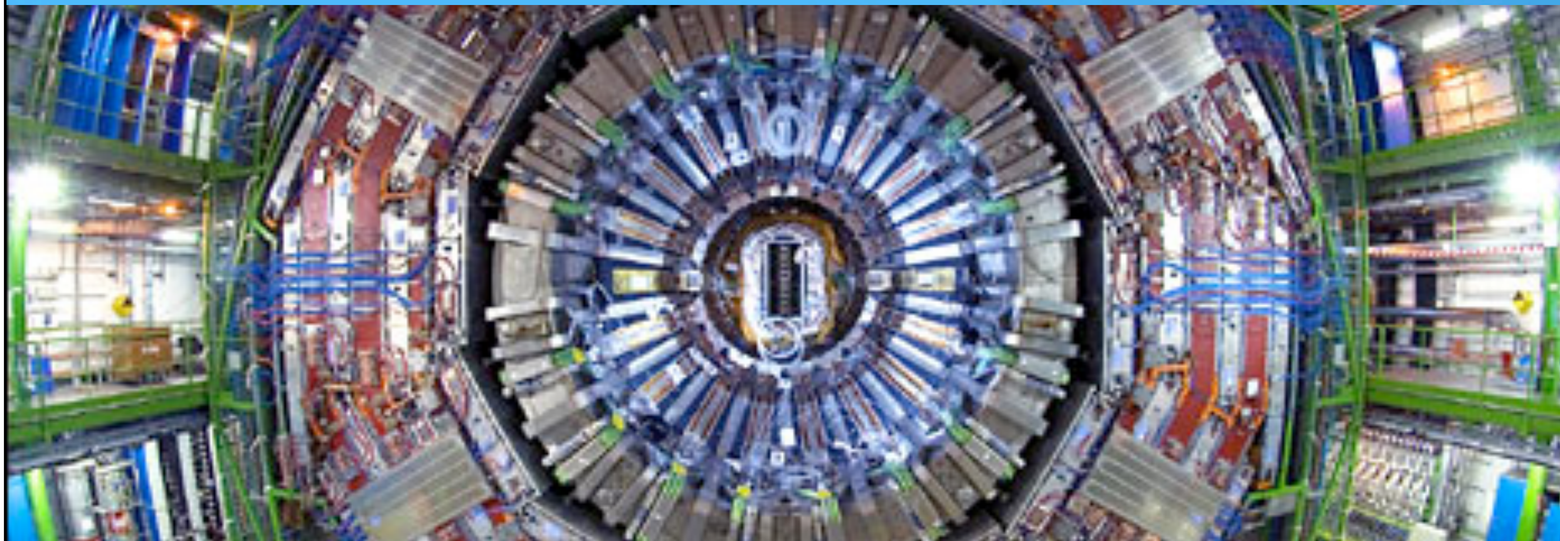

CMS 2010 Multilepton Results

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Outline for today

- Introduction
- SUSY Searches with Leptons and Jets
  - Multi-Leptons (≥ 3 Leptons)
- Conclusions.

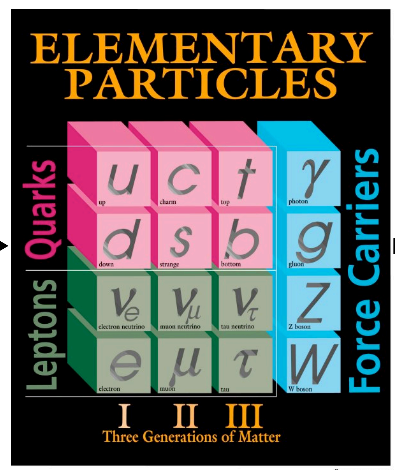
The Search for New Physics

Problems with the standard model indicate that there should be new particles at the ~TeV scale. At minimum, this includes the Higgs and a Dark Matter candidate. One possibility is Super Symmetry.

1950's

Gauge Bosons	γ
Leptons and neutrinos	e+, ν_e μ+, ν_μ
Mesons	K, π
Baryons	P, N

1995



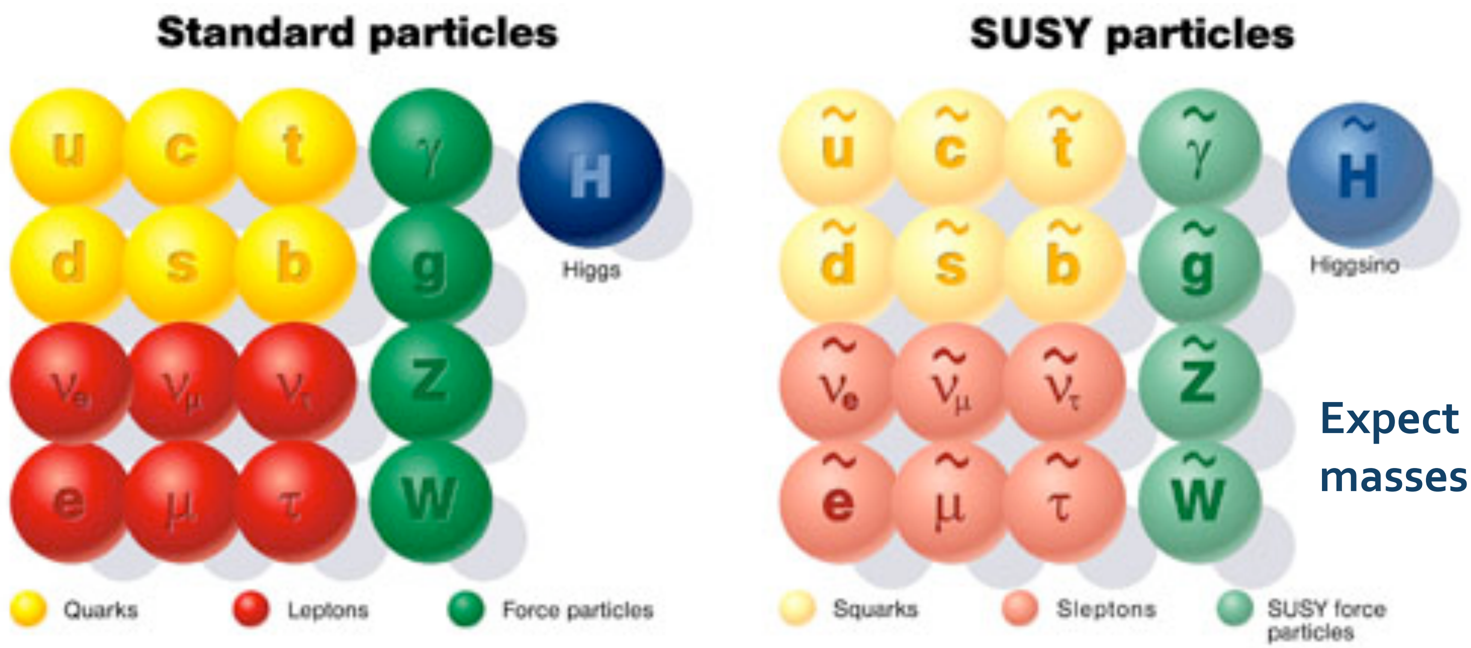
2012-2020?

Some Possibilities:

- **Super Symmetry**
- **Extra dimensions**
- **New quark generation**
- **Lepto-quarks**
- **Something unexpected!**

What is Supersymmetry?

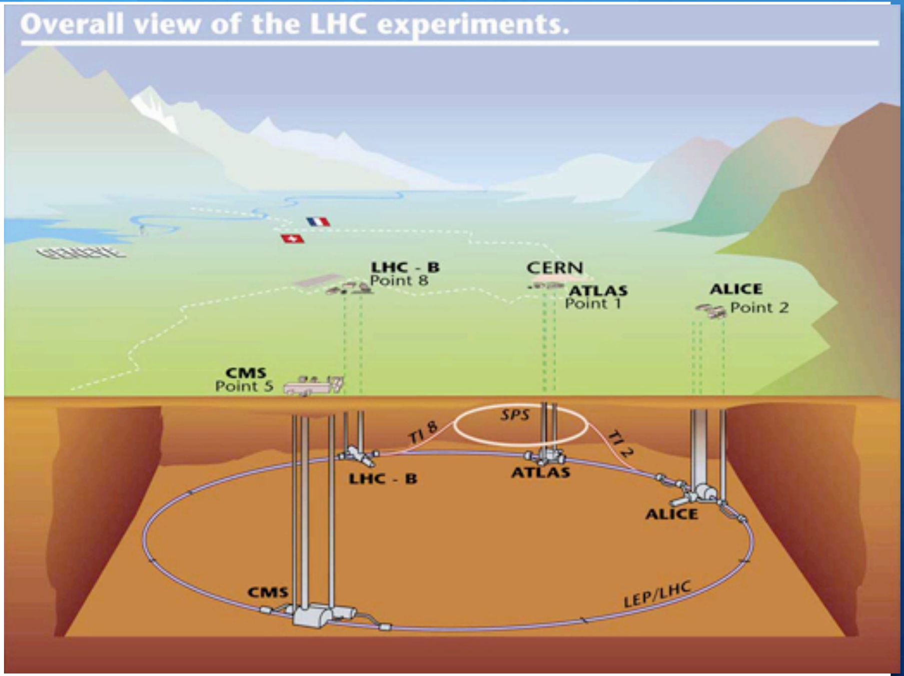
- Supersymmetry (SUSY) postulates the following:
  - For every standard particle there is a "super partner"
  - Super Partners differ by spin (1/2 difference) and mass



Expect SUSY masses ~TeV

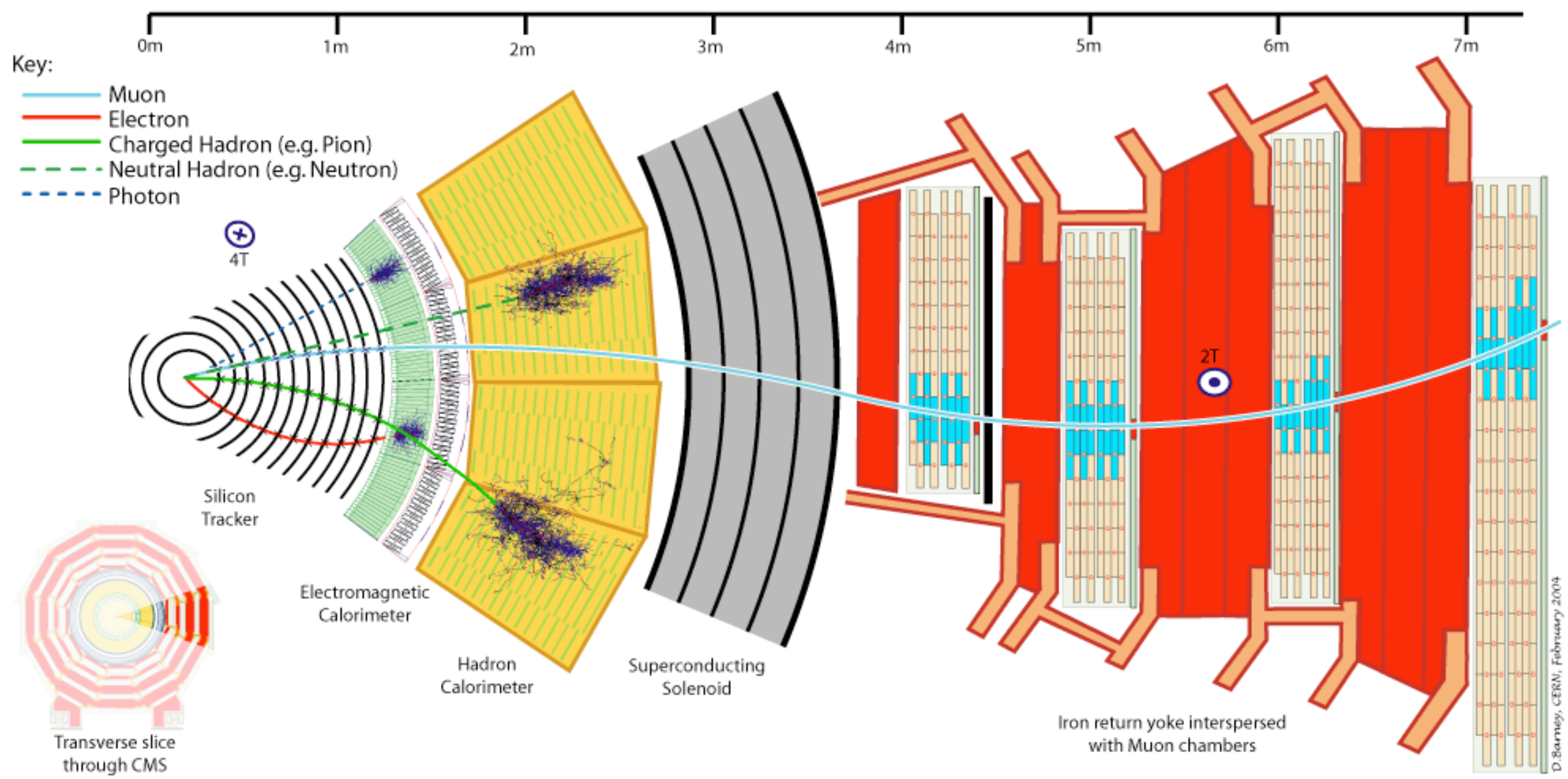
The LHC

- Circular tunnel 27 km in circumference.
- The tunnel is buried ~100m underground
- Proton (Ion) beams move around the LHC ring inside a continuous vacuum guided by superconducting magnets.
- The beams will be stored at high energy for hours. During this time collisions take place inside the four main LHC experiments:
  - CMS
  - ATLAS
  - LHCb → b physics (CP violation, rare decays)
  - ALICE → Heavy Ion experiment (quark-gluon plasma)

