Observation of the $Z \to \psi \ell^+ \ell^-$ Decay in pp Collisions at $\sqrt{s} = 13$ TeV

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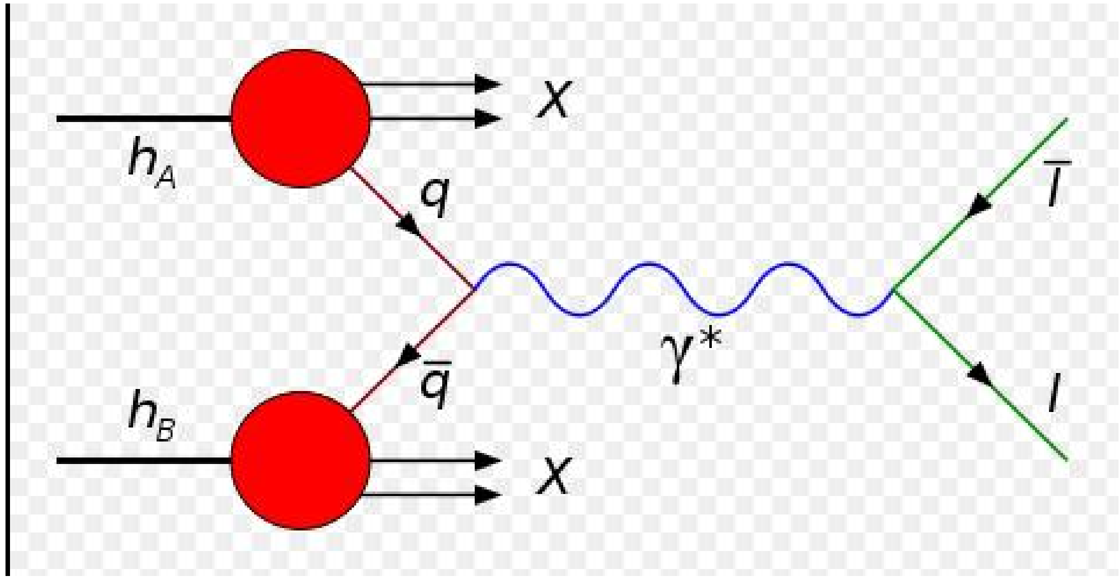
This Process is called as Drell-Yann Process.The Drell − Yan process occurs in High Energy hadron-hadron scattering.It takes place when a quark of one hadron and an antiquark from another hadron annihilate, creating a virtual photon or Z boson which then decays into a pair of oppositely-charged leptons. Importantly, the energy of the colliding quark-antiquark pair can be almost entirely transformed into the mass of new particles.



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This Letter presents the observation of the rare Z boson decay $Z \to \psi \ell^+ \ell^-$. Here, ψ represents contributions from direct J/ψ and $\psi(2S) \to J/\psi X$, $\ell^+\ell^-$ is a pair of electrons or muons, and the J/ψ meson is detected via its decay to $\mu^+\mu^-$. The sample of proton-proton collision data, collected by the CMS experiment at the LHC at a center-of-mass energy of 13 TeV, corresponds to an integrated luminosity of 35.9 fb^{-1}. The signal is observed with a significance in excess of 5 standard deviations. After subtraction of the $\psi(2S) \to J/\psi X$ contribution, the ratio of the branching fraction of the exclusive decay $Z \to J/\psi \ell^+ \ell^-$ to the decay $Z \to \mu^+\mu^-\mu^+\mu^-$ within a fiducial phase space is measured to be $\mathcal{B}(Z \to J/\psi \ell^+\ell^-)/\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-) = 0.67 \pm 0.18(\text{stat}) \pm 0.05(\text{syst})$.

