Dark Matter Searches at CMS

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on behalf of the CMS Collaboration

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Texas A&M University &

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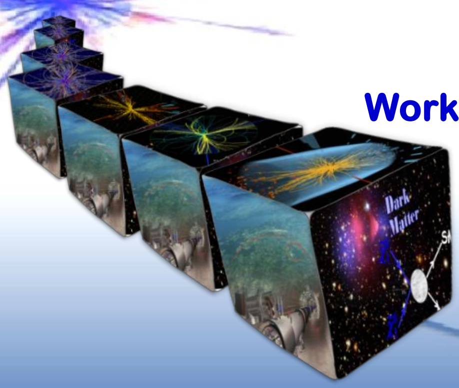
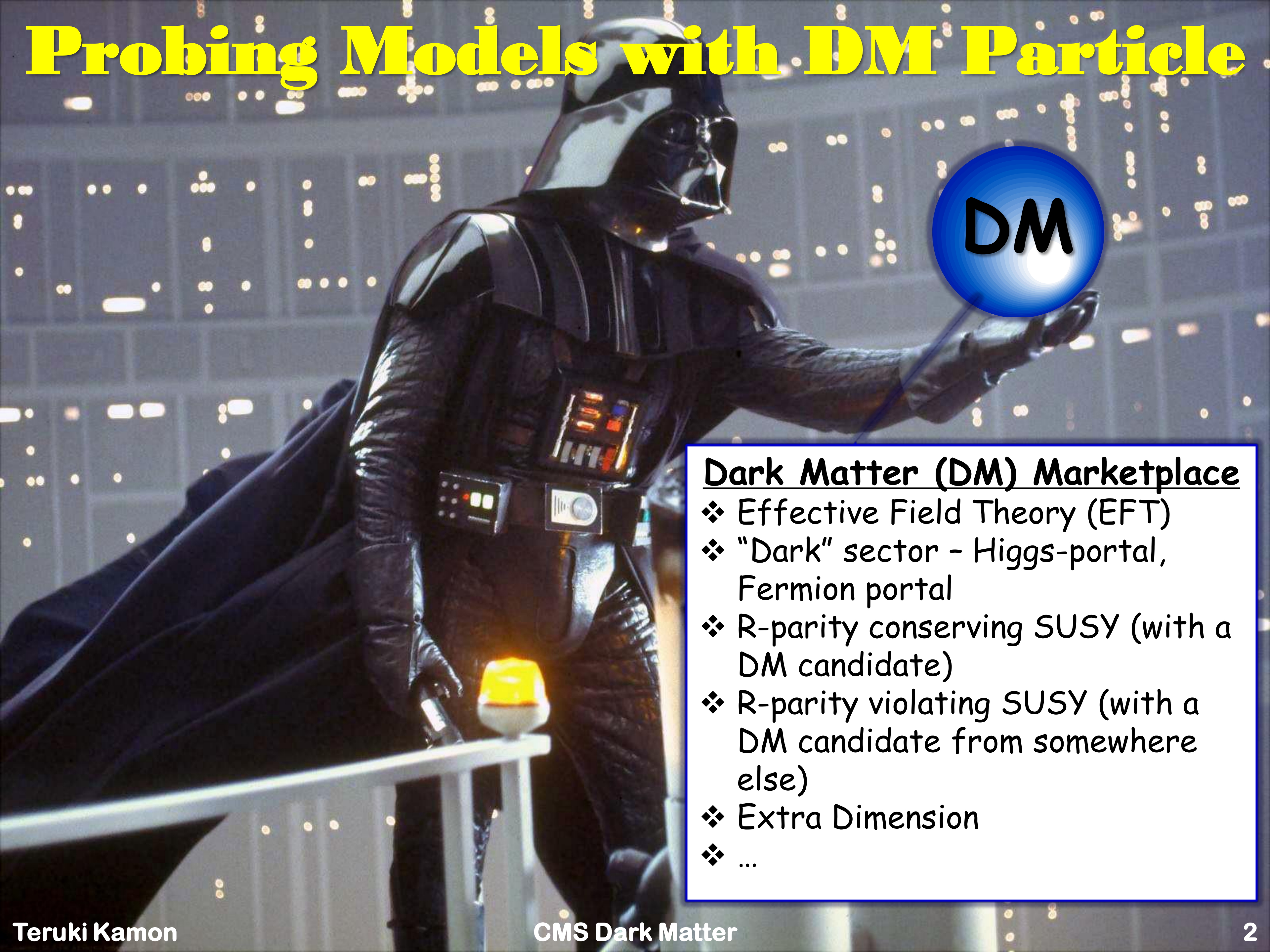


Workshop on the Interconnection between Particle Physics and Cosmology

(PPC2014)

June 26, 2014

Probing Models with DM Particle



<u>Dark Matter (DM) Marketplace</u>

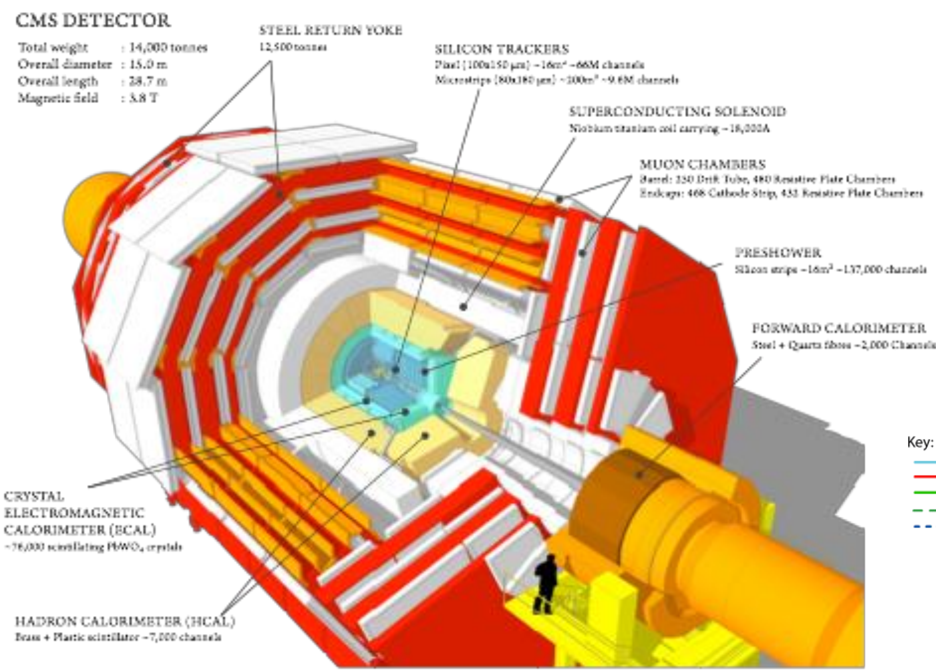
- ❖ Effective Field Theory (EFT)
- ❖ "Dark" sector – Higgs-portal, Fermion portal
- ❖ R-parity conserving SUSY (with a DM candidate)
- ❖ R-parity violating SUSY (with a DM candidate from somewhere else)
- ❖ Extra Dimension
- ❖ …

Compact Muon Solenoid (CMS) Experiment

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

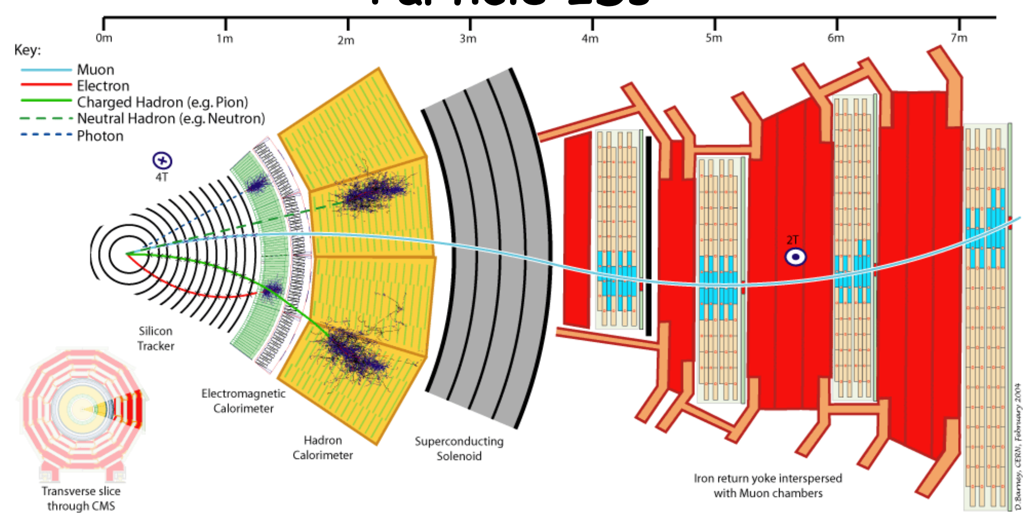
Schematic view of the CMS Detector showing its main components.



Triggers

1) Tagging energetic jets (+ MET) from cascade decays
2) Tagging leptons
3) Tagging photons
4) Tagging with timing
5) ISR jet(s)
6) VBF dijet
7) Disappearing track
8) …

Particle IDs

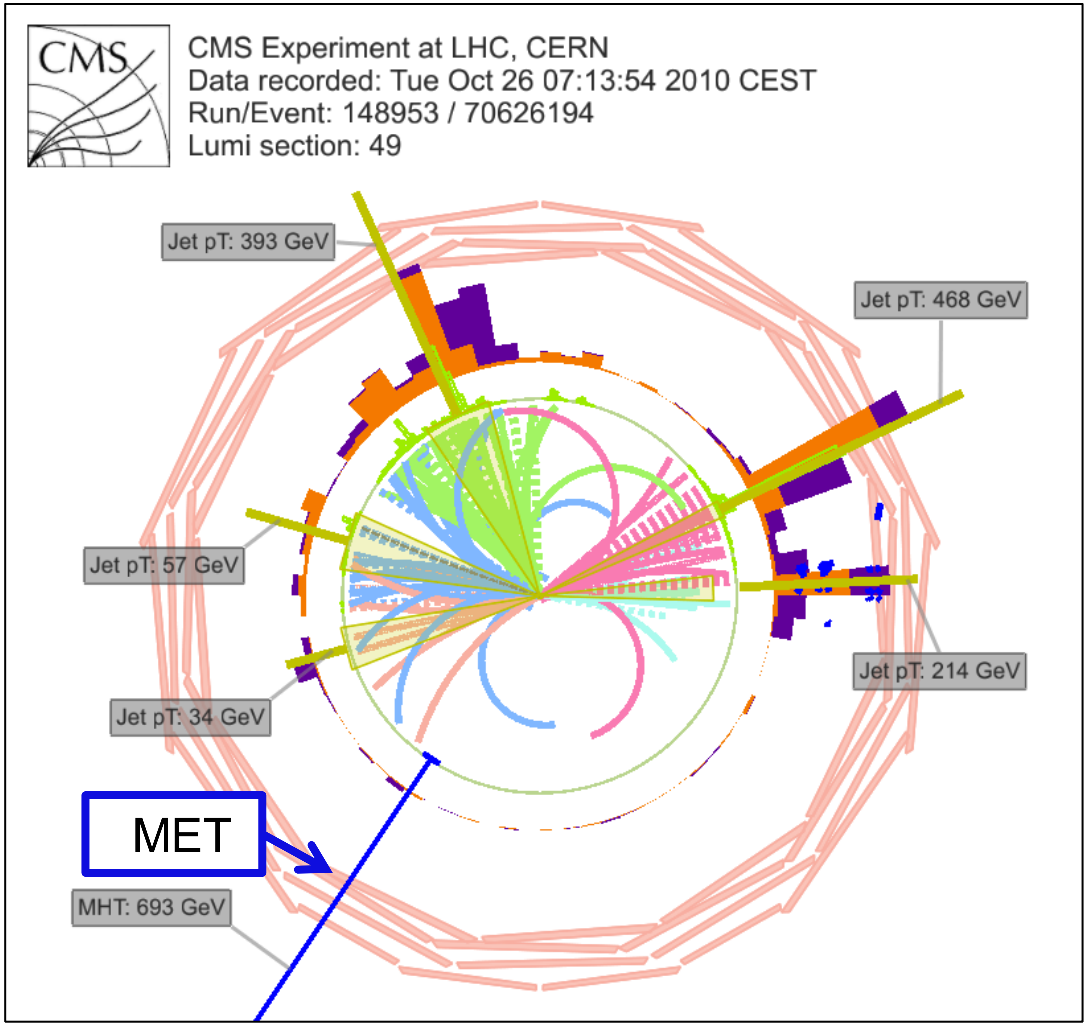


Also see **Maria Isabel Pedraza Morales' talk** on CMS Higgs

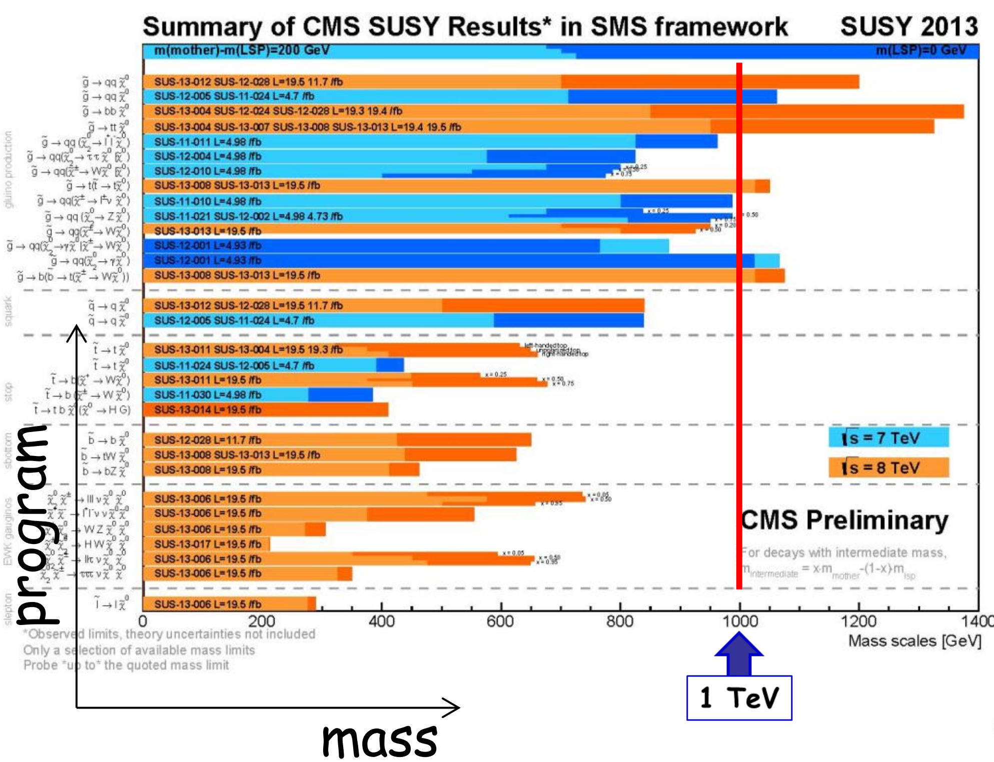
"Missing" Transverse Energy

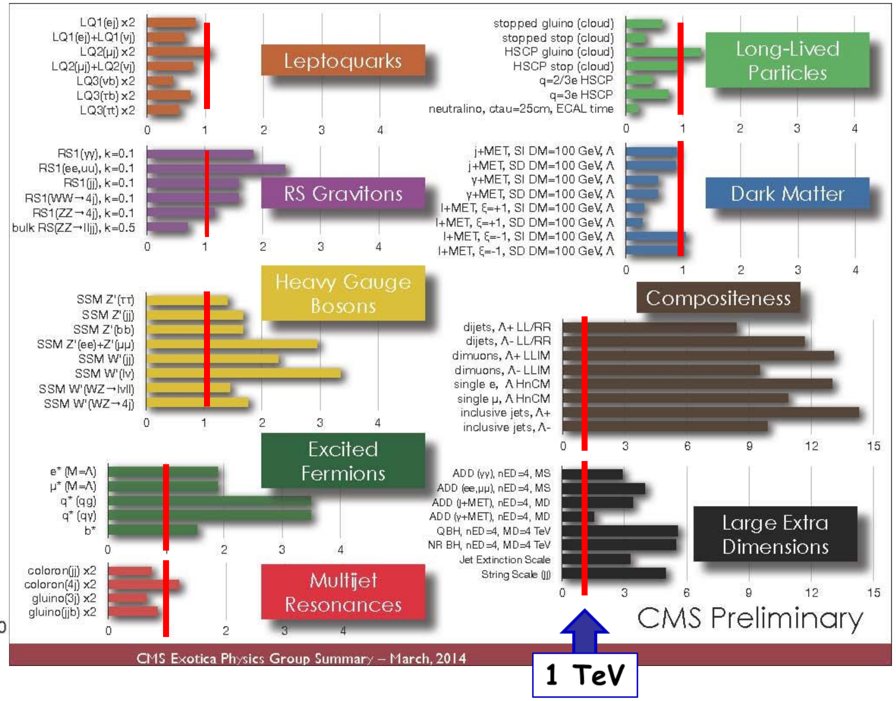
The hallmark signature for DM is a **momentum imbalance** or missing transverse energy (= "MET")

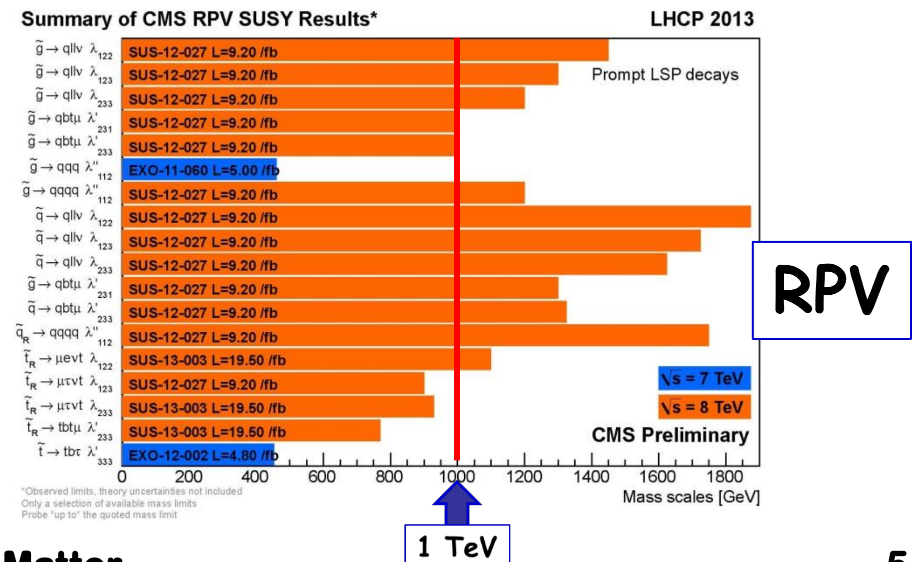
- DM particle escapes the detector undetected
- Nature still conserves momentum (always!)
- Infer presence of DM by undetected momentum



CMS "New Physics Searches" Charts





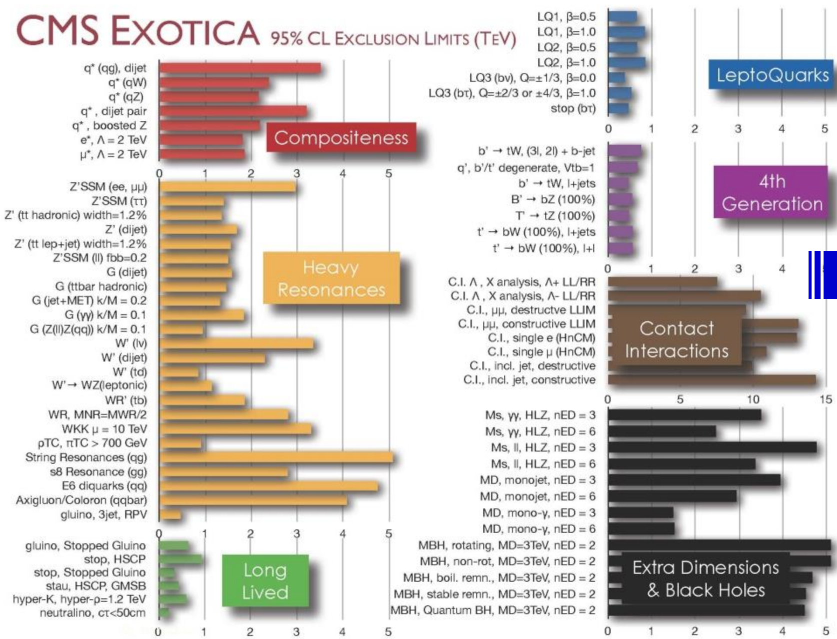


- ❖ **Probing a TeV scale at LHC8 ☺**
- ❖ No hints of NP (yet) in very diverse search programs ☹

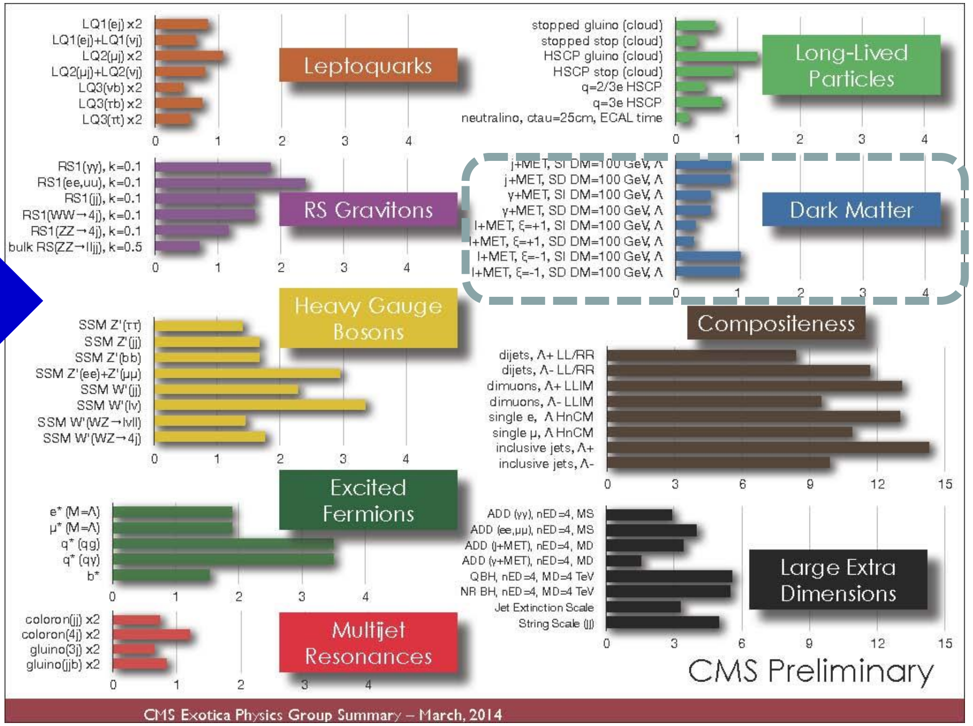
[Note] –1 sigma exclusion limits rather than the nominal value are also available in CMS papers.

DM (Interpretation) Working Group

June 2013



April 2014



May 2014: Exotica MC+Theory Working Group

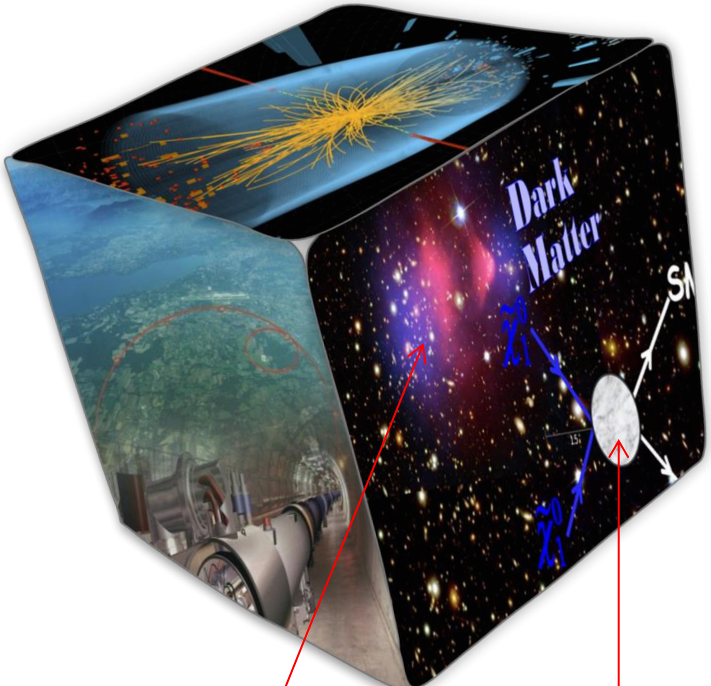
Cross Physics Analysis Groups (Exotic, SUSY, Higgs)

Selected topics:

[Part I] Mono-X in Effective Field Theory (EFT)

[Part II] Supersymmetry (SUSY) - Scalar top quark (stop), …

Part I : DM Effective Field Theory

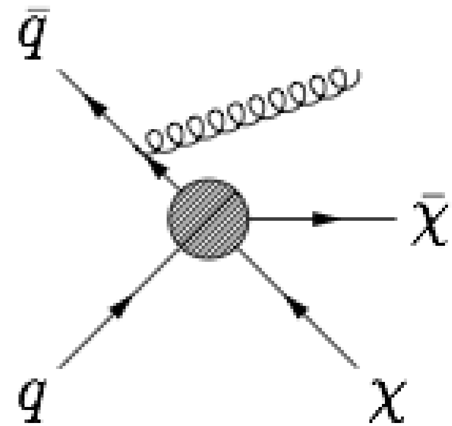


See Young Bai's talk on DM models (I)

See Bhaskar Dutta's talk on DM models (II)

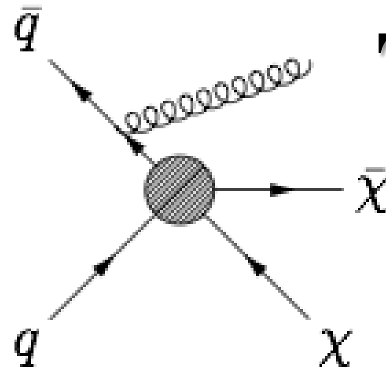
$$\underbrace{\Omega_{\tilde{\chi}_1^0}}_{0.23} h^2 = \mathcal{D}(\langle \sigma_{ann} v \rangle)$$

Part I



Effective field theory (EFT) … Interaction between DM and SM particles is contact interaction

DM Effective Field Theory (EFT)



Exhaustive list of …

Dirac fermion, 1008.1783

D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Majorana fermion, 1005.1286

M1	qq	$m_q/2M_*^3$
M2	qq	$im_q/2M_*^3$
M3	qq	$im_q/2M_*^3$
M4	qq	$m_q/2M_*^3$
M5	qq	$1/2M_*^2$
M6	qq	$1/2M_*^2$
M7	GG	$\alpha_s/8M_*^3$
M8	GG	$i\alpha_s/8M_*^3$
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$