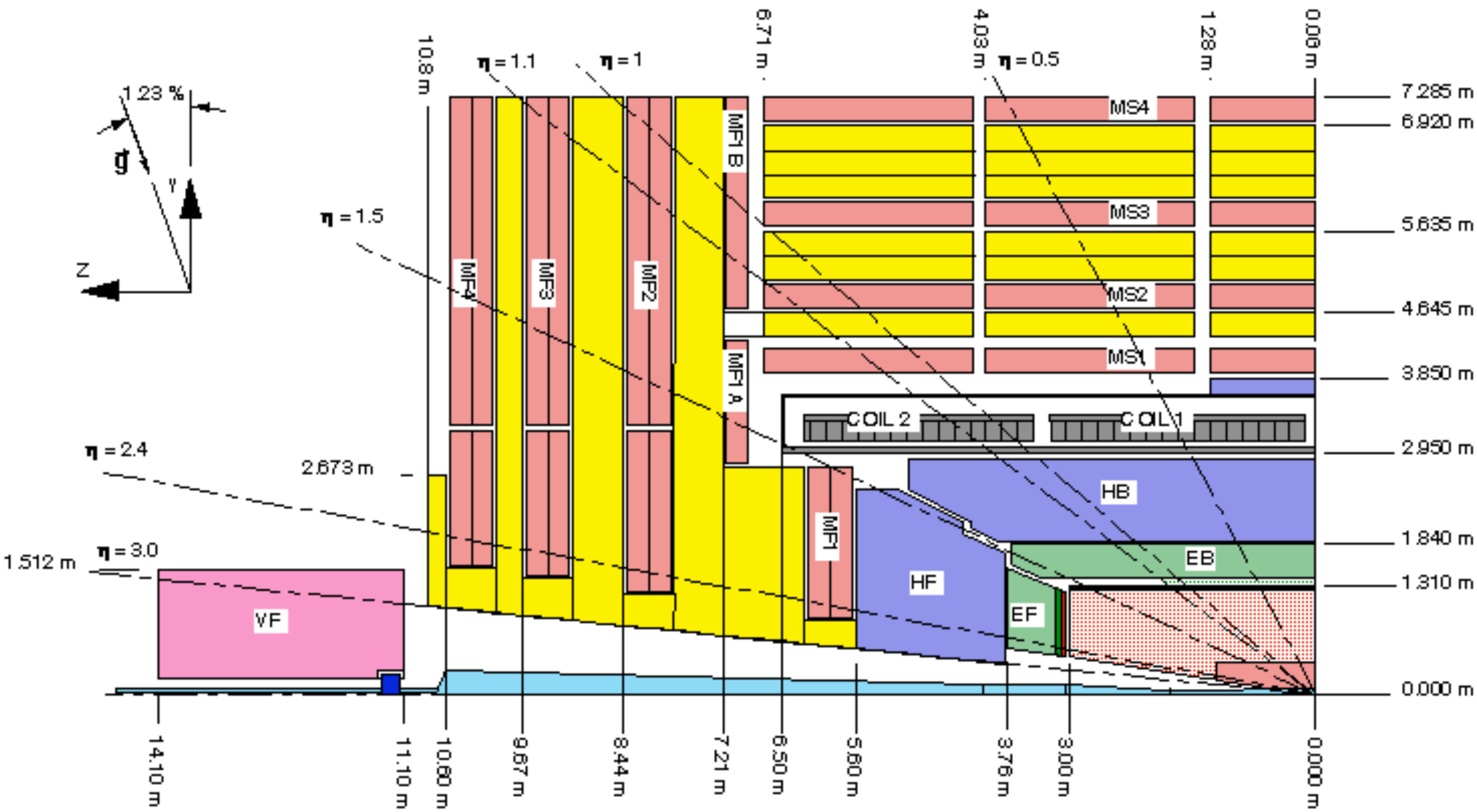


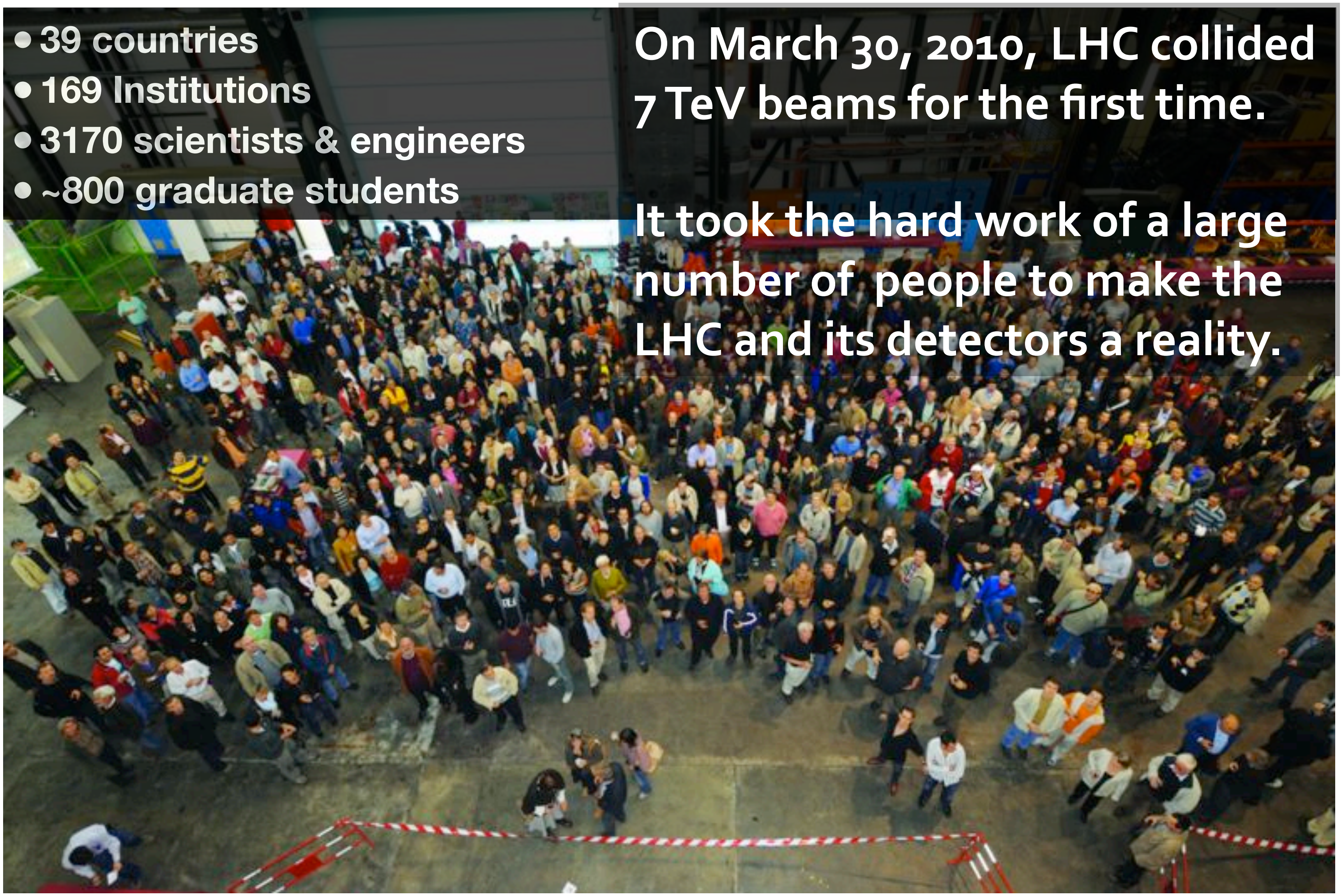
CMS is the focus of this talk

Section of the CMS Detector



CMS Cross Section

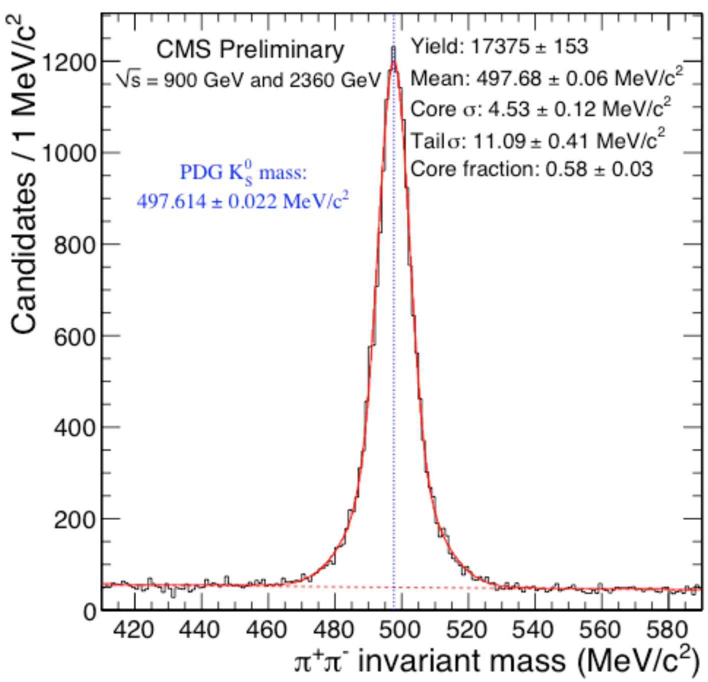



• 39 countries
• 169 Institutions
• 3170 scientists & engineers
• ~800 graduate students
On March 30, 2010, LHC collided 7 TeV beams for the first time.
It took the hard work of a large number of people to make the LHC and its detectors a reality.

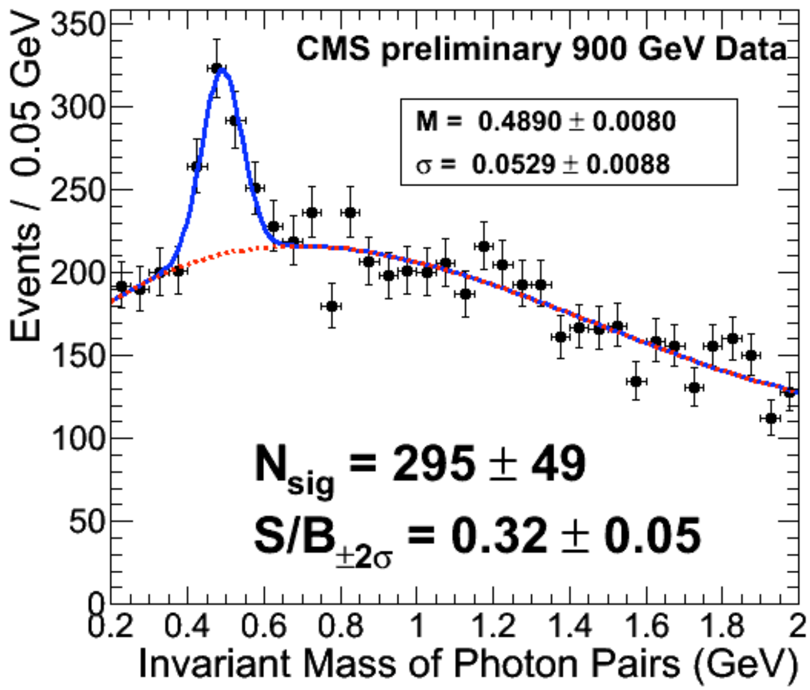
Particle Reconstruction: with photons and tracks

After cosmic runs, used √s= 900 GeV and √s=2.3 TeV running to test the detector.

