Search for narrow resonances in dimuons and dielectrons with CMS

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Cornell LEPP Journal Club

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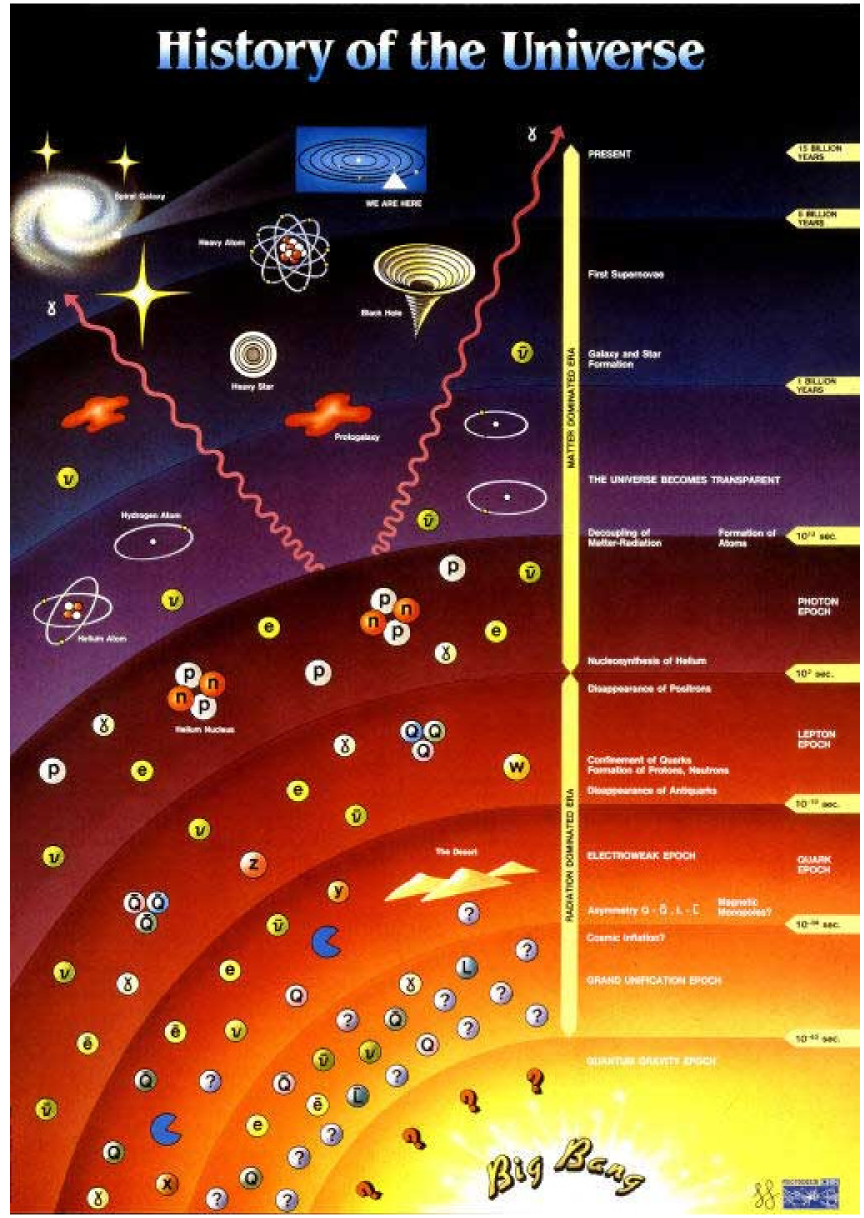
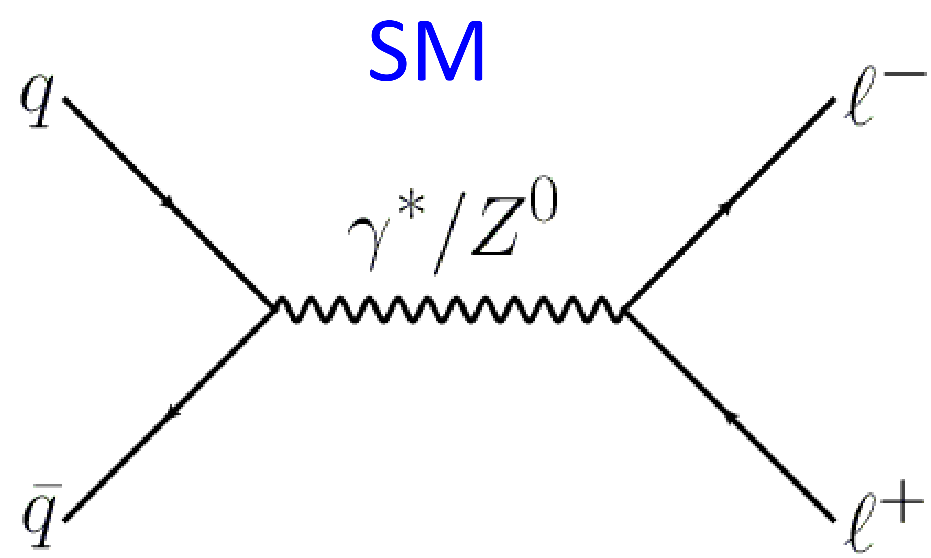
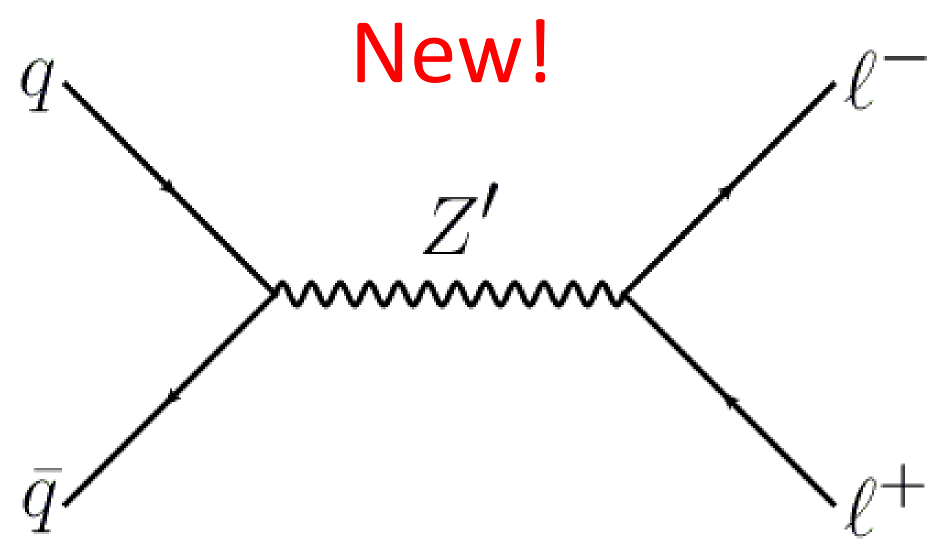


New Physics?

- Standard Model (SM):
  SU(3) x SU(2) x U(1)
- Grand unification: larger gauge group(s) broken at low energy into SM group times extra U(1) groups
- New U(1) ↔ new massive gauge boson Z′ (à la Z^0)
- Especially clean signature: resonant l^+l^- peak ("bump")
- Similar diagrams replacing Z′ with other new physics (e.g. massive gravitons in theories of extra dimensions)

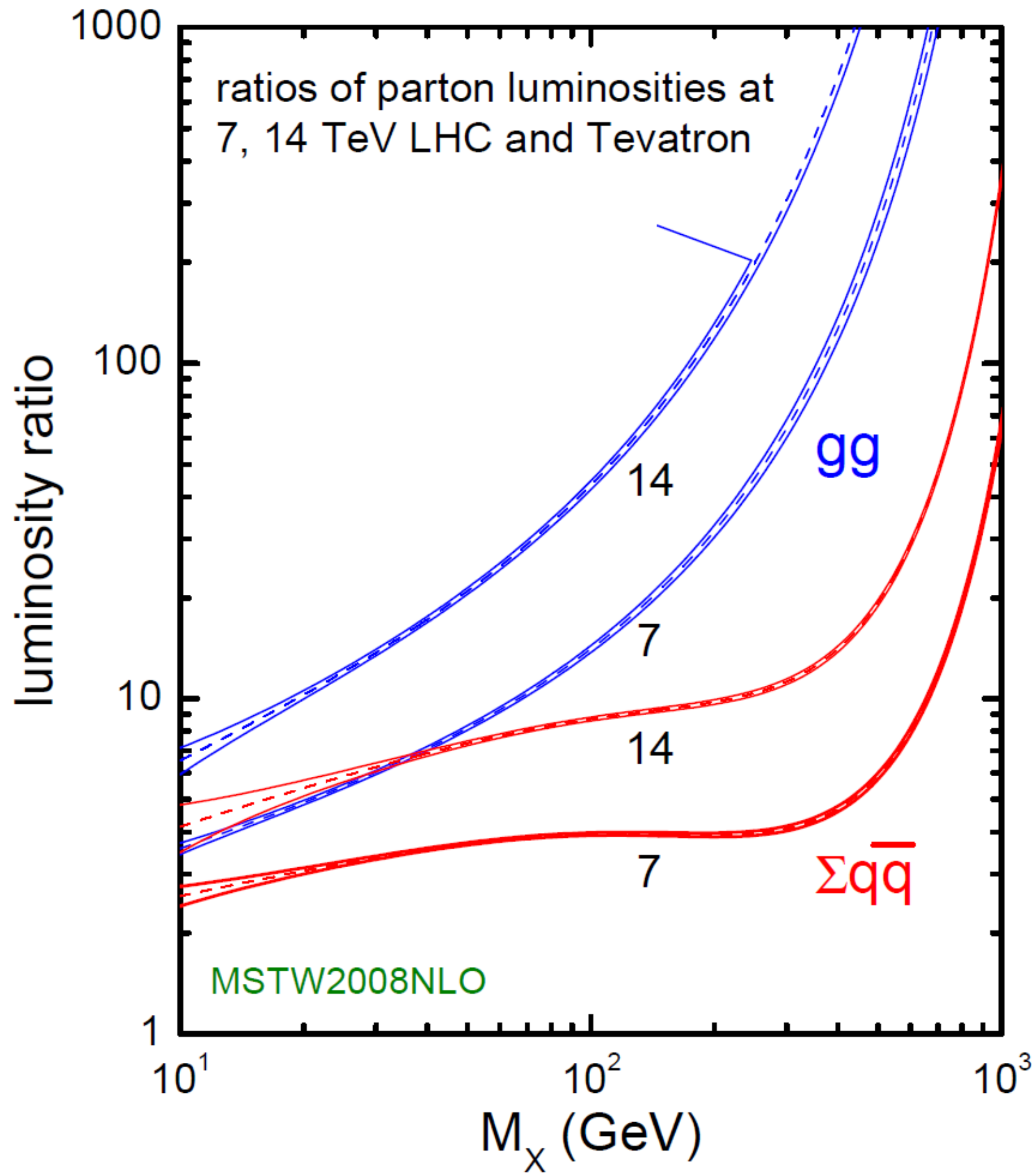




Z′ at the LHC

- Higher √s at the LHC → much more parton luminosity available to make high mass objects!
- ~5 fb^{-1} of usable data delivered to CMS and ATLAS so far.
  - Analysis described in this talk: 1.1 fb^{-1} taken by mid-summer 2011.

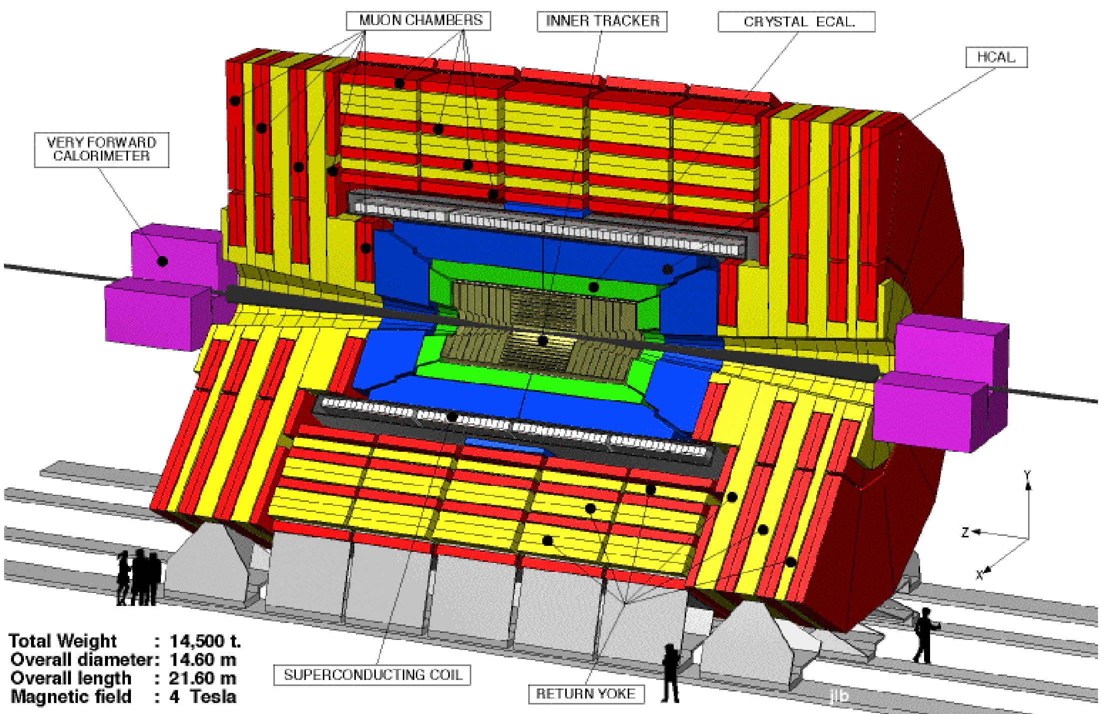
From James Stirling

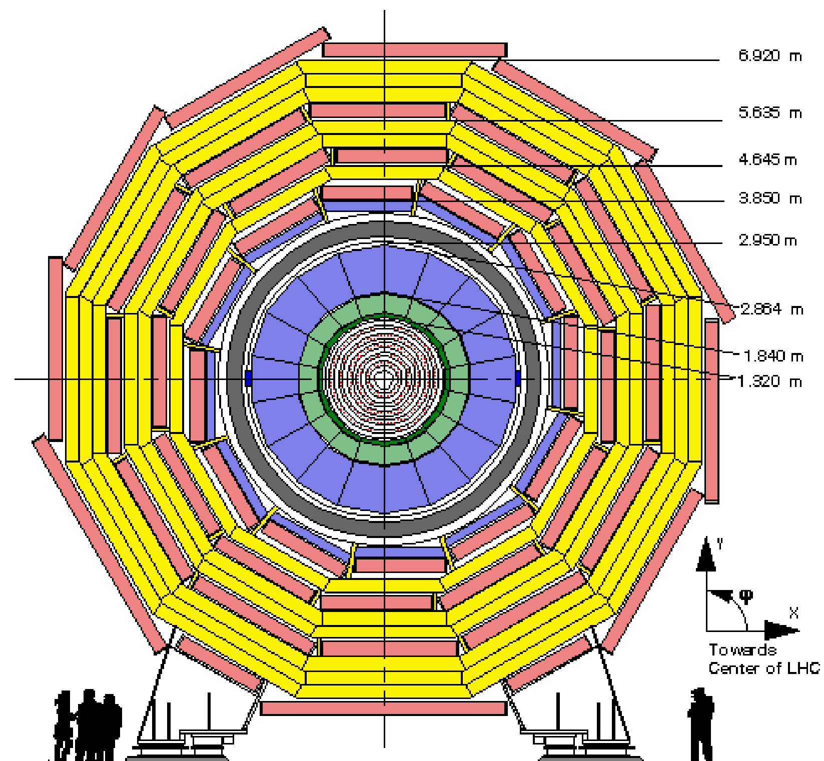


The Compact Muon Solenoid (CMS)

