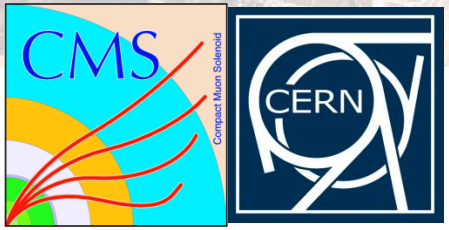
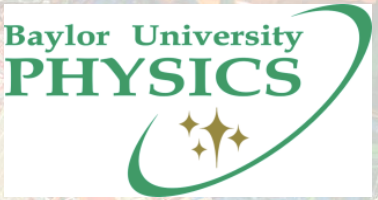
Results from Searches for Supersymmetry at CMS



Kenichi Hatakeyama
Baylor University



US LHC Users Organization Annual Meeting
Fermi National Accelerator Laboratory
October 18-20, 2012

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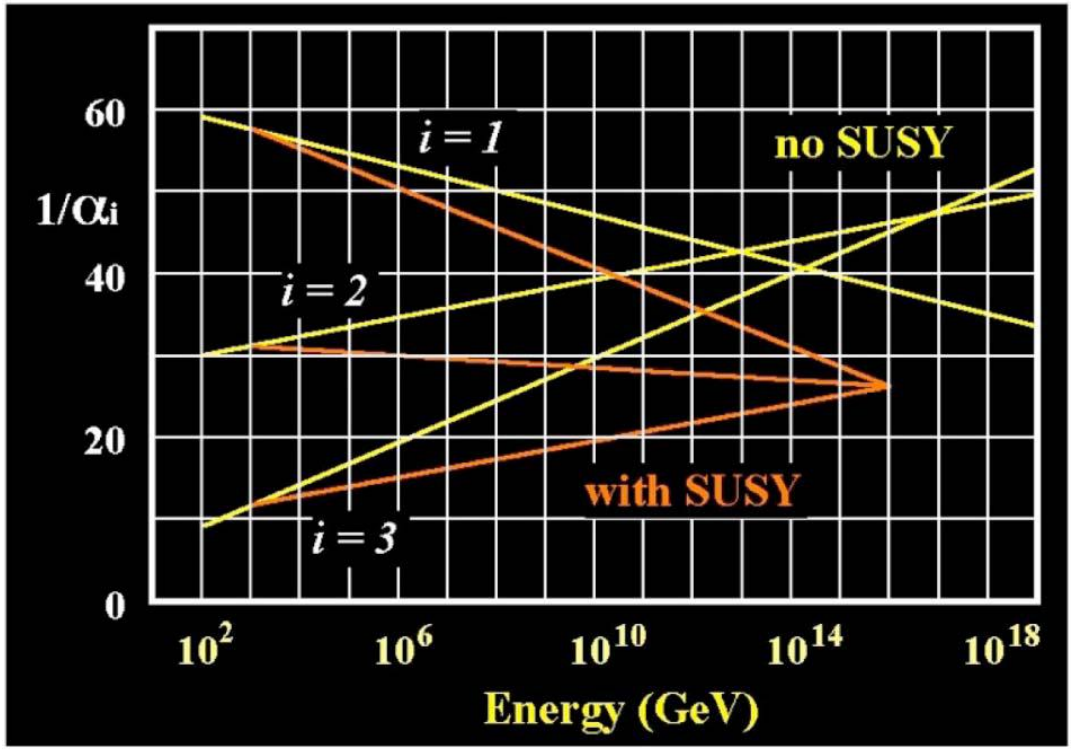

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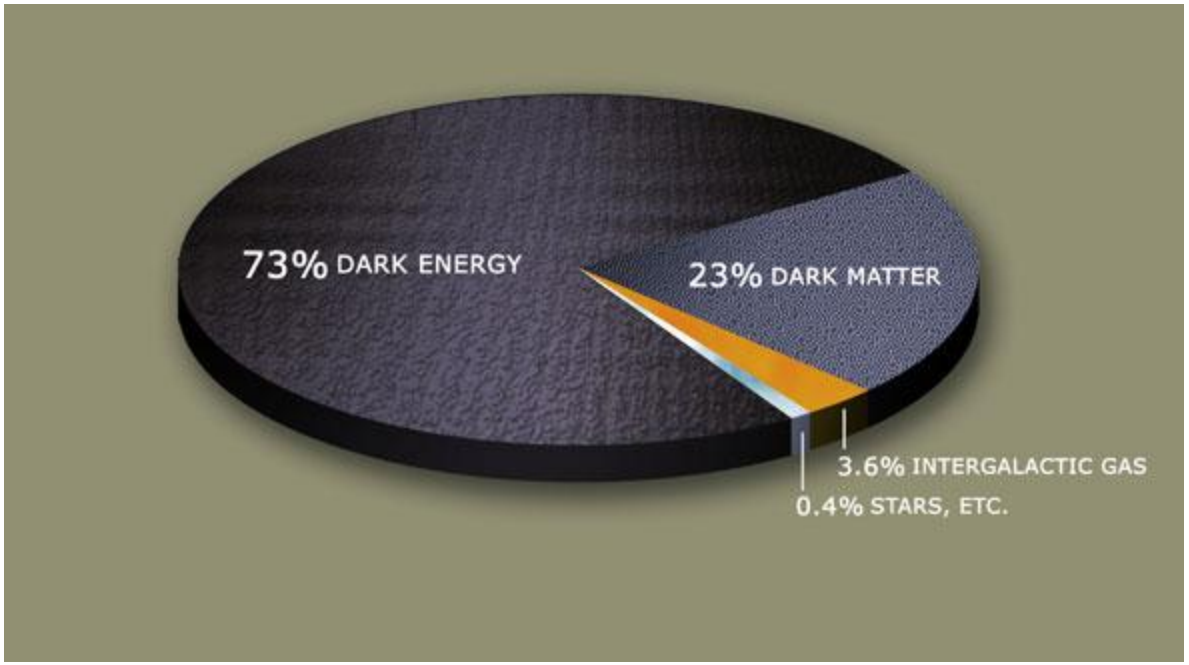

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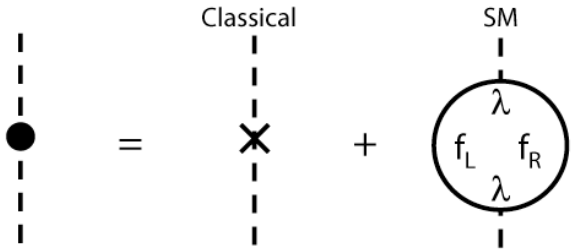

$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

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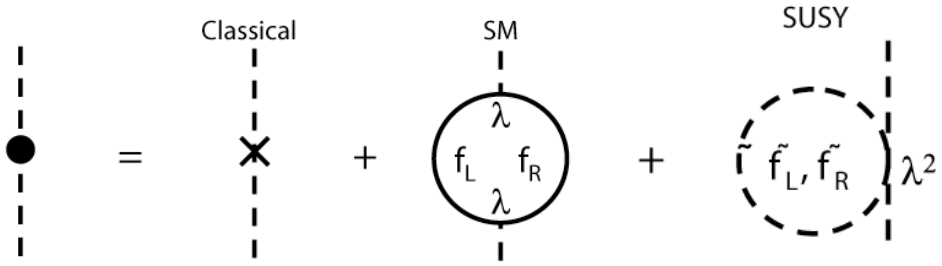
- Provide a solution to the hierarchy problem:

  Light Higgs (125 GeV!?) needs new physics to stabilize its mass
  - The contribution from a Dirac fermion loop diverges quadratically
  - The contribution from opposite spin super-partners would cancel the divergence resolving the hierarchy problem

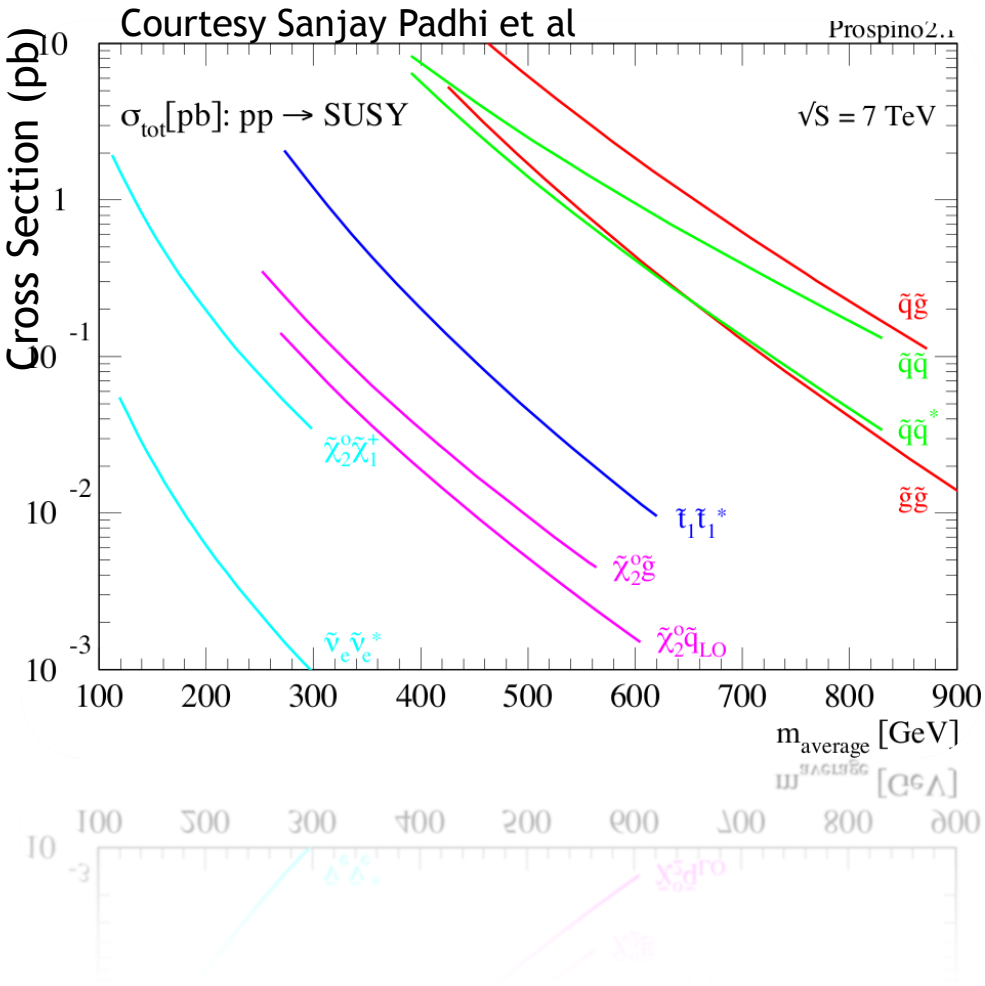


$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots$$

$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}),$$

SUSY Searches at CMS

- Many powerful "inclusive" searches have been pursued
  - Searching in a broad spectrum of new physics scenarios – main sensitivities to gluino/squark production
  - Different observables & search strategies have been used for complementarities and robustness
  - Some of them are even reaching to 3rd generation sparticles



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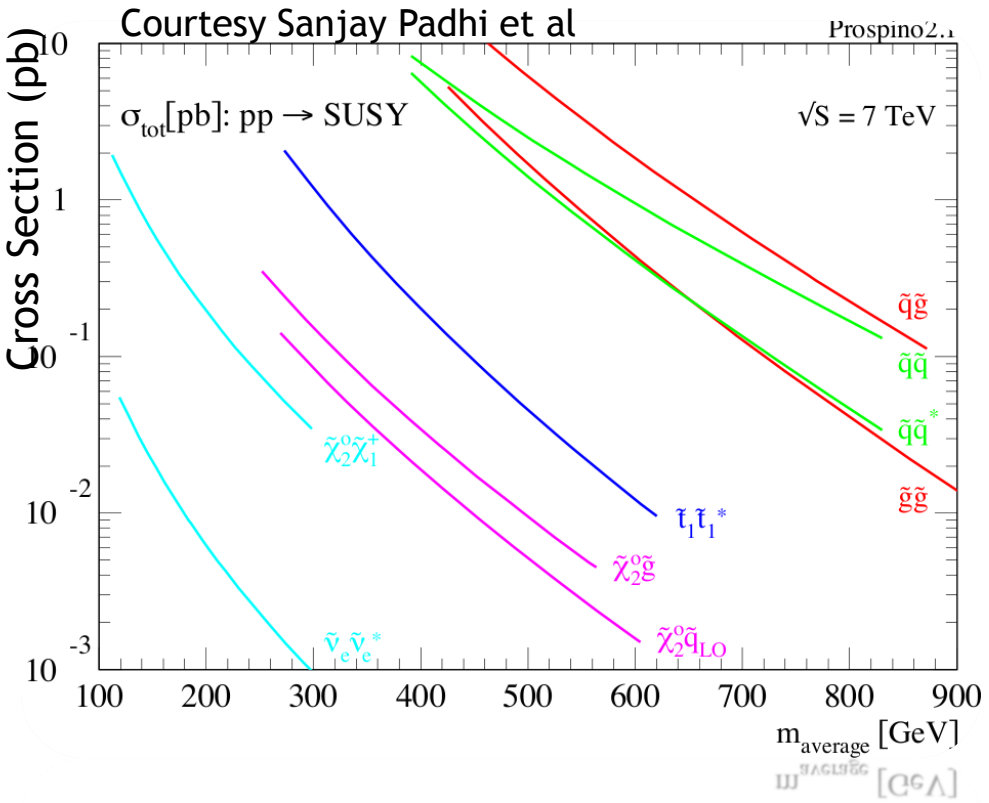

- More "targeted" searches also started to be very vigorously pursued
  - 3rd generation sparticles, gaugino production, etc
  - Difficult phase space (compressed spectra) and more SUSY scenarios

Inclusive Searches

- From the beginning of data taking, CMS deployed a series of inclusive searches to detect potentially-copiously-produced SUSY strong production
- Searches with different lepton categories
  - Different background (BG) compositions & less BG with more leptons
  - Different sensitivities to a variety of SUSY scenarios

All hadronic	Single lepton	OS dileptons	SS dileptons	Multileptons
• QCD • $Z \rightarrow \nu\nu$ • W+jets • ttbar	• W+jets • ttbar	• Z+jets • ttbar	• ZZ/ZW/WW • ttZ/W • Rare SM • ttbar	• ZZ/ZW/WW • ttZ/W • Rare SM

More signal rate/more BG

Smaller rate/more BG control

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More signal rate/more BG

Smaller rate/more BG control

  - Very challenging due to large amount and wide ranges of backgrounds
  - However most sensitive search for strongly-produced SUSY particles
  - Several complementary strategies based on kinematics and detector understanding

CMS-SUS-12-011, arXiv:1207.1898

Hadronic Search in Jets + MET

Selection

- Search variables:

$$H_T = \sum_{\mathrm{i}}^{\mathrm{jets}} |\vec{p}_{\mathrm{T,i}}|, \quad MH_T = \left| \sum_{\mathrm{i}}^{\mathrm{jets}} -\vec{p}_{\mathrm{T,i}} \right|.$$

  Other variable (CMS-SUS-12-002):

$$M_{\mathrm{T2}} = \min_{p_T^1 + p_T^2 = ME_T} \left[\max(m_T^1, m_T^2) \right]$$

- ≥3 jets with $|\eta|<2.5$, $p_T>50$ GeV
- Veto isolated e/mu
  - Suppress W & Top BGs
- $\Delta\varphi$(MHT,j1,2,3) > 0.5,0.5,0.3 (rad)
  - Suppress QCD background

Backgrounds

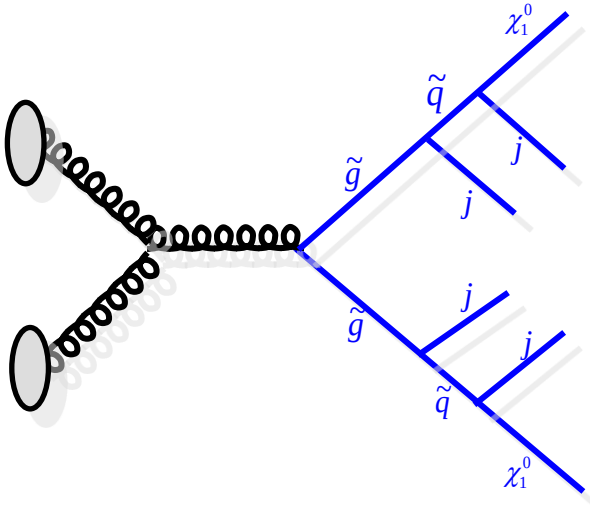
- QCD
- Top & W+jets
- Z($\rightarrow\nu\nu$)+jets

Determined by data-driven techniques

HT: Characterize visible energy of the event

MHT: Object-based MET. Characterize energy carried by undetected particle. Classic, yet powerful.

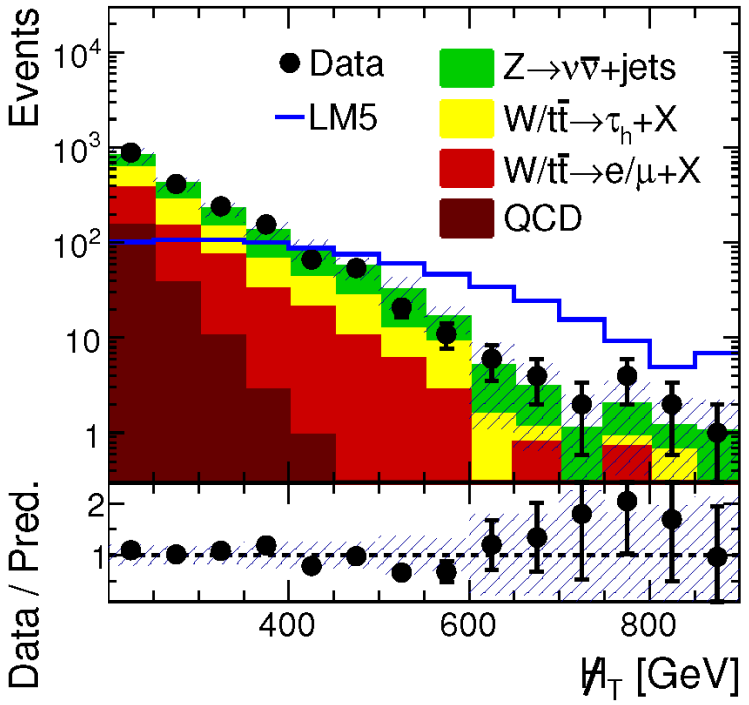
MT2: generalized MT for decay chains with two unobserved particles. MT2 peaks toward 0 and MT2<MET for QCD-like events.