$K_S \to \pi^+\pi^-$



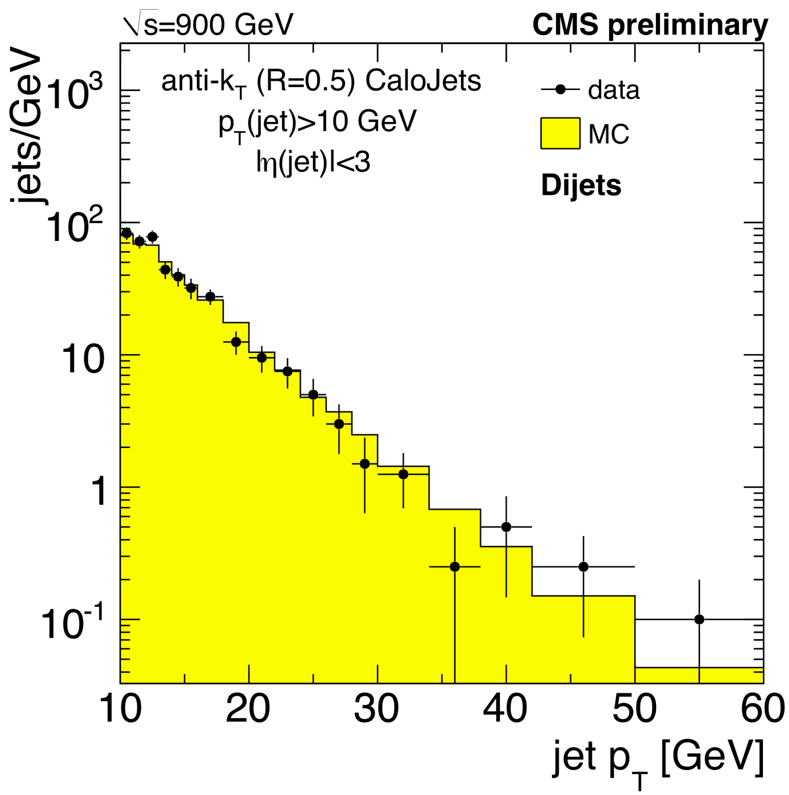
$\eta \to \gamma\gamma$

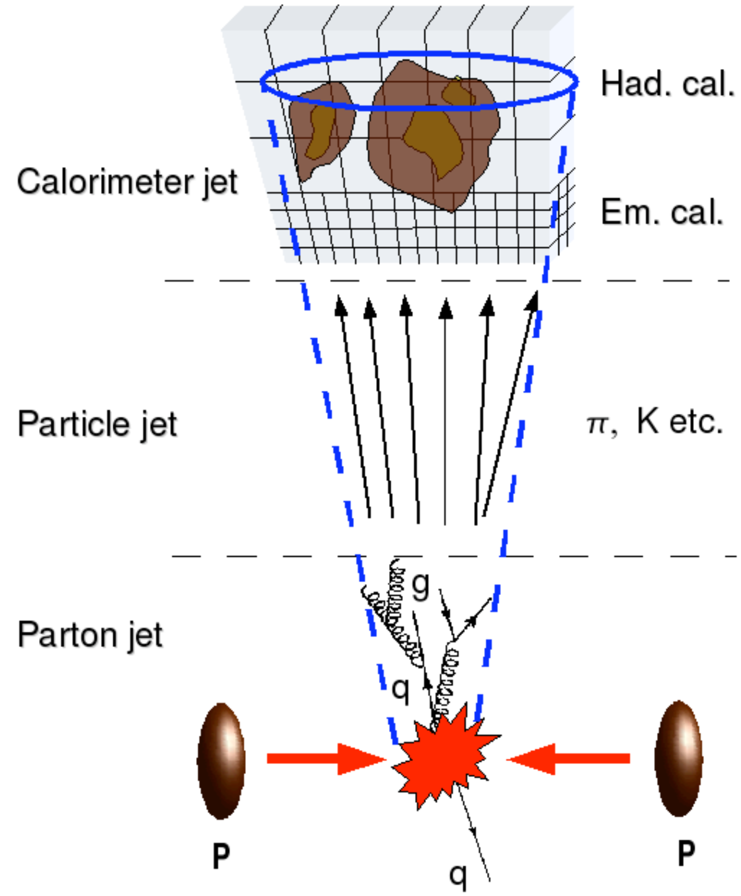


Jets

Quarks cannot roam far from other quarks (confinement). Strong force potential increases with distance. Highly energetic quarks initiate a shower of baryons and mesons with ~ the same energy and momentum as the original quark.

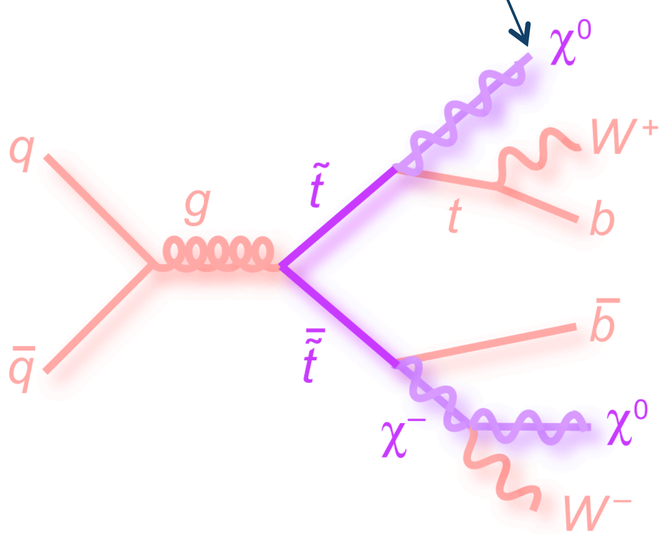
CMS: Jet p_T

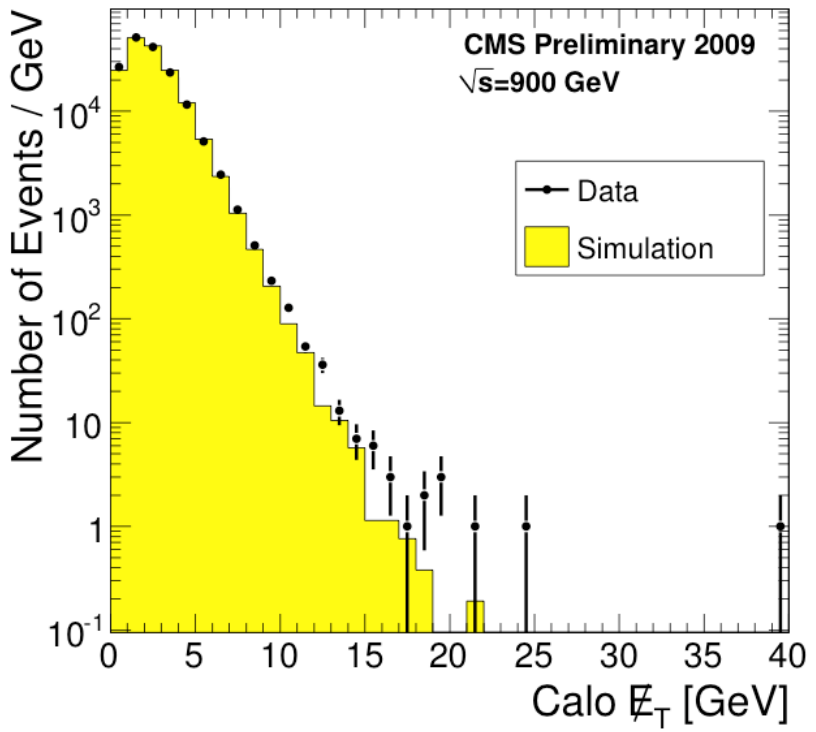




Missing Transverse Energy (MET)

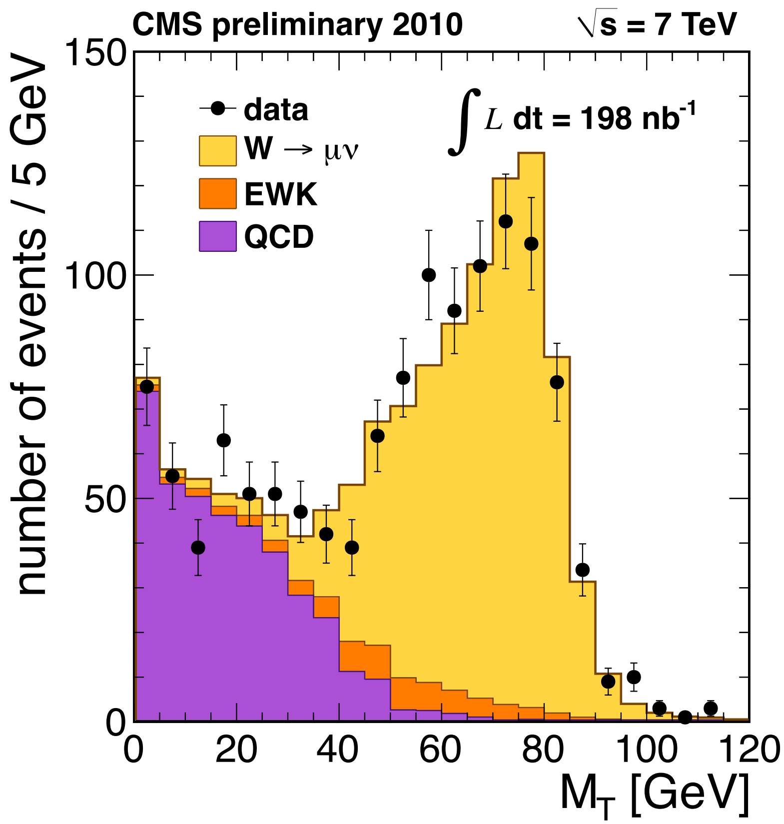
MET: momentum imbalance in the detector caused by neutral, weakly interacting particles (e.g. neutrinos … or SUSY neutralinos, "dark matter" candidates)

