Searches for Supersymmetry in Final States with Leptons with the CMS Detector at the LHC

Ben Hooberman,
on behalf of the CMS Collaboration

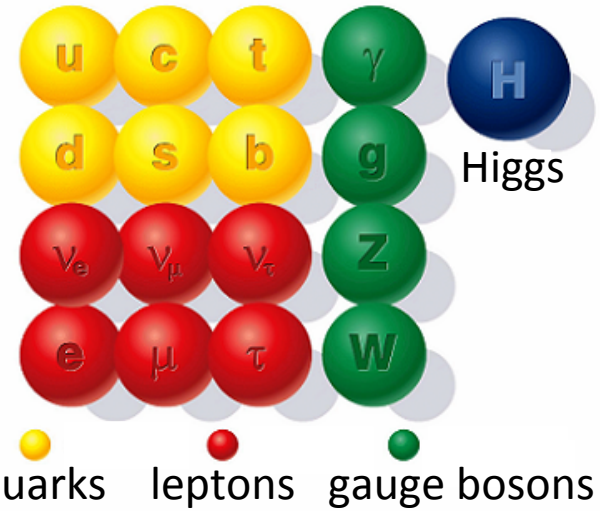
Outline

- **Introduction**
- SUSY Searches
  - Single Lepton
  - Same-sign leptons
  - Opposite-sign leptons
    - Generic (non-Z)
    - Z
- Interpretation of Results

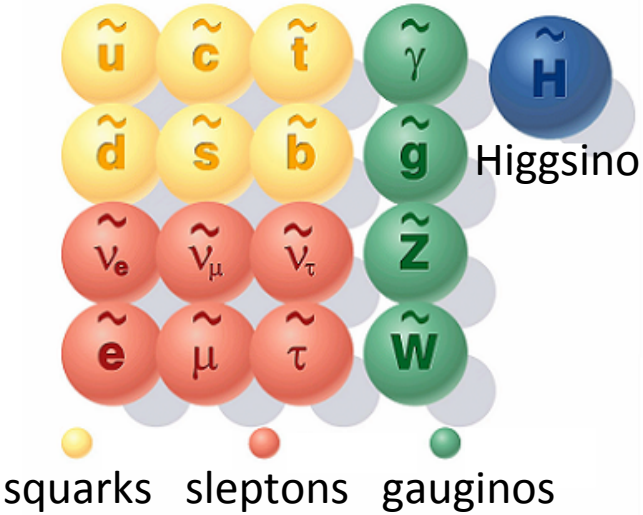
Intro to SUperSYmmetry

- Standard Model (SM) describes known particles/forces. Extremely successful at low energy, but several problems:
  - hierarchy problem
  - gauge coupling non-unification
  - dark matter (DM): preferred explanation WIMP with mass O(100 GeV) → **no SM candidate**
- SUSY: popular extension to SM, introduces "superpartners" to each SM particle
  - Solves many problems intrinsic to SM
  - Lightest SUSY particle (LSP): stable, weakly-interacting particle at EWSB scale ~100 GeV → **natural DM candidate**
  - **Implies DM may be produced at LHC!**

SM particles



SUSY particles

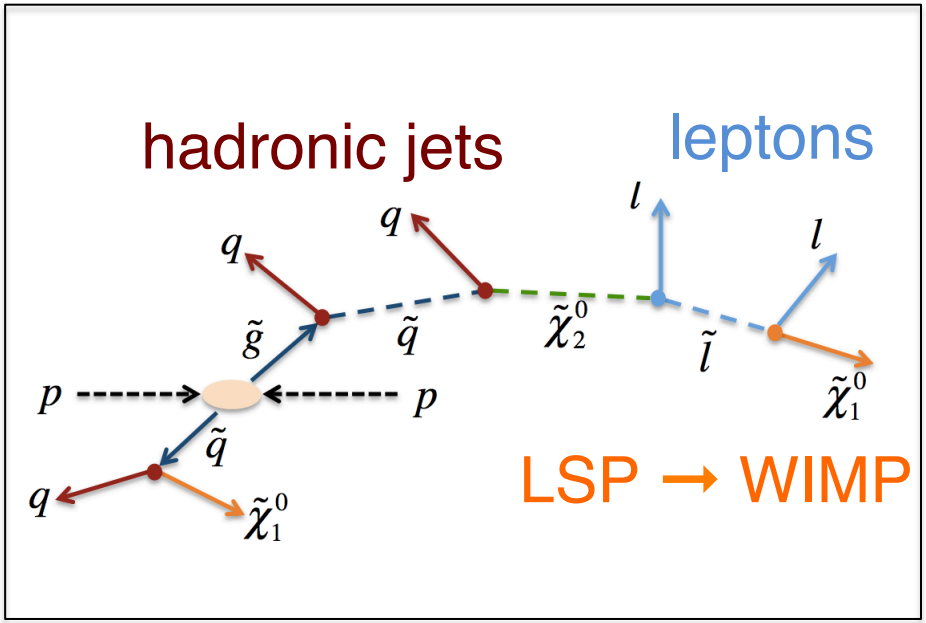


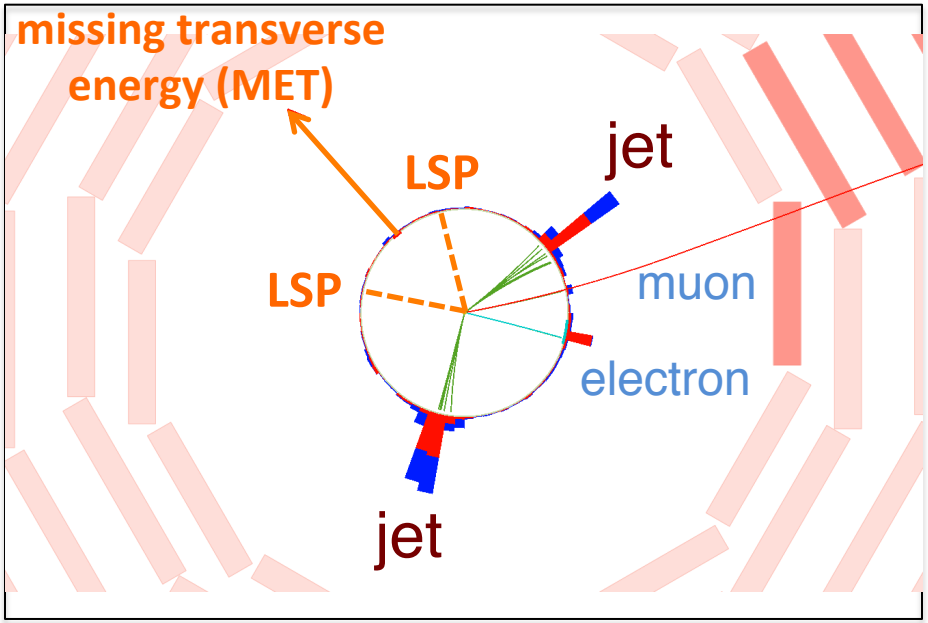
SUSY Production at Colliders

- Many SUSY models postulate conserved quantum number:

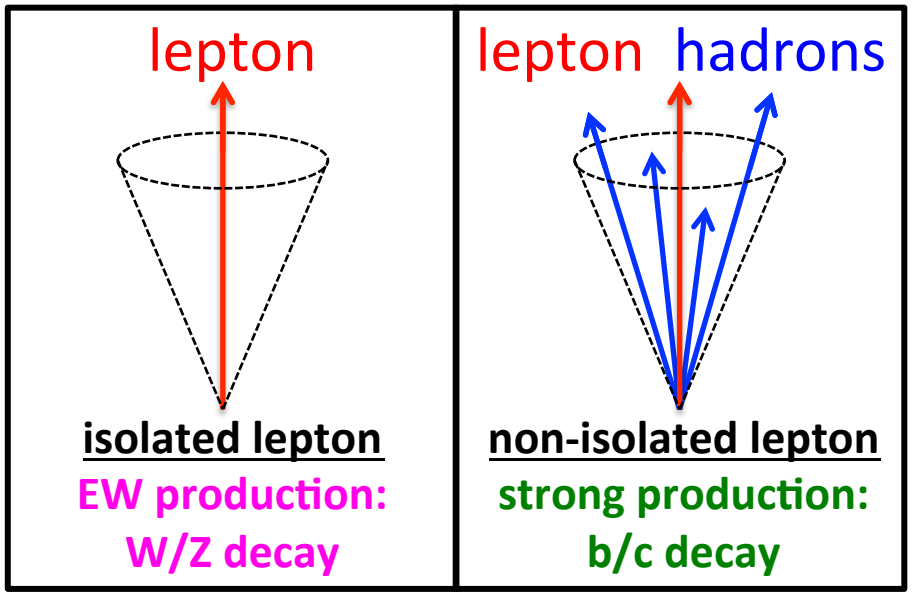
  "R-parity" = { +1 for SM particles / -1 for SUSY particles

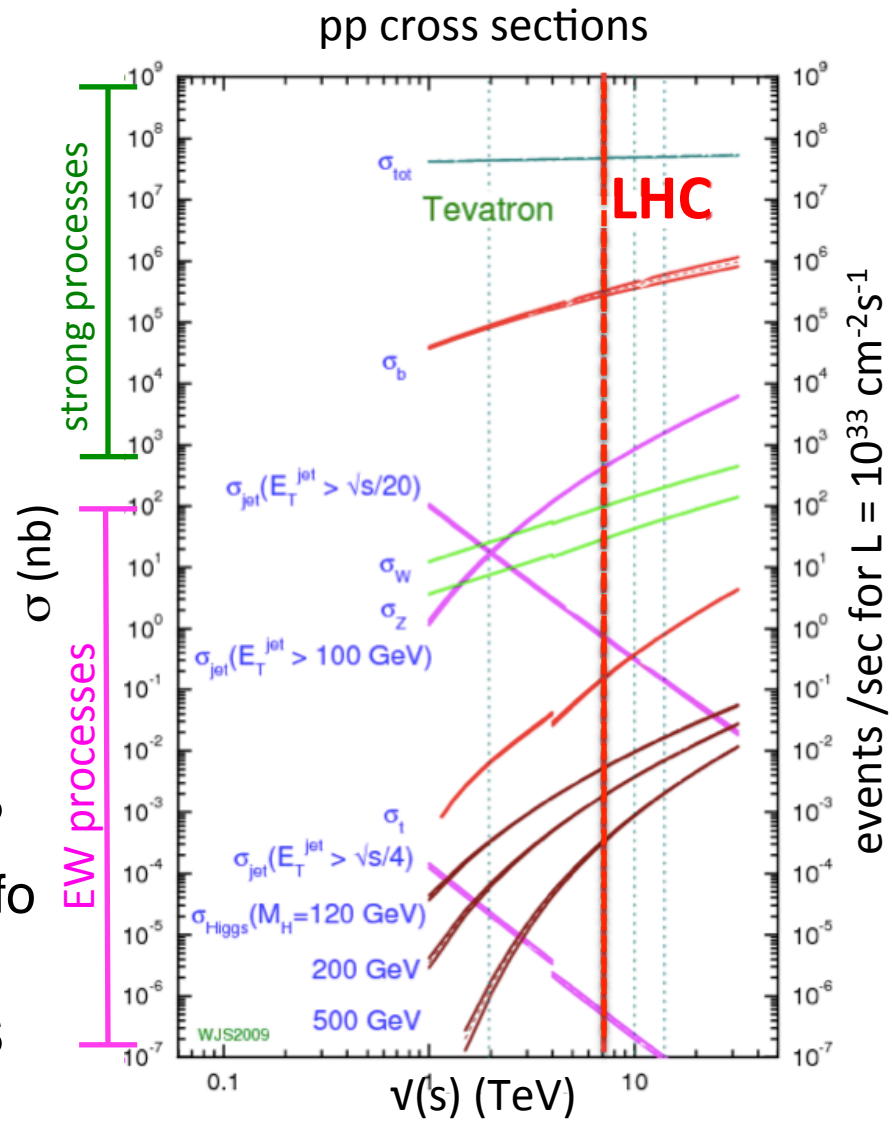
  - SUSY particles produced in pairs (usually strongly produced squarks/gluinos)
  - LSP is stable
- Squarks/gluinos decay via cascade, producing jets, (leptons), 2 LSP's→ spectacular events with several high p_T jets + (leptons) + MET
- **Strategy: search for excess of events w/ large MET, H_T (sum of jet p_T's)**





Why Search for New Physics with Leptons?

