III. Physikalisches Institut A

RWTH AACHEN UNIVERSITY

Search for massive resonance decaying to charged lepton pairs at CMS

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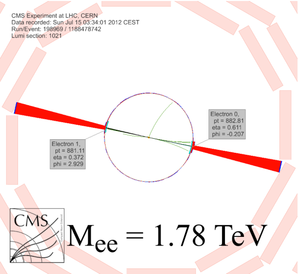
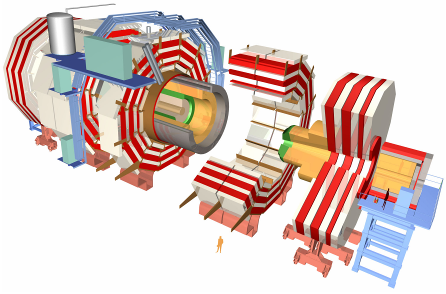
DFG

Introduction

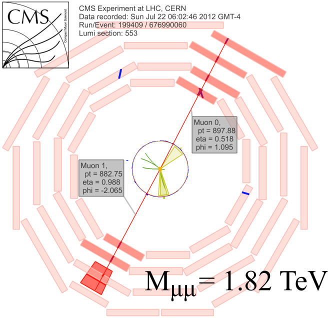
Outline

- CMS detector and performance
- Search for $Z' \to \mu\mu, ee$ at $\sqrt{s} = 8$ TeV
- Projections for $\sqrt{s} = 14$ TeV
- Conclusion





CMS-PAS-EXO-12-061
CMS-NOTE-2013-002



CMS detector

Relative dilepton invariant mass resolution

Electrons

~1% above M_{ee} > 500 GeV

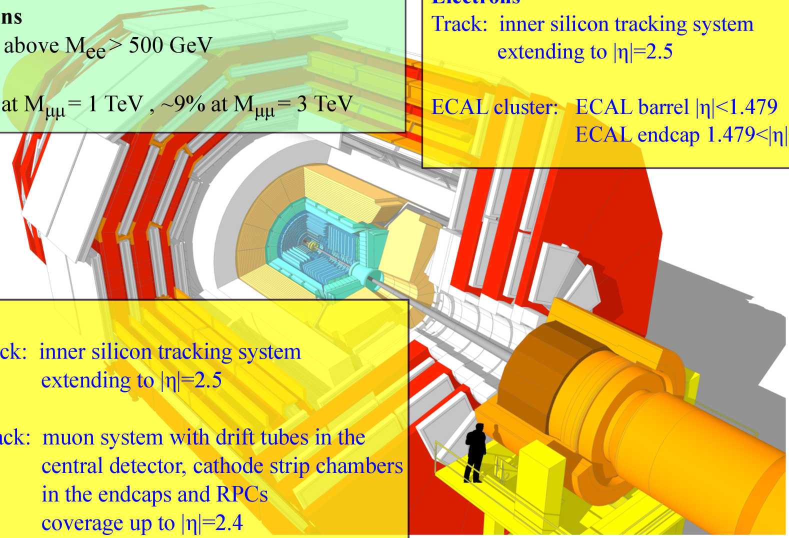
Muons

~4% at $M_{\mu\mu}$ = 1 TeV , ~9% at $M_{\mu\mu}$ = 3 TeV

Electrons

Track: inner silicon tracking system extending to |η|=2.5

ECAL cluster: ECAL barrel |η|<1.479
ECAL endcap 1.479<|η|<3.0



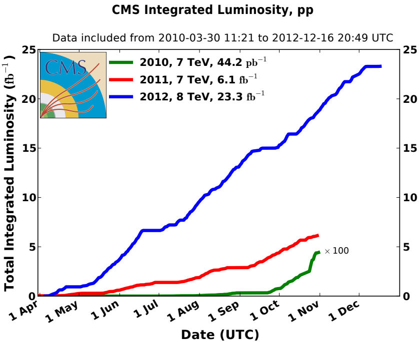
Muons

Inner track: inner silicon tracking system extending to |η|=2.5

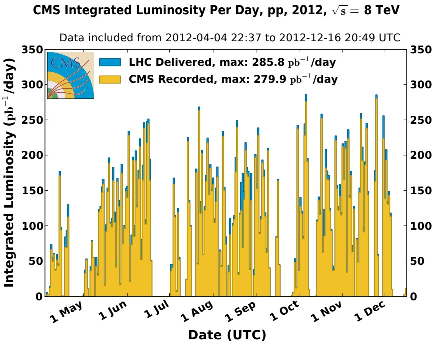
Outer track: muon system with drift tubes in the central detector, cathode strip chambers in the endcaps and RPCs coverage up to |η|=2.4

