Search for High Mass $ee/e\mu$ Resonances in CMS

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outline

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  - Object and event selection
  - Electron and muon ID efficiency and scale factor
  - Mass scale and resolution
  - Backgrounds estimation
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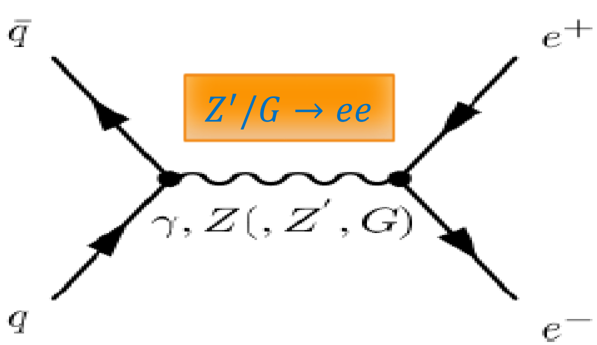
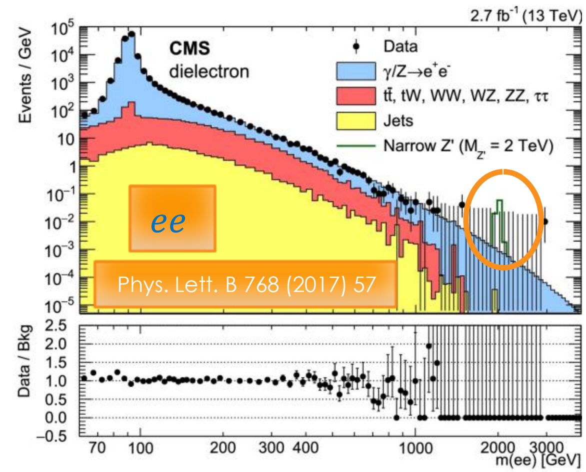
Introduction

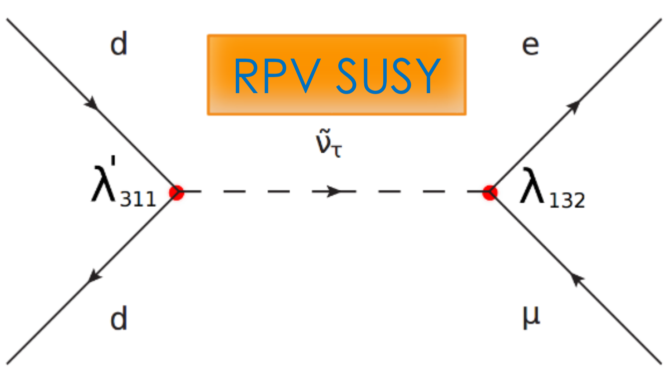
- There are several beyond standard models predict the existence of heavy neutral resonances such as GUT (arXiv:hep-ph/9805494), extra dimensions (arXiv:hep-th/9906064), RPV SUSY (arXiv:hep-ph/0406039), QBH (arXiv:0708.3017), …

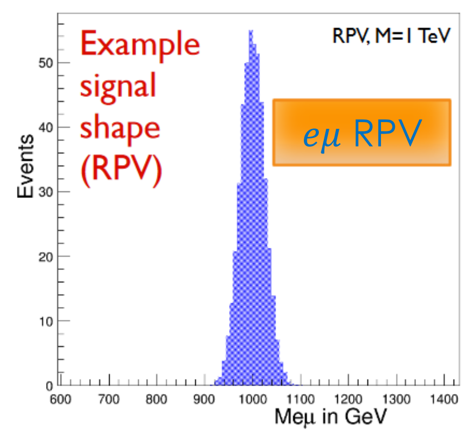
- Signal searching in *ee* final state

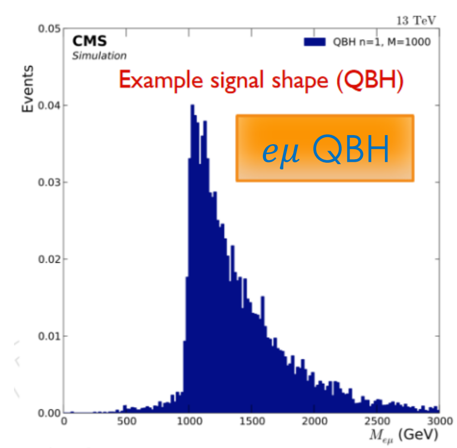




- Signal searching in $e\mu$ final state







Object and event selection

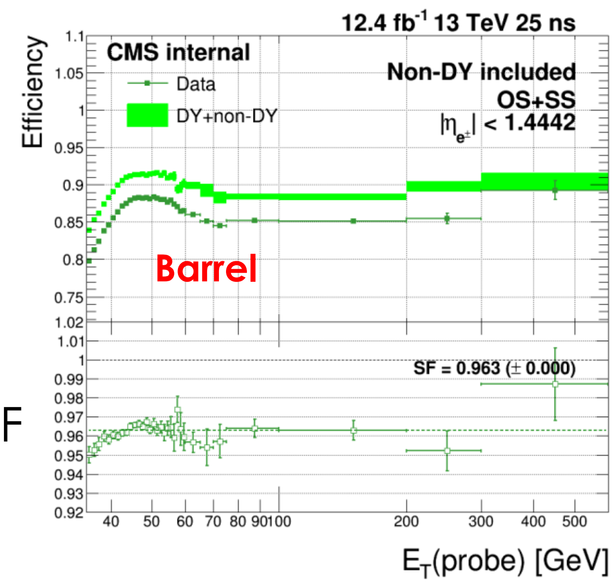
- Object selection
  - Electron
    - $E_T > 35$ GeV, $|\eta|<2.5$
    - Passing High Energy Electron Pairs (HEEP) ID selection
  - Muon
    - $P_T > 53$ GeV, $|\eta|<2.4$
    - Passing High-Pt muon ID
    - Passing Track-based relative isolation

- Event selection
  - For ee analysis
    - Dataset: 12.4fb^{-1} in 2016
    - Trigger: Double electron trigger
    - The two highest E_T of electrons are selected
    - Events categories: Barrel-Barrel (BB) and Barrel-Endcap (BE) channels
  - For $e\mu$ analysis
    - Dataset: 2.7fb^{-1} in 2015
    - Trigger: Single muon trigger
    - Passing MET filters
    - Veto the electron which are close to a muon ($\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.1$)
    - Choose the $e\mu$ pair with highest invariant mass

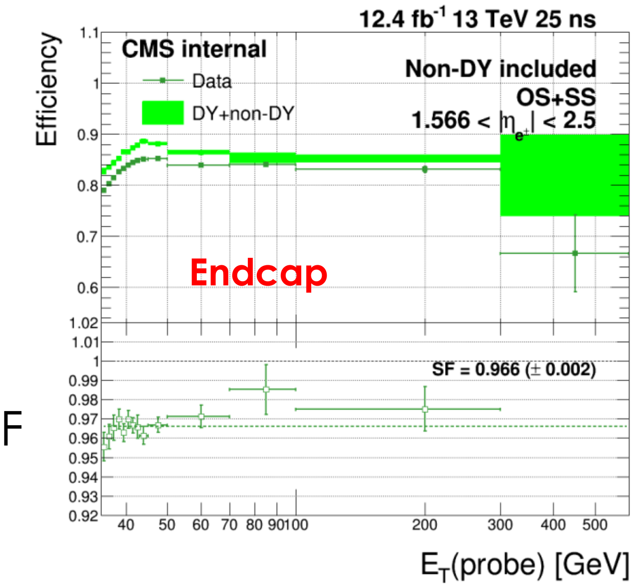
HEEP ID efficiency and scale factor

- ❑ The tag and probe counting method is used.
- ❑ Below plots shows the HEEP efficiency for data and MC simulations versus E_T of probe.

SF



SF



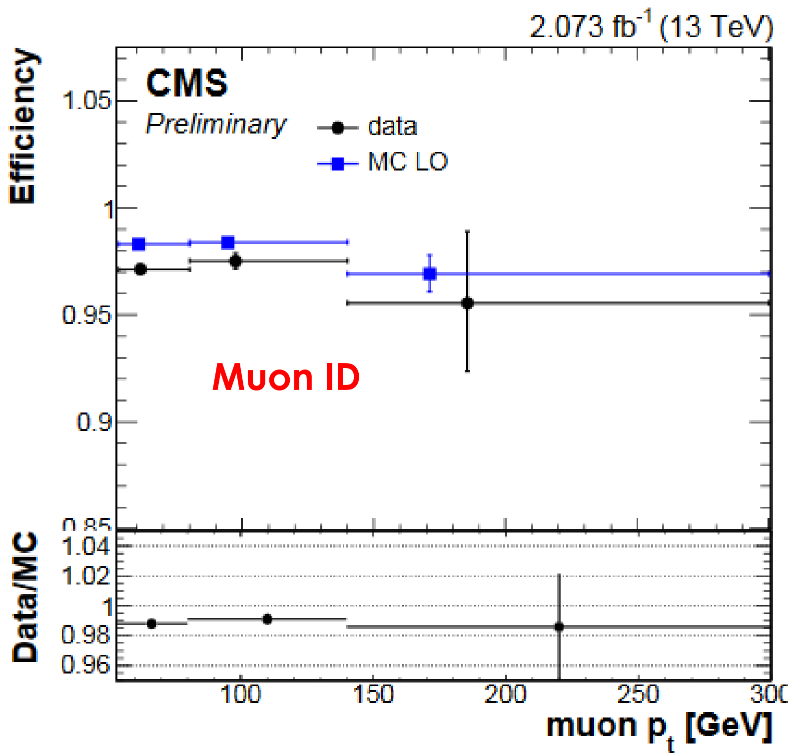
Run2(25ns)	2016 results (12.4 fb^{-1})		2015 results(2.5 fb^{-1})	
Region	Eff. (barrel)	Eff. (endcap)	Eff. (barrel)	Eff. (endcap)
Data	86.11% ± 0.02%(stat.)	83.26% ± 0.04%(stat.)	89.38% ± 0.03%(stat.)	88.12% ± 0.08%(stat.)
DY + Non-DY	89.58% ± 0.05%(stat.)	86.27% ± 0.13%(stat.)	89.98% ± 0.05%(stat.)	88.90% ± 0.11%(stat.)
Scale factor	0.961 ± 0.001(stat.) ± 0.005(syst.)	0.965 ± 0.002(stat.) ± 0.007(syst.)	0.993 ± 0.001(stat.) ±0.005(syst.)	0.991 ± 0.002(stat.) ±0.008(syst.)