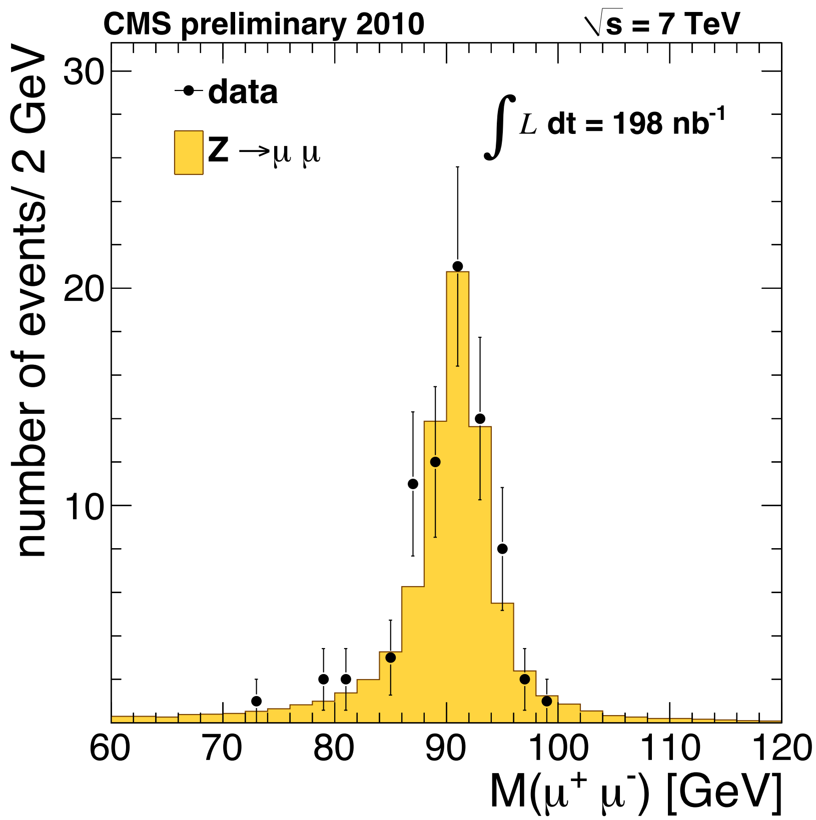




Before Looking for SUSY, Look for $W^{\pm}$ and Z^{0}

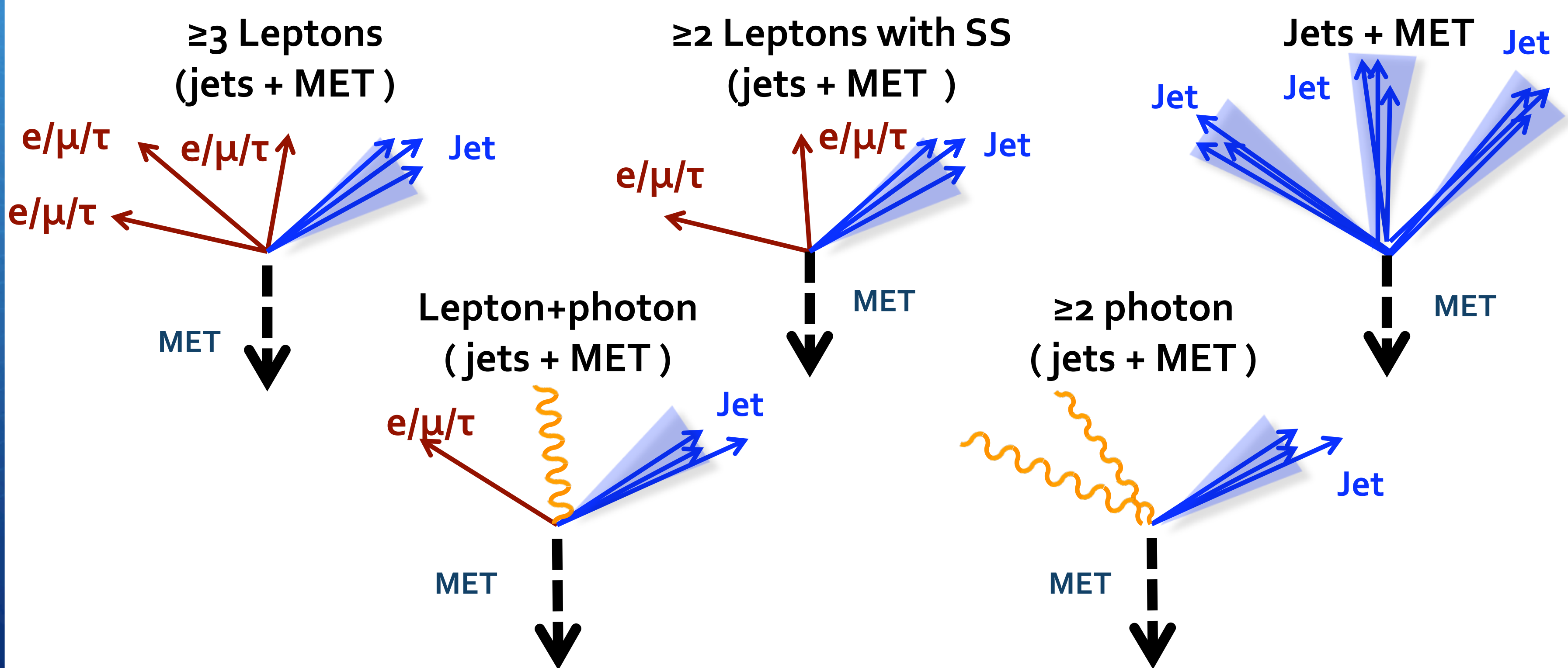
Plots from ICHEP-2010 with first 0.2 pb^{-1} of 7 TeV data





Searching for SUSY in 7 TeV 2010 Data

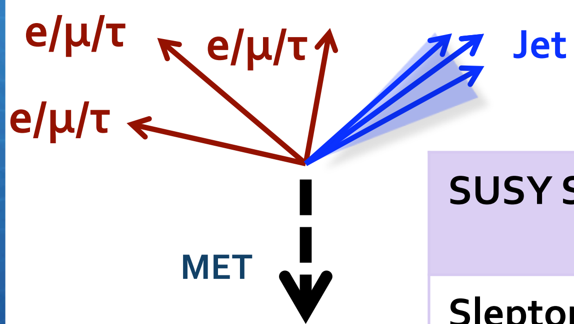
- In 2010 CMS collected an integrated luminosity of 35 pb^{-1} of data
  - Must search for signatures of SUSY that are rare in the SM
  - Problem: SUSY looks different depending on the mass spectrum.
- Some Examples of recent CMS analyses:



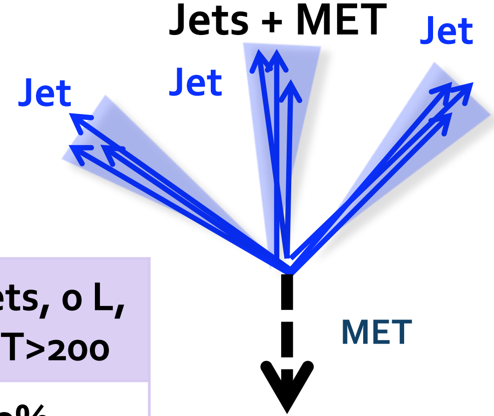
Searching for SUSY in 7 TeV 2010 Data

- Today, I will cover the following:
  - Emphasis on the ≥ 3 Lepton channel.
  - Briefly mention Jets+MET analysis to compare exclusions.

≥3 Leptons
(jets + MET)



Jets + MET

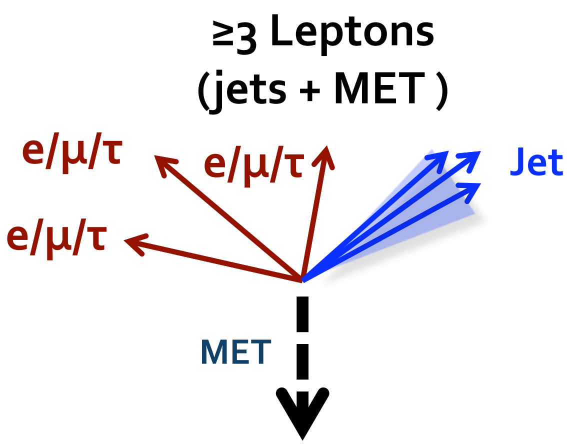


SUSY Scenario Examples	≥3L	≥2 Jets, 0 L, MET>200
Slepton co-NLSP	~100%	0%
Leptonic R-parity violating	~100%	0%
mSUGRA (M0=60, M1/2=190)	~23%	11.4%
mSUGRA (M0=200, M1/2=250)	~1.8%	35%

mSUGRA→CMSSM

Searching for SUSY with Multi-Leptons

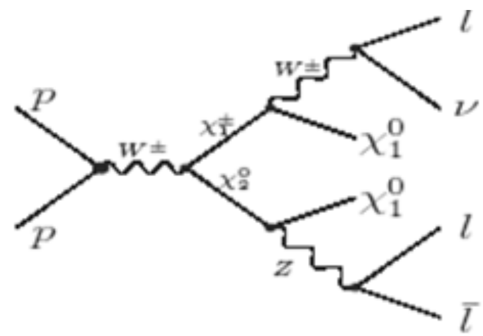
- Leptons that don't originate from jets are rare.
- SM events with ≥3 leptons are very rare!
  - Leptons isolated from jets come from gauge bosons γ^*, Z^o, $W^\pm$
- Many SUSY scenarios do produce large numbers of leptons.
  - Can also have large MET and large H_T



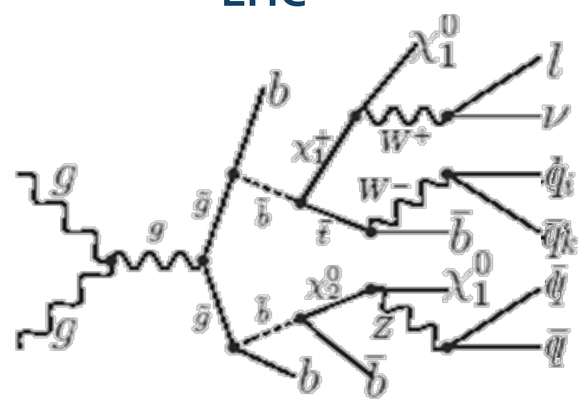
The SUSY Decays

- Leptons produced at the end of a chain of susy decays.
- Strongly coupled squarks and gluinos are generated in the proton collisions.
- Some combination of charginos, neutralinos, and sleptons decay to leptons and LSP (dark matter)

Tevatron

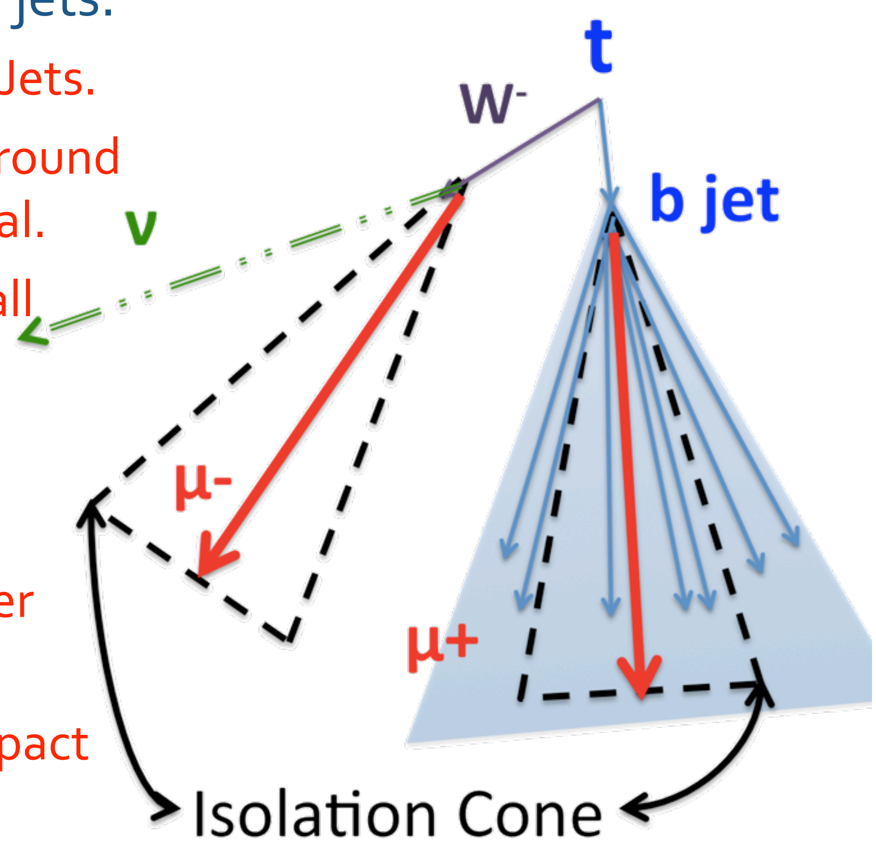


LHC



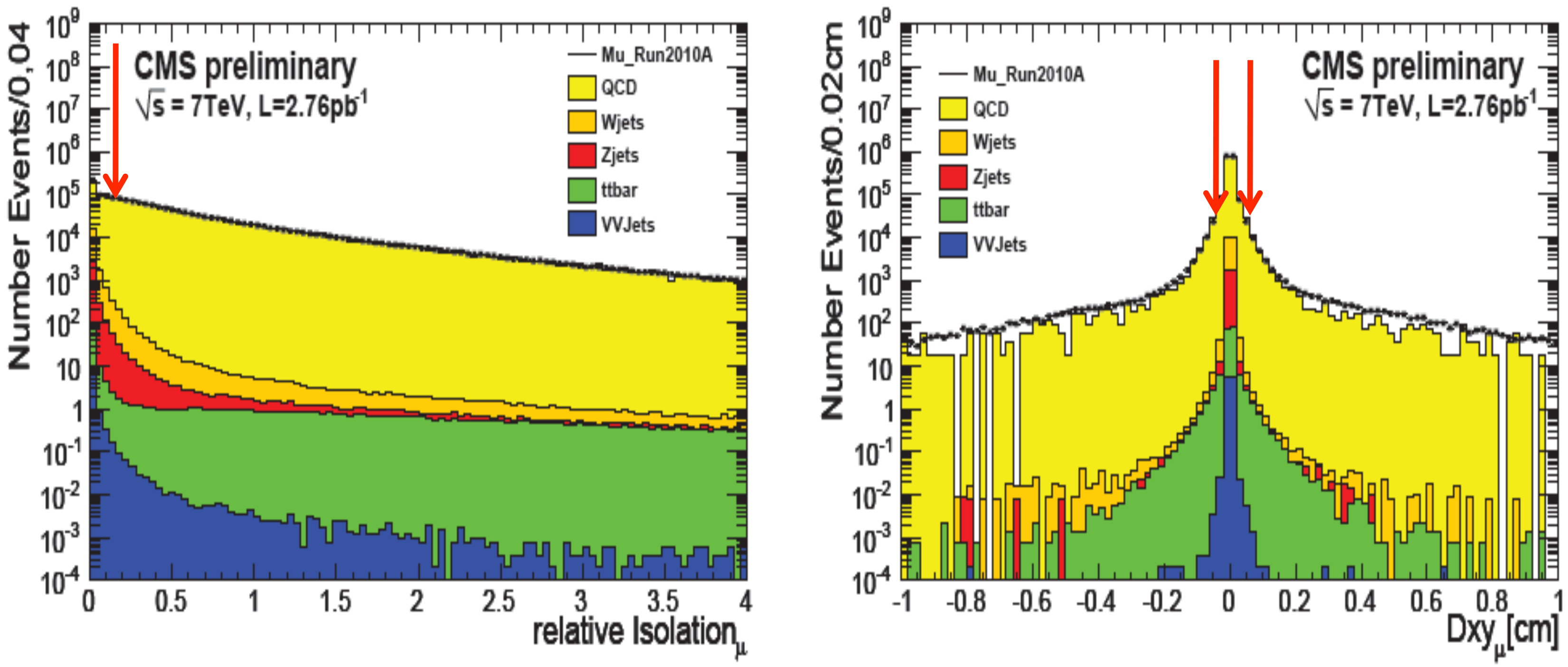
Distinguish Between Leptons from Jets and Leptons from SUSY

- We need to remove leptons from jets.
  - Leptons should be isolated from Jets.
  - Sum transverse energy in cone around lepton from tracks, HCal, and ECal.
  - Require energy in cone to be small compared to the lepton.
- Leptons must be from the collision.
  - Leptons should be "prompt"
  - Leptons from jets can start farther from interaction vertex
  - Require lepton to have small "impact parameter"



Isolation and Impact Parameter

Prompt and isolated leptons are defined by: Reliso<0.15 and d_{xy}<0.02 cm



Electron Selection

- Electrons:
  - ID selection ~90% efficient (WP90 or VBTF90).
    - Cut on shower shape variables and track+shower match.
    - ~90%-95% efficient for p_t > 20 GeV
  - Use Relative Isolation < 15%
    - Relative Isolation (relIso): ΣE_T in isolation region divided by lepton p_t
    - Efficiency varies with hadronic activity (N jets)
    - For electron p_t=20 GeV, Isolation Efficiency is ~75% if 2 jets (E_t > 30 GeV)
  - Electron P_t > 8 GeV

Muon Selection

- Muons:
  - ID selection >95% efficient.
    - Require track to match calorimeter and muon system hits
    - Calorimeter deposits must be consistent with minimum ionizing
    - A good global fit to hits in track and muon system.
  - Use Relative Isolation < 15%
    - Relative Isolation (relIso): ΣE_T in isolation region divided by lepton p_t
    - Efficiency varies with hadronic activity (N jets)
    - For muon p_t=20 GeV, Isolation Efficiency is ~80% if 2 jets (E_t > 30 GeV)
  - Muon P_t > 8 GeV

Hadronic Tau Selection

- Tau leptons are unstable and decay near the collision.

