Search via VBF Dijet and ISR Jet Tagging

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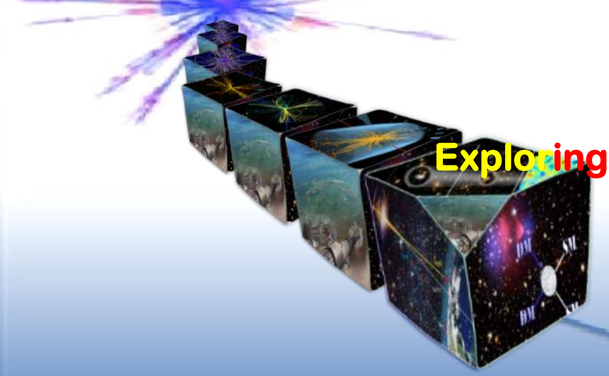


Aspen Winter Conference
Exploring the Physics Frontier with Circular Colliders

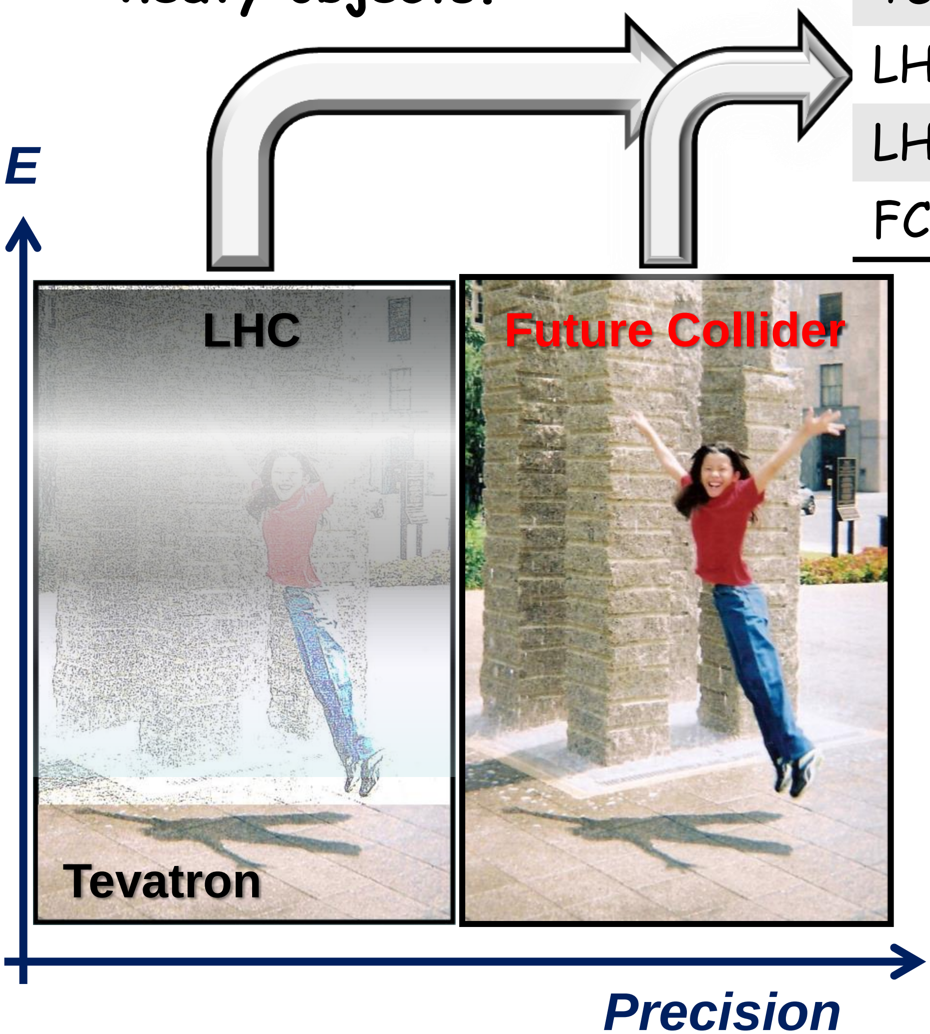
Jan 30, 2015

Outline

- A 100-TeV collider is powerful in producing heavy objects.

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

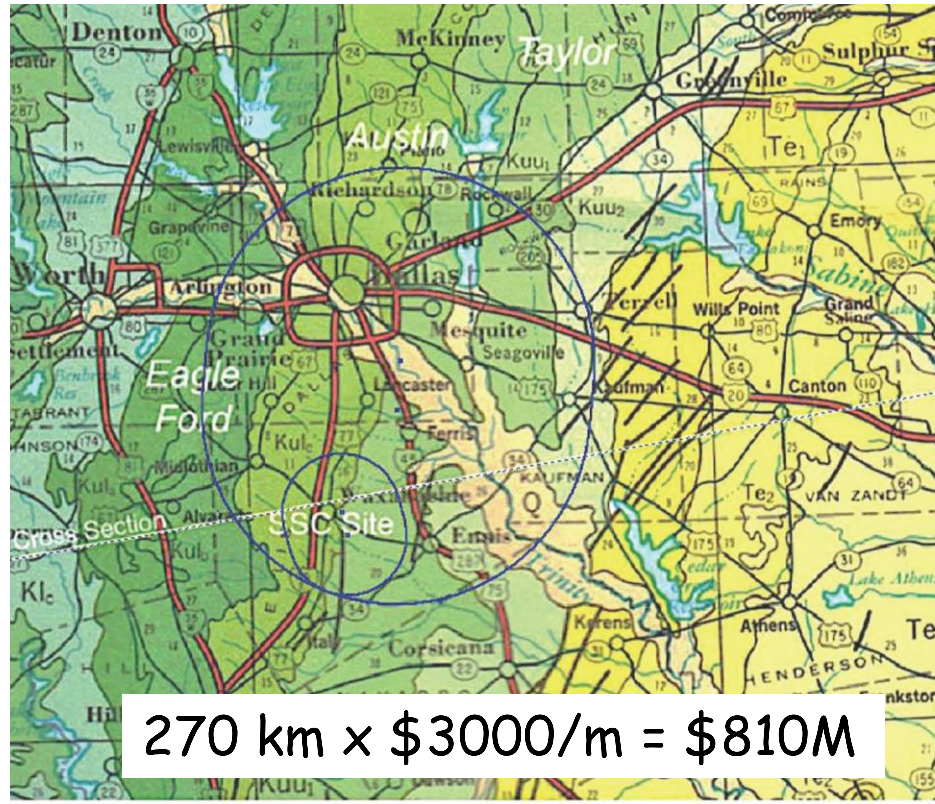
(*) just use a naïve scaling



- Understanding the limitations at the LHC14 will be an important step for FCC100pp
- Present results and/or prospects on selected topics from SUSY Searches via VBF dijet and ISR jet tagging
- Summary

100-300 TeV pp Collider

http://arxiv.org/abs/1402.5973



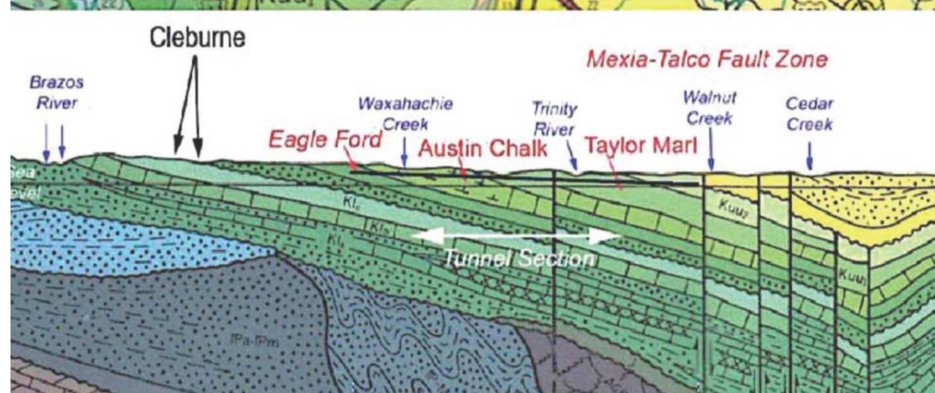


Table 3. Main parameters of hadron colliders of 100 and 270 km circumference.

	Higgs factory	hadron collider			
Circumference	100	100	270		km
Collision energy	0.24	100	100	300	TeV
Dipole field	0.046	15	4.5	14.5	Tesla
Luminosity/I.P.	5	5	5	10	10^{34} $cm^{-2}s^{-1}$
β*	50x0.1	110	50	100, 10	cm
Total synch. power	100	4.2	1.0	34	MW
Critical energy	430	4.0	1.0	28	keV
Synch power/meter/bore	580	26	2	80	W/m
Emittance damping time		1	19	.66	Hr
Luminosity lifetime	0.3	18	20	3.7	hr
Energy loss/turn	2100	4.3	1.3	114	MeV
RF accel. voltage:	6000	100	50	250	MV
Acceleration time	.01		.42	.25	H
Bunch spacing	250	50	25	25	ns
Beam-beam tune shift	0.09	.01	.01	.01	
# IPs	4	2+2	2+2	2+2	
# particles per beam	4.1	100	220	86	10^{13}
Injection energy	0.12	>3	15	50	TeV
Superconducting temp.	1.8 K in SRF	4.5	8	4.5	K