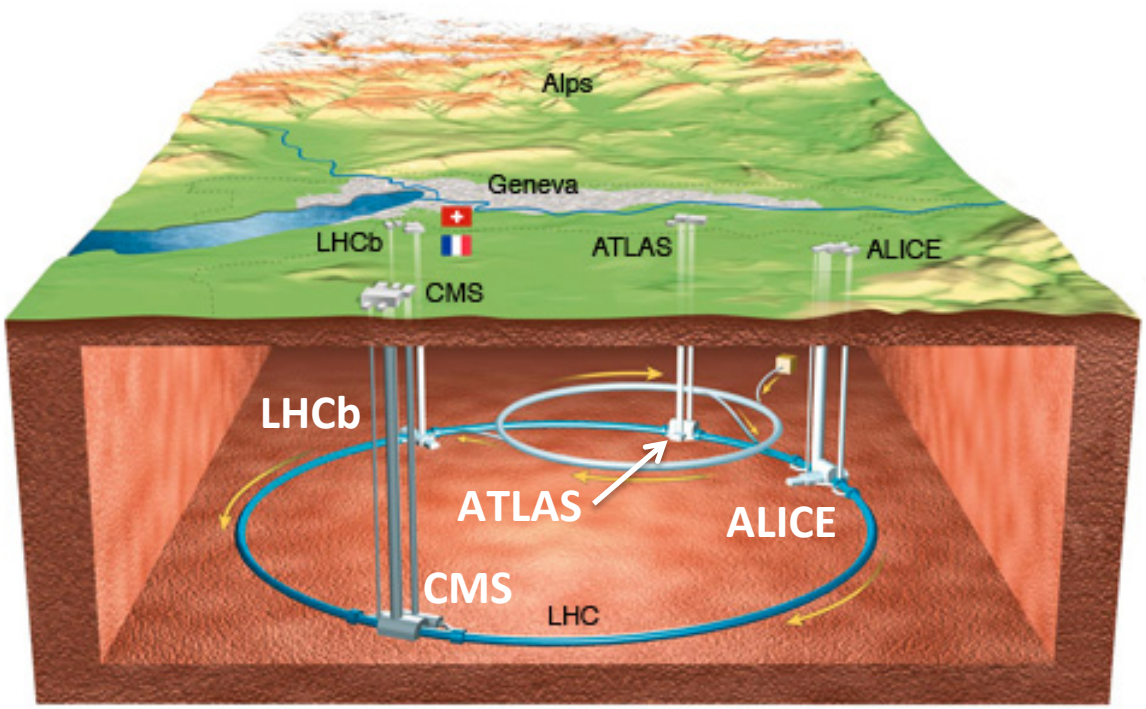


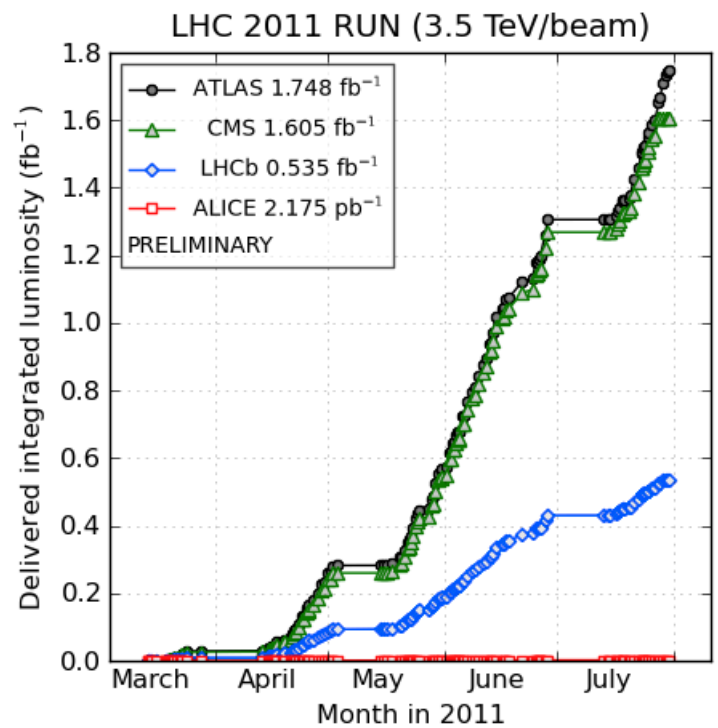


- **Isolated leptons** are very rare → **reduction of huge QCD/strong bkg**
  - Clean environment to search for NP
- Leptons provide additional kinematic info related to SUSY particle masses
  - eg. search for kinematic edge in OS dilepton M(ll) (see talk D. Barge)

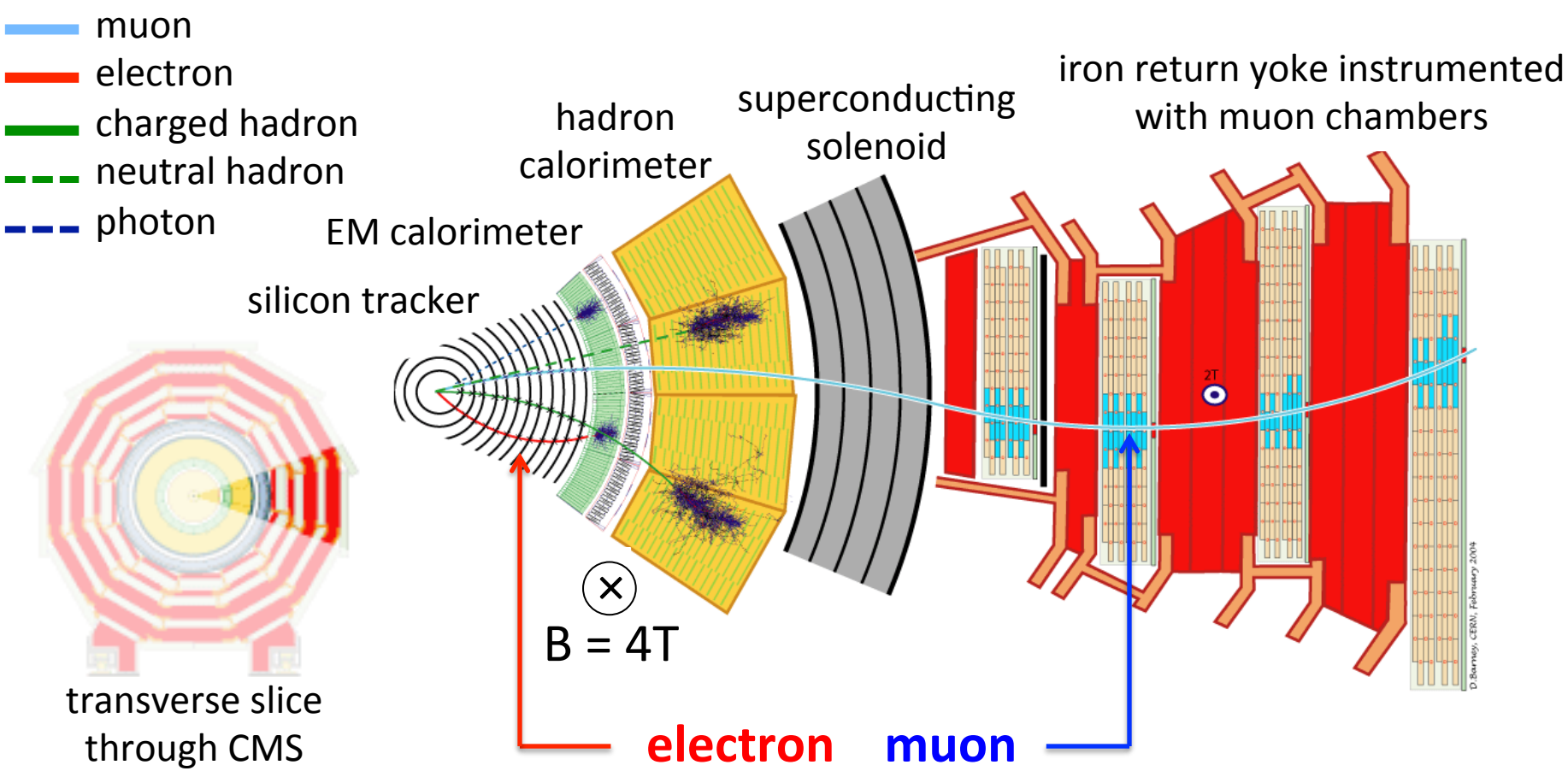
The LHC

- 27 km circumference ring on French-Swiss border
- Provides proton-proton collisions at $\sqrt{s}$ = 7 Trillion eV (TeV)
- Data collected by 1 of 4 experiments:
  - **CMS**, ATLAS, LHCb, ALICE
- Total integrated lumi presented in this talk: 0.98 fb^{-1} 2011 data





CMS detector and Lepton ID



- Most particles are hadrons → electrons/muons very rare
- Electrons: electromagnetic shower in EM calorimeter → deposit full energy
- Muons: minimum ionizing → penetrate deeply into muon system

Overview of SUSY searches

- **Perform broad program of searches in several final states**
  - **This talk: overview of newest results**, followed by more detailed talks
- Maintain sensitivity to broad range of models → signature-based searches, not optimized for any particular SUSY model
- Estimate backgrounds from data (data-driven bkg estimate) → minimize reliance on MC simulation (especially for bkg's with detector (mis)reconstruction effects, estimation of "tails" of kinematic distributions)

leptonic channels

channel	Signature	DPF talks
all-hadronic	jets + MET	S. Paramesvaran
single lepton	**e/μ + jets + MET**	
lepton-photon	e/μ + γ + MET	
di-lepton	**same-sign leptons + jets + MET**	M. Weinberg
	opposite-sign leptons + jets + MET	D. Barge
	Z + jets + MET	D. Barge
multi-lepton	≥3 leptons	S. Maruyama
photon(s)	γ / γγ + jets + MET	D. Nguyen

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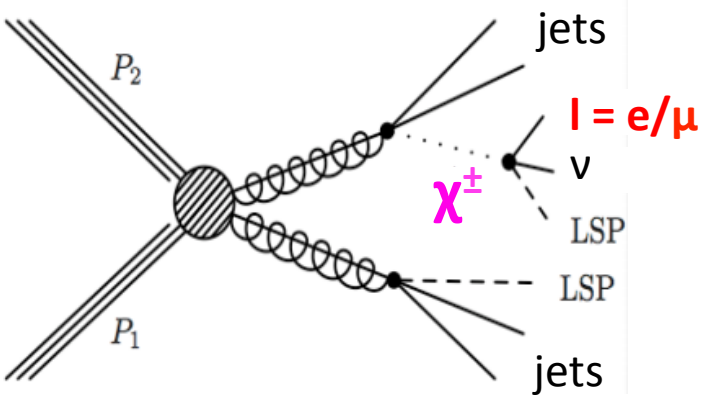
Intro: Single Lepton Search

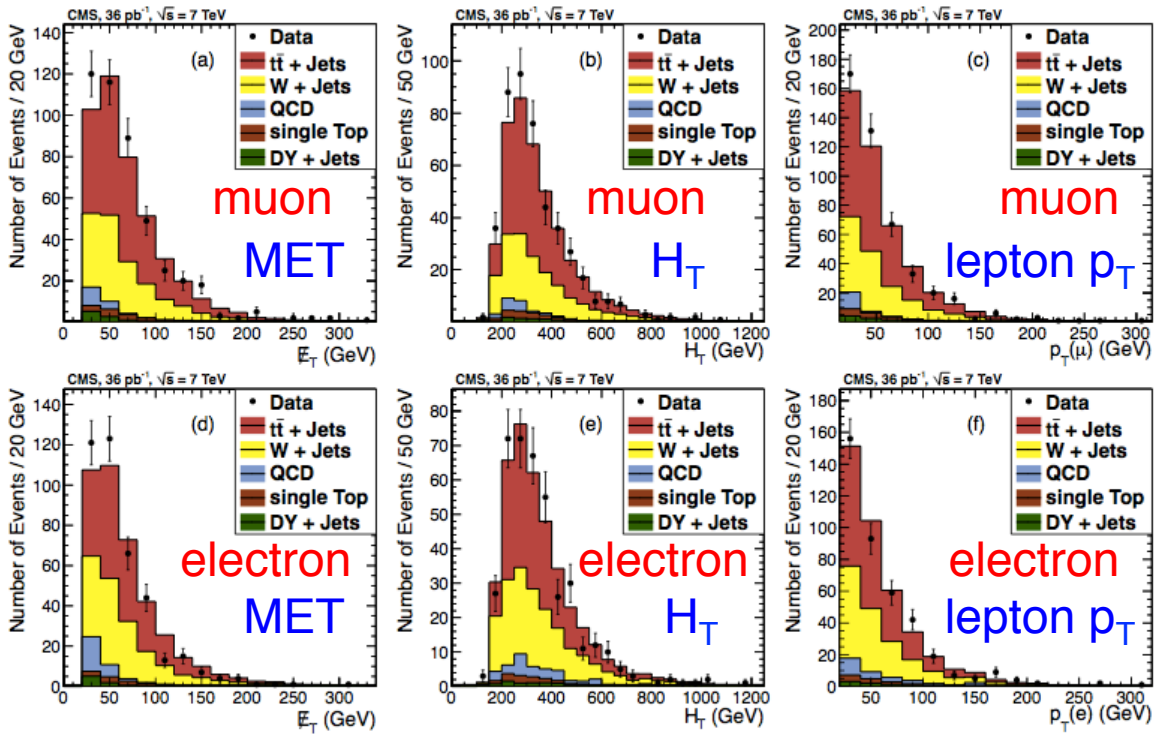
- **Signature: e/μ + ≥4 jets + MET**
  - Dominant bkgs: tt→lepton+jets, W+jets