LHC & CMS performance

Cumulative *pp* luminosity delivered

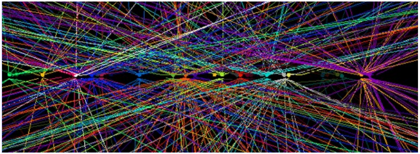


93.5% of delivered luminosity recorded



Analyzed datasets

- Z' analysis based on $\sqrt{s} = 8$ TeV data
- Subdetector requirements reduce analyzed integrated luminosity to:
  - dimuon: $L_{int} = 20.6$ fb^{-1}
  - dielectron: $L_{int} = 19.6$ fb^{-1}

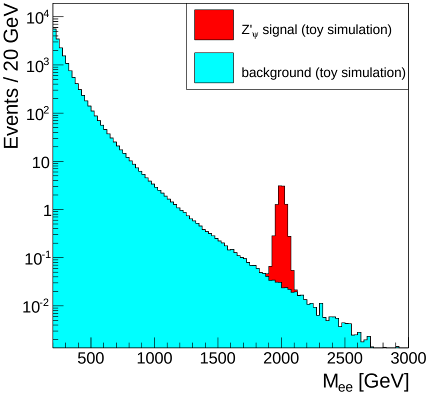


Luminosity up to 7.67 Hz/nb at 50 ns bunch spacing
→ On average 21 interactions per bunch crossing

Signal models

Z' models considered in this talk

- Z'_{SSM} (Sequential Standard Model) with the same couplings to quarks and leptons as Z
- Z'_{ψ} from theories with E_6 GUT group



Toy simulation of the invariant mass spectrum of dielectron events with a Z' signal at $M_{Z'} = 2$ TeV. The event yield is normalized to 19.6 fb^{-1} at $\sqrt{s} = 8$ TeV.

- Shape-based search for narrow resonance: Reduction of model-dependent effects (low-mass tails, Z'/Z interference)
- Further high-mass dilepton searches published by CMS:

RS graviton (spin-2 resonance)
Phys. Lett. B 720 (2013) 63

Large extra dimensions (non-resonant)
CMS-PAS-EXO-12-027 and CMS-PAS-EXO-12-031

Event selection: Muons

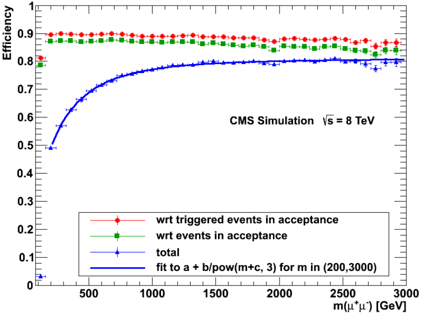
Muon selection

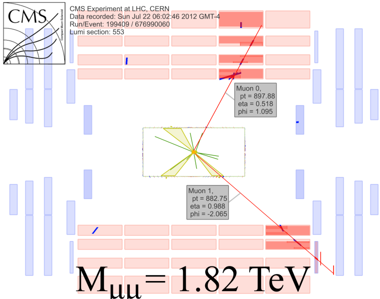
- Reconstructed in inner tracker and muon system, cuts on track quality
- Relative uncertainty on p_T^μ, $\frac{\delta p_T^\mu}{p_T^\mu} < 0.3$
- Isolation based on tracker information

Dimuon event selection

Single-muon trigger, $p_T^\mu > 40$ GeV, $|\eta^\mu| < 2.1$

- Two muons with $p_T^\mu > 45$ GeV, $|\eta^\mu| < 2.4$
- Muon tracks from the same vertex
- Muons carry opposite electric charge
- Cut on dimuon opening angle against muons from cosmic rays





