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

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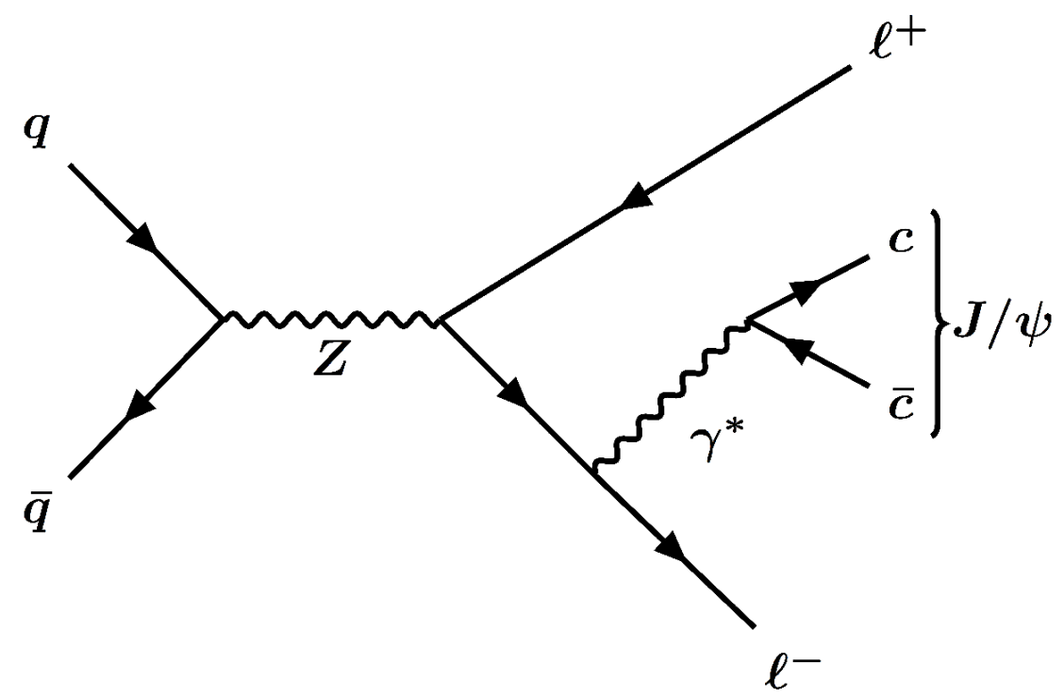
Analysis motivations

- **many rare exclusive Z decays are yet to be observed, only upper limits**
  - ATLAS $Z \to J/\Psi$ / $\Upsilon\,\gamma$, CDF $Z \to \pi^0\gamma$, ALEPH $Z \to \rho/\pi$ W and more
  - mostly in channels with γ's

- **we present the observation of the rare Z boson decay to a J/Ψ meson and two additional leptons**
  - fragmentation contribution not suppressed by M_Ψ^2/M_Z^2
  - BR($Z \to J/\Psi \ell\ell$) about one order of magnitude larger than BR($Z \to J/\Psi\gamma$)
  - in principle, any vector meson (ρ, ω, ϕ, Ψ(2S), Υ) can replace the J/Ψ (γ*-V transition)

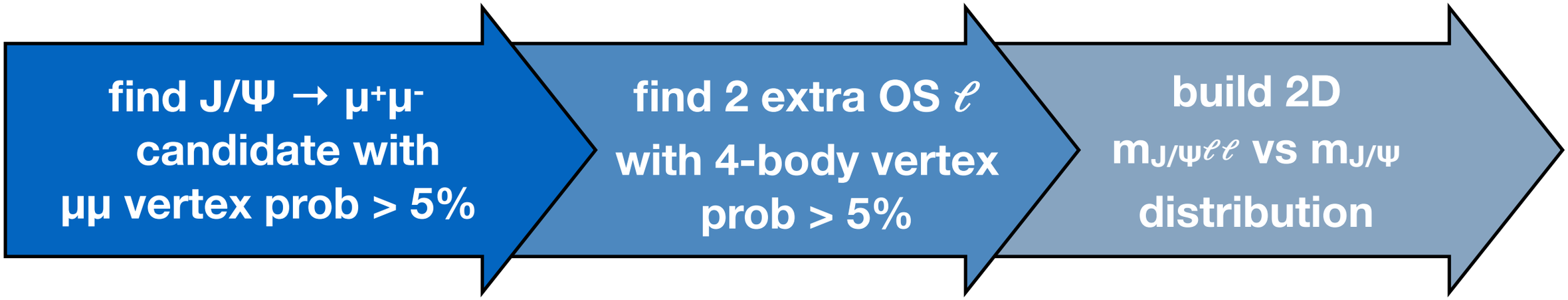


Analysis motivations

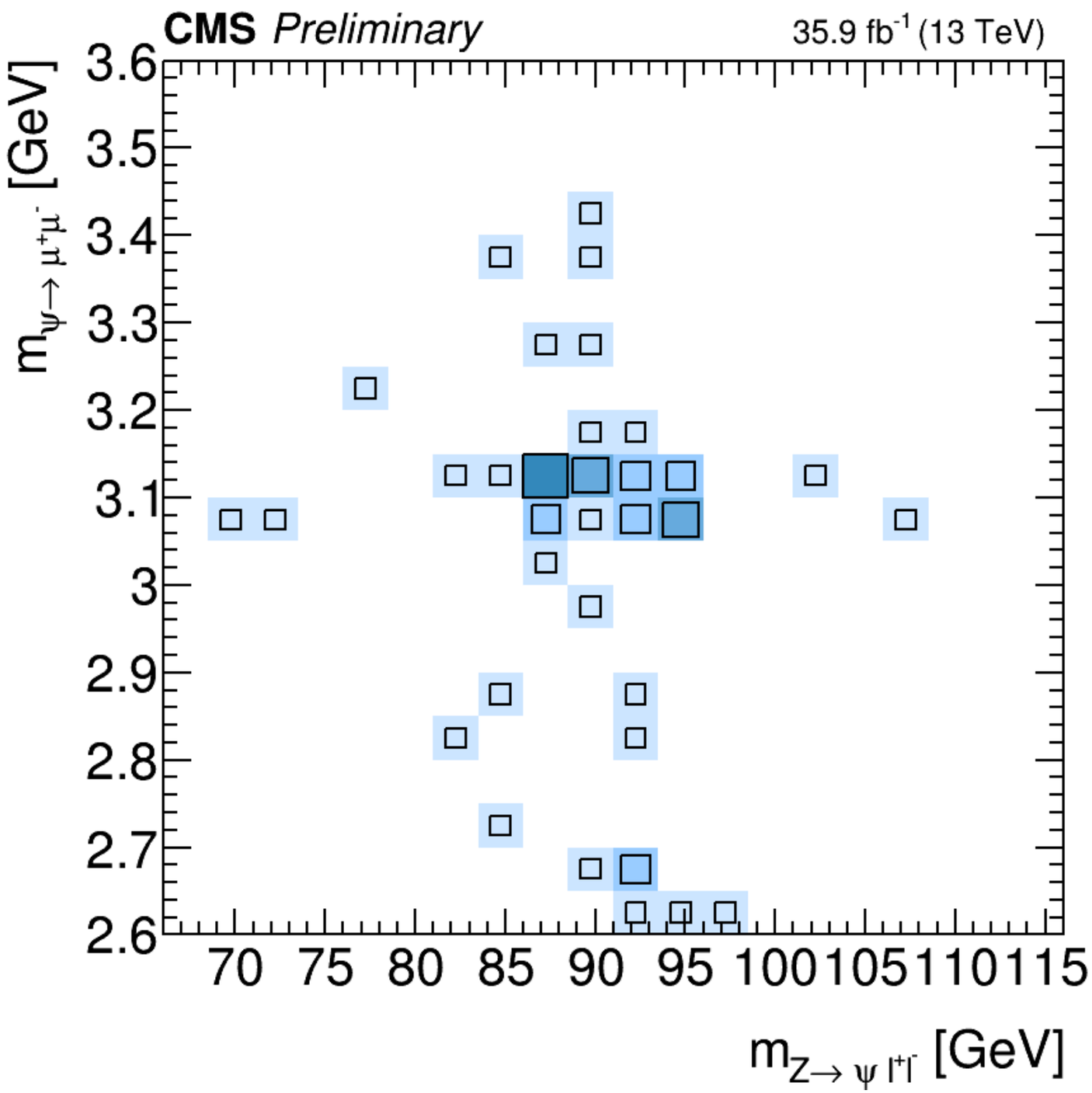
- **large Z production rate at LHC**
  - about 1k Z bosons per second are being produced in LHC collisions right now!
- **clean experimental signature**
  - 2 high-p_T leptons
  - isolated from hadronic activity
  - J/Ψ resonant structure, 2 softer leptons
- **prototypical for rare H→ZV searches**
  - which would allow access to couplings of the H boson to lighter quarks

