Z’ discrimination @27TeV
(In case discovery @14TeV)

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Outline

- Context of the study
- Discovery reach @14/27 TeV
  - Analysis context
- Discrimination @27 TeV
  - Pheno like analysis
  - Detector like analysis
- Summary
Context of the study

• At the very end of HL-LHC
  • Some significant excess in the di-lepton channel is seen
  • What would be HE-LHC model discrimination capabilities?

• Consider benchmark narrow resonances Z’
  • Coupling only to SM particles
  • Models: SSM, LRM, I, χ, ψ, η
Discovery reach @14TeV

- 14TeV HL-LHC with 3ab\(^{-1}\)
- Using the present ATLAS and CMS 13TeV results
- Estimate by extrapolation at 14TeV the significance reach of several models

### Mass reach in TeV with 3ab\(^{-1}\) @ √s=14TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>95% CL</th>
<th>3σ</th>
<th>5σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM</td>
<td>6.62</td>
<td>6.09</td>
<td>5.62</td>
</tr>
<tr>
<td>LRM</td>
<td>6.39</td>
<td>5.85</td>
<td>5.39</td>
</tr>
<tr>
<td>ψ</td>
<td>6.10</td>
<td>5.55</td>
<td>5.07</td>
</tr>
<tr>
<td>χ</td>
<td>6.22</td>
<td>5.68</td>
<td>5.26</td>
</tr>
<tr>
<td>η</td>
<td>6.15</td>
<td>5.59</td>
<td>5.16</td>
</tr>
<tr>
<td>I</td>
<td>5.98</td>
<td>5.45</td>
<td>5.05</td>
</tr>
</tbody>
</table>

For the following consider 6TeV Z’ for HE-LHC model discrimination
Z'->ll 27 TeV (detector like)

- Drell-Yan generated with MG5
  - In bins of HT
  - K-factor of 2 to account for N^xLO corrections
- Signals generated with Pythia8
  - Using the same couplings as pheno like analysis
  - Also consider Z’ interference with Drell-Yan
- Selection for limits and discovery:
  - Two same flavor leptons p_T>500GeV, |η|<4
  - m_\ll > 1TeV
- Selection for model discrimination
  - |η|<2.5 and |η|<4
  - m_{Z'} within 200GeV of the Z’ mass
FCC-hh Simulation (Delphes)

\( \sqrt{s} = 27 \text{ TeV} \)
\( L = 10 \text{ ab}^{-1} \)

**ee**

- \( m_Z = 6 \text{ TeV} \)
- Drell-Yan

**mumu**

- \( m_Z = 6 \text{ TeV} \)
- Drell-Yan
Z'->ll 27TeV

Better standalone results for di-muon channel due to electron isolation not tuned
Reach exclusion 9-12TeV
Discovery reach up to 13TeV
$Z' \rightarrow ll$ 27 TeV

$Z'$ rapidity distribution

**FCC-hh Simulation (Delphes)**

- $ee$
  - $m_z = 6$ TeV
  - Drell-Yan

- $mumu$
  - $m_z = 6$ TeV
  - Drell-Yan
27TeVe discrimination pheno

- 6TeV $Z'$
- Variables considered $\sigma_{Z'}$, $A_{FB}$, $r_y$
- In most cases, good for model discrimination

\[ \frac{d\sigma}{d \cos \theta^*} = C \left[ \frac{3}{8} (1 + \cos^2 \theta^*) + A_{FB} \cos \theta^* \right] \]

\[ r_y = \frac{\int^{y_1}_{-y_1} \frac{d\sigma}{dy} dy}{\left[ \int_{y_1}^{Y} + \int_{-Y}^{-y_1} \frac{d\sigma}{dy} dy \right]} \]  

$Y_1 = 0.5$, $Y = 2.5$
Variable definitions $A_{FB}$ (Detector level)

- Tried two definitions at detector level
  
  - $A_{FB} = A_C = \frac{(N(\Delta |y|>0) - N(\Delta |y|<0))}{(N(\Delta |y|>0) + N(\Delta |y|<0))}$
  
