Search for Supersymmetry at the LHC

V. Daniel Elvira
Fermi National Accelerator Laboratory

- Part I: Motivation and Physics Objects ID

  Why we search for SUSY. Detector properties and Physics Object reconstruction . The Standard Model benchmarks.

- Part II: Data analysis in SUSY Searches

  Elements of a SUSY analysis and their integration in a search result. Concepts of data selection, background estimation, control and signal samples, event excess, mass and cross section limits

- Part III: Search for SUSY in CMS

  Recent public results of SUSY searches in CMS (mostly) based on a 36 pb^{-1} data sample collected during 2010. Comparison with results from ATLAS.

Bibliography

CMS Physics Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

- Plots and Results
- Journal Publications
- Physics Analysis Summaries – public documents

ATLAS Physics Results

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

SUSY Searches in CMS

V. Daniel Elvira
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CMS Search Strategy

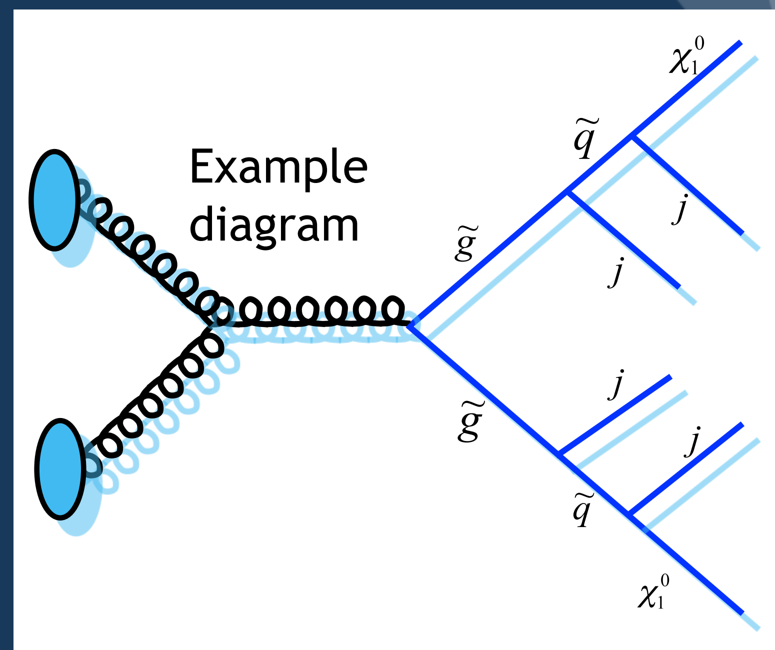
Summarizing what we already learned:

- Model independence. If we assume SUSY exists, we still do not know the details. We look everywhere, focus on topologies, cover as much phase space as possible
- Event Topology. Categorized by numbers of leptons and photons, may include jet requirement, use MET-like sensitive variables
- Counting experiments. In 2010, we suppressed SM background, estimated its residual, counted observed events in search for an excess
- Background predictions. Multiple methods for each background in each analysis based on actual data (not MC). Solid foundation built in preparation for a potential discovery.
- Set limits on MSSM, GGM, Simplified Models in absence of signal.

CMS Search Strategy: Topologies

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Most sensitive channel for strongly produced SUSY
- May include b, top, τ in final state
- Complementary analyses:
  - ➢ Generic search using MHT (previous lecture) – detector understanding
  - ➢ Search using α_T - background mitigation (kinematics)
  - ➢ "Razor" variables - background mitigation with high signal efficiency (kinematics)



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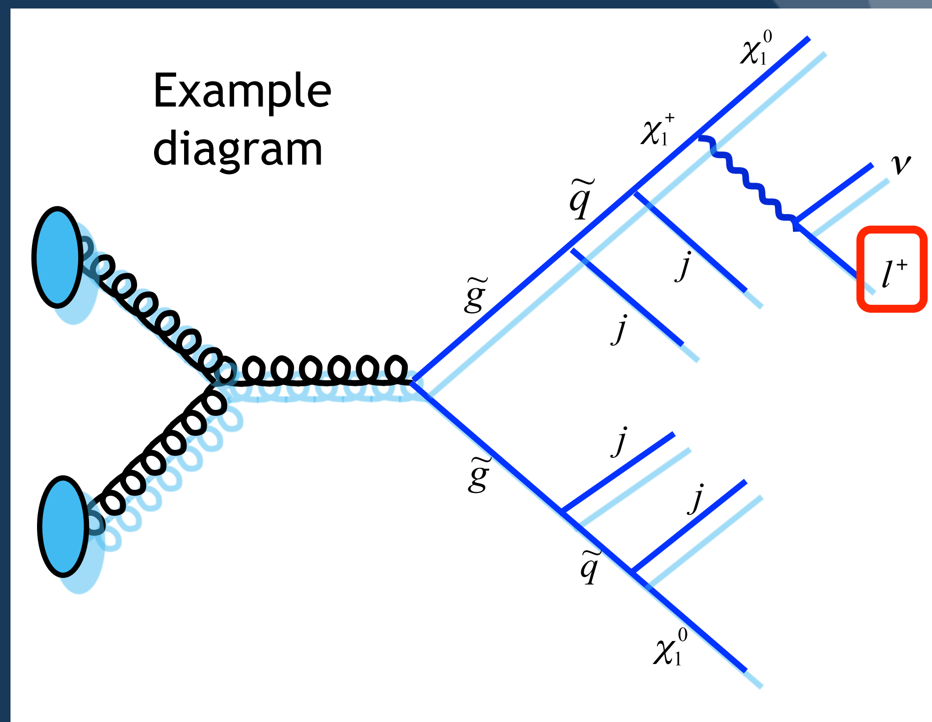
- Lepton requirement reduces the background significantly
- Top and W+jets remain
- Lower signal efficiency



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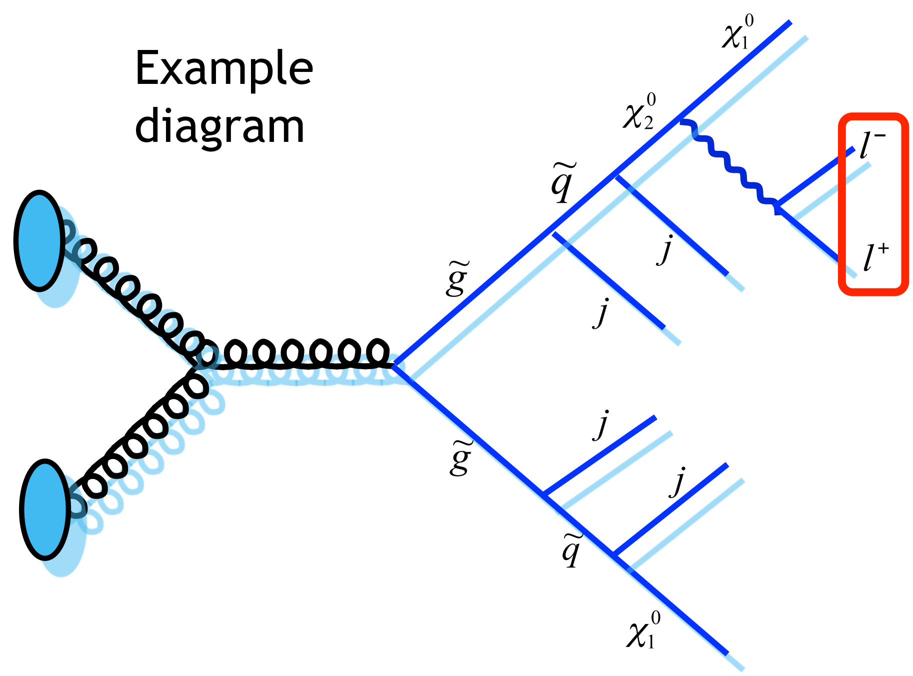
- A two lepton requirement reduces the W background
  - Inclusive and Z peak search analyses
- Even lower signal efficiency

Example diagram



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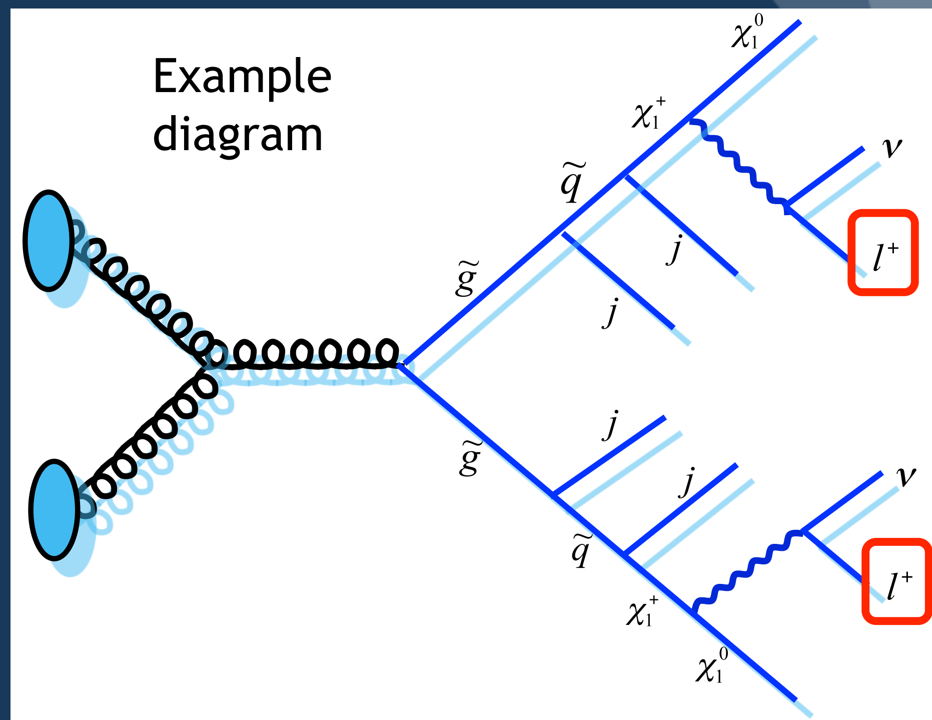
- Very small background and signal efficiency



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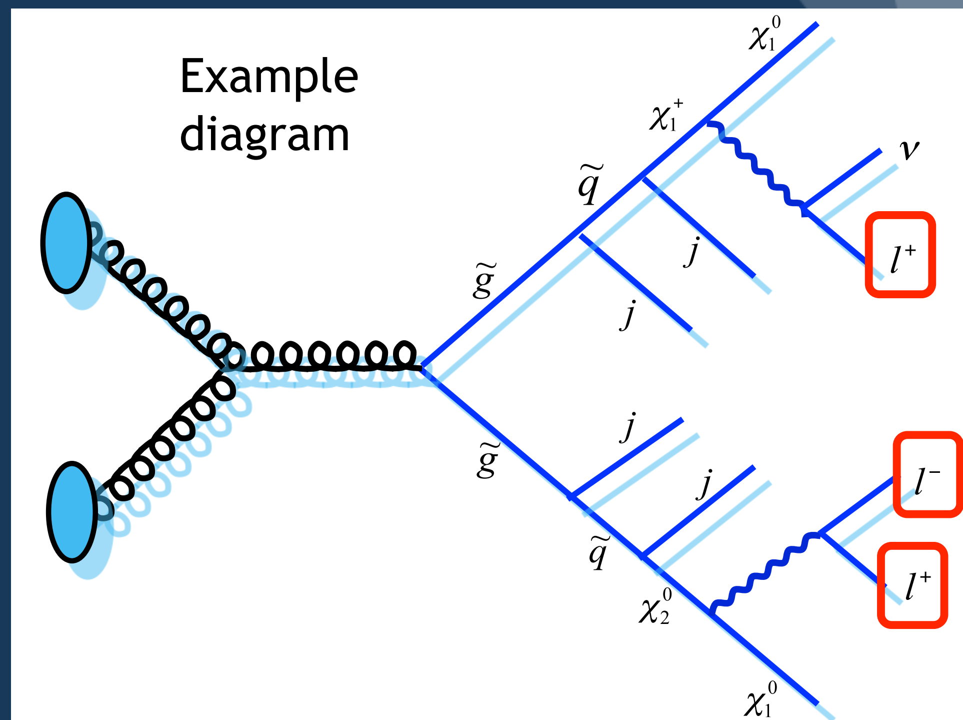
- Very low SM background
  - Clean events
  - Inclusive and Z peak search
- Analysis includes all combinations of the three lepton types (e, μ, τ)



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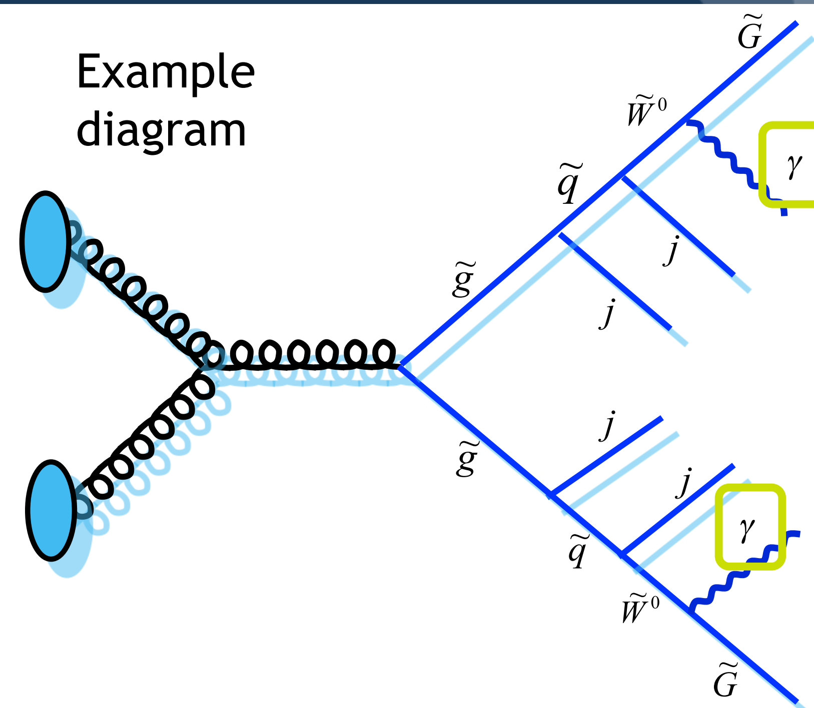
Example diagram



- Gauge Mediated (GGM) SUSY models predict photons in the final state
  - Two neutralinos ➔di-photon+jets+MET
- QCD & γ+jets backgrounds

CMS Search Strategy: Topologies

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
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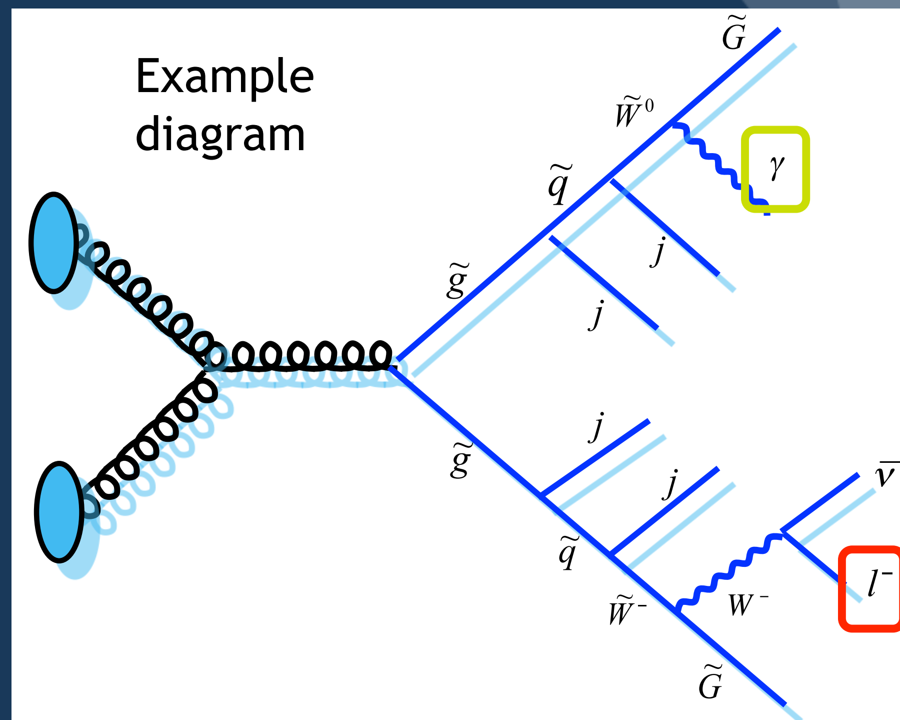
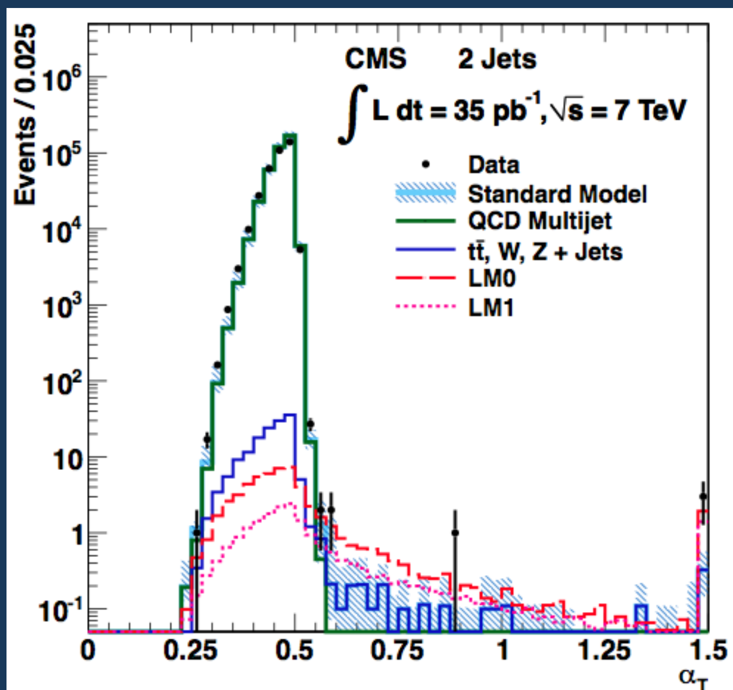
- Gauge Mediated (GGM) SUSY models predict photons in the final state
  - Chargino+neutralino ➔γ+lepton+jets+MET
- Background reduced



Jets+MET Search using α_T

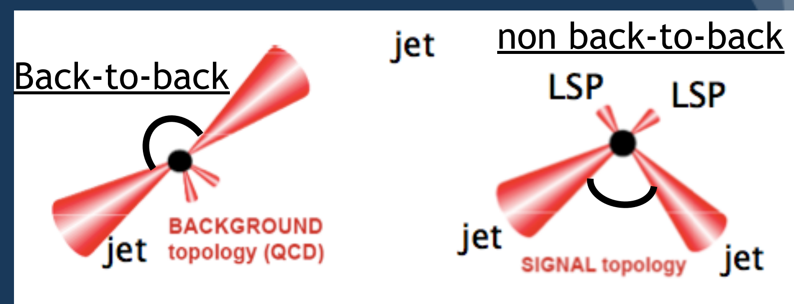
Simple and robust analysis with emphasis on background reduction at the cost of signal efficiency ➔ appropriate for early data

- Cut on kinematic info (α_T variable): signal region nearly QCD free
- Background dominated by events with real MET: EWK and top



PRL 101:221803 (2008) & arXiv:1101.1628

$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}} = \frac{1}{2}\frac{H_T-\Delta H_T}{\sqrt{H_T^2-\not{H}_T^2}}$$



Expectation for QCD: α_T=0.5

Jet mis-measurement: α_T<0.5

Signal enhanced: α_T>0.5

Jets+MET Search using α_T

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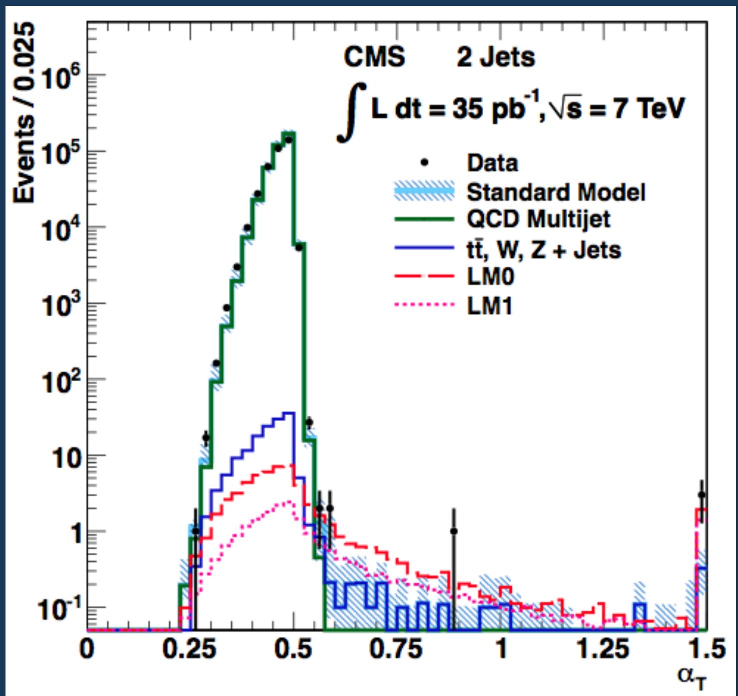

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Spill-over in α_T>0.5:

- Processes with real MET (EWK, top, SUSY)
- QCD remnants

Jets+MET Search using α_T

Simple and robust analysis with emphasis on background reduction at the cost of signal efficiency ➔ appropriate for early data

- Cut on kinematic info (α_T variable): signal region nearly QCD free
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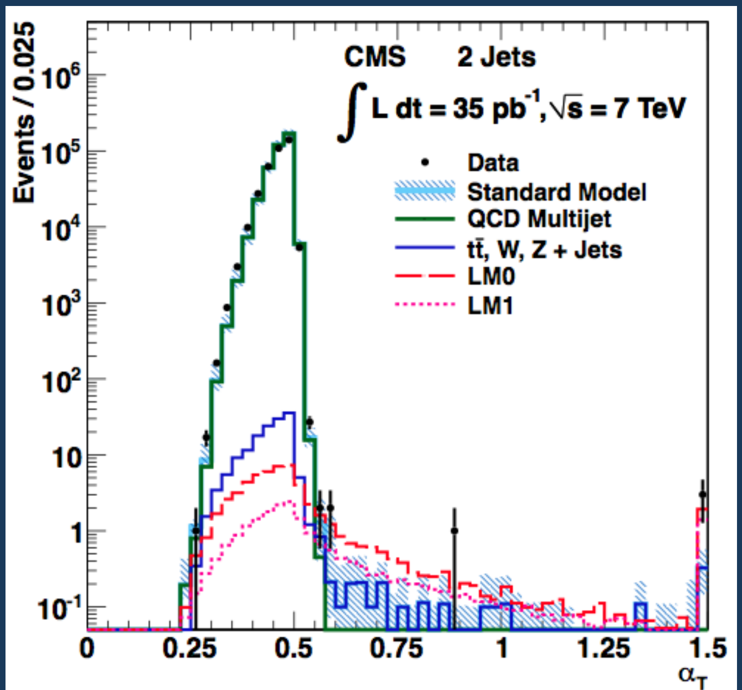
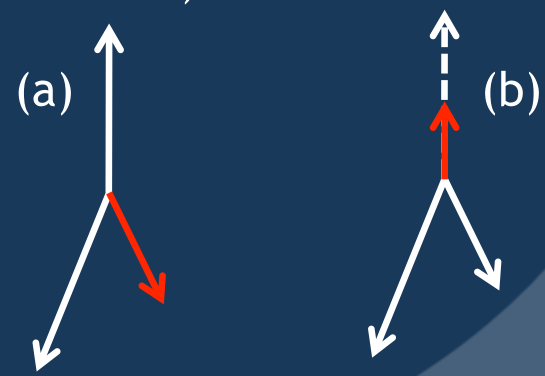


PRL 101:221803 (2008) & arXiv:1101.1628

QCD remnants (α_T>0.5):

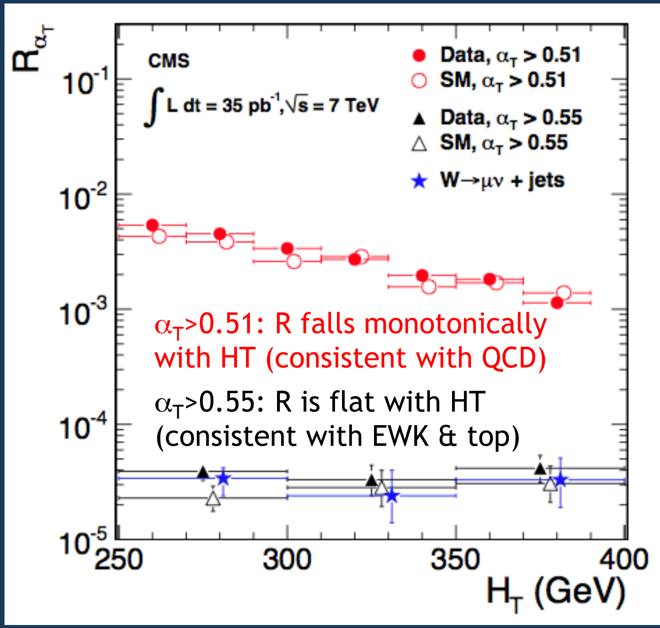
a) Jets lost due to min p_T cut in HT
b) Catastrophic mis-measurement (leading jet fluctuation below threshold)



Jets+MET Search using α_T

Event selection:

- HT triggers, # jets ≥ 2, p_T>50 GeV, |η|<3 (CaloJets, Anti-kT R=0.5)
- Background dominated by events with real MET: EWK and top
- Leading jet |η|<2.5, p_{Tj1}>100 GeV
- Veto events with isolated leptons or photons
- HT>350 GeV and α_T>0.55



Total background prediction:

- Define $R_{\alpha T}$=($N_{\alpha T}$>0.55)/($N_{\alpha T}$<0.55)
- Two control regions (background dominated):
  HT=[250,300] & [300,350] GeV
- Define ratio of ratios:

$$\frac{R_{\alpha_T}(HT300)}{R_{\alpha_T}(HT250)} = \frac{R_{\alpha_T}(HT350)}{R_{\alpha_T}(HT300)} = Const.$$

$$N^{evts}_{\alpha_T>0.55}(HT350) = N^{evts}_{\alpha_T<0.55}(HT350) \times R_{\alpha_T}(HT300) \times Const.$$

Jets+MET Search using α_T

PRL 101:221803 (2008) & arXiv:1101.1628

Events observed: 13

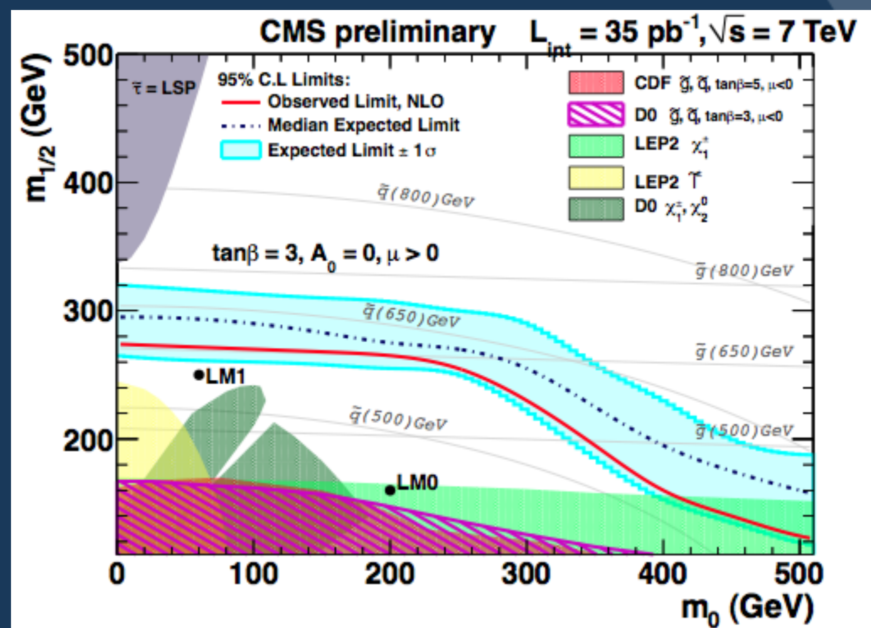
Total background estimate: $9.4^{+4.8}_{-4.0}$ (stat) ± 1.0 (syst)

Background cross verification:

- W and top from W($\mu\nu$)+jets control sample $6.1^{+2.8}_{-1.9}$ (stat) $\pm$ 1.8 (syst)
- Z($\nu\nu$) from γ+jets $4.4^{+2.3}_{-1.6}$ (stat) $\pm$ 1.8 (syst)

Alternate background estimation indicates final selection is QCD free

Significant extension of excluded regions over Tevatron experiments



Jets+MET Search using α_T

α_T: —
Published first

Weak dependence on tan β =3,10,50

Efficiency maps,
x-section limits (CMSSM & simplified models):

CMS-SUS-11-001

Jets+MET Search using α_T

α_T: — Published first

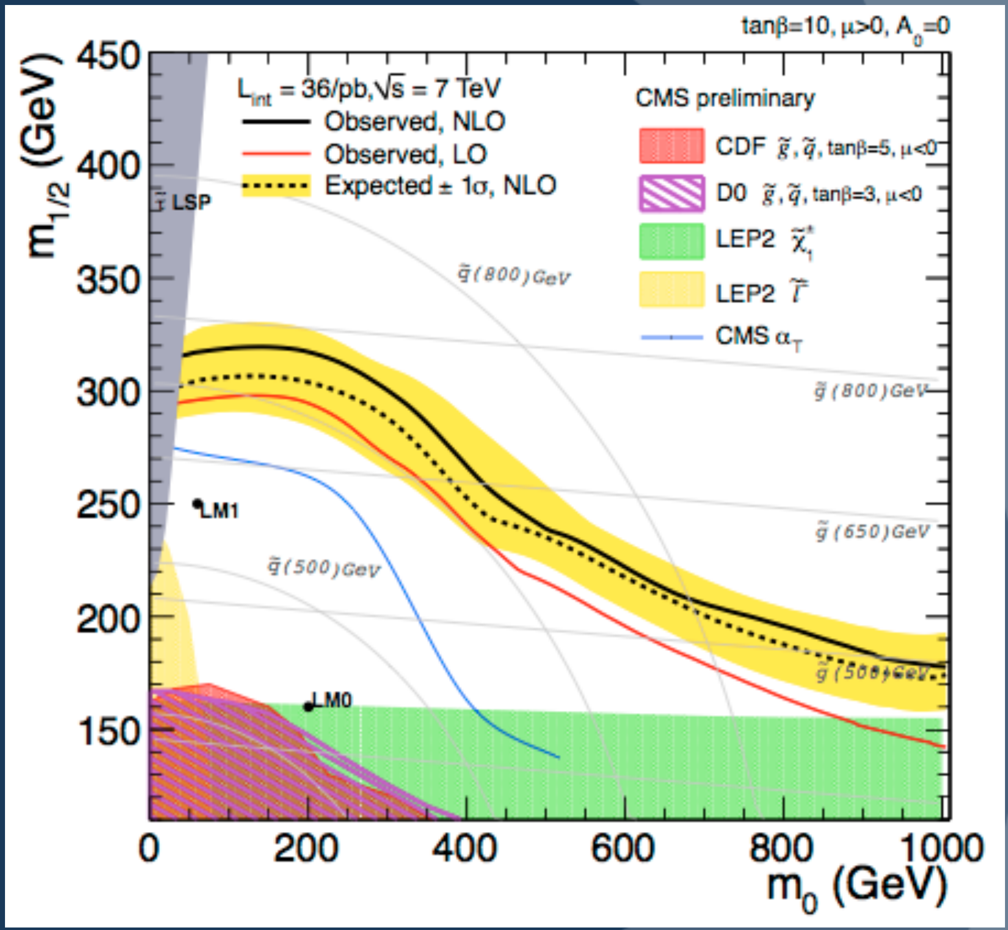
MHT: — (previous lecture) Superseeds α_T

Weak dependence on tan β (=3,10,50)

Efficiency maps, x-section limits (CMSSM & simplified models):

CMS-SUS-11-001

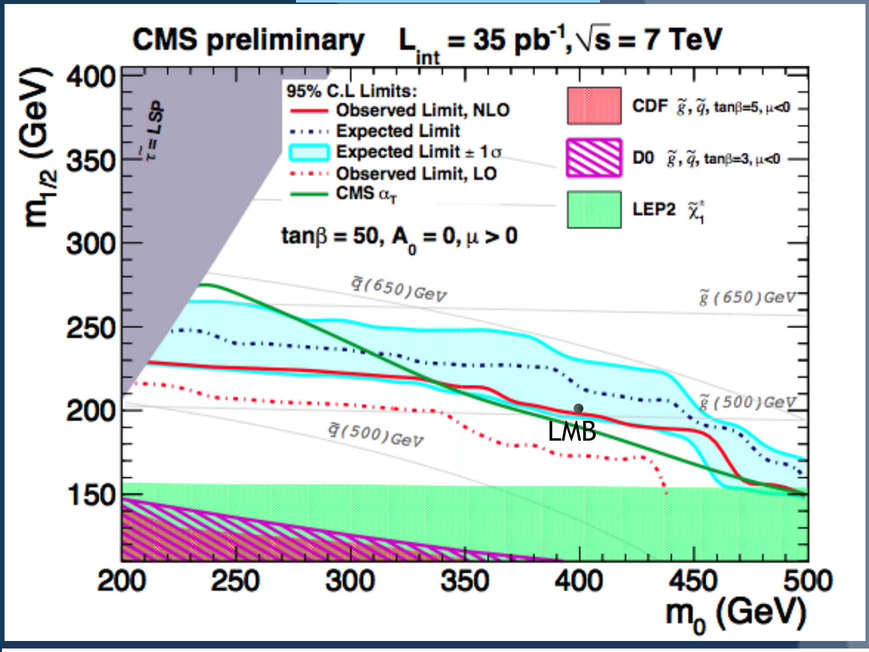
α_T and MHT result comparison



Jets+MET with α_T and a b-tag

CMS-SUS-10-011

- Same event selection as for the inclusive α_T and:
  - One jet is b-tagged (TCHP>3.41)
- Increased sensitivity for b-rich SUSY models
- b-jet requirement reduces QCD & EWK backgrounds
  - Top background dominates
- Background estimated as in the inclusive α_T
  - W/top cross checked with μ control sample
  - Z($\nu\nu$) cross checked with Z ($\mu\mu$)+jets



N-jets	MC	Background Prediction	Data	LM0
≥ 2	1.61 ± 0.26	$0.33^{+0.43}_{-0.33}$ (stat) ± 0.13 (syst)	1	14.2 ± 0.3

Excluded region is extended for m_0>350 GeV with respect to CMS-SUS-11-001

95% C.L. upper limits of 18.9, 15.4, 10.2 pb on x-sections for LM0, LM1, LMB

Jets+MET Search: The Razor

Razor search designed to discriminate heavy pair production kinematically from SM backgrounds

- No assumptions on MET or details of decay chain

CMS-SUS-10-009

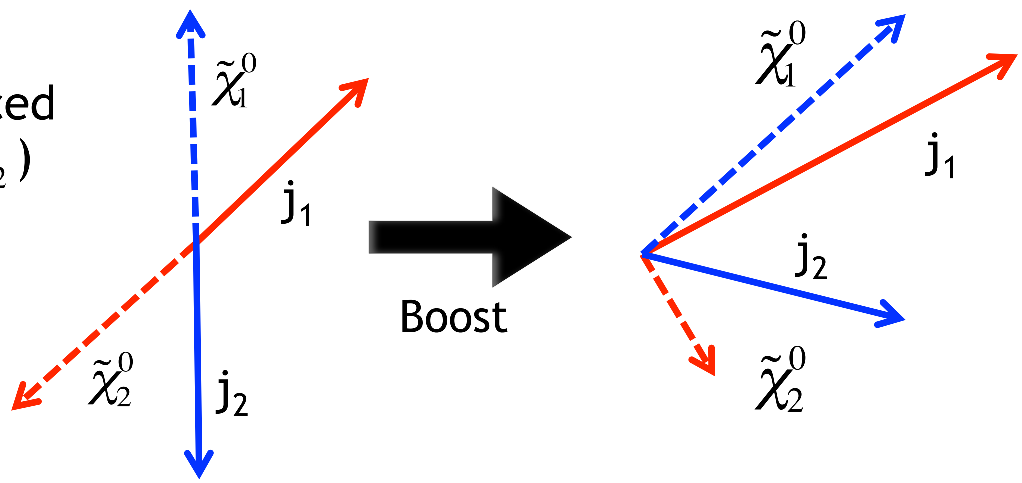
<u>CM frame</u>

M_R definition: signal

<u>Laboratory Frame</u>

- Two massive particles produced at rest (e.g. $\tilde{q}_1\tilde{q}_2$)

$$p_{j_{1,2}} = \frac{M_\Delta}{2} = \frac{1}{2}\frac{M^2_{\tilde{q}_{1,2}} - M^2_{\chi_{1,2}}}{M_{\tilde{q}_{1,2}}}$$



R frame equalizes 3-momentum of the two jets = *CM frame* if no ISR

$$M_R = 2p = M_\Delta$$

M_R peaks for the signal at the mass scale of the heavy particle, M_Δ

Jets+MET Search: The Razor

Razor search designed to discriminate heavy pair production kinematically from SM backgrounds

- No assumptions on MET or details of decay chain

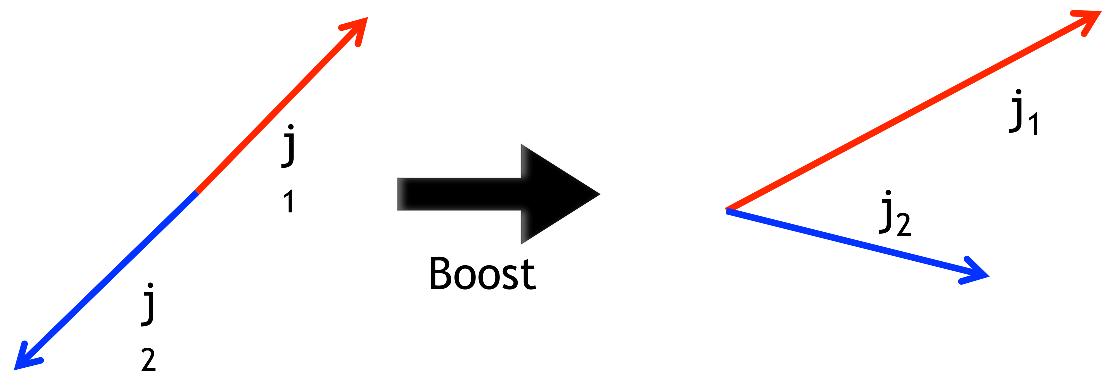
CMS-SUS-10-009

M_R definition: multijet background

<u>CM frame</u>

<u>Laboratory Frame</u>

• Two jets back-to-back



R frame equalizes 3-momentum of the two jets = *CM frame* if no ISR

$$M_R = 2p = \sqrt{\hat{s}}$$

M_R falls steeply

Jets+MET Search: The Razor

For the signal M_R is a measure of the mass of the heavy particle and peaks at the scale of the production

- Maximum of scalar sum of the p_T of the two jets is M_Δ
- The maximum value of MET is also M_Δ

Real life: multi-jet events ➔ define two hemispheres and combine jets into two mega-jets (force di-jet topology)

$$M_T^R = \sqrt{\frac{|E_T^{miss}|(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss}.(\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}$$

Transverse M_R has a kinematic edge of M_Δ

$$M_R = 2|\vec{p}_{j1}^R| = 2|\vec{p}_{j2}^R| \sqrt{\frac{(E^{j1}p_z^{j2} - E^{j2}p_z^{j1})^2}{(p_z^{j1} - p_z^{j2})^2 - (E^{j1} - E^{j2})^2}}$$

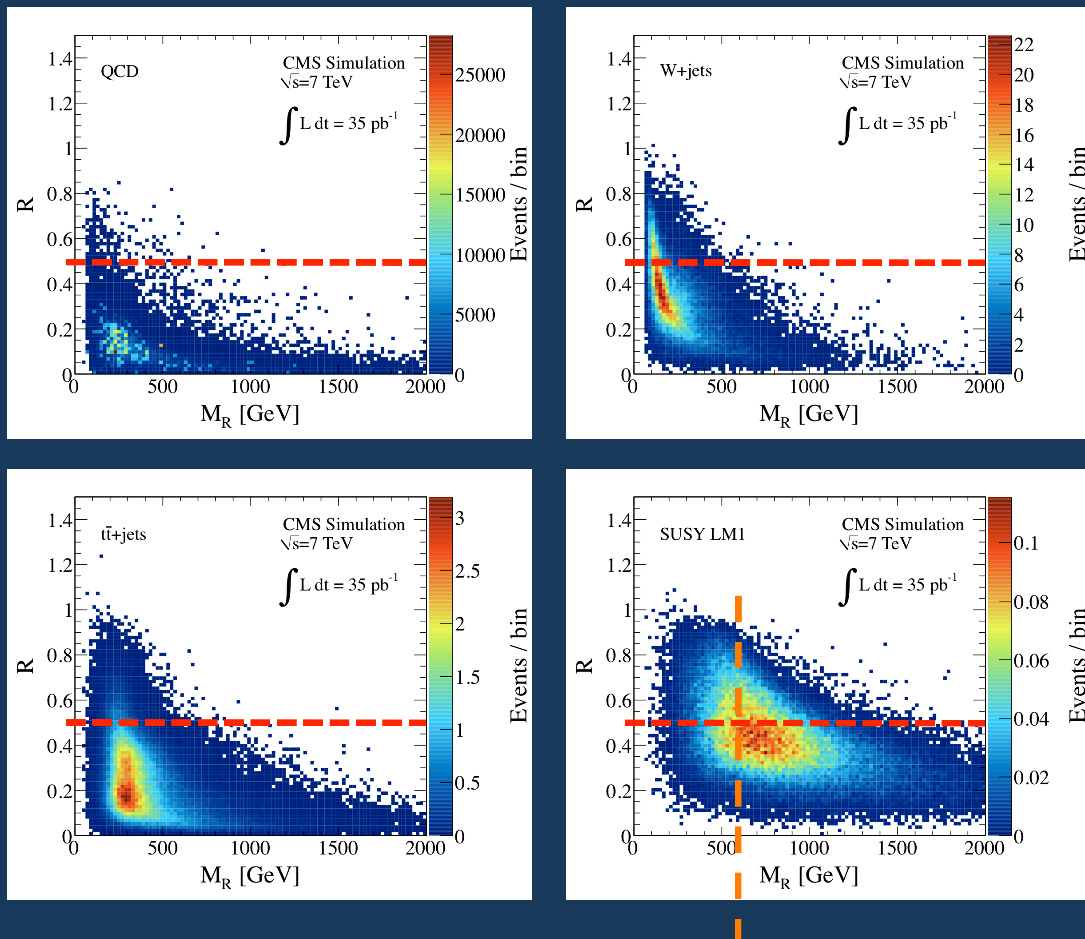
M_R peaks at mass scale M_Δ

$$R \equiv \frac{M_T^R}{M_R}$$

Razor (R) has a kinematic edge of 1, peaks at 0.5

Razor used to separate signal from background

Jets+MET Search: The Razor



CMS-SUS-10-009

Peak at M_{Δ}=597 GeV for LM1

A cut on R>0.5 leaves a good fraction of the signal

- QCD "free"
- Eliminates most of top
- Reduces W/Z+jets significantly

Razor search is a bump hunt

Jets+MET Search: The Razor

Baseline selection:

- HT triggers
- At least two CaloJets (Anti-kT D=0.5)
- Jet p_T>30 GeV, $|\eta|<3$
- Detector filters, jet ID cuts
- If more than two jets, combine them in mega-jets (minimize M_{jj}^2)
- Signal region defined with cuts on R and M_R

Disjoint boxes to isolate difference physics processes

Lepton, QCD control boxes used for data driven background prediction in the hadronic signal box

Electron box

Muon box

Lepton triggers, p_T^l>20 GeV

- Electron or muon ID
- e/μ isolation inversion for QCD control samples

Hadronic signal box

HT triggers

- Veto electrons or muons as defined in e/μ boxes

QCD control box

Dijet triggers

Jets+MET Search: The Razor

Background predictions:

- QCD
  - Shape taken from QCD control box
- W+jets, top+X
  - Data/MC ratio measured from lepton boxes
  - Ratio applied to MC calculation of each separate background process and this modified MC is used to predict background shapes
  - Normalization taken from CMS measured W+jets, top x-sections
- $Z(\nu\nu)$
  - Data/MC ratio measured from lepton boxes with leptons taken as "neutrinos" in mega-jet construction
  - Procedure to extract prediction same as for W+jets, top+X

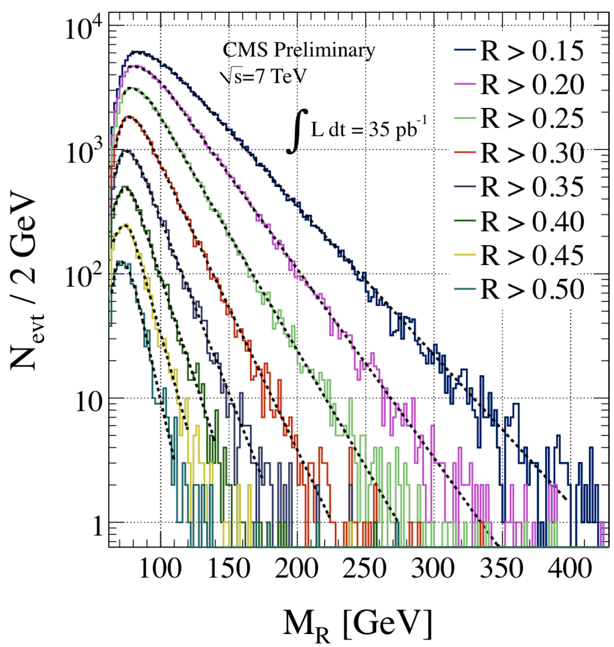
With shapes and normalization of all but QCD background fixed, determine QCD normalization from low M_R in hadronic box

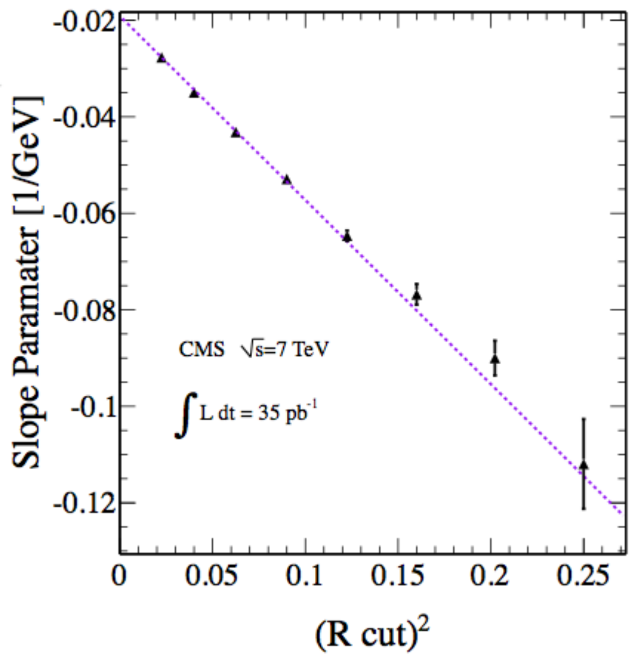
Measurement of ratios — Concept

- Ratio measurement allow to cancel systematic uncertainties when not known in detail
- Modified (scaled) MC by measured data/MC factor is a popular trick in HEP analysis to derive data driven estimates of efficiencies, calibration factors, backgrounds

Jets+MET Search: The Razor

Background predictions





<u>QCD control sample</u>

- R threshold ➔ exponential M_R
- M_R fitted slope scales with R^2 :

$$N^{evts} = e^{-SM_R}$$
$$S = a + bR^2$$

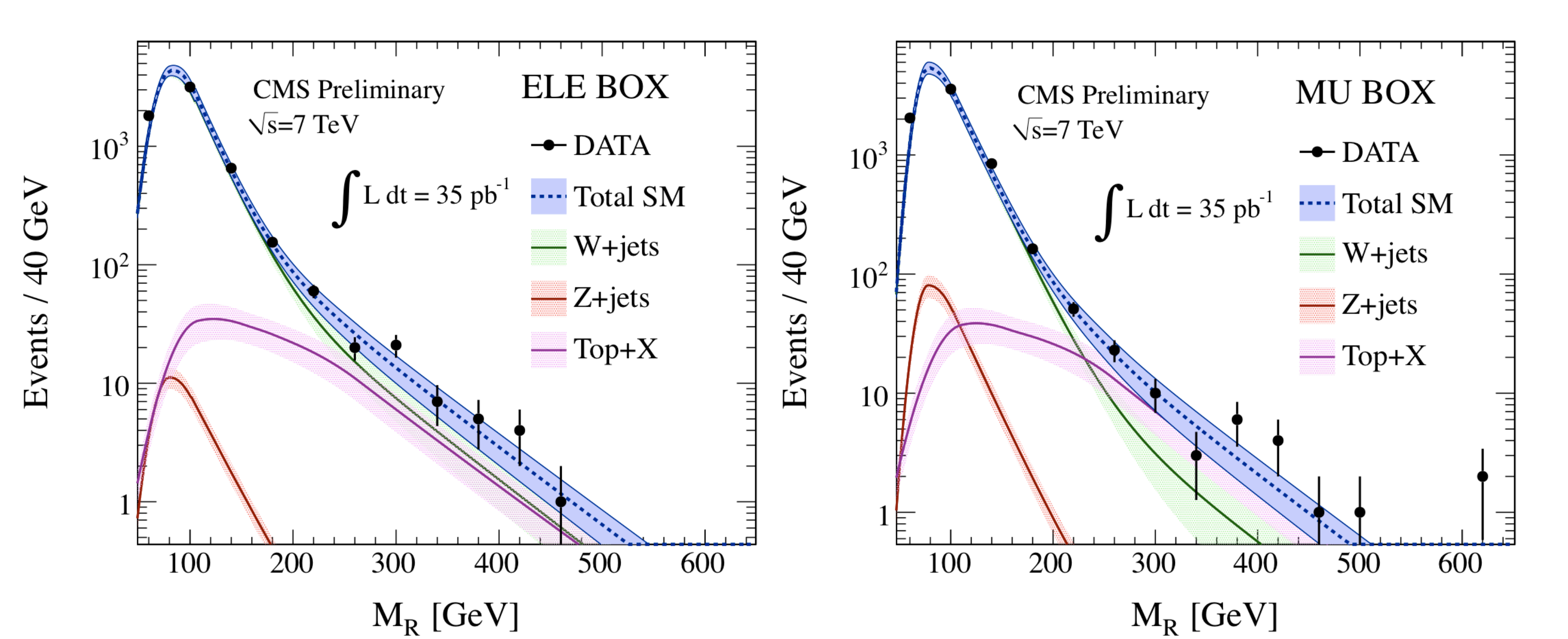
CMS-SUS-10-009

EWK and top background show similar scaling behavior

- Significant background reduction achieved through the Razor cut
- QCD, EWK, top measured in control regions and extrapolated to signal region R>0.5, M_R> 500 GeV

Jets+MET Search: The Razor

Results: electron and muon boxes



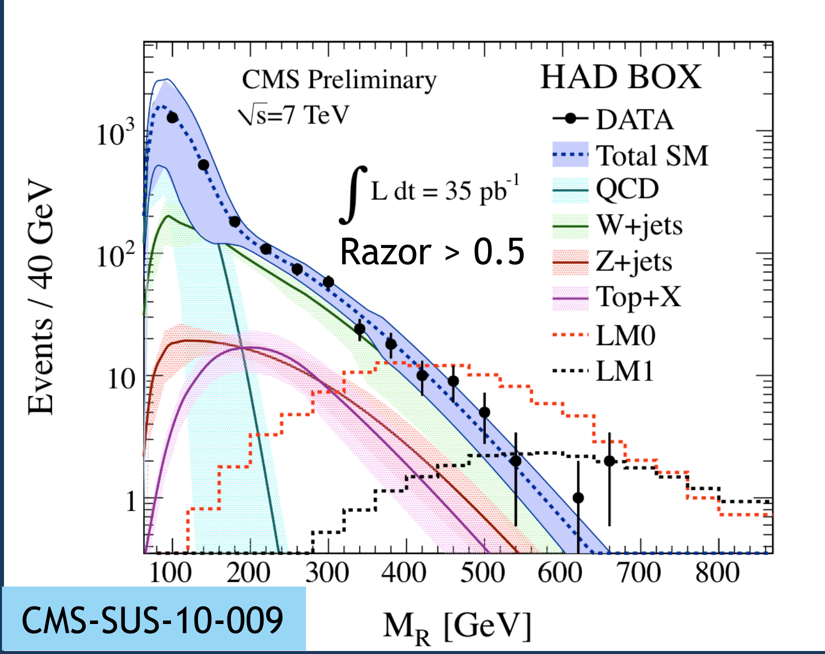
Only low M_R region used to predict backgrounds, higher M_R regions are also searches

R (0.45) / M_R (500)	Predicted	Observed
ELE box	0.63 ± 0.23	0
MU box	0.51 ± 0.20	3

CMS-SUS-10-009

Jets+MET Search: The Razor

Results: hadronic signal box (Razor > 0.5), no excess observed



CMS-SUS-10-009

M_R cut	Predicted	Observed
$M_R > 500$ GeV	5.5 ± 1.4	7

Model independent 95% C.L. limit on # of events using Bayesian procedure:

Box	Expected	Observed
MU	3.5±1.1	6.3
ELE	3.6±1.1	2.9
HAD	7.2±2.7	8.4

The limit is projected on the m_0 and $m_{1/2}$ plane for CMSSM and compared with the predicted yield

Limit also calculated for two benchmark simplified models: gluino-LSP and squark-LSP production

Jets+MET Search: The Razor

Parameter	Description	Relative Magnitude
Slope parameter a	systematic bias from correlations in fits	5%
Slope parameter b	systematic bias from correlations in fits	10%
Slope parameter a	uncertainty from Monte Carlo	1-10%
Slope parameter b	uncertainty from Monte Carlo	1-10%
$\rho(a)^{DATA/MC}$	measured from DATA	3%
$\rho(b)^{DATA/MC}$	measured from DATA	3%
Normalization	systematic+statistical component	8%
Trigger Parameters	systematic from fit toys	2%
f^W	extracted in MLFit (W only)	13%
$W/t\bar{t}$ cross-section ratio	CMS measurements (top only)	40%
W/Z cross-section ratio	CMS measurements (Z only)	19%

Background prediction uncertainties

CMS-SUS-10-009

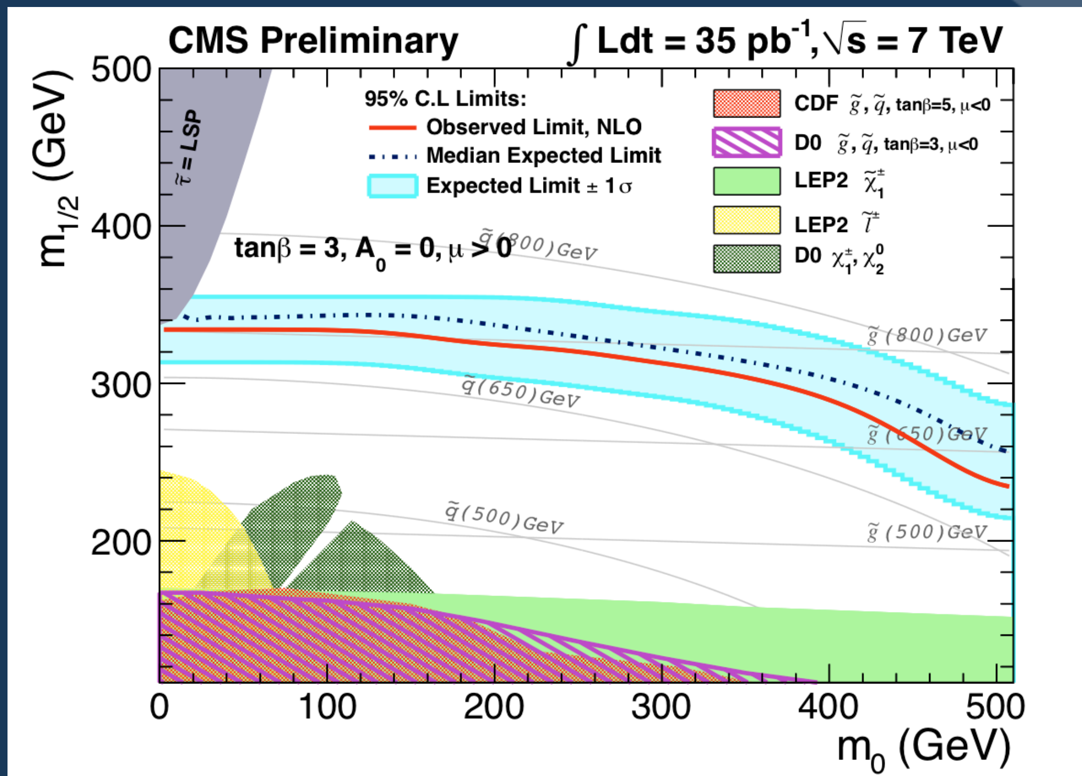
box	MU	ELE	HAD
Experiment			
JES	1%	1%	1%
Data/MC ϵ	6%	6%	6%
$\mathcal{L}$[23]	4%	4%	4%
Theory			
ISR	1%	1%	0.5%
PDF	3-6%	3-6%	3-6%
Total	8-9%	8-9%	8-9%
CMSSM			
NLO σ	16-18%	16-18%	16-18%
Total	17-19%	17-19%	17-19%

Signal modeling experimental and theoretical uncertainties

Jets+MET Search: The Razor

CMS-SUS-10-009

Interpretation within the CMSSM framework



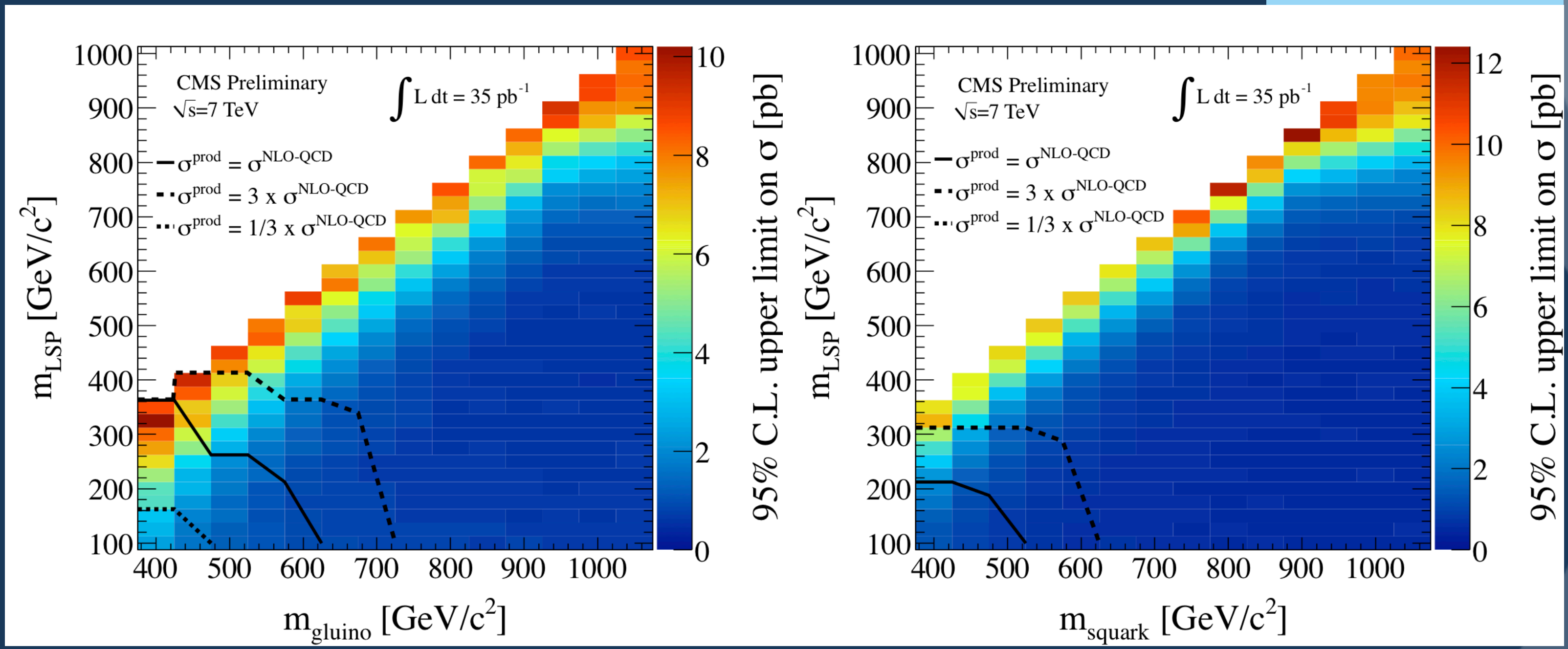
- Similar limits to the generic MHT analysis
- Complementary use of kinematics (Razor) versus detailed detector understanding (MHT)

Jets+MET Search: The Razor

Interpretation within the simplified models framework

gluino-LSP (left), squark-LSP (right)

CMS-SUS-10-009



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- Complementary use of kinematics (Razor) versus detailed detector understanding (MHT)

Jets+MET Search: Summary

Interpretation within the CMSSM framework

α_T:

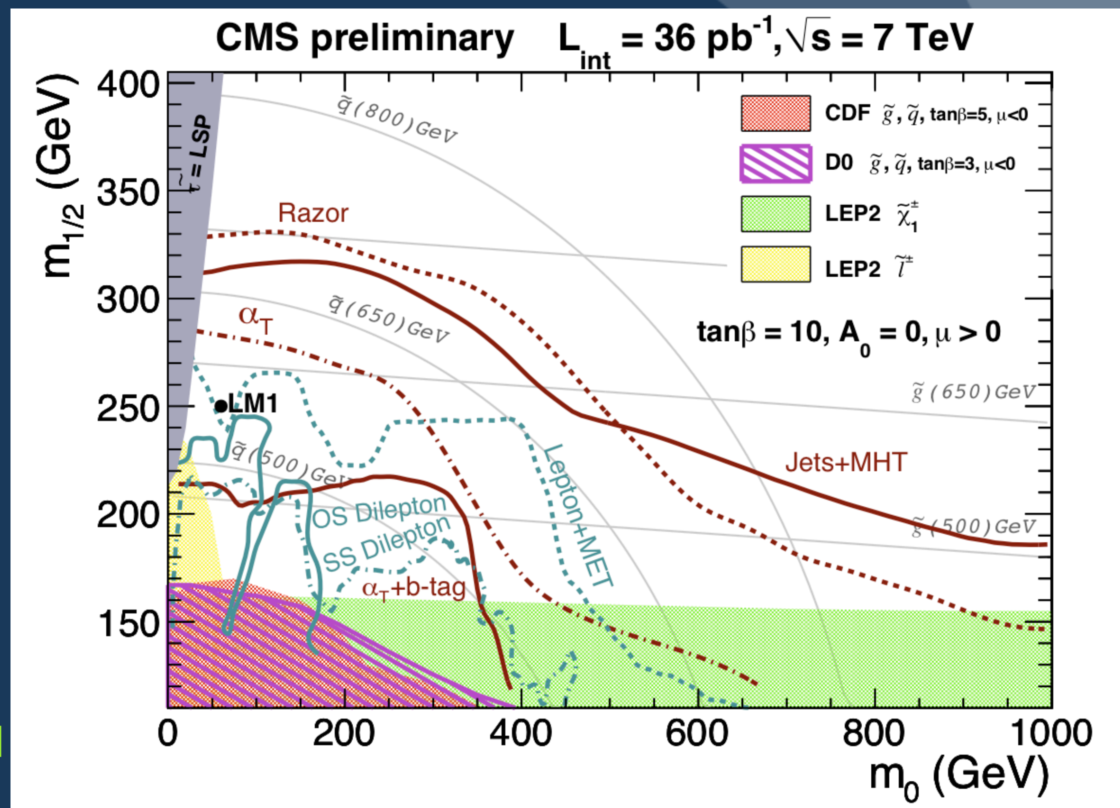
- First LHC SUSY paper
- Target discovery with early data

MHT:

- Good understanding of detector for …
- High signal efficiency, accurate bkgnd prediction

Razor:

- Clever use of kinematics for …
- High signal efficiency and background rejection

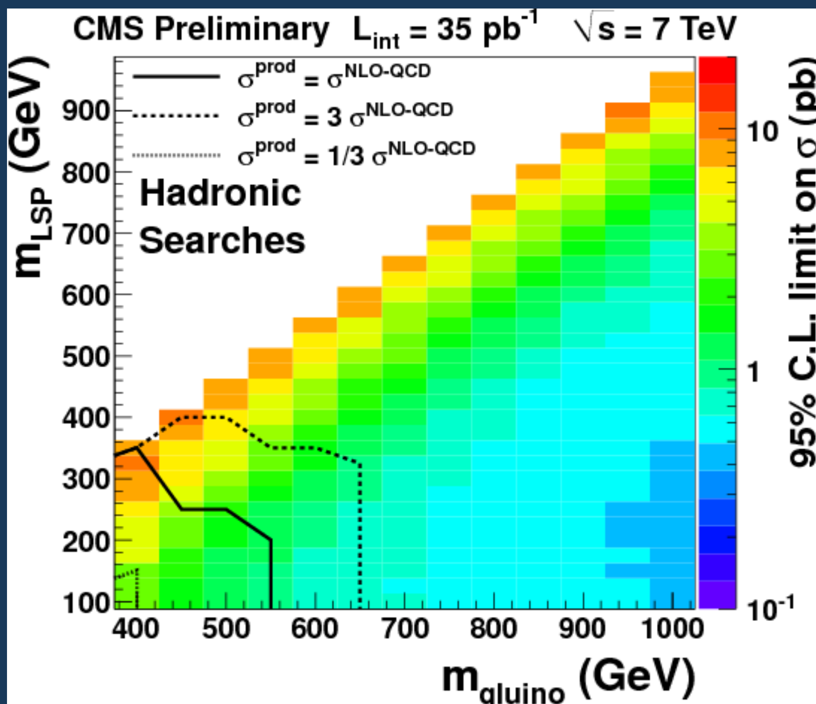


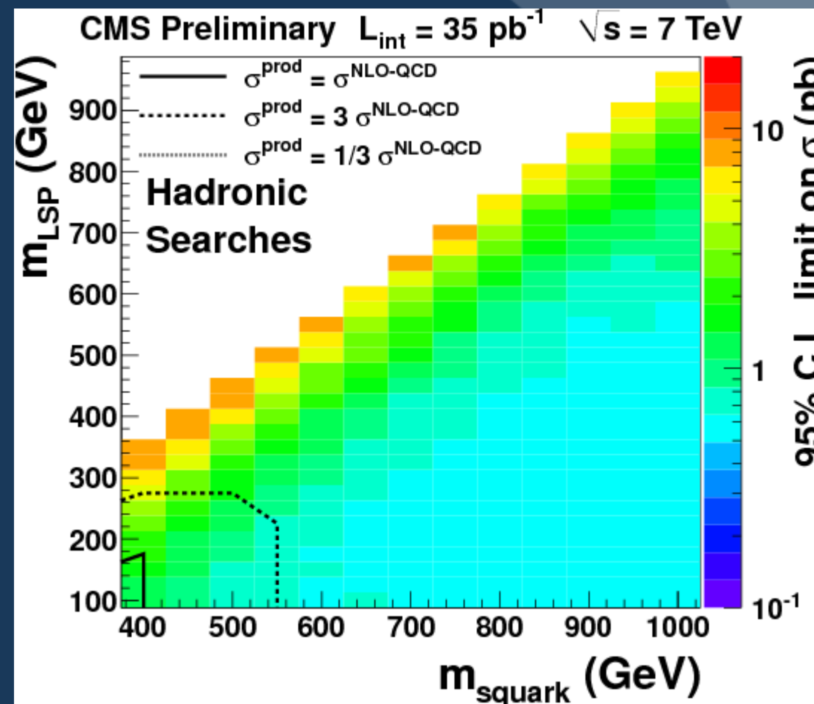
CMS strategy: redundancy and complementarity

Jets+MET Search: Summary

Interpretation within the simplified models framework:

α_T, MHT, Razor combined



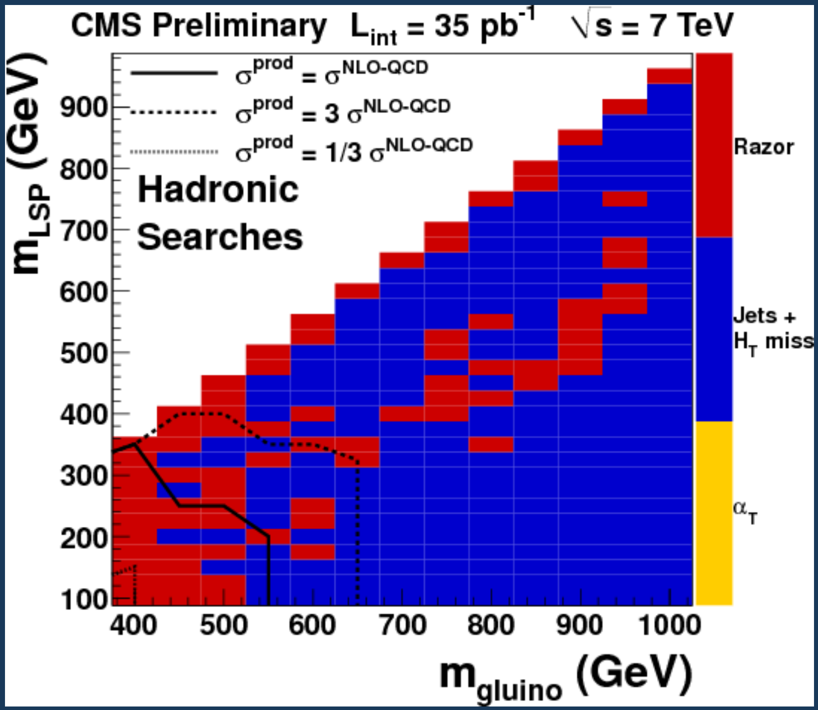


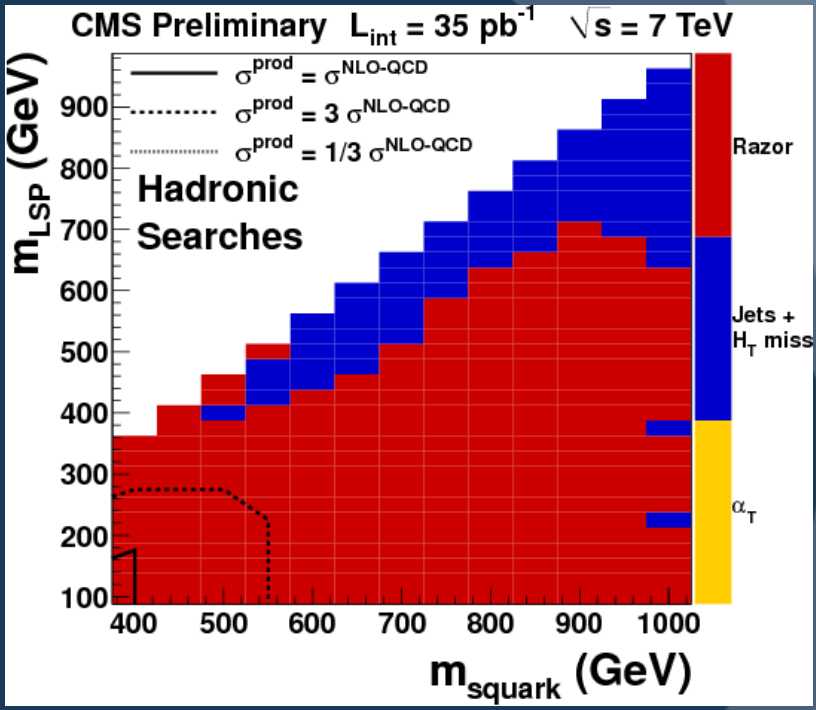
CMS strategy: redundancy and complementarity

Jets+MET Search: Summary

Interpretation within the simplified models framework:

Analysis identity providing upper limit (α_T, MHT, or Razor)





CMS strategy: redundancy and complementarity

l+jets+MET Search

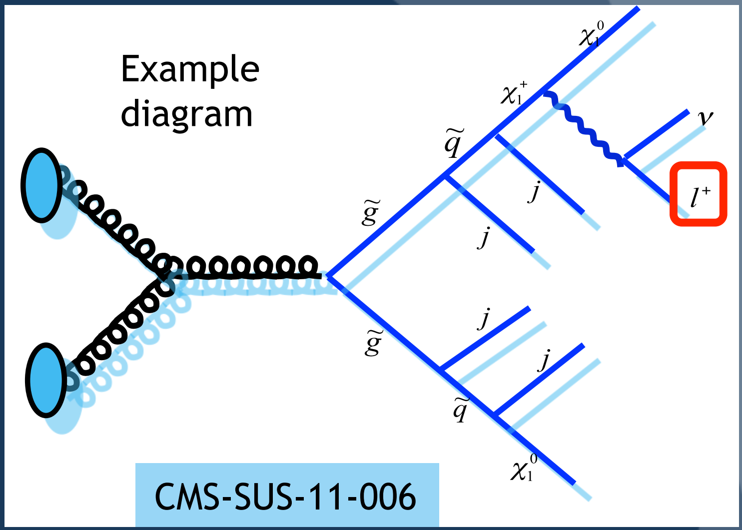
Adding a lepton requirement to the hadronic searches changes the background composition significantly

Baseline selection

- Exactly one e (μ), p_T>20 (15) GeV, $|\eta|$<2.4 (2.1)
- e/(μ) isolated from other objects: ΔR>0.3 and $I/p_T^{e(\mu)}$<0.1(0.07)

Relative Lepton Isolation $I = \sum_{\Delta R<0.3}(E_T + p_T)$

- ≥ 4 PF jets, p_T>30 GeV, $|\eta|$<2.4



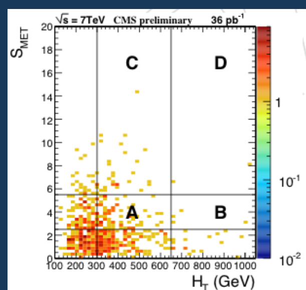
Backgrounds

- W+jets and ttbar largest
- ttbar dominates at medium and large MET
- QCD very small (isolated lepton requirement) - ABCD method
  - ✓ Assume MET and Relative Lepton Isolation (RelIso) uncorrelated
  - ✓ Control region (MET<25 GeV): Ratio= $N_{evts}^{control\ region}$(RelIso<0.1)/$N_{evts}^{control\ region}$(0.2<RelIso<0.5)
  - ✓ $N_{evts}^{signal\ region}$(high MET)= Ratio x $N_{evts}^{signal\ region}$(0.2<RelIso<0.5)

l+jets+MET Search

W+jets and ttbar backgrounds

- ABCD or factorization method
  - ➢ Based on S_{MET}=MET/√HT versus HT



D: signal region

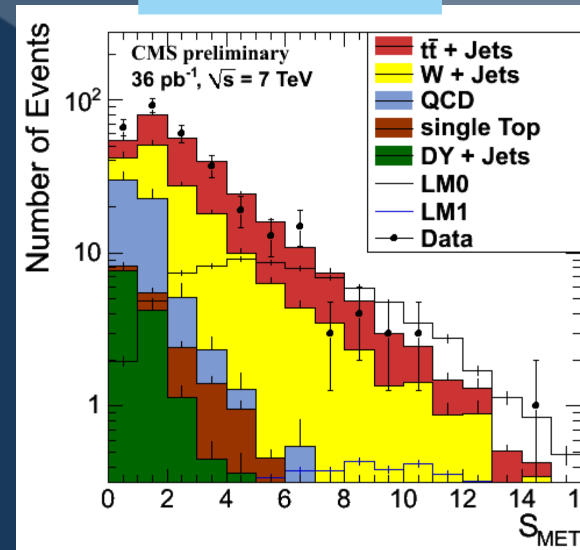
S_{MET} and HT uncorrelated

N(c)/N(A) = constant

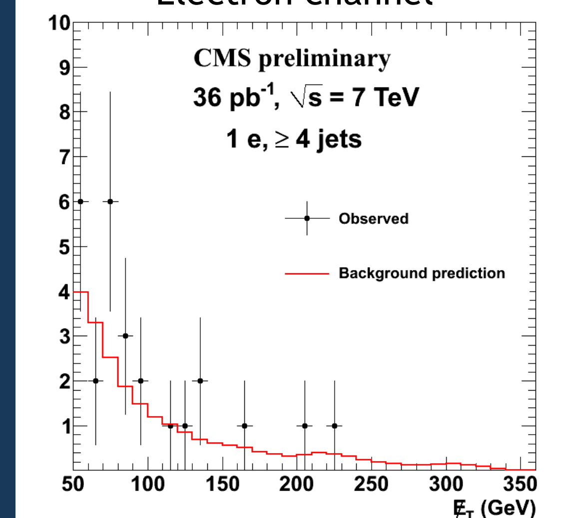
$$N(D) = [N(C)/N(A)]N(B)$$

- Lepton spectrum method - all but ttbar➔ll and τ(μ,e) decays
  - ➢ Lepton and ν p_T spectra are very similar, use p_T^l to predict MET
  - ➢ Take muon spectrum (cleaner)
    - ✓ Correct for A_{cc}, E_{ff}, polarization
    - ✓ MET resolution worse than for e/μ ➔ measure in data and smear
- ttbar➔ll and τ(μ,e) decays
  - ➢ From ee, eμ, μμ control samples modified to reflect lost lepton or the presence of a τ decay

CMS-SUS-11-006



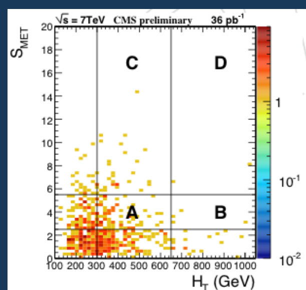
Electron channel



l+jets+MET Search

W+jets and ttbar backgrounds

- ABCD or factorization method
  - ➢ Based on S_{MET}=MET/√HT versus HT



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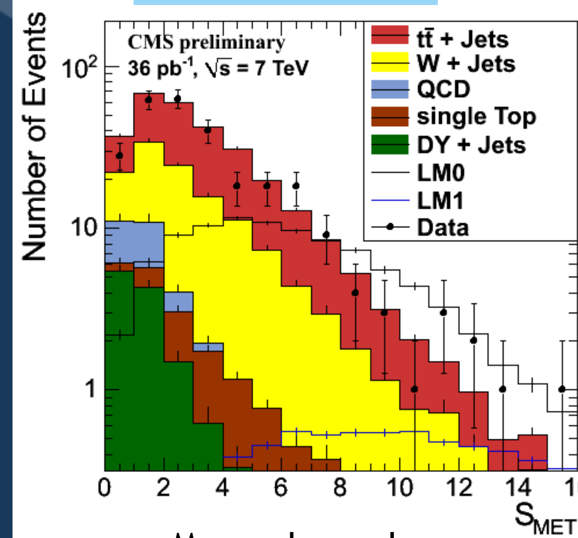
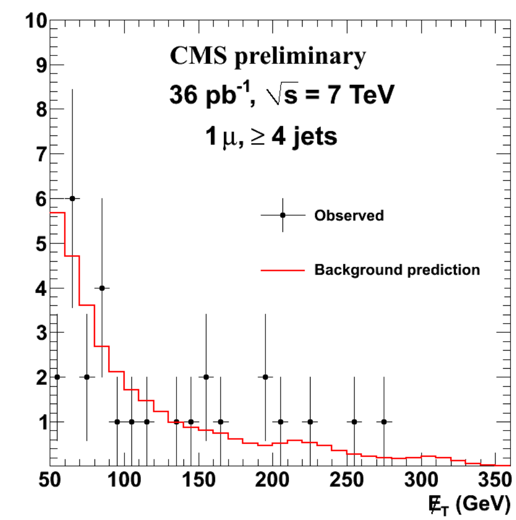
CMS-SUS-11-006



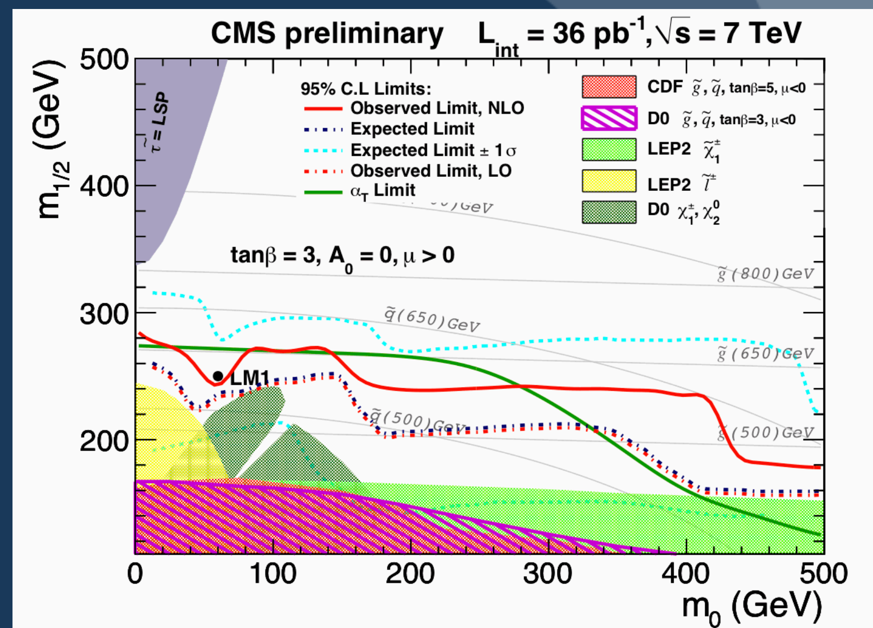
Muon channel



l+jets+MET Search

Final selection (signal region): MET>250 GeV, HT>500 GeV

Sample	$\ell = \mu$	$\ell = e$
Predicted SM 1 ℓ	1.7 ± 1.4	1.2 ± 1.0
Predicted SM dilepton	$0.0^{+0.8}_{-0.0}$	$0.0^{+0.6}_{-0.0}$
Predicted single τ	0.29 ± 0.22	$0.32^{+0.38}_{-0.32}$
Predicted QCD background	0.09 ± 0.09	$0.0^{+0.16}_{-0.0}$
Total predicted SM	2.1 ± 1.5	1.5 ± 1.2
Observed signal region	2	0



CMS-SUS-11-006

No excess observed
over SM predictions

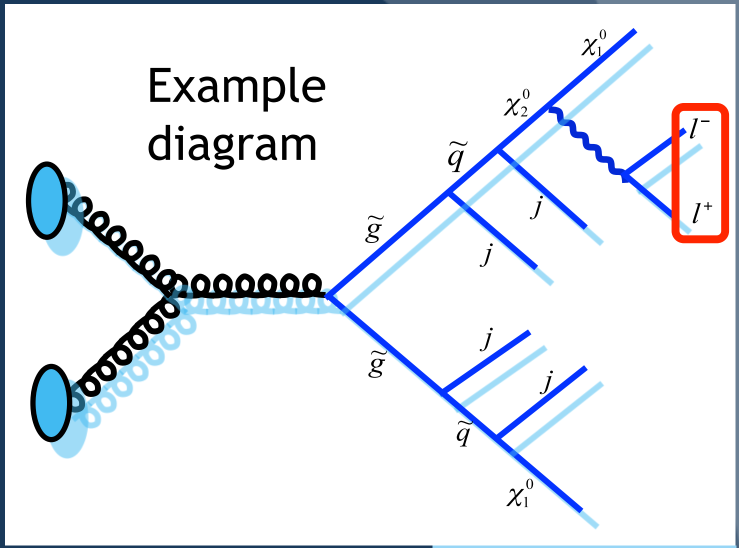
Limit similar to hadronic α_T search in CMSSM

Opposite-Sign Dilepton Search

Adding two opposite signed leptons to the hadronic search reduce the background to a small number of mostly ttbar events

Baseline selection

- Two isolated leptons ee, eμ, μμ, with p_T>20 (10) GeV for first (2^{nd}) leading lepton
- At least two JPT jets, p_T>30 GeV, $|\eta|<2.5$
- Veto events in Z mass window
- HT>100 GeV, tcMET>50 GeV



CMS-SUS-10-007
arxiv:1103.1348

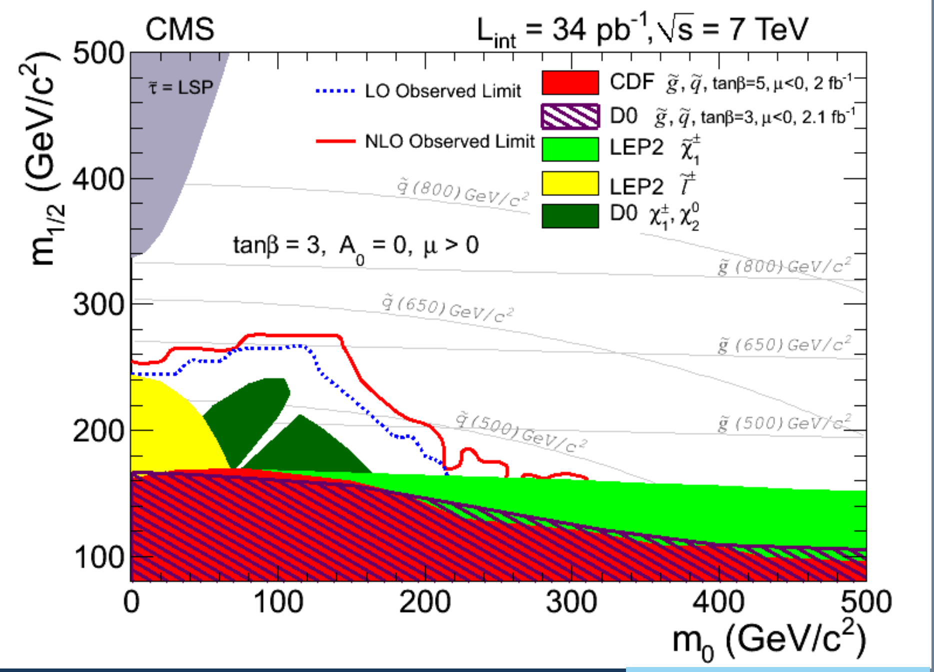
Backgrounds

- ttbar→dilepton largest (but small)
  - ✓ ABCD method applied on S_{MET}=MET/√HT versus HT (Signal region: HT>300 GeV, S_{MET}>8.5 $GeV^{1/2}$)
  - ✓ Also used lepton p_T spectrum method (p_T^{ll})
- QCD tiny: Estimated from lepton-fakeable (lf) and ff control samples

  $0.0\pm^{0.4}_{0.0}$ (lf) $0.0\pm^{0.04}_{0.0}$ (ff)

Opposite-Sign Dilepton Search

	Observed	Predicted
Data	1	
Tot. SM (ABCD)		1.3±0.8(stat) ±0.3(syst)
Tot. SM (p_T^{ll})		2.1±2.1(stat) ±0.6(syst)



CMS-SUS-10-007
arxiv:1103.1348

No excess observed over SM predictions

95% C.L. upper limit on # of signal events is 4.1

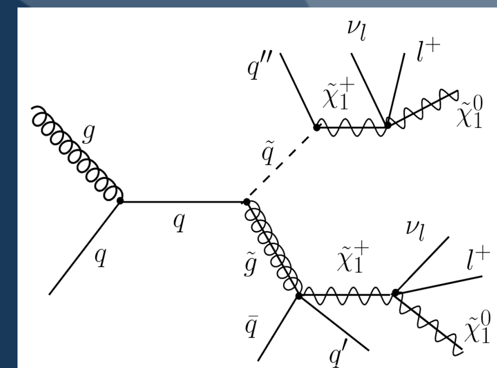
(used 1.4±0.8 for bkgnd)

Expected: 8.6±1.6 (LM0)
(signal) 3.6± 0.5 (LM1)

Limit in CMSSM beyond previous Tevatron searches

Same-Sign Dilepton Search

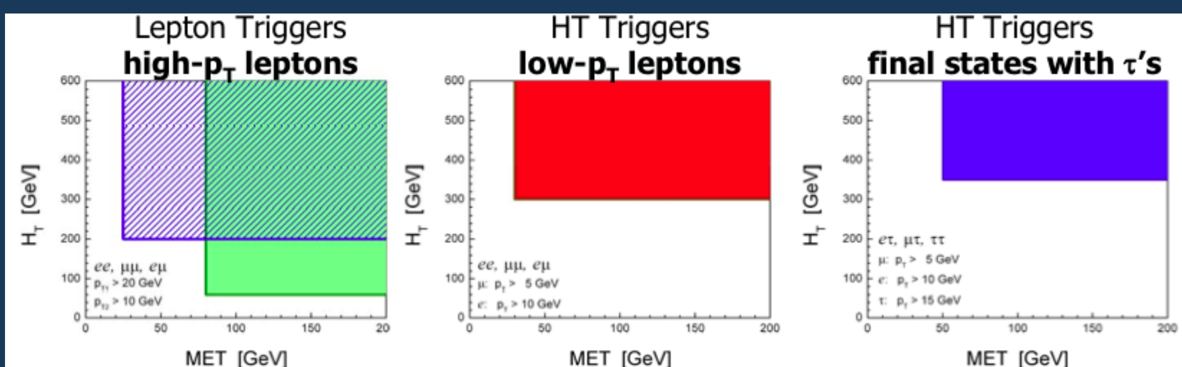
Same-sign isolated leptons are very rare in SM processes but appear naturally in new phenomena scenarios



CMS-SUS-10-004
arxiv:1104.3168

Baseline selection

- Search for all combinations of lepton species: ee, eμ, μμ, eτ, μτ, ττ
- Define four search regions:



Region A (ee, μμ, eμ):
leptons p_T > 20/10, RelIso<0.1
H_T > 60 (≥2 jets)
MET > 80

Region B (ee, μμ, eμ)
leptons p_T > 20/10, RelIso<0.1
H_T > 200 (≥2 jets)
MET > 30 (ee, μμ) / 20 (eμ)

Region C (ee, μμ, eμ)
muon p_T > 5, RelIso<0.15
electron p_T > 10, RelIso<0.15
H_T > 300 (≥2 jets)
MET > 30

Region D (eτ, μτ, ττ)
muon p_T > 5, RelIso<0.15
electron p_T > 10, RelIso<0.15
tau p_T > 15
H_T > 350 (≥2 jets)
MET > 50

Same-Sign Dilepton Search

Backgrounds

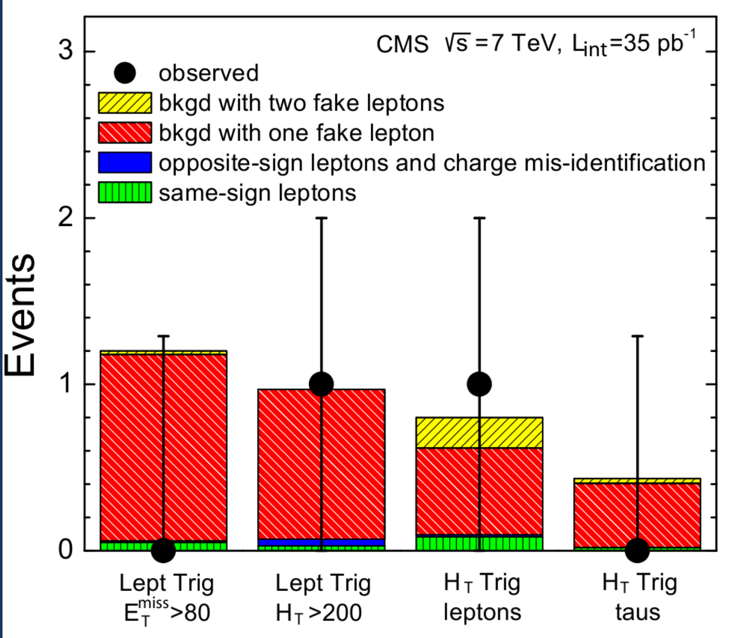
CMS-SUS-10-004
arxiv:1104.3168

1. Same-sign leptons: dibosons, ttbarW, qqWW
2. Opposite-sign leptons with charge mis-ID: ttbar, tW, DY, dibosons
3. Fake leptons from jets: tt , tW , tb, tbq, Wjets, Dyjets, dibosons
4. Fake leptons from γ conversions: $V\gamma$

1. Small, from MC; 2. Negligible; 3. and 4. derived with data driven methods

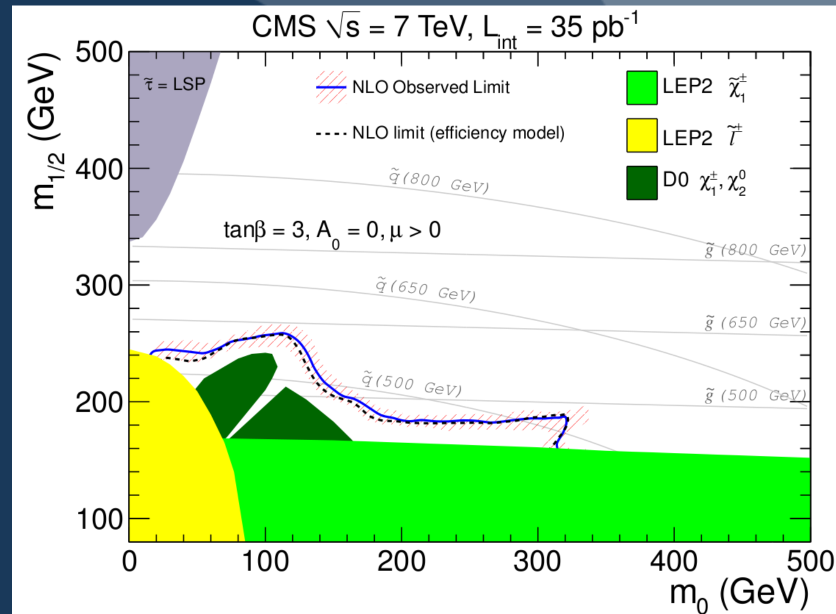
Fakes estimated with "Tight-Loose" method (TL)

- Control sample: dilepton+jets events with one tight lepton and one loose lepton
- Weight control sample by: $f_{TL}/(1-f_{TL})$
- f_{TL}: probability of loose to fake a tight
- Sum weights in signal region



Same-Sign Dilepton Search

Search Region	ee	$\mu\mu$	$e\mu$	total	95% CL UL Yield
Lepton Trigger					
$E_T^{miss} > 80$ GeV					
MC	0.05	0.07	0.23	0.35	
predicted BG	$\mathbf{0.23^{+0.35}_{-0.23}}$	$\mathbf{0.23^{+0.26}_{-0.23}}$	$\mathbf{0.74 \pm 0.55}$	$\mathbf{1.2 \pm 0.8}$	
observed	**0**	**0**	**0**	**0**	**3.1**
$H_T > 200$ GeV					
MC	0.04	0.10	0.17	0.32	
predicted BG	$\mathbf{0.71 \pm 0.58}$	$\mathbf{0.01^{+0.24}_{-0.01}}$	$\mathbf{0.25^{+0.27}_{-0.25}}$	$\mathbf{0.97 \pm 0.74}$	
observed	**0**	**0**	**1**	**1**	**4.3**
H_T Trigger					
Low-p_T					
MC	0.05	0.16	0.21	0.41	
predicted BG	$\mathbf{0.10 \pm 0.07}$	$\mathbf{0.30 \pm 0.13}$	$\mathbf{0.40 \pm 0.18}$	$\mathbf{0.80 \pm 0.31}$	
observed	**1**	**0**	**0**	**1**	**4.4**
	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	total	95% CL UL Yield
τ_h enriched					
MC	0.36	0.47	0.08	0.91	
predicted BG	$\mathbf{0.10 \pm 0.10}$	$\mathbf{0.17 \pm 0.14}$	$\mathbf{0.02 \pm 0.01}$	$\mathbf{0.29 \pm 0.17}$	
observed	**0**	**0**	**0**	**0**	**3.4**



CMS-SUS-10-004
arxiv:1104.3168

No excess observed over SM predictions

Lepton isolation efficiencies also provided (LM0)
(and dependence on event topology and charge multiplicity)

Limit in CMSSM similar to the opposite-sign case and better than Tevatron

Multilepton Search

Adding three isolated leptons to the hadronic search suppresses the backgrounds drastically

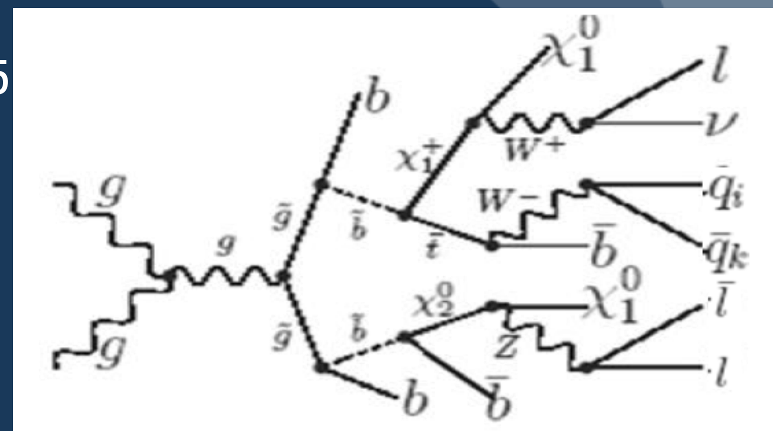
Baseline selection

- Require at least three leptons (e,μ,τ) with p_T>8 GeV, RelIso<0.15
- 55 channels, at least one non-τ lepton

Final selections :

MET>50 GeV (and HT>200 GeV)

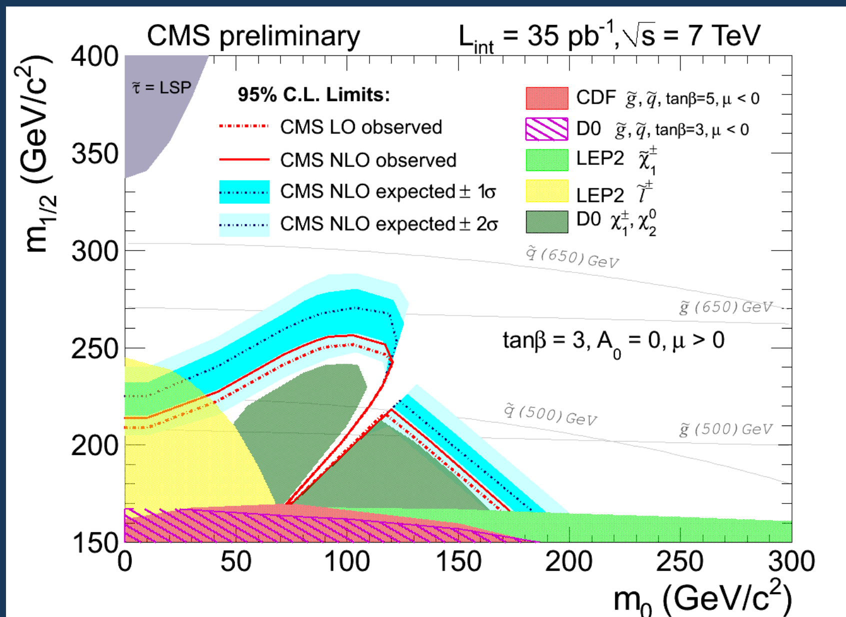
"inclusive" ("hadronic") analyses complementary in phase space

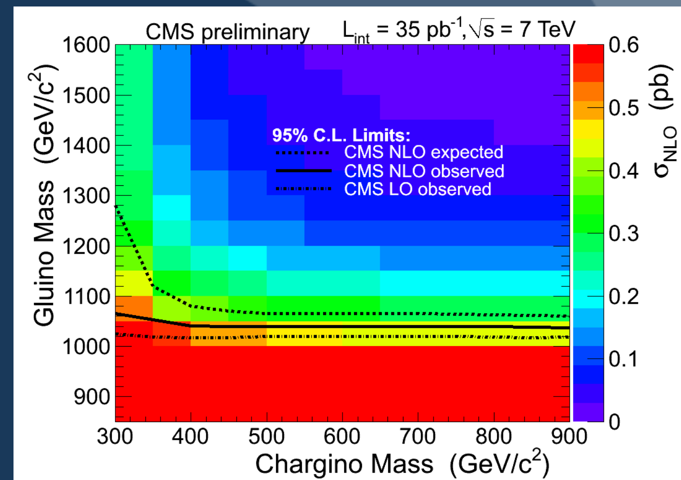


Backgrounds

- Irreducible: WZ+Jets, ZZ+Jets - estimated from simulation
- ttbar – simulation
- Z+Jets, WW+Jets, W+Jets, QCD - data-driven using "Tight-Loose"

Multilepton Search





No excess observed over SM predictions – limits in CMSSM

2 inclusive (3 hadronic) events observed and 1.3±0.3 (1.3±0.2) background events predicted

Multi-leptons in GMSM (right-handed sleptons co-NLSP (flavor-degenerate)

$$\tilde{B} \to \ell^\pm \tilde{\ell}^\mp_R \to \ell^\pm \ell^\mp + \tilde{G}$$
$$\tilde{\ell} \to \ell + \tilde{G}$$

95% C.L. limits

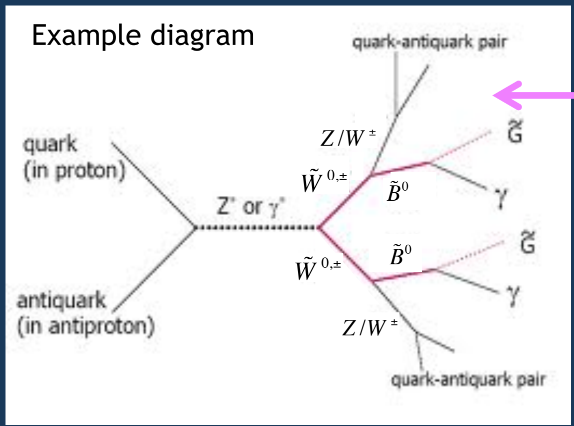
On # signal events ≈ 6

On slepton co-NLSP scenario x-section: 0.2-0.4 pb

General Gauge Mediation Search

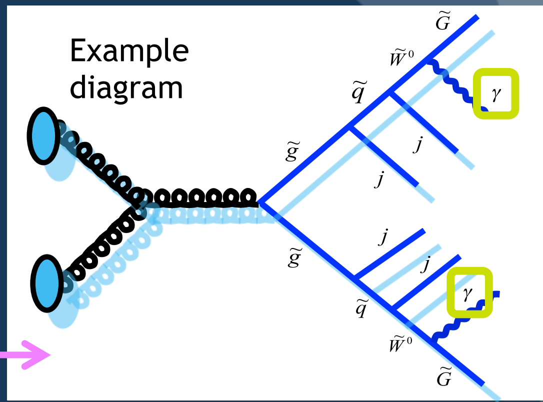
Gauge Mediation is a candidate mechanism for SUSY breaking (GMSB)

- Low scale symmetry breaking
- LSP is the Gravitino with $m_{3/2}$<<100 GeV



At the Tevatron (ppbar Collider), SUSY production mostly EWK

At the LHC (pp Collider), SUSY production mostly strong



mGMSB: mass hierarchy gluino:wino:bino = 6:2:1

- Limit on chargino (wino) mass measured at the Tevatron ➔ gluino mass 3 times larger
- Gluino (strong) production highly suppressed at current LHC energy and integrated luminosity

General Gauge Mediation (GGM): allows compressed mass spectrum for colored particles

- Gluino is light
- GGM search accessible to LHC at current 7 TeV CMS energy and small samples

GGM Search: $\gamma\gamma$+jets+MET

CMS-SUS-10-002, arXiv:1103.0953v2

Pre-selection

- Single photon trigger, $p_{T\gamma}$>30 GeV
- Two or more reconstructed photons with $p_{T\gamma}$>30 GeV and $|\eta|<1.4$
- At least one jet with p_T>30 GeV and separated ΔR>0.9 from photons (rejects cosmic and beam backgrounds ← out-of-time muons)

Control samples for background predictions

- Fake-fake photon sample (ff)
- Z→e^+e^- within Z mass window: 90±20 GeV (Z or ee sample)

Definitions of physics objects

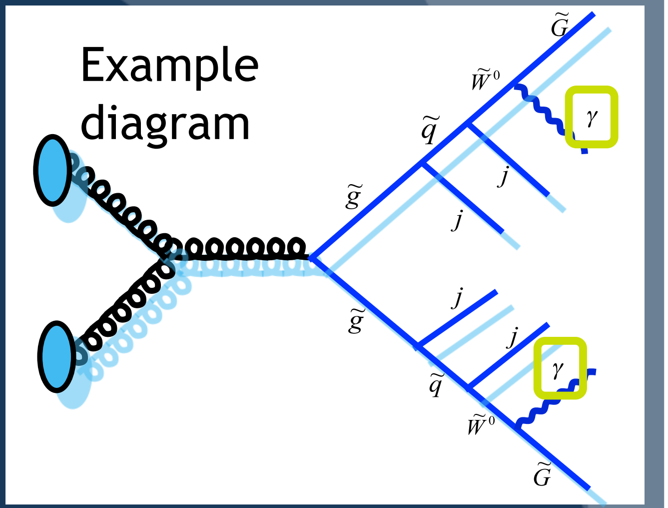
- Photon: Standard photon ID, includes pixel match
- Electron: SD electron ID, same as photon but with pixel match veto
- Fake photon: SD photon ID but failing track ISO or $\sigma_{i\eta i\eta}$ (shower shape)
- Jet: JetPlusTracks reconstruction clustered with Anti-kT (D=0.5)
- MET: Track Corrected CaloMET (tcMET)

GGM Search: $\gamma\gamma$+jets+MET

EWK Backgrounds – real MET

- Irreducible:
  - ✓ $Z\gamma\gamma$, $W\gamma\gamma$ very small for the $p_{T\gamma}$ range under consideration
- Electron mis-identification
  - ✓ $W\gamma$, $W(e\nu)$+jets with e mis-identified as γ
  - ✓ Top, with electron mis-identified as γ

$e\gamma$ + MET in final state



Data driven derivation of EWK backgrounds

- Start from the same single photon triggers
- Select two different data samples, requiring either ee or $e\gamma$
- Scale the $e\gamma$ MET distribution by $f_{e\gamma}/(1-f_{e\gamma})$ to get the EWK contribution to the signal sample
  - ✓ $f_{e\gamma}$: probability of an electron faking a photon (tag and probe)
  - ✓ $f_{e\gamma}$= 0.014±0.004 measured by counting events in Z peak for ee, $e\gamma$, $\gamma\gamma$

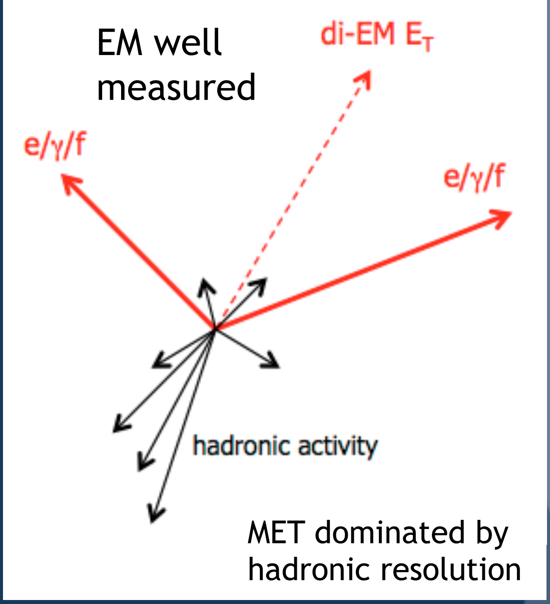
GGM Search: $\gamma\gamma$+jets+MET

QCD Background – fake MET

- Source: direct di-photon, photon+jets, multi-jets where jets fake photons and mis-measured jets originate MET

Data driven derivation of QCD backgrounds

- Assumption: ee, ff events have similar kinematics than candidate sample in the low MET (control) region
- Re-weighting: Events in ee and ff samples re-weighted to reproduce $\gamma\gamma$ p_T distribution in candidate sample



- Normalize: Candidate $\gamma\gamma$ MET minus EWK below 20 GeV matches ff and ee ➔ integrals above 50 GeV gives QCD background prediction

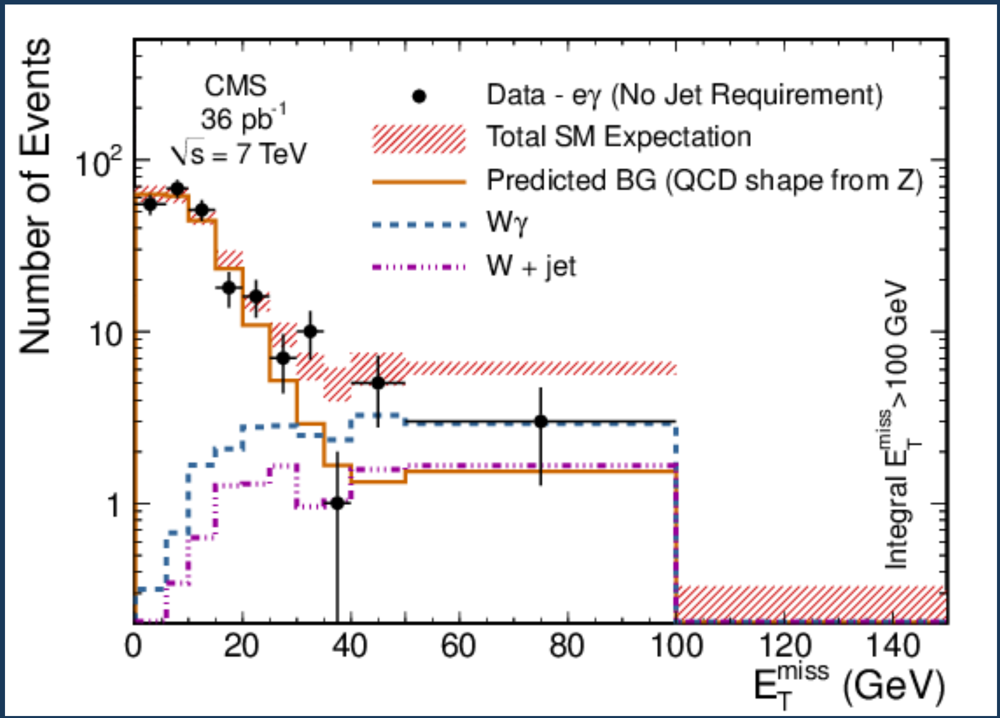
Muon Background – out of time events with fake MET

- Source: muons from beam halo or cosmic rays
- Removal: jet requirement enforces in-time event (pp collision)

GGM Search: γγ+jets+MET

Cross-check: Observation of Wγ and W+jets "signal" in eγ sample

- Can we predict the background correctly when there is signal?



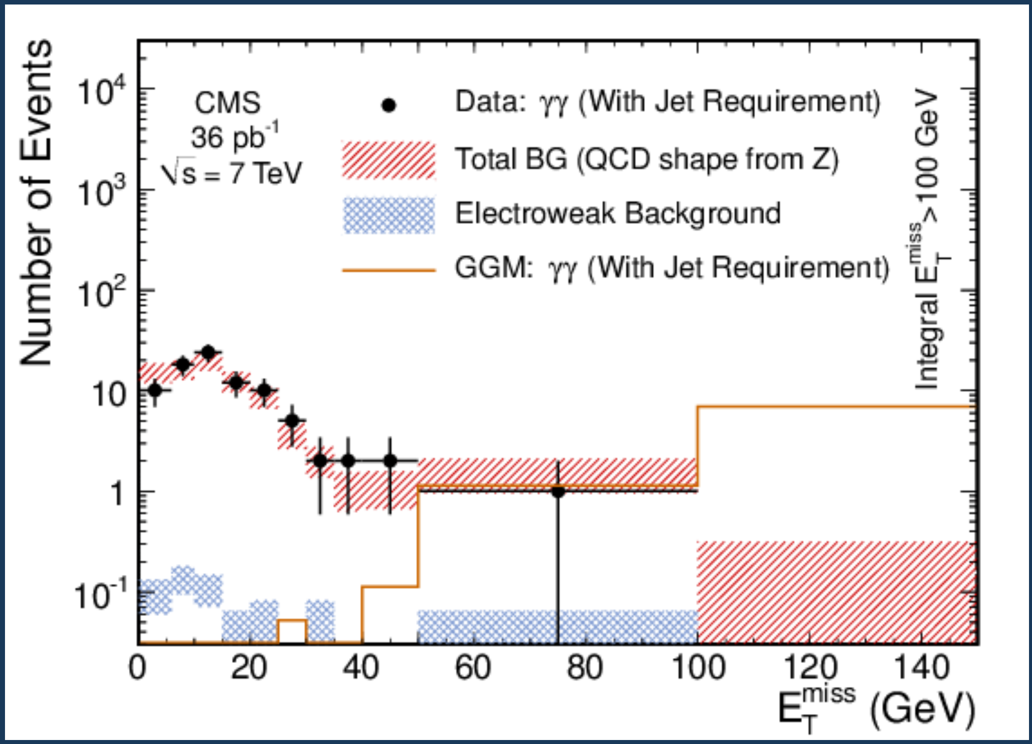
- Observed MET spectrum of eγ deviates from QCD prediction
- eγ spectrum consistent with QCD background plus Wγ and W+jets "signal"

CMS-SUS-10-002, arXiv:1103.0953v2

This is an example of a "closure test" based purely on collider data

GGM Search: $\gamma\gamma$+jets+MET

$\gamma\gamma$ sample compared with total background prediction



GGM sample point:

M_{squark}= M_{gluino}= 720 GeV

$M_{neutralino}$=150 GeV

NLO x-sec = 1.04 pb^{-1}

$E_{ff}xA_{cc}$=0.218±0.004±0.008

PDF, μ_R error ~ 13% each

CMS-SUS-10-002, arXiv:1103.0953v2

No excess of events observed

GGM Search: γγ+jets+MET

γγ observed events (MET>50 GeV), background prediction

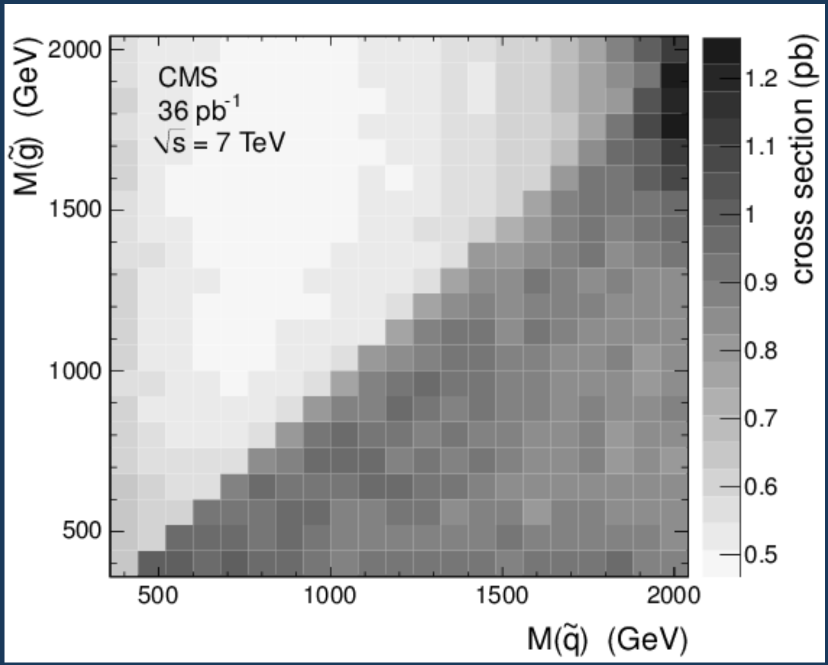
Type	Number of events	Stat error	Reweight error	Normalization error
$\gamma\gamma$ events	1			
Electroweak background estimate	0.04 ± 0.03	± 0.02	± 0.0	± 0.01
QCD background estimate (*ff*)	0.49 ± 0.37	± 0.36	± 0.06	± 0.07
QCD background estimate (*ee*)	1.67 ± 0.64	± 0.46	± 0.38	± 0.23
Total background (using *ff*)	0.53 ± 0.37			
Total background (using *ee*)	1.71 ± 0.64			
Combined total background	1.2 ± 0.8			
Expected from GGM sample point	8.0 ± 1.7			

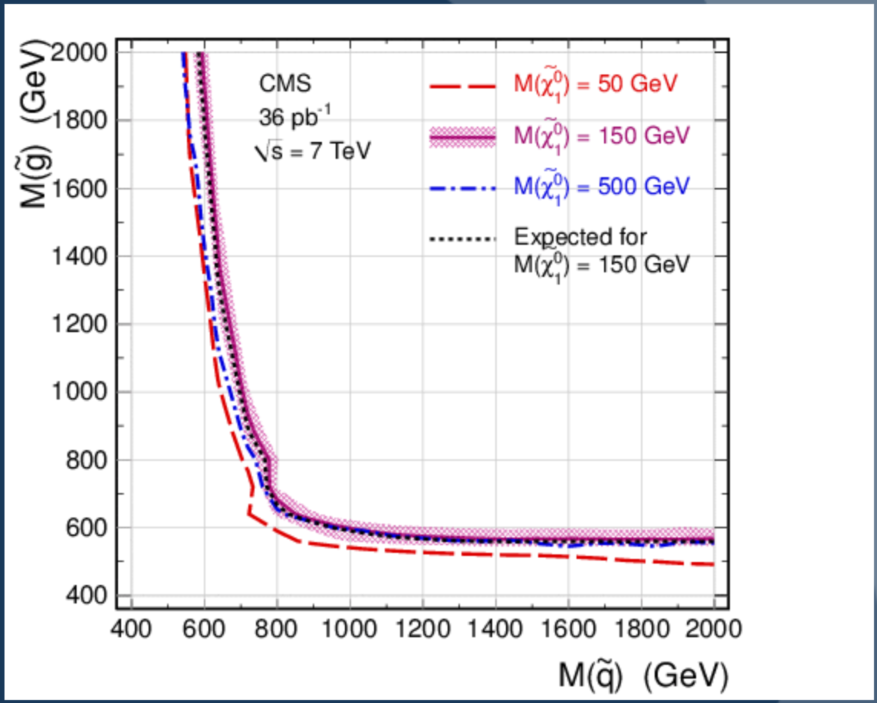
- No excess observed over SM predictions
- GGM sample point 95% C.L. upper limit on:
  - # of events = 8±1.7
  - Cross section: 0.585 pb (observed), 0.628 (expected)
    (Predicted x-section is 1.04 pb ➔GGM sample point excluded)

CMS-SUS-10-002, arXiv:1103.0953v2

GGM Search: γγ+jets+MET

Observe 1 event MET >50 GeV consistent with 1.2 ± 0.8 background





Consider GGM model with gluino, squark, neutralino (wino) decaying to jets + two photons + two Gravitinos

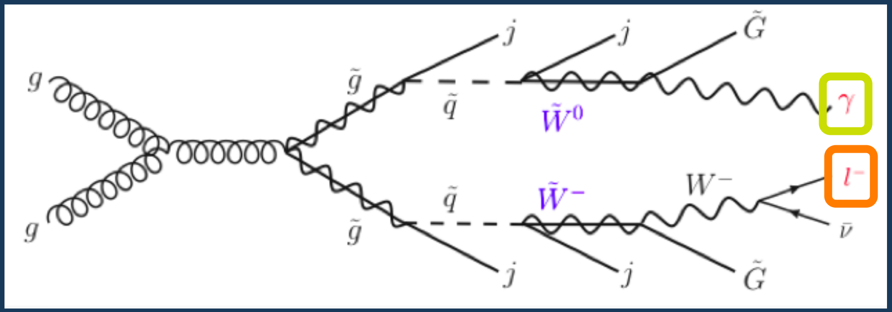
- 95% C.L. upper limit for $M_{neutralino}$ = 150 GeV is between 0.3 and 1.1 pb depending on squark and gluino masses

CMS-SUS-10-002, arXiv:1103.0953v2

GGM Search: γ+l+jets+MET

GGM with lightest charged and neutral gauginos (wino and bino) are mass degenerate and the NLSPs

CMS-SUS-11-002



Pre-selection

- Single e/μ trigger,
- At least a lepton with $p_T^{e/\mu}$>20 GeV and |η|<2.1
- At least a photon with p_T^{γ}>30 GeV and |η|<1.44

Backgrounds

- W(eν)γ dominates, predicted from simulation:
  - ✓ Madgraph (LO)+Pythia (parton showering)+NLO scaling from Baur – validated with Wγ CMS x-section measurement
- Jet is mis-identified as a γ
  - ✓ Source is W(e/μ ν)+jets and QCD. Taken from e/μ + FOJ sample and scaled by $f_{FO/\gamma}$ (prob. that FOJ is mis-identified as γ)
- Electron is mis-identified as a γ
  - ✓ Sources are Z(ee) and ttbar. Taken from e/μ + FOE sample and scaled by $f_{e\gamma}$ (prob. that FOE is mis-identified as γ)

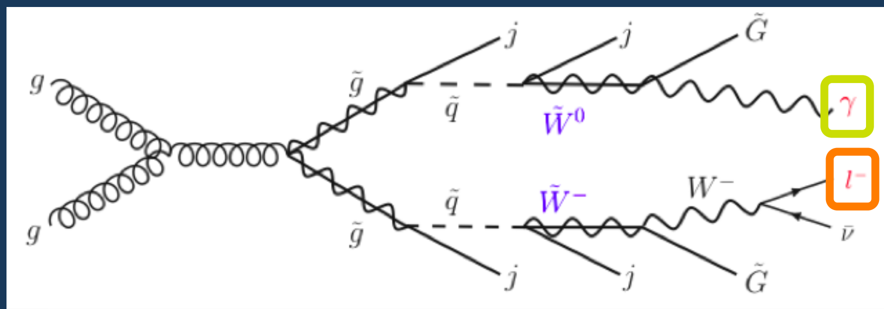
FOJ: fake object that comes from a jet, defined as a SD photon not passing track iso or $\sigma_{i\eta i\eta}$

FOE: fake object that comes from an electron, defined as a SD electron not passing track iso or $\sigma_{i\eta i\eta}$

GGM Search: γ+l+jets+MET

GGM with lightest charged and neutral gauginos (wino and bino) are mass degenerate and the NLSPs

CMS-SUS-11-002



Pre-selection

- Single e/μ trigger,
- At least a lepton with $p_T^{e/\mu}$>20 GeV and $|\eta|$<2.1
- At least a photon with p_T^{γ}>30 GeV and $|\eta|$<1.44

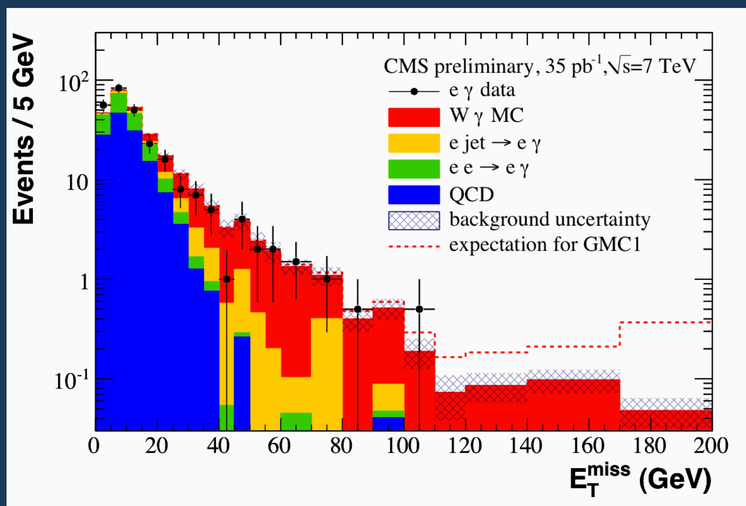
Backgrounds

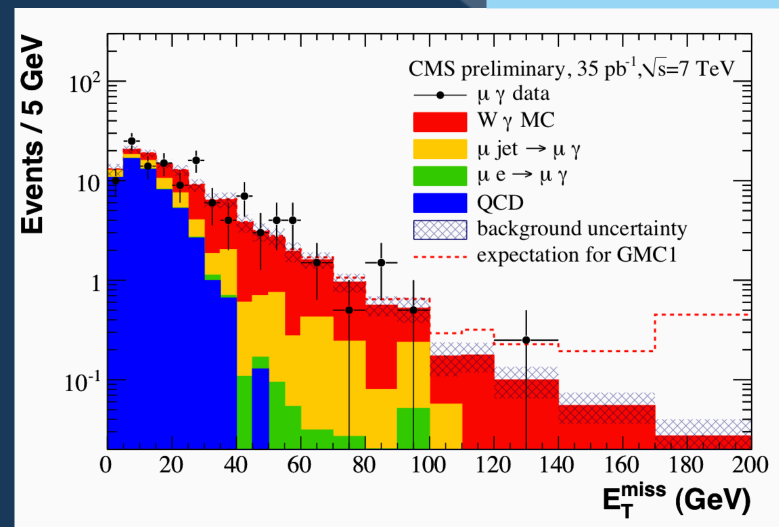
- W(eν)γ dominates, predicted from simulation:
  - ✓ Madgraph (LO)+Pythia (parton showering)+NLO scaling from Baur – validated with Wγ CMS x-section measurement
- Jet is mis-identified as a γ
  - ✓ Source is W(e/μ ν)+jets and QCD. Taken from e/μ + FOJ sample and scaled by $f_{FO/\gamma}$ (prob. that FOJ is mis-identified as γ)
- Electron is mis-identified as a γ
  - ✓ Sources are Z(ee) and ttbar. Taken from e/μ + FOE sample and scaled by $f_{e\gamma}$ (prob. that FOE is mis-identified as γ)
- QCD, similar to $\gamma\gamma$ but match Z(ee) sample to lγ kinematics by scaling $M_T^{l\gamma}$

GGM Search: γ+l+jets+MET

eγ (left) and μγ (right) MET distributions compared with total background and GMC1 benchmark GGM point

CMS-SUS-11-002





	No E_T^{miss} selection	$E_T^{miss} > 40$ GeV	$E_T^{miss} > 100$ GeV
Wγ	44.5 ± 9.2	16.1 ± 3.4	1.68 ± 0.42
jet→ γ	20.3 ± 4.5	3.1 ± 0.9	0.02 ± 0.02
e → γ	70.5 ± 19.1	0.3 ± 0.1	0.04 ± 0.03
QCD	134 ± 28	0.4 ± 0.2	0.00 ± 0.00
Total background	269 ± 18	19.9 ± 3.7	1.74 ± 0.43
data	264	16	1
SUSY GMC prediction	3.94 ± 0.79	3.76 ± 0.75	2.79 ± 0.56

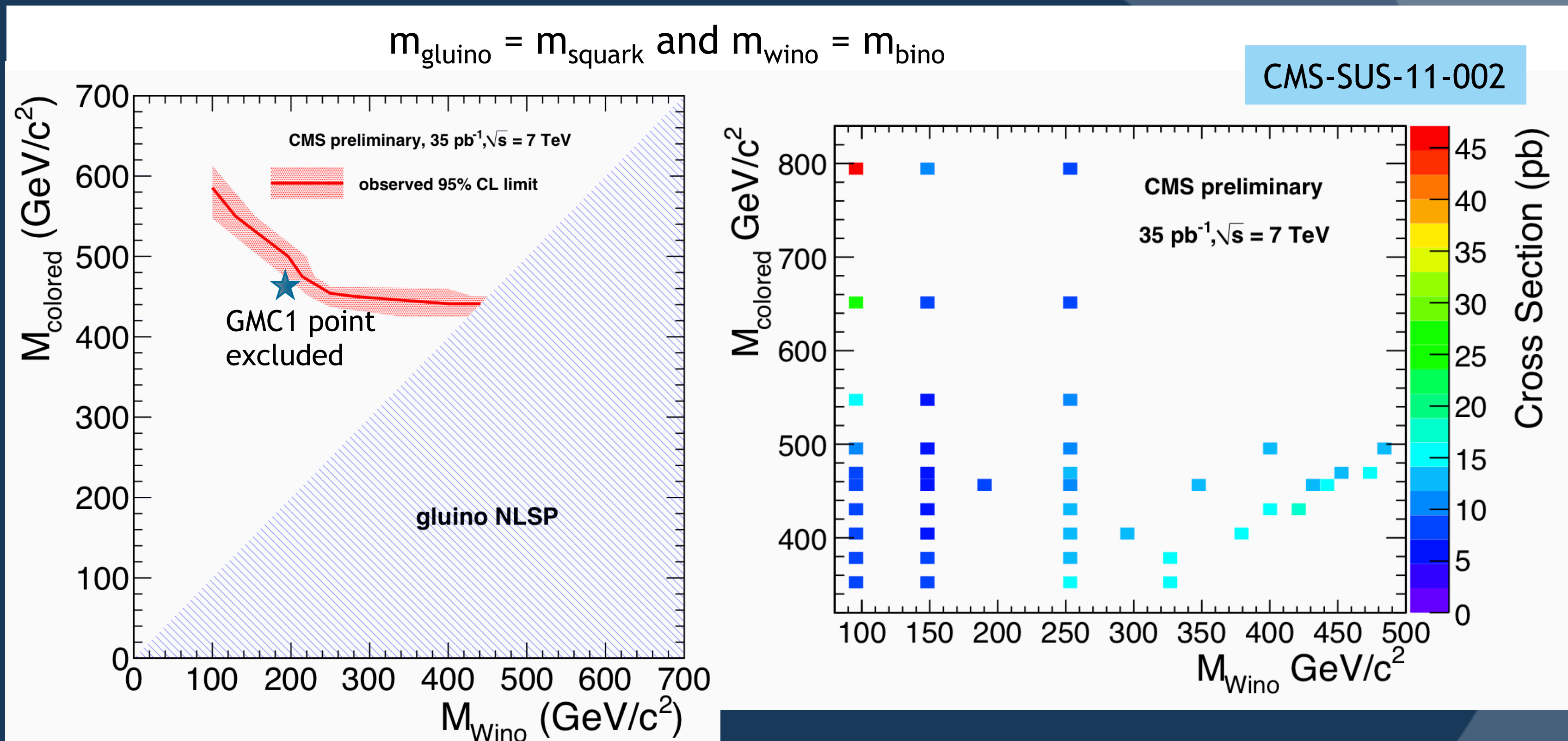
	No E_T^{miss} selection	$E_T^{miss} > 40$ GeV	$E_T^{miss} > 100$ GeV
Wγ	44.8 ± 9.3	15.9 ± 3.4	1.40 ± 0.37
jet→ γ	18.0 ± 4.0	3.7 ± 1.1	0.10 ± 0.09
e → γ	1.2 ± 0.4	0.6 ± 0.2	0.09 ± 0.04
QCD	58.3 ± 15.1	0.2 ± 0.1	0.00 ± 0.00
Total background	122.3 ± 12.3	20.4 ± 3.7	1.59 ± 0.39
data	126	27	1
SUSY GMC prediction	5.12 ± 1.02	4.84 ± 0.96	3.66 ± 0.73

GMC1 benchmark point: $m_{gluino} = m_{squark}$ = 450 GeV and $m_{wino} \approx m_{chargino}$ = 195 GeV

No excess observed over SM predictions

GGM Search: γ+l+jets+MET

95% C.L. limits on masses (left) and cross sections (right)



Area under red line excluded

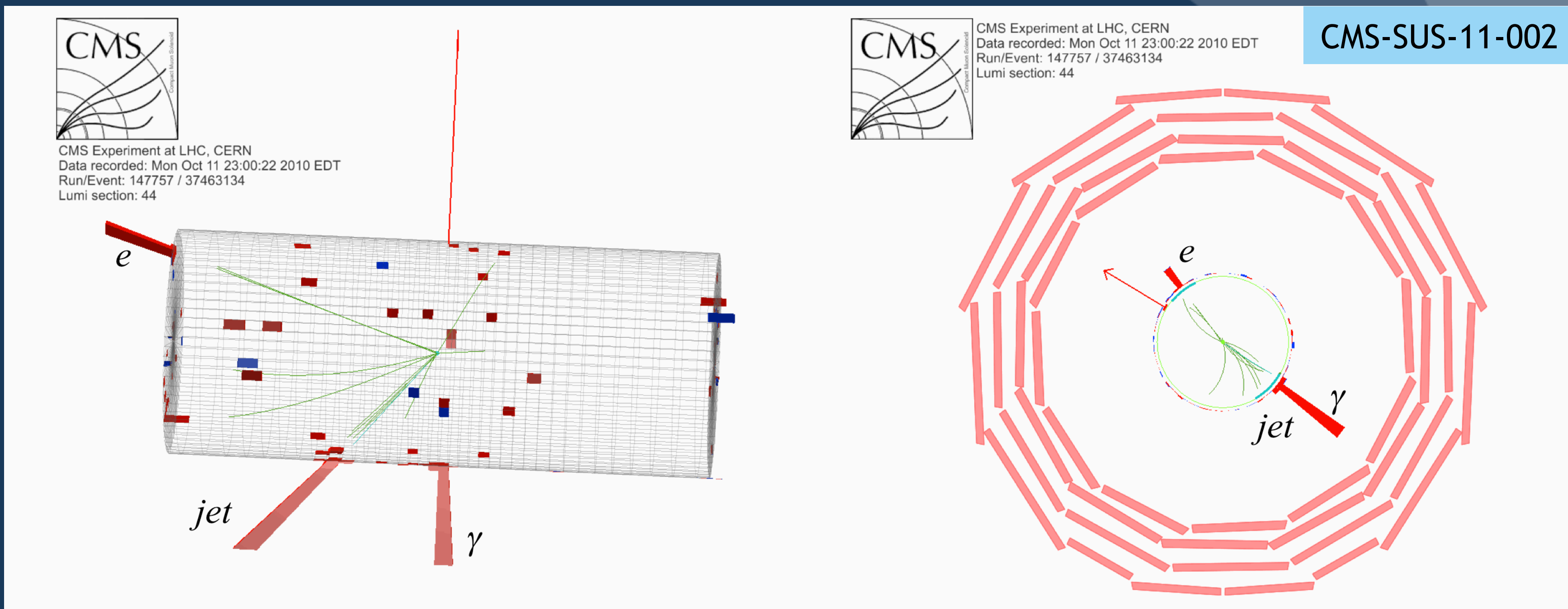
Band accounts for theoretical error in NLO calculation

Predicted (NLO) σ_{GMC1}^{pred}=12.3 pb

Measured upper limit: σ^{meas} = 6.9 pb

GGM Search: γ+l+jets+MET

Highest MET electron-gamma candidate event



CMS-SUS-11-002

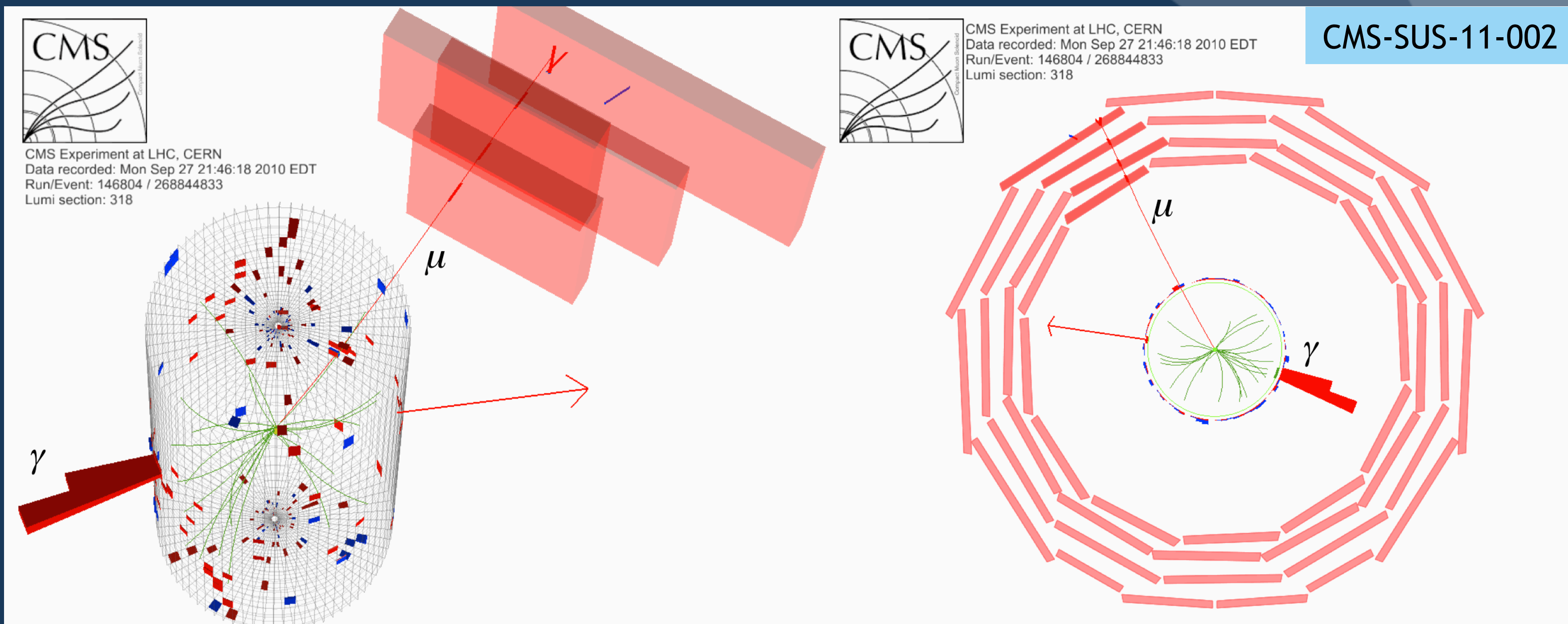
Photon p_T = 52.2 GeV/c,
Electron p_T = 45.4 GeV/c,
E^{miss} = 106 GeV.

The red arrow represents the direction of MET

Height of red/blue towers represents the amount of energy deposited in the Ecal/Hcal

GGM Search: γ+l+jets+MET

Highest MET muon-gamma candidate event



Photon p_T = 154GeV/c,
Muon p_T = 55.6 GeV/c,
E^{miss} = 127 GeV

The red arrow represents the direction of MET

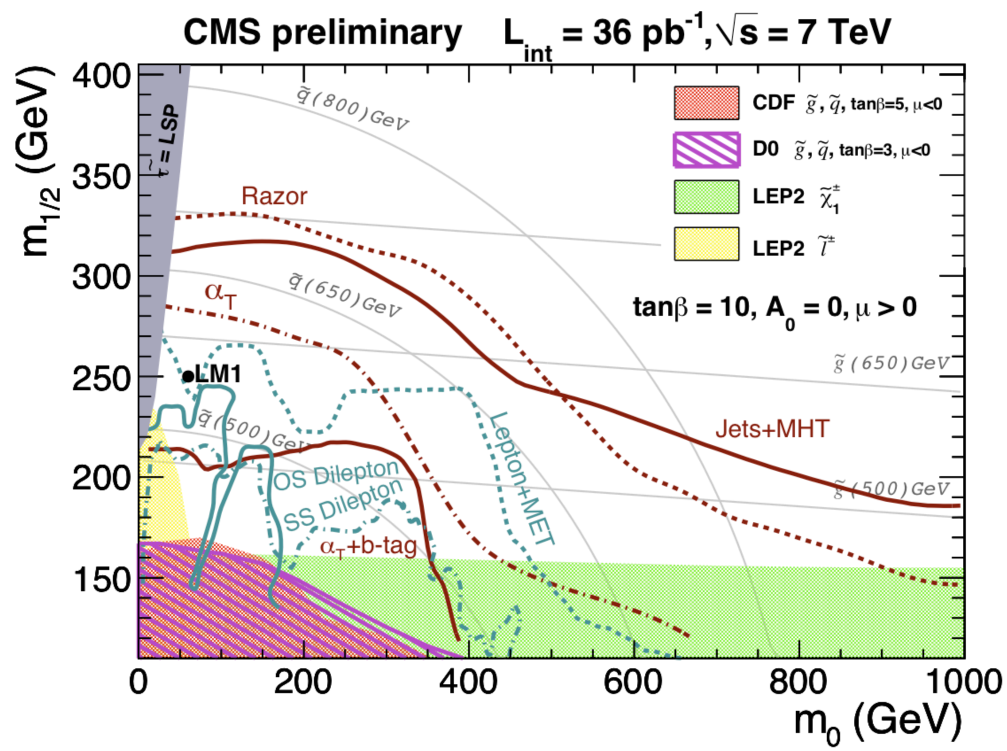
Height of red/blue towers represents the amount of energy deposited in the Ecal/Hcal

Summary of CMS SUSY Searches

No discovery so far

- Highest limits to date for CMSSM, Simplified Models
  - ➢ Better than Tevatron's
  - ➢ Beyond expectations for ≈40 pb^{-1} of LHC data
- Hadronic searches are the most sensitive – highest limits
- Leptonic searches are the cleanest for discovery
- Diversity: channels, sensitive variables, data driven background techniques

Interpretation within the CMSSM framework



CMS strategy based on redundancy and complementarity

What about ATLAS?

Similar strategy as CMS

- Final states with 0,1,2-leptons; 0,1-lepton+b-jets
- Variety of sensitive variables: MET, M_{eff}, MT2
- Background estimates base on MC and validated with data

Object identification and kinematic range, common to all MET-based analyses

Primary vertex
- At least 1 good vertex with $N_{tracks}>4$

Jets
- anti-k_T, R=0.4
- $p_T > 20$ GeV, $|\eta|<2.5$
- Reject events compatible with noise or cosmics

B-Jets
- Secondary vertex reconstruction algorithm (Svo), require decay length significance > 5.72 (50% b-tag eff)
- $p_T > 30$ GeV, $|\eta|<2.5$

Electrons
- $p_T > 20$ GeV, $|\eta|<2.47$
- reject events if electron candidates are in transition region ($1.37<|\eta|<1.52$)

Muons
- $p_T > 20$ GeV, $|\eta|<2.4$
- combined/extrapolated info from ID and Muon spectrometer
- Sum p_T of tracks <1.8 GeV in $\Delta R<0.2$

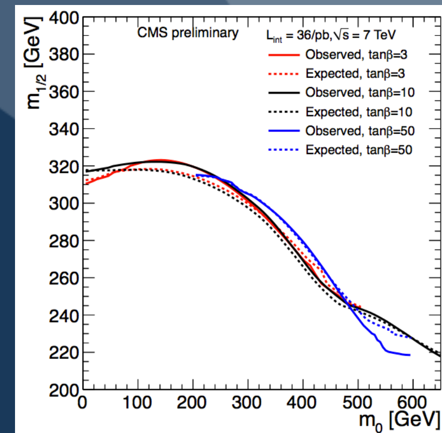
Missing E_T
- Calculated from objects and clusters

Remove overlapping objects
- If $\Delta R(jet,e)<0.2$, remove jet
- If $0.2<\Delta R(jet,e)<0.4$, veto electron
- If $\Delta R(jet,\mu)<0.4$, veto muon

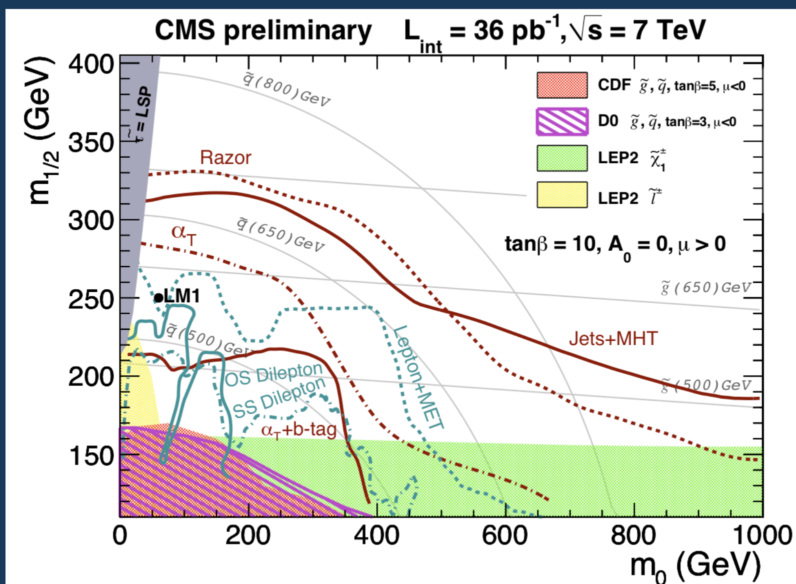
CMS-ATLAS Comparison

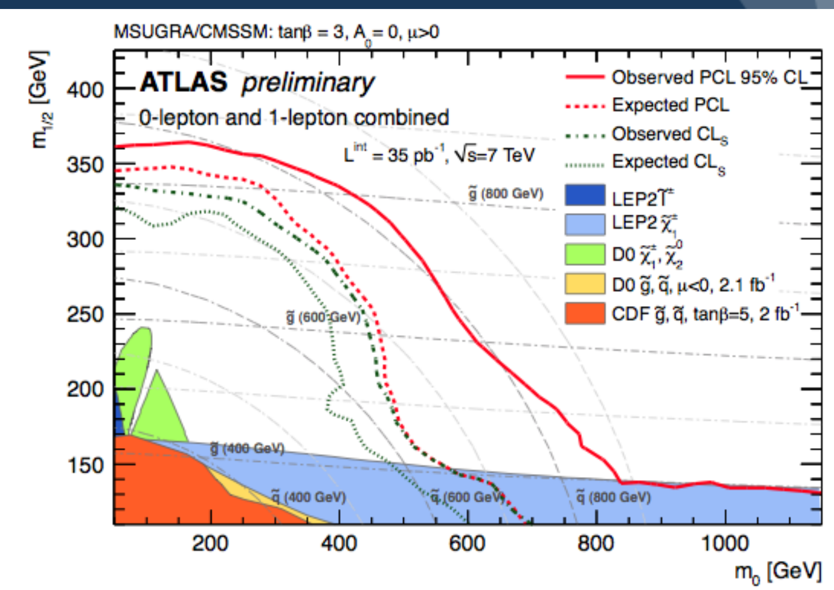
Compare CMS curves with ATLAS's green curves

- Same footing, using same CLs limit method
- ATLAS (tan b=3), CMS (tan b=10)
  red and black lines – almost identical →



CMS and ATLAS limits are very similar





This is not the end …

… but the beginning

of one of the most exciting periods in the history of particle physics

Joint the search, the fun, and hopefully the thrill of discovery