NEW! arXiv:1107.1870 [hep-ex] 36 pb^{-1} (submitted to JHEP)

- **Event preselection**
  - exactly 1 isolated e ($p_T > 20$ GeV, $|\eta| < 2.4$) or μ ($p_T > 15$ GeV, $|\eta| < 2.1$)
  - ≥4 jets ($p_T > 30$ GeV, $|\eta| < 2.4$)
  - MET > 25 GeV (moderate requirement)

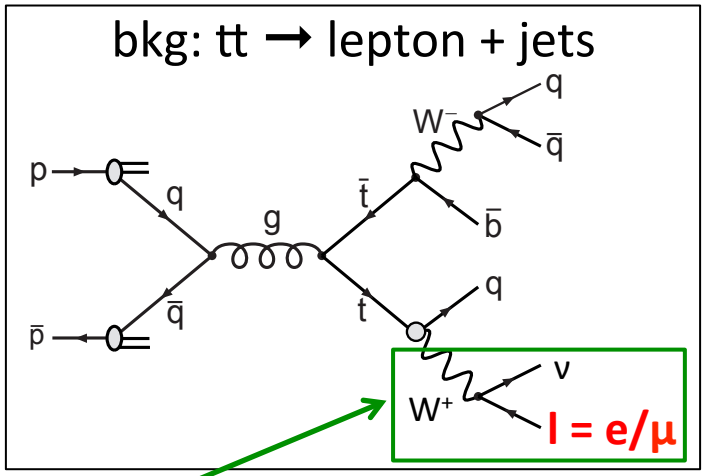
example signal: SUSY with $\chi^{\pm}$ decay



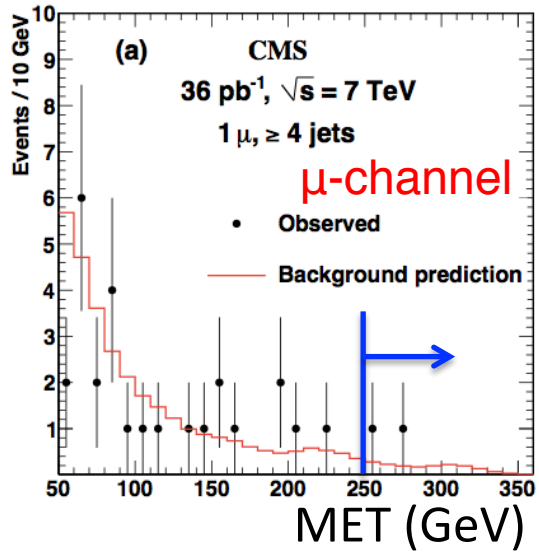


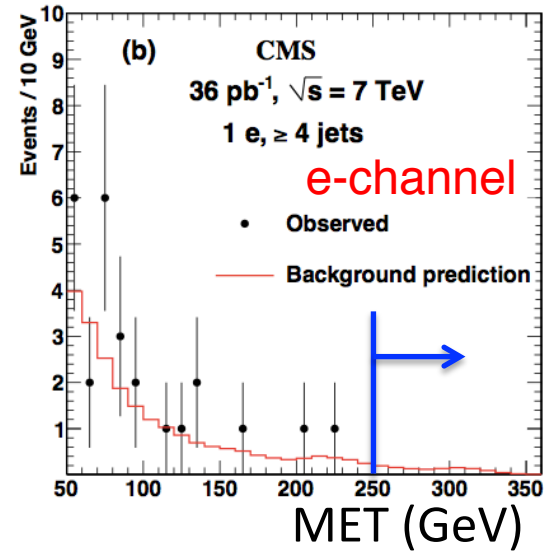
Single Lepton Search Results

- Define signal region: MET > 250 GeV
- Predict bkg with data-driven technique: for dominant bkgs tt, W+jets, $p_T(l)$ and $p_T(\nu)$ ~ MET distributions related
  - Use $p_T(l)$ to model MET → predict bkg yield in signal region
  - **Good agreement observation vs. prediction → no evidence for SUSY**



$\langle p_T(l)\rangle \sim \langle p_T(\nu)\rangle$





	μ-channel	e-channel
observed signal region	2	0
total prediction	1.8 ± 1.1 (stat) ± 0.8 (syst)	1.4 ± 0.9 (stat) ± 0.5 (syst)

set 95% CL upper limit on non-SM yield: 3.8 events

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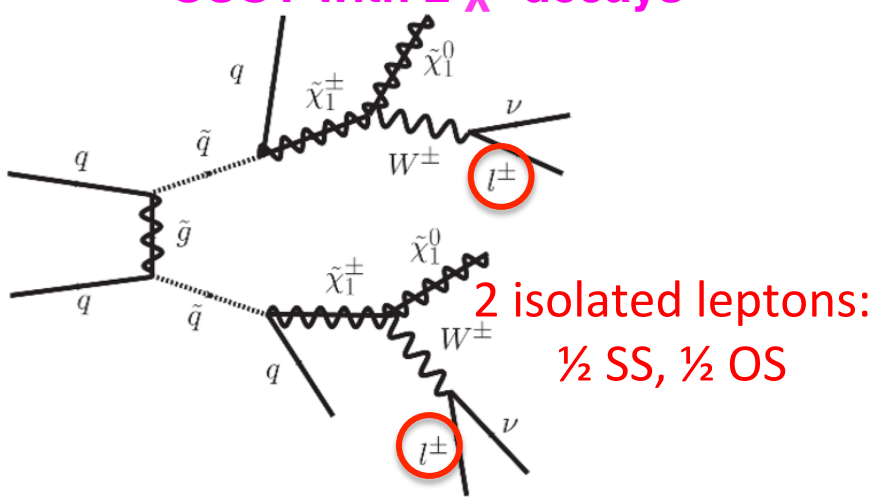
Intro: Same-Sign Dilepton Search

- SS lepton pairs extremely rare in SM, but appear naturally in many BSM scenarios

  NEW! CMS PAS-SUS-11-010 0.98 fb^{-1}

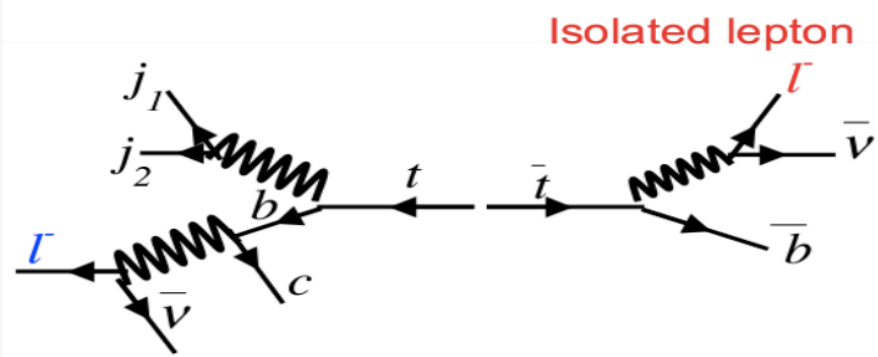
  – SUSY, universal extra dimensions, SS top pair production, heavy Majorana neutrinos
- Dominant SM backgrounds:
  – tt with "fake" leptons (eg. b/c → e/μ) ← estimate from data: "fake rate" method
  – Charge misreconstruction ← same-sign Z sample
  – Rare SM processes: $qq \to q'q'W^{\pm}W^{\pm}$, ttW ← estimate from MC

example signal:
SUSY with 2 $\chi^{\pm}$ decays



2 isolated leptons:
½ SS, ½ OS

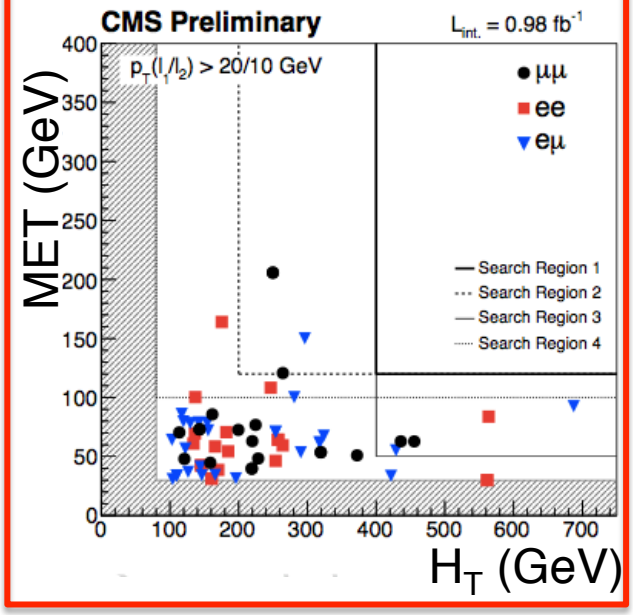
dominant background:
tt with fake lepton



