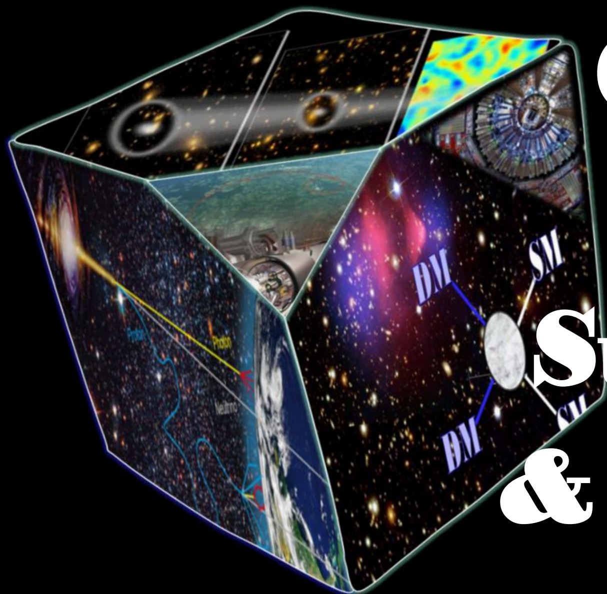


CMS Search for Supersymmetry & *X* at the LHC

[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

Teruki Kamon[1),2)]

on behalf of the CMS Collaboration

1) Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University

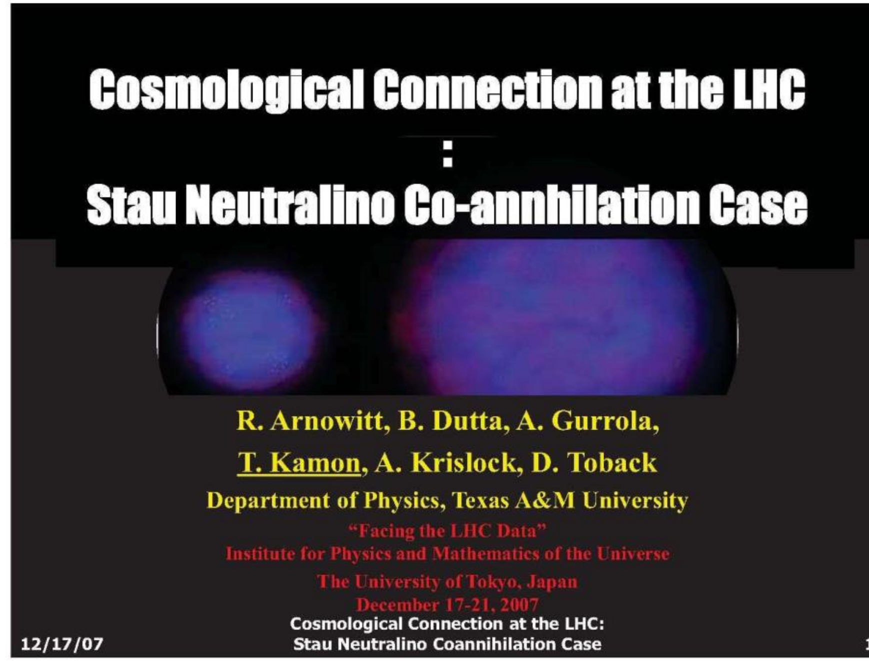
2) Kyungpook National University

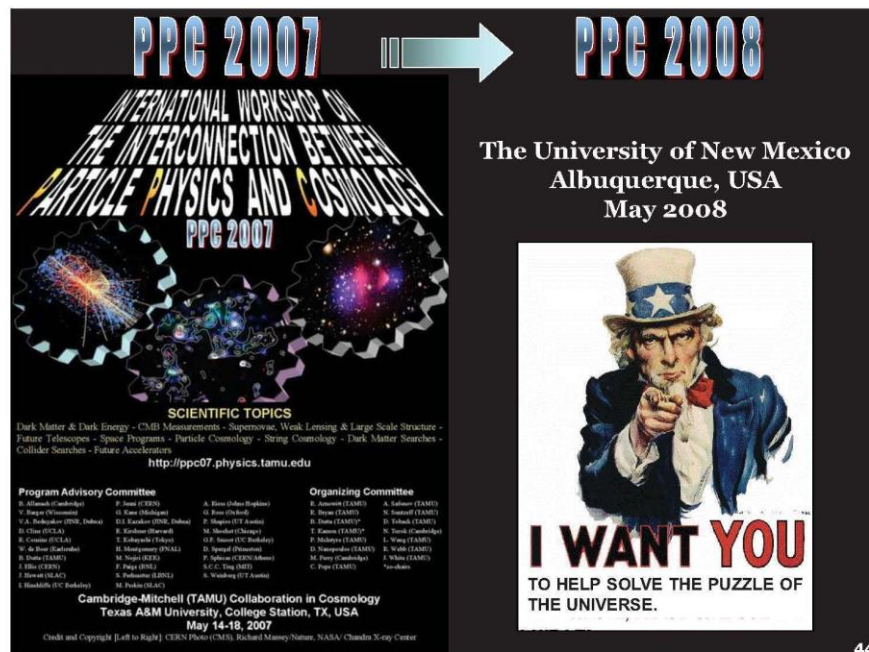
Kavli-IPMU-Durham-KIAS workshop:

New Particle Searches Confronting the First LHC Run-2 Data

Kavli-IPMU, Kashiwa, Japan, Sep 7 - 11, 2015

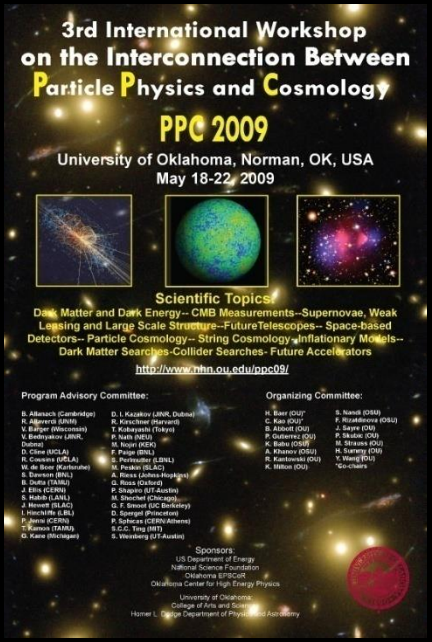
PAST (過去): LHC Workshop at IMPU in 2007…



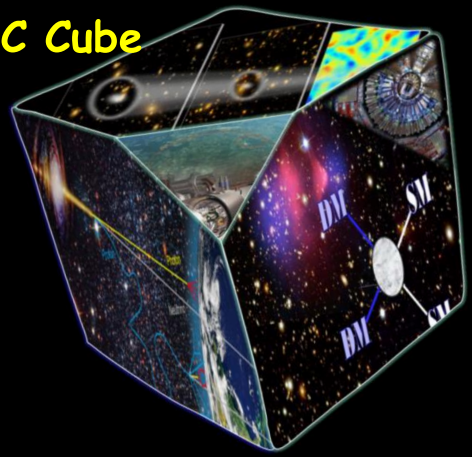


PRESENT (現在): PPCs

Interconnection between Particle Physics and Cosmology



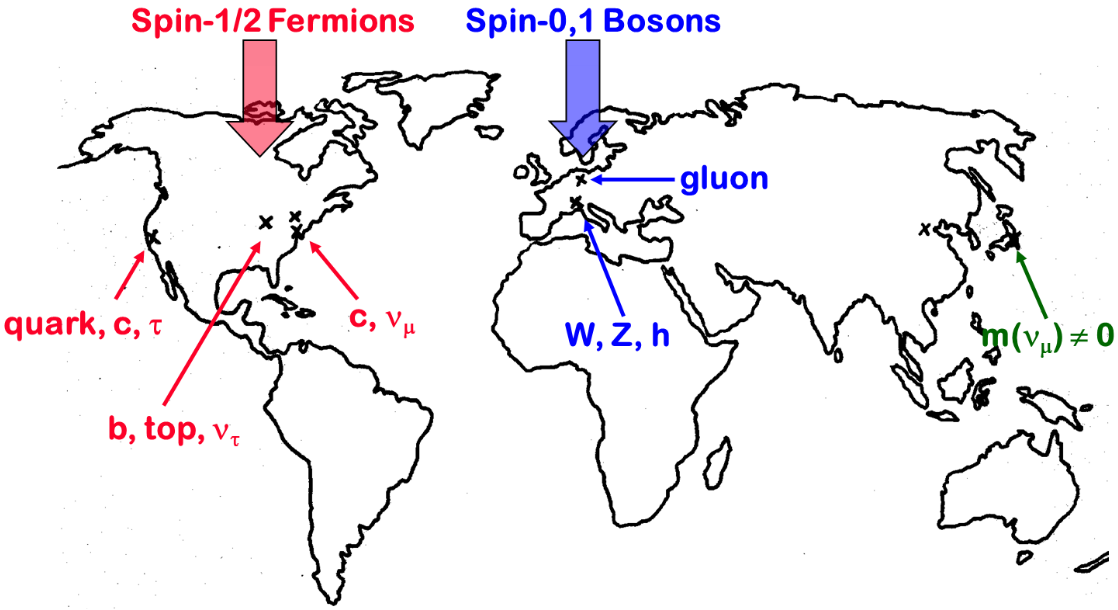
PPC Cube



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 CETUP*, SD, USA, June 29 - July 3
PPC 2016 at Brazil
PPC 2017 at ???

OUTLINE^3 - FUTURE (未来)

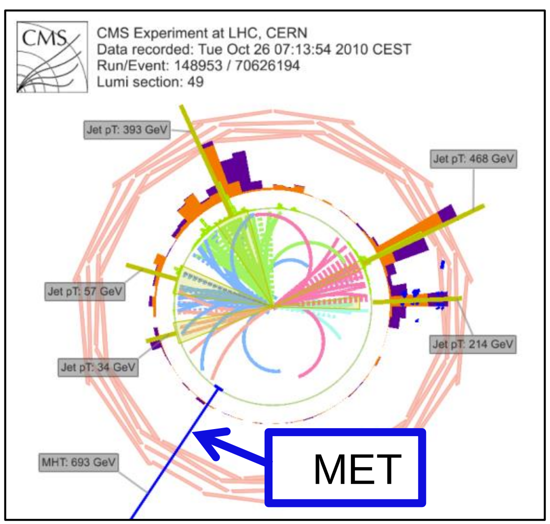
World "Discovery" Map



Where will next new particles be discovered?

How about the dark matter (DM) particles?

Examine pp collision events being consistent with models (or scenarios) that describe DM-SM particle interaction.



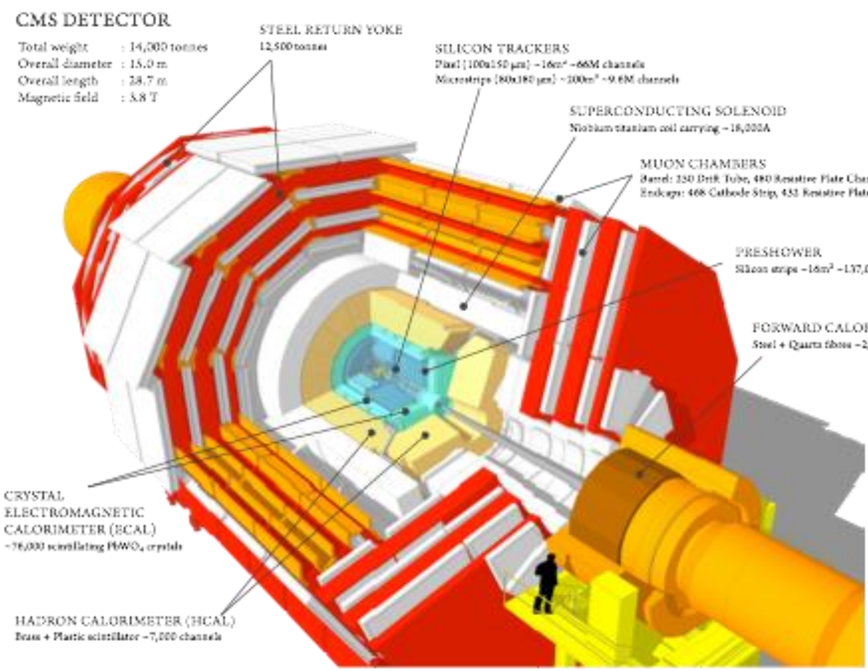
- DM = Weekly interacting massive particle
- MET = momentum imbalance or missing transverse energy - Hallmark signature for DM

1) Models with DM
2) MonoX for DM-SM interaction
3) Remarks & Summary

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

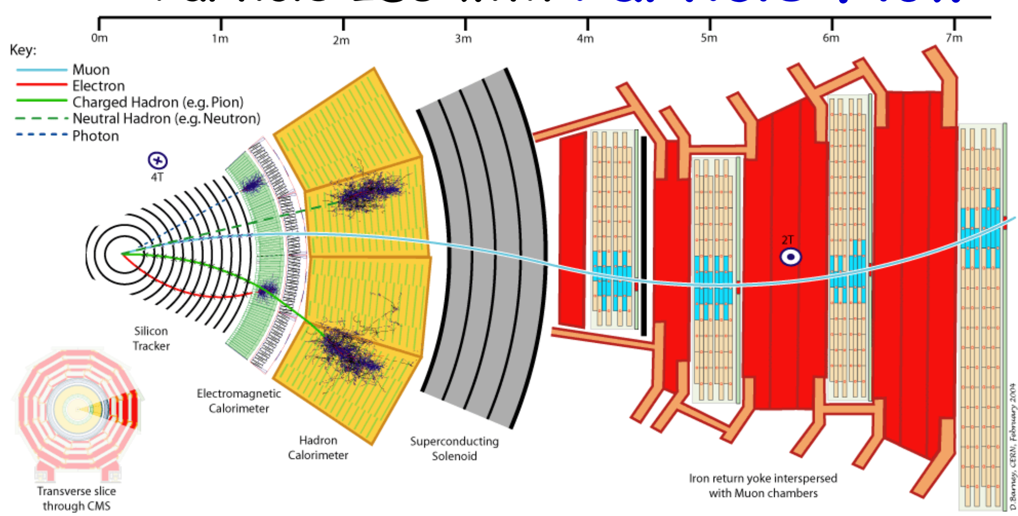
Schematic view of the CMS Detector showing its main components.



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) …

Particle IDs with Particle Flow

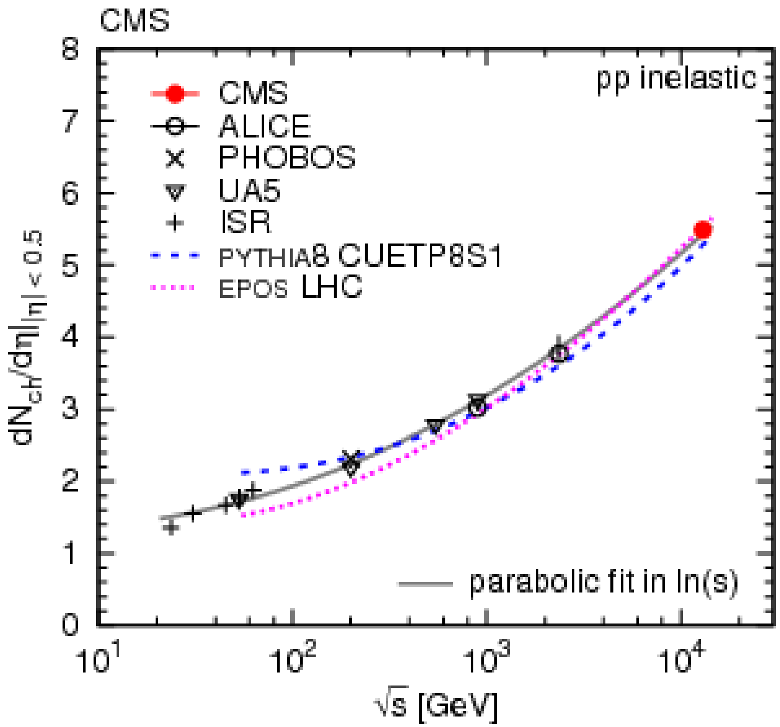


First 13-TeV Paper

[URL] http://cds.cern.ch/record/2036310

"Pseudorapidity distribution of charged hadrons in proton-proton collisions at sqrt(s) = 13 TeV" (FSQ-15-001, submitted in PLB)

The pseudorapidity distribution of charged hadrons in pp collisions at sqrt(s) =13 TeV is measured using a data sample obtained with the CMS detector, operated at zero magnetic field, at the CERN LHC. The yield of primary charged long-lived hadrons produced in inelastic pp collisions is determined in the central region of the CMS pixel detector (|η|<2) using both hit pairs and reconstructed tracks. For central pseudorapidities (|η|<0.5), the charged-hadron multiplicity density is dN/dη[charged, |η| < 0.5] = 5.49 +/- 0.01 (stat) +/- 0.17 (syst), a value obtained by combining the two methods. The result is compared to predictions from Monte Carlo event generators and to similar measurements made at lower collision energies.

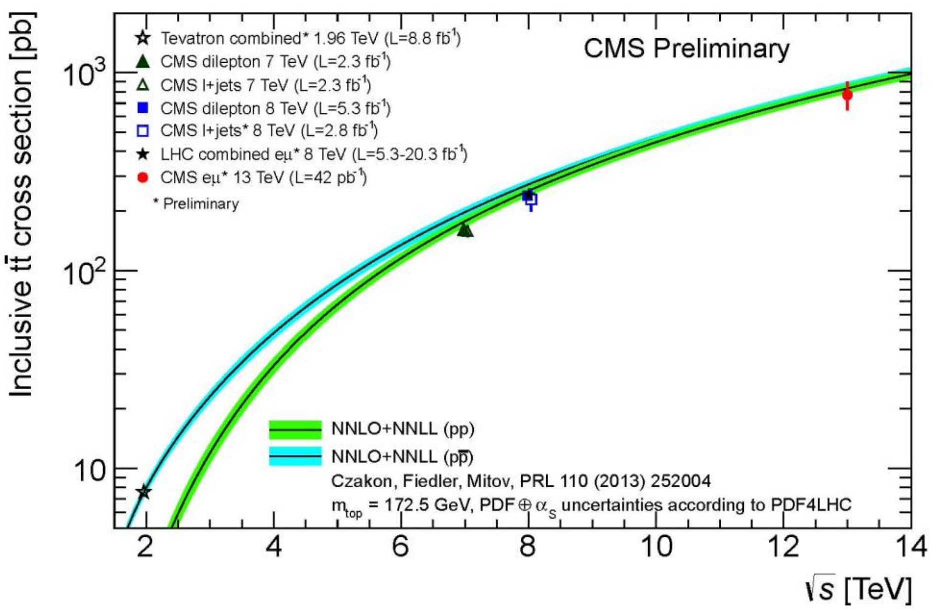


Top at 13 TeV

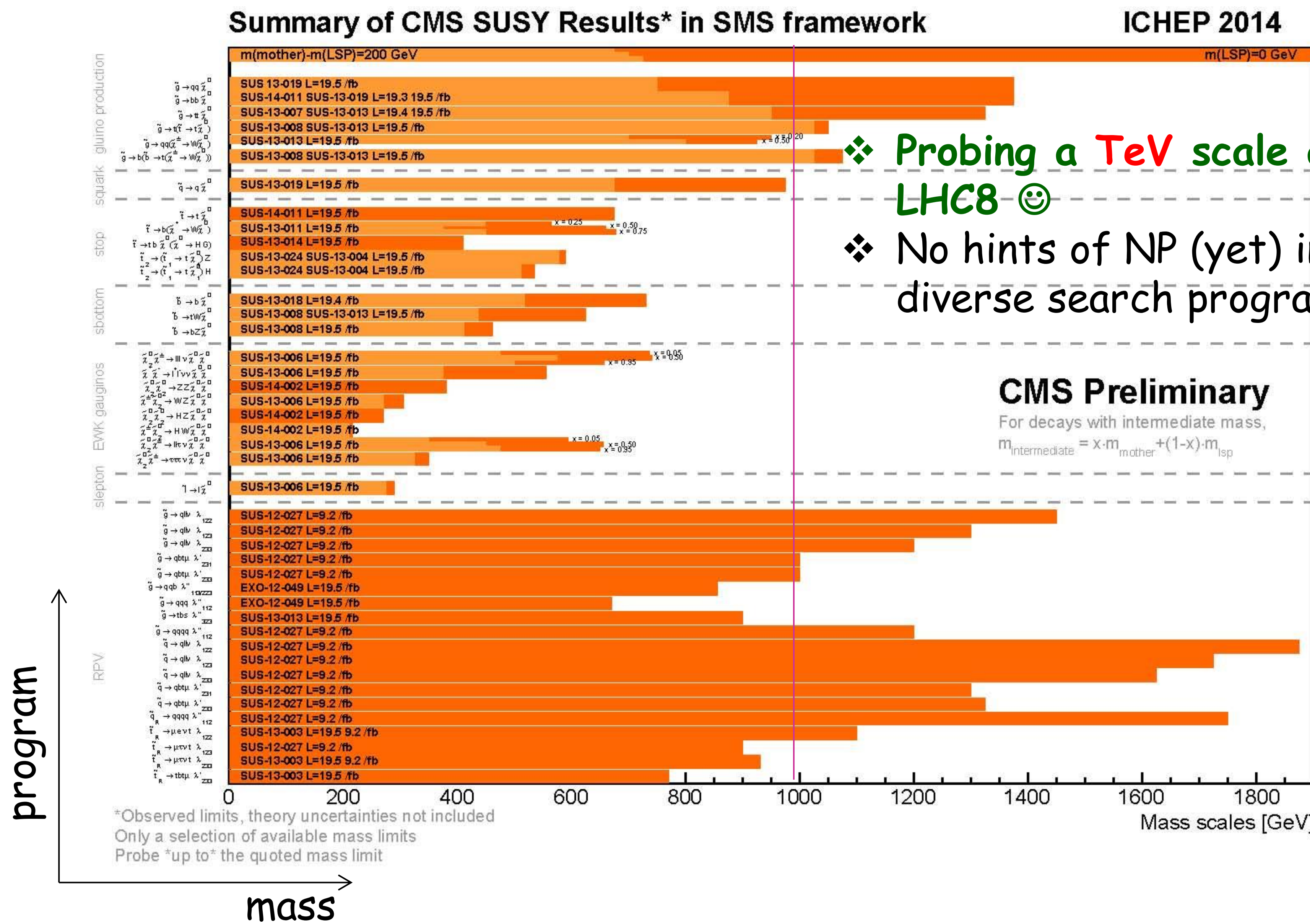
[URL] http://cds.cern.ch/record/2044918?ln=en

"Measurement of the top quark pair production cross section in proton-proton collisions at sqrt(s) = 13 TeV with the CMS detector" (TOP-15-003)

The top-antitop quark (ttbar) production cross section is measured for the first time by the CMS experiment in proton-proton collisions at $\sqrt{s}$ = 13 TeV at the CERN LHC, using data corresponding to an integrated luminosity of 42 pb−1. The measurement is performed by analyzing events with one electron and one muon and at least two jets. The measured cross section is σ(ttbar) = 772 ±60(stat) ±62(syst) ±93(lumi) pb, in agreement with the expectations from the standard model.



