Observation of the rare $Z \rightarrow J/\Psi \ell \ell$ decay

Riccardo Manzoni
on behalf of the CMS collaboration

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Analysis motivations

• many rare exclusive Z decays are yet to be observed, only upper limits
  • ATLAS \(Z \rightarrow J/\Psi / Y \gamma\), CDF \(Z \rightarrow \pi^0 \gamma\), ALEPH \(Z \rightarrow \rho/\pi W\) and more
  • mostly in channels with \(\gamma\)'s

• we present the observation of the rare Z boson decay to a \(J/\Psi\) meson and two additional leptons
  • fragmentation contribution not suppressed by \(M_{\Psi}^2/M_Z^2\)
  • \(BR(Z \rightarrow J/\Psi \ell \ell)\) about one order of magnitude larger than \(BR(Z \rightarrow J/\Psi \gamma)\)
  • in principle, any vector meson (\(\rho, \omega, \phi, \Psi(2S), Y\)) can replace the \(J/\Psi (\gamma^*-V\) transition)
Analysis motivations

• large Z production rate at LHC
  • about 1k Z bosons per second are being produced in LHC collisions right now!

• clean experimental signature
  • 2 high-\(p_T\) leptons
  • isolated from hadronic activity
  • J/\(\Psi\) resonant structure, 2 softer leptons

• prototypical for rare H→ZV searches
  • which would allow access to couplings of the H boson to lighter quarks
Analysis strategy

• 2016 CMS dataset: 35.9 fb\(^{-1}\) of pp collisions at 13 TeV

• two channels considered: \(Z \to J/\Psi (\to \mu\mu) \mu\mu\) and \(Z \to J/\Psi (\to \mu\mu) \text{ ee}\)
  - the \(J/\Psi\) is always required to decay into \(\mu\mu\)

• trigger and lepton selections similar to \(H \to ZZ \to 4\ell\)
  - mixture of single- and di-lepton triggers to maximise the acceptance
  - \textit{softID} (opt. for low \(p_T\)) for muons from the \(J/\Psi\) and \textit{tightID} for the other \(\ell\)

• control channel: non resonant \(Z \to \mu^+\mu^-\mu^+\mu^-\)

\begin{align*}
\text{find } J/\Psi & \to \mu^+\mu^- \text{ candidate with } \\
\mu\mu \text{ vertex prob } & > 5\% \\
\text{find 2 extra OS } \ell & \text{ with 4-body vertex } \\
\text{prob } & > 5\% \\
\text{build 2D } m_{J/\Psi\ell\ell} & \text{ vs } m_{J/\Psi} \\
\text{distribution}
\end{align*}
**m_{\psi} vs m_{J/\psi \ell \ell} distribution**

- Both $\Psi_{\mu\mu}$ and $\Psi_{ee}$ channels represented in the same plot.
- **29 Z$\rightarrow\Psi_{\mu\mu}$ events**
  **18 Z$\rightarrow\Psi_{ee}$ events** in the full 2D range.
- $\Psi$ indicates both direct J/$\Psi$ and feed down from $\Psi(2S)\rightarrow$ J/$\Psi$+X decays.
- 4 regions can be identified.
• Z signal - $\Psi$ signal
• Z signal - Ψ background
CMS Preliminary

35.9 fb⁻¹ (13 TeV)

- Z background - Ψ signal

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CMS Preliminary

35.9 fb\(^{-1}\) (13 TeV)

\(m_{\psi} \rightarrow \mu^+ \mu^-\) [GeV]

\(m_{Z \rightarrow \psi \rightarrow \mu^+ \mu^-}\) [GeV]

- Z bkg - \(\Psi\) bkg
Signal extraction

- un-binned maximum likelihood fit to the 2D $m_\Psi$ vs $m_{\Psi^\ell\ell}$ distribution
  - each channel is separately fitted

- **Z signal**: Breit-Wigner $\otimes$ Gaussian

- **$\Psi$ signal**: Gaussian

- **sidebands**: exponential

- 2D PDF is the product of the PDFs above
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\mathcal{R}_{J/\psi \mu^+\mu^-}$</th>
<th>$\mathcal{R}_{J/\psi \mu^+e^-}$</th>
<th>$\mathcal{R}_{J/\psi \ell^+\ell^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z signal shape</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Z background shape</td>
<td>6.9</td>
<td>0.5</td>
<td>3.7</td>
</tr>
<tr>
<td>$\psi$ signal modelling</td>
<td>4.8</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>$\psi$ background shape</td>
<td>1.5</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td>Fit procedure</td>
<td>3.0</td>
<td>8.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>0.9</td>
<td>5.9</td>
<td>4.0</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.7</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Decay model</td>
<td>0.7</td>
<td>1.6</td>
<td>0.8</td>
</tr>
<tr>
<td>$\psi(2S)$ feed-down</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9.2</strong></td>
<td><strong>10.8</strong></td>
<td><strong>7.6</strong></td>
</tr>
</tbody>
</table>