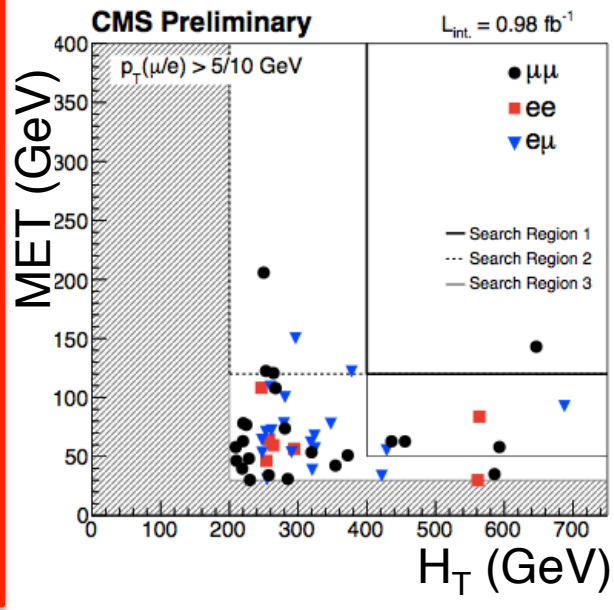
Non-isolated lepton = "fake" lepton

Search Regions

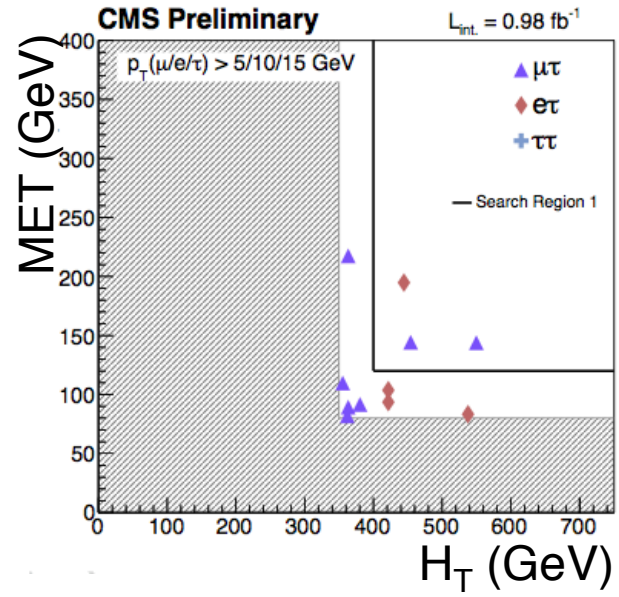
High p_T dileptons
dilepton triggers



Inclusive dileptons
lepton-H_T triggers



τ → hadrons
H_T-MET-lep triggers

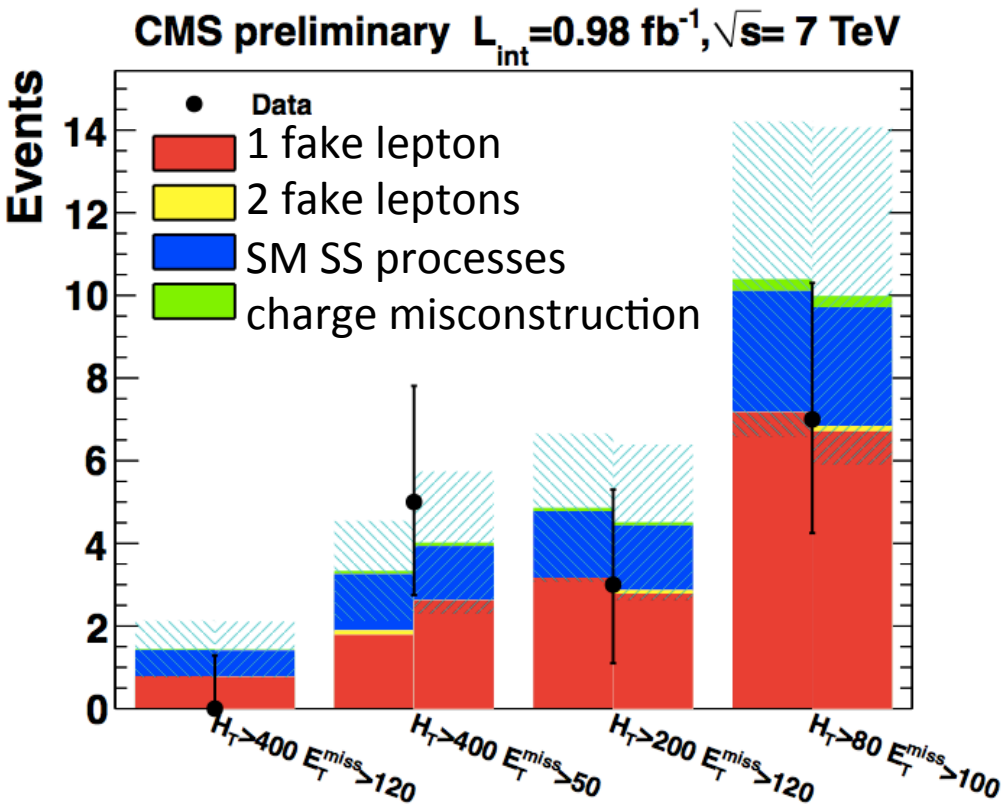


- Search for new physics in 3 complementary samples
  - High p_T dileptons: ←**will focus on this sample, for others see talk by M. Weinberg**
  - Inclusive leptons: extend search to low lepton p_T → compensate trigger rate by increasing H_T cut
  - τ → hadrons: improve sensitivity to 3rd generation
- Define preselection regions in MET-H_T plane (veto shaded regions)
  - Validate data-driven bkg estimates with ~10-100 events
- Define **4 search regions** by adding MET, H_T requirements → **estimate bkg's with data-driven techniques + MC estimates**

Results of SS Search

- All 4 signal regions: good agreement between observed yields and predicted background
- No evidence for SUSY → set 95% CL upper limits on non-SM yield

Search Region (minimum H_T / E_T^{miss})	Total	95% CL UL yield
Region 1 (400/120)		
Predicted background by (A1)	1.4 ± 0.7	
Predicted background by (A2)	1.4 ± 0.7	
Observed	0	3.0
Region 2 (400/50)		
Predicted background by (A1)	4.0 ± 1.7	
Predicted background by (A2)	3.3 ± 1.2	
Observed	5	7.5
Region 3 (200/120)		
Predicted background by (A1)	4.5 ± 1.9	
Predicted background by (A2)	4.9 ± 1.8	
Observed	3	5.2
Region 4 (80/100)		
Predicted background by (A1)	10 ± 4	
Predicted background by (A2)	10 ± 4	
Observed	7	6.0



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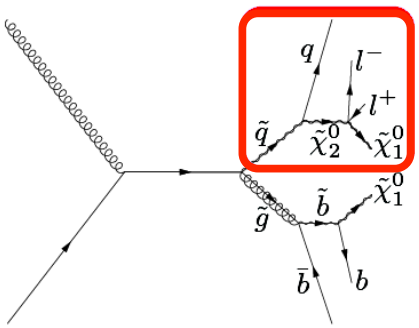
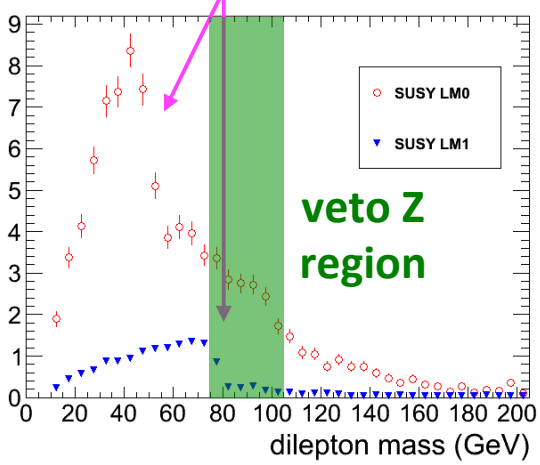
Sources of OS Dileptons in SUSY

neutralino decays

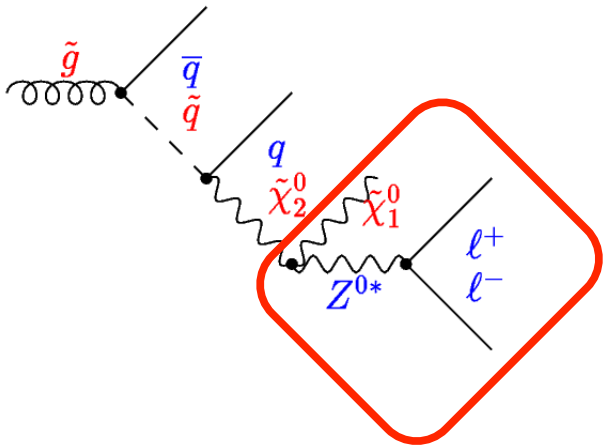
$$\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$$



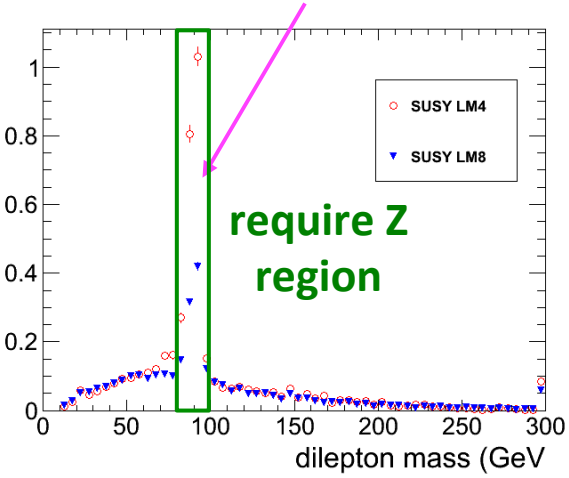
kinematic edge
(in **SOME** SUSY models)



Z production in cascade decays



Z-peak



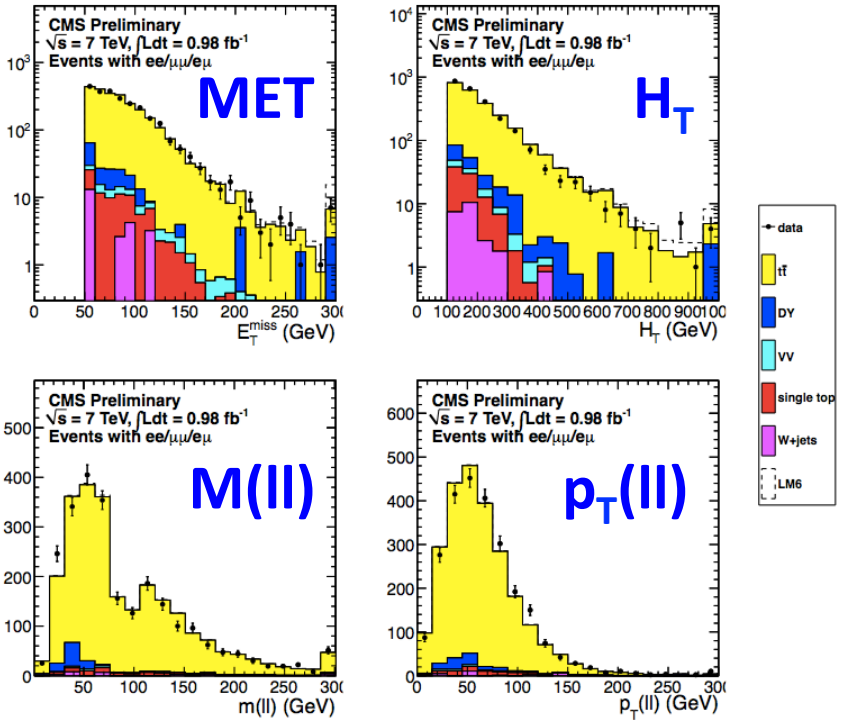
Perform separate OS SUSY searches outside vs. inside Z mass region

Intro: OS Non-Z Search

NEW! CMS PAS-SUS-11-011 0.98 fb^{-1}

- **Signature: OS leptons + ≥2 jets + MET**
  - Dominant background: tt → dilepton
- **Perform preselection to reject non-tt bkgs:**
  - ≥2 isolated leptons: (e or μ) p_T > (20,10) GeV
  - Reject same-flavor pairs consistent with Z mass
  - ≥2 jets (p_T > 30 GeV, |η| < 3.0), H_T > 100 GeV, MET > 50 GeV
- **Preselection region results**
  - Background is >90% tt (from MC)
  - Reasonable data/MC agreement in yields, kinematic distributions

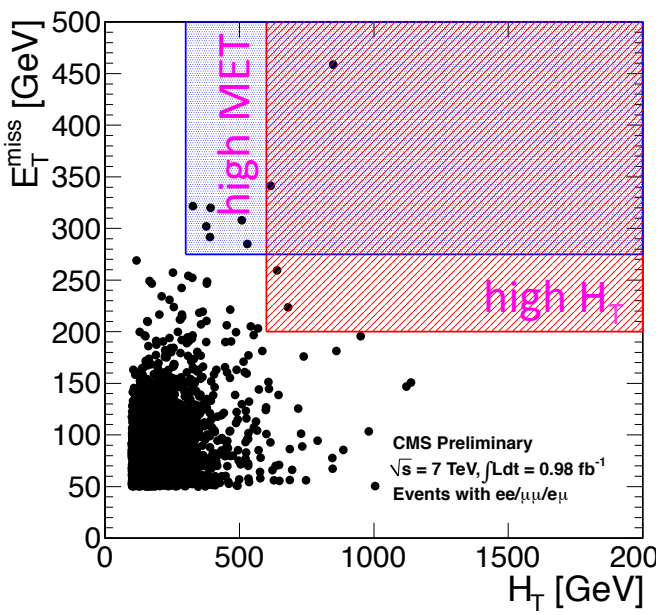
Sample	σ [pb]	ee	$\mu\mu$	$e\mu$	total
$t\bar{t} \to \ell^+\ell^-$	17	412.8 ± 8.9	465.4 ± 9.0	1095.6 ± 14.2	1973.8 ± 19.0
$t\bar{t} \to$ fake	141	12.6 ± 1.6	3.7 ± 0.8	22.7 ± 2.0	39.0 ± 2.7
DY$\to \ell^+\ell^-$	16677	18.6 ± 5.0	26.6 ± 6.0	37.6 ± 7.1	82.8 ± 10.6
W^+W^-	43	4.0 ± 0.5	4.3 ± 0.4	9.5 ± 0.7	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



OS Dilepton Results

- Define 2 signal regions:

	MET > 275 GeV, H_T > 300 GeV	MET > 200 GeV, H_T > 600 GeV
	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)
$p_T(\ell\ell)$ prediction	14.3 ± 6.3 (stat) ± 5.3 (syst)	10.1 ± 4.2 (stat) ± 3.5 (syst)
N_{bkg}	4.2 ± 1.3	5.1 ± 1.7
non-SM yield UL	10	5.3



