Constraining Z' widths from p_T measurements in Drell-Yan processes

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

Based on:
arXiv:1703.04360

Overview

- ***Z'* searches at the LHC Run-II**
  - State of art from CMS & ATLAS
  - The sensitivity of experimental analysis
- **The lepton p_T spectrum in single *Z'* models**
  - The appearance of the Focus Point
  - Properties of the Focus Point
- **Introducing the Asymmetry of the Focus Point (AFP)**
  - The sensitivity of the AFP
- **Conclusions**

Z'-bosons @ the LHC

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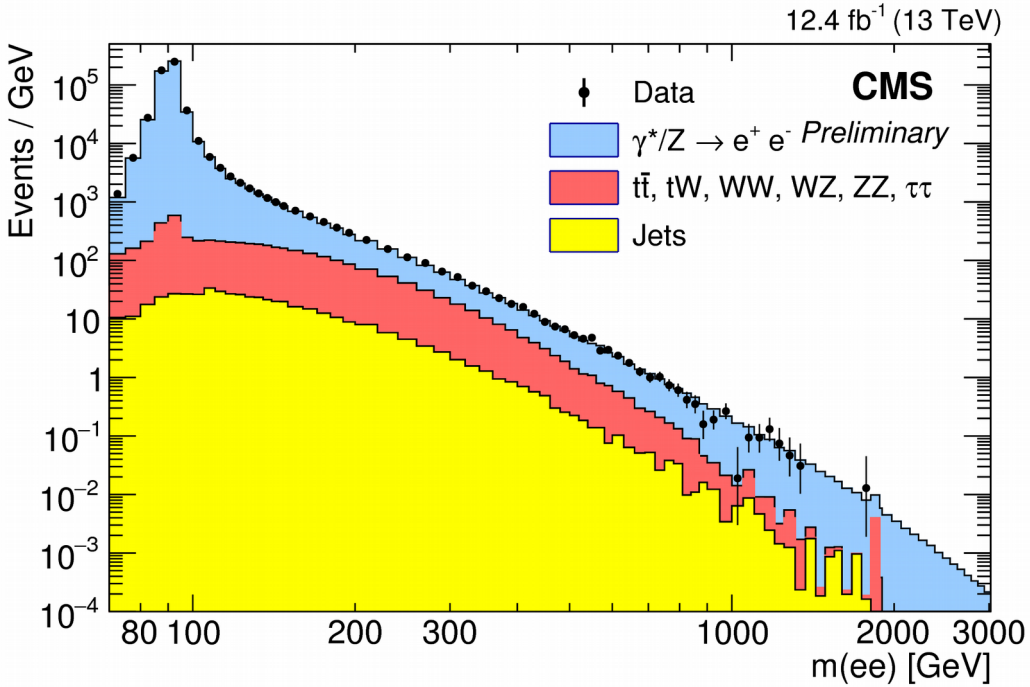
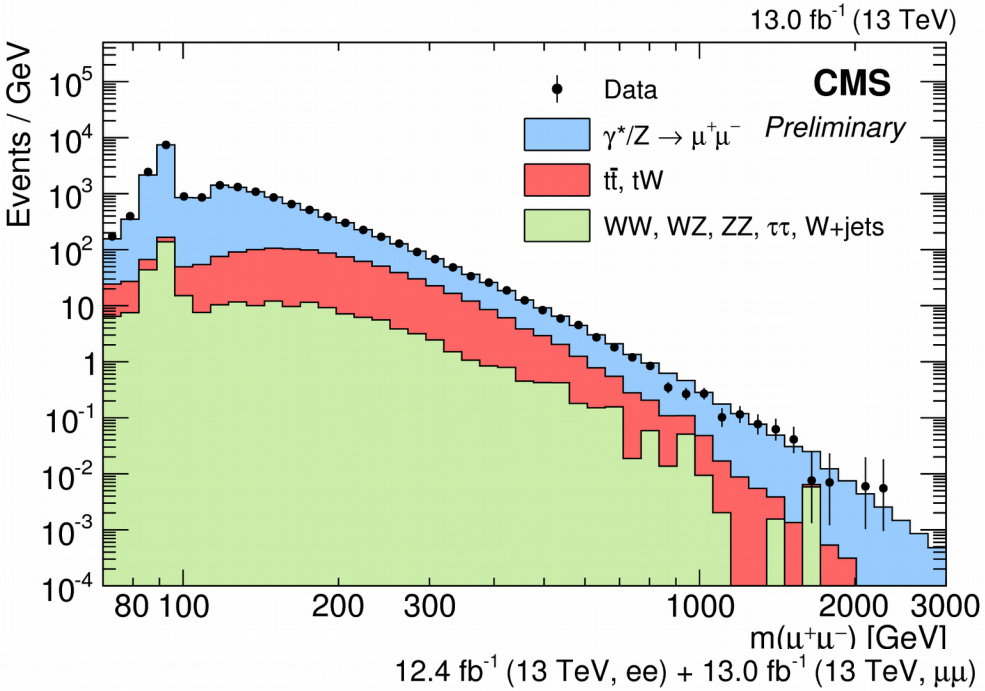
Updates from the LHC

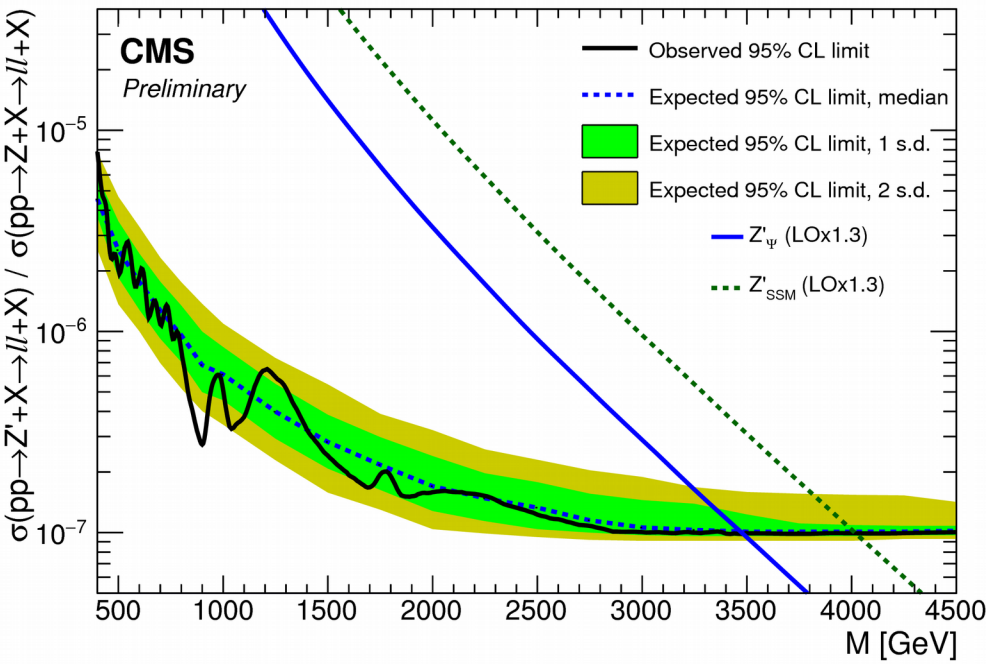




13 TeV data with $\mathscr{L}$ ~ 13 fb^{-1}

With the current Run-II data set we have already overcome Run-I sensitivity

Z' boson masses excluded up to **4 TeV**



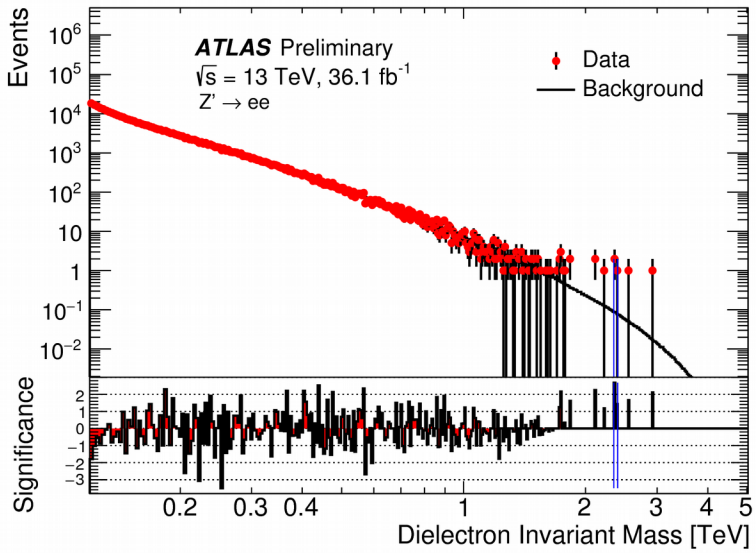
CMS-PAS-EXO-16-031

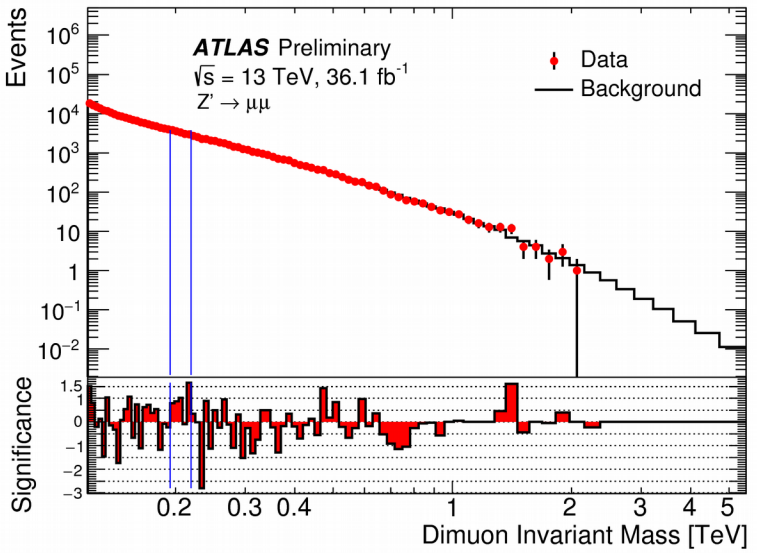
Updates from the LHC

ATLAS-CONF-2017-027

13 TeV data with $\mathcal{L} \sim 36.1\ fb^{-1}$

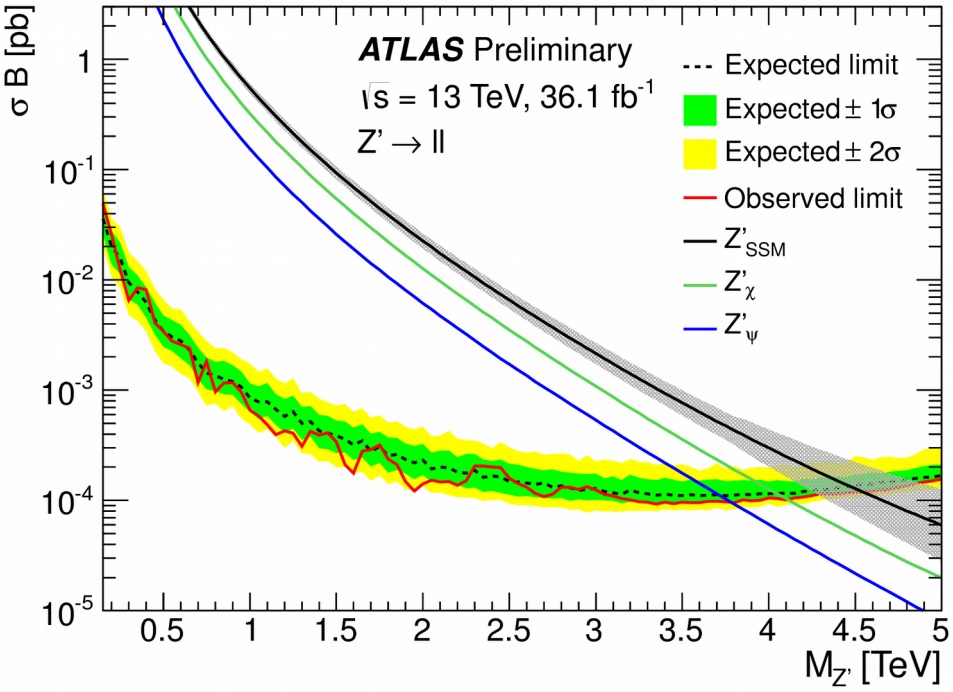
Some high invariant mass events (up to ***3 TeV***) observed in the **di-electron** channel. Still low significance.



