Search for Supersymmetry at CMS

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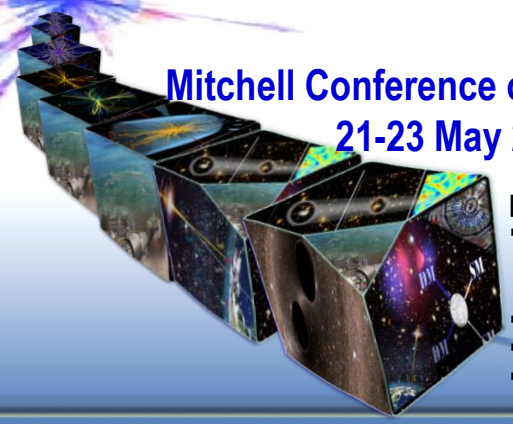
on behalf of the CMS Collaboration

Mitchell Institute for Fundamental Physics and Astronomy

Texas A&M University

Mitchell Conference on Collider Physics, Dark Mateer, Neutrino Physics

21-23 May 2018, College Station, TX (United States)

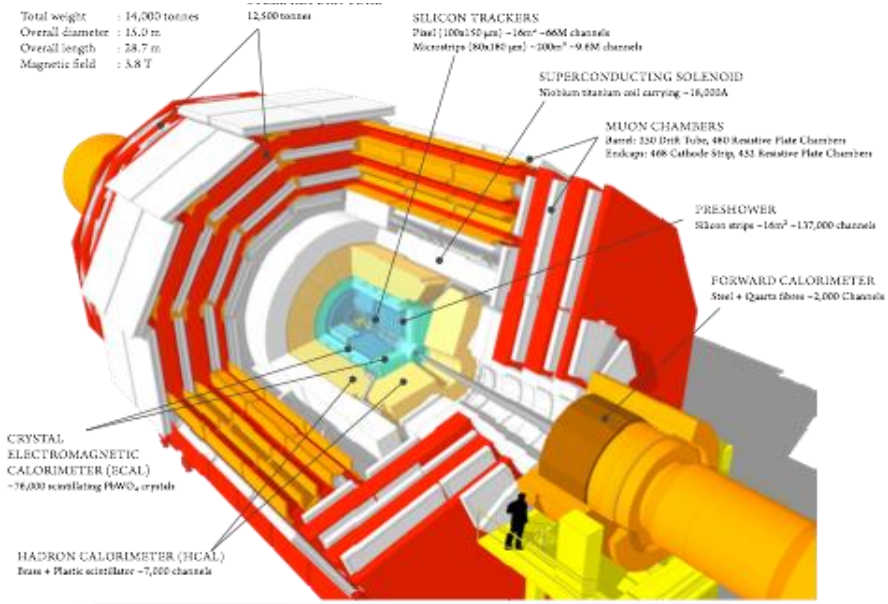


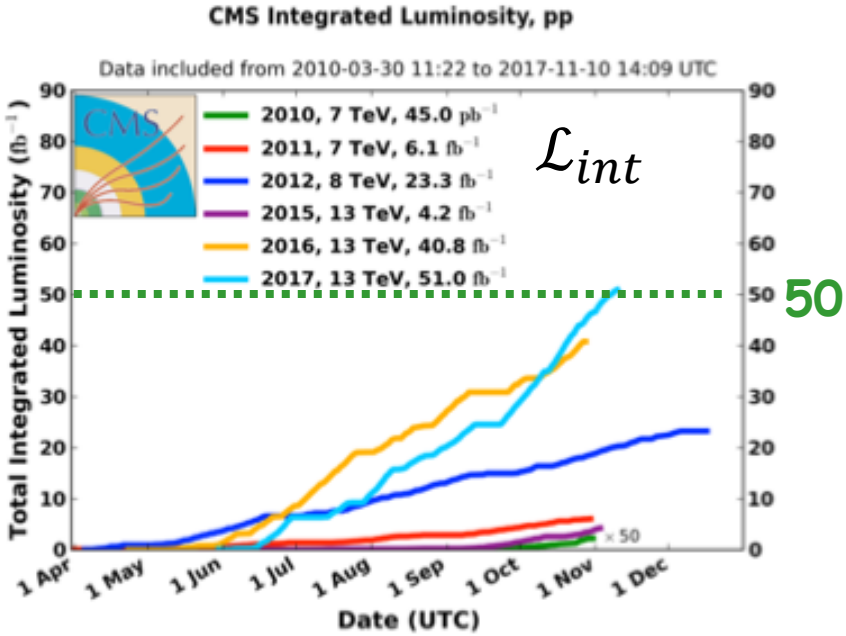
[Credits]

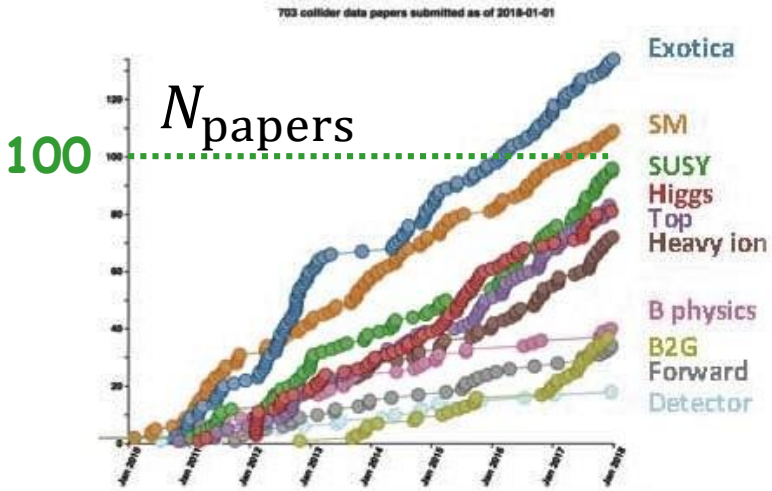
- Images of Baryon Acoustic Bscillations with Cosmic Microwave Background by E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian (Lawrence Berkeley National Laboratory)
- Image of Neutrino Astrophysics, taken from https://astro.desy.de/
- Image of the LHC by CERN Photo
- Image of Bullet Cluster by NASA/ Chandra X-ray Center

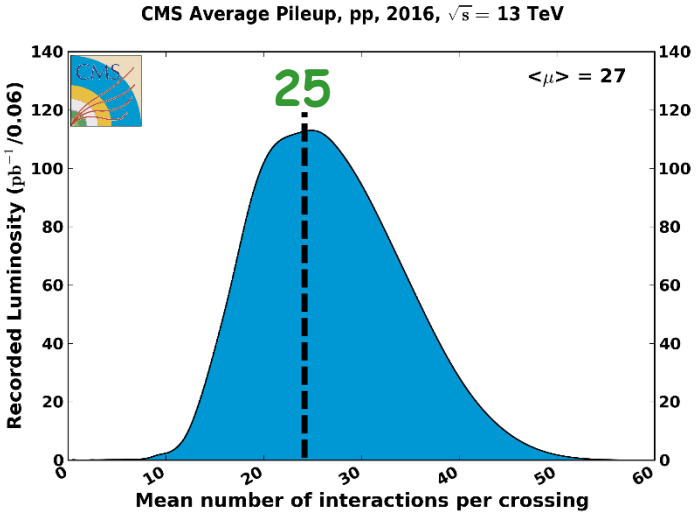
CMS Operation and Papers

Schematic view of the 12,500-ton CMS Detector with its main components.









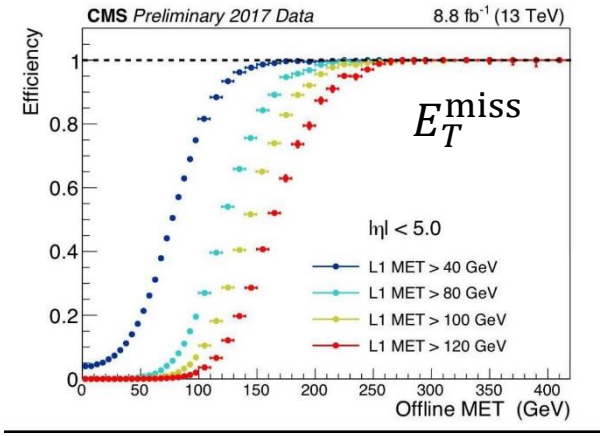
CMS Physics

links

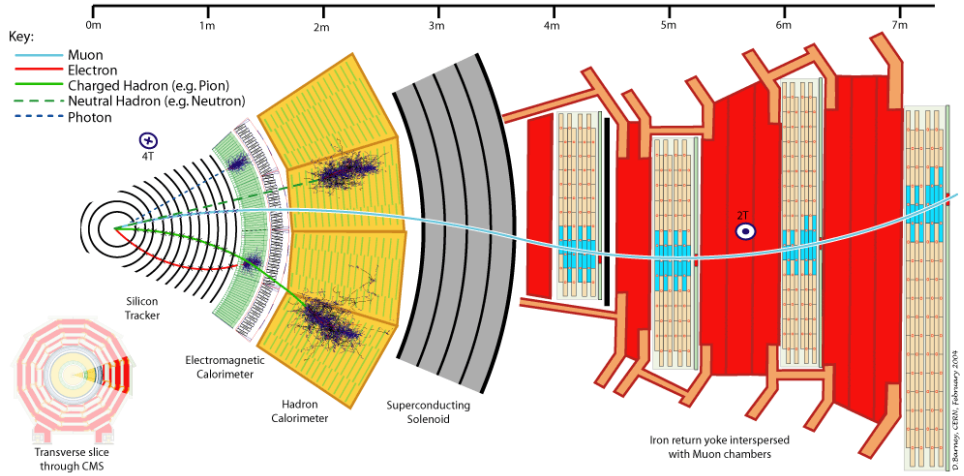
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

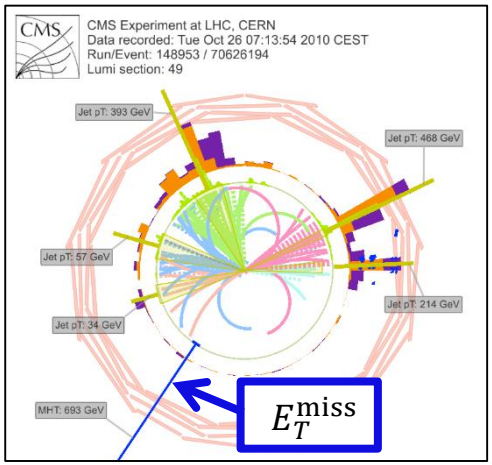
Triggers – JINST 12 (2017) P01020

1) Tagging energetic jets (+ MET) from cascade decays
2) Tagging leptons
3) Tagging photons
4) Tagging with timing
5) ISR jet(s), VBF dijet
6) …

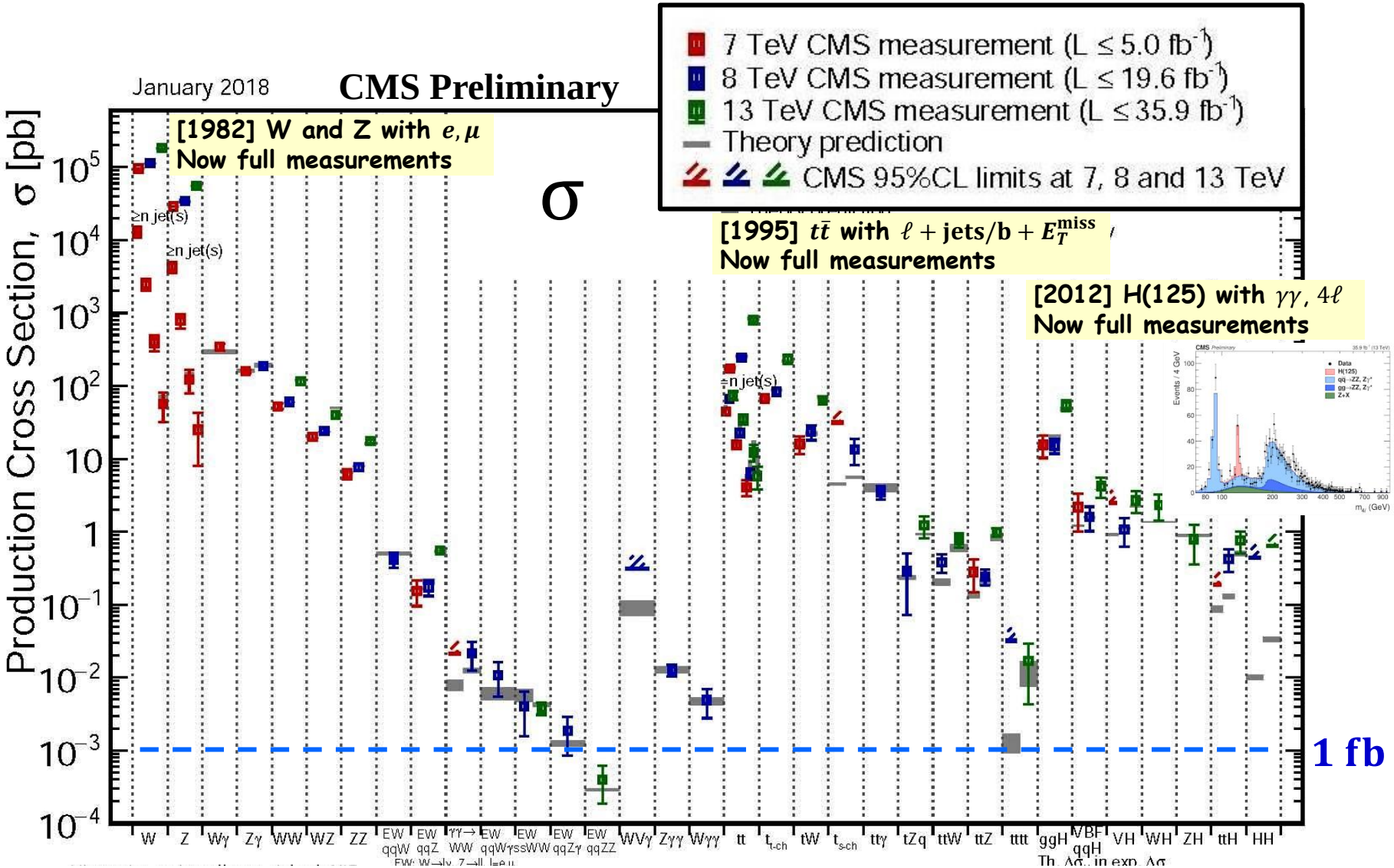


Particle IDs with Particle Flow – JINST 12 (2017) P10003





D4 = Digging Down, Down, and Down



This demonstrates the CMS detector is functioning well to test the SM.

