Lepton(s) + Jets + Missing E_T SUSY Searches at CMS

SUSY Workshop, BNL

Ben Hooberman (Fermilab),
on behalf of the CMS Collaboration

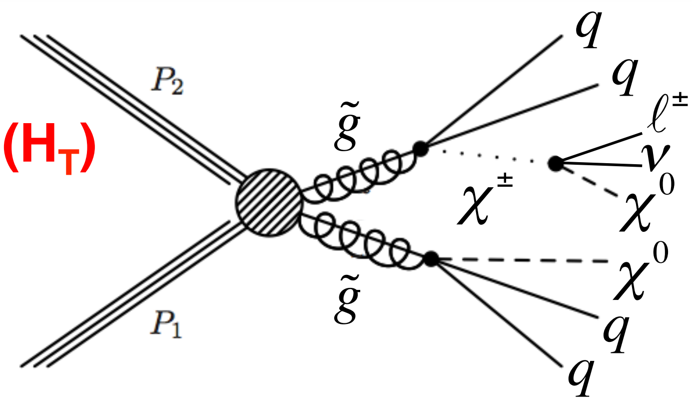
Contents

- **Introduction**
- Searches with leptons
  - Single lepton
  - Opposite-sign (non-Z) leptons
  - $Z \rightarrow \ell^+\ell^-$
- Interpretation & Efficiency Models
- Future Directions and Summary

Message of This Talk

- CMS strategy: perform broad array of inclusive, signature-based searches
  - **No evidence for SUSY in ~5 fb^{-1} 7 TeV 2011 data ☹**
- Developed multiple, complementary, robust data-driven bkg estimation methods → **critical for future discoveries**
- Set stringent constraints in several SUSY scenarios → **but still far more ground to cover**
  - **Improve sensitivity with more data at 8 TeV in 2012 data**
  - **Search for additional SUSY topologies**

Focus of This Talk



- **Search for events with:**
  - Strong production → large hadronic energy **(H_T)**
  - Invisible WIMPs → large missing E_T **(MET)**
  - Isolated leptons → clean final state
- **Single-lepton + jets + MET** — NEW: SUS-12-010
- **Opposite-sign leptons + jets + MET** — NEW: SUS-11-011
- **Z(ℓℓ) + jets + MET** **(arXiv:1204.3774v1)** — NEW: SUS-11-021
- Same-sign leptons (K. Ulmer) & multi-leptons (R. Gray) in other talks
- **Searches emphasize robust, data-driven methods (+MC corrections) with multiple techniques to cross-check results**
  - **All results with full 2011 data sample**

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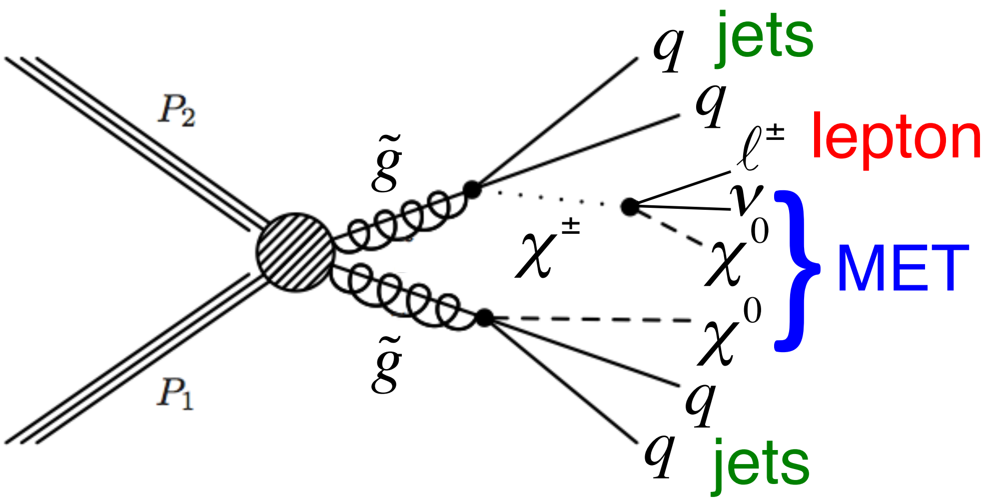
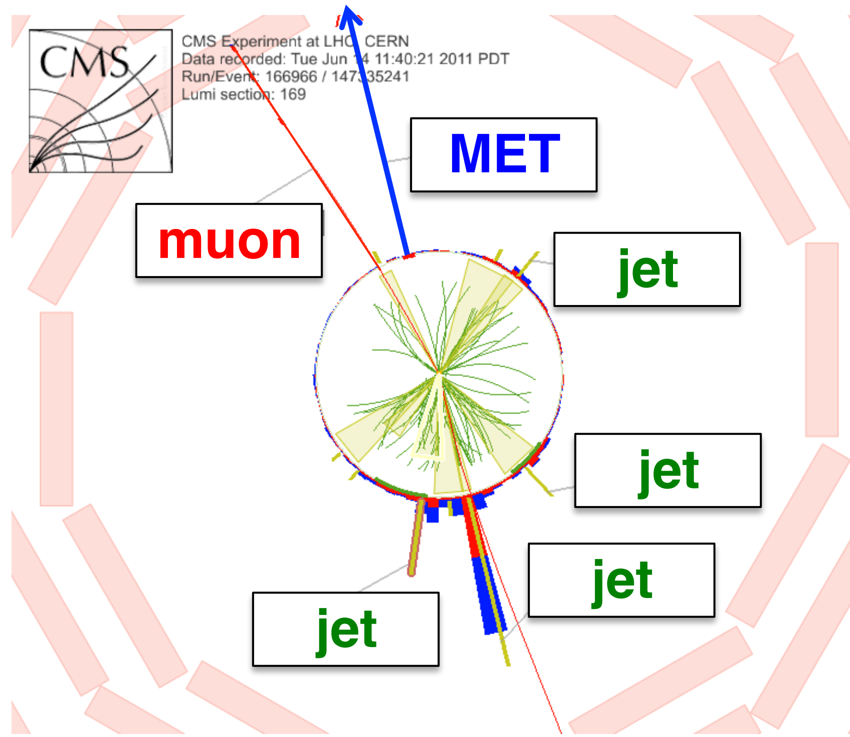
example signal:
SUSY with $\chi^{\pm}$ decay



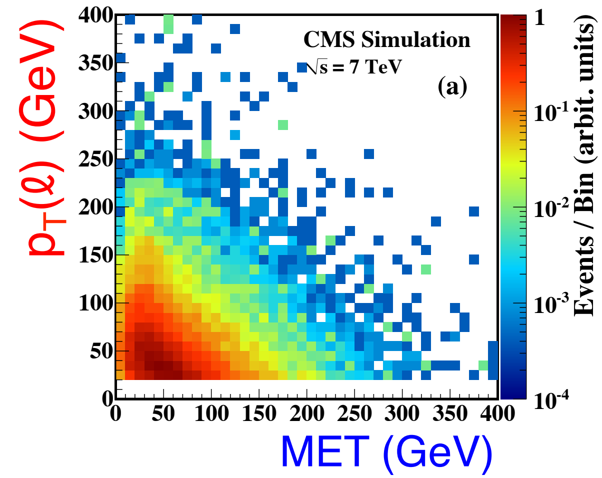


- **Signature: single isolated lepton (e/μ) + jets + MET**
- Challenge: estimation of dominant tt→ℓ+jets / W(ℓv)+jets backgrounds
  - Data-driven bkg estimates → **don't rely solely on MC for large top boost, ISR**

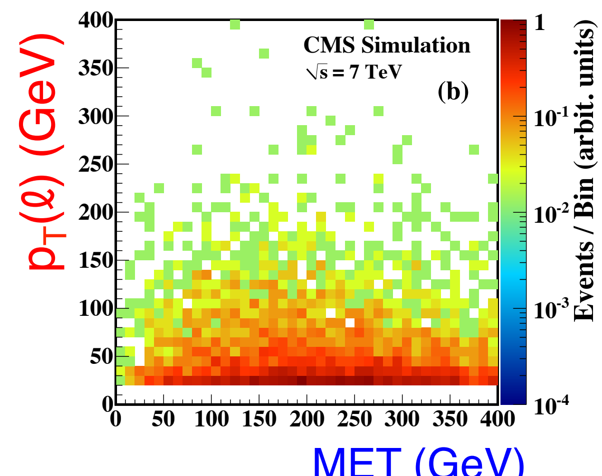
1-lep: Analysis Methods

- **2 data-driven approaches:** both exploit <u>**different correlation of $p_T(\ell)$ vs. MET for SUSY vs. SM bkg**</u>
  - <u>**SM bkg**</u>: $\langle p_T(\ell)\rangle \sim \langle MET\rangle$ related since ℓ and ν produced together via $W \to \ell\nu$
  - <u>**SUSY**</u>: $\langle MET\rangle \gg \langle p_T(\ell)\rangle$ due to LSP's

<u>SM background</u>



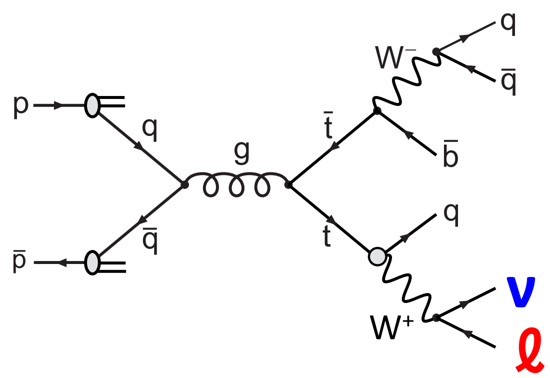
<u>example SUSY signal</u>



- <u>**"Lepton spectrum" method**</u>
  - Use $p_T(\ell)$ to predict MET → **sensitive to models with $\langle MET\rangle \gg \langle p_T(\ell)\rangle$**
- <u>**"Lepton polarization" method**</u>
  - Based on $\cos(\theta_\ell^*)$ → **sensitive to models where $\cos(\theta_\ell^*)$ differs from SM bkg**

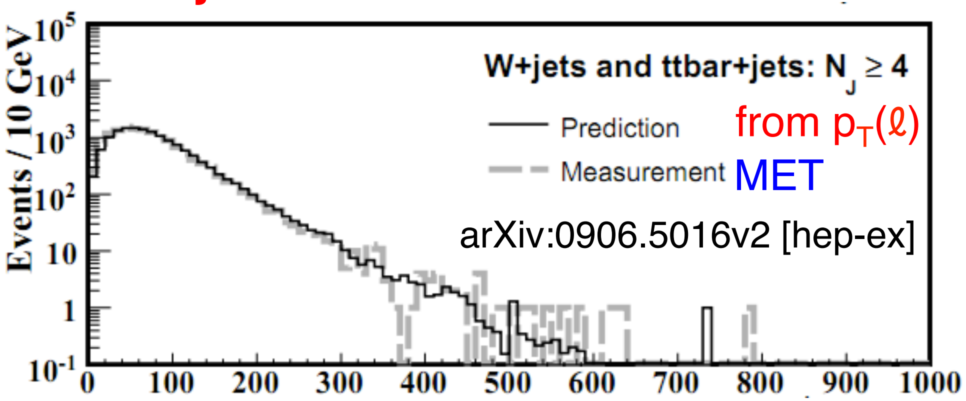
1-lep: “Lepton-Spectrum Method”

dominant SM bkg: ttbar→ℓ+jets



$<p_T(\nu)> \sim <p_T(\ell)>$

W+jets / ttbar MC closure test

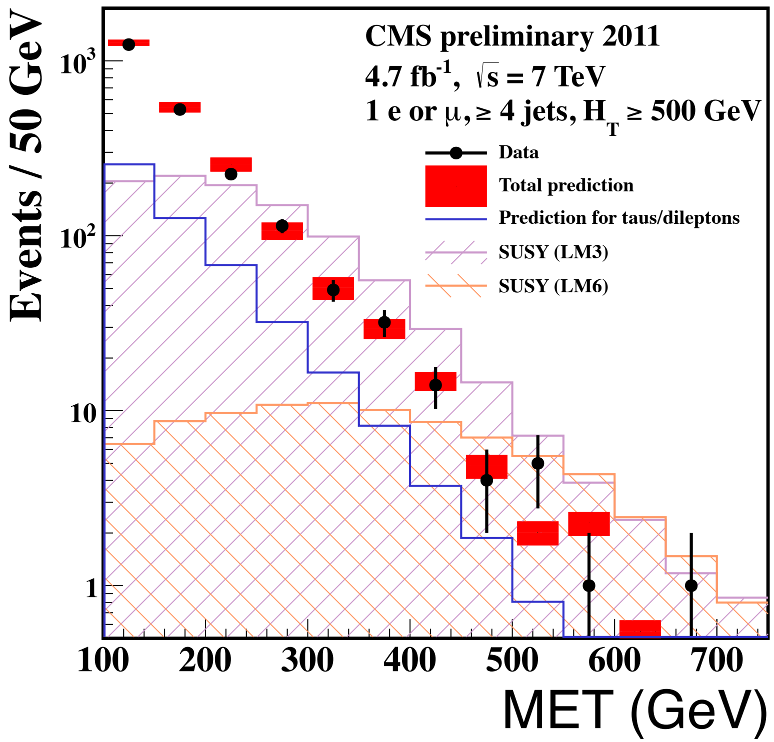


MET (GeV)

- Use $p_T(\ell)$ to model MET from dominant tt→ℓ+jets & W+jets bkg’s
- SUSY signal: invisible LSP’s cause MET >> $p_T(\ell)$ → **search for excess high MET events above prediction from $p_T(\ell)$ spectrum**

1-lep: Lepton-Spectrum Results

data
total bkg prediction
dilepton+τ prediction

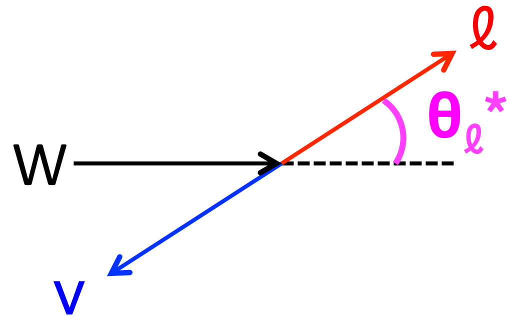


- Sub-leading backgrounds:
  - W → τ → e/μ & tt→ℓ$^+$ℓ$^-$
  - QCD & Z+jets (small)
- Predict MET in tt→ℓ+jets/W(ℓν) from p_T(μ)
- Search in multiple H_T regions
  - H_T > 500 GeV (shown), 750 GeV, 1 TeV
  - Compare data vs. prediction in exclusive MET regions
- Good agreement in all MET, H_T bins → **no evidence for SUSY**

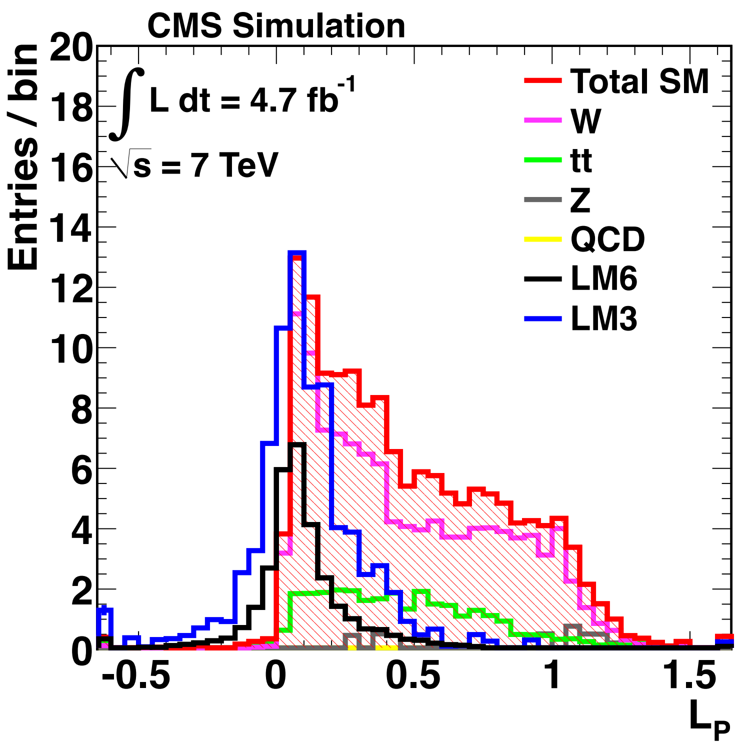
H_T > 500 GeV	MET 250-350 GeV	MET 350-450 GeV	MET 450-550 GeV	MET > 550 GeV
Predicted Bkg	159 ± 14 ± 18	44 ± 7.7 ± 6.0	6.6 ± 3.0 ± 1.8	4.3 ± 2.6 ± 1.6
Data: total (μ,e)	163 (84,79)	46 (21,25)	9 (8,1)	2 (1,1)

1-lep: Lepton-Projection "L_P" Variable

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



charged lepton helicity angle in W-frame

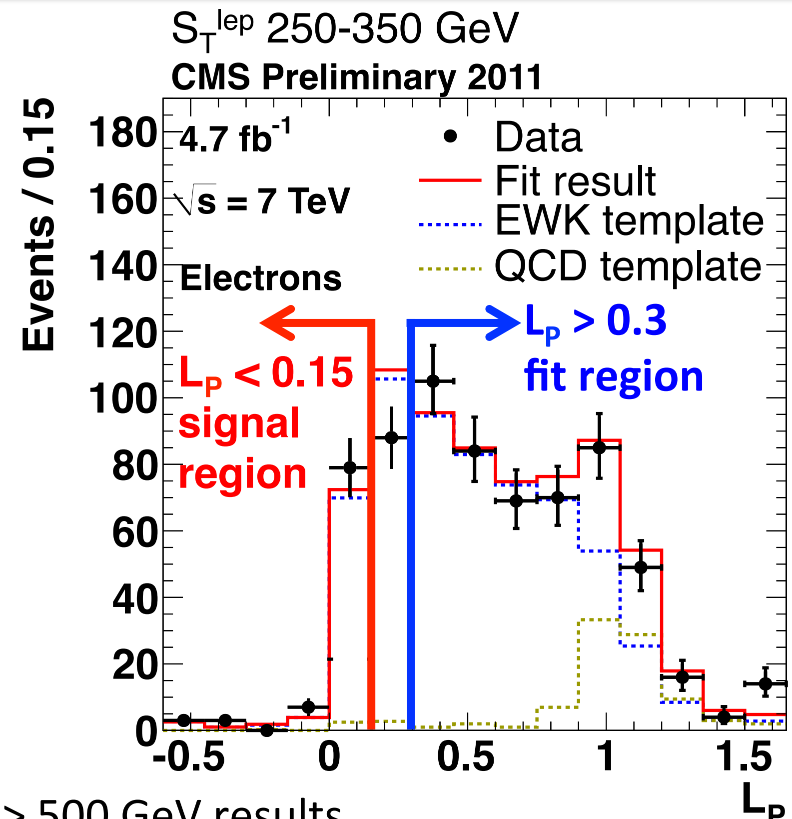


- **L_P strongly correlated to $\cos(\theta_\ell^*)$,** but based only on transverse quantities
  - Measure W polarization in W+jets (CMS, [1])
- **Good SUSY vs. bkg discriminant**
  - SUSY L_P peaked at ~ 0, due to small $p_T(\ell)$ and lack of correlation with $p_T(W)$

[1] http://dx.doi.org/10.1103/PhysRevLett.107.021802

1-lep: Lepton-Polarization Results

- Template fit to data in control region → extrapolate to signal region
  - L_P EWK (tt,W,Z) template from MC
  - L_P QCD template (e-channel only) from QCD-dominated sample
- Search in multiple regions:
  - $H_T > 500$ (shown), 750 GeV, 1 TeV
  - Bin in $S_T^{lep} = p_T(\ell)$+MET ~ $p_T(W)$
- Observed yields consistent with prediction in all regions → **no evidence for SUSY**



H_T > 500 GeV results

	Signal Region ($L_P < 0.15$)		
S_T^{lep} Range (GeV)	Total MC	SM estimate	Data
[150-250]	315±4	289±9±31	319
[250-350]	123±2	113± 5 ± 9	108
[350-450]	52.0±1.5	44.1± 3.5 ± 3.9	32
> 450	30.1±1.2	26.1± 2.9 ± 2.4	25

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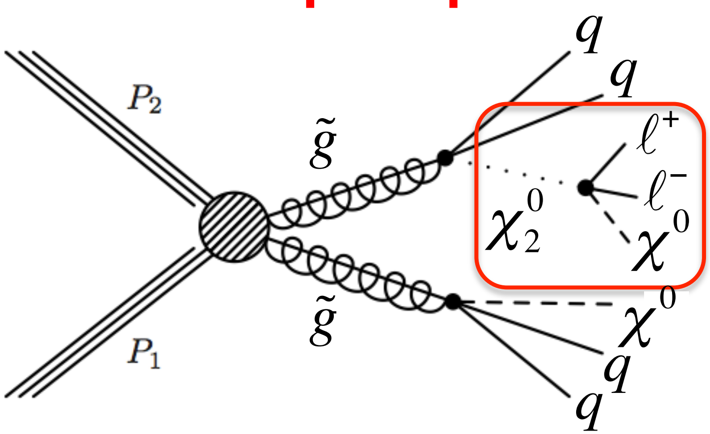
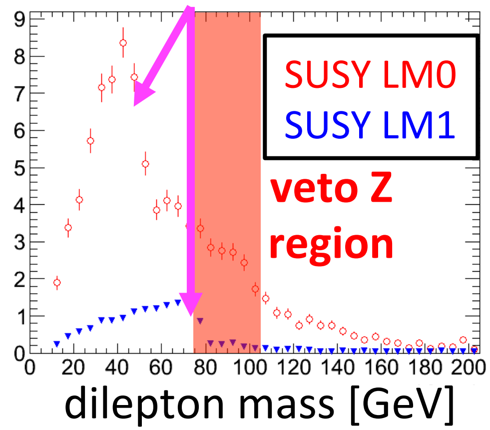
Search Strategy

non-Z lepton pairs

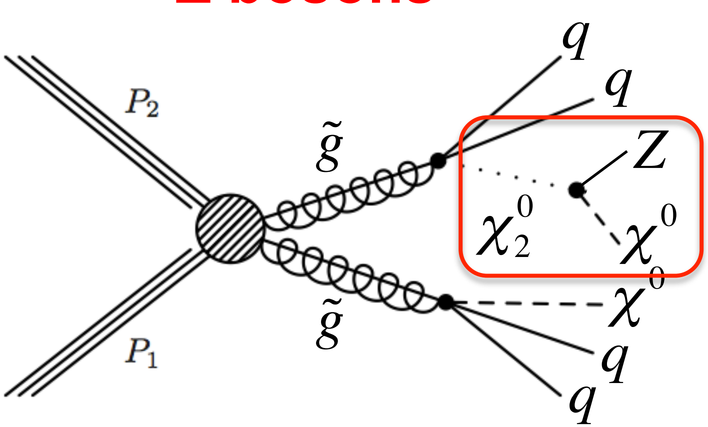


kinematic edge (in some models)

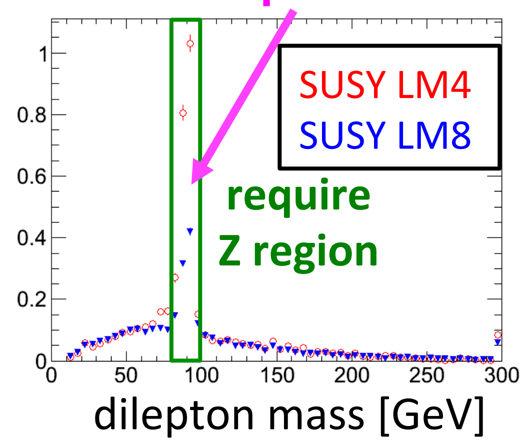


$\ell^+\ell^-$ + jets + MET

Z bosons



Z-peak



Z + jets + MET

- **Divide & conquer** → separate, targeted analyses for Z vs. non-Z regions

OS non-Z: Analysis Methods

- **Select events: $\ell^+\ell^-$ + jets + MET**
  - Suppress Z+jets: apply Z-veto, H_T, MET cuts
  - **Dominant background: tt → $\ell^+\ell^-$**

- 2 complementary techniques:

- **Counting experiments: large MET vs. H_T signal regions**
  - **"Light leptons:"** ee / μμ / eμ → clean final state
  - **"Hadronic taus:"** $e\tau_h$ / $\mu\tau_h$ / $\tau_h\tau_h$ → improve sensitivity for enhanced 3rd generation couplings

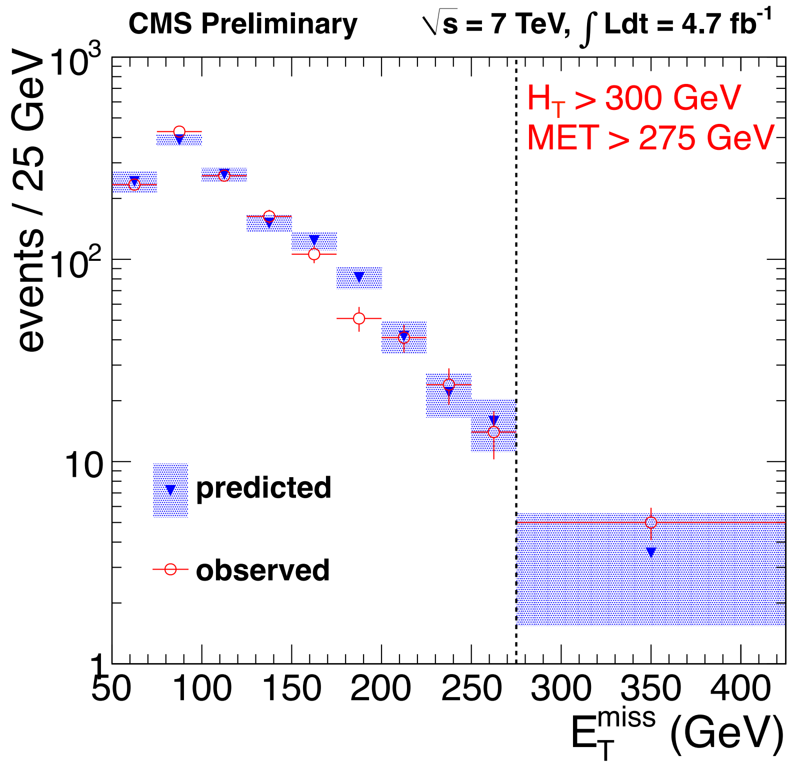
→ **sensitive to models with very large MET & H_T**

- **Search for $M(\ell\ell)$ kinematic edge**
  - Feature of SUSY models with $\chi_2^0 \rightarrow \ell^+\ell^-\chi_1^0$

→ **relax MET & H_T cuts, exploit shape info**

OS non-Z: ee/μμ/eμ Results

- **Predict MET in tt→ℓ⁺ℓ⁻ from $p_T(\ell\ell)$**
- Verify fake leptons (W(ℓν)+jets, QCD) & Z+jets negligible with data-driven methods
- Search in multiple H_T vs. MET regions
- Good agreement in all MET vs. H_T bins→ **no evidence for SUSY**



	MET > 275 GeV H_T > 300 GeV	MET > 200 GeV H_T > 600 GeV	MET > 275 GeV H_T > 600 GeV	MET > 275 GeV H_T > 125-300 GeV
total yield	**30**	**29**	**11**	**6**
$p_T(\ell\ell)$ prediction	**$21 \pm 8.9 \pm 8.0$**	**$22 \pm 7.5 \pm 6.9$**	**$11 \pm 5.8 \pm 3.8$**	**$12 \pm 4.9 \pm 5.7$**
MC prediction	30 ± 1.2	31 ± 0.9	12 ± 0.6	4.2 ± 0.3
non-SM yield UL	26	23	11	6.5
LM6	35 ± 0.6	33 ± 0.5	26 ± 0.5	0.6 ± 0.1

non-SM yield upper limits (for use with efficiency model)

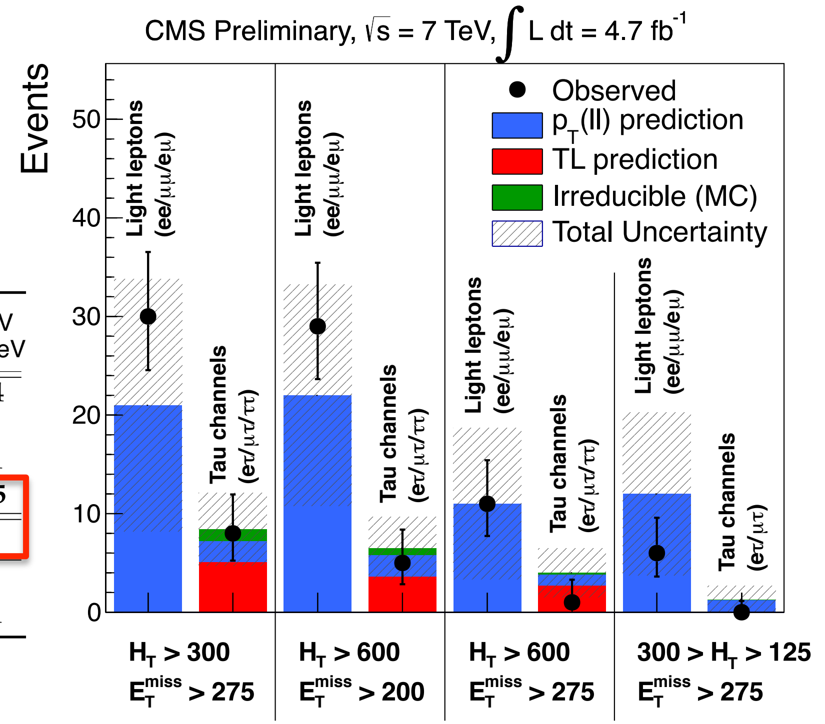
OS non-Z: $e\tau_h$ / $\mu\tau_h$ / $\tau_h\tau_h$ Results

- **2 dominant backgrounds:**
  - **"Genuine taus" ($tt \rightarrow e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$):** predict MET from $p_T(\ell\ell)$, with additional τ correction factor (for τ acceptance, efficiency, branching fractions)
  - **"Fake taus:"** estimate with "fake-rate method" (extrapolate in τ isolation)
- **Good agreement in all signal regions → no evidence for SUSY**

Hadronic tau results

	MET > 275 GeV H_T > 300 GeV	MET > 200 GeV H_T > 600 GeV	MET > 275 GeV H_T > 600 GeV	MET > 275 GeV H_T > 125-300 GeV
$p_T(\ell\ell)$ prediction	$2.1 \pm 0.9 \pm 0.8$	$2.2 \pm 0.8 \pm 0.9$	$1.1 \pm 0.6 \pm 0.4$	$1.2 \pm 0.5 \pm 0.4$
TL prediction	$5.1 \pm 1.7 \pm 0.8$	$3.6 \pm 1.4 \pm 0.5$	$2.7 \pm 1.3 \pm 0.4$	< 0.08
MC irreducible	$1.2 \pm 0.5 \pm 0.2$	$0.7 \pm 0.3 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$	$0.1 \pm 0.1 \pm 0.1$
$\sum$ predictions	**$8.4 \pm 2.0 \pm 1.1$**	**$6.5 \pm 1.6 \pm 1.0$**	**$4.0 \pm 1.4 \pm 0.6$**	**$1.3 \pm 0.5 \pm 0.5$**
total yield	**8**	**5**	**1**	**0**
non-SM yield UL	7.9	6.2	3.7	3.1
LM6	$4.2 \pm 1.3 \pm 0.7$	$4.8 \pm 1.4 \pm 0.8$	$4.0 \pm 1.3 \pm 0.7$	$0.4 \pm 0.4 \pm 0.1$

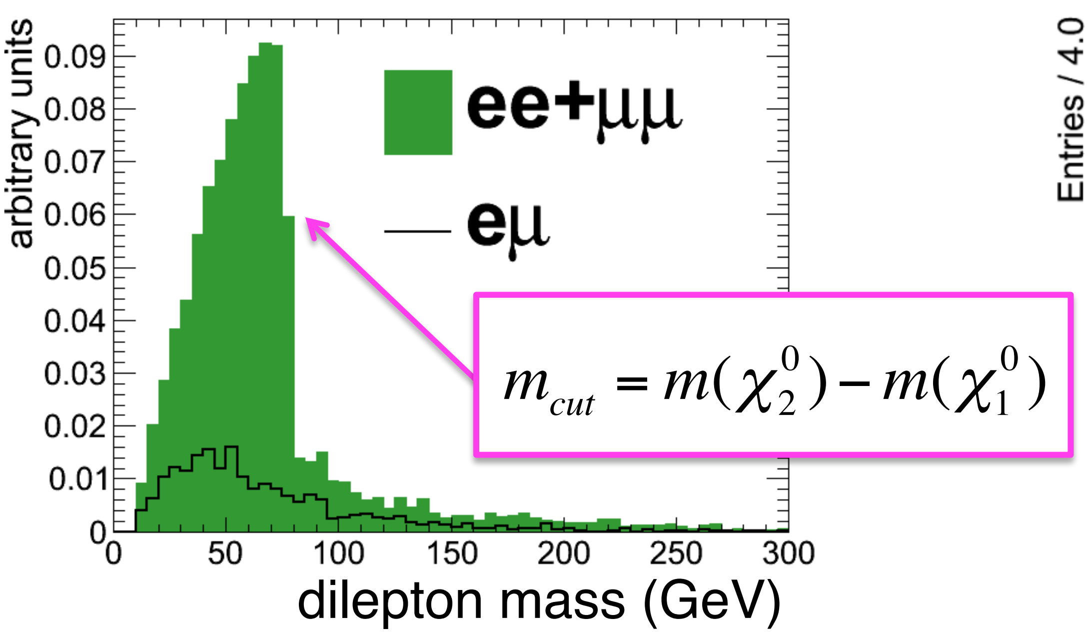
Summary: light leptons & hadronic taus



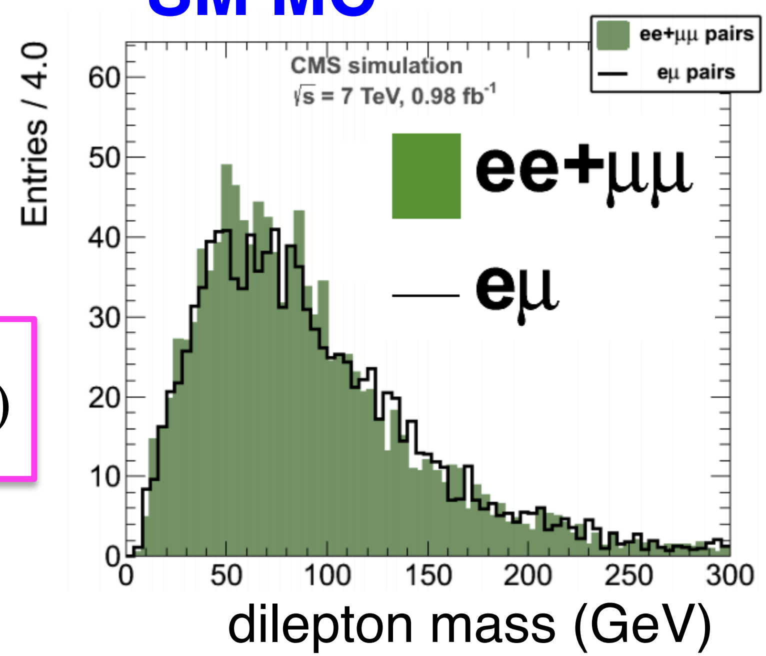
OS non-Z: Edge Search

- $\chi_2^0 \rightarrow \ell^+\ell^- \chi_1^0$ kinematic endpoint produces "edge" in ee/μμ M(ℓℓ) distribution
  - 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 eμ vs. ee+μμ → **search for edge in ee+μμ dilepton mass, model background shape from eμ sample**

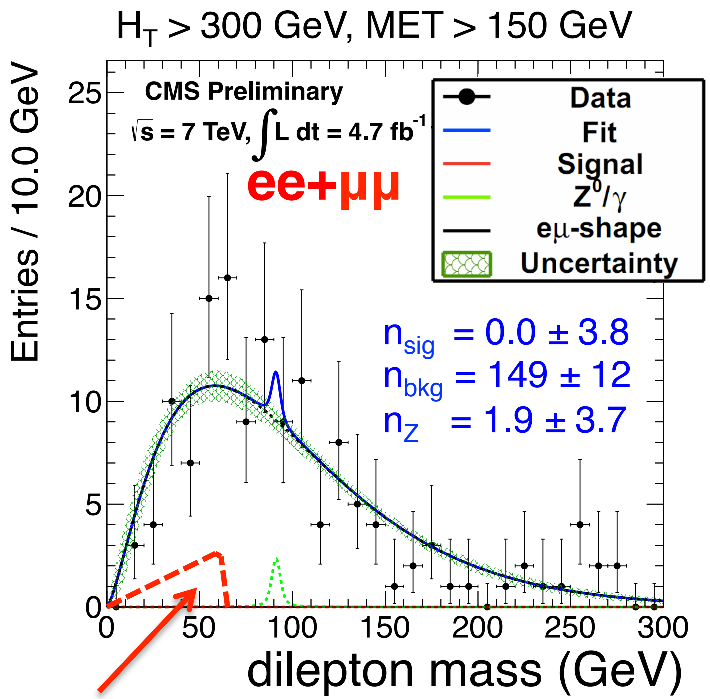
SUSY with $\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$

