International Conference on New Frontiers in Physics

OAC, Kolymbari, Crete – August 2, 2014

Searches for Supersymmetry in CMS

- Introduction
- Stop searches
  - Direct stop, Razor, monojet $\tilde{t}_1 \rightarrow c\tilde{\chi}$
- Search for Higgs in SUSY cascade
  - $\tilde{t}_2 \rightarrow \tilde{t}_1 H/Z$
- Electroweak SUSY: chargino, neutralino, slepton production
  - Searches with H, Z and W
  - Diphoton Razor search
  - Kinematic edge in multilepton
- Inclusive searches with M_{T2}: limits on gluino, squark masses
- Conclusions/Projections

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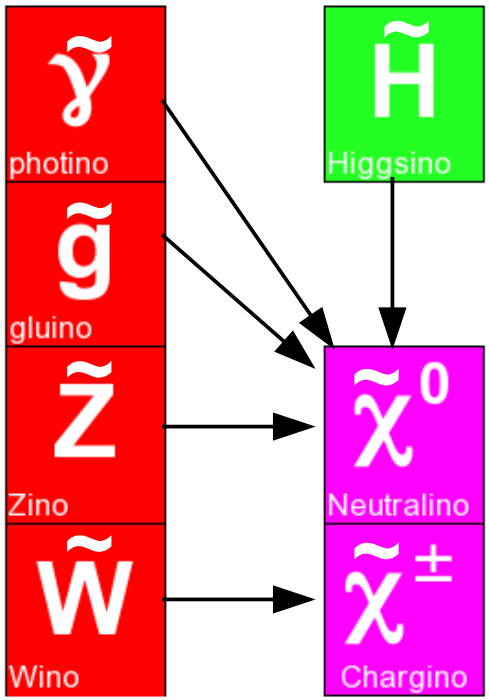
Supersymmetry

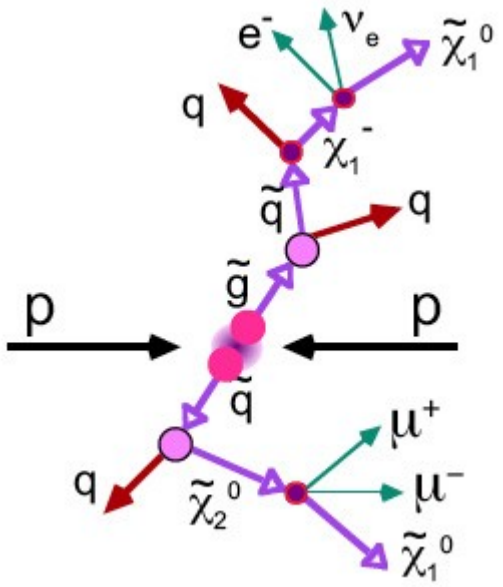
- Supersymmetry (SUSY) is one of the most appealing extensions beyond the SM
- Its signatures usually involve long decay chains of heavy particles
  - Expect large hadronic activity and large H_T (scalar sum of p_T of jets)
- R-parity [$P_R=(-1)^{2s+3B+L}$] conservation: pair-production and a stable SUSY particle
  - Dark matter candidate, remains undetected → large missing energy (MET)
- Strong production at LHC and branching ratios favor purely hadronic final states
  - Leptons and photons produce clean signatures

Sfermions: s=0

Squarks	$\tilde{u}$	$\tilde{c}$	$\tilde{t}$
	$\tilde{d}$	$\tilde{s}$	$\tilde{b}$
Sleptons	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$
	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$

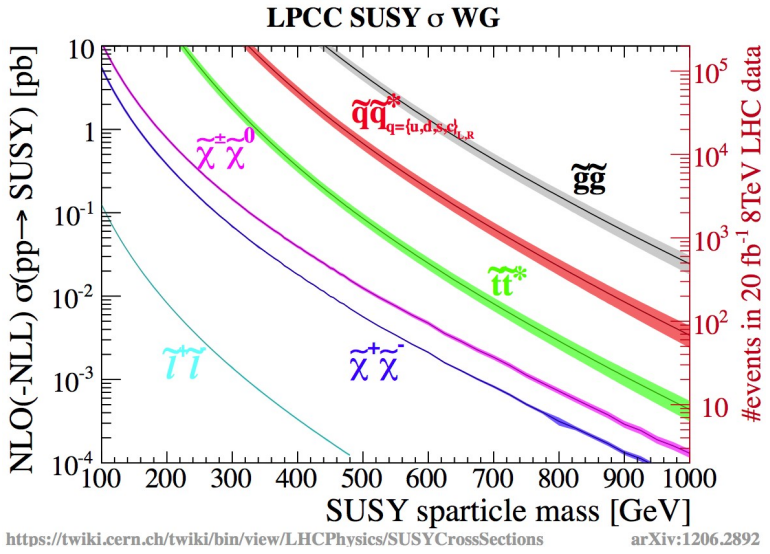
Bosinos: s=1/2

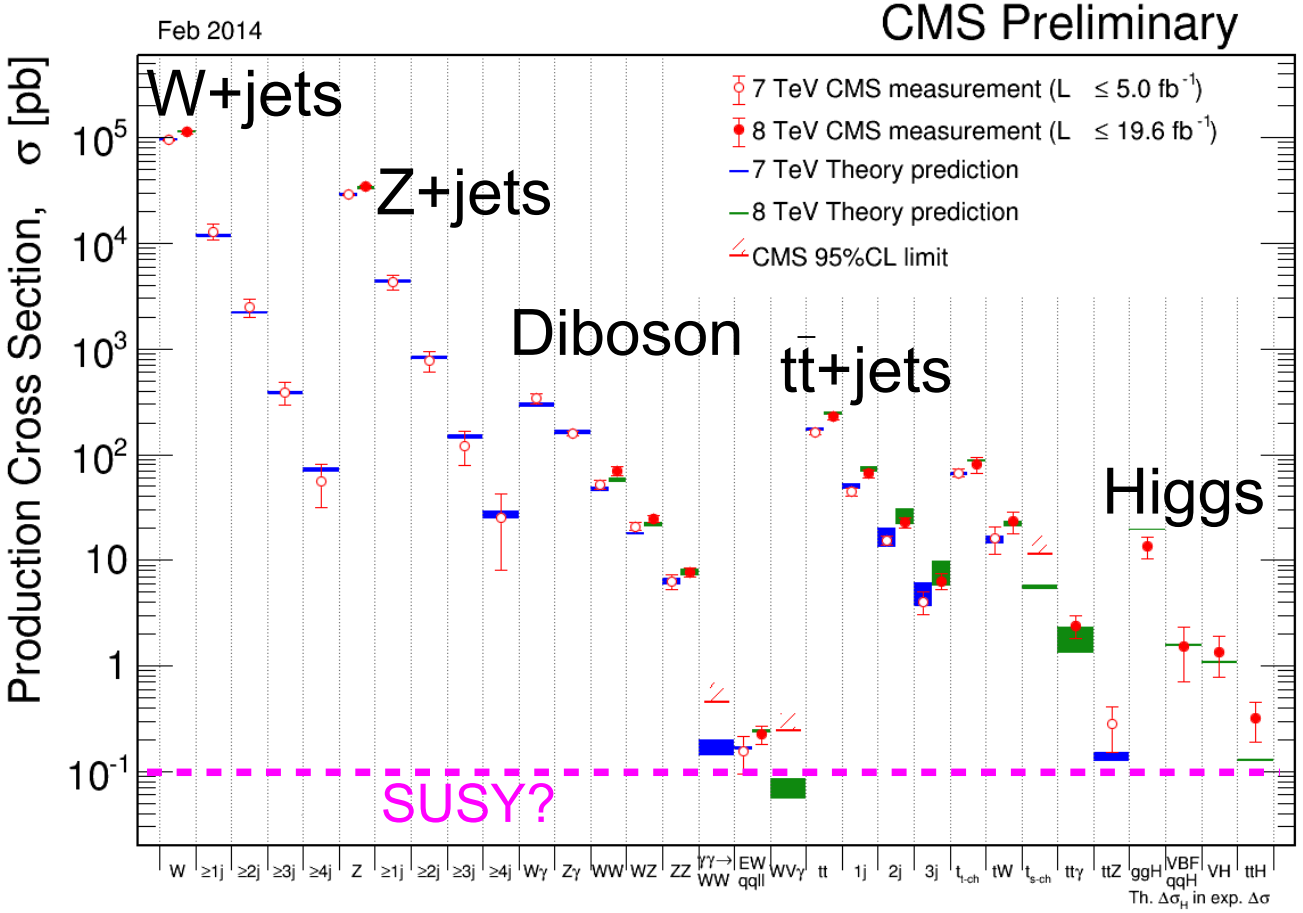




Experimental challenge

- Large QCD multijet production ~ mb
  - Exponential drop of cross section with jet p_T and jet multiplicity
- Inclusive cross sections are well measured
  - Details of kinematic distributions are important
  - SUSY searches depend on understanding the high p_T tails
- SUSY parameters determine phenomenology: many possible final states, and different signatures

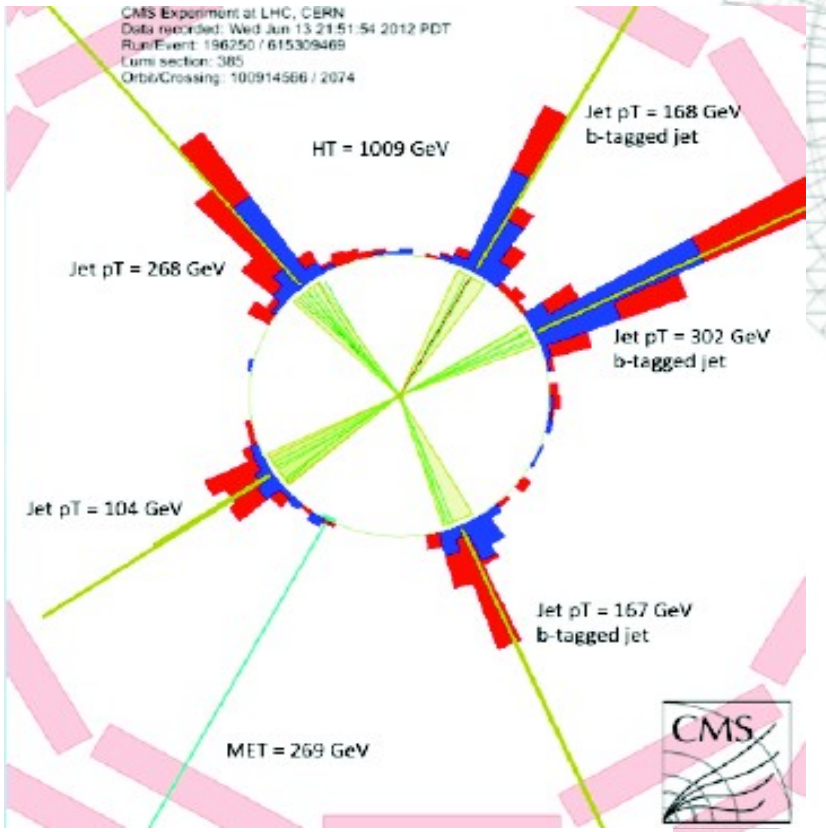


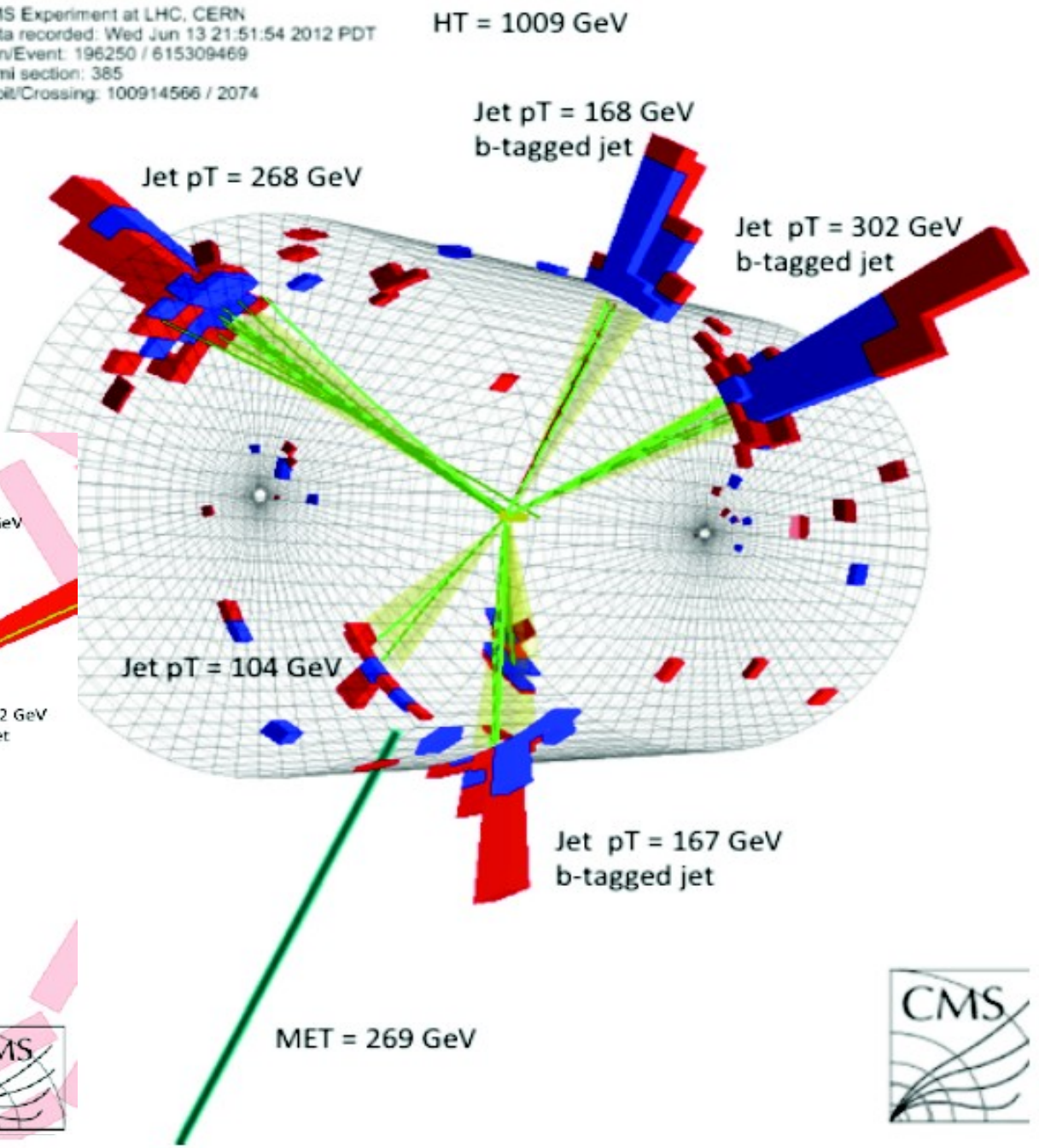


After LHC Run 1:

- Low σ×B
- Compressed spectra

Multi b-jet + MET candidate event

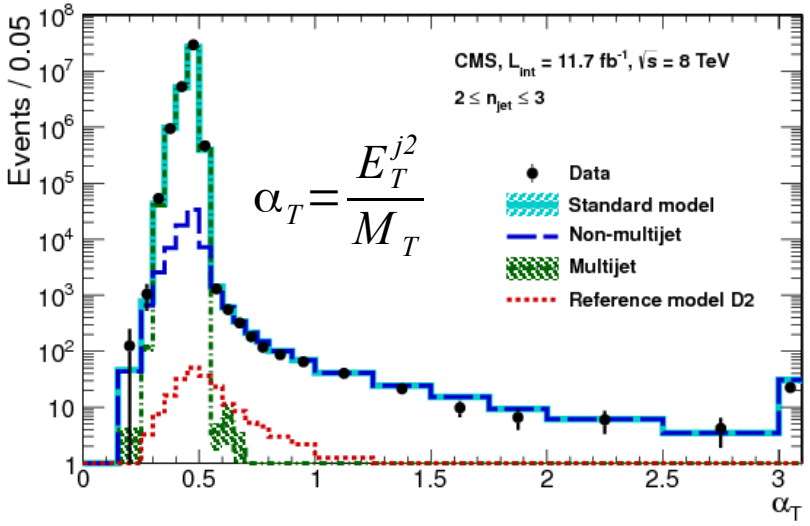




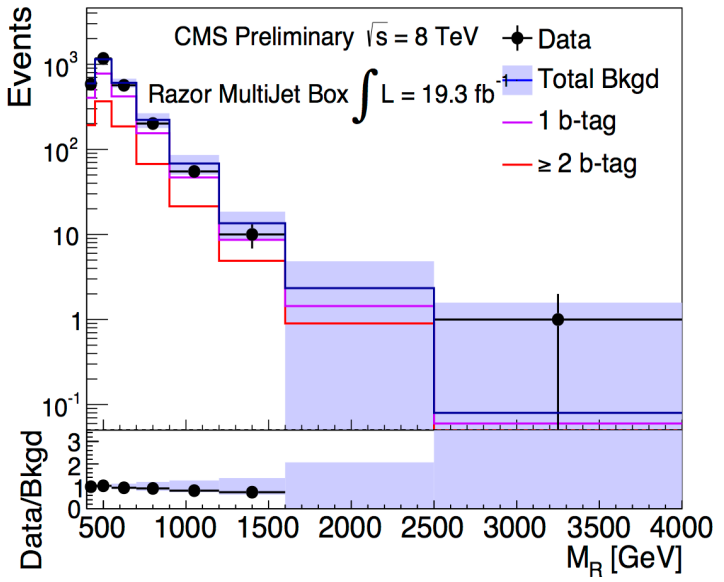
Search strategy

- Understand SM background contributions
- Several different signal regions can be defined, based on:
  - full SUSY models
  - simplified models
  - generalized models
  - signature-based
- Define selections based on discriminating variables M_{T2}, α_T, R, M_R devised to keep backgrounds small
- Use background-enriched regions which are kinematically similar to signal region
- Extrapolate from control → signal regions with factors derived in data wherever possible
- Verify extrapolation performance on independent control regions

  ➔ Open the box!

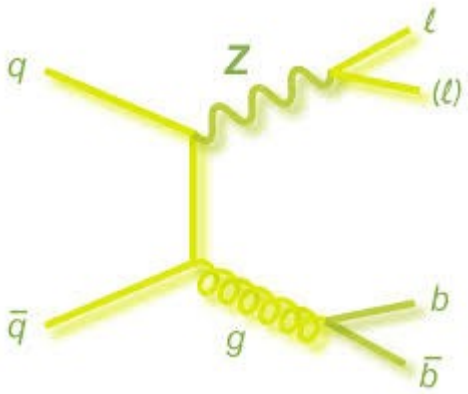


$$M_R = \sqrt{(|\vec{p}^{j1}| + |\vec{p}^{j2}|)^2 - (p_z^{j1} + p_z^{j2})^2}$$

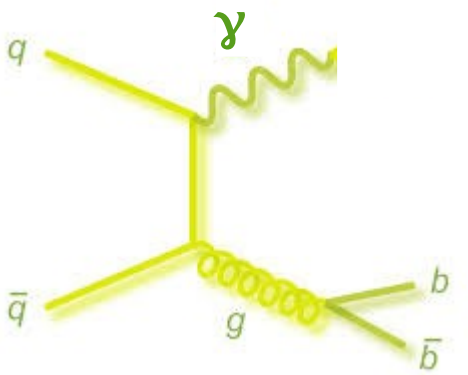


Background determination

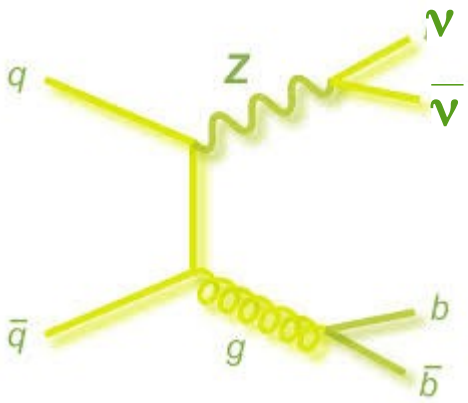
- Illustrative example: $Z \rightarrow \nu\nu$+jets (irreducible background in jets+MET)



- $Z \rightarrow \ell\ell$+jets control sample
  - Strength: very clean, easy to select
  - Weakness: low stats (1/6 of $Z \rightarrow \nu\nu$+jets)



- γ+jets control sample
  - Strength: large stats, clean for high E_γ
  - Weakness: Noisy for E_γ < 100 GeV, theory uncertainties



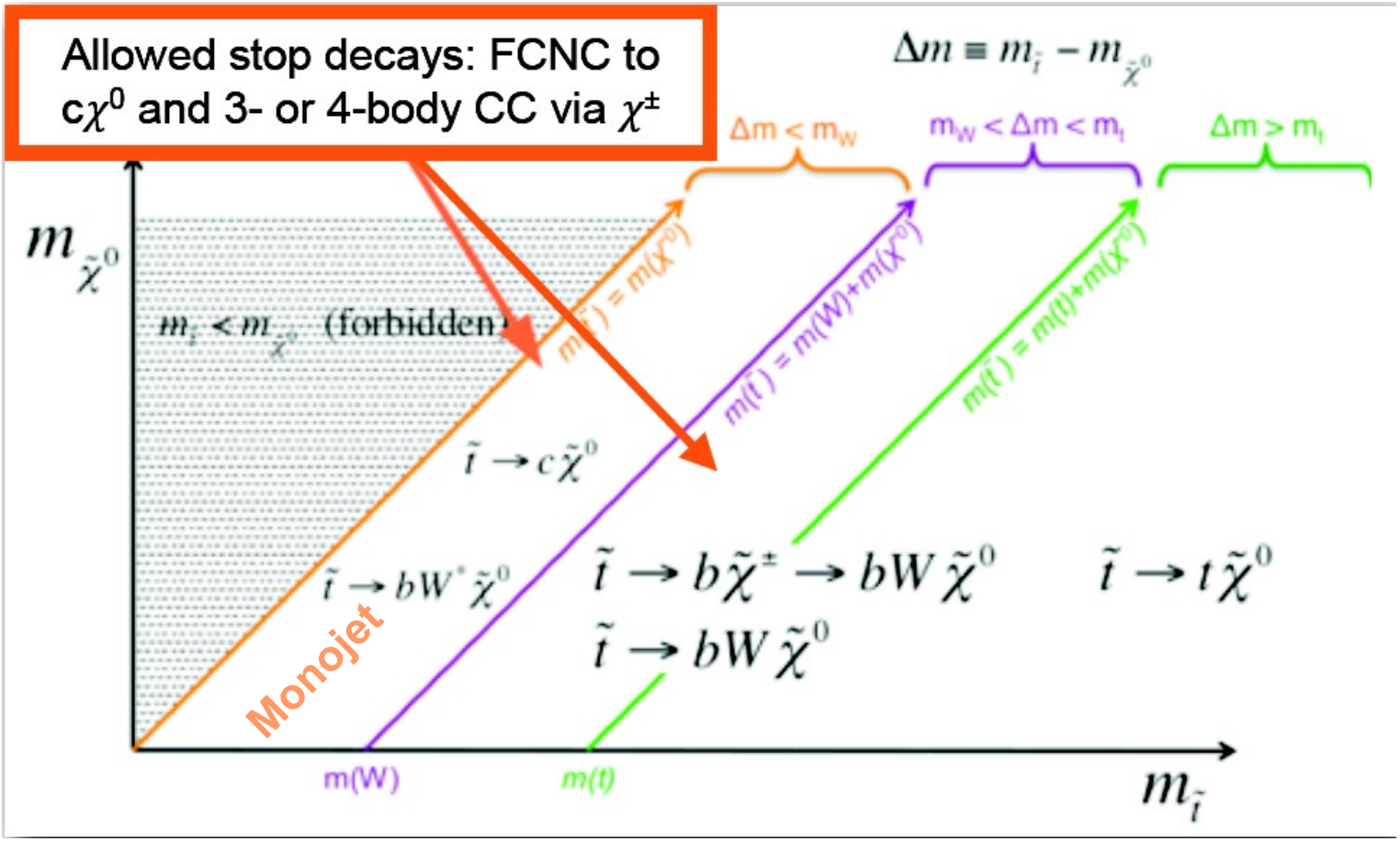
- $Z \rightarrow \nu\nu$+jets

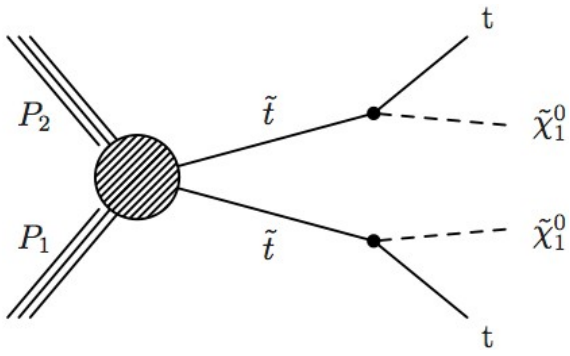
$$N^{predicted}_{Z\rightarrow\nu\nu} = \frac{N^{MC}_{Z\rightarrow\nu\nu}}{N^{MC}_{control}} \, x \, N^{data}_{control}$$

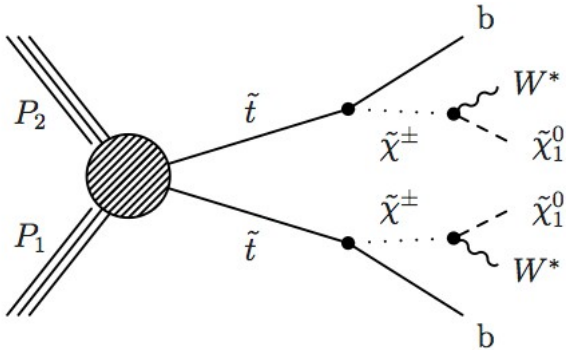
  - Study different control samples and understand their weaknesses and strengths
  - Verify MC extrapolation factor by predicting e.g. Z+jets from W+jets

Direct stop production

- Light stop (and sbottom) and/or small $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}^0}$ are well motivated
  - Stabilize Higgs mass, relic density (stop-χ co-annihilation), EWK baryogenesis
- Acceptance from ISR: signal at low N_{jet}, N_b, H_T
- Sub-percent A×ε and large uncertainties
- Monojet searches extend reach to $\Delta m < m_W$







Direct stop production: $\tilde{t} \to t\tilde{\chi}_1^0$

- Hadronic decay channel: veto ℓ, 5 jets+≥1btag, p_T^{miss}>200GeV → reconstruct tops
- Estimate $t\bar{t}$ background from $t\bar{t}\to\mu$+jets, correcting for the probability to not isolate the lepton (e or μ), and $t\bar{t}\to\tau_h$+jets by changing μ to a τ_h from simulation
- Estimate $Z\to\nu\nu$ from MC and correct based on $Z\to\mu\mu$ data sample
- Uses p_T^{miss}, M_{T2}, M_T^{3jet} and M_T^{Rsys} as discriminating variables

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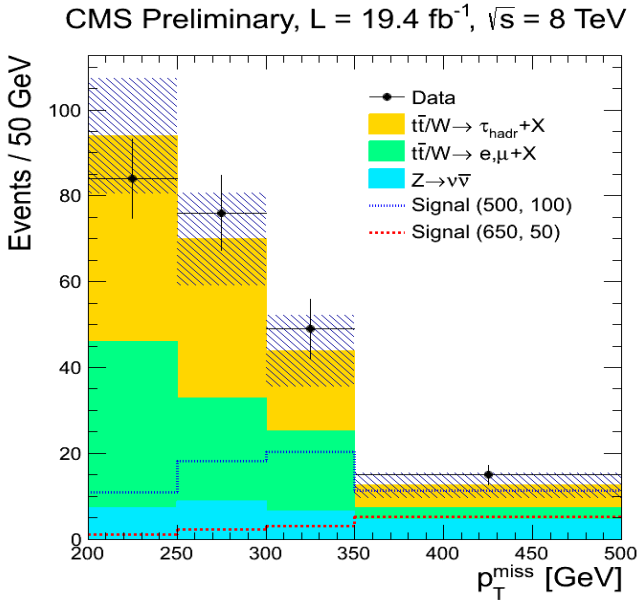
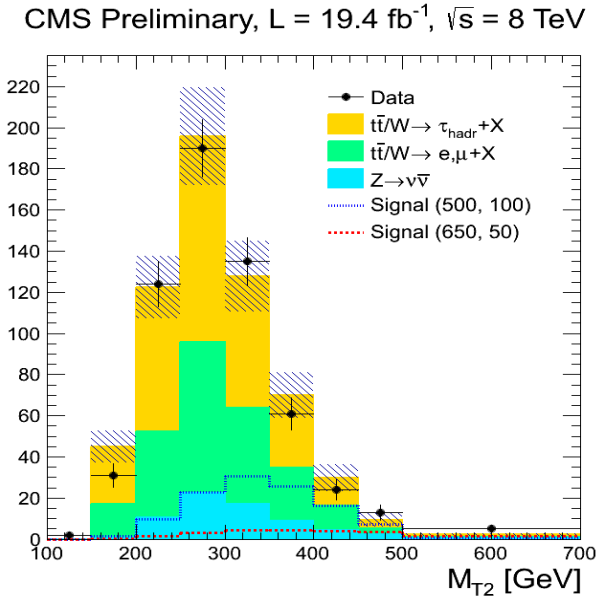
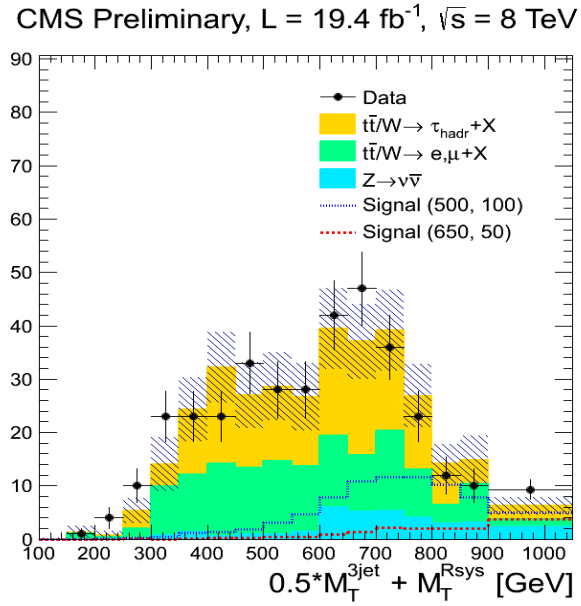
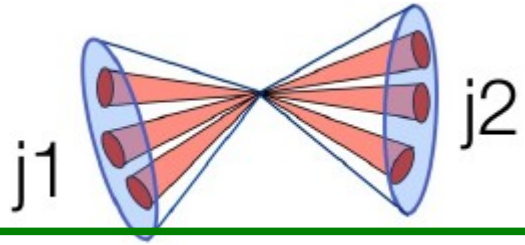