CMS "New Physics Searches" Chart 1



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

Closer Look at CMS SUSY Searches

gluino production

gluino production

$\tilde{g} \to qq\,\tilde{\chi}^0$

$\tilde{g} \to bb\,\tilde{\chi}^0$

$\tilde{g} \to tt\,\tilde{\chi}^0$

$\tilde{g} \to t(\tilde{t} \to t\tilde{\chi}^0)$

$\tilde{g} \to qq(\tilde{\chi}^\pm \to W\tilde{\chi}^0)$

$\tilde{g} \to b(\tilde{b} \to t(\tilde{\chi}^\pm \to W\tilde{\chi}^0))$

squark

squark

$\tilde{q} \to q\,\tilde{\chi}^0$

stop

stop

$\tilde{t} \to t\,\tilde{\chi}^0$

$\tilde{t} \to b(\tilde{\chi}^+ \to W\tilde{\chi}^0)$

$\tilde{t} \to t\,b\,\tilde{\chi}^0\,(\tilde{\chi}^0 \to H\,G)$

$\tilde{t}_2 \to (\tilde{t}_1 \to t\,\tilde{\chi}^0_1)\,Z$

$\tilde{t}_2 \to (\tilde{t}_1 \to t\,\tilde{\chi}^0_1)\,H$

sbottom

sbottom

$\tilde{b} \to b\,\tilde{\chi}^0$

$\tilde{b} \to tW\tilde{\chi}^0$

$\tilde{b} \to bZ\tilde{\chi}^0$

EWK *gaugino*

EWK gauginos

$\tilde{\chi}^0_2\tilde{\chi}^\pm \to lll\,\nu\,\tilde{\chi}^0\tilde{\chi}^0$

$\tilde{\chi}^+\tilde{\chi}^- \to l^+l^-\nu\,\nu\,\tilde{\chi}^0\tilde{\chi}^0$

$\tilde{\chi}^0_2\tilde{\chi}^0_2 \to Z\,Z\,\tilde{\chi}^0\tilde{\chi}^0$

$\tilde{\chi}^\pm\tilde{\chi}^0_2 \to W\,Z\,\tilde{\chi}^0\tilde{\chi}^0$

$\tilde{\chi}^0_2\tilde{\chi}^0_2 \to H\,Z\,\tilde{\chi}^0\tilde{\chi}^0$

$\tilde{\chi}^\pm\tilde{\chi}^0_2 \to H\,W\,\tilde{\chi}^0\tilde{\chi}^0$

$\tilde{\chi}^0_2\tilde{\chi}^\pm \to ll\tau\,\nu\,\tilde{\chi}^0\tilde{\chi}^0$

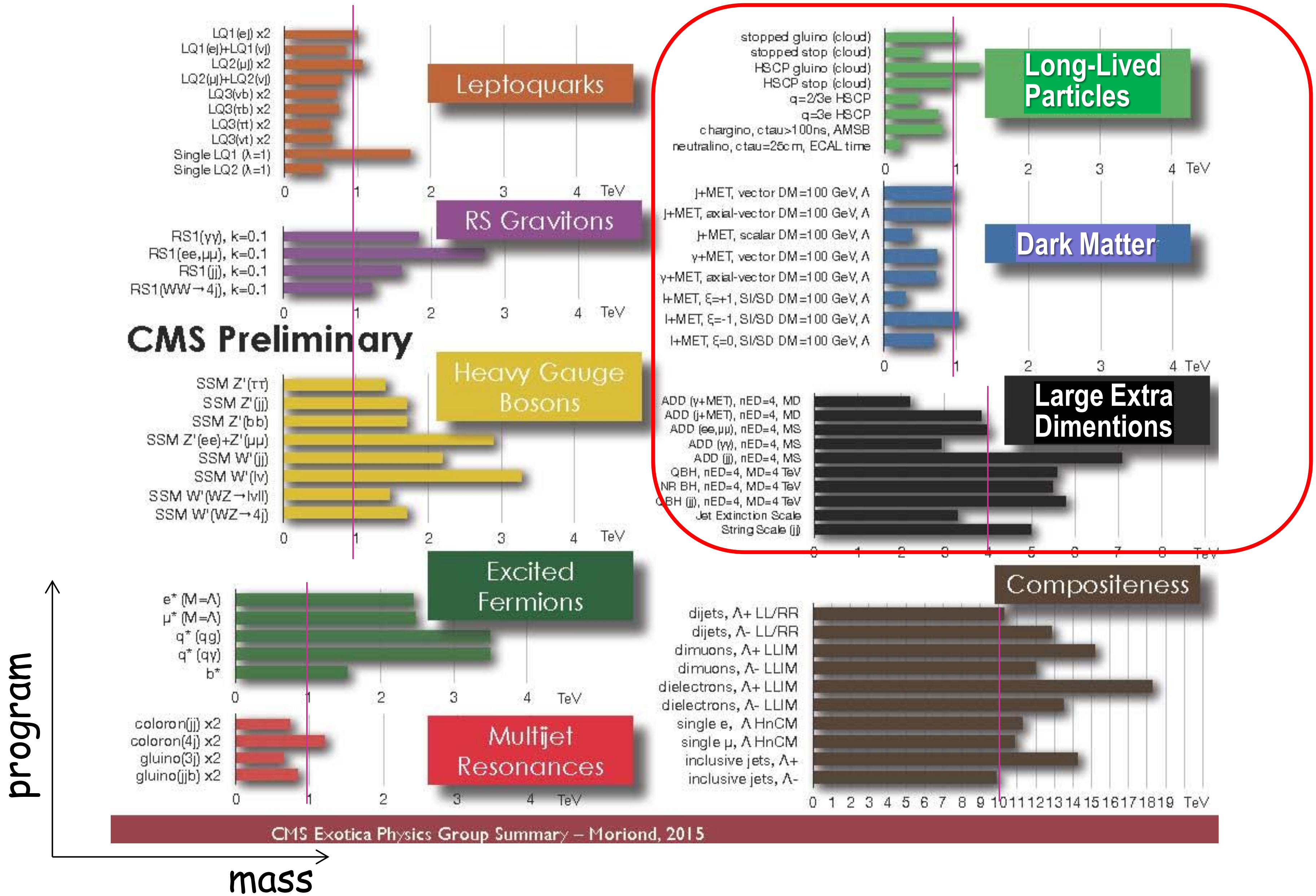
$\tilde{\chi}^0_2\tilde{\chi}^\pm \to \tau\tau\tau\,\nu\,\tilde{\chi}^0\tilde{\chi}^0$

slepton

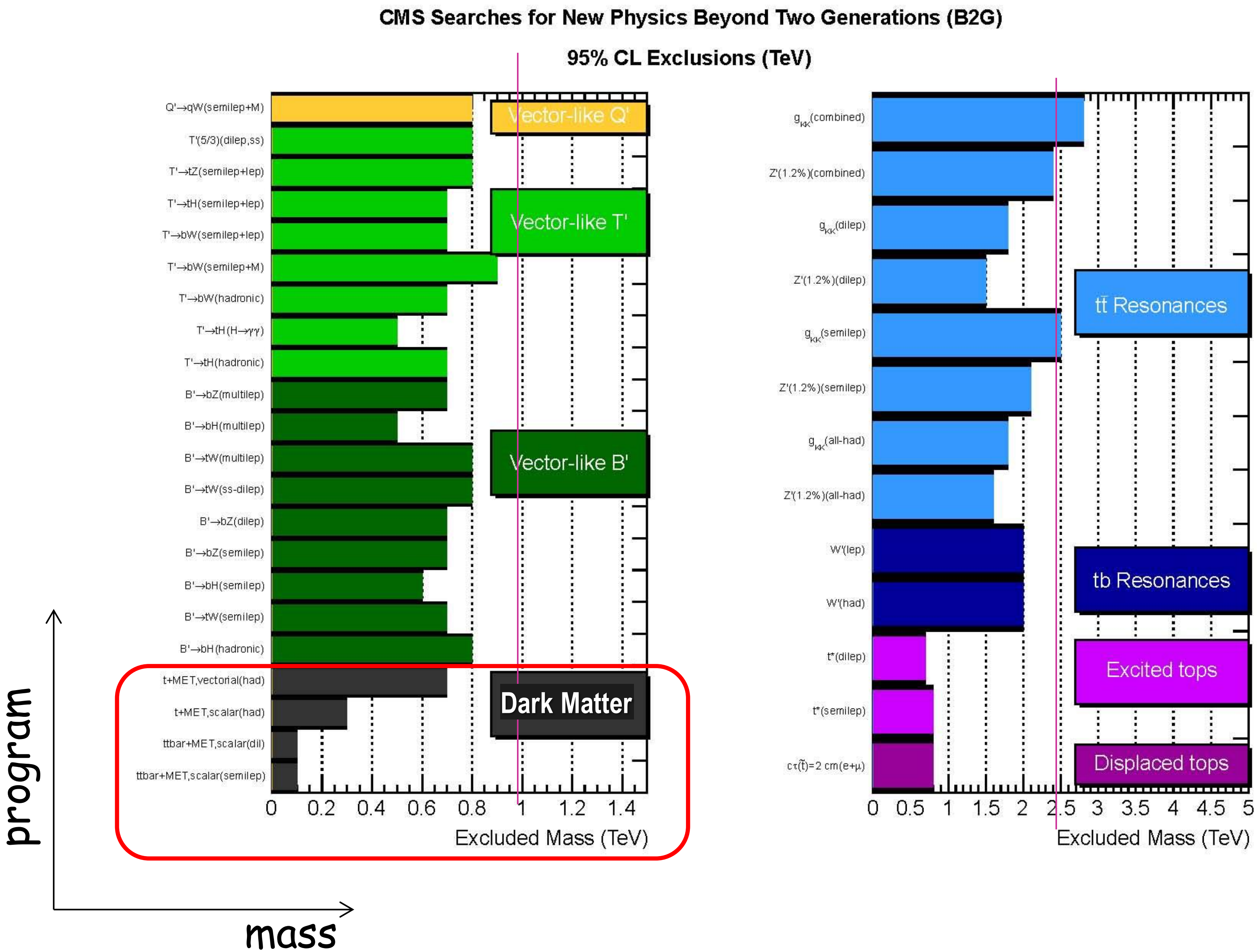
slepton

$\tilde{l} \to l\,\tilde{\chi}^0$

CMS "New Physics Searches" Chart 2

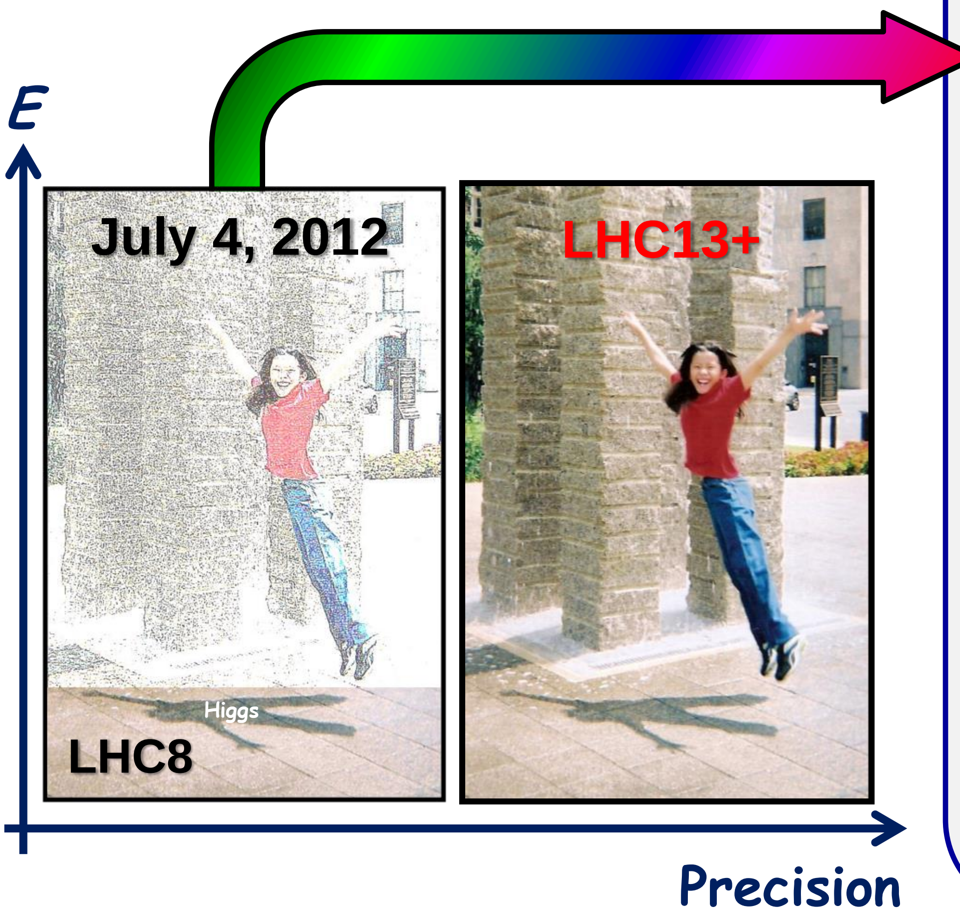


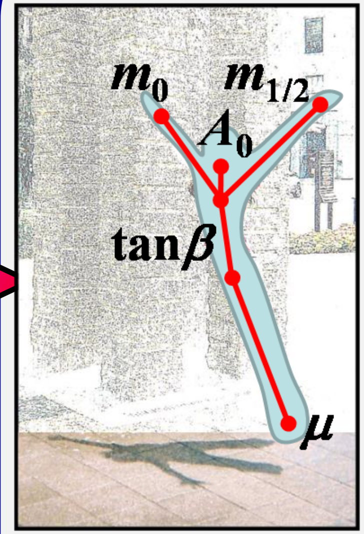
CMS "New Physics Searches" Chart 3



SUSY Probe Metric at LHC

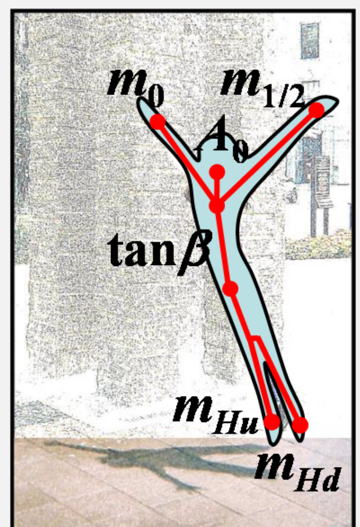
MSSM (>100 parameters) - impossible to have more than 100 measurements at the LHC. Consider a way to test a minimal scenario or simplified scenario, first. Then, expand to non-minimal scenarios.





Minimal Scenario

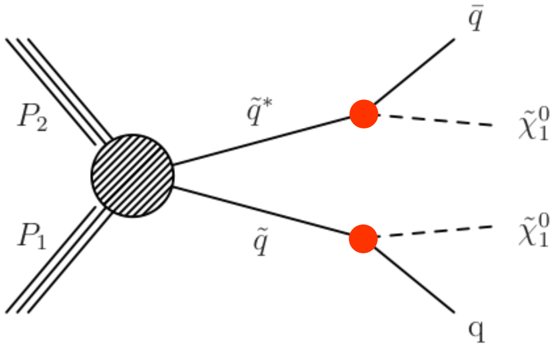
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathscr{D}(m_0, m_{1/2}, \tan\beta, A_0, \mu)$$

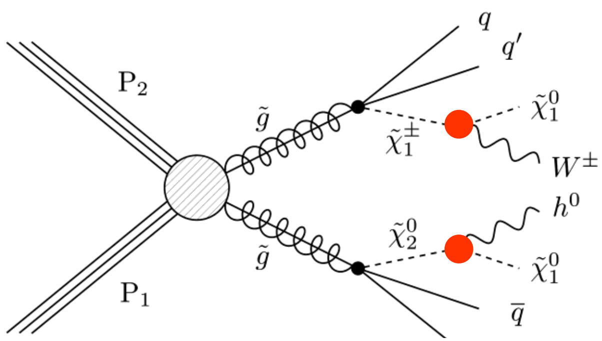


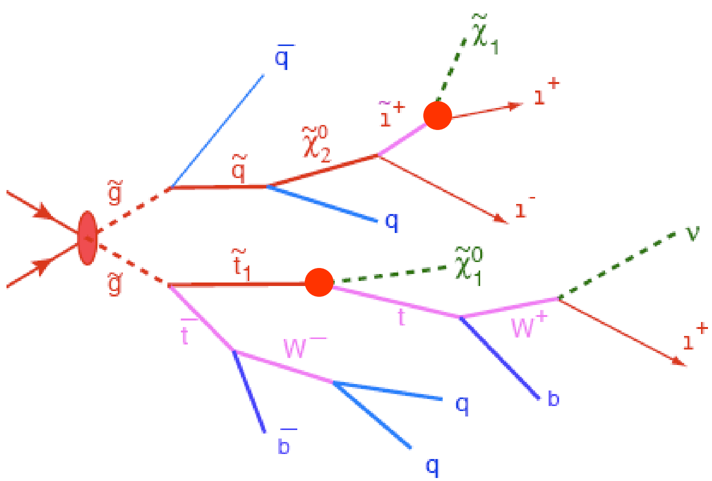
Non-minimal Scenario

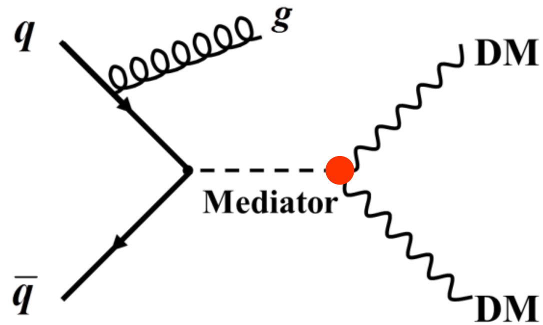
$$\Omega_{\tilde{\chi}_1^0} h^2 = \mathscr{D}(m_0, m_{1/2}, \tan\beta, A_0, m_{H_u}, m_{H_d})$$

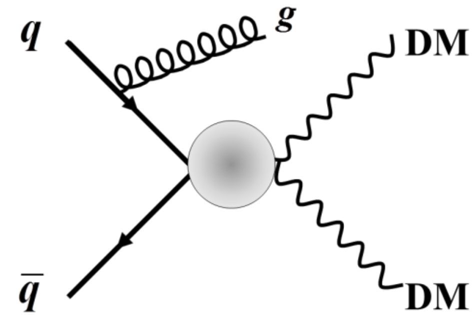
Cold DM (χ) Marketplaces











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

Selected topics:

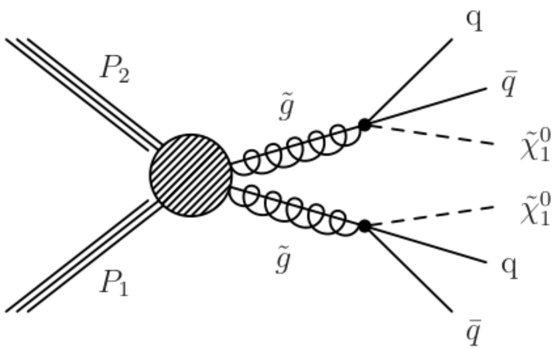
[I] Supersymmetry (SUSY)

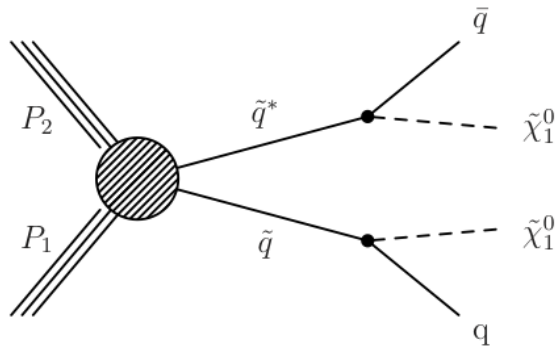
[II] Mono-X for DM-SM interaction

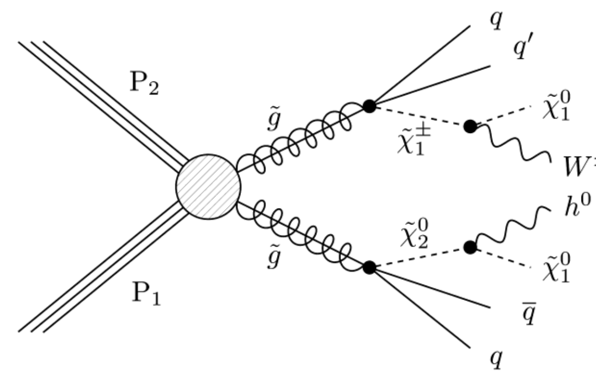
Squarks/Gluinos – Diagrams

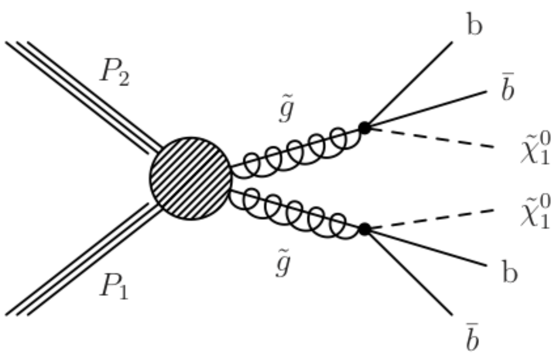
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13019

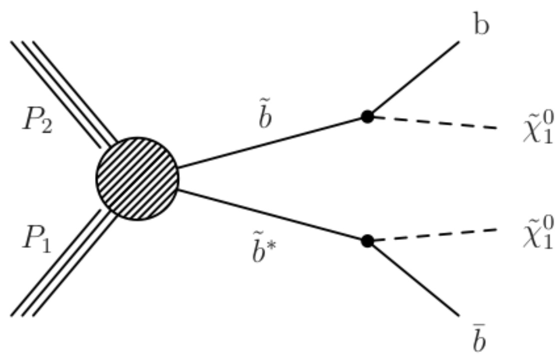
JHEP 05 (2015) 078 [1502.04358]

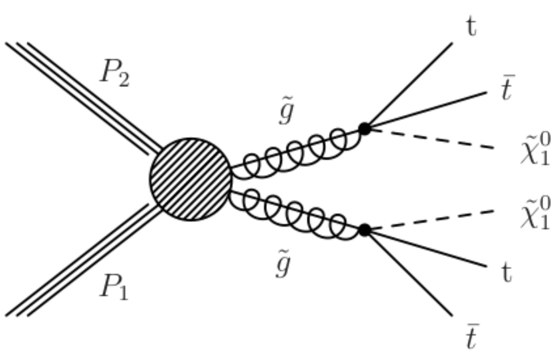


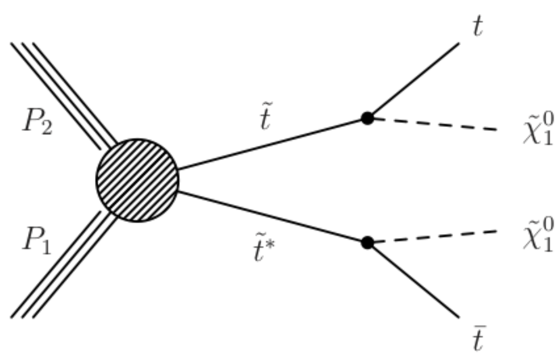




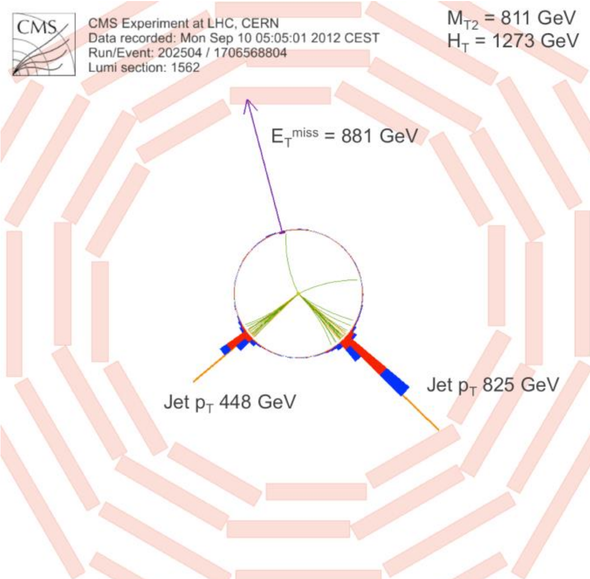


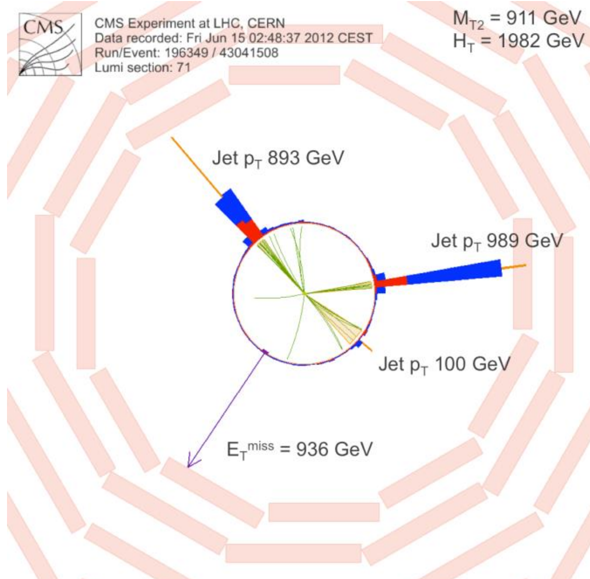


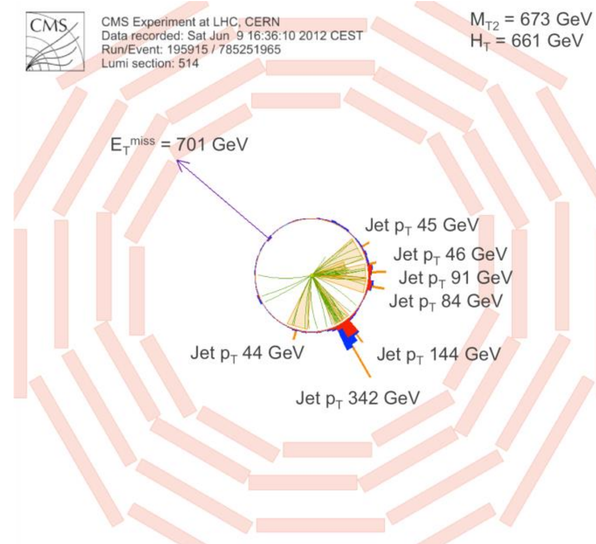


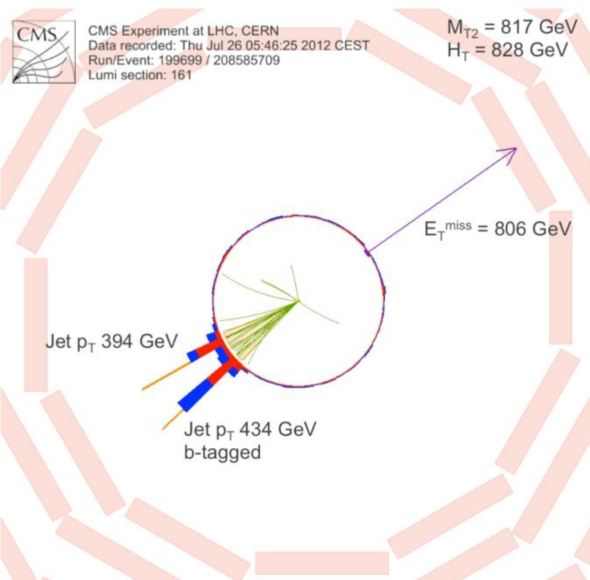


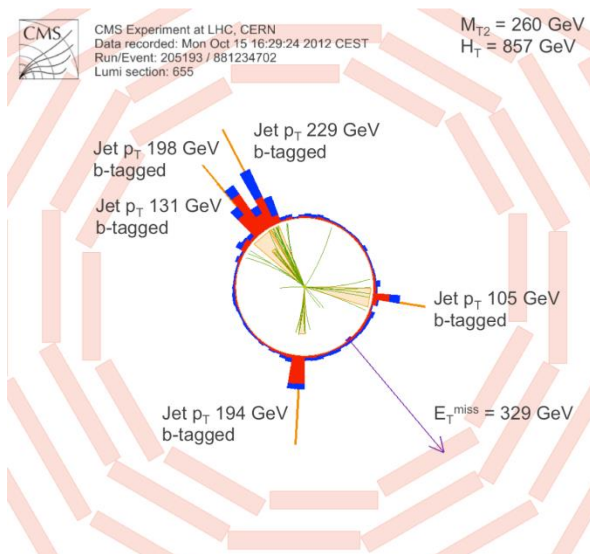
Squarks/Gluinos – Event Displays

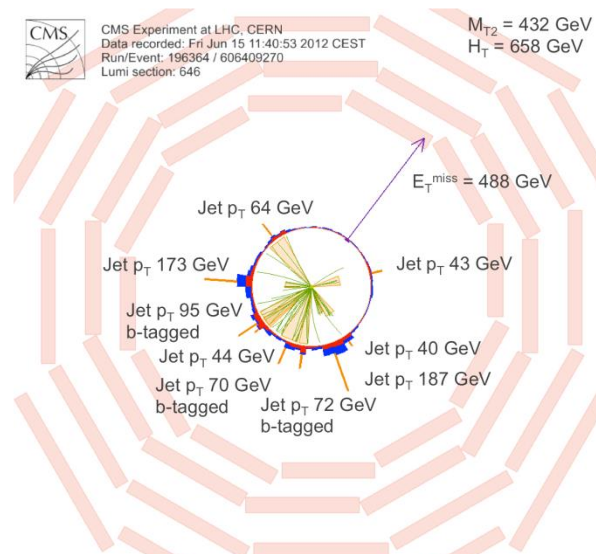








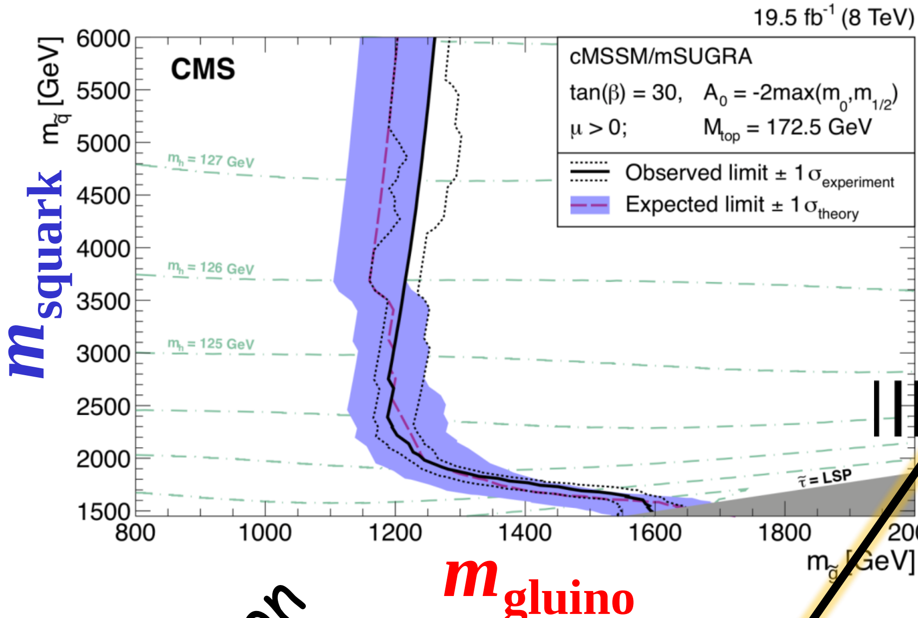


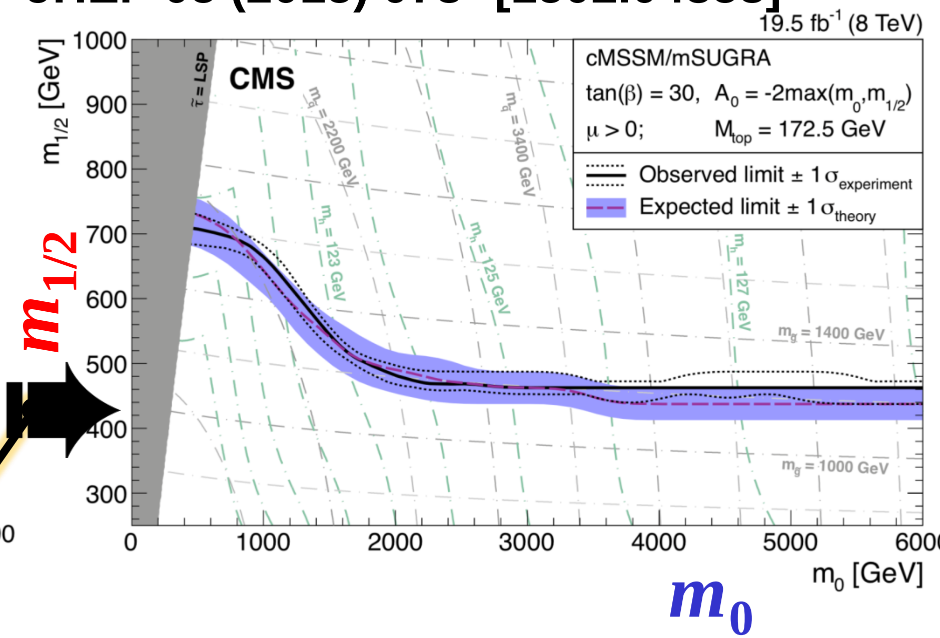


Gluinos/Squarks in mSUGRA/CMSSM

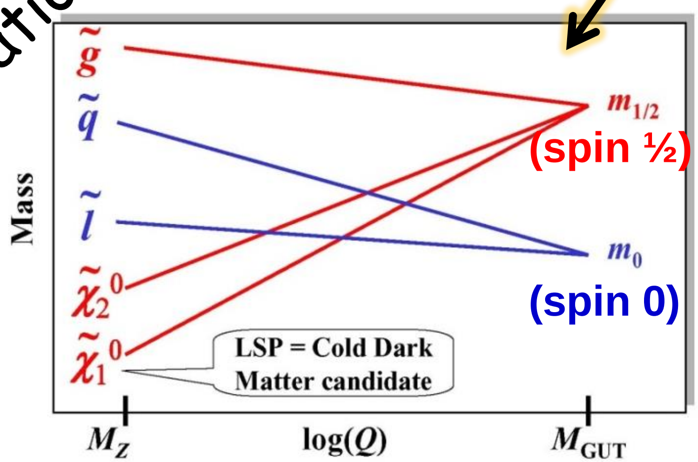
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13019

