University of BRISTOL

Searches for New Physics at the LHC

Jim Brooke, University of Bristol

IoP HEPP/APP conference, 2018

Beyond the Standard Model

Nature of dark matter ?

Unification of forces ?

Origin of EWSB ?

Naturalness vs fine-tuning ?

Are particles elementary ?

Origin of matter in the Universe ?

Why 3 families ?

Gravity ?

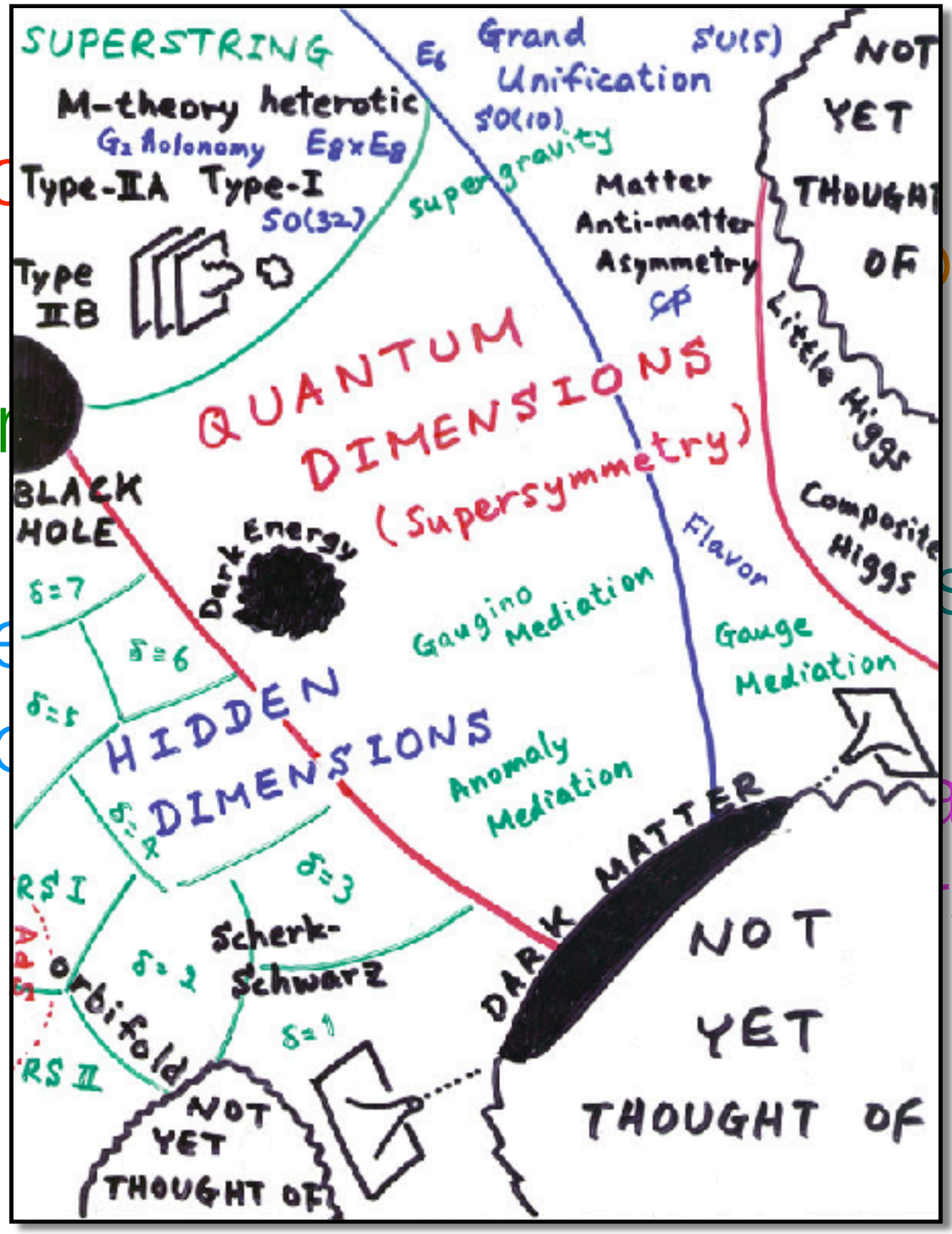
Beyond the Standard Model

Nature of d

Origi

Naturalne
hierarchy pro

Why 3



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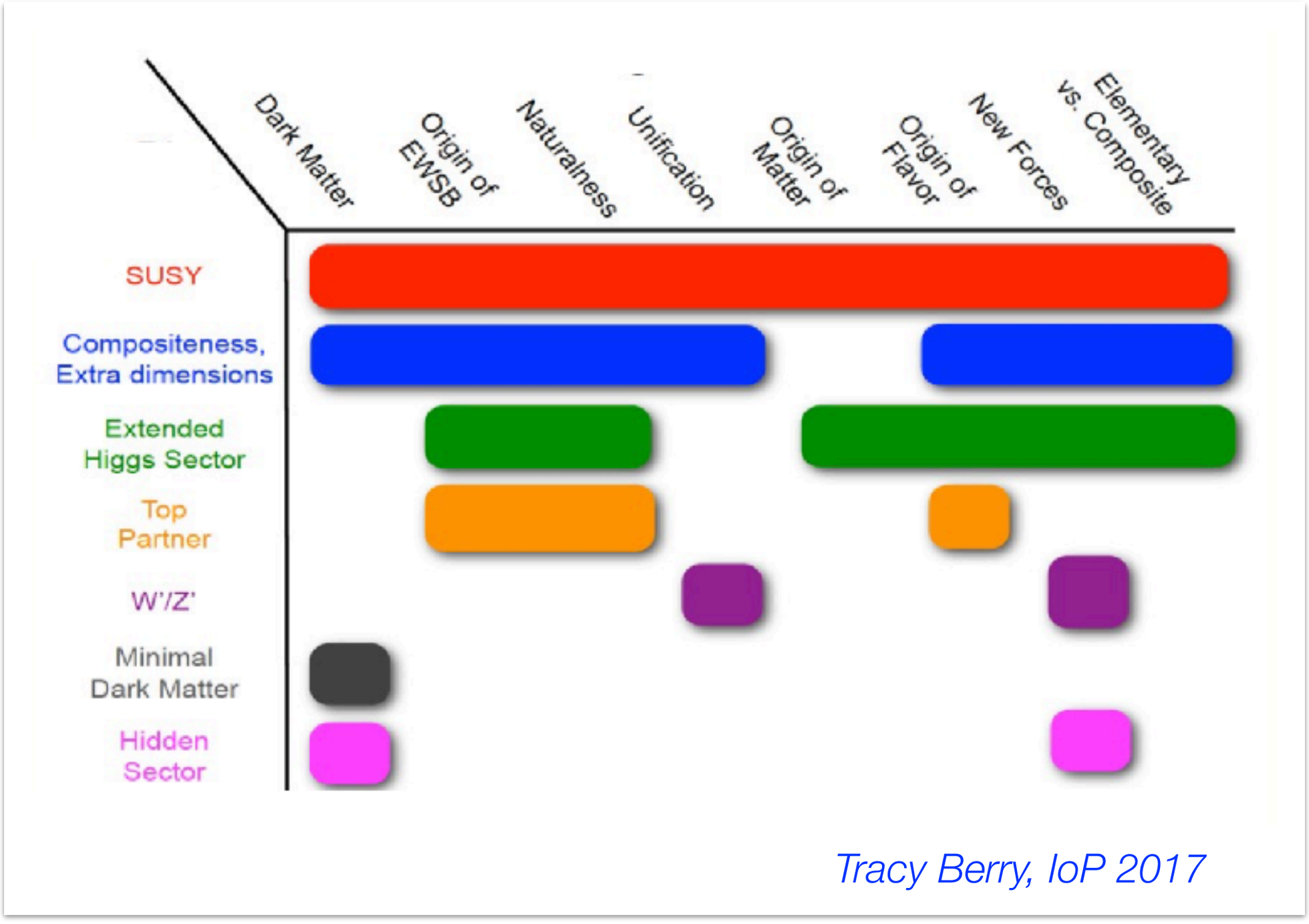
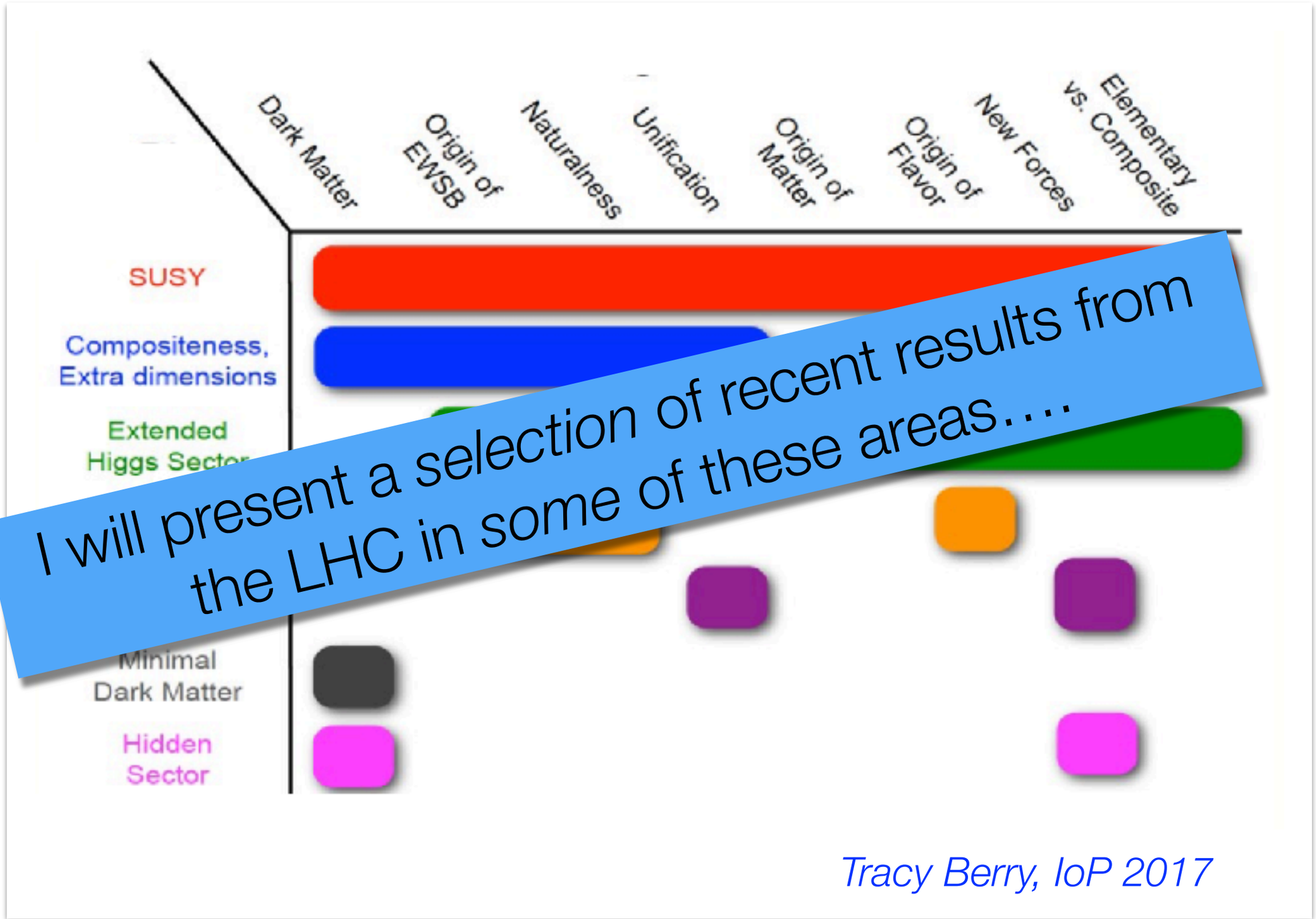
Beyond the Standard Model



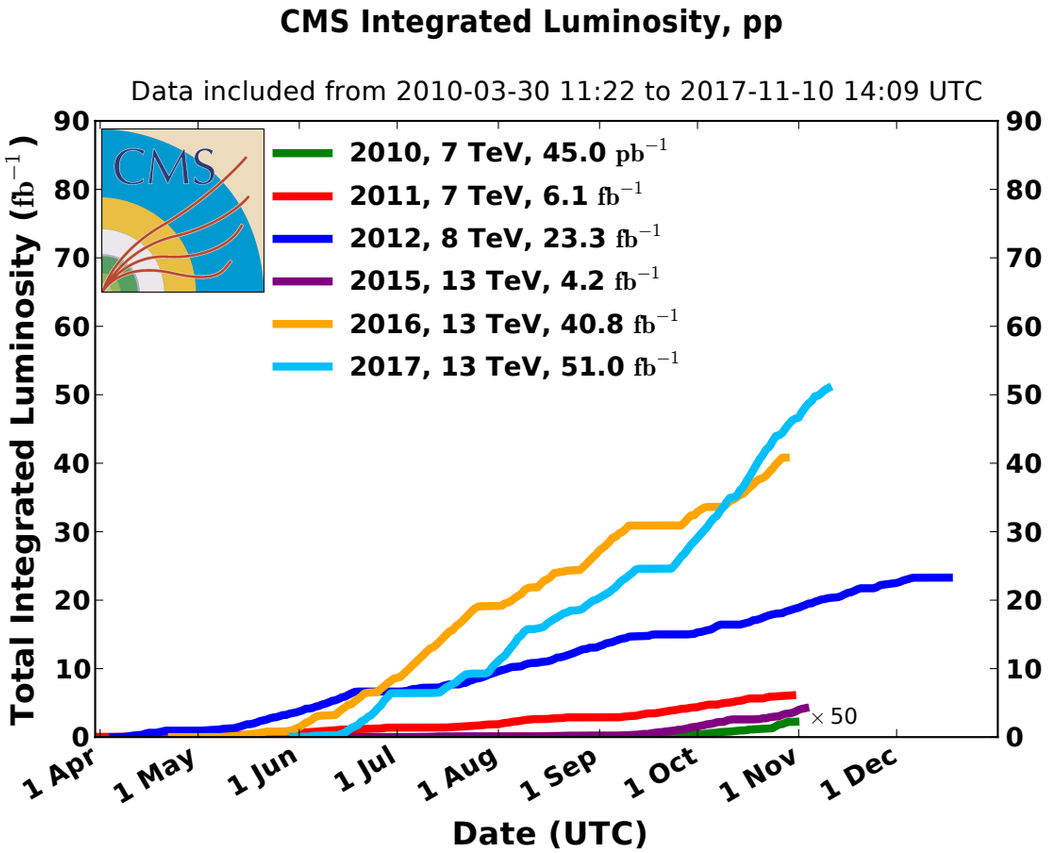
Tracy Berry, IoP 2017

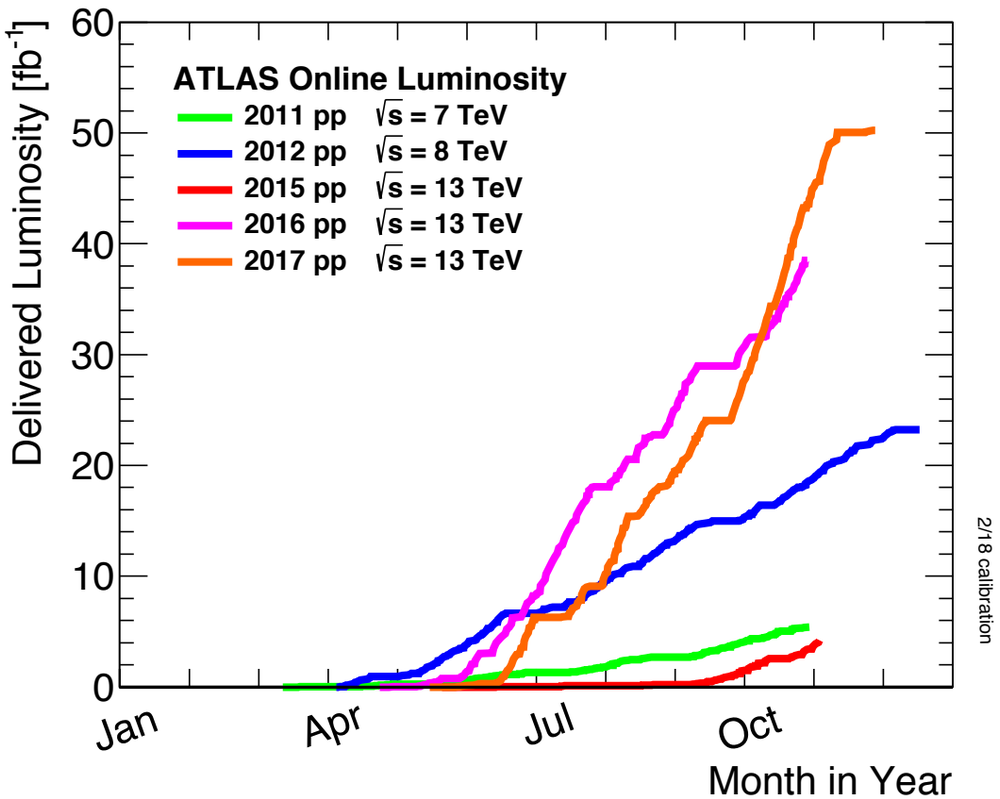
Beyond the Standard Model



Tracy Berry, IoP 2017

The LHC

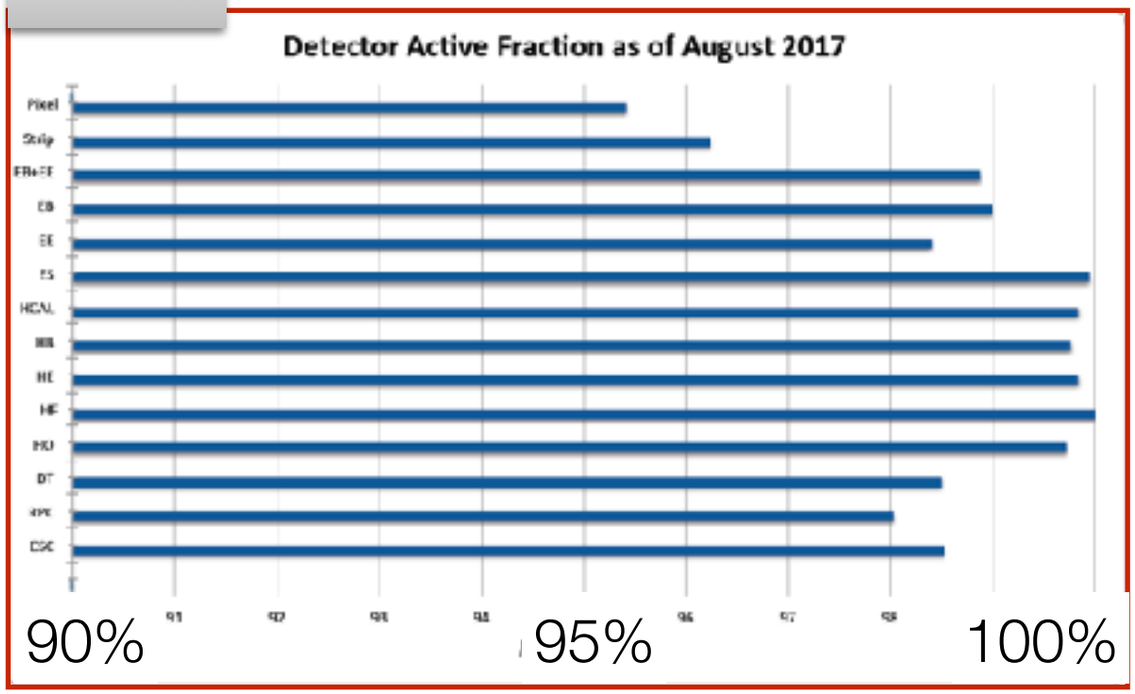




- Luminosity targets for 2017 exceeded, despite limited number of bunches due to the infamous Gruffalo
- Peak luminosity ~ 2.05×10^{34} cm^{-2}s^{-1}
- LHC has now delivered ~ 96 fb^{-1}at 13 TeV

Detector Performance

CMS



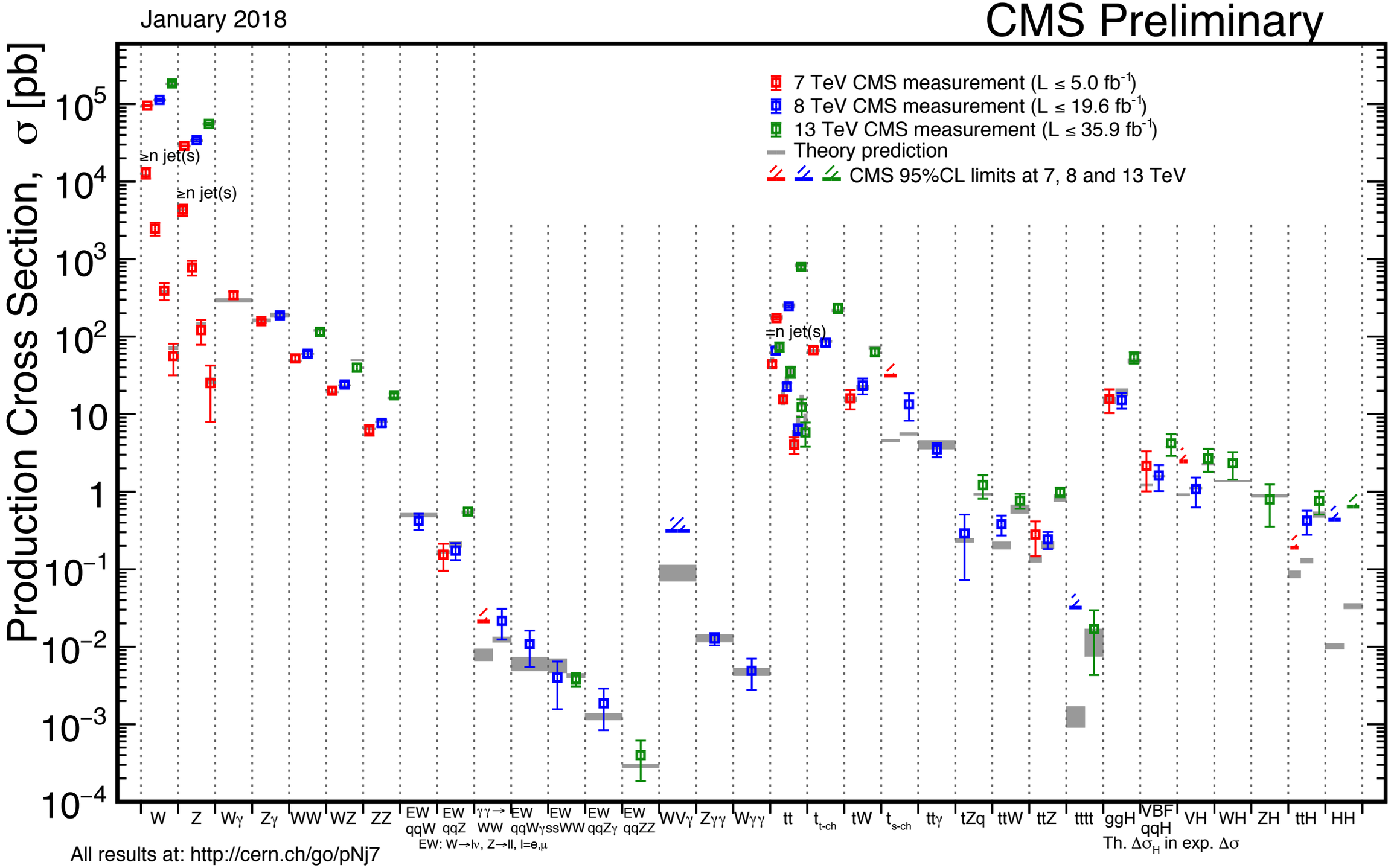
ATLAS

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	92 M	97.8%
SCT Silicon Strips	6.3 M	98.7%
TRT Transition Radiation Tracker	350 k	97.2%
LAr EM Calorimeter	170 k	100 %
Tile Calorimeter	5200	99.2%
Hadronic End-Cap LAr Calorimeter	5600	99.5%
Forward LAr Calorimeter	3500	99.7%
LVL1 Calo Trigger	7160	99.9%
LVL1 Muon RPC Trigger	383 k	99.8%
LVL1 Muon TGC Trigger	320 k	99.9%
MDT Muon Drift Tubes	357 k	99.7%
CSC Cathode Strip Chambers	31 k	95.3%
RPC Barrel Muon Chambers	383 k	94.4%
TGC End-Cap Muon Chambers	320 k	99.5%
ALFA	10 k	99.9%
AFP	430 k	93.8%

- Excellent LHC performance has been matched by the detectors
- Despite upgrades and teething problems…

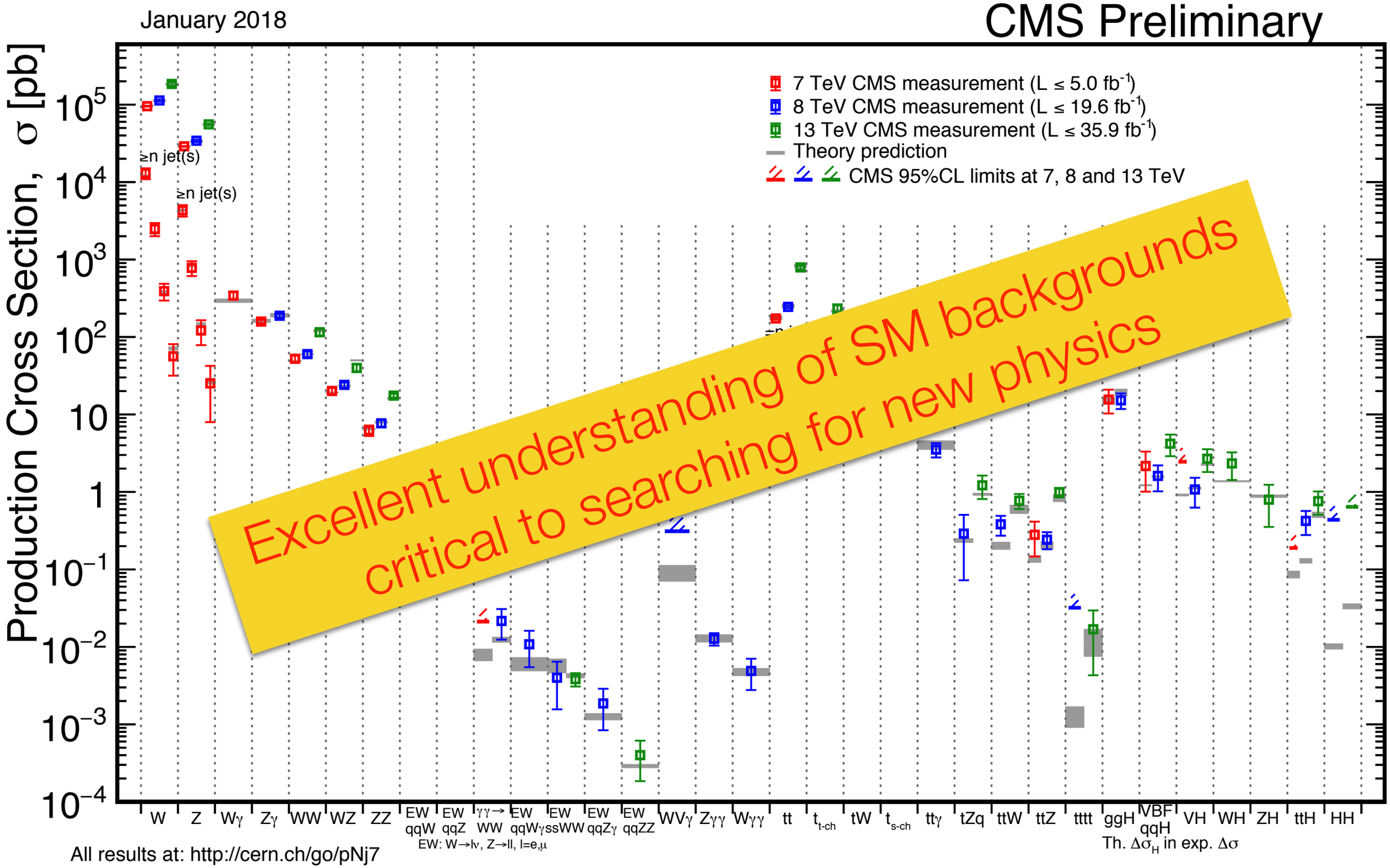
>95% channels operational in all sub-detectors in ATLAS & CMS

Standard Model



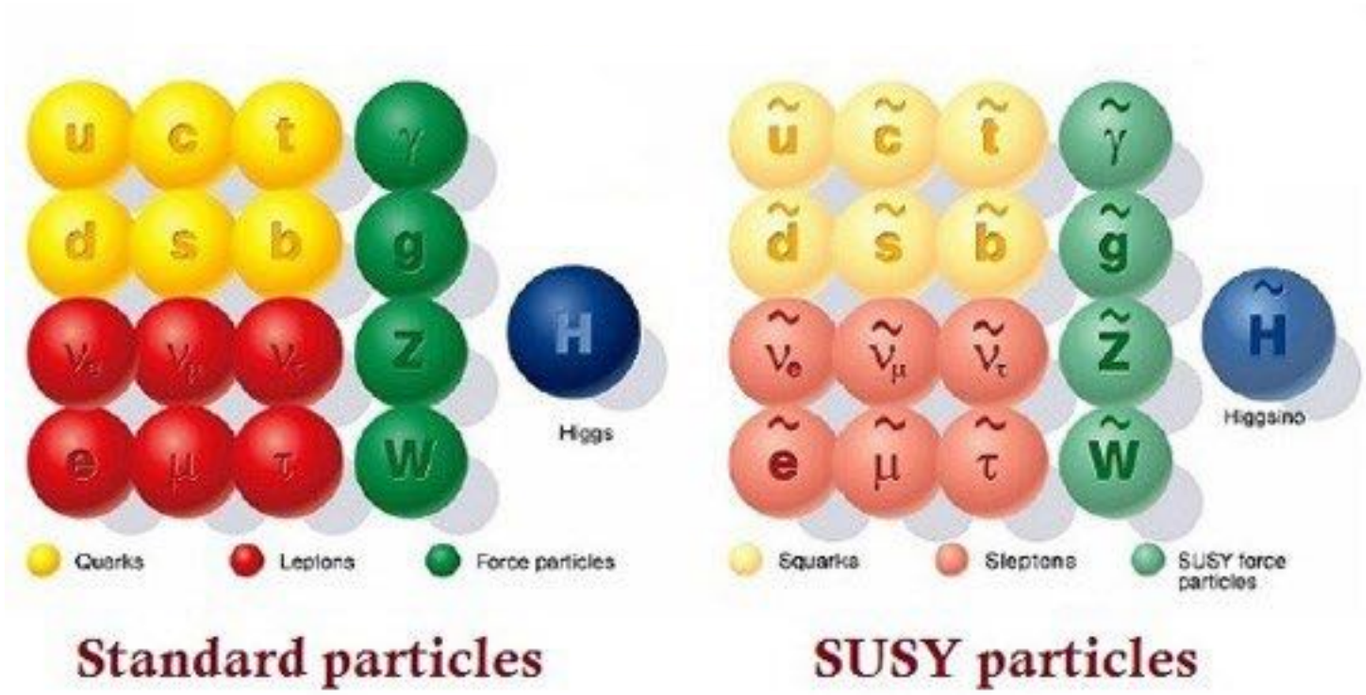
All results at: http://cern.ch/go/pNj7

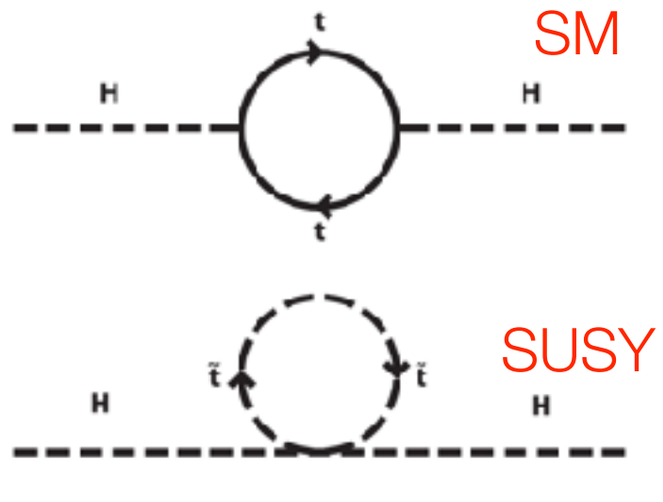
Standard Model



All results at: http://cern.ch/go/pNj7

Supersymmetry

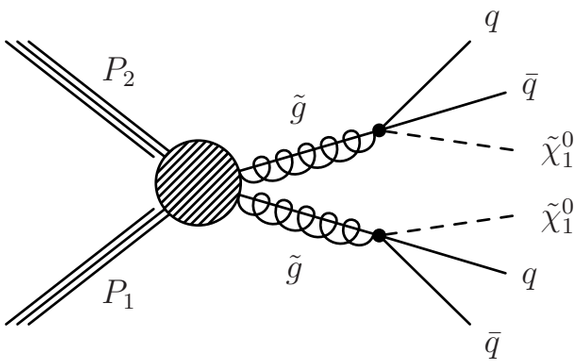


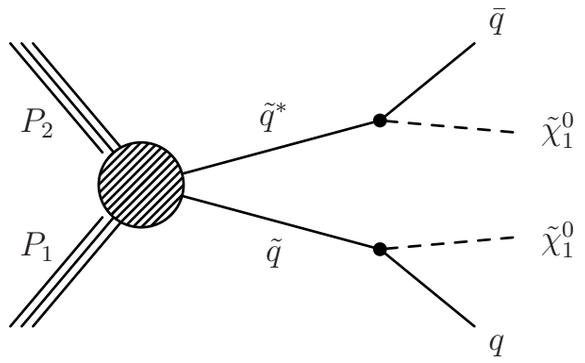


- Each SM particle has a supersymmetric partner, differing by spin 1/2
  - Cancelling divergences in Higgs propagator
  - Which otherwise require extreme fine-tuning of the bare Higgs mass