Search region	$Z \to \nu\bar{\nu}$	$t\bar{t}/W \to e,\mu+X$	$t\bar{t}/W \to \tau_h+X$	QCD	Rare processes	Total background	Obs. data
$p_T^{miss} > 200\,GeV$, $N_{b\text{-jets}} \geq 1$	$35.8\,^{+16.3}_{-19.0}$	$89.3\,^{+21.9}_{-21.0}$	$120.2\,^{+11.8}_{-11.9}$	$3.2\,^{+18.2}_{-3.2}$	$5.8\,^{+2.9}_{-2.9}$	$254.3\,^{+35.0}_{-31.0}$	254
$p_T^{miss} > 350\,GeV$, $N_{b\text{-jets}} \geq 1$	$13.2\,^{+6.5}_{-7.9}$	$8.2\,^{+4.0}_{-4.0}$	$16.5\,^{+3.4}_{-3.4}$	$1.0\,^{+1.9}_{-1.0}$	$2.0\,^{+1.0}_{-1.0}$	$40.9\,^{+8.6}_{-9.6}$	45
$p_T^{miss} > 200\,GeV$, $N_{b\text{-jets}} \geq 2$	$6.1\,^{+15.3}_{-5.5}$	$33.8\,^{+10.3}_{-10.0}$	$45.3\,^{+7.0}_{-7.0}$	$0.1\,^{+0.6}_{-0.1}$	$3.1\,^{+1.6}_{-1.6}$	$88.4\,^{+19.8}_{-13.5}$	83
$p_T^{miss} > 350\,GeV$, $N_{b\text{-jets}} \geq 2$	$1.8\,^{+6.8}_{-1.6}$	$1.2\,^{+1.0}_{-1.0}$	$4.3\,^{+1.7}_{-1.8}$	$0.1\,^{+0.5}_{-0.1}$	$1.2\,^{+0.6}_{-0.6}$	$8.6\,^{+7.1}_{-2.7}$	15

Direct stop: Razor

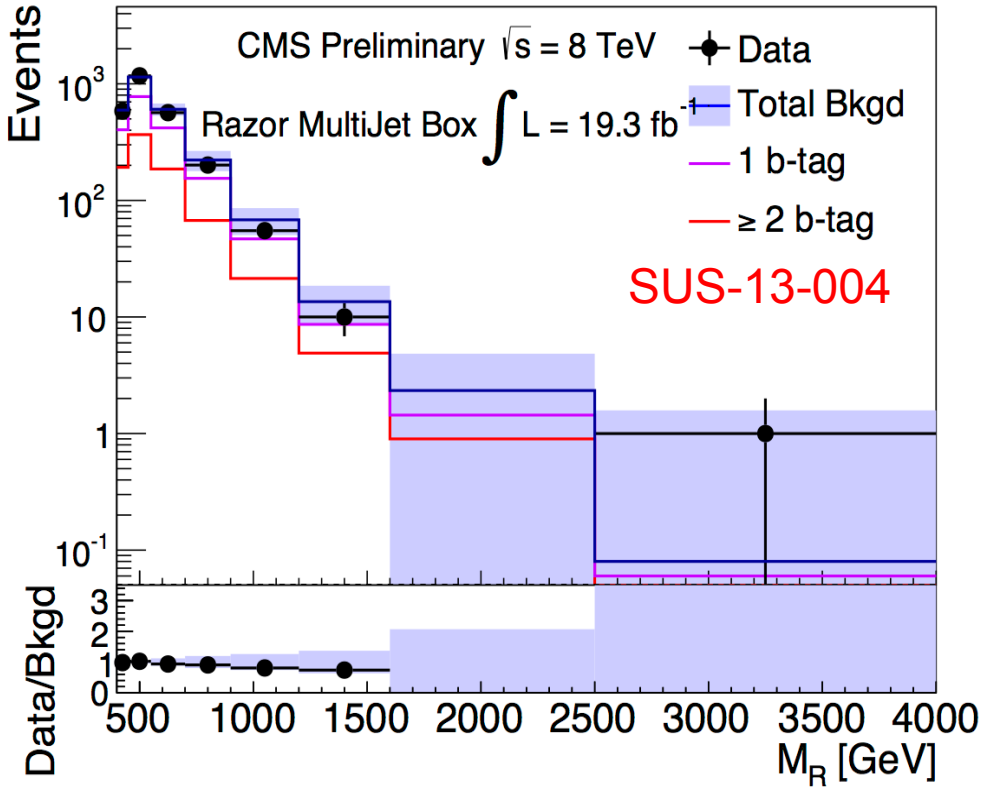


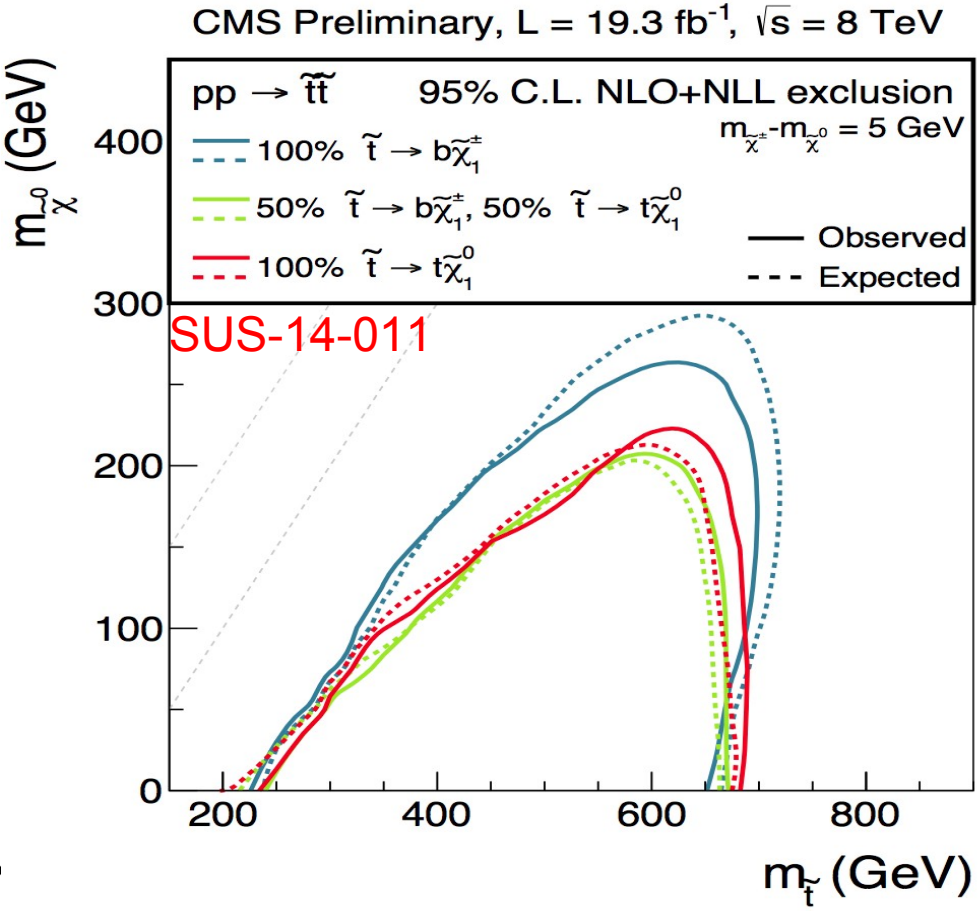
- Treat events as dijet+MET by clustering visible objects into two megajets
- M_R estimates p in true squark restframe
  - Peaks at characteristic mass scale $\frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{M_{\tilde{q}}}$
- SM: analytic shape in M_R-R^2 is fit in a bckgd-enriched sideband and extrapolated

$$M_T^R = \frac{1}{\sqrt{2}}\sqrt{\not{E}_T(p_T^{j1}p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}$$

$$M_R = \sqrt{(|\vec{p}^{j1}| + |\vec{p}^{j2}|)^2 - (p_z^{j1} + p_z^{j2})^2}$$

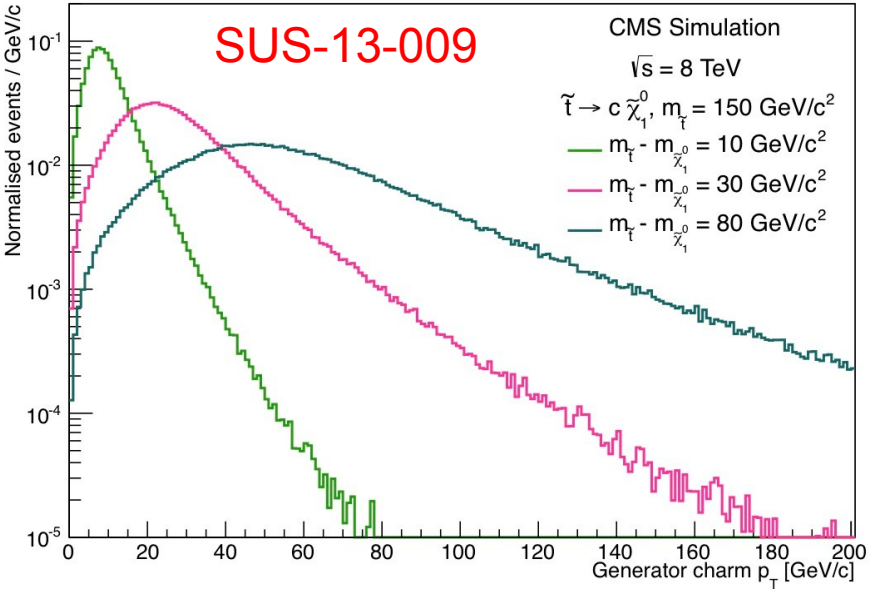
$$R \equiv \frac{M_T^R}{M_R}$$

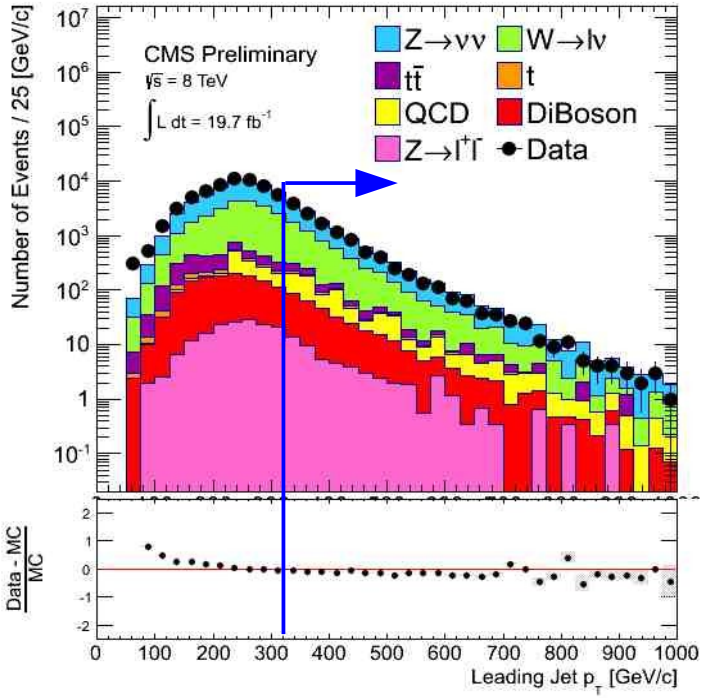


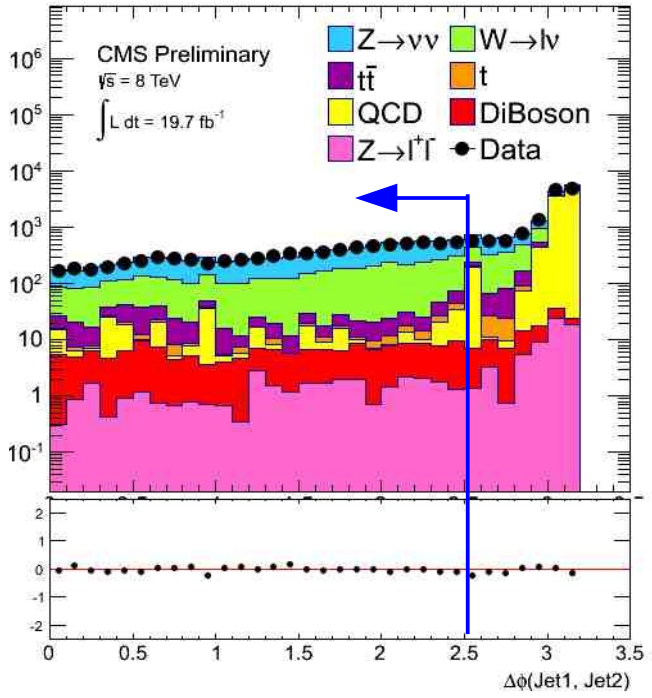


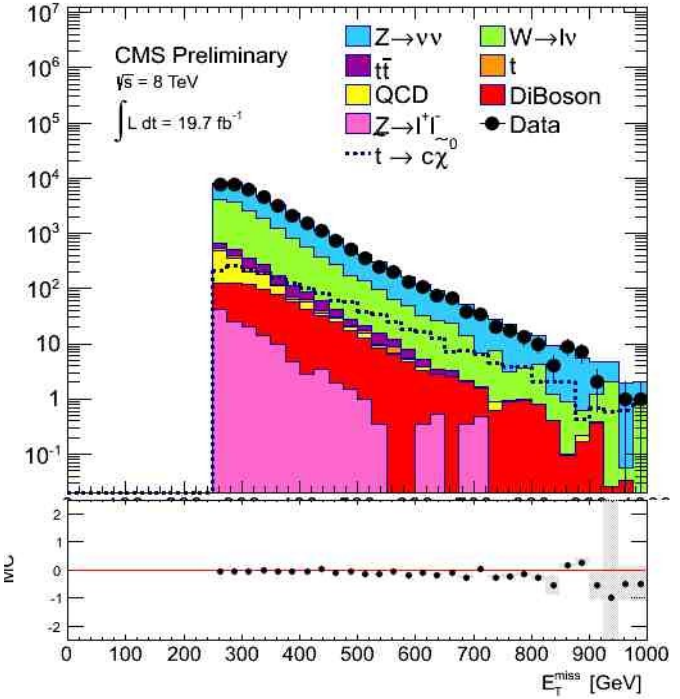
Monojet search: stop → charm $\tilde{\chi}_1^0$