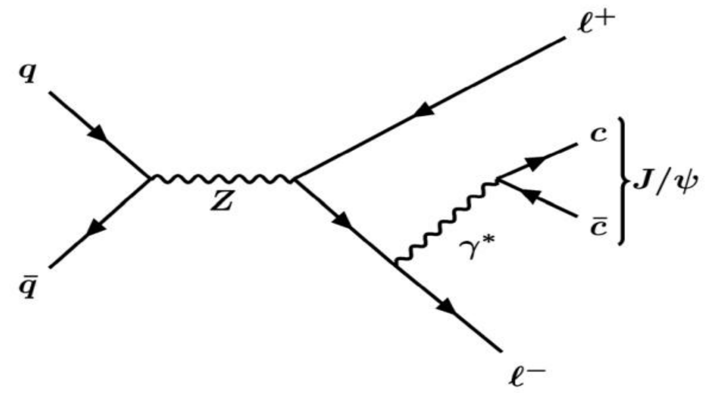

FIG. 1. Leading-order Feynman diagram for the production of the Z boson and its decay in the $Z \to J/\psi \ell^+ \ell^-$ channel.

- Z boson decay process has been exclusively only for one channel with Z->4l, apart from the dilepton final states.
- No resonant structure in the four-lepton decay has yet been observed.
- In this paper, Z boson to final state with Jpsi meson and two oppositely charged same-flavour leptons.
- The theoretical estimates of the branching fraction cover the range (6.7–7.7) × 10-7. Although this branching fraction is small, the dileptons and vector mesons in the final state offer a clean signature.
- The measurement of the Branching Fraction is valuable for the calculation of the fragmentation function for a virtual photon to split into Jpsi.
- Rare Higgs boson decays, such as those to quarkonia, will become accessible in the future, making it possible to search for nonstandard model signatures in these decays, including, e.g.,anamolous couplings or new exotic light states.
- Accurate knowledge of potential backgrounds from Z decays to quarkonia will be essential for these measurements.

- This analysis uses pp collision data at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb-1.
- Observation for Z->psi l+l-, where psi represents the contribuitions from direct Jpsi and Jpsi mesons from psi(2S) decays, and Jpsi detected via its mu+mu- channel.
- Measured the ratio of the branching fraction of this decay to that of the Z->mu+mu-mu+mu- decay, by partial cancellation of systematic uncertainities.
- The lepton candidates from Z boson decay are required to be isolated from the hadronic activity in the event. To satisfy this requirement the scalar sum of transverse energy deposits in the calorimeters and the pT of tracks is computed in a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ in eta-phi around the leptoon trajectory.

