Precision measurement of the Z invisible width at CMS

CMS-PAS-SMP-18-014

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Introduction

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z + \text{jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z + \text{jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

- Z invisible width extracted from ratio of experimentally measured cross sections of Z(vv) +jets to Z($\ell\ell$) +jets and partial width for Z—>$\ell\ell$.
- Use 36 fb^{-1} of 13 TeV data and
  - Jets+MET topology to select Z—>vv events
  - μμ+jets and ee+jets to select Z—>$\ell\ell$ events
- Largest background to jets+MET from W+jets events, estimated using data driven approach and l+jets control regions. Background from QCD is small but also estimated using data.
- Background to Z—>$\ell\ell$ is negligible, however contribution from γ*—>$\ell\ell$ and interference between γ*—>$\ell\ell$ and Z—>$\ell\ell$ is evaluated and accounted for.
- Invisible width extracted from simultaneous fit between jets+MET, $\ell\ell$+jets, ℓ+jets

Event Selection

Baseline

MET filters
$p_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$
$|p_{\mathrm{T,PF}}^{\mathrm{miss}} - p_{\mathrm{T,Calo.}}^{\mathrm{miss}}| / p_{\mathrm{T}}^{\mathrm{miss}} < 0.5$
Lead jet $p_{\mathrm{T}} > 200\,\mathrm{GeV}$ and $|\eta| < 2.4$ and $0.1 <$ Ch. Had. EF < 0.95
Veto jets $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $|\eta| \geq 2.4$
Loose photon veto $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.5$
Medium CSVV2 b-jet veto $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $|\eta| < 2.4$

Jets+MET

Baseline
Loose muon veto $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$
Veto electron veto $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$
Very loose tau veto $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.3$
$\min[\Delta\phi(j_{1,2,3,4}, p_{\mathrm{T}}^{\mathrm{miss}})] > 0.5$

Double Muon

Baseline
2 medium muons $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $|\eta| < 2.4$
Veto electron veto $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$
Very loose tau veto $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.3$
$71 < M_{\mu\mu} < 111\,\mathrm{GeV}$
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Double Electron

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Single Tau

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QCD sideband

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- MET trigger collects events for **jets+MET, μ+jets, μμ+jets, τ+jets, QCD sideband.**
- **Single electron trigger collects events for e+jets and ee+jets.**