Hadronic Search in Jets + MET

Background estimation:

- "Data-driven" and MC-free as possible: robustness!
- Z(→νν)+jets
  - γ+jets: remove γ, correct for Z(→νν)/γ
  - Z(→ll)+jets: remove ll, correct for Br(Z→νν/Z→ll)
- Top & W(lν)+jets: lost leptons (escape e/μ vetos) or W→τ hadronic decays
  - Start with μ+jets sample
  - Lost leptons:
    - Correct for lepton finding/losing probability
    - Use e-μ universality
  - W→τ hadronic decays:
    - Replace μ with hadronic τ response function
- QCD: Smear the well-balanced events in QCD control sample



MC-based backgrounds for illustration

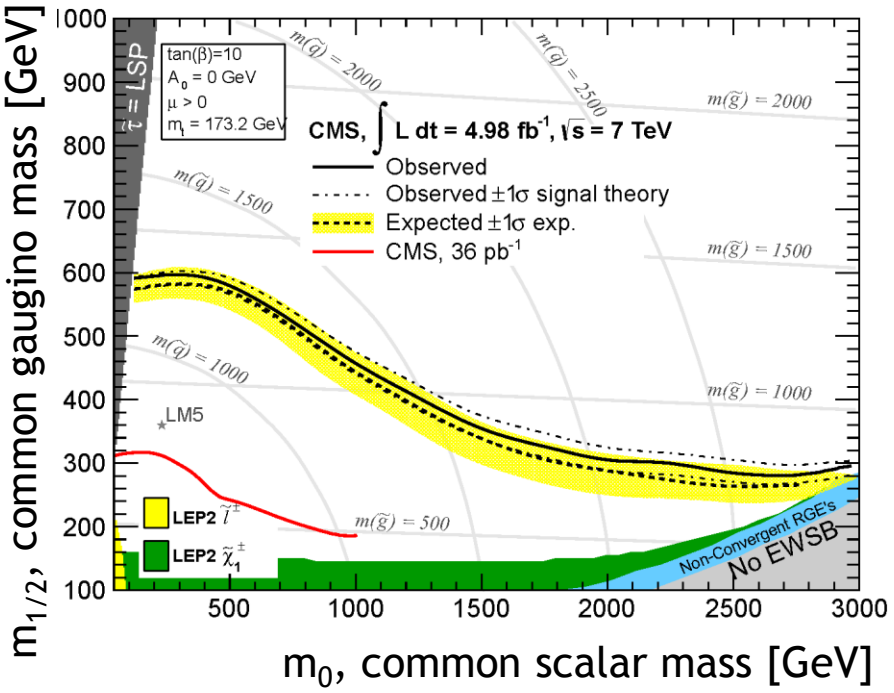
LM5*: m_0=230GeV, $m_{1/2}$=360 GeV, A_0=0, tanβ=10, sign(μ)>0

CMS-SUS-12-011, arXiv:1207.1898

CMSSM / mSUGRA

- Inclusive SUSY results have been conventionally shown in the context of "constrained" MSSM / mSUGRA

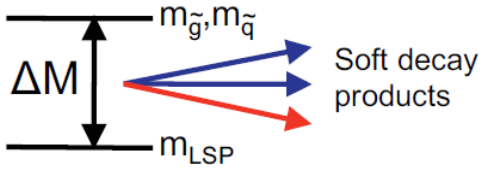
- CMSSM has only 5 parameters: universal scalar and gaugino masses, m_0, $m_{1/2}$, A_0, tanβ, sin(μ).
- Very predictive; however, the universality constraints result in significant restrictions on possible SUSY particle mass spectra
- Now, it's common to interprete results in more general topology-based "simplified model"



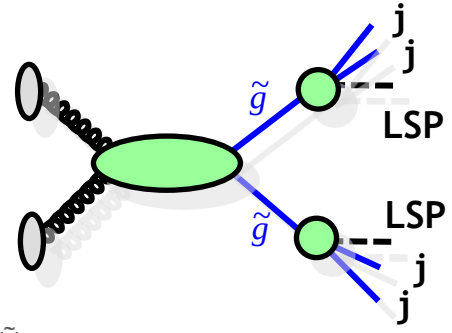
m(gluino) > 720 GeV
m(squark) > 1.2 TeV

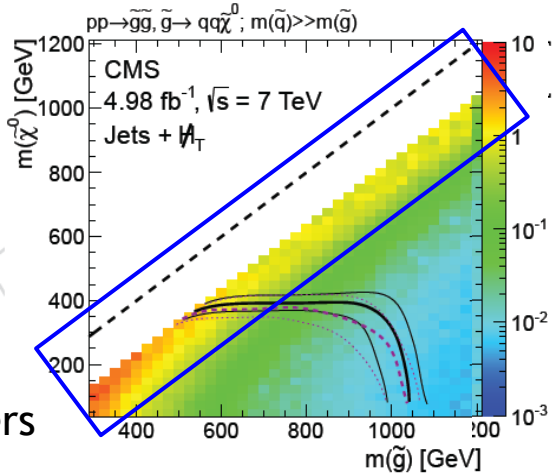
Simplified Model (SMS)

- Focus on topology instead of underlying physics model
- Any model with same topology (parent particle mass, decay chain, daughters mass) can be "easily" compared with experimental results.
  - Building blocks that can be used to generalize to a more complete 'model'-space
- The exclusions depends strongly on the LSP mass.
  - The compressed spectrum region (small LSP-gluino mass differences) are much less constrained



  - New analysis under development. Parked triggers with lower thresholds





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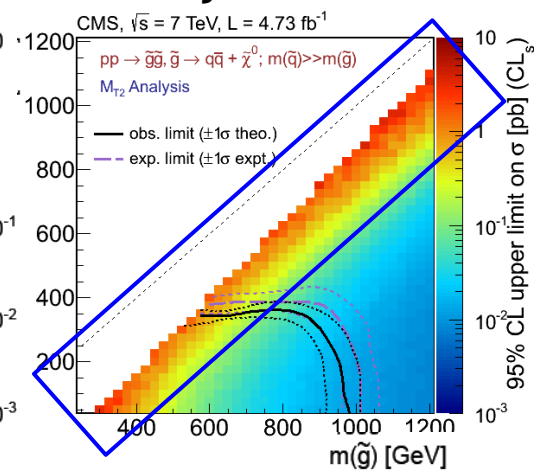

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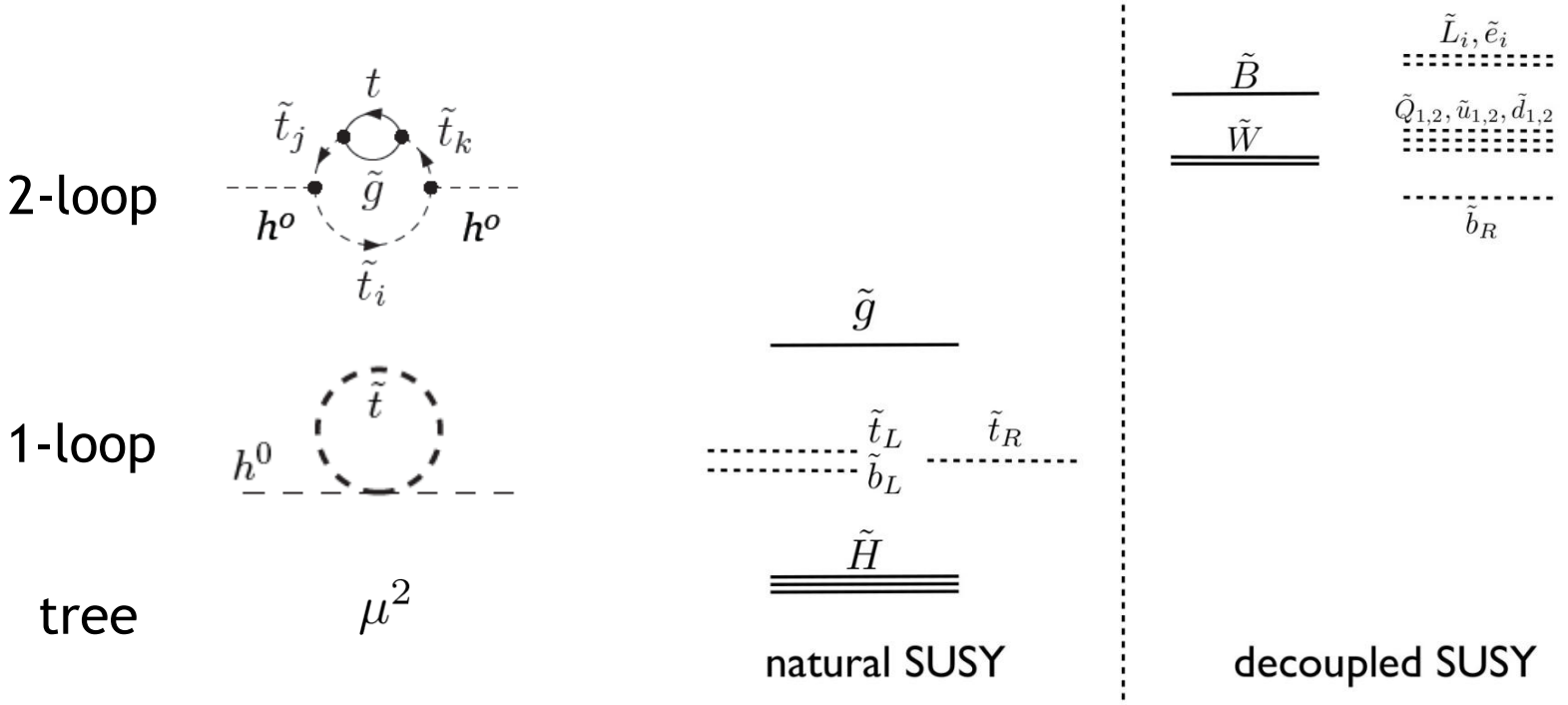
Natural SUSY

- Renewed focus on minimal SUSY requirements to protect Higgs mass, which motivates searches for scalar top quark like particle

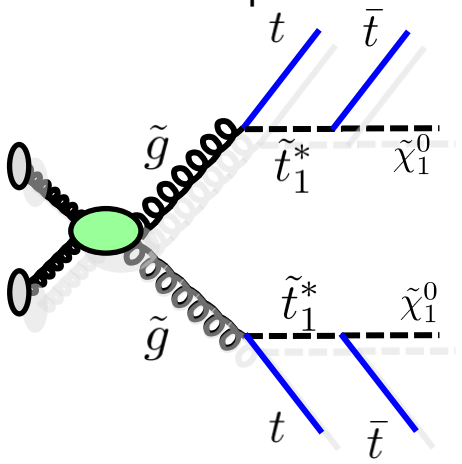


Papucci, Ruderman, Weiler, arXiv:1110.6926

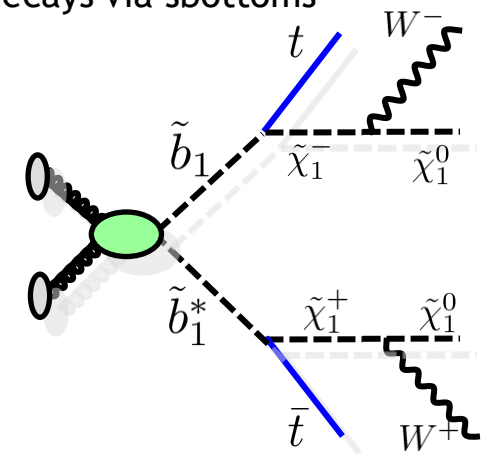
SS Dileptons with >=2 b Jets

- Same-sign leptons are classic SUSY searches
  - Leptons from many SUSY decay chains: chargino, neutralino, W, Z, sleptons…
  - Low SM backgrounds
- Adding b jets helps even more
  - Lower backgrounds
  - t→bW can give even more leptons
- Selection
  - ≥ 2 b-tagged jets with pT > 40 GeV
  - Isolated same sign e or μ pair pT > 20 GeV
  - Reject extra leptons consistent with Z's
  - MET > 30 GeV
- Dominant Background
  - ttbar (l+jets) with fake leptons
  - Charge mis-reconstruction
  - Rare SM processes (ttW, …)

Gluino pair production with decays to real and virtual stops



Sbottom pair production or gluino decays via sbottoms



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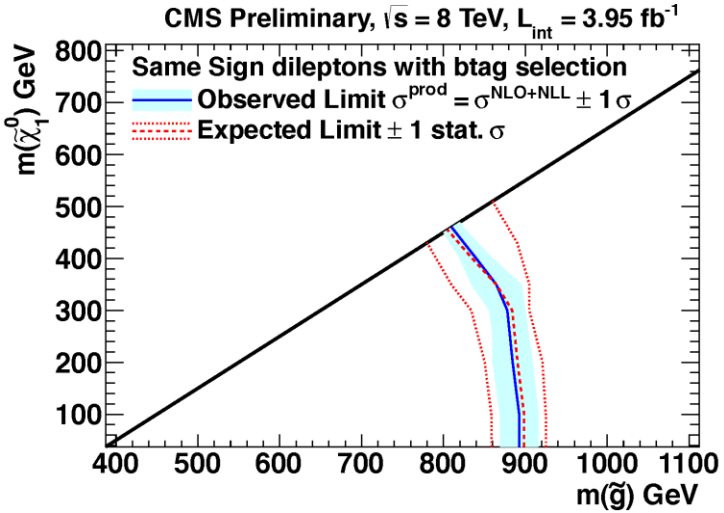
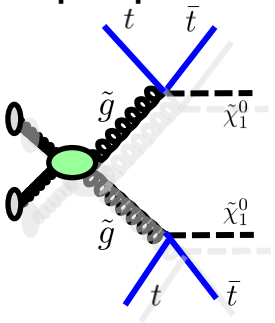
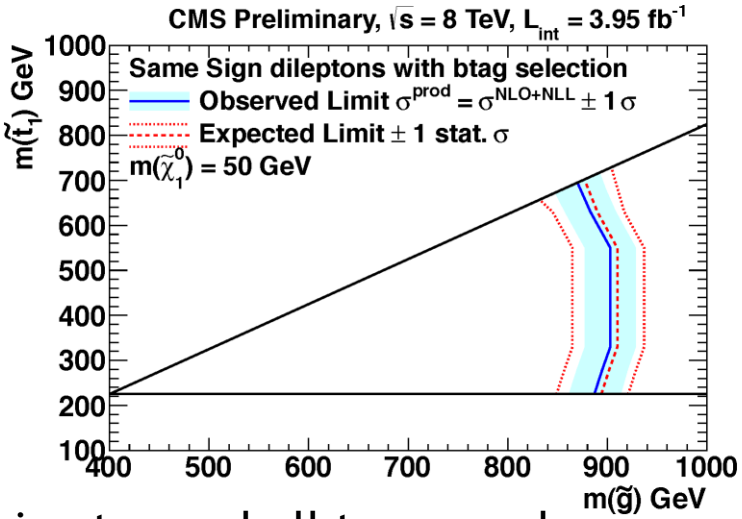
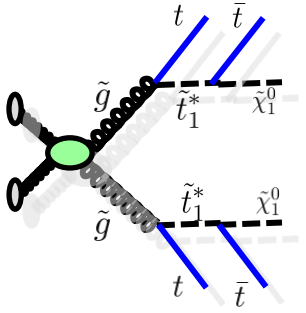


Guino to virtual top squarks





Gluino to on-shell top squarks



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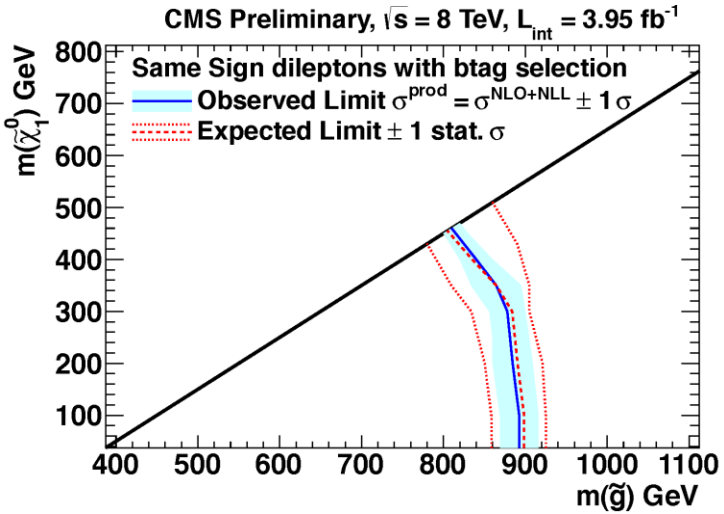

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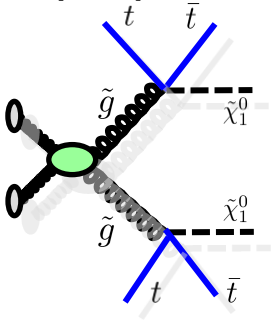

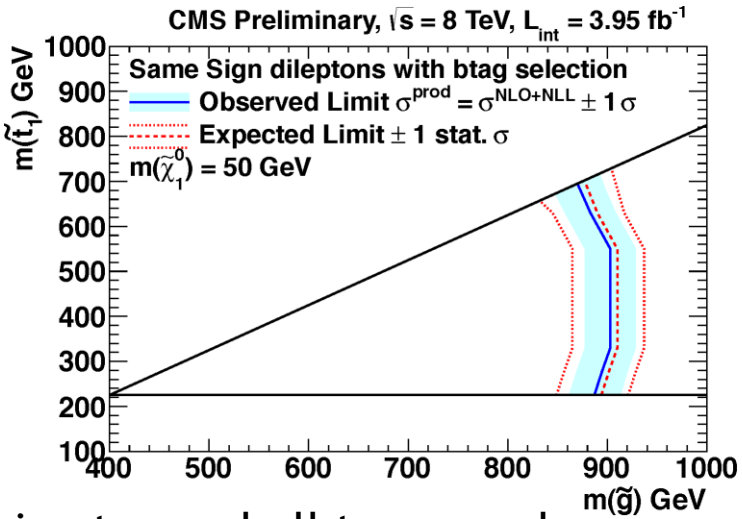

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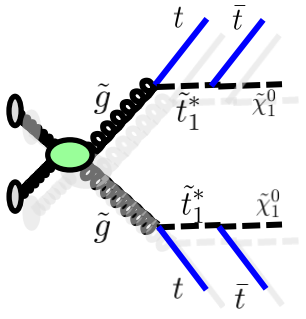


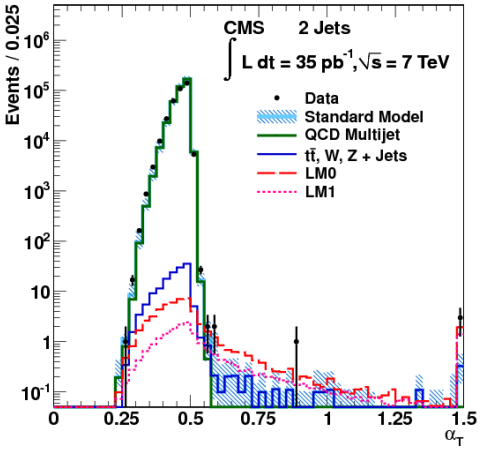
Gluinos have been excluded with masses up to ~880 GeV
(Lower limit on the bottom squark mass of 408 GeV)

α_T Search with 0,1,2,>=3 b's

- α_T variable:

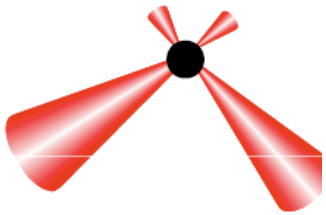
$$\alpha_T = \frac{E_{T,j2}}{M_{T,j12}} = \frac{\sqrt{E_{T,j2}/E_{T,j1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$

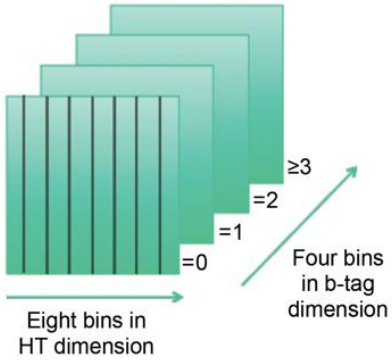
  - QCD: Peak around 0.5 and tail to lower α_T
  - αT>0.55 → Strong suppression of QCD BG



Event Selection

- ≥2 jets with pT>50 GeV, |η|<3
  - Jet1 with|η|<2.5 & pT>100 GeV
- Veto isolated electrons, muons, and photons
- 8 HT bins starting from 275 GeV
- Binned in 0, 1, 2, and >=3 b-tag bins





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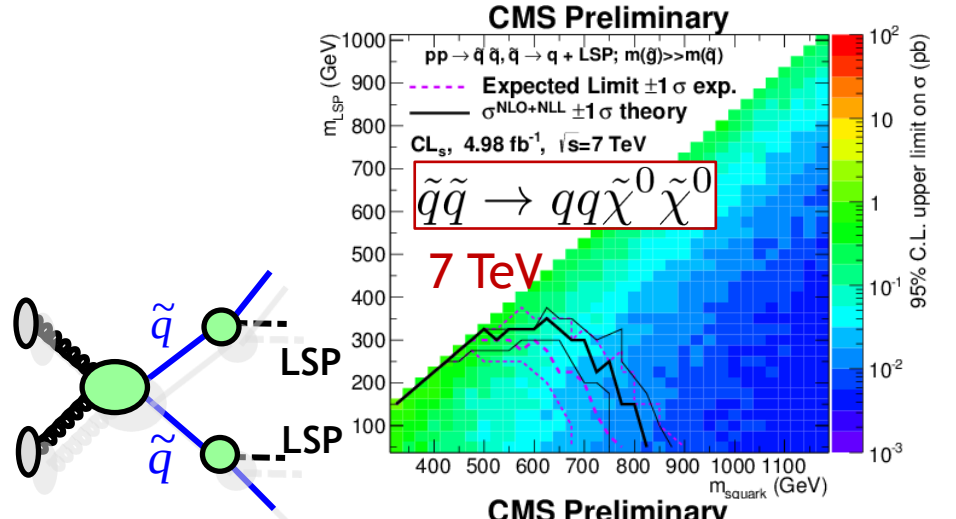
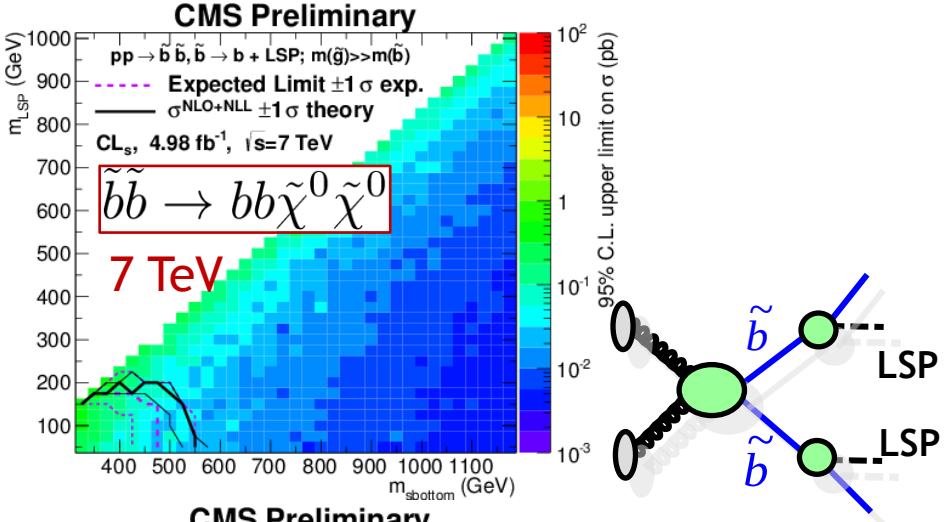
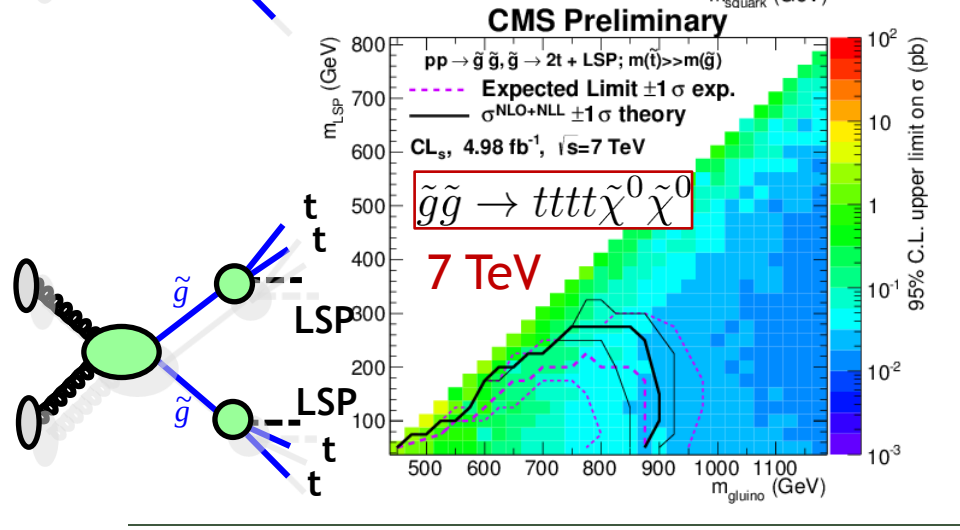
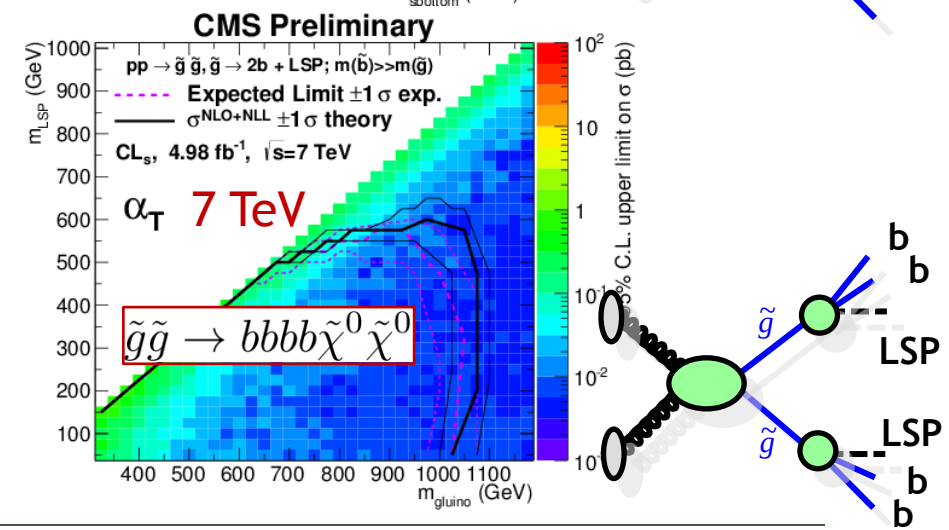
- Strong constraints on various SUSY topologies









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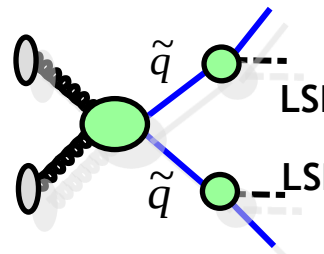
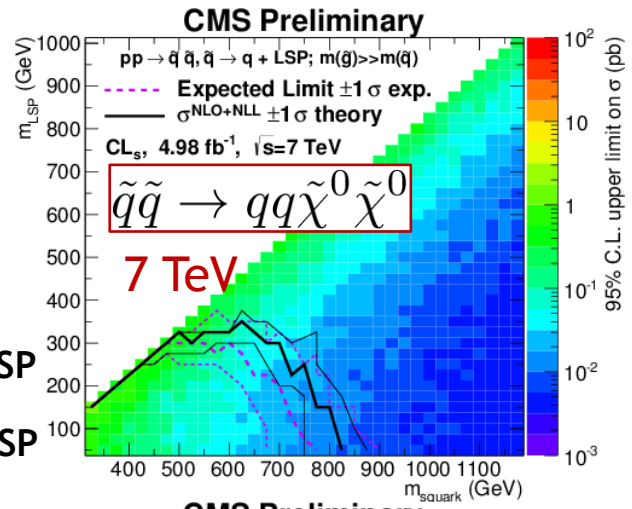
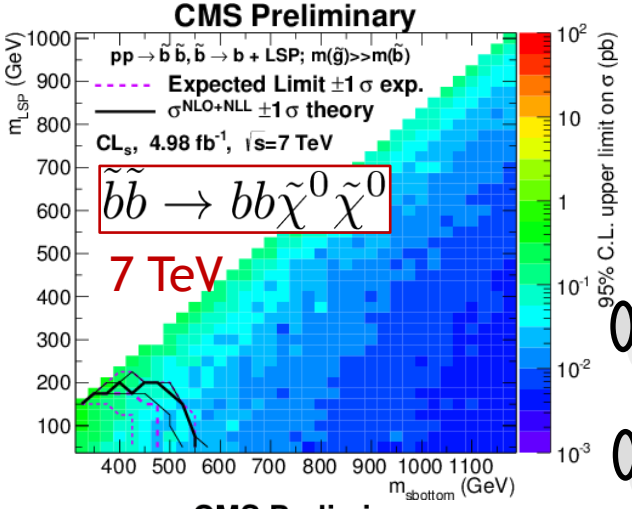
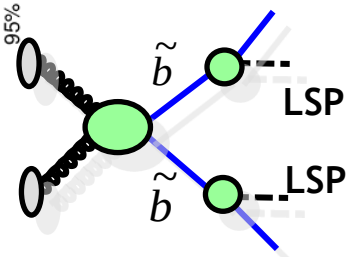
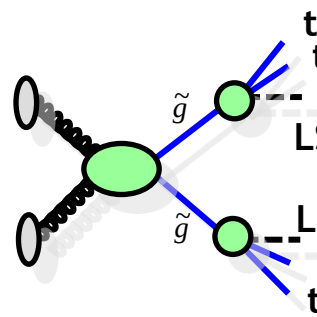
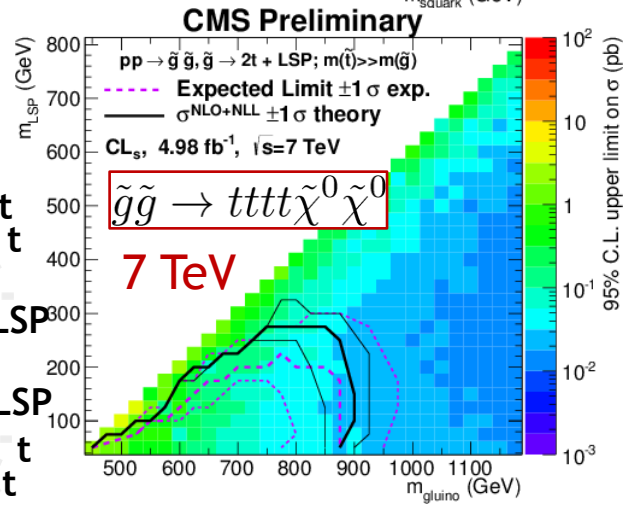


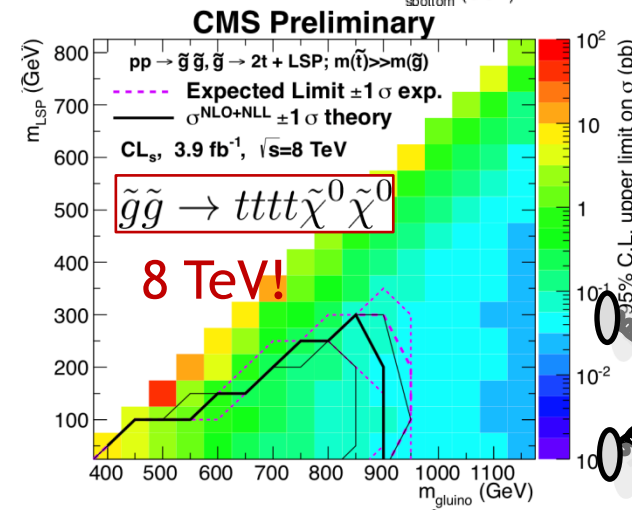


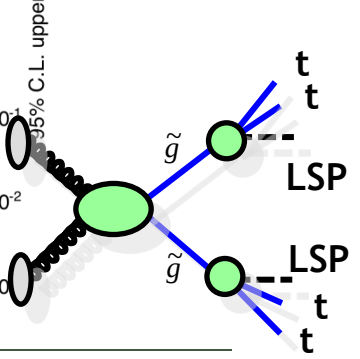




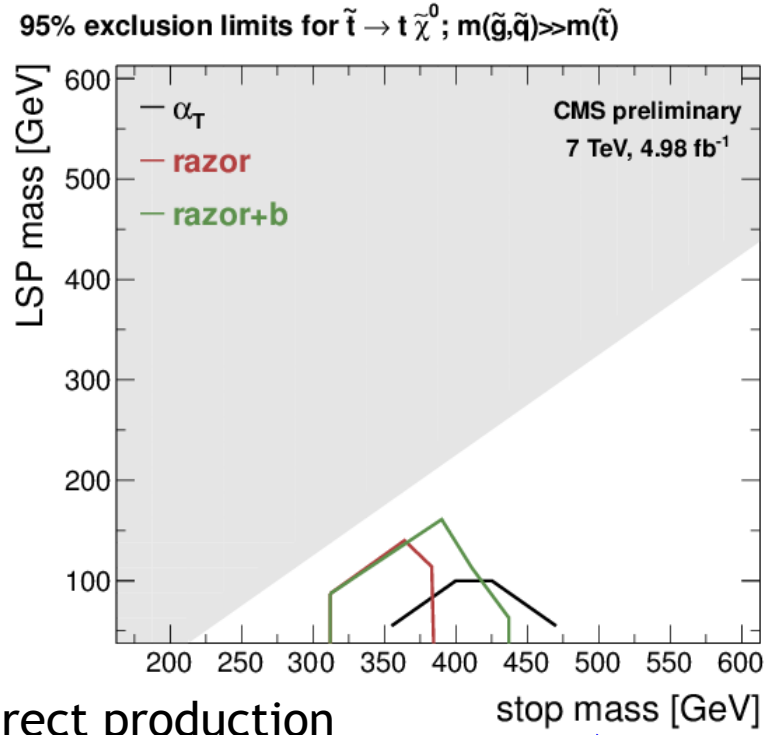




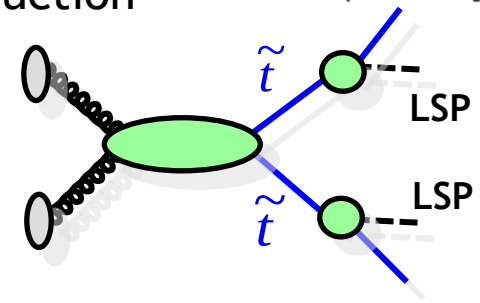


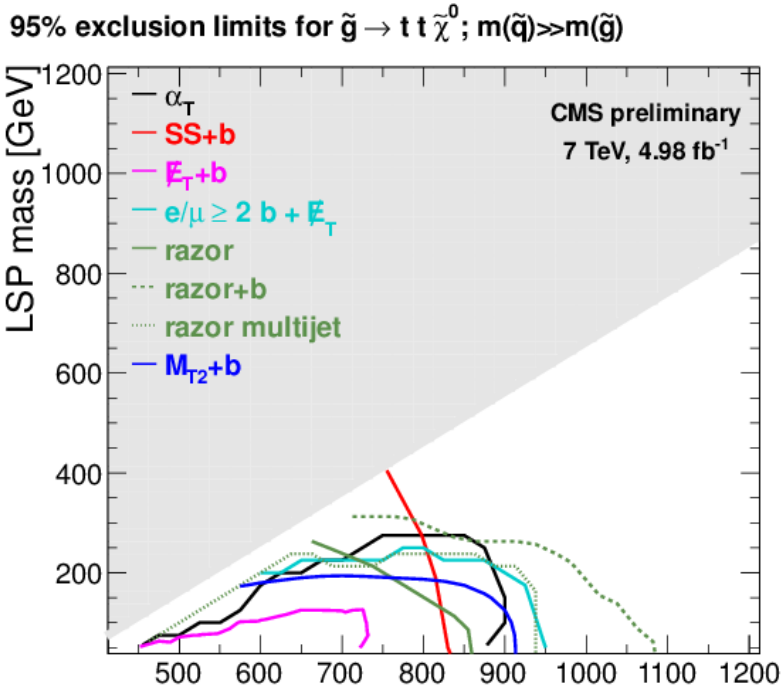


Limits on Stop Production

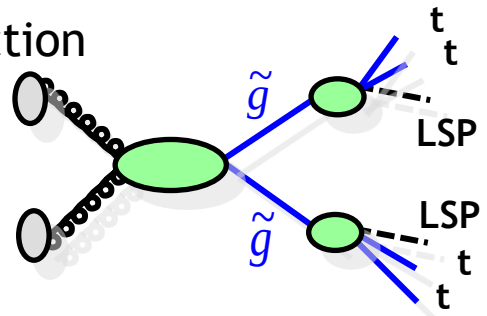


Direct production





Gluino-mediated production

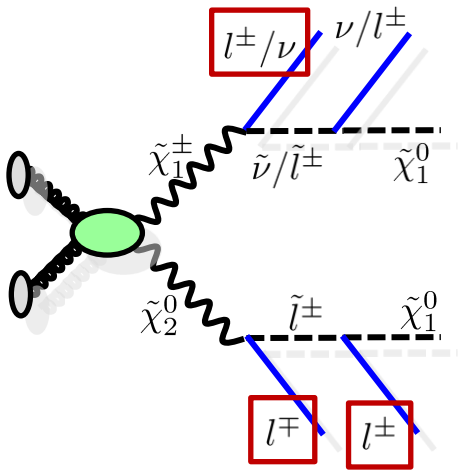


More dedicated searches in the pipeline

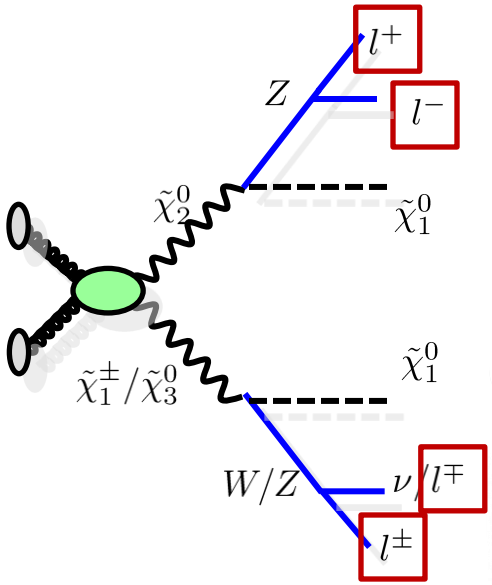
Direct Gaugino Searches

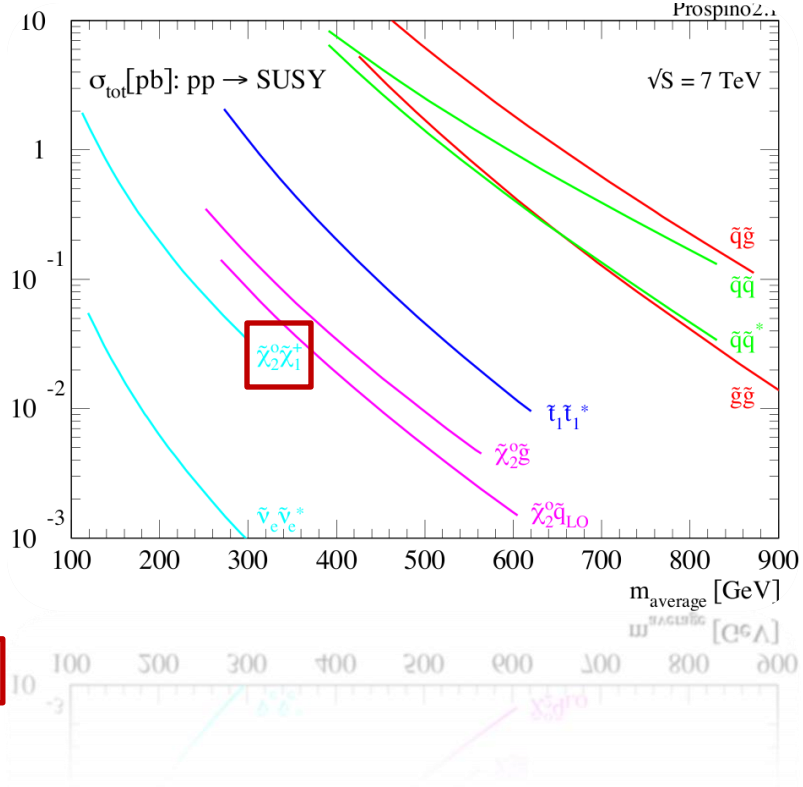
- Mass limits on gluinos and squarks have been pushed higher and higher. Direct production of gaugino may be dominant SUSY production at the LHC.
- Typical signature: multiple leptons

Decays to sleptons



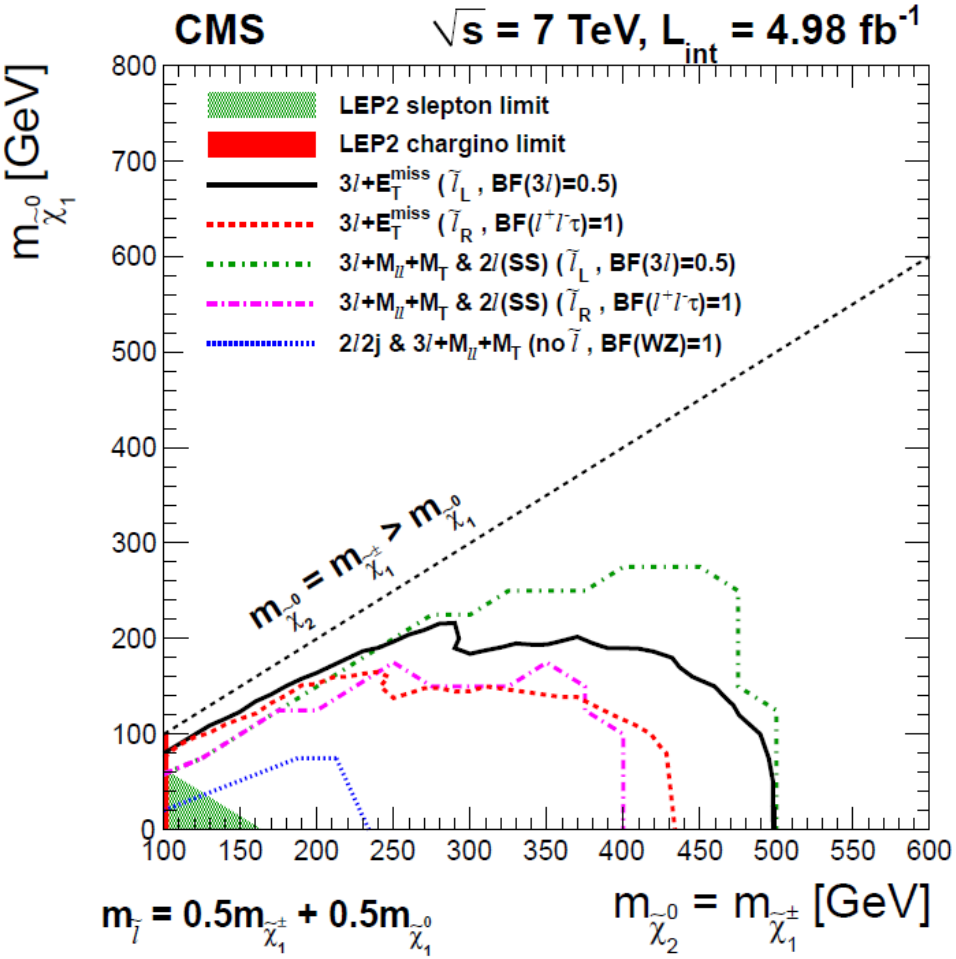
Decays to W/Z





CMS-SUS-12-006, arXiv:1209.6620

Direct Gaugino Searches



- 3(4)-leptons + MET
- 3-leptons + M(ℓℓ) + MT
- Same-sign di-leptons+MET
- Opposite-sign dileptons + dijet

Probe chargino/neutralino masses up to ~200-500 GeV, depending on decay mode

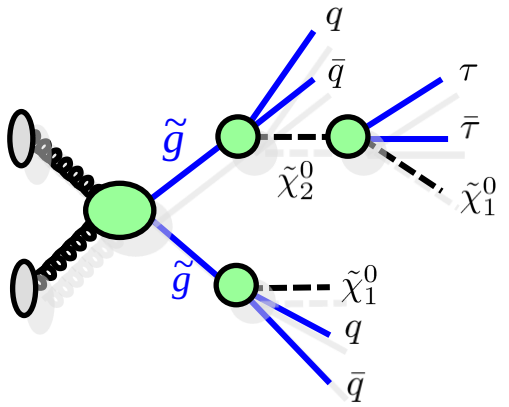
1st set of results/limits on direct EWKino production from CMS

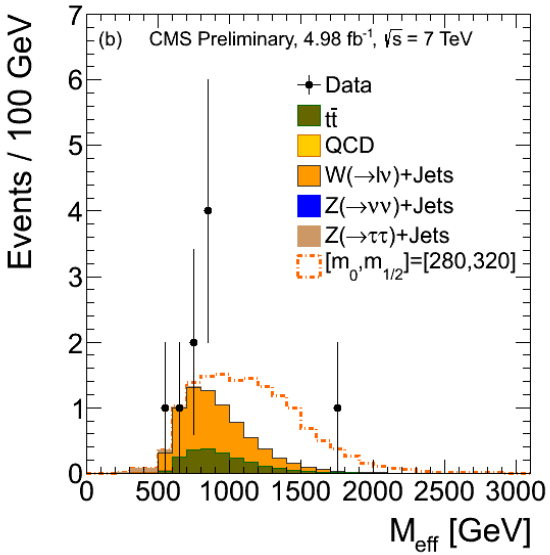
CMS-SUS-12-004

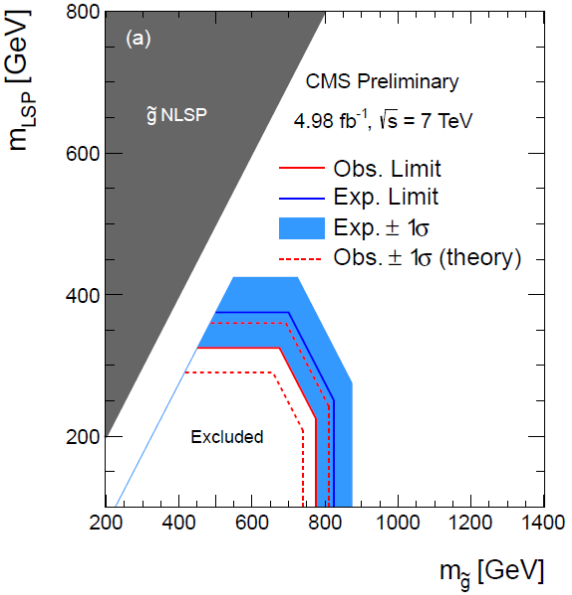
Searches with Taus

Motivation

- Measured relic density ($\Omega_{DM}h^2$~0.12) suggests
  - sufficient annihilation $\tilde{\chi}_0\tilde{\chi}_0 \to f\bar{f}$
  - or co-annihilation $\tilde{\chi}_0\tilde{\tau}_1 \to \tau\gamma$
- In CMSSM, staus often lightest sfermions
  - Large co-annihilation cross section
  - Cosmologically favored parameter region





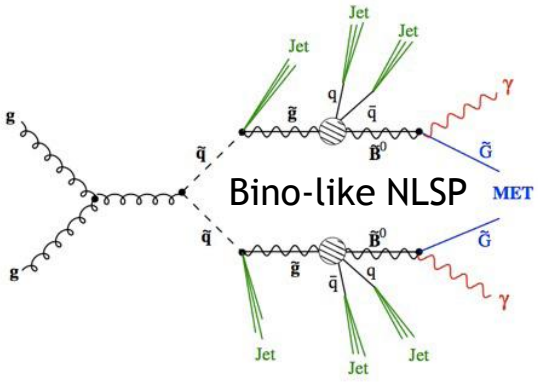


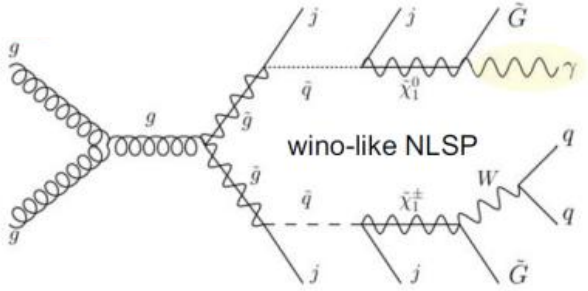
Gluino exclusinos up to ~800 GeV

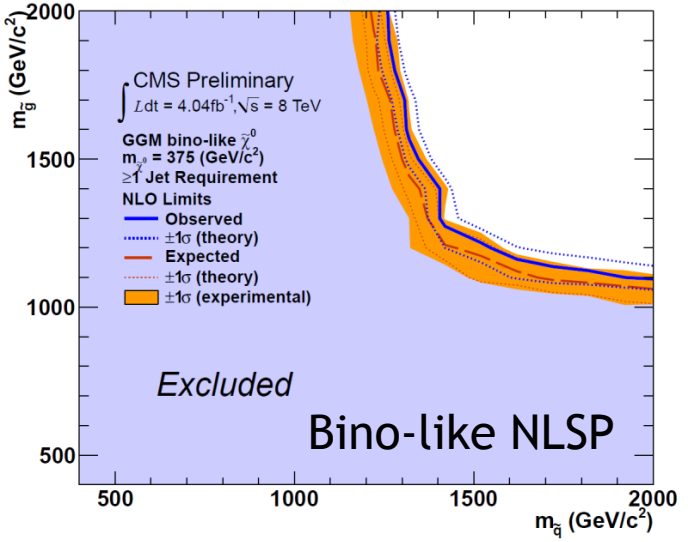
CMS-SUS-12-018

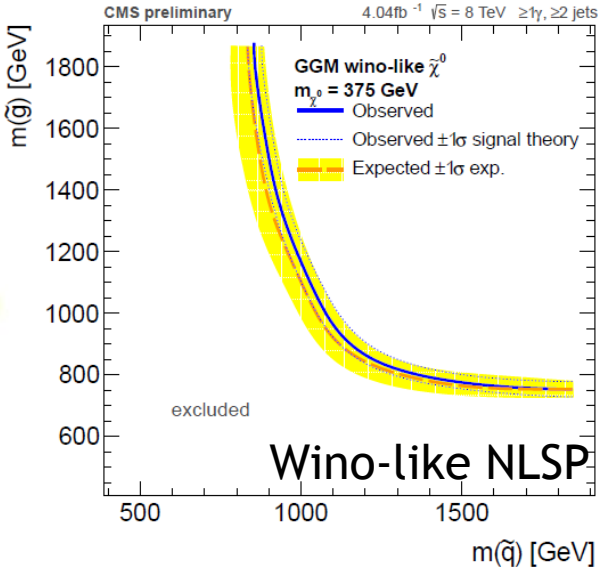
Searches with Photons + MET

- Motivation
  - Gauge mediated SUSY
  - Large extra dimensions
- Signature
  - 1, 2 or more photons pT > 80 (40/25) GeV; At least 1 (2) jets with pT > 30 GeV; MET > 100 GeV
- Backgrounds
  - QCD: jet-γ mis ID, mis-measured jet
  - W(ev)+γ: e-γ mis-ID





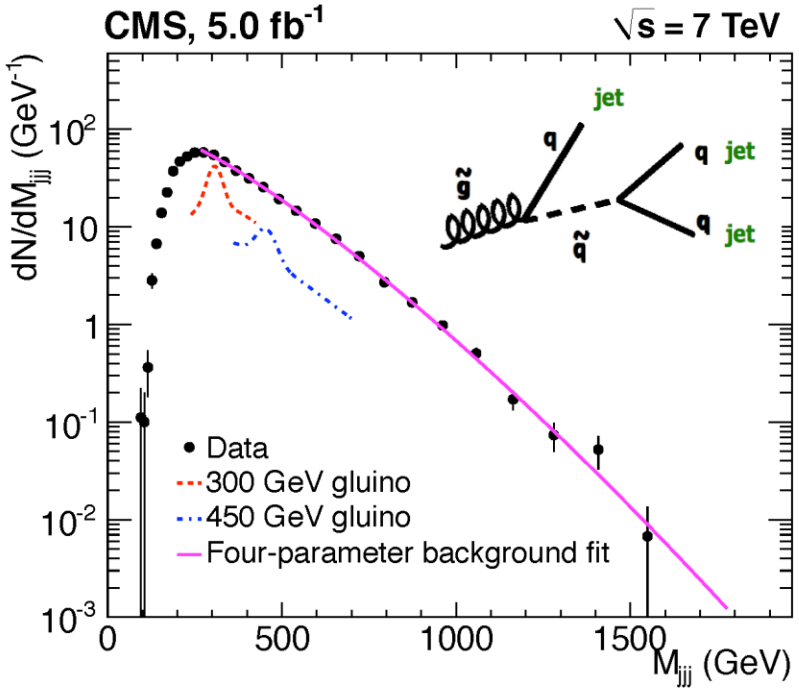


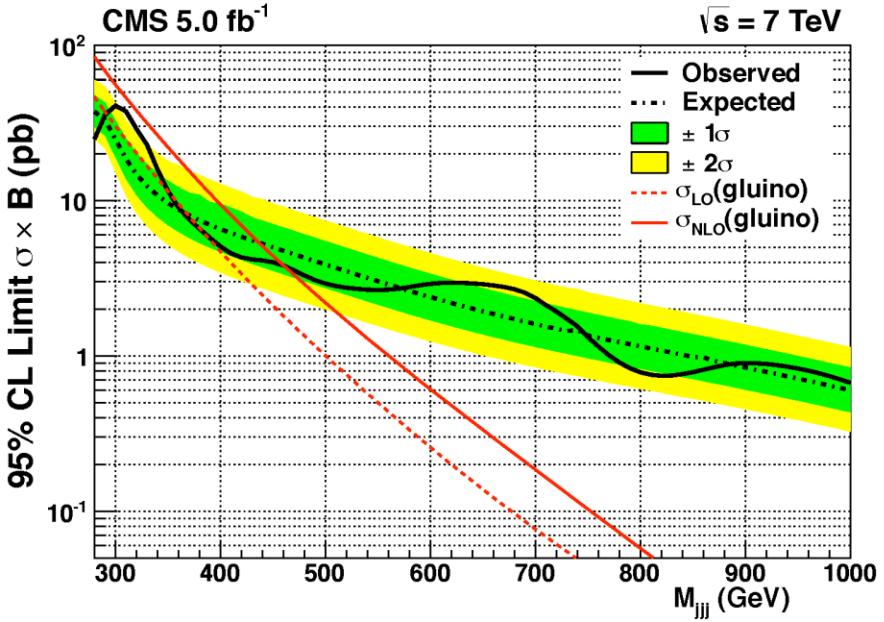


CMS-EXO-11-060, arXiv:1208.2931

RPV SUSY Searches

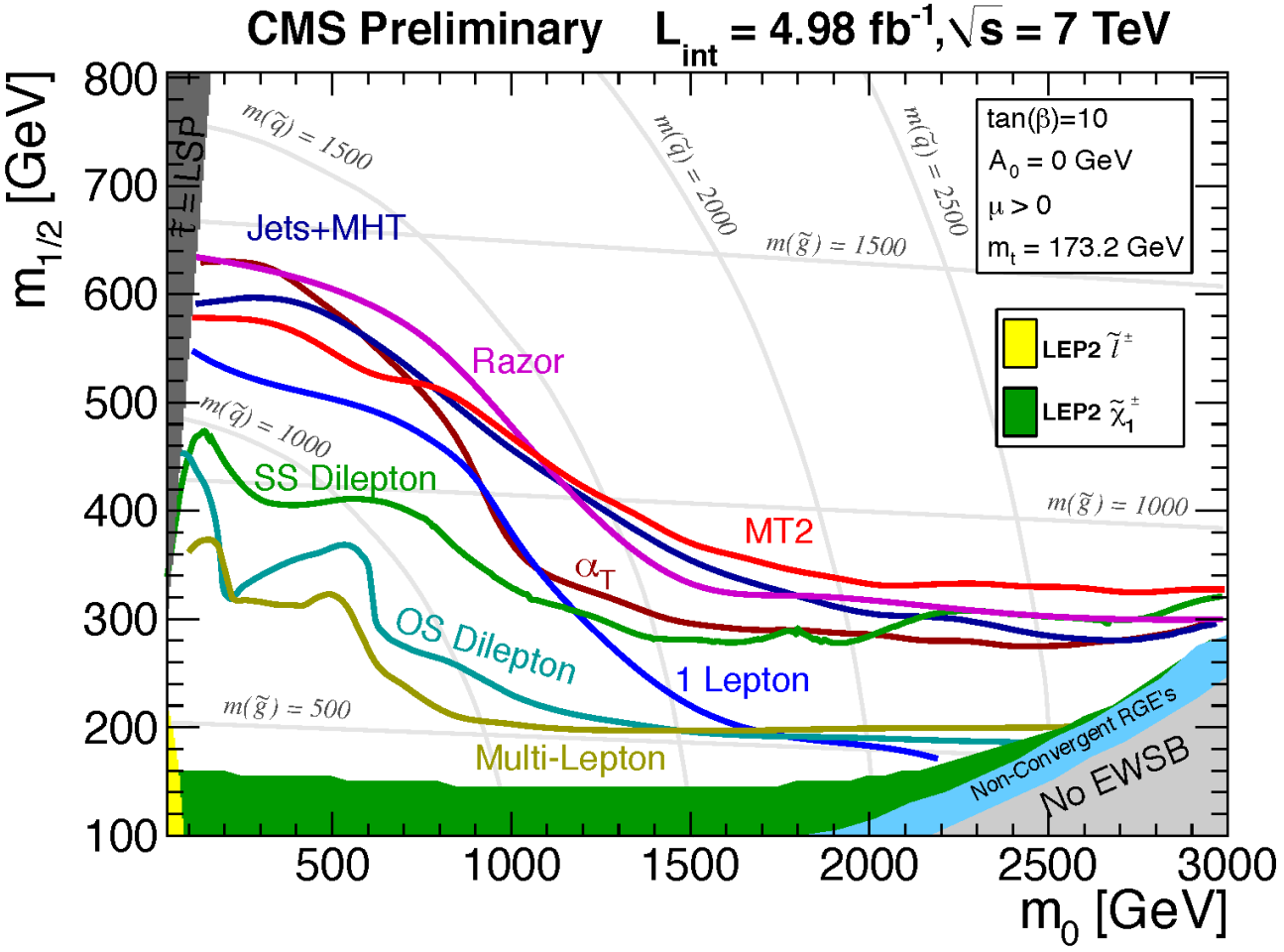
- Lots of possibilities, but not searched for thoroughly
  - Some "exotic searches" have sensitivities (See Jim Hirschauer's talk tomorrow)
- Example: Search for gluino decaying into 3 quarks





Exclude gluino masses below 460 GeV (assuming 100% BR into three jets)

CMSSM Summary



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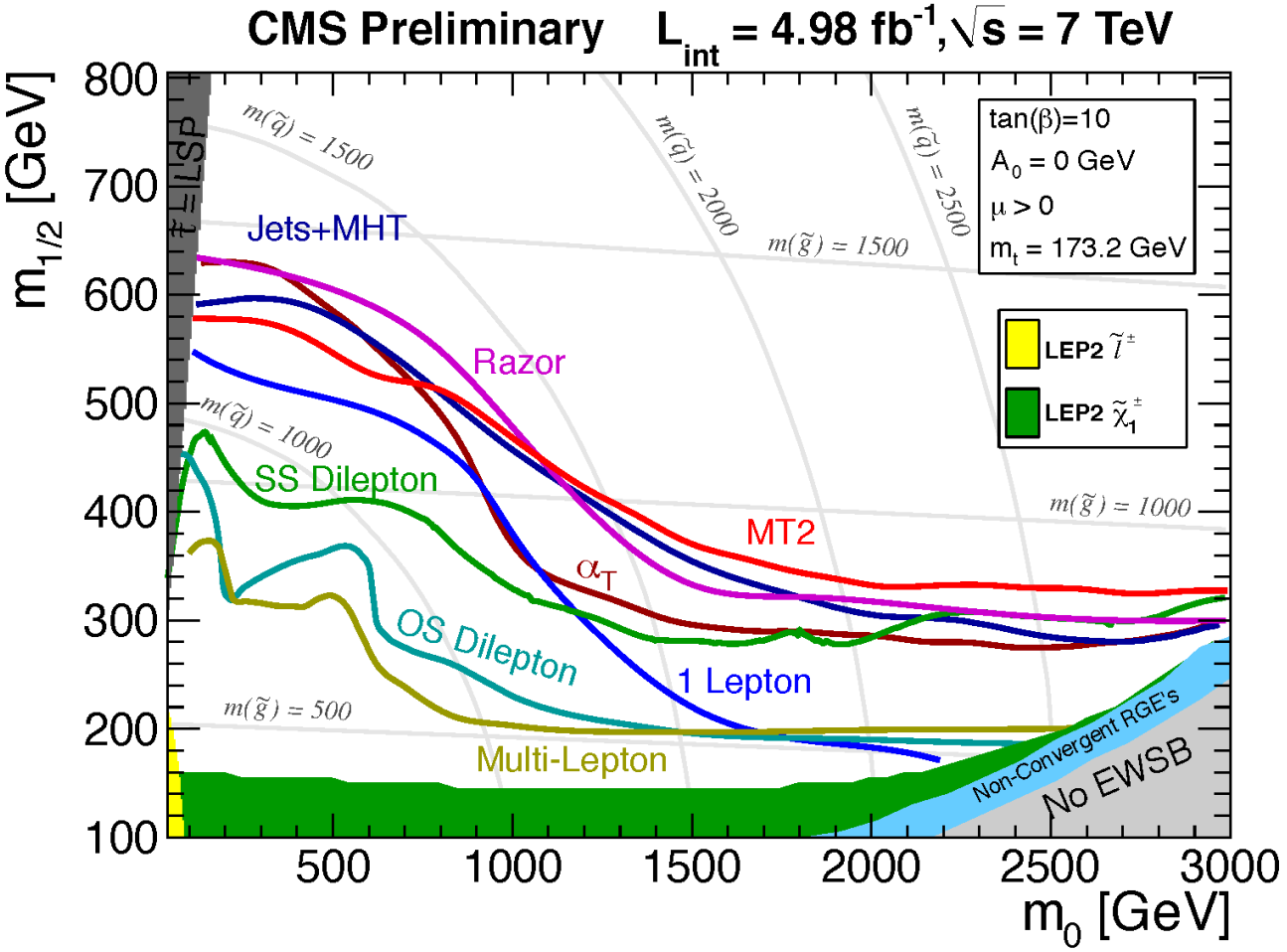
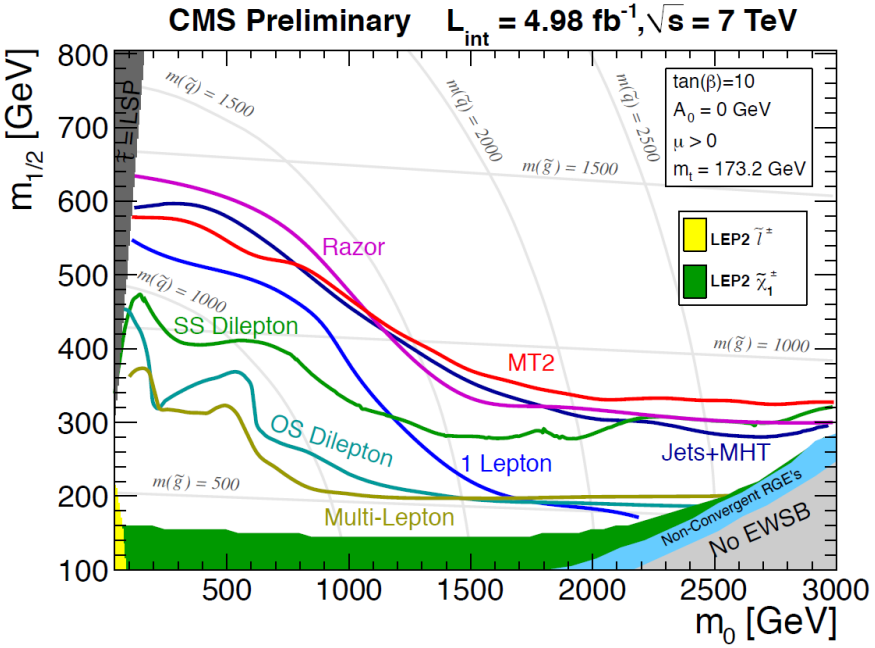


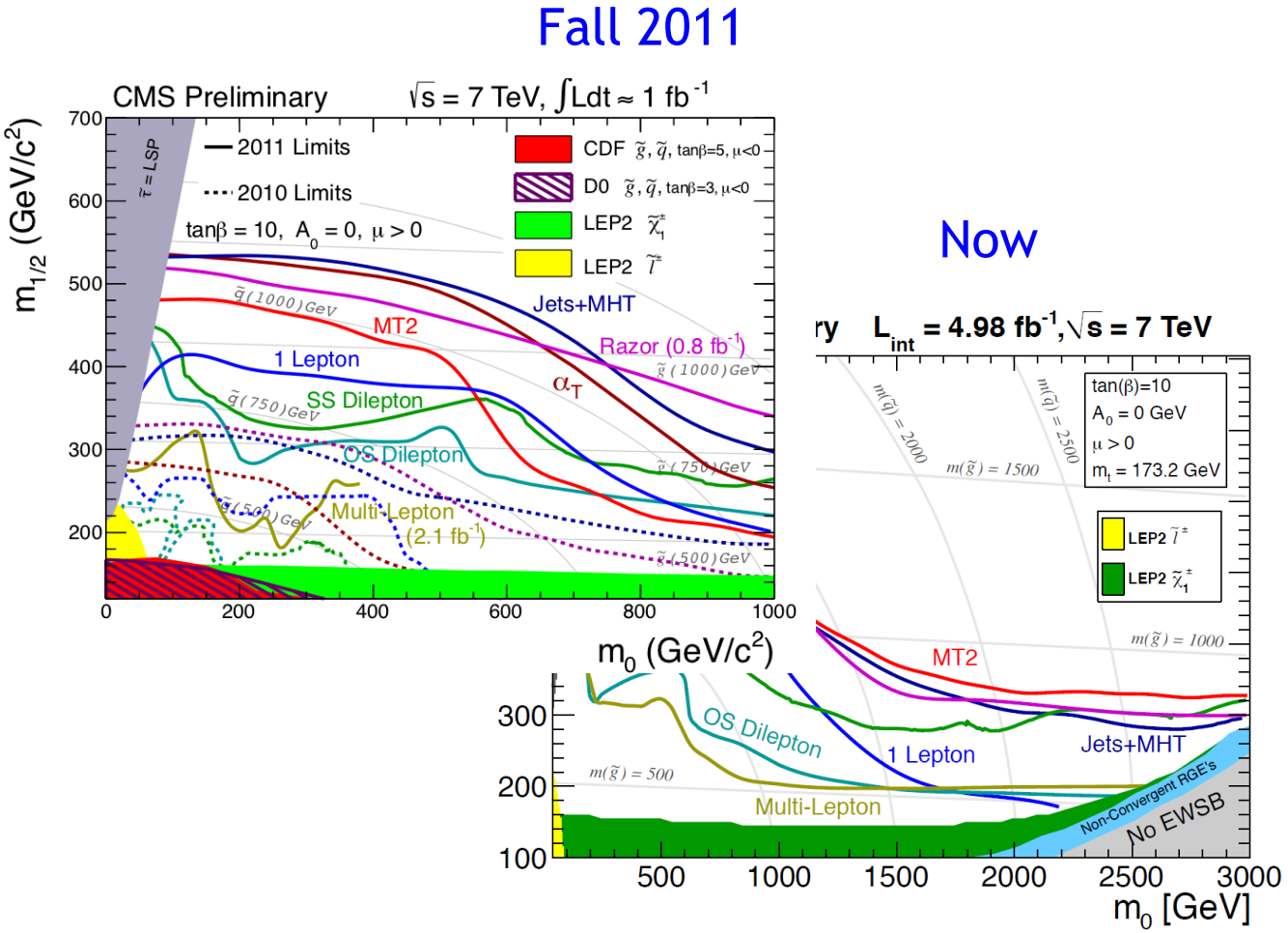
- Probing already 1 TeV mass scale and beyond for squarks or gluinos

CMSSM Summary from CMS

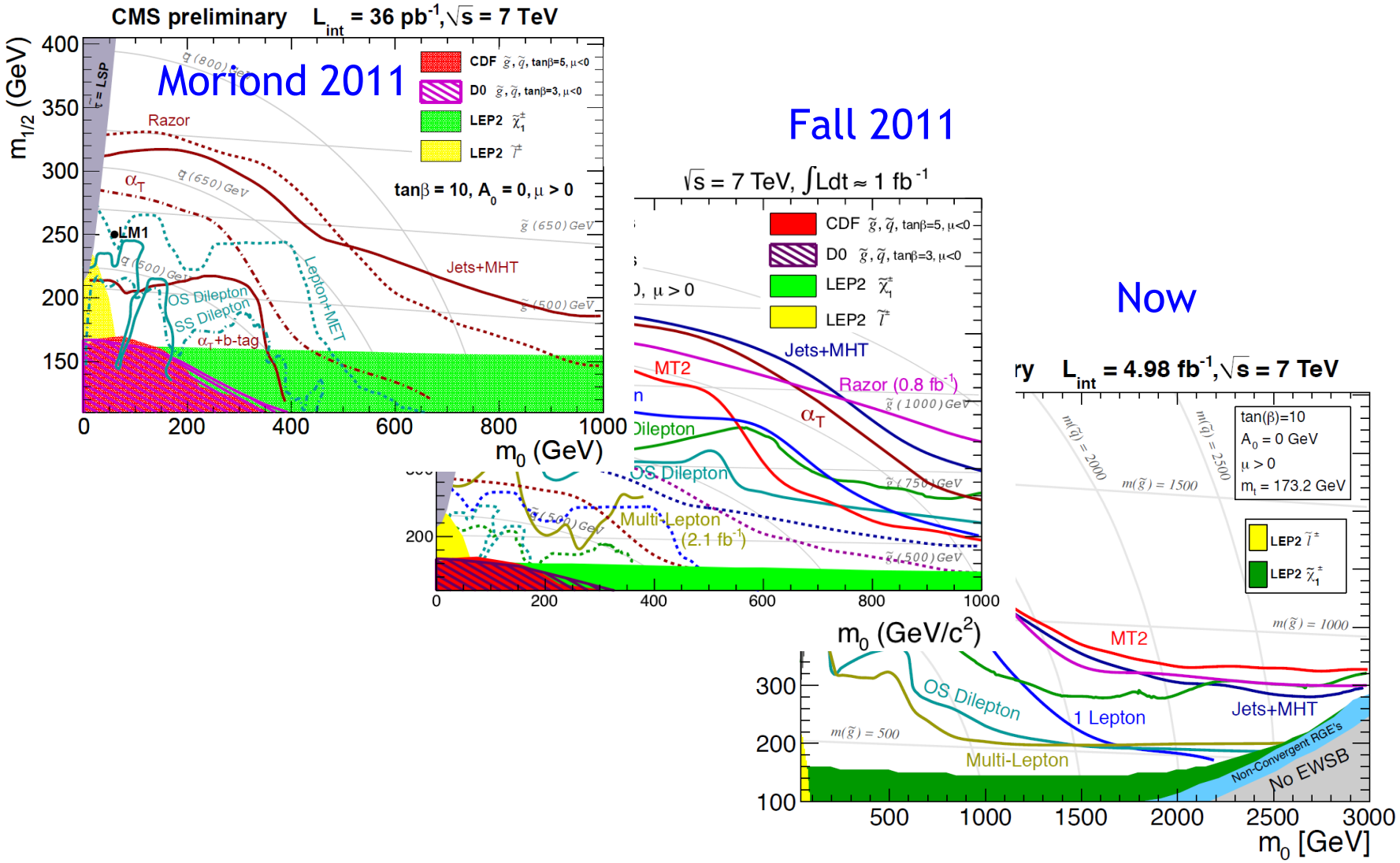
Now



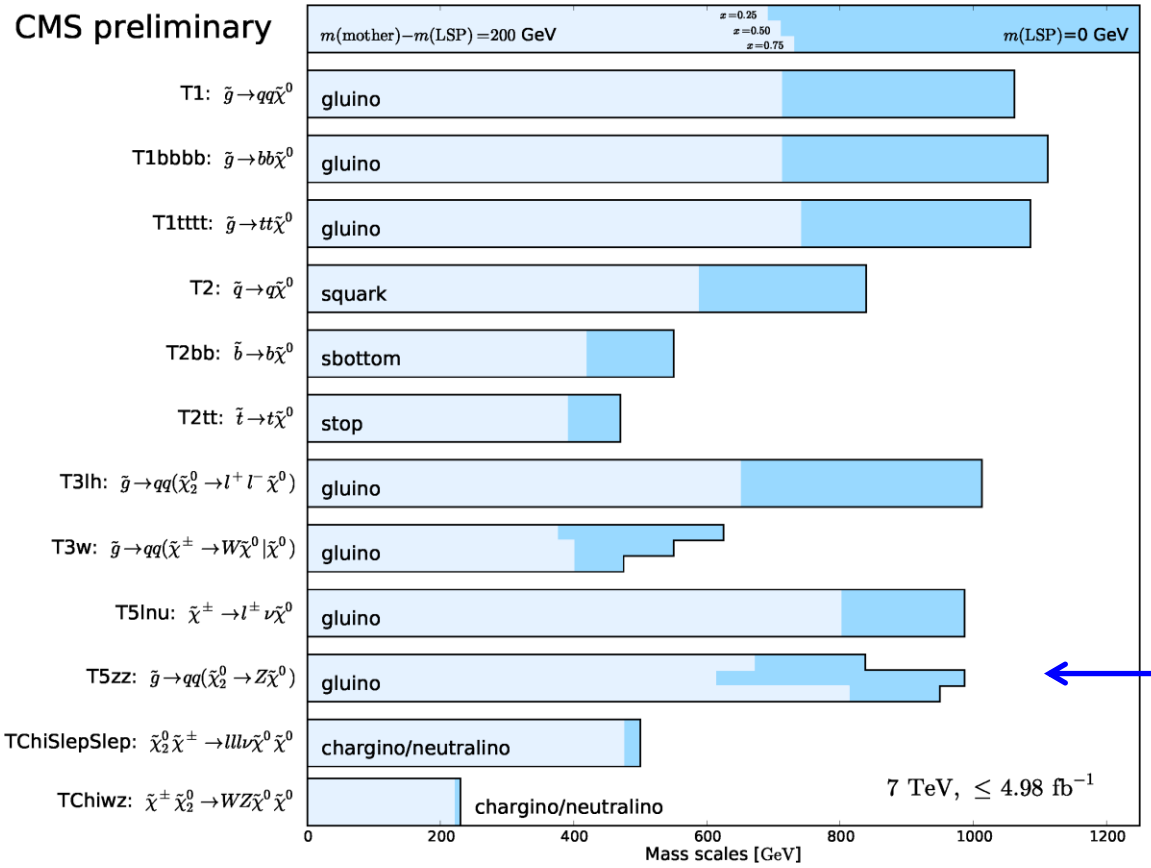
CMSSM Summary from CMS



CMSSM Summary from CMS



CMS Search Summary with SMS



3 bars for different intermediate x masses

- ~1 TeV scale limits on squarks & gluinos (strong production)
- Up to ~500 GeV for top squark and WEKinos
  - Limits often strongly depends on M(LSP), still large phase space to cover

Summary

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

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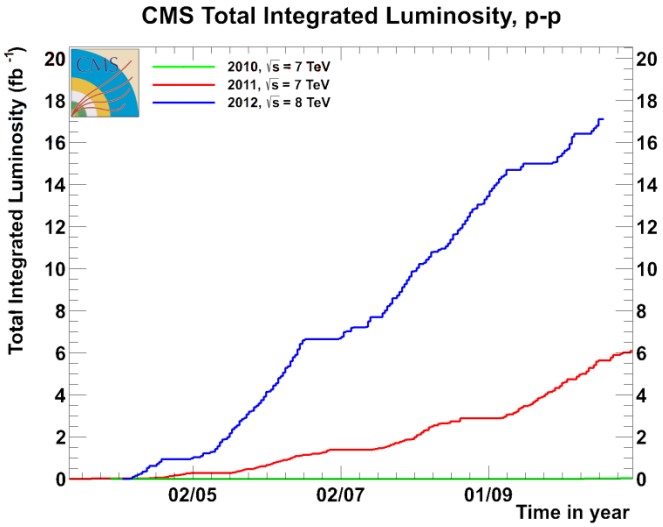

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  - Improved sensitivities in 2012 with higher √s and more data
    - Only a handful of searches with 2012 data have been made so far. A lot more data will come by the end of extended data taking period (pp data taking until Dec 16, 25-30 fb^{-1})
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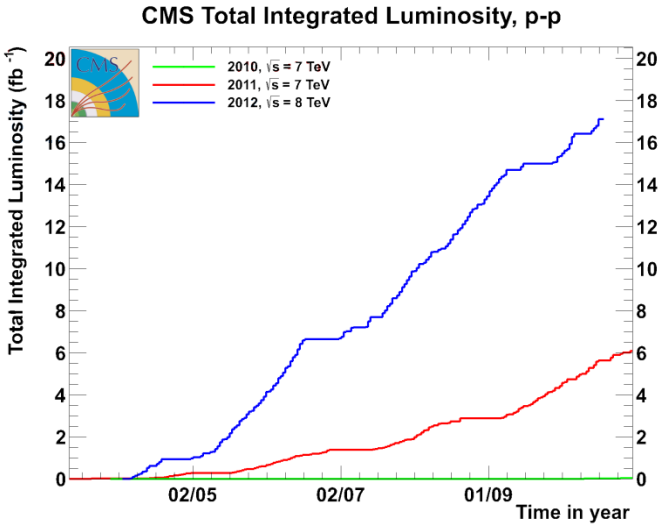

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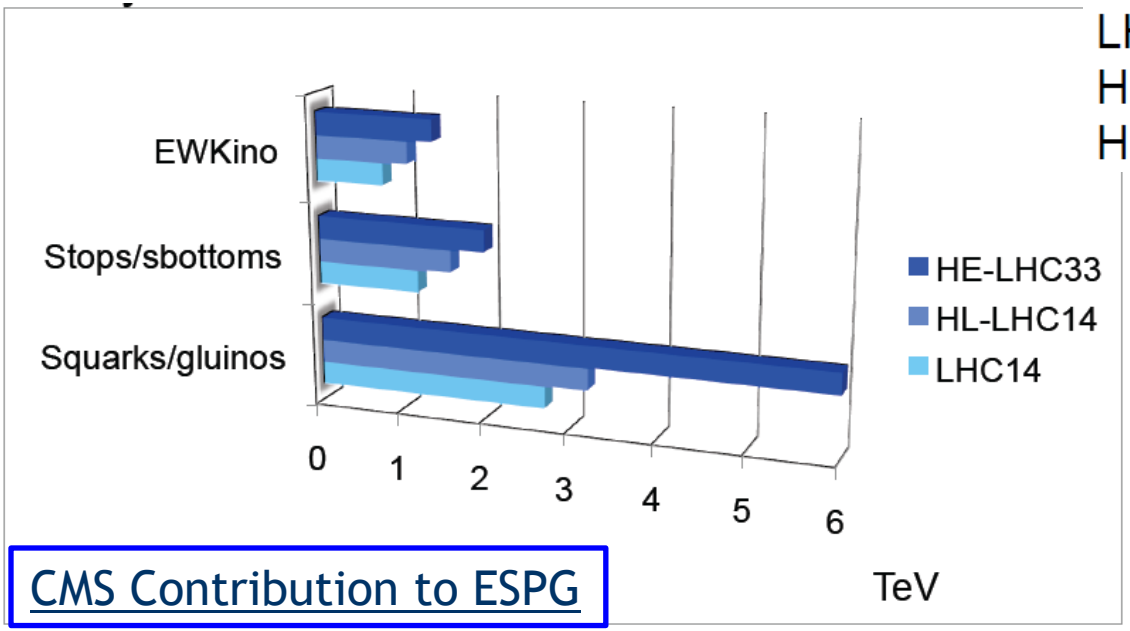
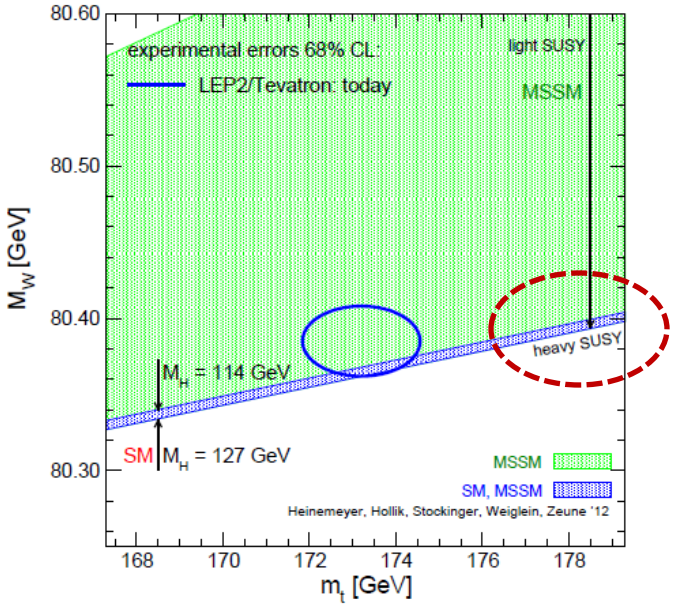
The SUSY is the next discovery frontier!

What's Beyond 2012?



CMS Contribution to ESPG

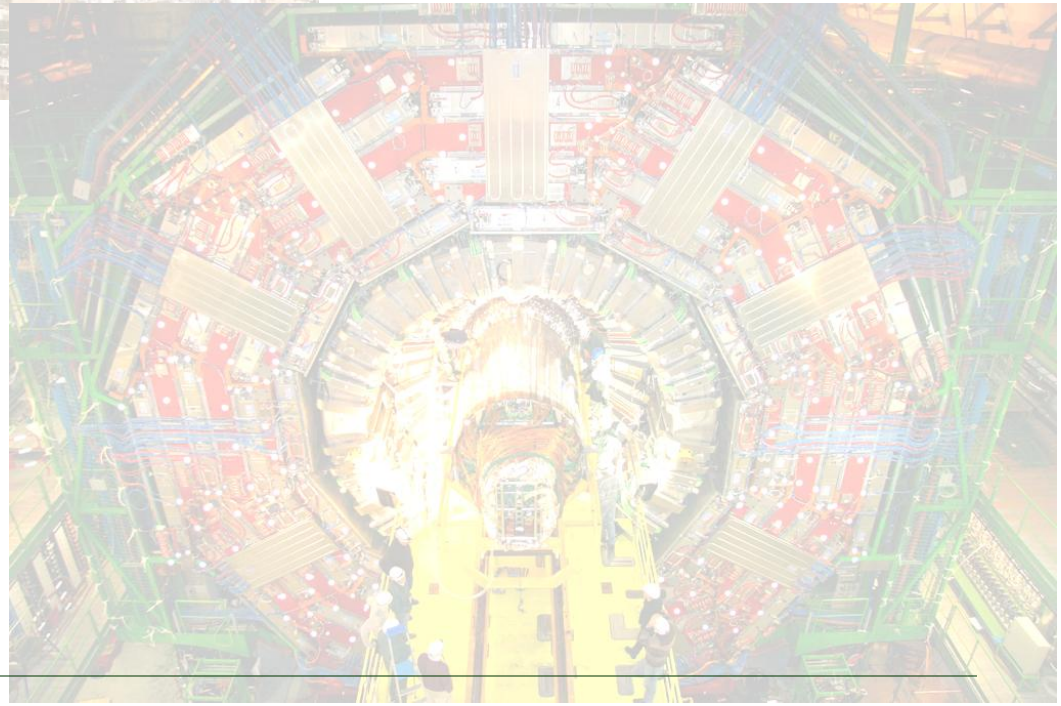
LHC 300 fb-1 @ 14 TeV
HL-LHC 3000 fb-1 @ 14 TeV
HE-LHC 300 fb-1 @ 33 TeV



Note: 125 GeV Higgs may lead to multi-TeV SUSY mass spectrum
Need high luminosity and/or high energy LHC running to explore that region(!?)

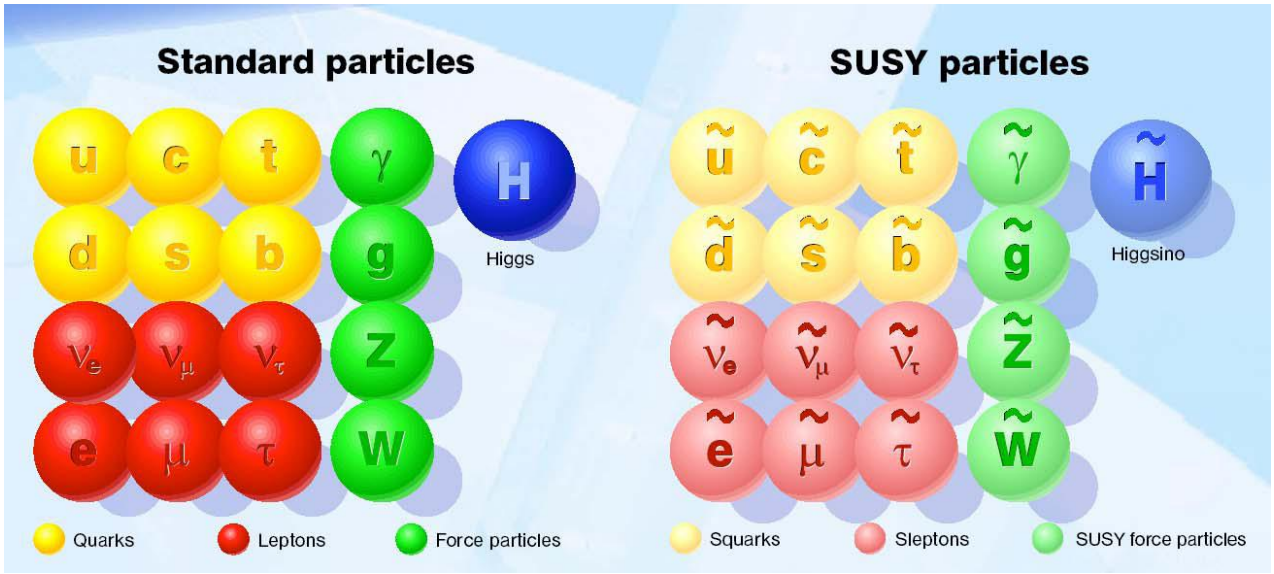
Join the snowmass 2013 long-term planning exercise

Backup



Supersymmetry

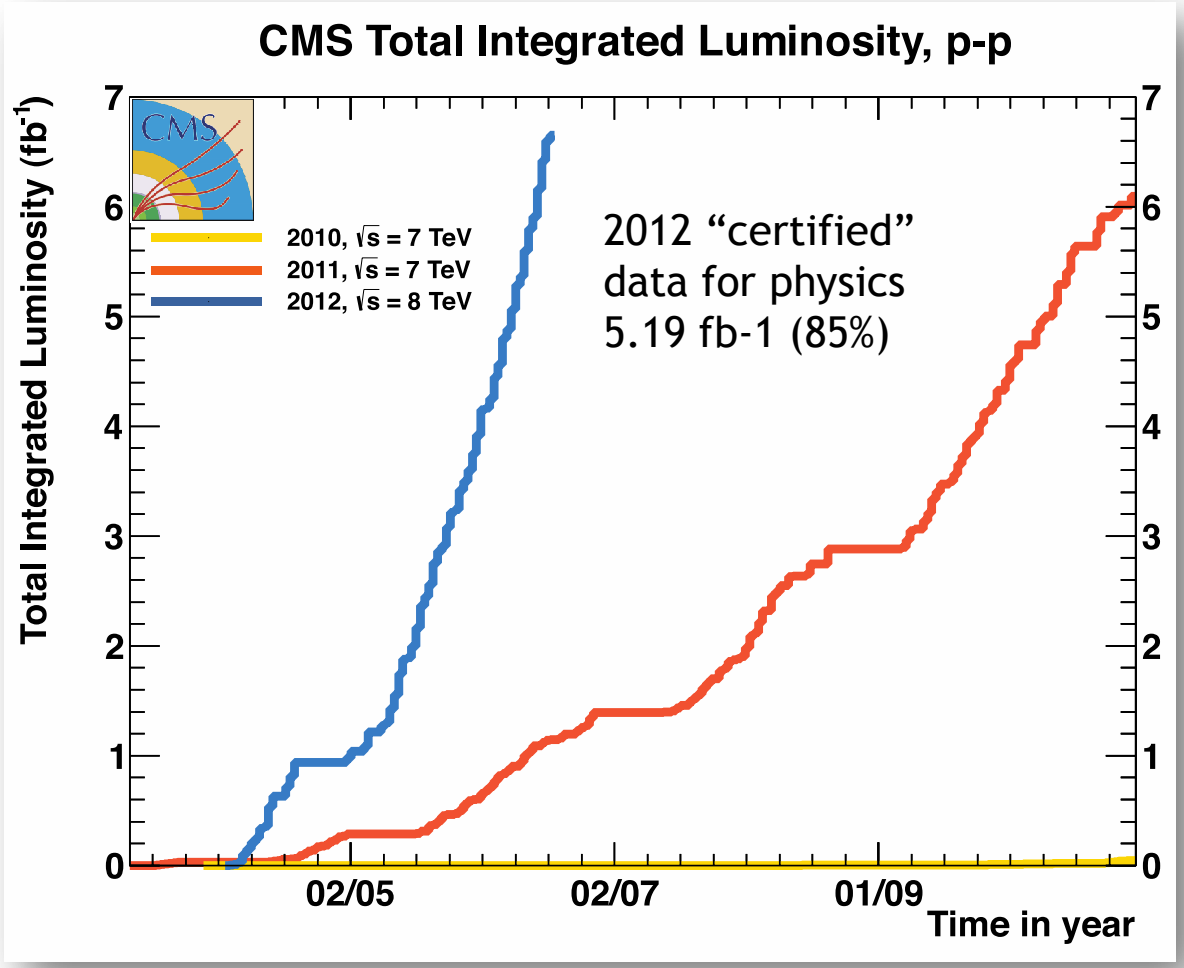
- Supersymmetry is an extension of the Standard Model, which introduces a new symmetry between bosons and fermions



New quantum number: R-parity $R=(-1)^{2S+3B+L}$ = +1 SM particle
-1 SUSY particle

R-parity conservation → Sparticles produced in pairs, decay to an odd number of Lightest Supersymmetry Particle (LSP)

LHC Performance



Peak luminosity in 2012:
~ 6.8 x10^{33} cm^{-2} s^{-1}

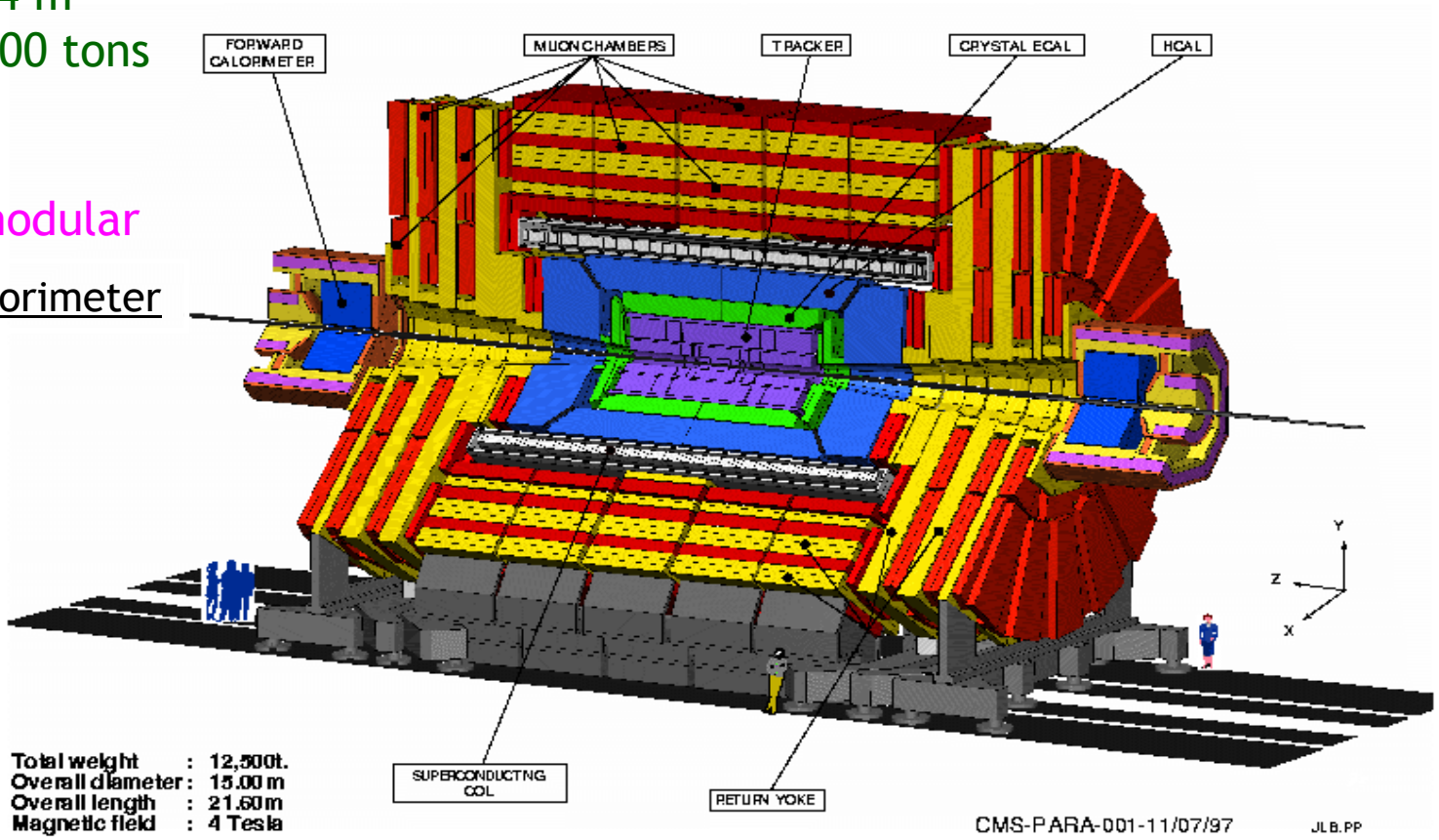
Many thanks to the LHC teams and the many others who made this possible!

CMS Detector

CMS

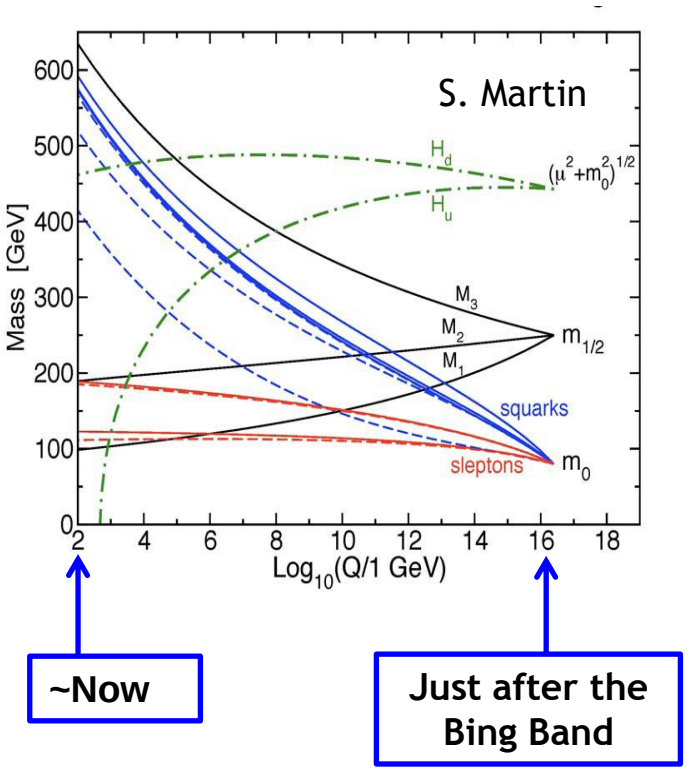
Length : ~22 m
Diameter : ~14 m
Weight : ~ 12,500 tons
Solenoid : 4 T
Fe yoke
Compact and modular

Excellent EM Calorimeter



CMSSM / mSUGRA

- Inclusive SUSY results have been conventionally shown in the context of "constrained" MSSM / mSUGRA
- CMSSM has only 5 parameters:
  - Universal scalar mass m_0
  - Universal gaugino mass $m_{1/2}$
  - Universal trilinear coupling A_0
  - Ratio of 2 Higgs doublet VEV tanβ
  - Sign of the Higgisino mixing parameter sgn(μ)
- Very predictive; however, the universality constraints result in significant restrictions on possible SUSY particle mass spectra



Particle Flow @ CMS

The PFlow algorithm is designed to:

- Reconstruct & identify all particles: γ, e, μ, charged & neutral hadrons, pileup, and converted photons & nuclear interactions
- Use a combination of all CMS subdetectors to get the best estimates of energy, direction, particle ID

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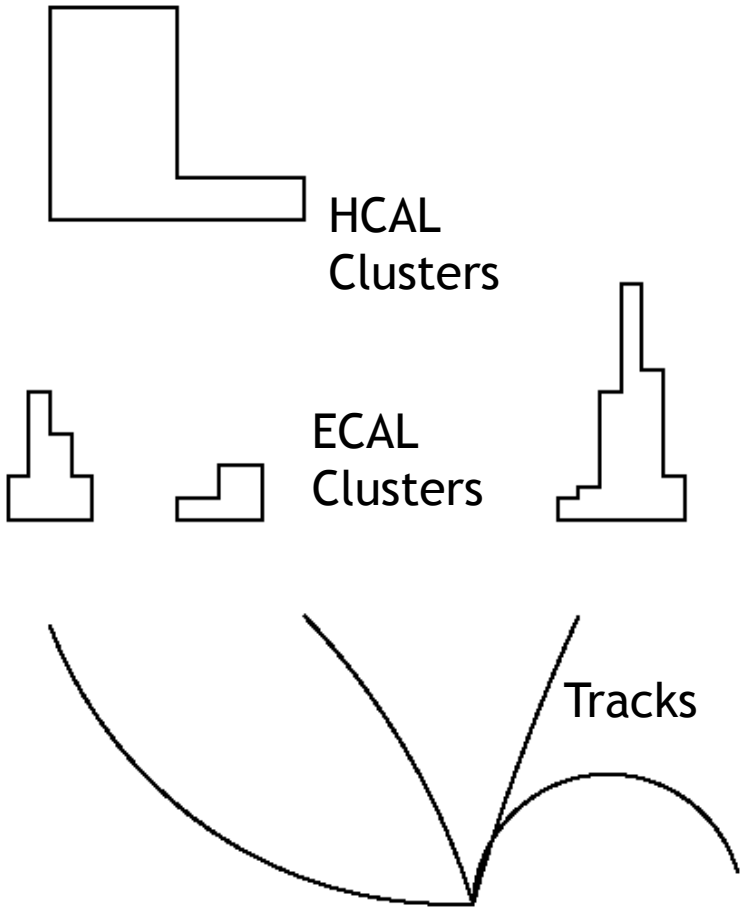

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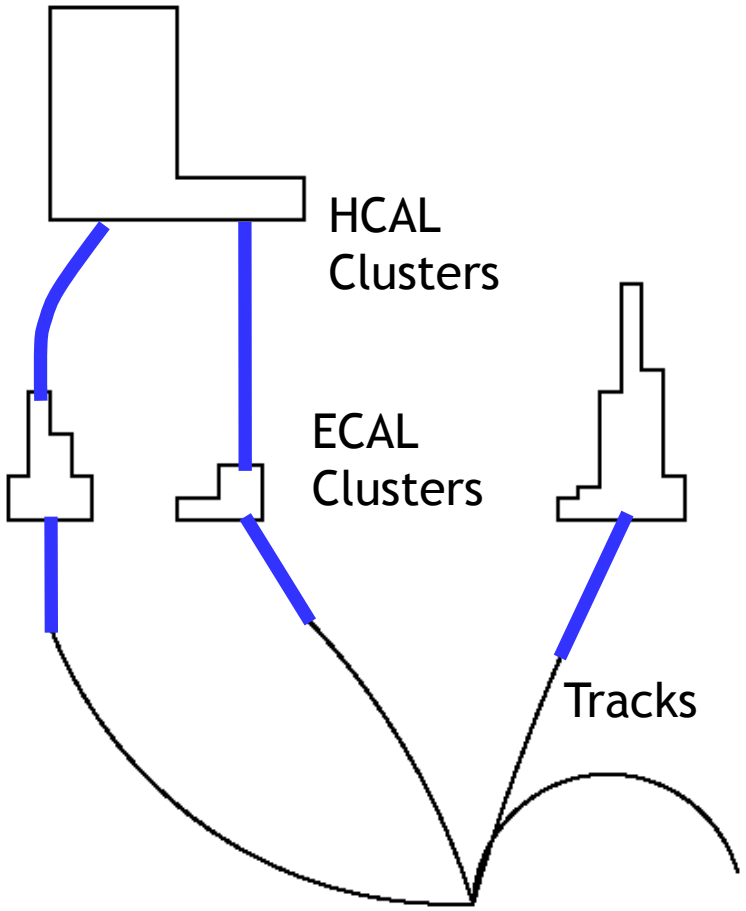

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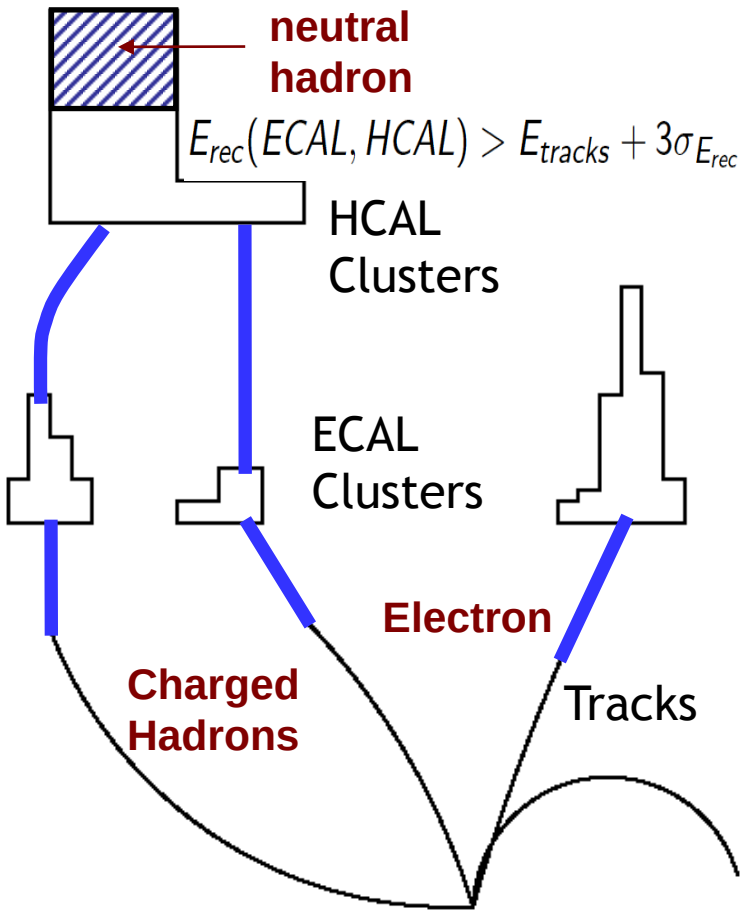
  3. Particle ID and separation



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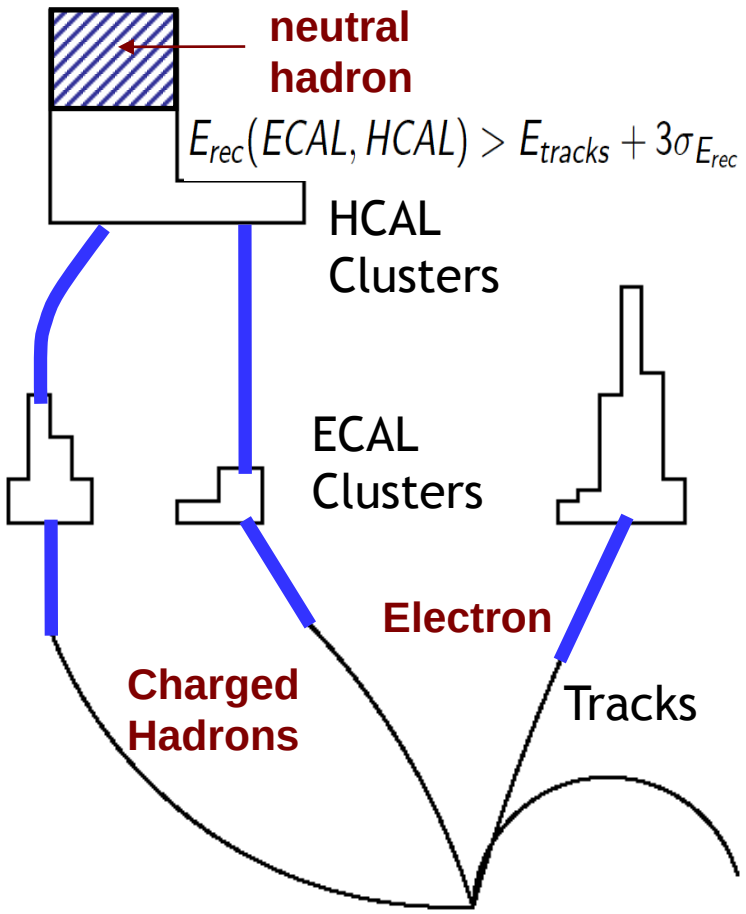
- Use a combination of all CMS subdetectors to get the best estimates of energy, direction, particle ID
  1. Associate hits within each detector
  2. Link across detectors
  3. Particle ID and separation
- Used in most CMS searches



Inclusive Searches

- From the 2010 data taking, CMS deployed a series of inclusive searches to detect possibly copiously produced SUSY strong production
- Searches with different lepton categories
  - Different background (BG) compositions & less BG with more leptons
  - Different sensitivities to a variety of SUSY scenarios

All hadronic	Single lepton	OS dileptons	SS dileptons	Multileptons
• QCD • Z → νν • W+jets • ttbar	• W+jets • ttbar	• Z+jets • ttbar	• ZZ/ZW/WW • ttZ/W • Rare SM • ttbar	• ZZ/ZW/WW • ttZ/W • Rare SM

More signal rate/more BG ← → Smaller rate/more BG control

- Adding b-jets lower BGs, become more sensitive SUSY 3rd gen squarks
- Adding photons, taus allow to explore even more SUSY scenarios
- Inclusive searches cut on hadronic activities (HT, jet multiplicity) and MET-like variables (MET, MHT, MT2, αT, razor, etc)

Razor

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

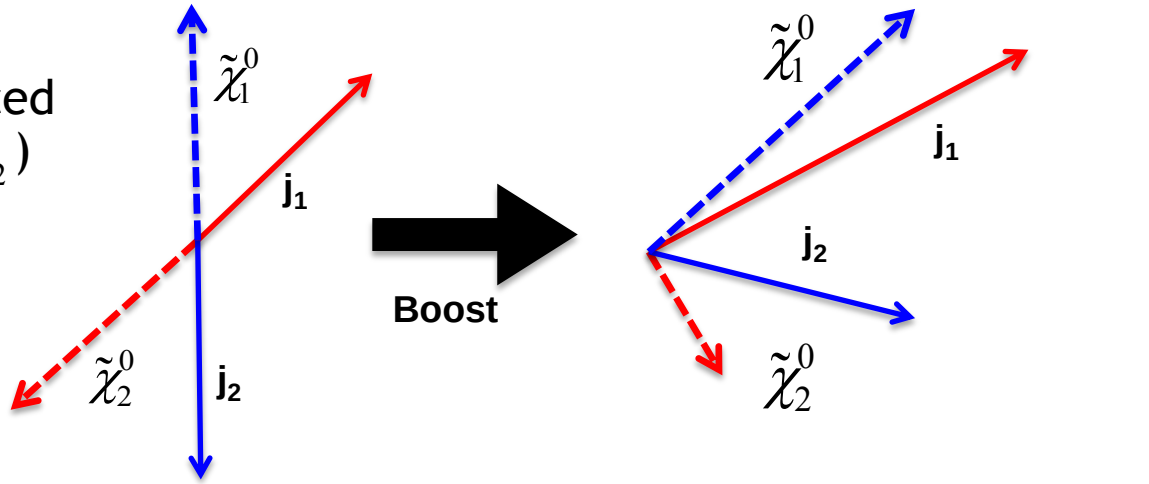
- No assumptions on MET or details of decay chain

CM frame

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

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

M_R definition: signal



Laboratory Frame

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

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

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

Razor

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

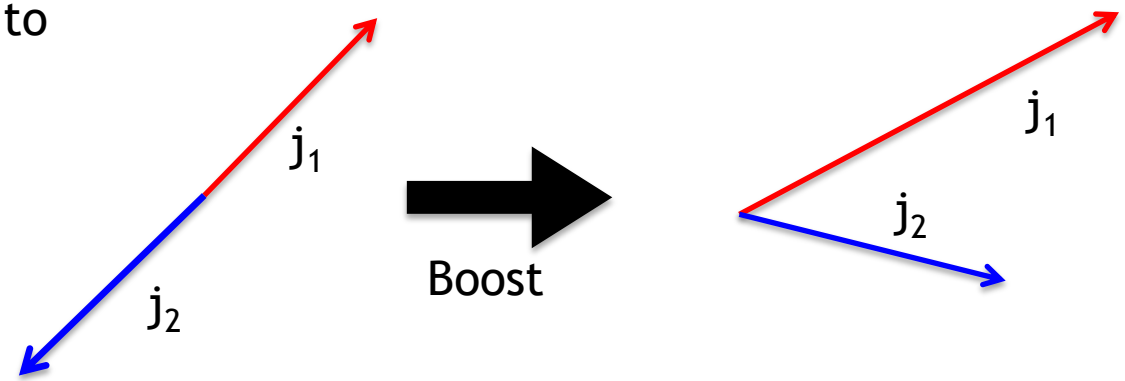
- No assumptions on Met or details of decay chain

CM frame

M_R definition: multijet background

Laboratory Frame

• Two jets back to back



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M_R falls steeply

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_D
- The maximum value of ME_T is also M_D

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

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

Transverse M_R has a kinematic edge of M_D

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

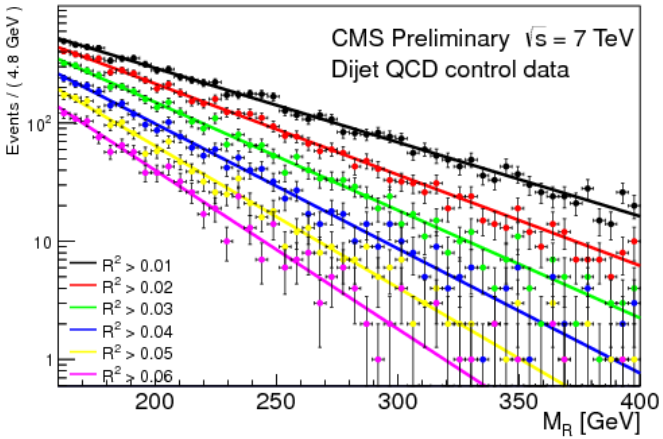
M_R peaks at mass scale M_D

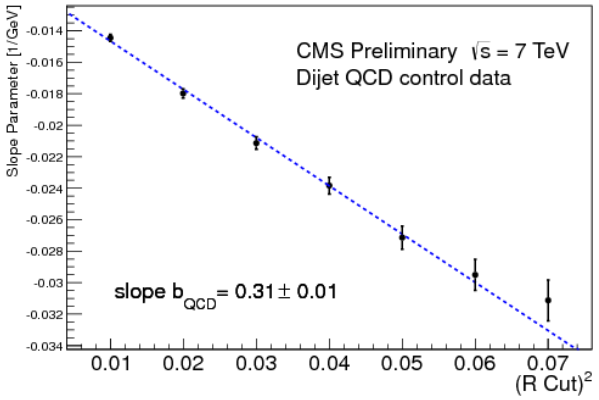
$$R \equiv \frac{M_T^R}{M_R}$$

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

Razor used to separate signal from background

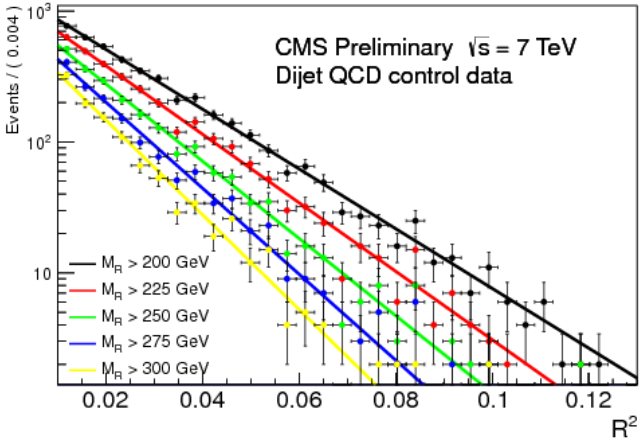
R and M_R Properties

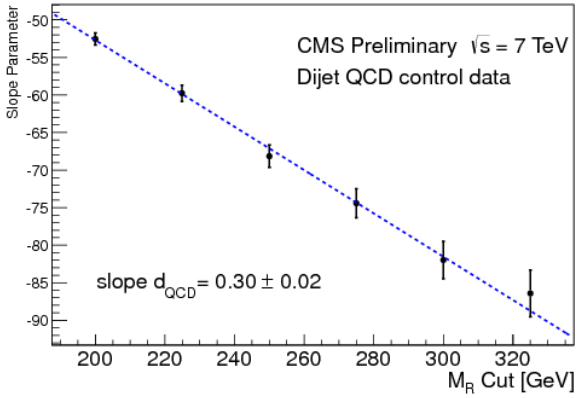




$$f(M_R) \propto e^{-SM_R}$$

$$S = a + b(R \text{ cut})^2$$





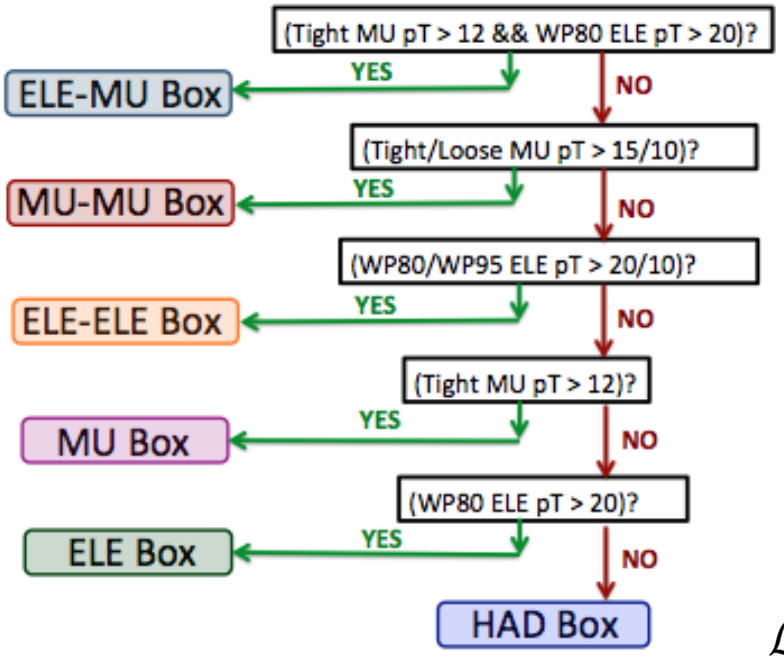
$$f(R^2) \propto e^{-SR^2}$$

$$S = a + b(M_R \text{ cut})$$

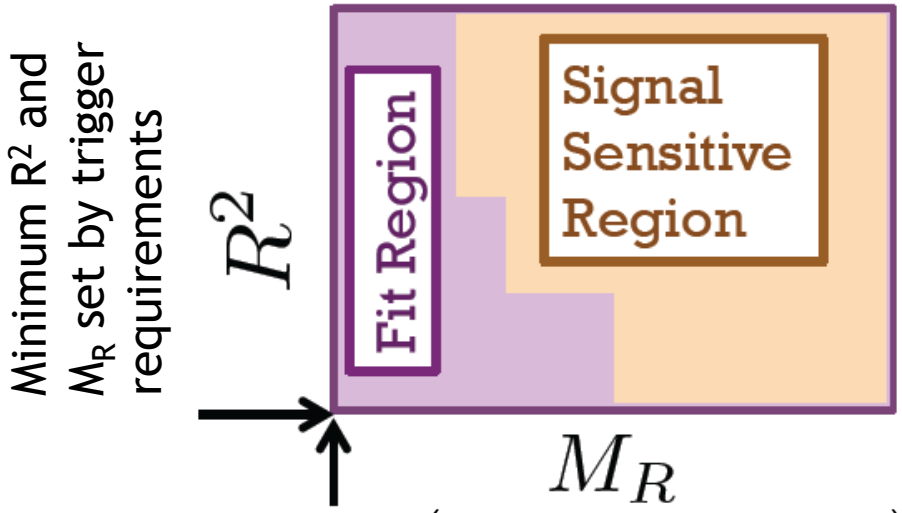
$$f(R^2, M_R) \propto \left[k(M_R - M_R^0)(R^2 - R_0^2)\right] e^{-k(M_R - M_R^0)(R^2 - R_0^2)}$$

$$b(\text{from } M_R \text{ view}) = d(\text{from } R^2 \text{ view}) = k(\text{from 2D view})$$

“Box” Definitions and Fits



Find state BOX classification based on lepton ID



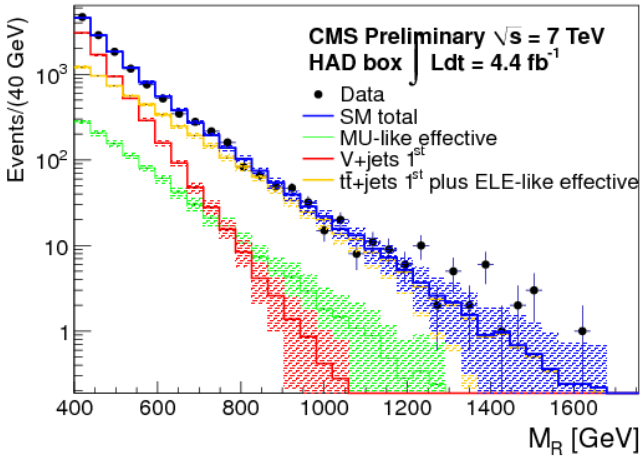
$$\mathcal{L}_b = \frac{e^{-(\sum_{j\in SM} N_j)}}{N!} \prod_{i=1}^{N} \left(\sum_{j\in SM} N_j P_j(M_{R,i}, R_i^2) \right)$$

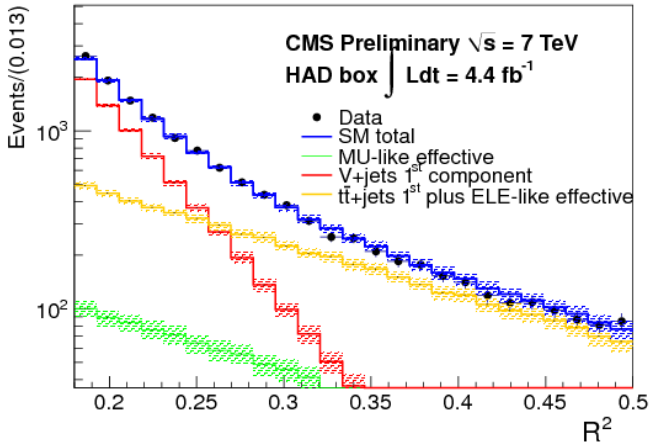
Extended and unbinned maximum likelihood fit performed in 2D R^2-M_R plane independently in each BOX

Background functionally extrapolated to signal region

Results

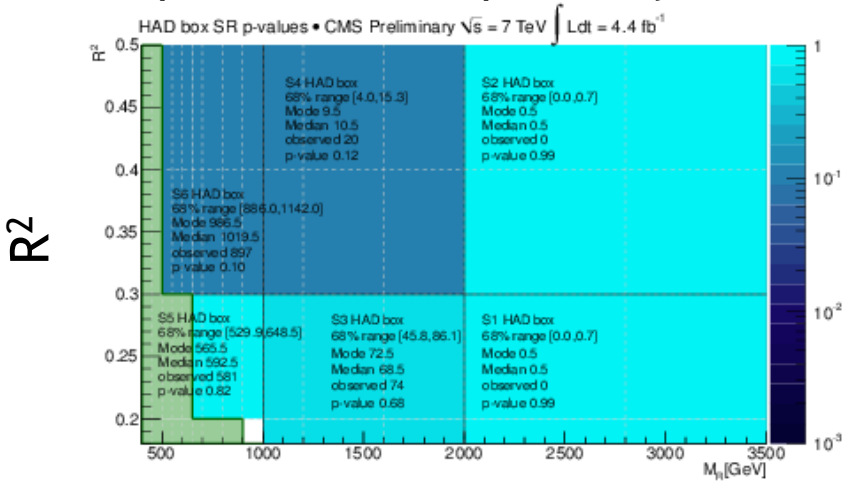
1D projections of 2D ML Fit – HAD Box

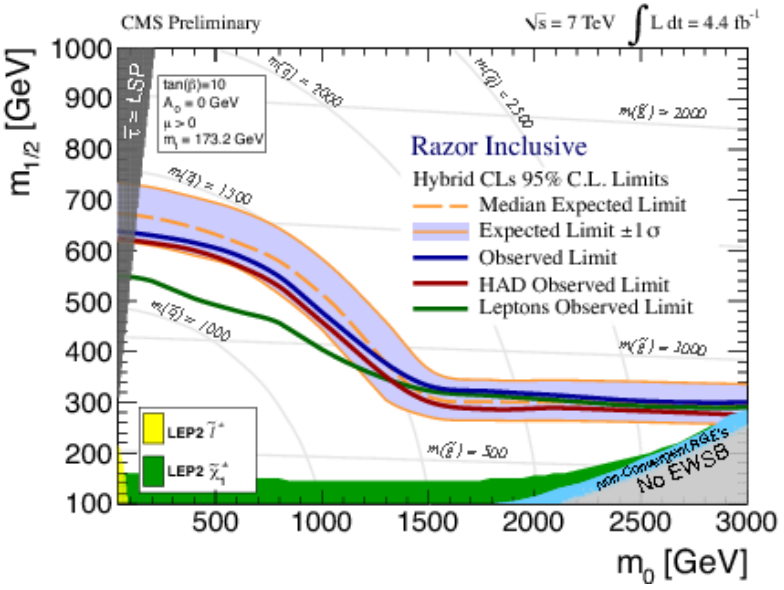




Observations consistent with SM expectations

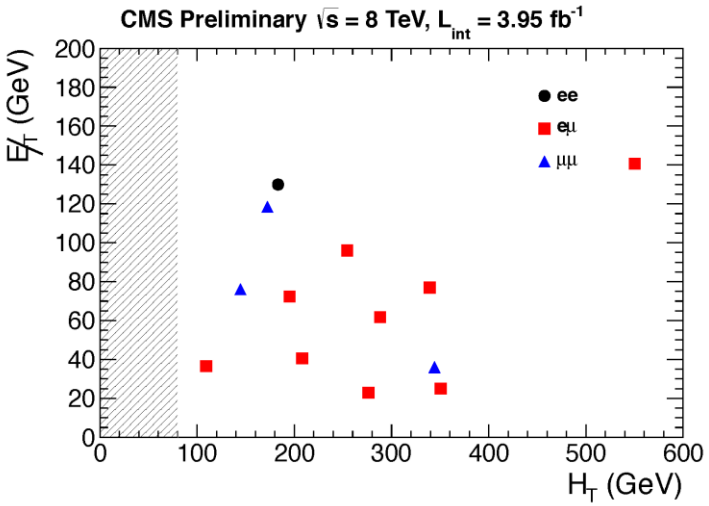
Model independent results showing data/prediction compatibility

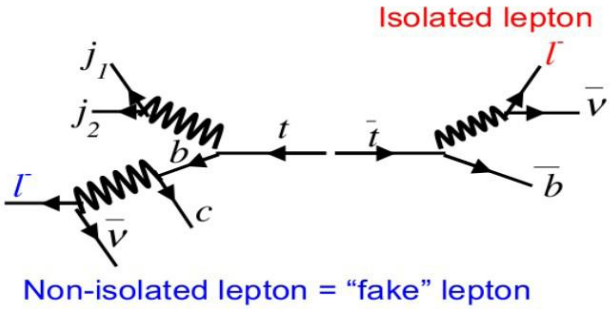


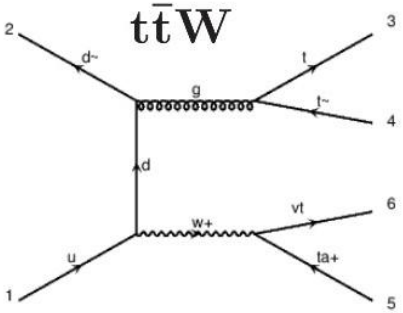


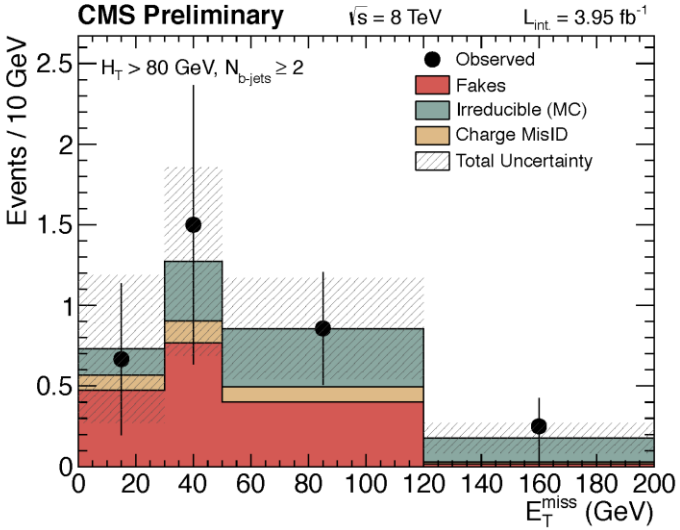
SS Dileptons with >=2 b Jets

- Dominant Background
  - ttbar (l+jets) with fake leptons: fake ratio with isolation extrapolation
  - Charge mis-reconstruction: use Z's for x-check. Apply to ttbar dileptons
  - Rare SM processes with high pT leptons & b-jets: estimate from MC





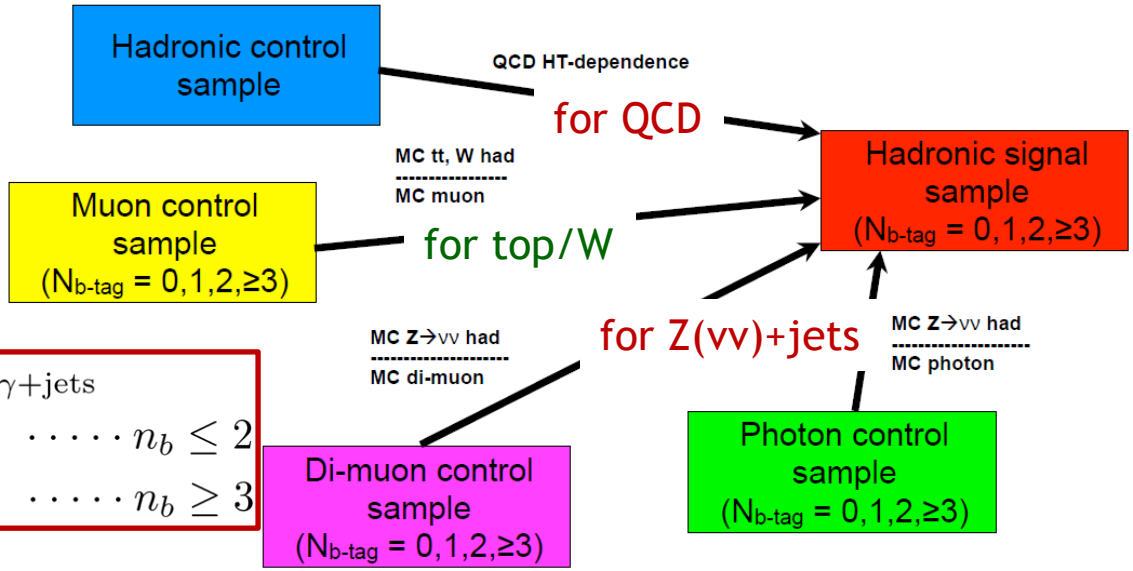




α_T Search with 0,1,2,>=3 b's

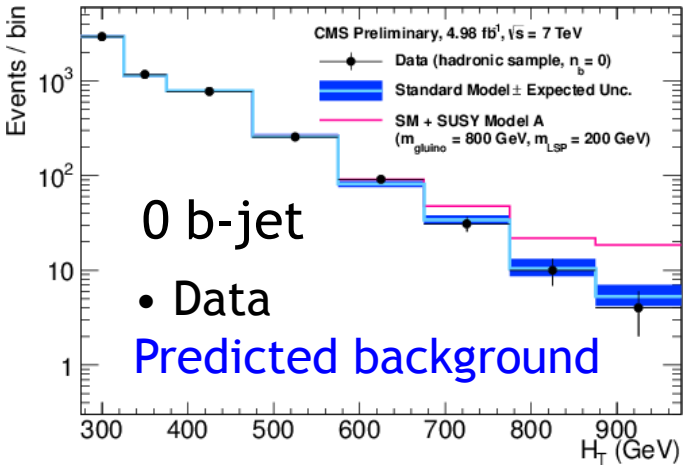
Background estimation

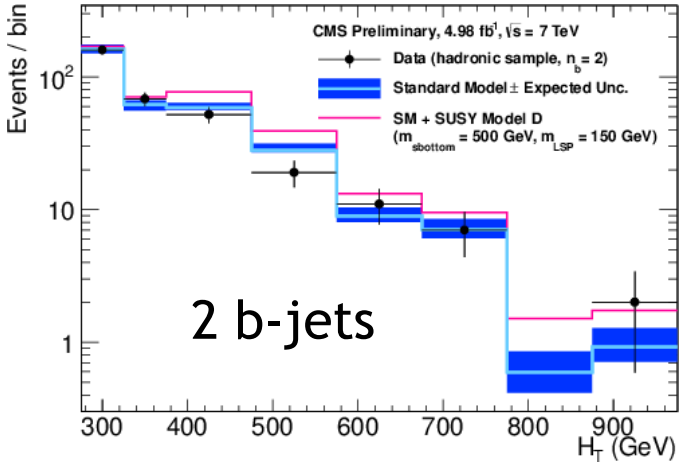
- A binned likelihood fit using all control samples maximize the total likelihood



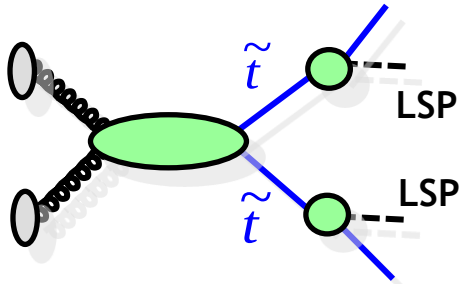
$$L_{\text{total}} = L_{\text{hadronic}} \cdot L_{\mu+\text{jets}} \cdot L_{\mu\mu+\text{jets}} \cdot L_{\gamma+\text{jets}} \quad \cdots\cdots n_b \leq 2$$

$$L_{\text{total}} = L_{\text{hadronic}} \cdot L_{\mu+\text{jets}} \quad \cdots\cdots n_b \geq 3$$

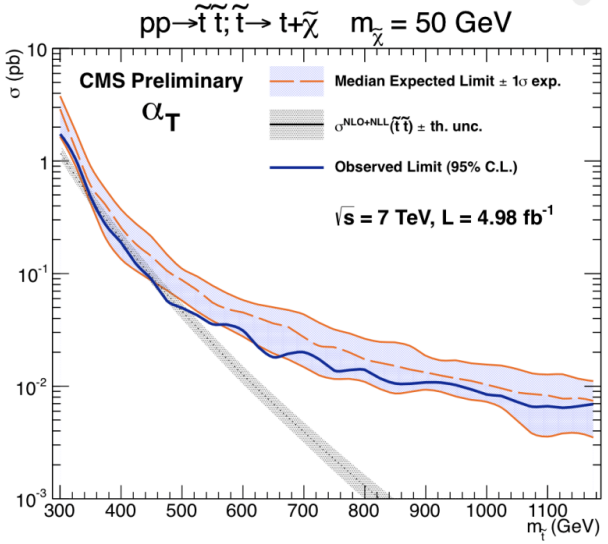




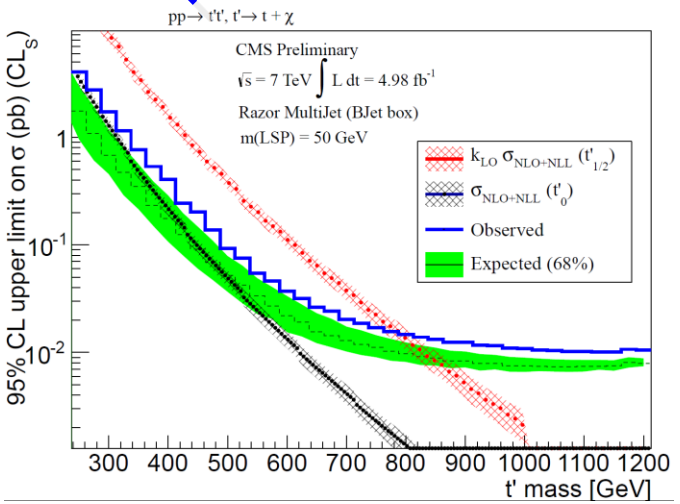
Direct Stops in Inclusive Searches



α_T: CMS-SUS-11-022



Razor: CMS-SUS-12-009



Search with "Razor" variables: M_R & R

Designed to characterize pair-production of heavy particles. Combine all particles into two hemispheres, boost back to rest frame (see Will Reece's talk at ICHEP for more details)

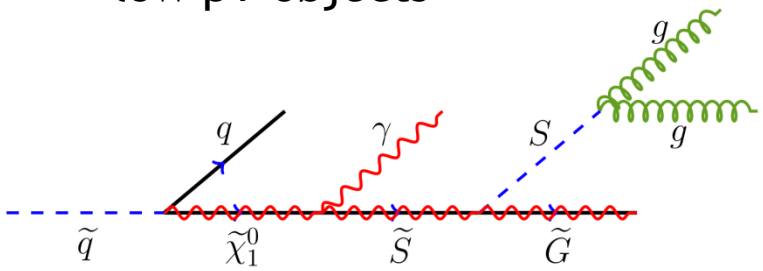
Even inclusive searches started to become sensitive to direct stop production!

