RUTGERS

Search for Leptonic R-Parity Violation with Three or More Leptons

CMS @ LHC 2010

Sanjay Arora
Rutgers University

Outline

- Theoretical motivation.
- Three or more lepton analysis.
- Background estimation.
- Results.
- Summary / plans.

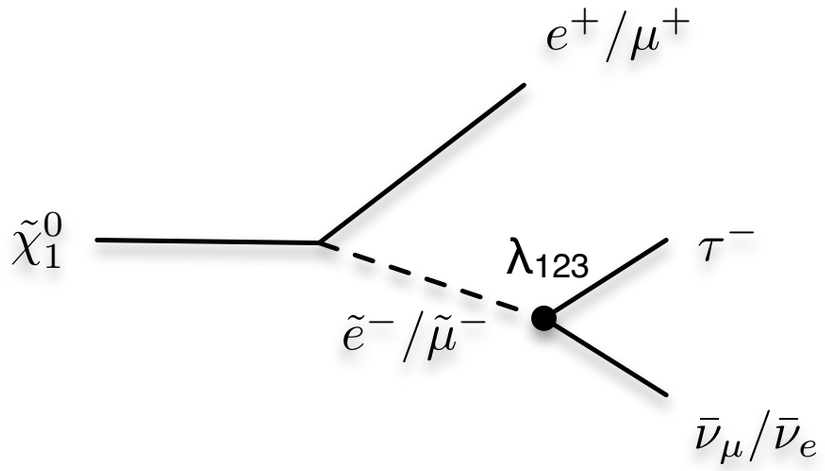
Leptonic R-parity Violation

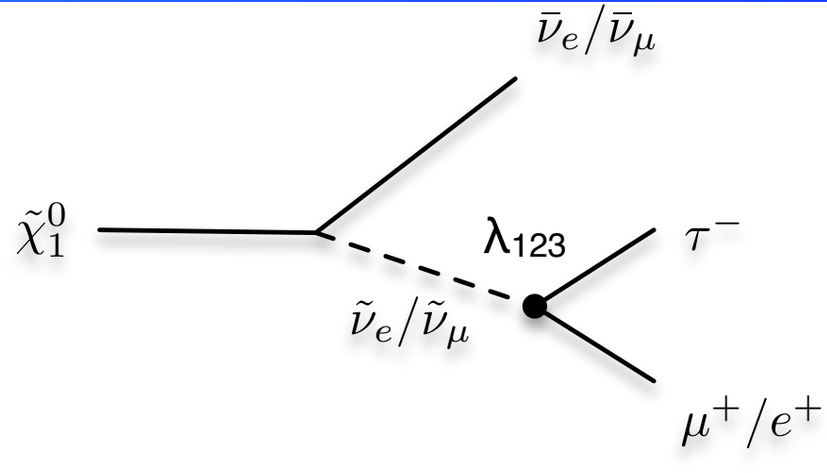
(special case of the more general picture)

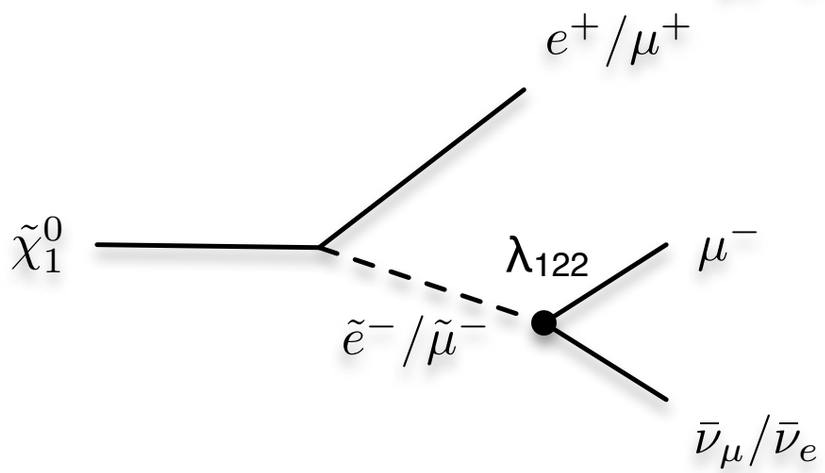
- R-parity = $(-1)^{2S+3B+L}$
- For Standard Model particles, R = +1.
- For SUSY particles, R = -1.
- Violation of the R-parity implies decay of the LSP to Standard Model particles.

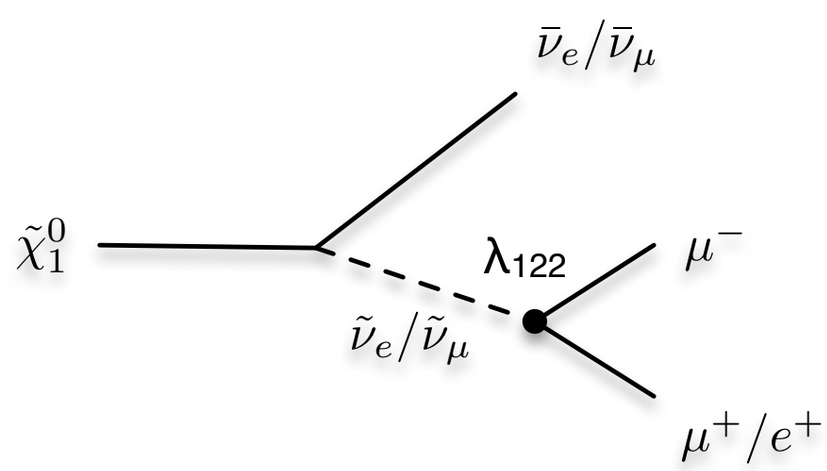
L-RPV Signature

(Neutralino decays)









- Signature is at least 4 leptons (from 2 neutralinos)!
  - Neutralinos (LSP candidates) are decaying but MET will come from neutrinos.
- We focus the search on 2 λ_{ijk} couplings. Setting them separately $\neq 0$
  - λ_{122} - signature 2μ and 2(e/μ)
  - λ_{123} - signature 2τ and 2(e/μ)

Key Features of the Method

- Multi-channel search for new physics with a signature of three or more leptons in the final state based on data collected by CMS in the LHC 2010 run (35 pb^{-1}).

- Categorize the events into exclusive search channels and, using both Monte Carlo and data driven methods, estimate the backgrounds for each channel.

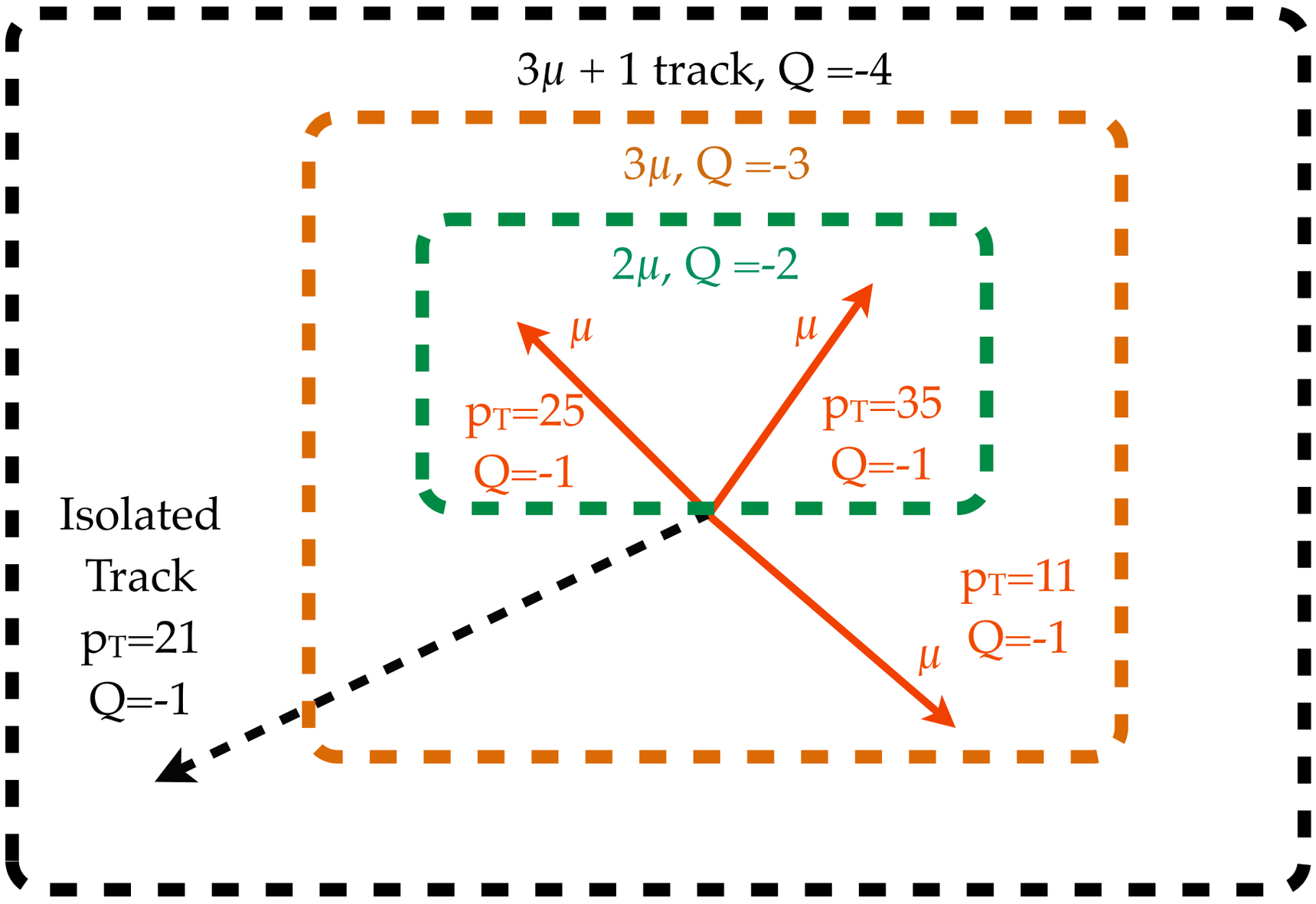
- Organize the channels in a hierarchical order that is in order of increasing background, i.e. channels with least background (and most signal) go first.