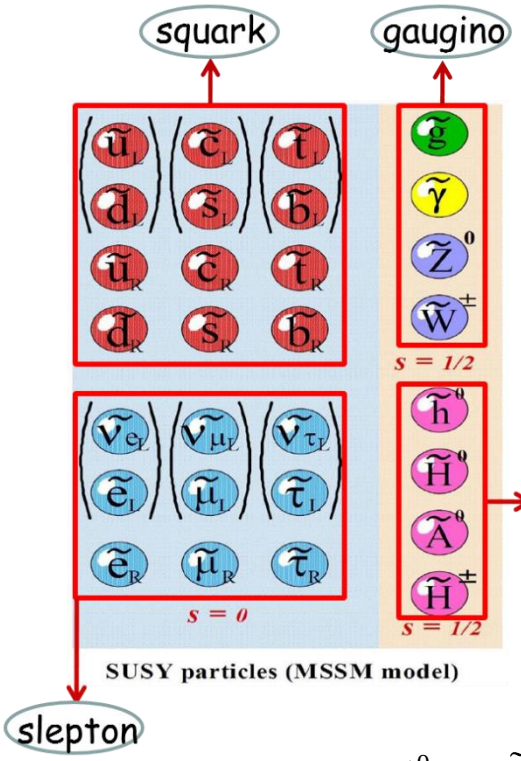
Deviation from the SM

The SM is successful in explaining a wide variety of physics, aside from two to three standard deviation effects, despite possessing "structural" defects.

SM

Supersymmetry (SUSY)

The SM is successful in explaining a wide variety of physics, aside from two to three standard deviation effects, despite possessing "structural" defects. So far, no sign of "Beyond the SM" (e.g., SUSY) in very diverse search programs. SUSY in splitting scenario? Compressed-mass spectra scenarios? We should continue studying various challenging final states.



Nature of colored and non-colored sectors?

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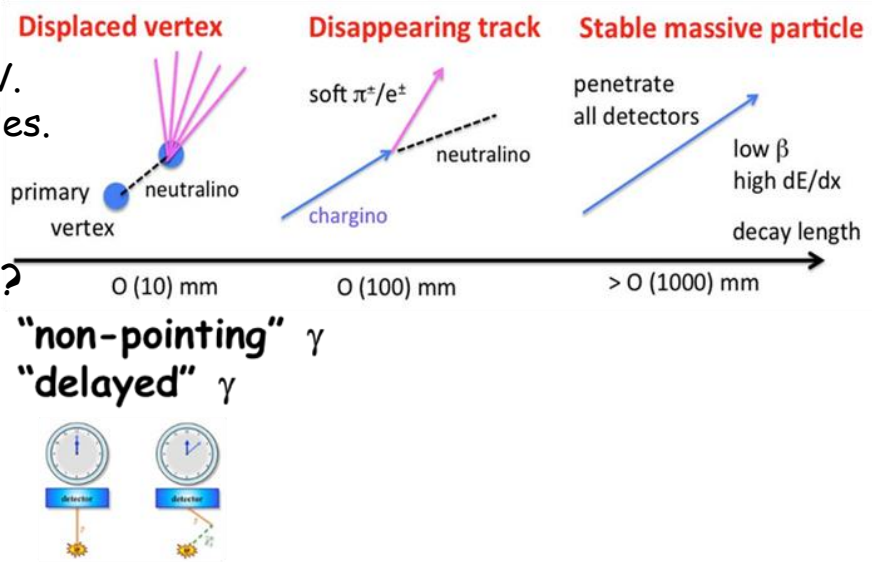
$\tilde{\chi}_1^0 \in (\tilde{B},\ \tilde{W},\ \tilde{H}_d,\ \tilde{H}_u)$ $\quad \tilde{\chi}_1^+ \in (\tilde{W}^+,\ \tilde{H}_u^+)$ $\quad \tilde{\chi}_1^- \in (\tilde{W}^-,\ \tilde{H}_d^-)$

"SUSY + Another Higgs" Menu

- MSSM Higgs (e.g., A $H^{\pm}$ and $H^{+}H^{-}$), Non-MSSM Higgs
- Colored Sectors
  - Gluinos
  - Heavier(?) 1st/2nd generation scalar quarks (squaks)
  - Lighter(?) 3rd generation squarks (stop, sbottom)
- Charginos (C1, C2), Neutralinos (N1, N2, N3, N4), decaying into:
  - Leptons, Higgs, W, Z
- LSP?
  - Lightest Neutralino (N1): Bino-like, Wino-like, Higgsino-like, Bino-Higgsino-like ..

  [Example] Higgsino LSP → chargino and neutralinos below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.
  - Gravitino
- Sleptons
  - Selectrons and smuons - mass degenerate?
  - Special case: Stau is lighter.
- Displaced Tracks
- Long-Lived (LL)
- RPV + ???

Compressed scenarios at hadron collides

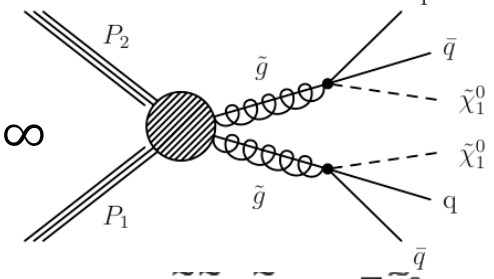


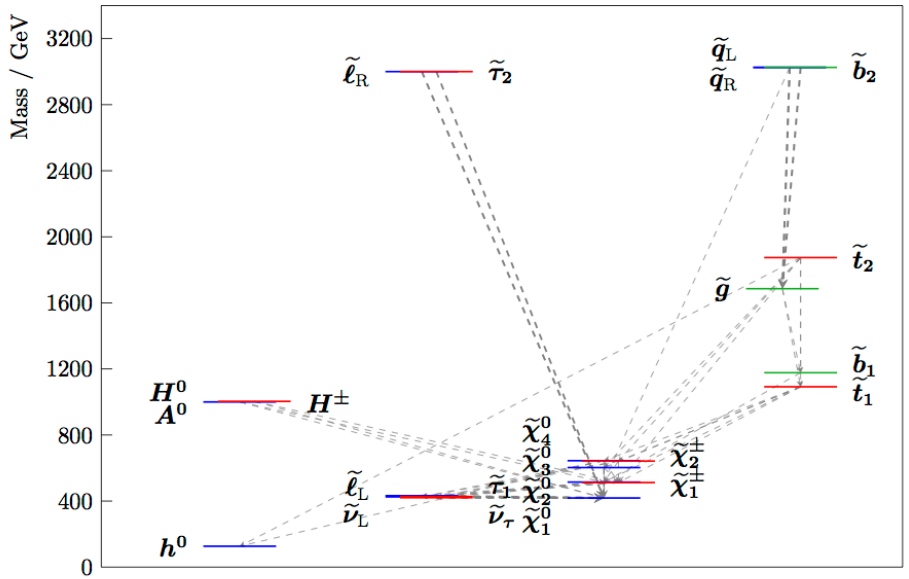
SUSY Exploration Map

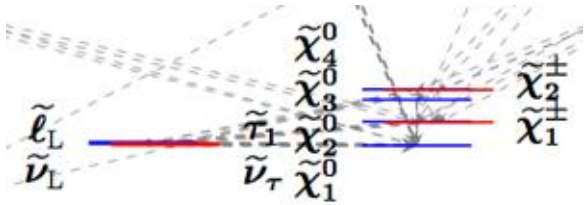
1) Selected CMS searches for SUSY in colored sectors ($\tilde{g}$, $\tilde{q}$) and non-colored sectors.
2) Summary & Remarks

$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_1^0$

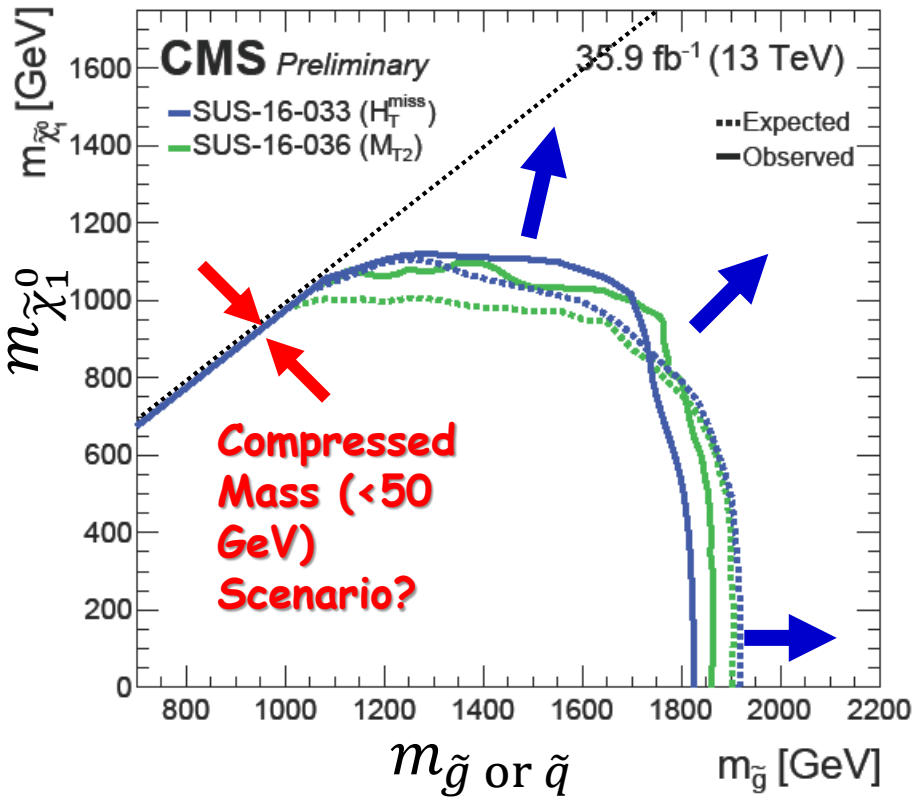
$m_{\tilde{q}} = \infty$





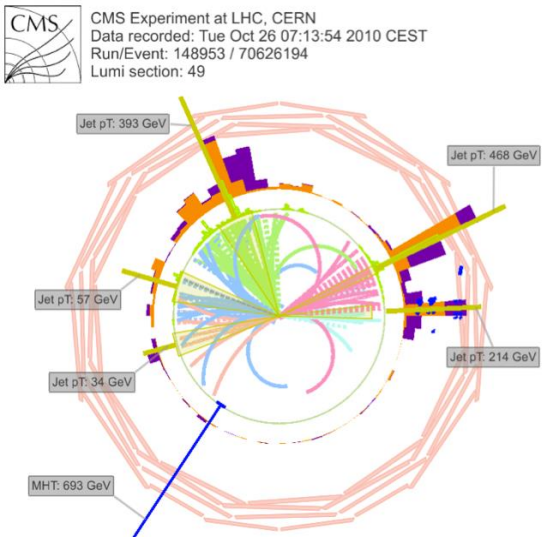


$pp \to \tilde{g}\tilde{g},\ \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$ *Moriond 2017*

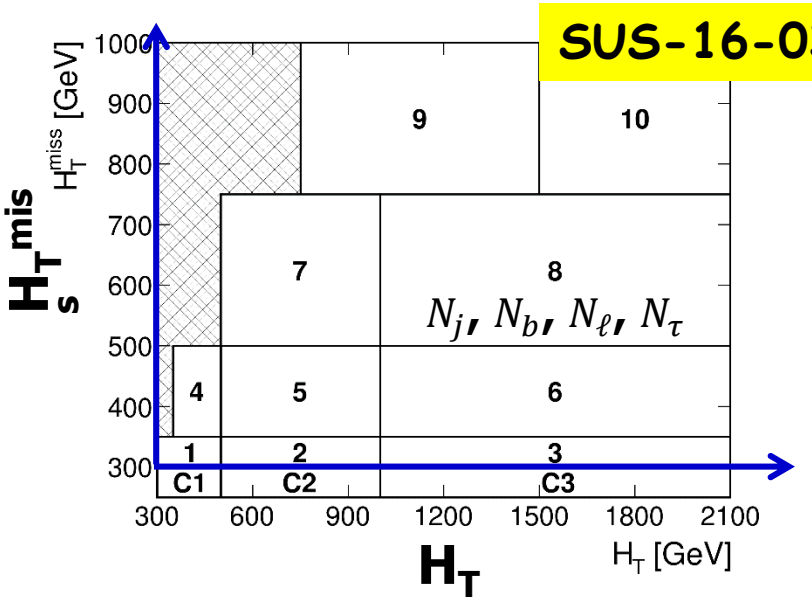


$\tilde{\chi}_1^0 \in (\tilde{B},\ \tilde{W},\ \tilde{H}_d,\ \tilde{H}_u)$ $\quad \tilde{\chi}_1^+ \in (\tilde{W}^+,\ \tilde{H}_u^+)$ $\quad \tilde{\chi}_1^- \in (\tilde{W}^-,\ \tilde{H}_d^-)$