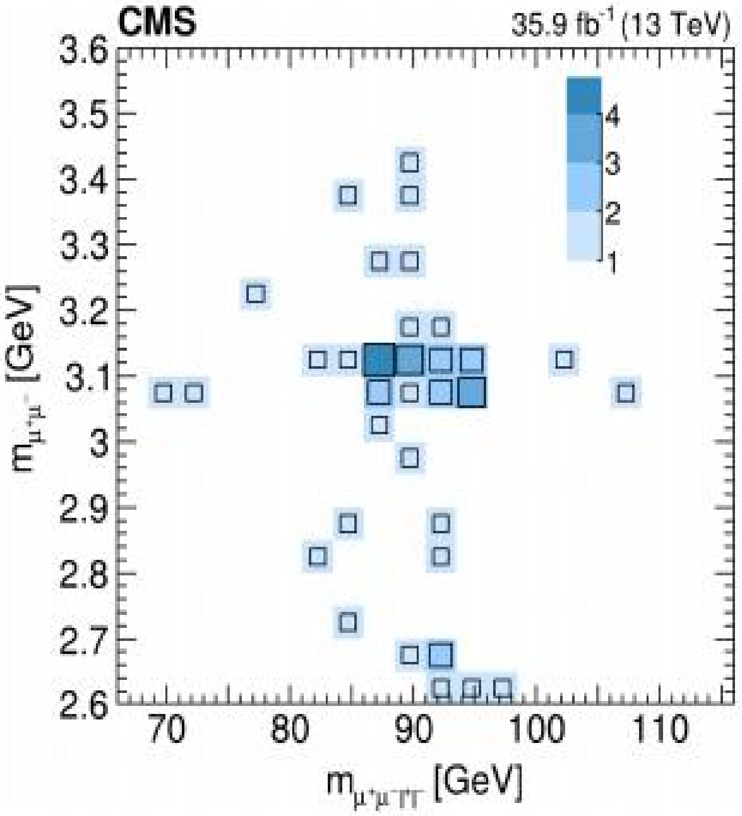

FIG. 2. Distribution of invariant masses $m_{\mu^+\mu^-}$ vs $m_{\mu^+\mu^-\ell^+\ell^-}$ for the selected candidates. The values in the legend give the numbers of candidates per bin, which are also indicated by the sizes of the open black boxes.

Following the application of the selection criteria described above, 29 (18) events remain in the $\psi\mu^+\mu^-$ (ψe^+e^-) sample. Figure 2 shows a two-dimensional plot of the $\mu^+\mu^-$ versus $\mu^+\mu^-\ell^+\ell^-$ invariant masses for the candidate events. The signal appears as a concentration of events in the overlap region of the J/ψ meson and Z boson masses. The events outside the central cluster along the Z boson mass band indicate contributions from the $Z \to$ (continuum $\mu^+\mu^-$)$\ell^+\ell^-$ decay, and along the J/ψ meson mass band, nonresonant $J/\psi\ell^+\ell^-$ production.

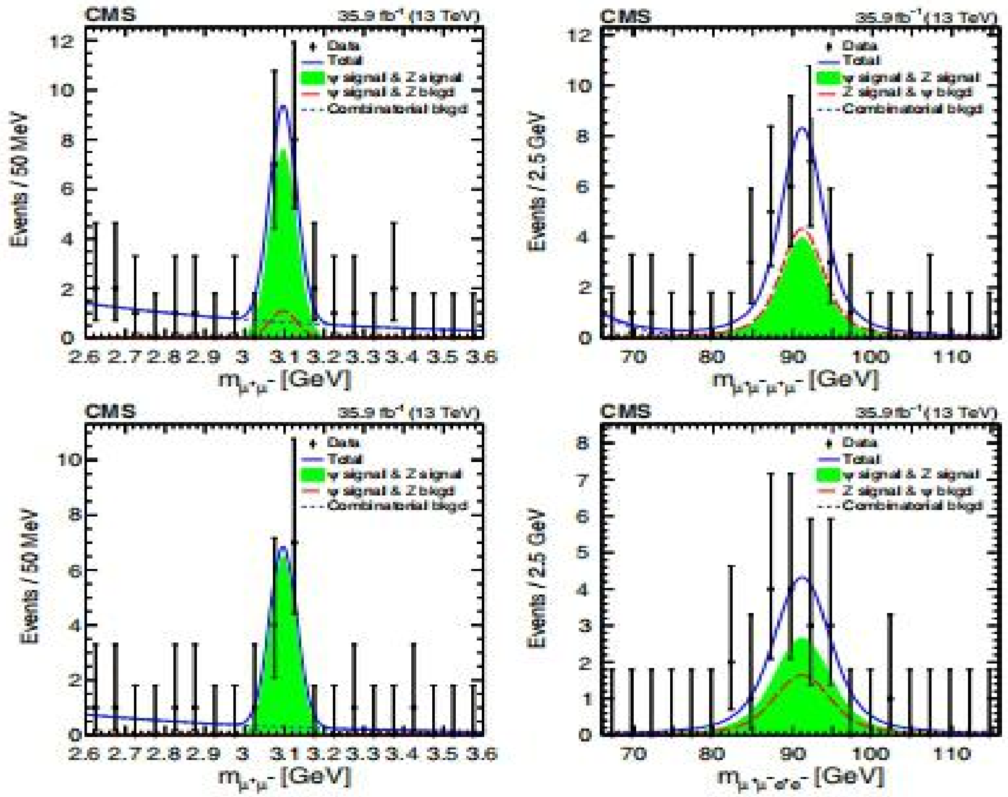

FIG. 3. Invariant mass distributions for the ψ muon pairs (left) and for $\psi\ell^+\ell^-$ (right), for $Z \to \psi\mu^+\mu^-$ (upper) and $Z \to \psi e^+e^-$ (lower) candidates. In each histogram the data are represented by the points, with the vertical bars showing the statistical uncertainties, and the solid curve is the overall fit to the data. The shaded region corresponds to the signal yield, while the long-dashed lines are the ψ meson signal from the Z boson background (left) and the Z boson signal from the ψ meson background (right). The short-dashed line represents the combinatorial background.

