Supersymmetry Searches at CMS
Fermilab Wine & Cheese Seminar

Ben Hooberman,
on behalf of CMS

Overview of Talk

- Search for supersymmetry in a wide variety of signatures → many backgrounds and experimental challenges
  - **This talk**: focus on experimental techniques used to control and estimate the backgrounds → ***critical for preparing for future discovery***
- For more on interpretation of results:
  - see joint FNAL theory / LPC talk October 5th

Outline

- **Introduction**
- SUSY Searches
  - all-hadronic
  - single lepton
  - opposite-sign dilepton
  - same-sign dilepton
- Interpretation of Results
- Outlook and Conclusions

Intro to SUperSYmmetry

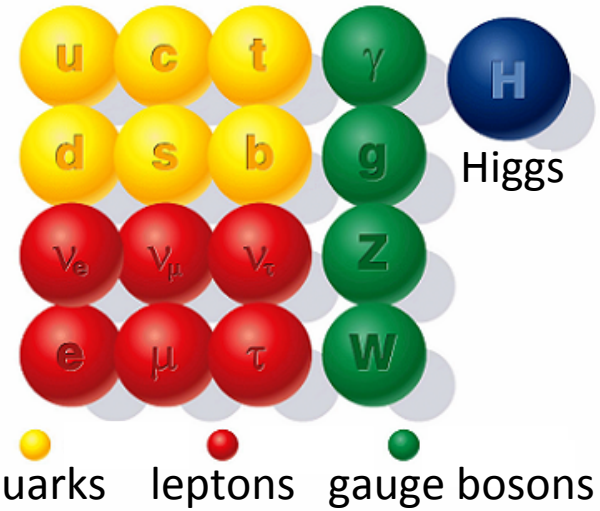
- SUSY: popular extension to SM, introduces "superpartners" to each SM particle (Δspin = ½)

- Problem: SUSY mediates proton decay, can be prevented with conserved quantum number:

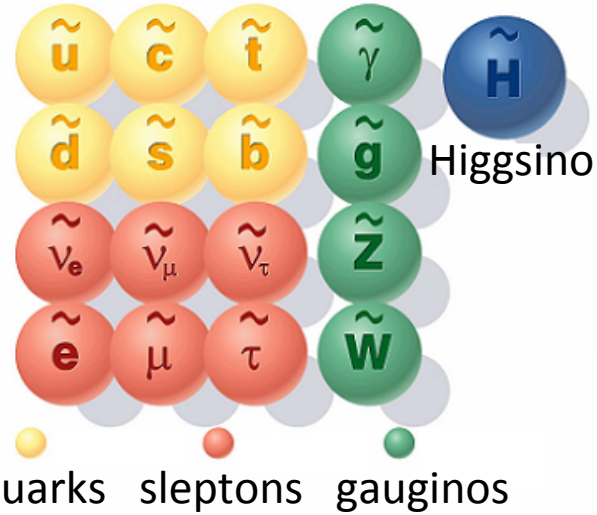
$$\text{“R-parity”} = (-1)^{3(B-L)+2s} = \begin{cases} +1 & \text{SM particles} \\ -1 & \text{SUSY particles} \end{cases}$$

- If R-parity is conserved:
  - **SUSY particles must be pair-produced**
  - **lightest SUSY particle (LSP) is stable → DM WIMP candidate**
    - Usually χ^0, also gravitino, $\tilde{\nu}$ possible

SM particles

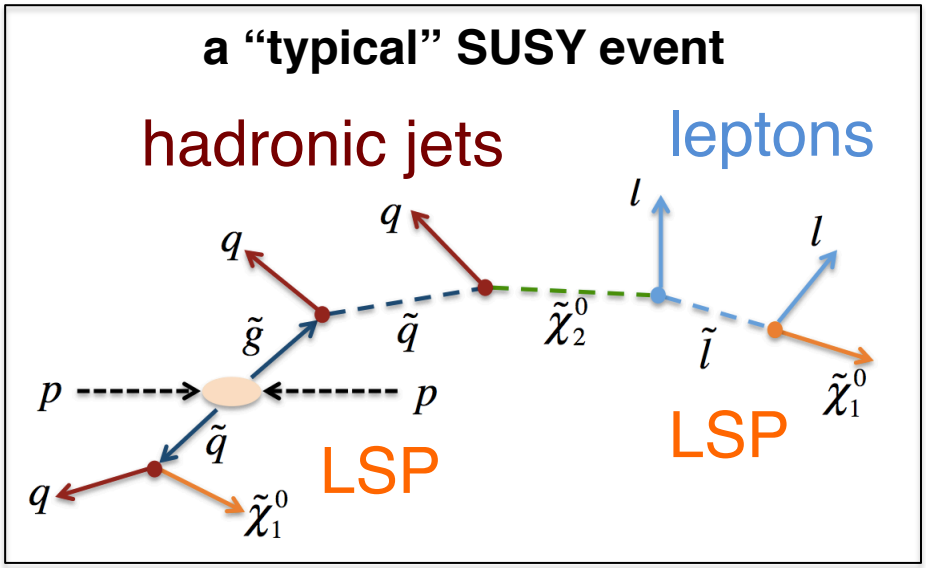


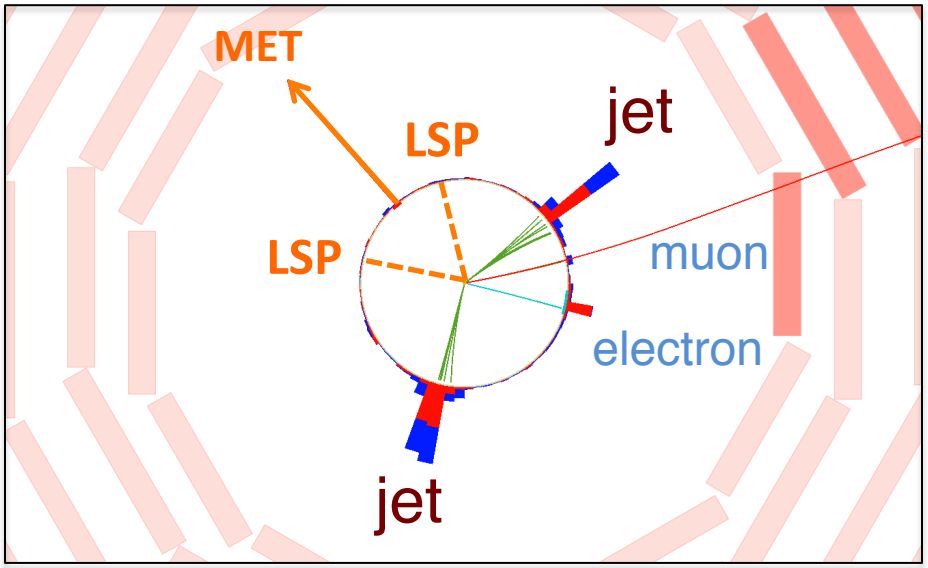
SUSY particles



SUSY Search Strategies

- Start by targeting SUSY with best early discovery potential:
  - Models with large σ: strong production of **heavy, colored objects** (squarks/gluinos)→ **lots of hadronic activity (H_T)**
  - **Stable, invisible LSP → lots of missing E_T (MET)**
  - **Search for excess events with large MET & H_T in various final states**
- Also target alternative, more difficult scenarios (not covered here)
  - EW production (gauginos) → small σ, lower H_T
  - Unstable LSP → low MET



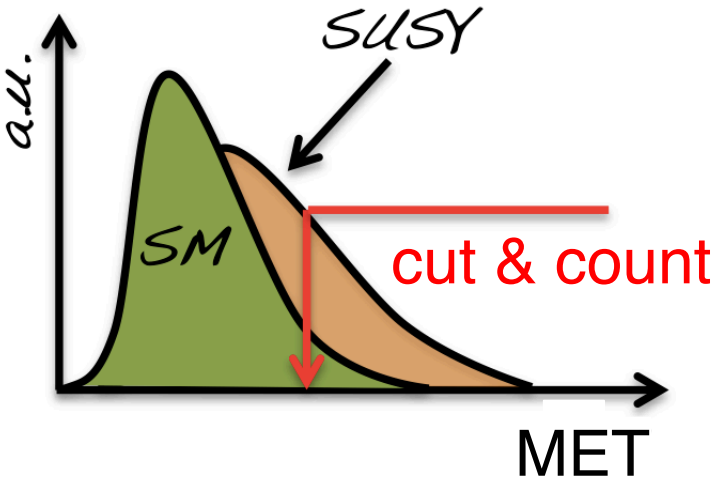


SUSY Challenges

- **Theoretical**
  - Minimal SUSY extension to SM (MSSM) → **>100 free parameters!**
  - Wide range of possible signatures
  - **Strategy: broad program of signature-based searches**

- **Experimental**
  - Invisible LSP's → incomplete event reconstruction → no peaks
  - **Search for SUSY in "tails" of distributions (eg. MET, H_T) → robust bkg estimates critical**
    - Emphasize data-driven techniques when MC may be unreliable
    - Use MC for well-understood properties

Possible SUSY Signatures
all-hadronic
1 lepton
opposite-sign dilepton
Z
same-sign dilepton
multi-lepton
lepton+photon
photons
heavy/long-lived particles

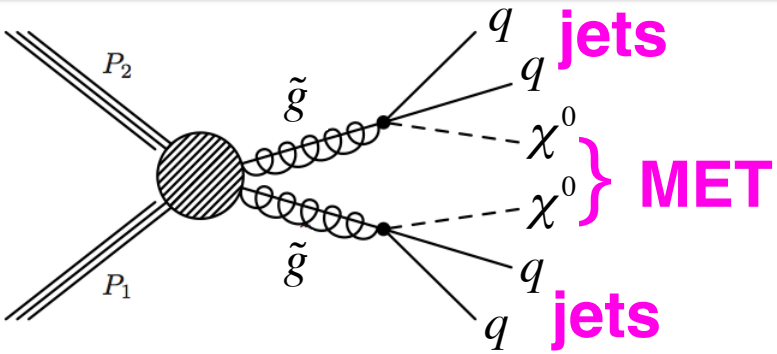


CMS SUSY Analyses

Channel	Signature	Documentation	Lumi
all-hadronic	inclusive jets+MHT	SUS-11-004	1.1 fb^{-1}
(0-leptons)	$\alpha_T + H_T$	SUS-11-003	1.1 fb^{-1}
	MT2	SUS-11-005	1.1 fb^{-1}
	razor	arXiv:1107.1279	35 pb^{-1}
	b-jets + MET	arXiv:1106.3272	35 pb^{-1}
single lepton	e/μ + jets + MET	SUS-11-015	1.1 fb^{-1}
di-lepton	opposite-sign	SUS-11-011	0.98 fb^{-1}
	Z + (MET templates)	SUS-11-017	0.98 fb^{-1}
	Z + (JZB)	SUS-11-012	0.19 fb^{-1}
	same-sign	SUS-11-010	0.98 fb^{-1}
mullti-lepton	≥3 leptons	arXiv:1106.0933	35 pb^{-1}
lepton+photon	e/μ + γ + MET	arXiv:1105.3152	35 pb^{-1}
photons	γ/γγ + jets + MET	SUS-11-009	1.1 fb^{-1}
long-lived	displaced fermions	EXO-11-004	1.1 fb^{-1}
particles	stopped gluinos	EXO-11-020	0.89 fb^{-1}
	R-hadrons	EXO-11-022	1.1 fb^{-1}

- Broad program of searches
- 12 preliminary results (~1 fb^{-1} 2011 data)
- **This talk: highlight 4 analyses covering broad array of analysis challenges and techniques**

Overview of Analyses

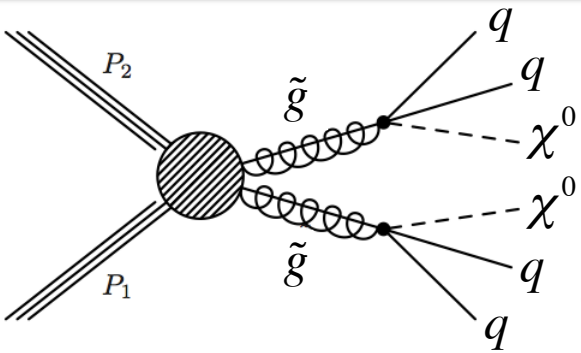


all-hadronic (jets + MET)

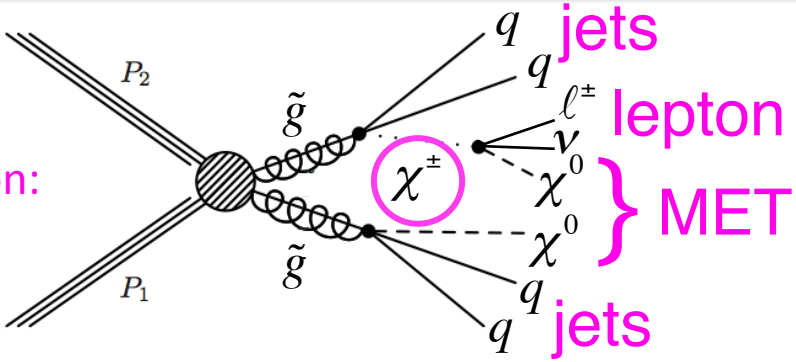
bkgs: QCD, Z(νν)+jets, W(ℓν)+jets, ttbar

challenge: QCD suppression/modeling

Overview of Analyses



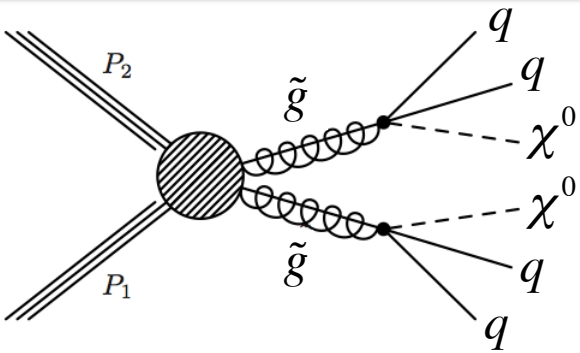
require isolated lepton:
suppress QCD



all-hadronic (jets + MET)
bkgs: QCD, Z(vv)+jets, W(ℓv)+jets, ttbar
challenge: QCD suppression/modeling

single-lepton (e/μ + jets + MET)
bkgs: W(ℓv)+jets, tt→ℓ+jets
challenge: estimating "tails" of W/ttbar

Overview of Analyses



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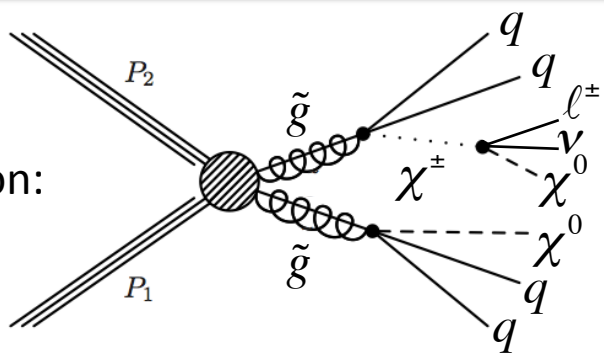
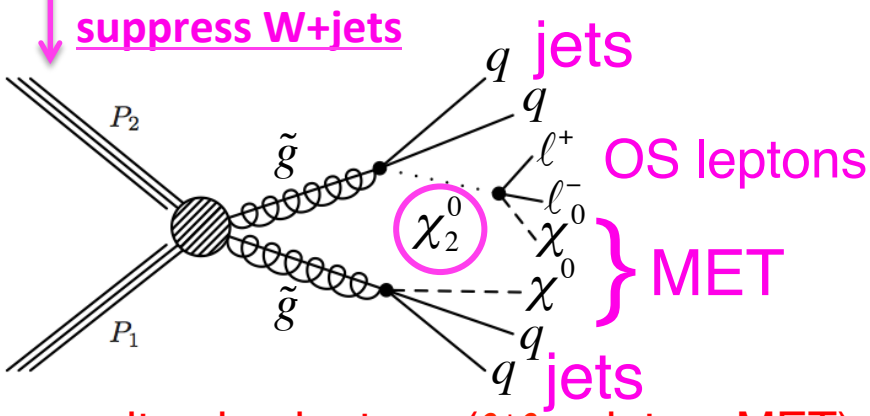


all-hadronic (jets + MET)
bkgs: QCD, Z(νν)+jets, W(ℓν)+jets, ttbar
challenge: QCD suppression/modeling

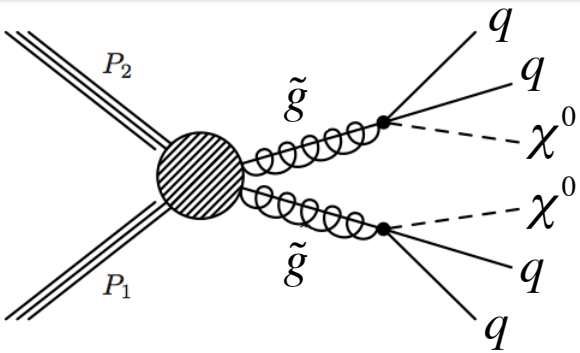
single-lepton (e/μ + jets + MET)
bkgs: W(ℓν)+jets, tt→ℓ+jets
challenge: estimating "tails" of W/ttbar

require 2nd OS lepton:
suppress W+jets



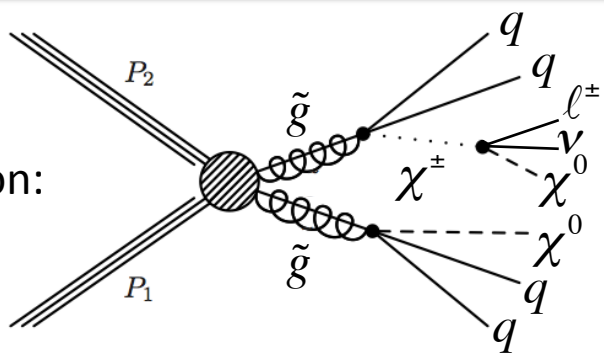
opposite-sign leptons ($\ell^+\ell^-$ + jets + MET)
bkgs: tt→$\ell^+\ell^-$
challenge: estimating "tails" of ttbar

Overview of Analyses



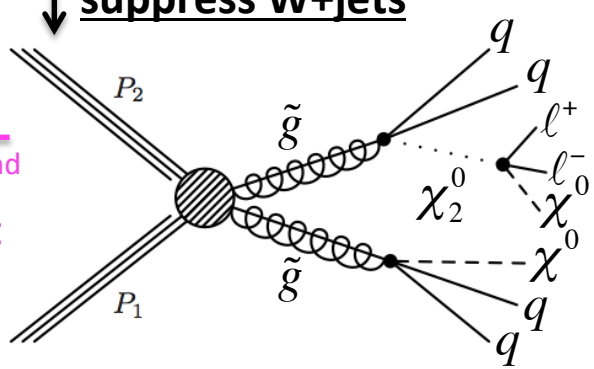
all-hadronic (jets + MET)
bkgs: QCD, Z(νν)+jets, W(ℓν)+jets, ttbar
challenge: QCD suppression/modeling

require isolated lepton:
suppress QCD

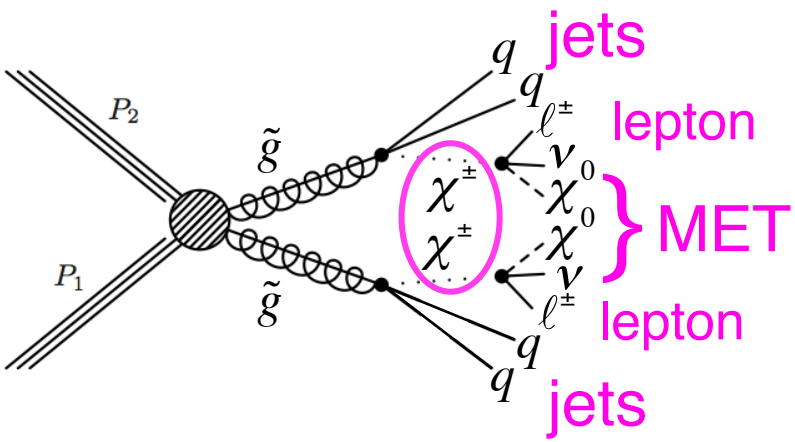


single-lepton (e/μ + jets + MET)
bkgs: W(ℓν)+jets, tt→ℓ+jets
challenge: estimating "tails" of W/ttbar

require 2nd OS lepton:
suppress W+jets



require 2nd SS lepton:
suppress SM bkg's

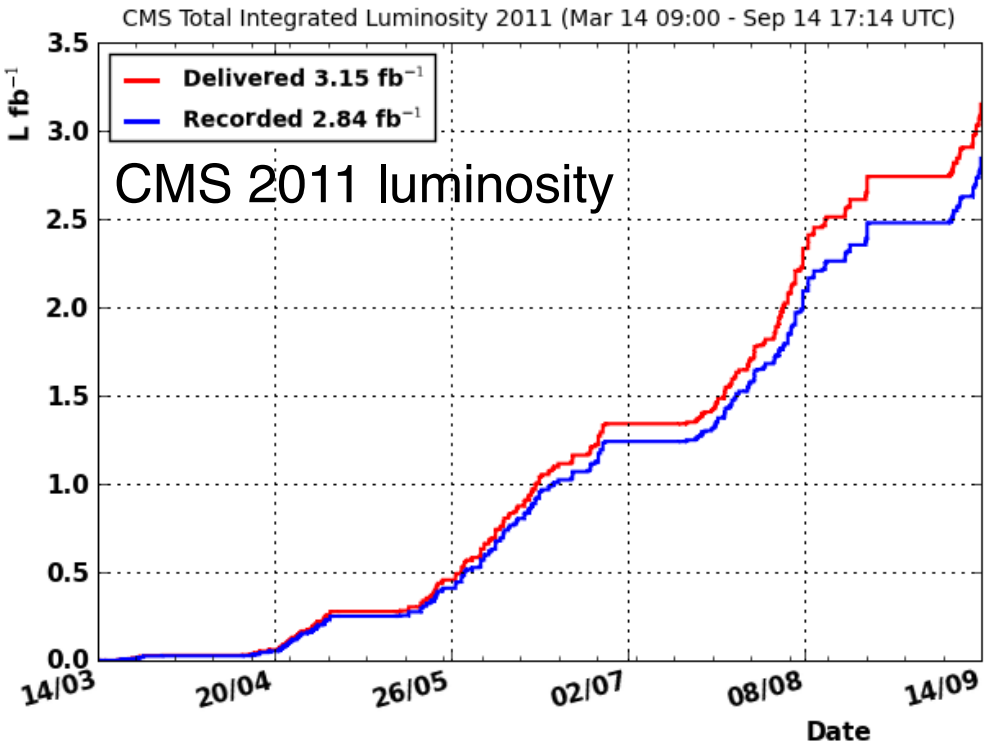


same-sign leptons (ℓ±ℓ± + jets + MET)
bkgs: tt→ℓ+jets with "fake" b→ℓ±
challenge: estimating fake leptons

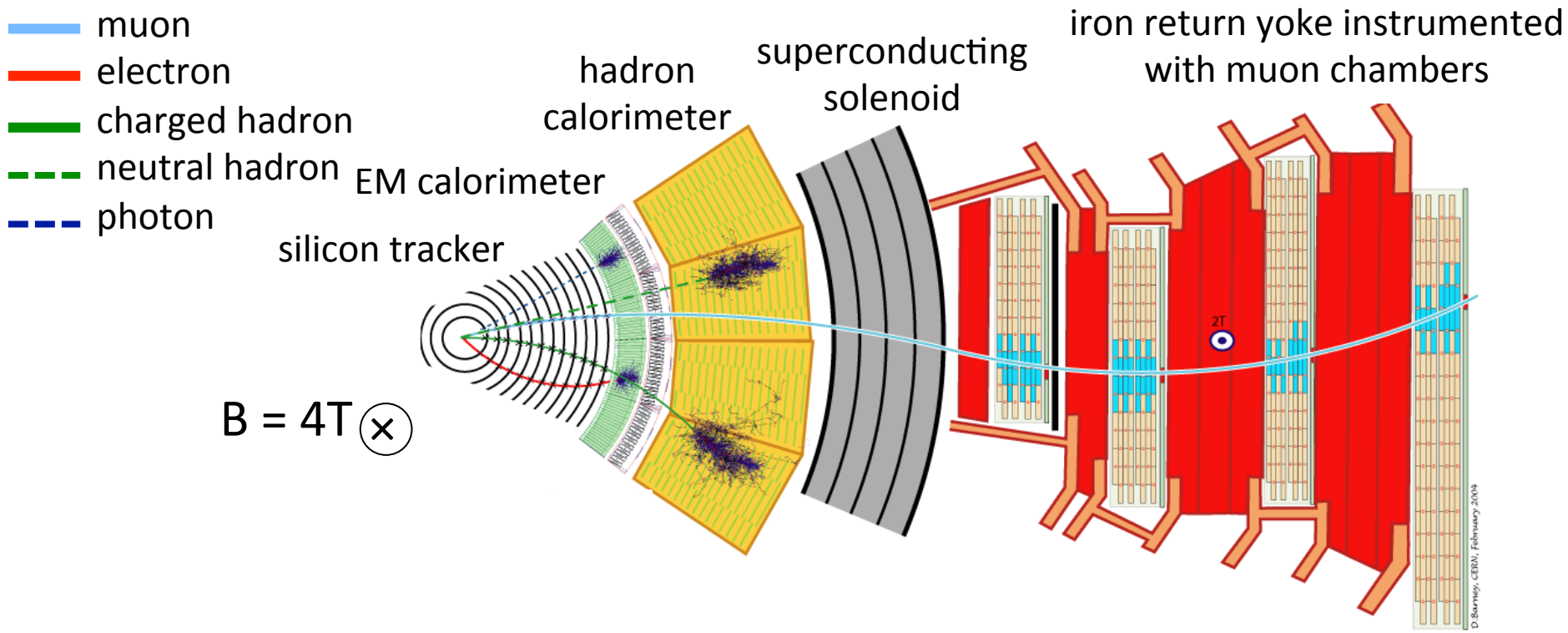
opposite-sign leptons (ℓ+ℓ- + jets + MET)
bkgs: tt→ℓ+ℓ-
challenge: estimating "tails" of ttbar

LHC Data

- **This talk: ~1 fb^{-1} 7 TeV data**
  - **Preliminary results for summer conferences**
- Total collected: ~3 fb^{-1}, expect ~5 fb^{-1} by end 2011



CMS Detector



- SUSY searches presented here rely most critically on:
  - **electrons**: tracks matched to clusters in EM calorimeter
  - **muons**: minimum ionizing tracks, penetrate deep into muon system
  - **jets / H_T**: constructed with combined tracking + calo info
  - **MET**: constructed with combined tracking + calo info, hermetic detector

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  - **all-hadronic**
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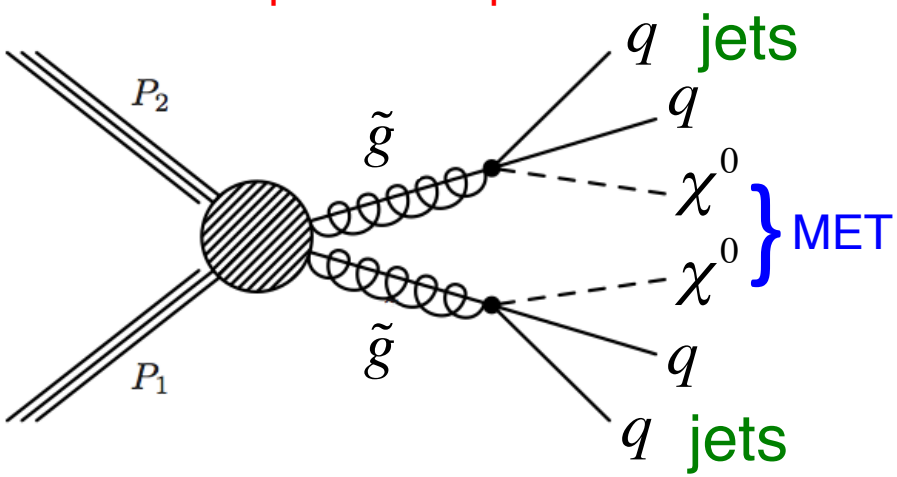
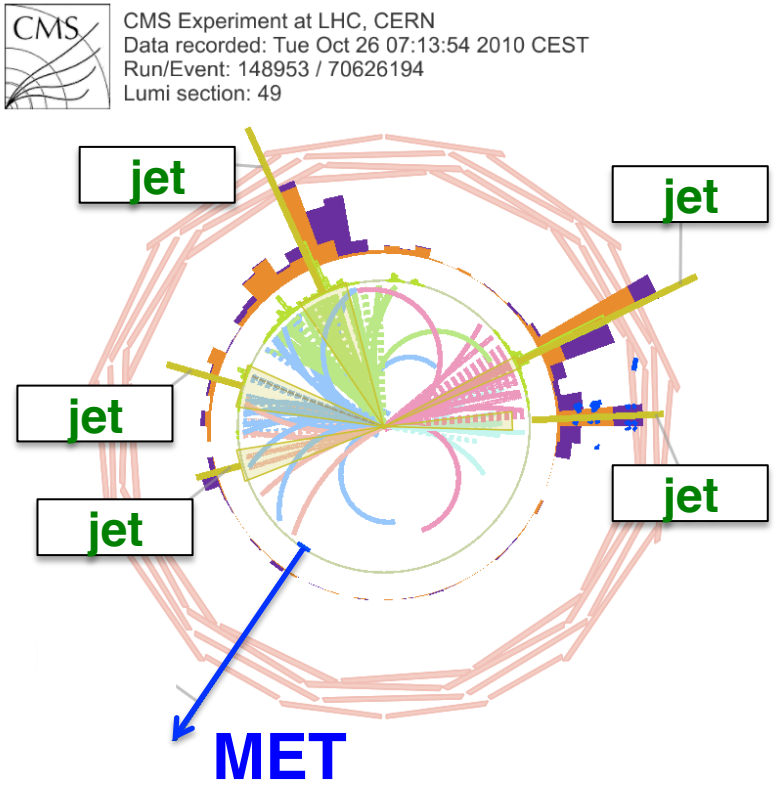
covering here "inclusive jets+MET" analysis SUS-11-004

other CMS searches in all-hadronic channel use kinematic variables to suppress QCD and/or characterize new physics mass scale (α_T, MT2, razor variables)

all-hadronic: Introduction

an example SUSY process



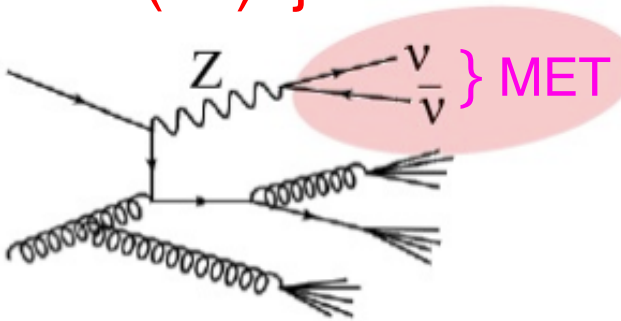


- **Signature: energetic jets with large MET**
- Challenge: modeling MET tails from several backgrounds (especially QCD multi-jets)