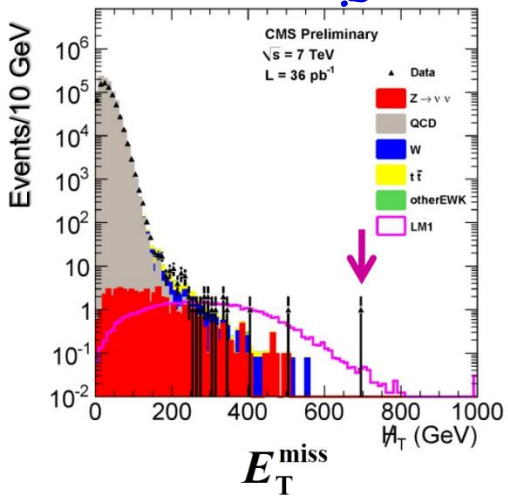
Multi-dimensional Search Regions

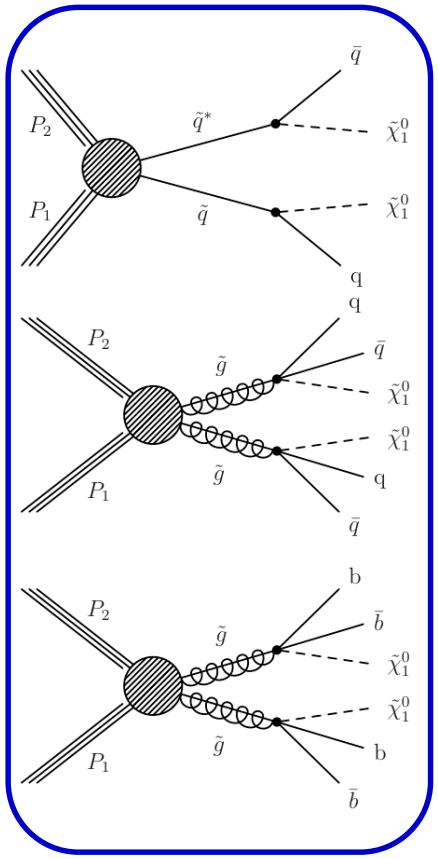


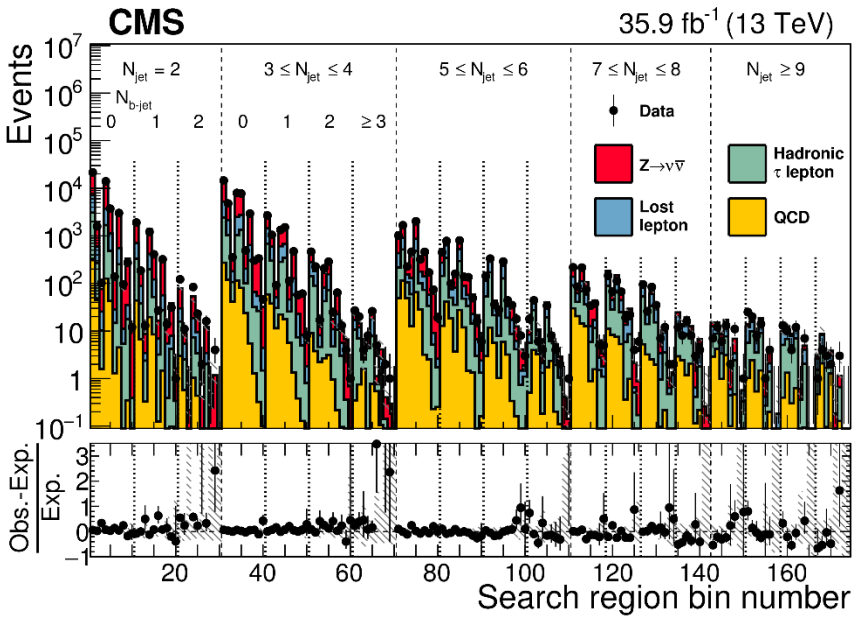
$H_T^{\text{miss}} > 300$ GeV
$H_T > 300$ GeV
$N_{jets} \geq 2$



Reversible?

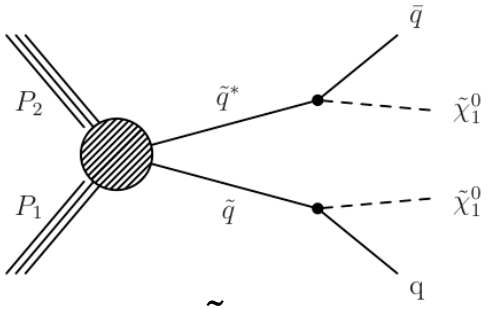




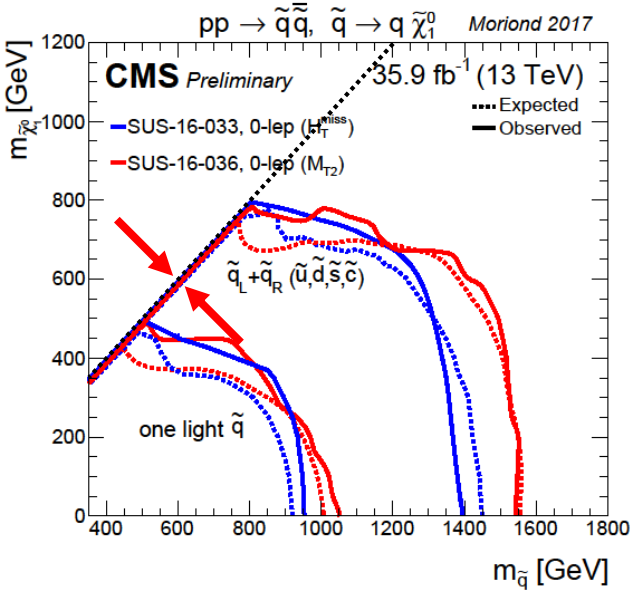


Squarks/Gluinos

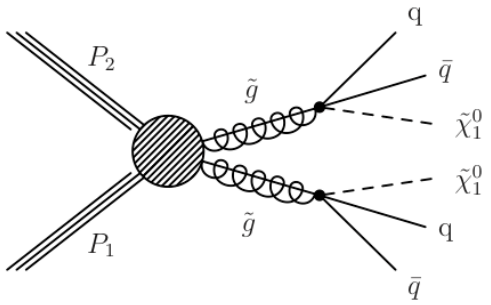
$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_1^0$



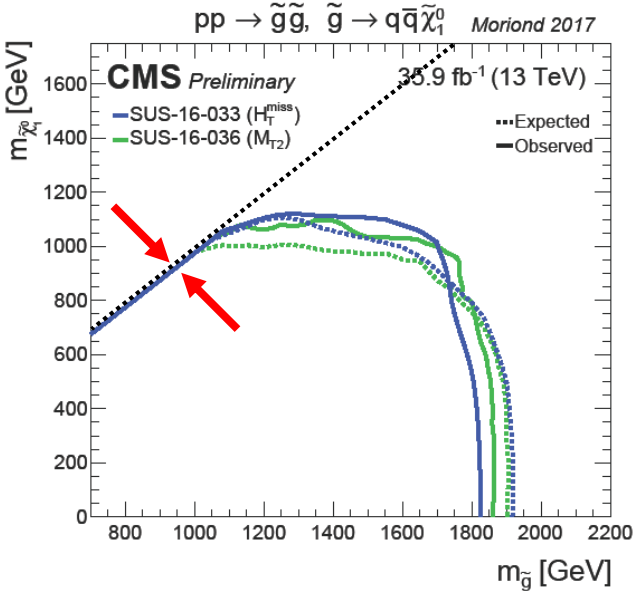
$\tilde{q} = \tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$



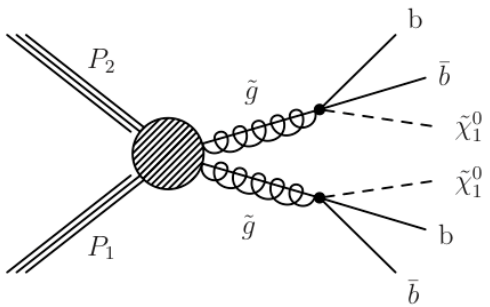
$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_1^0$



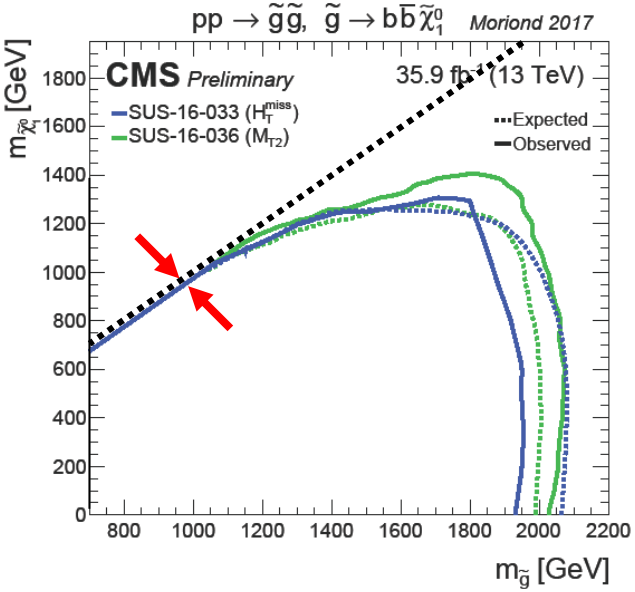
$m_{\tilde{q}} = \infty$



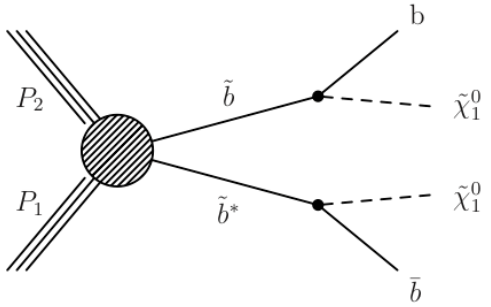
$\tilde{g} \to \bar{b}\tilde{b} \to \bar{b}b\tilde{\chi}_1^0$



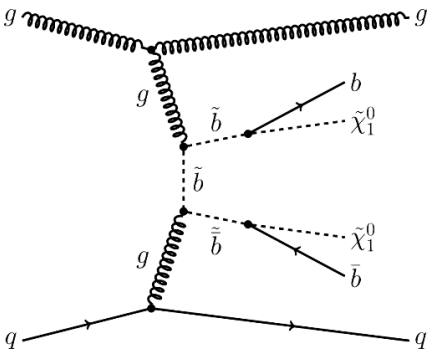
$m_{\tilde{b}} = \infty$



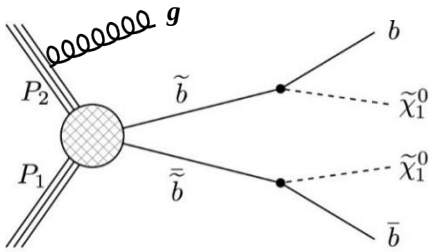
Bottom Squarks

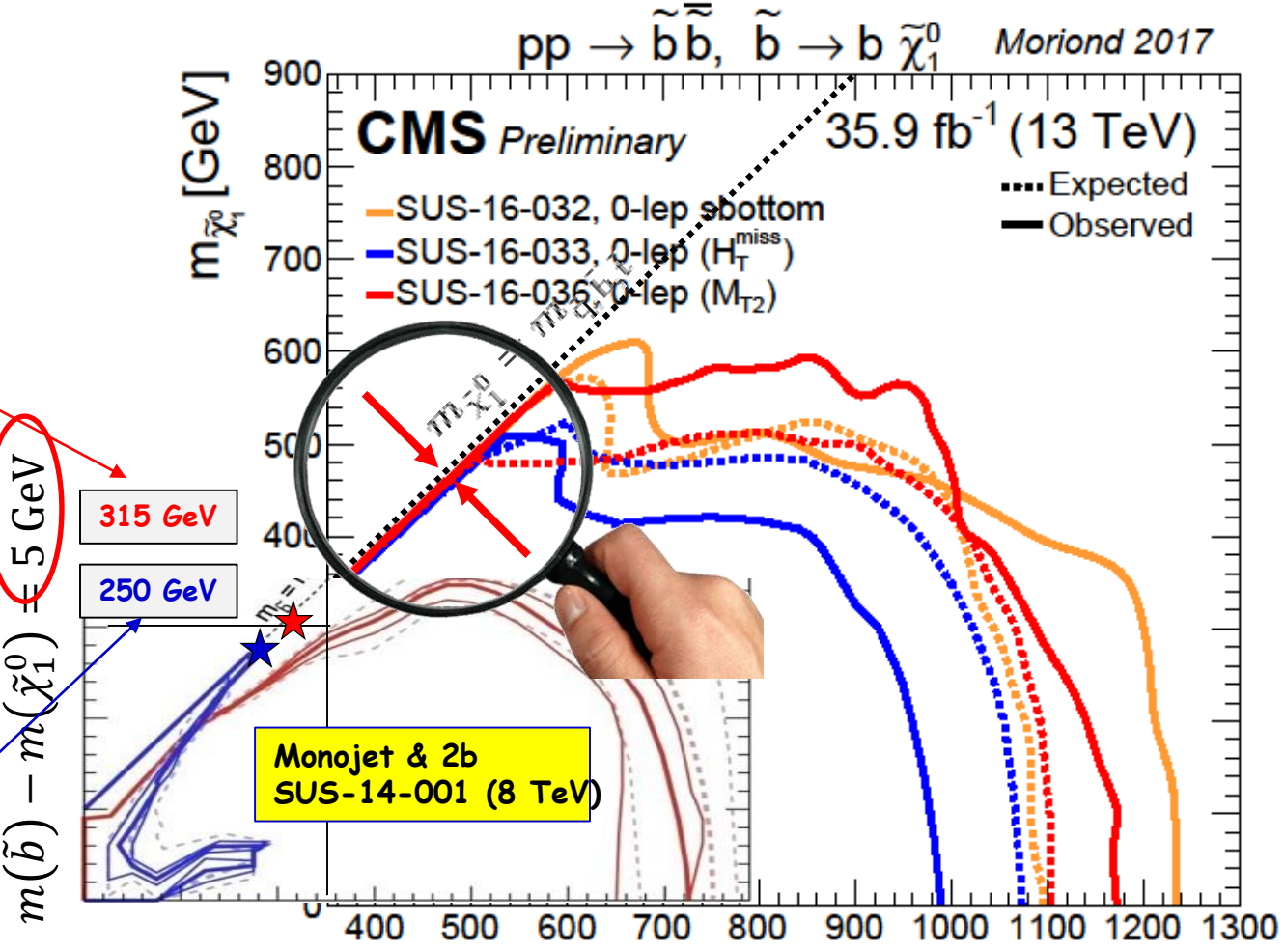


VBF: SUS-14-019



Monojet: SUS-14-001

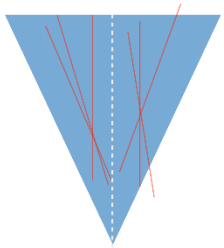


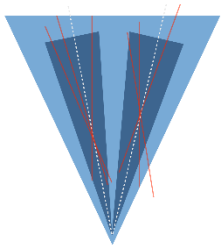


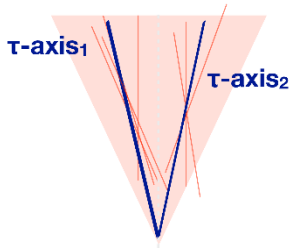
[Q] Do we still care of the extremely compressed mass (< 10 GeV) scenario?