  - $\Delta |y| = |y| - |y_{\text{bar}}|$
  
  - $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$
  
  - With $\sigma_F = N(\cos\theta*\text{cs}) > 0$ and $\sigma_B = N(\cos\theta*\text{cs}) < 0$

- With $\cos\theta*\text{cs} = \frac{Q_z}{|Q_z|} \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{|Q| \sqrt{Q^2 + Q_T^2}}$

| model | $A_{FB} \Delta |y|$ | $A_{FB} \cos\theta$ |
|-------|-----------------|------------------|
| SSM   | 0.0329          | 0.0330           |
| ETA   | -0.0295         | -0.0285          |
| CHI   | -0.1220         | -0.1232          |
| LRM   | 0.0831          | 0.0836           |
| PSI   | -0.0079         | -0.0074          |
| I     | -0.2582         | -0.2593          |

Both definition are equivalent, use $A_{FB}$ from $\cos\theta$ in the following
Get similar values as pheno analysis
Variable definitions \( r_y \)

- \( R_y = N(|y'_z|<x)/N(x<|y'_z|<y) \)
- From pheno study \( x=0.5 \) and \( y=2.5 \)

At detector level get closer values if \( x=0.25 \), but not yet understood why can’t reproduce pheno values

<table>
<thead>
<tr>
<th>Model</th>
<th>( x=0.5, y=2.5 )</th>
<th>( x=0.25, y=2.5 )</th>
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<tbody>
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<td>ETA</td>
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<td>CHI</td>
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<td>LRM</td>
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</table>

Possible explanations that will be checked:
- Shower effects
- gq production mode
- Selection
- PDFs
27TeV model discrimination

Pheno 15ab$^{-1}$

No Background

10 ab$^{-1}$

Detector
27TeV model discrimination

Tiny background under the peak
- very small effect of adding $\sigma_B/B$

Pheno 15ab$^{-1}$

$\sigma_B/B = 5\%$

10 ab$^{-1}$

Detector
27TeV model discrimination

Tiny background under the peak
-> very small effect if very large $\sigma_B/B$

Pheno 15ab$^{-1}$

$\sigma_B/B = 100$

$10 \text{ ab}^{-1}$

Detector
27TeV model discrimination

Changing fiducial acceptance does not improve the discrimination

![Graph showing 27 TeV model discrimination](image)

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σ_{B}/B = 5% extend eta 4.5

10 ab^{-1}

Pheno 15 ab^{-1}

Detector
27TeV model discrimination

As relatively narrow resonances are considered, small effect observed if interference with Drell-Yan considered.

Considering Interference $Z'/Z,\gamma^*$

10 ab$^{-1}$

Pheno 15 ab$^{-1}$
27TeV model discrimination

As relatively narrow resonances are considered, small effect observed if interference with Drell-Yan considered.

Considering Interference $Z'/Z, \gamma^*$

Pheno 15ab$^{-1}$

Detector

The detector level analysis can reproduce well the pheno analysis. Numbers are not exactly the same, but they follow the same pattern. Further checks are ongoing.
Fitting the $\mu$ value of signal

- In profile likelihood fit the signal $\mu$ value in the analysis.
- The background under the mass peak is so tiny that it does not influence the $\mu$ value. There is a lot of side-bands.
- From cross-section fit it seems that the model discrimination is already good enough.
- But need angular variables in order to get rid of the couplings to quarks and also possible other decays mode.
$R_y$, $A_{FB}$ versus lumi SSM/PSI

$r_y$ versus Int. Lumi  No background  $A_{FB}$ versus Int. Lumi
$r_y$, $A_{FB}$ versus lumi SSM/PSI

$r_y$ versus Int. Lumi

$\sigma_B/B = 5\%$

$A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/PSI

$r_y$ versus Int. Lumi  Interference $Z'/Z,\gamma^*$  $A_{FB}$ versus Int. Lumi

Interference reduces
Difference between models
$R_y$, $A_{FB}$ versus lumi SSM/PSI

