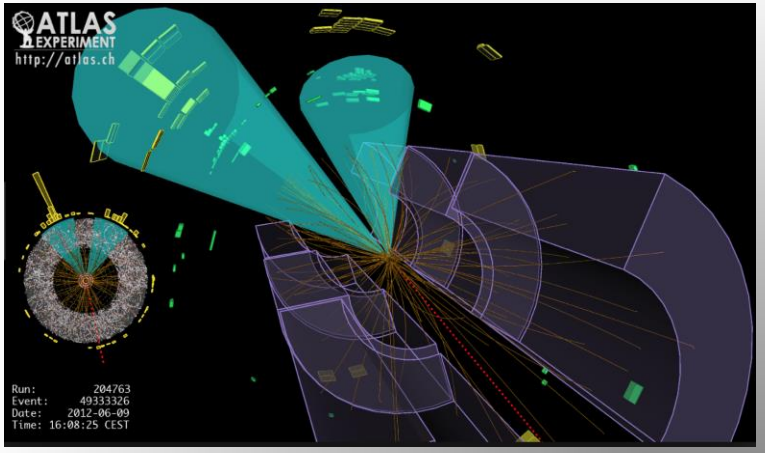
Searches Beyond the Standard Model with the Large Hadron Collider

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
NTU, Singapore

8th June 2018



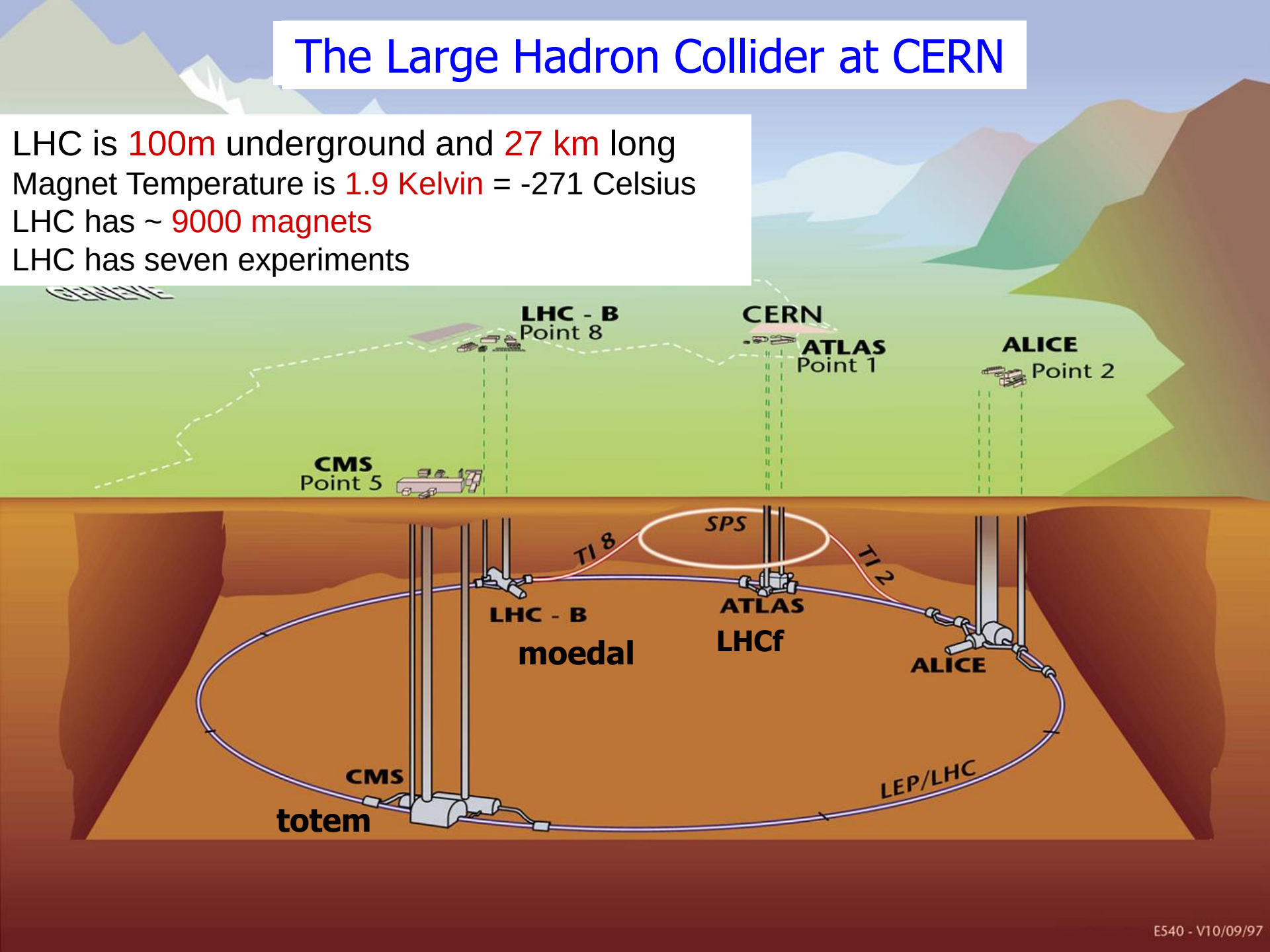
Collision at 7 TeV in ATLAS with large missing E_T

Outline

- Introduction: The LHC
- A bit of news on the Higgs
- Supersymmetry Searches
- Exotica Searches
- A problem with flavor?
- New Experiments at the LHC?
- Summary

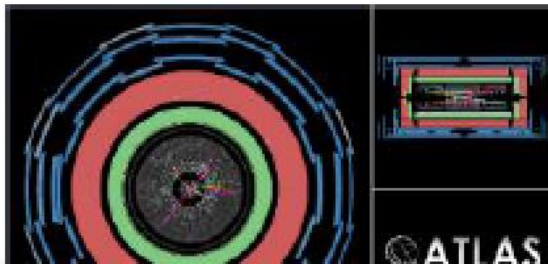
The Large Hadron Collider at CERN

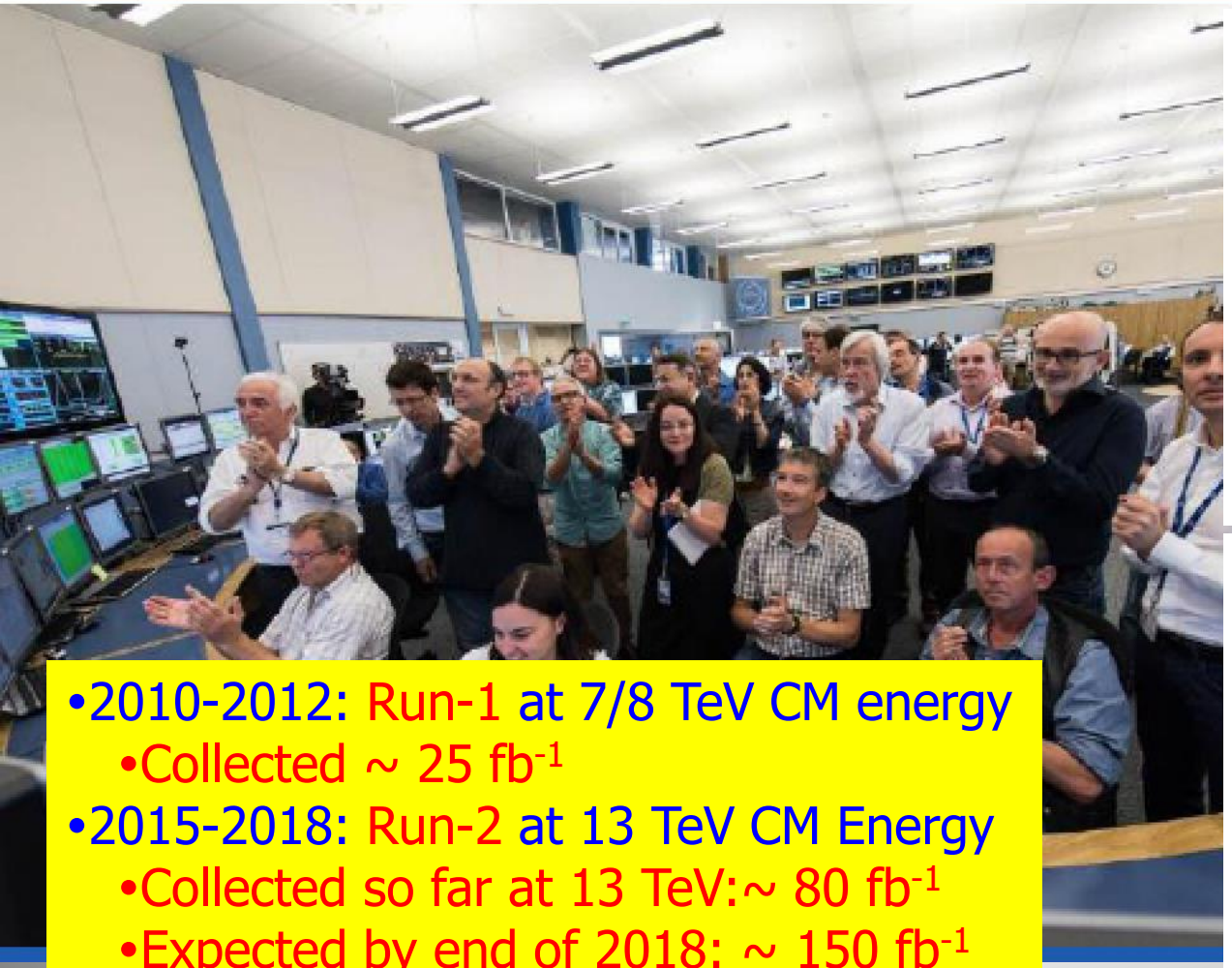
LHC is 100m underground and 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC has seven experiments

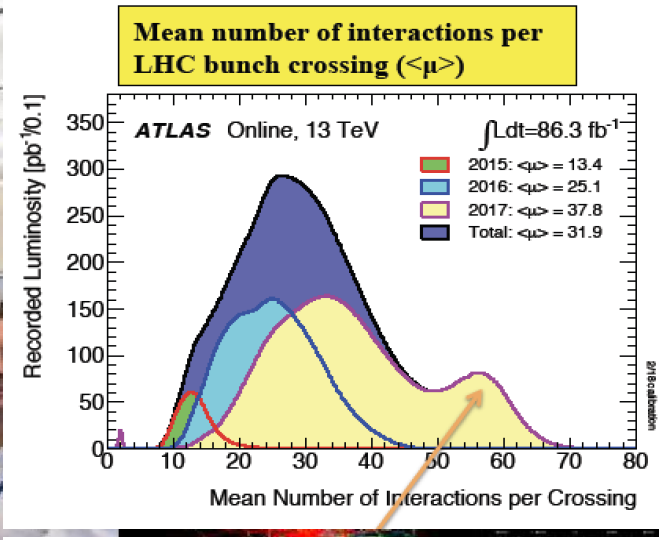


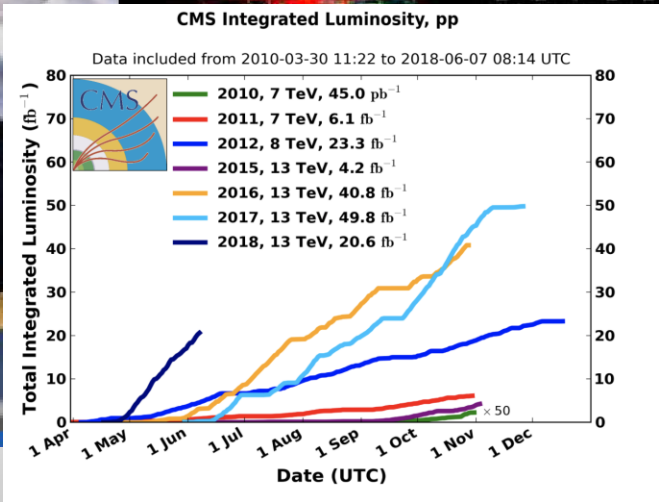
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015 Run-2 starts









- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 25 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM Energy
  - Collected so far at 13 TeV:~ 80 fb^{-1}
  - Expected by end of 2018: ~ 150 fb^{-1}

LHC Operation 2018: Going Very Well!!

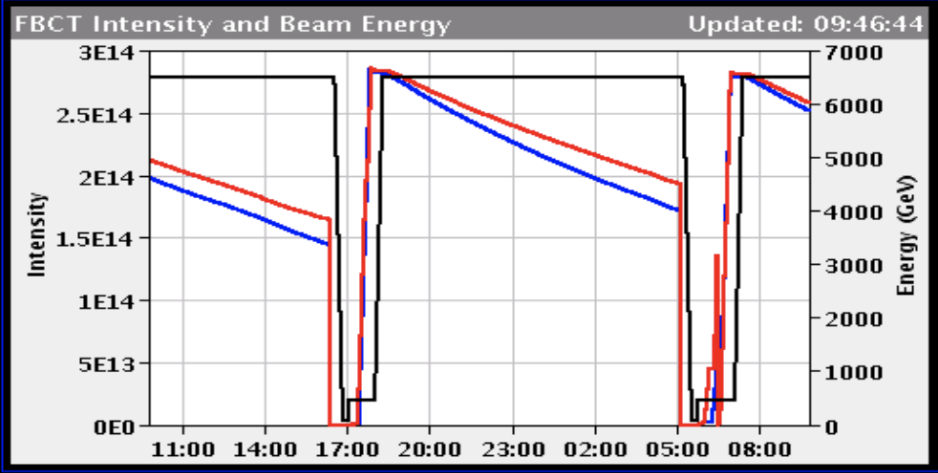
LHC Page1 | Fill: 6714 | E: 6499 GeV | t(SB): 01:57:38 | 23-05-18 09:46:44

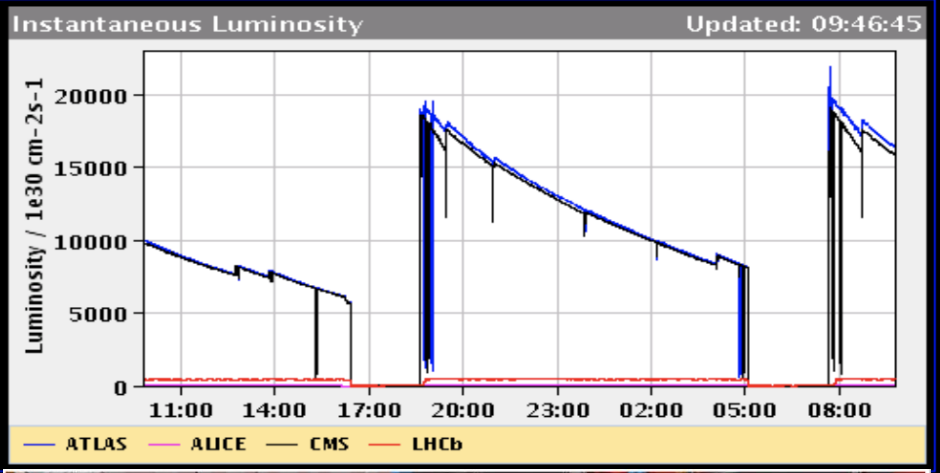
* LHC1 *

PROTON PHYSICS: STABLE BEAMS

Energy:	6499 GeV	I(B1):	2.52e+14	I(B2):	2.58e+14

Inst. Lumi [(ub.s)^-1] IP1: 16386.48 IP2: 2.61 IP5: 15831.62 IP8: 431.68





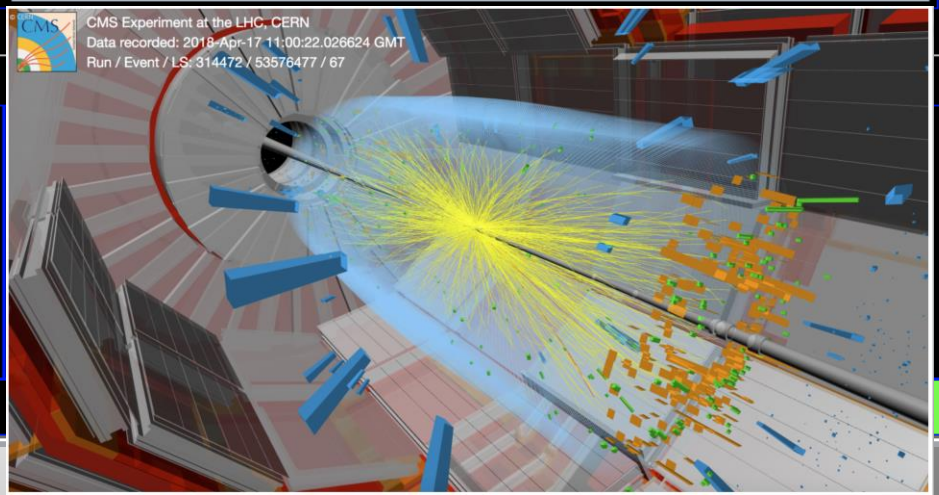
Comments (23-May-2018 08:08:51)

pots in

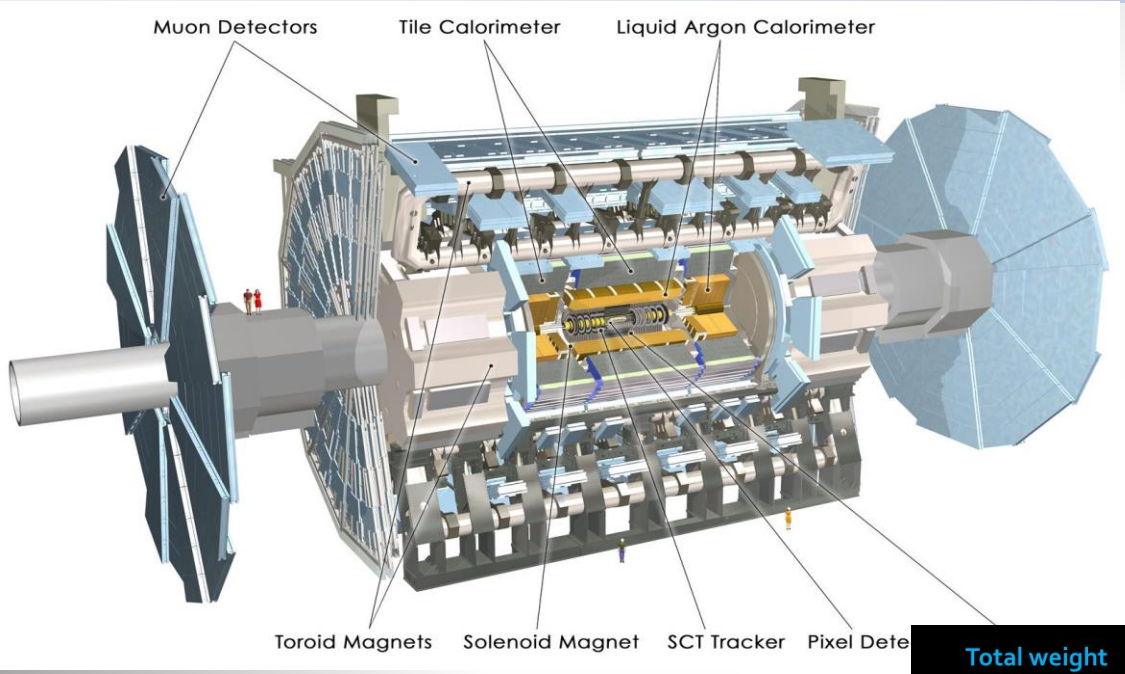
Angle levelling IP1 IP5

Physics fill with 2556b

AFS: 25ns_2556b_2544_2215_2332_144bpi_20injV2

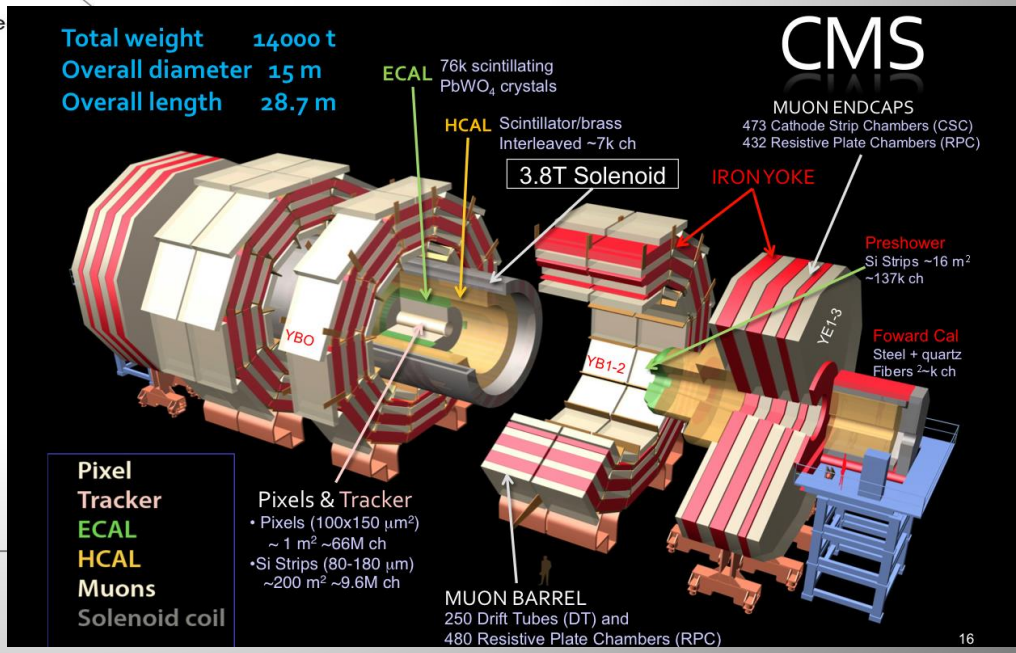


New Physics Hunters @ the LHC

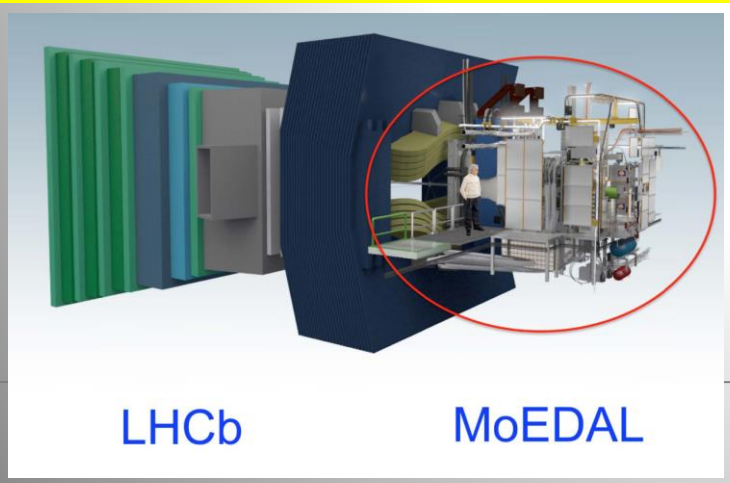


The ATLAS experiment

The CMS experiment

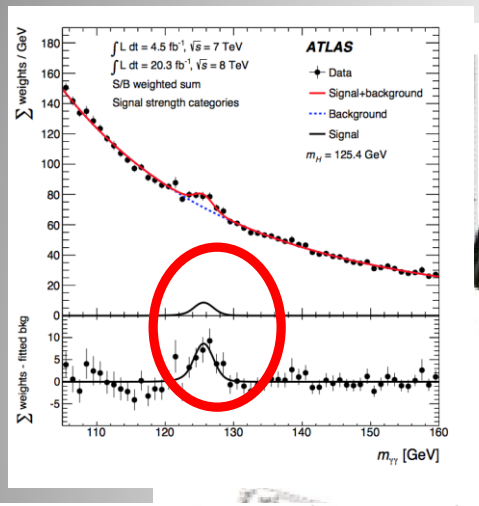


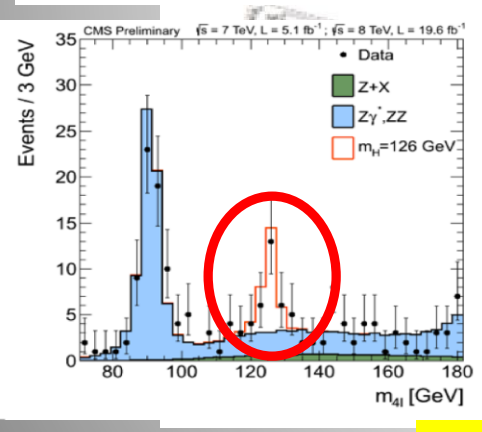
...And also LHCb and MoEDAL



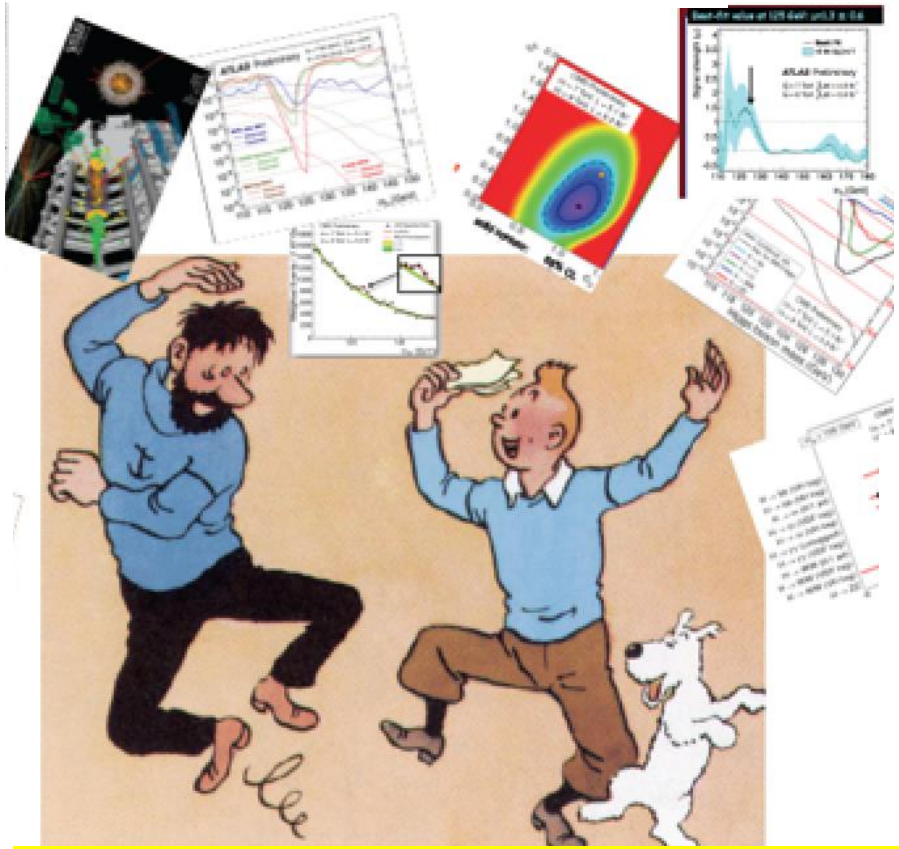
2012: The Higgs

The party in 2012!





