# SUSY Multilepton Search at CMS

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# Outline

- LHC and CMS Detector
- Motivation
- ***Analysis***

**CMS PAPER SUS-10-008**

## DRAFT
## CMS Paper

*The content of this note is intended for CMS internal use and distribution only*

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### Search for Physics Beyond the Standard Model Using Multilepton Signatures in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration


**Abstract**

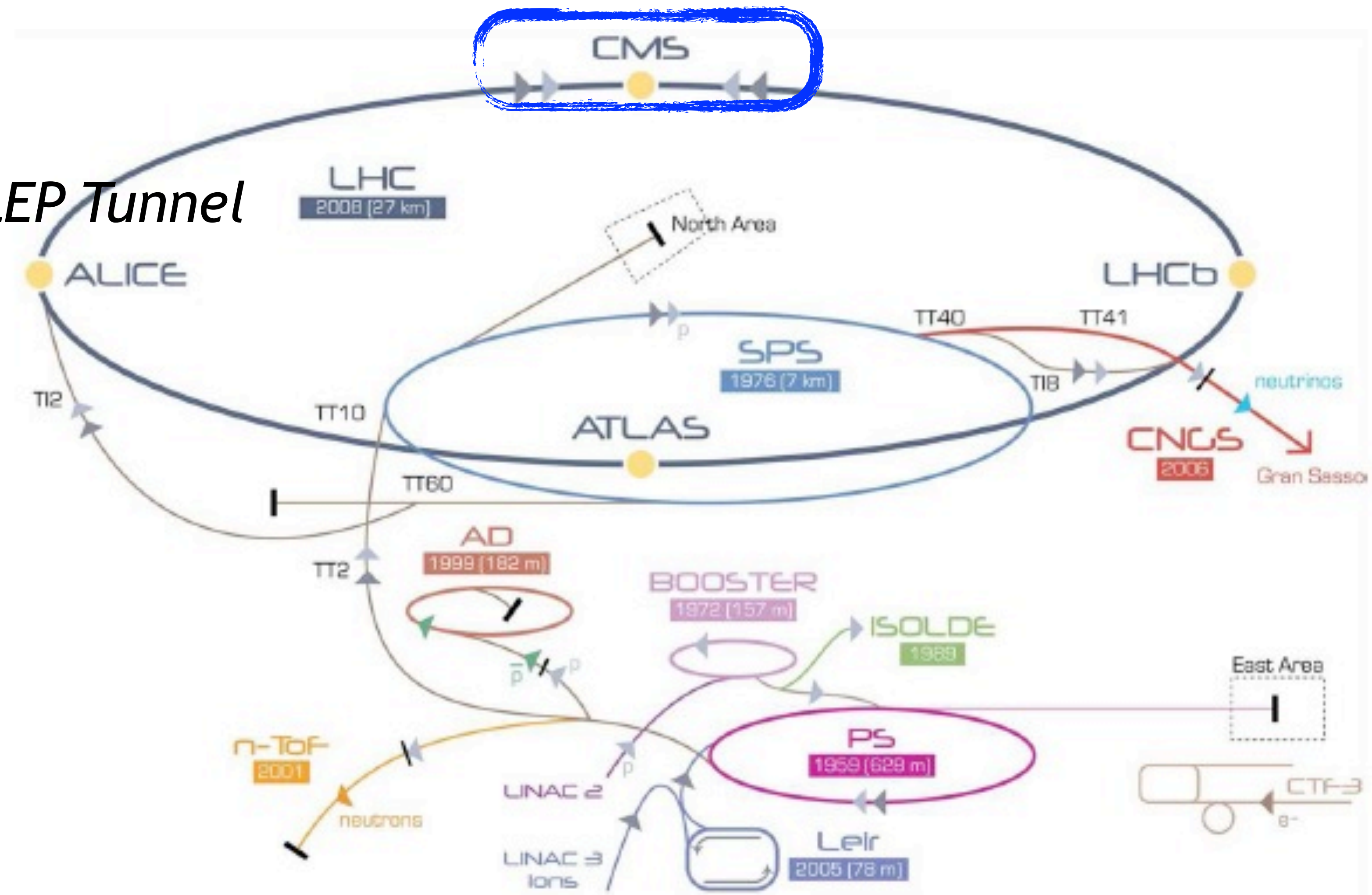
A search for physics beyond the standard model in events with at least three leptons and any number of jets is presented. The data sample corresponds to 35 $pb^{-1}$ of integrated luminosity in pp collisions at $\sqrt{s} = 7$ TeV collected by the CMS experiment at the LHC. A number of exclusive multileptonic channels are investigated and standard model backgrounds are suppressed by requiring sufficient missing transverse energy, invariant mass inconsistent with that of the Z boson, or high jet activity. Control samples in data are used to ascertain the robustness of background evaluation techniques and to minimise the reliance on simulation. The observations are consistent with background expectations. These results constrain previously unexplored regions of supersymmetric parameter space.


*with Colorado, Rutgers, KIT 2010*
*submitted to PLB*

# *LHC and CMS Detector*

# Large Hadron Collider

*former LEP Tunnel*

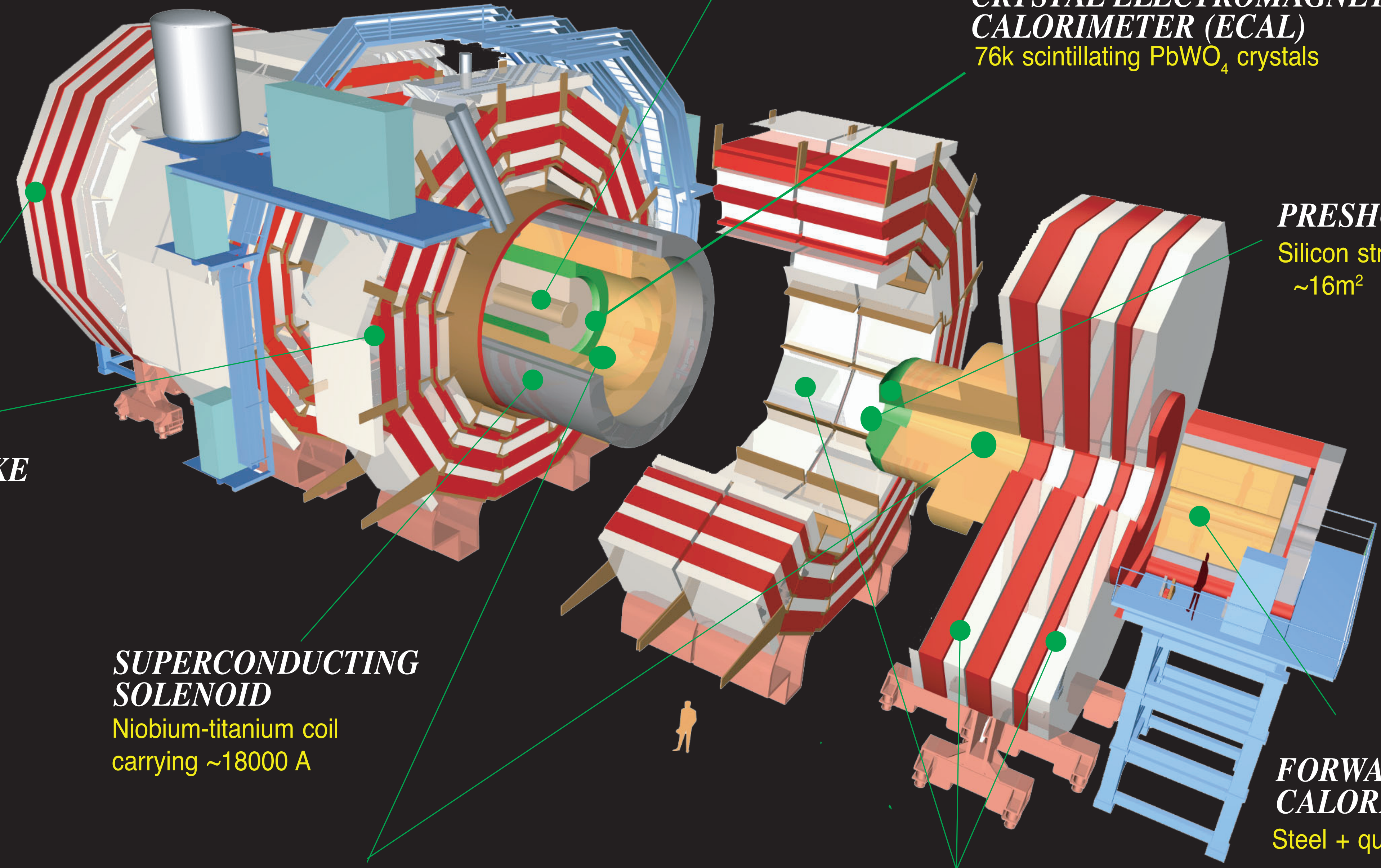



*CERN Outreach*

- Proton-proton beams
- 7 TeV center-of-mass energy (designed for 14 TeV)
- Peak inst. luminosity $O(10^{33}cm^{-2}s^{-1})$ so far (designed for $10^{34}cm^{-2}s^{-1}$)
- Integrated luminosity $O(fb^{-1})$ in 2011

# CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



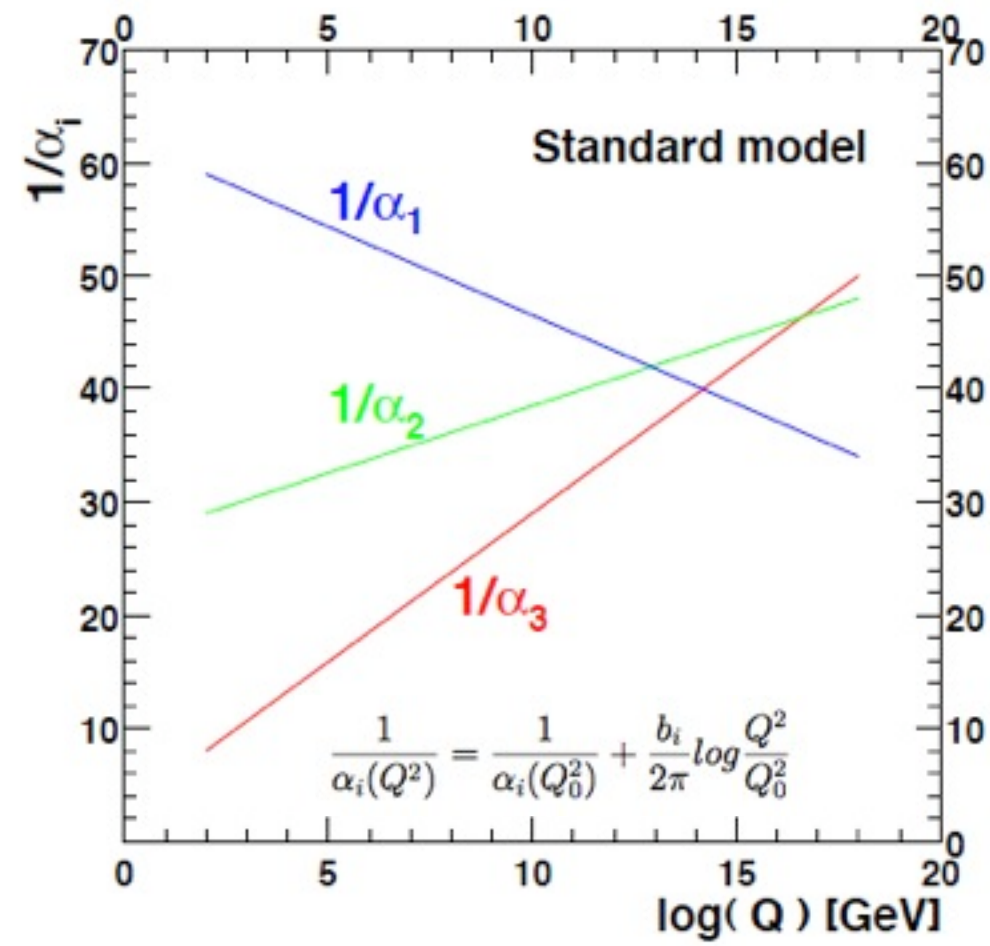

**Total weight : 14000 tonnes**
**Overall diameter : 15.0 m**
**Overall length : 28.7 m**
**Magnetic field : 3.8 T**

# *Motivation*

# Problems in SM

- **SM higgs boson**
  - LEP Ewk Fit + LEP bound (1σ)
  - LEP Ewk precision measurements $A_{FB}$ (3σ)
  - Needs fine tuning to stabilize mass
- **No grand unification of theories**
- **Astrophysics**
  - No cold dark matter candidate (23% of Universe's energy)

$$b_1 = 0 - \frac{4}{3}N_F - \frac{1}{10}N_H$$
$$b_2 = \frac{22}{3} - \frac{4}{3}N_F - \frac{1}{6}N_H$$
$$b_3 = 11 - \frac{4}{3}N_F + 0$$




W. deBoer, 1991

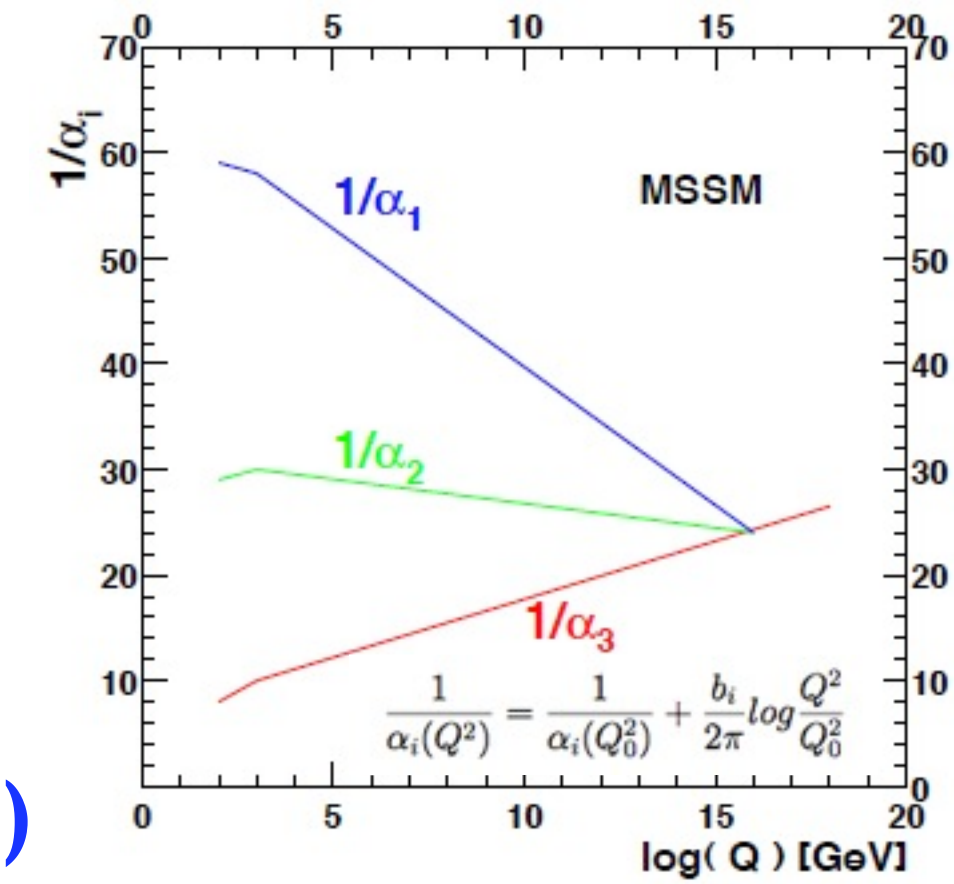
*Great even if one of them can be solved*

# SUSY

- **Supersymmetry = symmetry between fermions and bosons**
  - Less severe fine tuning
  - Nearly doubles #particles
  - Grand Unification
  - Provides a dark matter candidate(if R-parity conserved)

$$R\text{-parity} = (-1)^{2S}\,(-1)^{3B+L}$$

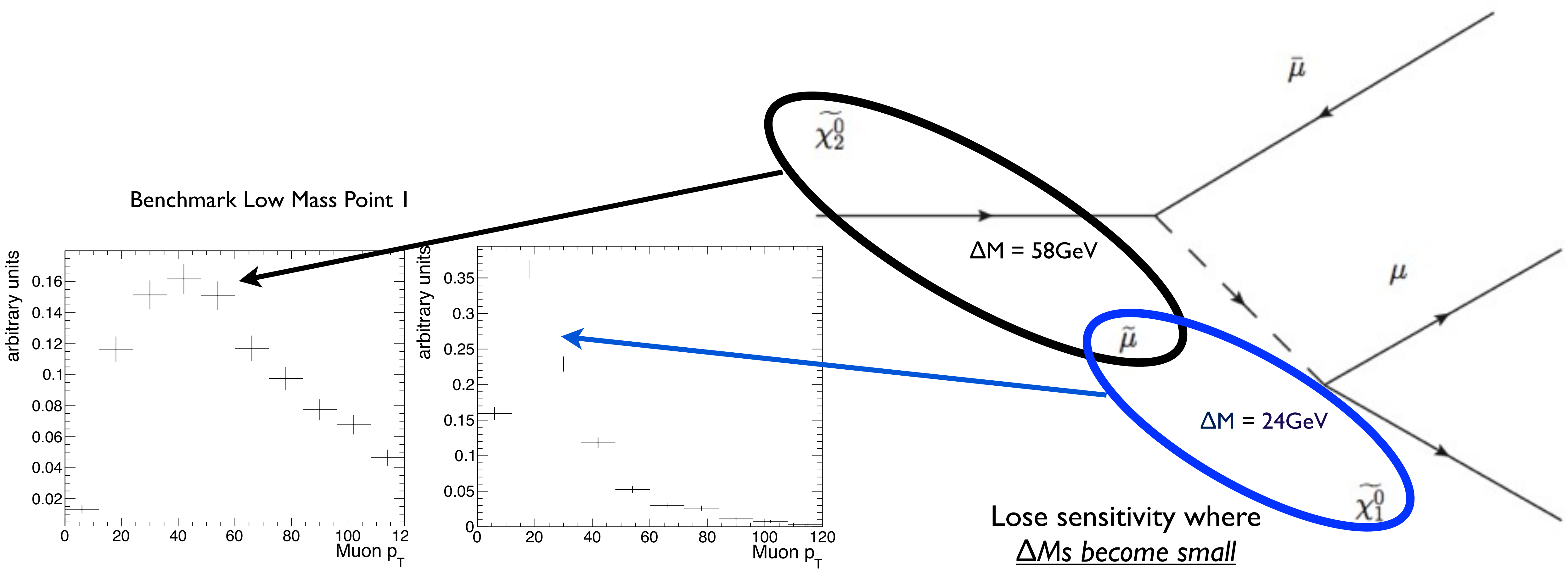
$$\begin{aligned} b_1 &= 0 - 2N_F - \frac{3}{10}N_H \\ b_2 &= 6 - 2N_F - \frac{1}{2}N_H \\ b_3 &= 9 - 2N_F - 0 \end{aligned}$$




W. deBoer, 1991

# SUSY Phenomenology

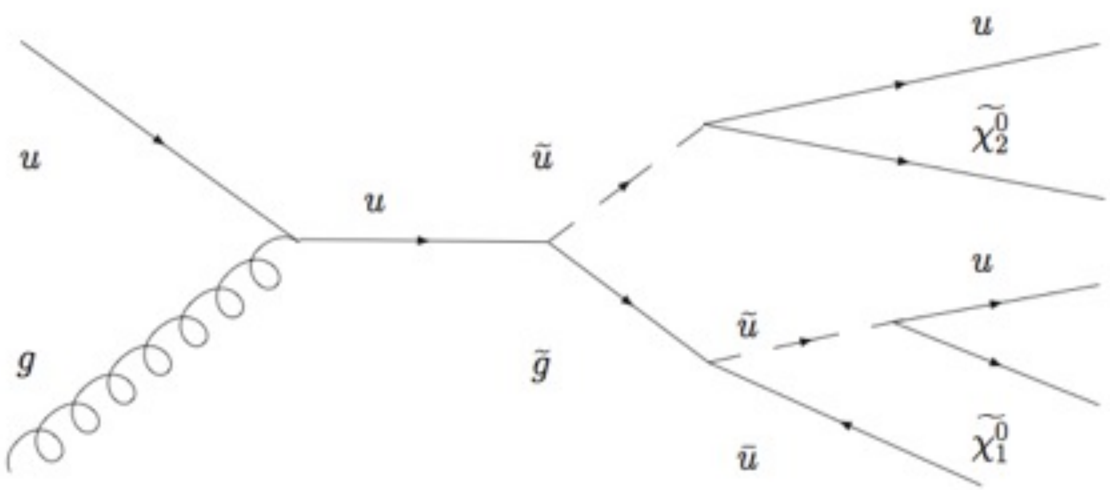
- **Lightest SUSY Particles are stable** *→large MET*
  - if R-parity(SUSY-ness) is conserved
- **Mass difference between LSP and other SUSY particles roughly sets $p_T$ spectra for decay products**