JHEP 05 (2015) 078 [1502.04358]





illustration



- mSUGRA/CMSSM are severely put under pressure by the LHC limits.
- Simplified SUSY benchmarks for the interpretations.
- With the discovery of a Higgs boson, the experimental search strategy shifts towards other scenarios (e.g., 3rd generation squark searches).

Squarks/Gluinos in SMS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS13019

JHEP 05 (2015) 078 [1502.04358]

Searches for supersymmetry using the MT2 variable in hadronic events produced in pp collisions at 8 TeV

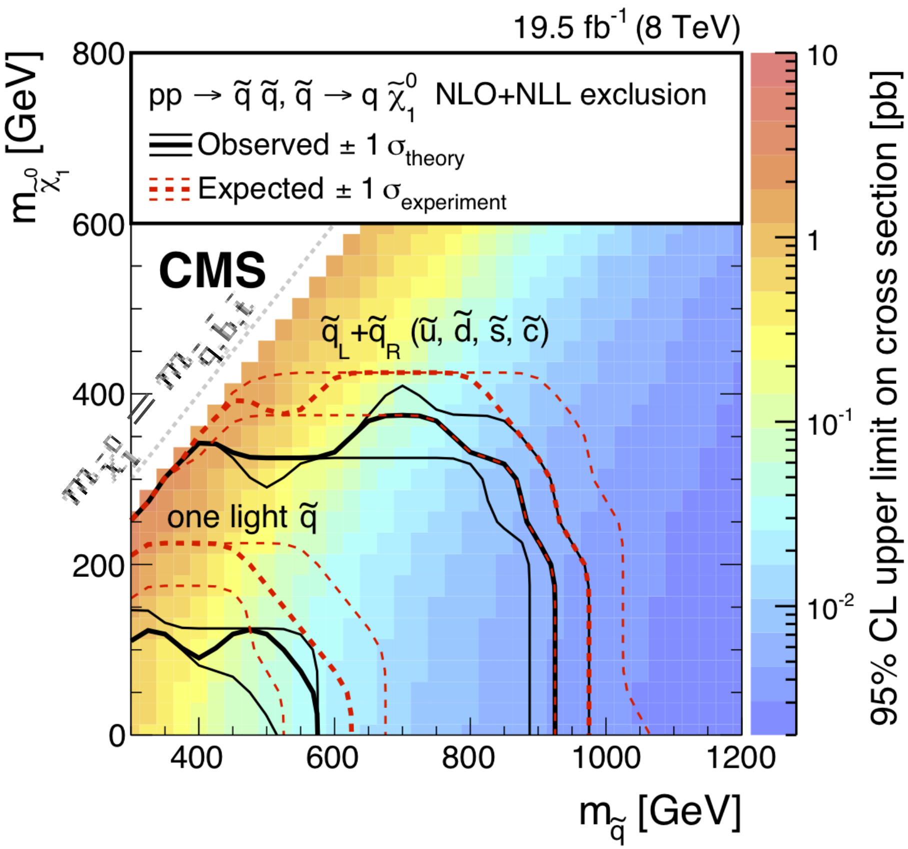
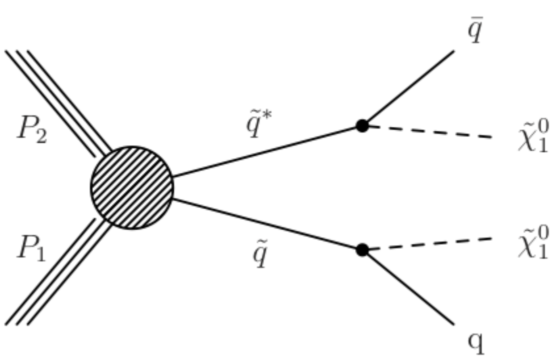


Figure 12 (a): Exclusion limits at 95% CL for direct squark production. The upper set of curves corresponds to the scenario where the first two generations of squarks are degenerate and light, while the lower set corresponds to only one accessible light-flavour squark.

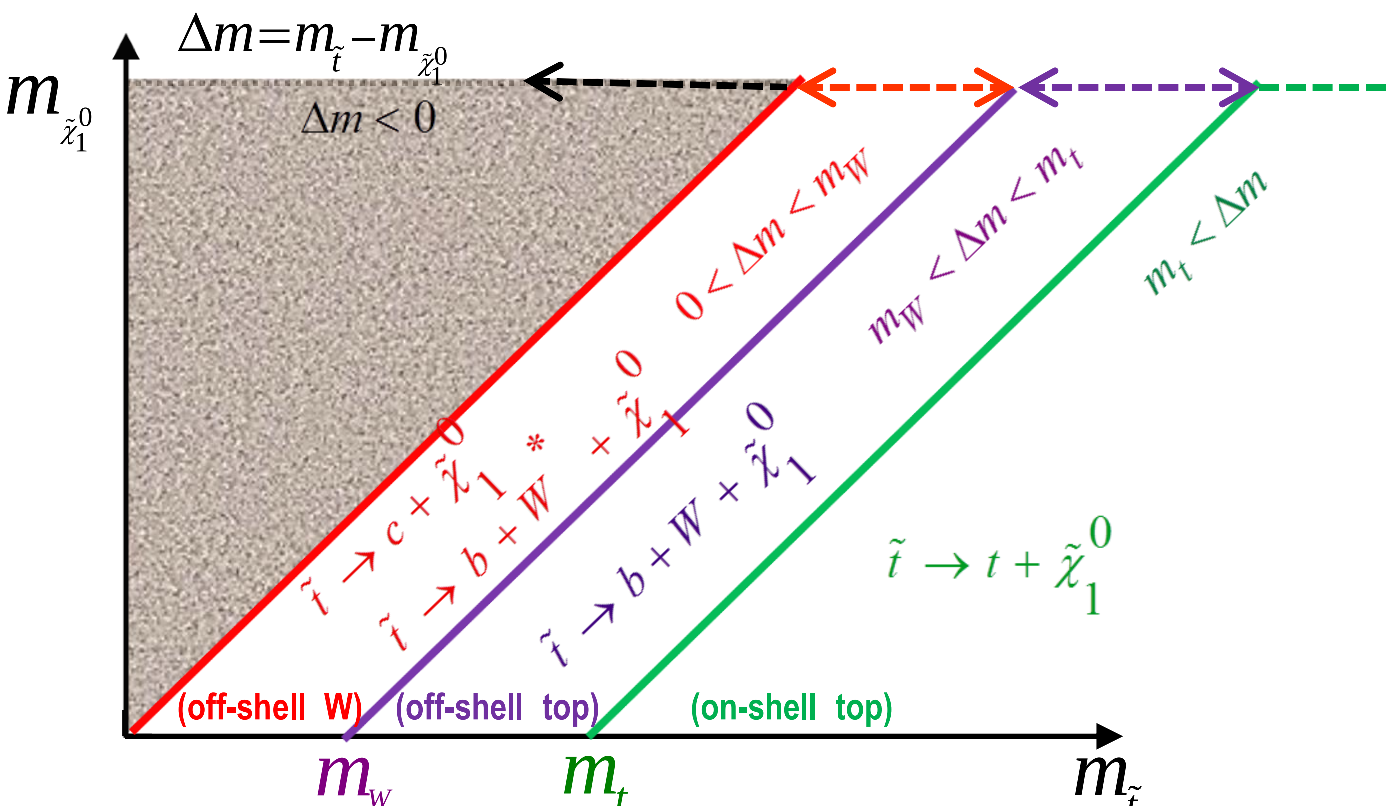


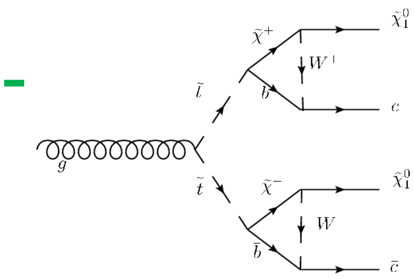
See also earlier results on SUS-13-012, JHEP 06 (2014) 055 [1402.4770]

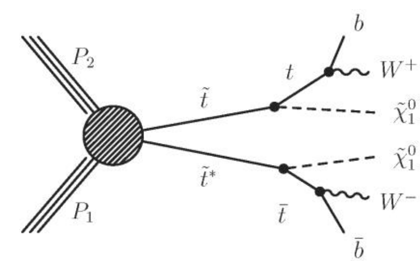
Top Squark Decay Modes

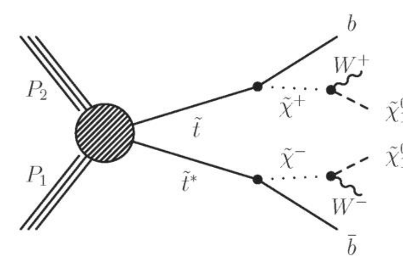
Stop decay ← Stop mixing & neutralino/chargino composition & $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$

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)

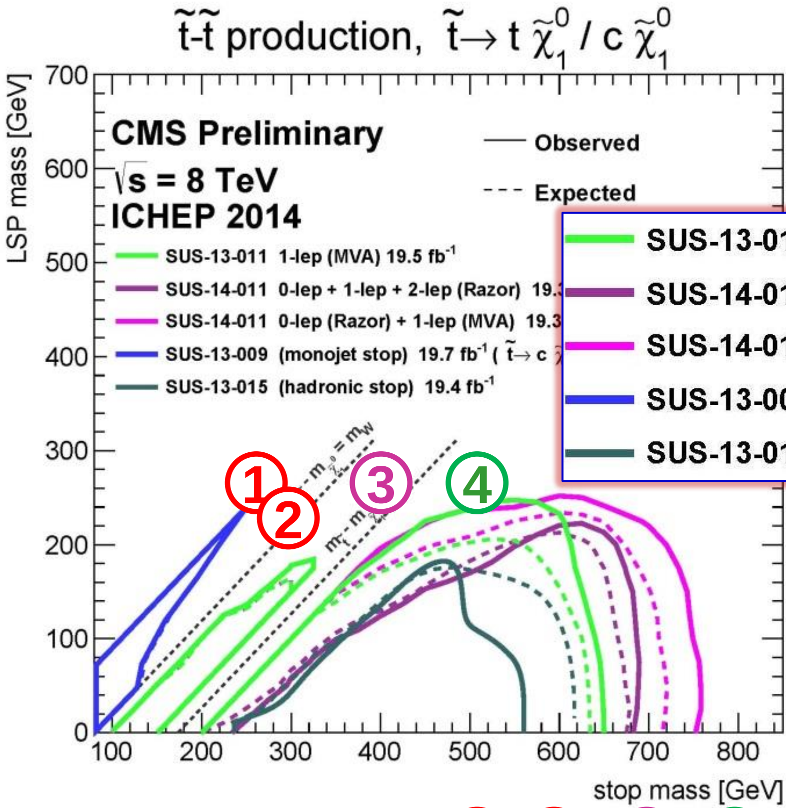




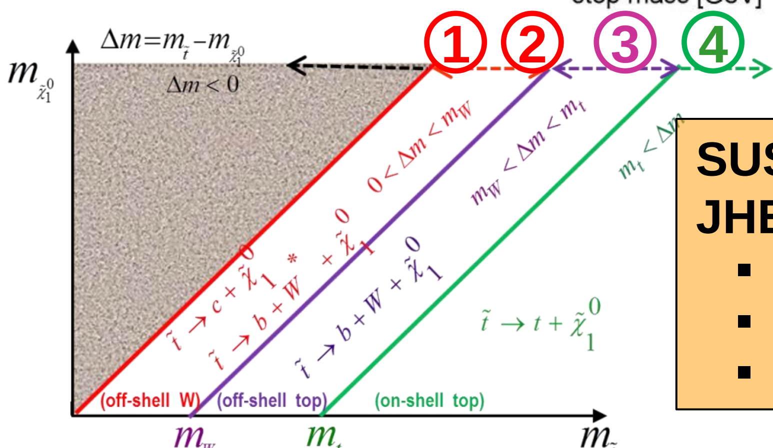




3rd Generation Squark

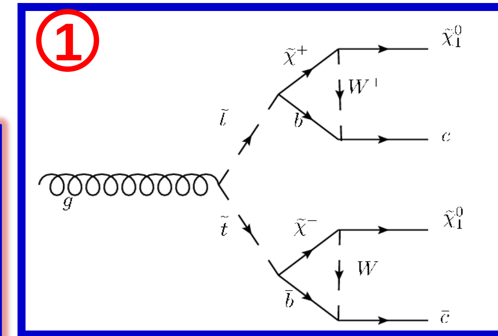


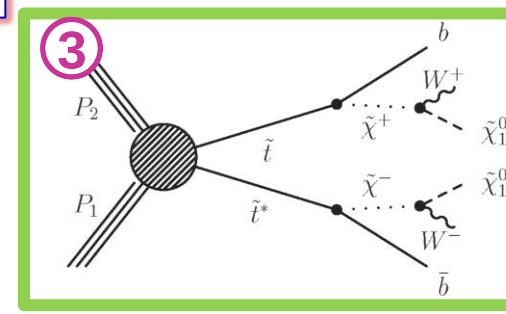
SUS-13-011 1-lep (MVA) 19.5 fb^{-1}
SUS-14-011 0-lep + 1-lep + 2-lep (Razor) 19.3 fb^{-1}
SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.3 fb^{-1}
SUS-13-009 (monojet stop) 19.7 fb^{-1} ($\tilde{t} \to c\, \tilde{\chi}_1^0$)
SUS-13-015 (hadronic stop) 19.4 fb^{-1}

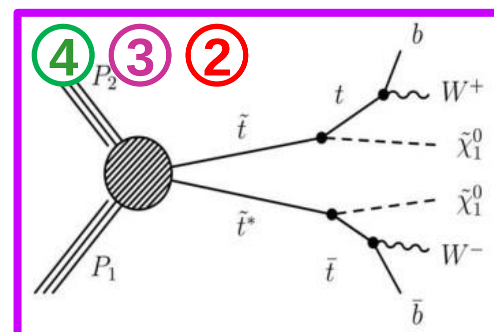


SUS-14-001 [1503.08037]
JHEP 06 (2015) 116

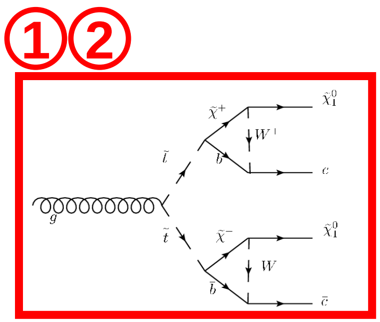
- **SUS-13-009 (monojet stop)**
- **SUS-13-015 (stop)**
- **SUS-13-018 (sbottom)**