Key Features of the Method

- Each event assigned to one and only one channel
  - Otherwise the combining individual channels will be too difficult.
  - Method was first developed for CDF trileptons analysis.

- Example:
  - 2μ SS
    vs
  - 3μ SS
    vs
  - 3μ + 1T

- Put it in 3μ +1T category as it has the best S/B



Key Features of the Method

- $N_{leptons} > 4$
- $N_{leptons} = 4$
  - $Q = 4$ (exotic^2)
  - $Q = 2$ (exotic)
  - $Q = 0$
    - add Z veto and MET bins

- Other channels:
  - $N_{bodies} = N_{leptons}(3) + N_{tracks}(1)$
  - $N_{bodies} = N_{leptons}(3) + N_{tracks}(2)$
  - $N_{bodies} = N_{leptons}(3)$
  - $N_{bodies} = N_{leptons}(2) + N_{tracks}(1)$
  - $N_{bodies} = N_{leptons}(1) + N_{tracks}(2)$

Q - Total Charge

Key Features of the Method

Muon/Electron/Tau Selection Criteria

Muons:

- GlobalPromptTight + Tracker
- pT>8 GeV, |eta|<2.1
- |dxy(BS)|<0.02 cm
- |dz(vertex)|< 1 cm
- N tracker hits > 10
- Relative Isolation < 0.15

Standard CMS muon selection

Taus:

- **We use isolated tracks as a tau proxy (extra 12% of tau decays)**
- Same isolation and tracker cuts as muon
- Must be ΔR>0.1 from selected muons and electrons

Electrons:

- WP90 based selection
  - HoE<0.12 B (0.05 E)
  - |σIηIη|<0.01 B (0.03 E)
  - |Δφ|<0.8 B (0.7 E)
  - |Δη|<0.007 B (no cut E)
  - N missing inner hits ≤ 1
  - Conversion distance > 0.02
  - cot(θ) >0.02

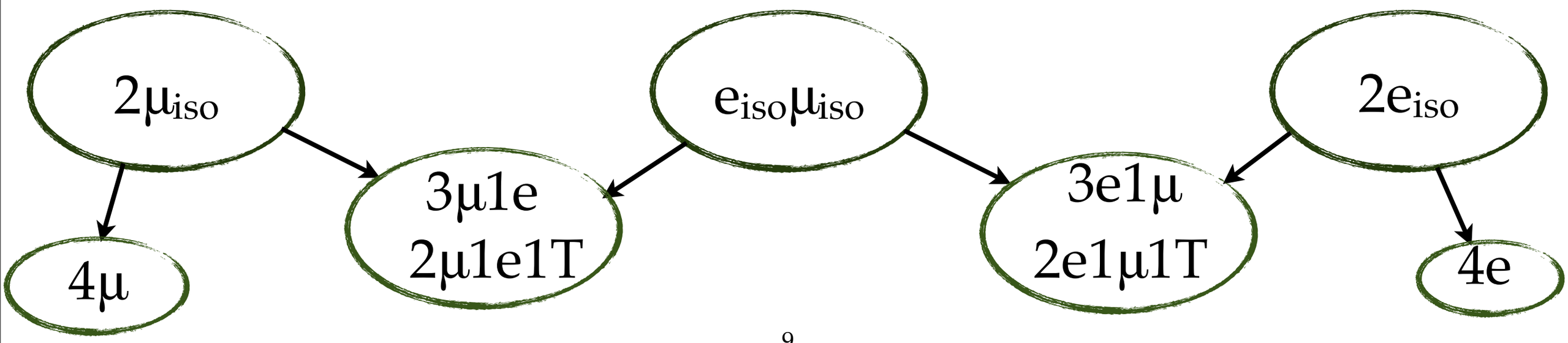
Standard CMS electron selection

- pT > 8 GeV
- |η|<2.1
- ΔR>0.1 from selected muons
- (Max(Eiso-X,0.0)+Hiso+Tiso)/ pT<0.15

  X is 1 GeV in Barrel and 0 GeV in Endcap

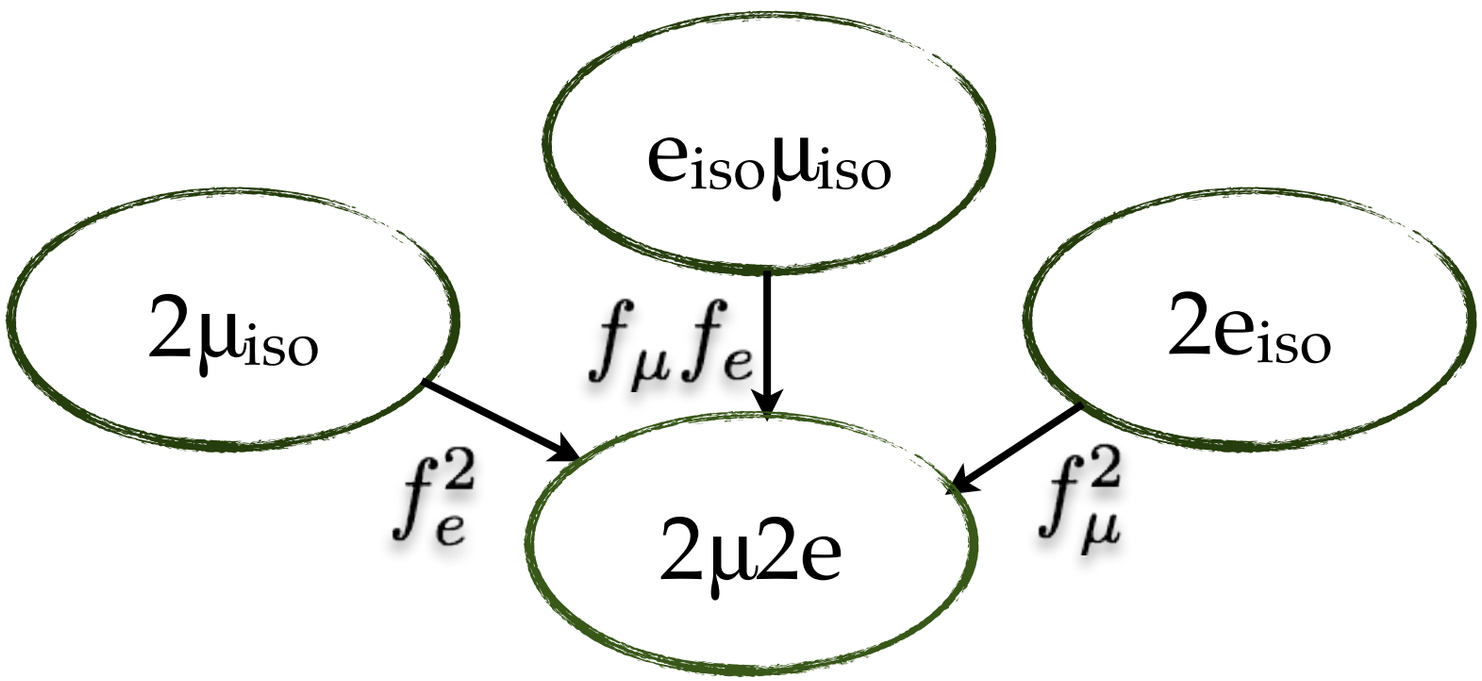
Background Estimation Using Data

- Use MC for TTbar, FSR, WZ, and ZZ.
- For everything else use di-Leptons samples.
  - Count "fakeable object" in dileptons to predict 2 lepton + 2 fakes.