- Stop decay is "invisible"
  - Charm p_T is very soft
- MET>250 GeV, $p_T^{(j1)}$>110 GeV, allow $p_T^{(j2)}$>60 GeV, veto 3rd jet
- Seven inclusive regions:
  - p_T^{j1} > 250,300,350,400,450,500,550 GeV
  - Scan Δm between 10 and 80 GeV



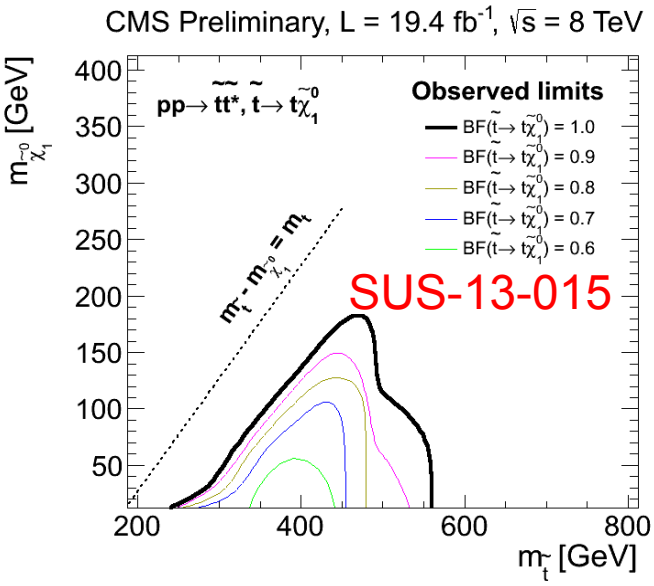


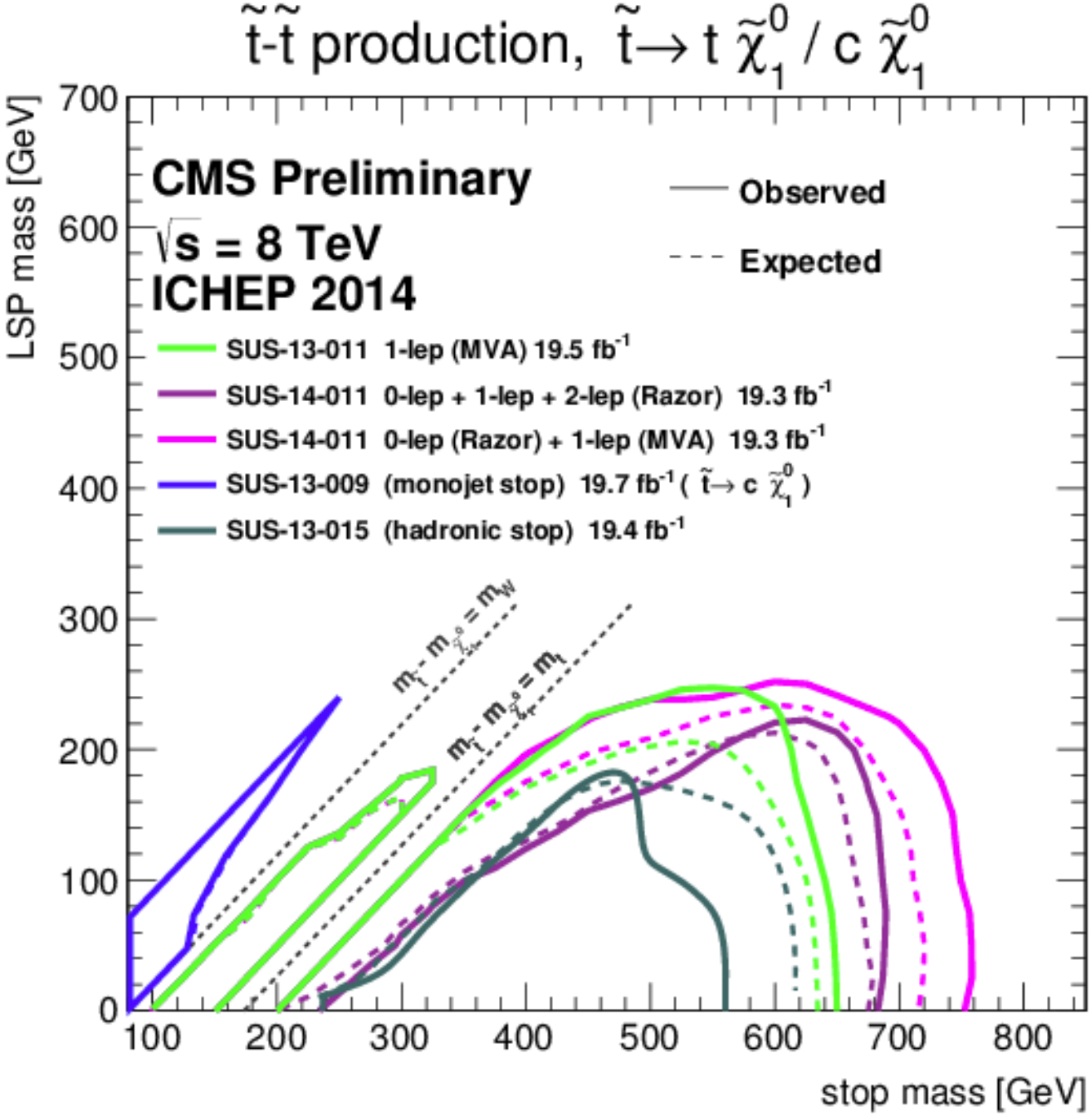




Summary of limits on stop

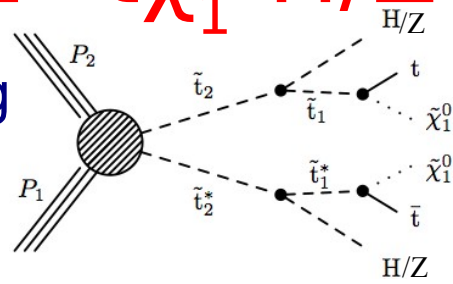
- Depends on BF($\tilde{t} \to t\tilde{\chi}_1^0$)

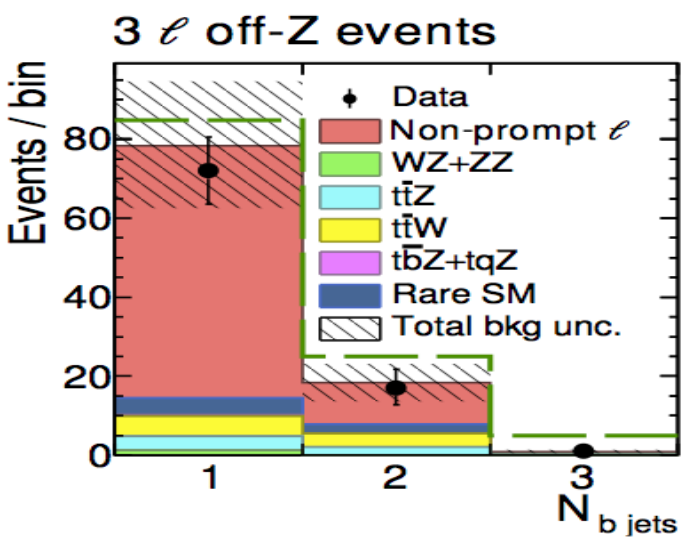


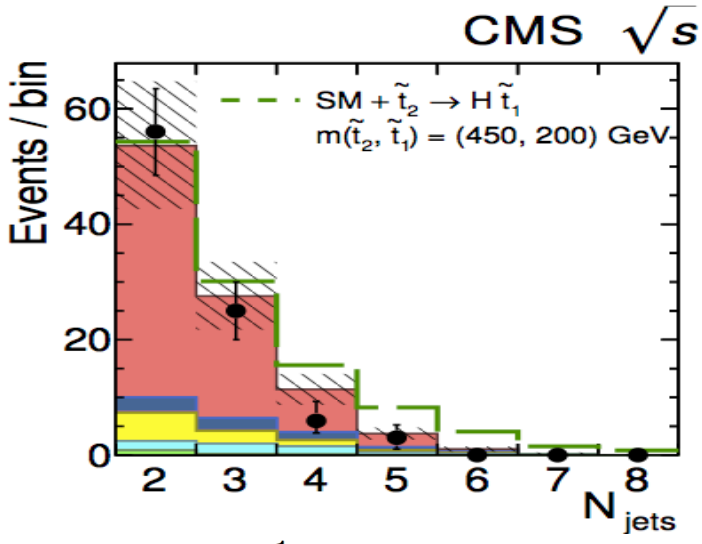


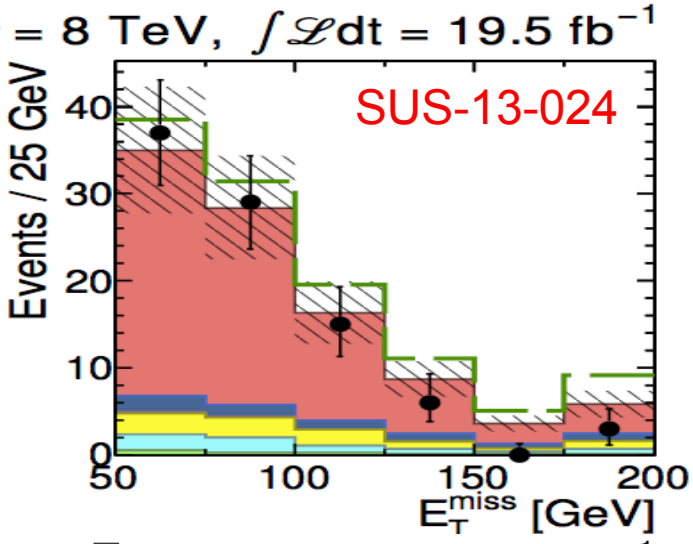
Mind the gap ($m_{\tilde{t}}$-$m_{\tilde{\chi}}$=m_t): $\tilde{t}_2 \to \tilde{t}_1 H/Z \to t\tilde{\chi}_1^0 H/Z$

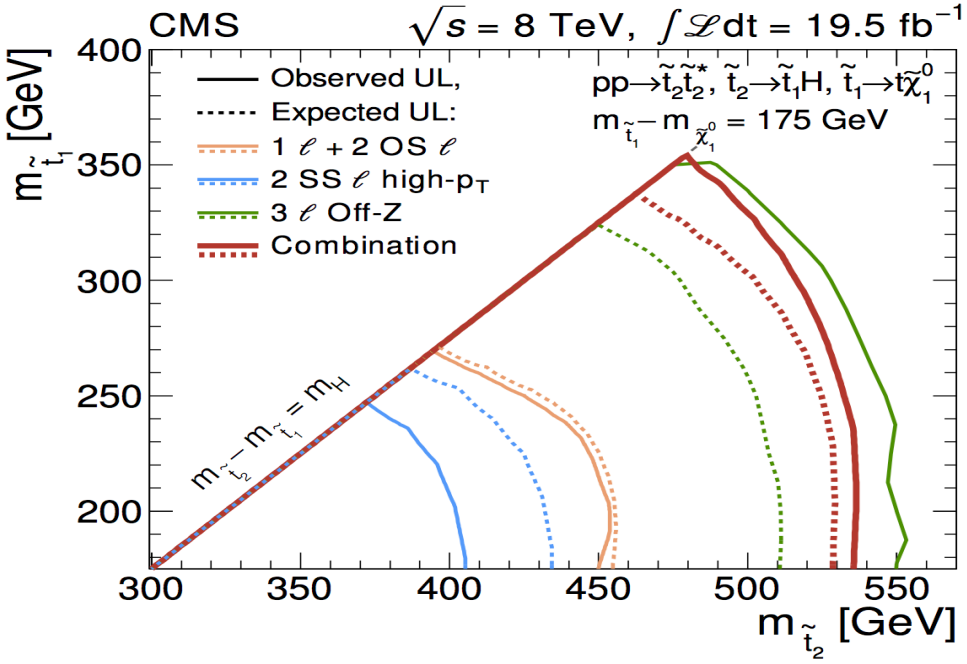
- Search in 1ℓ or 2ℓ OS+≥3 b-tags, and 2ℓ SS or ≥3ℓ+≥1 b-tag
  - Sensitive to H→bb̄/ZZ/WW decays
- 3ℓ selection is the most sensitive