- ❑ SF: 4% off(2016), 1% off(2015).
- ❑ SF is flat across wide range of E_T.

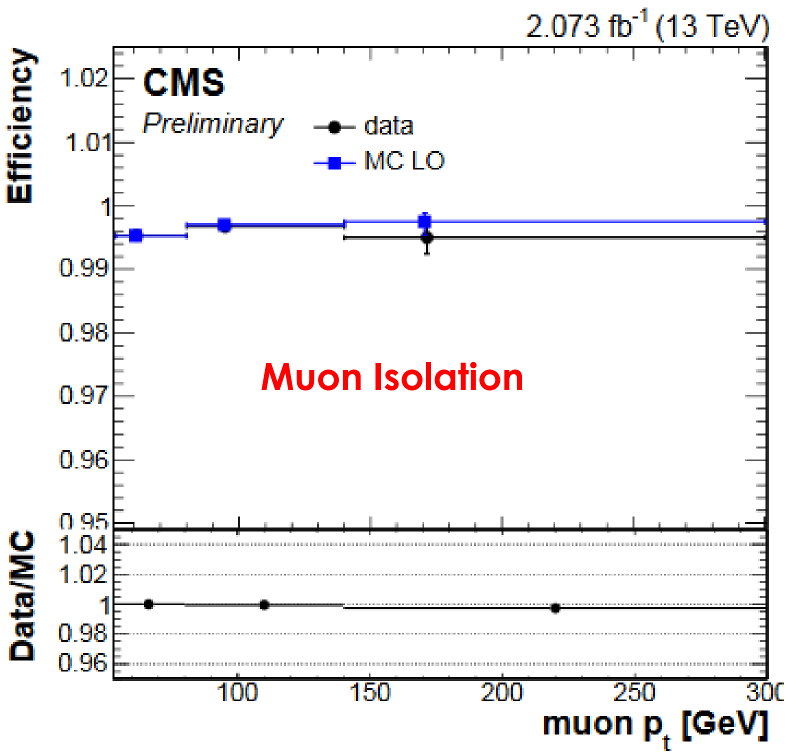
Muon ID and Isolation efficiency and scale factor

- The tag and probe fitting method is used.
- Below plots shows the Muon ID (left) and Isolation (right) efficiency for data and MC simulations versus P_T of probe.

$$p_T > 53 \text{ GeV}$$



$$p_T > 53 \text{ GeV}$$



- SF is close to 1.
- SF is flat across wide range of P_T .

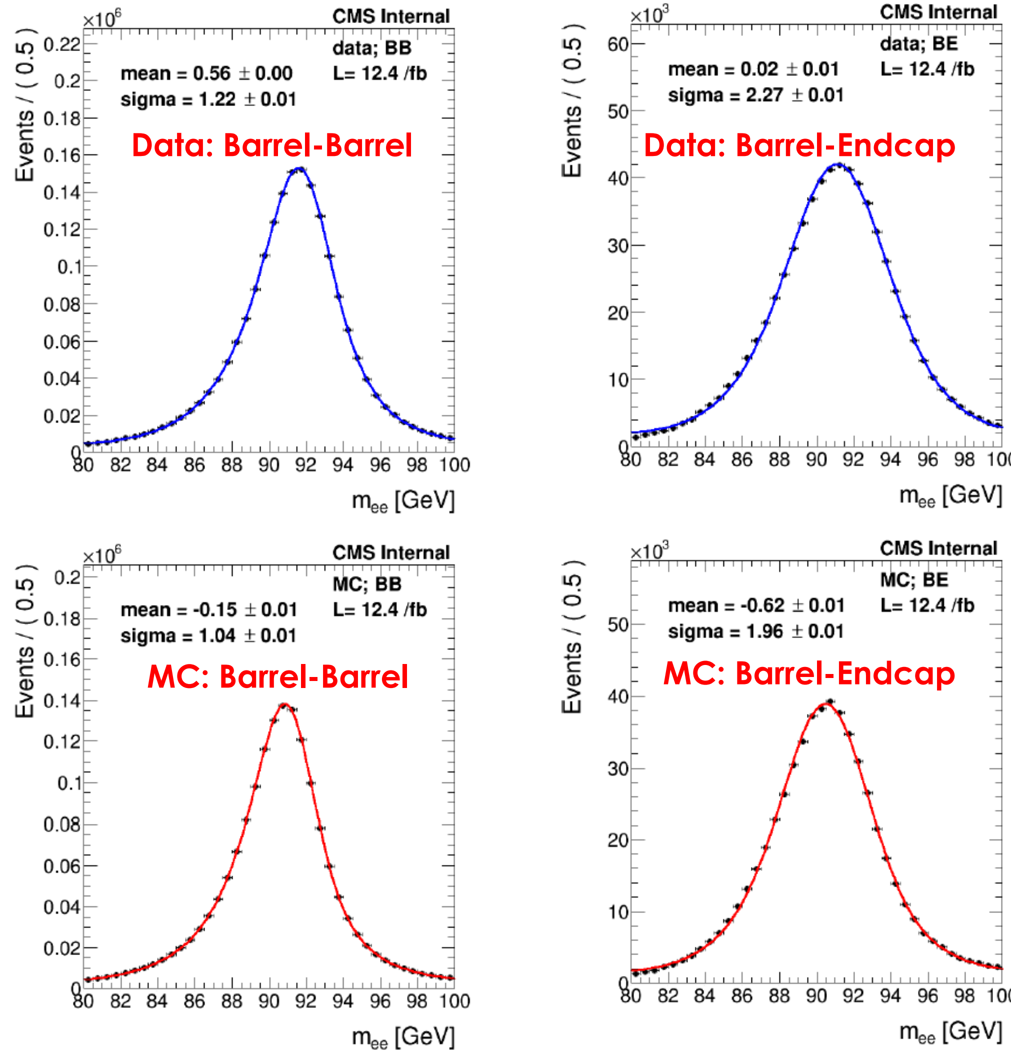
Mass scale and resolution (ee analysis)

- We estimate it in two steps:
  - **1-** using data and MC at Z peak
  - **2-** using MC only for high masses

- **step1-** At the Z peak (80-100 GeV) Distributions are fitted with Breit-Wigner convoluted with double-sided Crystal Ball (dCB)
  - Mean and sigma of gaussian part in dCB are quoted.
  - The values in the table are expressed in percentage [%] of the Z peak mass value(M_Z PDG 91.1876GeV)

Category	$\Delta M/M$ [%]	σ_{data} [%]	σ_{MC} [%]	σ_{extra} [%]
BB	0.79$\pm$ 0.01	1.34$\pm$ 0.01	1.14$\pm$ 0.01	0.71$\pm$ 0.03
BE	0.70$\pm$ 0.01	2.49$\pm$ 0.01	2.15$\pm$ 0.01	1.26$\pm$ 0.03

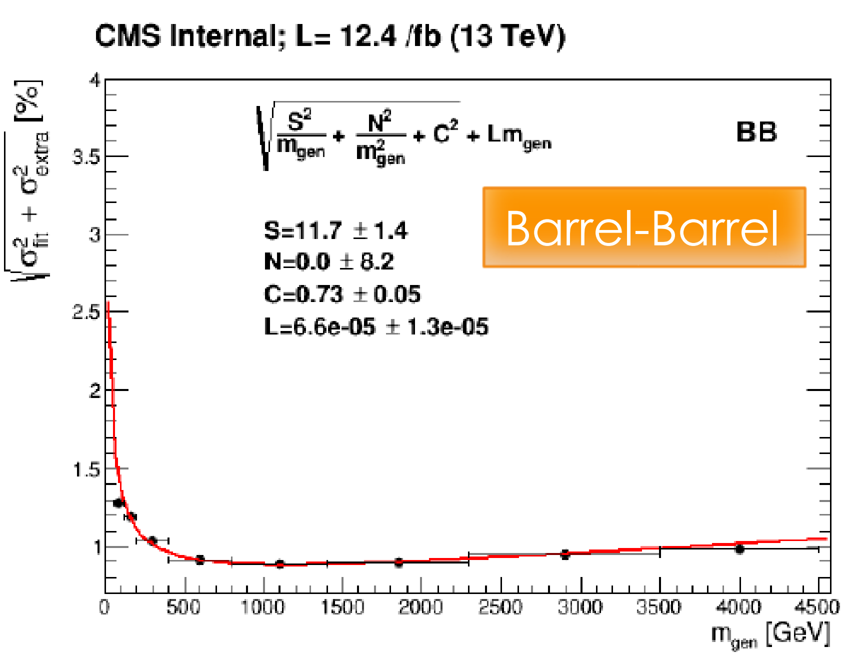
  - Computing the resolution discrepancy between data and MC, $\sigma^2_{extra} = \sigma^2_{data} - \sigma^2_{MC}$

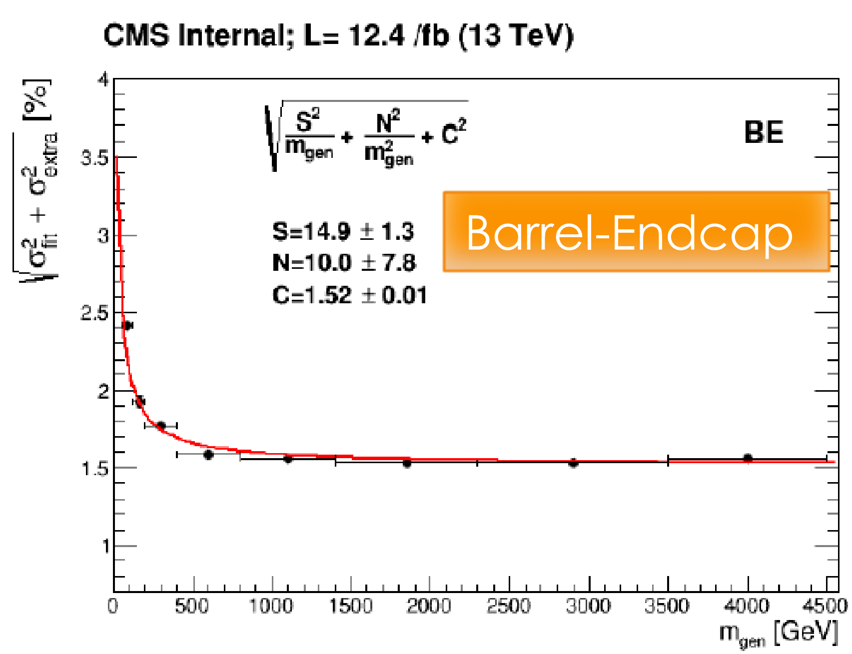


- Energy scale in barrel is 0.991 (to data)
- Energy scale in endcap is 0.993 (to data)
- Energy smearing in barrel is 1.1275% (to MC)
- Energy smearing in endcap is 2.205% (to MC)
- More details in back up