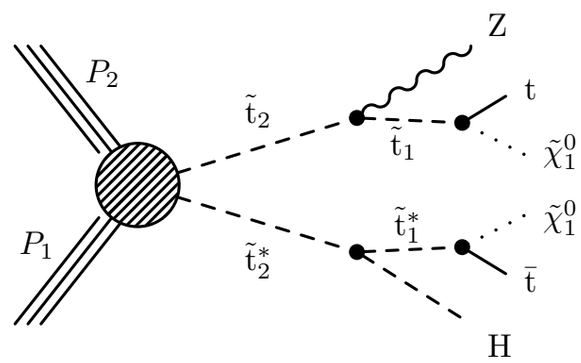
Supersymmetry

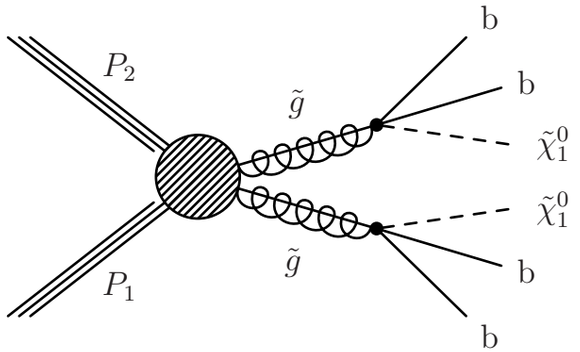
- Vast parameter space yields rich phenomenology
- Map experimental coverage using simplified models

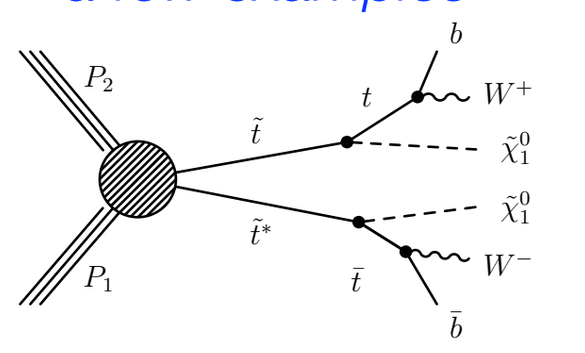


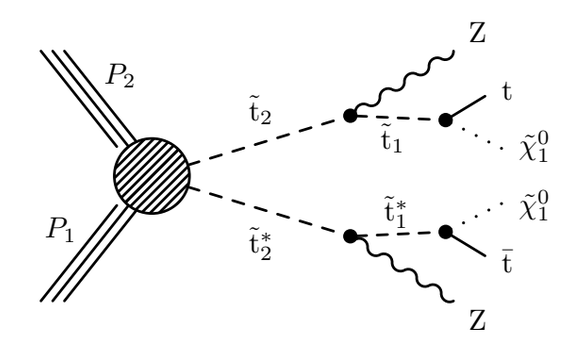


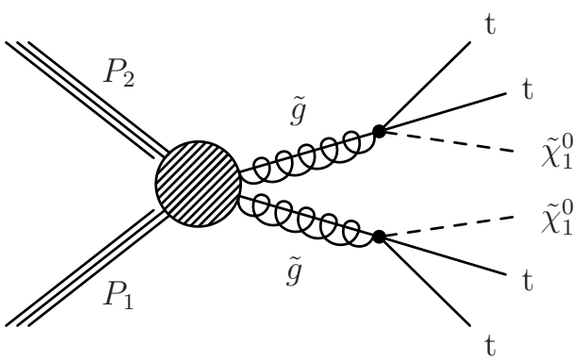
a few examples

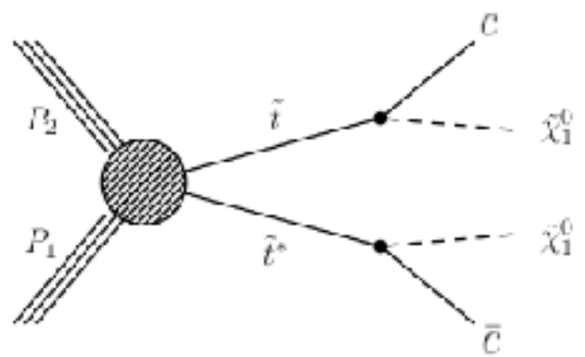


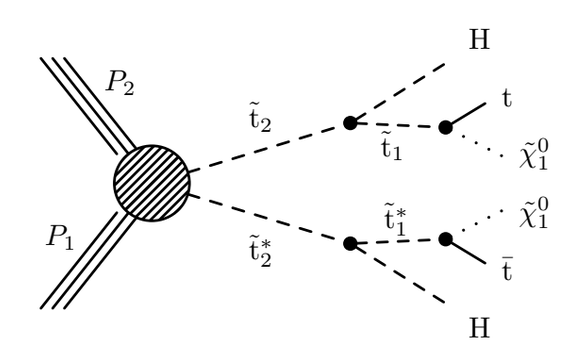








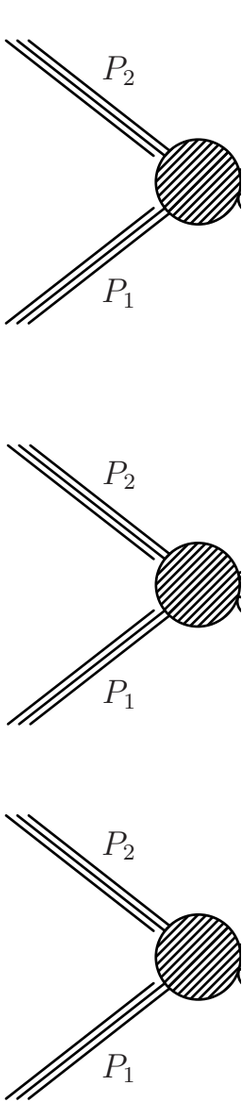


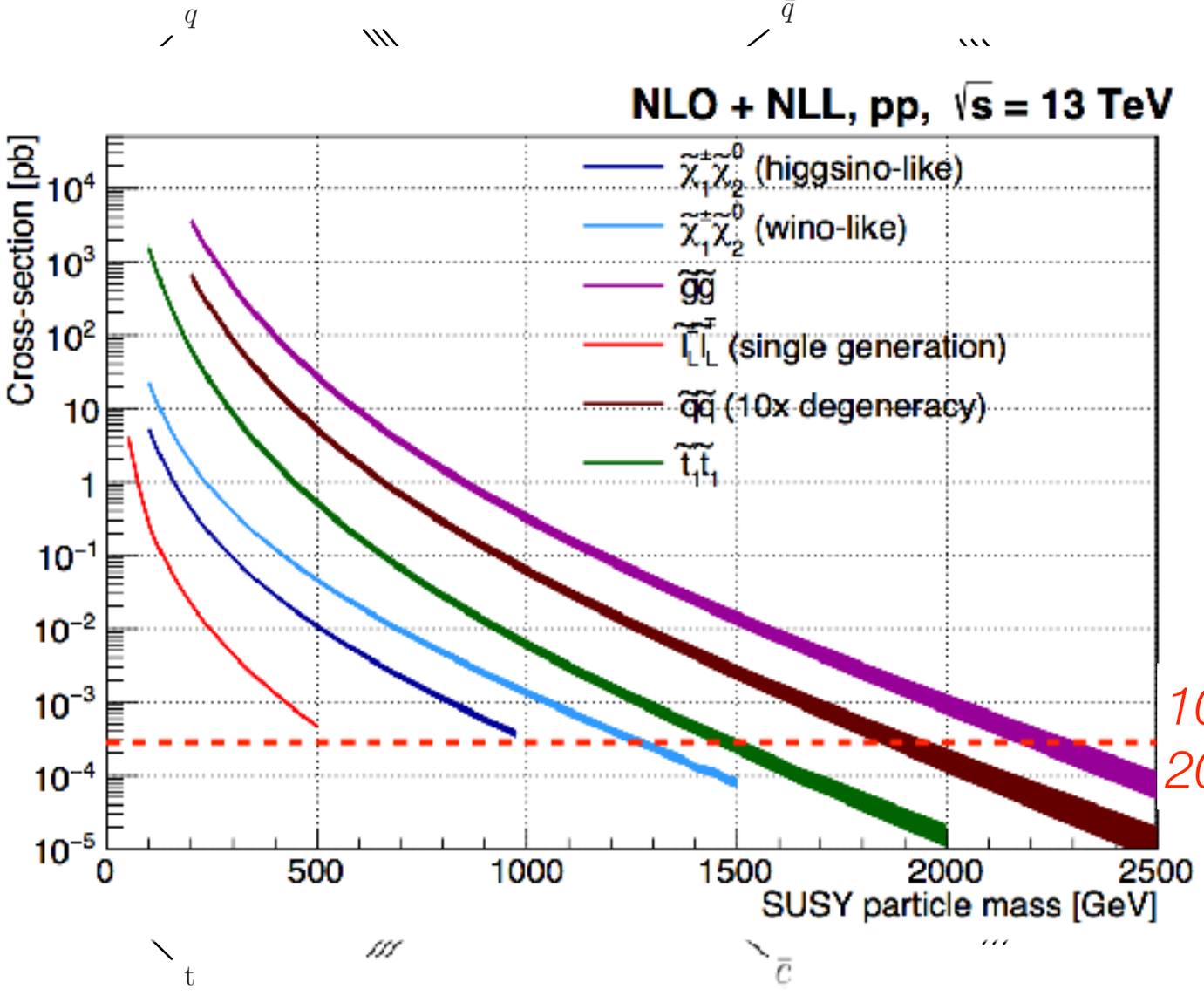


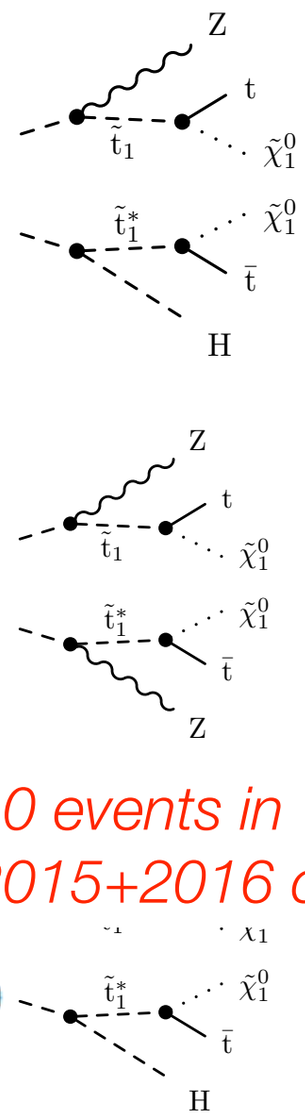
Supersymmetry

- Vast parameter space yields rich phenomenology
- Map experimental coverage using simplified models

Large cross-sections
SUSY should be easy !

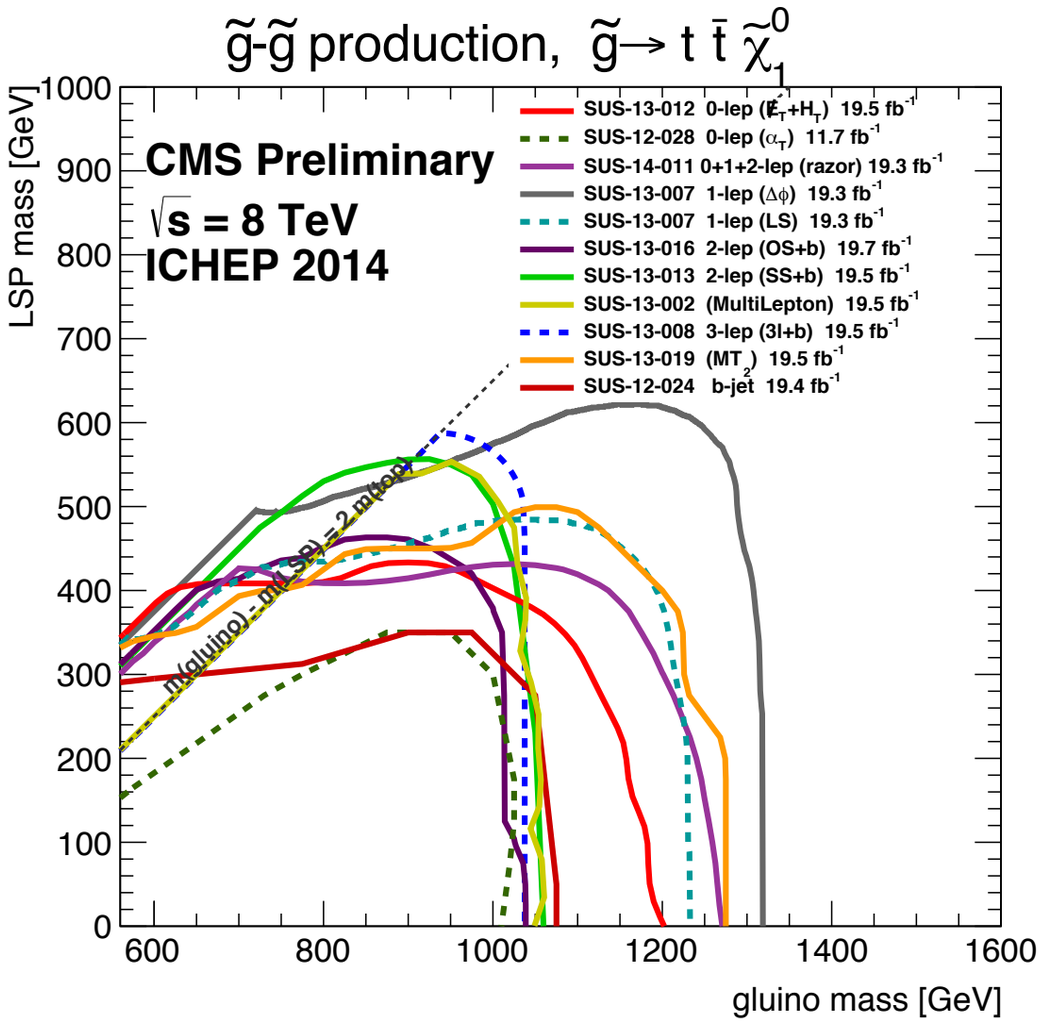


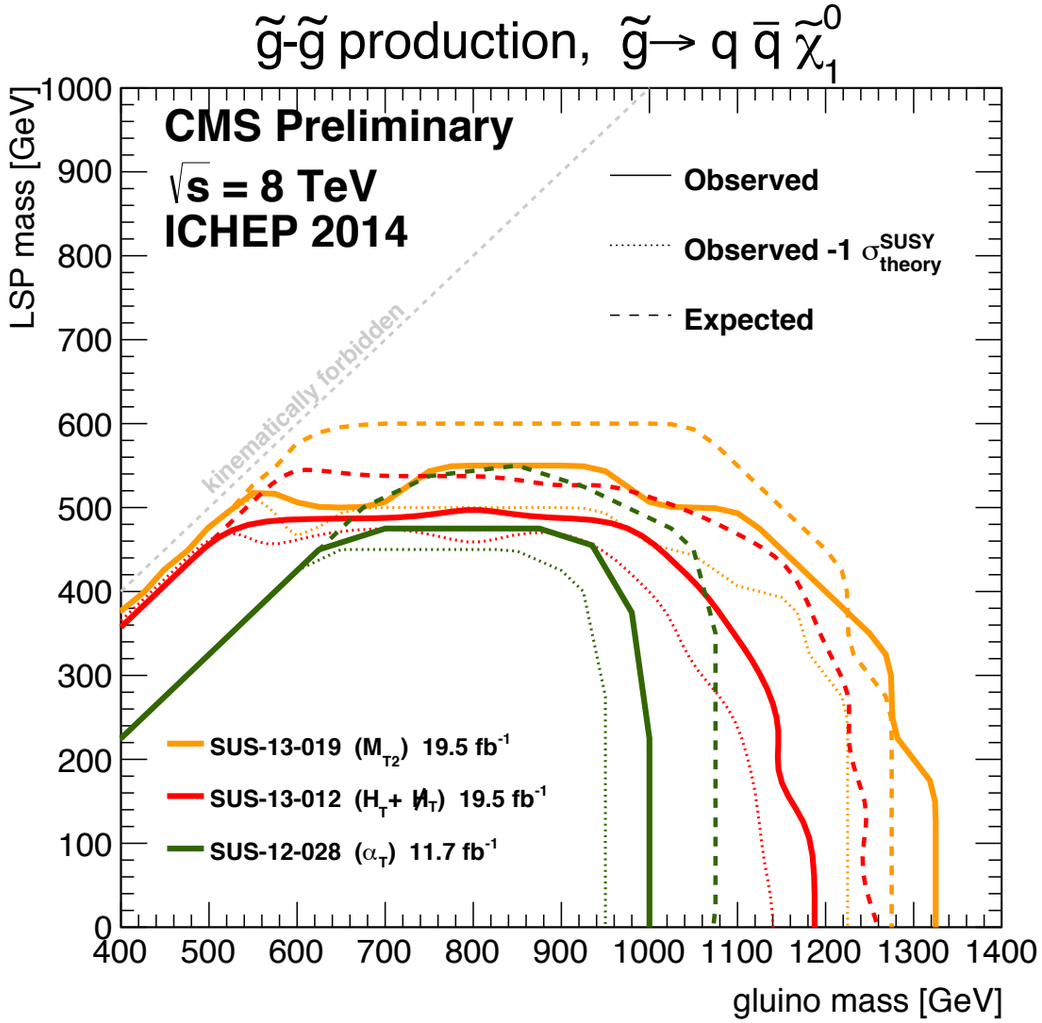


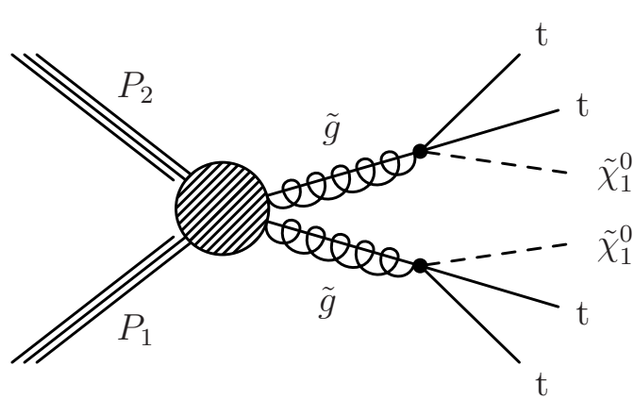


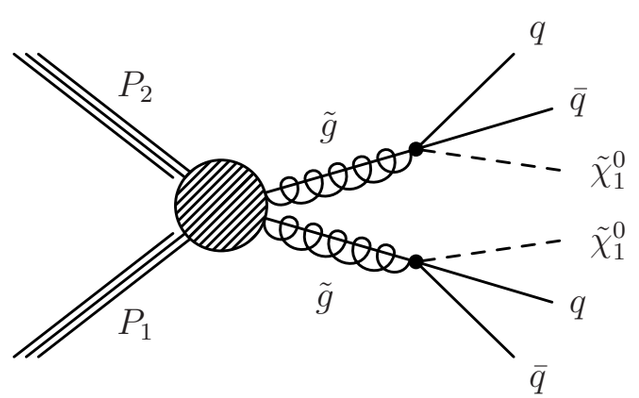
10 events in 2015+2016 data

SUSY : Run 1

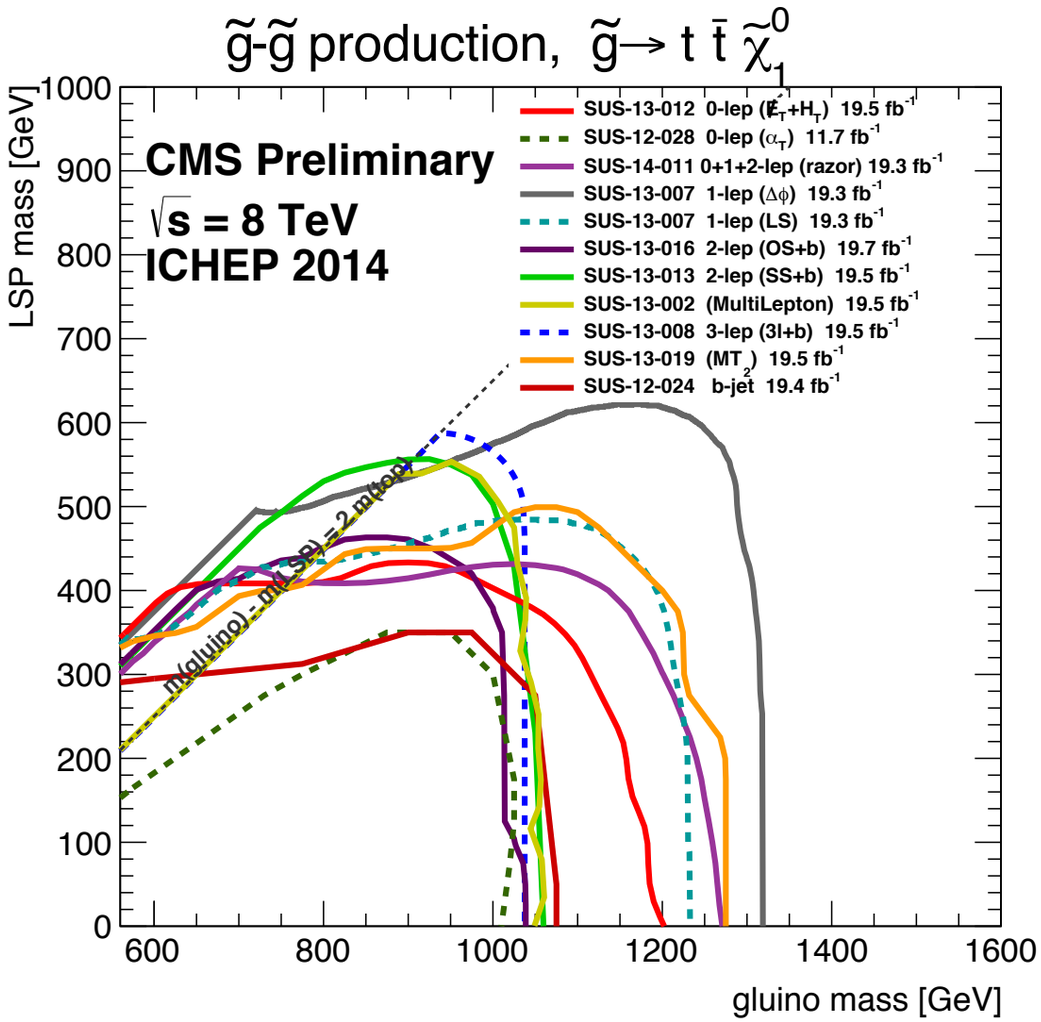

g̃-g̃ production, g̃→ t t̄ χ̃⁰₁
CMS Preliminary
√s = 8 TeV
ICHEP 2014
SUS-13-012 0-lep (H_T+Ḣ_T) 19.5 fb⁻¹
SUS-12-028 0-lep (α_T) 11.7 fb⁻¹
SUS-14-011 0+1+2-lep (razor) 19.3 fb⁻¹
SUS-13-007 1-lep (Δφ) 19.3 fb⁻¹
SUS-13-007 1-lep (LS) 19.3 fb⁻¹
SUS-13-016 2-lep (OS+b) 19.7 fb⁻¹
SUS-13-013 2-lep (SS+b) 19.5 fb⁻¹
SUS-13-002 (MultiLepton) 19.5 fb⁻¹
SUS-13-008 3-lep (3l+b) 19.5 fb⁻¹
SUS-13-019 (MT2) 19.5 fb⁻¹
SUS-12-024 b-jet 19.4 fb⁻¹
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
gluino mass [GeV]

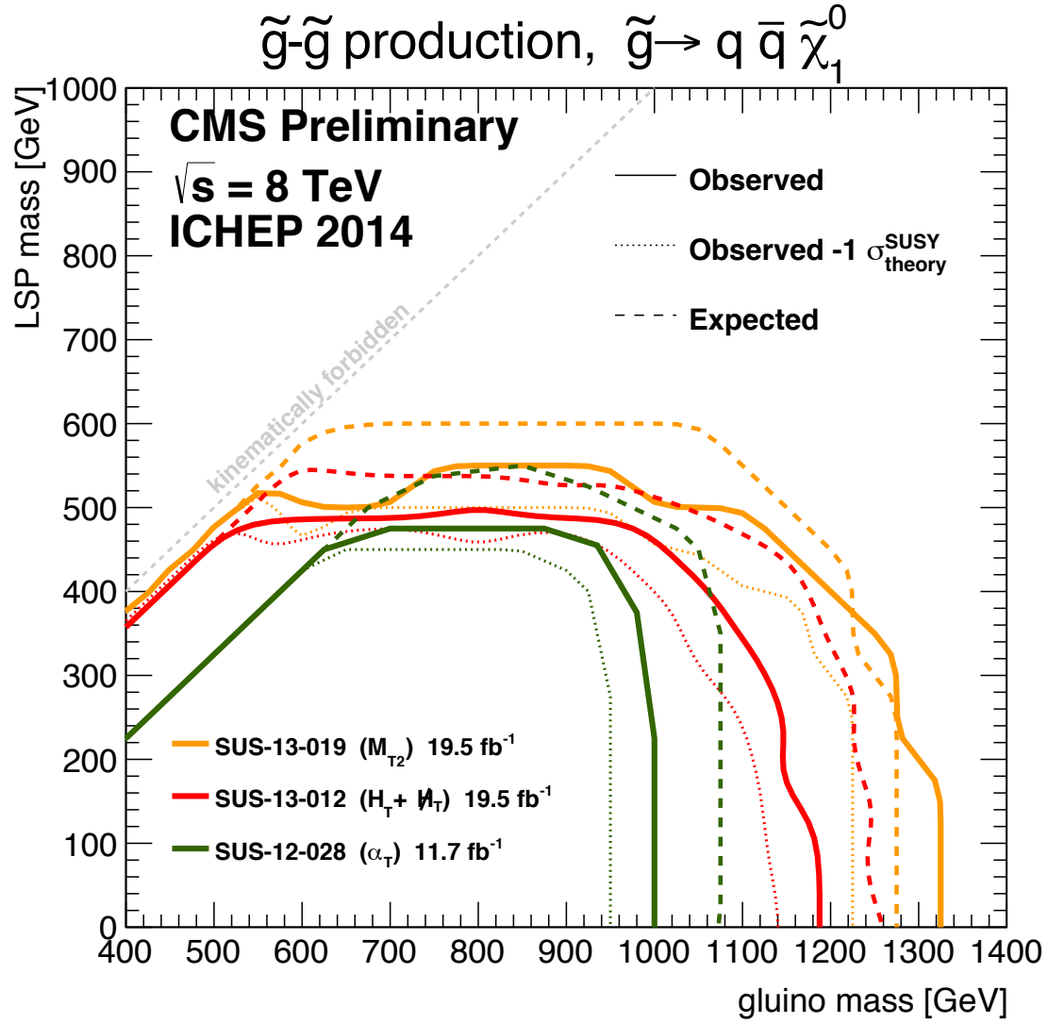

g̃-g̃ production, g̃→ q q̄ χ̃⁰₁
CMS Preliminary
√s = 8 TeV
ICHEP 2014
Observed
Observed -1 σ^SUSY_theory
Expected
Kinematically forbidden
SUS-13-019 (M_T2) 19.5 fb⁻¹
SUS-13-012 (H_T+ Ḣ_T) 19.5 fb⁻¹
SUS-12-028 (α_T) 11.7 fb⁻¹
LSP mass [GeV]
gluino mass [GeV]

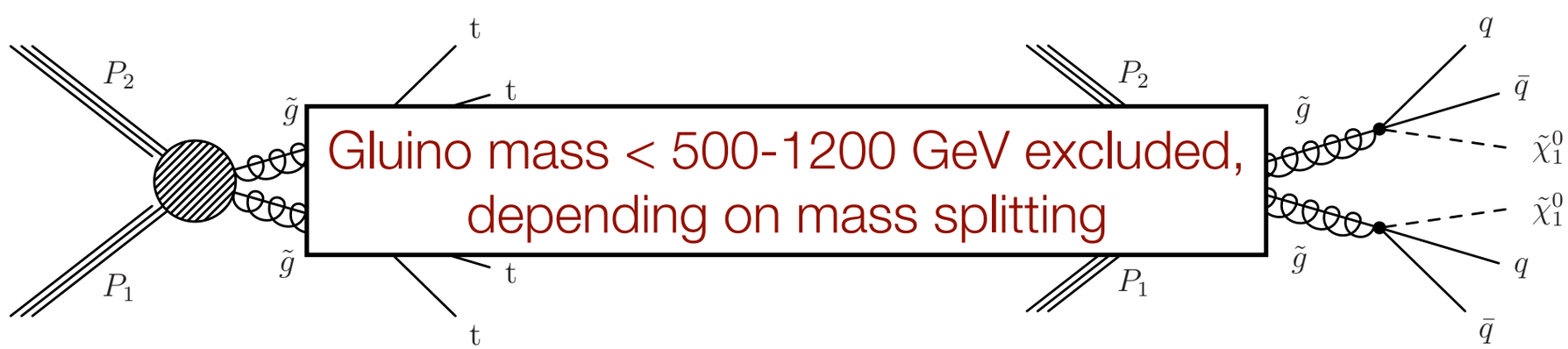

P_2
P_1
$\tilde{g}$
$\tilde{g}$
t
t
t
t
$\tilde{\chi}^0_1$
$\tilde{\chi}^0_1$


P_2
P_1
$\tilde{g}$
$\tilde{g}$
q
$\bar{q}$
q
$\bar{q}$
$\tilde{\chi}^0_1$
$\tilde{\chi}^0_1$