Analysis strategy

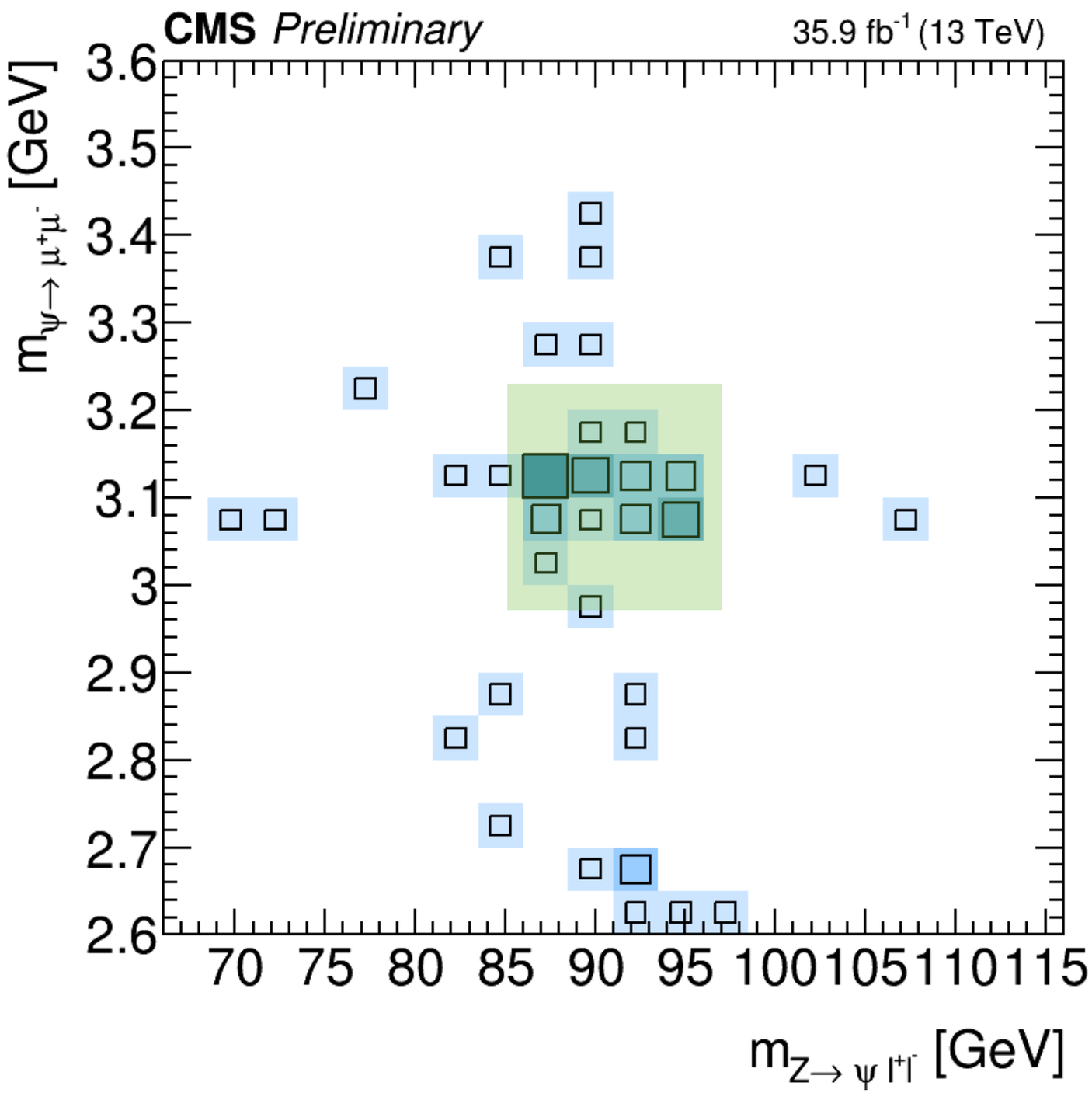
- **2016 CMS dataset: 35.9 fb^{-1} of pp collisions at 13 TeV**
- **two channels considered: $Z \to J/\Psi(\to \mu\mu)\ \mu\mu$ and $Z \to J/\Psi(\to \mu\mu)\ ee$**
  - the J/Ψ is always required to decay into μμ
- **trigger and lepton selections similar to $H \to ZZ \to 4\ell$**
  - mixture of single- and di-lepton triggers to maximise the acceptance
  - `softID` (opt. for low p_T) for muons from the J/Ψ and `tightID` for the other ℓ
- control channel: non resonant $Z \to \mu^+\mu^-\mu^+\mu^-$