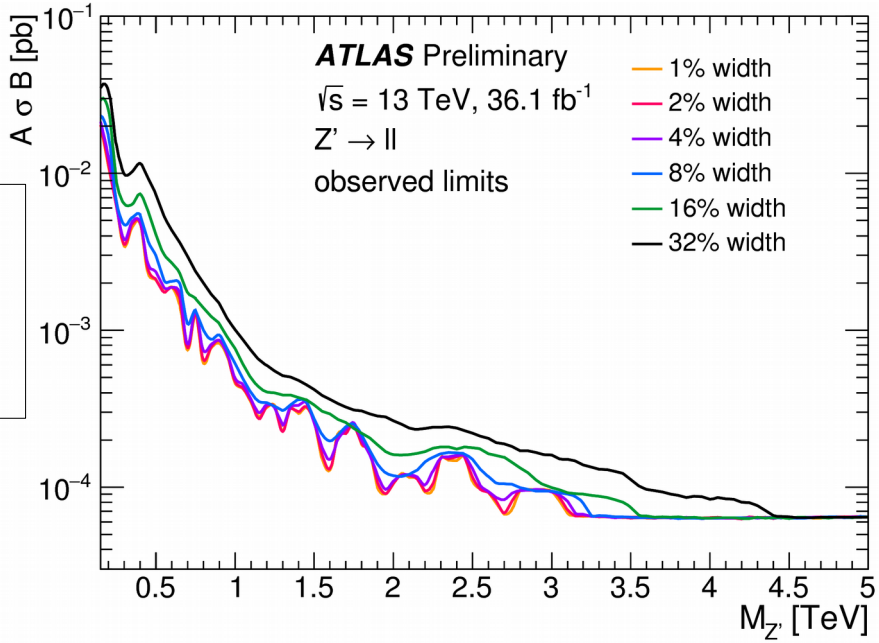


ATLAS provides the curves with the acceptance of the integrated signal in the *($M_{Z'}$ ± 1 width)* region for different ***Z'* widths.**

Exclusion limits can be rescaled accordingly.



Limits on ***Z'*** masses increased to **4.5 TeV**



Experimental analysis

Narrow resonances (*Γ/M < 5%*)

Experimental fits scan the invariant mass spectrum assuming a **Breit-Wigner (BW)** line-shape for the new physics signal standing over a smooth background.

The interpretation of an hypothetical ***Z'*** signal requires the fit of two independent parameters: the Mass and the Width of the resonance

The extraction of ***Z'*** mass limits follows model independent procedures, based on the Narrow Width Approximation (**NWA)**, or exploiting the invariant mass "optimal cut" $|M_{ll} - M_{Z'}| < 5\%\ E_{LHC}$

Accomando, Becciolini, Belyaev, Moretti, Shepherd-Themistocleous, **JHEP 10, 2013, 153**

The extracted mass bounds are easy to reinterpret

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The interpretation of an hypothetical ***Z'*** signal requires the fit of two independent parameters: the Mass and the Width of the resonance

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Wide resonances ($\Gamma/M > 5\%$)

Experimental analyses are essentially counting experiments where an excess of events is searched for above an estimated SM background

A wide resonance does not have a well-defined BW line-shape. It appears instead as a broad shoulder over the SM background.

Heavy rely on the good understanding and control of the SM background. Systematic uncertainties on the high invariant mass region might affect the experimental sensitivity.

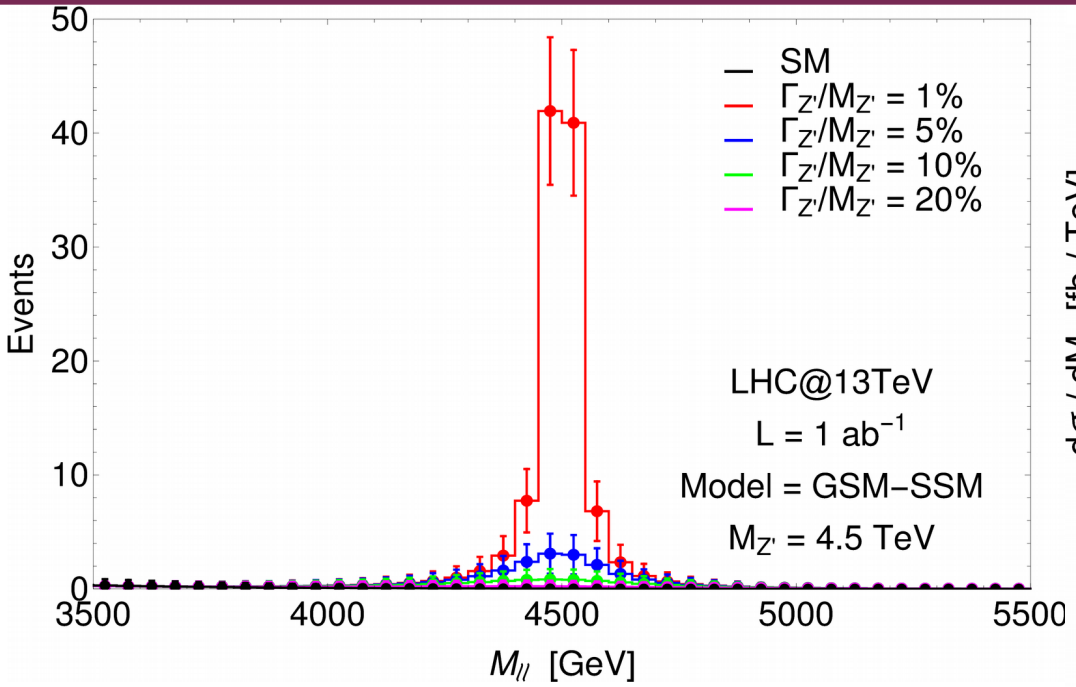
Other observables can help disentangling a ***Z'*** signal:

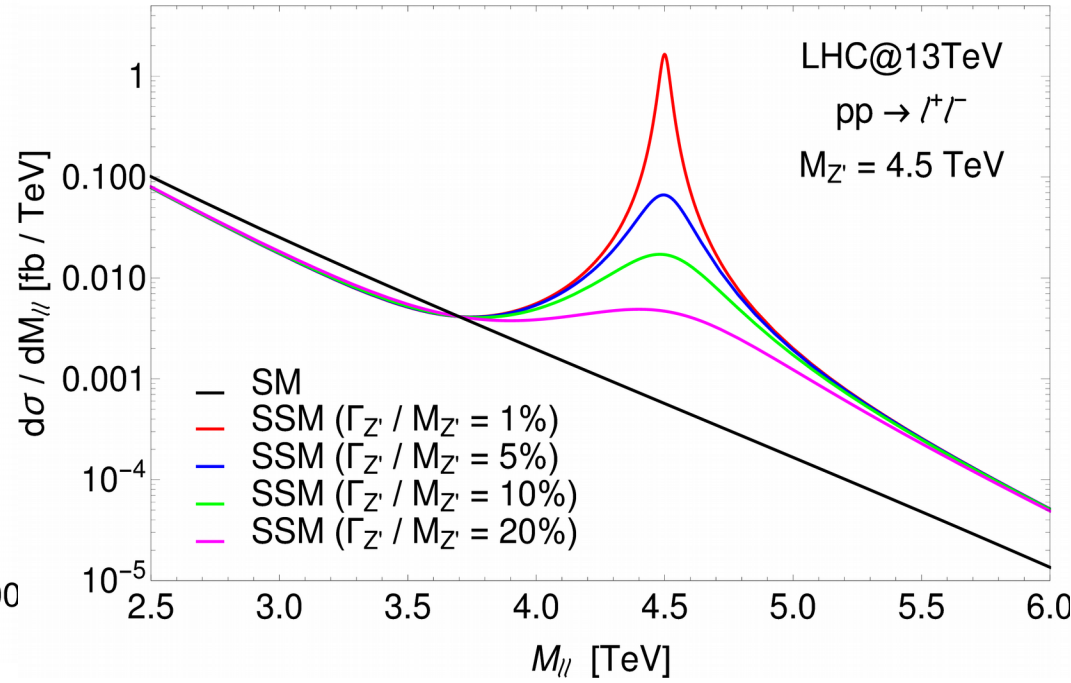
- The **Forward-Backward Asymmetry (AFB)** for instance maintains a visible line-shape even for large values of the resonance width.

Accomando, Fiaschi, Hautmann, Moretti, Shepherd-Themistocleous, **Phys. Rev. D, 95 (2017), 035014, Phys. Lett. B, 770 (2017), 1-7**

Accomando, Belyaev, Fiaschi, Mimasu, Moretti, Shepherd-Themistocleous, **JHEP, 01 (2016), 127**

Cross section





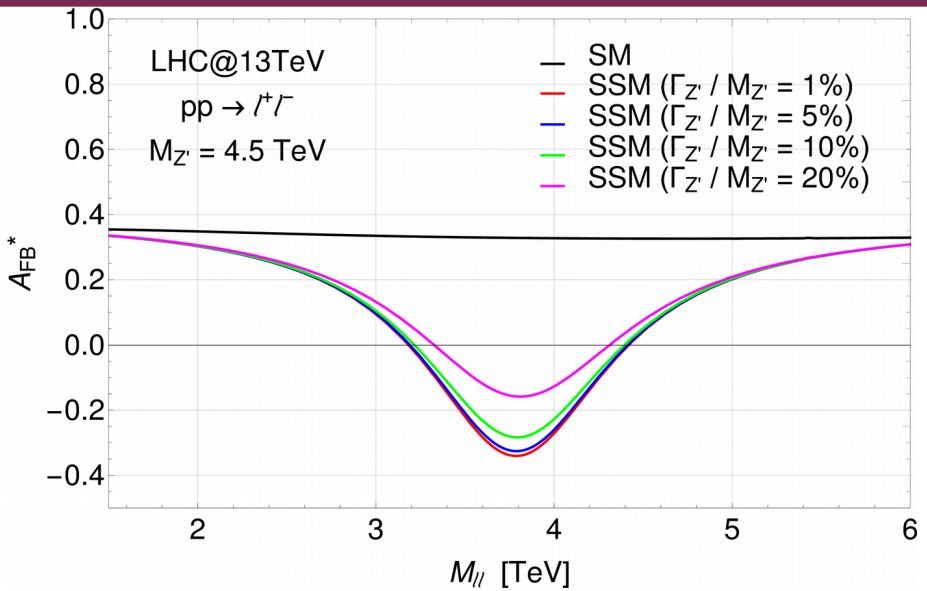
In the case of a very narrow resonance (Γ/M < 1%), the measurement of the width using the mass spectrum is limited by the detector resolution.

