Search for narrow resonances in the lepton final state at CMS

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New resonances

- Popular BSM models predict narrow resonances that would decay to a pair of leptons. We use as benchmarks
  - Sequential Standard Model Z'
    - Couplings similar to the Standard Model ones
  - Superstring-motivated (ψ) Z'
    - Motivated by grand unification considerations, E6
  - Kaluza-Klein graviton excitations in Randall-Sundrum model

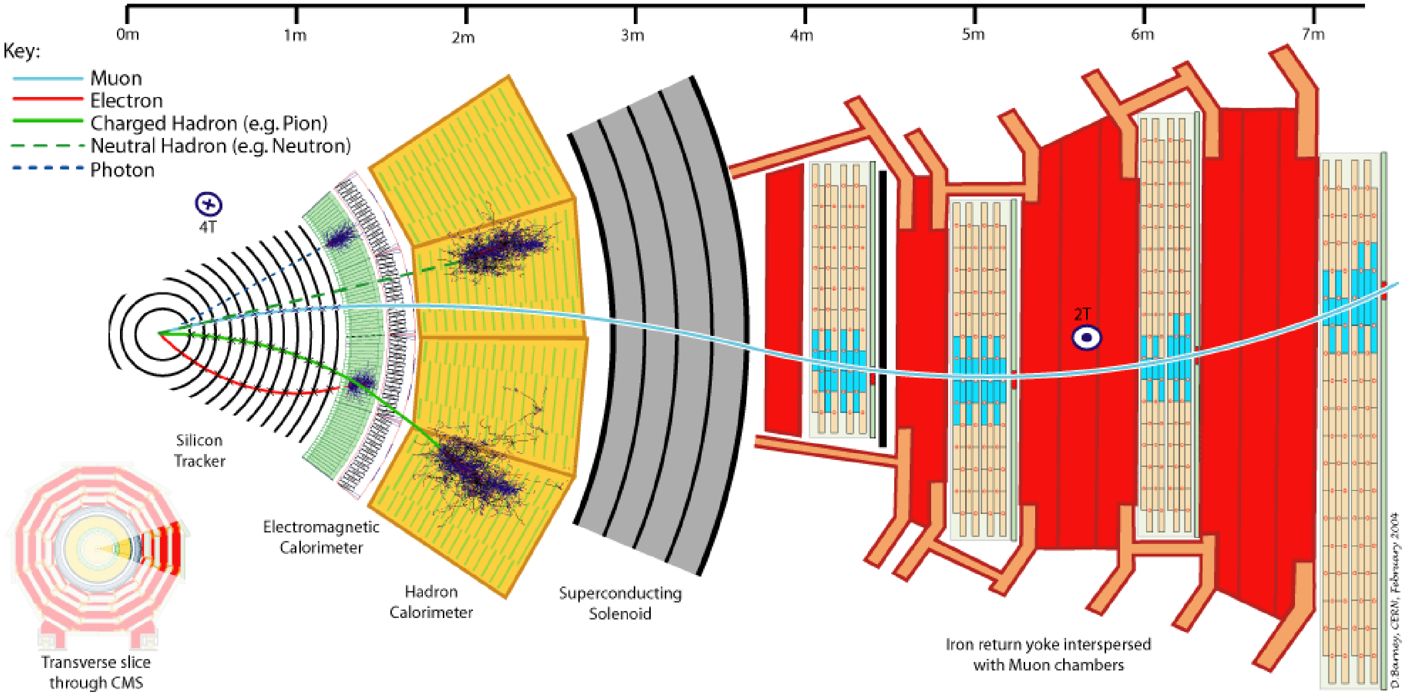
The CMS experiment

Fine-grained ECAL and HCAL for precise measurement of EM/hadronic energies – $\Delta E/E < 0.5\%$ for $E > 100$ GeV.

→ Excellent m_{ee} resolution, but challenge is on id of e vs. jets!

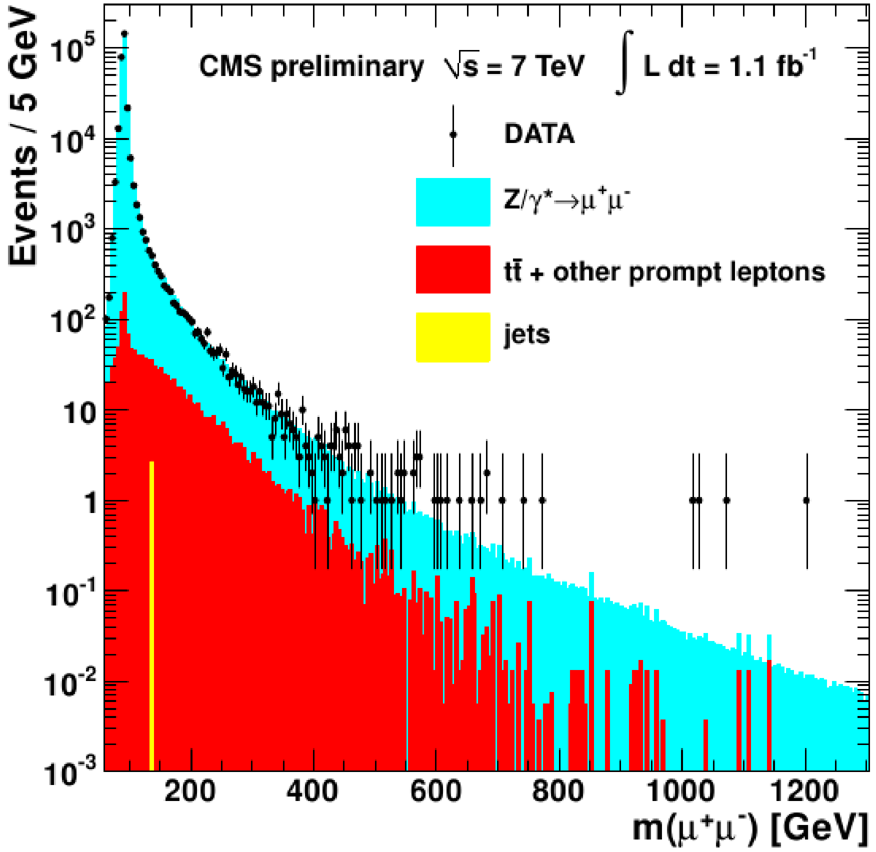
Inner silicon tracker in 3.8 T magnetic field, plus muon system for triggering, id, and to improve high-p_T measurement – together with tracker, $\Delta p_T/p_T < 10\%$ at $p_T \sim 1$ TeV.

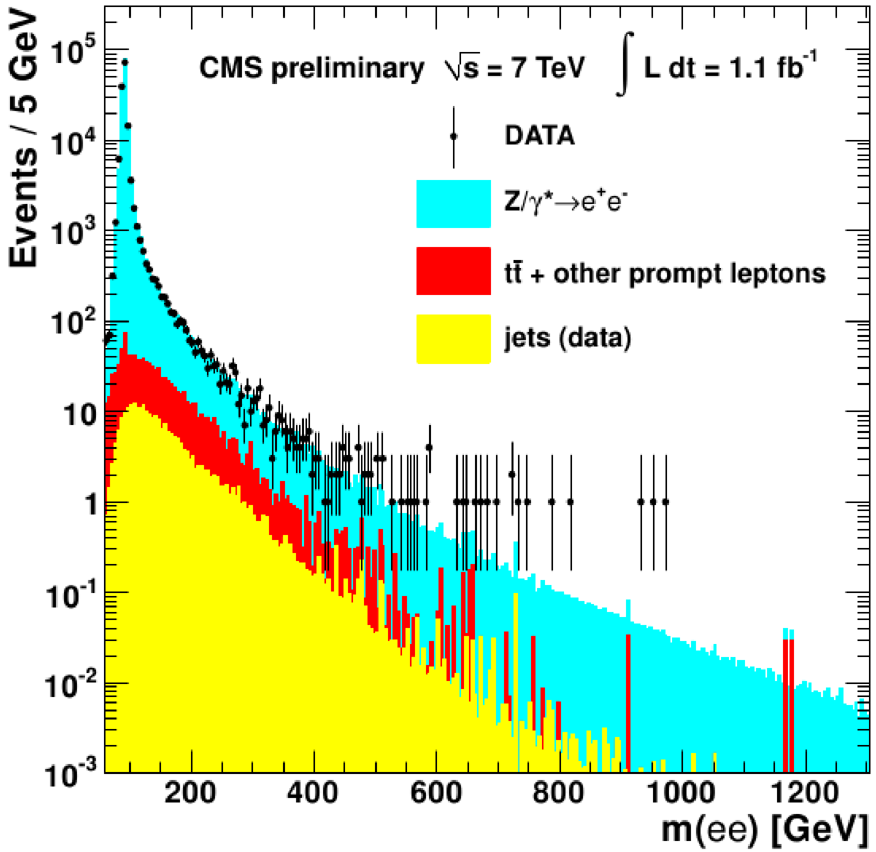
→ Muon id much easier, but challenge is to improve $m_{\mu\mu}$ resolution!



Analysis strategy

- We perform a shape-based analysis to search for a resonance over the Drell-Yan continuum using an unbinned maximum likelihood fit without any normalization assumption
- Results are interpreted in terms of a ratio: $$\frac{\sigma \times BR(Z')}{\sigma \times BR(Z^0)} = \frac{N(Z')}{N(Z^0)} \times \frac{A(Z^0)}{A(Z')} \times \frac{\epsilon(Z^0)}{\epsilon(Z')}$$
- Taking the ratio makes the analysis robust against absolute normalization (luminosity) and many known and unknown systematic effects





Difference between ee and μμ

- E_T/p_T measurement with calorimeter/tracking
  - Opposite charge requirement only used for muons
  - Muon resolution gets worse with energy, electron resolution gets better
- But for muons we can use cosmics to do data-driven studies of reconstruction performance
- Electrons have higher backgrounds from fakes (eg. QCD)
  - Tighter ID cuts and smaller acceptance

Trigger and lepton reconstruction

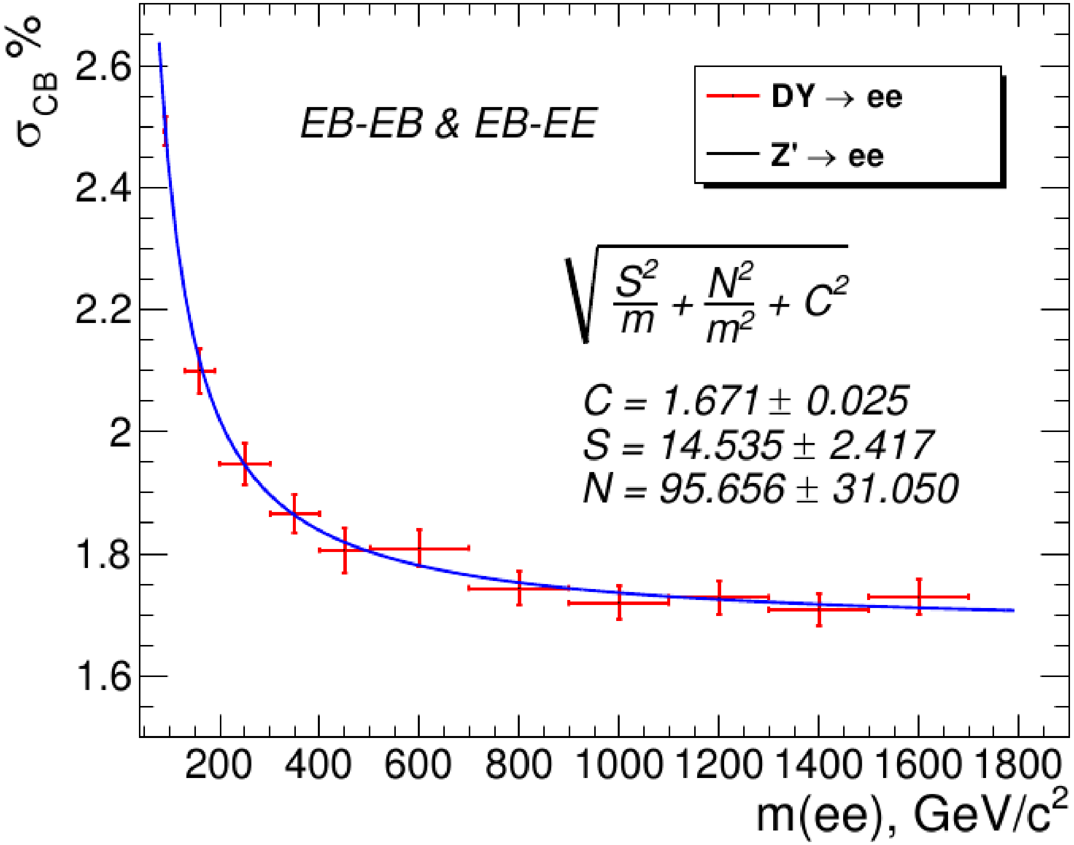
- Trigger
  - Sufficiently high-p_T muon (30 GeV) matched to a track in the silicon tracker
  - Two sufficiently energetic ECAL clusters (33 GeV), with the corresponding HCAL deposit small (<15%), at least one matches the L1 deposit. In later portion of the data, required a match to the pixel hits.
- Lepton Reconstruction
  - The track consistent with the collision point
  - Topologically isolated from hadronic signatures
  - Sufficiently energetic in the transverse plane
  - Muons. Global fit of a muon detector track and a silicon track with appropriate quality requirements
    - Enough hits in the silicon and the pixel trackers
    - Extrapolated tracker-only track matches enough muon system hits
  - Electrons. ECAL cluster associated with the track in the silicon tracker, with quality requirements
    - An ECAL cluster seeds a pixel track
    - The pixel track seeds the silicon track
    - Require enough hits in the silicon, the candidate within the acceptance, the energy deposit mostly in ECAL
    - Transverse shape of the energy deposit must be consistent with an electron signature
    - Good match between the track and the cluster