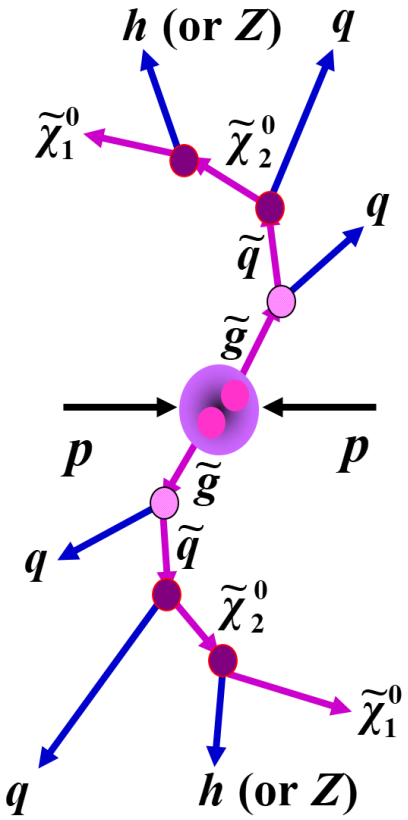
Gluino with H(→bb)

CMS-PAS-BTV-15-002



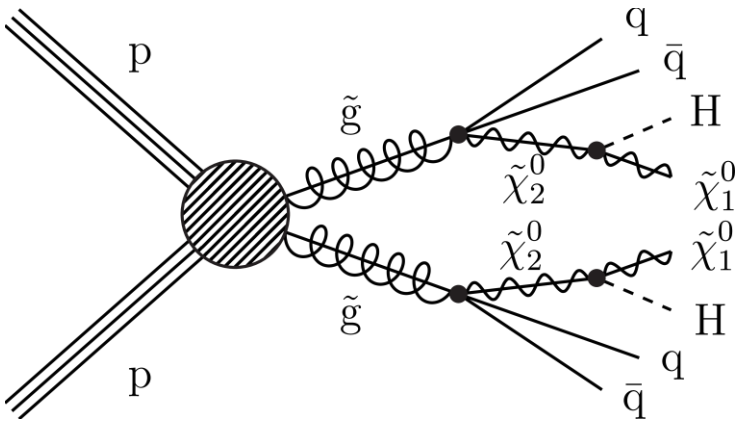






$$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0$$

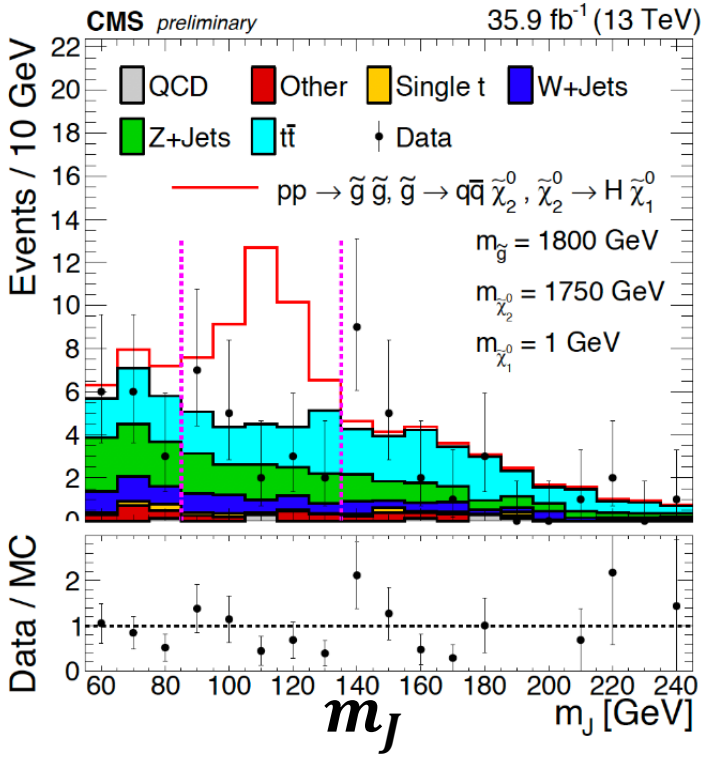
$$m_{\tilde{q}} = \infty$$



$$m_{\tilde{g}} - m_{\tilde{\chi}_2^0} = 50$$

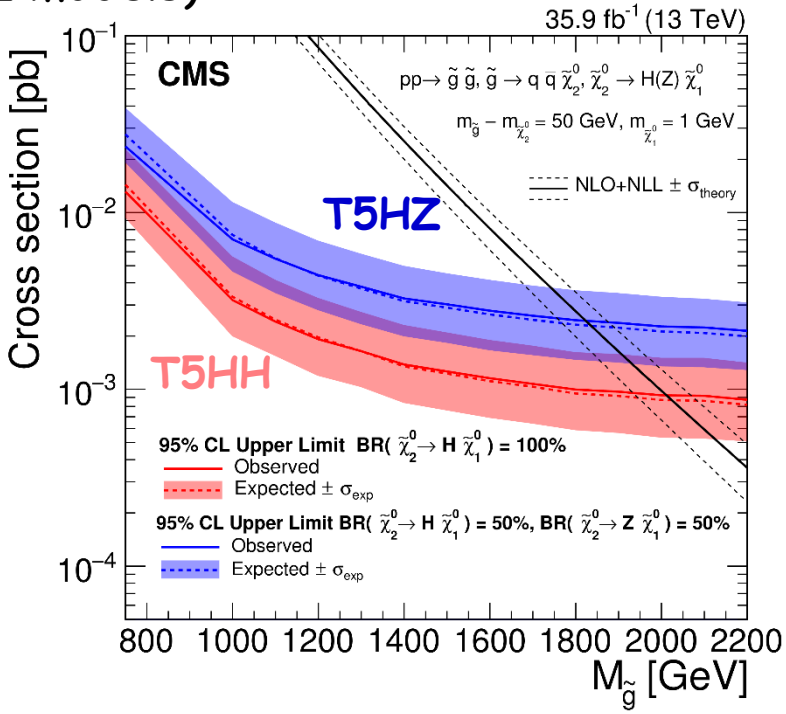
"Gluino with H(→bb)" Results

CMS-SUS-17-006; CERN-EP-2017-322



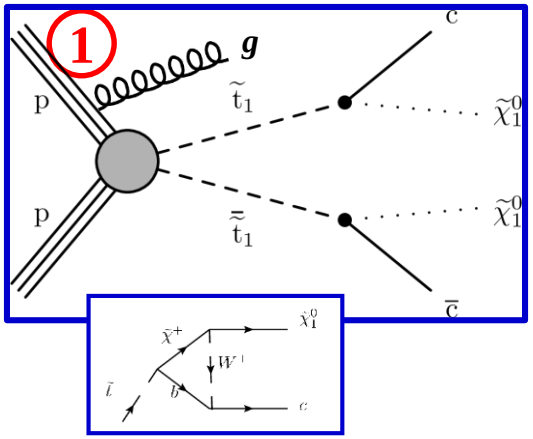
NH	p_T^{miss} (GeV)	κ	Predicted	Observed
1	300 – 500	0.98 ± 0.11	17.7 ± 3.8	15
1	500 – 700	0.86 ± 0.16	3.4 ± 1.5	2
1	>700	0.86 ± 0.17	0.61 ± 0.45	1
2	300 – 500	0.73 ± 0.14	1.52 ± 0.57	1
2	500 – 700	0.43 ± 0.12	0.09 ± 0.08	0
2	>700	0.62 ± 0.30	$0.09^{+0.11}_{-0.09}$	0

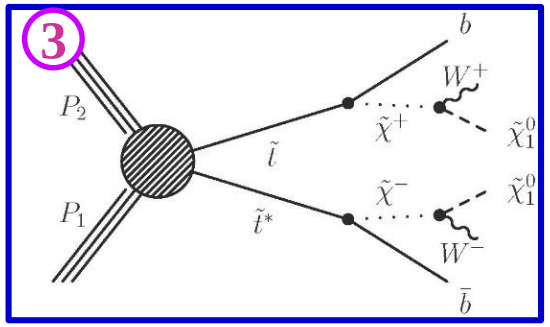
- $\tilde{\chi}_2^0 \to H\tilde{\chi}_1^0$ or $Z\tilde{\chi}_1^0$ in heavy gluino ($\tilde{g}$) decay … high p_T $H \to bb$ decay with small opening angle
- Event with p_T^{miss} > 300 GeV; Use large cone (AK8) jets to capture full Higgs decay (presence of two displaced subjets).
- Jet mass shows clear peaking structure
- Search for 2H and 1H events (T5HH and T5HZ models)

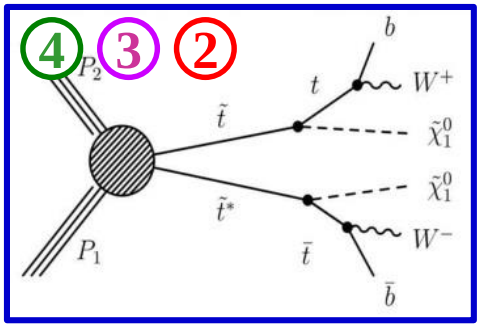


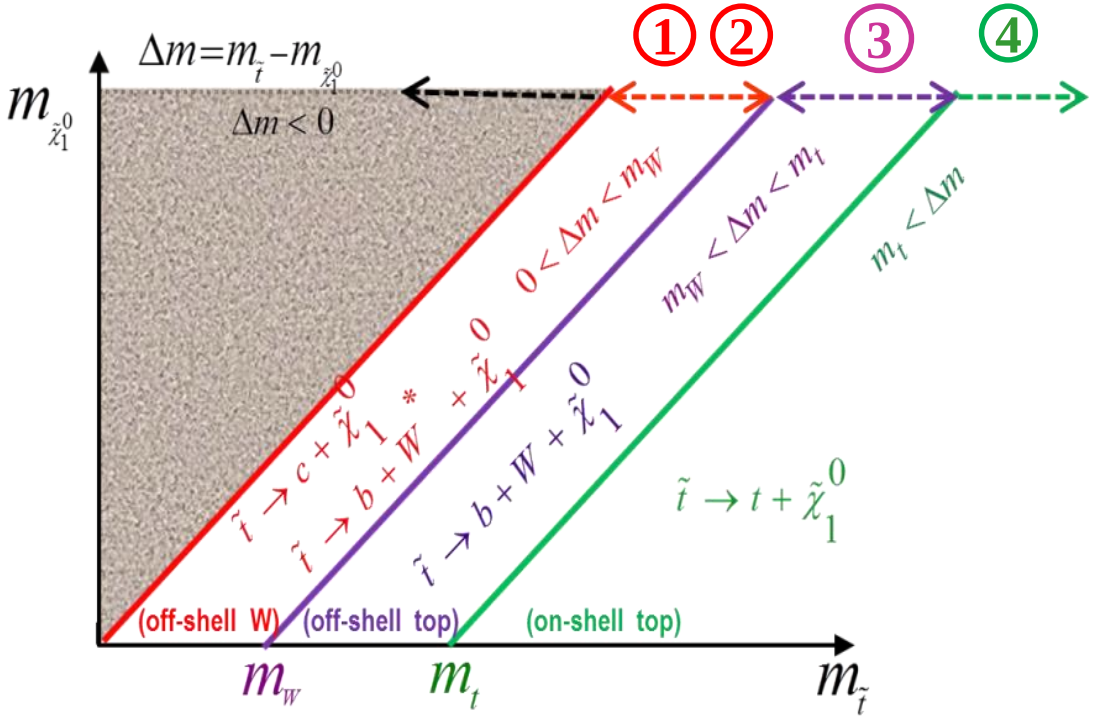
Top Squarks

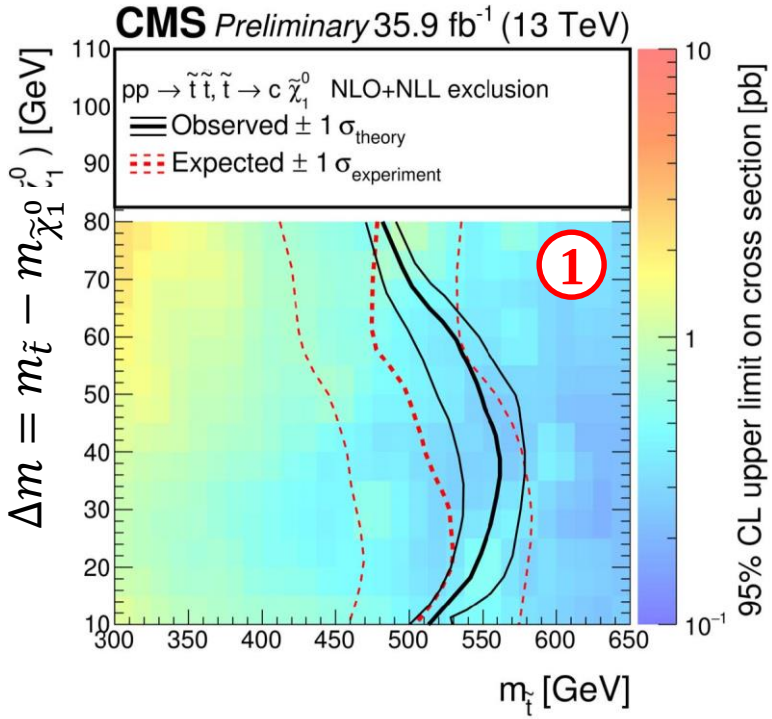
Stop decay ← Stop mixing & neutralino/chargino composition & $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$