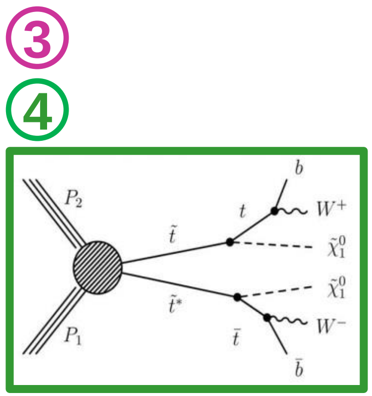


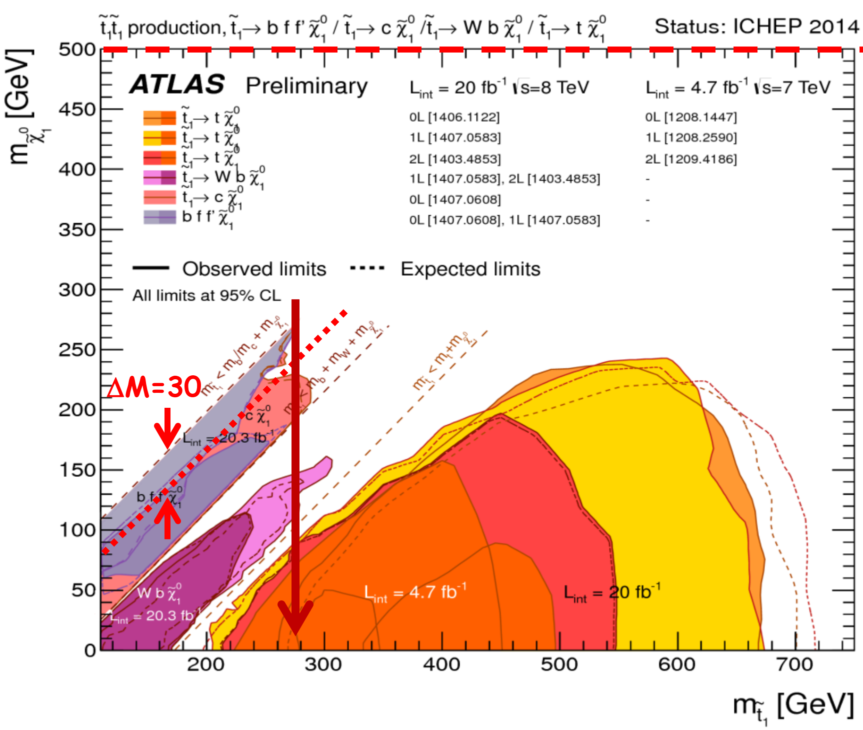


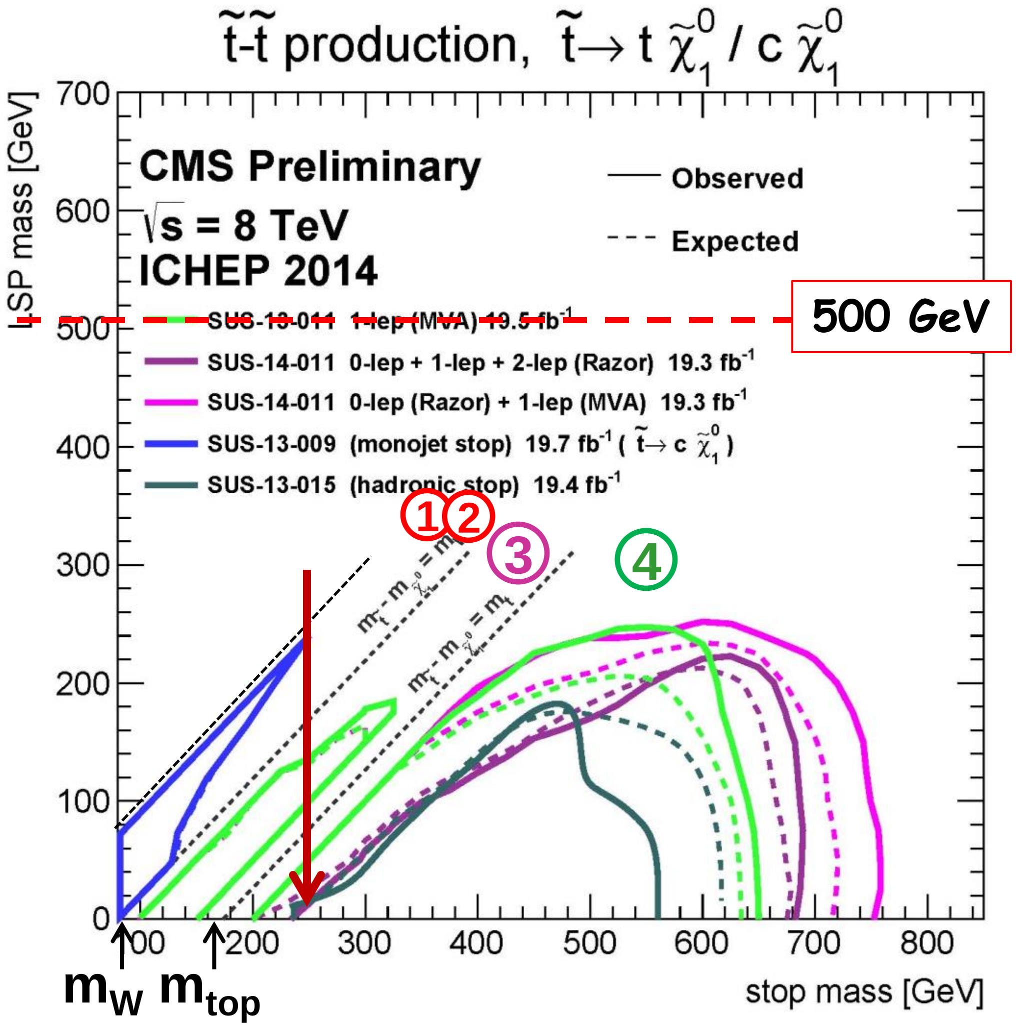


Top Squark Results at 8 TeV





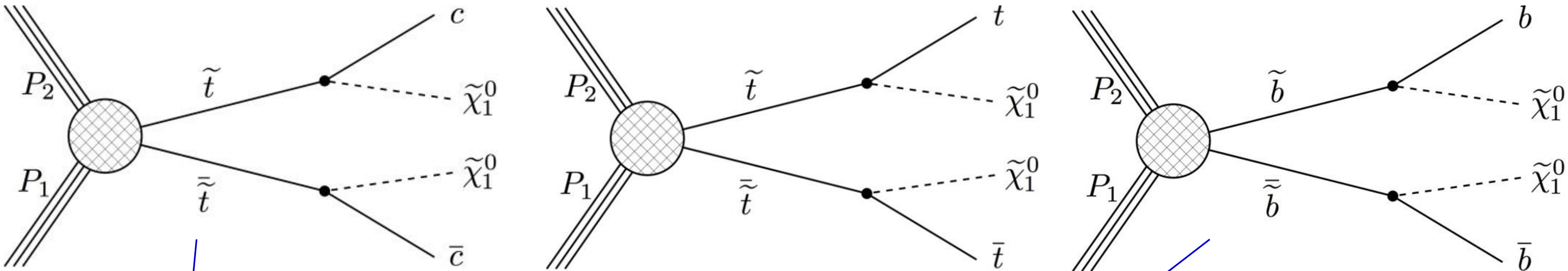


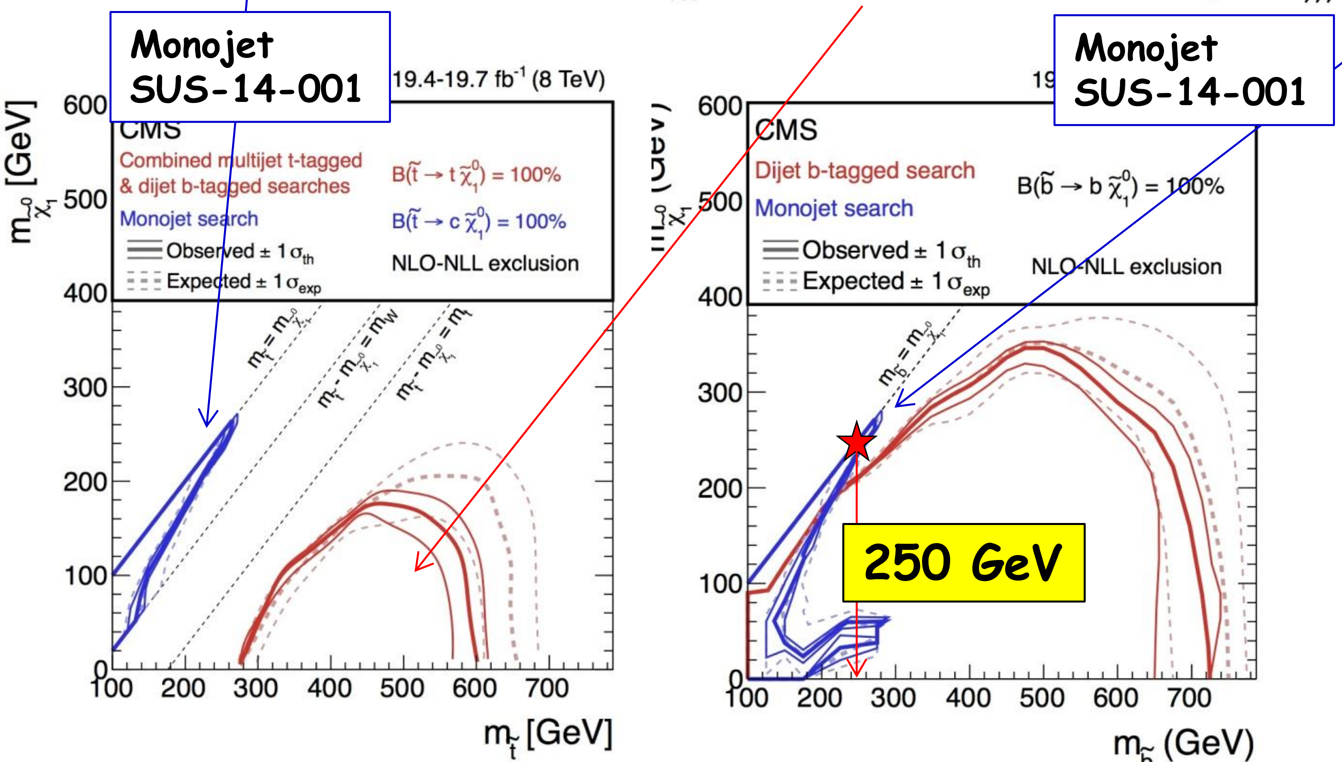


Compressed 3rd Generation Squark

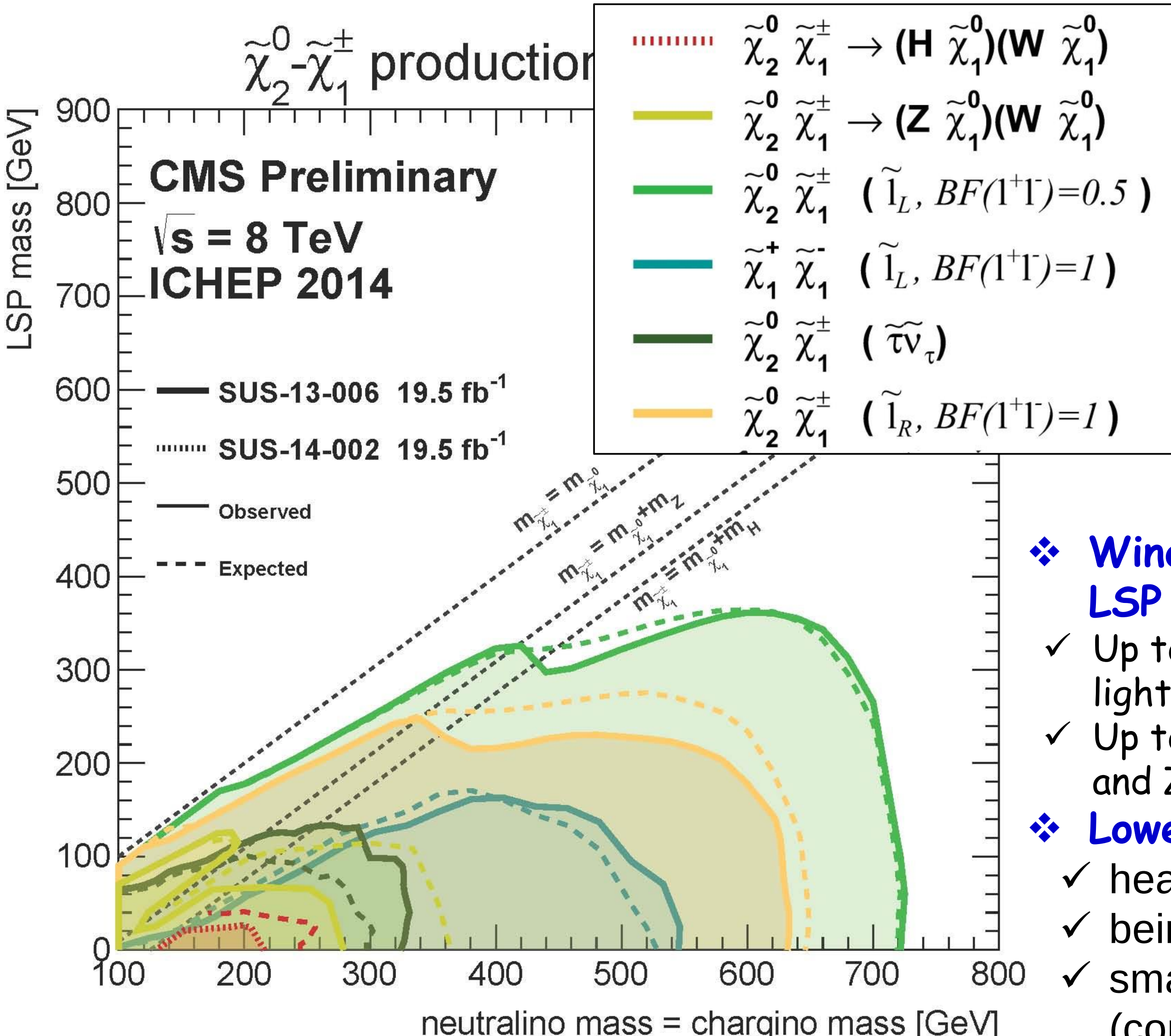
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS14001

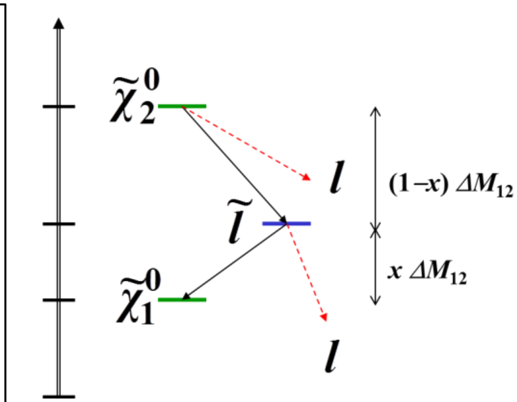
JHEP06(2015)116 [1503.08037]





Electroweak (EWK) Sector





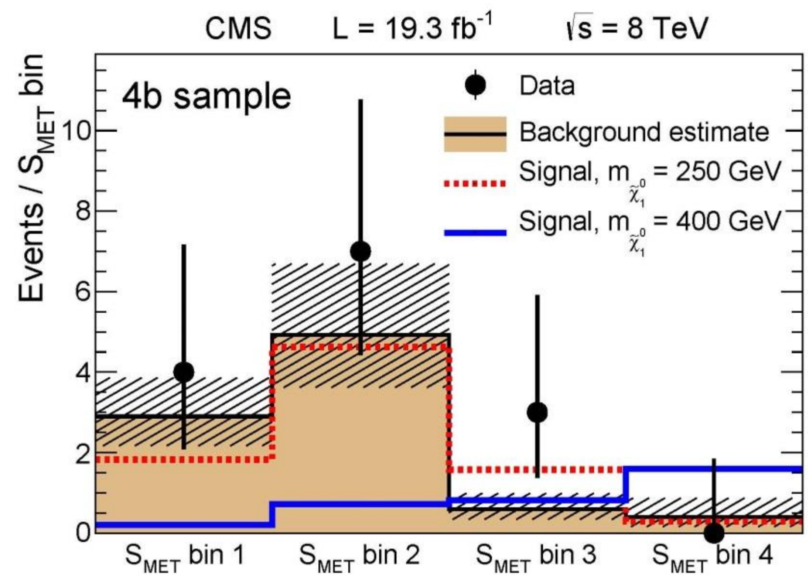
x = 0.5 (maximum sensitivity)

- **Wino-Chargino and Bino-LSP**
  - ✓ Up to ~700 and ~300 GeV for light slepton case
  - ✓ Up to 320 and 100 GeV for W and Z cases
- **Lower limits for**
  - ✓ heavy slepton
  - ✓ being Higgsinos
  - ✓ small mass difference (compressed spectra)

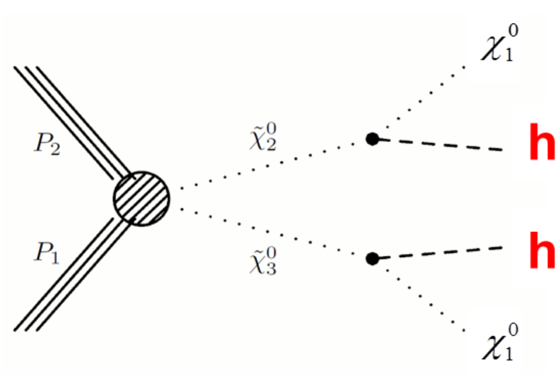
EWK Production of Higgsinos

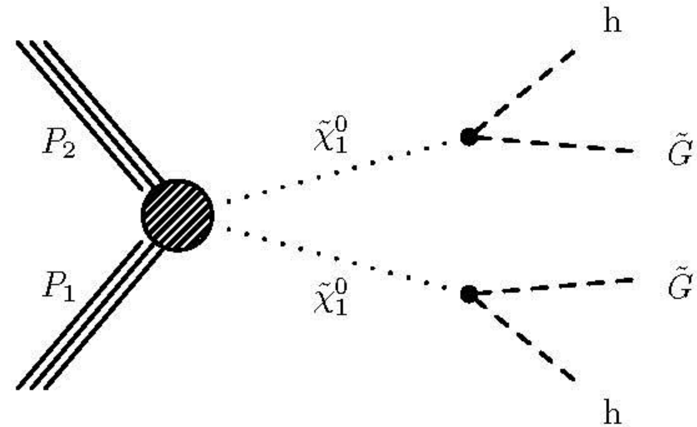
Phys. Rev. D 90 (2014) 092007 [SUS-14-002]

- Some small excess in data, compared with the SM prediction, but results are consistent with background only expectation within uncertainties
- Interpret null search result as limits on Higgsino production



- Interested in this final state as it could distinguish NMSSM from MSSM?

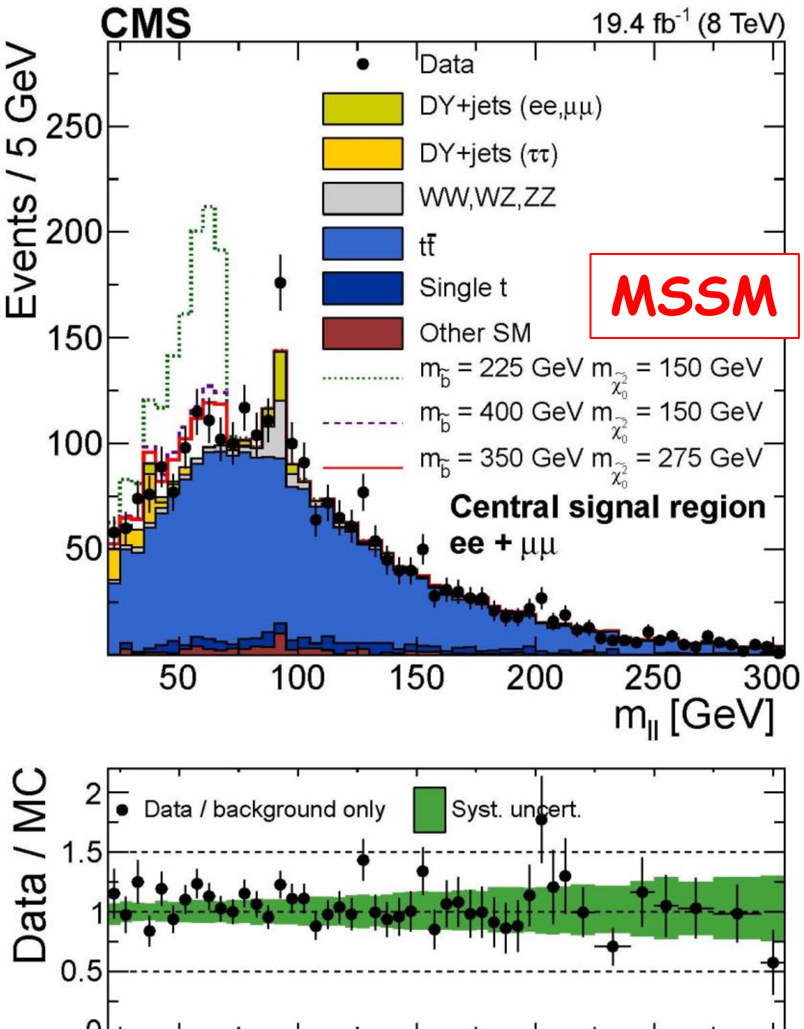


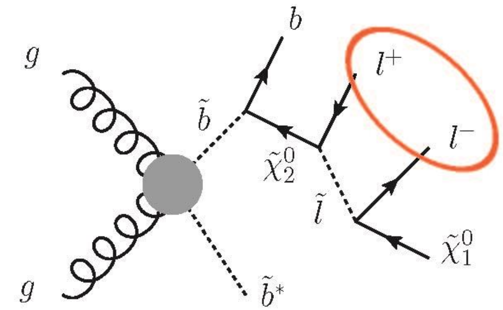


MSSM or NMSSM Bottom Squark Decays?

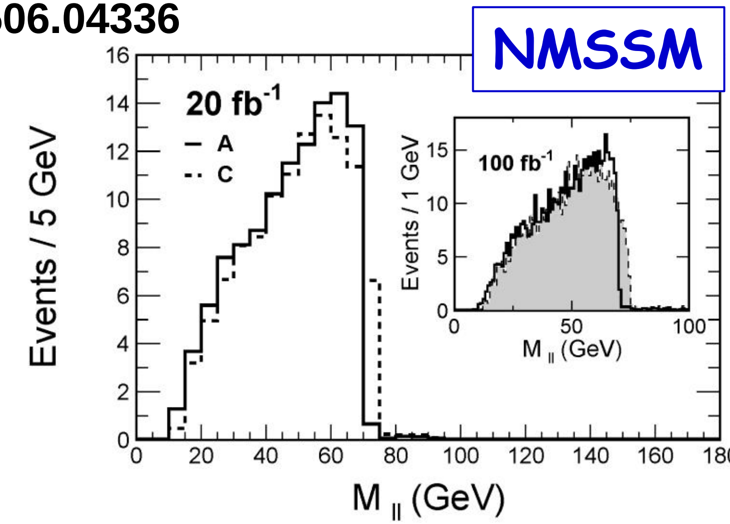
JHEP 04 (2015) 124 [SUS-14-014]

Also see CMS PAS SUS-12-019
http://cds.cern.ch/record/1751493?ln=en





B. Dutta, Y. Ga, T. Ghosh, TK, and N. Kolev, 1506.04336

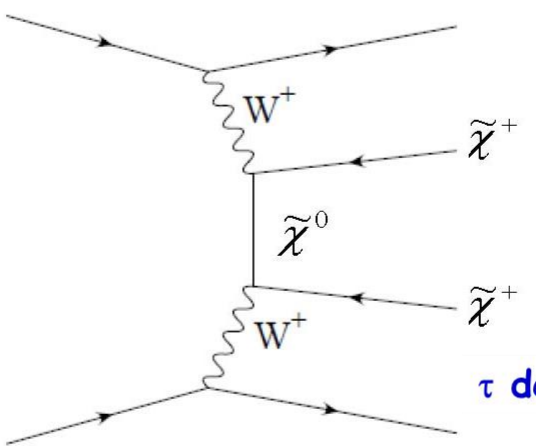


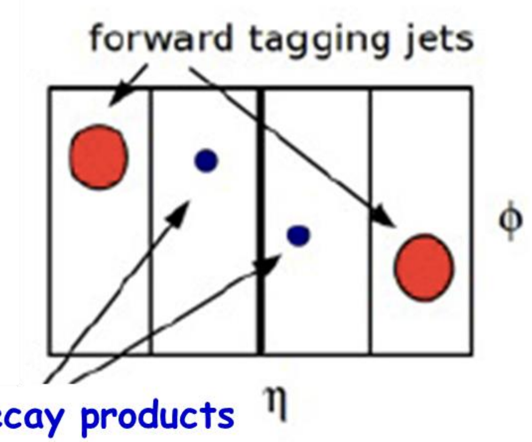
… not ruled out by the direct detection experiments and with unique features in the neutralino sector compared to the MSSM.

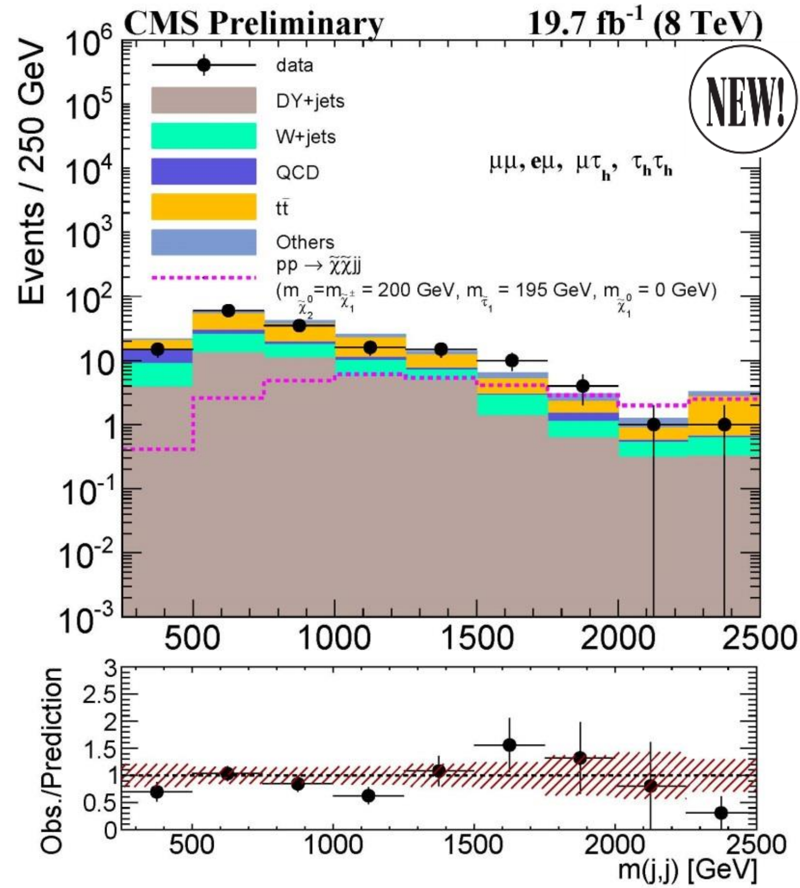
SUSY VBF + MET + 2 Leptons

[SUS-14-005] "Search for supersymmetry with the vector boson fusion topology in proton-proton collisions at /s = 8 TeV", Physics Analysis Summary (CERN link: http://cds.cern.ch/record/2002647?ln=en)

- The first SUSY search of its kind in VBF topology (arXiv:1508.07628; submitted to JHEP)
- Inclusive muon trigger and diTau trigger
- mu-mu, mu-e, mu-tau, tau-tau ; OS & LS



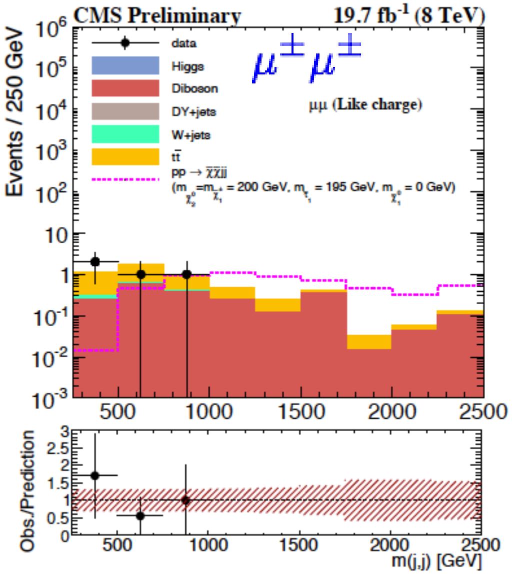


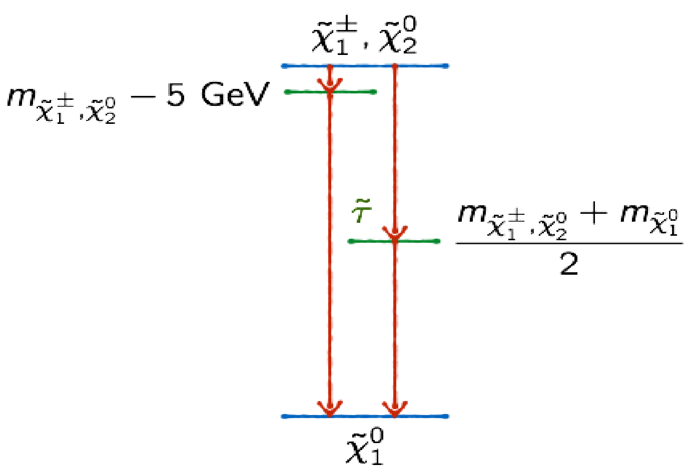


- **Run 2: VBF + soft lepton triggers**

SUSY VBF: Some details

Process	$\mu^{\pm}\mu^{\pm}jj$	$e^{\pm}\mu^{\pm}jj$	$\mu^{\pm}\tau_h^{\pm}jj$	$\tau_h^{\pm}\tau_h^{\pm}jj$
DY + jets	< 0.01	$0\pm^{1.7}_{0}$	0.5 ± 0.2	< 0.01
W + jets	$0.1 \pm 8.2 \times 10^{-4}$	$0\pm^{3.0}_{0}$	9.3 ± 2.3	0.5 ± 0.1
VV	2.1 ± 0.3	$1.9\pm^{0.4}_{0.2}$	1.1 ± 0.2	$0.1 \pm 6.5 \times 10^{-2}$
$t\bar{t}$	3.1 ± 0.1	$3.5\pm^{0.7}_{0.9}$	6.7 ± 2.8	$0.1 \pm 1.2 \times 10^{-2}$
Single top	–	–	–	< 0.1
QCD	–	–	–	7.6 ± 0.9
Higgs	–	–	–	< 0.01
Total	5.4 ± 0.3	$5.4\pm^{3.5}_{0.9}$	17.6 ± 3.8	8.4 ± 0.9
Observed	4	5	14	9





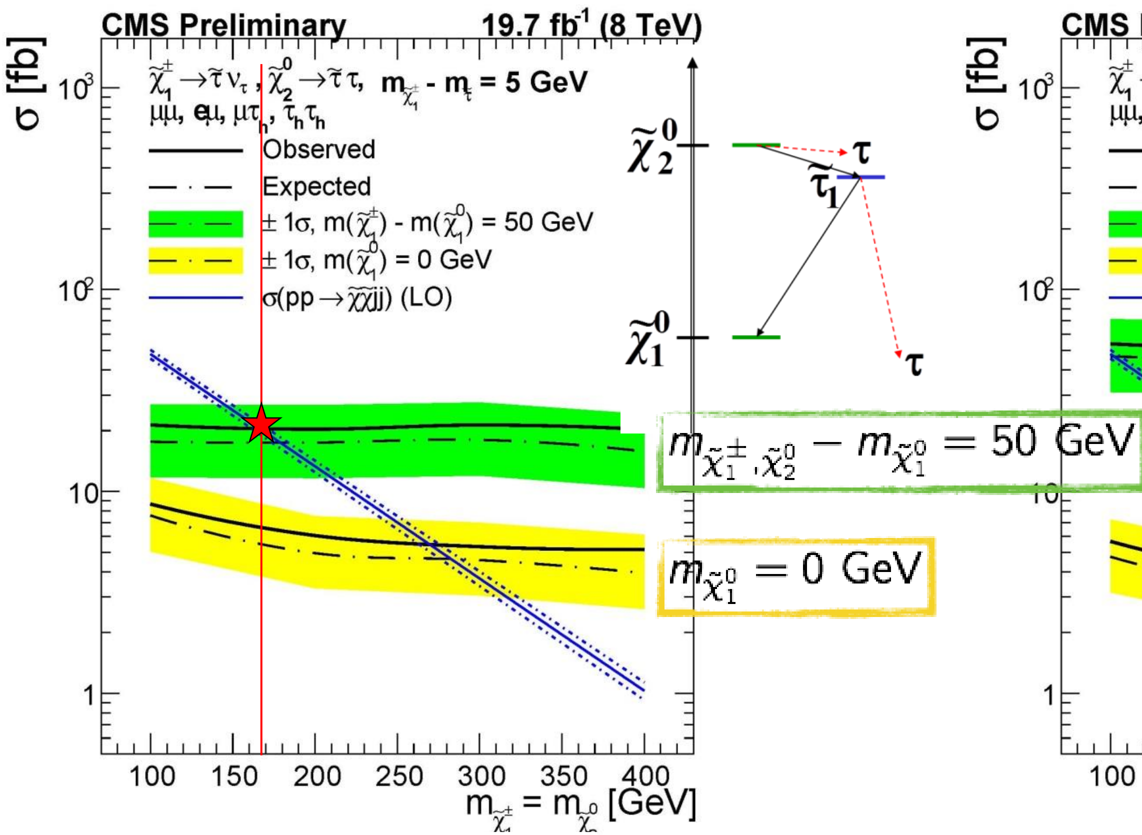
SUS-14-005

One of first SUSY searches with VBF signature

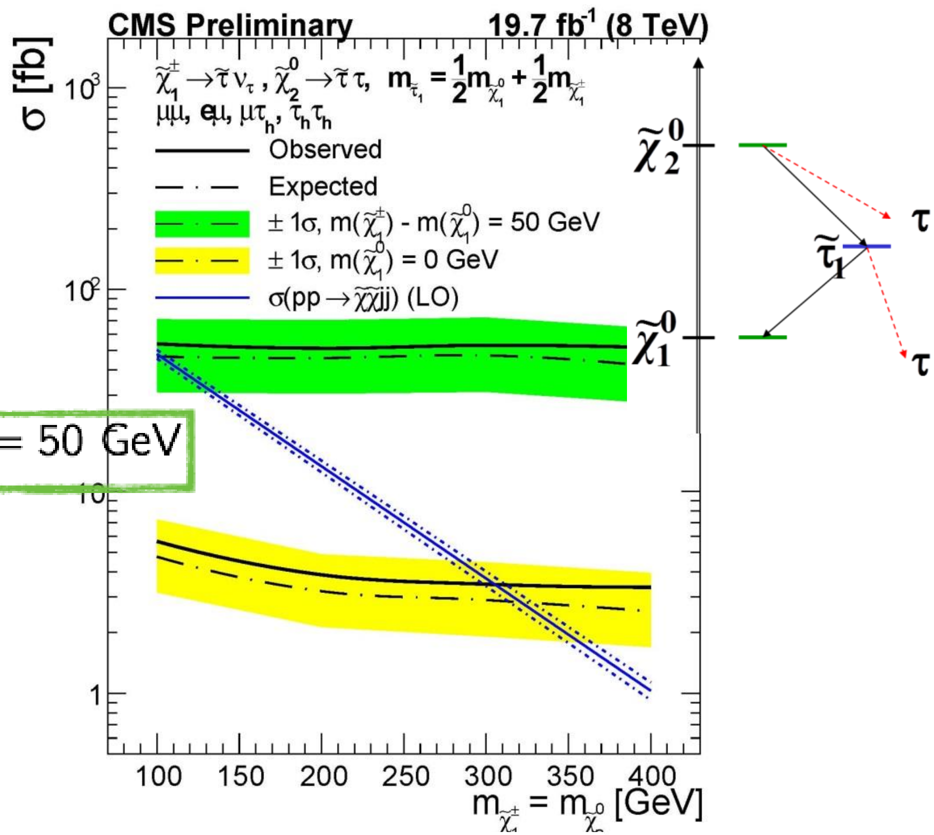
SUSY VBF + MET + 2L

MG5, |Δη| > 4.2
QCD2QED2 + QCD0QED4

NEW!