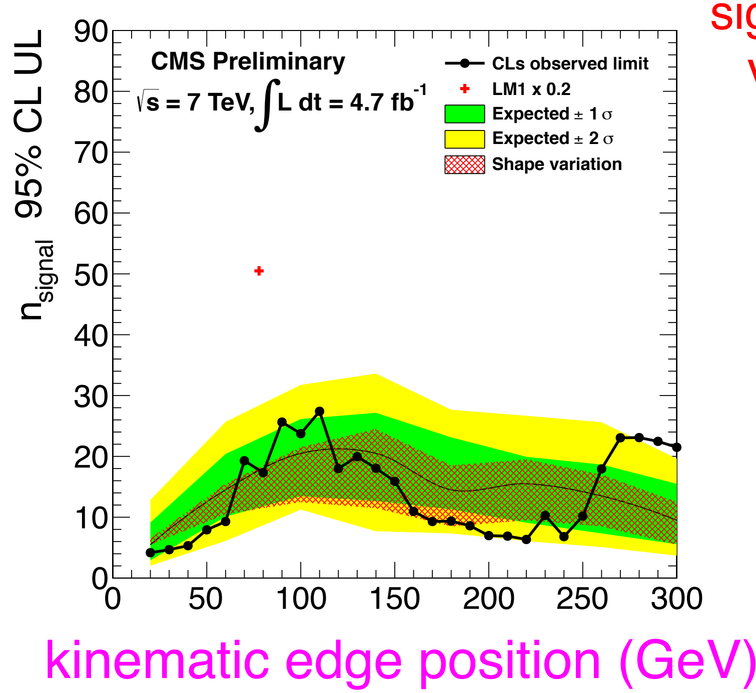


SM MC

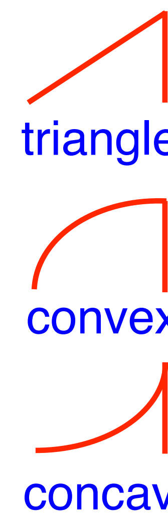


OS non-Z: Edge Search Results





signal shape variation:



example signal shape:
triangle ⊕ gaus

- **No edge observed** → extract signal yield UL using ML fit
- Scan **kinematic edge position**, extract signal yield upper limit at each point
  - Observed/expected limits consistent within ~2σ over full range

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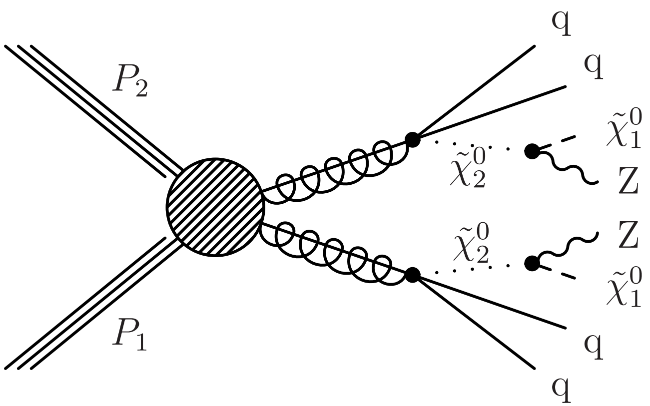
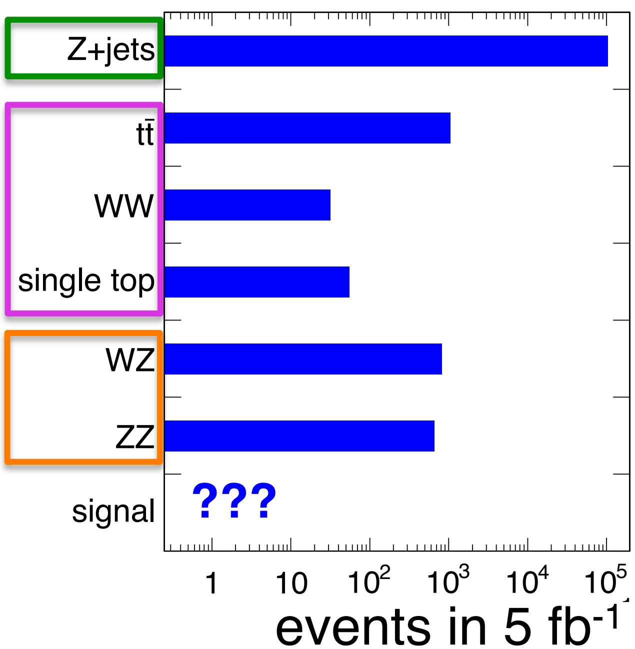
Z: Backgrounds & Strategy

- In SUSY, Z's produced in χ^0 decays, eg:
  - $\chi_2^0 \rightarrow Z\,\chi_1^0, \quad \chi_1^0 \rightarrow Z\,\tilde{G}$
- **Search for Z(ee/μμ) + jets + MET**



Z(ee/μμ) + ≥2 jets:
MC sample composition



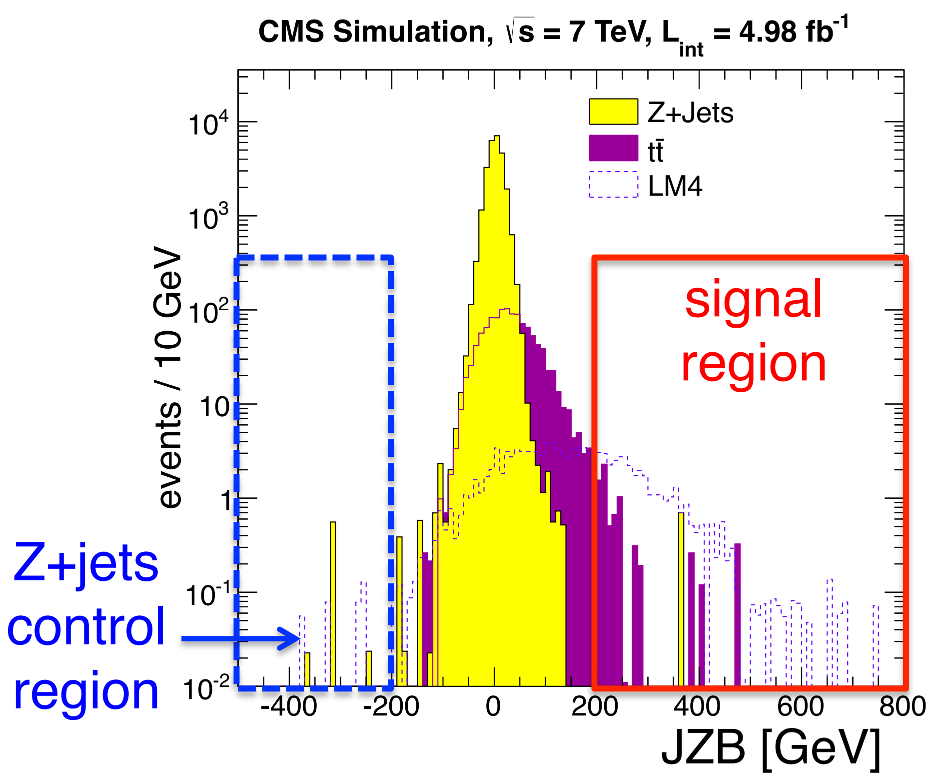
- ***Z+jets*** → ***critical analysis challenge***
  - Very large σ, ***MET not well-reproduced in MC***
  - **Suppress/estimate with 2 methods:**
    - **"Jet-Z balance" method**
    - **"MET template" method**
- **"Flavor-symmetric" ($N_{ee} + N_{\mu\mu} = N_{e\mu}$) bkgs:**
  - **Estimate from eμ data, M(ℓℓ) sidebands**
- **Diboson production**
  - WZ and ZZ → **estimate from MC**

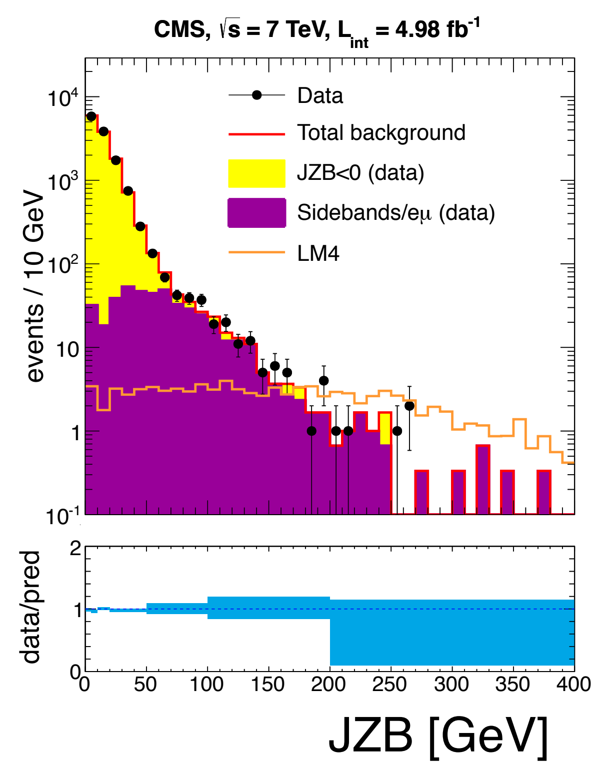
Z: JZB Method

$$\mathrm{JZB} = \left|\sum_{\mathrm{jets}} p_{\mathrm{T}}\right| - \left|\vec{p_{\mathrm{T}}}^{(\mathrm{Z})}\right|$$

→ imbalance between p_T of Z and hadronic system

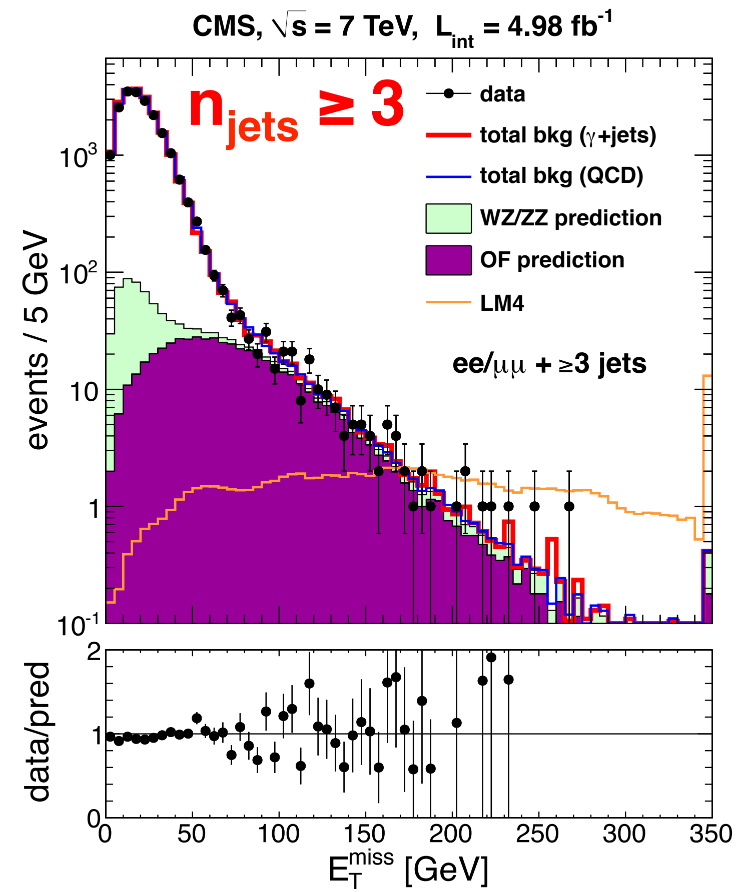
- JZB ~symmetric about 0 for SM Z + multi-jets, JZB >> 0 for signal → estimate Z+jets contribution in JZB>>0 signal region using JZB<<0 control region
- **Good agreement between data and prediction → no evidence for SUSY**





Z: MET templates method

- MET in Z+jets arises from jet mismeasurements → **model MET in Z+jets with γ+jets / QCD data control samples**
- Search in $n_{jets} \geq 2$ bin (γ+jets, in backup) and $n_{jets} \geq 3$ (QCD & γ+jets → consistent predictions, shown)
- **Good agreement between data and prediction in all signal regions → no evidence for SUSY**



	$E_T^{miss} > 30$ GeV	$E_T^{miss} > 60$ GeV	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 300$ GeV
total bkg (QCD)	4533 ± 804	500 ± 64	128 ± 16	10 ± 2.5	1.6 ± 0.6
total bkg (γ + jets)	4429 ± 1253	496 ± 67	131 ± 13	11 ± 2.5	1.9 ± 0.6
total bkg (average)	**4481 ± 1034**	**498 ± 66**	**129 ± 15**	**11 ± 2.7**	**1.8 ± 0.6**
data	**4501 (2272,2229)**	**479 (267,212)**	**137 (73,64)**	**8 (3,5)**	**0**

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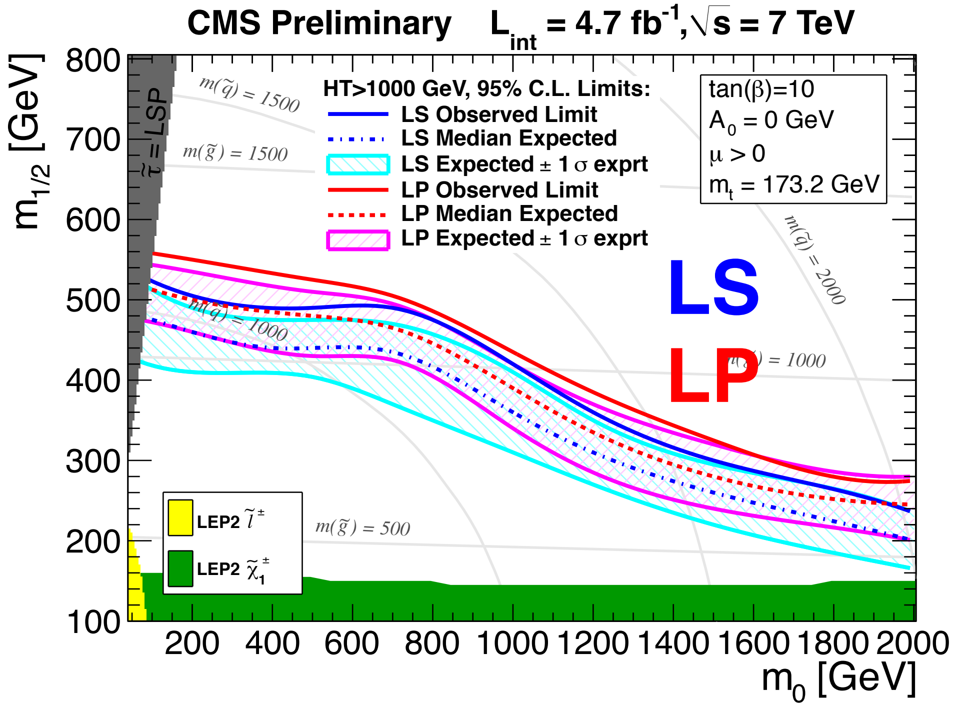
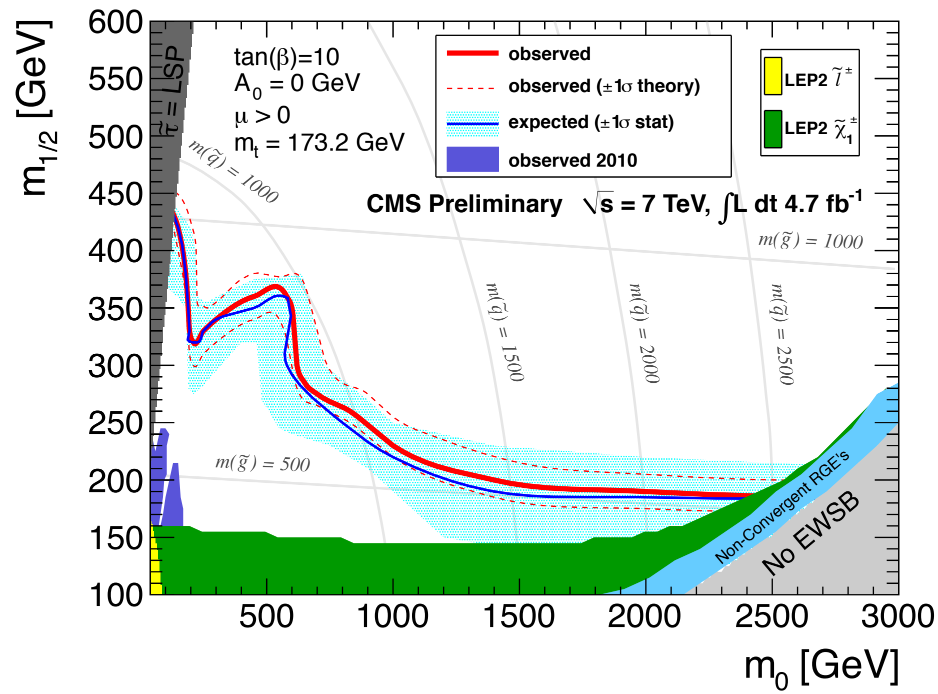
CMSSM Interpretations

ℓ + jets + MET

(lepton spectrum and lepton polarization)



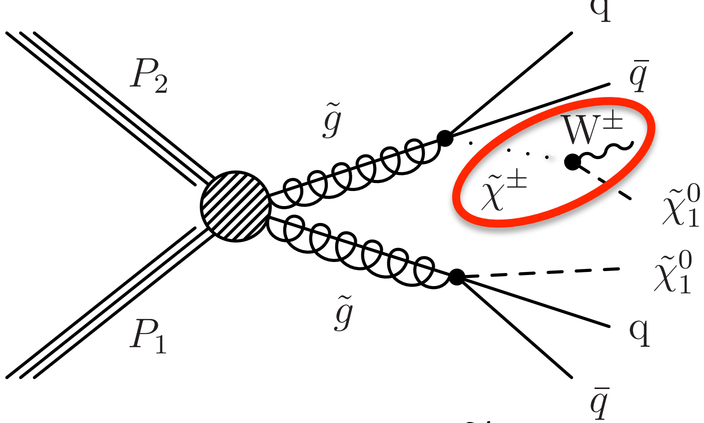
OS (ee/μμ/eμ) + jets + MET



- Significant enhancement w.r.t. previous experiments
  - Exclude gluinos below ~500 GeV, 1st/2nd generation squarks below ~1 TeV
- More stringent limits from all-hadronic analyses (See talk K. Hatakeyama)

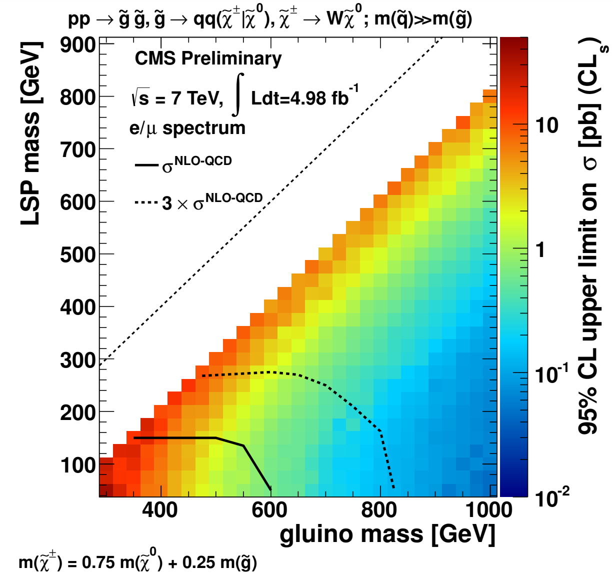
1-lep: SMS Limits

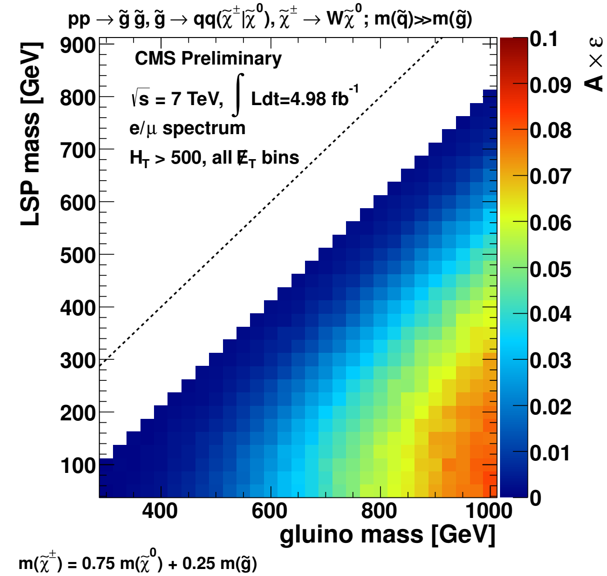
- Set limits in "simplified model spectra"



- Scan 2 parameters: M($\tilde{g}$) and M(χ^0)

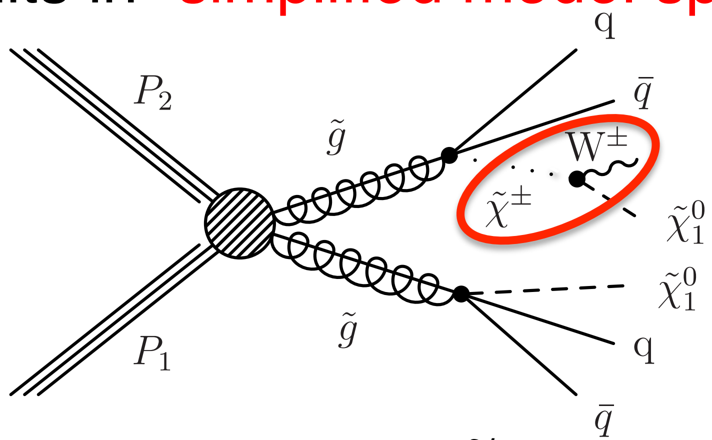
$m(\tilde{\chi}^{\pm}) = 0.75\ m(\tilde{\chi}^{0}) + 0.25\ m(\tilde{g})$





1-lep: SMS Limits

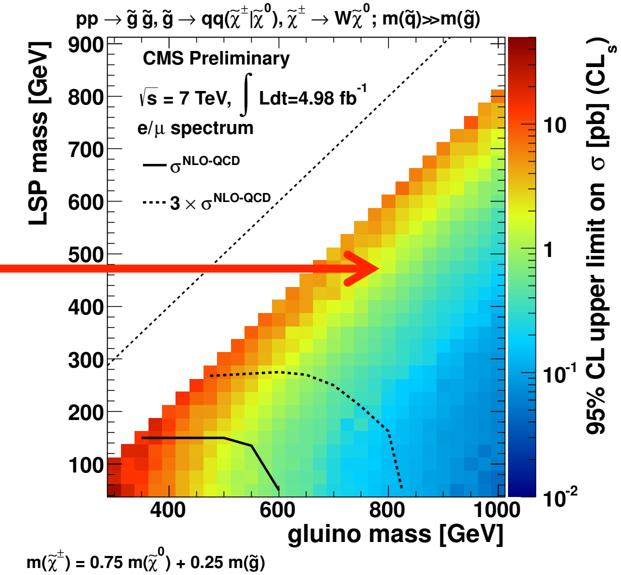
- Set limits in "simplified model spectra"

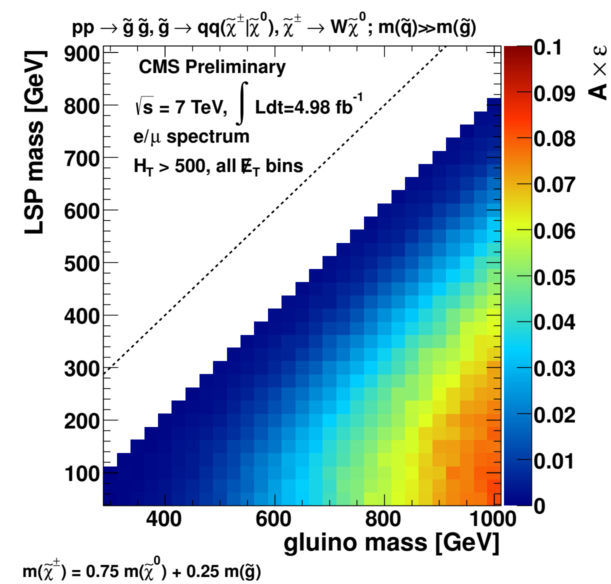


- Scan 2 parameters: M($\tilde{g}$) and M(χ^0)

$$m(\tilde{\chi}^{\pm}) = 0.75\ m(\tilde{\chi}^{0}) + 0.25\ m(\tilde{g})$$

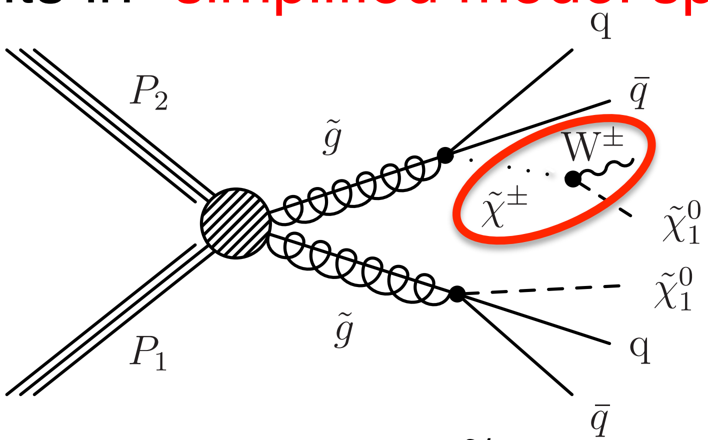
- 1) Set UL($\sigma \times$ BF) vs. M(g), M(χ^0)





1-lep: SMS Limits

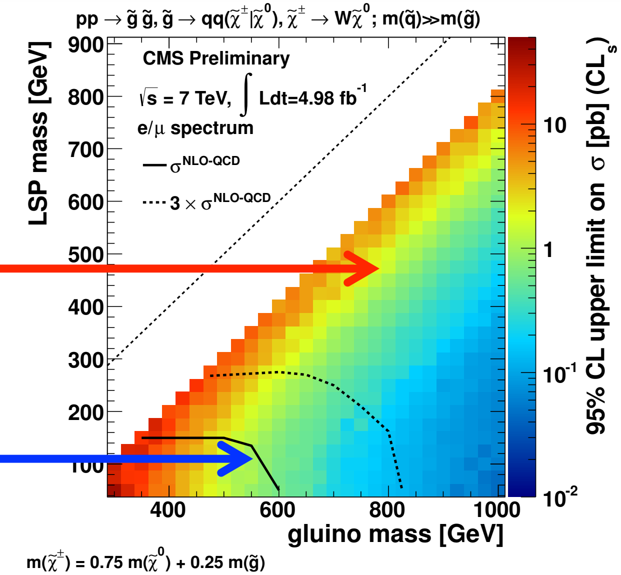
- Set limits in "simplified model spectra"

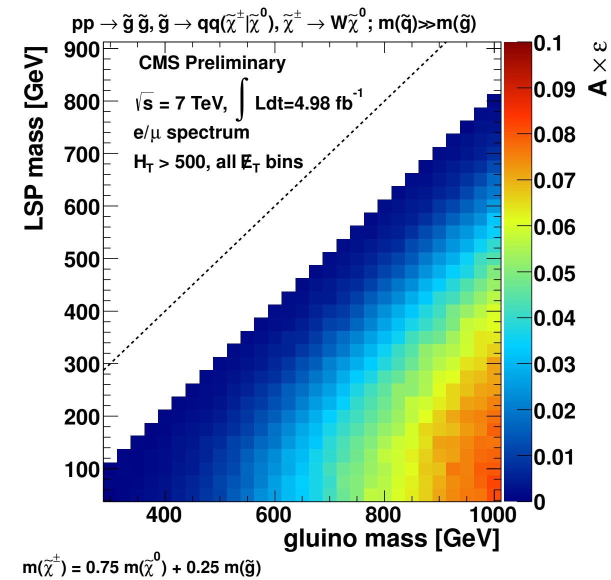


- Scan 2 parameters: M($\tilde{g}$) and M(χ^0)

$$m(\tilde{\chi}^{\pm}) = 0.75\, m(\tilde{\chi}^{0}) + 0.25\, m(\tilde{g})$$

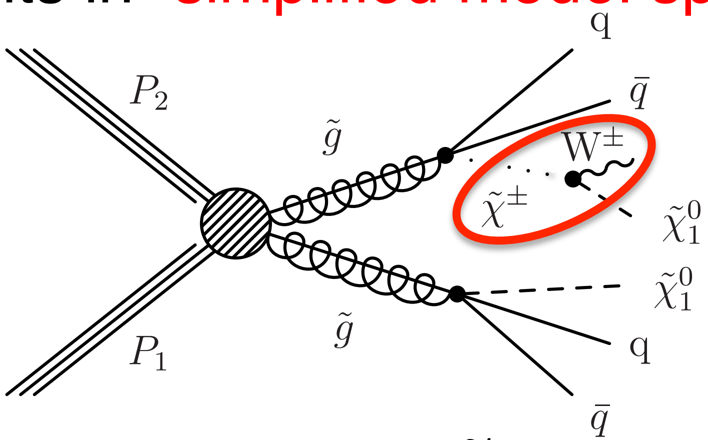
- 1) Set UL($\sigma \times$ BF) vs. M(g), M(χ^0)
- 2) Assume $\sigma^{\text{NLO-QCD}}$ and BF=1 → exclude region of parameter space





1-lep: SMS Limits

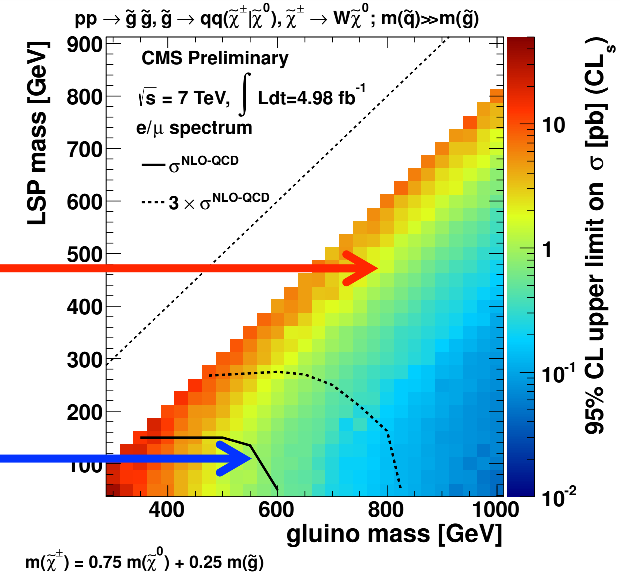
- Set limits in "simplified model spectra"

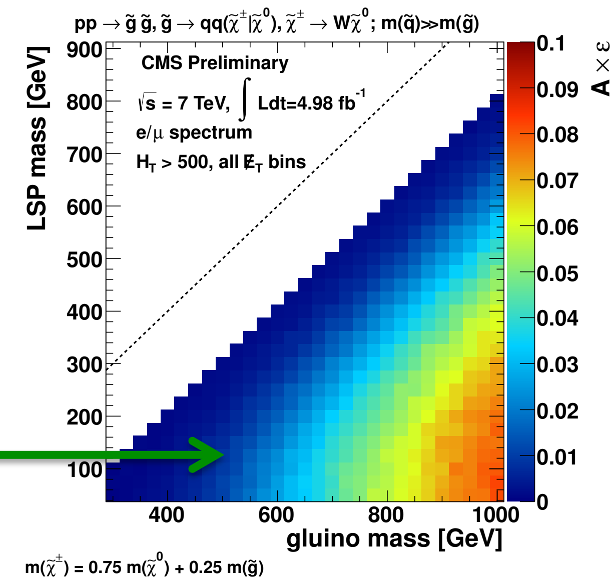


- Scan 2 parameters: M($\tilde{g}$) and M(χ^0)

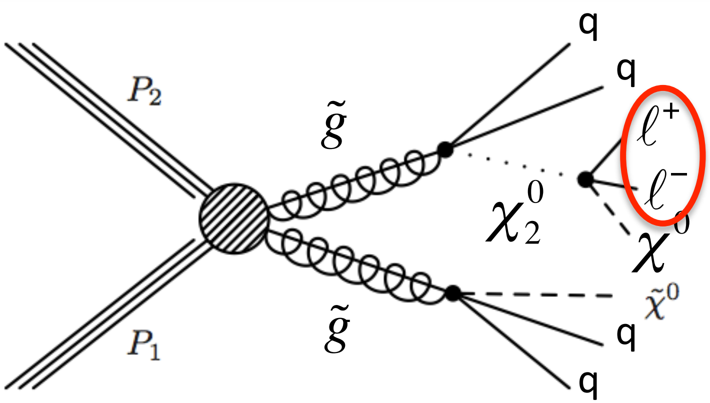
$$m(\tilde{\chi}^{\pm}) = 0.75\ m(\tilde{\chi}^{0}) + 0.25\ m(\tilde{g})$$

- 1) Set UL(σ × BF) vs. M(g), M(χ^0)
- 2) Assume $\sigma^{NLO\text{-}QCD}$ and BF=1 → exclude region of parameter space
- 3) Provide efficiency map (fastsim calibration/validation)