Background Estimation Using Data

- To predict isolated lepton (track) background
  - Start with di-Lepton samples.
  - Count the number of 2 iso-lepton + 1 iso-track (side-band track) events
  - Multiply by conversion coefficient to predict 2 leptons + 1 fake background
  - Count the number of 2 iso-lepton + 2 iso-track (side-band track) events
  - Twice multiply by conversion coefficient to predict 2 leptons + 2 fake background



Background Estimation for Leptons. Isolated Tracks as Fakeable Objects (FO)

$$N^{Iso}_{lepton} = f_{lepton} \times N^{Iso}_{Track}$$

- Higher statistics in comparison to loose e or μ
  - Isolation properties of tracks similar to e or μ

Measure in dilepton sample. Compare to QCD

Measure in Jet-enriched sample parameterized of jet flavor ratio

$$f_\mu = \frac{N^{Iso}_\mu}{N^{Iso}_T} = \frac{N_\mu}{N_T} \times \frac{\epsilon^\mu_{Iso}}{\epsilon^T_{Iso}}$$

$$f_\mu = 0.022 \pm 0.006$$

$$f_e = 0.016^{+0.002}_{-0.003}$$

Background Estimation for Tracks.
Side Band Method (relative isolation)

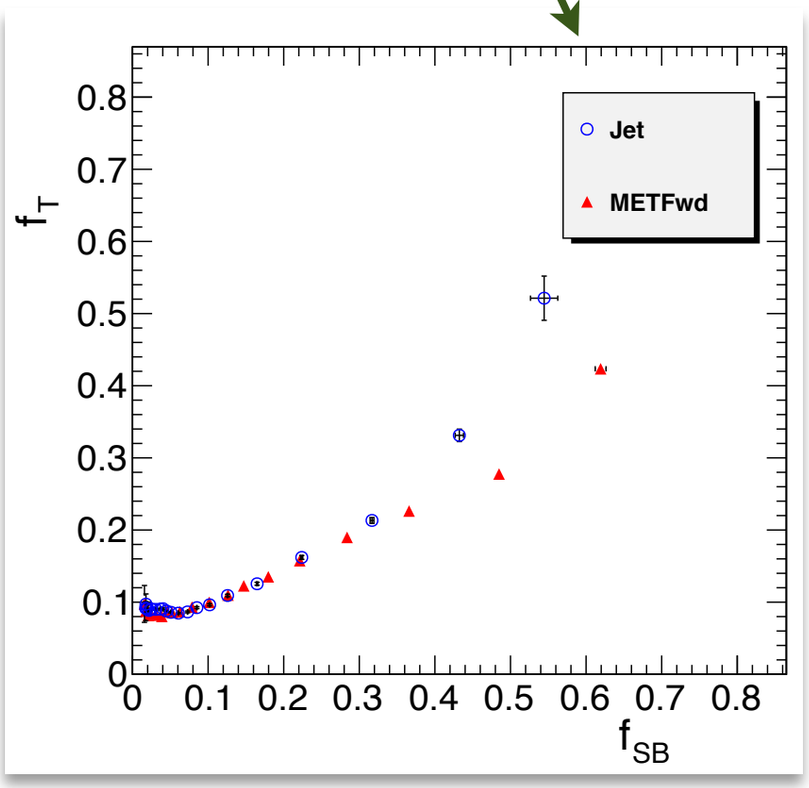
$$N^{iso}_{Track} = f_T(f_{SB}) \times N^{SB}_{Track}$$

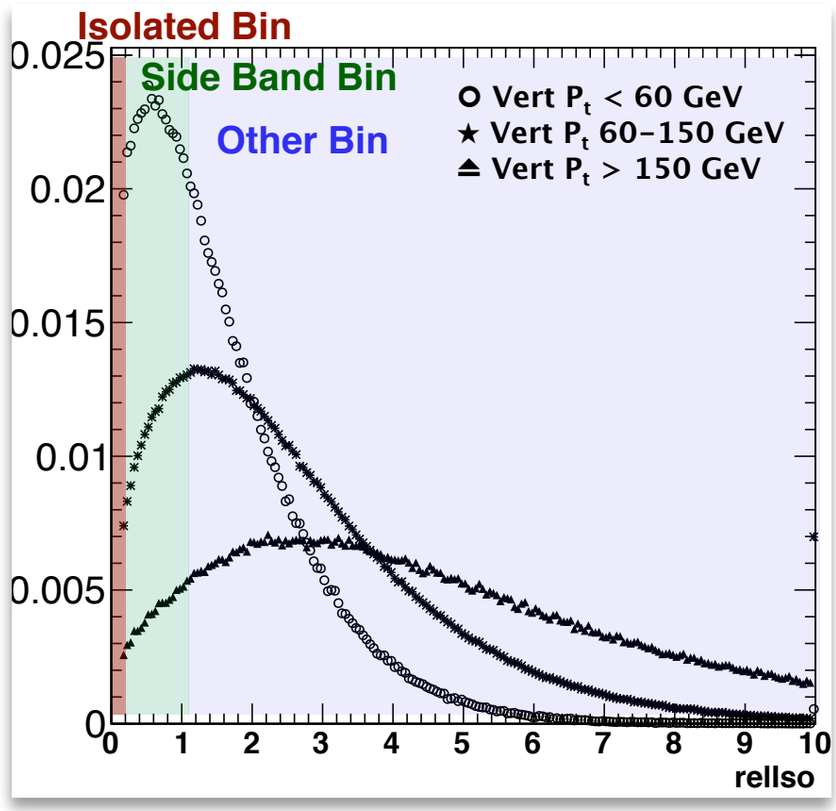
Measure in di-lepton sample.

f_T = conversion factor between medium-isolated fake taus and highly-isolated taus

f_{SB} = measure of jet activity (low for high jet activity)

$$f_{SB} = \frac{N^{SB}_{Track}}{N^{noniso}_{Track}}$$





Results: 35 pb^{-1} 2010 Data
(exclusive channels)

- Combining all background estimation from data and from MC into 1 table
- Channels prioritized by S/B ratios.
  - MET>50 GeV and/or Z veto (10GeV < m_{ll} < 75GeV, 105 GeV < m_{ll}) over low MET and Zs.

Bodies (event cut)
exclusive Final State
>4
4 ($\|Q\| = 4$)
4 (MET+ZV)
4 (MET)
4 (ZV+low MET)
4 (on Z + low MET)
3 ($\|Q\| = 3$ or SSSF)
3 (MET+ZV)
3 (MET+onZ)
3 (low MET+ZV)
3 (low MET+onZ)
Totals
Totals 4L
Totals 3L

Results: 35 pb^{-1} 2010 Data
(exclusive channels)

- Combining all background estimation from data and from MC into 1 table
- Channels prioritized by S/B ratios.
  - MET>50 GeV and/or Z veto (10GeV < m_{ll} < 75GeV, 105 GeV < m_{ll}) over low MET and Zs.

Bodies (event cut)	0T	1T	2T
exclusive Final State			
>4			
4 ($\|Q\| = 4$)			
4 (MET+ZV)			
4 (MET)			
4 (ZV+low MET)			
4 (on Z + low MET)			
3 ($\|Q\| = 3$ or SSSF)			
3 (MET+ZV)			
3 (MET+onZ)			
3 (low MET+ZV)			
3 (low MET+onZ)			
Totals			
Totals 4L			
Totals 3L			

- Channels with 0 isolated track over events with 1 or 2 tracks.