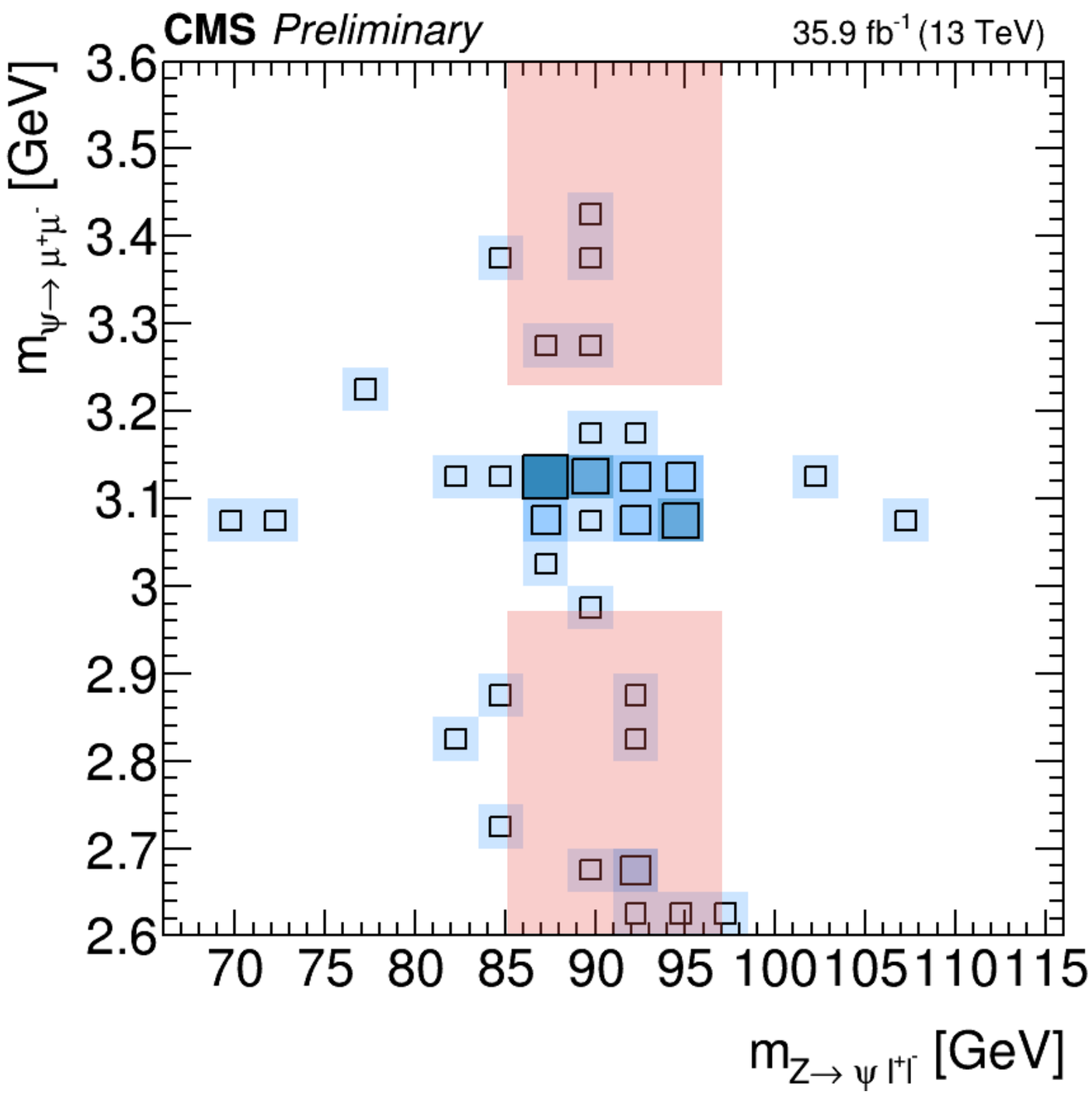
m_Ψ vs $m_{J/\Psi\ell\ell}$ distribution



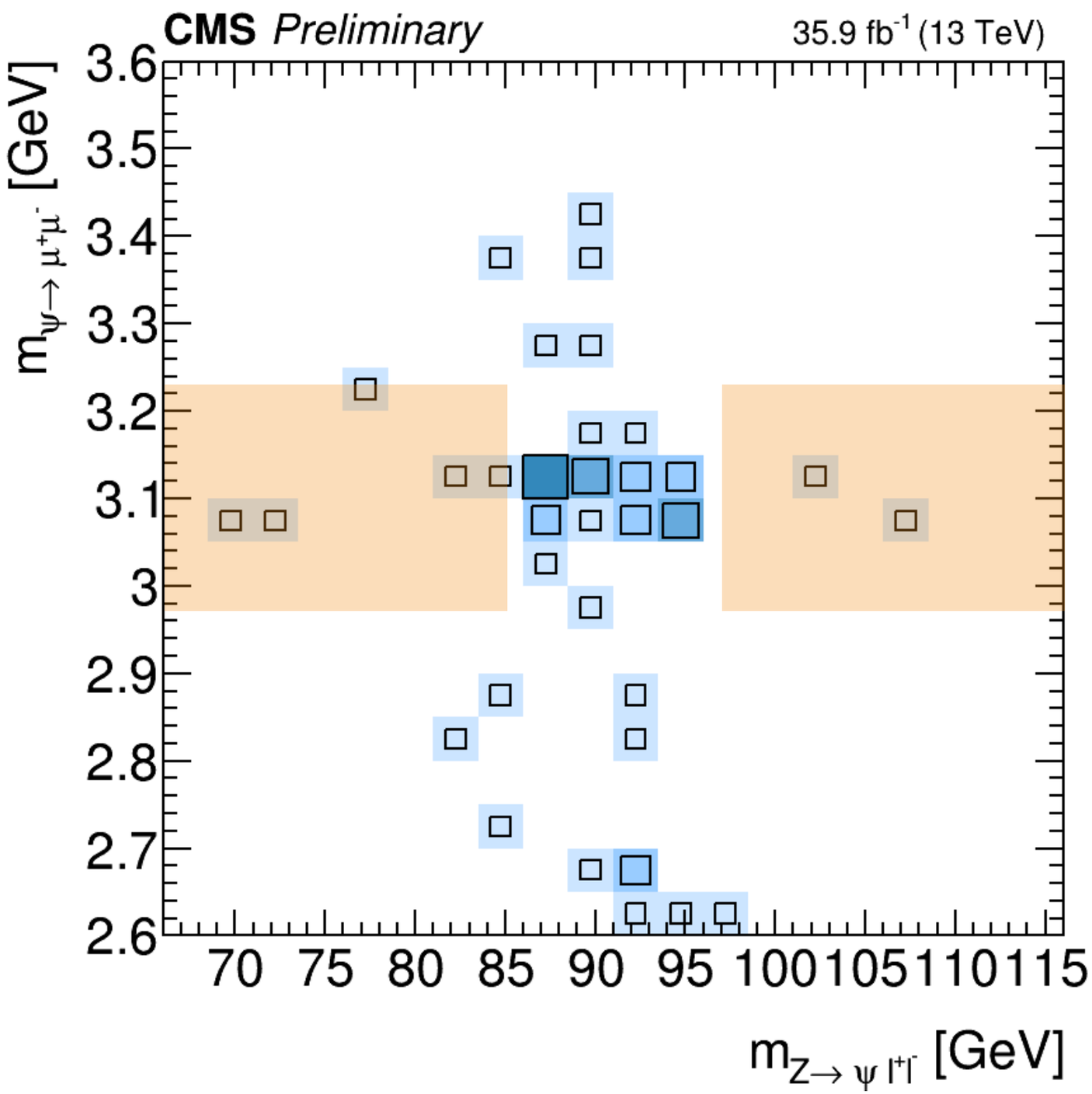
- both Ψμμ and Ψee channels represented in the same plot
- **29 Z→Ψμμ events**
  18 Z→Ψee events
  in the full 2D range
- ***Ψ*** indicates both direct J/Ψ and feed down from Ψ(2S)→J/Ψ+X decays
- 4 regions can be identified