SUSY + Another Higgs Wanted

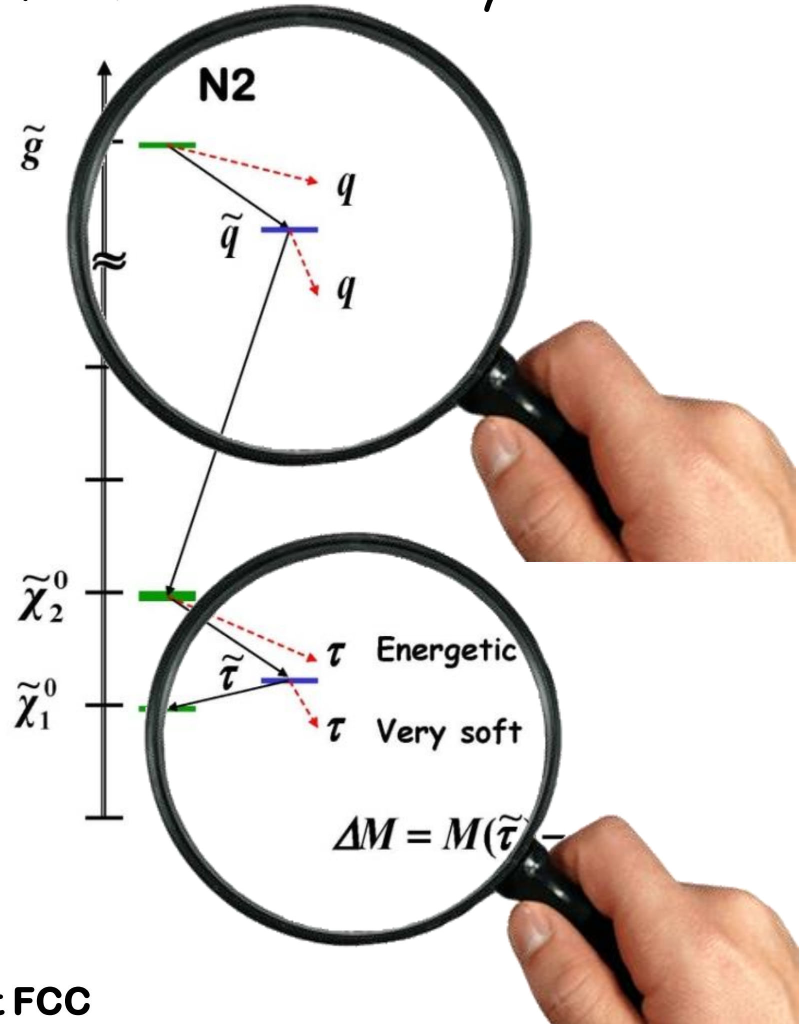
- MSSM Higgs (e.g., A $H^{\pm}$ and $H^{+}H^{-}$), Non-MSSM Higgs
- Gluinos
- Heavier(?) 1st/2nd generation scalar quarks (squaks)
- Lighter(?) 3rd generation squarks (**stop**, sbottom)
- Charginos (C1, C2), Neutralinos (N1, N2, N3, N4), decaying into:
  - Leptons
  - Higgs
  - W, Z
- LSP?
  - Lightest 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 are mass degenerate.
  - Special case: Stau is lighter.
- RPV
- Dark matter connection

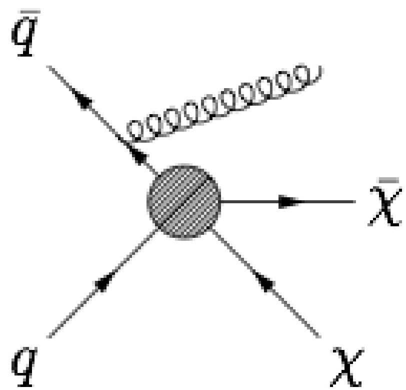
$$\underbrace{\Omega_{\tilde{\chi}_1^0} h^2}_{0.23} = \mathcal{D}(\langle \sigma_{ann} v \rangle)$$

Questions

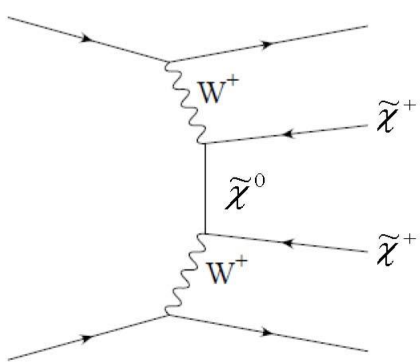
- What do we do with (i) heavy 1st/2nd generation squarks and/or gluino, and (ii) small ΔM (mass difference between NLSP and LSP)?
- How can we probe **SUSY sectors**?
    1) Tagging energetic jets (+ MET) from cascade decays
    2) Tagging leptons
    3) Tagging photons
    4) Tagging with timing, vetexing
    5) ISR jet, VBF dijet
- Let me focus on ISR and VBF



ISR jet tagging



VBF-like dijet tagging



Selected Papers on ISR and VBF

Yang Bai and Tim M.P. Tait, "**Inelastic Dark Matter at the LHC**", PLB 710 (2012) 335 [arXiv:1109.4144] (MonoJet + decay vertex)

Ning Zhou, David Berge, Daniel Whiteson, "**Mono-everything: combined limits on dark matter production at colliders from multiple final states**", PRD 87 (2013) 095013 [arXiv:1302.3619]

Chengcheng Han, Archil Kobakhidze, Ning Liu, Aldo Saavedra, Lei Wu and Jin Min Yang, "**Probing light higgsinos in natural SUSY from monojet signals at the LHC**," JHEP 02 (2014) 049 [arXiv:1310.4274]

Pedro Schwaller and Jose Zurita, "**Compressed electroweakino spectra at the LHC,** JHEP 03 (2014) 060 [arXiv:1312.7350]

Howard Baer, Azar Mustafayev, Xerxes Tata, "**Monojets and mono-photons from light higgsino pair production at LHC14",** PRD 89 (2014) 055007 [arXiv:1401.1162]

Zhenyu Han, Graham D. Kribs, Adam Martin, Arjun Menon, "**Hunting quasi-degenerate higgsinos",** PRD 89, 075007 (2014) [arXiv:1401.1235]

Howard Baer, Azar Mustafayev and Xerxes Tata, "**Monojet plus soft dilepton signal from light higgsino pair production at LHC14**", PRD 90 (2014) 115007 [arXiv:1409.7058]

Zhenyu Han and Yandong Liu, "**MT2 to the rescue -- searching for sleptons in compressed spectra at the LHC**", [arXiv:1412.0618]

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.

G. Giudice, T. Han, K. Wang, and L.T. Wang, "**Nearly degenerate gauginos and dark matter at the LHC**", PRD 81 (2010) 115011

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

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 ,atter at the LHC using vector boson fusion processes**", PRL 111 (2013) 061801

B. Dutta, W.Flanagan, A. Gurrola, W. Johns, T. Kamon, P. Sheldon, K. Sinha, K. Wang, S. Wu, "**Probing compressed top squarks at the LHC at 14 TeV".** PRD 90 (2014) 095022.

Marco Cirelli, Filippo Sala, Marco Taoso, "**Wino-like Minimal Dark Matter and future colliders",** JHEP 10 (2014) 033, Erratum-ibid. 01 (2015) 041 [arXiv:1407.7058]

“VBF” Cross Sections

PRL 111 (2013) 061801

Tathagata Ghosh

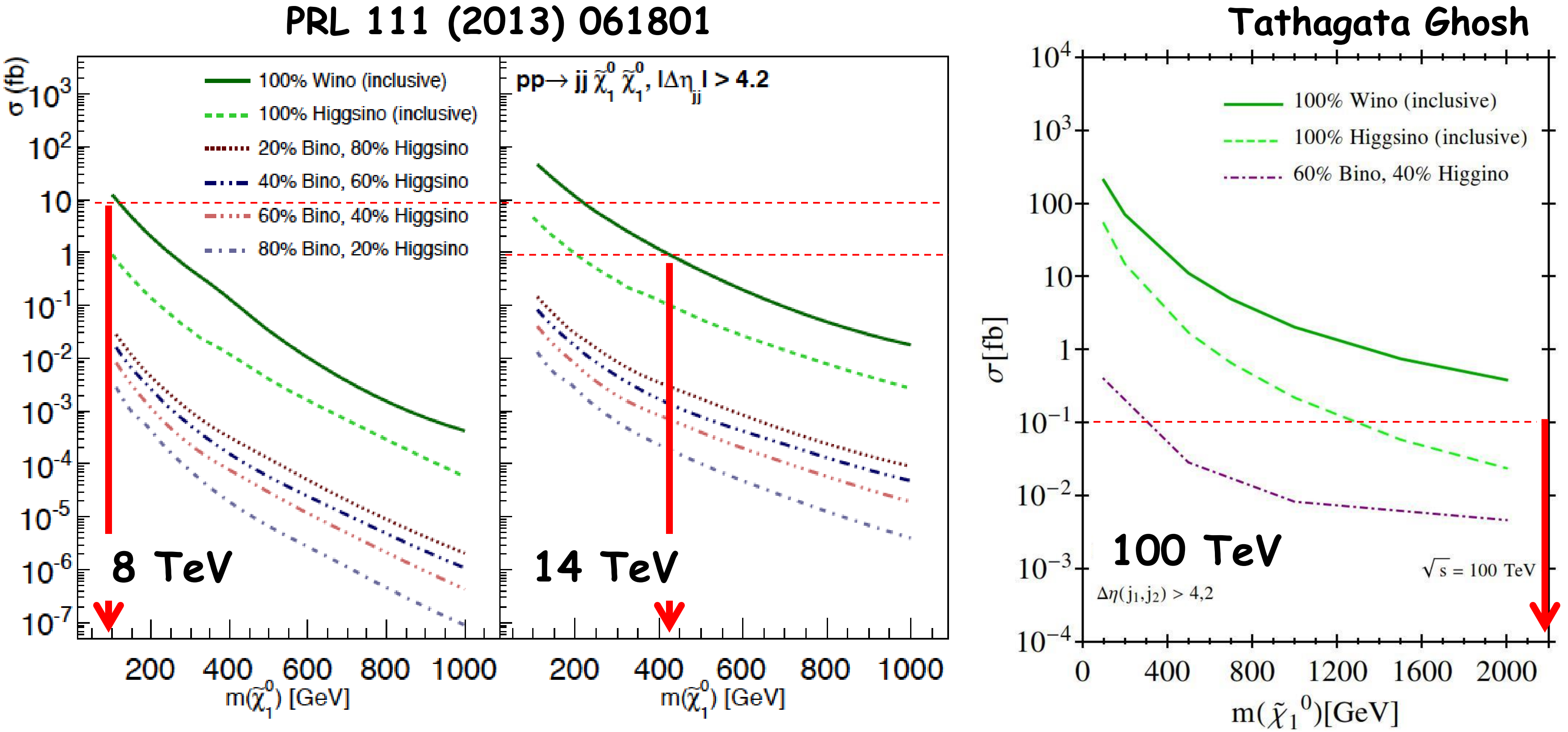


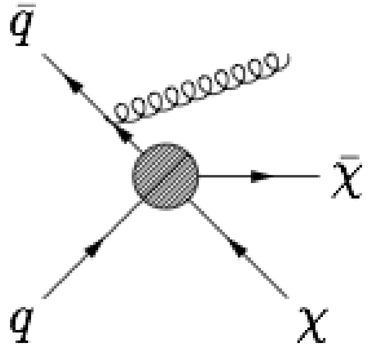
FIG. 1: Production cross section as a function of $m_{\tilde{\chi}_1^0}$ after requiring $|\Delta\eta(j_1, j_2)| > 4.2$, at LHC8 and LHC14. For the pure Wino and Higgsino cases, inclusive $\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$, and $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ production cross sections are displayed.

