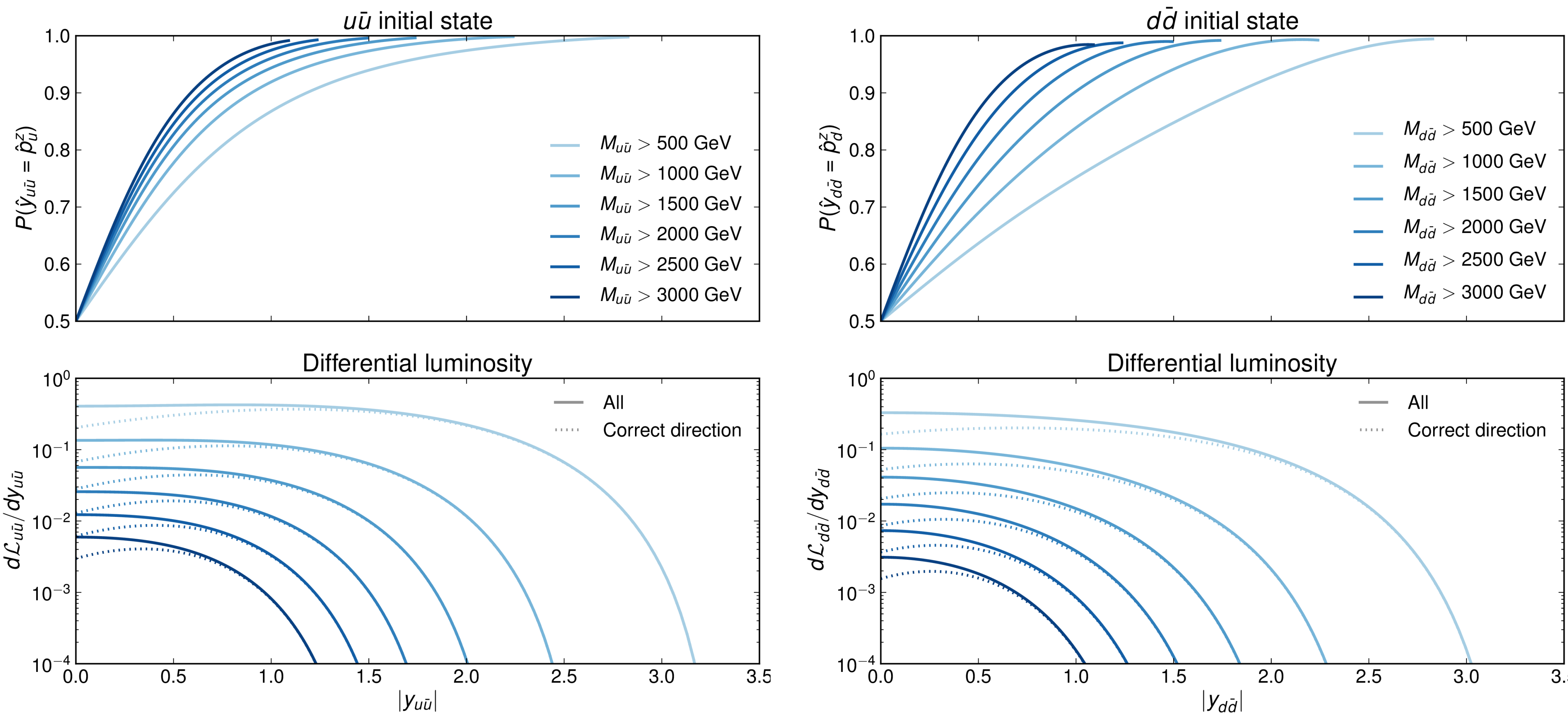


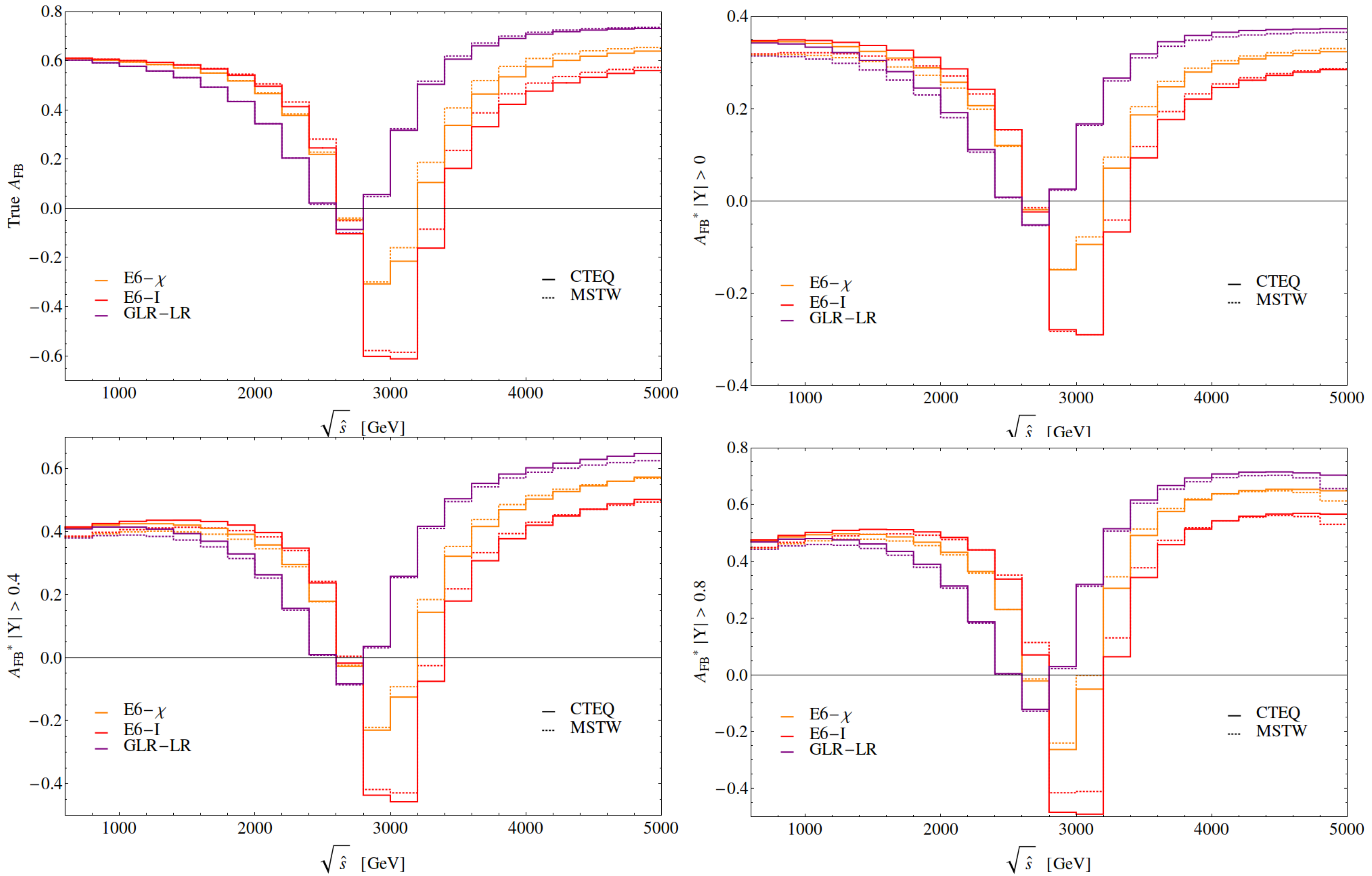
Models with <u>different couplings</u> to ***u*** and ***d*** quarks have a <u>different behaviour</u> under the application of rapidity cuts