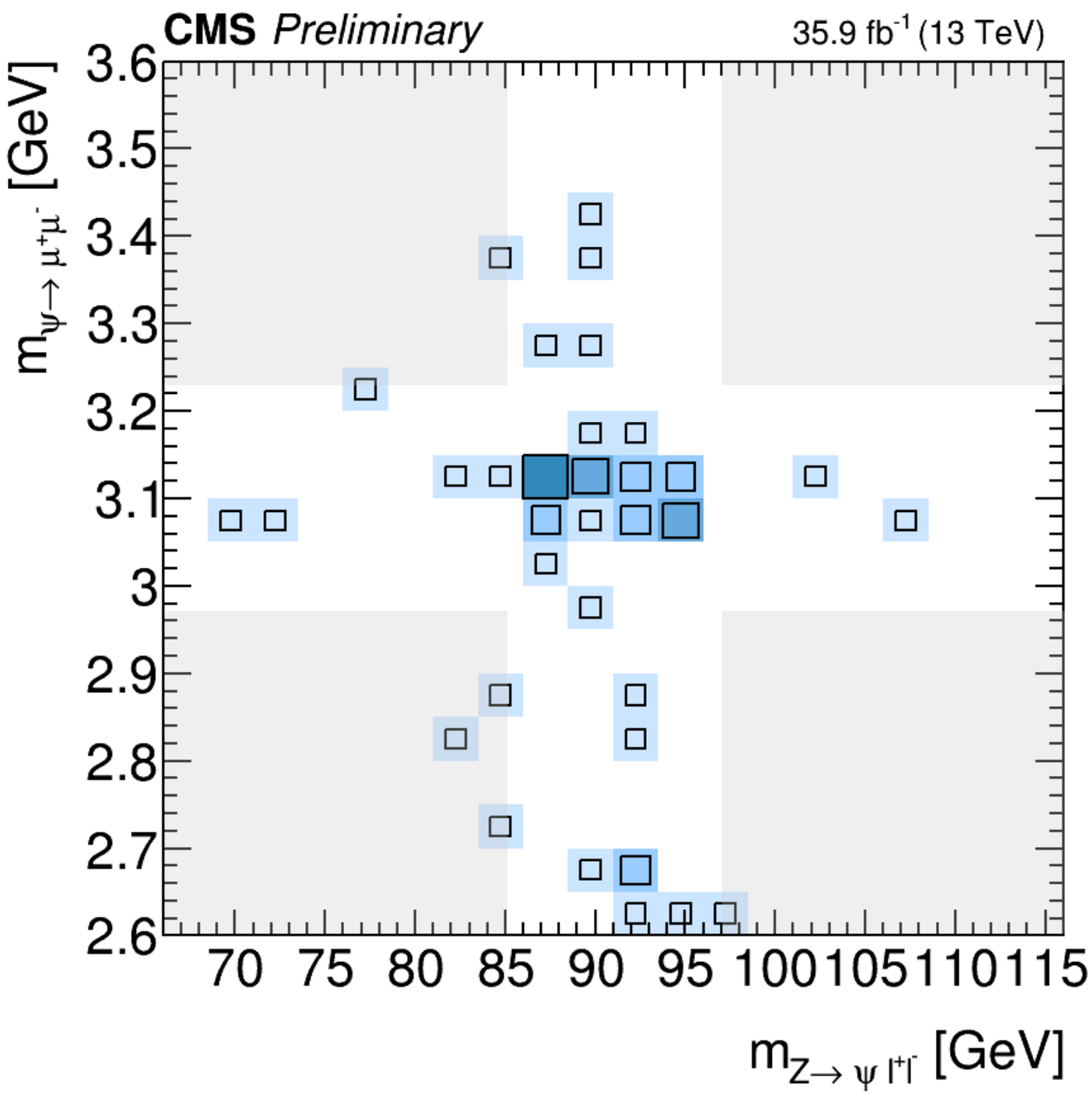
- **Z signal - Ψ signal**



- **Z signal - Ψ background**

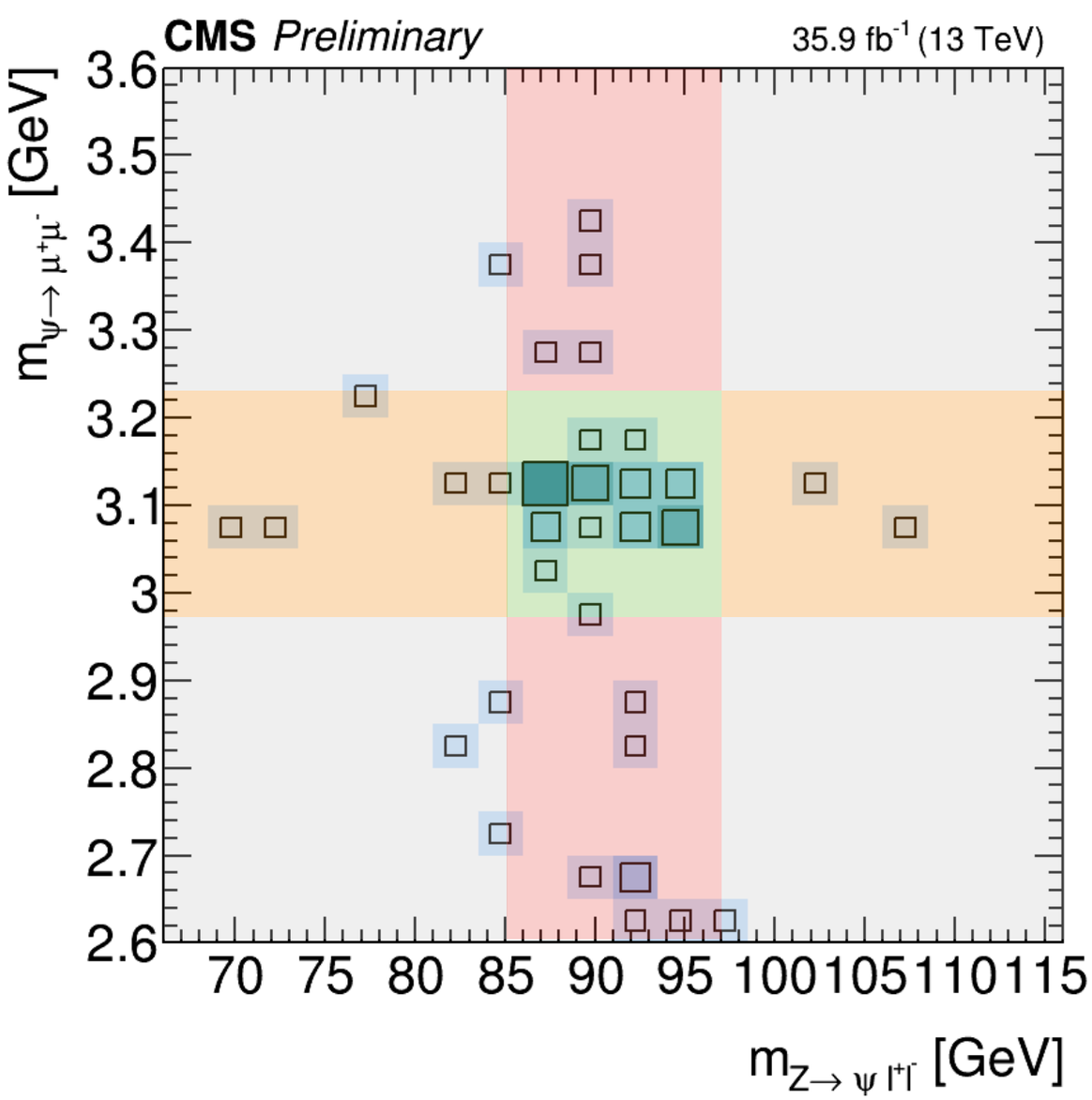


- **Z background - Ψ signal**


CMS Preliminary
35.9 fb-1 (13 TeV)
m ψ→ μ+μ- [GeV]
3.6
3.5
3.4
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
70 75 80 85 90 95 100 105 110 115
m Z→ ψ l+l- [GeV]

- **Z bkg - Ψ bkg**

Signal extraction



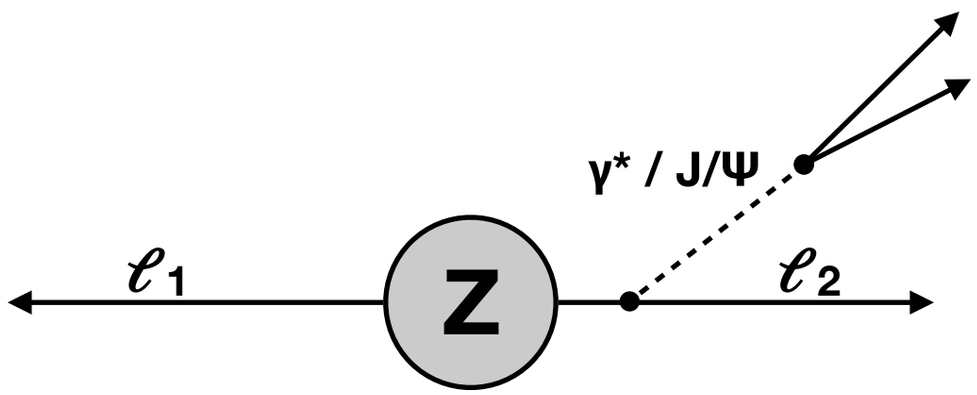
- **un-binned maximum likelihood fit to the 2D mψ vs mψℓℓ distribution**
  - each channel is separately fitted
- **Z signal :** Breit-Wigner ⊗ Gaussian
- **Ψ signal:** Gaussian
- **sidebands:** exponential
- 2D PDF is the product of the PDFs above