A. Pomarol ICHEP2012

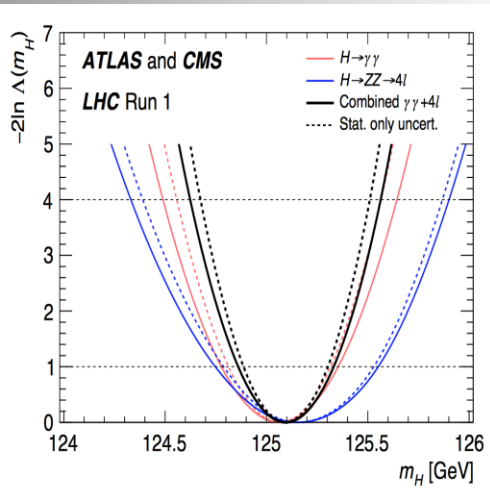


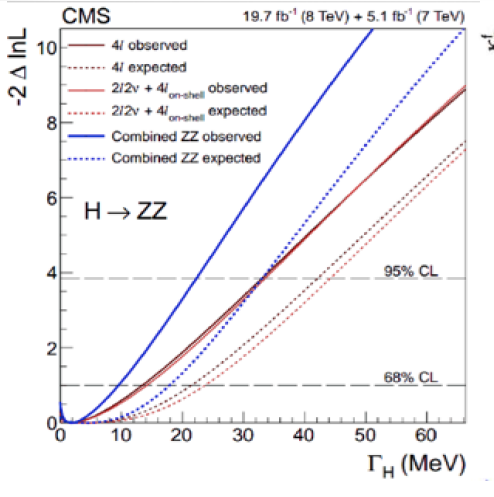
Not everybody at the party
eg higgsless models…

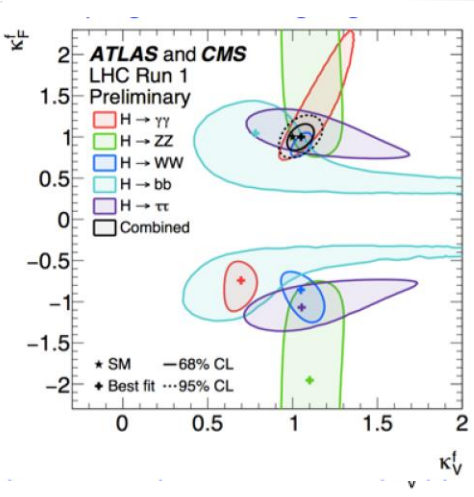
But careful about resurrections, Higgs imposters…

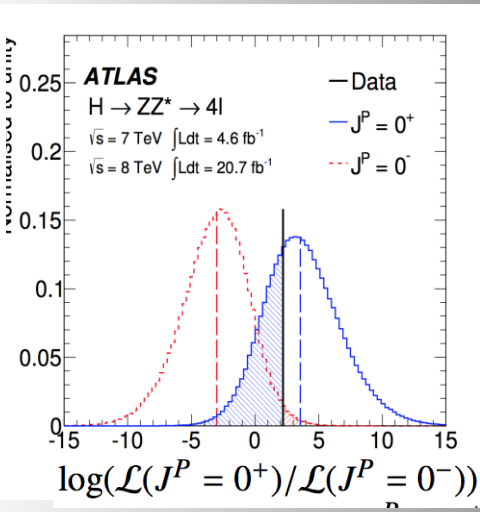
Brief Higgs Summary from Run1

We know already a lot on this Brand New Higgs Particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width
< 24 MeV
(95%CL)

Couplings are within ~20% of the SM values

Spin =
$0^{+(+)}$ preferred over 0^-,1,2

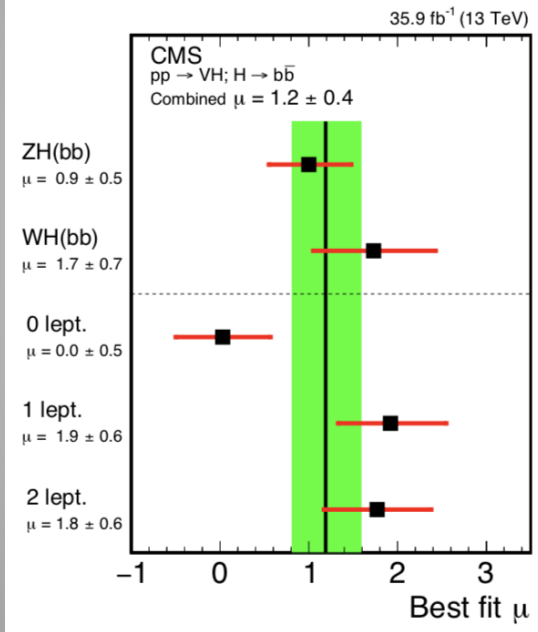
SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production…

Higgs Results @ 13 TeV

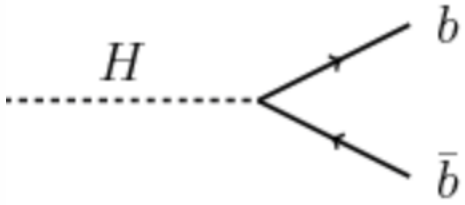
Run-1 observed H→ γγ, H→ZZ, H→WW, H→ττ, but not yet H→bb

Higgs to bb using the associated channels WH and ZH, with W,Z→ leptons

arXiv:1709.07497



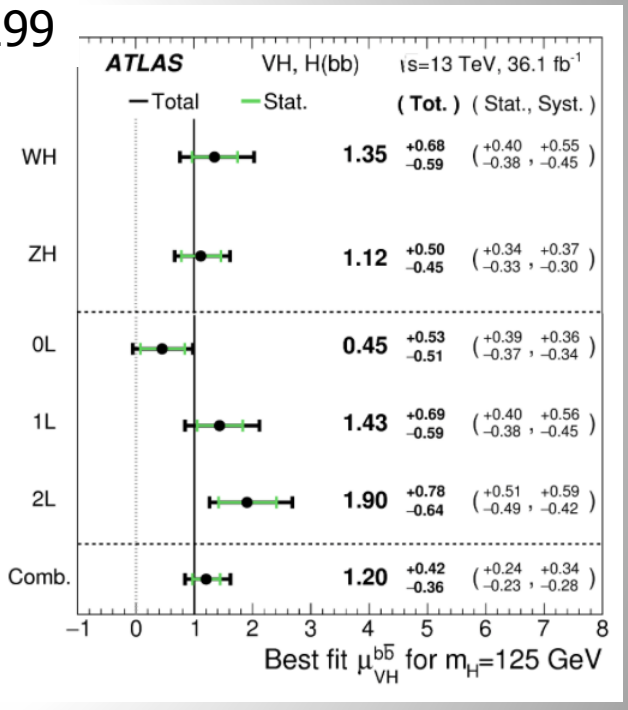
- CMS: 3.8σ (3.8σ exp)
  $\mu = 1.06^{+0.31}_{-0.29}$



$\mu := \sigma/\sigma_{SM}$

Combination 7/8/13 TeV

arXiv:1708.03299



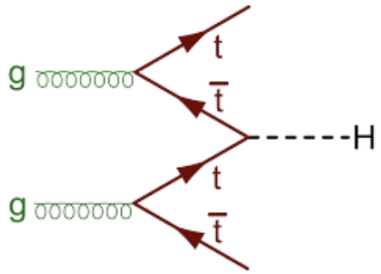
- ATLAS: 3.6σ (4.0σ exp)
  $\mu = 0.90 \pm 0.18(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$

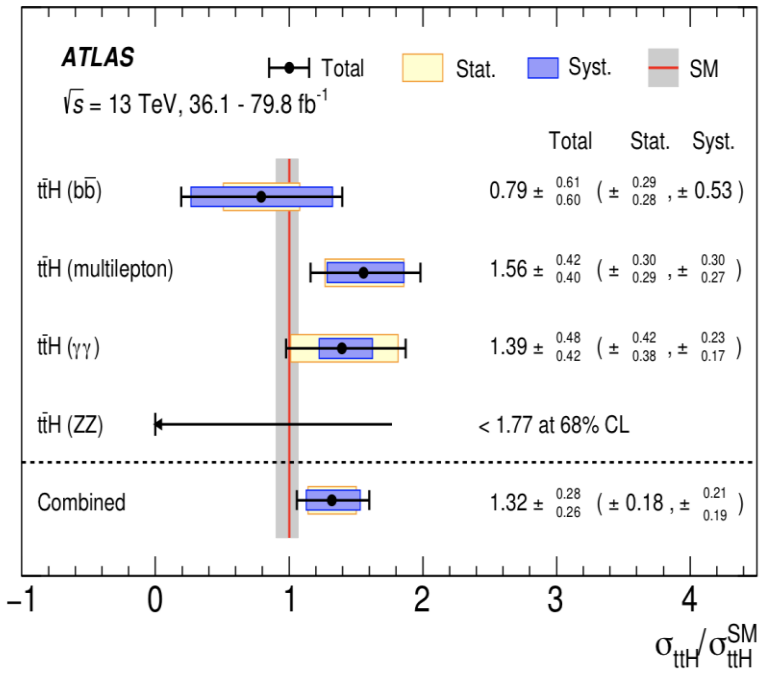
Direct evidence for H->bb in CMS and ATLAS!!

Higgs Results @ 13 TeV

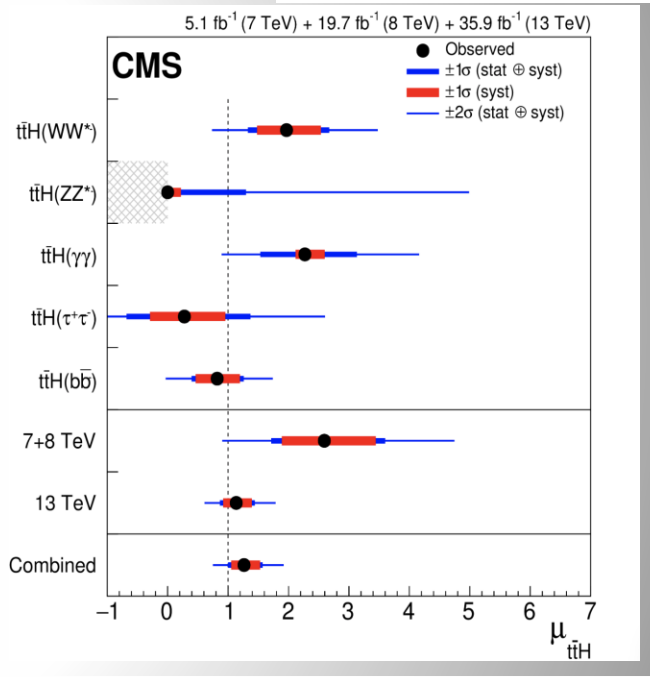
ttH production: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1

arXiv:1806.0425





arXiv:1804.0261



Observation of ttH production with:
-- **Run-2 alone: 5.8 σ significance (4.9 σ expected)**
-- **Run-1 and Run-2 combined: 6.3 σ significance (5.1 σ expected)**

7+8+13 TeV data

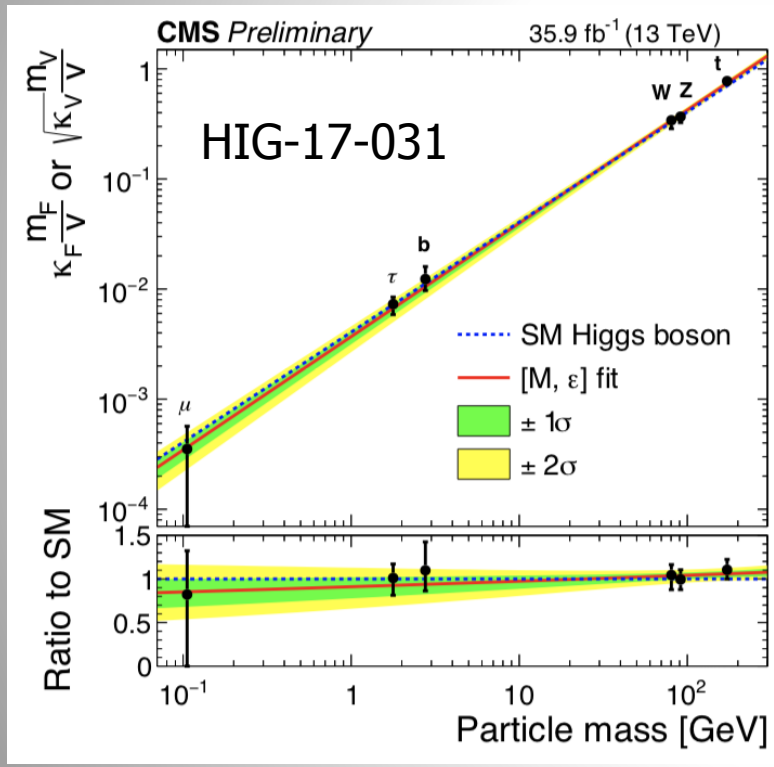
$$\mu_{t\bar{t}H} = 1.26\ ^{+0.31}_{-0.26}$$

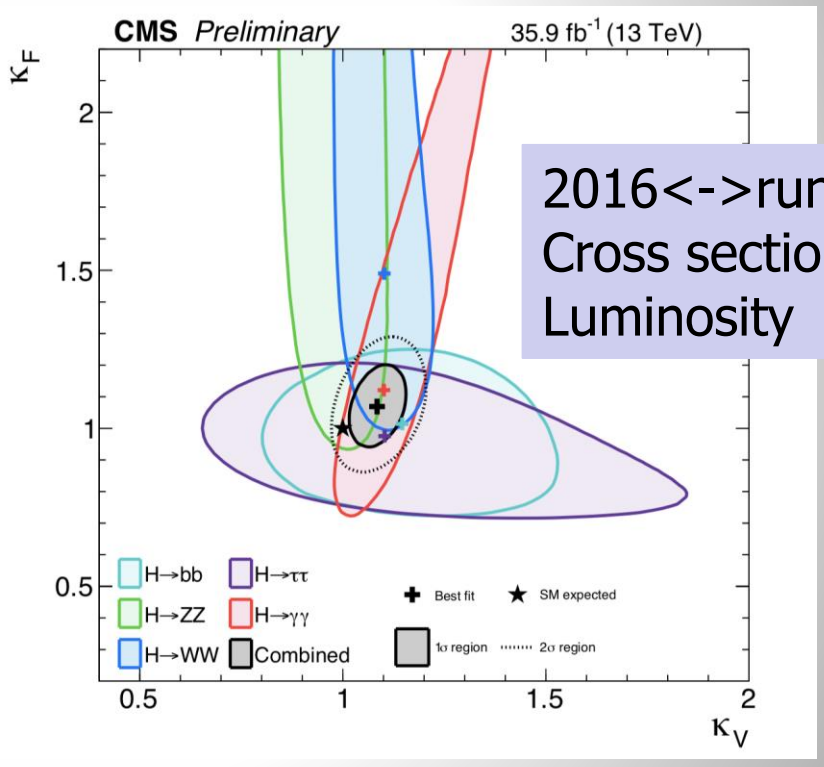
Significance = 5.9σ (exp 4.2σ)

Observation of ttH!
Results in agreement with the Standard Model

Higgs Results @ 13 TeV

Combination of all Higgs production/decay channels at 13 TeV
Check overall consistency of the couplings (CMS only)





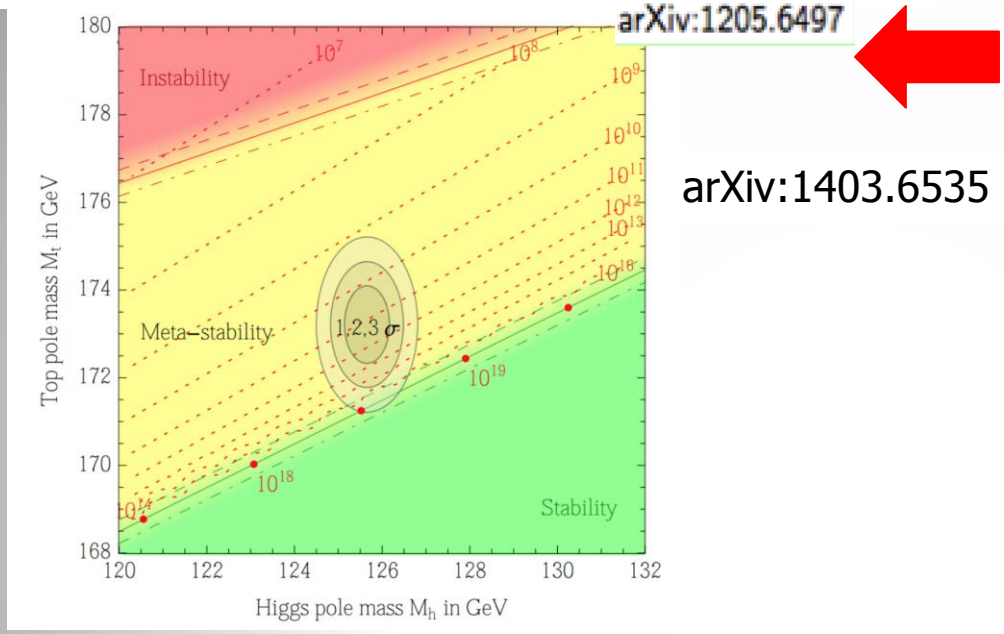
2016<->run-1 data:
Cross section ~ x 2
Luminosity ~ x 1.5

Results in agreement with the Standard Model

$$\mu = 1.17^{+0.10}_{-0.10}$$
$$= 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

Physics Beyond the Standard Model?

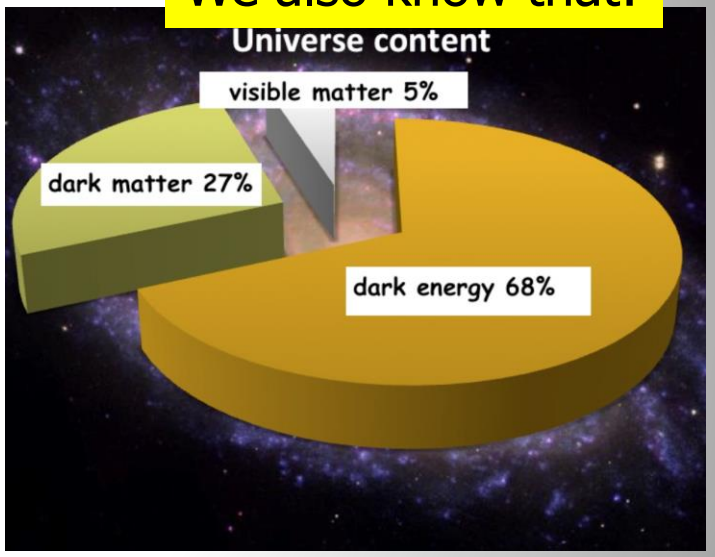
Important SM parameter → stability of EW vacuum



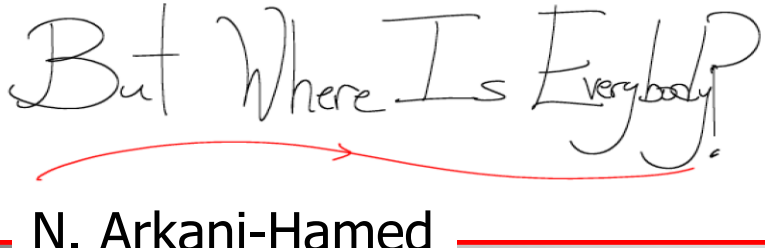
arXiv:1403.6535

A Higgs at 125 GeV
Precise measurements of the top quark and the Higgs mass

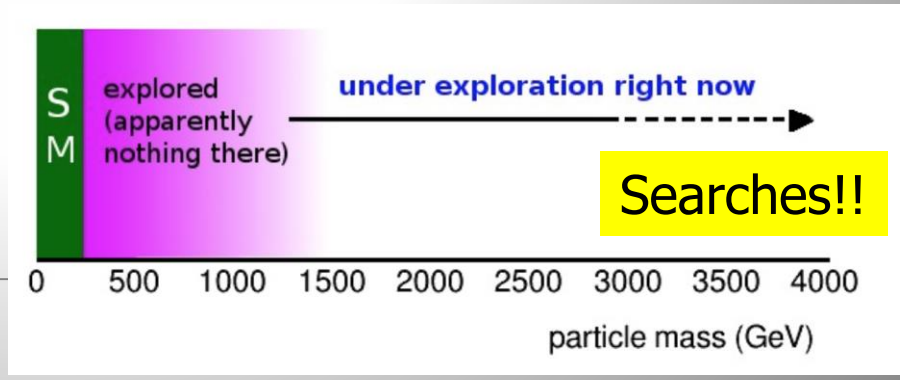
We also know that:



New Physics inevitable?
But at which scale/energy?

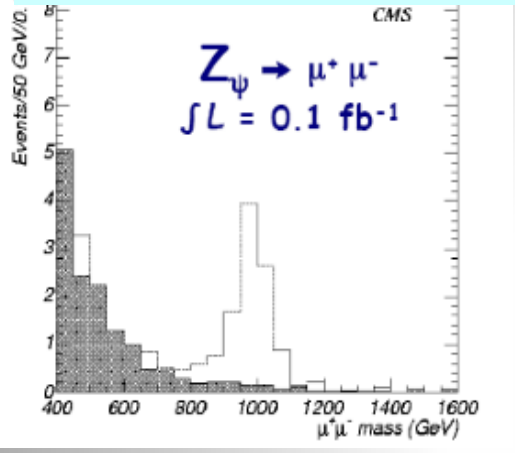


N. Arkani-Hamed

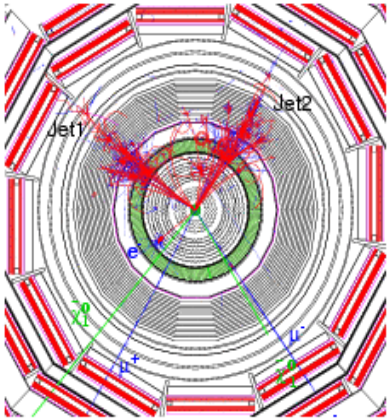


New Physics?

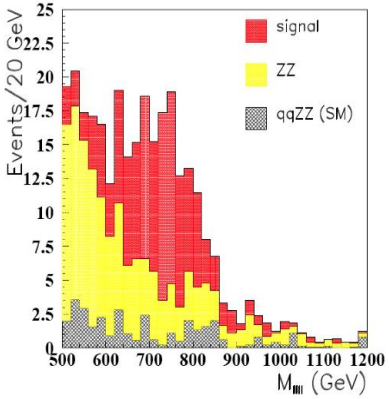
New Gauge Bosons?



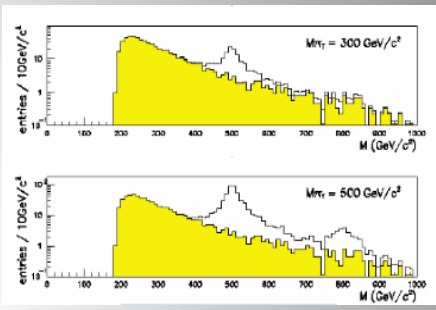
Supersymmetry



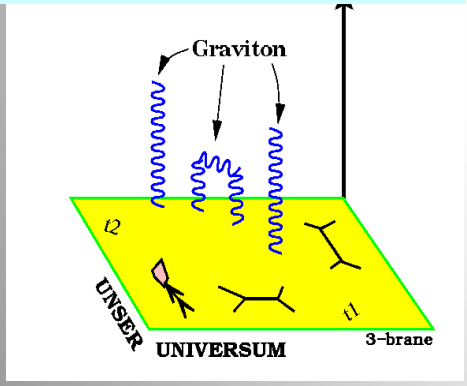
ZZ/WW resonances?



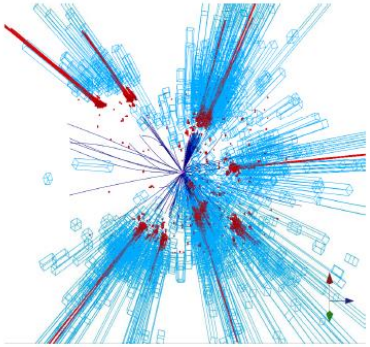
Technicolor?



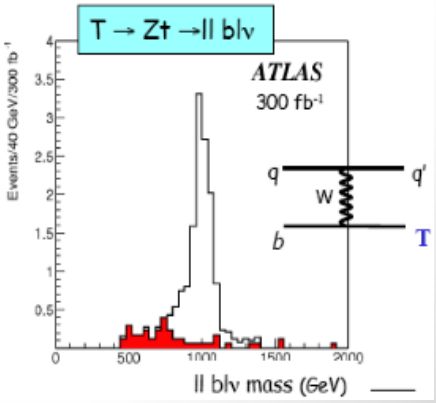
Extra Dimensions?



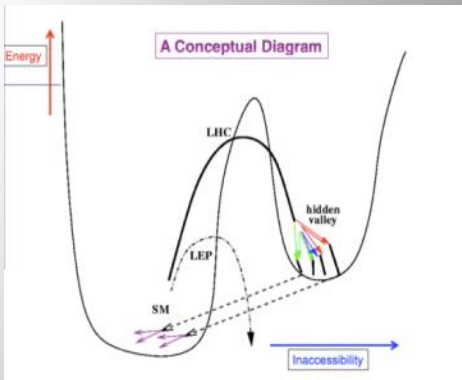
Black Holes???



Little Higgs?



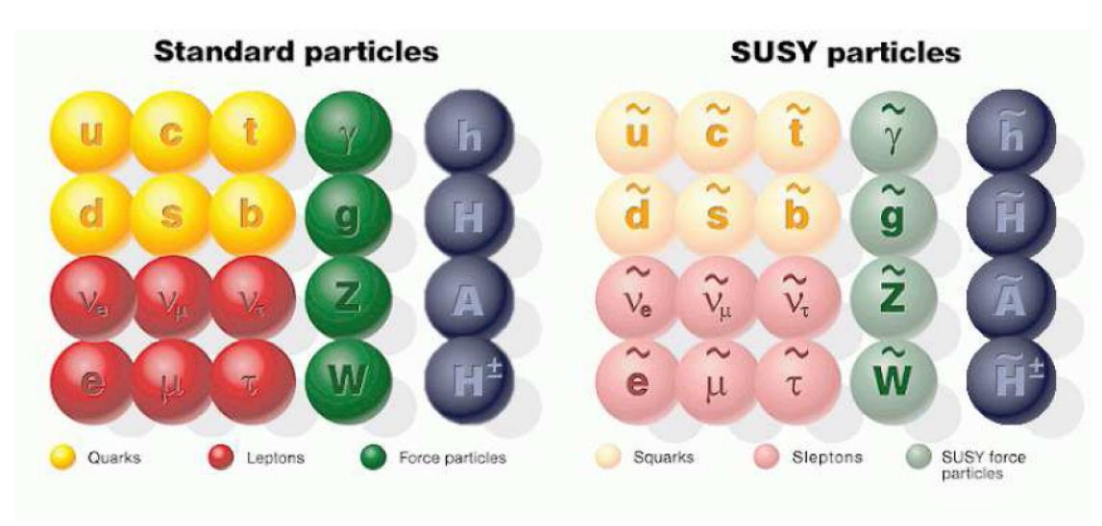
Hidden Valleys?