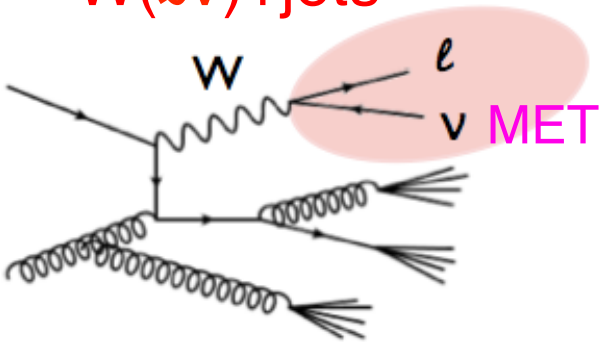
all-hadronic: EWK Backgrounds

- **Z/W/ttbar backgrounds:**
  - **challenge**: don't rely on MC for multi-jet, large H_T modeling → use data-driven techniques
- **Z(νν)+jets**
  - Irreducible background
  - Estimate using Z(ℓℓ)+jets and γ+jets data control samples
- **W(ℓν)+jets / tt→ℓ+jets**
  - W→ℓν with "lost" lepton
  - W→τν, τ→hadrons
  - Estimate using μ+jets data control samples
- **Methods predicts bkg kinematic distributions → estimate yields in baseline region & 3 signal regions:**
  - medium H_T & MET, high H_T, high MET

Z(νν)+jets

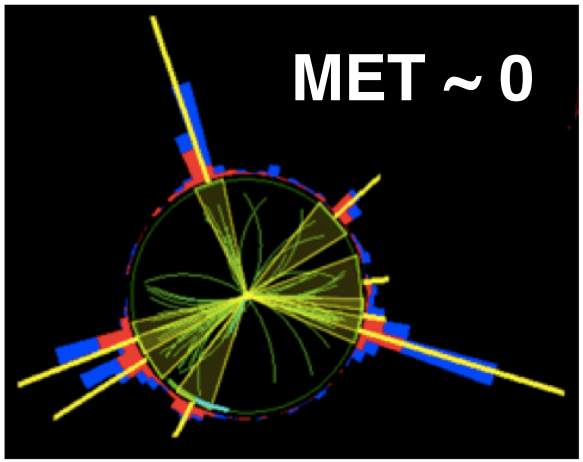


W(ℓν)+jets

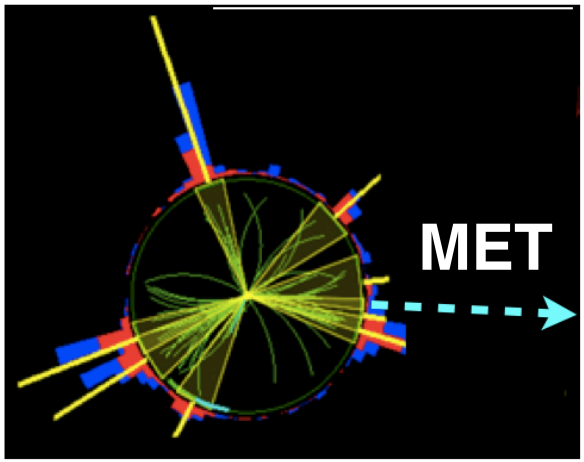


all-hadronic: QCD Background

QCD: well-measured

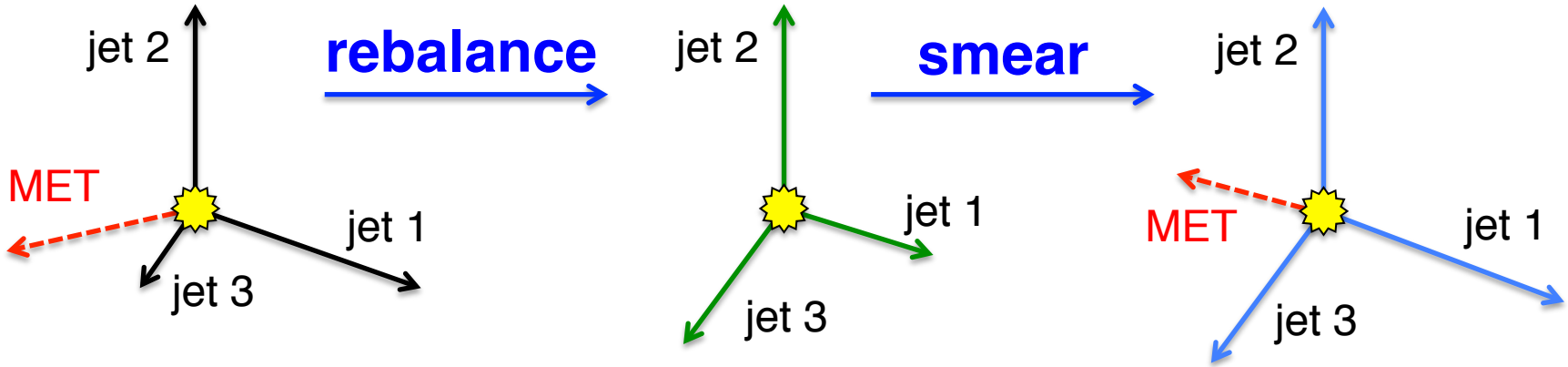


QCD: mismeasured jet

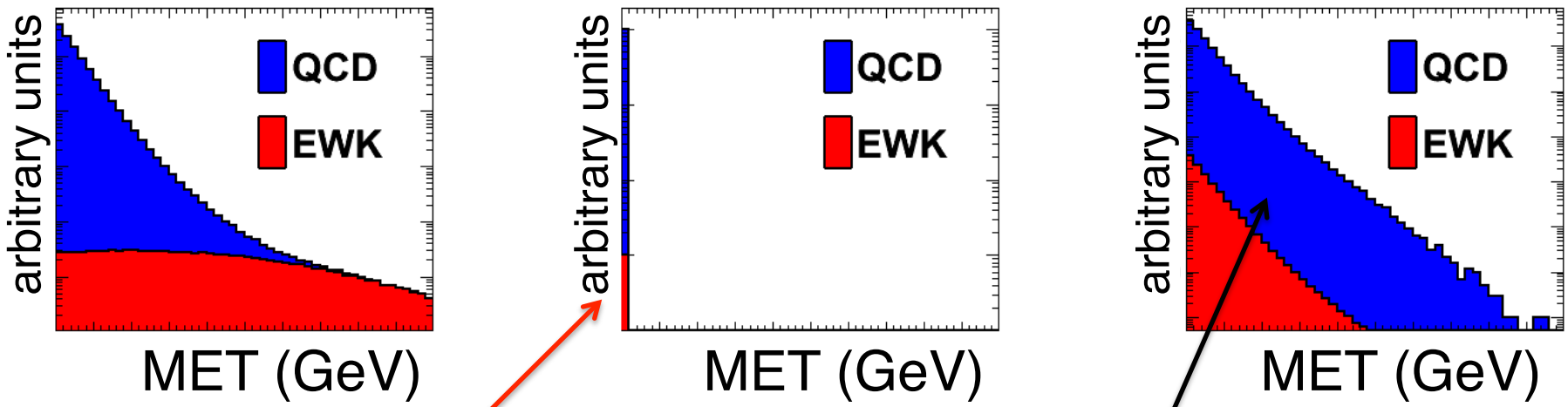


- **QCD multi-jets**
  - Instrumental MET, or MET from b,c→$\ell^{\pm}$ decays
  - Not the dominant bkg, but the most challenging one: huge σ, instrumental MET, large theory uncertainties
- Model QCD using ***"rebalance-and-smear"*** technique
  - Method predicts full QCD event kinematics from data → estimate yield in baseline region and 3 signal regions

all-hadronic: QCD bkg (R+S)



for illustration only: NOT ACTUAL MC

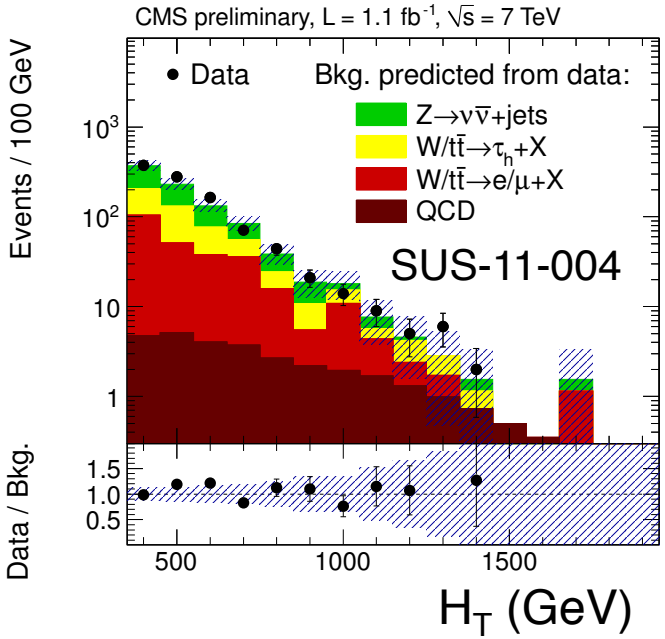


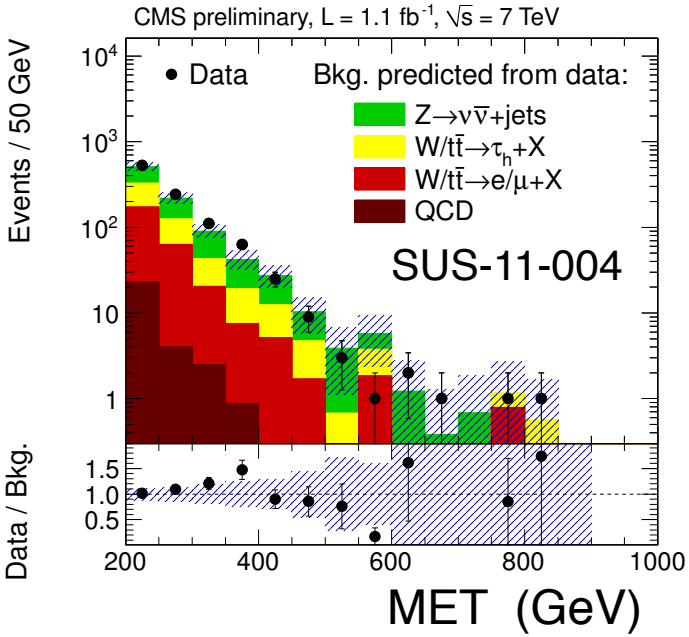
EWK bkg strongly suppressed since σ(EWK) << σ(QCD)

R+S predicts QCD kinematic distributions from data

all-hadronic: Results

all backgrounds predicted from data:





Method	**Baseline** H_T > 350 GeV and H_T^{miss} > 200 GeV	**Medium** H_T > 500 GeV and H_T^{miss} > 350 GeV	**High H_T** H_T > 800 GeV and H_T^{miss} > 200 GeV	**High H_T^{miss}** H_T > 800 GeV and H_T^{miss} > 500 GeV
Total background	927.5 ±103.1	73.9 ±11.9	79.4 ±12.2	4.6 ±1.5
Observed in data	986	78	70	3

- Good agreement observed vs. predicted yields → **no evidence for SUSY**
  - Results interpreted in context of CMSSM (will show later)

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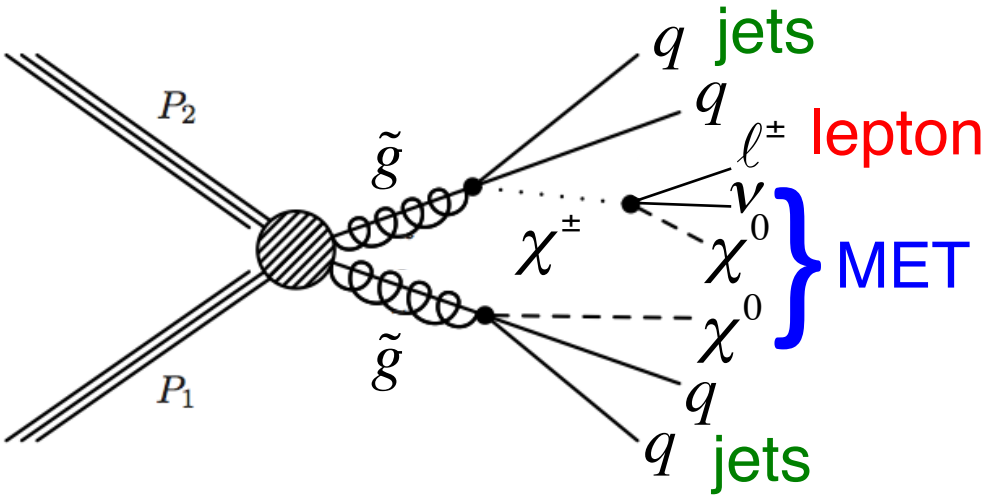
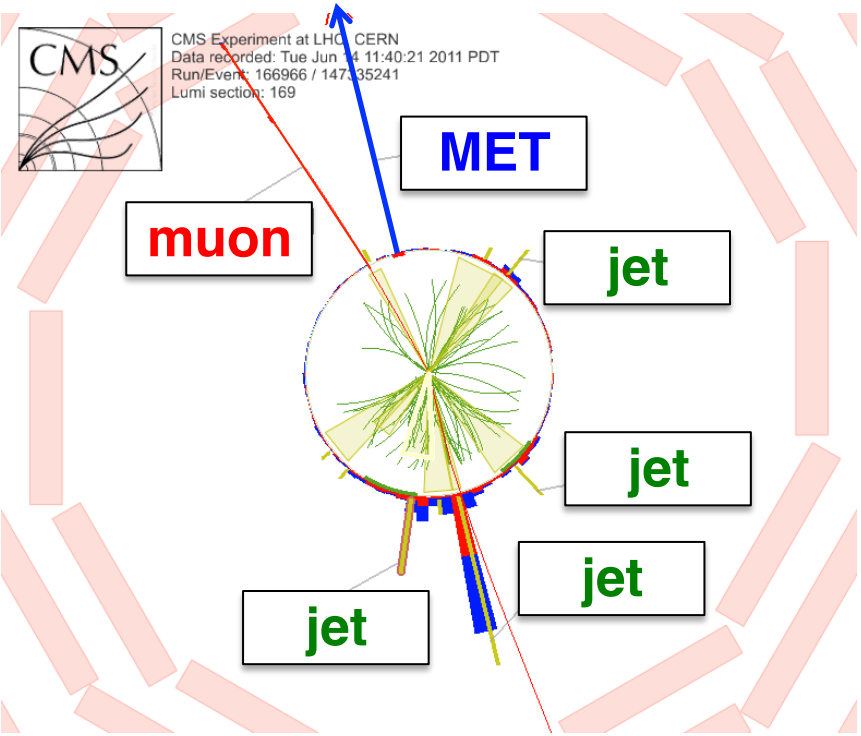
single lepton: Introduction

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





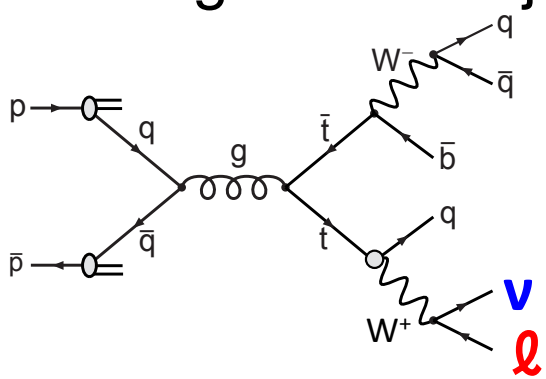
- Require isolated lepton → suppress QCD
- **Signature: single lepton (e/μ) + jets + MET**
- Challenge: estimating "tails" of ttbar/W+jets MET, H_T distributions

single lepton: Overview of Backgrounds

- **W+jets and tt→ℓ+jets (~75%)**
  - **Challenge**: dominant bkg, don't want to rely solely on MC for tails of initial state radiation, large top boost
  - Data-driven technique: model MET using lepton p_T spectrum (next slide)
- **tt→$\ell^+\ell^-$ (~15%)**
  - With lost lepton (not reconstructed/isolated, outside acceptance)
  - Estimate using dilepton data control sample, scale by probability to lose lepton
- **W+jets/ttbar with W→ τ → e/μ decays (~10%)**
  - Estimate using μ+jets data control sample, replace μ with expected τ response
- **QCD bkg (~1%)**
  - Small → verify using data-driven technique, 2D extrapolation isolation vs. MET
- **Other backgrounds (~1%)**
  - DY, single top → small, obtained from MC

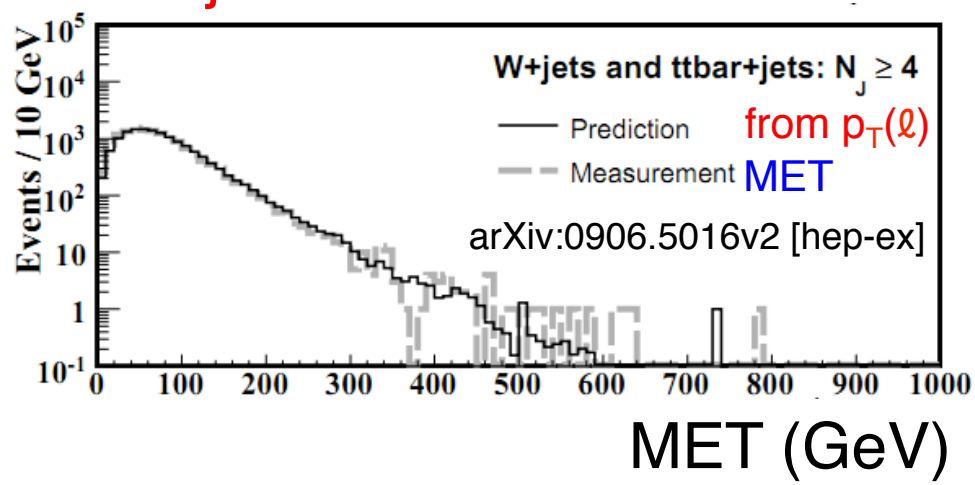
single lepton: "Lepton-Spectrum" Method

SM bkg: ttbar→ℓ+jets



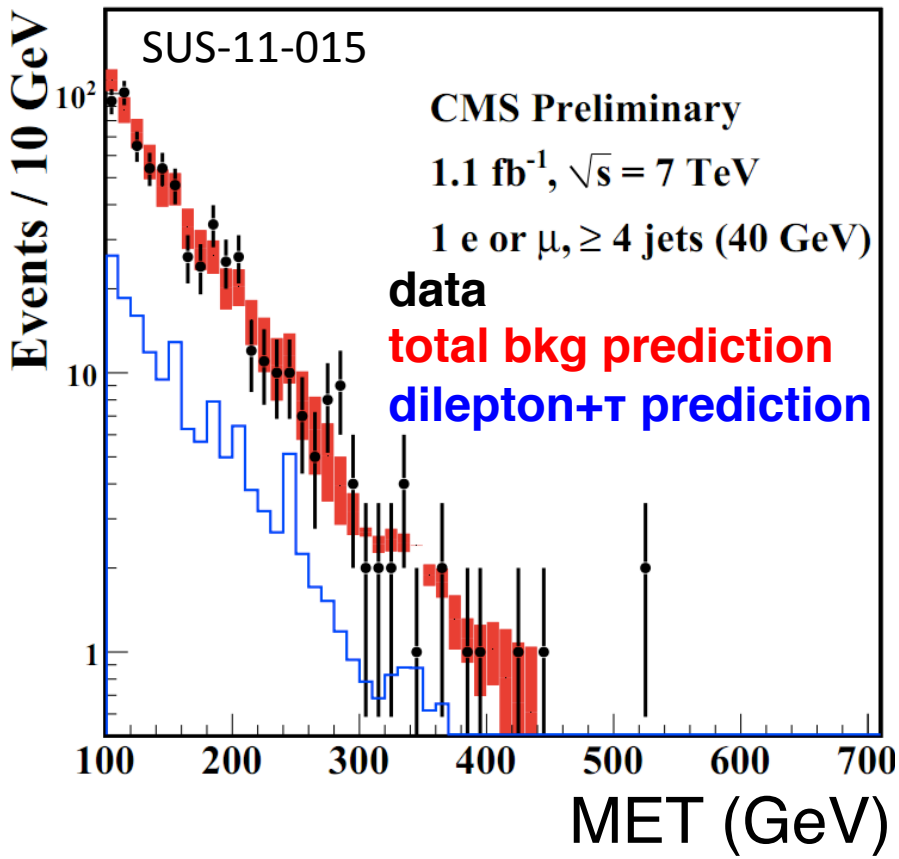
$\langle p_T(\nu)\rangle \sim \langle p_T(\ell)\rangle$

W+jets/ttbar MC closure test



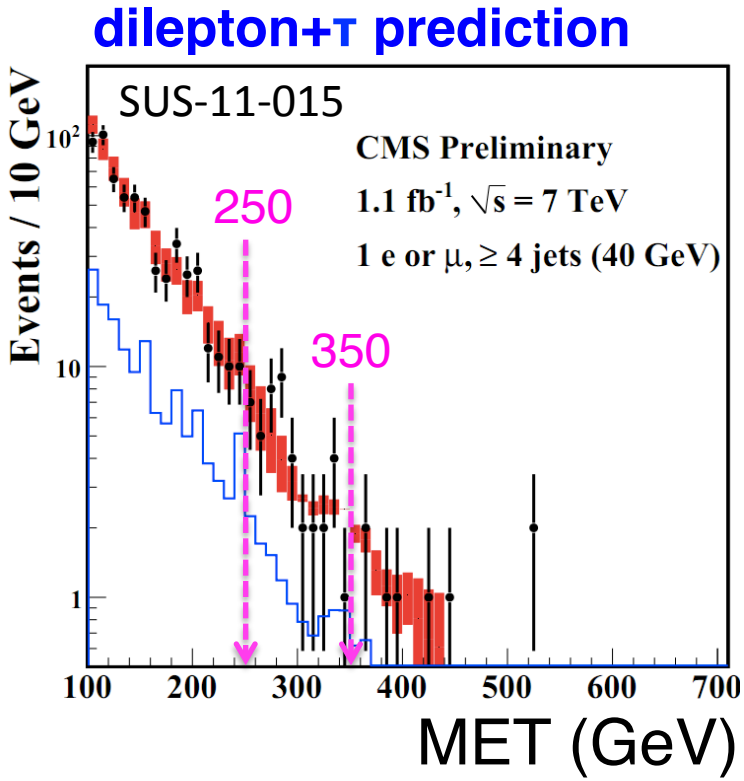
- Dominant backgrounds (tt→ℓ+jets/W+jets) with W→ℓν: $p_T(\ell)$ related to $p_T(\nu)$ ~ MET → **use $p_T(\ell)$ to model MET from bkg**
- SUSY signal: invisible LSP's cause MET >> $p_T(\ell)$ → **search for excess high MET events above prediction from $p_T(\ell)$ spectrum**

single lepton: Results



- Good agreement between predicted and observed MET distributions

single lepton: Results



2 signal regions (defined a priori):

MET > 250 GeV (loose)

MET > 350 GeV (tight)

	MET > 250 GeV	MET > 350 GeV
predicted	49.8 ± 8.8 ± 10.8	12.1 ± 4.3 ± 3.6
observed	52	8

- Observed yields agree well with total bkg predictions in both signal regions → **no evidence for SUSY**
  - Results interpreted in context of CMSSM (will show this later)

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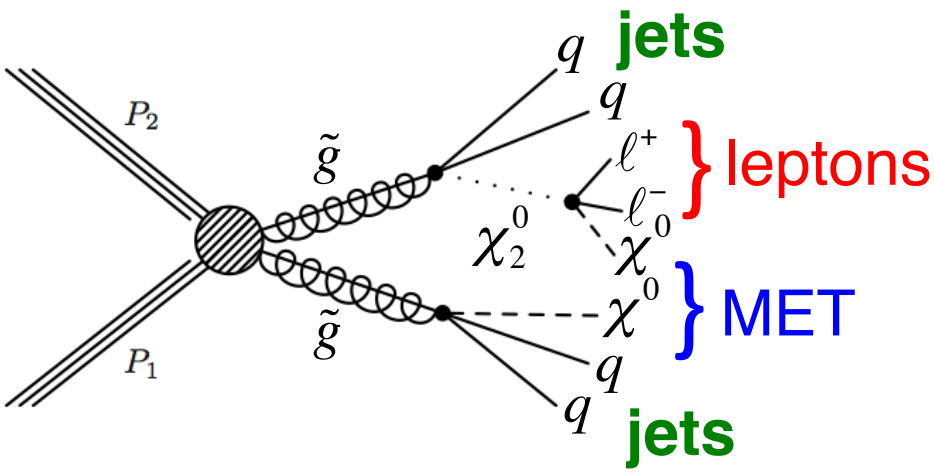
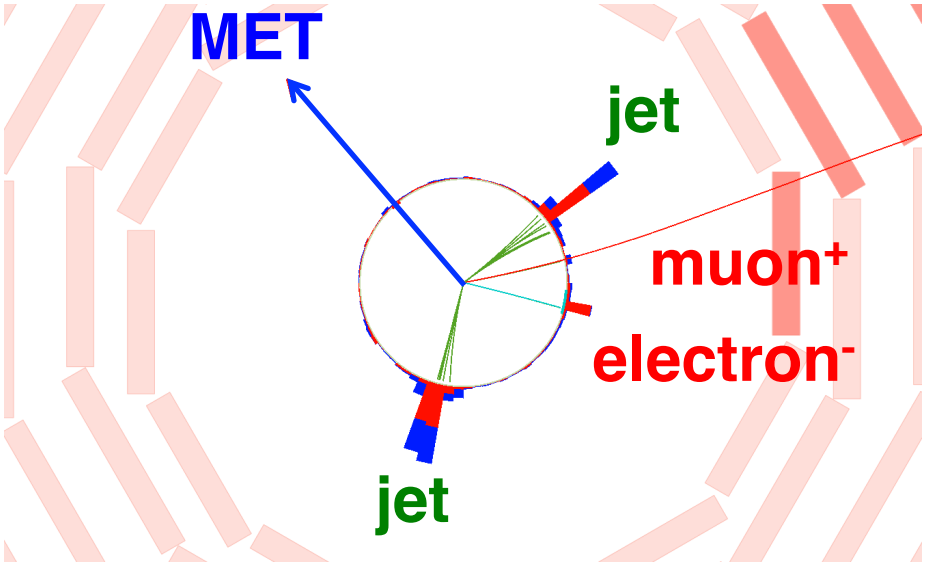
OS: Introduction

example signal:
SUSY with $\chi_2^0 \rightarrow \ell^+ \ell^- \chi^0$ decay



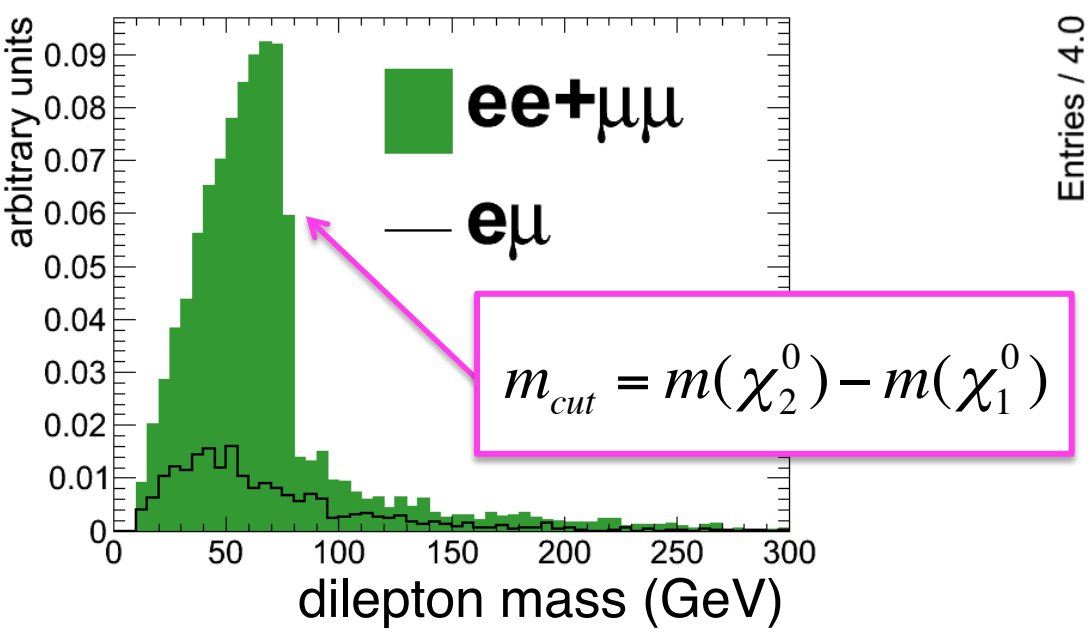


- Require 2nd opposite-sign lepton → suppress W+jets
- **Signature: opposite-sign (OS) leptons (ee/eμ/eμ) + jets + MET**
- **Search for "kinematic edge" in dilepton mass distribution**
  - Also perform counting experiment in high MET vs. H_T signal region