SUS-14-005

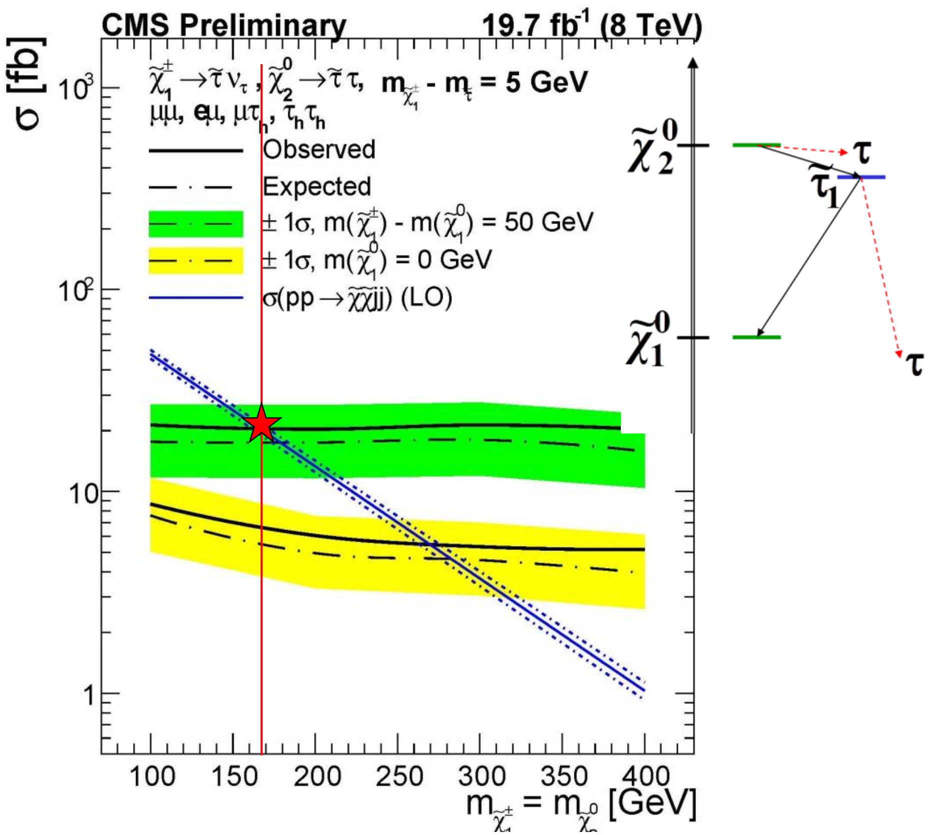


SUS-14-005

SUSY VBF 2L vs. Direct 3L

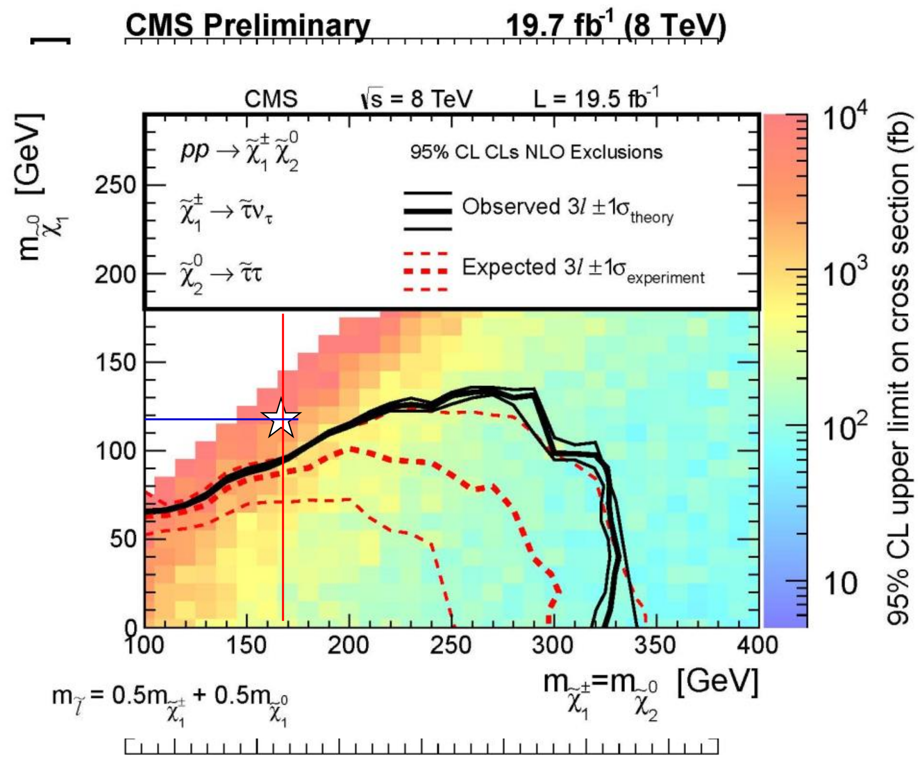
MG5, |Δη| > 4.2
QCD2QED2 + QCD0QED4

NEW!



SUS-14-005

x ~ 0.95 (maximum sensitivity)



SUS-13-006

EPJC 74 (2014) 3036 [1405.7570]

x = 0.5 (maximum sensitivity)

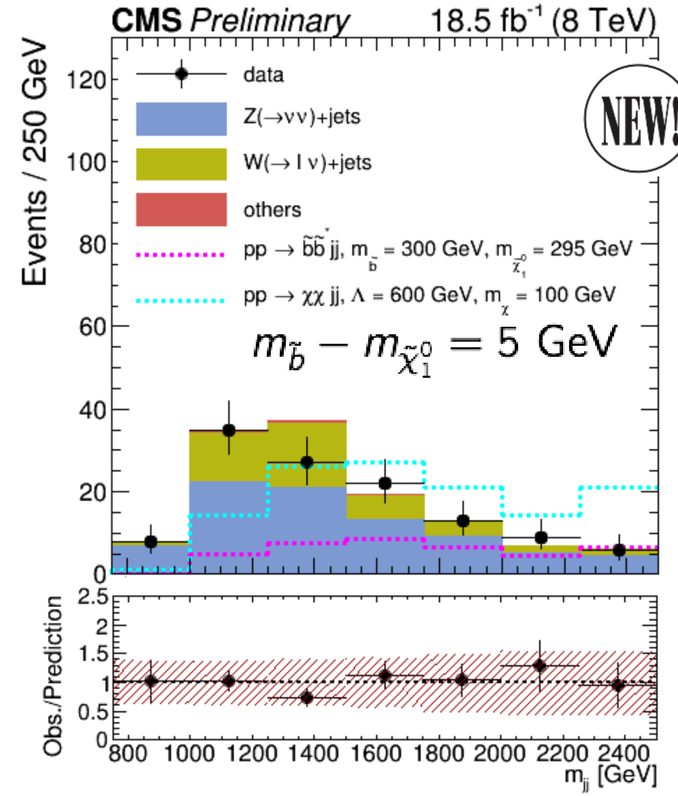
VBF + MET: Compressed SUSY / DM

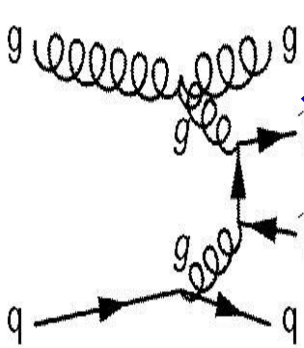
[Trigger] MET65+VBFDiJet35

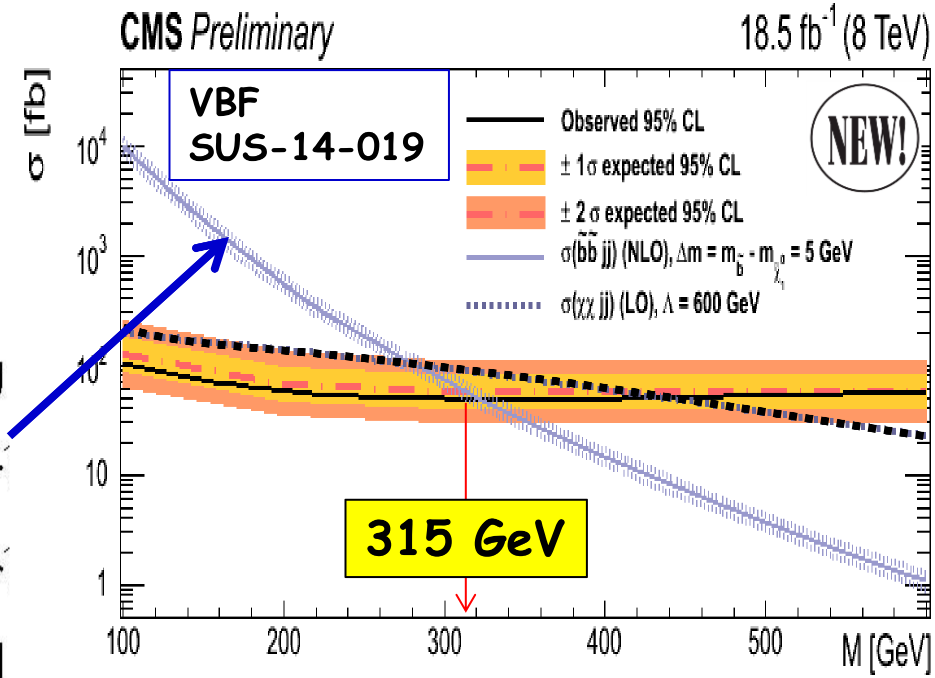
[Selection] Two jets (p_T > 50 GeV with $\eta_1\eta_2$ < 0; $|\eta_1-\eta_2|$ > 4.2 and invariant mass m_{12}>750 GeV; no b-tag); MET > 250 GeV;

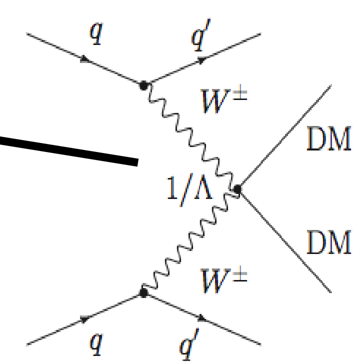
veto further jets (p_T> 30 GeV)

[Dominant BG]: $(Z \to \nu\nu) + \text{jets}$ & $(W^\pm \to l^\pm\nu) + \text{jets}$ are estimated from data.

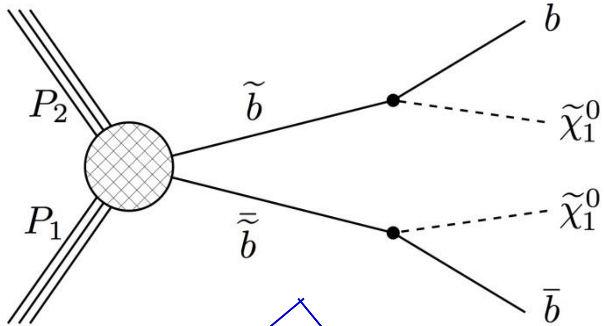






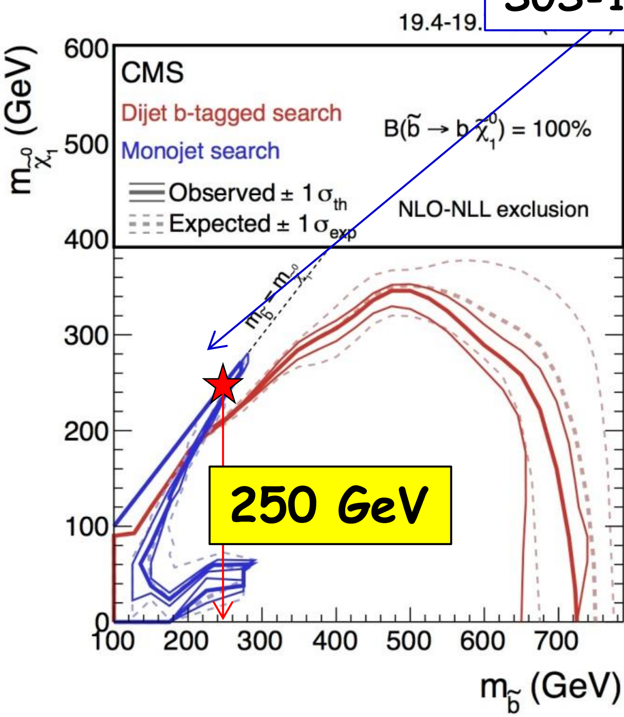


ISR vs. VBF in Case of Compressed SUSY

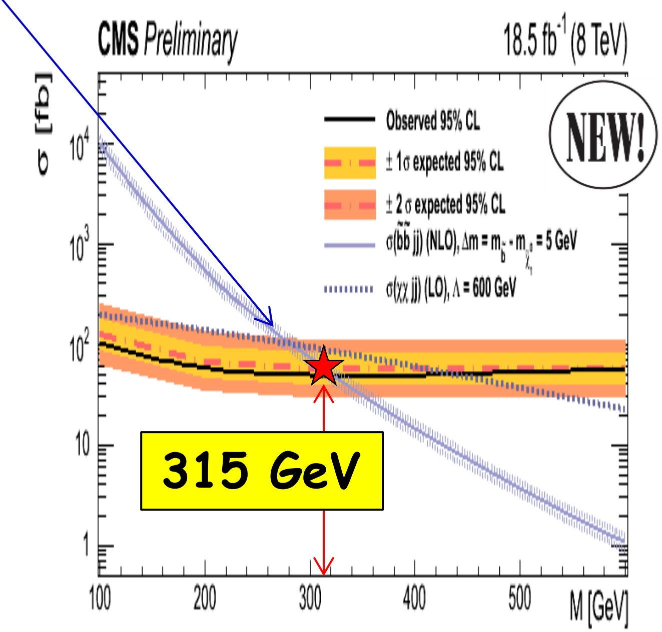


Monojet
SUS-14-001

VBF
SUS-14-019



Vs.

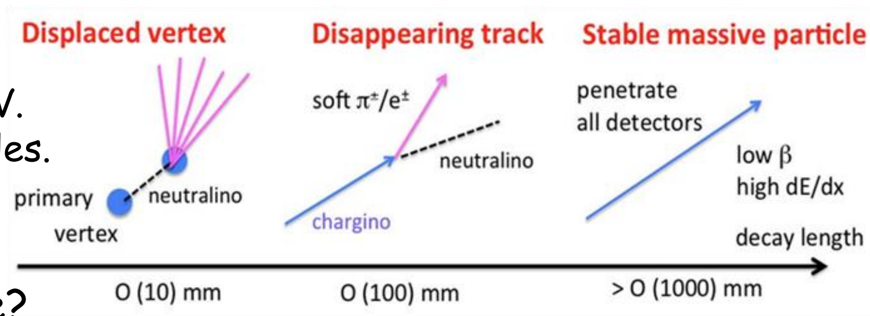


SUSY + Another Higgs Wanted

- 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 ..

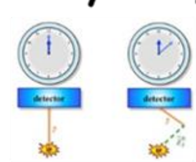
  [Example] Higgsino LSP → chargino and neutralinos below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.
  - Gravitino
- Sleptons
  - Selectrons and smuons - mass degenerate?
  - Special case: Stau is lighter.
- Displaced Tracks
- Long-Lived (LL)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

Compressed scenarios at hadron collides

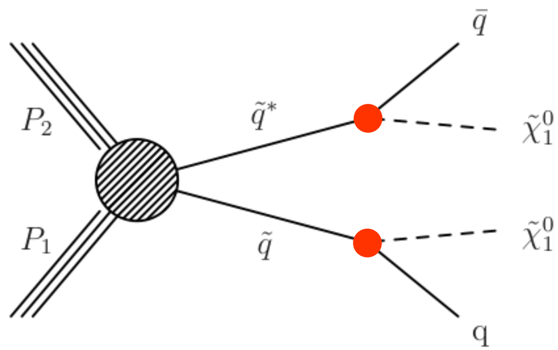


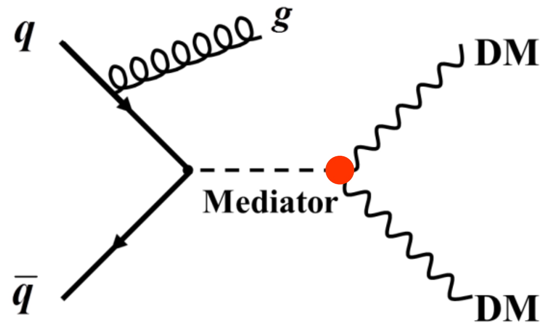
"non-pointing" γ

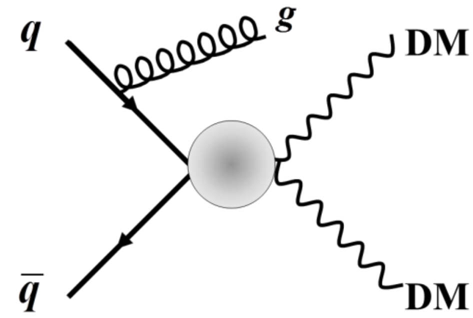
"delayed" γ

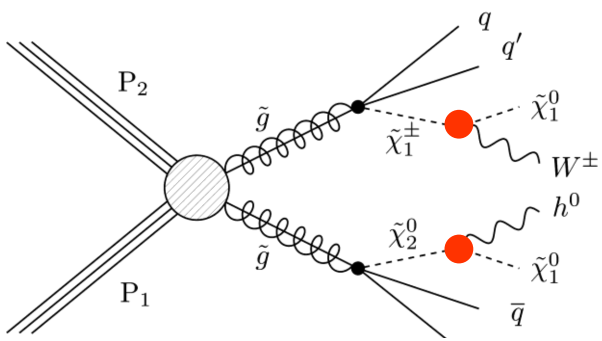


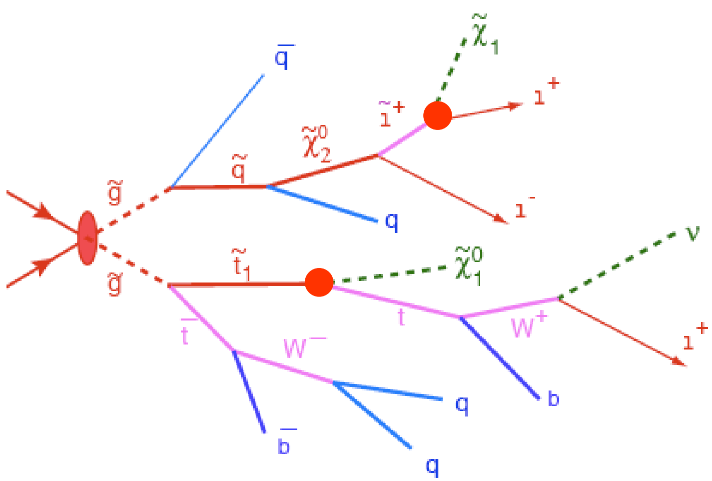
Cold DM (χ) Marketplaces









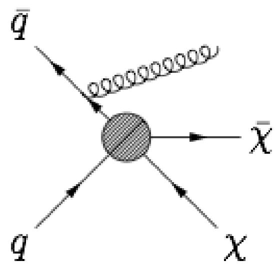


- Simplified Models, including Effective Field Theory (EFT)
- Full Models:
  - R-parity conserving SUSY (with a DM candidate)
  - R-parity violating SUSY (with a DM candidate from somewhere else)
  - "Dark" sector – Higgs-portal, Fermion portal
  - Extra Dimension
  - …

Selected topics:
[I] Supersymmetry (SUSY)
[II] Mono-X for DM-SM interaction

One Page Summary of DM 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	$G\tilde{G}$	$i\alpha_s/8M_*^3$

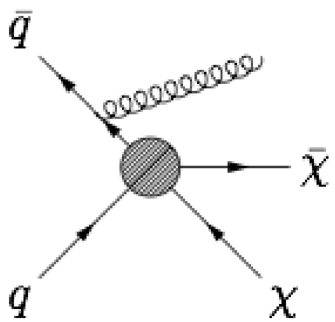
Real scalar, 1008.1783

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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

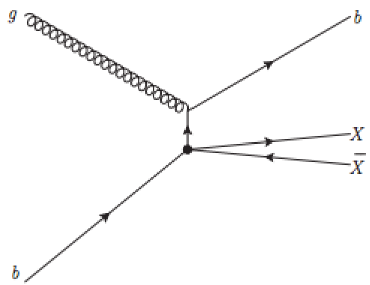
Complex scalar, 1008.1783

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	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

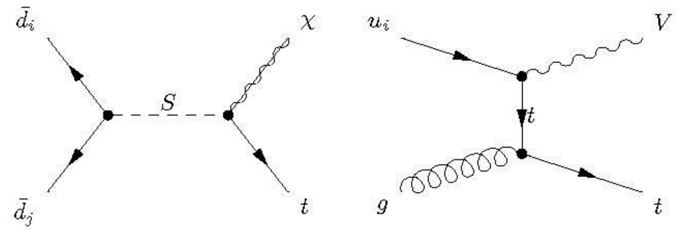
Extensive MET + X Searches



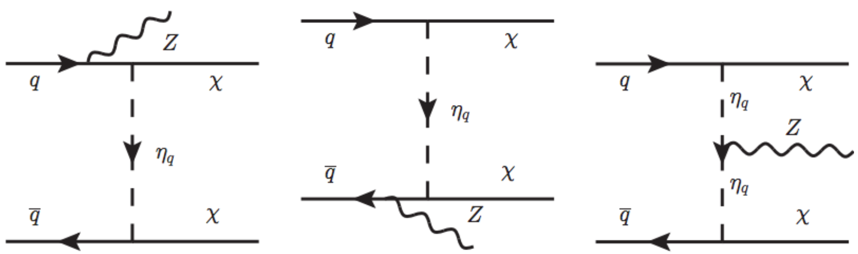
Monojet



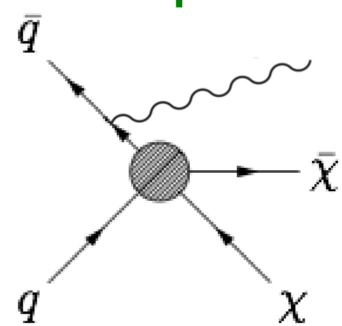
MonoB



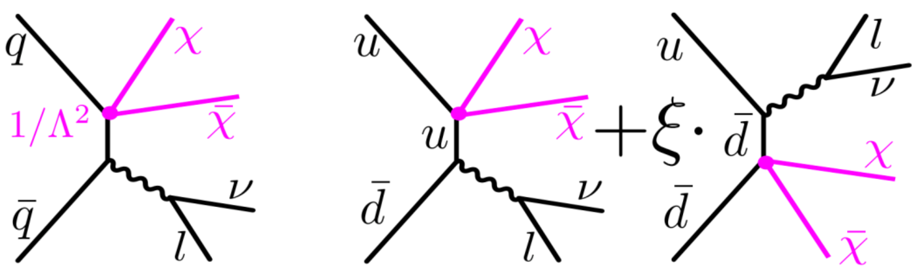
MonoTop



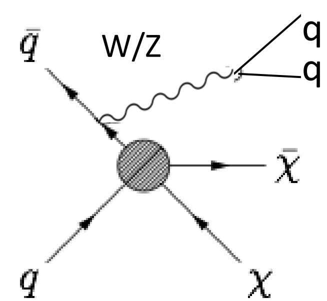
MonoZ



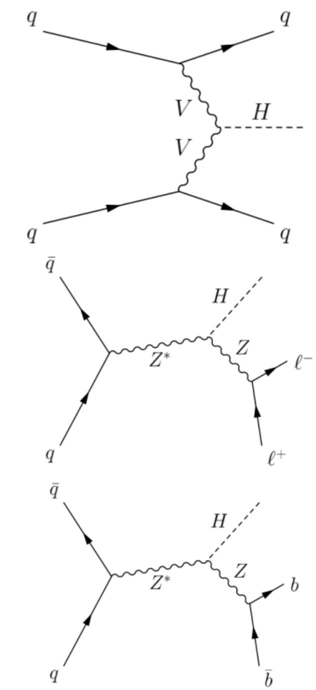
MonoPhoton



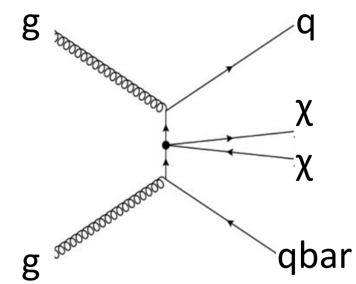
MonoW (monoLepton)



MonoW/Z (Hadronic)