A wide resonance signal can't be approximated by a BW. A model specific approach would be required.

We vary the width by hand, without a rescaling of the couplings:
- ***σ*** production is unchanged
- ***Br*** scales linearly with the width

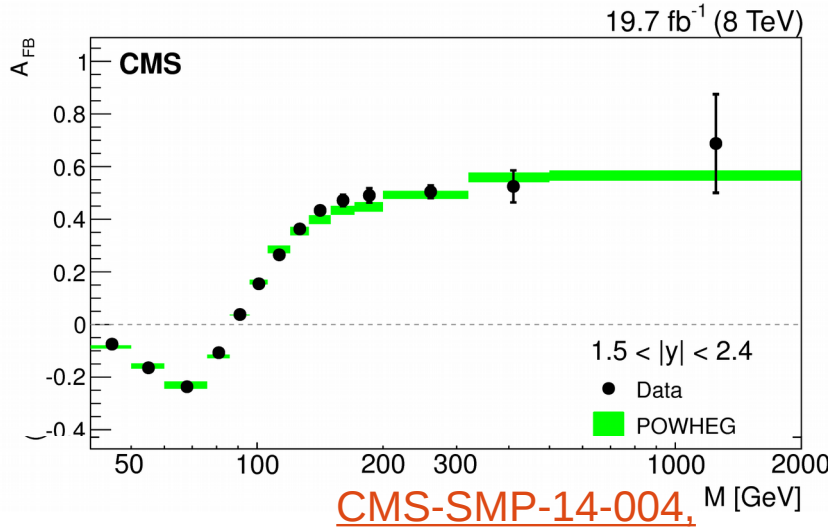
Representative of the case where exotic decay channels are opened

AFB



The AFB can support the evidence of an excess, also in the case of wide resonances. However due to this property it is difficult to extract information on the resonance width.

Very few data points in the high invariant mass region.
Being a ratio of cross sections, the systematics cancel out.
Statistical uncertainty dominates



CMS-SMP-14-004,
Eur. Phys. J., C76 (2016) 6, 325

The **AFB** can help the interpretation of possible signals, as it carries complementary informations with respect to the cross section on the ***Z'*** couplings

The AFB shape analysis requires a model dependent implementation as it is strongly affected by interference effects

Accomando, Belyaev, Fiaschi, Mimasu, Moretti, Shepherd-Themistocleous,
JHEP, 01 (2016), 127

The p_T spectrum

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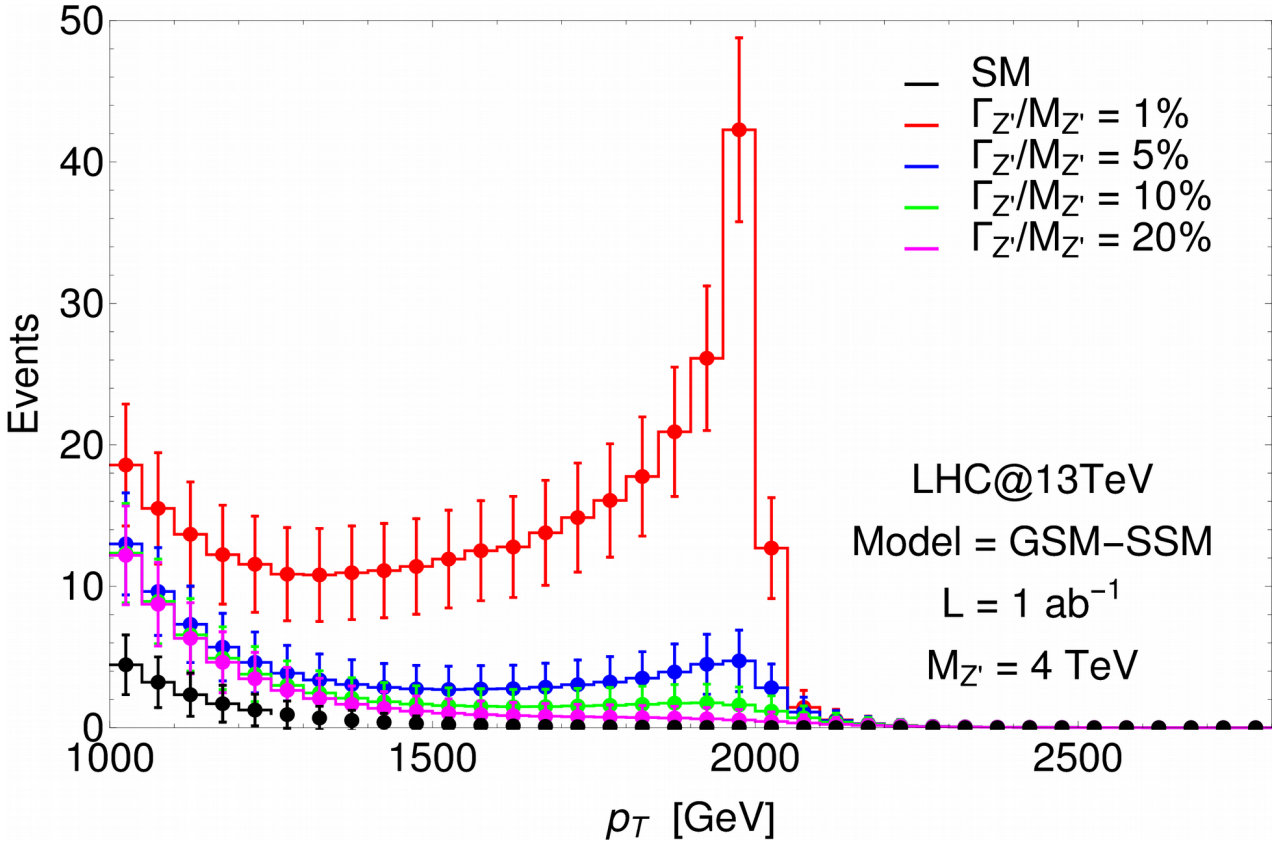
The p_T spectrum

Let's have a look at the p_T distribution!

Consider the behaviour of one benchmark single ***Z'*** model for different values of its width



At tree-level the two leptons in the final state have the same transverse momentum, thus there is no ambiguity.

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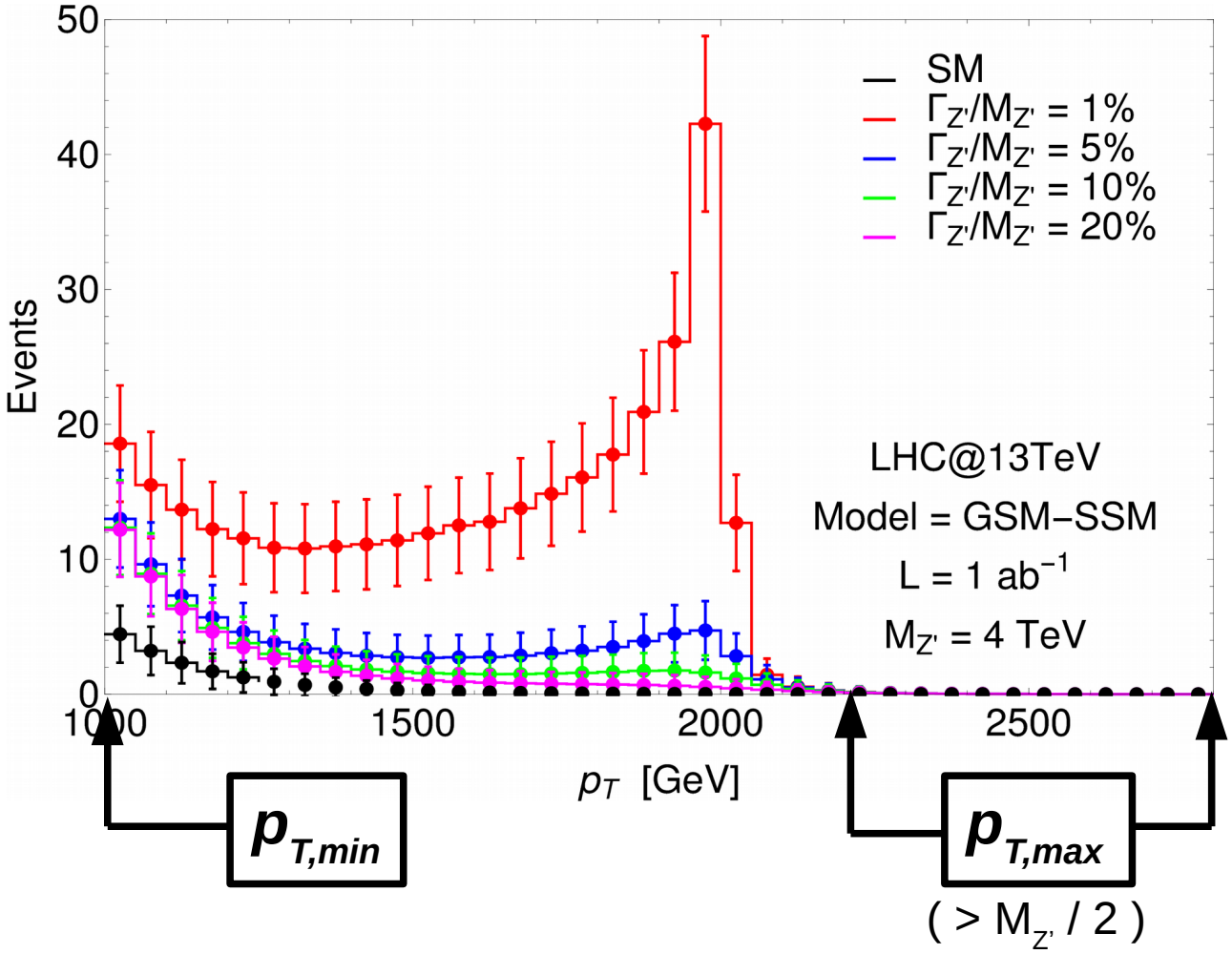


At tree-level the two leptons in the final state have the same transverse momentum, thus there is no ambiguity.