*alternative PDFs*

*toy experiments*

*see next slides*
Decay model uncertainty

- $Z \rightarrow J/\Psi \ell\ell$ decay is not among those considered by the generators currently on the market

- best compromise was to use PYTHIA8 and force $Z$ to decay into $\ell\ell + J/\Psi$
  - 3-body $Z$ decay as opposed to $\gamma^*$ radiated off of one lepton
  - data-MC agreement checked with $sPlot$ technique
    - $p_T$, $\eta$, $\phi$ well modelled
    - angular $\Delta\phi(\ell_2,\Psi)$ not well described
      - systematic uncertainty added and MC reweighed to match the data
**ψ(2S) feed down**

- $Z → ψ(2S)(→ J/ψ+X)ℓℓ$ non distinguishable from the main process
  - the mixture of direct $J/ψ$ and $ψ(2S) → J/ψ+X$ is labeled simply $ψ$

- both $J/ψ$ and $ψ(2S) → J/ψ$ contributions are considered in establishing the observation of the $Z → ψℓℓ$ process

- the contribution from $ψ(2S)$ is evaluated using the following information:
  - branching fraction of $ψ(2S) → J/ψ + X = 61$
  - it amounts to 1.9 (1.7) events in the $J/ψμμ (J/ψee)$ channel

- no contribution from other resonances are observed
1D projections - J/Ψμμ channel

fitted signal yield 13.0 ± 3.9 events, observed significance 4.0σ
1D projections - J/Ψee channel

fitted signal yield 11.2 ± 3.4 events, observed significance 4.3σ

combined significance 5.7σ
Fiducial branching fraction ratio wrt $Z \rightarrow \mu\mu\mu\mu$

$$\mathcal{R}_{J/\psi \ell^+ \ell^-} \equiv \frac{\mathcal{B}(Z \rightarrow J/\psi \ell^+ \ell^-)}{\mathcal{B}(Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-)} = \sum_\ell \left( \frac{1}{2} \frac{N_{Z \rightarrow J/\psi \ell^+ \ell^-}}{\epsilon_{Z \rightarrow J/\psi \ell^+ \ell^-}} \right) \frac{\epsilon_{Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-}}{N_{Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-}} \frac{1}{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)} \cdot \ell = \mu, e,$$

- normalisation channel $Z \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ yield $250 \pm 20$ events
  - from 1D fit to the $m_{4\mu}$ distribution, Breit-Wigner \(\otimes\) Gauss signal PDF
  - ratio allows for partial cancellation of systematics

- feed down from $Z \rightarrow \Psi(2S)\ell\ell$ is subtracted to isolate $Z \rightarrow J/\Psi\ell\ell$
  - $1.9 \ (1.7)$ events are subtracted from the $J/\Psi\mu\mu \ (J/\Psi ee)$ channel

- final yields: $11.1 \ (9.5) \ J/\Psi\mu\mu \ (J/\Psi ee)$

- efficiencies: $\epsilon_{\mu\mu\mu\mu} = 81.1\% \ , \ \epsilon_{J/\Psi\mu\mu} = 80.8\% \ , \ \epsilon_{J/\Psi ee} = 79.6\%$
Fiducial branching fraction ratio wrt $Z \rightarrow \mu\mu\mu\mu$

$$R_{J/\Psi \ell \ell} = 0.70 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst)}$$

- normalisation channel $Z \rightarrow \mu^+\mu^-\mu^+\mu^-$ yield 250 ± 20 events
  - from 1D fit to the $m_{4\mu}$ distribution, Breit-Wigner $\otimes$ Gauss signal PDF
  - ratio allows for partial cancellation of systematics
- feed down from $Z \rightarrow \Psi(2S)\ell\ell$ is subtracted to isolate $Z \rightarrow J/\Psi \ell\ell$
  - 1.9 (1.7) events are subtracted from the $J/\Psi \mu\mu$ ($J/\Psi ee$) channel
  - final yields: 11.1 (9.5) $J/\Psi \mu\mu$ ($J/\Psi ee$)
- efficiencies: $\epsilon_{\mu\mu\mu\mu} = 81.1\%$, $\epsilon_{J/\Psi \mu\mu} = 80.8\%$, $\epsilon_{J/\Psi ee} = 79.6\%$