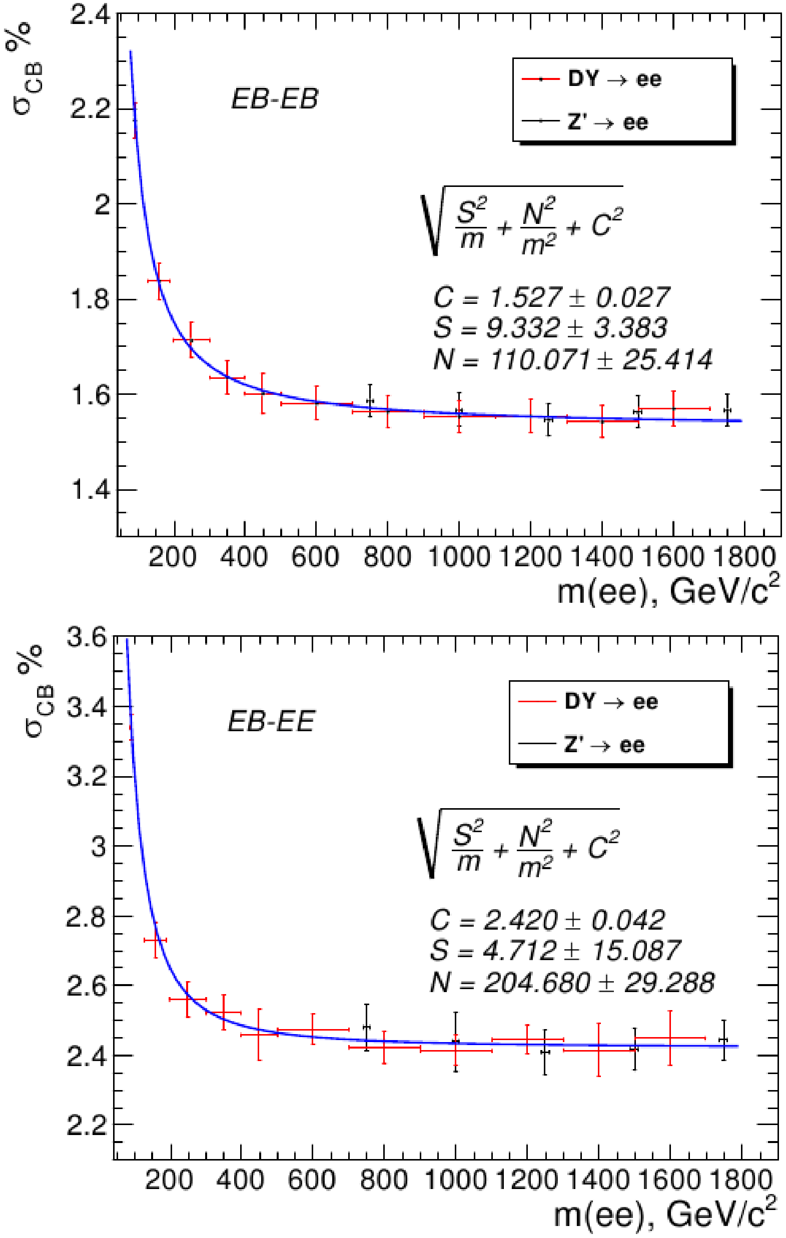
Event selection

- Require a well-reconstructed primary vertex (cosmic bacground)
- Muons
  - Suppress events with a large fraction of poorly reconstructed tracks (beam background)
  - Two muons of the opposite charge
  - One of them has to be matched to an HLT muon
  - Suppress muons that move almost exactly in the opposite directions, to suppress cosmics
  - Additional muon reconstruction quality requirement: we require the dimuon vertex-constrained fit to have $\chi 2 < 1$
  - One of the muons must match the trigger muon
- Electrons
  - Two electrons, at least one of them in the barrel part of the detector (no opposite charge requirement)
  - Topological considerations against the electrons from photon conversions

Energy scale and resolution

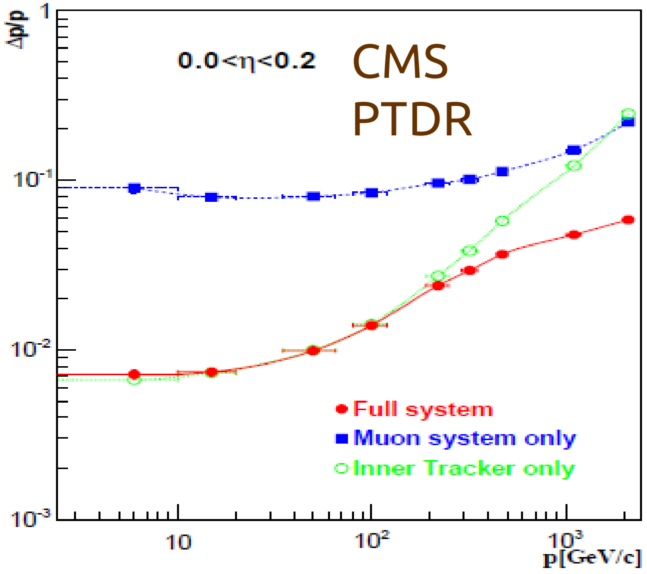
- Model the resolution with the Crystal Ball shape
- Fit $Z^0 \rightarrow ee$ peak in data and MC with the signal shape convoluted with Crystal Ball and smear MC if needed
- Take resolution from MC

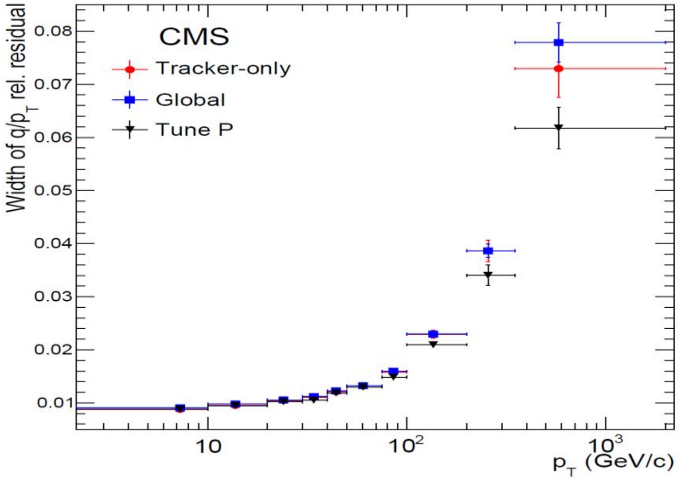




Momentum and mass resolution

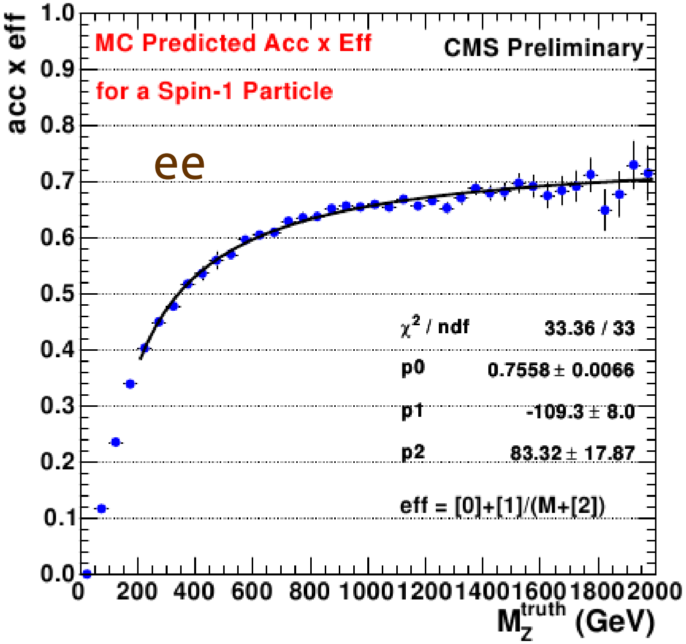
- Narrow mass peak broadened by resolution. Adding muon system hits to tracker-only fit helps for $p_T > \sim 200$ GeV:
- But energy loss in steel yoke and showers in muon chambers can spoil fit.
- More degradation where muon system not precisely aligned to tracker.
- Use muon hits selectively: take only first station with hits, drop incompatible hits in chambers flooded by showers, etc.
- Can do better choosing between these algorithms track-by-track ("Tune P" on the plot).
- Gauge impact in data using cosmic-ray muons, reconstructing both halves separately and comparing fits.
- Unlike electrons, for the muons the resolution is worsen with mass

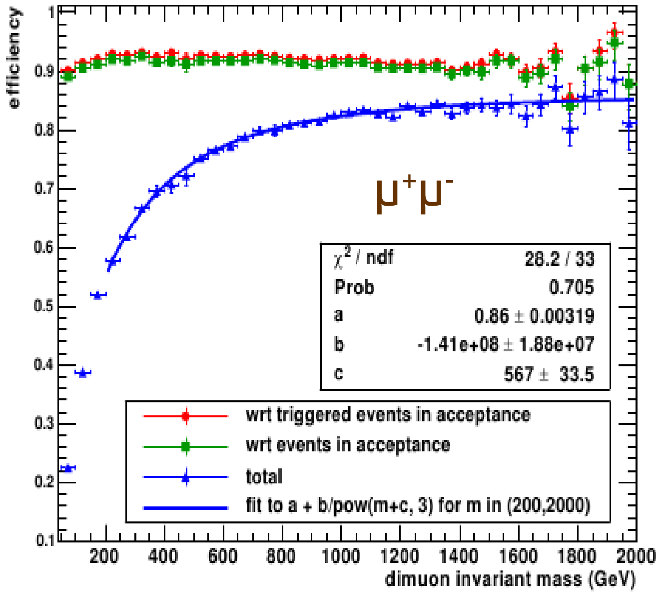




Efficiency

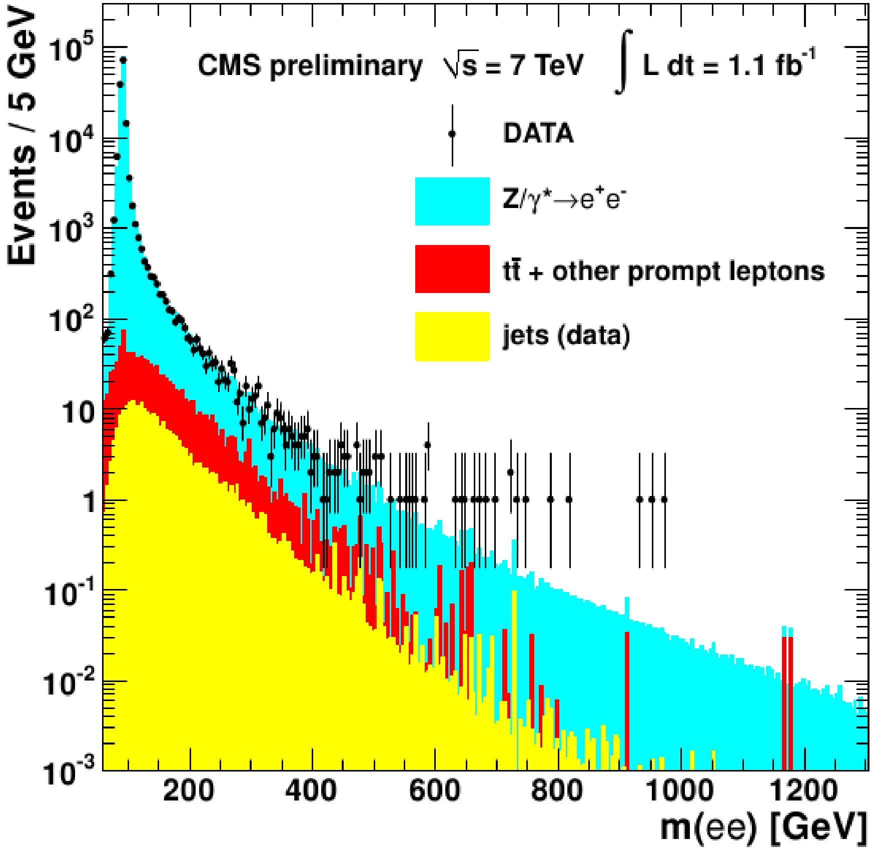
- Trigger, ID and lepton reconstruction
  - “Tag and probe”: from high-purity sample of Z events
  - Muon trigger efficiency ~90-95% depending on the detector region, data/MC scale factors ~0.97-0.98
  - Tracking efficiency ~99%
  - Muon ID ~96%, with data/MC scale factors ~0.98-1.0
  - Double EM cluster trigger efficiency ~100%, with scale factors ~1.01-1.02
- Event selection and acceptance from MC
- In the cross section ratio, scale factors and much of uncertainty cancel out