SUSY : Run 1

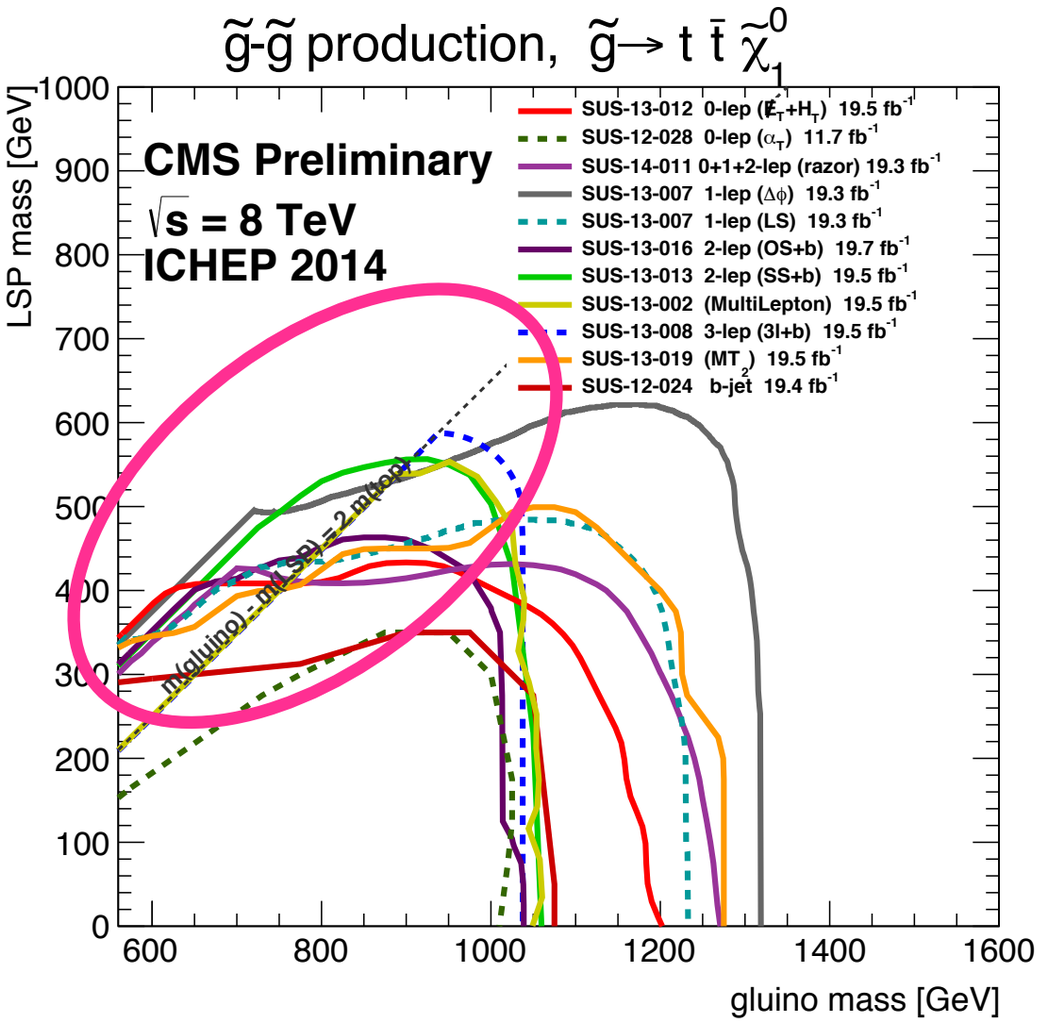


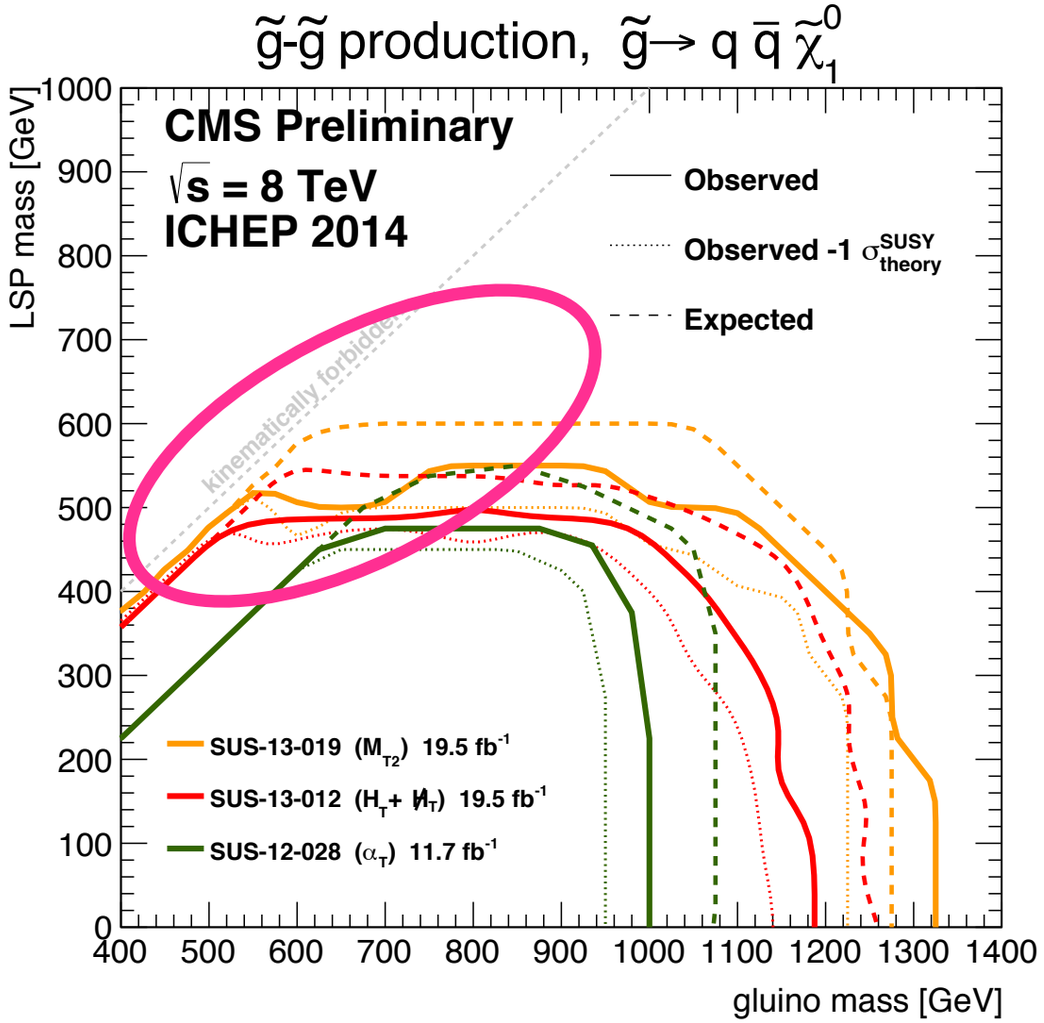


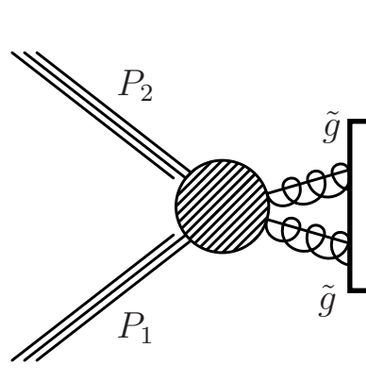


Gluino mass < 500-1200 GeV excluded, depending on mass splitting

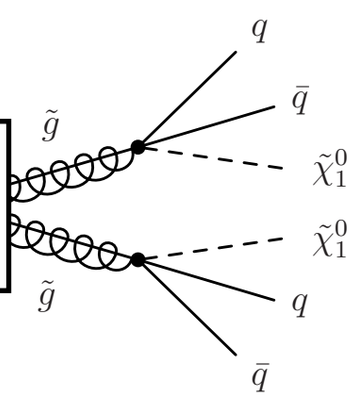
SUSY : Run 1



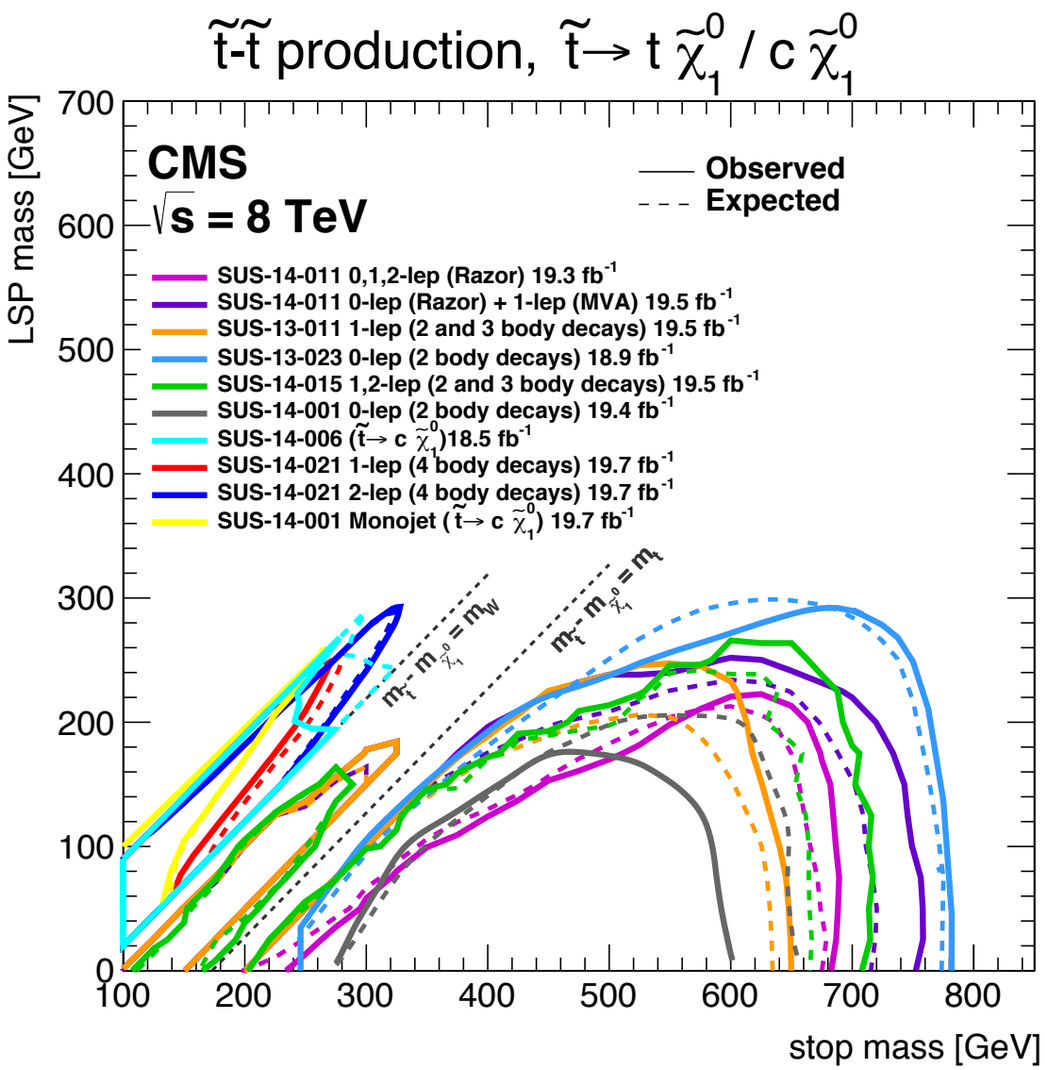


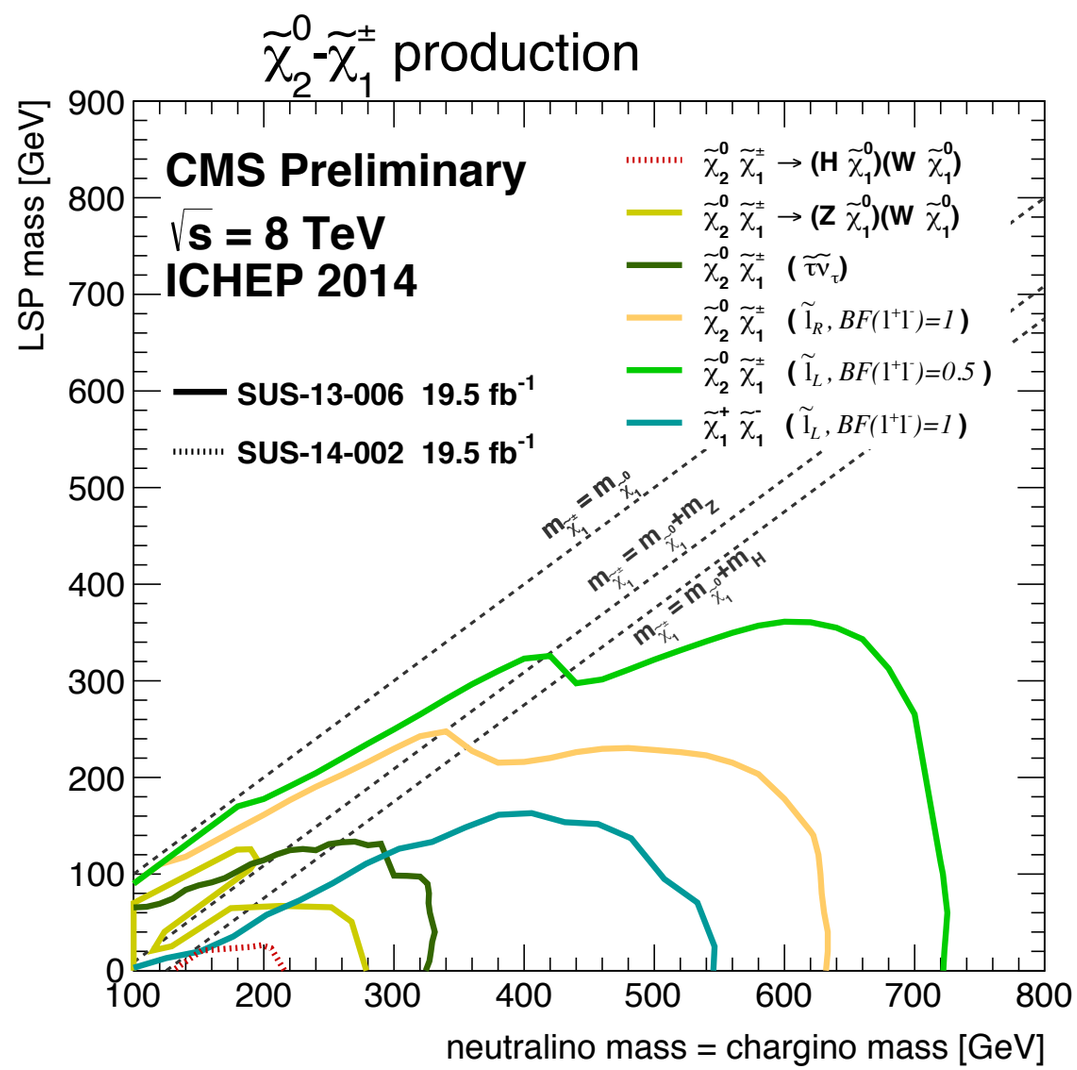


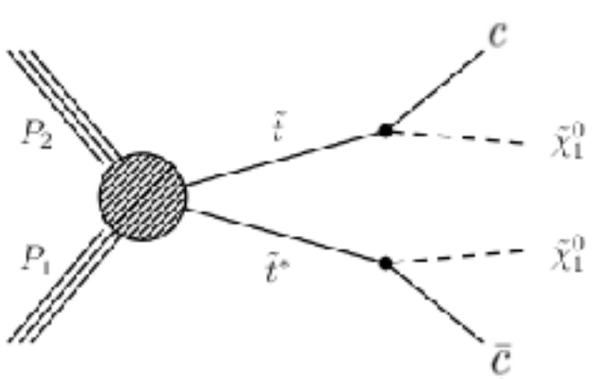
Gluino mass < 500-1200 GeV excluded, depending on mass splitting

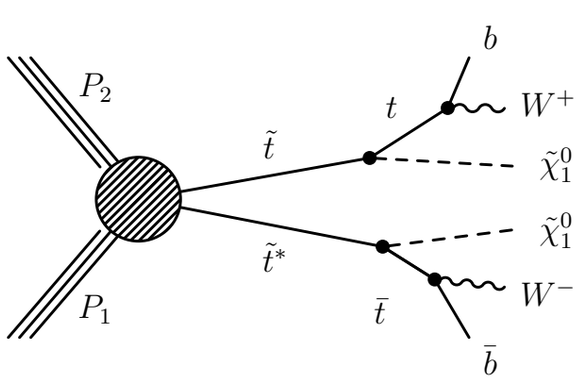


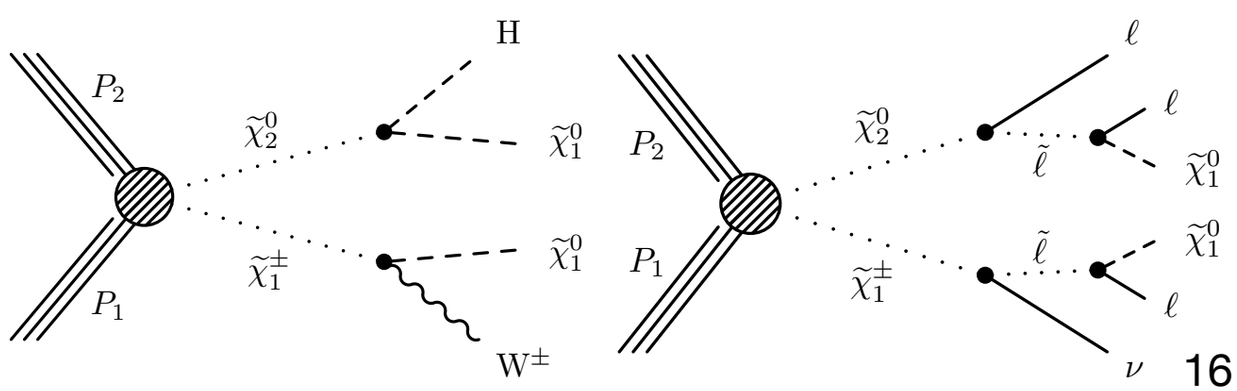
SUSY : Run 1


$\tilde{t}$-$\tilde{t}$ production, $\tilde{t}\to$ t $\tilde{\chi}_1^0$ / c $\tilde{\chi}_1^0$
CMS
$\sqrt{s}$ = 8 TeV
Observed
Expected
SUS-14-011 0,1,2-lep (Razor) 19.3 fb^{-1}
SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.5 fb^{-1}
SUS-13-011 1-lep (2 and 3 body decays) 19.5 fb^{-1}
SUS-13-023 0-lep (2 body decays) 18.9 fb^{-1}
SUS-14-015 1,2-lep (2 and 3 body decays) 19.5 fb^{-1}
SUS-14-001 0-lep (2 body decays) 19.4 fb^{-1}
SUS-14-006 ($\tilde{t}\to$ c $\tilde{\chi}_1^0$)18.5 fb^{-1}
SUS-14-021 1-lep (4 body decays) 19.7 fb^{-1}
SUS-14-021 2-lep (4 body decays) 19.7 fb^{-1}
SUS-14-001 Monojet ($\tilde{t}\to$ c $\tilde{\chi}_1^0$) 19.7 fb^{-1}
$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = m_W$
$m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = m_t$
LSP mass [GeV]
stop mass [GeV]

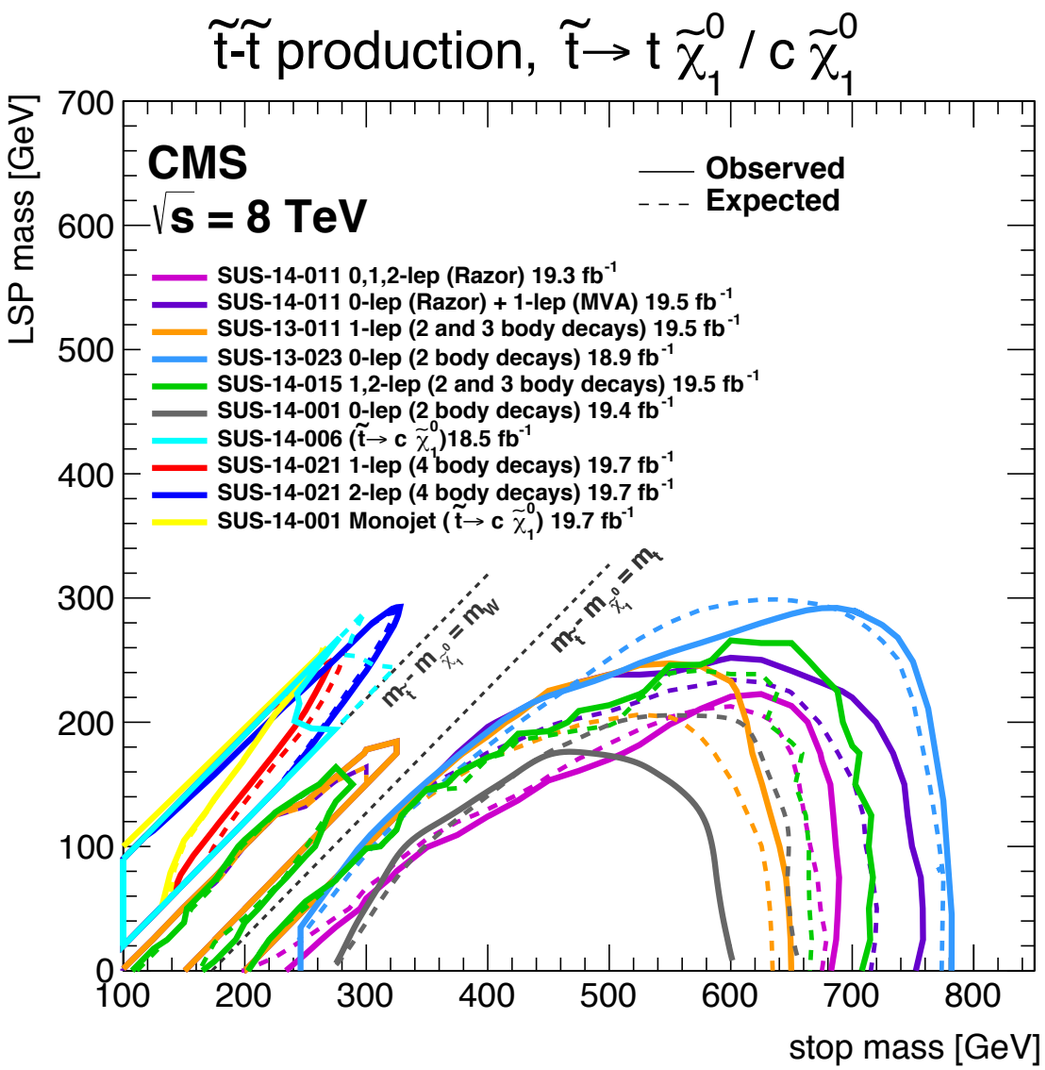

$\tilde{\chi}_2^0$-$\tilde{\chi}_1^\pm$ production
CMS Preliminary
$\sqrt{s}$ = 8 TeV
ICHEP 2014
SUS-13-006 19.5 fb^{-1}
SUS-14-002 19.5 fb^{-1}
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm \to$ (H $\tilde{\chi}_1^0$)(W $\tilde{\chi}_1^0$)
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm \to$ (Z $\tilde{\chi}_1^0$)(W $\tilde{\chi}_1^0$)
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$ ($\tilde{\tau}\nu_\tau$)
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$ ($\tilde{l}_R$, $BF(l^+l^-)=1$)
$\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$ ($\tilde{l}_L$, $BF(l^+l^-)=0.5$)
$\tilde{\chi}_1^+\,\tilde{\chi}_1^-$ ($\tilde{l}_L$, $BF(l^+l^-)=1$)
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_H$
LSP mass [GeV]
neutralino mass = chargino mass [GeV]

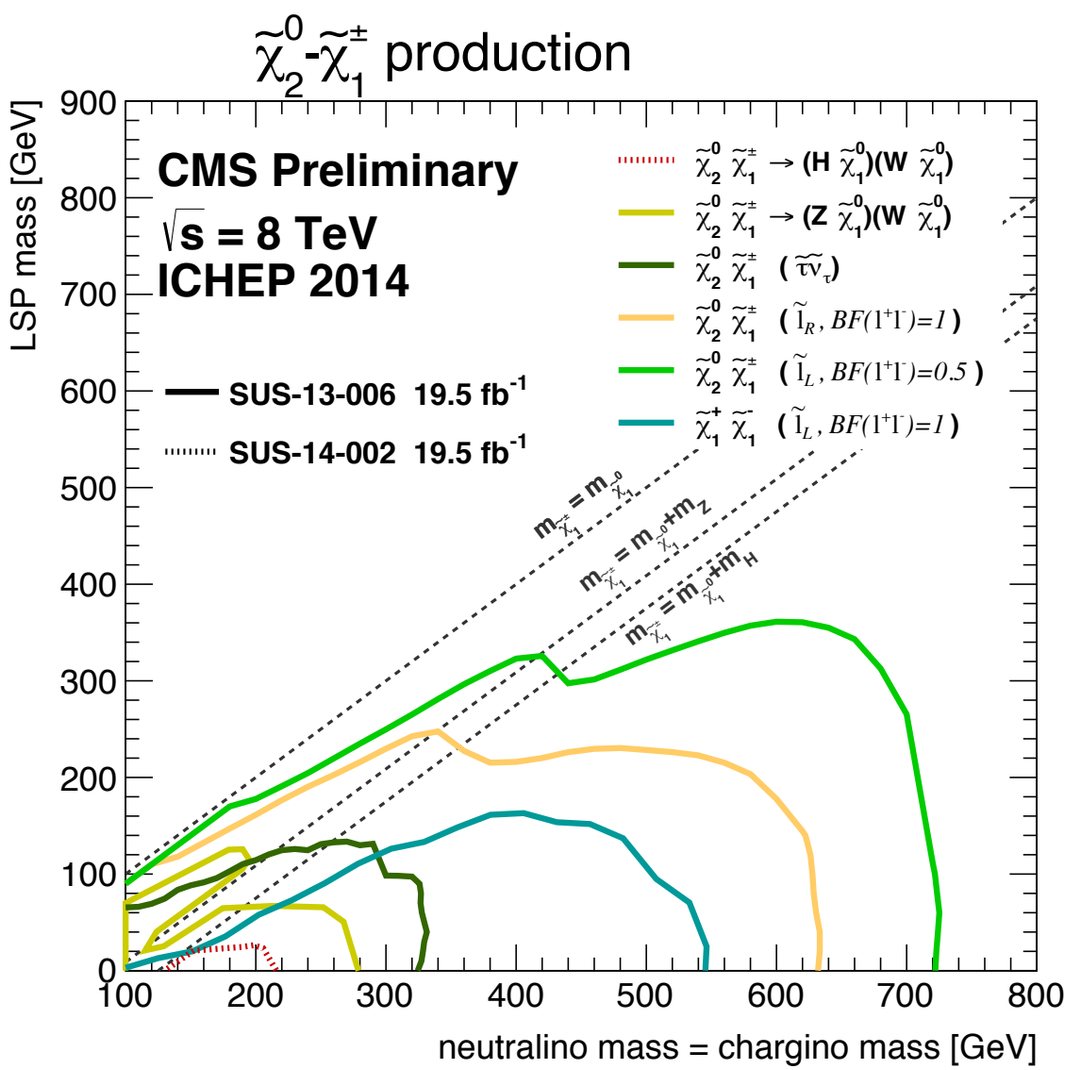

P_2
P_1
$\tilde{t}$
$\tilde{t}^*$
c
$\bar{c}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$

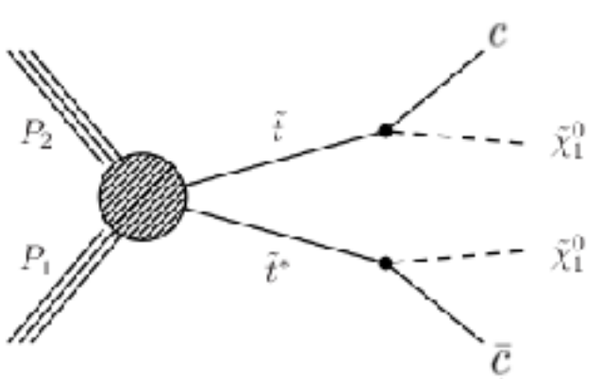

P_2
P_1
$\tilde{t}$
$\tilde{t}^*$
t
$\bar{t}$
b
$\bar{b}$
W^+
W^-
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$


P_2
P_1
H
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
$W^\pm$
ℓ
$\tilde{\ell}$
ν