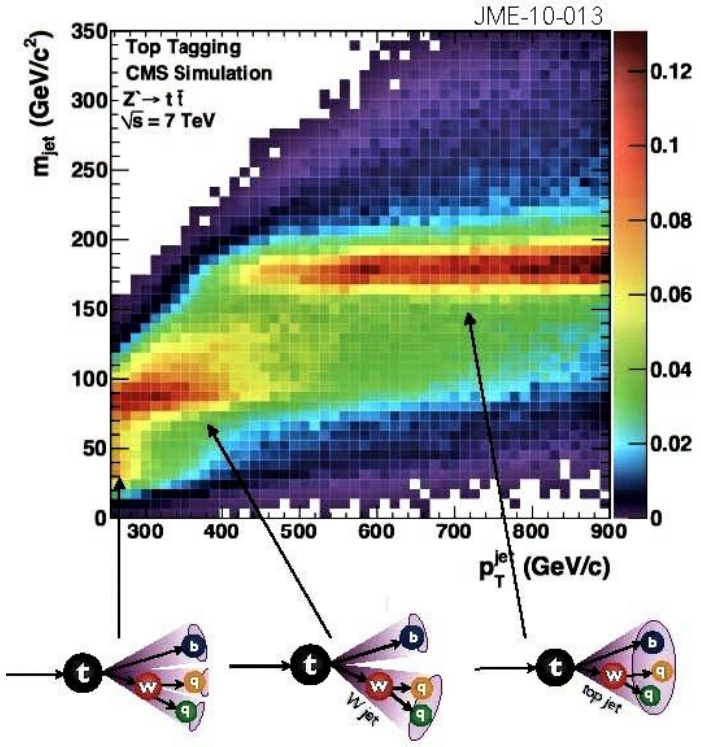






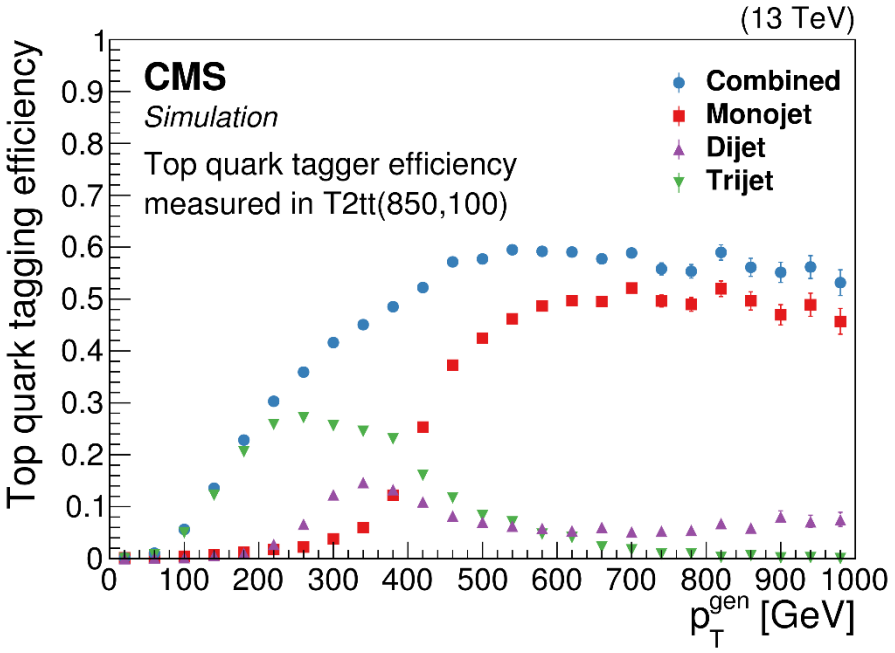
"Tops"

CMS-SUS-16-050; CERN-EP-2017-257



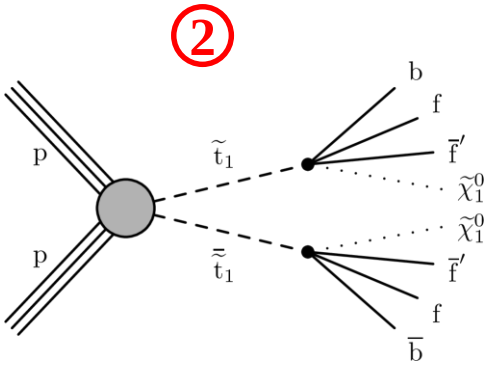
Region	N_t	N_b	m_{T2} [GeV]	p_T^{miss} [GeV]	Motivation
1	≥1	≥1	≥200	≥250	Events satisfying selection criteria
2	≥2	≥2	≥200	≥250	Events with $N_t \geq 2$ and $N_b \geq 2$
3	≥3	≥1	≥200	≥250	Events with $N_t \geq 3$ and $N_b \geq 1$
4	≥3	≥3	≥200	≥250	T5tttt; small $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ and $m_{\tilde{\chi}_1^0} < m_t$
5	≥2	≥1	≥200	≥400	T2tt; small $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$
6	≥1	≥2	≥600	≥400	T2tt; large $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$
Region	N_t	N_b	H_T [GeV]	p_T^{miss} [GeV]	Motivation
7	≥1	≥2	≥1400	≥500	T1tttbb & T5ttcc; large $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
8	≥2	≥3	≥600	≥350	T1tttt; small $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
9	≥2	≥3	≥300	≥500	T1/T5tttt & T1tttbb; intermediate $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$
10	≥2	≥3	≥1300	≥500	T1/T5tttt; large $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$

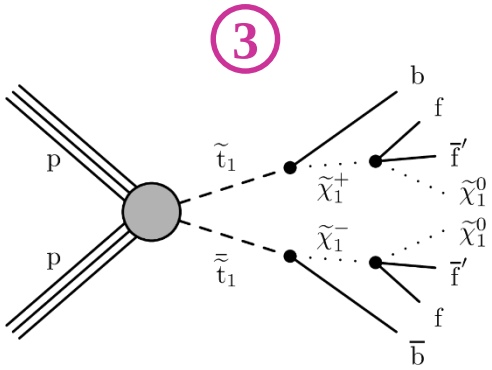
- Top (t) quarks in top squarks ($\tilde{t}$) or gluinos ($\tilde{g}$) decay … high p_T t decay with small opening angle
- Event with p_T^{miss} > 250 GeV and H_T > 300 GeV; Use AK8 jets to capture full top decay (3 subjets); two or three AK4 jets
- Search for $\geq 1t$ and $\geq 1b$ events