Mass scale and resolution (ee analysis)

- **step2-** At high masses, use MC only
  - For each bin of M_{ee} : resolution = $(M_{reco} - M_{gen})/M_{gen}$
  - Distributions are fitted with a Crystal Ball (CB) function (Gaussian core + power-law tail)
  - The σ_{extra} is added in quadrature to the sigma of the CB to get the mass resolution of data in high mass region ($\sigma = \sqrt{\sigma_{fit}^2 + \sigma_{extra}^2}$) .
- The signal pdf is Breit-Wigner$(m, \Gamma) \otimes$ Gaussian $(0, \sigma)$



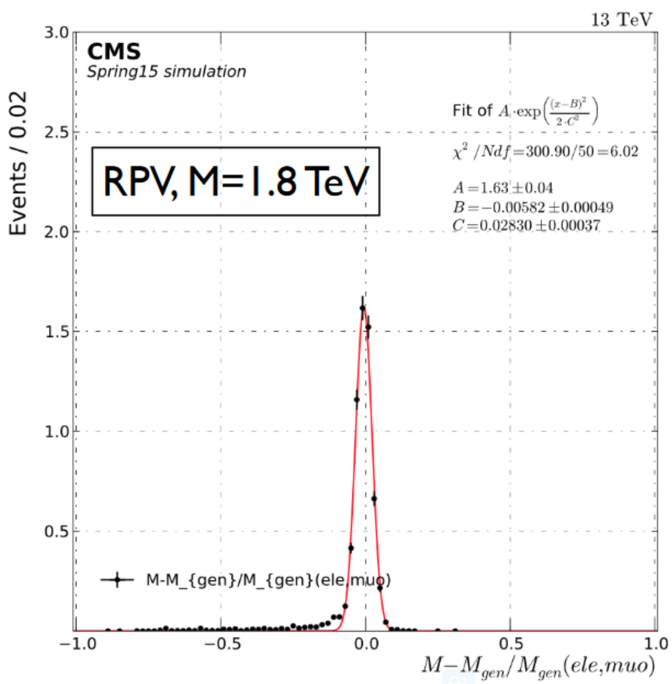


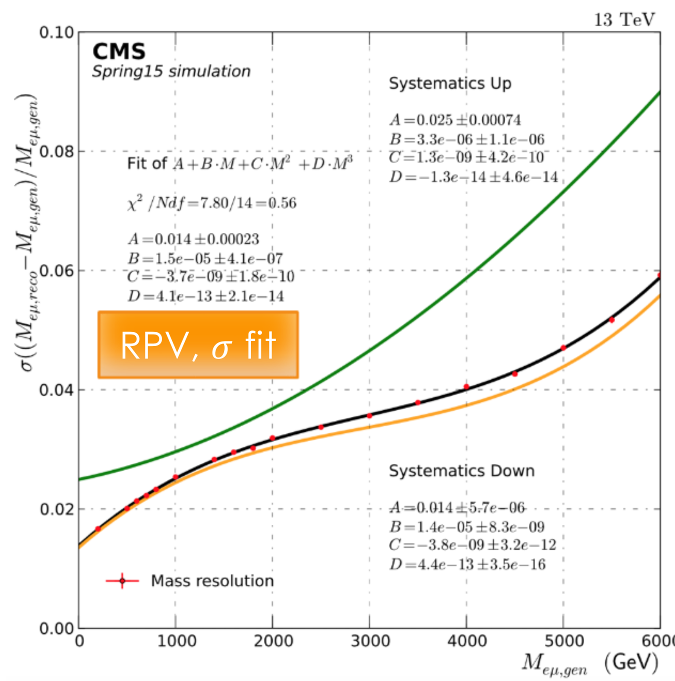
Mass resolution ($e\mu$ analysis)

❑ For RPV signal

- Relative mass resolution : $M_{res} = \frac{M_{reco} - M_{gen}}{M_{gen}}$
- Fitting the core of M_{res} distribution using Gaussian.
- The width of Gaussian is taken as a measure of the mass resolution.
- Signal pdf = Gaussian(m, σ)
- The difference between two muon alignment scenarios (asymptotic(default) and startup) covered by assigned systematic uncertainties.

❑ For QBH signal: the shape is taken from MC simulation



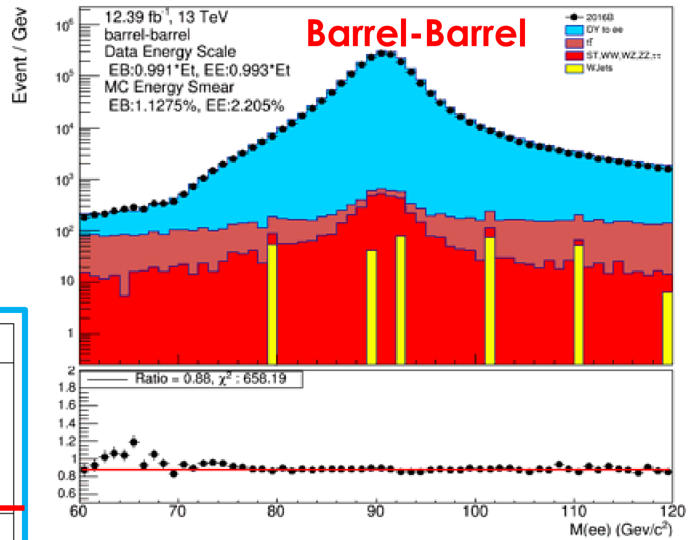


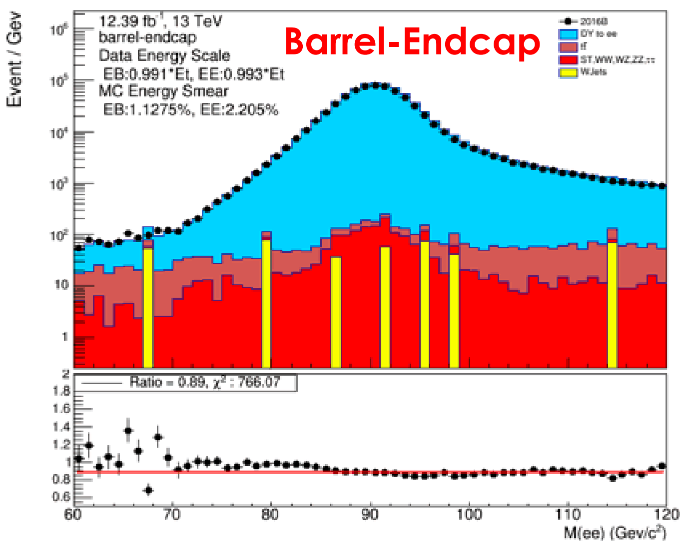
Backgrounds: Drell-Yan process

- It is predicted using MC simulation.
- For *ee* analysis it is main background and a cross check is performed by measuring the cross section of Z peak (60-120 GeV).

variable	barrel-barrel	barrel-endcap
nr data events (E corr)	1899912±1378	688938±830
nr expect bkg	11334	4133
MC acc×eff	0.0901±0.001	0.0324±0.001
data/MC Eff SF	0.923±0.001	0.927±0.001
cross-sec (E corr)	1831 ± 3 (stat) ± 109(lumi) pb	1841 ± 4 (stat) ±110 (lumi) pb

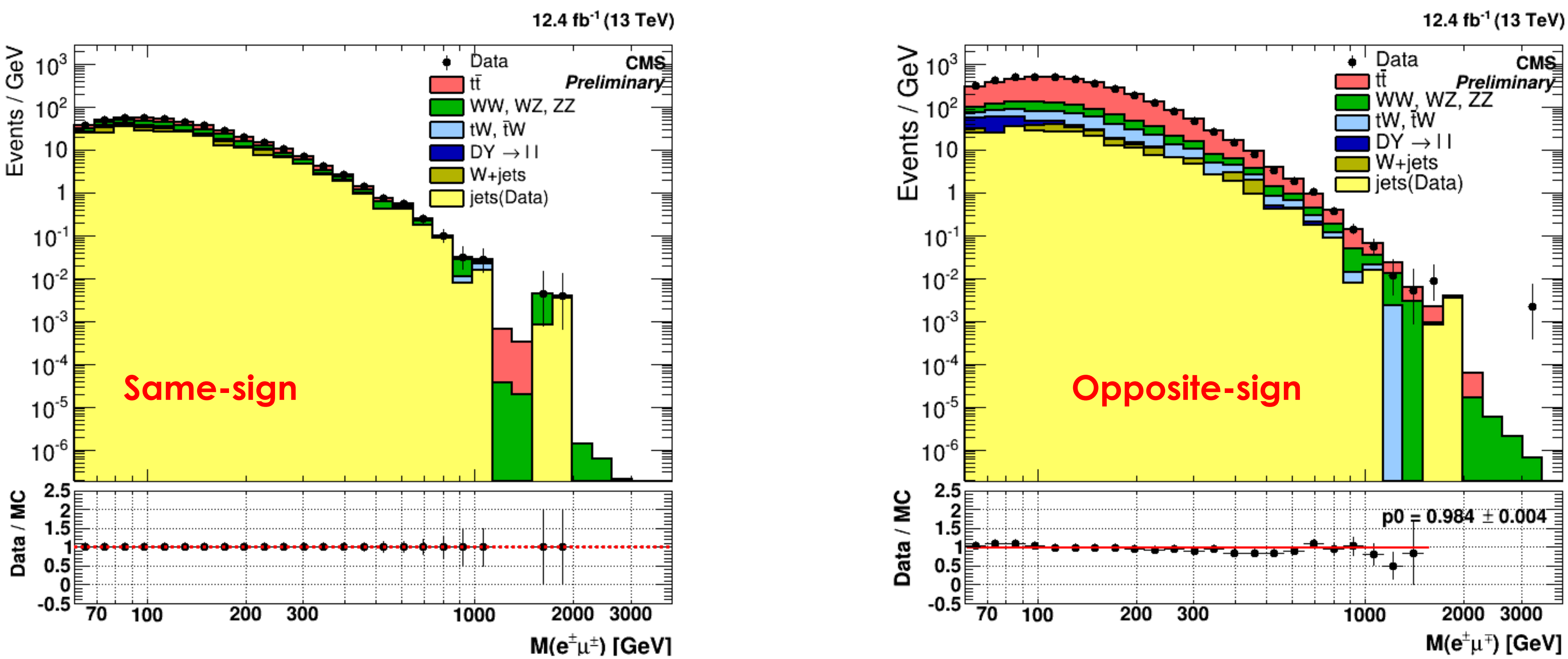
- Results: Consistent with theoretical prediction (1928 pb (NNLO)) within the uncertainty both for barrel-barrel and barrel-endcap channels.