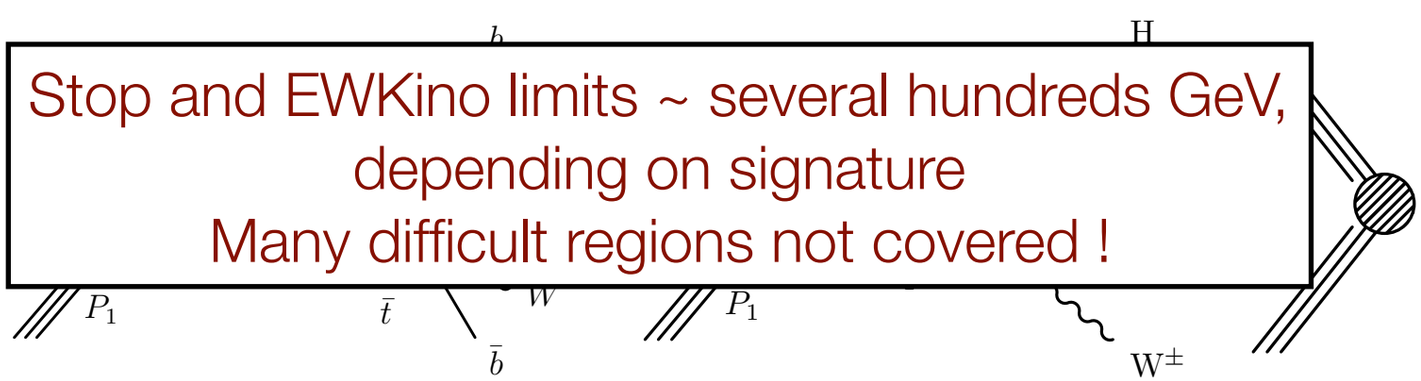
SUSY : Run 1

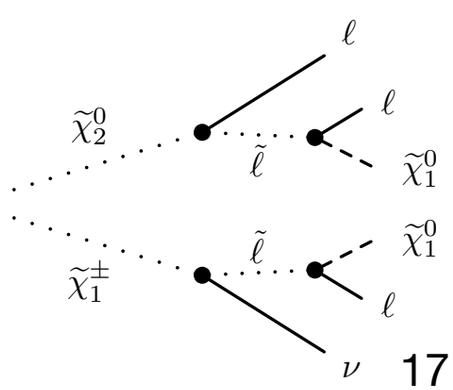




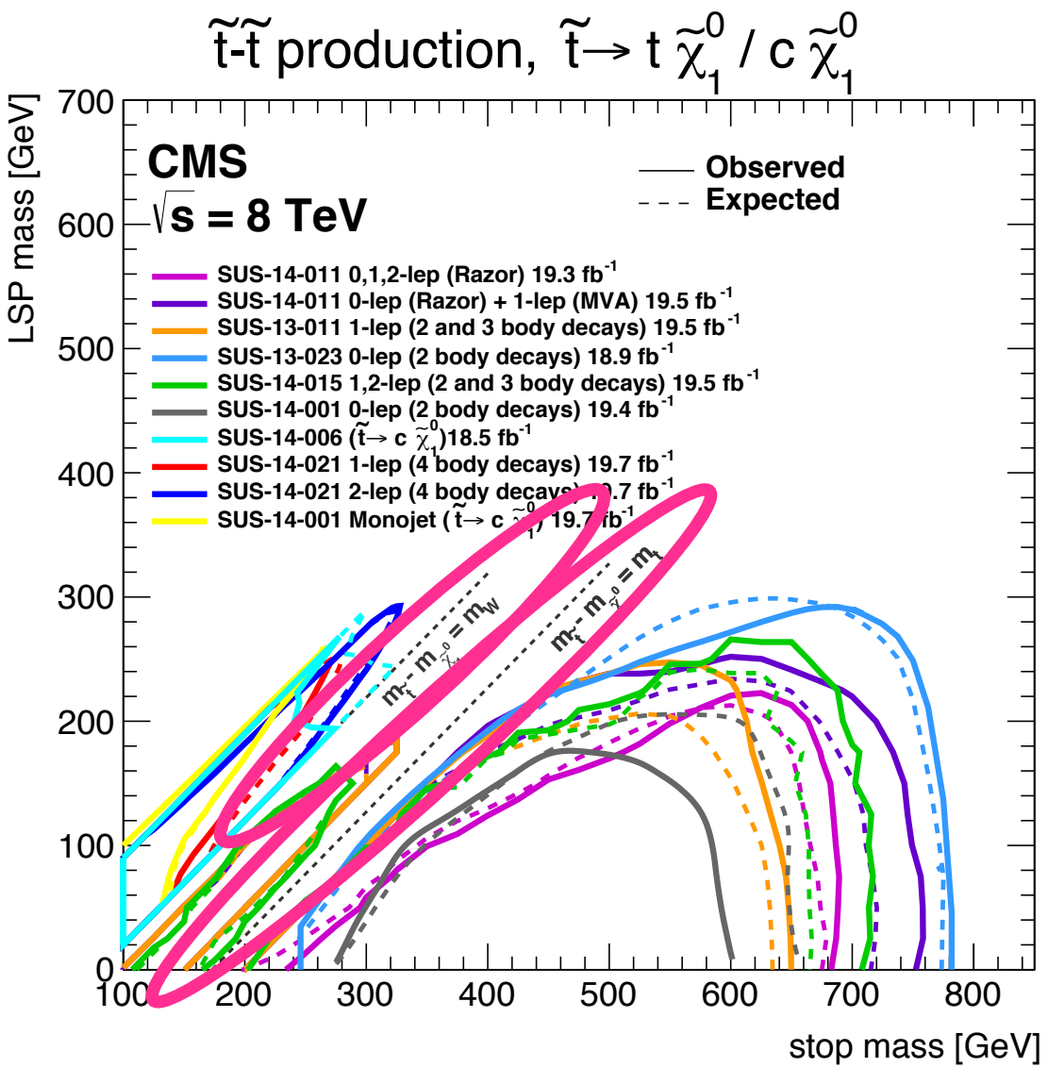


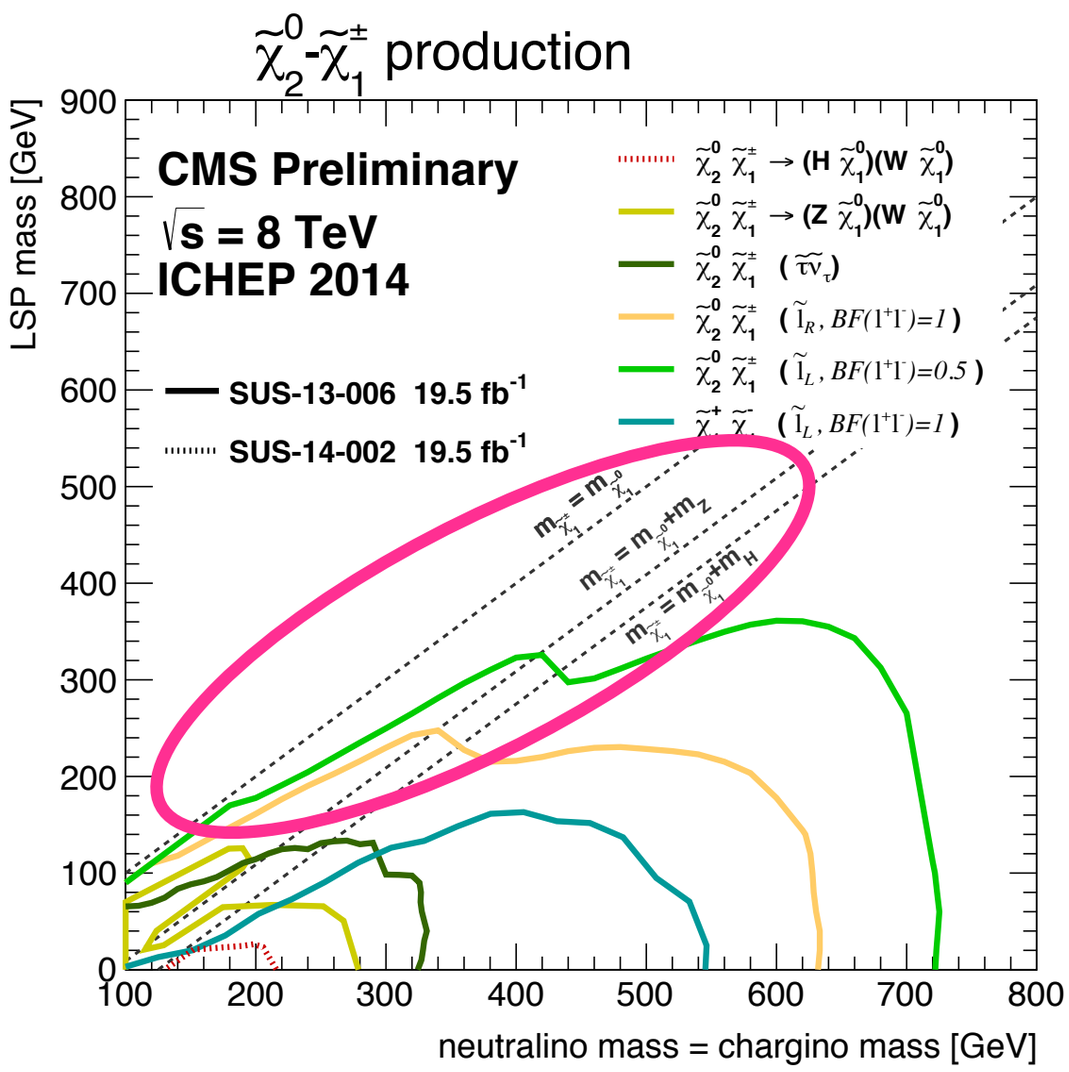
Stop and EWKino limits ~ several hundreds GeV, depending on signature
Many difficult regions not covered !

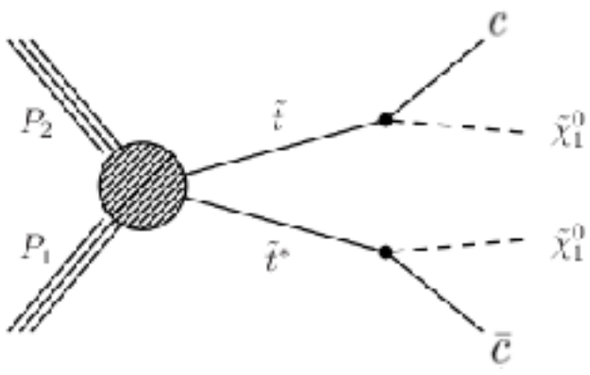




SUSY : Run 1

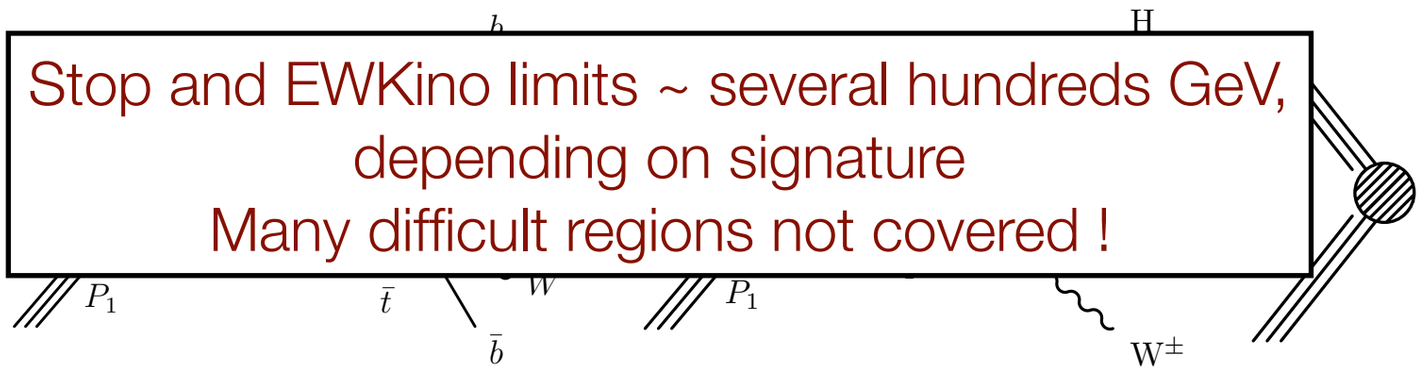


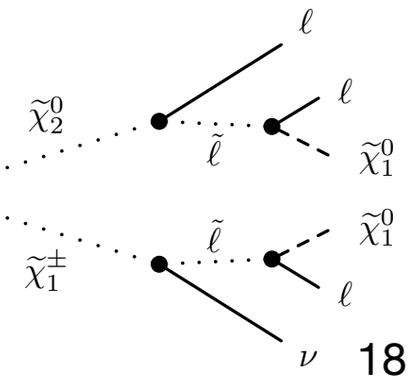




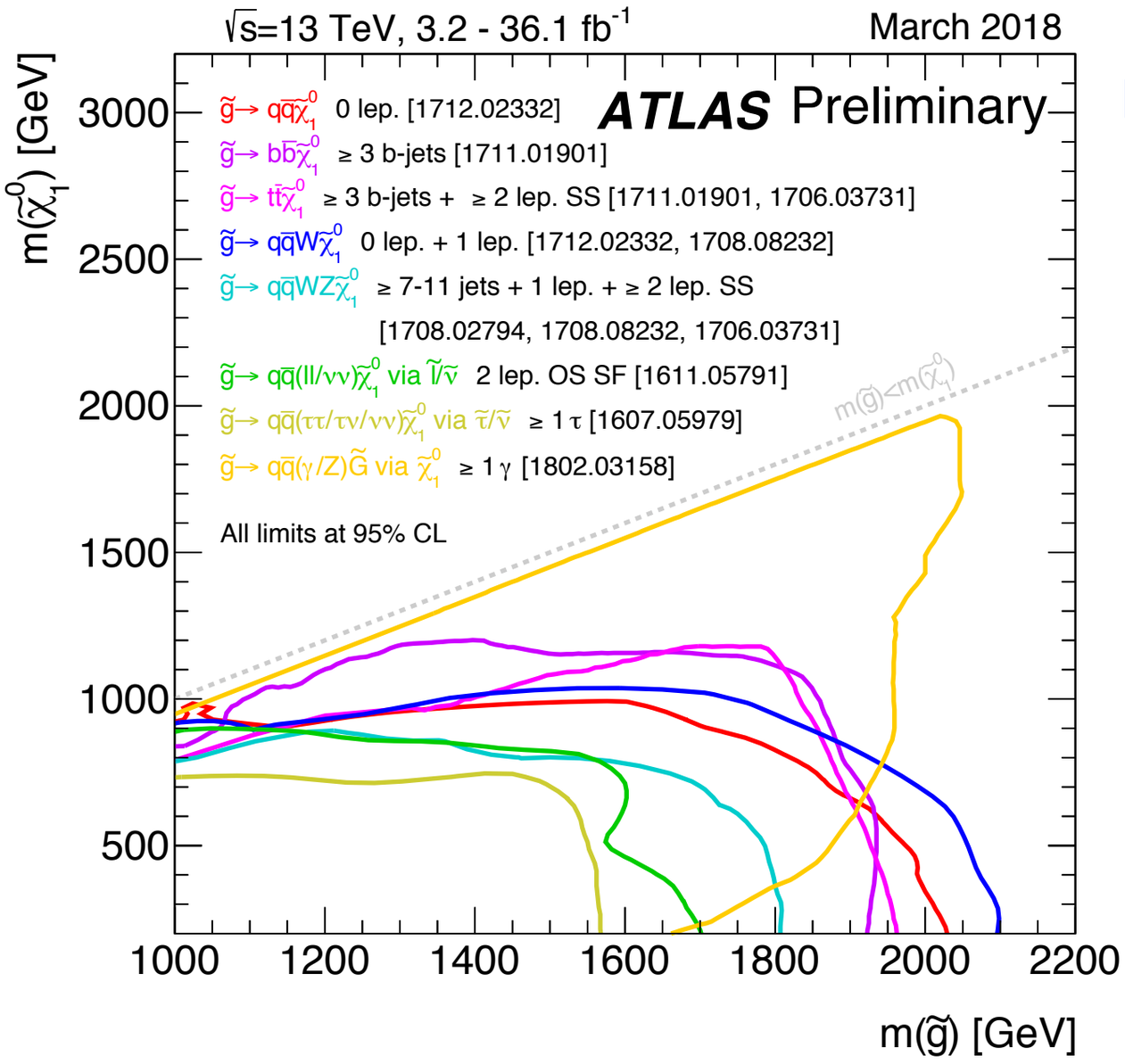
Stop and EWKino limits ~ several hundreds GeV, depending on signature

Many difficult regions not covered !





SUSY : Gluino

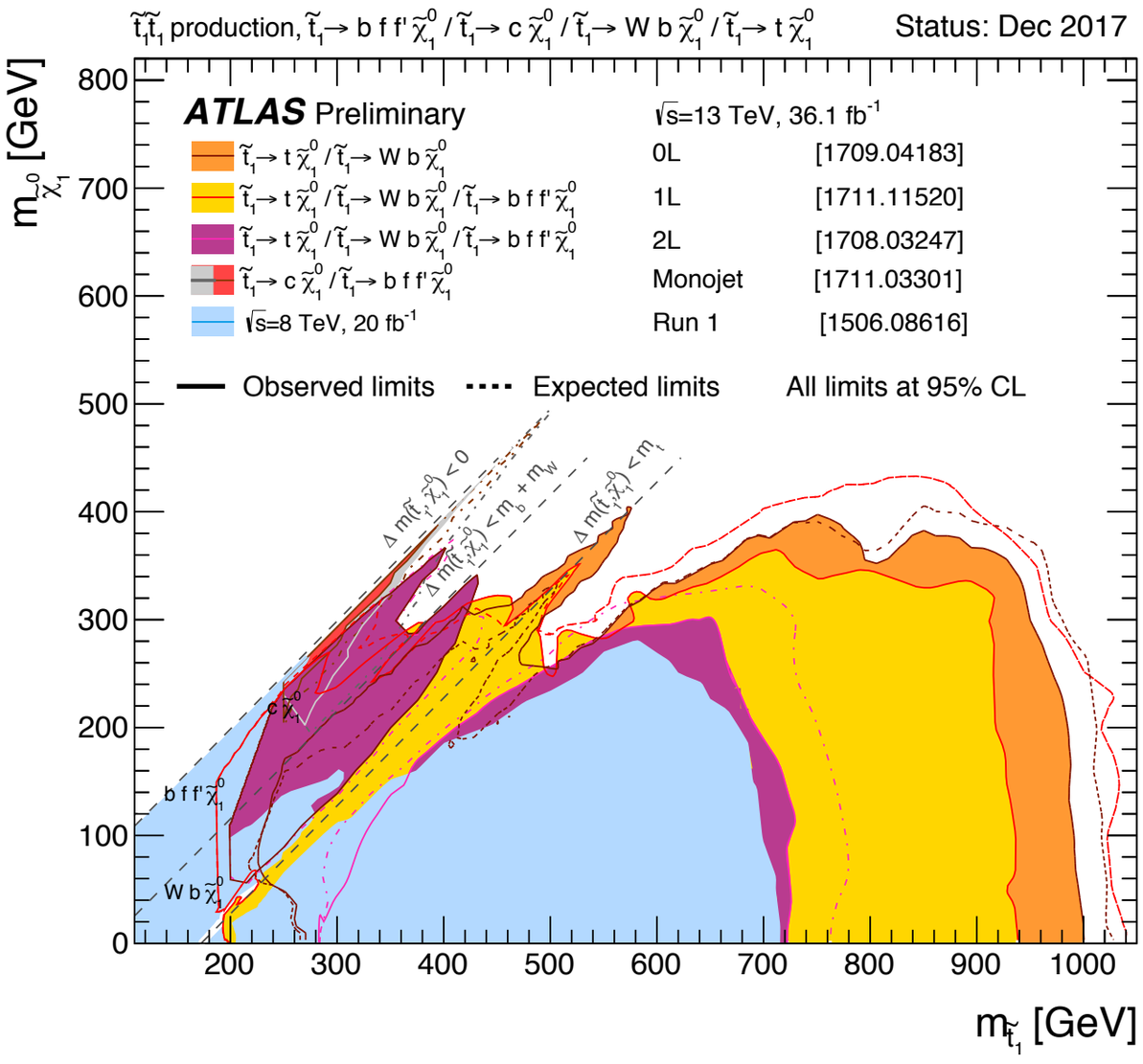


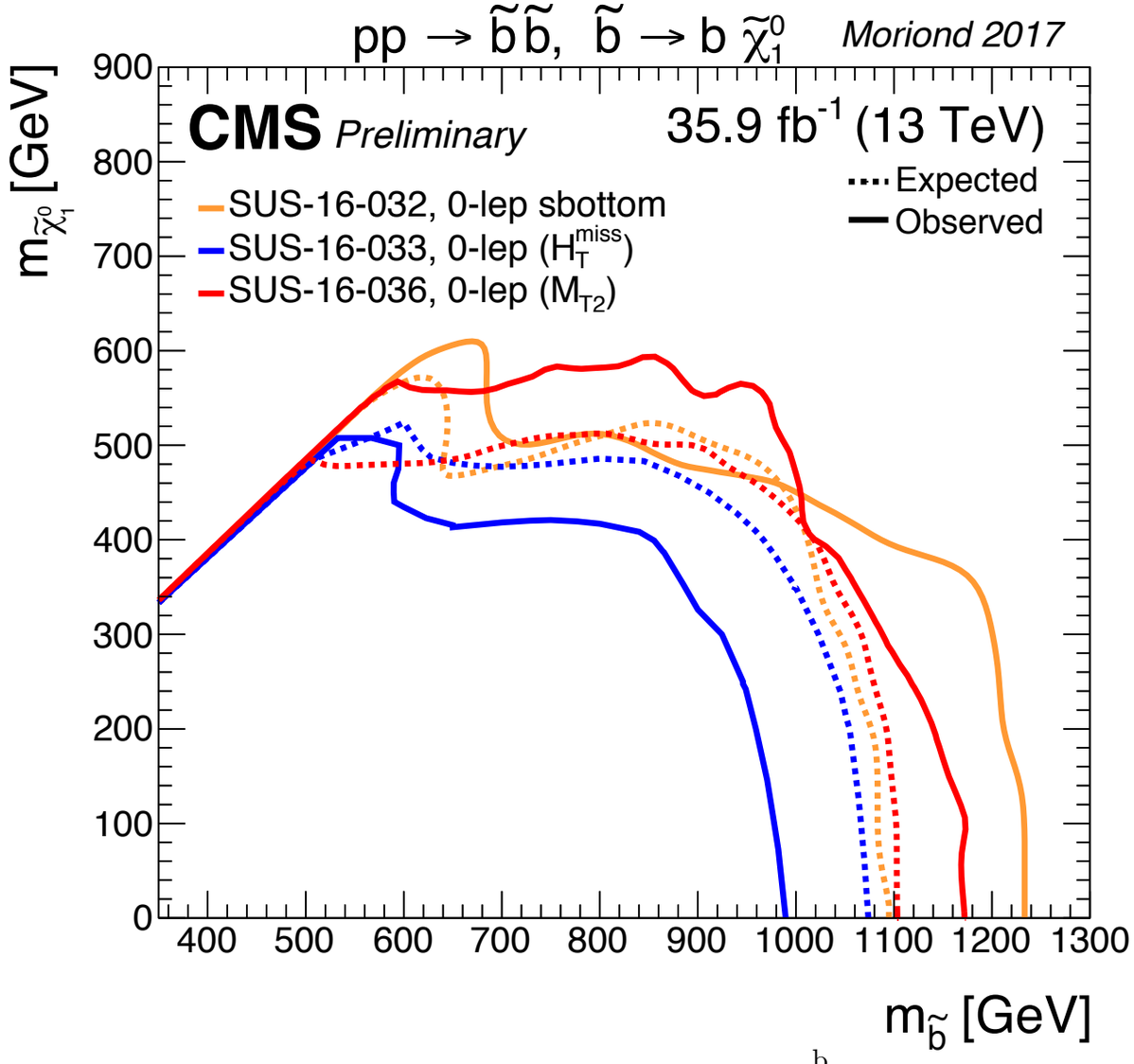
Broad coverage of signatures with jets+MET+

- b-tagged jets
- 1 lepton (electron, muon)
- 2 leptons opposite-sign on-Z / off-Z
- 2 leptons same-sign
- photon(s)
- hadronic-tau(s)

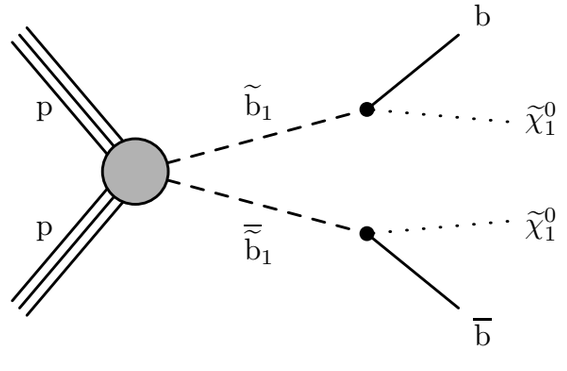
Exclude gluinos up to 1-2 TeV, depending on mass splitting

SUSY : Stop & Sbottom

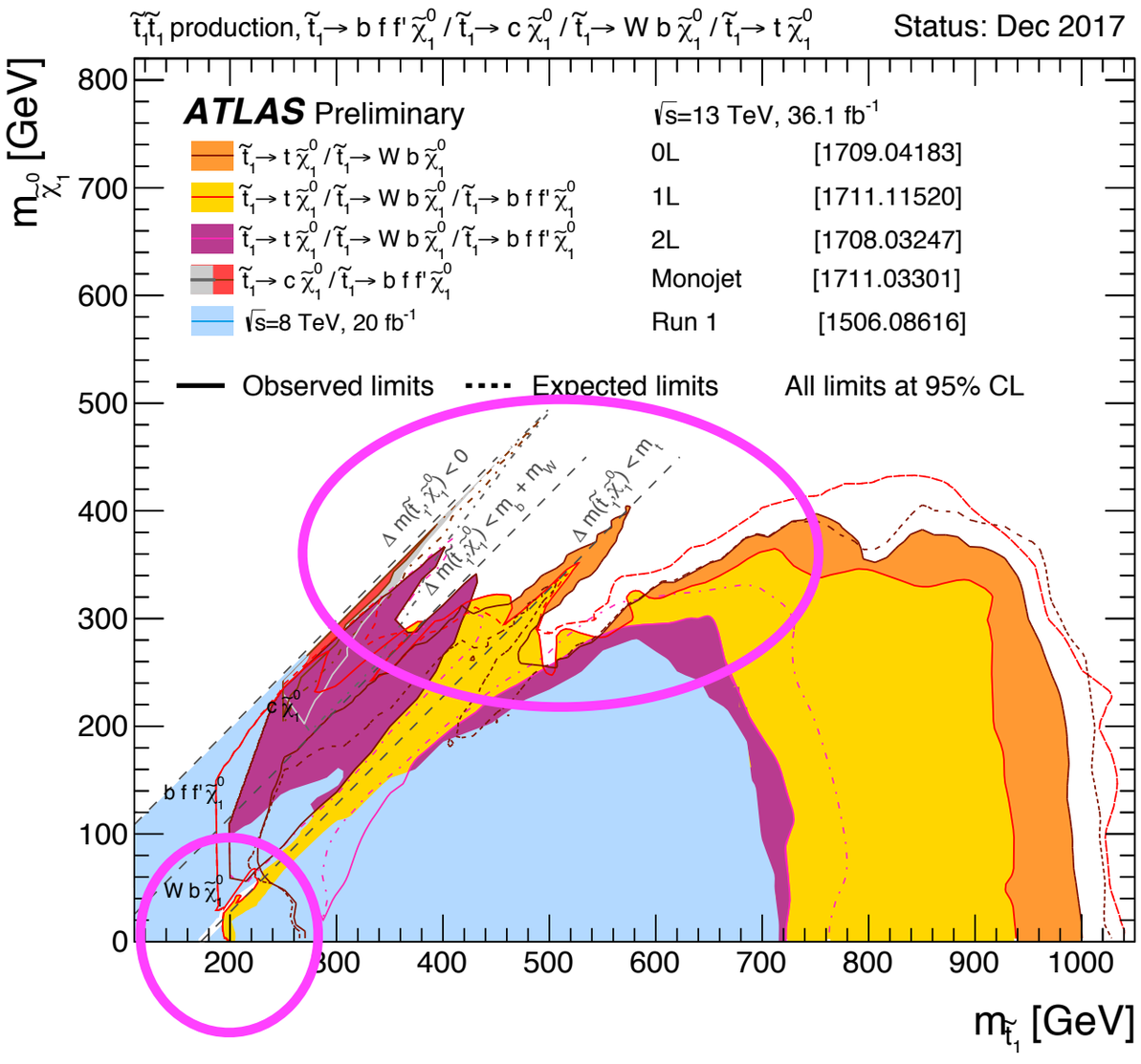


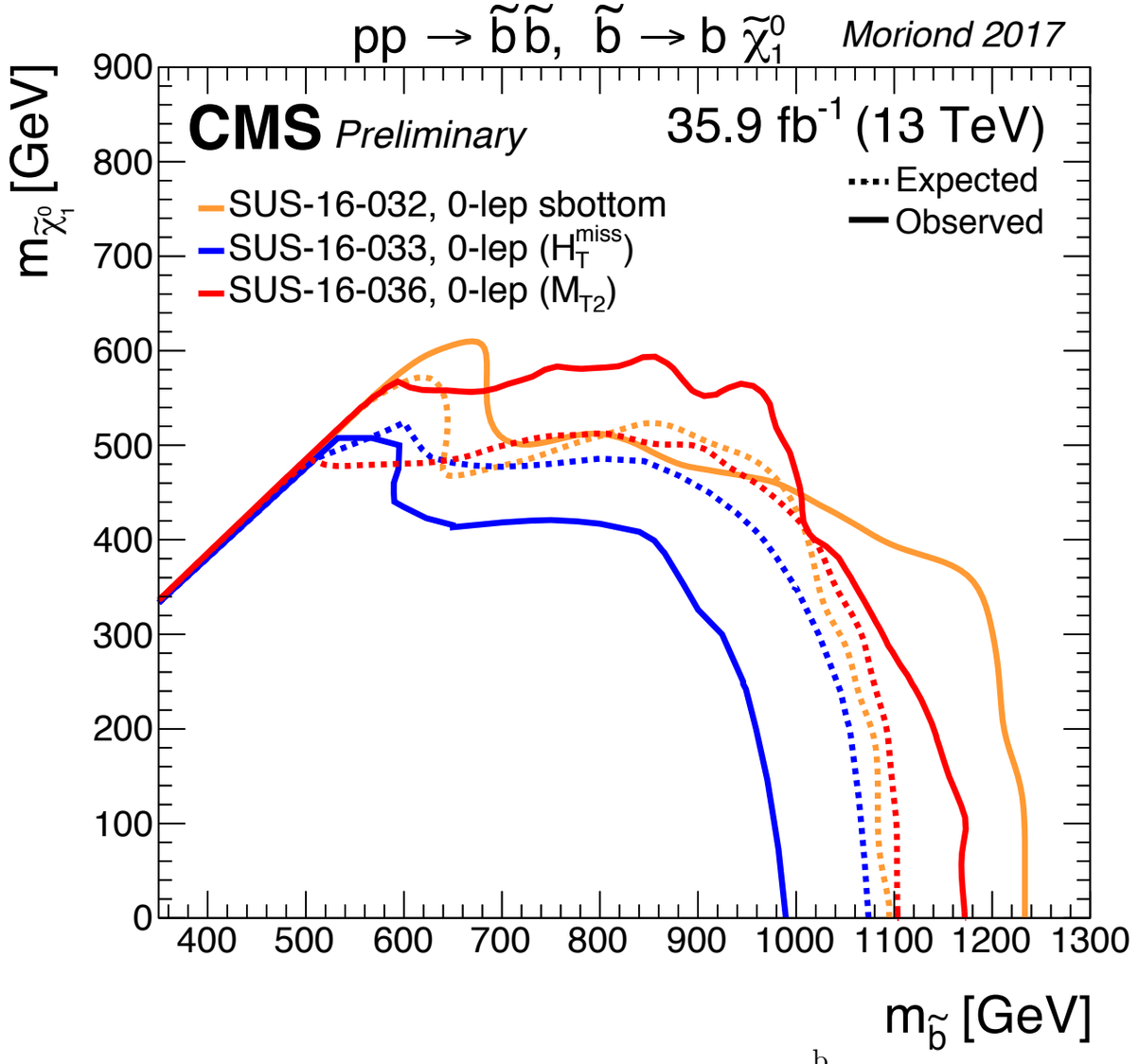


Exclude stop/sbottom up to ~1 TeV
but many difficult regions !