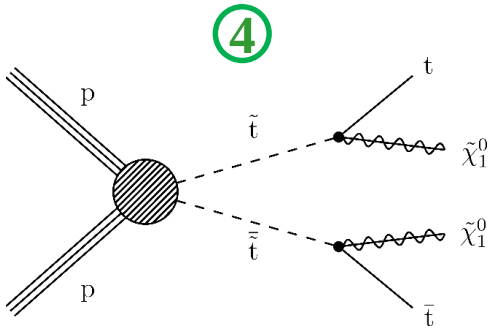
Top Sqaurk Results

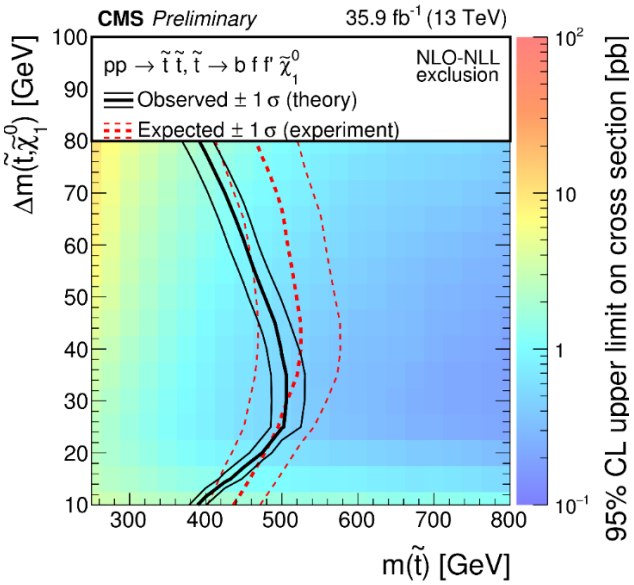
CMS-PAS-SUS-16-052

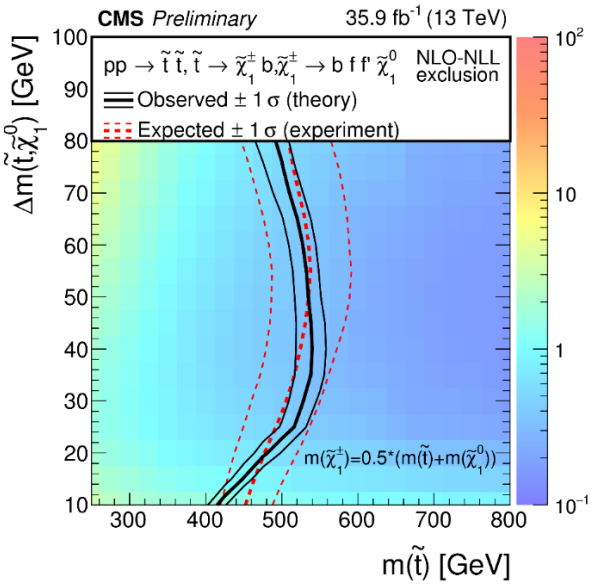


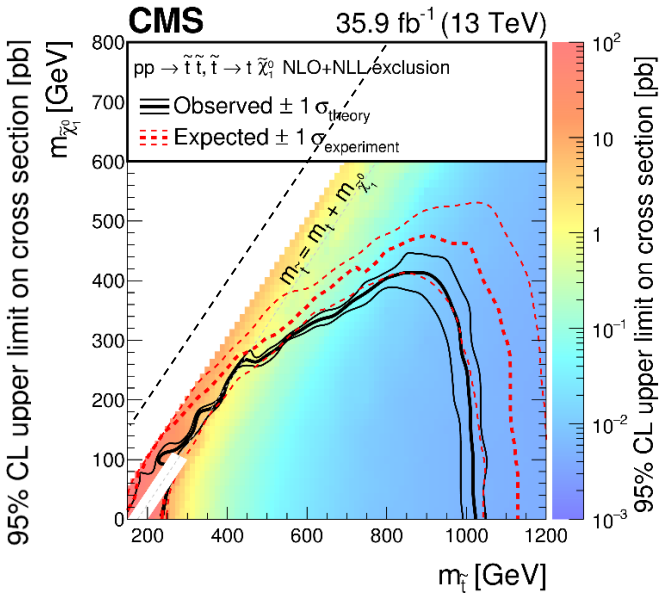


CMS-SUS-16-050;
CERN-EP-2017-257



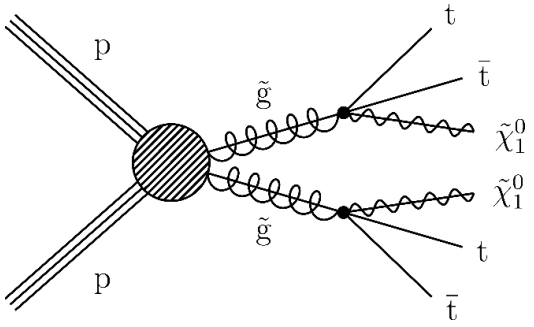


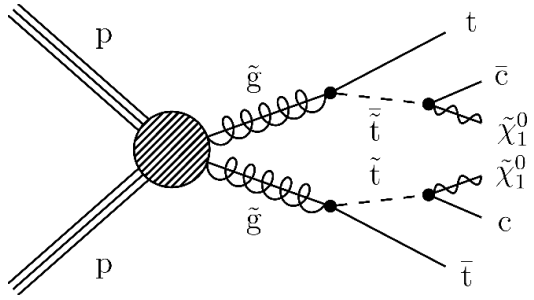


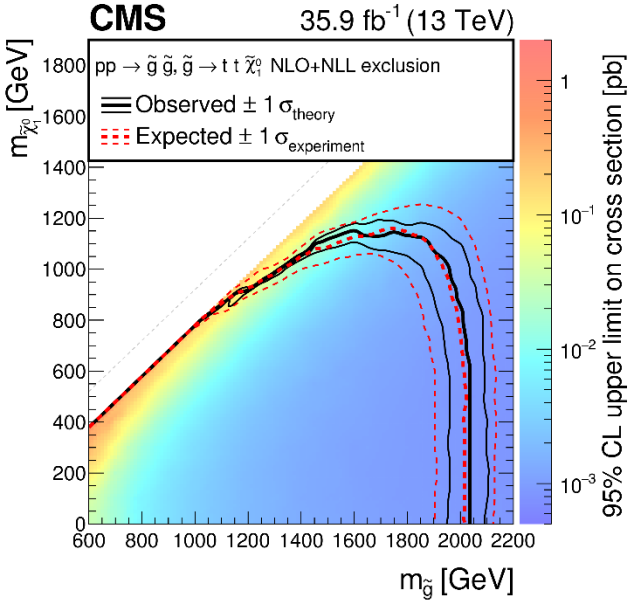


"Gluino with Tops" Results

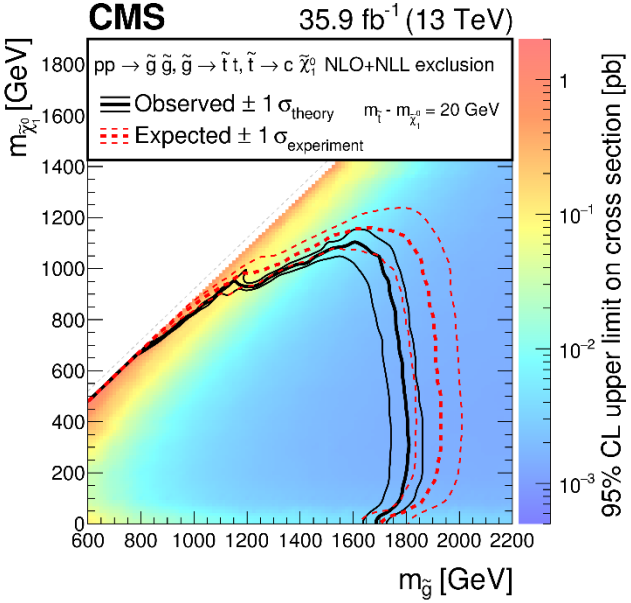
CMS-SUS-16-050; CERN-EP-2017-257







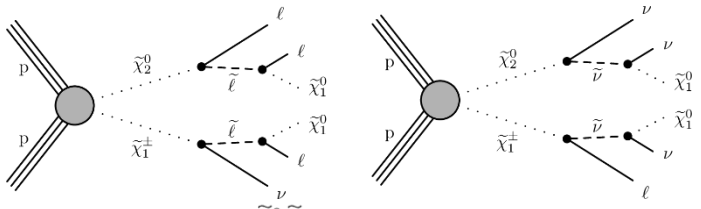
$m_{\tilde{t}} = \infty$

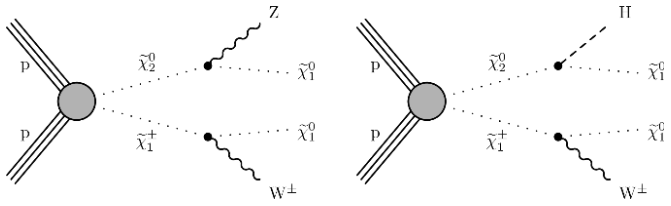


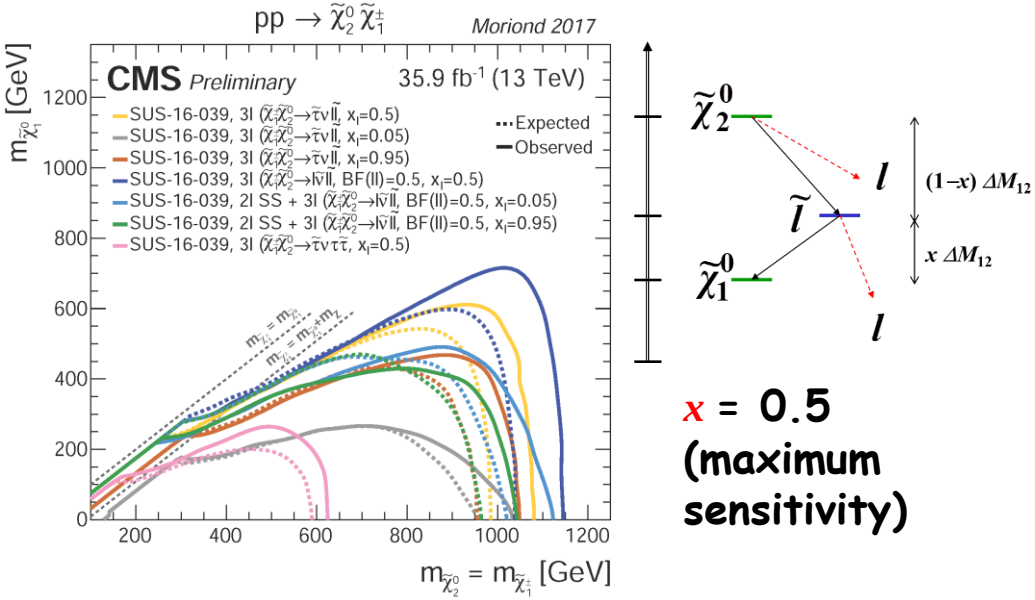
$\mathrm{m}(\tilde{t})$-$\mathrm{m}(\tilde{\chi}_1^0)$=20 GeV

Chargino-Neutralino

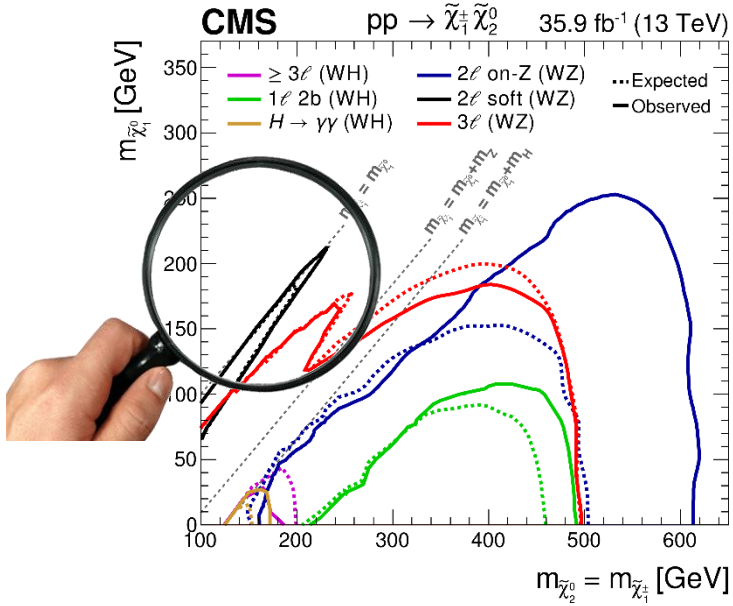
Limits on $\sigma(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0)$ with decays via (a) sleptons or (b) W/Z/H







x = 0.5 (maximum sensitivity)

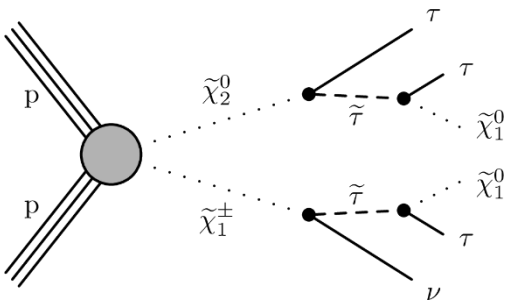


- ❖ Wino-Chargino and Bino-LSP
  - ✓ Up to ~1150 and ~700 GeV for light slepton case;
  - ✓ Up to 450 and 150 GeV for W and Z cases
- ❖ Weaker limits for
  - ✓ Heavy slepton; being Higgsinos; small mass difference (compressed mass spectra)

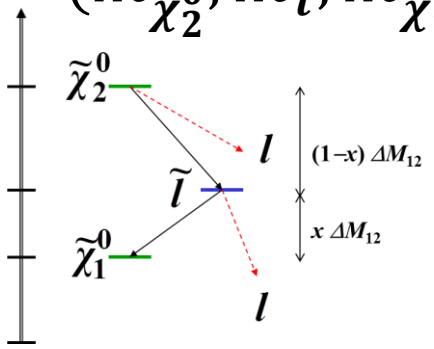
Dimuon (3 GeV) + MET (50 GeV) trigger (offline: p_T > 5 GeV and MET > 125 GeV) → Soft OS dilepton in compressed mass spectra (ΔM < 20 GeV).

Chargino-Neutralino with Taus

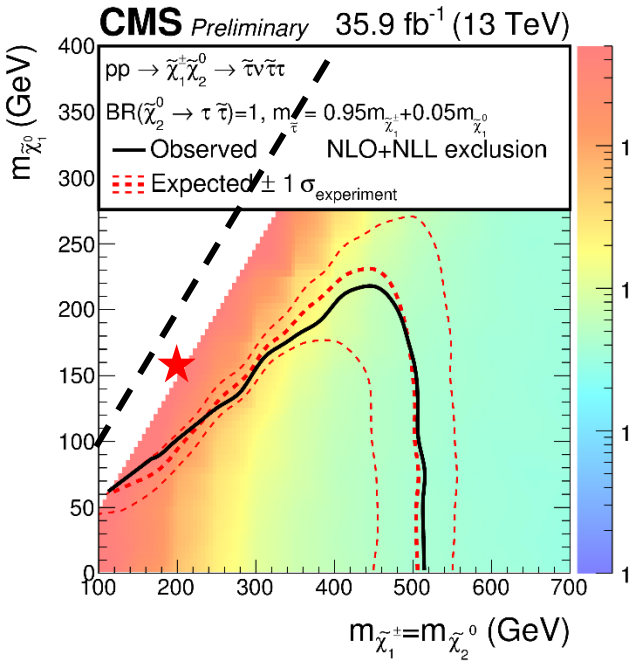
CMS-PAS-SUS-17-002

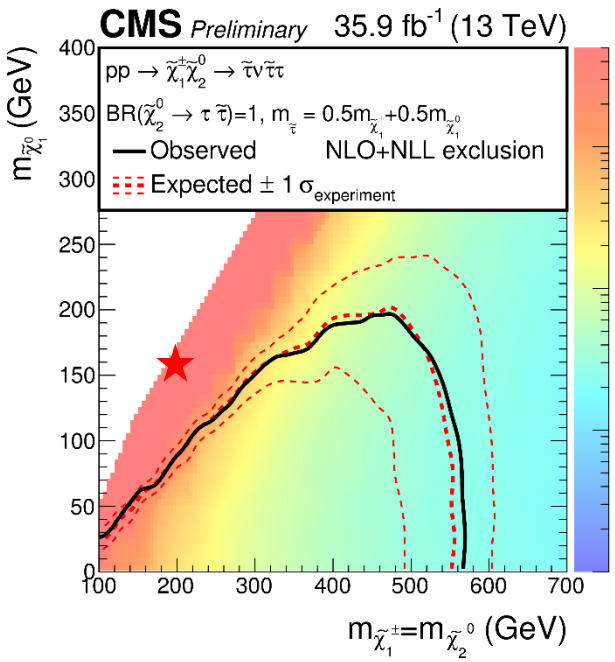


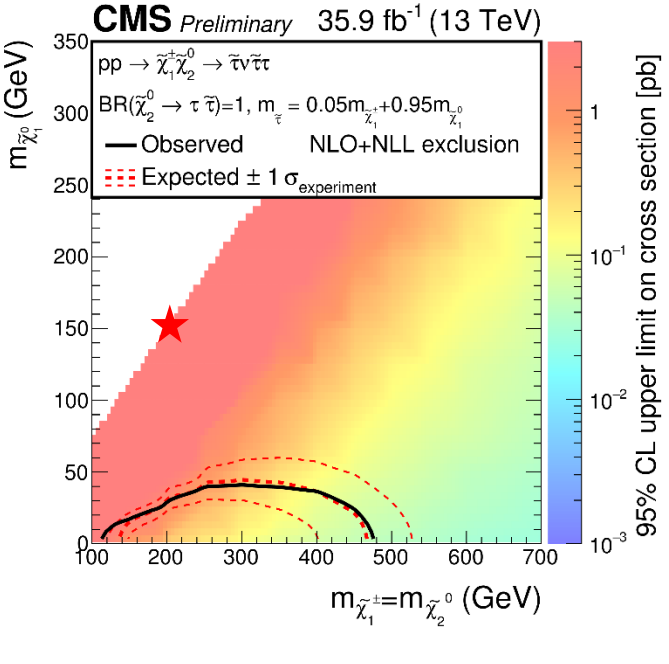
$(m_{\tilde{\chi}_2^0}, m_{\tilde{\tau}}, m_{\tilde{\chi}_1^0})$



- $\tau_h + \ell$ or $e + \mu$
- Event with $\Delta\phi(\tau\tau)$, ΣM_T, and/or p_T^{miss}
- Search for OS 2τ





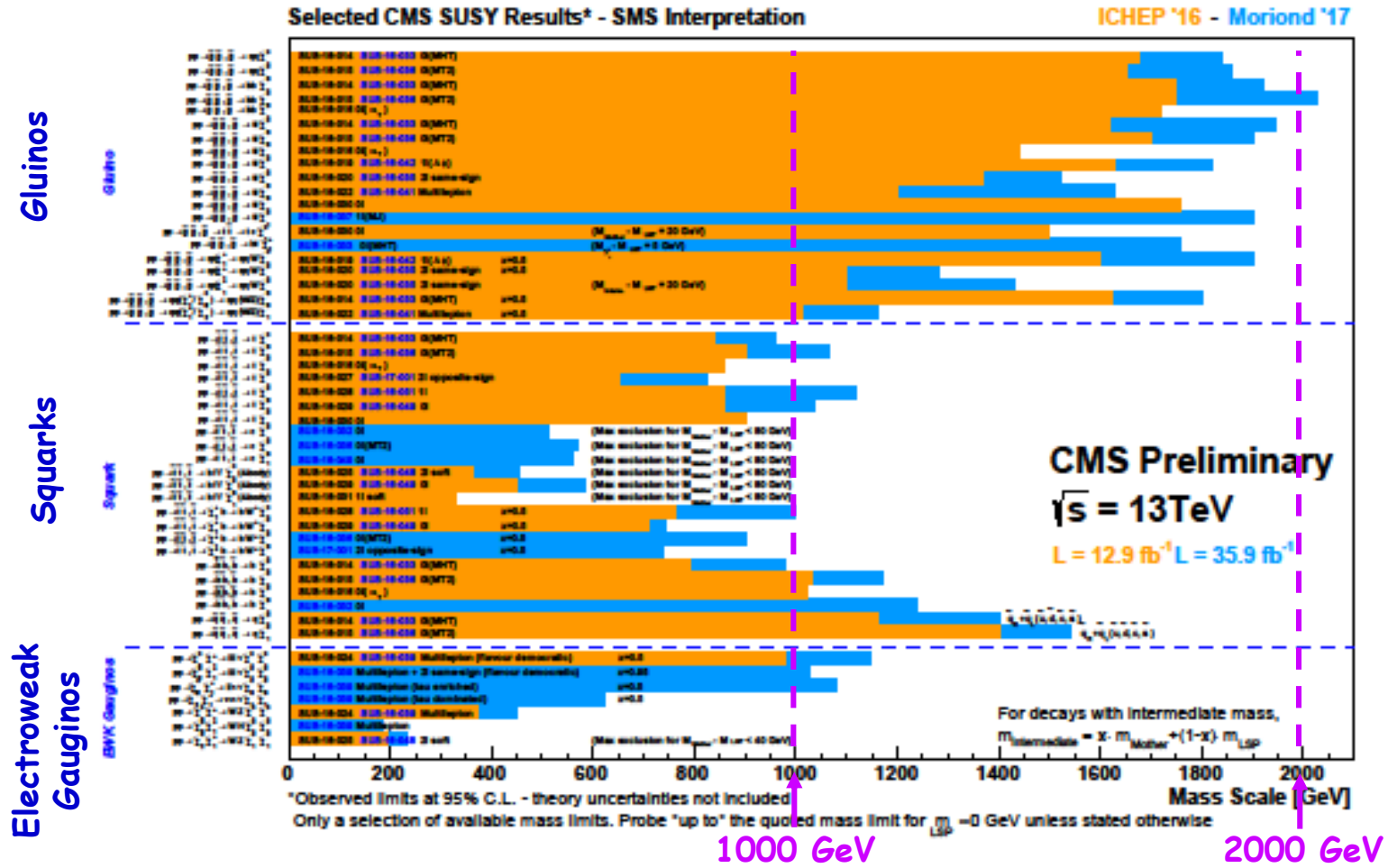


x = 0.95 (200, 197,5, 150) x = 0.50 (200, 175, 150) x = 0.05 (200, 152,5, 150)

Can we access to the compressed mass scenarios (★)?