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Jets+MET

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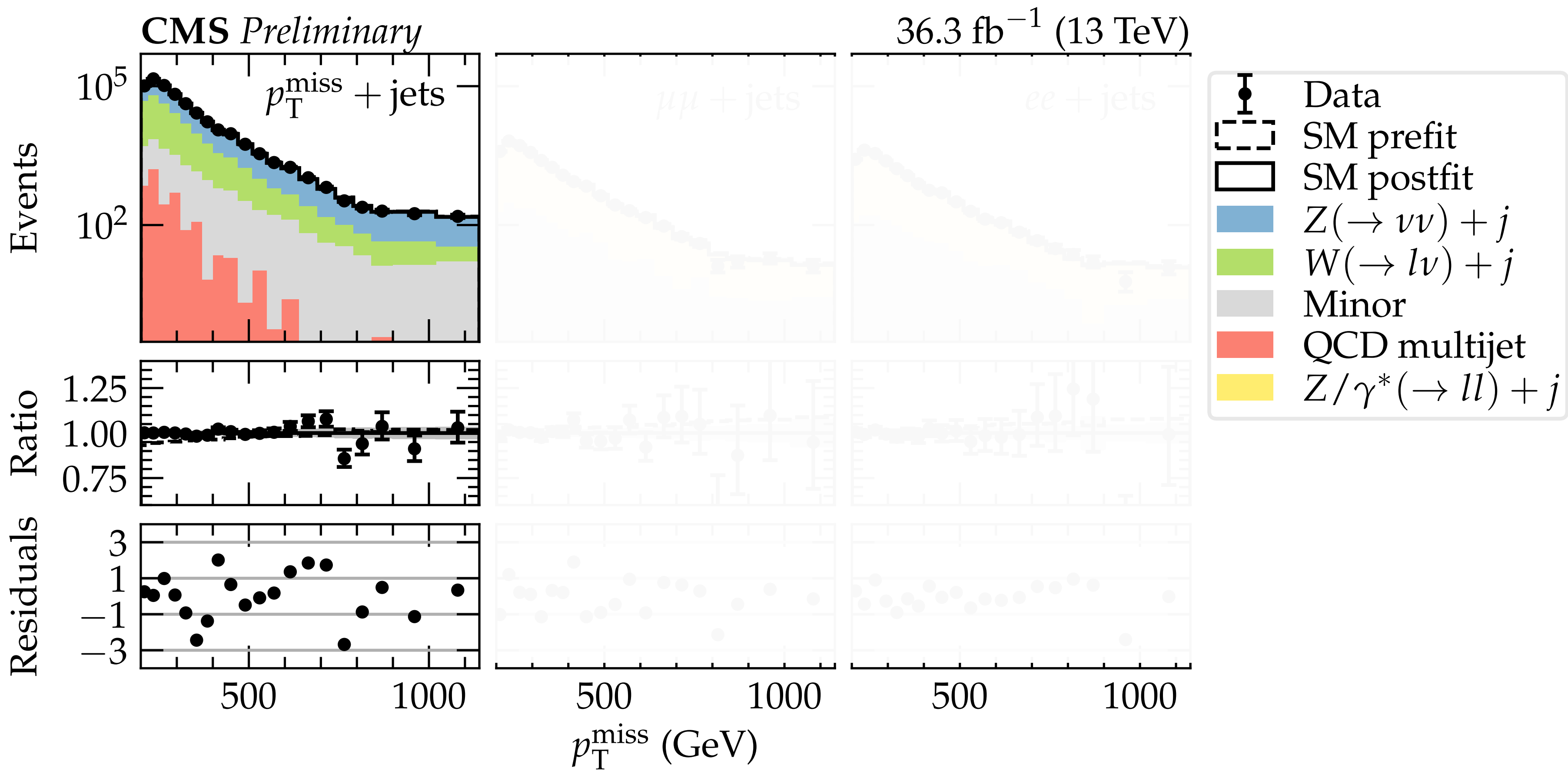


Main background contributing to Jets+MET channel is W+jets

W+jets prediction

Dominant background from W+jets is estimated using transfer factor method from control regions:

- **Single muon**
- **Single electron**
- **Single tau (used for validation cross-check)**

$$t_{\ell+\text{jets}}^{p_{\text{T}}^{\text{miss}}+\text{jets}}(\text{W}+\text{jets}) = \frac{N_{\text{MC}}^{p_{\text{T}}^{\text{miss}}+\text{jets}}(\text{W}+\text{jets})}{N_{\text{MC}}^{\ell+\text{jets}}(\text{W}+\text{jets})}$$

Validation tests of transfer factor

The first test verifies the **consistency of the μ + jets and e + jets region** to validate using the combined decay channels in measuring the W + jets process

A likelihood fit is performed between the two regions, with two additional unconstrained parameters

parameter to extract difference in normalization between the e+jets and u+jets region

$$r_{\mathrm{W}} s^{e+\mathrm{jets}}_{\mathrm{W}\to\ell\nu} \mapsto \left(r_e + \beta_e(\mathcal{U}/\langle\mathcal{U}\rangle - 1)\right) r_{\mathrm{W}} s^{e+\mathrm{jets}}_{\mathrm{W}\to\ell\nu}$$

parameter to vary the shape of MET in the e+jets linearly w.r.t u+jets

Post-fit values for these parameters shows consistency between electron and muon channels

All systematic uncertainties are included in the fit. Dominant uncertainties from electron trigger, muon ID (syst.), electron ID (syst.), MET trigger

Validation tests of transfer factor

This test probes the extrapolation performed by the transfer factor method, using the μ + jets and e + jets region to predict the W + jets process in the signal region which mostly consists of τ_h decays of the W boson

parameter to extract difference in normalization between the combined e+jets + u+jets region and the hadronic tau region

$$(r_\tau + \beta_\tau(\mathcal{U}/\langle\mathcal{U}\rangle - 1))\, r_{\mathrm{W}} s_{\mathrm{W}\to\ell\nu}^{\tau+\mathrm{jets}} \,.$$

parameter to vary the shape of MET in the combined e+jets and u+jets region linearly w.r.t tau+jets

Post-fit values for these parameters shows consistency between combined electron+ muon channels and τ_h channel

All systematic uncertainties are included in the fit. Dominant uncertainties from τ_h ID, muon ID (syst.), and electron trigger.