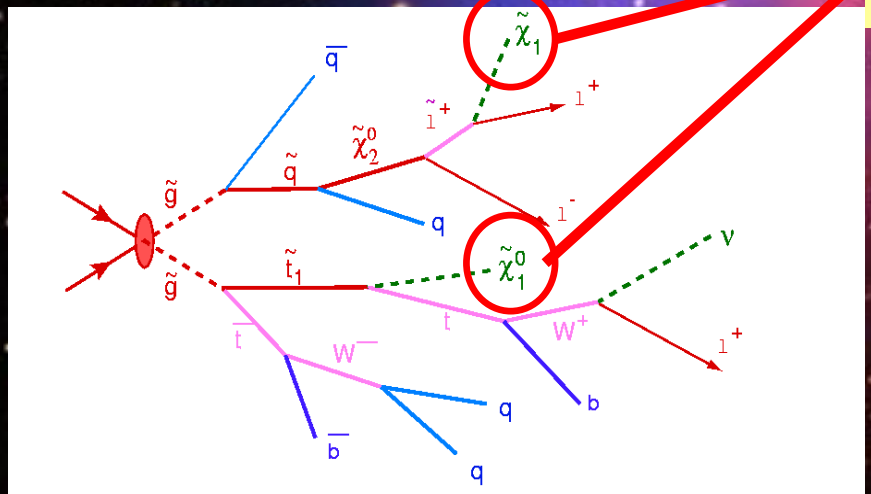
What stabelizes the Higgs Mass? Many ideas, not all popular any more

A large variety of possible signals. We have to be ready for that

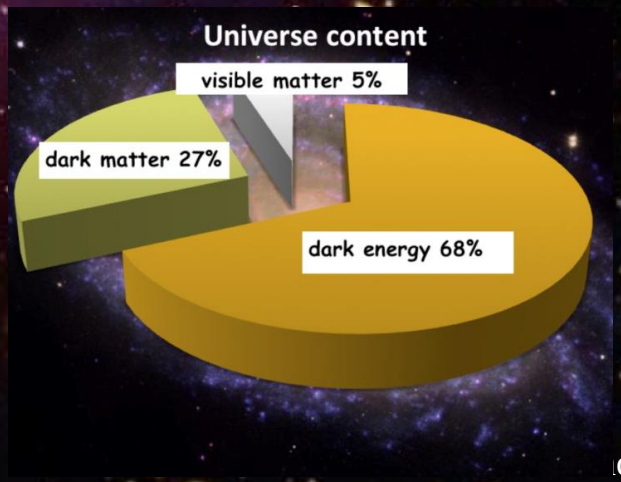
Supersymmetry: a new symmetry in Nature?



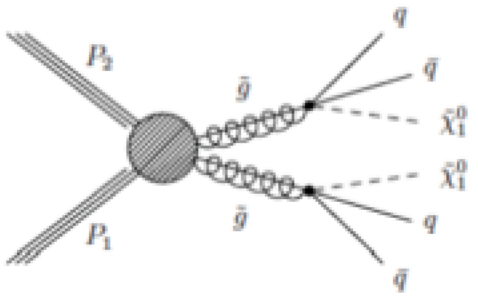
Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

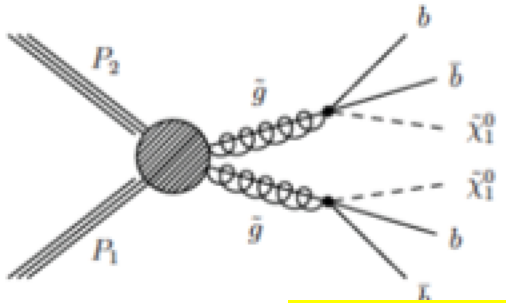


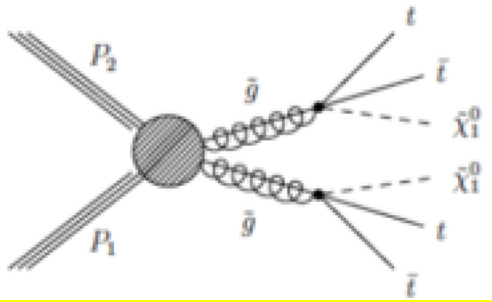
SUSY particle production at the LHC



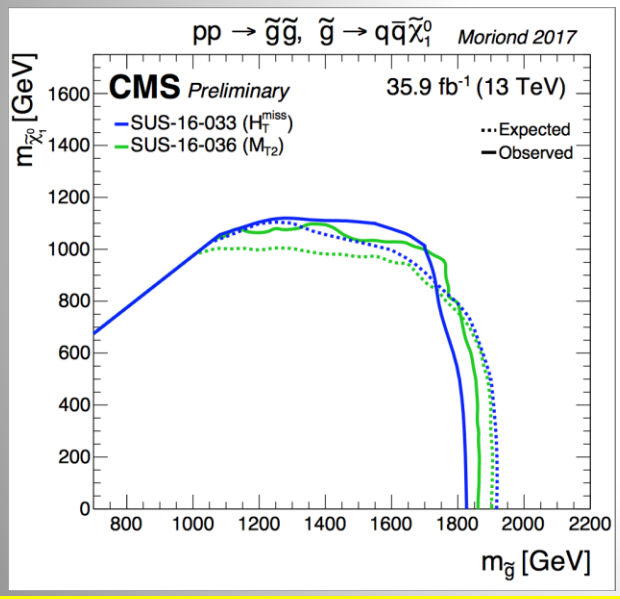
Supersymmetry: Gluinos

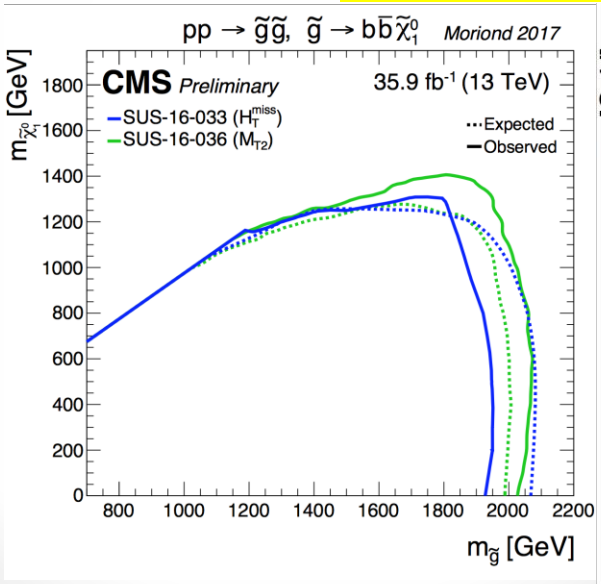


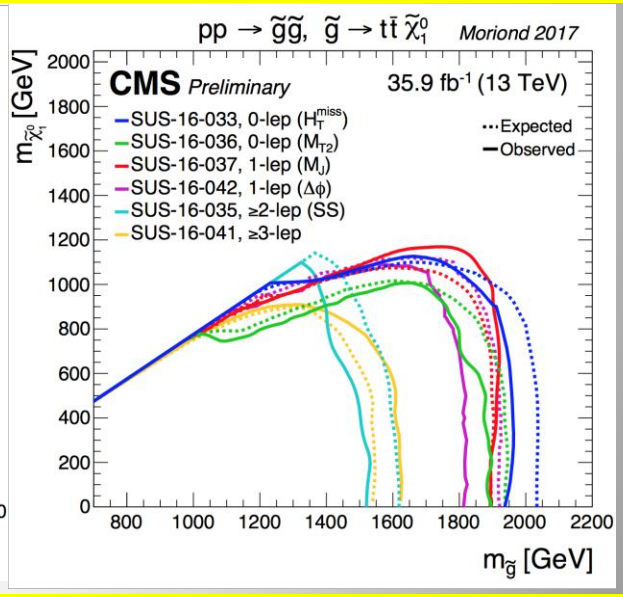




Interpretation in simplified models (SMS)







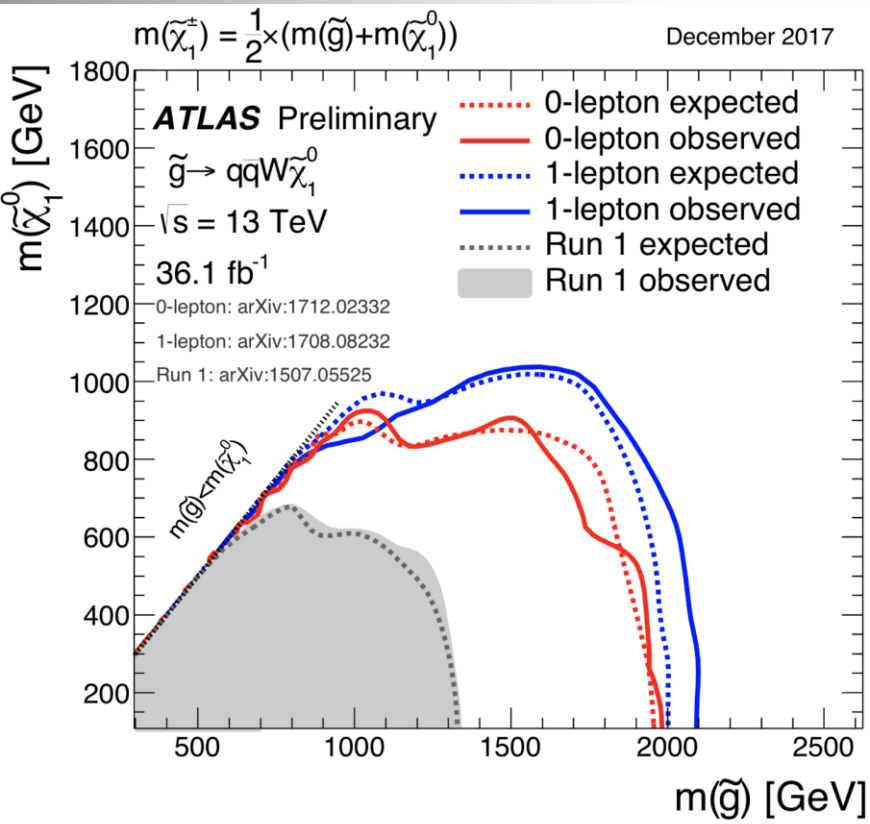
No significant signal to date

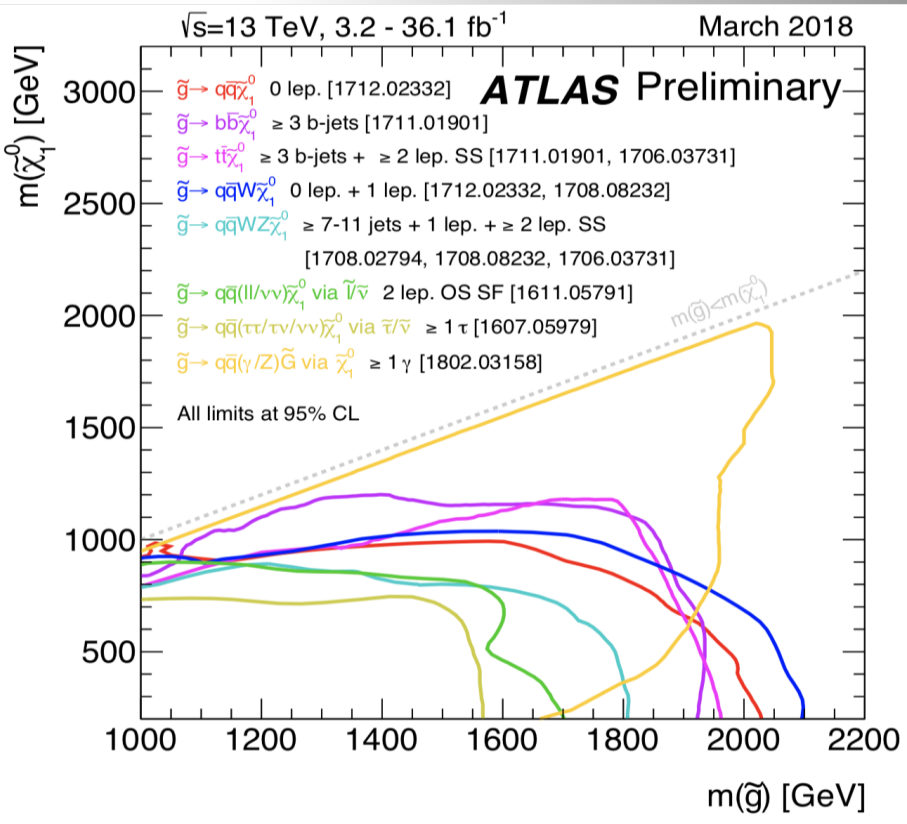
Within the context of the SMS:

Exclude with gluino masses ~ 2100 GeV for neutralino masses up to 800 GeV

Supersymmetry: Gluinos

Gluino production with decay chains with direct decay to the lightest SUSY particle or via cascade chains.



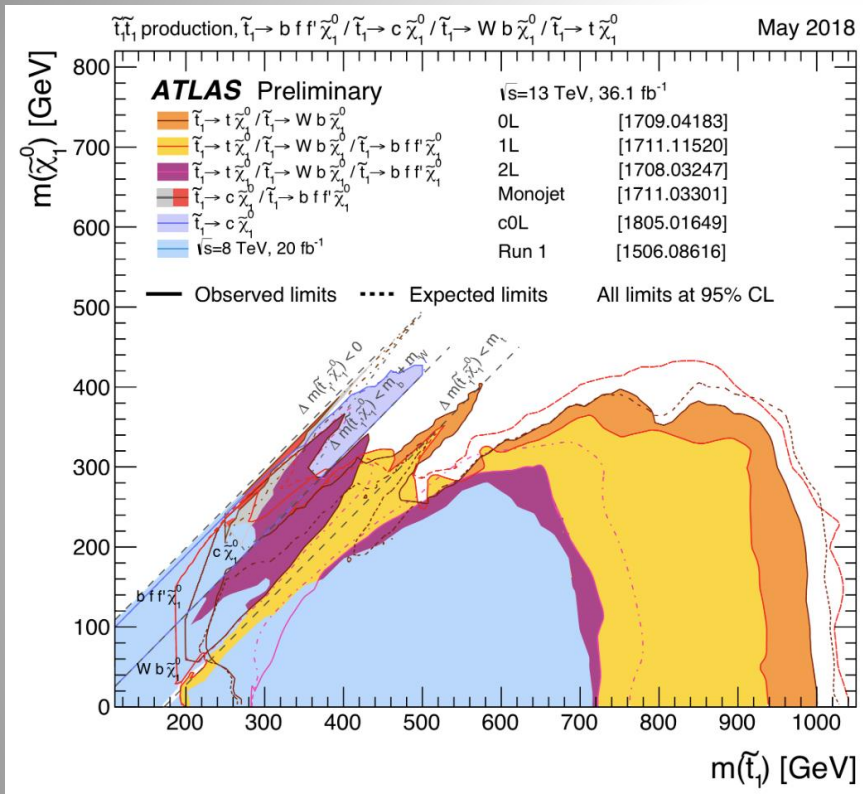


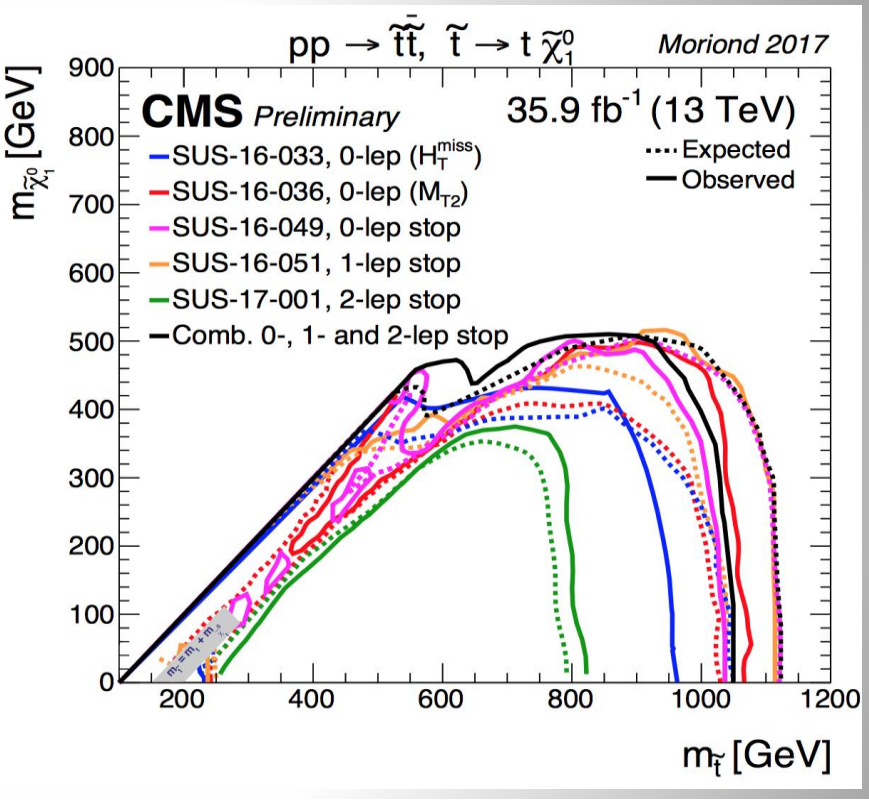
No significant signal to date

Within the context of the SMS: Exclude with gluino masses ~ 2000 GeV

Top Squark Search Summaries

Partner of the top quark – the stop– plays prominent role in Natural Models





Within the context of the SMS:

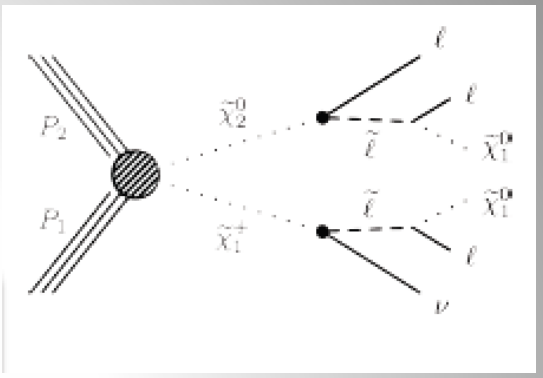
Exclude with masses up to 1100 GeV for neutralino masses up to 500 GeV

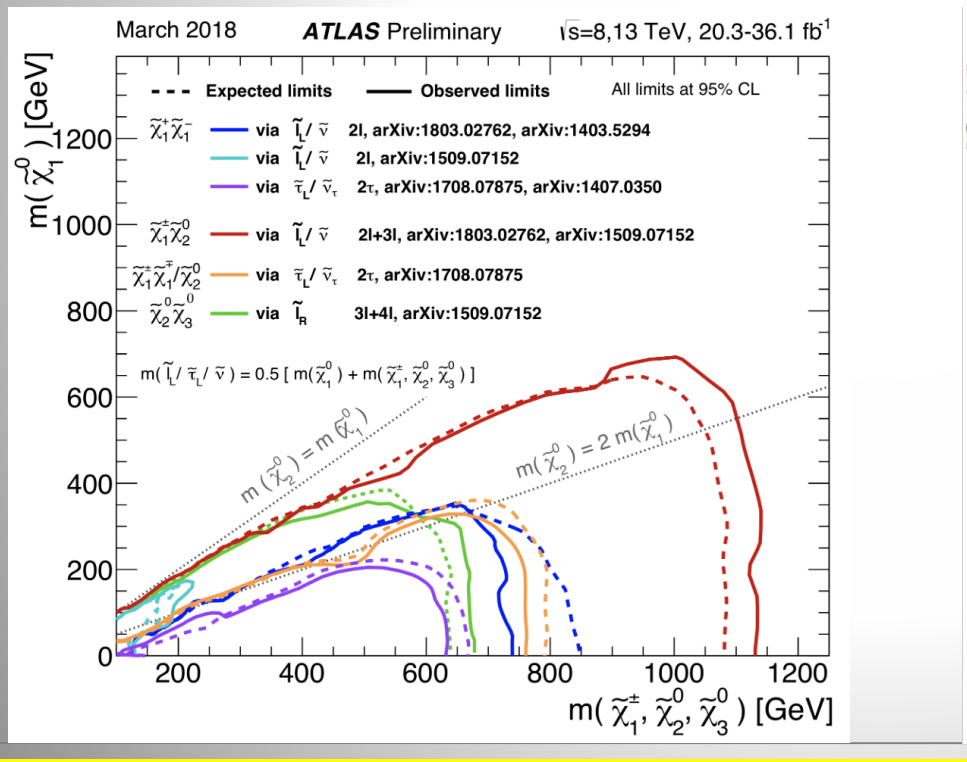
Sensitivity is ~ 200-400 GeV better than Run-1 reach & gaps being covered

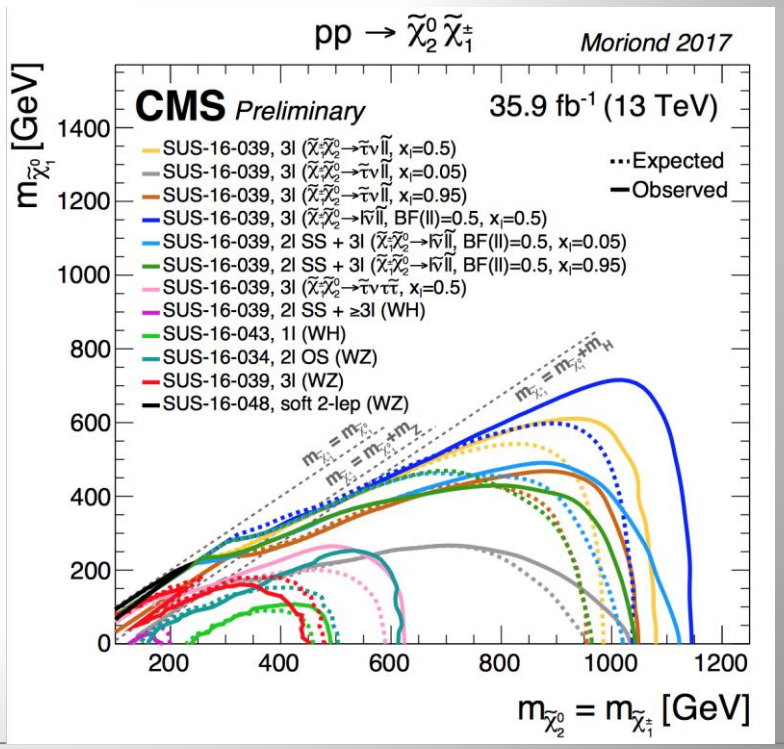
Is this getting critical for Natural Models??

Chargino and Neutralino Production

Direct production of "electro-weakino pairs
- Decays via sleptons /sneutrinos
- Using benchmarks to illustrate different scenarios
- Multilepton searches (incl. taus)



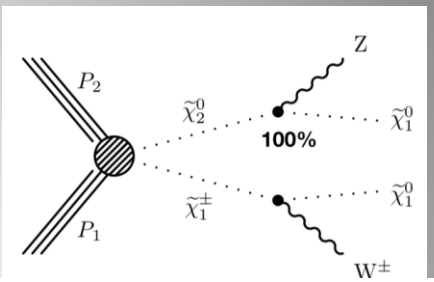




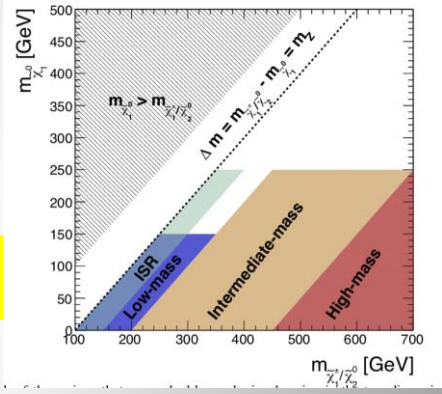
Exclude masses up to 1100 GeV for neutralino masses up to 600 GeV

Chargino and Neutralino Production

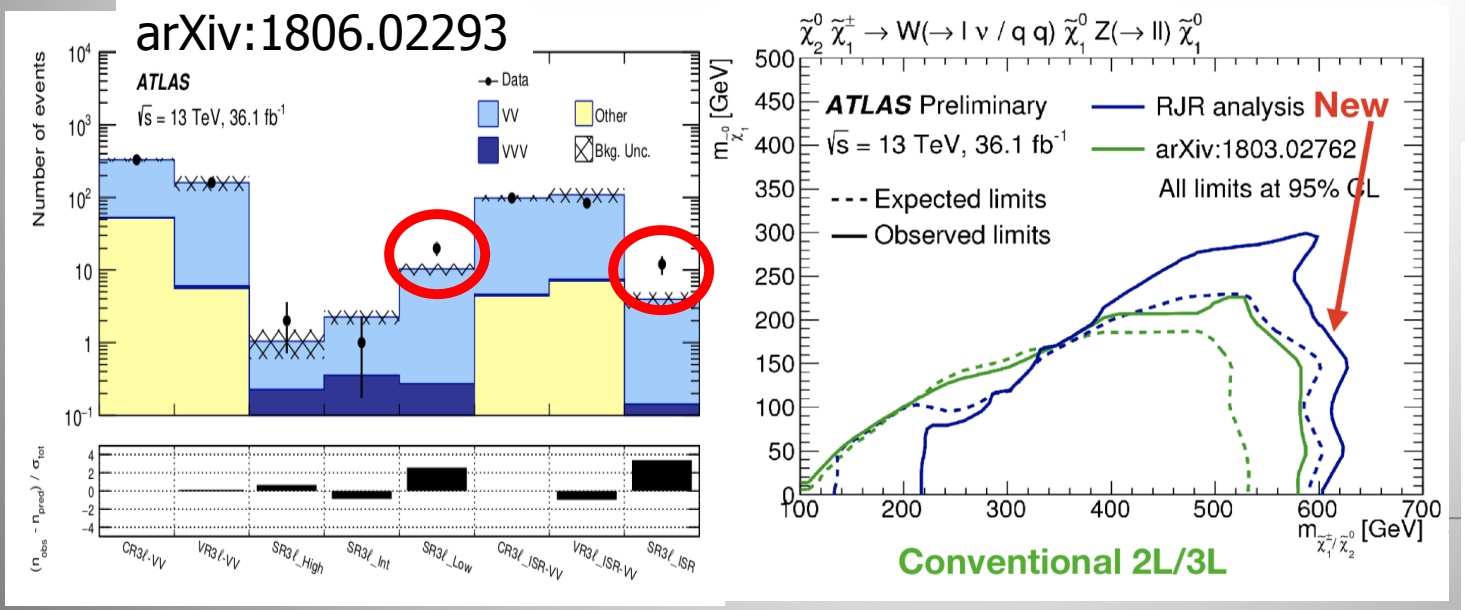
Chargino–neutralino pair production in WZ +MET channel
- Address scenarios with small mass-splittings between the parent particle and lightest SUSY particle plus Z
- Use a new reconstruction technique: Recursive Jigsaw Reco



Signal region	SR3ℓ_Low	SR3ℓ_ISR	SR2ℓ_Low	SR2ℓ_ISR
Total observed events	20	12	19	11
Total background events	10 ± 2	3.9 ± 1.0	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$



Excess observed in 4 low ΔM regions ranging from 1.5σ->3σ

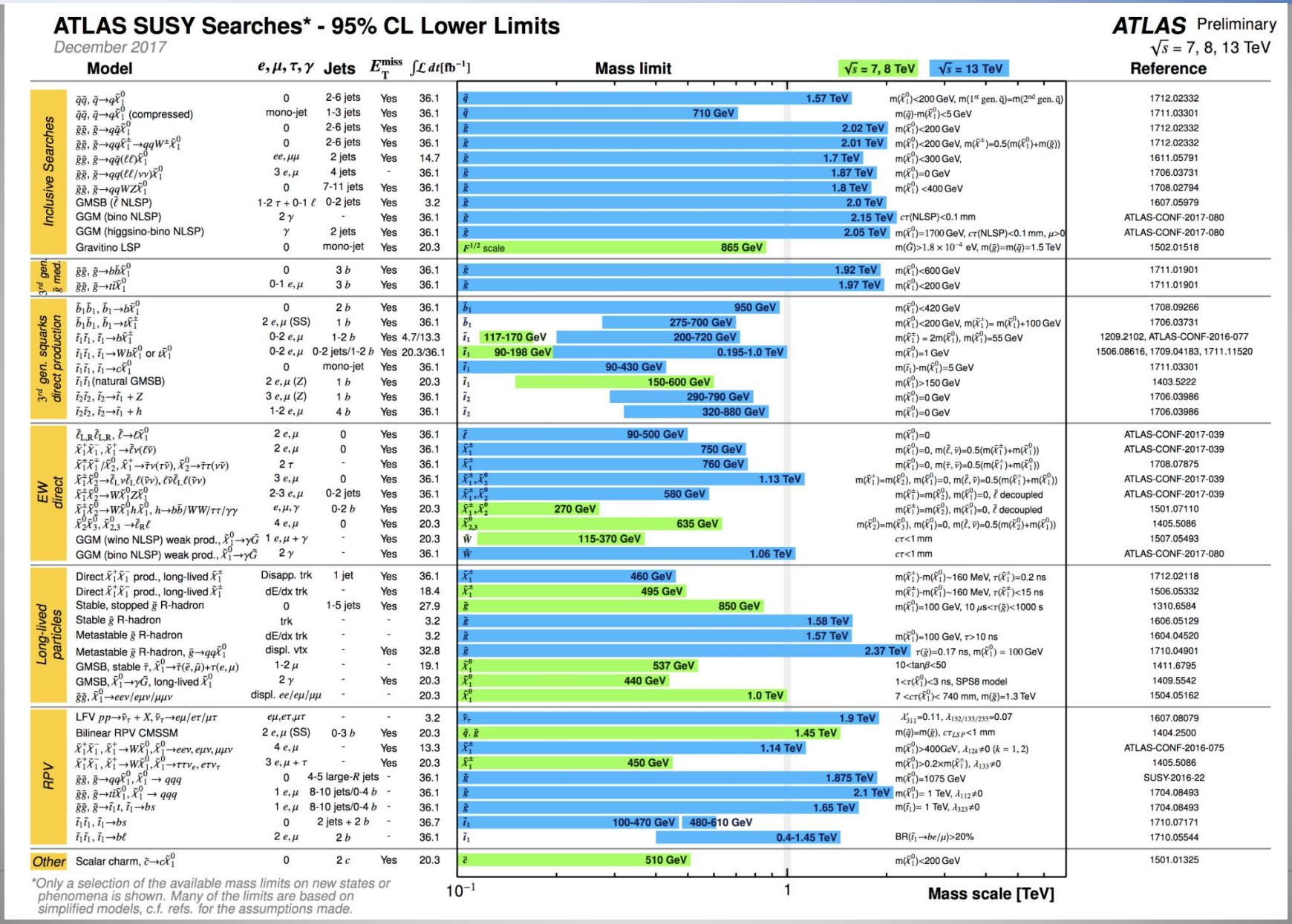


Compatible with previous studies?