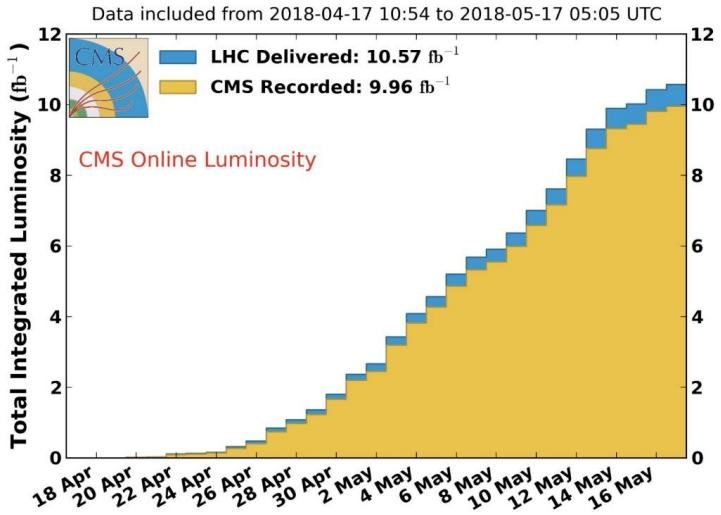
Summary of Run2 in 2016-17

- Covering a large variety of possible final states even with <PU> ~25
- Setting stringent limits on many SUSY scenarios including compressed mass SUSY. See the public result pages: http://cms-results.web.cern.ch/cms-results/public-results/publications/



Remarks on Run2 and Beyond

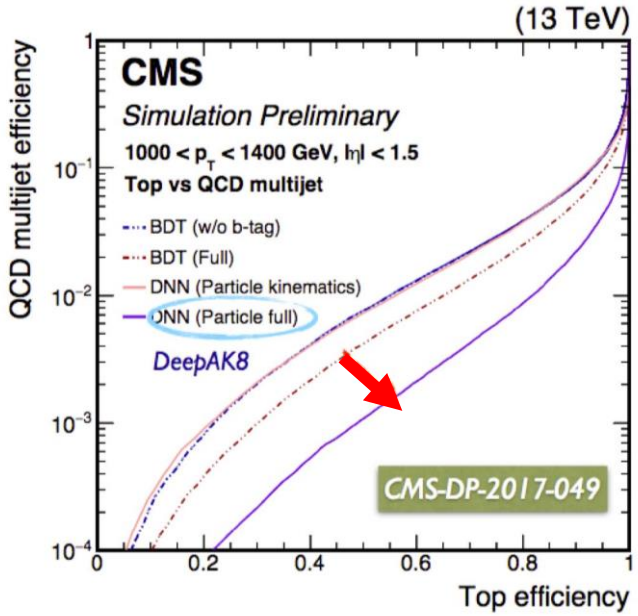
- Good LHC duty cycle in 2018; Fills with $2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$; CMS: $\sim 10\ \mathrm{fb}^{-1}$;



Hadron Collider ($\sqrt{s}$)	$\tilde{g}/\tilde{q}$ Mass Reach (M)	$M/\sqrt{s}$
Tevatron (2 TeV)	~400 GeV	0.20
LHC (8 TeV)	~1.7 TeV	0.21
LHC (14 TeV)	~2.8 TeV*	0.20*
FCC (100 TeV)	~20 TeV*	0.20*

(*) just use a naïve scaling

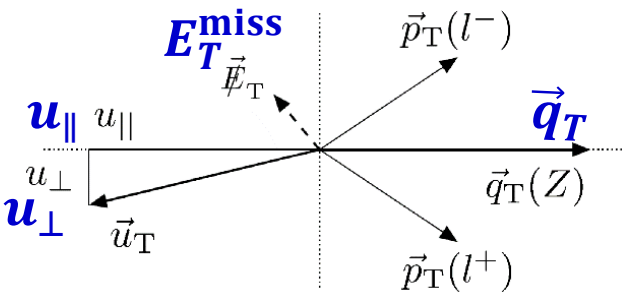
- Various improvements and optimizations:
  - Dedicated heavy object tagging by utilizing Deep Learning
    - DeepAK8: tagger for boosted t/W
    - DeepResolved: tagger for resolved top with 3-jet combination
  - Dedicated triggers for compressed-mass spectra scenarios



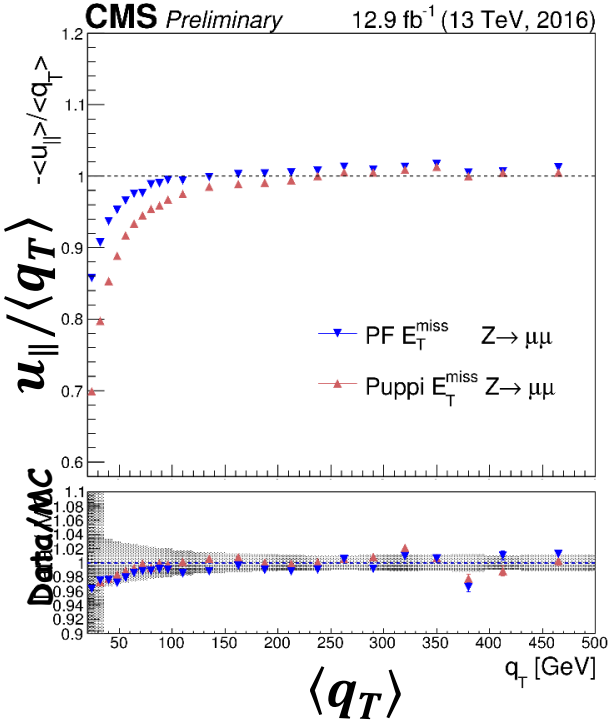
Appendix


CMS
Compact Muon Solenoid
LHC, CERN
Visit us: CMS Public Website, CMS Physics ; Contact us: CMS Publications Committee

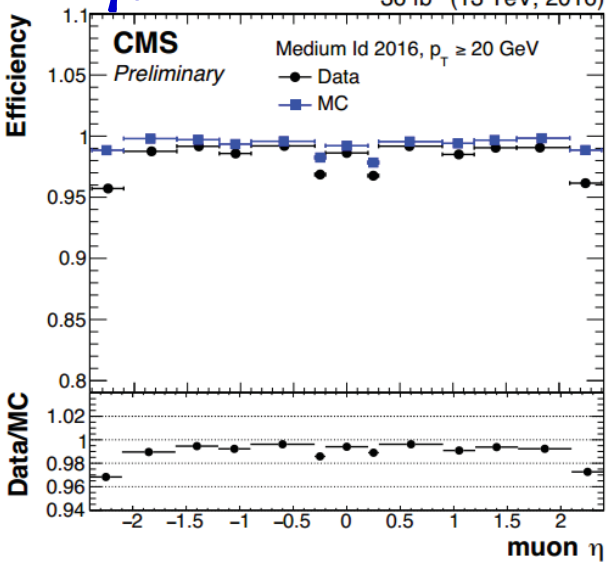
Challenges with High Luminosity (= PU)