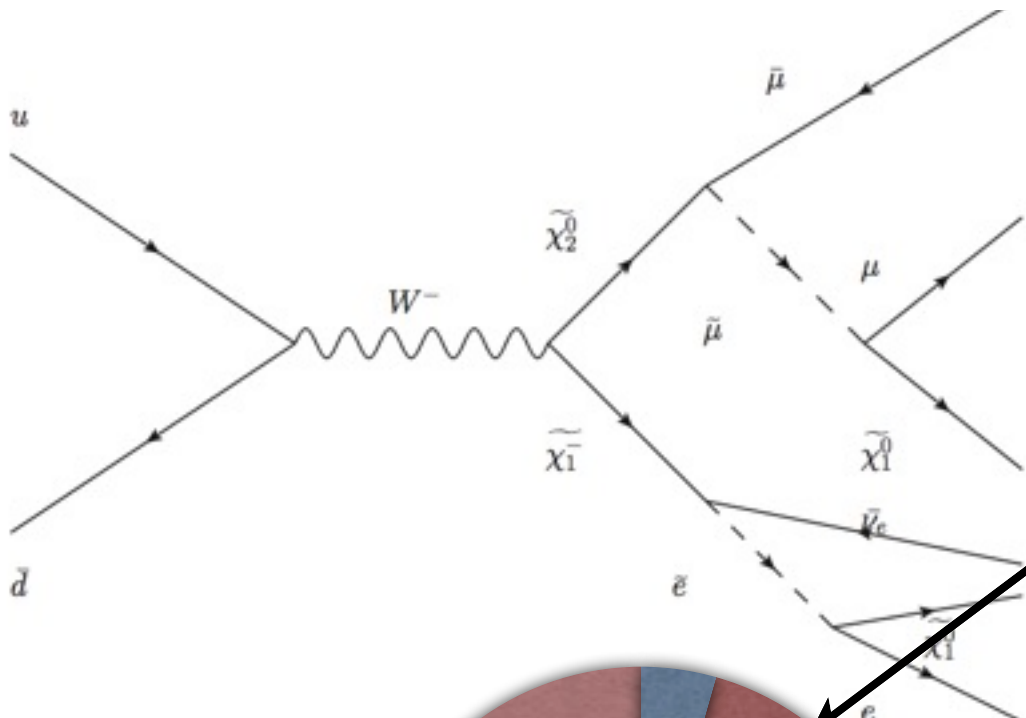

plots normalized to unity

# *Analysis*

# SUSY Multilepton Production

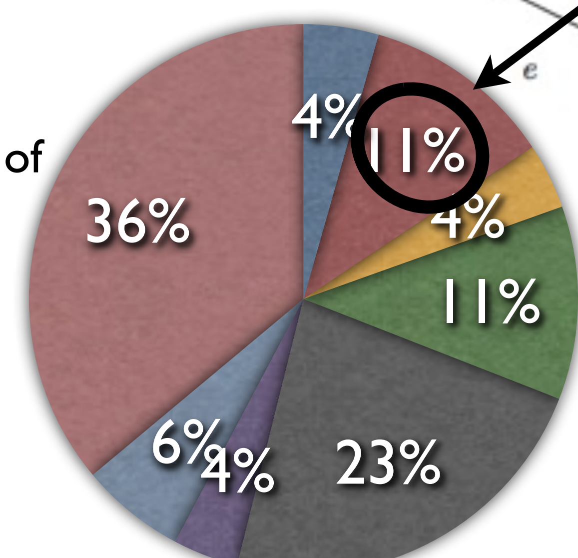



- **Cascade decay**
  - Higher cross section O(10pb)
  - Multilepton + high hadronic activities + MET




- **neutralino/chargino pair production**
  - Smaller cross section O(pb)
  - Multilepton + MET

Subprocess fraction of Low Mass Point 1 Cross section




*mSUGRA, Slepton co-NLSP, and RPV scenarios are considered*

# Theories

- **mSUGRA**
  - Unification at GUT scale (leaves 5 parameters)
  - SUSY breaking by hidden sector via gravity
  - Used as a benchmark in CMS
- **Slepton co-NLSP**
  - A subset of Gauge mediated SUSY breaking model
    - *Sets the weak and strong SUSY breaking scales separately*
  - NNLSPs (neutralino, chargino) decay to NLSPs (sleptons) & leptons
- **R-parity Violating SUSY**
  - Baryon number is conserved but Lepton number is violated (to be consistent with proton decay)
  - LSPs decay to leptons
    - *No dark matter candidate*

# Search Channels

- Require at least 3 good leptons
- Include at most 2 taus or tracks
- 24 channels

*tau = hadronic decaying tau*

- 4 or more leptons
  - *Ordered in #(muons) to avoid ambiguity*
    - 4e + 1m → 3e + 1m + X channel

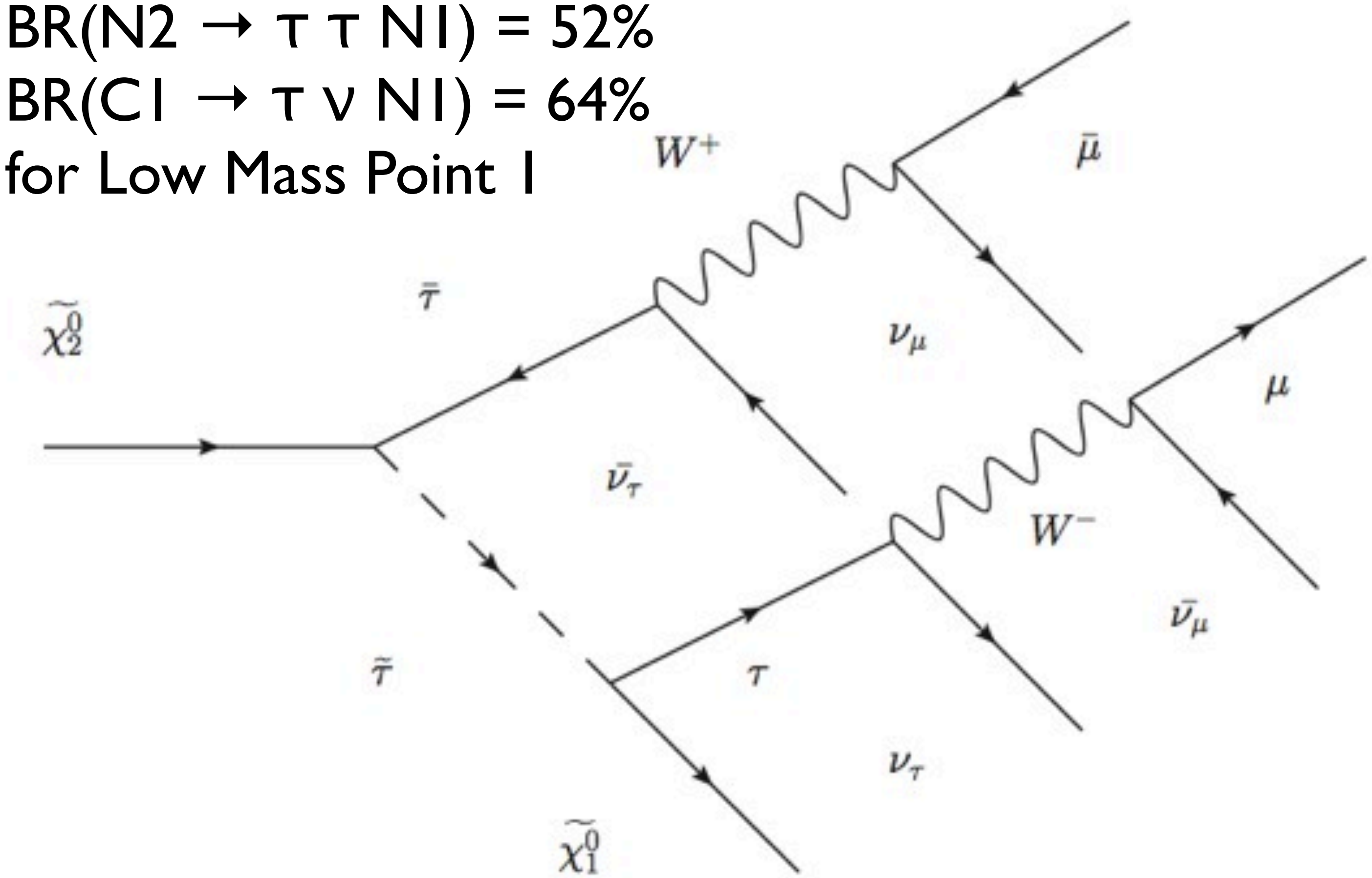
| same flavor trilepton | same flavor OS and LS | full flavor OS and LS modes | 4 or more leptons |
|---|---|---|---|
| eee, μμμ | eeμ, eeτ, μμe, μμτ | eμτ | eeee, eeeμ, eeμμ, eμμμ, μμμμ, μμμτ, μμττ, eμττ, eeττ, eeeτ, eeμτ, eμμτ |

*similar channels with tracks*

# Inclusion of Taus

- BR(N2→ττN1) and BR(C1→τνN1) can be higher than other lepton modes when tanβ is high
- Even if no enhancement, more events (signal and BG)