Event selection: Electrons

Electron selection

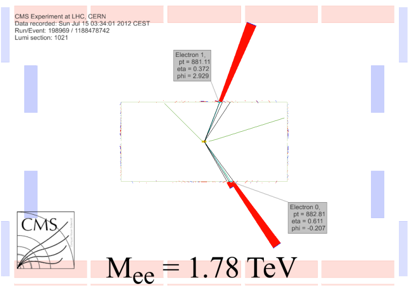
- ECAL cluster satisfying shower shape criteria
- Small relative energy deposit in HCAL behind the ECAL cluster
- Isolation in both ECAL and HCAL
- ECAL cluster matched to isolated track
- Cuts to reject converted photons
- E_T assignment based on ECAL cluster

Dielectron event selection

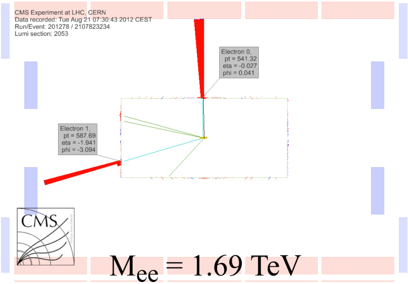
Double-electron trigger, $E_T > 33$ GeV

- Two selected electrons with $E_T > 35$ GeV
- Analysis split into two channels
  - Both electrons in barrel $|\eta| < 1.422$
  - One electron in barrel and one in endcap $1.560 < |\eta| < 2.5$

Both electrons in the barrel



One electron in the barrel, one in the endcap



Background expectation

Three different types of background:

Irreducible Z/γ^* background

- Largest background: $\sim 75\%$ (ee), 80% ($\mu\mu$) of expected events above $M_{\ell\ell} = 200$ GeV
- Shape from simulation (POWHEG)
- Higher-order corrections studied with FEWZ (NNLO QCD) and HORACE (NLO EWK)

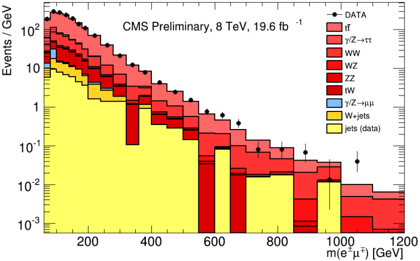
$t\bar{t}$, tW, diboson backgrounds

- $\sim 20\%$ above $M_{\ell\ell} = 200$ GeV
- Flavor symmetric $\rightarrow$ Examine $e\mu$ spectrum in data to cross-check simulation

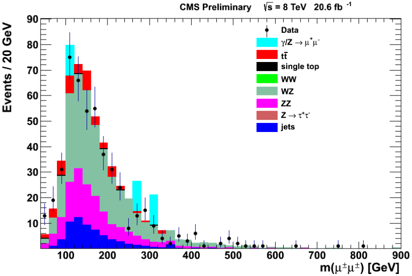
Jets misidentified as leptons

- W+jet, QCD multijet, γ+jet
- Negligible for muon channel
- Derived from data

$M_{e\mu}$ distribution of $e\mu$ events



$M_{\mu\mu}$ of dimuon events with same-sign charge combination



Invariant mass spectra

Mass spectra devided into three regions:

60 GeV $< M_{\ell\ell} <$ 120 GeV: Z peak

- Normalization of the simulated background
- Measurement of reconstruction, ID and trigger efficiencies up to $p_T^{\mu}, E_T^{e} \sim 300$ GeV
- Study of electron energy/muon momentum scale and resolution

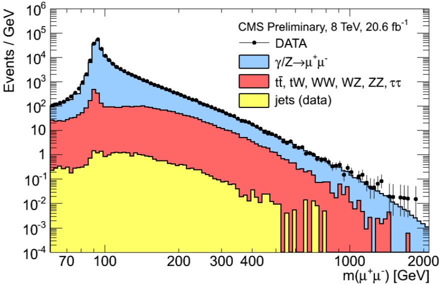
120 GeV $< M_{\ell\ell} <$ 200 GeV: Control region

- No new physics expected (Tevatron)
- Test agreement of data and expectation beyond the Z peak