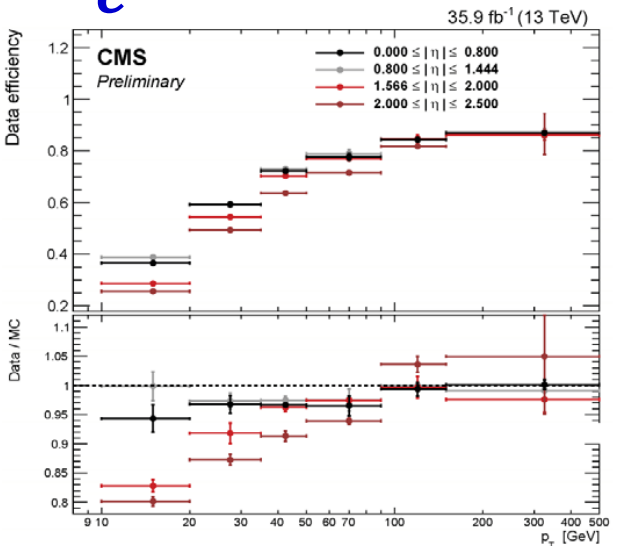
CMS-PAS-JME-16-004



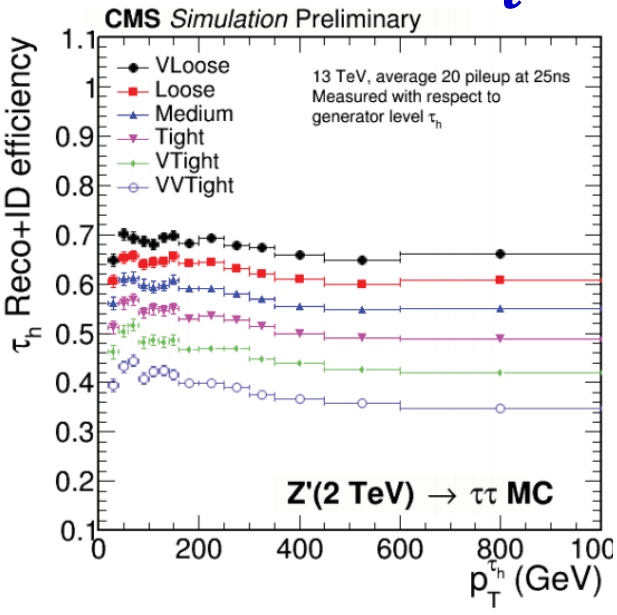
μ



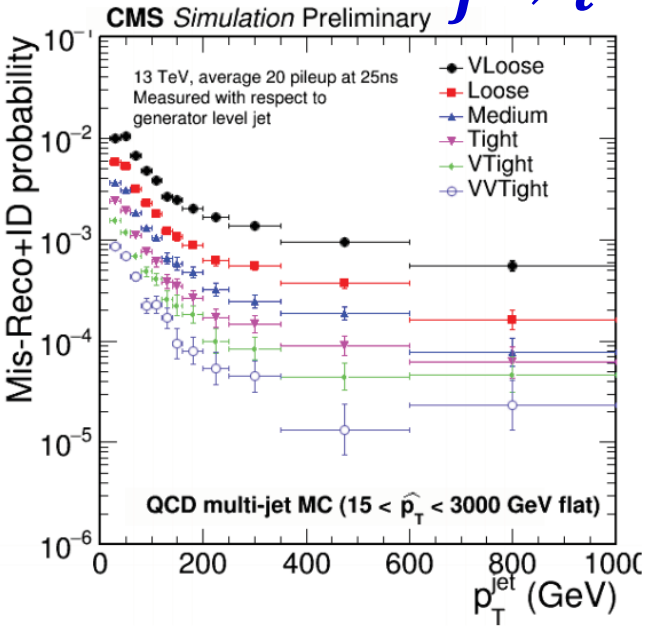
e



τ

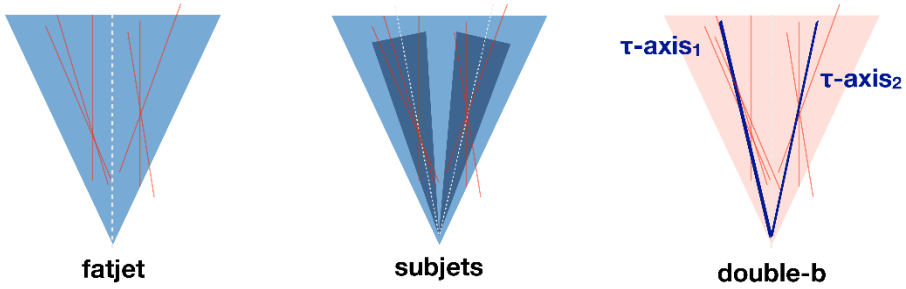


$j \rightarrow \tau$

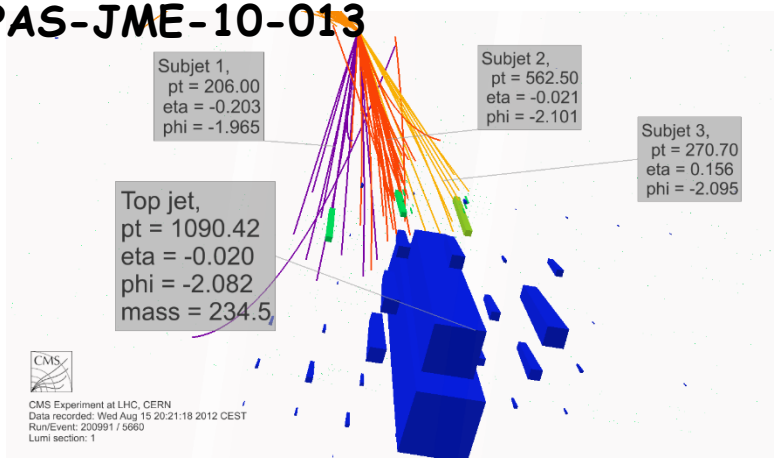


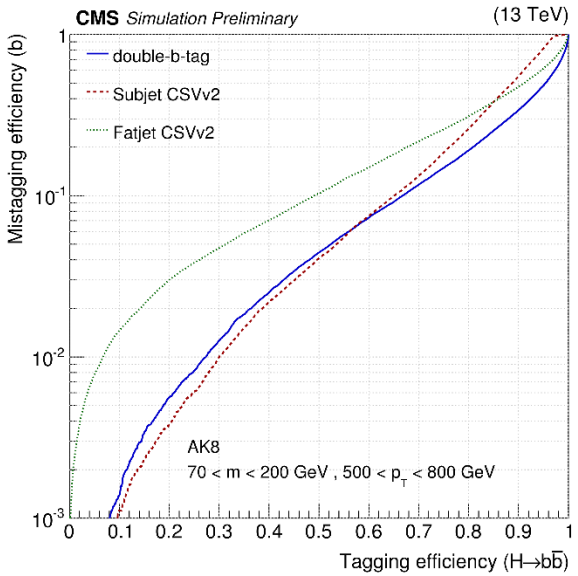
Tagging Boosted Objects

CMS-PAS-BTV-15-002

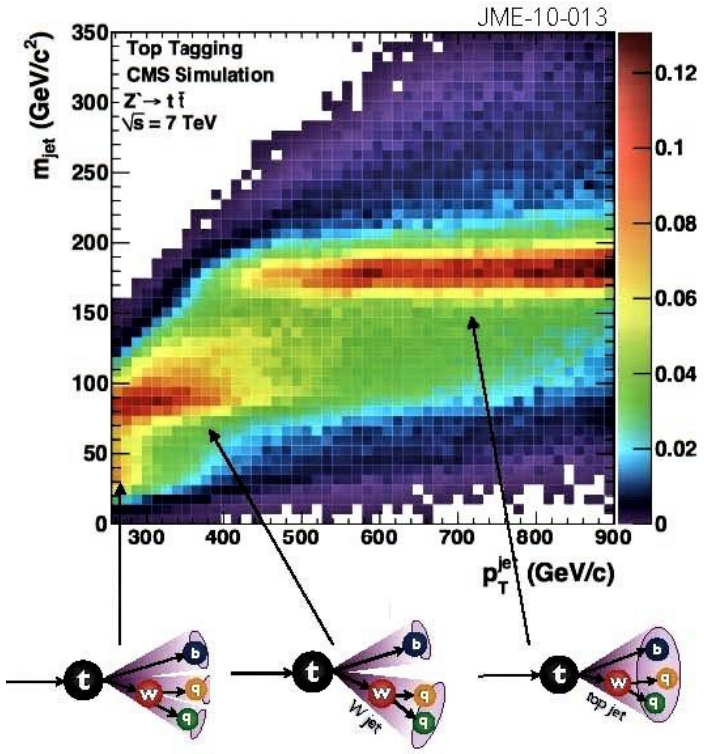


CMS-PAS-JME-10-013



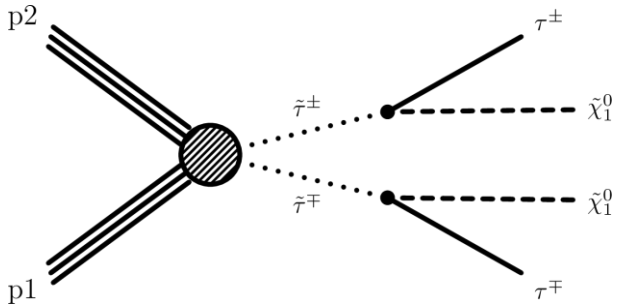


$$\Delta R \sim \frac{2m_{particle}}{p_T}$$

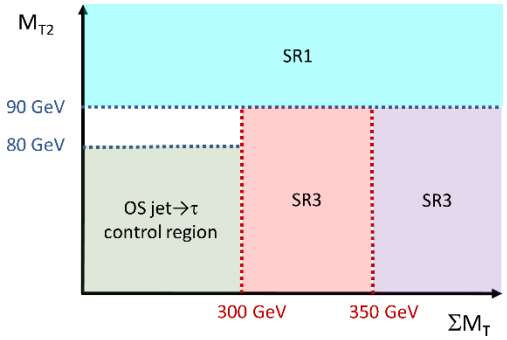


Appendix: Tau Spelton Pair with Taus

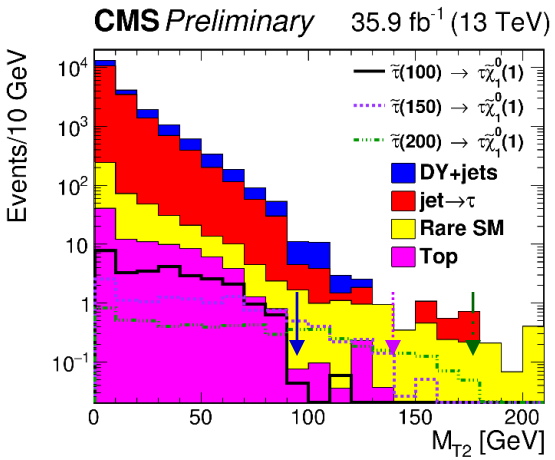
CMS-PAS-SUS-17-003

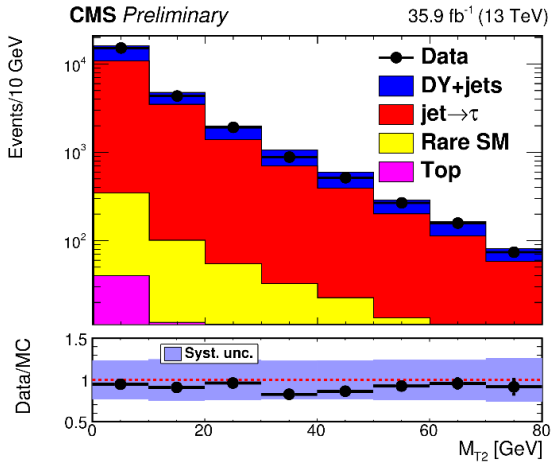


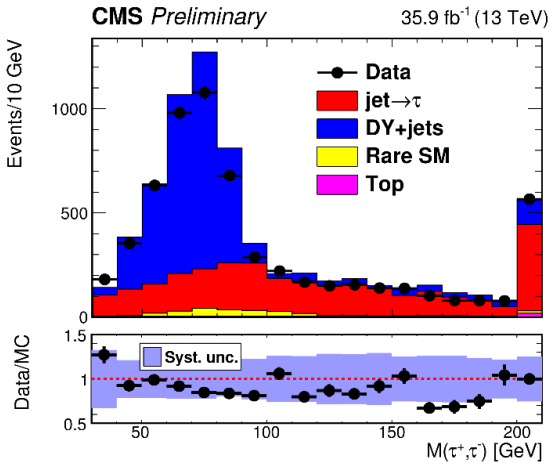
- **Hadronically decayoing tau (τ_h) leptons in tau slepton ($\tilde{\tau}$) decay**
- **Event with M_{T2}, $\Delta\phi(\tau\tau)$, ΣM_T, and/or p_T^{miss}**
- **Search for OS 2τ**



	SR1	SR2	SR3
Non-prompt and misidentified taus	$0.68^{+0.90}_{-0.68}$	2.49 ± 1.83	<1.24
Drell-Yan background	$0.80^{+0.97}_{-0.80}$	< 0.71	< 0.71
Top-quark related background	$0.02^{+0.03}_{-0.02}$	0.73 ± 0.31	1.76 ± 0.68
Rare SM processes	0.72 ± 0.38	0.20 ± 0.15	$0.20 \pm ^{+0.25}_{-0.20}$
Total background	$\mathbf{2.22}^{+1.37}_{-1.12}$	$\mathbf{4.35}^{+1.75}_{-1.53}$	$\mathbf{3.70}^{+1.52}_{-1.08}$
Left (150,1)	1.25 ± 0.40	2.91 ± 0.59	1.53 ± 0.33
Right (150,1)	1.09 ± 0.26	1.27 ± 0.20	0.74 ± 0.17
Mixed (150,1)	1.04 ± 0.22	1.39 ± 0.27	0.92 ± 0.15
Observed	**0**	**5**	**2**



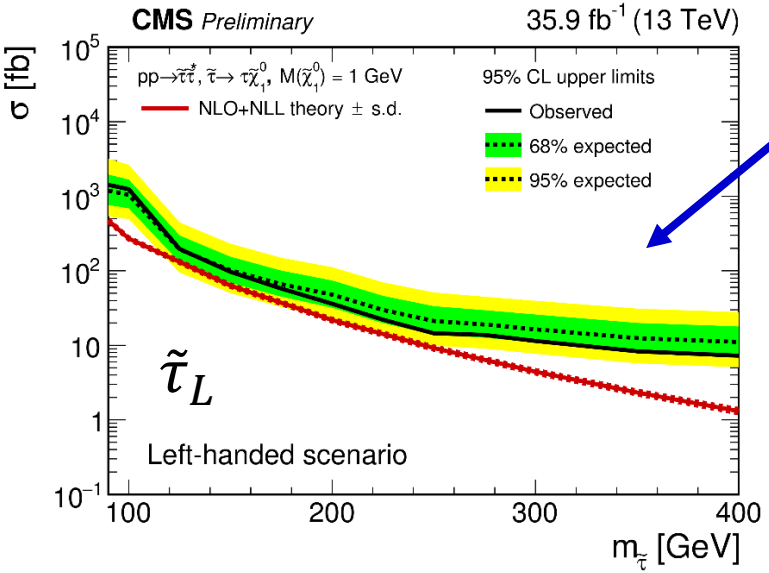




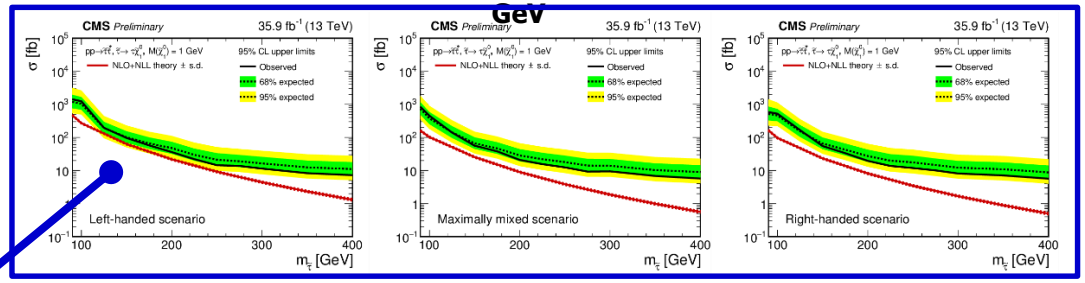
Appendix: Tau Slepton Pair with Taus

CMS-PAS-SUS-17-003

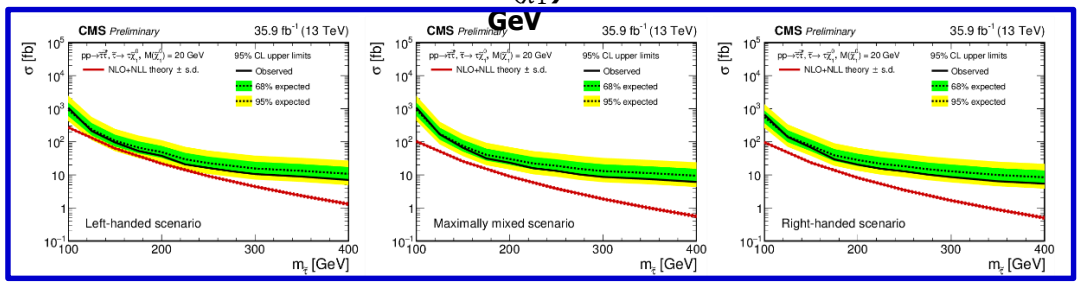
$m(\tilde{\chi}_1^0)$= 1 GeV



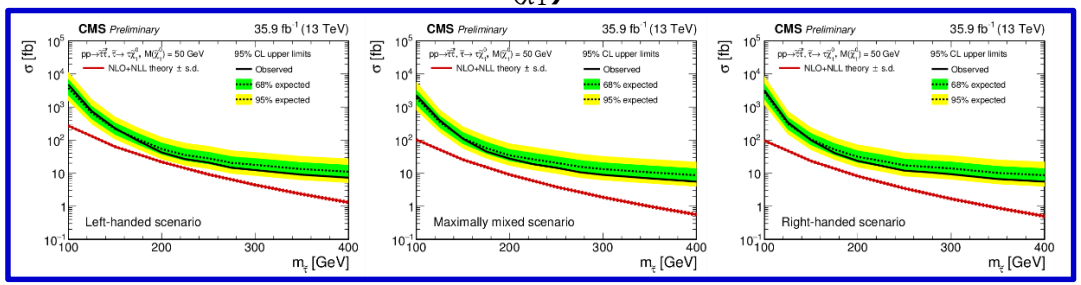
$m(\tilde{\chi}_1^0)$= 1 GeV



$m(\tilde{\chi}_1^0)$= 20 GeV



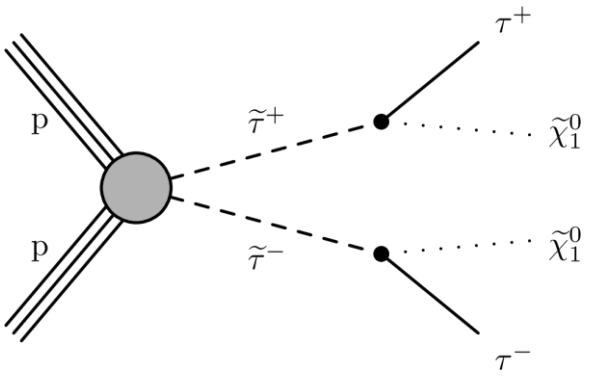
$m(\tilde{\chi}_1^0)$= 50 GeV



$\tilde{\tau}_L$ $\tilde{\tau}_{mixed}$ $\tilde{\tau}_R$

Appendix: Tau Slepton Pair with Taus

CMS-PAS-SUS-17-002



- $\tau_h + \ell$ **or** $e + \mu$ from tau leptom decays
- **Event with** $\Delta\phi(\tau\tau)$, ΣM_T, **and/or** p_T^{miss}
- **Search for OS** 2τ