- Estimate bkg in signal regions with 2 data-driven techniques → consistent predictions
  - ABCD': variant of ABCD method using 2 weakly-correlated variables: $y \equiv MET/\sqrt{(H_T)}$ and H_T
  - $p_T(ll)$: use $p_T(ll)$ to model $p_T(\nu\nu) \sim MET$
  - N_{bkg}: error-weighted average of 2 predictions
- Observed yields consistent with MC, data-driven bkg estimates → **no evidence for SUSY**
- Extract 95% CL upper limits on non-SM yields

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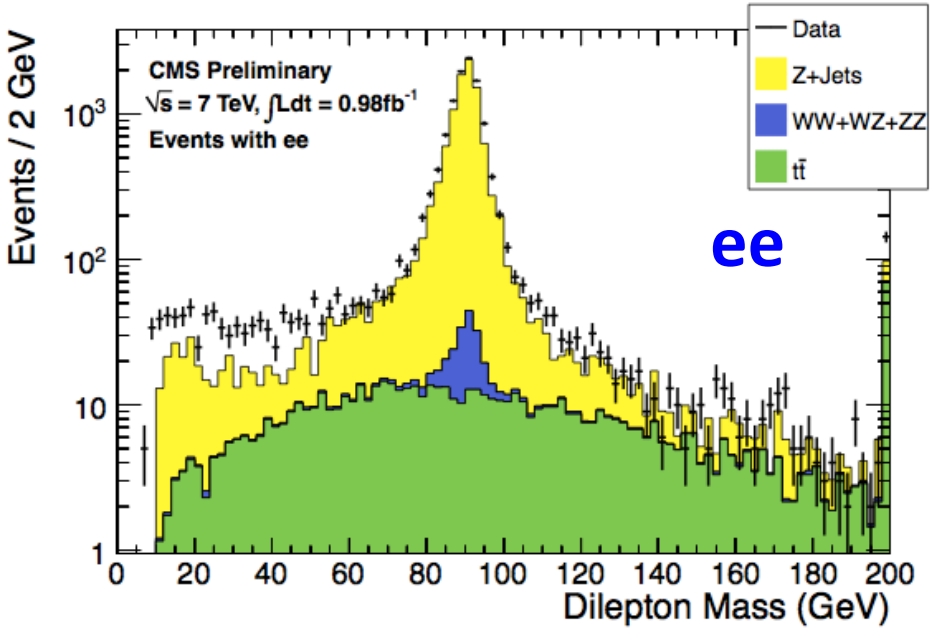
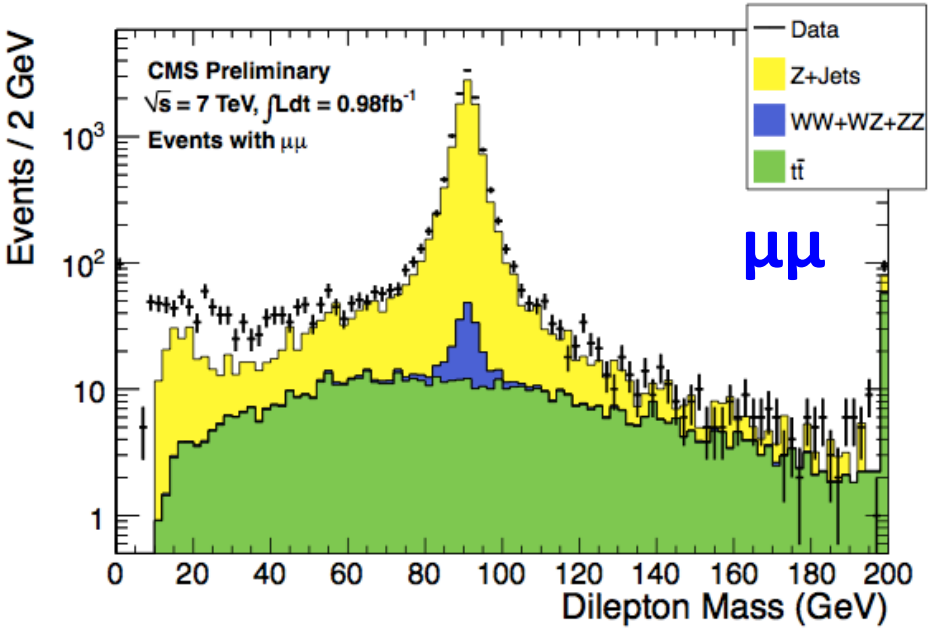
Introduction: Z+MET Search

- **Signature: Z→ee/μμ + ≥2 jets + large MET**
- **Dominant backgrounds:**
  - **fake MET**: Z+jets (fake MET from jet mismeasurements)
  - **real MET**: tt (dominant), DY→$\tau^+\tau^-$, W^+W^-

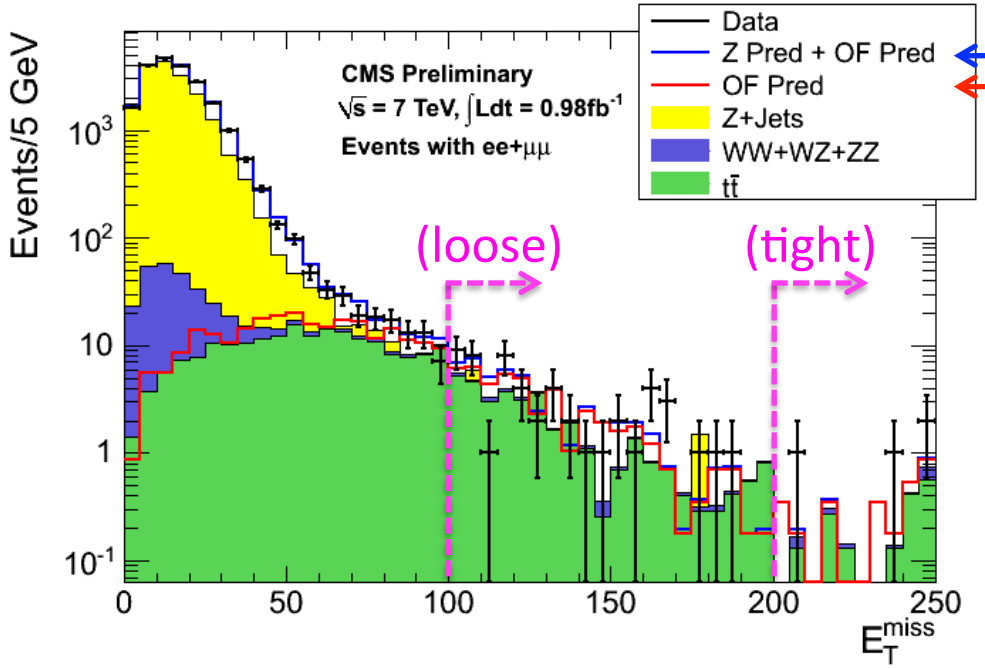
NEW! CMS PAS-SUS-11-017 0.98 fb^{-1}

- **Event preselection**
  - 2 isolated electrons/muons ($p_T > 20$ GeV, $|\eta| < 2.5$)
  - ≥2 jets from strong production ($p_T > 30$ GeV, $|\eta| < 3.0$)





Results of Z+MET Search



Compare observed MET distribution with sum of **2 data-driven predictions:**

- **fake MET**: Z+jets MET predicted from γ+jets control sample
- **real MET**: tt/DY→$\tau^+\tau^-$/W^+W^- MET predicted from eμ events

Define 2 signal regions:

total (ee,μμ)

	(loose) $E_T^{miss} > 100$ GeV	(tight) $E_T^{miss} > 200$ GeV
Z Pred	$5.1 \pm 1.0 \pm 0.8$	$0.09 \pm 0.04 \pm 0.01$
tt̄ Pred	$50.6 \pm 2.8 \pm 4.6$	$3.2 \pm 0.7 \pm 0.3$
Prediction	$55.7 \pm 3.0 \pm 4.6$	$3.3 \pm 0.7 \pm 0.3$
Data	**57 (25,32)**	**4 (1,3)**
UL	20	5.9

- Good agreement between observed, predicted yields → **no evidence for SUSY**
- Set 95% CL upper limits on non-SM yields

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Step 1) **Model-Independent** Yield Upper Limits

Channel	Lumi	Signal Region	Non-SM Yield UL
Single lepton	36 pb^{-1}	MET > 250 GeV, H_T > 500 GeV	3.8 events
Same-sign leptons	0.98 fb^{-1}	MET > 120 GeV, H_T > 400 GeV	3.0 events
		MET > 50 GeV, H_T > 400 GeV	7.5 events
		MET > 120 GeV, H_T > 200 GeV	5.2 events
		MET > 100 GeV, H_T > 80 GeV	6.0 events
Opposite-sign leptons	0.98 fb^{-1}	MET > 275 GeV, H_T > 300 GeV	10 events
		MET > 200 GeV, H_T > 600 GeV	5.3 events
Z	0.98 fb^{-1}	MET > 100 GeV	20 events
		MET > 200 GeV	5.9 events

- Extract 95% CL upper limits on non-SM yields for each channel, in various kinematic regions
- **Any new physics model which predicts a yield in excess of one of these upper limits is excluded**

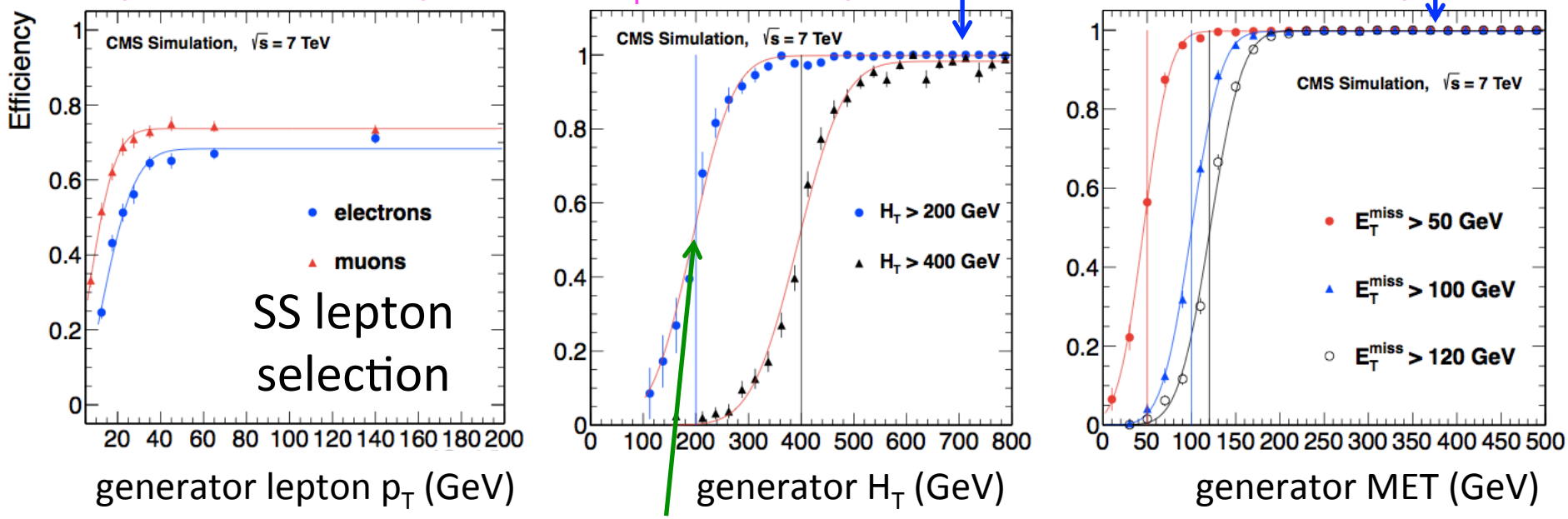
Step 2) Detector Efficiencies

plateau efficiency ~100%

lepton efficiency

H_T efficiency

MET efficiency



mid-points match reco cut

- Provide information on detector selection efficiencies vs. generator-level quantities → allows to estimate selection efficiency for arbitrary new physics model
- **Use efficiency to estimate signal region yield → compare with quoted upper limits to determine if excluded**