τ^- Decay	Branching Fraction	Detector Signature
$\mu^- \nu_\mu \nu_\tau$	17%	Isolated μ
$e^- \nu_e \nu_\tau$	18%	Isolated e
$(\pi^-$ or $K^-) \nu_\tau$	12%	Isolated Track
$(\pi^-$ or $K^-) \nu_\tau + \geq 1 \pi^0$	37%	Tracker and Hcal iso Track
3 prong	15%	Skinny Jet with 3 tracks

Hadronic Tau Selection

- 35% of Tau decays are to e or μ + neutrinos

τ^- Decay	Branching Fraction	Detector Signature
$\mu^- \nu_\mu \nu_\tau$	17%	Isolated μ
$e^- \nu_e \nu_\tau$	18%	Isolated e
(π- or K-) ν_τ	12%	Isolated Track
(π- or K-) ν_τ + ≥1 π^0	37%	Tracker and Hcal iso Track
3 prong	15%	Skinny Jet with 3 tracks

Hadronic Tau Selection

- 12% of Tau decays are to single track + neutrinos

τ^- Decay	Branching Fraction	Detector Signature
$\mu^- \nu_\mu \nu_\tau$	17%	Isolated μ
$e^- \nu_e \nu_\tau$	18%	Isolated e
$(\pi^-$ or $K^-) \nu_\tau$	12%	Isolated Track
$(\pi^-$ or $K^-) \nu_\tau + \geq 1\, \pi^0$	37%	Tracker and Hcal iso Track
3 prong	15%	Skinny Jet with 3 tracks

Hadronic Tau Selection

+ 52% of Tau decays to 1 or 3 track "skinny jets" with Ecal deposits.

τ^- Decay	Branching Fraction	Detector Signature
$\mu^- \nu_\mu \nu_\tau$	17%	Isolated μ
$e^- \nu_e \nu_\tau$	18%	Isolated e
(π- or K-) ν_τ	12%	Isolated Track
(π- or K-) ν_τ + ≥1 π^0	37%	Tracker and Hcal iso Track
3 prong	15%	Skinny Jet with 3 tracks

Hadronic Tau Selection
(Divided into two Categories)

Isolated Track

- Sensitive to $\tau^{\pm} \rightarrow \pi^{\pm}\upsilon\upsilon$ and poorly reconstructed e's and μ's
- Relative Isolation < 15%
- Simple object that can be used at first data with small systematic uncertainties.
- Higher efficiency, and lower background than more complicated tau candidates.

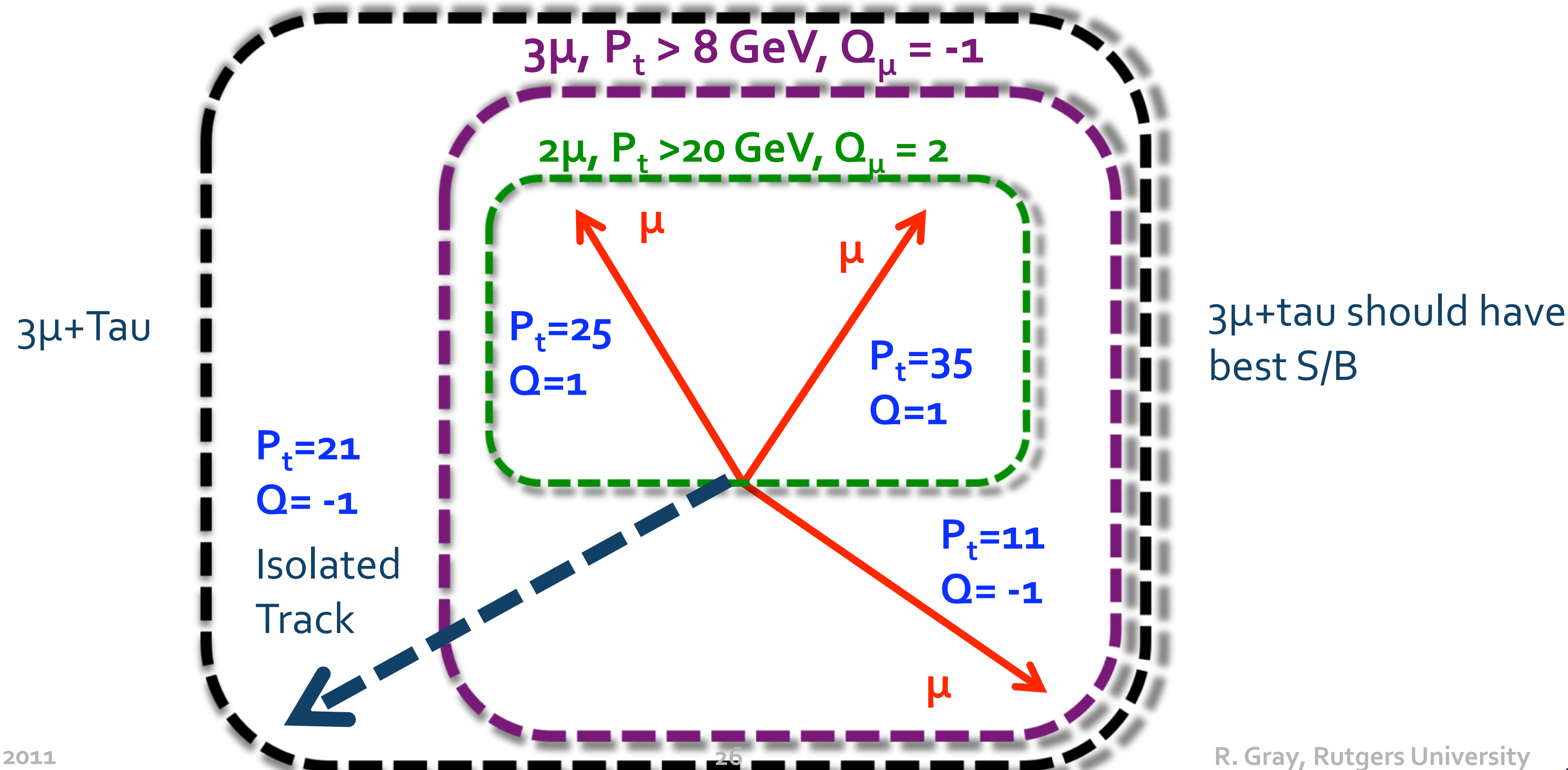
"Particle Flow" (PF) Tau

- Sensitive to $\tau^{\pm} \rightarrow \pi^{\pm} \geq 1\pi^{0}$ and $\tau \rightarrow 3\pi^{\pm}$ with 4× branching fraction of isolated track.... but smaller efficiency.
- Look for signal tracks (1 or 3) and showers in narrow "signal" cone.
  - Tracks have $p_t > 5$ GeV
  - Signal cone shrinks: ΔR 0.1 or 5 GeV / p_T
- Require low energy in a larger "isolation" cone. (ΔR=0.5 to signal)
- More complicated object with large (~30%) systematic uncertainty.

Exclusive Channels

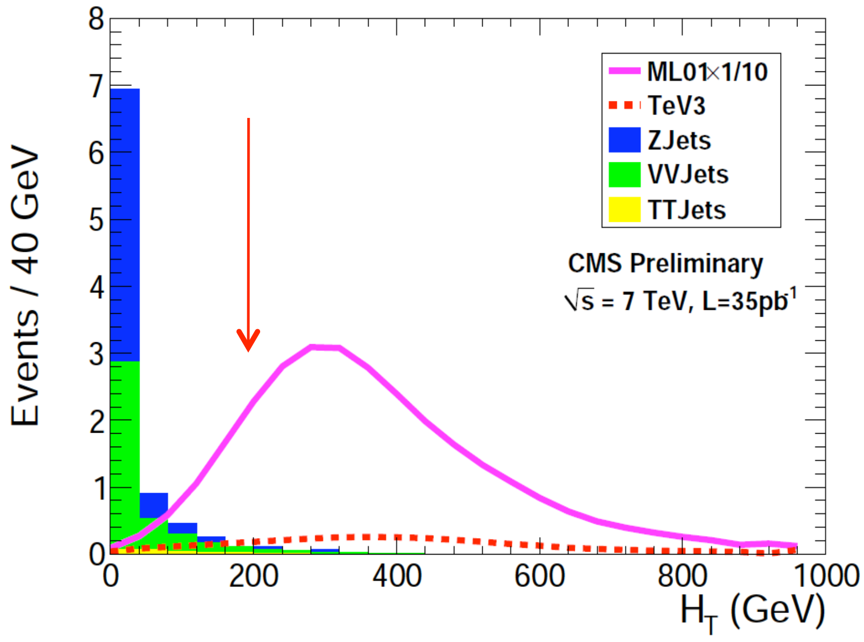
- Each event must be in one and only one final state.
  - Object priority given in order: μ, e, τ(track), τ(PF), Jet
  - Final State Priority given to channel with the most leptons

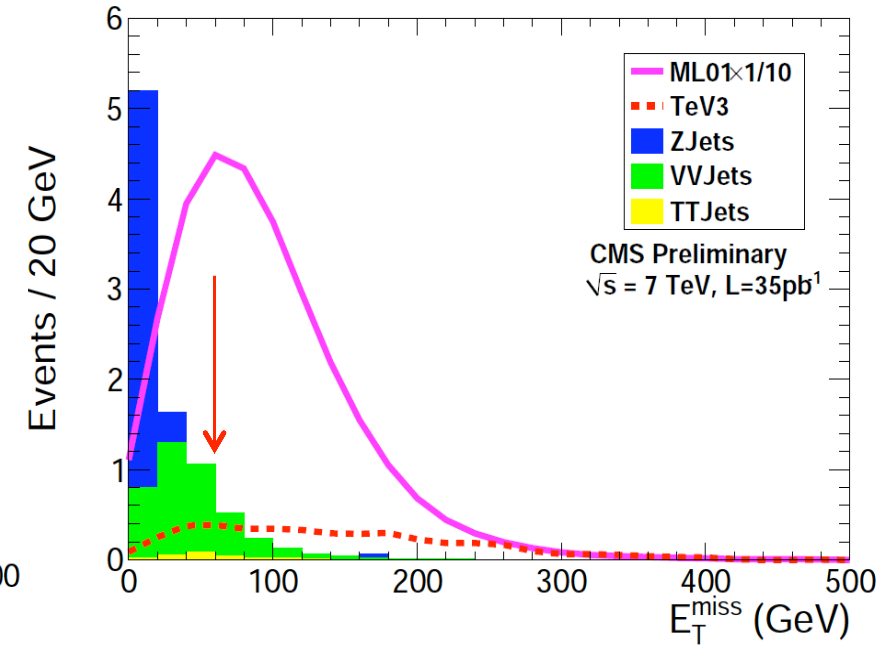
Example: 2μ (SS) vs 3μ vs 3μ+Tau



Background reduction variables

Even after requiring 3 or more leptons, there are still some SM backgrounds. These can be removed by cutting on missing transverse energy or H_T .