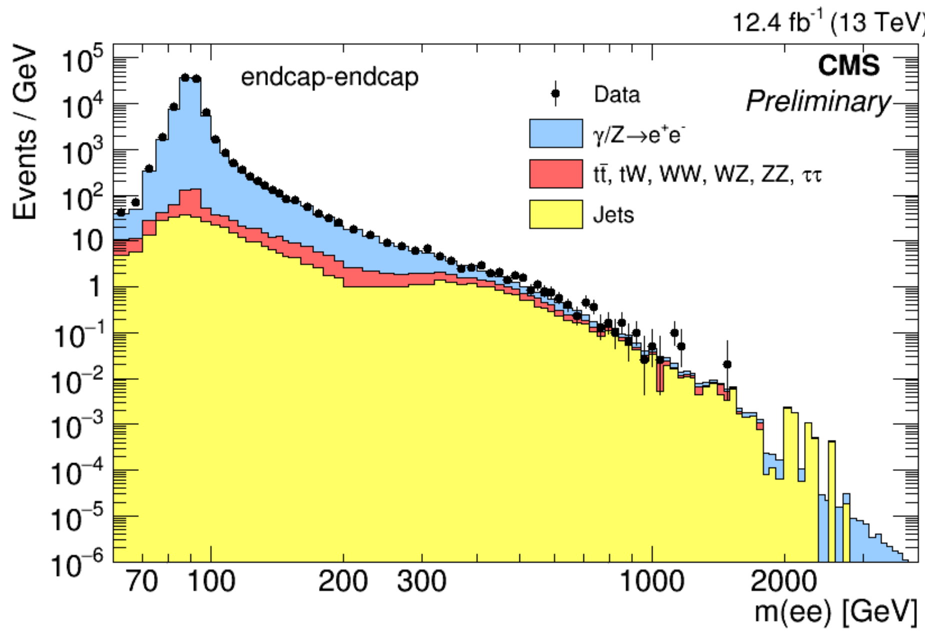
Backgrounds: $t\bar{t}$ and $t\bar{t}$ like

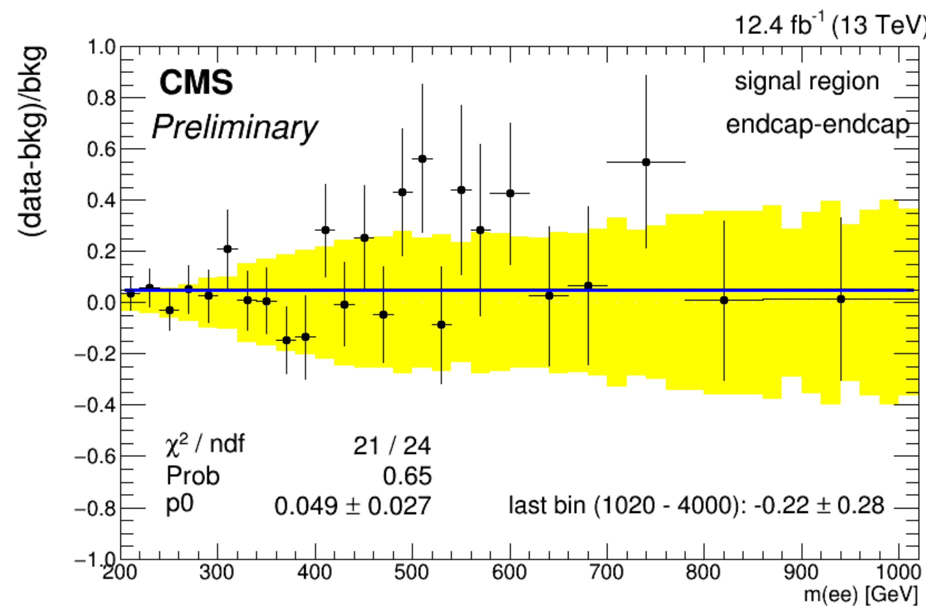
- Flavour symmetric backgrounds ($t\bar{t}, tW, WW, WZ, ZZ, Z \rightarrow \tau\tau$) are predicted by MC.
- For ee analysis these backgrounds are cross checked using the $e-\mu$ invariant mass spectrum.
  - Here the QCD contribution is estimated from same-sign region.
  - Good agreement between data and MC.



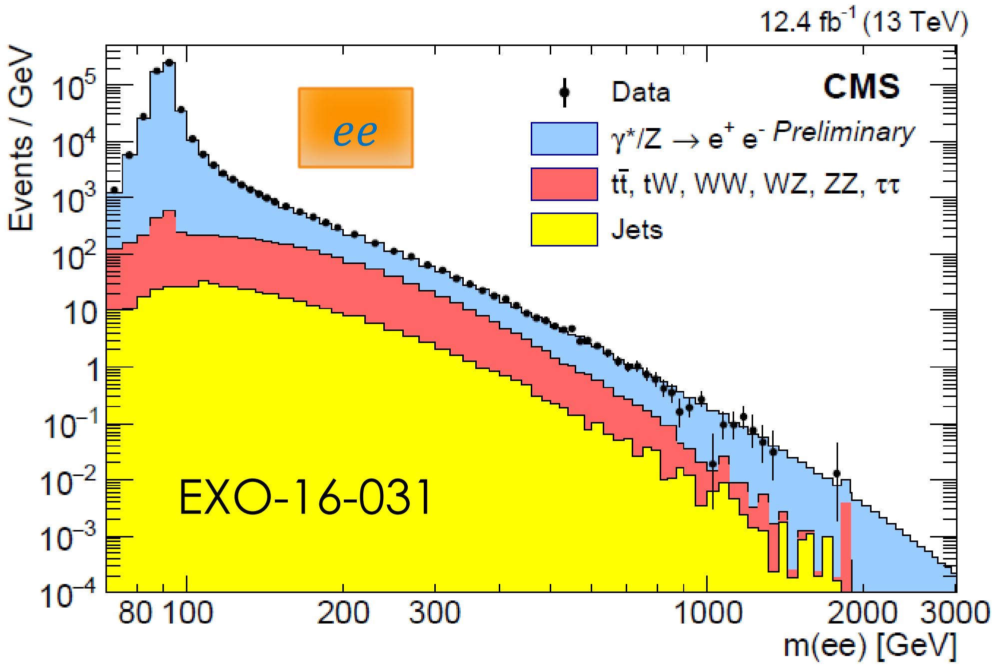
Jet Background: W+jets, multijet

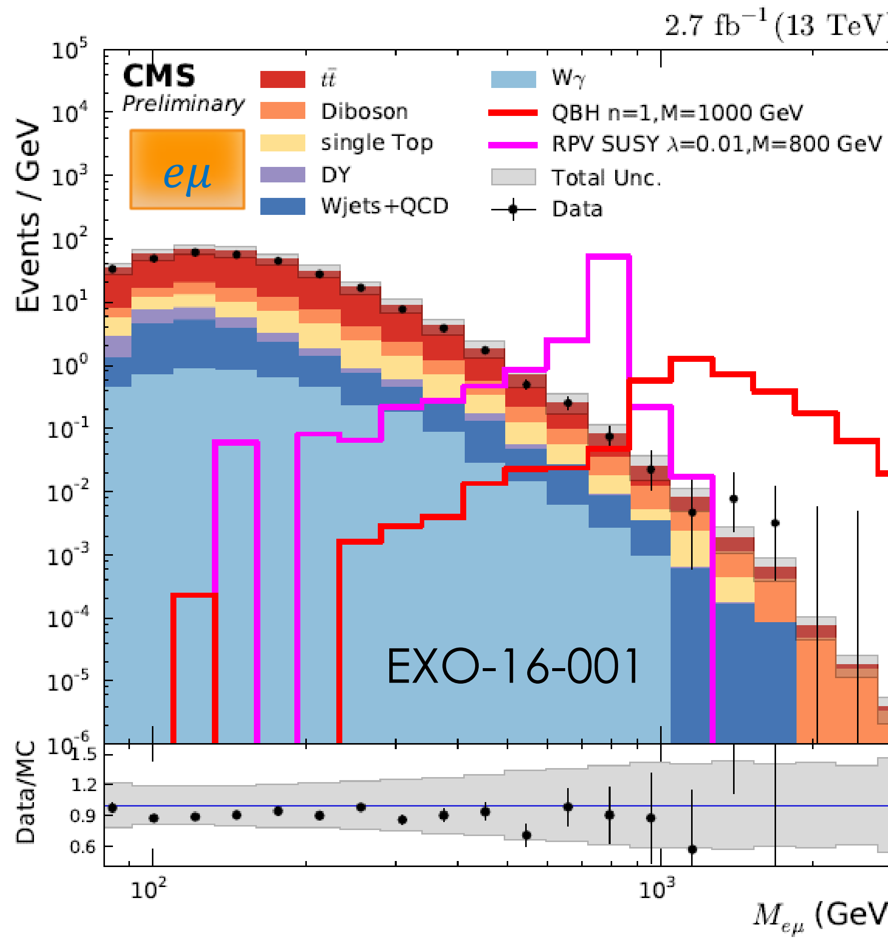
- When the jets are misidentified as electrons.
- Estimated using fake-rate method.
  - Fully data driven.
  - Quoting a 50% uncertainty.
- Validated in *ee* endcap-endcap channel which is mostly jets.
  - Very good agreement.