γ^* correction

- $Z \rightarrow \nu\nu$ channel contains a pure Z interaction, while the $Z/\gamma^* \rightarrow \mu\mu/ee$ channel also contains a γ^* interference term that needs to be corrected for.

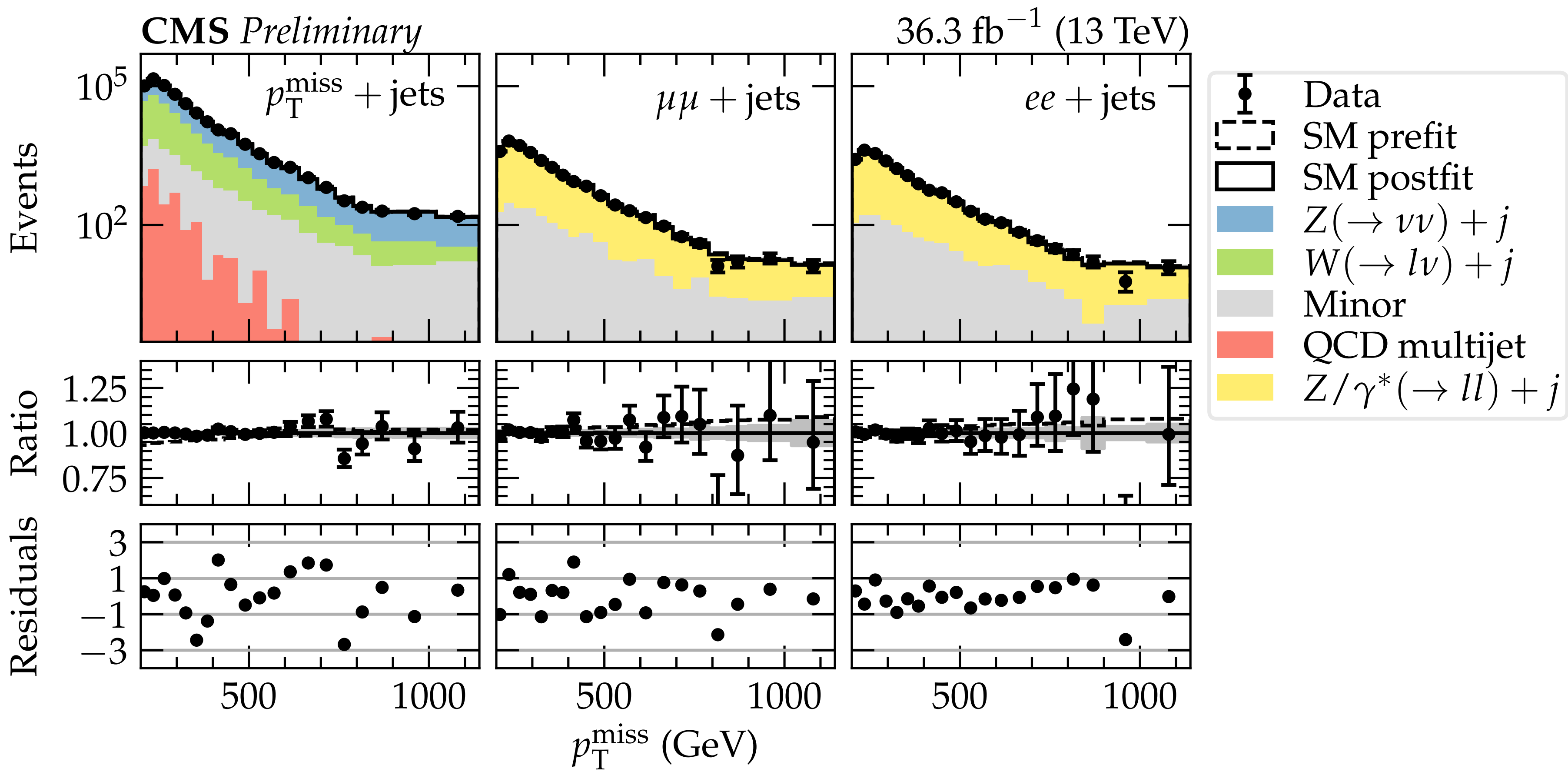
- Obtained using the privately generated sample of $Z \rightarrow \mu\mu$ and $\gamma^* \rightarrow \mu\mu$ events, all generated with MGaMC@NLO to ensure consistency.