BR(N2 → τ τ N1) = 52%
BR(C1 → τ ν N1) = 64%
for Low Mass Point 1




- Taus decay to e/μ which become softer due to extra neutrinos

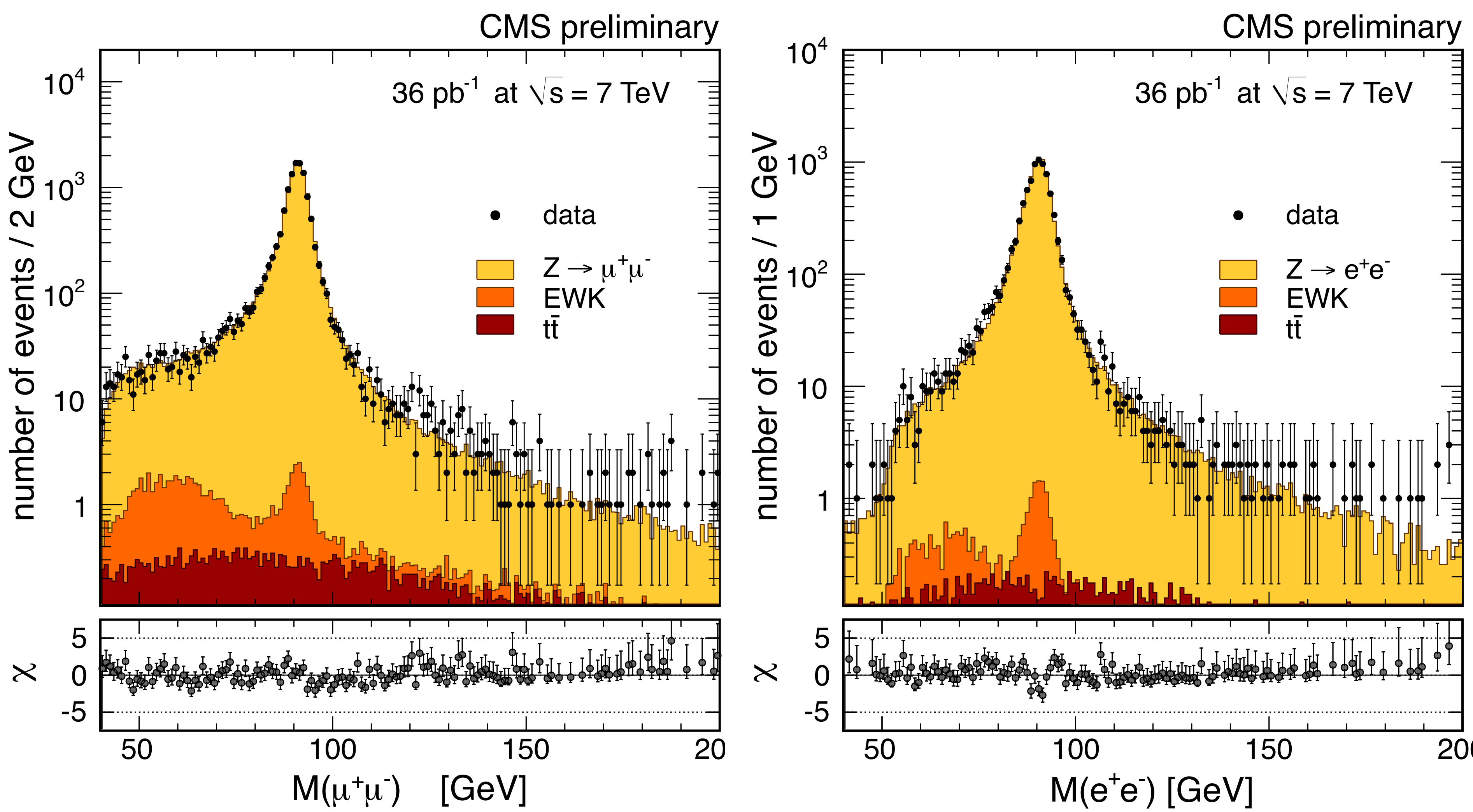
*BR(tau)*

| | |
|---|---|
| $\mu^- \bar{\nu}_\mu \nu_\tau$ | (17.36±0.05) % |
| $e^- \bar{\nu}_e \nu_\tau$ | (17.85±0.05) % |

# Muon & Electron Selection

*Using standard selection developed by Physics Object Groups*

- $p_{\mathrm{T}} \geq 8$ GeV/c
- $|\eta| \leq 2.1$
- $(TrackerIso + ECALIso + HCALIso)/p_{\mathrm{T}} < 0.15$




*EWK group*

# Tau & Track Selection

- **Using Shrinking Cone**
  - One of LPC Tau contributions
- **Using standard selection**

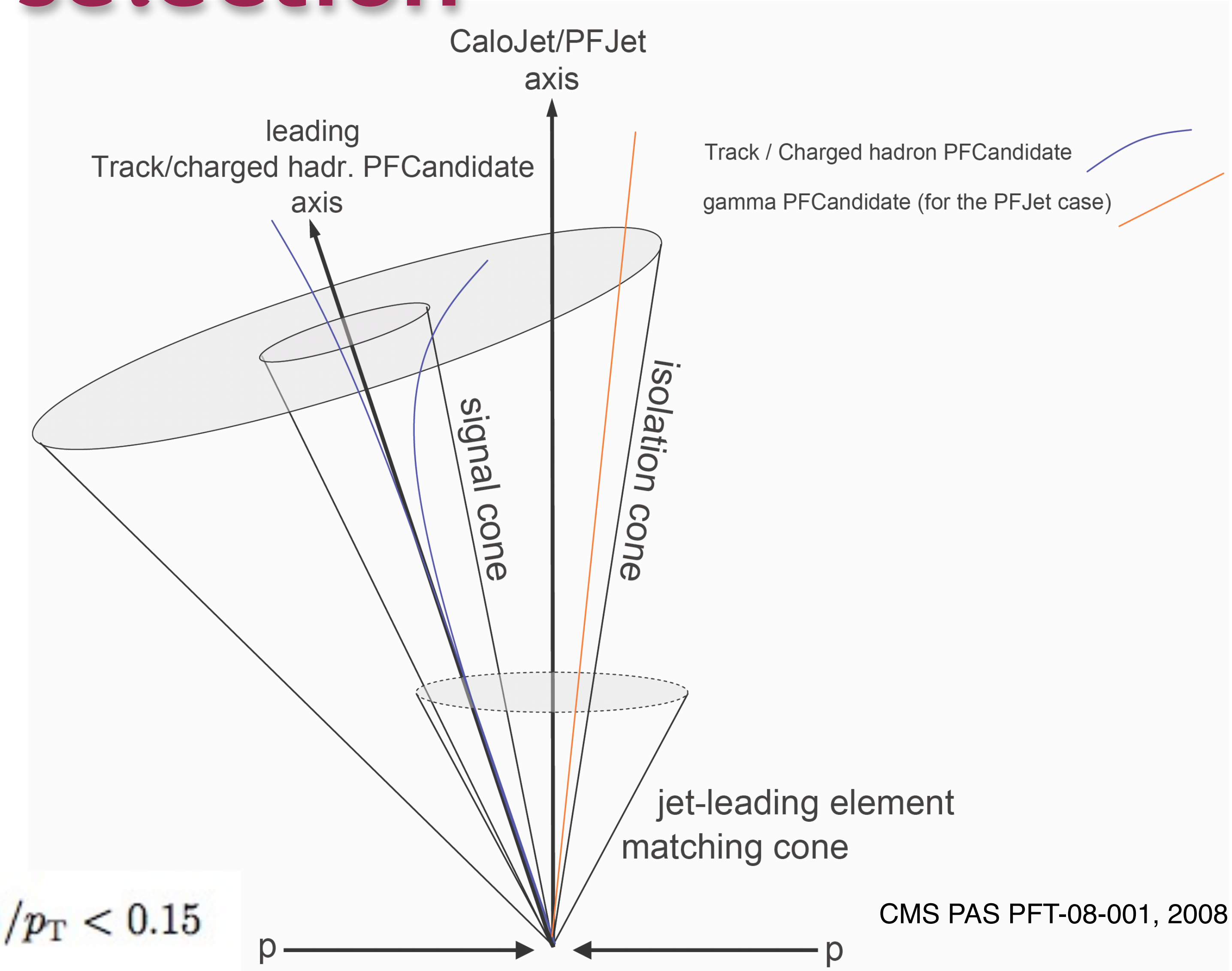
- $p_T \geq 8$ GeV/c
- $|\eta| \leq 2.1$

*Isolation requirements for taus*

- No track with $p_T > 1$ GeV/c
- No $\gamma$ with $E_T > 1.5$ GeV

*Isolation requirements for Tracks*

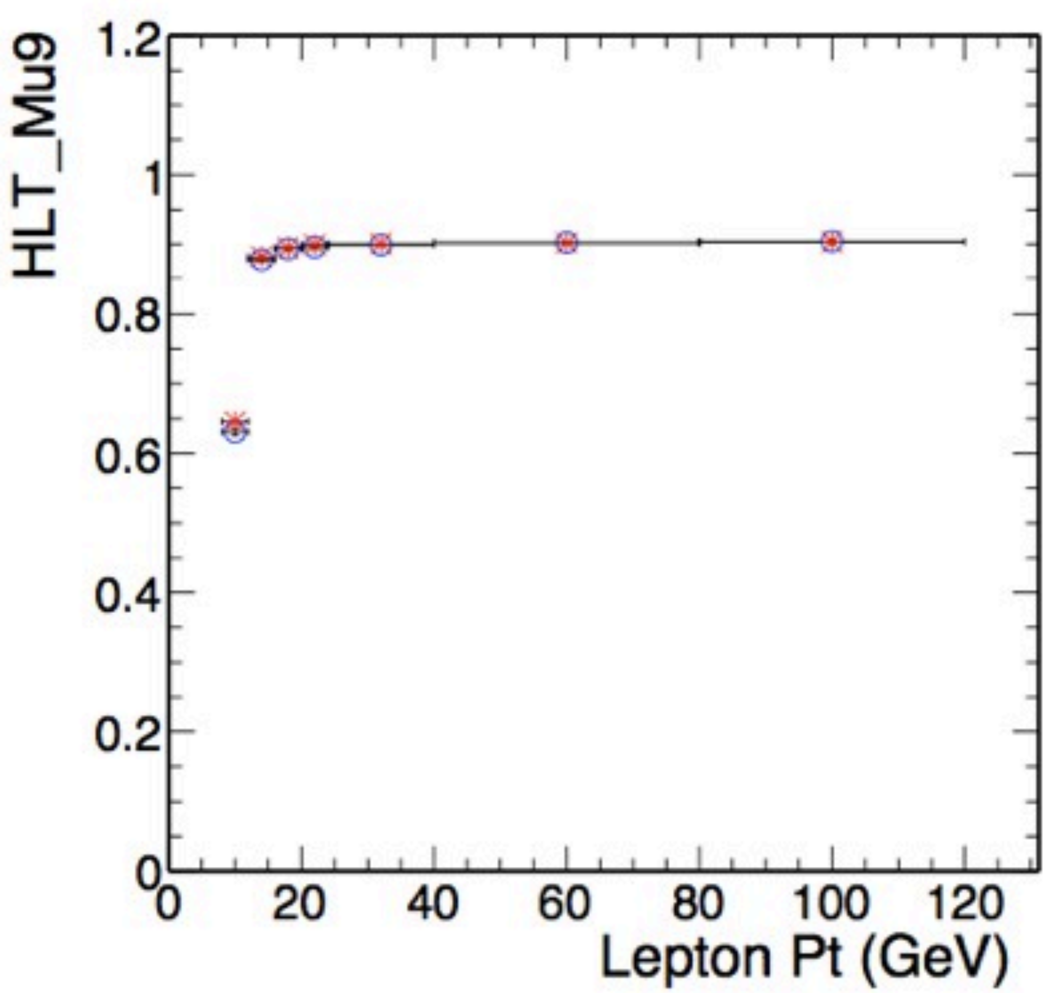
- $(TrackerIso + ECALIso + HCALIso)/p_T < 0.15$