- Question: (Yuzhen) What is the Fiducial Phase Space?
- Answer: The meaning of “**fiducial**” is taken as “**standard of reference**”.

The Fiducial Phase space means to set an environment for a specific process in particle physics by applying some limits or threshold conditions to avoid background.

Fiducial cross section, in particle physics experiments, a cross section for the subset of a process in which the distinctive process signatures are visible within the sensitive regions of the detector volume. The definition now commonly means a cross section with kinematic and other selection cuts consistent with the sensitive detector acceptance applied, but in which detector inefficiencies are corrected for within that volume. These corrections are typically derived by applying the fiducial cuts on collections of simulated collision events, with and without detector simulation, and inverting the resulting detector transfer function. Fiducial cross sections are favoured for many purposes because they minimise extrapolation into experimentally invisible phase space, and are hence maximally model-independent.

Fiducial volume, in low-background physics experiments, an inner volume of particle detector media in which background events are largely excluded.

wikipedia:https://en.wikipedia.org/wiki/Fiducial

From the observed signal yield we compute a ratio of branching fractions defined over the fiducial phase space of the measurement defined in Table I. The entries consist

TABLE I. Definition of the fiducial phase space for the measurement of the ratio of branching fractions. Here, ℓ refers to a prompt muon or electron from the signal decay, or to either of the two muons from the higher invariant-mass pair in the reference-channel decay, and μ refers to a J/ψ daughter or a member of the lower invariant-mass pair in the reference-channel decay. The symbol ℓ_1 (ℓ_2) refers to the prompt lepton having the higher (lower) value of p_T. The $p_T^{J/\psi}$ threshold is applied to the signal and the $m(\mu^\pm\mu^\mp)$ requirement to the reference channel.

Fiducial requirement
$40 < m_{\ell^+\ell^-} < 80$ GeV
$\lvert\eta(\text{electrons})\rvert < 2.5$, $\lvert\eta(\text{muons})\rvert < 2.4$
$p_T(\ell_1, \ell_2, \mu, \mu) > (30, 15, 3.5, 3.5)$ GeV
Signal: $p_T^{J/\psi} > 8.5$ GeV
Reference channel: $4 < m(\mu^\pm\mu^\mp) < 80$ GeV

- Question: (Xin) Based on the Fig.1 Feynman diagram, how to derive the gamma *–V transition strength from the measured $V \rightarrow l^+l^-$ electromagnetic decays?
- Answer: It's a theoretical question and I can't give this answer for now. I will have to read more about this.

- Question:(Yuhang) The probability density function (pdf) of signal is a sum of four terms, each of which is a yield parameter multiplying a component pdf. How to use the four terms account for four different backgrounds?
- Answer:
- The four terms account for the z->psil+l- signal and the backgrounds from Z->l+l- accompanied by nonresonant mu+mu-, nonresonant Jpsil+l-, abd nonresonant mu+mu-l+l-. I didn't understand too?

$J/\psi\ell^+\ell^-$, and nonresonant $\mu^+\mu^-\ell^+\ell^-$. The pdf for the $J/\psi \to \mu^+\mu^-$ invariant mass distribution is a Gaussian function of $m_{\mu^+\mu^-}$ with the mean fixed to the J/ψ meson mass [17] and the width as a free parameter of the fit. The $Z \to \mu^+\mu^-\ell^+\ell^-$ pdf is a Breit-Wigner function of $m_{\mu^+\mu^-\ell^+\ell^-}$ with its central value and width fixed to the mass and width of the Z boson [17], convolved with a Gaussian function whose width is a free parameter. The pdfs for the continuum background in each dimension of the fit, representing backgrounds that are both peaking and non-peaking in the orthogonal dimension, are exponential functions with free decay parameters. The projections in each variable are shown in Fig. 3, along with the pdf components resulting from the fits.