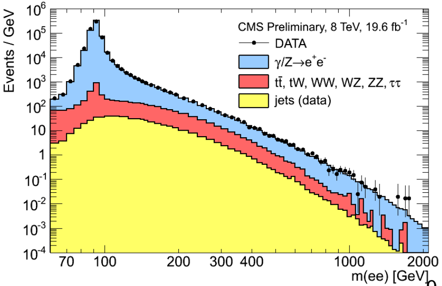
$M_{\ell\ell} >$ 200 GeV: Signal region

Data well described by the expectation

Muons



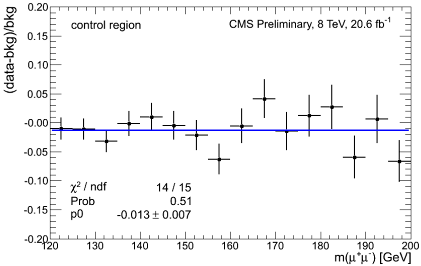
Electrons

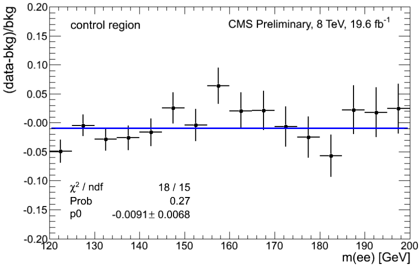


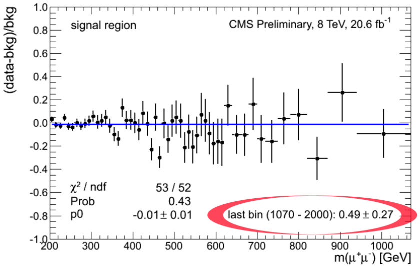
Invariant mass spectra - data/expectation ratio plots

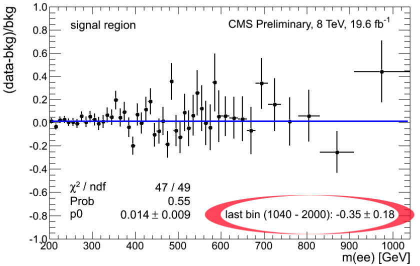
Muons

Electrons









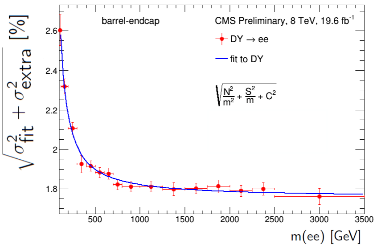
Plots show statistical uncertainties, only. No excess observed, setting limits.

Model and limit setting

Model & signal region

- Signal model: $BW(M_{\ell\ell}|M_{Z'}, \Gamma_{Z'}) \otimes Gauss(M_{\ell\ell}|\sigma_{resolution})$
- Background model: Parameterized function, shape from fit to simulation
- Data considered: Events with $M_{\ell\ell} > 200$ GeV
- Mass window: $M_{Z'} \pm 6$ times mass resolution

Relative invariant mass resolution (electron barrel-endcap)



Limit setting

Bayesian 95% CL upper limits on Z' to Z cross section ratio R_σ

$$R_\sigma = \frac{\sigma\left(pp \to Z' + X \to \ell^+\ell^- + X\right)}{\sigma\left(pp \to Z + X \to \ell^+\ell^- + X\right)} = \frac{N\left(Z' \to \ell^+\ell^-\right)}{N\left(Z \to \ell^+\ell^-\right)} \cdot \frac{A\left(Z \to \ell^+\ell^-\right)}{A\left(Z' \to \ell^+\ell^-\right)} \cdot \frac{\epsilon\left(Z \to \ell^+\ell^-\right)}{\epsilon\left(Z' \to \ell^+\ell^-\right)}$$

$\sigma(Z')$ evaluated in mass range $M_{Z'} \pm 40\%$, $\sigma(Z)$ evaluated in 60 GeV $< M_{\ell\ell} <$ 120 GeV

- Uncertainty on the luminosity cancels in the ratio R_σ
- Uncertainties on the absolute values of $\epsilon_{trigger}$, $\epsilon_{reconstruction}$ and mass scale reduce to uncertainties on their evolution from the Z peak to high mass

