Opposite Sign DiLepton Searches at CMS

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Outline

- **Introduction**

- **Opposite Sign DiLepton Searches**
  - Outside the Z Window
  - Inside the Z Window

PAS-SUS-11-011 0.98 / fb

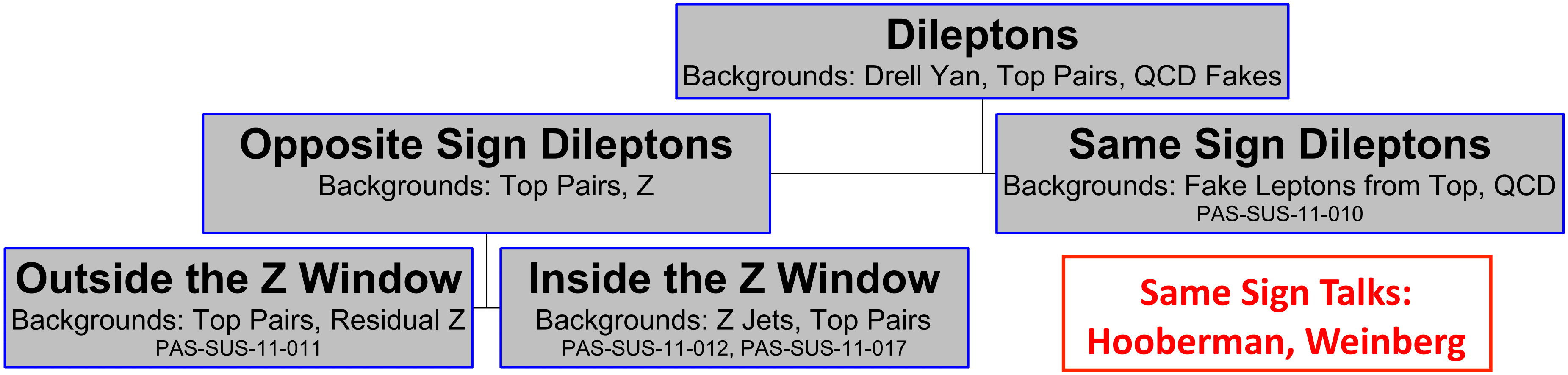
PAS-SUS-11-012 0.19 / fb

PAS-SUS-11-017 0.98 / fb

  - Will Explain Methods used to Estimate Backgrounds and Present Results

DiLepton Searches

- Why DiLeptons?
  - DiLeptons in the Standard Model (and beyond) are Rare and Interesting: *top pairs, Z, WW, Higgs, Maybe Supersymmetry*
  - Clean Experimental Signature
  - Natural Suppression of QCD Backgrounds
- Search Strategy for DiLepton Final States:



Dileptons
Backgrounds: Drell Yan, Top Pairs, QCD Fakes

Opposite Sign Dileptons
Backgrounds: Top Pairs, Z

Same Sign Dileptons
Backgrounds: Fake Leptons from Top, QCD
PAS-SUS-11-010

Outside the Z Window
Backgrounds: Top Pairs, Residual Z
PAS-SUS-11-011

Inside the Z Window
Backgrounds: Z Jets, Top Pairs
PAS-SUS-11-012, PAS-SUS-11-017

Same Sign Talks:
Hooberman, Weinberg

- Searches for Events in Excess of Standard Model Predictions in Final States with Opposite Sign DiLeptons are covered in this talk

Search in The Z Mass Window

MET Search

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Jet – Z Balance

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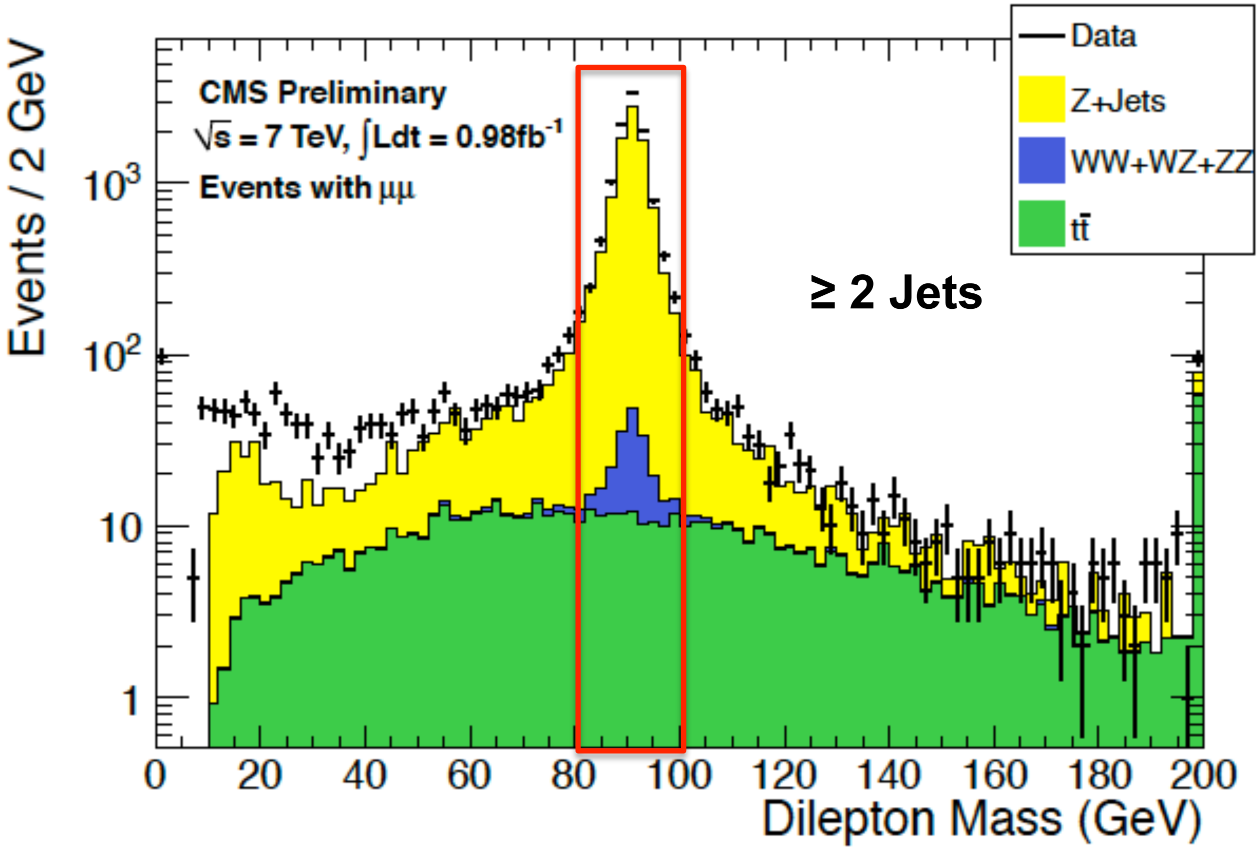
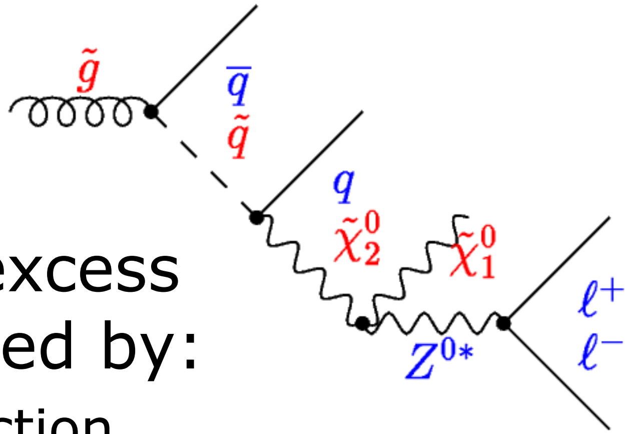


Z Window MET Search

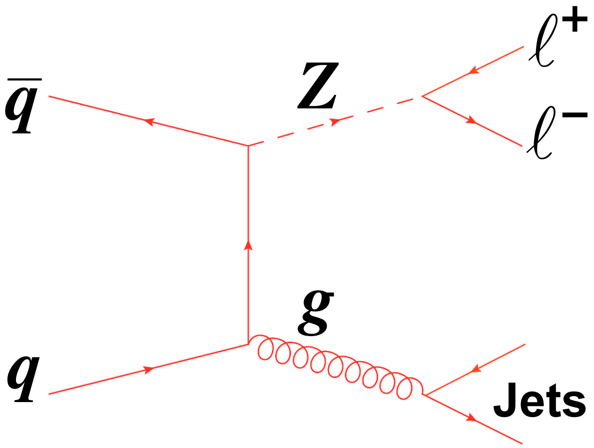
- Leptons pair produced by Z’s are a feature common to many models of new physics.
  Here is an example in SUSY:



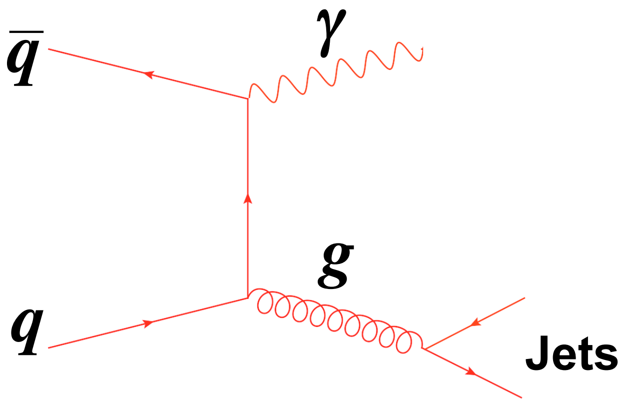
- This motivates a search for an excess of MET in a **signal region** defined by:
  - **2 or more jets** from strong production
  - **2 isolated leptons** ($P_T > 20$ GeV, $|\eta| < 2.5$)
    - **Invariant DiLepton mass within 10 GeV of the Z Mass**
  - Missing Transverse Energy (MET)
    - Search in 2 regions: **MET > 100 GeV, MET > 200 GeV**
- **Fake MET** from badly measured Jets, and real **MET from top pairs** are the dominant backgrounds.

Estimating Fake MET

- The background of fake MET from badly measured jets in Z+Jets is modeled by γ+Jets <u>data</u>



Background

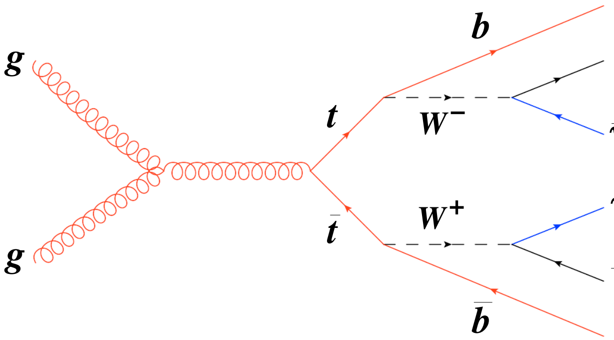


Data Driven Background Estimate

- The MET prediction for each Z + Jets event is the (unit normalized) MET distribution taken from the γ+Jets control sample with corresponding jet multiplicity and Ht. QCD is also used to corroborate γ+Jets results.

Estimating Real MET from Top Pairs

- Real MET from top pair production is also a background to MET searches in Z+Jets



Real MET

- In top decays, the number of SF and OF pairs are equal
  - **For Real MET from top pairs, Same Flavor MET can be estimated by Opposite Flavor MET**
  - Differences between e & μ efficiencies are corrected for

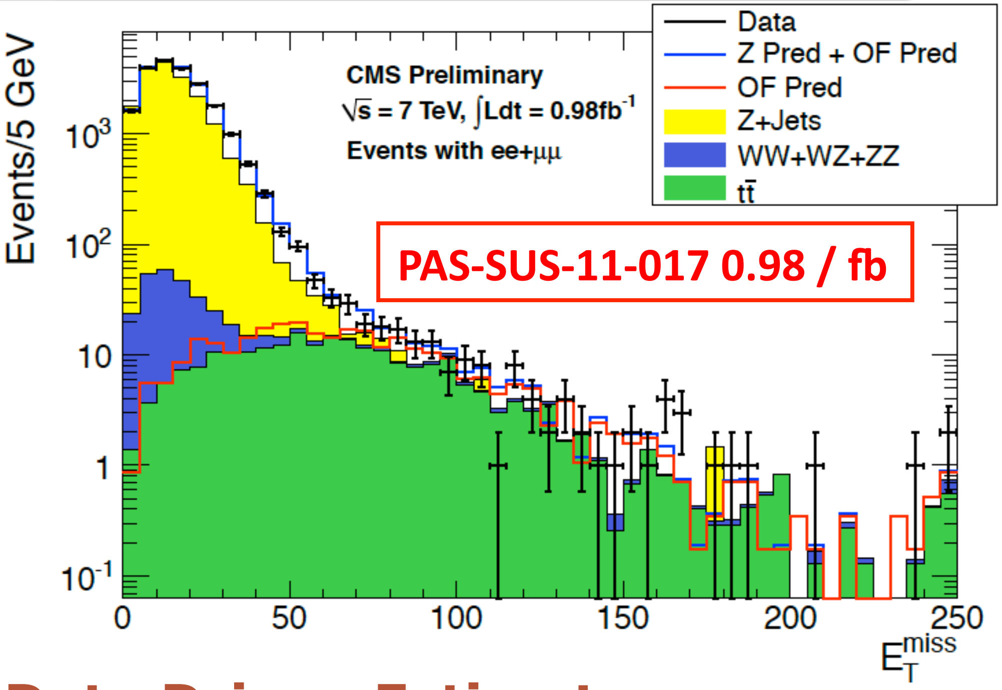
- **Both Fake and Real MET backgrounds are Predicted by _Data Driven_ Methods.**

Z Window: Summer 2011 Results

- **MET Predictions**

  Real SF MET From top pairs predicted by OF MET

  Fake MET predicted by γ + Jets (added to the red)



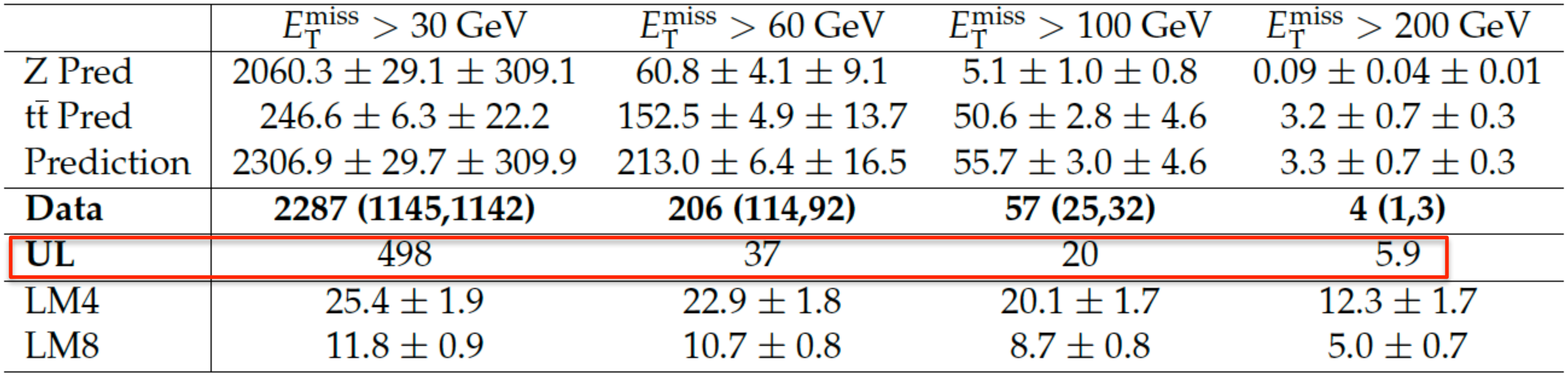
- **No Signal Observed. Observations Agree with Data Driven Estimates.**

	$E_T^{miss} > 30$ GeV	$E_T^{miss} > 60$ GeV	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV
Z Pred	2060.3 ± 29.1 ± 309.1	60.8 ± 4.1 ± 9.1	5.1 ± 1.0 ± 0.8	0.09 ± 0.04 ± 0.01
$t\bar{t}$ Pred	246.6 ± 6.3 ± 22.2	152.5 ± 4.9 ± 13.7	50.6 ± 2.8 ± 4.6	3.2 ± 0.7 ± 0.3
Prediction	2306.9 ± 29.7 ± 309.9	213.0 ± 6.4 ± 16.5	55.7 ± 3.0 ± 4.6	3.3 ± 0.7 ± 0.3
Data	**2287 (1145,1142)**	**206 (114,92)**	**57 (25,32)**	**4 (1,3)**

(ee,μμ)

Z Window: Summer 2011 Limits

- **No Signal Observed. Upper Limits Set at 95% CL.**



	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV
Z Pred	$2060.3 \pm 29.1 \pm 309.1$	$60.8 \pm 4.1 \pm 9.1$	$5.1 \pm 1.0 \pm 0.8$	$0.09 \pm 0.04 \pm 0.01$
$t\bar{t}$ Pred	$246.6 \pm 6.3 \pm 22.2$	$152.5 \pm 4.9 \pm 13.7$	$50.6 \pm 2.8 \pm 4.6$	$3.2 \pm 0.7 \pm 0.3$
Prediction	$2306.9 \pm 29.7 \pm 309.9$	$213.0 \pm 6.4 \pm 16.5$	$55.7 \pm 3.0 \pm 4.6$	$3.3 \pm 0.7 \pm 0.3$
Data	**2287 (1145,1142)**	**206 (114,92)**	**57 (25,32)**	**4 (1,3)**
UL	498	37	20	5.9
LM4	25.4 ± 1.9	22.9 ± 1.8	20.1 ± 1.7	12.3 ± 1.7
LM8	11.8 ± 0.9	10.7 ± 0.8	8.7 ± 0.8	5.0 ± 0.7

- Limits also set on **σ** × **A** for SUSY benchmarks LM4 & LM8. **A** is the acceptance. **LM4 is excluded**.