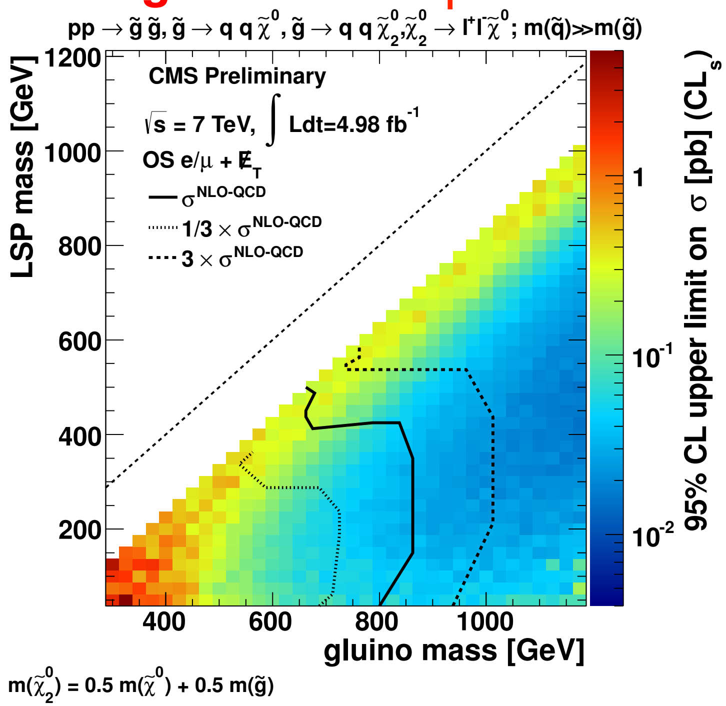


OS non-Z: SMS Limits

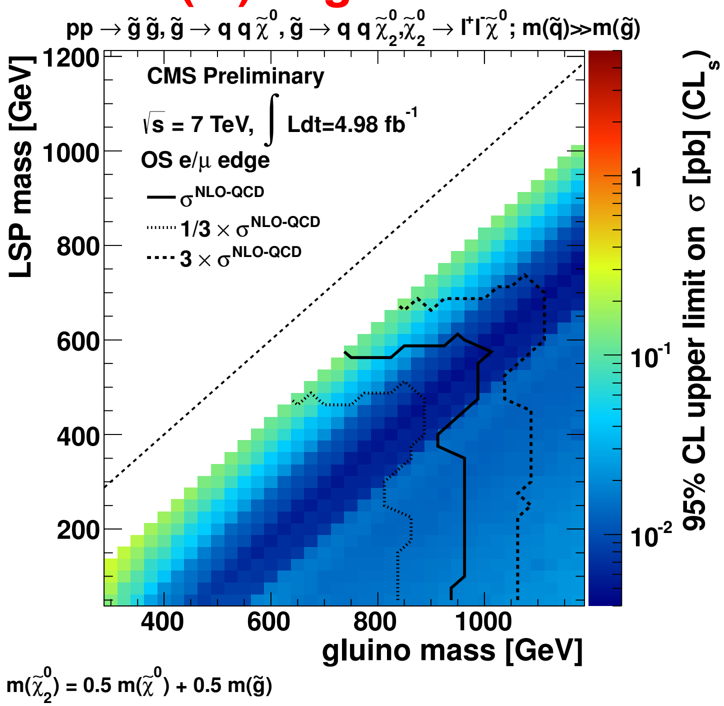


- Enhanced sensitivity to this specific SMS from M(ℓℓ) edge search
- Results probe gluinos up to ~1 TeV

large MET vs. H_T search



M(ℓℓ) edge search

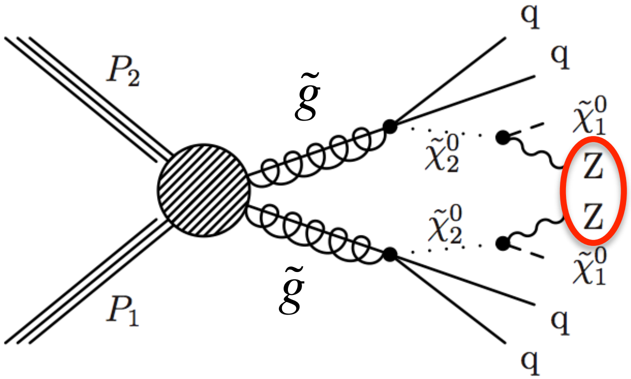


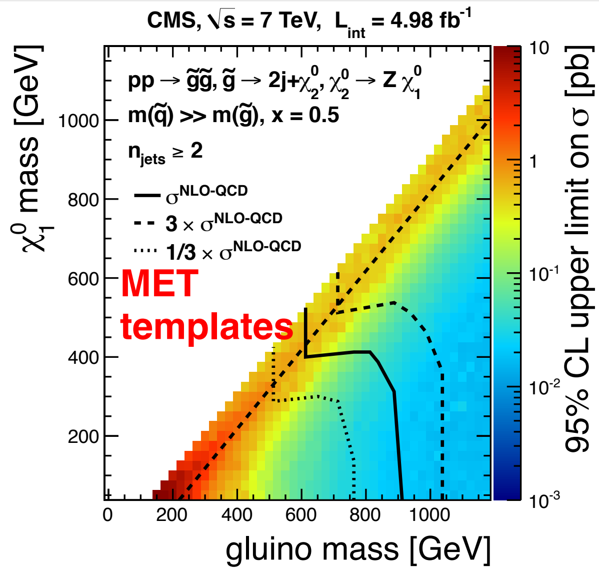
Z: SMS Limits

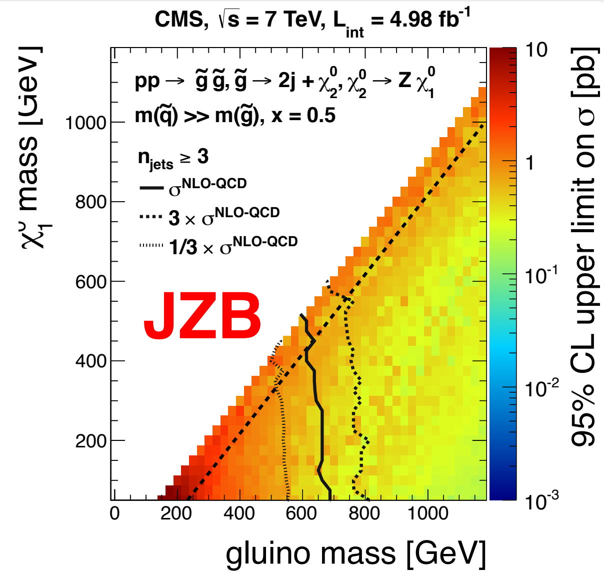
Neutralino LSP Scenario

scan $M(\chi_1^0)$ vs. $M(\tilde{g})$

$M(\chi_2^0) = ½ [M(\tilde{g}) + M(\chi_1^0)]$



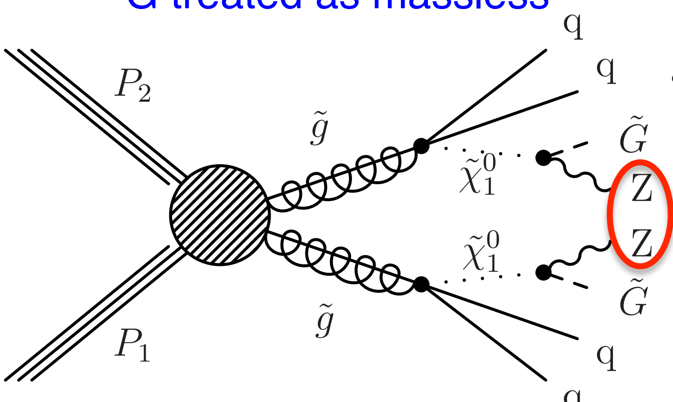


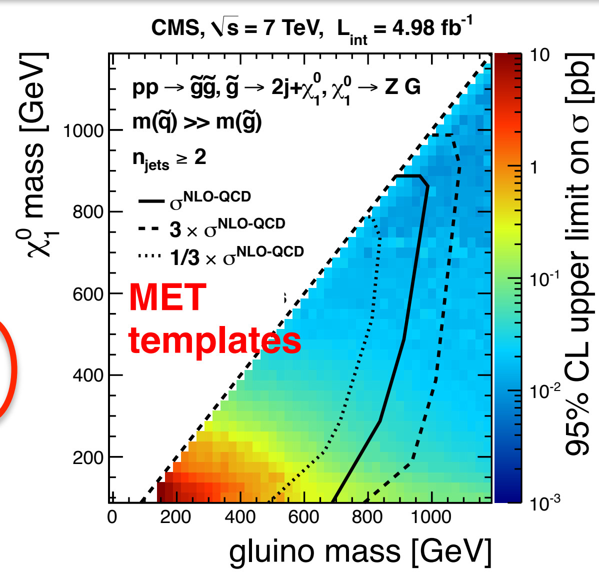


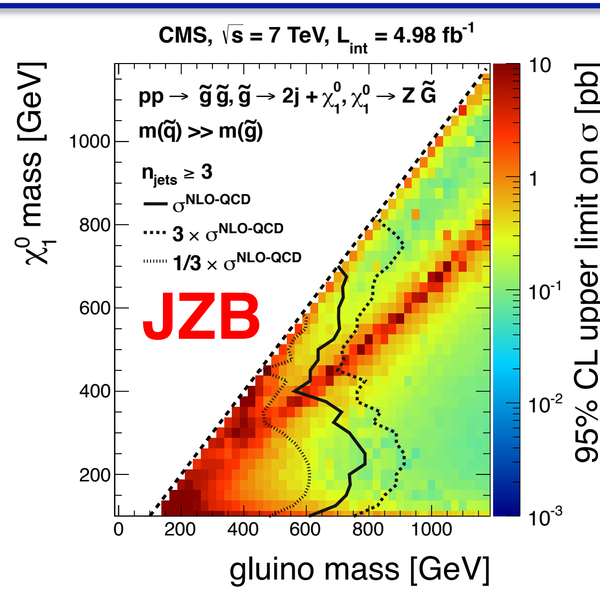
Gravitino LSP Scenario

scan $M(\chi_1^0)$ vs. $M(\tilde{g})$

$\tilde{G}$ treated as massless

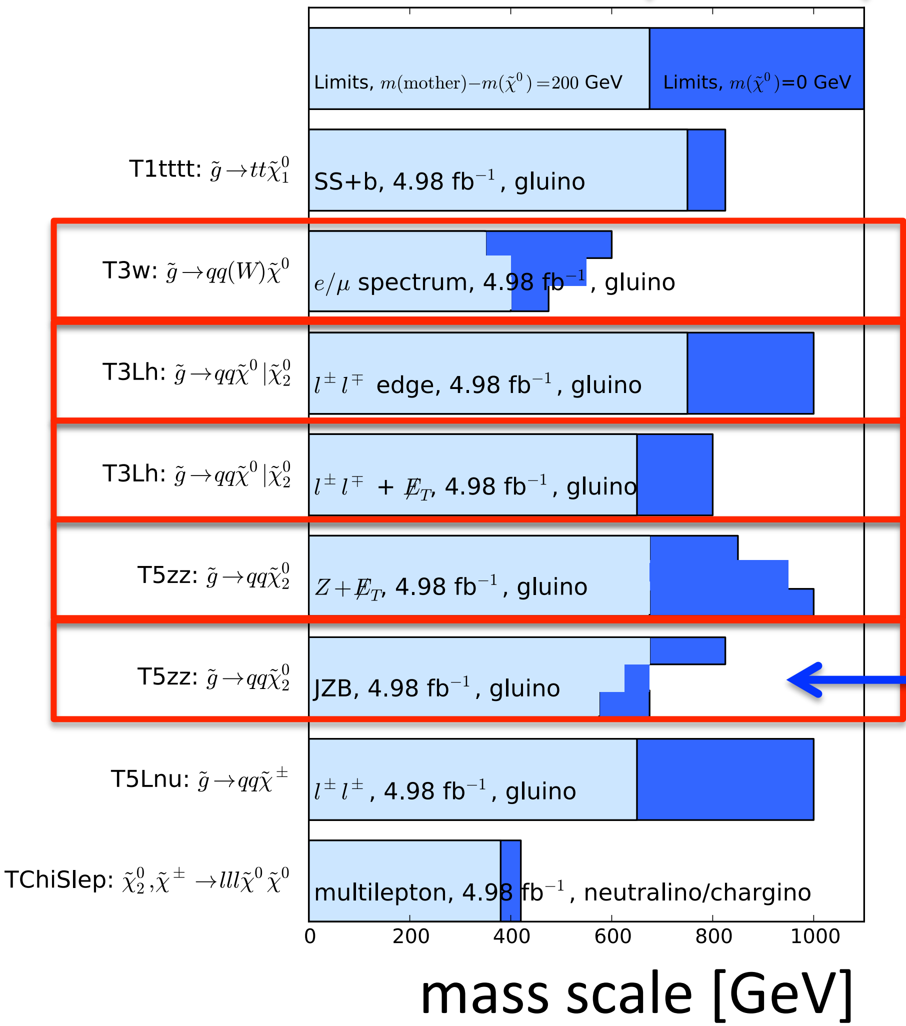






SMS Summary: Gluino Limits

gluino mass limit, m(χ⁰) = 0 GeV
m(g̃) – m(χ⁰) = 200 GeV



- Results probe gluino masses **up to** ~1 TeV
  - **Assumes BF = 1**
  - Maximum reach for massless LSP

3 bars for different intermediate χ masses

covered in this talk

Efficiency Model

- **Problem:** how to apply these results to an arbitrary model?
- **Goal**: allow others to determine if arbitrary model X is excluded by comparing expected yield to signal yield UL

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

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

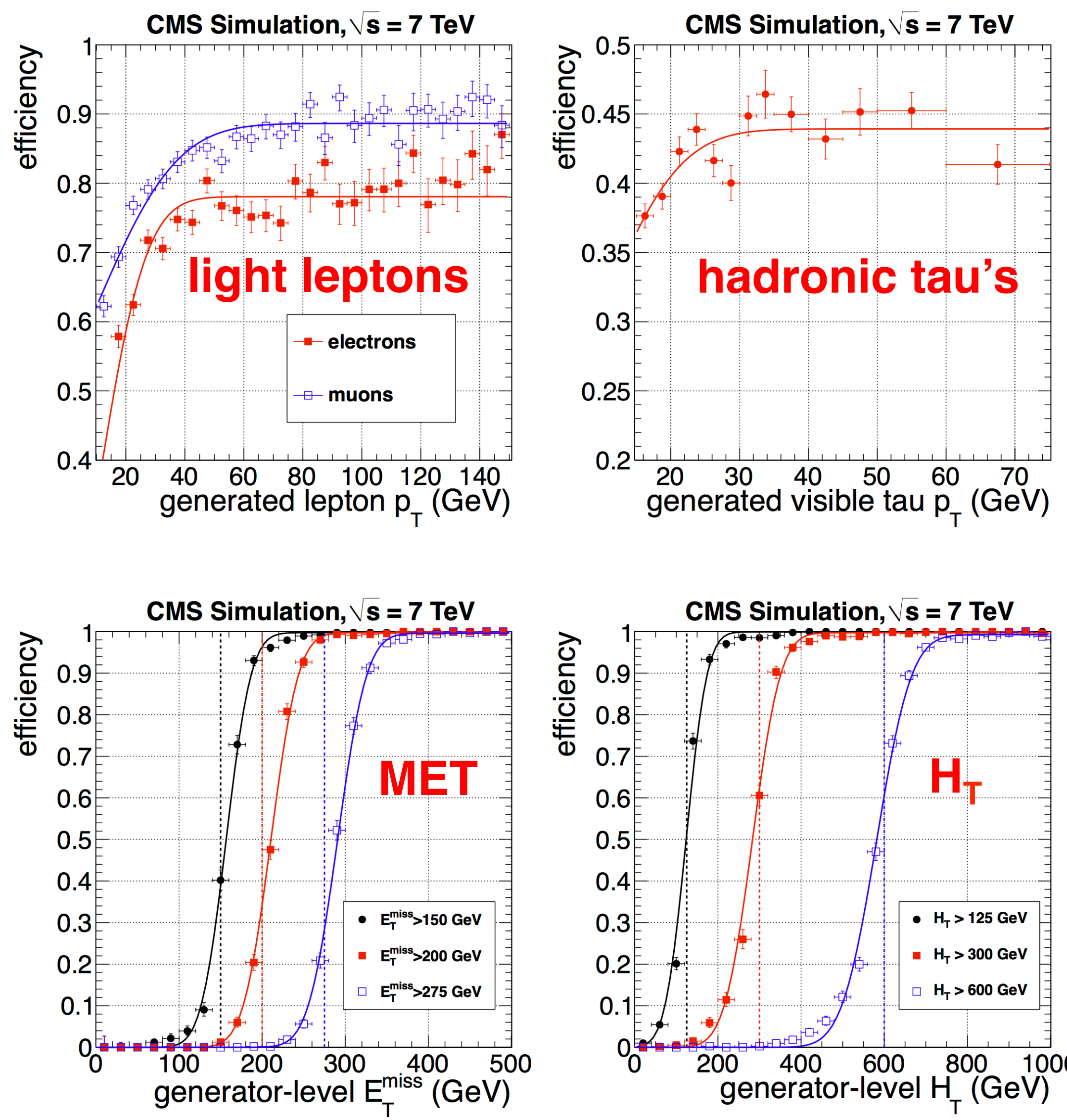
- Recipe: provide selection efficiencies for **basic physics objects** (leptons, H_T, MET) → allow estimation of model X efficiency using simple generator-level studies

Efficiency Model

- **Efficiency model:**
  - **Shown**: OS analysis, provided for other analyses as well
  - Efficiencies of physics objects vs. gen-level quantities

- **Procedure:**
  - Implement model X in MC
  - Apply analysis selections to gen-level quantities
  - Use efficiency model to scale gen-level yields to “reco-level”

- **This is an approximation**
  - Tested ***with several CMSSM points***, agreement within ~15%

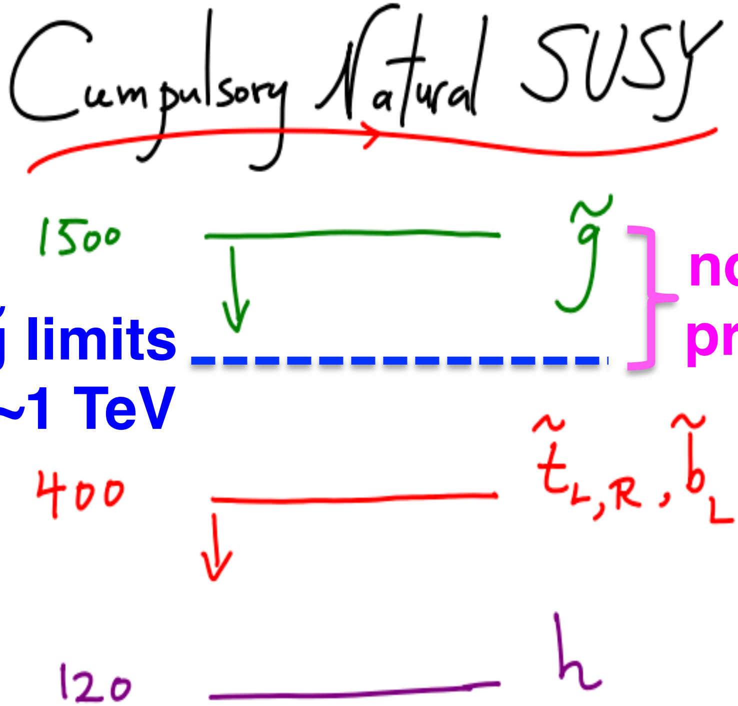


Contents

- Introduction
- Searches with leptons
  - Single lepton
  - Opposite-sign (non-Z) leptons
  - $Z \rightarrow \ell^{+}\ell^{-}$
- Interpretation & Efficiency Models
- **Future Directions and Summary**

Ongoing/Future Directions (1)

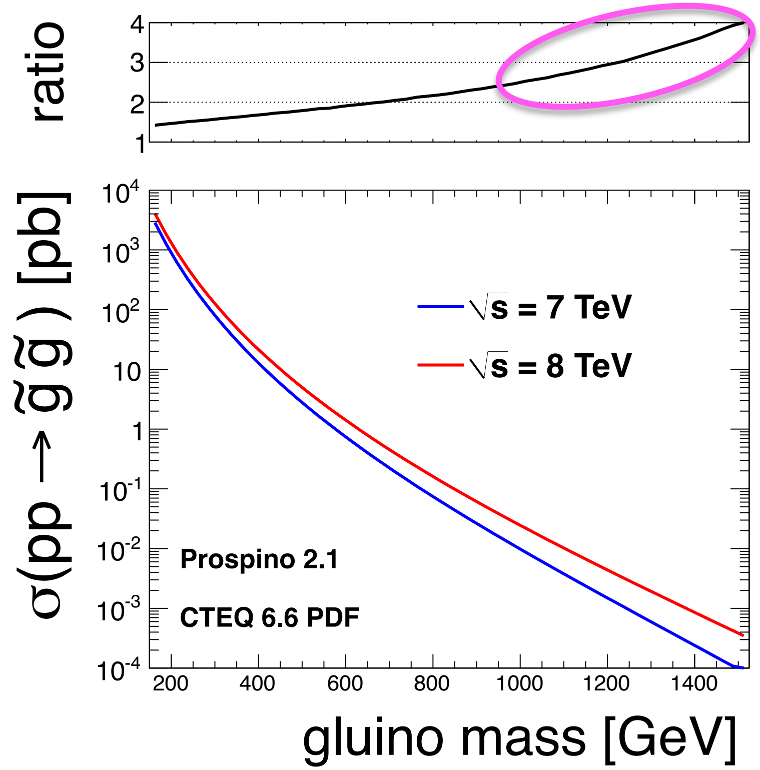
[1] N. Arkani Hamed
https://indico.cern.ch/getFile.py/access?contribId=7&sessionId=2&resId=0&materialId=slides&confId=157244



2011 $\tilde{g}$ limits up to ~1 TeV

not yet probed

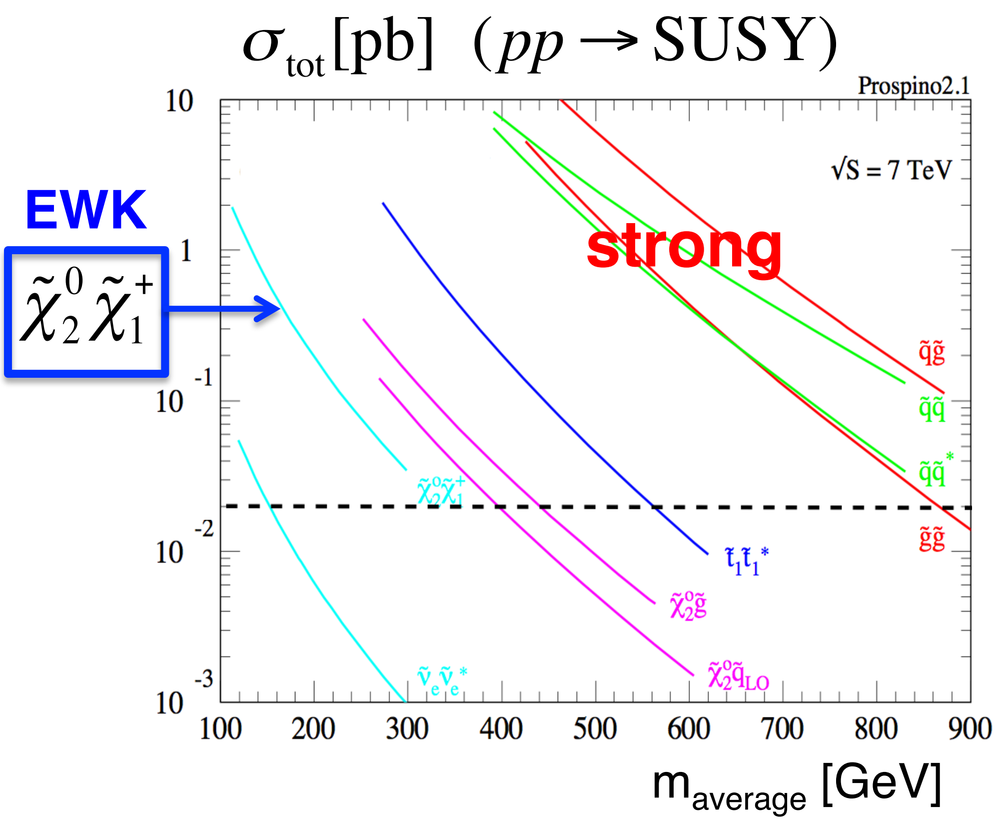
7 → 8 TeV:
~×2-4 σ enhancement



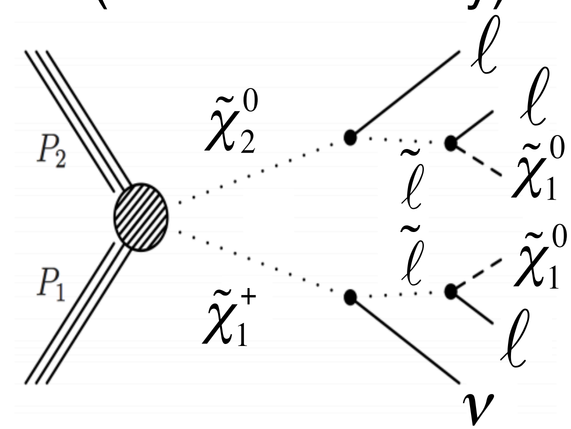
- 2011 results constrain “strong SUSY”, but still more ground to cover
- **Expect significant sensitivity enhancement 7 → 8 TeV**

Ongoing/Future Directions (2)

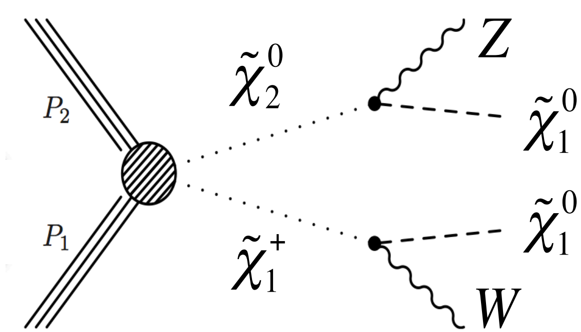
- Search for SUSY ***EWK production*** → relax/remove n_{jets} / H_T requirements
  - Smaller σ → benefit from ~10-20 fb^{-1} 8 TeV 2012 sample



slepton-mediated $\chi^0/\chi^\pm$ decays
(see talk R. Gray)



heavy sleptons:
χ^0 → Z LSP, $\chi^\pm$ → W LSP



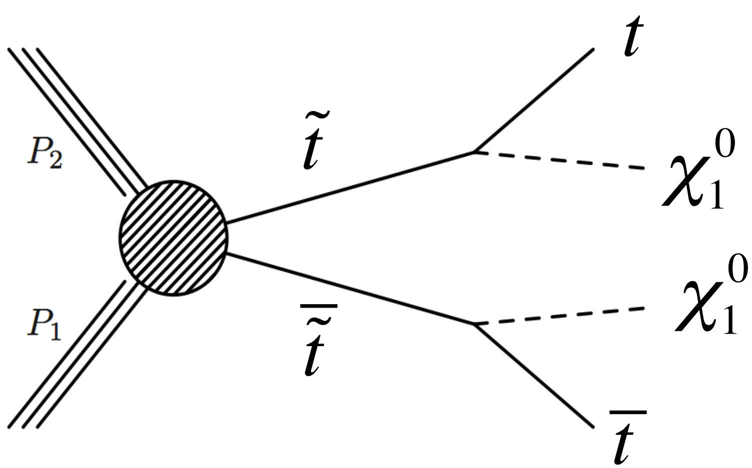
- **Leptonic searches offer ideal strategy for EWK SUSY**

- Search for **stop squarks** → critical for regulating hierarchy problem
  - Requires "light" stops, mass < ~few hundred GeV

direct stop-pair production

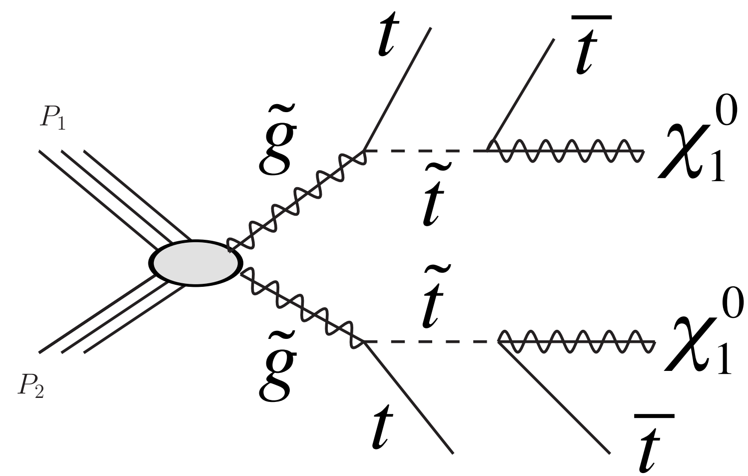
$m(\tilde{t}) = 400$ GeV: $\sigma(\mathrm{pp} \to \tilde{t}\bar{\tilde{t}}) = O(0.1)$ pb $\to$

few × 10^2 stop pairs in 2011 7 TeV data sample



gluino-mediated stop production

(see talk K. Ulmer)



- **Multi-top final states → large branching fraction to lepton(s)**

Summary

- Performed several SUSY searches in leptonic final states
  - No evidence for excesses observed in 5 fb^{-1}…
- **LHC SUSY program has more ground to cover**
  - Improved sensitivity in 2012 → more data, higher $\sqrt{s}$
  - New search channels and strategies
  - **Future searches to benefit from robust modeling of backgrounds with data-driven methods commissioned in 2011 data**

References

CMS SUSY

public twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

single lepton

public document: http://cdsweb.cern.ch/record/1445275?ln=en

public twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS12010

OS non-Z

public twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS110115fb

Z+MET

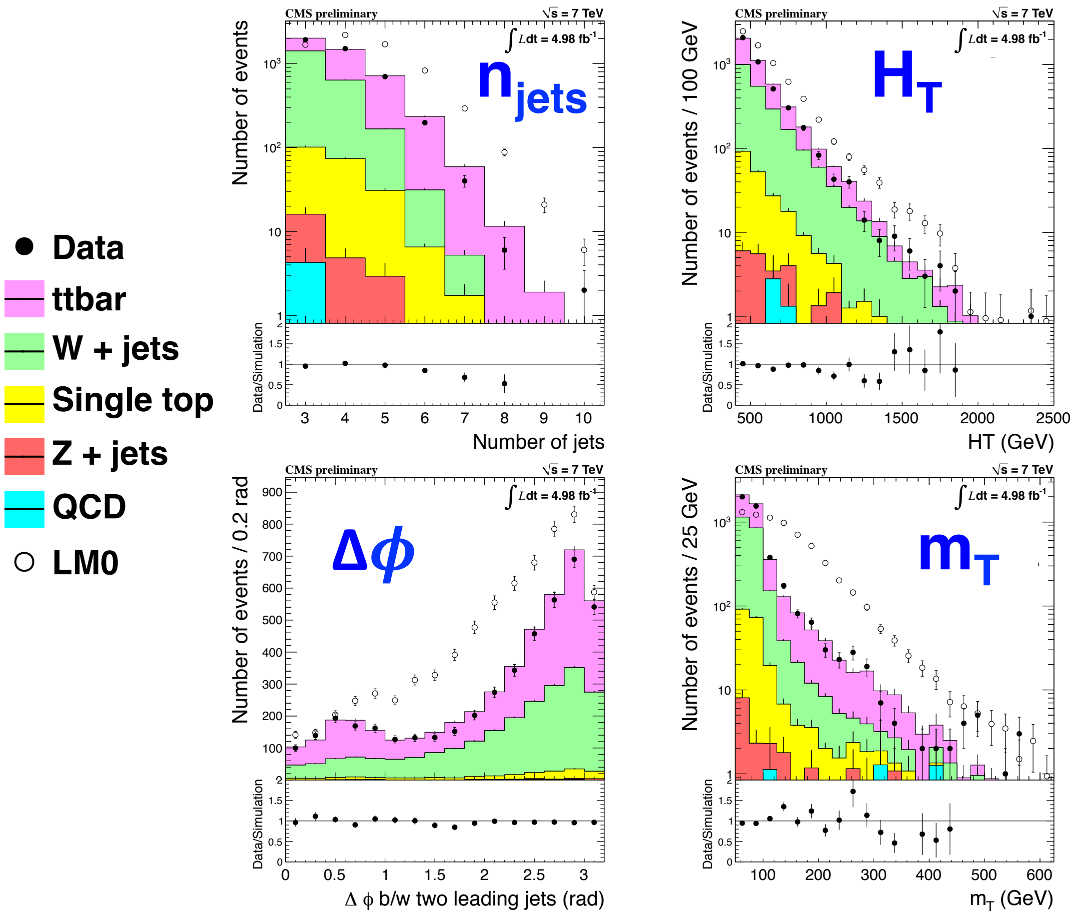
arXiv: http://arxiv.org/abs/1204.3774

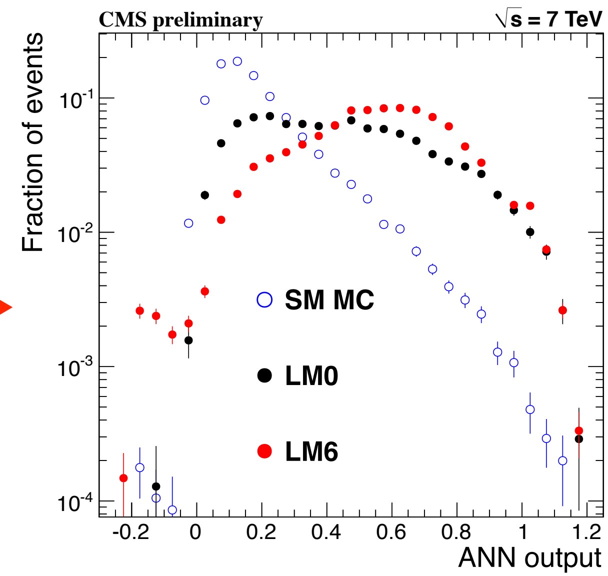
public twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS11021

Additional Material

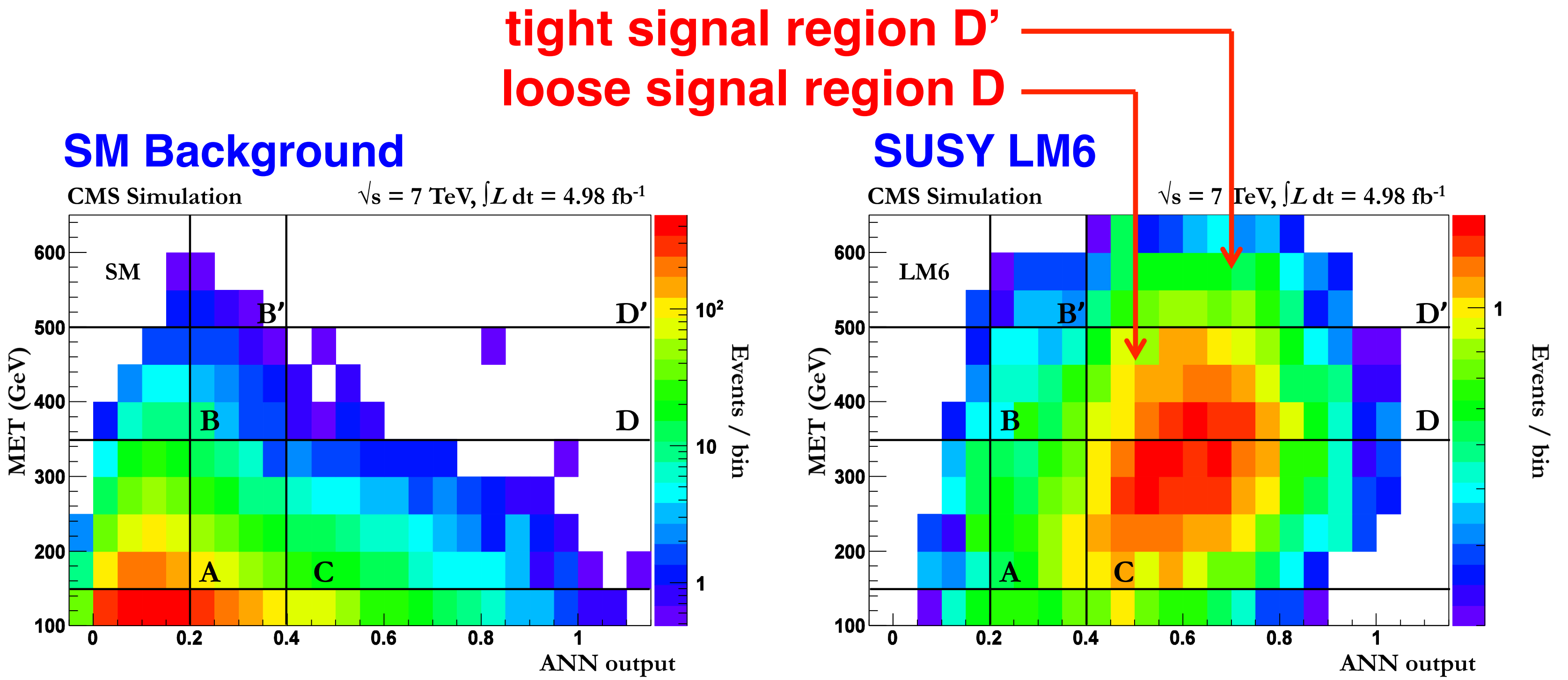
1-lep: ANN Introduction

- Strategy: combine variables into **A**rtificial **N**eural **N**etwork
  - **n_{jets}, H_T, $\Delta\phi(jet_1,jet_2)$, $m_T(\ell,MET)$**
- Train ANN LM0 vs. SM bkg → **good SUSY vs. bkg discrimination**





1-lep: ANN Background Estimate



- ANN and MET are weakly correlated for SM background → predict background in signal regions using ABCD technique:

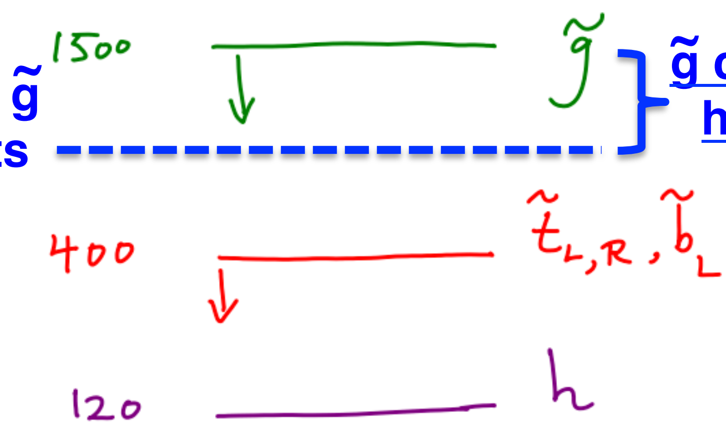
$$D_{pred}\ (\text{loose}) = B \times C / A$$
$$D'_{pred}\ (\text{tight}) = B' \times C / A$$

Ongoing/Future Directions (1)

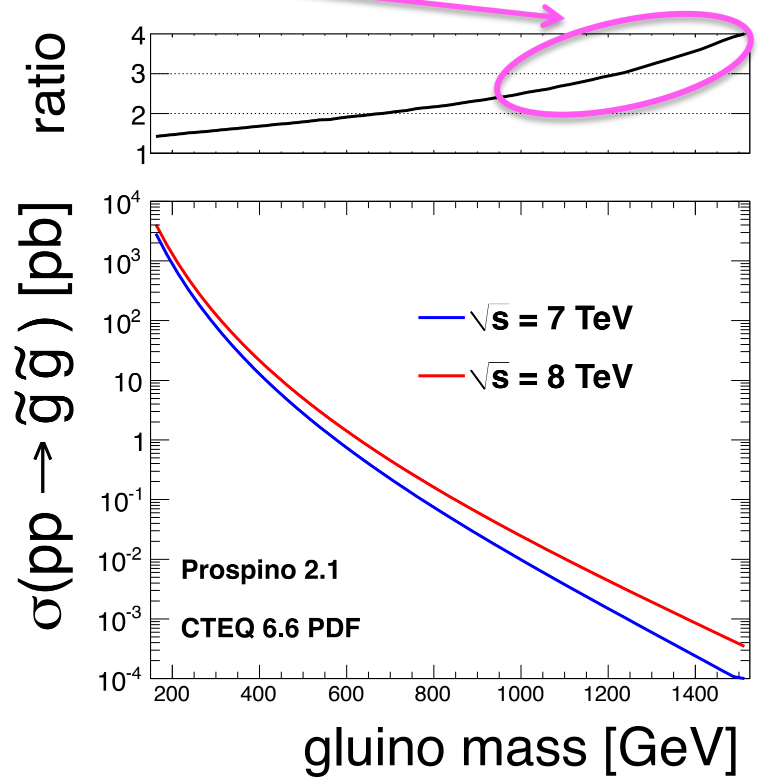
- 2011 results probe gluinos up to ~800 GeV – 1 TeV
  - Especially all-hadronic searches (see talk K. Hatakeyama)
- Naturalness ➞ m($\tilde{g}$) < ~1.5 TeV [1] ➞ **still far more ground to cover**
  - Expect ~10-20 fb^{-1} 8 TeV data in 2012 ➞ **~×2-4 increase in gluino pair production cross section in ~1-1.5 TeV range**

Compulsory Natural SUSY

2011 $\tilde{g}$ limits



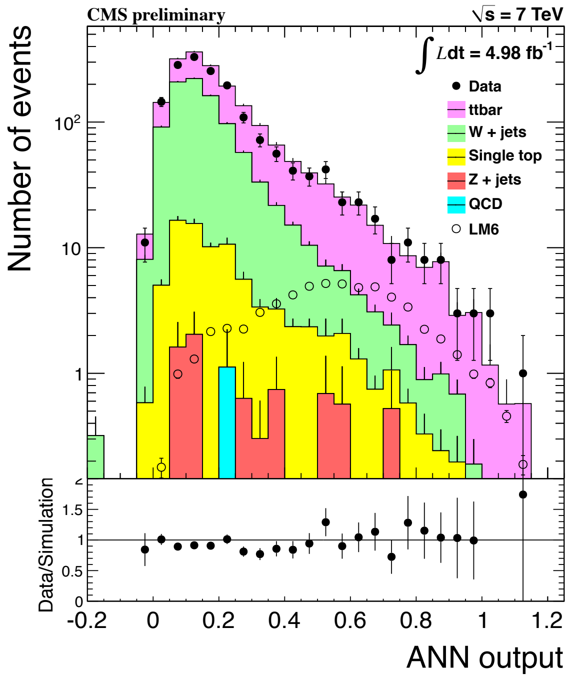
$\tilde{g}$ could still be hiding here!