Lepton pair background

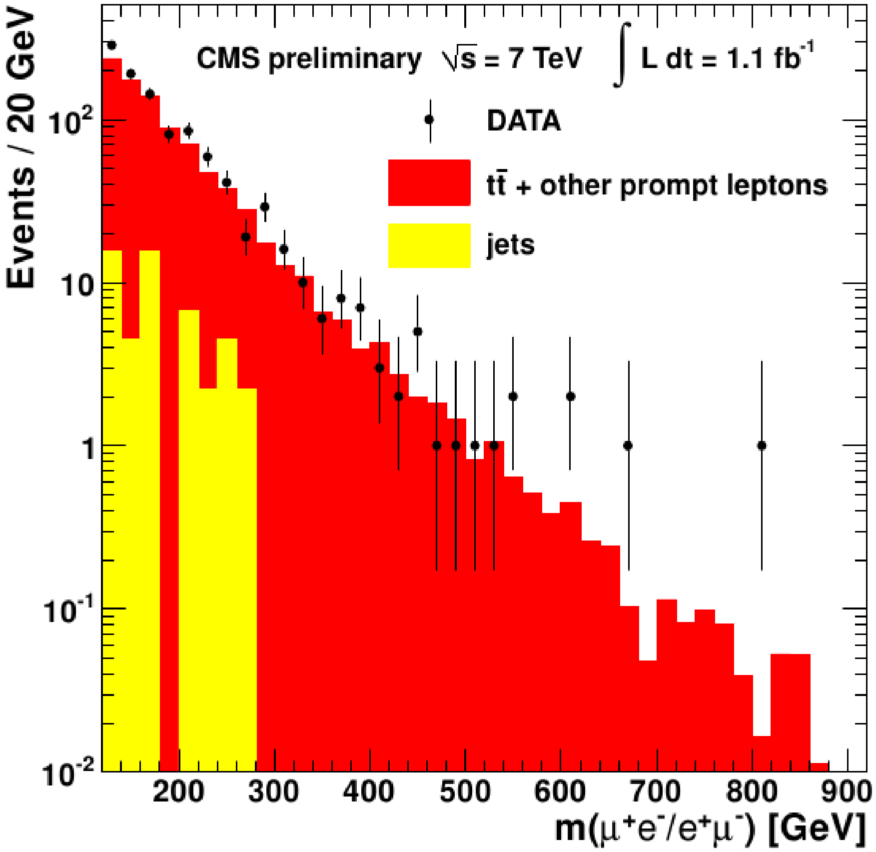
- Drell-Yan: dominate irreducible background
  - Shape from MC, normalize to the Z peak
  - Relative uncertainty when normalizing to the Z pole is ~10% in the mass range of interest. Include as systematic uncertainty, negligible effect on the limits



- Top pair and other "top-like" events.
  - The next biggest contribution, ~5-10% of Drell-Yan in the mass range of interest
- Jet misidentification.
  - 1-5% depending on the channel
  - Estimate from the data with loosened selection
  - Estimate with same-sign muons
- Cosmic muons.
  - Estimate to be negligible (less than 0.1 event) in data sidebands.

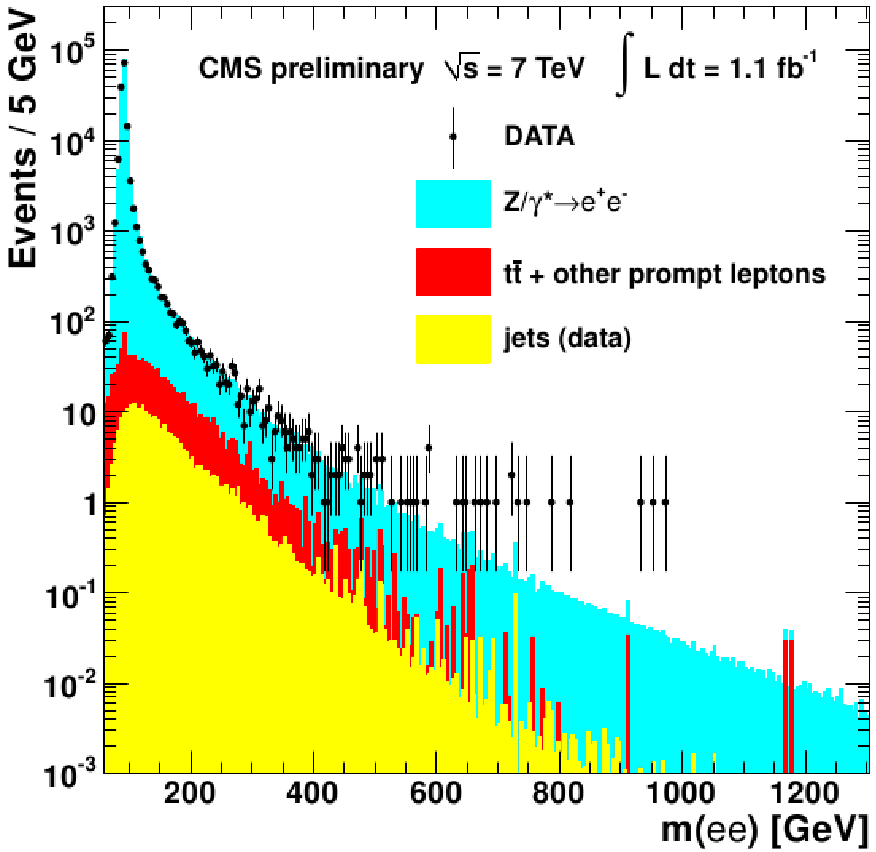
Top-like background

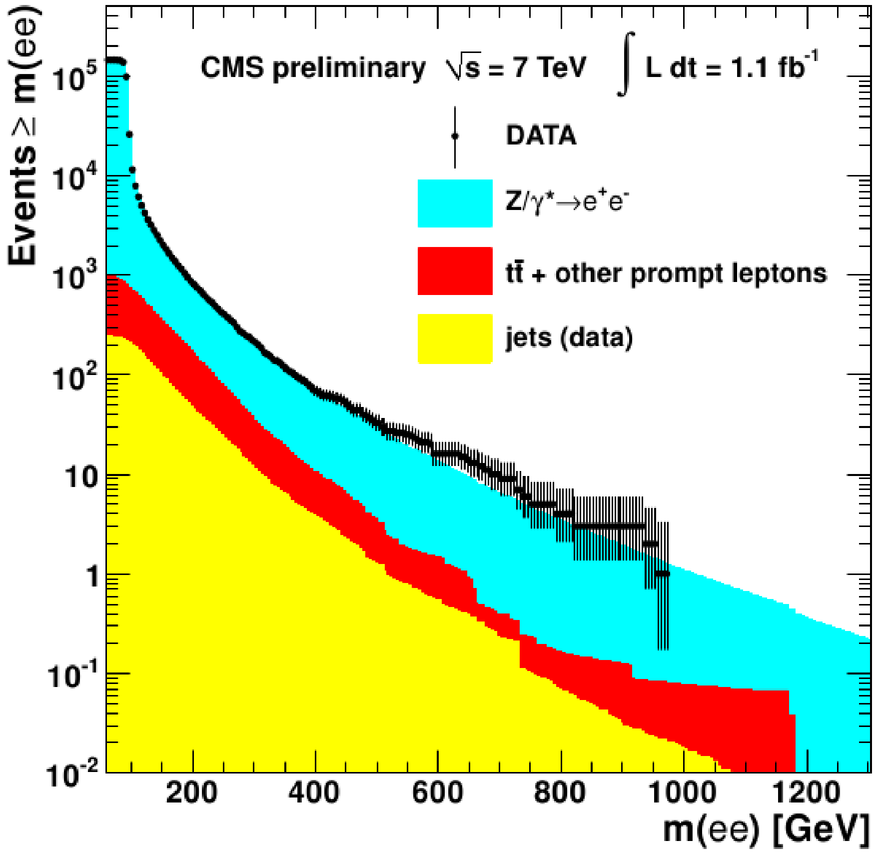
- "eμ" method.
  - Expected two eμ events for each ee and μμ event
  - Correction factor due to different efficiencies
- Currently, we do it as a cross check and do not use the shape in the fit
- Observe an agreement between data and MC



Electron pair mass spectra

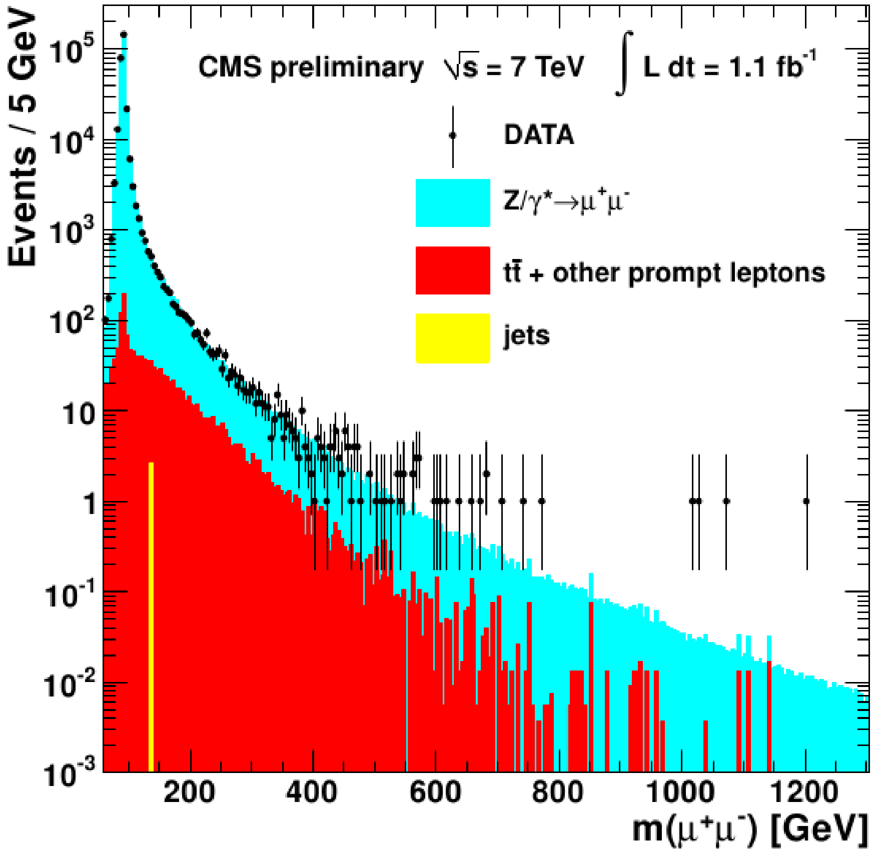
- “Other prompt leptons” stand for tW, VV, Z → ττ
- “Jets” are QCD dijets, W+jets
- Normalize individual MC contributions to NLO, then together to the Z peak in data
- Most significant signal-like pattern in the data is at 950 GeV, local Z = 2.2

