Search for heavy gauge bosons at CMS

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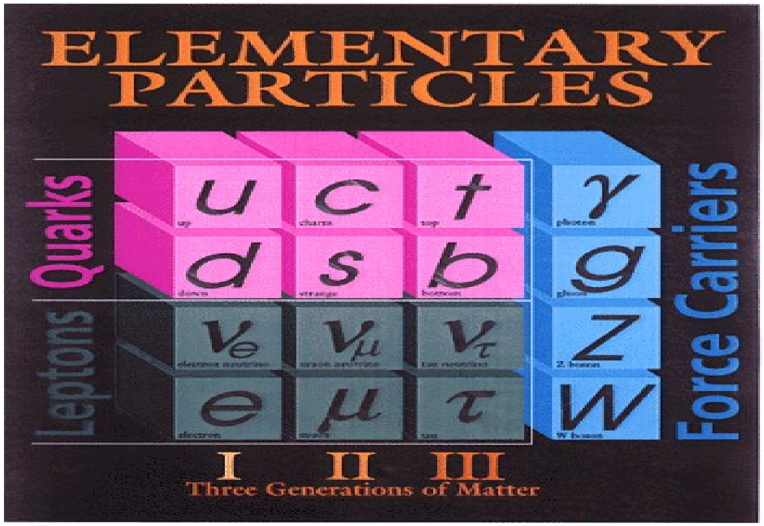
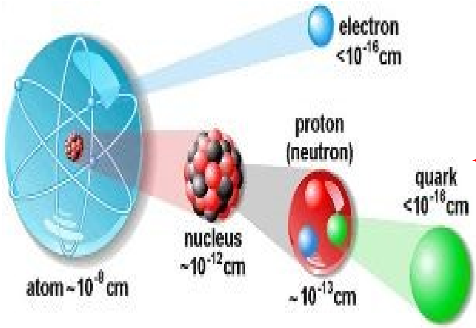
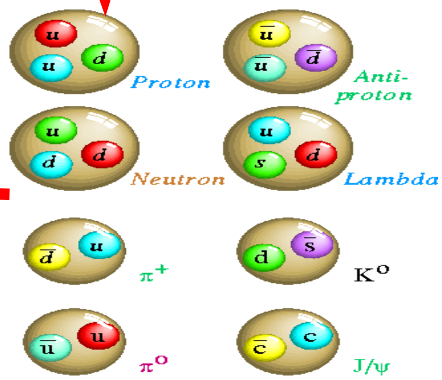
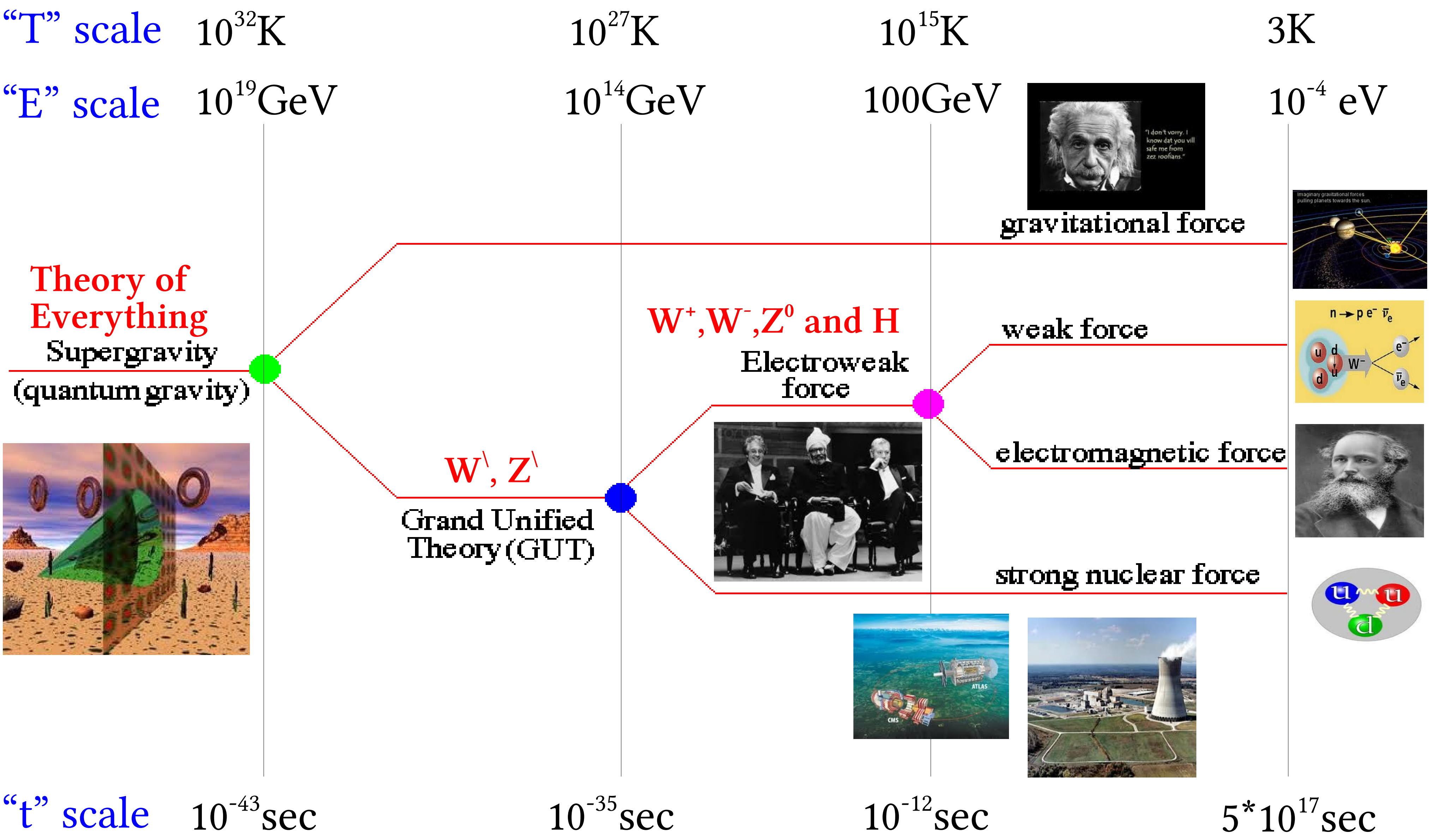
The Origin of Matter and Anti-Matter







Fields and Unification

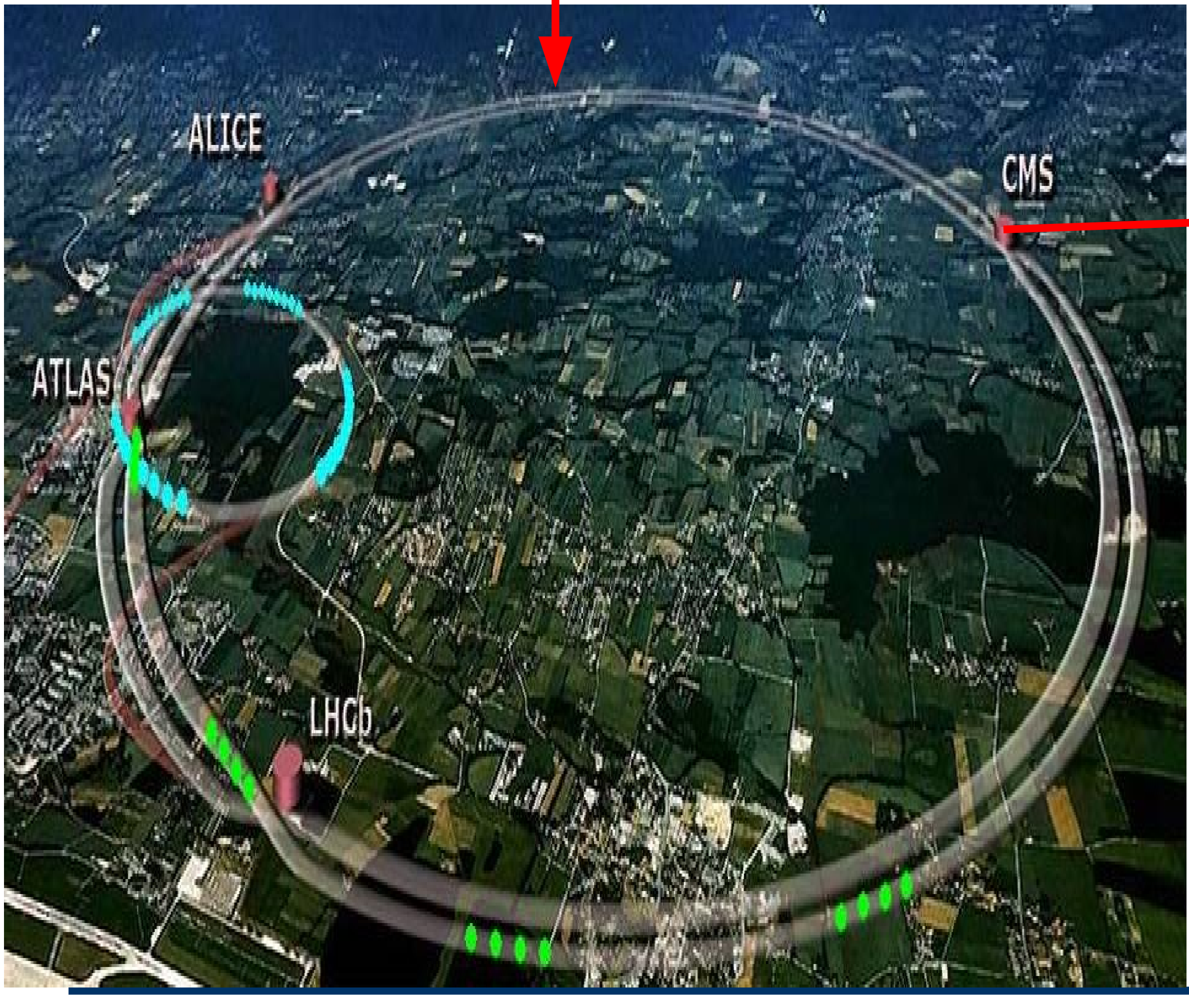


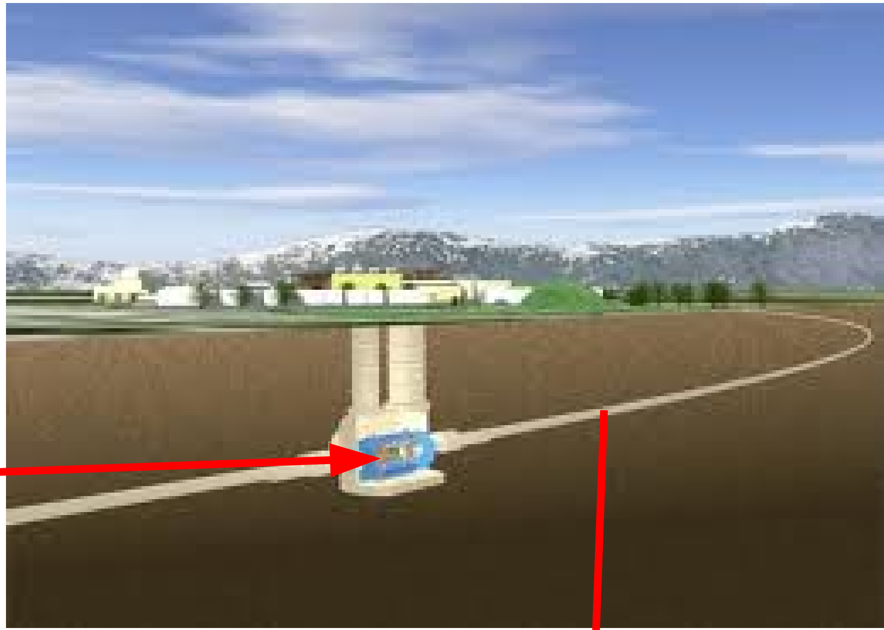
What is CERN?

- CERN is European Organization for Nuclear Research
- Founded in 1954
- The CERN laboratory locates at Franco – Swiss border near Geneva
- The instruments used at CERN are particle accelerators and detectors
- 20 countries are now member states at CERN (**Egypt is observer state since 2009**)
- The aims of CERN researches:
  * Seeking and finding answers to questions about the Universe
  * Technology: Advancing the frontiers of technology
  * Collaborating: Bringing nations together through science
  * Education: Training the scientists of tomorrow

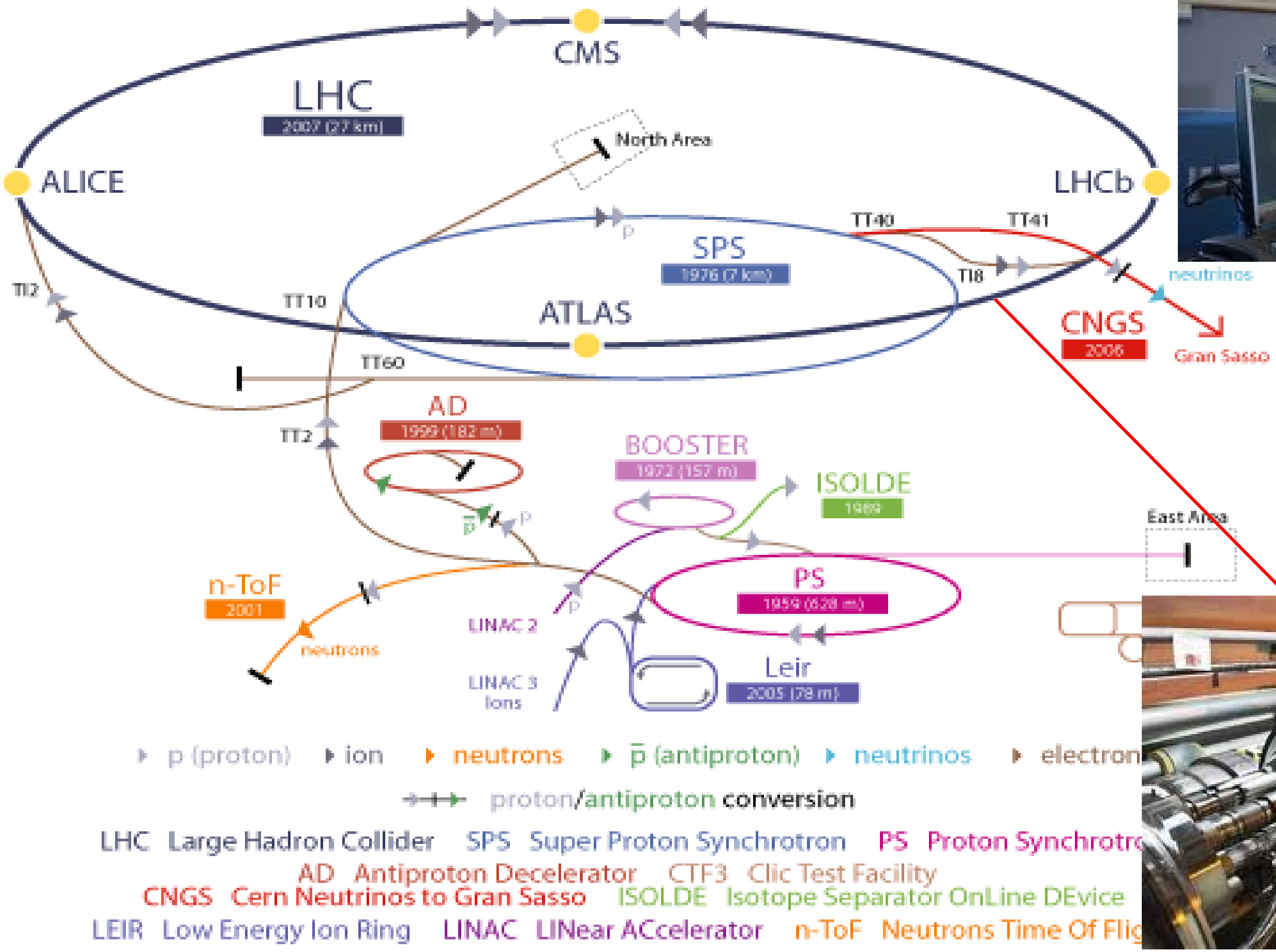
What is the LHC?