Mass spectrum





- For *ee* analysis: The MC in the Z peak is normalized to data.
- No evidence for a significant deviation from the SM expectations is observed.
- Systematic uncertainies are explained in next slide.

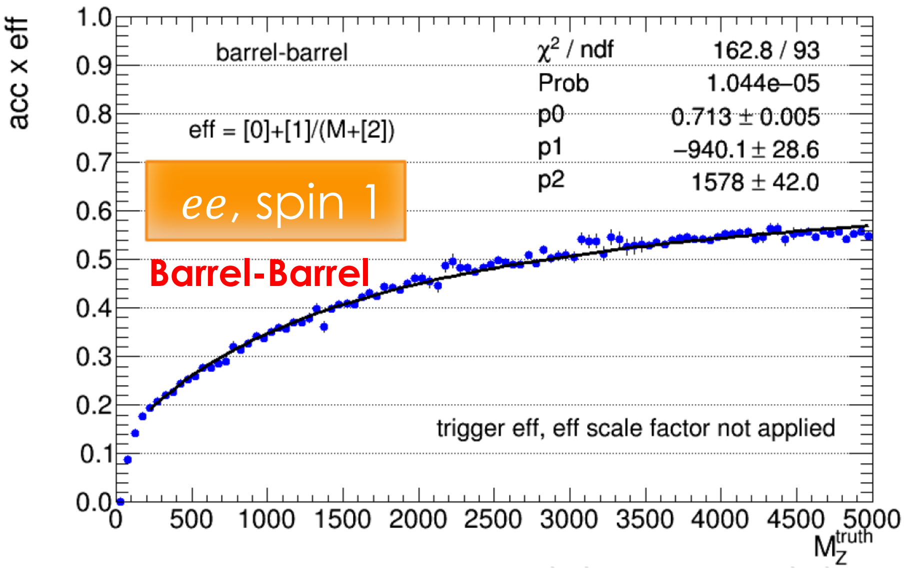
Systematic uncertainty

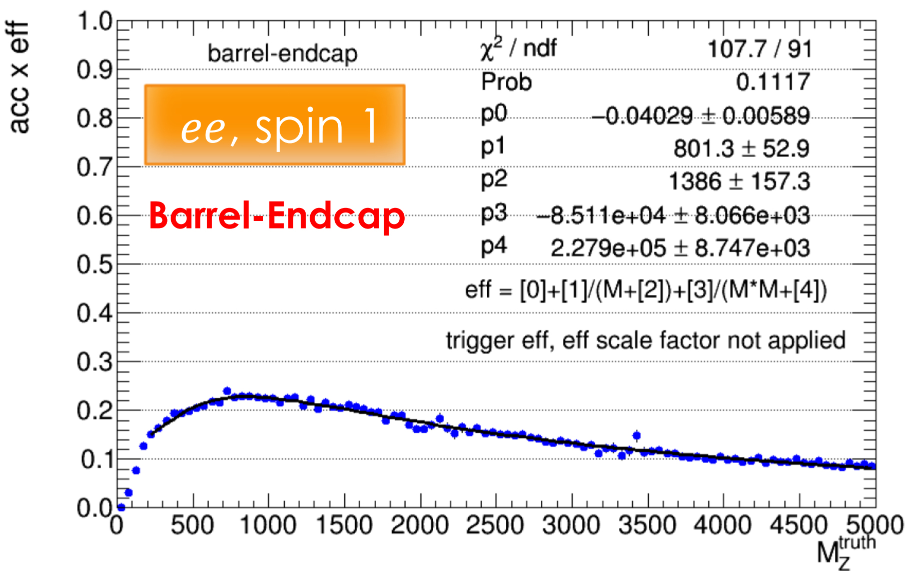
- For ee analysis:
  - Electron ID at high energy (assign 4%(Barrel) -6%(Endcap) per lepton).
  - DY PDF uncertainties (mass dependent) range from 5% at 400 GeV to 19% at 3 TeV.
  - Energy scale uncertainties (values @ RUN1 are 1-2%).
  - The jet background uncertainty (50%) and the non DY BG (7%).
  - Normalization at the Z peak (2%).
  - Here the luminosity uncertainty do not come in because we are calculating limit on R_σ .

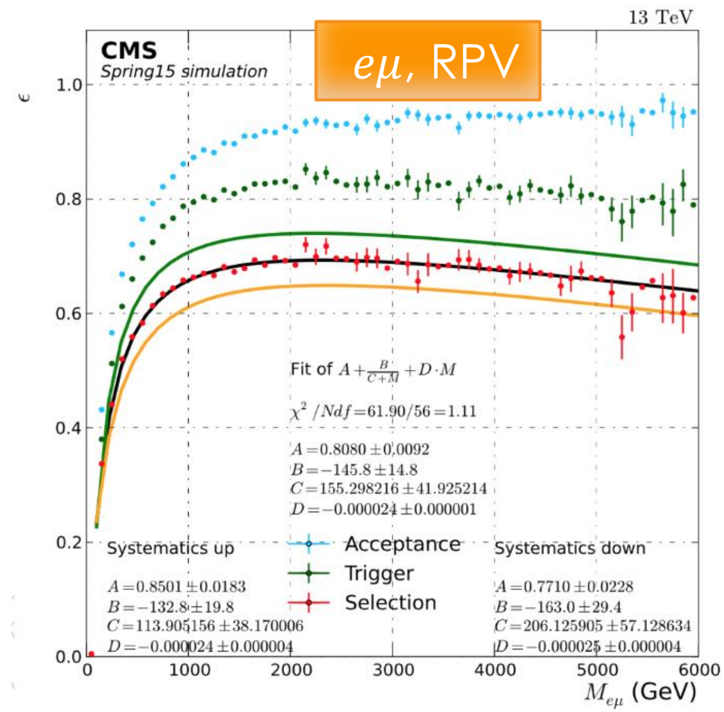
$$R_\sigma = \frac{\sigma(pp \to Z' + X \to e^+e^- + X)}{\sigma(pp \to Z + X \to e^+e^- + X)} = \frac{N(Z' \to e^+e^-)}{N(Z \to e^+e^-)} \times \frac{A(Z \to e^+e^-)}{A(Z' \to e^+e^-)} \times \frac{\varepsilon(Z \to e^+e^-)}{\varepsilon(Z' \to e^+e^-)}$$

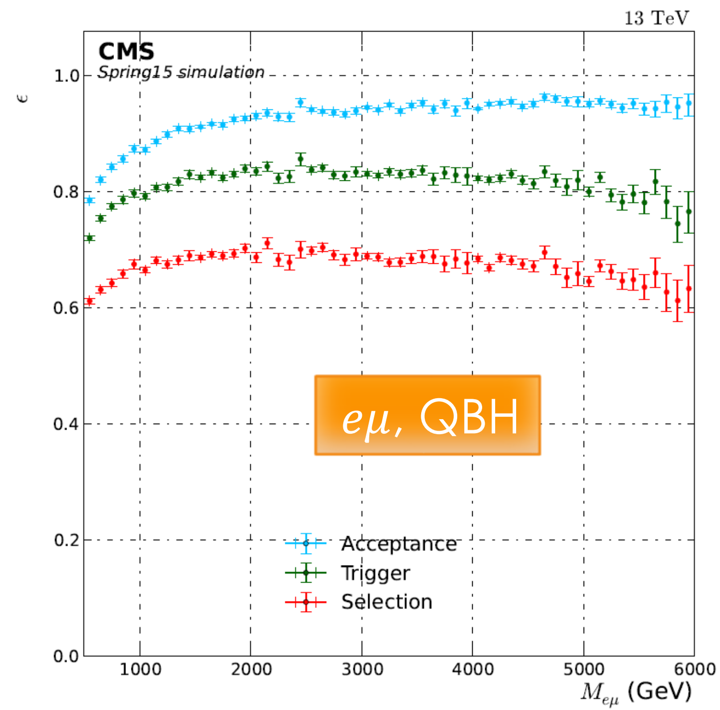
- For $e\mu$ analysis:
  - Luminosity (2.7%).
  - Pile-up (5%).
  - $t\bar{t}$ shape uncertainty.
  - PDF uncertainty : Officical PDF4LHC recommendations for run 2.
  - Muon Pt scale (10% per TeV), Pt resolution (4%).
  - Muon trigger SF (0.5%), ID and isolation SF (1%).
  - Electron energy scale (0.4% for barrel, 0.8% for endcap).
  - Electron ID at high energy (assign 4%(Barrel) -6%(Endcap) per lepton).
  - Normalization of background cross section : 5% for $t\bar{t}$, single top, DY, WZ, ZZ. 4% for WW. 50% for Wγ and jet background.