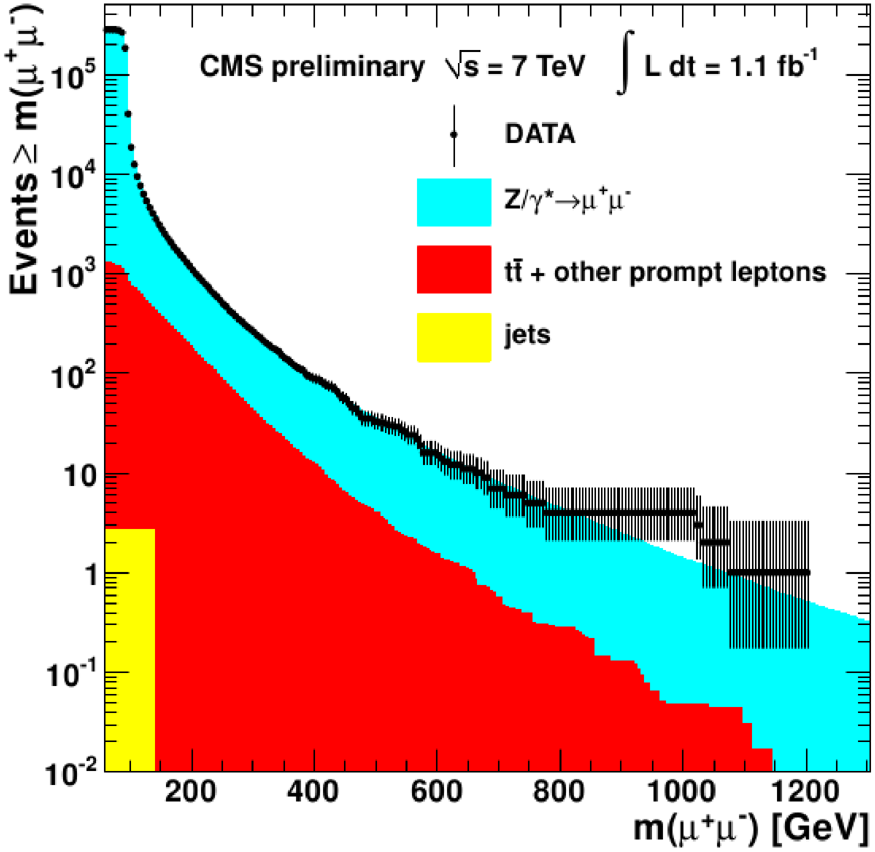




Muon pair mass spectra

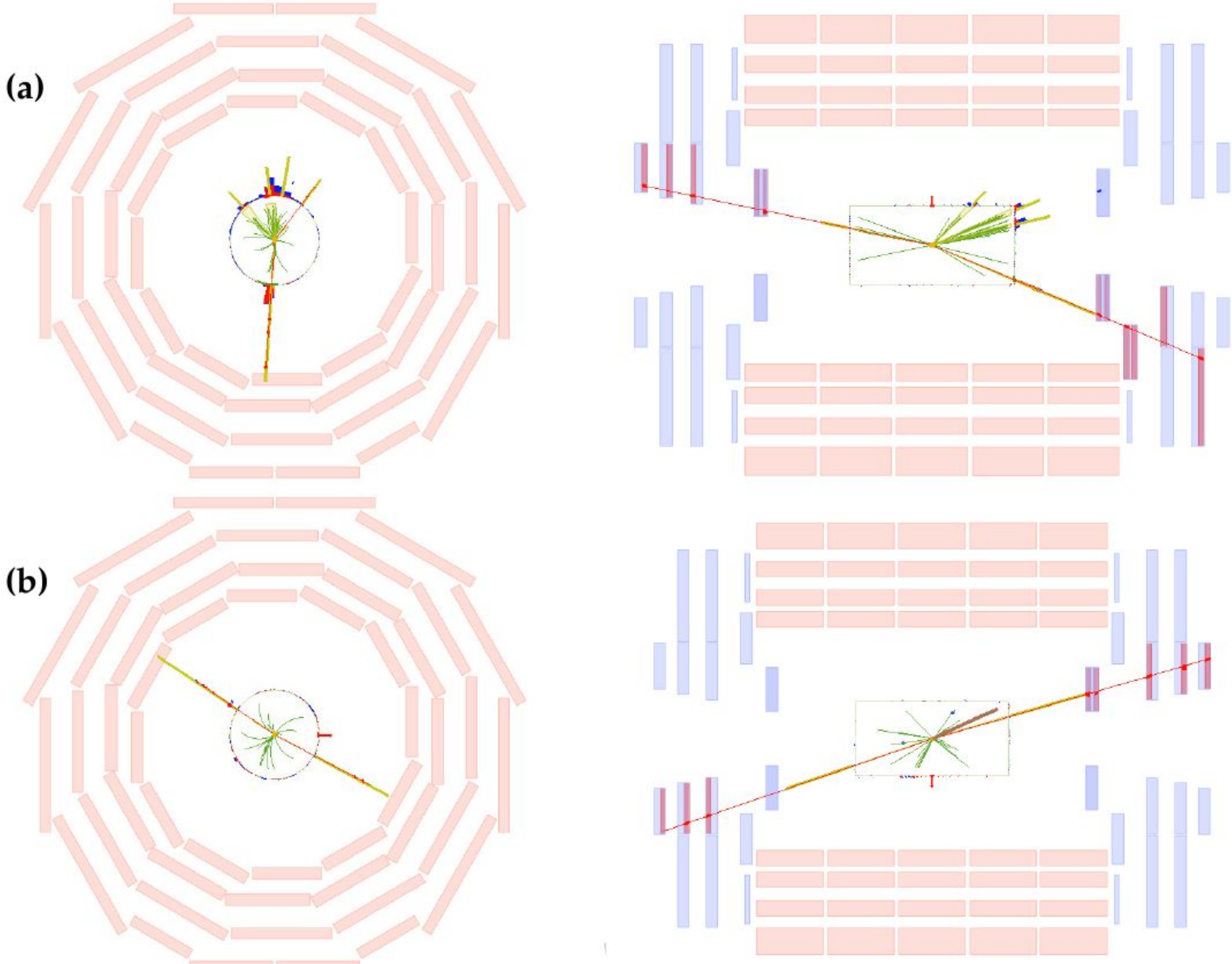
- “Other prompt leptons” stand for tW, VV, $Z \rightarrow \tau\tau$
- “Jets” are QCD dijets, W+jets
- Normalize individual MC contributions to NLO, then together to the Z peak in data
- Most significant signal-like pattern in the data is at 1080 GeV, local Z = 1.7





High-mass event scrutiny

Event	mass (GeV)	p_t (GeV)	p (GeV)	(η, ϕ)
(a)	1203	104 , 272	547, 1422	(-2.29, +0.91), (+1.61, -1.63)
(b)	1074	153 , 167	547, 1422	(-1.80, -0.49), (+1.97, +2.56)



Two more event displays
In the appendix

Statistical Inference

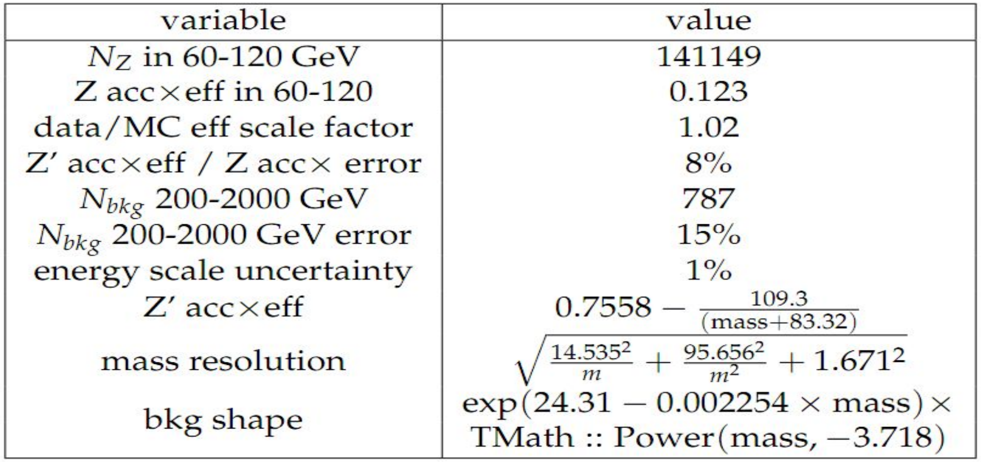
- The core likelihood (extended unbinned)

$$\mathcal{L}(\boldsymbol{m}|R_\sigma, M, \Gamma, w, \alpha, \kappa, \mu_B) = \frac{\mu^N e^{-\mu}}{N!} \prod_{i=1}^{N} \left(\frac{\mu_S(R_\sigma)}{\mu} f_S(m_i|M,\Gamma,w) + \frac{\mu_B}{\mu} f_B(m_i|\alpha,\kappa) \right)$$

$$R_\sigma = \frac{\sigma(\mathrm{pp} \to +X \to \ell\ell + X)}{\sigma(\mathrm{pp} \to +X \to \ell\ell + X)} = \frac{N(\mathrm{Z}')}{N(\mathrm{Z}^0)} \times \frac{A(\mathrm{Z}^0)}{A(\mathrm{Z}')} \times \frac{\epsilon(\mathrm{Z}^0)}{\epsilon(\mathrm{Z}')}$$

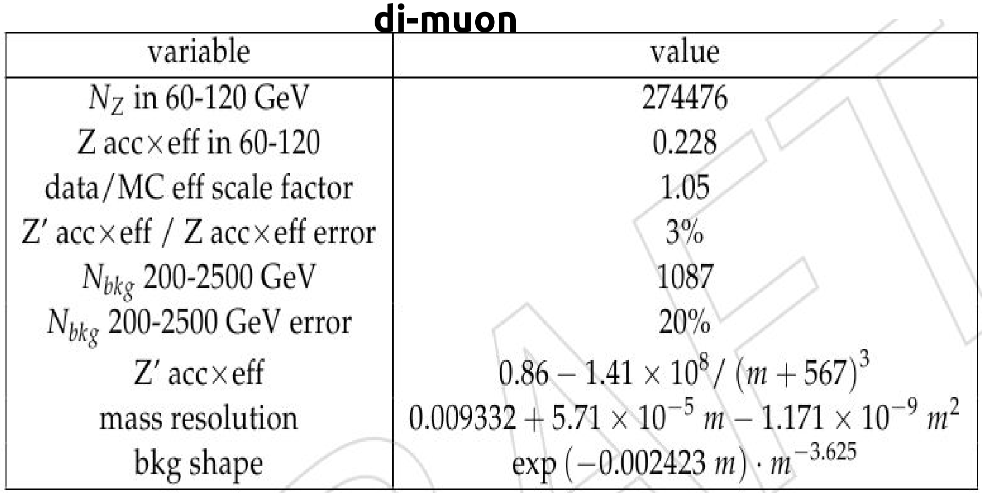
- Bayesian credible interval (95% C.L. Upper limit) with flat prior on the parameter of interest
- Systematic uncertainty modeled as a dedicated likelihood term

di-electron



variable	value
N_Z in 60-120 GeV	141149
Z acc×eff in 60-120	0.123
data/MC eff scale factor	1.02
Z′ acc×eff / Z acc× error	8%
N_{bkg} 200-2000 GeV	787
N_{bkg} 200-2000 GeV error	15%
energy scale uncertainty	1%
Z′ acc×eff	$0.7558 - \frac{109.3}{(\mathrm{mass}+83.32)}$
mass resolution	$\sqrt{\frac{14.535^2}{m} + \frac{95.656^2}{m^2} + 1.671^2}$
bkg shape	$\exp(24.31 - 0.002254 \times \mathrm{mass}) \times$ TMath :: Power(mass, −3.718)