Backup slide

Partonic correct direction and luminosity

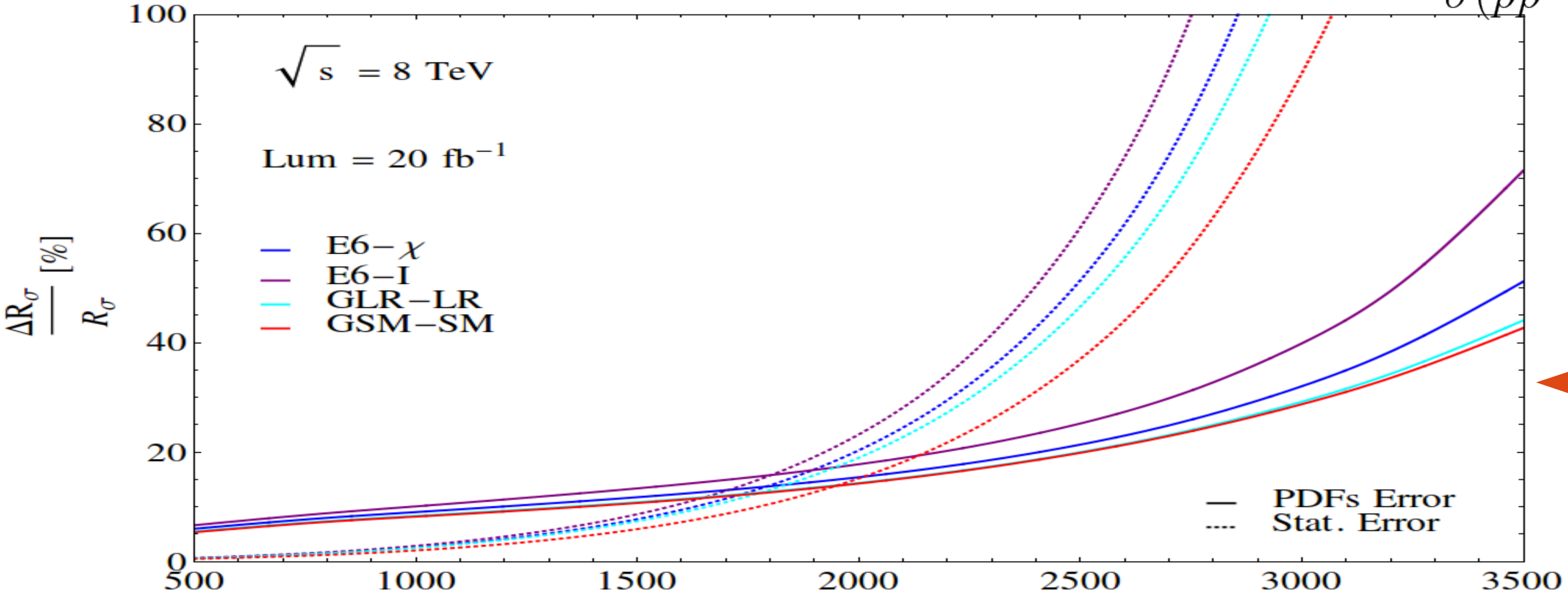


PDFs comparison

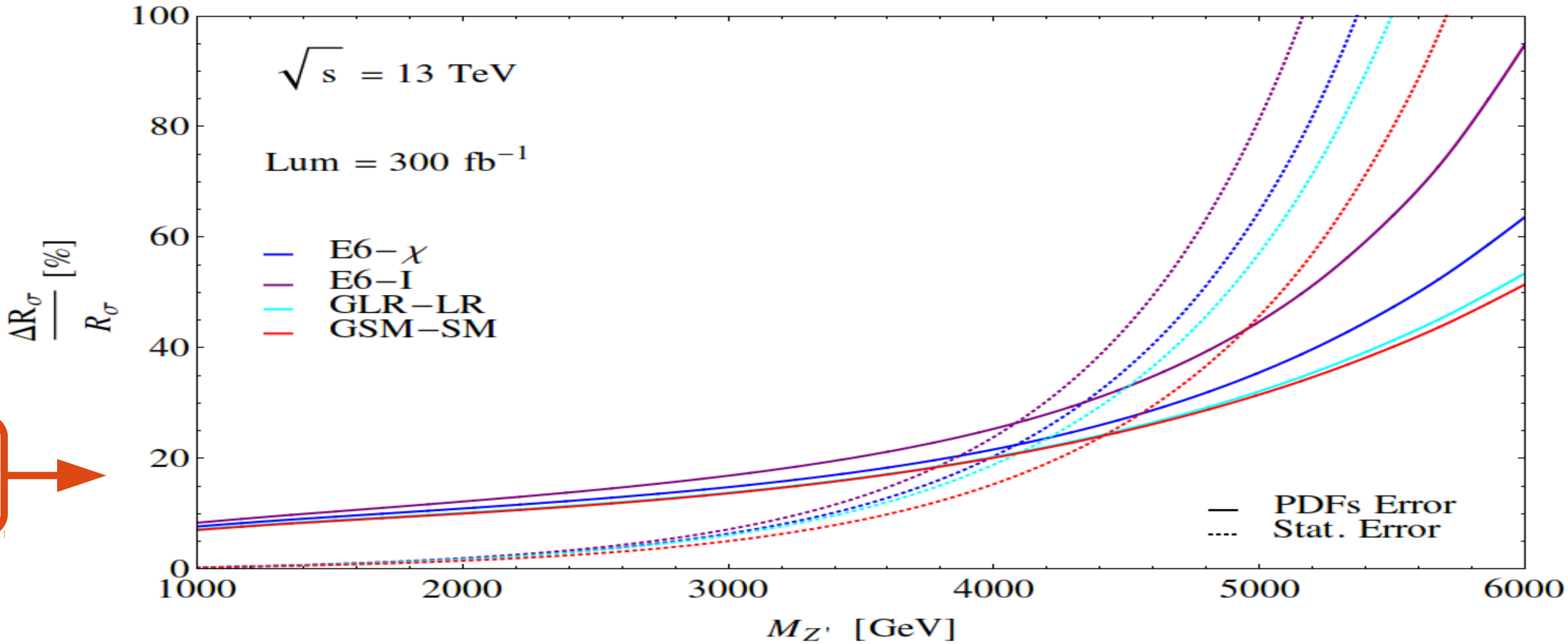


R_σ error

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



8 TeV
20 fb^{-1}



13 TeV
300 fb^{-1}

Wide resonance

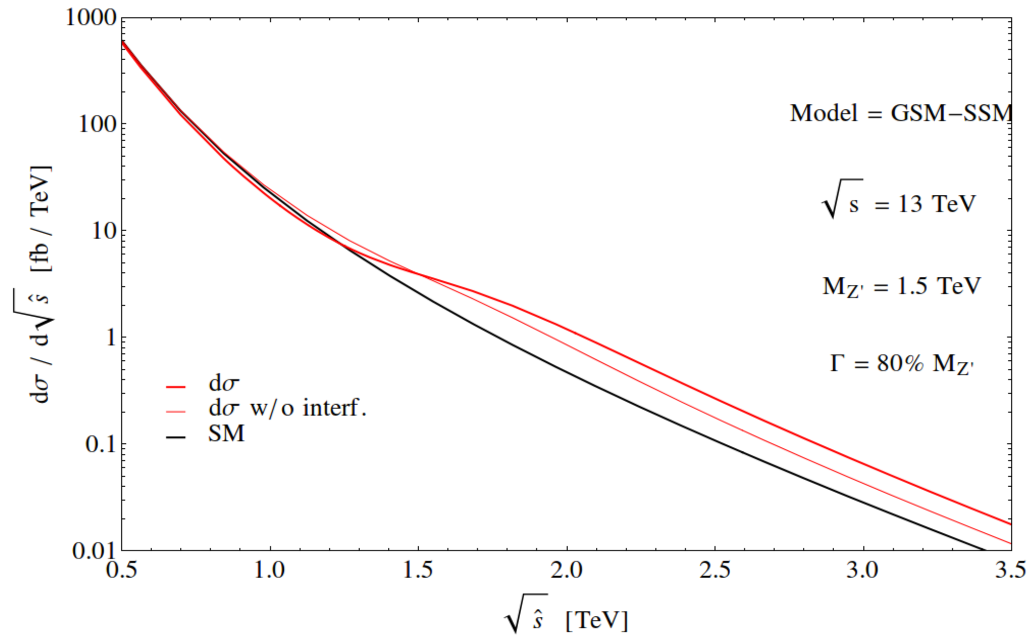