Acceptance × efficiency





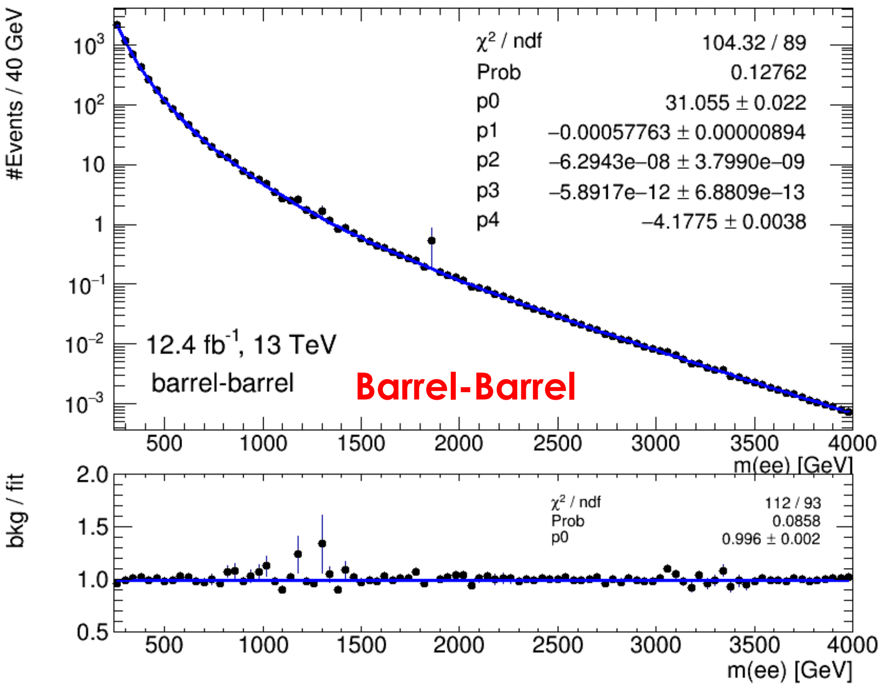


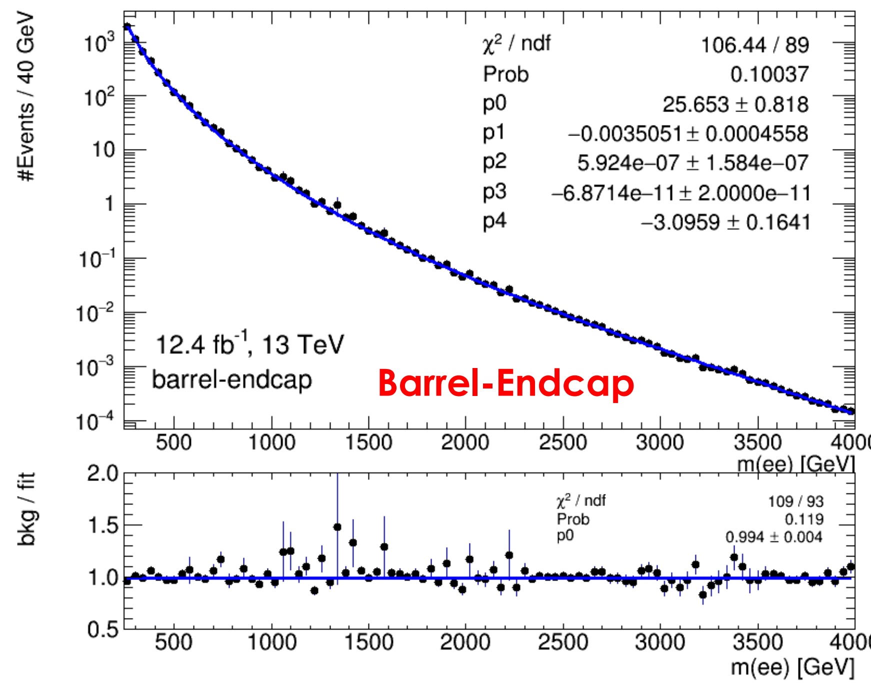


Background shape

- For ee analysis
  - Background shape comes from the fit of the MC + data-driven background.

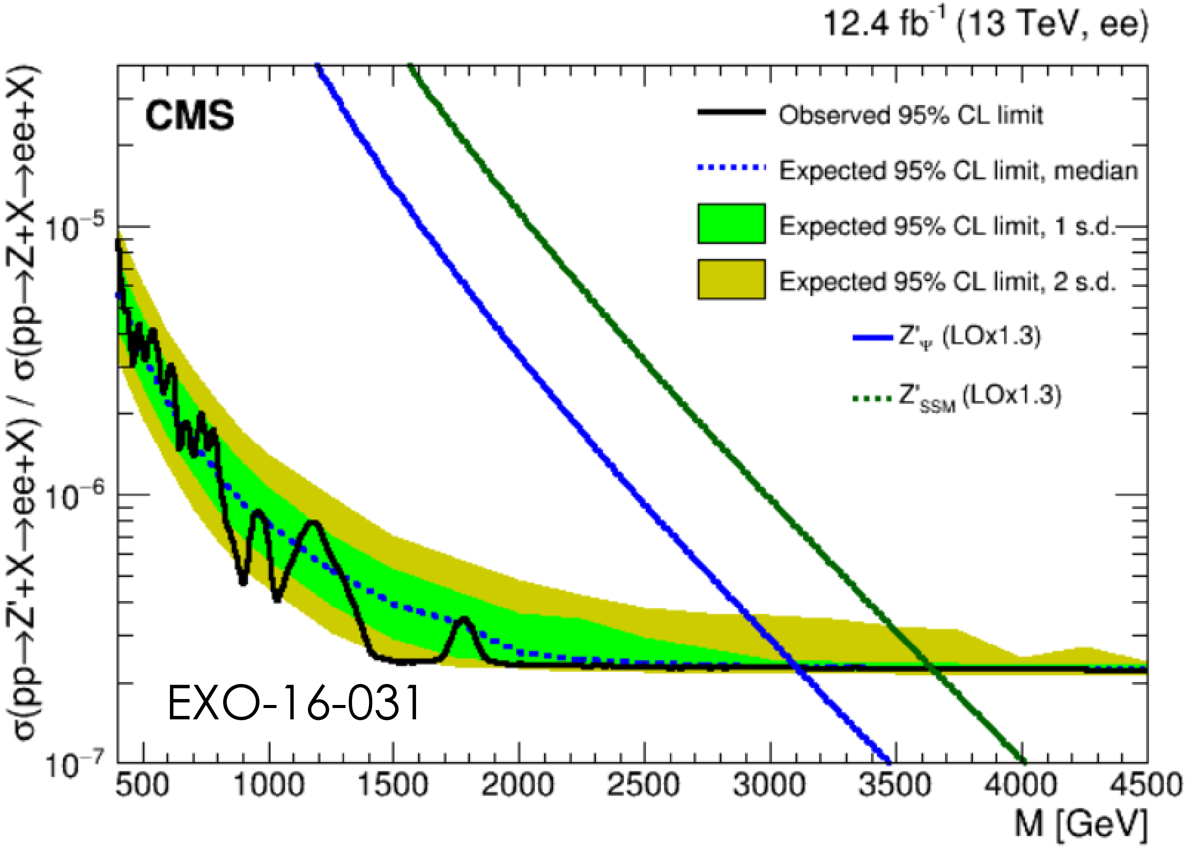
$$f = e^{am+bm^2+cm^3} * m^d$$





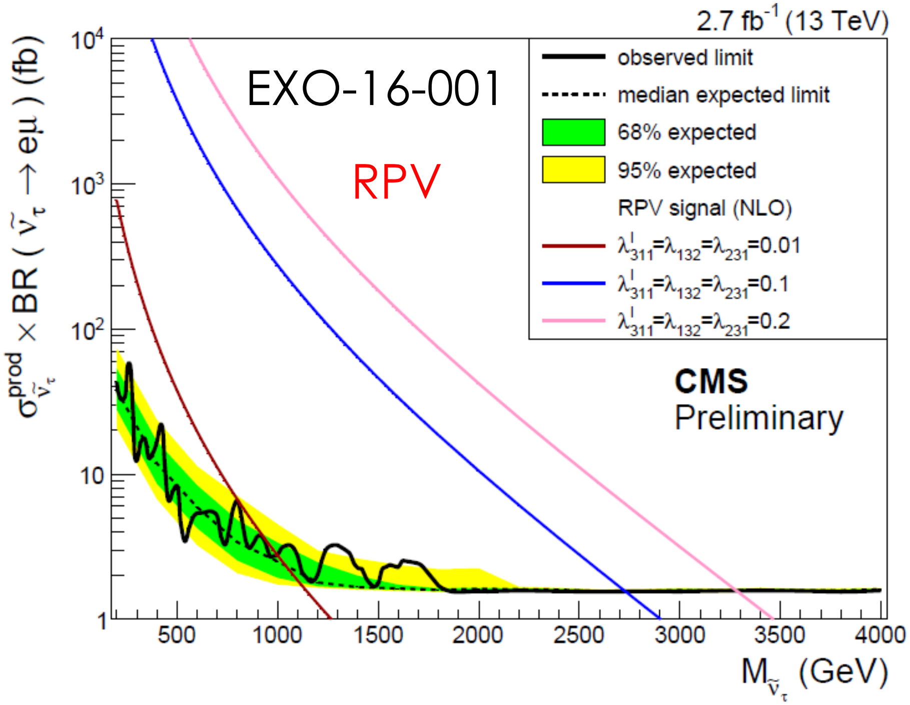
- For $e\mu$ analysis
  - Using histograms from MC + data-driven background and normalized to luminosity.

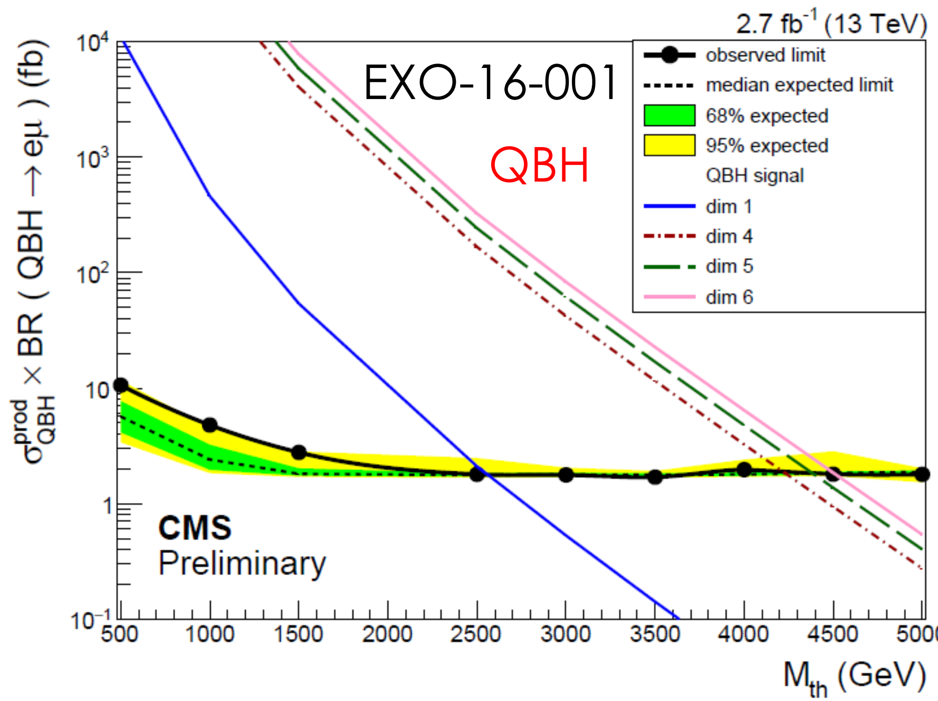
Result (limits) on *ee* analysis



	Obs.(Exp.) limit on threshold mass in TeV
$Z'(\Psi)$	3.1(3.1)
$Z'(SSM)$	3.6(3.6)

Result (limits) on $e\mu$ analysis





Coupling	Obs.(Exp.) limit on mass of τ-sneutrino in TeV
$\lambda'_{311} = \lambda_{132} = 0.01$	1.0(1.0)
$\lambda'_{311} = \lambda_{132} = 0.1$	2.6(2.5)
$\lambda'_{311} = \lambda_{132} = 0.2$	3.1(3.1)

N_{dim}	Obs.(Exp.) limit on threshold mass in TeV
N=1 (RS)	2.5(2.5)
N=4 (ADD)	4.2(4.2)
N=5 (ADD)	4.3(4.3)
N=6 (ADD)	4.5(4.5)

Summary

- Searching heavy resonances decay to ee $(e\mu)$ final state have been preformed using 12.4 (2.7) fb^{-1} CMS 13 TeV data.
- Final mass spectra looking healthy and shows no relevant excess over the background.
- Upper limits are set on cross section ratio of Z' model for ee analysis and the cross section of $\boldsymbol{\tau}$-sneutrino and QBH for $e\mu$ analysis.
- The analysis with full 2016 data is on-going, hope to see it soon.