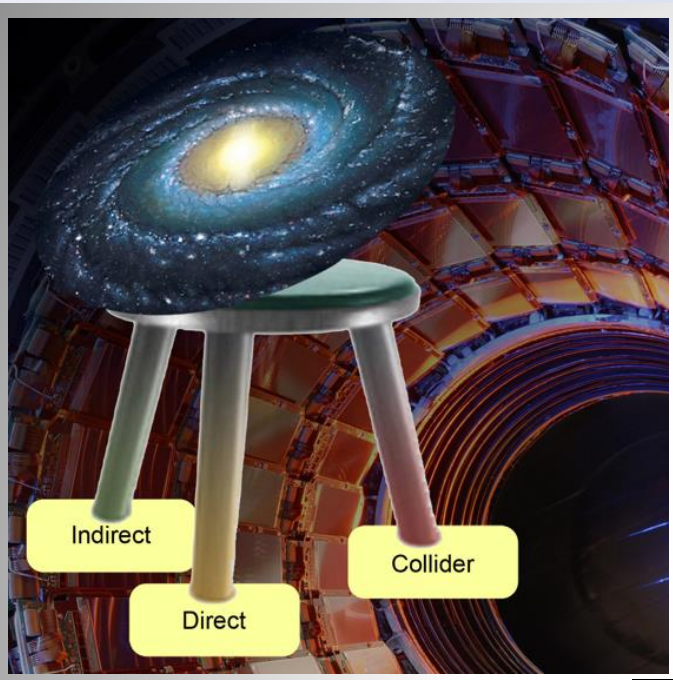
To be watched…

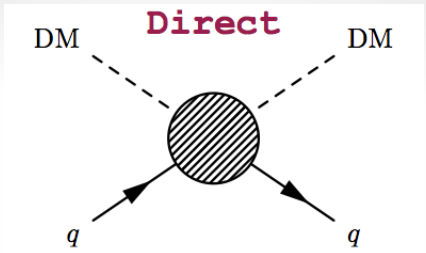
But "3σ"s have come and gone..

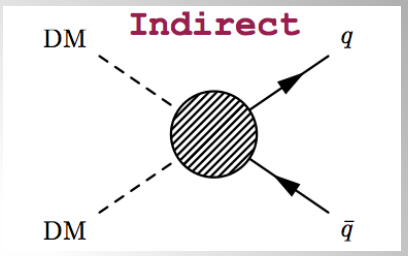
The SUSY SEARCH Chart So Far…

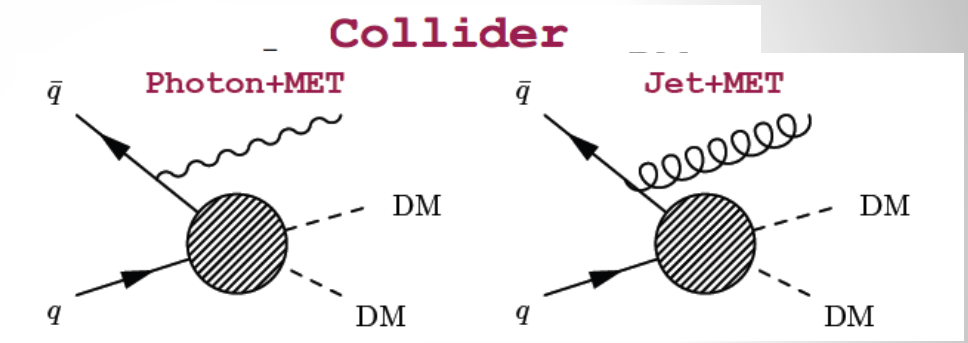


Dark Matter Searches at the LHC

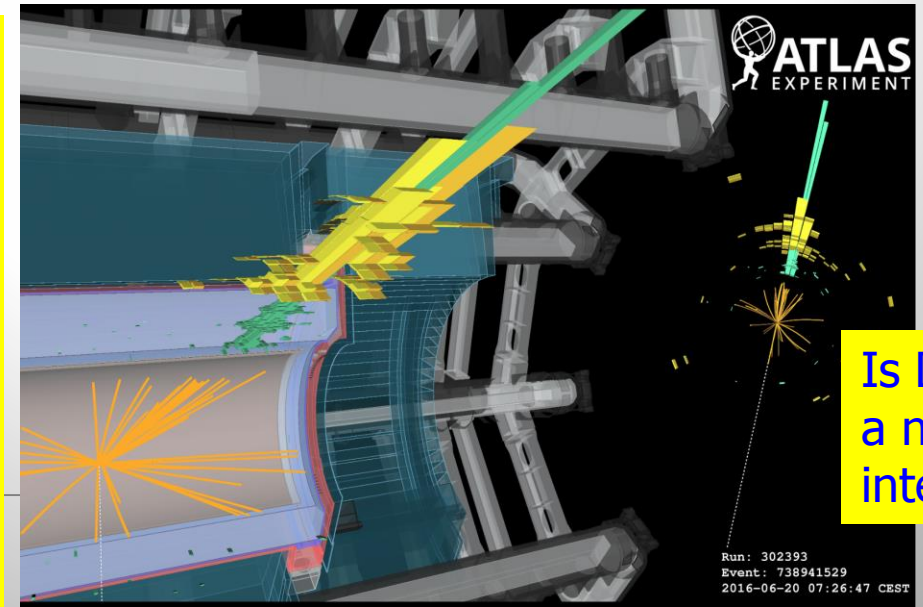








- Identifying Dark Matter is one of the most important questions in physics today!
- It is likely a new as yet undetected particle
- Can it be produced at the LHC?



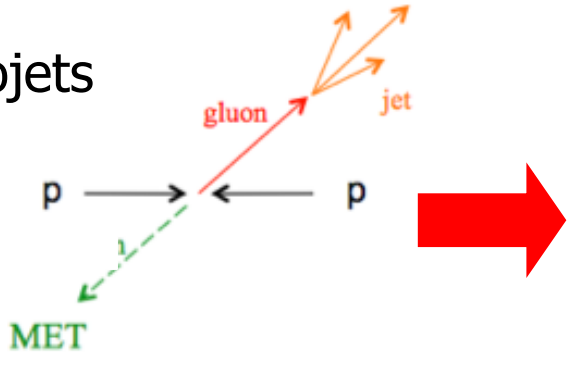
Is Dark Matter a new weakly interacting particle?

Mono-object Searches in CMS

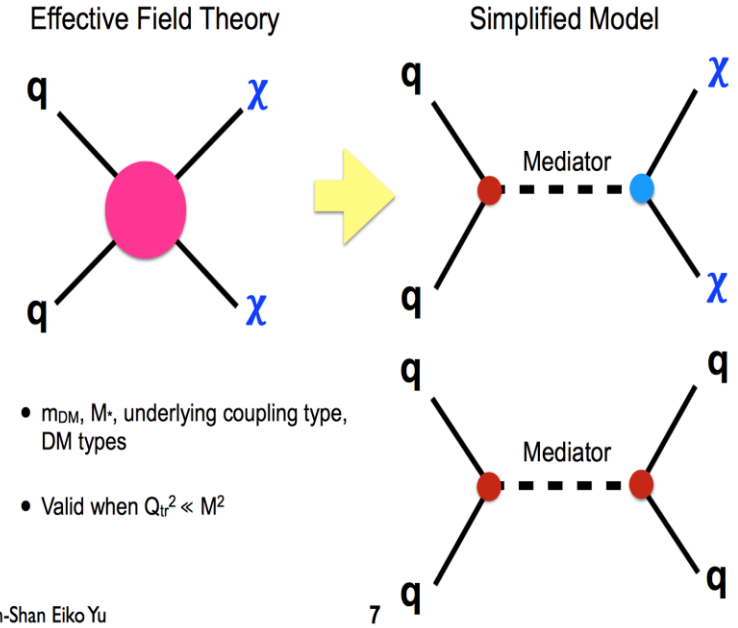
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Are Dark Matter weakly interacting massive particles (WIMPs?)

Example Monojets



Dark Matter?

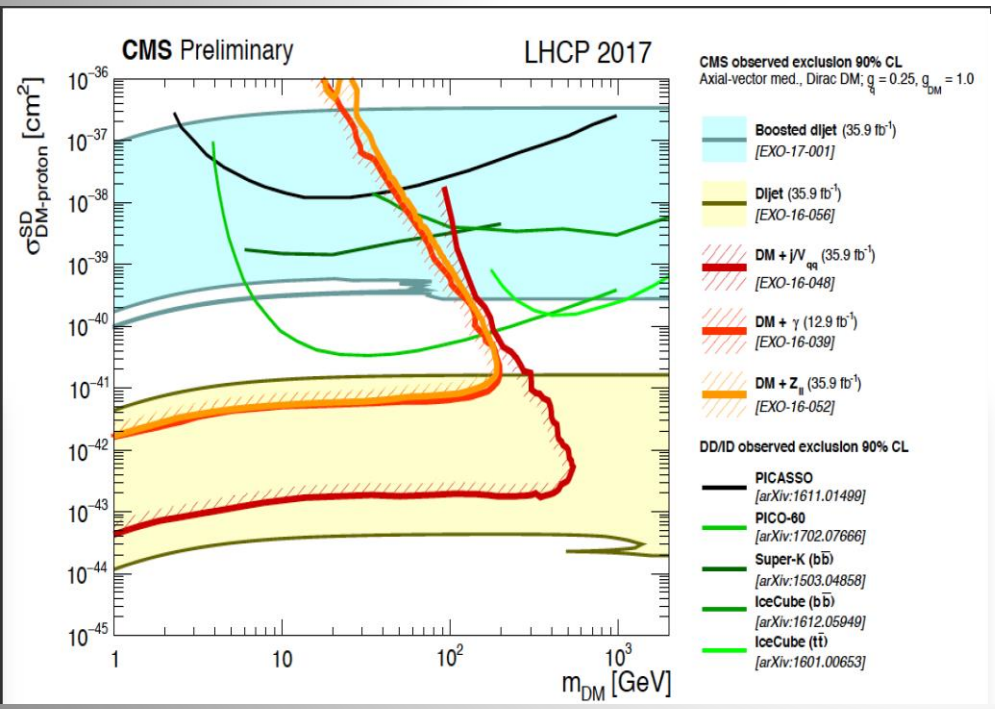


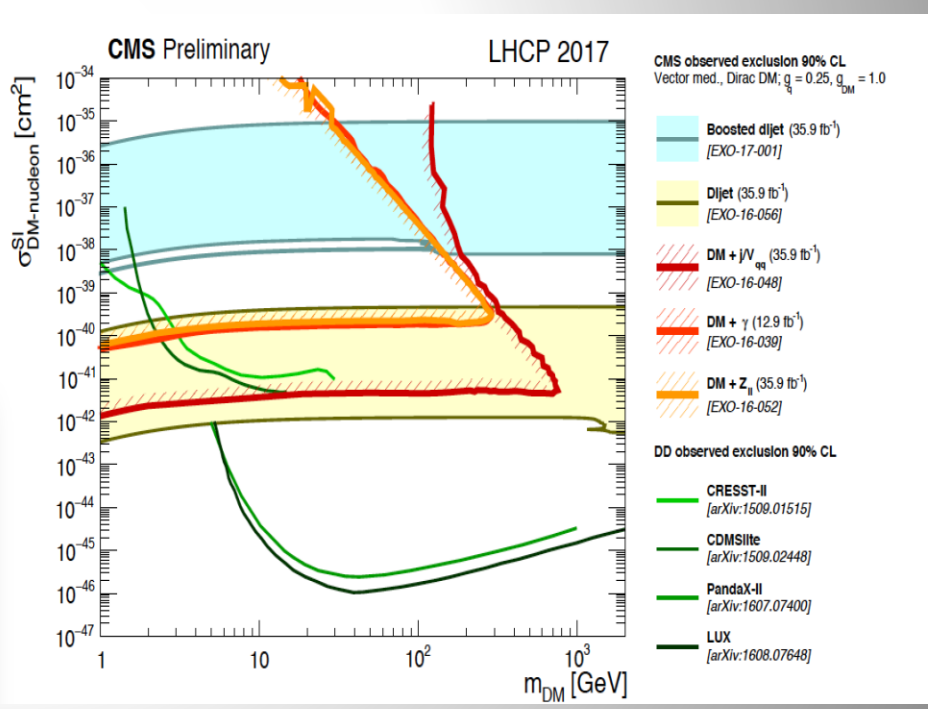
Comparison with Direct Detection

No signal seen in any of the "mono"-signals so far -> limits

Axial-vector mediator and
Spin-dependent direct limits

Vector mediator and
Spin-independent direct limits





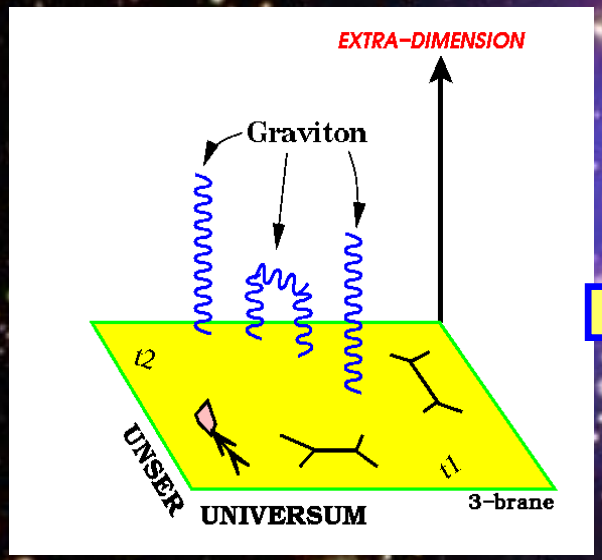
Mono-jet/V searches are typically the most sensitive ones

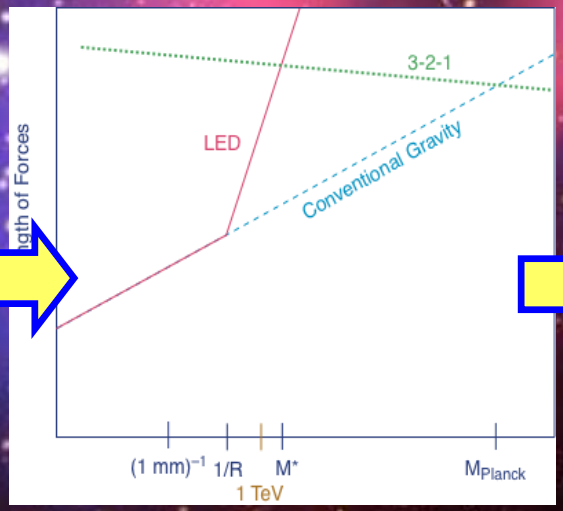
90% CL limits

Extra Space Dimensions

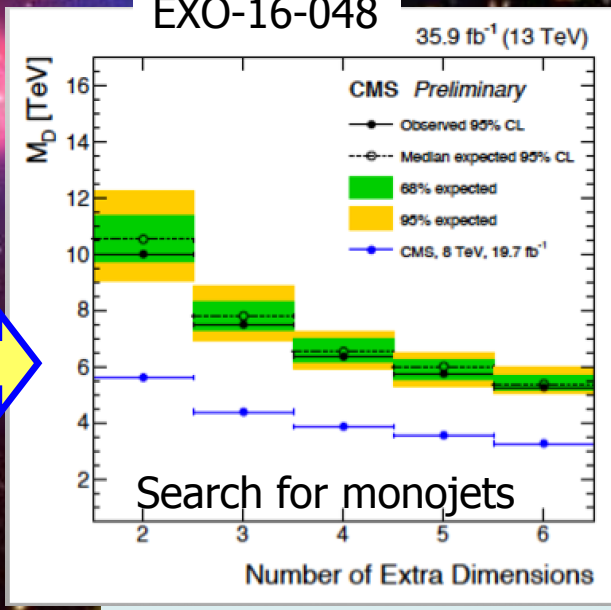
Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\ \text{GeV} \quad \Leftrightarrow \quad M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19}\ \text{GeV}$$





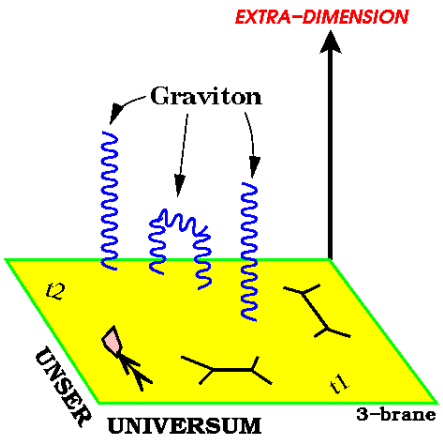
EXO-16-048



The Gravitational force can become strong!

No signal found yet
New Planck scale is larger than 6-10 TeV

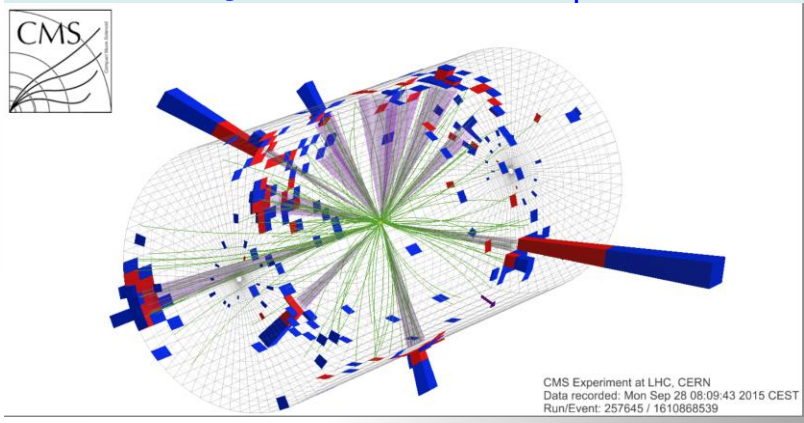
Search for Micro Black Holes



Extra Dimensions!

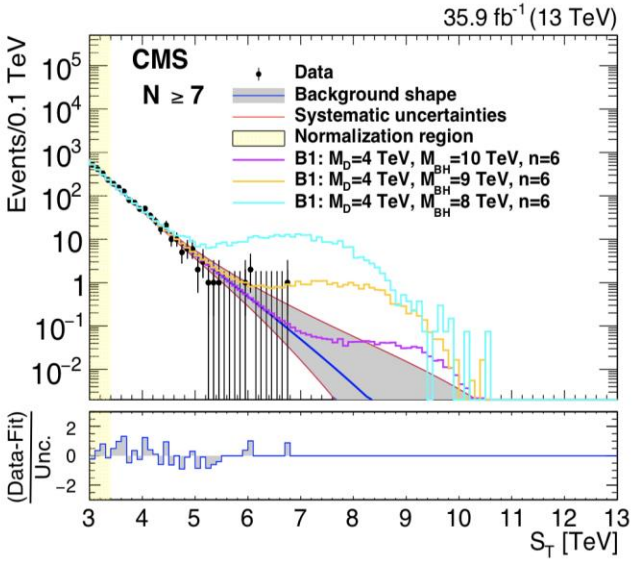
Planck scale
a few TeV?

2015: 12 jet event with S_T=5.4 TeV

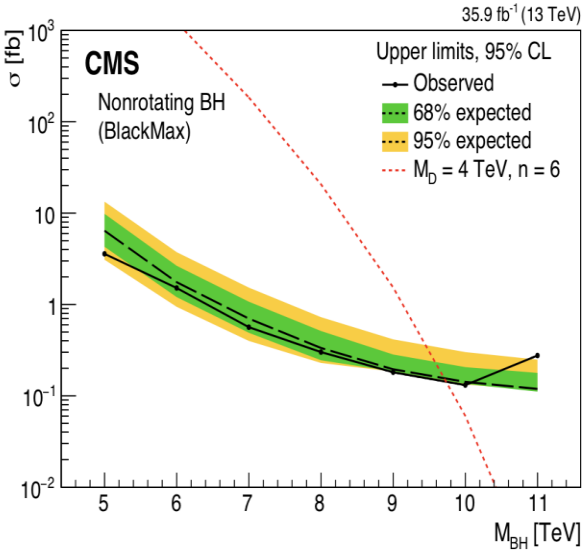


Look for the decay producs of an evaporating black hole

-Define S_T to be the scalar sum of all high p_T objects found in the event
-Look for deviations at high S_T