Results: 35 pb^{-1} 2010 Data
(expected background)

- Little or no background events expected in the 4 or more lepton channels.
  - 0.2 in 4 lepton on Z with low missing E_T channel due to ZZ
- Low background expected in most 3 leptons + 1T channels

Bodies (event cut)	0T	1T	2T
exclusive Final State	exp B	exp B	exp B
>4	0 ± 0	0 ± 0	0 ± 0
4 ($\|Q\| = 4$)	0 ± 0	0 ± 0.07	0 ± 0.05
4 (MET+ZV)	0 ± 0	0 ± 0	0 ± 0
4 (MET)	0 ± 0	0 ± 0	0 ± 0
4 (ZV+low MET)	0 ± 0	0.01 ± 0.06	0.07 ± 0.02
4 (on Z + low MET)	0.21 ± 0.02	0.06 ± 0.08	0 ± 0.06
3 ($\|Q\| = 3$ or SSSF)	0.25 ± 0.1	0.82 ± 0.38	6.45 ± 1.43
3 (MET+ZV)	0.2 ± 0.07	0.35 ± 0.13	–
3 (MET+onZ)	0.95 ± 0.13	0.79 ± 0.19	0.36 ± 0.1
3 (low MET+ZV)	1.63 ± 0.6	25.41 ± 5.13	–
3 (low MET+onZ)	6.22 ± 2.1	98.73 ± 20.53	40.87 ± 9.13
Totals	9.46 ± 2.19	126.17 ± 21.17	47.75 ± 9.24
Totals 4L	0.21 ± 0.02	0.07 ± 0.122	0.07 ± 0.08
Totals 3L	9.25 ± 2.19	126.1 ± 21.17	47.68 ± 9.24

- High background in 3 lepton channels with low MET.
  - Use to check the background prediction.

Results: 35 pb^{-1} 2010 Data

(observed data)

Expected 0.2 background events, observed 2

- Does not affect our sensitivity because it is not much of a signal channel

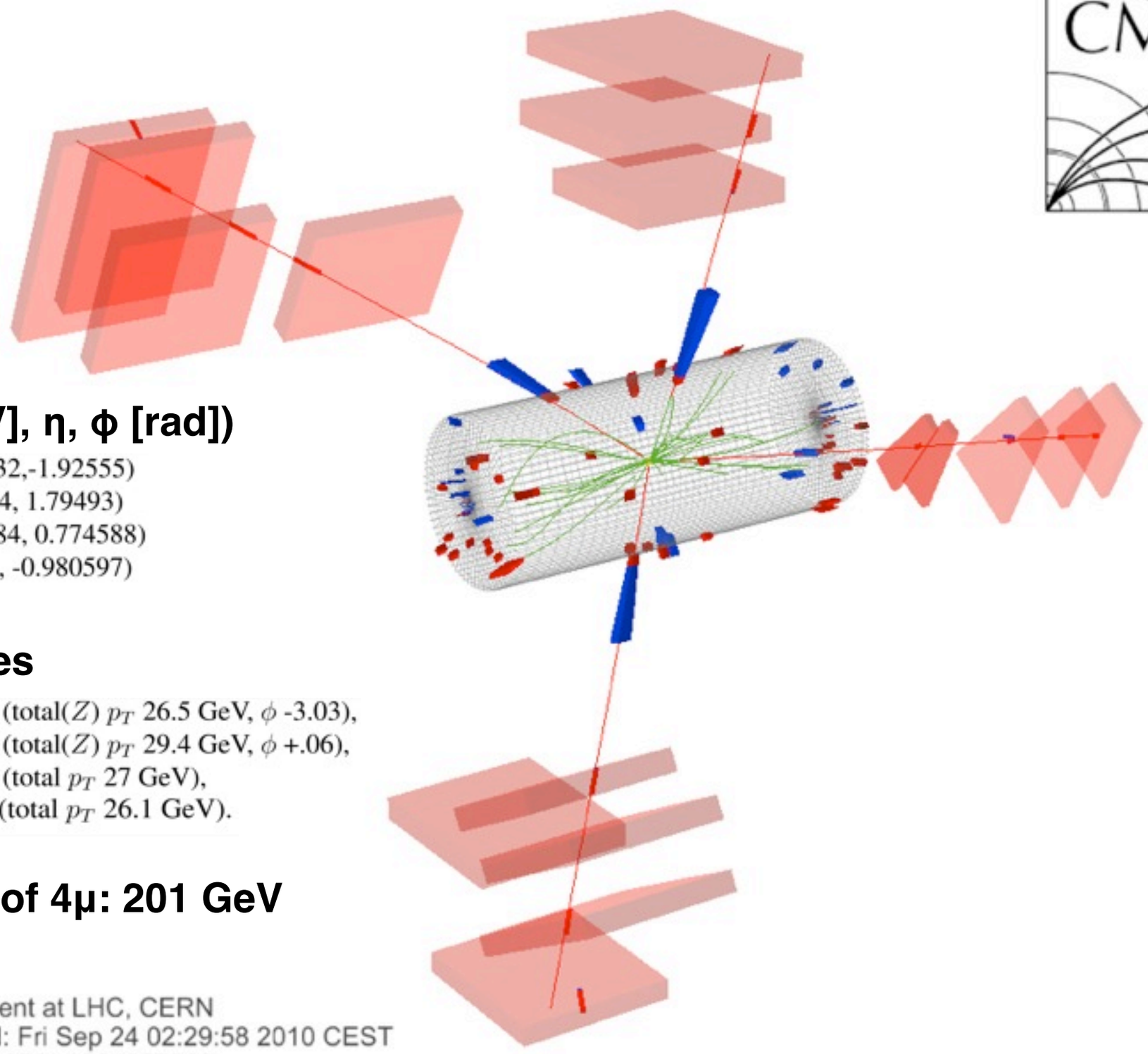
Bodies (event cut)	0T		1T		2T	
exclusive Final State	obs	exp B	obs	exp B	obs	exp B
>4	0	0 ± 0	0	0 ± 0	0	0 ± 0
4 ($\|Q\| = 4$)	0	0 ± 0	0	0 ± 0.07	0	0 ± 0.05
4 (MET+ZV)	0	0 ± 0	0	0 ± 0	0	0 ± 0
4 (MET)	0	0 ± 0	0	0 ± 0	0	0 ± 0
4 (ZV+low MET)	0	0 ± 0	0	0.01 ± 0.06	0	0.07 ± 0.02
4 (on Z + low MET)	2	0.21 ± 0.02	0	0.06 ± 0.08	0	0 ± 0.06
3 ($\|Q\| = 3$ or SSSF)	0	0.25 ± 0.1	3	0.82 ± 0.38	4	6.45 ± 1.43
3 (MET+ZV)	0	0.2 ± 0.07	0	0.35 ± 0.13	–	–
3 (MET+onZ)	3	0.95 ± 0.13	2	0.79 ± 0.19	0	0.36 ± 0.1
3 (low MET+ZV)	3	1.63 ± 0.6	32	25.41 ± 5.13	–	–
3 (low MET+onZ)	6	6.22 ± 2.1	96	98.73 ± 20.53	26	40.87 ± 9.13
Totals	14	9.46 ± 2.19	133	126.17 ± 21.17	30	47.75 ± 9.24
Totals 4L	2	0.21 ± 0.02	0	0.07 ± 0.122	0	0.07 ± 0.08
Totals 3L	12	9.25 ± 2.19	133	126.1 ± 21.17	30	47.68 ± 9.24

Expected 1 background event, observed 3

- Also does not affect our sensitivity

Background prediction in good agreement with observed data

4 lepton event (1) (ZZ)



Muons (p_T [GeV], η, ϕ [rad])

μ_0^-(48.1422, -0.412532,-1.92555)
μ_1^+(43.4421, 0.204654, 1.79493)
μ_2^+(25.8769, -0.782084, 0.774588)
μ_3^-(19.5646, 2.01112, -0.980597)