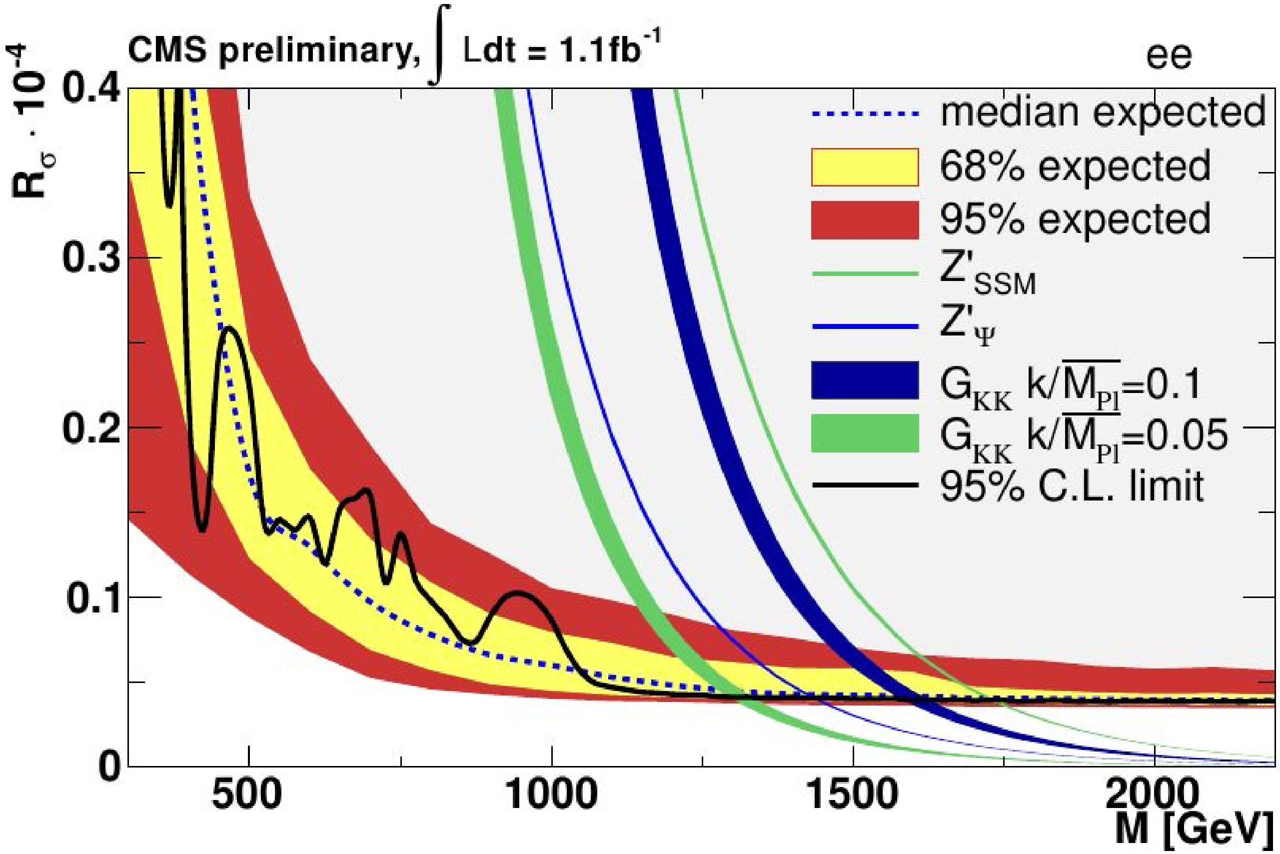
di-muon



variable	value
N_Z in 60-120 GeV	274476
Z acc×eff in 60-120	0.228
data/MC eff scale factor	1.05
Z′ acc×eff / Z acc×eff error	3%
N_{bkg} 200-2500 GeV	1087
N_{bkg} 200-2500 GeV error	20%
Z′ acc×eff	$0.86 - 1.41 \times 10^8 / (m + 567)^3$
mass resolution	$0.009332 + 5.71 \times 10^{-5}\, m - 1.171 \times 10^{-9}\, m^2$
bkg shape	$\exp(-0.002423\, m) \cdot m^{-3.625}$

Cross section and mass limits

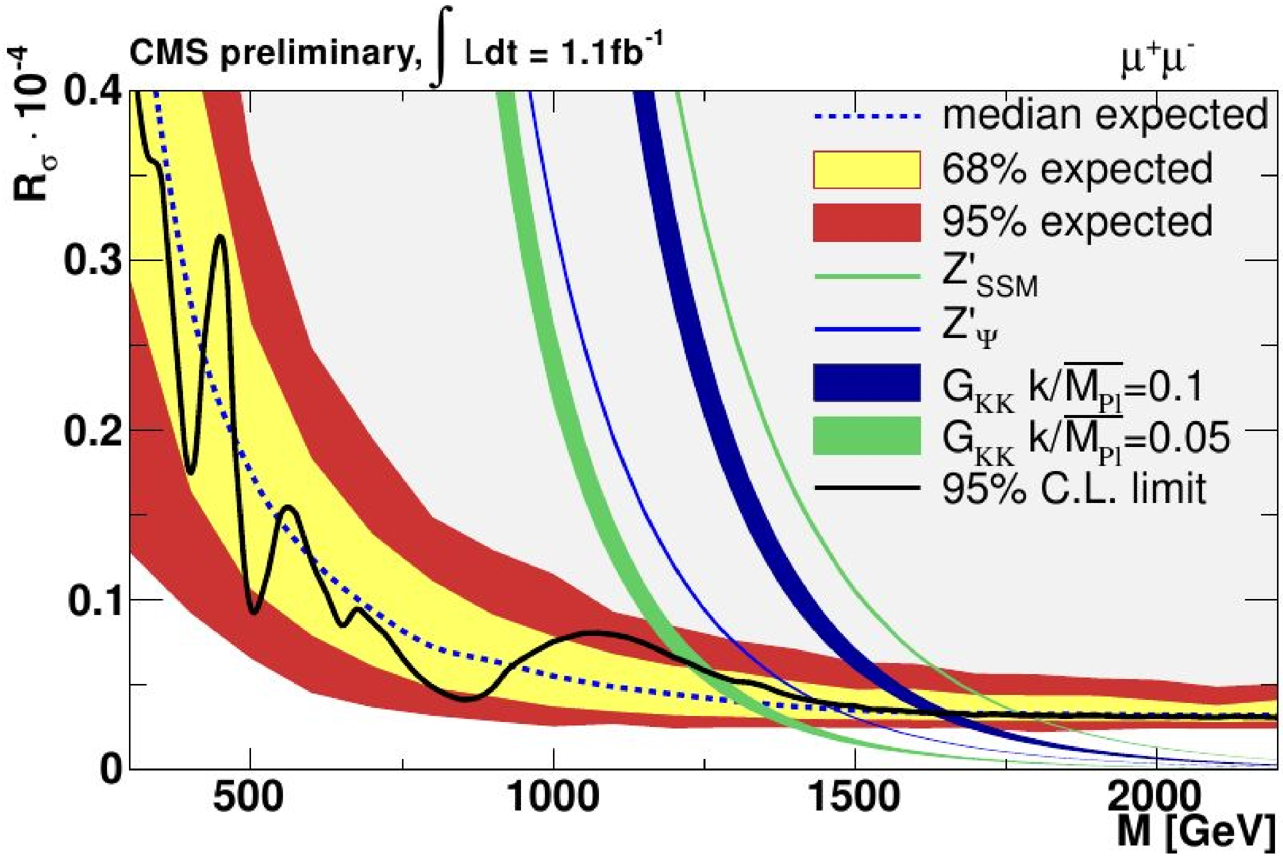
- Electron pair cross section ratio limits



- Mass limits
  - SSM: 1730 Gev
  - Psi: 1440 GeV
  - Kaluza-Klein gravitons: 1300 (1590) GeV for couplings 0.05 (0.1)

Cross section and mass limits

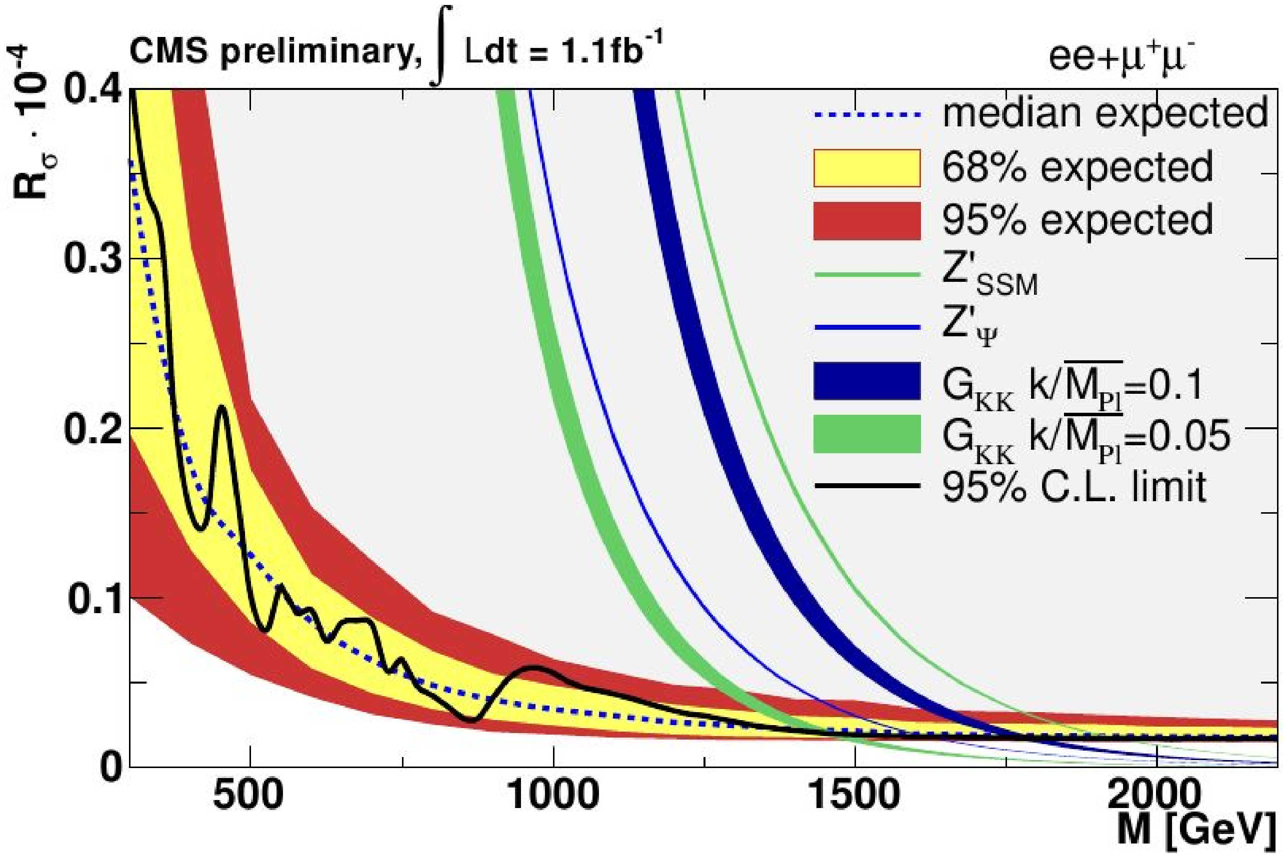
- Muon pair cross section ratio limits



- Mass limits
  - SSM: 1780 Gev
  - Psi: 1440 GeV
  - Kaluza-Klein graviton excitations in RS model: 1240 (1640) GeV for couplings 0.05 (0.1)