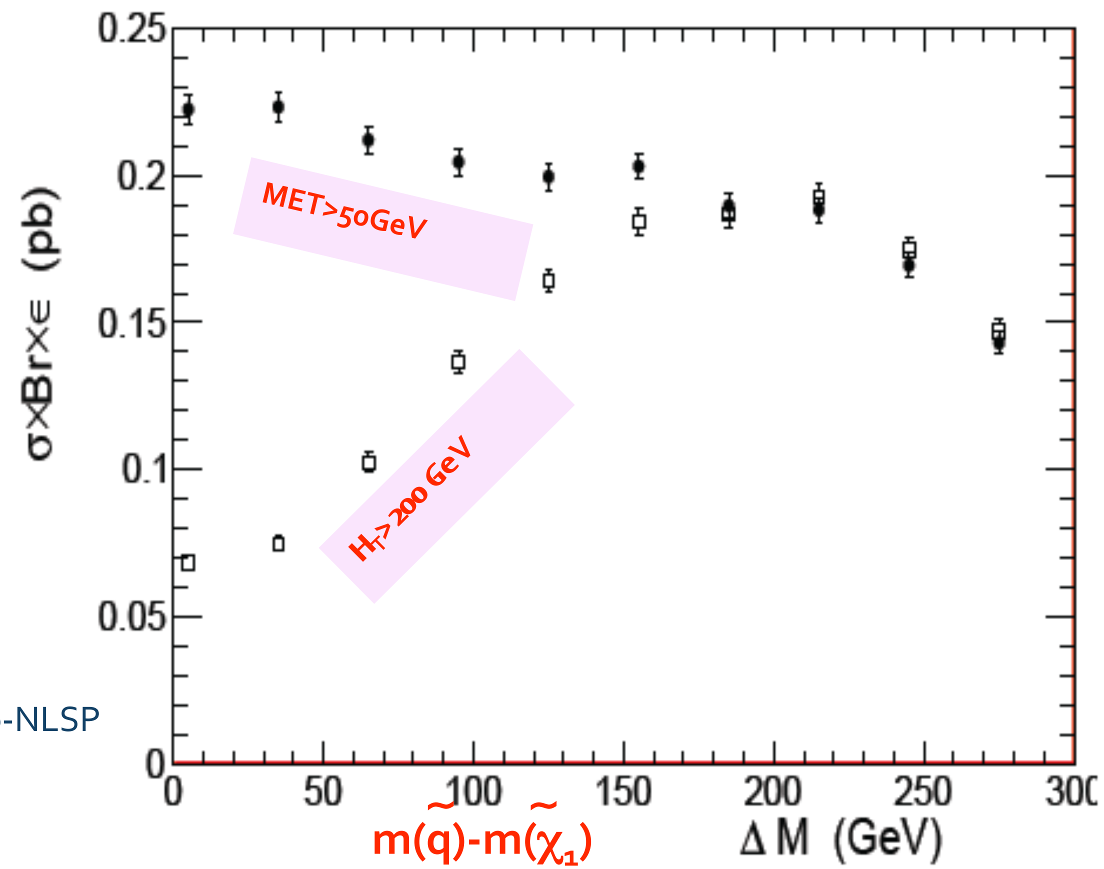




H_T is the total jet E_T for jets with E_T> 30 GeV

Background reduction variables

Beware, models vary. Not all of them have large H_T.



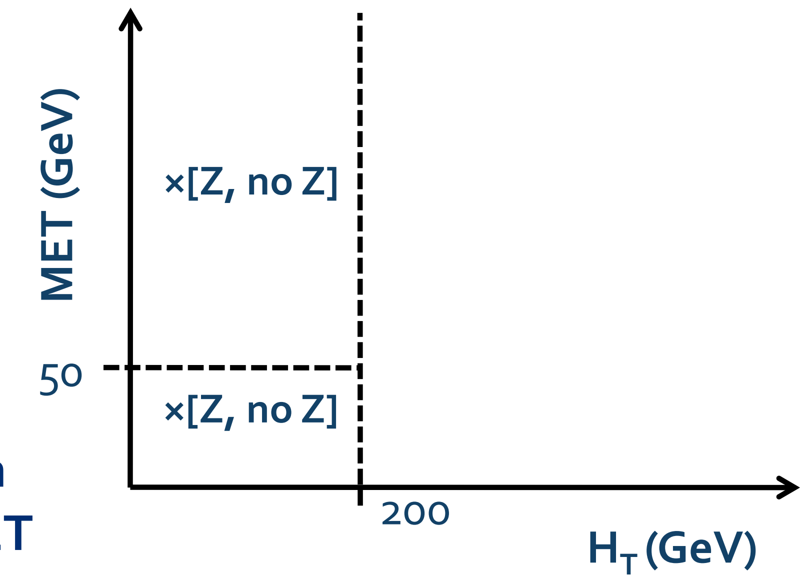
Example:
slepton co-NLSP
scenario
m(q)=500

Importance of ≥3 Leptons

- Is a ≥2 lepton analysis a superset of a ≥3 lepton analysis?
  - In other words, wouldn't ≥2 leptons catch all of the ≥3 leptons?
- 2 lepton analysis needs tight MET or H_T (or both) to control background.
  - New physics with ≥ 3 leptons, but marginal MET or H_T, would be missed by a ≥2 lepton analysis.
- Analysis of ≥3 lepton important because 3rd of 4th leptons reduces or eliminate the need to cut on MET or H_T.
- In multilepton analysis we bin in MET and H_T quantities rather than cut on them.
  - Maximizes range of SUSY sensitive to the analysis.
  - Don't miss a discovery because of choice of background reduction.

Event selection

- Include 3 and ≥4 lepton combinations with ≤2 τ's
  - Use single e and single μ Triggers
  - Veto events where M(l+l-) < 12 GeV (J/ψ, Upsilon)
  - Require ≥1 μ with pt > 15 GeV or ≥1 e with pt > 20 GeV
- Divide remaining events into 5 bins defined by background reducing variables.
  - H_T>200 GeV
  - MET>50 GeV
  - 75 GeV <$M(l^+l^-)$<105 GeV
- PF Tau backgrounds are large enough that we only consider them if both MET and HT are large.



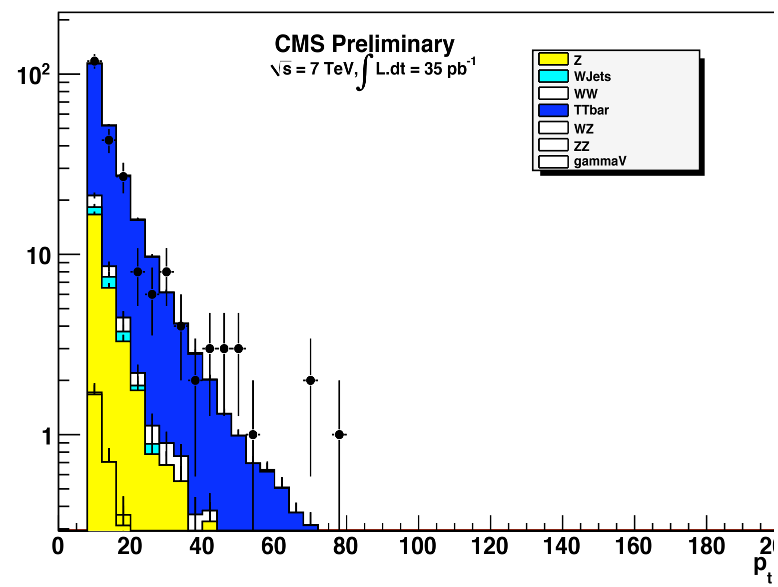
Background Predictions

- Some are directly from Monte Carlo (MC)
  - Irreducible backgrounds: WZ+Jets, ZZ+Jets
    - Corrected to match efficiency measurements.
    - Small cross sections.
- Some are from MC with Data Controls or Scale Factors
  - Including TTbar and FSR from dileptons
    - Correct MC to match efficiency measurements
- The rest are completely "Data Driven"
  - Z+Jets, WW+Jets, W+Jets, QCD
    - No MC required.
    - Use variation on fake rate method (CFO)

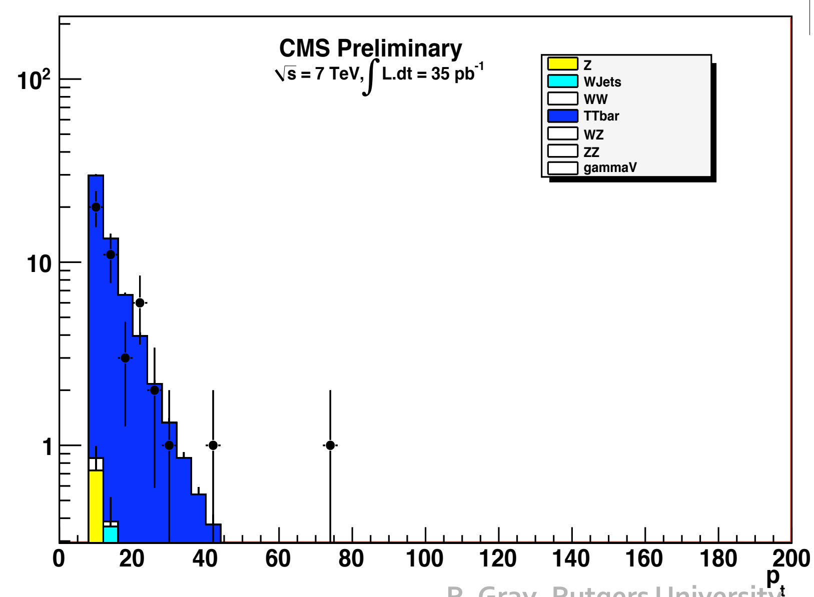
TTbar Background

- Obtained from Monte Carlo but validated in control data.
  - Compare to relevant distributions in data dominated by TTbar.
- Compare non-isolated tracks in $e^+\mu^-$ events
  - Look at large and small impact parameter
  - Related to # of fake leptons, # of b-jets

$e^+\mu^-$: p_t of Tracks with $|d_{xy}(BS)| < 0.02$ cm



$e^+\mu^-$: p_t of Tracks with $|d_{xy}(BS)| > 0.02$ cm



Data Driven Background Predictions

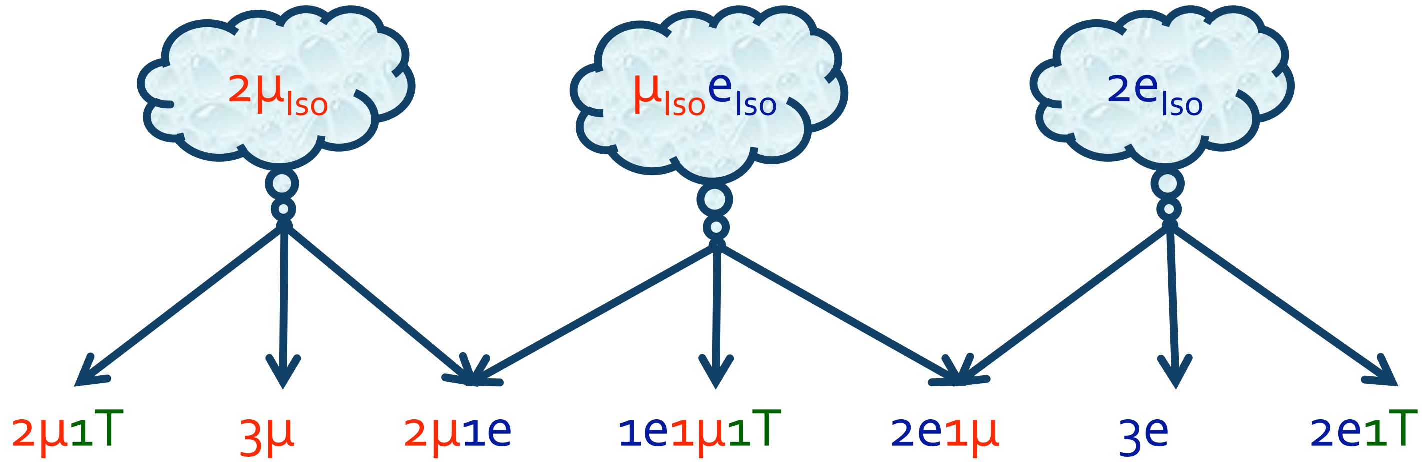
- We want to avoid trusting our MC for our background predictions.

- We use a variation on the CDF (Tevatron) Fake Rate Method
  - Used in CDF 2 fb^{-1} 3-lepton analysis--(Dube, Somalwar)
  - Fake Rate Method may have different names in literature:
    - "Fake Rate" method: CDF Tevatron and CMS Multi-Leptons
    - "Tight-Loose" method: CMS SS Leptons, recent ATLAS papers.

- Goal: Predict backgrounds with fake leptons just using data
  - Fakes include: real e/μ from jets or K/π/γ passing selection.

Data Driven Predictions

- Use 2L data as a seed to predict ≥3L background
  - Example: 2e(SS) to predict 2e(SS)μ background



- Apply background estimation procedures to seeds.
  - Fake e or μ "fake rate" method with isolated tracks
  - Fake iso-track uses loose isolation tracks.

Fake Rate Basics

- Basic Idea:
  - Select an object to act as a proxy for fake leptons
    - Pick something related to the fakes
    - But should occur more frequently than fakes.
  - Determine a conversion factor (f_{μ}) from control data (di-jet).
    - $f_{\mu} = N_{FAKE}/N_{PROXY}$
  - Substitute fake proxy as a lepton in your analysis.
  - Scale events by f_{μ} to get background prediction.