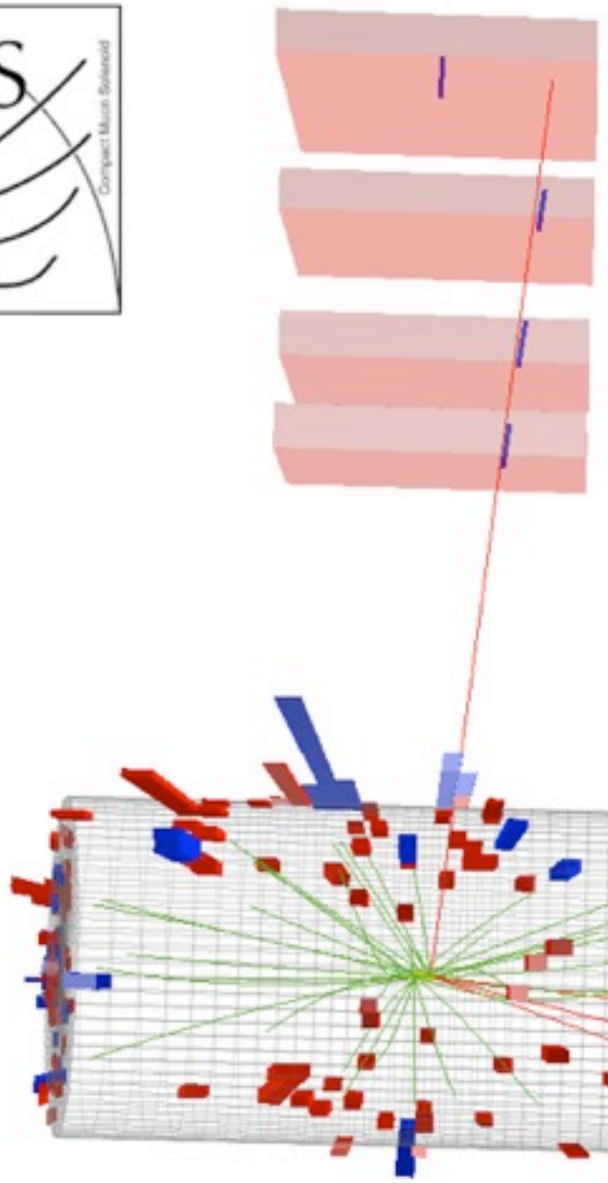
Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

CMS Experiment at LHC, CERN
Data recorded: Fri Sep 24 02:29:58 2010 CEST
Run/Event: 146511 / 504867308

4 lepton event (2)

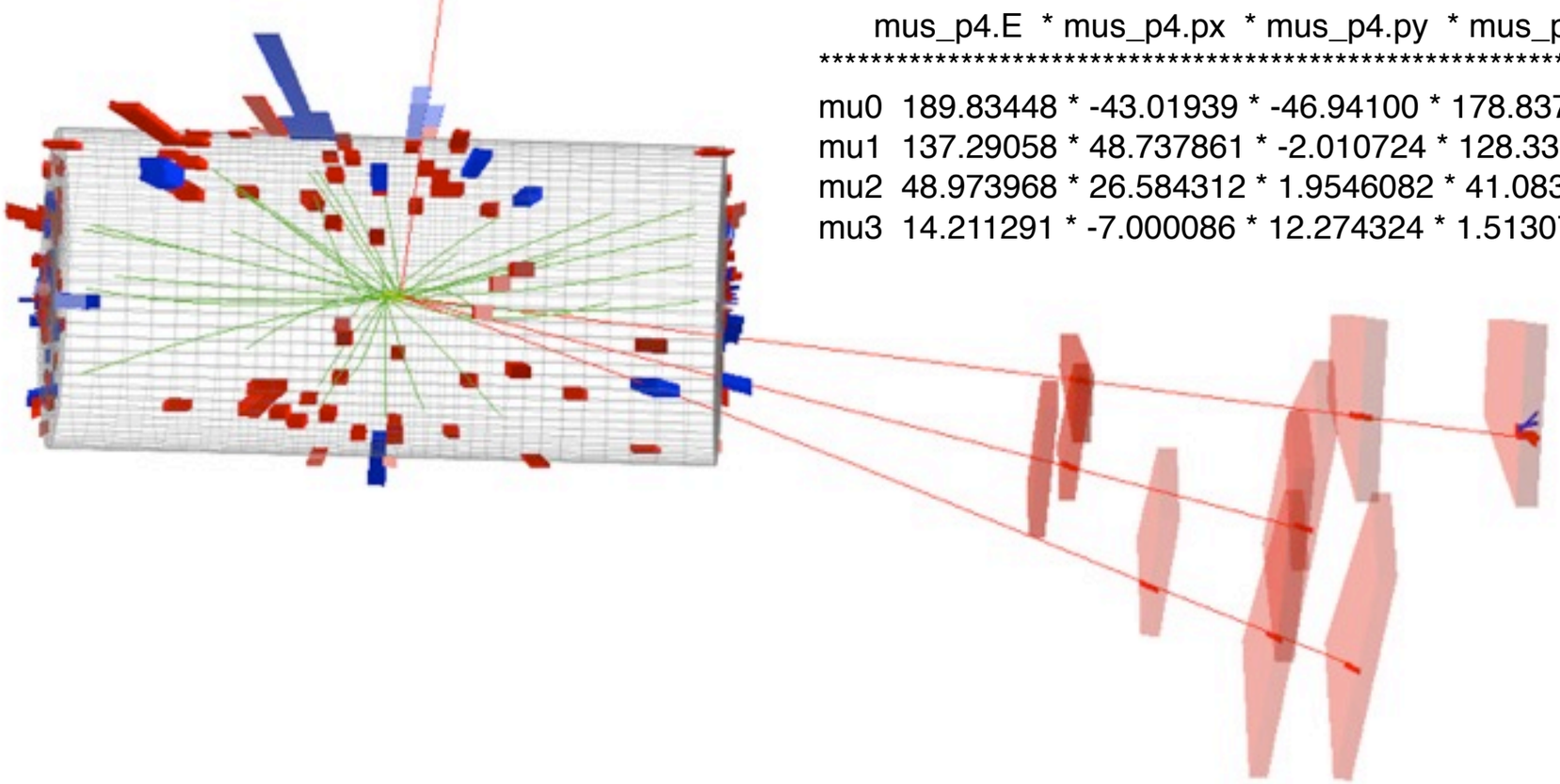


CMS Experiment at LHC, CERN
Data recorded: Thu Oct 14 05:25:53 2010 CEST
Run/Event: 147926 / 368148849

mu0+mu1 : 101 GeV
mu0+mu2: 80 GeV
mu0+mu3: 74 GeV
mu1+mu2: 18 GeV
mu1+mu3: 65 GeV
mu2+mu3: 40 GeV

where mu0, mu1, mu2, mu3:

	mus_p4.E *	mus_p4.px *	mus_p4.py *	mus_p4.pz *	Charge
mu0	189.83448 *	-43.01939 *	-46.94100 *	178.83790	-1
mu1	137.29058 *	48.737861 *	-2.010724 *	128.33265	1
mu2	48.973968 *	26.584312 *	1.9546082 *	41.083965	1
mu3	14.211291 *	-7.000086 *	12.274324 *	1.5130779	-1



Results: 35 pb^{-1} 2010 Data (Excluded point $\lambda_{122} \neq 0$)

Expected 17.6 events. No evidence for the signal

0.3 signal events expected where we saw diZ

Low amount of signal expected

Bodies (event cut)	0T			1T			2T		
exclusive Final State	obs	exp B	exp S	obs	exp B	exp S	obs	exp B	exp S
>4	0	0 ± 0	0.03	0	0 ± 0	0.06	0	0 ± 0	0
4 ($\|Q\| = 4$)	0	0 ± 0	0	0	0 ± 0.07	0	0	0 ± 0.05	0
4 (MET+ZV)	0	0 ± 0	12.49	0	0 ± 0	2.12	0	0 ± 0	0.13
4 (MET)	0	0 ± 0	3.61	0	0 ± 0	0.31	0	0 ± 0	0
4 (ZV+low MET)	0	0 ± 0	1.5	0	0.01 ± 0.06	0.17	0	0.07 ± 0.02	0
4 (on Z + low MET)	2	0.21 ± 0.02	0.26	0	0.06 ± 0.08	0.02	0	0 ± 0.06	0
3 ($\|Q\| = 3$ or SSSF)	0	0.25 ± 0.1	2.66	3	0.82 ± 0.38	0.41	4	6.45 ± 1.43	0
3 (MET+ZV)	0	0.2 ± 0.07	7.85	0	0.35 ± 0.13	0.57	–	–	–
3 (MET+onZ)	3	0.95 ± 0.13	1.29	2	0.79 ± 0.19	0.5	0	0.36 ± 0.1	0.03
3 (low MET+ZV)	3	1.63 ± 0.6	0.73	32	25.41 ± 5.13	0.01	–	–	–
3 (low MET+onZ)	6	6.22 ± 2.1	0.06	96	98.73 ± 20.53	0.03	26	40.87 ± 9.13	0
Totals	14	9.46 ± 2.19	30.48	133	126.17 ± 21.17	4.2	30	47.75 ± 9.24	0.16
Totals 4L	2	0.21 ± 0.02	17.89	0	0.07 ± 0.122	2.68	0	0.07 ± 0.08	0.13
Totals 3L	12	9.25 ± 2.19	12.59	133	126.1 ± 21.17	1.52	30	47.68 ± 9.24	0.03