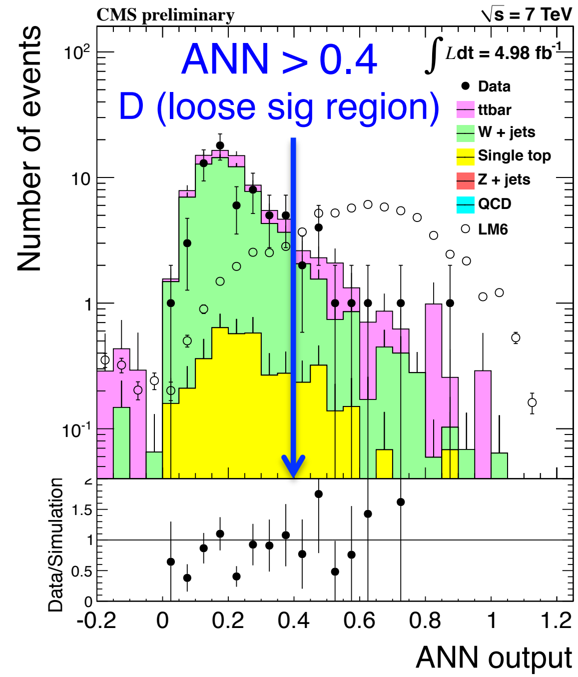
[1] N. Arkani Hamed
https://indico.cern.ch/getFile.py/access?contribId=7&sessionId=2&resId=0&materialId=slides&confId=157244

1-lep: ANN Results

MET 150-350 GeV (control region)



MET > 350 GeV (signal region)



- ANN well-described by MC in low MET control region & high MET signal region
- Good agreement data vs. prediction in signal regions → **no evidence for SUSY**

Signal Region	Predicted	Observed
D (loose): MET > 350 GeV, ANN > 0.4	9.5 ± 2.2	10
D' (tight): MET > 500 GeV, ANN > 0.4	0.7 ± 0.5	1

Ongoing/Future Directions (1)

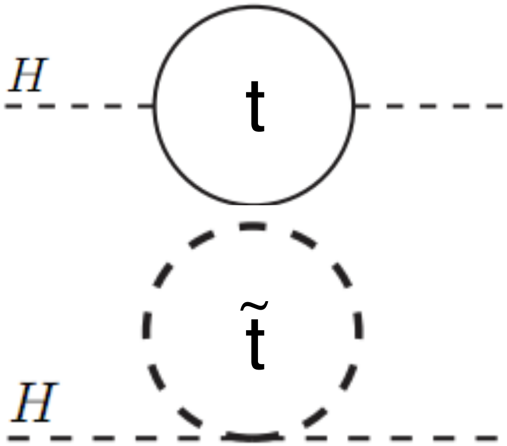
- So far, focused on "low-hanging fruit" → BSM physics with large σ, large MET and H_T
- Haven't found SUSY/BSM physics in ~5 fb^{-1} → where might it be hiding?
  - Electroweak production (e.g. SUSY gauginos)
    - Smaller σ → becomes relevant with large luminosity
    - Target by relaxing/removing jets/H_T requirements
  - Models without WIMP's (e.g. R-parity violating SUSY)
    - Target by relaxing/removing MET requirements
  - Compressed spectra
    - 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.

- Targeted searches into sub-categories, eg. n(b-tags)

Ongoing/Future Directions (2)

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



- **Direct stop pair production, eg:**

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

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

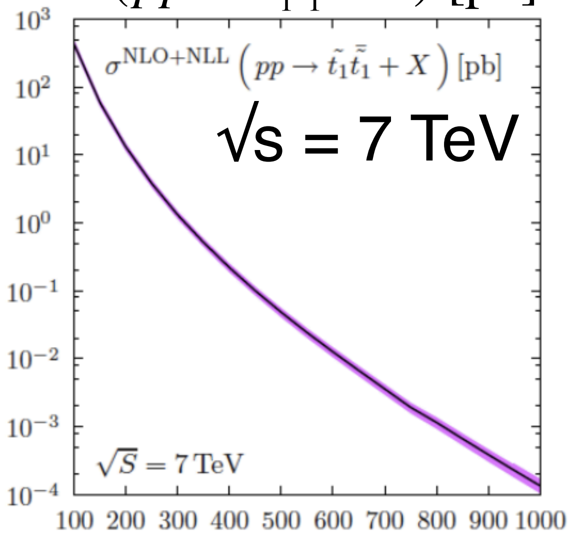
  - **Expect few × 10^2 stop pairs in ~5 fb^{-1}**
  - 2 W's → large BF to single lepton final state

- **Stops from gluinos (see talk K. Ulmer), eg:**

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

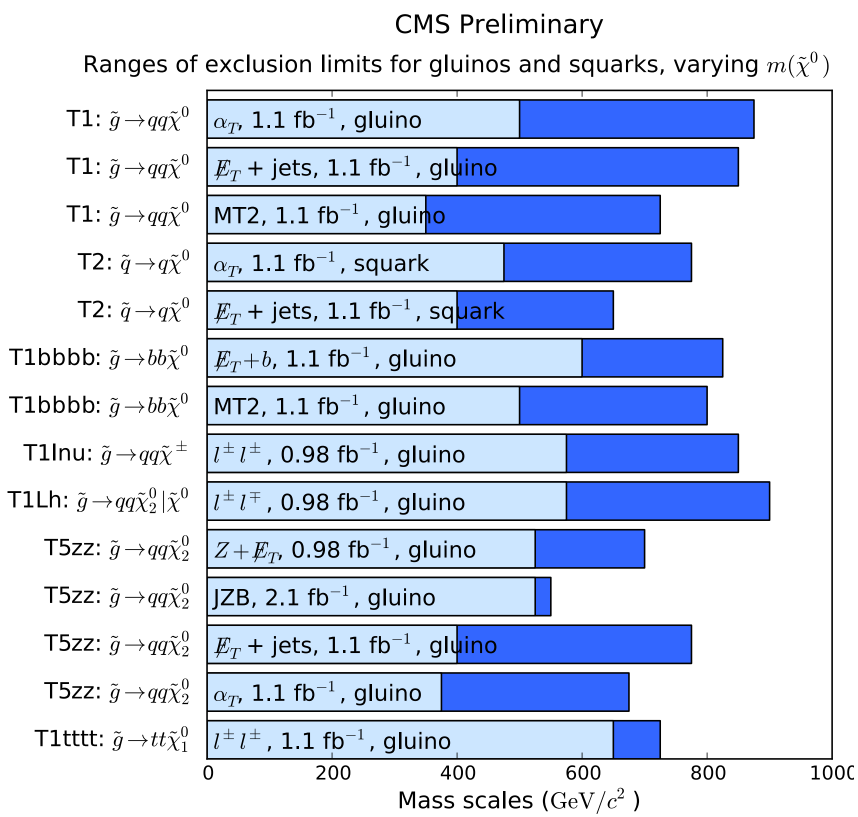
  - 4 tops! → lepton(s) + (b-)jets + MET

$\sigma(pp \to \tilde{t}_1\tilde{t}_1 + X)$ [pb]

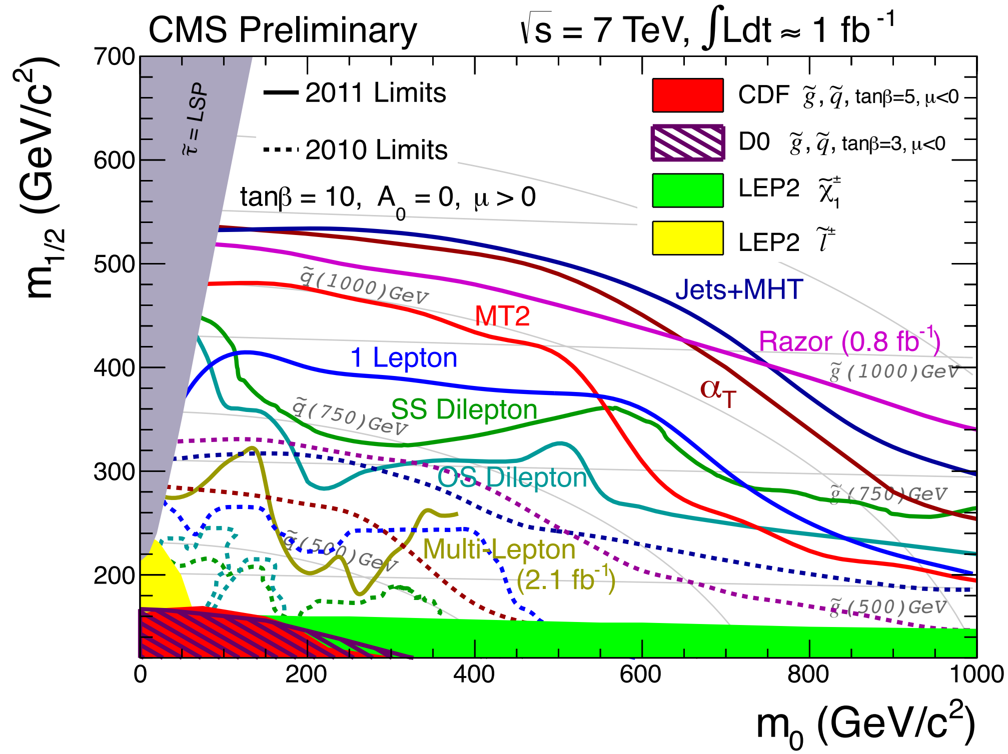


http://arxiv.org/pdf/1006.4771 stop mass (GeV)

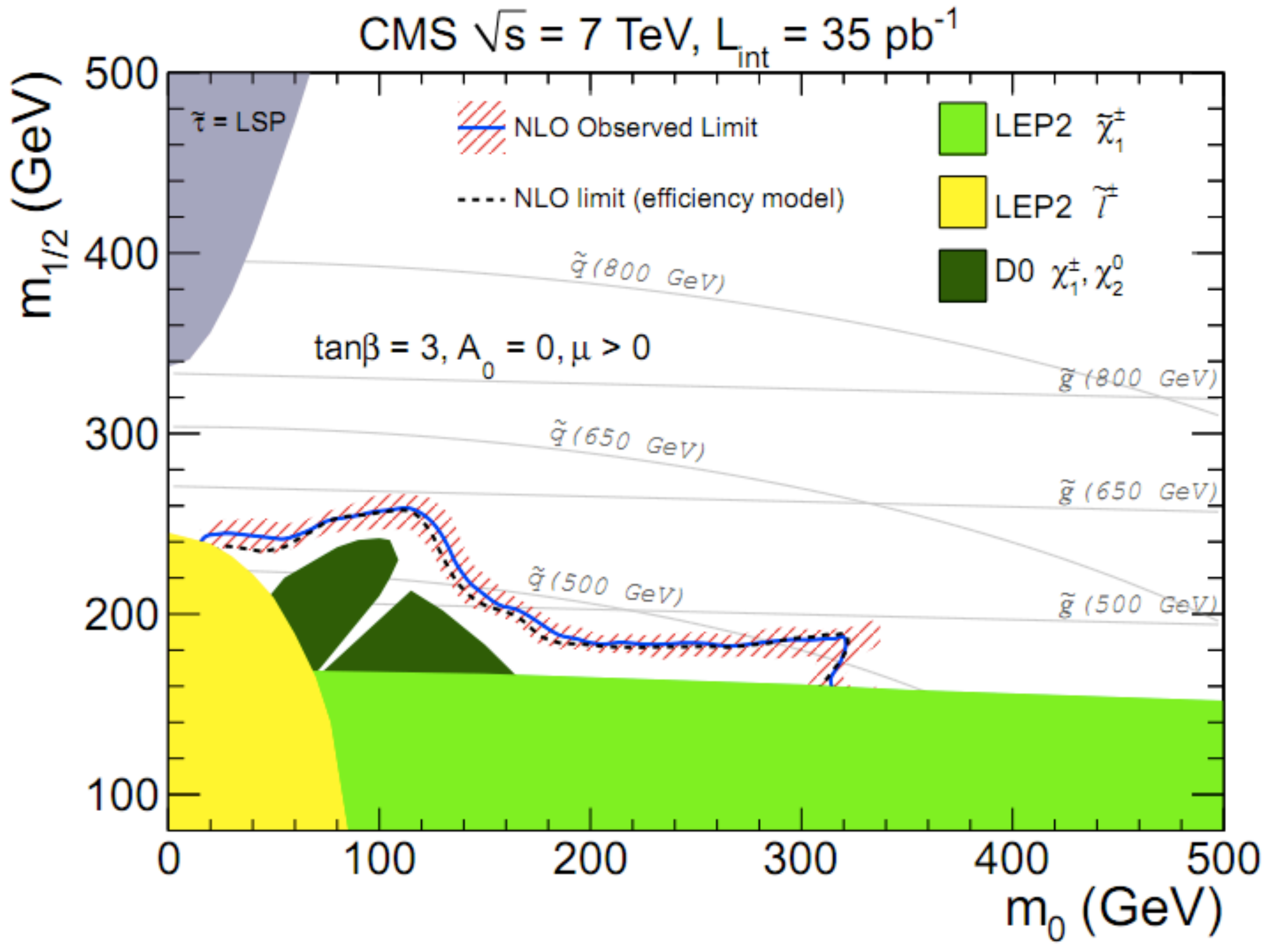
Summary: 1 fb^{-1} SUSY Results



For limits on $m(\tilde{g}), m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{\rm prod} = \sigma^{\rm NLO-QCD}$.
$m(\tilde{\chi}^{\pm}), m(\tilde{\chi}^0_2) \equiv \frac{m(\tilde{g})+m(\tilde{\chi}^0)}{2}$.
$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})-200$ GeV/c^2 (light blue).



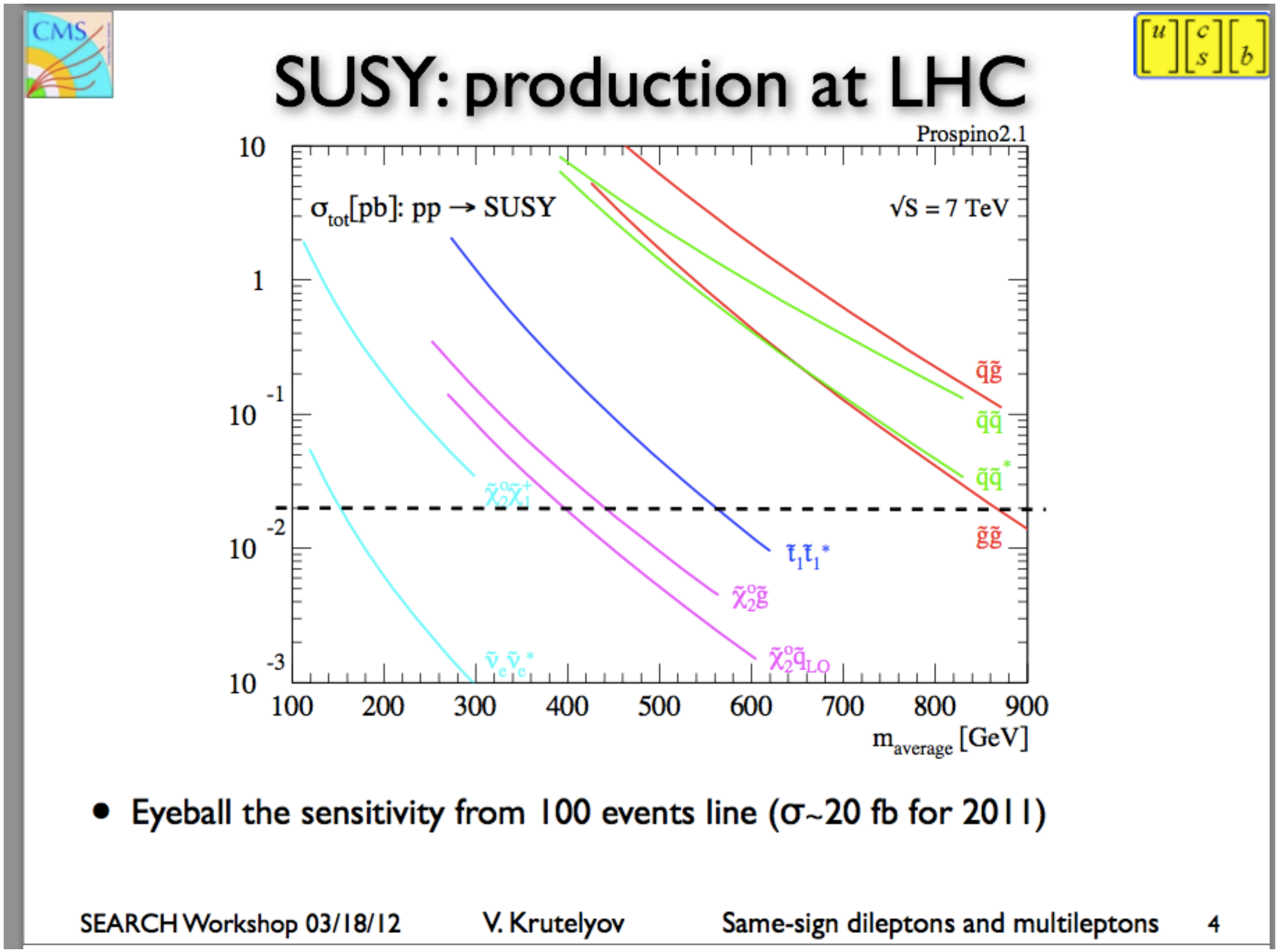
CMSSM Limits



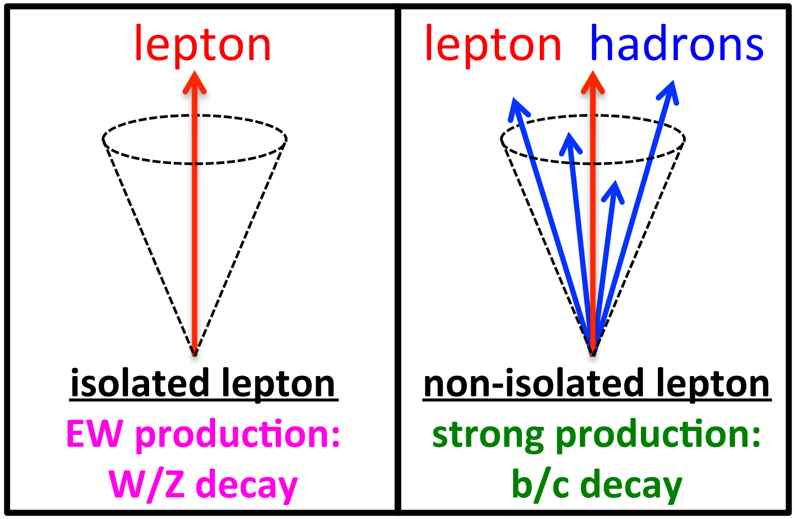
- CMSSM limit from efficiency model agrees well with limit from CMS MC

Expected Cross Sections

V. Krutelyov SEARCH

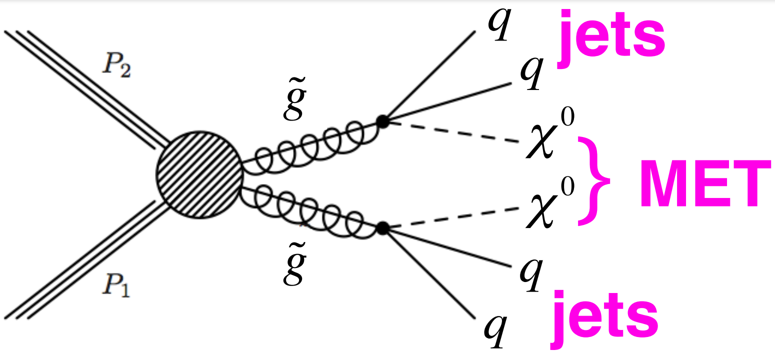


Motivation



- Why search for BSM physics with ***isolated*** leptons?
  - **BACKGROUND SUPPRESSION** (compared to all-hadronic searches)
    - **Requiring isolated lepton(s) suppresses: QCD, Z(νν)+jets, W(ℓν)+jets**
    - Reduced bkg allows looser eg. MET, H_T requirements → ***explore phase space complementary to all-hadronic searches***
  - Leptons provide additional kinematic info related to new particle masses
    - Example: search for $M(\ell^+\ell^-)$ kinematic edge

Overview of Analyses



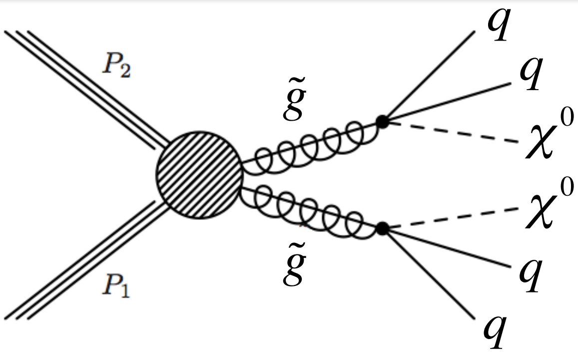
all-hadronic (jets + MET)

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

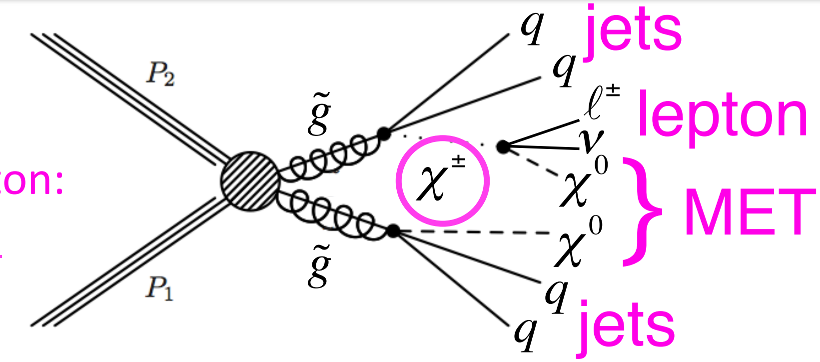
challenge: QCD suppression/modeling

NOT COVERED IN THIS TALK

Overview of Analyses



require isolated lepton:
suppress QCD/Z(νν)

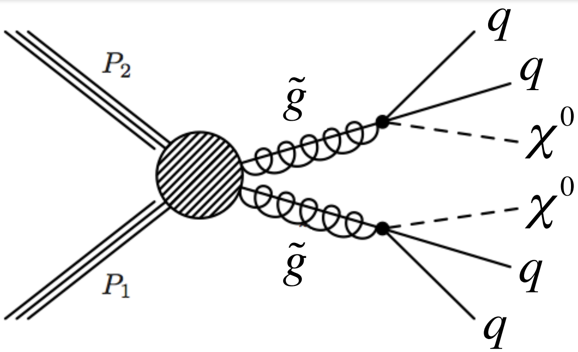


all-hadronic (jets + MET)
bkgs: QCD, Z(νν)+jets, W(ℓν)+jets, ttbar
challenge: QCD suppression/modeling

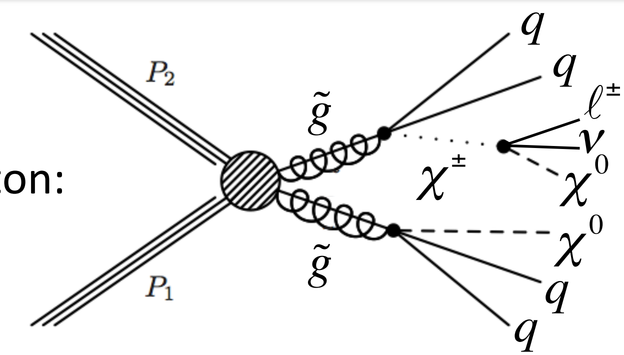
single-lepton (e/μ + jets + MET)
bkgs: W(ℓν)+jets, tt→ℓ+jets
challenge: estimating dominant W/ttbar

THIS TALK

Overview of Analyses



require isolated lepton:
suppress QCD

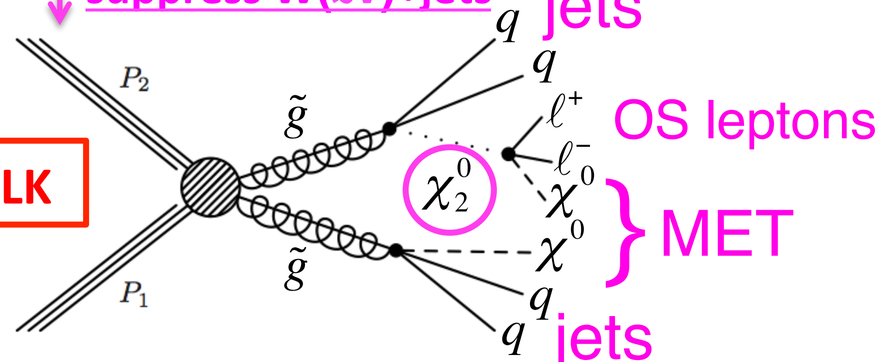


all-hadronic (jets + MET)
bkgs: QCD, Z(νν)+jets, W(ℓν)+jets, ttbar
challenge: QCD suppression/modeling

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

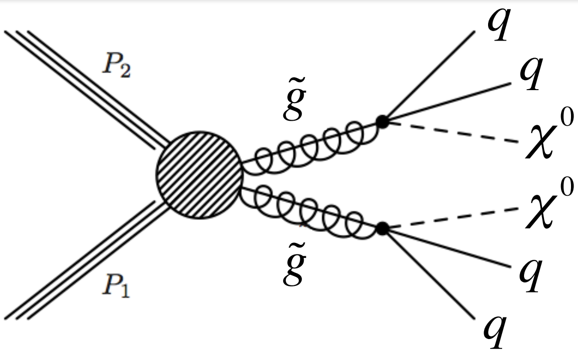
require 2nd OS lepton:
suppress W(ℓν)+jets

THIS TALK

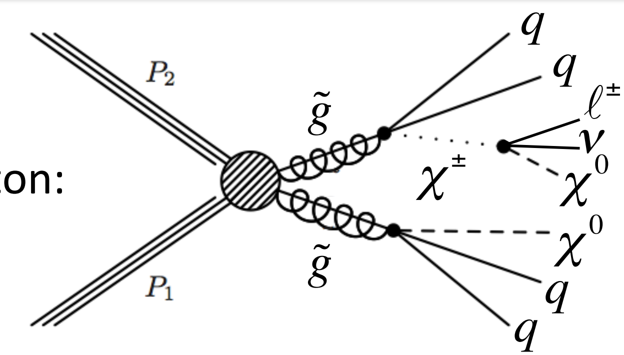


opposite-sign leptons (ℓ⁺ℓ⁻ + jets + MET)
bkgs: tt→ℓ⁺ℓ⁻
challenge: estimating "tails" of tt→ℓ⁺ℓ⁻

Overview of Analyses



require isolated lepton:
suppress QCD

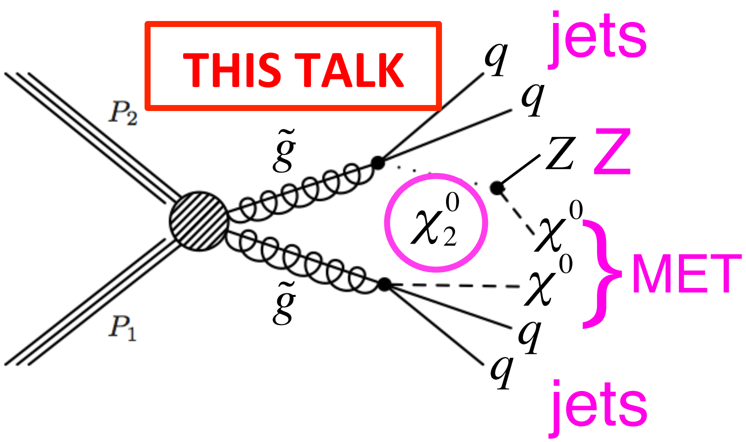


all-hadronic (jets + MET)
bkgs: QCD, Z(νν)+jets, W(ℓν)+jets, ttbar
challenge: QCD suppression/modeling

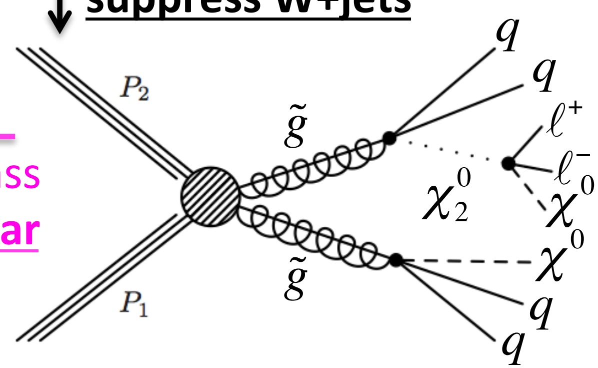
single-lepton (e/μ + jets + MET)
bkgs: W(ℓν)+jets, tt→ℓ+jets
challenge: estimating "tails" of W/ttbar

require 2nd OS lepton:
suppress W+jets

THIS TALK



require Z mass
suppress ttbar

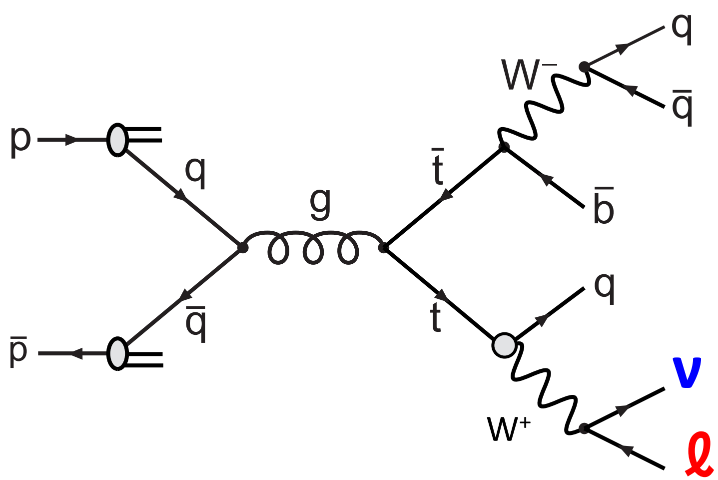


Z boson (Z(ℓℓ) + jets + MET)
bkgs: Z+jets, tt→ℓ+ℓ-
challenge: understanding MET in Z+jets

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

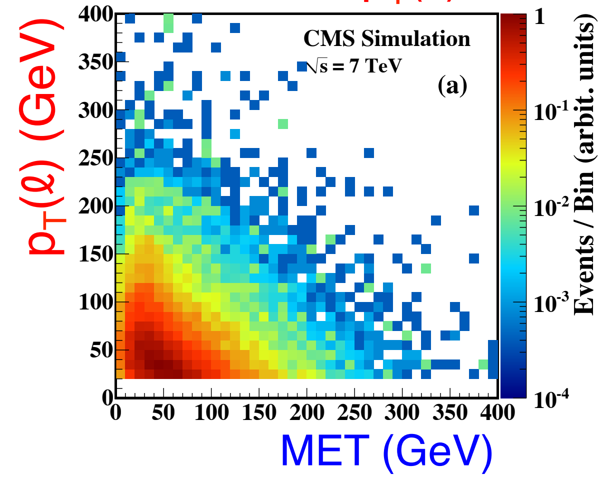
Additional Material

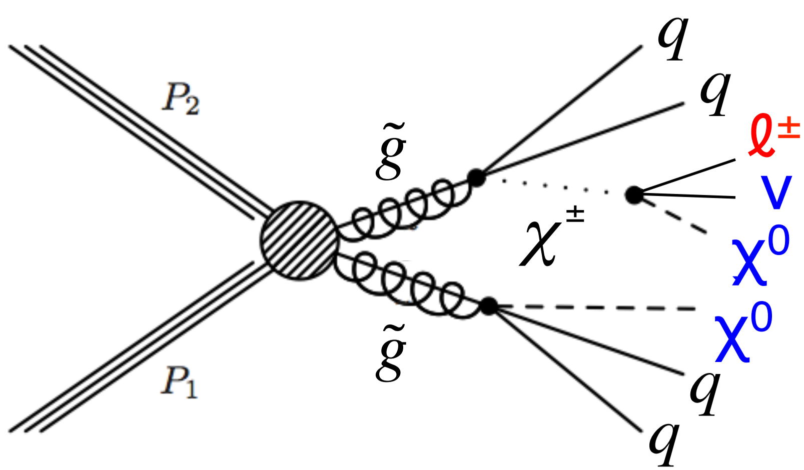
- **1-lepton**
- OS non-Z
- Z
- OS ANN



SM background:

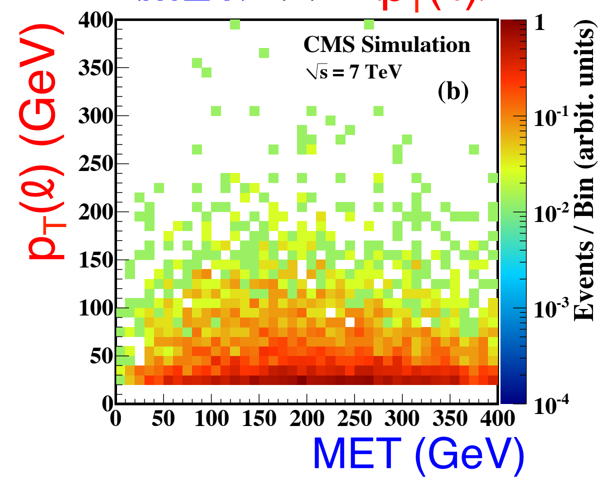
$\langle MET \rangle \sim \langle p_T(\ell) \rangle$





example SUSY signal

$\langle MET \rangle \gg \langle p_T(\ell) \rangle$



Event Selection

- Triggers: ℓ + jets + MET
- Jets ($p_T > 40$ GeV, $|\eta| < 2.4$, anti-kt 0.5) and MET reconstructed with particle flow algo
  - njets ≥ 4 (lepton-spectrum), ≥3 (lepton-polarization)
- Require primary vertex $|z| < 24$ cm, $|\rho| < 2$ cm
- Electrons
  - $p_T > 20$ GeV, $|\eta| < 1.4$, $1.6 < |\eta| < 2.4$
  - Combined relative isolation < 0.07 (barrel) and 0.06 (endcap)
  - $|d_0| < 0.02$ cm, $|d_z| < 1$ cm
  - Reject electrons from conversion (partner track passing dist, dcot(θ) cuts)
- Muons
  - $p_T > 20$ GeV, $|\eta| < 2.1$
  - Combined relative isolation < 0.1
  - $|d_0| < 0.02$ cm, $|d_z| < 1$ cm
- Veto 2nd lepton $p_T > 15$ GeV, reliso < 0.15, $|d_0| < 0.1$ cm

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

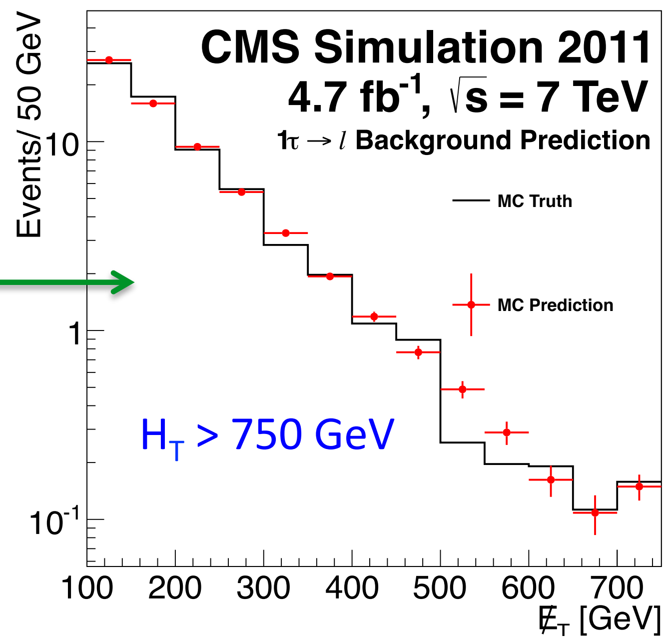
- For W+jets, theory calculates W polarization to NLO and helicity fractions stable with respect to QCD corrections. Experimental measurement at CMS (based on the L_P variable used in this SUSY search) consistent with theory.