Step 3) CMSSM Exclusion

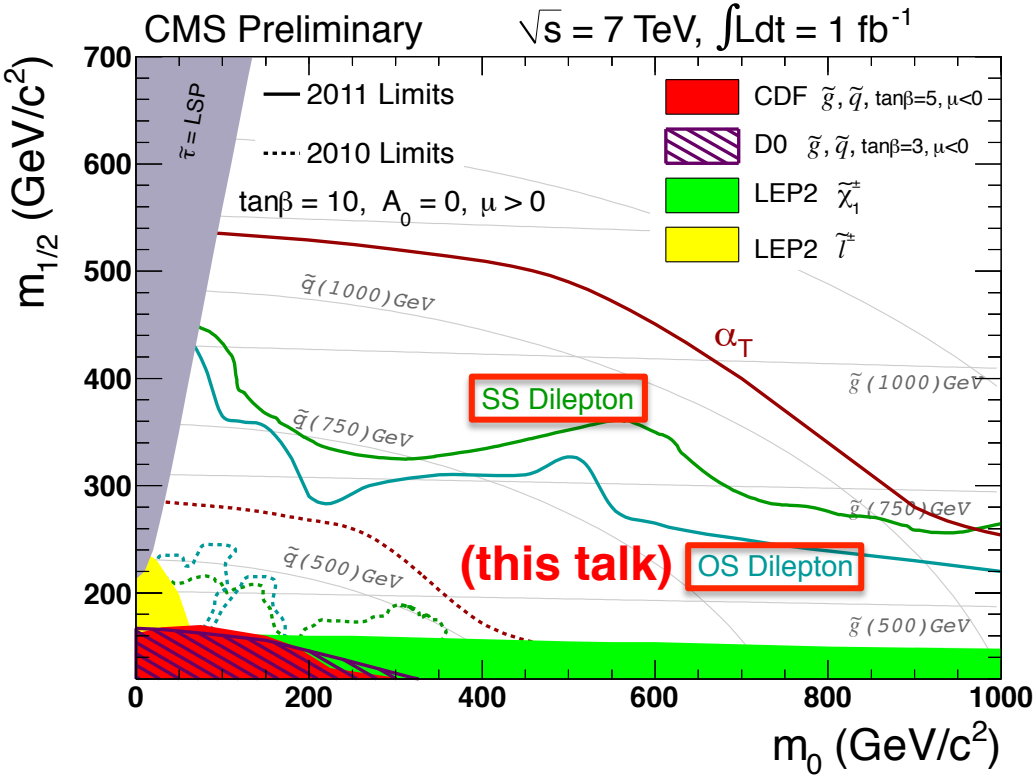
Constrained **M**ininimal **S**USY extension to the **SM:** simplified SUSY model with 5 parameters:

$m_{1/2}$ (m_0): mass of spin ½ (0) particles at GUT scale

tanβ: ratio of 2 Higgs VEV's

μ: Higgsino mass parameter

A_0: trilinear coupling



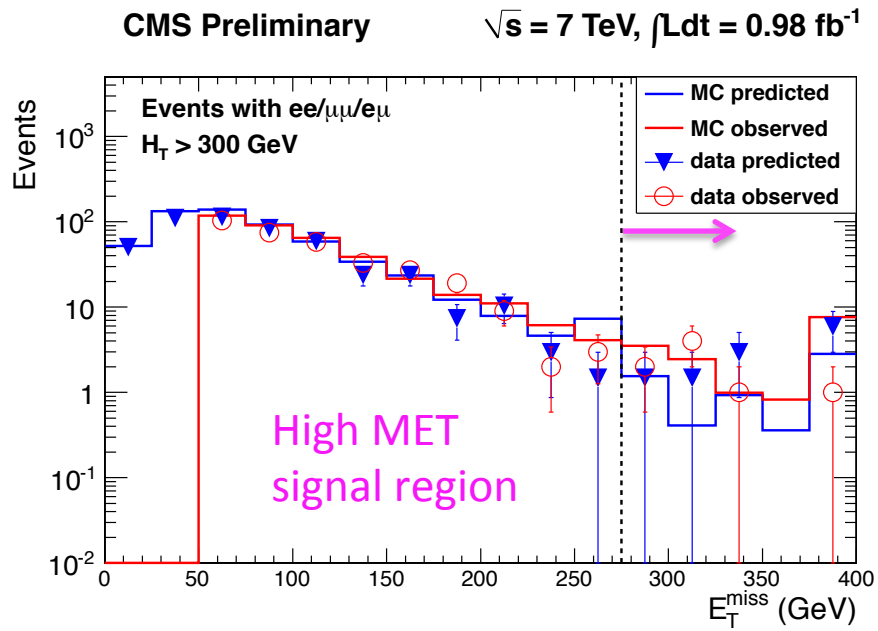
- Example of interpretation in specific new physics scenario → exclusion in CMSSM parameter space
  - Allows comparison of sensitivity with other analyses, experiments
- CMS results extend well beyond previous Tevatron/LEP exclusions

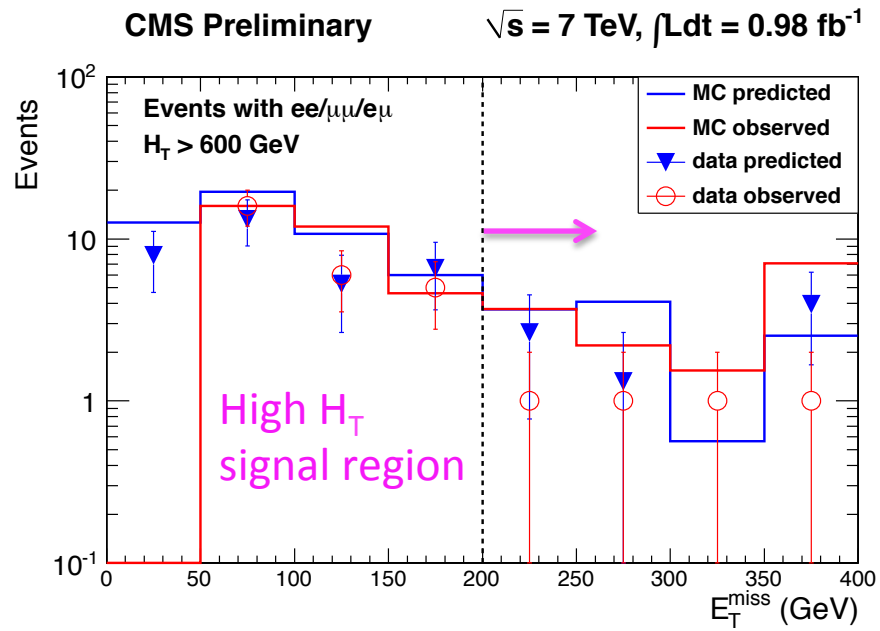
Summary

- Performed broad program of SUSY searches in various final states with leptons
  - Signature based searches → not optimized for particular SUSY scenario
  - Backgrounds determined with data-driven methods
- No evidence for new physics observed in 1 fb^{-1}…
  - Extracted upper limits on non-SM yields in various channels, kinematic regions
  - Provided information to allow testing if specific new physics models are excluded by our results
  - Performed CMSSM exclusion

Backup Slides

$p_T(ll)$ Method Results



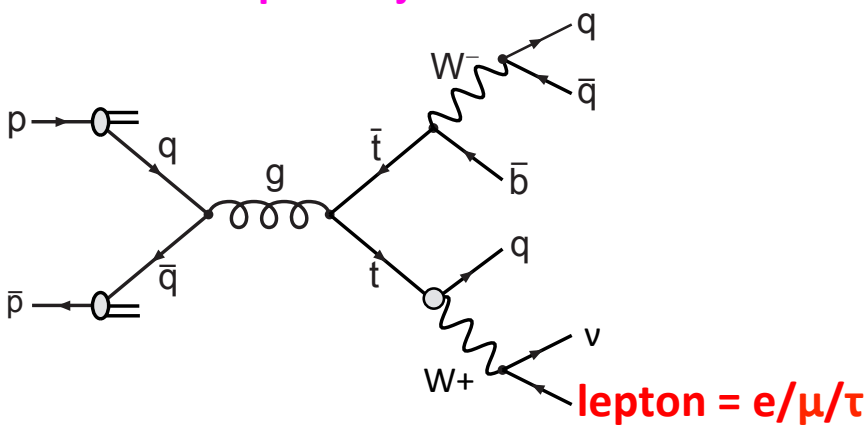


- **Predicted yields consistent with MC, observed yields**

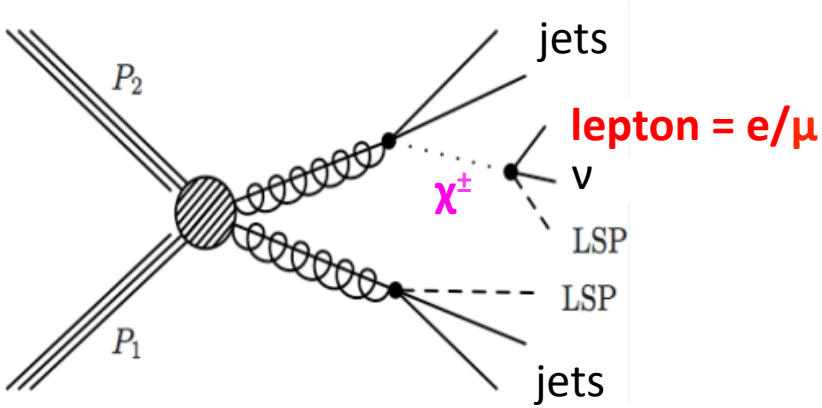
observed yield	8	4
MC prediction	7.3 ± 2.2	7.1 ± 2.2
ABCD′ prediction	4.0 ± 1.0 (stat) ± 0.8 (syst)	4.5 ± 1.6 (stat) ± 0.9 (syst)
$p_T(\ell\ell)$ prediction	14.3 ± 6.3 (stat) ± 5.3 (syst)	10.1 ± 4.2 (stat) ± 3.5 (syst)

Intro to Single Lepton Search

dominant bkg:
tt → lepton + jets



example signal:
SUSY with $\chi^{\pm}$ decay

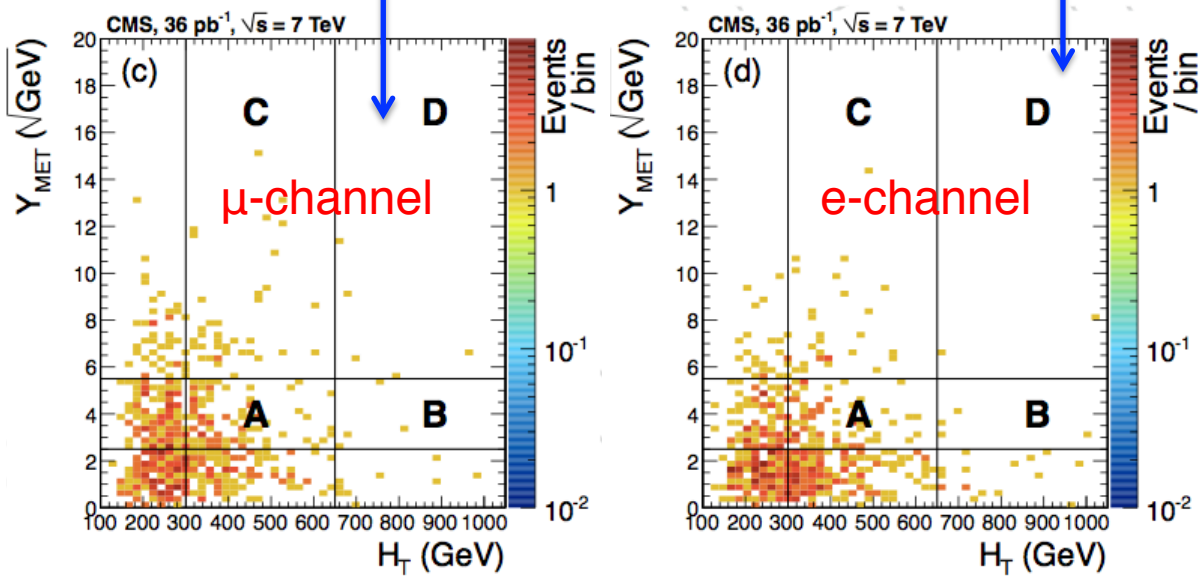


- Signature: e/μ + ≥4 jets + MET
  - Dominant bkgs: tt → lepton + jets, W + jets
- Strategy
  - Define preselection → compare data/MC yields/kinematic distributions
  - Define signal regions by adding requirements of large H_T = sum of jet p_T's, large MET
  - Cut-and-count in signal regions: compare yield to 2 data-driven bkg estimates
    - ABCD and lepton p_T methods
  - No excess observed → set upper limits on SUSY

ABCD Background Estimate

- Exploit 2 weakly correlated variables: $Y_{MET} = MET/\sqrt{(H_T)}$ and H_T
- Define signal region (D): $H_T > 650$ GeV, $Y_{MET} > 5.5$ GeV$^{1/2}$
- Predicted background in signal region D: $N_D = N_C \times N_B / N_A$