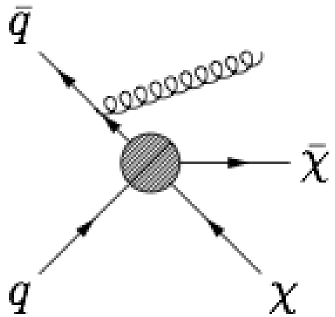
Real scalar, 1008.1783

R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

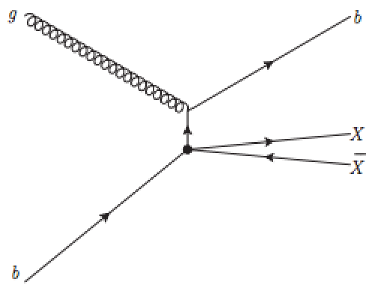
Complex scalar, 1008.1783

C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

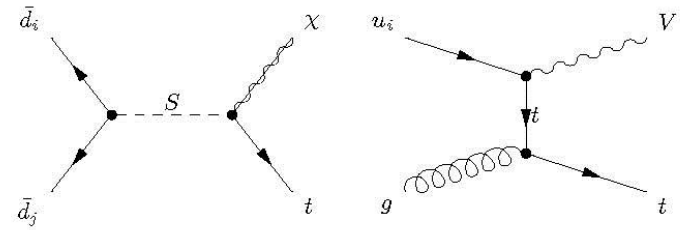
Extensive MET + X Searches



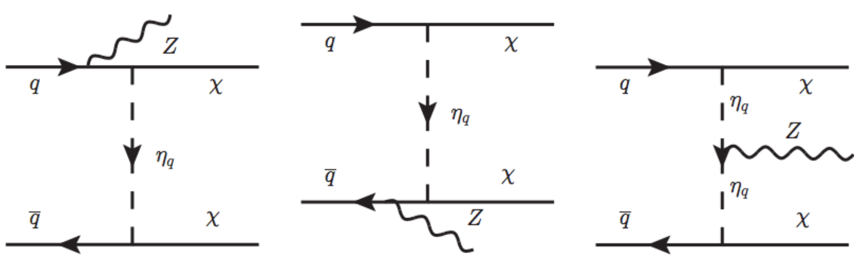
Monojet



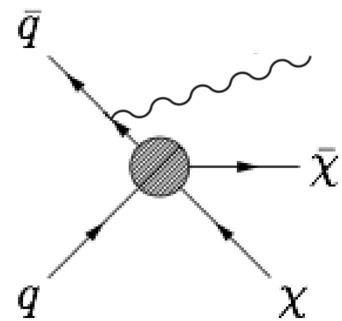
MonoB



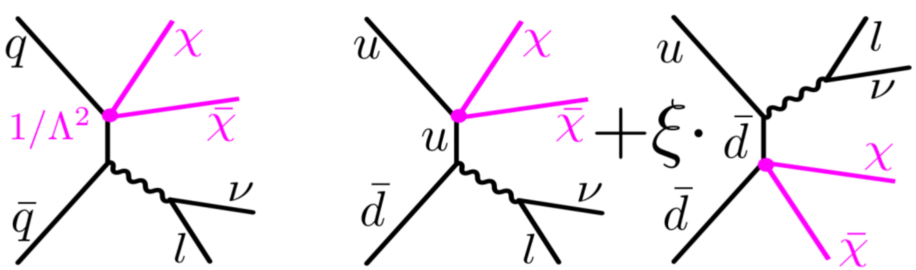
MonoTop

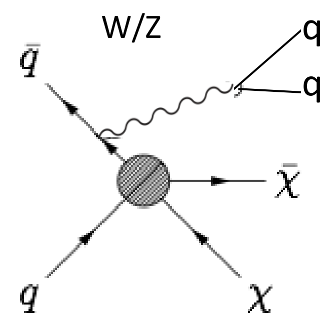


MonoZ

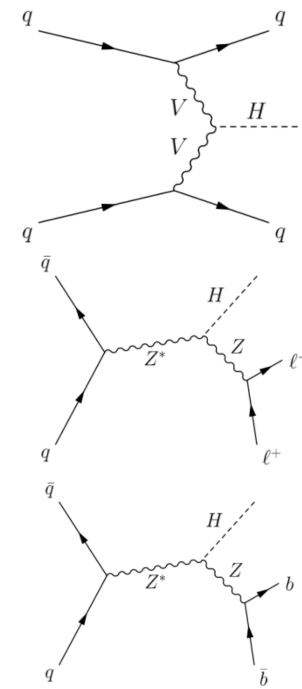


MonoPhoton

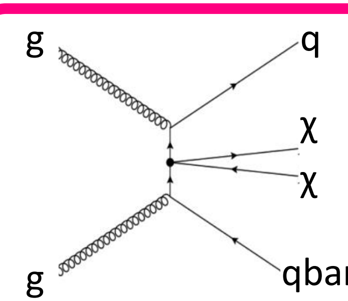




MonoW (monoLepton) MonoW/Z (Hadronic)



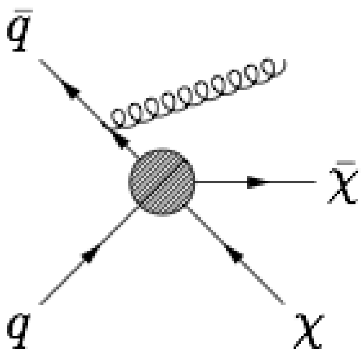
Higgs Portal



BBbar /TTbar

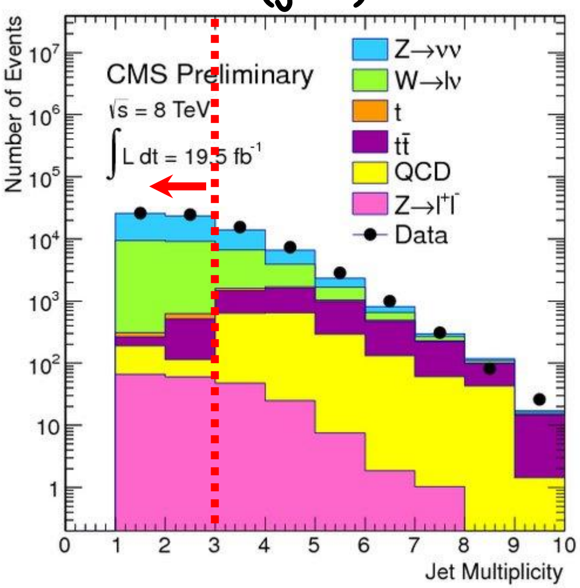
Monojet

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

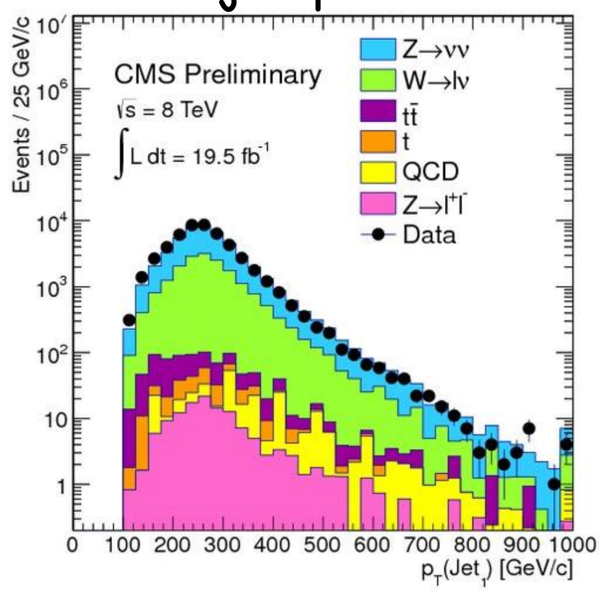


- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4, and allow an additional jet (p_T > 30 GeV); MET > 250 GeV
- Veto event if j_3 p_T > 30 GeV Veto event if $\Delta\phi(j_1,j_2)$ > 2.5
- Veto event if they contain isolated electrons or muons with p_T > 10 GeV; or hadronic tau with > 20 GeV

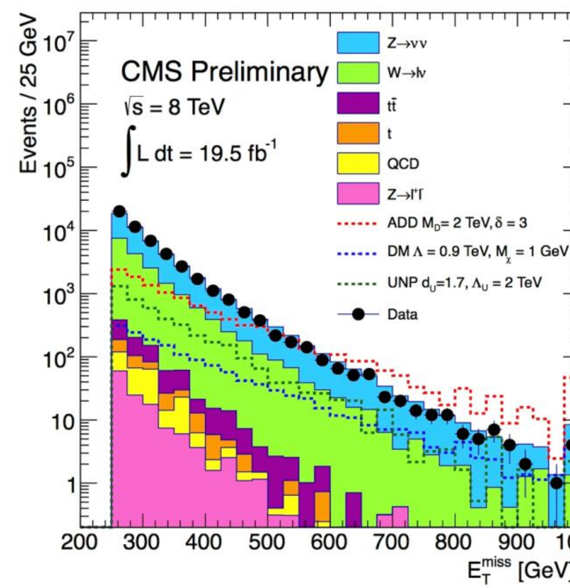
N(jet)

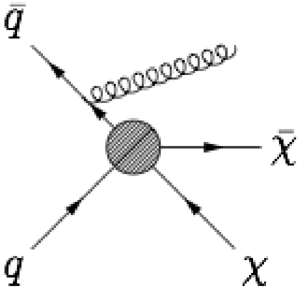


jet p_T



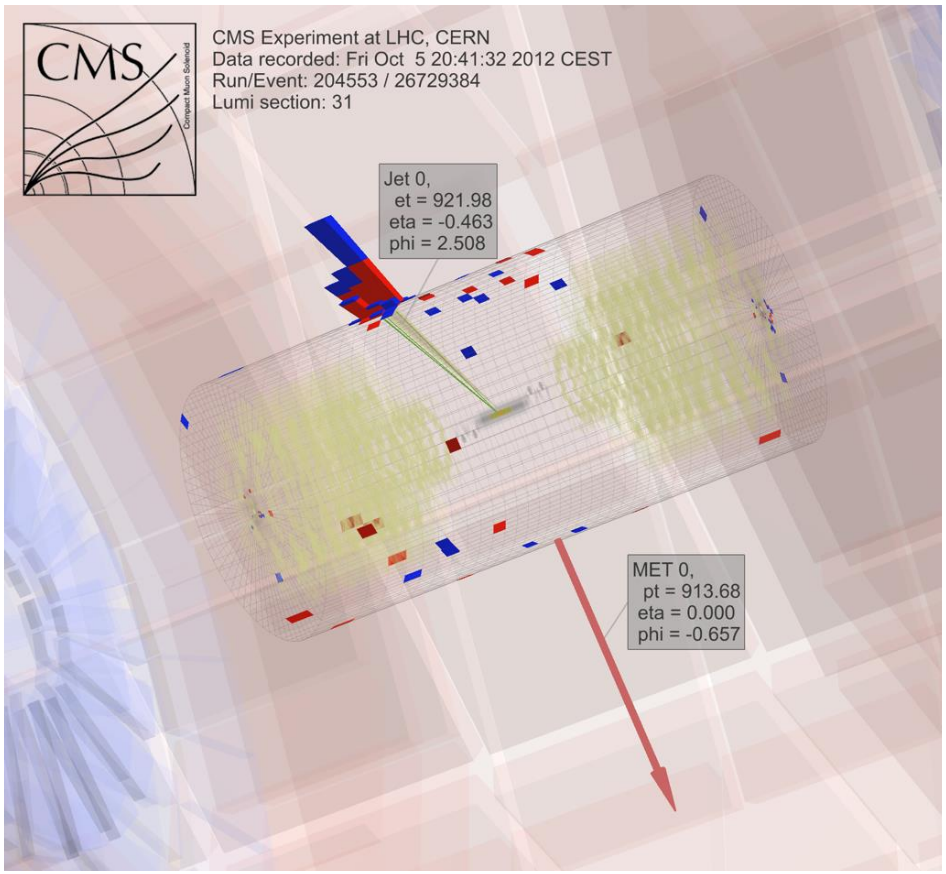
MET

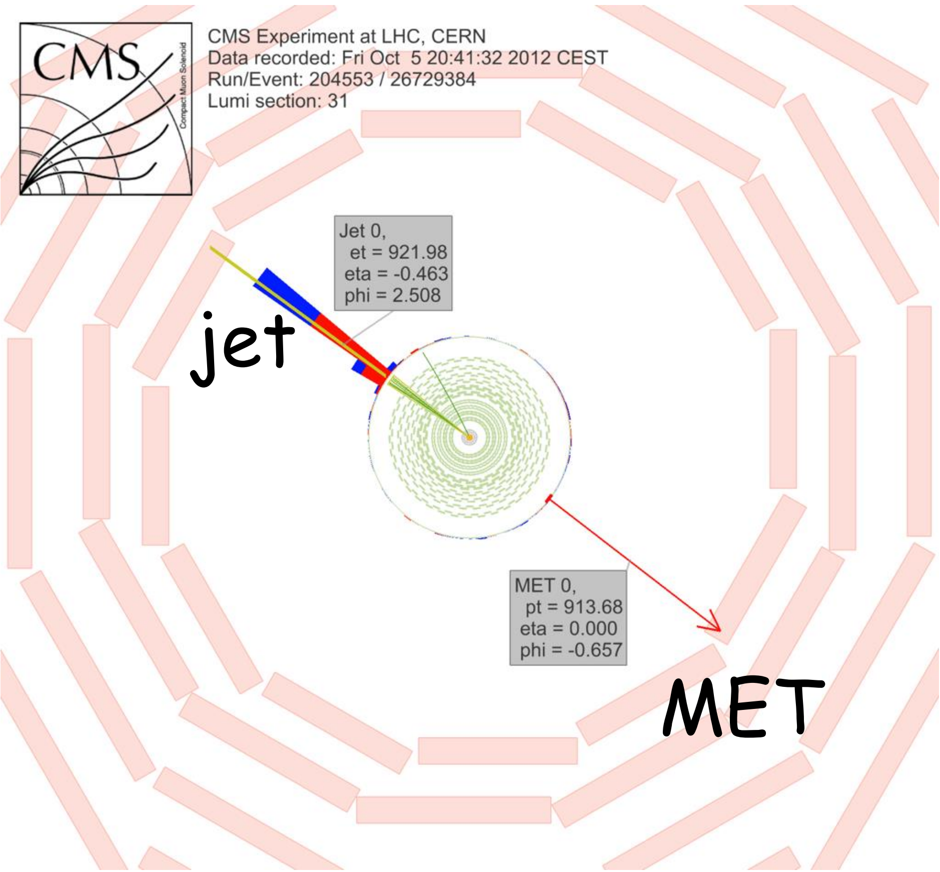


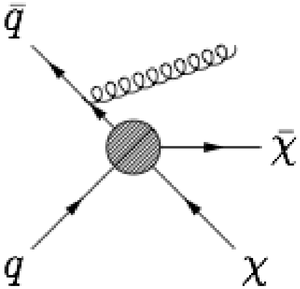


Monojet Event in CMS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

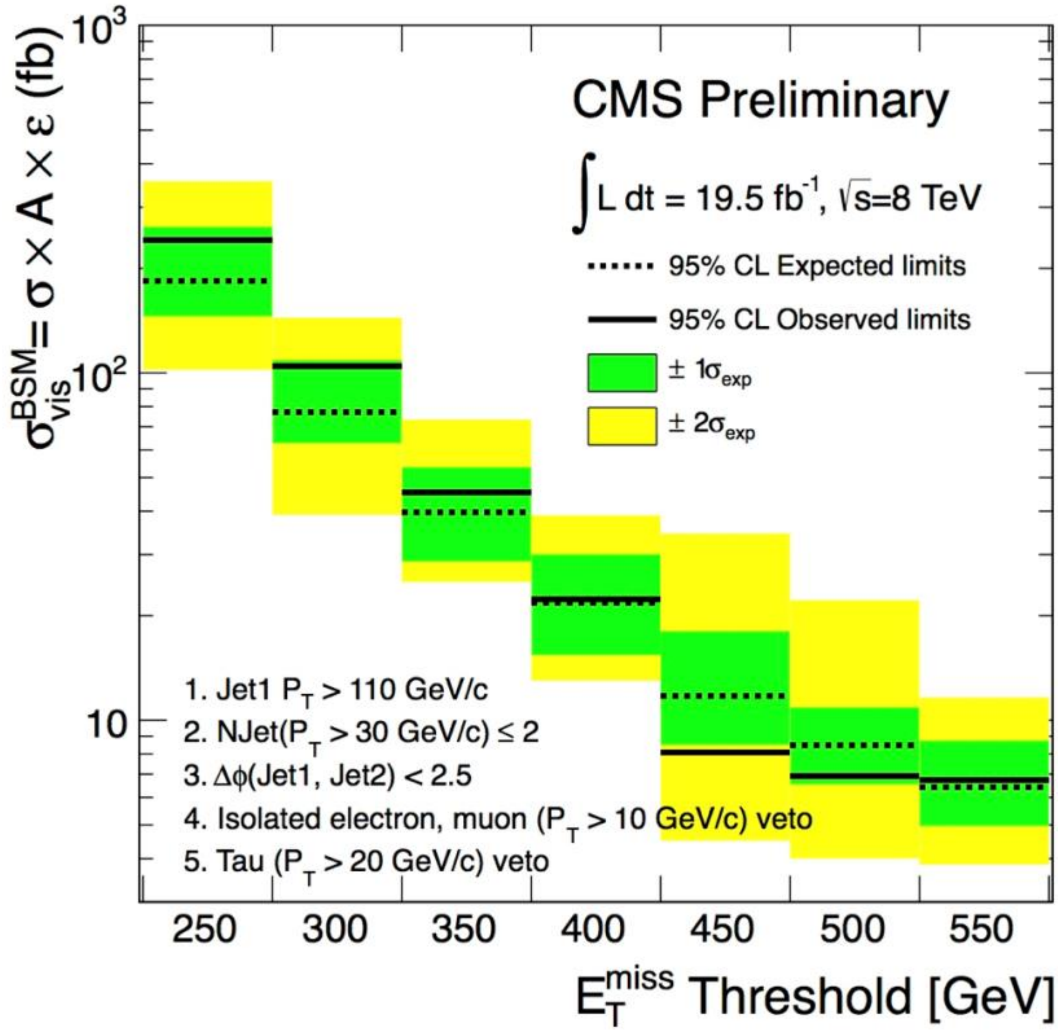


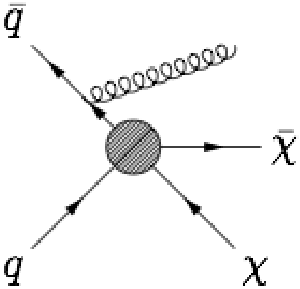




Monojet: Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

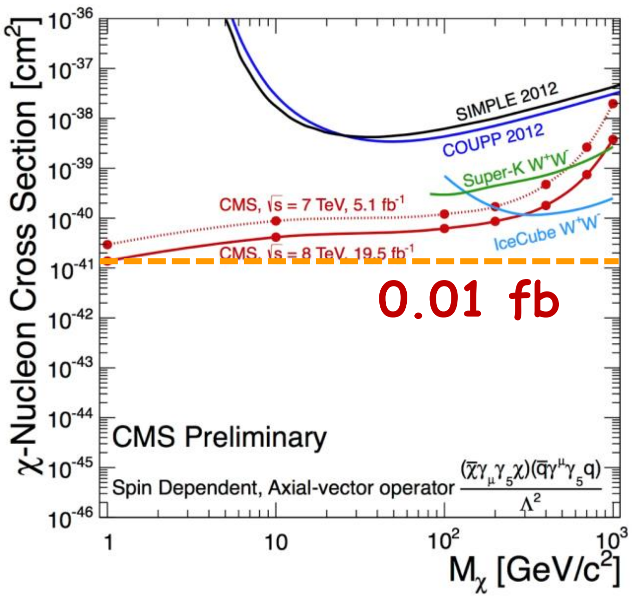


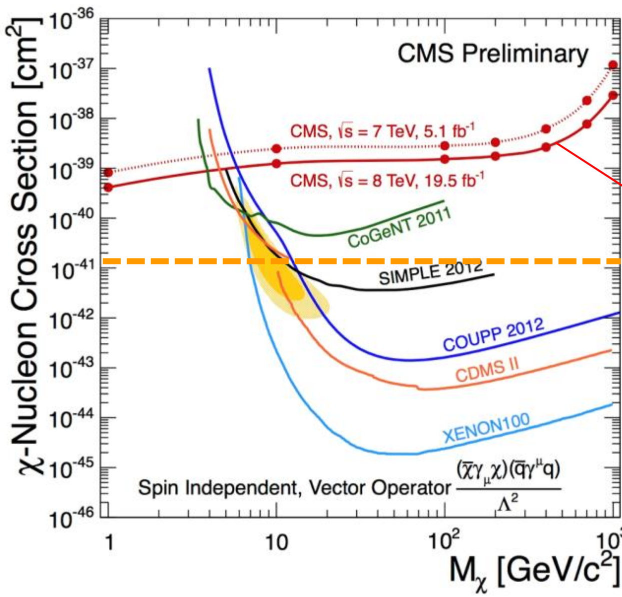


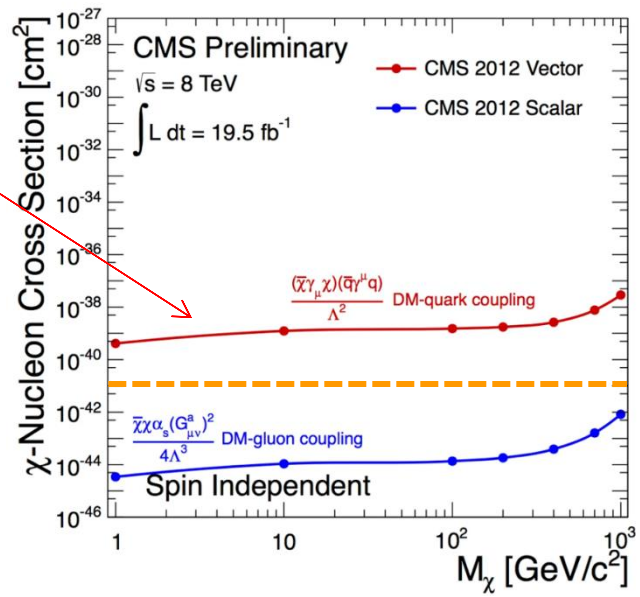
Monojet: Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

MET > 400 GeV







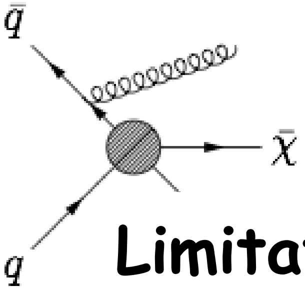
Axial-vector operator
spin-dependent (SD)

Vector operator
spin independent (SI)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

$$\mathcal{O}_{V} = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Λ = Contact interaction scale

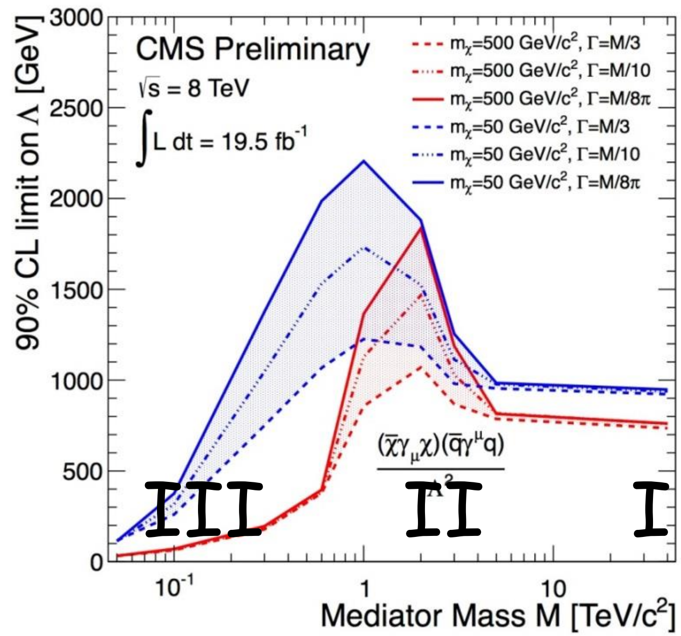


Monojet: Remarks

Limitation of EFT → Simplified Model with M_*

- EFT is valid when mediator mass (M_*) > a fewTeV
- The couplings required are large comparing this with known couplings:
  - strong interaction ~1.2
  - weak interaction ~0.6
- Theory is non-perturbative if $\sqrt{g_q g_{DM}} > 4\pi$
- Width larger than mass, so unlikely mediator will be identified as a particle

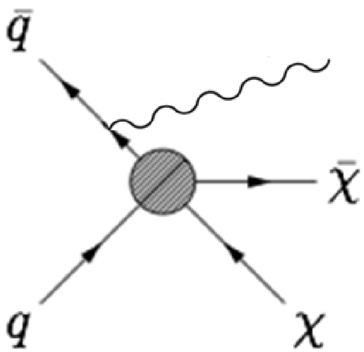
- Region I: EFT limit is good!
- Region II: EFT limit is too weak!
- Region III: EFT limit is too strong!



See, for example, arXiv:1308.6799 for further reading; **Matthew Buckley's talk**

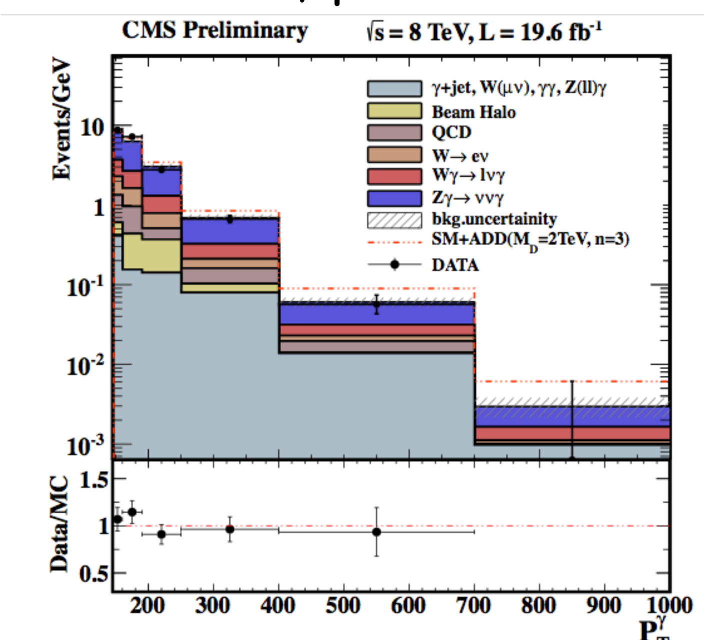
Monophoton

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12047

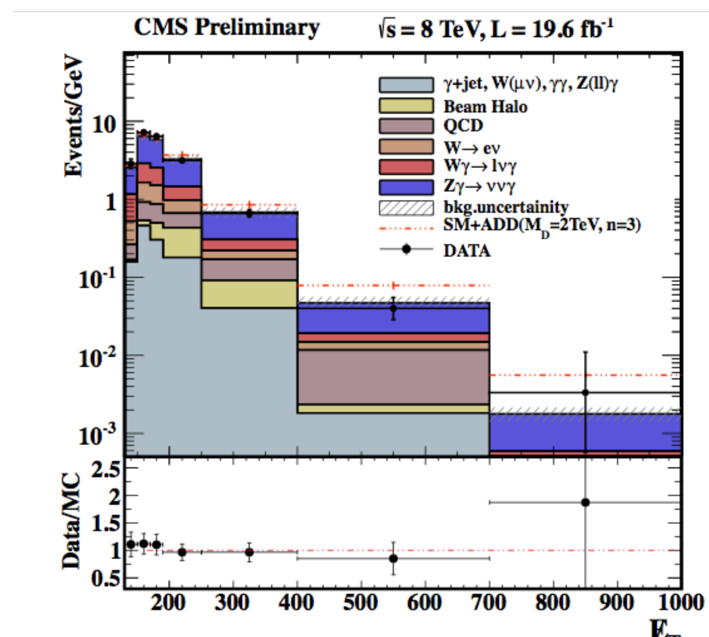


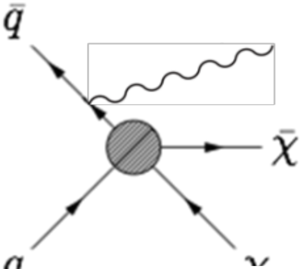
- MET > 140 GeV
- One energetic photon, p_T > 145 GeV, $|\eta|$ < 1.4442
- Veto on jets, leptons, and pixel seeds (hit pattern in the pixel detector) $\Delta\phi$(photon,MET) > 2
- MinMET > 120 GeV, Prob(χ^2) (Reduce fake MET events)