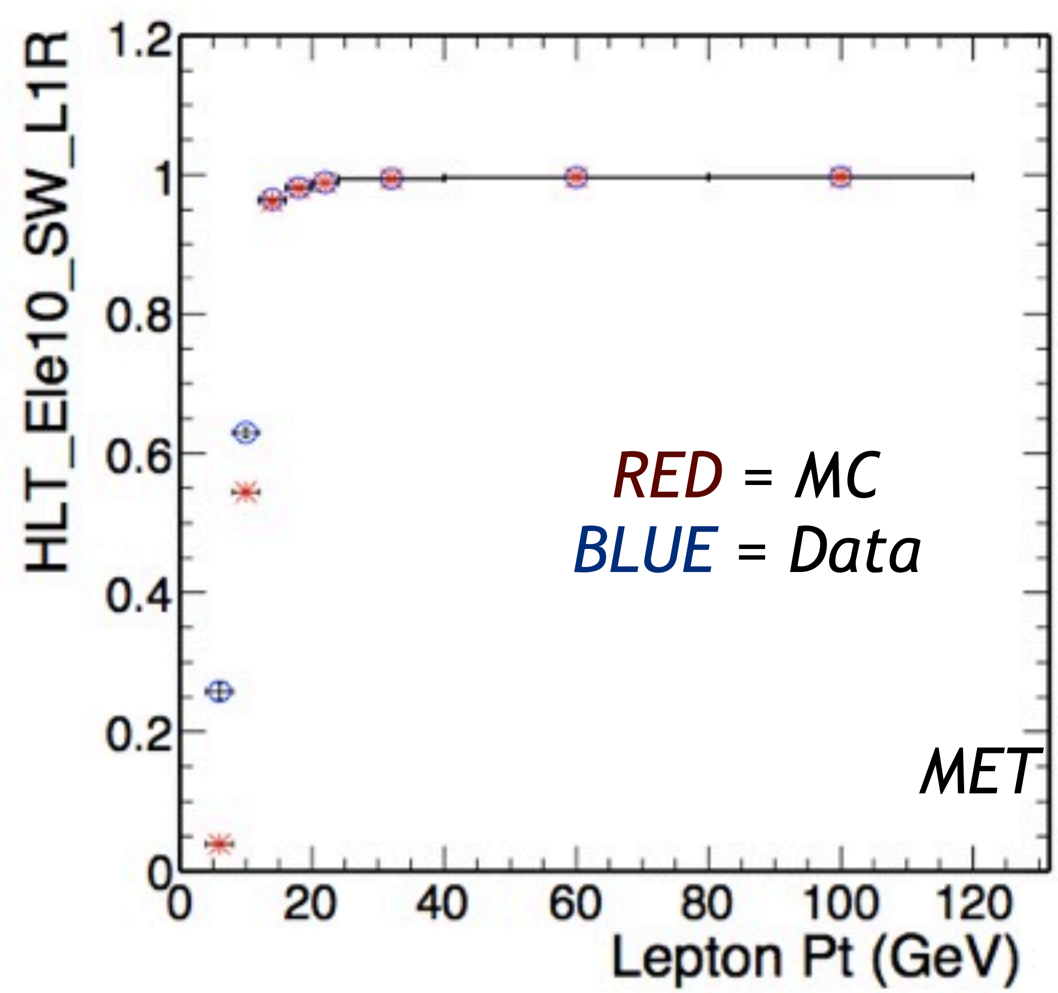



CMS PAS PFT-08-001, 2008

# Trigger

- *Trigger Strategy in 2010, L = 35pb$^{-1}$*
  - *Relies on many lepton paths (single, double, cross trigger)*



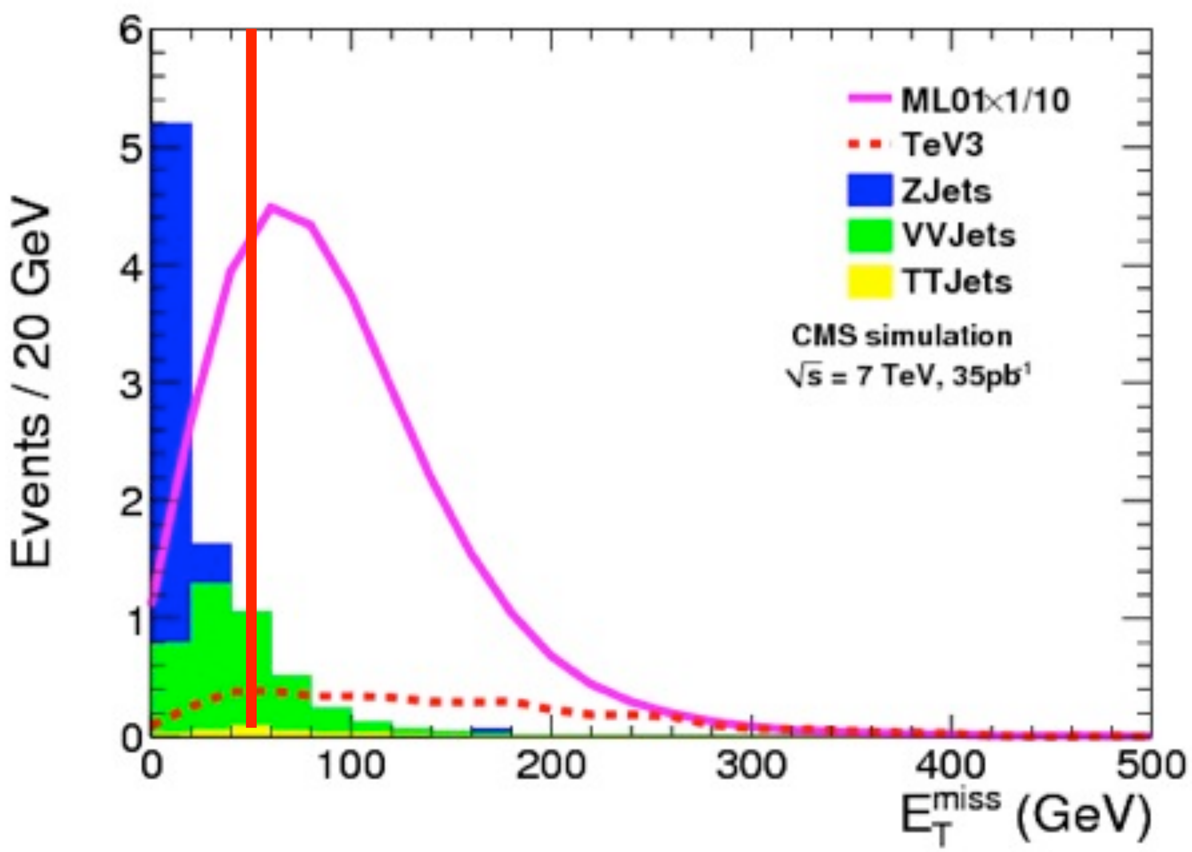



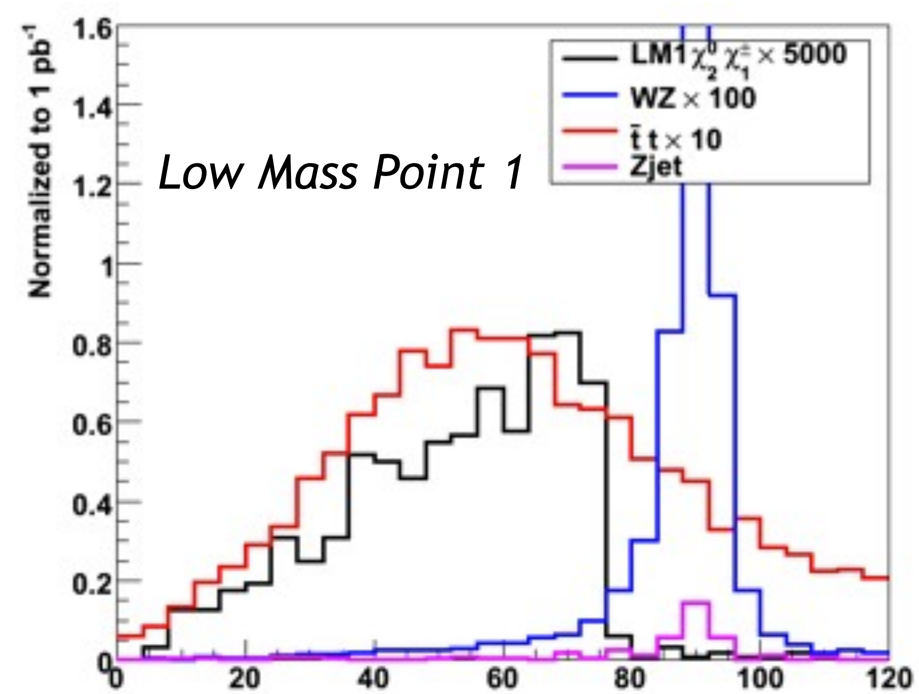

*MET sample*

- *By combining all trigger paths, ~100% trigger efficiency*
- *Uncertainty on Trigger Eff is negligible w.r.t. other ones*