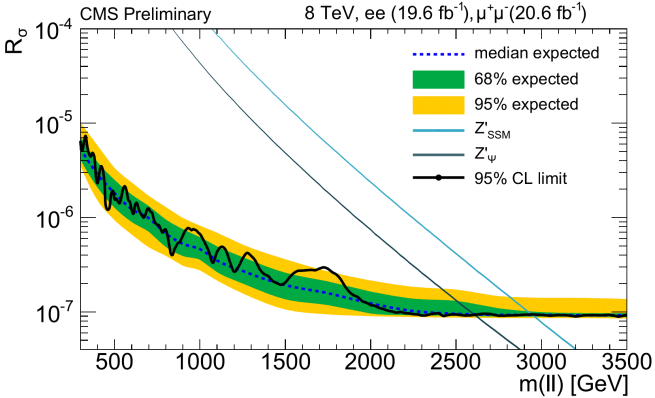
Systematic uncertainties

Systematic uncertainties

- Dominant uncertainty on the limits:
  Ratio of acceptance times efficiency between Z' and Z
  3% for dimuon, 4% for barrel-barrel and 6% for barrel-endcap dielectron channel
- Z/γ^* background:
  Shape uncertainty on the background fit from PDFs and higher order corrections ranges from 2% at $M_{\ell\ell} = 200$ GeV to 30% at $M_{\ell\ell} = 3000$ GeV
- Uncertainties on the subleading backgrounds studied but less important
- Impact of uncertainty on the muon momentum scale and resolution studied with different detector misalignment scenarios and found to be small

Limits

Bayesian 95% CL upper limits on R_σ, assuming narrow spin-1 resonance
Limits for combination of dimuon and dielectron channels



Signal cross sections for Z'_{SSM} and Z'_ψ scaled to NNLO QCD

95% CL lower limits on Z' mass

Z'_{SSM} : $M_{Z'} > 2.96$ TeV , Z'_ψ : $M_{Z'} > 2.60$ TeV

Projection for $\sqrt{s} = 14$ TeV

Long term projections

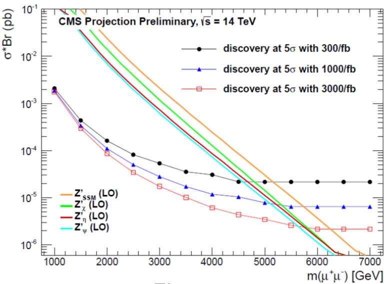
- Discovery reach at $\sqrt{s} = 14$ TeV studied with integrated luminosities of 300 fb^{-1}, 1000 fb^{-1}, 3000 fb^{-1}
- Generator level events smeared to the detector response
- $A \cdot \epsilon$ and resolution from $\sqrt{s} = 8$ TeV analysis

Expect sensitivity to Z's with $M_{Z'} \gtrsim 5$ TeV

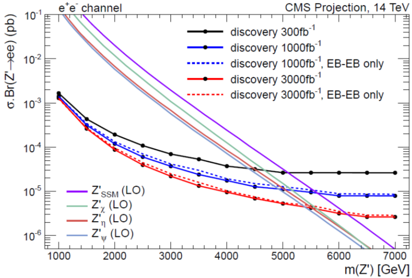
Short term outlook for 2015

Expect to extend current discovery reach early in the planned $\sqrt{s} = 13$ TeV run

Muons



Electrons



Reference: CMS-NOTE-2013-002; arXiv:1307.7135

Summary

Z' searches at CMS up to now

- Electron and muon pairs offer very clean final states in which BSM physics might be hiding
- No excess observed in the dilepton invariant mass spectra in $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data
- 95% CL limits on Z' boson models in the multi-TeV range:

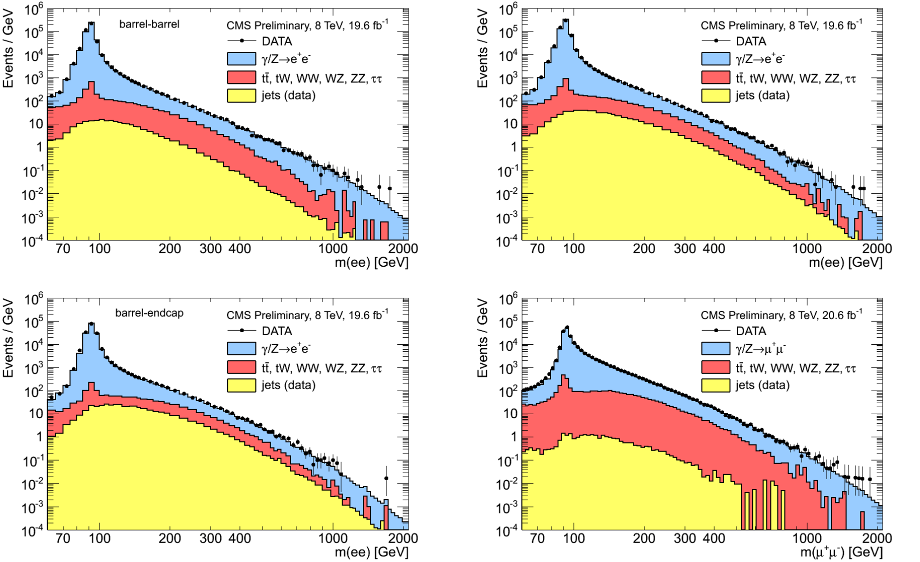
$$Z'_{SSM}: \; M_{Z'} > 2.96 \text{ TeV} \quad , \quad Z'_{\psi}: \; M_{Z'} > 2.60 \text{ TeV}$$