γ p_T



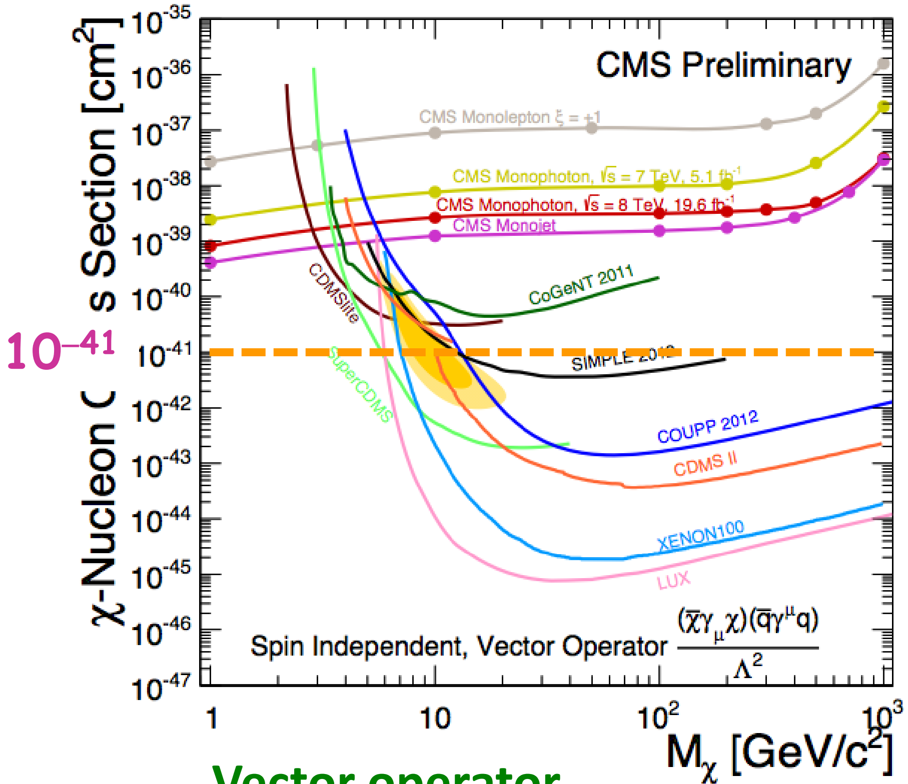
MET

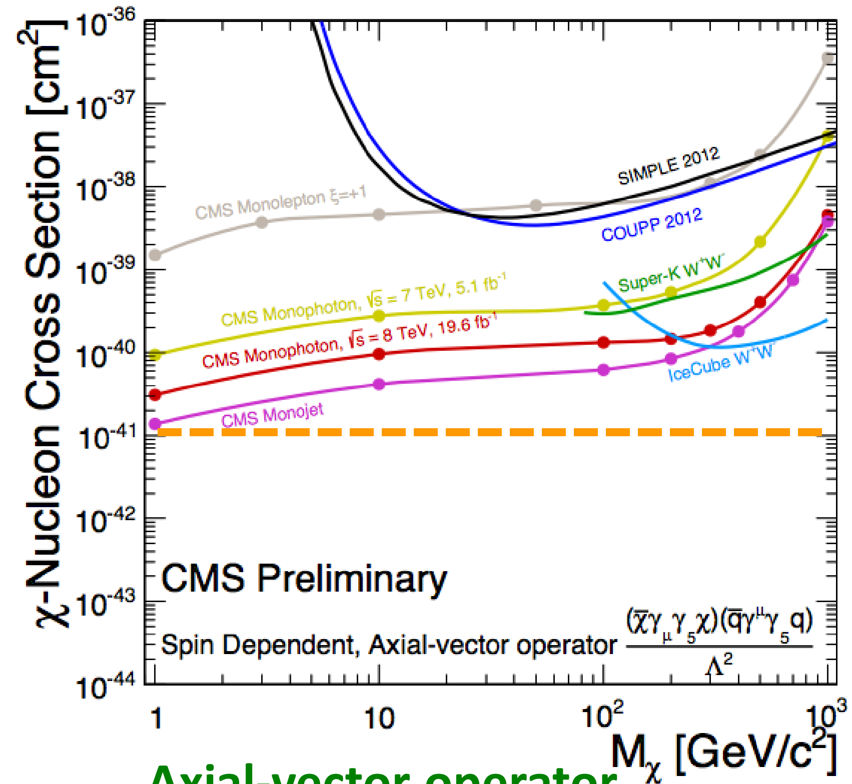




Monophoton: Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12047





Vector operator spin independent (SI)

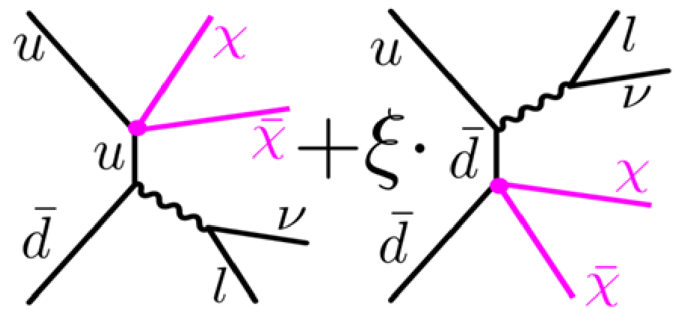
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Axial-vector operator spin-dependent (SD)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Monolepton (W → lν)

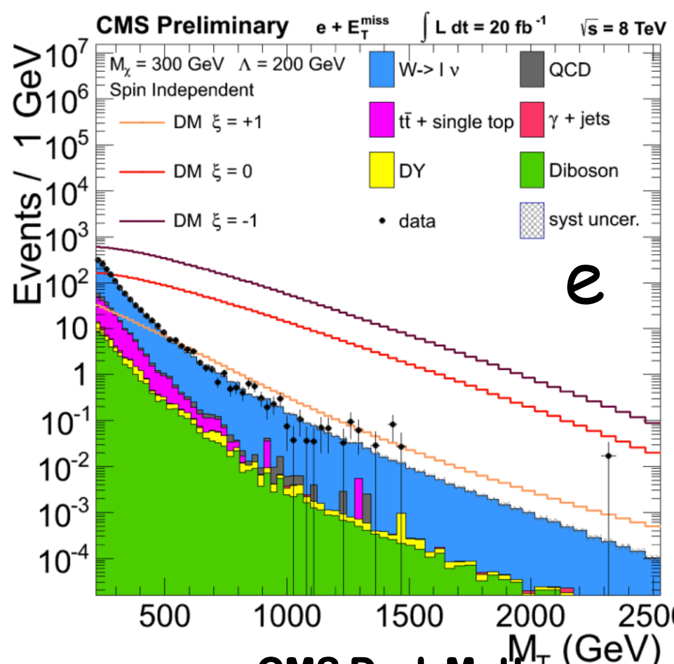
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO13004

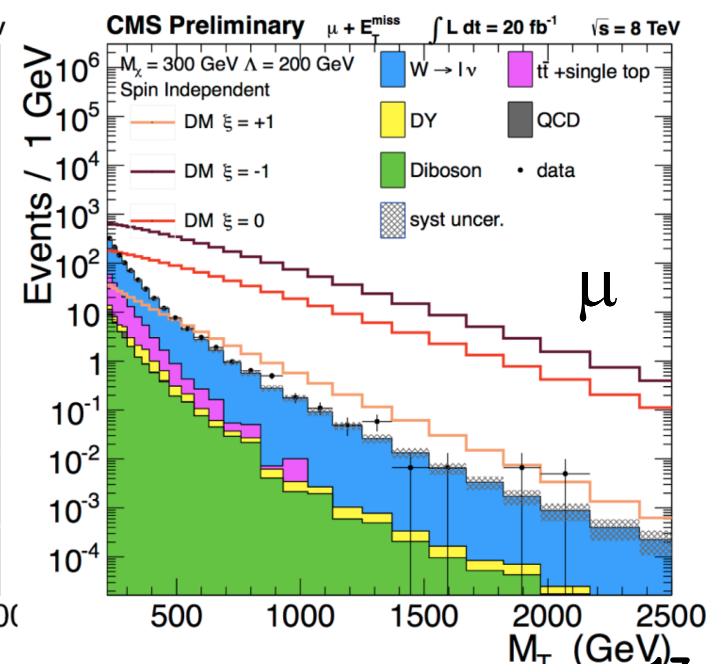


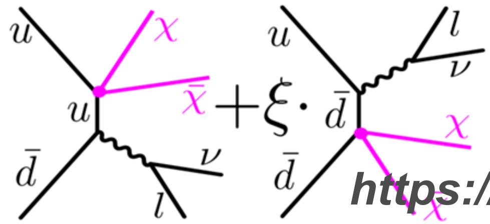
- Dark Matter production with a W boson
- W recoiling against pair-produced DMs
- Vector- and axial-vector couplings considered
- Interference effects parameterized by ξ

$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

- μ(e) P_T > 45(100) GeV
- 0.4 < P_T/MET < 1.5
- Δφ(lepton,MET) > 0.8*π

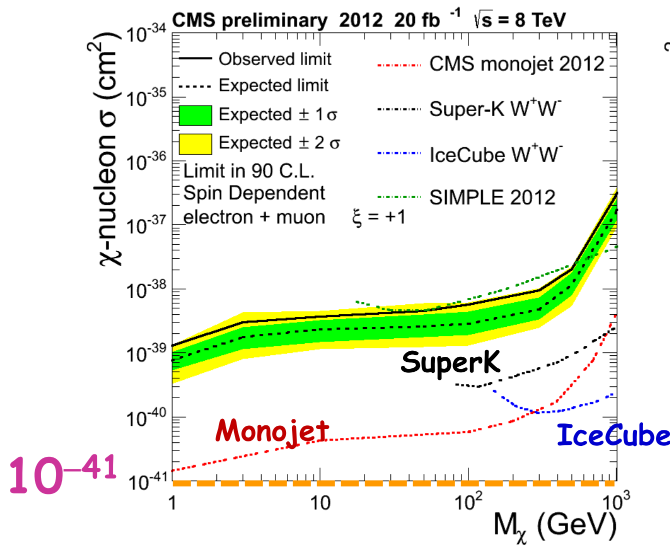


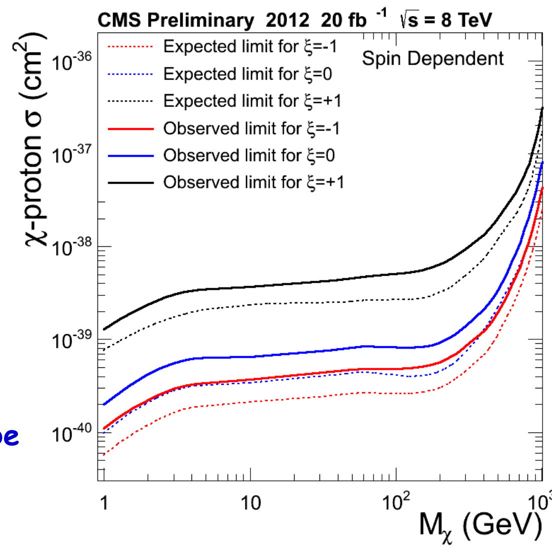




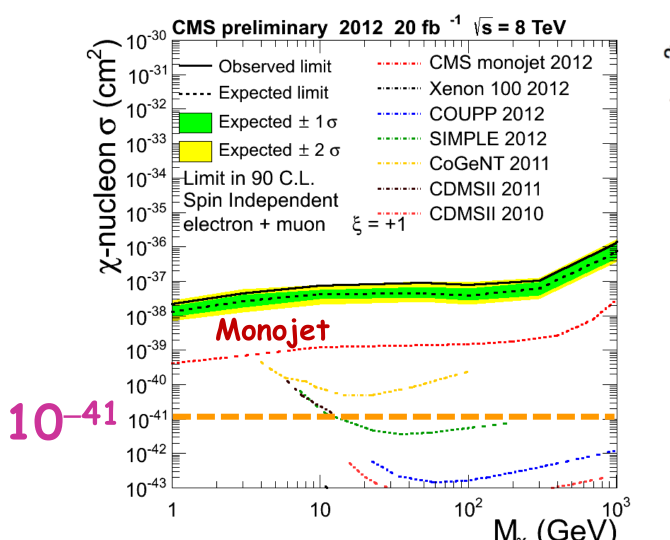
Monolepton: Results

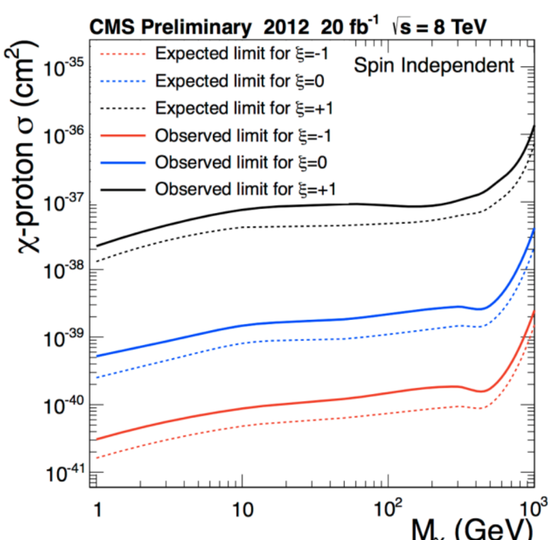
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO13004





Axial-vector operator spin-dependent (SD)

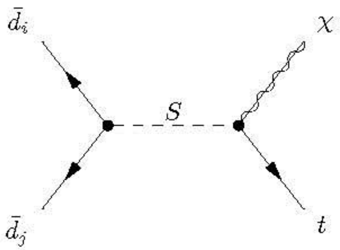


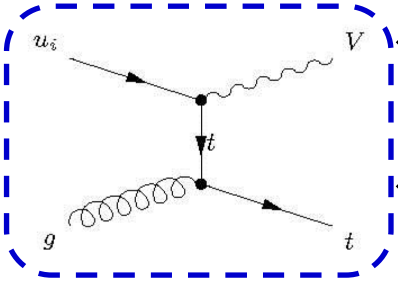


Vector operator spin independent (SI)

Monotop ($t \rightarrow jjb$)

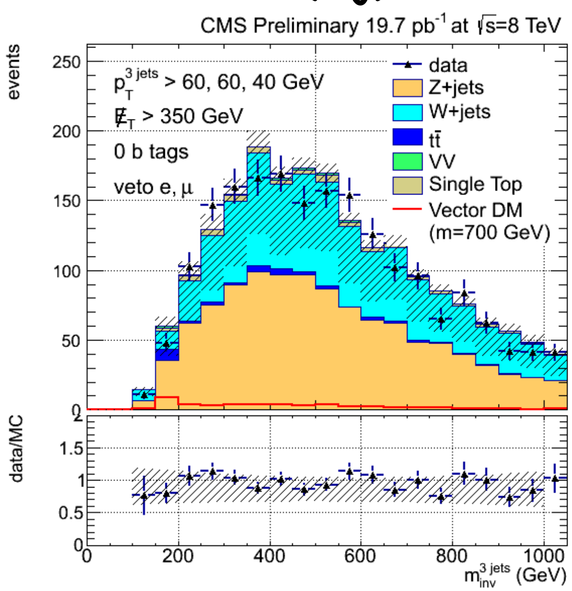
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12022



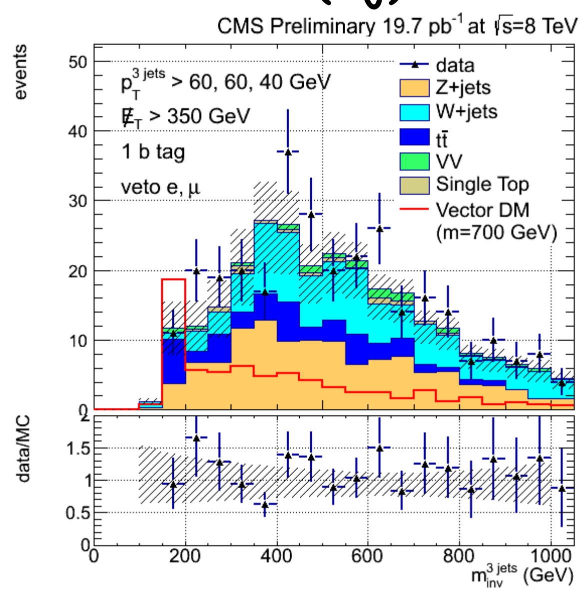


- Three jets, with j_1, and j_2 $p_T > 60$ GeV and j_3 $p_T > 40$ GeV; One jet is tagged b-jet
- Veto events with j_4 $p_T > 35$ GeV or isolated $e(\mu)$ $p_T > 20(10)$ GeV
- $M(j_1j_2j_3) < 250$ GeV
- MET> 350 GeV

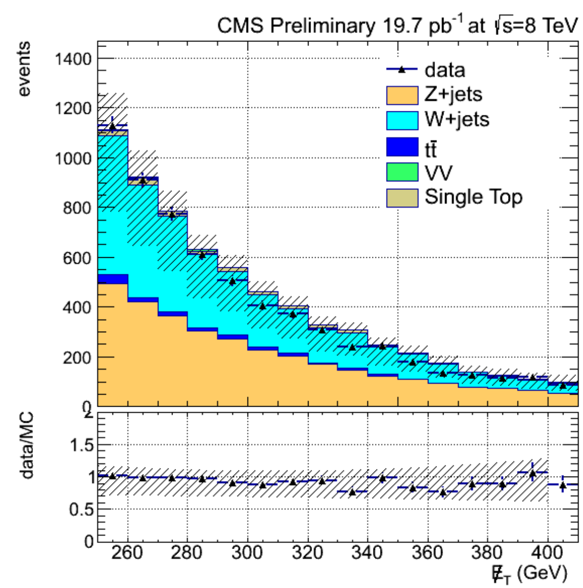
$M(3j)^{0b}$

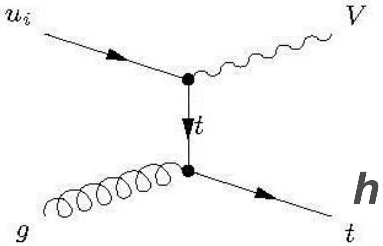


$M(3j)^{1b}$



MET



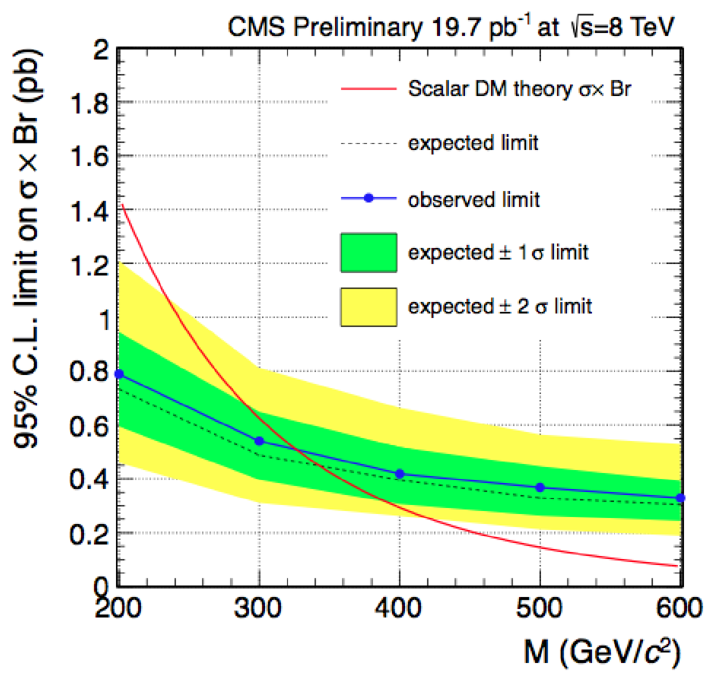


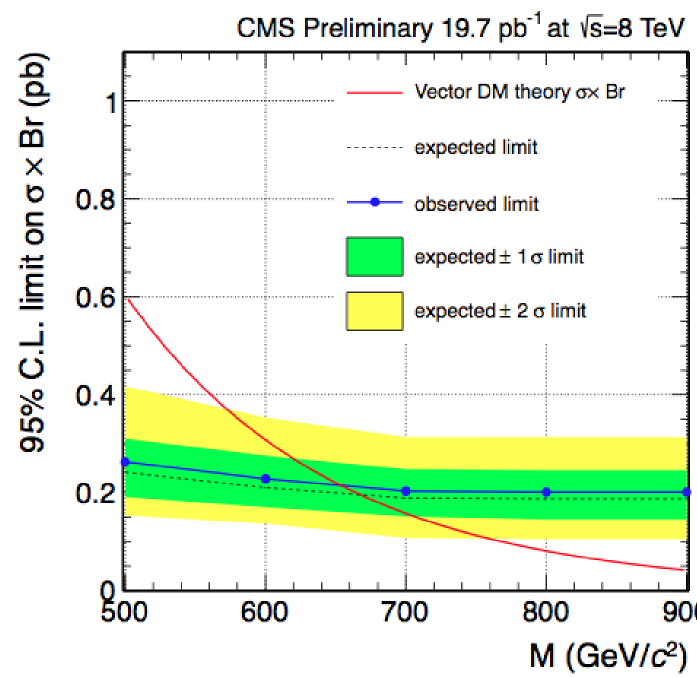
Monotop: Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12022

- Excellent agreement with data
- DM coupling set to 0.1 for q = u/d [arXiv:1106.6199]
- Exclude scalar (vector) DM masses below 327 (655) GeV

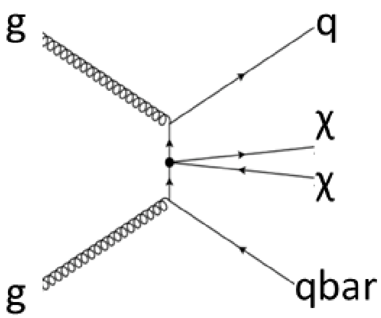
# of b tags	Zero CSVm b tag	One CSVm b tag
$t\bar{t}$	$6\pm0\pm5$	$12\pm0\pm12$
W+jets	$18\pm9\pm7$	$3\pm1\pm2$
Z+jets	$103\pm33\pm9$	$11\pm10\pm1$
Single top	$2\pm1\pm1$	$1\pm1\pm1$
VV	$5\pm0\pm0$	$0\pm0\pm0$
QCD	6	1
sum	140 ± 36	28 ± 16
Data	143	30





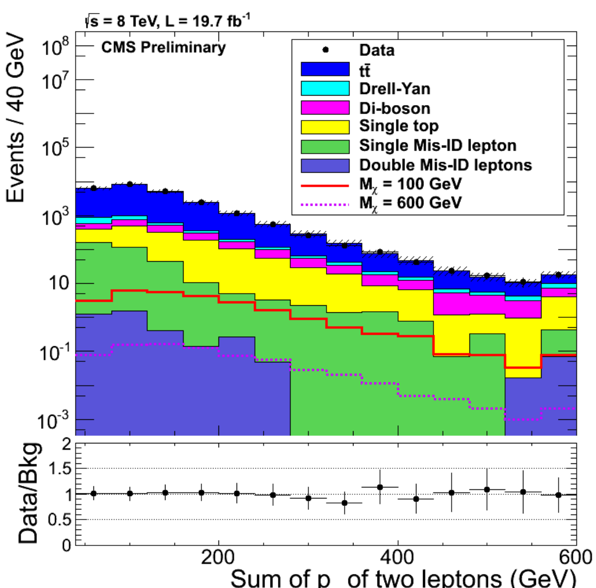
Ditop

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G13004

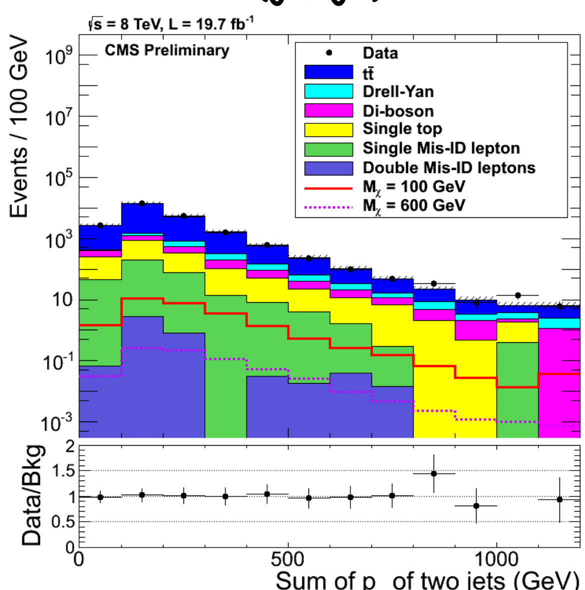


- ❖ Select pairs of top quarks in the di-lepton channels
- ❖ Exactly two identified leptons, and at least two jets are selected.
- ❖ M(ll) > 20 GeV and |M(ll) – 91 GeV| > 15 GeV
- ❖ MET > 320 GeV
- ❖ $HT(j_1, j_2) < 400$ GeV, $HT(l_1, l_2) > 120$ GeV, $\Delta\phi(l_1, l_2) < 2$

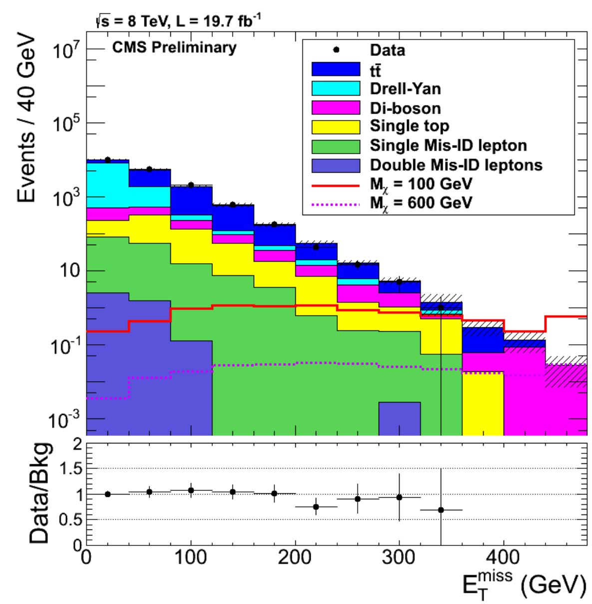
$HT(l_1, l_2)$

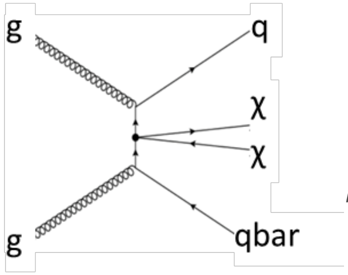


$HT(j_1, j_2)$



MET





Ditop: Results

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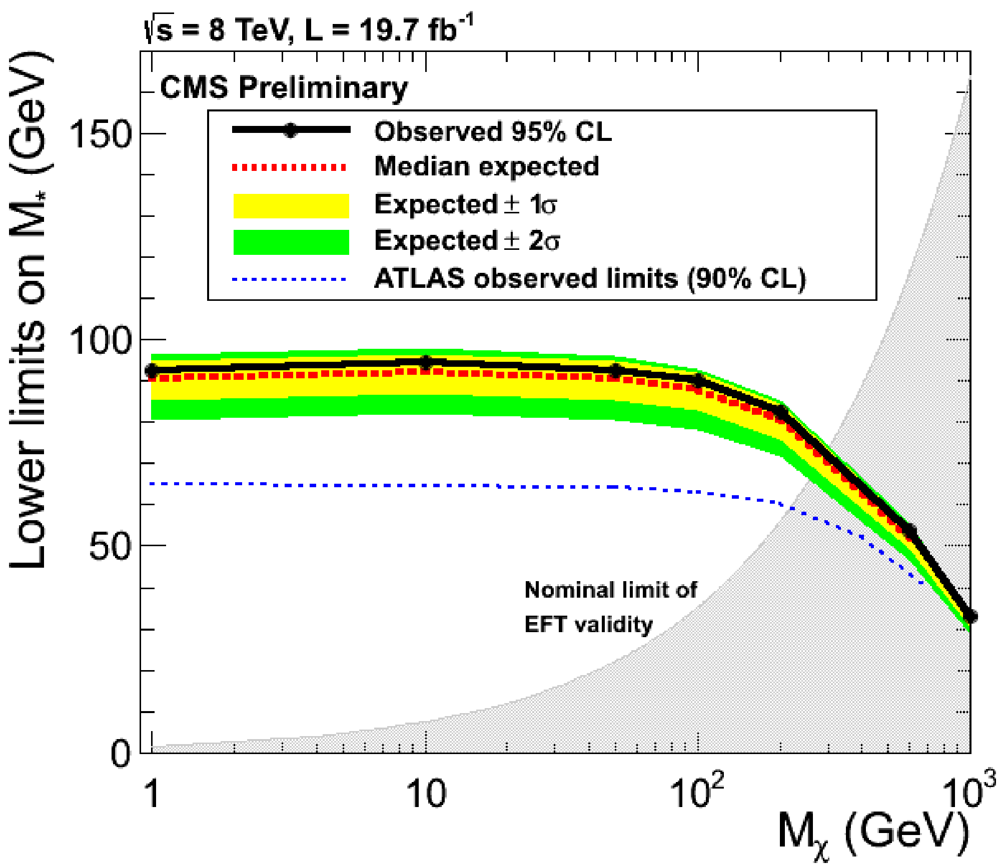
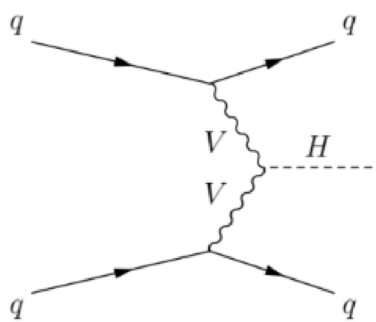


Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$

M_χ (GeV)	Signal efficiency (%)	$\sigma^{\mathrm{lim}}_{\mathrm{exp}}$	$\sigma^{\mathrm{lim}}_{\mathrm{obs}}$
1	$1.28 \pm 0.09 \pm 0.04$	0.35	0.31
10	$1.45 \pm 0.10 \pm 0.05$	0.31	0.27
50	$1.65 \pm 0.11 \pm 0.05$	0.27	0.24
100	$1.96 \pm 0.12 \pm 0.06$	0.23	0.20
200	$2.31 \pm 0.12 \pm 0.05$	0.19	0.17
600	$3.45 \pm 0.17 \pm 0.09$	0.13	0.11
1000	$4.35 \pm 0.24 \pm 0.10$	0.10	0.09

Higgs portal to DM: VBF H(inv)

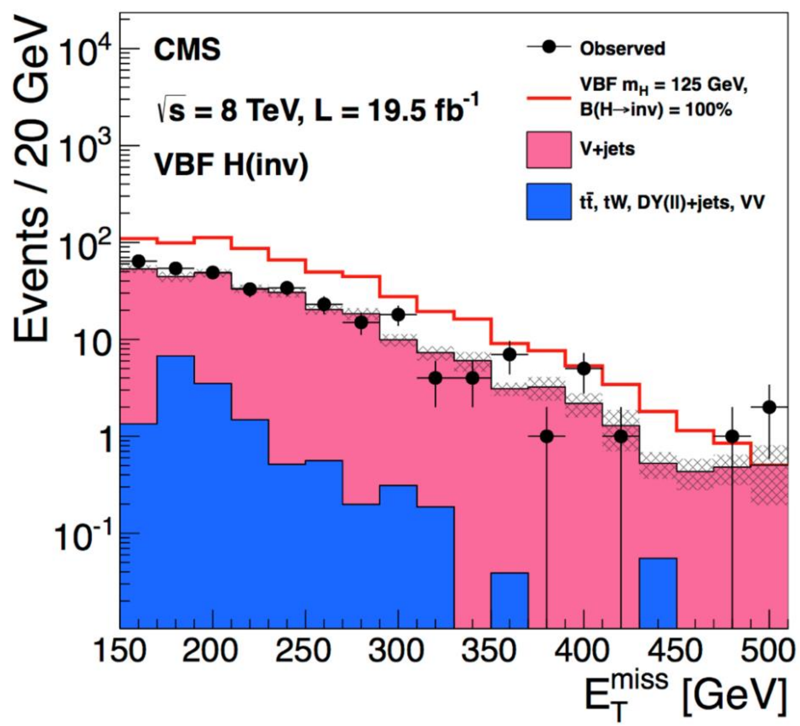
arXiv:1404.1344v2



DM particles have the direct couplings to the SM Higgs sector, $H \rightarrow \chi\chi$

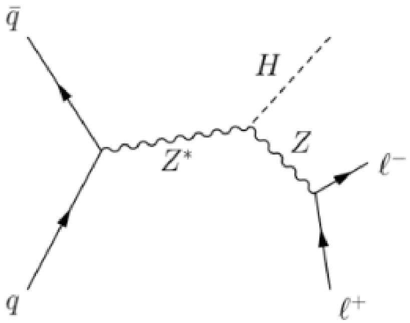
- Limits on branching fraction of Higgs to "invisible" particles used for limits on DM
- Can be scalar, vector or fermionic couplings
- Limits only up to DM mass $M_X < M_H/2$

- Veto events with an identified electron, or muon with $p_T > 10$ GeV.
- VBF tag jet pair, $p_{T,j1}$, $p_{T,j2} > 50$ GeV, $|\eta| < 4.7$, η_{j1}, $\eta_{j2} < 0$, $\Delta\eta_{jj} > 4.2$, and $M_{jj} > 1100$ GeV
- MET > 130 GeV
- $\Delta\phi(j_1,j_2) < 1.0$
- Central jet veto (event that has an additional jet with $p_T > 30$ GeV and pseudorapidity between those of the two tag jets)

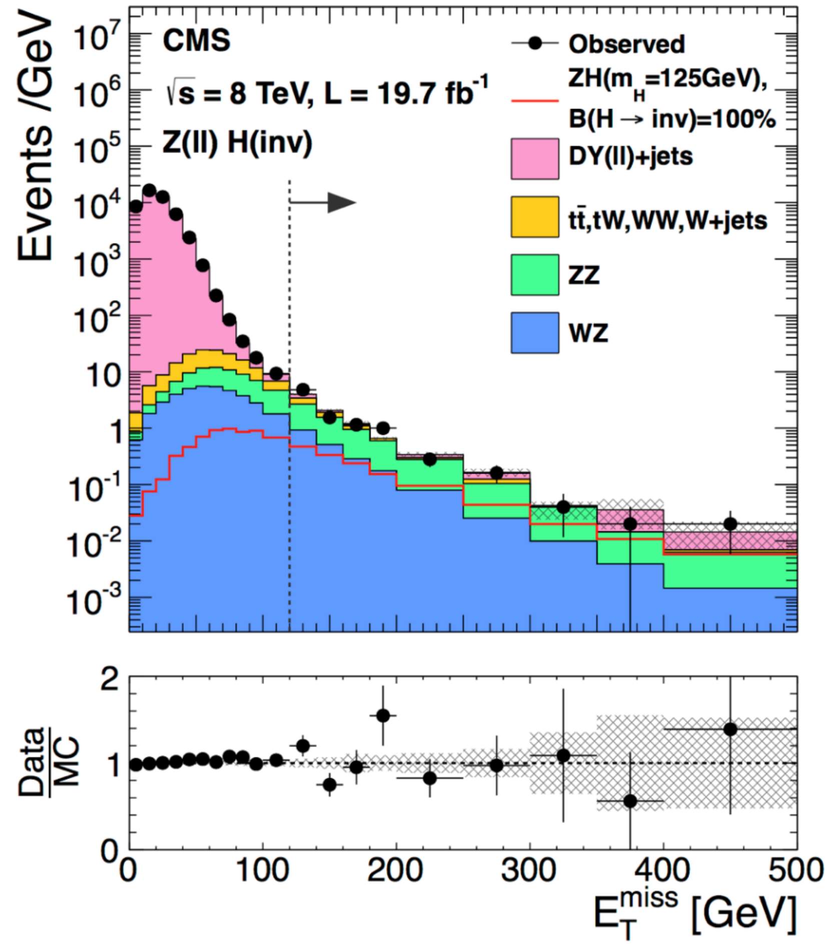


Higgs portal to DM: Z(ll)+H(inv)

arXiv:1404.1344v2

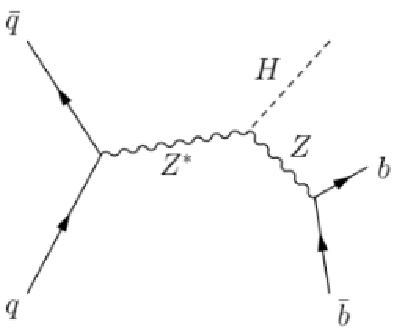


- Two well-identified, isolated leptons of the same flavor and opposite signwith $P_T > 20$ GeV, M(ll) is within ±15 GeV of Z mass
- Veto event if there are two or more jets with $P_T > 30$ GeV
- Veto event containing a bottom-quark decay identified by either the presence of a soft-muon or by the CSV b-tagging algorithm
  - MET > 120 GeV
  - $|E_T^{miss} - p_T^{\ell\ell}| / p_T^{\ell\ell} < 0.25$
  - $\Delta\phi(\ell\ell, E_T^{miss}) > 2.7$

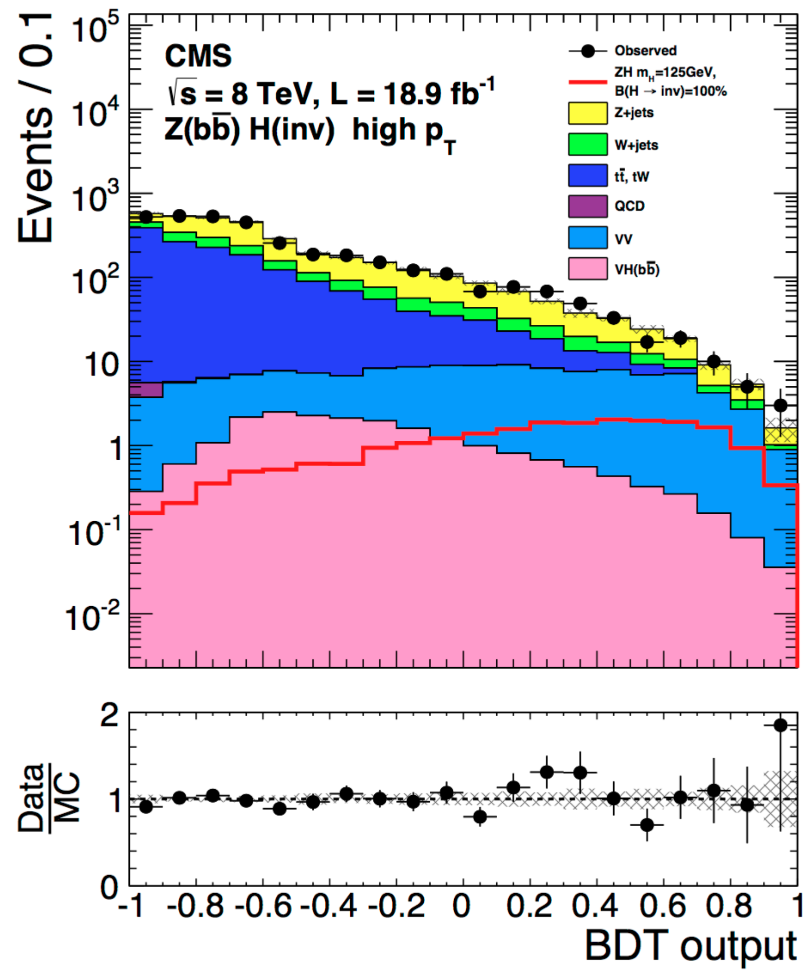


Higgs portal to DM: Z(bb)+H(inv)

arXiv:1404.1344v2

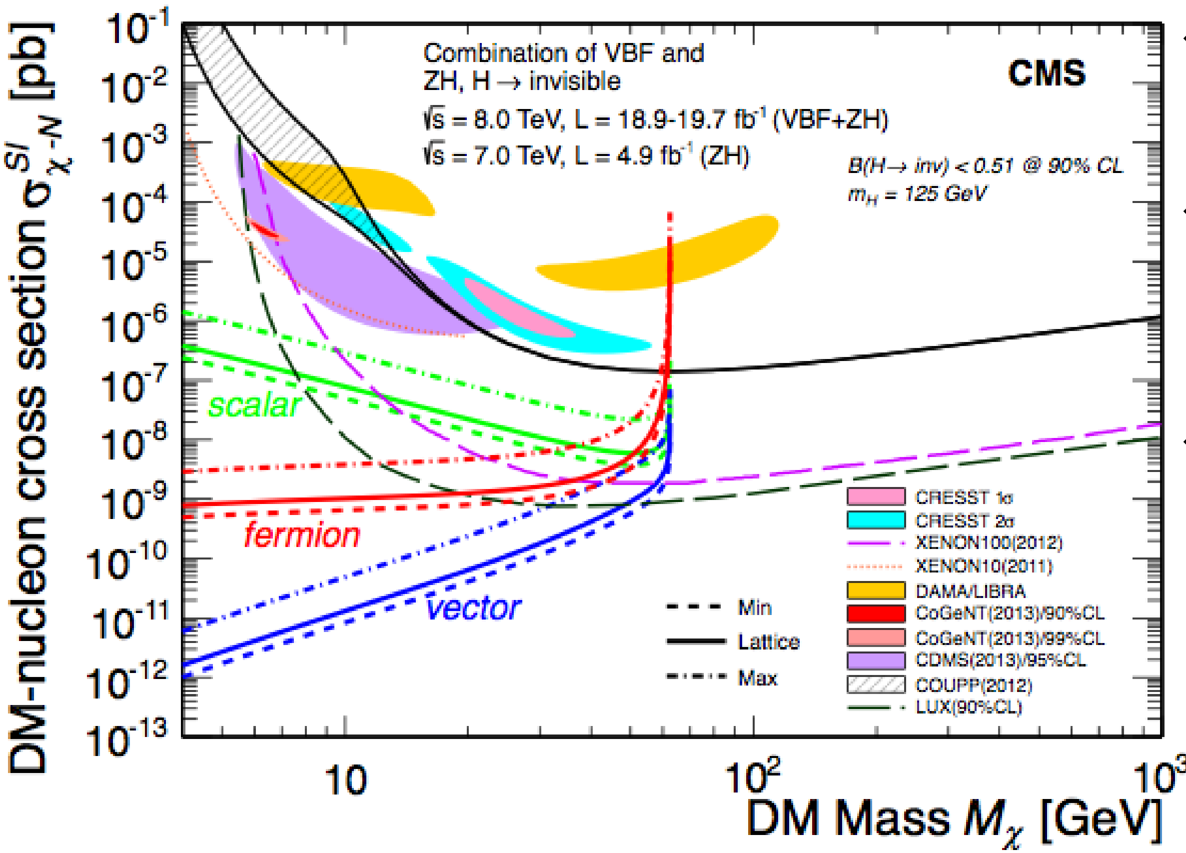


Variable	Selection Low p_T	Intermediate p_T	High p_T
E_T^{miss}	100–130 GeV	130–170 GeV	>170 GeV
p_T^{j1}	>60 GeV	>60 GeV	>60 GeV
p_T^{j2}	>30 GeV	>30 GeV	>30 GeV
p_T^{jj}	>100 GeV	>130 GeV	>130 GeV
M_{jj}	<250 GeV	<250 GeV	<250 GeV
CSV_{max}	>0.679	>0.679	>0.679
CSV_{min}	>0.244	>0.244	>0.244
N additional jets	<2	—	—
N leptons	=0	=0	=0
$\Delta\phi(Z,H)$	>2.0 radians	>2.0 radians	>2.0 radians
$\Delta\phi(E_T^{miss},j)$	>0.7 radians	>0.7 radians	>0.5 radians
$\Delta\phi(E_T^{miss},E_{T\,trk}^{miss})$	<0.5 radians	<0.5 radians	<0.5 radians
E_T^{miss} significance	>3	not used	not used



Higgs portal to DM: Combined Results

arXiv:1404.1344v2

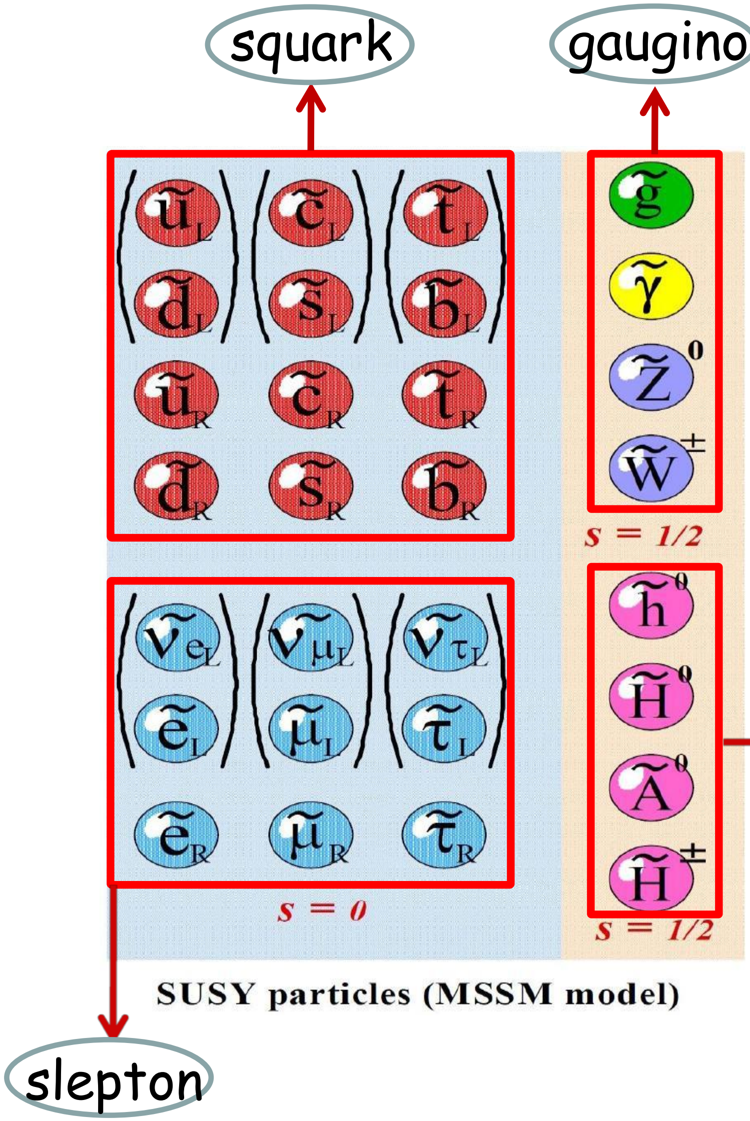


- 90% CL observed upper (expected) limit on B(H→inv) = 0.51(0.38)
- 95% CL observed upper (expected) limit on B(H→inv) = 0.58(0.44)
- Upper limits on the spin-independent DM-nucleon cross section in Higgs-portal models, derived for mH = 125GeV, and B(H→inv) < 0.51 at 90% CL, as a function of the DM mass.

See, for example, arXiv:1405.3530 for further reading; **Pyungwon Ko's talk**

Part II : Supersymmetry (SUSY)

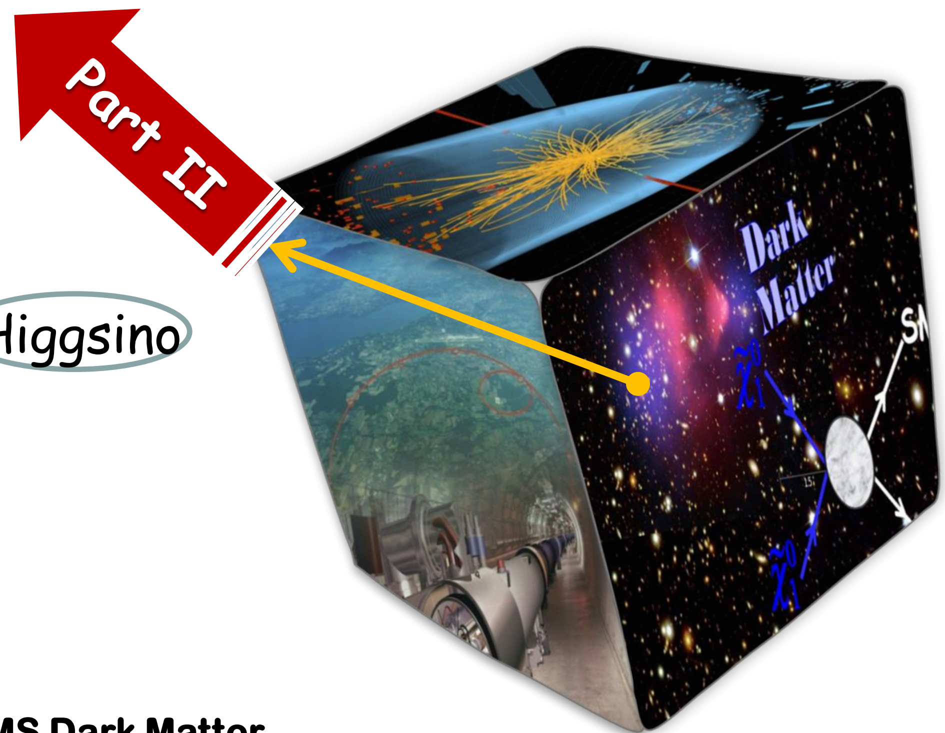
- Fermion ↔ Boson
- R parity conserving SUSY: Lightest neutralino (Lightest non-colored gaugino) $\tilde{\chi}_1^0$ → cold dark matter candidate



SUSY particles (MSSM model)

After EW symmetry breaking,

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



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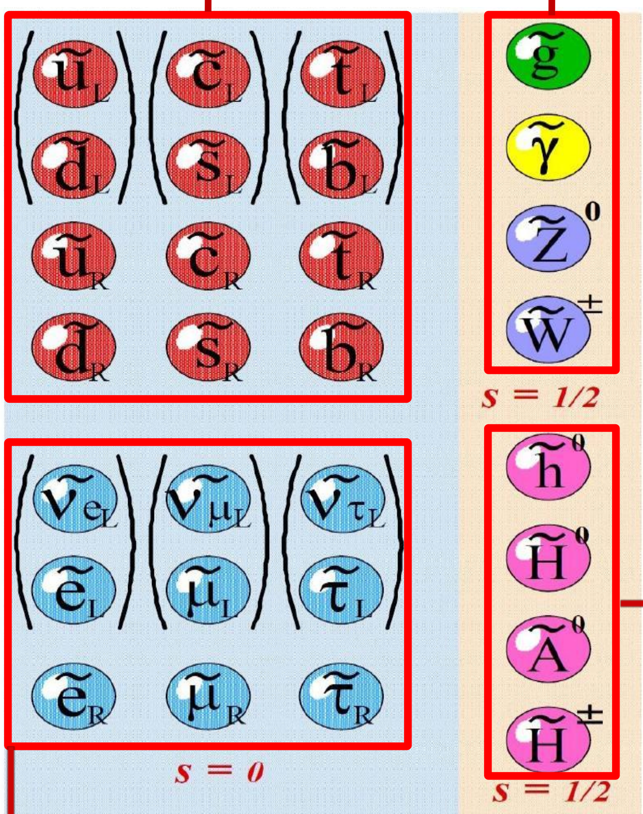

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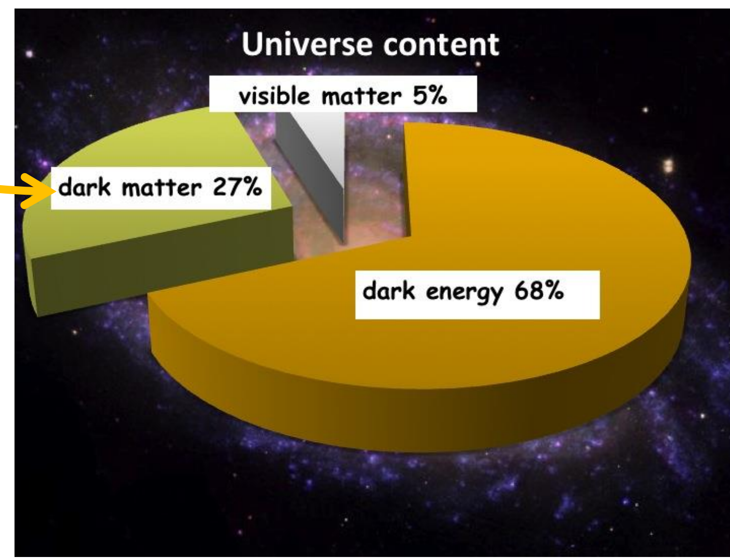
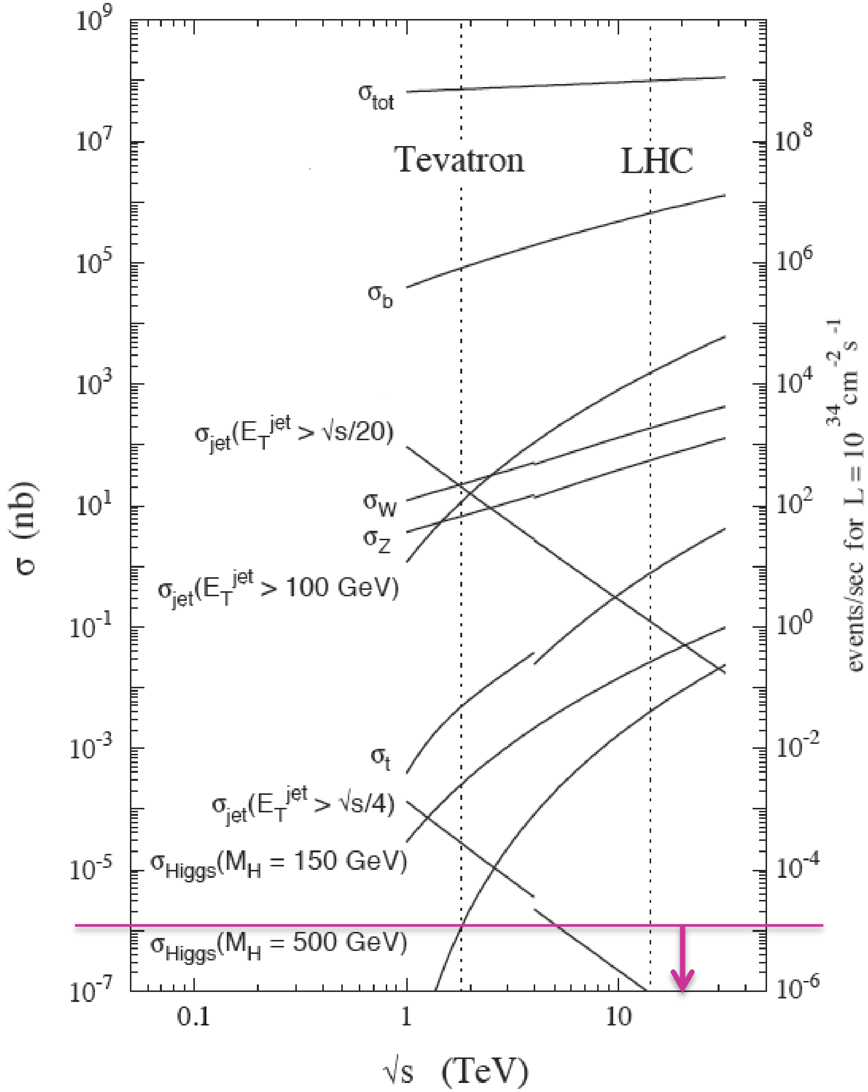


(Planck, 2013)

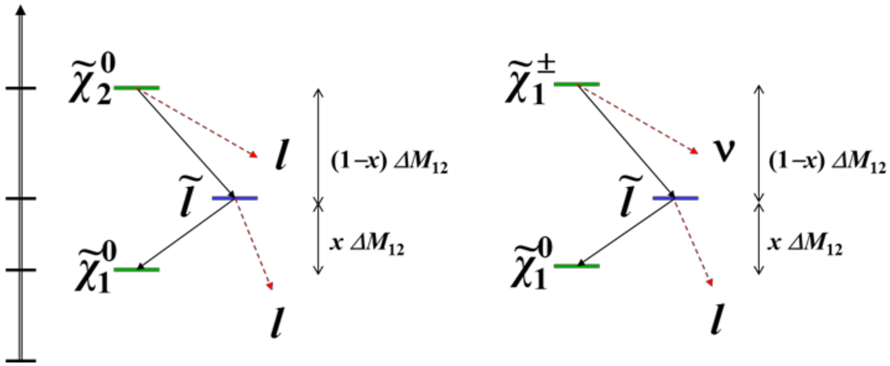
SUSY Wanted



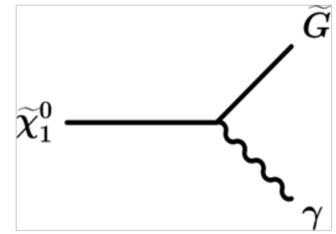
- ❖ Gluinos
- ❖ $1^{st}/2^{nd}$ generation scalar quarks (squaks)
- ❖ 3^{rd} generation squarks (stop, sbottom)
  - ○ Stop could be light to give the 125-GeV Higgs mass a reasonable correction.
- ❖ Charginos (C1, C2), Neutralinos (N1, N2, N3, N4), decaying into:
  - ❑ Leptons
  - ❑ Higgs
  - ❑ Z
- ❖ LSP?
  - ❑ Lightest Neutralino (N1): Bino-like, Wino-like, Higgsino-like, Bino-Higgsino-like ..
  - ❑ Gravitino
- ❖ Sleptons
  - ❑ Selectrons and smuons are mass degenerate.
  - ❑ Special case: Stau is lighter.
- ❖ RPV