Thank You For Your Attention!

Backup

ΔM/M vs DPG scale corrections @ 12.9/fb

Given that: $M_{ee} = \sqrt{E_1 E_2 (1 - cos(\theta))}$

- the Mass scale $\approx \sqrt{scale(1) \times scale(2)}$

Using DPG mean scale corrections (0.991 for EB and 0.993 for EE):

- $(Mass\ scale)_{EBEB} \approx mean\ scale\ EB\ per\ electron = 0.9\%$
- $(Mass\ scale)_{EBEE} \approx \sqrt{mean\ scale\ EB \times mean\ scale\ EE} = 0.7\%$

To be compared with $\frac{\Delta M}{M}$ of Table 5:

- $(Mass\ scale)_{EBEB} \approx 0.8\%$ (vs 0.9%)
- $(Mass\ scale)_{EBEE} \approx 0.7\%$ (vs 0.7%)

σ_{extra} vs DPG smearings @ 12.9/fb

Smearing coefficients ($smear$) can be thought as relative errors on the energy, so:

- $smear = \frac{\Delta E}{E}$

The σ_{extra} coefficient can be thought as the relative error on the mass:

- $\frac{\Delta M}{M} = \frac{1}{2}\sqrt{(\frac{\Delta E_1}{E_1})^2 + (\frac{\Delta E_2}{E_2})^2}$

Running the numbers:

$$(\frac{\Delta M}{M})_{EBEB} = \frac{1}{2}\sqrt{2 \times (mean\ smear\ in\ EB)^2} = \frac{(mean\ smear\ in\ EB)}{\sqrt{2}} \quad (1)$$

$$(\frac{\Delta M}{M})_{EBEE} = \frac{1}{2}\sqrt{(mean\ smear\ in\ EB)^2 + (mean\ smear\ in\ EE)^2} \quad (2)$$

mean smear in EB $\approx$ 1.127
mean smear in EE $\approx$ 2.205

$(\frac{\Delta M}{M})_{EBEB} \approx 0.79$ vs fitted value of 0.71 (see σ_{extra} Table 5)

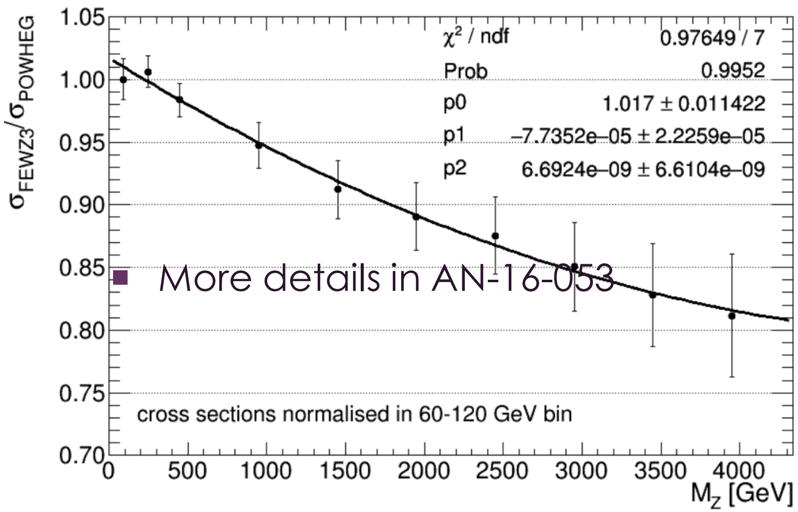
$(\frac{\Delta M}{M})_{EBEE} \approx 1.24$ vs fitted value of 1.26 (see σ_{extra} Table 5)

Uncertainties on the DY Background

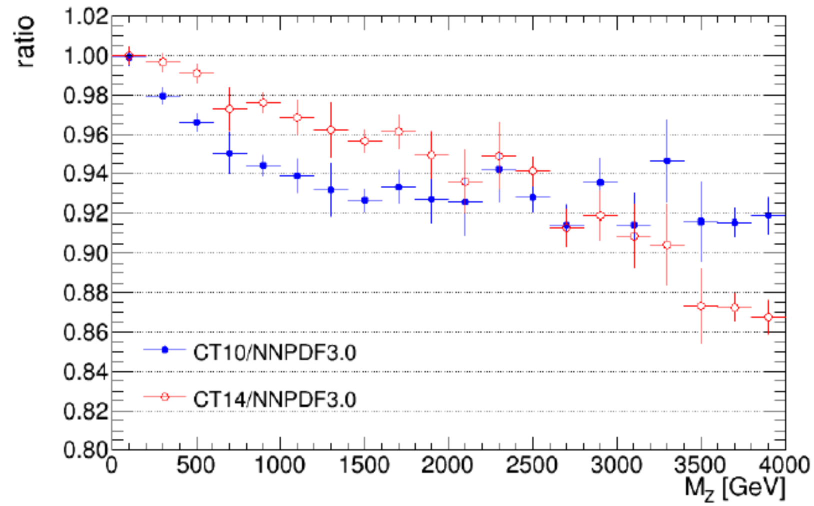
- The main uncertainties on the Drell-Yan background come from PDF and NNLO effects.

- Left figure shows the ratio of FEWZ3 cross-sections to that predicted by our POWHEG samples generated with NNPDF3.0. It is noted that the POWHEG NNPDF3.0 prediction is increasingly higher than the FEWZ prediction when the mass increases. (see the mass spectrum after applying the reweighting on slides 25)(Note: QCD(NNLO) and EWK(NLO) corrections are include in FEWZ and this is without detector simulation and particle reconstruction in both cases)

- Right figure shows the ratio of the POWHEG cross-section predictions when using CT10 and CT14 over the prediction using NNPDF3.0. The ratio decrease when the mass increase. It should be noted that ATLAS in their 2015 result used CT10.



- More details in AN-16-053



- The PDF uncertainties relative to Z peak region for FEWZ 3.1 at NNLO with the PDF4LHC15nnlo PDF set :

mass range (GeV)	200-300	400-500	900-1000	1400-1500	1900-2000	2400-2500	2900-3000	3400-3500	3900-4000
relative uncert	1.6%	1.9%	2.4%	2.9%	3.5%	4.0%	4.8%	5.1%	7.3%

Limit results

- Likelihood (Note that background amplitude information from sidebands is in this likelihood.)

$$\mathcal{L}(m|\theta,\nu) = \frac{\mu^N e^{-\mu}}{N!}\cdot\prod_{i=1}^{N}\left(\frac{\mu_{SIG}(\theta,\nu)}{\mu} f_{SIG}(m|\theta,\nu) + \frac{\mu_{BG}(\theta,\nu)}{\mu} f_{BG}(m|\theta,\nu)\right)$$

Background Model;

$$f_{BG}(m|\theta,\nu) = e^{am+bm^2+cm^3}\, m^d$$

Signal Model;

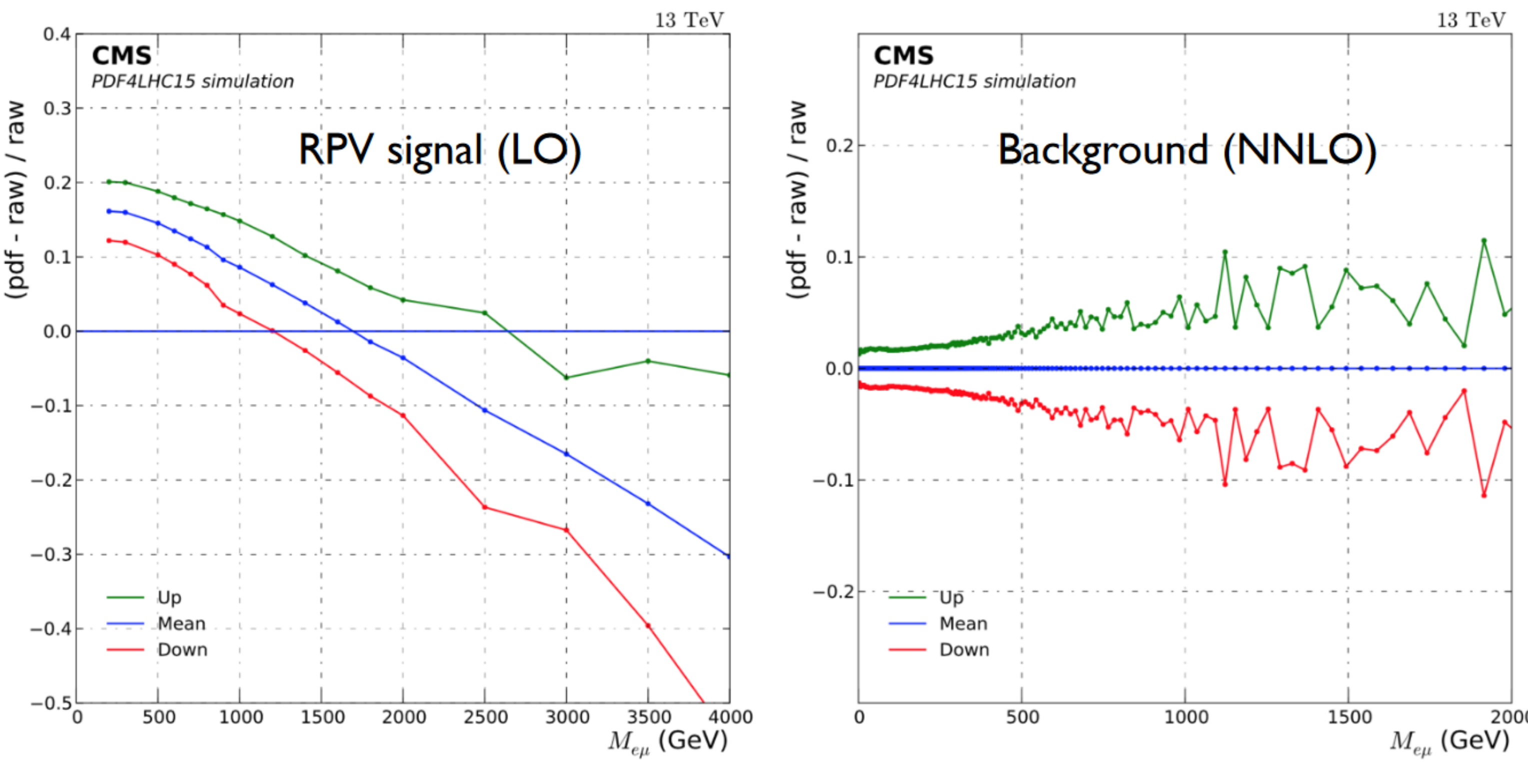
$$f_{SIG}(m|\theta,\nu) = BW(m|\Gamma)\otimes Gauss(m|\sigma)$$