No evidence of excess beyond MC and data-driven bkg estimates



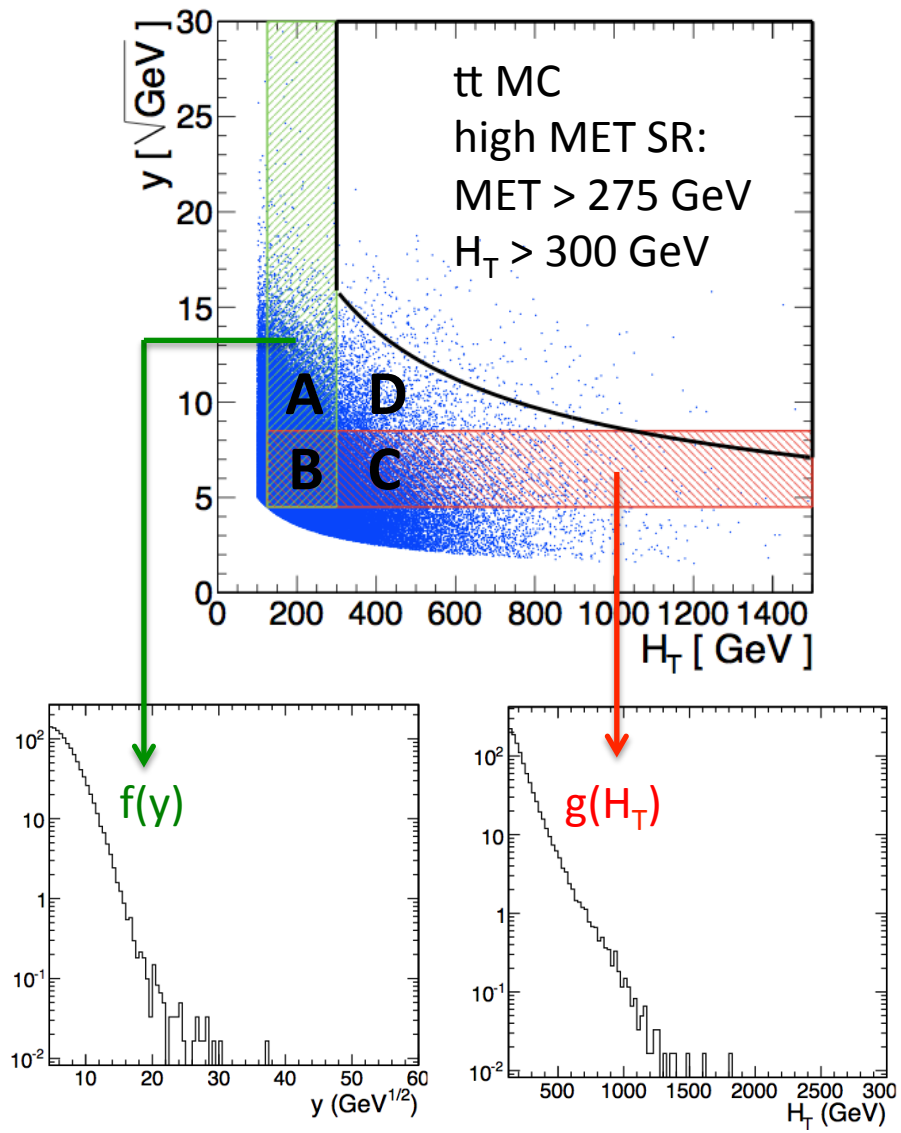
	μ-channel	e-channel
data	5	2
MC prediction	3.4 ± 0.2	2.9 ± 0.2
ABCD prediction	1.7 ± 0.9 (stat) ± 0.3 (syst)	1.5 ± 0.8 (stat) ± 0.3 (syst)

The ABCD' Method

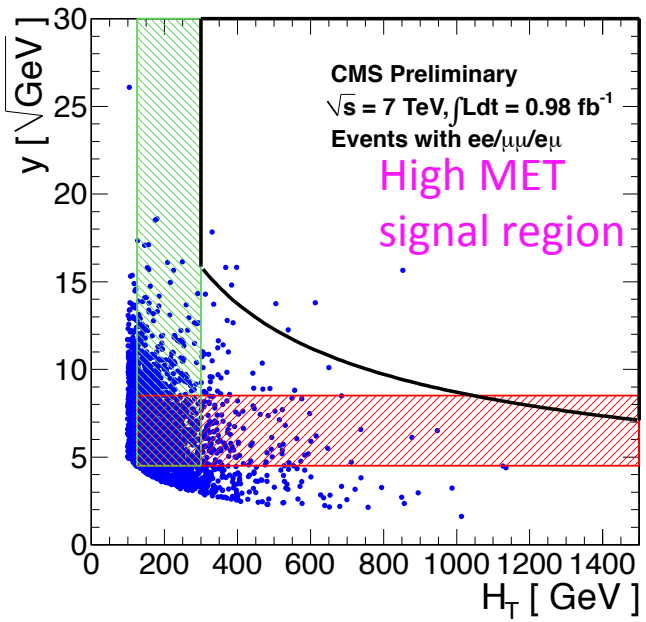
- Exploits 2 weakly-correlated kinematic variables
  - $y \equiv MET/\sqrt{(H_T)}$ and H_T
  - ABCD method: predict bkg in (y,H_T) region D: $N_D = N_A \times N_C / N_B$
  - Searches in (MET,H_T) region more sensitive: ABCD can't predict bkg
- Predict bkg in (MET, H_T) region using variant of ABCD method → ABCD' method
  - **Measure in data** the $f(y)$, $g(H_T)$ distributions in control regions dominated by bkg
  - Predict yield in signal region using:

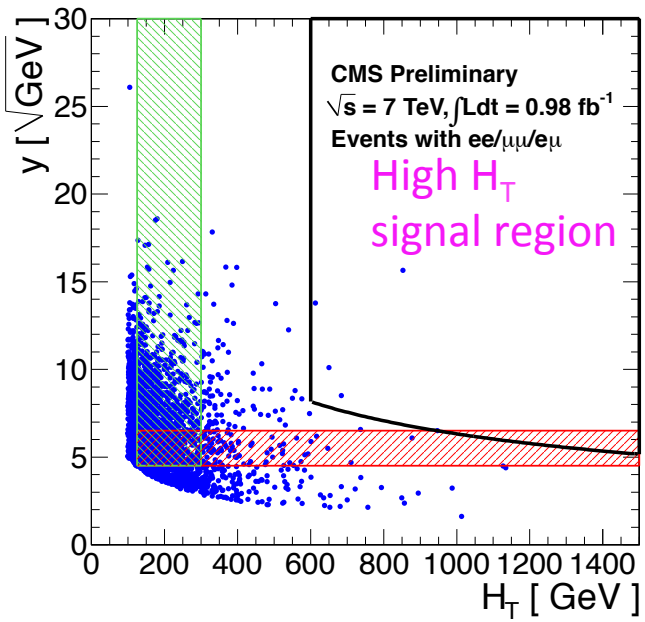
$$\frac{\partial^2 N}{\partial y \partial H_T} = f(y) g(H_T)$$

- Method validated using toy MC studies with event sizes corresponding to ~1 fb^{-1}



OS Search Results Results





	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-SM yield UL	10	5.3

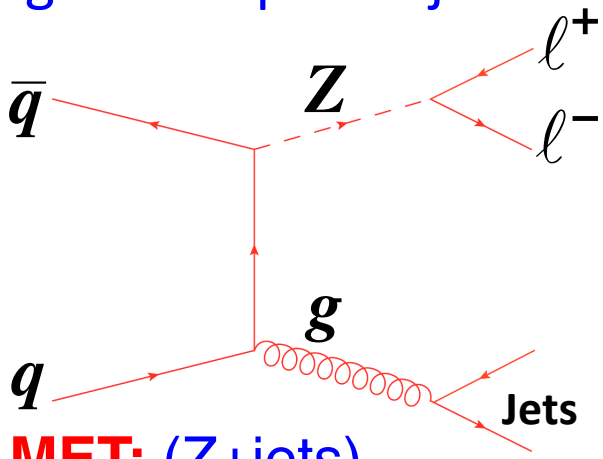
- **Observed yields consistent with MC, ABCD' prediction**
- **Extract 95% CL upper limits on non-SM yields**

Interpretation of Results

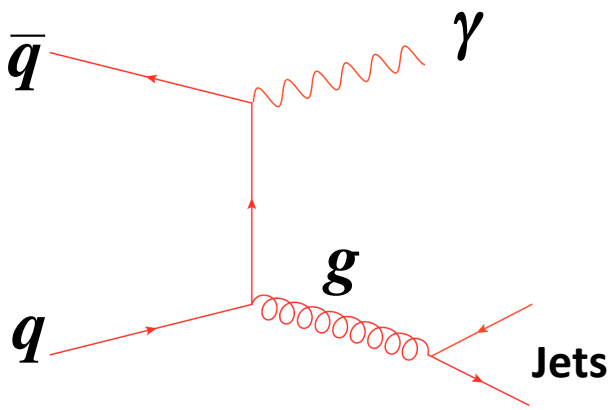
- Challenge: present results which can be applied to a broad class of models
  - Allow testing whether specific models are excluded
- Strategy:
  - Present model-independent yield upper limits
  - Give quantitative information on detector response/ efficiencies → allows to estimate efficiency for a specific model → estimate yield in signal region and compare to UL to determine if excluded
  - As an example of interpretation in specific model, quote limits in context of CMSSM
    - Constrained minimal supersymmetric extension of the SM → simplified SUSY model with 5 free parameters

Background Estimates

signal sample: Z+jets



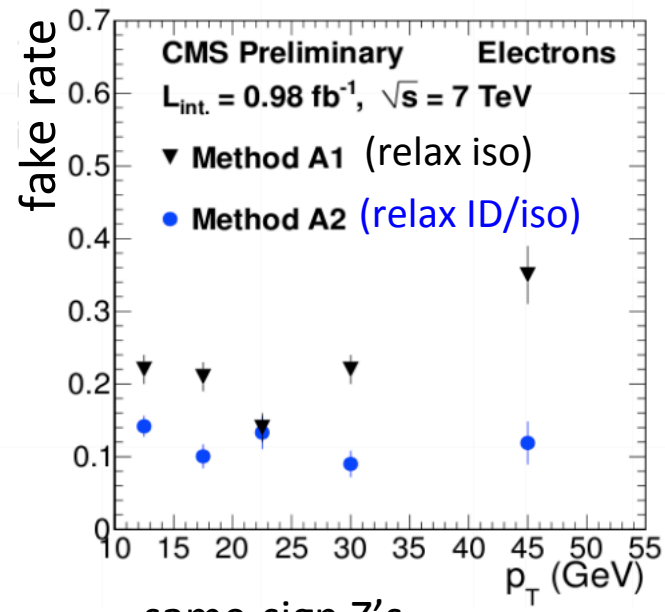
control sample: γ+jets



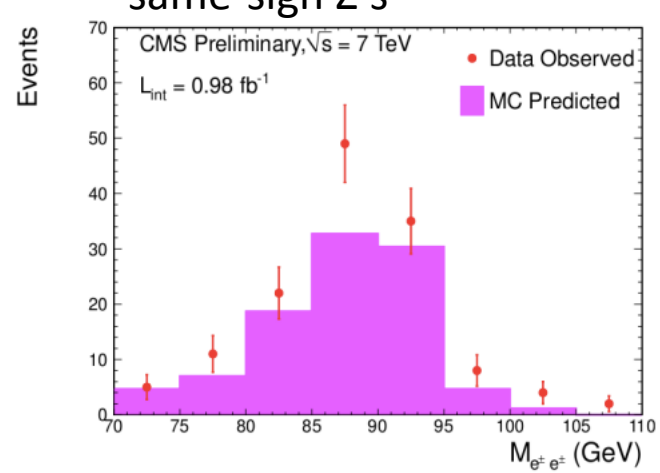
- **fake MET:** (Z+jets)
  - MET dominated by jet mismeasurements → model using control samples with similar topology, and no real MET: γ + jets
  - MET templates method: for each Z event, model MET using γ + jets events with same jet multiplicity and H_T
  - Cross-check with QCD control sample → consistent predictions
- **real MET:** (tt (dominant), DY → $\tau^+\tau^-$, W^+W^-)
  - These backgrounds have uncorrelated lepton flavors → same-flavor (ee+μμ) yield = opposite-flavor (eμ) yield
  - OF prediction: predict yield in same-flavor final state using eμ yield, corrected for (small) difference e vs. μ selection efficiency