Examples of SUSY Probe Metric

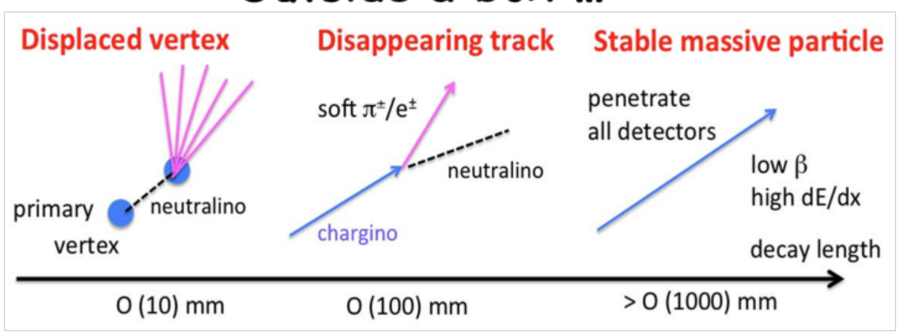
Multiple Leptons + MET



Photons + MET

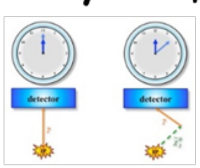


Outside a box …



"non-pointing" γ

"delayed" γ

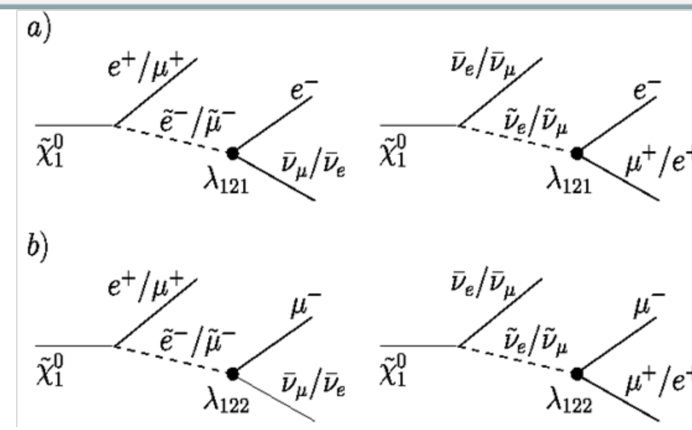


Multiple Leptons + no "MET"

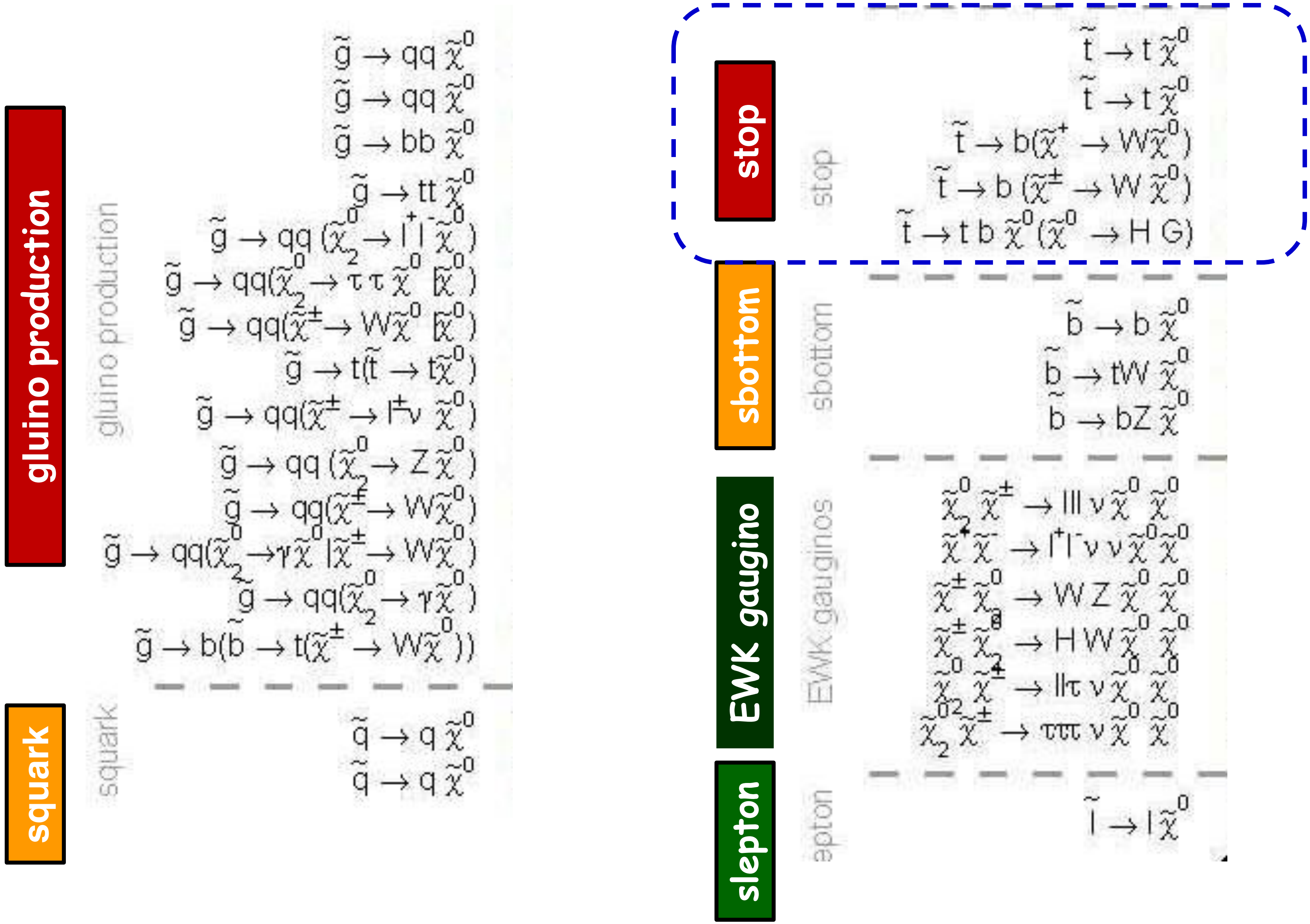
$$W_{RPV} = \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + k_i L_i H_u + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k$$

Lepton Number Violation

Baryon Number Violation

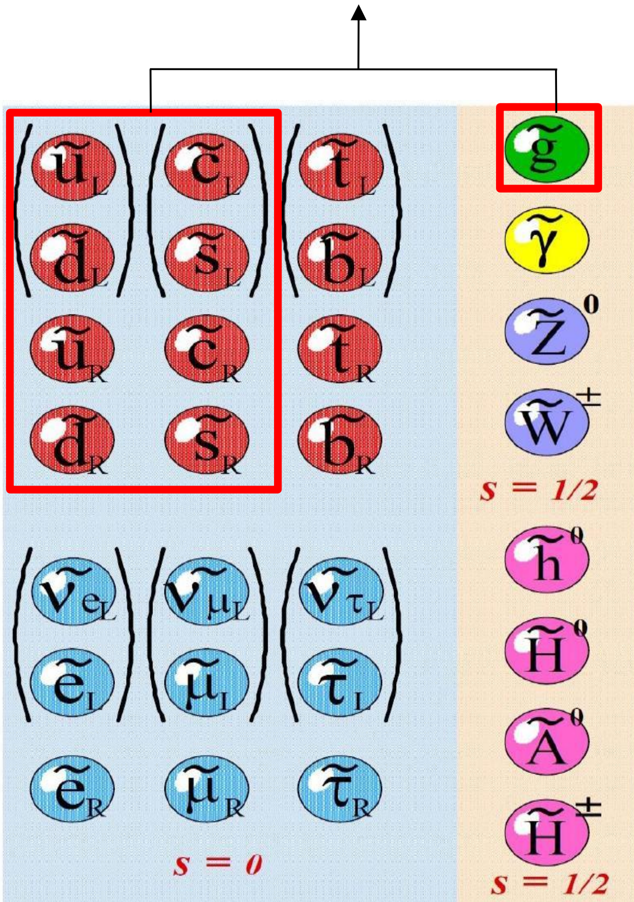


Closer Look at CMS SUSY Searches

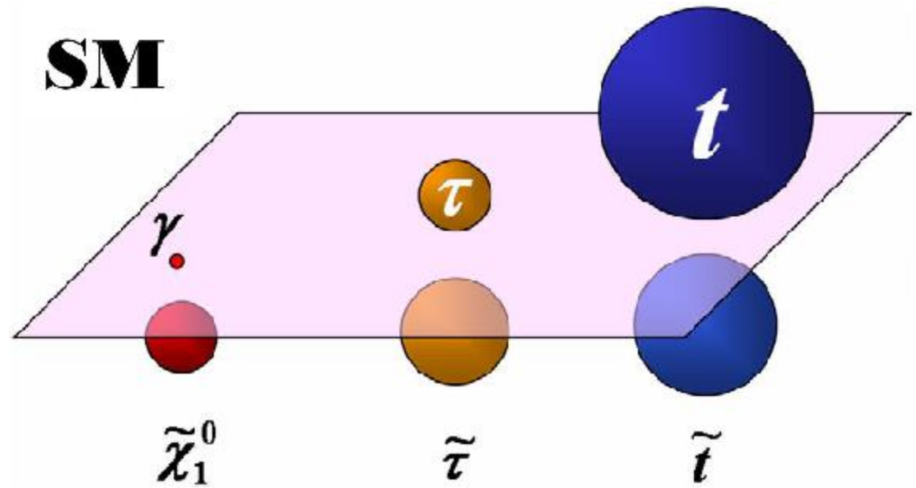


Light 3rd Generation Squarks

ATLAS and CMS 8-TeV: > 1.5 TeV
if $m_{\tilde{g}} \approx m_{\tilde{q}}$
[hep-ex/1208.0949], [1206.1760], [1207.1898]



SUSY particles (MSSM model)

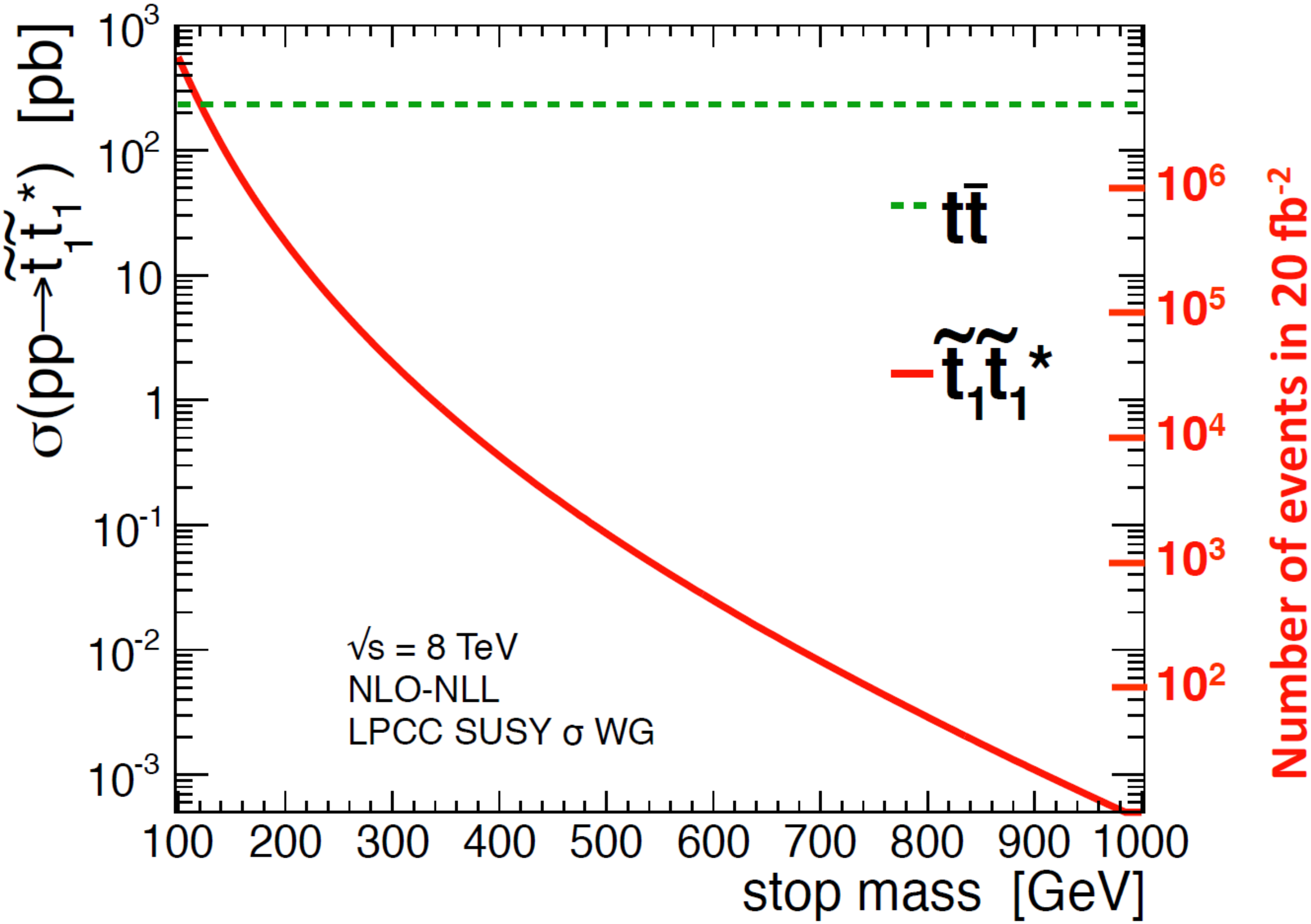


Neutral-ino S-tau S-top

SUSY

Top Squark Search Challenge

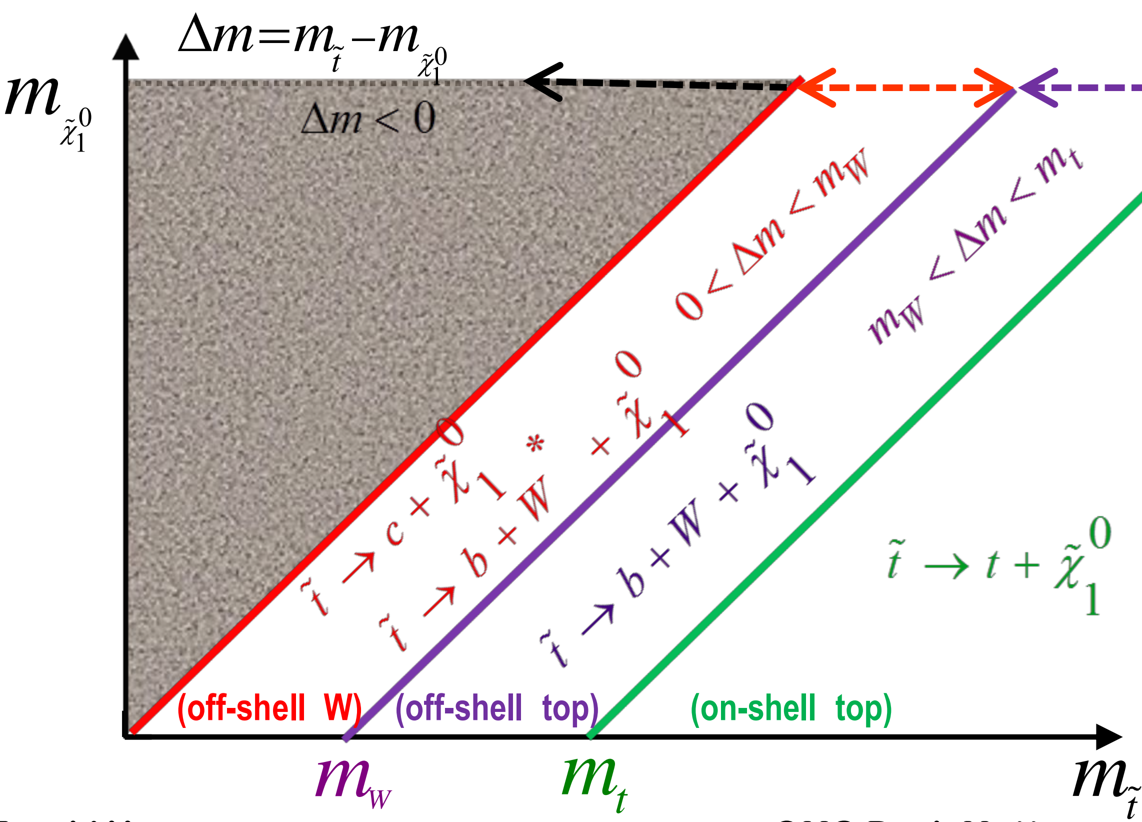
- Small production cross section.
- t-tbar background is huge.

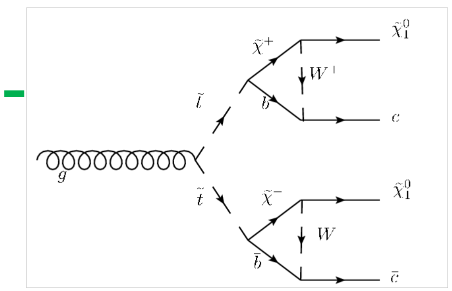


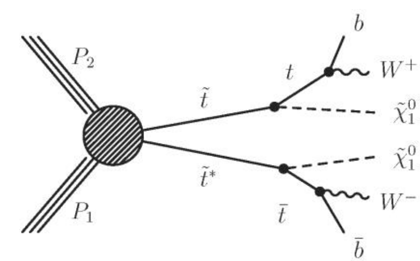
Top Squark Decay Modes

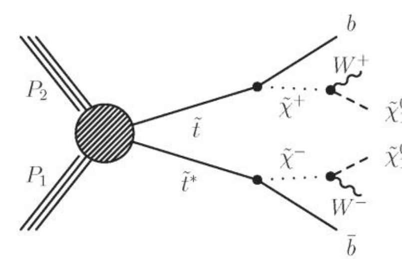
Stop decay ← Stop mixing & neutralino/chargino composition & $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$

LSP	Allowed stop decays	Why
$\tilde{\chi}_1^0 = \tilde{B}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_R \tilde{\chi}_1^0$	U(1) couples L to L and R to R
$\tilde{\chi}_1^0 = \tilde{W}_3$	$\tilde{t}_L \to t_L \tilde{\chi}_1^0$	SU(2) only acts on L
$\tilde{\chi}_1^0 = \tilde{H}_d^0$	none	Only couples to down-type
$\tilde{\chi}_1^0 = \tilde{H}_u^0$	$\tilde{t}_L \to t_R \tilde{\chi}_1^0 \quad \tilde{t}_R \to t_L \tilde{\chi}_1^0$	Higgs couple L to R (mass term)

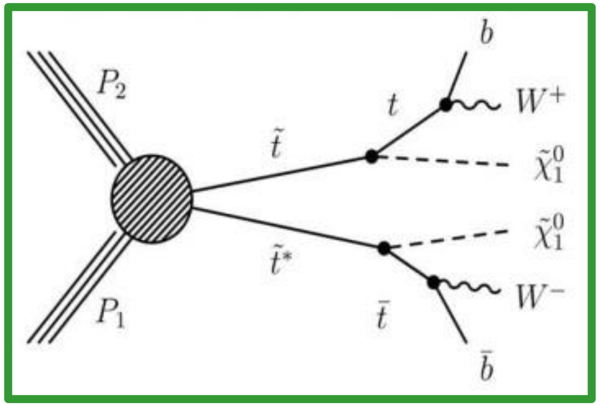


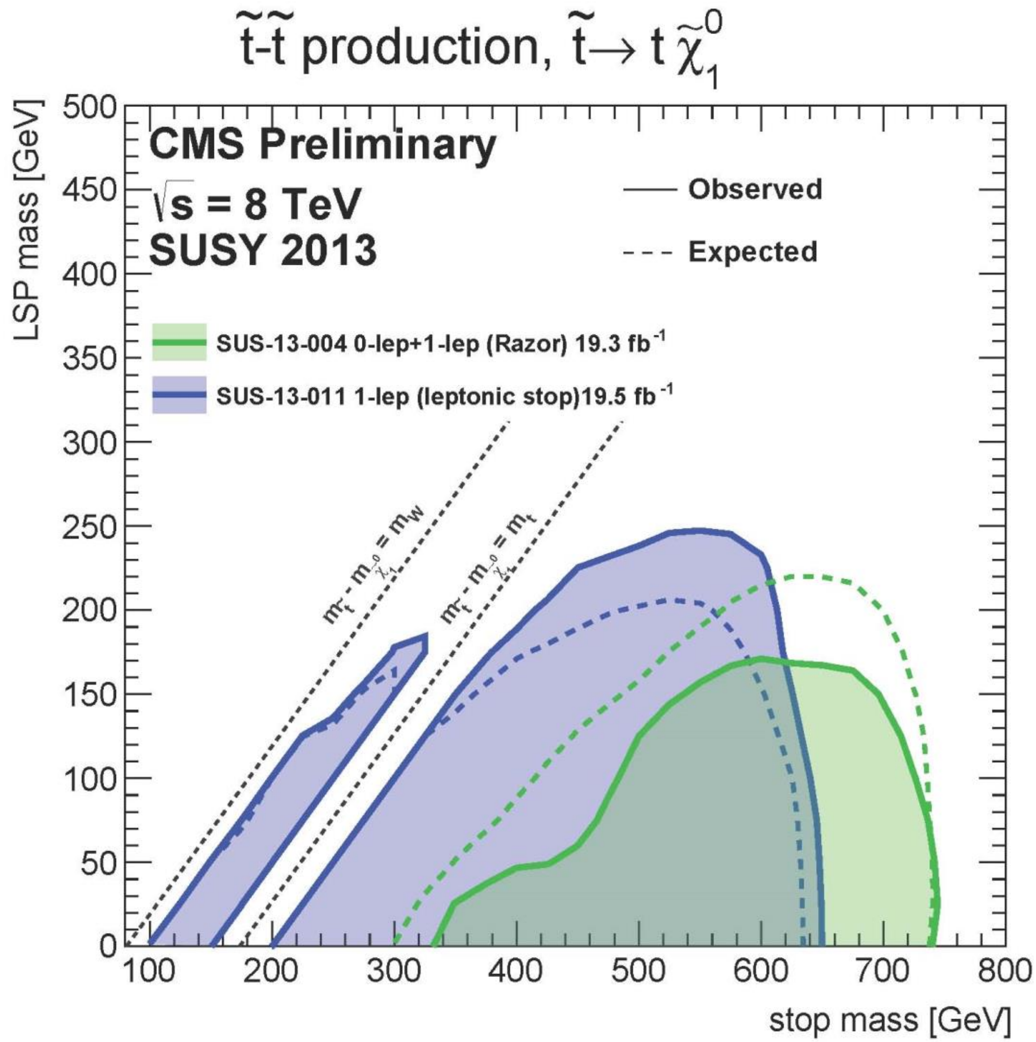




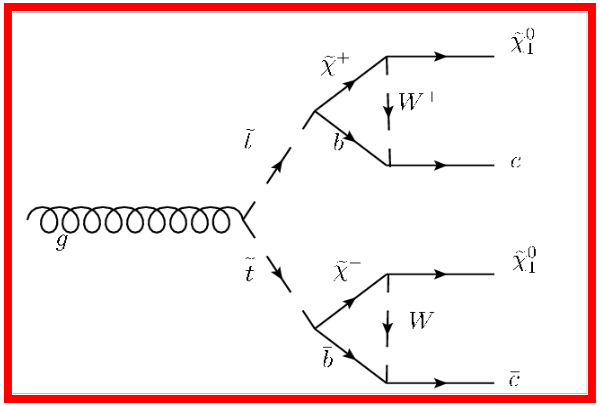


Top Squark: Result (I)

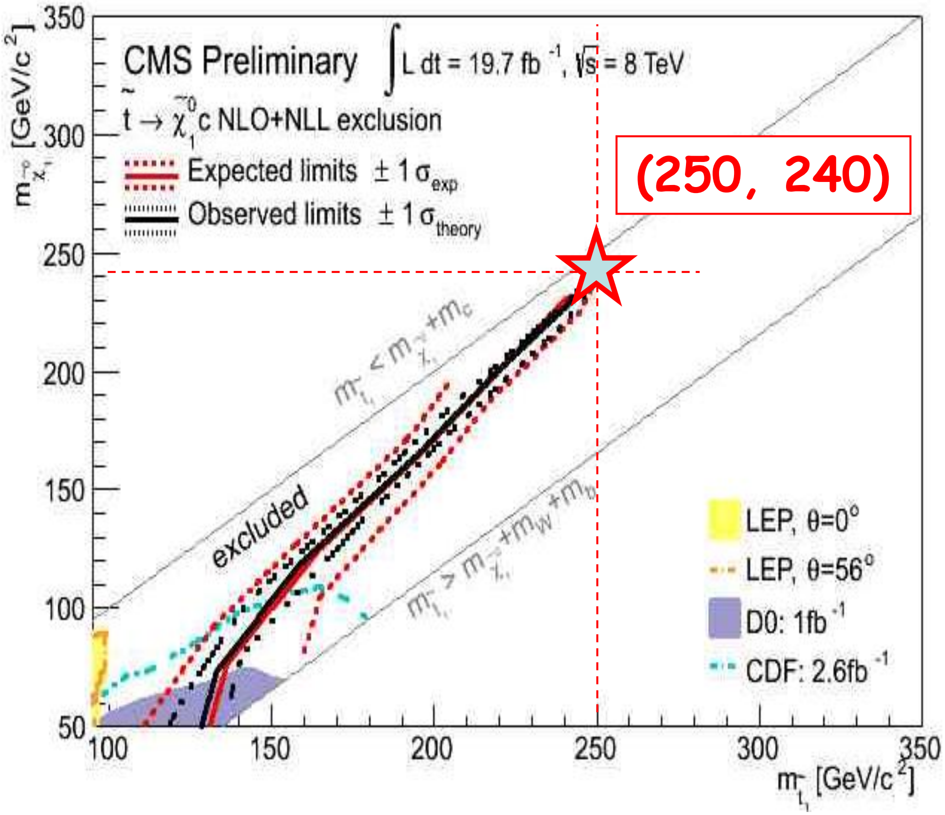


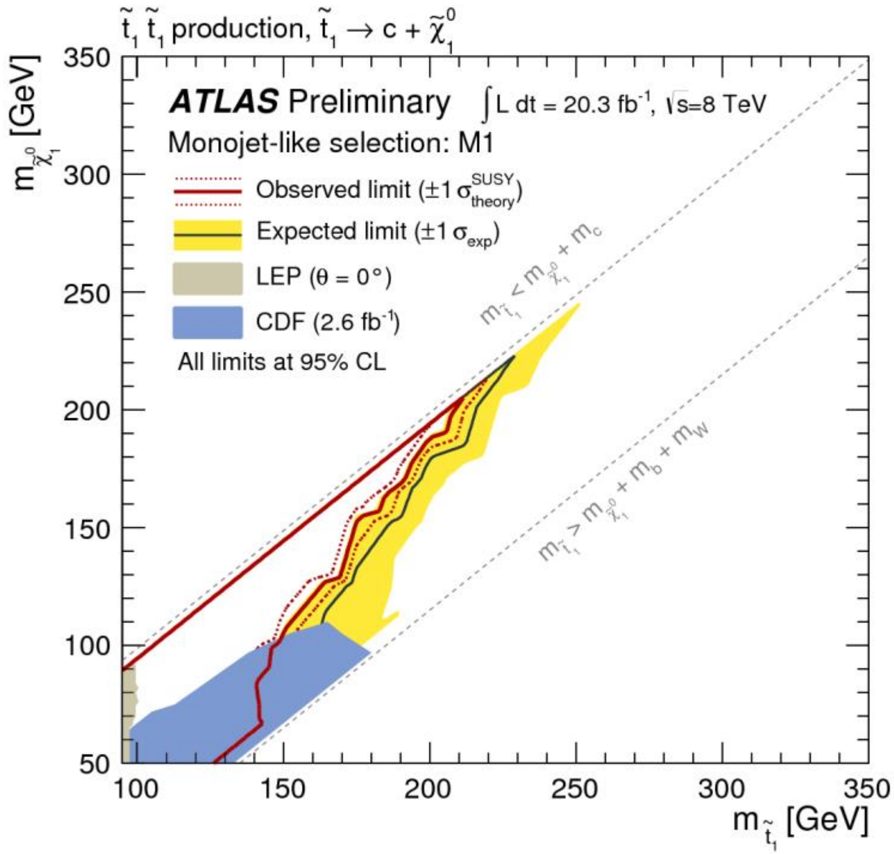


Top Squark: Result (II)