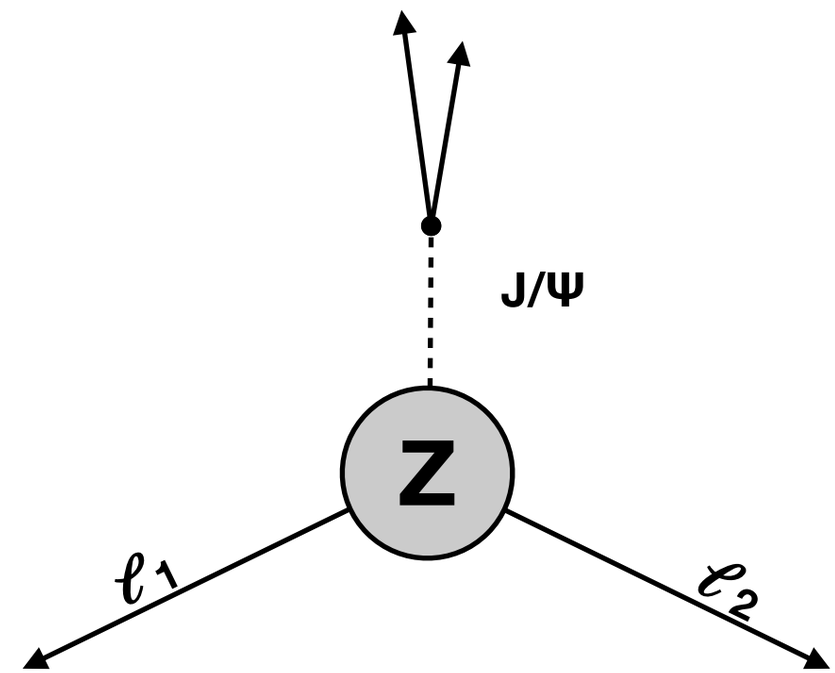
Systematic uncertainties

Source of uncertainty	$\mathcal{R}_{J/\psi\mu^+\mu^-}$	$\mathcal{R}_{J/\psi e^+e^-}$	$\mathcal{R}_{J/\psi\ell^+\ell^-}$	
Z signal shape	0.8	0.8	0.8	
Z background shape	6.9	0.5	3.7	alternative PDFs
ψ signal modelling	4.8	2.0	2.8	
ψ background shape	1.5	1.5	1.1	
Fit procedure	3.0	8.4	4.2	toy experiments
Reconstruction efficiency	0.9	5.9	4.0	
MC statistics	0.7	0.8	0.5	
Decay model	0.7	1.6	0.8	see next slides
$\psi(2S)$ feed-down	0.3	0.3	0.3	
Total	9.2	10.8	7.6	

Decay model uncertainty

- **Z→J/Ψ$\ell\ell$ decay is not among those considered by the generators currently on the market**