CMS-SUS-12-014

Stealth SUSY

Motivation

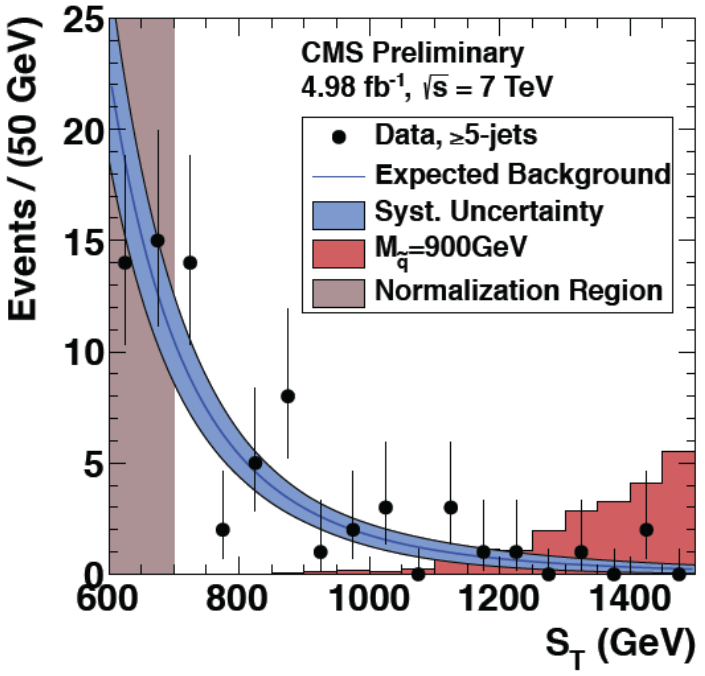
- SUSY requires hidden sector to break supersymmetry
- Light hidden sector particles can mediate decays to many low pT objects



Signatures

- Can include many b-jets, photons, γjj resonances, long-lived particles etc

Search in events with γγ+<=4 jets and large total energy S_T



CMS-SUS-12-004

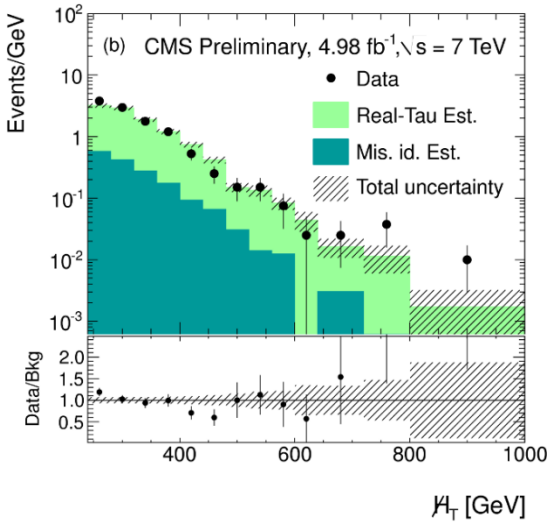
Searches with Taus

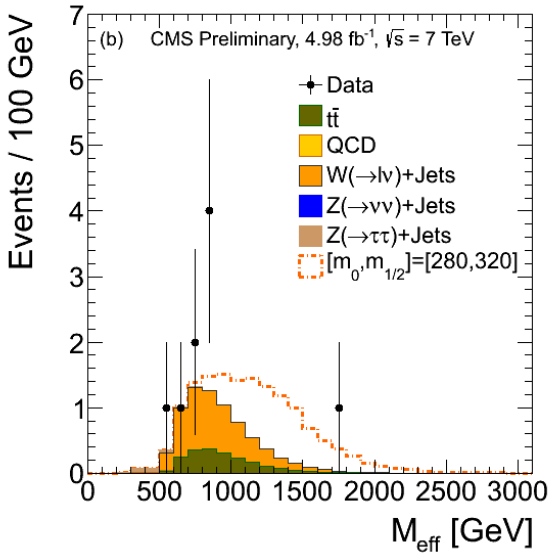
- **Selection**
  - Tau ID for hadronically decaying taus

  1-tau
  - Exactly 1 tau: pT > 15 GeV, |η| < 2.1
  - No isolated light leptons, pT > 10 GeV
  - HT>400/600, MHT>250/400 GeV

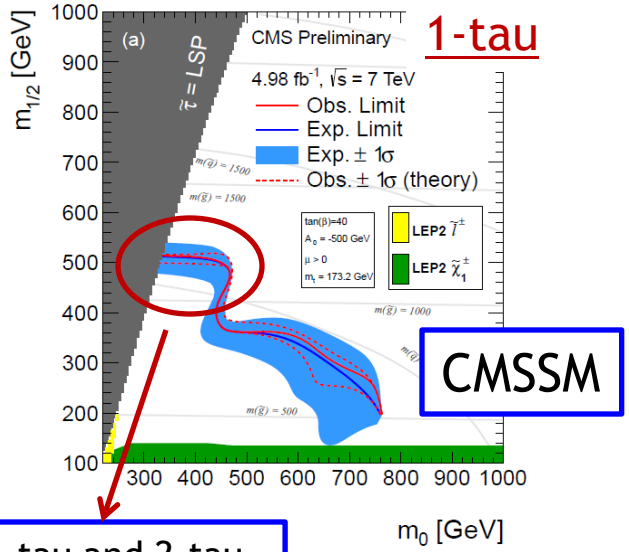
  2-taus
  - 2 jets: pT > 100 GeV, |η| < 3
  - |Δϕ(MHT, jet2)| > 0.5
  - >=2 taus: pT > 15 GeV, |η| < 2.1
  - ΔR(τ, jet1/2) > 0.3, ΔR(τ1, τ2) > 0.3
  - MHT > 250 GeV
- **Backgrounds**

  W ($\longrightarrow \tau\nu$) + jets / ttbar / Z ($\longrightarrow \nu\nu$) + jets / Drell-Yan ($\longrightarrow \tau\tau$) + jets / QCD
  - 1-tau: manly from real taus
  - 2-taus: mainly from fake taus





Searches with Taus

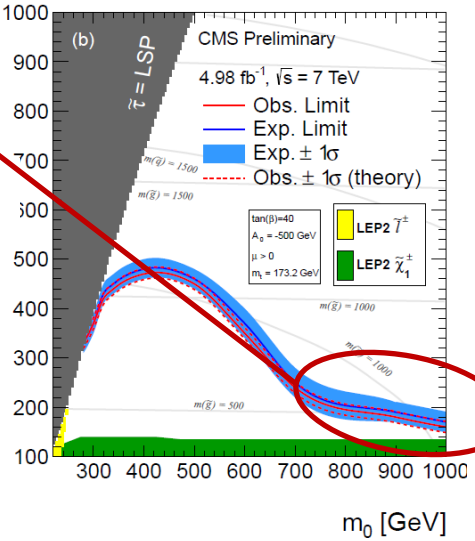


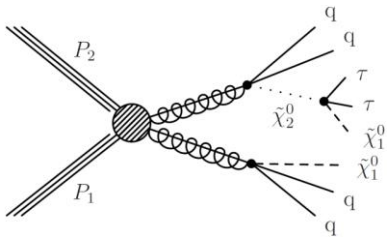
1-tau

CMSSM

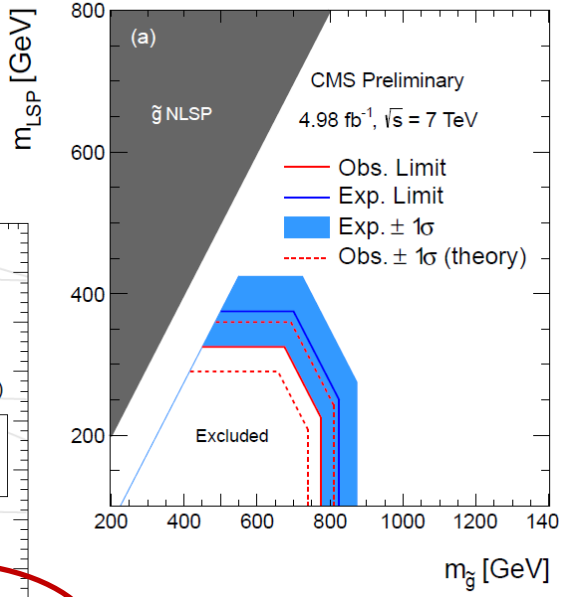
1-tau and 2-tau searches are complementary

2-taus





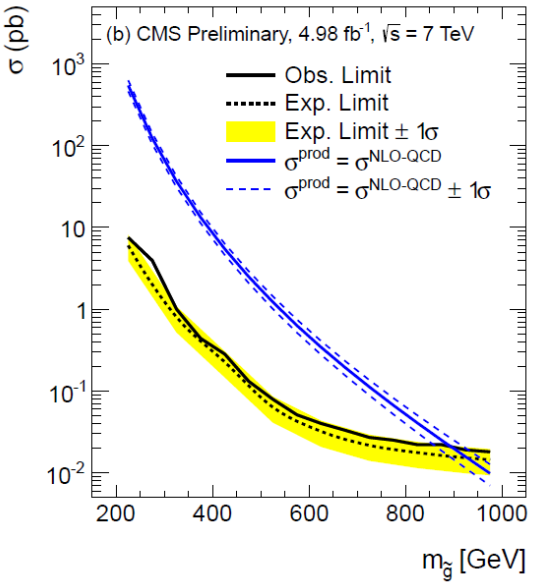
SMS



Gluino exclusinos up to ~800 GeV

Stau NLSP GMSB

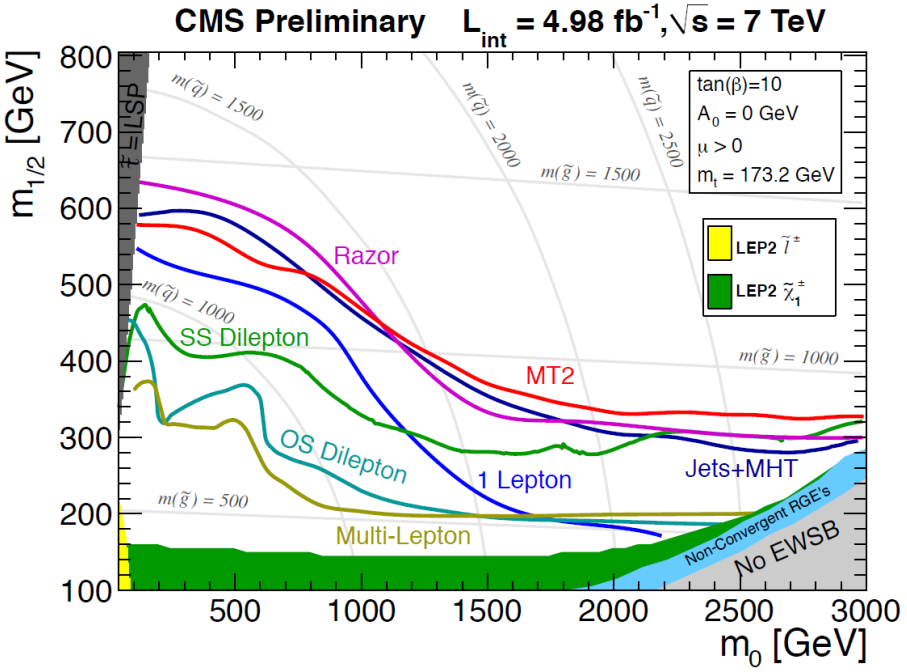
$\tilde{\chi}_2^0 \rightarrow \tau\tilde{\tau} \rightarrow \tau\tau\tilde{G}$



Gluino with masses below 860 GeV excluded

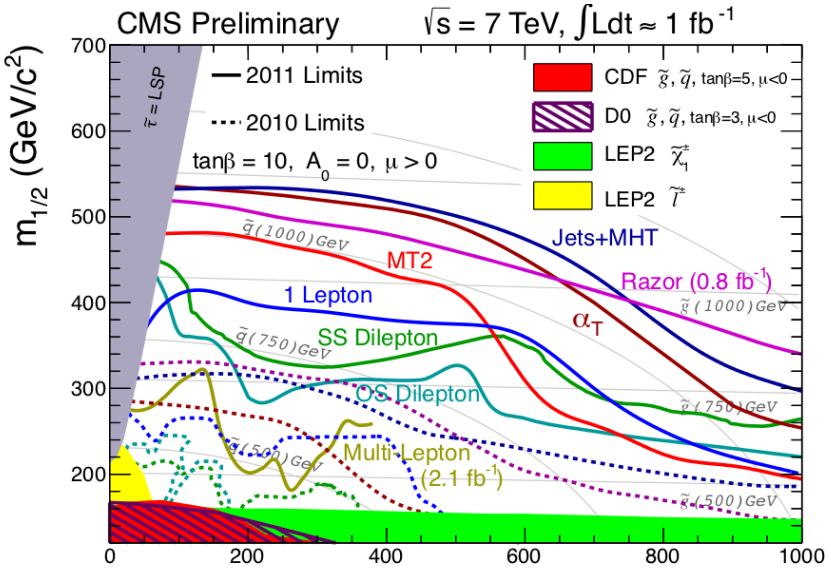
CMSSM Projections: Pre LHC Data

ICHEP 2012

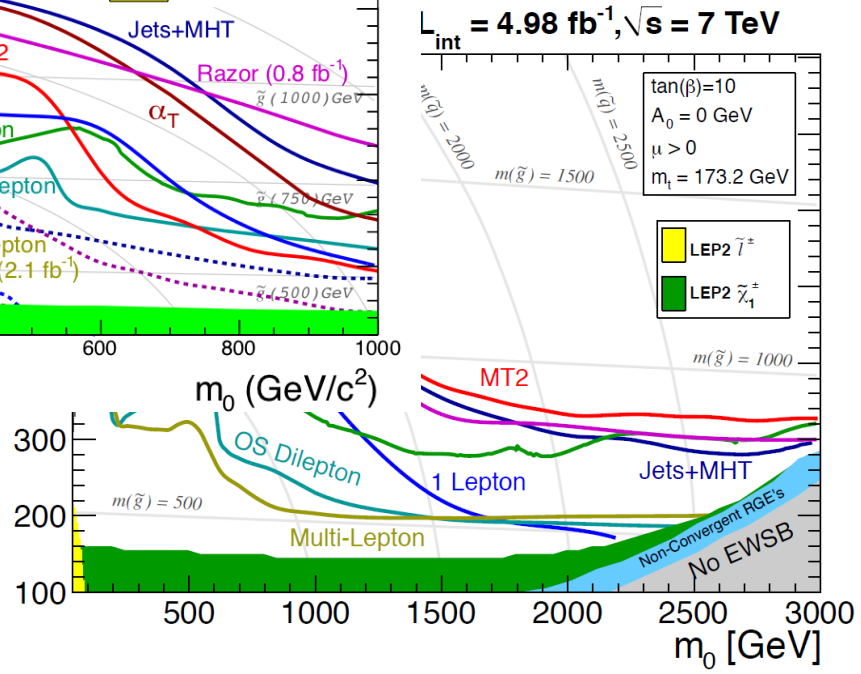


CMSSM Projections: Pre LHC Data

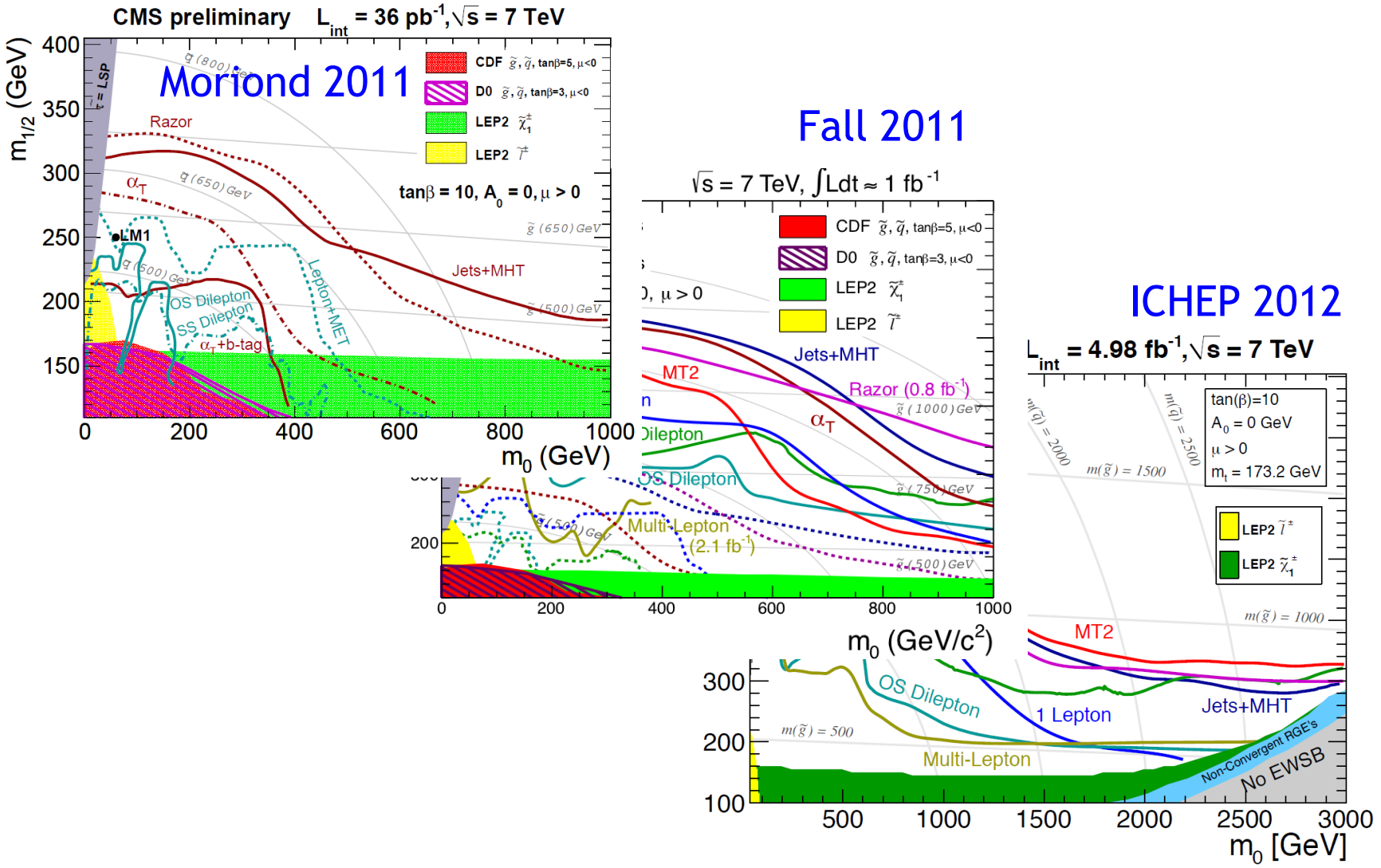
Fall 2011



ICHEP 2012



CMSSM Projections: Pre LHC Data



CMSSM Projections: Pre LHC Data