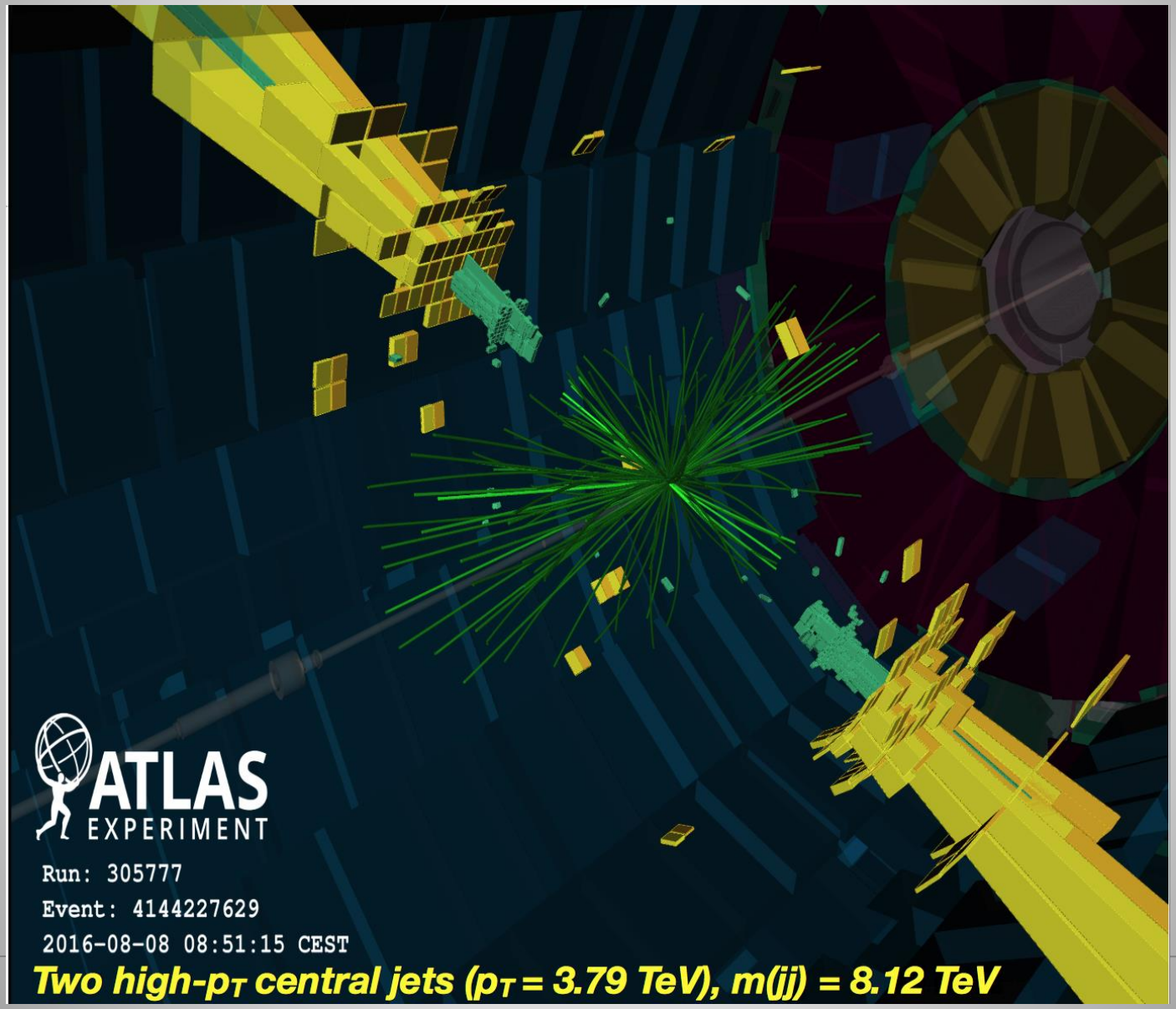


arXiv:1805.06013



Black hole mass excluded up to ~10 TeV depending on model assumptions

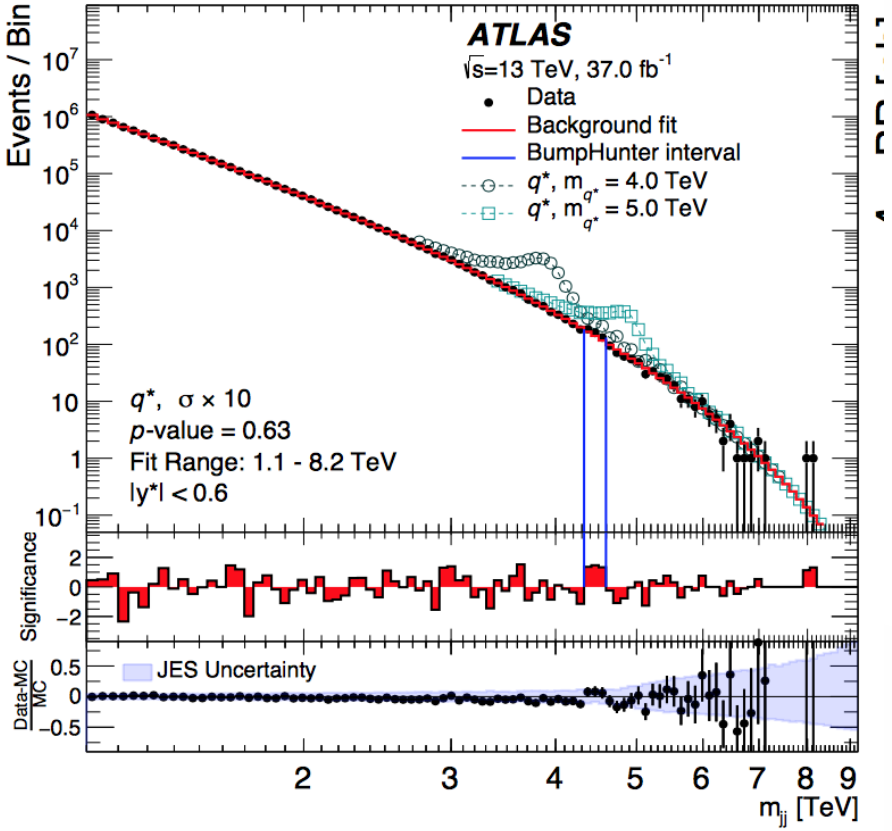
Dijet Resonance Searches @13TeV

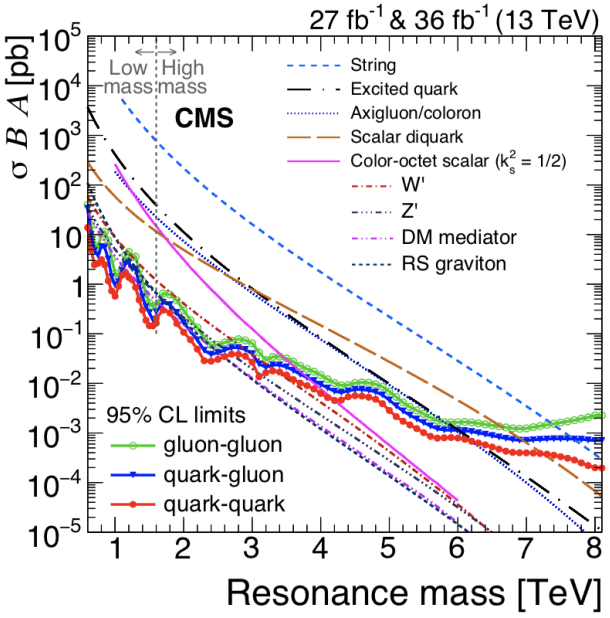


Dijet Resonance Searches @13TeV

arXiv:1703.09127

Background: QCD smooth shape fit





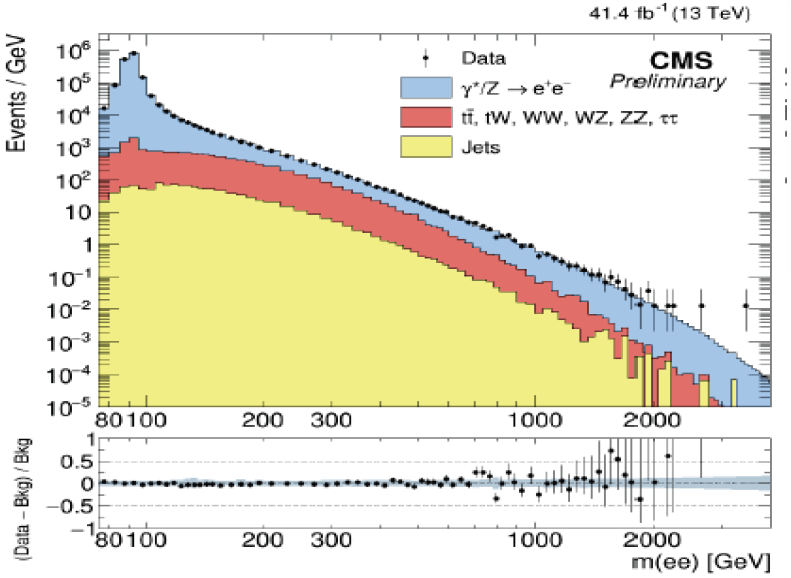
arXiv:1806.00843

Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1}	Ref. [4], 12.9 fb^{-1}
String resonance	qg	7.7 (7.7)	7.4 (7.4)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	5.5 (5.6)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)
W′ SM-like	$q\bar{q}$	3.3 (3.6)	2.7 (3.1)
Z′ SM-like	$q\bar{q}$	2.7 (2.9)	2.1 (2.3)
RS graviton ($k/\overline{M}_{\rm Pl} = 0.1$)	$q\bar{q}$, gg	1.8 (2.3)	1.9 (1.8)
DM mediator ($m_{\rm DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.0 (2.0)

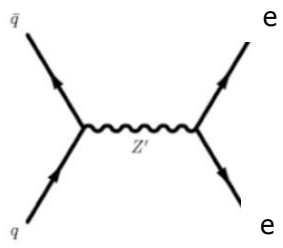
36 fb^{-1} limits from 13 TeV between 1.8 and 7.7 TeV, dependent on model

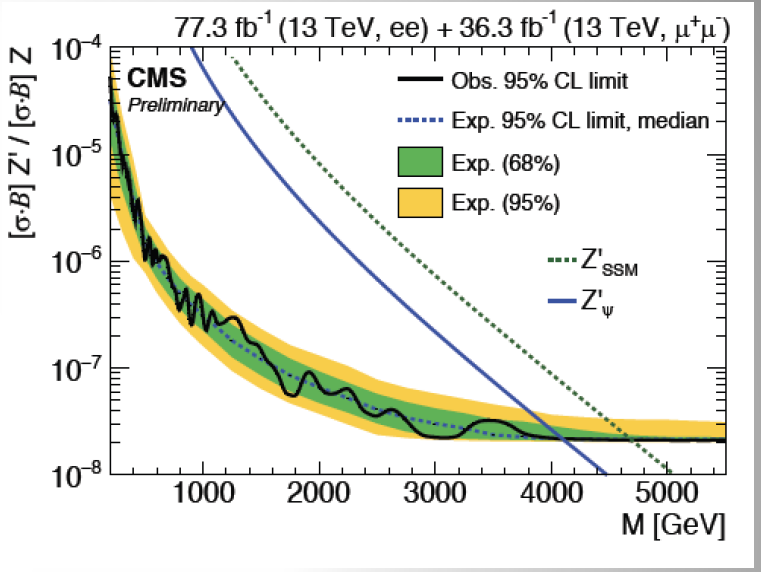
Lepton+MET/Dilepton Searches

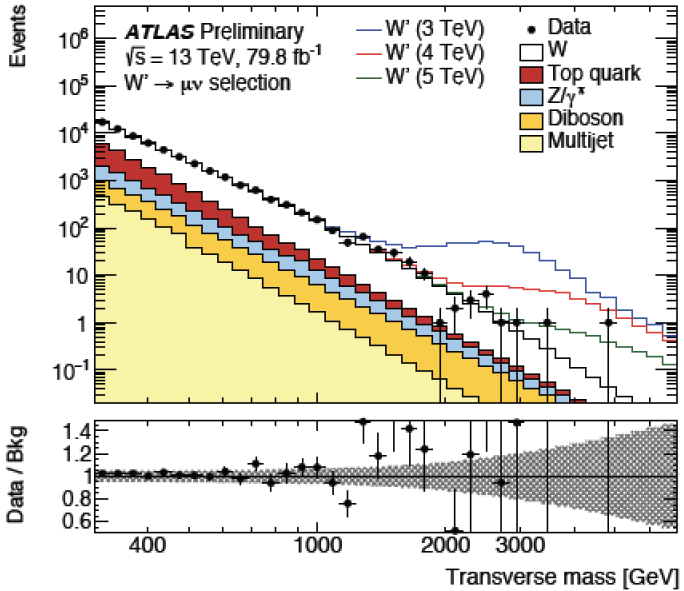
Search for dilepton resonances (Z'...) or lepton+MET (W'...) searches



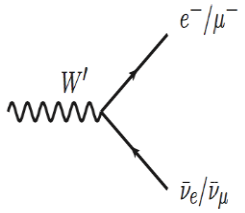
EXO-18-006







ATLAS-2018-17



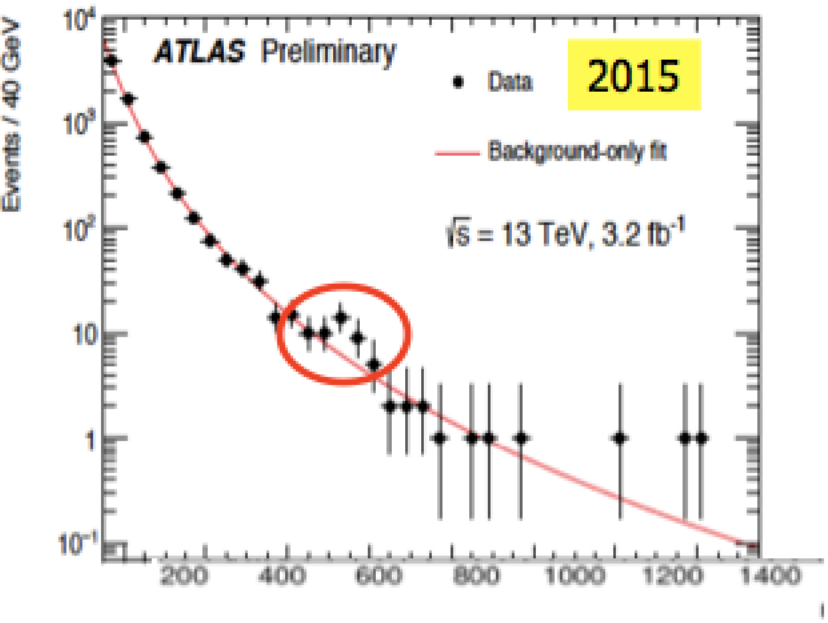
Analyses that include 2017 data!

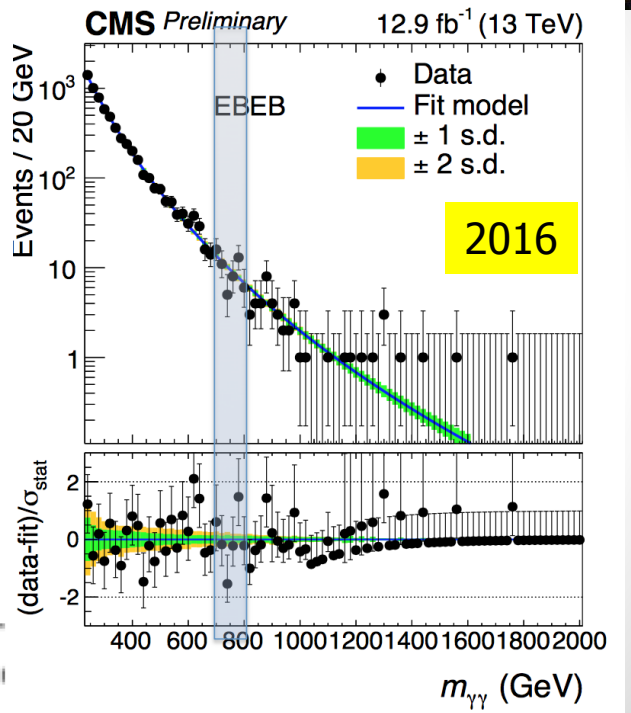
W' in context of sequential SM excluded up to 5.5 TeV wth 80 fb^{-1}
Extended from 5.2 TeV (36 fb^{-1})

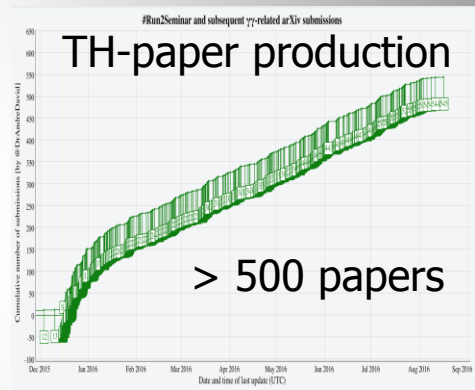
A New Particle at 750 GeV: $X \rightarrow \gamma\gamma$?

Excitement in December 2015
->Some excitement on an mild observed excess in both experiments for a diphoton mass of around 750 GeV

ATLAS-CONF-2015-081 CMS EXO-15-004





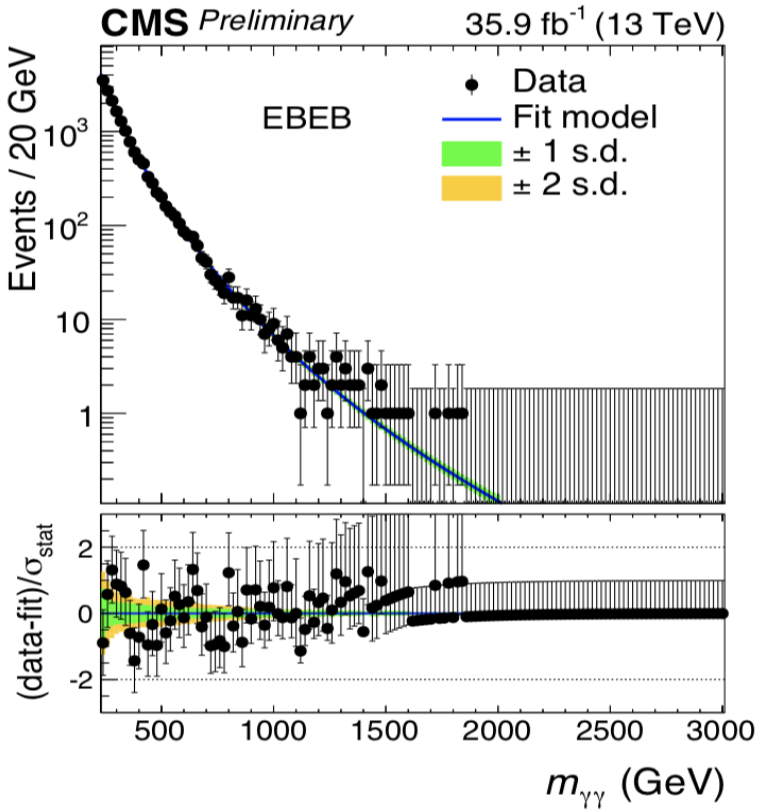


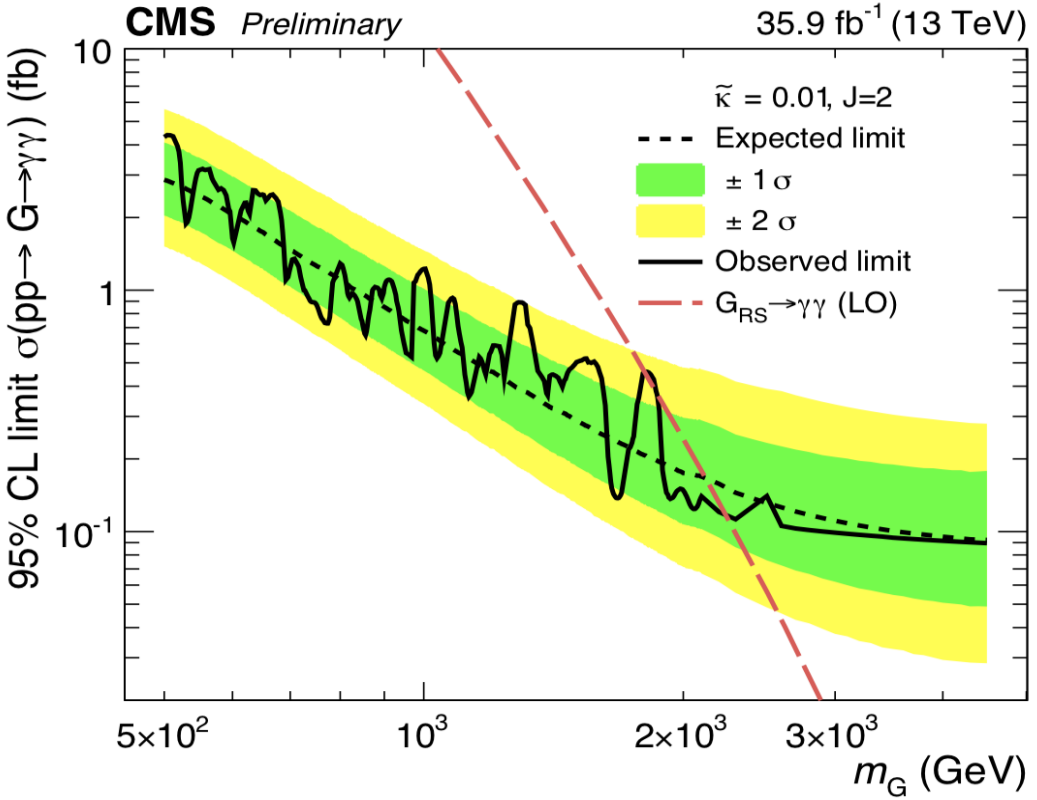
2015: Statistical fluctuation? A new resonance? ???
2015 data: CMS: 3.4 σ ! ATLAS up to 3.9 σ !! (local significances)
2016 data: 13 fb^{-1} CMS and ATLAS Nada!!

Search for a Di-photon Resonance

EXO-17-017

The search with the full 2016 data





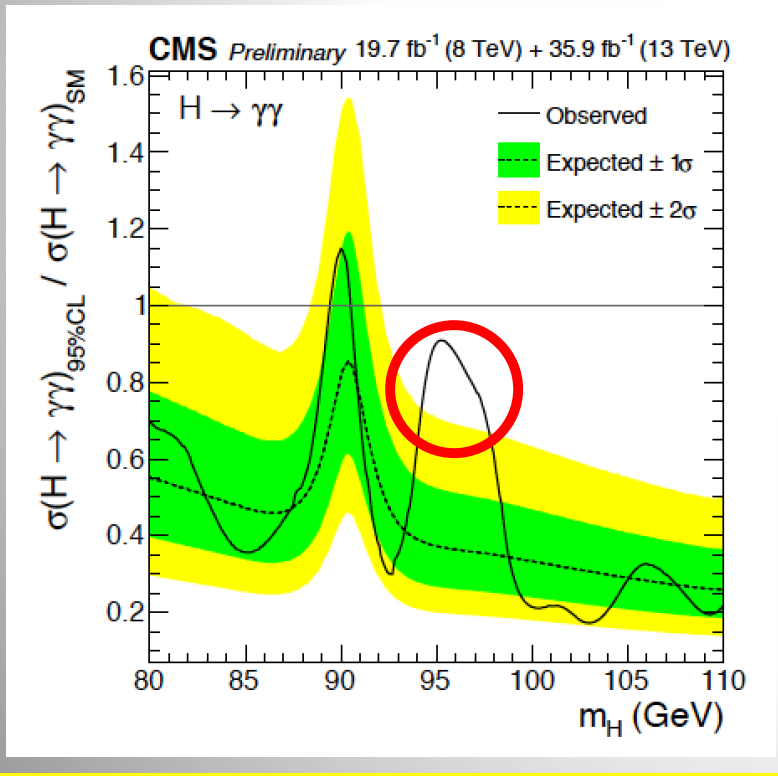
2016 data: Full statistics CMS … nothing special

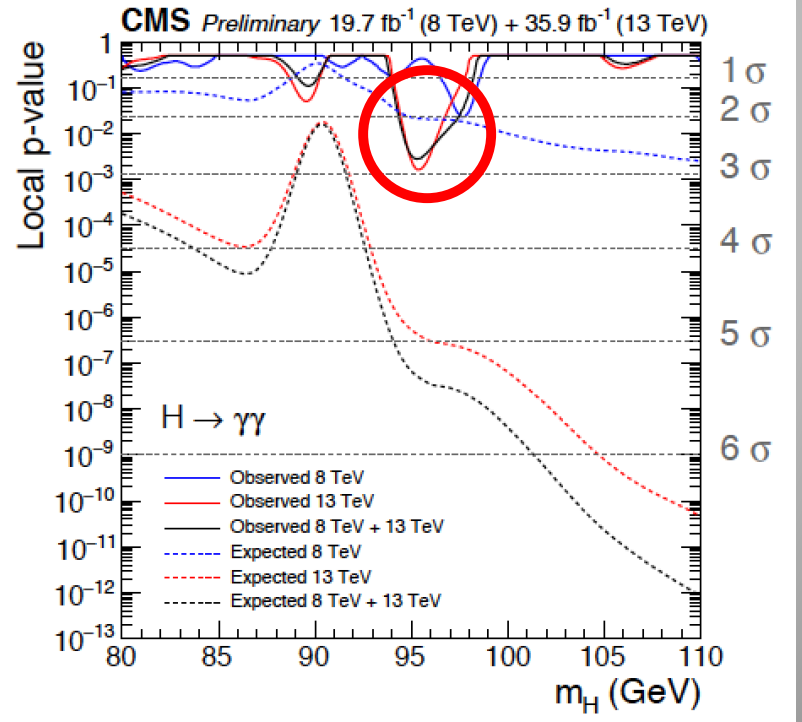
Is 96 GeV the New 750 GeV (?)

August 2017: A search for X->γγ at low mass

An excess is observed in the 8 TeV data (2σ at 97.6 GeV) and 13 TeV (2.9σ at 95.3 GeV) -> Combined gives a 2.8σ excess at 95.3 GeV

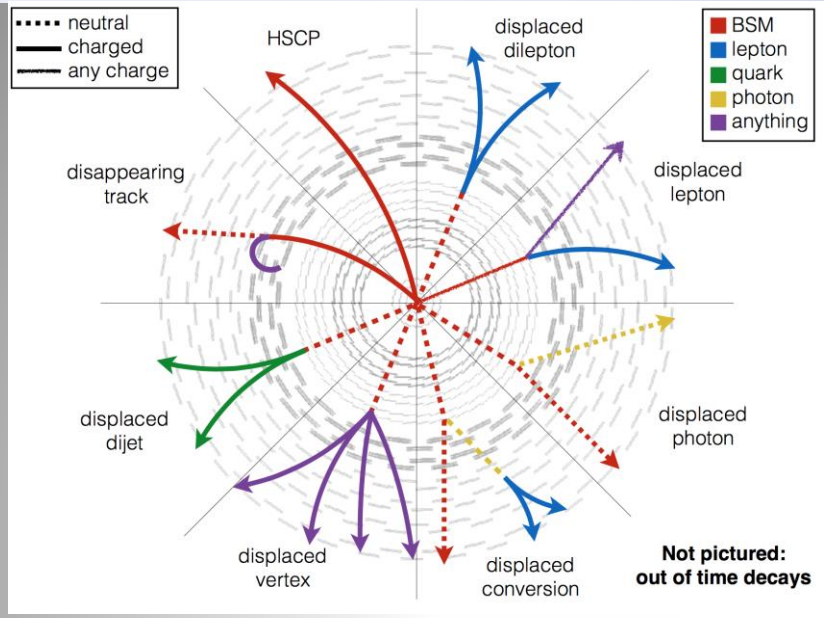
CMS-HIG-17-013





So far seen only in CMS. Waiting for the ATLAS data to be released... ☺ !!

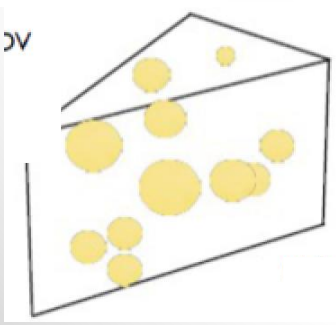
Searches for Long Lived Particles

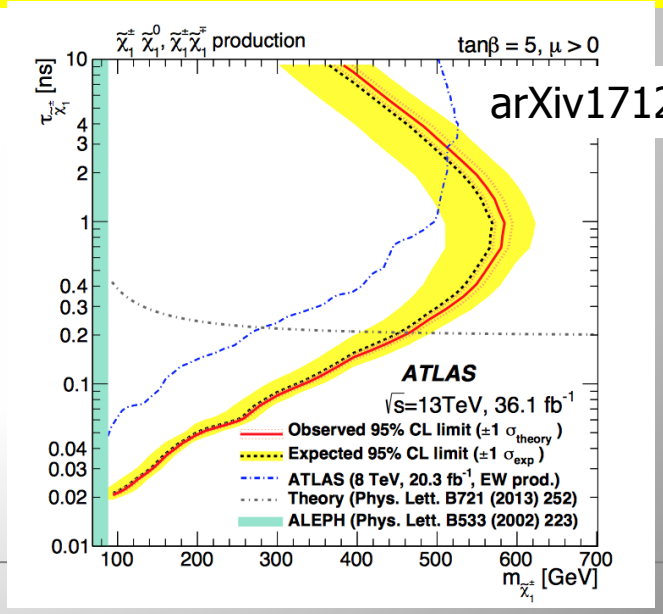


Increasing interest and effort:
Look for unusual signals in the detector from long-lived particles

- Example disappearing tracks ->
- Search for charginos, almost degenerate with neutralinos (eg AMSB models)

Present coverage?