$r_y$ versus Int. Lumi

No background

$A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/PSI

$r_y$ versus Int. Lumi

$A_{FB}$ versus Int. Lumi

$\sigma_B/B = 5\%$
**R_y, A_{FB} versus lumi SSM/PSI**

- **r_y versus Int. Lumi**: Interference $Z'/Z,\gamma^*$
- **A_{FB} versus Int. Lumi**: Interference reduces Difference between models
$A_{FB} R_y$ vs mass (in 200GeV mass bins)

$r_y$ versus Int. Lumi  \quad \sigma_B/B = 5\%

$r_y$ versus Int. Lumi

10 ab$^{-1}$

$\sigma_B/B = 5\%$
$A_{FB}$ $R_y$ vs mass (in 200GeV mass bins)

$r_y$ versus Int. Lumi $\sigma_{B/B} = 5\%$

$\sigma_{B/B} = 5\%$

100 ab$^{-1}$

$r_y$ versus Int. Lumi

Mass GeV

Mass TeV
Heavier/lighter $Z'$

4TeV $Z'$

8TeV $Z'$

$A_{FB} \cos \theta_{cs}$

$10 \text{ ab}^{-1}$
Heavier/lighter $Z'$

4TeV $Z'$

8TeV $Z'$

10 ab$^{-1}$

100 ab$^{-1}$

$A_{FB} \cos \theta_{cs}$

$S$SM

$\eta$

$I$

$\chi$

$\psi$

$LRM$
Conclusions

- Presented a study on $Z'$ discrimination at 27TeV in case of a discovery at HL-LHC
- Apart from a possible near degeneracy in models $\psi, \eta$, a reasonable $Z'$ model separation can be achieved
- Systematics error on the background estimate don’t play a role
- In narrow width the interference with Drell-Yan is negligible
- Increasing lepton acceptance from 2.5 to 4.5 does not help discrimination
- Need to continue the study and estimate the effect of PDF on the observables
- If $Z' > 6$TeV Model discrimination will be much harder if only $10 \text{ab}^{-1}$ is collected
- Other resonances analysis are being re-done from 100 to 27TeV for the YR
- Will start to document all of this in the overleaf document
Bonus
## Couplings

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$R_y$, $A_{FB}$ versus lumi SSM/CHI

$r_y$ versus Int. Lumi

No background

$A_{FB}$ versus Int. Lumi
$R_y, A_{FB}$ versus lumi SSM/CHI

$r_y$ versus Int. Lumi

$\sigma_B/B = 5\%$

$A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/CHI

$r_y$ versus Int. Lumi  Interference $Z'/Z,\gamma^*$  $A_{FB}$ versus Int. Lumi
$r_y$, $A_{FB}$ versus lumi SSM/ETA

$r_y$ versus Int. Lumi

No background

$A_{FB}$ versus Int. Lumi
$r_y$, $A_{FB}$ versus lumi SSM/ETA

$r_y$ versus Int. Lumi

$\sigma_{B/B} = 5\%$

$A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/ETA

$r_y$ versus Int. Lumi  Interference $Z'/Z, \gamma^*$  $A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/LRM

$r_y$ versus Int. Lumi

No background

$A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/LRM

$r_y$ versus Int. Lumi

$\sigma_{B/B} = 5\%$

$A_{FB}$ versus Int. Lumi

SSM  |  LRM
$R_y$, $A_{FB}$ versus lumi SSM/LRM

$r_y$ versus Int. Lumi

Interference $Z'/Z,\gamma^*$

$A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/I

$r_y$ versus Int. Lumi

No background

$A_{FB}$ versus Int. Lumi
$R_y$, $A_{FB}$ versus lumi SSM/I

$r_y$ versus Int. Lumi  $\sigma_B/B = 5\%$  $A_{FB}$ versus Int. Lumi

![Graph showing $r_y$ versus Int. Lumi and $A_{FB}$ versus Int. Lumi for SSM and I.](image)
$R_y$, $A_{FB}$ versus lumi SSM/I

$r_y$ versus Int. Lumi  Interference $Z'/Z,\gamma^*$  $A_{FB}$ versus Int. Lumi