Question:(Kai) this paper only shown the invariant mass distributions for the psi muon pairs and psi lepton pairs, but they do not show plots for the other leptons. how to get the conclusion that the other leptons from Z, not from other intermediate states from Z?

Answer: Becase of the short life-time of the tau particle, it promptly decays once produced. Hence, it is very difficult to construct Z boson decay with tau lepton than other leptons such as electrons and muons.

- Question:(Suyu) why is J/psi required from psi(2S)?
- Answer:

Calculated contributions from $\psi(2S) \rightarrow J/\psi X$ decays, the dominant feed-down source of J/ψ mesons, are subtracted from the signal yields, since the natural width of the Z boson does not allow the separation of the process $\psi(2S) \rightarrow J/\psi X$ from direct J/ψ production. The predicted production ratio of $Z \rightarrow J/\psi \ell^+\ell^-$ to $Z \rightarrow \psi(2S)\ell^+\ell^-$ is 3.5 [11]. Taking into account the branching fraction of $\psi(2S)$ to $J/\psi X$ [17], the ratio of $N(Z \rightarrow J/\psi \ell^+\ell^-)$ to $N(Z \rightarrow \psi(2S)[\rightarrow J/\psi X]\ell^+\ell^-)$ is 5.7 ± 0.1. Using this scale factor, we subtract 1.9 (1.7) events from the $N_{Z\rightarrow\psi\mu^+\mu^-}$ ($N_{Z\rightarrow\psi e^+e^-}$) yield, considering them as J/ψ events from $\psi(2S)$ meson decays.

- Question: (Gu Shan) In this sentence: the experimental efficiencies to reconstruct events within the fiducial phase space are determined from simulation; combined with the trigger efficiencies given above they are 81%,80%,81%. Why thest efficiencies are so high?
- Answer: As far as I think for these high efficiencies because they have a seperate muon chamber in CMS. Like in BESIII we have muan detection chamber at the outer surface of the detector. So, muons can be detected at both the places.

- Question:(Ryuta) How we can interpret the obtained value R (=0.67+-0.18+-0.05) itself ?
- Answer:

The uncertainty in the fraction of J/ψ events that potentially originate from $\psi(2S)$ is propagated from the uncertainty of the $N(Z \to J/\psi \ell^+\ell^-)$ to $N(Z \to \psi(2S) [\to J/\psi X]\ell^+\ell^-)$ ratio.

The total systematic uncertainty of 7.6% for $\mathcal{R}_{J/\psi\ell^+\ell^-}$ is calculated by adding the sources of uncertainty given in the last column of Table II in quadrature.

After subtracting the $\psi(2S)$ feed-down we extract from Eq. (1) the branching fraction ratio $\mathcal{R}_{J/\psi\ell^+\ell^-}$, for the phase-space region defined in Table I:

$$\mathcal{R}_{J/\psi\ell^+\ell^-} = 0.67 \pm 0.18(\text{stat}) \pm 0.05(\text{syst}). \qquad (2)$$

Assuming that the factors applied to extrapolate the signal and reference-channel branching fractions from the phase space defined in Table I to the full phase space approximately cancel in the ratio, we use the measured value of $\mathcal{B}(Z \to \mu^+\mu^-\mu^+\mu^-) = (1.20 \pm 0.08) \times 10^{-6}$ [4] for $m(\mu^+\mu^-) > 4$ GeV to obtain an estimate for $\mathcal{B}(Z \to J/\psi\ell^+\ell^-)$ of 8×10^{-7}. This estimate is consistent with standard model predictions of $(6.7 \pm 0.7) \times 10^{-7}$ [10] and 7.7×10^{-7} [11].

I can not say you more about these limits for the branching fractions as I need to know more about these techniques.

Thank You