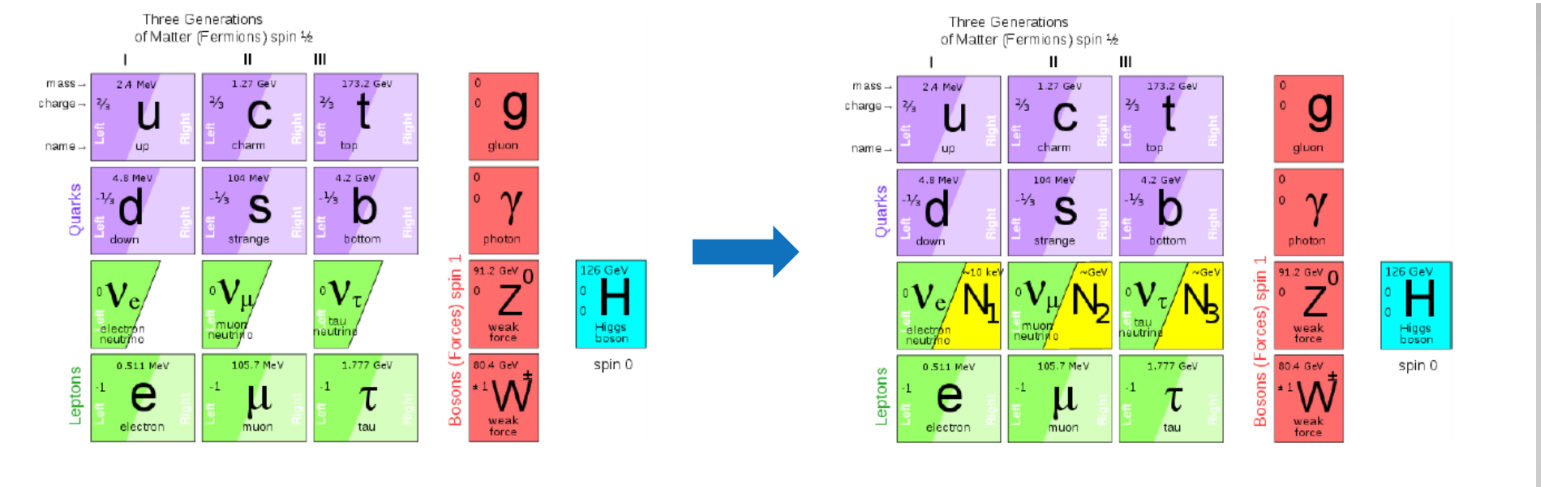


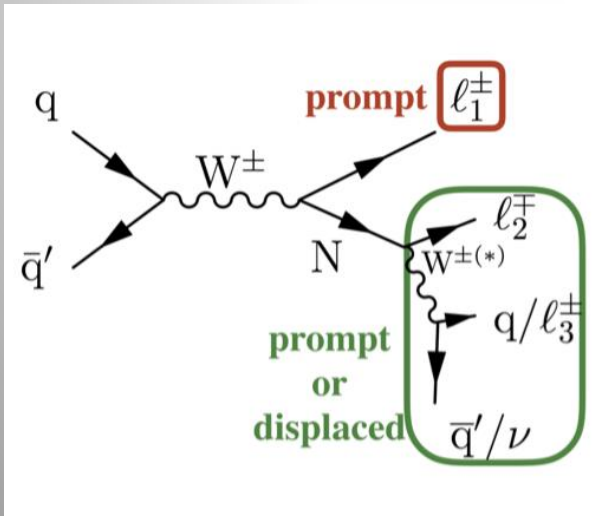
LHC-wide organized study ->
https://indico.cern.ch/e/LHC_LLP_October_2017

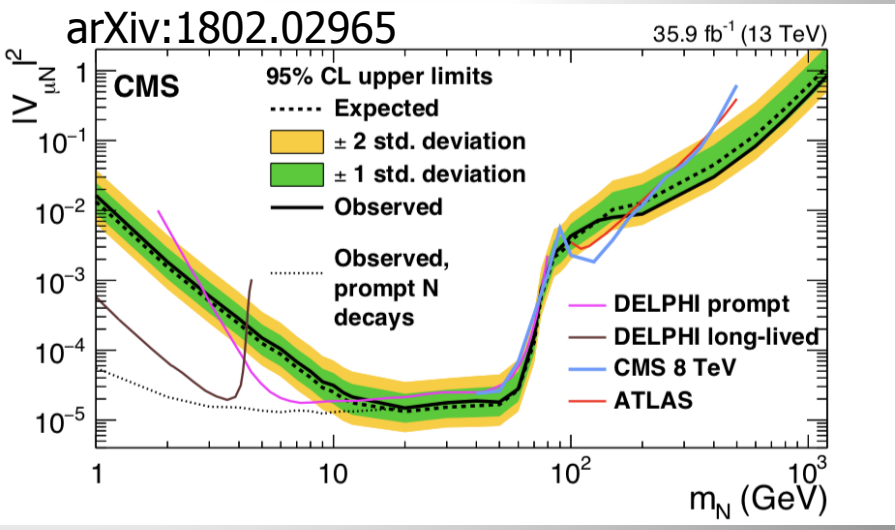
A White Paper in preparation!

Search for Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)
Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.







-> HNL hunting also focus of the SHIP experiment proposal

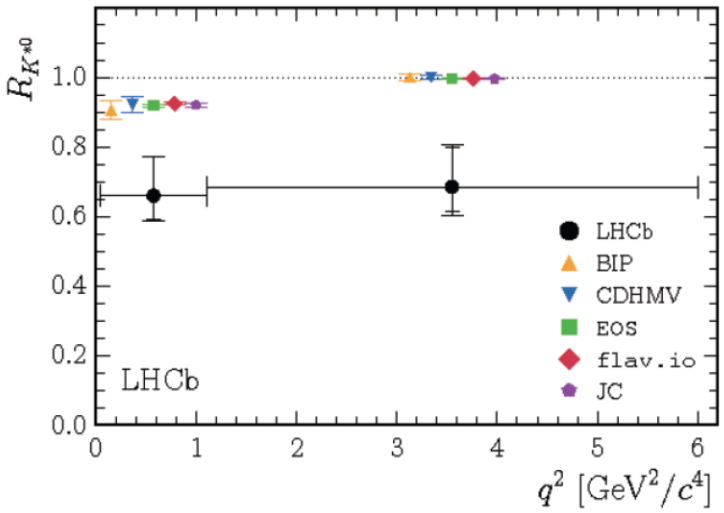
LHCb: Test of Lepton Universality

A puzzling results from the LHCb experiment...

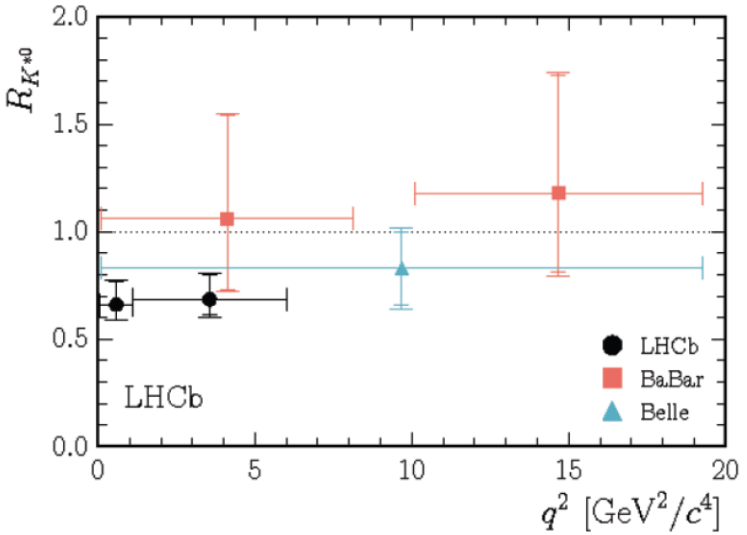
Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to He^+e^-$ $\quad H = K, K^*, \phi, \ldots$

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

Comparison with SM predictions



Comparison with BaBar & Belle



$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\,\text{GeV}^2 \end{cases}$$

2.1 - 2.3 σ
2.4 - 2.5 σ

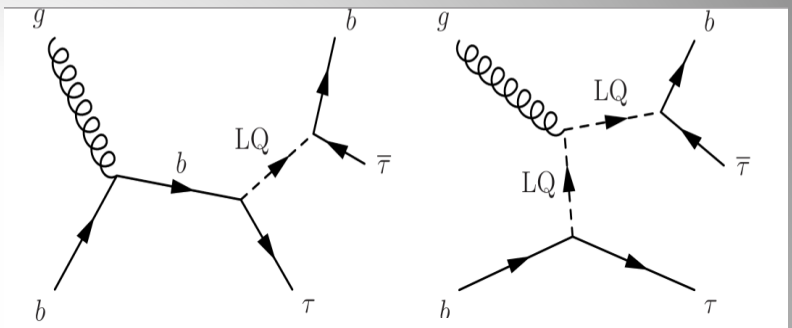
?

Also: $R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$

?

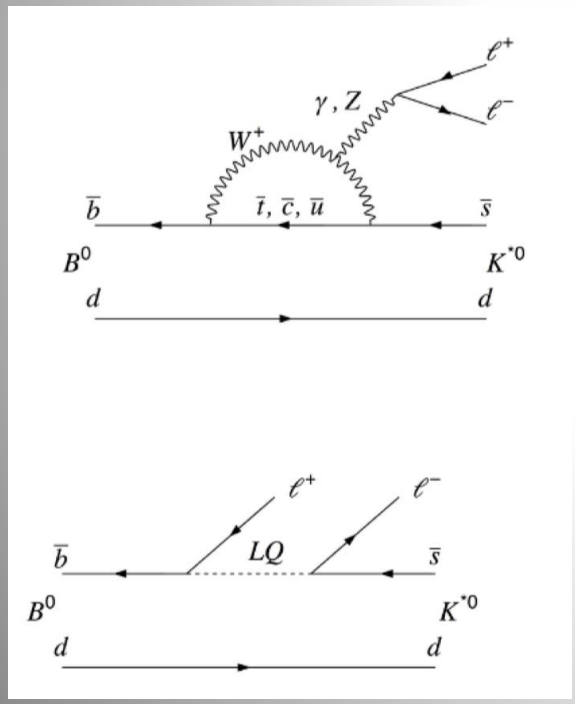
Third Generation Leptoquarks

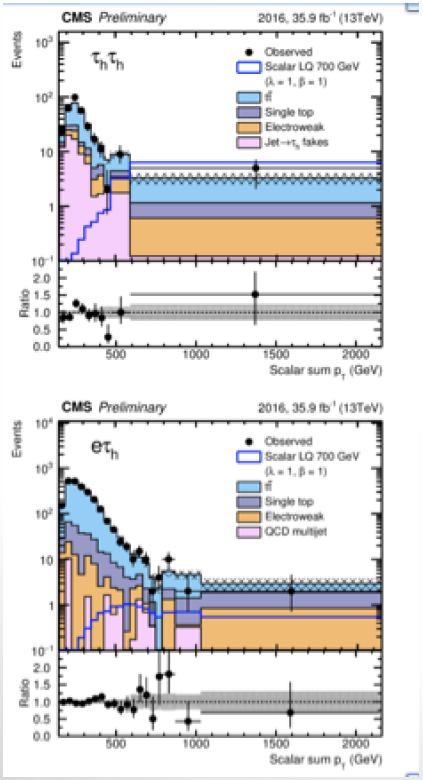
Candidate explanation: Leptoquarks with couplings to second/third generation.
-> Check in ATLAS and CMS

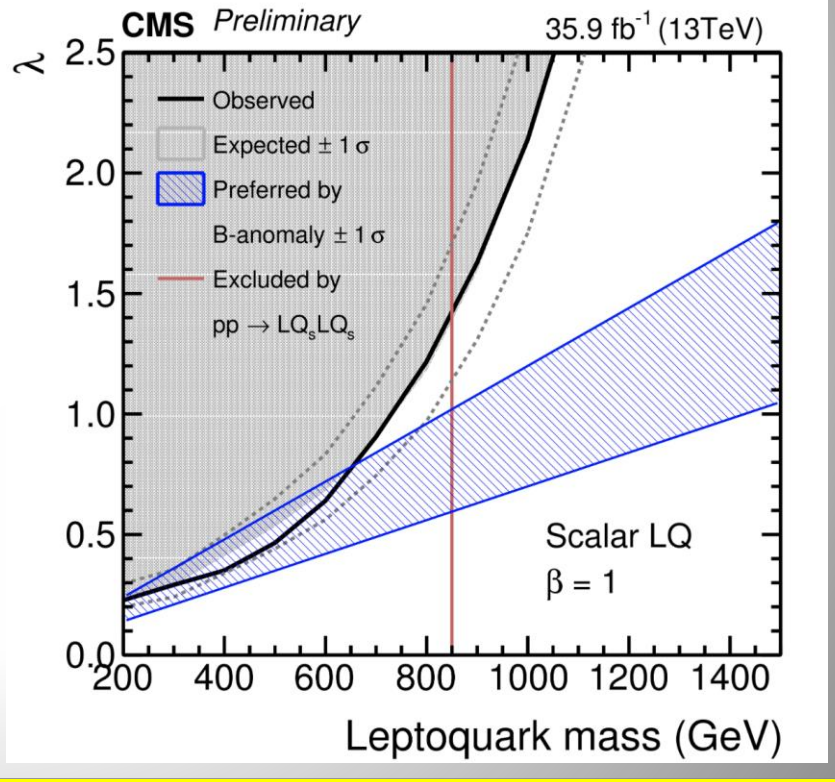


EXO-17-029

Example search in the tau-b final state



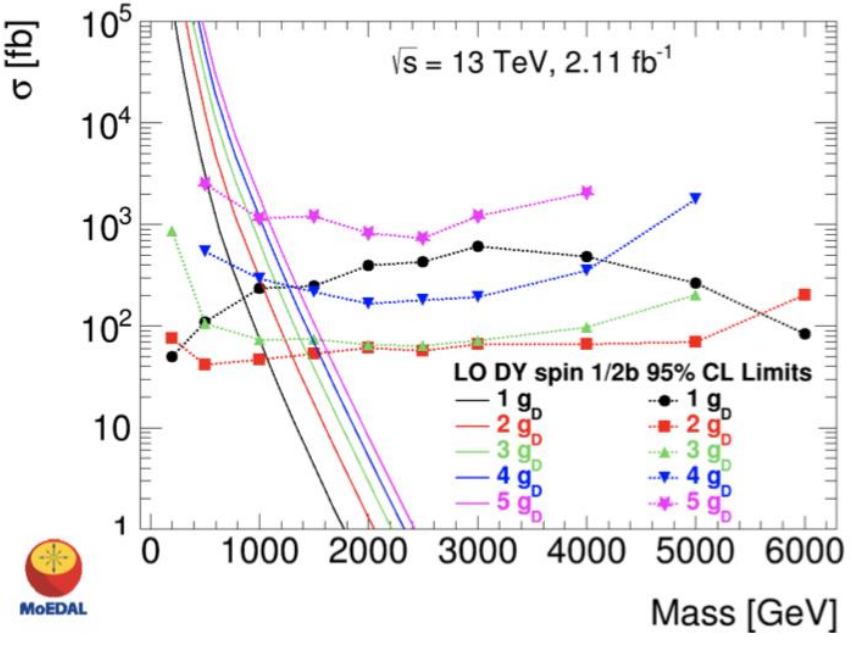


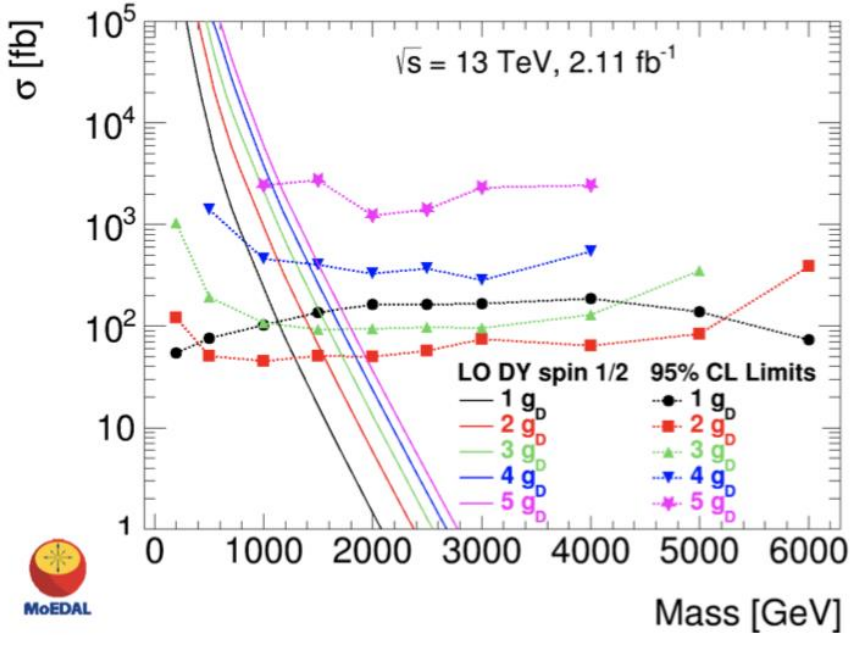


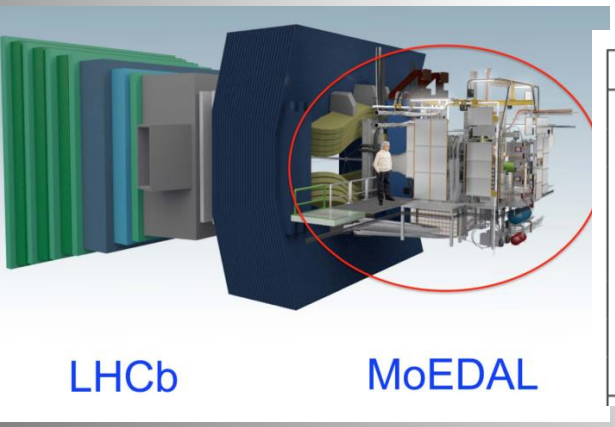
Blue region is preferred by the B-anomalies…

Monopole Searches: MoEDAL @ 13TeV

2016 data analysis base on 222 kg Aluminium to "stop" the monopoles and search for them with a SQUID precision magnet (2.11fb^{-1}) arXiv:1712.09849





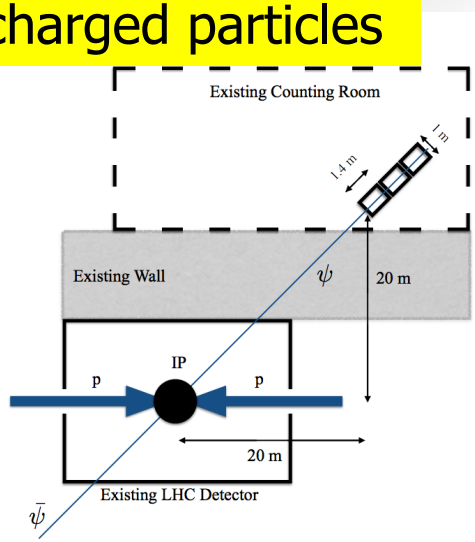


Mass limits [GeV]	$1g_D$	$2g_D$	$3g_D$	$4g_D$	$5g_D$
MoEDAL 13 TeV (2016 exposure)					
DY spin-0	600	1000	1080	950	690
DY spin-$\frac{1}{2}$	1110	1540	1600	1400	–
DY spin-1	1110	1640	1790	1710	1570
DY spin-0 β-dep.	490	880	960	890	690
DY spin-$\frac{1}{2}$ β-dep.	850	1300	1380	1250	1070
DY spin-1 β-dep.	930	1450	1620	1600	1460

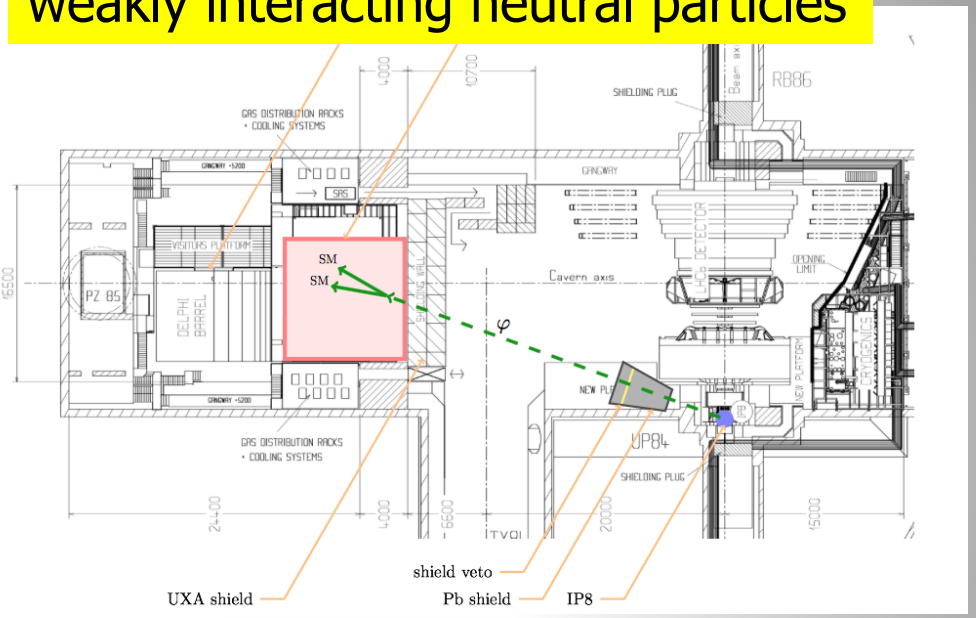
- Limits for different monopole charges
- First monopole search result @LHC at 13 TeV No signal (yet)..

Possible New Experiments @LHC

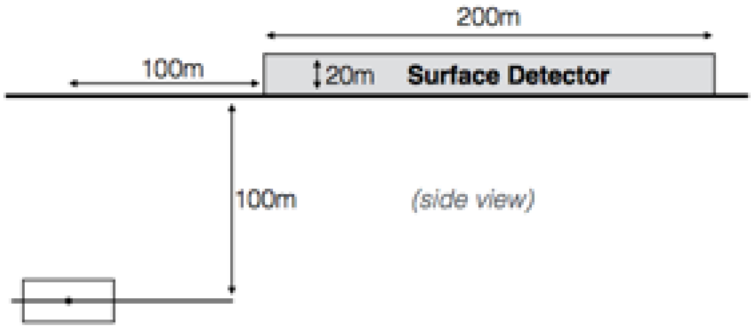
MilliQan: searches for millicharged particles



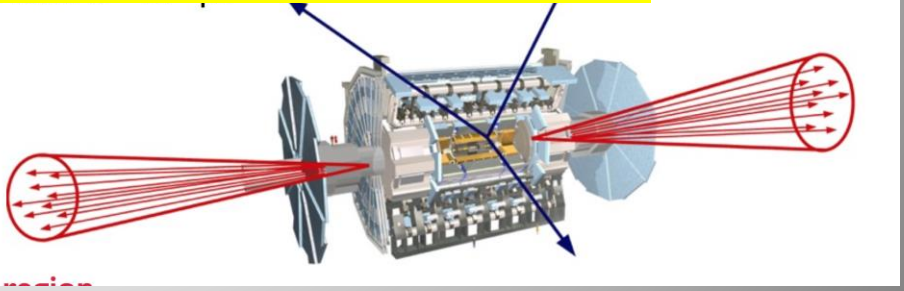
CODEX-b: searches for long lived weakly interacting neutral particles



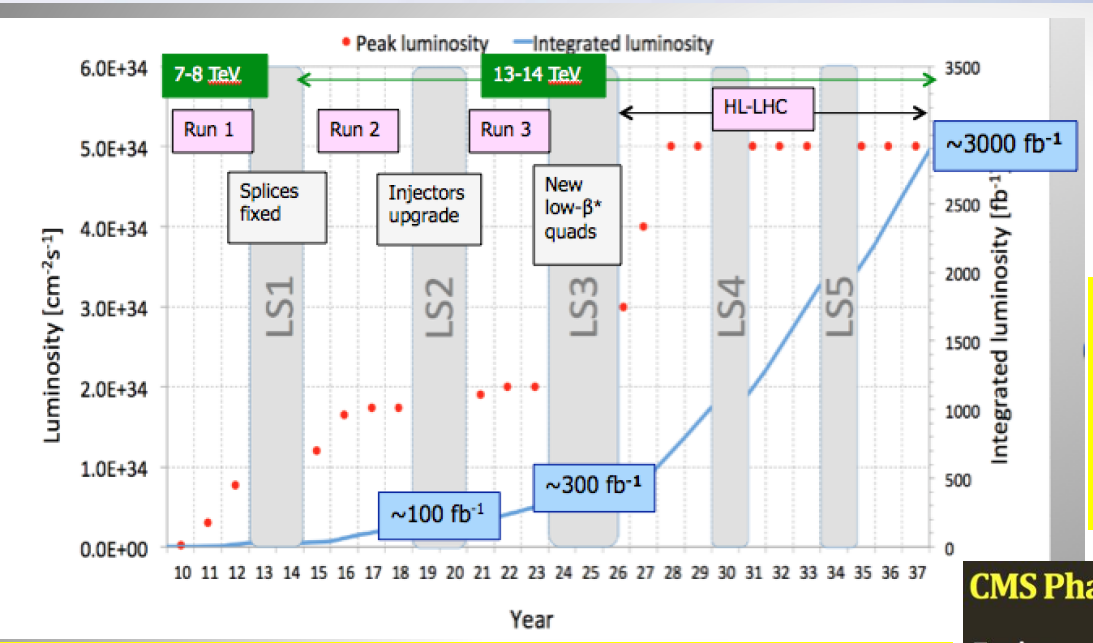
MATHUSLA: searches for long lived weakly interacting neutral particles



FASER: searches for long lived dark photons-like particles



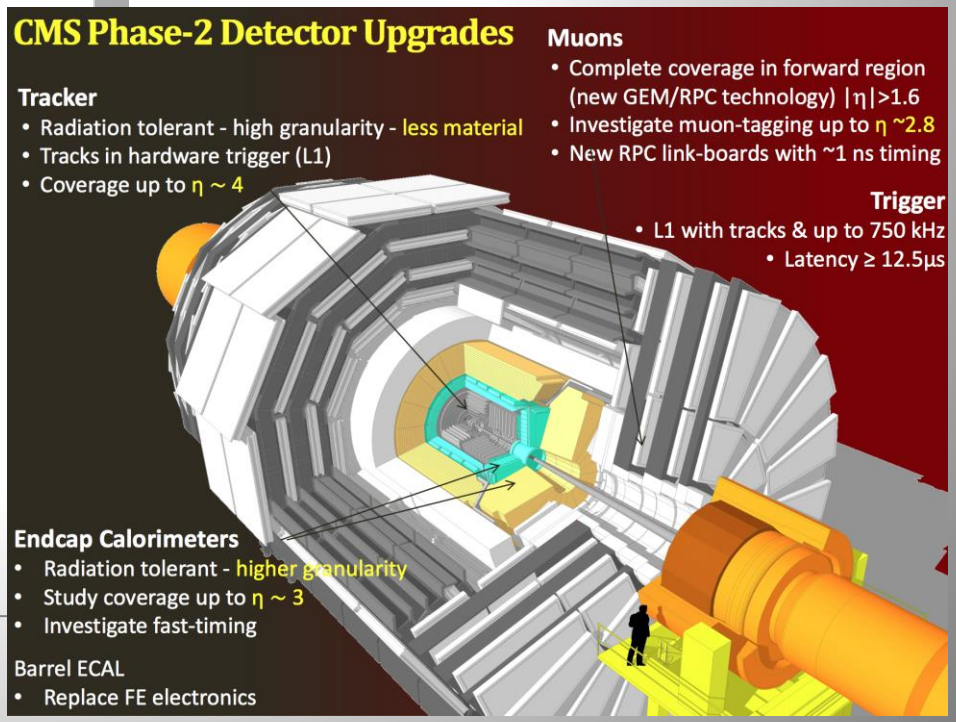
LHC Outlook and Plans



All LHC experiments plan upgrades for either 2019-2020 or 2024-2026 for the High Luminosity LHC upgrade (ATLAS and CMS)

Approved LHC program to collect 3000 fb^{-1} in total with the LHC (HL-LHC)
Maximize the reach for searches and for precision measurements (eg Higgs)

LHC will run till ~2037
Only 3% of the collisions delivered so far…
Then a high energy LHC (28 TeV)?