- Sample SUSY point with L-RPV
  - $\lambda_{122} \neq 0$
  - $m_{Bino} = 300$ GeV
  - $m_{Gluino} = 700$ GeV
  - $m_{squark} = 700$ GeV
  - All other super-partners are decoupled

Results: 35 pb^{-1} 2010 Data (Excluded point $\lambda_{123} \neq 0$)

Expected 4.7 signal events, observed 0

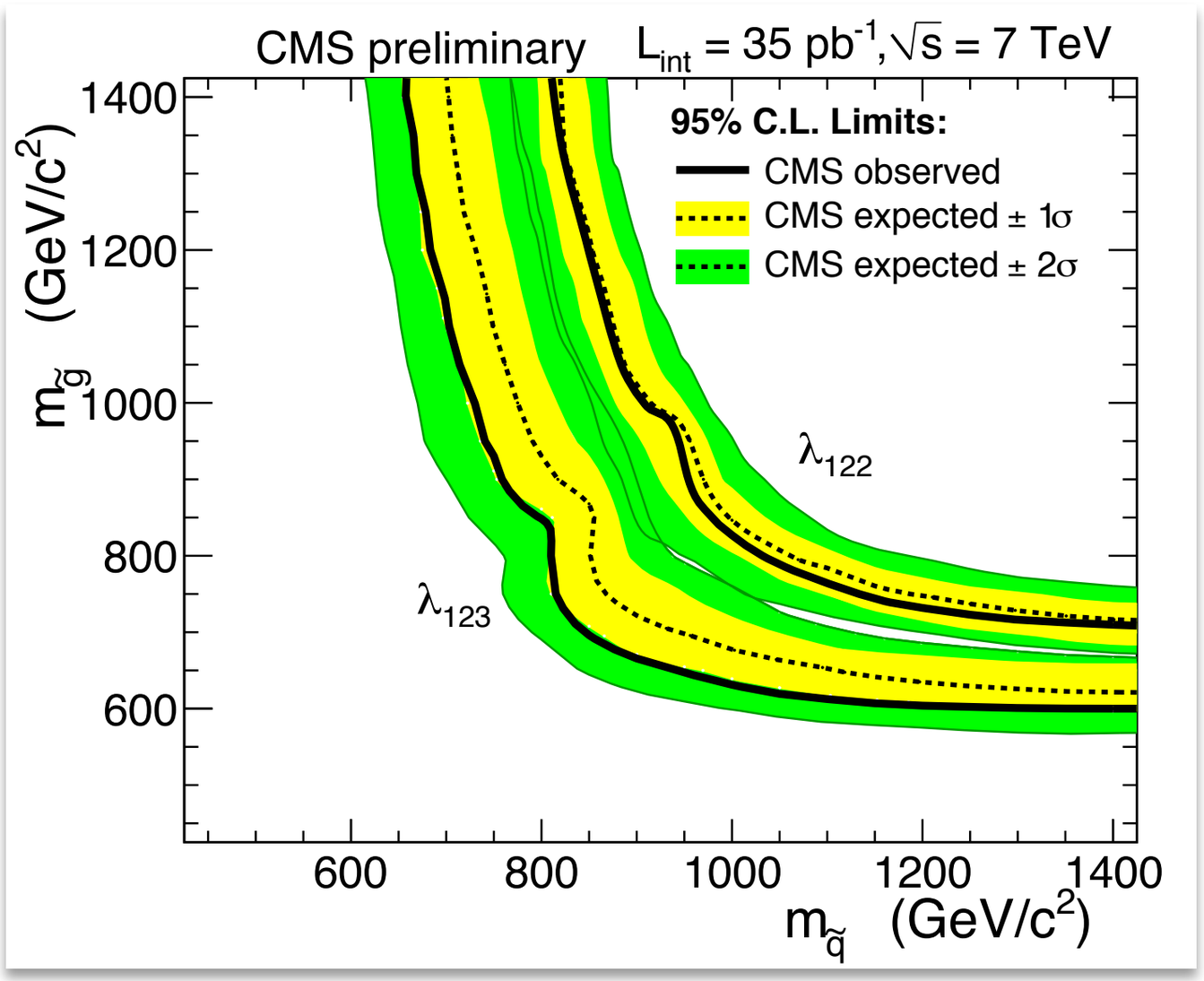
Expected 2.9 signal events, observed 0

Bodies (event cut)	0T			1T			2T		
exclusive Final State	obs	exp B	exp S	obs	exp B	exp S	obs	exp B	exp S
>4	0	0 ± 0	0	0	0 ± 0	0.2	0	0 ± 0	0
4 ($\|Q\| = 4$)	0	0 ± 0	0	0	0 ± 0.07	0	0	0 ± 0.05	0
4 (MET+ZV)	0	0 ± 0	0.56	0	0 ± 0	1.53	0	0 ± 0	1.32
4 (MET)	0	0 ± 0	0.32	0	0 ± 0	0.32	0	0 ± 0	0
4 (ZV+low MET)	0	0 ± 0	0.07	0	0.01 ± 0.06	0.1	0	0.07 ± 0.02	0.09
4 (on Z + low MET)	2	0.21 ± 0.02	0.02	0	0.06 ± 0.08	0.01	0	0 ± 0.06	0
3 ($\|Q\| = 3$ or SSSF)	0	0.25 ± 0.1	1.42	3	0.82 ± 0.38	1.99	4	6.45 ± 1.43	0.01
3 (MET+ZV)	0	0.2 ± 0.07	3.27	0	0.35 ± 0.13	1.49	–	–	–
3 (MET+onZ)	3	0.95 ± 0.13	0.95	2	0.79 ± 0.19	3.64	0	0.36 ± 0.1	1.33
3 (low MET+ZV)	3	1.63 ± 0.6	0.26	32	25.41 ± 5.13	0.1	–	–	–
3 (low MET+onZ)	6	6.22 ± 2.1	0.05	96	98.73 ± 20.53	0.33	26	40.87 ± 9.13	0.11
Totals	14	9.46 ± 2.19	6.92	133	126.17 ± 21.17	9.71	30	47.75 ± 9.24	2.86
Totals 4L	2	0.21 ± 0.02	0.97	0	0.07 ± 0.122	2.16	0	0.07 ± 0.08	1.41
Totals 3L	12	9.25 ± 2.19	5.95	133	126.1 ± 21.17	7.55	30	47.68 ± 9.24	1.45

- Sample SUSY point with L-RPV
  - $\lambda_{123} \neq 0$
  - $m_{Bino} = 300$ GeV
  - $m_{Gluino} = 700$ GeV
  - $m_{squark} = 700$ GeV
  - All other super-partners are decoupled

Results

Exclusion limits for leptonic RPV



- Excluded region in MSSM parameter space:

  gluino mass vs squark mass

Other parameters:

- m_{Bino} = 300 GeV
- All other super-partners are decoupled

2011 Analysis Plans

- 2011 Analysis is still going through the approval stage at CMS.
- Now, we have more than 1 fb^{-1} of data.
- Exciting Things Ahead!!! Look out for talk at SUSY2011.

Summary

- Performed combined exclusive multichannel channel search for leptonic R-parity violating physics.
  - 3 and more lepton channels combined in hierarchical order.
- Background was estimated using data driven and MC methods.
  - Background is low for all high signal channels.
- Made an exclusion of leptonic R-parity violating models using accessible topology in MSSM parameter space.
- Looking forward to discovery with the coming 2011 data!

Backup Slides

Generalized Matter Symmetries

(Organized by Scott Thomas)

- Theories with partner particles that respect a symmetry that stabilizes the proton.
  - SUSY with R-parity violation is a subset.
    - SUSY with R-parity conservation is a further subset.
  - Most extra dimensional theories with and without T-parity are also a subset.
- If matter symmetry is preserved, partner particles are stable and escape the detector. In contrast if matter symmetry is violated,partner particles decay to Standard Model particles.