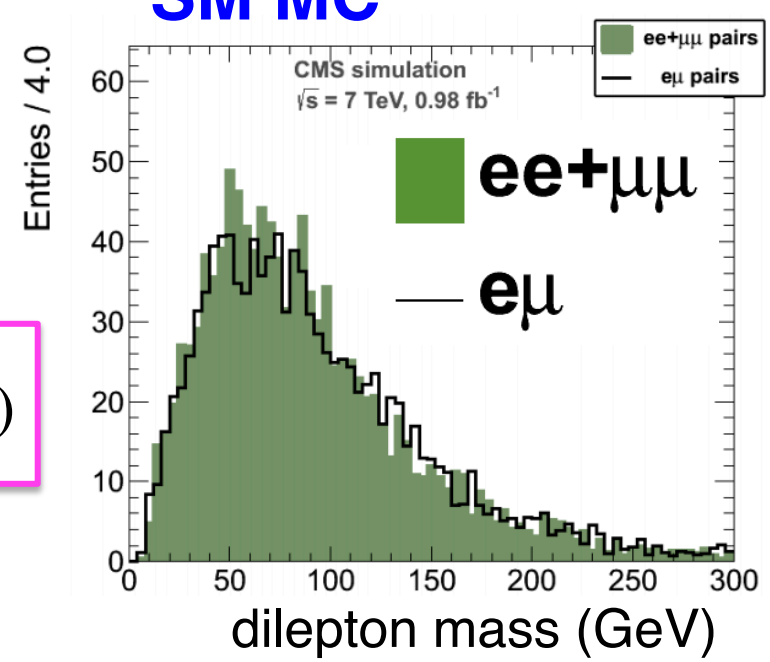
OS: Edge Search

- $\chi_2^0 \rightarrow \ell^+\ell^- \chi_1^0$ kinematic endpoint produces "edge" in ee+μμ dilepton mass distribution
  - Potential "smoking gun" for new physics observation
  - Relax cuts, exploit shape info → complementary to high MET, H_T searches
  - **Edge position (m_{cut})** → precise measurement related to SUSY particle masses
- SM background: same yield/shape in opposite-flavor (eμ) vs. same-flavor (ee+μμ)
- **Search for edge in ee+μμ dilepton mass, take bkg shape from eμ sample**

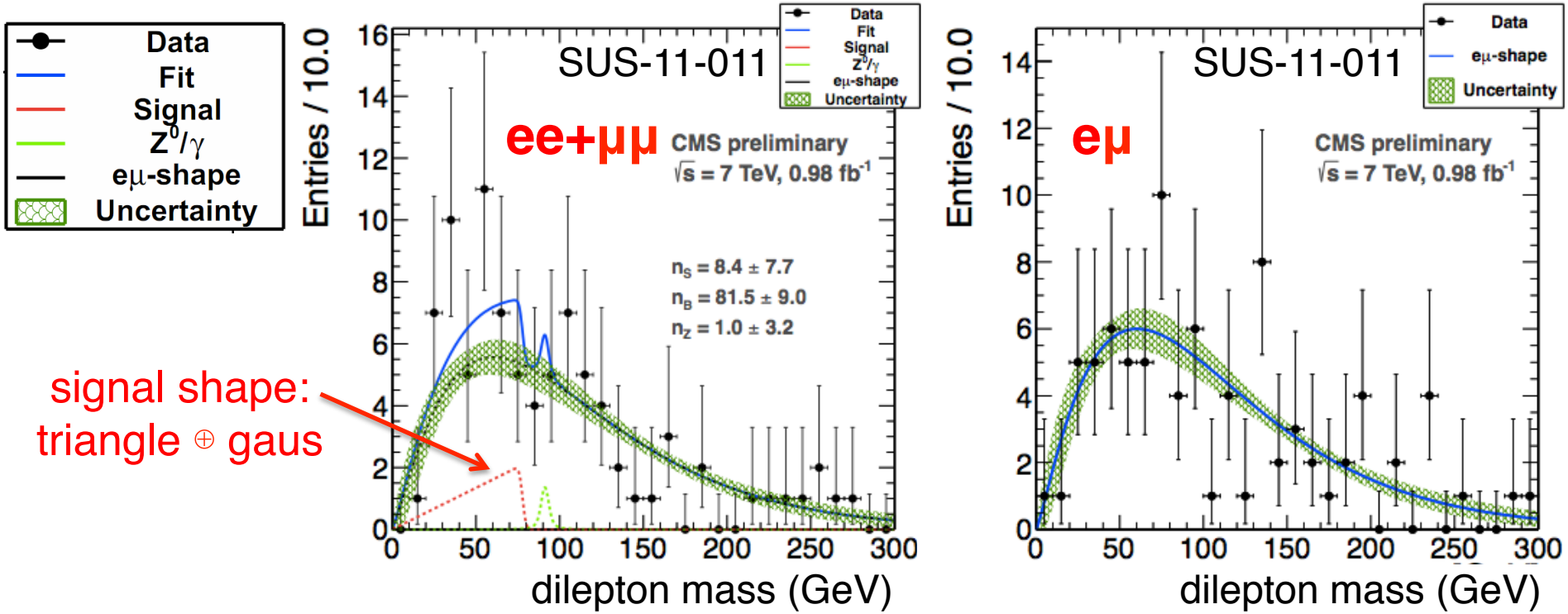
SUSY with $\chi_2^0 \rightarrow \chi_1^0 \ell^+\ell^-$



SM MC



OS: Results



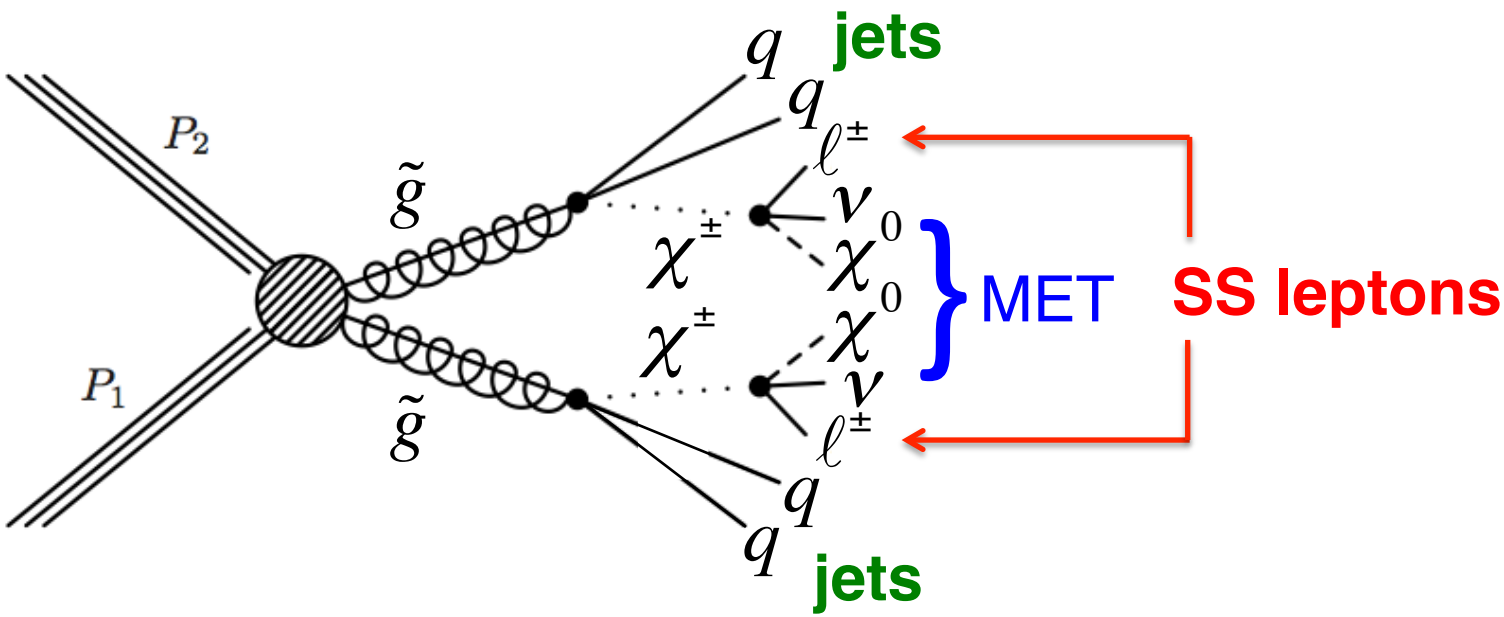
- **No edge observed** → extract signal yield UL using maximum likelihood fit
- Signal shape depends on 1 parameter only (edge position m_{cut}) → scan m_{cut} and extract signal yield, and upper limit, at each point
  - Signal yield consistent with 0 within ~2σ over full m_{cut} range (backup)
  - Example fit shown: m_{cut} ~ 80 GeV

Outline

- Introduction
- **SUSY Searches**
  - all-hadronic
  - single lepton
  - opposite-sign dilepton
  - **same-sign dilepton**
- Interpretation of Results
- Outlook and Conclusions

SS: Introduction

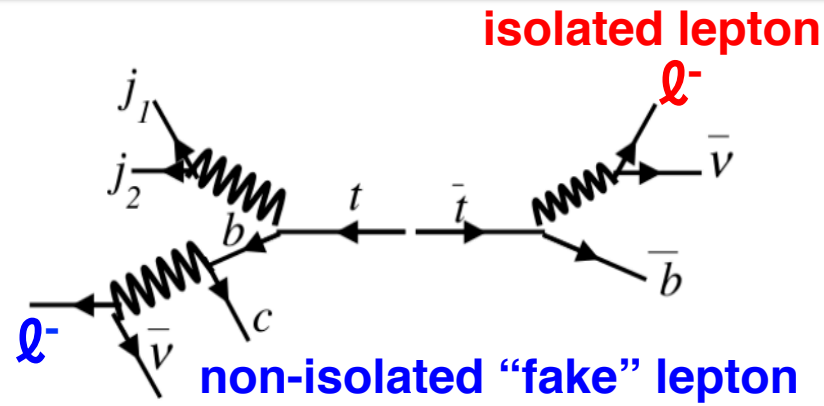
example signal:
SUSY with 2 $\chi^{\pm}$ decays



- Require 2nd same-sign lepton → **suppress SM backgrounds**
- **Signature: sign-sign (SS) leptons + jets + MET**
- **Challenge: estimating backgrounds from fake leptons**

SS: Overview of Backgrounds

dominant background: ttbar with "fake" lepton from b→ℓ±



- Events with "fake" (non-W/Z) leptons (dominant)
  - **challenge**: MC under-predicts fakes→ use 2 data-driven methods
    - Tight-loose (TL) ratio method (a.k.a. "fake rate" method) → next slide
    - B tag-and-probe → extract b→ℓ± isolation distributions from b-enriched sample (used in inclusive lepton p_T sample, see backup)
- Rare SM processes with SS leptons
  - Estimate from MC
  - ttW, qq→q'q'W±W±: never measured in pp collisions → **measurement critical for future SS analysis**
- Opposite-sign leptons with charge mis-ID (~10%)
  - Charge mis-ID rate validated using same-sign Z sample in data

SS: tight-loose (TL) Method

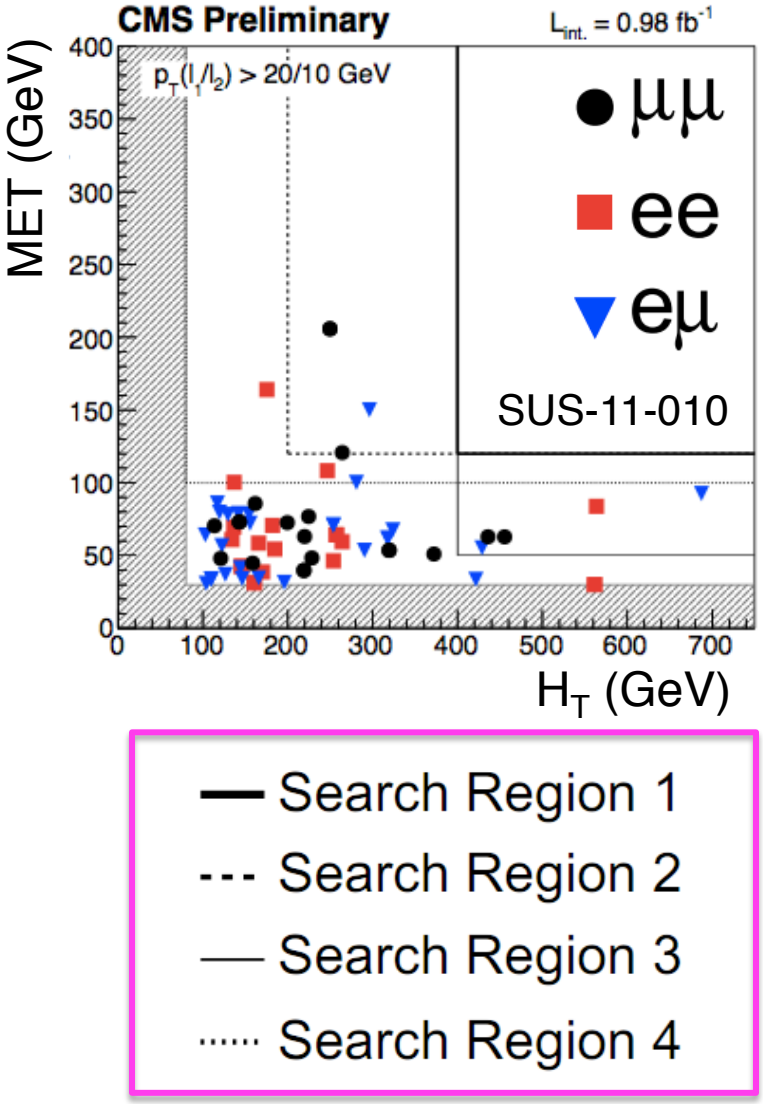
- Estimate fakes using control sample of leptons passing relaxed selection → extrapolate to analysis lepton selection
- Define loose lepton selection by relaxing ID and/or iso requirements

$$\text{TL ratio: } R_{TL}(p_T,\eta) = \frac{\text{leptons passing analysis selection}}{\text{leptons passing loose selection}}$$

- Measure R_{TL} in independent, QCD-dominated sample
  - R_{TL} ~ 10-30%
- Estimate background from events with:
  - 1 fake lepton: count events with 1 loose lepton + 1 analysis lepton
  - 2 fake leptons: count events with 2 loose leptons
- Weight events by appropriate R_{TL} → **sum of weights is predicted background from fake leptons**

SS: Search Strategy

- Search for SUSY in 3 complementary samples
  - **high-p_T dileptons**: (shown)
  - **inclusive leptons**: lower lepton p_T cuts, sensitive to compressed spectra
  - **hadronic τ's**: sensitive to enhanced 3rd generation coupling
- Define preselection regions in MET-H_T plane (veto shaded regions)
  - Test bkg estimates with O(100) events
  - Good agreement observed vs. predicted yields (see backup)
- Define ***4 search regions*** by adding MET, H_T requirements → **search for excesses above predicted bkg**



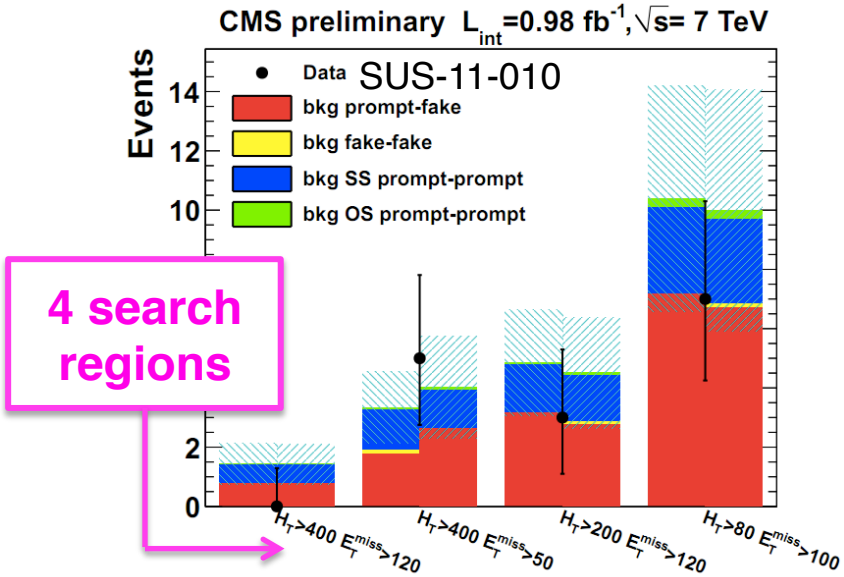
SS Results: Signal Regions

single fake
double fake
SM SS processes
charge mis-ID

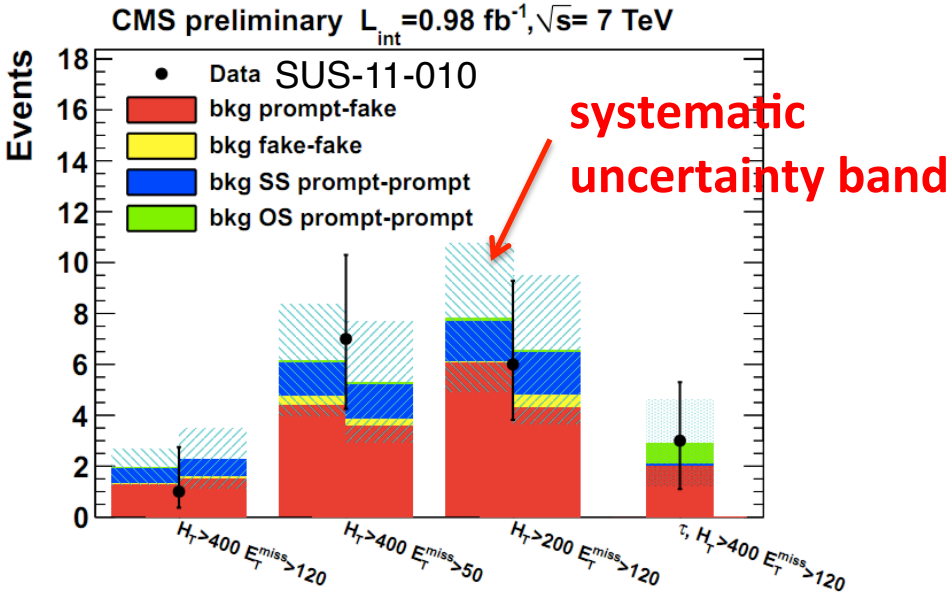
left: R_{TL} (relax ID+iso)
right: R_{TL} (relax iso)

left: b tag-and-probe
right: R_{TL} (relax iso)

high p_T lepton sample



inclusive lepton + τ → hadrons sample



- Good agreement observed yields vs. both bkg predictions in all samples and signal regions → **no signs of new physics**
  - Note sizable contribution from **SM SS processes**

SS: Model-Independent Limits

- Allow results to be applied to arbitrary new physics models → **quote upper limits on non-SM contributions to 4 signal regions**
  - Limits shown for high p_T lepton sample
  - Results interpreted in context of CMSSM (will show later)

Region	Predicted Background	Observed Yield	95% CL UL yield
MET > 120 GeV, H_T > 400 GeV	1.4 ± 0.7	0	3.0
MET > 50 GeV, H_T > 400 GeV	3.3 ± 1.2	5	7.5
MET > 120 GeV, H_T > 200 GeV	4.5 ± 1.9	3	5.2
MET > 100 GeV, H_T > 80 GeV	10 ± 4	7	6.0

95% CL limits using CLs technique, use bkg estimate giving more conservative UL

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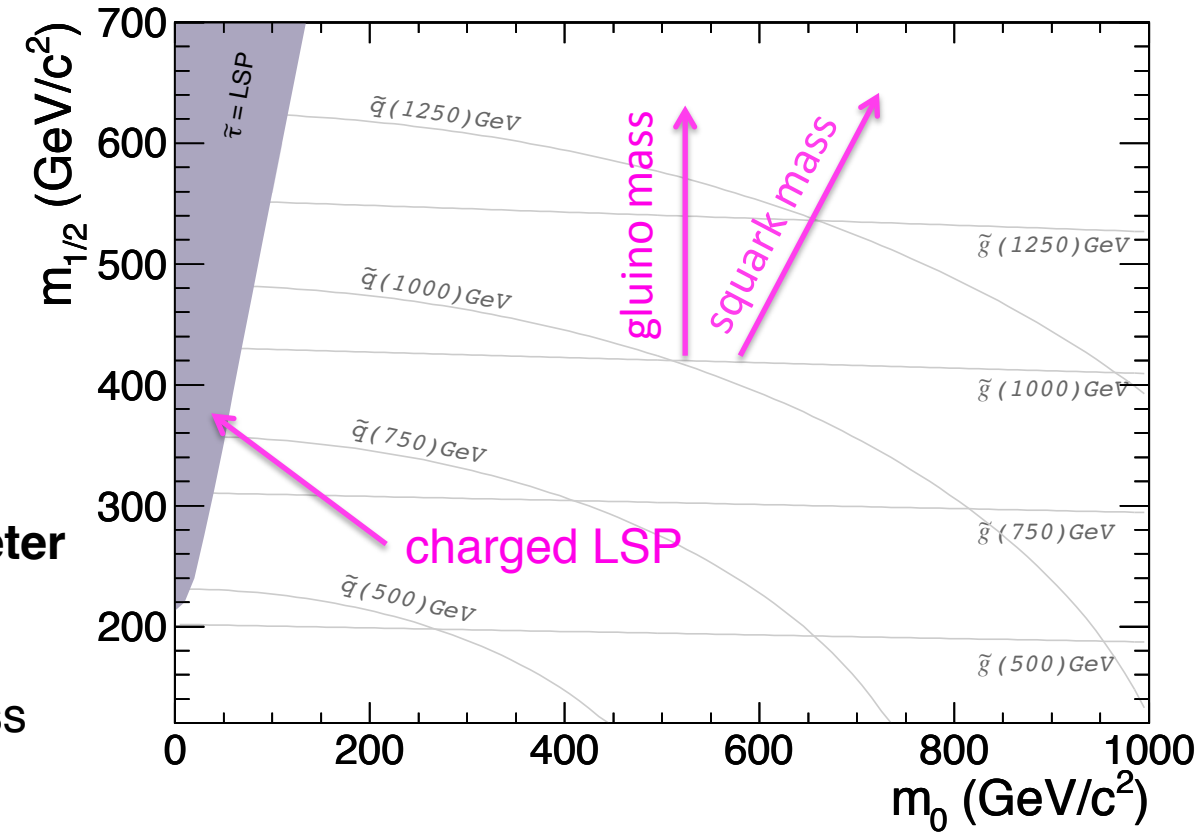
Intro to CMSSM

minimal SUSY extension to SM (MSSM):
>100 free parameters

↓

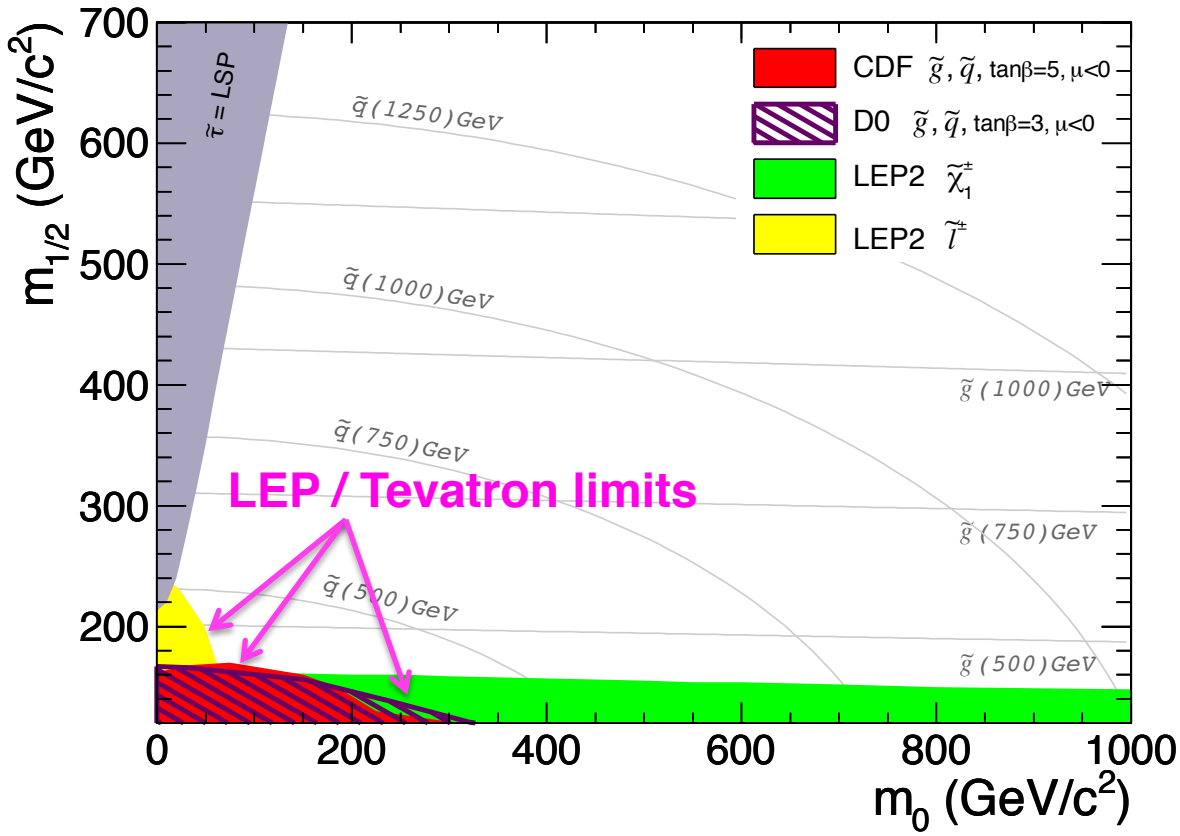
<u>constrained</u> MSSM:
5 parameters

m_0: scalar mass parameter
$m_{1/2}$: gaugino mass parameter
tan β: ratio of Higgs VEV's
A_0: trilinear coupling
sign(μ): sign of Higgsino mass



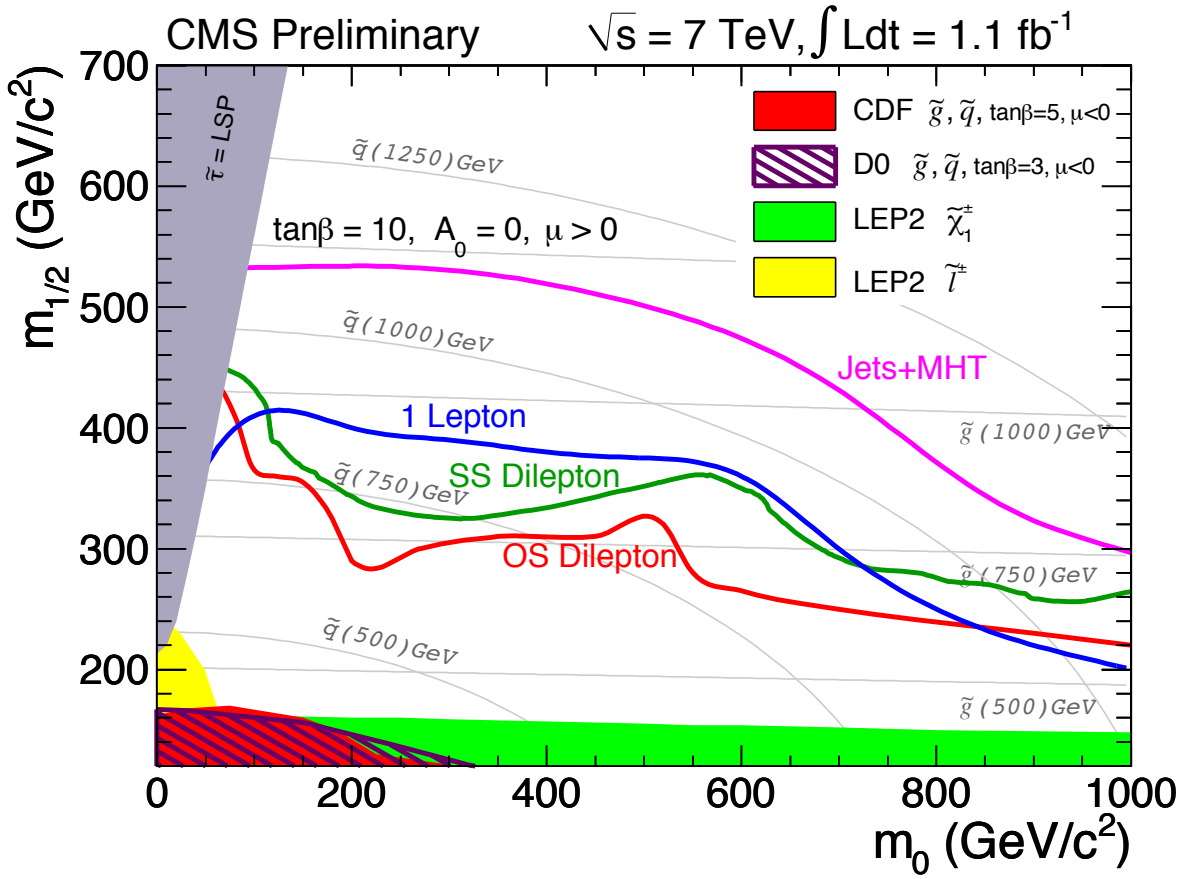
CMSSM: LEP/Tevatron Limits

CMSSM provides common reference point for comparison of multiple experiments



CMSSM: CMS Results

- All-hadronic analysis: best CMSSM sensitivity
  - **M(squarks) ≳ 1 TeV**
  - **M(gluino) ≳ 0.5 TeV**
- Leptonic analyses competitive at high m_0



SUSY Interpretations

- Drawbacks of CMSSM:
  - Doesn't cover full range of possible SUSY phenomenology
    - Constrained relations between SUSY particle masses, eg. M(gluino) ~ 6 × M(LSP)
  - Multiple processes contribute at each CMSSM point
    - Difficult to apply results to other SUSY, new physics models
- **Goal: provide "<u>model-independent results</u>" → allow application to arbitrary new physics models**
  - 1) Provide **efficiency models** → allow estimation of arbitrary model signal efficiency
  - 2) Interpret results in context of **Simplified Models**

Efficiency Model

- ***Goal***: determine if arbitrary model X is excluded by comparing expected yield to signal yield upper limit

$$N(\text{model X}) = \mathcal{L} \times \sigma \times A \times \varepsilon$$

$\mathcal{L}$ (luminosity) → provided by experimentalists
σ (cross section) and A (acceptance) → calculated by theorists for model X
ε (efficiency) → depends on detector AND model X kinematics