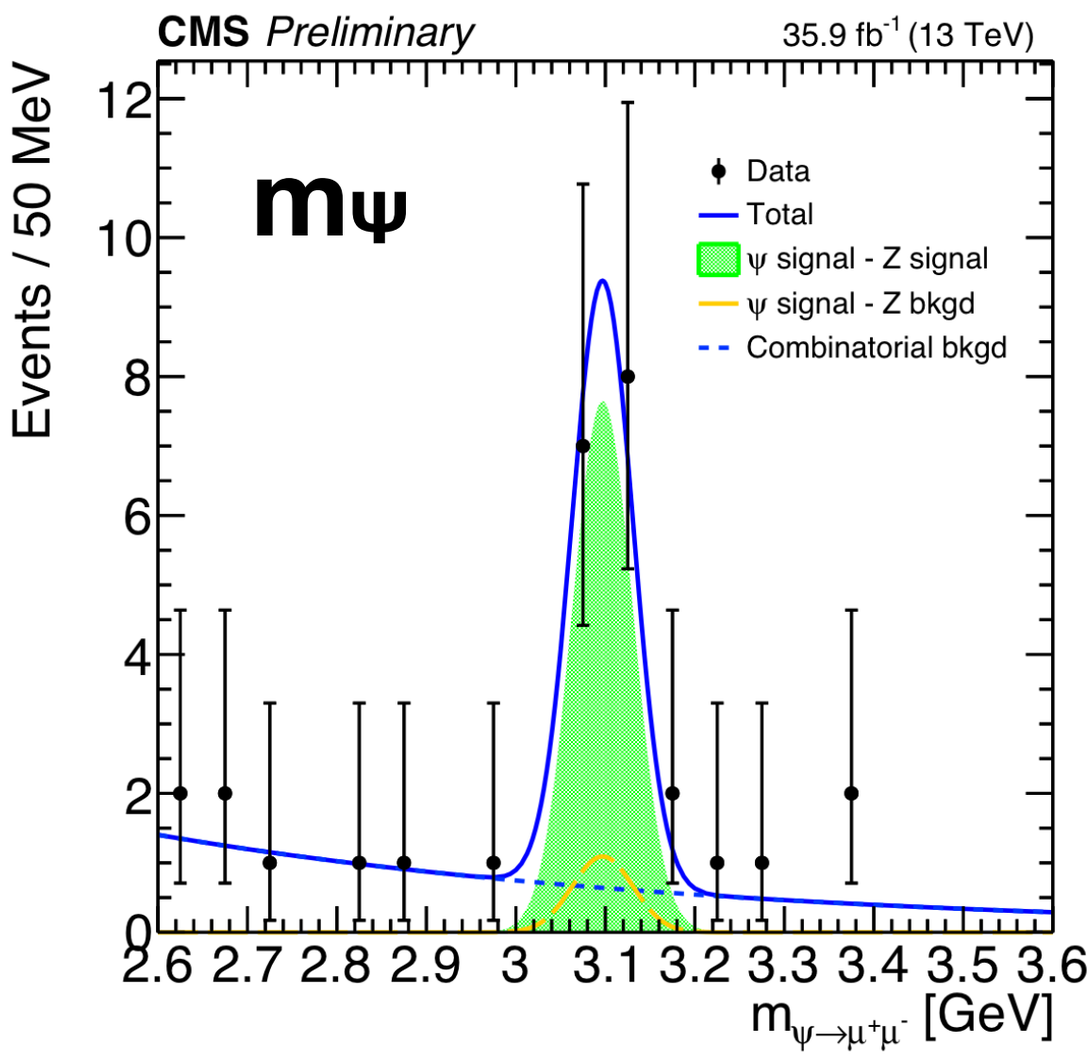


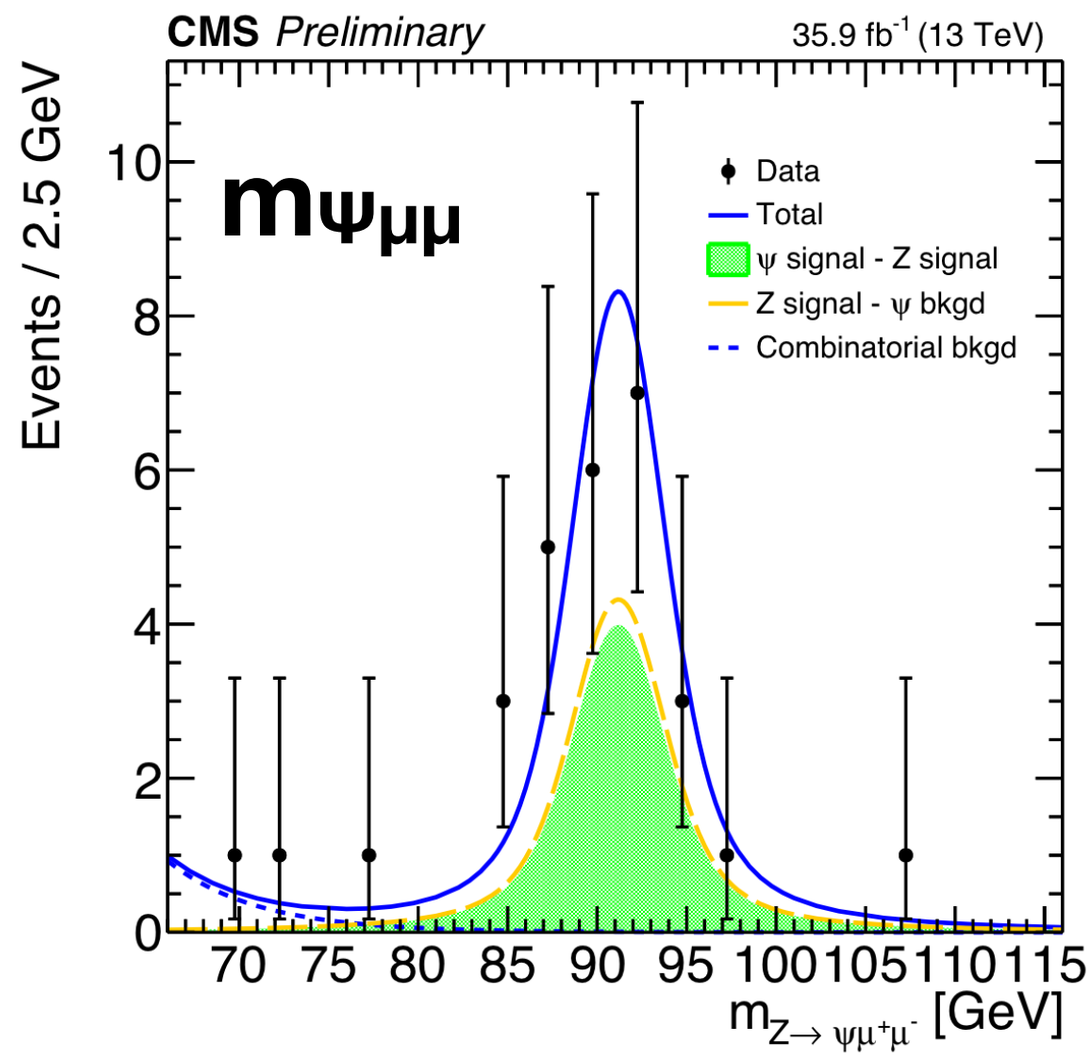
- **best compromise was to use PYTHIA8 and force Z to decay into $\ell\ell$+J/Ψ**
  - 3-body Z decay as opposed to γ* radiated off of one lepton
  - data-MC agreement checked with *sPlot* technique
    - **p_T, η, ϕ well modelled**
    - **angular Δϕ(ℓ_2,Ψ) not well described**
      - systematic uncertainty added and MC reweighed to match the data