Looking forward to (early) 2015 and beyond

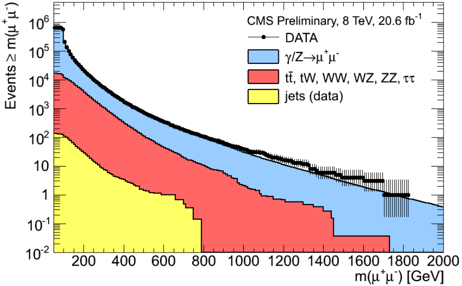
- Looking forward to first Z' results with $\sqrt{s} = 13$ TeV data
- Long term: Expect to be sensitive to Z's with masses beyond 5 TeV

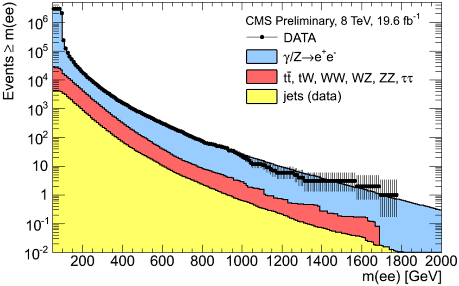
Backup slides

Invariant mass spectra - all channels

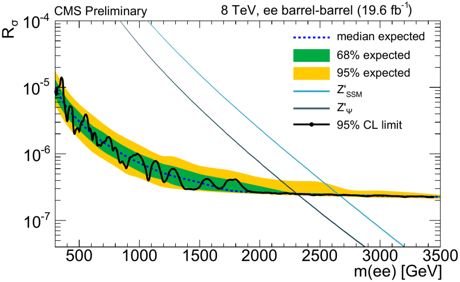


Invariant mass spectra - cumulative distributions

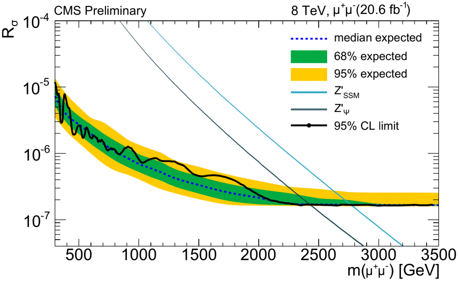




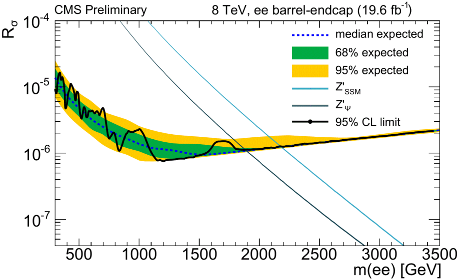
Limits - all channels



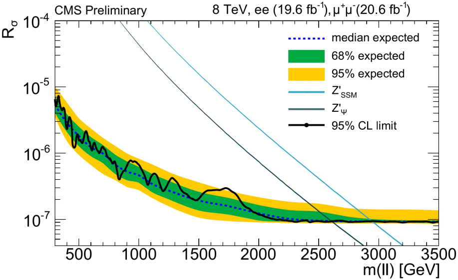
Z'_{SSM} : $M_{Z'} > 2.65$ TeV , Z'_{ψ} : $M_{Z'} > 2.31$ TeV



Z'_{SSM} : $M_{Z'} > 2.77$ TeV , Z'_{ψ} : $M_{Z'} > 2.43$ TeV



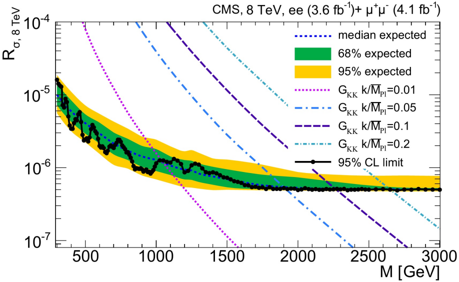
Z'_{SSM} : $M_{Z'} > 2.18$ TeV , Z'_{ψ} : $M_{Z'} > 1.90$ TeV