# Event Selection (1)

- At least 3 isolated leptons
- At least 1 isolated lepton with $p_T$ > 17, 20 GeV for μ, e *for triggering purpose*
- Particle-flow MET greater than 50 GeV for OS (eeτ, eμτ, μμτ)
- Applying Z-mass veto may not be a good idea



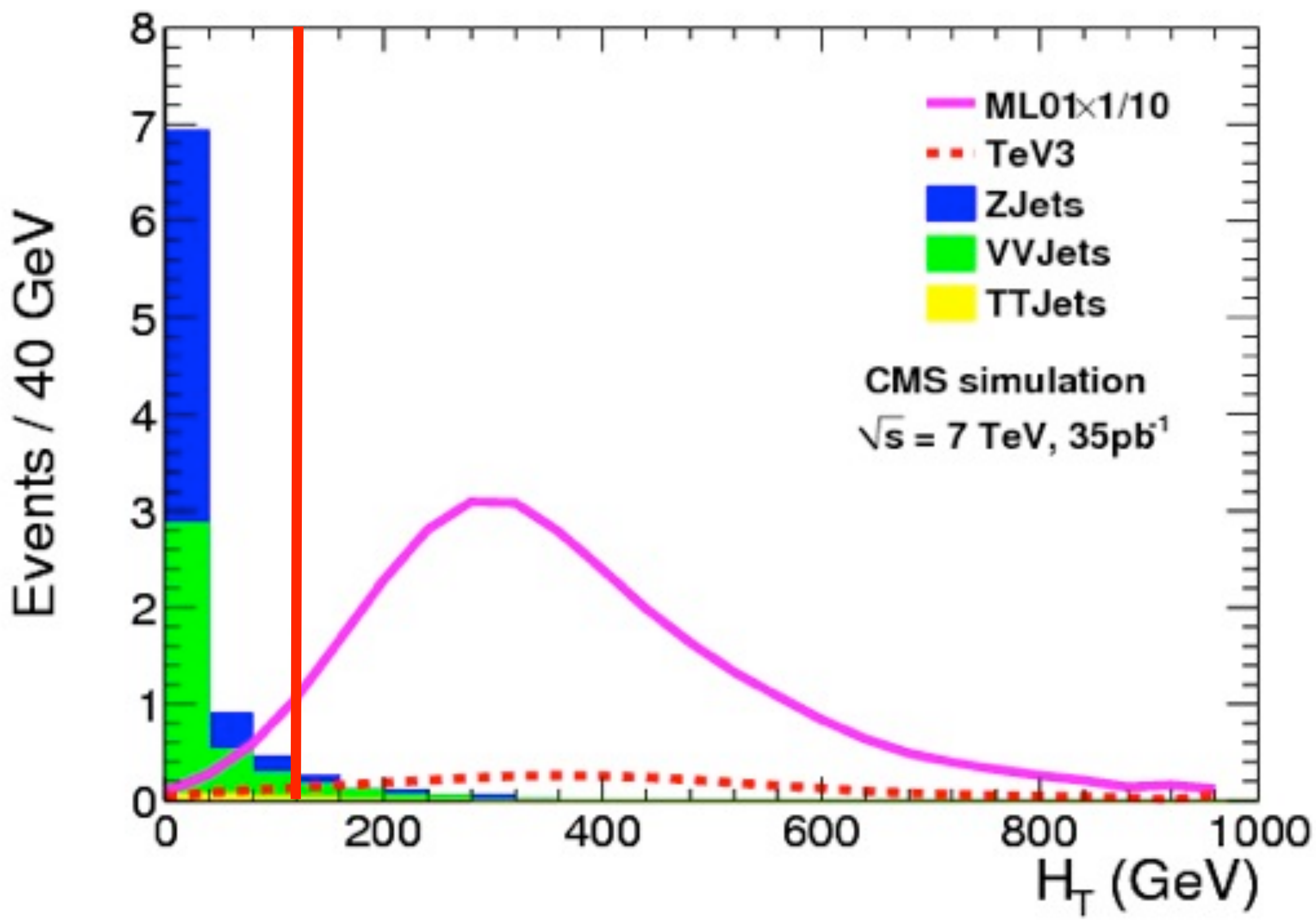




*Mass of dilepton from Neutralino*

$$M_{ll'}^{max} = \sqrt{4 \cdot E_l \cdot E_{l'}} = \sqrt{\frac{(m_{\tilde{l}}^2 - m_{\tilde{\chi}_1^0}^2) \cdot (m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}}^2)}{m_{\tilde{l}}^2}}$$

# Event Selection (2)

- **Jet $E_T$ scalar sum ($H_T$) greater than 200 GeV**




*Jet Selection for $H_T$*

*Standard Jet ID from JetMET group*

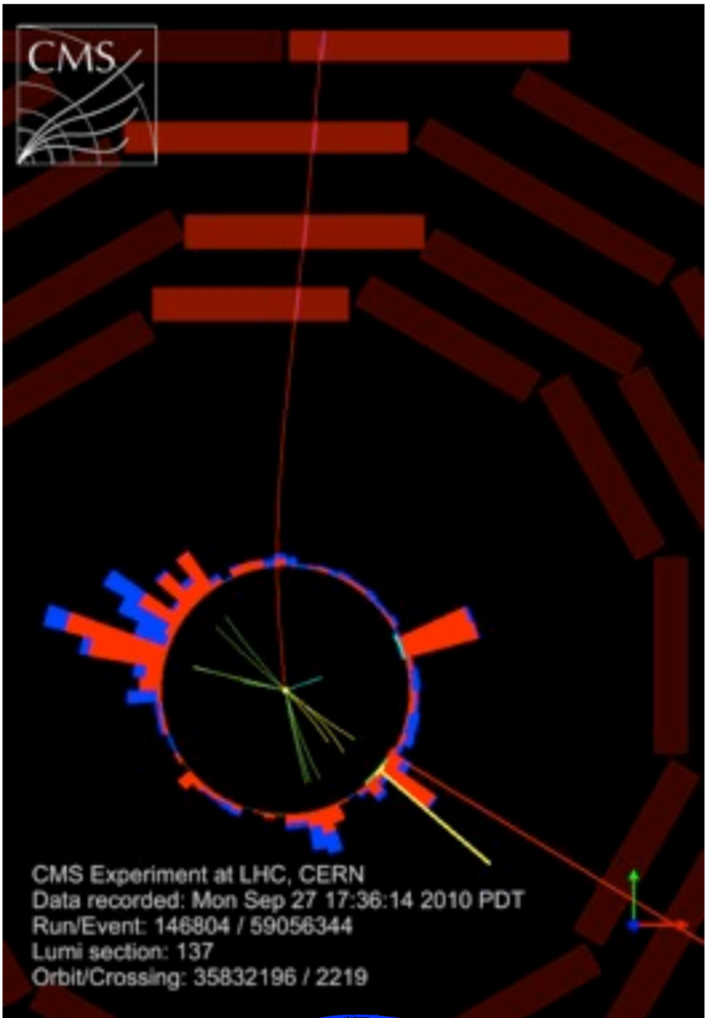
- $p_T \geq 30$ GeV/c
- $|\eta| \leq 2.5$
- Neutral hadron energy fraction $< 0.99$
- Neutral EM energy fraction $< 0.99$
- Charged EM energy fraction $< 0.99$