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

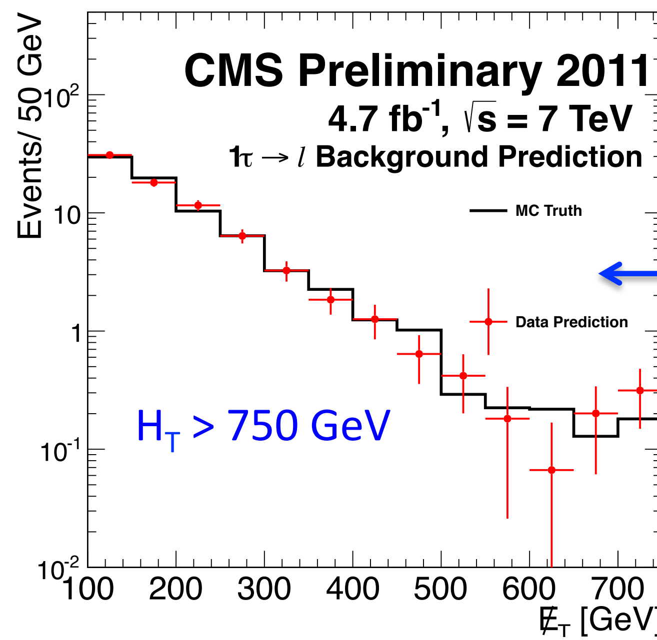
Lepton-Spectrum: τ → ℓ Bkg Estimate

- **Estimate background from W→τ→ℓ (either in ttbar or W+jets)**
- Select single lepton control sample: μ + jets
- Replace μ with expected τ response (from MC), scale by BF(τ→e/μ)
- Apply corrections & syst. uncertainties from MC closure studies
- Data-driven prediction in reasonable agreement with MC

MC closure test



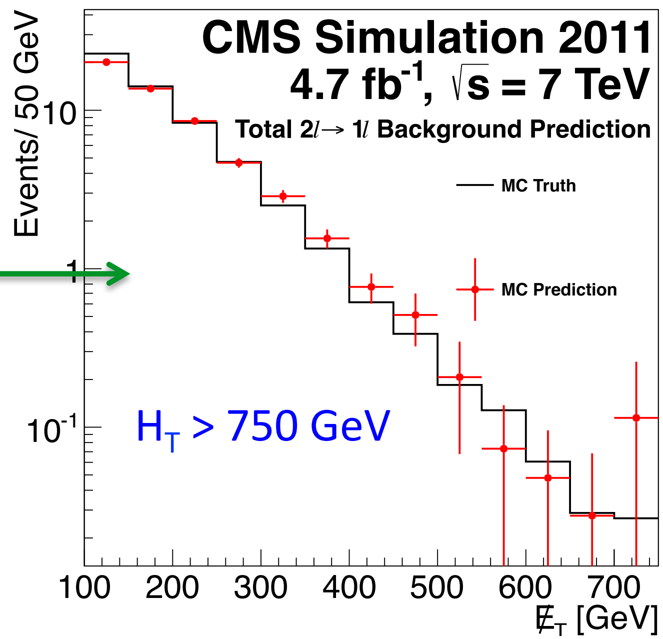
data prediction vs. MC



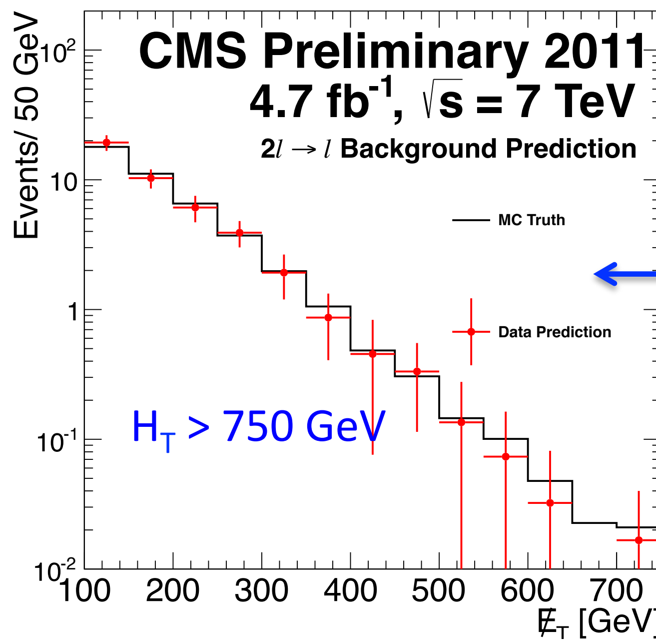
Lepton-Spectrum: $\ell^+\ell^-$ Bkg Estimate

- **Estimate background from tt→$\ell^+\ell^-$, several contributions:**
- "Lost/ignored" e/μ lepton (2nd lepton outside acceptance or doesn't pass reco/ID/iso requirements):
  - Estimate from MC, normalize to data in dilepton data control sample
- ℓ + τ(hadrons) OR ℓ + τ(e/μ):
  - Select dilepton data control sample, replace lepton with simulated leptonic/hadronic τ response scaled by BF(τ→hadrons) and BF(τ→e/μ)
- Correction factors and syst. uncertainties from MC closure studies
- Data-driven prediction in reasonable agreement with MC

MC closure test



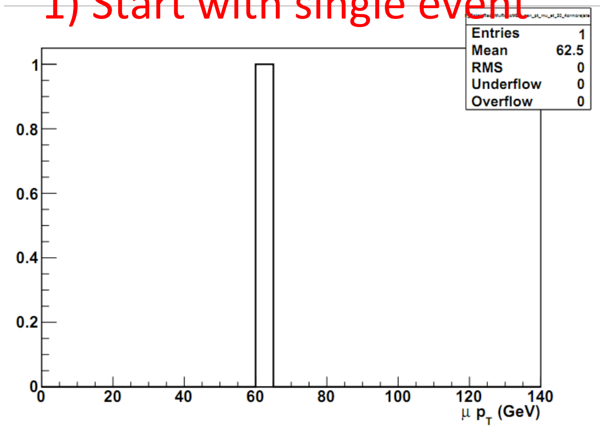
data prediction vs. MC



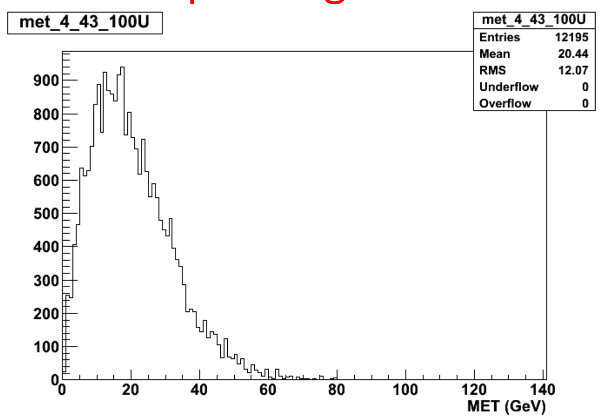
MET resolution: smearing $p_T(\mu)$

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

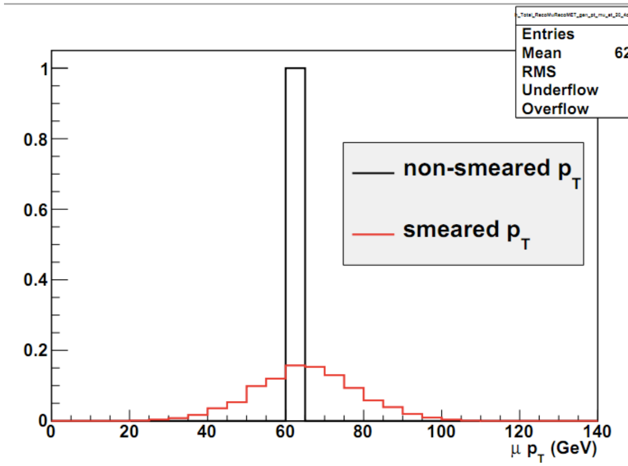
1) Start with single event



2) Find MET template corresponding to event HT

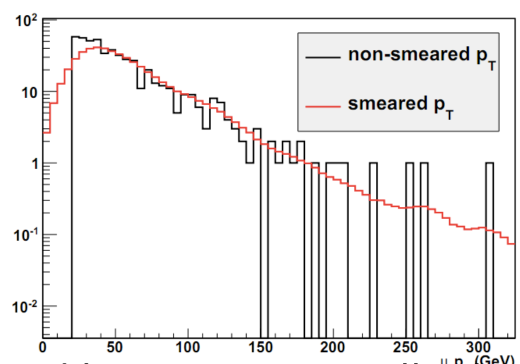


3) Smear μ pT using MET template



turn single event into 1000 events with weight 1/1000

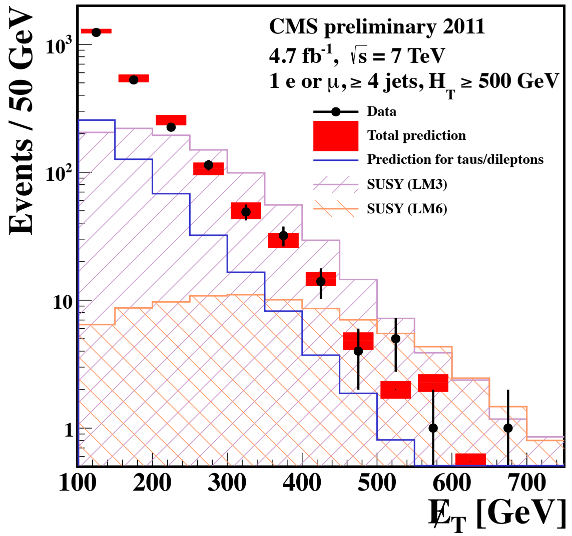
Final result: smeared μ pT distribution (10-15% effect)



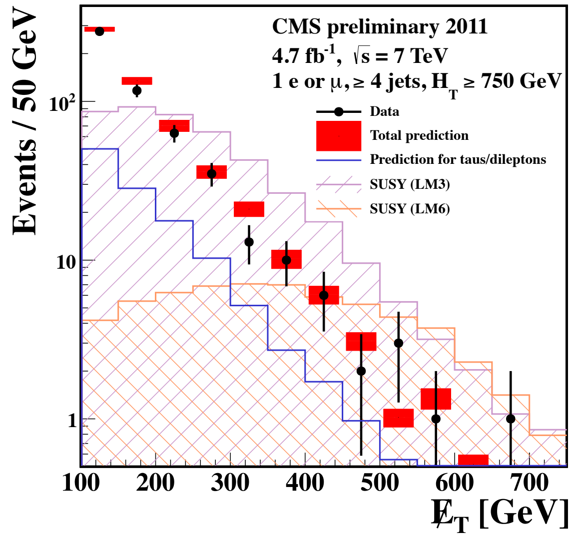
MET prediction is sum of smeared lepton pT over all 1-lepton events

Lepton-Spectrum Results

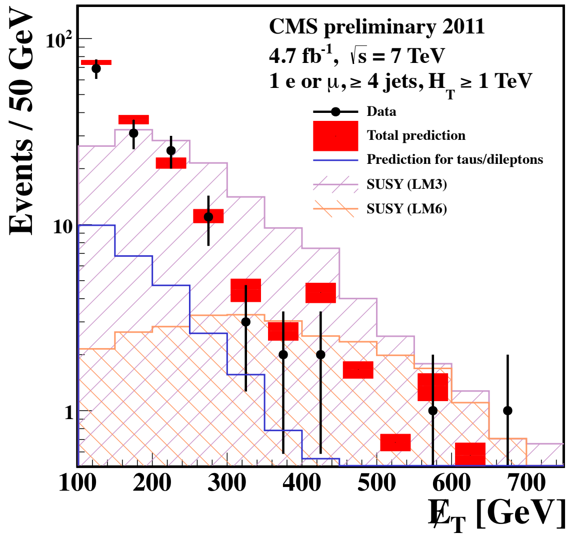
H_T > 500 GeV



H_T > 750 GeV



H_T > 1000 GeV



Lepton-Spectrum Results

H_T > 500 GeV results

$\not{E}_T$:	[250; 350)	[350; 450)	[450; 550)	$\geq$ 550 GeV
MC:				
1 l	137.0 ± 2.0	32.5 ± 1.0	7.9 ± 0.5	2.7 ± 0.3
Dilepton	18.6 ± 0.5	3.5 ± 0.2	0.7 ± 0.1	0.3 ± 0.1
1 τ	28.6 ± 0.9	7.4 ± 0.5	1.9 ± 0.2	0.8 ± 0.2
Z+jets	1.2 ± 0.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Total SM (MC)	185.4 ± 2.3(stat)	43.4 ± 1.1(stat)	10.5 ± 0.6(stat)	3.7 ± 0.4(stat)
SUSY LM3 (MC)	254.8 ± 3.5(stat)	217.9 ± 3.5(stat)	146.0 ± 2.7(stat)	117.1 ± 2.4(stat)
SUSY LM6 (MC)	21.9 ± 0.3(stat)	18.7 ± 0.3(stat)	12.5 ± 0.2(stat)	10.0 ± 0.2(stat)
Data-driven prediction:				
1 l	109.1 ± 13.4 ± 17.5	32.1 ± 7.5 ± 5.8	3.9 ± 2.6 ± 1.3	3.1 ± 2.3 ± 1.0
Dilepton	15.8 ± 1.9 ± 1.8	3.0 ± 0.9 ± 0.5	0.5 ± 0.3 ± 0.2	0.1 ± 0.2 ± 0.2
1 τ	33.0 ± 1.8 ± 1.7	8.9 ± 1.0 ± 0.5	2.1 ± 0.5 ± 0.2	1.1 ± 0.3 ± 0.2
QCD	0.0 ± 1.2 ± 1.2	0.0 ± 1.2 ± 1.2	0.0 ± 1.2 ± 1.2	0.0 ± 1.2 ± 1.2
Z+jets	1.2 ± 0.8 ± 1.2	0.0 ± 0.0 ± 0.0	0.0 ± 0.0 ± 0.0	0.0 ± 0.0 ± 0.0
Total (predicted):	159.1 ± 13.8 ± 17.8	44.0 ± 7.7 ± 6.0	6.6 ± 3.0 ± 1.8	4.3 ± 2.6 ± 1.6
Data (observed):	163 (84, 79)	46 (21, 25)	9 (8, 1)	2 (1, 1)

H_T > 750 GeV results

$\not{E}_T$:	[250; 350)	[350; 450)	[450; 550)	$\geq$ 550 GeV
MC:				
1 l	44.1 ± 1.1	13.9 ± 0.7	5.0 ± 0.4	2.5 ± 0.3
Dilepton	7.7 ± 0.3	2.2 ± 0.2	0.6 ± 0.1	0.2 ± 0.1
1 τ	8.6 ± 0.5	2.8 ± 0.3	1.1 ± 0.2	0.6 ± 0.1
Z+jets	0.7 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Total SM (MC)	61.1 ± 1.4(stat)	18.9 ± 0.8(stat)	6.7 ± 0.5(stat)	3.4 ± 0.3(stat)
SUSY LM3 (MC)	162.6 ± 2.8(stat)	149.8 ± 2.7(stat)	112.4 ± 2.4(stat)	107.0 ± 2.3(stat)
SUSY LM6 (MC)	13.9 ± 0.2(stat)	12.8 ± 0.2(stat)	9.6 ± 0.2(stat)	9.2 ± 0.2(stat)
Data-driven prediction:				
1 l	41.7 ± 8.7 ± 5.4	11.7 ± 5.0 ± 1.9	2.6 ± 2.3 ± 0.6	3.1 ± 2.4 ± 0.8
Dilepton	5.9 ± 1.1 ± 0.7	1.3 ± 0.5 ± 0.2	0.5 ± 0.2 ± 0.1	0.1 ± 0.1 ± 0.3
1 τ	9.6 ± 0.9 ± 0.6	3.1 ± 0.6 ± 0.3	1.1 ± 0.3 ± 0.2	0.8 ± 0.2 ± 0.1
QCD	0.0 ± 0.5 ± 0.5	0.0 ± 0.5 ± 0.5	0.0 ± 0.5 ± 0.5	0.0 ± 0.5 ± 0.5
Z+jets	0.7 ± 0.5 ± 0.7	0.0 ± 0.0 ± 0.0	0.0 ± 0.0 ± 0.0	0.0 ± 0.0 ± 0.0
Total (predicted):	57.9 ± 8.9 ± 5.6	16.2 ± 5.0 ± 2.0	4.2 ± 2.4 ± 0.8	4.0 ± 2.4 ± 1.0
Data (observed):	48 (27, 21)	16 (7, 9)	5 (4, 1)	2 (1, 1)

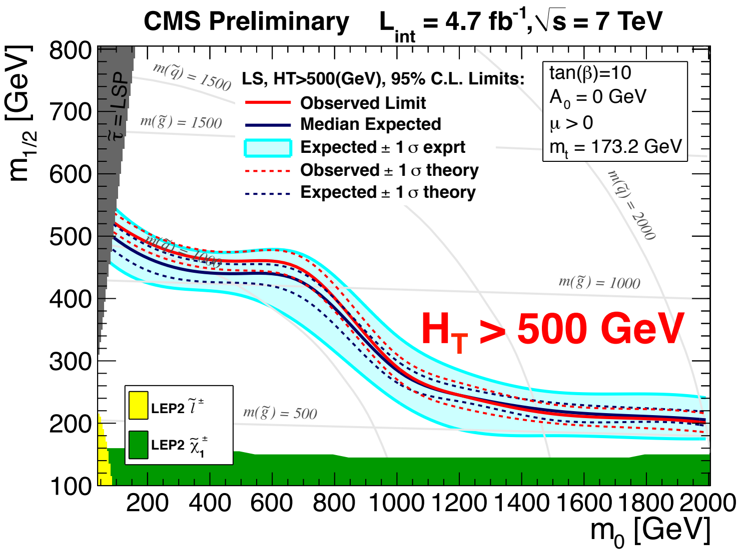
H_T > 1 TeV results

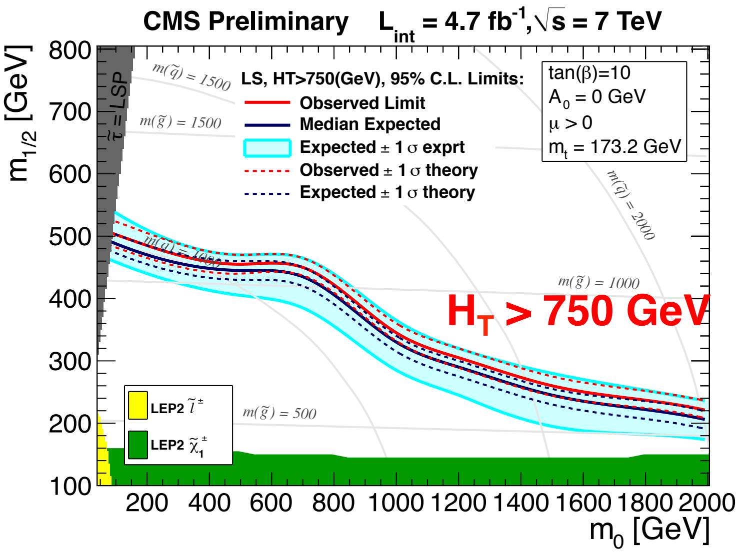
$\not{E}_T$:	[250; 350)	[350; 450)	[450; 550)	$\geq$ 550 GeV
MC:				
1 l	12.5 ± 0.6	4.5 ± 0.4	1.9 ± 0.2	1.2 ± 0.2
Dilepton	2.5 ± 0.2	0.9 ± 0.1	0.3 ± 0.1	0.2 ± 0.0
1 τ	2.0 ± 0.2	0.7 ± 0.1	0.5 ± 0.1	0.4 ± 0.1
Z+jets	0.5 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Total SM (MC)	17.6 ± 0.8(stat)	6.0 ± 0.4(stat)	2.7 ± 0.3(stat)	1.7 ± 0.2(stat)
SUSY LM3 (MC)	76.2 ± 1.9(stat)	64.7 ± 1.8(stat)	50.5 ± 1.6(stat)	56.1 ± 1.7(stat)
SUSY LM6 (MC)	6.5 ± 0.2(stat)	5.6 ± 0.2(stat)	4.3 ± 0.1(stat)	4.8 ± 0.1(stat)
Data-driven prediction:				
1 l	11.7 ± 4.6 ± 1.8	5.5 ± 3.6 ± 1.0	2.0 ± 2.2 ± 0.6	3.1 ± 2.3 ± 1.0
Dilepton	1.2 ± 0.6 ± 0.1	0.4 ± 0.4 ± 0.1	0.2 ± 0.2 ± 0.1	0.1 ± 0.2 ± 0.2
1 τ	3.0 ± 0.5 ± 0.5	0.9 ± 0.3 ± 0.2	0.4 ± 0.2 ± 0.2	0.8 ± 0.2 ± 0.2
QCD	0.0 ± 0.1 ± 0.1	0.0 ± 0.1 ± 0.1	0.0 ± 0.1 ± 0.1	0.0 ± 0.1 ± 0.1
Z+jets	0.5 ± 0.5 ± 0.5	0.0 ± 0.0 ± 0.0	0.0 ± 0.0 ± 0.0	0.0 ± 0.0 ± 0.0
Total (predicted):	16.3 ± 4.7 ± 1.9	6.8 ± 3.6 ± 1.0	2.6 ± 2.2 ± 0.6	4.0 ± 2.4 ± 1.0
Data (observed):	14 (7, 7)	4 (1, 3)	0 (0, 0)	2 (1, 1)

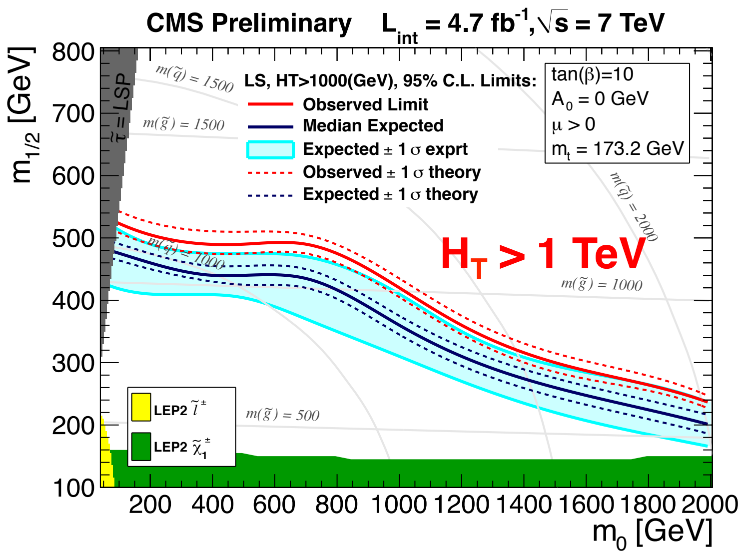
systematic uncertainties

E_T^{miss} :	[250; 350) (%)	[350; 450) (%)	[450; 550) (%)	$\geq$ 550 GeV (%)
$\not{E}_T$ and jet energy scale	11	13	14	16
W polarization in $t\bar{t}$	1	1	1	1
W polarization in W+jets	3	4	12	11
$\sigma(t\bar{t})$ and $\sigma(W)$	1	1	4	4
lepton efficiency (μ) vs. p_T	1	1	1	1
lepton efficiency (e) vs. p_T	1	1	1	1
Z+jets background	4	4	4	4
μ p_T measurements	1	2	6	2
Total (μ, no K-factors)	12	14	20	20
Total (e, no K-factor)	12	14	20	20
MC statistics (K-factors)	4	7	12	17
Total (μ)	13	16	24	27
Total (e)	13	16	24	27

CMSSM Limits: Lepton-Spectrum







Lepton-Polarization: Results

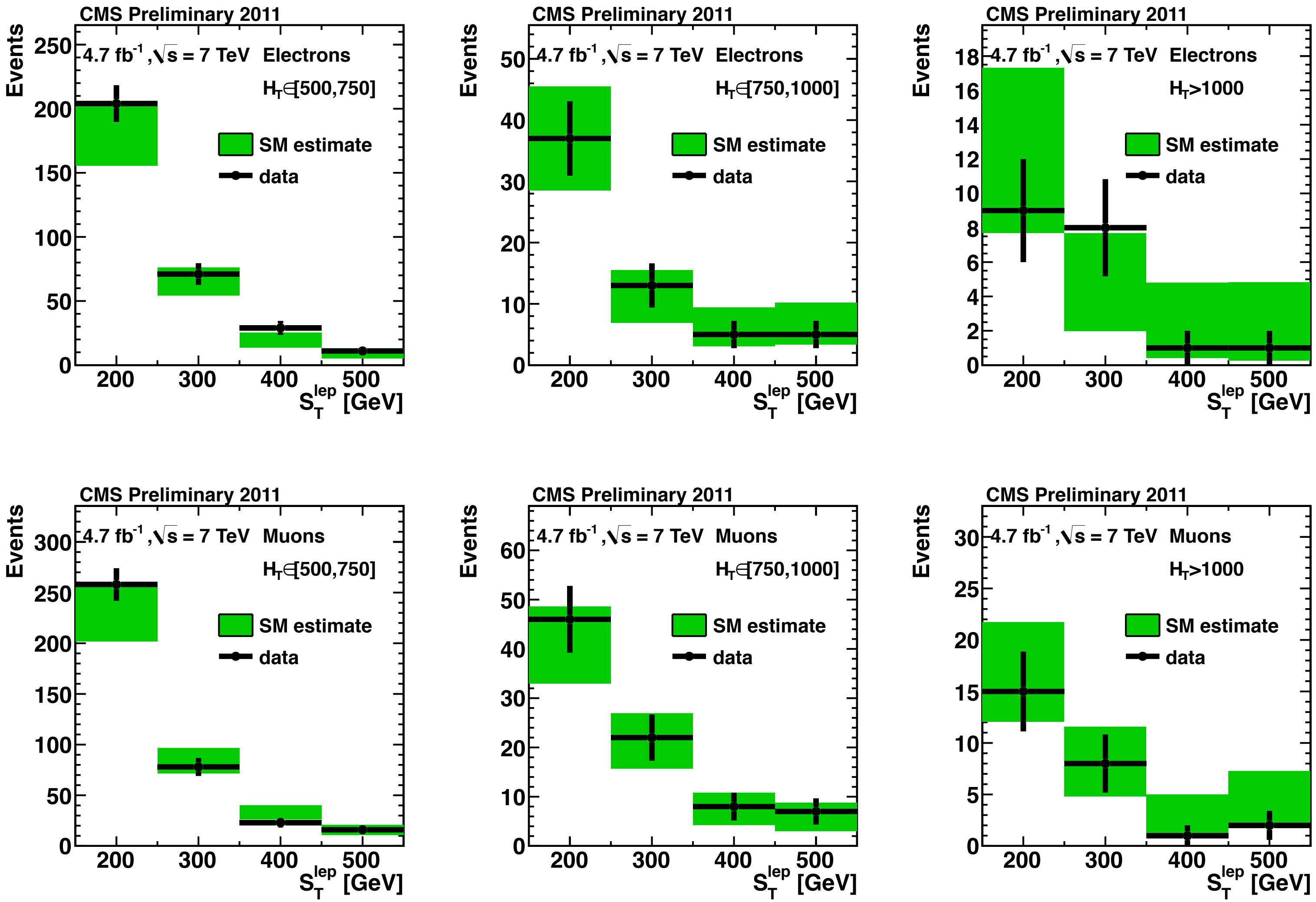
Muon Channel

S_T^{lep} Range (GeV)	Total MC	DATA	Total MC	SM estimate	DATA
	Control Region (L_P >0.3)		Signal Region (L_P <0.15)		
$500 < H_T < 750$ GeV					
[150-250]	1383±10	1297	246±3.0	231±7±24	258
[250-350]	427±4.9	383	93.7±2.0	84.1±4.2±7.3	78
[350-450]	146±2.9	128	37.9±1.3	33.3±3.0±2.6	23
> 450	55.8±1.8	50	17.5±0.9	15.7±2.2±2.0	16
$750 < H_T < 1000$ GeV					
[150-250]	264.4±3.8	218	49.4±1.5	40.8±2.9±3.5	46
[250-350]	86.7±1.9	88	21.0±0.9	21.3±2.3± 2.2	22
[350-450]	32.6±1.3	25	9.8±0.6	7.5±1.5±1.0	8
> 450	25.2±1.3	18	8.3±0.6	5.9±1.4±0.7	7
$1000 \text{ GeV} < H_T$					
[150-250]	87.1±2.3	76	19.3±0.9	16.9±1.9±1.7	15
[250-350]	31.0±1.2	31	8.2±0.7	8.2±1.5 ±1.0	8
[350-450]	10.3±0.6	7	4.3±0.4	2.9± 1.1 ± 0.6	1
> 450	11.2±0.7	12	4.3±0.4	4.6±1.4±0.7	2

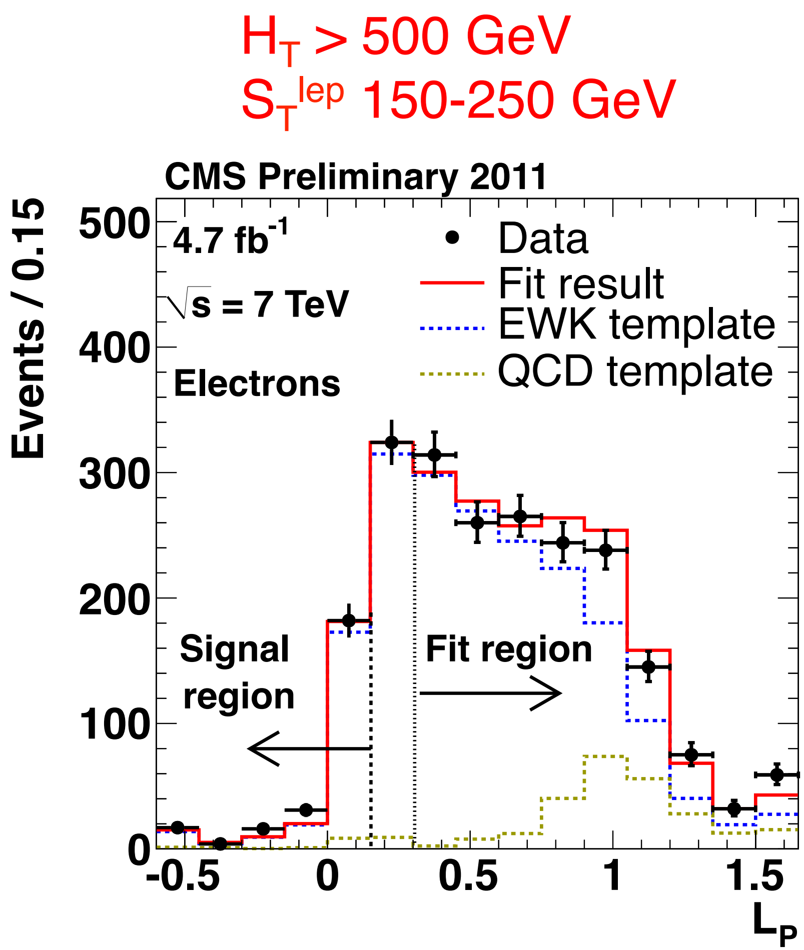
Electron Channel

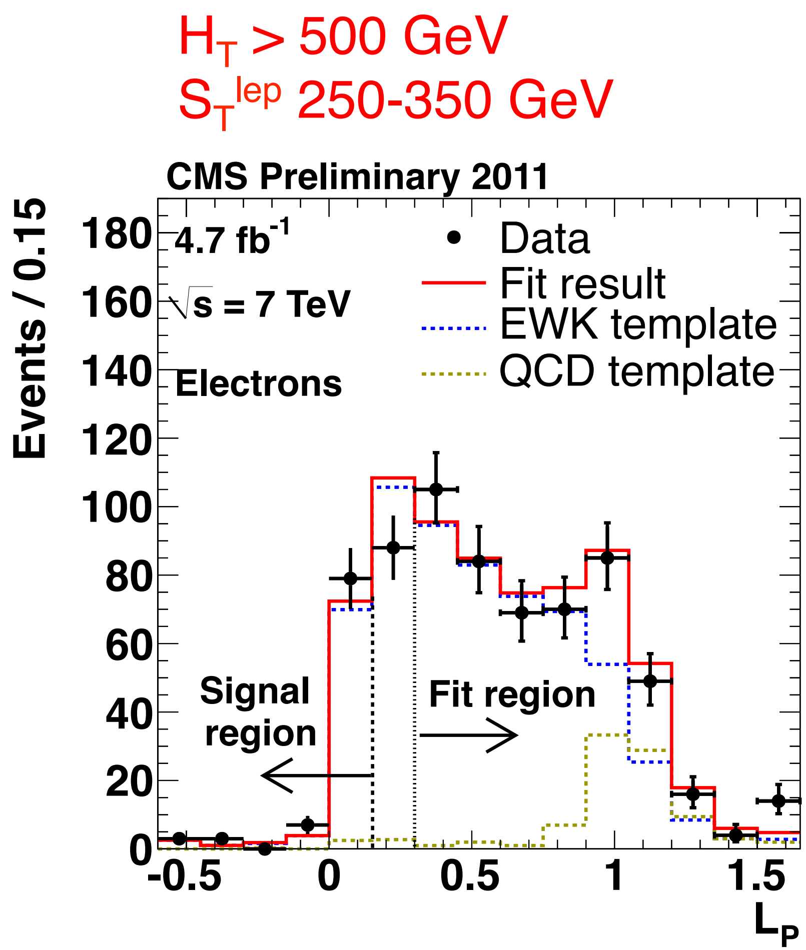
	Control Region (L_P >0.3)			Signal Region (L_P <0.15)			
S_T^{lep} Range (GeV)	QCD	EWK	DATA	QCD	EWK	SM estimate	DATA
$500 < H_T < 750$ GeV							
[150-250]	184±33	1122±45	1306	9.1±1.6	170±7	179±7±18	204
[250-350]	66.3±14.5	334±22	400	2.1±0.5	63.3±4.1	65.3±4.3±5.9	71
[350-450]	26.6±7.6	93.4±11.1	120	0.3±0.1	19.2±2.3	19.4±2.4±2.9	29
> 450	17.1±5.1	33.9±6.6	51	0.2±0.0	9.0±1.8	9.2±1.9±1.7	11
$750 < H_T < 1000$ GeV							
[150-250]	39.3±14.7	210±20	249	1.9±0.7	35.1±3.3	37.0±3.5±4.8	37
[250-350]	5.8±5.5	59.2±9.1	65	0.2±0.2	11.0±1.7	11.2±2.0±1.8	13
[350-450]	0.0±0.0	26.0±5.1	26	0	6.3±1.2	6.3±1.2±1.5	5
> 450	8.7±3.4	22.3±5.0	31	0.1±0.03	6.7±1.5	6.8±1.6±1.5	5
$1000 \text{ GeV} < H_T$							
[150-250]	14.9±7.7	62.1±10.3	77	0.7±0.38	11.7±1.9	12.5±2.2±2.4	9
[250-350]	10.4±4.3	20.6±5.4	31	0.3±0.13	4.5±1.2	4.8±1.5±1.1	8
[350-450]	0.5±1.7	11.5±3.7	12	0	2.6±0.8	2.6±1.2±0.9	1
> 450	4.4±2.5	6.6±2.9	11	0.0±0.02	2.5±1.1	2.6±1.3±0.9	1