- γ^* component is treated as a background (1.5%) while the interference (0.6%) is treated as scaling parameter for the $Z \rightarrow ll$ signal

Systematic uncertainties

- **MET trigger efficiency** : systematic uncertainties covering the MET trigger efficiency estimation
- **Muon based systematics**: Uncertainties relating to the data/MC scale factors for the muon identification, isolation and reconstruction.
- **Electron based systematics**: Uncertainties relating to the data/MC scale factors for the electron trigger, identification, isolation and reconstruction.
- **Jet energy scale** : Uncertainty based on the jet energy scale correction propagated to the jets and MET.
- **Jet energy resolution**: Uncertainty related to the scale-factor on the p_T resolution of jets and propagated through jets and MET.
- **Tau based systematics**: Uncertainty on the data/MC scale factors for tau identification.
- **Unclustered energy** : Uncertainty from unclustered energy resulting in a variation of the p_T . The uncertainty is determined from the width of the distribution in events with an expected *MET* of zero ($Z \rightarrow ll$ and γ plus jets)
- **Pileup** : Uncertainty from varying the minimum bias cross section up and down by 4.6% in determining the pileup weights
- **Theoretical uncertainties** from : PDFs, renormalisation/factorisation scale, NNLO QCD and NLO EWK corrections.

Post-fit results



Likelihood fit

- **Z invisible width is extracted from a simultaneous likelihood fit to the jets+MET, ℓ+jets, ℓℓ+jets regions**

$$\mathcal{L}(n_j, n_\ell, n_{\ell\ell} | r, r_Z, r_W, \boldsymbol{\theta}) =$$

$$\text{Poisson}\left(n_j \,\middle|\, r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta}) + r_W \cdot b_{j,W}(\boldsymbol{\theta}) + b_{\text{bkg.},j}(\boldsymbol{\theta})\right)$$

Jets+MET

$$\text{Poisson}\left(n_\ell \,\middle|\, r_W \cdot b_{\ell,W}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell}(\boldsymbol{\theta})\right)$$

Single lepton

$$\text{Poisson}\left(n_{\ell\ell} \,\middle|\, r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta}) + \sqrt{r_Z} \cdot s_{\text{int.},\ell\ell} + s_{\gamma^*,\ell\ell}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell\ell}(\boldsymbol{\theta})\right)$$

Double lepton

$$\cdot\, p(\tilde{\boldsymbol{\theta}}, \boldsymbol{\theta})$$

$$\begin{aligned}\Gamma(Z \to \nu\bar{\nu}) &= \frac{\sigma(Z+\text{jets}) \cdot B(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets}) \cdot B(Z \to \ell\ell)} \Gamma(Z \to \ell\ell) \\ &= \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta})}{r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell) \\ &= r \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{s_{Z,j}(\boldsymbol{\theta})}{s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell).\end{aligned}$$

$$\Gamma_{\text{MC}}(Z \to \nu\bar{\nu}) = \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{s_{Z,j}(\boldsymbol{\theta})}{s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma_{\text{MC}}(Z \to \ell\ell)$$

$$r_{\text{inv}} \equiv r = \frac{\Gamma(Z \to \text{inv})}{\Gamma_{\text{MC}}(Z \to \text{inv})}$$

Z invisible width

r_{inv} is $1.049 \pm 0.006\,(\text{stat})^{+0.032}_{-0.031}\,(\text{syst})$.

Input Z invisible width

This value is calculated at generator level with MADGRAPH5 aMC@NLO from the ratio of Z → $\nu\bar{\nu}$ and Z → *ll* cross sections for an invariant mass range of 71 – 111 GeV.

