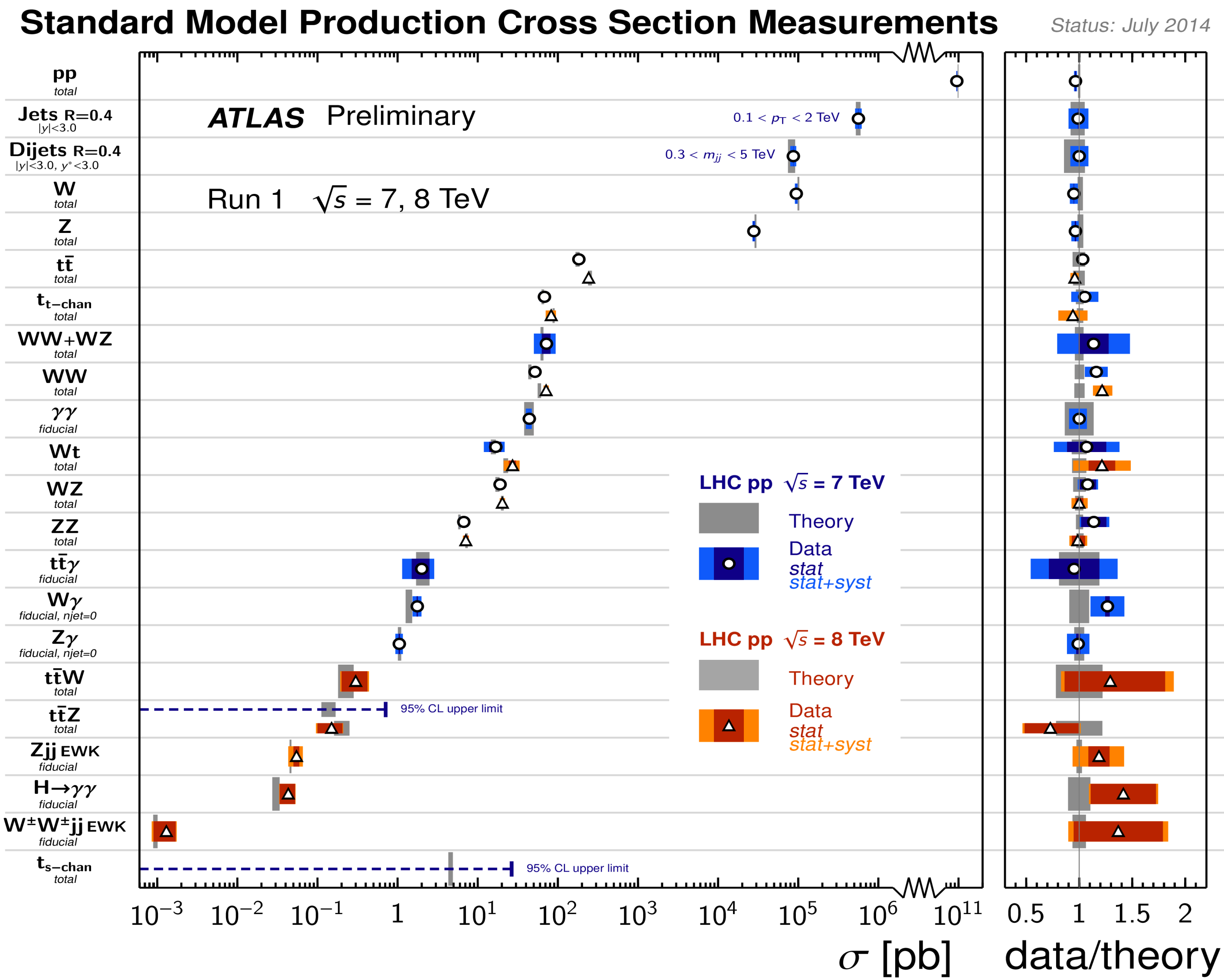
Particle Physics after LHC Run I

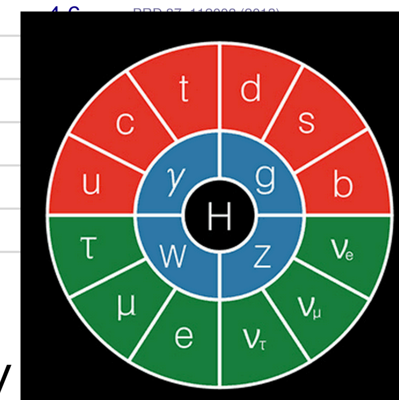
J. Hewett

SLAC NATIONAL ACCELERATOR LABORATORY

Boost 2014

Run I Data Well Described by SM Processes





Pre-LHC
Colloquium

New Physics @ the Terascale

- Electroweak Symmetry breaks at
  energies ~ 1 TeV (SM Higgs or ???)
- WW Scattering unitarized at energies ~ 1 TeV (SM Higgs or ???)
- Gauge Hierarchy: Nature is fine-tuned or Higgs mass must be stabilized by
  New Physics ~ 1 TeV
- Dark Matter: Weakly Interacting Massive Particle must have mass ~ 1 TeV to reproduce observed DM density

REVOLUTIONS
ON THE HORIZON

Pre-LHC Colloquium

New Physics @ the Terascale

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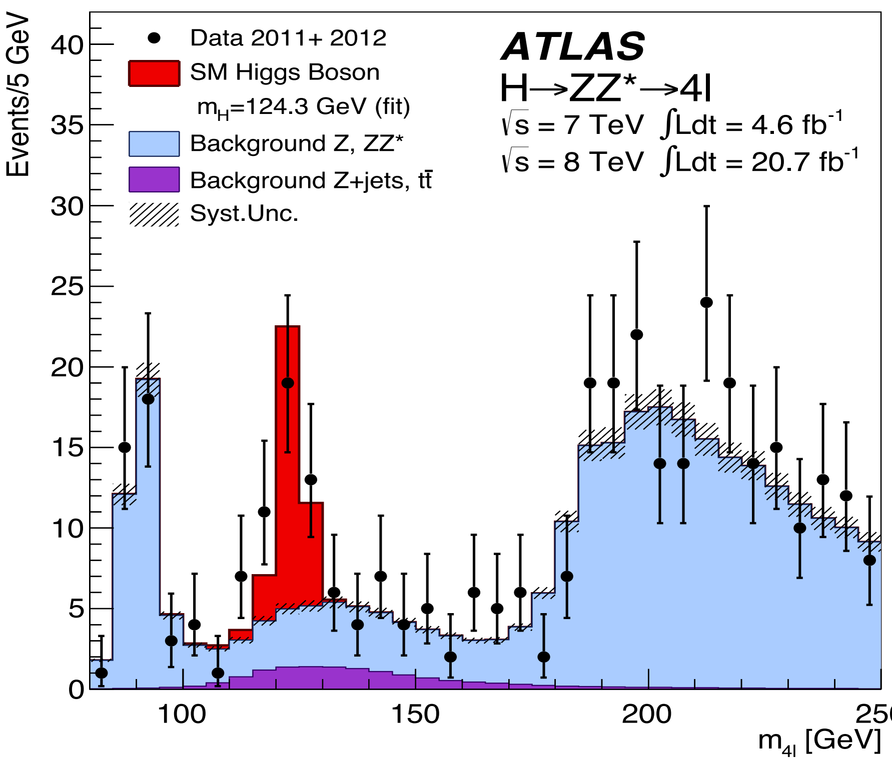
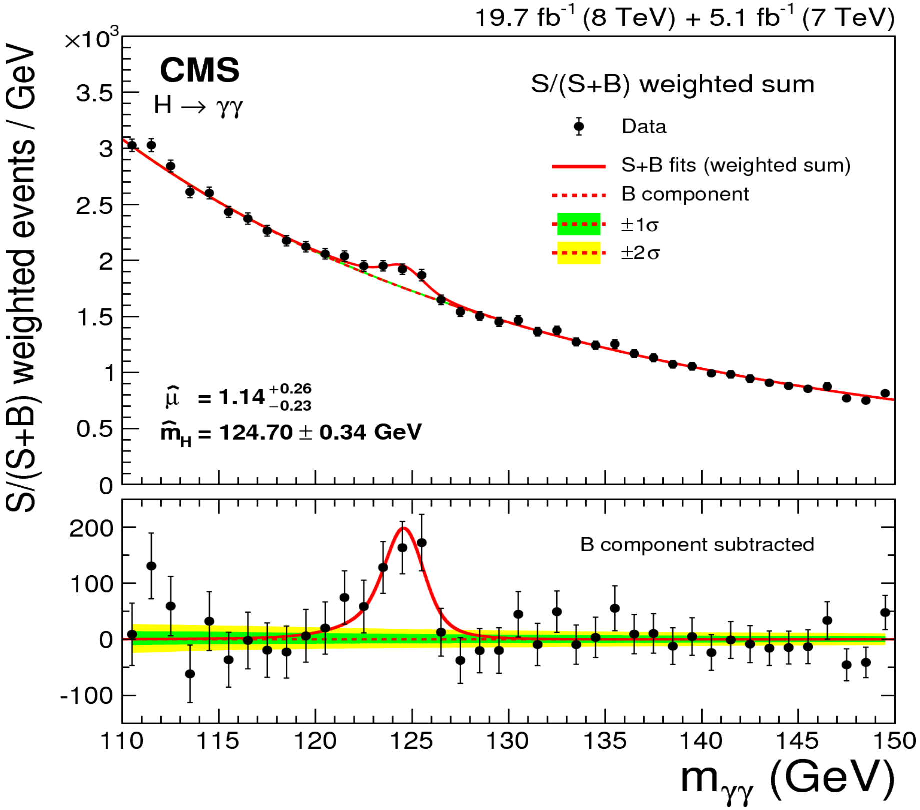
Higgs!! `I Think We Have It'

- Our shiny new Boson!
- $\delta m_h^{theory} \sim 3$ GeV
  - » Well exceeds exp't error!





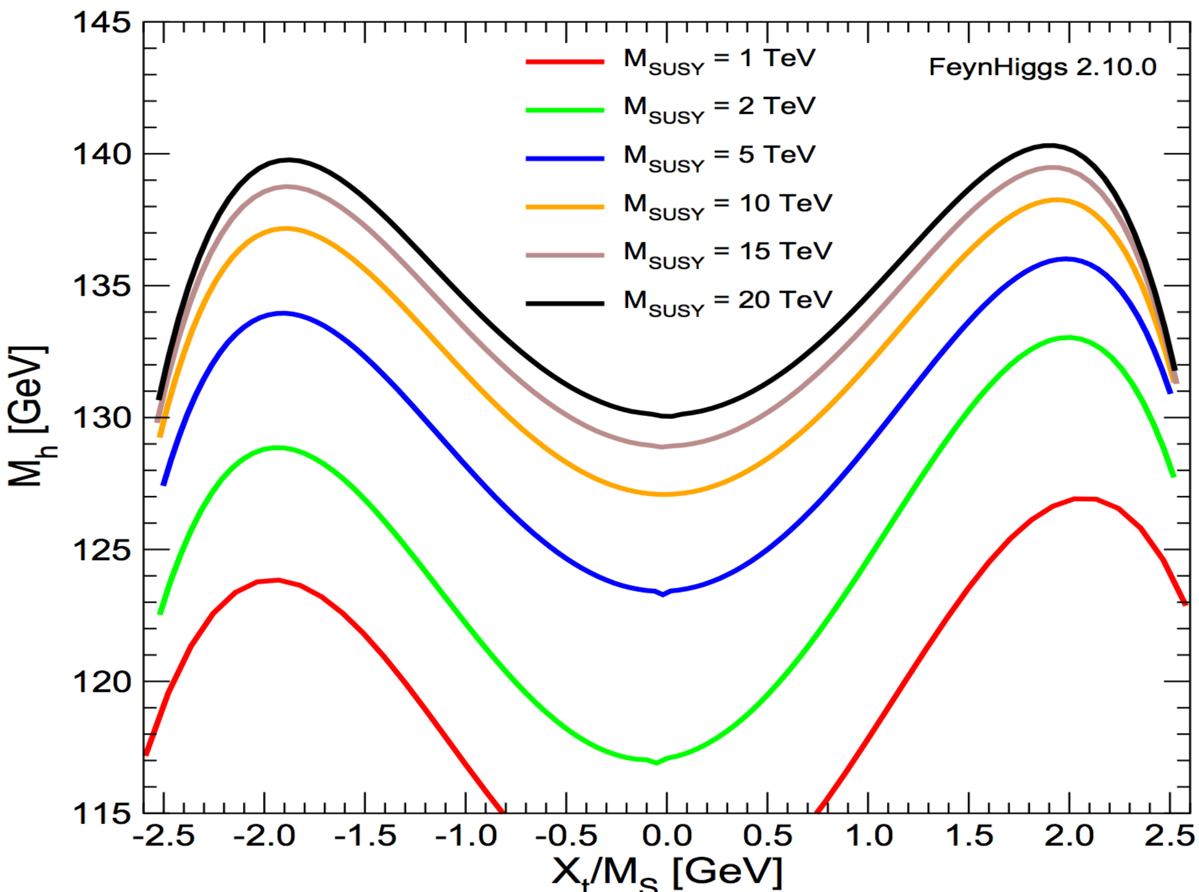
Use Higgs as a Tool for Discovery

- Higgs offers unique portal for discovery
- Key properties we need to understand
  - Total width
  - Couplings to SM particles
  - Shape of Higgs potential: self-interactions
  - Is there a CP-odd component?
  - Do Higgs couplings violate flavor?
  - How does Higgs interact with neutrinos?
  - Does the Higgs generate mass for Dark Matter?
  - How many Higgs Bosons are there?
  - Is Higgs elementary or composite?
  - Is the universe in a false vacuum?

Study the Higgs in as much detail as possible!

Higgs Mass: Tension with SUSY?

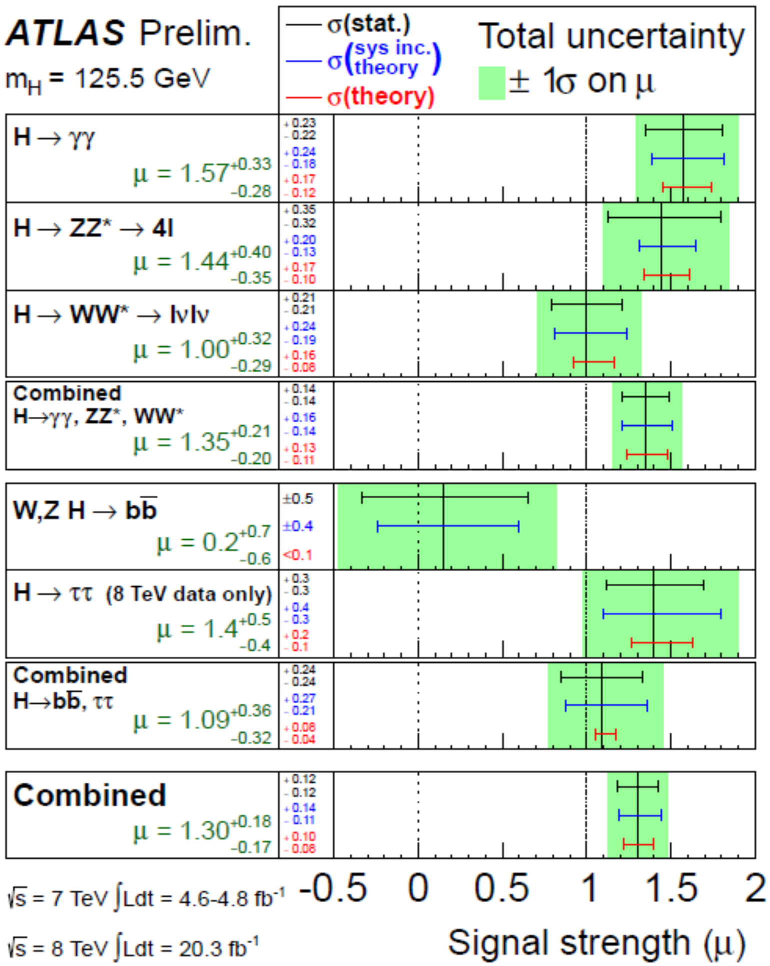
- 125 GeV Higgs requires SUSY `sweet-spot’
  - » Large stop mass/mixing



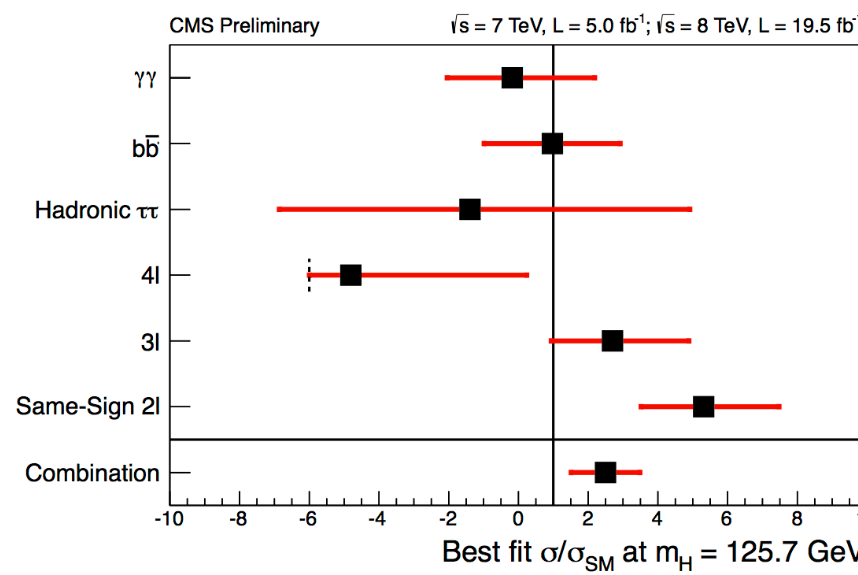
Hahn etal 1404.0186

Higgs Couplings

- Higgs is looking more-or-less SM-like, but measurements have large errors at present



- **tth is 2σ from SM value**
- **Something to watch!**



Higgs Couplings: Model Independent Approach

- In a complete analysis all 34 + 25 4–fermion operators need to be considered.
- Demonstrates the art of choosing a basis

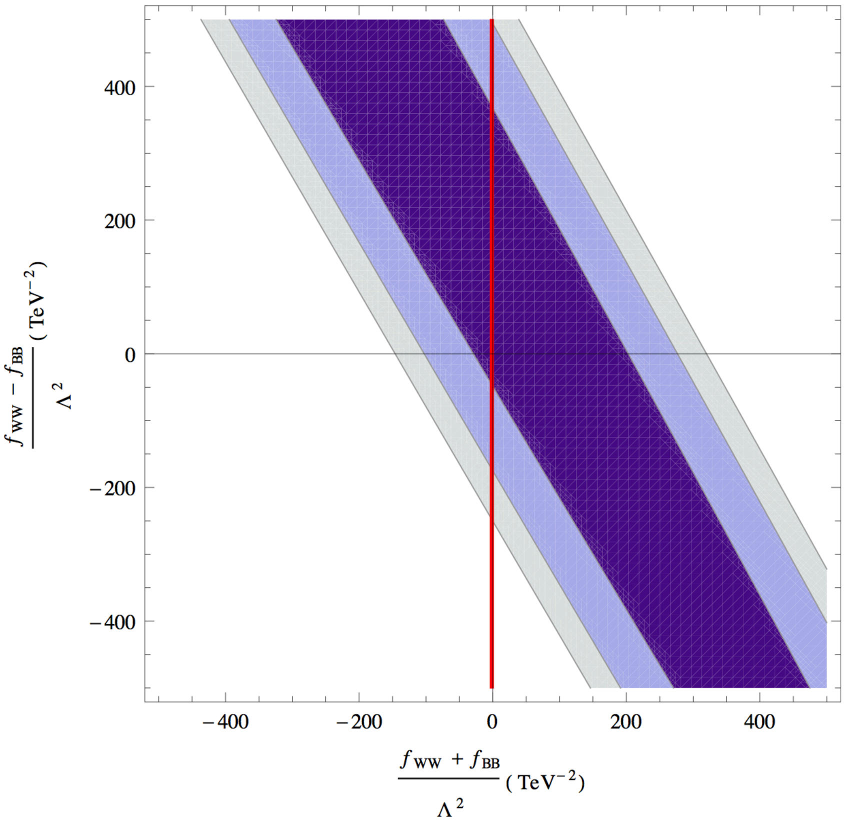
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

Grzadkowski etal 1008.4884

Higgs Couplings: Model Independent Approach

- Effective Field Theory of EW Gauge sector + Higgs
- Finite set of Dimension-6 operators



Comparison of bounds from

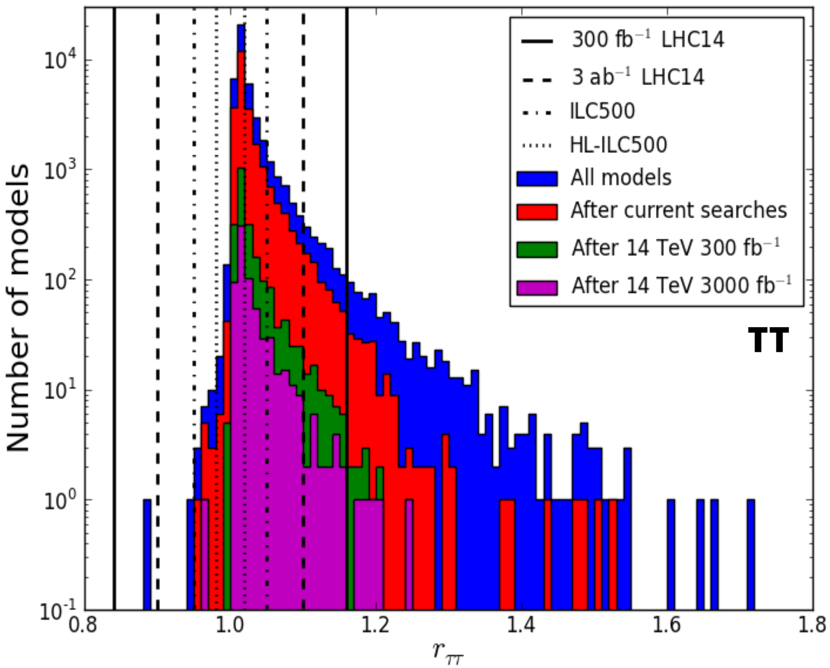
- Oblique parameters S,T,U from EW precision measurements
- 95% CL gg➔h➔γγ
- Demonstrates the complementarity

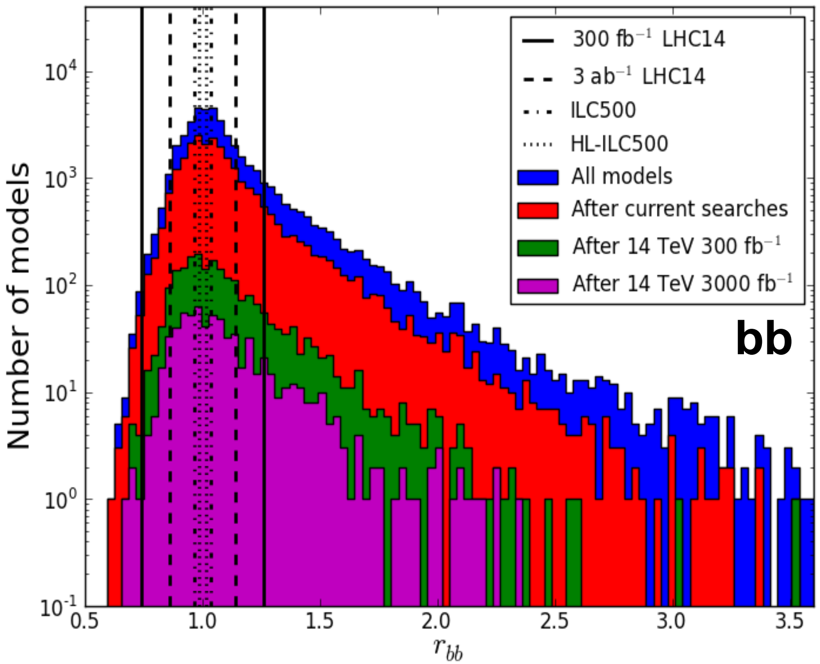
Chen, Dawson, Zhang, 1311.3107

Precision Measurements of Higgs Couplings

- Indirect effects of Supersymmetry affects Higgs couplings
- pMSSM Study: Higgs coupling measurements sensitive to models not accessible to HL-LHC

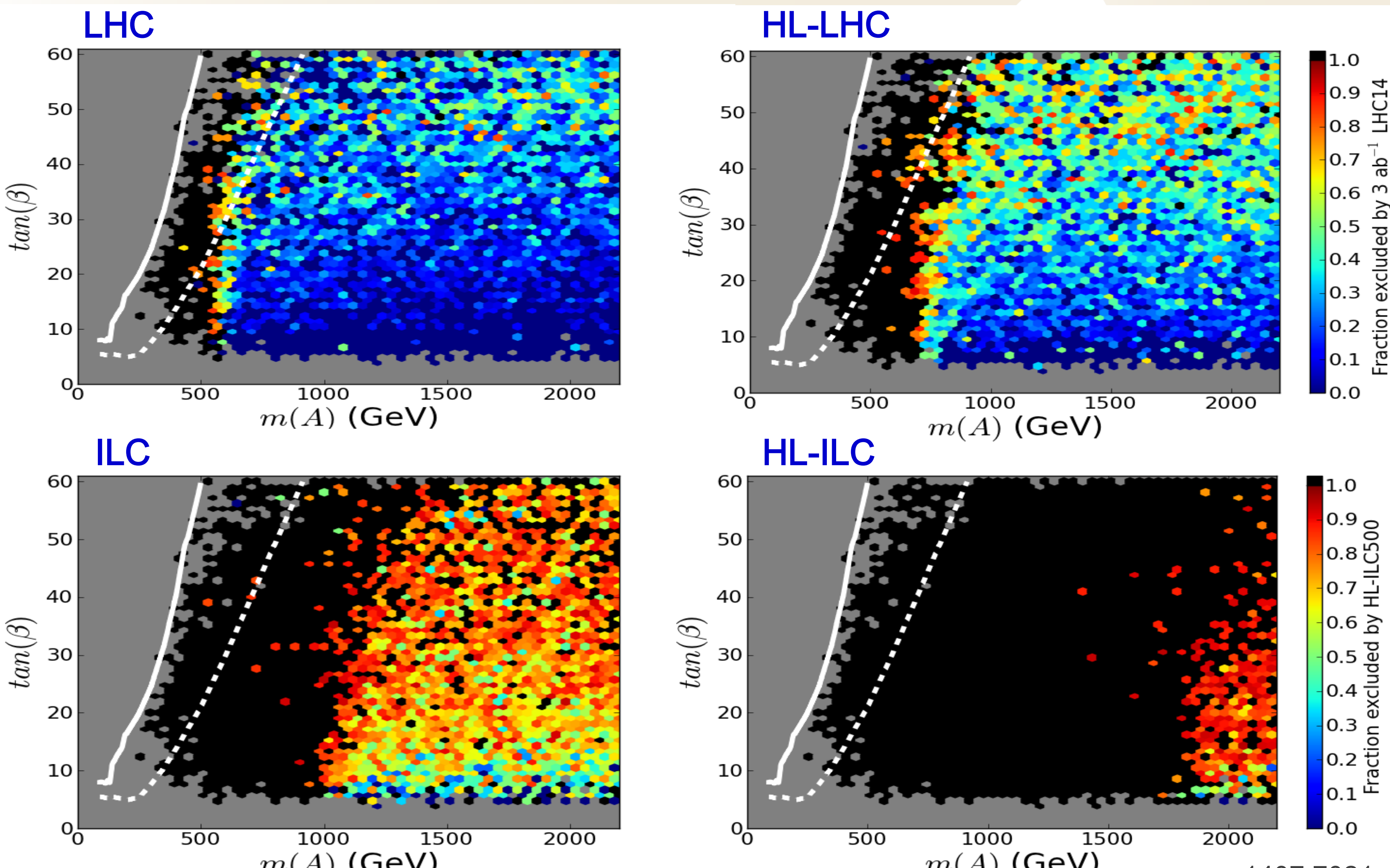
Study Ratio: $\Gamma_{pMSSM}/\Gamma_{SM}$





Cahill-Rowley etal, 1407.7021

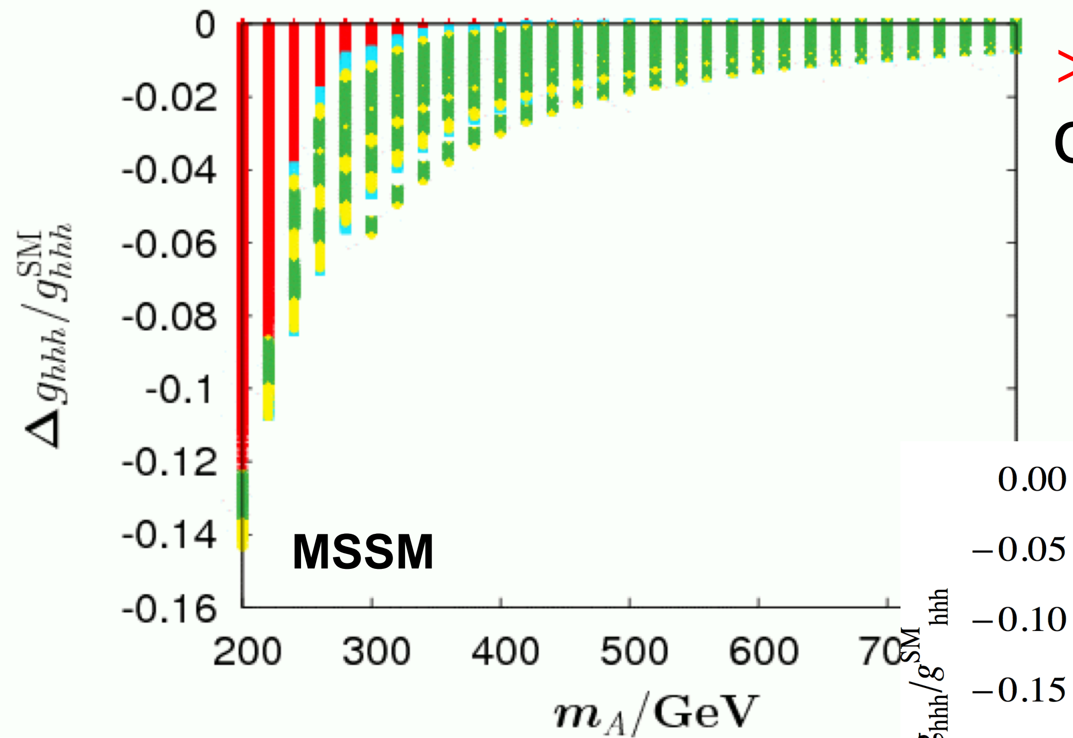
Combined Effect of γγ, ττ, bb Channels vs Direct A Search



1407.7021

Higgs Triple Self-Coupling

- Study of Supersymmetric effects
- What level of precision is necessary?



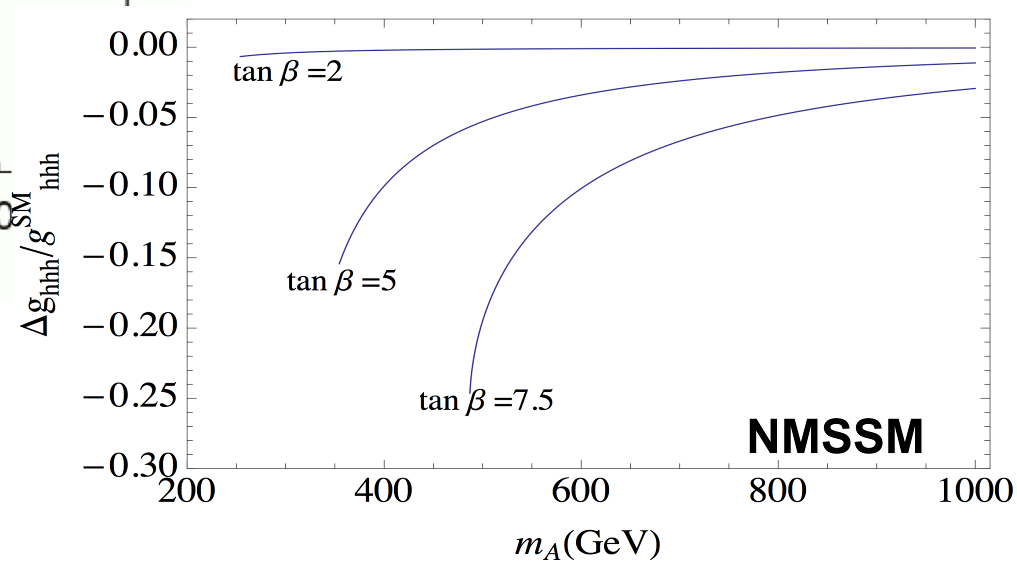
>1 Higgs observed @LHC

Only 1 Higgs @LHC

Stop mass < 1 TeV

1 TeV < Stop < 2.5 TeV

2.5 TeV < Stop mass



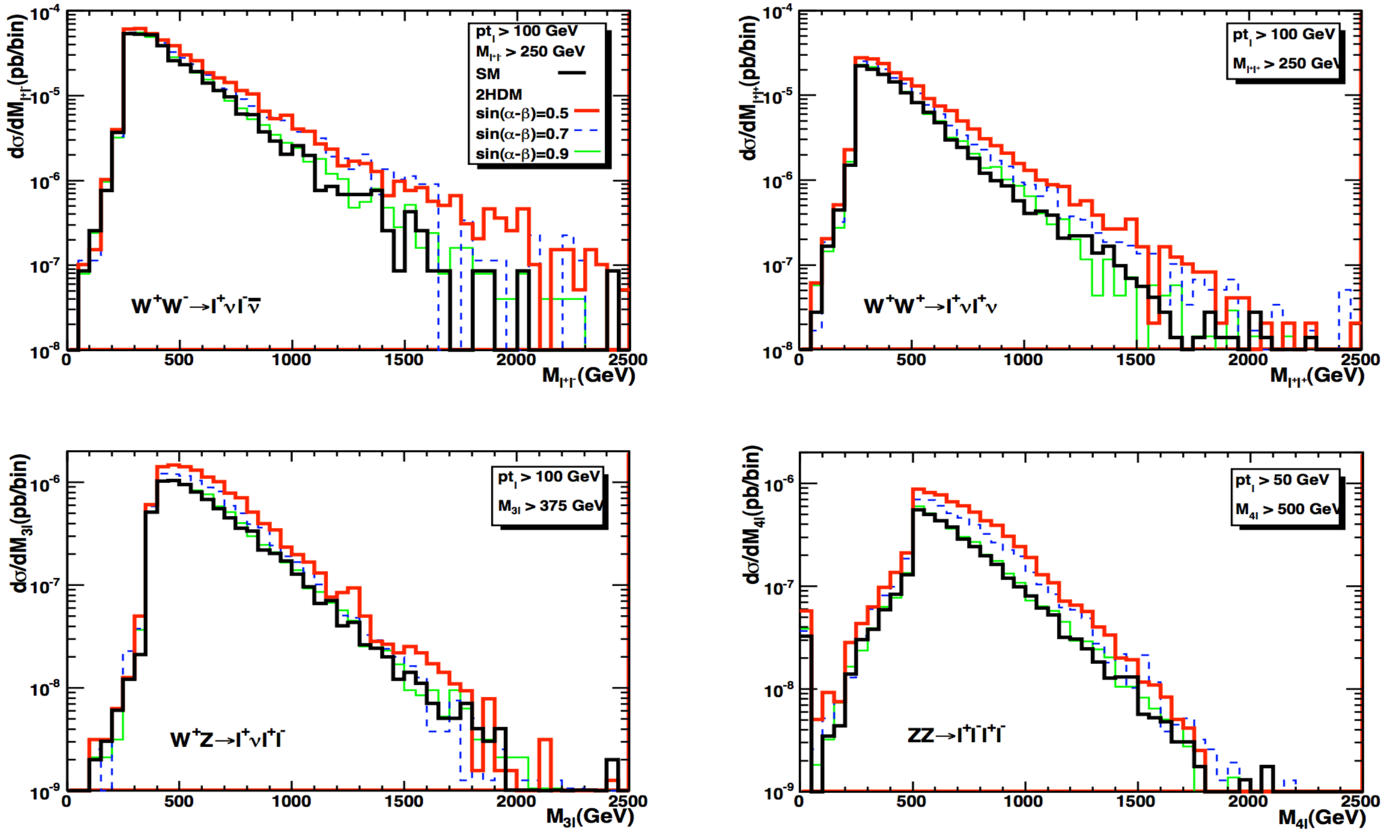
Eventual expected exp't precision Δg_{hhh} ~ 20%

Gupta, Rzehak, Wells 1305.6397

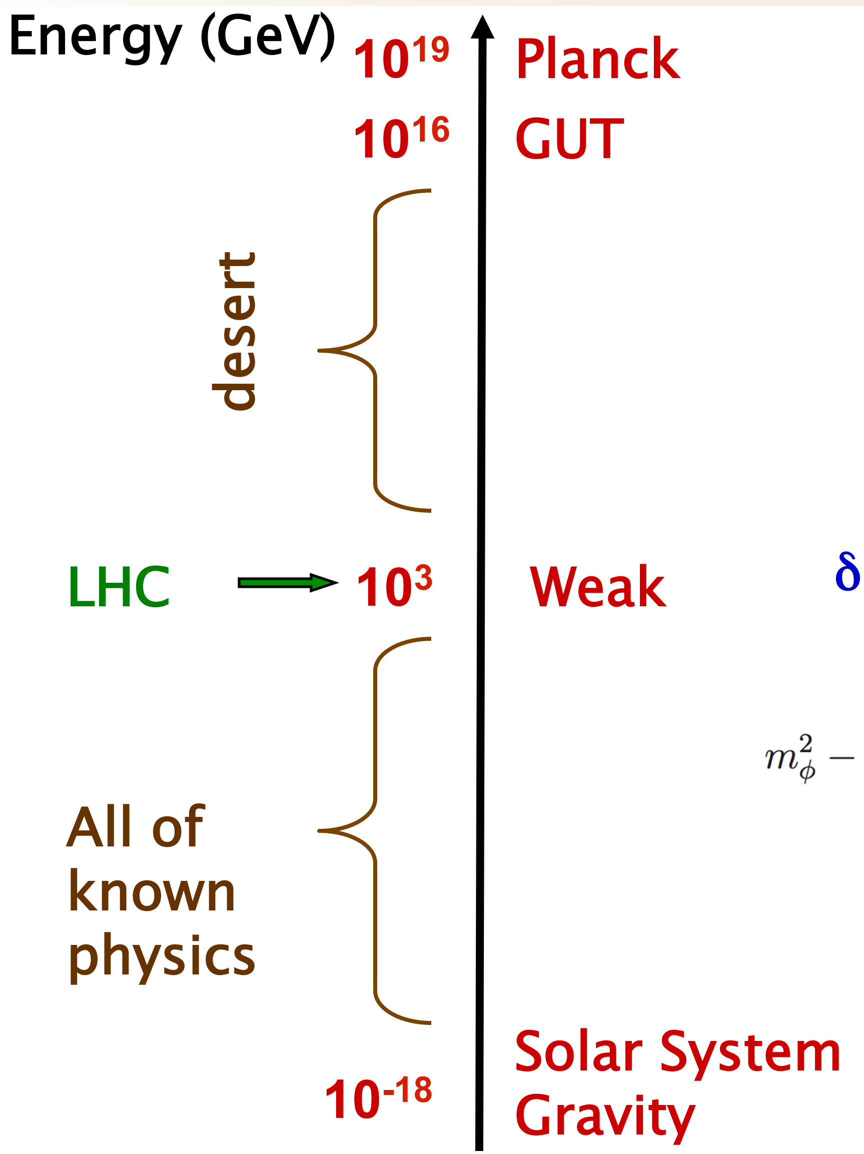
Test Unitarity in WW/ZZ Scattering

- Important for HL-LHC program!!
- Invariant mass distributions in Two-Higgs-Doublet-Model

Chang, Cheung, Luy, Yuan, 1303.6335

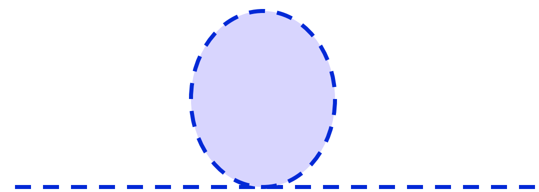


The Hierarchy Problem



Quantum Corrections:

Virtual Effects drag Weak Scale to M_{Pl}

$\delta m_H^2 \sim$  $\sim M_{Pl}^2$

$$m_\phi^2 - m_{\phi 0}^2 = C_1 \frac{g^2}{16\pi^2}\Lambda^2 + C_2 \frac{g^2}{16\pi^2} m_{\rm low}^2 \log\left(\frac{\Lambda^2}{m_{\rm low}^2}\right) + C_3 \frac{g^2}{16\pi^2} m_{\rm low}^2$$

A Cellar of New Ideas

'67	The Standard Model	a classic! aged to perfection
'77	Vin de Technicolor	better drink now
'70's	Supersymmetry: MSSM	mature, balanced, well developed – the Wino's choice
'90's	SUSY Beyond MSSM	svinters blend
'90's	CP Violating Higgs	all upfront, no finish lacks symmetry
'98	Extra Dimensions	bold, peppery, spicy uncertain terrior
'02	Little Higgs	complex structure
'03	Fat Higgs	young, still tannic needs to develop
'03	Higgsless	sleeper of the vintage what a surprise!
'04	Split Supersymmetry	finely-tuned
'05	Twin Higgs	double the taste

J. Hewett

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

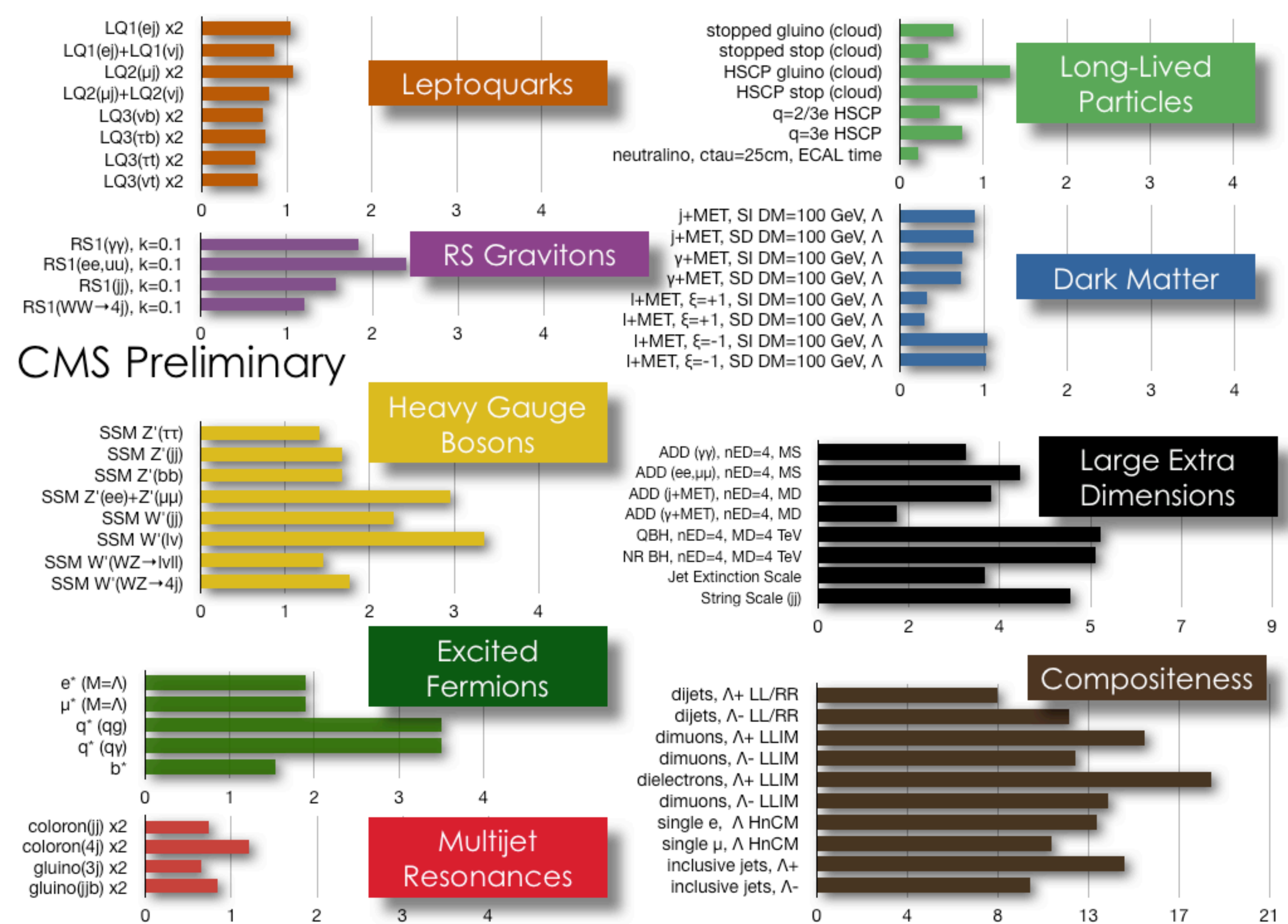
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

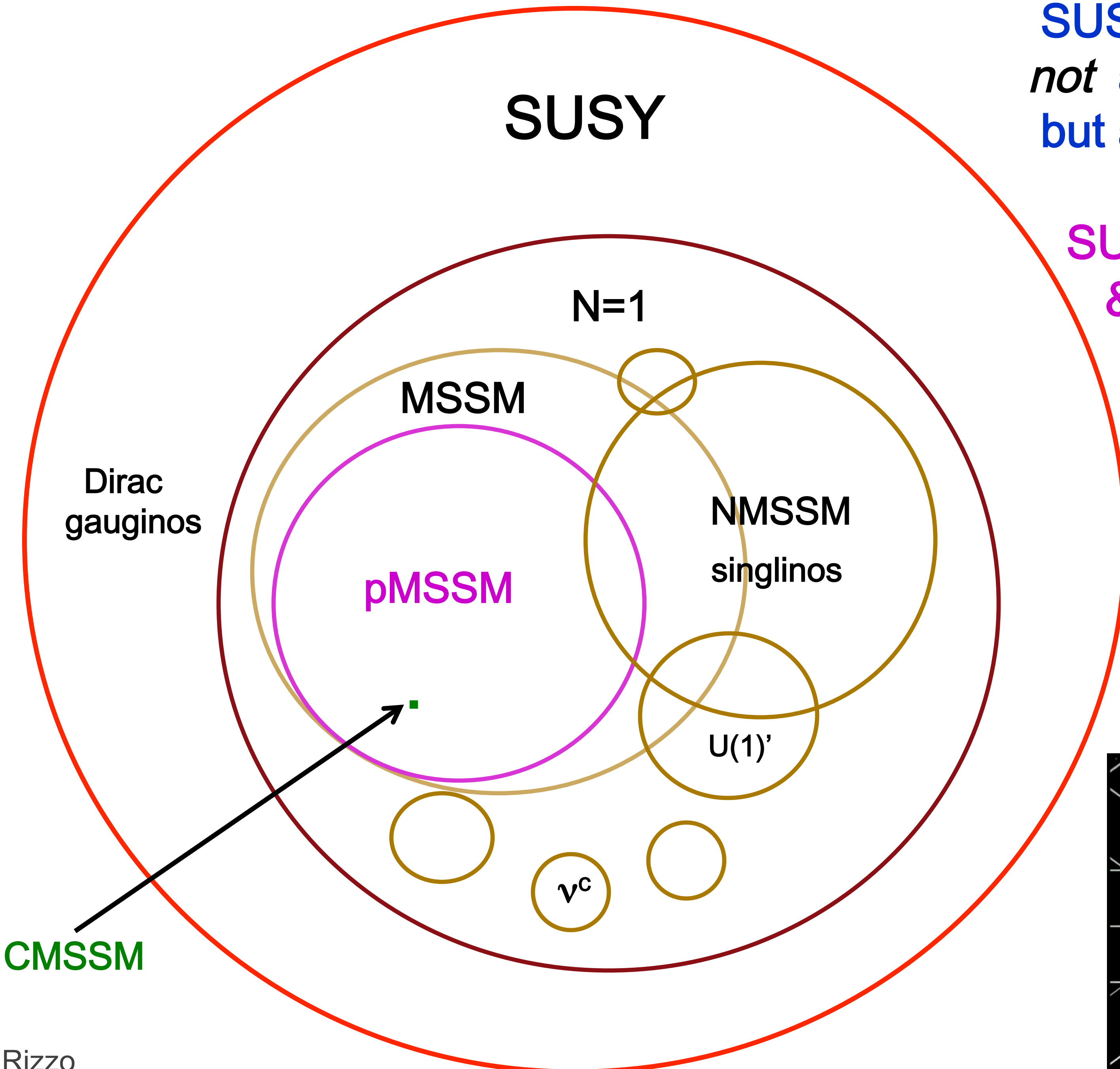
	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq 2/\geq 1$ b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^\pm$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

Mass scale [TeV]: 10^{-1}, 1, 10

*Only a selection of the available mass limits on new states or phenomena is shown.

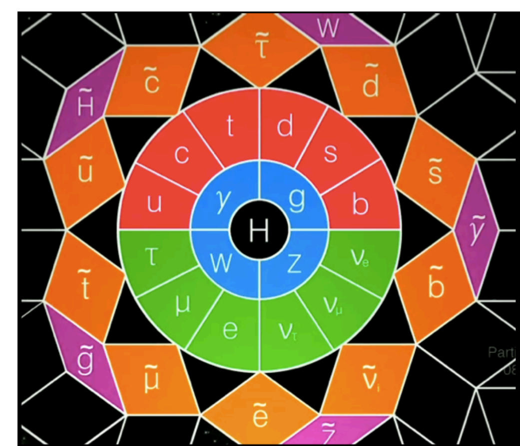

CMS Preliminary
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
0 1 2 3 4
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
0 1 2 3 4
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
0 1 2 3 4
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
0 1 2 3 4
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
0 1 2 3 4
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 2 4 5 7 9
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 4 8 13 17 21



SUSY is complex:
not a single model
but a large framework

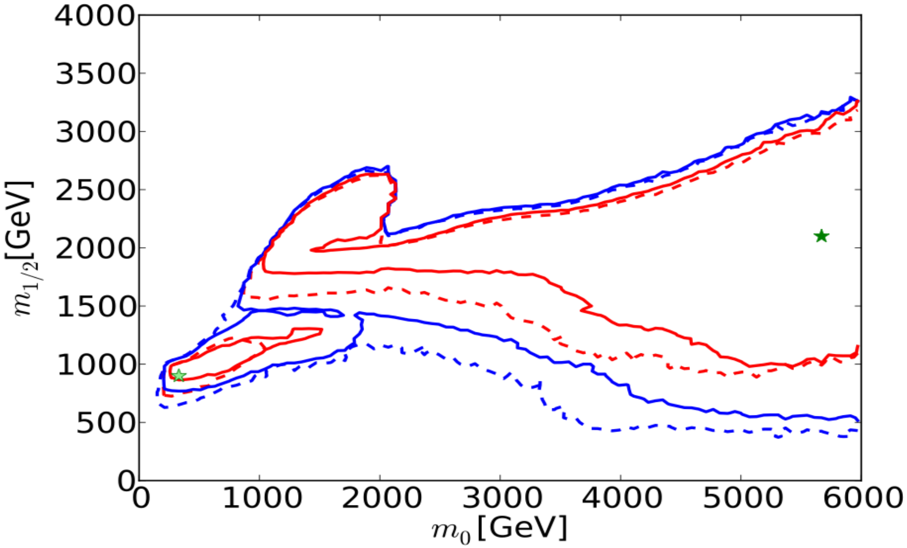
SUSY can be hiding
& may only appear
at 14 TeV

SUSY is too big
to explore without
SOME assumptions



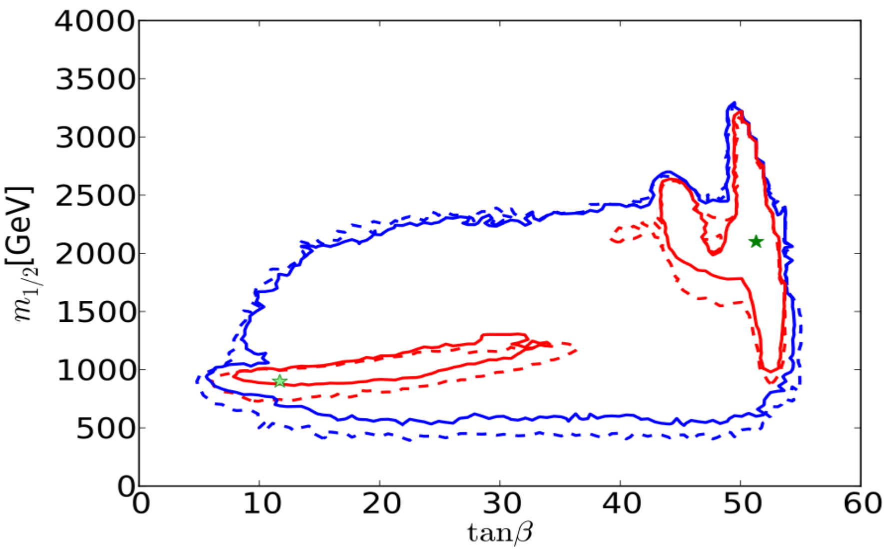
Rizzo

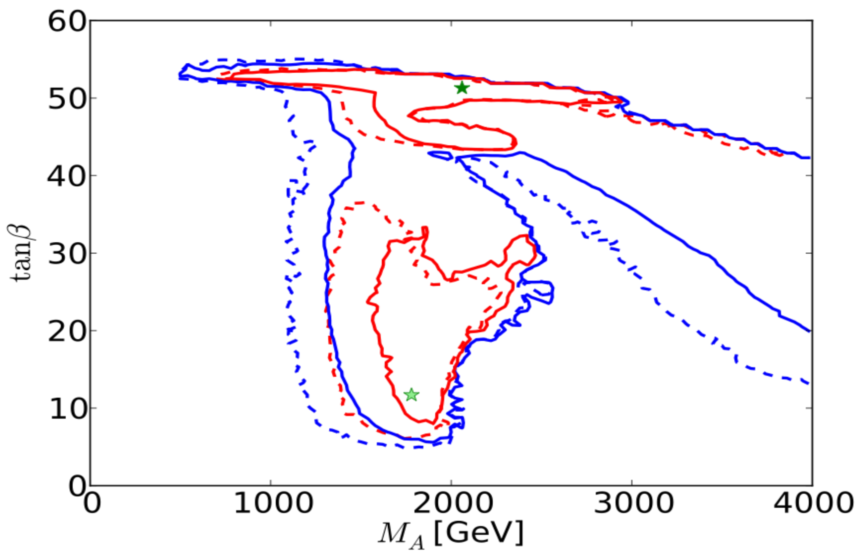
CMSSM After LHC Run I



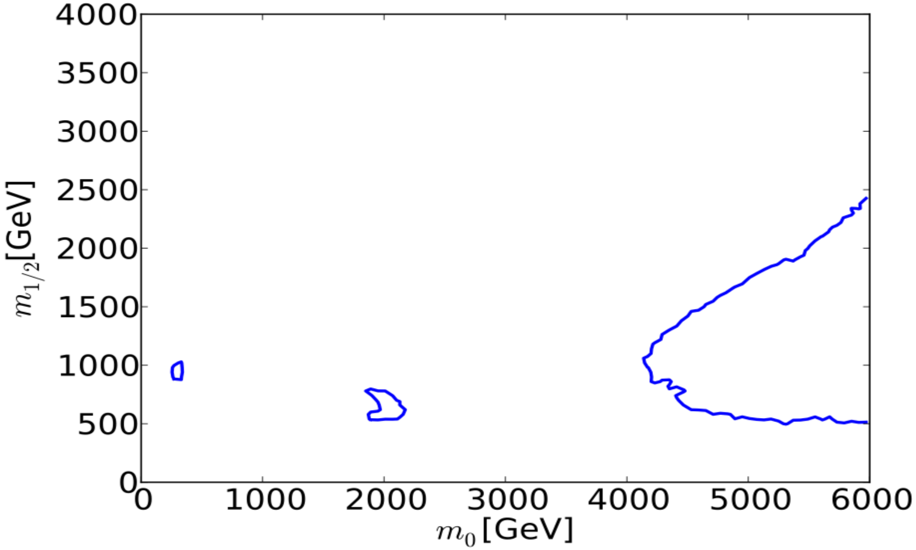
- CMSSM: m_0, $m_{1/2}$, A_0, tan β, sgn(μ)
- Fit to global data set
- μ > 0
- 68% CL, 95% CL (solid curves)
- best fit point ★

Buchmueller etal, 1312.5250





CMSSM After LHC Run I



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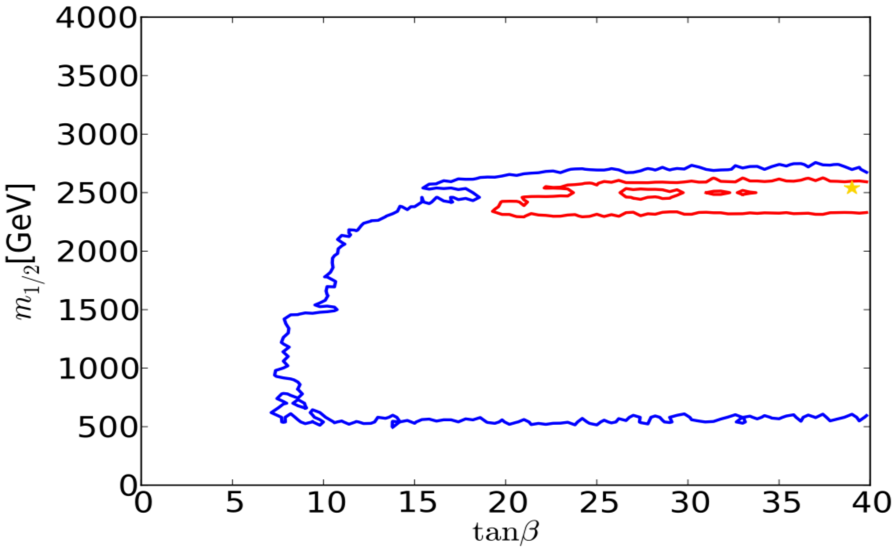
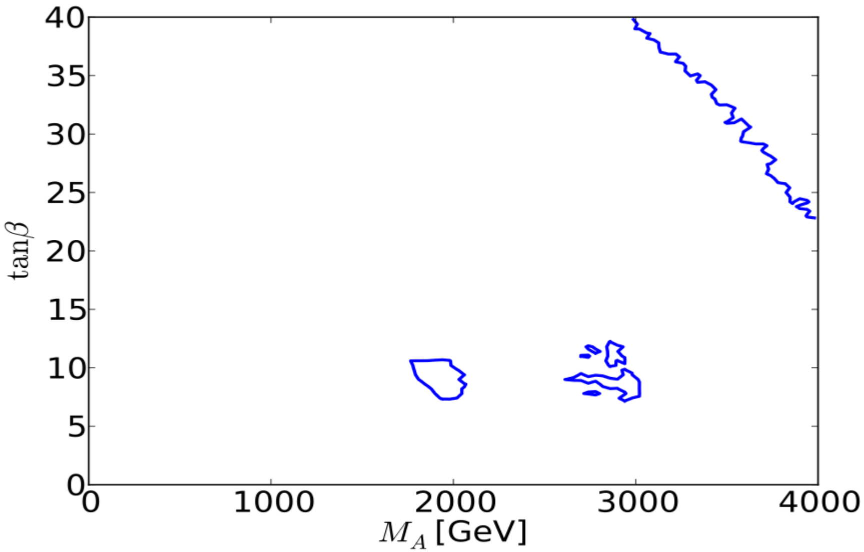
- Fit to global data set
- μ < 0
- 68% CL, 95% CL (solid curves)
- best fit point ★
- Constrained by g-2, b➔sγ, m_h

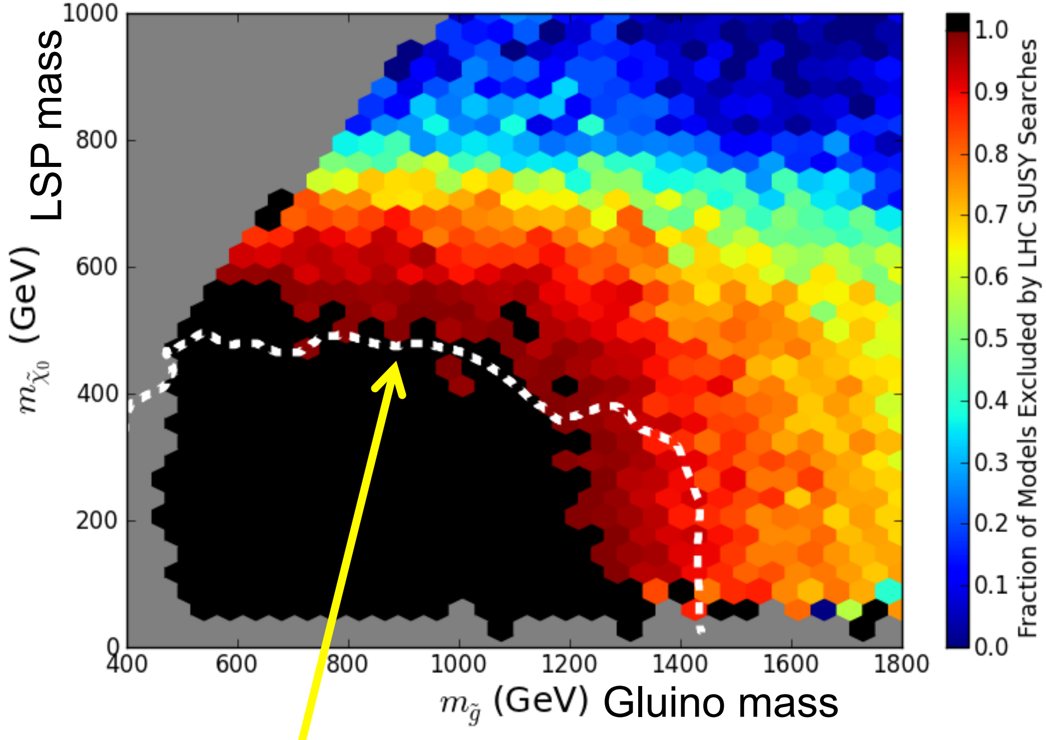
Buchmueller etal, 1312.5250





pMSSM after LHC Run I

- 19-parameter MSSM with Neutralino LSP
- Consistent with global data set
- Subjected to ~40 LHC Run I SUSY Searches



Cahill-Rowley etal, 1407.4130

pMSSM after LHC Run I

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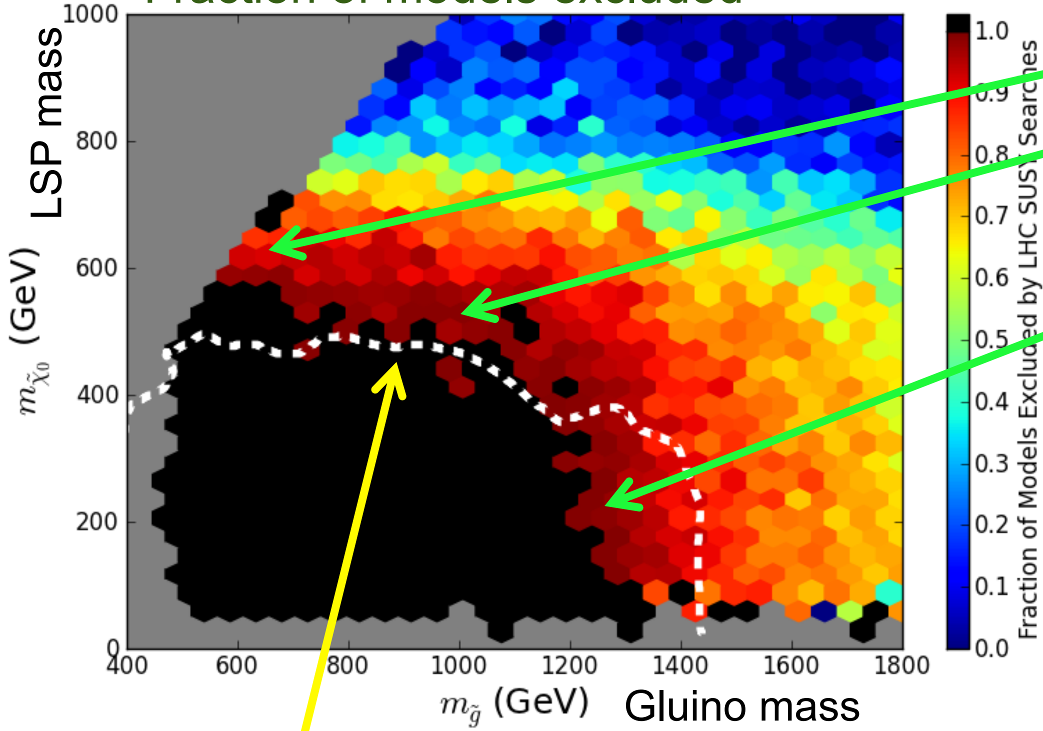
Fraction of models excluded



- Compressed Spectra
- Stealth SUSY
  - Complicated dk chains
- Kinematics

- 2-parameter Simplified Model provides good approximation

Simplified Model Limit (ATLAS)

Cahill-Rowley etal, 1407.4130

pMSSM after LHC Run I

- 19-parameter MSSM with Neutralino LSP
- Consistent with global data set
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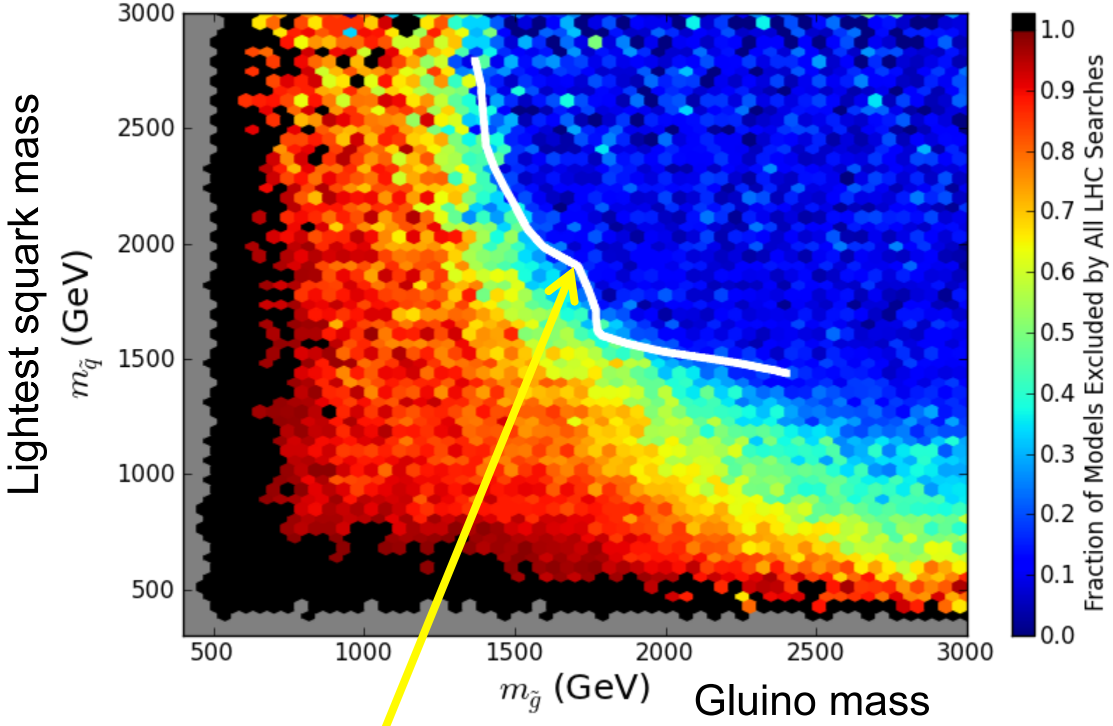


Simplified Model Limit (ATLAS)

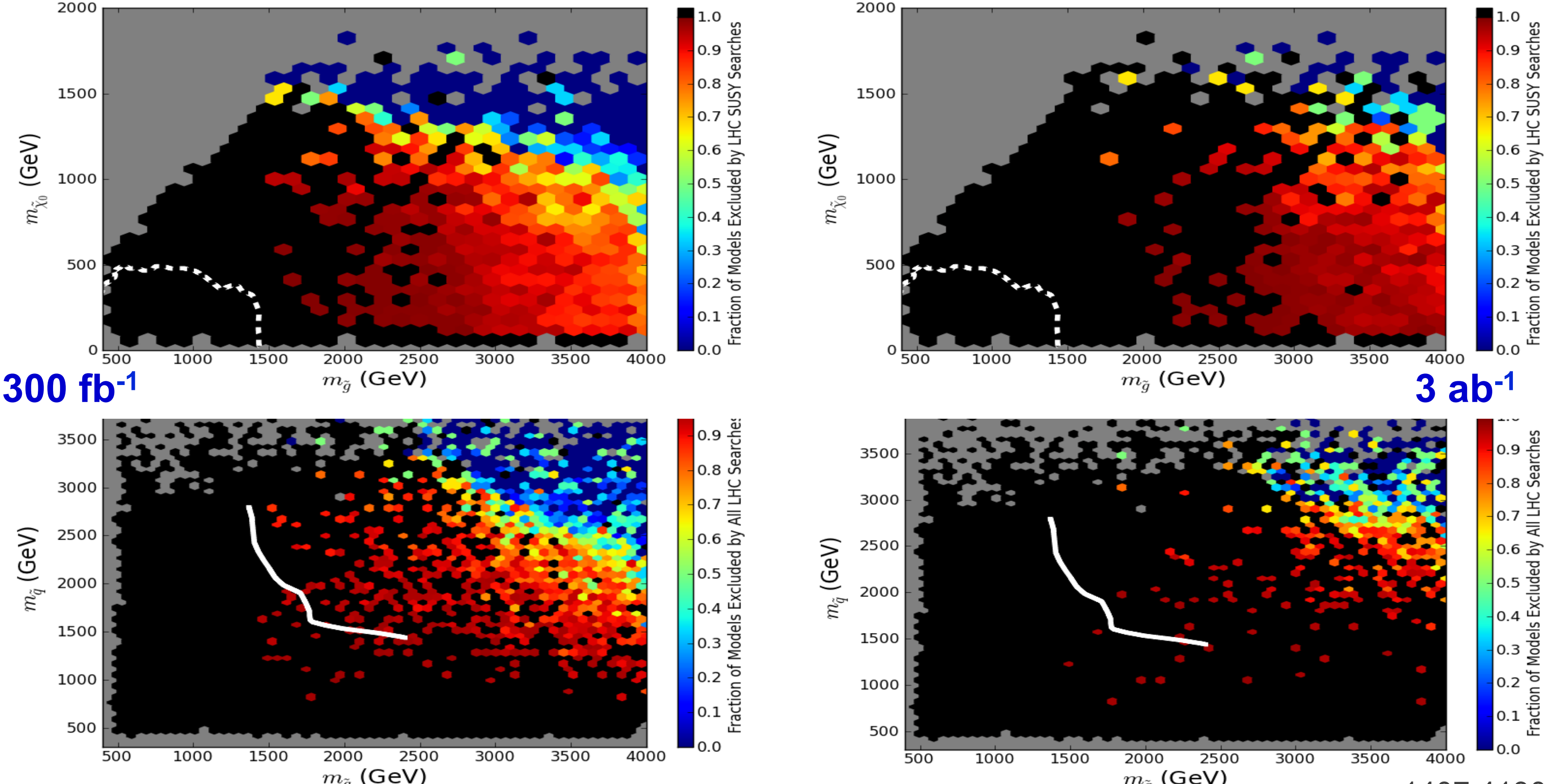
- Light Squarks / Gluinos still allowed!

- 3-parameter Simplified Model does NOT provide a good approximation

Cahill-Rowley etal, 1407.4130

pMSSM Expectations for 14 TeV

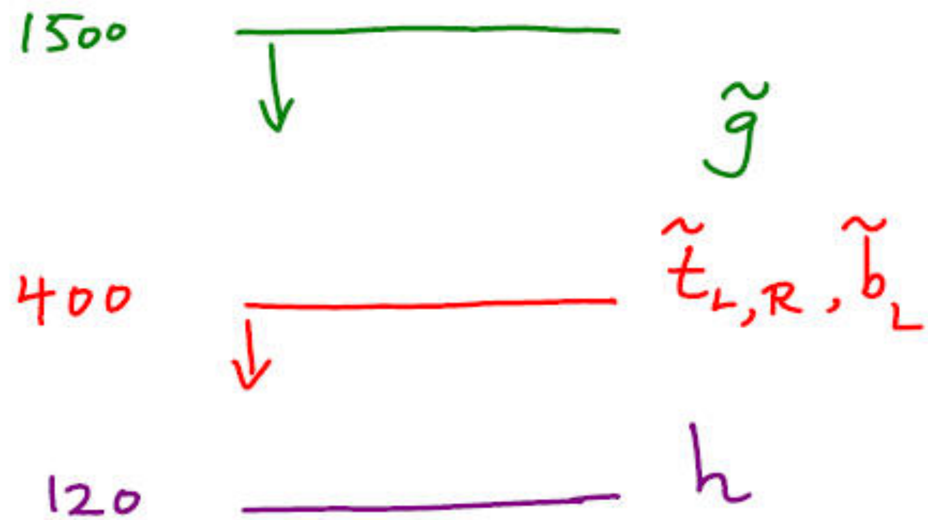
Jets+MET & Stop Search (ATLAS European Strategy & Snowmass Study)



1407.4130

Whither Naturalness?

Cumpulsory Natural SUSY



Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2, \left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

Arkani-Hamed

Naturalness Crisis!

Is the CNMSSM more natural than the CMSSM?

Andrew Fowlie[*]

What is a Natural SUSY scenario?

J. Alberto Casas,[a] Jesús M. Moreno,[a] Sandra Robles,[a] Krzysztof Rolbiecki[a] and Bryan Zaldívar[b]

Implications of naturalness for the heavy Higgs bosons of supersymmetry

Kyu Jung Bae[1*], Howard Baer[1†], Vernon Barger[2‡], Dan Mickelson[1§] and Michael Savoy[1¶]

Natural Supersymmetry in Warped Space

Ben Heidenreich and Yuichiro Nakai

EFT naturalness: an effective field theory analysis of Higgs naturalness

Shaouly Bar-Shalom,[1,*] Amarjit Soni,[2,†] and Jose Wudka[3,‡]

Naturalness in low-scale SUSY models and "non-linear" MSSM

I. Antoniadis[a], E. M. Babalic[b], D. M. Ghilencea[a,b,]

NATURAL SCALARS IN THE NMSSM

DARIO BUTTAZZO

Triplet-extended scalar sector and the naturalness problem

Indrani Chakraborty[*] and Anirban Kundu[†]

Natural Supersymmetry and Dynamical Flavour with Meta-stable Vacua

Steven Abel[◊] and Moritz McGarrie[†]

The 126 GeV Higgs boson mass and naturalness in (deflected) mirage mediation

Hiroyuki Abe[*] and Junichiro Kawamura[†]

Leaving no stone unturned in the hunt for SUSY naturalness: A Snowmass whitepaper

H. Baer[1], V. Barger[2], P. Huang[2], D. Mickelson[1], A. Mustafayev[3], W. Sreethawong[4] and X. Tata[3]

Naturalness of scale-invariant NMSSMs with and without extra matter

Maien Y. Binjonaid,[a,b] and Stephen F. King[a]

Naturalness Crisis!

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Implications of naturalness for the heavy Higgs bosons of supersymmetry

Kyu Jung Bae[1*], Howard Baer[1†] …
Dan Mickelson[1§] …

What is a Natural SUSY …

EFT naturalness: an effecti…

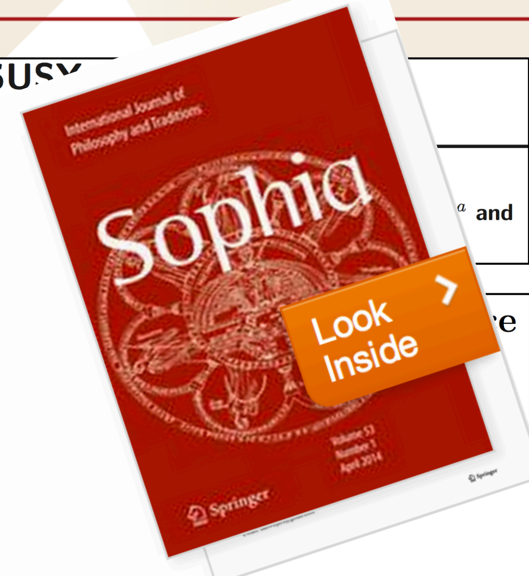
Sha…

Sophia
April 2014, Volume 53, Issue 1, pp 1-18

Date: 28 Sep 2013

Optimistic Naturalism: Scientific Advancement and the Meaning of Life

Dan Weijers



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…alar sector and the naturalness problem

Indrani Chakraborty * and Anirban Kundu †

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…bel◇ and Moritz McGarrie†

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Naturalness of scale-invariant NMSSMs with and without extra matter

Maien Y. Binjonaid,[a,b] and Stephen F. King[a]

Naturalness

- How is naturalness quantified?

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- Traditional (Barbieri–Giudice):

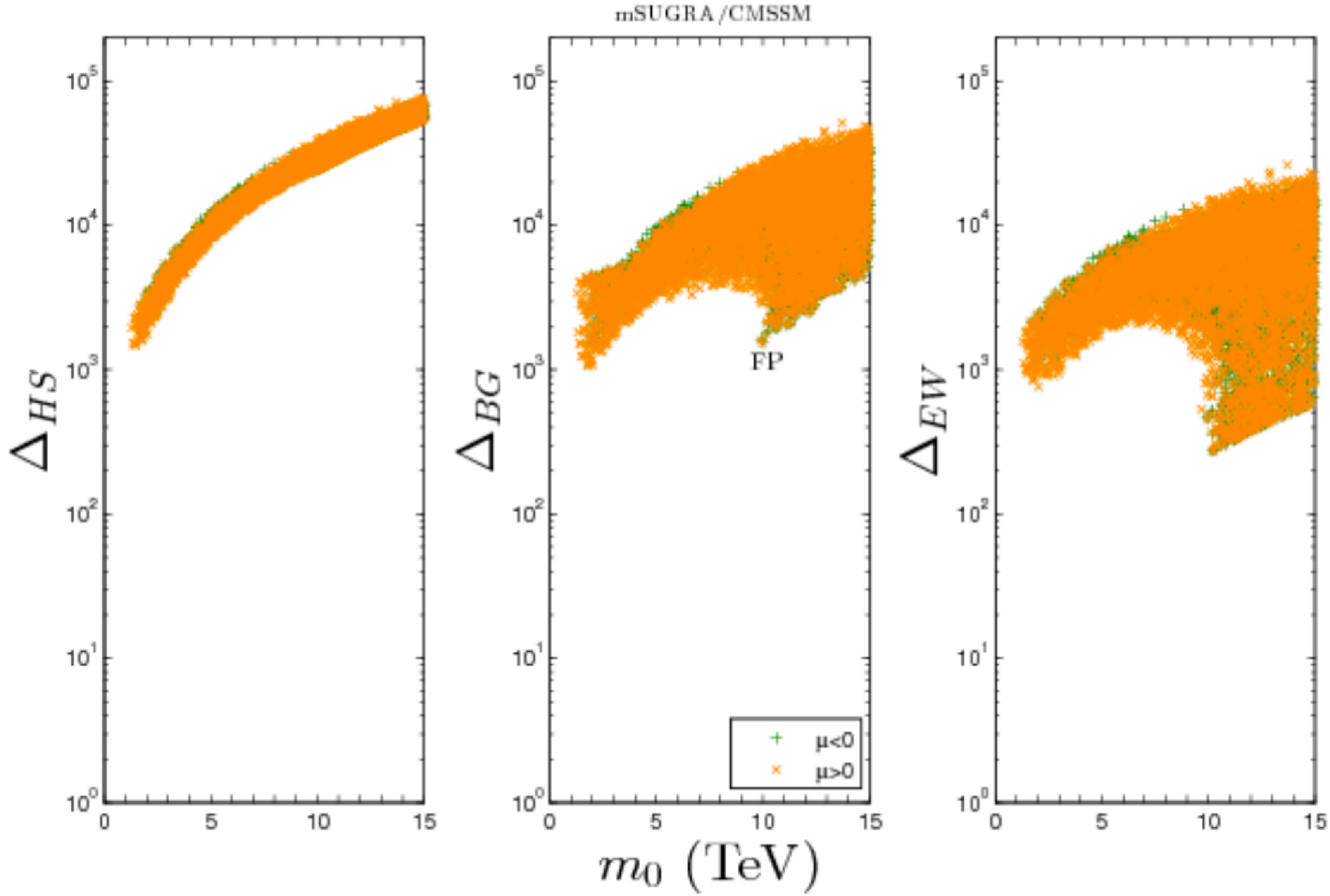
$$\Delta_{\rm BG} = max_i|c_i| \equiv max_i \left| \frac{a_i}{M_Z^2} \frac{\partial M_Z^2}{\partial a_i} \right|$$

- High–Scale: $\Delta_{\rm HS} \equiv max_i|B_i|/(M_Z^2/2)$

- Electroweak Scale: $\Delta_{\rm EW} \equiv max_i\,|C_i|\,/(M_Z^2/2)$

Generally $\boxed{\Delta_{\rm EW} \leq \Delta_{\rm BG} \lesssim \Delta_{\rm HS}}$

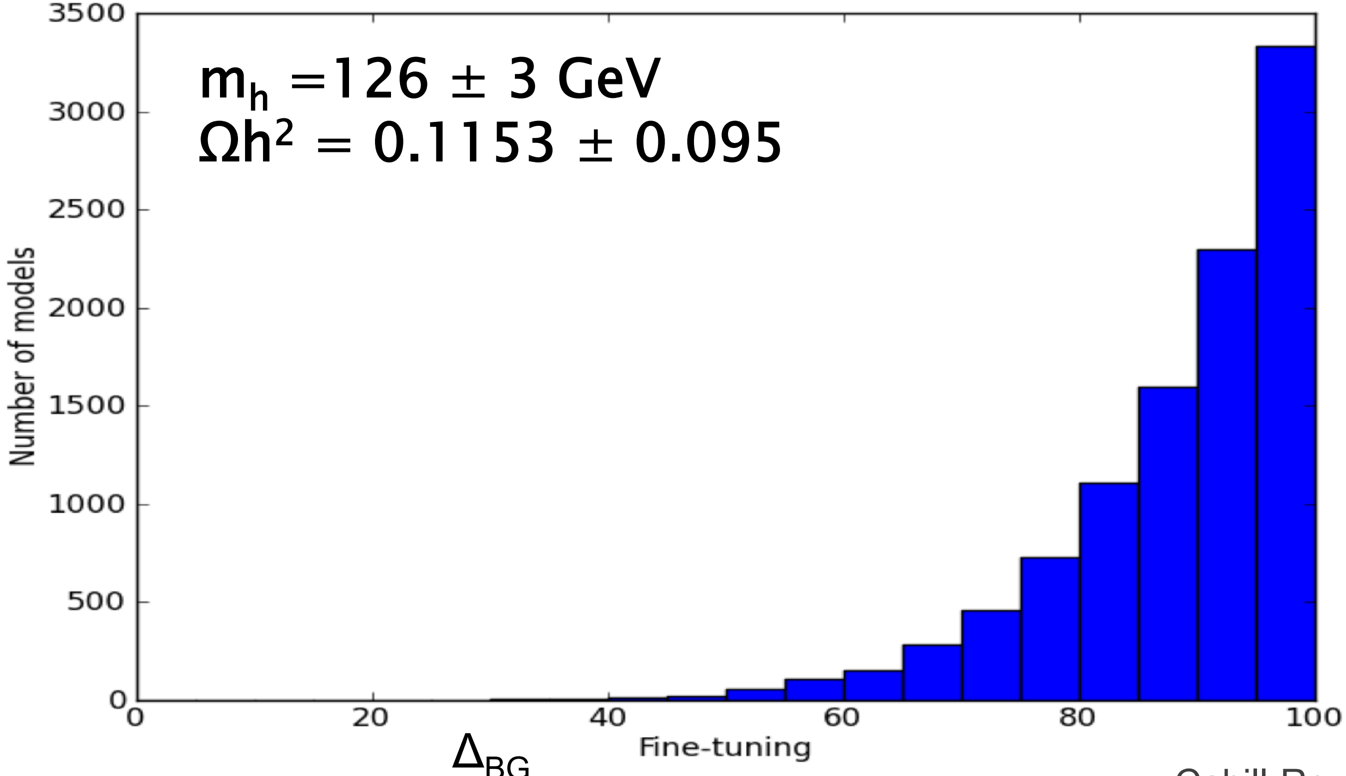
Naturalness: CMSSM



Baer etal, 1309.2984

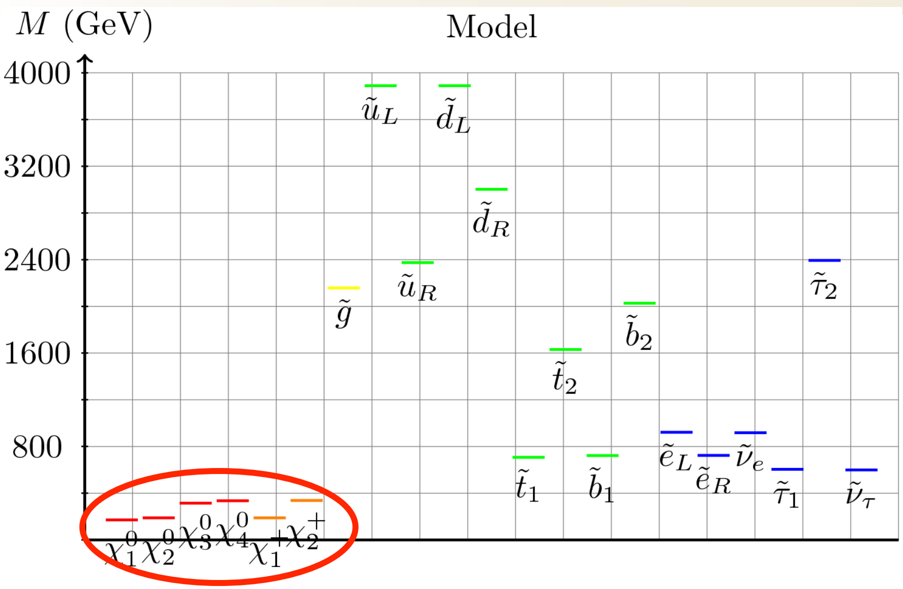
Low Fine-Tuned pMSSM Model Sample

- Generated specific pMSSM model set with low fine-tuning
- Consistent with global data set
- Barbieri-Giudice formalism

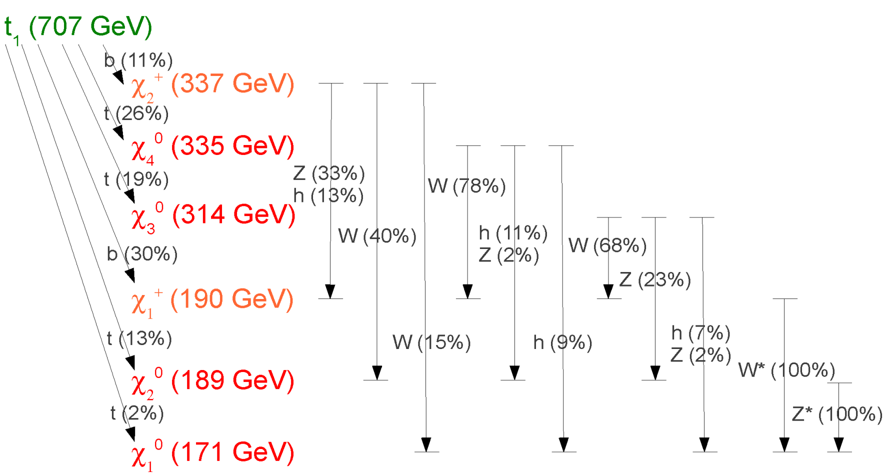


Cahill-Rowley etal, 1407.4130

pMSSM Low Fine-Tuning Sample Spectrum



Model 3010059

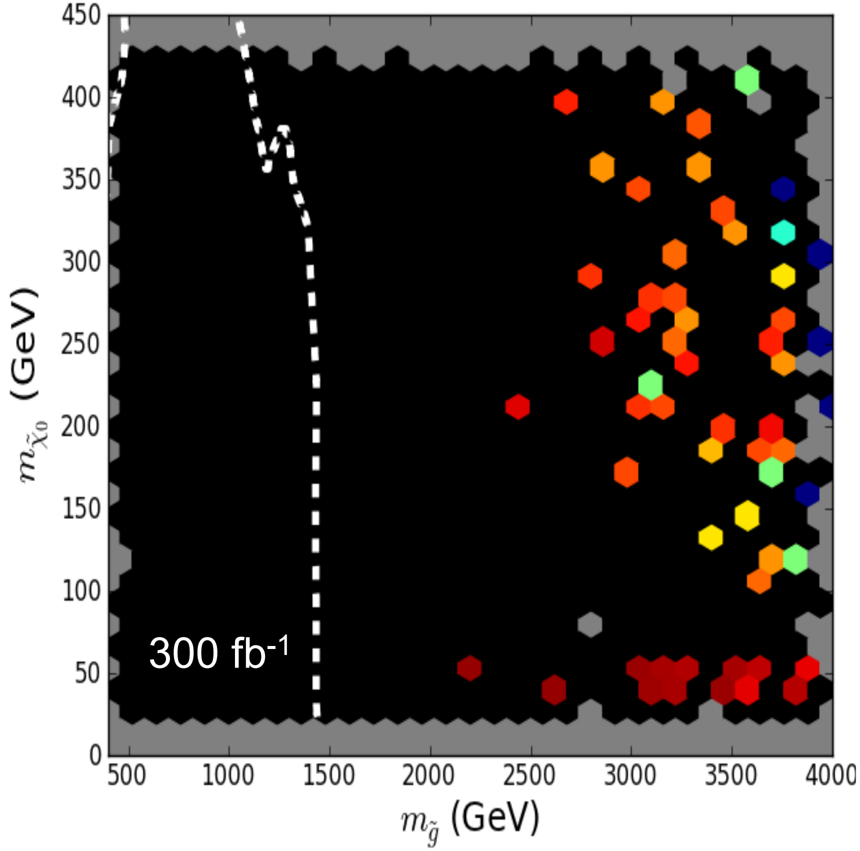


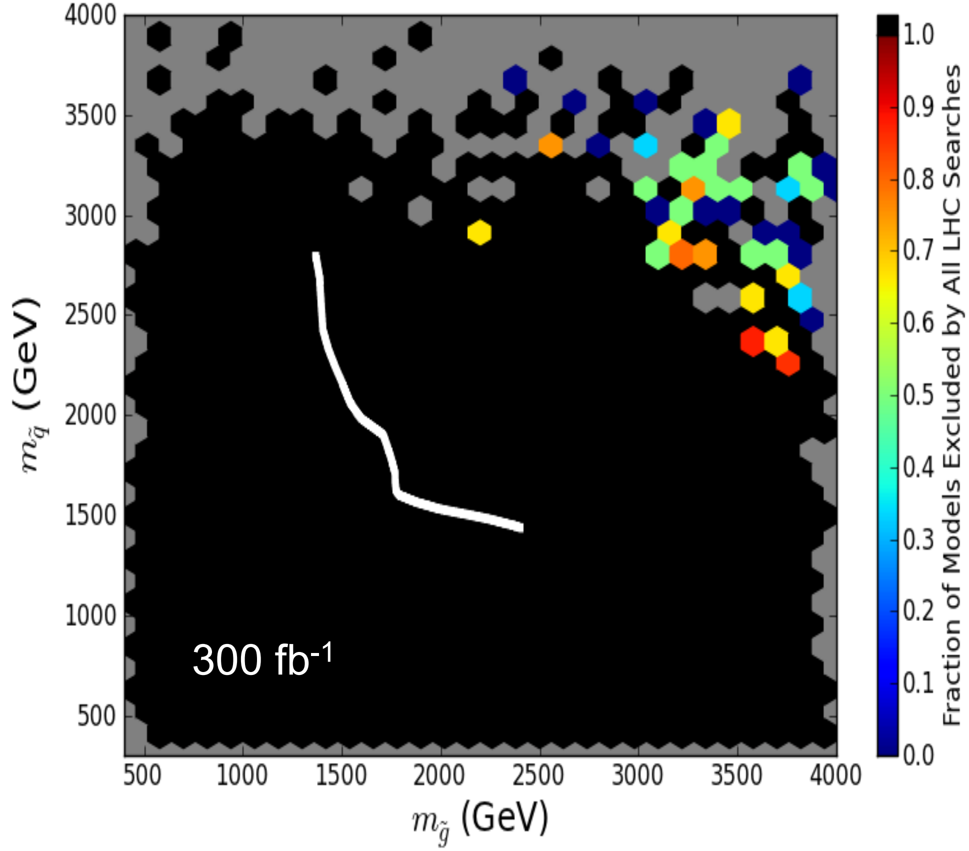
- Light stop/sbottom
- Suite of light EW gauginos

- The necessity of both a light bino for relic density, a light Higgsino & a not too heavy wino for low-FT can make the stop decays quite complex !

14 TeV Coverage of pMSSM Low Fine-Tuning Models

- Jets+MET & Stop Search (ATLAS European Strategy & Snowmass Study)
- 3 ab^{-1} covers entire set!





Maximally Natural Supersymmetry

- 5-dimensional SUSY with Scherk-Schwarz SUSY breaking at KK scale (1/R) of several TeV
- Gauginos, Higgsinos, 1st two generations of sfermions get masses of 1/2R
- 3rd family is localized on 4D brane
- Only H_u acquires a vev – no μ-term
  - » Higgs is SM-like
- Broken U(1)' raises Higgs mass, with $m_{Z'} \sim 1/R$

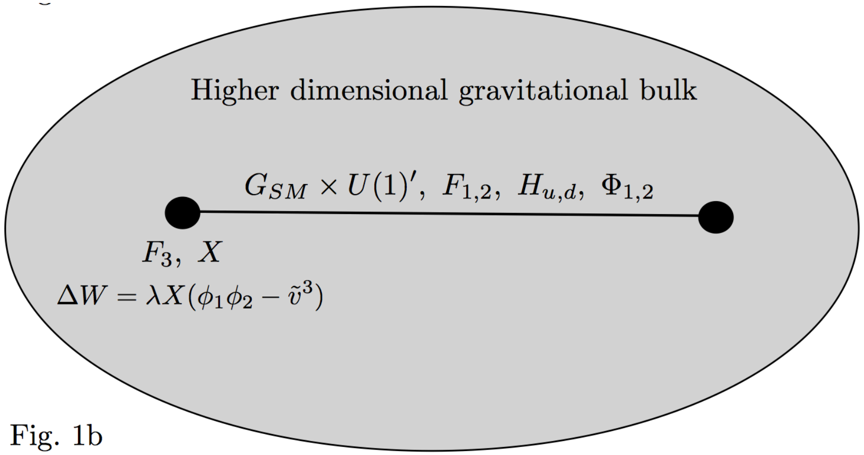
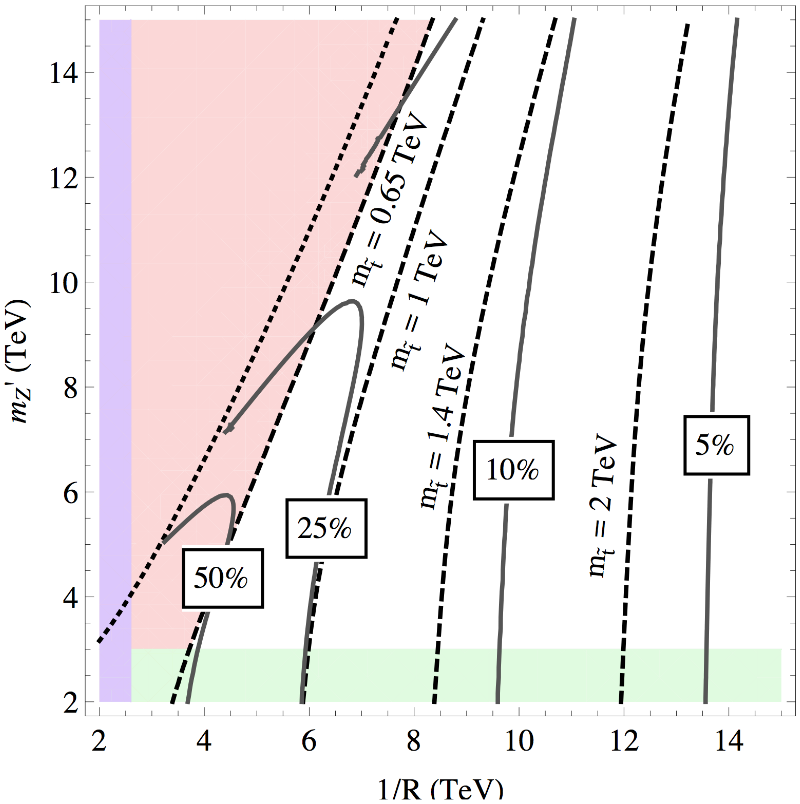


Fig. 1b

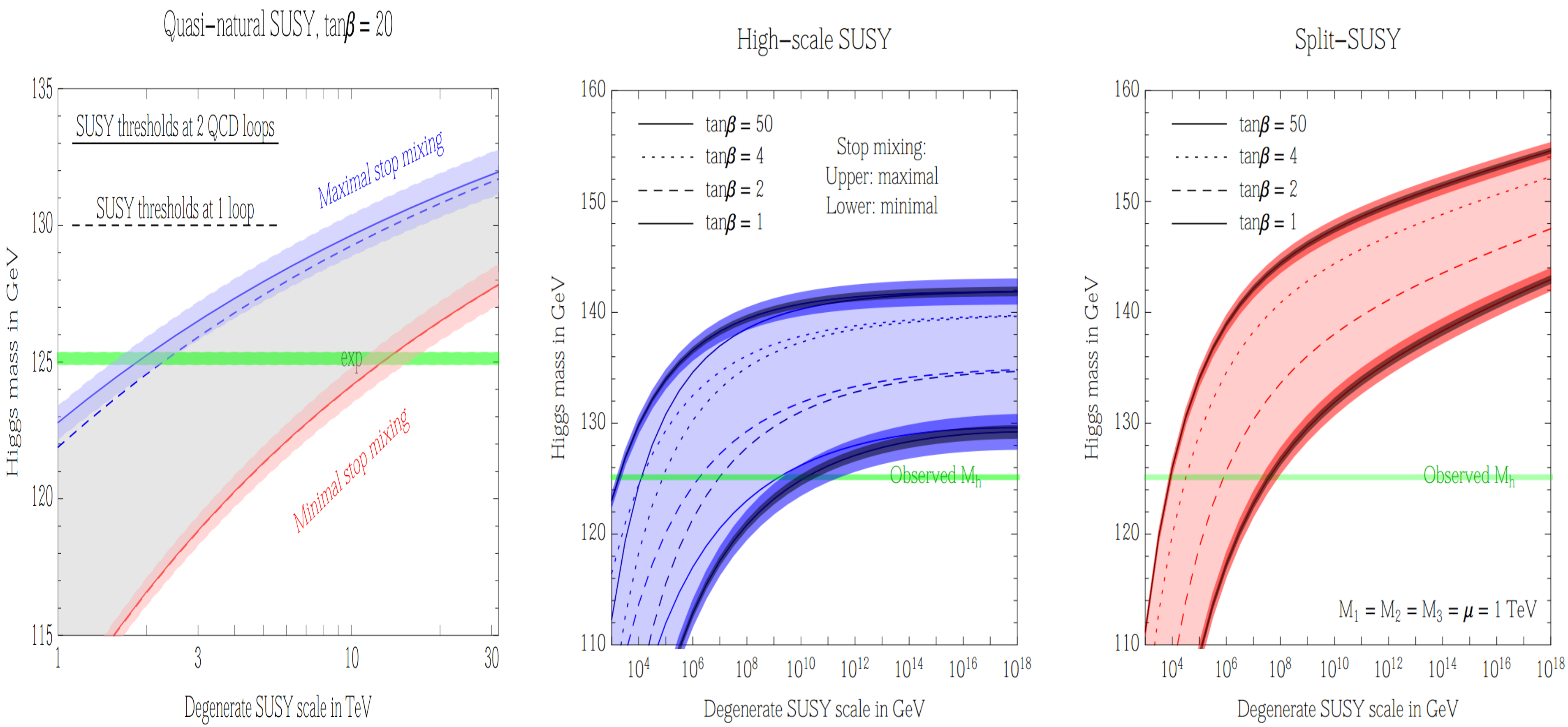
Dimopoulos, Howe, March-Russell
1404.7554



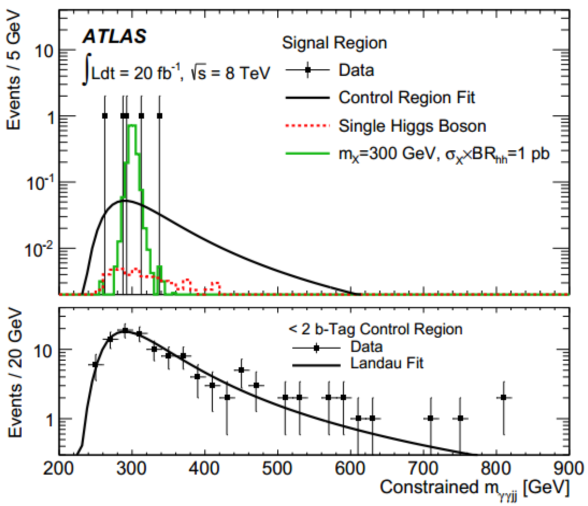
Higgs Mass and Unnatural Supersymmetry

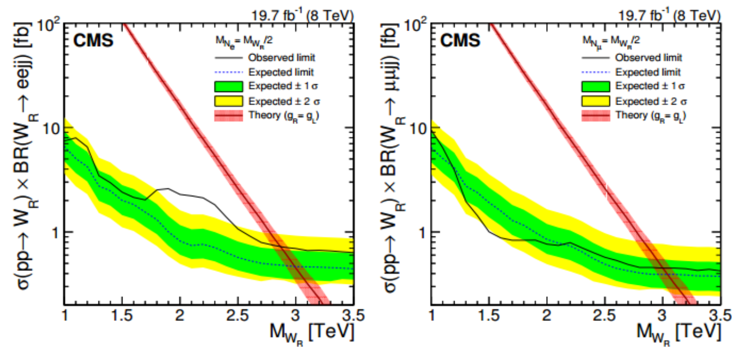
- High-scale or Split Supersymmetry
- Compute matching conditions for Higgs mass with high intermediate SUSY scale

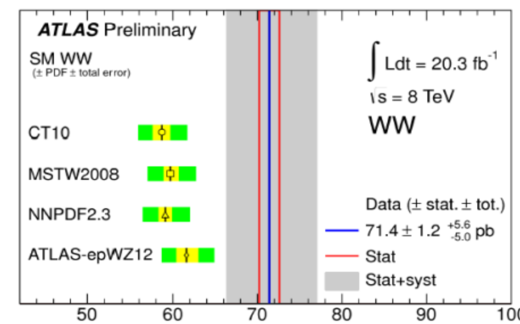
Bagnaschi, Giudice, Slavich, Strumia
1407.4081



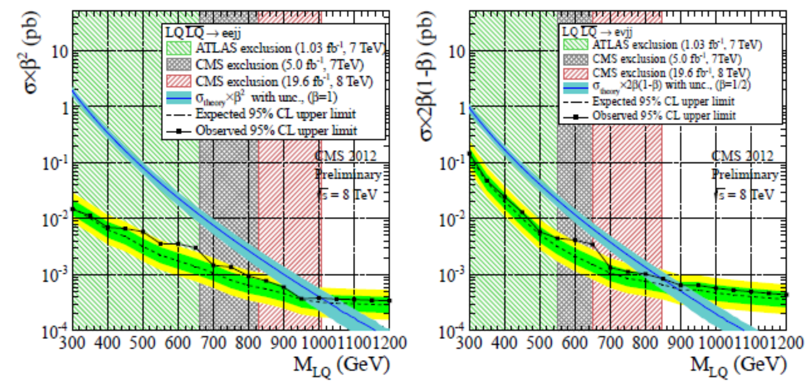
No Sign of SUSY or any other New Physics…

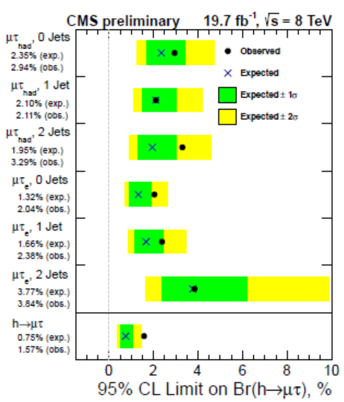


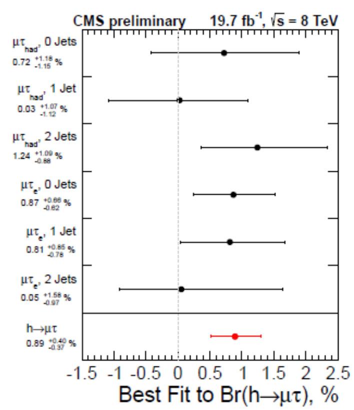




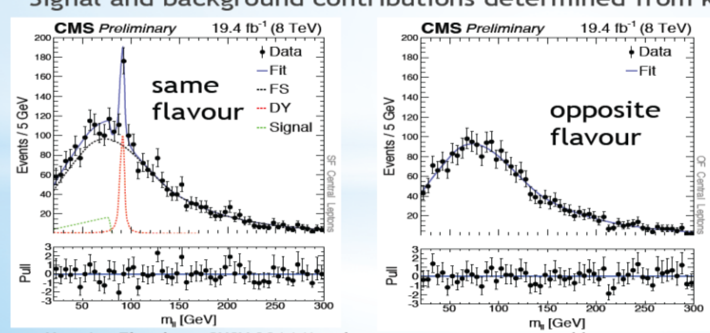
…or is there??







* Signal and background contributions determined from kinematic fit



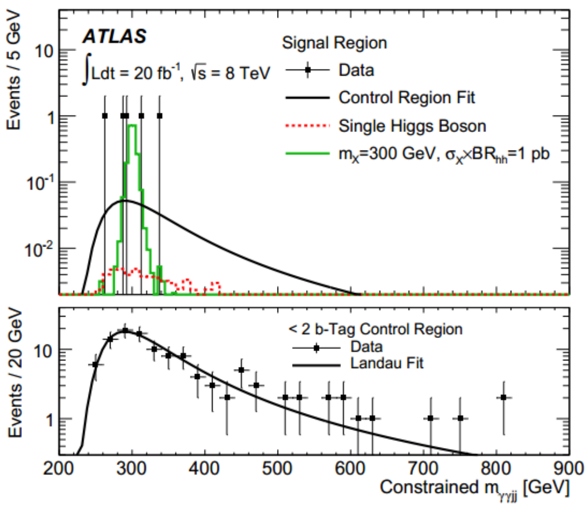
Signal as triangular shape convolved with Gaussian:

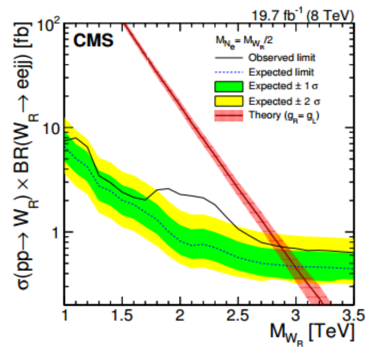
$$\mathcal{P}_S(m_{\ell\ell}) = \frac{1}{\sqrt{2\pi}\sigma_{\ell\ell}} \int_0^{m_{\ell\ell}^{edge}} y \cdot \exp\left(-\frac{(m_{\ell\ell}-y)^2}{2\sigma_{\ell\ell}^2}\right) dy.$$

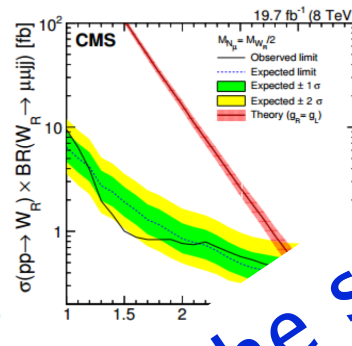
	Central	Forward
Drell–Yan	158 ± 23	71 ± 15
Flav. Sym. [OF]	2270 ± 44	745 ± 25
$R_{SF/OF}$	1.03	1.02
Signal events	126 ± 41	22 ± 20
$m_{\ell\ell}^{edge}$ [GeV]	78.7 ± 1.4	

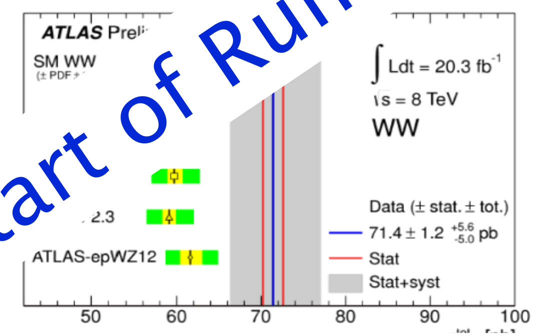
Henning Flaecher - SUSY 2014 Manchester 41 23rd July 2014

No Sign of SUSY or any other New Physics…



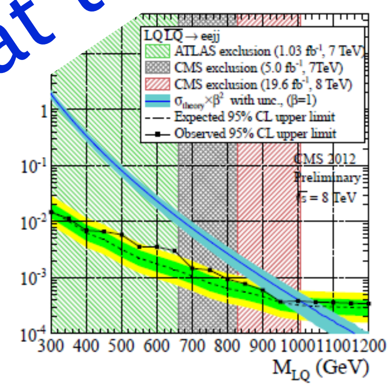


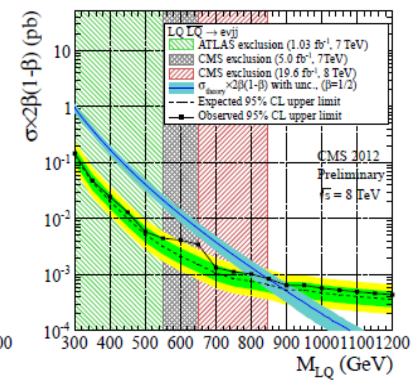


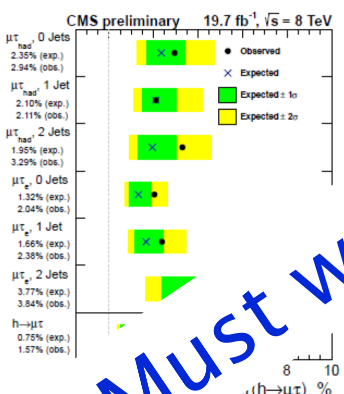


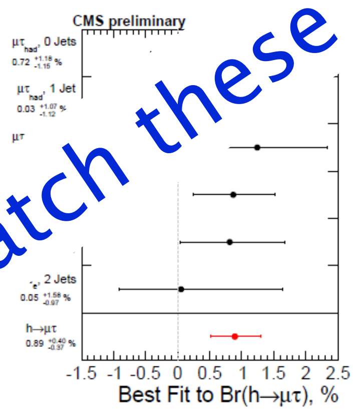
…or is the…

Must watch these anomalies at the start of Run 2!

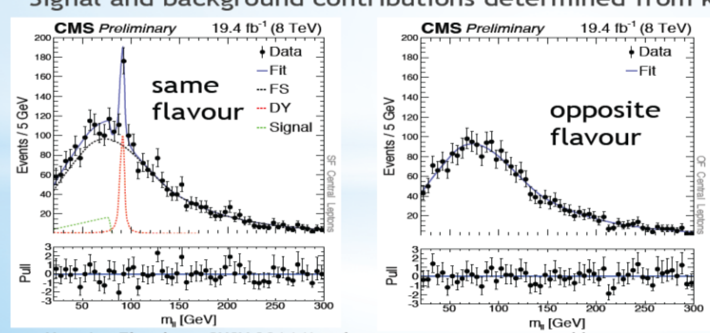








* Signal and background contributions determined from kinematic fit



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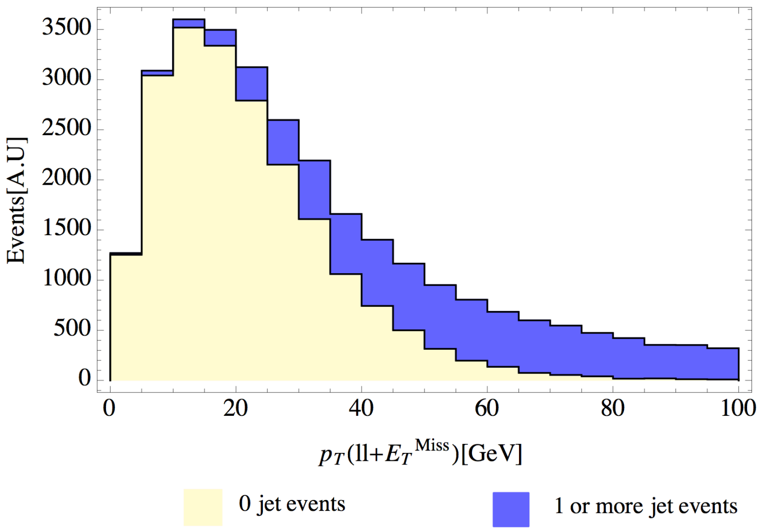
Anomaly: High WW cross section(?)

- Several potential explanations



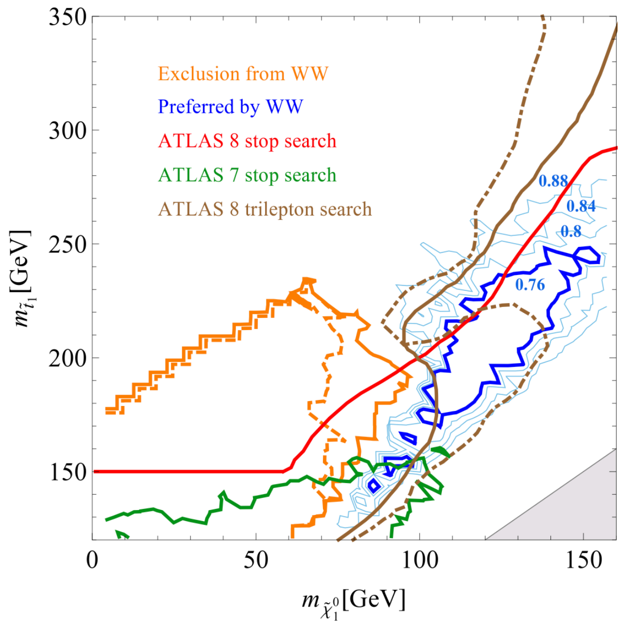
Jet-veto in SM WW production

Meade, Ramani Zeng, 1407.4481

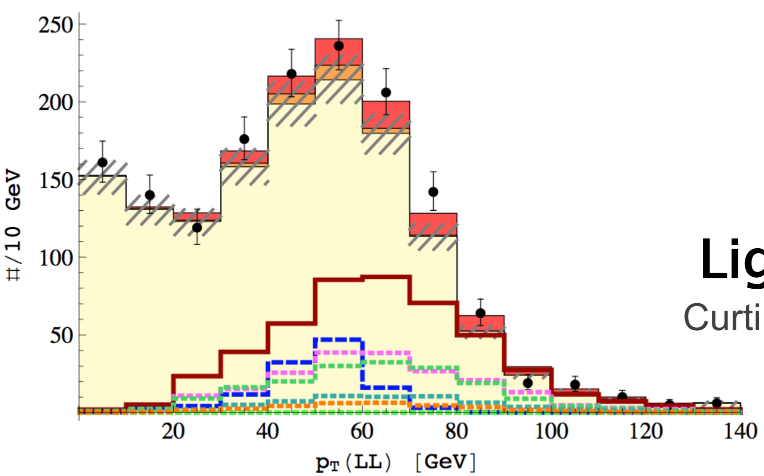
It's part of science to have this type of discussion!

Light Stops

Curtin, Meade, Tien, 1406.0848



(c) CMS 8 TeV 3.5 fb^{-1} [20]

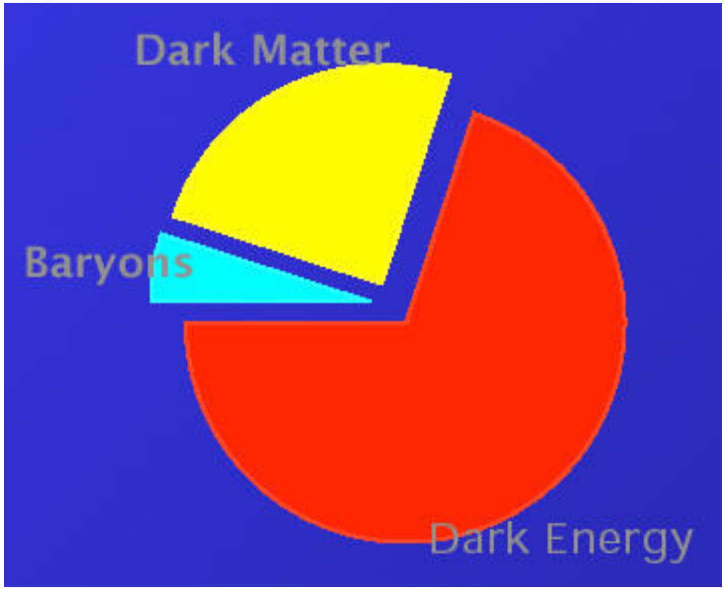


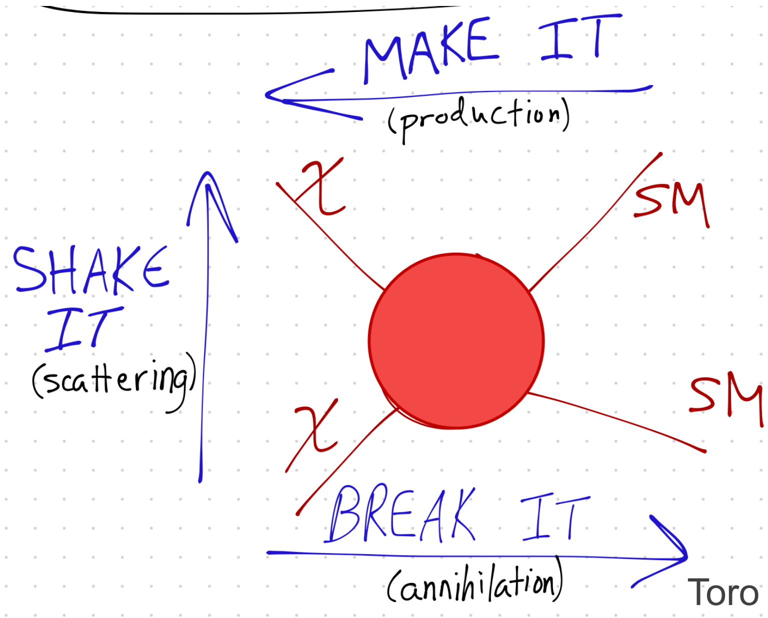
Light Charginos

Curtin, Jaisal, Meade, 1206.6888

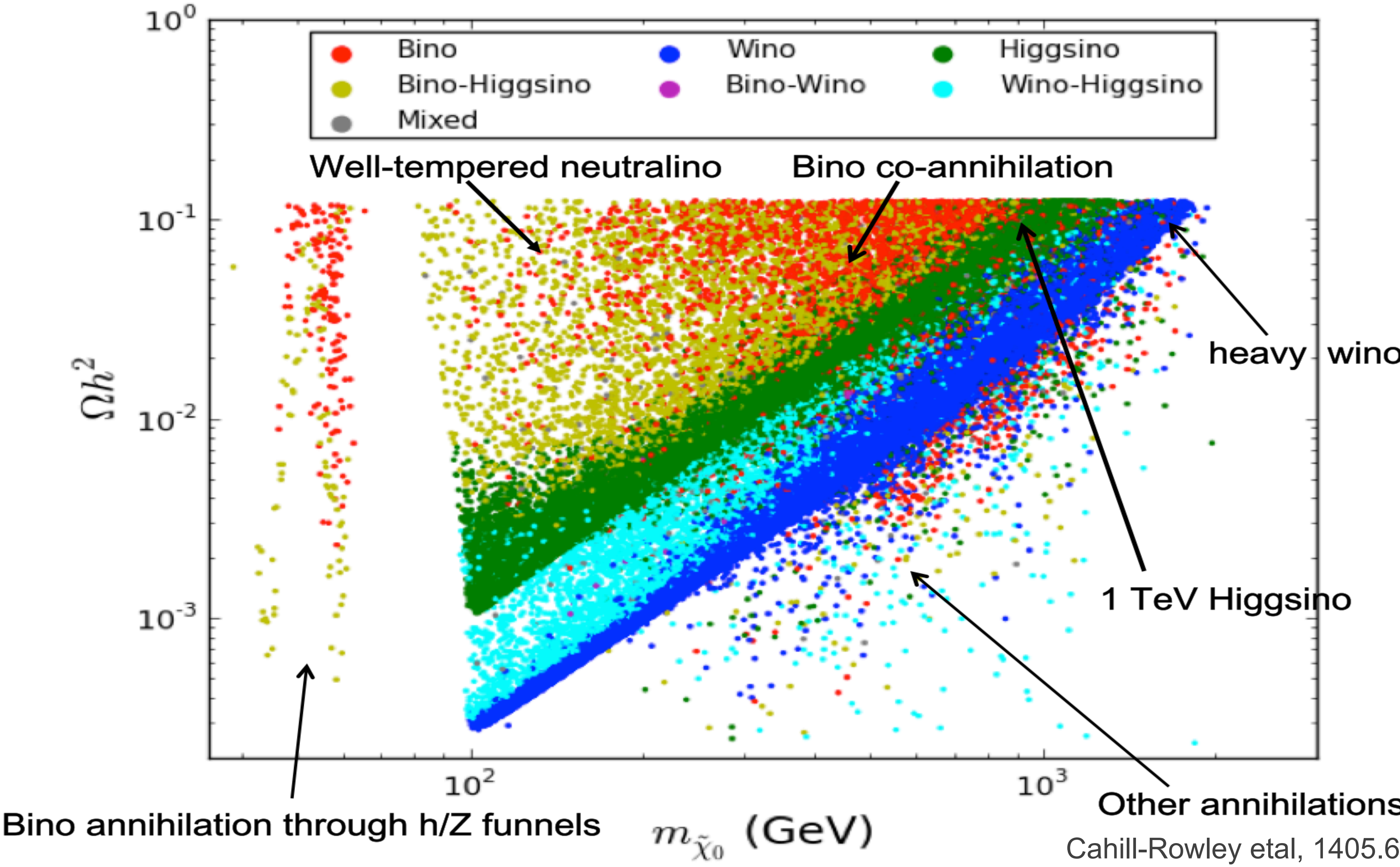
Dark Matter

- ~85% of the matter in the universe!
- New physics that we know exists!
- WIMP miracle
- Unitarity sets upper bound on DM mass ~tens of TeV





Dark Matter in Supersymmetry

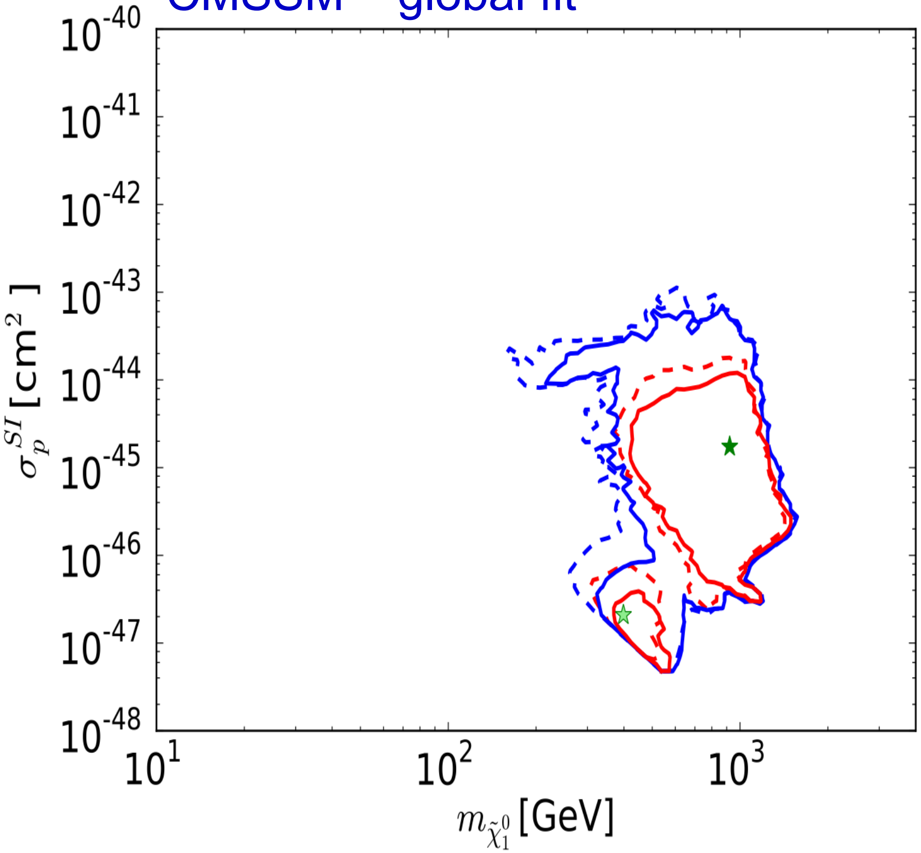


Cahill-Rowley etal, 1405.6716

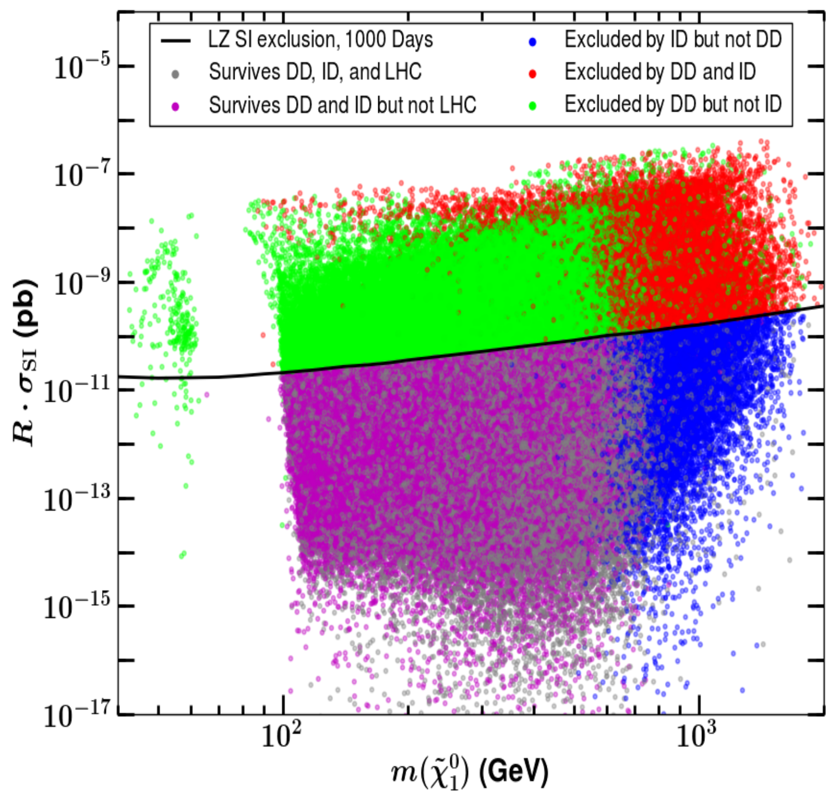
Direct Detection in the MSSM

- Spin-independent cross section

CMSSM – global fit



pMSSM



Buchmueller etal, 1312.5250

Cahill-Rowley etal, 1405.6716

Indirect Detection of Dark Matter

A Number of Unexplained or Ambiguous Observations Persist:

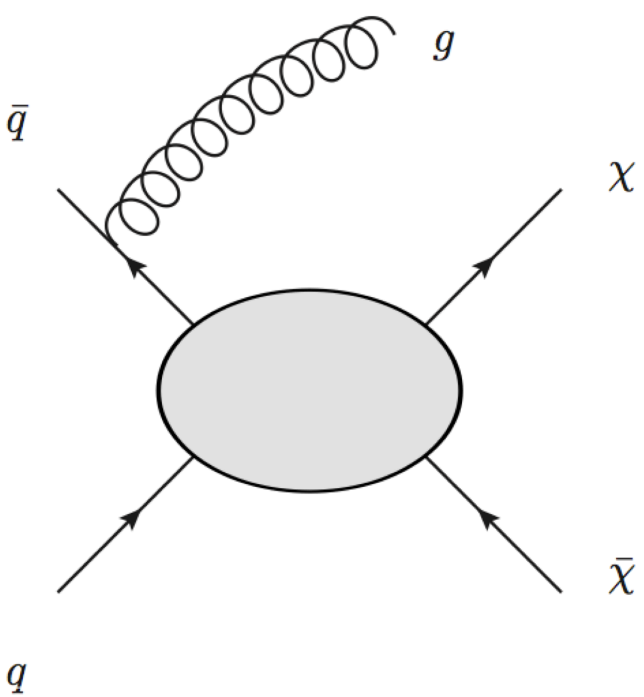
- Excess 511 keV emission from Galactic Bulge (INTEGRAL)
- Excess high-energy cosmic ray positrons (PAMELA, AMS)
- Excess isotropic radio emission (ARCADE, etc.)
- 130 GeV line from the Galactic Center (Fermi)
- 3.5 keV line from Galaxy Clusters (XMM-Newton, Chandra)
- Excess GeV emission from the Galactic Center (Fermi)

Any of these signals could plausibly be the result of annihilating/decaying dark matter particles (although most probably are not)

Stay Tuned!

Dark Matter at the LHC: Mono–Whatever

We want to use **The LHC** (an experiment) to bound DM interactions with **The SM** (some SM particles) and to compare these limits with those from **Direct/Indirect Detection** (another experiment) on these same interactions.



- Mono–jet
- Mono–photon
- Mono–W/Z
- Mono–Higgs
- Mono–everything!

Dark Matter Effective Theory

- Dark Matter is only state accessible to exp't
- Mediating particles are heavy compared to exp't energies

Example: Majorana WIMP

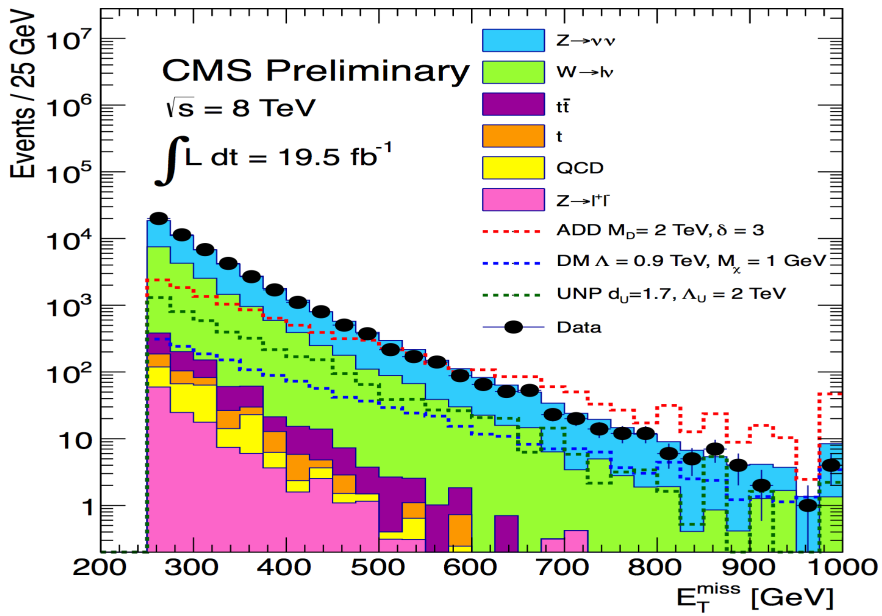
- Described by 10 operators with Lorentz and $SU(3) \times U(1)_{EM}$ invarianant coupling to quarks & gluons
- Strength of operator is parametrized by M_*

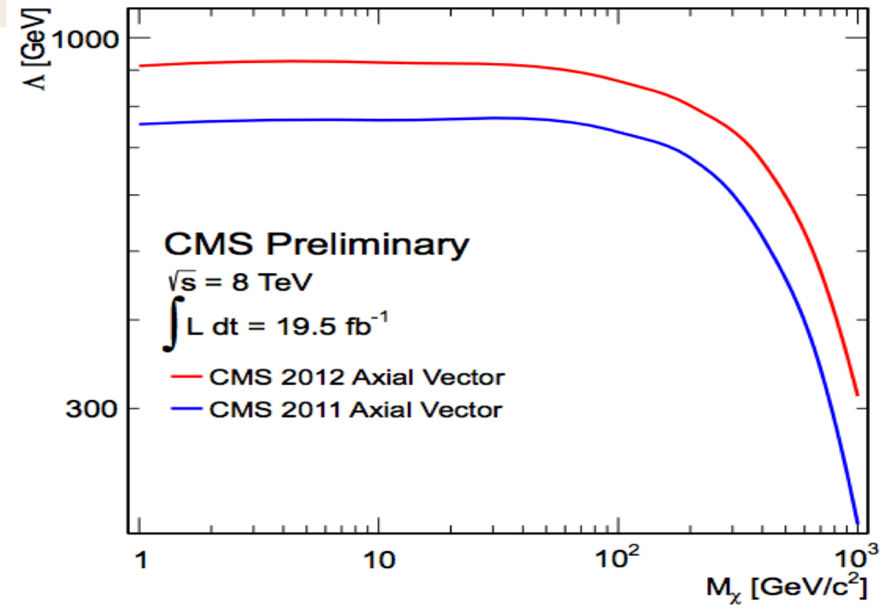
Majorana WIMP operators

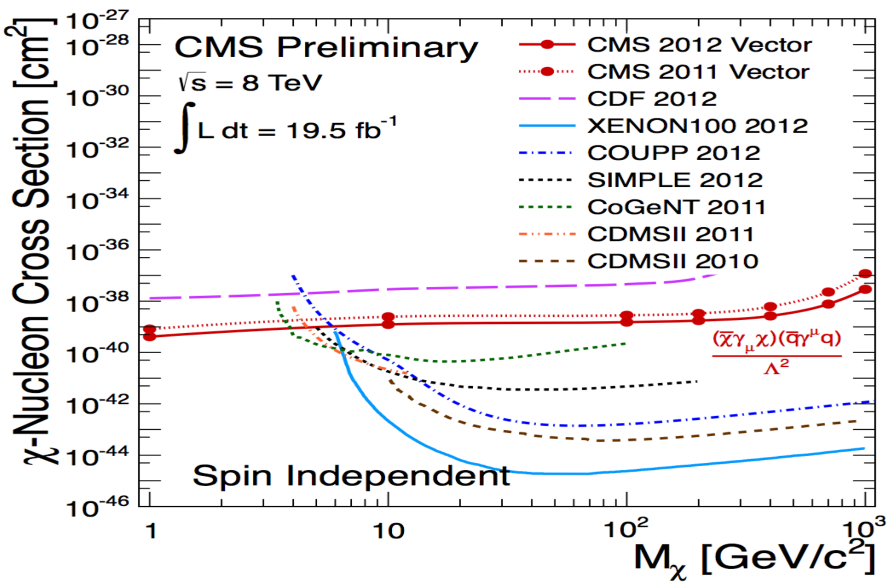
Name	Type	G_χ	Γ^χ	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

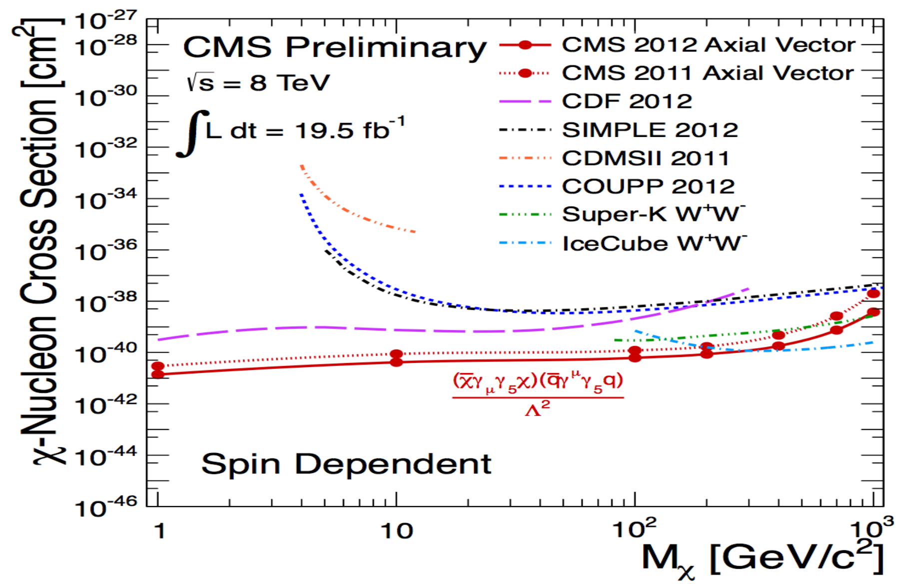
Goodman etal, 1005.1286

DM Effective Theory: Collider Results





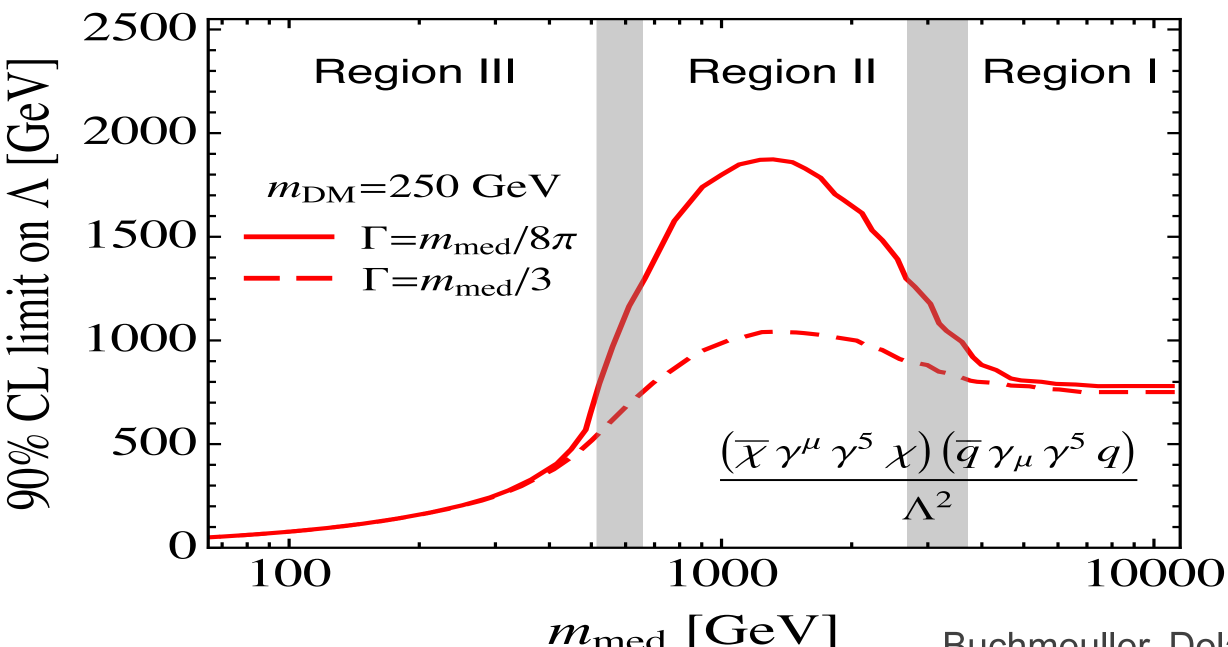




Validity of Effective Theory

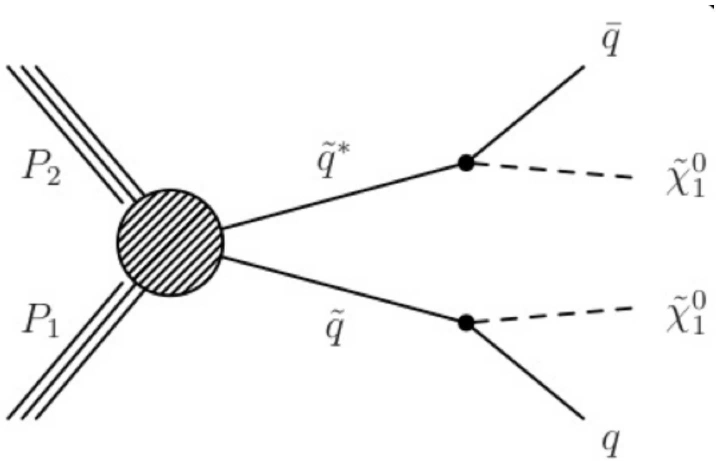
- Collision energy can be > bounds on scale of contact interactions!

  $M_{med} >> E_{CM}$, the correct limit is obtained
  $M_{med} \sim E_{CM}$, the limit is underestimated
  $M_{med} << E_{CM}$, the limit is overestimated



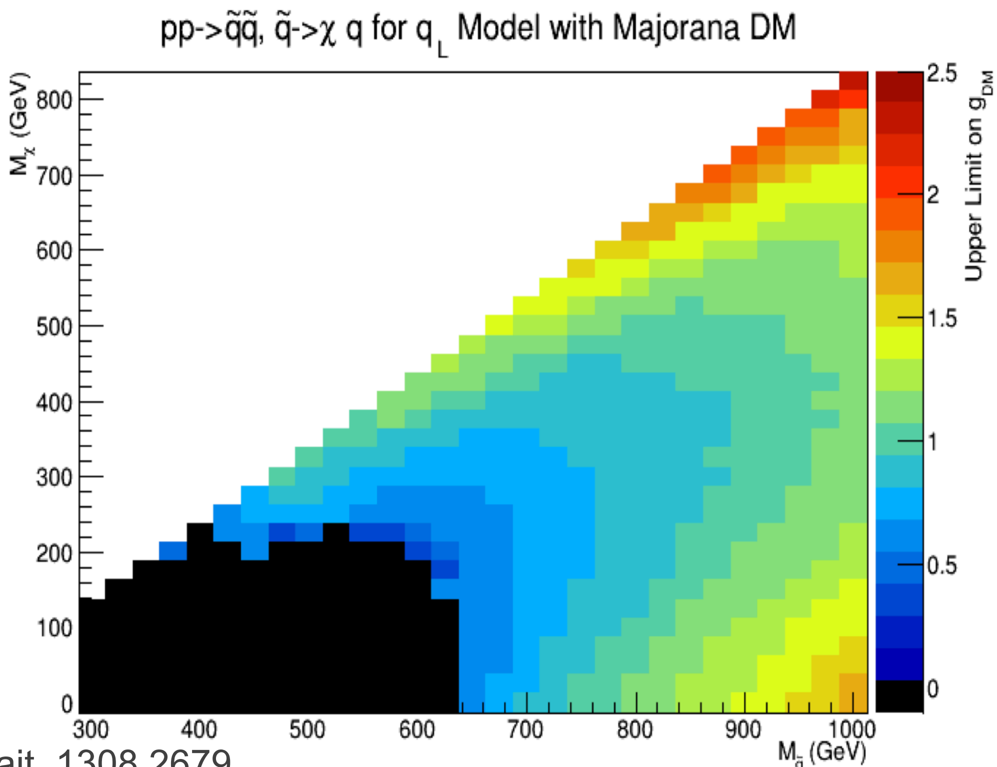
Buchmeuller, Dolan, McCabe, 1308.6799

Simplified Model of Dark Matter



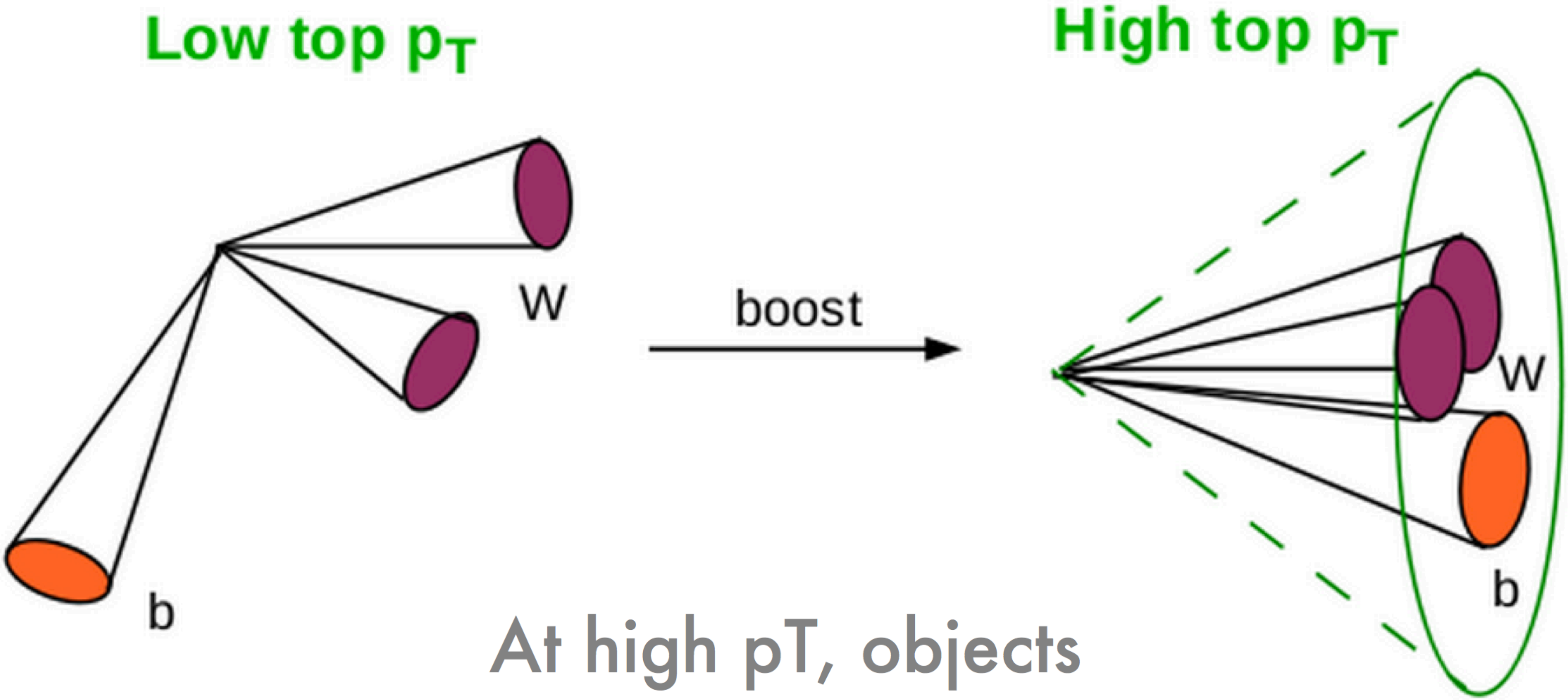
- Heavy squark Mediator
- Strong collider bounds for Majorana DM!

- Collider bounds compete with those from direct detection
- Can forecast the largest possible Spin-Dependent cross sections



DiFranzo, Nagao, Rajaraman, Tait, 1308.2679

Why Jet Sub-structure?



At high pT, objects get boosted and become closer together

Boost

- Boosted techniques are essential for every analysis in this talk!
  - Increase signal statistics
  - Extend discovery reach
- Higgs interactions with heavy quarks
- Diboson production at high p_T
- Search for new physics
- Mono-whatever
- Simplified Dark Matter models
- Plus many, many more!!

- Don't forget $\sqrt{s} = 100$ TeV, where everything is boosted!

Prospects for Run 2

- Determination of Higgs properties is key
- Continue search for new physics
- Watch present anomalies closely

There is MUCH discovery space left!!

Looking forward to data from Run 2 at 13/14 TeV!

Discoveries await!