$$R_{J/\Psi \ell \ell} \equiv \frac{B(Z \rightarrow J/\psi \ell^+\ell^-)}{B(Z \rightarrow \mu^+\mu^-\mu^+\mu^-)} = \sum_{\ell} \left( \frac{1}{2} \frac{N_{Z \rightarrow J/\psi \ell^+\ell^-}}{\epsilon_{Z \rightarrow J/\psi \ell^+\ell^-}} \right) \frac{\epsilon_{Z \rightarrow \mu^+\mu^-\mu^+\mu^-}}{N_{Z \rightarrow \mu^+\mu^-\mu^+\mu^-}} \frac{1}{B(J/\psi \rightarrow \mu^+\mu^-)}, \ell = \mu, e,$$
Fiducial branching fraction ratio wrt $Z \to \mu\mu\mu\mu$

$$R_{J/\psi \ell^+ \ell^-} \equiv \frac{B(Z \to J/\psi \ell^+ \ell^-)}{B(Z \to \mu^+ \mu^- \mu^+ \mu^-)} = \sum_{\ell} \left( \frac{1}{2} \frac{N_{Z \to J/\psi \ell^+ \ell^-}}{e_{Z \to J/\psi \ell^+ \ell^-}^\ell} \frac{\epsilon_{Z \to \mu^+ \mu^- \mu^+ \mu^-} \epsilon_{J/\psi \ell^+ \ell^-} \epsilon_{J/\psi \ell^+ \ell^-}}{N_{Z \to \mu^+ \mu^- \mu^+ \mu^-} B(J/\psi \to \mu^+ \mu^-)} \right), \ell = \mu, e,$$

- normalisation channel $Z \to \mu^+ \mu^- \mu^+ \mu^-$ yield $250 \pm 20$ events
  - from 1D fit to the $m_{4\mu}$ distribution, Breit-Wigner $\otimes$ Gauss signal PDF
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- feed down from $Z \to \Psi(2S)\ell\ell$ is subtracted to isolate $Z \to J/\Psi\ell\ell$
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- efficiencies: $\epsilon_{\mu\mu\mu\mu} = 81.1\%$, $\epsilon_{J/\Psi\mu\mu} = 80.8\%$, $\epsilon_{J/\Psi ee} = 79.6\%$

$$B(Z \to J/\Psi \ell\ell) \approx 8 \cdot 10^{-7}$$ assuming $B(Z \to \mu\mu\mu\mu)$ from PDG

J/Ψ polarisation hypotheses

- Nominal results are obtained for the unpolarised J/Ψ case
  - Polarised state affect the μ kinematics and therefore the acceptance

- Fully longitudinal and transversal J/Ψ polarisation hypotheses are tested
  - Extremes range from -25% to +23% acceptance

<table>
<thead>
<tr>
<th>Polarization scenario</th>
<th>$R_{J/Ψ\mu^+\mu^-}$</th>
<th>$R_{J/Ψe^+e^-}$</th>
<th>$R_{J/Ψ\ell^+\ell^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>25</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Transverse 0</td>
<td>21</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Transverse +</td>
<td>23</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Transverse −</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

Values in this table are percent
CMS reports the first observation of the rare \( Z \to \Psi \ell \ell \) decay with 5.7\( \sigma \) significance.

Measurement of the fiducial branching fraction ratio

\[
\frac{B[Z \to J/\Psi \ell \ell]}{B[Z \to \mu \mu \mu \mu]} = 0.70 \pm 0.18 \text{ (stat)} \pm 0.05 \text{ (syst)}
\]

in agreement with theory.
Backup
Z → J/Ψ ℓℓ diagrams

lepton propagator
order of 1/M_{ψ}²

NLO
Selections

• **$J/\Psi \rightarrow \mu\mu$**
  - $p_T^{\mu} > 3.5$ GeV and $|\eta^{\mu}| < 2.4$
  - muon ID soft + global
  - $p_T^{J/\Psi} > 8.5$ GeV and $J/\Psi$ vertex probability > 5%

• **non-resonant $\mu\mu$**
  - $p_T^{\mu_1} > 30$ GeV, $p_T^{\mu_2} > 15$ GeV and $|\eta^{\mu}| < 2.4$
  - muon ID tight + global

• **non-resonant $ee$**
  - $p_T^{e_1} > 30$ GeV, $p_T^{e_2} > 15$ GeV and $|\eta^{e}| < 2.5$
  - MVA electron ID tight

• **4-lepton**
  - 4-lepton vertex probability > 5% and $L/\sigma < 4$ (significance of impact parameter)
  - relative isolation $R_{0.3} < 0.35$