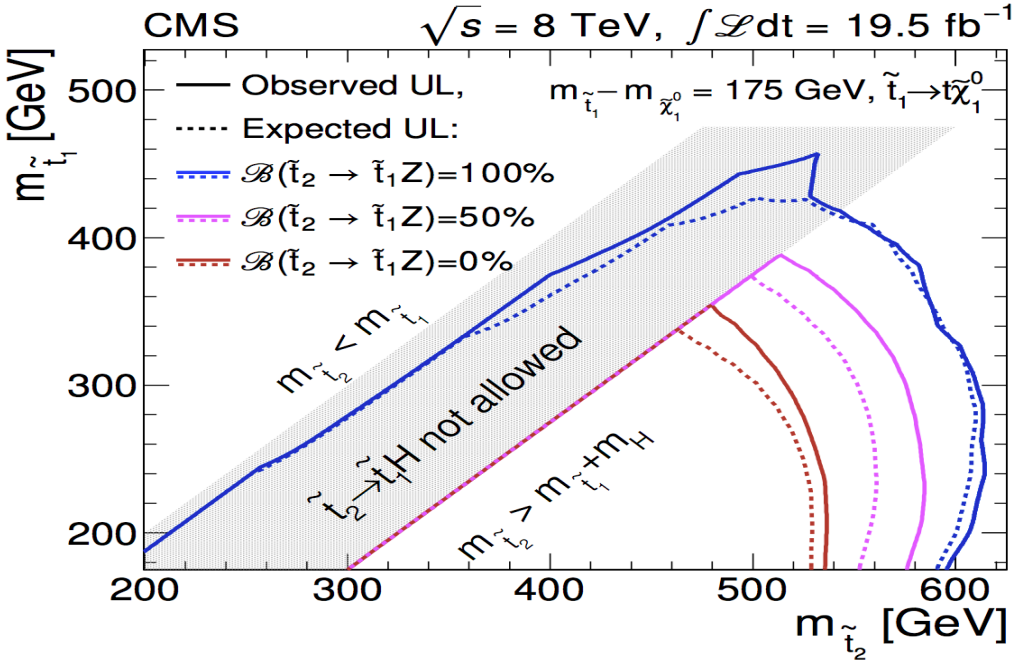












Searches for EWK SUSY production

- Production of neutralinos, charginos, and sleptons
- Covered diboson+MET final states with h → ZZ, WW (arXiv:1405.7570):
  - WZ with 3 leptons
  - ZZ with 4 leptons
  - $W^{(*)}Z^{(*)}$ with SS dileptons
  - WZ/ZZ with Z(ℓℓ) + jj
  - Wh with 1-lepton bb
  - Wh with SS dileptons
  - Wh with multileptons
  - WW with OS dileptons
- Now finalize program with hh and Zh final states (including h → bb, γγ)
  - Multileptons
  - hZ with Z(ℓℓ) + h(bb)
  - hh → 4b
  - hh, hZ, hW with h→γγ
  - ZZ with Z(ℓℓ) + jj

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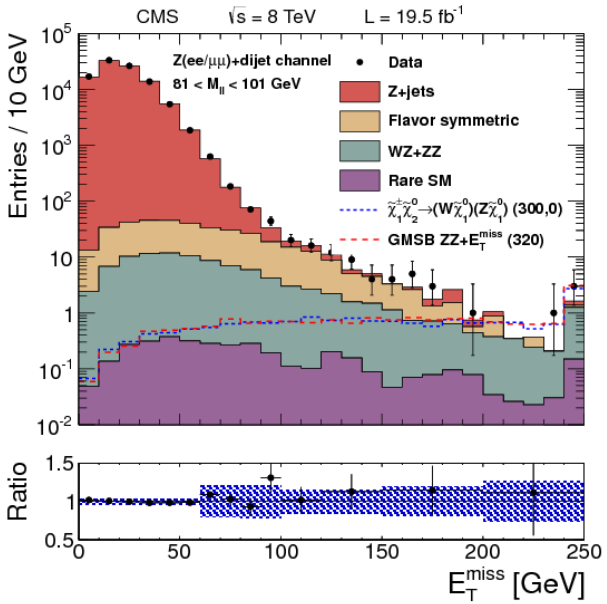
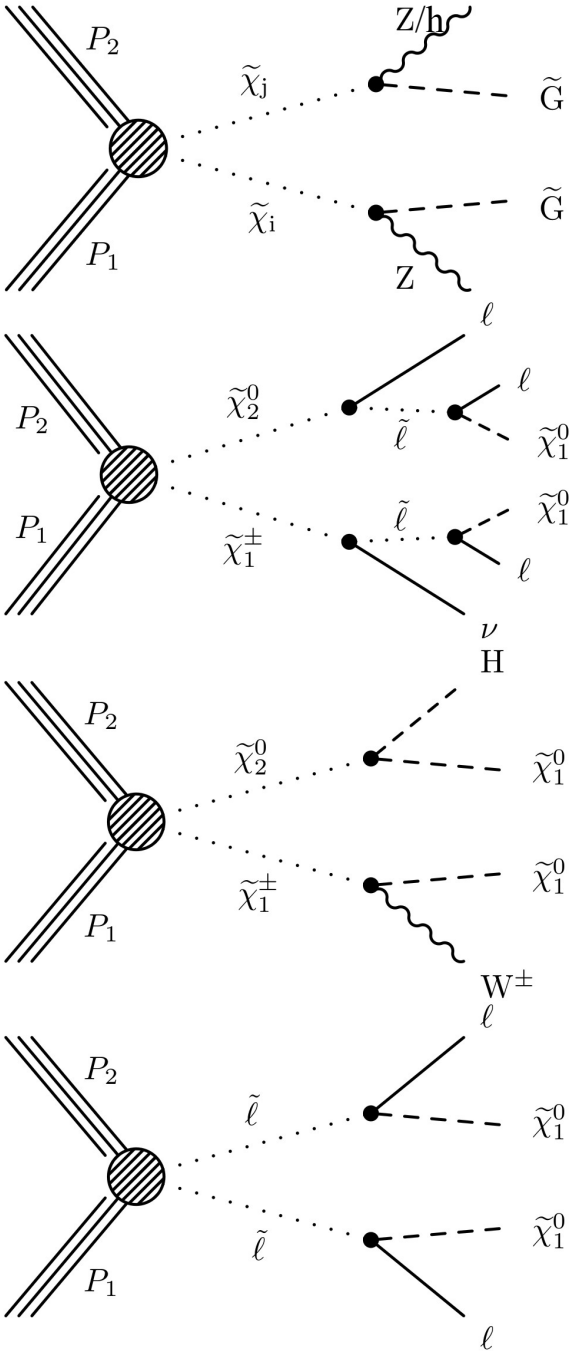
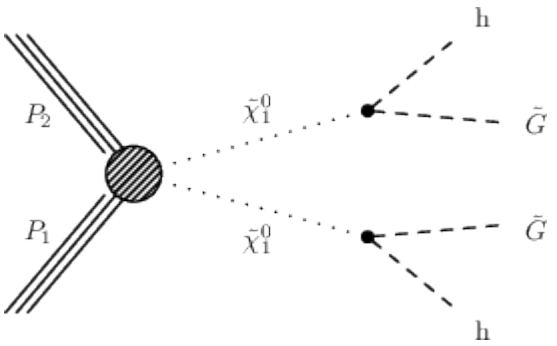
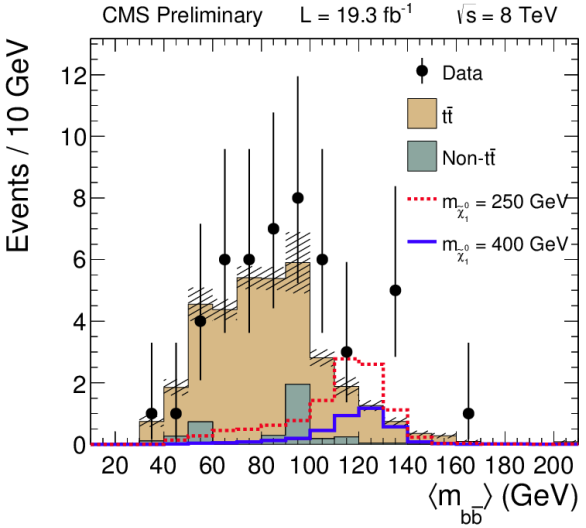


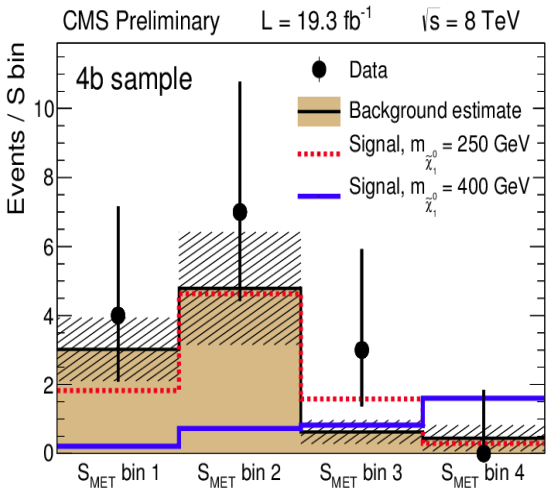


Study $\chi_1\chi_1 \rightarrow$ hh and Zh

- hh → bbbb

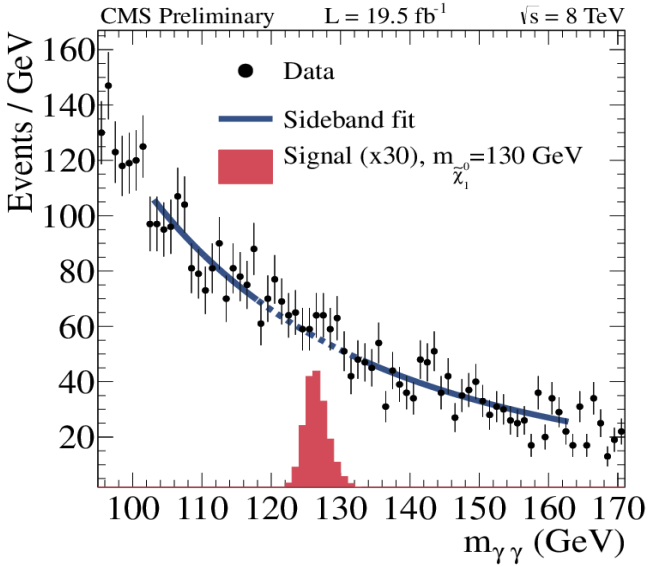




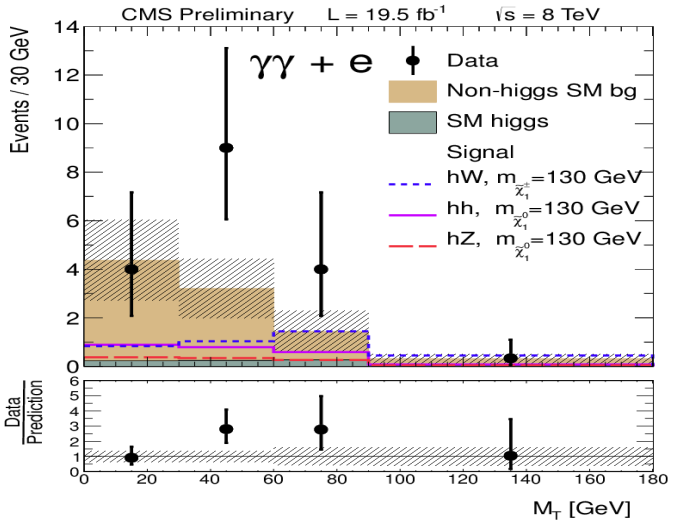


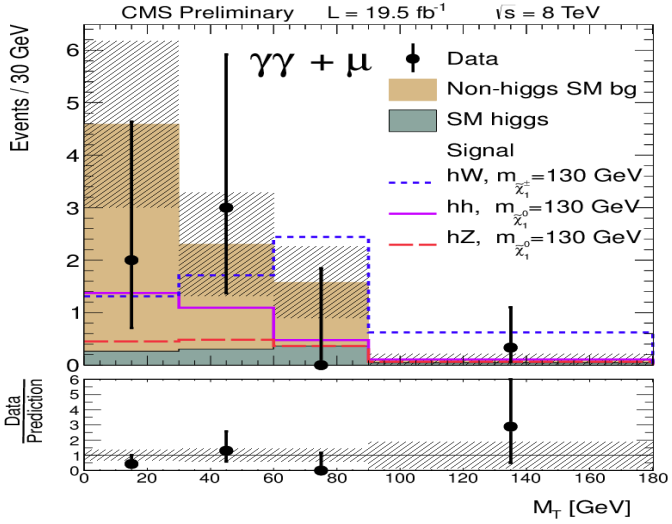
- hh, Zh, Wh with one h → $\gamma\gamma$ decay