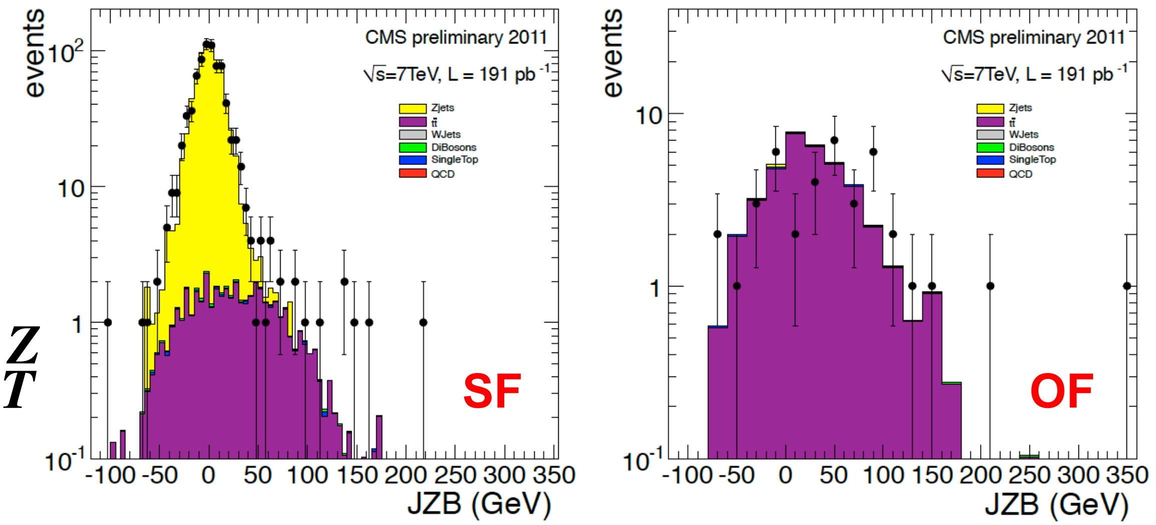
$E_{\mathrm{T}}^{\mathrm{miss}} > $ **200 GeV**	efficiency (%)	acceptance (%)	UL($\sigma \times A$) (fb)	$\sigma \times A$(fb)
LM4	50 ± 6	0.84	13	23
LM8	43 ± 5	0.98	15	11

$E_{\mathrm{T}}^{\mathrm{miss}} > $ **100 GeV**	efficiency (%)	acceptance (%)	UL($\sigma \times A$) (fb)	$\sigma \times A$(fb)
LM4	53 ± 3	1.4	39	37
LM8	44 ± 3	1.7	47	19

Jet - Z Balance

- **Separate Analysis**
- Same Backgrounds:
  - Fake MET
  - MET from Top

$$JZB = \left(\sum_i \vec{p}_T^{\,Jet\ i} \right) - \vec{p}_T^{\,Z}$$



- **Events Selections:**
  - 2 isolated ($P_T > 20$ GeV) SF leptons within a 20 GeV window of the Z Mass
  - 3 or more Jets
  - **Signal Region: JZB > X (X > 50 GeV, X > 100 GeV)**
- **Backgroud Estimation**
  - JZB corresponding to **real MET** From SF top pairs **estimated by OF JZB**
  - **JZB > X** corresponding to **fake MET** estimated by **JZB < - X**
    Opposie Flavor JZB < - X is subtracted off to avoid double counting.

Jet - Z Balance: Results

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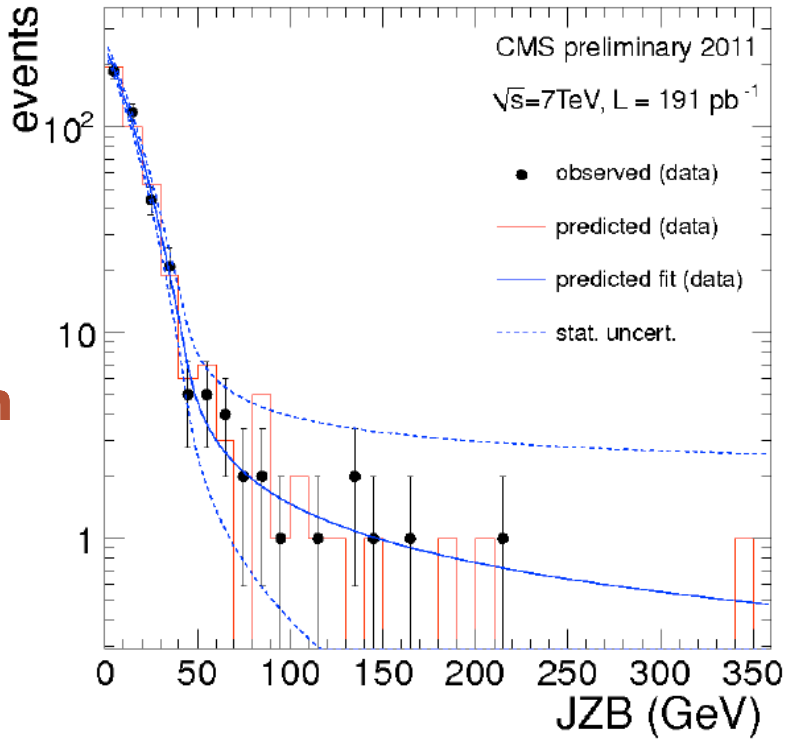
- **Data** and **JZB Prediction** agree. **Predicted Fit** also shown.
- **No Signal in 0.191 fb^{-1}. Will be updated with more data. Observation in agreement with data driven prediction in both signal regions.**
- **Upper Limits Set at 95% CL**
  - JZB > 50 GeV **11.1**
  - JZB > 100 GeV **6.6**



Region	Observed events	Background prediction	MC expectation
$JZB > 50\,\text{GeV}$	20	$24 \pm 6(\text{stat}) \pm 1.4(\text{peak})^{+1.2}_{-2.4}(\text{sys})$	16.0 ± 1.2 (MC stat)
$JZB > 100\,\text{GeV}$	6	$8 \pm 4(\text{stat}) \pm 0.1(\text{peak})^{+0.4}_{-0.8}(\text{sys})$	3.6 ± 0.4 (MC stat)

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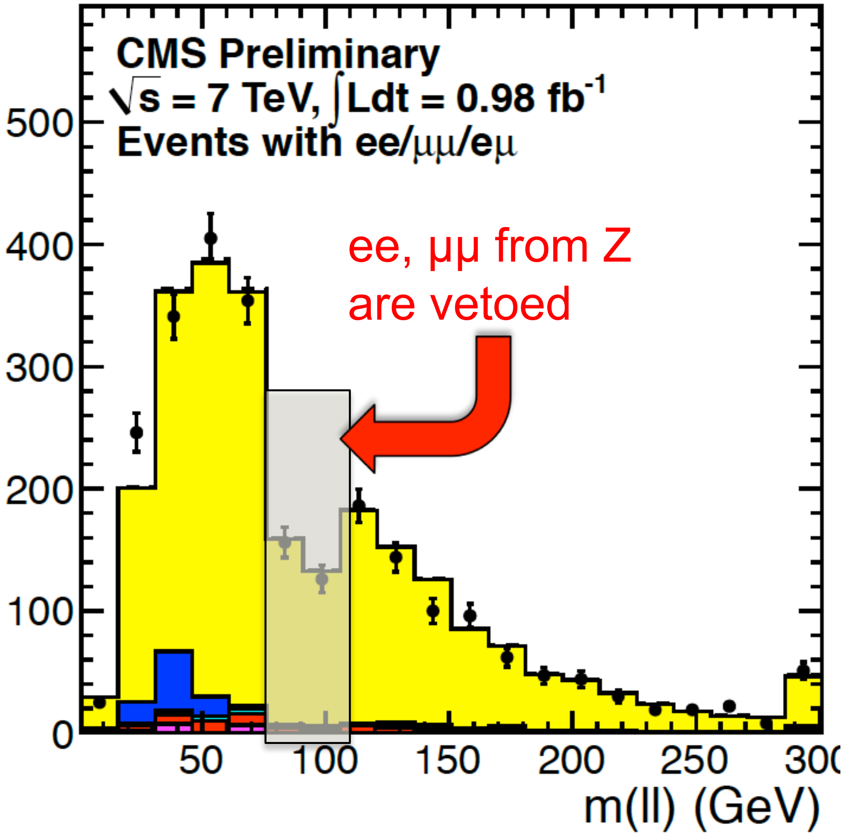
Search Outside The Z Mass Window