Combined limits

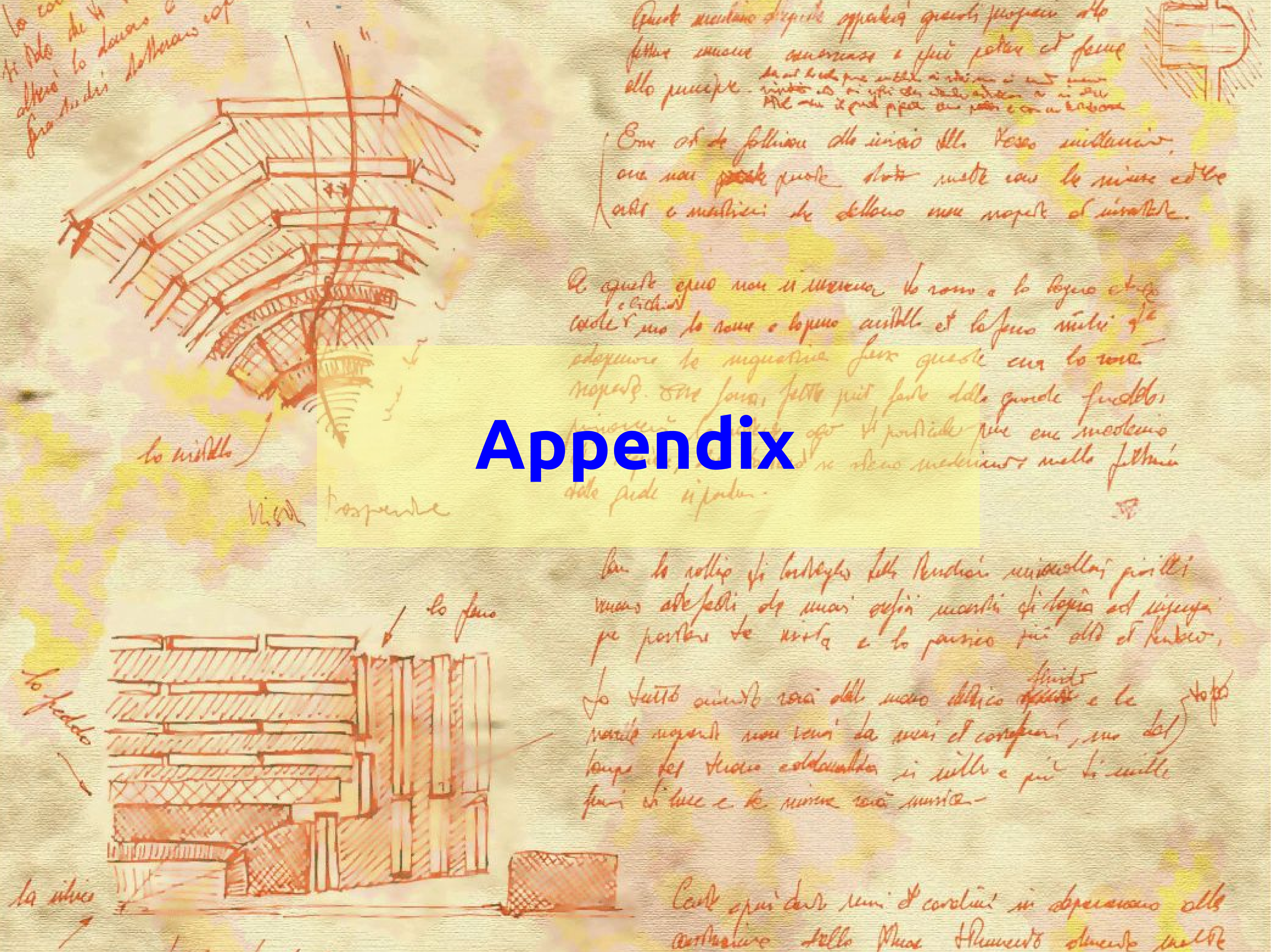
- Combined electron pair and muon pair cross section ratio limits



- Mass limits
  - SSM: 1940 Gev
  - Psi: 1620 GeV
  - Kaluza-Klein graviton excitations in RS model: 1450 (1780) GeV for couplings 0.05 (0.1)

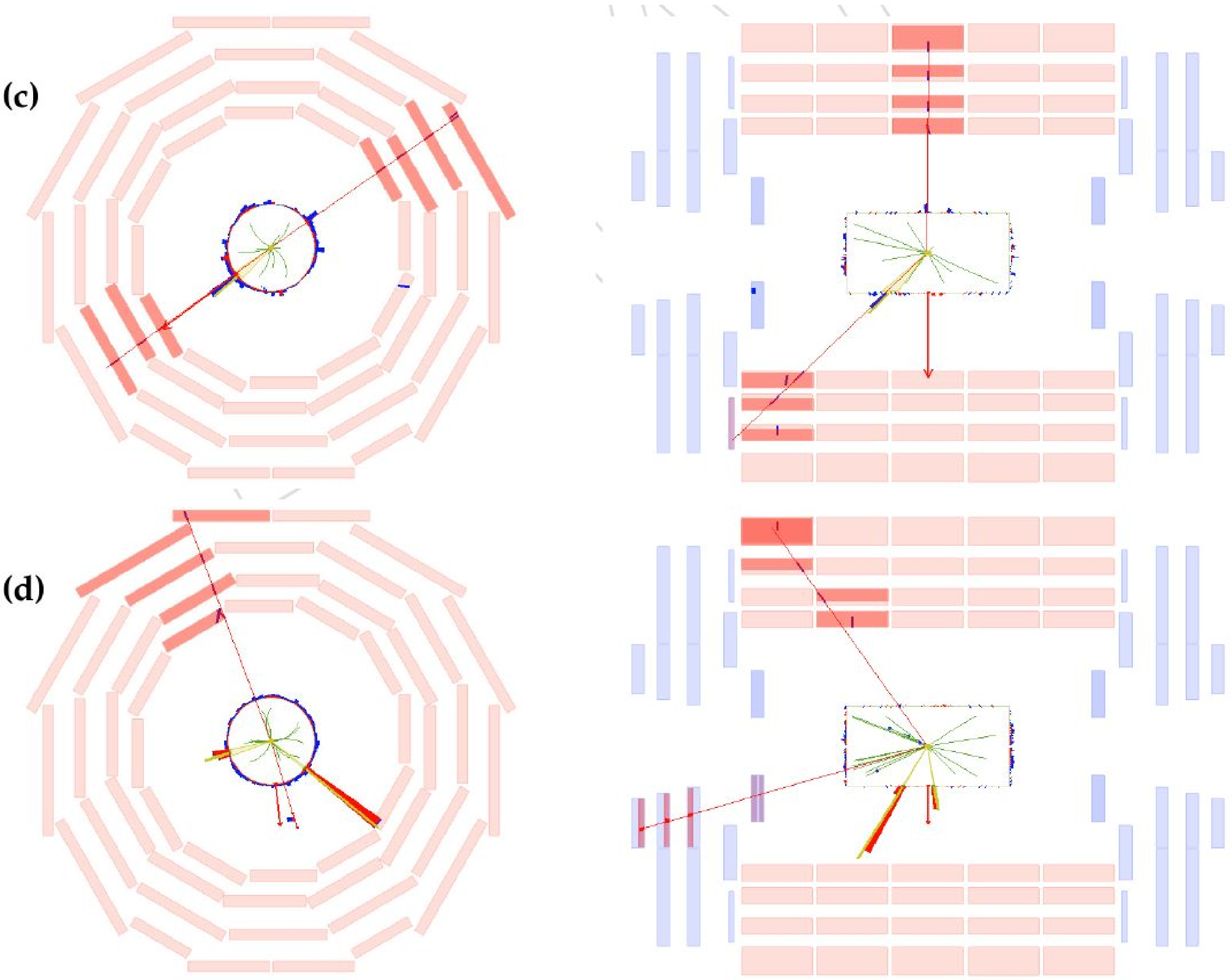
Outlook

- Analysis uses 1.1/fb data recorded by CMS
- No significant excess is observed, the most extreme signal-like pattern in the data is consistent with the peak at 1075 GeV with “local significance” of 2.0, corrected for the trial factor, it becomes 0.2
- At 95 % CL we exclude Z’SSM below 1940 GeV, Z’ψ below 1620 GeV and G_{KK} c=0.1 (c=0.05) below 1780 GeV (1450 GeV)



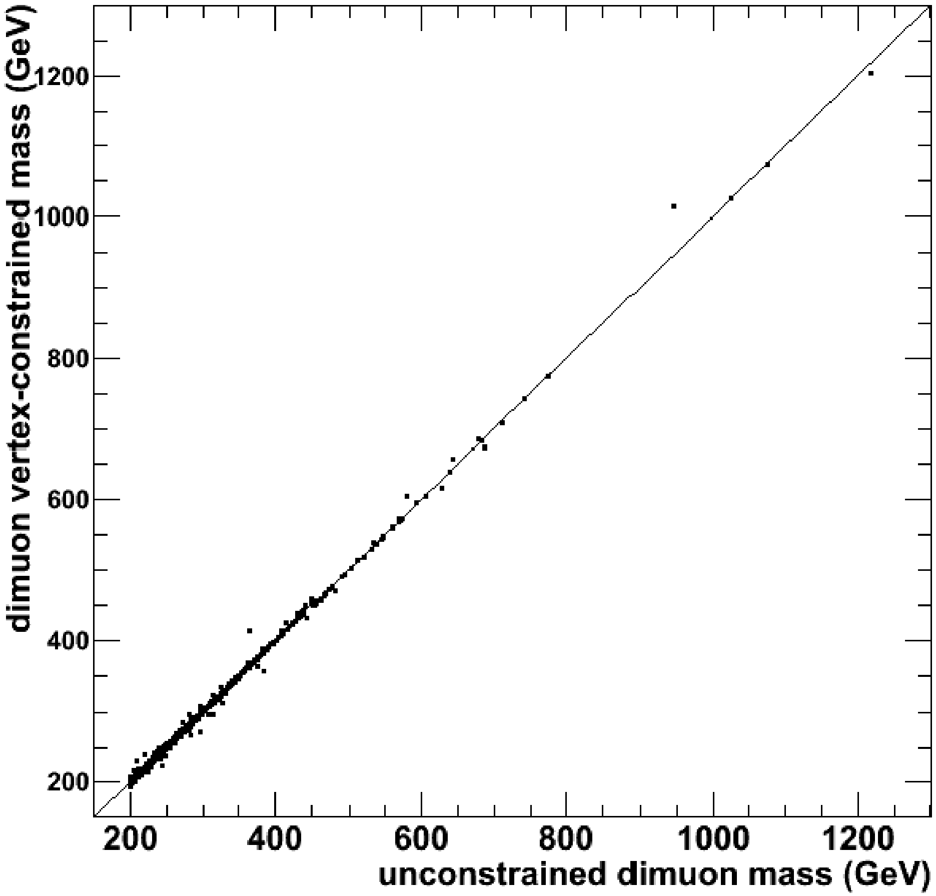
Appendix

More high-mass events



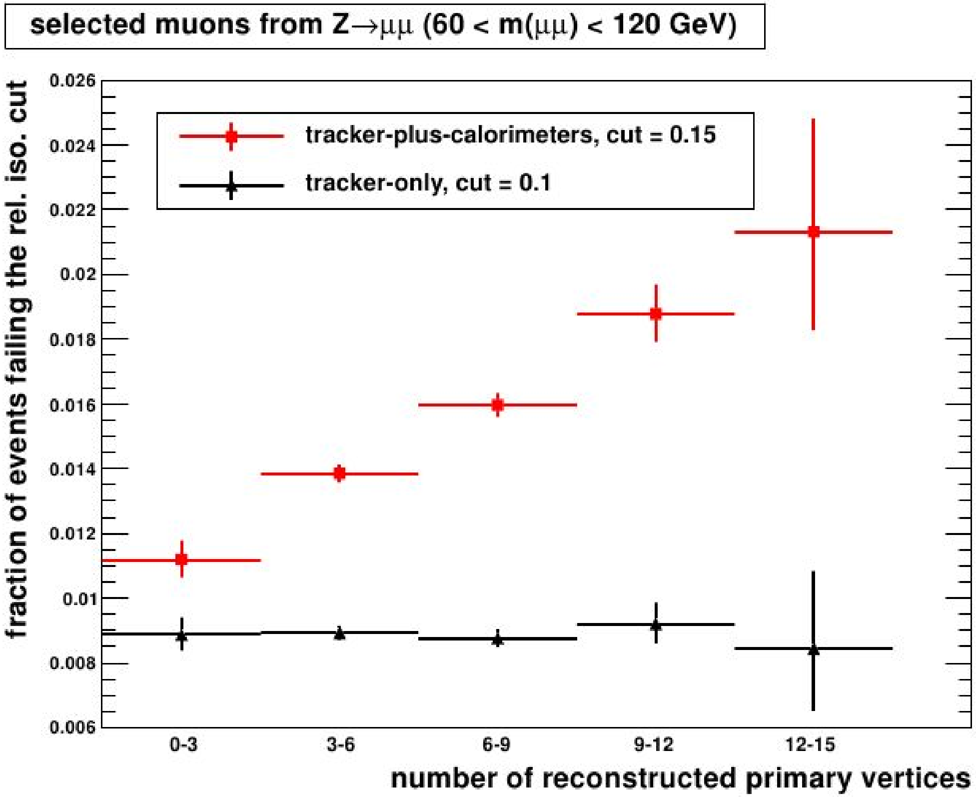
Dimuon vertex-constrained fit

- one high-mass event stands out
- Refit the primary vertex with and without the two muons – outcomes consistent



Muon isolation and pile-up

- A potential concern in 2011 is the higher pileup
- Muon reconstruction mostly unaffected, but pileup could have an impact on isolation efficiency
- Checked efficiency of track-based rel. isolation (as used in the analysis) and combined rel. isolation
- No pileup dependance visible for track-based isolation