ISR Invisible vs. VBF Invisible

In case of CMS …

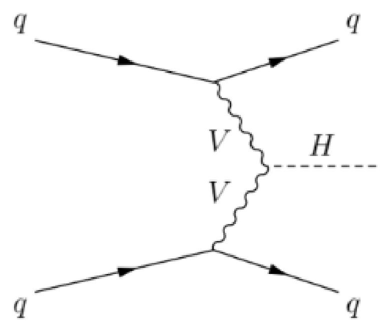
arXiv:1408.3583, CMS-EXO-12-048, CERN-PH-EP-2014-164

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 → 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

arXiv:1404.1344, CMS-HIG-13-030, CERN-PH-EP-2014-051, EPJC 74 (2014) 2980.



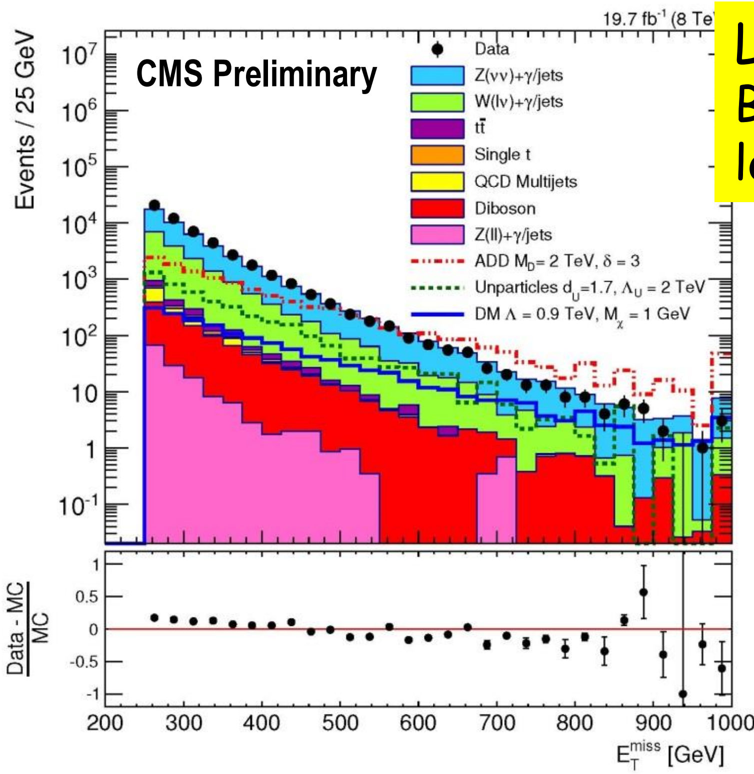
- Veto events with an identified electron, or muon with $p_T > 10$ GeV.
- VBF tag jet pair, $p_{T,j1}$, $p_{T,j2} > 50$ GeV, $|\eta| < 4.7$, $\eta_{j1}*\eta_{j2} < 0$, $\Delta\eta_{jj} > 4.2$, and $M_{jj} > 1100$ GeV
- **MET > 130 GeV**
- $\Delta\phi(j_1,j_2) < 1.0$
- Central jet veto (event that has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

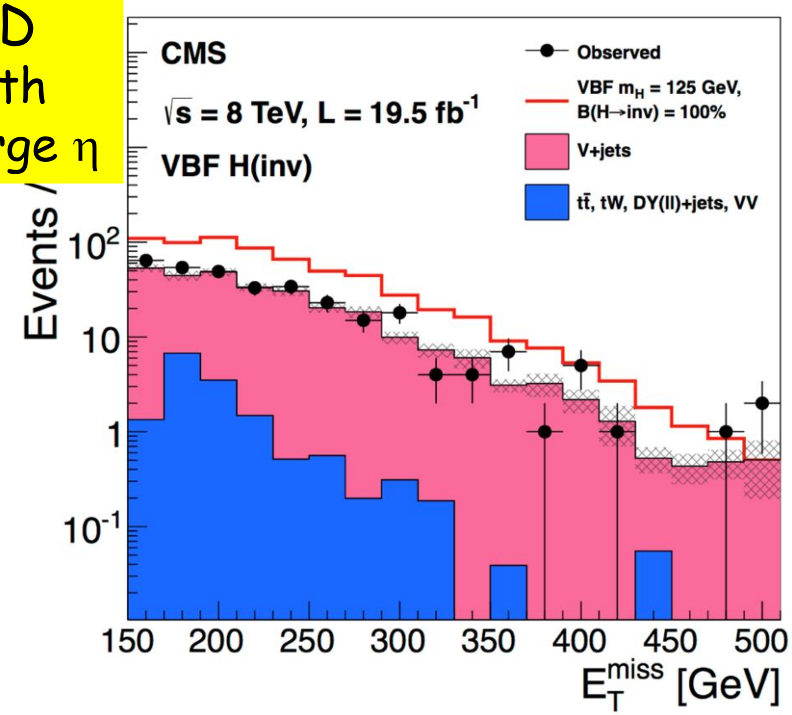
VBF Invisible vs. ISR Jet Invisible

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 +1σ	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

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





VBF Invisible – Δφ(jj)

PLB 495 (2000) 147
arXiv:0009158

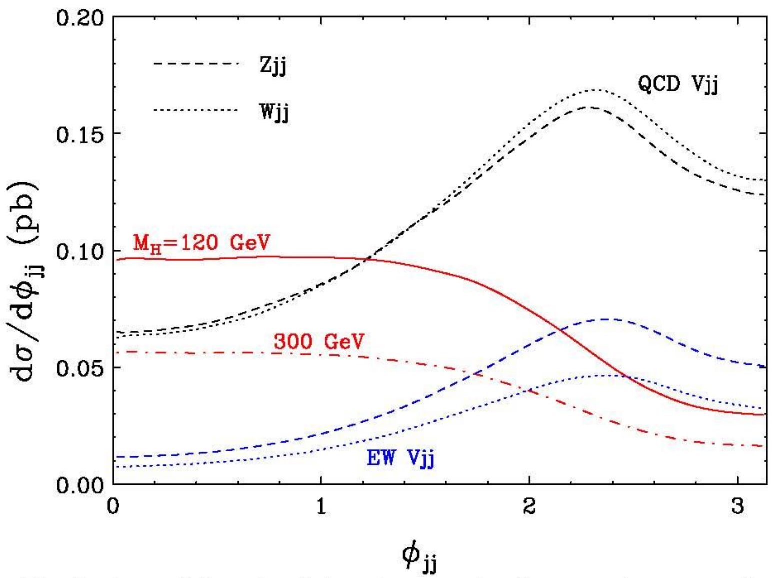
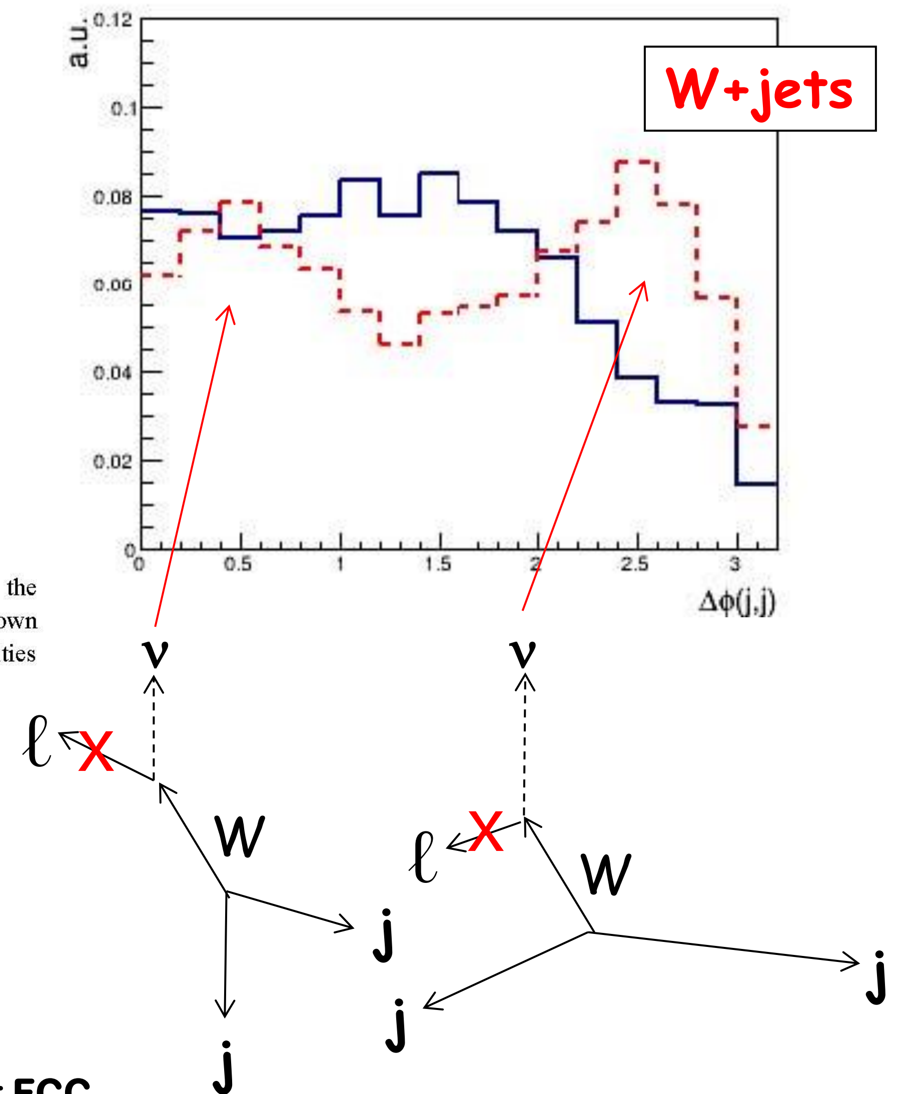


FIG. 3. Distributions of the azimuthal angle separation between the two tagging jets for the various background processes and the Higgs signal at $M_H = 120$ and 300 GeV. Results are shown after applying the cuts (1-3) and including the effect of a central jet veto with the survival probabilities of Table I. The lines follow the same convention as in Fig. 1.

Auxiliary plot using PGS4 using the cuts in PRL 111 (2013) 061801



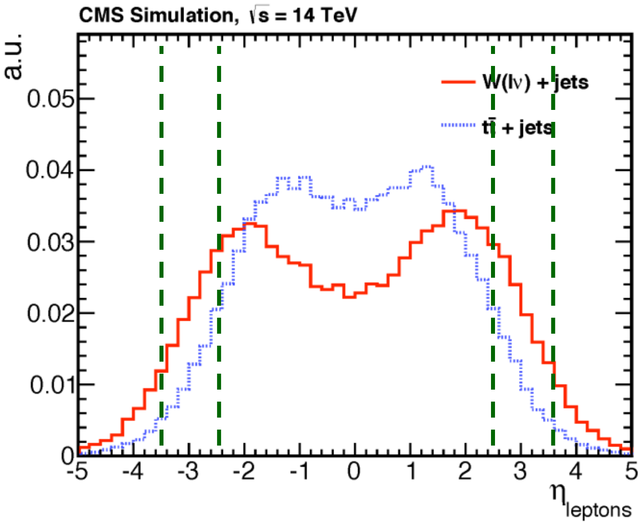
Forward Detector Challenge

"Lost-lepton" is a dominant BG source in many SUSY searches. The veto efficiency increases with forward detector (tracker/muon/calorimeter)

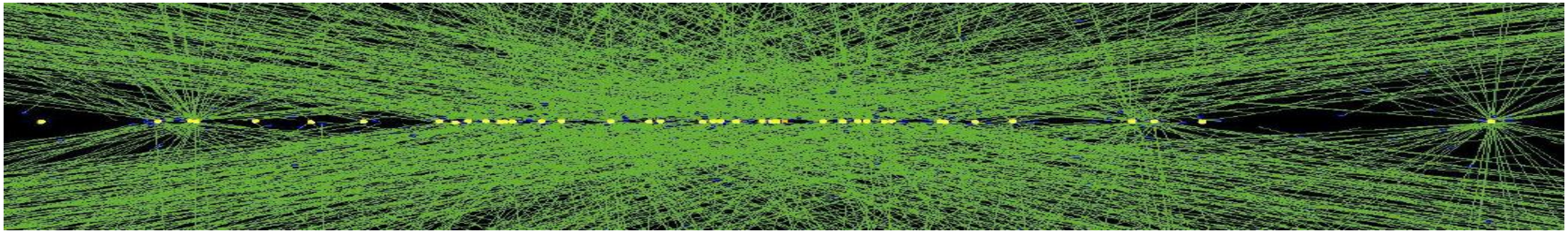
The VBF SUSY was one of representative CMS SUSY projections for the ECFA (European Committee for Future Accelerator) workshop in 2013 [CMS PAS FTR-13-014 "Study of the Discovery Reach in Searches for Supersymmetry at CMS with 3000 fb^{-1}"]

One of key conclusions was *"... the possible gain from extending the tracker up to a pseudo-rapidity of four is studied for vector boson fusion processes."*

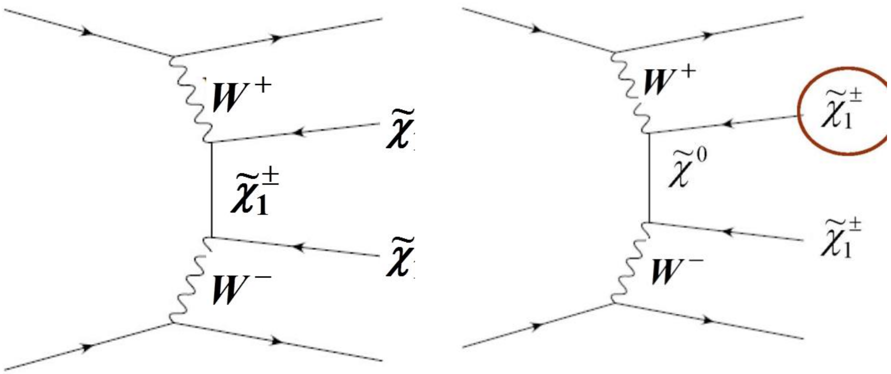
CMS PAS FTR-13-014



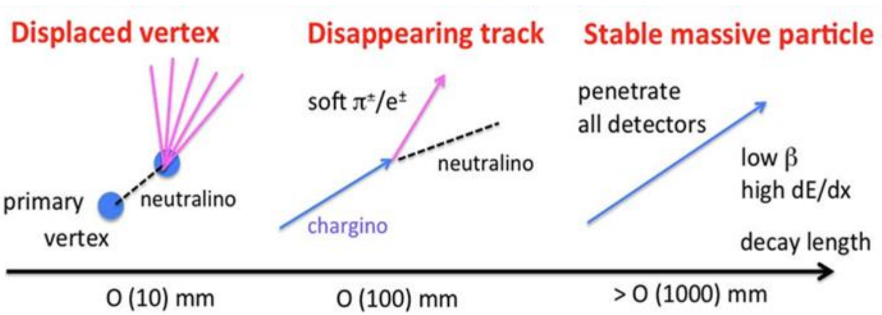
Pile-ups: Ultra-fast timing on forward calorimeter to reject out-of-time jets?



"DM" Production via VBF

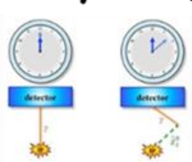


$jj + MET + X$



"non-pointing" γ

"delayed" γ



- The final state is same as invisible Higgs signal, but, larger p_T jets
- Cross sections?
  - ✓ Wino-like DM
  - ✓ Higgsino-like DM
  - ✓ Bino-Higgsino DM
- Feasibility?
  - ✓ ~50 GeV Wino-DM at 8 TeV
  - ✓ ?? GeV Wino-DM at 14 TeV
  - ✓ ?? GeV Wino-DM at 100 TeV
- More?
  - ✓ Example, disappearing tracks (DTs)?

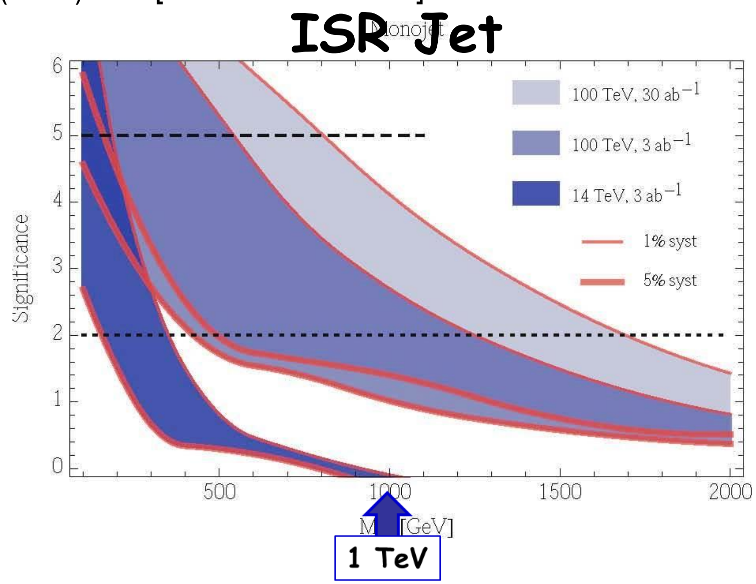
$$\Delta M = M(\tilde{\chi}_1^{\pm}) - M(\tilde{\chi}_1^{0}) \sim 100\, MeV$$

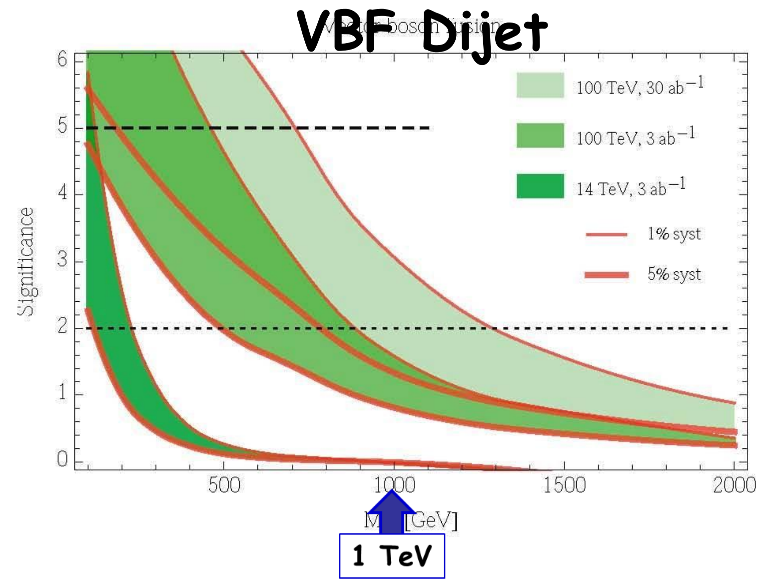
$$\Rightarrow Br(\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^{0}\pi^{\pm}) \sim 100\%$$

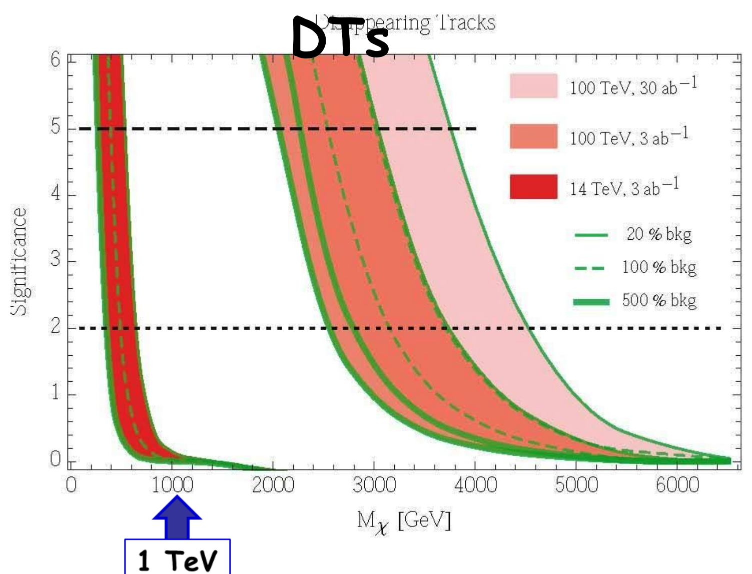
$$P_T(\pi^{\pm}) \sim \Delta M \sim 100\, MeV$$

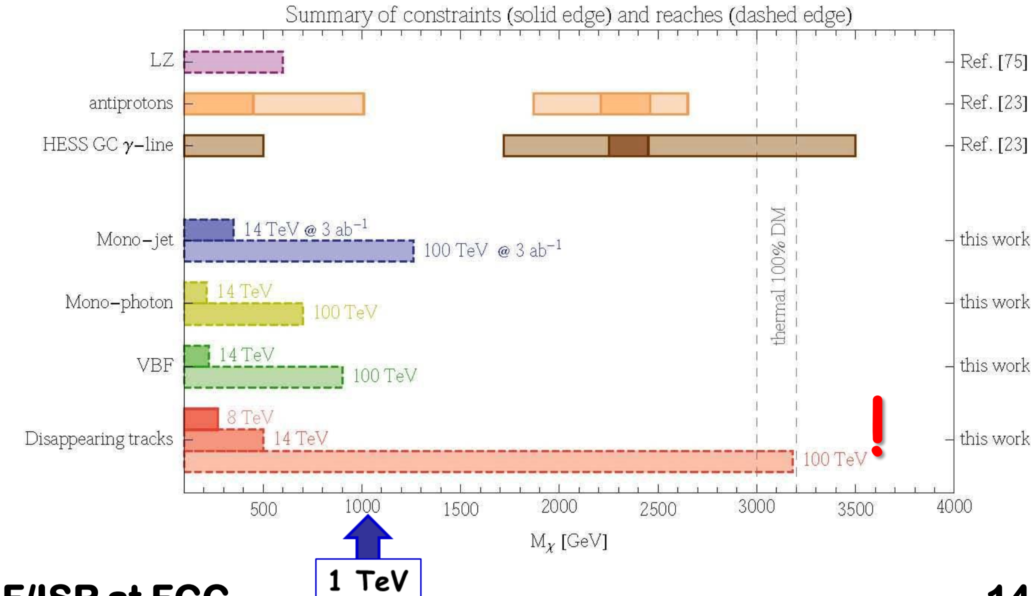
Wino DM with ISR, VBF and DT

Marco Cirelli, Filippo Sala, Marco Taoso, “**Wino-like Minimal Dark Matter and future colliders”,** JHEP 10 (2014) 033, Erratum-ibid. 01 (2015) 041 [arXiv:1407.7058v2]



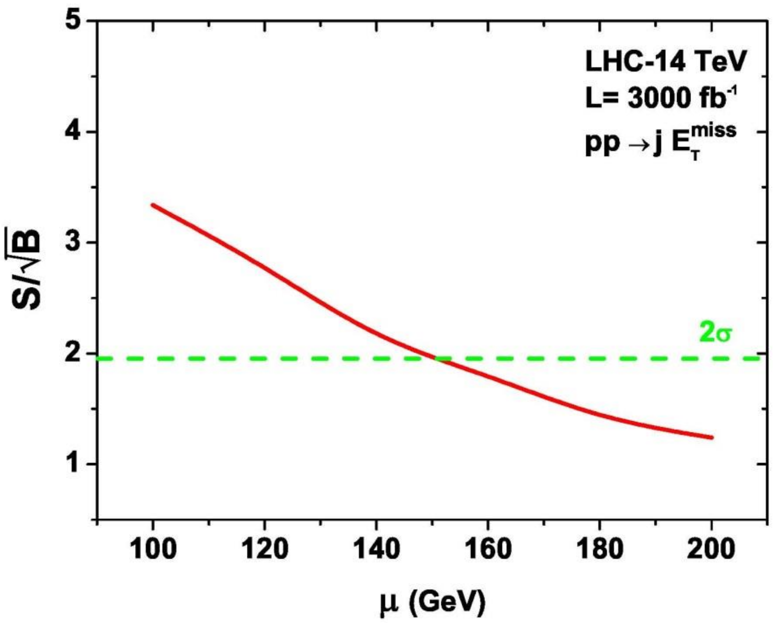


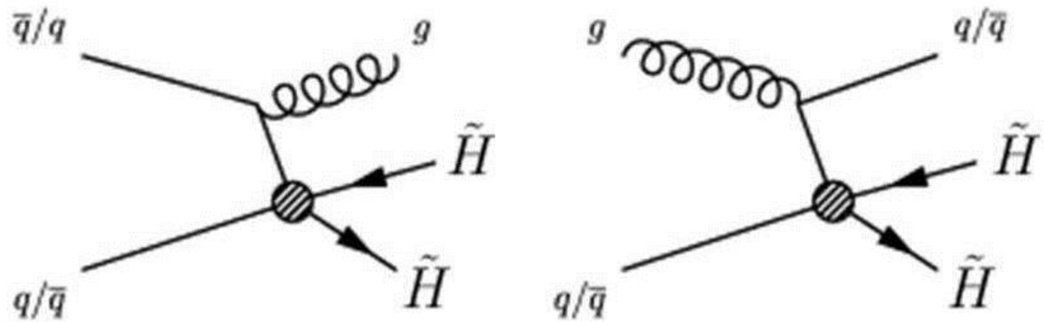


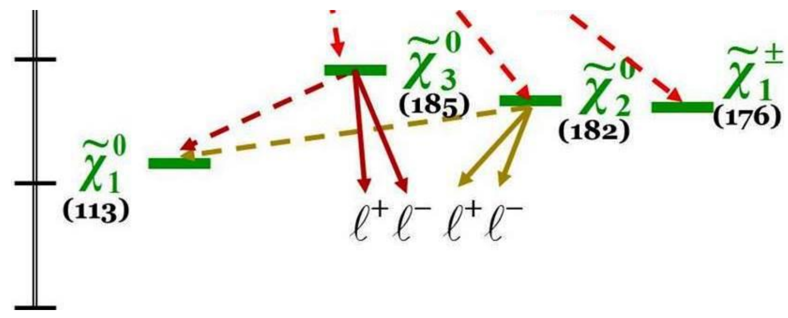


Light Higgsinos in MonoJet

Detecting light Higgsinos in ISR jet tagging (Monojet events)". See arXiv:1310.4274(*), for example. See also the next page. We see a reach at ~200 GeV at 14 TeV → 100 TeV?







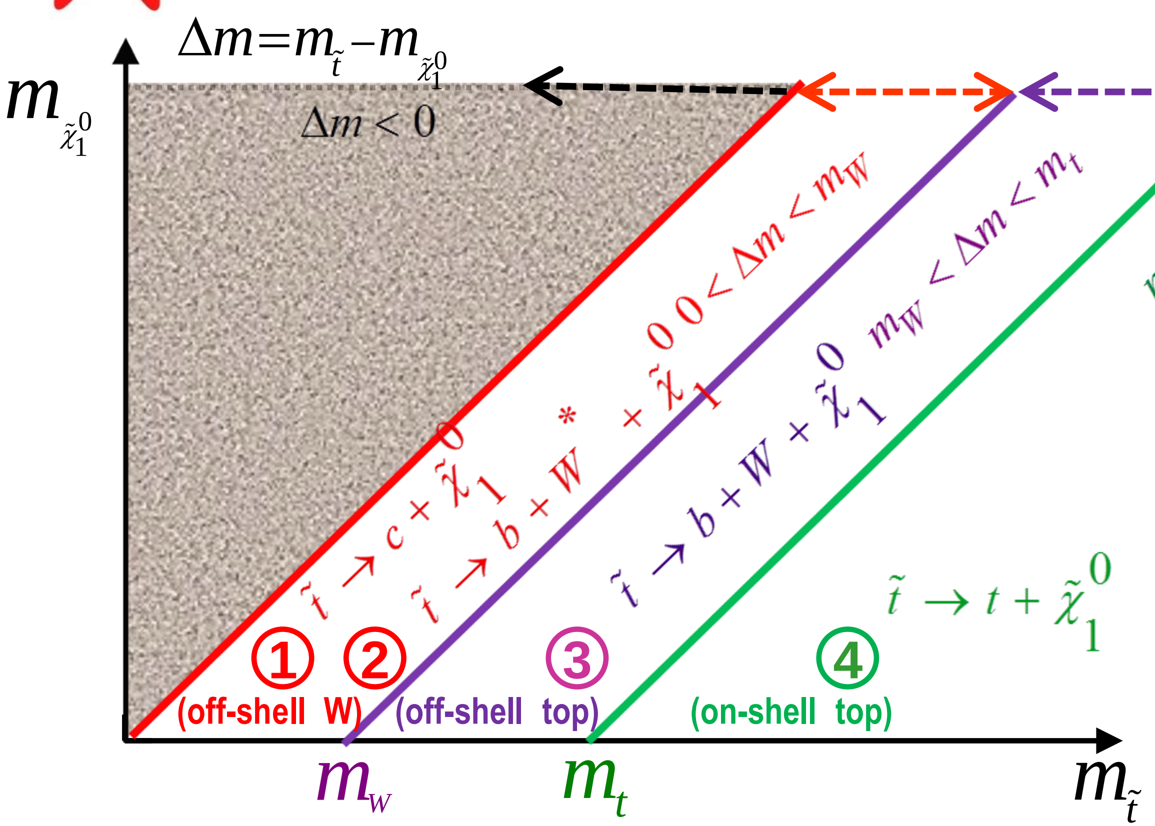
(*) Chengcheng Han, Archil Kobakhidze, Ning Liu, Aldo Saavedra, Lei Wu and Jin Min Yang, "**Probing light higgsinos in natural SUSY from monojet signals at the LHC**," JHEP 02 (2014) 049 [arXiv:1310.4274]

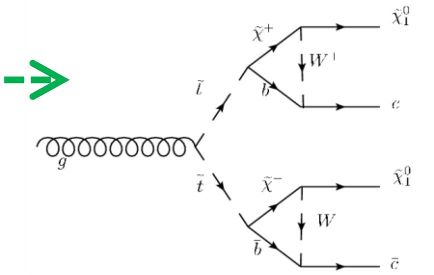
More on Higgsinos with ISR Jet

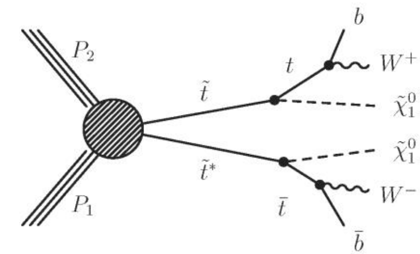
arXiv:	**1409.7058**	**1401.1235**	**1312.735**
Authors:	Baer, Tata, Mustafayev	Han, Kribs, Martin, Menon	Schwaller, Zurita
Channel:	1 jet + OSSF 2 leptons + MET	1 jet + 2 leptons + MET	1 jet + (0,1,2) leptons + MET
Δm	10 GeV	5-50 GeV	< 5 GeV
Mass Reach:	250 GeV [3 σ, 1000 fb^{-1}] no systematic error	μ= 165 GeV [3 σ, 100 fb^{-1}] systematics not clear	170 GeV [3 σ, 3000 fb^{-1}] 1% systematic error
Backgrounds:	t t~ Z/γ*(-> τ+ τ–) + j -> l+ l– j + MET WW + j Z(-> $\nu\nu$~) + j & Z/γ* (-> l+ l–) + j t W, t q Z(-> $\nu\nu$~) + b b~ + jets W(-> l/τ ν) + Z(-> ll/$\tau\tau$) + j	t t~ Z/γ*(-> τ+ τ–) + j -> l+ l– j + MET W(->lν)W(->lν) + j Z(-> $\nu\nu$~) + j & Z/γ*(-> l+ l–) + j	t t~ V + jets
Cuts:	MET > 100 GeV p_T(j1) > 100 GeV |η(j1) | < 2.5 N(jet) = 1 b-veto N(lep) >= 2 m($\tau\tau$)^2 < 0 OS/SF m(ll) < 10 GeV	MET > 100 GeV p_T(j1) > 100 GeV |η(j1) | < 2.5 N(jet) = 1 b-veto 2 isolated leptons m($\tau\tau$) > 150 m(ll) < ~10-20 GeV	MET > 300 GeV p_T(j1) > 300 GeV N(jet) =< 2 $\Delta\varphi$(j1,j2) , 2.5 e, μ, τ veto Addititional MET, pT(j1) > 500-700 GeV pT(j2)<100, |η(j2)|<2

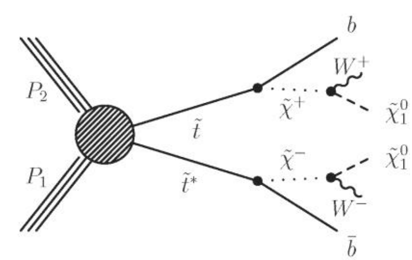
HW: with VBF?

Top Squark Decay Modes



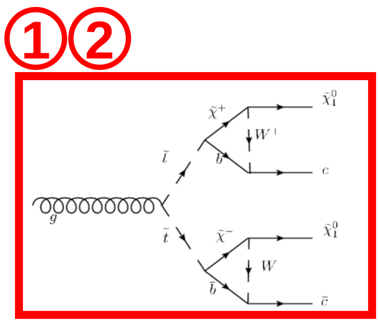


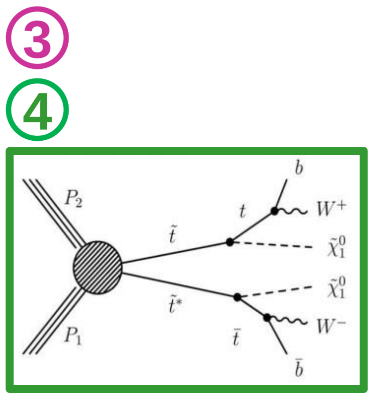


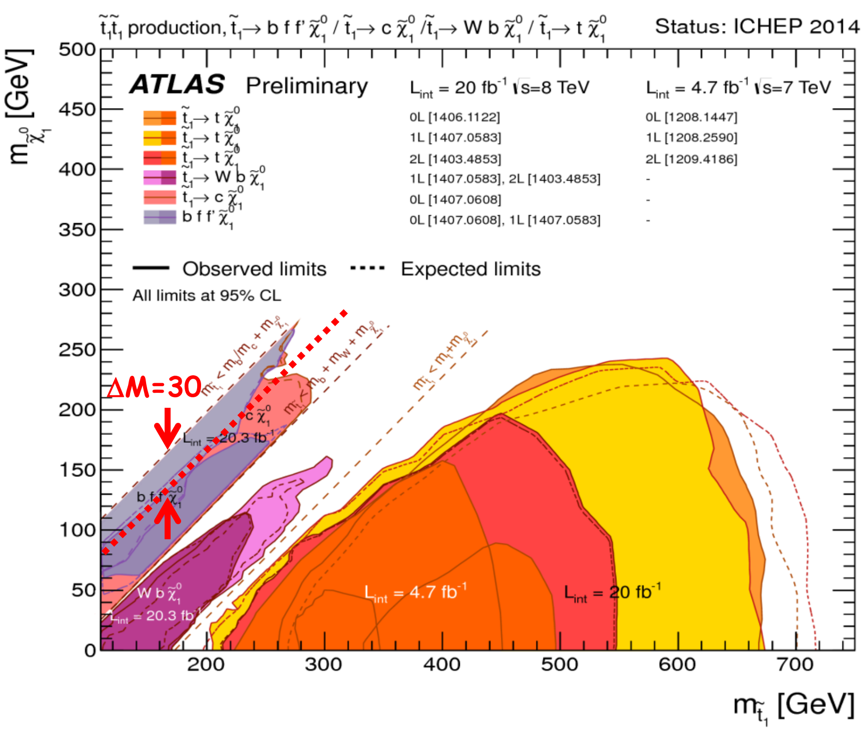


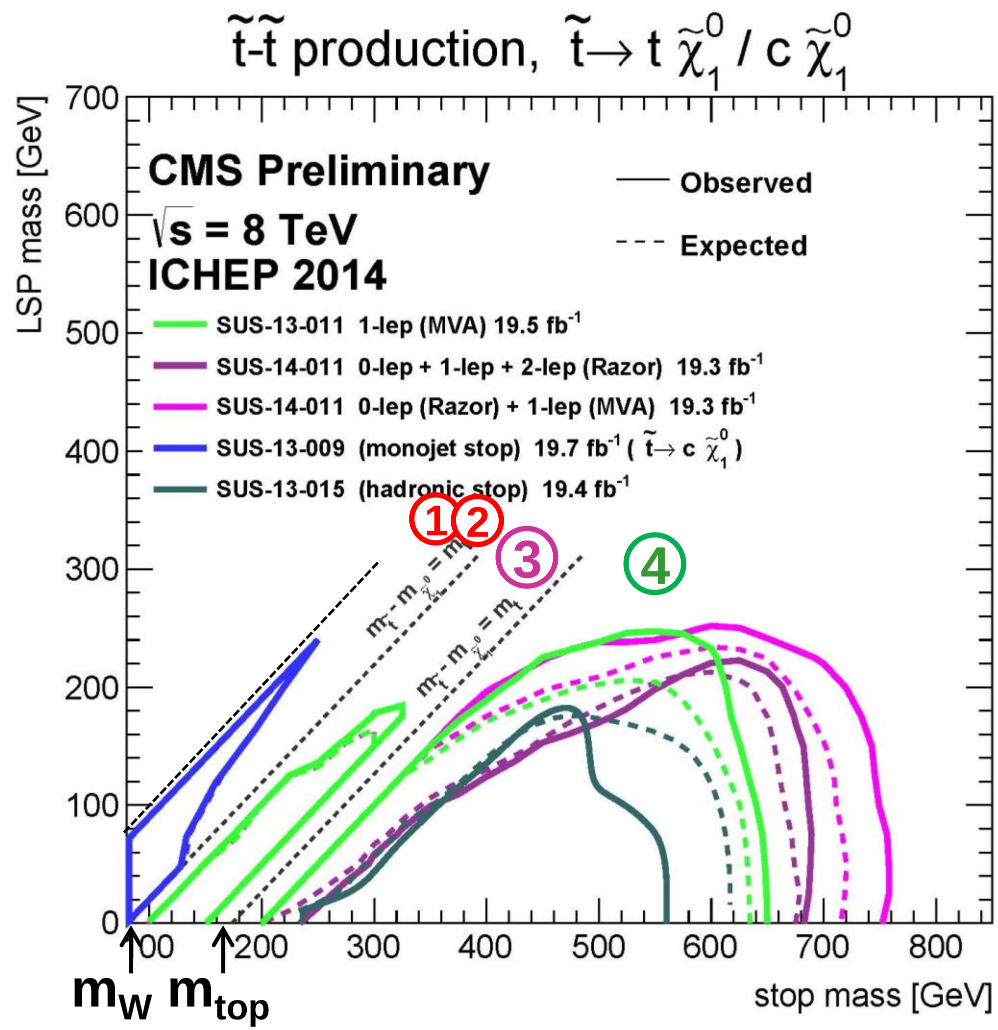
Top Squark Results at 8 TeV

ICHEP 2014





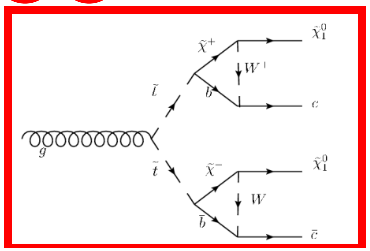




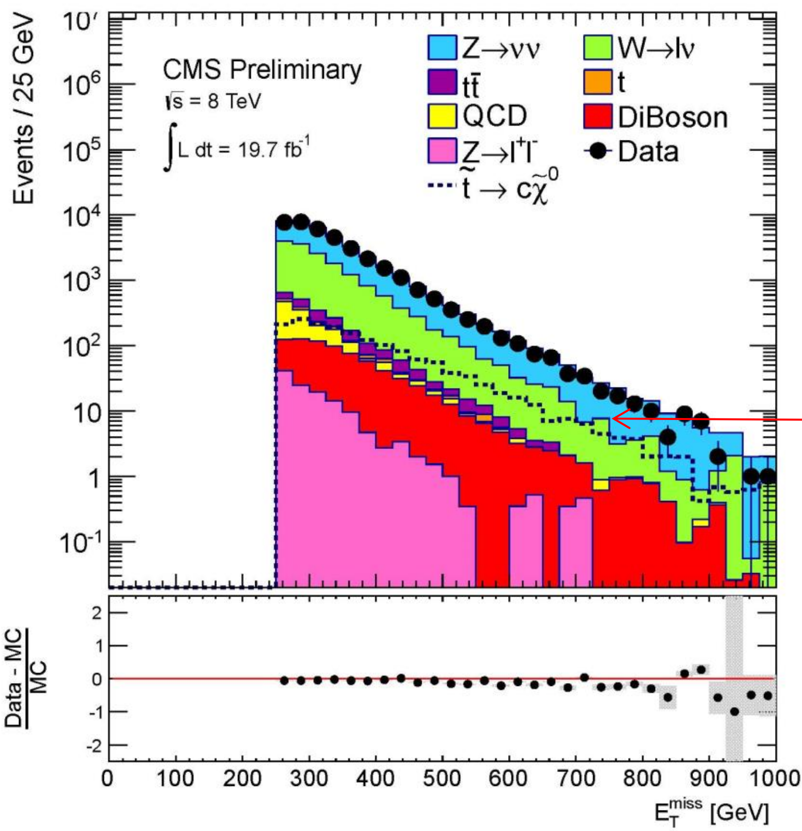
MET in Compressed Top Squark 8 TeV

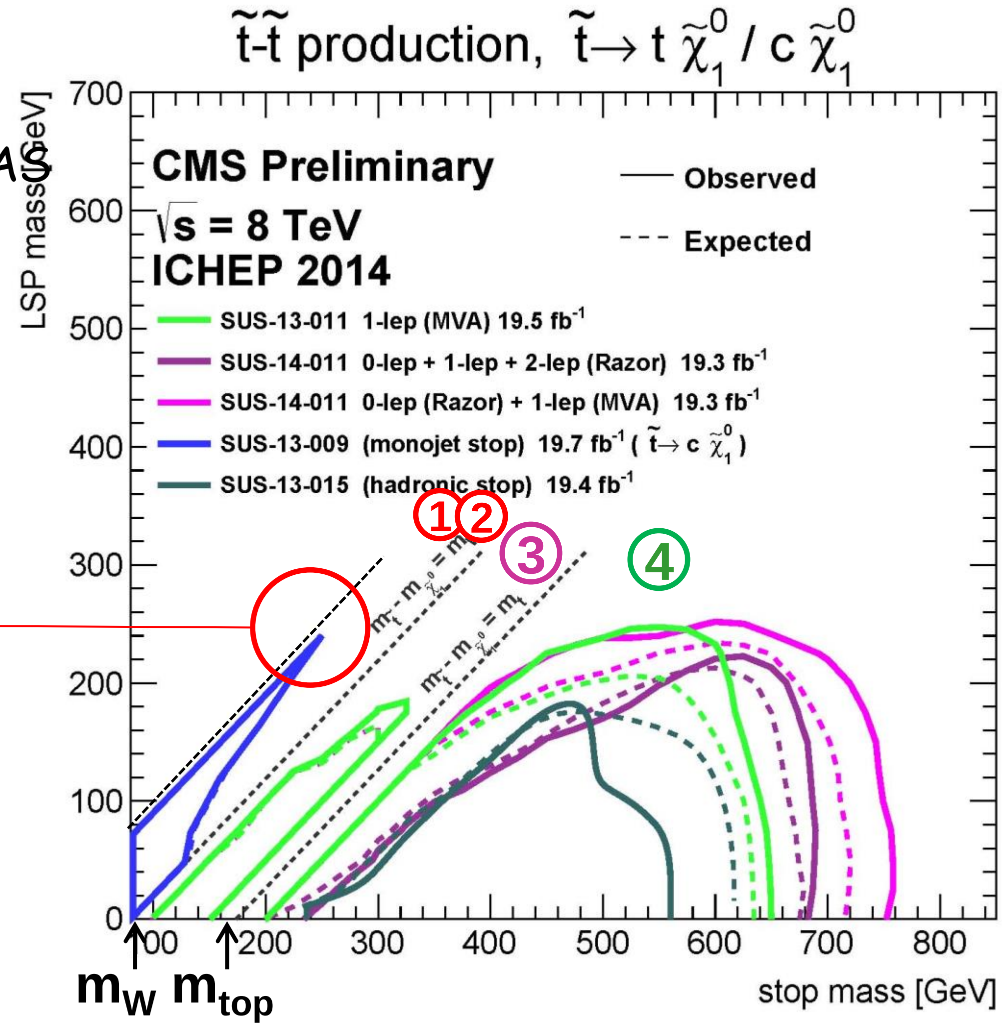
ICHEP 2014

①②

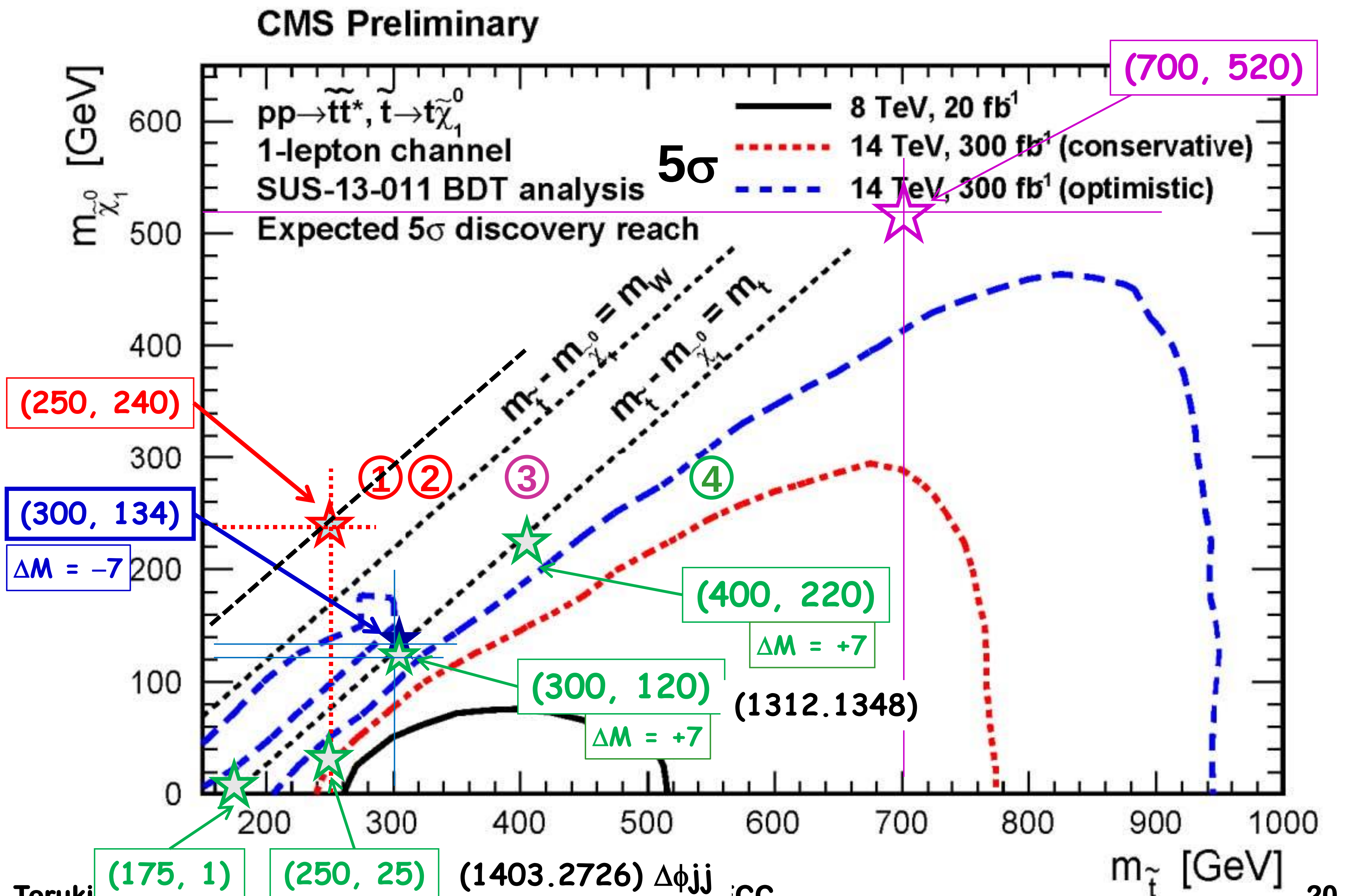


CMS-SUS-13-009 PAS

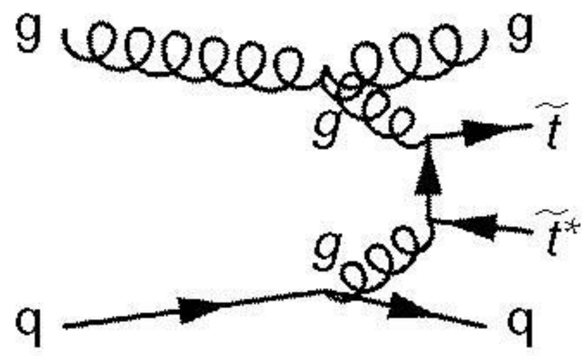


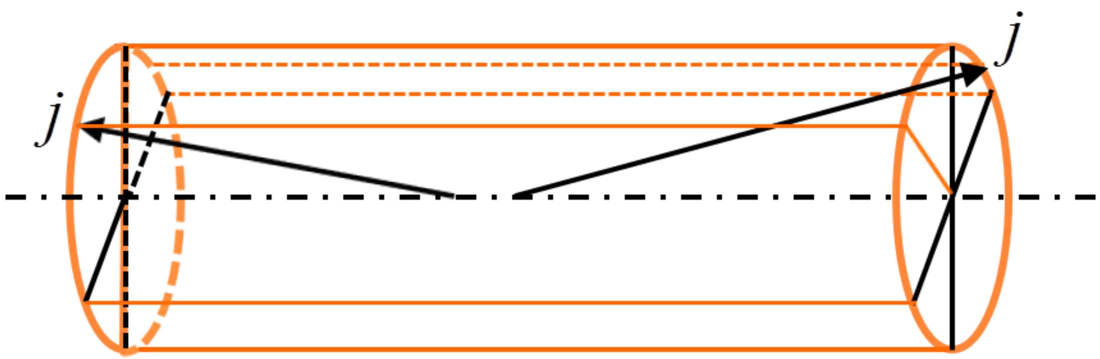


Challenging Compressed Stop at 14 TeV

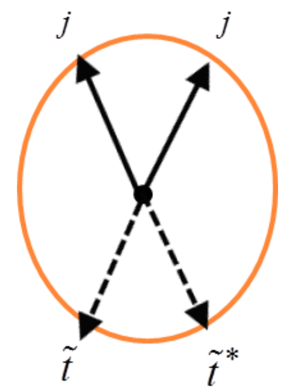


VBF as Tool for Compressed SUSY

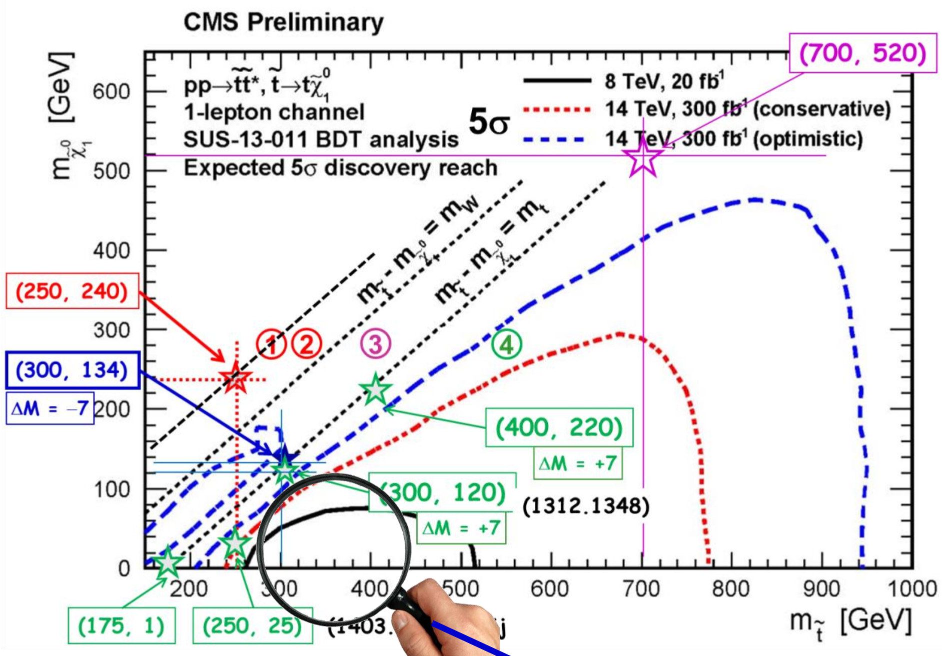




VBF tagged jets (2 energetic jets with large $\Delta\eta$ separation: large M(jj)) in forward region, opposite hemispheres)



VBF production topology in transverse plane



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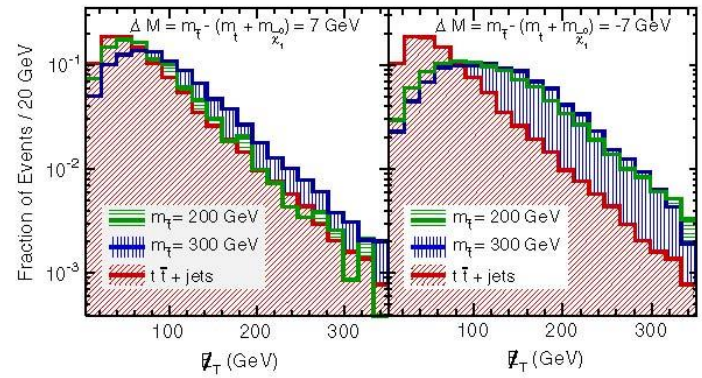
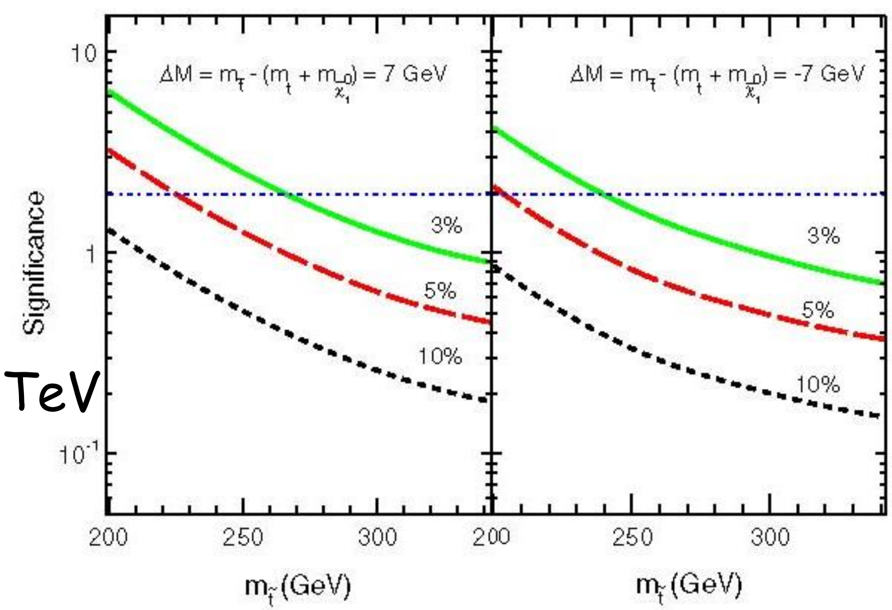


FIG. 1 (color online). Distributions of $\not{E}_T$ normalized to unity for signal (green horizontally dashed histogram) and $t\bar{t}$ + jets background (red diagonally dashed histogram) after VBF selections and lepton and b-jet requirements for the benchmark point with $m_{\tilde{t}} = 400$ GeV, $m_{\tilde{\chi}_1^0}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



VBF+stop – 200-250 GeV at 2σ at 14 TeV

- Better at 100 TeV?
- ISR+stop??

Summary

- 100 TeV collider, powerful, "VBF" luminosity, stronger.
- Physics menu with VBF dijet and ISR jet tagging: Invisible, Higgsino, Wino, Stop, Sbottom(*), Slepton(*)
- But, the forward detector system (tracking, calorimeter, muon) must be good – lepton veto, vertexing for forward jets.
- Ultra-fast timing on VF calorimeter for trigger?
- Central tracking, calorimeter, muon – lepton ID from 3-5 GeV??

(*) I didn't cover today.