Choosing a Fake Proxy

- Systematics arise from assumption that fake rate is constant.
- Choice of fake proxy affects the type and size of systematic
  - Examples:
    - Loose isolation requirement: Sensitive to jet spectra
    - Loose Lepton ID: Sensitive to types of jets (b, c, uds, glue).
- Systematic uncertainties increase the looser the proxy
- Multilepton analysis uses isolated tracks for e/μ predictions.
  - Lots of statistics---needed for the low stats in multi-lepton.
  - Fake rate insensitive to jet spectra.
  - BUT! Fake rate sensitive to jet types (b, c, uds, glue)

Controlling Fake Rate Systematics
(Addition to CDF Fake Rate Method)

- Write track→lepton fake rate (f_L), in terms of:
  - Non-isolated leptons (N_L)
  - Non-isolated tracks (N_T)
  - Ratio isolation efficiencies. ($\epsilon^{\mu}_{Iso}/\epsilon^{T}_{Iso}$)

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

Parameterize from control data. Measure parameters in dilepton data.

Other fake rate (tight-loose) methods constrain isolation. Here, we can use full range (factor of 10).

Measure this ratio in both control and dilepton data

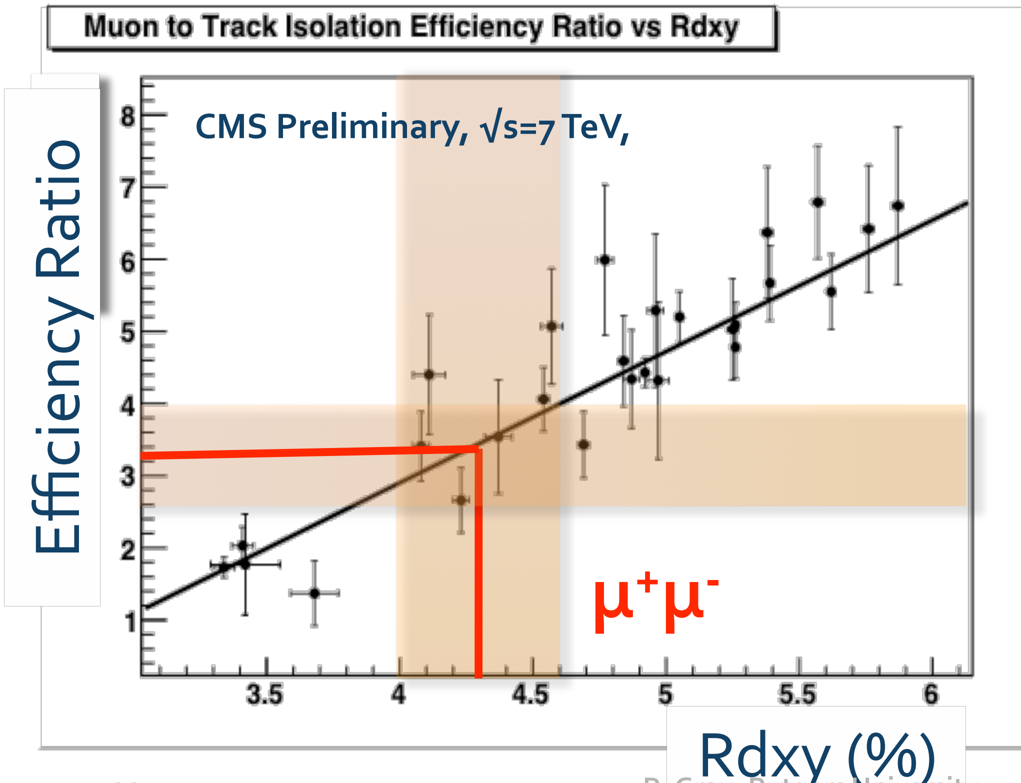
Parameterize Efficiency Ratio

$$f_\mu = \frac{N_\mu^{Iso}}{N_T^{Iso}} = \frac{N_\mu}{N_T} \times \frac{\epsilon_{Iso}^{\mu}}{\epsilon_{Iso}^{T}}$$

- Correlated with fraction of heavy flavor in jets.
  - B, or D mesons in b and c jets (also glue)
- Heavy flavor have large impact parameter $|d_{xy}|$
- Define Ratio R_{dxy}
  - #tracks with large $|d_{xy}|$ (0.02cm – 0.2 cm) divided by # with small $|d_{xy}|$ (< 0.02 cm).
  - Indicates, on average, #tracks from heavy flavor.

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

- For μ+μ- data:
  - $N_\mu/N_T = 0.67\% \pm 0.13\%$
  - $R_{dxy} = 4.3\% \pm 0.3\%$
  - $\varepsilon_\mu/\varepsilon_T(R_{dxy}) = 3.3 \pm 0.6$
- $f_\mu = 2.2\% \pm 0.6\%$



Background Tests

- $\mu^+\mu^-\mu^\pm$ (MET < 50 GeV, H_T <200 GeV, with Z candidate)

Obs	SM Total	Data Driven	TTbar	WZ(ZZ) +Jets	FSR
2	1.8±0.3	1.1	0.01	0.7	0

- $\mu^+\mu^-e^\pm$ (MET < 50 GeV, H_T<200 GeV, with Z Candidate)

Obs	SM Total	Data Driven	TTbar	WZ(ZZ) +Jets	FSR
2	1.4 ± 1.1	0.7	0.005	0.5	0.2

- $\mu^+\mu^-T^\pm$ (MET < 50 GeV, H_T<200 GeV, with Z Candidate)

Obs	SM Total	Data Driven	TTbar	WZ(ZZ) +Jets	FSR
43	56 ± 12	55.8	0.02	0.25	0.3

Observations and Backgrounds

Observed and Predicted are Consistent

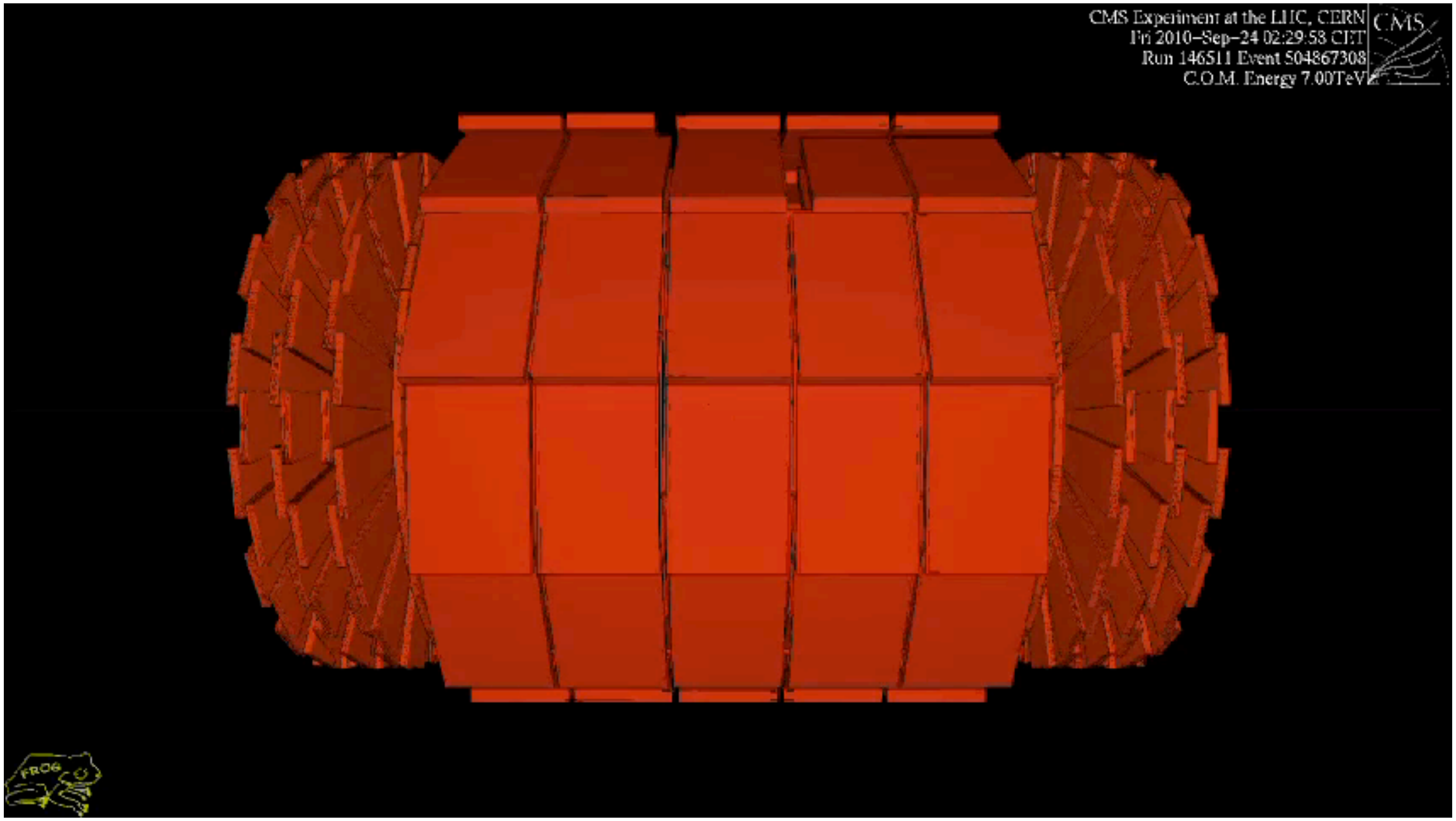
Before MET cut | After MET cut

Channel	ΣSM (before MET cut)	Data (before MET cut)	ΣSM (after MET cut)	Data (after MET cut)
	3-lepton channels			
$ll(OS)e$	4.4 ± 1.5	6	0.1 ± 0.1	0
$ll(OS)\mu$	4.7 ± 0.5	6	0.10 ± 0.1	0
$ll(OS)T$	123 ± 16	127	0.4 ± 0.1	0
$ll(OS)\tau$	484 ± 77	442	–	–
$ll'T$	1.7 ± 0.7	3	0.4 ± 0.2	2
$ll'\tau$	11.2 ± 2.5	10	–	–
$ll(SS)l'$	0.2 ± 0.1	0	0.2 ± 0.1	0
$ll(SS)T$	0.7 ± 0.4	3	0.1 ± 0.1	0
$ll(SS)\tau$	3.0 ± 1.1	3	–	–
$\Sigma\, lll(T)$	135 ± 16	145	1.3 ± 0.2	2
$\Sigma\, lll(\tau)$	507 ± 77	467	–	–
lTT	48 ± 9	30	0.4 ± 0.1	0
Channel	4-lepton channels			
$llll$	0.2 ± 0.1	2	0	0
$lllT$	0.1 ± 0.1	0	0	0
$lll\tau$	0.1 ± 0.1	0	–	–
$llTT$	0.0 ± 0.1	0	0	0
$ll\tau\tau$	3.2 ± 0.7	5	–	–
$\Sigma\, llll(T)$	0.3 ± 0.1	2	0	0
$\Sigma\, llll(\tau)$	3.5 ± 0.7	5	–	–

Famous ZZ(4μ) event here
(over 5,000 views on YouTube)
I first saw it Sunday 10/10/2010

ZZ→4μ Event

- Bragging rights for being the first person to spot an interesting event.
  - Spotted on Sunday 10-10-2010 early in data set.



Multi-Lepton Summary Table

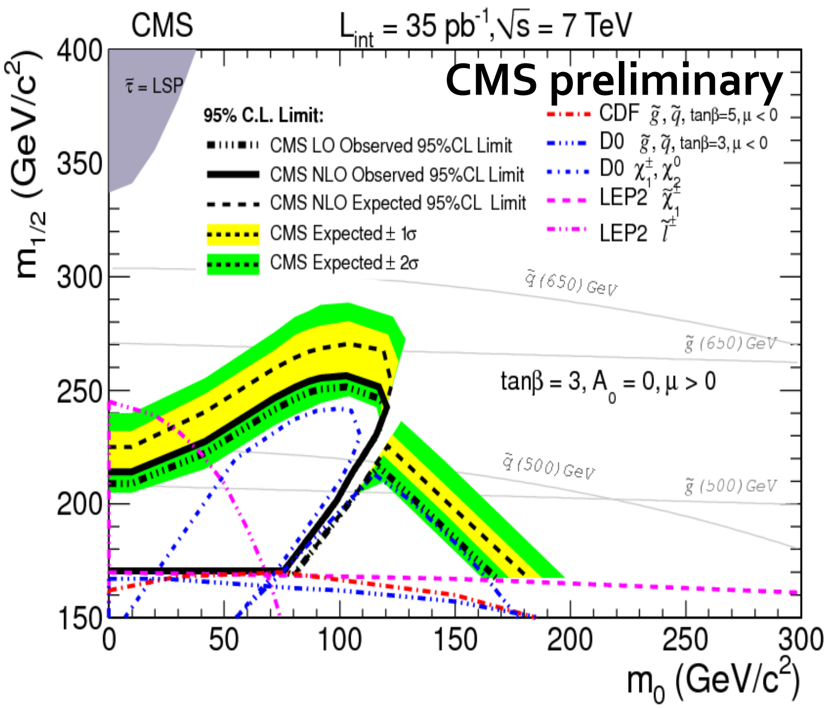
No statistically significant deviation from the standard Model.