Ψ(2S) feed down

- **Z→Ψ(2S)(→J/Ψ+X)$\ell\ell$ 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 the Z→Ψ$\ell\ell$ process**
- **the contribution from Ψ(2S) is evaluated using the following information:**
  - branching fraction of Ψ(2S) → J/Ψ + X = 61%
  - theory Phys.Rev. D48 (1993) 1914-1916: B[Z→J/Ψ$\ell\ell$] / B[Z→Ψ(2S)$\ell\ell$] = 3.5
  - this gives N[Z→J/Ψ(→μμ)$\ell\ell$] / B[Z→Ψ(2S)(→J/Ψ(→μμ)+X)$\ell\ell$] = 5.7
- **it amounts to 1.9 (1.7) events in the J/Ψμμ (J/Ψee) channel**
- no contribution from other resonances are observed

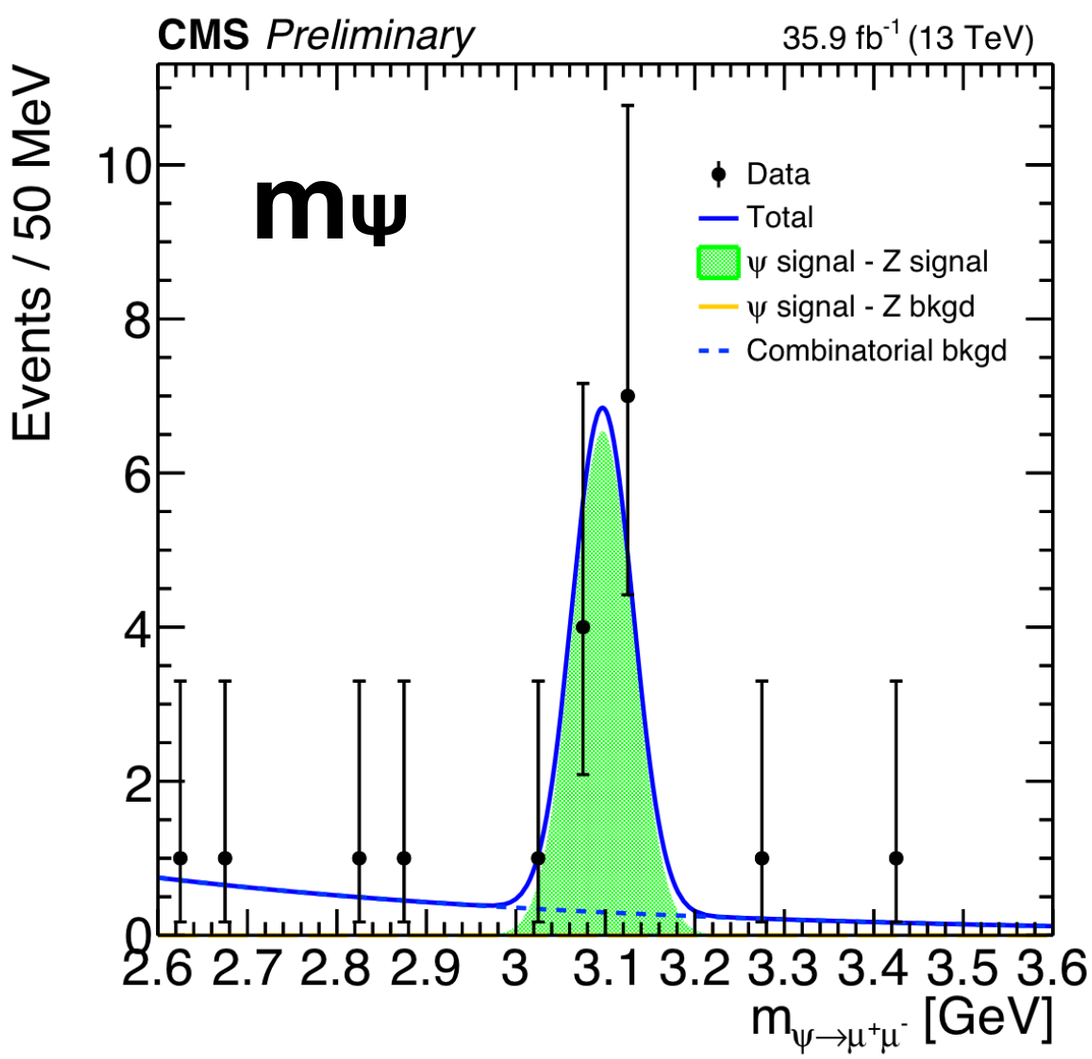
1D projections - J/Ψμμ channel

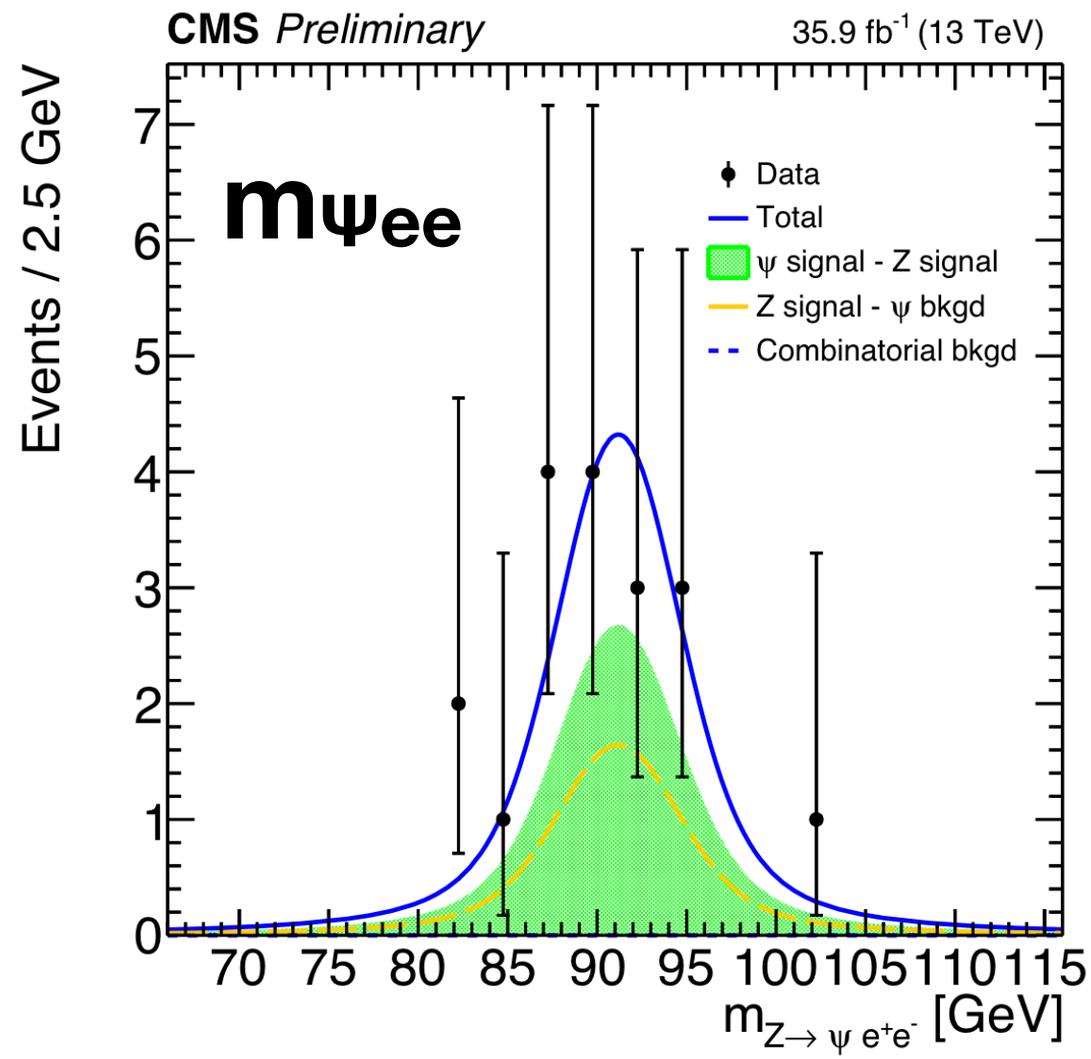




fitted signal yield 13.0 ± 3.9 events, observed significance 4.0σ

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→μμμμ

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

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

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

Fiducial branching fraction ratio wrt Z→μμμμ

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$B(Z\to J/\Psi\ell\ell) \approx 8\cdot10^{-7}$ assuming B(Z→μμμμ) from PDG

consistent with theoretical predictions Phys. Lett. B245 (1990) 249–250 and Phys. Rev. D50 (1994) 5808–5815