After multiplying this ratio by the Z → *ll* partial width of 84.2MeV, the Γ^{MC} is found to be 498.7 MeV

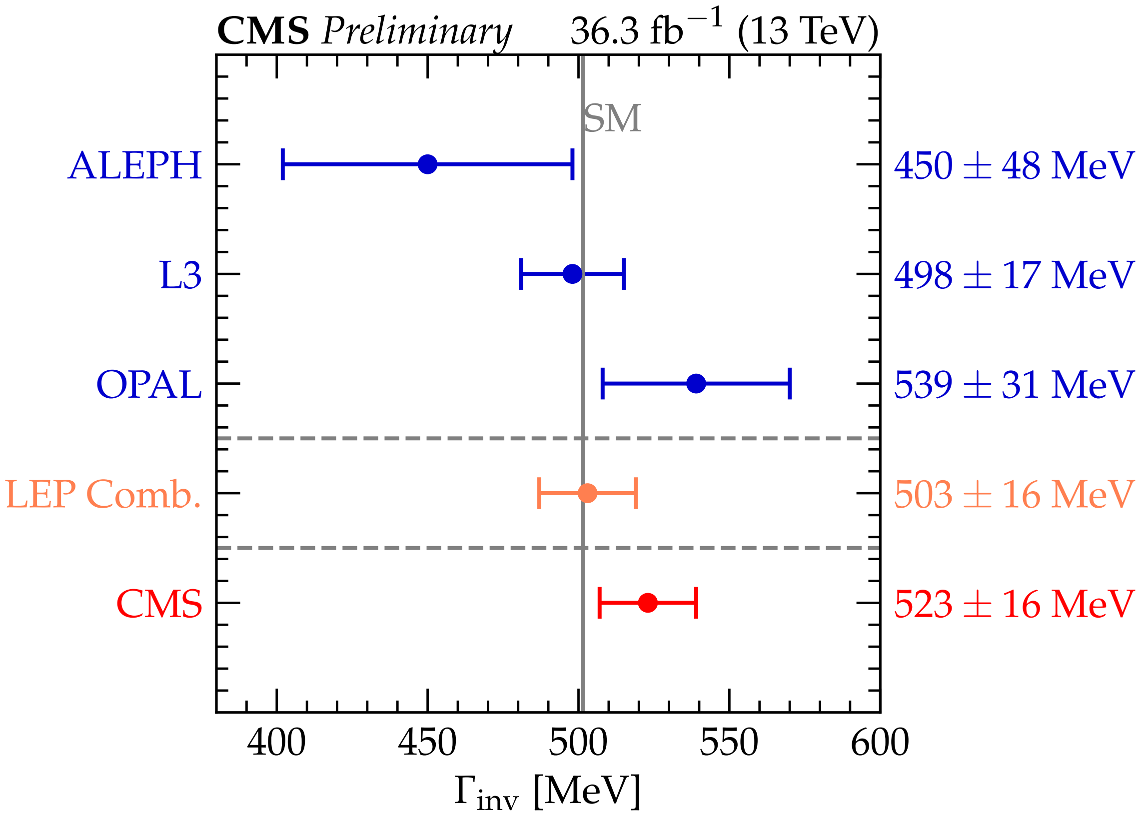
Multiplying r_{inv} with the input Z width, the observed width is found to be

$$\Gamma_{inv} = 523 \pm 3\,(\text{stat}) \pm 16\,(\text{syst})\,\text{MeV}.$$

Systematic uncertainties on result

Source of uncertainty	%
Muon identification efficiency (syst.)	2.05–2.06
Jet energy scale	1.83–1.86
Electron identification efficiency (syst.)	1.55
Electron identification efficiency (stat.)	0.98–1.01
Pileup	0.93–0.96
Electron trigger efficiency	0.71–0.72
τ_h veto efficiency	0.63–0.70
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency (jets plus $p_{\mathrm{T}}^{\mathrm{miss}}$ region)	0.65
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency ($Z/\gamma^* \to \mu\mu$ region)	0.55–0.56
Boson p_{T} dependence of QCD corrections	0.49–0.51
Jet energy resolution	0.34–0.47
$p_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency ($\mu +$ jets region)	0.42–0.44
Muon identification efficiency (stat.)	0.31–0.32
Electron reconstruction efficiency (syst.)	0.30–0.31

Results



- **First direct measurement of invisible Z width at a hadron collider**
- **Precision competitive with LEP direct measurement**