Wide GSM-SSM benchmark

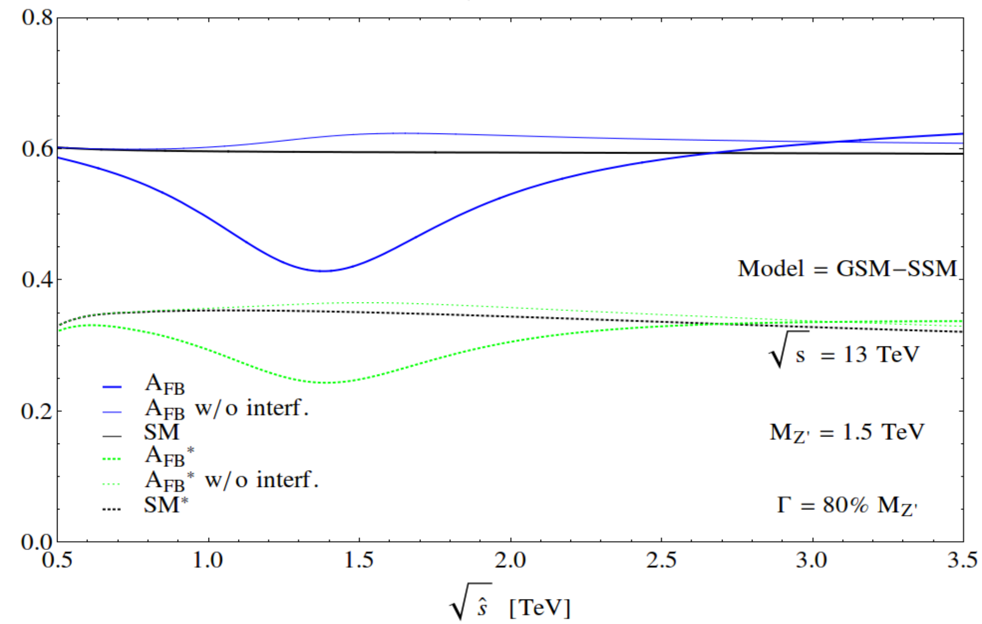
$$\Gamma(Z' \to W^+W^-) = \frac{\alpha}{48} cotg\theta_W M_{Z'} \left(\frac{M_{Z'}}{M_W}\right)^4 \left(1 - 4\frac{M_W^2}{M_{Z'}^2}\right)^{3/2} \left[1 + 20\left(\frac{M_W}{M_{Z'}}\right)^2 + 12\left(\frac{M_W}{M_{Z'}}\right)^4\right]$$