Data-Driven Background Estimates

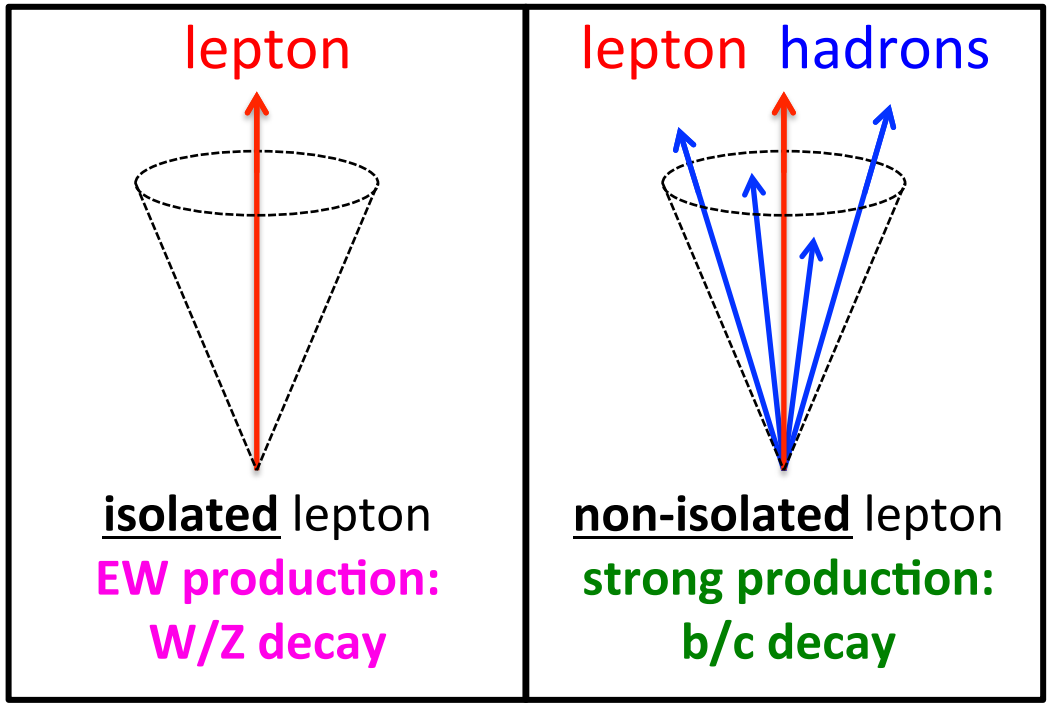
- Backgrounds from detector (mis)reconstruction events not necessarily well-modeled in MC → use data-driven methods
- **Fake leptons**
  - "Fake rate" method: define 2 lepton selections:
    - tight (same as analysis selection)
    - loose (relax ID and/or iso requirements)
  - Measure "fake rate" FR = (#tight leptons)/(#loose leptons) in independent data control sample
    - Measure vs. p_T, η → FR(p_T,η) ~ 10-40%
  - In signal sample, count events with leptons passing loose lepton selection, weight events by FR/(1-FR) → sum of weights is data-driven prediction
- **Charge misreconstruction**
  - Estimate electron mis-charge rate using same-sign Z sample (negligible muon mischarge rate)
  - Mischarge rate = N(SS)/(N(SS)+N(OS)) = ~10^{-4} (barrel), increasing to ~10^{-3} for |η| ~ 1.5

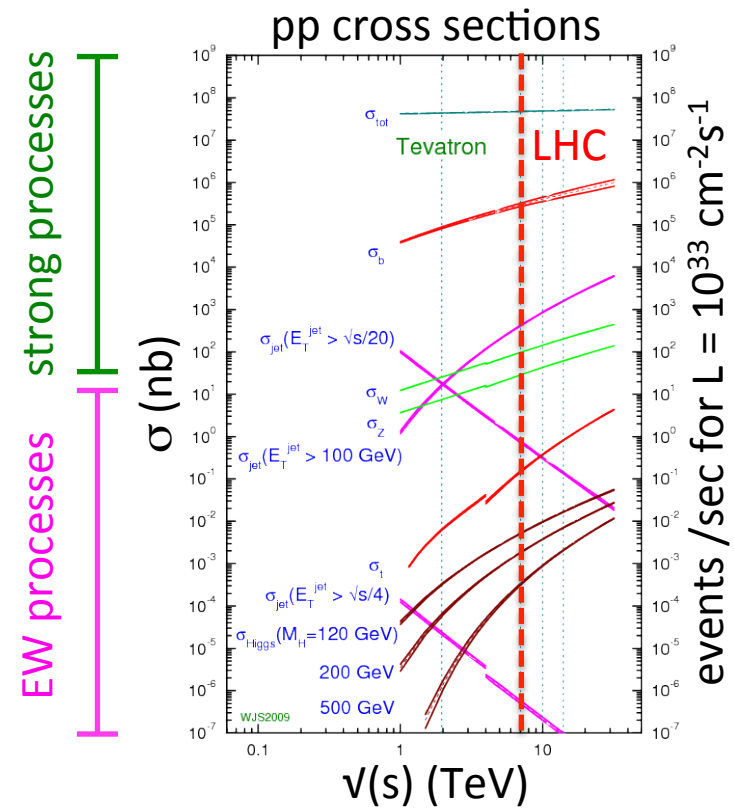


same-sign Z's



Why Search for New Physics with Leptons?





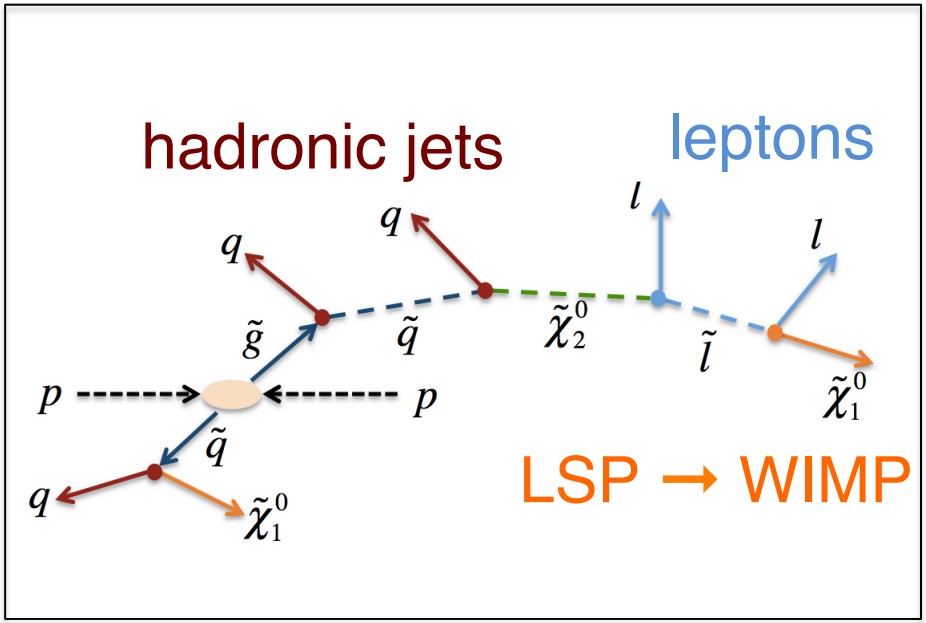
- **Isolated leptons** are very rare → **reduction of huge QCD background**
  - Provides clean environment to search for new physics
- Leptons provide additional kinematic info related to SUSY particle masses
  - eg. search for kinematic edge in OS dilepton M(ll) (see talk D. Barge)

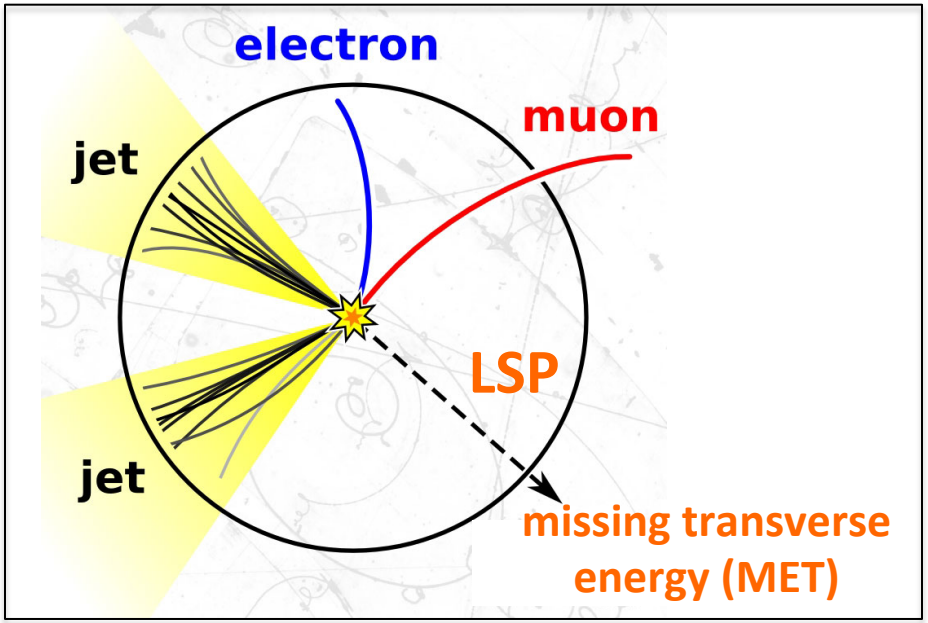
SUSY Production at Colliders

- Many SUSY models postulate conserved quantum number:

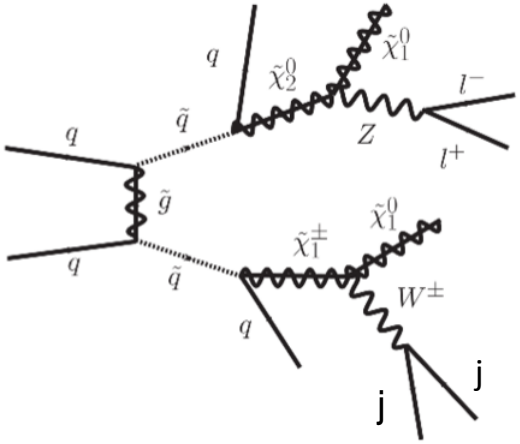
  "R-parity" = { +1 for SM particles / -1 for SUSY particles

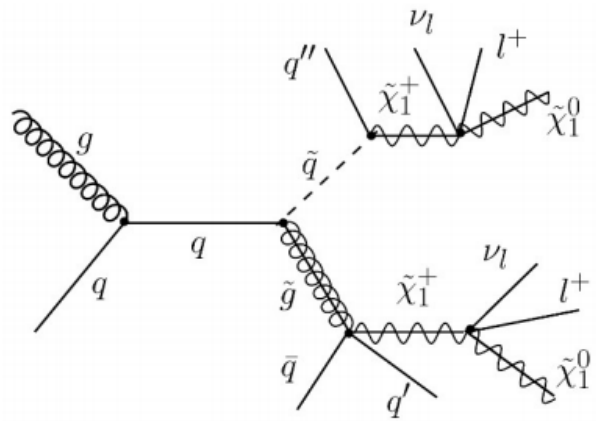
  - SUSY particles (heavy, colored squarks/gluinos) produced in pairs
  - LSP is stable
- Squarks/gluinos decay via cascade, producing jets, (leptons), MET → spectacular events with several high p_T jets + (leptons) + MET
- **Strategy: search for excess of events w/ large MET, H_T (sum of jet p_T's)**

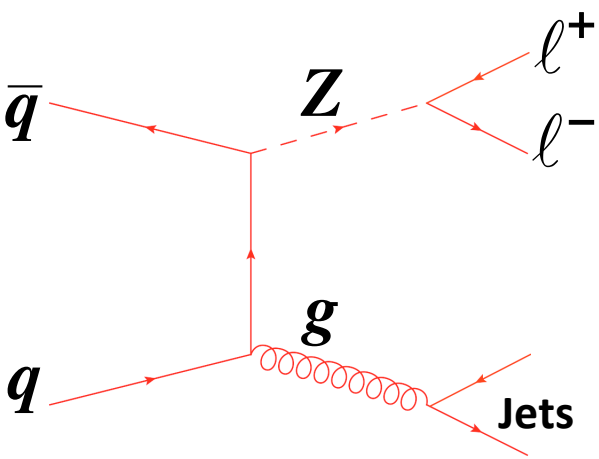




Random Stuff







The Bullet Cluster