Summary

- New Higgs measurements at 13 TeV. So far the Higgs is very consistent with Standard Model expectations.
- No sign of new physics in the 13 TeV data so far… This starts to cut into the 'preferred regions' for a large number of models, like SUSY. Naturalness?

  There are a number of 3-sigma effects, as always, but… ☺
- Dark Matter and Long Lived Particle searches are being explored in a systematic way. White paper on LLPs to appear.
- First results from the 2017 data being released.
- New physics in the flavour sector? New TH paradigms?
- The LHC is continuing to explore the Terascale. much data to look forward to: it takes on significa to show the way!! Collected >80 fb^{-1}@ 13 TeV sc

  And hopefully one day soon:

Backup

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

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

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\text{fb}^{-1}]$	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	$\geq 2/\geq 1$ 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

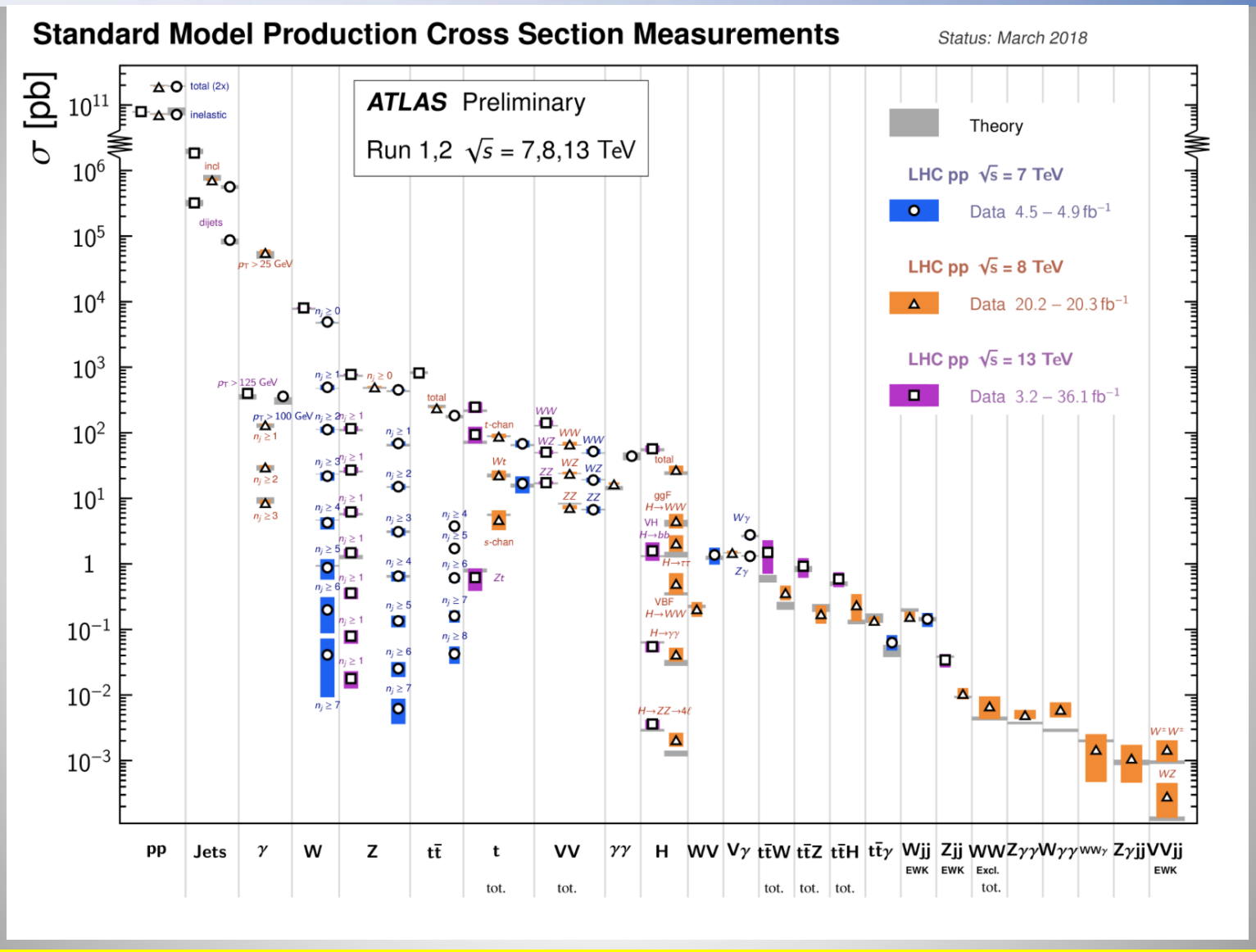
$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

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).

Summary: Cross Sections 7/8/13 TeV



All measurements in good agreement with the Standard Model predictions!!

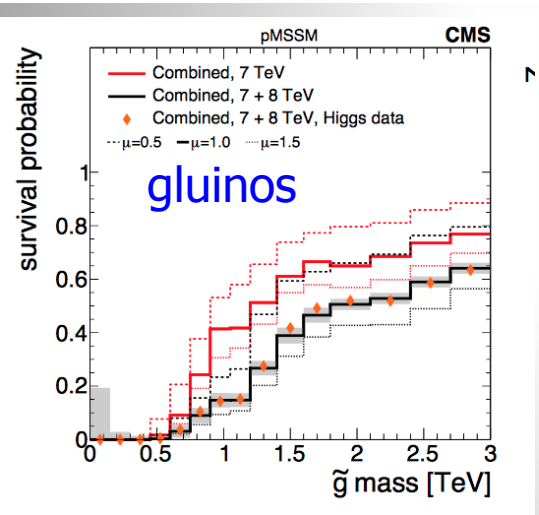
Phenomenological MSSM analysis

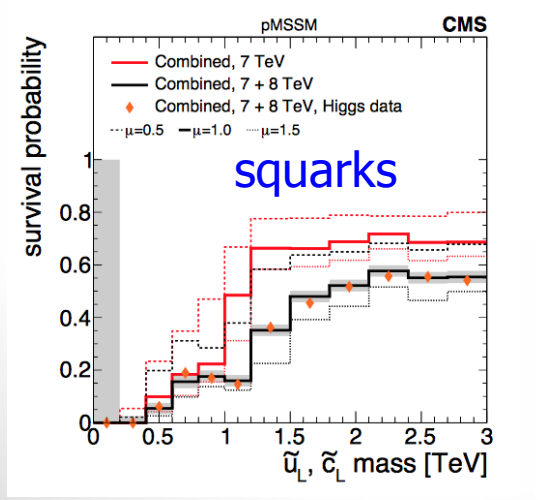
SMS don't always fully cover signatures…
-> the 19 parameter phenomenological MSSM (pMSSM) analyses

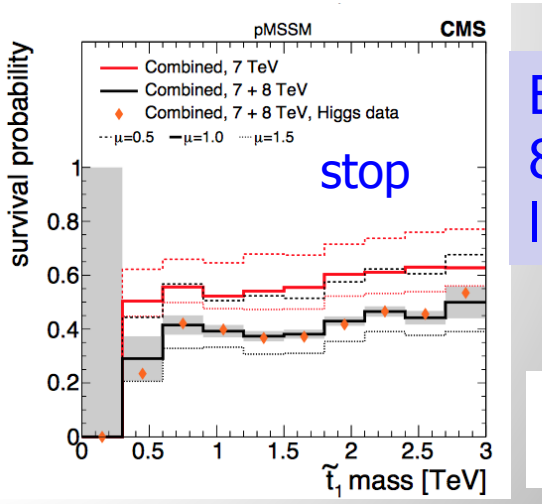
arXiv:1606.03577

- three independent gaugino mass parameters M_1, M_2, and M_3,
- the ratio of the Higgs vacuum expectation values $\tan\beta = v_2/v_1$,
- the higgsino mass parameter μ and the pseudoscalar Higgs boson mass m_A,
- 10 independent sfermion mass parameters $m_{\tilde{F}}$, where $\tilde{F} = \tilde{Q}_1, \tilde{U}_1, \tilde{D}_1, \tilde{L}_1, \tilde{E}_1, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3$ (for the 2nd generation we take $m_{\tilde{Q}_2} \equiv m_{\tilde{Q}_1}, m_{\tilde{L}_2} \equiv m_{\tilde{L}_1}, m_{\tilde{U}_2} \equiv m_{\tilde{U}_1}, m_{\tilde{D}_2} \equiv m_{\tilde{D}_1}$, and $m_{\tilde{E}_2} \equiv m_{\tilde{E}_1}$; left-handed up- and down-type squarks are by construction mass degenerate), and
- the trilinear couplings A_t, A_b and A_τ.

$$
\begin{aligned}
-3 \le\ & M_1, M_2 \le 3\,\text{TeV},\\
0 \le\ & M_3 \le 3\,\text{TeV},\\
-3 \le\ & \mu \le 3\,\text{TeV},\\
0 \le\ & m_A \le 3\,\text{TeV},\\
2 \le\ & \tan\beta \le 60,\\
0 \le\ & m_{\tilde{Q}_{1,2}}, m_{\tilde{U}_{1,2}}, m_{\tilde{D}_{1,2}}, m_{\tilde{L}_{1,2}}, m_{\tilde{E}_{1,2}}, m_{\tilde{Q}_3}, m_{\tilde{U}_3}, m_{\tilde{D}_3}, m_{\tilde{L}_3}, m_{\tilde{E}_3} \le 3\,\text{TeV},\\
-7 \le\ & A_t, A_b, A_\tau \le 7\,\text{TeV},
\end{aligned}
$$







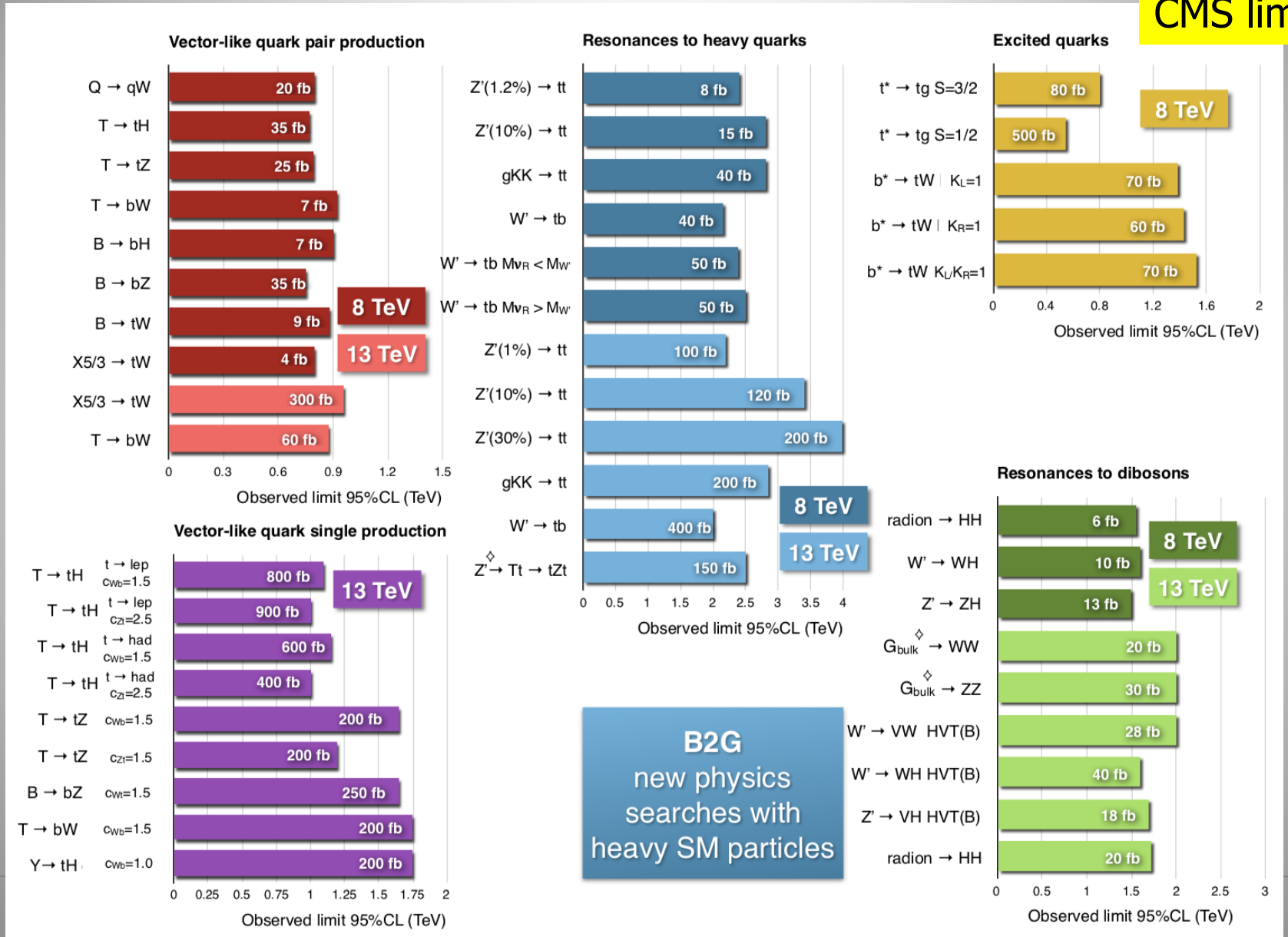
Based on 8 TeV data limits

ATLAS: arXiv:1508.06608

10^8 points sampled: Leads to softer limits on the sparticles masses
Gluinos > 500 GeV, stops > 300 GeV => there is still low mass phase space left!

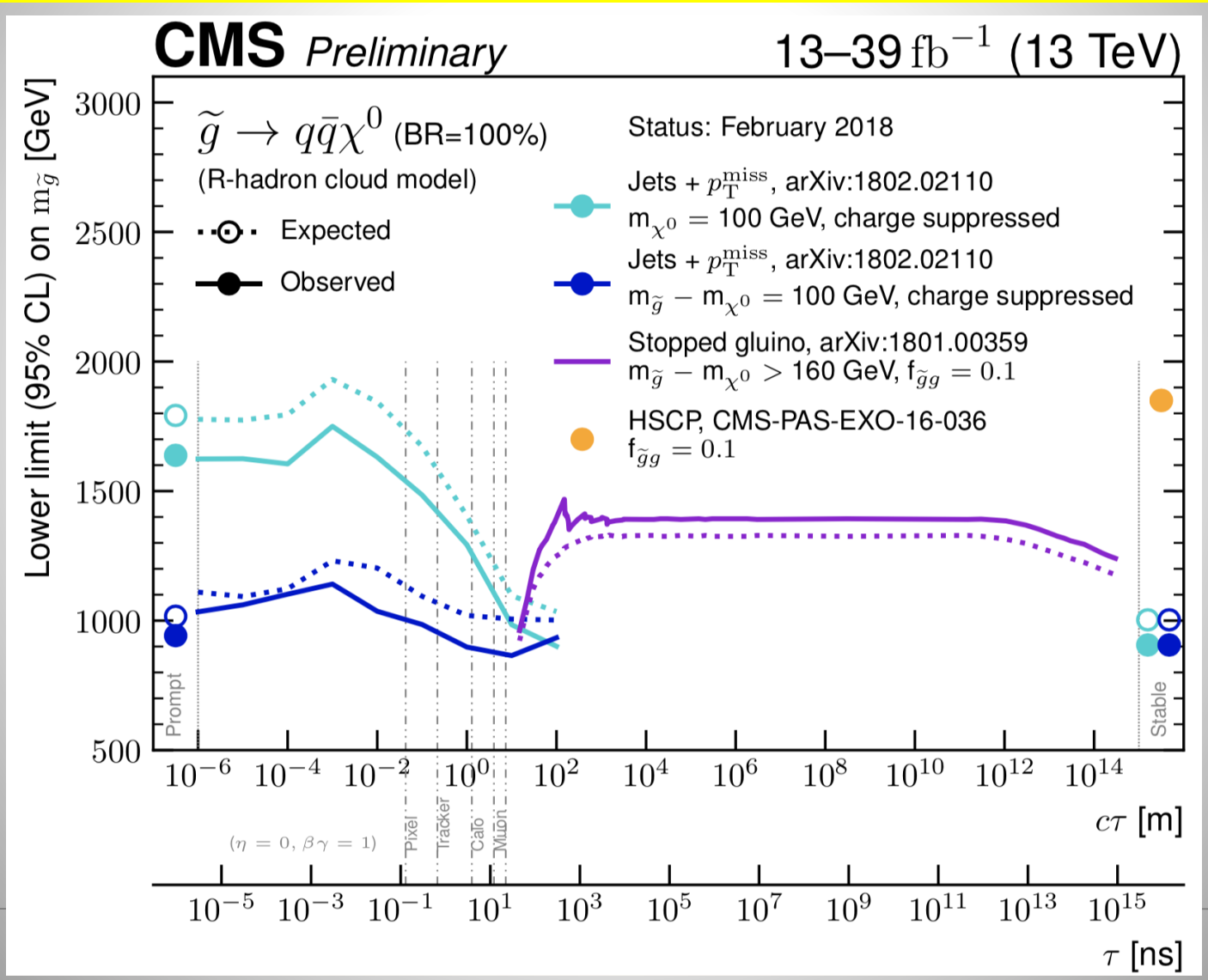
Vector-like Quarks...

CMS limits



Prompt versus Displaced Searches

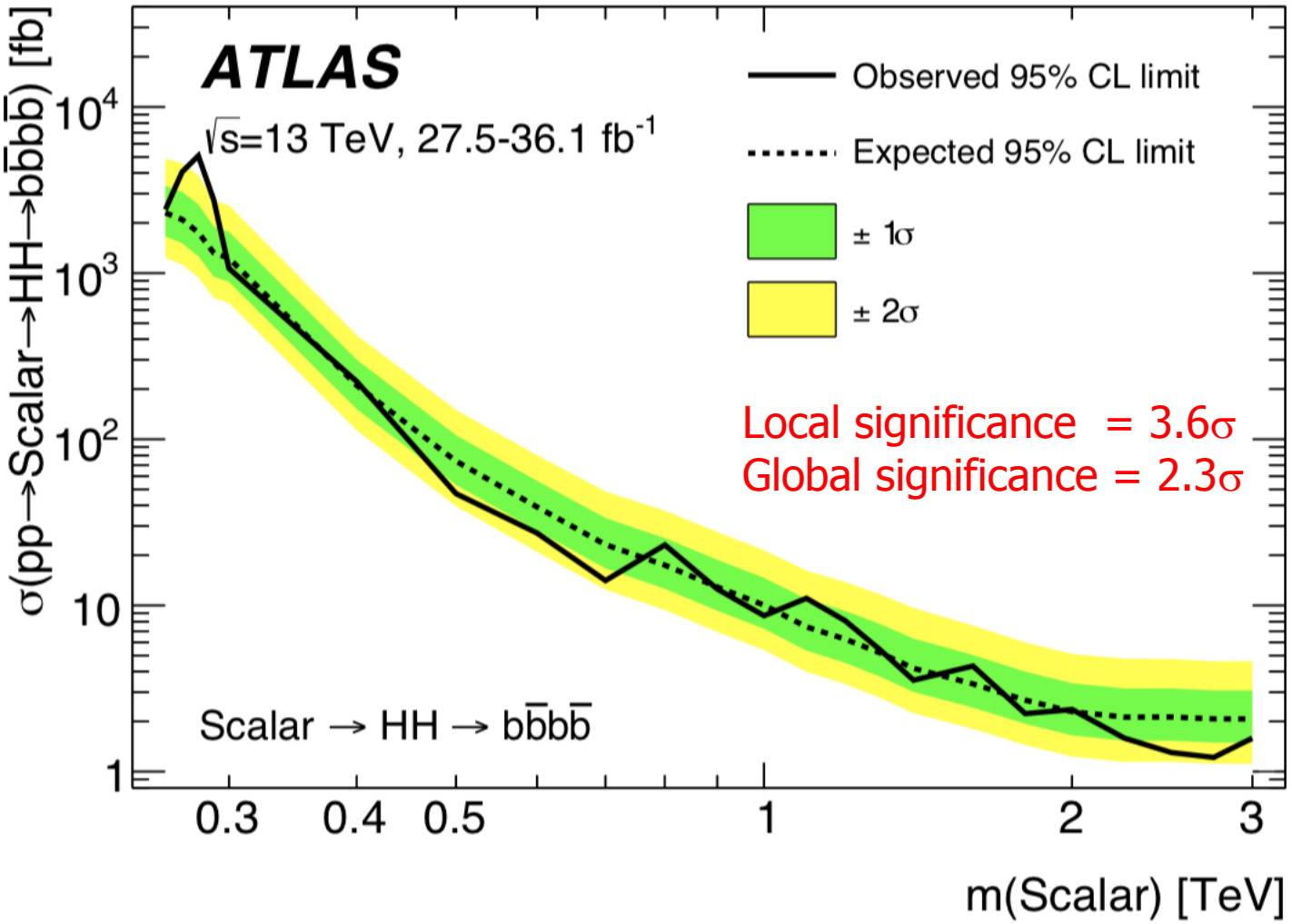
How far does the sensitivity of 'inclusive prompt analysis' cover?



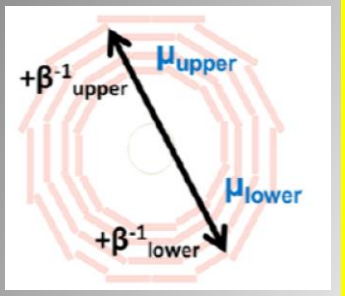
Search for HH to bbbb

arXiv:1804.06174

Search for 2 pairs of b-quarks with mass close to the Higgs (125 GeV), including boosted scenarios



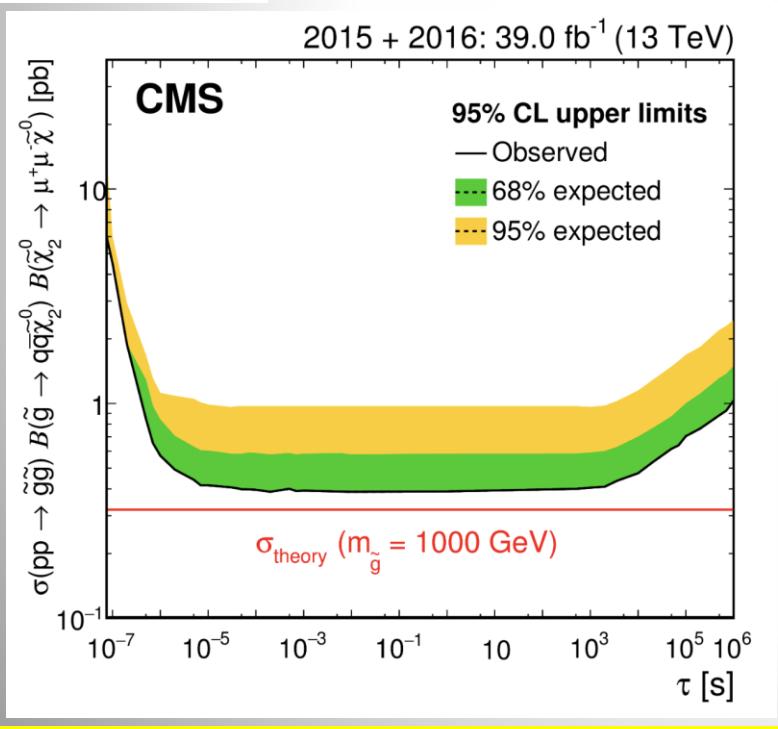
Search for Stopped Long Lived Particles

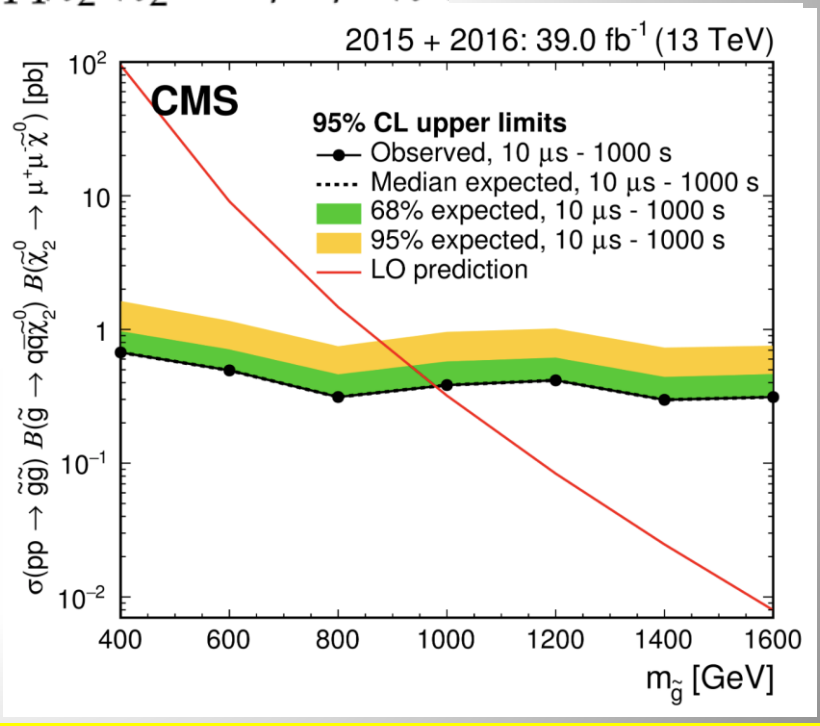


- Search for long lived particles that stop in the detector and decay into jets after some time, non-coincident with pp collisions
- 744 hours trigger lifetime in 2015/16 included in this search.
- Searches for long lived gluinos with delayed muons
- No events observed in 2015/16.

arXiv:1801.00359

Benchmark $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow \mu^+\mu^-\tilde{\chi}^0$



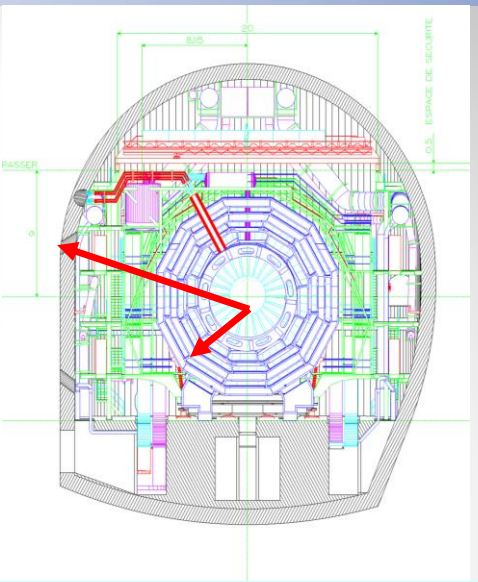


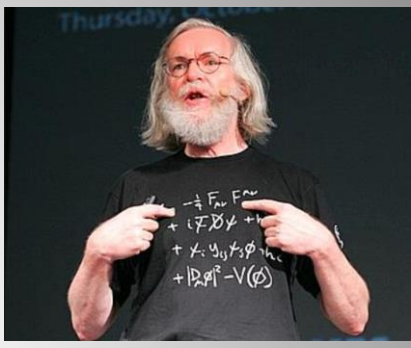
Limits on $400 < M_{gluino} < 970$ GeV 95%CL for lifetimes from 10 µsec to 1000s

Searches for Exotic Long Lived Particles

E.g. Split Supersymmetry

- The only light particles are the Higgs and the gauginos
  - Gluino can live long: sec, min, years!
  - R-hadron formation (eg: gluino+ gluon): slow, heavy particles
- Hidden valley models: Plethora of possibilities for long lived neutrals
- Many more models: Neutral Naturalness, GMSB, AMSB, Dark showers





EG:ADR, J. Ellis et al. hep-ph/0508198

Sparticles stopped in the detector, walls of the cavern, or dense 'stopper' detector. They decay after hours---months…

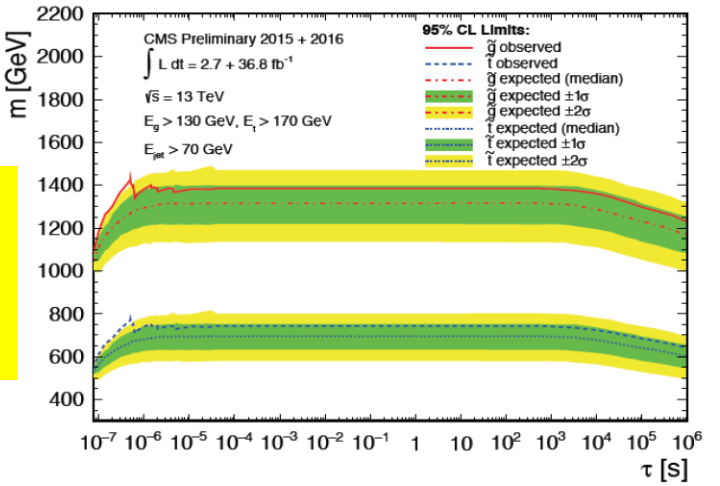
⇒Challenges to the experiments!