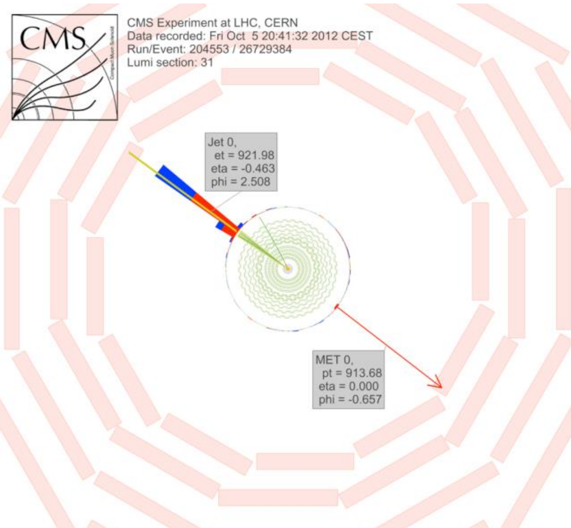


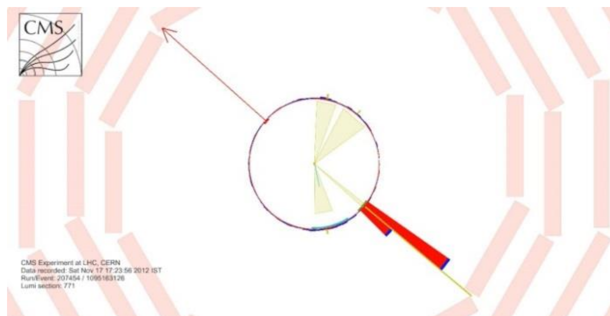
Higgs Portal

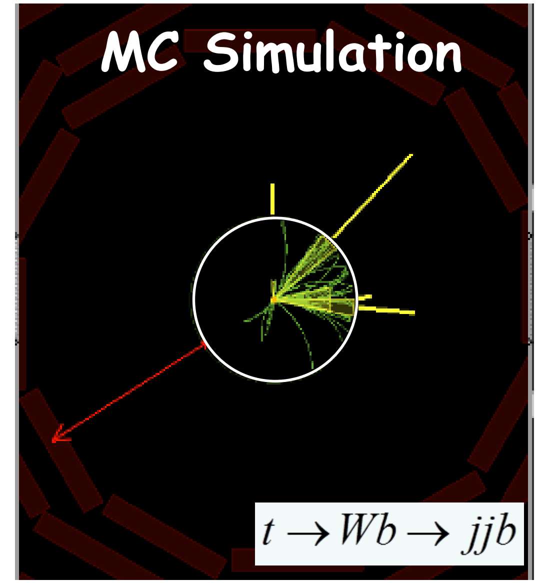


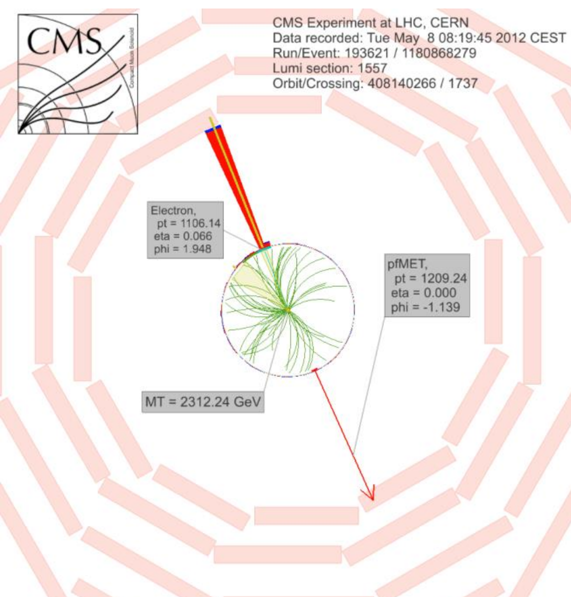
BBbar /TTbar

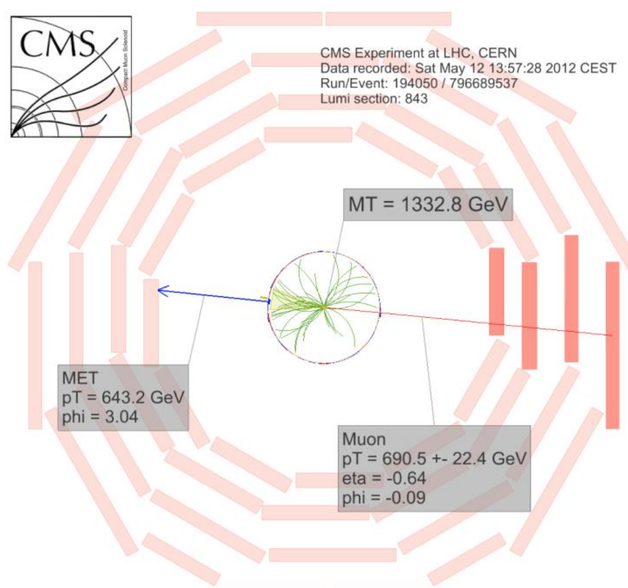
MonoX – Event Displays

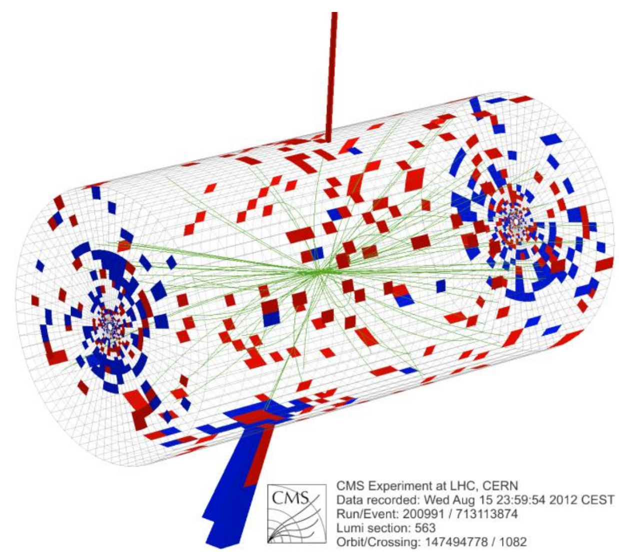






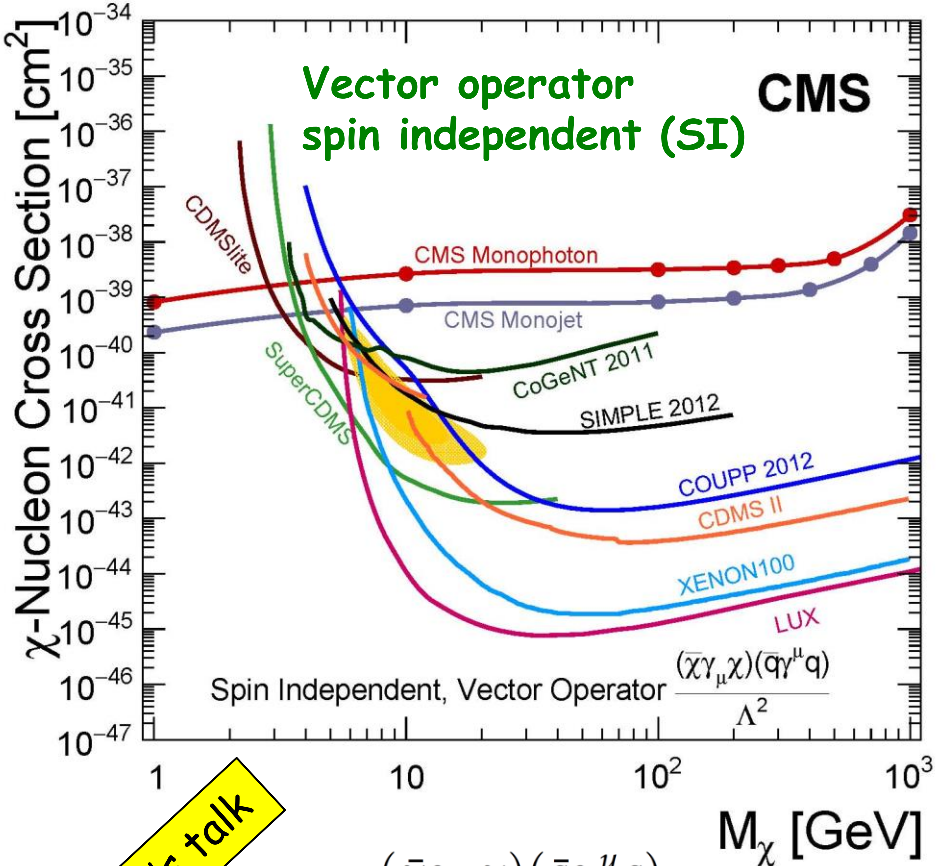


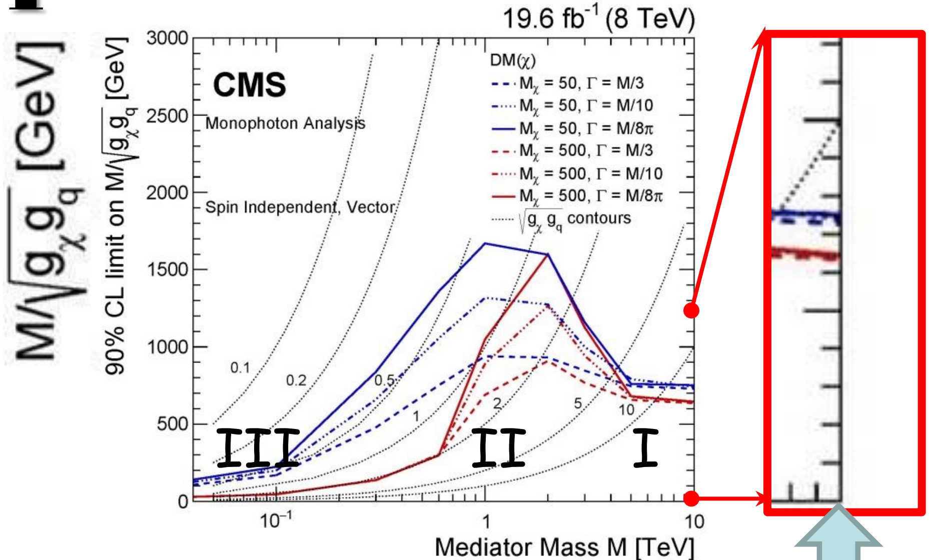




A few words ….

Monojet/Monophoton Results





10 TeV

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

Yang Bai's talk

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

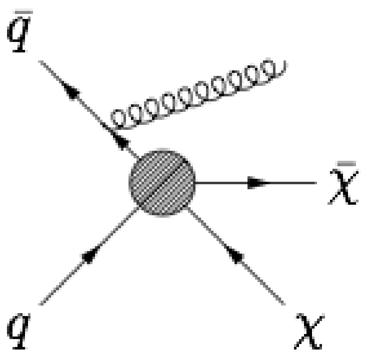
Λ = Contact interaction scale

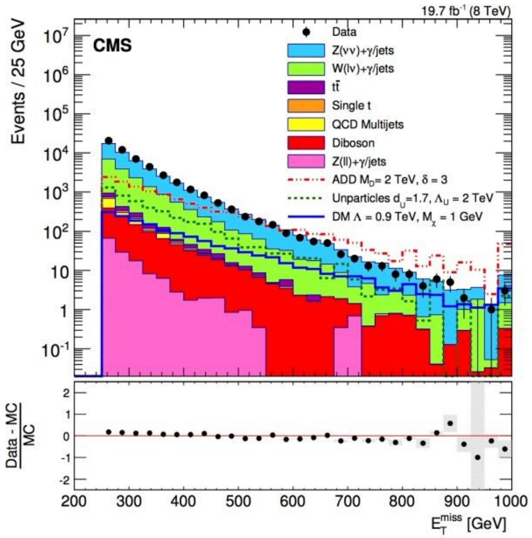
- ❖ EFT is valid for heavy mediator mass (M_*) > a few 10 TeV; The couplings required are large comparing this with known couplings:
- ❖ Theory is non-perturbative if $\sqrt{g_q g_{DM}} > 4\pi$
- ❖ Width larger than mass, so unlikely mediator will be identified as a particle

EFT (Λ) → a minimal framework (M*, couplings, DM types) for a comprehensive interpretation of collider results with other experiments (e.g., Direct Detection). See O. Buchmueller, S. Malik, M. Dolan, and C. McCabe, arXiV:1407.8257

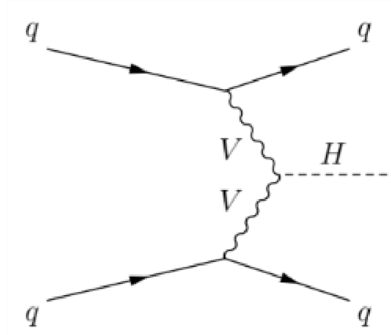
ISR Invisible vs. VBF Invisible

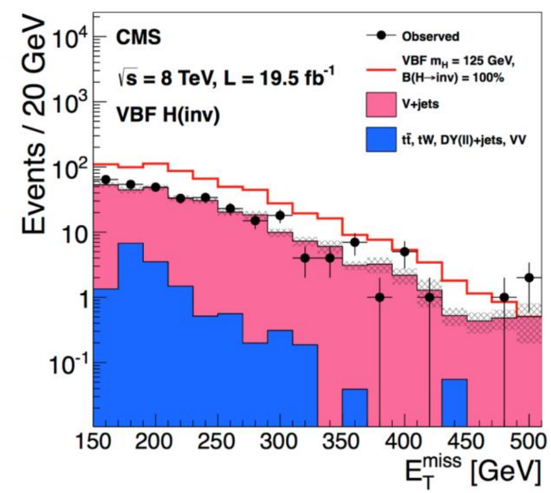
EPJC 75 (2015) 235 [1408.3583], CMS-EXO-12-048, CERN-PH-EP-2014-164





EPJC 74 (2014) 2980 [1404.1344], CMS-HIG-13-030, CERN-PH-EP-2014-051





- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4, and allow an additional jet (p_T > 30 GeV)
- **MET > 250 GeV → 500 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

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

ISR Invisible vs. VBF Invisible

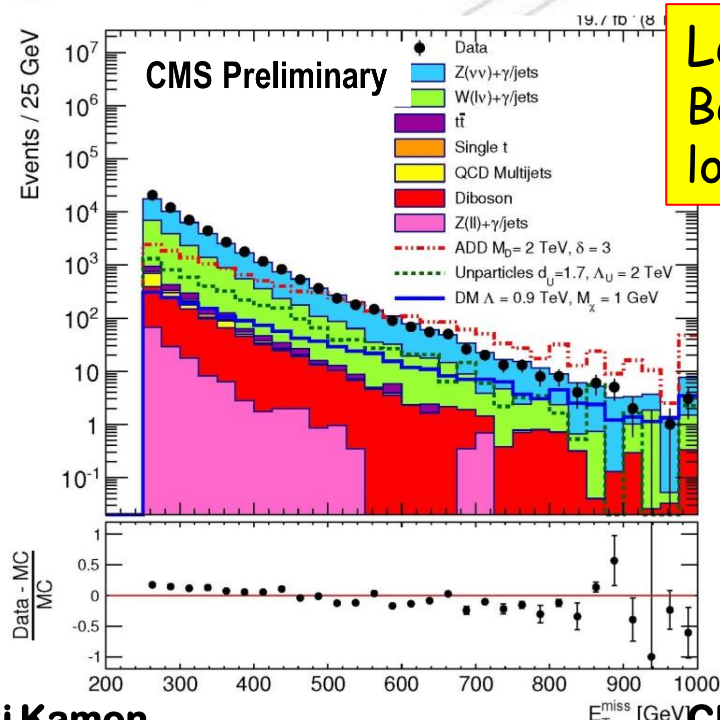
Z/W ratio ~ 3

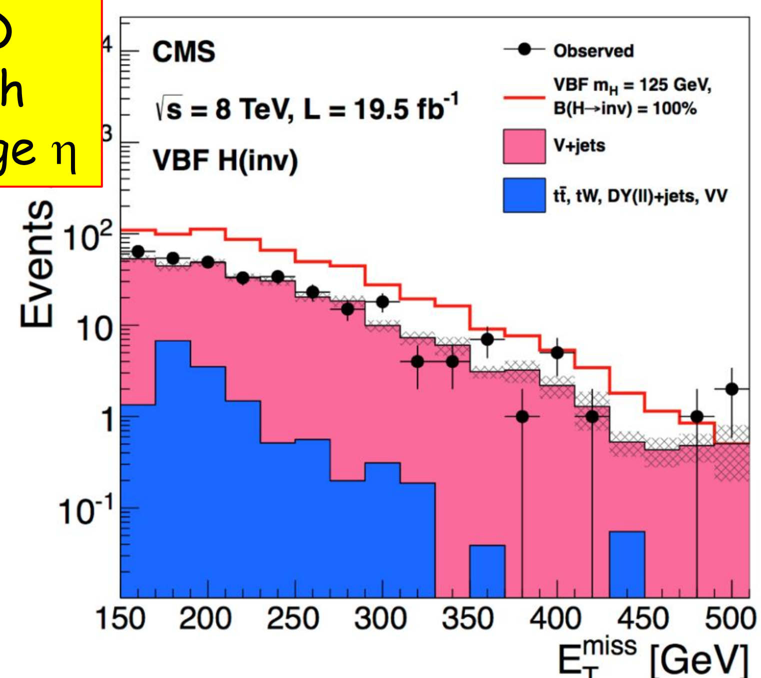
E_T^{miss} (GeV) →	> 400	> 450	> 500	> 550
$Z(\nu\nu)$+jets	2740 ± 220	1460 ± 140	747 ± 96	362 ± 64
W+jets	1030 ± 65	501 ± 36	249 ± 22	123 ± 13
$t\bar{t}$	31 ± 16	15 ± 7.7	6.6 ± 3.3	2.8 ± 1.4
$Z(\ell\ell)$+jets	8.9 ± 4.4	5.2 ± 2.6	2.3 ± 1.2	1.0 ± 0.5
Single t	6.1 ± 3.1	0.9 ± 0.4	—	—
QCD Multijets	4.9 ± 3.0	2.0 ± 1.2	1.0 ± 0.6	0.5 ± 0.3
Diboson	118 ± 59	65 ± 33	36 ± 18	20 ± 10
Total SM	3930 ± 230	2050 ± 150	1040 ± 100	509 ± 66
Data	3830	1830	934	519
Exp. upper limit $+1\sigma$	639	410	221	187
Exp. upper limit -1σ	357	168	123	104
Exp. upper limit	452	266	173	137
Obs. upper limit	397	154	120	142

Z/W ratio ~ 1/2

Process	Event yields
$Z(\nu\nu)$+jets	99 ± 29 (stat) ± 25 (syst)
$W(\mu\nu)$+jets	67 ± 5 (stat) ± 16 (syst)
$W(e\nu)$+jets	63 ± 9 (stat) ± 18 (syst)
$W(\tau_h\nu)$+jets	53 ± 18 (stat) ± 18 (syst)
QCD multijet	31 ± 5 (stat) ± 23 (syst)
Sum ($t\bar{t}$, single top quark, VV, DY)	20.0 ± 8.2 (syst)
Total background	332 ± 36 (stat) ± 45 (syst)
VBF H(inv.)	210 ± 29 (syst)
ggF H(inv.)	14 ± 10 (syst)
Observed data	390
S/B	70%

Lepton ID
Better with
low p_T, large η

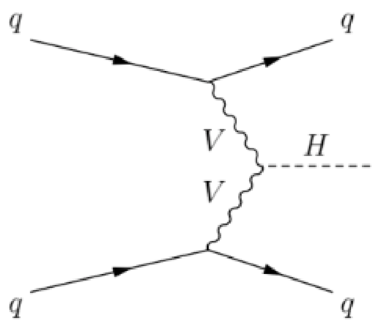


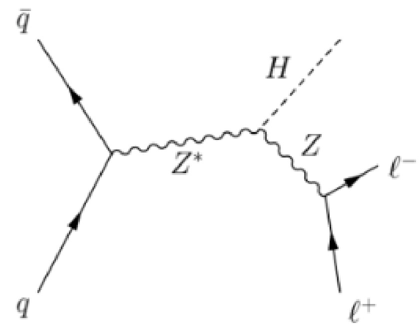


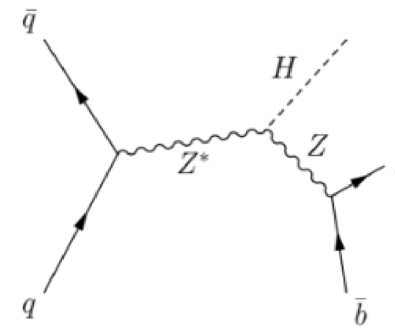
Higgs portal to DM: H(inv)

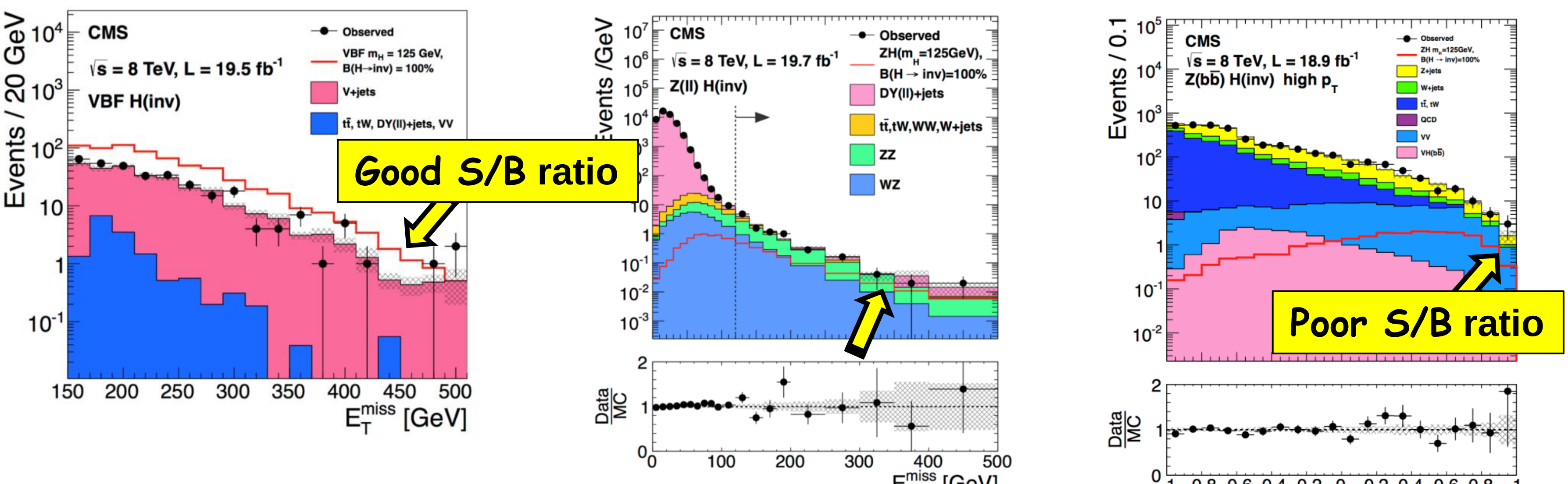
EPJC 74 (2014) 2980 [1404.1344], CMS-HIG-13-030, CERN-PH-EP-2014-051

DM particles have the direct couplings to the SM Higgs boson sector, $H \to \chi\chi$: (a) Limits on branching fraction of Higgs to "invisible" particles used for limits on DM, (b) Scalar, vector or fermionic couplings, (c) Limits only up to DM mass $M_\chi < M_H/2$



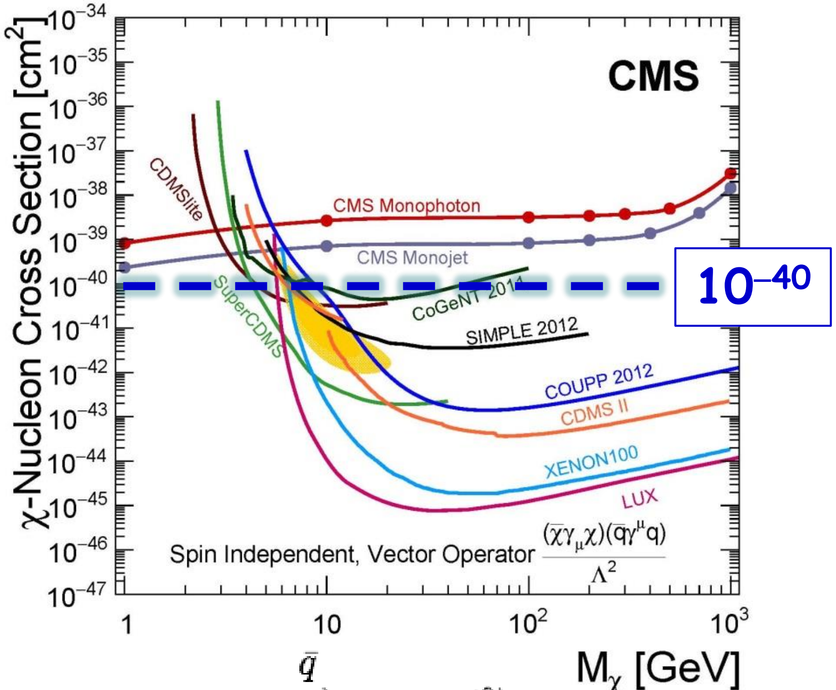


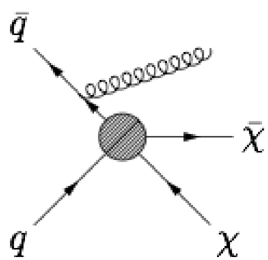




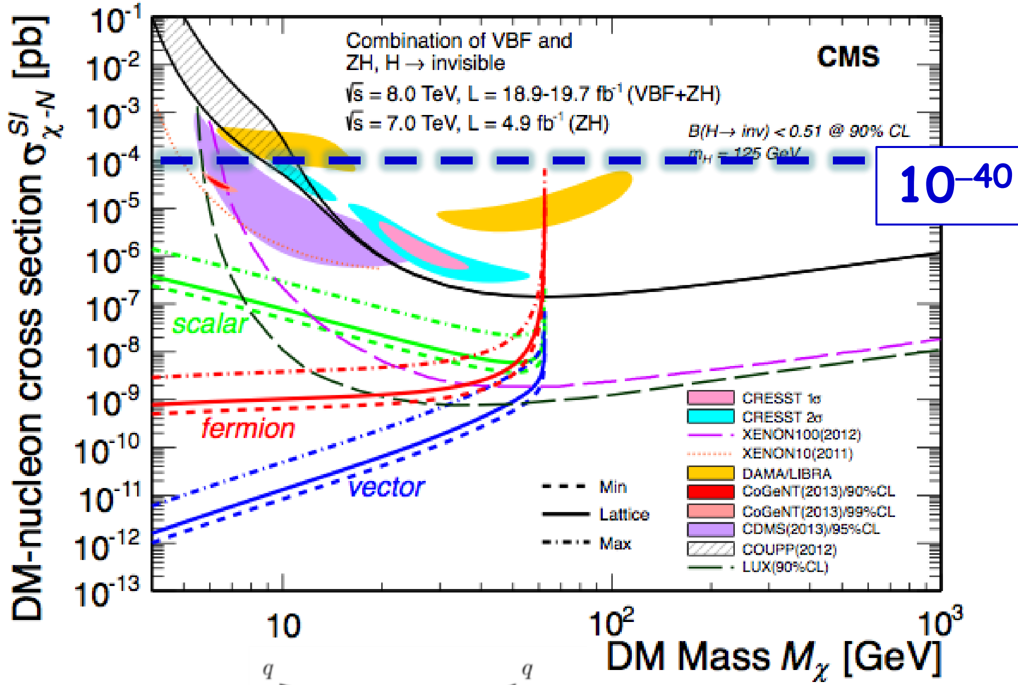
ISR Invisible vs. VBF Invisible

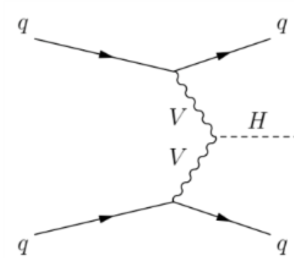
EPJC 75 (2015) 235 [1408.3583], CMS-EXO-12-048, CERN-PH-EP-2014-164





EPJC 74 (2014) 2980 [1404.1344], CMS-HIG-13-030, CERN-PH-EP-2014-051

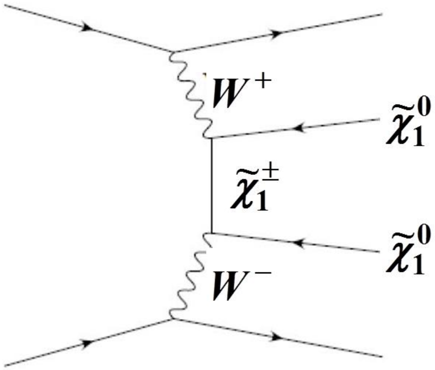


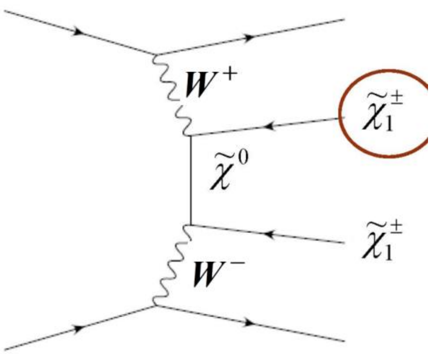


[Beyond EFT approach] See, for example, S. Baek, P. Ko, and W. Park, PRD 90 (2014) 055014 [1405.3530] for explicit expressions within UV completions

Next Gen. Searches via VBF

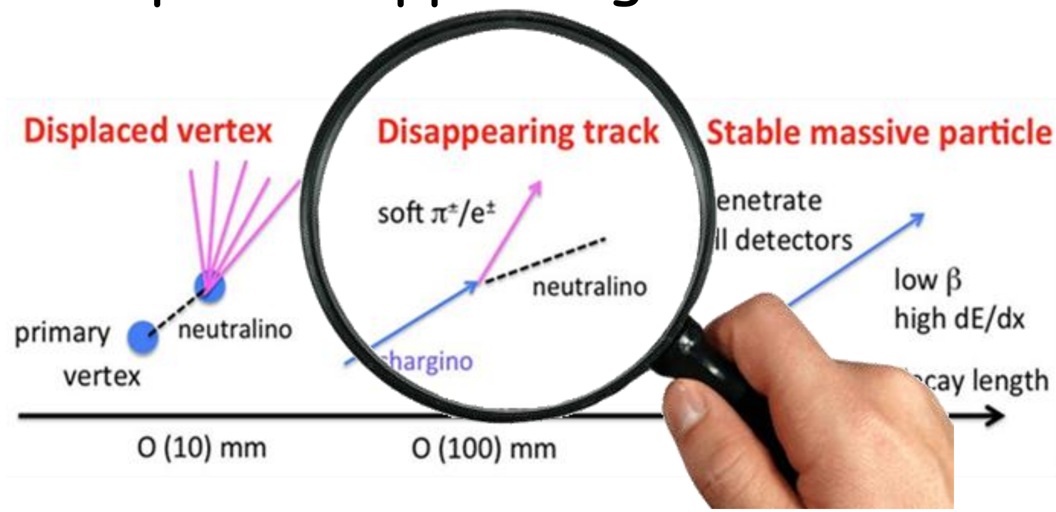
REMARK!