Zh , Wh → $\gamma\gamma$+2 jets



hh, Zh, Wh → $\gamma\gamma$+e's and μ's





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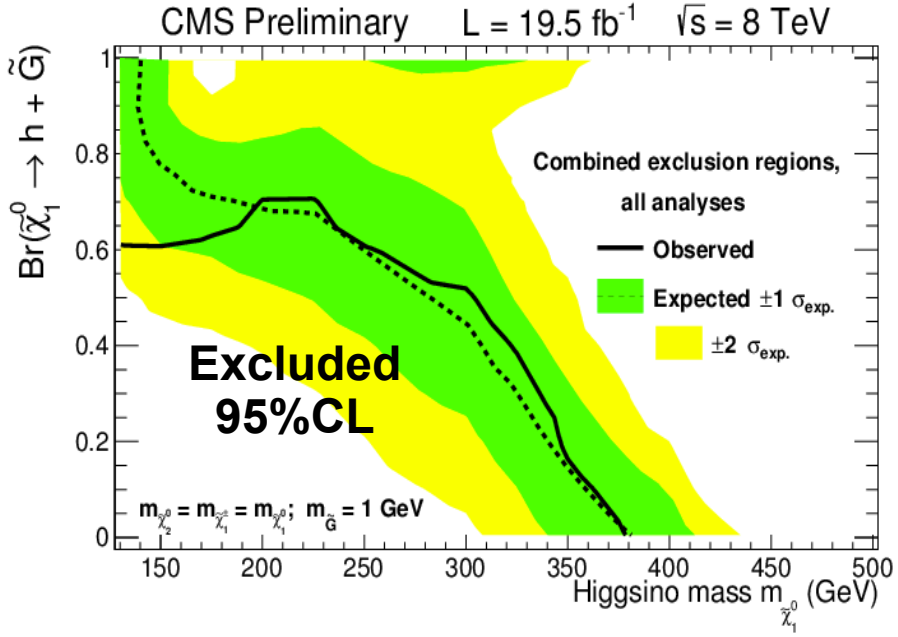
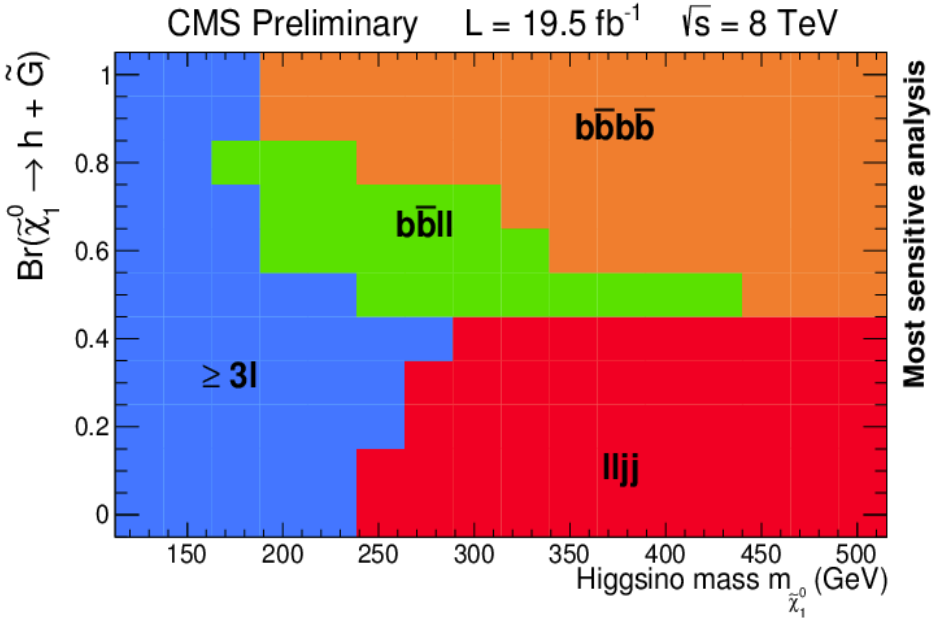
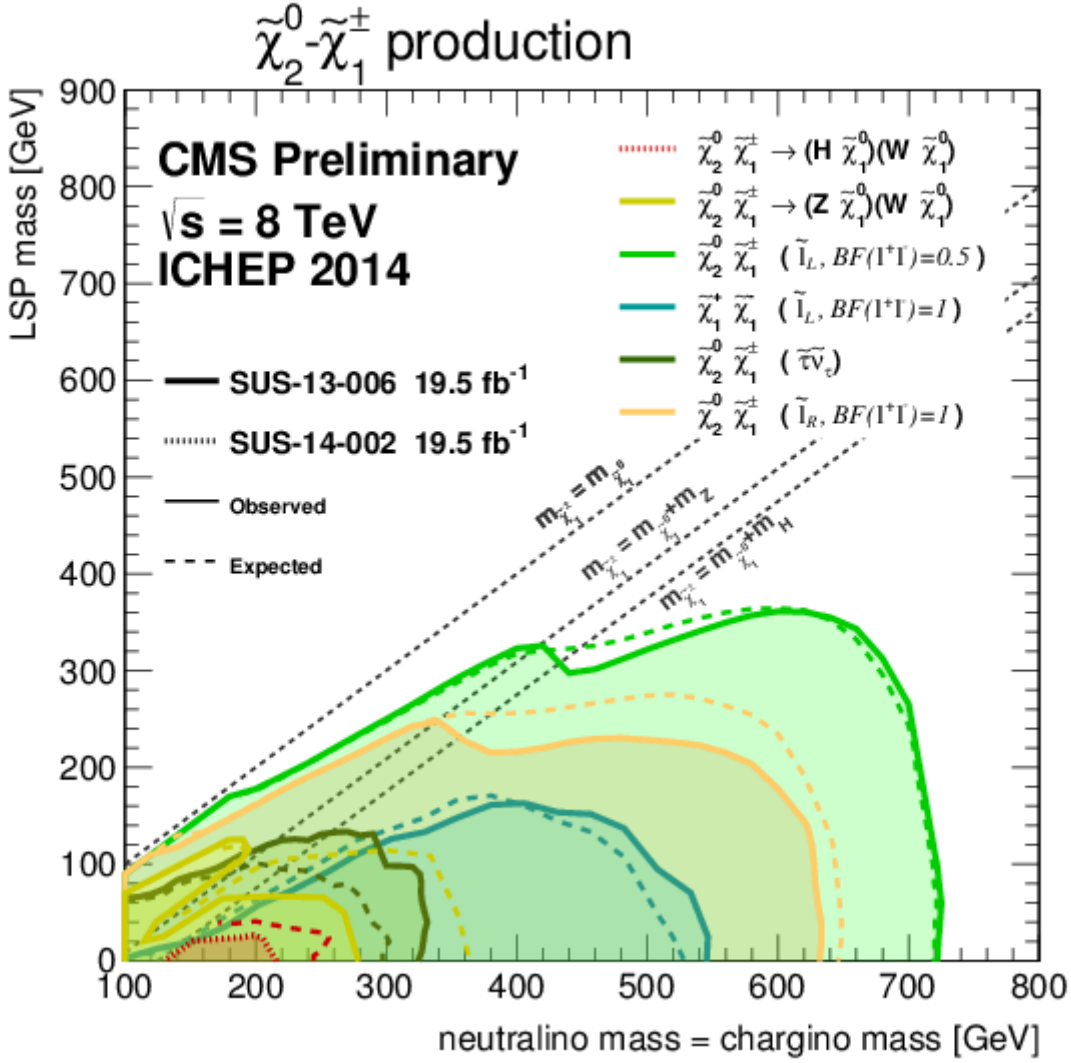
Interpretation in simplified models

- GMSB higgsino





- EWKino

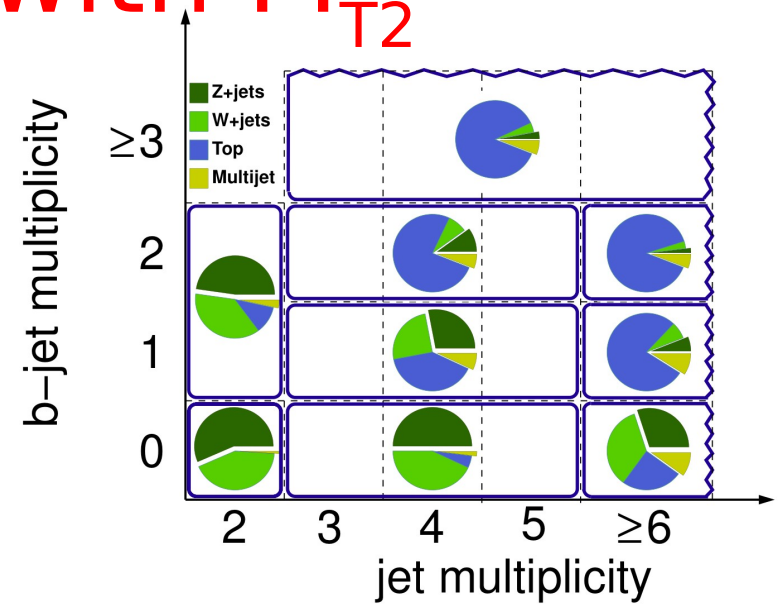


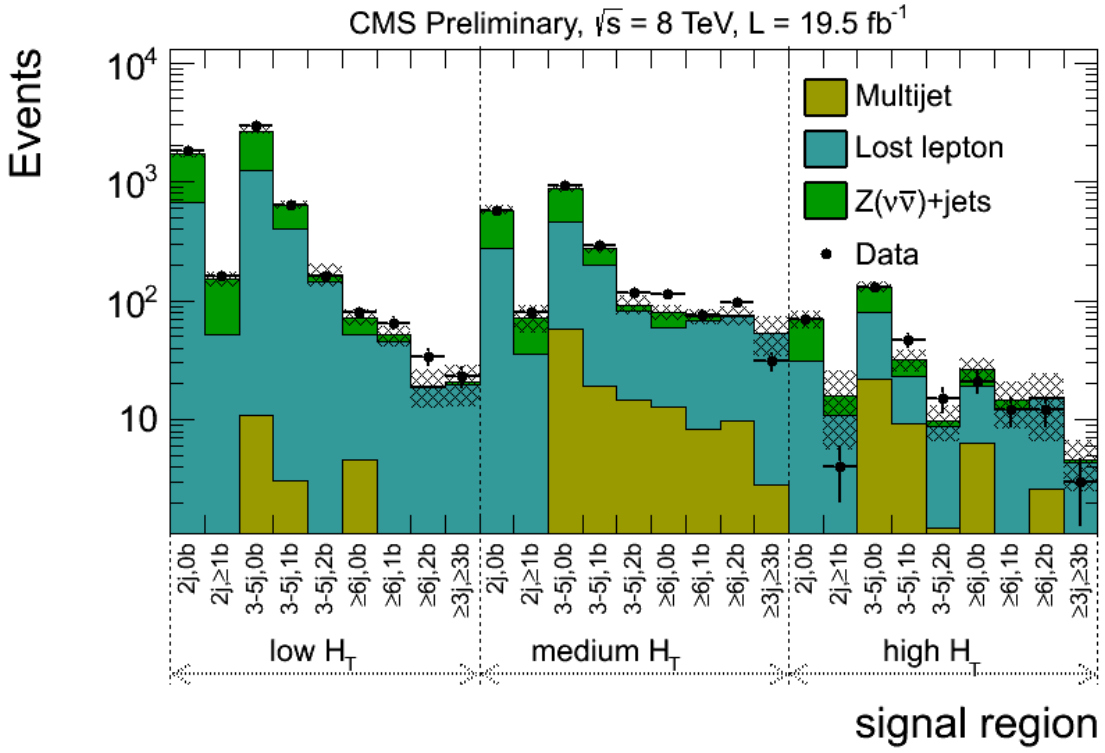
Inclusive search with M_{T2}

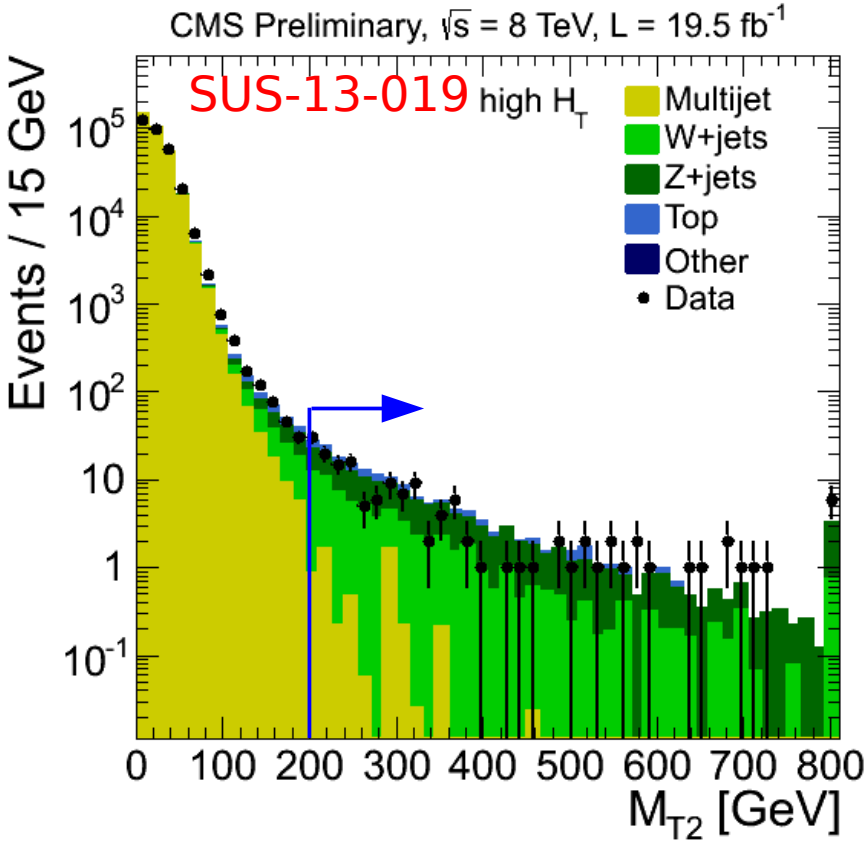
- Data-driven background estimations
  - Single muon sample for W+jets and $t\bar{t}$+jets
  - Photon+jets and di-muon sample for Z+jets
  - QCD from M_{T2} sideband extrapolation
- Search in bins of M_{T2} with M_{T2}>200 GeV

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

$$m_T^{(i)} = \sqrt{(m^{vis(i)})^2 + m_\chi^2 + 2\left(E_T^{vis(i)}E_T^{\chi(i)} - \mathbf{p}_T^{vis(i)}\cdot\mathbf{p}_T^{\chi(i)}\right)}.$$





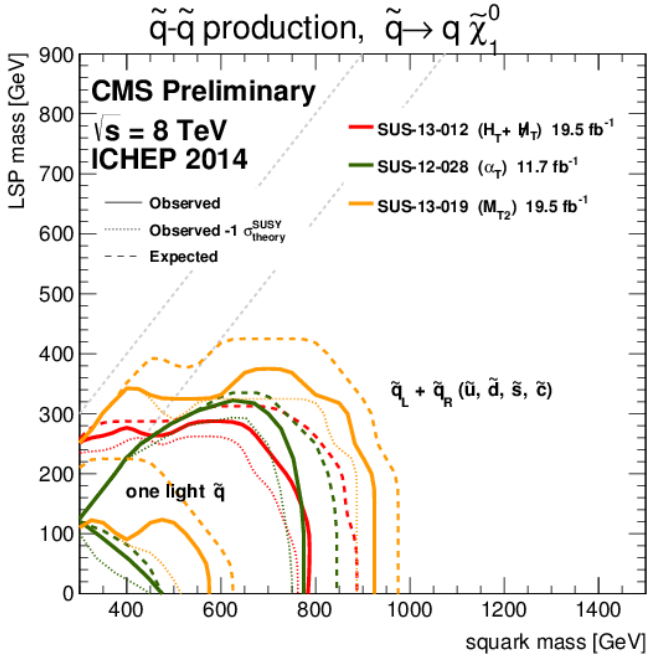


Overview squark and gluino searches

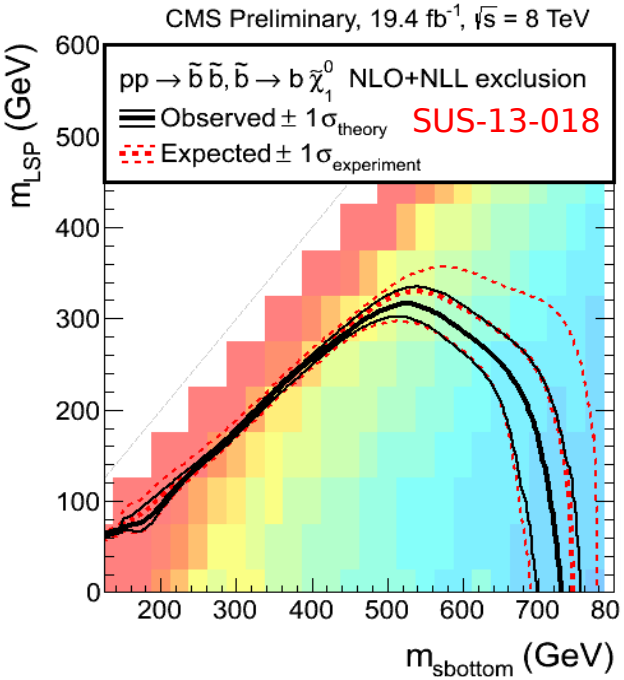
Direct squark production
Reach ~ 600-700 GeV