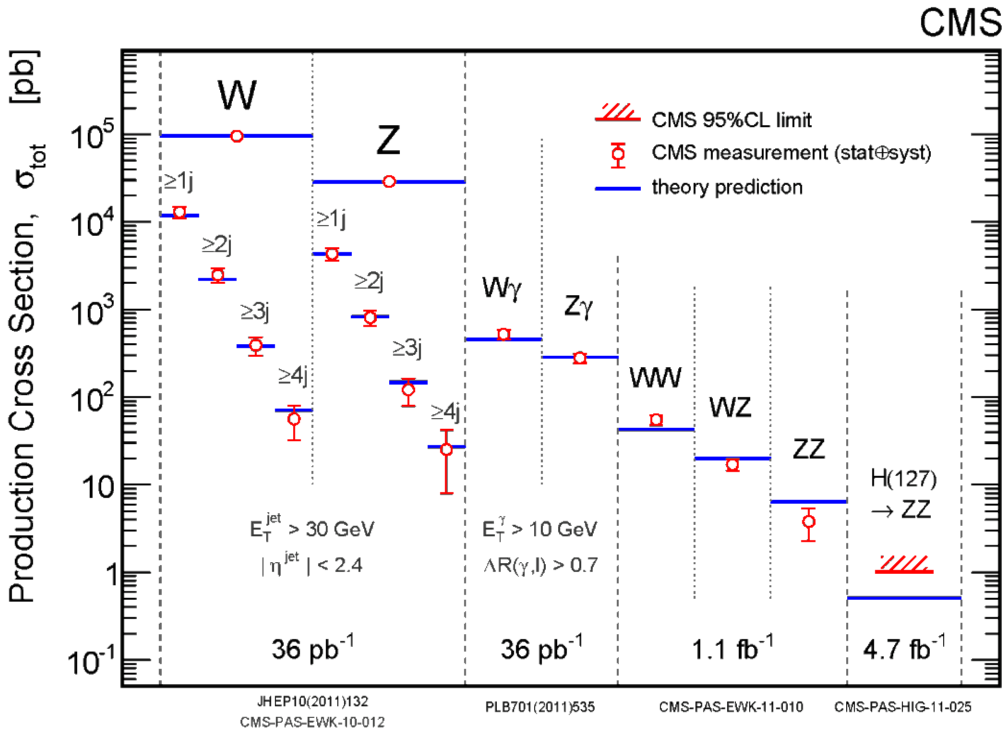
Onion-like structure for particle id and measurement:

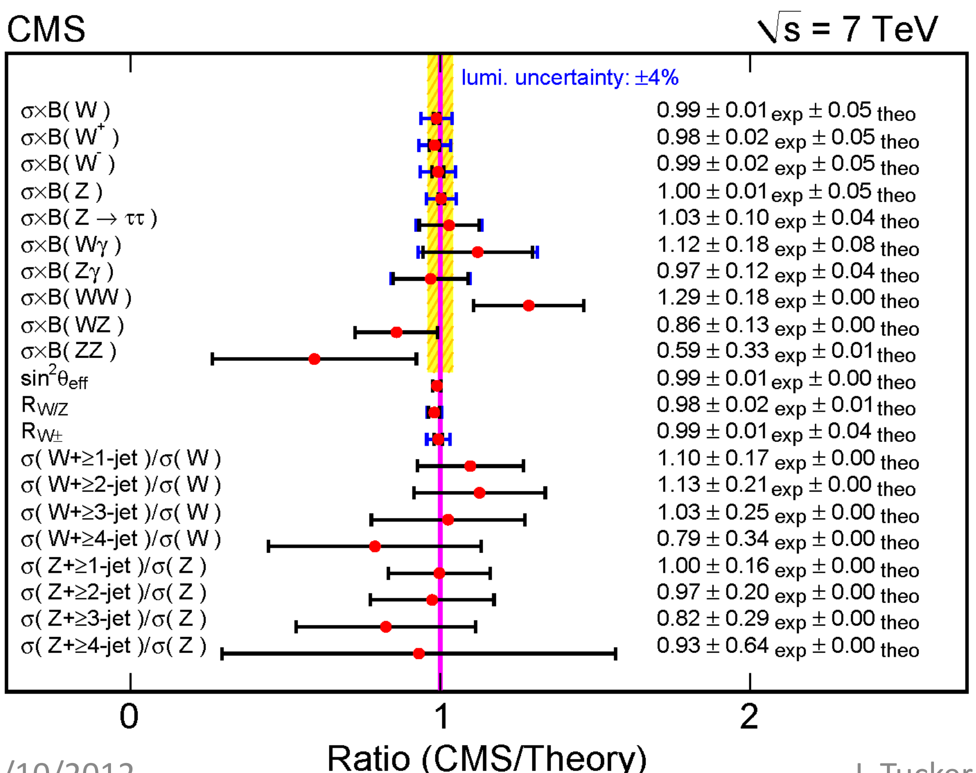
- Inner tracker
- Electromagnetic and hadronic calorimeters
- Superconducting magnet
- Outer muon system

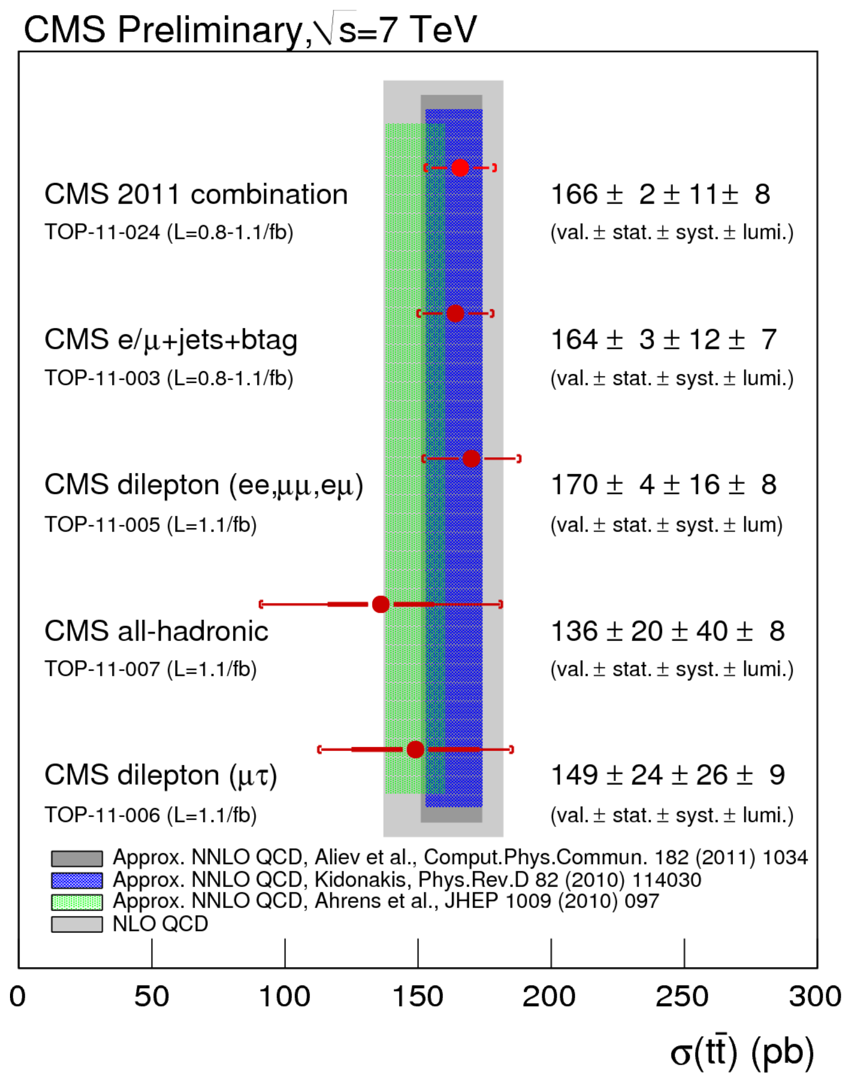




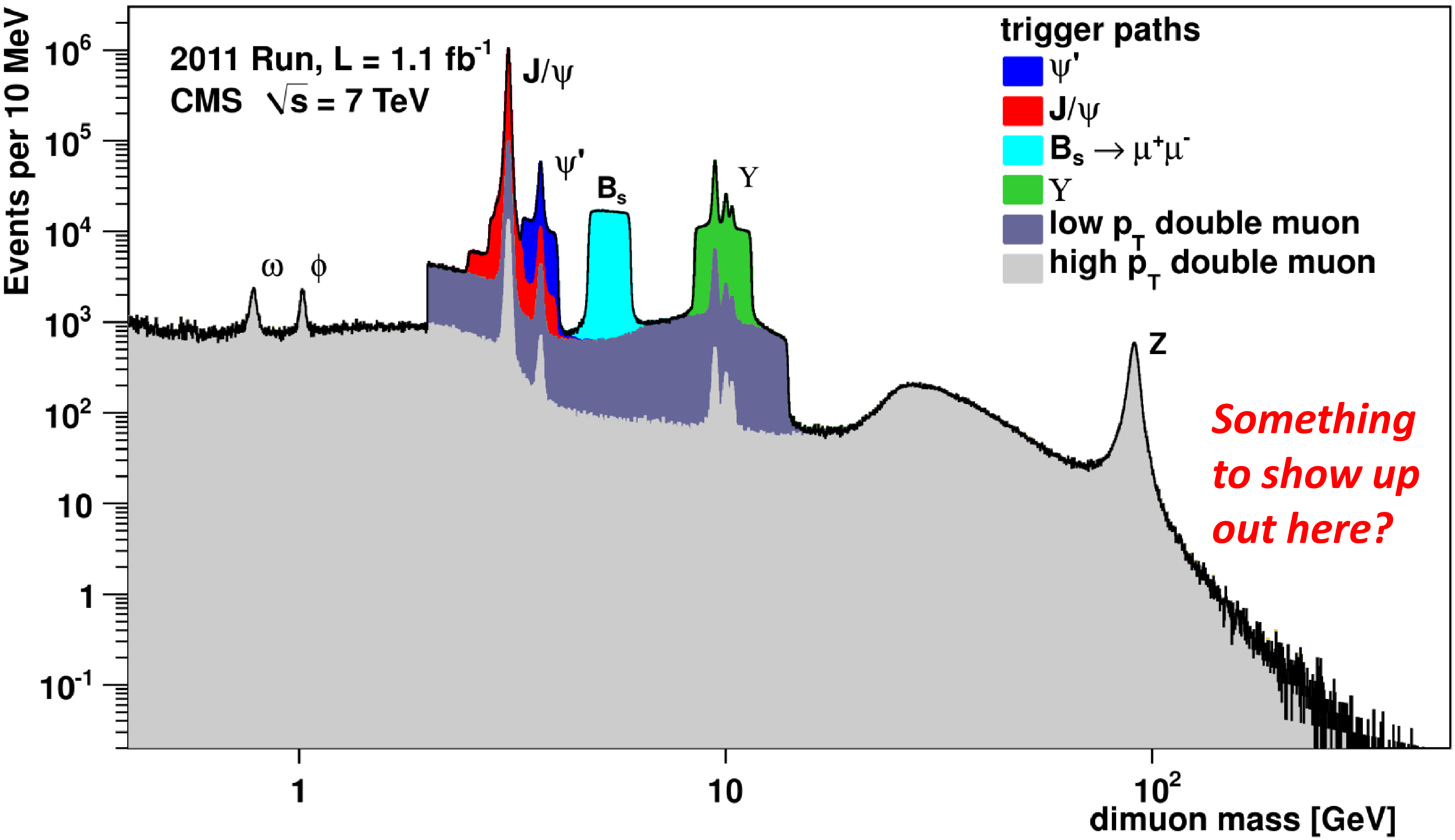
Beautiful confirmation of SM predictions! A few examples:







Dimuons in data:



Something to show up out here?

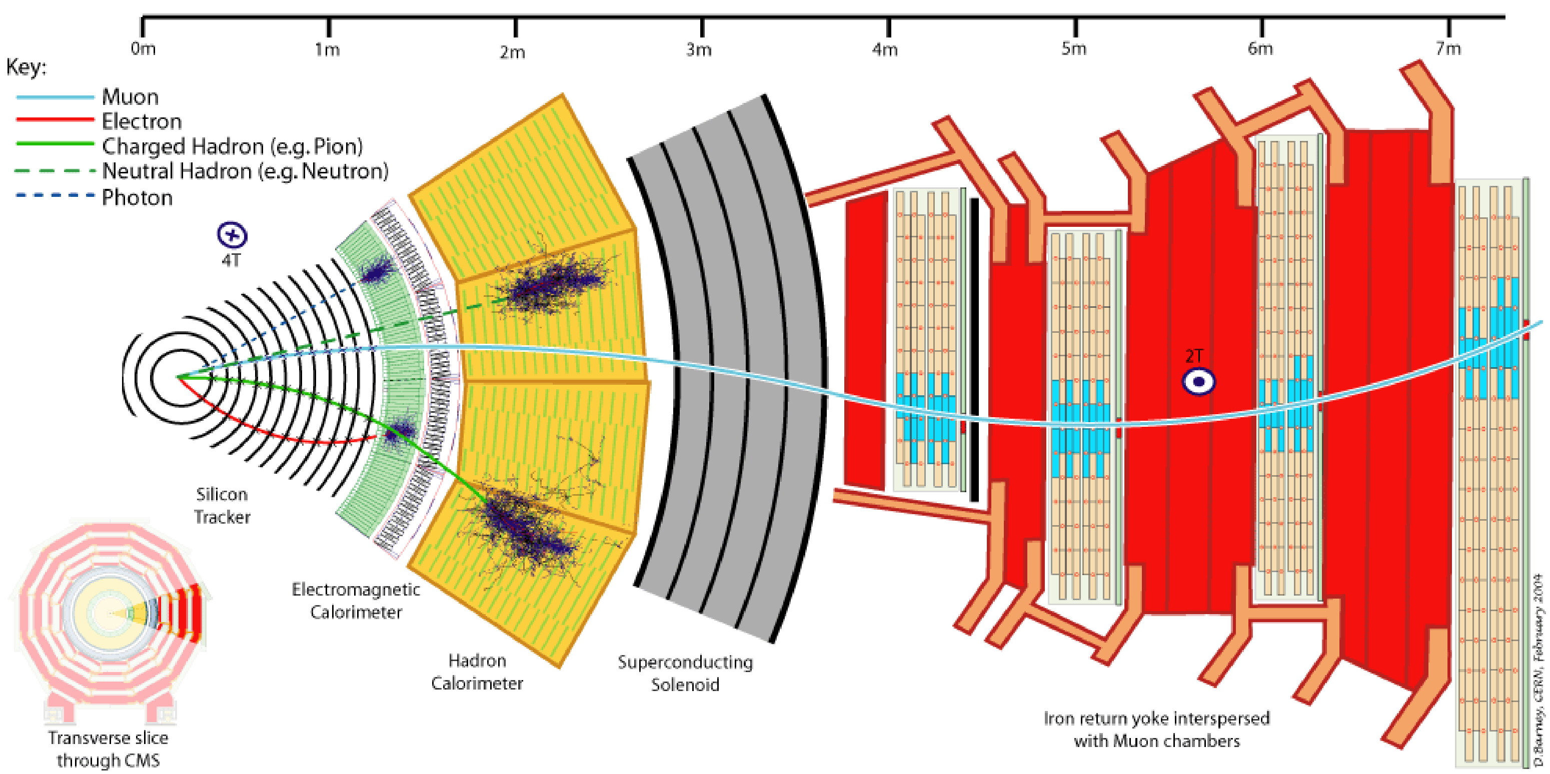
Measuring muons and electrons with CMS

Fine-grained ECAL for precise measurement of EM energies – currently, $\Delta E/E < 2\%$ for $E > 100$ GeV.