Efficiency and acceptance

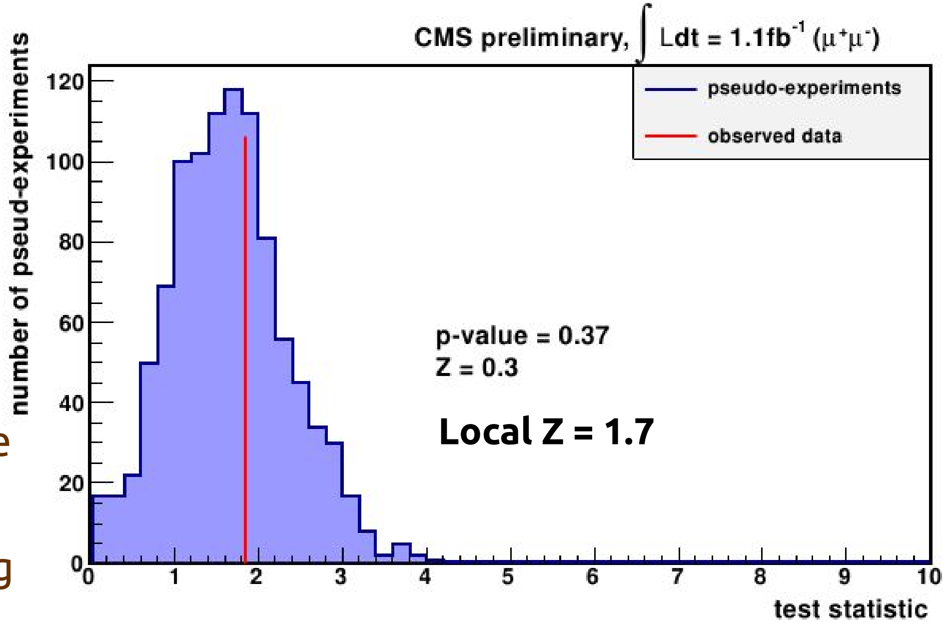
- Efficiency of individual „tight” muons studied with tag&probe
- Good agreement with MC
- Quantity of interest for this analysis: ratio of efficiencies at the Z peak and the high mass region
- We use a MC-based parametrization and assign a 3% systematic uncertainty
  - Study with cosmic muons improve uncertainty compared to the electron channel

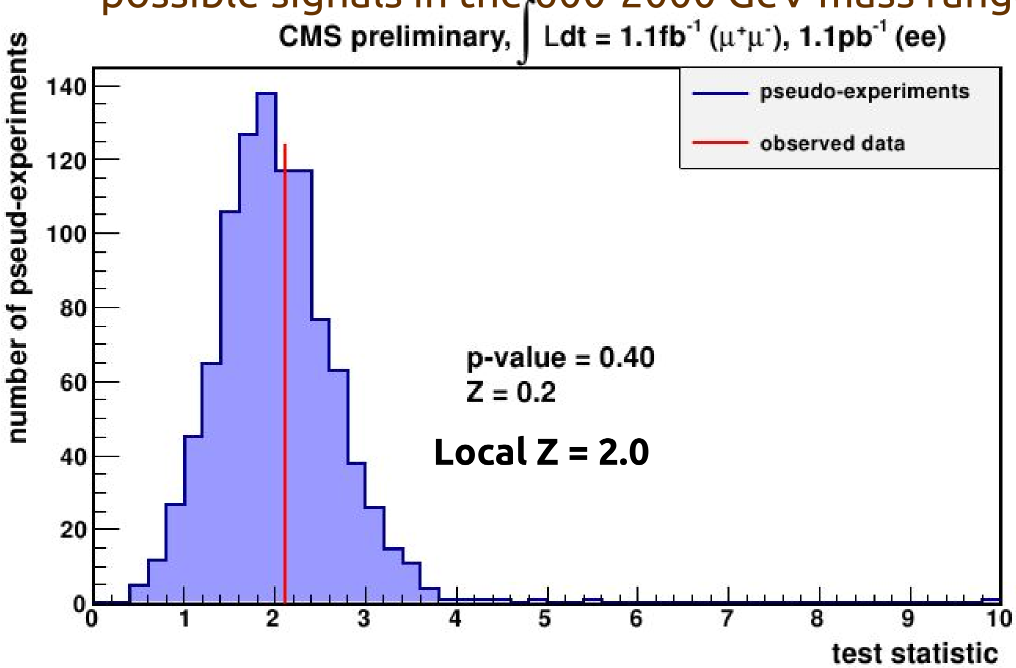
Systematic uncertainty

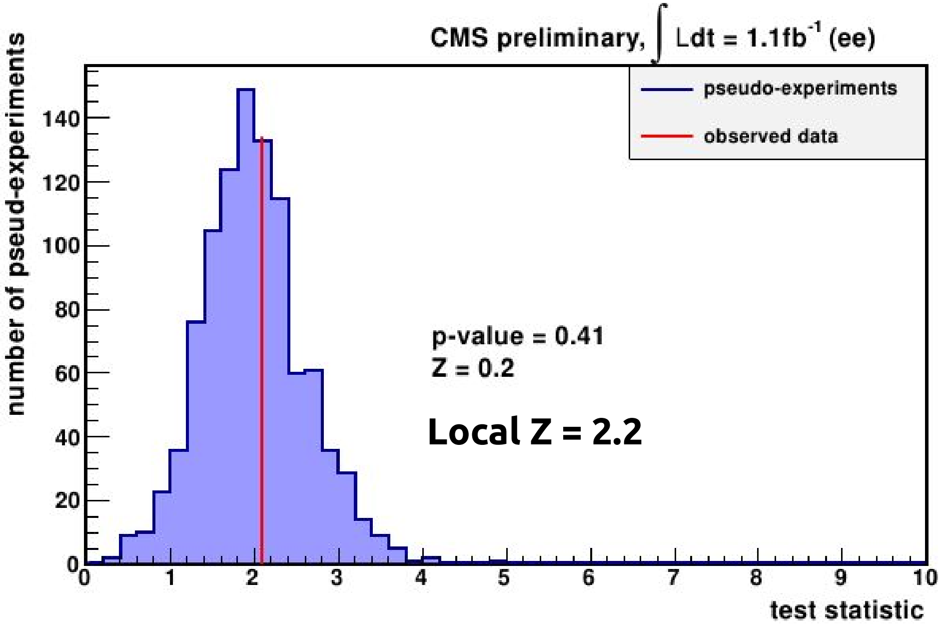
- 3% on the acceptance times efficiency ratio evolution from low to high mass, which includes PDF uncertainties (relevant to the acceptance) and the mass dependence of K-factors.
- Sensitivity study to mass scale uncertainty (affecting only the region below 500 GeV where there are events) showed negligible impact up to the maximum possible from alignment effects.
- Effect of possible x^2-invariant "weak mode", which corresponds to a muon tracking curvature bias, folded into estimate of Gaussian width for signal pdf.
- Shape systematics:
  - including an extra background shape representing the ttbar component and varying its amplitude;
  - trying a different functional form for the background pdf;
  - and changing the low-mass cut-off point for the DY shape fit from 200 GeV down to 150 GeV, which changes the background shape parameters.

Statistical significance

- We estimate the significance of the most extreme signal-like signatures in the data with a few considerations
  - Test statistic: profiled likelihood ratio of S+B and B-only hypotheses
  - Wilks' theorem estimates asymptotically the local significance based on the test statistic value
  - Significance from the sampling distribution for the test statistic from B-only model
  - Look-elsewhere-corrected significance considering possible signals in the 600-2000 GeV mass range

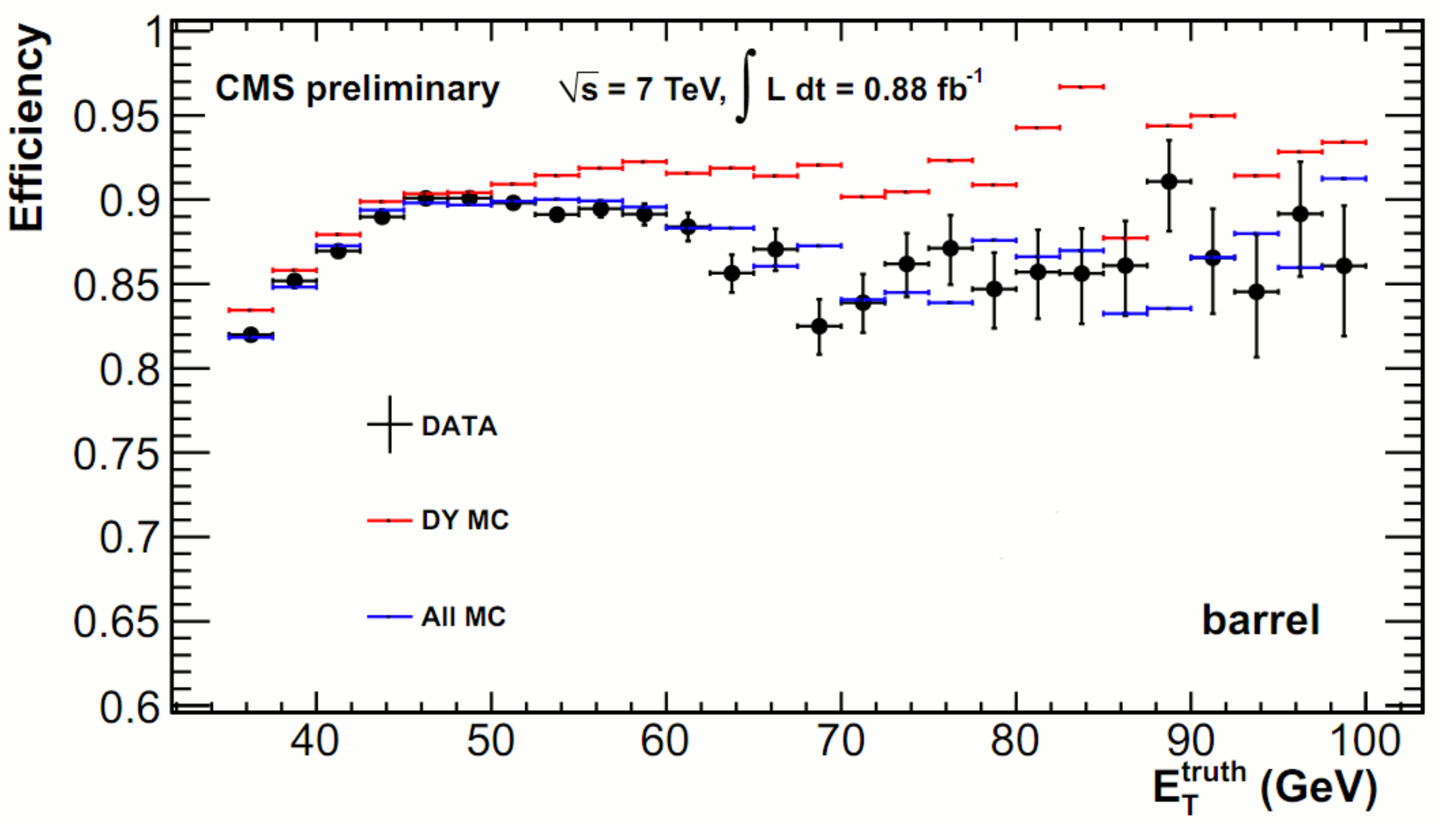






Electron ID efficiency

A comparison of the ID efficiency for electrons in the barrel calorimeter as measured in data and as predicted by Monte Carlo simulation. This is done at the Z peak region from 60-120 GeV. Rather than the background being subtracted from the data, simulated background samples are added to the Monte Carlo since this is not meant to measure the efficiency of real electrons but to measure how much the data and the Monte Carlo disagree. The overall ratio of data/MC efficiencies is 1.008 +/- 0.001 (stat) +/- 0.011 (sys)