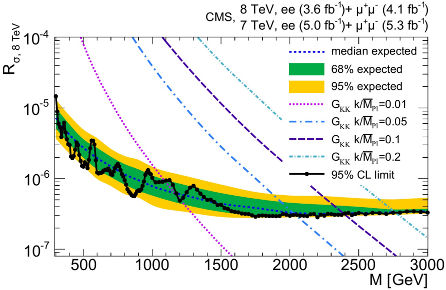
Z'_{SSM} : $M_{Z'} > 2.96$ TeV , Z'_{ψ} : $M_{Z'} > 2.60$ TeV

Limits on spin-2 resonance (RS graviton)

Limits for $\sqrt{s} = 8$ TeV data only



Limits for combination $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data



- Spin-2 resonance
- Couplings to $q\bar{q}$ and gg $\rightarrow$ different acceptance compared to Z'_{SSM} and Z'_{ψ}
- Combination of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV datasets only valid for models with the same $q\bar{q}$ to gg coupling ratio as RS graviton

Lower mass limits

$\sqrt{s} = 8$ TeV data only:

- $G_{KK}(k/\bar{M}_{Pl} = 0.1)$: 2260 GeV
- $G_{KK}(k/\bar{M}_{Pl} = 0.05)$: 1900 GeV

$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data:

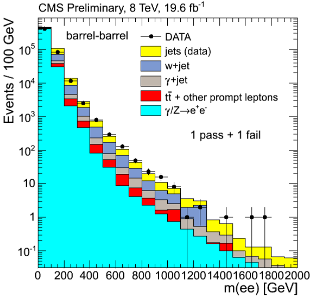
- $G_{KK}(k/\bar{M}_{Pl} = 0.1)$: 2390 GeV
- $G_{KK}(k/\bar{M}_{Pl} = 0.05)$: 2030 GeV

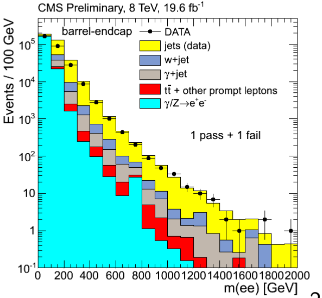
Reference: Phys. Lett. B 720 (2013) 63;
DOI:10.1016/j.physletb.2013.02.003

Background from jets misidentified as electrons

- Measure rate of jets identified as electron candidates with a 'loose' electron ID passing the electron ID used in the analysis
  - Select jet enriched control sample using single photon triggers and asking for a single 'loose' electron candidate
  - Subtract contamination from processes with real electrons from simulation
  - Determine so-called 'fake-rate' *FR*
- Apply the measured 'fake-rate'
  - Multijet contribution:
    Select multijet background enriched control sample with two 'loose' electron candidates that fail the electron ID used in the analysis

    Weight each electron by $FR/(1-FR)$
  - For further contributions (W+jet, γ+jet) apply measured 'fake-rate' to simulation
- 40% systematic uncertainty applied



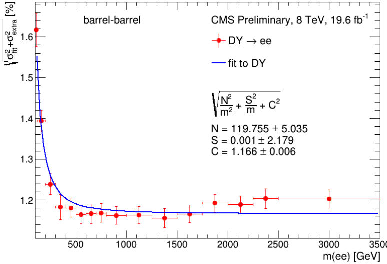


Invariant mass resolution

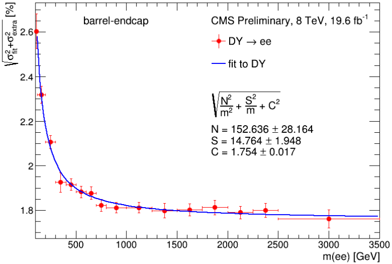
Dielectron channels:

- Fit double-sided Crystal Ball function convoluted with Breit Wigner function to $M_{\ell\ell}^{reco} - M_{\ell\ell}^{true,MC}$ in simulated Drell-Yan samples in different mass bins
- Invariant mass resolution from simulation corrected for difference between resolutions at the Z peak obtained from data and simulation

Resolution in barrel-barrel channel



Resolution in barrel-endcap channel



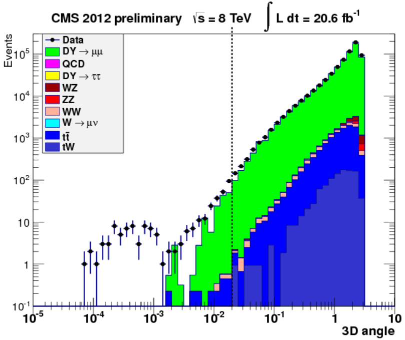
Dimuon channel:

- Invariant mass resolution obtained from Gaussian fits to $(M_{\ell\ell}^{reco} - M_{\ell\ell}^{true,MC})/M_{\ell\ell}^{true,MC}$ in simulated Drell-Yan samples
- Different detector misalignment scenarios consistent with alignment studies compared
- Invariant mass resolution in the dimuon channel is $\sim 4\%$ at $M_{\mu\mu} = 1$ TeV and $\sim 9\%$ at $M_{\mu\mu} = 3$ TeV

Background from muons from cosmic rays

Opening angle between the two muons required to be smaller than $\pi - 0.02$ rad

Plotted: $\alpha = \pi -$ opening angle



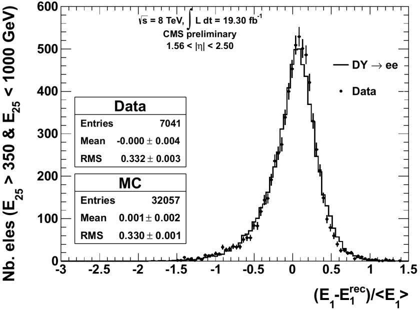
Both the cut on α and the primary vertex requirement have been removed in this plot

The already small contribution from cosmic muons lies mainly in the region $\alpha < 0.002$

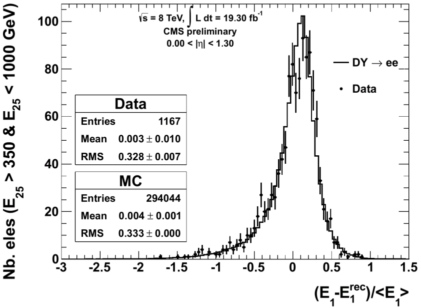
ECAL response at high electron energy

- Single ECAL crystal readout electronics saturate at high energies ($\sim$ 1.7 TeV in the barrel, $\sim$ 3.0 TeV in the endcaps)
- Linearity of ECAL energy response at high energies tested by relating the energy deposit in the single crystal with the highest energy deposit (E_1) to the energy deposits in the 24 surrounding crystals in a 5×5 crystal matrix (E_{25})
- Algorithm describing this relation takes into account the impact point position on the crystal face
- Parameters of the algorithm taken from simulation
- Measured energy deposit E_1 compared to E_1^{rec} determined from the 24 surrounding crystals

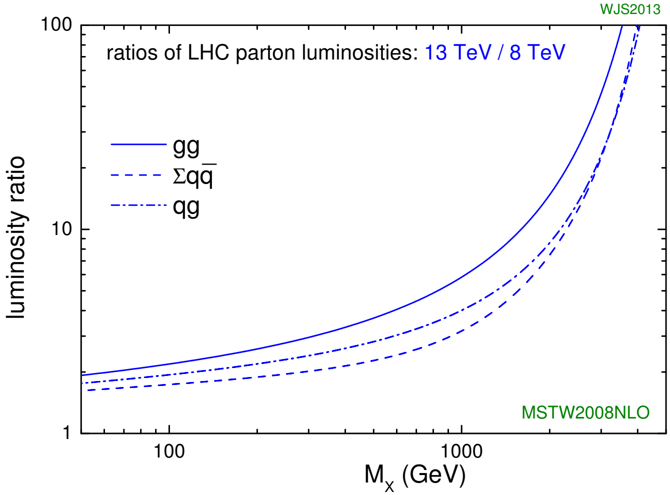
Electrons with $E_{25} > 350$ GeV in the endcaps



Electrons with $E_{25} > 350$ GeV in the barrel



Parton luminosity ratios $\sqrt{s} = 13$ TeV$/\sqrt{s} = 8$ TeV



W.J. Stirling, private communication