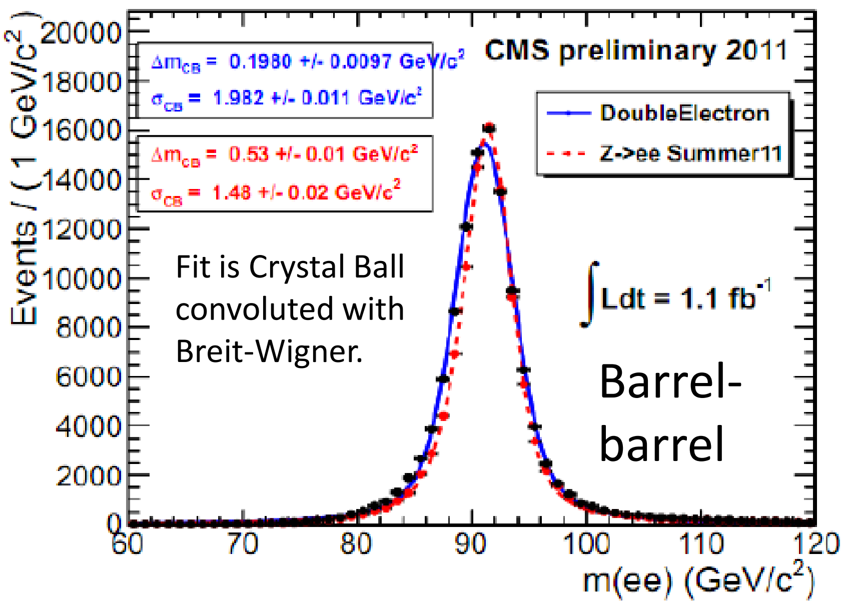
$\rightarrow$ Excellent m_{ee} resolution, challenge on id of electrons vs. jets!

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

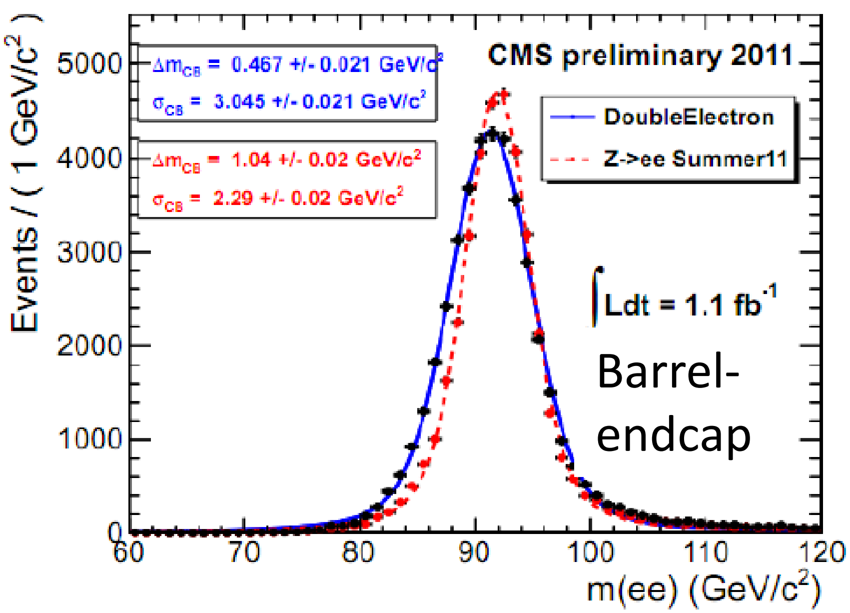
$\rightarrow$ Muon id much easier than electron id, $m_{\mu\mu}$ resolution is the challenge!

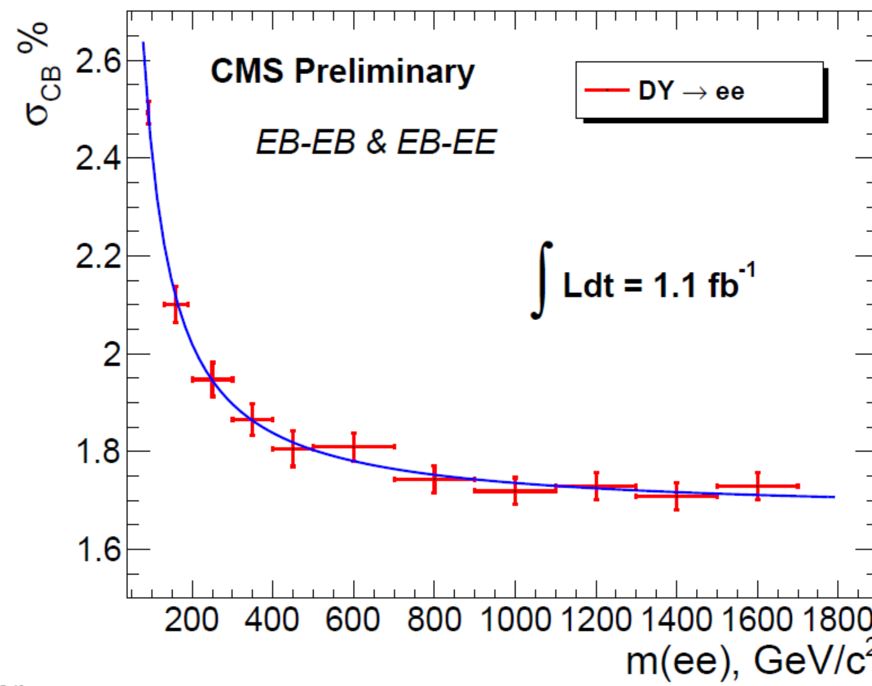


Dielectron energy scale/resolution



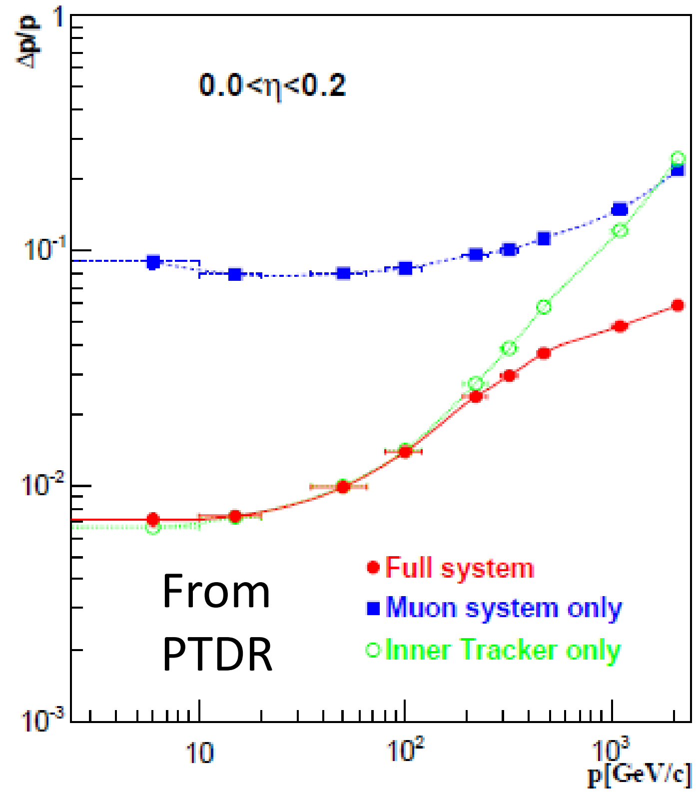
- Linearity of ECAL response at high energy checked with test beam and in data
  - Use surrounding 5x5 crystals to predict central crystal measurement and compare: good agreement
- Take resolution at high mass from simulation with additional smearing derived using Z^0 peak events in data/MC

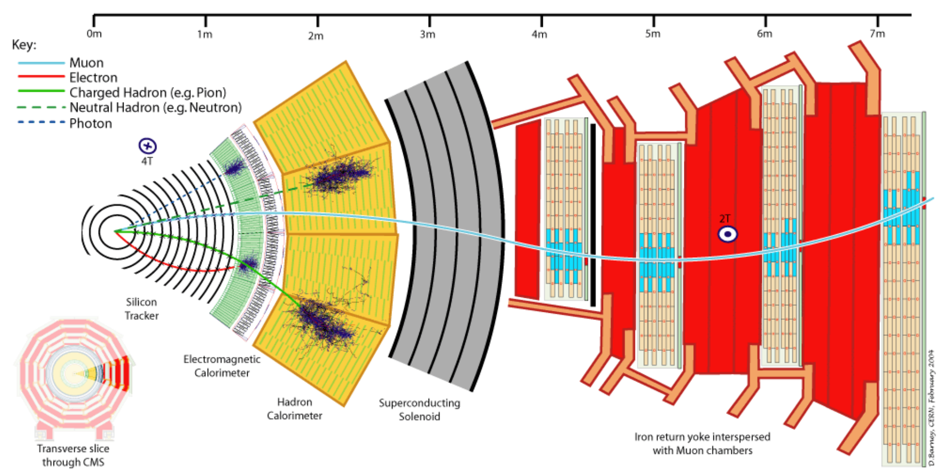




Muon reconstruction in CMS

- Muon system's role in measurement:
  - Low-to-intermediate-p_T: inner tracker dominates
  - High-p_T: ~straight track over tracker extent → "lever arm" out to first muon chamber hits helps
- Energetic muons can "shower" in the steel (extra particles from radiative processes): extra hits can confuse reconstruction
- Selectively pick muon chamber hits for the fit, e.g.:
  - Only first station with hits
  - Be "picky" and drop incompatible hits in busy chambers
- Best from "cocktail": for each muon, choose based on e.g. goodness-of-fit criteria





Confirming performance in data

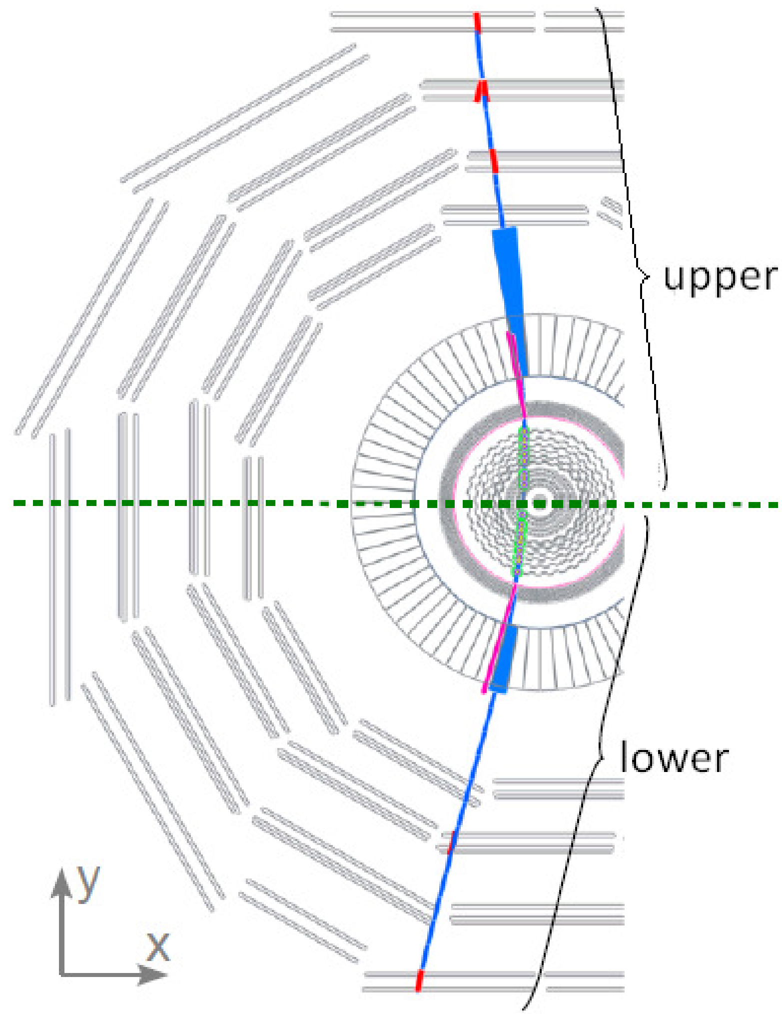
- Cosmic-ray muons that pass through the center of CMS give handle: independent reconstruction of upper and lower legs
- For different algorithms, examine distributions of relative residuals

$$R(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{2}(q/p_T)^{\text{lower}}}$$

and pulls

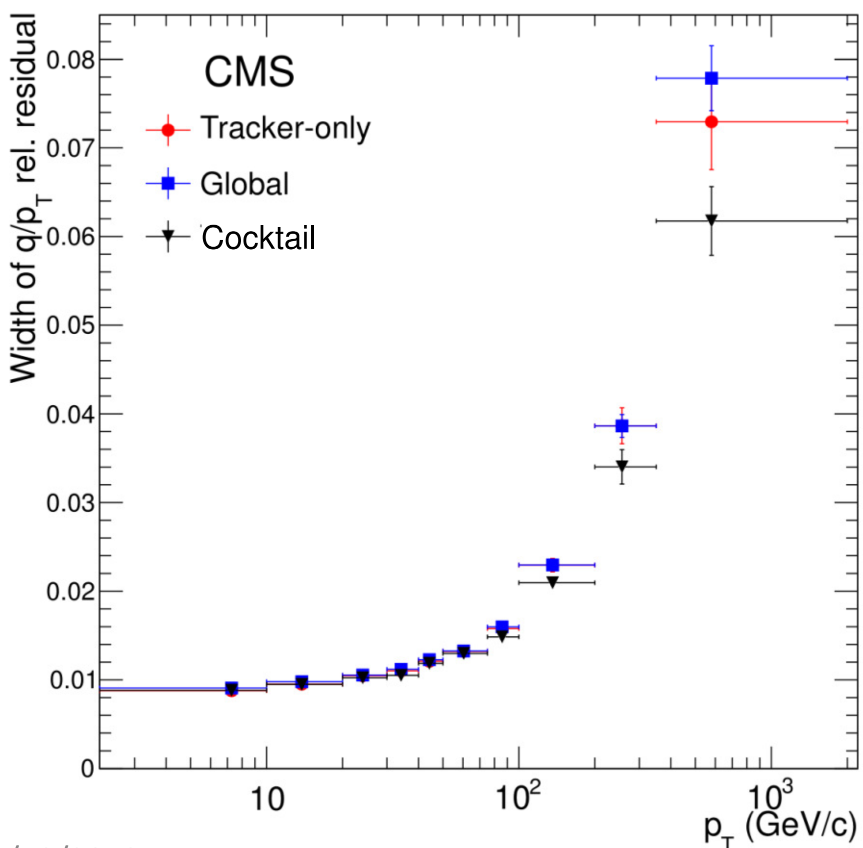
$$P(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{\sigma^2_{(q/p_T)^{\text{upper}}} + \sigma^2_{(q/p_T)^{\text{lower}}}}}$$