Partner ΔJ	Continuous Matter Symmetry	Discrete Matter Symmetry	Baryon or Lepton Symmetry
0* (Same Spin Partners)	No Models Yet	T-parity	TPV (T-parity violation)
1/2 (Supersymmetry)	$U(1)_R$ MSSM★	MSSM★★ R-parity	RPV (R-parity violation)
1 (Spin-1 Partners)	No Models Yet	N=2 MS1SM	No Models Yet

∗ **Kaluza-Klein, Little Higgs, Universal extra Dimensions, Randall-Sundrum, Higgless**

★ **($\Delta J=1/2$) $U(1)_R$ MSSM also has an N=2 version. Produces Opposite Sign Leptons**

★★ **($\Delta J=1/2$) MSSM produces both opposite sign and same-sign pairs**

We do this search in leptonic sector

General Selections

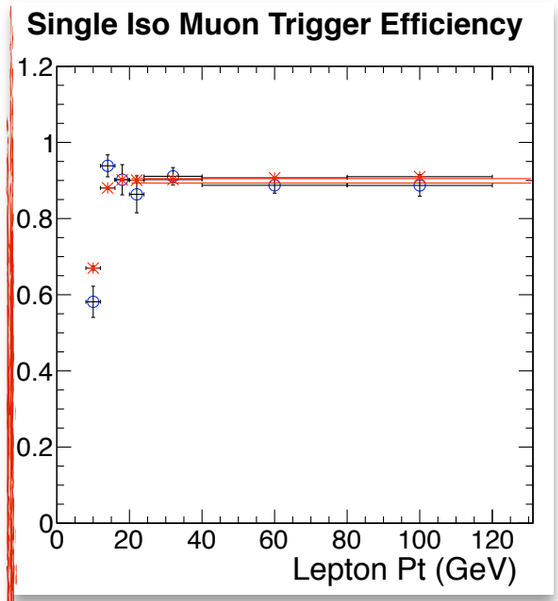
- Jet Selection (used for HT).
  - Particle Flow, $|\eta|<2.4$
  - $\Delta R > 0.1$ from isolated e,μ,track
  - $E_T > 20$ GeV
- Event selection
  - Non-scraping
  - At least 1 good vertex
    - N d.o.f.> 4, r<2 cm, $|z| < 24$ cm

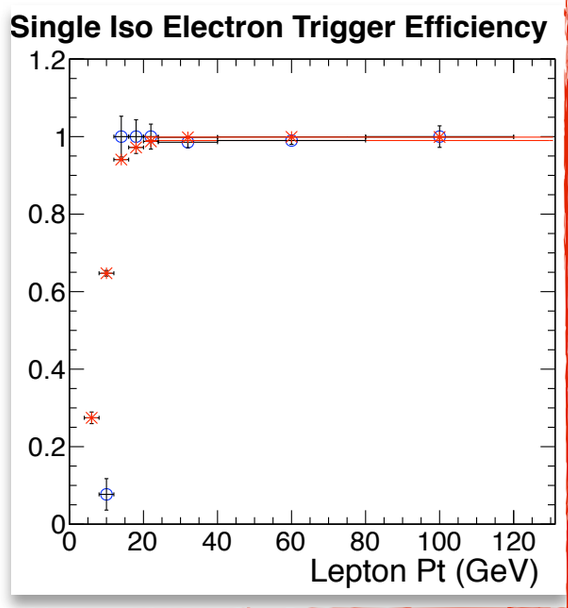
Trigger strategy

- Trigger table changed throughout the 35 pb^{-1}
  - single lepton trigger thresholds increased
  - isolation added, electron ID changed, etc.
- Trigger table is different in MC and the data.
- Trigger strategy - Aim for consistency!
  - Use only single lepton triggers with prescale 1
  - Artificially raise the thresholds on MC on the full dataset.
    - Only accept Mu trigger if at least 1 isolated muon with $p_T > 15$ GeV
    - Only accept Electron trigger if at least 1 isolated electron with $p_T > 20$ GeV
  - Measure trigger efficiency for the "OR" of single lepton triggers. Scale MC to match.

Trigger Efficiency

- Measure efficiency for single lepton triggers.
- Select 1 isolated lepton with MET or HT trigger.
- What fraction fired single lepton trigger.
- If triggers i and j are uncorrelated then:
  - $\varepsilon_{ij} = \varepsilon_i \times \varepsilon_j$
  - $\varepsilon_j = N_{ij}/N_j$



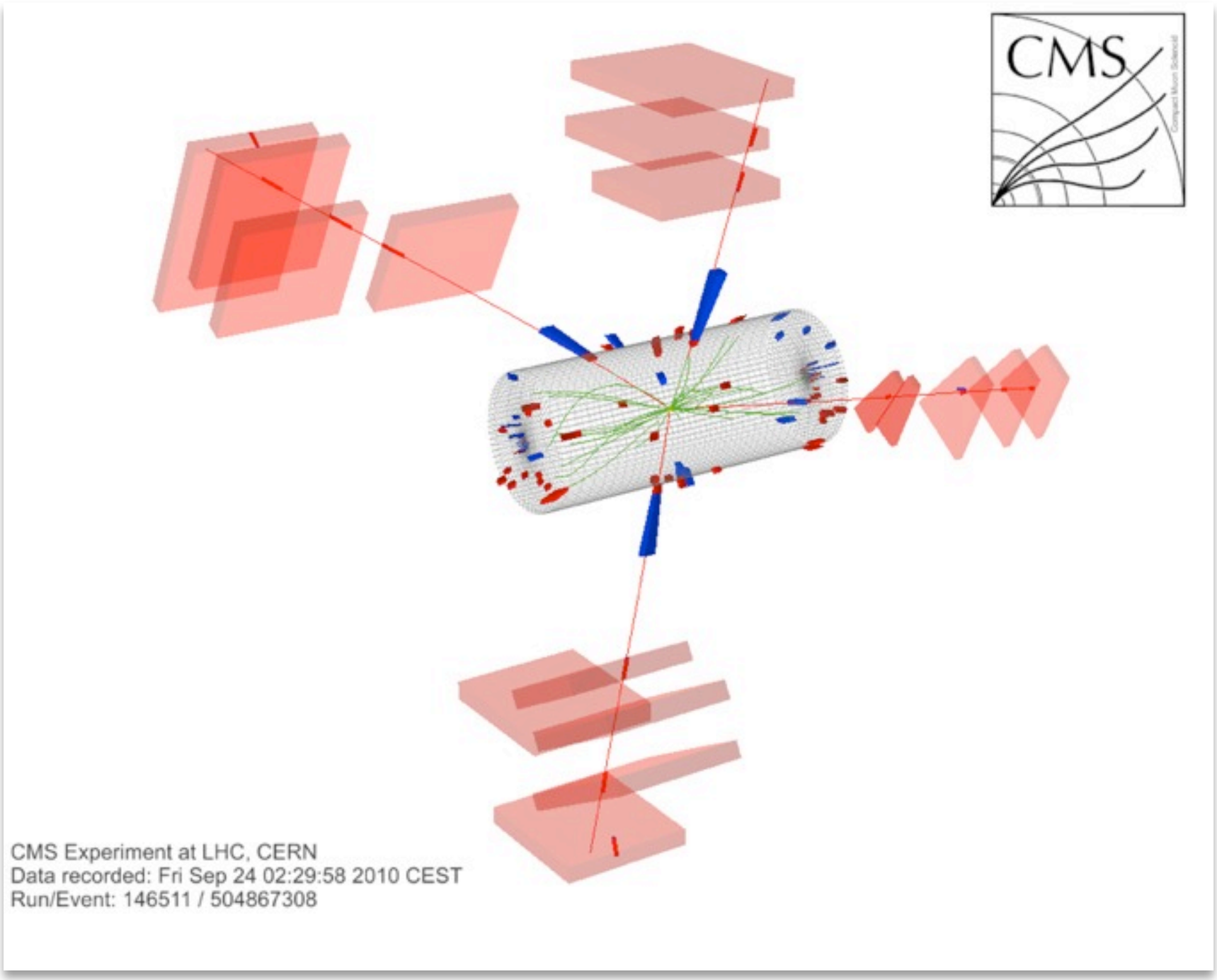


Tag Trigger	Run Range	Electron "OR" Efficiency	Muon "OR" Efficiency
HLT_MET45	< 148031	99.0%±0.2%	89.1%±0.9%
HLT_MET65	< 147116	99.0%±0.8%	89.9%±1.4%
HLT_MET100_v3	148822 to 149294	96%±3.3%	91.7%±2.3%
HLT_MET120_v3	148822 to 149294	95.9%±5.3%	91.1%±3.6%
HLT_MET80_v1	147196 to 148058	96.2%±1.5%	88.8%±1.5%
HLT_MET45_HT100U_v1	147196 to 148058	96.5%±0.6%	89.3%±1.3%
HLT_MET45_HT120U_v1	147196 to 148058	96.3%±0.8%	89.4%±1.5%

Results
(observed data)

Expected 0.2 background events, observed 2

- here is one of them



Where expected background comes from and how we deal with it.