Lepton-Polarization: Results

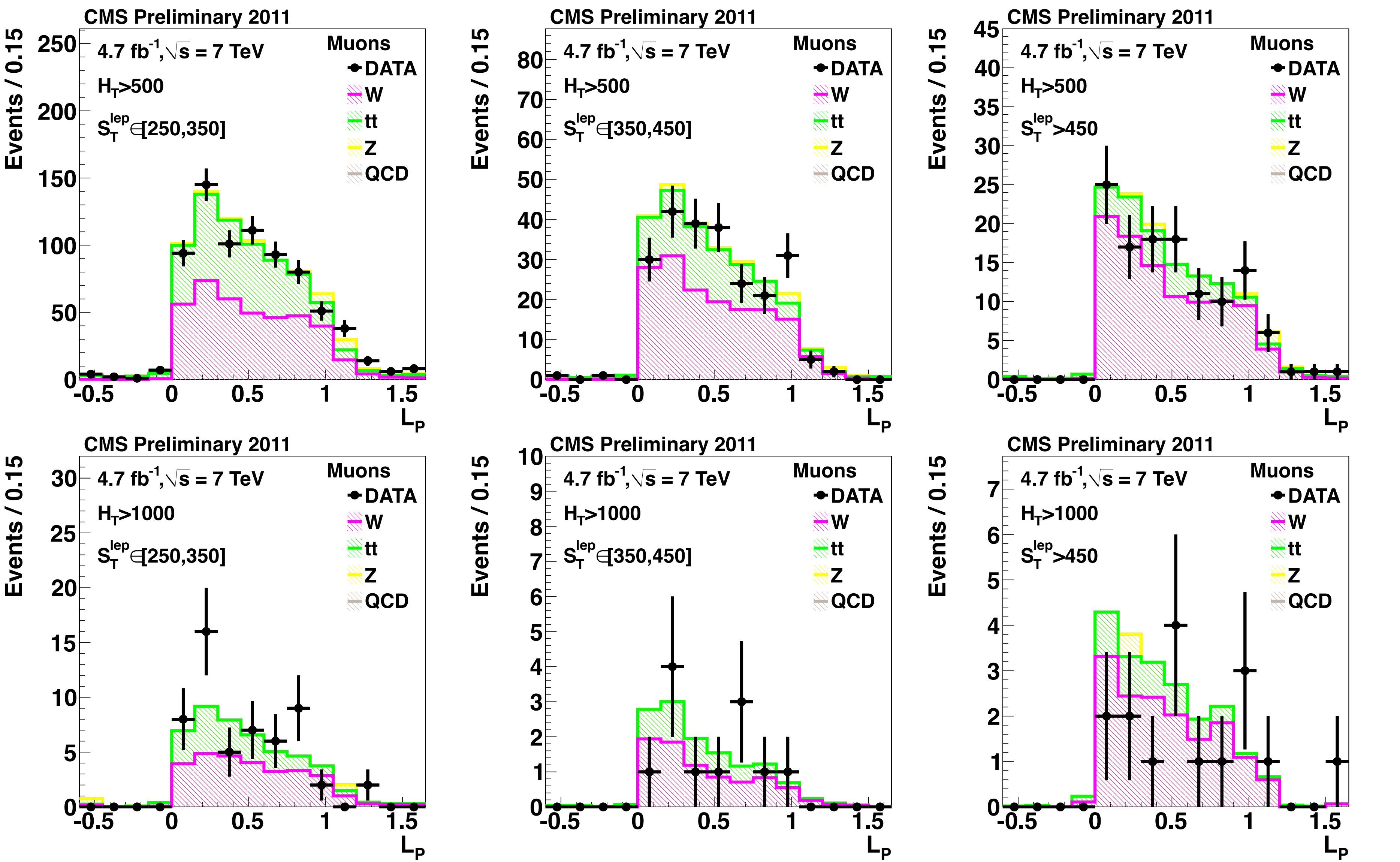


Lepton Polarization: Fit Results

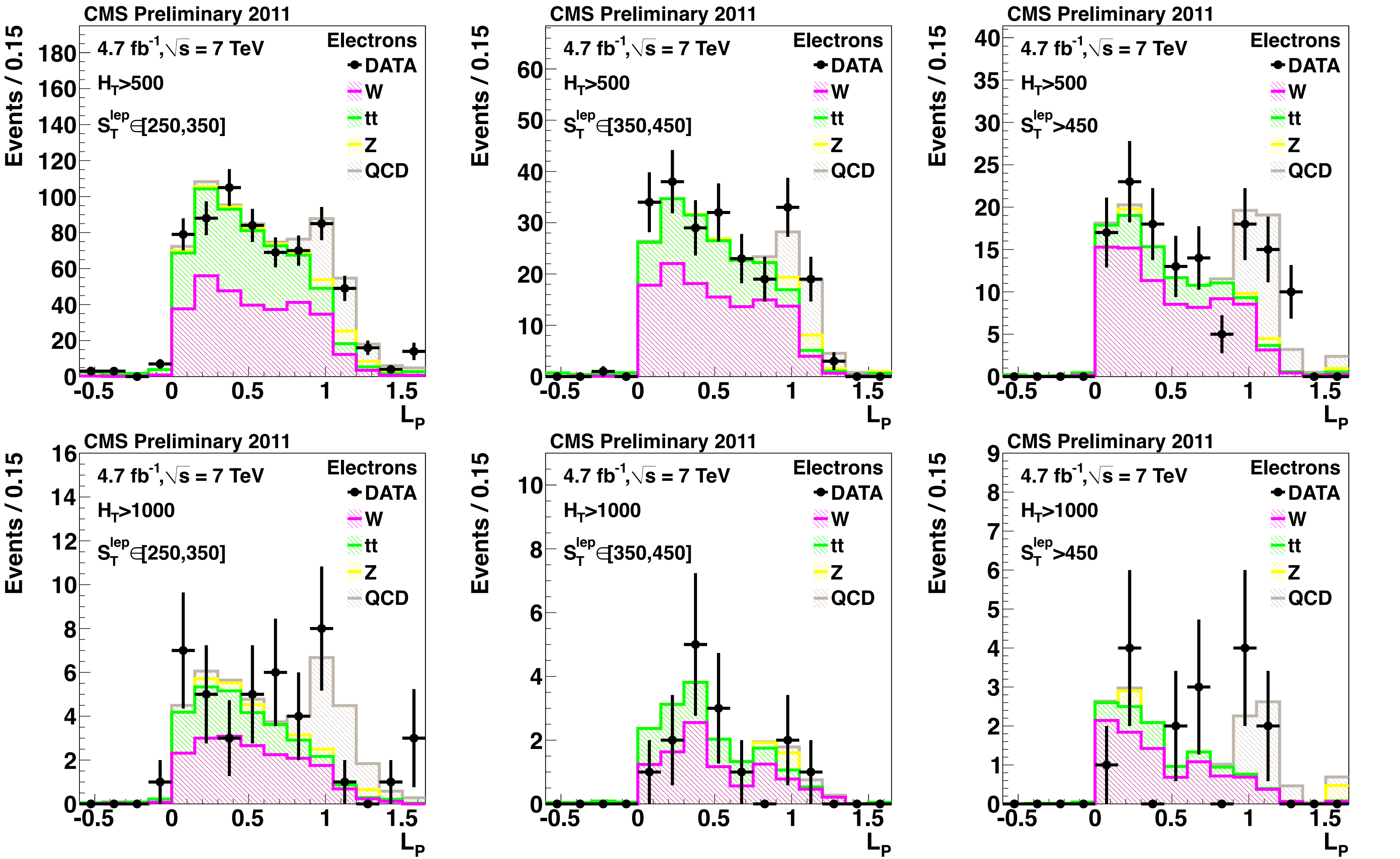




Lepton Polarization: Fit Results



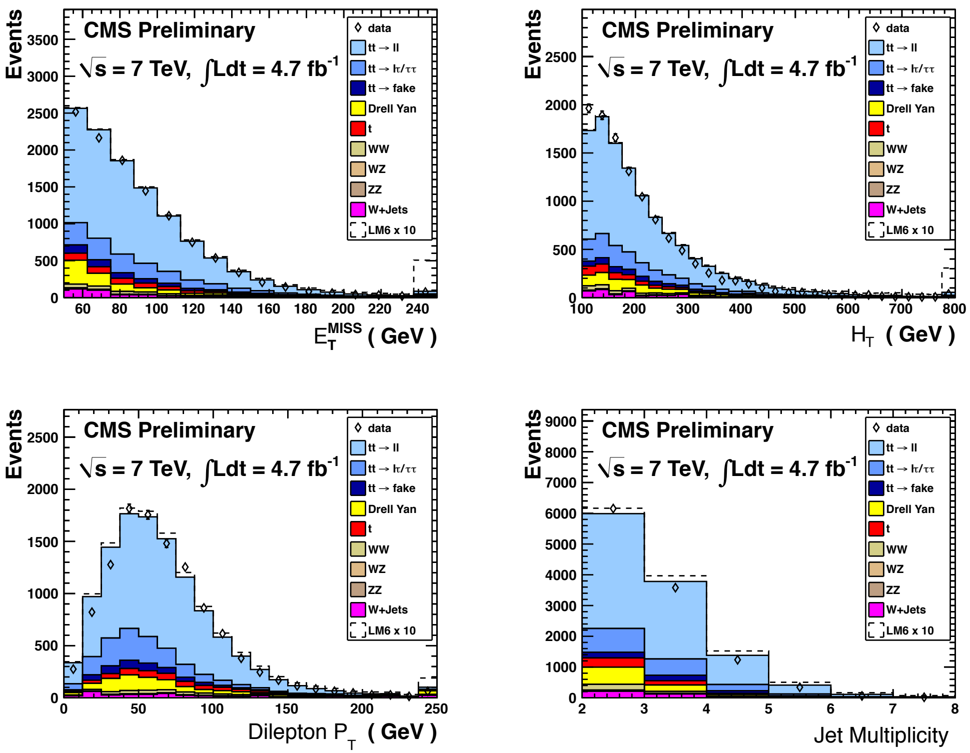
Lepton Polarization: Fit Results



Additional Material

- 1-lepton
- **OS non-Z**
- Z
- OS ANN

ee/μμ/eμ Preselection



Sample	σ [pb]	ee	$\mu\mu$	$e\mu$	total
$t\bar{t} \to \ell^+\ell^-$	7	1465.8 ± 66.1	1872.4 ± 84.4	4262.2 ± 192.0	7600.4 ± 342.2
$t\bar{t} \to \ell^\pm\tau^\mp / \tau^+\tau^-$	9	302.8 ± 13.8	397.5 ± 18.0	888.6 ± 40.1	1588.9 ± 71.7
$t\bar{t} \to$ fake	141	50.2 ± 2.4	15.0 ± 0.8	90.0 ± 4.2	155.2 ± 7.1
DY$\to \ell\ell$	16677	192.6 ± 13.6	236.6 ± 15.6	311.8 ± 19.1	740.9 ± 39.0
W^+W^-	43	55.0 ± 2.7	66.2 ± 3.2	150.7 ± 7.0	272.0 ± 12.5
$W^\pm Z^0$	18	13.4 ± 0.7	15.0 ± 0.7	24.6 ± 1.2	53.0 ± 2.4
Z^0Z^0	5.9	2.6 ± 0.1	3.3 ± 0.2	3.3 ± 0.2	9.1 ± 0.5
single top	102	94.6 ± 4.9	119.6 ± 6.0	278.1 ± 13.1	492.3 ± 22.8
$W +$ jets	96648	47.3 ± 10.7	9.8 ± 4.7	59.4 ± 11.7	116.6 ± 17.0
MC		$\mathbf{2224.3 \pm 101.4}$	$\mathbf{2735.4 \pm 123.9}$	$\mathbf{6068.8 \pm 273.8}$	$\mathbf{11028.5 \pm 497.1}$
data		**2333**	**2873**	**6184**	**11390**
LM1	6.8	271.8 ± 13.5	342.1 ± 16.6	165.6 ± 8.7	779.6 ± 36.4
LM3	4.9	106.9 ± 5.6	125.2 ± 6.4	180.7 ± 9.0	412.8 ± 19.4
LM6	0.4	19.5 ± 1.0	23.2 ± 1.1	26.2 ± 1.3	68.8 ± 3.2

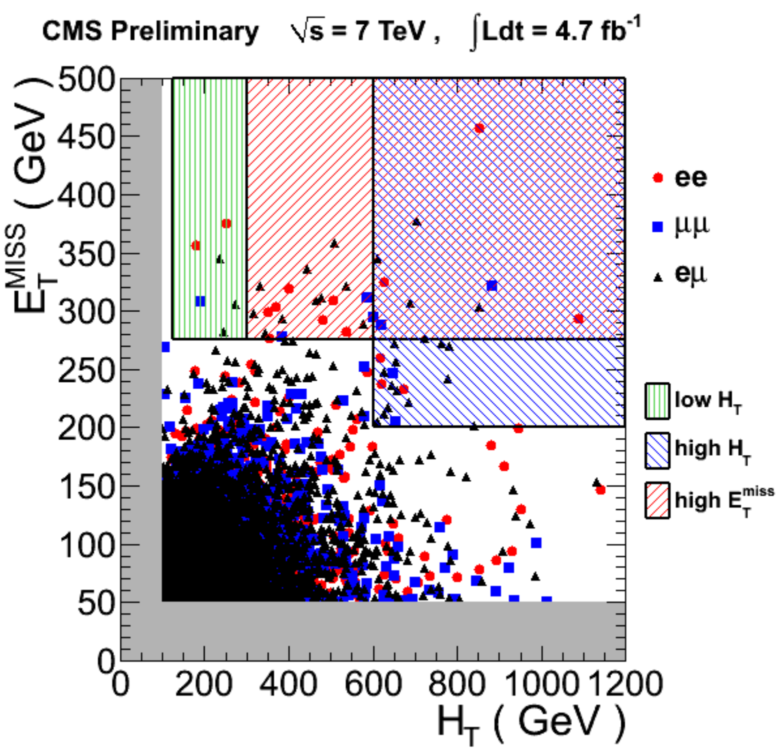
Sample	$e\tau$	$\mu\tau$	total
$Z \to \ell\ell$	48.4 ± 12.9	44.0 ± 10.7	92.4 ± 23.6
$t\bar{t}$ + jets	155.7 ± 47.4	193.4 ± 58.8	349.1 ± 106.1
VV	10.5 ± 2.1	10.2 ± 2.0	20.7 ± 4.0
single top	6.8 ± 2.6	7.7 ± 2.7	14.5 ± 4.8
$\sum$MC True	137.8 ± 39.9	157.4 ± 45.1	295.8 ± 85.0
$\sum$MC Fake	83.7 ± 24.6	96.8 ± 27.9	179.9 ± 51.8
$\sum$SM	221.5 ± 63.7	255.3 ± 73.4	476.7 ± 136.8
Data	215	302	517
LM1	33.7 ± 7.5	43.3 ± 8.6	77.0 ± 13.5
LM6	2.6 ± 1.0	4.0 ± 1.3	6.6 ± 1.8
LM13	84.6 ± 14.6	111.4 ± 17.8	195.9 ± 29.2

- Reasonable data/MC agreement but MC not used quantitatively in the search

OS: Light Leptons & Hadronic Taus

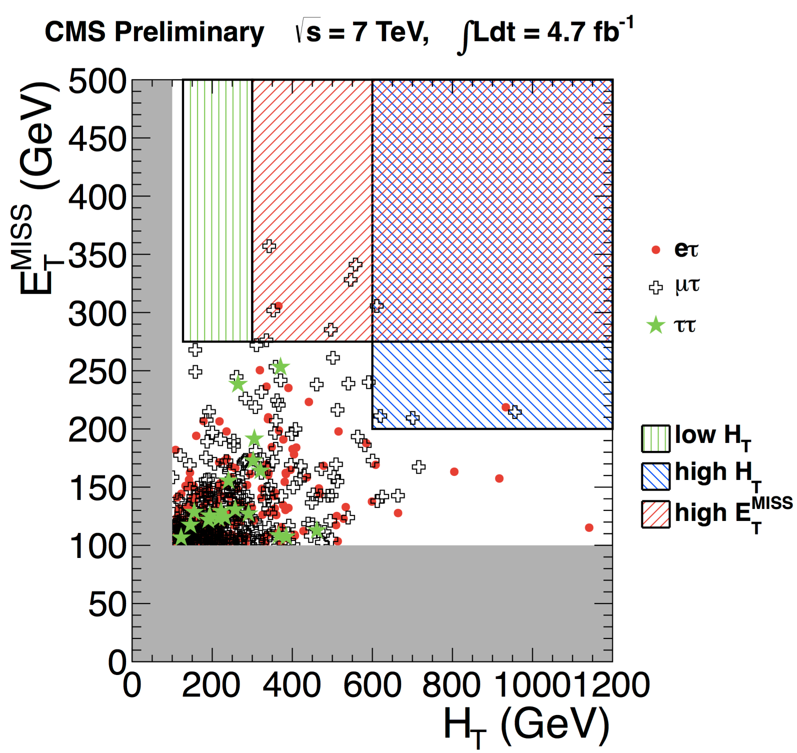
Light leptons: ee / μμ / eμ

- Background dominated by $tt \rightarrow \ell^+\ell^-$
- Predict bkg in MET vs. H_T signal regions using $p_T(\ell\ell)$ (lepton spectrum method)



Hadronic Taus: $e\tau_h$ / $\mu\tau_h$ / $\tau_h\tau_h$

- Background from $tt \rightarrow \ell^+\ell^-$ and fake taus
- Bkg prediction from $p_T(\ell\ell)$ ($tt \rightarrow \ell^+\ell^-$) and "fake rate" method (fake tau's)



OS: Results

light leptons
ee/eμ/μμ

	high E_T^{miss}	high H_T	tight	low H_T
SF yield	15	11	6	3
OF yield	15	18	5	3
total yield	**30**	**29**	**11**	**6**
$\mathbf{p_T(\ell\ell)}$ **prediction**	$\mathbf{21 \pm 8.9 \pm 8.0}$	$\mathbf{22 \pm 7.5 \pm 6.9}$	$\mathbf{11 \pm 5.8 \pm 3.8}$	$\mathbf{12 \pm 4.9 \pm 5.7}$
MC prediction	30 ± 1.2	31 ± 0.9	12 ± 0.6	4.2 ± 0.3
non-SM yield UL	26	23	11	6.5
LM1	221 ± 5.1	170 ± 4.5	106 ± 3.5	6.2 ± 0.9
LM3	79 ± 2.4	83 ± 2.5	44 ± 1.8	2.3 ± 0.4
LM6	35 ± 0.6	33 ± 0.5	26 ± 0.5	0.6 ± 0.1

hadronic tau's
$e\tau_h/e\tau_h/\tau_h\tau_h$

	high E_T^{miss}	high H_T	tight	low H_T
$\sum$MC true τ_h	$5.5 \pm 1.6 \pm 1.1$	$3.5 \pm 1.2 \pm 0.7$	$1.9 \pm 1.0 \pm 0.4$	$0.4 \pm 0.2 \pm 0.1$
$\sum$MC fake τ_h	$1.3 \pm 0.3 \pm 0.3$	$2.6 \pm 1.0 \pm 0.5$	$0.2 \pm 0.1 \pm 0.0$	$0.2 \pm 0.1 \pm 0.0$
$\sum$MC	$6.7 \pm 1.6 \pm 1.3$	$6.1 \pm 1.5 \pm 1.2$	$2.1 \pm 1.0 \pm 0.4$	$0.7 \pm 0.2 \pm 0.1$
$p_T(\ell\ell)$ prediction	$2.1 \pm 0.9 \pm 0.8$	$2.2 \pm 0.8 \pm 0.9$	$1.1 \pm 0.6 \pm 0.4$	$1.2 \pm 0.5 \pm 0.4$
TL prediction	$5.1 \pm 1.7 \pm 0.8$	$3.6 \pm 1.4 \pm 0.5$	$2.7 \pm 1.3 \pm 0.4$	< 0.08
MC irreducible	$1.2 \pm 0.5 \pm 0.2$	$0.7 \pm 0.3 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$	$0.1 \pm 0.1 \pm 0.1$
$\sum$ **predictions**	$\mathbf{8.4 \pm 2.0 \pm 1.1}$	$\mathbf{6.5 \pm 1.6 \pm 1.0}$	$\mathbf{4.0 \pm 1.4 \pm 0.6}$	$\mathbf{1.3 \pm 0.5 \pm 0.5}$
total yield	**8**	**5**	**1**	**0**
non-SM yield UL	7.9	6.2	3.7	3.1
LM1	$29.9 \pm 5.5 \pm 5.1$	$13.5 \pm 3.5 \pm 2.3$	$7.6 \pm 2.5 \pm 1.3$	-
LM6	$4.2 \pm 1.3 \pm 0.7$	$4.8 \pm 1.4 \pm 0.8$	$4.0 \pm 1.3 \pm 0.7$	$0.4 \pm 0.4 \pm 0.1$
LM13	$65.3 \pm 7.7 \pm 11.1$	$49.1 \pm 6.5 \pm 8.3$	$36.9 \pm 5.7 \pm 6.3$	-

- Good agreement data vs. prediction in all channels

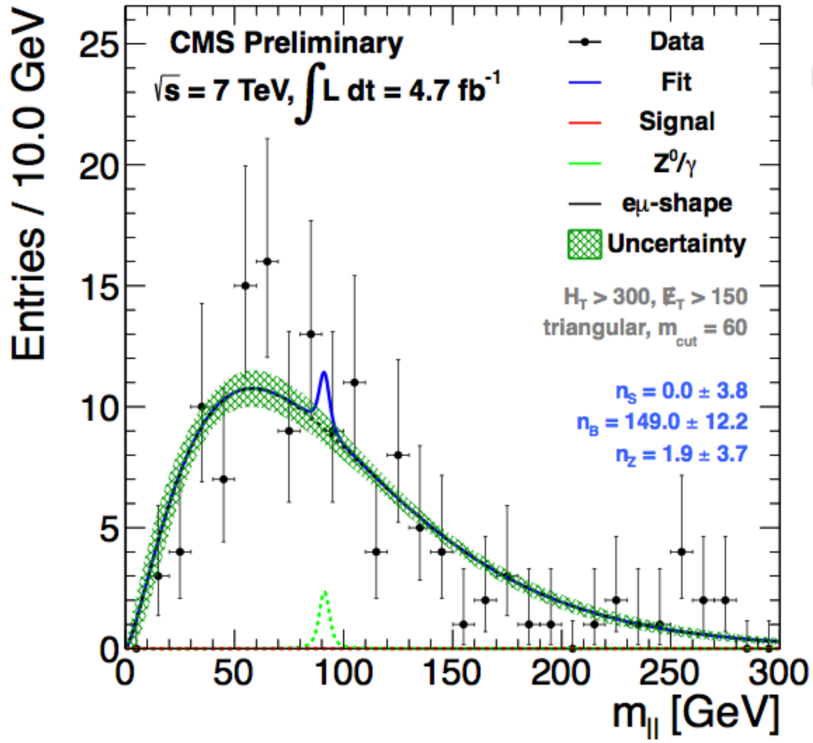
- Simultaneous fit to SF (ee+μμ) & OF (eμ)

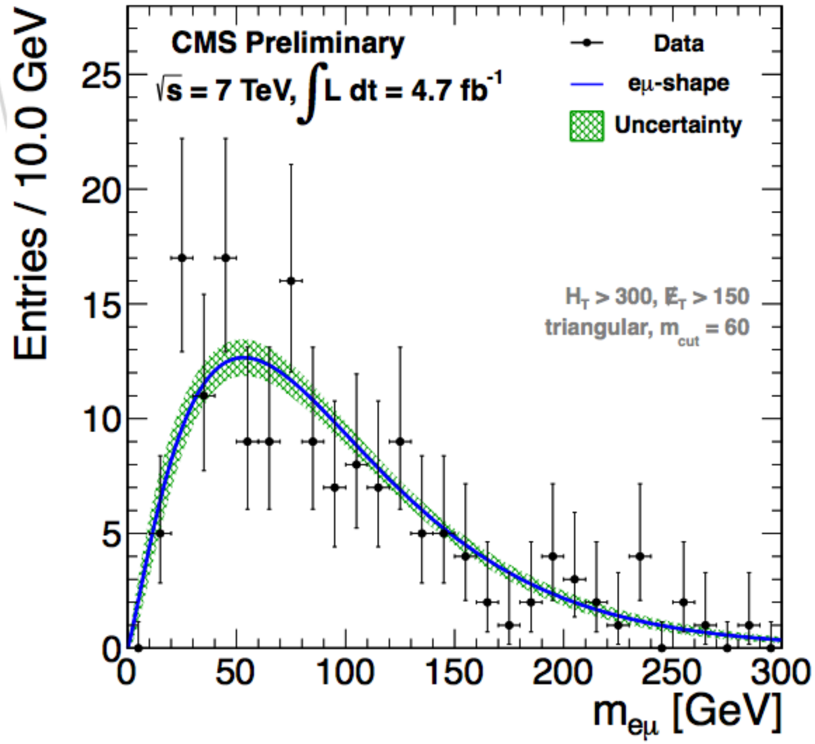
background shape

$$B(m_{\ell\ell}) = m_{\ell\ell}^{a} e^{-b m_{\ell\ell}}$$

signal shape

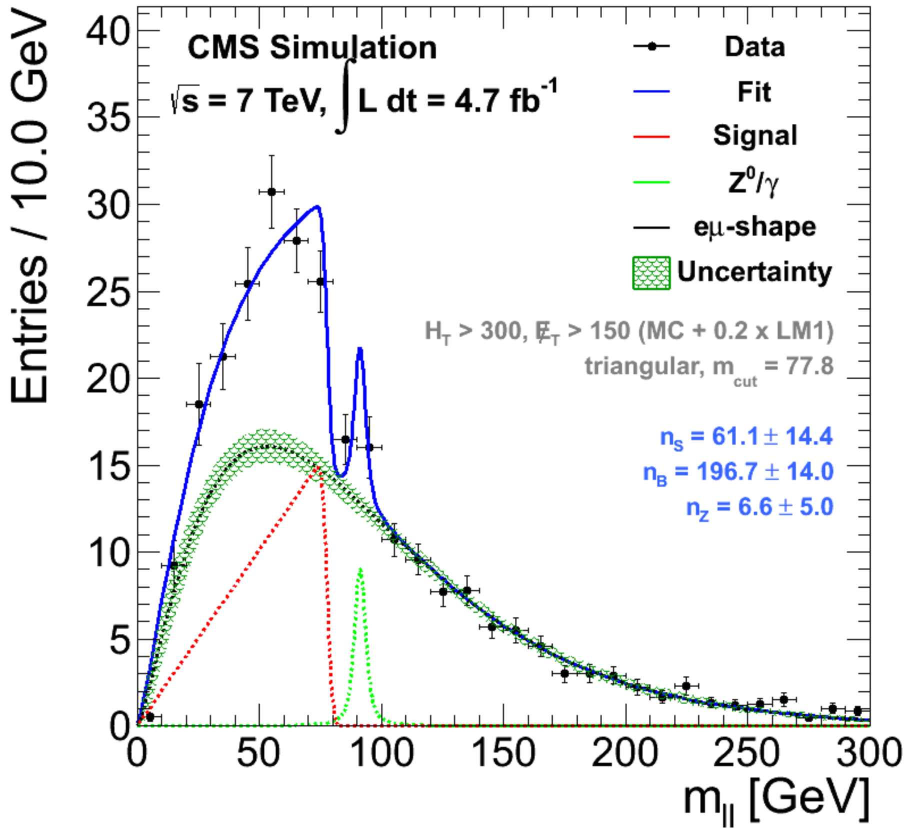
$$T(m_{\ell\ell}) = \frac{1}{\sqrt{2\pi}\sigma_{ll}} \int_0^{M_{cut}} dy\, y^{\alpha} e^{\frac{-(m_{\ell\ell}-y)^2}{2\sigma^2}}$$





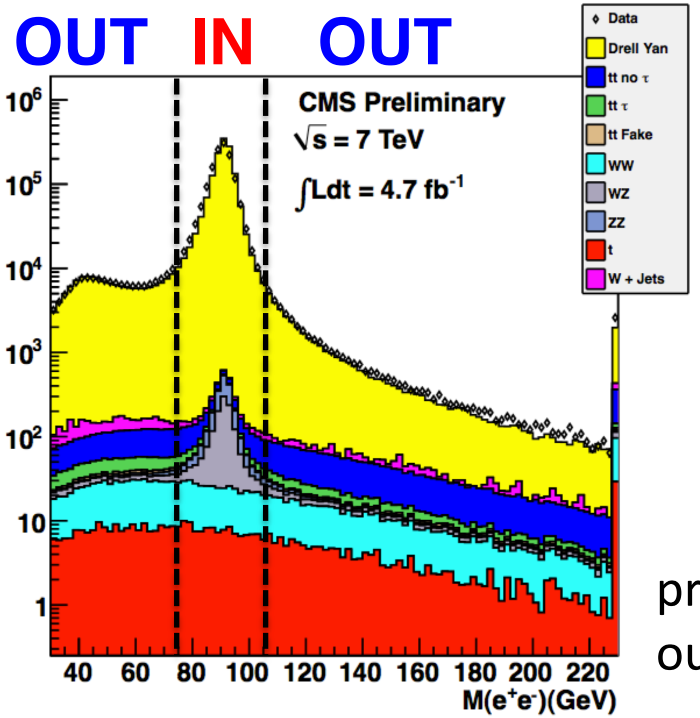
Edge Search: Simulation

MC ONLY: NO DATA!!!



- Expected fit results with signal (LM1 × 0.2)

The "$R_{out/in}$" Method



- **Goal**: estimate number of Z events outside Z mass region

$$N^{Z}_{out} \approx R_{out/in} \left(N^{ee+\mu\mu}_{in} - N^{e\mu}_{in} \right)$$

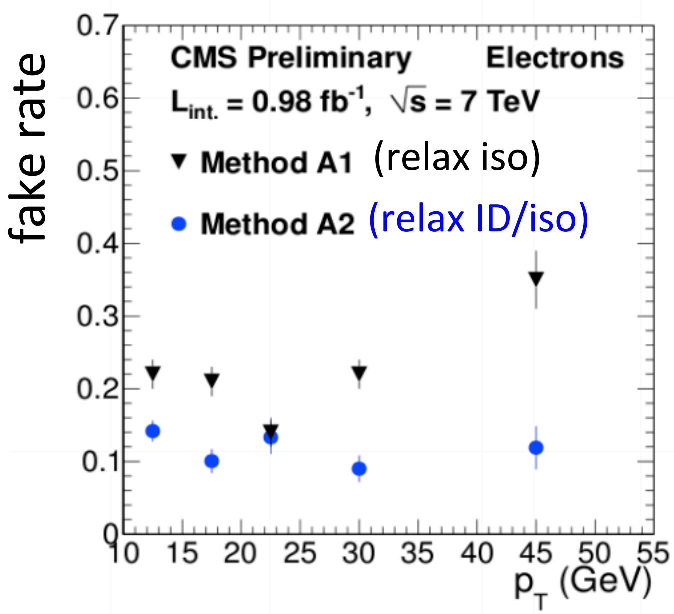
predicted Z yield outside Z mass region

ratio of Z yield outside/inside Z mass region (from MC)

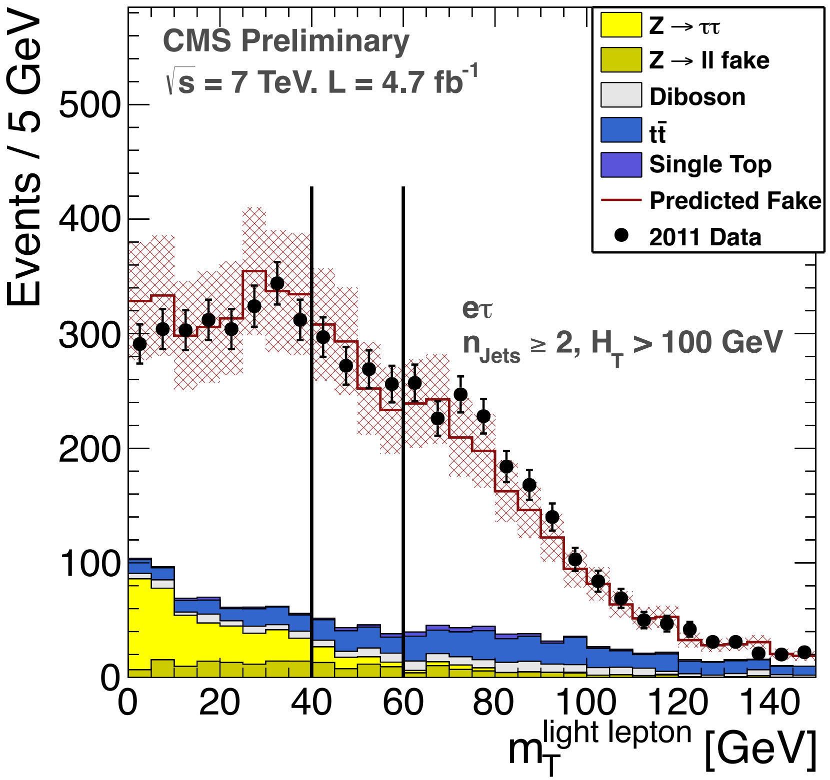
data yield inside Z mass region in ee+μμ and eμ channels

The Fake-Rate Method

- **Define 2 lepton selections:**
  - tight (same as analysis selection)
  - loose (relax ID and/or iso)
- **Measure "fake rate" in QCD sample**
  - FR = (#tight leptons)/(#loose leptons)
  - Measure FR(p_T,η) ~ 10-40%
- **Estimate number of fake leptons passing analysis lepton selection**
  - Count events with leptons passing loose selection but failing tight selection
  - Weight events by FR/(1-FR) → sum of weights is data-driven prediction



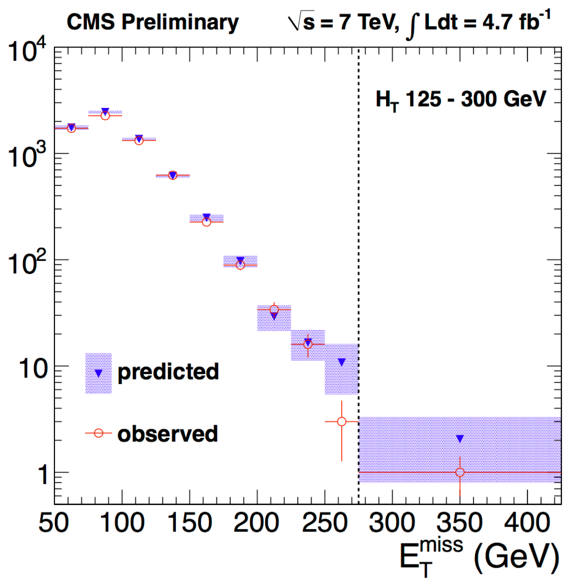
Hadronic Tau: Fake Estimate



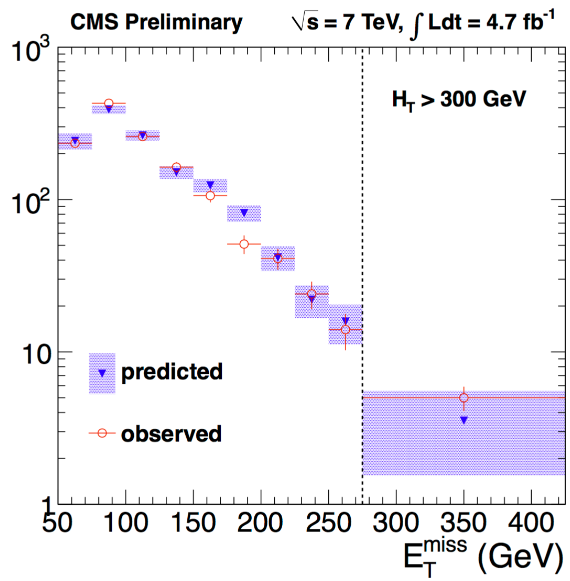
- Validate tau fake rate estimate in background dominated region
- Good agreement between data and predicted fake contribution