SUSY : Stop & Sbottom





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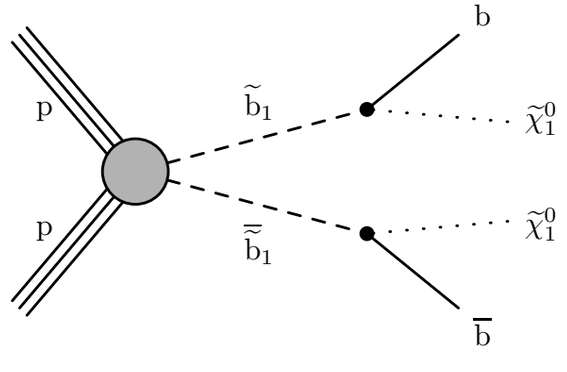
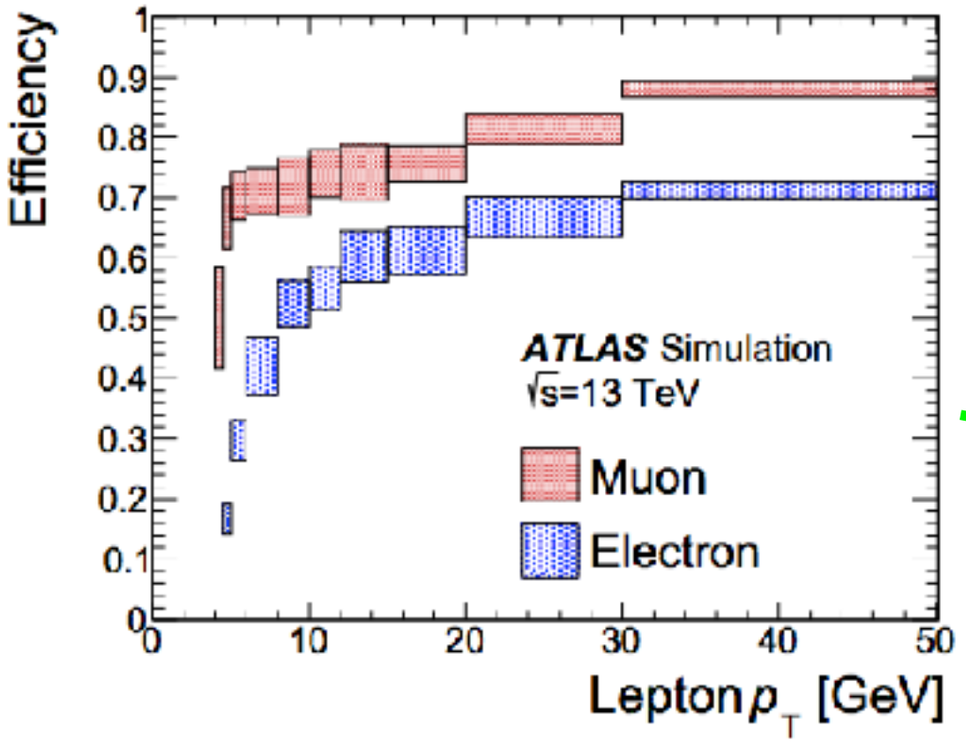
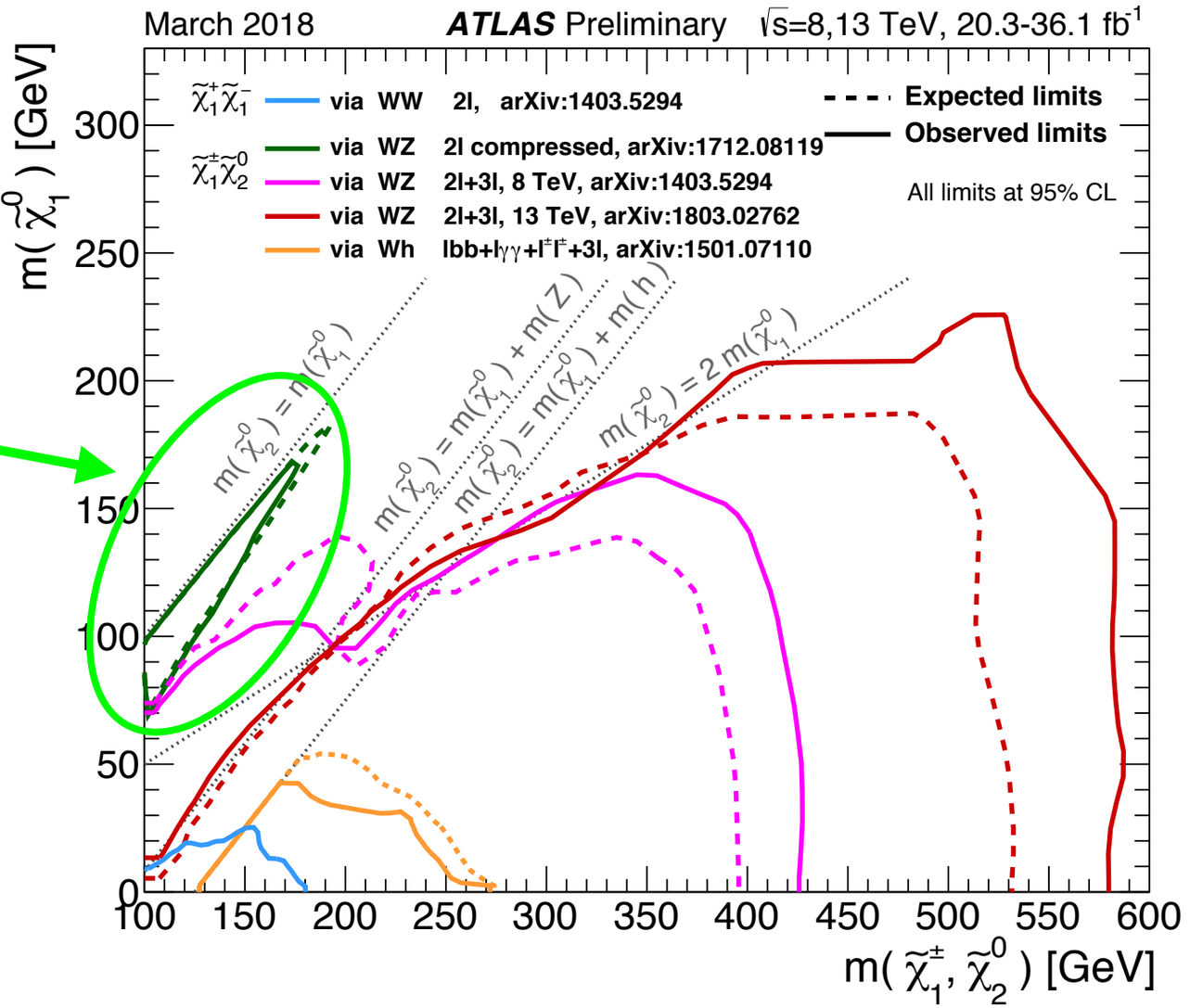


SUSY : EWKinos

Talk by Jesse Liu

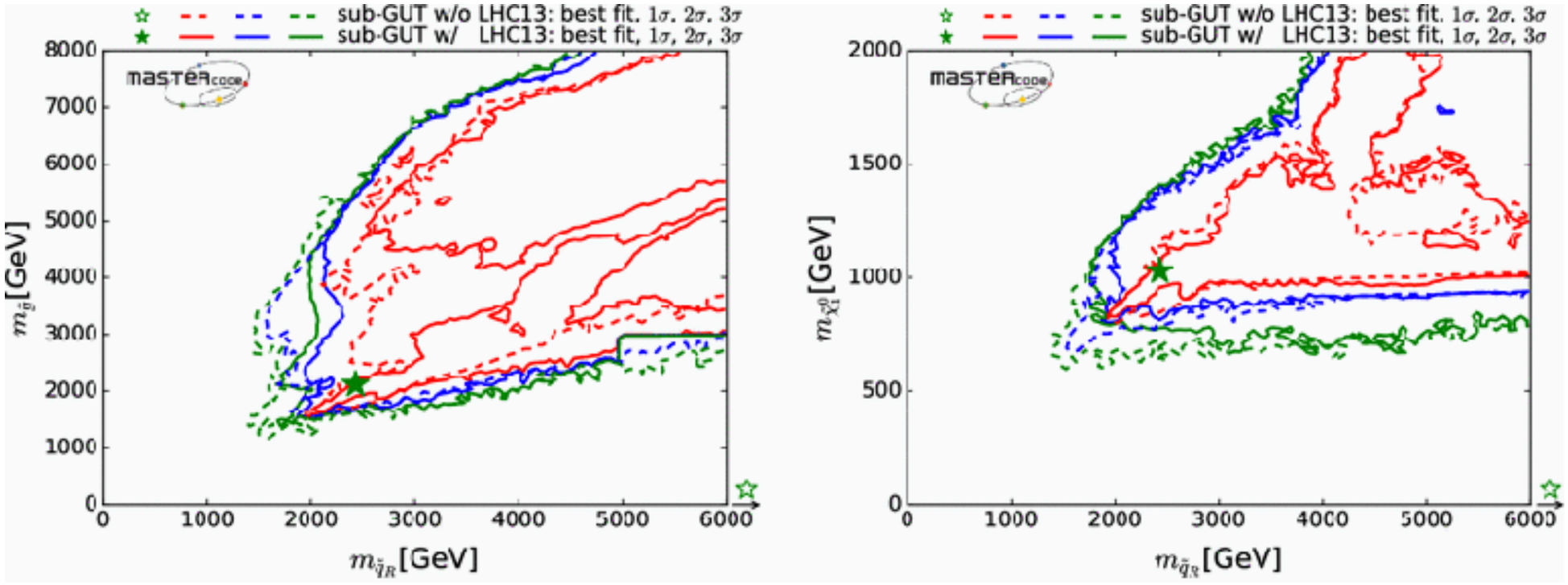




Extending p_T threshold as low as possible (4 GeV for muons) allows regions of constrained phase space to be probed.

Supersymmetry

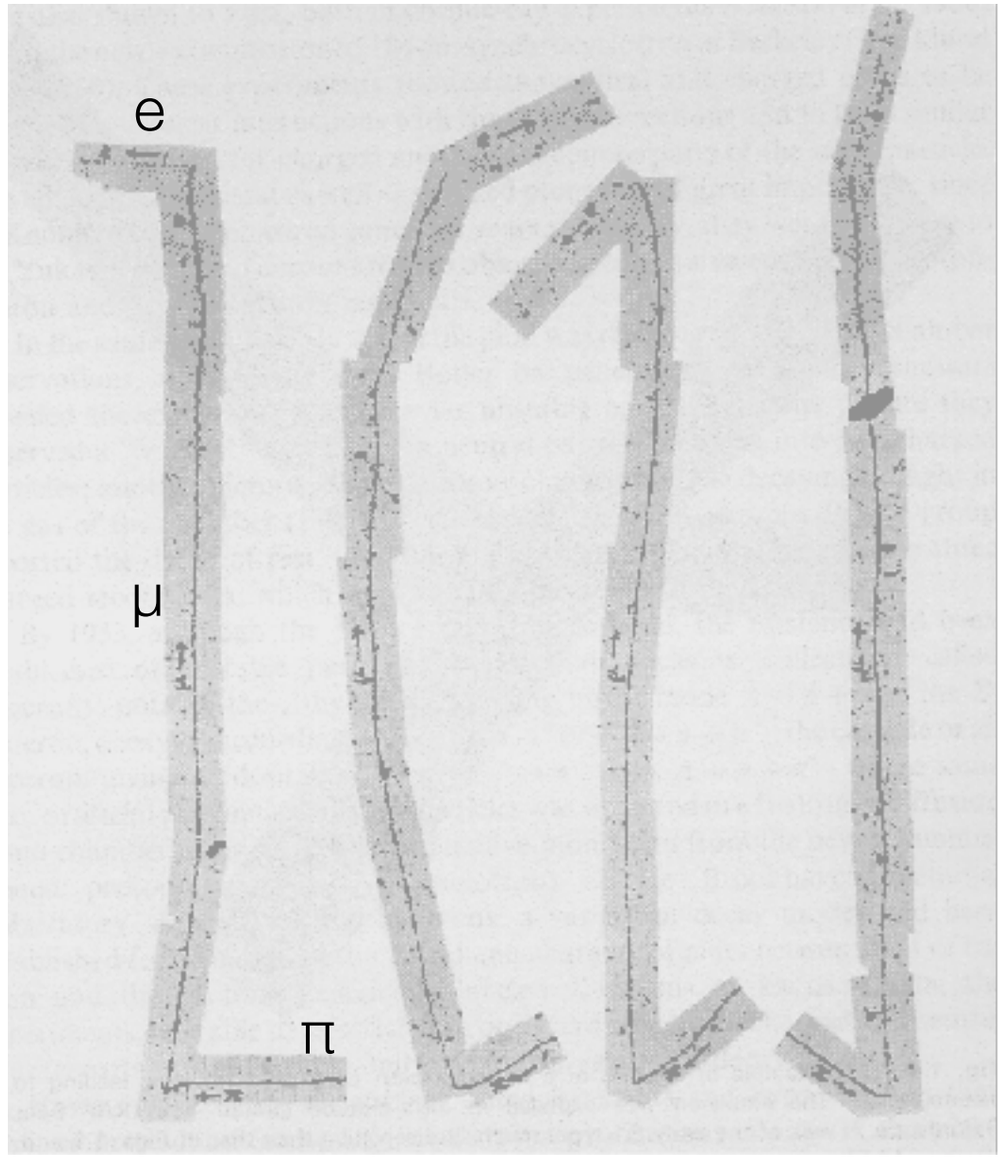
Talk by Jonathan Costa



- Global fits of SUSY models to LHC results + other observables
  - Many models are heavily constrained ! Tension reduced in models that give rise to difficult regions for LHC, eg. compressed spectra
  - Best fit results for a sub-GUT model - soft-SUSY breaking occurs at a scale below the GUT scale

Long-Lived Particles

- Searches mentioned so far assume new particles have lifetime << 10^{-12} s
- Plenty of evidence in SM for long lifetimes !
  - Constrained interaction + potential barrier



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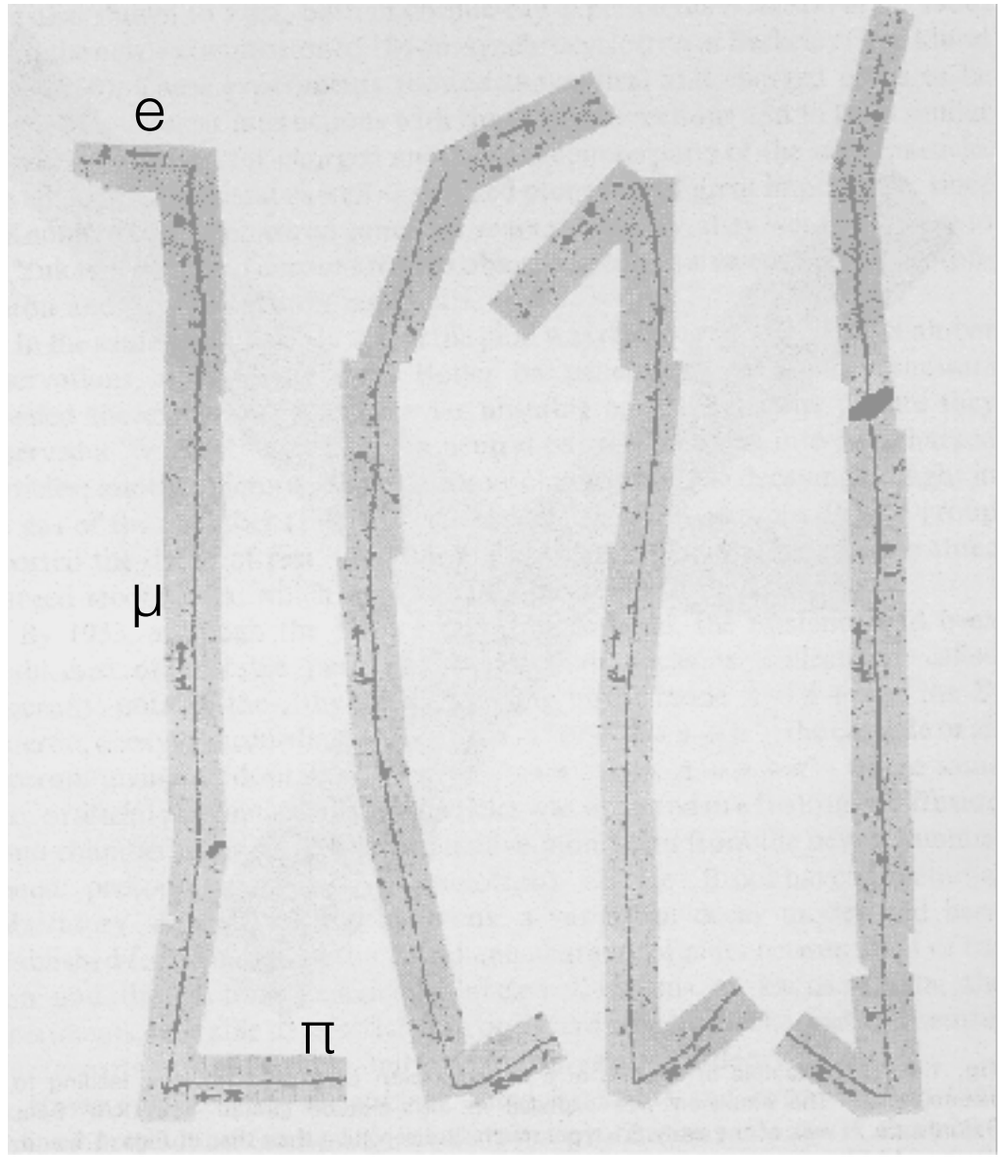
"Regular" mass hierarchy



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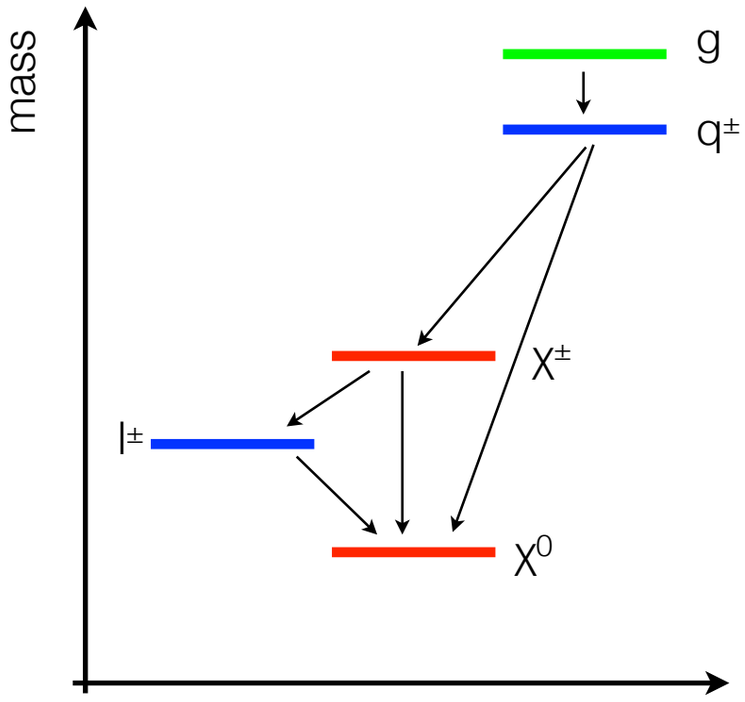
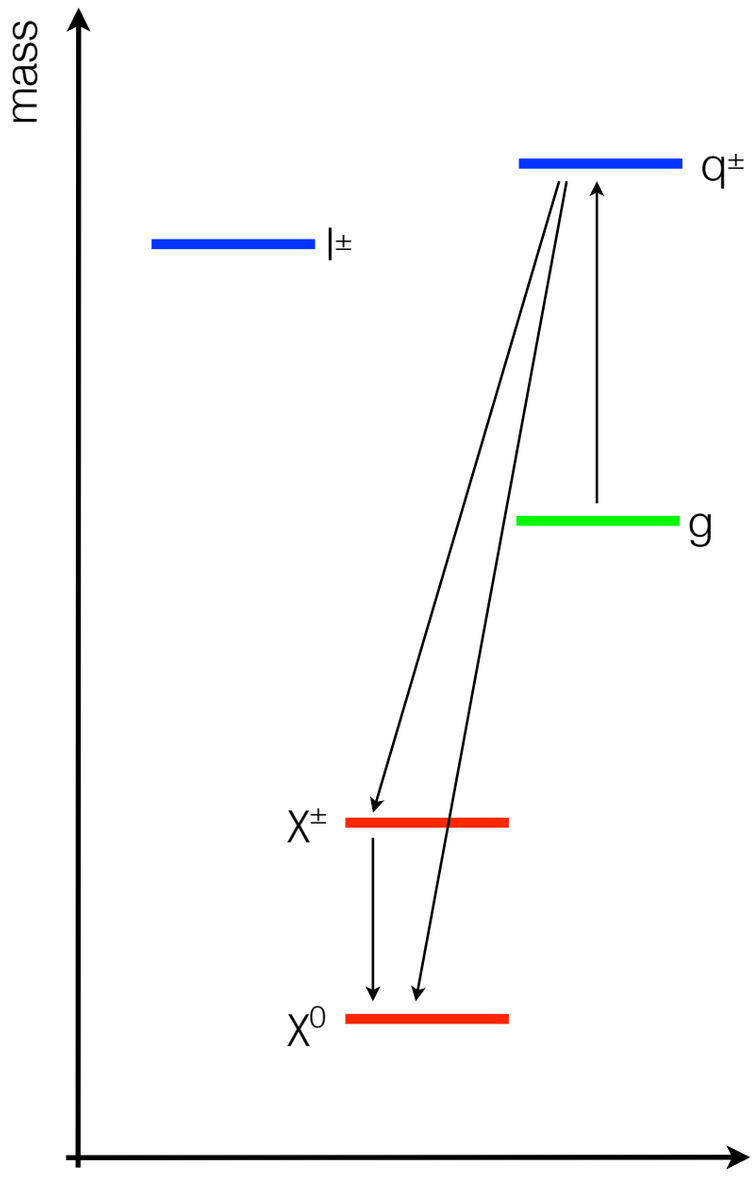


"Regular" mass hierarchy

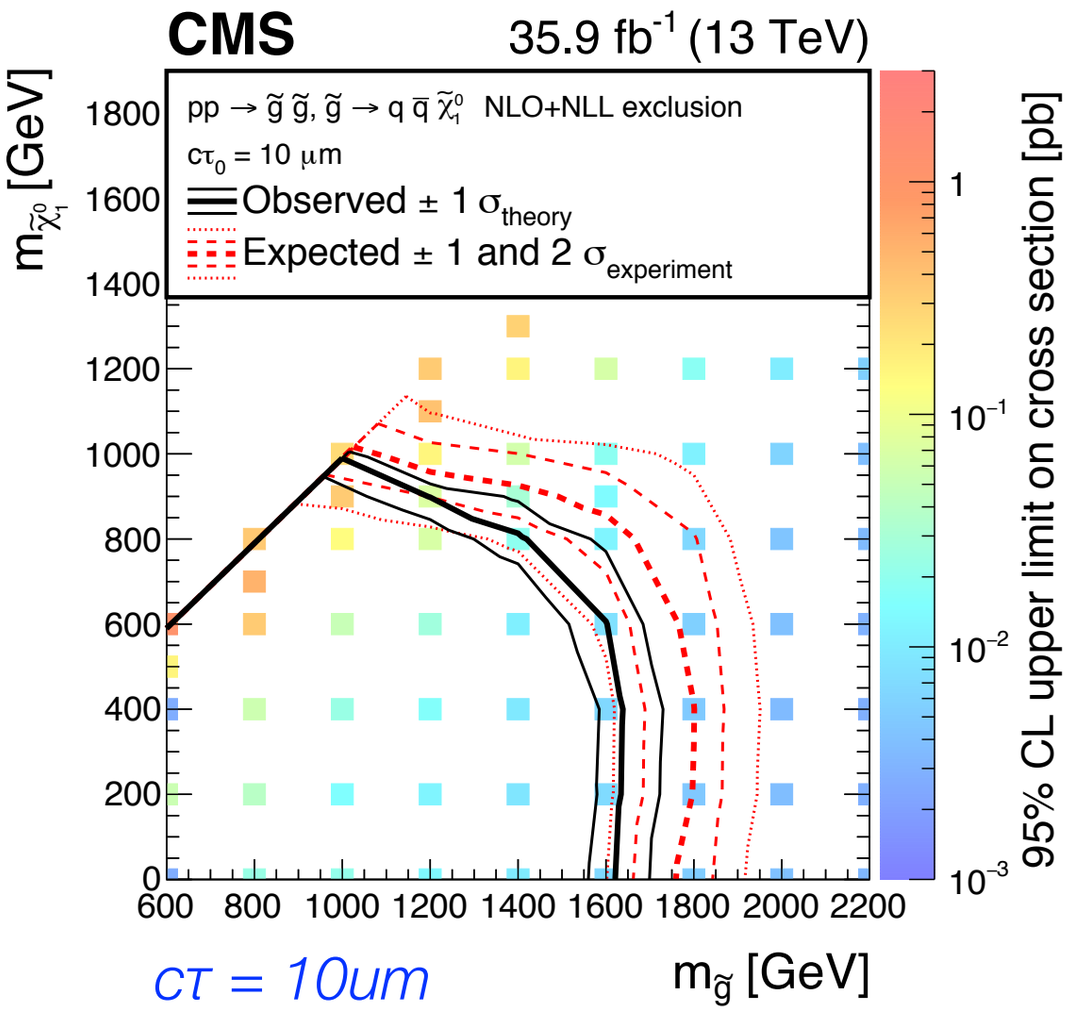


"Split-SUSY"

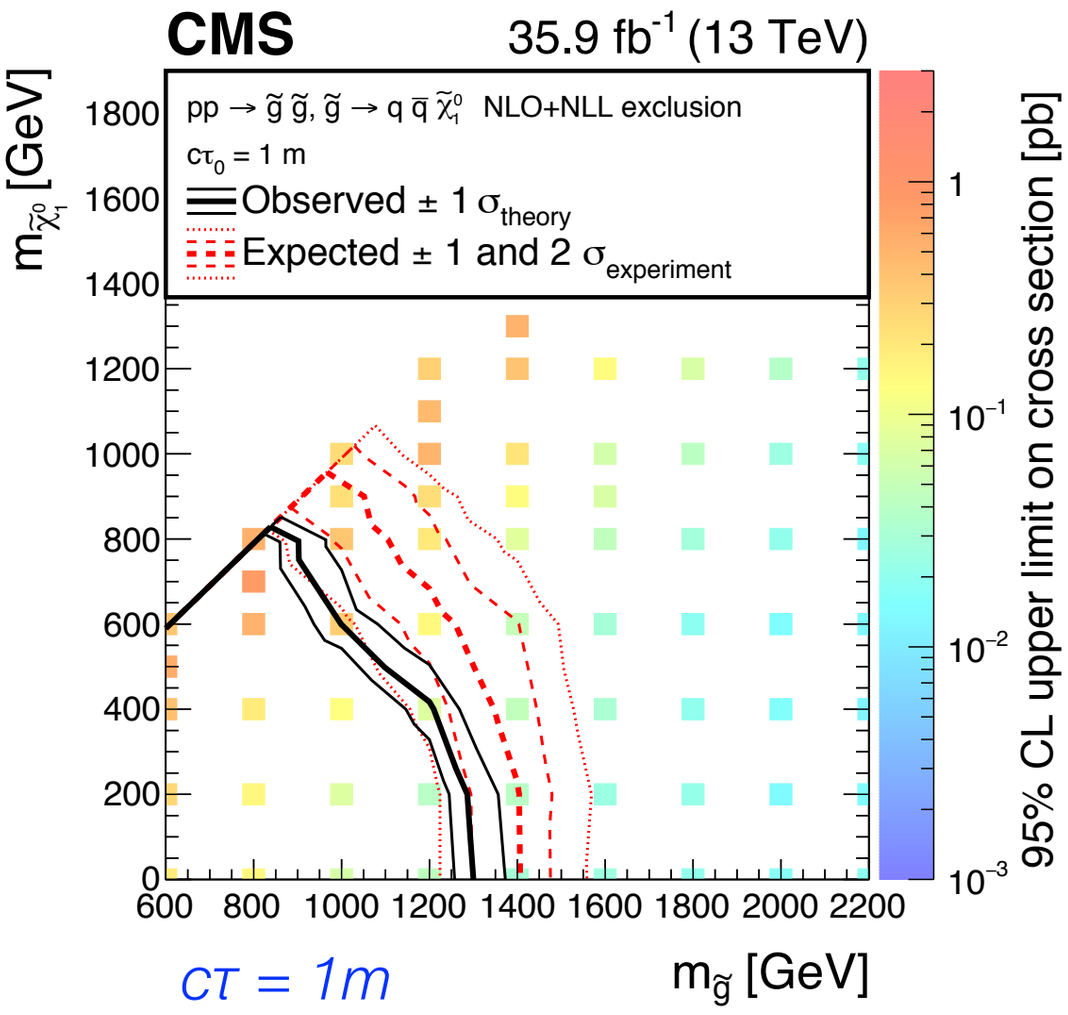
LLPs : Regular Searches

arXiv:1802.02110

- Regardless of mean lifetime; most probable real decay length is zero
- Existing searches (that look for promptly decaying objects) are sensitive