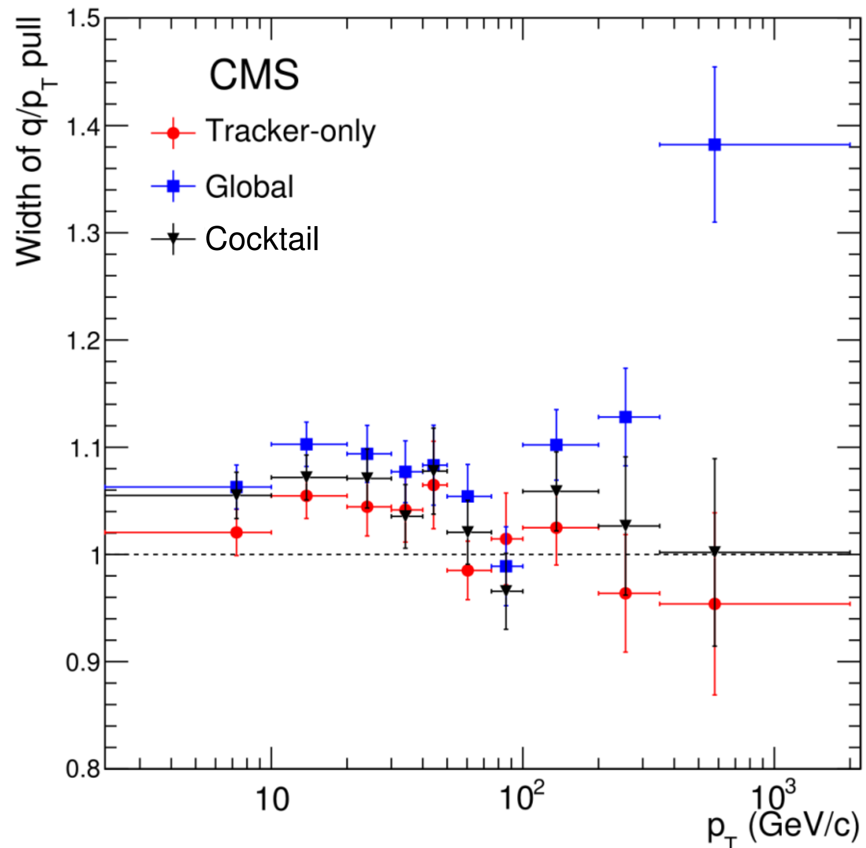
- Limitation: cosmic-ray muons mainly in barrel



Resolution using cosmic-ray muons

- q/p_T relative resolution (left) results from cosmics in good agreement with that from particle gun simulation.
- Pulls (right) show effect of missing alignment position errors in muon track reconstruction: work in progress implementing them.

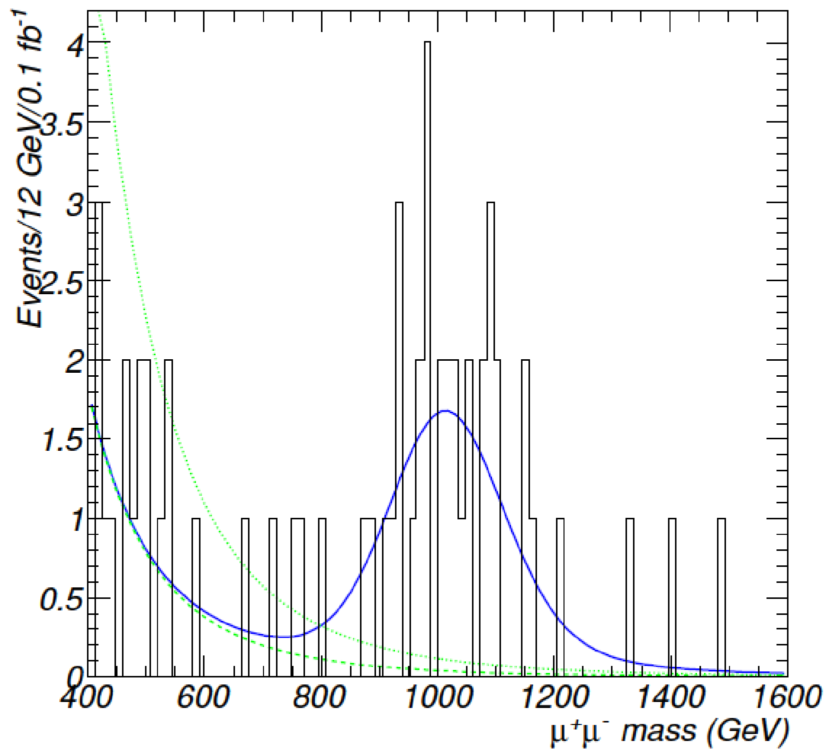




Look for a bump!

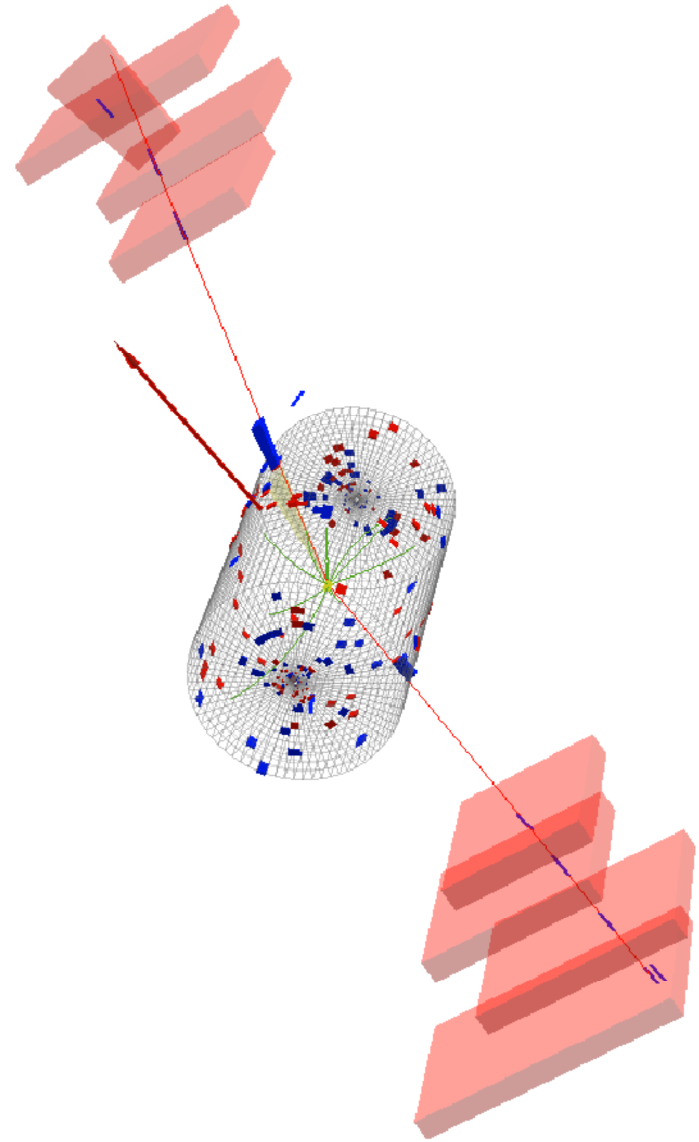
- Narrow resonant signal in histogram of reconstructed dilepton masses
- Drell-Yan dilepton production → steeply falling background
- No prediction for Z′ mass
- Shape-based search

Sim. studies done for CMS Physics TDR (2006): bump from Z′ on SM background



Dilepton selection

- As Z^0 cross section measurement, adapted for high-E_T/p_T leptons.
  - Differences $\rightarrow$ small extra systematic uncertainties.
- Record events with double EM or single muon trigger, then offline require two isolated leptons.
- Selection highly efficient: > 85% for masses above 1 TeV.
  - Inefficiency due mostly to geometrical acceptance.

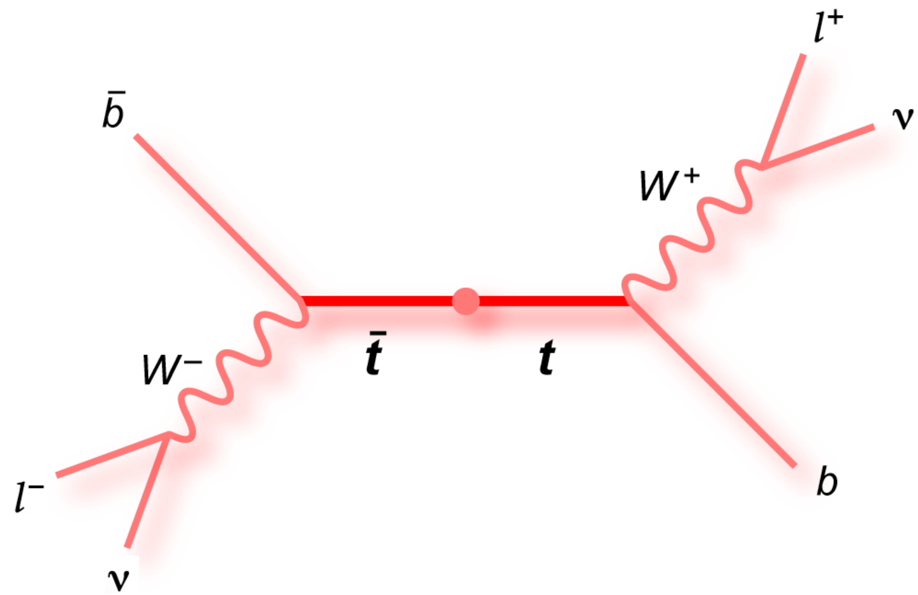


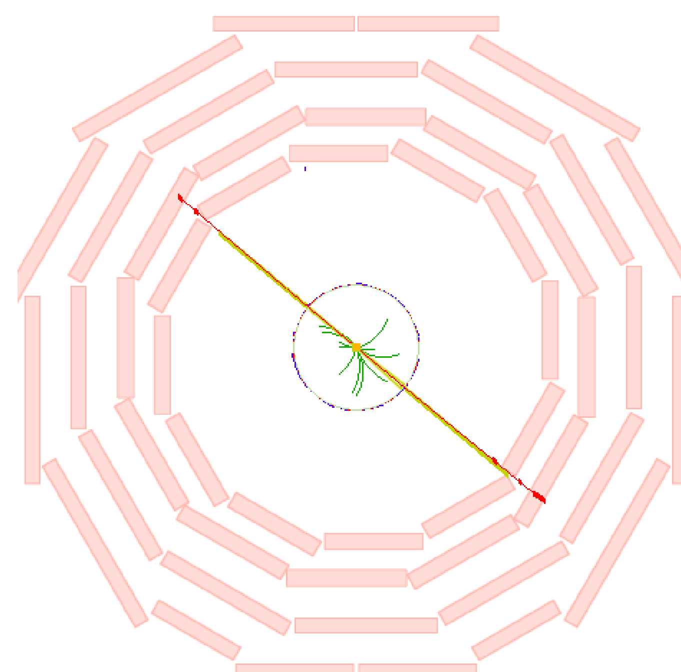
Dielectron/dimuon differences

- Looser muon selection: smaller background from jets for muons.
- Smaller dielectron acceptance: no endcap-endcap electron pairs allowed, gap between ECAL barrel and endcap.
- Opposite charges required for dimuons, but not for dielectrons.
- Cosmic-ray muons used to aid in understanding high-p_T collision muons.

Backgrounds

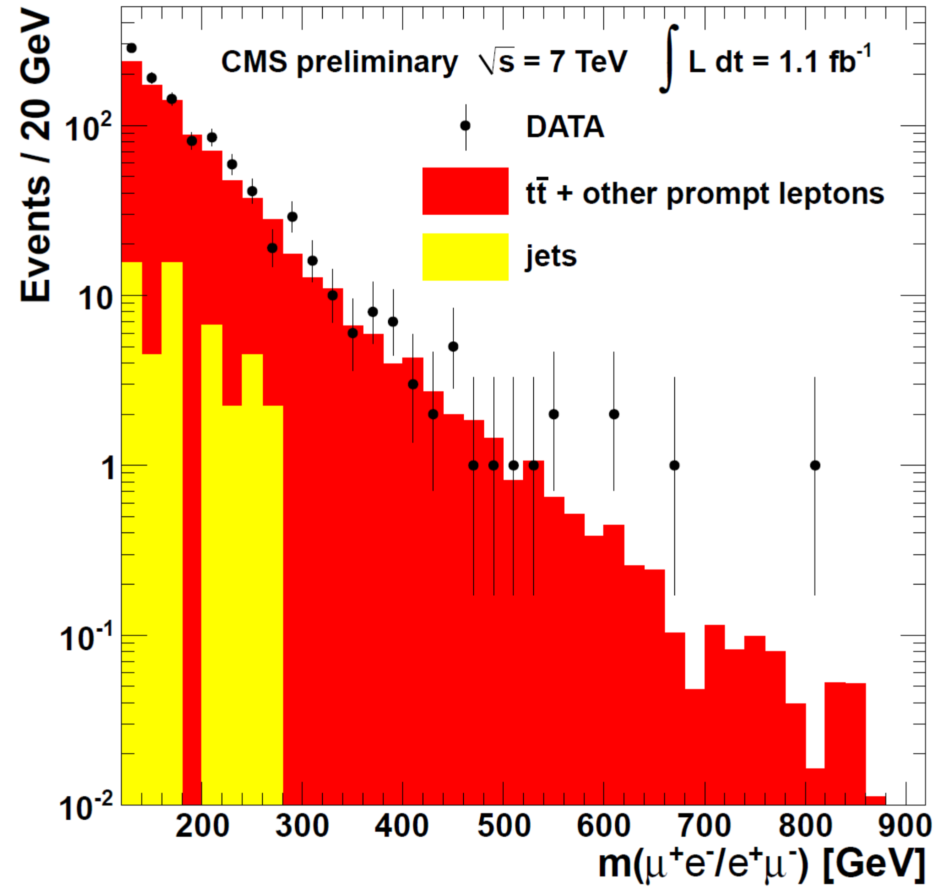
- Dominant: Drell-Yan (DY)
  - Use shape from simulation in search
- Next biggest: $t\bar{t}$, other sources of "prompt" leptons
  - Total ~10% of DY rate above 120 GeV
  - "eμ method" to check in data
- Dileptons from misidentified jets:
  - Negligible for dimuons (<1% of DY rate above 120 GeV).
  - Dielectrons suffer more: about 5% of the DY rate above 120 GeV.
  - Estimate in data by loosening cuts (e.g. isolation).
- Cosmic-ray muons: using sidebands, estimate less than 0.1 event above 120 GeV.





eμ method to check $t\bar{t}$

- Lepton universality: two eμ events for every ee/μμ event
- Scale by different e, μ efficiencies.
  - N(ee, μμ)/N(eμ) taken from simulation in bins of dilepton mass
- Currently just a cross-check, good agreement between data and simulation
  - Final search result insensitive to $t\bar{t}$



Mass range	N(eμ), data	eμ-predicted N(μμ)	Simulation-predicted N(μμ)
> 120 GeV	999	578 ± 25	560 ± 71
> 200 GeV	300	194 ± 15	171 ± 22

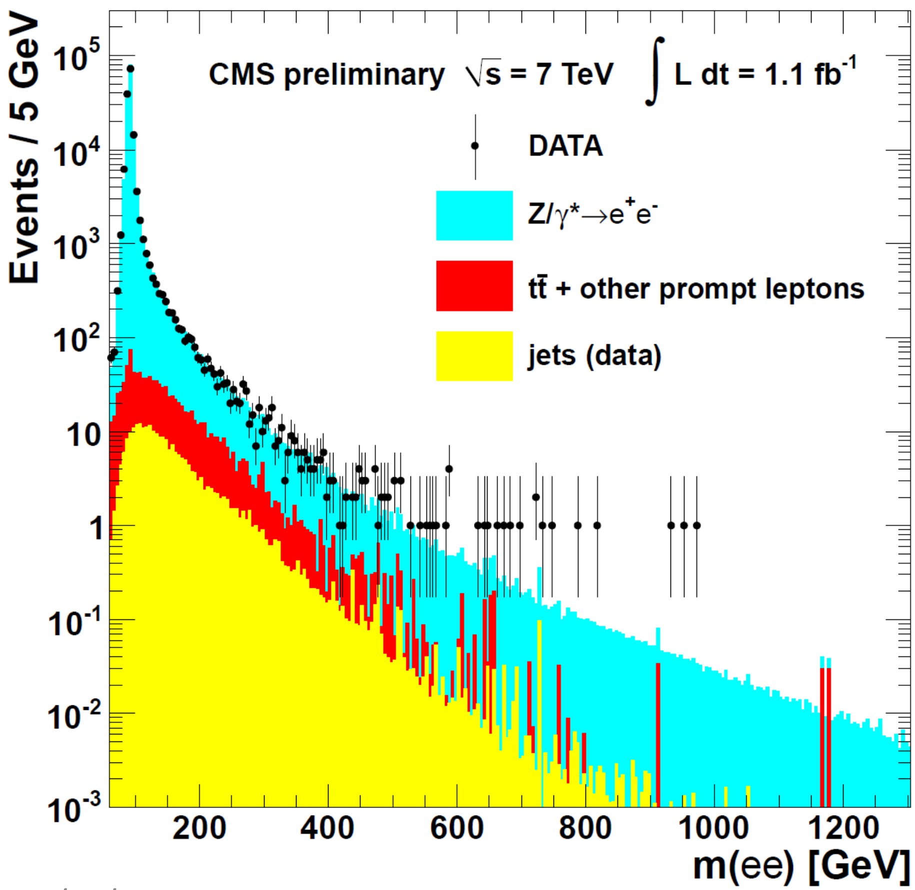
Dielectron mass spectrum

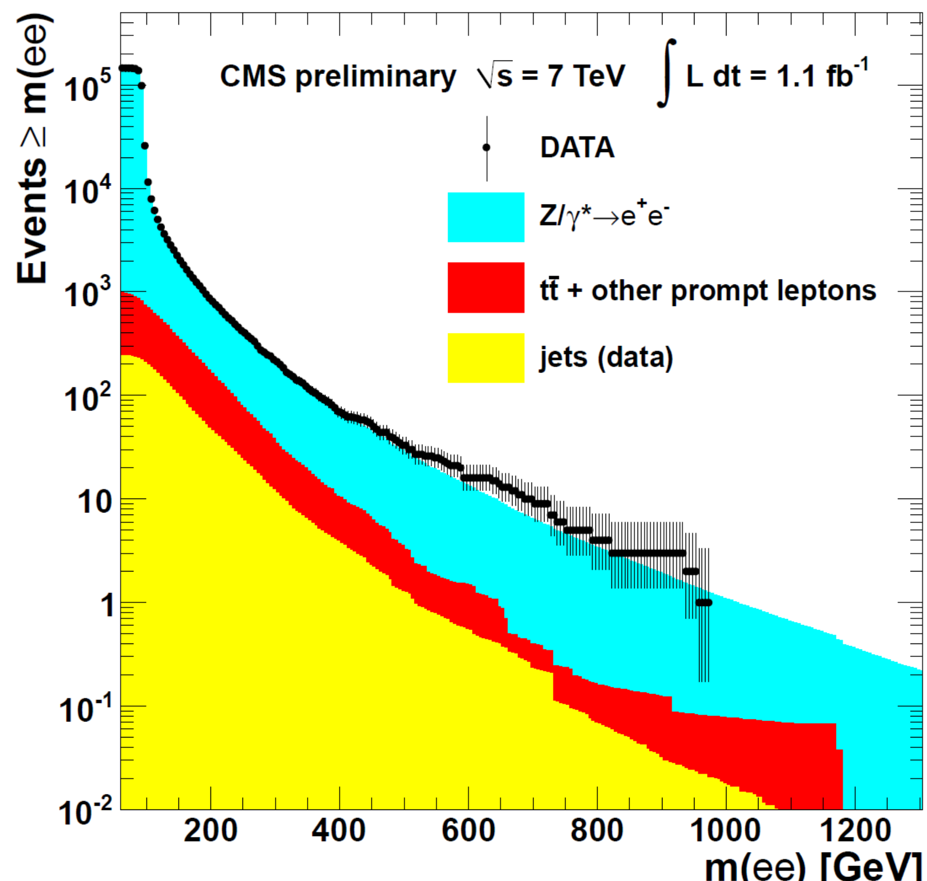
Other prompt leptons: VV, tW, Z→ττ.
Jets: QCD dijets, W+jets.

Sim. distributions normalized to NLO cross sections, then overall to the data at Z peak (60-120 GeV).

Uncertainties in table: statistical ⊕systematic.

Source	Number of events	
	(120 − 200) GeV	>200 GeV
CMS data	3410	809
Total background	3375 ± 161	787 ± 67
Z/γ^*	2992 ± 149	622 ± 62
$t\bar{t}$ + other prompt leptons	275 ± 41	118 ± 17
Multi-jet events	107 ± 43	46 ± 18





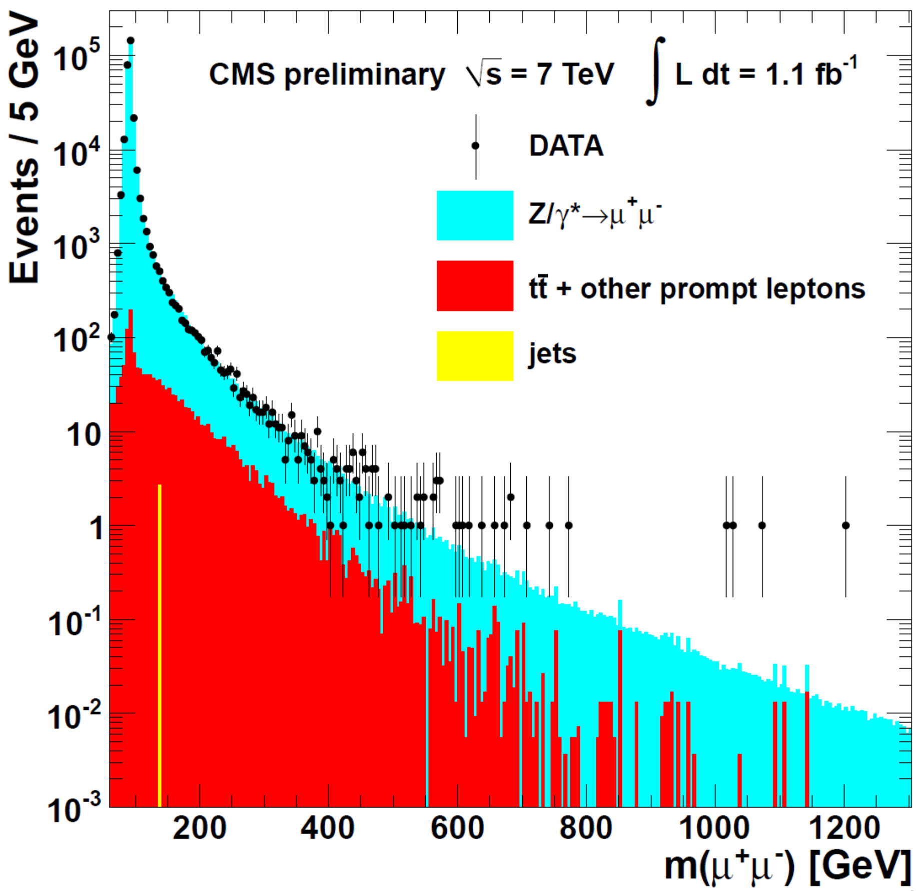
Dimuon mass spectrum

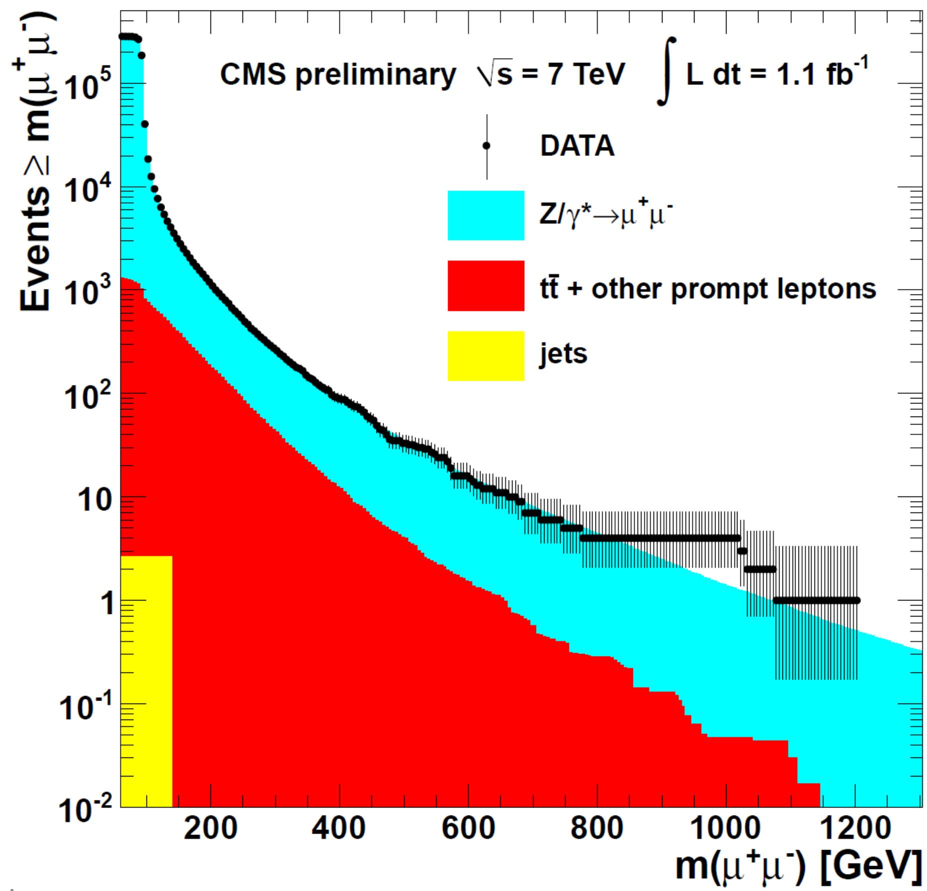
Other prompt leptons: VV, tW, Z→ττ.
Jets: QCD dijets, W+jets.

Sim. distributions normalized to NLO cross sections, then overall to the data at Z peak (60-120 GeV).

Uncertainties in table: statistical ⊕systematic.

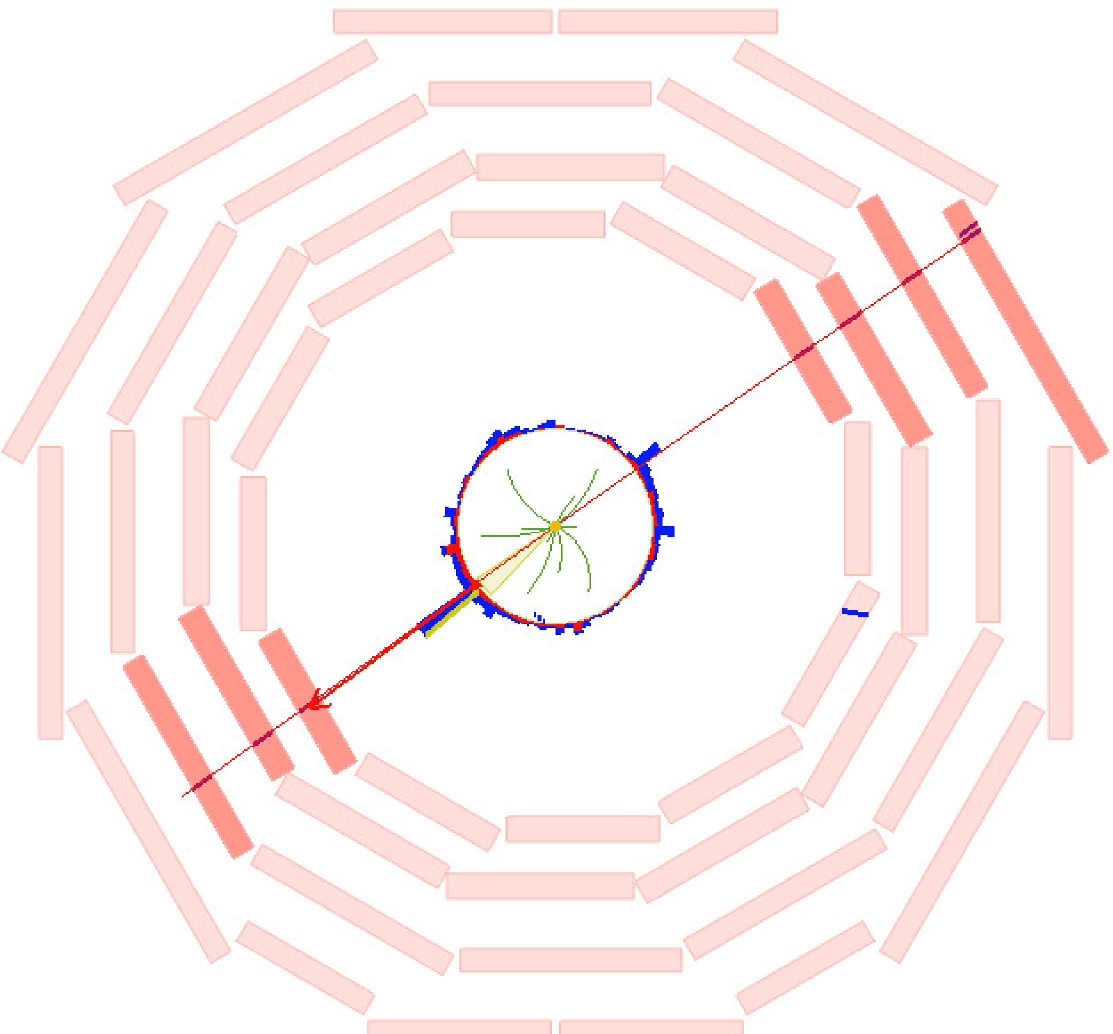
Source	Number of events (120 – 200) GeV	Number of events >200 GeV
CMS data	5216	1095
Total background	5537 ± 250	1100 ± 48
Z/γ^*	5131 ± 246	922 ± 44
$t\bar{t}$ + other prompt leptons	404 ± 46	178 ± 20
Multi-jet events	3 ± 3	0

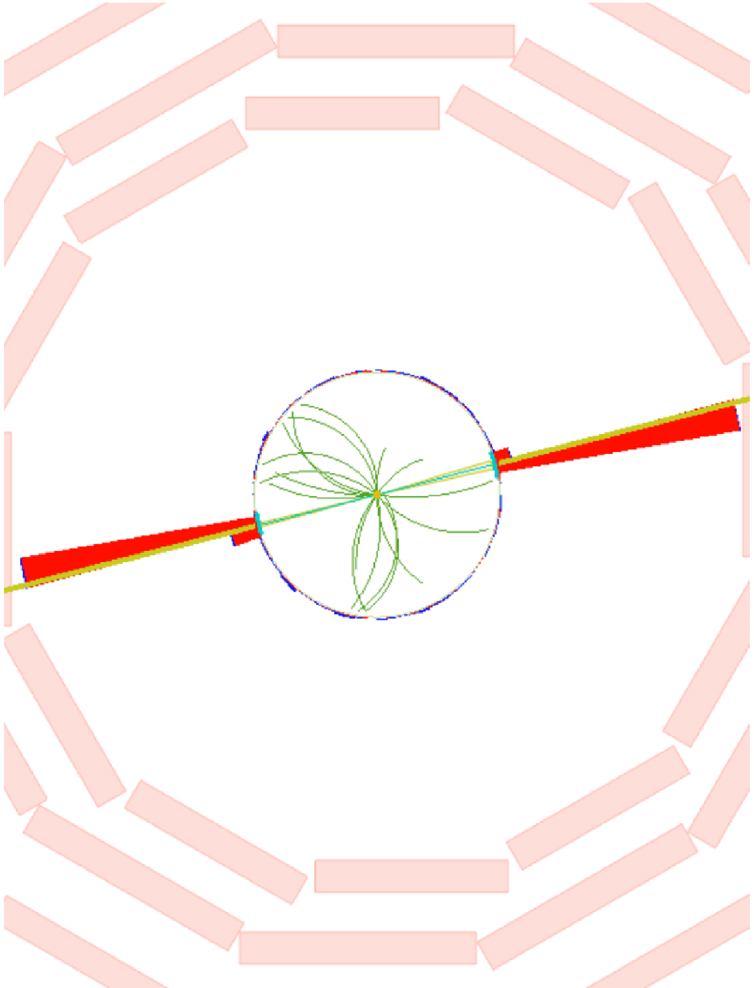




High-mass event displays

$\mu^+\mu^-$





e^+e^-

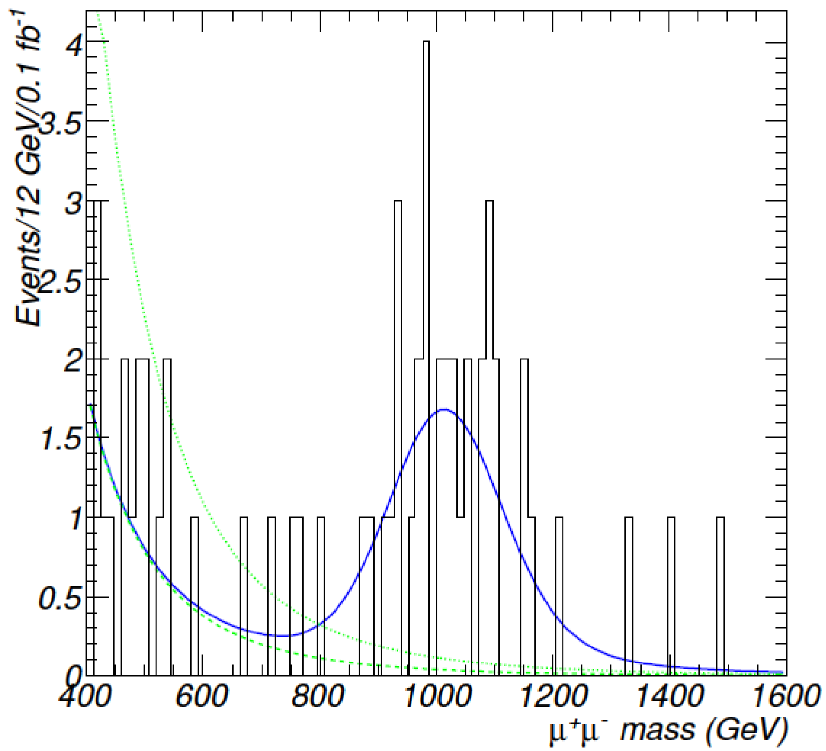
Search formalism

- Unbinned maximum likelihood fit for both the bump hunt and limit setting
- The pdf is a simple sum of signal and background shapes
- Parameters (slopes, widths) from theory/simulation
- Fit on data explores difference in shapes, insensitive to absolute background level

$$\mathcal{L} \sim \prod_i f_{\text{signal}} + f_{\text{background}}$$

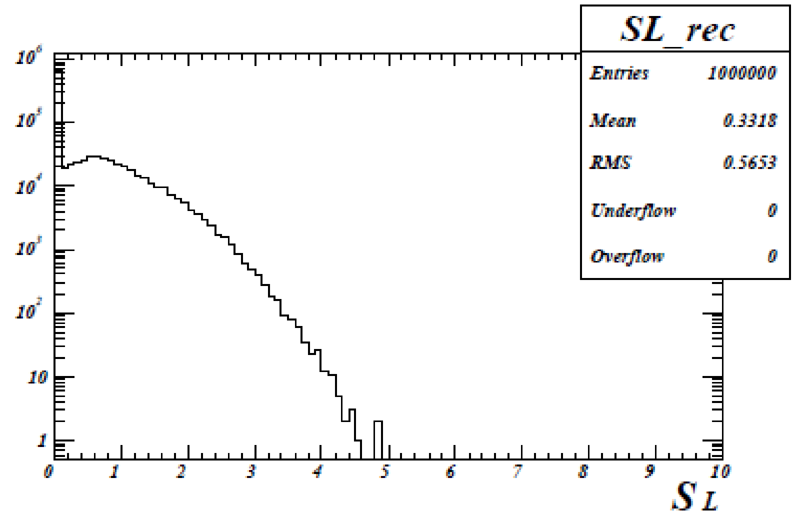
$$f_{\text{signal}} \sim \text{Breit-Wigner}(m|M,\Gamma) \otimes \text{Gaussian}(m|M,w)$$

$$f_{\text{background}} \sim \exp(-am)/m^b$$



Quantifying a discovery

- Statistical hypothesis testing with two hypotheses:
  - Background-only null hypothesis with max likelihood (ML) fit L_b;
  - Alternative signal-plus-background hypothesis, with ML fit L_{s+b}
- Test statistic: likelihood ratio $\lambda = L_{s+b} / L_b$
- With all parameters except signal fraction fixed: Wilks's theorem says $S_L = \sqrt{-2 \log \lambda}$ distributed normally $\rightarrow$ use error function to get p-value.



The bump hunt

- Calculate local significance as a function of Z′ mass.
- Mass not predicted by the theory, so look "everywhere".
- Then: correct for probability of getting at least as extreme of a fluctuation as observed, but anywhere from just background-only ("look-elsewhere effect", LEE).
  - "Elsewhere" definition is arbitrary: here, defined as masses above 600 GeV.

Channel	Most sig. bump at M (GeV)	Local Z (σ)	LEE-corrected Z (σ)
ee	950	2.2	0.2
μμ	1080	1.7	0.3
Combined	970	2.0	0.2

Setting limits + normalizing to Z^0

- Set limit on cross section ratio (R_σ), Z′ to Z^0:

$$R_\sigma = \frac{\sigma(\mathrm{pp} \to \mathrm{Z}') \cdot \mathrm{Br}(\mathrm{Z}' \to \mu^+\mu^-)}{\sigma(\mathrm{pp} \to \mathrm{Z}^0) \cdot \mathrm{Br}(\mathrm{Z}^0 \to \mu^+\mu^-)} = \frac{N(\mathrm{Z}')}{N(\mathrm{Z}^0)} \times \frac{A(\mathrm{Z}^0)}{A(\mathrm{Z}')} \times \frac{\epsilon(\mathrm{Z}^0)}{\epsilon(\mathrm{Z}')}$$

- Benefits of normalizing to the Z^0 peak:
  - Avoid uncertainty from luminosity estimate (4-6%)
  - Known and unknown systematic effects can cancel
- Limits computed using a Bayesian technique with uniform prior for Poisson mean (leading to mild overcoverage).
- Take ratio of acceptances (A) and efficiencies (E) from simulation.
- Estimate $N(Z^0)$ by counting events with $60 < m < 120$ GeV.

Systematic effects/uncertainties

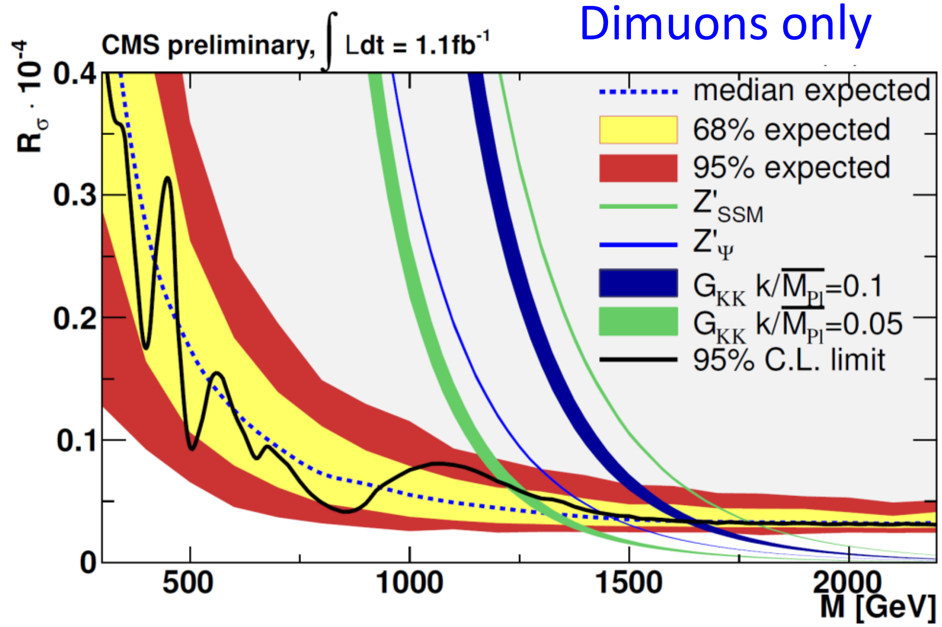
- Main: 3% (muons) and 8% (electrons) on the acceptance times efficiency ratio (included in posterior pdf via log-normal prior); includes:
  - Parton distribution function uncertainties (relevant to acceptance)
  - Mass dependence of K-factors
- For dimuons, alignment effects folded into estimate of Gaussian width for signal pdf.
- Negligible impact of mass scale on limits (only affects region with events)
- Shape systematics studies producing no effect:
  - Using different background pdf form
  - Varying background shape parameters
  - Varying ttbar component

Exclusion limits

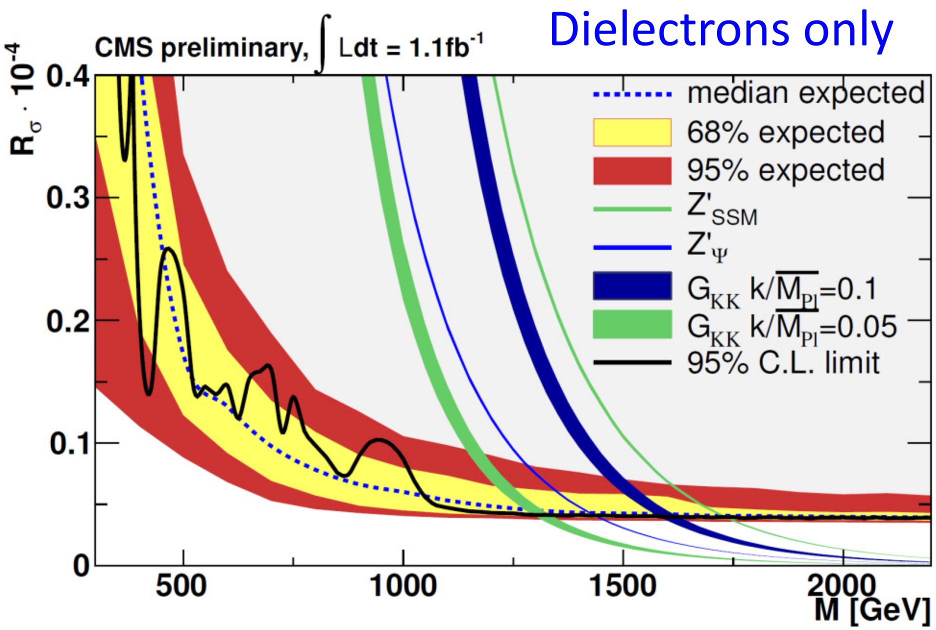
Limits robust against statistical technique: cross-checked with frequentist method. 95% CL limits:

Channel	μμ	ee	μμ+ee
Z_{SSM}	1780 GeV	1730 GeV	1940 GeV
Z_{ψ}	1440 GeV	1440 GeV	1620 GeV
G_{KK}, c = 0.05	1240 GeV	1300 GeV	1450 GeV
G_{KK}, c = 0.1	1640 GeV	1590 GeV	1780 GeV

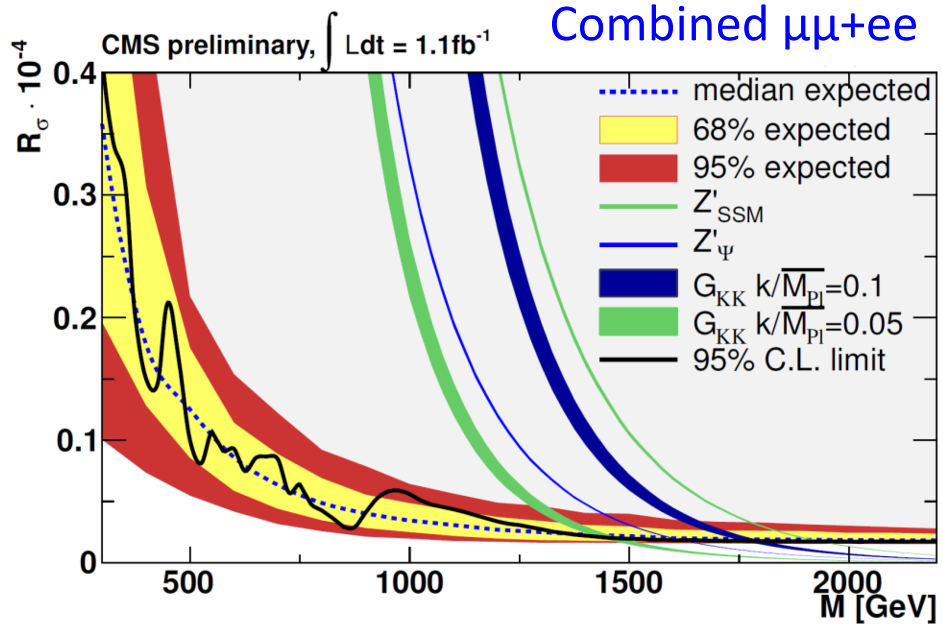
Dimuons only



Dielectrons only



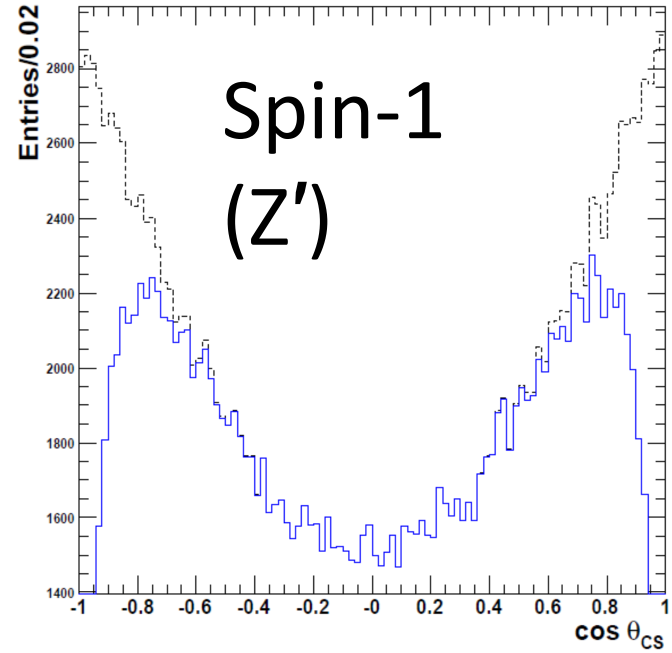
Combined μμ+ee

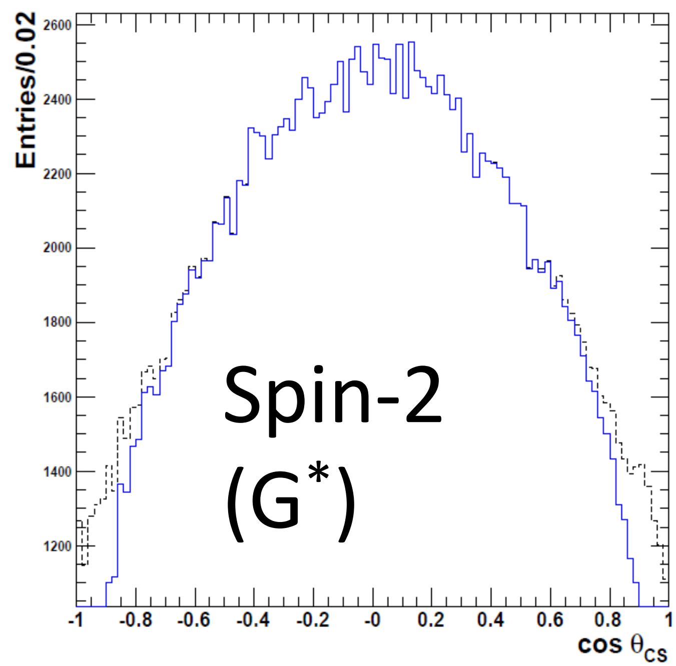


OK – no new physics for now. But what to do when (!) it shows up?

Which New Physics?

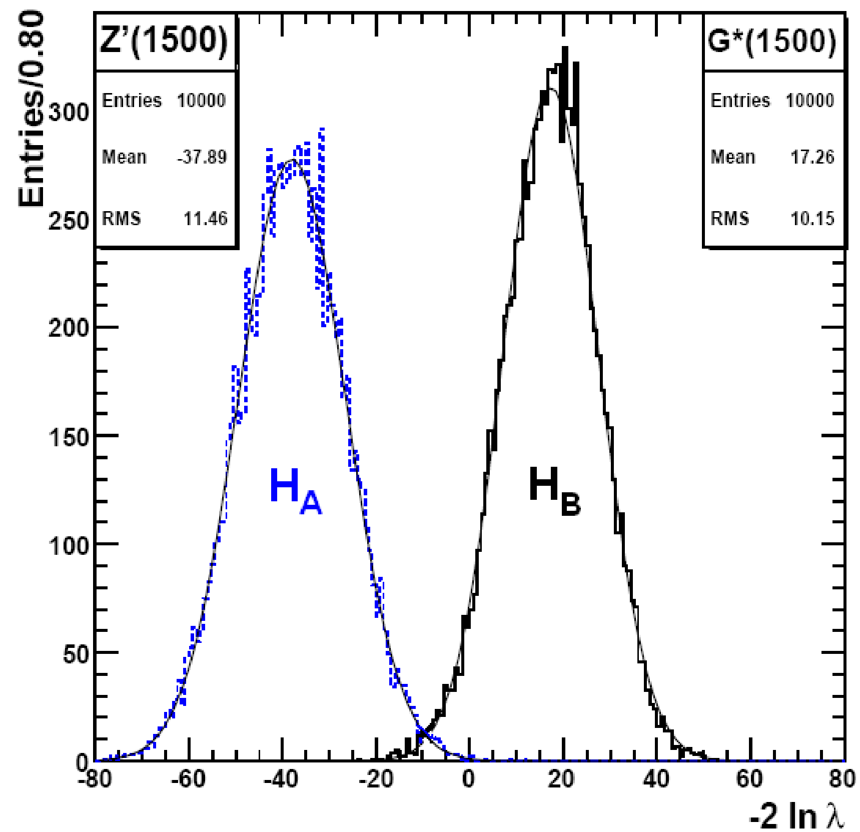
- Powerful discriminating variable: angle θ between incoming quark and outgoing negative lepton
- Decays into two spin-1/2 leptons of spin-1 Z′ versus spin-2 graviton result in quite different angular distributions





Distinguishing models

- Simple hypothesis testing: no free parameters since pdfs are completely specified by conservation of angular momentum
- Construct test statistic λ taking hypothesis H_A for spin 1 and the alternative H_B for spin 2
- With data, reject H_A (accept H_B) if the value of λ lies in a critical region (and vice versa)

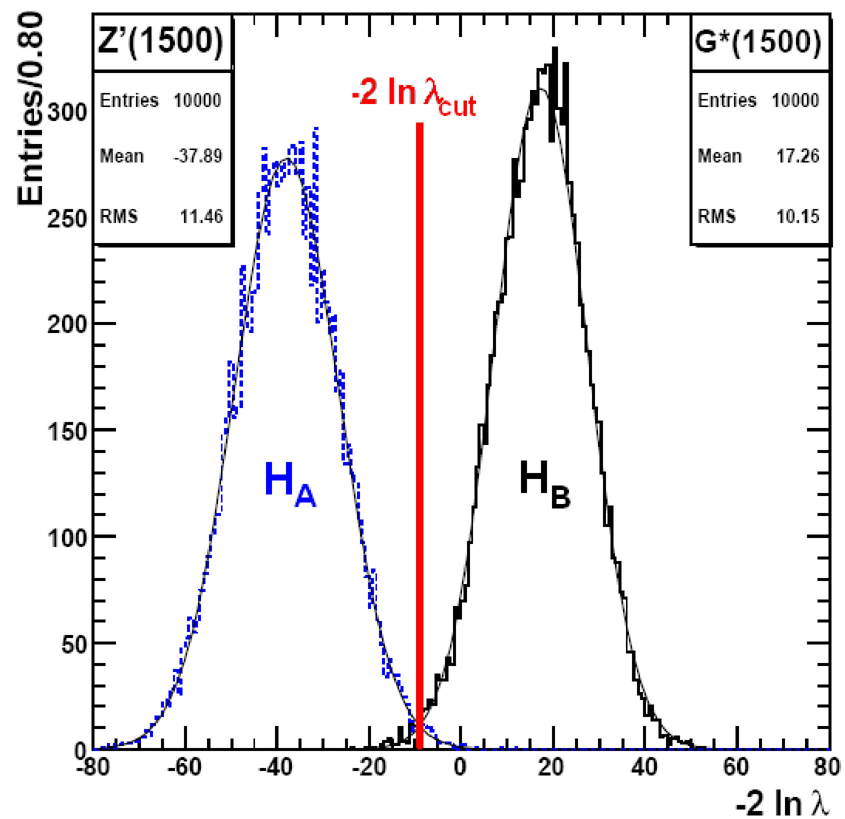


Picking the critical region

- Critical region defined by significance level of the test (the type I error rate α)
- Probability of accepting H_A when it is false (the type II error rate β) is probability of λ being outside critical region
- Power to accept H_B if it is true is 1 - β
- Neyman and Pearson: for fixed α, the test statistic that maximizes the power is the likelihood ratio

$$\lambda = \frac{\mathcal{L}(H_A)}{\mathcal{L}(H_B)}$$

- No reason to prefer either spin 1 or 2: choose α = β
- For a 1-2 TeV resonance, need about N=31 events to distinguish spins 1 and 2 at 68% CL (i.e. 1σ, scaling with √N).



Conclusions

- Data/simulation agreement looks good: no Z′ bump jumping out to the eye yet. ☹
- Cross-checks/systematic studies show non-DY backgrounds and other issues are under control.
- Once we find new physics, the analysis technique is in place to start determining what it is.
- I am deeply grateful to all of my collaborators on CMS and the LHC for making this exciting work possible, and especially to those I borrowed pictures from for this talk.
- Thanks to you for listening!

Backup information

Electron selection

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

Muon selection

Both “loose” muons must pass these criteria:

- identified as global muons,
- $p_T > 20$ GeV,
- relative tracker isolation ($\Sigma\, p_T$ in cone of $dR=0.3$) / (p_T of the muon) < 10%,
- and has at least 10 silicon tracker hits.

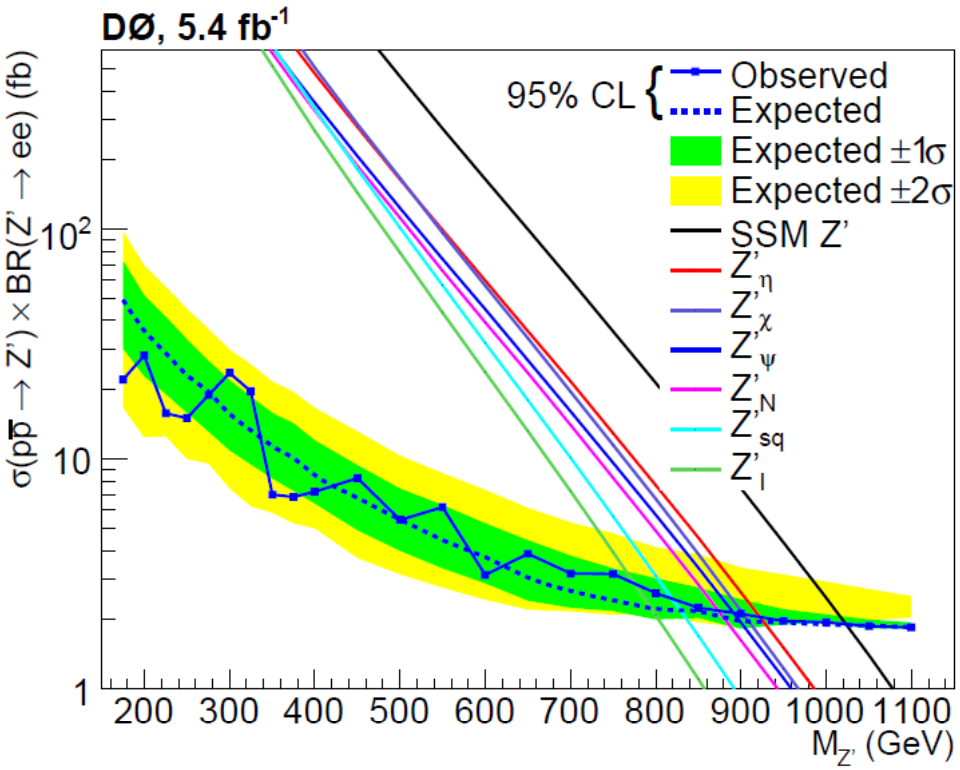
The “tight” muon must pass these criteria:

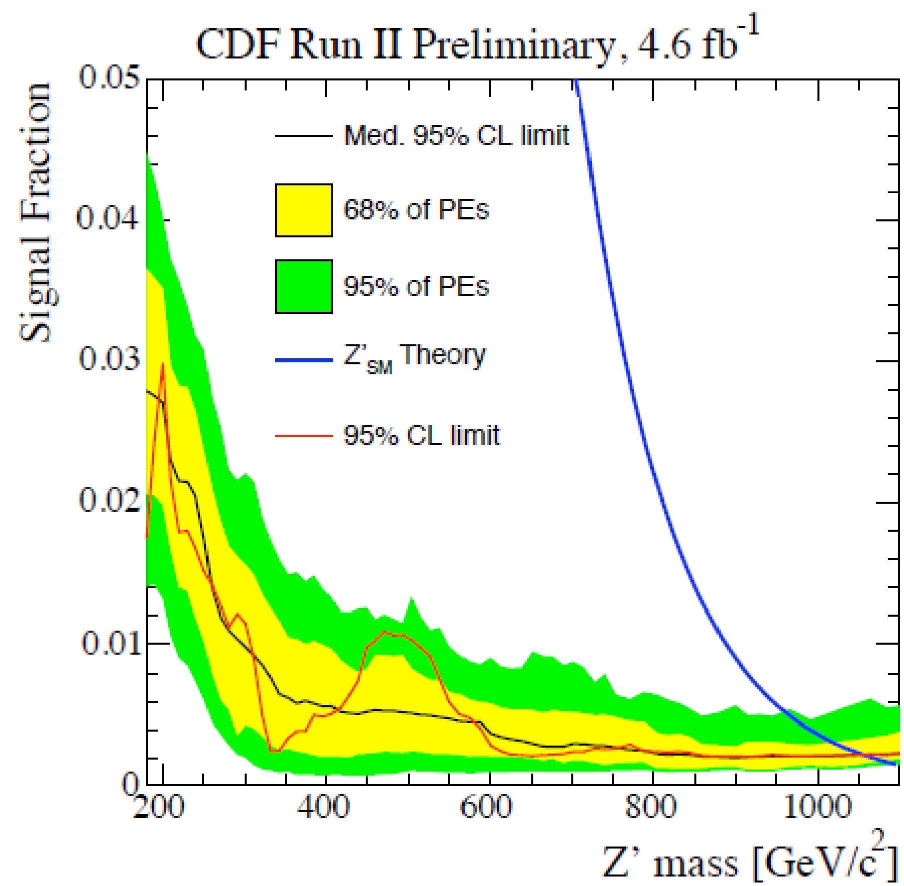
- $|d_{xy}|$ wrt beamspot < 0.2 cm;
- $\chi^2/ndf < 10$;
- identified as a tracker-muon;
- at least one pixel hit;
- two muon stations with segments on the global fit, of which at least one hit survives the fit;
- and was matched ($\Delta R < 0.2$, $\Delta p_T/p_T < 1$) to a HLT muon that triggered.

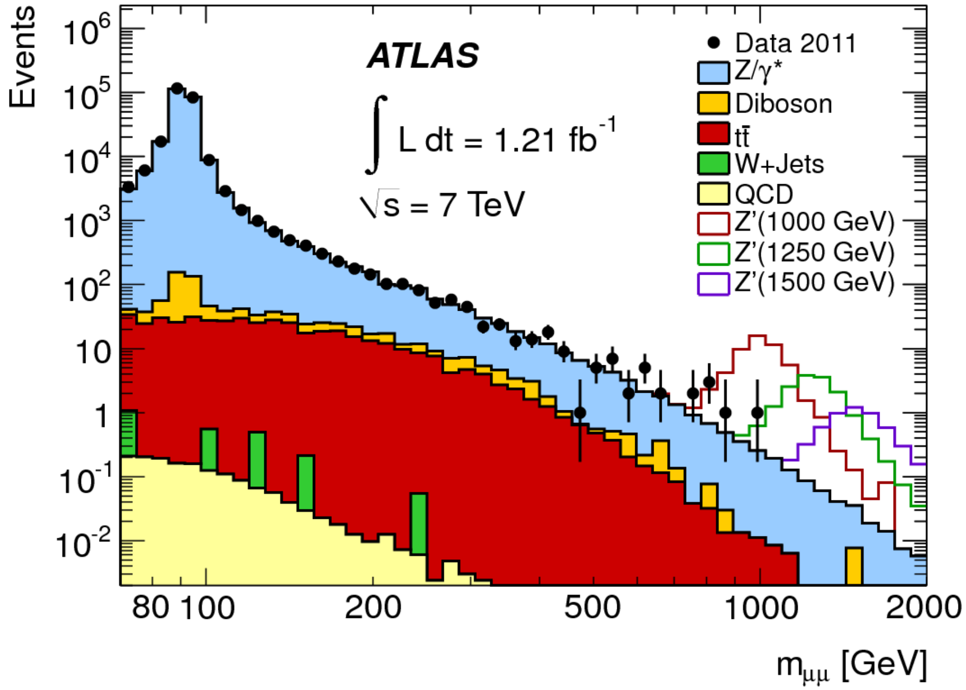
$$\mathcal{L}(m|R_\sigma, M, \Gamma, w, \alpha, \kappa, \mu_B) = \frac{\mu^N e^{-\mu}}{N!} \prod_{i=1}^{N} \left(\frac{\mu_S(R_\sigma)}{\mu} f_S(m_i|M, \Gamma, w) + \frac{\mu_B}{\mu} f_B(m_i|\alpha, \kappa) \right)$$

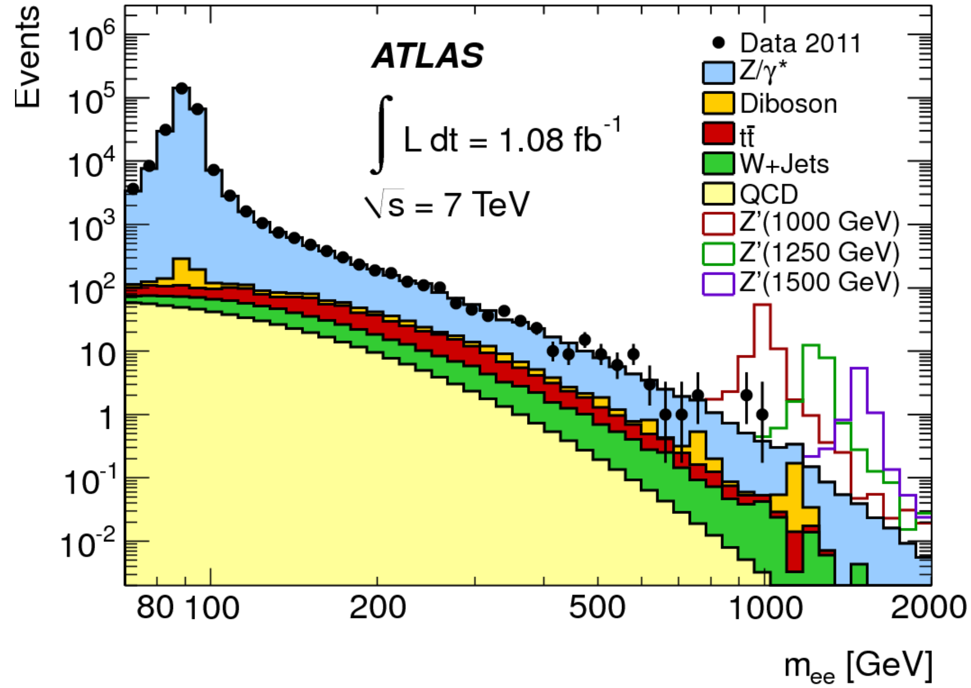
with:

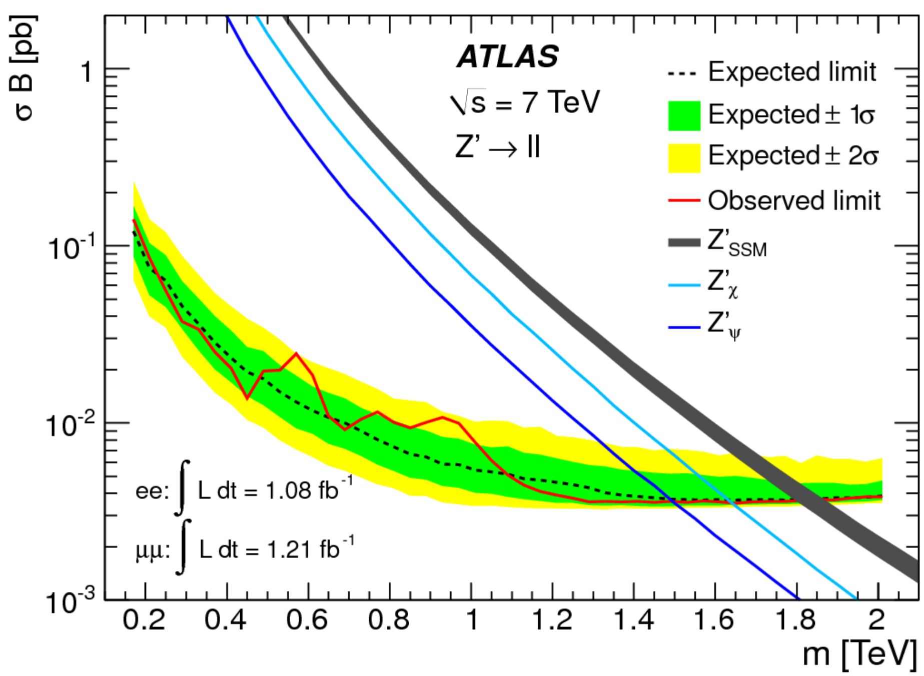
- m_i = observed mass spectrum;
- $f_S(m_i|M, \Gamma, w)$ = signal pdf, Breit-Wigner of width Γ and mass M, convoluted with Gaussian with width w;
- $f_B(m_i|\alpha, \kappa) \sim \exp(-\alpha m) m^{-\kappa}$ = background pdf;
- $R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$ = the cross section ratio, which goes into the likelihood function as part of the signal Poisson mean $\mu_S = R_\sigma \cdot \mu_Z \cdot R_\epsilon$, where μ_Z is the Poisson mean number of $Z^0 \to ee$ or $\mu\mu$ events, and R_ϵ is the ratio of total efficiency for Z′ and Z^0 decays;
- μ_B is the Poisson mean of the total background yield, $\mu = \mu_S + \mu_B$, and N is the total number of events with mass above 600 GeV.

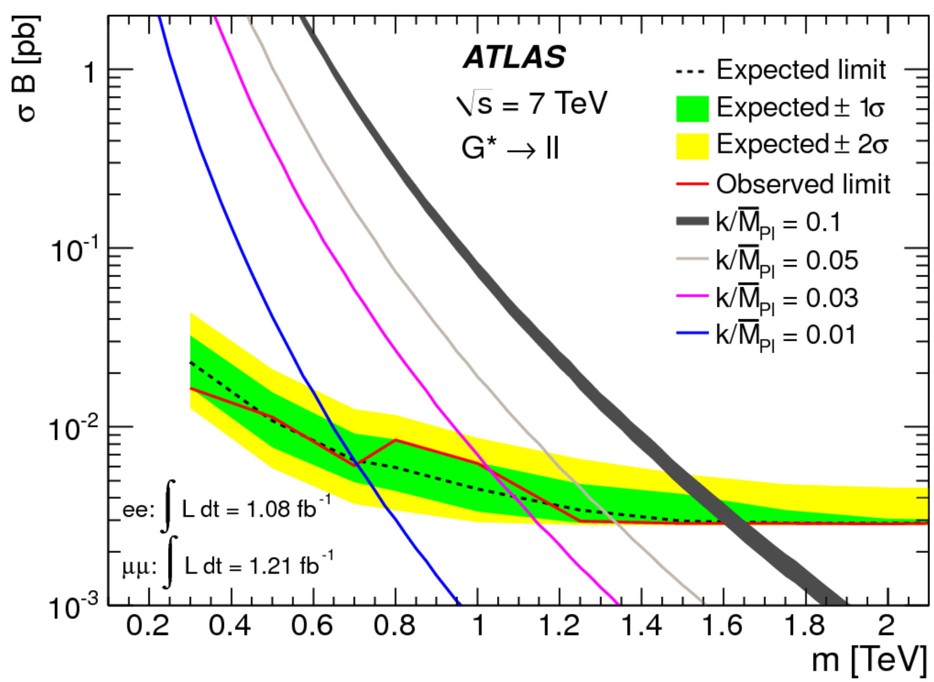

DØ, 5.4 fb^{-1}
95% CL
Observed
Expected
Expected ±1σ
Expected ±2σ
SSM Z'
Z'$_\eta$
Z'$_\chi$
Z'$_\psi$
Z'$_N$
Z'$_{sq}$
Z'$_I$
σ(pp̄ → Z') × BR(Z' → ee) (fb)
1
10
10^2
200 300 400 500 600 700 800 900 1000 1100
M$_{Z'}$ (GeV)


CDF Run II Preliminary, 4.6 fb^{-1}
Med. 95% CL limit
68% of PEs
95% of PEs
Z'$_{SM}$ Theory
95% CL limit
Signal Fraction
0
0.01
0.02
0.03
0.04
0.05
200 400 600 800 1000
Z' mass [GeV/c^2]


Events
ATLAS
$\int L\,dt = 1.21\ fb^{-1}$
$\sqrt{s} = 7$ TeV
Data 2011
Z/γ^*
Diboson
$t\bar{t}$
W+Jets
QCD
Z'(1000 GeV)
Z'(1250 GeV)
Z'(1500 GeV)
$m_{\mu\mu}$ [GeV]


Events
ATLAS
$\int L\,dt = 1.08\ fb^{-1}$
$\sqrt{s} = 7$ TeV
Data 2011
Z/γ^*
Diboson
$t\bar{t}$
W+Jets
QCD
Z'(1000 GeV)
Z'(1250 GeV)
Z'(1500 GeV)
m_{ee} [GeV]


σ B [pb]
ATLAS
$\sqrt{s} = 7$ TeV
$Z' \rightarrow ll$
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'_{SSM}
Z'_{χ}
Z'_{ψ}
ee: $\int L\,dt = 1.08\ fb^{-1}$
μμ: $\int L\,dt = 1.21\ fb^{-1}$
m [TeV]


σ B [pb]
ATLAS
$\sqrt{s} = 7$ TeV
$G^* \rightarrow ll$
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
$k/\overline{M}_{Pl} = 0.1$
$k/\overline{M}_{Pl} = 0.05$
$k/\overline{M}_{Pl} = 0.03$
$k/\overline{M}_{Pl} = 0.01$
ee: $\int L\,dt = 1.08\ fb^{-1}$
μμ: $\int L\,dt = 1.21\ fb^{-1}$
m [TeV]