	After Lepton ID Requirement					MET > 50 GeV		HT > 200 GeV		ML01 Signals	
	Z+jets	$t\bar{t}$	VV+jets	ΣSM	Data	ΣSM	Data	ΣSM	Data	Incl.	Hadr.
Channel	3-lepton channels										
$ll(OS)e$	1.7	0.1	1.2	4.4 ± 1.5	6	0.1 ± 0.1	0	0.2 ± 0.1	1	121.4	141.5
$ll(OS)\mu$	2.83	0.2	1.7	4.7 ± 0.5	6	0.10 ± 0.1	0	0.1 ± 0.1	0	123.6	120.8
$ll(OS)T$	121.5	0.5	0.7	123 ± 16	127	0.4 ± 0.1	0	–	–	80.5	–
$ll(OS)\tau$	476	2.7	3.9	484 ± 77	442	–	–	0.6 ± 0.2	1	–	68
$ll'T$	0.72	0.5	0.2	1.7 ± 0.7	3	0.4 ± 0.2	2	–	–	18.6	–
$ll'\tau$	4.7	2.9	0.6	11.2 ± 2.5	10	–	–	0.4 ± 0.1	1	–	12.3
$ll(SS)l'$	0.13	0.1	0.0	0.2 ± 0.1	0	0.2 ± 0.1	0	0	0	2.8	2.8
$ll(SS)T$	0.25	0.0	0.1	0.7 ± 0.4	3	0.1 ± 0.1	0	–	–	9.0	–
$ll(SS)\tau$	1.4	0.0	0.1	3.0 ± 1.1	3	–	–	0.0 ± 0.1	0	–	6.9
$\Sigma\, lll(T)$	127.1	1.4	3.8	135 ± 16	145	1.3 ± 0.2	2	–	–	355.9	–
$\Sigma\, lll(\tau)$	486.8	6.0	7.5	507 ± 77	467	–	–	1.3 ± 0.3	3	–	349.5
lTT	47.1	0.33	0.1	48 ± 9	30	0.4 ± 0.1	0	–	–	8.0	–
Channel	4-lepton channels										
$llll$	0	0	0.2	0.2 ± 0.1	2	0	0	0	0	163.9	149.2
$lllT$	0	0	0.1	0.1 ± 0.1	0	0	0	–	–	62.3	–
$lll\tau$	0	0	0.1	0.1 ± 0.1	0	–	–	0	0	–	33.2
$llTT$	0	0	0	0.0 ± 0.1	0	0	0	–	–	20.6	–
$ll\tau\tau$	3.1	0.1	0.1	3.2 ± 0.7	5	–	–	0	0	–	16.8
$\Sigma\, llll(T)$	0	0	0.3	0.3 ± 0.1	2	0	0	–	–	246.8	–
$\Sigma\, llll(\tau)$	3.1	0.1	0.4	3.5 ± 0.7	5	–	–	0	0	–	199.2

no MET

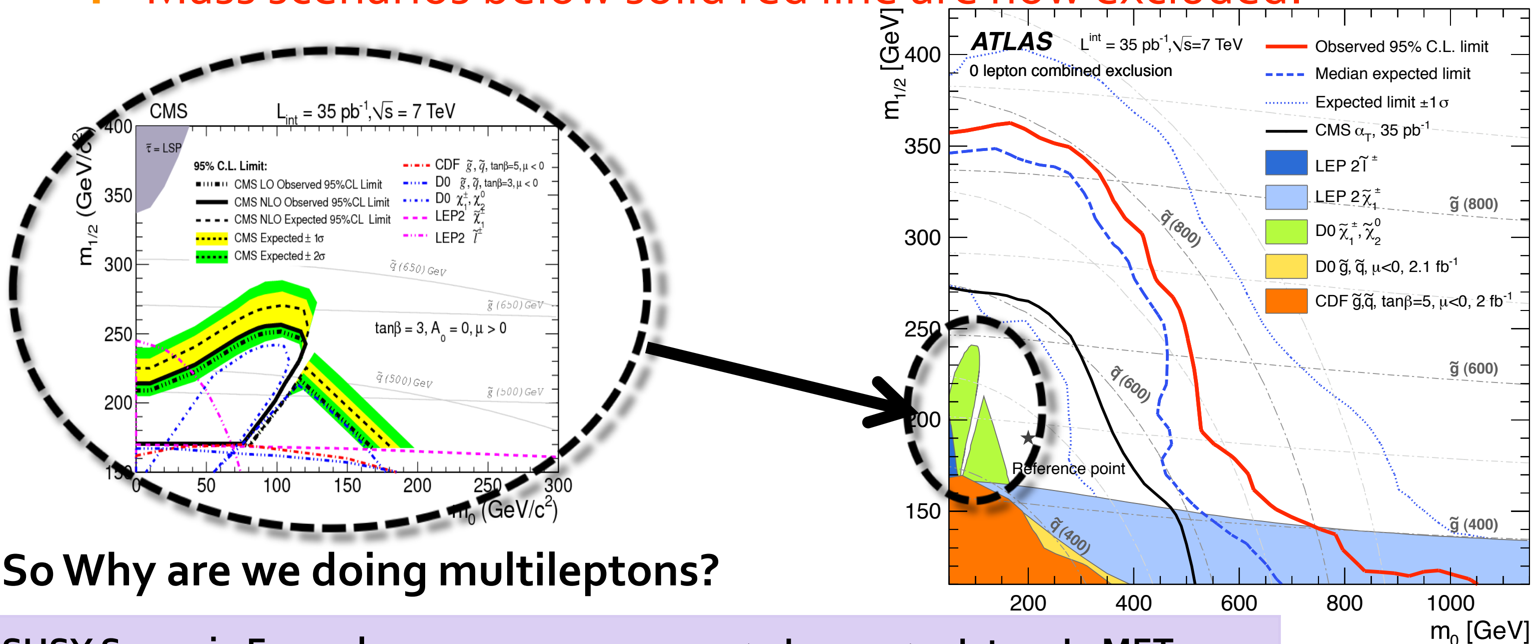
95% Excluded Scenarios (Multi-Leptons)

- mSUGRA (CMSSM)
  - Popular scenario that reduces SUSY parameters down to 5.
    - M0, M1/2, a0, sign(μ), tan(β)
  - No theorist believes mSUGRA, but it has become a standard to compare experiments.
  - Mass scenarios below solid line are now excluded.



95% Excluded Scenarios

- mSUGRA (CMSSM) (Jets + MET (α_T))
  - Mass scenarios below solid red line are now excluded.



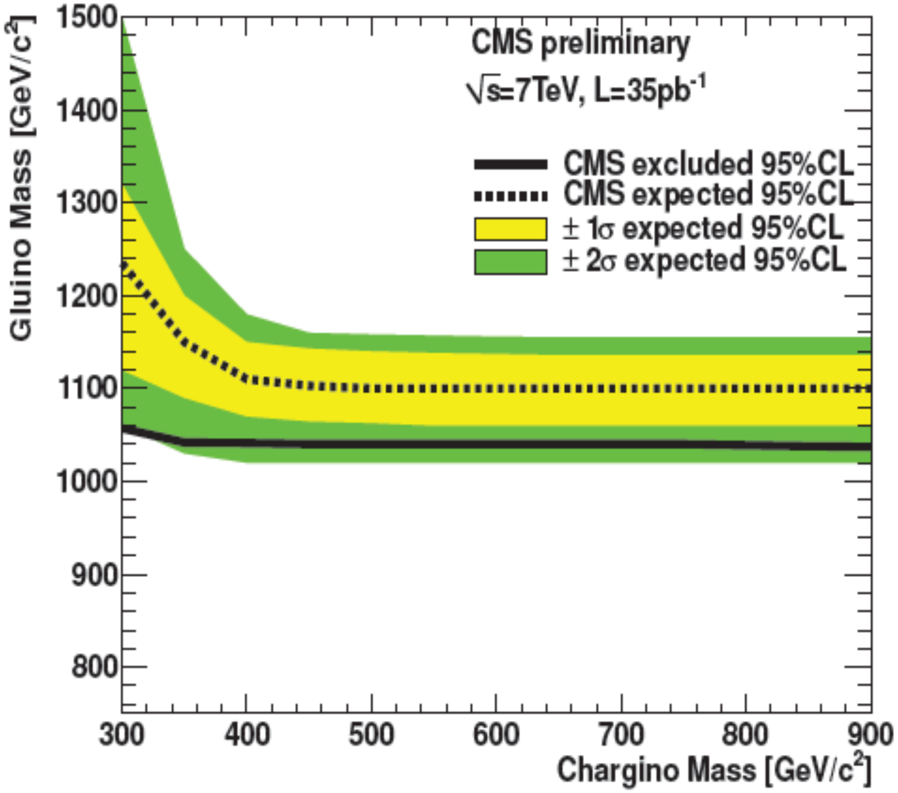
So Why are we doing multileptons?

SUSY Scenario Examples	≥3L	≥2 Jets, 0 L, MET>200
Slepton co-NLSP	~100%	0%
Leptonic R-parity violating	~100%	0%
mSUGRA (M0=60, M1/2=190)	~23%	11.4%
mSUGRA (M0=200, M1/2=250)	~1.8%	35%

mSUGRA isn't friendly to multileptons, but other scenarios are.

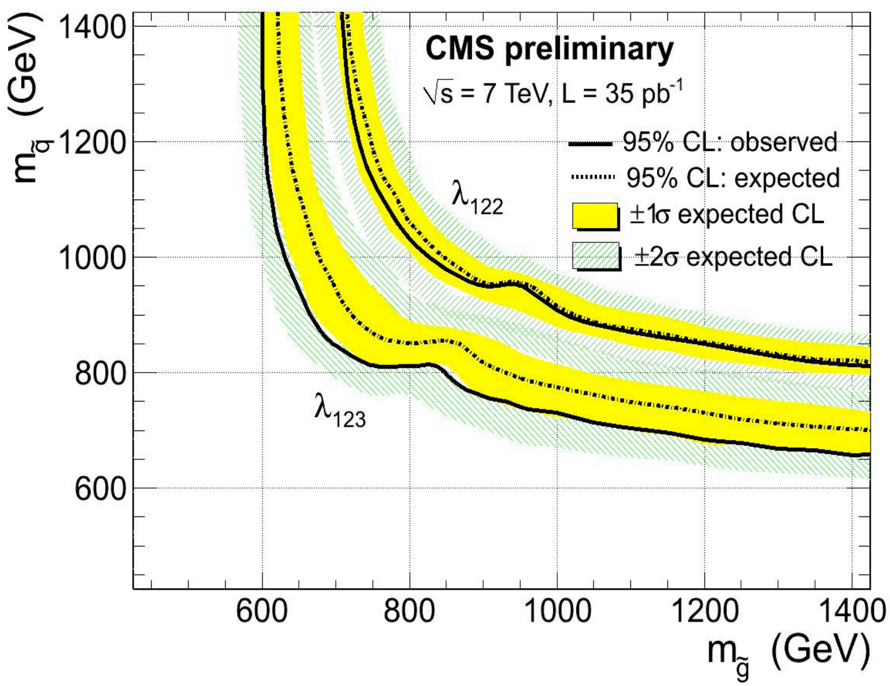
95% Excluded Scenarios (Multi-Leptons)

- Slepton co-NLSP
  - Sleptons have ~ the same mass, and are closest to the lightest SUSY particle which happens to be a gravitino.
  - At least 4 leptons produced per event.
  - Mass scenarios below solid line are now excluded.
  - Tevatron only excluded gluino mass < 400 GeV



95% Excluded Scenarios (Multi-Leptons)

- R-parity violation
  - R-parity is conserved in most SUSY scenarios. But it might be violated.
  - If violated leptonically, can be 4 or more leptons produced per event.
  - Two curves for two different scenariois.
    - λ_{123} contains 2L+2Tau
    - λ_{122} contain no Tau.
  - Mass scenarios below solid line are now excluded.



Conclusions

- Various searches have been performed to look for new physics.
- Presented SUSY in multi-leptons
  - Use combination of MC and data-driven SM background predictions
  - Make use of control objects to understand/control fake rate systematics.
  - Results consistent with the standard model.
  - Set new limits on slepton co-NLSP topology and R-Parity violating SUSY.
- So far data still consistent with the SM, but have constrained the range of many SUSY possibilities beyond the reach of the Tevatron.
- More data is coming… another ~5 pb^{-1} of golden data. The search will continue!