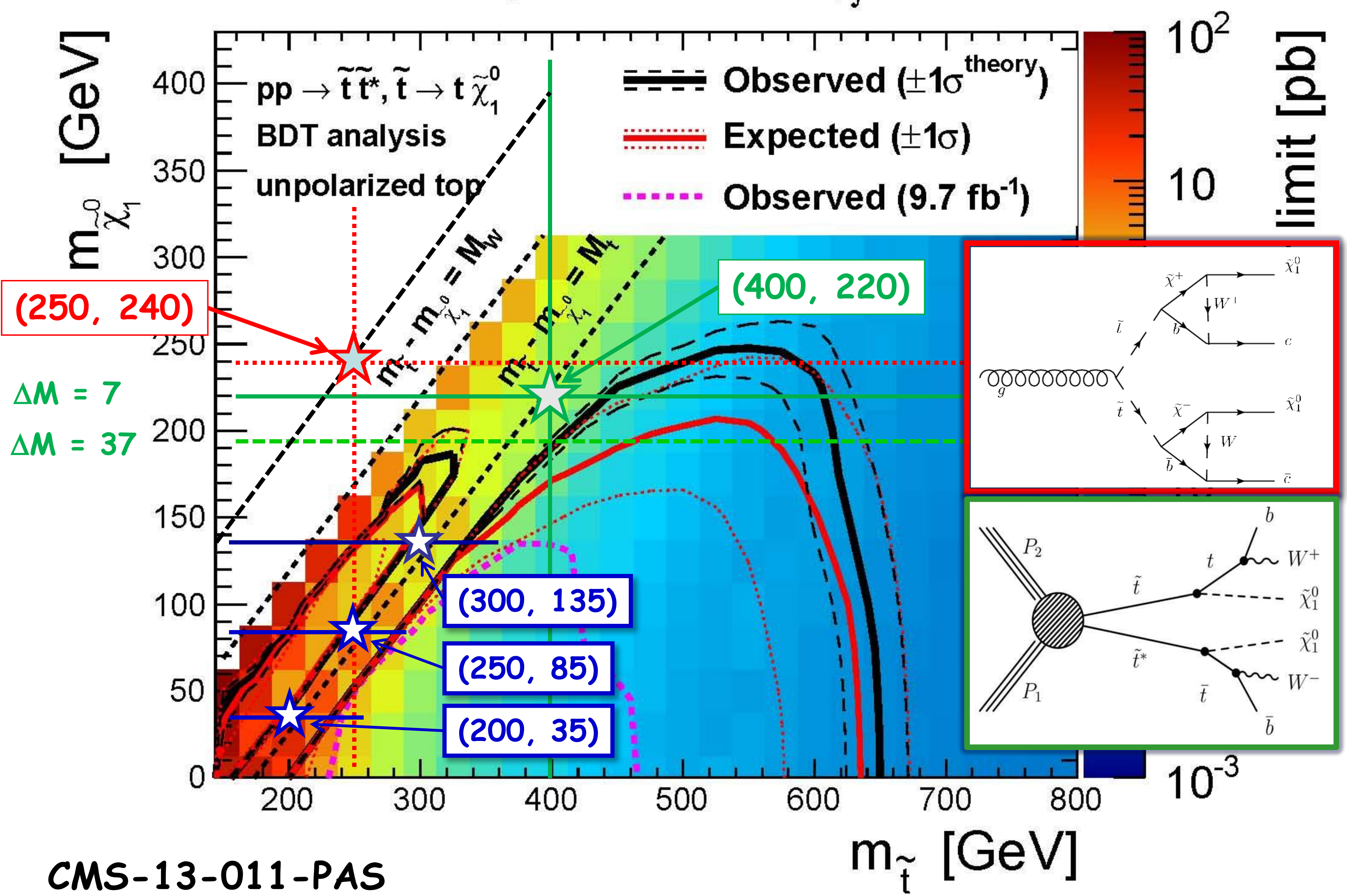


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13009



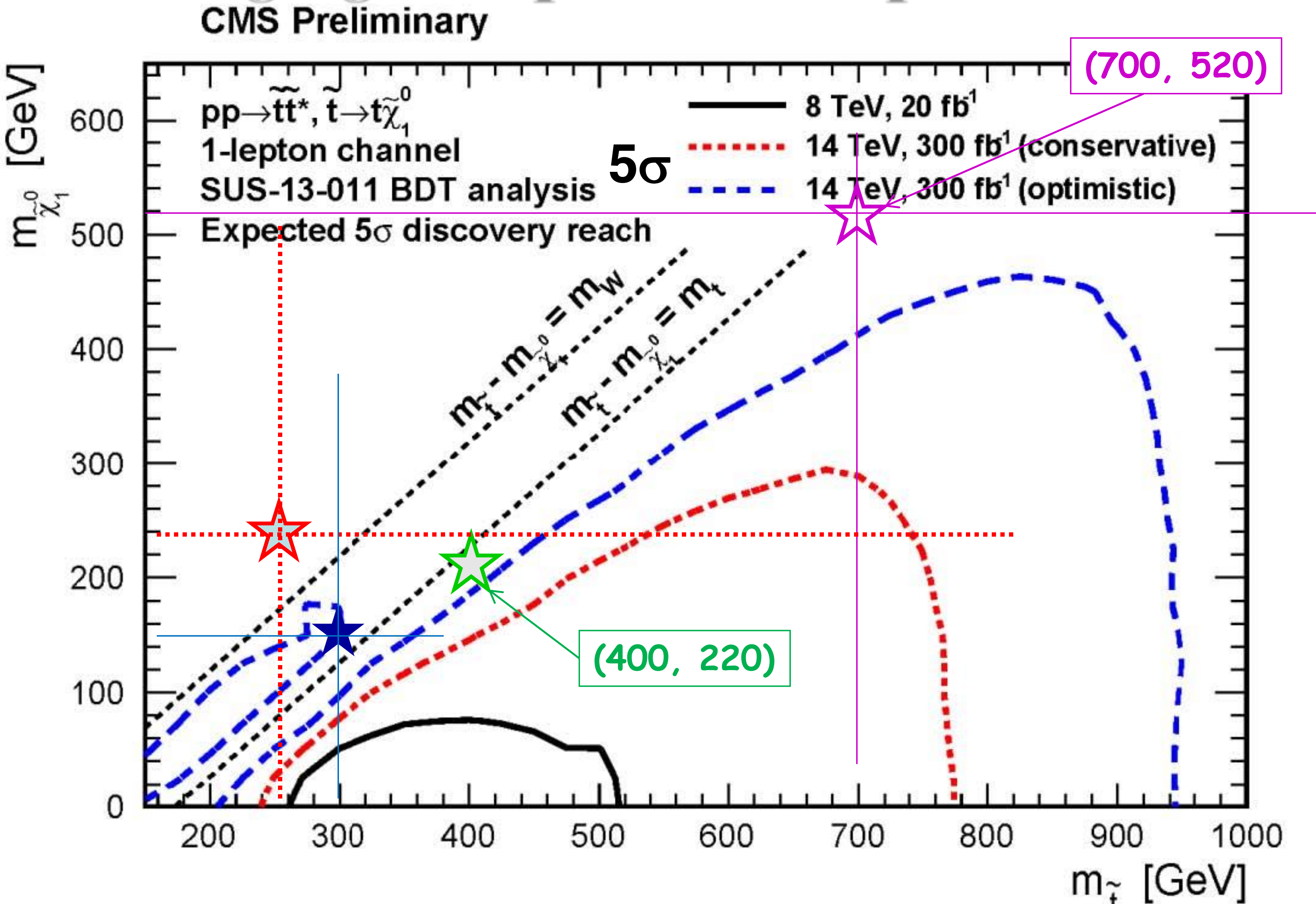


EPJC 73 (2013) 2677: Fig.10(a)

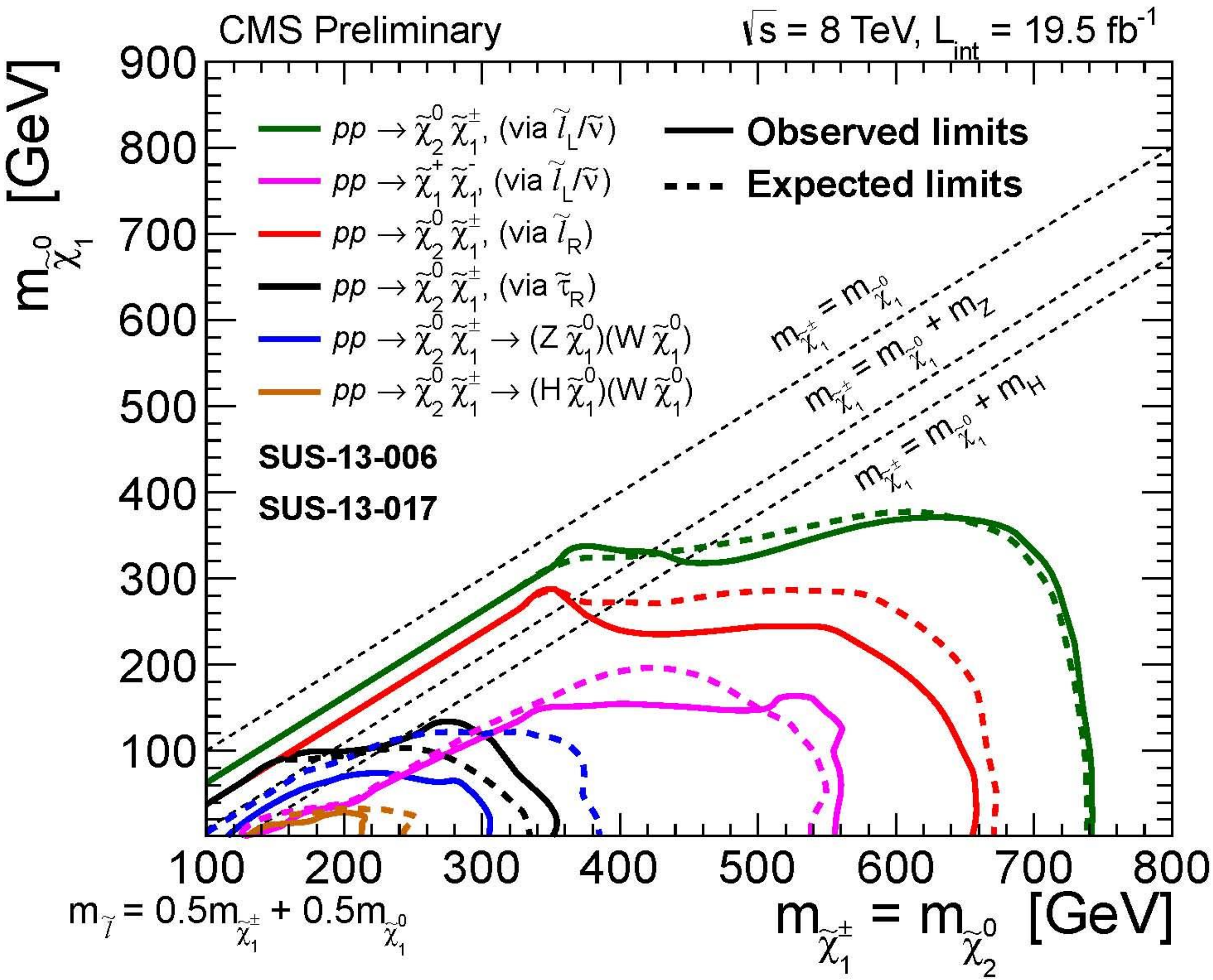


CMS-13-011-PAS

Challenging Compressed Stop at 14 TeV

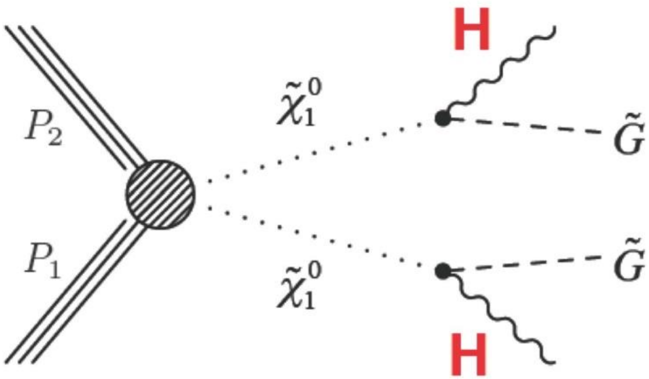


Charginos/Neutralinos

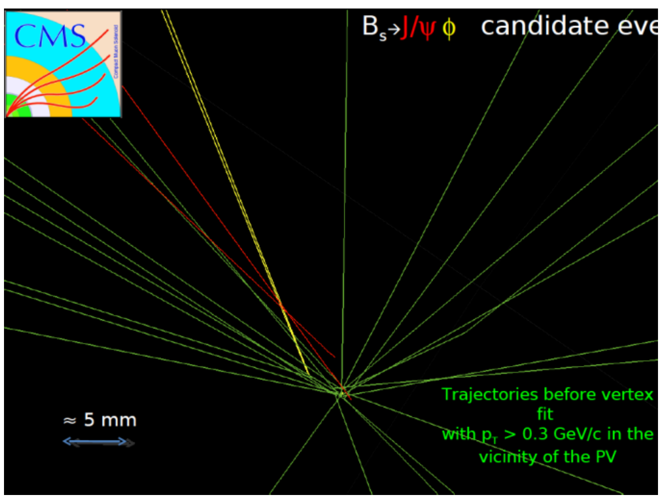


Electroweak Production of Higgsinos

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13022

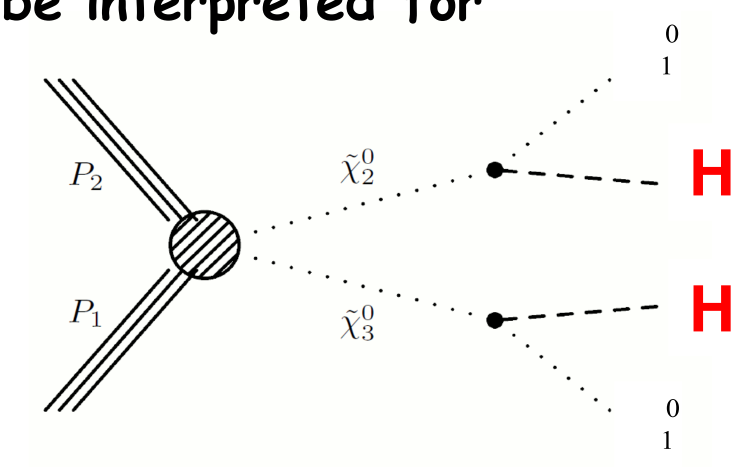


- Search for SUSY partner of the Higgs boson
- Each Higgsino decay into a Higgs boson and dark matter
- Each Higgs boson decays into 2 bottom quarks most often, so search for that



- Lifetime of B meson is 1.5×10^{-12} seconds
- Silicon tracker detector precise enough to identify B's from "displaced" particles!

Can be interpreted for

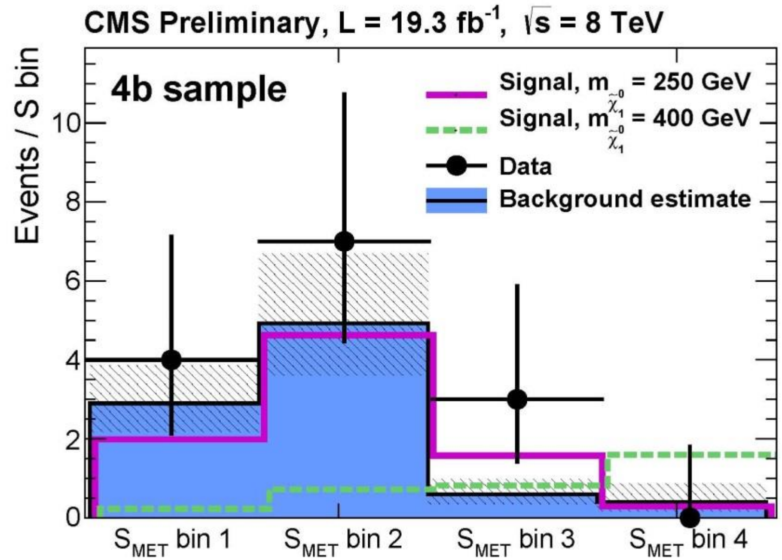


Lighter LSP

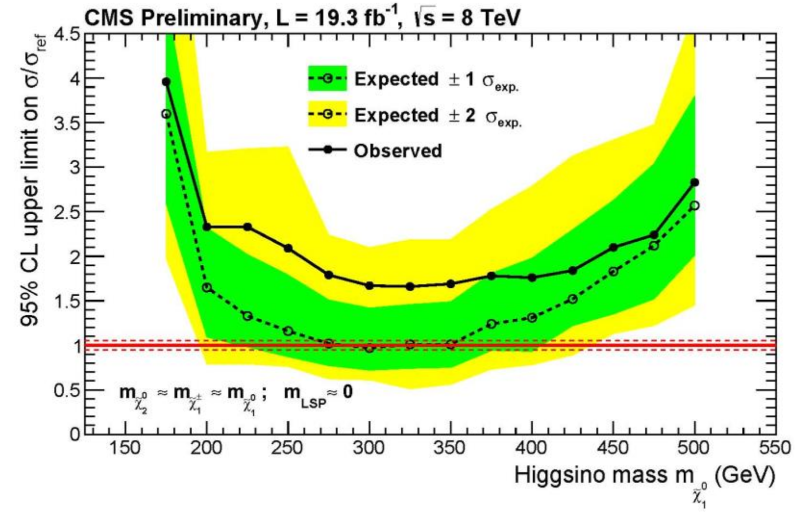
Higgsino Search Interpretation

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13022

- After all selection and background estimation, compare standard model prediction with observation in data
- Some small excess in data, but results consistent with background only expectation within uncertainties



- Interpret null search result as limits on Higgsino production
- The first search of its kind!

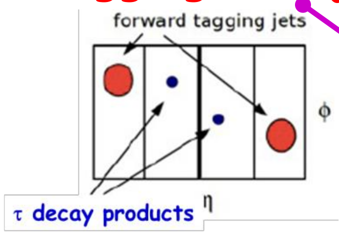


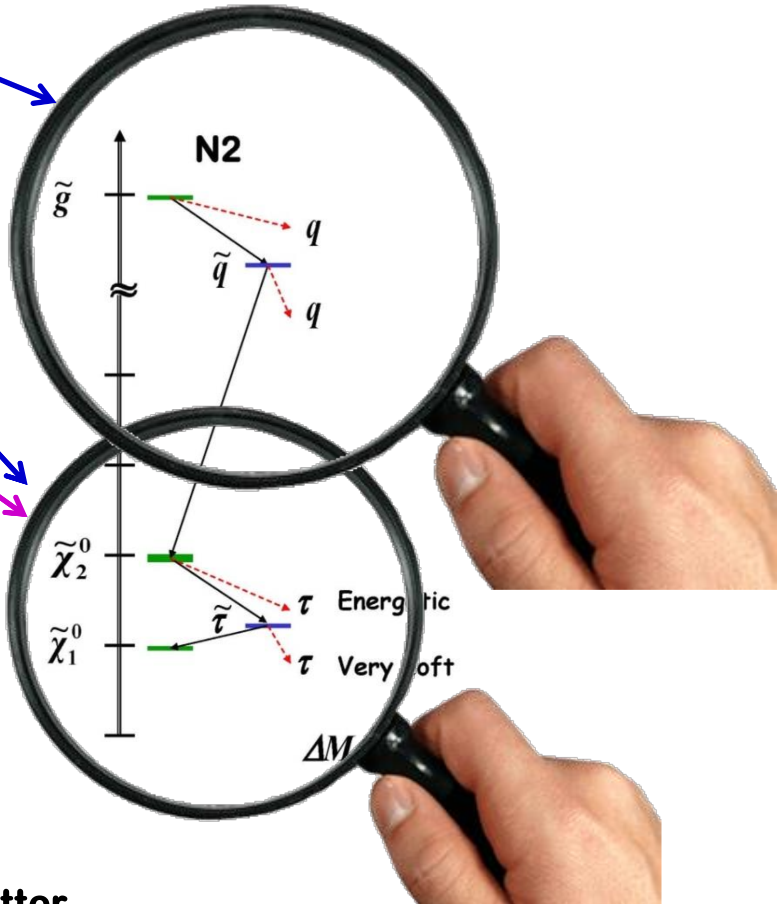
EWKino Summary

- Wino-Chargino and Bino-LSP
  - ✓ Up to 640 and 300 GeV for light slepton case
  - ✓ Up to 340 and 100 GeV for W and Z cases
- Weaker limits for
  - ✓ heavy slepton
  - ✓ being Higgsinos
  - ✓ small mass difference (compressed spectra)

Personal Remark 1: VBF Topology

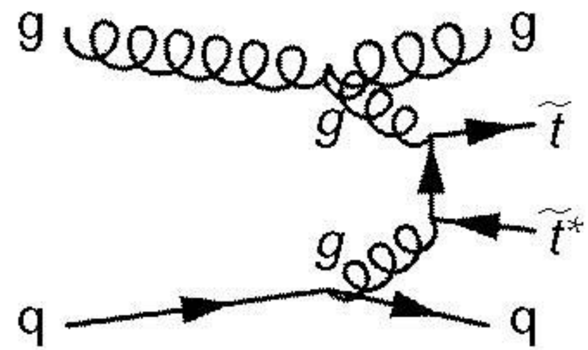
- [Question] How can we probe colorless SUSY sector if (i) heavy 1st/2nd generation squarks and gluino, and (ii) small ΔM (mass difference between NLSP and LSP)?
- [Answer]
  1) Tagging energetic jets (+ MET) from cascade decays?
  2) Tagging leptons?
  3) Tagging VBF jets → WW Collider

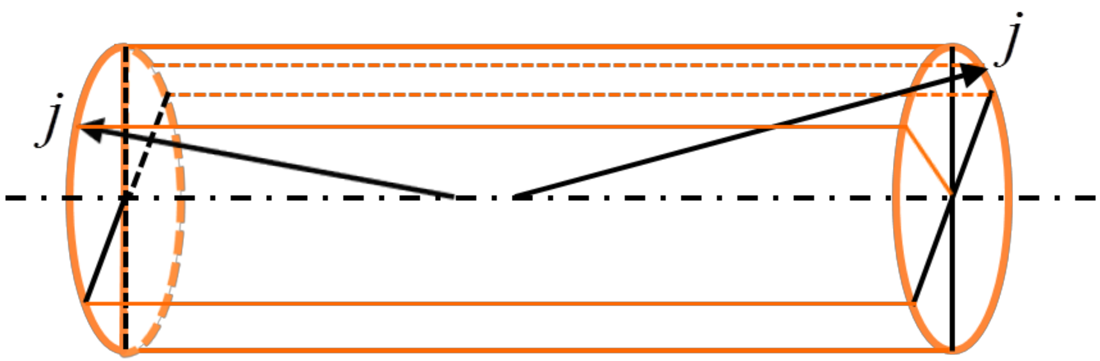




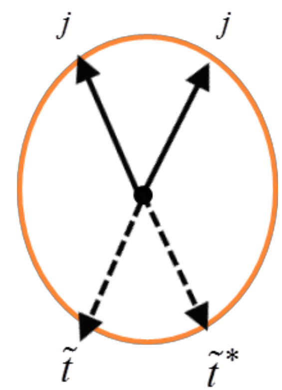
1) A. Datta, P. Konar, and B. Mukhopadhyaya, "Invisible Charginos and Neutralinos from Gauge Boson Fusion: A Way to Explore Anomaly Mediation", PRL 88 (2002) 181802.
2) G. Giudice, T. Han, K. Wang, and L.T. Wang, "Nearly Degenerate Gauginos and Dark Matter at the LHC", PRD 81 (2010) 115011
3) B. Dutta, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, K. Sinha, "Vector Boson Fusion Processes as a Probe of Supersymmetric Electroweak Sectors at the LHC", PRD 87 (2013) 035029
4) A.G. Delannoy, B. Dutta, A. Gurrola, W. Johns, T. Kamon, E. Luiggi, A. Melo, P. Sheldon, K. Sinha, K. Wang, S. Wu, "Probing Dark Matter at the LHC using Vector Boson Fusion Processes", PRL 111 (2013) 061801

VBF as Tool for Compressed SUSY





VBF tagged jets (2 energetic jets with large $\Delta\eta$ separation: large M(jj)) in forward region, opposite hemispheres)



VBF production topology in transverse plane

Personal Remark 2: X-PAG DM Searches

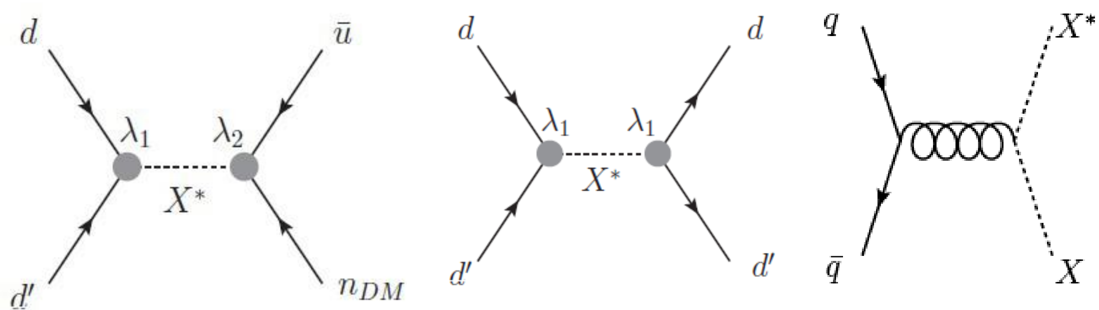
R. Allahverdi and B. Dutta, PRD 88 (2013) 023525
B. Dutta, Y. Gao, and T. Kamon, PRD. 89 (2014), 096009 (2014)

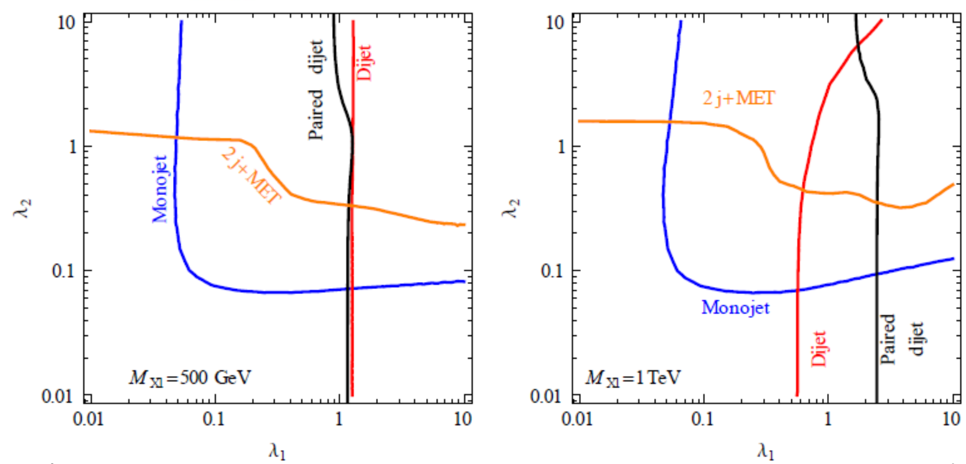
- A minimal extension to SM with ~TeV scalar color triplet(s) (X_1 and X_2) and a 1-GeV fermionic DM candidate (n_{DM})
- Baryon-number violating interaction mediated by heavy scalars (X)

$$\mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta} \epsilon^{ijk} X_{\alpha,i} \bar{d}^c_{\rho,j} \mathbf{P}_R d_{\delta,k} + \lambda_2^{\alpha,\rho} X^*_\alpha \bar{n}_{\rm DM} \mathbf{P}_R u_\rho + \mathrm{C.C.}$$

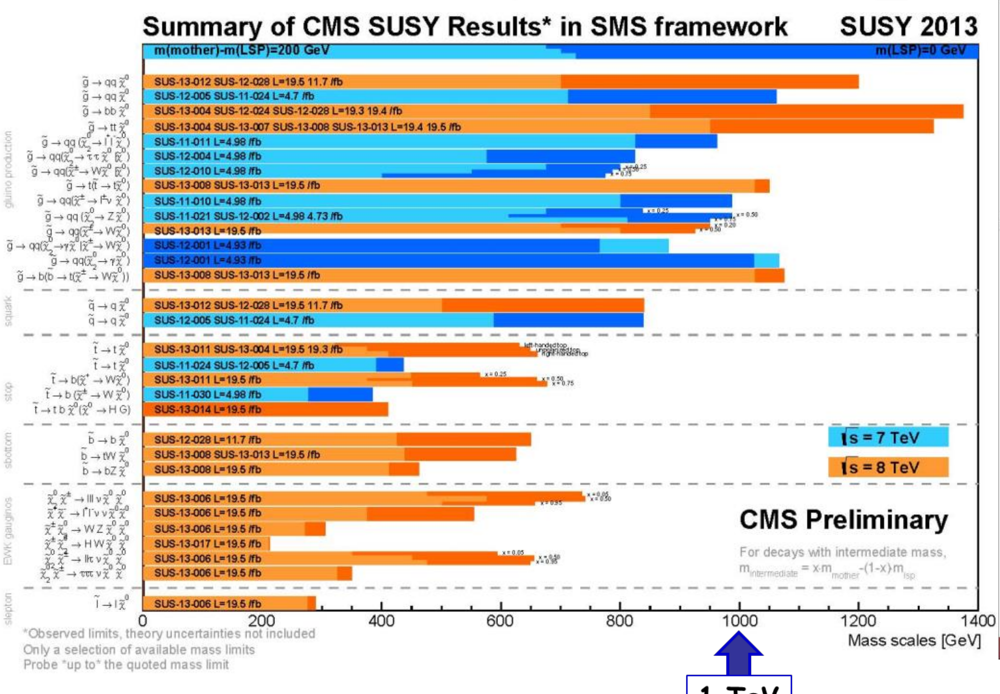
(e.g.) X-PAG DM Searches:

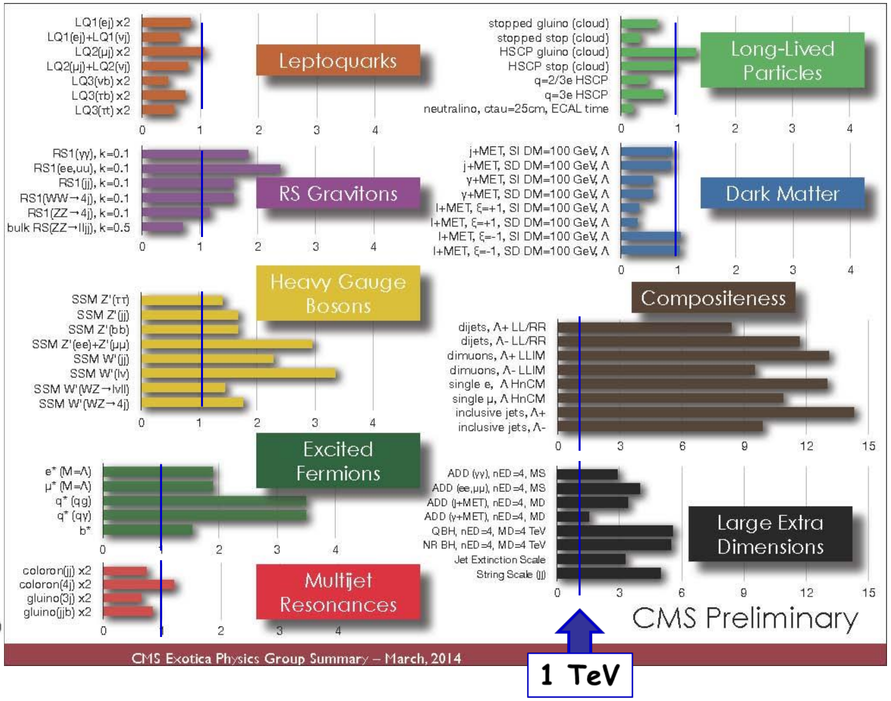
EXO-12-048 ... Monojet
EXO-12-059 ... Dijet resonance
EXO-12-052 ... Paired dijet
B2G-12-022 ... top + MET
B2G-13-004 ... di-top + MET
SUS-13-011 ... top squark production (di-top + MET)
JME-13-007 ... top tagging

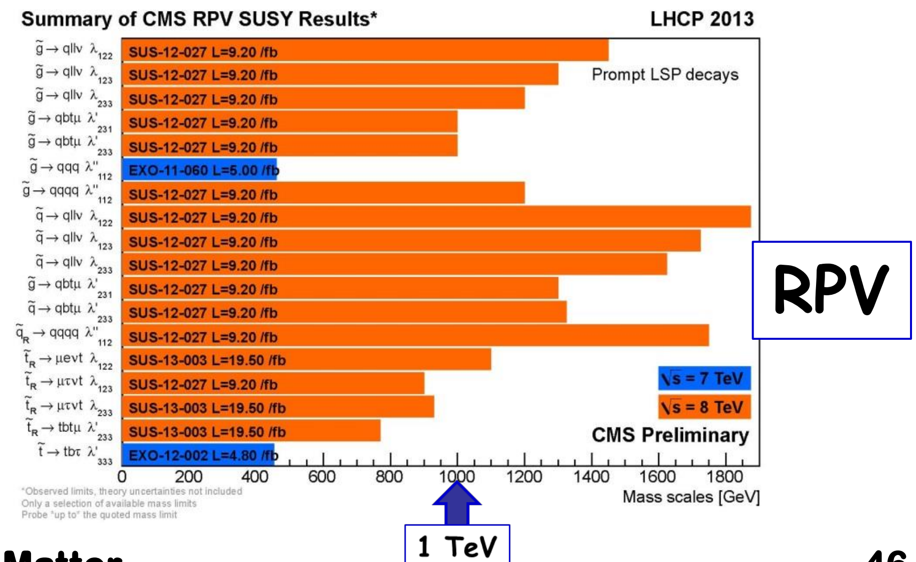




Summary: CMS probed a TeV scale

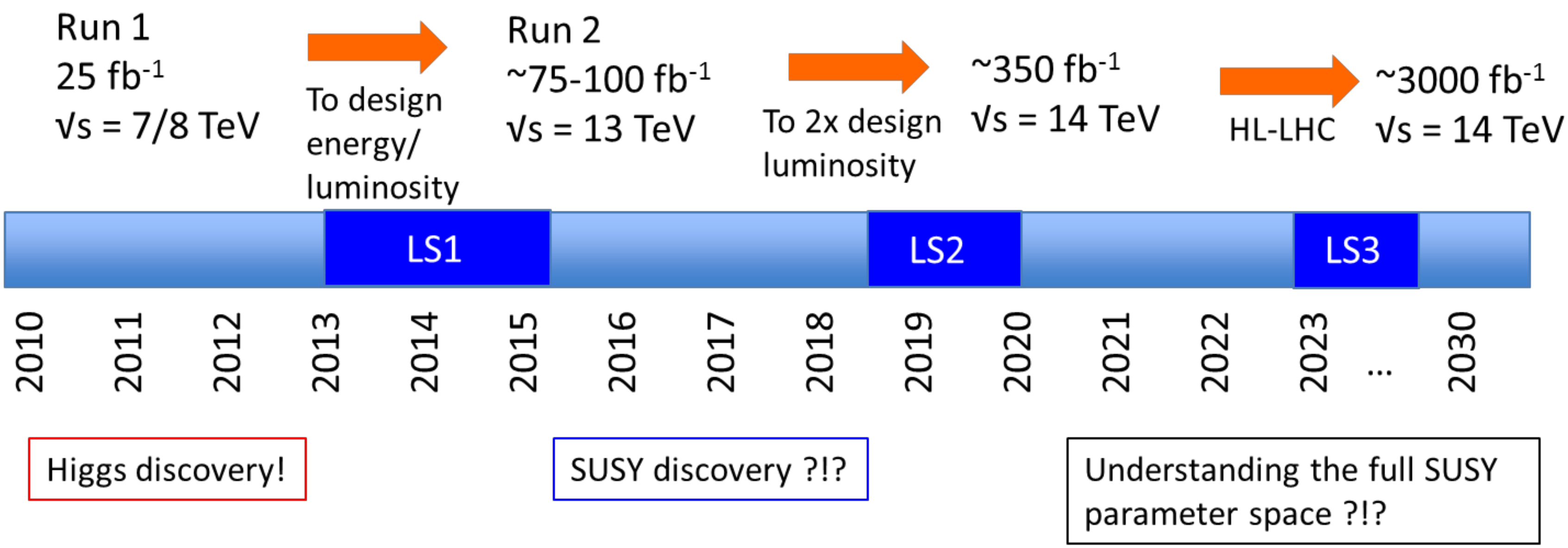




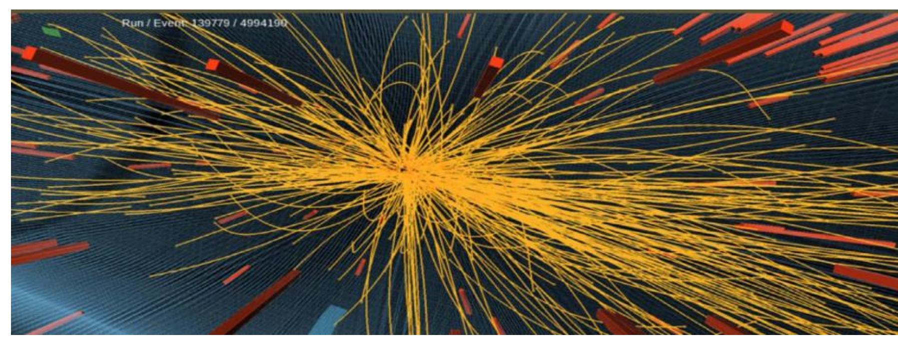


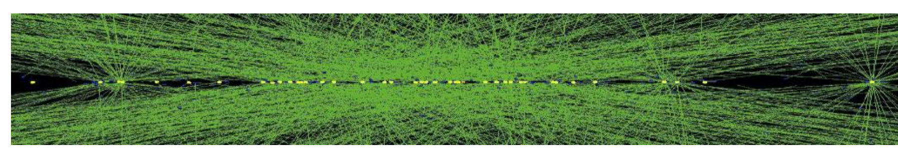
- ❖ No hints of DM particle (yet) in very diverse search programs
- ❖ LHC13/LHC33, ILC, FCC along with direct/indirect DM programs

CMS will probe a few TeV scale



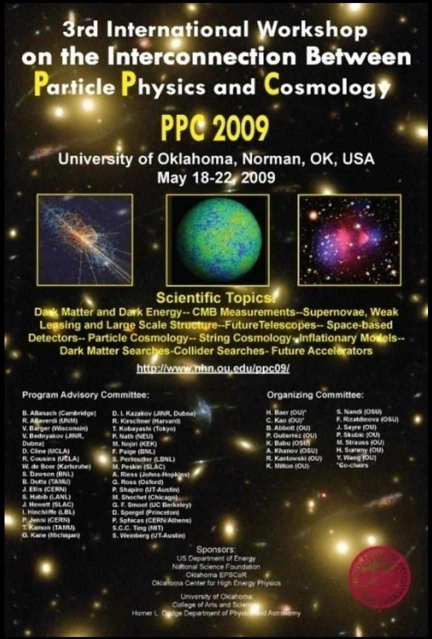
- No hints of DM particle (yet) in very diverse search programs
- LHC13/LHC33, ILC, FCC along with direct/indirect DM programs
- Upgraded detectors to maintain or improve triggers and physics object reconstruction
- Better understanding of BG



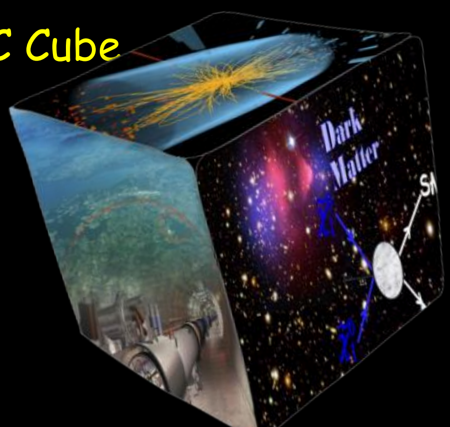


“PPC”

Interconnection between Particle Physics and Cosmology



PPC Cube



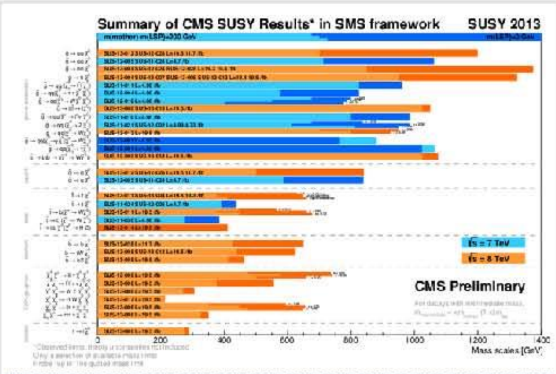
PPC 2011 at CERN, June 14-18
PPC 2012 at KIAS, Korea, Nov. 5-9
PPC 2013 at CETUP*, SD, USA, July 8-13
PPC 2014 at Univ. de Guanajuato, Mexico, June 23-27
PPC 2015 at ???

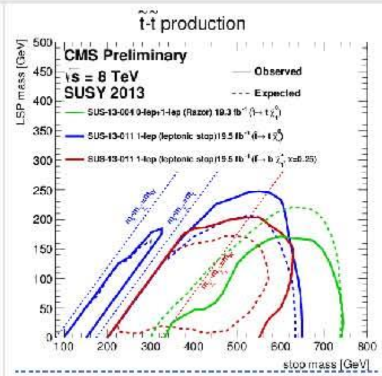
Backup

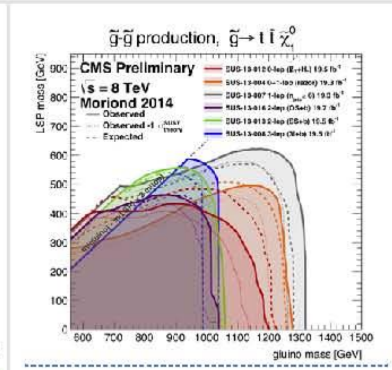
More CMS SUSY Searches

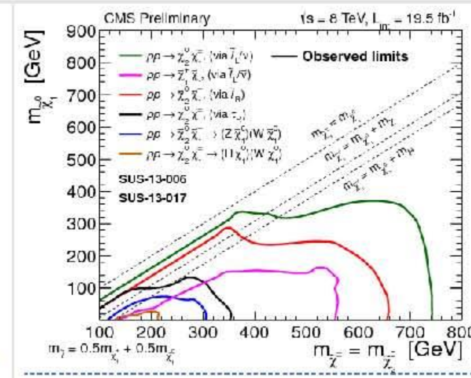
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Summary plots for 8TeV dataset (click here) NEW









Summary of exclusion limits of CMS SUSY searches	Summary of limits for direct stop searches	Summary of observed and expected limits for gluino pair production with gluino decaying via the 3-body decay top anti-top neutralino	Summary of observed limits for EWKino models

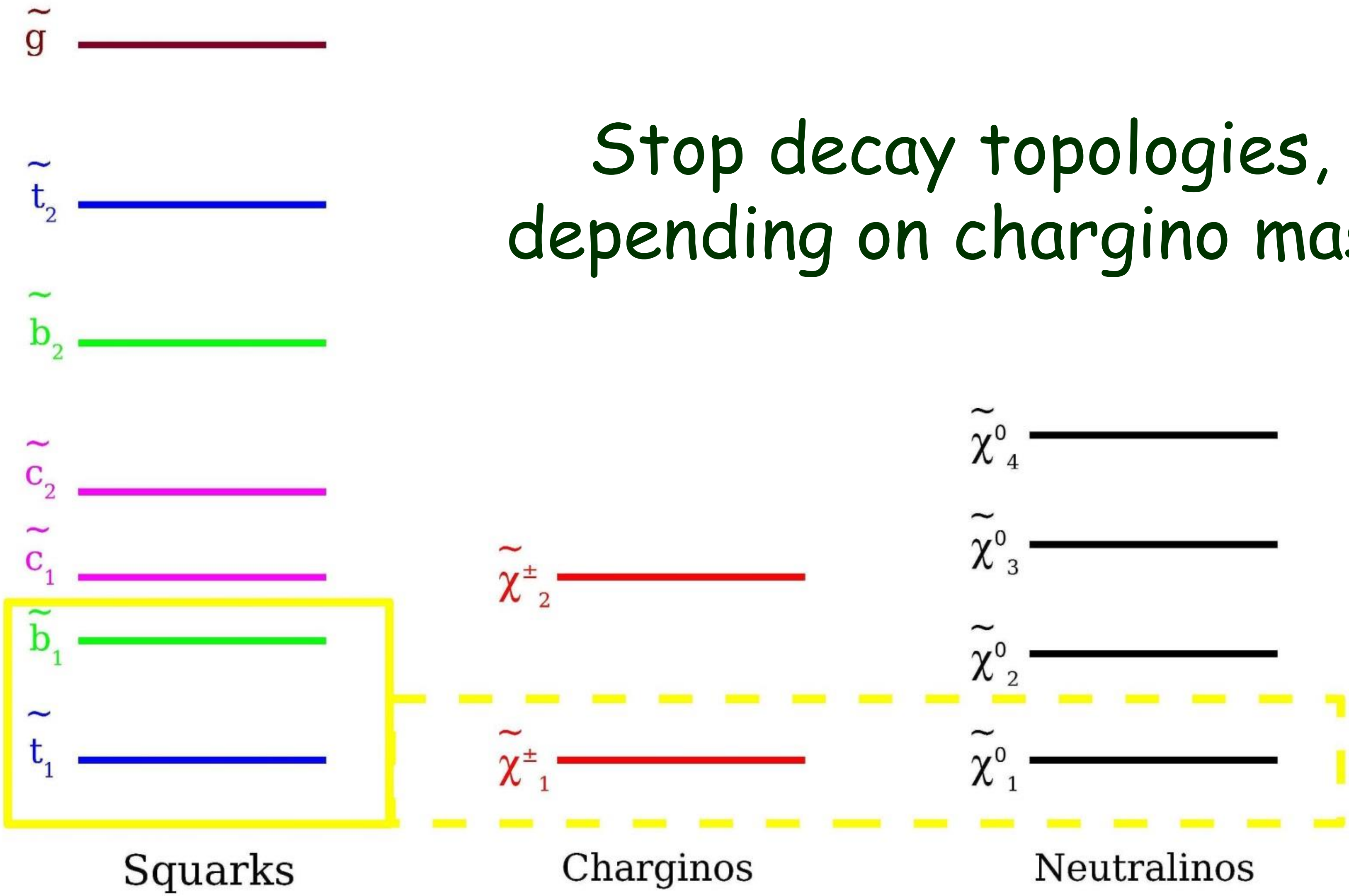
Journal Publications with 2012 8 TeV Data

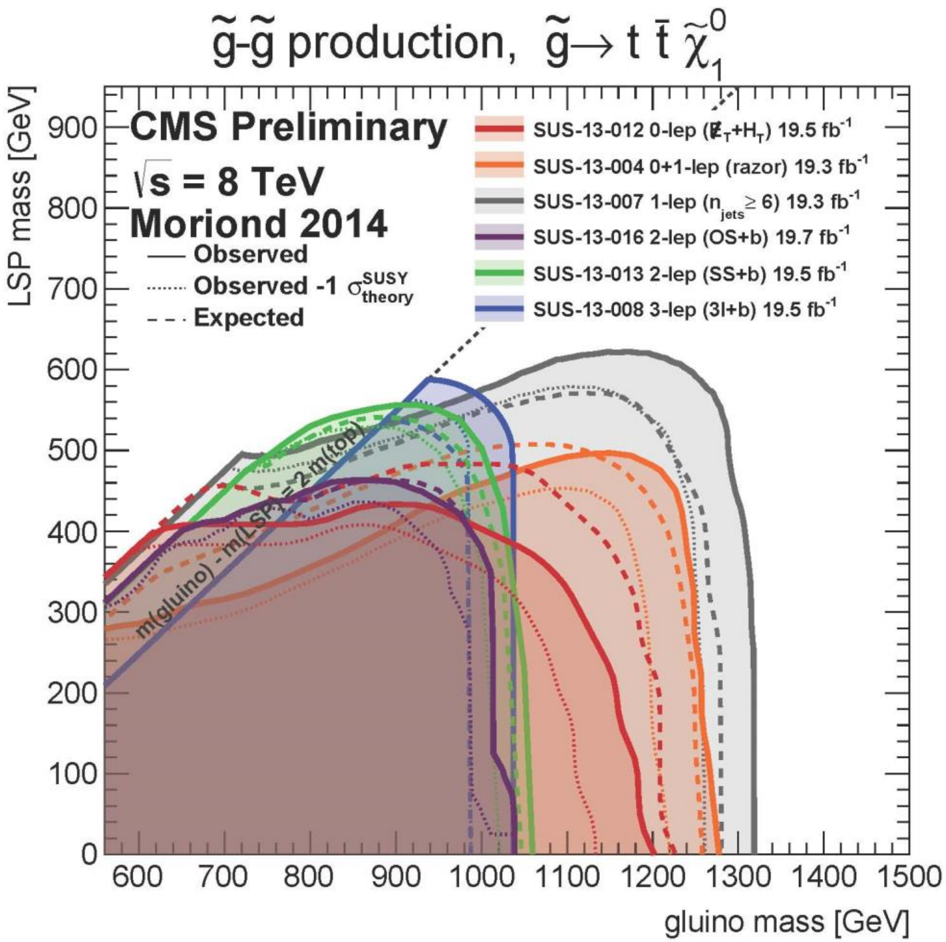
Analysis	Approved Plots	CDS Entry	Luminosity	Comment
Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W,Z, and Higgs bosons in pp collisions at 8 TeV		CMS-SUS-13-006	19.5/fb	Submitted to EPJC arXiv:1405.7570 NEW
Search for top-squark pair production with Higgs and Z bosons in the final state in pp collisions at 8 TeV	SUS13024	CMS-SUS-13-024	19.5/fb	Submitted to PLB arXiv:1405.3886 NEW
Search for anomalous production of events with three or more leptons in pp collisions at 8 TeV	SUS13002	CMS-SUS-13-002	19.5/fb	Submitted to PRD arXiv:1404.5801 NEW
Search for New Physics in Multijets and Missing Momentum Final State in pp collisions at 8 TeV	SUS13012	CMS-SUS-13-012	19.5/fb	JHEP 06 (2014) 055 arXiv:1402.4770
Search for SUSY Partners of Top and Higgs Using Diphoton Higgs Decays in pp collisions at 8 TeV	SUS13014	CMS-SUS-13-014	19.5/fb	Accepted by PRL arXiv:1312.3310
Search for new physics in events with same-sign dileptons and jets in pp collisions at 8 TeV	SUS13013	CMS-SUS-13-013	19.5/fb	JHEP 01 (2014) 163 arXiv:1311.6736
Search for supersymmetry using events with a single lepton, multiple jets, and b-tags	SUS13007	CMS-SUS-13-007	19.3/fb	Submitted to PLB arXiv:1311.4937
Search for top-squark pair production in the single lepton final state in pp collisions at 8 TeV	SUS13011	CMS-SUS-13-011	19.5/fb	EPJC 73 (2013) 2677 arXiv:1308.1586
Search for stop in R-parity-violating supersymmetry with three or more leptons and b-tags	SUS13003	CMS-SUS-13-003	19.5/fb	PRL 111, 221801 (2013), arXiv:1306.6643
Search for supersymmetry using the shape of the HT and MET, and b-jet multiplicity distributions	SUS12024	CMS-SUS-12-024	19.4/fb	PLB 725 243 (2013), arXiv:1305.2390
Search for supersymmetry in final states with missing transverse energy and 0, 1, 2, 3, or = 4 b jets in 8 TeV pp collisions	SUS12028	CMS-SUS-12-028	11.7/fb	EPJC 73 (2013) 2568, arXiv:1303.2985
Search for new physics in events with same-sign dileptons and b-tagged jets in pp collisions at vs = 8 TeV	SUS12017	CMS-SUS-12-017	10.5/fb	JHEP03 (2013) 037, JHEP07(2013)041, arXiv:1212.6194

Recent Preliminary Results with 2012 8 TeV Data

Analysis	Approved Plots	CDS Entry	Luminosity	Comment
Phenomenological MSSM Interpretation of the 7 and 8 TeV results	SUS13020	PAS-SUS-13-020	19.5/fb	NEW
Search for direct production of a pair of bottom squarks	SUS13018	PAS-SUS-13-018	19.4/fb	NEW
Search for electroweak production of higgsinos in channels with two Higgs bosons decaying to b quarks in pp collisions at 8 TeV	SUS13022	PAS-SUS-13-022	19.5/fb	NEW
Search for supersymmetry in hadronic final states using MT2 with the CMS detector at 8 TeV	SUS13019	PAS-SUS-13-019	19.5/fb	NEW
Search for direct production of stops decaying to a charm and LSP using the monojet + MET final state	SUS13009	PAS-SUS-13-009	19.7/fb	NEW
Search for top squarks in multijet events with large missing momentum in pp collisions at 8 TeV	SUS13015	PAS-SUS-13-015	19.4/fb	NEW
A search for new physics in events with one lepton, high jet multiplicity and high b-tagged jet multiplicity in pp collisions at 8 TeV	SUS12015	PAS-SUS-12-015	19.3/fb	
Search for Direct Top Squark Pair Production with Higgs bosons in the Final State in pp collisions at 8 TeV	SUS13021	PAS-SUS-13-021	19.5/fb	
Search for SUSY in Opposite Sign Dilepton events, large number of jets, b-jets and MET in pp collisions at 8 TeV	SUS13016	PAS-SUS-13-016	19.7/fb	
Search for electroweak production of charginos and neutralinos in final states with a Higgs boson in pp collisions at 8 TeV	SUS13017	PAS-SUS-13-017	19.5/fb	
Search for SUSY using razor variables in events with b-jets in pp collisions at 8 TeV	SUS13004	PAS-SUS-13-004	19.3/fb	
Search for supersymmetry in the 3 lepton + b-tag final state in pp collisions at 8 TeV	SUS13008	PAS-SUS-13-008	19.5/fb	
Search for RPV SUSY in the 4-lepton final state in pp collisions at 8 TeV	SUS13010	PAS-SUS-13-010	19.5/fb	
A Search for Anomalous Production of Events with three or more leptons using 9.2 fb-1 of vs = 8 TeV CMS Data	SUS12026	PAS-SUS-12-026	9.2/fb	Updated with more data above
Search for RPV supersymmetry with three or more leptons and b-tags	SUS12027	PAS-SUS-12-027	9.2/fb	
Search for electroweak production of charginos, neutralinos and sleptons using leptonic final states in pp collisions at 8 TeV	SUS12022	PAS-SUS-12-022	9.2/fb	Updated with more data above
Search for Supersymmetry in Events with Photons and Missing Energy vs = 8 TeV	SUS12018	PAS-SUS-12-018	4.04/fb	
Search for direct top squark pair production in events with a single isolated lepton, jets and missing transverse energy at vs = 8 TeV	SUS12023	PAS-SUS-12-023	9.7/fb	Updated with more data above
Search for supersymmetery in final states with missing transverse energy and 0, 1, 2, or = 3 b jets in 8 TeV pp collisions	SUS12016	PAS-SUS-12-016	3.9/fb	Updated with more data above

Stop decay topologies, depending on chargino mass

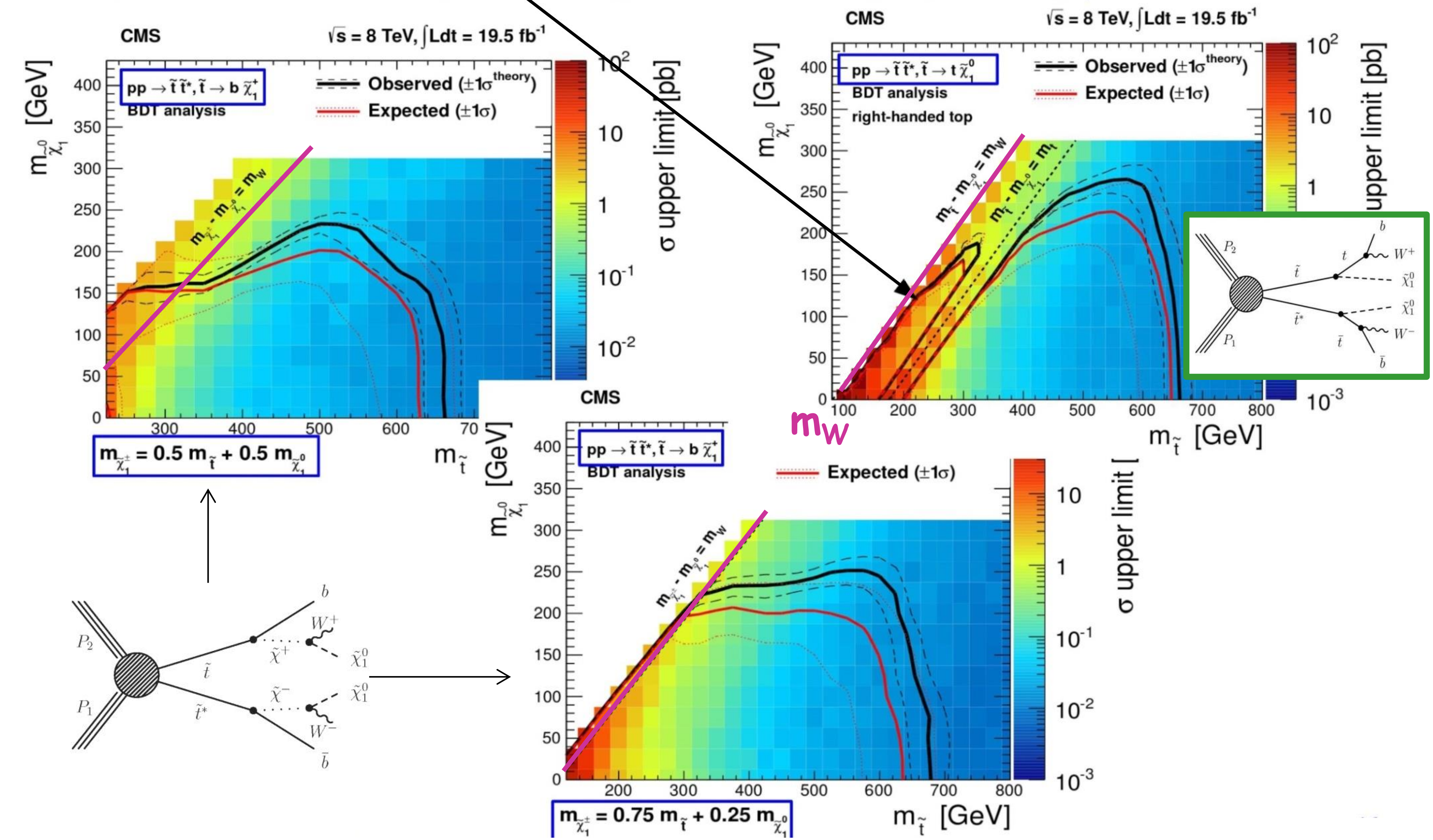


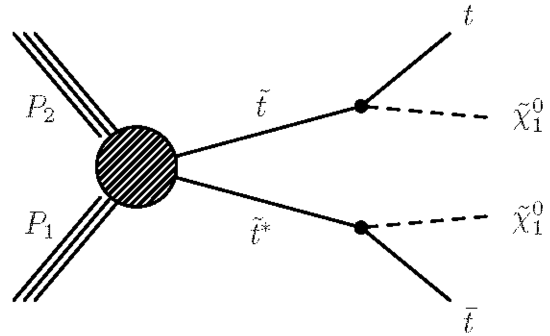


- Sensitivity to a gluino mass of O(TeV) for m(LSP) ~ 100 GeV
- No hints of SUSY. This could still mean the gluino is heavy and stop may be light. → direct stop searches