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

Polarization scenario	$\mathcal{R}_{J/\psi\mu^+\mu^-}$	$\mathcal{R}_{J/\psi e^+e^-}$	$\mathcal{R}_{J/\psi\ell^+\ell^-}$
Longitudinal	-25	-24	-24
Transverse 0	21	20	20
Transverse +	23	21	22
Transverse $-$	18	18	18

values in this table are percent

CMS reports
the first observation of the rare $Z \to \Psi \ell\ell$ decay
with 5.7σ significance

measurement of the fiducial
branching fraction ratio
$B[Z \to J/\Psi \ell\ell]/B[Z \to \mu\mu\mu\mu]$

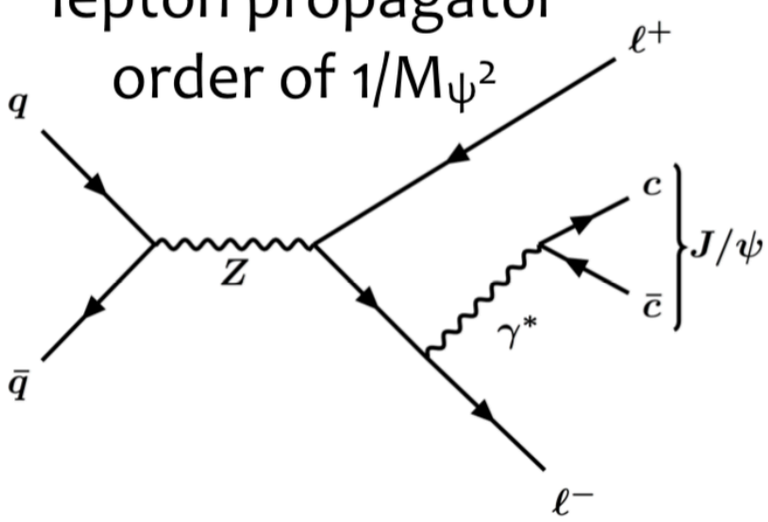
$R_{J/\Psi \ell\ell} = 0.70 \pm 0.18\ (stat) \pm 0.05\ (syst)$

in agreement with theory

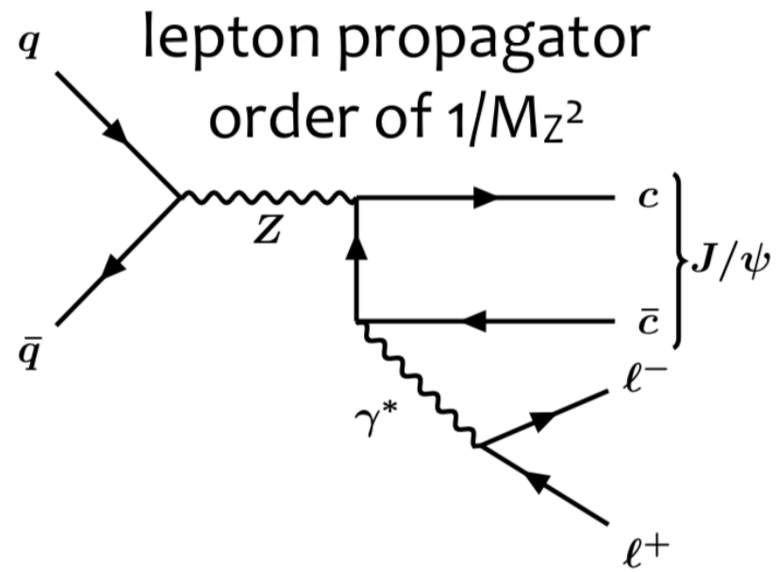
Backup

Z→J/Ψ$\ell\ell$ diagrams

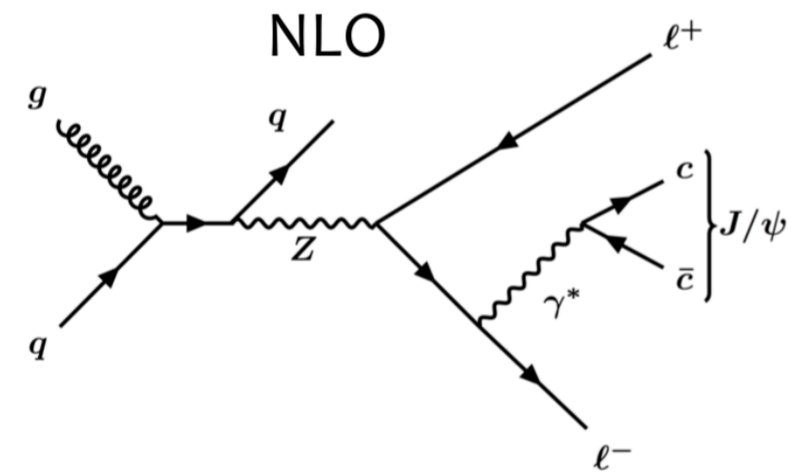
lepton propagator
order of $1/M_\psi^2$



lepton propagator
order of $1/M_Z^2$



NLO



Selections

- **J/Ψ → μμ**
  - $p_T^{\mu} > 3.5$ GeV and $|\eta^{\mu}| < 2.4$
  - muon ID `soft` + `global`
  - $p_T^{J/\Psi} > 8.5$ GeV and J/Ψ vertex probability > 5%
- **non-resonant μμ**
  - $p_T^{\mu 1} > 30$ GeV, $p_T^{\mu 2} > 15$ GeV and $|\eta^{\mu}| < 2.4$
  - muon ID `tight` + `global`
- **non-resonant ee**
  - $p_T^{e1} > 30$ GeV, $p_T^{e2} > 15$ 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 $R_{0.3} < 0.35$