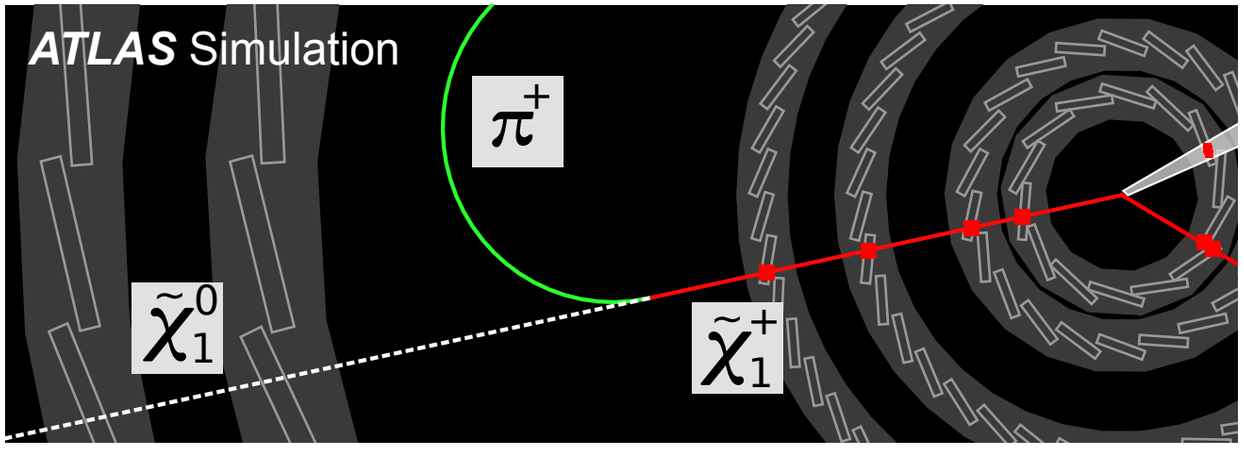
cτ = 10um

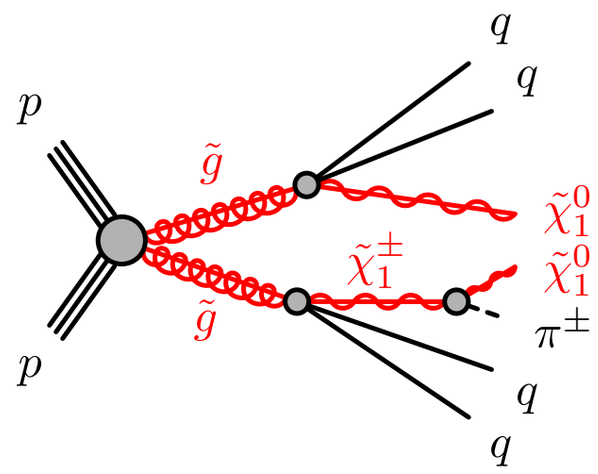


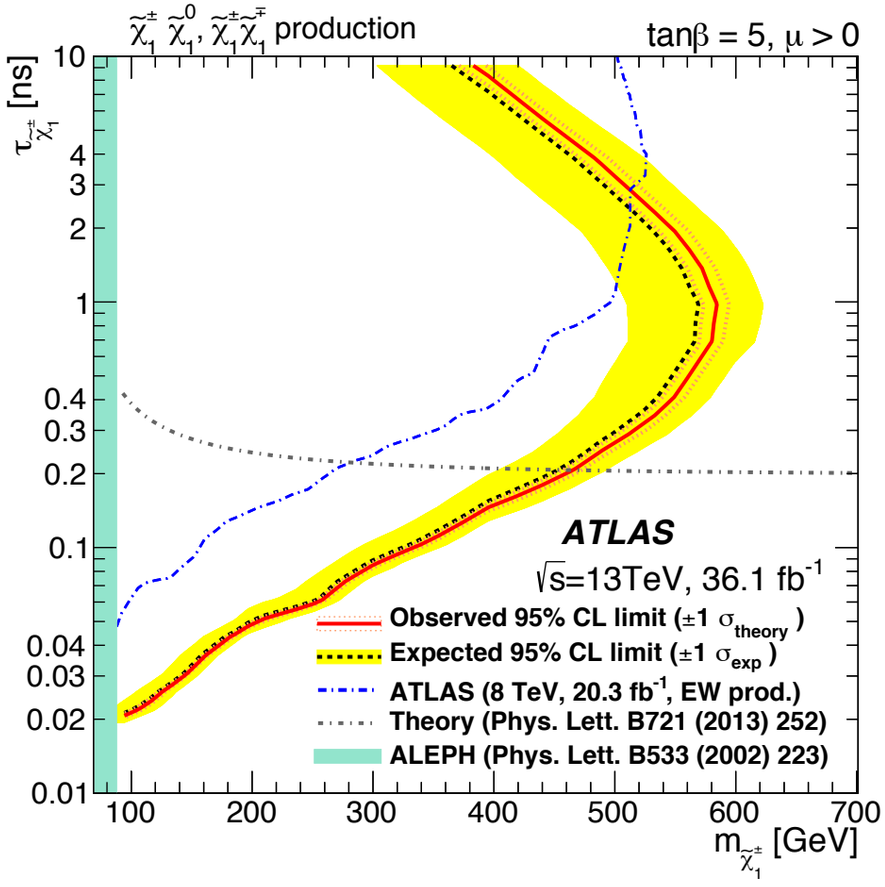
cτ = 1m

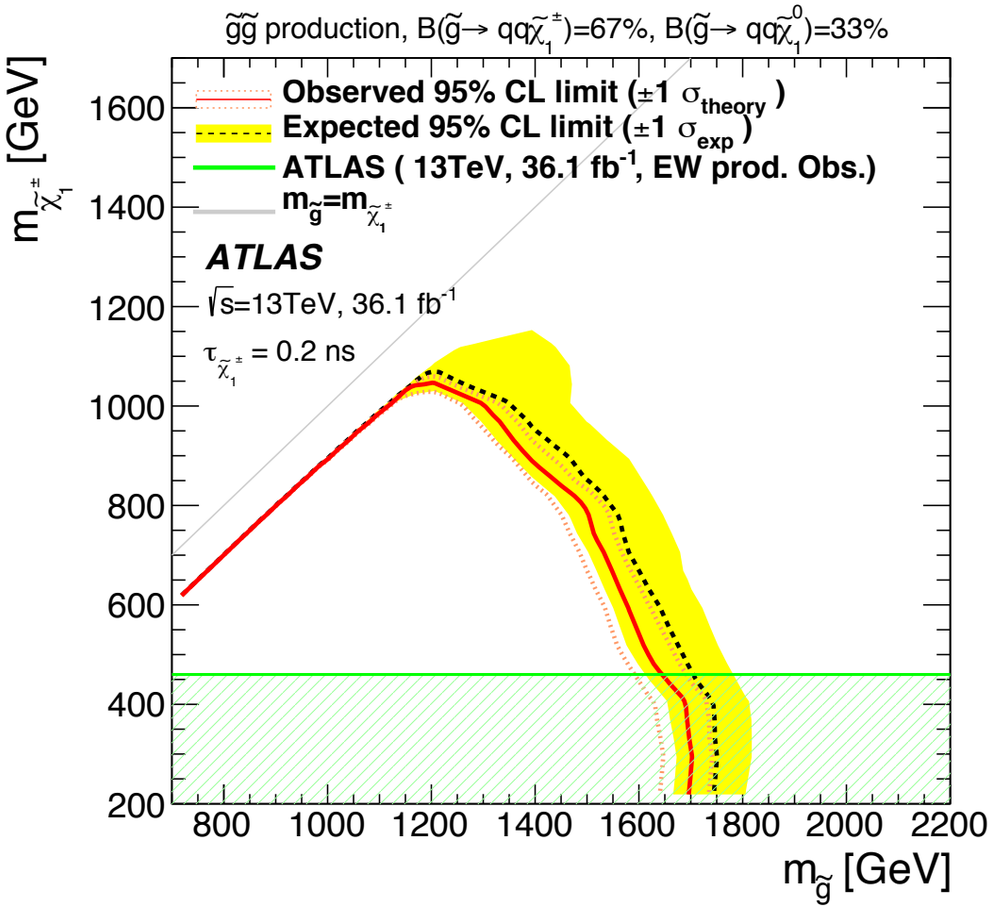
LLPs : Disappearing Tracks

arXiv:1712.02118



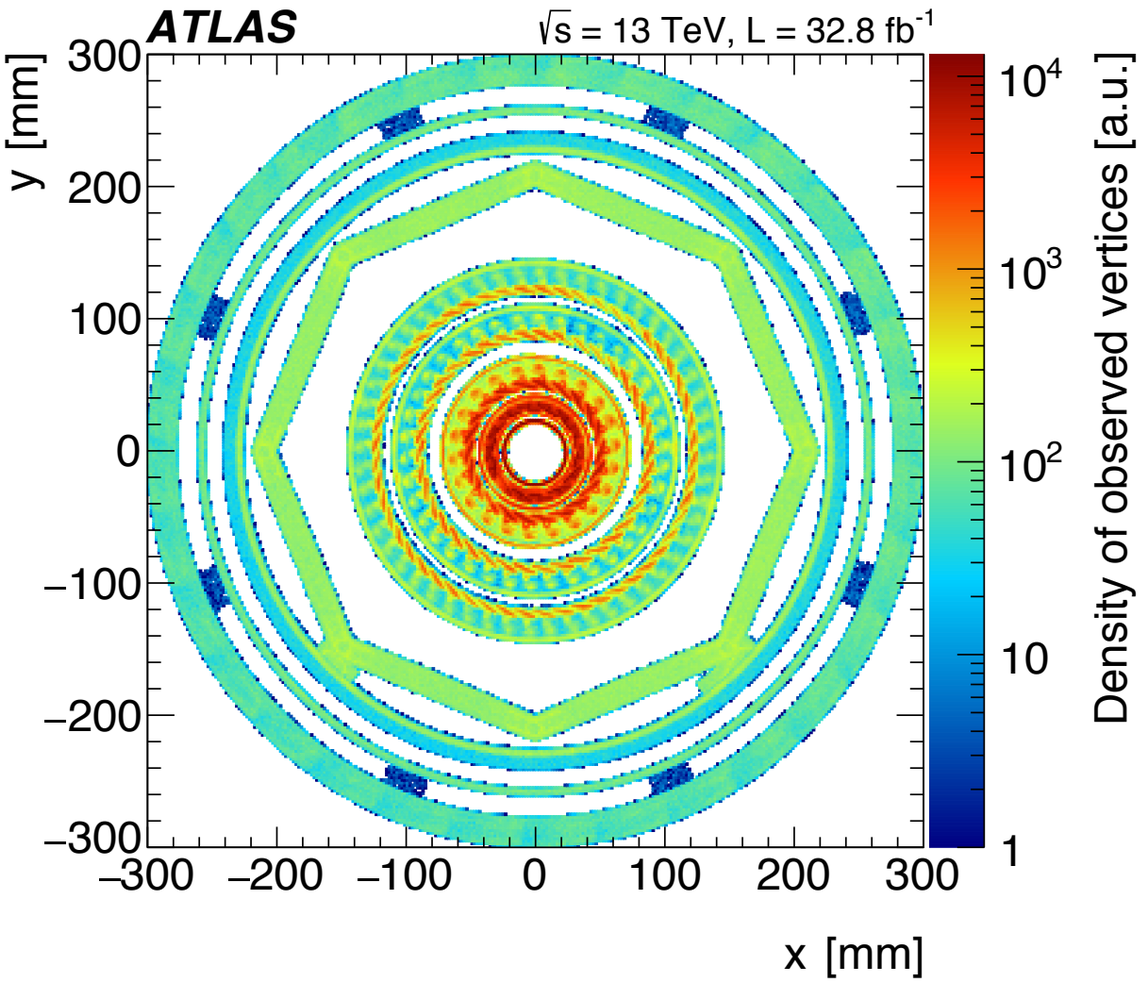


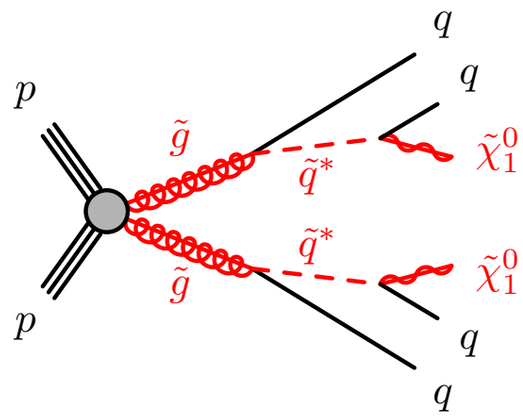


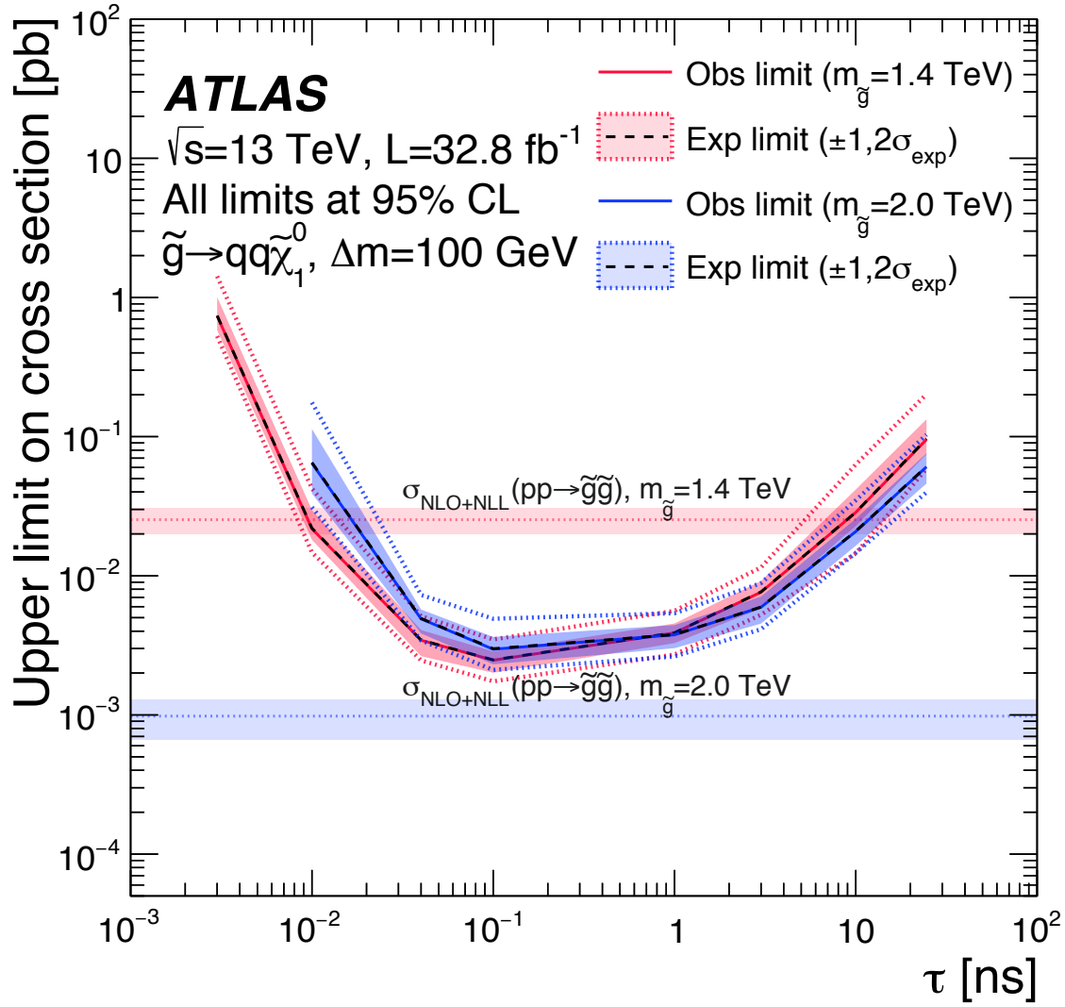


LLPs : Displaced Vertices

arXiv:1710.04901

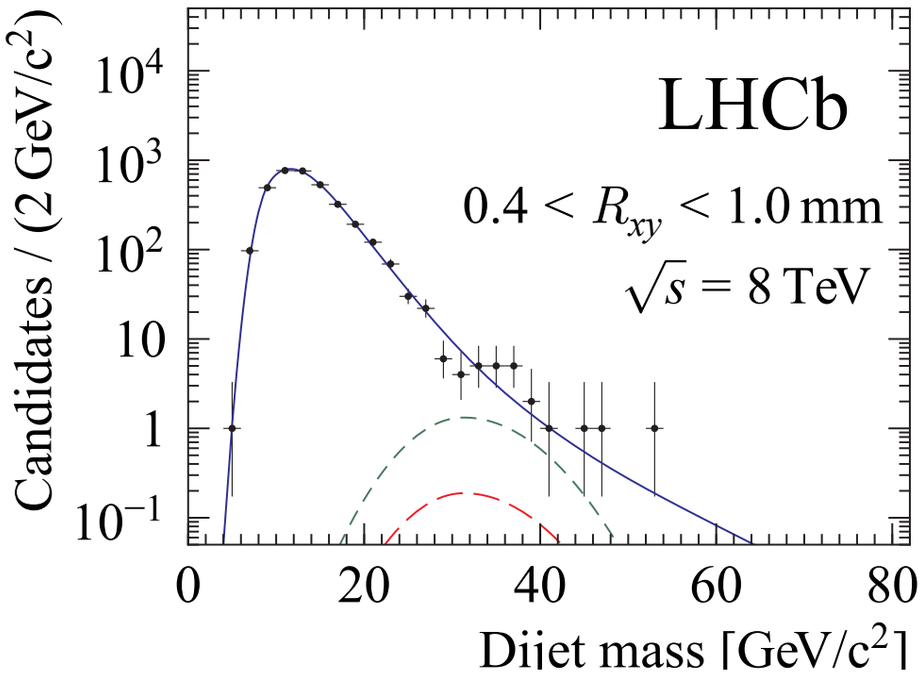


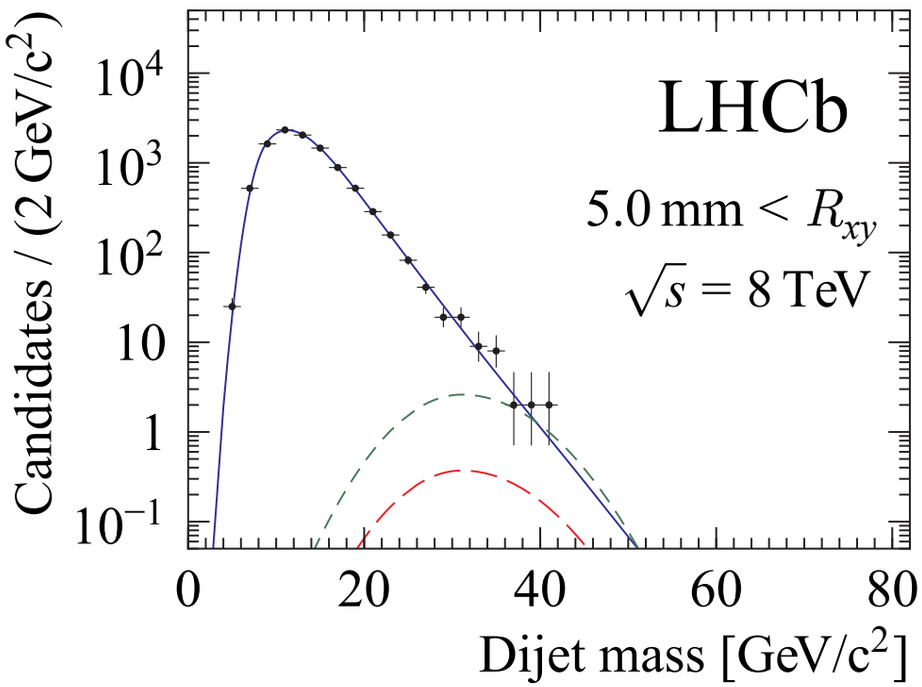




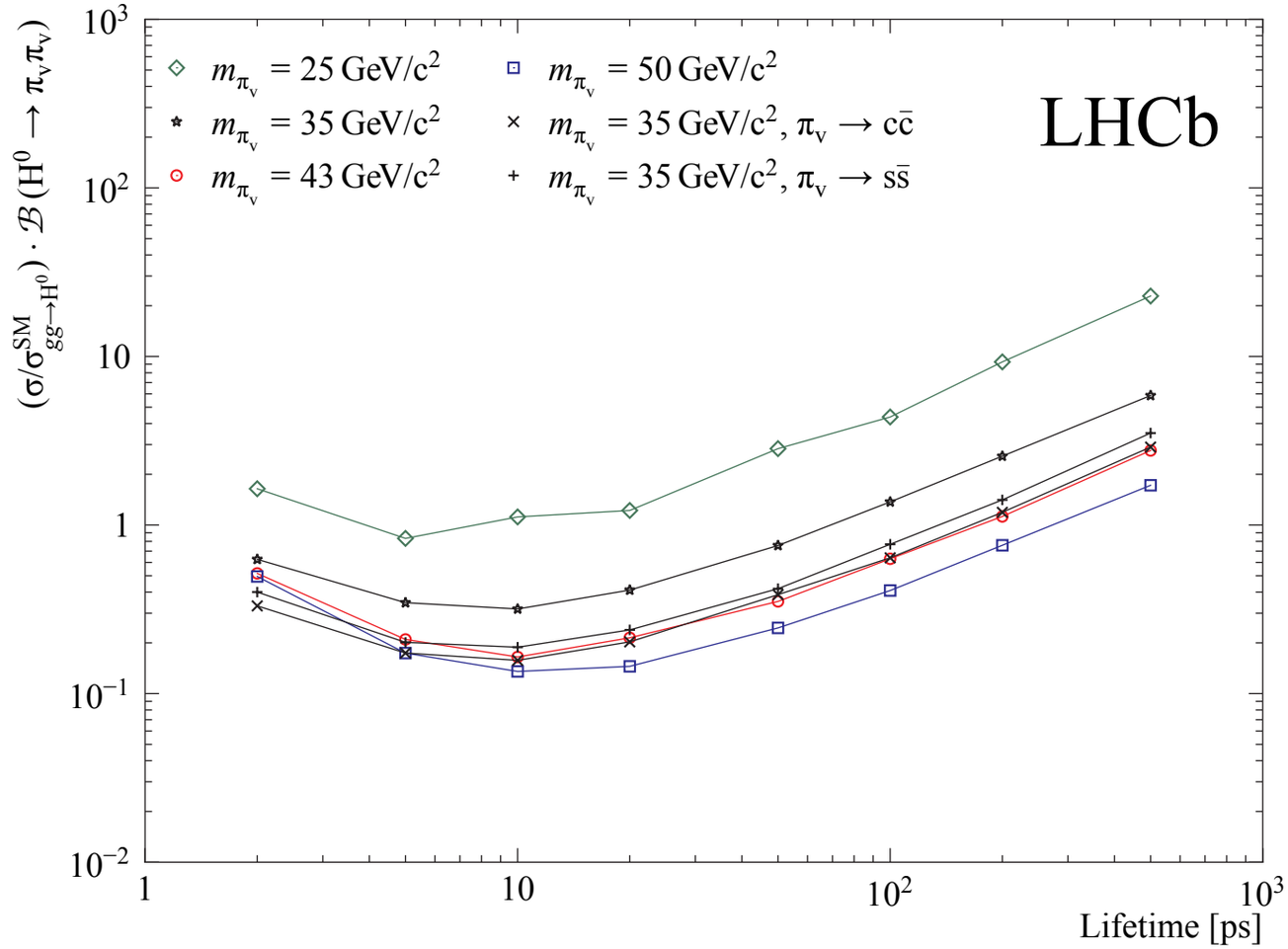
LLPs : Displaced Vertices

arXiv:1612.00945





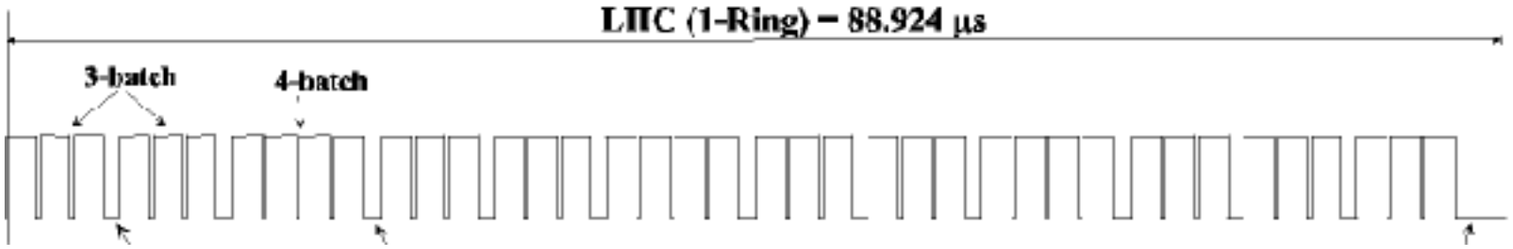
- Not only ATLAS & CMS performing direct searches !
- LHCb search for LLP decaying to pairs of jets (b, c, s)



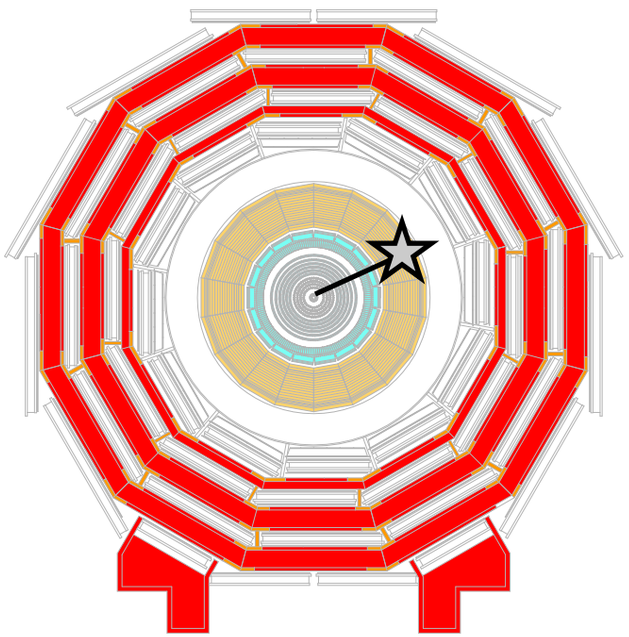
LLPs : Stopped Particles

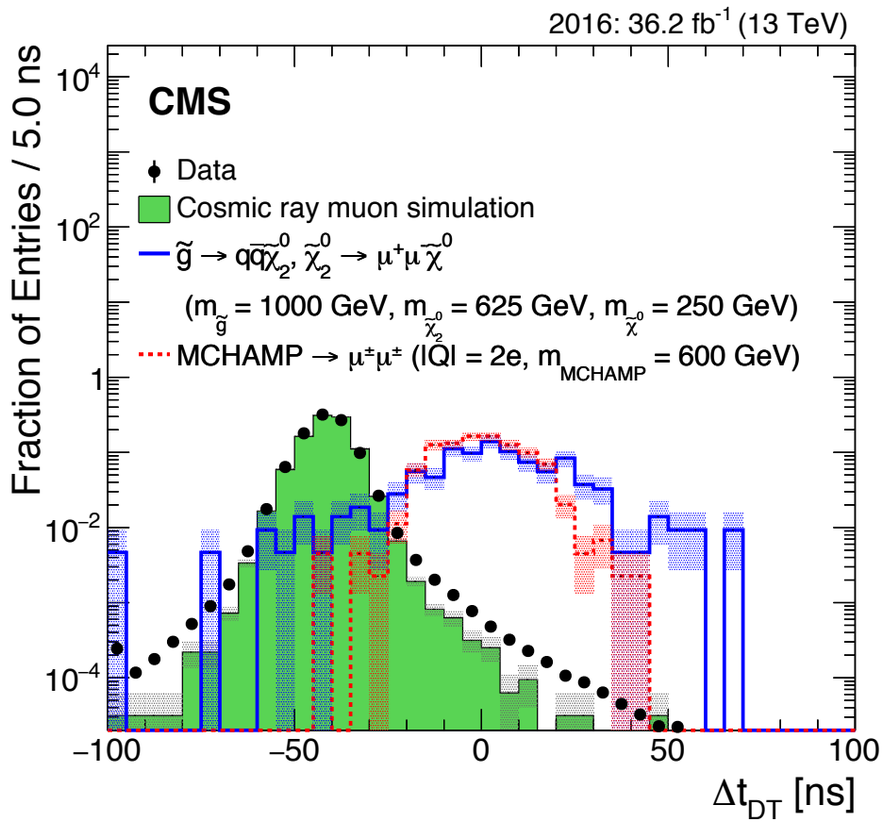
arXiv:1801.00359

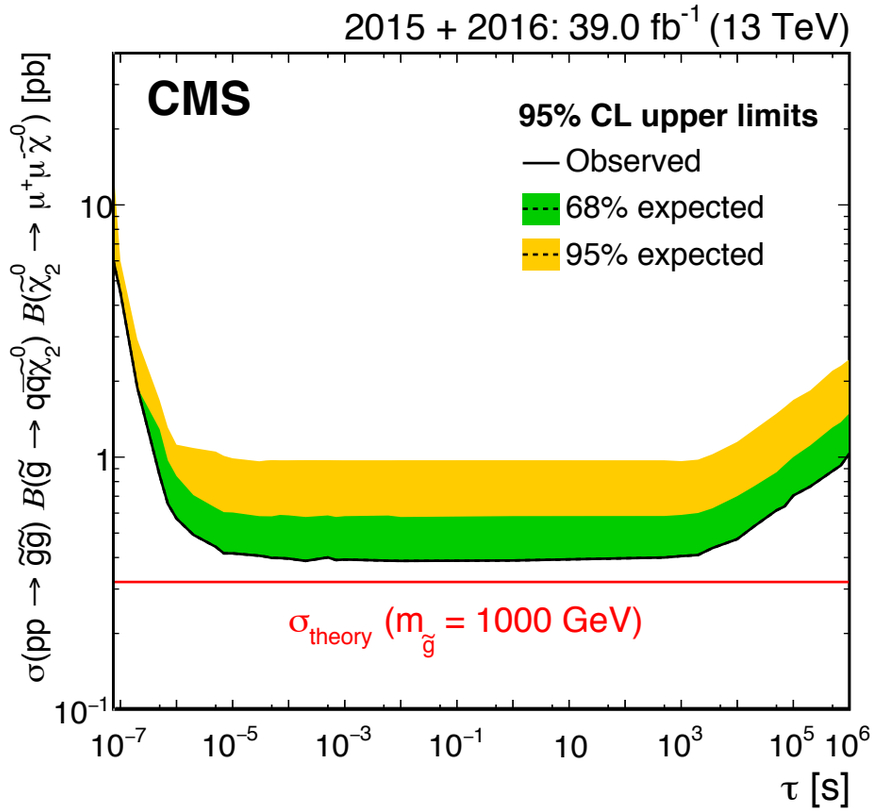
- Strongly interacting long-lived particles that stop in the detector
- Look for large calorimeter energy deposits at times when there are no collisions



New from CMS : decays to muons

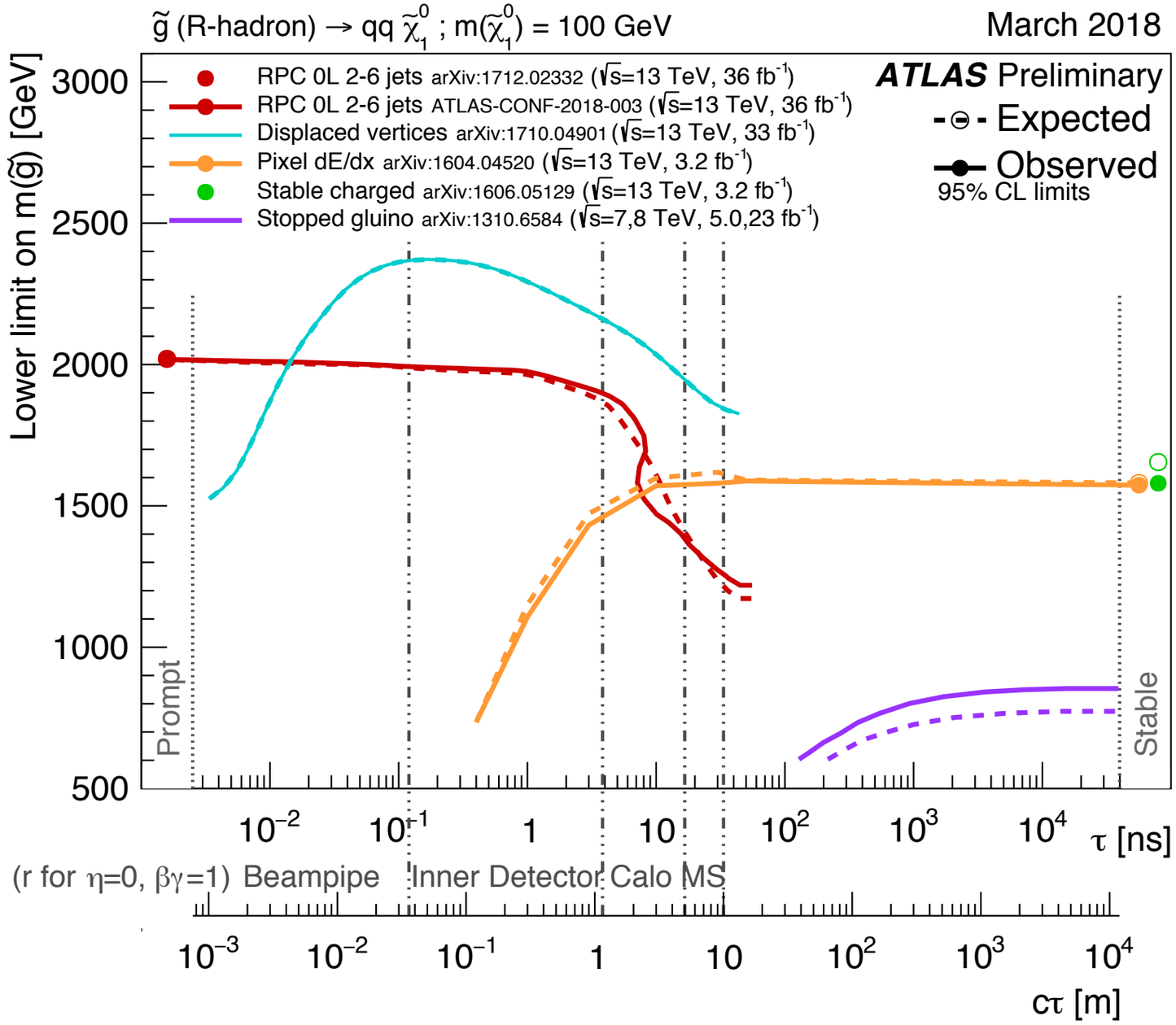






~11 orders of magnitude in t !