$jj + MET + X$

- ❖ The final state is same as invisible Higgs signal, but larger p_T jets
- ❖ Cross section?
  - ✓ Wino-like DM
  - ✓ Bino-Higgsino DM
- ❖ Example, disappearing tracks?



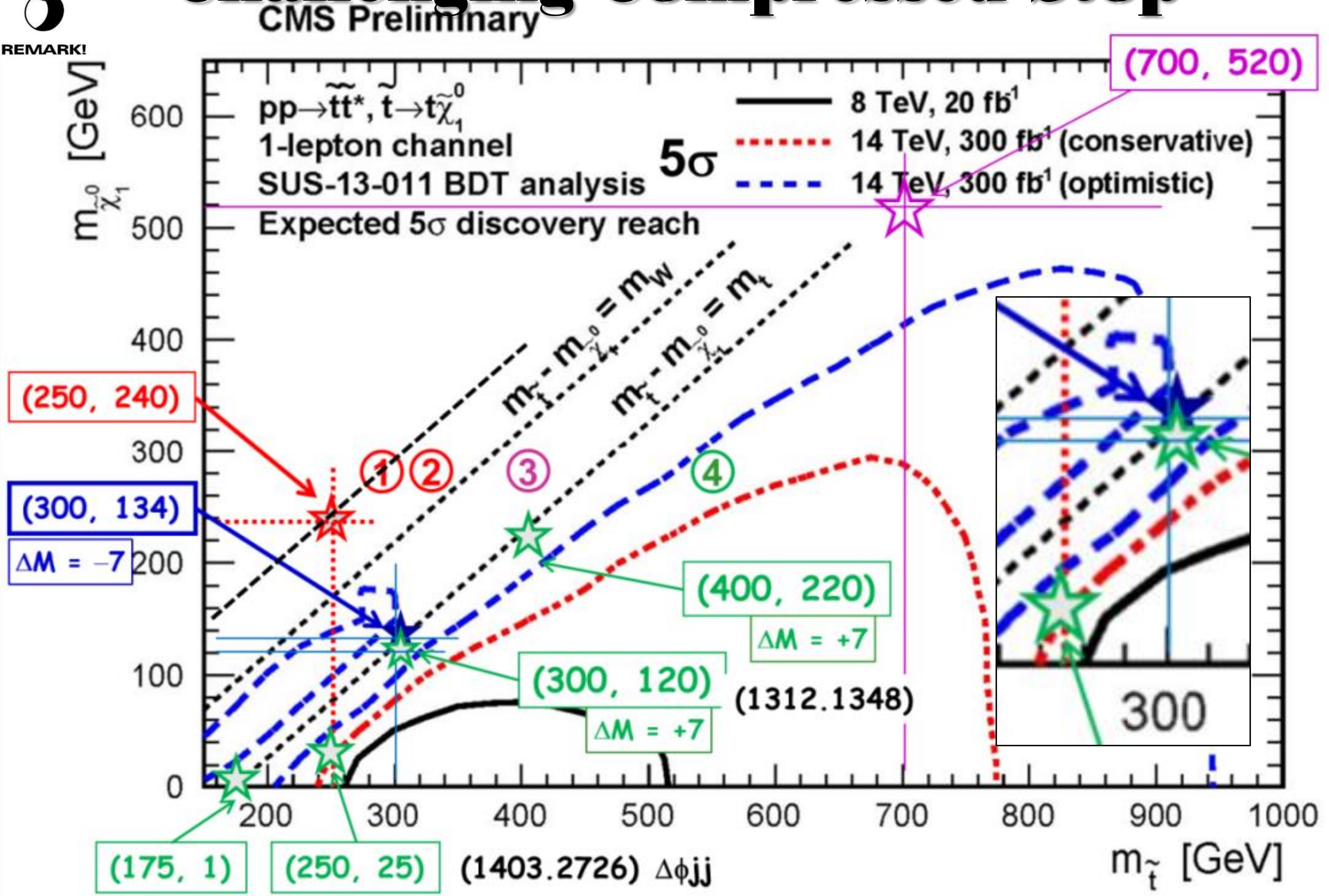
CMS-EXO-12-034, JHEP 01 (2015) 096 [1411.6006]
Search for disappearing tracks in events with jet p_T > 100 GeV, MET > 100 GeV for direct production of C1N2 and C1C1.

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

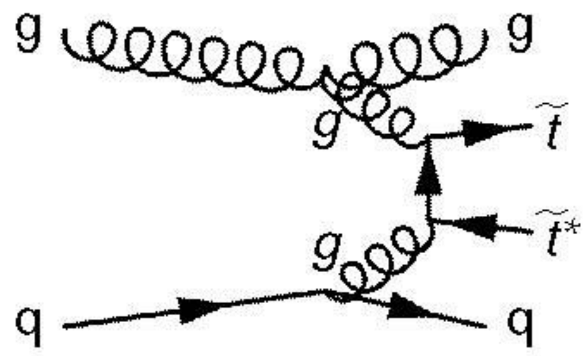
$$\Rightarrow Br(\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm) \sim 100\%$$

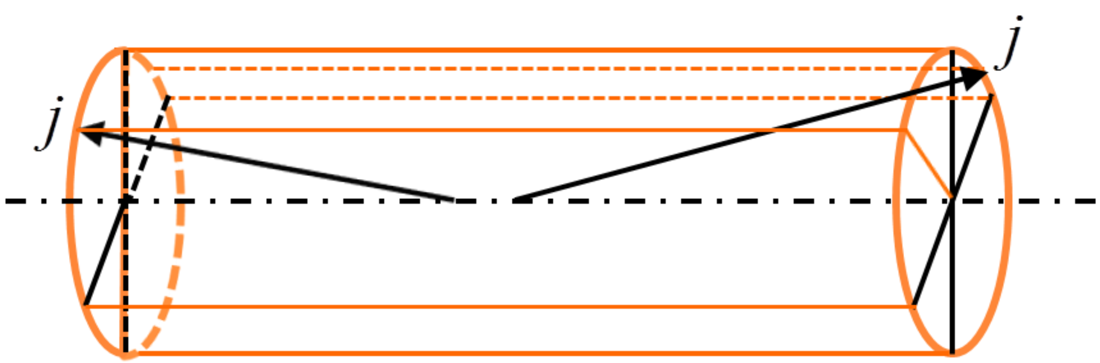
$$P_T(\pi^\pm) \sim \Delta M \sim 100\ MeV$$

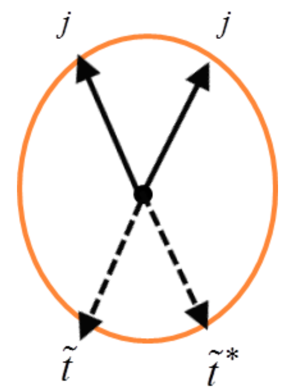
Challenging Compressed Stop



VBF as Tool for Compressed SUSY





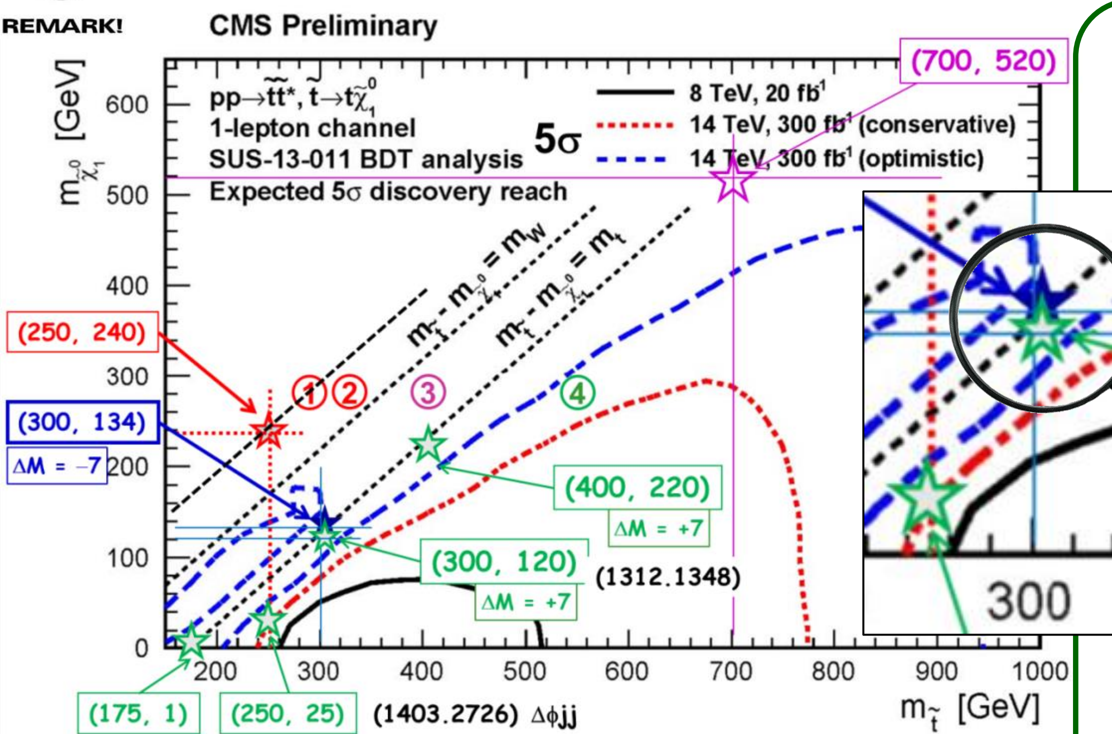


VBF tagged jets (2 energetic jets with large $\Delta\eta$ separation: large M(jj)) in forward region, opposite hemispheres)

VBF production topology in transverse plane

Next Gen. Search for Compressed "X"

REMARK!



VBF+stops: 200-250 GeV at 2σ at 14 TeV

PRD 90 (2014) 095022

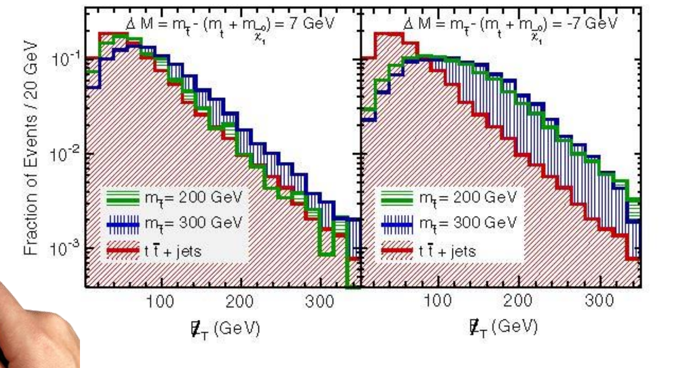
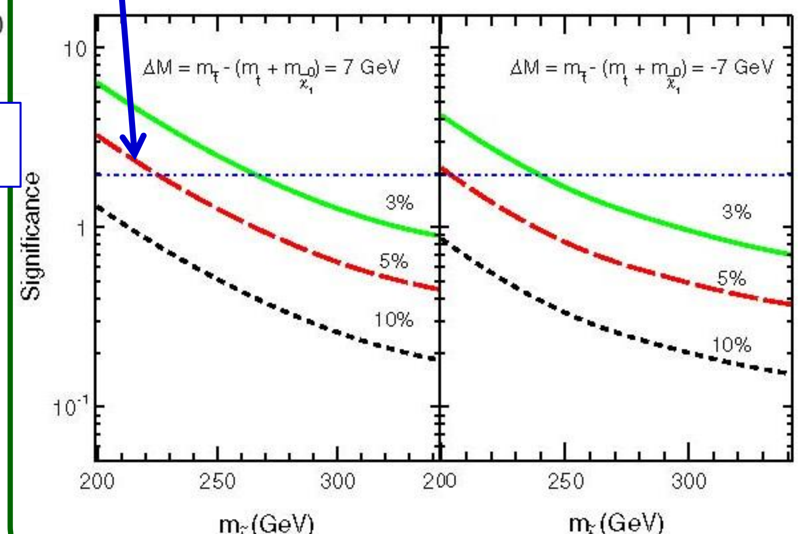


FIG. 1 (color online). Distributions of $\not{E}_T$ normalized to unity for signal (green horizontally dashed histogram) and $t\bar{t}$ + jets background (red diagonally dashed histogram) after VBF selections and lepton and b-jet requirements for the benchmark point with $m_{\tilde{t}} = 400$ GeV, $m_{\tilde{\chi}_1^0} = 220$ GeV.



VBF jj + stops
ISR jet + stops?
ISR γ + stops?

Stops in Monojets

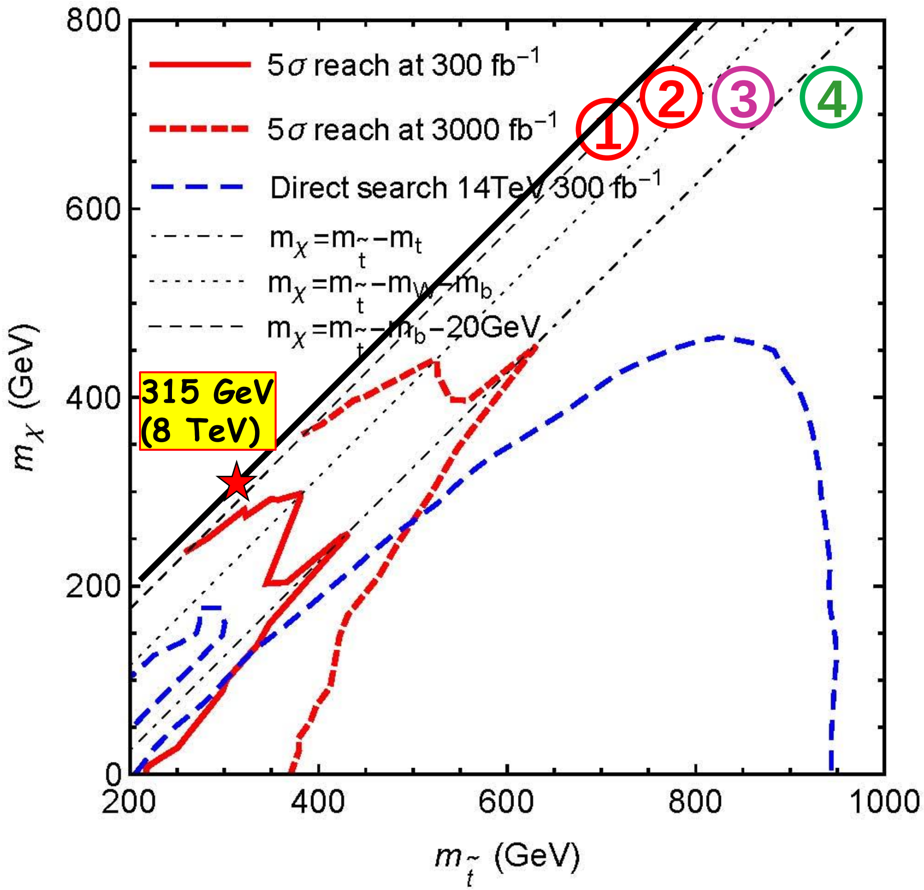
REMARK!

Haipeng An and Lian-Tao Wang, arXiv:1506.00653

The search feasibility for stop events in **M(stop) – M(chi) >~ 20 GeV**, where a pair of stops are produced in association **with a hard jet**.

The investigated region includes the region in **VBF stop paper** (arXiv:1312.1348, Phys. Rev. D 90 (2014) 095022)

See Fig. 3. On the line for M(chi) = M(stop) – M(top), the 5-sigma reach is 400 (600) for 300 fb-1 (3000 fb-1) in ISR tagging, while we could obtain those reaches via VBF.



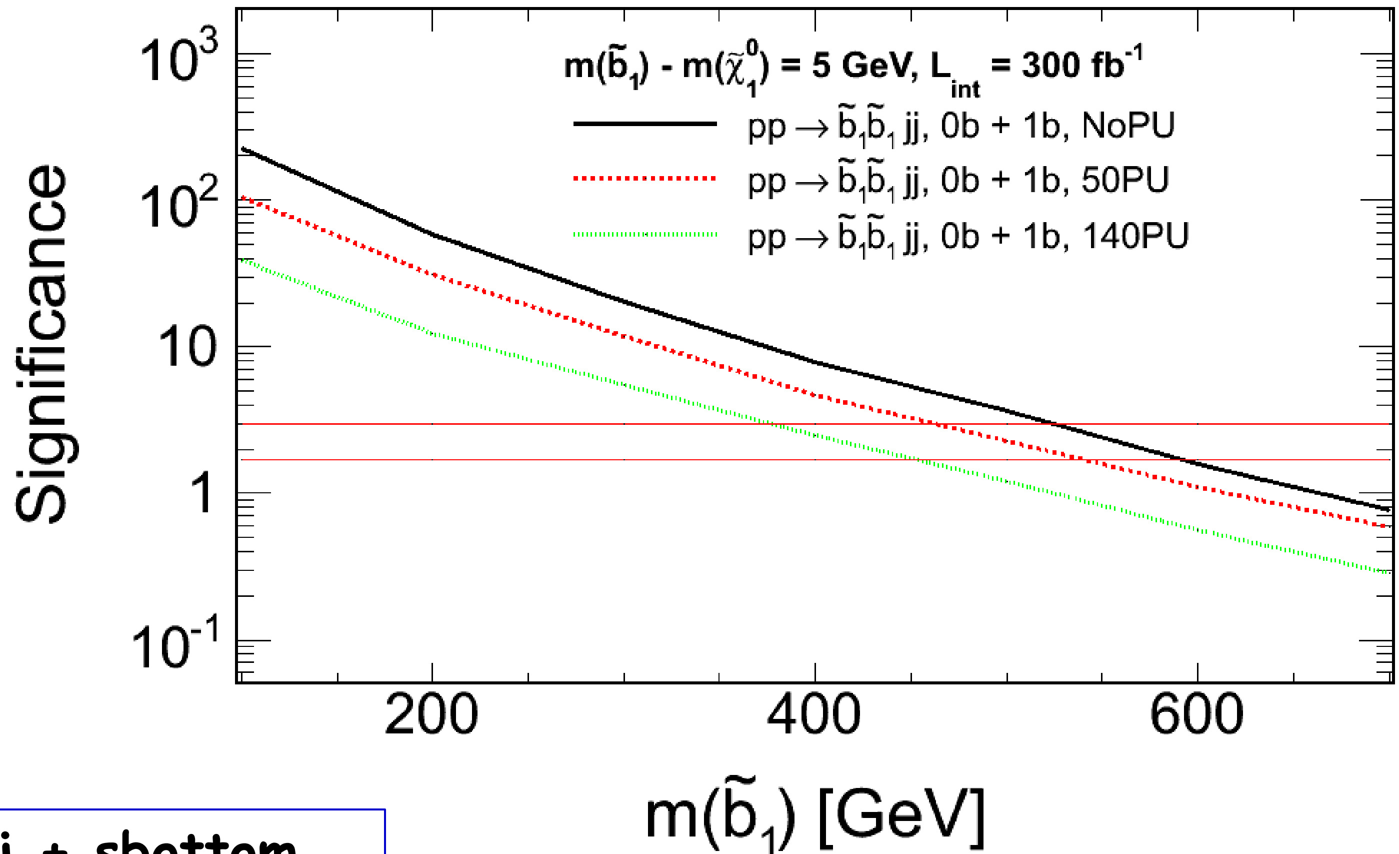
David Shih: http://arxiv.org/abs/1506.07885

Hagiwara: http://arxiv.org/abs/1307.1553

Next Gen. Search for Compressed "X"

REMARK!

B. Dutta, A. Gurrola, K. Hatakeyama, W. Johns, T.K, P. Sheldon, K. Sinha, S. Wu, **Zhenbin Wu**, "**Probing Compressed Bottom Squarks with Boosted Jets and Shape Analysis**", [1507.01001]



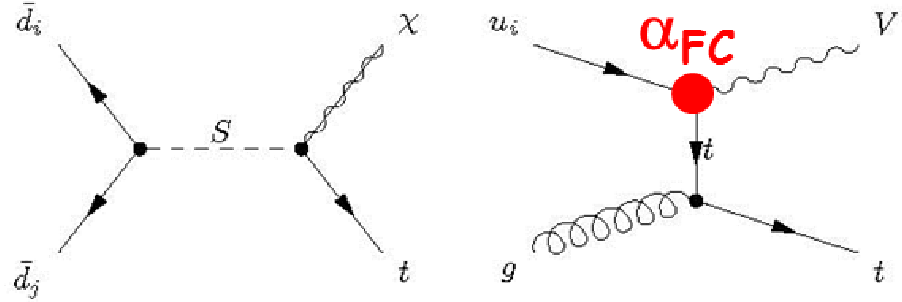
VBF jj + sbottom
ISR jet + sbottom?
ISR γ + sbottom?

VBF+sbottom: 541 (462) GeV at 95%CL (3σ) for 50PU at 14 TeV

"Non-thermal" DM-SM Interaction

REMARK!

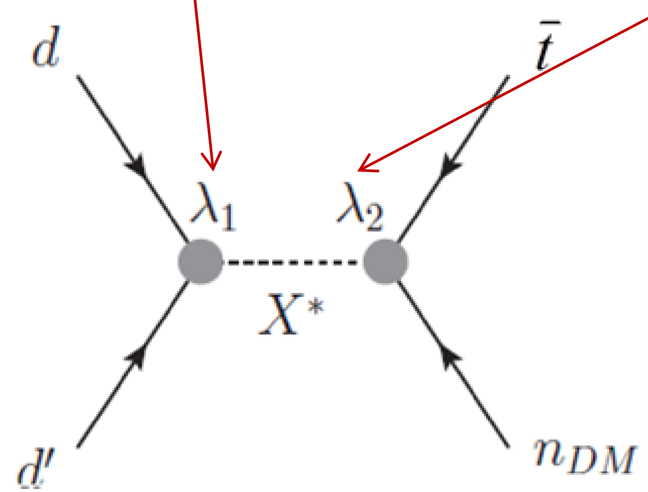
- Simplified Models vs. Full Models:
  - Example: non-thermal DM model - At least two X fields, X_α (α = 1, 2), are required for successfully explaining baryogenesis.



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

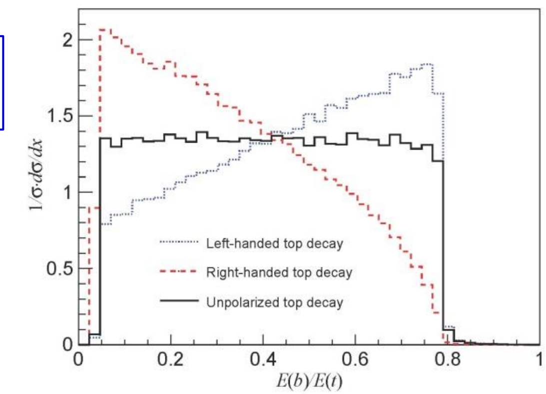
$$\mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta}\epsilon^{ijk}X_{\alpha,i}\bar{d}^c_{\rho,j}\mathbf{P}_R d_{\delta,k} + \lambda_2^{\alpha,\rho}X^*_\alpha \bar{n}_{\mathrm{DM}}\mathbf{P}_R u_\rho + \mathrm{C.C.}$$

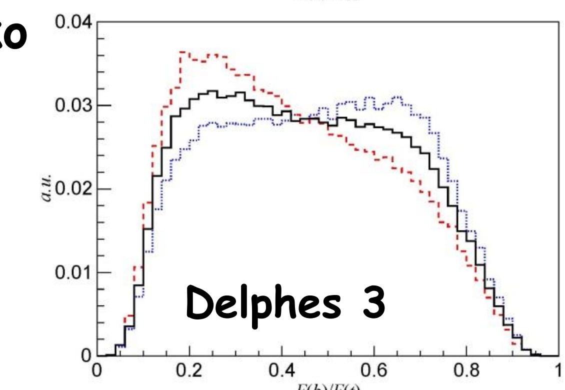
Right handed u-type quark



Doyoun Kim's talk
On O(1) GeV DM

Y. Gao &
M. Dalchenko
[1507.02271]





Wino and Higgsino via VBF

REMARK!