Analysis searching for "decays" in calorimeter

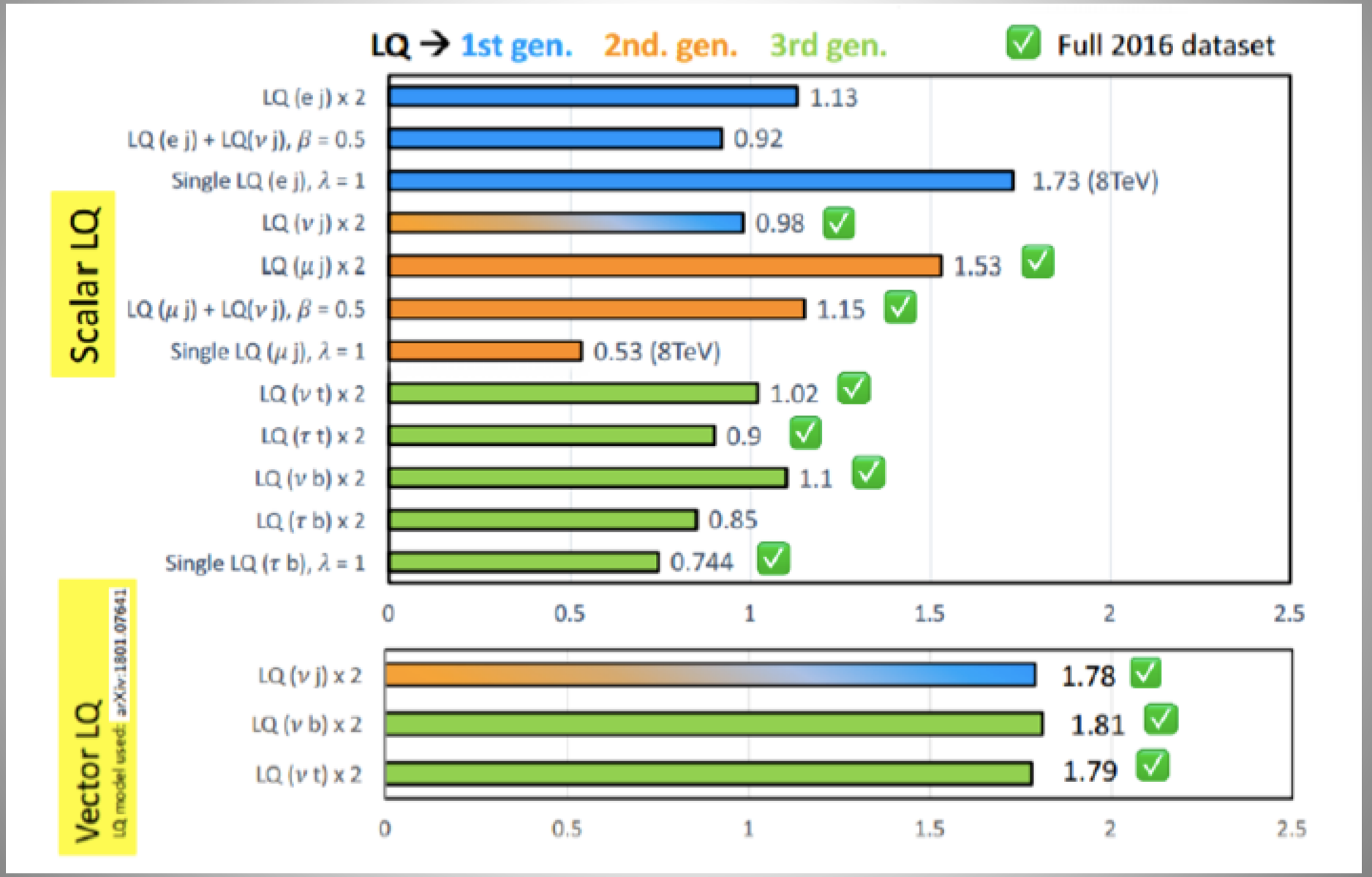
Limits on M_{stop} ~744 GeV and M_{gluino} ~1385 GeV

95% CL for lifetimes from 10 μsec to 1000s

EXO-16-004

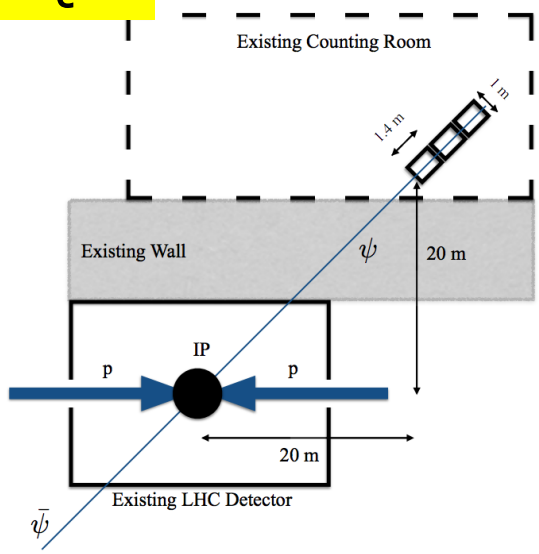


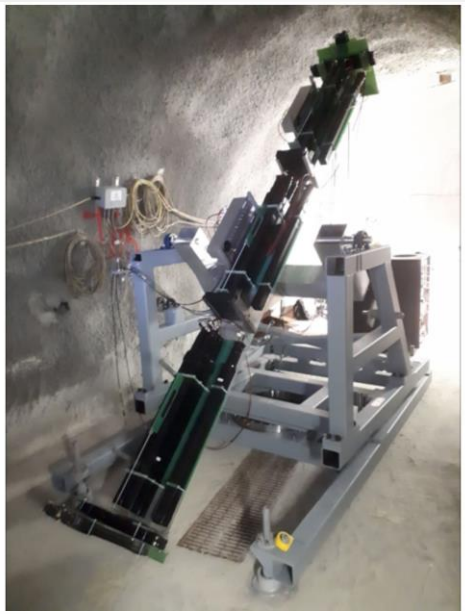
Leptoquark Limits



Possible New Experiments @LHC

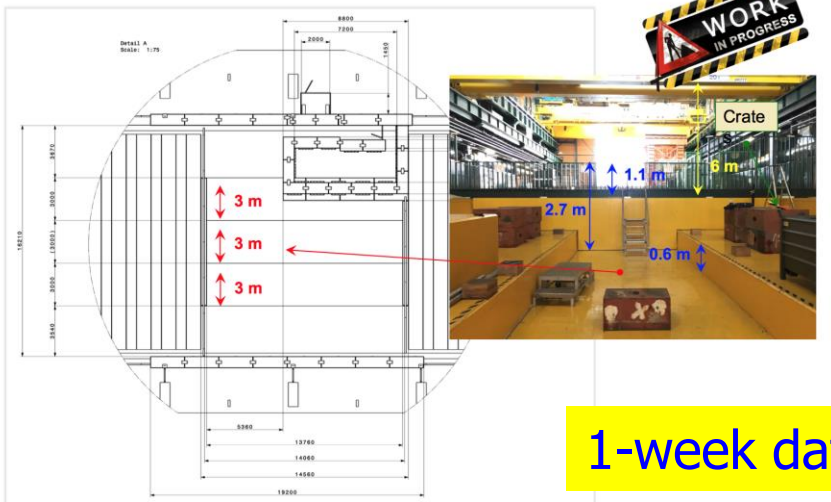
MilliQan

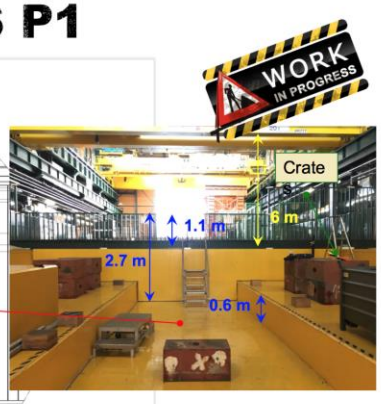




- September 2017: Installation of a 1% demonstrator.
- Collected ~ 27 fb^{-1} mostly for technical tests

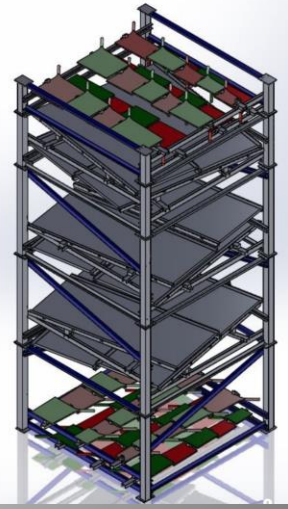
Installation in ATLAS P1





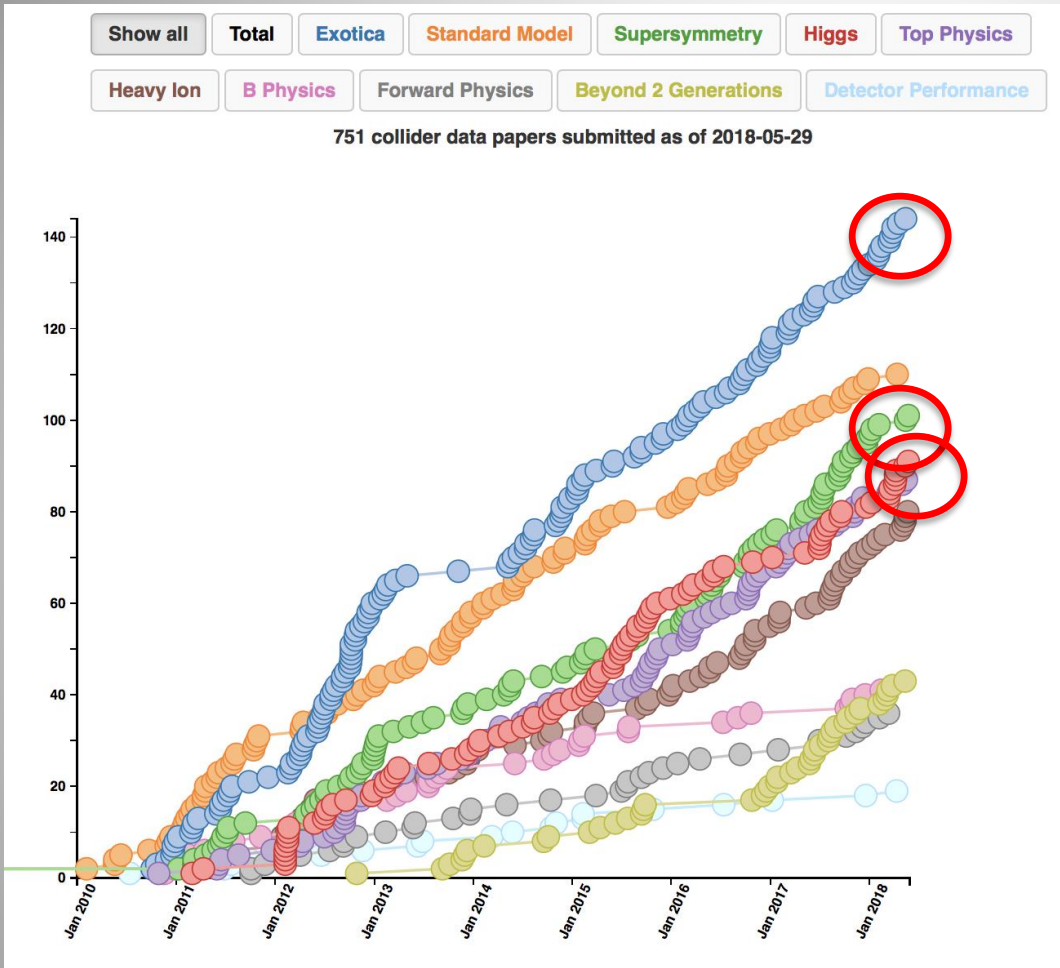
MATHUSLA Test Stand

- Two scintillator layers
- Three layers of 4 RPCs each, two in x-coordinate and two in y-coordinate
- 5 m tall, 2.5 m by 2.8 m surface area
- ~1.5 ns resolution for scintillators, ~1 ns resolution for RPCs
- TDC and ADC information for each scintillator
- RPCs have readout system from ARGO which includes TDC information



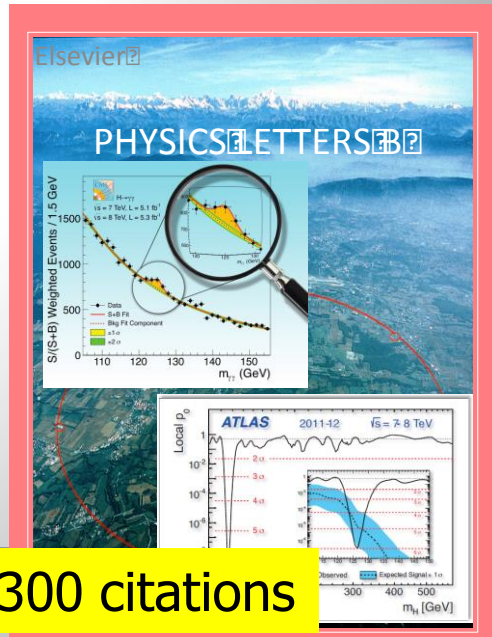
1-week data taken in November

LHC Publications: Example CMS



~ 750 publications on pp (and pPb/PbPb) physics since 1/2010

About 90 papers on Higgs studies!!
Paper 16 was the discovery paper!



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

Similar for ATLAS

>8300 citations

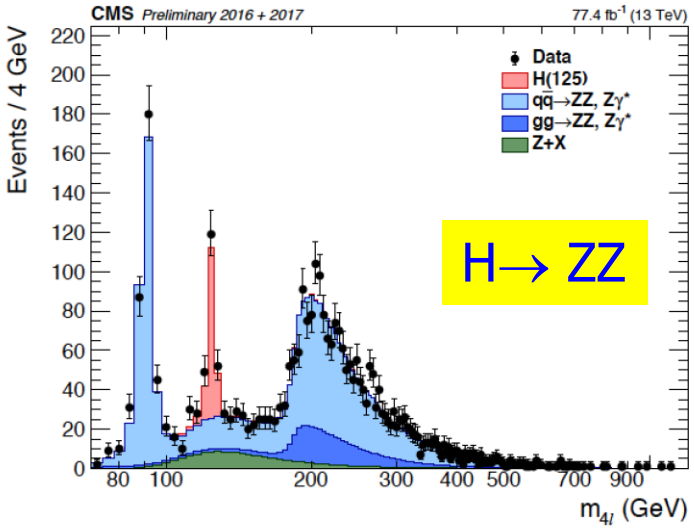
Searches for BSM Physics

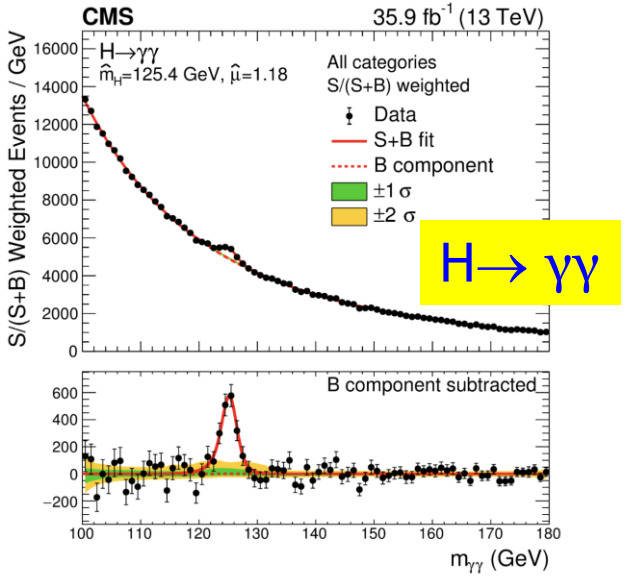
- First Searches at the LHC (2010-2012)
  - Supersymmetry with MET plus jets, lepton(s), photons
  - Extra Dimensions and black holes, heavy resonances, leptoquarks, excited leptons and quarks, 4^{th} generation, exotica…
- Evolved Searches (2013-…)
  - Supersymmetry on third generation squarks, compressed spectra, stealth SUSY, EWKinos, VBF processes…
  - Higgs in decays or as study object, vector-like quarks, boosted objects, long lived particles, fractional charges…
  - More dedicated Dark Matter searches!
- Searches at 13 TeV (2015-2016 data)

  Strategy now a combination of the above!
- Searches at Higher Luminosity (2017-… data)
  - Sensitivity to higher masses will increase only slowly
  - Search for phenomena with smaller couplings or smaller SM deviations, new exotica, exploring more challenging channels…

Higgs @ 13 TeV in Run 2

- Higgs particle is still there ! ☺





- The mild deviations seen in Run-1 seem to be gone ☹
- Evidence for H→bb in the associated production channel
- Direct observation of ttH production
- No deviations from Standard Model Higgs expectations yet!!

The Higgs Boson is still very much Standard Model-like!

$$\mu = 1.17^{+0.10}_{-0.10}$$

Desperately Seeking SUSY?

Many SUSY analyses ongoing in ATLAS & CMS

- More searches for topologies with top quarks
- Searches for Vector Boson Fusion SUSY production
- Searches for EWK SUSY particles
- Charm squark searches
- Compressed spectra and related difficult regions

  -> Cover different parts of the phase space, allowing to find SUSY in more different corners… but nothing so far
- So far results released on the full 2016 statistics
- New results on the full 2016/2017 data set expected by ICHEP (July) .

Dijet Angular Distributions

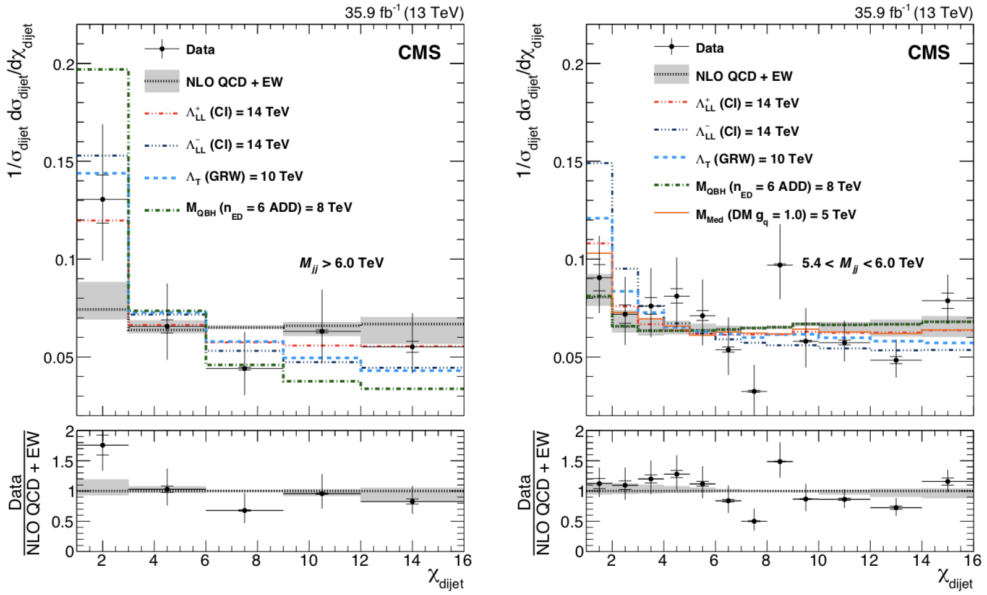
- Distribution of the di-jet angular variable

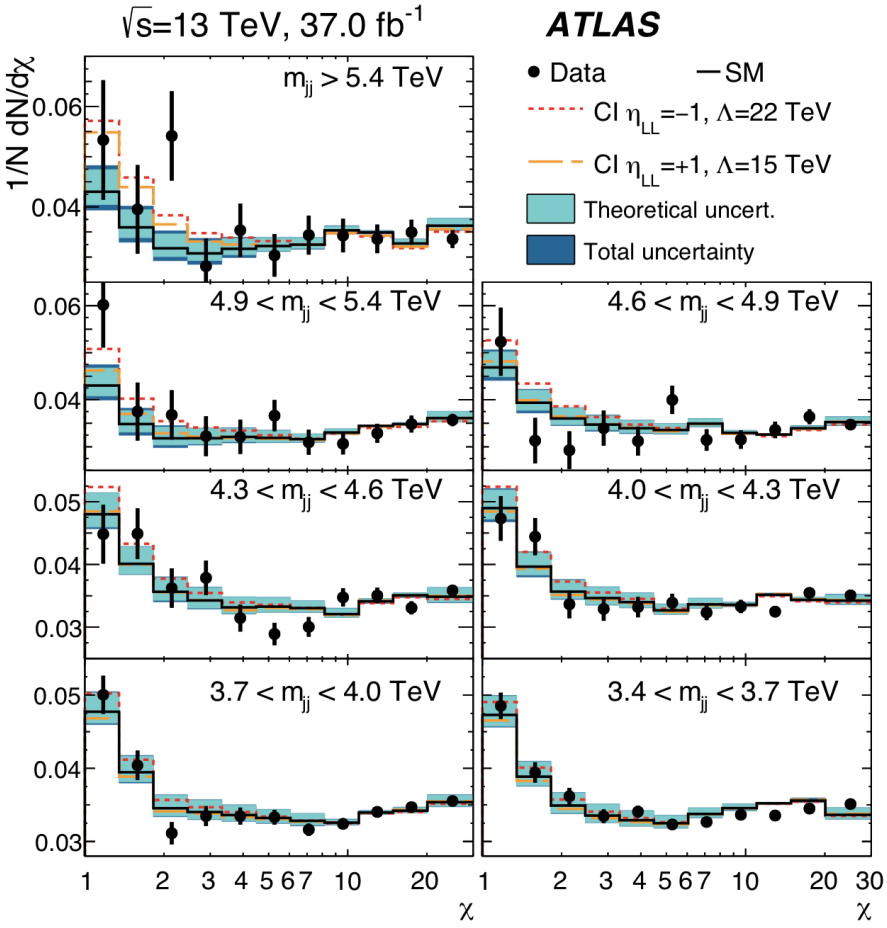
$$\chi = e^{2|y^*|} \approx (1+\cos\theta)/(1-\cos\theta)$$

- Mass dependent deviations -> study several mass regions

arXiv:1703.09127

arXiv:1803.08030





Limits from Angular Analyses

Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
$Z'(g_q = 0.1)$	2.1 TeV	2.1 TeV
$Z'(g_q = 0.2)$	2.9 TeV	3.3 TeV
Contact interaction ($\eta_{LL} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{LL} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

	Model	Observed lower limit (TeV)	Expected lower limit (TeV)
CI	$\Lambda^{+}_{LL/RR}$	12.8	14.6 ± 0.8
	$\Lambda^{-}_{LL/RR}$	17.5	23.5 ± 3.0
	Λ^{+}_{VV}	14.6	16.4 ± 0.8
	Λ^{-}_{VV}	22.4	30.7 ± 3.7
	Λ^{+}_{AA}	14.7	16.5 ± 0.8
	Λ^{-}_{AA}	22.3	30.6 ± 3.8
	$\Lambda^{+}_{(V-A)}$	9.2	11.5 ± 1.0
	$\Lambda^{-}_{(V-A)}$	9.3	11.8 ± 1.1
ADD	Λ_T (GRW)	10.1	11.4 ± 0.9
	M_S (HLZ) $n_{ED} = 2$	10.7	12.4 ± 1.0
	M_S (HLZ) $n_{ED} = 3$	12.0	13.6 ± 1.1
	M_S (HLZ) $n_{ED} = 4$	10.1	11.4 ± 0.9
	M_S (HLZ) $n_{ED} = 5$	9.1	10.3 ± 0.8
	M_S (HLZ) $n_{ED} = 6$	8.5	9.6 ± 0.8
QBH	M_{QBH} (ADD $n_{ED} = 6$)	8.2	8.5 ± 0.4
	M_{QBH} (RS $n_{ED} = 1$)	5.9	6.3 ± 0.7
DM	Vector/Axial-vector M_{Med}	2.0 – 4.6	2.0 – 5.5

- Various lower limits on the masses of ADD, Quantum black holes, W'W* bosons, excited quarks, DM and Z' bosons for selected coupling values from the resonance search, as well as on the scales of contact interactions for constructive/destructive interference from the angular analysis.