1

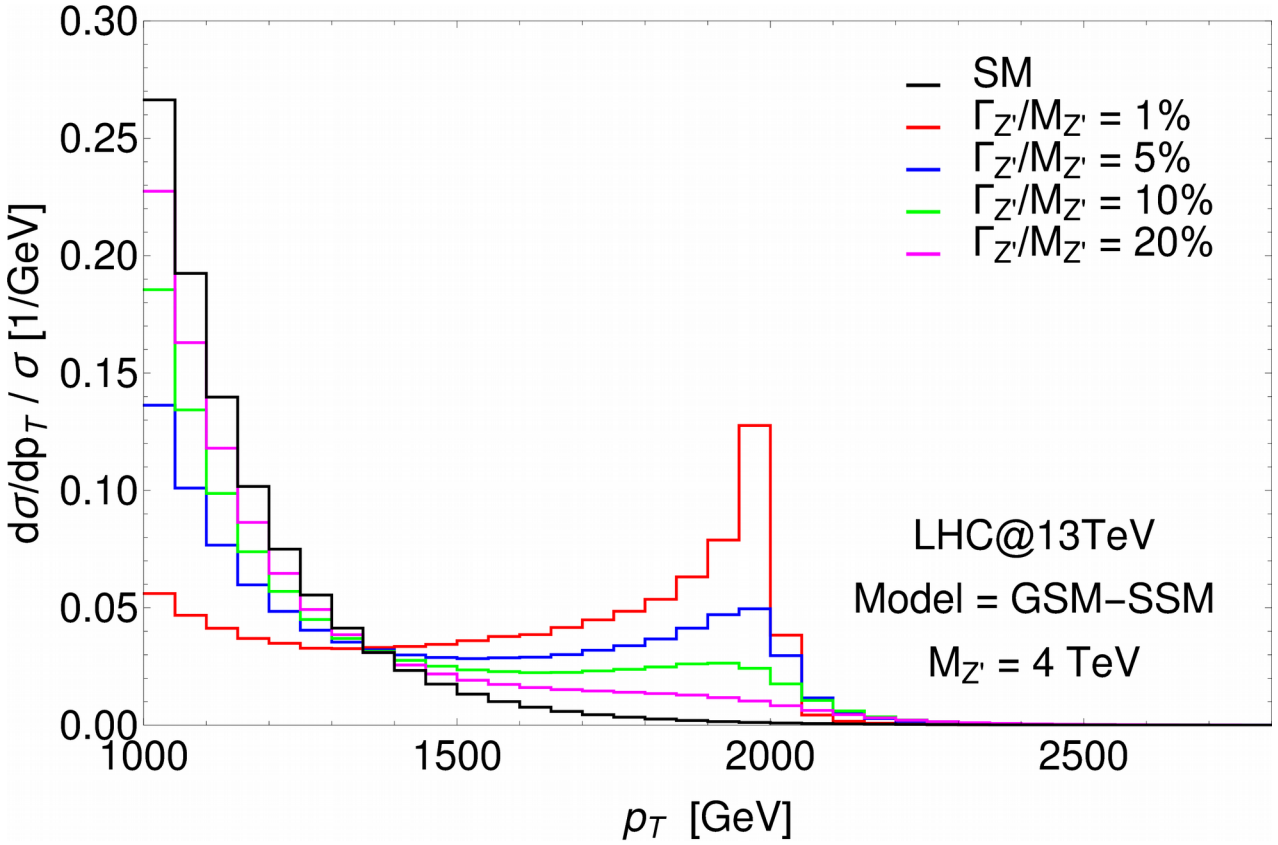
Consider an interval in the p_T spectrum that we want to probe

Normalise the distributions in the selected interval

The p_T spectrum

Let's have a look at the p_T distribution!

Normalised p_T distributions in the interval defined by $p_{T,min}$



All the curves cross the same point, independently on their width.
The Standard Model as well follows the same behaviour.

The p_T spectrum

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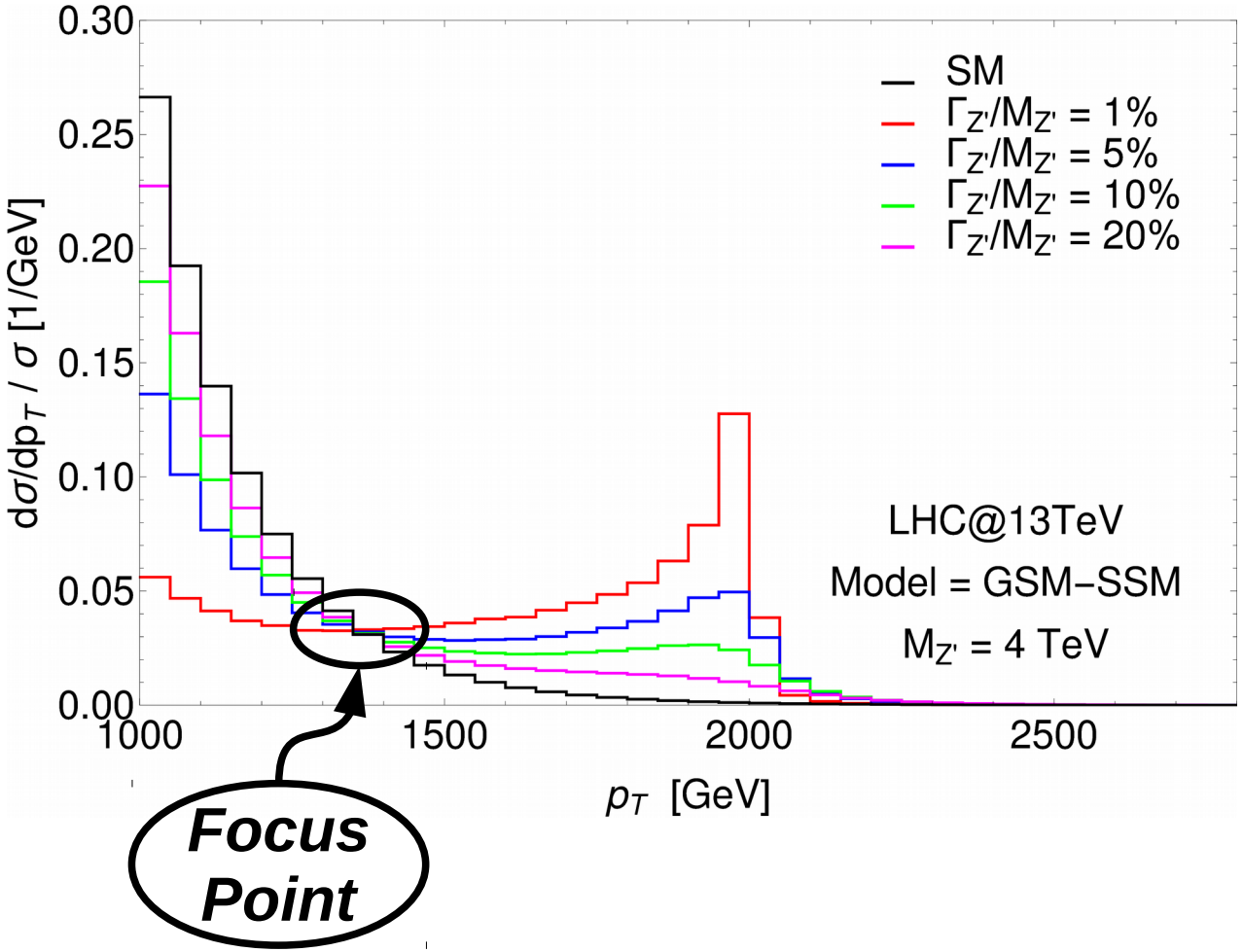
Normalised p_T distributions in the interval defined by $p_{T,min}$



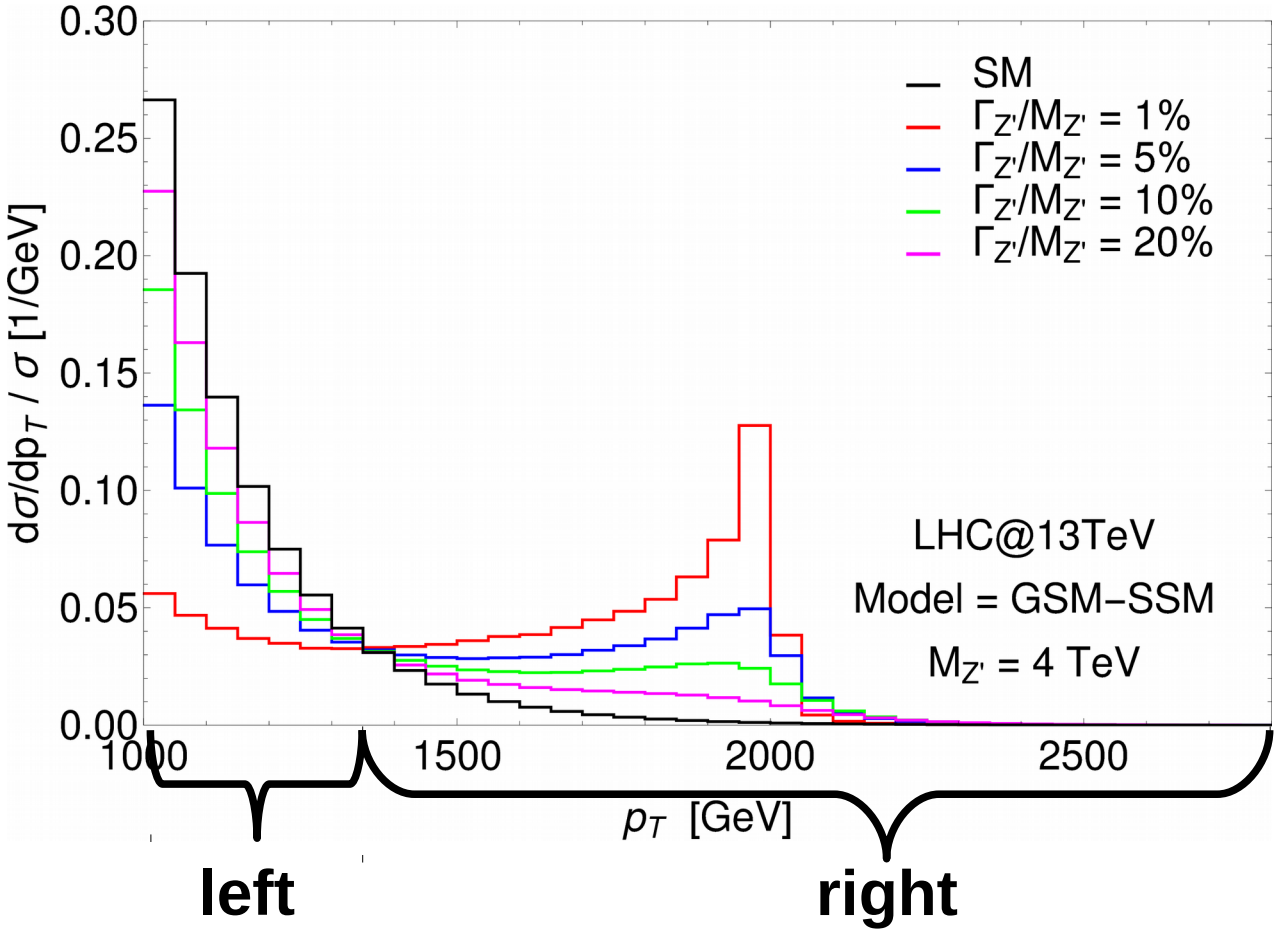
All the curves cross the same point, independently on their width.
The Standard Model as well follows the same behaviour.

A **Focus Point (FP)** appears

The p_T spectrum

Let's have a look at the p_T distribution!