OS: ee/μμ/eμ $p_T(\ell\ell)$ Estimates

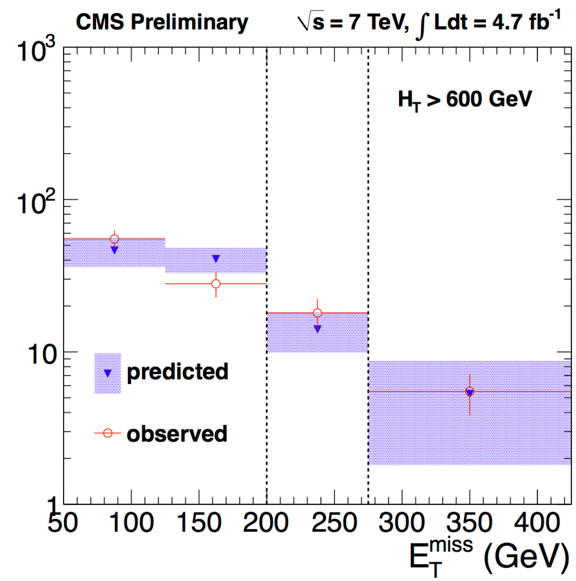
H_T 125-300 GeV



H_T > 300 GeV

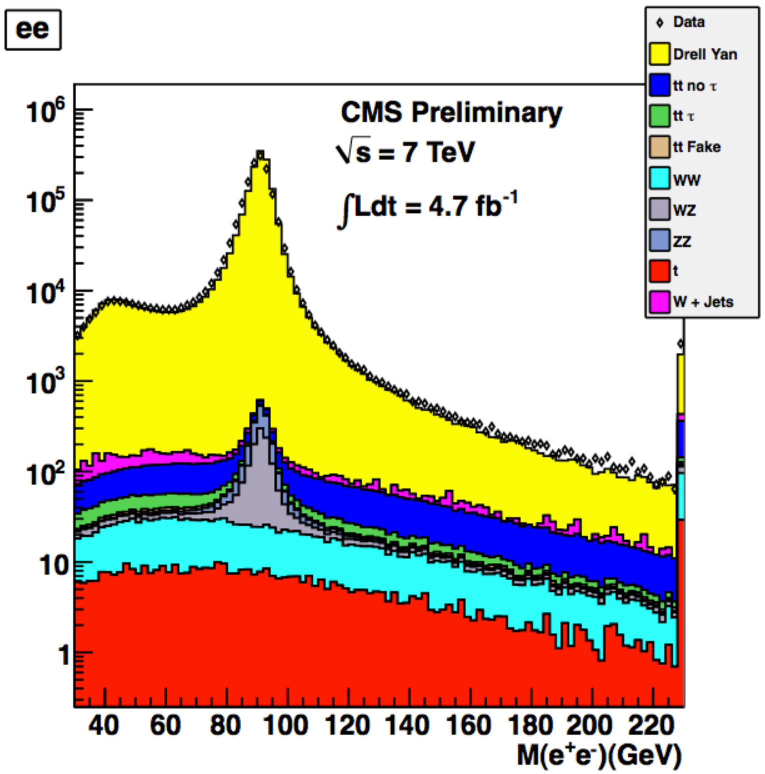


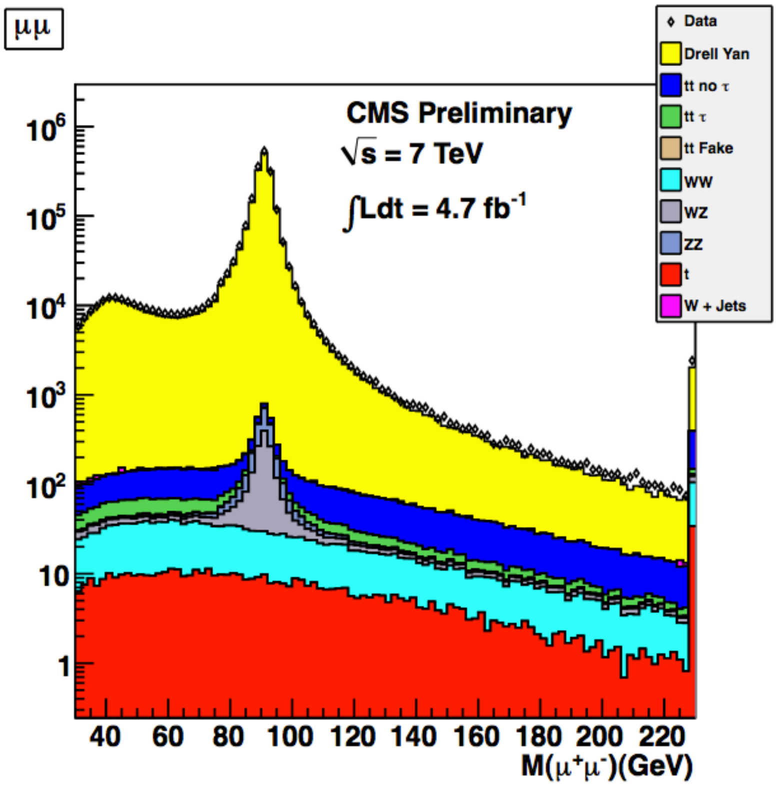
H_T > 600 GeV



- Good agreement over full MET range in all H_T bins

OS analysis: Dilepton Mass

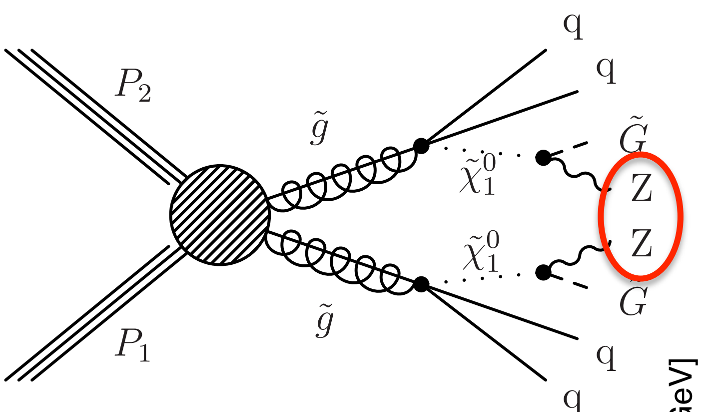




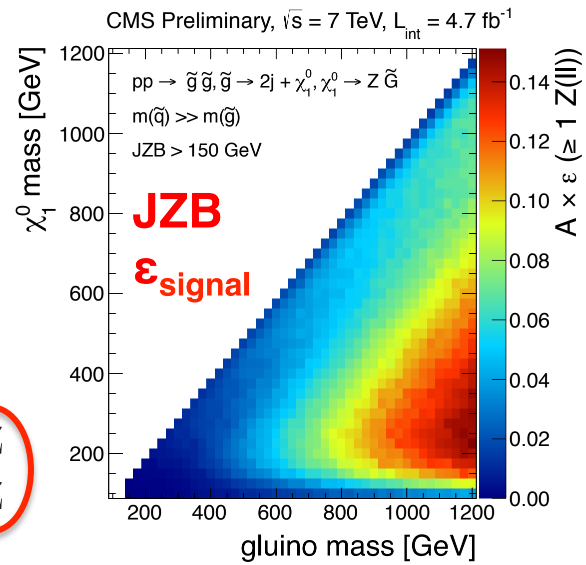
- Reasonable data/MC agreement after dilepton selection

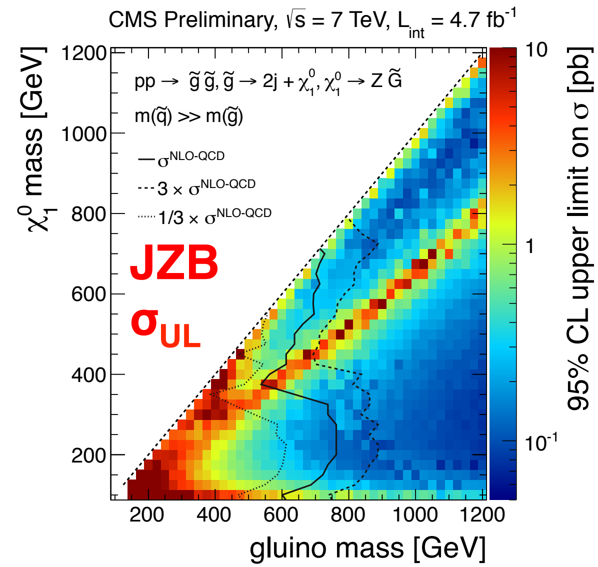
Z: Interpretation

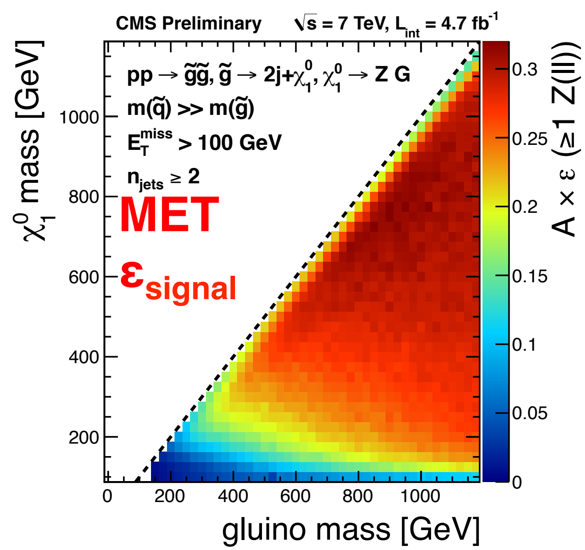
- No excess → set limits in SMS topology:

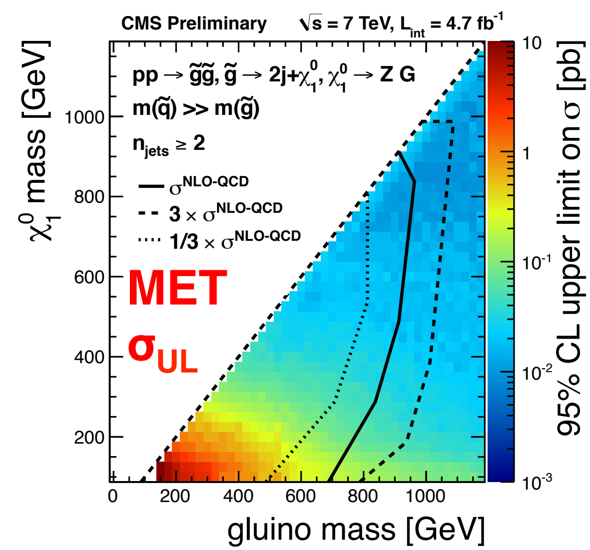


- Scan in M($\tilde{g}$) vs. M(χ_1^0)
  – Gravitino LSP treated as massless
- ε_{signal}, σ_{UL}, excluded region (BF=1, $\sigma^{NLO\text{-}QCD}$)



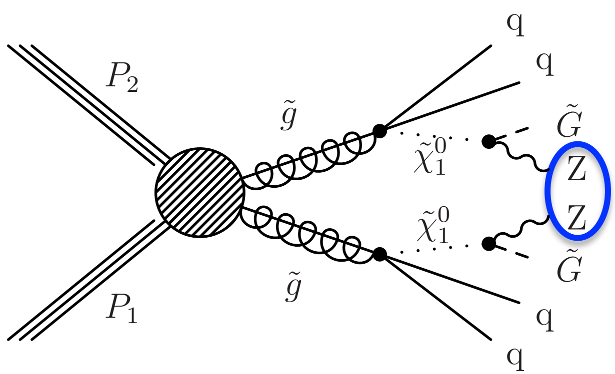




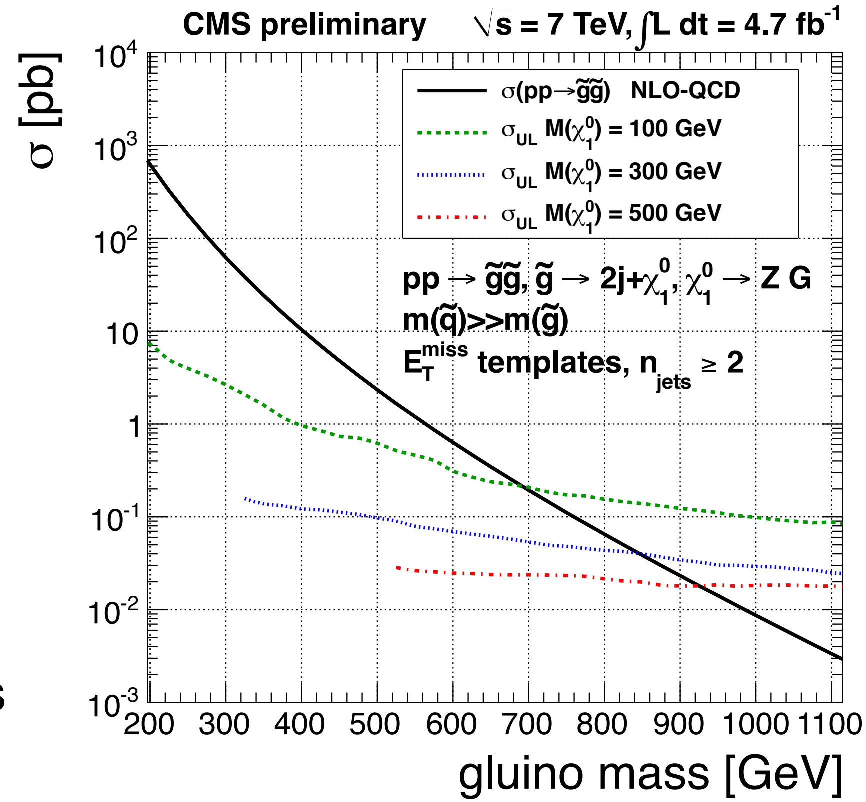


$\mathbf{Z}$: Interpretation

- **Shown: σ_{UL} vs. $\sigma^{NLO\text{-}QCD}$ for:**



- Scan in $M(\tilde{g})$ for 3 choices of $M(\chi_1^0)$
  - Gravitino LSP treated as massless

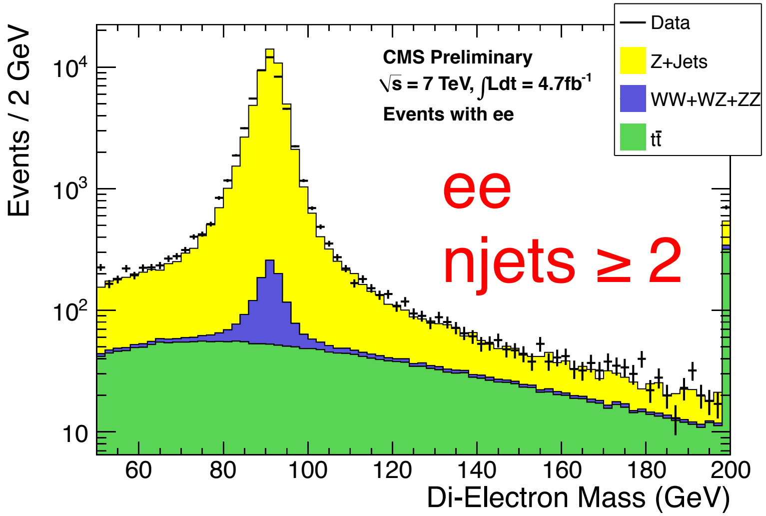


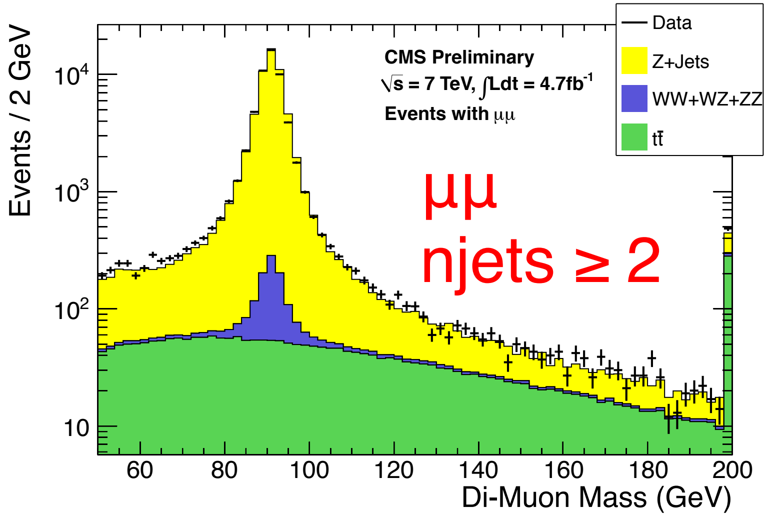
- Gravitino LSP exclusion from MET templates method, projected onto M(gluino) axis
- Assuming 100% BF ➞ limits on M(gluino) in range ~700-900 GeV
- Limits improve with increased $M(\chi_1^0)$

Additional Material

- 1-lepton
- OS non-Z
- **Z**
- OS ANN

Preselection





njets ≥ 2

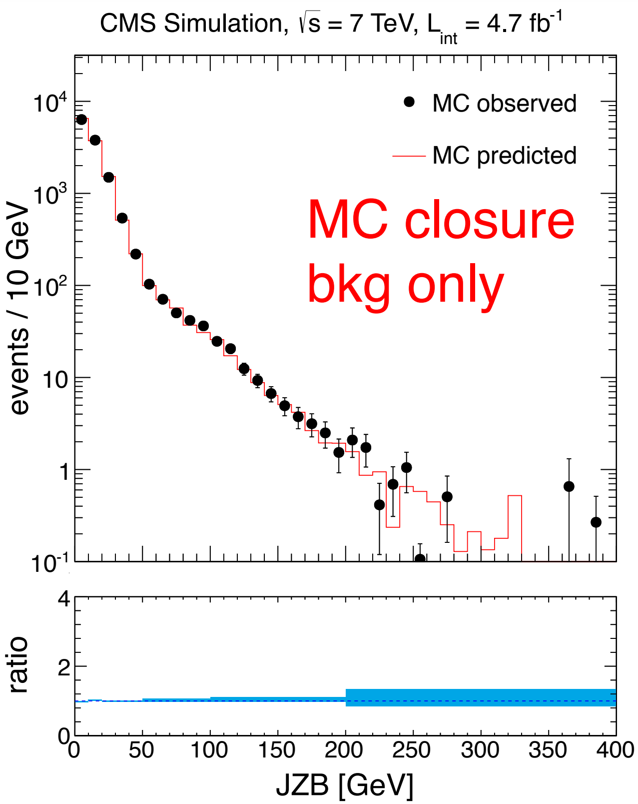
Sample	ee	$\mu\mu$	$e\mu$	tot
WJets	10.8 ± 4.4	0.0 ± 0.0	8.5 ± 3.8	19.3 ± 5.8
WW	14.8 ± 0.5	17.2 ± 0.5	32.9 ± 0.8	64.9 ± 1.1
WZ	405.7 ± 1.8	411.7 ± 1.7	5.0 ± 0.1	822.4 ± 2.5
ZZ	313.3 ± 1.2	349.1 ± 1.2	0.8 ± 0.0	663.2 ± 1.6
Single Top	29.3 ± 1.2	26.1 ± 1.0	50.8 ± 1.5	106.2 ± 2.1
$t\bar{t}$	523.2 ± 2.6	529.0 ± 2.5	1056.7 ± 3.6	2108.8 ± 5.1
Z+Jets	51051.4 ± 147.5	53149.1 ± 143.0	16.2 ± 2.6	104216.8 ± 205.4
Total MC	52348.5 ± 147.6	54482.2 ± 143.0	1171.0 ± 6.1	108001.6 ± 205.6
Data	49214	52757	1256	103227

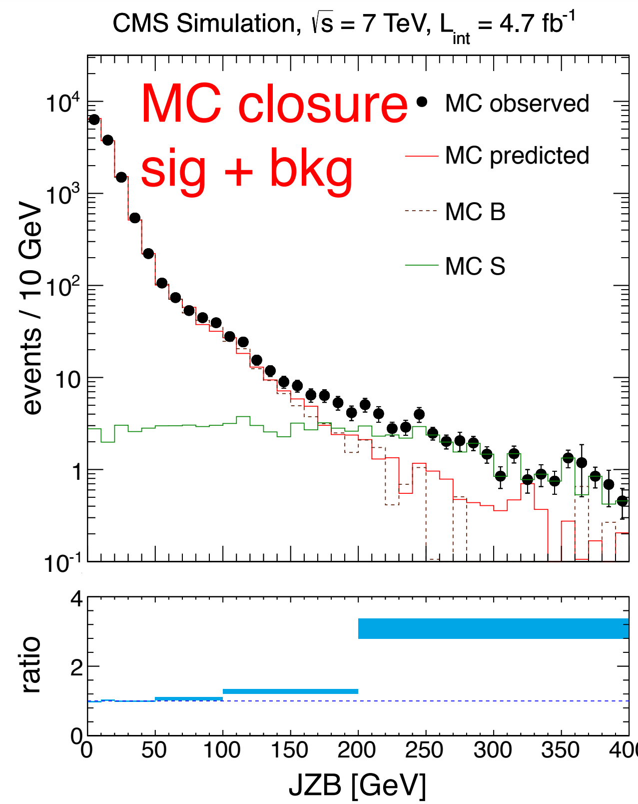
njets ≥ 3

Sample	ee	$\mu\mu$	$e\mu$	tot
WJets	0.0 ± 0.0	0.0 ± 0.0	1.7 ± 1.7	1.7 ± 1.7
WW	3.7 ± 0.3	4.0 ± 0.3	7.4 ± 0.4	15.2 ± 0.5
WZ	118.1 ± 1.0	117.8 ± 0.9	1.4 ± 0.1	237.3 ± 1.3
ZZ	71.0 ± 0.6	79.2 ± 0.6	0.2 ± 0.0	150.5 ± 0.8
Single Top	8.0 ± 0.6	7.0 ± 0.5	14.2 ± 0.8	29.1 ± 1.1
$t\bar{t}$	237.1 ± 1.7	238.3 ± 1.7	479.1 ± 2.4	954.4 ± 3.4
Z+Jets	9932.0 ± 65.1	10147.2 ± 62.4	5.3 ± 1.5	20084.4 ± 90.2
Total MC	10369.8 ± 65.1	10593.5 ± 62.4	509.3 ± 3.4	21472.6 ± 90.3
Data	9760	10356	506	20622

- Reasonable data/MC agreement in preselection region (Z(ℓℓ) + jets), but MC not used quantitatively in search

JZB MC Studies

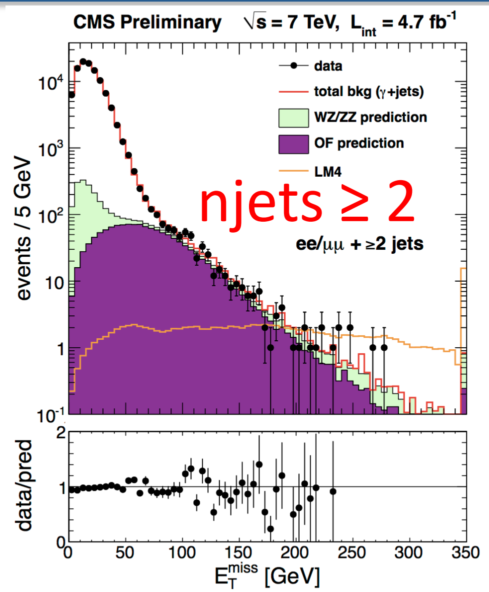


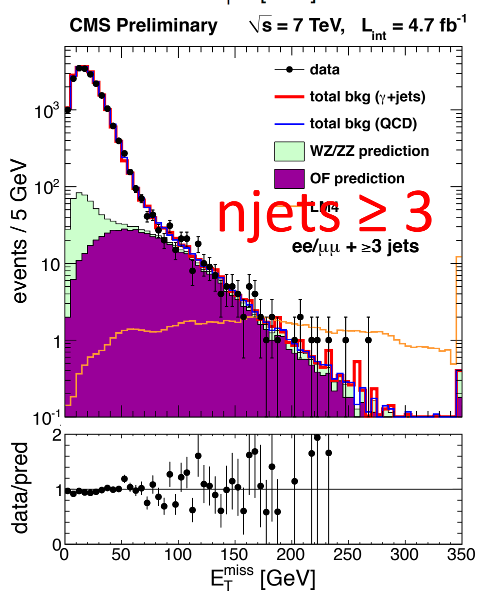


Region	MC observed	MC predicted
JZB $>$ 50 GeV	400 ± 10	$391 \pm 15 \pm 56$
JZB $>$ 100 GeV	97 ± 5	$93 \pm 6 \pm 13$
JZB $>$ 150 GeV	24 ± 2.0	$23 \pm 3 \pm 3$
JZB $>$ 200 GeV	8.0 ± 1.4	$7.3 \pm 1.7 \pm 1.0$
JZB $>$ 250 GeV	2.0 ± 0.8	$3.1 \pm 1.2 \pm 0.4$

- JZB method closes in MC bkg only
- Adding signal MC leads to observed excess

MET Templates Results





njets ≥ 2

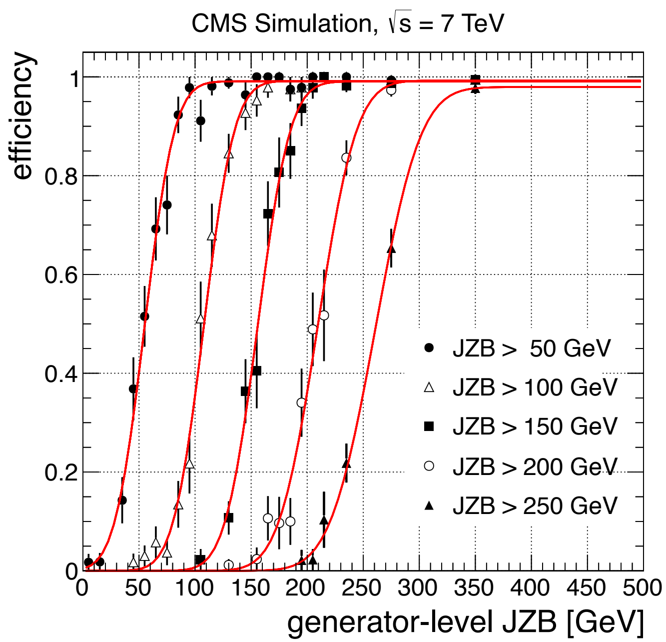
	$E_T^{miss} > 30$ GeV	$E_T^{miss} > 60$ GeV	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 300$ GeV
Z bkg	15070 ± 4825	484 ± 156	36 ± 12	2.4 ± 0.9	0.4 ± 0.3
OF bkg	1116 ± 101	680 ± 62	227 ± 21	11.4 ± 3.2	1.6 ± 0.6
VZ bkg	252 ± 126	79 ± 39	32 ± 16	5.0 ± 2.5	1.1 ± 0.7
total bkg	**16438 ± 4828**	**1243 ± 173**	**295 ± 29**	**18.8 ± 4.2**	**3.1 ± 1.0**
data	**16483 (8243,8240)**	**1169 (615,554)**	**290 (142,148)**	**14 (8,6)**	**0**
upper limit	6389	239	57	8.3	2.9
LM4	113 ± 9.1	102 ± 8.5	88 ± 7.9	50 ± 7.4	22 ± 6.0
LM8	49 ± 4.1	43 ± 3.7	35 ± 3.2	19 ± 2.9	9 ± 2.2

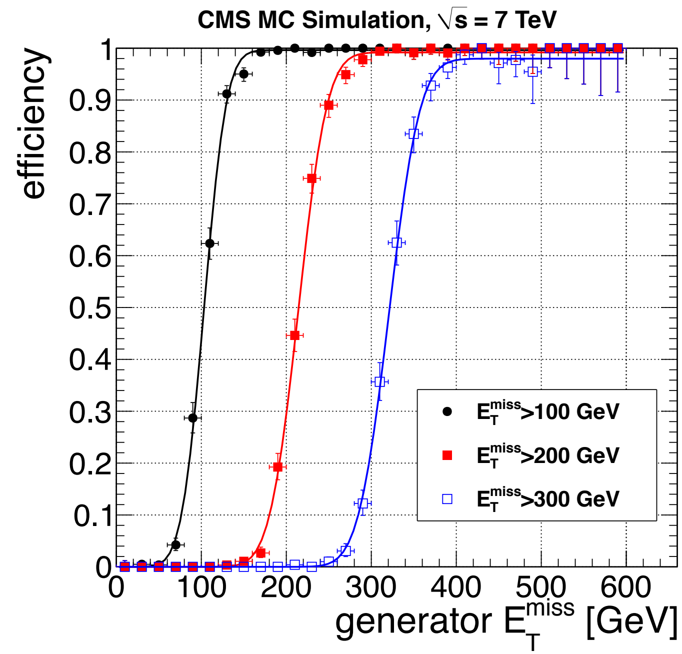
njets ≥ 3

	$E_T^{miss} > 30$ GeV	$E_T^{miss} > 60$ GeV	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV	$E_T^{miss} > 300$ GeV
Z bkg (QCD)	4010 ± 802	191 ± 57	11 ± 11	0.7 ± 0.7	0.1 ± 0.1
Z bkg (γ + jets)	3906 ± 1252	187 ± 61	14 ± 5	1.7 ± 0.7	0.3 ± 0.2
OF bkg	442 ± 41	284 ± 26	107 ± 10	7.5 ± 2.2	1.1 ± 0.5
VZ bkg	80 ± 40	24 ± 12	10 ± 5	1.8 ± 0.9	0.4 ± 0.3
total bkg (QCD)	4533 ± 804	500 ± 64	128 ± 16	10 ± 2.5	1.6 ± 0.6
total bkg (γ + jets)	4429 ± 1253	496 ± 67	131 ± 13	11 ± 2.5	1.9 ± 0.6
total bkg (average)	**4481 ± 1034**	**498 ± 66**	**129 ± 15**	**11 ± 2.7**	**1.8 ± 0.6**
data	**4501 (2272,2229)**	**479 (267,212)**	**137 (73,64)**	**8 (3,5)**	**0**
upper limit	1513	121	42	6.9	2.9
LM4	91 ± 7.7	85 ± 7.5	75 ± 7.5	42 ± 7.1	18 ± 5.2
LM8	40 ± 3.3	37 ± 3.1	31 ± 2.9	18 ± 2.7	8 ± 2.1

- Good agreement observed vs. predicted for njets ≥ 2, njets ≥3, in all MET regions

Z+MET Efficiency Model





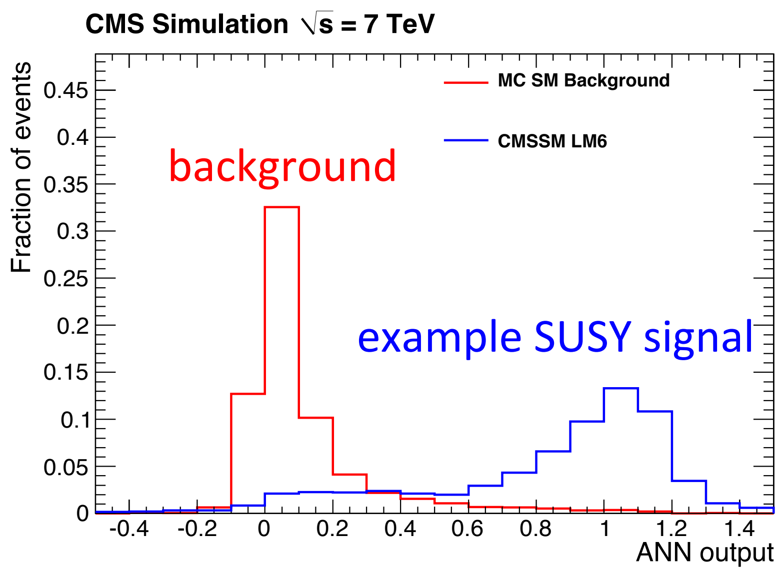
Region	σ [GeV]	x_{thresh} [GeV]	$\varepsilon_{\text{plateau}}$
JZB > 50 GeV	30	55	0.99
JZB > 100 GeV	30	108	0.99
JZB > 150 GeV	32	156	0.99
JZB > 200 GeV	39	209	0.99
JZB > 250 GeV	45	261	0.98
$E_T^{\text{miss}} > 100$ GeV	29	103	1.00
$E_T^{\text{miss}} > 200$ GeV	38	214	0.99
$E_T^{\text{miss}} > 300$ GeV	40	321	0.98

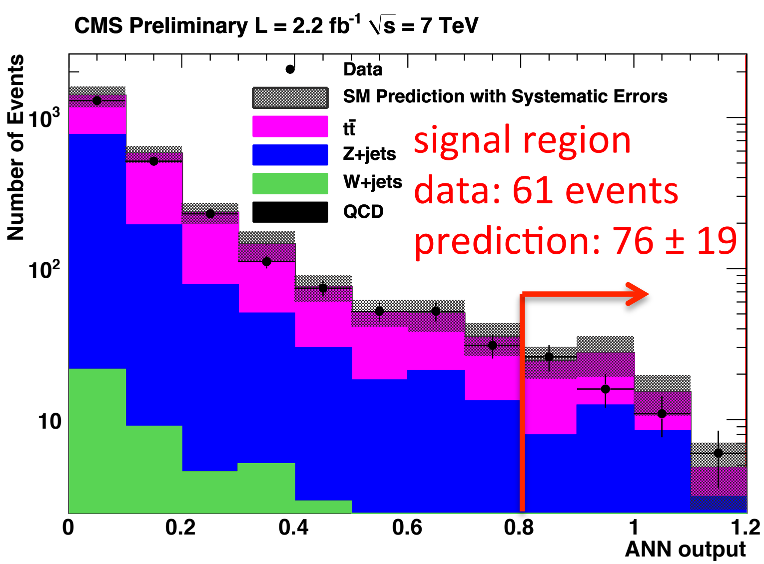
Additional Material

- 1-lepton
- OS non-Z
- **Z**
- OS ANN

OS NN: Artificial Neural Network

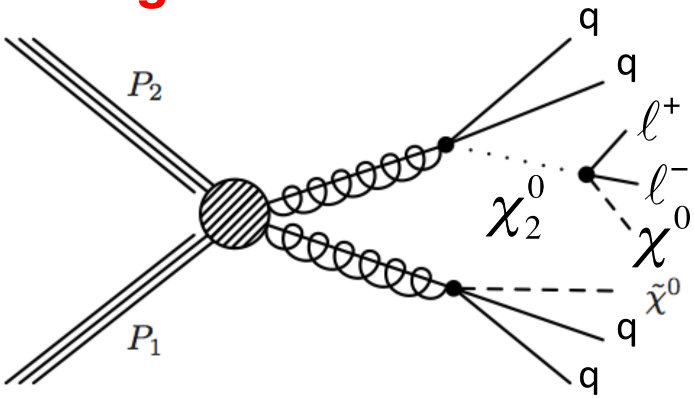
- Analyze combined Z + non-Z sample with multivariate approach
  - Relax kinematic selection (MET & H_T) → explore complementary phase space
- ANN built from 7 quantities with good signal vs. bkg discrimination
  - MET, n_{jets}, E_T(leptons)/E_T(event), 1st and 2nd jet p_T's, M(ℓℓ), M_T
- Define control sample by inverting preselection requirements, predict ANN output in signal sample using MC extrapolation factor
- Define signal region ANN > 0.8 → good agreement data vs. prediction, no evidence for BSM physics

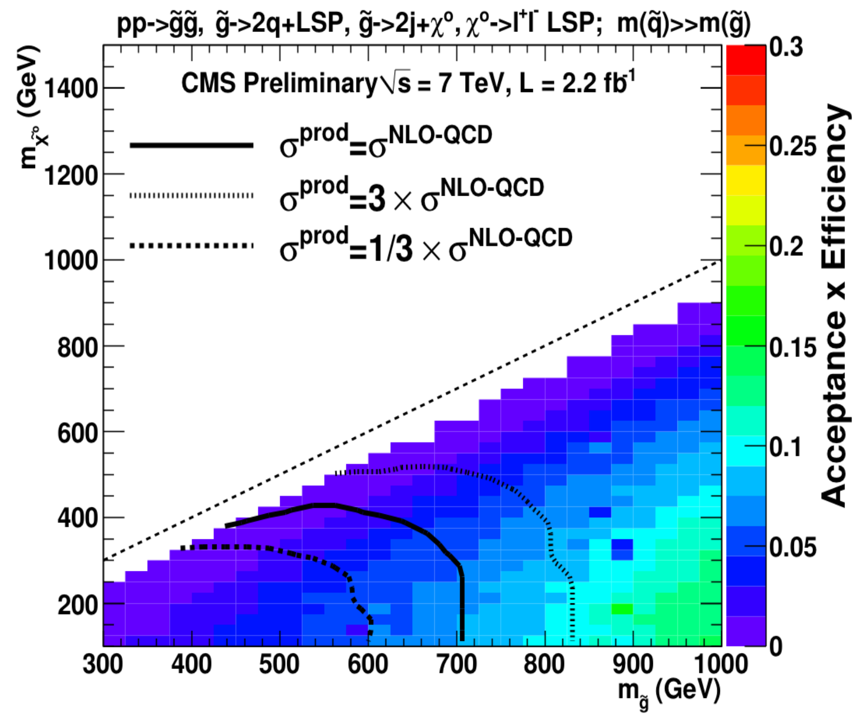




OS NN: Interpretation

- No excess → set limits in SMS topologies
- **Shown: signal region efficiencies excluded region for:**



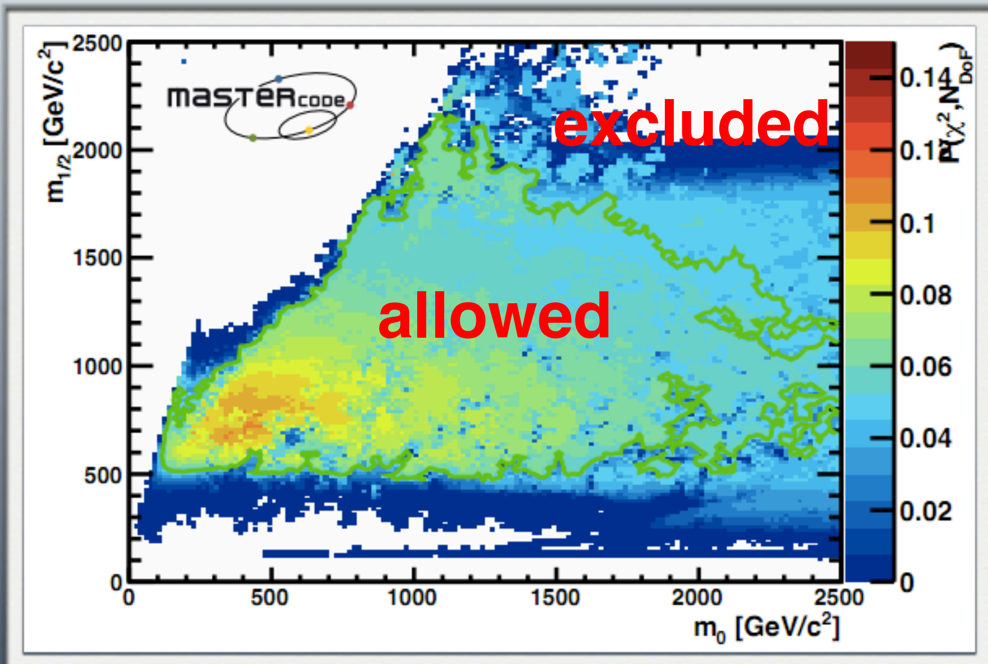


- 2 parameters: M(g) and M(χ_1^0)
  - M(χ_2^0) set to average of M(g) and M(χ_1^0)

CMSSM Constraints

Confronting SUSY with LHC Data

mastercode



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

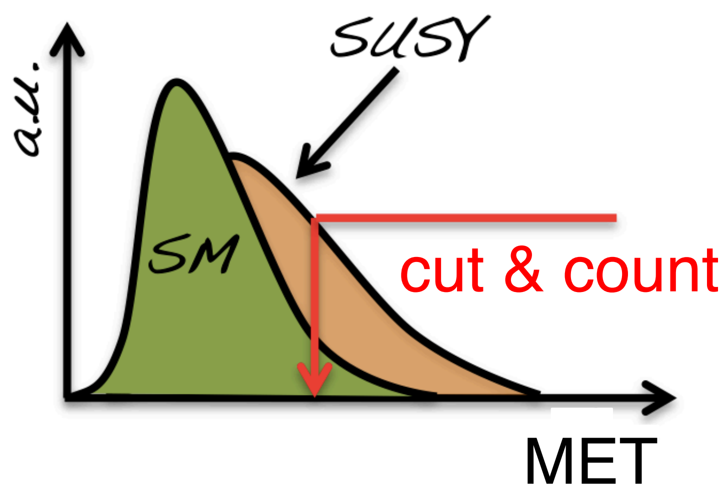
O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

SUSY11
Fermilab, 28 August to 02 September, 2011

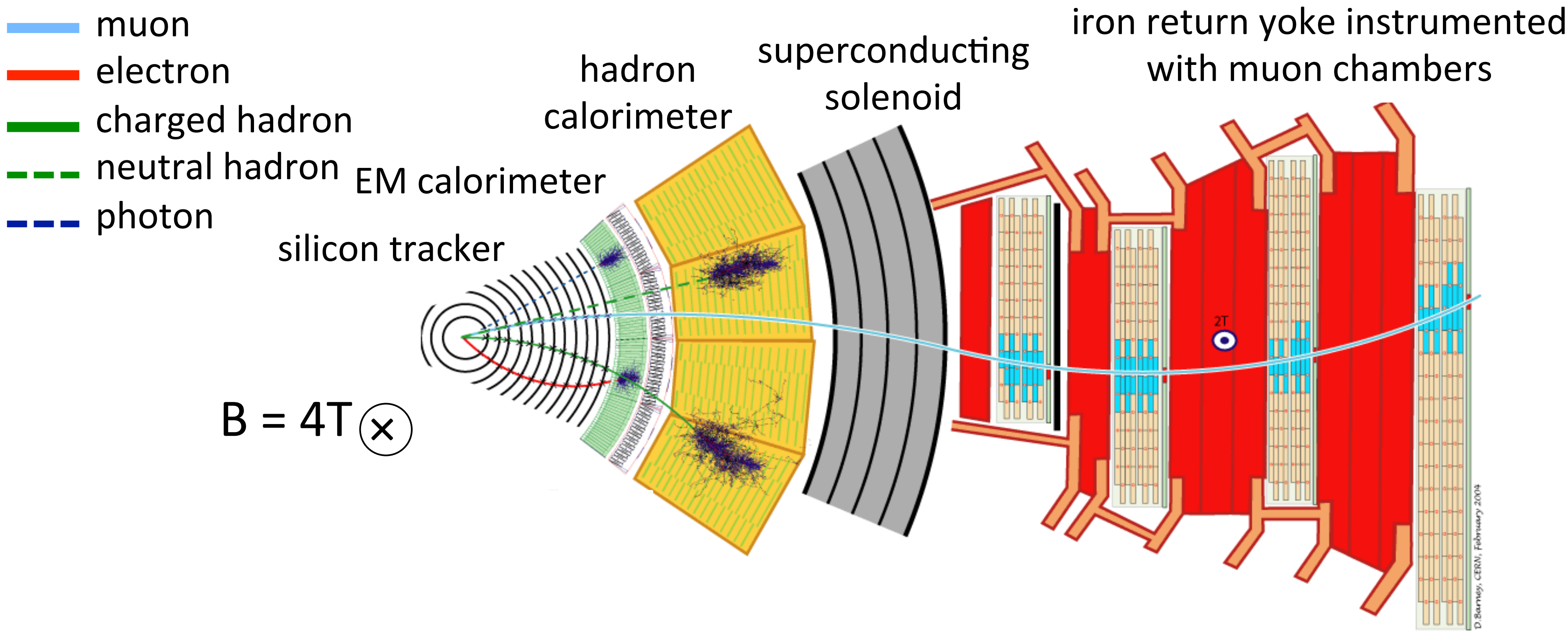
BSM/SUSY Challenges

- **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 background 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 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

1-lep "Lepton-Spectrum": Backgrounds & Strategy

- **Select events with: exactly 1 isolated e/μ ($p_T > 20$ GeV) + ≥4 jets ($p_T > 40$ GeV)**

expected background composition:

- **W+jets and tt→ℓ+jets (~75%)**
  - **Challenge**: dominant bkg, don't want to rely solely on MC for tails of ISR, large top boost
  - **Estimate using "lepton-spectrum method" (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

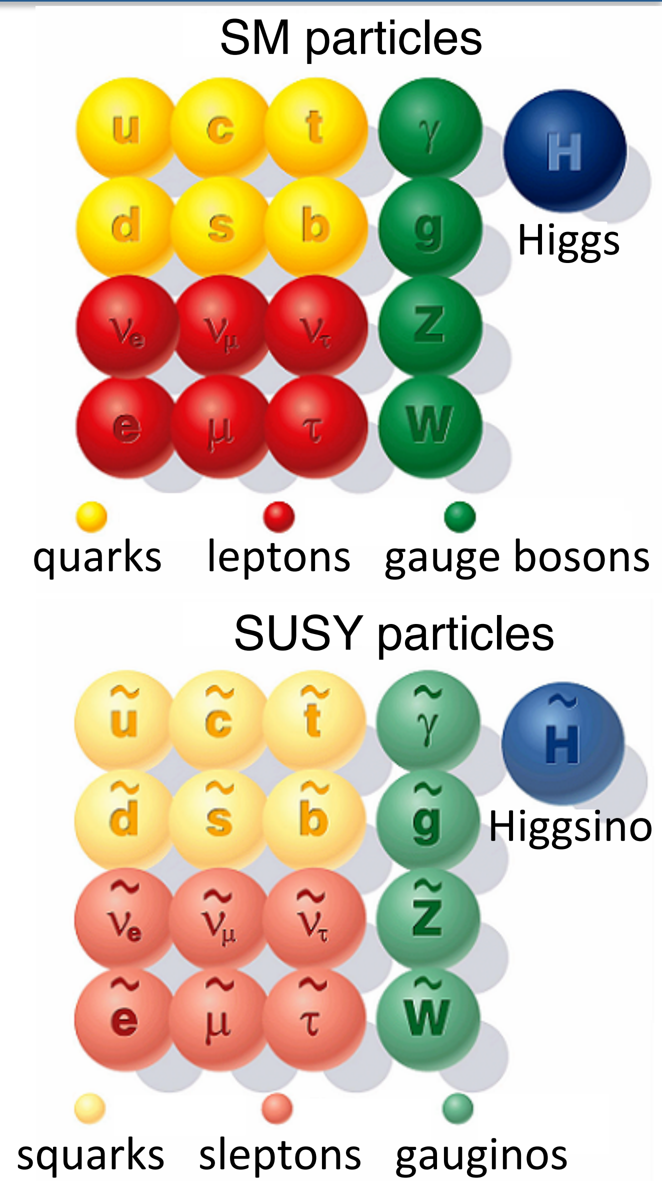
Intro to **SU**per**SY**mmetry

- 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:

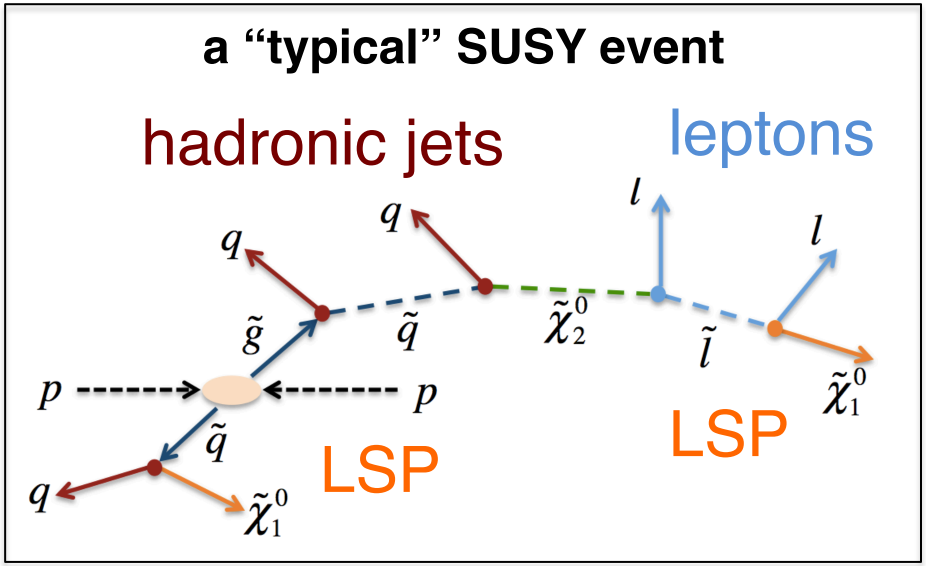
"R-parity" = $(-1)^{3(B-L)+2s}$ = { +1 SM particles, -1 SUSY particles

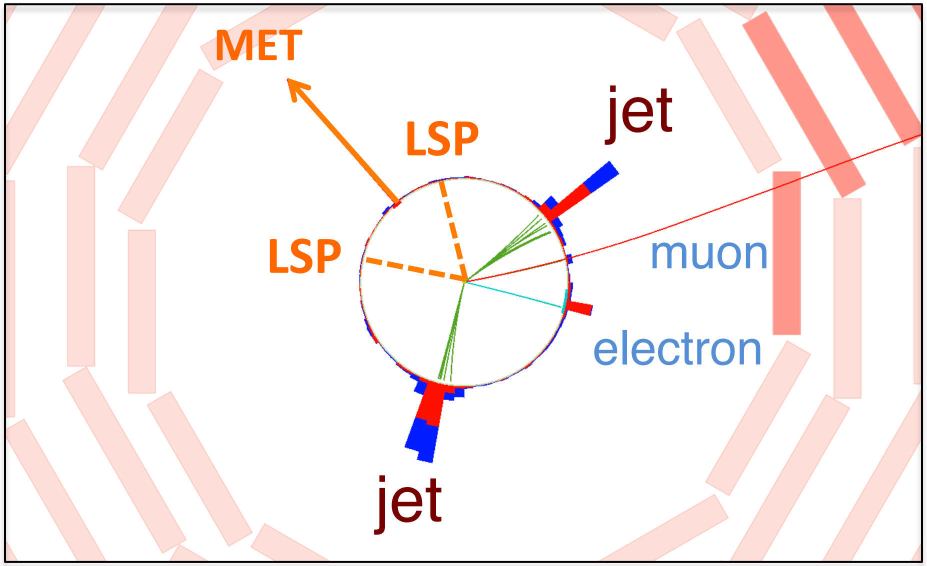
- If R-parity is conserved:
  - **SUSY particles must be pair-produced**
  - **lightest SUSY particle (LSP) is stable → DM WIMP candidate**
    - Usually χ^0, also gravitino, $\tilde{\nu}$ possible



SUSY Search Strategies

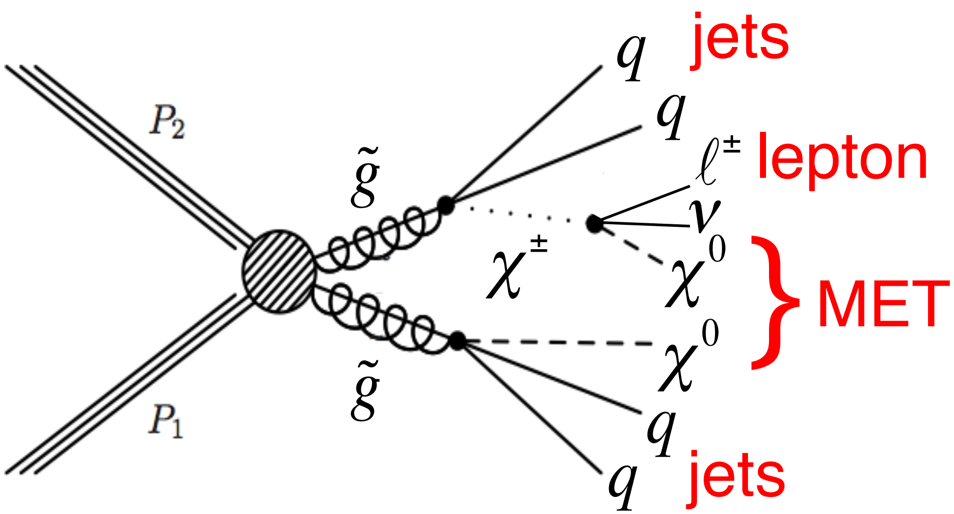
- Start by targeting SUSY with best early discovery potential:
  - Models with large σ: strong production of **heavy, colored objects** (squarks/gluinos)→ **lots of hadronic activity (H_T)**
  - **Stable, invisible LSP → lots of missing E_T (MET)**
  - **Search for excess events with large MET & H_T 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





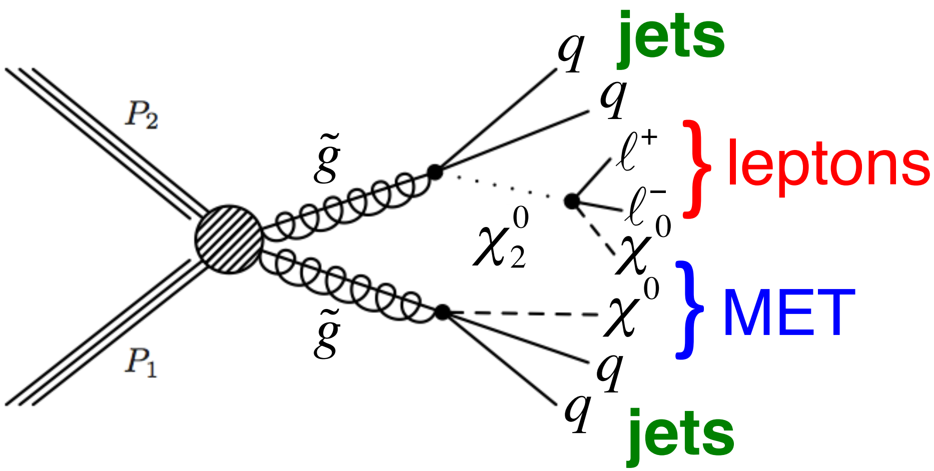
Targeted BSM Physics

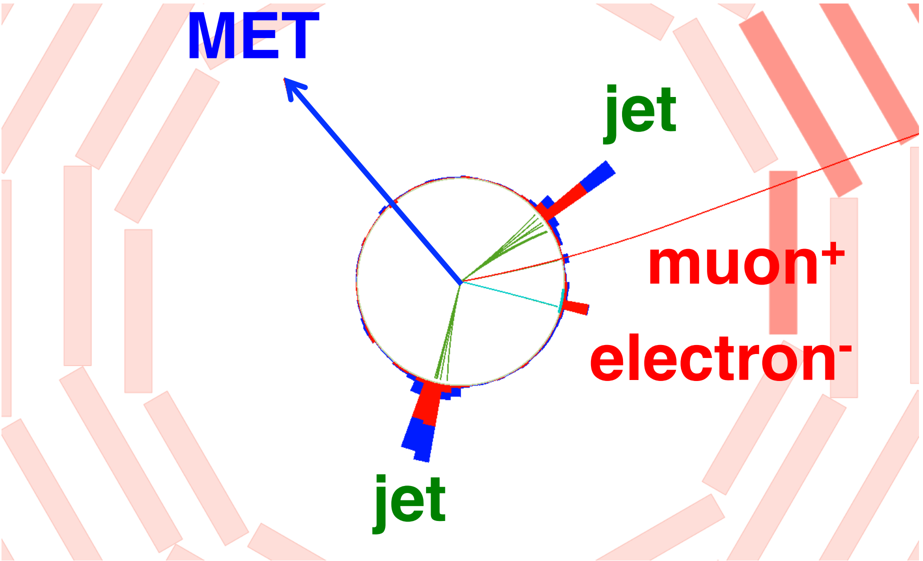
- Signatures considered here common in **SUSY** (especially R-parity conserving SUSY → large MET)
  - Results often interpreted in SUSY models
  - BUT: ***results not optimized for SUSY models***, sensitive also to other BSM physics, eg. models with extra dimensions
- **Example**: $\ell^{\pm}$ + jets + MET
  - gluino pair production, gluino decays → jets
  - 2 invisible χ^0's → MET
  - $\chi^{\pm}$ decay → lepton



OS: Introduction

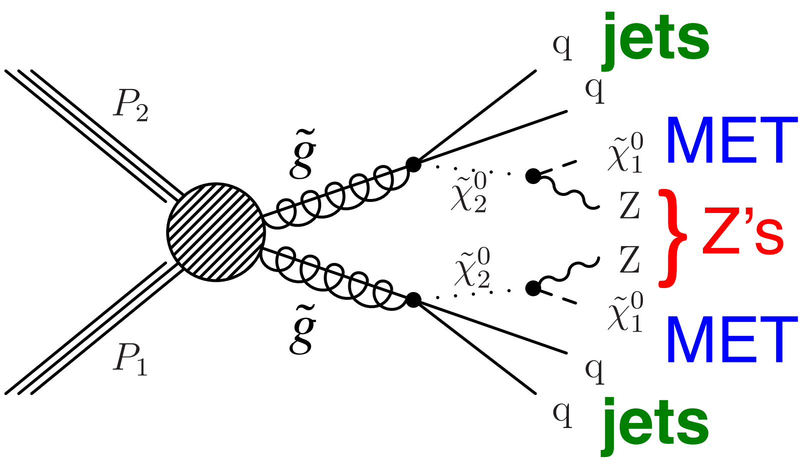
example signal:
SUSY with $\chi_2^0 \rightarrow \ell^+ \ell^- \chi^0$ decay

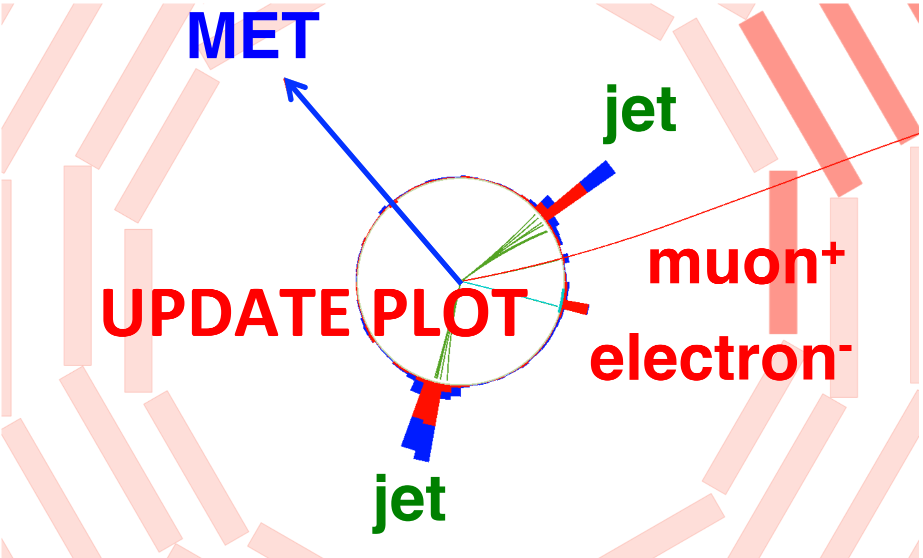




- Require 2nd opposite-sign lepton ➞ suppress W+jets
- **Signature: opposite-sign (OS) leptons (ee/eμ/μμ/eτ/μτ/ττ) + jets + MET**
- **Perform counting experiments in large MET vs. H_T signal regions and search for "kinematic edge" in M(ℓℓ) distribution**

example signal:
SUSY with $\chi_2^0 \rightarrow Z\,\chi^0$ decay's





- Require $Z \rightarrow \ell^+\ell^-$ → suppress W+jets, ttbar
- **Signature: $Z \rightarrow ee/\mu\mu$ + jets + MET**
- **Critical experimental aspect: understand artificial MET from jet mis-measurements in SM Z+jets**

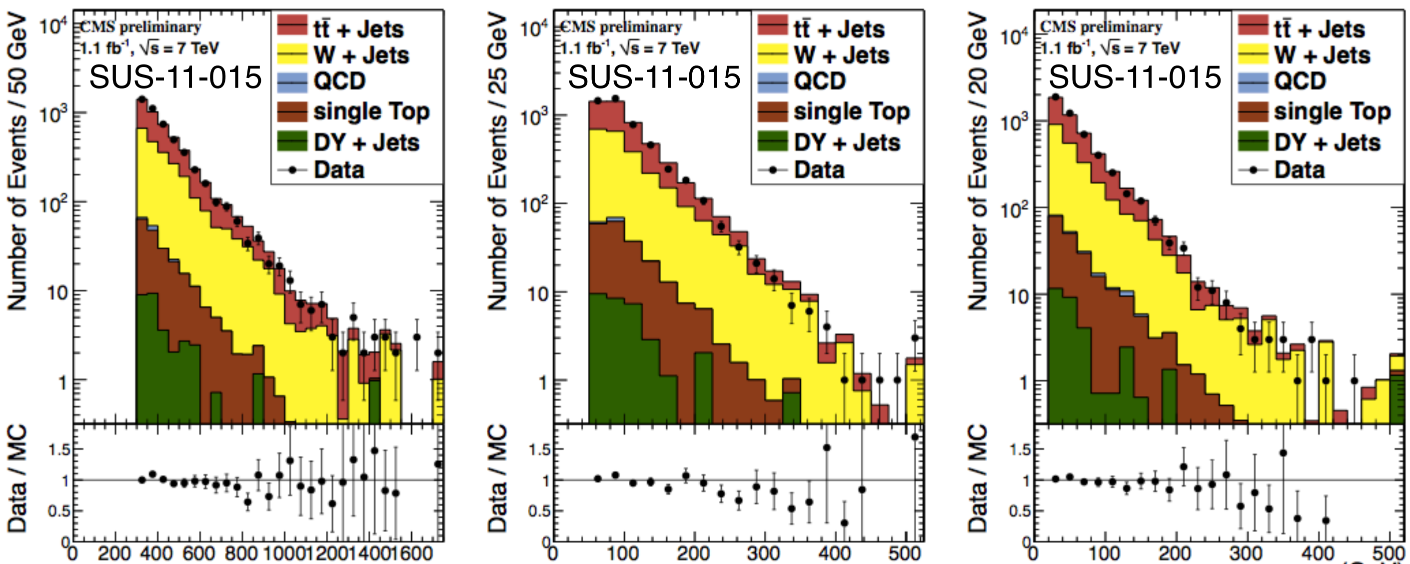
SUSY Interpretations

- 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 "model-independent results" → 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**

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)



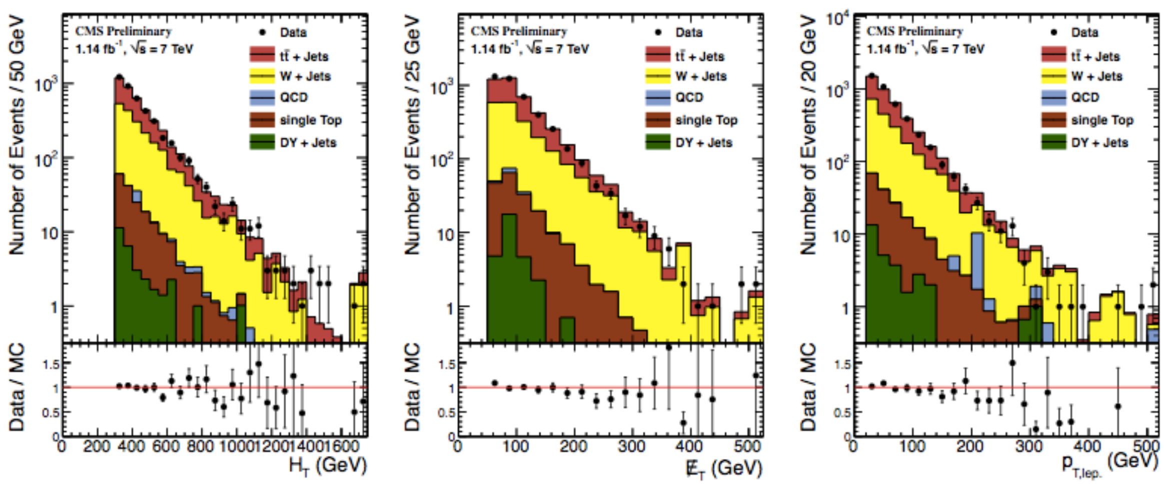
H_T (GeV) MET (GeV) μ p_T (GeV)

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

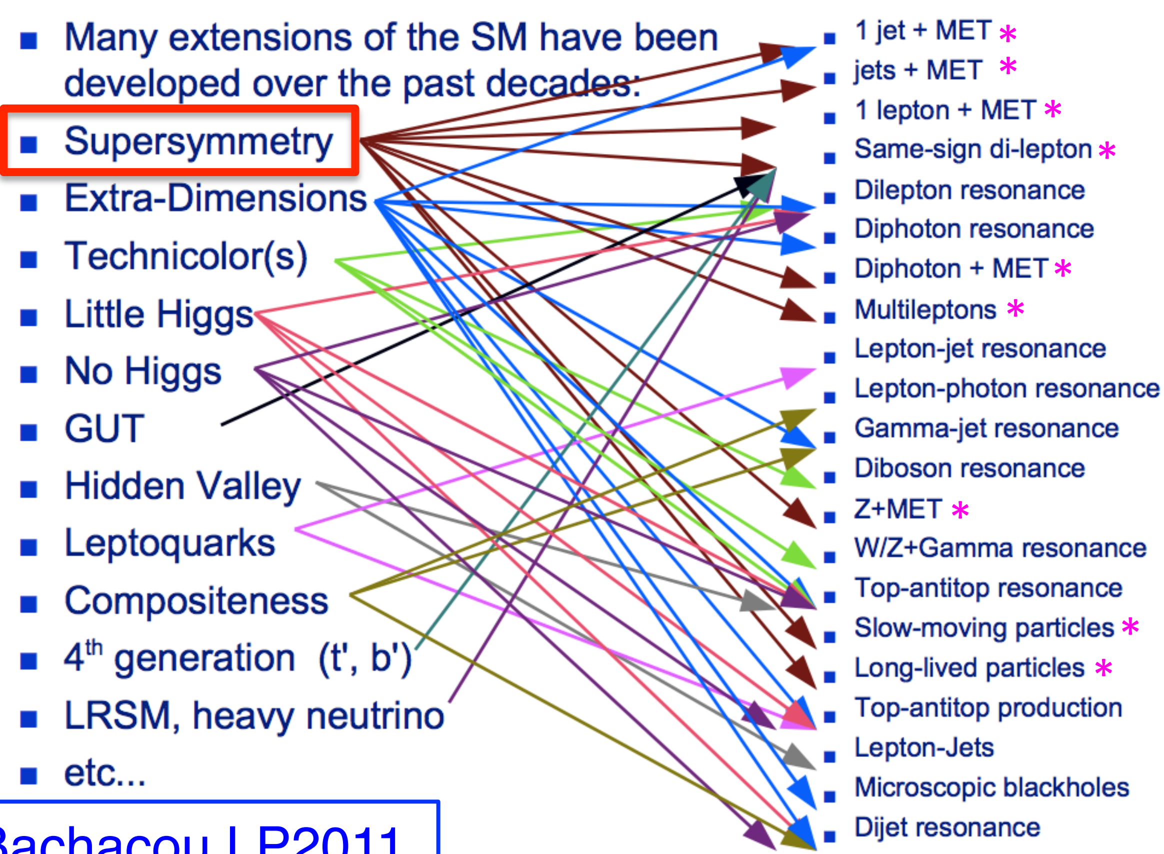


(d) e: H_T (e) e: $\not{E}_T$ (f) e: p_T

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.

SUSY Signatures

new physics scenarios **signatures**

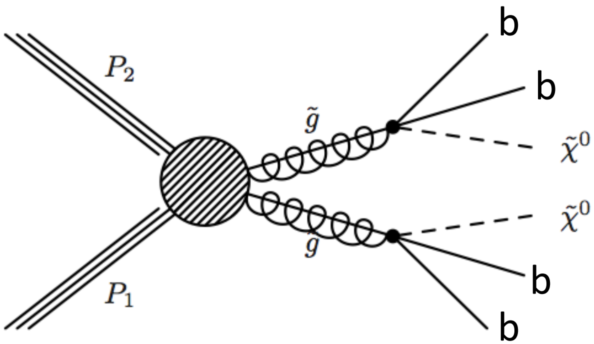


Bachacou LP2011

* possible SUSY signatures

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

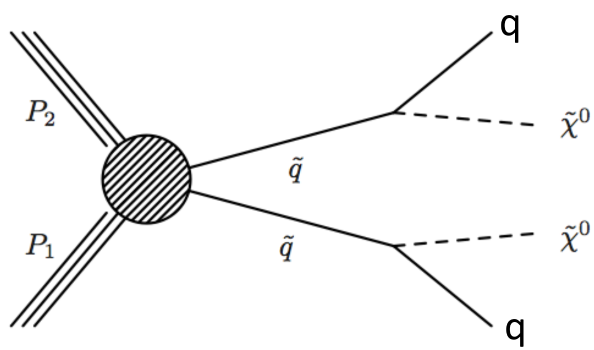
More Simplified Models



gg → 4 b-jets + MET

all-hadronic w/ b-tags

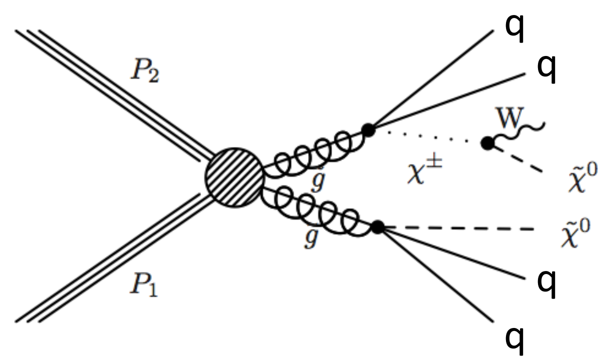
M(g), M(χ^0)



qq → 2 jets + MET

all-hadronic

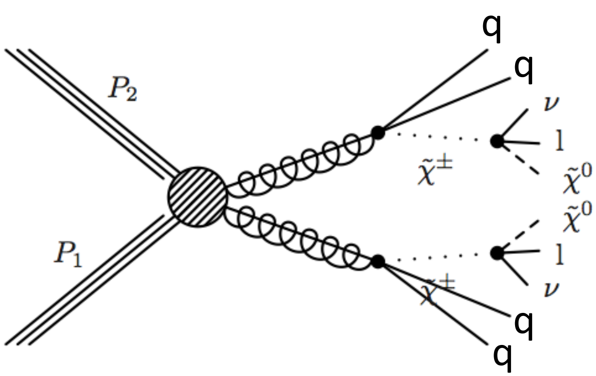
M(q), M(χ^0)



gg → 4 jets + $l^{\pm}$ + MET

single-lepton

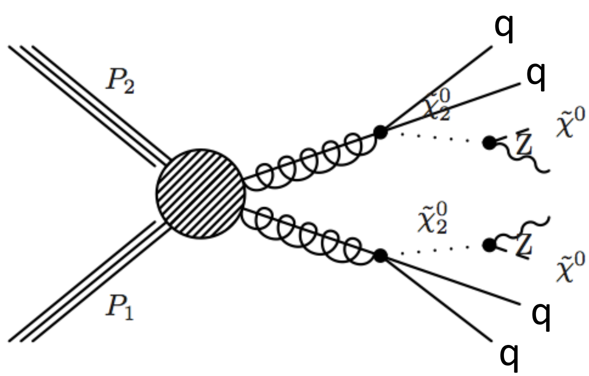
M(g), M($\chi^{\pm}$), M(χ^0)



qq → 4 jets + ll + MET

dilepton (SS best sensitivity)

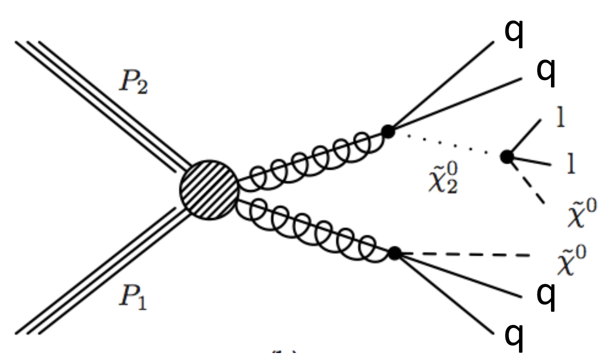
M(g), M($\chi^{\pm}$), M(χ^0)



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)

Z+jets+MET: Motivation

- Search for BSM physics in final states with **Z→ee/μμ + jets + MET**
  - Focus on strong production (large σ) → **jets**
  - Focus on events with invisible WIMP's → **MET**
  - **Z→ee/μμ provides clean final state** (suppresses QCD, W+jets, Z→νν, etc)

- In SUSY, **Z's produced in χ^0 decays** → large branching fraction if χ^0 has large wino/higgsino component

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$

$\tilde{\chi}_1^0$ = lightest neutralino LSP

$\tilde{\chi}_1^0 \rightarrow \tilde{G} Z$

$\tilde{G}$= gravitino LSP