SUSY LLPs



- Cover a wide range of cτ using different reconstruction techniques

ATLAS Long-lived Particle Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L}\, dt$ = (18.4 - 20.3) fb^{-1} $\sqrt{s}$ = 8 TeV

	Model	Signature	$\int \mathcal{L}\, dt$[fb^{-1}]	Lifetime limit		Reference
SUSY	RPV $\chi_1^0 \to ee\nu/e\mu\nu/\mu\mu\nu$	displaced lepton pair	20.3	χ_1^0 lifetime	7-740 mm	$m(\tilde{g}) = 1.3$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	GGM $\chi_1^0 \to Z\tilde{G}$	displaced vtx + jets	20.3	χ_1^0 lifetime	6-480 mm	$m(\tilde{g}) = 1.1$ TeV, $m(\chi_1^0) = 1.0$ TeV	1504.05162
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	disappearing track	20.3	$\chi_1^\pm$ lifetime	0.22-3.0 m	$m(\chi_1^\pm) = 450$ GeV	1310.3675
	AMSB $pp \to \chi_1^\pm\chi_1^0, \chi_1^+\chi_1^-$	large pixel dE/dx	18.4	$\chi_1^\pm$ lifetime	1.31-9.0 m	$m(\chi_1^\pm) = 450$ GeV	1506.05332
	GMSB	non-pointing or delayed γ	20.3	χ_1^0 lifetime	0.08-5.4 m	SPS8 with $\Lambda = 200$ TeV	1409.5542
	Stealth SUSY	2 ID/MS vertices	19.5	$\tilde{S}$ lifetime	0.12-90.6 m	$m(\tilde{g}) = 500$ GeV	1504.03634
Higgs BR = 10%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.41-7.57 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.31-25.4 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 2\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime	14-140 mm	$H \to 2\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime	15-260 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
Higgs BR = 5%	Hidden Valley $H \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.6-5.0 m	$m(\pi_v) = 25$ GeV	1501.04020
	Hidden Valley $H \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.43-18.1 m	$m(\pi_v) = 25$ GeV	1504.03634
	FRVZ $H \to 4\gamma_d + X$	2 $e-, \mu-, \pi-$jets	20.3	γ_d lifetime	28-160 mm	$H \to 4\gamma_d + X$, $m(\gamma_d) = 400$ MeV	1409.0746
300 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.29-7.9 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.19-31.9 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
900 GeV scalar	Hidden Valley $\Phi \to \pi_v\pi_v$	2 low-EMF trackless jets	20.3	π_v lifetime	0.15-4.1 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1501.04020
	Hidden Valley $\Phi \to \pi_v\pi_v$	2 ID/MS vertices	19.5	π_v lifetime	0.11-18.3 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
Other	HV Z'(1 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime	0.1-4.9 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634
	HV Z'(2 TeV) $\to q_v q_v$	2 ID/MS vertices	20.3	π_v lifetime	0.1-10.1 m	$\sigma\times$BR = 1 pb, $m(\pi_v) = 50$ GeV	1504.03634

0.01 0.1 1 10 100 $c\tau$ [m]

$\sqrt{s}$ = 8 TeV

**Only a selection of the available lifetime limits on new states is shown.*

Beyond SUSY

Compositeness

Vector-like quarks

Extra gauge bosons

Leptoquarks

Dark Sectors

Resonances

Extra fermions

Mini black holes

Extra dimensions

Hidden Valleys

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)$ fb^{-1} $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV	η_{LL}^-	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

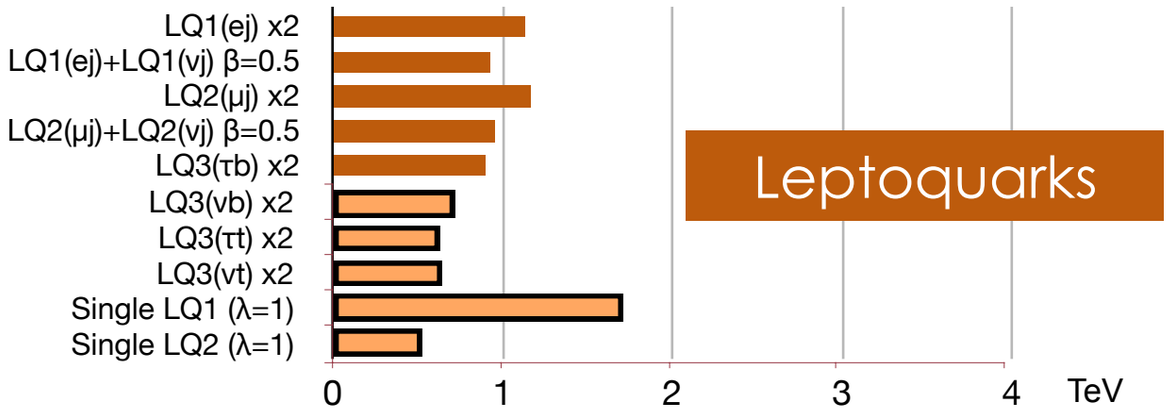
$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

10^{-1} 1 10 **Mass scale [TeV]**

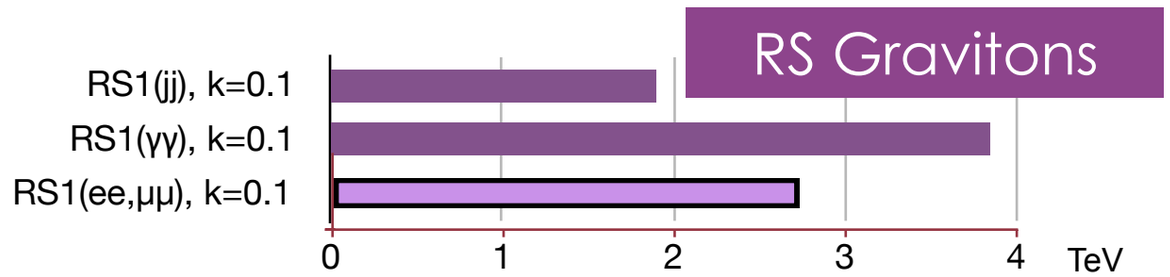
**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

13 TeV 8 TeV

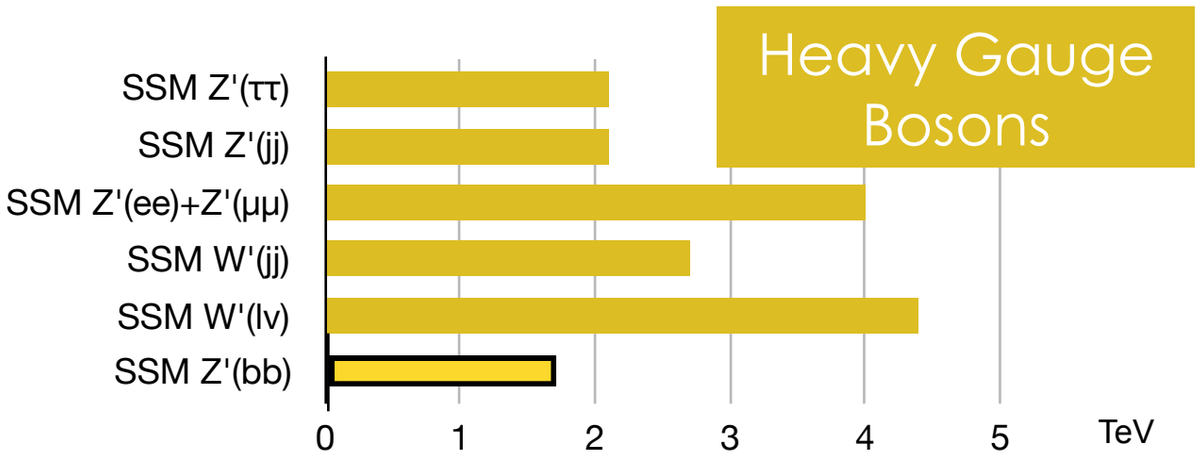


Leptoquarks

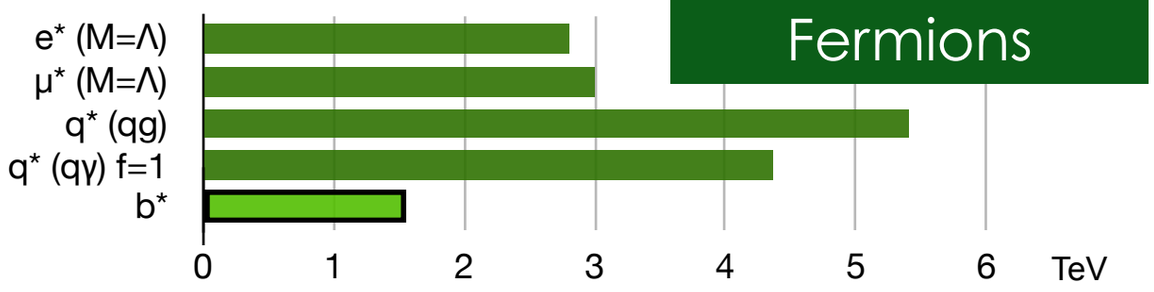


RS Gravitons

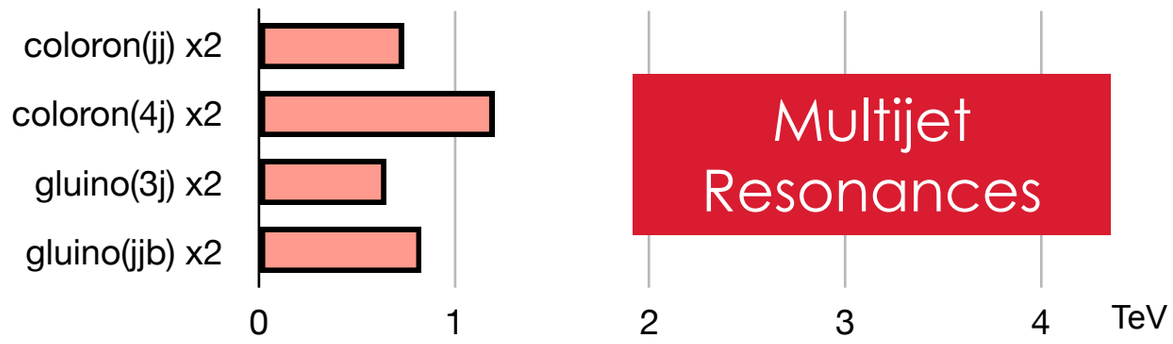
CMS Preliminary



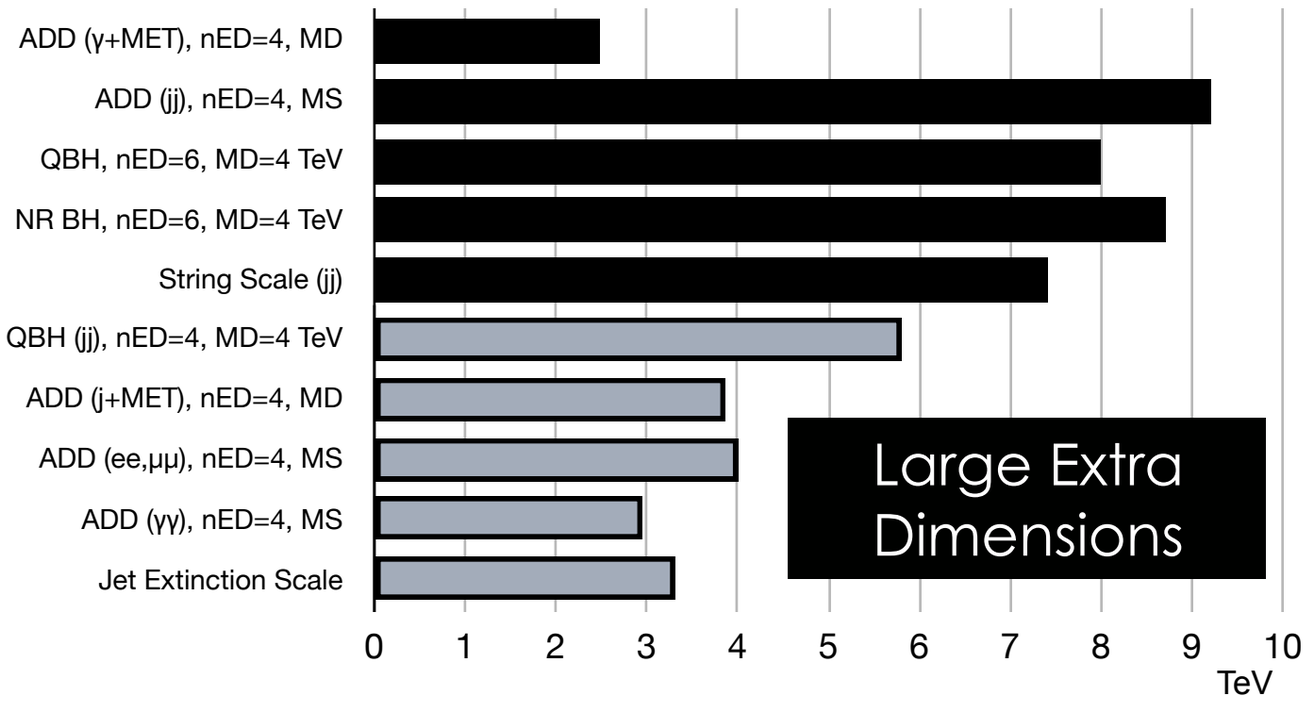
Heavy Gauge Bosons



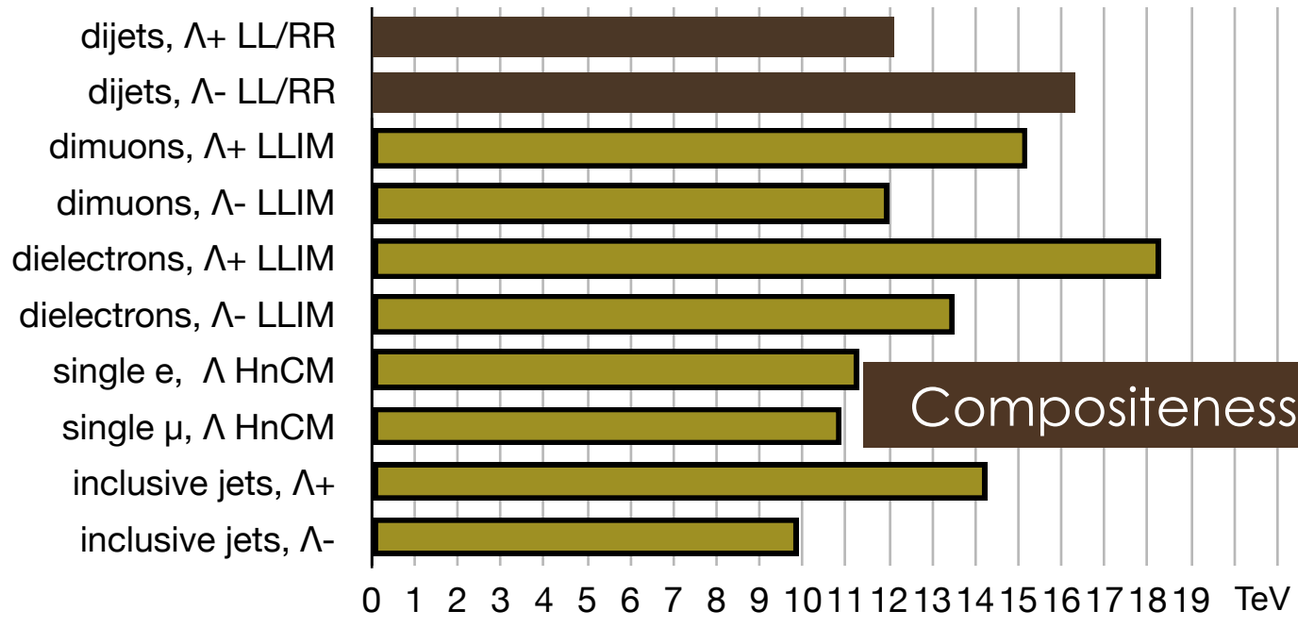
Excited Fermions



Multijet Resonances



Large Extra Dimensions

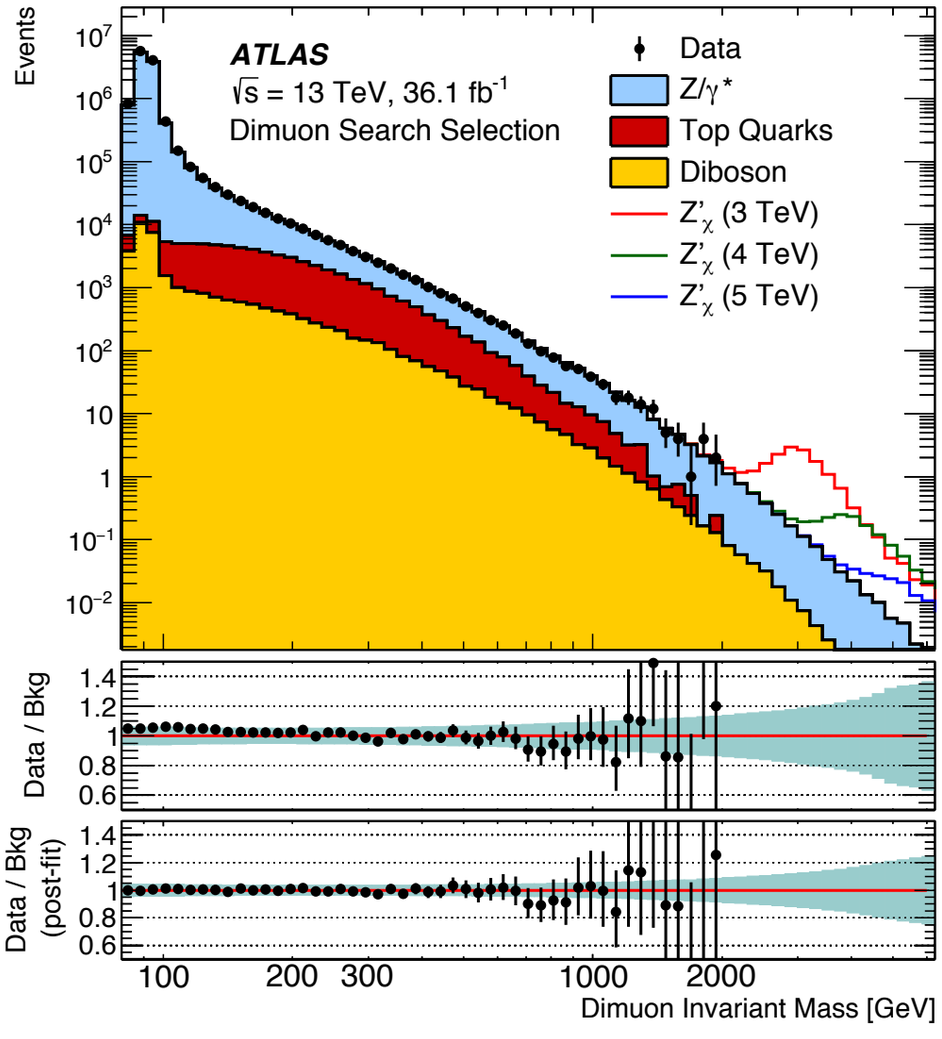


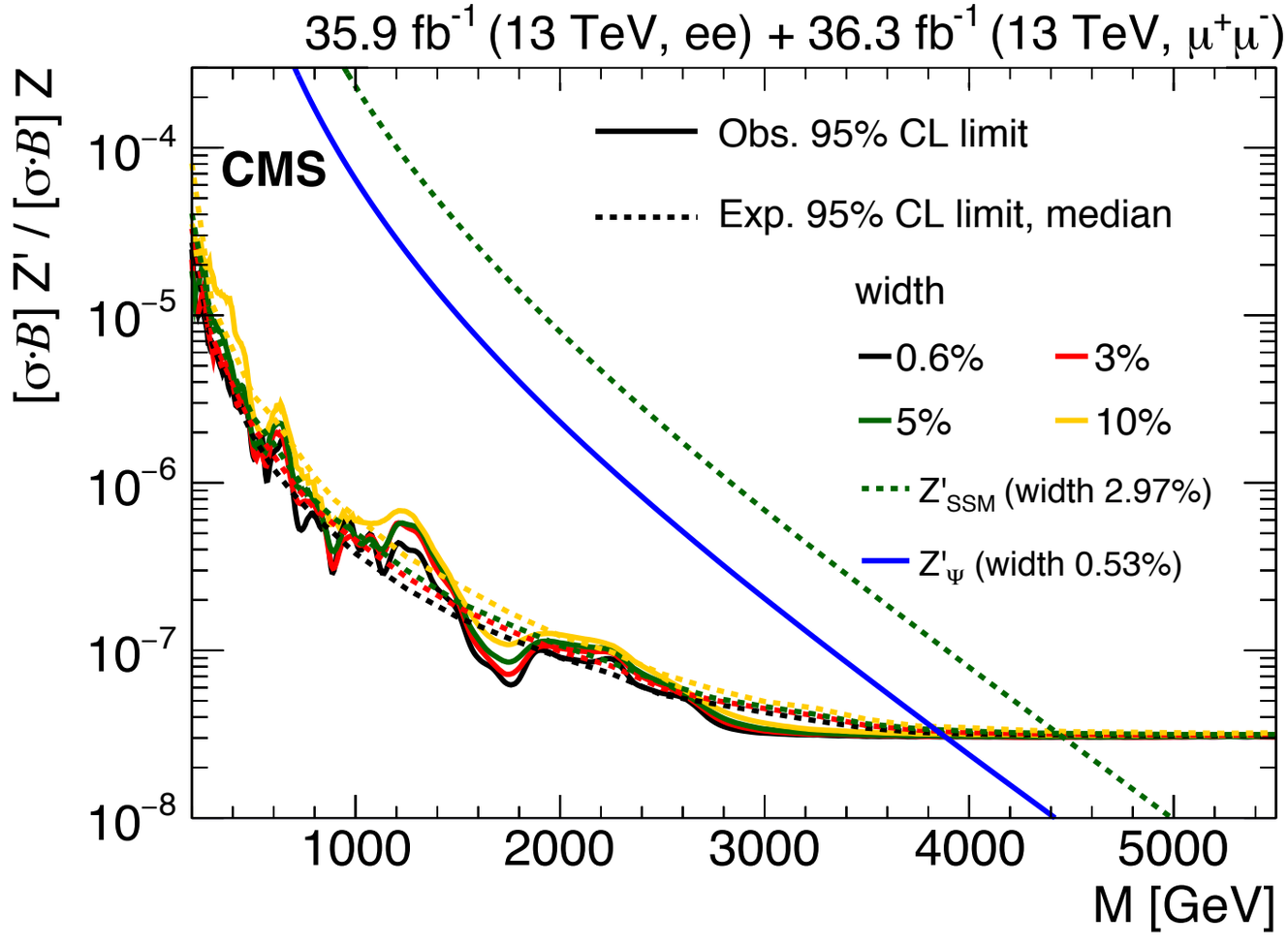
Compositeness

Di-Lepton Resonances

arXiv:1803.06292,arXiv:1707.02424

- Search for a heavy Z-like boson decaying to lepton pair
- Recent ATLAS result sets limits in the 4-4.5 TeV range, depending on model

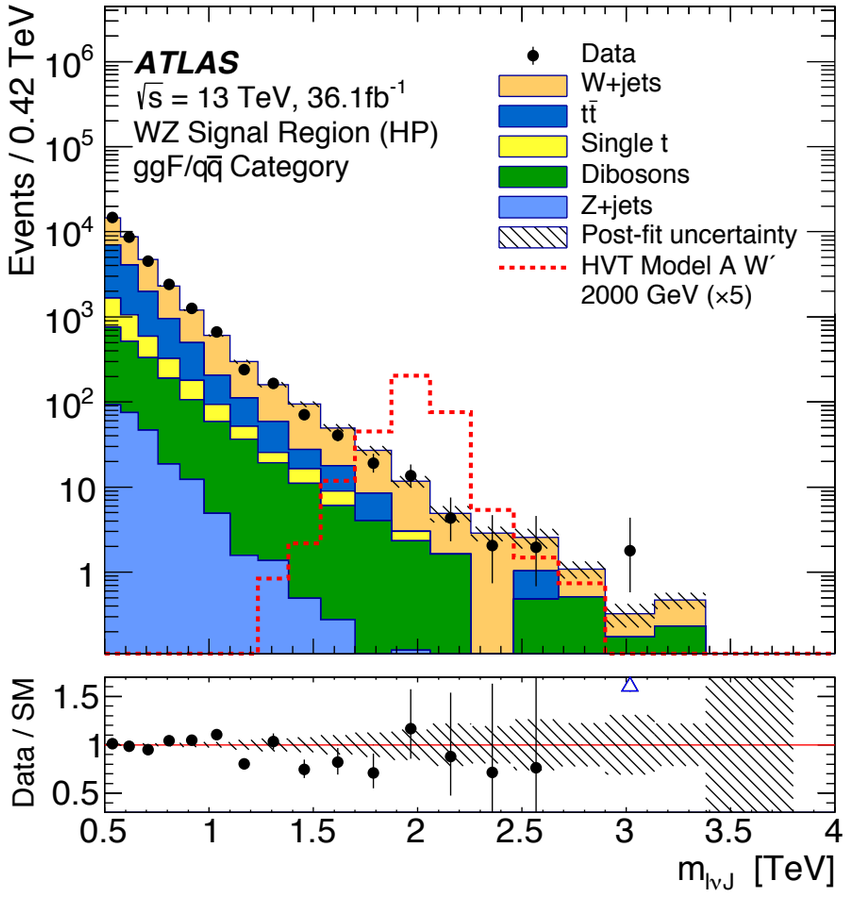


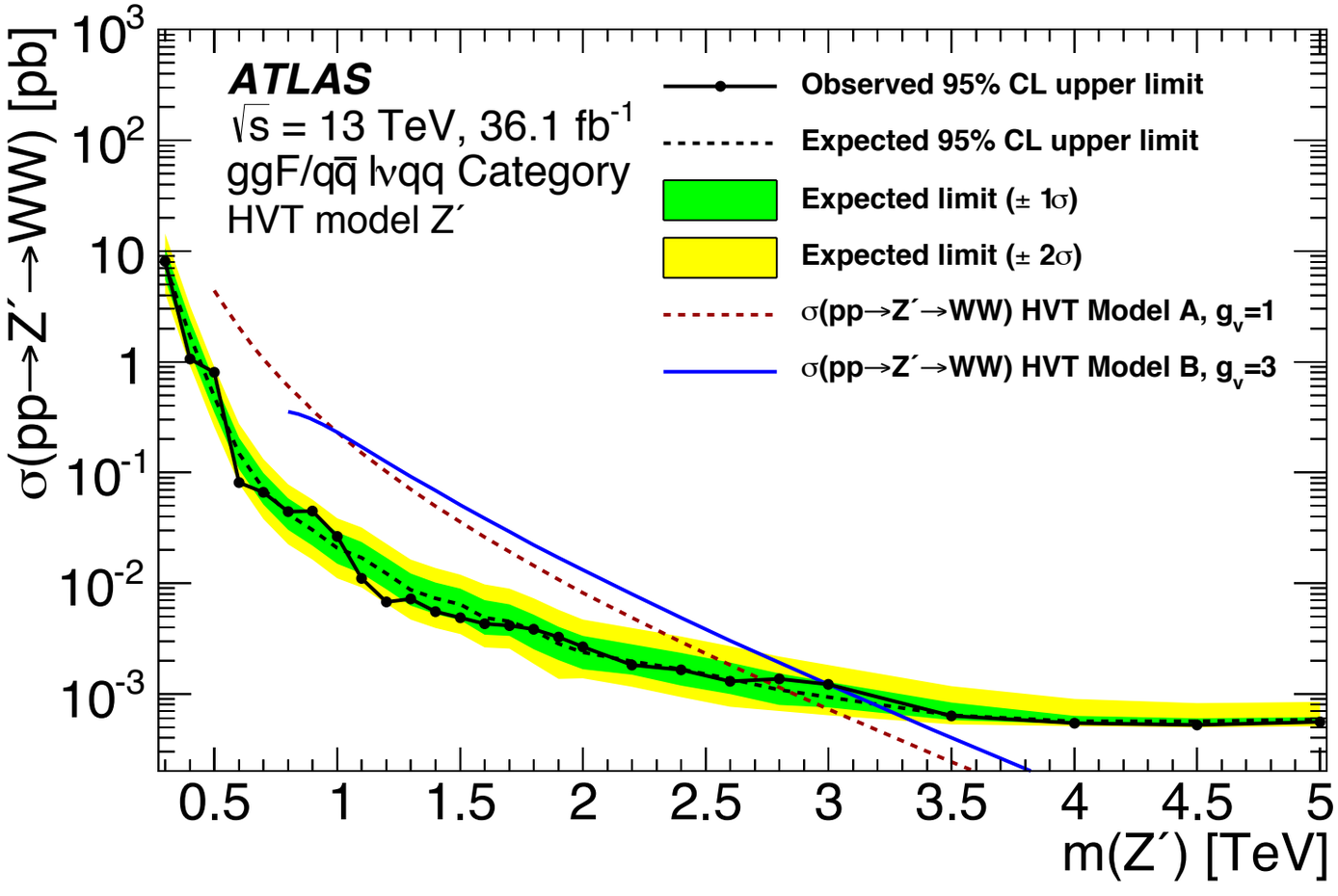


Di-Boson Resonances

Talk by David Lack

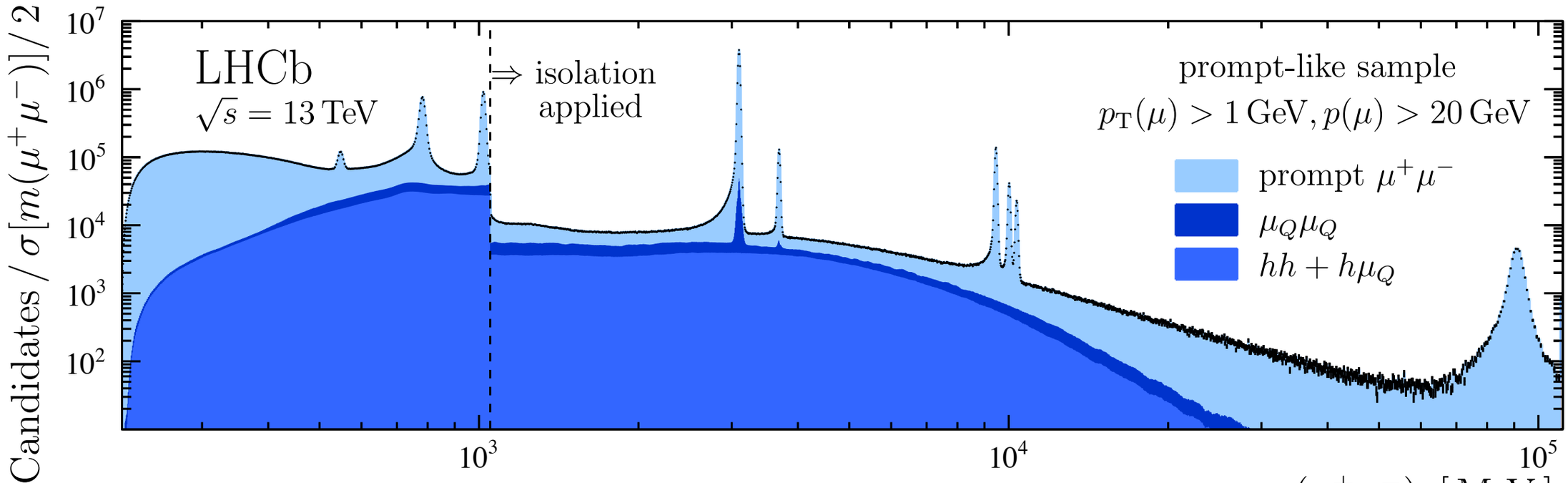
- Hint of an excess around 2 TeV in di-boson searches at the end of Run 1
  - Clearly not present in Run 2 data





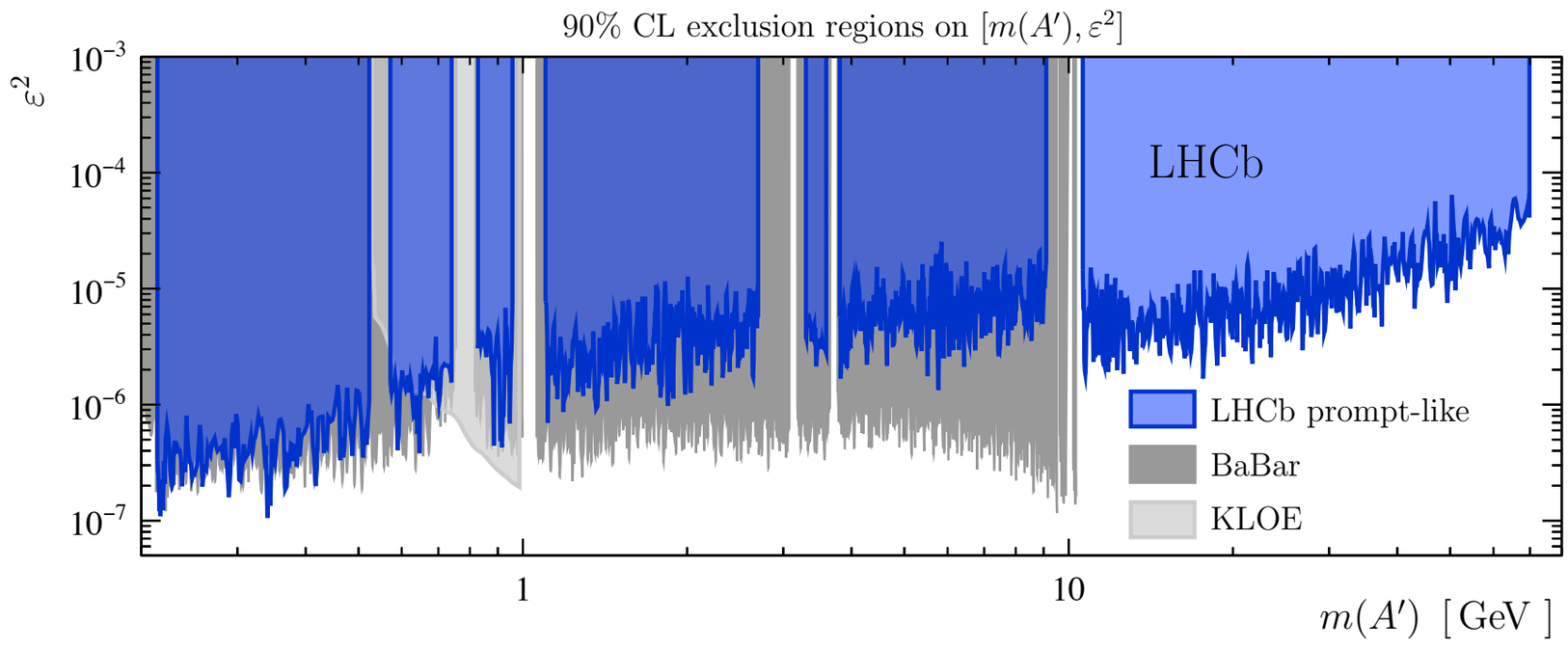
Di-Muon Resonances

arXiv:1710.02867



Search for dark photons decaying to $\mu^+\mu^-$

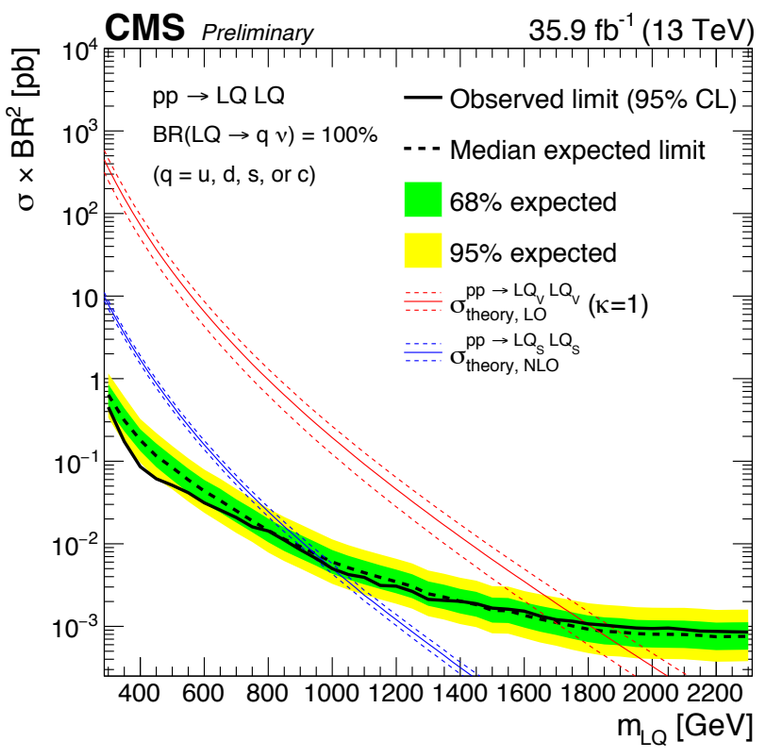
Also include long-lifetimes!