A. Berlin, T. Lin, M. Low, L.-T. Wang, "**Neutralinos in Vector Boson Fusion at High Energy Colliders**," PRD 91 (2015) 115002 [1502.05044]

Given a systematic uncertainty of 5% with 3000 fb-1
[LHC14] 125 GeV Winos and 55 GeV Higgsinos

[100 TeV] 750 GeV Winos and 180 GeV Higgsinos

Cut	14 TeV Wino	14 TeV Higgsino	100 TeV Wino	100 TeV Higgsino
$n_{\rm jet}$	2	2	2	2
$\|\eta(j)\|$	5	5	7	7
$p_T(j_{\rm tag})$ (GeV)	45	45	75	50
$\Delta\eta(j_1, j_2)$	3.75	3.75	4.25	4.25
$\Delta\phi(j_1, j_2)$	2	2	2	3
$M(j_1, j_2)$ (TeV)	2	1	10	5
$\not{E}_T$ (GeV)	400 – 700		1100 – 2500	
$p_T(j_{\rm veto})$ (GeV)	45	45	50	50
$p_T(e,\mu)$ (GeV)	20	20	20	20
$p_T(\tau)$ (GeV)	30	30	40	40
$\eta(e)$	2.5	2.5	2.5	2.5
$\eta(\mu)$	2.1	2.1	2.1	2.1
$\eta(\tau)$	2.3	2.3	2.3	2.3

[Comments]

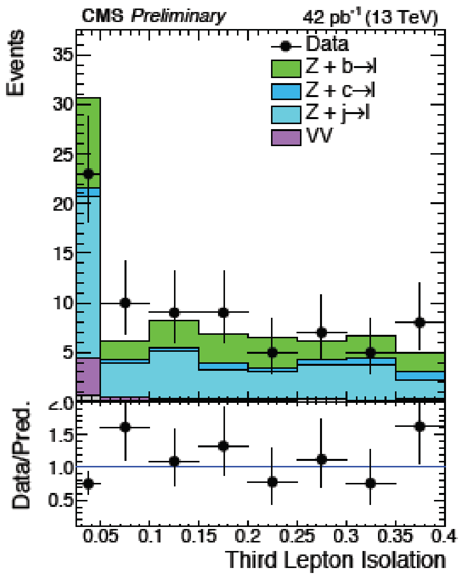
- The forward detector system (tracking, calorimeter, muon) must be good for lepton veto and vertexing for forward jets.
- Ultra-fast timing on forward calorimeter for trigger?
- Central tracking, calorimeter, muon – lepton ID from 5 GeV??

We want to lower lepton p_T threshold and cover larger η coverage for future detector.

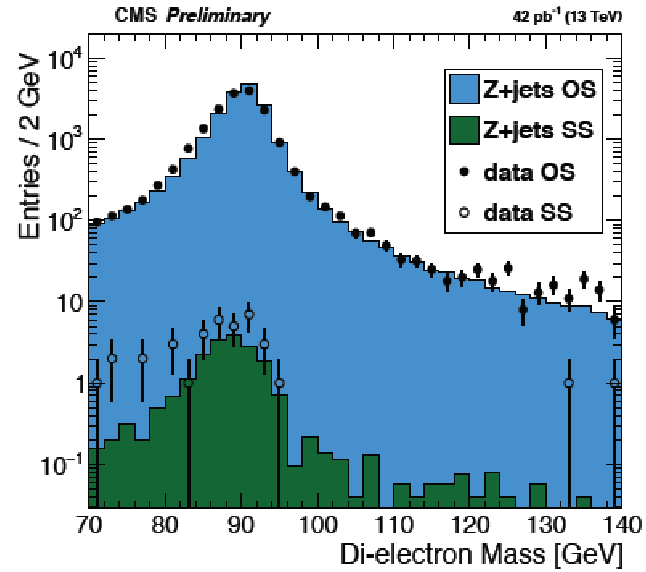
Commissioning @ 13 TeV

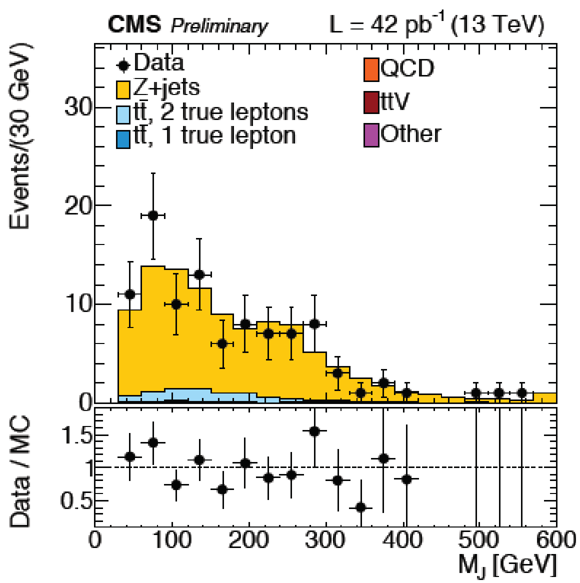
new!

Lepton isolation of third lepton in l^+l^- control sample

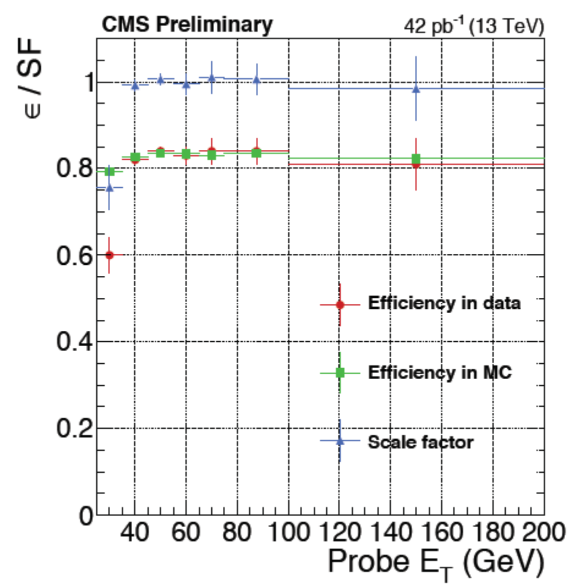


Electron charge mis-identification





Jet mass of ΔR=1.2 fat jets: Study tails from ISR



Photon ID efficiency from Tag & Probe

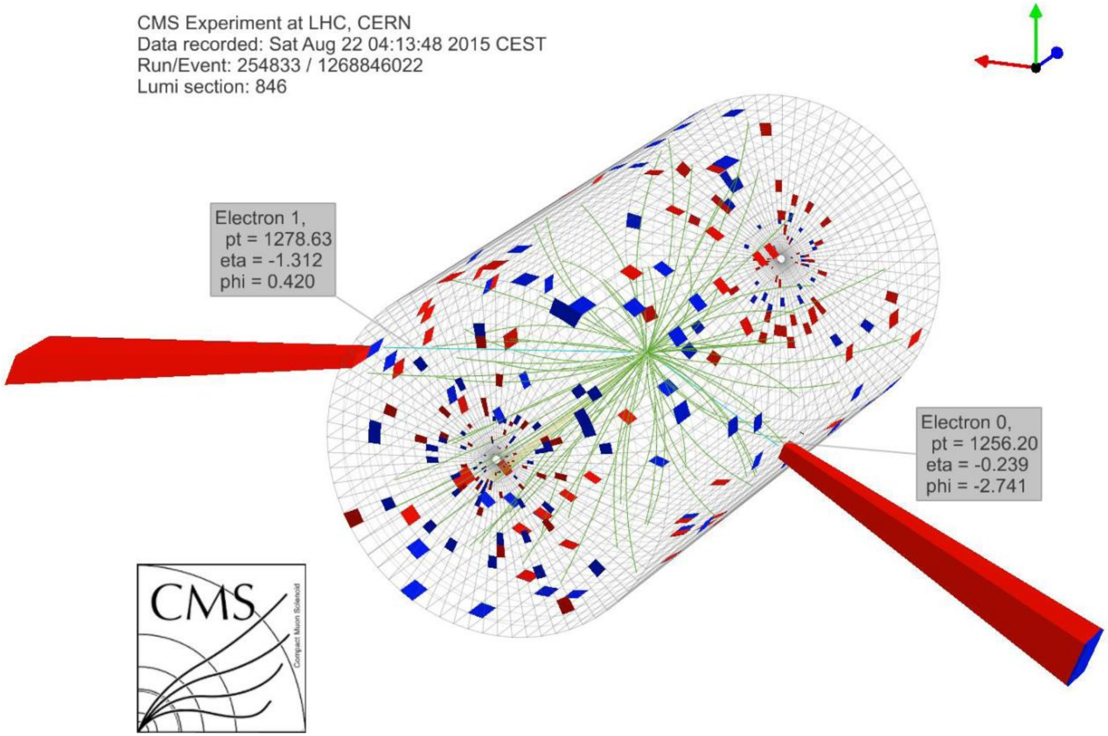
SUSY DPS

High Mass Dilepton Event @ 13 TeV

https://cds.cern.ch/record/2048626/files/DP2015_039.pdf

CMS-DP-2015-039 ; CERN-CMS-DP-2015-039

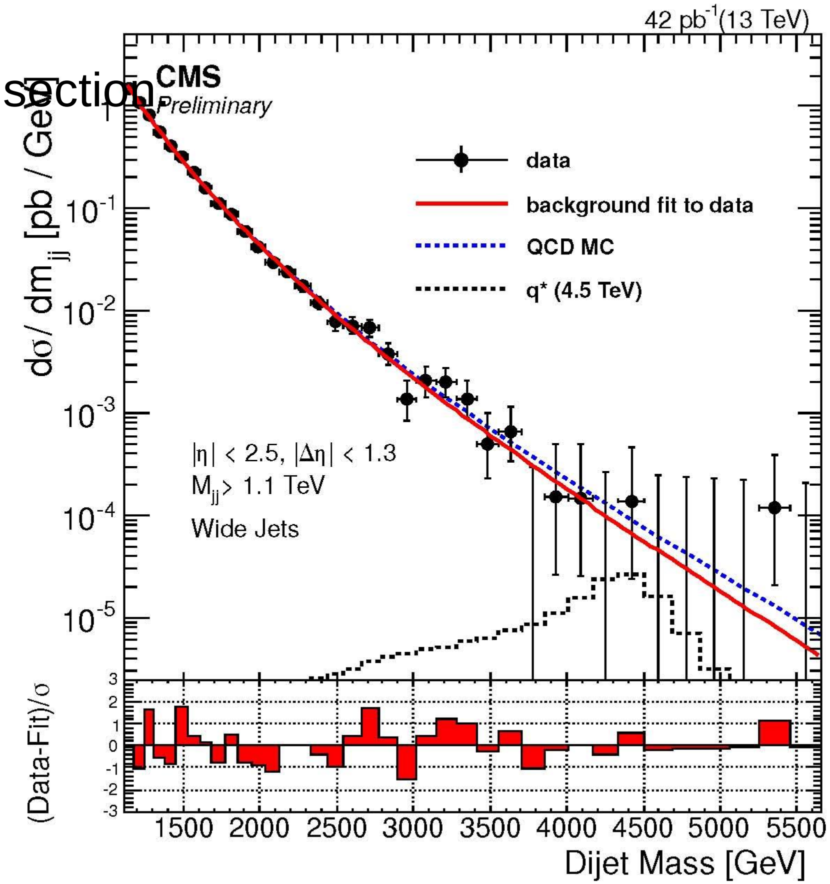
This performance note shows the event display together with some kinematic quantities for a candidate electron-positron pair with an invariant mass of 2.9 TeV. The background expected from the SM above m(ee) = 1 TeV, 2 TeV and 2.5 TeV for an integrated luminosity of 65 pb-1 is also stated.



High Mass Dijet Event @ 13 TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO15001

- Dijet mass distribution of the two leading jets with the data corresponding to an integrated luminosity of 42 pb^{-1} from Run 2 of the LHC.
- Pseudorapidity separation of the two jets is required to be < 1.3 with each jet inside the region $|\eta| < 2.5$.
- The highest observed dijet mass is 5.4 TeV.
- 95% CL upper limits on the resonance cross section.
- Lower limits on the mass of resonances:
  - string resonances … 5.1 TeV
  - excited quarks
  - Axigluons
  - colorons,
  - scalar diquarks and
  - color octet scalars.

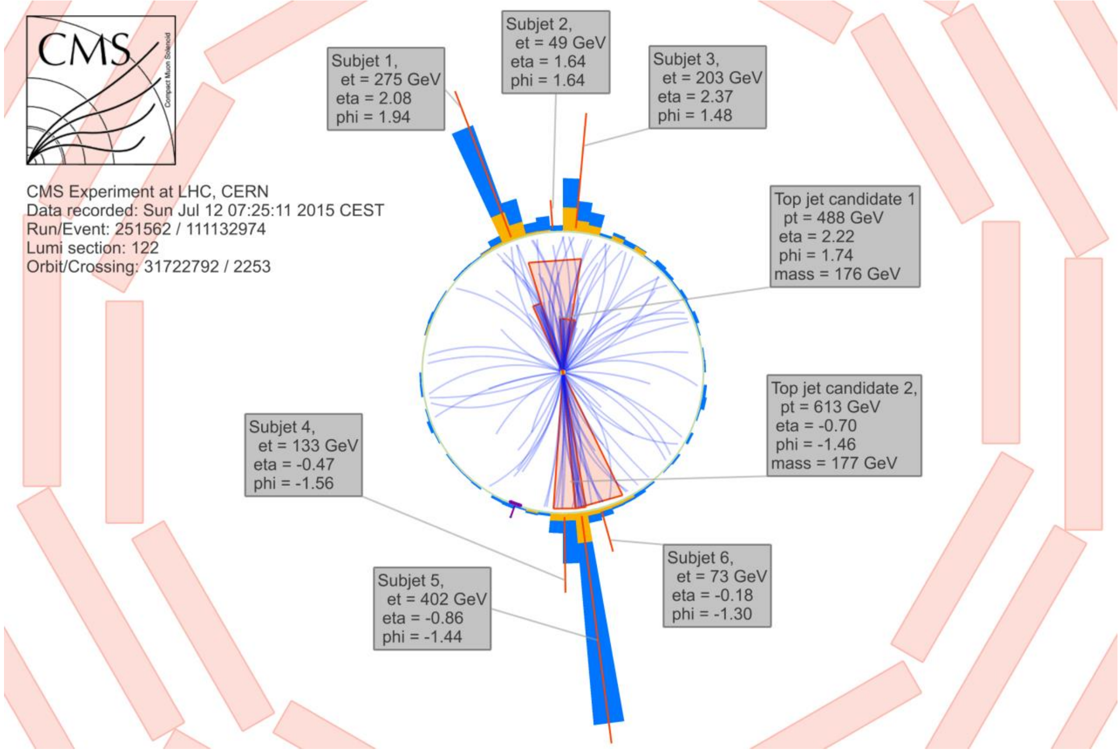


Boosted DiTop Event @ 13 TeV

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

[Event ID] 251562:122:111132974 (CMSTopJet subjets in yellow)

[Selection] 2 x CMSTopTagged jets, pT > 300 GeV, m(ttbar) > 2 TeV, $\Delta\phi$(topjets) > 2.1

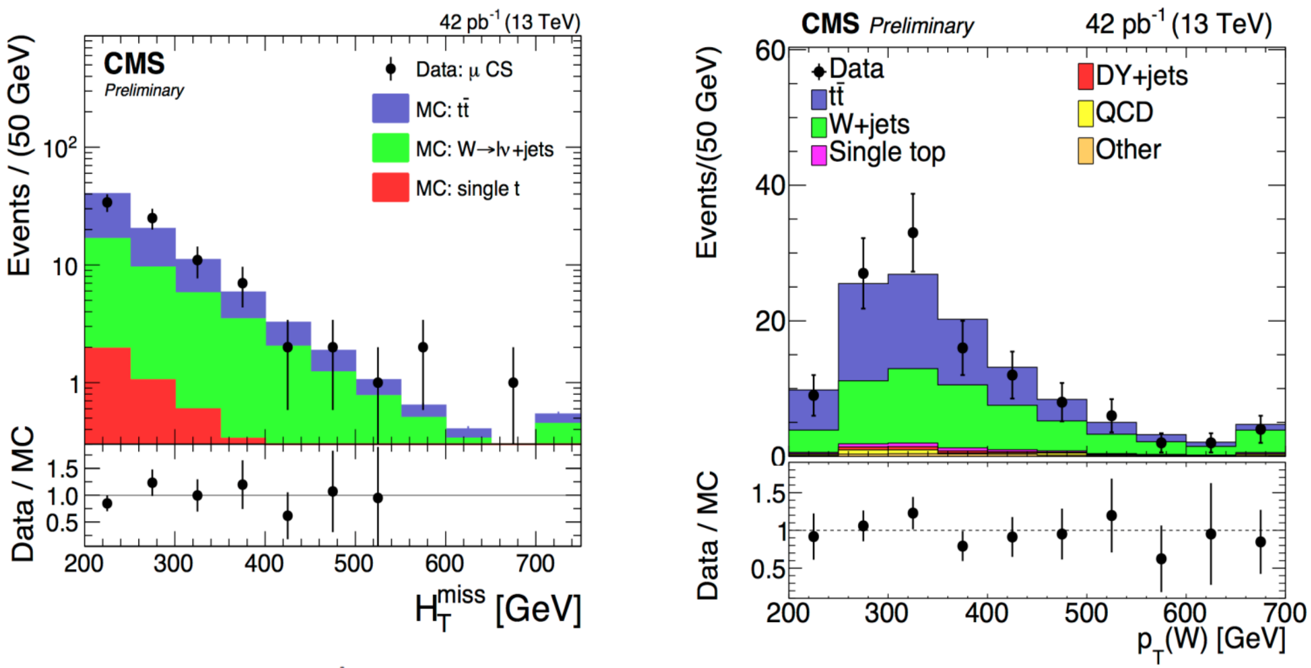


- m(topjet1)=177 GeV, pT(topjet1)=613 GeV
- m(topjet2)=176 GeV, pT(topjet2)=488 GeV
- m(ditop jets) = 2491 GeV,
- 1 b-tagged subjet (CSVIVFv2 medium OP)

All-hadronic Search in H_T and H_T^{miss}

[CERN-CMS-DP-2015-035] Inclusive search at high H_T and H_T^{miss} in bins of N_j and N_b. … An important background is W or top with missed leptons, being measured in single μ control sample (CS), as a function of kinematics. Measure the hard-to-model W p_T and use well known W decay properties from MC.

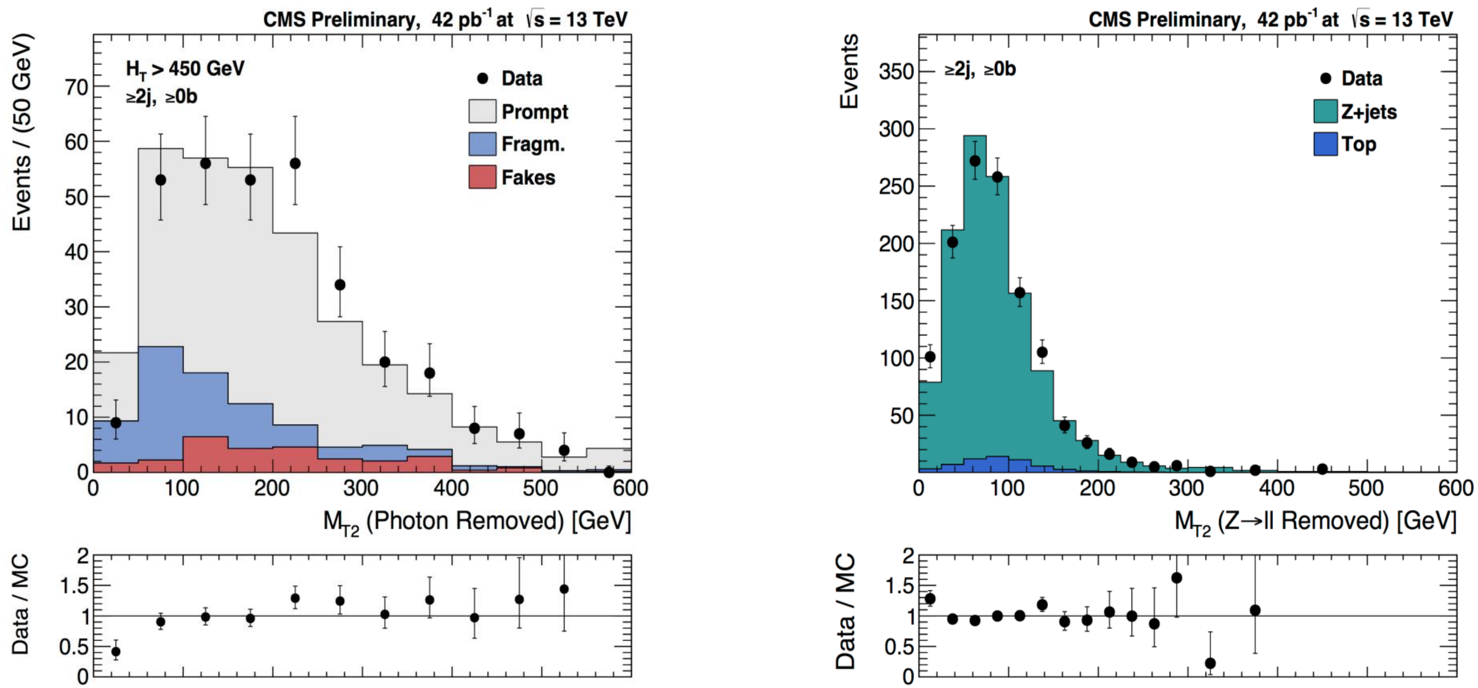
SUS-13-012/12-024



Left: Comparison of H_T^{miss} in data and (normalized) MC using a single μ control sample selected with baseline requirements (4 jets, $H_T > 500$, $H_T^{\mathrm{miss}} > 200$). Right: Comparison of $p_T(W)$ in single lepton (e,μ; $p_T > 10$) events with baseline selection, $E_T^{\mathrm{miss}} > 200$ and $M_T < 100$.

All-hadronic Search Using M_{T2}

[**CERN-CMS-DP-2015-035**] M_{T2} in bins of H_T, N_j and N_b, where M_{T2} is sTransverse mass, designed for final states with 2 missing particles. Another important background is $Z \rightarrow \nu\nu$. Check modeling of M_{T2} variable in $Z \rightarrow \ell\ell$ and γ samples.



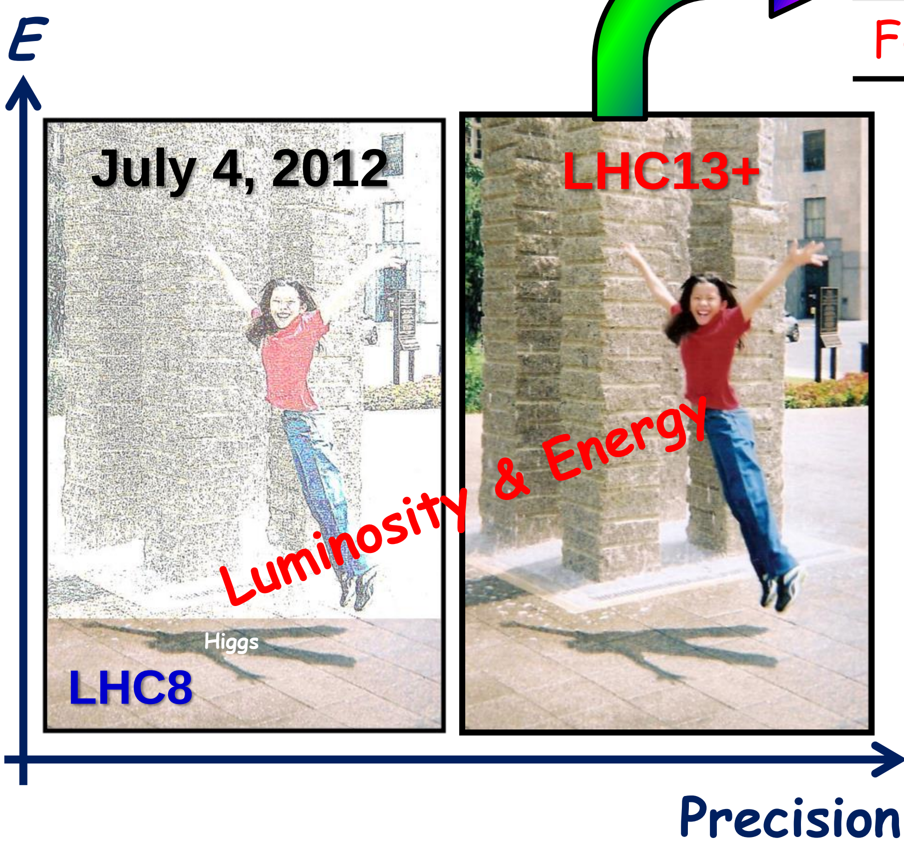
Comparison of M_{T2} distribution in data and (normalized) MC for photon (left) and $Z \rightarrow \ell^+\ell^-$ (right) control regions, where the M_{T2} calculation treats γ and Z candidates as invisible.

Run2 and Beyond

Hadron Collider (√s)	Gluino/Squark Mass Reach (M)	M/√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

LHC and beyond will be powerful in producing heavy objects.



Run1 at 8 TeV – the LHC8 has started probing a TeV physics: discovery of a Higgs boson with null results on BSM.

Run2 at 13 TeV - Exciting! Understanding the limitations of the LHC13 will be an important step toward the next energy frontier

Prospects for Run 2

- [Goal] Search for physics beyond the SM (SUSY, DM χ, more) … one of the main motivations for the LHC experiments
- [8 TeV] CMS covers a large variety of possible final states, closing in on challenging scenarios such as compressed SUSY, setting stringent limits on many SUSY and X scenarios (with a few anomalies?)
- [13 TeV] Promising performance in a first look
  - [Compared to 8 TeV] Similar sensitivity on gluino mass expected after first ~ fb^{-1} ; on light neutralinos/charginos/stops after first ~5-10 fb^{-1}
  - [Challenge] Large pile-up <PU> ~25 … 50
- For MANY more results, see the public result pages:

http://cms-results.web.cern.ch/cms-results/public-results/publications/