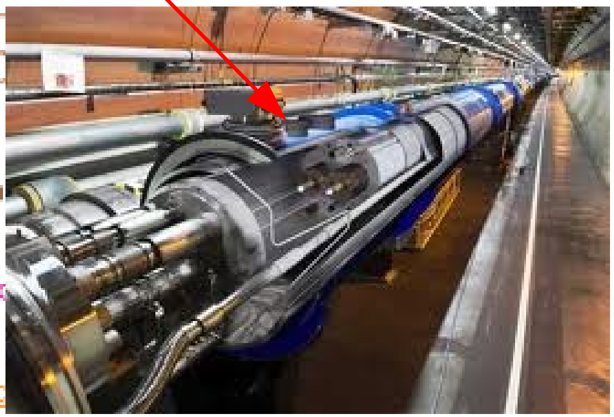
CERN **Large Hadron Collider** (LHC)



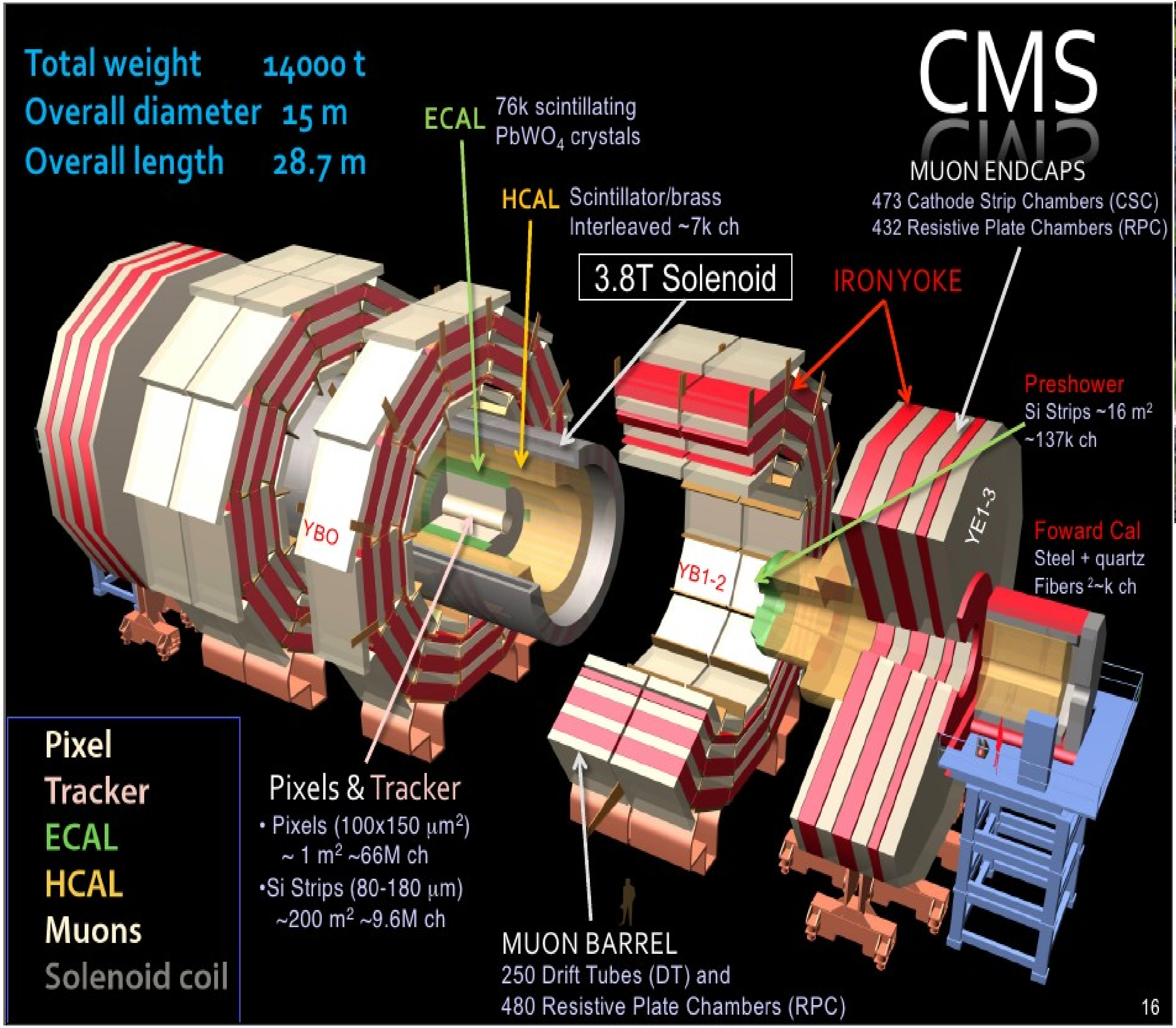


CERN Accelerator Complex





Compact Muon Solenoid (CMS) Detector



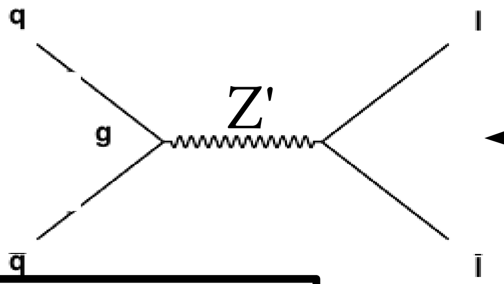
Search for,

*Higgs boson

*Extra-dimensions

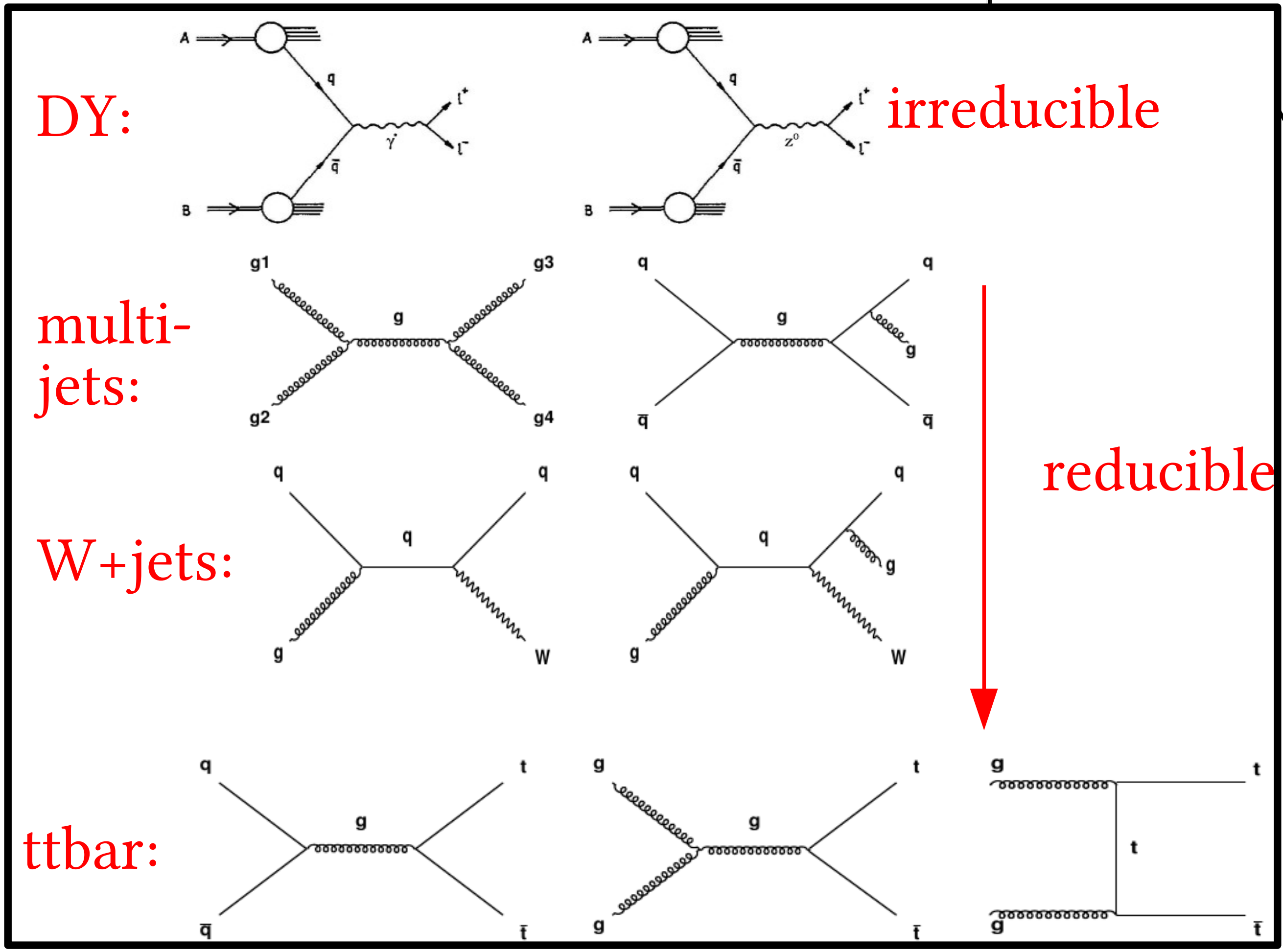
* particle that can make dark matter

Physics we are interested in !



Signal

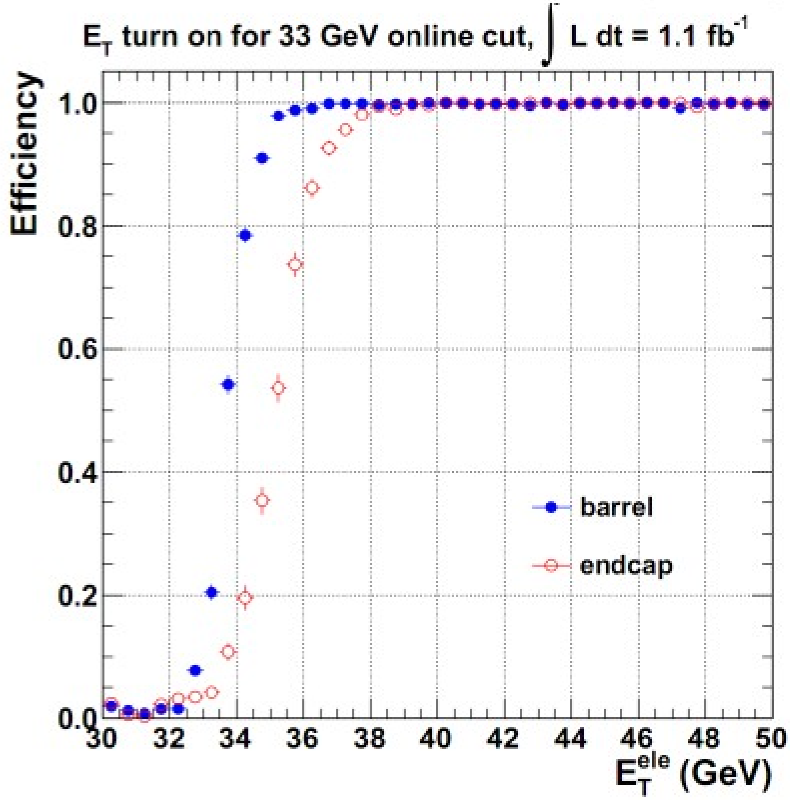
Backgrounds



Trigger	L1 Seed	run range	purpose
HLT_DoublePhoton33	L1_SingleEG20	160404-163869	signal, tag&probe
HLT_DoubleEle33_CaloIdL	L1_SingleEG20	165088-167913	signal, tag&probe
HLT_PhotonX_CaloIdVL	L1_SingleEG20	160404-167913	fake rate
HLT_Photon125	L1_SingleEG20	165088-166967	fake rate, sig. backup
HLT_Photon135	L1_SingleEG20	166968-167913	fake rate, sig. backup
HLT_Ele17_Y_Ele8_Y with Y=CaloIdL_CaloIsoVL	L1_SingleEG12	160404-167913	energy scale measurement
HLT_Mu15_Photon20_CaloIdL	L1_MuOpen_EG5	160404-167913	e-mu method

Reduce data size from 40MHz ~ 10^9 interactions/s to only 100Hz

- For eles passing HEEP ID, trigger efficiencies are:
  - L1: 99.66±0.01% (but only one required to pass)
  - DoubleEle33_CaloIdL vs DoublePhoton33: 99.85±0.04%



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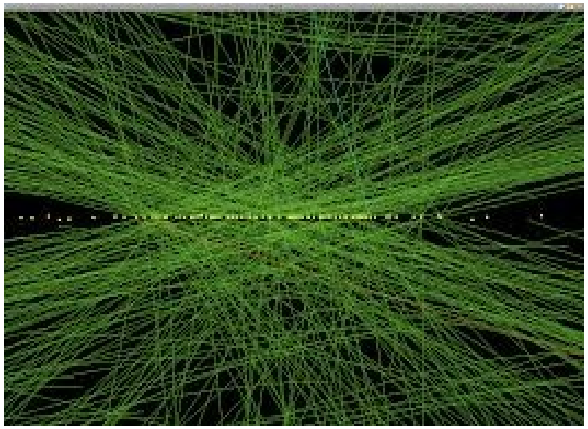
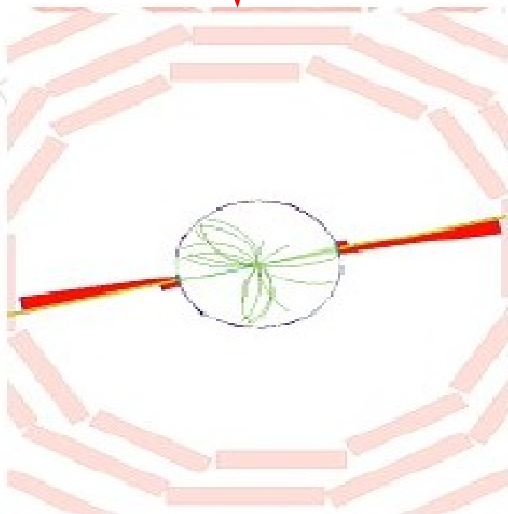
Event Selection

Before selection



After selection



Kinematics cuts

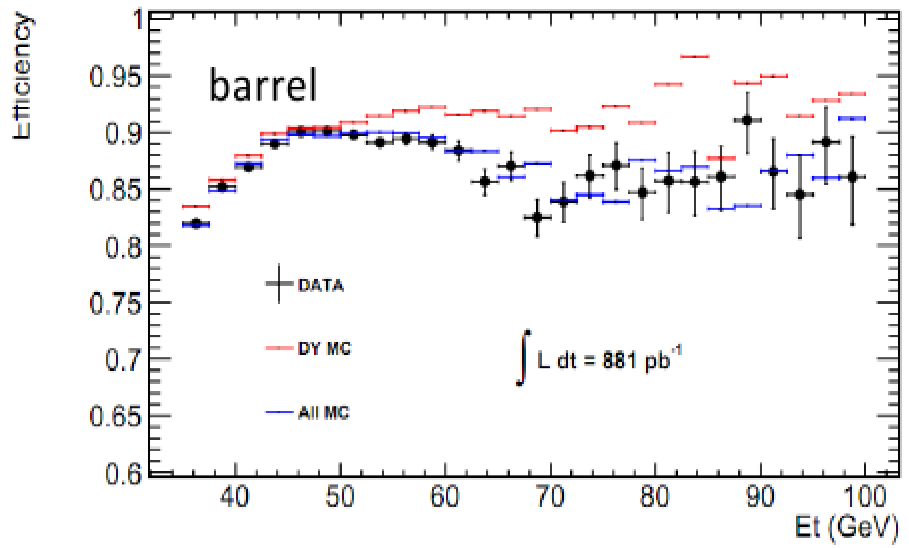
Shower shape cuts

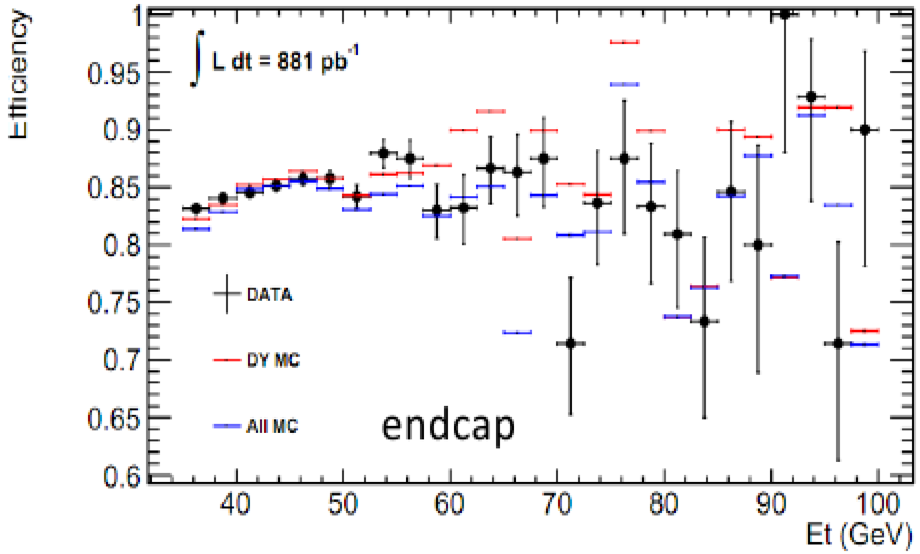
Isolation cuts

variable	barrel	endcap
E_T	> 35 GeV	> 40 GeV
$\|\eta_{SC}\|$	< 1.442	$1.56 < \|\eta\| < 2.5$
seed	ECAL seeded	ECAL seeded
missing hits	=0	=0
$\Delta\eta_{in}$	< 0.005	< 0.007
$\Delta\phi_{in}$	< 0.09	< 0.09
H/E	< 0.05	< 0.05
E^{2x5}/E^{5x5}	> 0.94 OR $E^{1x5}/E^{5x5} > 0.83$	-
$\sigma_{i\eta i\eta}$	-	< 0.03
isol Em + Had Depth 1	$< 2 + 0.03 \times E_T$ GeV	< 2.5 GeV for $E_T < 50$ GeV $< 2.5 + 0.03 \times (E_T - 50)$ GeV
isol Had Depth 2	-	< 0.5 GeV
isol Pt Tracks	< 7.5 GeV/c	< 15 GeV/c

Selection Efficiency (low mass)

- T&P: 60 < M(t&p) 120 GeV, (AN2011/270)
  - Tag: HEEP Candidate in Barrel with E/p < 1.5
  - Probe: GSF Electron, Et > 35 GeV
- Assume RECO scale factor to be 1
  - do this by measuring data/MC scale factor at Z
    - scale factor:
      - EB: $1.008 \pm 0.001^{stat} \pm 0.011^{sys}$
      - EE: $1.017 \pm 0.002^{stat} \pm 0.010^{sys}$

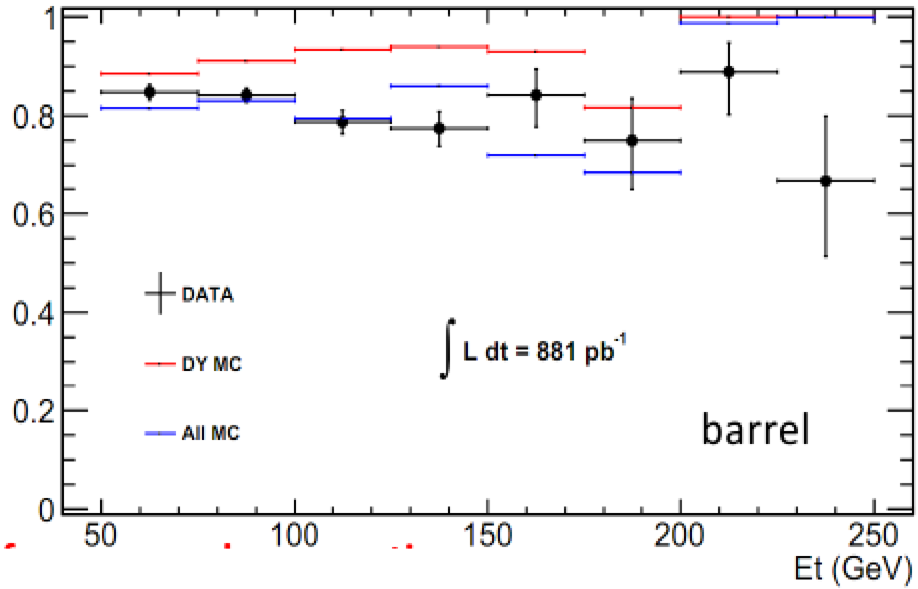


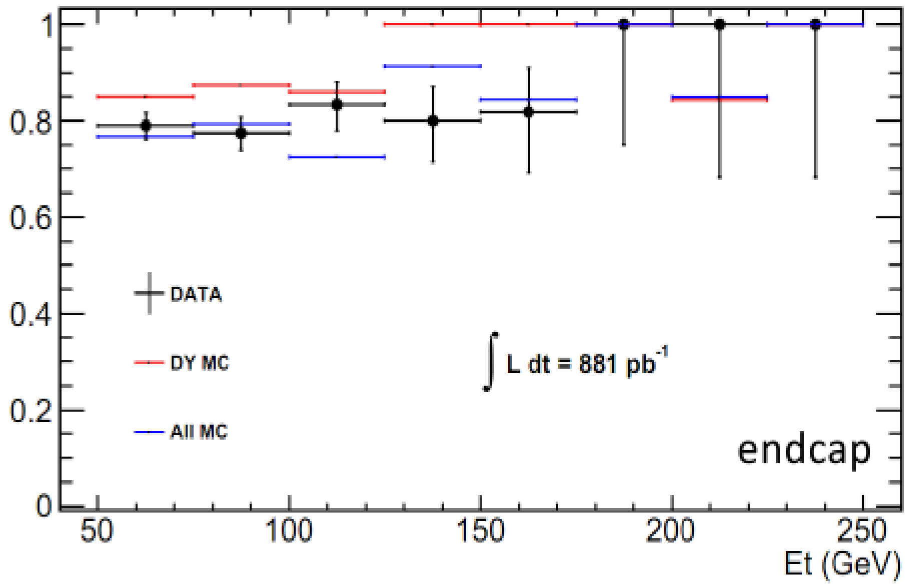


Selection Efficiency (high mass)

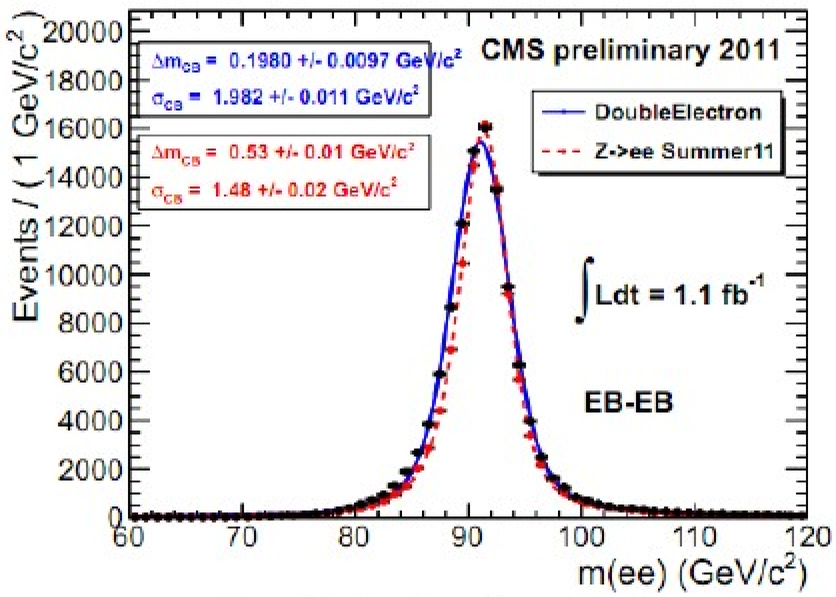
- data/MC agree at Z, but need to check agreement at high mass
- do T&P at high mass
  - M>140 GeV
- large bkgs:
  - apply tight cuts on tag
  - MET<40, opposite charge
  - diff of ele's p_T < 0.1 of their sum
- scale factor:
  - EB: $1.002 \pm 0.011^{stat} \pm 0.018^{sys}$
  - EE: $1.030 \pm 0.024^{stat} \pm 0.021^{sys}$

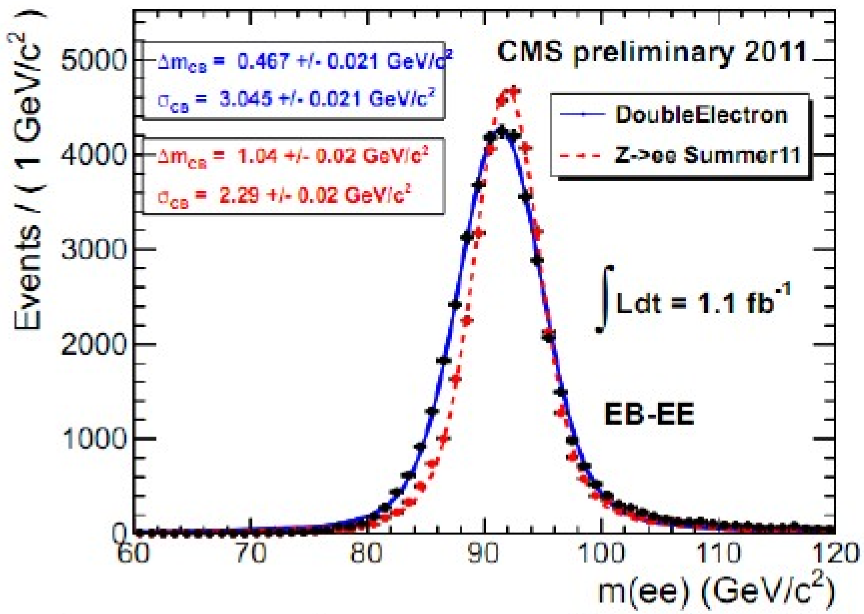
	HEEP Eff. (barrel)	HEEP Eff. (endcaps)
Drell-Yan	91.1 % ± 0.6 % (stat.)	86.4 % ± 1.5 % (stat.)
Drell-Yan + BG	82.7 % ± 0.6 % (stat.)	77.2 % ± 1.3 % (stat.)
Data	82.8 % ± 0.9 % (stat.)	79.5 % ± 1.9 % (stat.)
Scale factor	1.002 ± 0.011 (stat.) ± 0.018 (syst.)	1.030 ± 0.024 (stat.) ± 0.021 (syst.)





Energy scale & Resolution



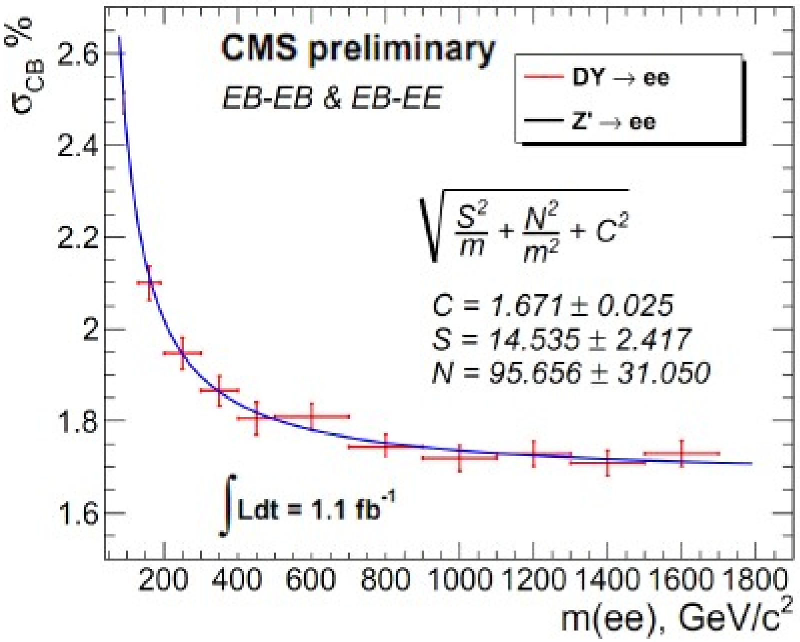


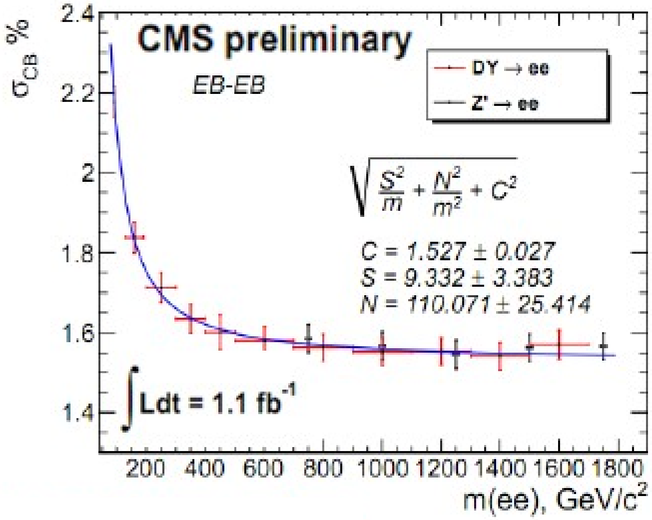
- use standard crystal ball fit technique used by ECAL DPG

region	$\Delta m_{CB}(Data), GeV$	$\Delta m_{CB}(MC), GeV$	$\frac{\Delta m_{CB}(Data)-\Delta m_{CB}(MC)}{m(Z^0)}, \%$
EB-EB	0.198 ± 0.010	0.53 ± 0.01	-0.36 ± 0.02
EB-EE	0.467 ± 0.021	1.04 ± 0.02	-0.63 ± 0.03
EE-EE	-1.247 ± 0.030	1.09 ± 0.03	-2.56 ± 0.05
EB-EB & EB-EE	0.252 ± 0.010	0.644 ± 0.01	-0.43 ± 0.02

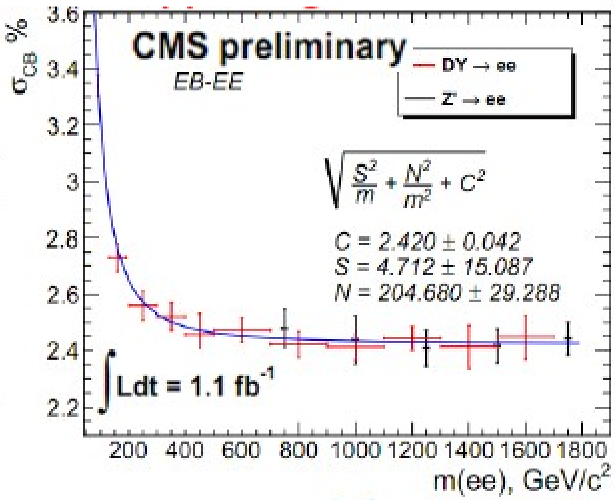
- endcap scale worsens a little with new data but our 1% scale uncertainty covers it
  - no analysis level correction needed
  - method documented in AN2011/204

Mass Resolution





region	$\sigma_{CB}(Data)$, %	$\sigma_{CB}(MC)$, %	$\sigma_{CB}(extra)$, %
EB-EB	2.17 ± 0.02	1.62 ± 0.02	1.45 ± 0.03
EB-EE	3.34 ± 0.03	2.51 ± 0.02	2.20 ± 0.03
EE-EE	4.29 ± 0.03	2.40 ± 0.04	3.55 ± 0.05
EB-EB & EB-EE	2.49 ± 0.01	1.92 ± 0.01	1.59 ± 0.02



- MC estimate of mass resolution corrected by addition of constant term to match data at Z

SM Backgrounds

There are 3 significant SM bkgs:

- SM Drell-Yan
  - irreducible background
- TTbar + ttbar like
  - two real electrons
  - tt, WZ, WW, tW, Z->tt)
- Jet background
  - W+jet, di-jet where jet fakes an electron

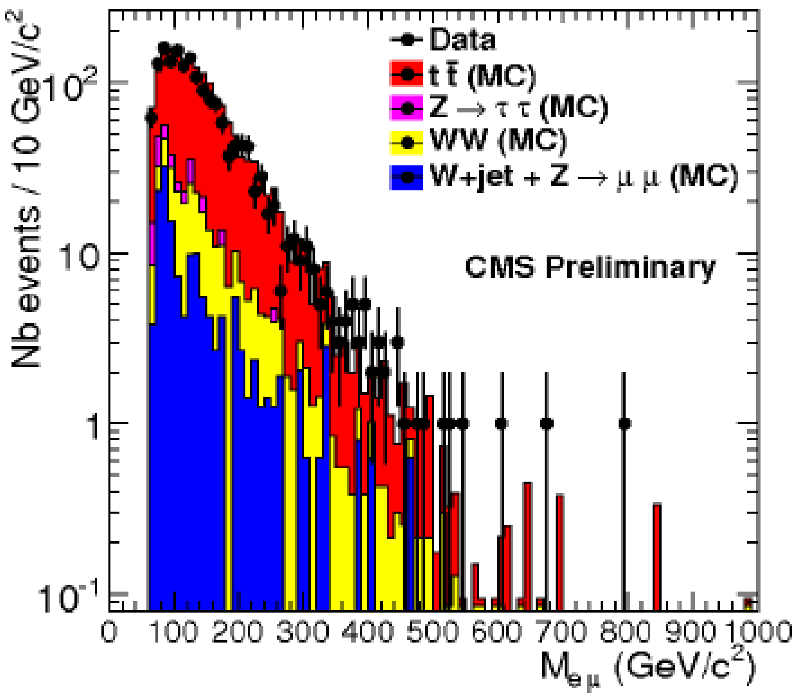
(SM Drell-Yan and TTbar + ttbar like:)

- both est. from MC
- ttbar has data driven e-mu cross-check
- both are common between electron and muon channels

(Jet background:)

- data driven estimate
- only significant in the electron channel

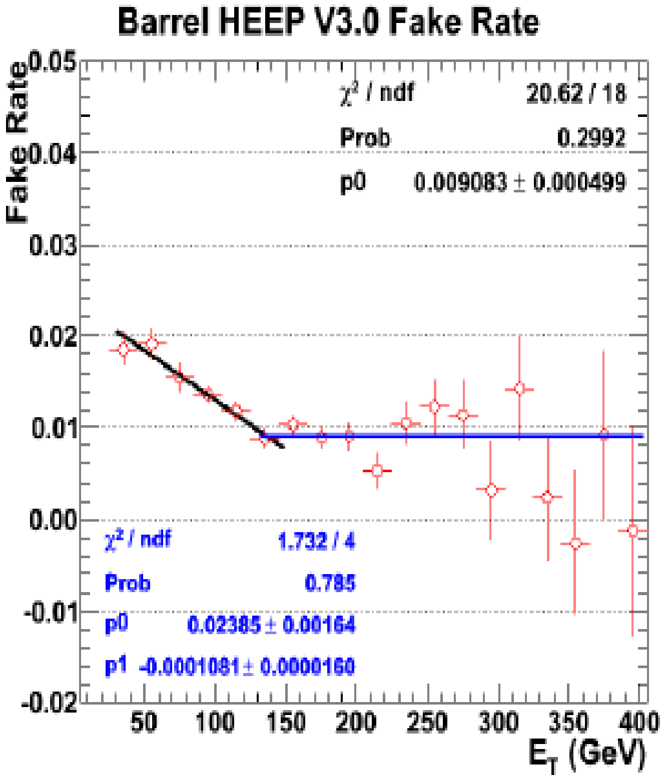
ttbar + ttbar like Backgrounds

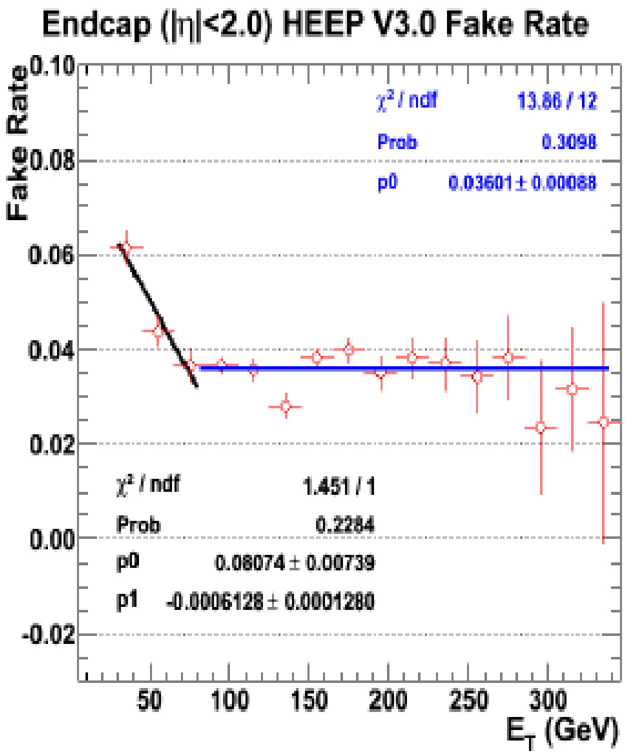


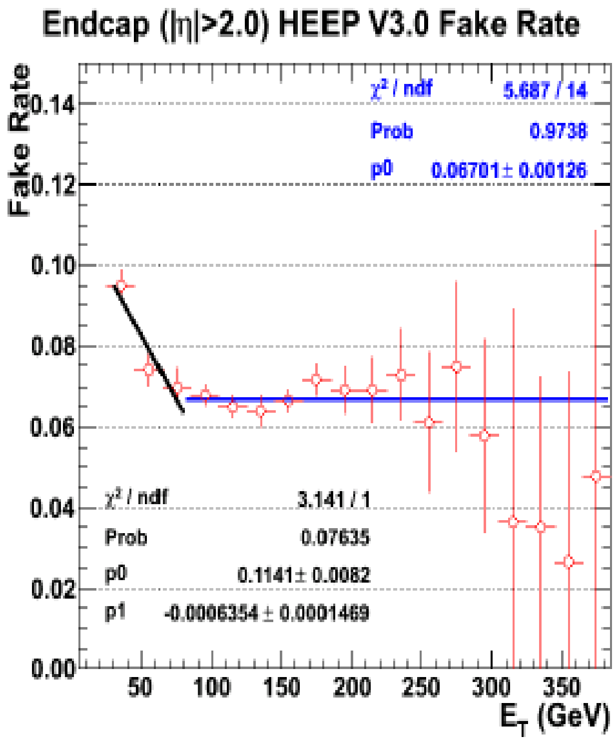
- equivalent plot from HEEP analysis
  - uses slightly different muon selection: VBTF 2010 with p_T > 35 GeV
  - main different keep global X^2 cut and eta <2.1 + veto on muon showering
- same conclusion as muon analysis
  - ttbar MC describes data well

Mass (GeV)	Data	MC
>60	1678±41	1791 ± 161^{sys}
>120	914±30	1032 ± 93^{sys}
>200	283±17	300 ± 27^{sys}

Fake Rate





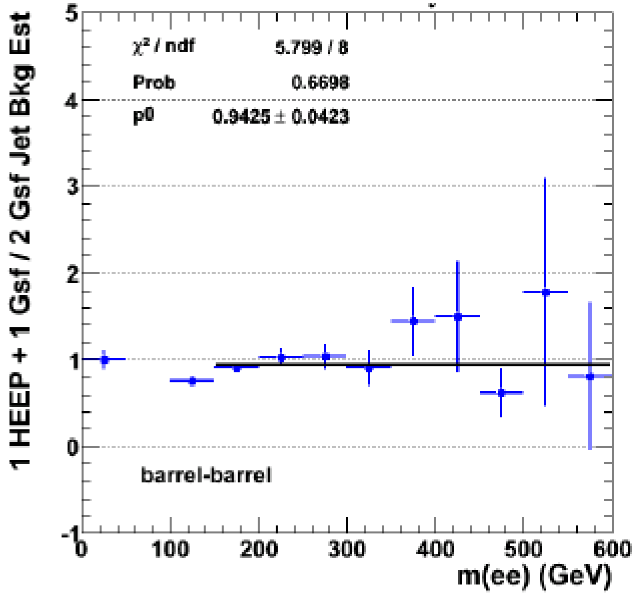


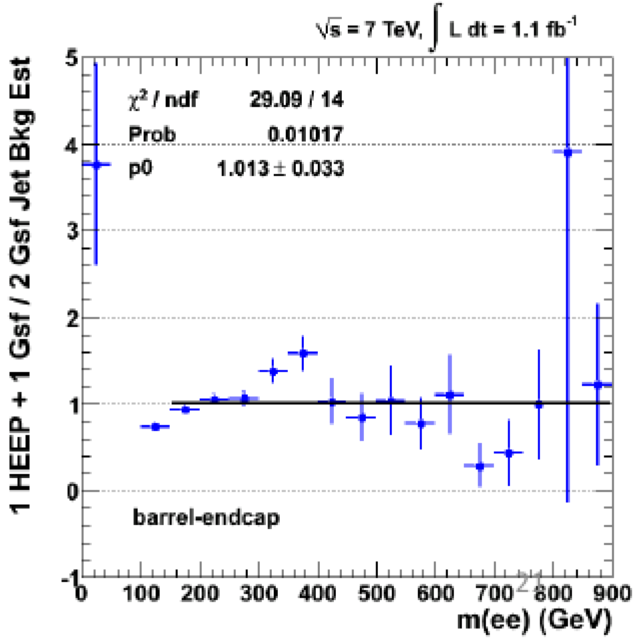
Fake rate = (nb. HEEP electrons)/(nb. GSF passing fakeRate pre-selection)

variable	barrel	endcap
$\sigma_{i\eta i\eta}$	0.013	0.034
H/E	0.15	0.10
nr. missing hits	=0	=0

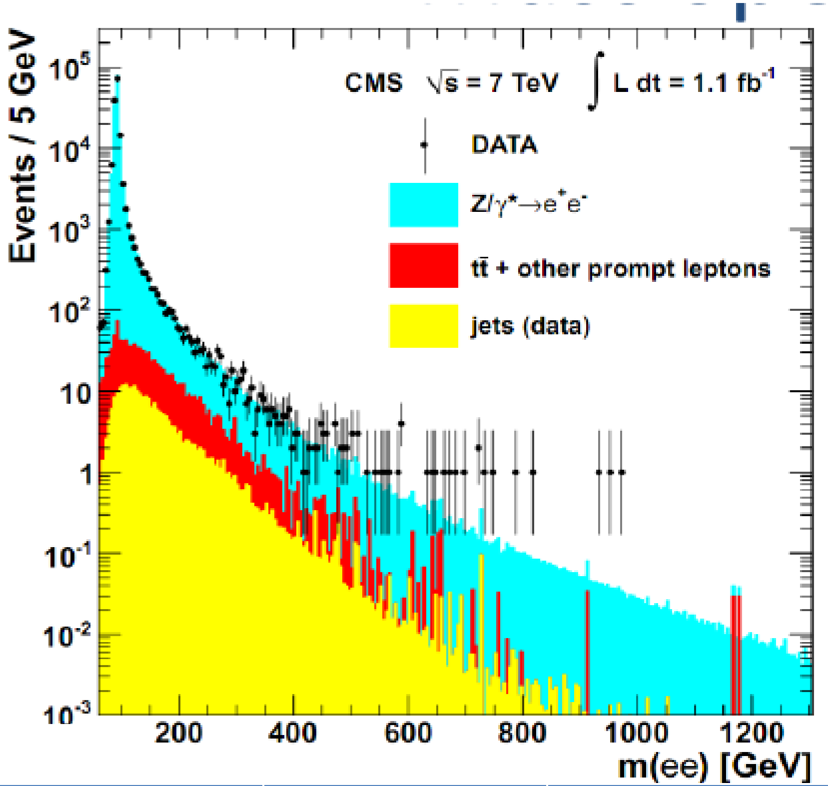
Jet Background

- measure probability (or fakerate) for jet which is reconstructed as GsfElectron with loose $\sigma_{i\eta i\eta}$ + H/E to pass HEEP selection
  - starting point efficiently triggered by signal trigger
  - collect events on PhotonX_CaloIdVL trigger
  - <=1 ele, use MC to subtract W+jet, Pho+Jet, Zee contamination
- apply it to 2 Gsf or 1 Gsf + 1 HEEP
  - 2 Gsf will not include W+jet, Pho+jet so add in MC prediction (with data fake rate)
  - 1 Gsf has large Z contamination so subtract MC estimate
  - use 2 Gsf as higher stats
- good agreement
  - 300-400 in EB-EE has less good agreement

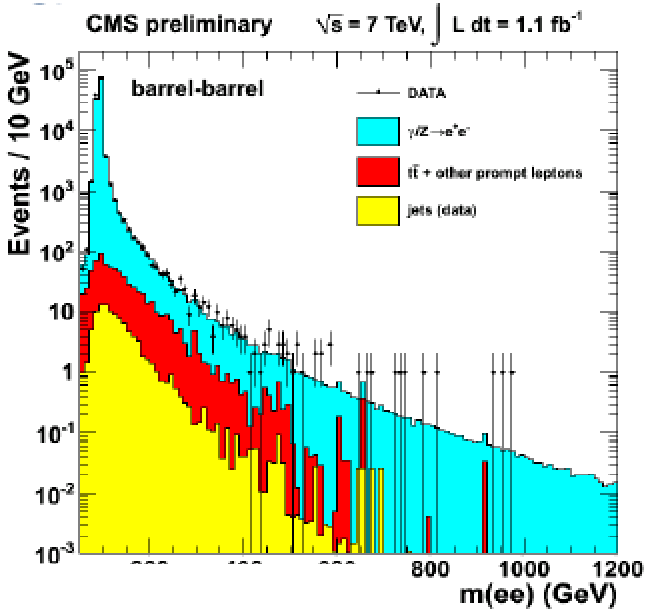


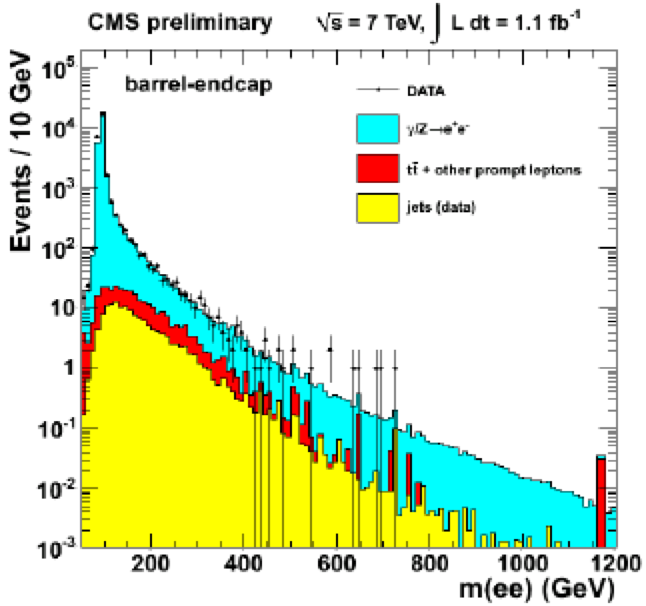


Mass Spectra

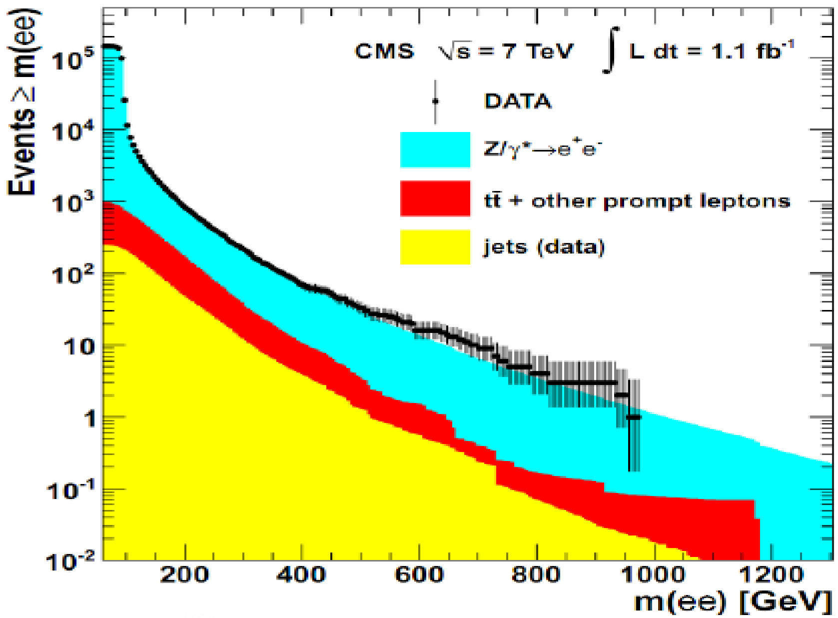


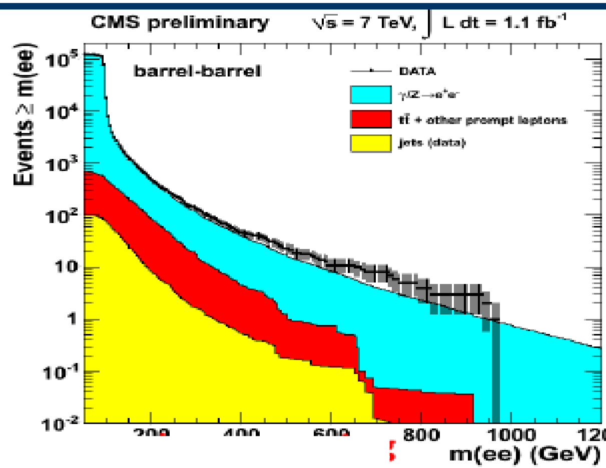
	120-200 GeV	>200 GeV
data	3410	809
tot bkg	3375±161	787±67
Drell-Yan	2992±149	622±62
tt+tt like	275±41	118±17
jet events	107±43	46±18

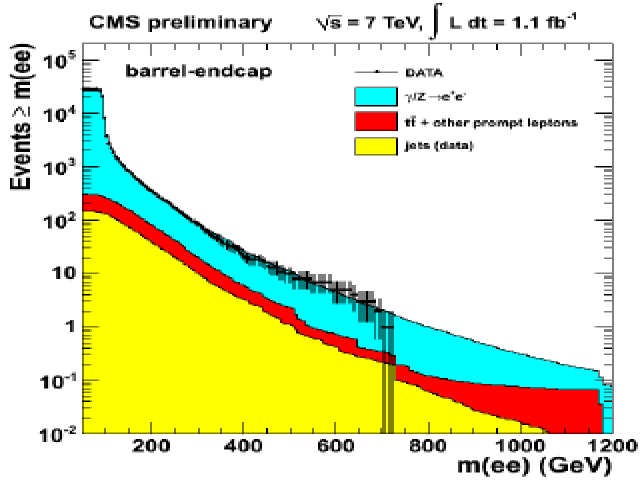


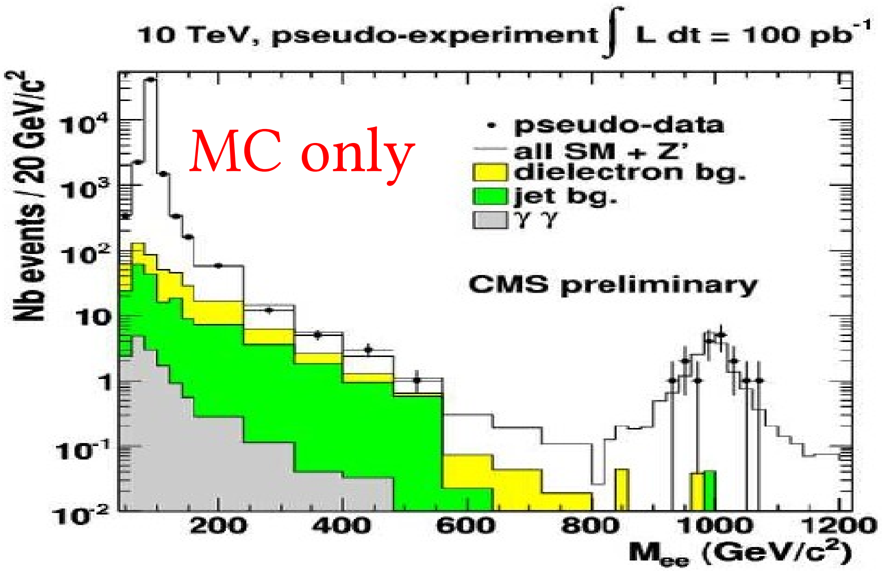


Integral Mass Spectra

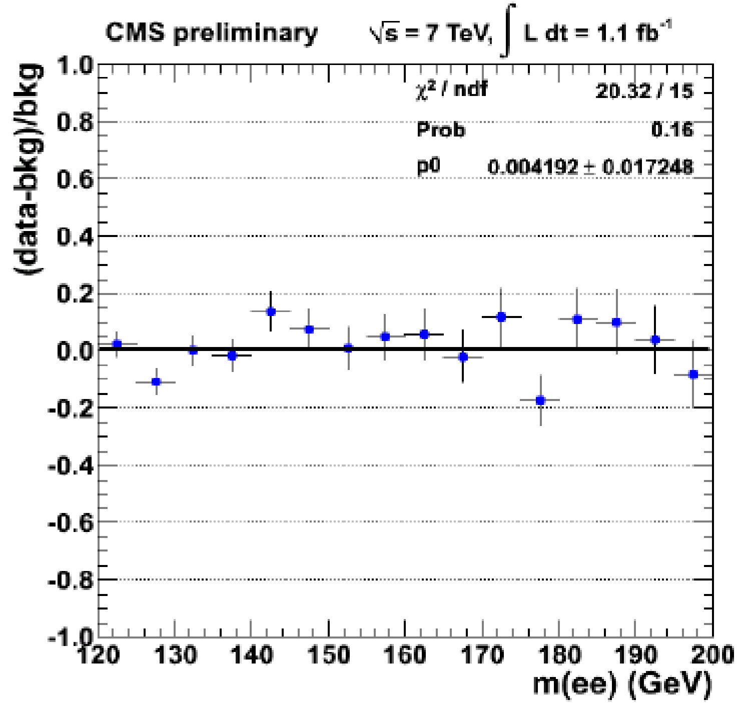


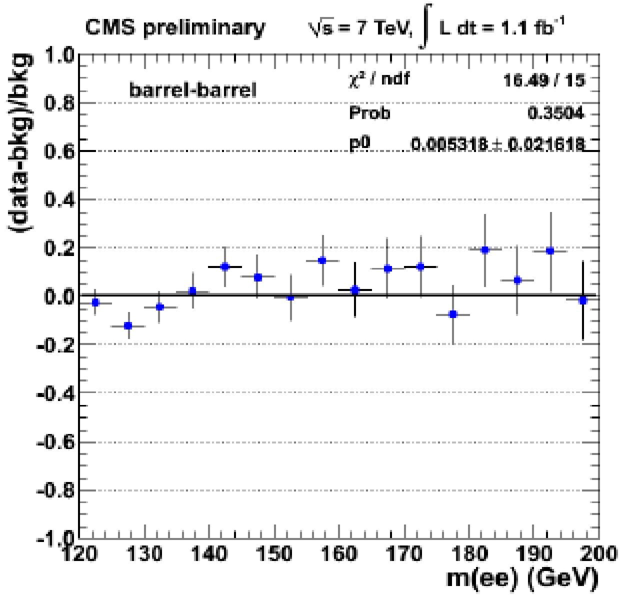


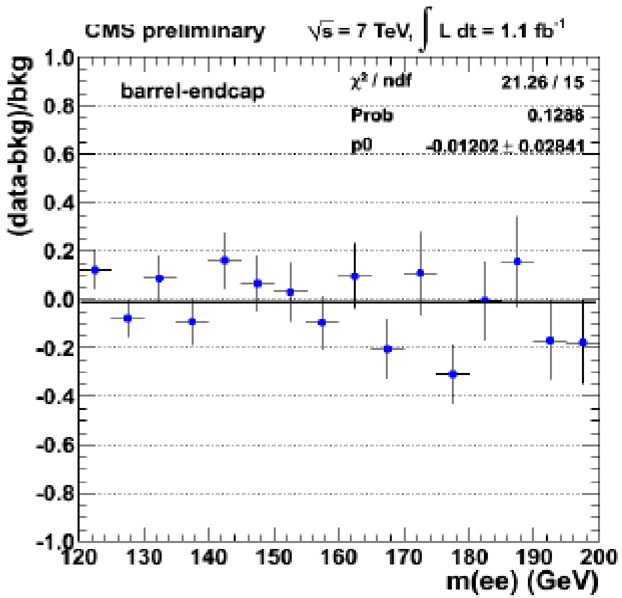




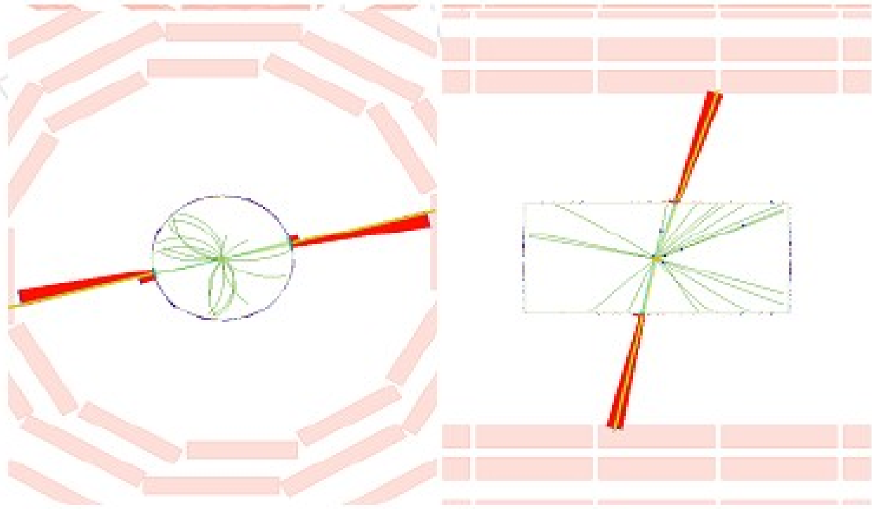
Control Region

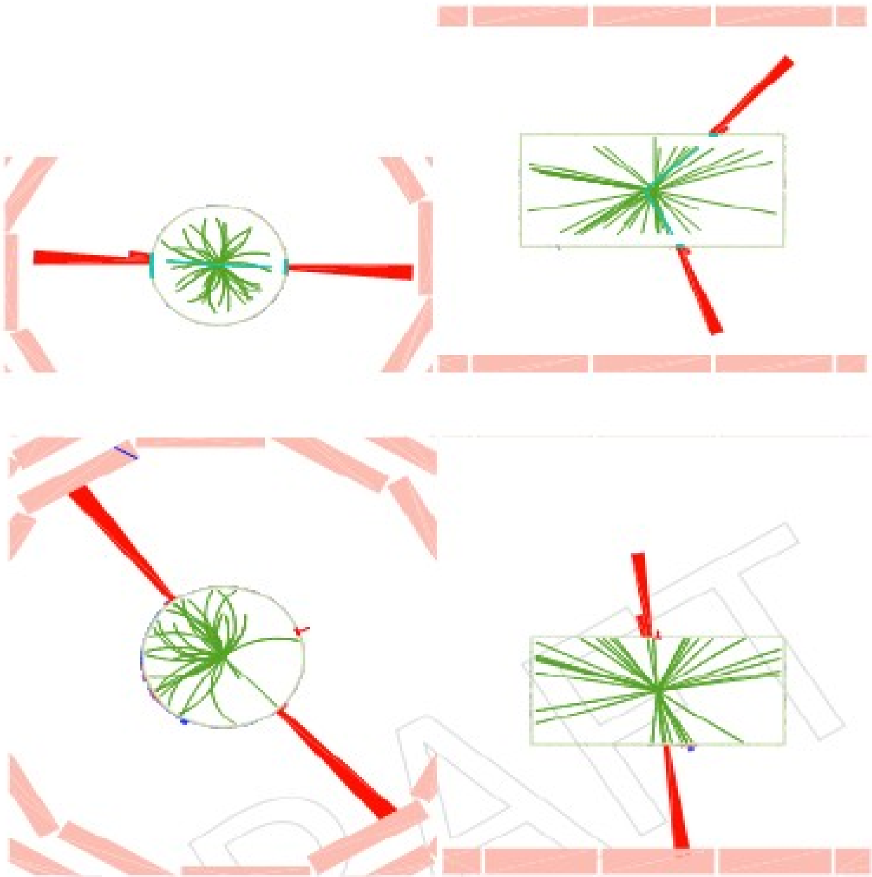






- define 120-200 GeV region as a control region
  - last years control region
- very good agreement
  - data consistent with MC

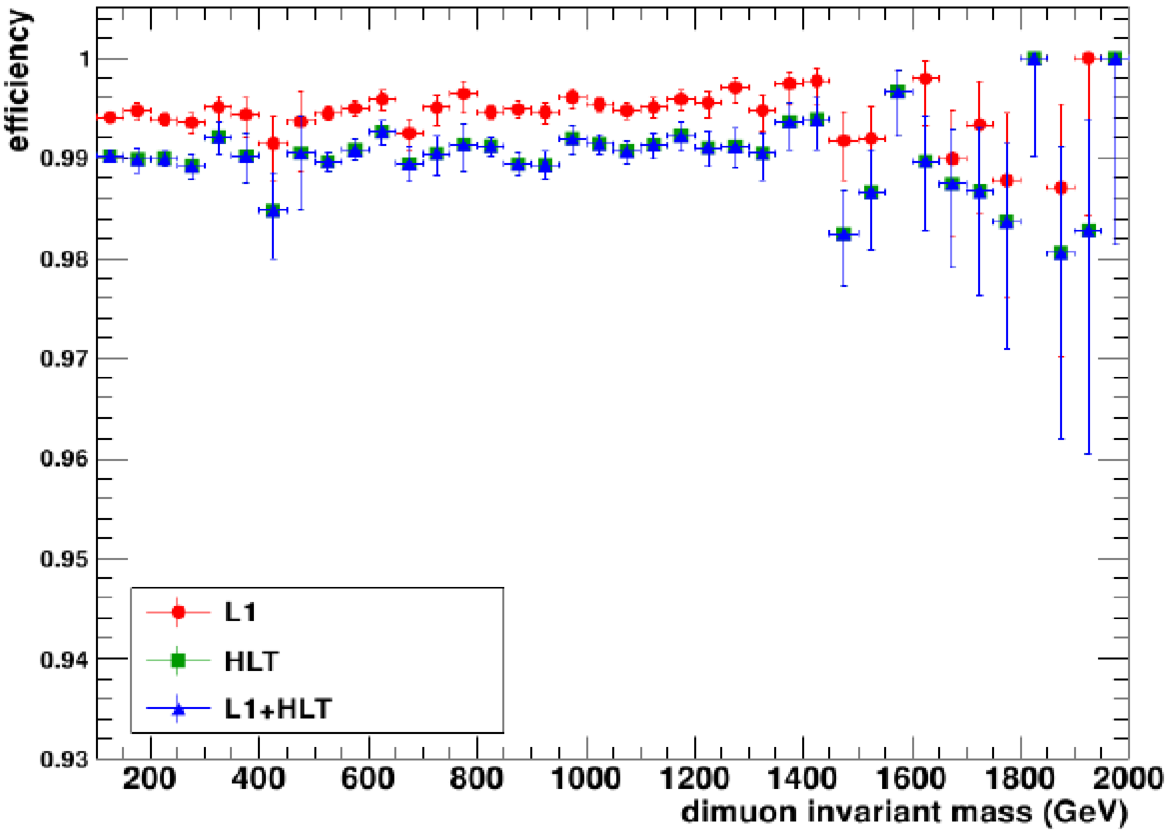




Event	mass (GeV)	cluster energies (GeV)	Hadronic/EM energy	(η, ϕ)
(a)	952	717 , 520	0.001 , 0.0	(0.95,3.06) , (0.54,-0.05)
(b)	971	500 , 473	0.003 , 0.008	(0.14,-0.81) , (-0.16,2.24)
(c)	930	466 , 465	0.006 , 0.0	(0.21,-2.89) , (0.32,0.26)

Muon Triggers

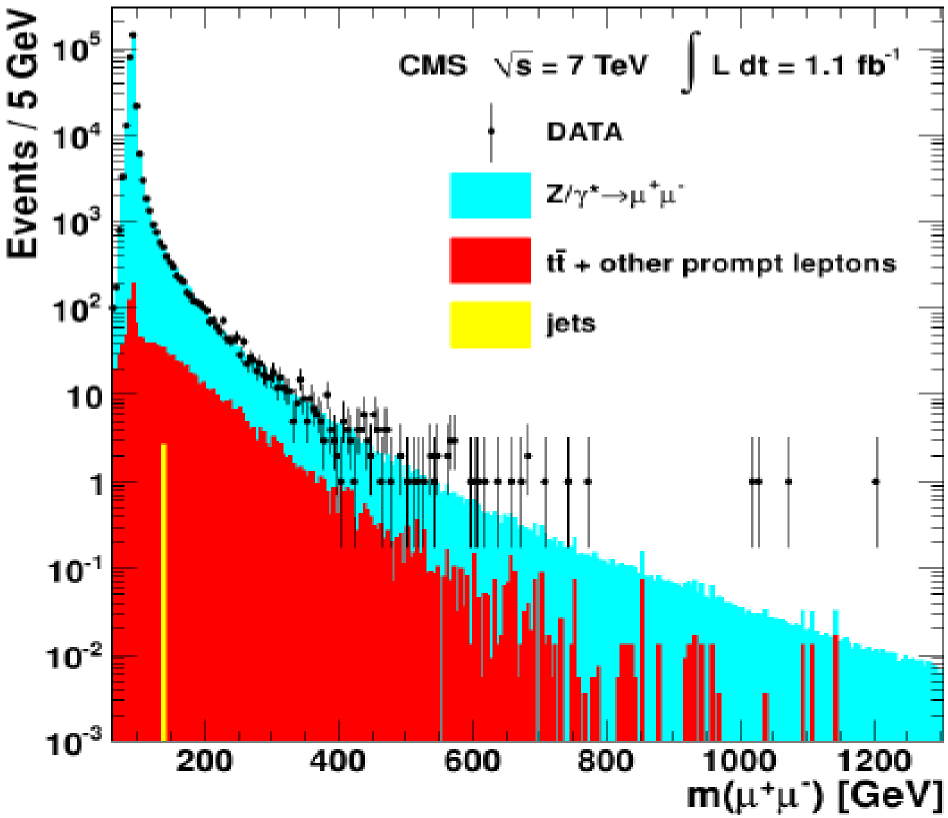
- „MuonPhys" JSON corresponding to ~1.1 fb-1
- Trigger: lowest unprescaled single muon non-iso trigger – HLT_Mu30 up to now
- NoScraping and good Primary Vertex reqirements
- Trigger efficiency checked in MC to be at or above 98% for events passing our selection Drell-Yan MC

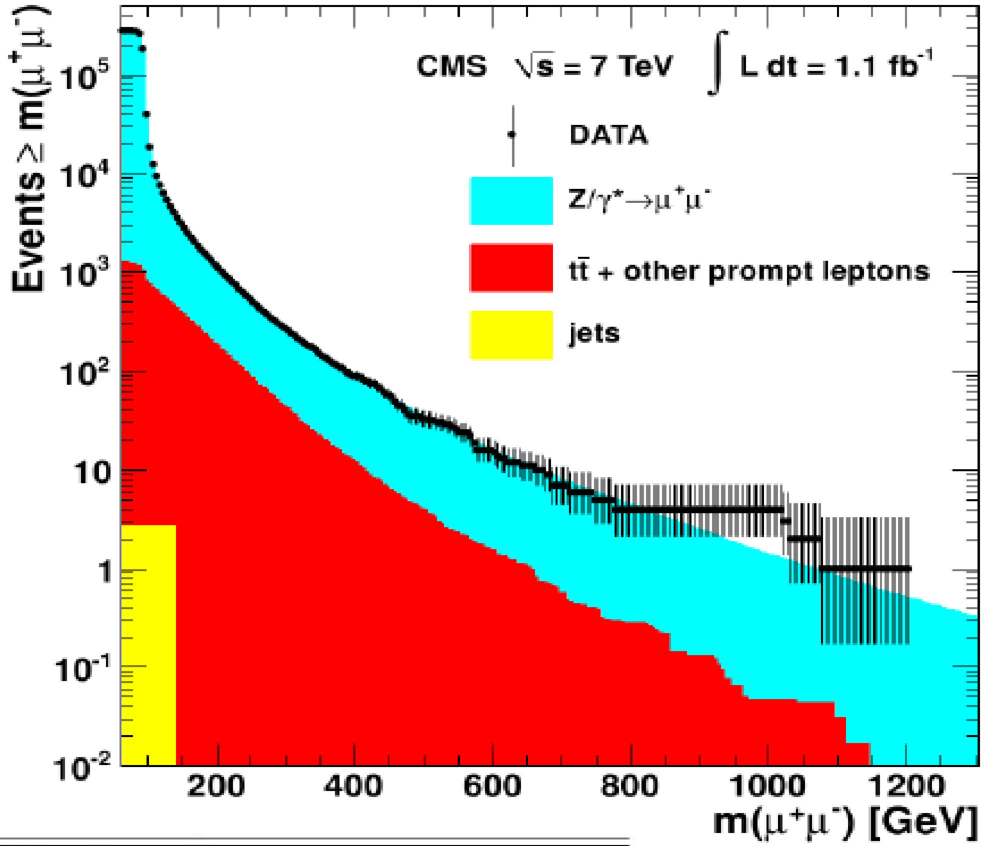


Muon Selection

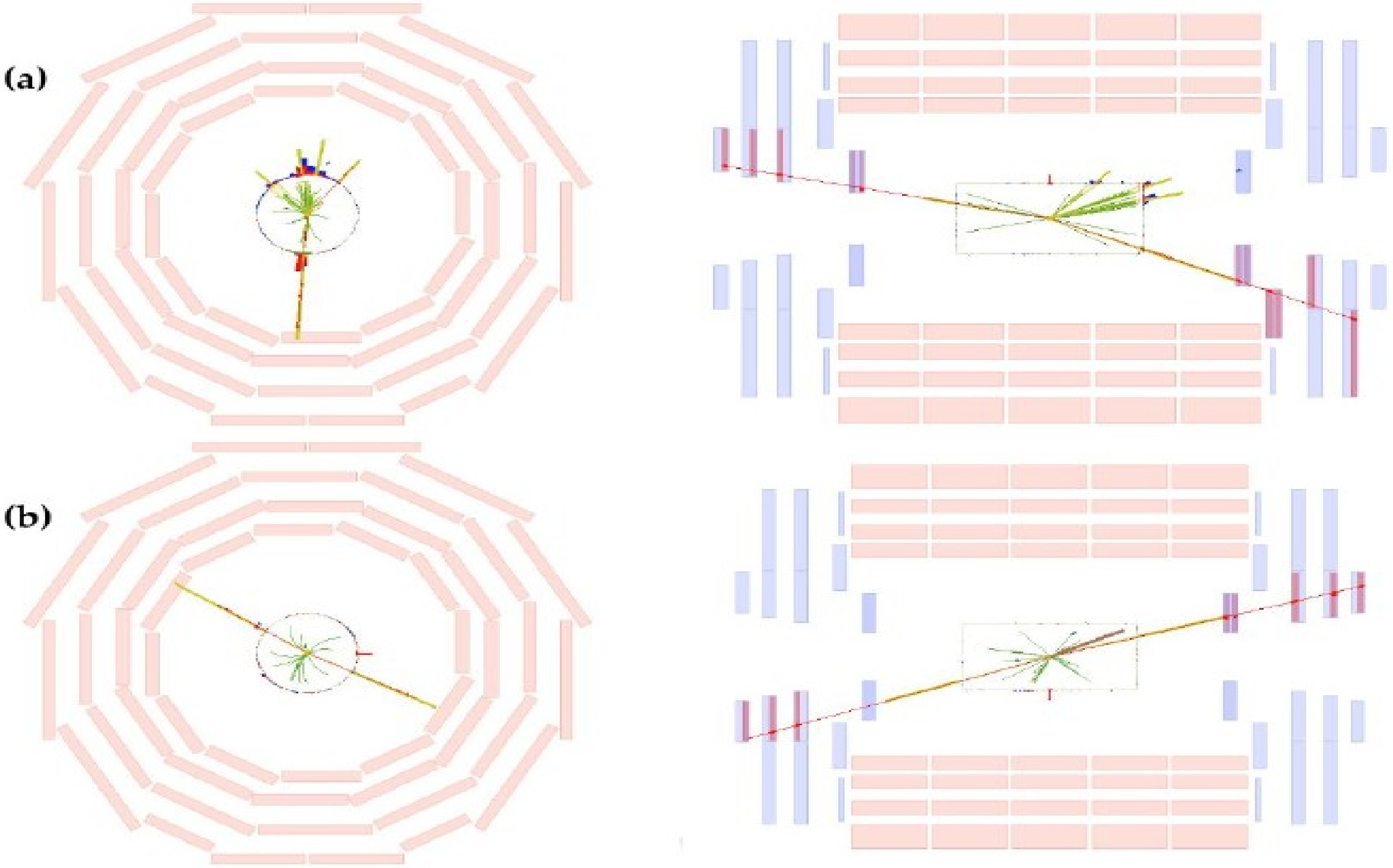
- Muons pass the “tight” muon POG selection
- Two muons forming a dimuon candidate must be opposite-sign
- One of them has to be matched to an HLT muon
- The 3D opening angle between the muons' momenta is requred to be smaller than π-0.02, to suppress cosmics
- Additional muon reconstruction quality requirement: we require the dimuon vertex-constrained fit to have $\chi 2 < 10$

Muon Invariant Mass Spectrum





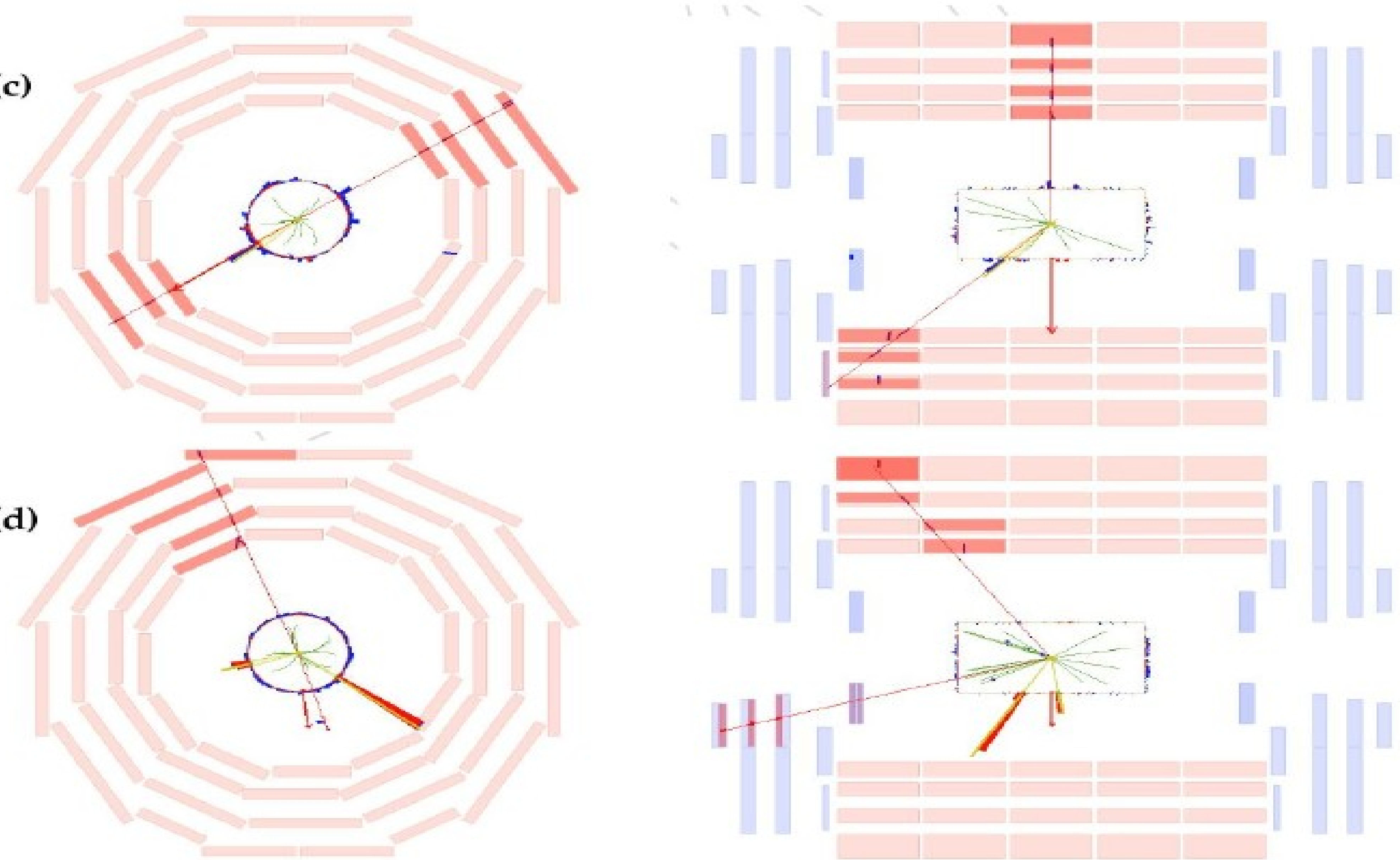
Source	Number of events			
	Dimuon sample		Dielectron sample	
	(120 – 200)	>200	(120 – 200)	>200
CMS data	5216	1095	3410	809
Total background	5537 ± 250	1100 ± 48	3375 ± 161	787 ± 67
Z/γ^*	5131 ± 246	922 ± 44	2992 ± 149	622 ± 62
$t\bar{t}$+ other prompt leptons	404 ± 46	178 ± 20	275 ± 41	118 ± 17
Multi-jet events	3 ± 3	0	107 ± 43	46 ± 18


(a)
(b)

More Event Display

(c)

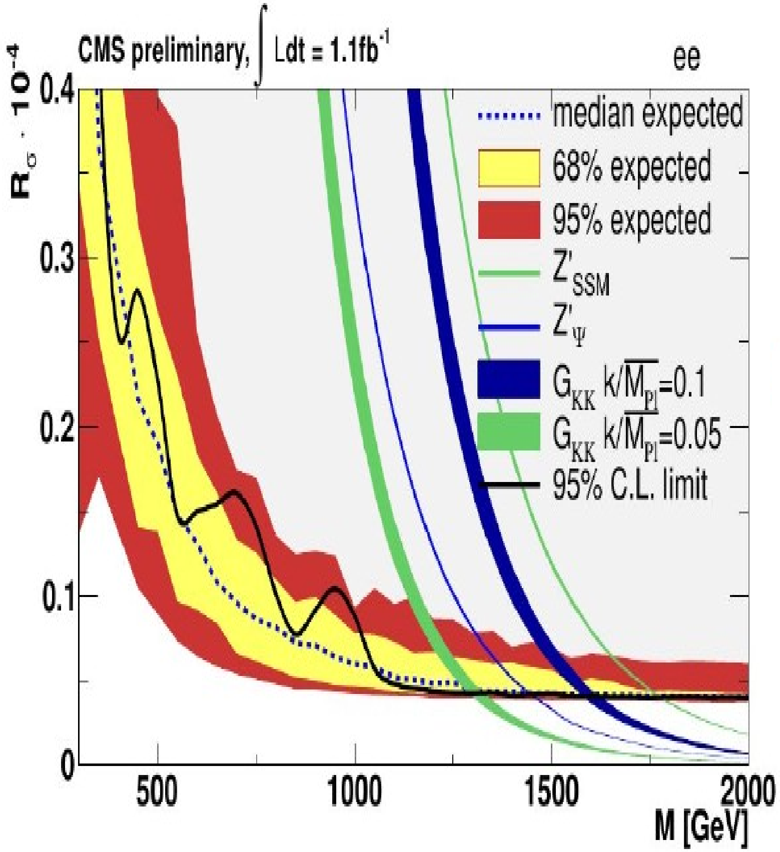
(d)



Cross Section Ratio to Z^0

- Di-electron cross section ratio limits

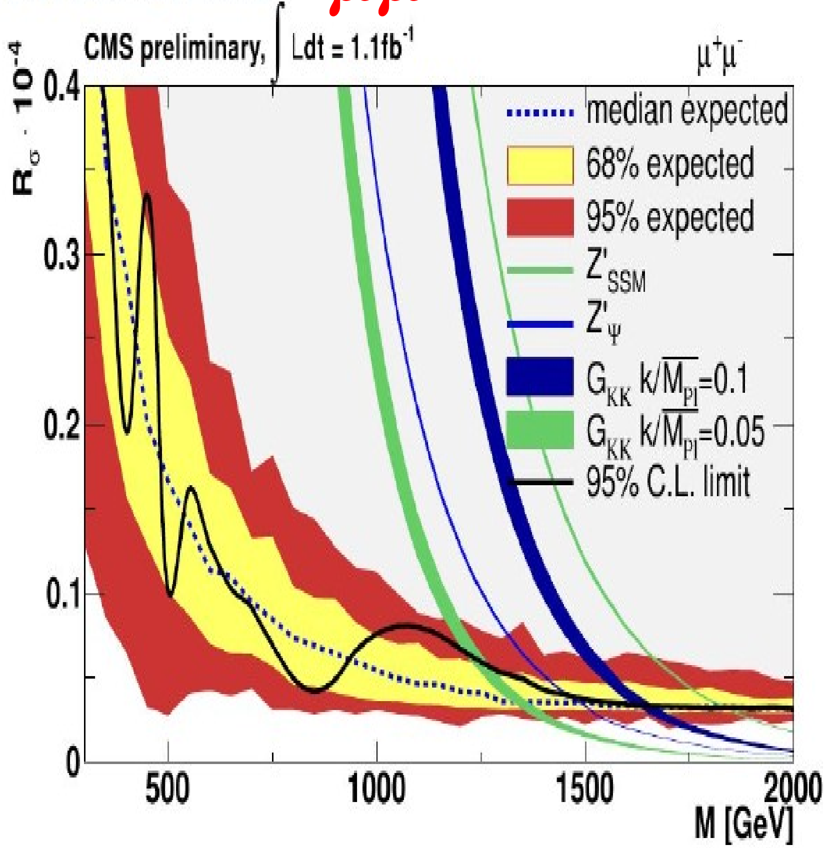
ee channel



- Mass limits
  - SSM: 1769 Gev
  - Psi: 1450 GeV
  - Kaluza-Klein gravitons: 1314 (1598) GeV for couplings 0.05 (0.1)

- Di-muon cross section ratio limits

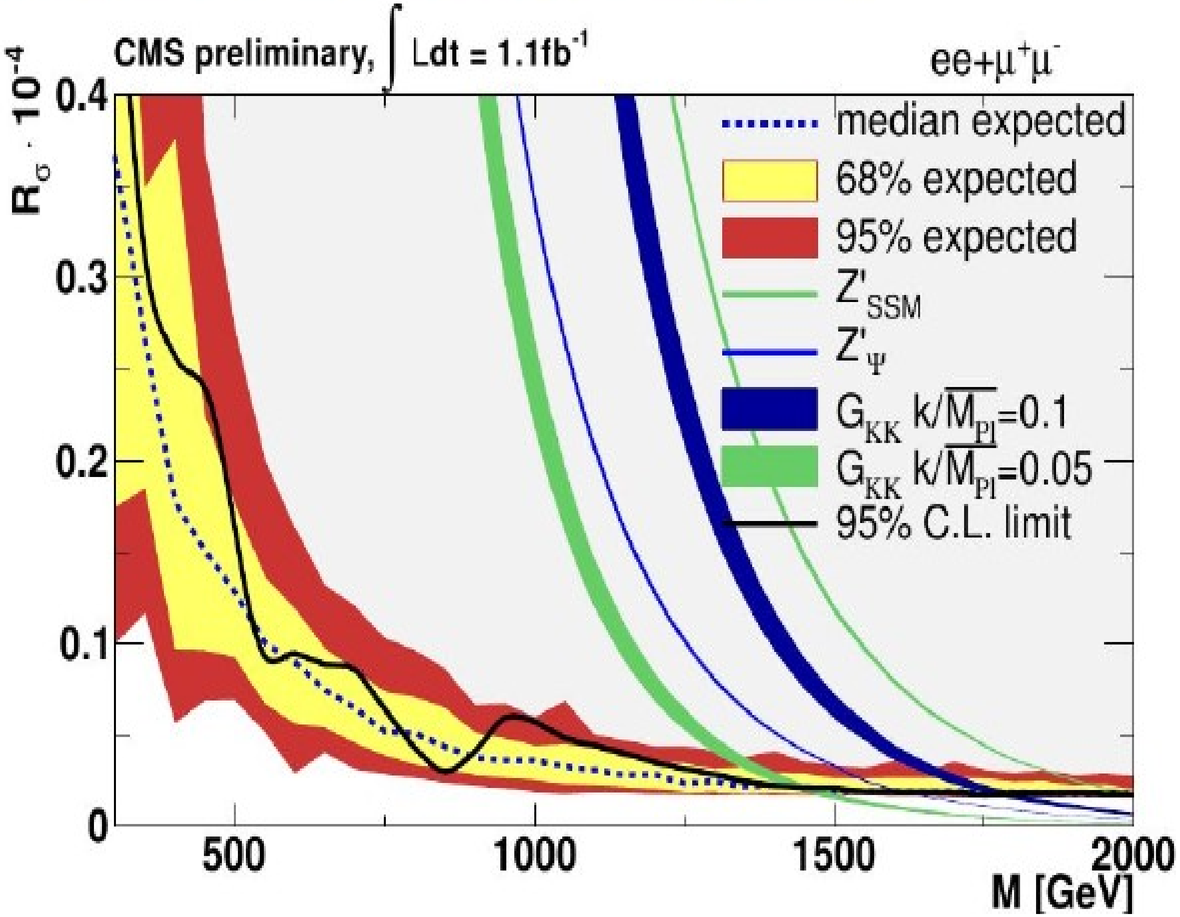
$\mu\mu$ channel



- Mass limits
  - SSM: 1841 Gev
  - Psi: 1449 GeV
  - Kaluza-Klein gravitons: 1241 (1640) GeV for couplings 0.05 (0.1)

Cross Section Ratio to Z^0

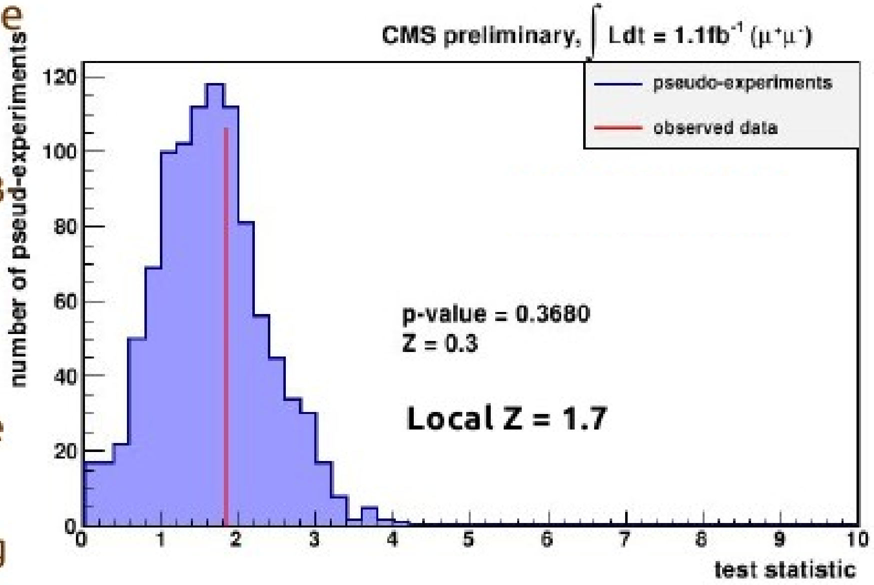
- Combined di-electron and di-muon cross section ratio limits

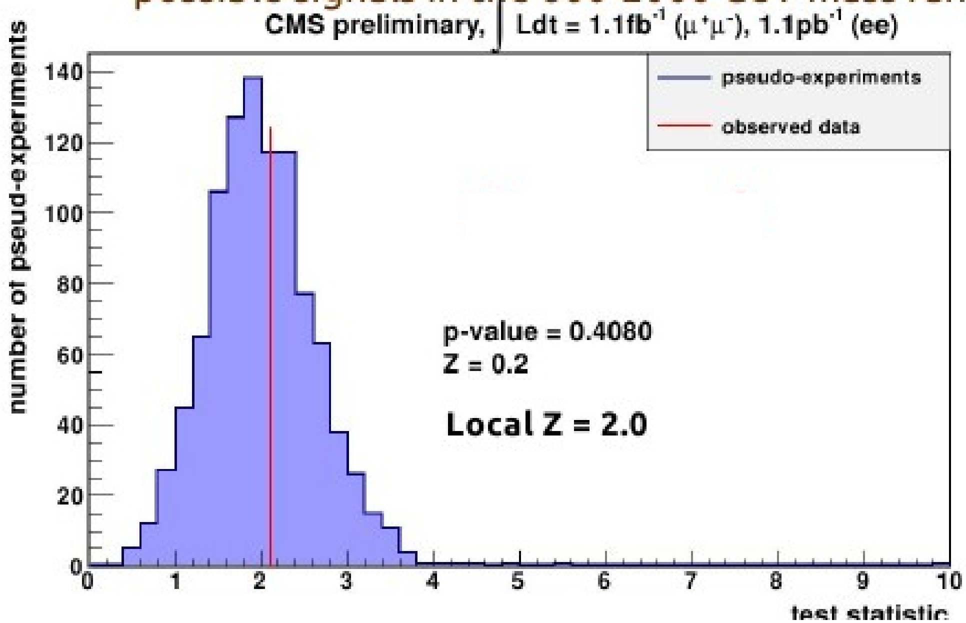


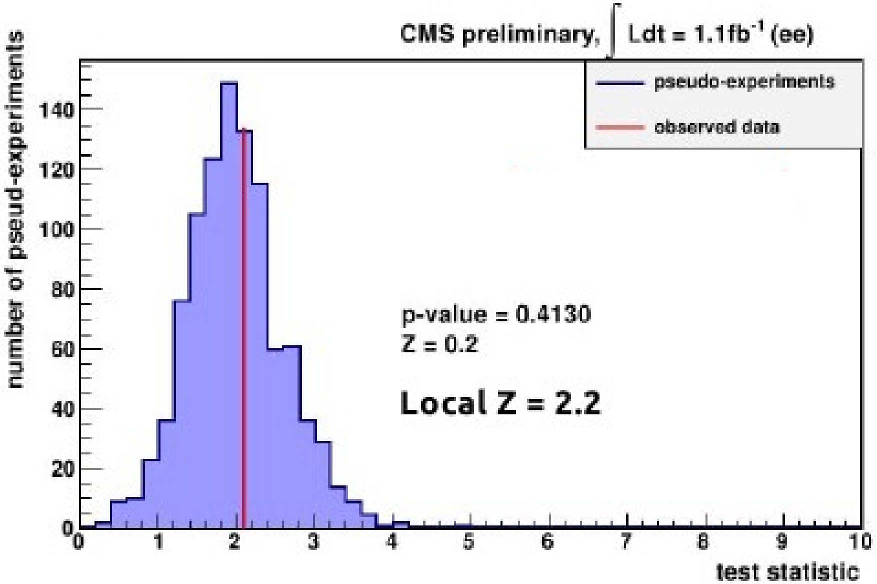
- Mass limits
  - SSM: 2003 Gev
  - Psi: 1614 GeV
  - Kaluza-Klein gravitons: 1453 (1786) GeV for couplings 0.05 (0.1)

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







Summary

- 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 1.7, corrected for LEE it becomes 0.3
- At 95 % CL we exclude Z'SSM below 2003 GeV, Z'ψ below 1614 GeV and GKK c=0.1 (c=0.05) below 1786 GeV (1453 GeV)

Backup

low mass

	HEEP Eff. (barrel)	HEEP Eff. (endcaps)
Drell-Yan	87.9% ± 0.1% (stat.)	83.9% ± 0.2% (stat.)
Drell-Yan + BG	86.9% ± 0.1% (stat.)	83.1% ± 0.2% (stat.)
Data	87.6% ± 0.1% (stat.)	84.6% ± 0.2% (stat.)
Scale factor	1.008 ± 0.001 (stat.) ± 0.011 (syst.)	1.017 ± 0.002 (stat.) ± 0.010 (syst.)

High mass

	HEEP Eff. (barrel)	HEEP Eff. (endcaps)
Drell-Yan	91.1 % ± 0.6 % (stat.)	86.4 % ± 1.5 % (stat.)
Drell-Yan + BG	82.7 % ± 0.6 % (stat.)	77.2 % ± 1.3 % (stat.)
Data	82.8 % ± 0.9 % (stat.)	79.5 % ± 1.9 % (stat.)
Scale factor	1.002 ± 0.011 (stat.) ± 0.018 (syst.)	1.030 ± 0.024 (stat.) ± 0.021 (syst.)

Statistical Interpretation

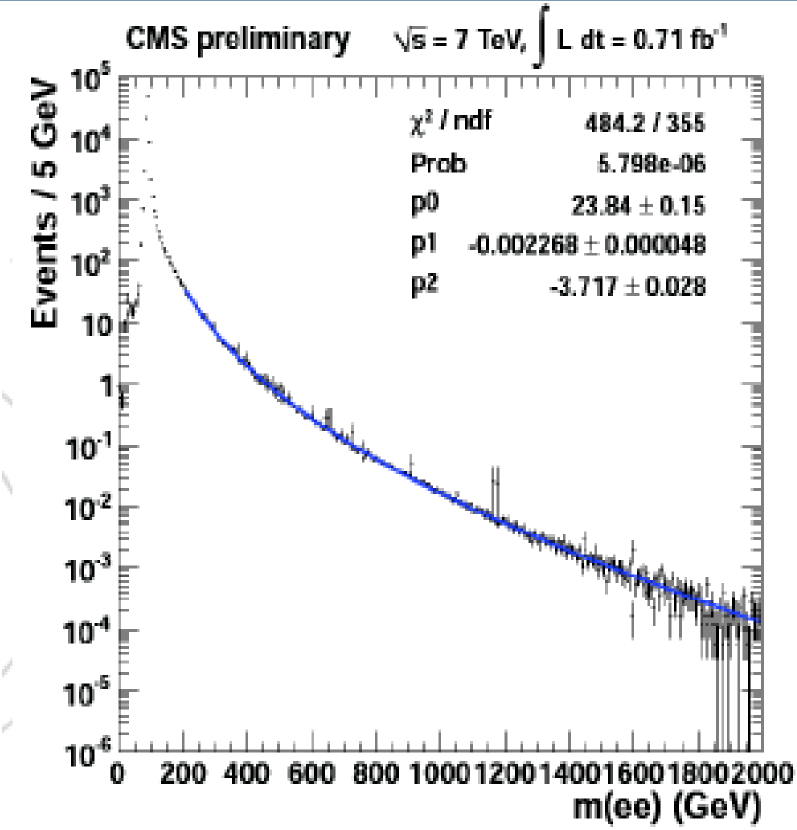
- Signal is parameterized as BW(x)Gauss
  - BW width from signal MC
  - Gauss width – estimate of detector resolution
- Background parameterized as e^{-am}/m^{b} measured from MC

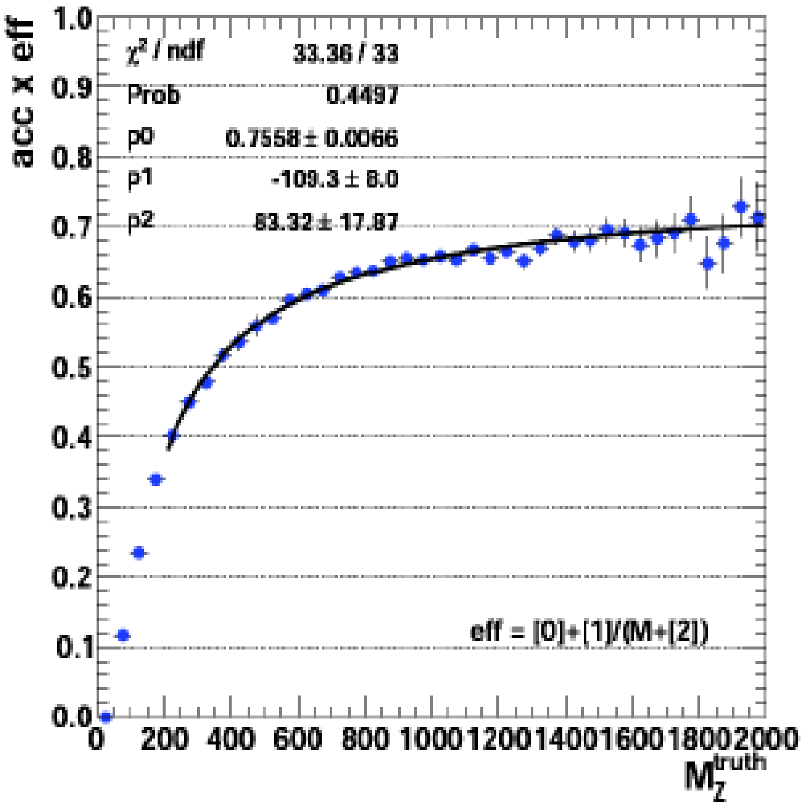
- Likelihood function: sum of Signal and Background PDF
- Systematic uncertainties are included as log-normal priors

- Exclusion limits: Bayesian technique implemented with Markov Chain Monte Carlo in RooStats (AN-10-312)
  - Limit is set on: $R_\sigma = \dfrac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$

- For combined limit simultaneous fit to both distributions is performed

MC parametrization & Systematics : Electron





observable	origin	uncertainty
Z' acc×eff / Z acc× eff	MC evolution of efficiency with energy	8%
SM Drell-Yan Bkg	NLO effects	6%
SM Drell-Yan Bkg	PDF effects	5-20% (10% average)
jet bkg	fake rate uncertainty	40%
$t\bar{t}$	cross-section uncertainty	15%

Systematics uncertainty (e & μ)

- Di-muon

observable	origin	uncertainty
Z' acc×eff / Z acc× eff	MC evolution of efficiency with energy	3%
Z bkg	NLO effects	6%
Z bkg	PDF effects	5-20% (10% average)
$t\bar{t}$	cross-section uncertainty	15%

- Di-electron

observable	origin	uncertainty
Z' acc×eff / Z acc× eff	MC evolution of efficiency with energy	8%
SM Drell-Yan Bkg	NLO effects	6%
SM Drell-Yan Bkg	PDF effects	5-20% (10% average)
jet bkg	fake rate uncertainty	40%
$t\bar{t}$	cross-section uncertainty	15%

General Idea

"Prompt" electron or muon

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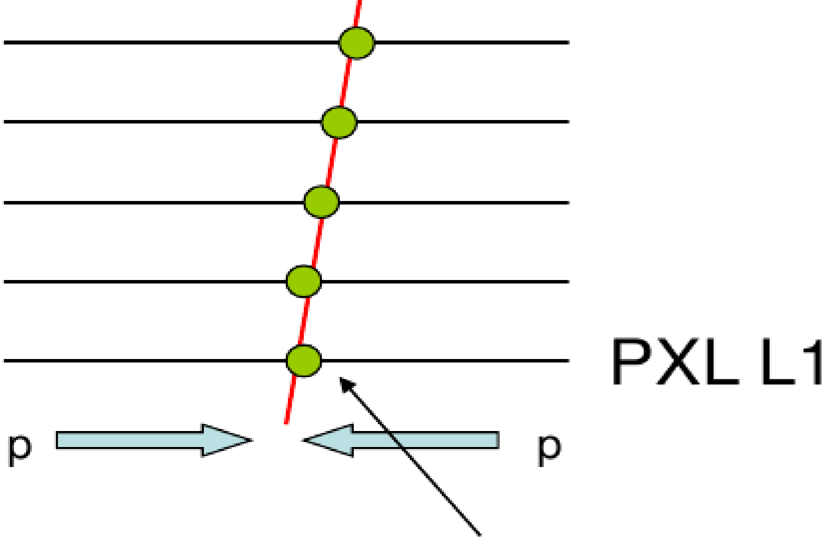
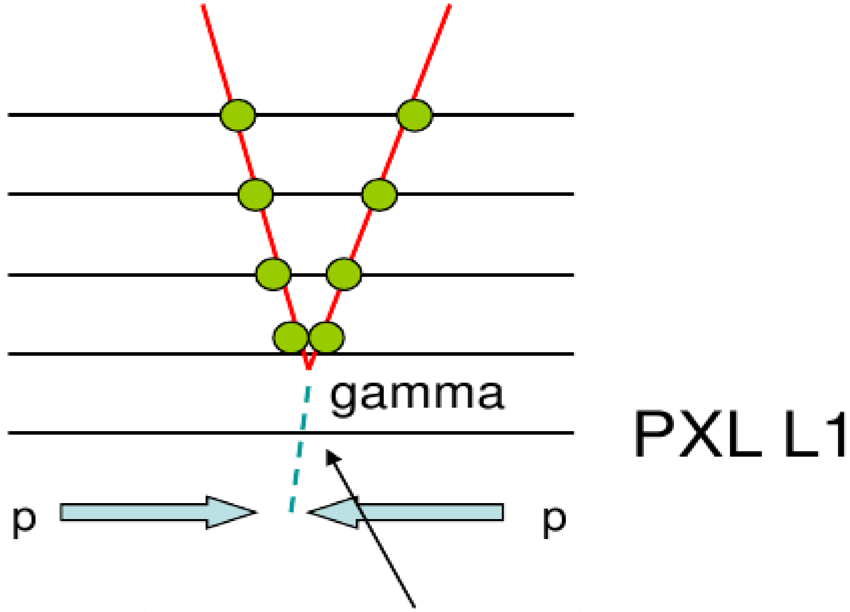


Electrons from conversion



Most of the time, tracks of prompt particles have an hit on the innermost Pixel layer

Most of the time, tracks of electrons from conversions miss a hit on the innermost Pixel layer

Cut on the "presence of hit on the innermost pxl layer" in order to reject electrons from conversions

Prompt electrons implies ==> Nb. Of Missing Hits == 0

Statistical Interface

- The core likelihood (extended unbinned)

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

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

- Bayesian credible interval (95% C.L. Upper limit) with flat prior on the parameter of interest
- Systematic uncertainty modeled as Lognormal constraint terms in the likelihood on the corresponding nuisance parameters
- Inputs for the calculation

di-electron

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	$\exp(-0.002423\, m) \cdot m^{-3.625}$

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	$\exp(-0.002423\, m) \cdot m^{-3.625}$