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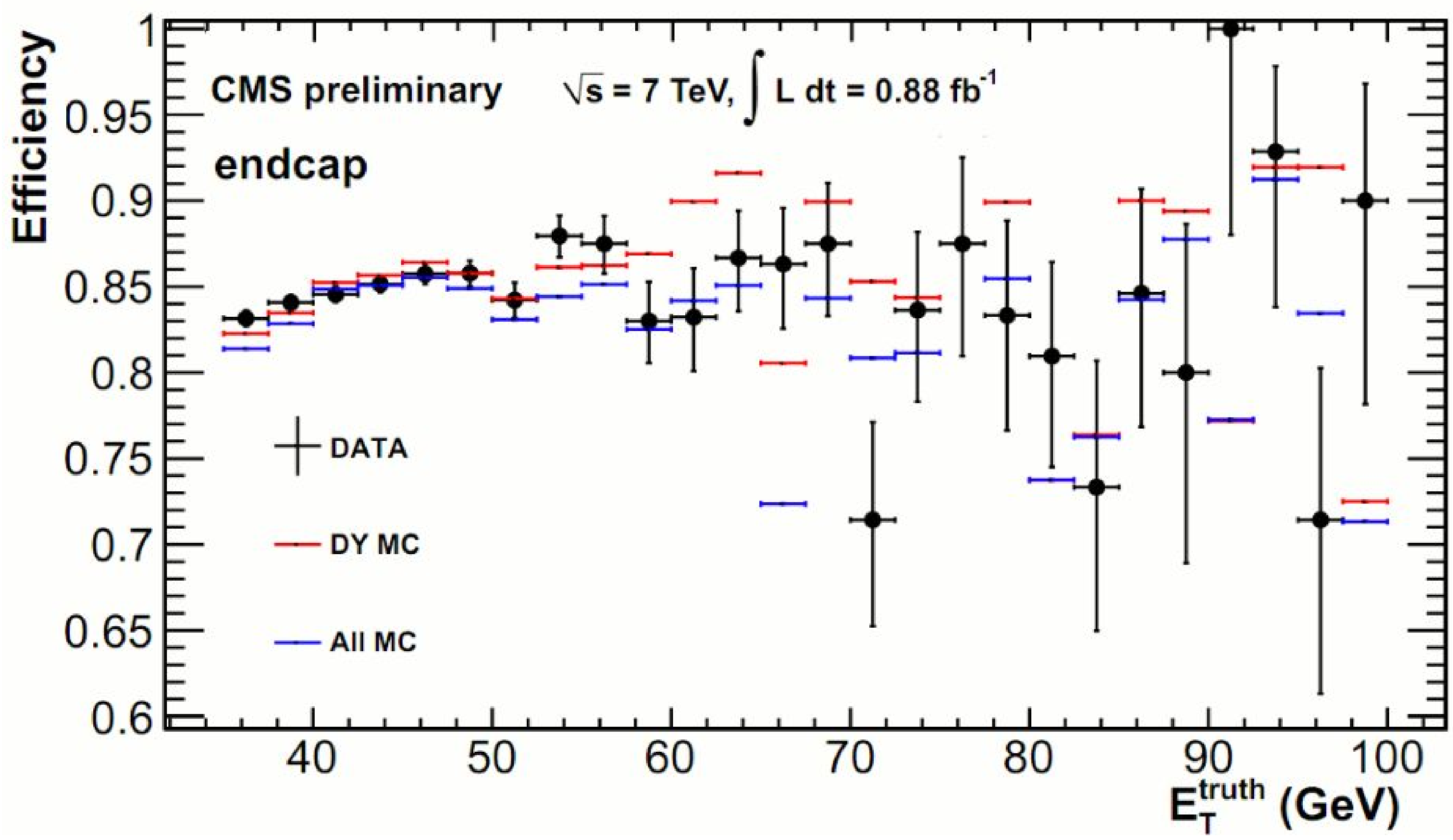
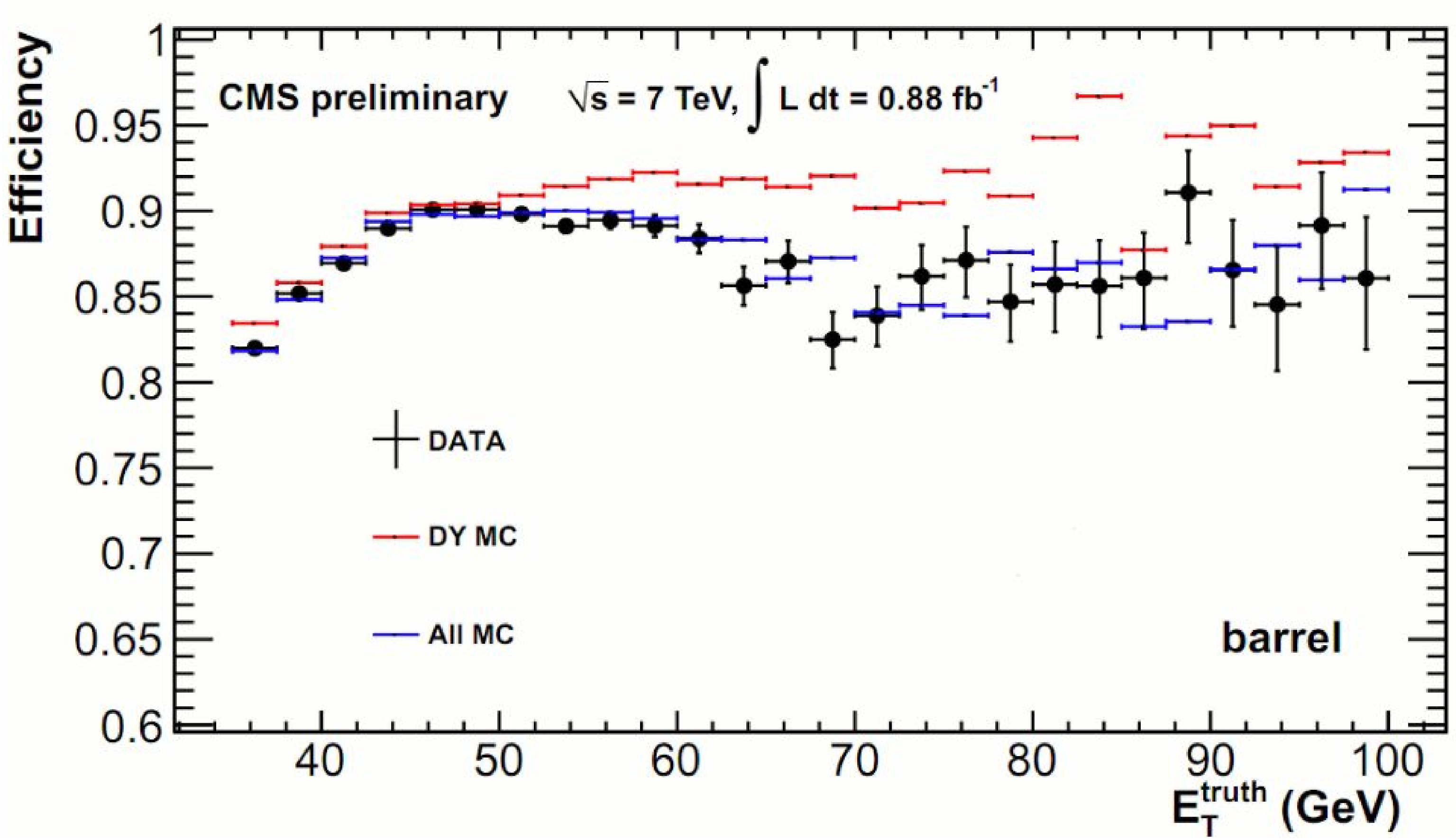


Electron ID efficiency

A comparison of the ID efficiency for electrons in the barrel calorimeter as measured in data and as predicted by Monte Carlo simulation. This is done in the region above 120 GeV. Rather than the background being subtracted from the data, simulated background samples are added to the Monte Carlo since this is not meant to measure the efficiency of real electrons but to measure how much the data and the Monte Carlo disagree.



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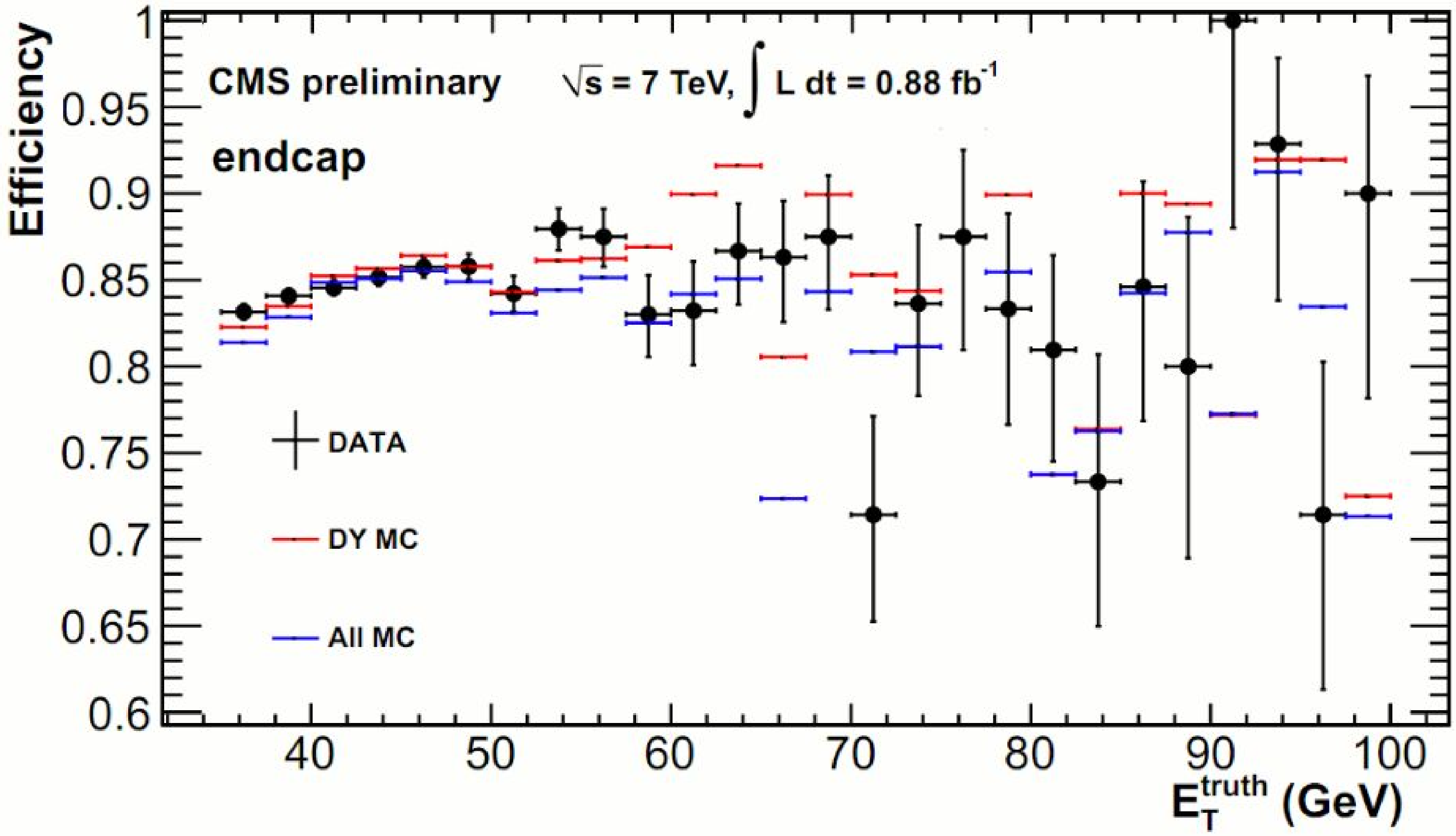
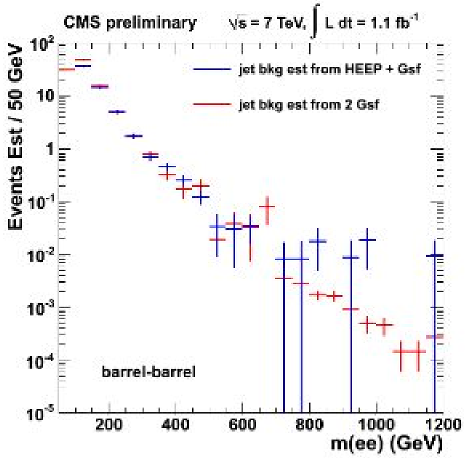


Electron background control

- A comparison of the jet background estimates for the di-electron channel where both electrons are in the barrel calorimeter obtained by applying the fake rate either once to a selected electron + loose electron sample or (1 HEEP + 1 Gsf) and by applying the fake rate twice to a 2 loose electron sample (2 Gsf). The 1 HEEP + 1Gsf estimate is corrected by Monte Carlo for a residual Z contamination while the 2 Gsf estimate has the Monte Carlo predictions of W+jet and pho+jet added to it using the data measured fake rate. The two estimates should agree and their agreement gives confidence in the jet background estimate.



- A comparison of the jet background estimates for the di-electron channel where one electron is barrel calorimeter and one electron is in the endcap caloreimter obtained by applying the fake rate either once to a selected electron + loose electron sample or (1 HEEP + 1 Gsf) and by applying the fake rate twice to a 2 loose electron sample (2 Gsf). The 1 HEEP + 1Gsf estimate is corrected by Monte Carlo for a residual Z contamination while the 2 Gsf estimate has the Monte Carlo predictions of W+jet and pho+jet added to it using the data measured fake rate. The two estimates should agree and their agreement gives confidence in the jet background estimate.