The **FP** divides the p_T spectrum in two regions



2

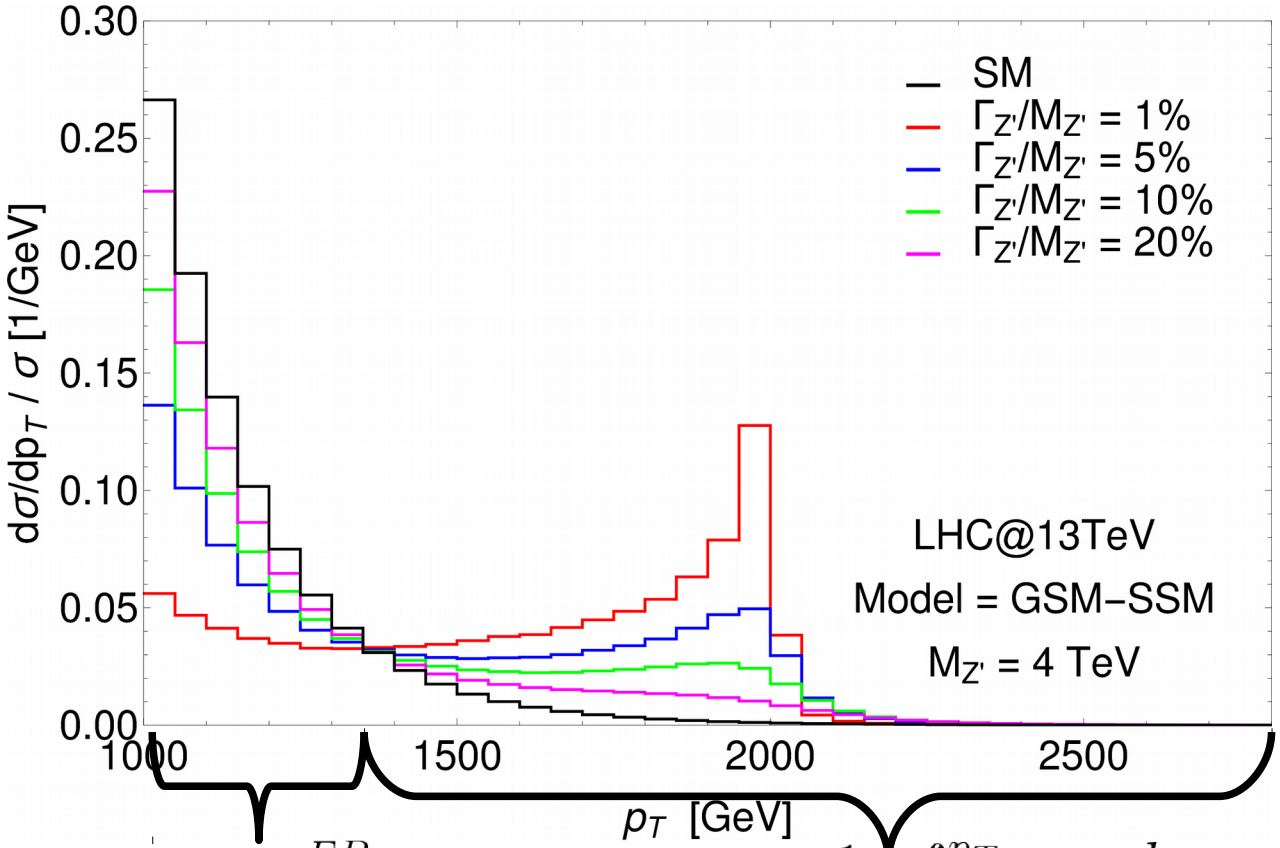
For each curve calculate the integral in the two regions of the p_T spectrum on the *left* and on the *right* side of the **FP**.

The results of the integrations will be called **L** and **R**, respectively.

The p_T spectrum

Define the Asymmetry of the Focus Point (AFP)

The values of the **AFP** only depends on the choice of the *left* and *right* integration regions.



$$L = \frac{1}{\sigma}\int_{p_{T,min}}^{FP} \frac{d\sigma}{dp_T} dp_T \qquad R = \frac{1}{\sigma}\int_{FP}^{p_{T,max}} \frac{d\sigma}{dp_T} dp_T$$

3

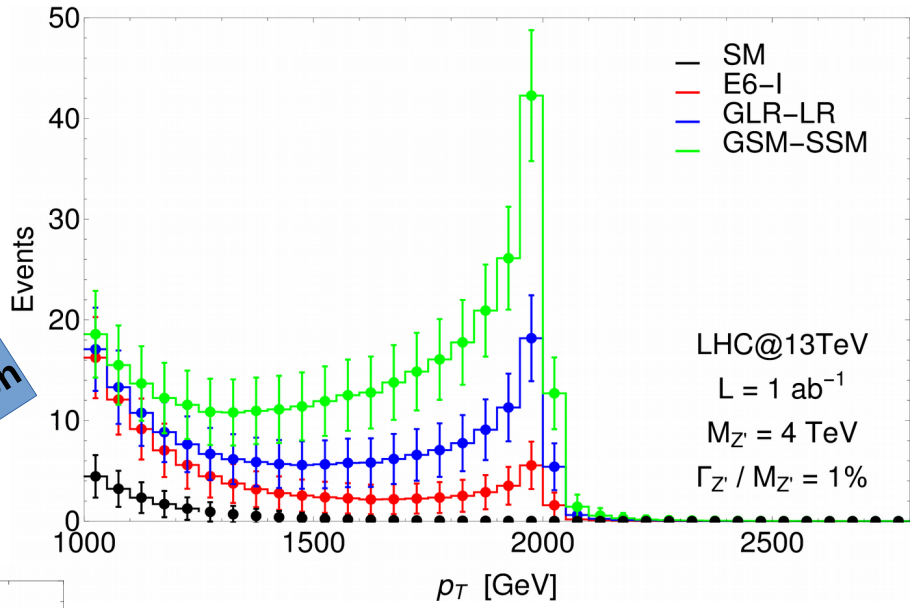
$$A_{FP} = \frac{L - R}{L + R}$$

This variable will provide an independent information on the resonance width, without relying on the modelling of the signal shape.

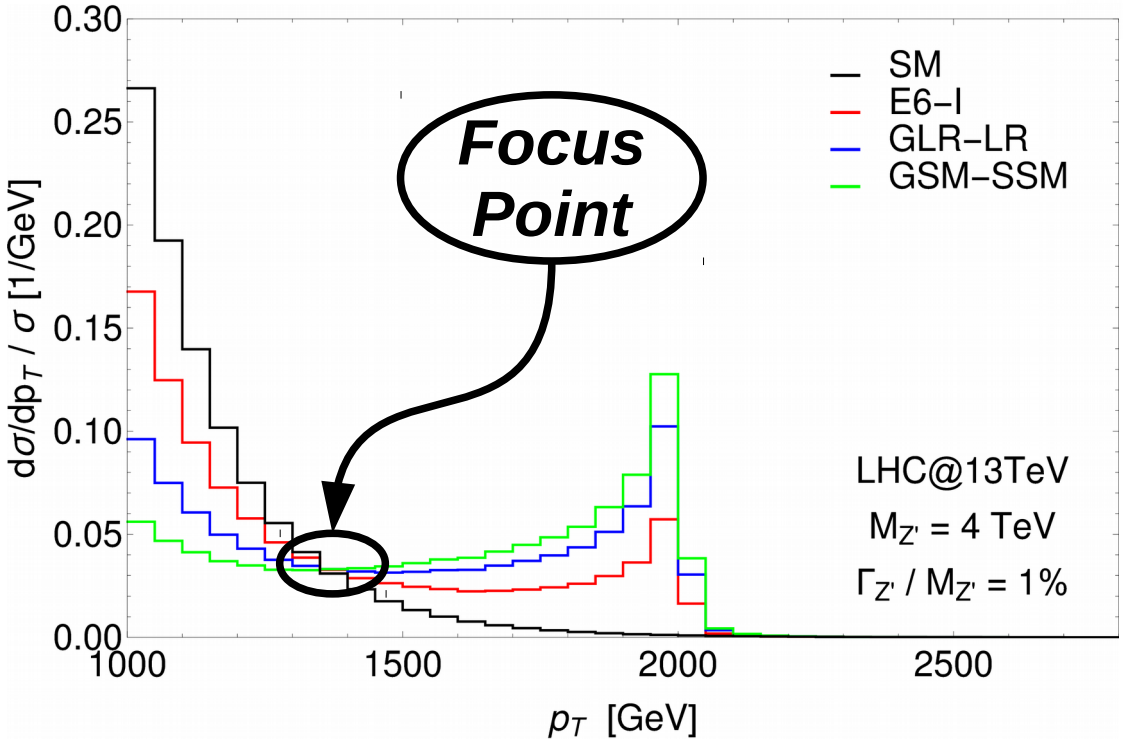
Properties of the Focus Point

The FP is model independent!

Fix the resonance width and for each model normalise the p_T spectrum.



Normalization

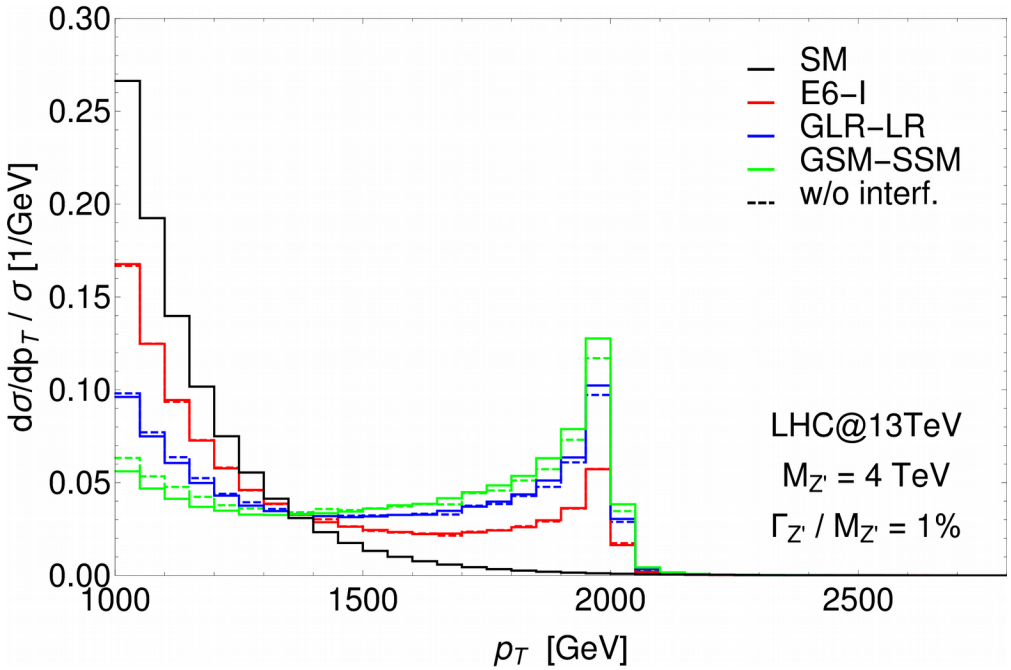


The model dependence contained in the couplings cancels out in the normalisation.

The normalisation will naturally reduce other sources of systematics (PDFs, Luminosity)

Properties of the Focus Point

The FP is model independent!

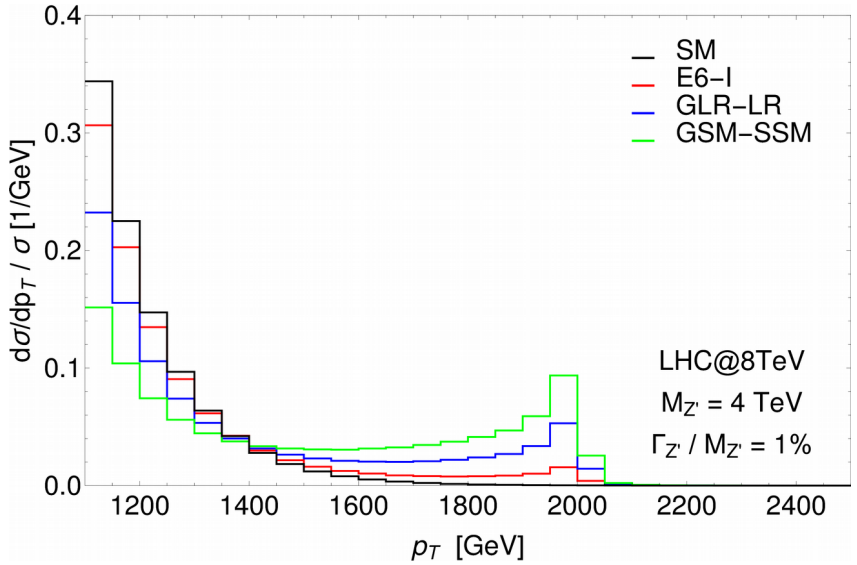


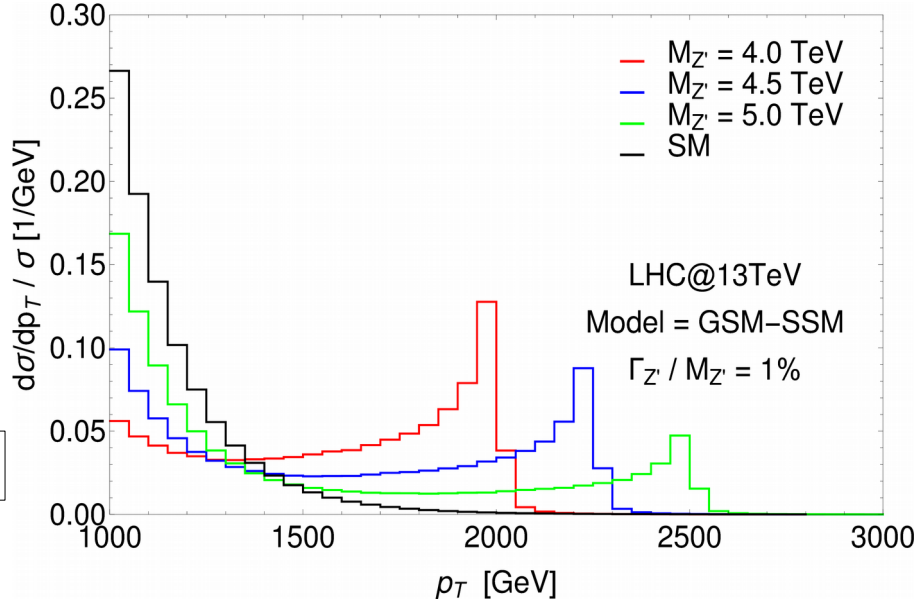
The $\mathbf{p_T}$ spectrum is marginally affected by the interference.
Its model dependent effect on the curves is negligible.

For a fixed c.o.m. energy, the position of the **FP** depends only on the ***Z'*** mass and on the choice of the $\boldsymbol{p_{T,min}}$

Empirical relation valid for the LHC@13TeV → $FP = p_{T_{min}} + 10\% M_{Z'}$

The FP depends on the collider energy and on the *Z'* mass





The AFP

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The AFP

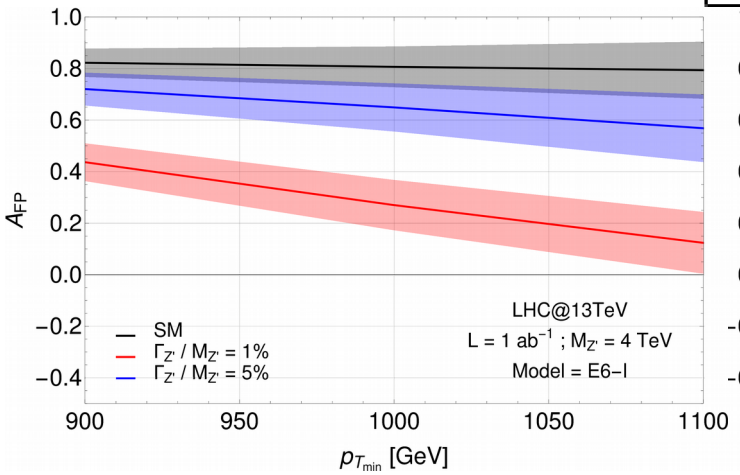
Predictions for the AFP

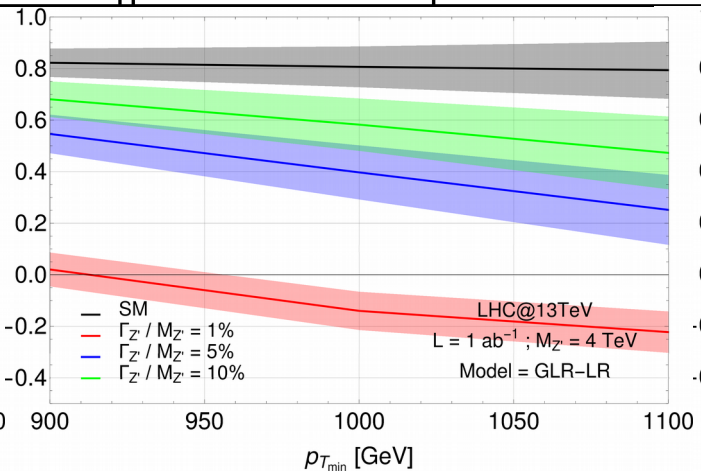
Statistical error evaluated for $\mathscr{L} = 1\ ab^{-1}$

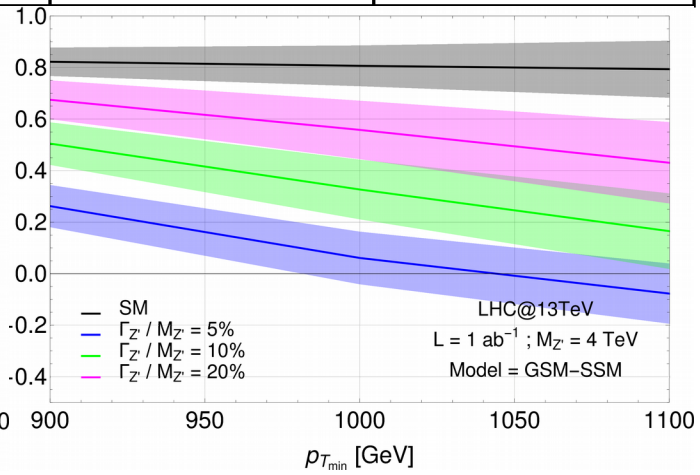
$M_{Z'} = 4$ TeV

For some models we can constrain ***Z'*** widths up to Γ/M ~ 20%

Model	$\Gamma_{Z'}/M_{Z'} = 1\%$	$\Gamma_{Z'}/M_{Z'} = 5\%$	$\Gamma_{Z'}/M_{Z'} = 10\%$	$\Gamma_{Z'}/M_{Z'} = 20\%$
$M_{Z'} = 4$ TeV				
$p_T^{\min} = 900$ GeV				
SM	0.822±0.055			
E_6^I	0.437±0.073	0.720±0.064	0.768±0.060	0.796±0.057
LR	0.020±0.066	0.546±0.075	0.681±0.069	0.758±0.063
SSM	-0.291±0.049	0.262±0.082	0.505±0.083	0.675±0.075
$p_T^{\min} = 1000$ GeV				
SM	0.807±0.079			
E_6^I	0.270±0.098	0.649±0.094	0.725±0.088	0.768±0.083
LR	-0.140±0.074	0.397±0.105	0.582±0.102	0.701±0.094
SSM	-0.371±0.051	0.061±0.102	0.327±0.116	0.558±0.113
$p_T^{\min} = 1100$ GeV				
SM	0.793±0.111			
E_6^I	0.124±0.120	0.568±0.131	0.677±0.124	0.742±0.116
LR	-0.223±0.080	0.252±0.136	0.473±0.141	0.637±0.134
SSM	-0.376±0.054	-0.077±0.117	0.165±0.147	0.430±0.158







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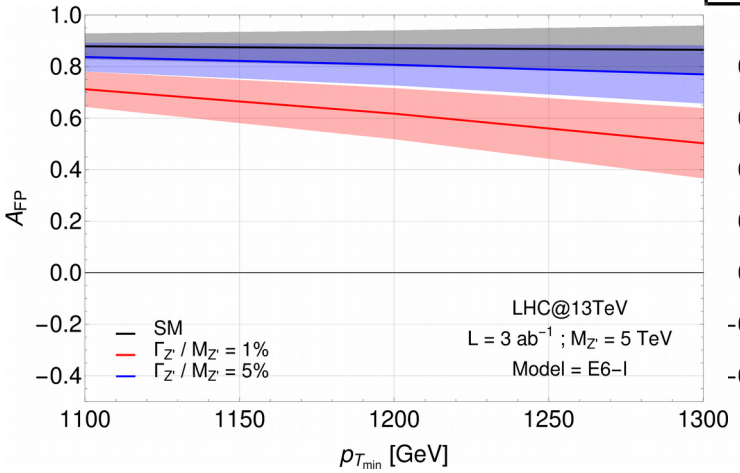
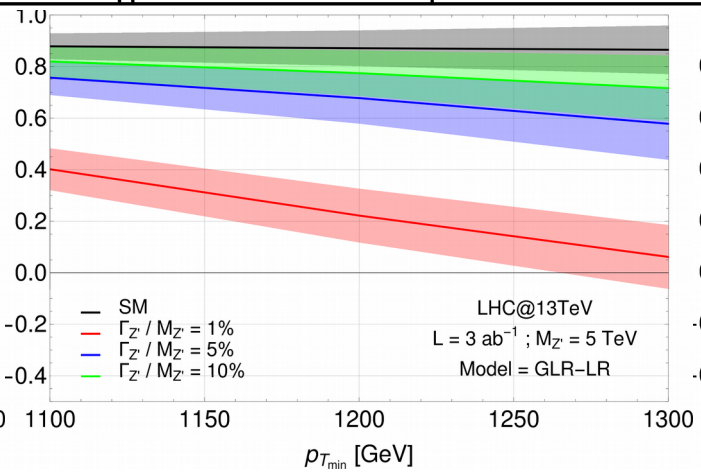
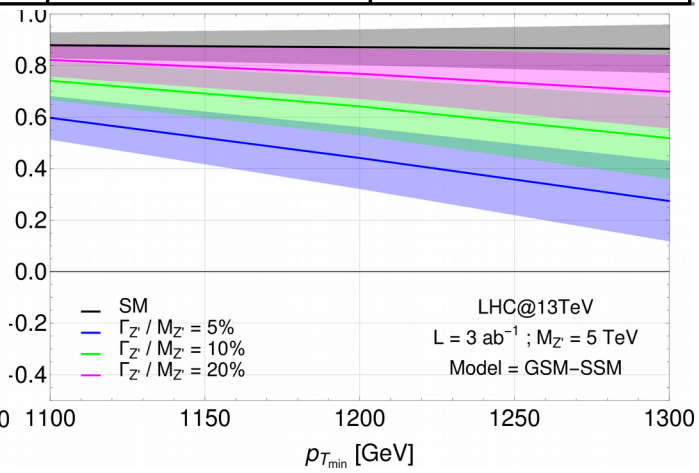
$M_{Z'} = 5$ TeV