$$\Gamma(Z' \to f\bar{f}) = \frac{\alpha}{48} N_c \frac{M_{Z'}}{\sin^2\theta_W \cos^2\theta_W} \left[1 + (1 - 4|Q_f|\sin^2\theta_W)^2\right]$$

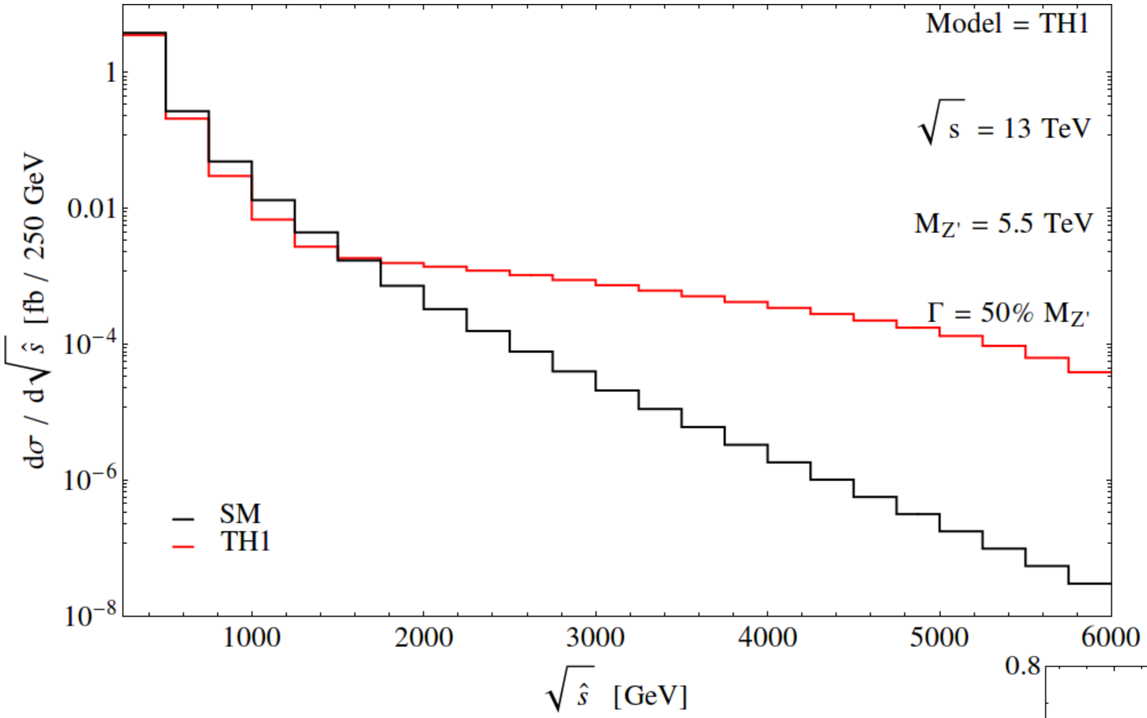
Altarelli, Mele, Ruiz-Altaba : Z.Phys. C45 109 (1989)

In the case of a very <u>wide resonance</u> the cross section can be confused with a normalization of the background, while the AFB maintain a <u>definite shape</u>





Wide resonance



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

Yeong Gyun, Kang Young :
arXiv:1405.7762 (May 2014)

Model with an extra Higgs doublet
and non universal fermion couplings

AFB can be used in association with a <u>counting strategy</u> in order to <u>identify</u> a neutral resonance.