- Using (pseudo) Bayesian method with known good frequentist properties and multipling this likelihood by priors: uniform in cross section (known good frequentist for upper limits), lognormal representing uncertainties for systematics in quantities such as scale etc. and vague prior for background amplitude, so that sidebands in likelihood determine background amplitude, not the prior.
- likelihood times priors = posterior. Inference is from posterior: we integrate out nuisances, etc. The integration is doing via the Metropolise-Hasting algorithm .
- Results are presented as a ratio of cross sections at high mass to those at the Z.
- Many uncertainties cancel out, especially those independent of mass (both known and unknown) and the CMS luminosity measurement cancels out in the ratio.

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to e^+e^- + X)}{\sigma(pp \to Z + X \to e^+e^- + X)} = \frac{N(Z' \to e^+e^-)}{N(Z \to e^+e^-)} \times \frac{A(Z \to e^+e^-)}{A(Z' \to e^+e^-)} \times \frac{\varepsilon(Z \to e^+e^-)}{\varepsilon(Z' \to e^+e^-)}$$

PDF Uncertainty

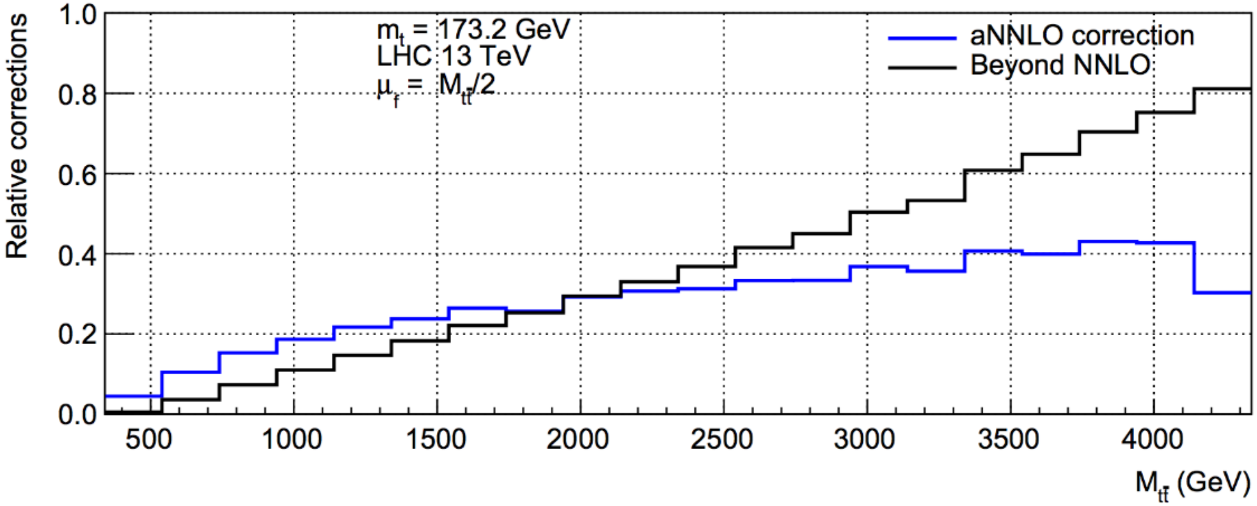
- Evaluated using the Run 2 PDF4LHC recommendation. Used PDF4LHC15_mc set with 100 Monte Carlo replicas
- PDF uncertainty on event yield is difference between colored lines



Mean of 100 replicas : $\alpha_S(M^2_Z)$=0.118, Down variation : $\alpha_S(M^2_Z)$=0.1165, Up variation : $\alpha_S(M^2_Z)$=0.1195

Reweighted sample : labelled 'pdf', unweighted sample from the generator : labelled 'raw'

ttbar shape uncertainty

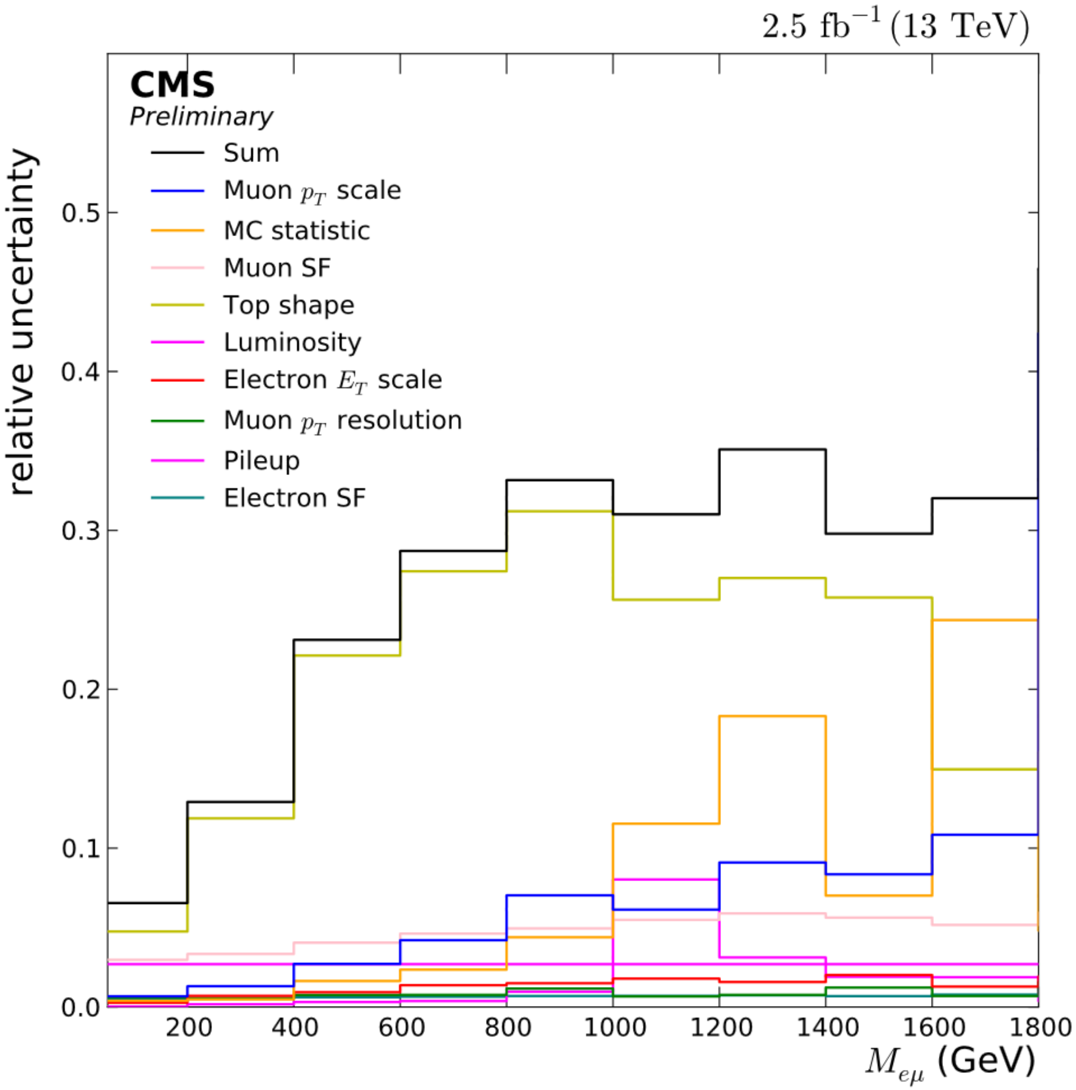


arxiv 1601.07020 v2

Theory paper by Benjamin D. Pecjak, Darren J. Scott, Xing Wang, Li Lin Yang

- Plot shows relative cross section difference w.r.t MCFM NLO calculation.
- Full difference split in two parts → we combine them
- From this, obtained event weights (up,down) for our NLO POWHEG simulation as a function of M(ttbar)
- MC samples reweighted. Obtained the M(e,mu) distribution up/down → get M(e,mu)-dependent uncertainty estimate.
- Corrections not applied to ttbar baseline estimate. Only used to get an uncertainty.

Systematic Uncertainty - Impact on $M_{e\mu}$ distribution



- Dominant uncertainty ttbar shape
- Muon pT scale important in high mass

Statistical Interpretation

- No significant excess w.r.t SM expectation.
- Limit Setting Procedure : Shape-based limit using binned likelihood.
  - 95% CL exclusion limits on signal cross-section times branching ratio using Higgs combine tool
  - MarkovChainMC Bayesian method with flat prior for signal cross section
  - **Background** → Histograms from MC/data-driven fake estimate normalized to $\sigma.BR.L_{int}$
  - **QBH signal** → Shape taken directly from MC, normalized to $\sigma.BR.L_{int}$
  - **Resonant RPV signal** → Modelled with a single Gaussian, width taken from fit to mass resolution, scaled to $\sigma.BR.A.\epsilon.L_{int}$ → Allows fine scan of invariant mass spectrum according to resolution.

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