Gluino pair production
Reach ~ 1.0-1.3 TeV

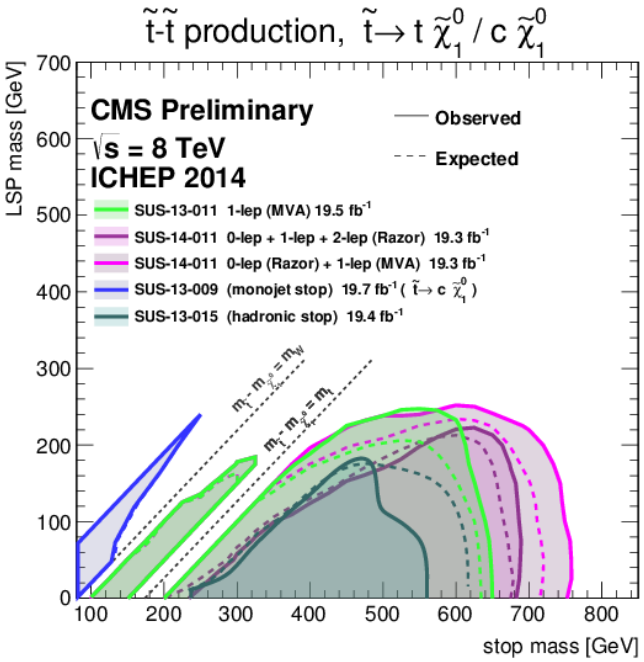
1st & 2nd generation

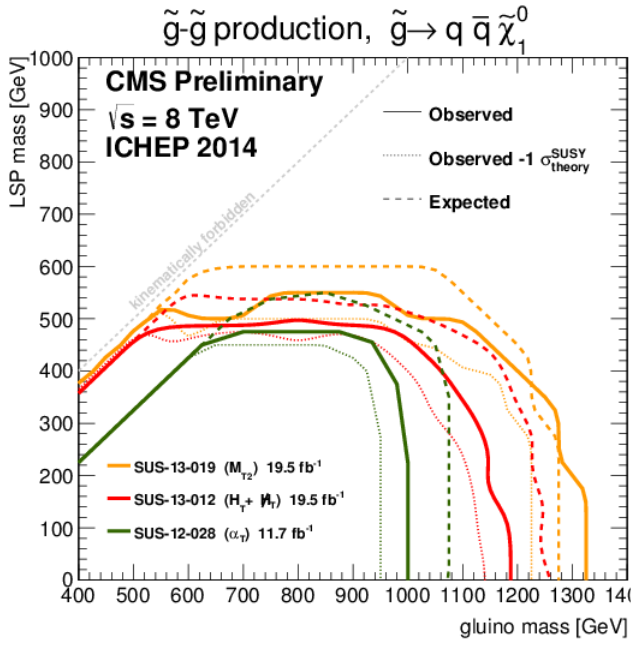


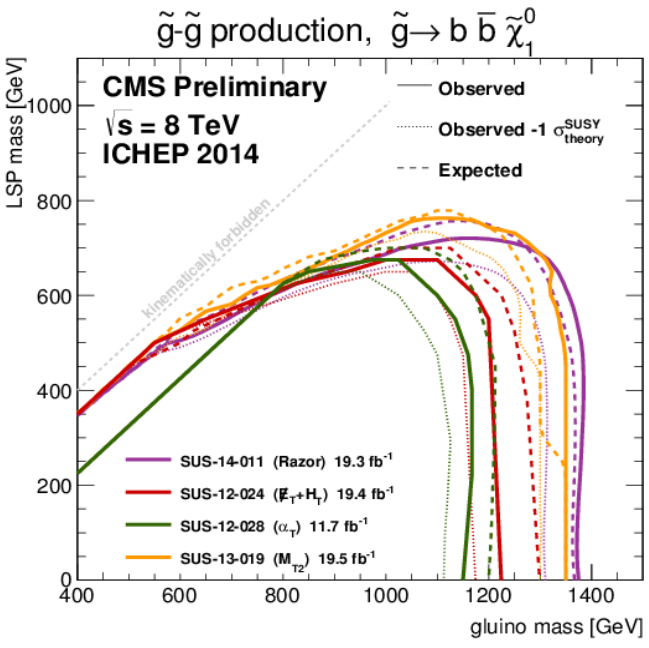
sbottoms

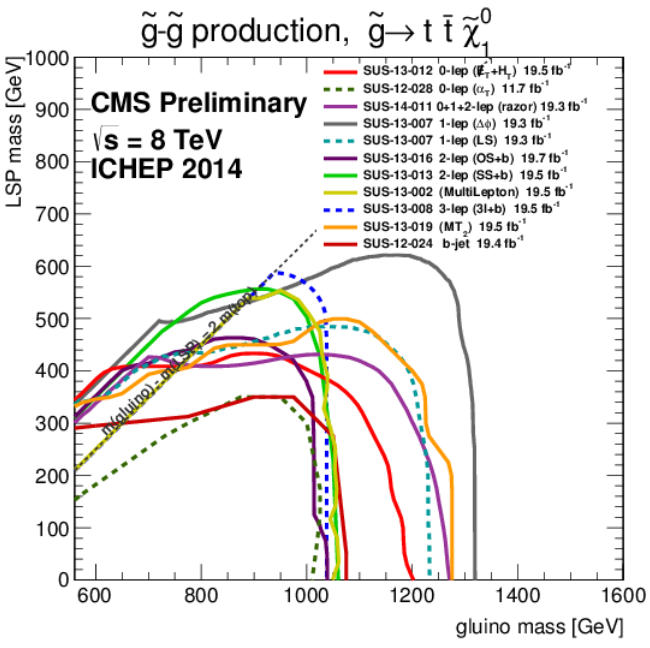


stops





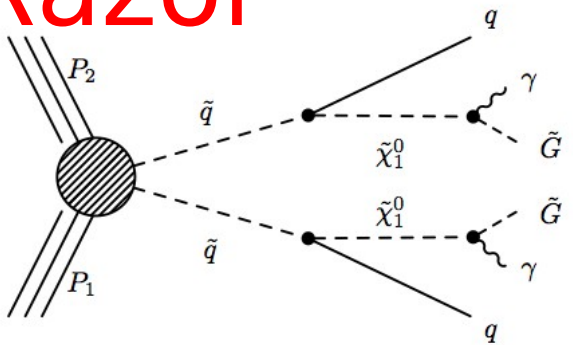




Arái

Diphoton search with Razor

- General Gauge Mediated models produce signals with photons
  - Bino-like χ decays to γ+gravitino (LSP)
  - m_{χ} fixed at 375 GeV
- Background falls exponentially in M_R
- Signal peaks at characteristic mass scale in M_R
- Estimate bkgd from fit to M_R and check closure in data control sample



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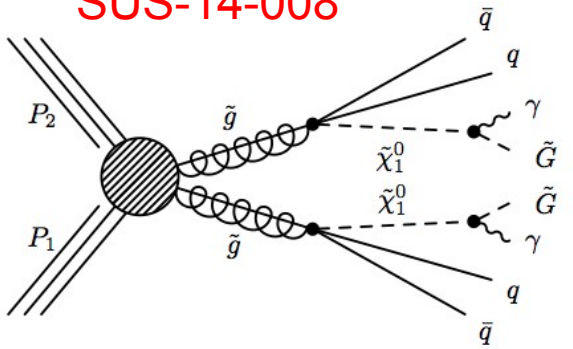
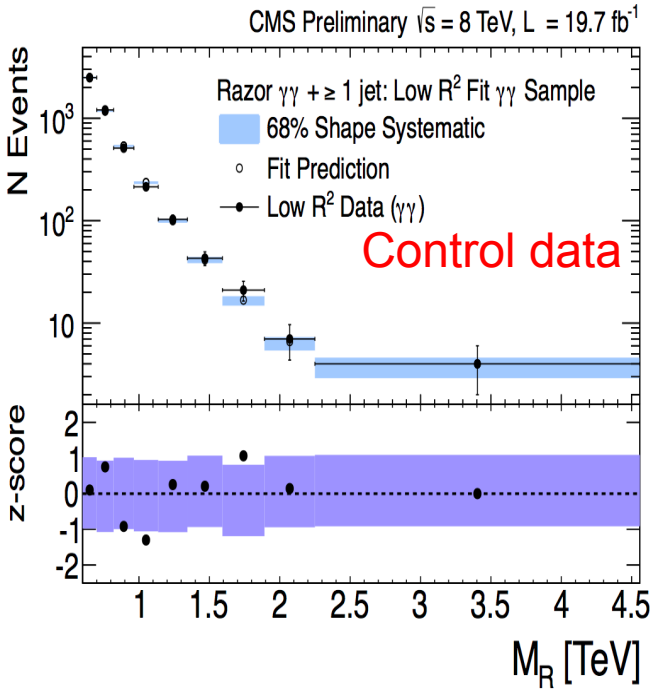
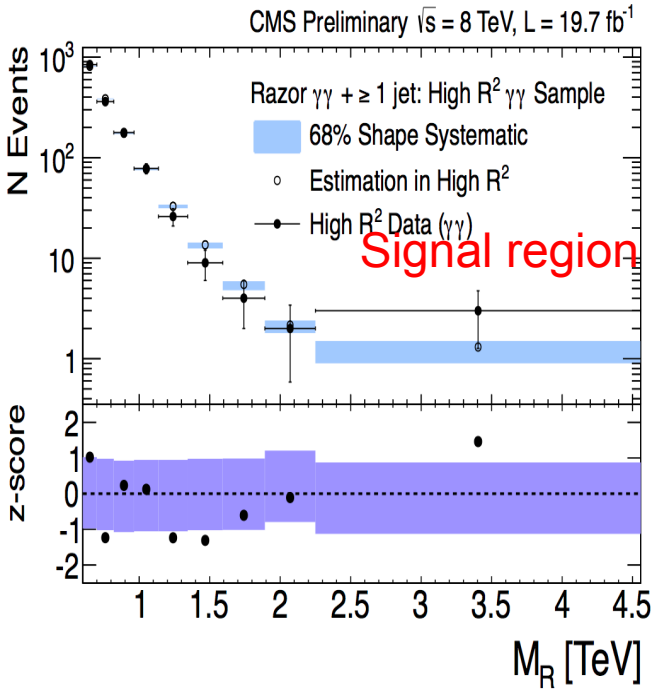
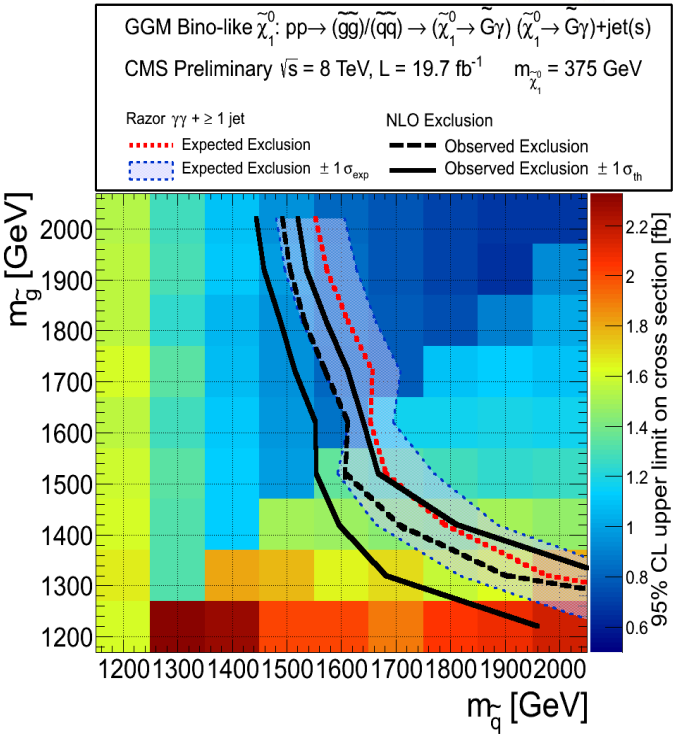