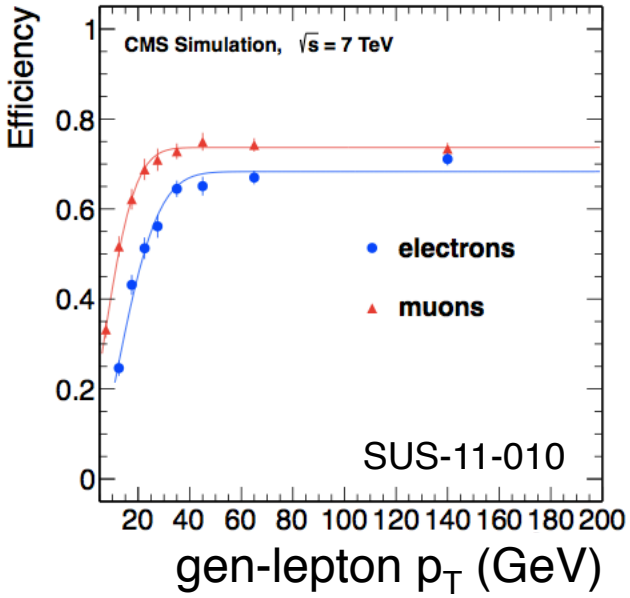
- Recipe: provide selection efficiencies for **basic physics objects** (leptons, H_T, MET) → allow estimation of model X efficiency using simple generator-level studies

Efficiency Model

- Efficiency model: parameterization of the efficiencies of the physics objects: leptons (shown), MET and H_T (in backup)

- ***Procedure:***
  - Implement model X in favorite MC
  - Apply analysis selections to gen-level quantities
  - Use efficiency model to scale gen-level yields to "reco-level"
  - Compare expected model X yield to quoted upper limit to determine if excluded

lepton efficiency
(same-sign analysis)



- Compare CMSSM limit from efficiency model vs. CMS simulation → **good agreement (backup)**

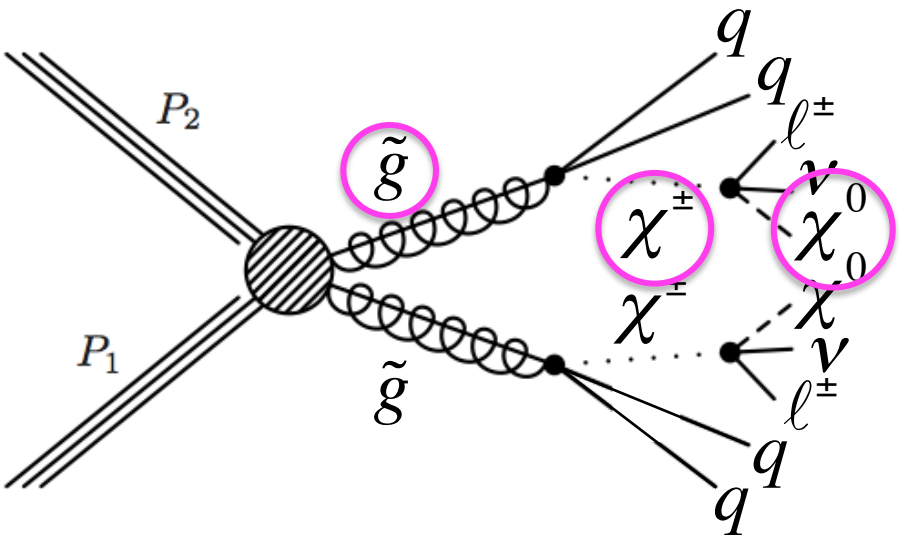
Simplified Models

- Simplified Model Spectra (SMS)
  - Individual processes parameterized directly by the masses of participating particles

example:

gg, g→ qq$\chi^{\pm}$, $\chi^{\pm}$ → $\ell^{\pm}\nu\chi^{0}$

SS leptons + 4 jets + MET



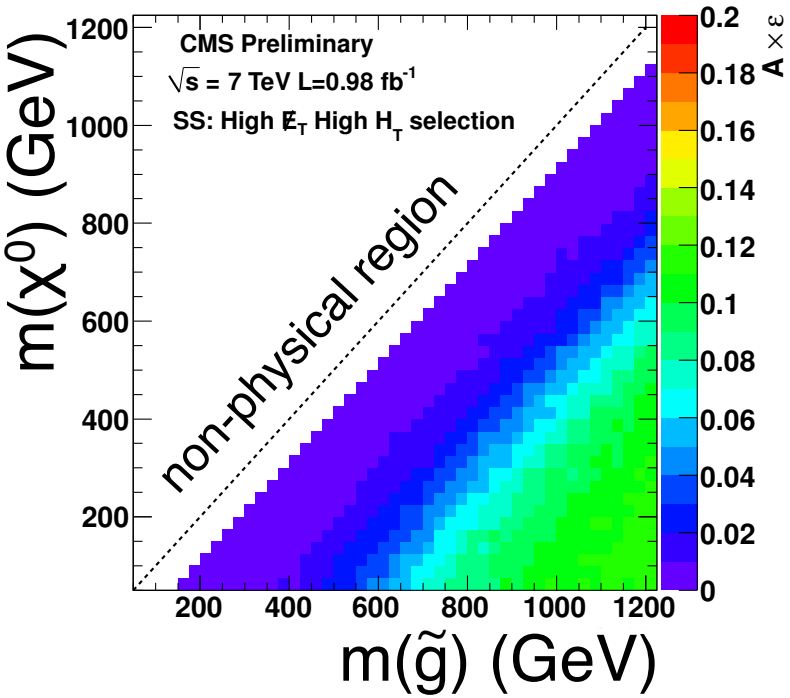
- Kinematics fully specified by **3 parameters**: **M(g), M($\chi^{\pm}$), M(χ^{0})**

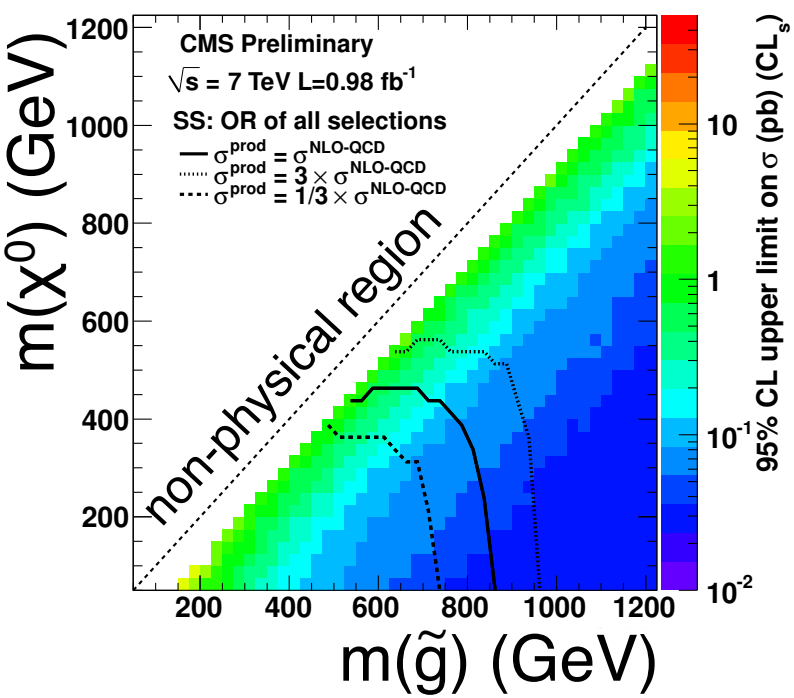
SMS Results

- Example shown: same-sign search results applied to SS+ jets + MET

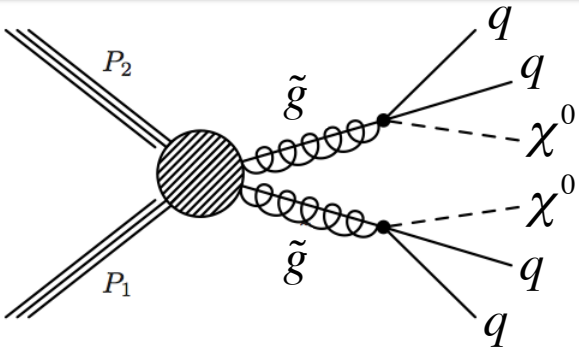
- signal region efficiency map
  - Identify regions of low efficiency (eg. small mass splitting region)
  - Validate efficiency models, fastsim (eg. Delphes/PGS)

- cross section upper limit
  - Apply to arbitrary model X: calculate model masses and $\sigma_X \rightarrow$ excluded if $\sigma_X > \sigma_{UL}$
  - Exclude region of parameter space (for $\sigma^{NLO\text{-}QCD}$, BF=1)

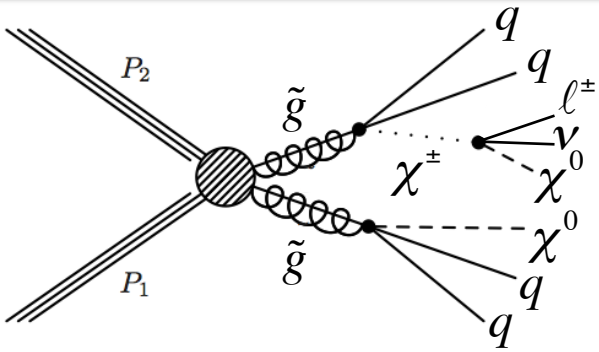




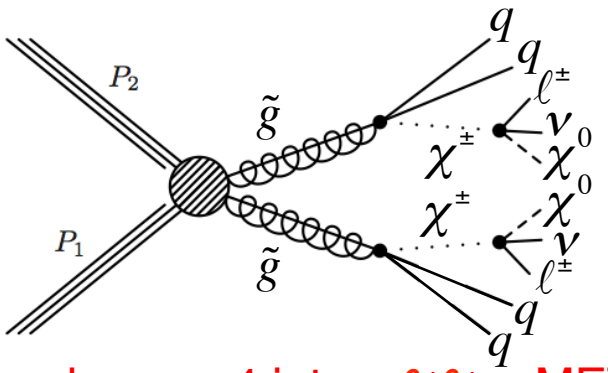
More SMS



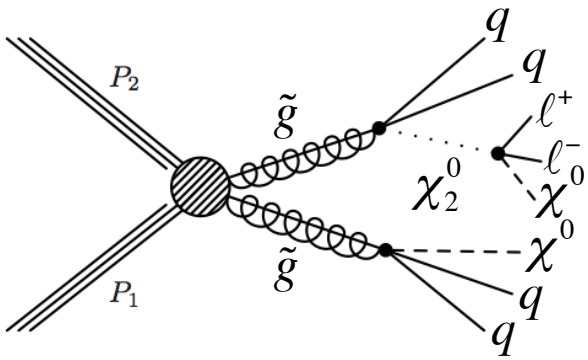
channel: gg → 4 jets + MET
analysis: all-hadronic



channel: gg → ℓ± + 4 jets + MET
analysis: single-lepton



channel: gg → 4 jets + ℓ±ℓ± + MET
analysis: SS dilepton



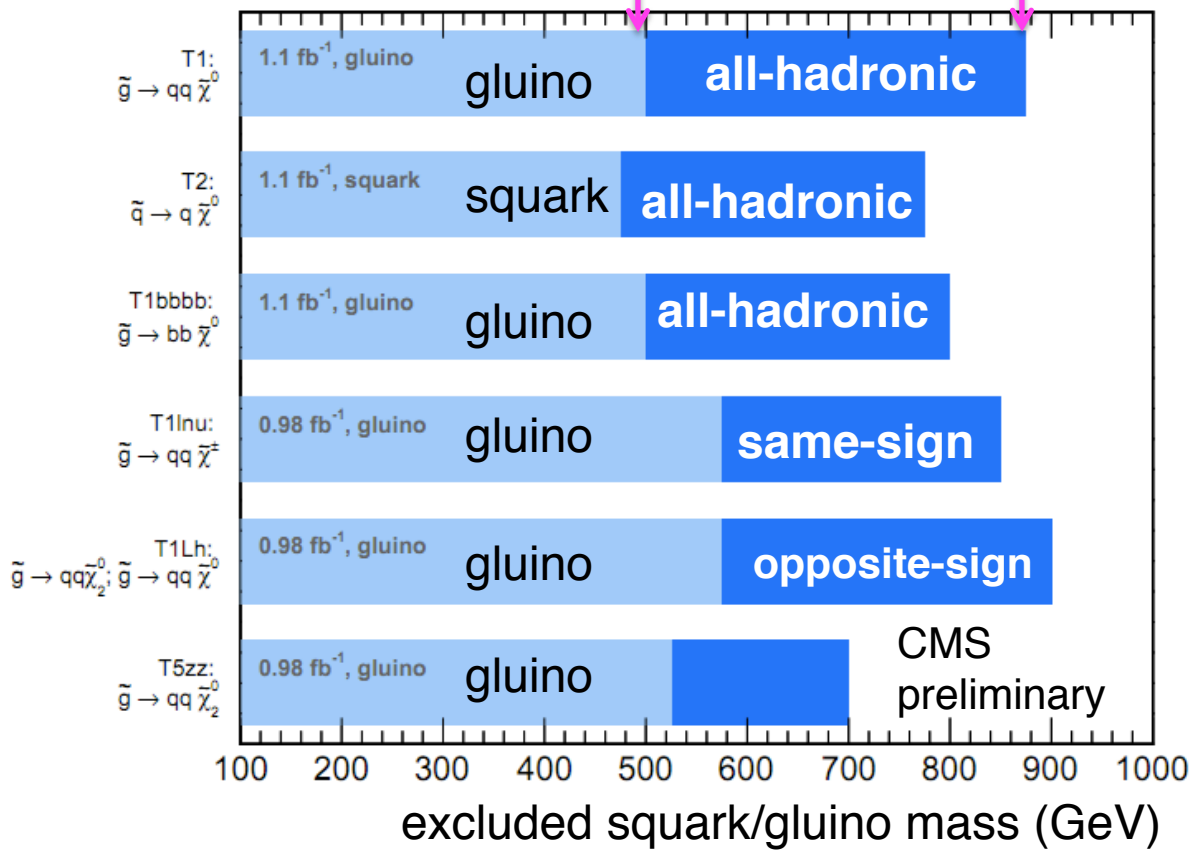
channel: gg → 4 jets + ℓ+ℓ- + MET
analysis: OS dilepton

- Results interpreted in variety of SMS models

Squark/Gluino Mass Limits

$M(\chi^0) = 0$ GeV

$M(\chi^0) = M(g) - 200$ GeV



assumptions

- $\sigma = \sigma^{\text{NLO-QCD}}$ and BF = 1
- For gluino mass limits, m(squark) >> m(gluino) (and vice-versa)

$$m(\tilde{\chi}^\pm),\ m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}.$$

- Exclude range of squark/gluino masses in various simplified model topologies

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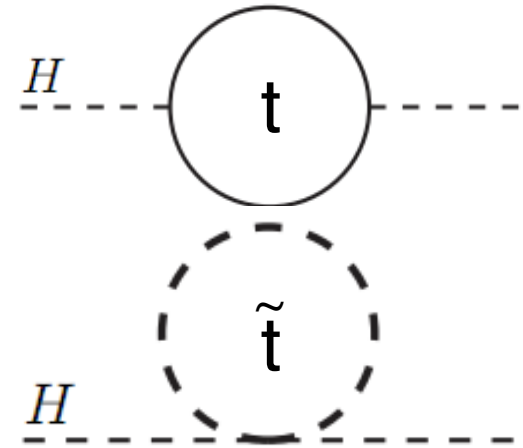
Future Directions (1)

- So far, focused on "low-hanging fruit" → SUSY with large σ, large MET and H_T
- Haven't found SUSY in ~1 fb^{-1} → where might it be hiding?
  - Electroweak production (of gauginos)
    - Smaller σ → becomes relevant with large luminosity
    - Target by relaxing/removing jets/H_T requirements
  - R-parity violating models
    - Target by relaxing/removing MET requirements
  - Compressed spectra / small mass splittings between sparticles
    - Target low p_T objects (eg. leptons)
- Probe low H_T and/or low MET models with rare final states
  - Same-sign, multi-lepton, lepton+photon, etc.

Future Directions (2)

- ***Search for stop quarks*** → special role in SUSY solution to hierarchy problem
  - **M_H naturalness → m(stop) ≲ 0.5 – 1 TeV**



- Search for direct stop pair production, eg:

$$pp \to \tilde{t}\tilde{t} \to t\bar{t}\,\chi^0\chi^0$$ (ttbar + extra MET)

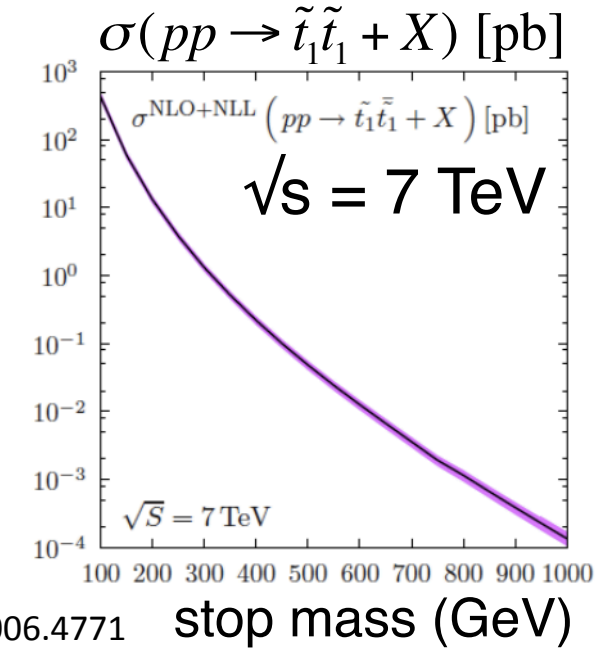
$$m(\tilde{t}) \sim 0.5 \text{ TeV} \to \sigma \sim 0.1 \text{ pb}$$

  - **Expect few × 10^2 stop pairs in ~5 fb^{-1}**

- Search for stops from gluino decay, eg:

$$pp \to \tilde{g}\tilde{g} \to (\tilde{t}t)(\tilde{t}t) \to t\bar{t}t\bar{t}\,\chi^0\chi^0$$

(4 tops! → 2-4 leptons + b-tags + MET)

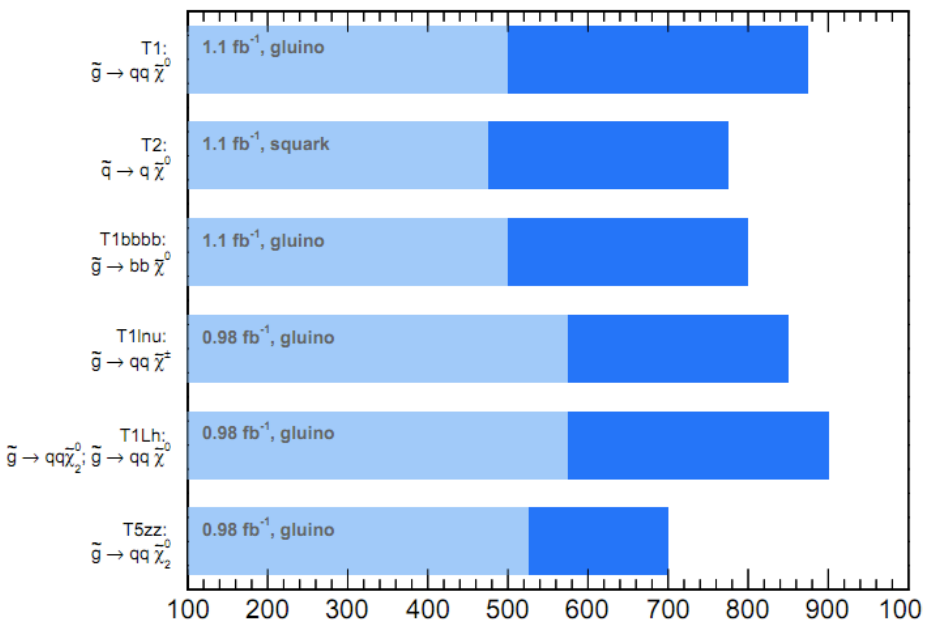


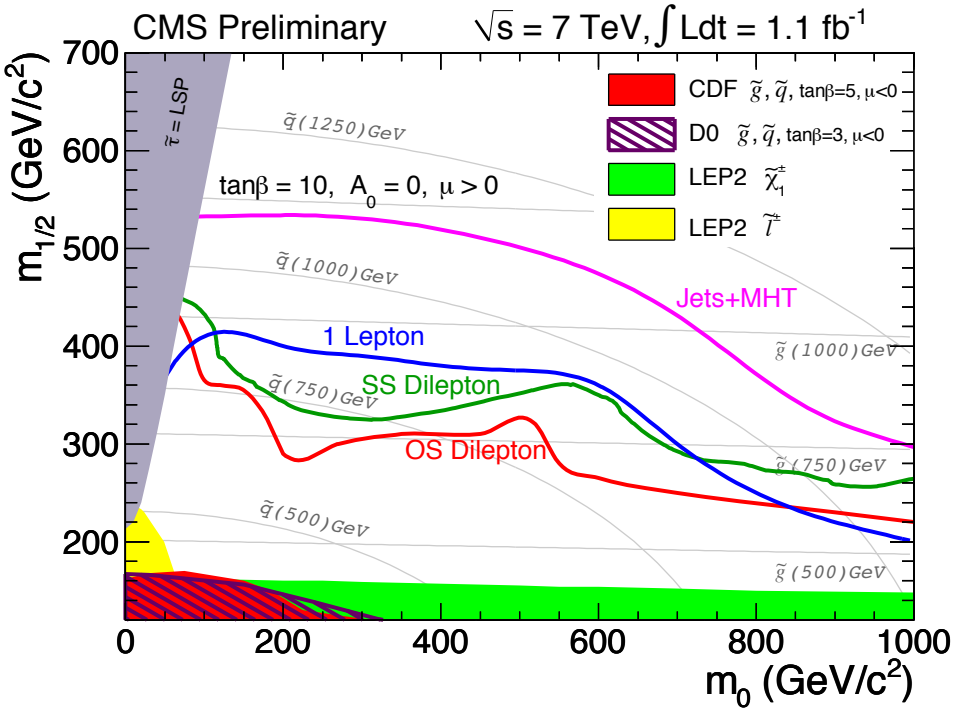
http://arxiv.org/pdf/1006.4771

Summary

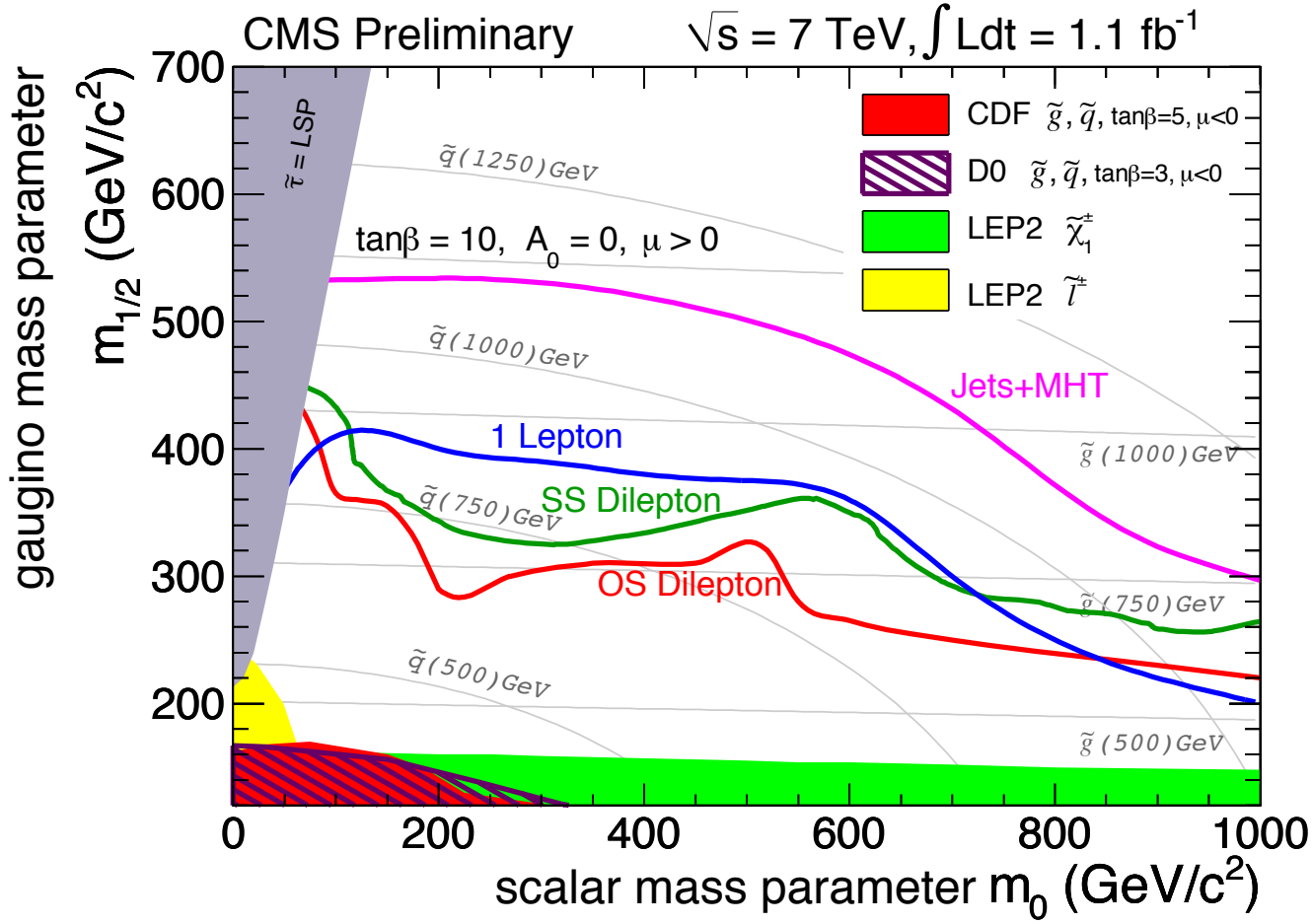
- Performed broad program of SUSY searches in wide variety of final states
  - Backgrounds determined with robust data-driven methods
- No evidence for SUSY observed in 1 fb^{-1}…
- **LHC SUSY program has far more ground to cover**
  - Sensitivity improvement: ~5× more data (expected 2011)
  - New search channels and strategies

Backup Material





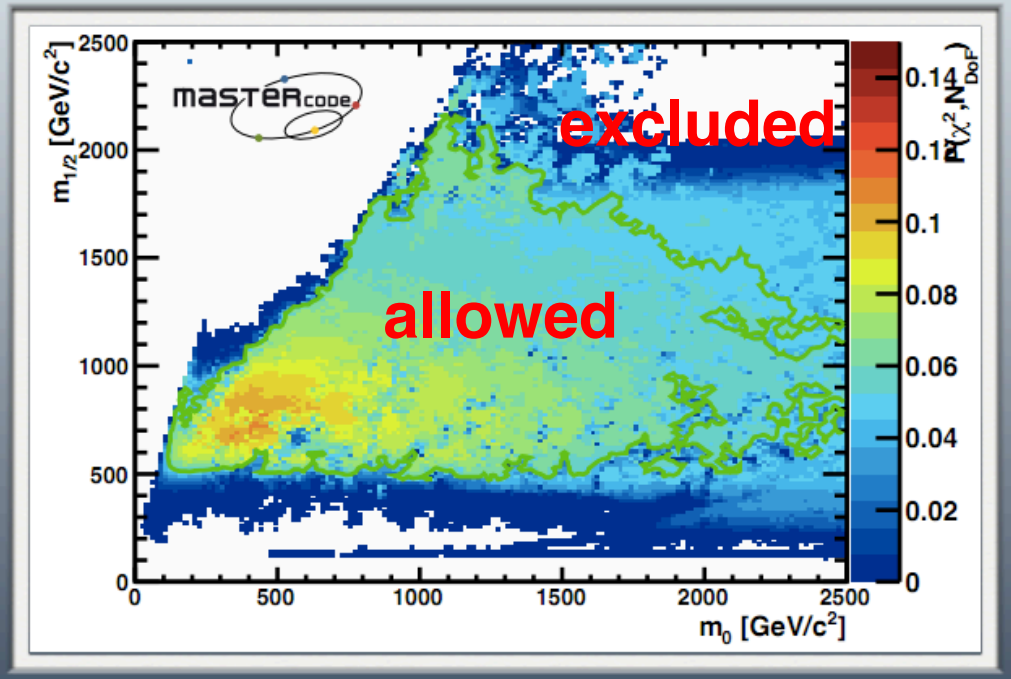
CMSSM Exclusions



- All-hadronic analysis: best sensitivity to CMSSM
  - **M(squarks) ≳ 1 TeV and M(gluino) ≳ 0.5 TeV**
- Leptonic analyses competitive at high m_0

CMSSM Constraints

Confronting SUSY with LHC Data



probability to be consistent w/experimental constraints:
direct searches
indirect constraints
cosmology

O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

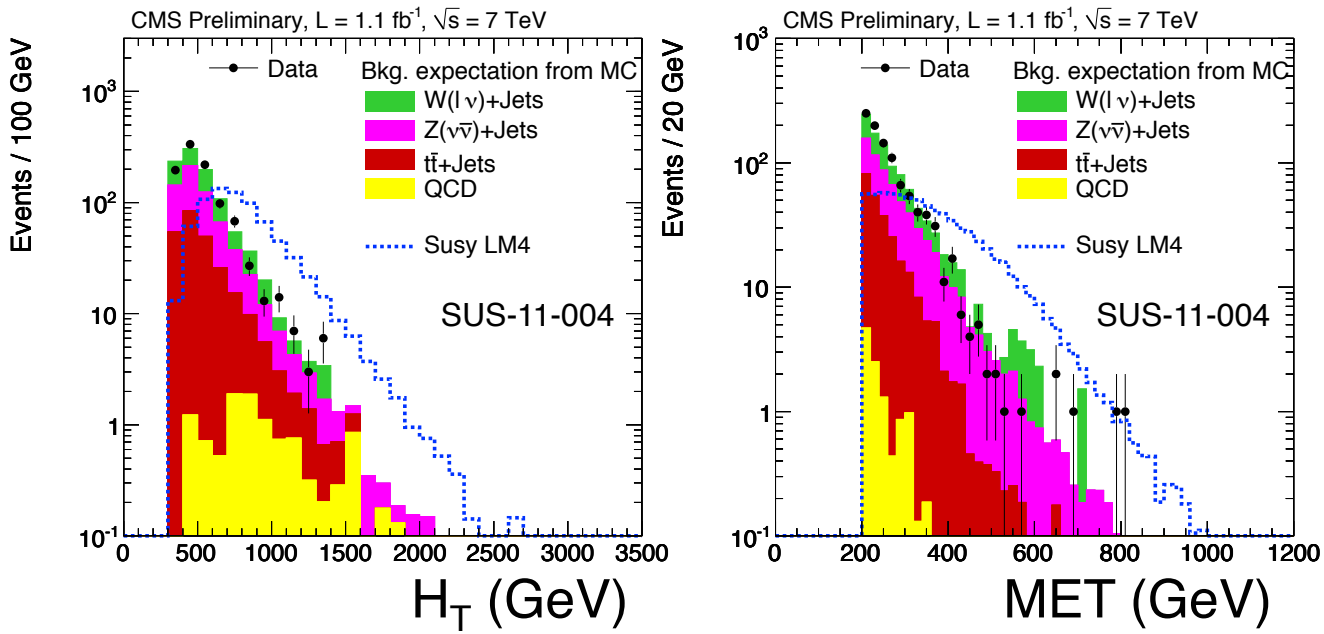
SUSY11
Fermilab, 28 August to 02 September, 2011

Backup Material

- all-hadronic
- single lepton
- opposite-sign leptons
- same-sign leptons

all-hadronic: Event Preselection

- ≥3 high p_T jets with large H_T
- Large MET → QCD suppression
- Cut on $\Delta\phi(\text{jet}_{(1,2,3)},\text{MET})$ → suppress QCD with 1 mismeasured jet
- Veto isolated e/μ → suppress bkg's with $W \to \ell\nu$
- **Reasonable data/MC agreement**
  - But background estimates are fully data-driven



backgrounds:

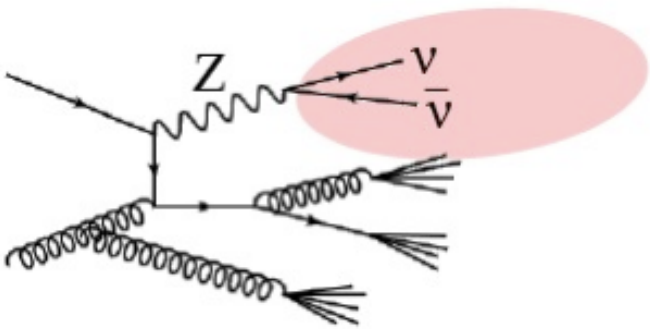
- W(l ν)+Jets
- Z(νν̄)+Jets
- tt̄+Jets
- QCD

signal:

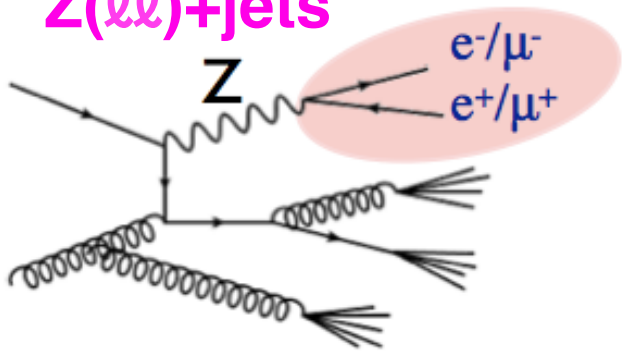
- LM4 SUSY scenario
  σ_{NLO} = 2.5 pb
  $m(\tilde{q})$ ~ 500-700 GeV
  $m(\tilde{g})$ ~ 700 GeV

all-hadronic: Z→νν Bkg Estimate

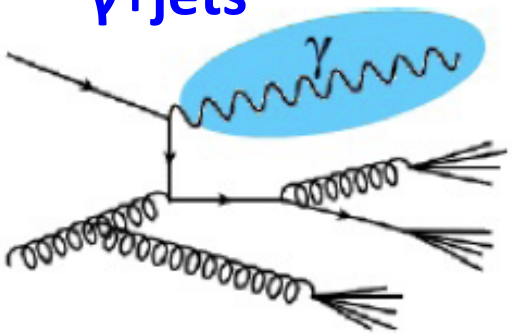
targeted background



control sample 1: Z(ℓℓ)+jets

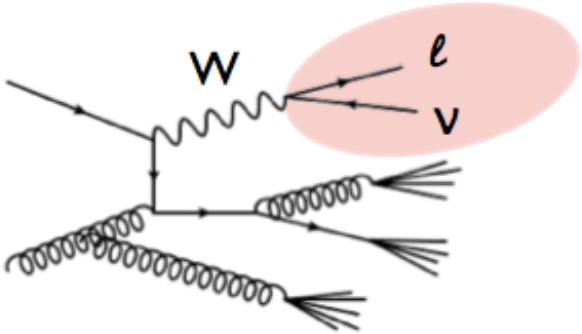


control sample 2: γ+jets

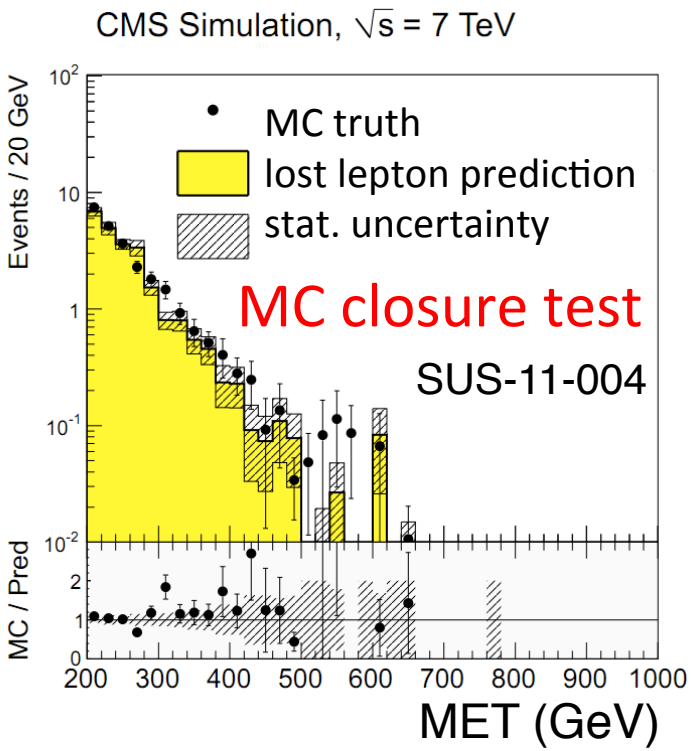


- **Model Z(νν)+jets background using Z(ℓℓ)+jets and γ+jets data control samples**
- Option 1) estimate using **Z(ℓℓ)+jets** control sample
  - Straightforward, but low stats (small BF(Z→ℓℓ)) → **use as cross-check**
- Option 2) estimate using high statistics **γ+jets** control sample
  - $p_T(\gamma,Z) >> M(Z)$ → hadronic part of the event is similar γ+jets vs. Z+jets
- **γ+jets used as primary measurement, Z(ℓℓ)+jets gives consistent results in baseline region**

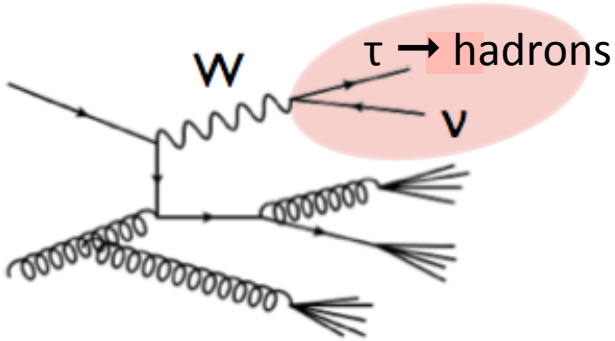
all-hadronic: W/ttbar lost lepton bkg



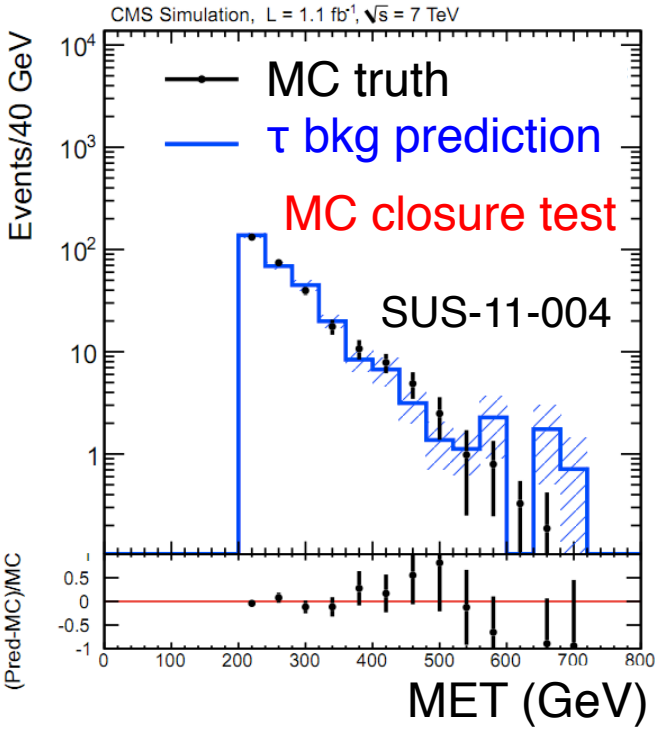
- Recall: we veto identified, isolated leptons
- Events with W→ℓν (from W+jets or ttbar) will pass selection if lepton is "lost" due to:
  - lepton fails identification or isolation
  - lepton is out of detector acceptance
- Strategy: select μ+jets data control sample, weight by probability to "lose" lepton
- Method reproduces key kinematic distributions
  - Verified in MC studies



all-hadronic W/ttbar τ→hadrons bkg

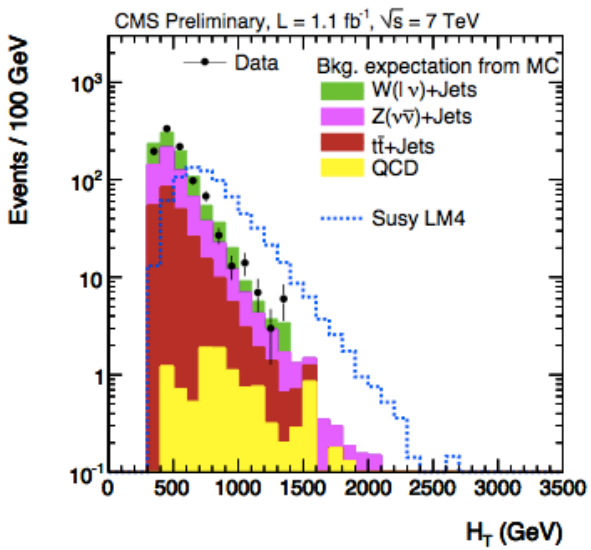


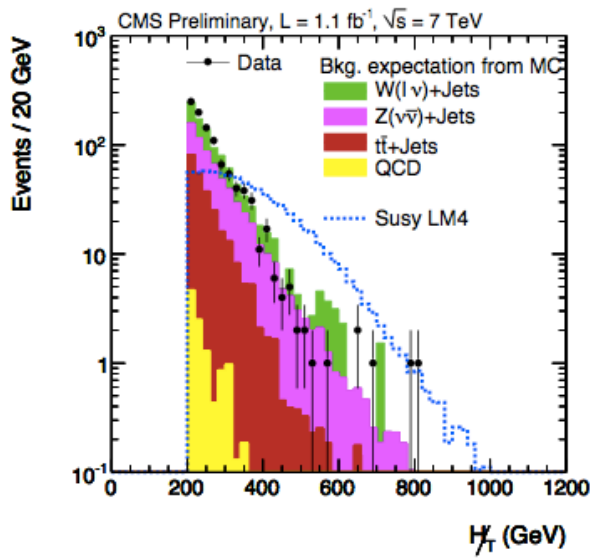
- Estimate bkg from W→τν with hadronic τ reconstructed as a jet
- Strategy:
  - Select μ + jets control sample
  - Replace the μ with τ jet using expected τ jet response (from MC)
    - response = (reco jet p_T)/(gen τ p_T)
  - Recalculate H_T, MET including τ jet
- Method reproduces key kinematic distributions
  - Verified in MC studies

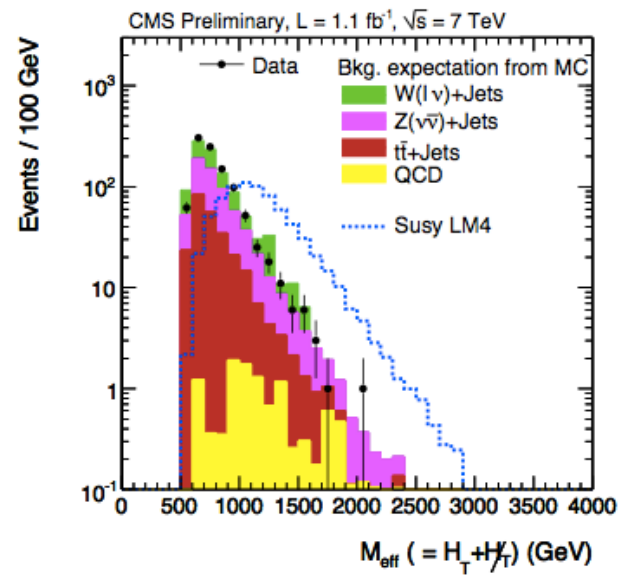


Data/MC Comparison

	Baseline	Baseline $\geq$ 3jets	Baseline $\geq$ 3jets $\Delta\phi$ cuts	Baseline $\geq$ 3jets $\Delta\phi$ cuts e/μ veto	Medium	High H_T	High $\not{H}_T$
Data	6377	3408	1640	986	78	70	3
Sum SM MC	6406	3227	1709	987	95	83	7.5
QCD multijet (PYTHIA)	1143	549	11.4	11.3	0.3	6.9	0.0
$Z(\nu\bar{\nu})$+jets (MG)	1370	481	387	386	46.3	29	4.2
$W(\ell\nu)$+jets (MG)	2963	1365	784	346	37.5	28	2.9
$t\bar{t}$ (MG)	930	832	527	244	11.3	18	0.4
LM4 (PYTHIA)	1477	1179	942	742	318	304	54







Z(vv) Estimate

systematic uncertainties and results

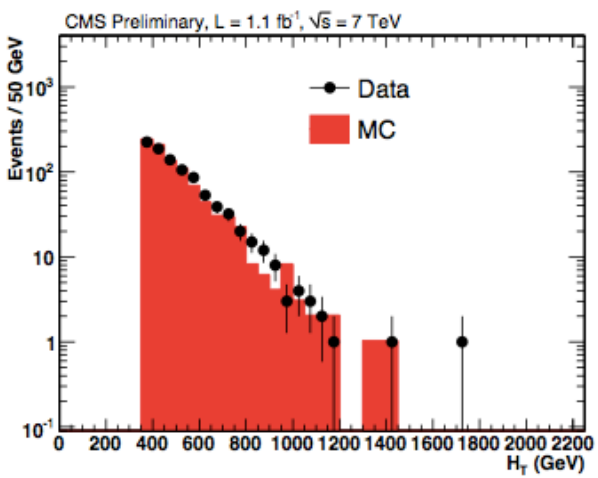
Table 2: Overview of all correction factors and corresponding systematic uncertainties.

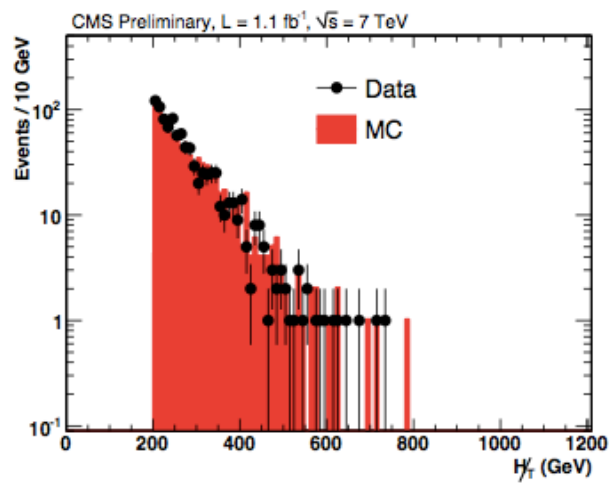
	Baseline	Medium	High H_T	High $\not{H}_T$
Fragmentation	0.95±1 %	0.95±1 %	0.95±1 %	0.95±1 %
Photon purity	0.93±7.8 %	0.99±4.6 %	0.94±7.1 %	1.00±4.5 %
Photon mistag	1.00±1.4 %	1.00±1.4 %	1.00±1.4 %	1.00±1.4 %
±scale	±12 %	±12 %	±12 %	±12 %
Z/γ correction±acceptance	0.47±5 %	0.48±5 %	0.57±5 %	0.51±5 %
±MC stat	±14.25 %	±14.28 %	±14.25 %	±15.66 %
ID data/MC ratio	0.98±3 %	0.98±3 %	0.98±3 %	0.98±3 %
Total correction	0.40±21.0 %	0.47±20.1 %	0.57±20.9 %	0.51±20.8 %

Table 3: The $Z \to \nu\bar{\nu}$ background predicted for each of the selections with the statistical and systematic uncertainties. The prediction corresponds to 1.1 fb^{-1}.

	Baseline	Medium	High H_T	High $\not{H}_T$
Prediction	376 ±12 ±79	42.6 ±4.4 ±8.9	24.9 ±3.5 ±5.2	2.4 ±1.1 ±0.5

γ+jets data vs. MC comparison





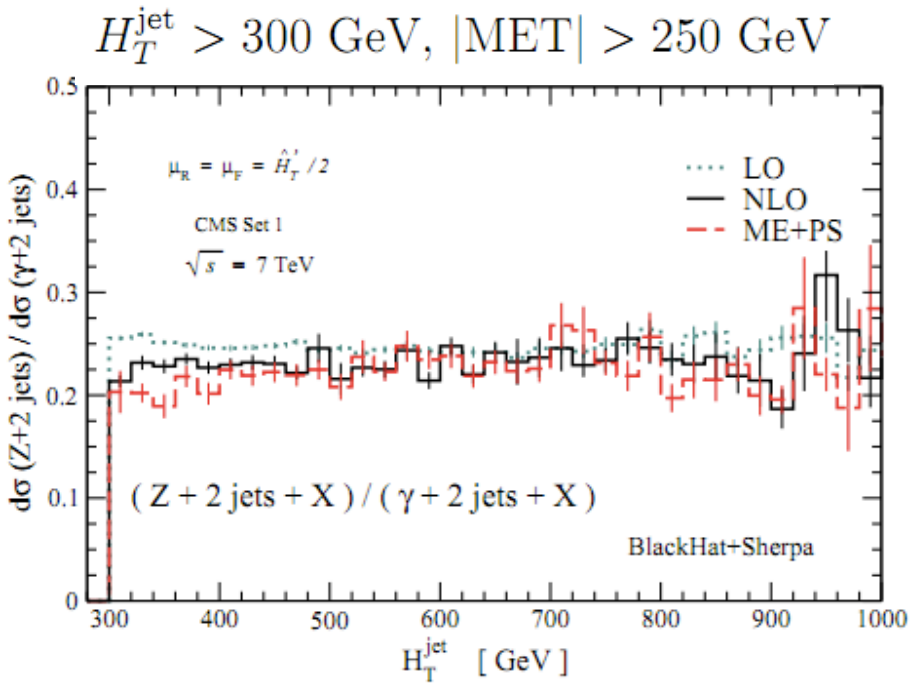
Z(vv) estimate

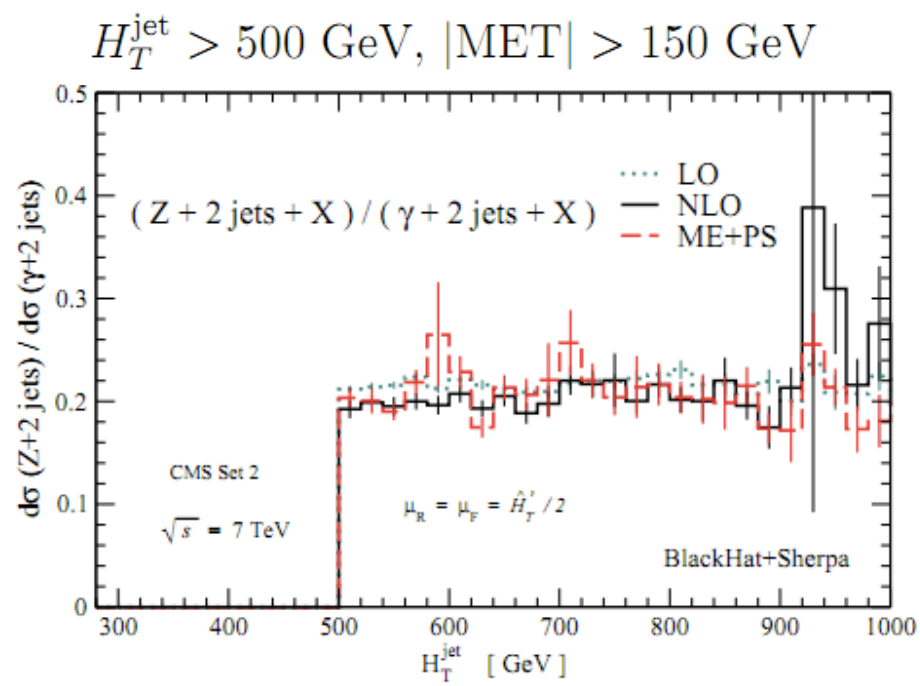
- Start with γ+jets sample
  - Subtract fragmentation photons: NLO JETPHOX → (5 ± 1)% contribution
  - subtract π^0, η contribution, using data-driven technique with isolation template fit → purity (92.9 ± 7.8)%
  - correct for Z(vv)+jets/γ+jets σ×A → ~(0.5±0.1)

γ vs. Z production

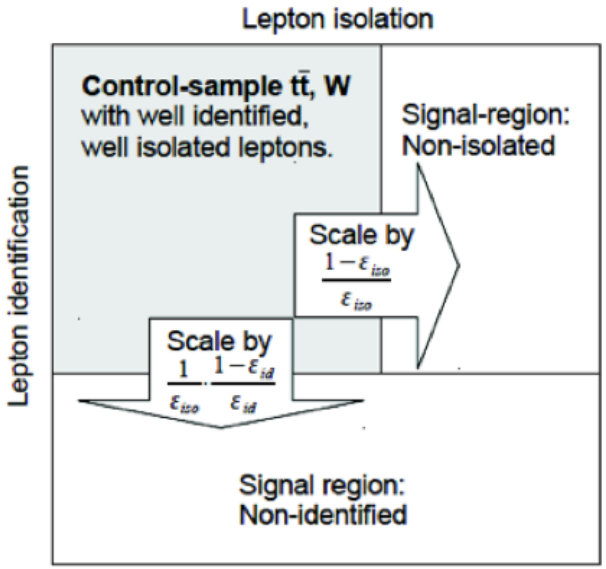
http://arxiv.org/pdf/1106.1423

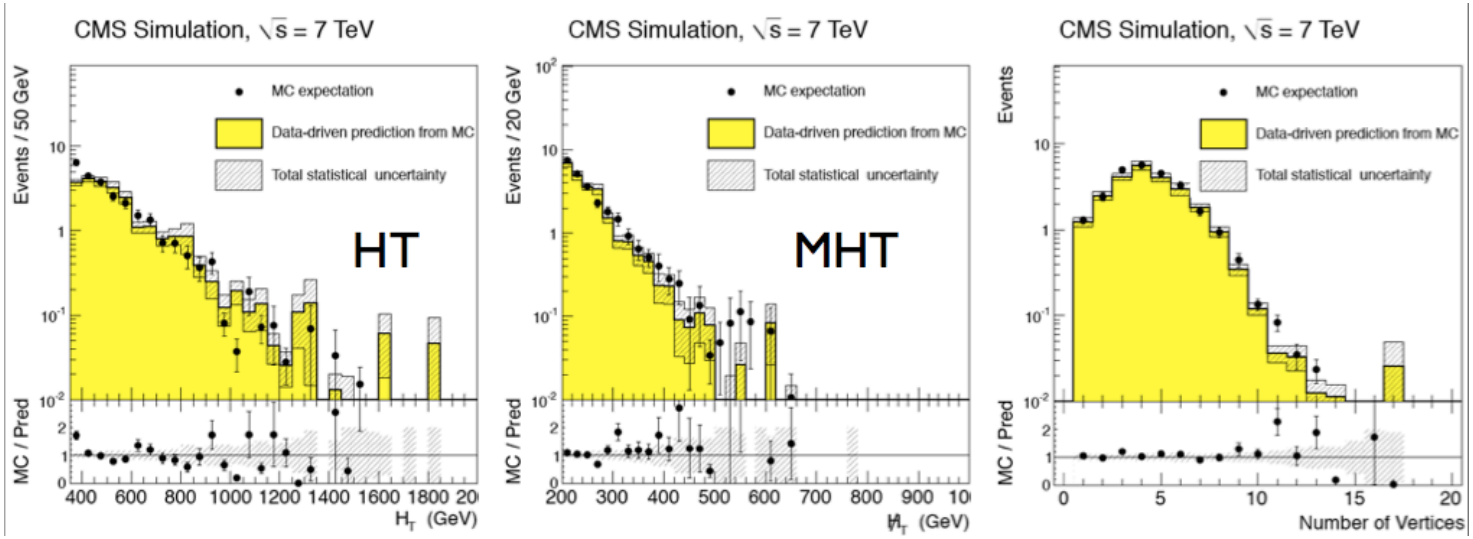
- γ+jets and Z+jets: for p_T >> M(Z), total production cross section same within ~20%
  - σ(Z(νν)+jets)/σ(γ+jets) flat vs. H_T, equal to ~0.2 (including BF(Z→νν)
  - theory uncertainty ~20% (from LO vs. NLO value)





W/tt lost lepton bkg





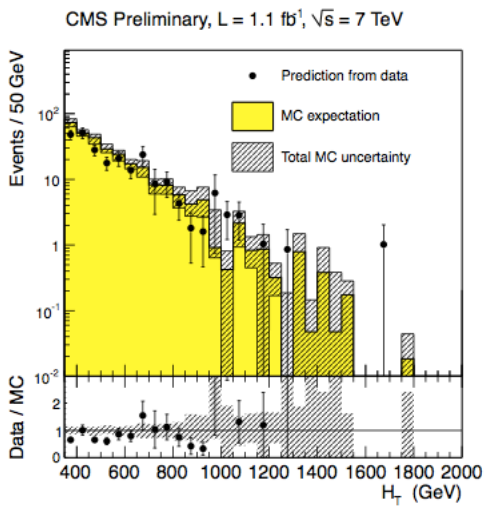
W/tt lost lepton bkg

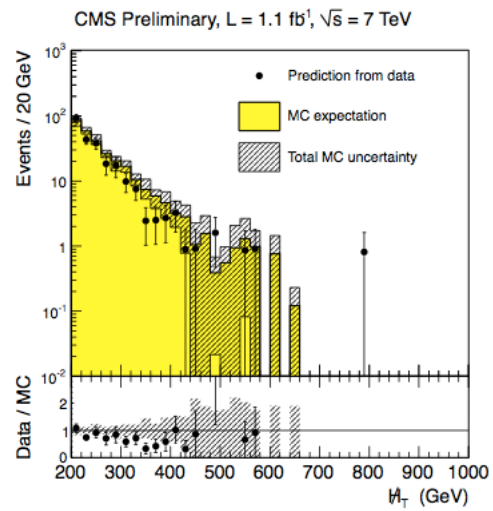
Table 5: Systematic uncertainties (in the number of events) of the lost-lepton background prediction.

Source	Systematic Uncertainties
Statistics of control-sample	-19.8 $+19.8$
Iso- & id- efficiencies (statistical)	-10.2 $+10.2$
Differences $t\bar{t}$, W, Z-samples and kinematic in control vs. signal region	-24.4 $+24.4$
SM background in control-region	-7.3 $+0$
MC use for acceptance calculation	-9.5 $+9.5$
Transverse W-mass-cut	-10.5 $+10.5$
Total, combined uncertainty	-36.7 $+35.9$

Table 4: The lost-lepton background predicted for each of the selections with the statistical and systematic uncertainties. The prediction corresponds to 1.1 fb^{-1}.

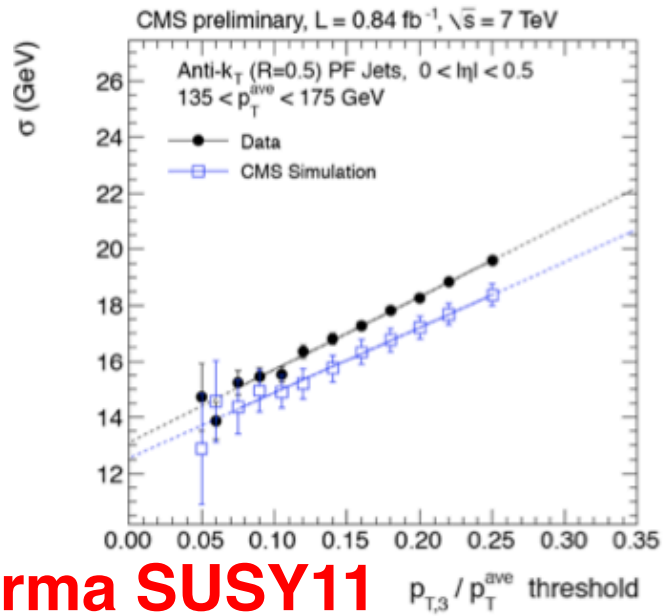
	Baseline	Medium	High H_T	high $\not{H}_T$
Prediction	$244 \pm 20 \; ^{+30}_{-31}$	$12.7 \pm 3.3 \pm 1.5$	$22.5 \pm 6.7 \; ^{+3.0}_{-3.1}$	$0.8 \pm 0.8 \pm 0.1$

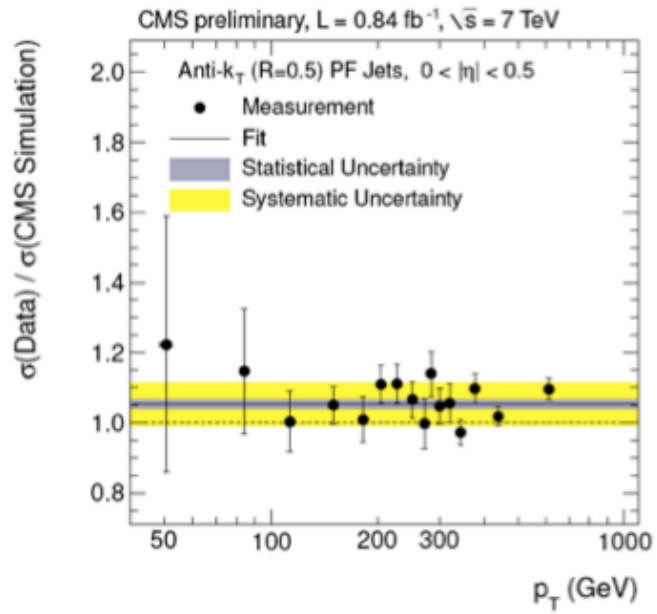




Jet Resolution (core)

- Measurement using maximum likelihood fit of measured pt imbalance in dijet eve
- Strategy :
  - Extrapolate the measured resolution to zero 3rd jet pT
  - Measure the ratio σ(Data)/σ(MC) (common biases cancel)
  - Correct MC truth response functions with the measured ratio



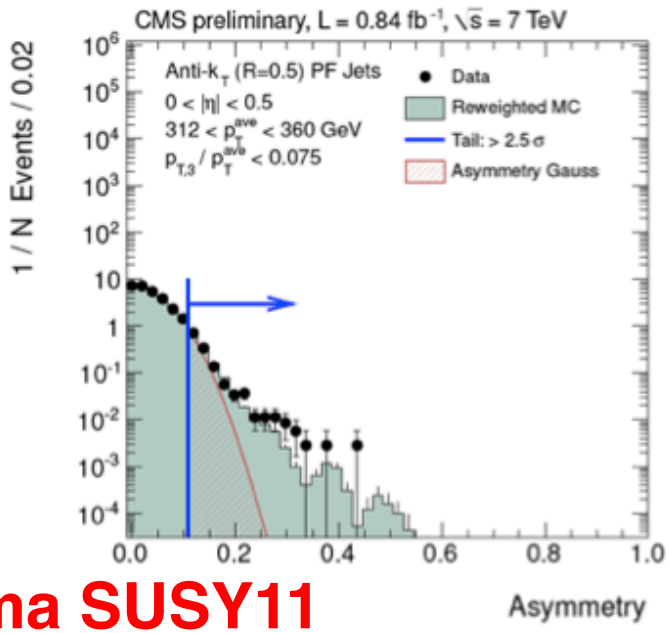


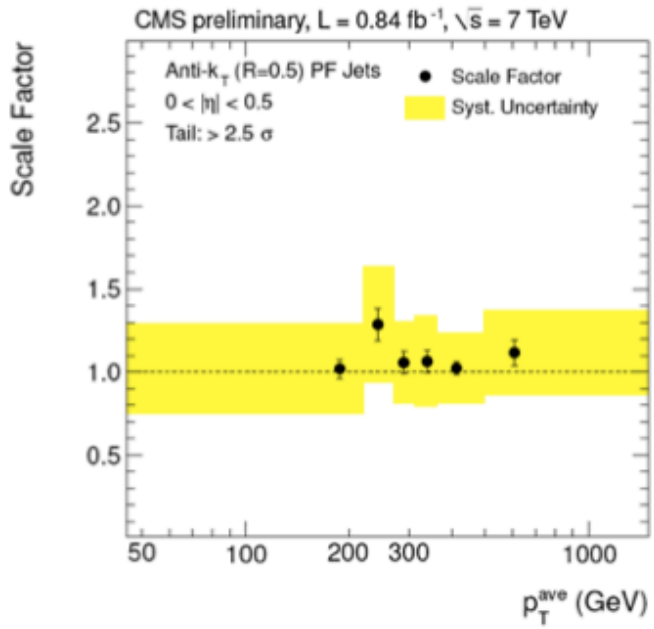
S. Sharma SUSY11

- Correction is ~5% in central regions and 25% in very forward region
- Dominant uncertainties : jet energy scale, extrapolation procedure (5-25%)

Jet Resolution (tails)

- Strategy : compare dijet asymmetry distributions in Data and MC
  - MC dijet asymmetry is corrected for larger core resolution in Data
  - Extrapolate the number of events in tail region to zero 3rd Jet pT
  - Scale the tails in MC truth response functions with Data/MC ratio

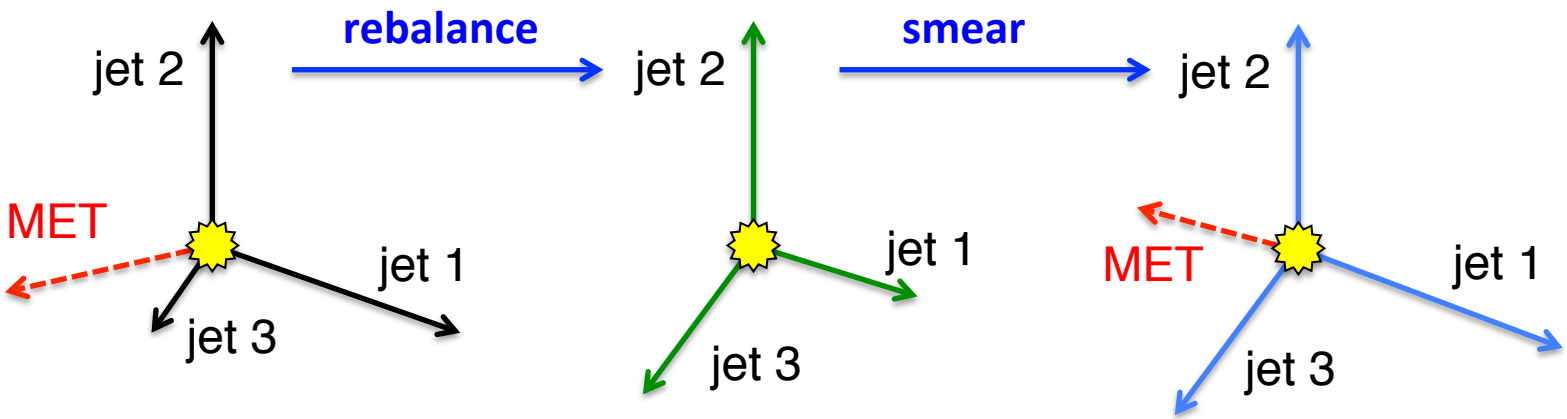




S. Sharma SUSY11

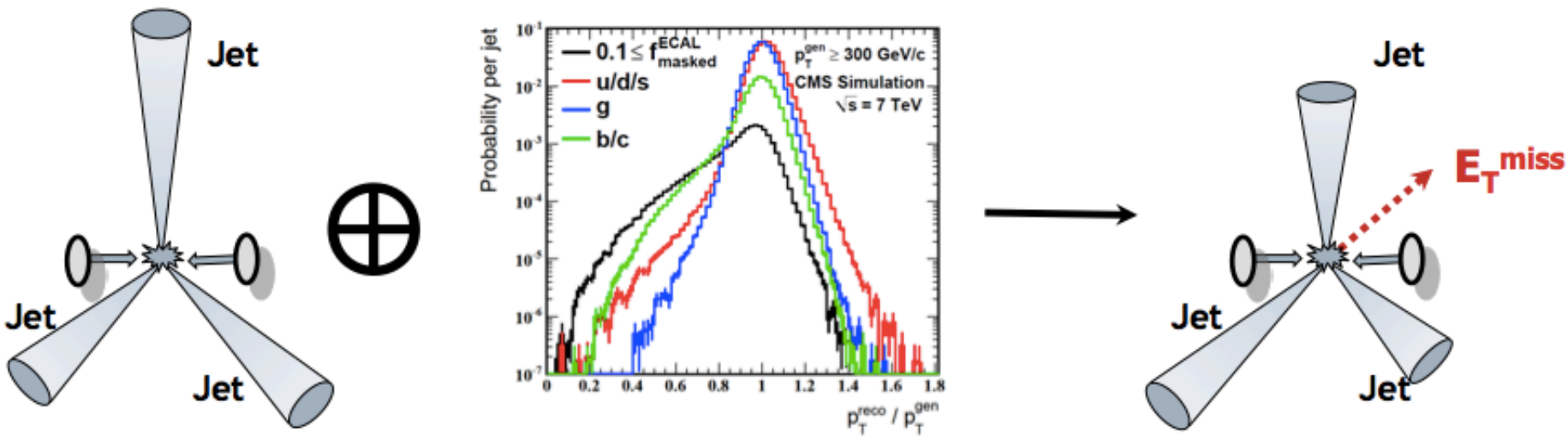
- Data/MC ratio of number of events in non-Gaussian component of response function is ~1 - simulation describes the data reasonably well.
- Dominant uncertainties : Core resolutions (others : pile-up, non-closure)

all-hadronic: QCD bkg (R+S)

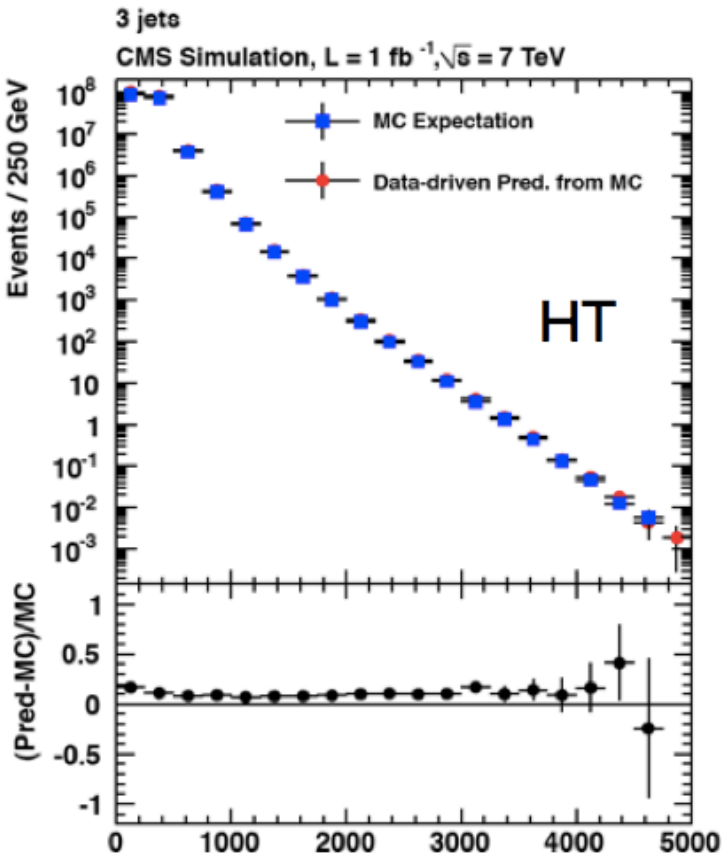


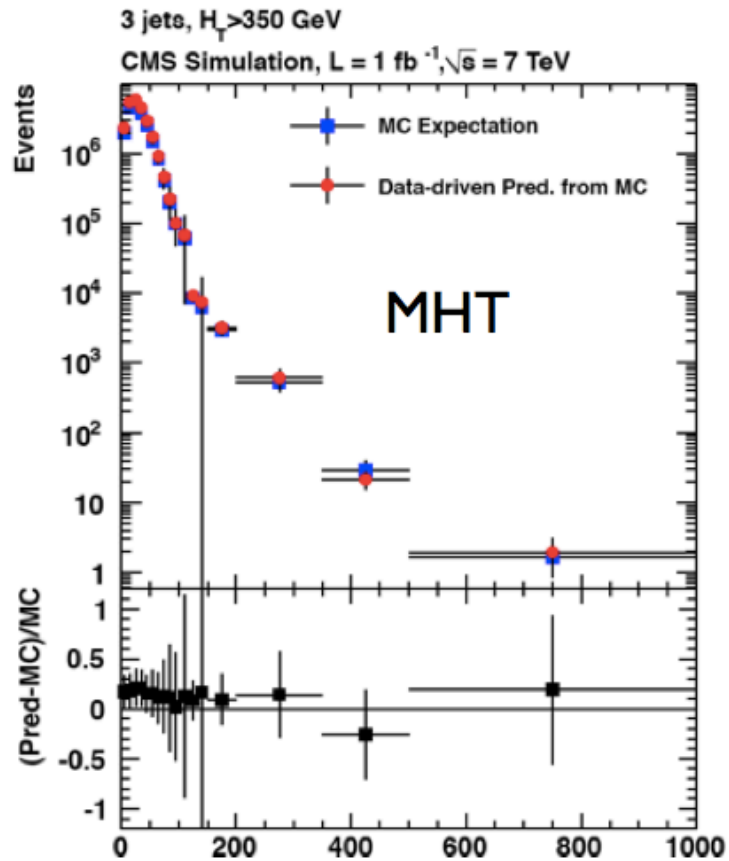
- Don't rely on MC for QCD multi-jet modeling → use data-driven R+S technique
  - Start with inclusive multi-jet sample in data
  - **Rebalance**: adjust jet $p_{T's}$ using kinematic fit with MET = 0 → "seed jets" estimate parton level p_T's
    - **Backgrounds with real MET are suppressed: σ(Z/W/tt) << σ(QCD)**
  - **Smear**: smear p_T's of "seed jets" using jet resolution functions
  - **R+S predicts full QCD multi-jet kinematics from data**
- ***Critical component***: jet resolution functions parameterized by p_T, η → extracted from MC, corrected for data/MC differences

R+S


Jet
Jet
Jet
Probability per jet
0.1 ≤ f^ECAL_masked
u/d/s
g
b/c
p_T^gen ≥ 300 GeV/c
CMS Simulation
√s = 7 TeV
p_T^reco / p_T^gen
Jet
E_T^miss
Jet
Jet

R+S Closure Test





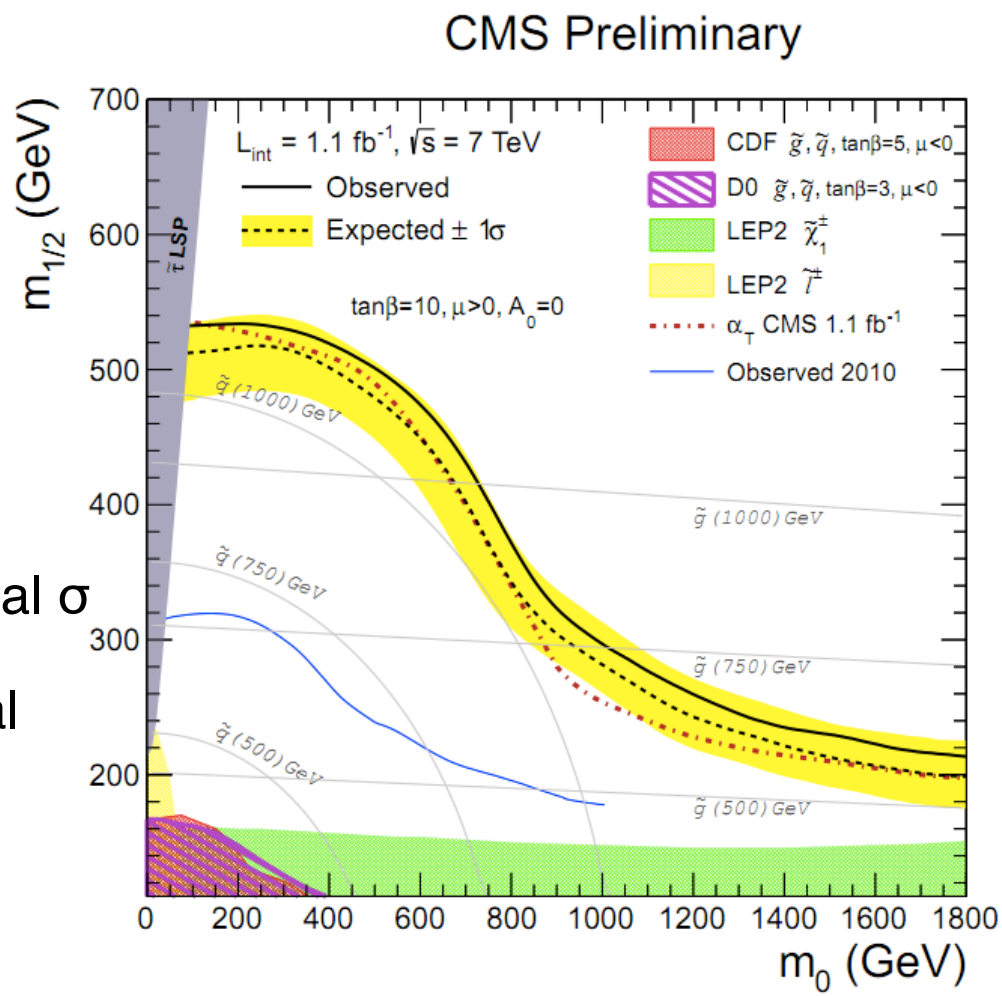
- Compare QCD MC truth vs. R+S prediction

all-hadronic: CMSSM Interpretation

CMSSM: constrained minimal SUSY extension to the SM: simple SUSY model with 5 parameters

m_0: boson mass parameter
$m_{1/2}$: fermion mass parameter
tan β: ratio of Higgs VEV's
A_0: trilinear coupling
sign(μ): sign of Higgsino mass

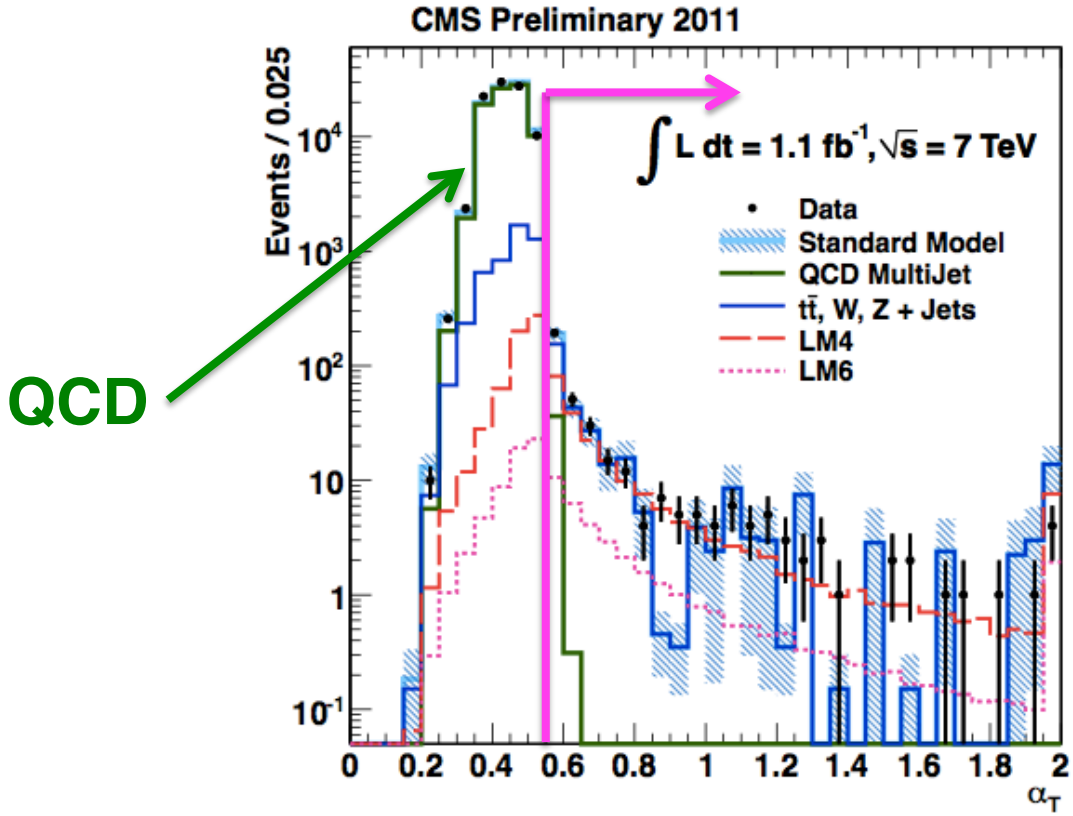
- Observed and expected 95% CL upper limits (CLs) using NLO signal σ
- Exclusion contour: best sensitivity envelope of contours from 3 signal regions
- **exclusions: M(squarks) $\gtrsim$ 1 TeV and M(gluino) $\gtrsim$ 0.5 TeV**



The α_T Analysis

$$\alpha_T \equiv \frac{E_T^{jet2}}{M_T}$$ = (2nd leading jet p_T / transverse mass)

- $\alpha_T > 0.55$ → strong QCD suppression



Backup Material

- all-hadronic
- single lepton
- opposite-sign leptons
- same-sign leptons

W polarization

SUSY11: Finn Rebassoo

Data-driven methods and reliance on W polarization

- Both lepton spectrum and lepton projection methods data-driven and rely on well understood properties of W polarization
- For ttbar, W polarization very precise prediction of SM theory, calculated to NNLO [f_0=0.687±0.005, f_+=0.0017±0.0001, f_-=0.311±0.005]. D0 and CDF measurements agree with the theory prediction.

Theory: doi/10.1103/PhysRevD.81.111503
D0: doi/10.1103/PhysRevLett.107.021802
CDF: doi/10.1103/PhysRevLett.105.042002

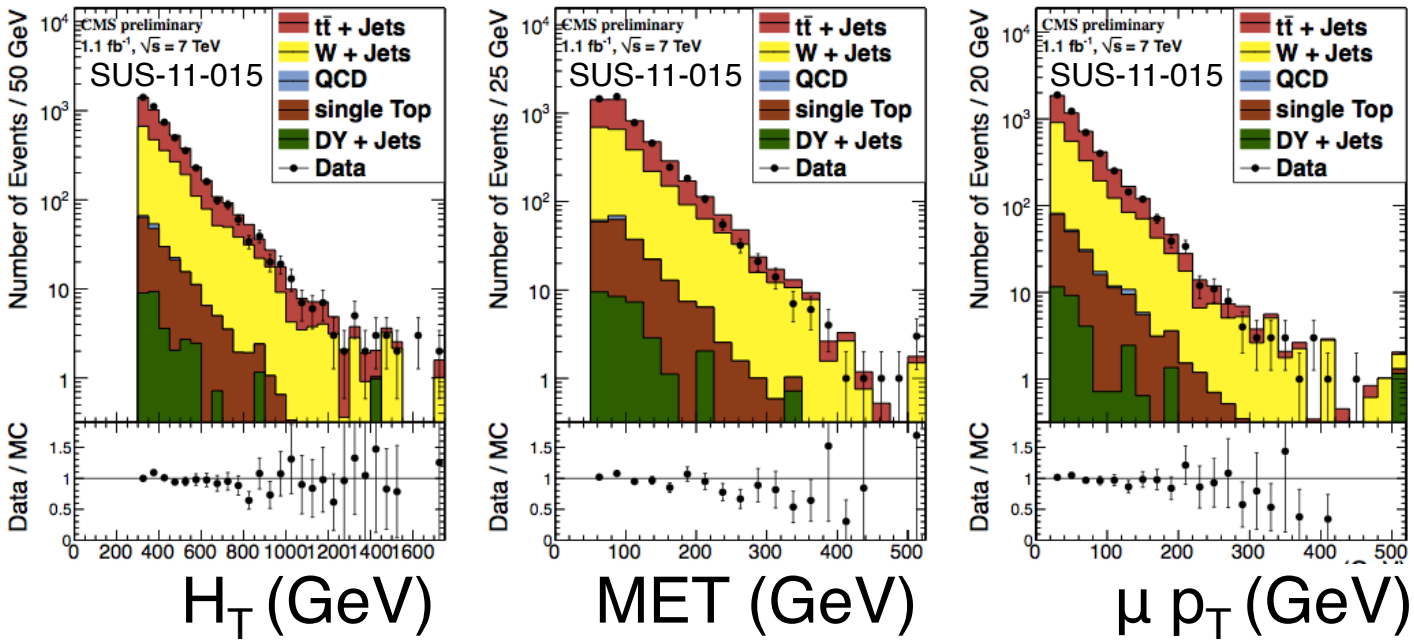
- For W+jets, theory calculates W polarization to NLO and helicity fractions stable with respect to QCD corrections. Experimental measurement at CMS (based on the L_P variable used in this SUSY search) consistent with theory.

Theory: arXiv:1103.5445
CMS: doi/10.1103/PhysRevLett.107.021802

single lepton: Event Preselection

- Exactly 1 high p_T isolated e or μ
- ≥3 high p_T jets with large H_T → suppress W+jets
- Moderate MET requirement → consistency with trigger

plots shown for μ-channel (e-channel similar, in backup)

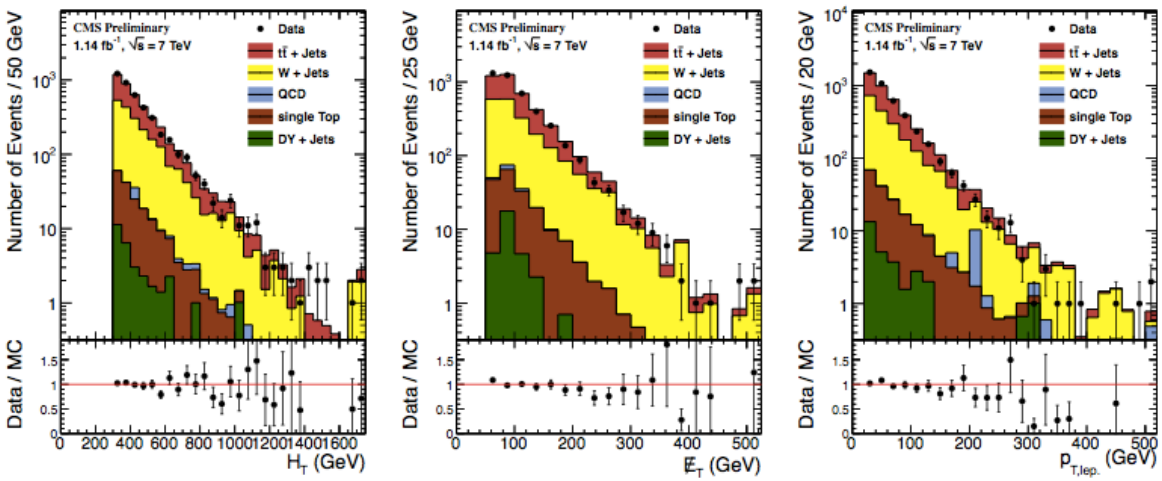


- Good agreement data vs. MC shapes (MC scaled to data)
  - Dominant backgrounds: ttbar, W+jets

Data/MC Comparison

SUS-11-015

Quantity	Requirement
Jet p_T threshold	> 40 GeV
Jet η range	$\lvert\eta\rvert < 2.4$
Number of jets	≥ 3 (LP Variable method),
	≥ 4 (Lepton Spectrum method)
Lepton p_T threshold	> 20 GeV
Muon η range	$\lvert\eta\rvert < 2.1$
Muon isolation (relative)	< 0.10
Electron isolation (relative)	< 0.07 (barrel), < 0.06 (endcaps)
Electron η range	$\lvert\eta\rvert < 1.4$, $1.6 < \lvert\eta\rvert < 2.4$
Lepton p_T threshold for veto	> 15 GeV

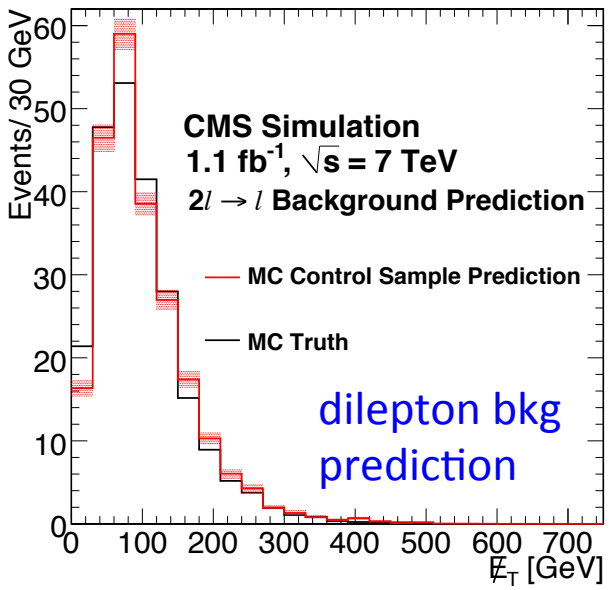


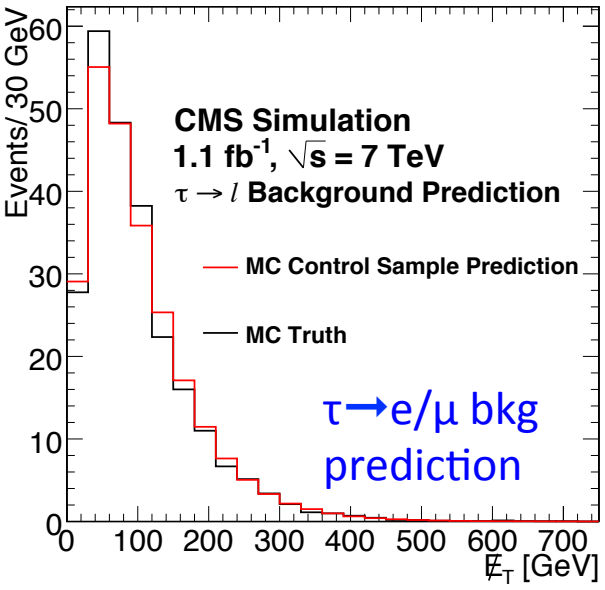
(d) e: H_T (e) e: $\not{E}_T$ (f) e: p_T

Figure 1: Distributions of H_T (left), E_T^{miss} (center) and lepton p_T (right) in the muon (a, c, and c) and electron (d, e, and f) channels. The data are shown by the points with error bars, while the stacked histograms show the simulated event samples. The preselection as well as the requirements $H_T > 300$ GeV and $\not{E}_T > 60$ GeV have been applied, and the overall yield from simulation is normalized to the data. The yields from the simulated event samples are not the basis for the background predictions in this analysis, which are derived from control samples in the data.

single lepton: dilepton, τ→e/μ bkg's

- Lepton p_T spectrum doesn't predict these backgrounds → estimate from data control samples
  - dilepton ttbar events (~15% of total bkg)
    - Use dilepton (ee,μμ,eμ) data control samples, scale by probability to not reconstruct a lepton or lose a lepton outside detector acceptance to predict MET
  - ttbar/W+jets with τ→e/μ (~10% of total bkg)
    - Use single lepton (e,μ) control sample, discard a fraction of lepton p_T to model τ decay and recalculate MET
- Methods predict key kinematic distributions → verified in MC closure tests
- Data-driven prediction in reasonable agreement with MC (see backup)

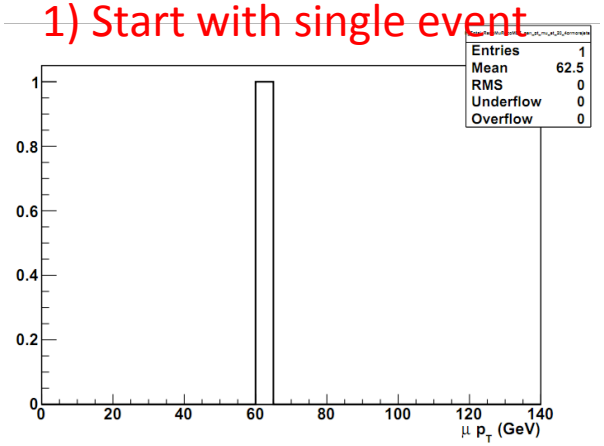




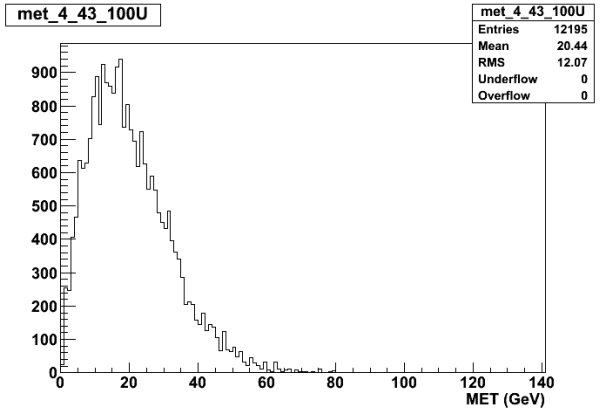
MET resolution: smearing $p_T(\mu)$

- Smear lepton pT to model instrumental MET effects
  - use artificial "MET templates" from QCD control sample in data

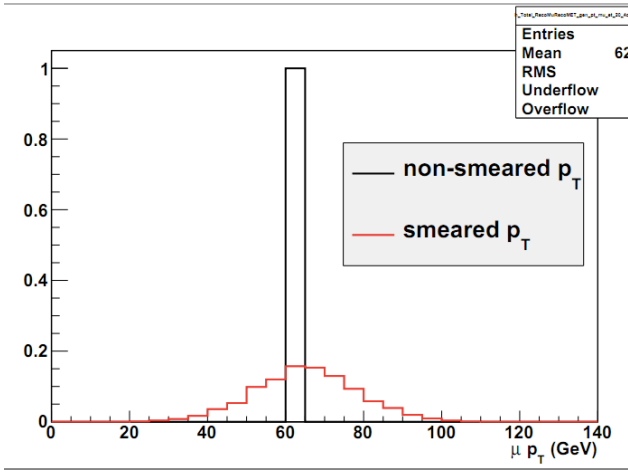
1) Start with single event



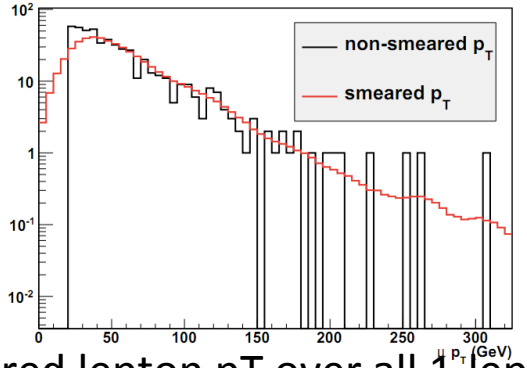
2) Find MET template corresponding to event HT



3) Smear μ pT using MET template



Final result: smeared μ pT distribution (10-15% effect)



turn single event into 1000 events with weight 1/1000

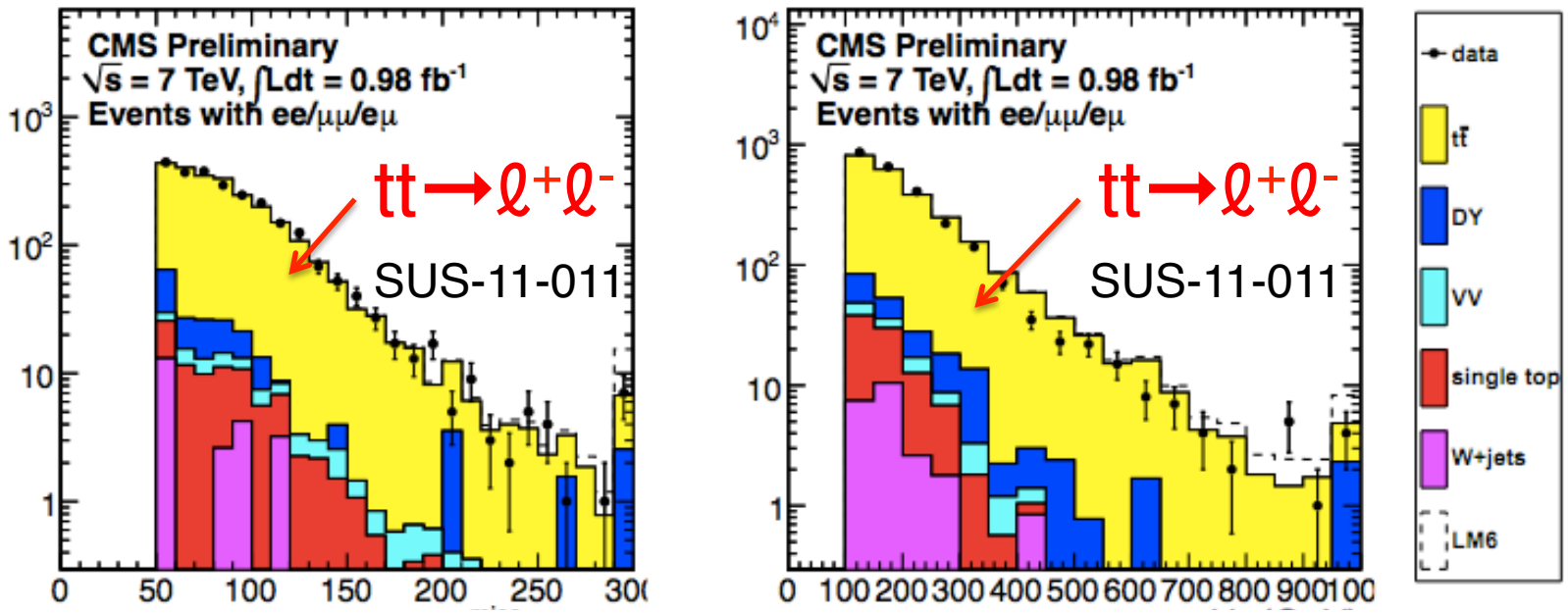
MET prediction is sum of smeared lepton pT over all 1-lepton events

Backup Material

- all-hadronic
- single lepton
- opposite-sign leptons
- same-sign leptons

OS: Preselection

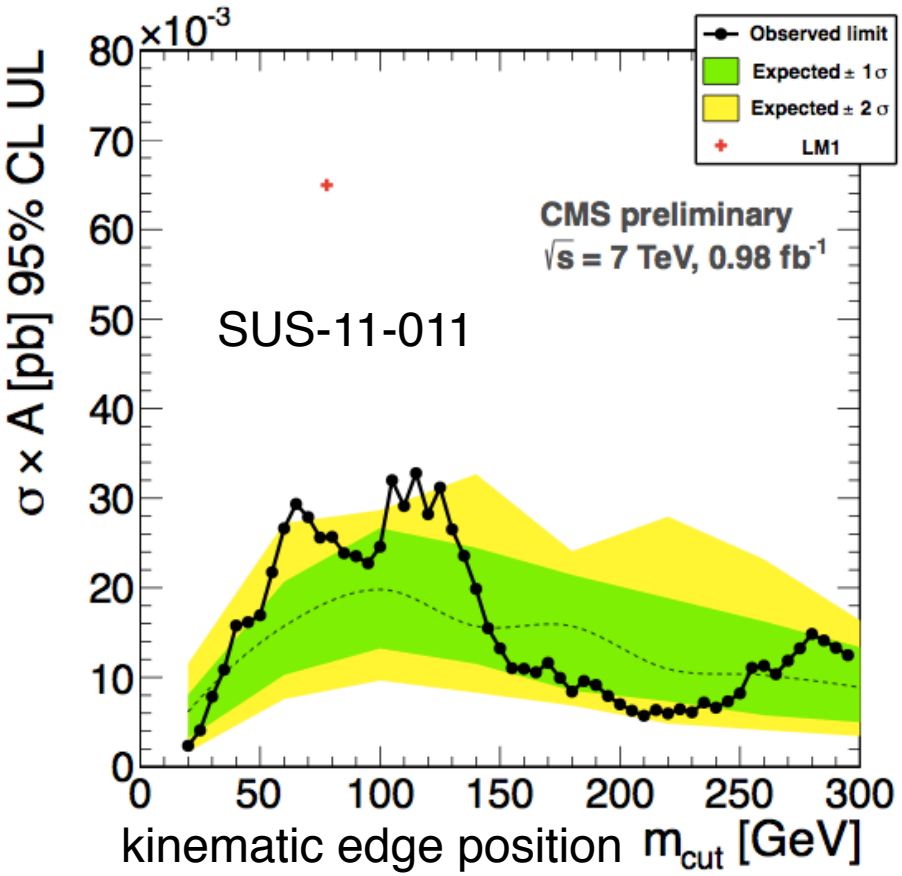
- ≥2 isolated high p_T opposite-sign leptons (e or μ)
- ≥2 high p_T jets, large MET and H_T → suppress DY
- Reasonable data/MC agreement in yields, key kinematic distributions
  - **Sample dominated by $tt \to \ell^+\ell^-$ (>90% purity)**



MET (GeV) H_T (GeV)

OS: Upper Limits

- Extract 95% CL upper limits on σ × A as function of edge position m_{cut}
  - Assumes triangular shape, efficiency and uncertainty from LM1 SUSY scenario

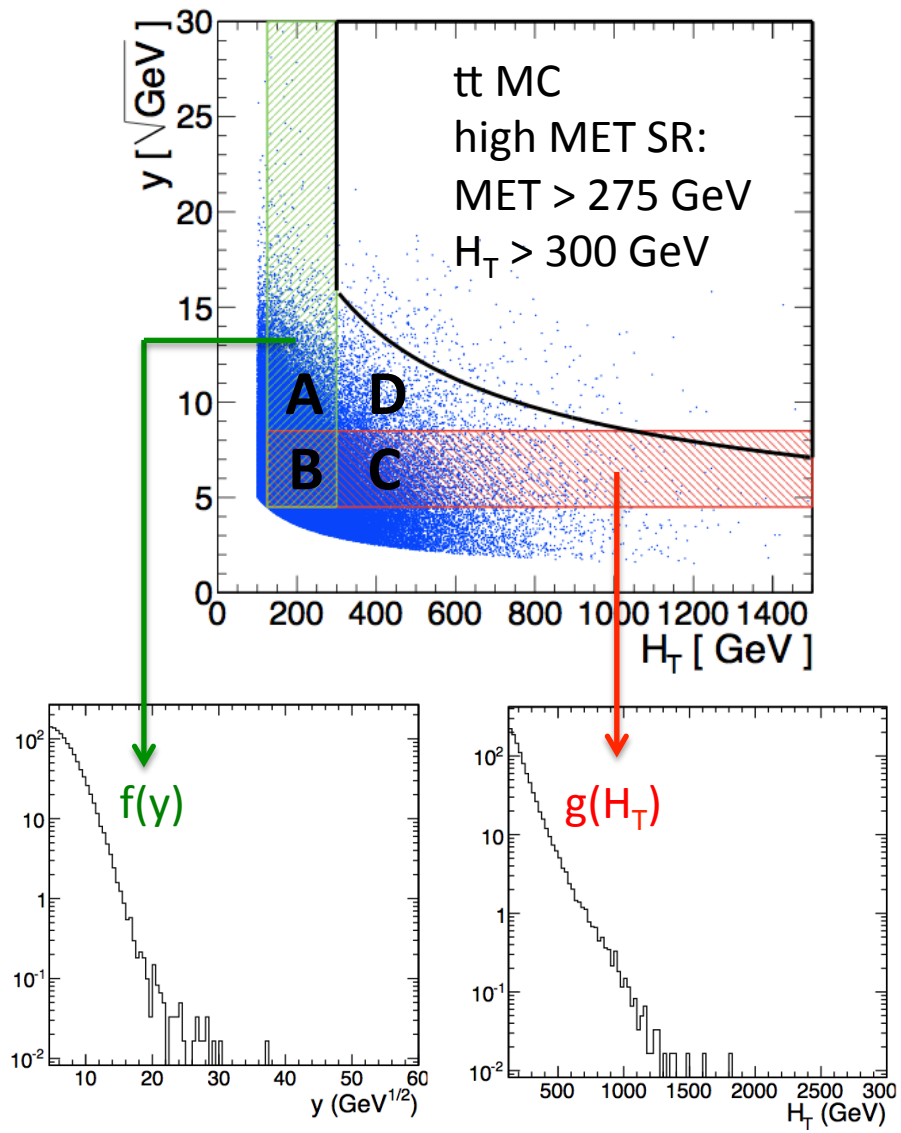


The ABCD' Method

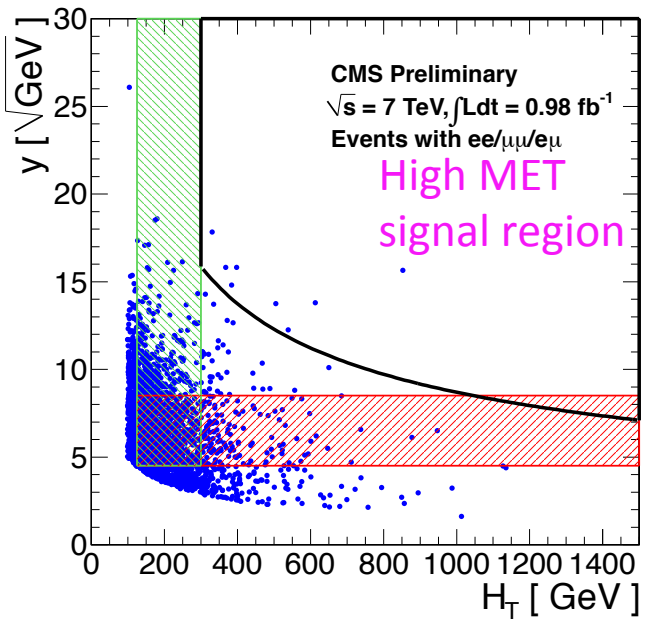
- Exploits 2 weakly-correlated kinematic variables
  - $y \equiv MET/\sqrt{(H_T)}$ and H_T
  - ABCD method: predict bkg in (y,H_T) region D: $N_D = N_A \times N_C / N_B$
  - Searches in (MET,H_T) region more sensitive: ABCD can't predict bkg
- Predict bkg in (MET, H_T) region using variant of ABCD method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

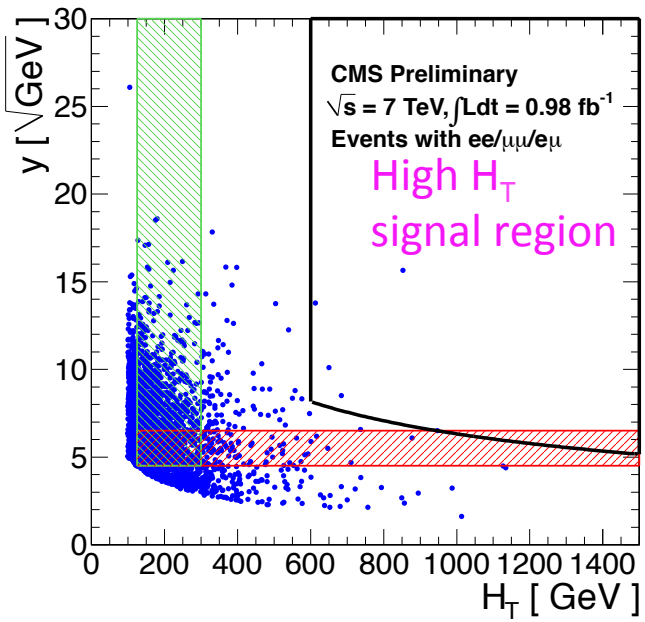
$$\frac{\partial^2 N}{\partial y \partial H_T} = f(y) g(H_T)$$

- 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

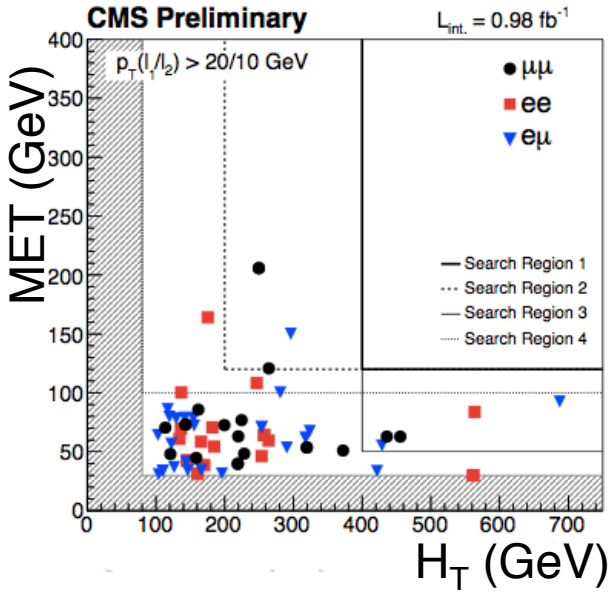
- **Observed yields consistent with MC, ABCD' prediction**
- **Extract 95% CL upper limits on non-SM yields**

Backup Material

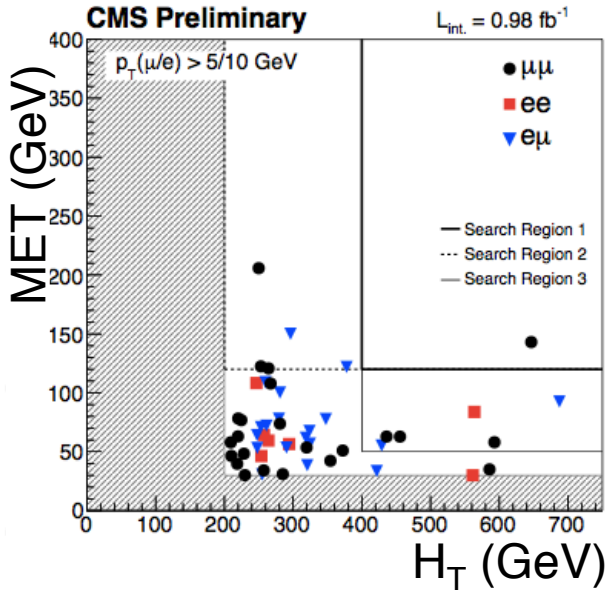
- all-hadronic
- single lepton
- opposite-sign leptons
- same-sign leptons

Samples & Search Regions

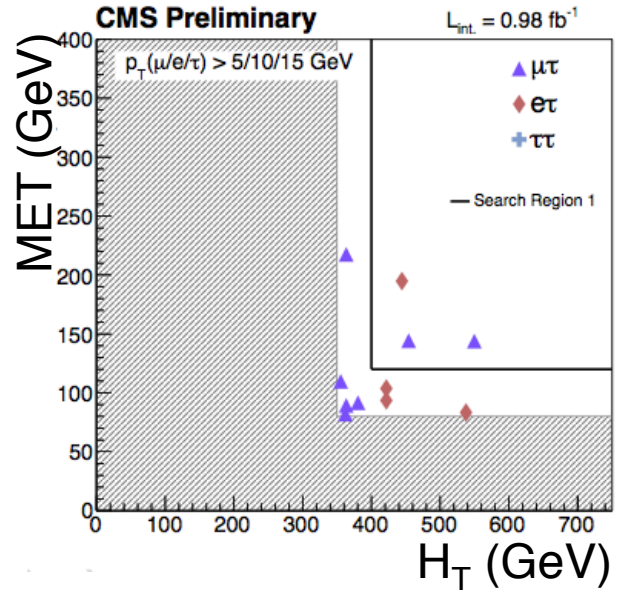
High p_T dileptons
dilepton triggers



Inclusive dileptons
lepton-H_T triggers



τ → hadrons
H_T-MET-lep triggers

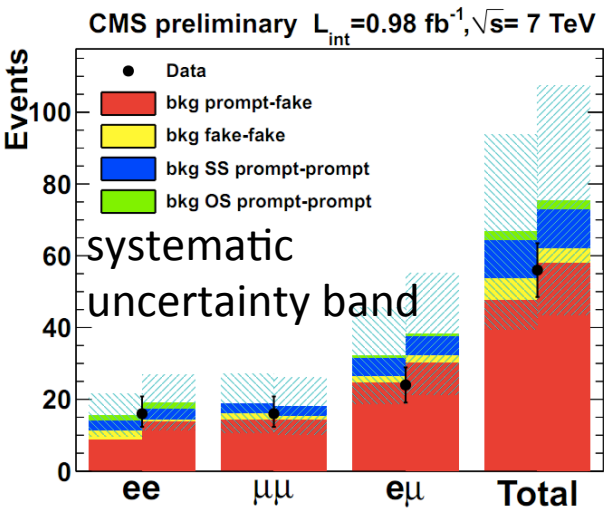


- Search for new physics in 3 complementary samples
- Define preselection regions in MET-H_T plane (veto shaded regions)
  - Validate data-driven bkg estimates with ~10-100 events
- Define **4 search regions** by adding MET, H_T requirements

SS Results: Baseline Selection

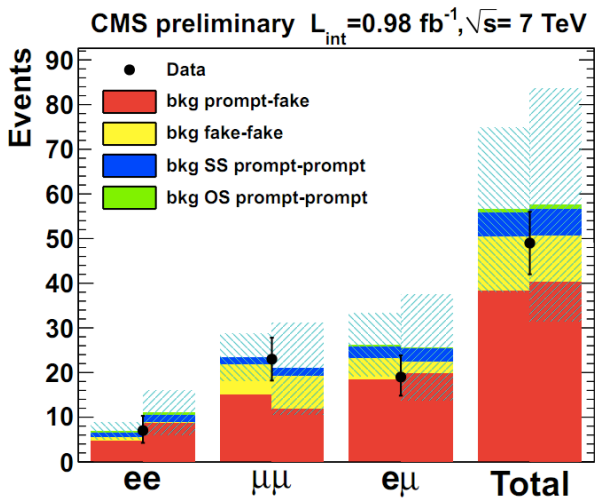
- Validate bkg estimates → apply in **bkg-dominated baseline region**
- **Good agreement observed vs. predicted in all samples**
- Next, search for new physics in signal regions…

high p_T lepton sample



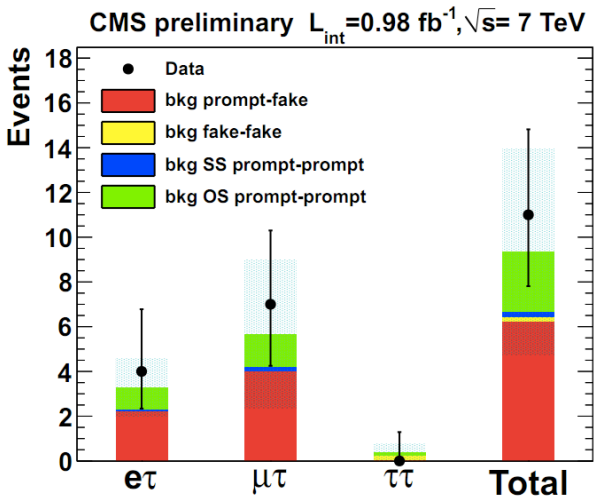
left: R_{TL} (relax ID+iso)
right: R_{TL} (relax iso)

inclusive lepton sample



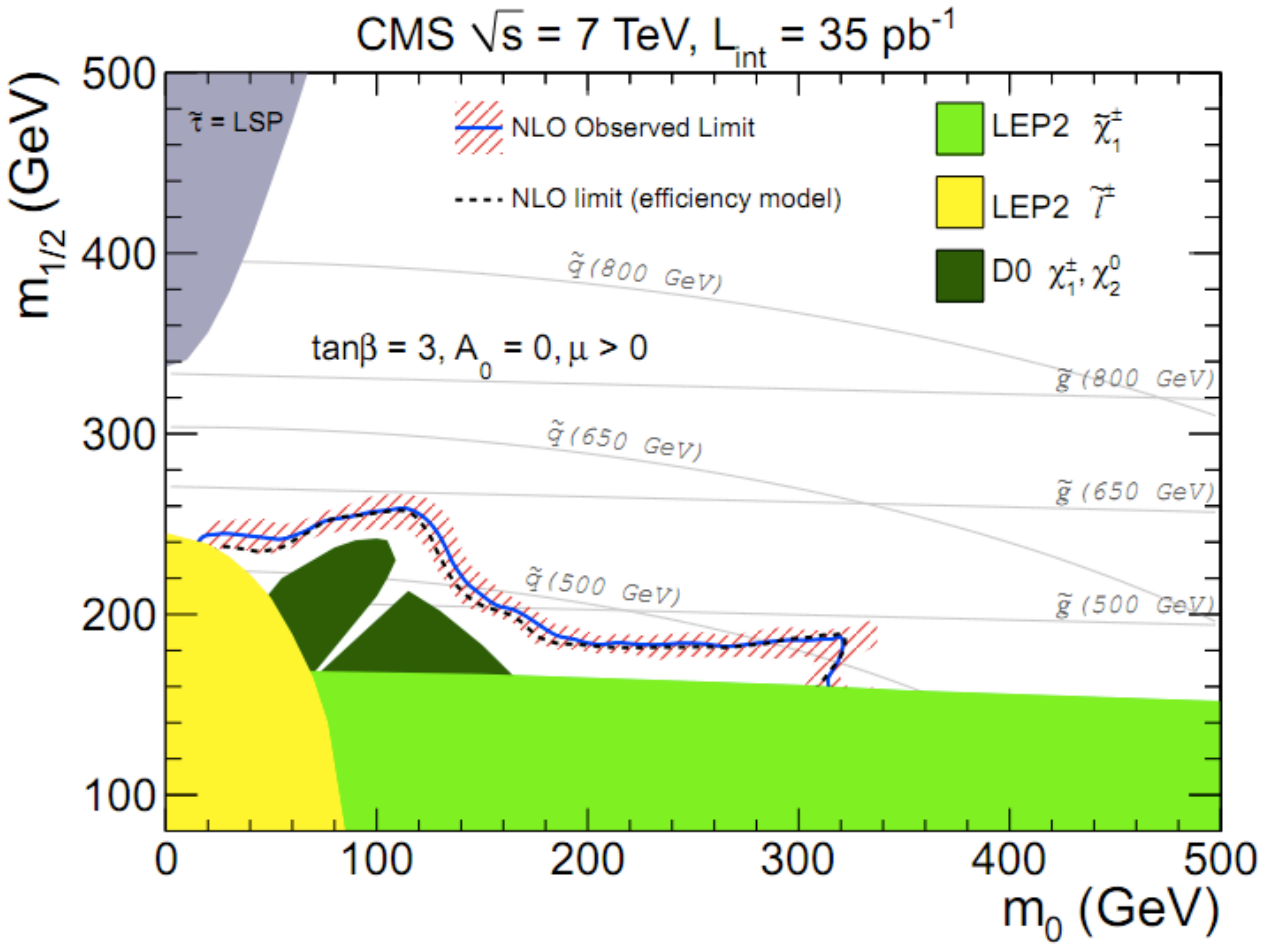
left: b tag-and-probe
right: R_{TL} (relax iso)

τ → hadrons sample



- single fake
- double fake
- SM SS processes
- charge mis-reconstruction

CMSSM Limits



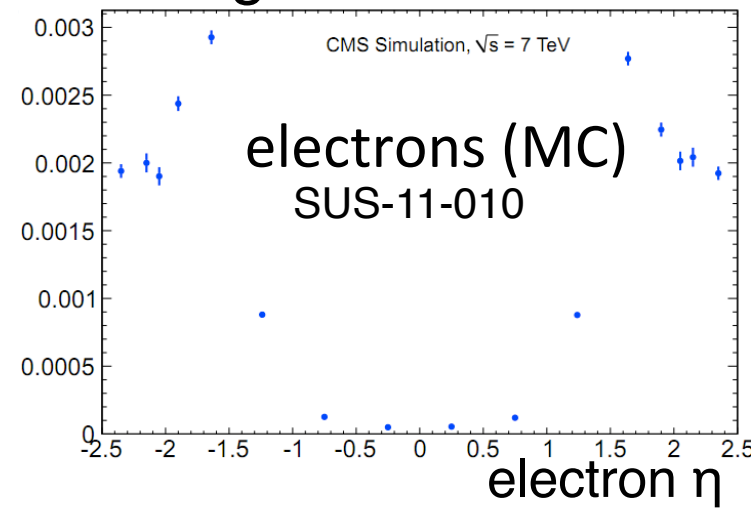
- CMSSM limit from efficiency model agrees well with limit from CMS MC

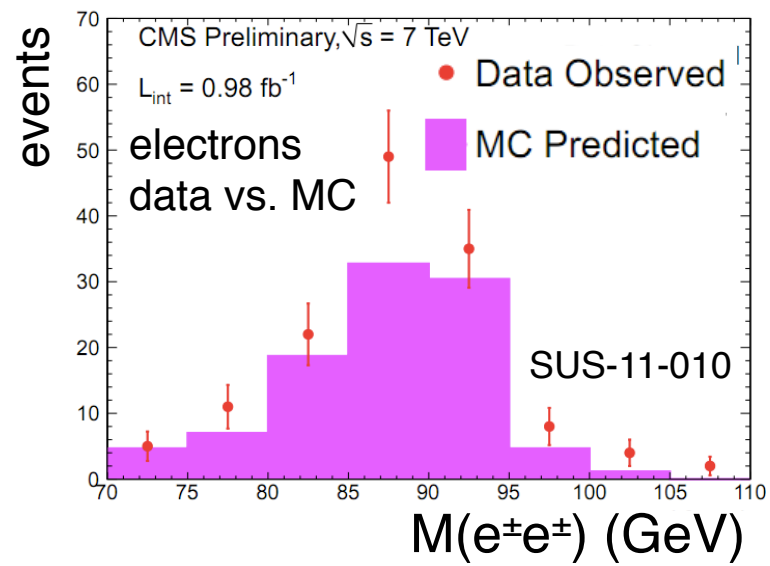
SS: Charge Mismeasurement Bkg

- Events with opposite-sign leptons (eg. DY, ttbar) contribute bkg if a lepton charge is mis-measured
  - Need to estimate charge mis-ID rate
- Extract charge mis-ID rates from MC, parameterize vs. p_T, η
  - e: ε ~ 10^{-4} (central) – 10^{-3} (high η)
  - μ: negligible
  - τ: ε ~ 0.07
- Compare data vs. MC using same-sign Z sample (M(ll) 70-110 GeV)
  - MC slightly underestimates charge mis-ID rate → scale by ~1.2 to match data
- **Estimate bkg from OS sample:**

$$N(\ell^{\pm}\ell^{\pm}) = N(\ell_1^{+}\ell_2^{-})\left(\frac{\varepsilon_1}{1-\varepsilon_1} + \frac{\varepsilon_2}{1-\varepsilon_2}\right)$$

charge mis-ID rate





Efficiency Model

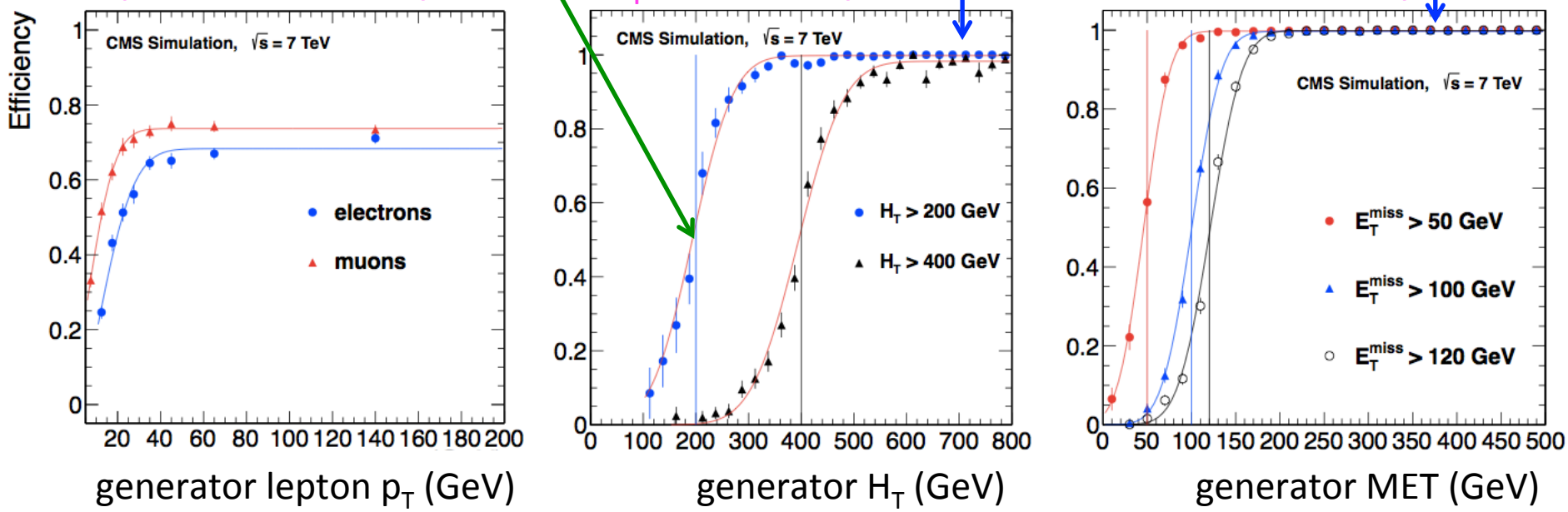
mid-points match reco cut

plateau efficiency ~100%

lepton efficiency

H_T efficiency

MET efficiency



- Step 1) select model X events passing signal region selection applied to gen-level quantities
- Step 2) assign event weights based on physics object selection efficiencies: “gen-level” → “reco-level”
- Step 3) sum of weights is predicted model X yield

SS: b tag-and-probe

- Relax isolation on the least isolated lepton (probe). **F. Golf SUSY11**
- **Measure efficiency with tag-and-probe.**
  - Tag is b-tagged away jet → enrich sample in fake leptons.
  - Re-weight efficiency measured in data QCD events by the p_T, N_{jets} distributions expected from ttbar MC.

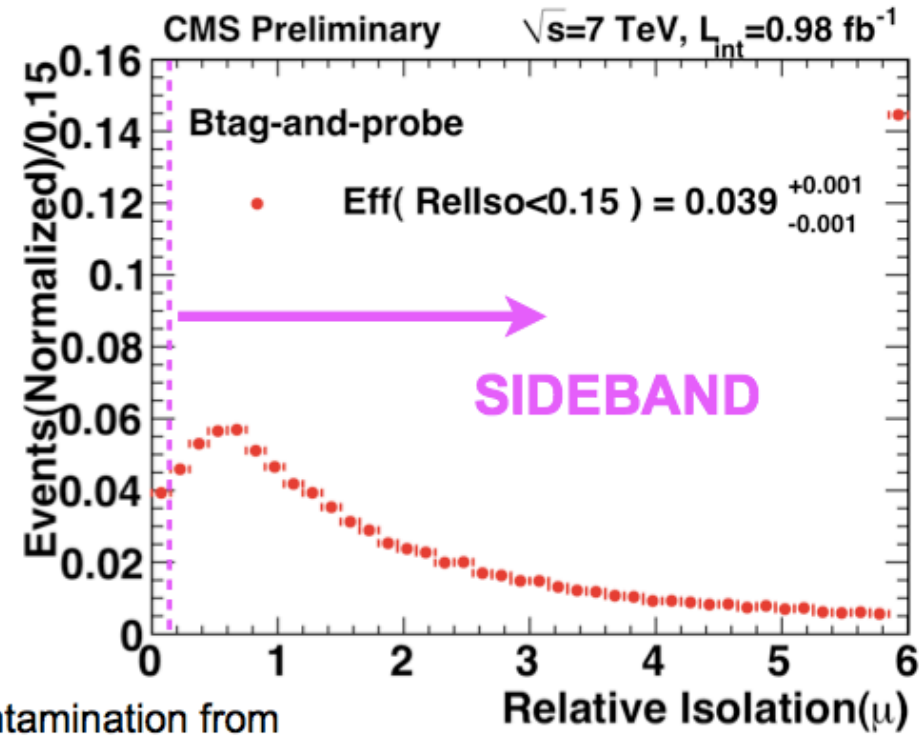
$$\epsilon = \frac{\text{leptons with relIso} < 0.15}{\text{leptons with relIso} > 0.15}$$

- **Isolation templates are used to estimate the background from events with one fake lepton:**

$$N^{SS}_{p-f} = (N_{sideband} - N^{SS}_{f-f})\varepsilon$$

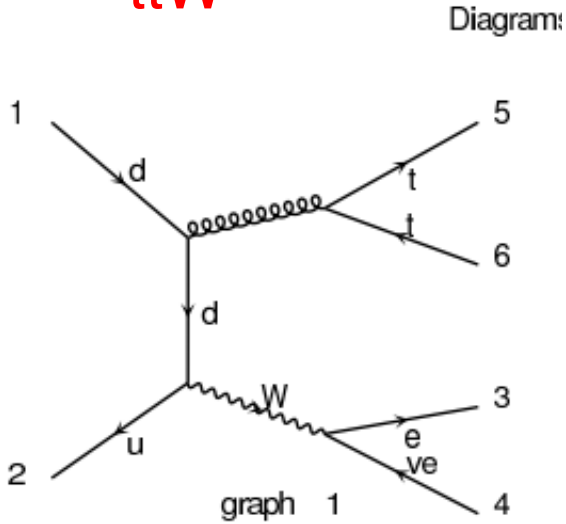
Events passing tight selection with isolation relaxed on least isolated lepton.

Remove contamination from events with two fake leptons.

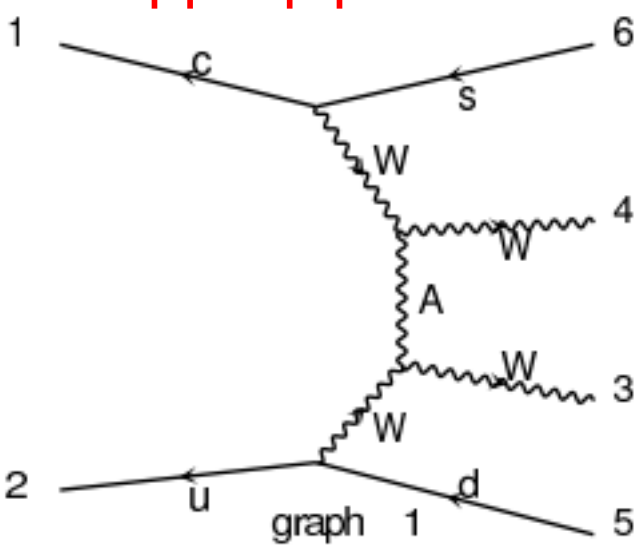


SS: Irreducible Backgrounds

ttW



qq→q'q'W±W±



SUSY Signatures

new physics scenarios | **signatures**

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- No Higgs
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4th generation (t', b')
- LRSM, heavy neutrino
- etc...

Bachacou LP2011

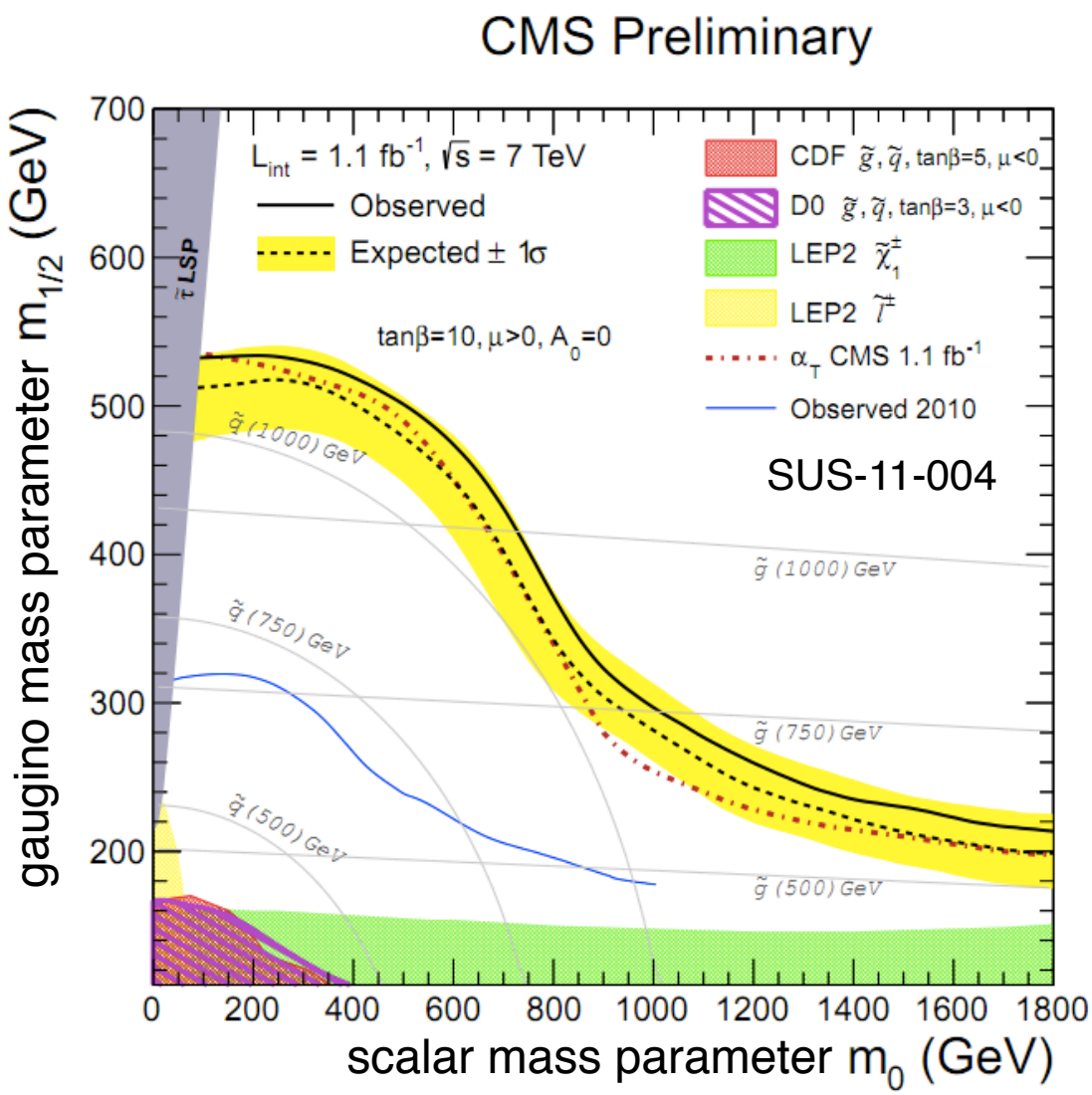
- 1 jet + MET *
- jets + MET *
- 1 lepton + MET *
- Same-sign di-lepton *
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET *
- Multileptons *
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET *
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles *
- Long-lived particles *
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

* possible SUSY signatures

- **Wide variety of possible SUSY signatures**
- Other scenarios (eg. extra dimensions) may lead to similar signatures

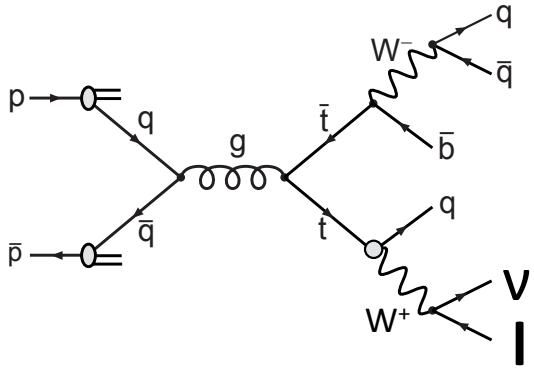
all-hadronic: CMSSM Interpretation

- Observed & expected 95% CL upper limits (CLs) using NLO signal σ
- Exclusion contour: best sensitivity envelope from 3 signal regions
- **Exclusions:**
  - **M(squarks) ≳ 1 TeV**
  - **M(gluino) ≳ 0.5 TeV**



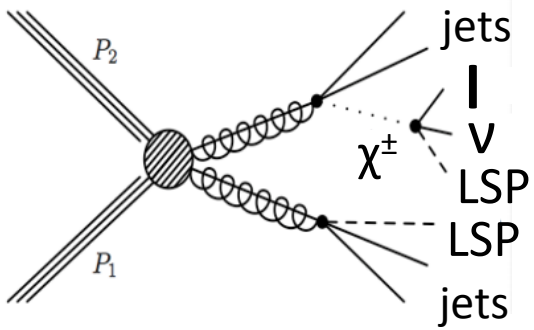
Results: Lepton Projection (L_P) Method

bkg: tt → l + jets



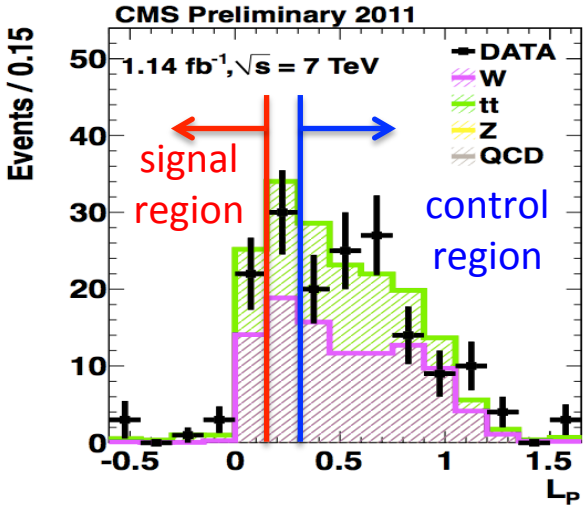
L_P broad ~0-1

SUSY signal



L_P peaked at 0

μ-channel, S_T^{lep} 250-350 GeV



$$L_P = \frac{\vec{p}_T(\ell)\cdot\vec{p}_T(W)}{|\vec{p}_T(W)|^2} \propto \cos(\theta^*_\ell)$$

(cos charged lepton helicity angle)

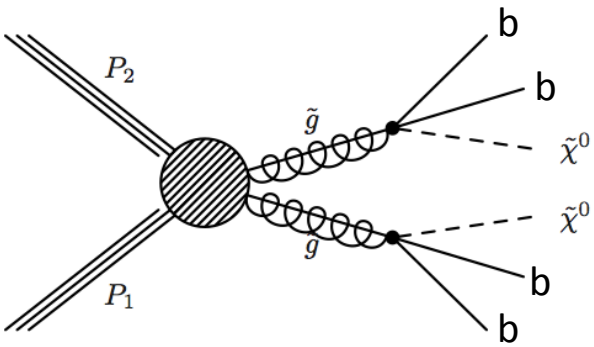
signal region: ≥3 jets + H_T > 500 GeV, 4 bins S_T^{lep} = p_T(l) + MET

	Control Region (L_P >0.3)		Signal Region (L_P <0.15)		
S_T^{lep} Range (GeV)	Total MC	Data	Total MC	SM estimate	Data
[150-250]	385±7	368	73.9±3.0	70.6±11	84
[250-350]	116±2	112	28.1±1.1	27.2±4.6	29
[350-450]	43.4±2.	41	11.5±0.7	10.9± 2.3	9
> 450	18.4±0.8	15	6.5±0.4	5.3± 1.8	6

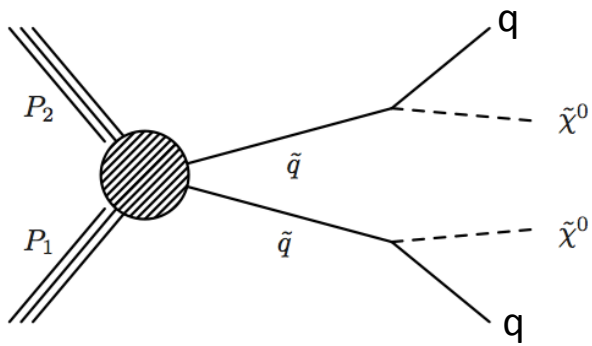
- **Good agreement between observed vs. predicted yields** → results used to perform CMSSM exclusion

public SUS-11-015 1.1 fb^{-1} (SUSY11)

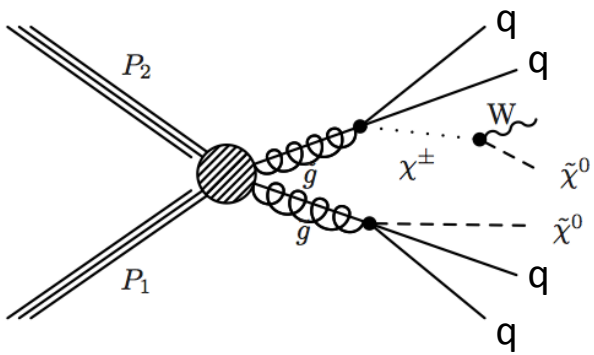
More Simplified Models



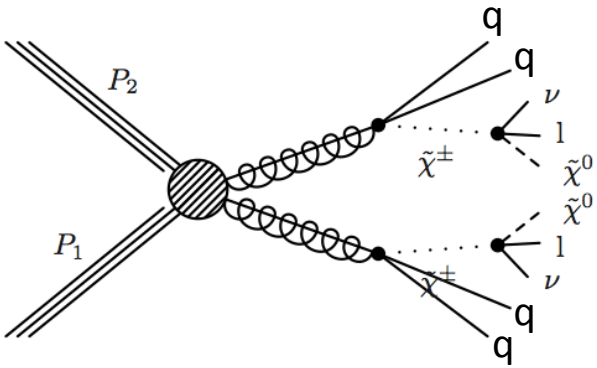
gg → 4 b-jets + MET
all-hadronic w/ b-tags
M(g), M(χ^0)



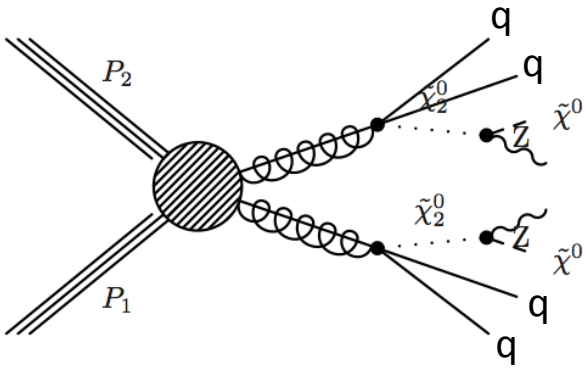
qq → 2 jets + MET
all-hadronic
M(q), M(χ^0)



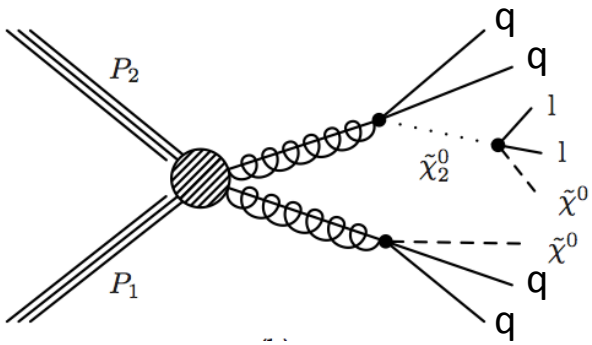
gg → 4 jets + $l^{\pm}$ + MET
single-lepton
M(g), M($\chi^{\pm}$), M(χ^0)



qq → 4 jets + ll + MET
dilepton (SS best sensitivity)
M(g), M($\chi^{\pm}$), M(χ^0)

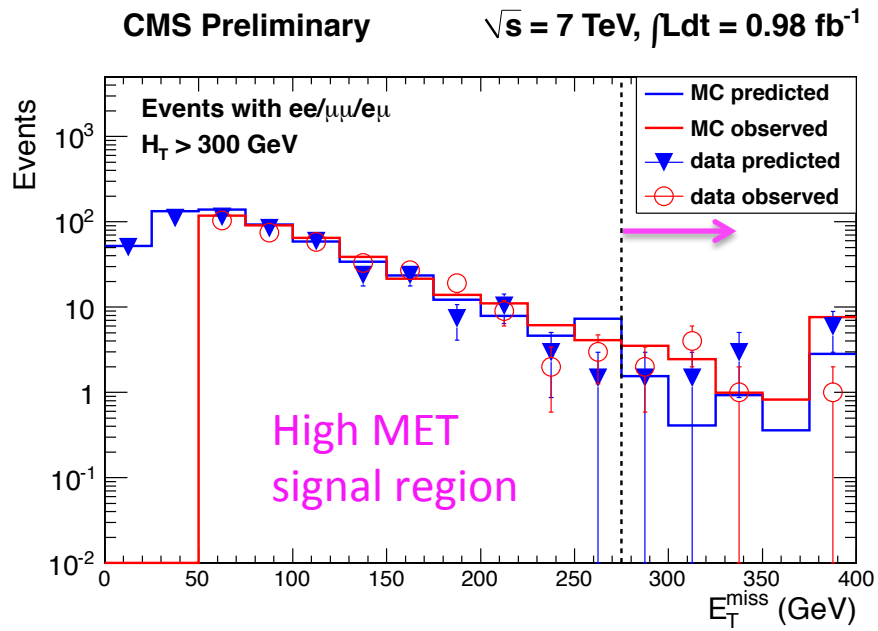


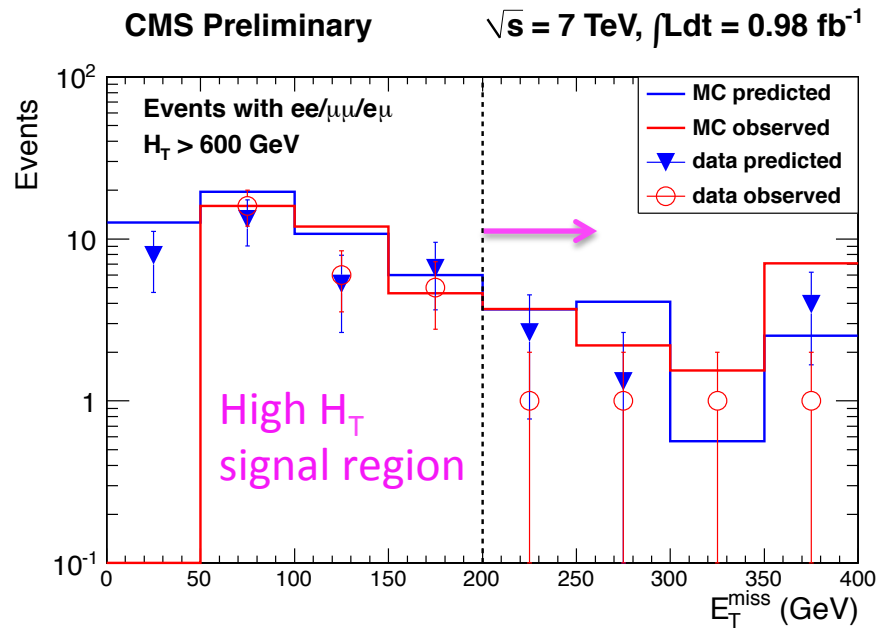
qq → 4 jets + ZZ + MET
Z+jets+MET/JZB
M(g), M(χ_2^0), M(χ^0)



qq → 4 jets + l^+l^- + MET
OS,τ-pairs
M(g), M(χ_2^0), M(χ^0)

$p_T(ll)$ Method Results

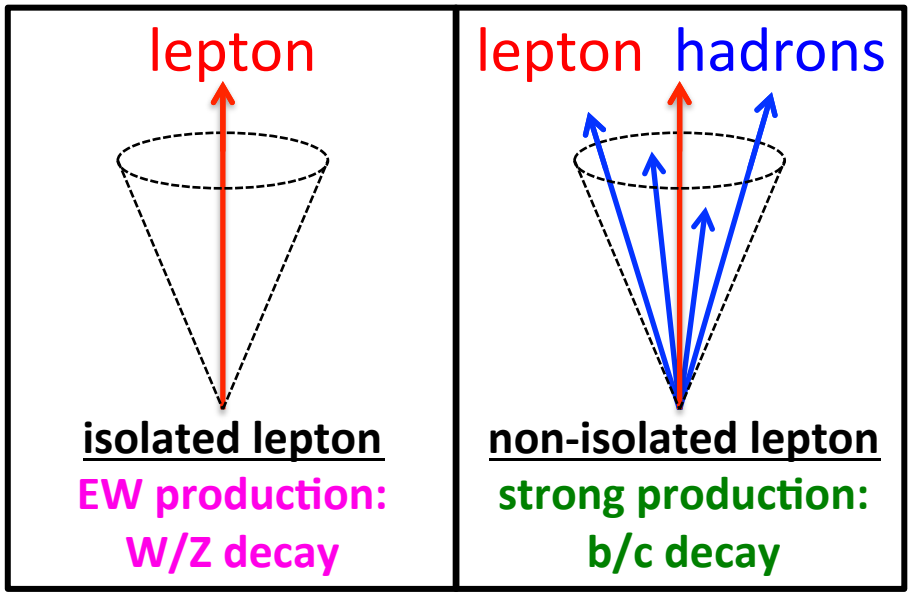


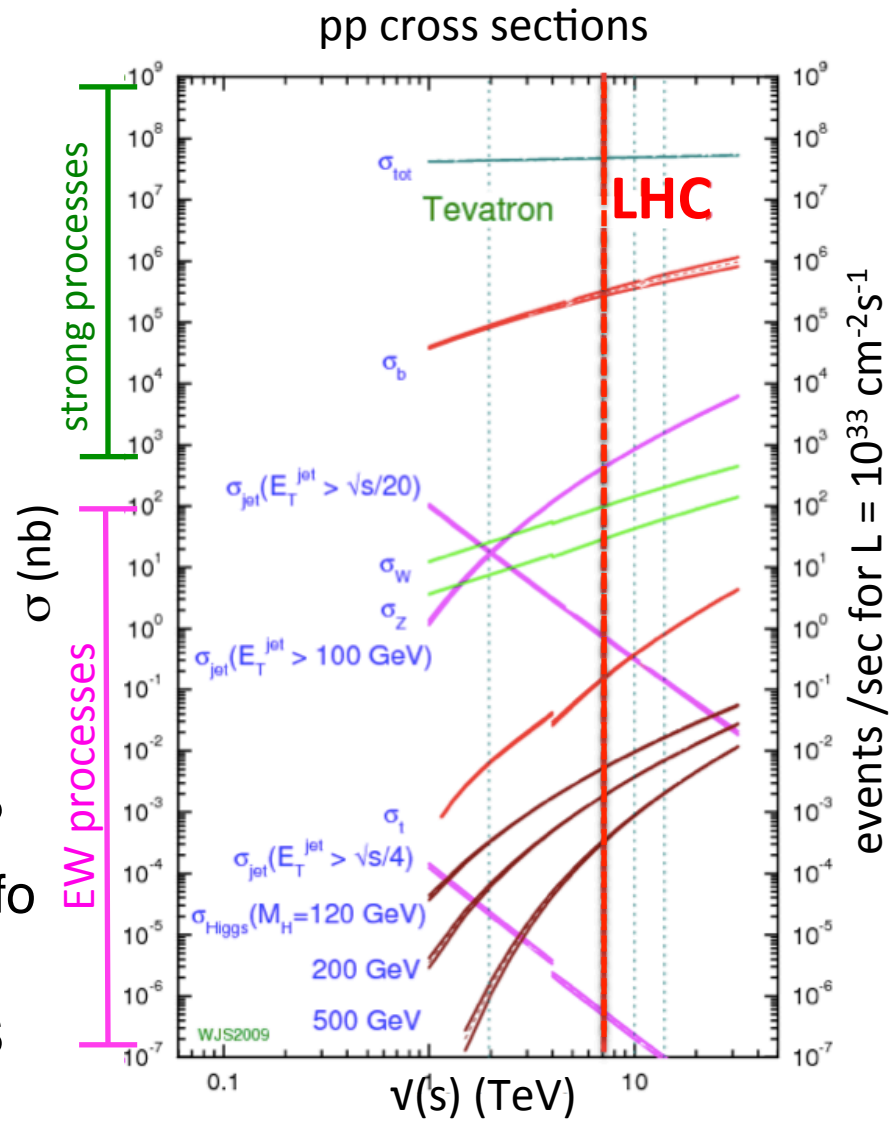


- **Predicted yields consistent with MC, observed yields**

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)

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)