For some models we can constrain ***Z'*** widths up to Γ/M ~ 20%

$M_{Z'} = 5$ TeV				
Model	$\Gamma_{Z'}/M_{Z'} = 1\%$	$\Gamma_{Z'}/M_{Z'} = 5\%$	$\Gamma_{Z'}/M_{Z'} = 10\%$	$\Gamma_{Z'}/M_{Z'} = 20\%$
$p_T^{\min} = 1100$ GeV				
SM	0.879±0.050			
E_6^I	0.712±0.069	0.837±0.056	0.855±0.053	0.866±0.052
LR	0.402±0.081	0.757±0.067	0.820±0.060	0.853±0.056
SSM	0.0378±0.077	0.597±0.084	0.741±0.075	0.822±0.065
$p_T^{\min} = 1200$ GeV				
SM	0.871±0.069			
E_6^I	0.617±0.099	0.807±0.080	0.837±0.075	0.854±0.072
LR	0.222±0.105	0.678± 0.099	0.774±0.089	0.828±0.080
SSM	-0.136±0.087	0.441±0.120	0.642±0.112	0.768±0.097
$p_T^{\min} = 1300$ GeV				
SM	0.865±0.094			
E_6^I	0.502±0.136	0.770±0.113	0.815±0.105	0.842±0.099
LR	0.0614±0.124	0.578±0.140	0.716±0.127	0.798±0.113
SSM	-0.242±0.092	0.274±0.156	0.518±0.159	0.699±0.143







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Conclusions

The experimental analysis in the di-lepton channel is designed to have the best sensitivity on narrow ***Z'*** resonances ($\Gamma/M < 5\%$). The "bump" searches performed by ATLAS and CMS have excluded heavy resonances up to ~ 4.5 TeV.

Wide ***Z'*** resonances require a model dependent analysis as the signal shape in the invariant mass distribution cannot be described with a simple Briet-Wigner, since interference effects can be large.

The normalised p_T distributions of either lepton of any single ***Z'*** model, all cross the same point, as well as the SM predictions.
This is defined as the **Focus Point (FP)** and its position shows interesting features:

- It is model independent.
- It is width independent.
- It depends only on the choice for the normalisation ($p_{T,min}$) and on the ***Z'*** mass.
  (An empirical relation valid for the LHC@13TeV between the **FP** position to the parameters above holds.)

We define the **Asymmetry of the Focus Point (AFP)** observable, which exploit the properties above in order to provide information on the resonance width. It can be used

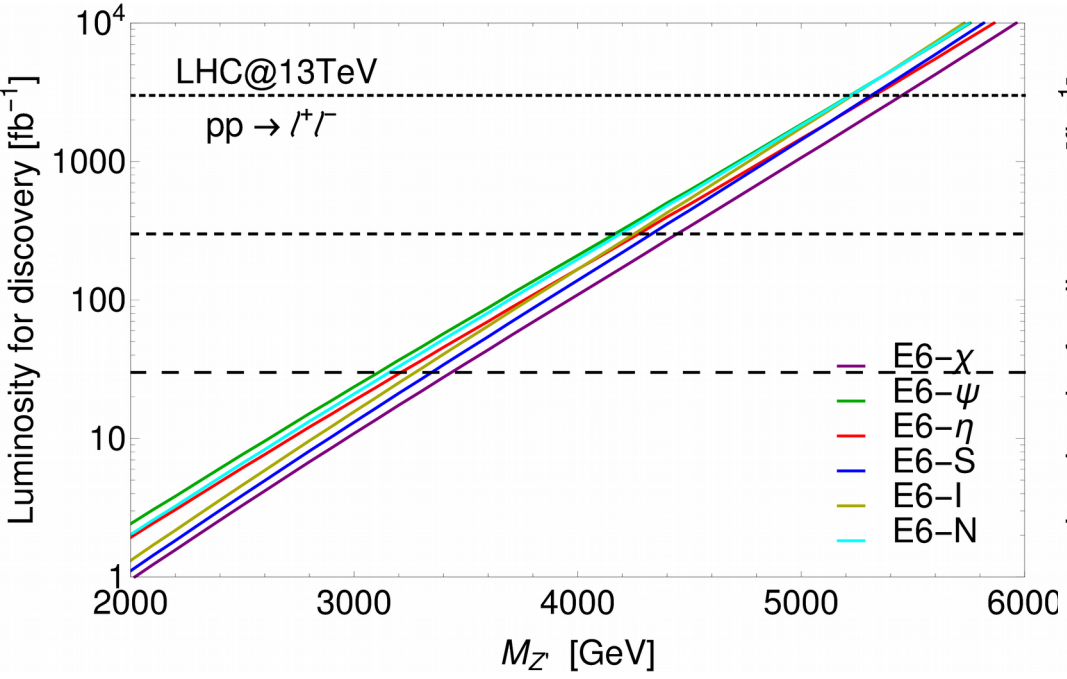
- As search tool to detect wide resonances.
- As diagnostic tool to extract independent constrains on the Z' width, which can be imported in the invariant mass analysis to improve the quality of the fit.
- As interpretation tool, as for a given width, it can provide indication on the class of model which the ***Z'*** is belonging.

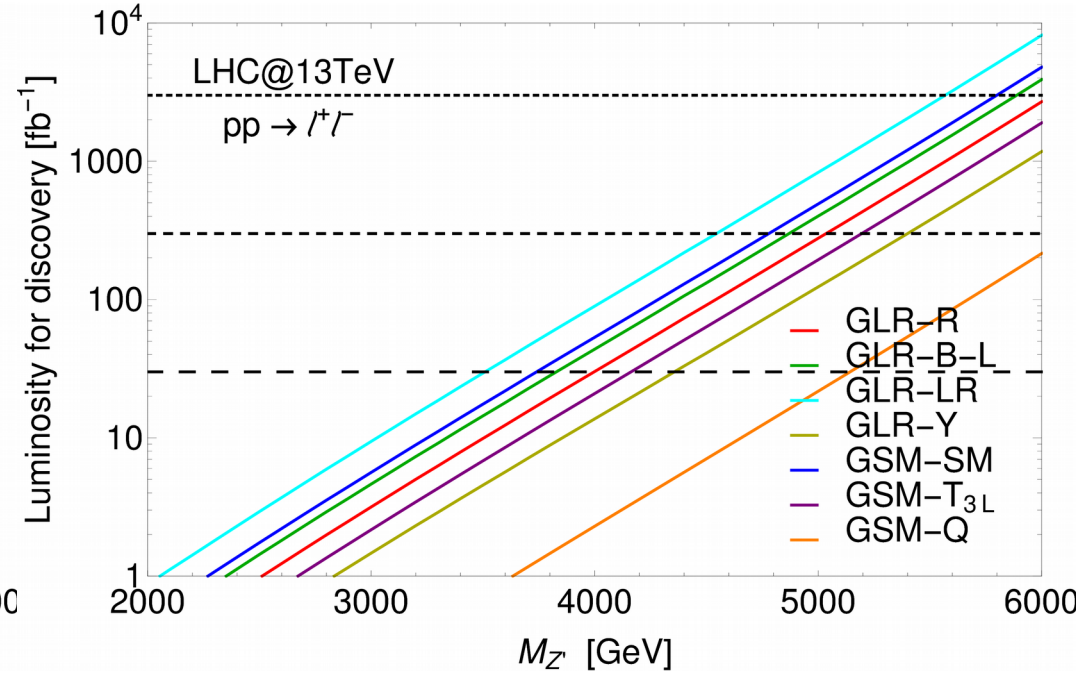
Thank you!

Narrow *Z'* discovery projections

The use we would like for the LHC

Luminosity required for ***Z'*** discovery as function its mass for popular models





LHC will be sensitive to narrow resonances with masses up to:

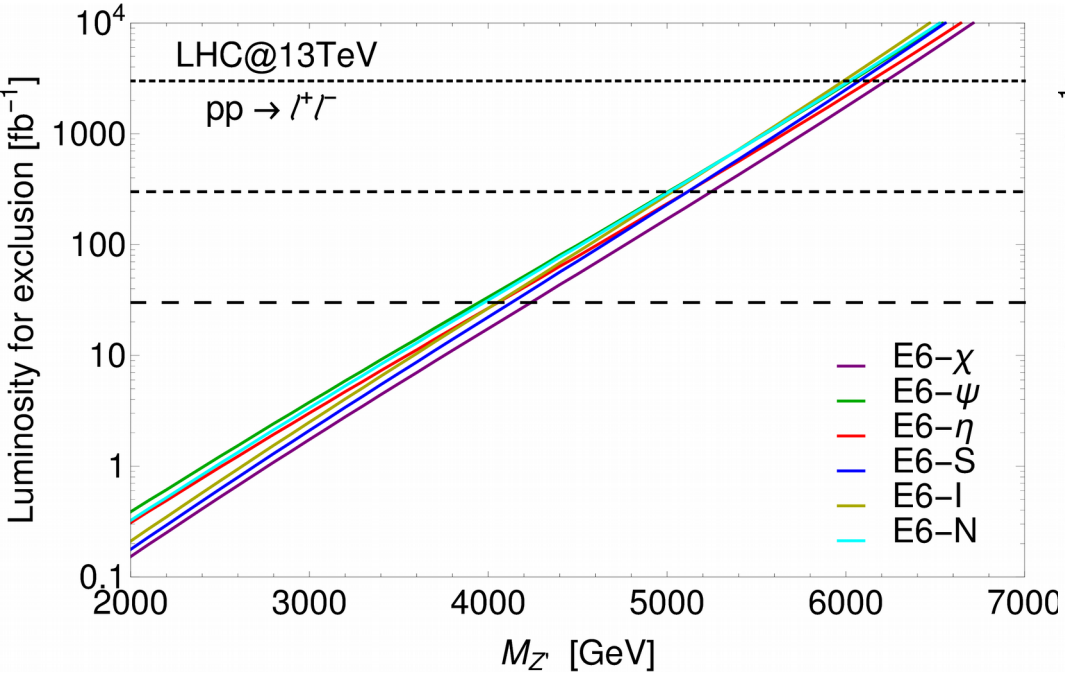
- **4 TeV – 5 TeV** by the end of the Run-II stage ($\mathscr{L}$ **= 300 fb^{-1}**)
- **5 TeV – 6.5 TeV** by the end of the High Luminosity stage ($\mathscr{L}$ **= 3000 fb^{-1}**)