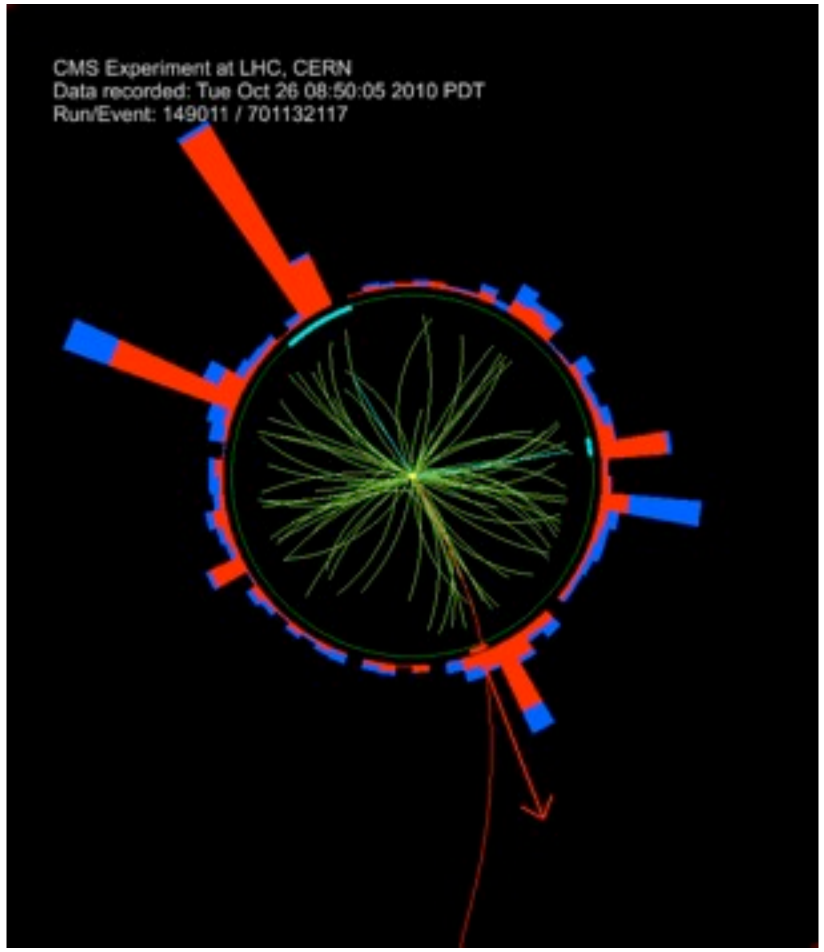
# Results

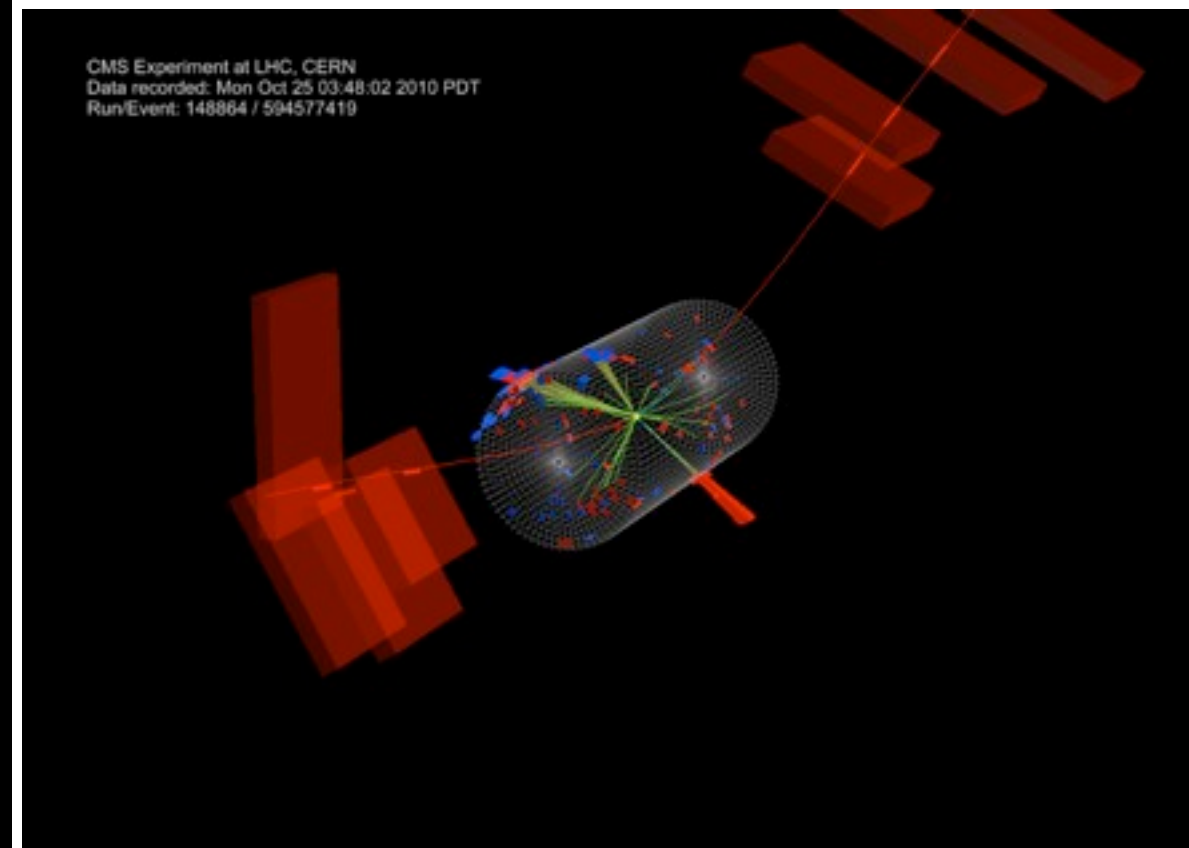
| | After Lepton ID Requirement | | | | | Inclusive | | Hadronic | | ML01 Signals | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Z$+jets | $t\bar{t}$ | $VV$+jets | $\Sigma$SM | Data | $\Sigma$SM | Data | $\Sigma$SM | Data | Incl. | Hadr. |
| Channel | 3-lepton channels | | | | | | | | | | |
| $ll(OS)e$ | 1.7 | 0.1 | 1.2 | $4.4 \pm 1.5$ | 6 | $0.1 \pm 0.1$ | 0 | $0.2 \pm 0.1$ | 1 | 121.4 | 141.5 |
| $ll(OS)\mu$ | 2.83 | 0.2 | 1.7 | $4.7 \pm 0.5$ | 6 | $0.10 \pm 0.1$ | 0 | $0.1 \pm 0.1$ | 0 | 123.6 | 120.8 |
| $ll(OS)T$ | 121.5 | 0.5 | 0.7 | $123 \pm 16$ | 127 | $0.4 \pm 0.1$ | 0 | – | – | 80.5 | – |
| $ll(OS)\tau$ | 476 | 2.7 | 3.9 | $484 \pm 77$ | 442 | – | – | $0.6 \pm 0.2$ | 1 | – | 68 |
| $ll'T$ | 0.72 | 0.5 | 0.2 | $1.7 \pm 0.7$ | 3 | $0.4 \pm 0.2$ | 2 | – | – | 18.6 | – |
| $ll'\tau$ | 4.7 | 2.9 | 0.6 | $11.2 \pm 2.5$ | 10 | – | – | $0.4 \pm 0.1$ | 1 | – | 12.3 |
| $ll(SS)l'$ | 0.13 | 0.1 | 0.0 | $0.2 \pm 0.1$ | 0 | $0.2 \pm 0.1$ | 0 | 0 | 0 | 2.8 | 2.8 |
| $ll(SS)T$ | 0.25 | 0.0 | 0.1 | $0.7 \pm 0.4$ | 3 | $0.1 \pm 0.1$ | 0 | – | – | 9.0 | – |
| $ll(SS)\tau$ | 1.4 | 0.0 | 0.1 | $3.0 \pm 1.1$ | 3 | – | – | $0.0 \pm 0.1$ | 0 | – | 6.9 |
| $\Sigma\ lll(T)$ | 127.1 | 1.4 | 3.8 | $135 \pm 16$ | 145 | $1.3 \pm 0.2$ | 2 | – | – | 355.9 | – |
| $\Sigma\ lll(\tau)$ | 486.8 | 6.0 | 7.5 | $507 \pm 77$ | 467 | – | – | $1.3 \pm 0.3$ | 3 | – | 349.5 |
| $lTT$ | 47.1 | 0.33 | 0.1 | $48 \pm 9$ | 30 | $0.4 \pm 0.1$ | 0 | – | – | 8.0 | – |
| Channel | 4-lepton channels | | | | | | | | | | |
| $llll$ | 0 | 0 | 0.2 | $0.2 \pm 0.1$ | 2 | 0 | 0 | 0 | 0 | 163.9 | 149.2 |
| $lllT$ | 0 | 0 | 0.1 | $0.1 \pm 0.1$ | 0 | 0 | 0 | – | – | 62.3 | – |
| $lll\tau$ | 0 | 0 | 0.1 | $0.1 \pm 0.1$ | 0 | – | – | 0 | 0 | – | 33.2 |
| $llTT$ | 0 | 0 | 0 | $0.0 \pm 0.1$ | 0 | 0 | 0 | – | – | 20.6 | – |
| $ll\tau\tau$ | 3.1 | 0.1 | 0.1 | $3.2 \pm 0.7$ | 5 | – | – | 0 | 0 | – | 16.8 |
| $\Sigma\ llll(T)$ | 0 | 0 | 0.3 | $0.3 \pm 0.1$ | 2 | 0 | 0 | – | – | 246.8 | – |
| $\Sigma\ llll(\tau)$ | 3.1 | 0.1 | 0.4 | $3.5 \pm 0.7$ | 5 | – | – | 0 | 0 | | 199.2 |