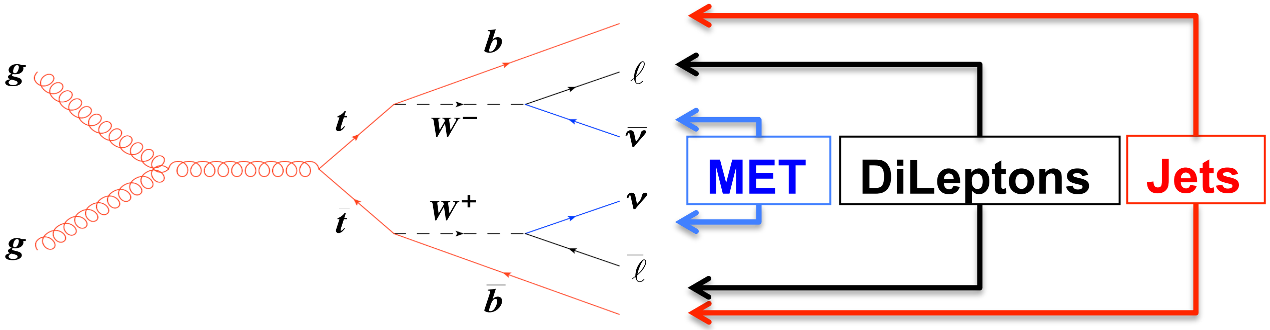


ee, μμ from Z are vetoed

 # Jets ≥ 2
HT > 100 GeV
MET > 50 GeV

Search Outside the Z Window

- Look for Events in Excess of Standard Model Predictions.
  Top Pairs are the Principal Background.

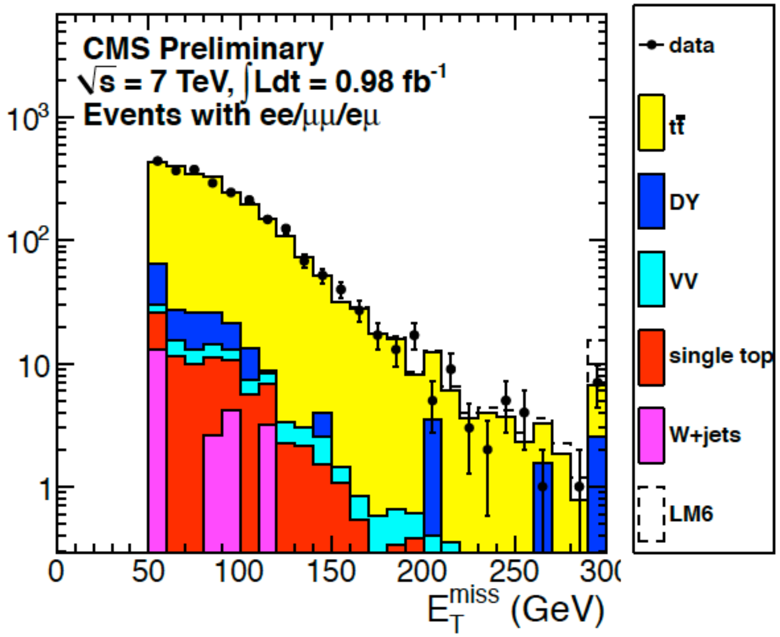


- **2 Signal Regions**
  - Chosen to reduce top background to ~ 0.1%
  - High MET: MET > 275 Gev, H_T > 300 GeV
  - High H_T: MET > 200 GeV, H_T > 600 GeV
- **4 Background Estimation Methods (and MC)**
  - MET Predicted by DiLepton Pt
  - ABCD'
  - Opposite Flavor Subtraction
  - Search for an Edge in DiLepton Mass

Event Selection (Non-Z)

- Choose Selections to Reduce SM backgrounds:
  - **<u>2 opposite sign leptons</u>** that are **<u>inconsistent with Z</u>**
  - **<u>2 jets or more</u>** with at least **<u>100 GeV scalar pt sum</u>**
  - **<u>MET ≥ 50 GeV</u>**
- Remaining Background is more than <u>90% top </u>(MC)

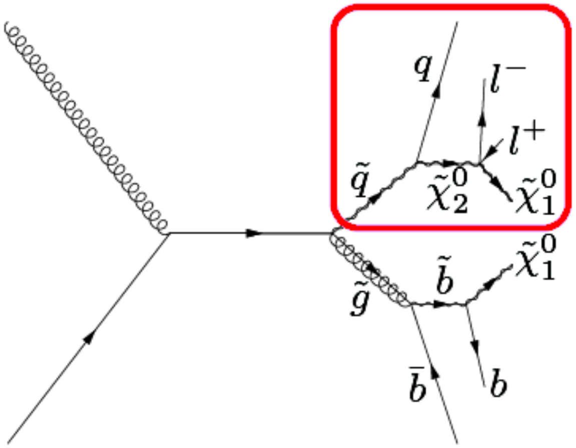
Sample	σ [pb]	ee	$\mu\mu$	$e\mu$	total
$t\bar{t} \rightarrow \ell^+\ell^-$	17	412.8 ± 8.9	465.4 ± 9.0	1095.6 ± 14.2	1973.8 ± 19.0
$t\bar{t} \rightarrow$ fake	141	12.6 ± 1.6	3.7 ± 0.8	22.7 ± 2.0	39.0 ± 2.7
DY$\rightarrow \ell^+\ell^-$	16677	18.6 ± 5.0	26.6 ± 6.0	37.6 ± 7.1	82.8 ± 10.6
W^+W^-	43	4.0 ± 0.5	4.3 ± 0.4	9.5 ± 0.7	17.7 ± 0.9
$W^\pm Z^0$	18	0.8 ± 0.1	1.0 ± 0.1	1.9 ± 0.1	3.8 ± 0.2
Z^0Z^0	5.9	0.3 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	1.2 ± 0.1
single top	102	12.6 ± 0.6	14.0 ± 0.6	33.2 ± 1.0	59.9 ± 1.3
$W +$ jets	96648	12.6 ± 5.4	0.0 ± 0.0	7.8 ± 4.6	20.5 ± 7.1
total SM MC		474.5 ± 11.7	515.4 ± 10.8	1208.6 ± 16.7	2198.5 ± 23.1
data		524	576	1381	2481



- Observed Reasonable Agreement Between Data & MC in 0.98 / fb

Opposite Flavor Subtraction

- New physics that might produce leptons via a cascade decay will result only in **same flavor lepton pairs**, provided that lepton flavor is conserved



- For the dominant ttbar background, the flavor of the 2 leptons is not correlated and we expect equal amounts of same flavor (SF) and opposite flavor (OF) lepton pairs

- Searches for an excess of SF events in Di-Lepton events are therefore well motivated

Opposite Flavor Subtraction Results

- We quantify the SF – OF difference as:

$$\Delta = R_{\mu e} N(ee) + \frac{1}{R_{\mu e}} N(\mu\mu) - N(e\mu)$$

- $R_{\mu e}$ = 1.12 is the ratio of muon to electron efficiencies
- Z-Veto is applied to OF leptons for consistency with SF
- OF Subtraction is applied to the high MET (left) and High HT (right) signal regions

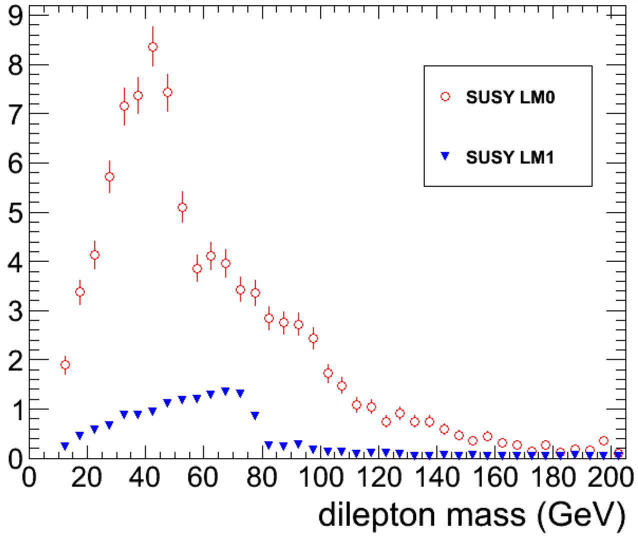
	high E_T^{miss} signal region	high H_T signal region
observed Δ	3.6 ± 2.9 (stat) $\pm$ 0.4 (syst)	-0.9 $\pm$ 1.8 (stat) $\pm$ 1.1 (syst)
UL	7.9	3.6

- **We Observe No Excess of Same Flavor Events.**

Search for an Edge

- Search for a kinematic edge in SF DiLepton mass
  - **Z-Veto is removed** to look at the full mass distribution
  - The Drell-Yan let in by removing the Z-Veto is again reduced by raising the MET cut:
    - **MET > 100 GeV**
- A search for an edge is performed by fitting the DiLepton mass in 2 region
  - **300 Gev > HT > 100 GeV** (Control)
  - **300 GeV < HT** (Signal)

$$\tilde{\chi}_2^0 \to \tilde{\ell}^+\ell^- \to \tilde{\chi}_1^0 \ell^+\ell^-$$



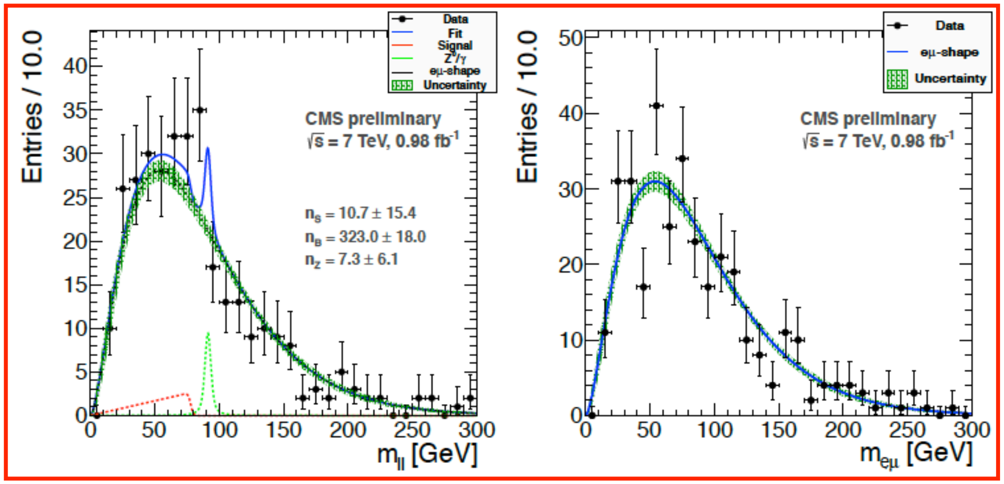
Example of how mass edges may present

Search for an Edge: The Fit

- The background is modeled by a Breit-Wigner convoluted with a Gaussian and added with B(m_{ll}): $B(m_{\ell\ell}) = m_{\ell\ell}^{a} e^{-b m_{\ell\ell}}$
- The signal is modeled by a special function:

$$T(m_{\ell\ell}) = \frac{1}{\sqrt{2\pi}\sigma_{ll}} \int_0^{M_{cut}} dy\, y e^{\frac{-(m_{\ell\ell}-y)^2}{2\sigma^2}}$$

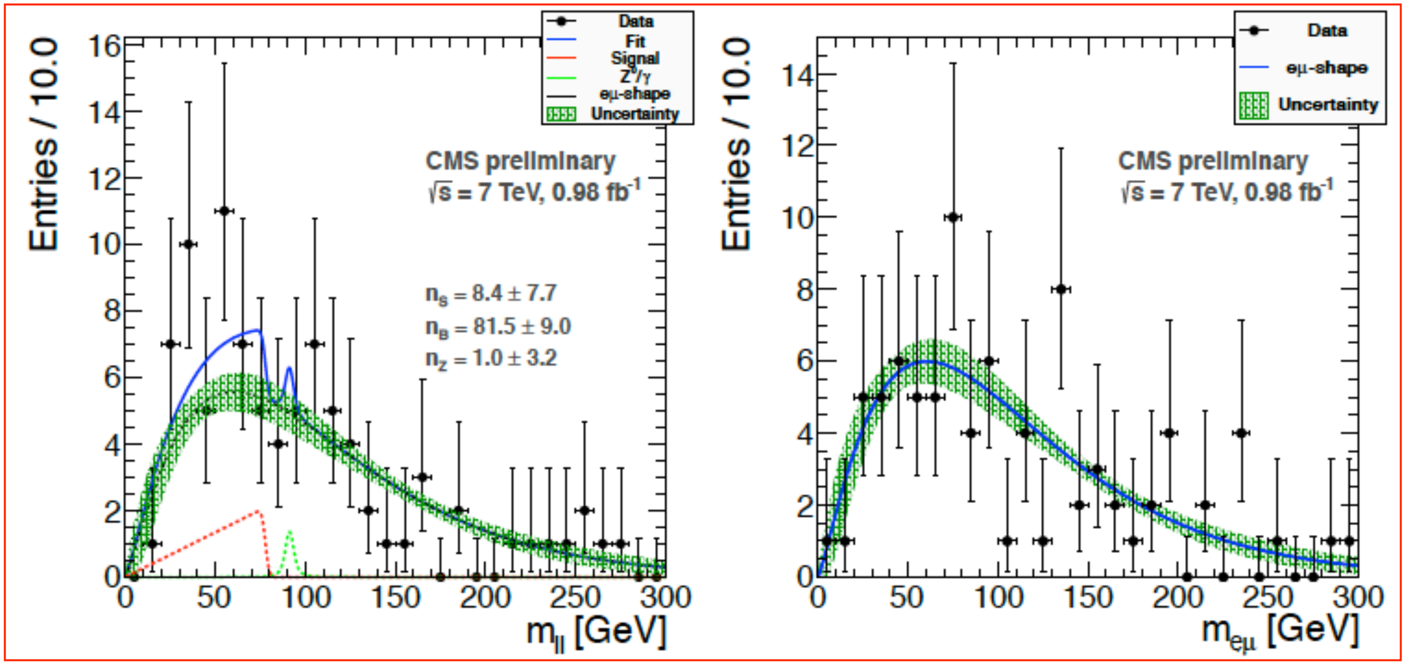
- A simultaneous maximum likelihood fit is performed first in the **<u>control region</u>** with the tt, Z, and signal yields free to vary.



- **The extracted signal yield of 10.7 ± 15.4 is consistent with the background only hypothesis**

Search for an Edge: Results

- A fit is performed again, now in the signal region HT > 300 GeV
- The Z yield from the preselection is extrapolated to the signal region MET > 100 GeV, HT > 300 GeV in order to constrain the Z yield used in the signal region fit



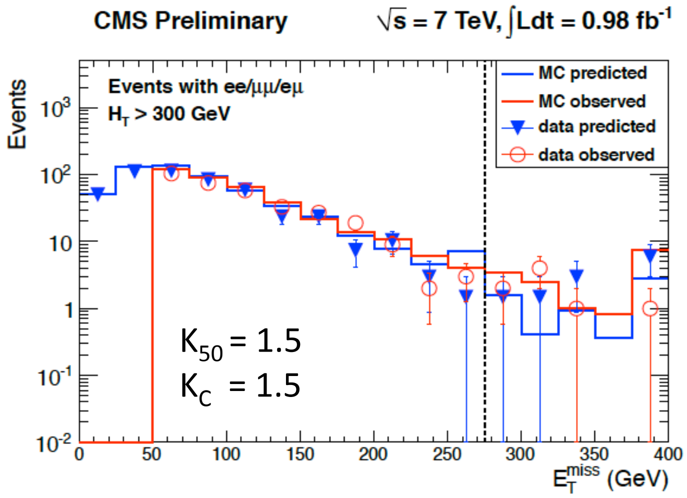
- **The extracted signal 8.4 ± 7.7 is consistent with BG only.**

DiLepton Pt

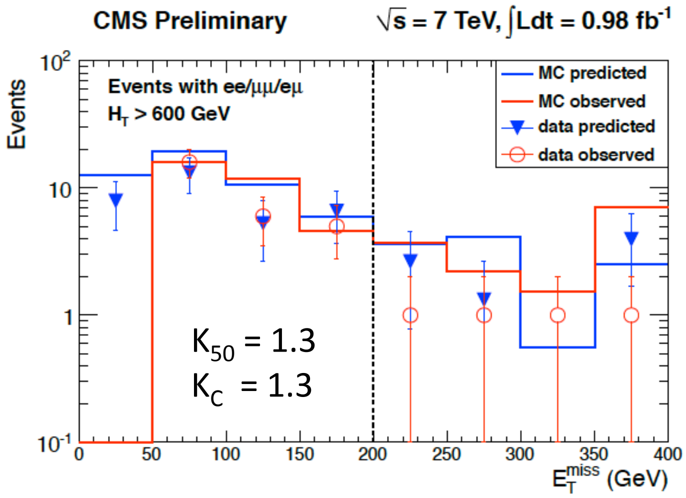
- MET is a search variable used in this analysis
- ttbar is the dominant background
  - In DiLeptonic ttbar, true MET arises when each top decays to a W boson and b quark, and each W subsequently decays to a lepton and neutrino.
  - The transverse momentum of the 2 neutrinos is the true MET.
- **MET can be estimated with DiLepton Pt**
  - Ignoring W polarization, the spectrum of Di-Lepton Pt is the same as the MET spectrum on average.
  - W polarization results in the Di-Lepton spectrum being softer than the MET spectrum. This is corrected for by scaling the Di-Lepton Pt up by a factor of **$K_C \sim 1.3 – 1.5$** (K_C from MC)

DiLepton Pt: Results

- **Results of the Data Driven Pt(ll) Method**



MET > 275 GeV , H_T > 300 GeV



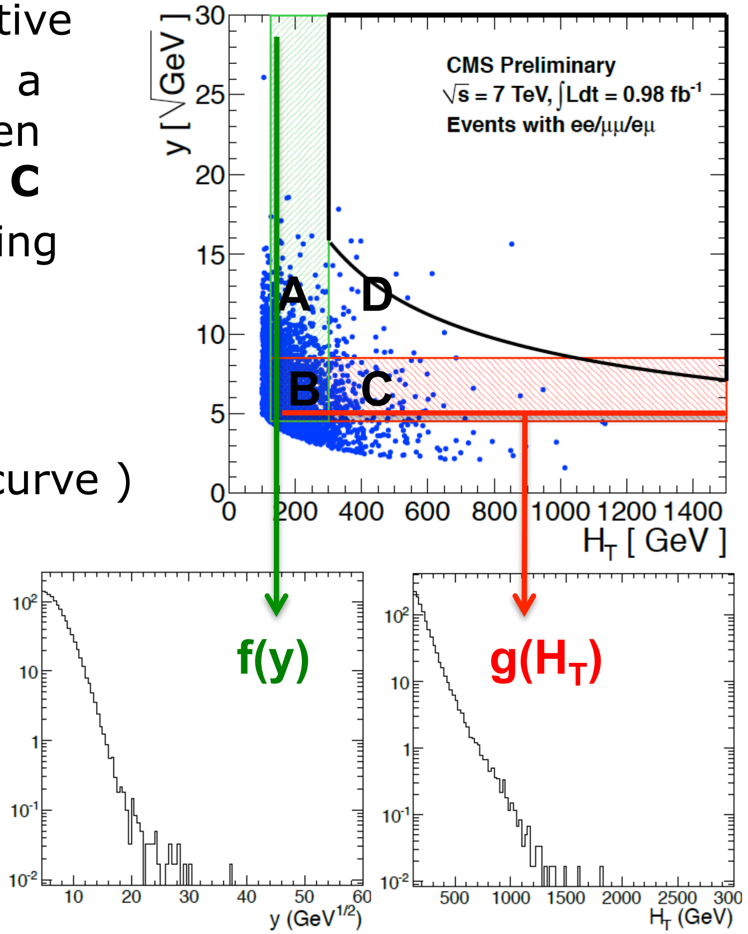
MET > 200 GeV , H_T > 600 GeV

- **Pt(ll) Prediction in Agreement with Observation & Monte Carlo**

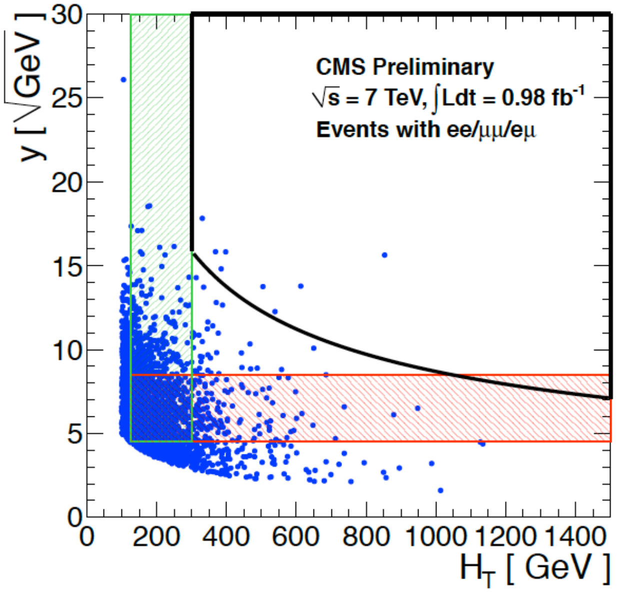
	high E_T^{miss} signal region	high H_T signal region
observed yield	8	4
MC prediction	7.3 ± 2.2	7.1 ± 2.2
$p_T(\ell\ell)$ prediction	14.3 ± 6.3 (stat) ± 5.3 (syst)	10.1 ± 4.2 (stat) ± 3.5 (syst)

ABCD’ Method

- **MET is not correlated with y = MET / √HT**
  - Events in a (y, H_T) signal region can be predicted: $\mathbf{N_D = (N_A \times N_C)/N_B}$
  - But… searches in (MET, H_T) are more sensitive
  - The functions **f(y)** & **g(H_T)** allow events in a (MET, H_T) signal region to be predicted given events in the (y, H_T) control regions: **A, B, C**
  - (MET, H_T) predictions are given by integrating the probability **P(y, H_T) = f(y)×g(H_T)**
- $\mathbf{N_{SIGNAL} = R \times N_{CONTROL}}$
  - $\mathbf{N_{SIGNAL}}$ are the events in the (MET, H_T) signal region we want to estimate (black curve)
  - $\mathbf{N_{CONTROL}}$ are the events in the (y, H_T) control region (A or B or C)
  - **R** is the ratio of random (y, H_T) pairs take f(y) & g(H_T) which lie in the signal region t which lie in the control region



ABCD' Results



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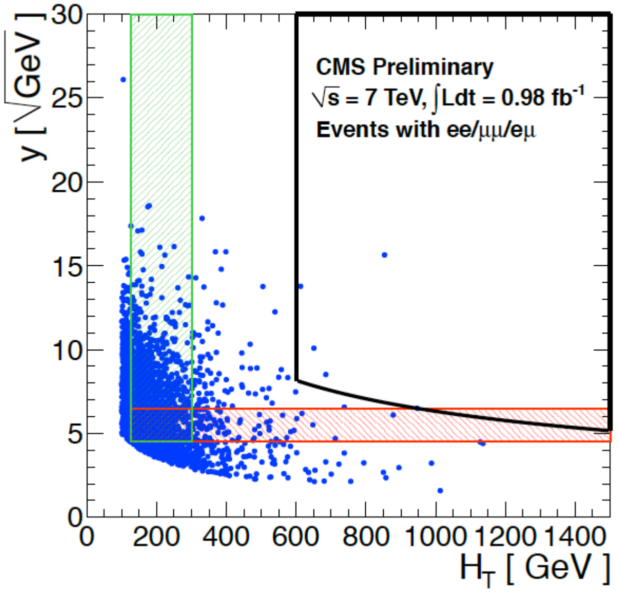

MET > 200 GeV , H_T > 600 GeV

- **ABCD' Prediction in Agreement with Observation & Monte Carlo**

	high E_T^{miss} signal region	high H_T signal region
observed yield	8	4
MC prediction	7.3 ± 2.2	7.1 ± 2.2
ABCD' prediction	4.0 ± 1.0 (stat) ± 0.8 (syst)	4.5 ± 1.6 (stat) ± 0.9 (syst)

Non-Z Search Summary

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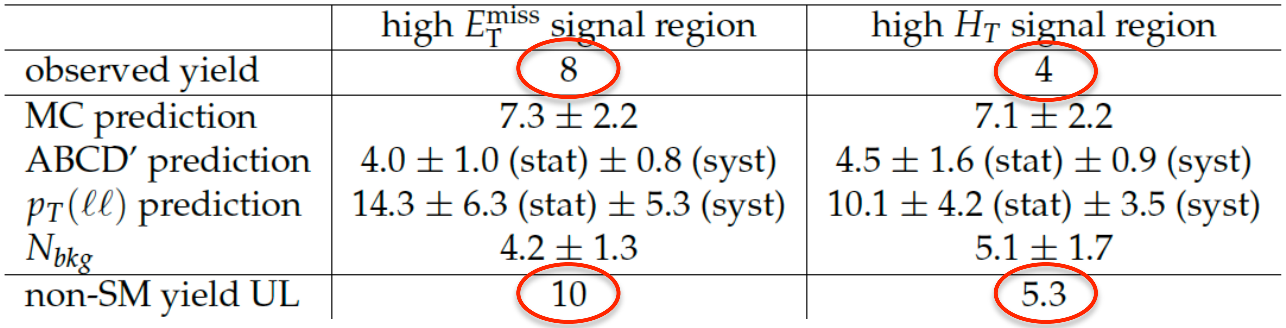
- 3 Data Driven Methods: **ABCD'**, **DiLepton Pt** and **Opposite Flavor Subtraction** are consistent with Data & Monte Carlo
  - *No Evidence for Non Standard Model Physics*
- **Upper Limits Set at 95% Confidence Level**
  - Set Upper Limits on Number of Events Allowed in 2 Signal Regions (using N_{bkg}, the error-weighted Average of ABCD', & DiLepton Pt)



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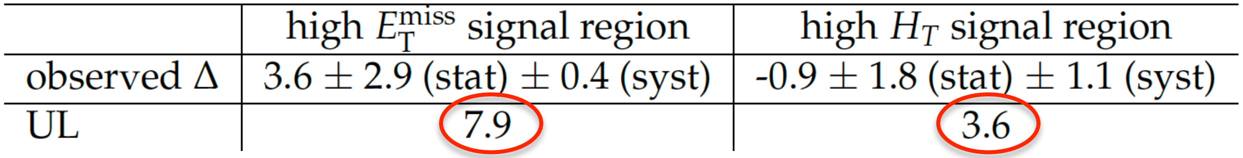
$p_T(\ell\ell)$ prediction	14.3 ± 6.3 (stat) $\pm$ 5.3 (syst)	10.1 ± 4.2 (stat) $\pm$ 3.5 (syst)
N_{bkg}	4.2 ± 1.3	5.1 ± 1.7
non-SM yield UL	10	5.3

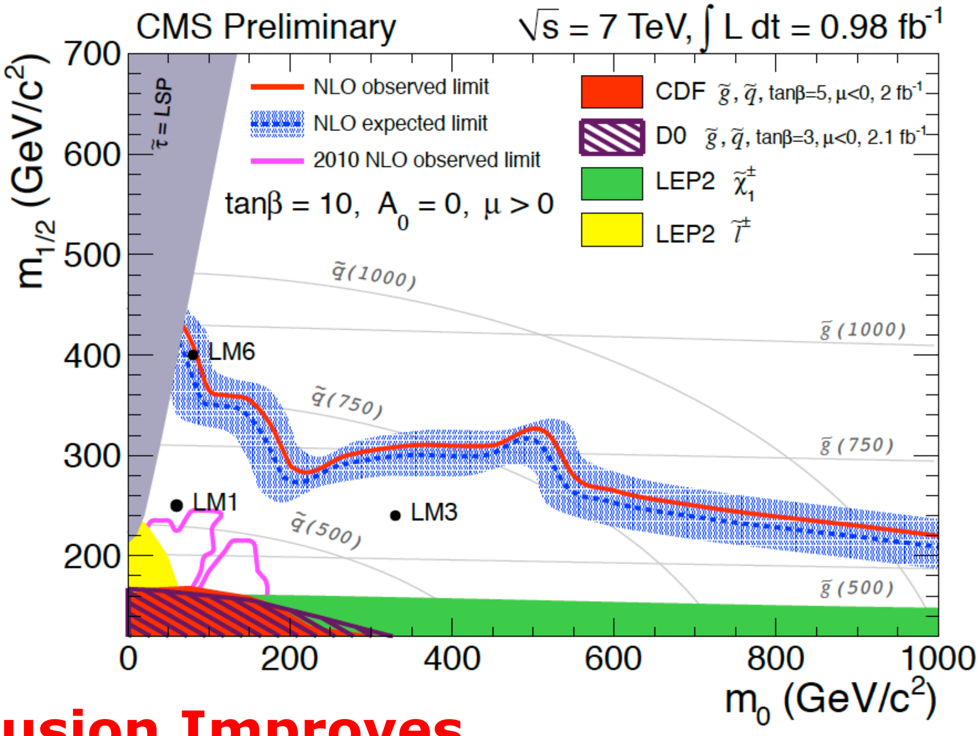
  - Set Upper Limits on the SF Excess. (An OF Z Veto is Applied)



	high $E_{\mathrm{T}}^{\mathrm{miss}}$ signal region	high H_T signal region
observed Δ	3.6 ± 2.9 (stat) $\pm$ 0.4 (syst)	-0.9 ± 1.8 (stat) $\pm$ 1.1 (syst)
UL	7.9	3.6

CMSSM Limits (Non- Z)

- Upper limits on the number of allowed non Standard Model events can be interpreted in the context of a particular model



- **CMSSM** is a benchmark SUSY model used conventionally by the LHC & Tevatron

- An exclusion is made in terms of $\mathbf{m_0}$ and $\mathbf{m_{1/2}}$ (2 of 5 parameters in the CMSSM Lagrangian)

- **Summer 2011 CMS Exclusion Improves on Previous CMS & Tevatron Results**

Conclusion

- Searches for New Physics in Final States with **Opposite Sign DiLeptons**, **Jet Activity**, and **MET** were completed in Summer 2011.
  - Both inside and outside the Z Window
  - **0.98 $\mathbf{fb^{-1}}$** of Data Analyzed

- **Evidence For New Physics Not Observed**

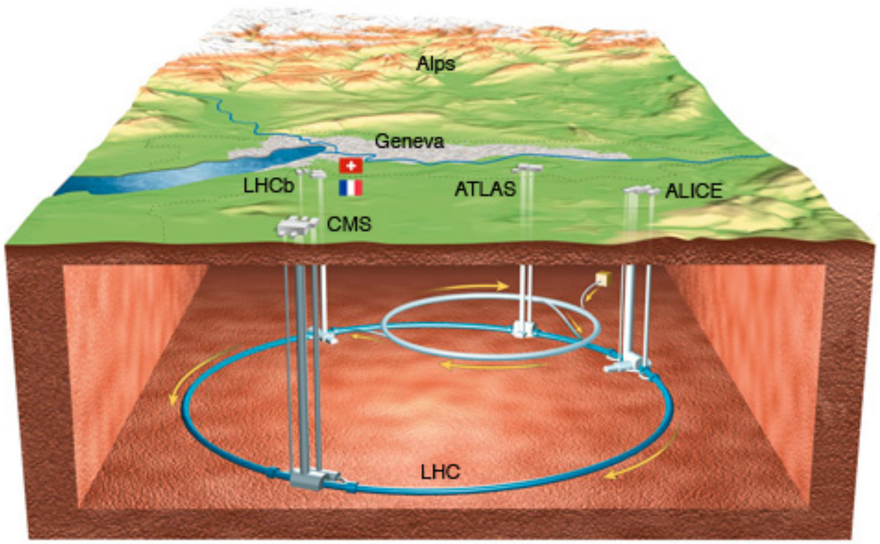
- Upper Limits Set on Non Standard Model Events
  - Provided Experimental Efficiencies to Allow Arbitrary Models to be Tested for Compatibility with our Observed Results

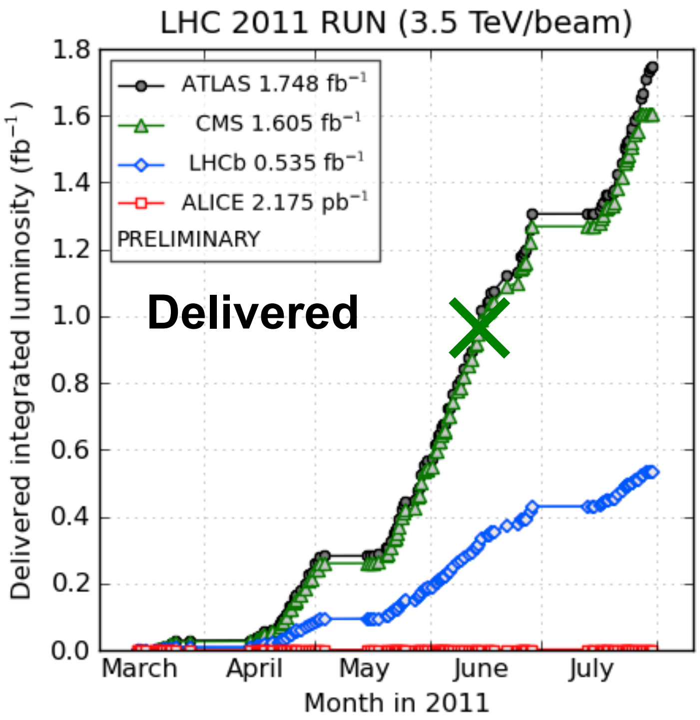
- Excluded Region of CMSSM Space as an Illustration of what the Observed Limits exclude in a particular model

Backup

Large Hadron Collider

- The LHC collides protons at **$\sqrt{s}$ = 7 Trillion eV** Center of Mass Energy



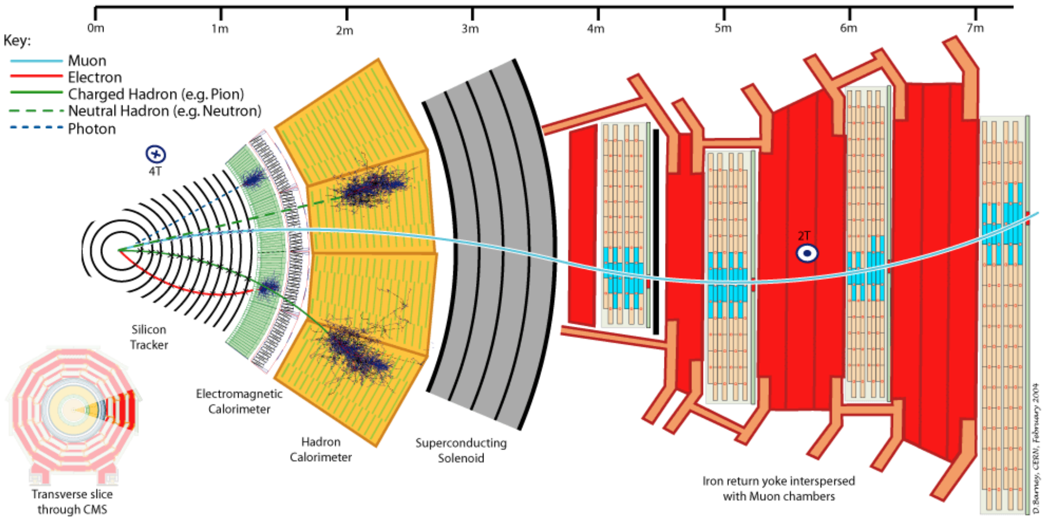


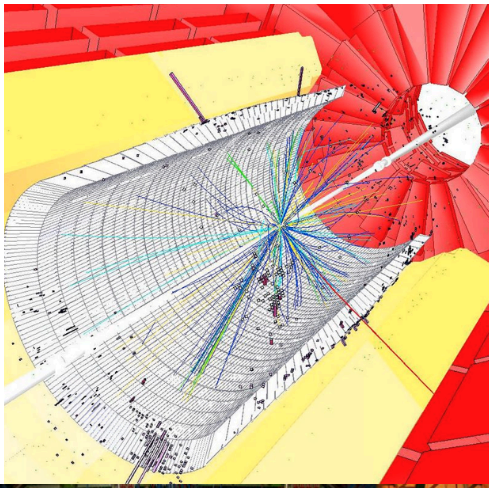
- Collision Data is recorded by one of 4 detectors: ATLAS, **CMS**, ALICE, LHCb

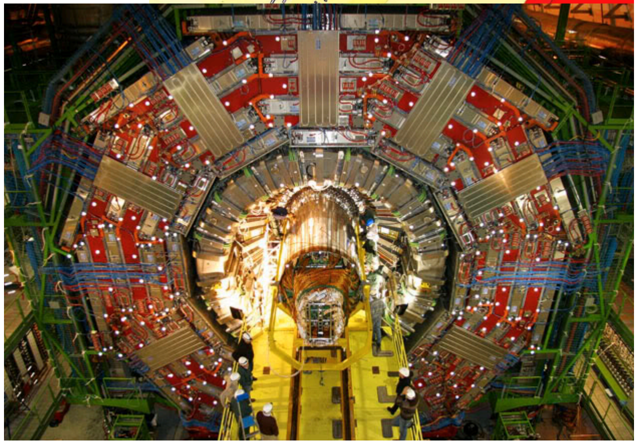
- Results with **0.98 fb^{-1}** of data presented today

Compact Muon Solenoid Detector

- The CMS Detector Reconstructs Final State **Electrons**, **Photons**, **Jets**, **Muons** **& MET**







- Charged particle momentum inferred from curvature in **3.8 T** magnetic field

Di-Lepton Pt

- **DiLepton Pt is used to model MET**
  - DiLepton Pt is <u>renormalized</u> (scaled up) to correct for the <u>MET > 50</u> GeV DiLepton selection
    - The renormalization factor K_{50} is the ratio of all events to those with MET > 50 GeV (K_{50} ~ 1.3 – 1.5)
- **MET is replaced with DiLepton Pt in the signal selections to estimate backgrounds**
  - The number of background events with **MET > 275 GeV** can be estimated by counting the number of events with **DiLepton Pt > 275 GeV** for example

References

- CMS Notes
  - Inside Z Window

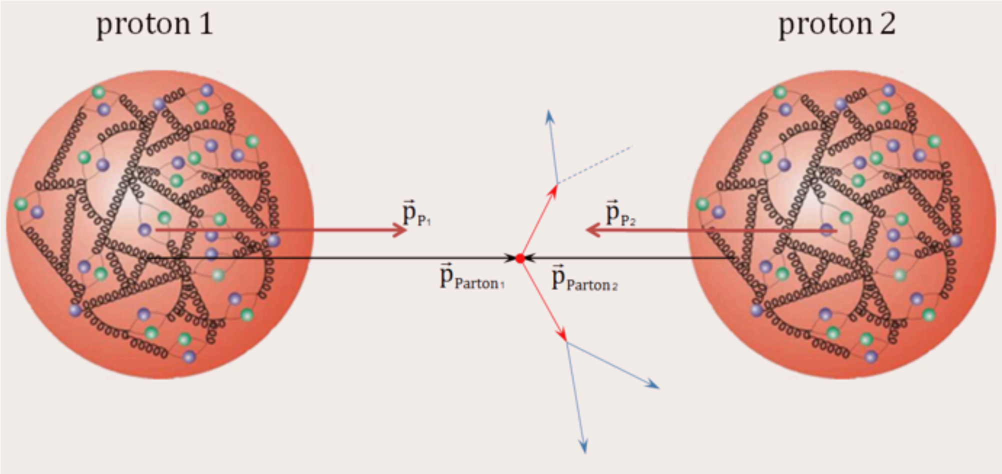
    http://cms.cern.ch/iCMS/jsp/openfile.jsp?tp=draft&files=AN2011_274_v5.pdf

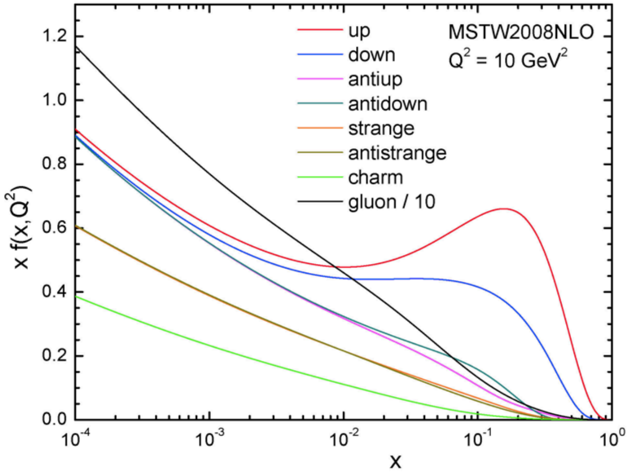
  - Outside Z Window

    http://cms.cern.ch/iCMS/jsp/openfile.jsp?tp=draft&files=AN2011_269_v5.pdf

Hadron Collider Physics

- Protons are made of constituent partons.
  - A proton consists of 3 valence quarks (2 up and 1 down) as well as gluons and other (c, s) “sea” quarks
- Interactions between partons are interesting.





- The initial state longitudinal momentum of interacting partons is not known definitely, but as a probability
  - Leads to interesting *transverse* physics