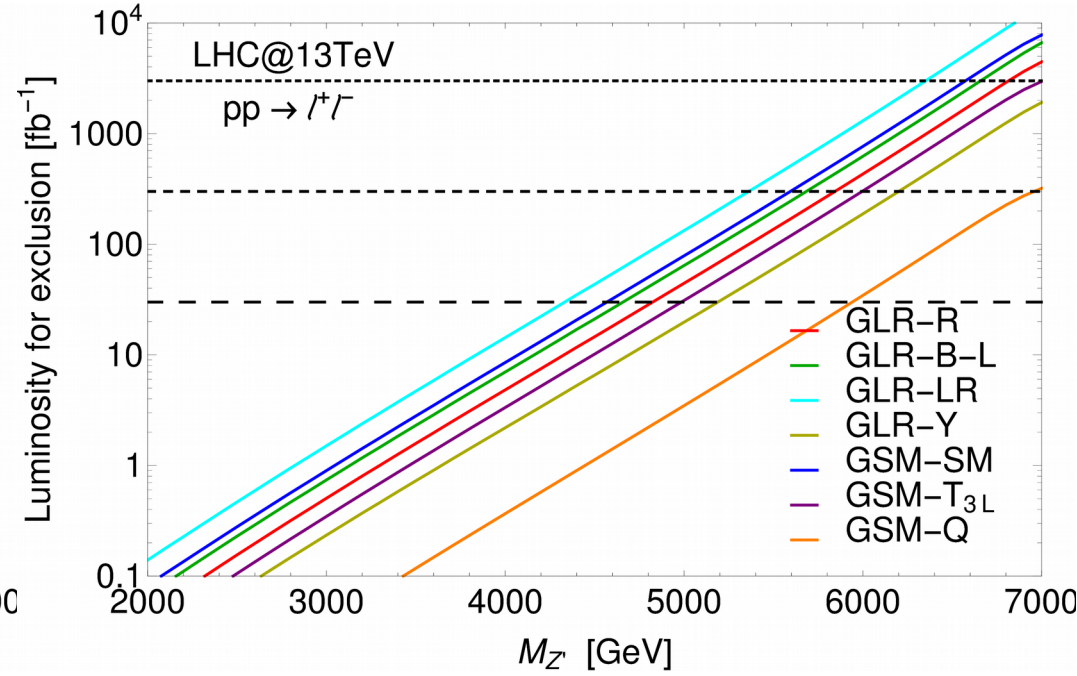
Accomando, Belyaev, Fiaschi, Mimasu, Moretti, Shepherd-Themistocleous, **JHEP, 01 (2016), 127**

Narrow *Z'* exclusion projections

The use we make of the LHC

Luminosity required for ***Z'*** exclusion as function its mass for popular models



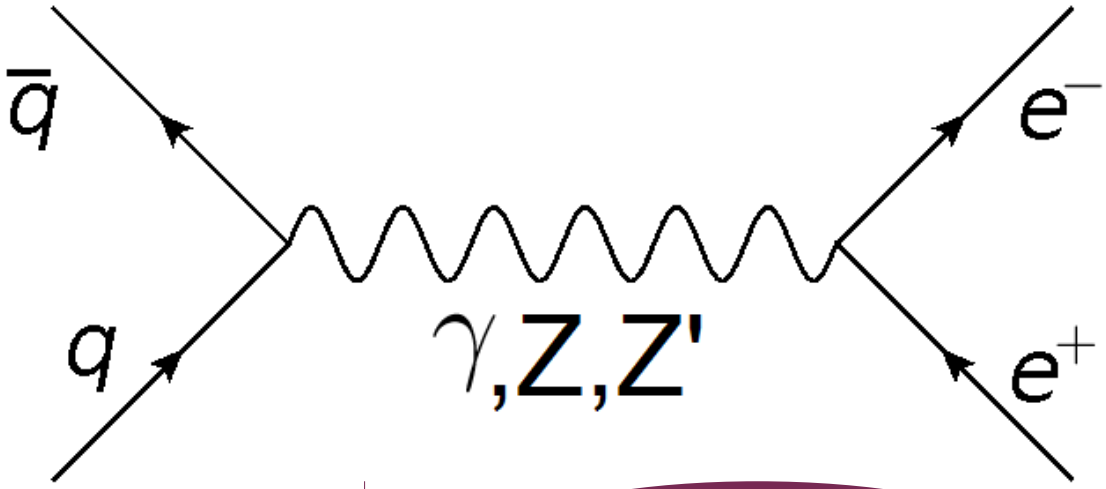


LHC will be able to exclude narrow resonances with masses up to:

- **5 TeV – 6 TeV** by the end of the Run-II stage ($\mathscr{L}$ **= 300 fb^{-1}**)
- **6 TeV – 6.5 TeV** by the end of the High Luminosity stage ($\mathscr{L}$ **= 3000 fb^{-1}**)

Accomando, Belyaev, Fiaschi, Mimasu, Moretti, Shepherd-Themistocleous, **JHEP, 01 (2016), 127**

Z'-bosons @ the LHC



Bump search / Counting strategy

Experimentally unobserved signal

Excluded cross section

Optimal invariant mass cut:
$|M_{ll} - M_{Z'}| < 5\% E_{LHC}$

Narrow Width Approximation (NWA)

Finite width and interference effects are neglected

Z' mass bounds

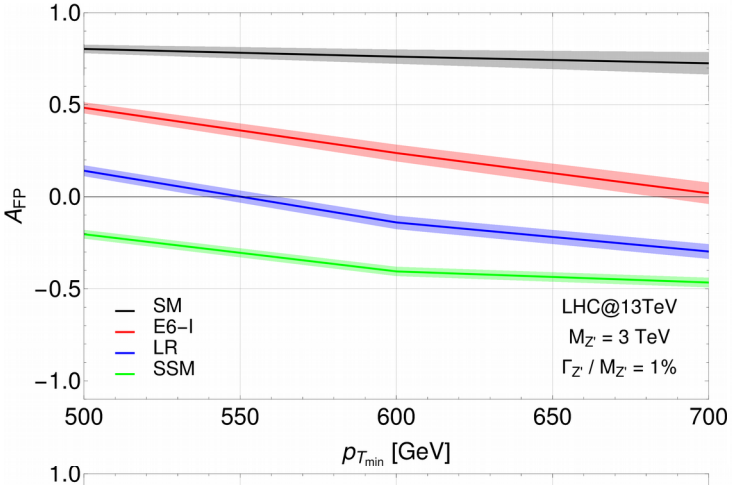
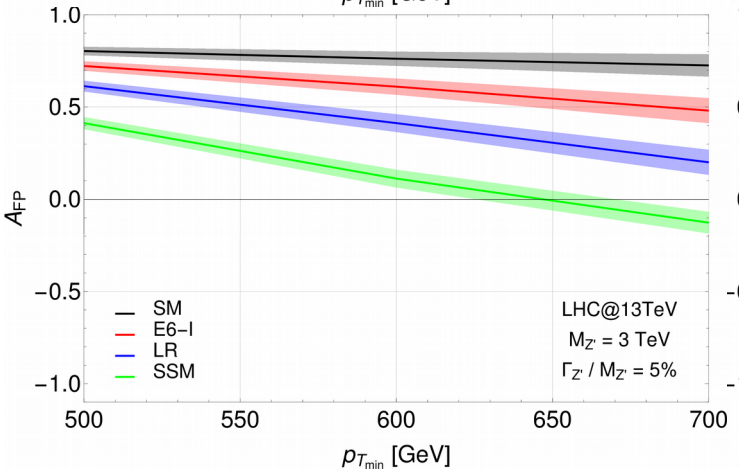
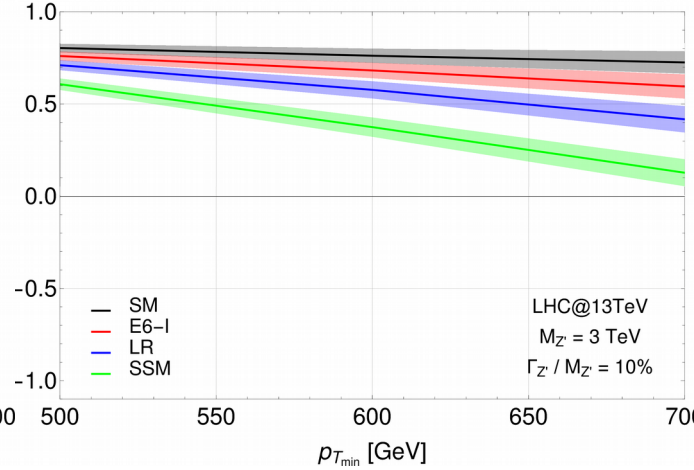
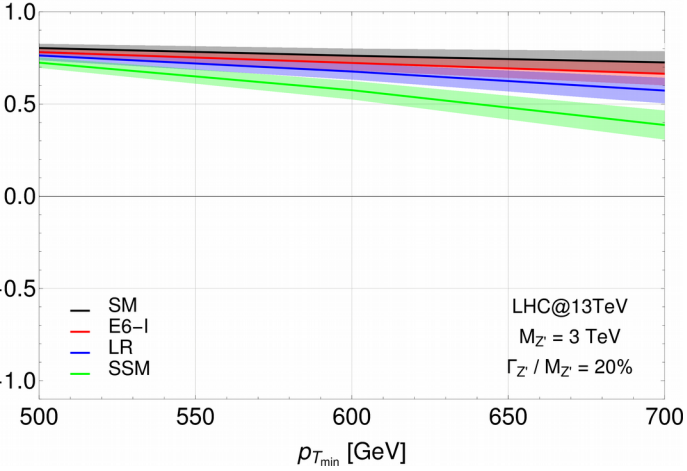
Finite width and interference effects are kept under control (< 10%) in narrow single ***Z'*** models

Accomando, Becciolini, Belyaev, Moretti, Shepherd-Themistocleous, **JHEP 10, 2013, 153**

The AFP

Predictions for the AFP

Statistical error evaluated for $\mathscr{L} = 300\ fb^{-1}$

$M_{Z'} = 3$ TeV

$M_{Z'} = 3$ TeV				
Model	$\Gamma_{Z'}/M_{Z'} = 1\%$	$\Gamma_{Z'}/M_{Z'} = 5\%$	$\Gamma_{Z'}/M_{Z'} = 10\%$	$\Gamma_{Z'}/M_{Z'} = 20\%$
$p_T^{\min} = 500$ GeV				
SM	0.804±0.023			
E_6^I	0.483±0.030	0.723±0.026	0.760±0.025	0.781±0.024
LR	0.141±0.030	0.613±0.030	0.711±0.027	0.763±0.025
SSM	-0.204±0.024	0.413±0.033	0.608±0.031	0.724±0.028
$p_T^{\min} = 600$ GeV				
SM	0.762±0.039			
E_6^I	0.237±0.046	0.611±0.044	0.682±0.042	0.723±0.041
LR	−0.140±0.037	0.413±0.049	0.577±0.047	0.676±0.044
SSM	−0.406±0.026	0.112±0.049	0.375±0.053	0.575±0.050
$p_T^{\min} = 700$ GeV				
SM	0.726±0.061			
E_6^I	0.019±0.058	0.481±0.068	0.595±0.066	0.664±0.063
LR	−0.298±0.040	0.200±0.068	0.417±0.072	0.573±0.069
SSM	−0.466±0.027	−0.127±0.059	0.128±0.073	0.386±0.079