- ZZ → 4l (MC)
- Z+Jets → 2l + 2 fakes (Data)
- Z+Jets → 2l + 1 fakes + 1FSR (MC)
- Z+Jets → 2l + 2 FSR (MC)
- TTbar → 2l + 2 fakes (Data)
- TTbar → 2l + 1 fakes + 1FSR (MC)
- TTbar → 2l + 2 FSR (MC)
- WZ + Jets → 3l + 1 fake (MC , Data)
    - ✳ FSR - photon radiated by lepton which converts to electron

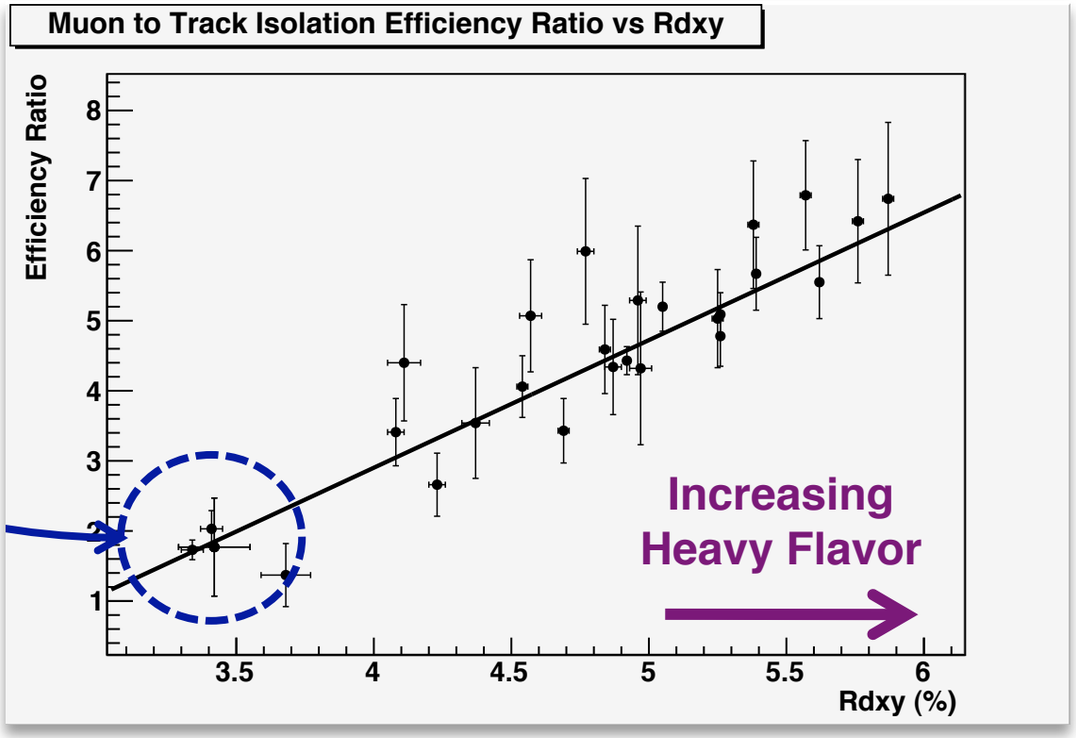
Datasets

- Mu and EG/Electron Primary datasets
  - /Mu/Run2010B-PromptReco-v2
  - /Mu/Run2010A-Sep17ReReco_v2
  - /EG/Run2010A-Sep17ReReco_v2
  - /Electron/Run2010B-PromptReco-v2

- Run over Mu:
  - Single Mu Trigger if ≧ 1 isolated Mu with $p_T > 15$ GeV
- Run over EG/Electron:
  - Single E triggers if ≧ 1 isolated Electron with $p_T > 20$ GeV
  - Veto single Mu triggers if ≧ 1 isolated Mu with $p_T > 15$ GeV
    - Make sure we have no duplicates

Jet Composition Dependence: ($\varepsilon_{Fake}/\varepsilon_{Track}$) vs R_{dxy}

- $R_{dxy} = N(|dxy>0.02\ cm)/N(|dxy|<0.02\ cm)$
- For tracks from uds jets $R_{dxy} \sim 3\%$
- For tracks from b-jets $R_{dxy} \sim 30\%$
- Measure R_{dxy} in dilepton seed
- Determine efficiency ratio dependence on R_{dxy} in QCD.

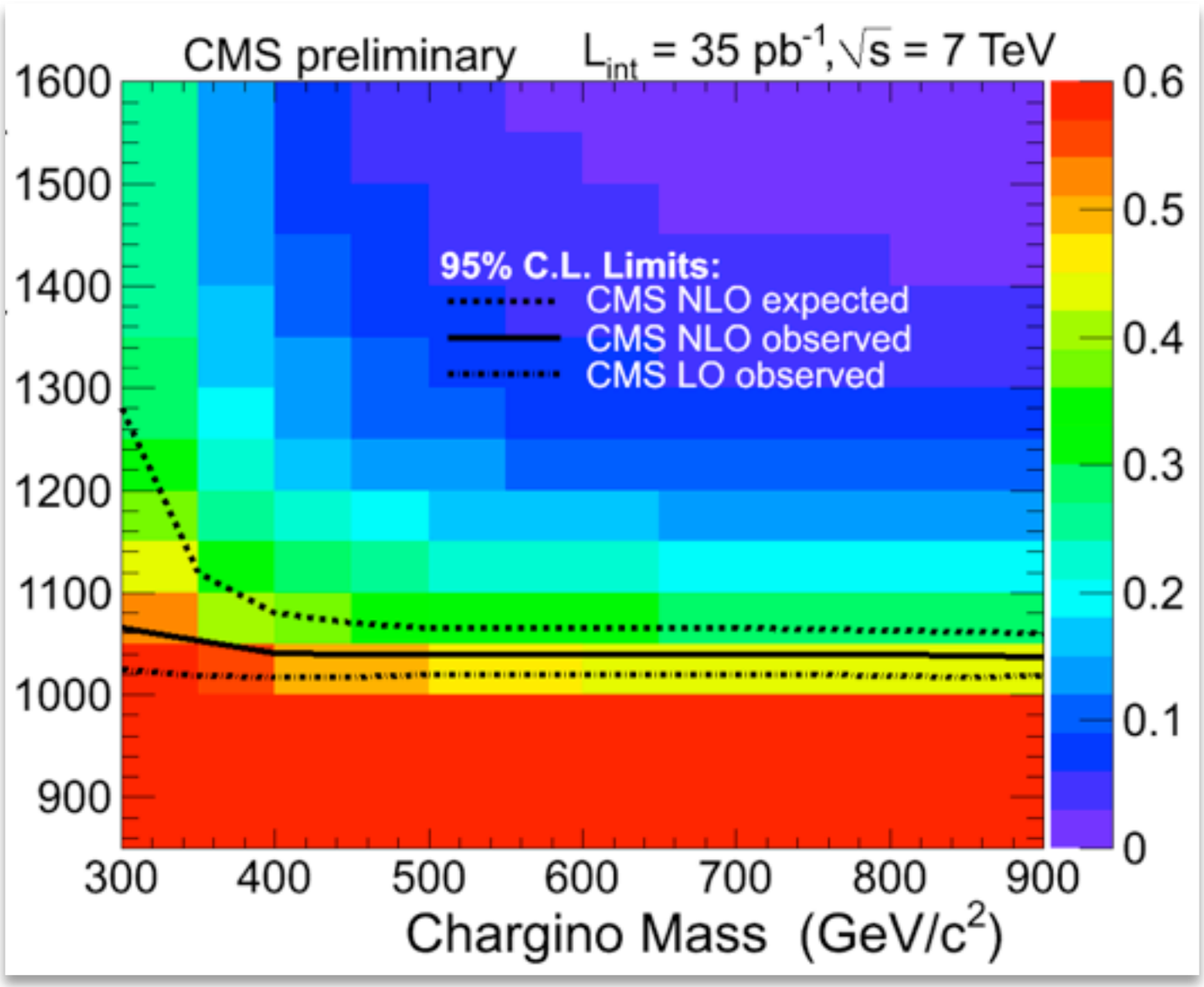


L-RPV analysis method

- Combine a number of exclusive three and more lepton channels that have a large S/B for the L-RPV signal.
  - Lepton number, lepton flavor, charge combinations, etc
  - Treat each channel as separate experiment.
- Sort the channels by expected S/B
  - Hierarchical order from high signal/low background to low signal/high background.
  - All channels contribute to search sensitivity.

Results

Exclusion limits for co-NLSP model.



- Example of MSSM region ruled out by CMS beyond Tevatron (Suggested by Scott Thomas).
  - R-parity is not violated here.