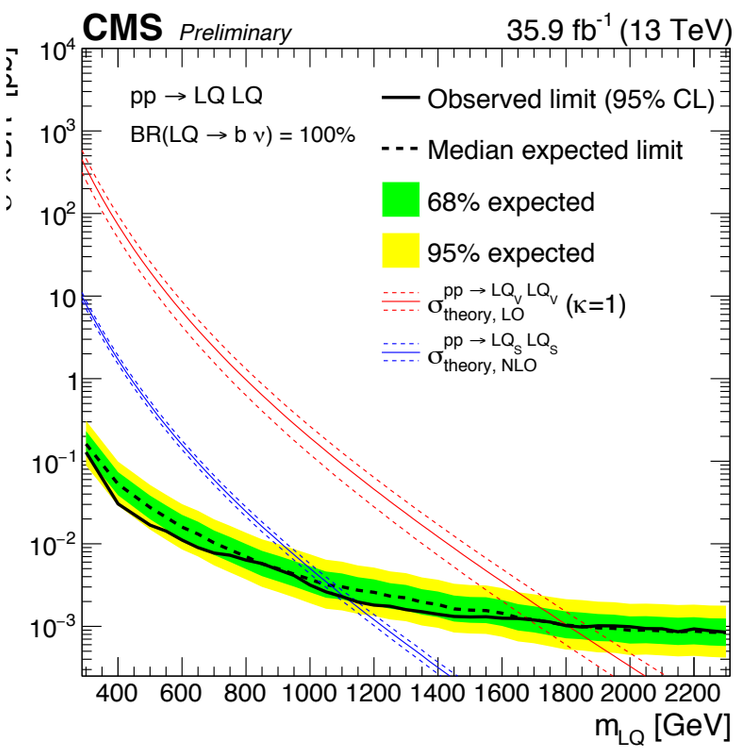
Leptoquarks

CMS-PAS-SUS-18-001

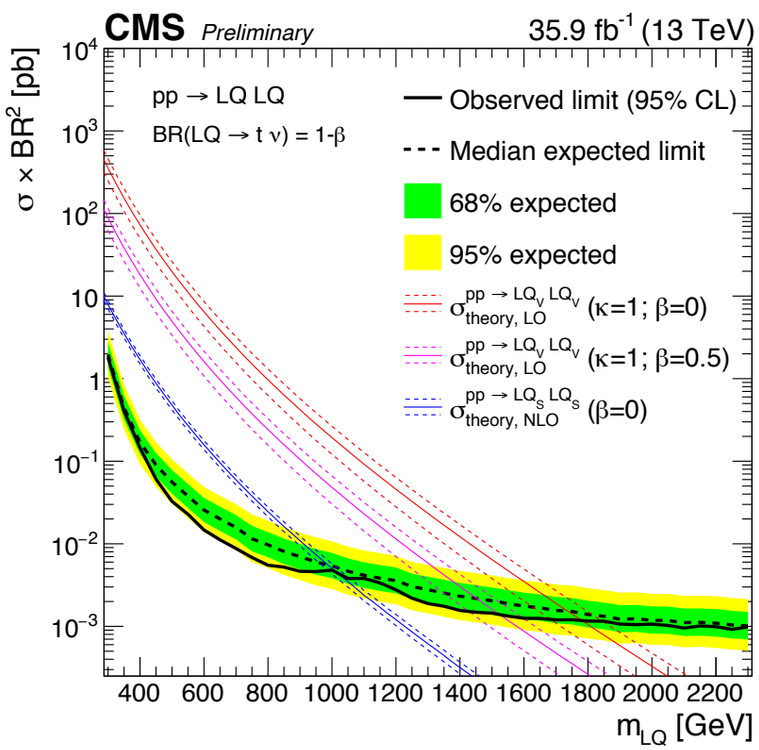
- Hypothetical particle with couplings to both leptons and quarks
  - Vector LQ proposed as solution to flavour anomalies -
- SUSY searches for jets+MET are sensitive to LQ → q ν
  - Re-interpretation of CMS M_{T2} search : vector LQ mass > ~1800 GeV



LQ → u/d/s/c + ν



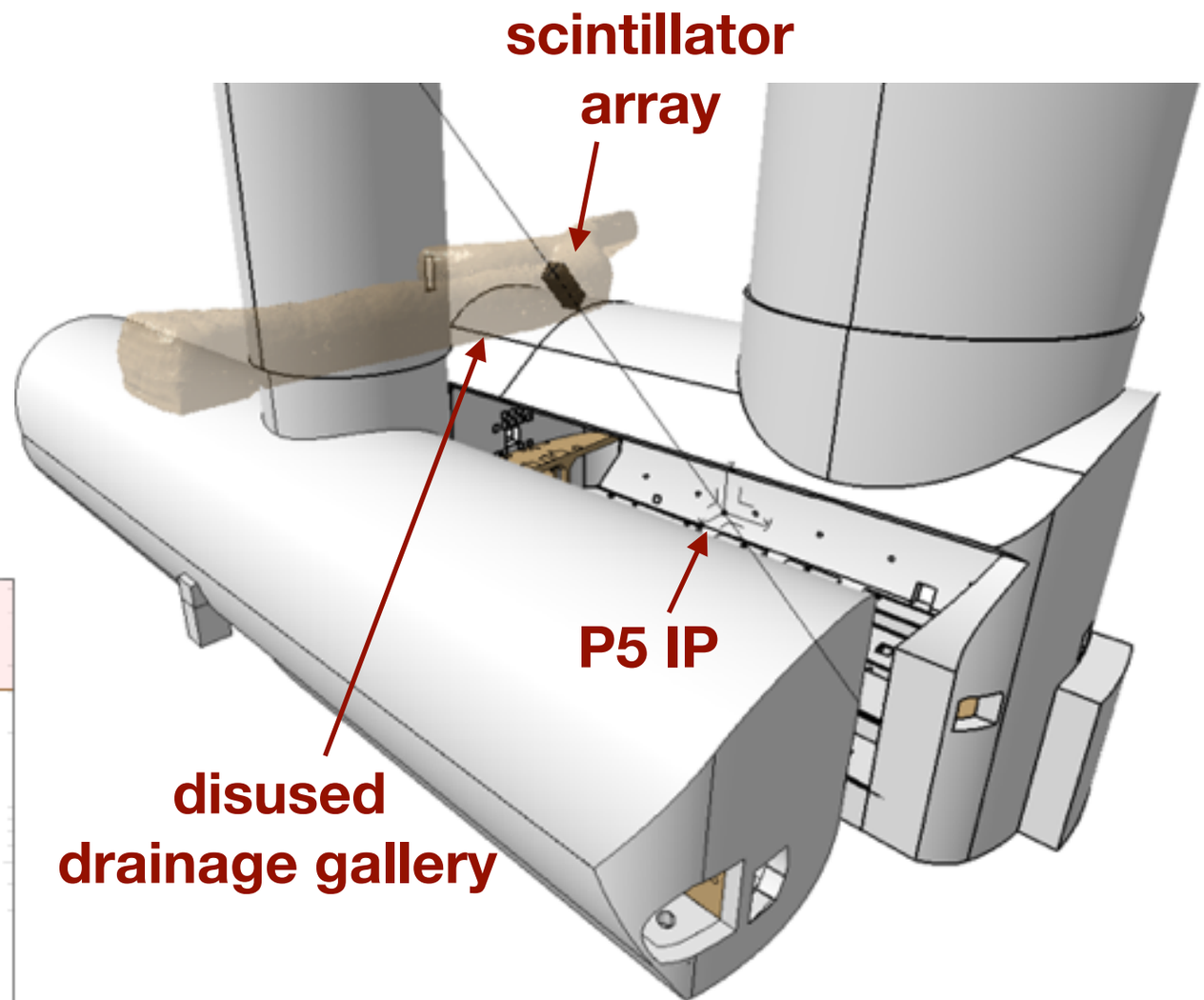
LQ → b + ν

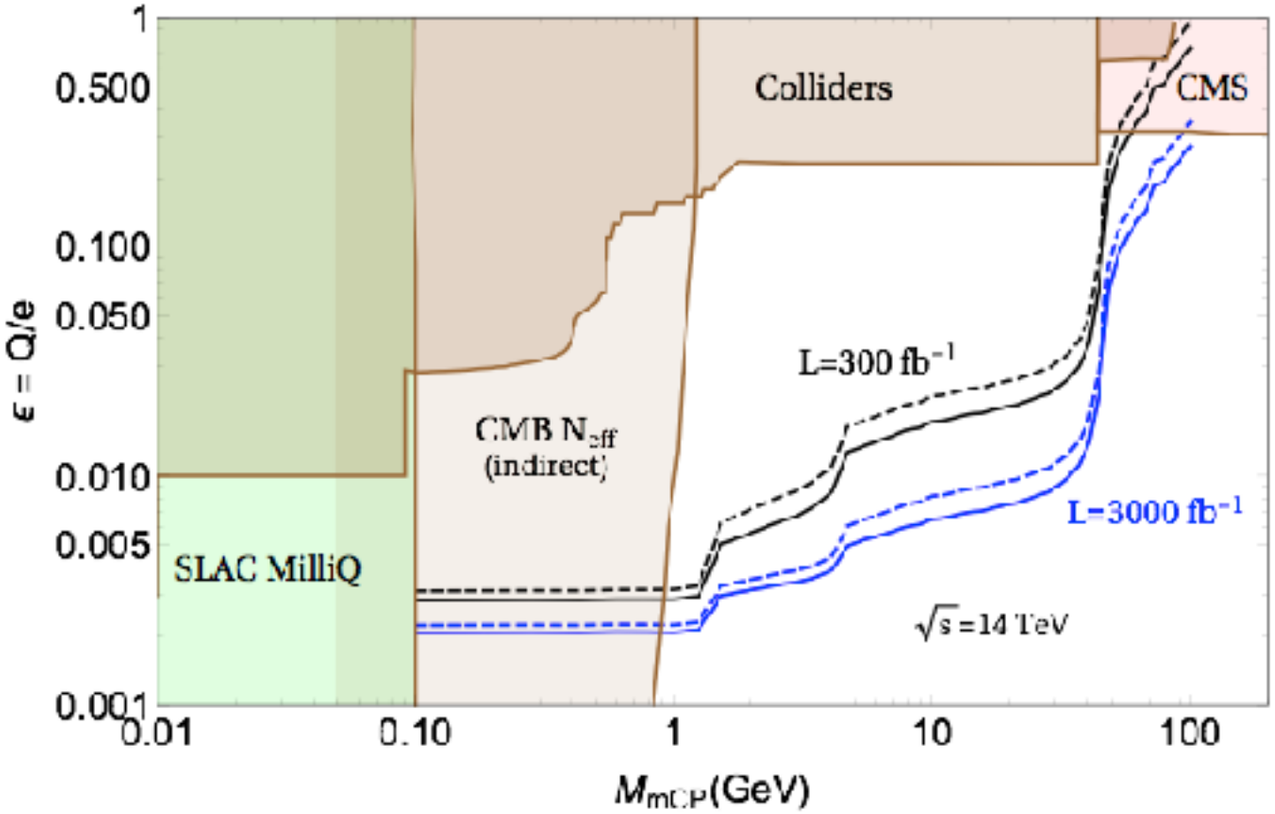


LQ → t + ν

MilliCharged Particles

- Millicharged particles arise from a dark sector with a new U(1) gauge symmetry
- Dark photon mixes with SM photon, giving effective charge to dark fermions
- Not detectable with GPDs





Haas, Hill, Izaguirre, Yavin PLB 746 (2015)

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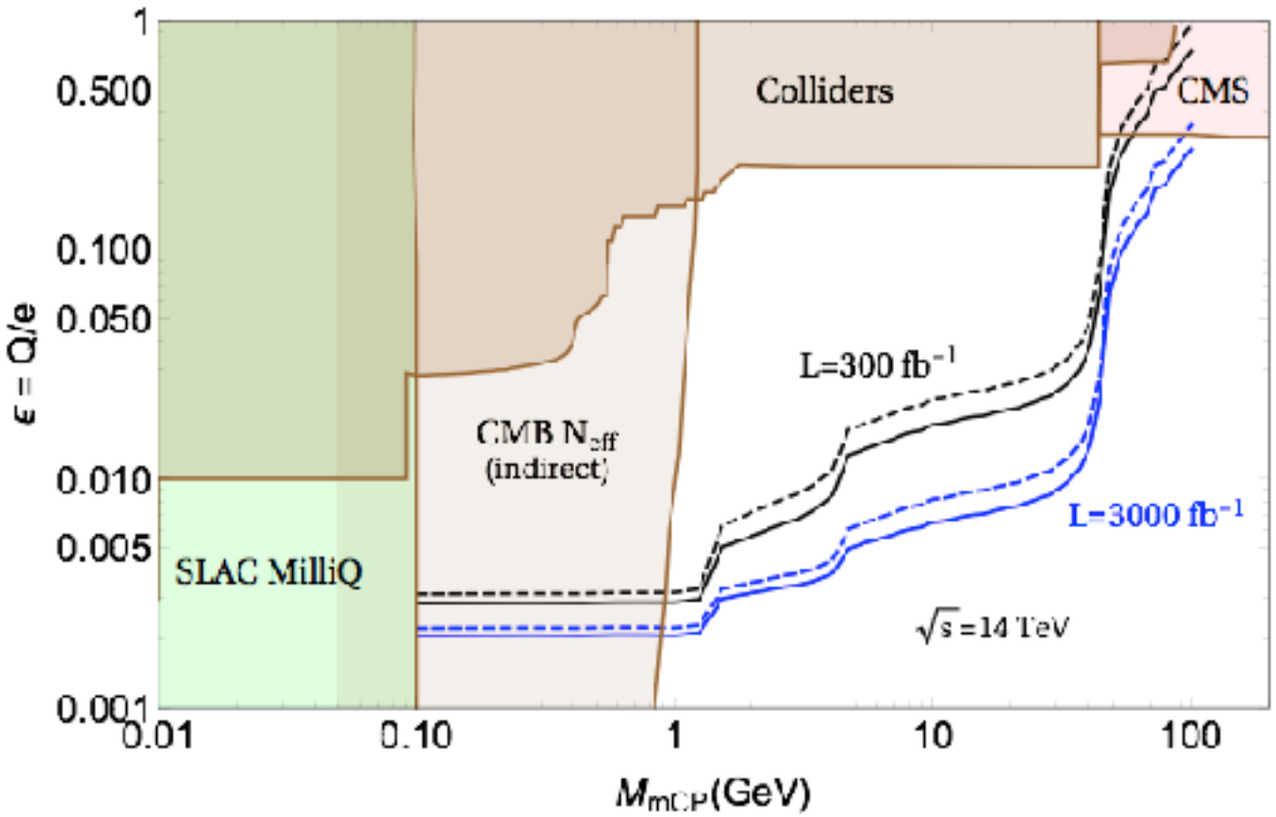
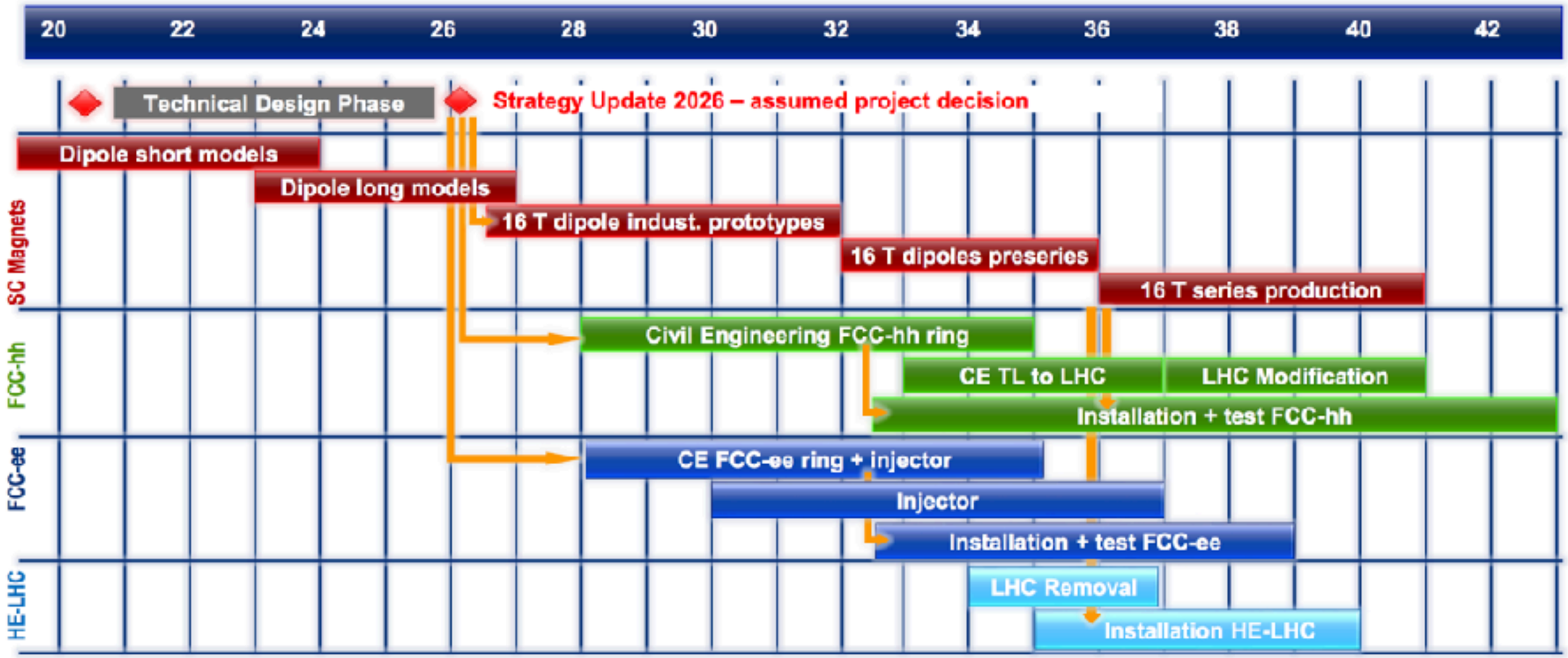


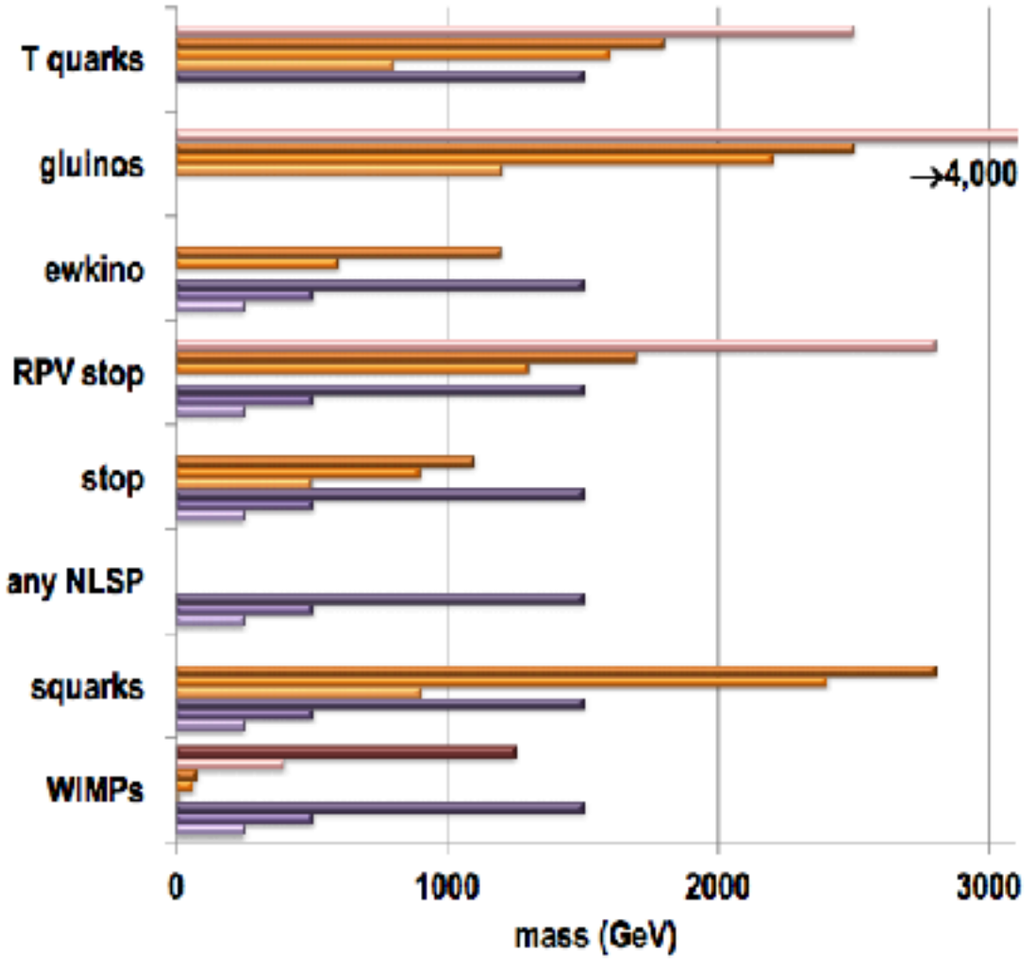
Haas, Hill, Izaguirre, Yavin PLB 746 (2015)

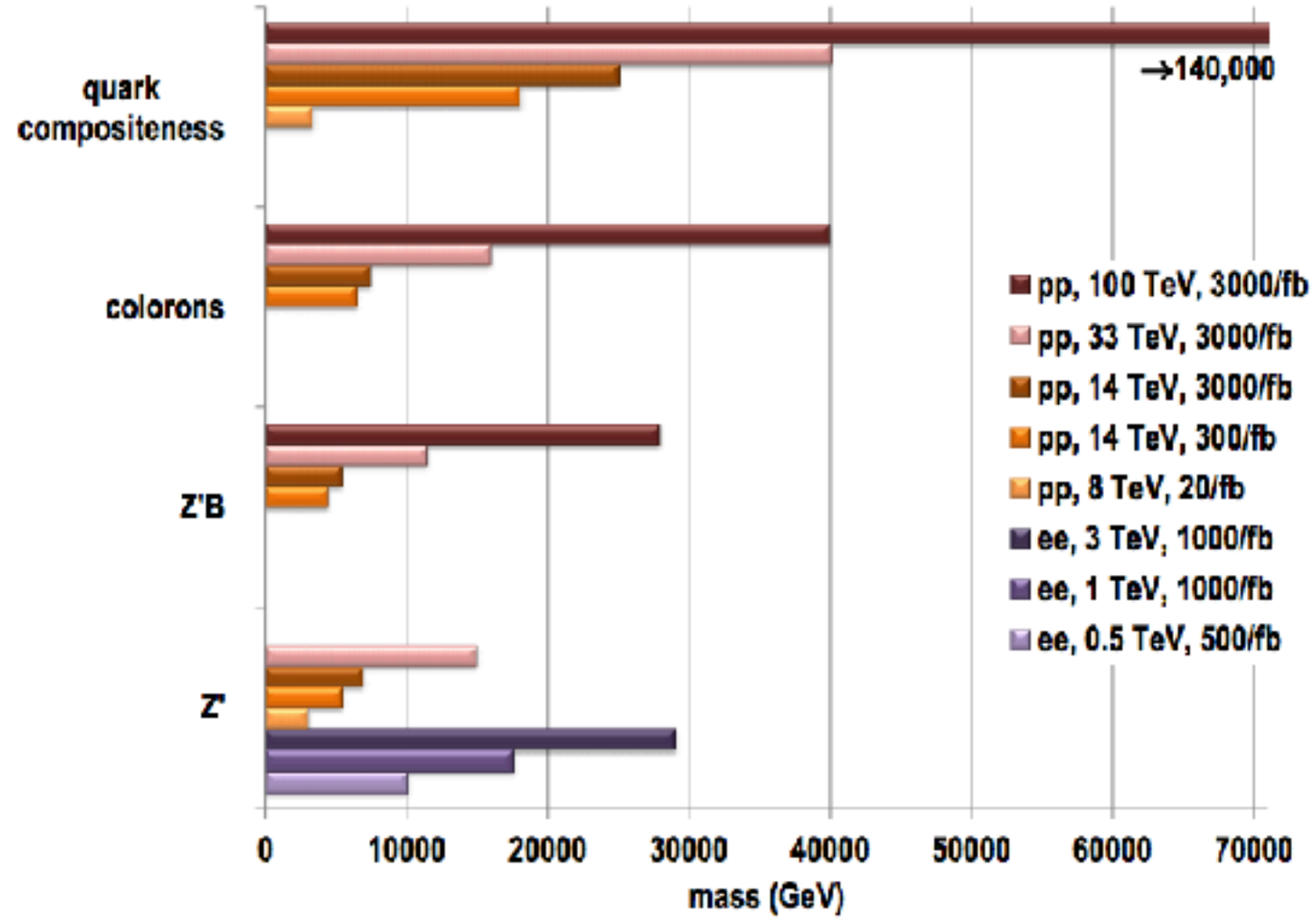
Future Prospects



- Design studies underway for Future Circular Collider at CERN
- May see 33 TeV / 100 TeV hadron colliders in future - but you will have to wait

Future Prospects





- And of course, preparations for HL-LHC are well underway…
- Prospects for discoveries down the road

Conclusions

- Supersymmetry still not found

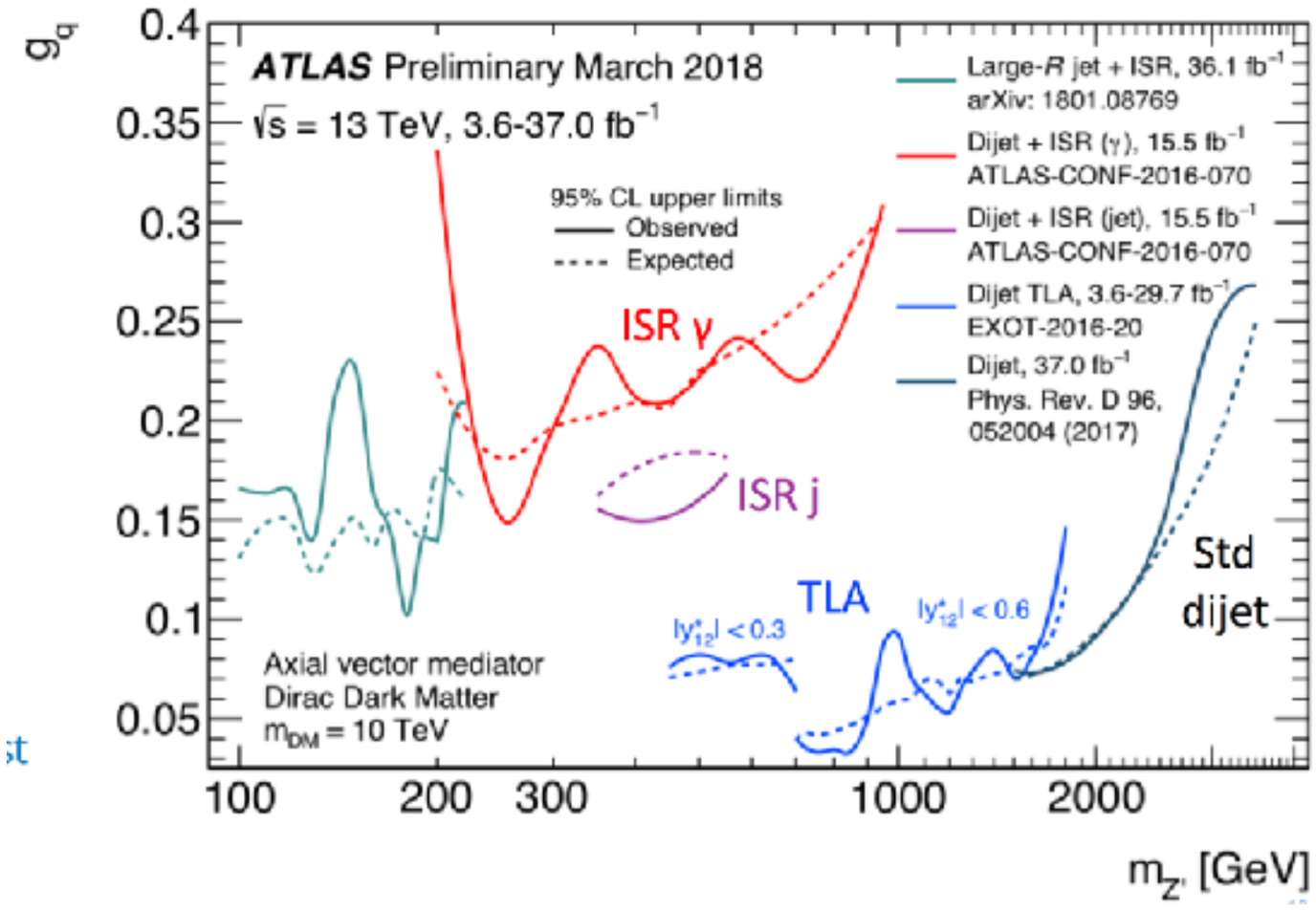
Conclusions

- Supersymmetry still not found
  - Focus on the difficult regions, eg. compressed spectra
- Wide range of searches for exotics
  - Increasing focus on long lifetimes, in context of SUSY & DM too
- May have to wait for HL-LHC to really probe the difficult regions
- Not just CMS & ATLAS performing direct searches for new physics!
- Future experiments and facilities in the pipeline

Backup

Di-Jet Resonances

- Searches for low mass di-jet resonances affected by trigger p_T thresholds
- Accept lower pT events by only writing out objects reconstructed by the trigger



SUSY : Current Status

All the SUSY plots