- 3 events found in 2010
- Similar Results with Taus and Tracks

# 3lepton Events



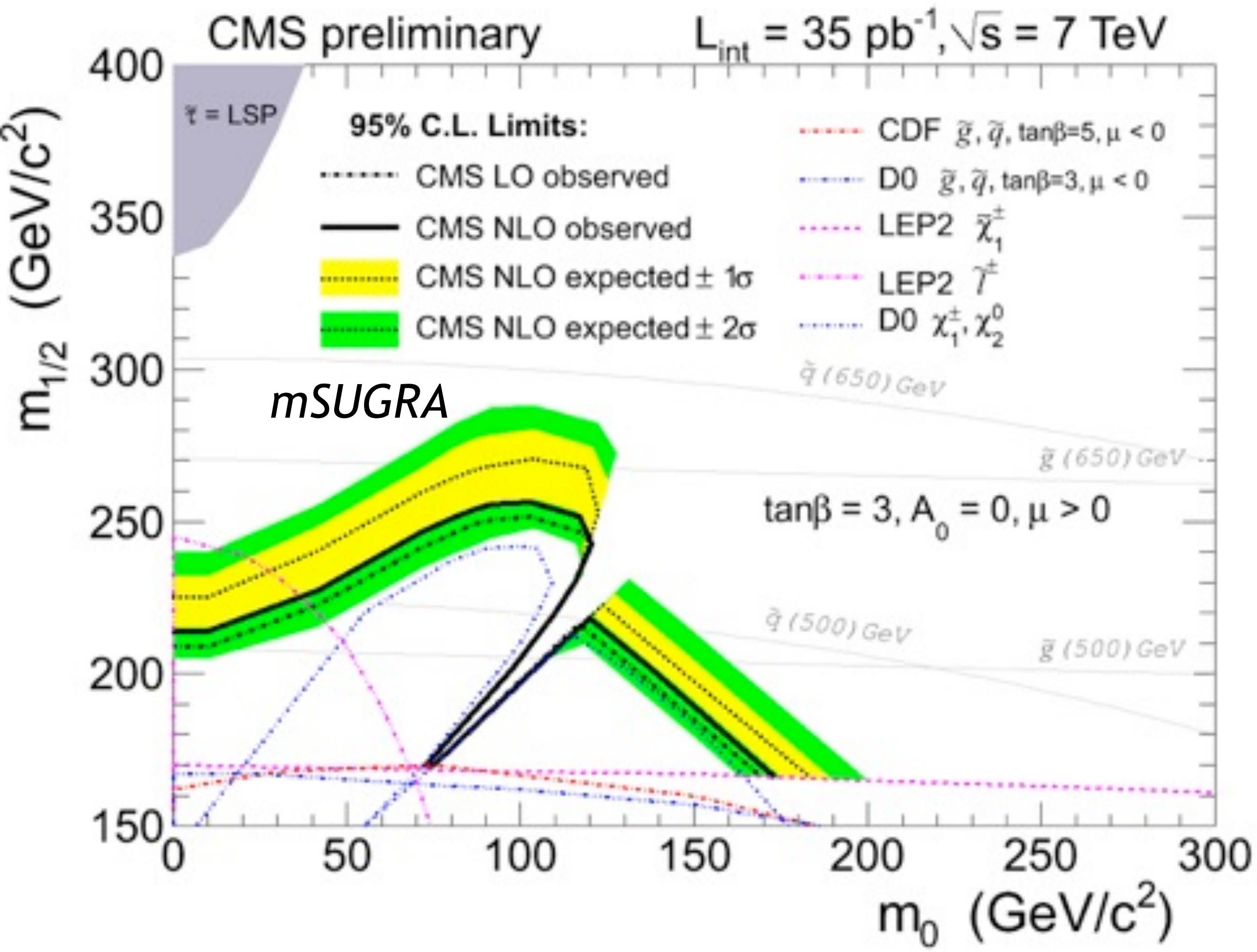



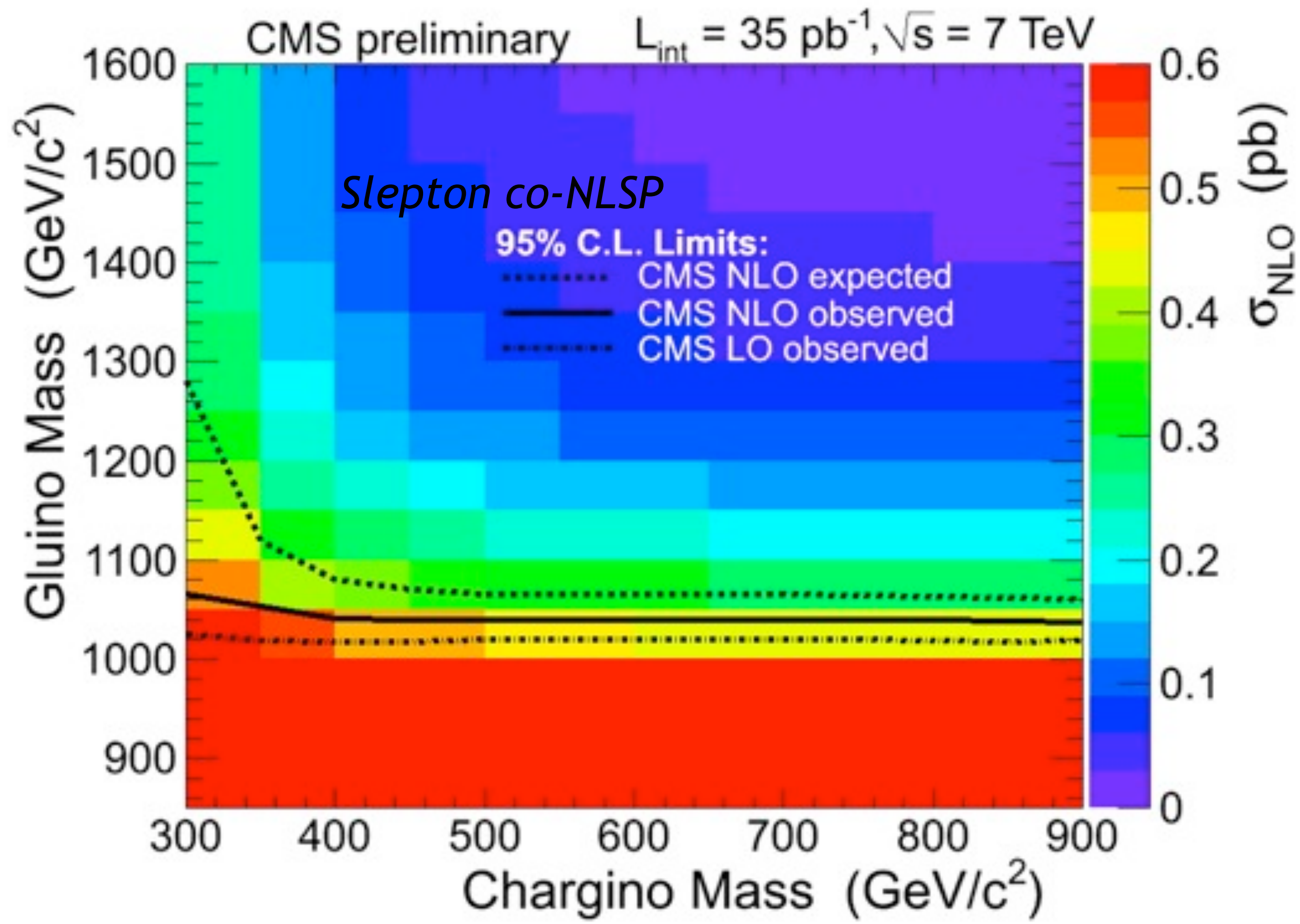

| Event Type | $e^+\mu^+\tau^+$ | | |
|---|---|---|---|
| Run # | 146804 | | |
| Event # | 59056344 | | |
| $H_T$ (GeV) | 279.9 | | |
| pfMET (GeV) | 129.0 | | |
| Lepton/Jet | $p_T$ or $E_T$ (GeV) | $\eta$ | $\phi$ |
| $e^+$ | 32.7 | -2.02 | 0.36 |
| $\mu^+$ | 16.7 | 0.57 | 1.69 |
| $\tau^+$(3-prong) | 31.6 | -0.91 | -0.70 |
| Jet 1 | 177.7 | 0.81 | 2.74 |
| Jet 2 | 53.2 | 0.81 | -1.37 |
| Jet 3 | 49.0 | 0.13 | 2.09 |

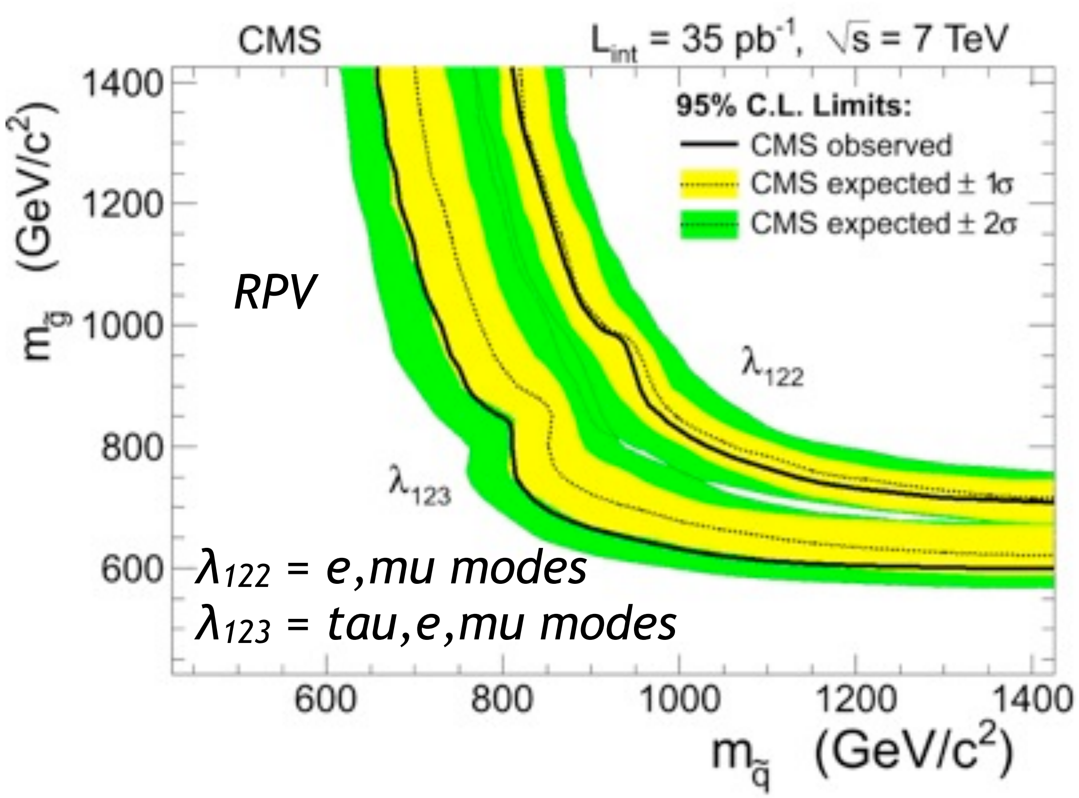
| Event Type | $e^+e^-\tau^+$ | | |
|---|---|---|---|
| Run # | 149011 | | |
| Event # | 701132117 | | |
| $H_T$ (GeV) | 384.3 | | |
| pfMET (GeV) | 79.5 | | |
| Lepton/Jet | $p_T$ or $E_T$ (GeV) | $\eta$ | $\phi$ |
| $e^+$ | 106.7 | -1.98 | 2.12 |
| $e^-$ | 29.5 | -0.73 | 0.13 |
| $\tau^+$(1-prong) | 13.1 | -1.61 | 0.95 |
| Jet 1 | 138.0 | -0.82 | 2.74 |
| Jet 2 | 107.3 | 0.68 | -1.09 |
| Jet 3 | 84.5 | 0.21 | -0.18 |
| Jet 4 | 54.4 | -1.46 | -2.80 |

| Event Type | $\mu^+\mu^-e^+$ | | |
|---|---|---|---|
| Run # | 148864 | | |
| Event # | 594577419 | | |
| $H_T$ (GeV) | 246.4 | | |
| pfMET (GeV) | 39.1 | | |
| Lepton/Jet | $p_T$ or $E_T$ (GeV) | $\eta$ | $\phi$ |
| $\mu^-$ | 21.8 | 0.18 | -0.43 |
| $\mu^+$ | 14.5 | 0.68 | 2.34 |
| $e^+$ | 129.5 | 0.87 | -2.00 |
| Jet 1 | 172.0 | -1.34 | 0.83 |
| Jet 2 | 74.4 | -1.13 | 1.62 |

# Exclusion Curves




- *mSUGRA: Extended Tevatron+LEP limits*
- *RPV: Extended Tevatron limits*
- *Slepton co-LSP: Excluded Gluino mass below 1040 GeV*

# Conclusion

- LHC and CMS working very well
- 2010 data sample provided excellent physics analysis startup
- 2010 Multilepton analysis demonstrated lepton performance robust to low $p_T$, and set limits on various models
- 2011 data sample already 30 times that of 2010 with more to come
- Next round of multilepton analysis: triggers and advanced tau ID prepared
- Hope to find out (soon) what nature has been hiding!

*Backup Slides*

# Systematic Uncertainties

- Jet Energy Scale
  - ~5% for signal
  - ~30% for ttbar+jets
- Cross section ~ 10%
- Lumi = 11%
  - later became smaller, but not significant
- MC Statistics
  - ~10%
- Ele & Mu
  - ID, 1-1.5%
  - Isolation, 1.5%
- Tau ID = 30%
- Trigger~5%

- *Total Uncertainty:*
  - *-Signal*
    - *e,mu channels ~20%*
    - *tau channels ~30%*
  - *-BG*
    - *e,mu channels ~30%*
    - *tau channels ~40%*