Stop Semi-Leptonic: Interpretations

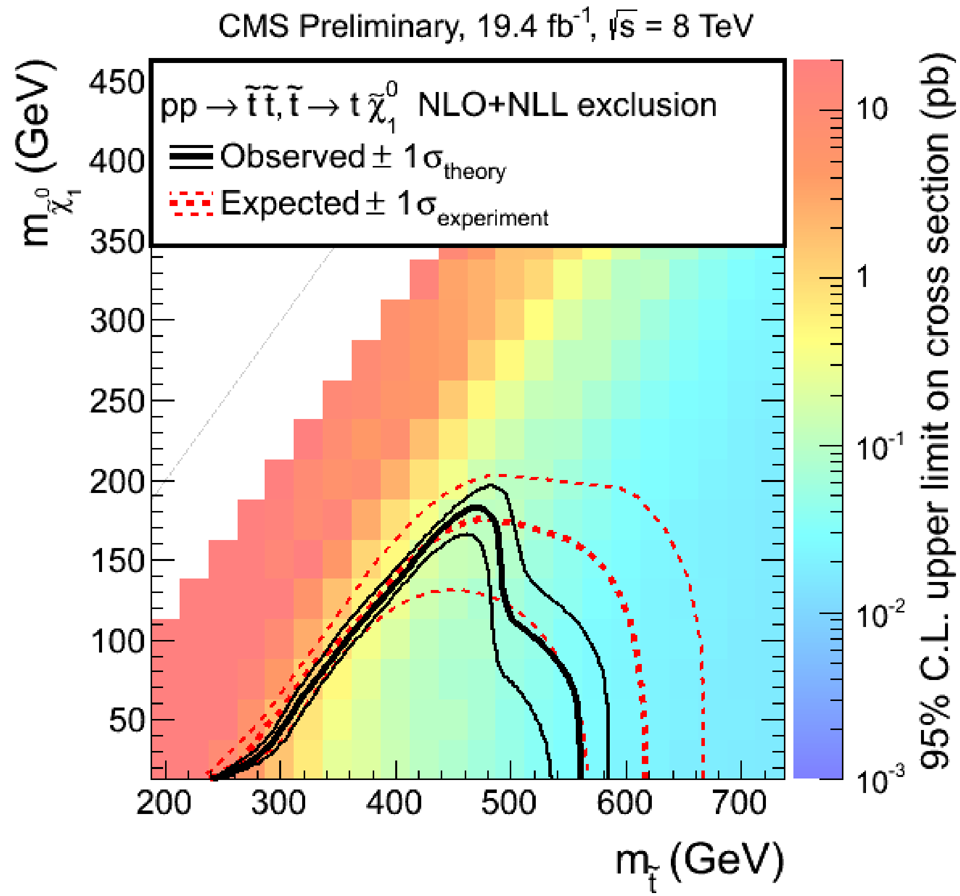
- Sensitivity at small ΔM: Selection variables independent of top reconstruction
- Specific BDT training for virtual top region to be sensitive up to LSP ~ 180 GeV

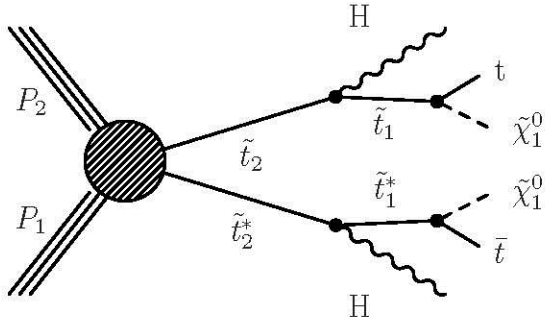




https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13015

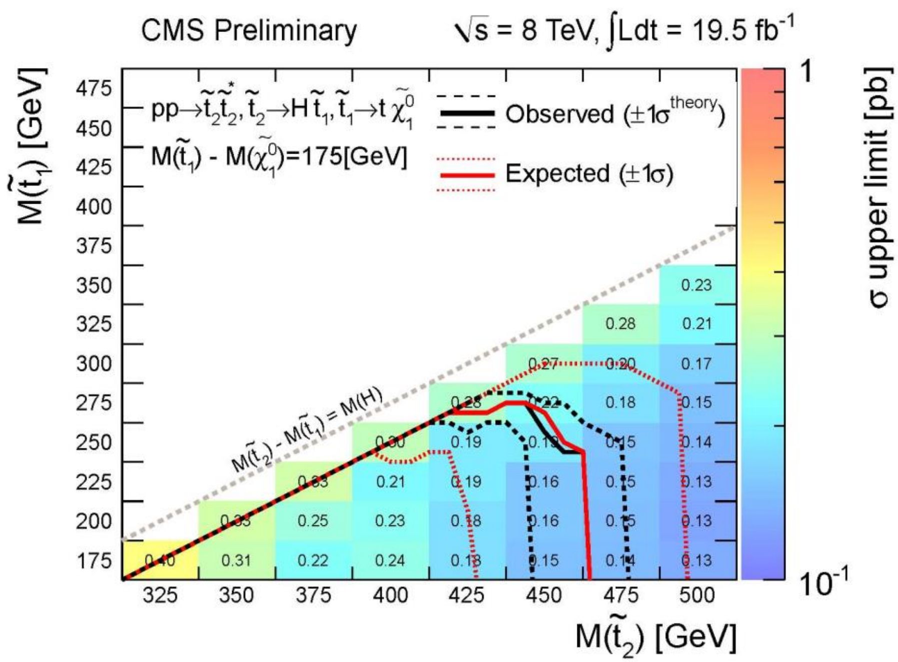
- Pairs of top squarks decaying to a top quark and a stable, weakly interacting, massive particle using events containing multiple jets, with at least one identified as originating from a b-quark, and large missing transverse momentum.
- A novel top quark tagging algorithm for identifying a top quark candidate decaying hadronically.
- 19.4 fb^{-1} at 8 TeV
- The production of top squarks with mass less than 535 GeV is excluded at 95% confidence-level for small LSP masses less than 10 GeV.



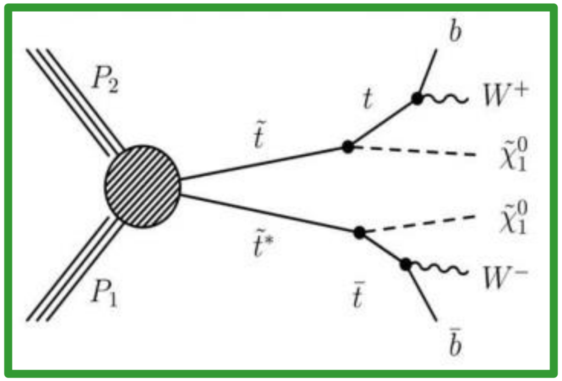


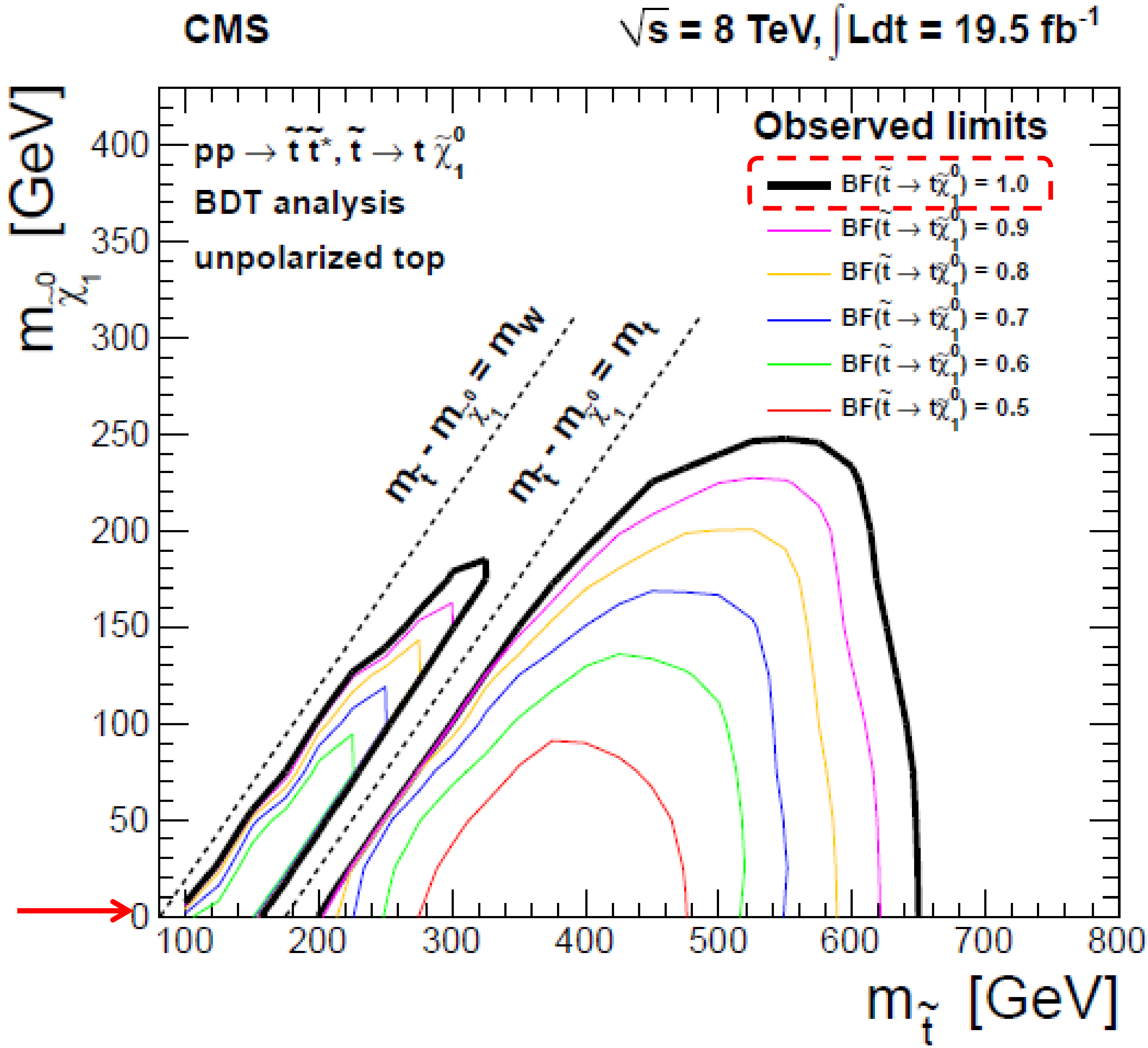
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13021

- Direct heavier top squark ($\tilde{t}_2$) pair production followed by $\tilde{t}_2 \to H\,\tilde{t}_1$, $\tilde{t}_1 \to t\tilde{\chi}^0$, using events with one or two electrons or muons and several jets, with at least 3 of them identified as originating from a b quark.
- 19.5 fb^{-1} at $\sqrt{s}$ = 8 TeV
- The interpretation concentrates on the region of signal mass parameter space $M(\tilde{t}_1) - M(\tilde{\chi}^0) \sim M(t)$, which is not covered by existing searches. The analysis excludes at the 95% CL top squarks with masses $M(\tilde{t}_2)$ up to about 450 GeV for $M(\tilde{t}_1)$ up to about 250 GeV



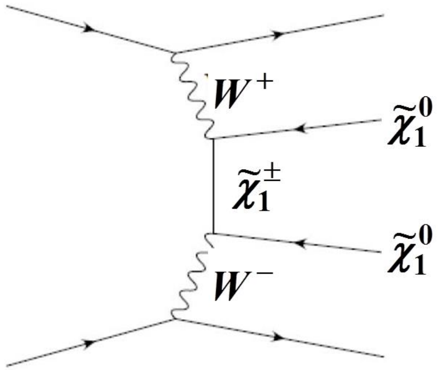
Stop Re-Interpretations for Nonthermal DM

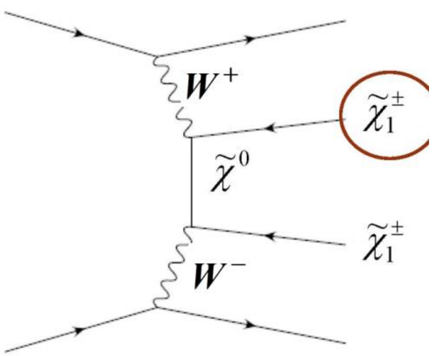




DM Production via VBF

A.G. Delannoy, B. Dutta, A. Gurrola, W. Johns, T. Kamon, E. Luiggi, A. Melo, P. Sheldon, K. Sinha, K. Wang, and S. Wu, "Probing Dark Matter at the LHC using Vector Boson Fusion Processes", arXiv:1304.7779 [hep-ph]





$jj + MET + X$

- The final state is same as invisible Higgs signal.
- But, Larger p_T jets
- Cross section?
  - ✓ Wino-like DM
  - ✓ Bino-Higgsino DM
- Feasibility?
  - ✓ ~50 GeV Wino-DM at 8 TeV
  - ✓ ~1000 GeV Wino-DM at 14 TeV
  - ✓ Bino-Higgsino DM at 14 TeV
- More?
  - ✓ Example, disappearing tracks?

$$\Delta M = M(\tilde{\chi}_1^\pm) - M(\tilde{\chi}_1^0) \sim 100\,MeV$$

$$\Rightarrow Br(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm) \sim 100\%$$

$$P_T(\pi^\pm) \sim \Delta M \sim 100\,MeV$$

Very Rich RPV MSSM Program

1209.0764
J.A. Evans
Y. Kats

final state	collaboration	$\mathcal{L}$ (fb^{-1})	ref.
pairs of dijets	ATLAS	0.034, 4.6	[41, 42]
	CMS	2.2	[43]
leptoquark pairs	CMS	5.0	[44]
	CMS	4.8	[45]
$t\bar{t}$	ATLAS	0.70	[46]
	CMS	2.0-2.3	[47, 48]
$t\bar{t}$ + jet	CMS	5.0	[49]
$t\bar{t} + m_T$	ATLAS	1.04	[50]
leptonic m_{T2}	ATLAS	4.7	[51]
ℓ + jets + MET	CMS	4.7	[52]
	ATLAS	4.7	[53, 54]
OS $\ell\ell$ + MET	CMS	4.98	[55]
	ATLAS	1.04, 4.7	[56, 57]
SS $\ell\ell$ + MET	ATLAS	1.04, 2.05	[56, 58]
SS $\ell\ell$	ATLAS	1.6, 4.7	[59, 60]
SS $\ell\ell$ (+ MET)	CMS	4.98	[61, 62]
SS $\ell\ell$ + b (+ MET)	CMS	4.98	[63]
b' (SS $\ell\ell$ or 3ℓ + b)	CMS	4.9	[64]
b' (SS $\ell\ell$)	ATLAS	4.7	[65]
3 or 4 ℓ	ATLAS	1.02	[66, 67]
3 ℓ + MET	ATLAS	2.06, 4.7	[68, 69]
4 ℓ + MET	ATLAS	2.06	[70]
3 or 4 ℓ (+ MET)	CMS	4.98	[7]
1 or 2 τ + jets + MET	ATLAS	2.05, 4.7	[71–73]
τ + ℓ + jets + MET	ATLAS	4.7	[73]
	CMS	5.0	[55]
b + jets + MET	ATLAS	2.05, 4.7	[74, 75]
	CMS	1.1, 4.98	[76, 77]
b + ℓ + jets + MET	ATLAS	2.05	[74]
	CMS	4.96-4.98	[78, 79]
Z + jets + MET	CMS	4.98	[80]
	ATLAS	2.05	[81]
jets + MET	ATLAS	4.7	[82, 83]
	CMS	1.1, 4.98	[84, 85]
(b)-jets with α_T	CMS	1.14, 4.98	[86, 87]

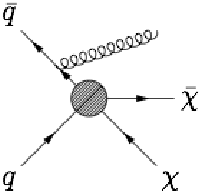
Table 5: 7 TeV LHC searches used for inferring limits.

Final state	b-jets	Scenario(s)
$(\tau^+ j)(\tau^- j)$	0	LQD332
$(jj)(jj)$	0, 2	UDD312/323
$8j$	4, 6	UDD312/323 with $\tilde{H}$ decaying via $\tilde{t}$; UDD213 with $\tilde{H}^\pm \to \tilde{H}^0$
$\ell^+\ell^- + 6j$	2, 4, 6	LQD232/233 with $\tilde{H}/\tilde{W}$ (unless decays via $\tilde{b}_L$ or $\tilde{b}_R$) LQD221/123 with $\tilde{W}$
$\tau^+\tau^- + 6j$	2, 4, 6	LQD332/333 with $\tilde{H}/\tilde{W}$ (unless decays via $\tilde{b}_L$ or $\tilde{b}_R$) LQD321/323 with $\tilde{H}$-$\tilde{\nu}_\tau/\tilde{\tau}_L$ or $\tilde{W}$ (with or without $\tilde{\chi}^\pm \to \tilde{\chi}^0$)
$\tau^\pm\tau^\pm + 6j$	2, 4	LQD321/323 with $\tilde{H}$-$\tilde{\nu}_\tau/\tilde{\tau}_L$ or $\tilde{W}$, with $\tilde{\chi}^\pm \to \tilde{\chi}^0$
$t\bar{t} + 6j$	2, 4	UDD212/213 with $\tilde{g}/\tilde{B}$; UDD213 with $\tilde{H}$
$t\bar{t} + 4j + \mathrm{MET}$	2, 4, 6	LQD321/323 with $\tilde{g}/\tilde{B}$ LQD323/233/333 with $\tilde{H}$ decaying via $\tilde{b}_R$ LQD232/233/332/333 with $\tilde{H}/\tilde{W}$ decaying via $\tilde{b}_L$ LQD232/233/332/333 with $\tilde{B}$ (unless decays via $\tilde{t}$)
(tt or $\bar{t}\bar{t}$) + $6j$	4, 6	UDD312/323 with $\tilde{H}^\pm \to \tilde{H}^0$
$t\bar{t} + 2\tau + 4j$ $t\bar{t} + \tau + 4j + \mathrm{MET}$	2, 4	LQD321/323 with $\tilde{g}/\tilde{B}$; LQD323 with $\tilde{H}$-$\tilde{b}_R$
$\tau^+\tau^- W^+W^- + 2j$ $\tau + W^+W^- + 2j + \mathrm{MET}$ $W^+W^- + 2j + \mathrm{MET}$	0	LQD323 with $\tilde{b}_R$
4 tops + $4j$	4, 6	UDD312/323 with $\tilde{B}$
$6j + \mathrm{MET}$	2, 4	LQD221/123/321/323 with $\tilde{W}$ LQD321/323 with $\tilde{W}^\pm \to \tilde{W}^0$ LQD232/332 with $\tilde{W}^\pm \to \tilde{W}^0$ (unless decays via $\tilde{t}$) LQD323 with $\tilde{H}^\pm \to \tilde{H}^0 \to \tilde{b}_R$
$\ell + 6j + \mathrm{MET}$	2, 4	LQD221/123 with $\tilde{W}$
$\tau + 6j + \mathrm{MET}$	2, 4	LQD321/323 with $\tilde{W}$ (with or without $\tilde{W}^\pm \to \tilde{W}^0$) LQD323 with $\tilde{H}^\pm \to \tilde{H}^0 \to \tilde{b}_R$
$\tau^+\tau^- + 2b + \mathrm{MET}$	2	LLE123/233 with heavy $\tilde{W}$
$W^+W^- + 4j$	0	UDD213 with $\tilde{b}_R$

Table 6: Dominant final states in scenarios for which the coverage is insufficient (for $m_{\mathrm{stop}} \lesssim 500$ GeV). See tables 1–4 for more detailed descriptions of the scenarios mentioned. The chargino is assumed to decay directly via a sfermion and its RPV coupling (rather than transition to a neutralino first), except where explicitly noted otherwise. As before, couplings related by interchanging electrons and muons, or first and second generation quarks, are listed just once. The second column indicates the possible number of b-jets in each scenario (including those coming from top decays, where relevant).

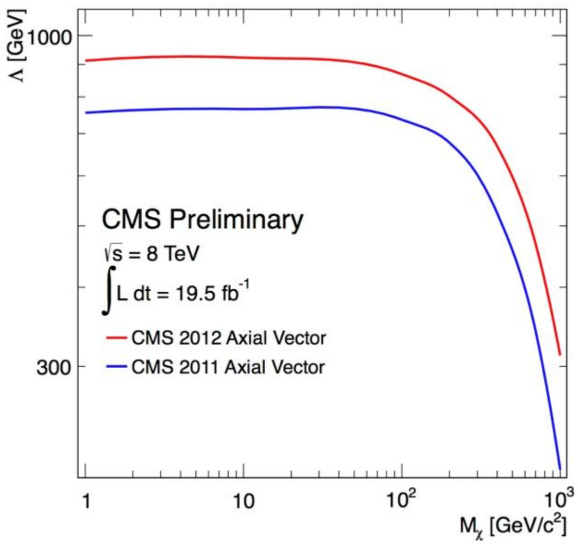
Backup

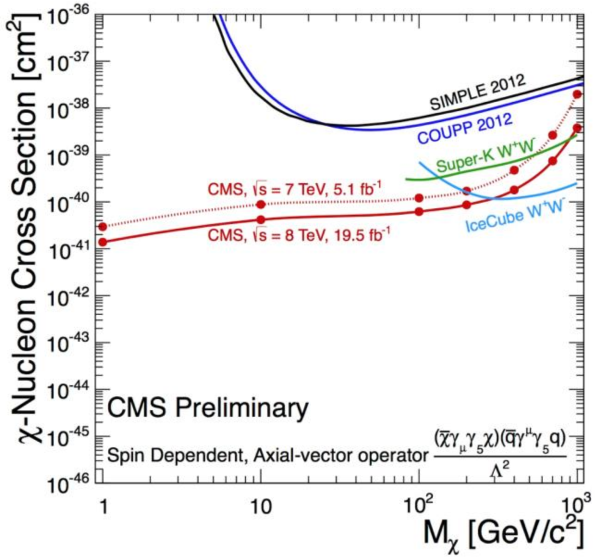
MonoX



Monojet: Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

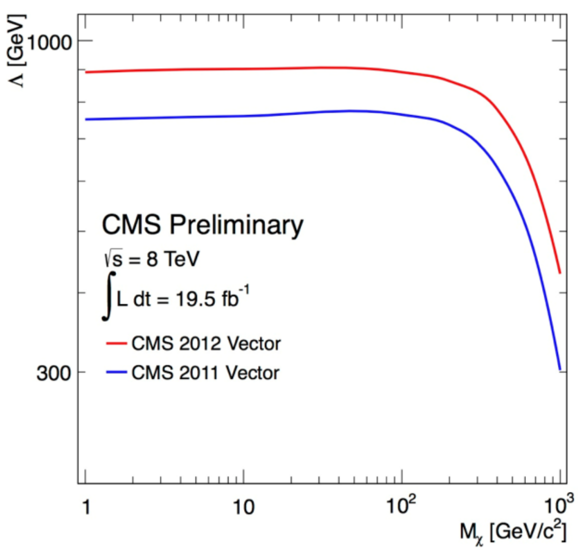


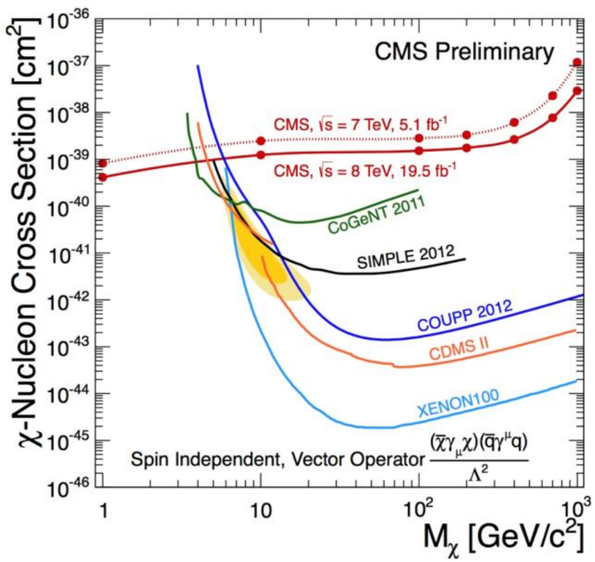


Axial-vector operator
spin-dependent (SD)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Λ = Contact
interaction scale





Vector operator
spin independent (SI)

$$\mathcal{O}_{V} = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Backup

minMET, BDT

minMET in Monophoton

MHT Minimization

A way to identify and reduce the fake met contribution, where you minimize the unclustered energy in the event by trying to re-distribute the energy back into the visible objects.

$$\hat{\not{E}}_{x,y} = \not{E}^{reco}_{x,y} + \sum_{i=objects} (p^{reco}_{x,y})_i - (\hat{p}_{x,y})_i$$

$$\not{E}_T{}^2 = \not{E}_x^2 + \not{E}_y^2$$

$$\chi^2 = \sum_{i=objects} \left(\frac{(p_T^{reco})_i - (\hat{p}_T)_i}{(\sigma_{p_T})_i} \right)^2 + \left(\frac{\hat{\not{E}}_x}{\sigma_{\not{E}_x}} \right)^2 + \left(\frac{\hat{\not{E}}_y}{\sigma_{\not{E}_y}} \right)^2 .$$

If the Met is intrinsic, balancing the object momenta wouldn't be easy and will result in high χ^2 .

The variables that give good discrimination are the Prob(χ^2) and the recalculated minimized Met.

BDT Parameters in Z(bb)+H(inv)

Table 6: Input variables to the $Z(b\bar{b})H(inv)$ BDT.

Variable	
p_T^{j1}, p_T^{j2}	Transverse momentum of each Z boson daughter
M_{jj}	Dijet invariant mass
p_T^{jj}	Dijet transverse momentum
E_T^{miss}	Missing transverse energy
N_{aj}	Number of additional jets ($p_T > 25$ GeV and $\lvert\eta\rvert < 4.5$)
CSV_{max}	Value of CSV for the Z boson daughter with largest CSV value
CSV_{min}	Value of CSV for the Z boson daughter with second largest CSV value
$\Delta\phi(Z, H)$	Azimuthal angle between E_T^{miss} and dijet
$\Delta\eta_{jj}$	Difference in η between Z daughters
ΔR_{jj}	Distance in η-ϕ between Z daughters
$\Delta\theta_{pull}$	Color pull angle [62]
$\Delta\phi(E_T^{miss}, j)$	Azimuthal angle between E_T^{miss} and the closest jet
CSV_{aj}	Maximum CSV of the additional jets in an event
$\Delta R(H, aj)$	Minimum distance between an additional jet and the Z boson candidate
m_T	Transverse mass of the ZH system