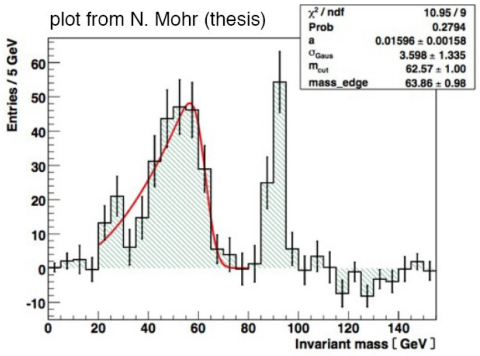


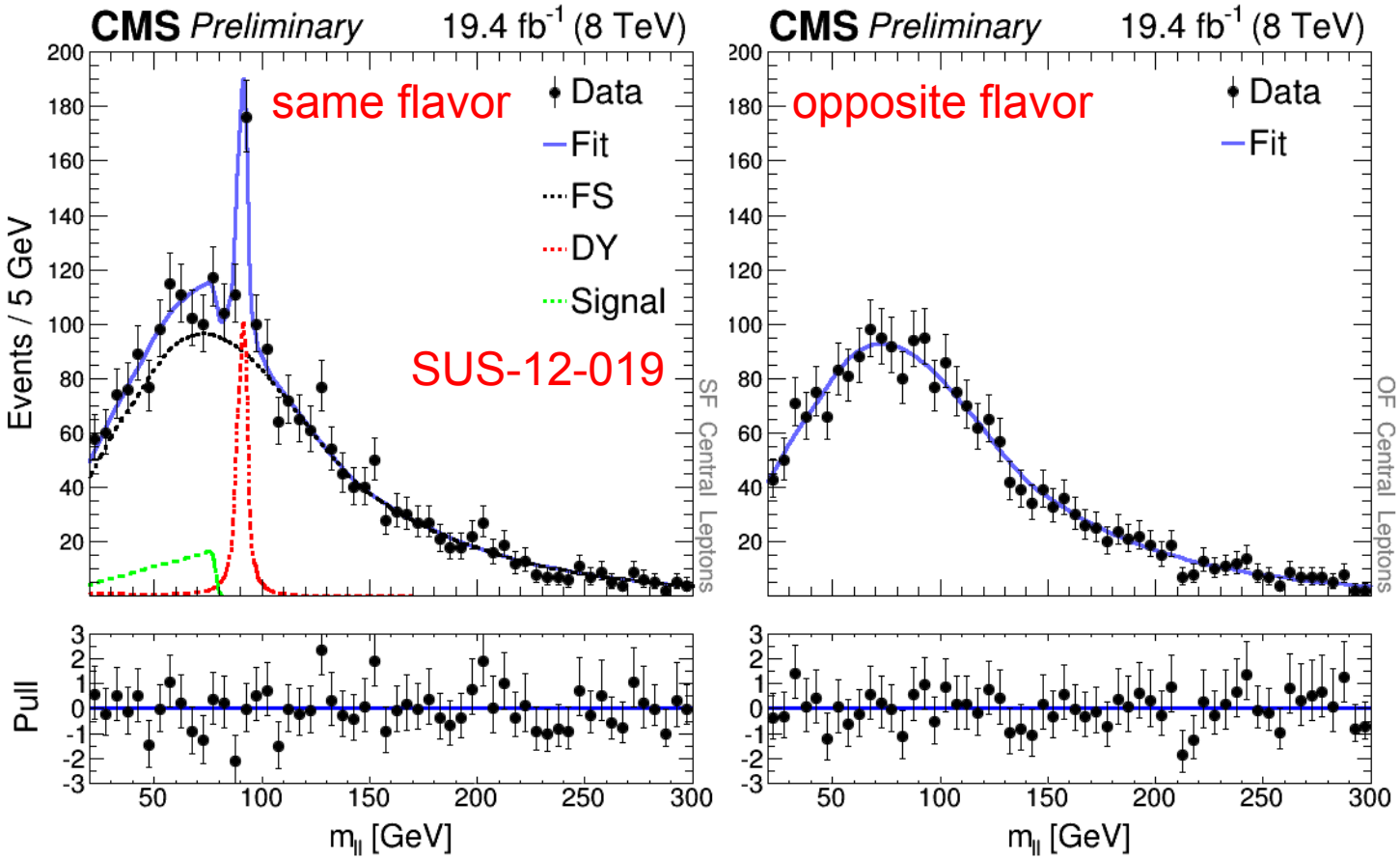




Kinematic edge in OS same-flavor $\ell\ell$

- Sequential: $\tilde{\chi}_2^0 \to \ell\tilde{\ell} \to \tilde{\chi}_1^0 \ell^+\ell^-$ or 3body: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+\ell^-$
  - Produce triangle shape (3B: +edge) in $m_{\ell\ell}$ distribution
- $N_{lep} \geq 2$ with $p_T > 20$GeV, $N_{jets} \geq 2$ with $p_T > 40$GeV
- Background estimation with OS, OF leptons
- Two search regions: central $|\eta|<1.4$, forward $1.6<|\eta|<2.4$
- Signal and background contributions determined from kinematic fit





- Signal modeled with triangle⊗Gaussian

$$\mathcal{P}_S(m_{\ell\ell}) = \frac{1}{\sqrt{2\pi}\sigma_{\ell\ell}} \int_0^{m_{\ell\ell}^{edge}} y \cdot \exp\left(-\frac{(m_{\ell\ell}-y)^2}{2\sigma_{\ell\ell}^2}\right) dy$$

	Central	Forward
Drell–Yan	158 ± 23	71 ± 15
Flav. Sym. [OF]	2270 ± 44	745 ± 25
$R_{SF/OF}$	1.03	1.02
Signal events	126 ± 41	22 ± 20
$m_{\ell\ell}^{edge}$ [GeV]	78.7 ± 1.4	

In addition, performed cut and count analysis in $20<m_{\ell\ell}<70$ GeV (no shape assumption)

Outlook: 8 TeV vs 14 TeV

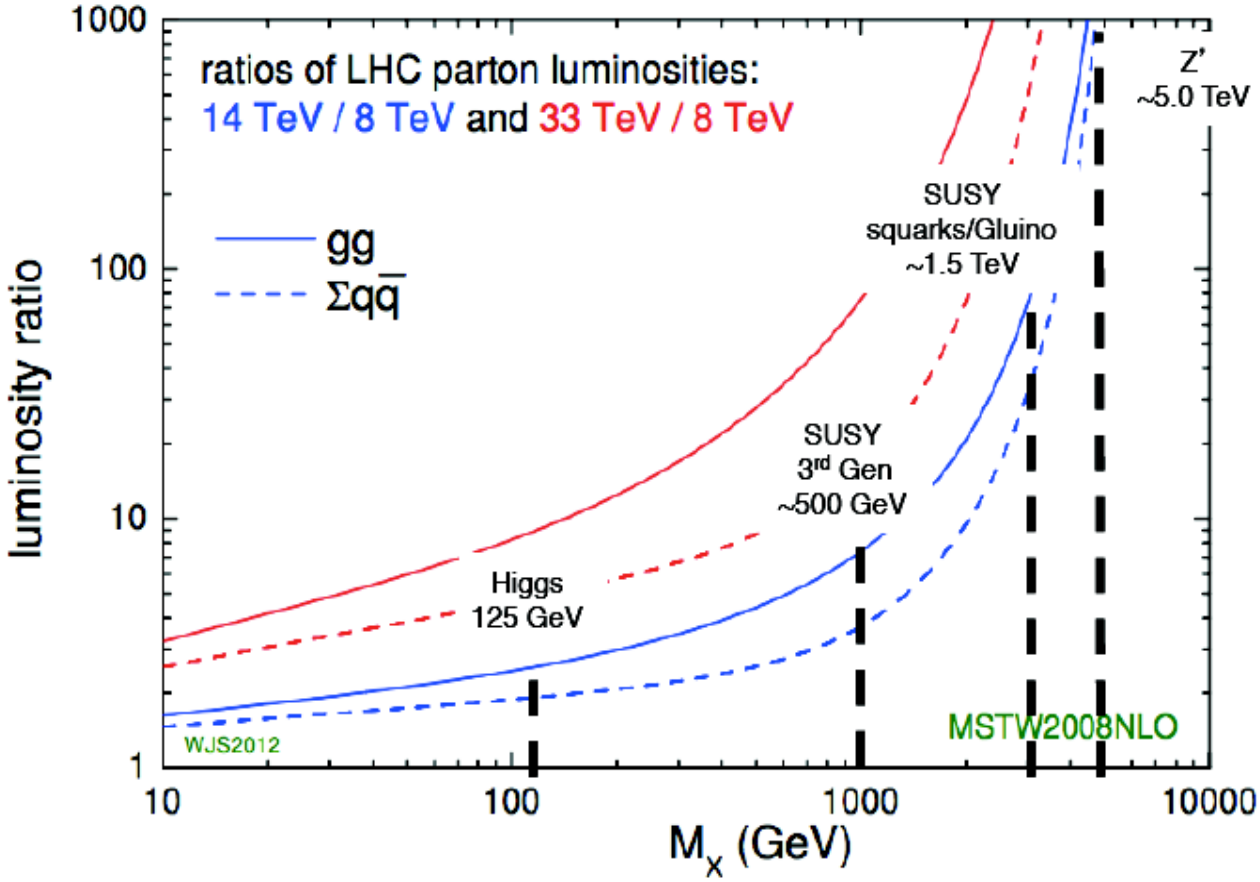
Use parton luminosities to illustrate the gain of 14 vs 8 TeV

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: factor ~2

SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: factor ~3 to 6

SUSY – Squarks/Gluino:
Mass scale ~ 1.5 TeV
qq,gg,qg: factor ~40 to 80

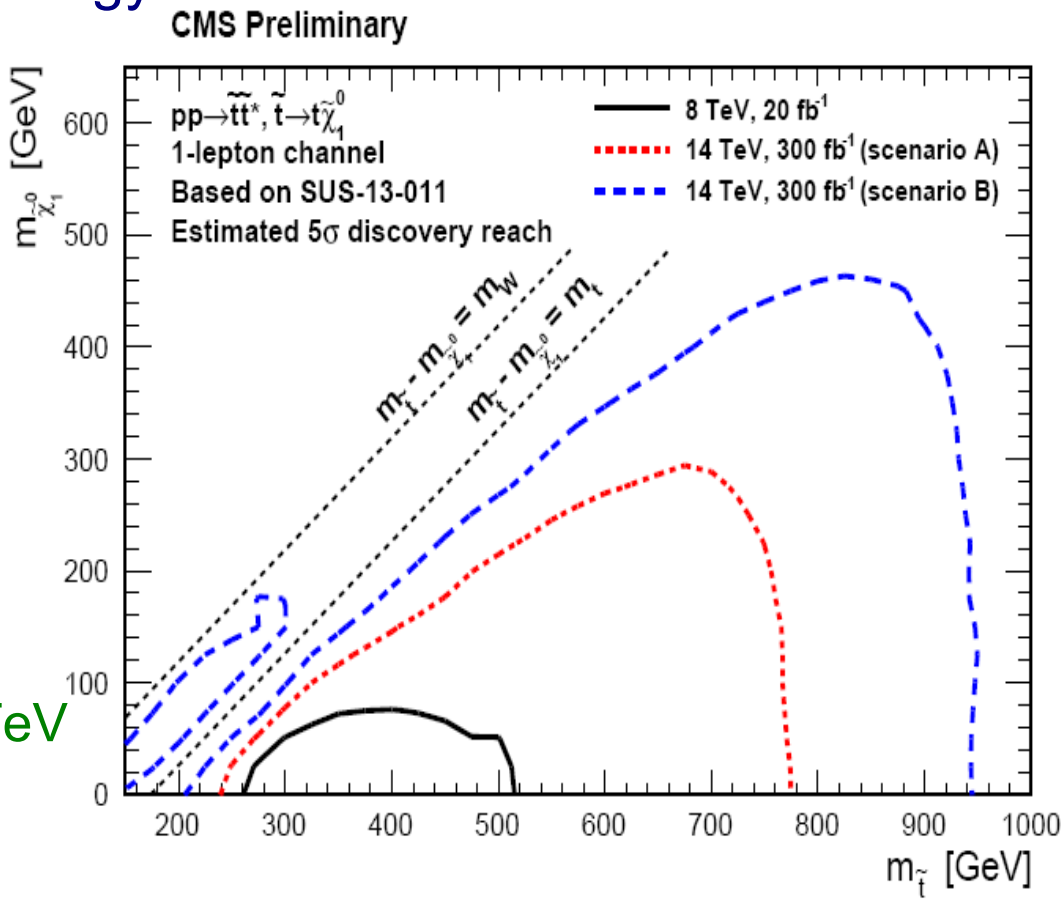
Z' :
Mass scale ~ 5 TeV
qq: factor ~1000



Increase in energy will help a lot!
Not just for SUSY...

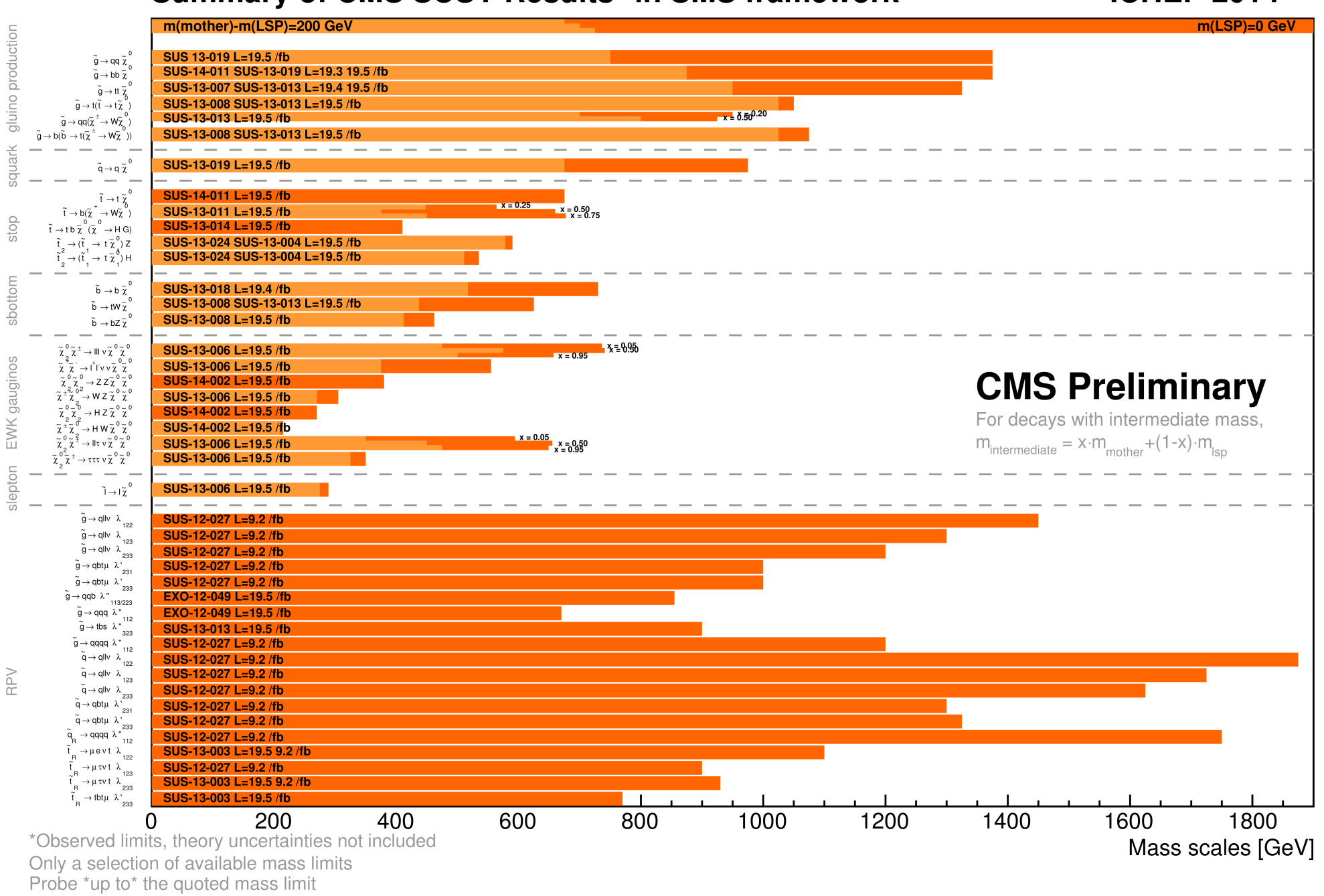
Conclusions/Projections

- Broad program of SUSY searches in CMS
- Covering many different signatures
  - Working on hard regions of parameter space
- No evidence yet, but Run2 will boost the reach
- Now working hard to exploit new energy
  - Higher pileup
  - New triggers
  - Harder to define isolation
  - Boosted jets
- 14 TeV with 300 fb^{-1} will cover:
  - $m_{\tilde{t}}$ up to 1 TeV
  - $m_{\tilde{\chi}}$ up to 500 GeV
  - In $\tilde{g}$ mediated models, $m_{\tilde{g}}$ up to 2 TeV



Many more results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Additional material



*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit