Searches Beyond the Standard Model

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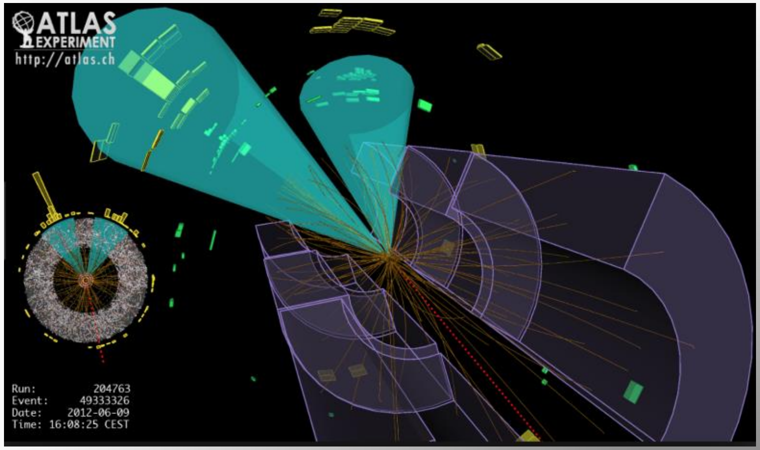
March 30th- April 2nd Muscat

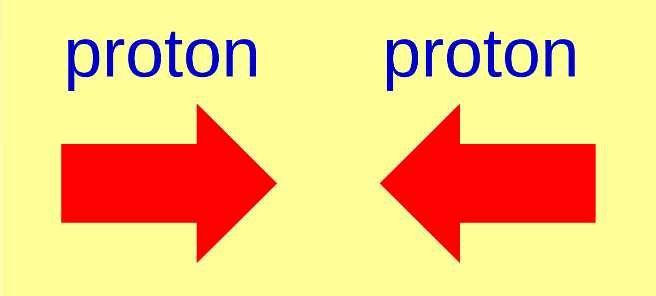


Collision at 7 TeV in ATLAS with large missing E_T

Outline

- Introduction: Searches for New Physics
- A bit of news on the Higgs
- Supersymmetry Searches
- Exotica Searches
- New Experiments at the LHC?
- Summary

Reminder: This is what we do!

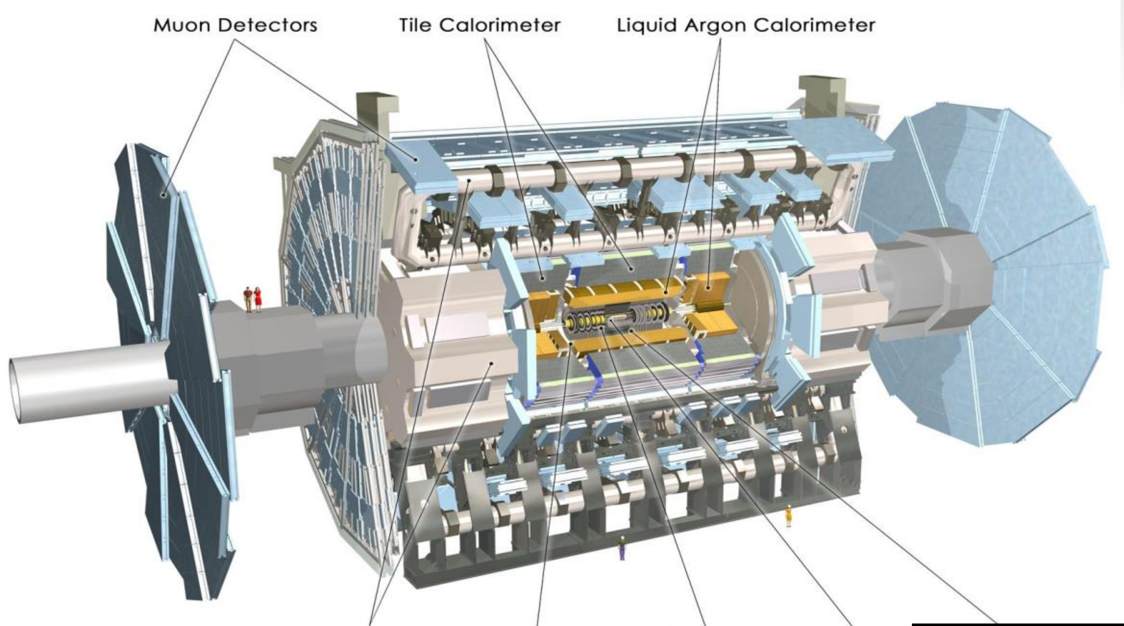


13 TeV

…40 Million times a second - 24/7 (if we could)

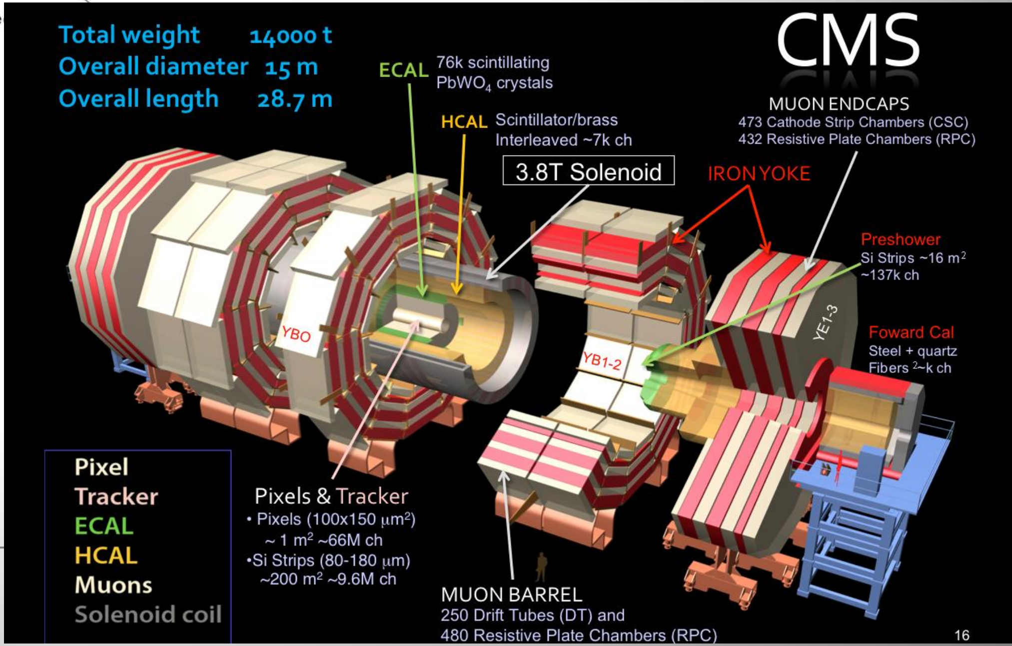
Out comes the new physics (or not)

New Physics Hunters @ the LHC

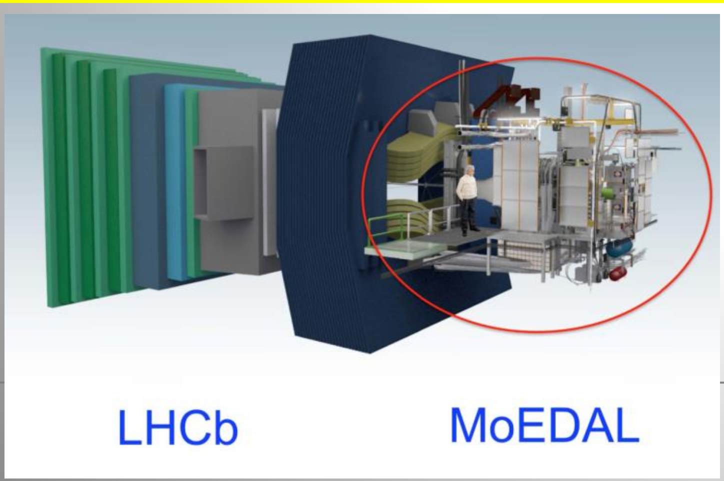


The ATLAS experiment

The CMS experiment

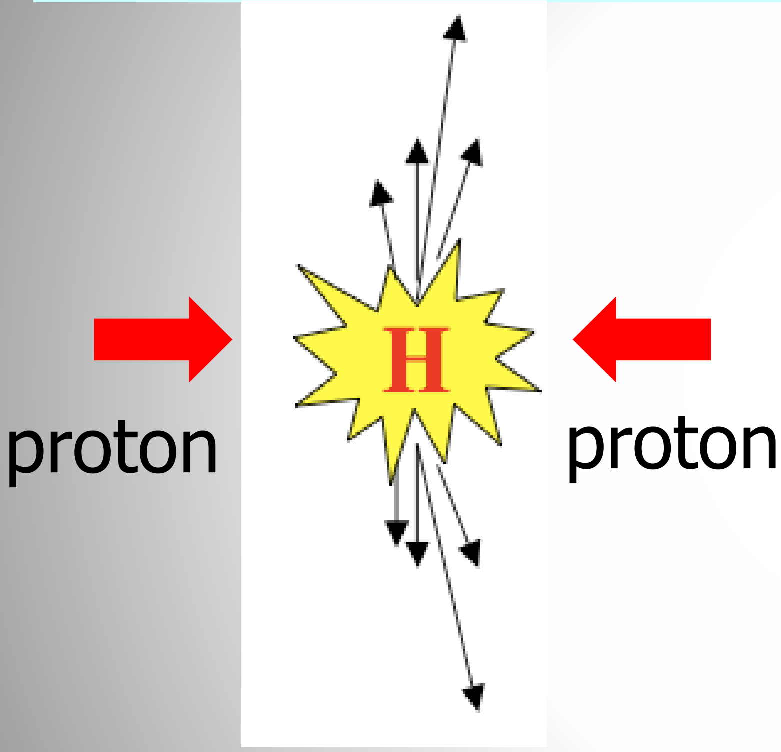


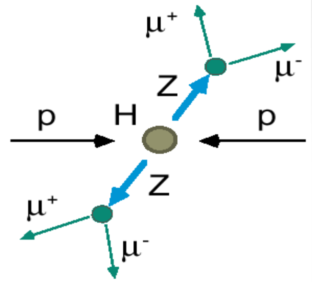
…And also LHCb and MoEDAL

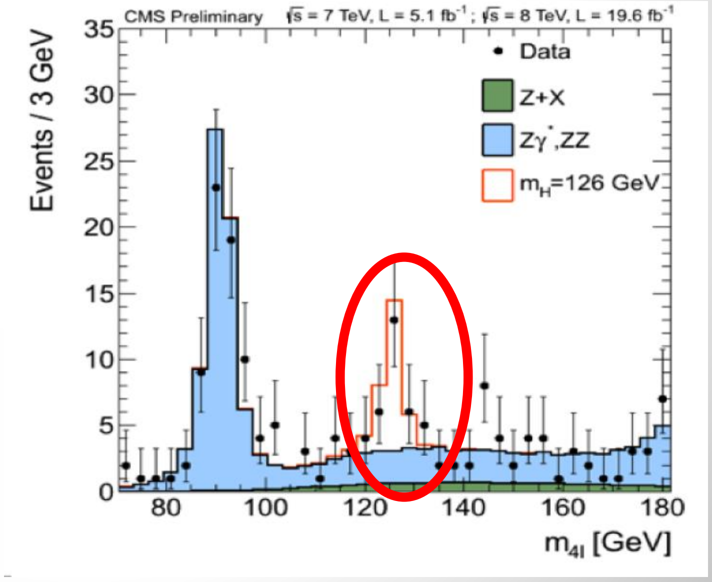


2012: A Milestone in Particle Physics

Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it





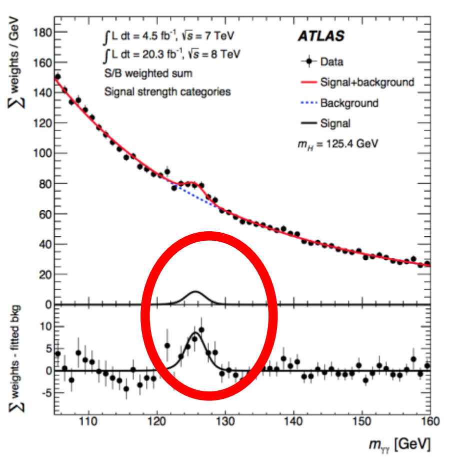


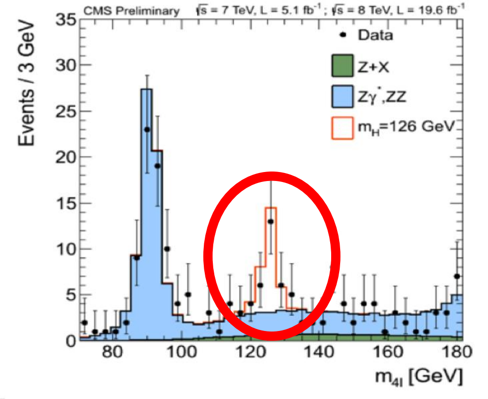
2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

2012: The Higgs

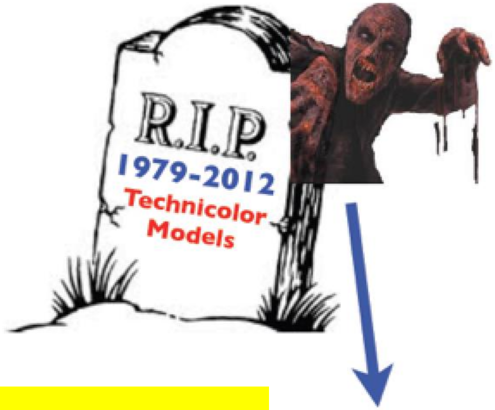
The party in 2012!





A. Pomarol ICHEP2012

Not everybody at the party eg higgsless models…



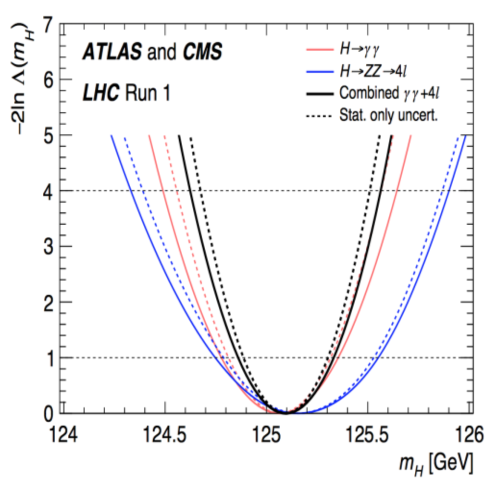
But careful about resurrections, Higgs imposters…

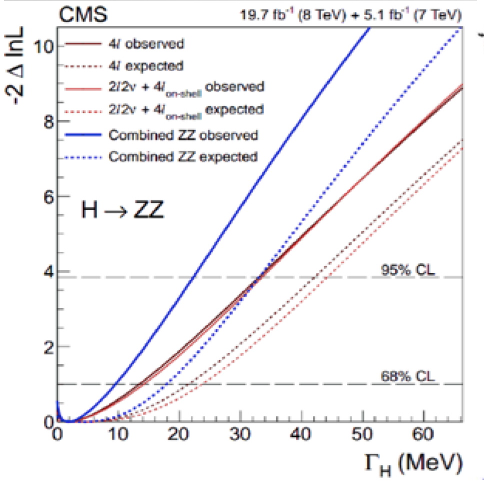
Dilaton

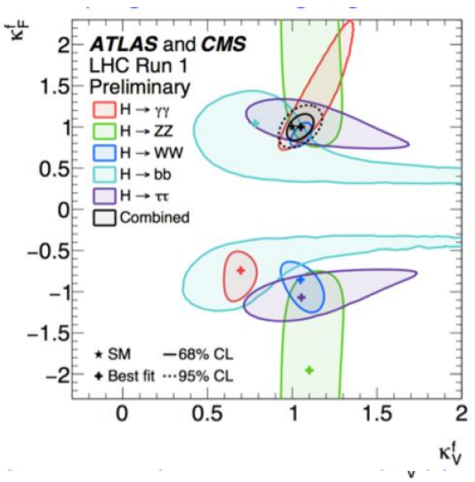
However: since then a PHD effect with theorists? (Post Higgs Depression?)

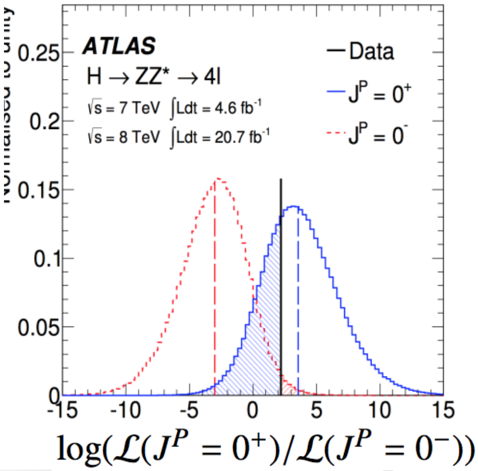
Brief Higgs Summary from Run1

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









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

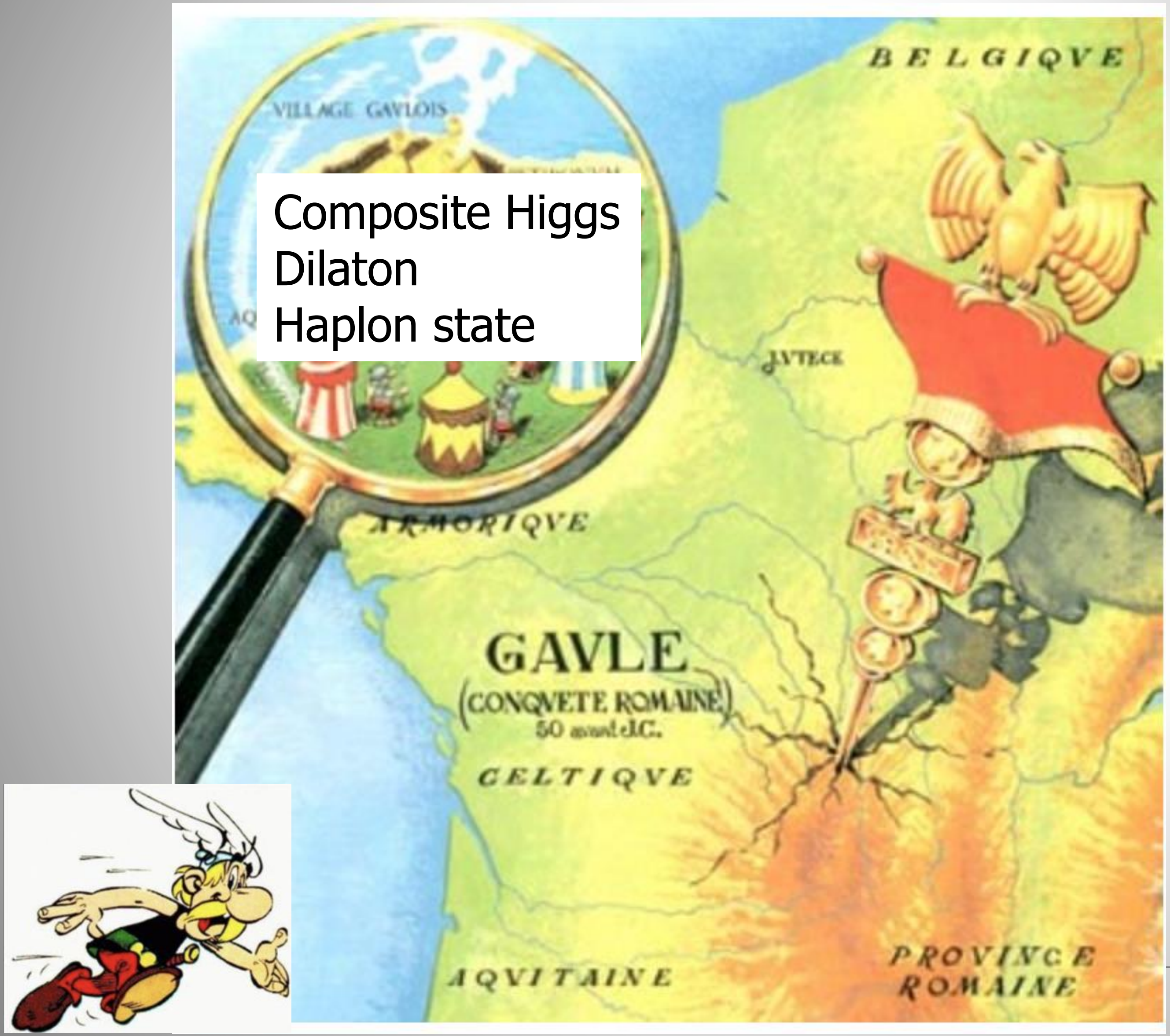
Width
< 24 MeV
(95%CL)

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…

We call it a Higgs Boson



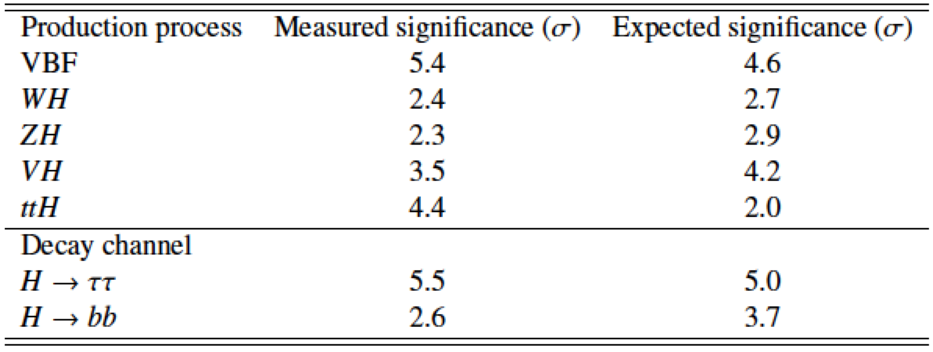
Composite Higgs
Dilaton
Haplon state

Everybody?

Not Everybody!

-> Need more precision, searches for deviations, new particles…

Higgs: ATLAS+CMS Combination



Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

The Run-1 Higgs Legacy!

arXiv:1606.02266 /
JHEP 1608 (2016) 045

5153 authors!!

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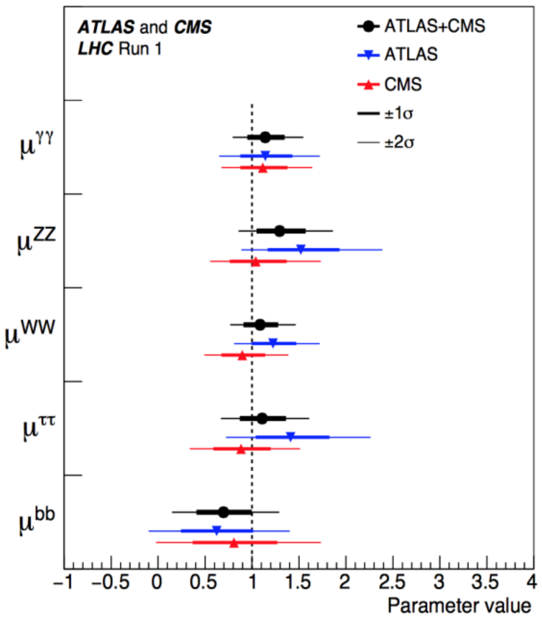
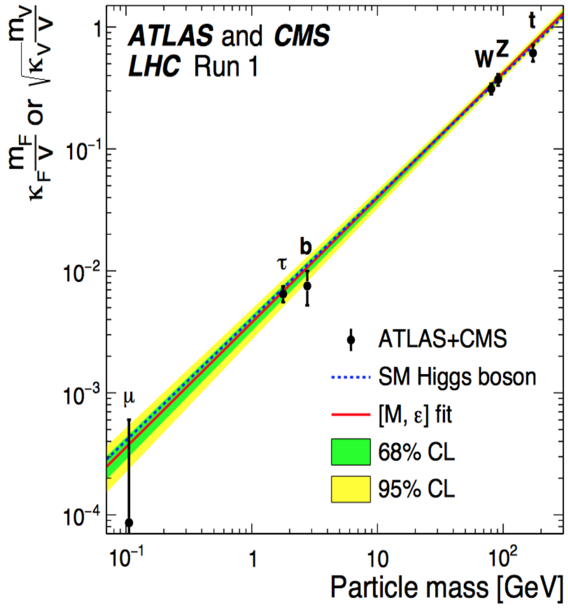
NATURE | NEWS

Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.





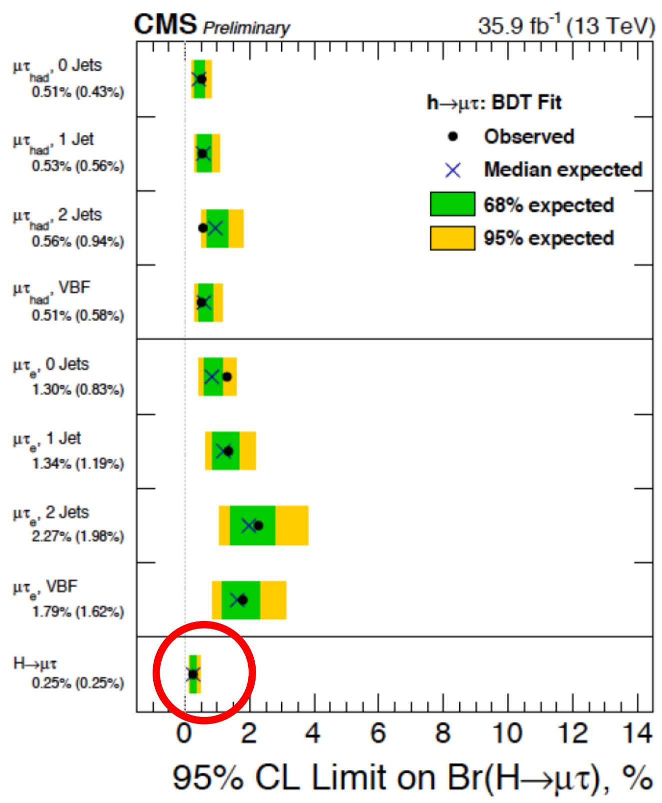
The newly found boson has properties as expected for a Standard Model Higgs

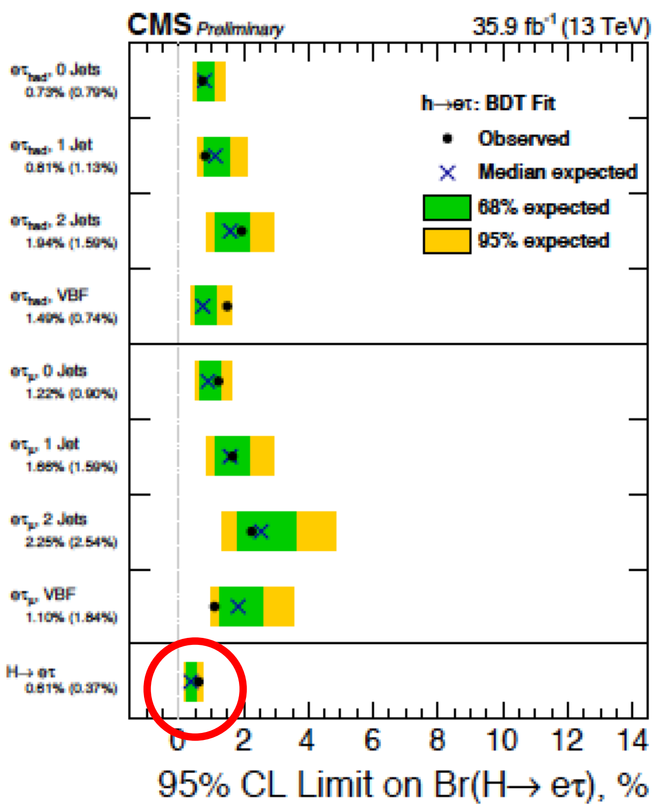
Signal strength/SM:

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig}),$$

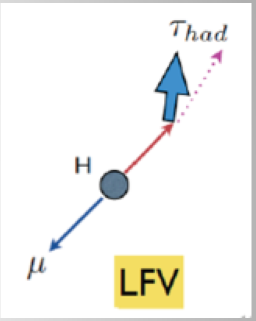
Search for LFV Decays: H →μτ, eτ

The 2016 data does NOT confirm the 2.4σ excess seen in Run-1

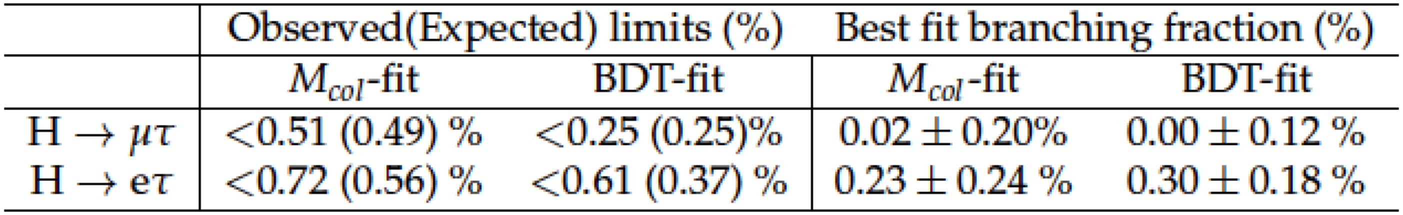




arXiv:1712.07173



☹ It would have been nice…

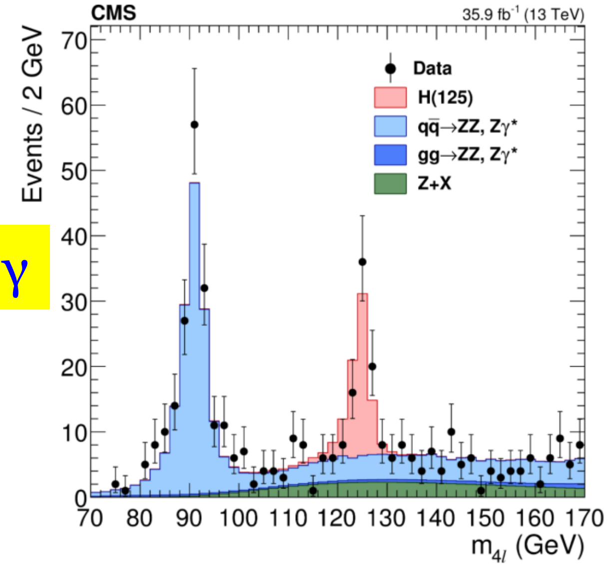


	Observed(Expected) limits (%)		Best fit branching fraction (%)	
	M_{col}-fit	BDT-fit	M_{col}-fit	BDT-fit
$H \to \mu\tau$	<0.51 (0.49) %	<0.25 (0.25)%	0.02 ± 0.20%	0.00 ± 0.12 %
$H \to e\tau$	<0.72 (0.56) %	<0.61 (0.37) %	0.23 ± 0.24 %	0.30 ± 0.18 %

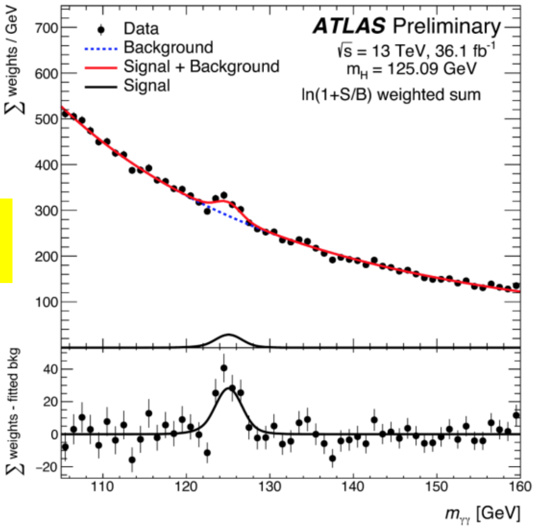
Higgs @ 13 TeV in Run 2

- Higgs particle is still there ! ☺

H→ γγ



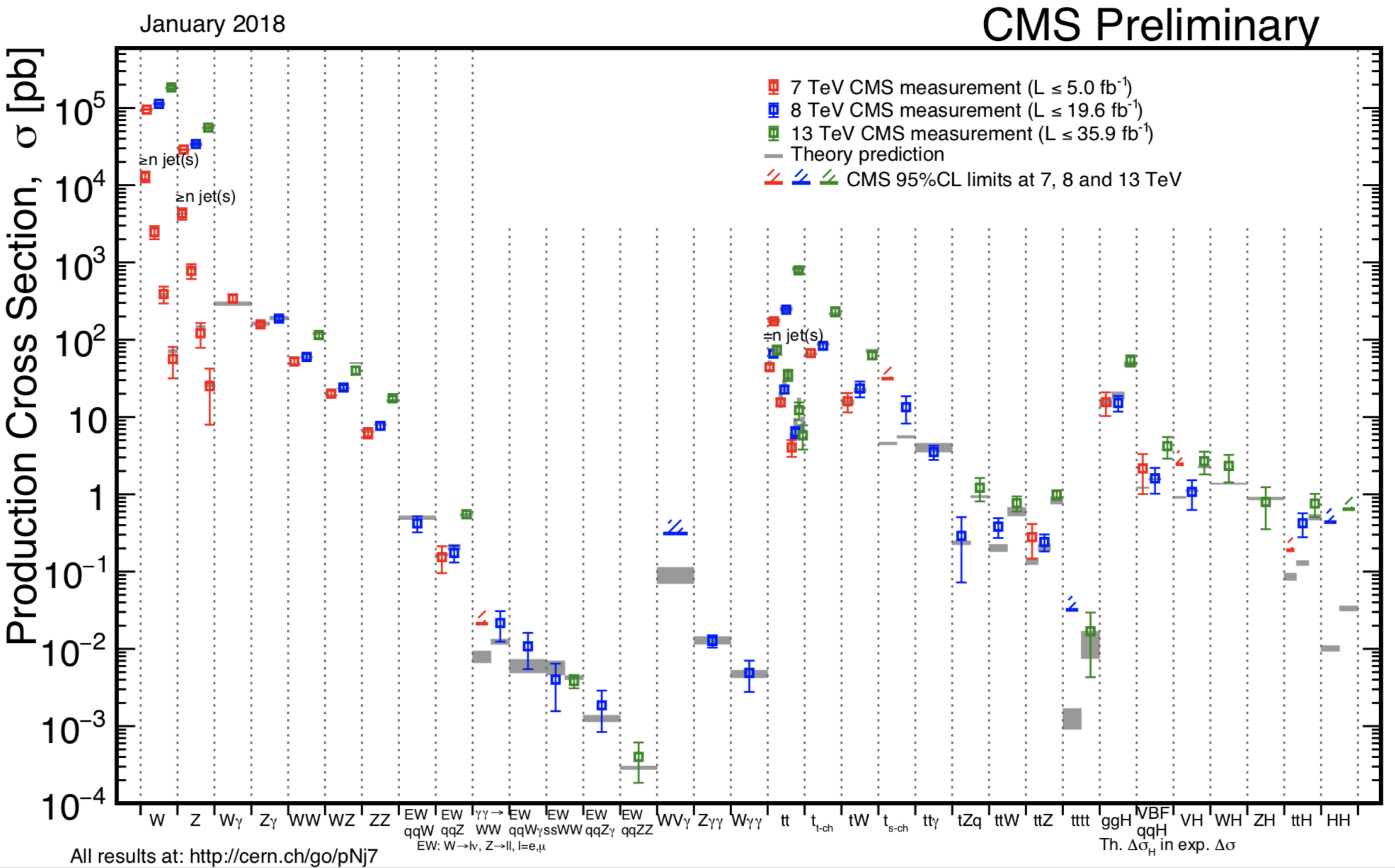
H→ ZZ



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

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

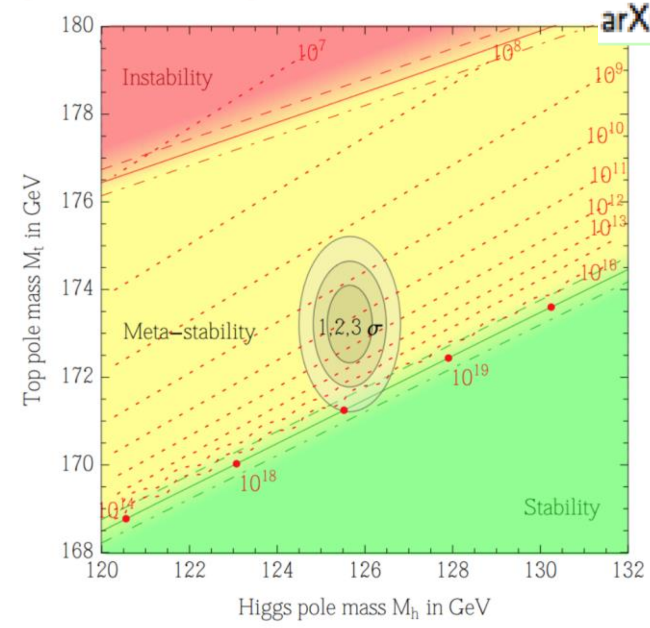
Standard Model Cross Sections at 7/813 TeV



Measurements in good agreement with the Standard Model predictions

Physics Beyond the Standard Model?

Important SM parameter → stability of EW vacuum



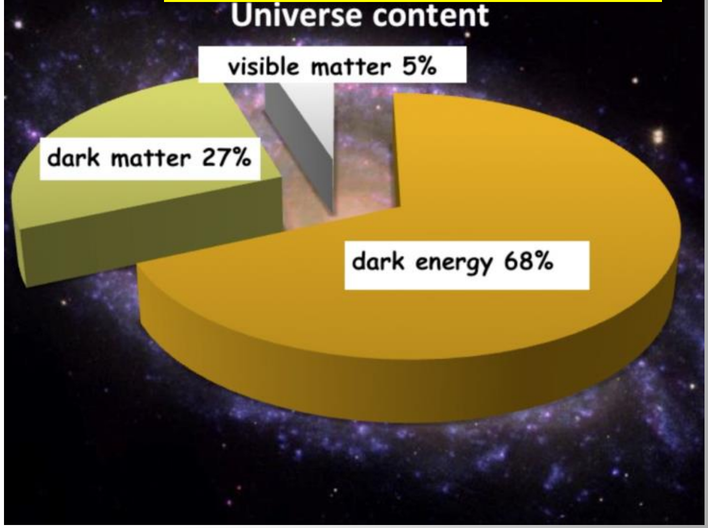
arXiv:1205.6497

arXiv:1403.6535

A Higgs at 125 GeV

Precise measurements of the top quark and the Higgs mass

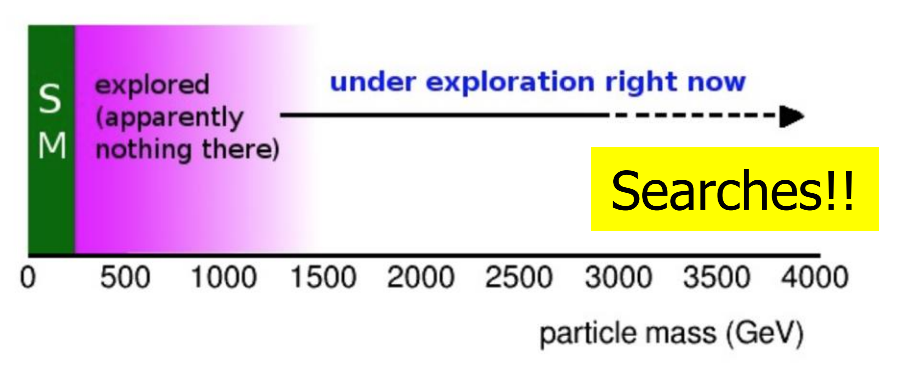
We also know that:



New Physics inevitable?
But at which scale/energy?

But Where Is Everybody?

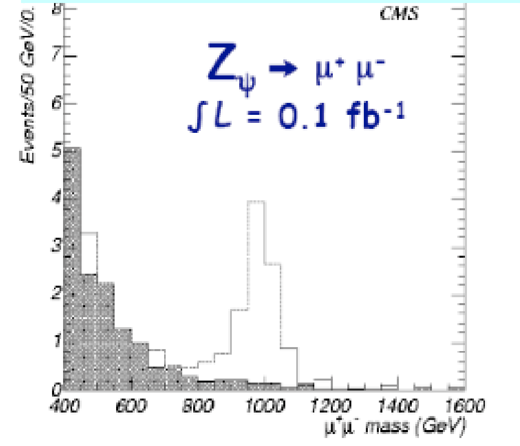
N. Arkani-Hamed



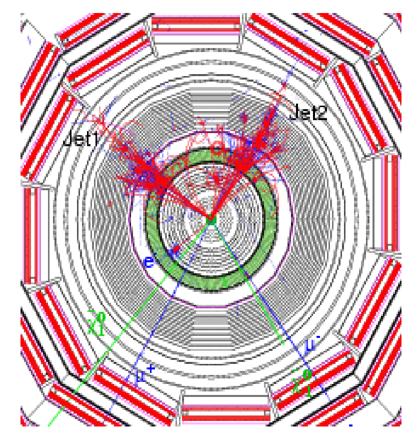
Searches!!

New Physics?

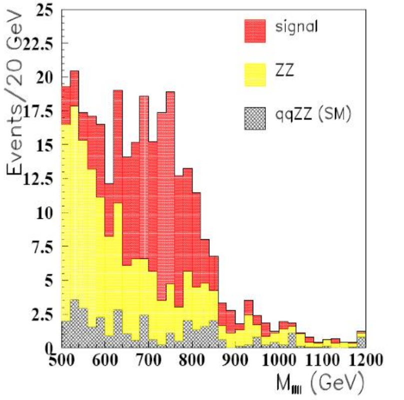
New Gauge Bosons?



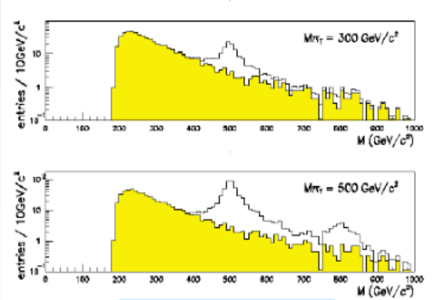
Supersymmetry



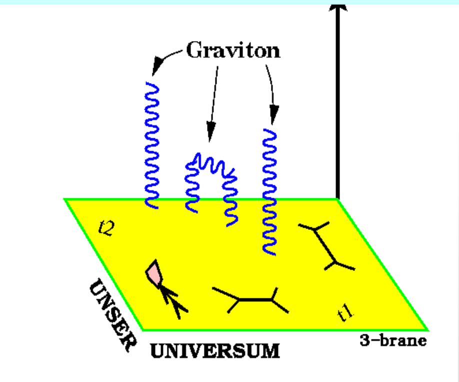
ZZ/WW resonances?



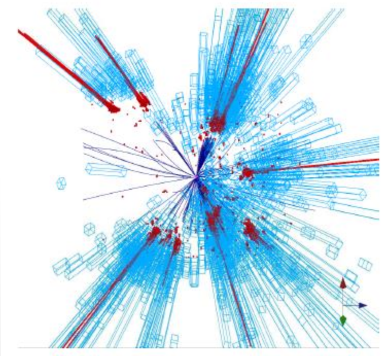
Technicolor?



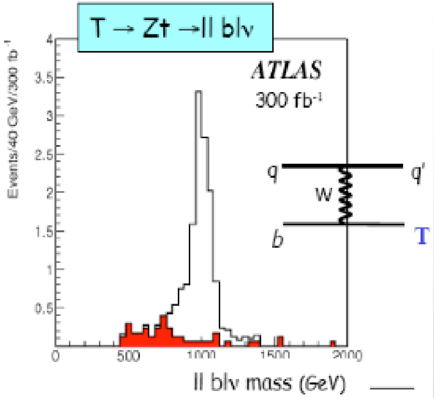
Extra Dimensions?



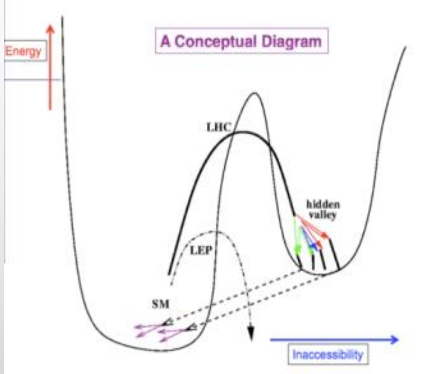
Black Holes???



Little Higgs?



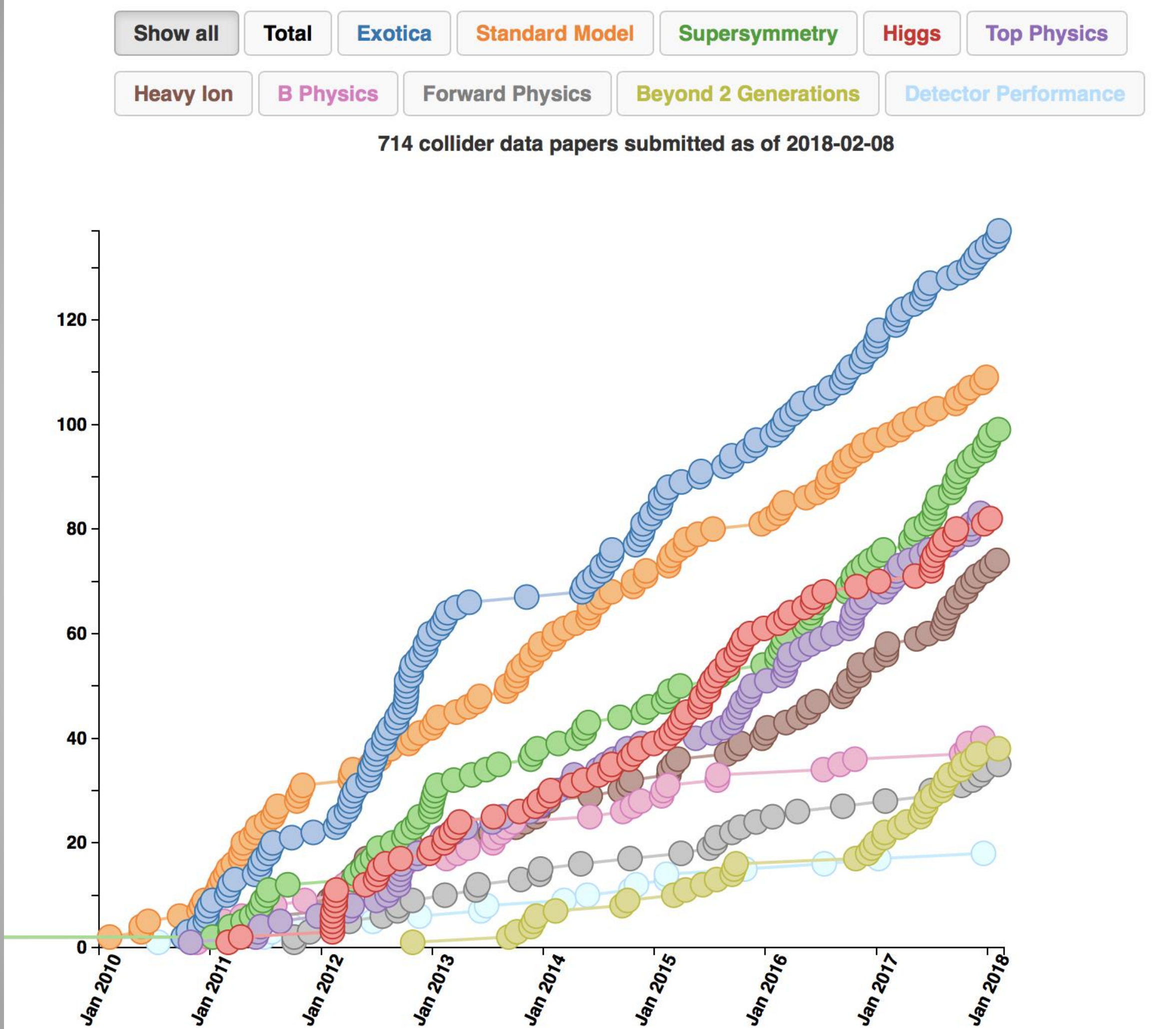
Hidden Valleys?



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

LHC Publications: Example CMS

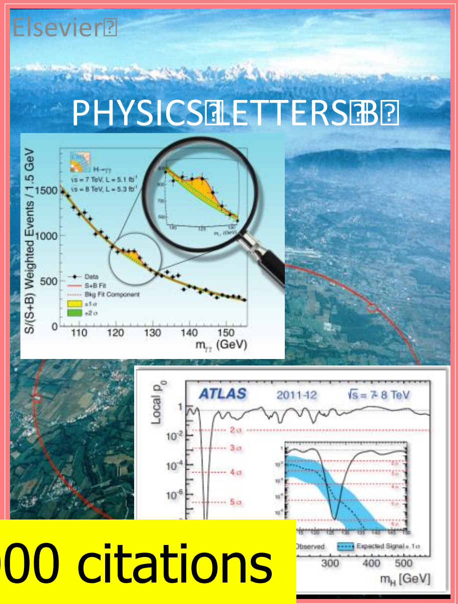


714 collider data papers submitted as of 2018-02-08

> 700 publications on pp (and pPb/PbPb) physics since 1/2010

About 80 papers on Higgs studies!!

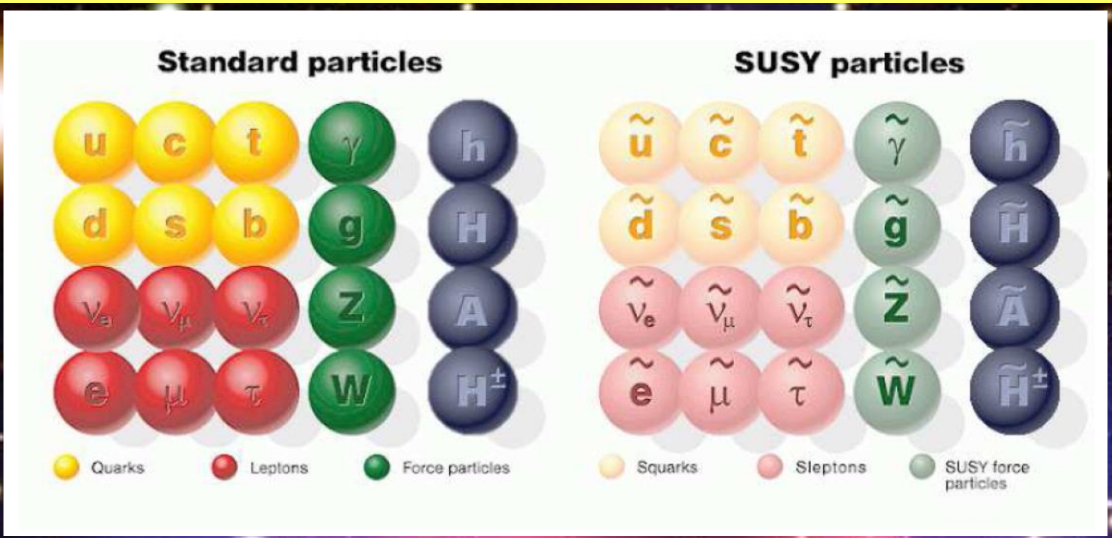
Paper 16 was the discovery paper!



>8000 citations

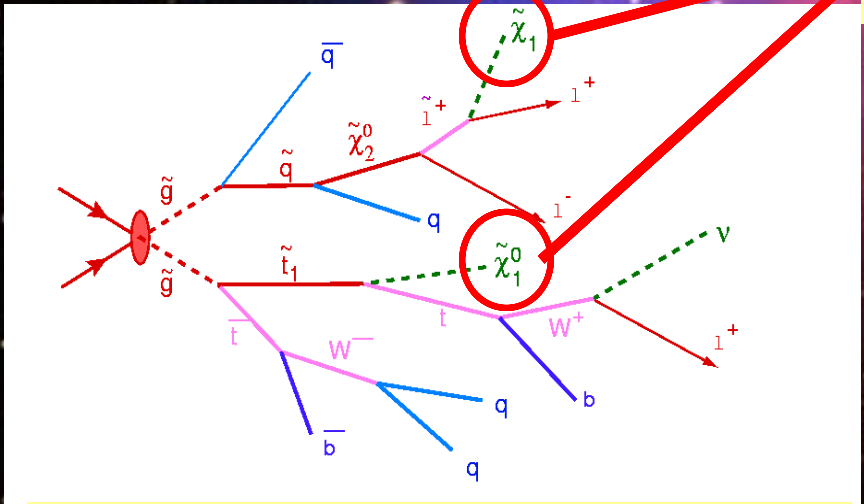
http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/

Supersymmetry: a new symmetry in Nature?

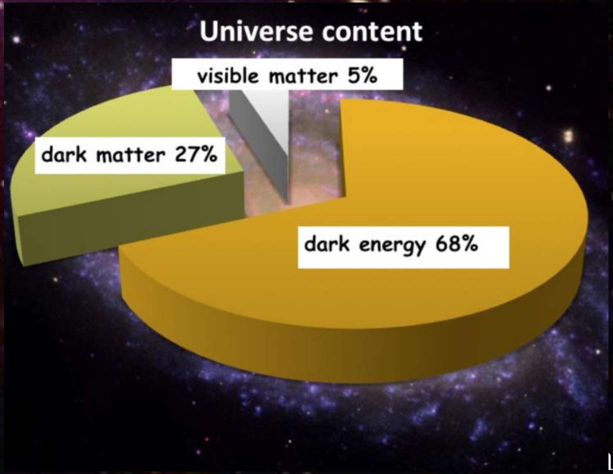


Candidate particles for Dark Matter

⇒ Produce Dark Matter in the lab

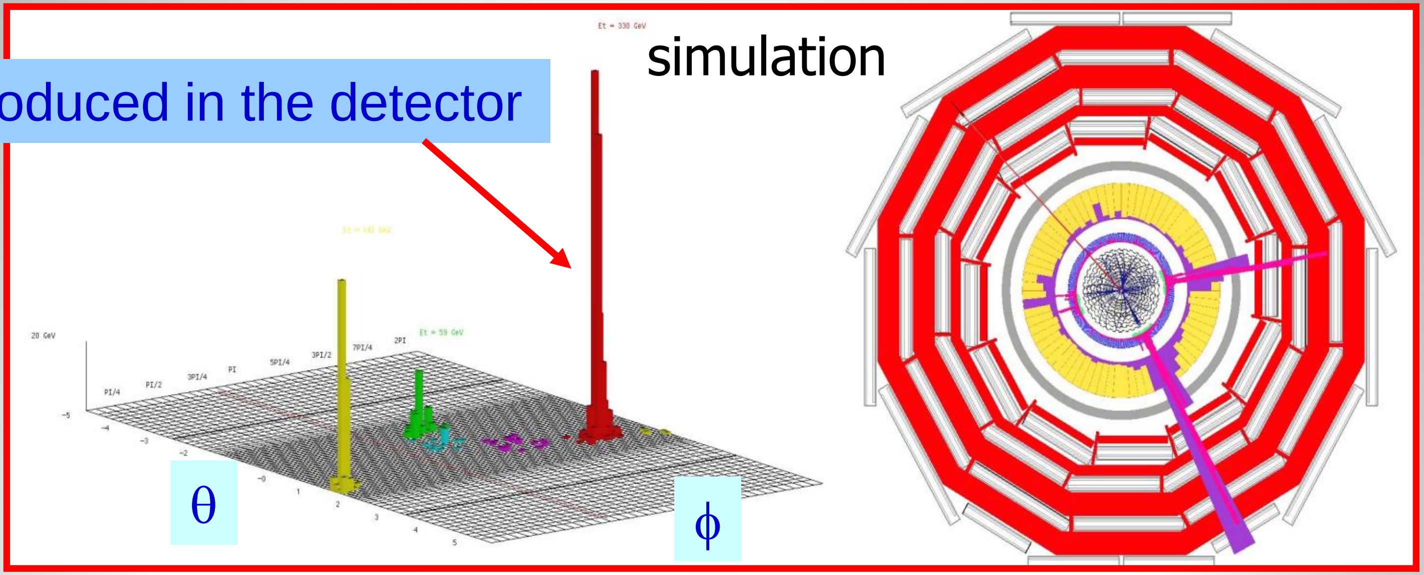


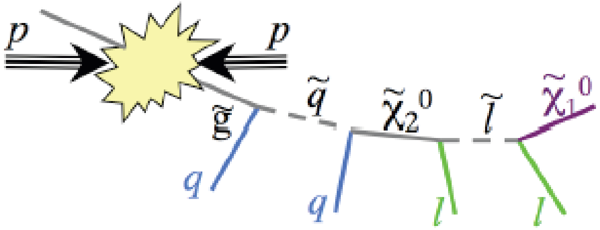
SUSY particle production at the LHC



Detecting Supersymmetric Particles

Energy produced in the detector



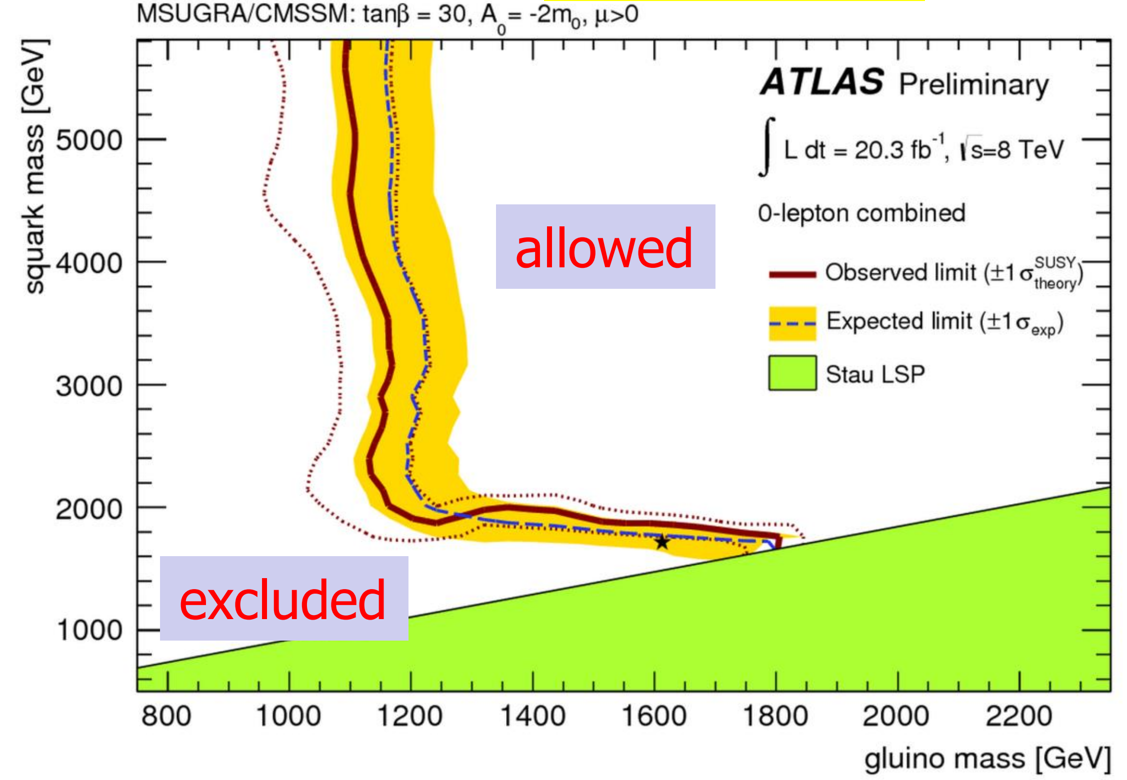


Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping ‘dark matter’ particle candidates

➡ Very prominent signatures in CMS and ATLAS

SUSY Searches: No signal yet to date…

Status in 2013

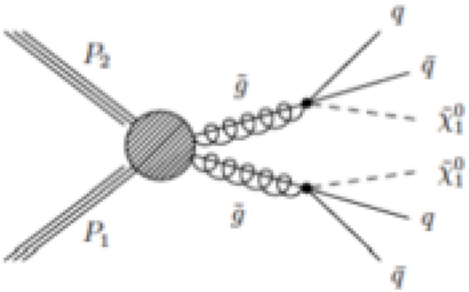


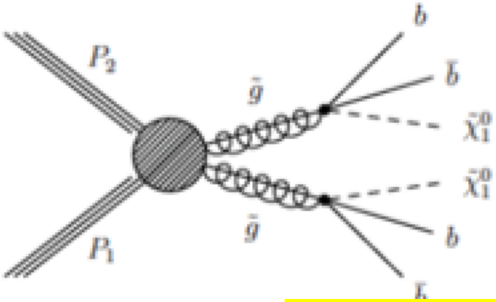
- So far NO clear signal of supersymmetric particles has been found
- We can exclude regions where the new particles could exist.
- Searches continued for the higher energy in 2016

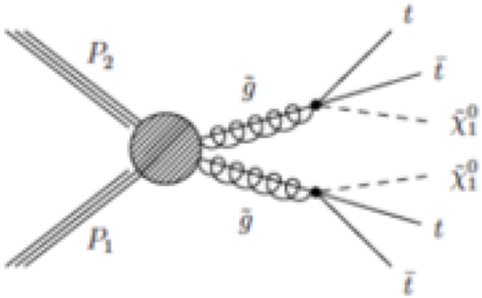
Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy

Also special searches for 'difficult' model regions

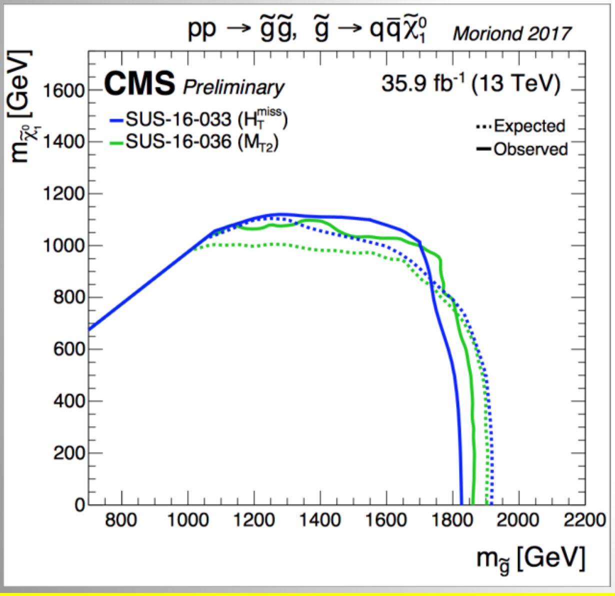
Supersymmetry: Gluinos

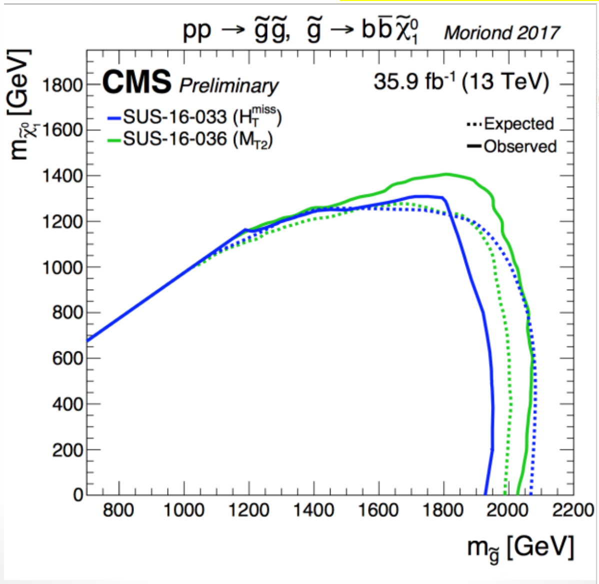


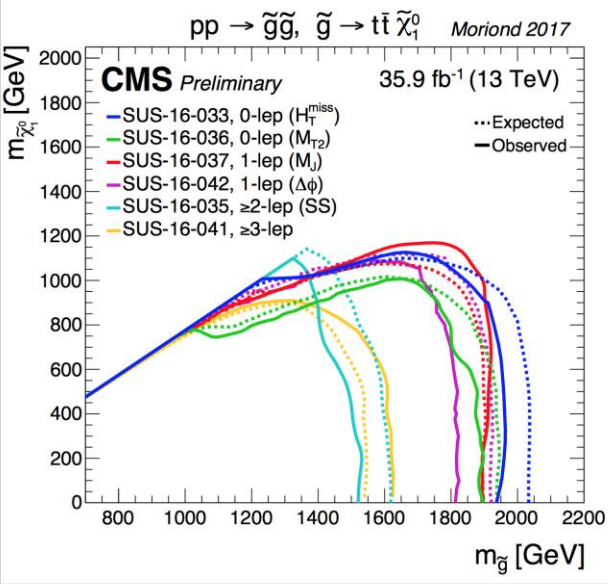




Interpretation in simplified models (SMS)







No significant signal to date

Within the context of the SMS:

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

What is really needed from SUSY?

End 2011: Revision!

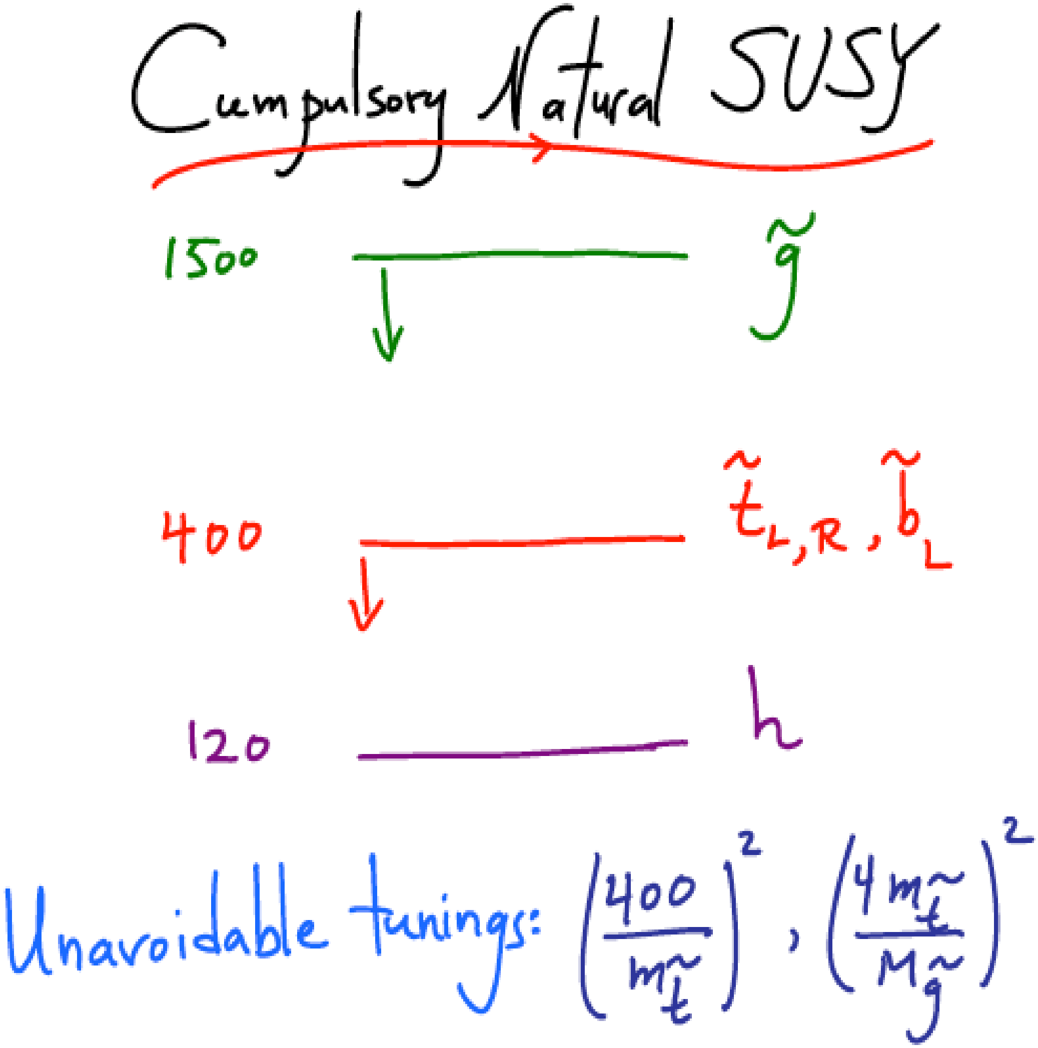
N. Arkani-Ahmed
CERN Nov 2011

and many many more ..

LHC data end 2011
Stops > 200-300 GeV
Gluino > 600-800 GeV

Moving away from constrained SUSY models to ‘natural’ models

Natural SUSY survived LHC so far, but we are getting close to push it to its limits!

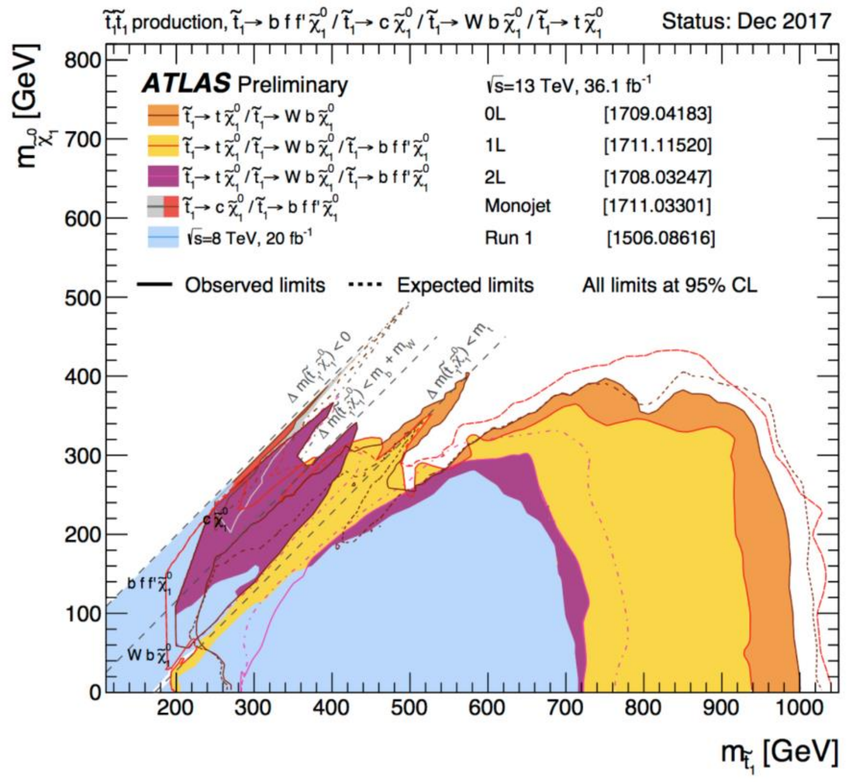


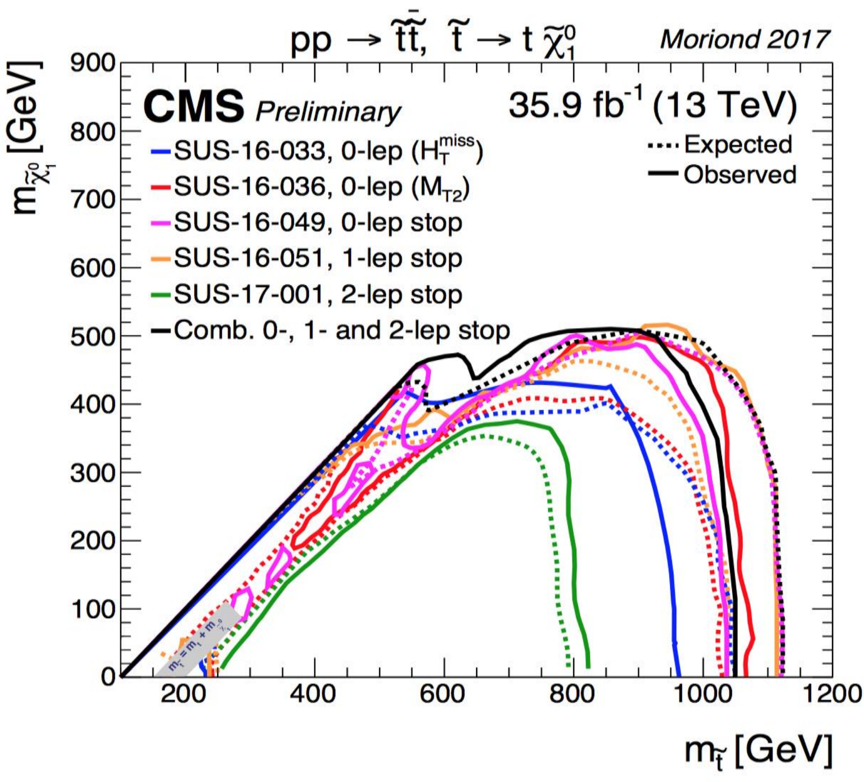
Unavoidable tunings: $\left(\frac{400}{m_{\tilde{t}}}\right)^2, \left(\frac{4 m_{\tilde{t}}}{M_{\tilde{g}}}\right)^2$

Also:Barbieri & Giudice (1988): Natural Models!

Top Squark Search Summaries

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





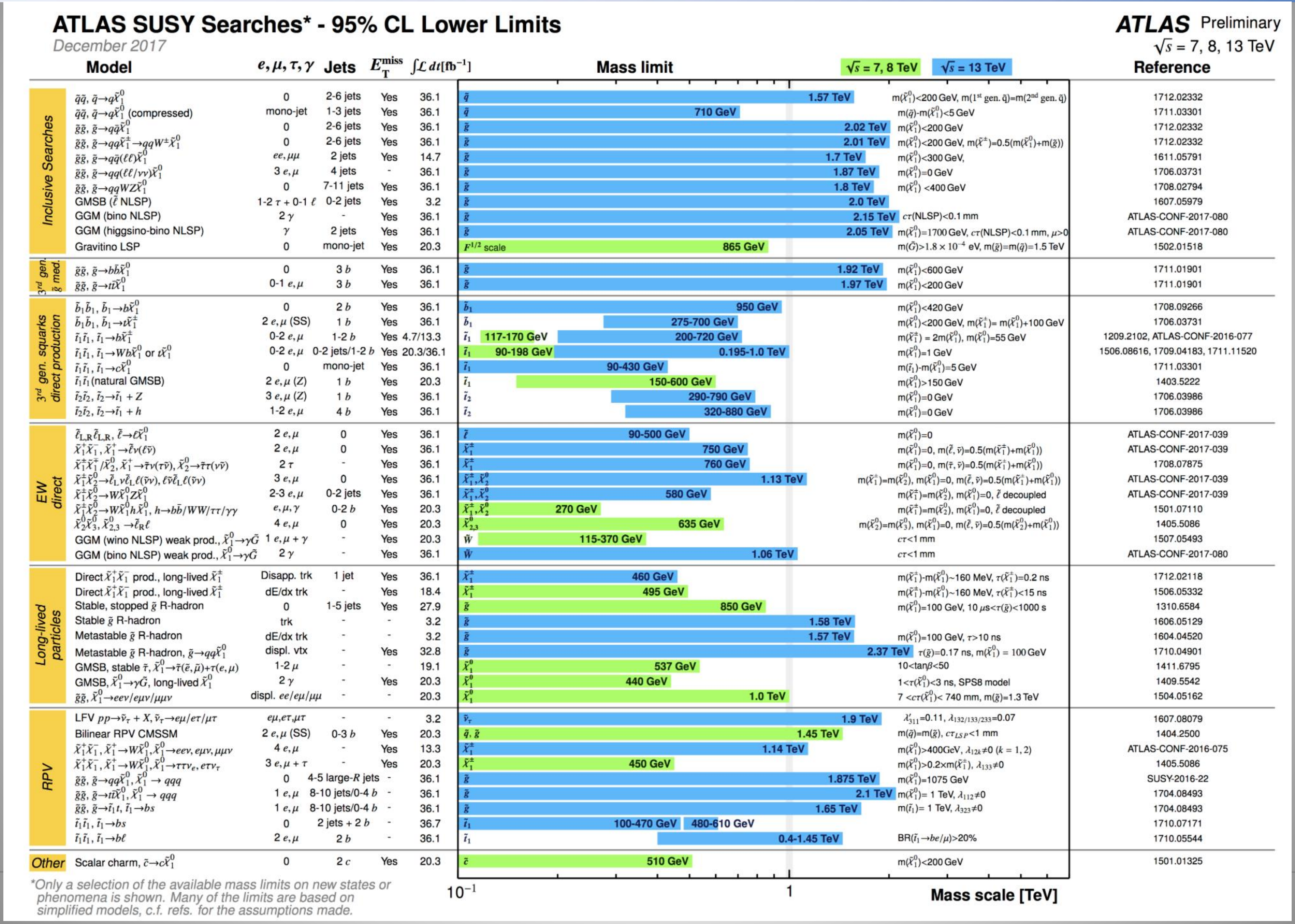
Within the context of the SMS:

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??

The SUSY SEARCH Chart So Far…



ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 🟦 1.57 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ 🟦 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.02 TeV	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^{\pm}_1\to qqW^{\pm}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.01 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$ 🟦 1.7 TeV	m($\tilde{\chi}^0_1$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 🟦 1.87 TeV	m($\tilde{\chi}^0_1$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 🟦 1.8 TeV	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$ 🟦 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$ 🟦 2.05 TeV	m($\tilde{\chi}^0_1$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 🟩 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.92 TeV	m($\tilde{\chi}^0_1$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.97 TeV	m($\tilde{\chi}^0_1$)<200 GeV	1711.01901
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	36.1	$\tilde{b}_1$ 🟦 950 GeV	m($\tilde{\chi}^0_1$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}^{\pm}_1$	2 e, μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$ 🟦 275-700 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^{\pm}_1$)= m($\tilde{\chi}^0_1$)+100 GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^{\pm}_1$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}^{\pm}_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 🟩 90-198 GeV 🟦 0.195-1.0 TeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	36.1	$\tilde{t}_1$ 🟦 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 🟩 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 🟦 290-790 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 🟦 320-880 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 🟦 90-500 GeV	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}^{\pm}_1$ 🟦 750 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1/\tilde{\chi}^0_2, \tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}^0_2\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}^{\pm}_1$ 🟦 760 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}^{\pm}_1, \tilde{\chi}^0_2$ 🟦 1.13 TeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}^{\pm}_1, \tilde{\chi}^0_2$ 🟦 580 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}^{\pm}_1, \tilde{\chi}^0_2$ 🟩 270 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3, \tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$ 🟩 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	1 e, μ + γ	-	Yes	20.3	$\tilde{W}$ 🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{W}$ 🟦 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}^{\pm}_1$ 🟦 460 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^{\pm}_1$ 🟩 495 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 🟩 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 🟦 1.57 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	displ. vtx	-	Yes	32.8	$\tilde{g}$ 🟦 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}^0_1$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}, \tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 🟩 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$ 🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}^{\pm}_1$ 🟦 1.14 TeV	m($\tilde{\chi}^0_1$)>400GeV, $\lambda_{12k}\neq0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e, μ + τ	-	Yes	20.3	$\tilde{\chi}^{\pm}_1$ 🟩 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^{\pm}_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ 🟦 1.875 TeV	m($\tilde{\chi}^0_1$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 2.1 TeV	m($\tilde{\chi}^0_1$)= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ 🟦 100-470 GeV 🟦 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 🟦 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 🟩 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

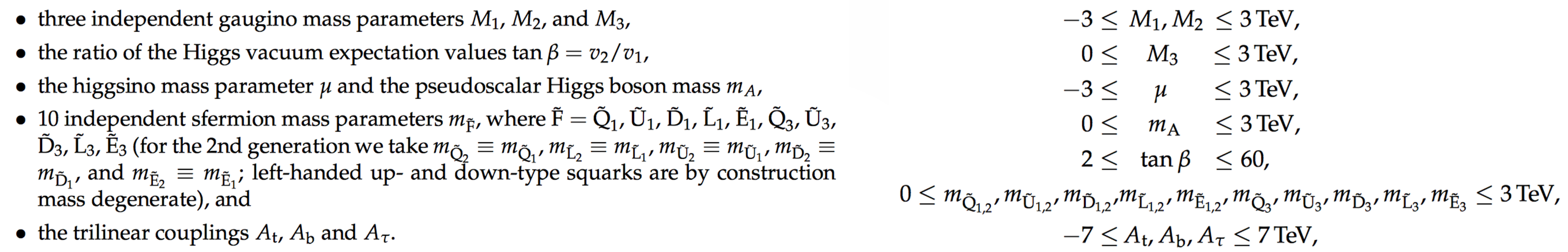
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Phenomenological MSSM analysis

SMS don't always fully cover signatures…

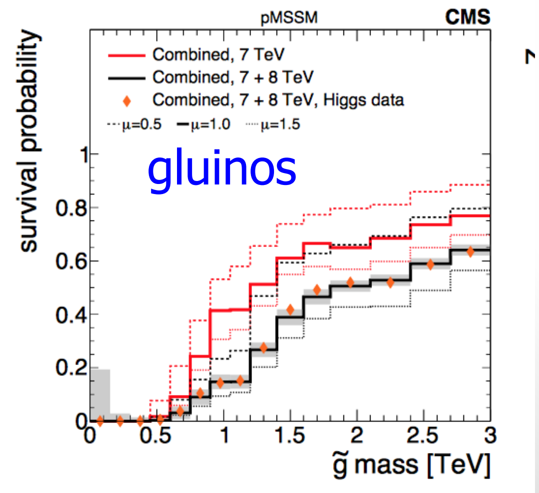
-> the 19 parameter phenomenological MSSM (pMSSM) analyses

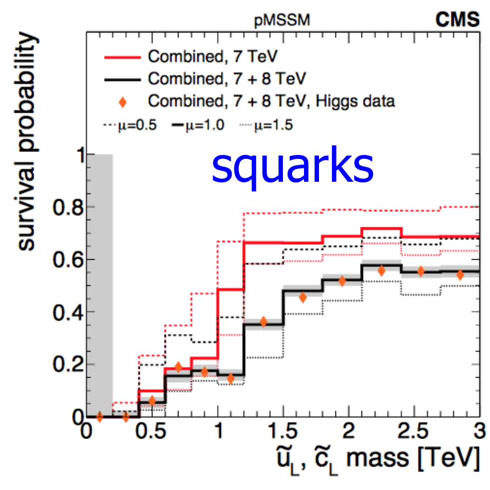
arXiv:1606.03577

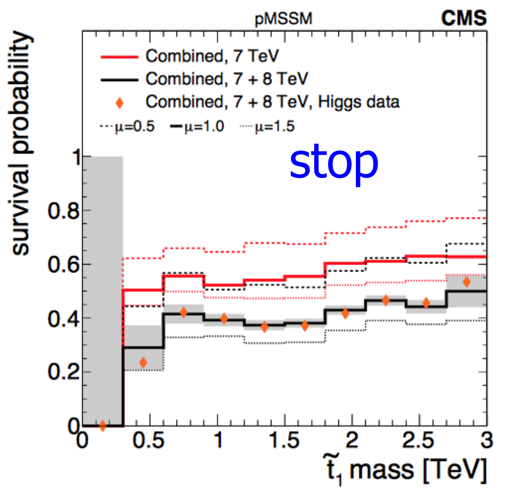


- three independent gaugino mass parameters M_1, M_2, and M_3,
- the ratio of the Higgs vacuum expectation values $\tan\beta = v_2/v_1$,
- the higgsino mass parameter μ and the pseudoscalar Higgs boson mass m_A,
- 10 independent sfermion mass parameters $m_{\tilde{F}}$, where $\tilde{F} = \tilde{Q}_1, \tilde{U}_1, \tilde{D}_1, \tilde{L}_1, \tilde{E}_1, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3$ (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.

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







Based on 8 TeV data limits

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!

Desperately Seeking SUSY?

Many SUSY analyses ongoing in ATLAS & CMS

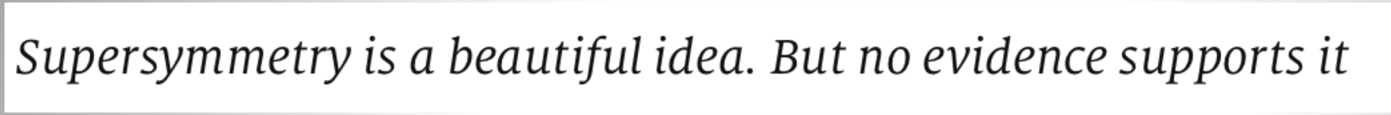
- More searches for topologies with top quarks
- Searches for Vector Boson Fusion SUSY production
- Searches for EWK SUSY particles
- Charm squark searches
- Compressed spectra and related difficult regions

-> Cover different parts of the phase space, allowing to find SUSY in more different corners… but nothing so far

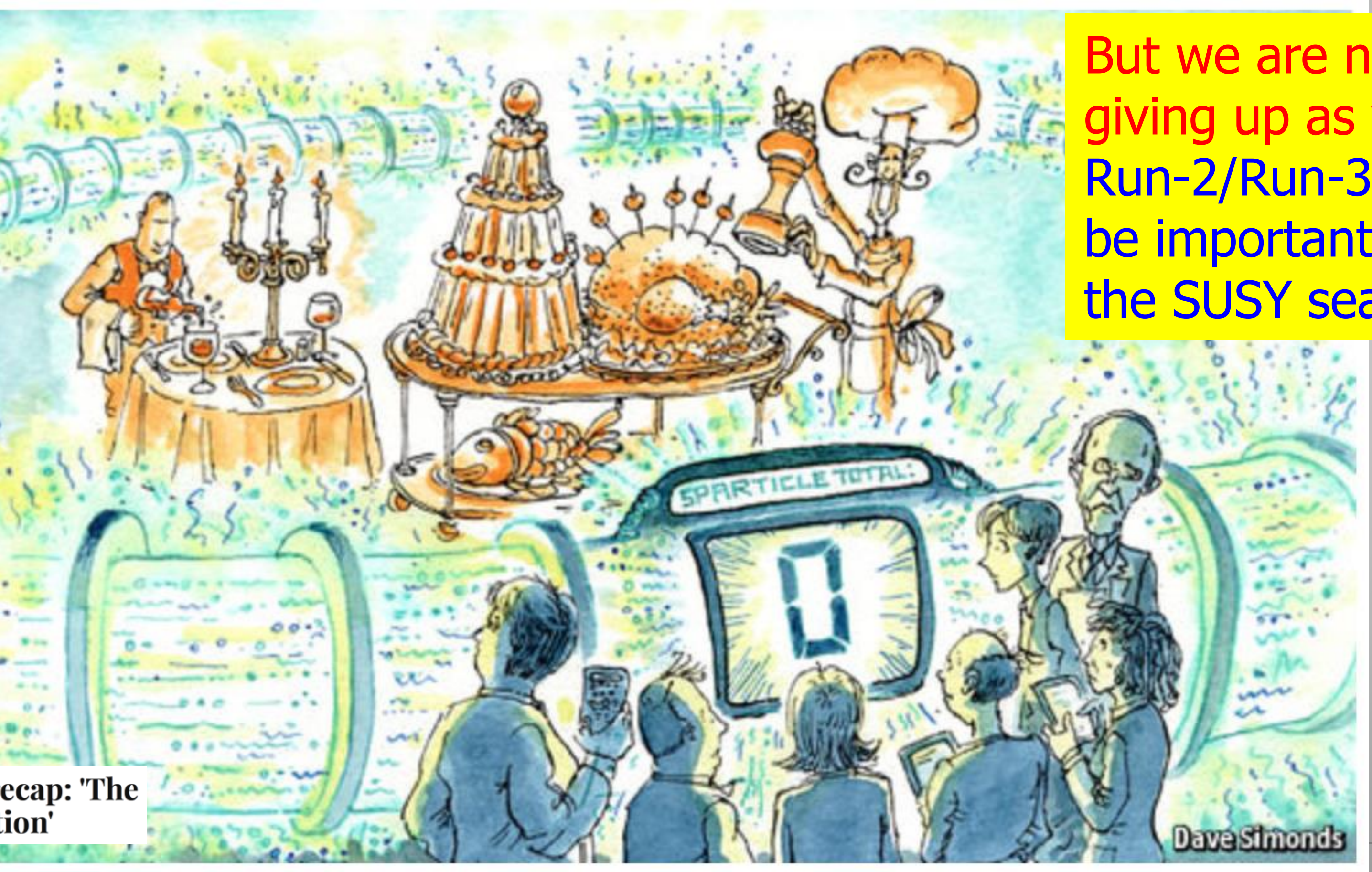
- So far results released on the full 2016 statistics
- New results on the full 2016/2017 data set expected by the European Summer Conferences. These are mostly still blinded at present

SUSY (as seen outside HEP…)

November ’16 on the web page of The Economist (!?!):



Supersymmetry is a beautiful idea. But no evidence supports it



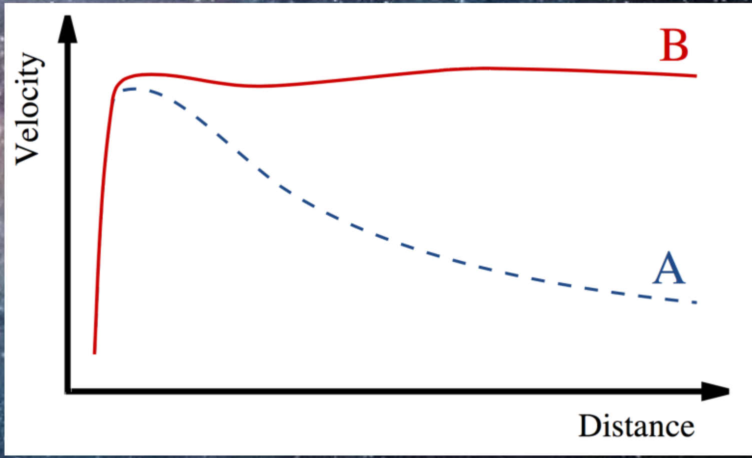
But we are not giving up as yet!!! Run-2/Run-3 will be important for the SUSY searches

***The Big Bang Theory* recap: 'The Retraction Reaction'**

http://www.economist.com/news/science-and-technology/21709946-supersymmetry-beautiful-idea-there-still-no-evidence-support-it

Dark Matter in the Universe

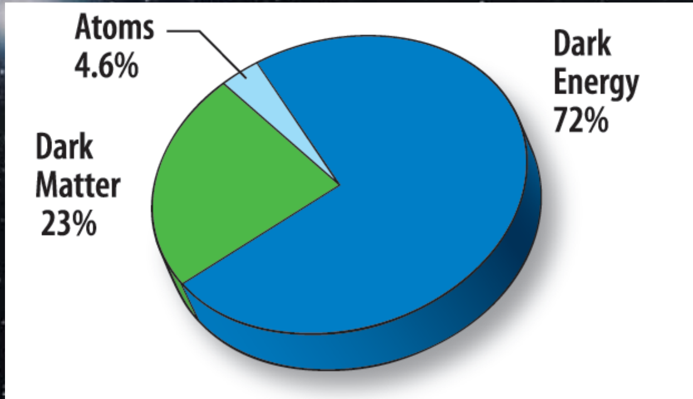
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



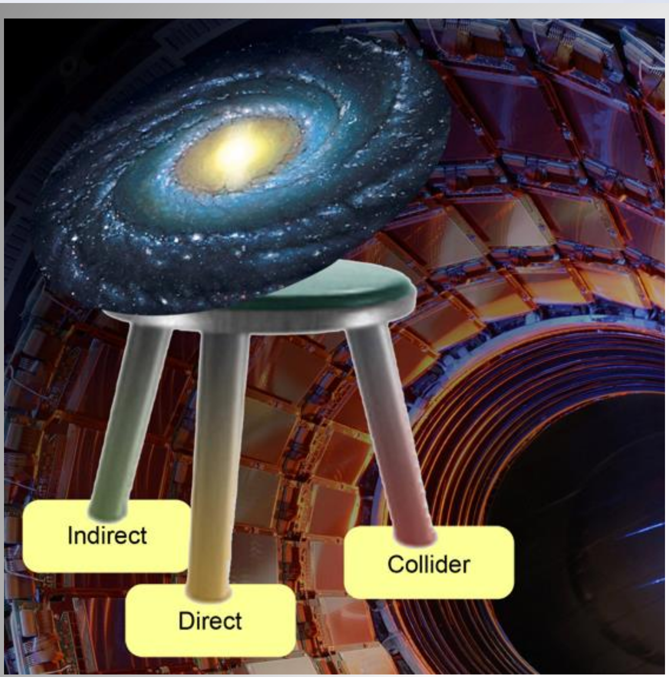
'Supersymmetric' particles ?

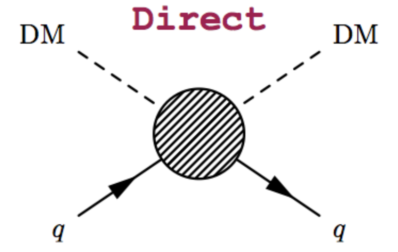

F. Zwicky 1898-1974

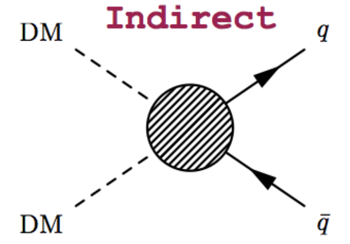

Vera Rubin ~ 1970

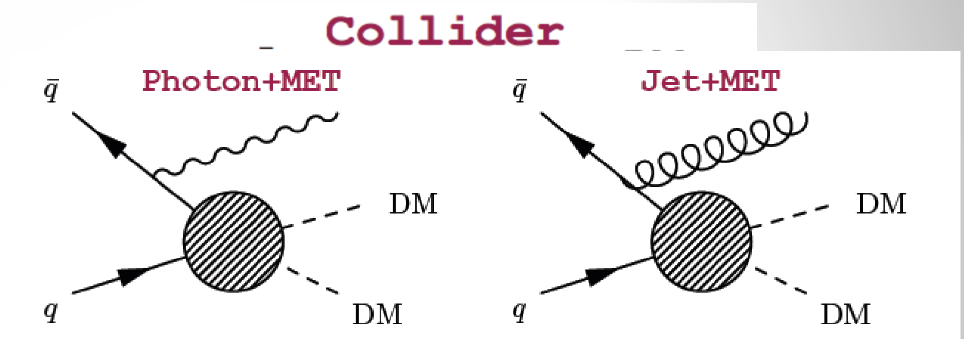


Dark Matter Searches at the LHC

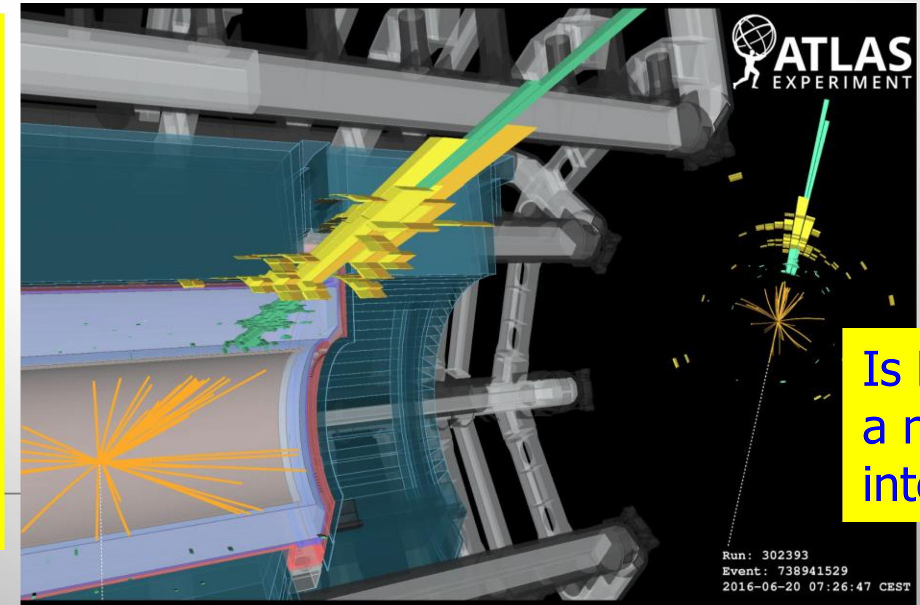






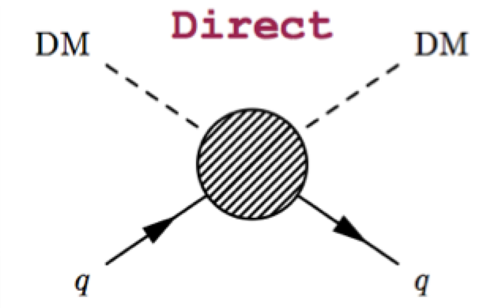


- Identifying Dark Matter is one of the most important questions in physics today!
- It is likely a new as yet undetected particle
- Can it be produced at the LHC?

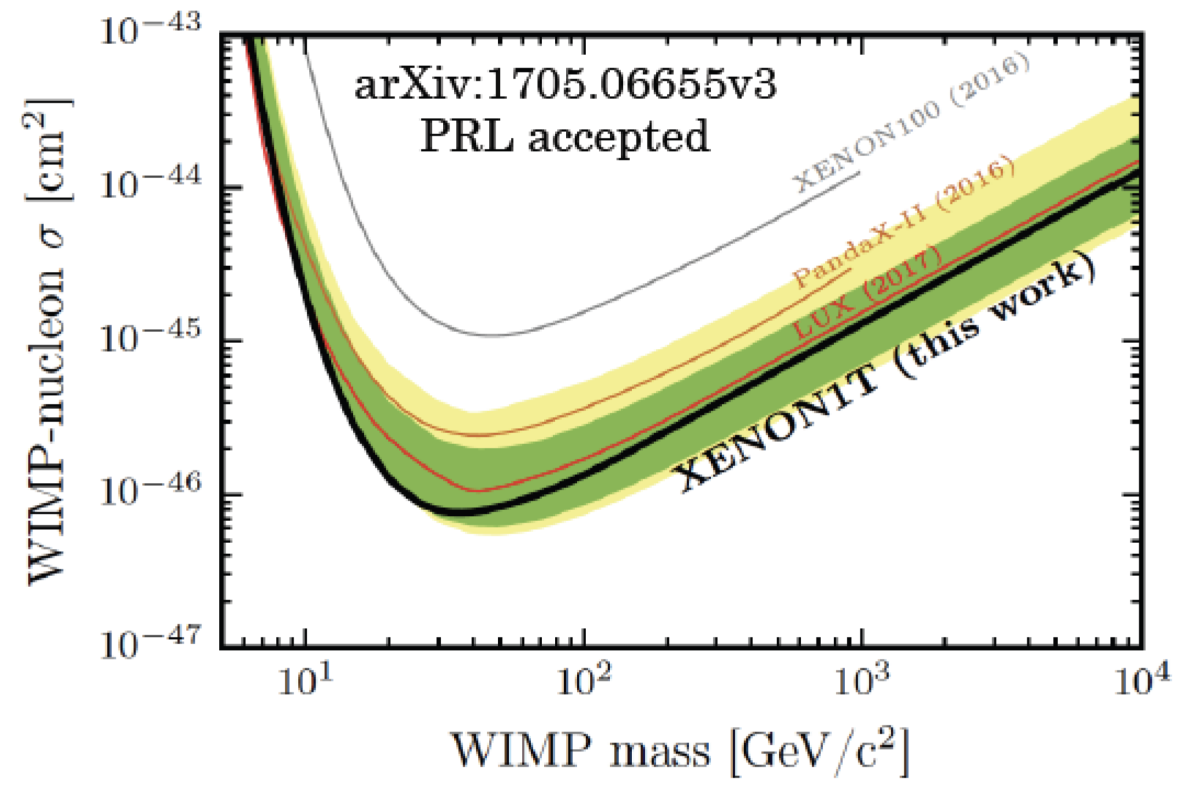


Is Dark Matter a new weakly interacting particle?

Direct Searches for Dark Matter



State of the art today:
Driven by the results of the LUX, Panda-X and XENON 1T experiment



Intensive campaign of direct detection experiments since more than ~20 years

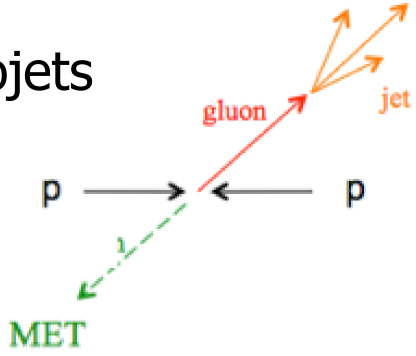
No (real) sign so far…

Mono-object Searches in CMS

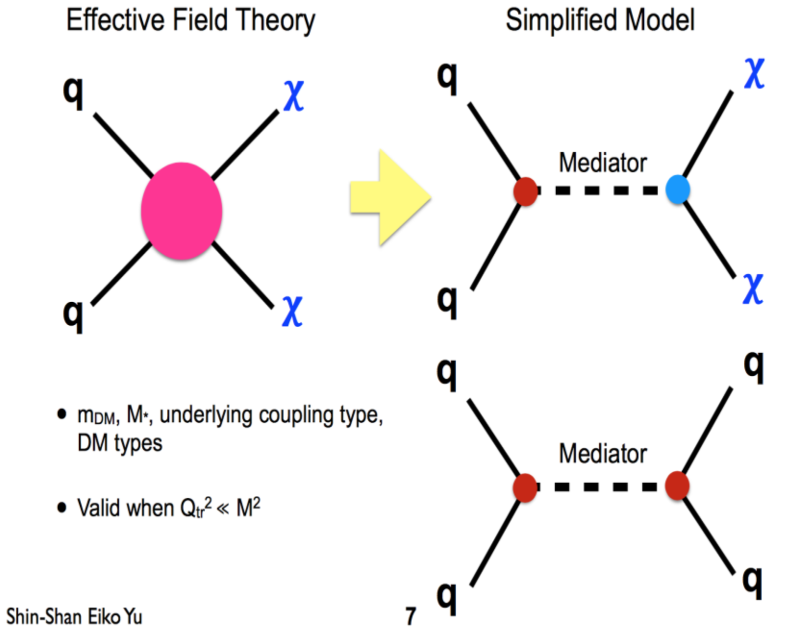
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Are Dark Matter weakly interacting massive particles (WIMPs?)

Example Monojets



Dark Matter?



- m_{DM}, M_*, underlying coupling type, DM types
- Valid when $Q_{tr}^2 \ll M^2$

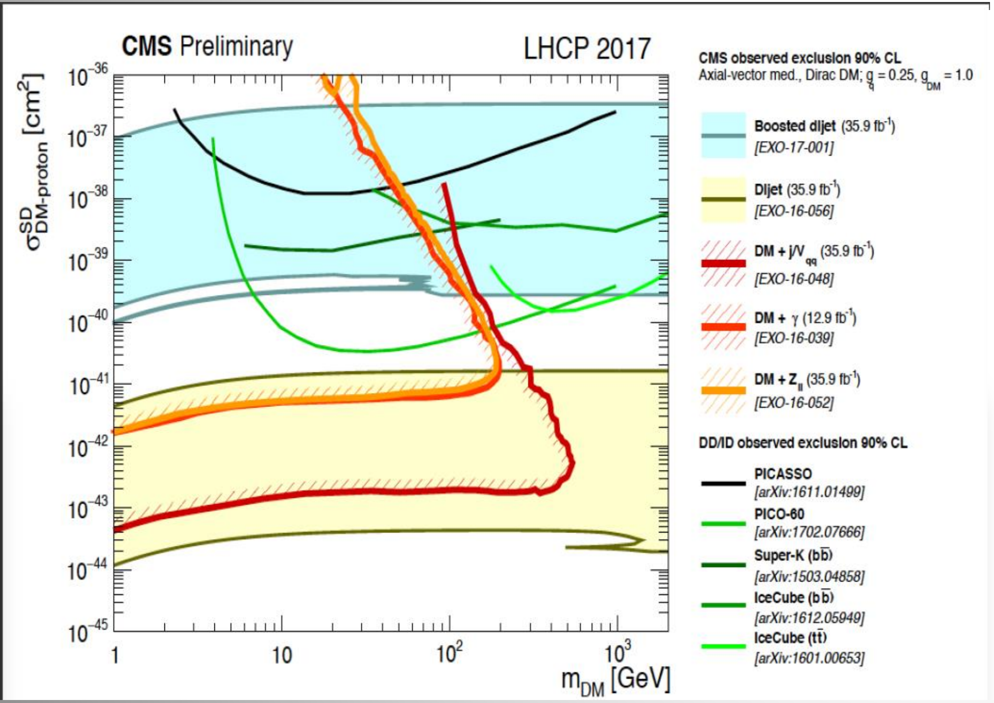
Shin-Shan Eiko Yu

7

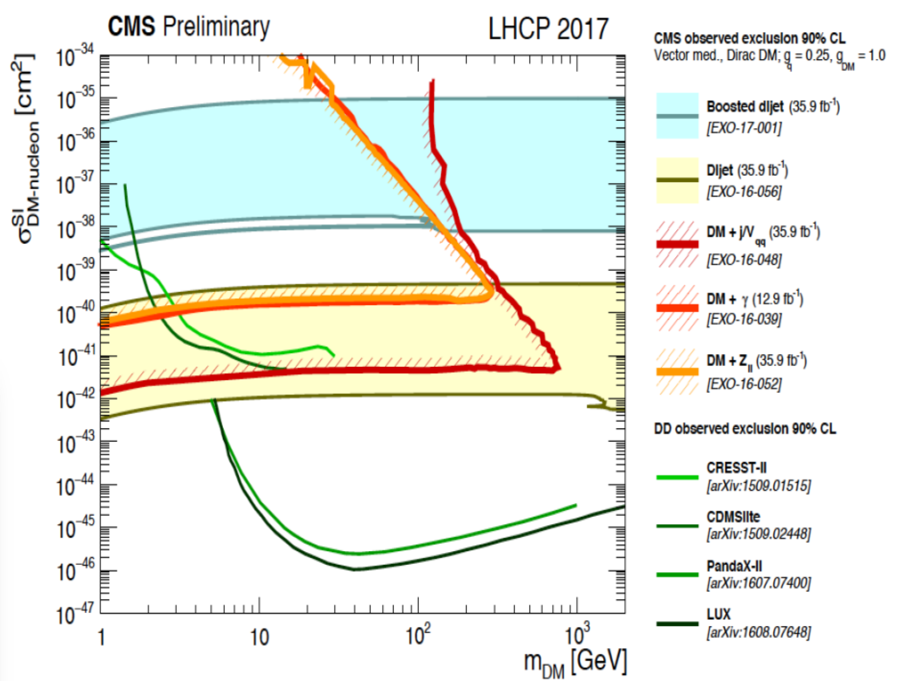
Comparison with Direct Detection

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

Axial-vector mediator and
Spin-dependent direct limits

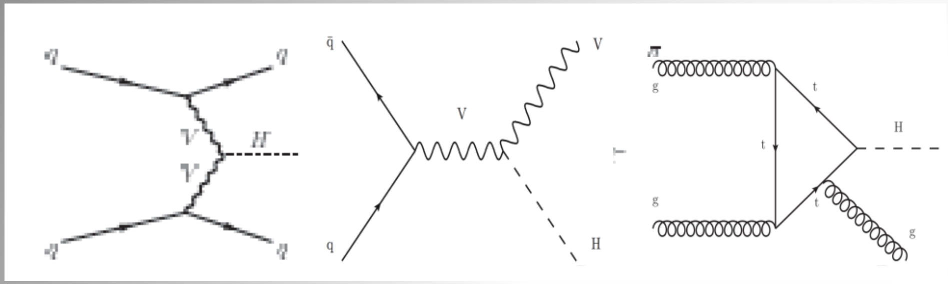


Vector mediator and
Spin-independent direct limits



90% CL limits

Invisible Higgs Decay Channel



Search for invisible Higgs decays using

Z+H → 2 leptons + missing E_T

VBF H → 2 jets + missing E_T

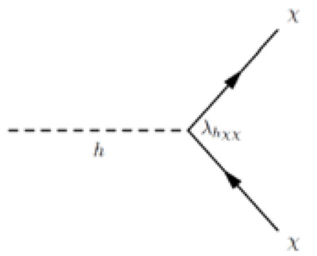
Possible decay in Dark Matter particles (if $M<M_H/2$): Higgs Portal Models

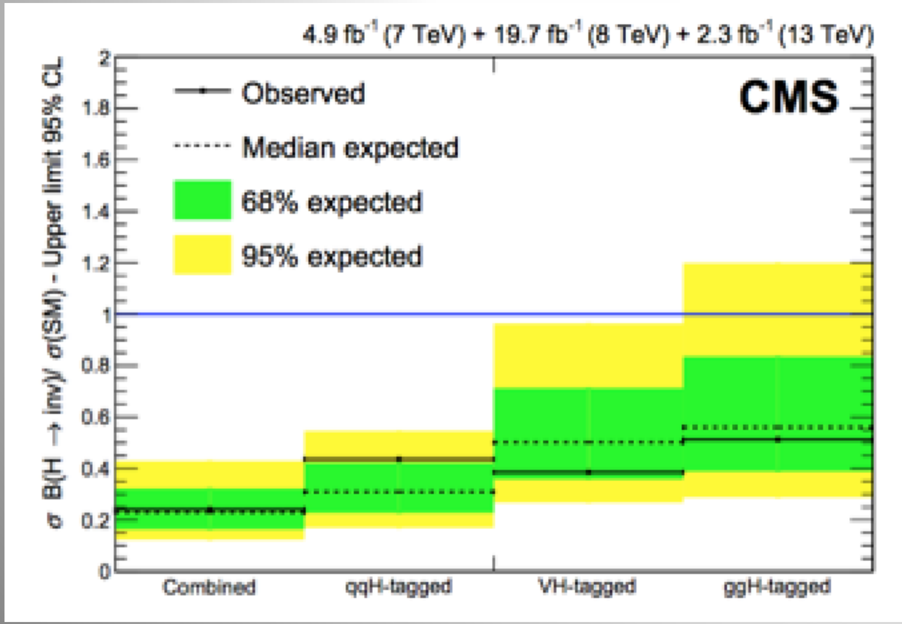
Combined result from the three channels

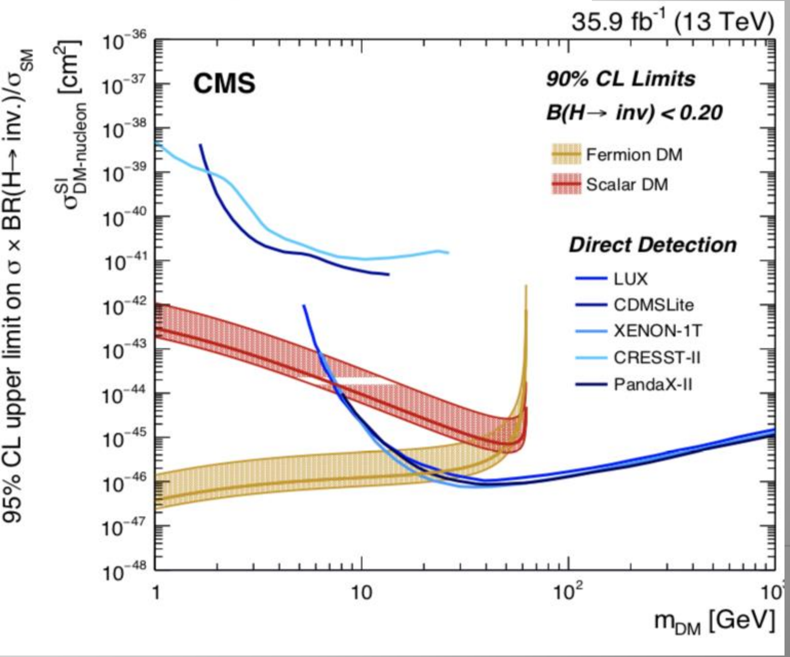
BR(H→invisible)<24%(20% exp) at 95% CL.

for a Higgs with a mass of 125 GeV

arXiv:1610.09218
HIG-17-023





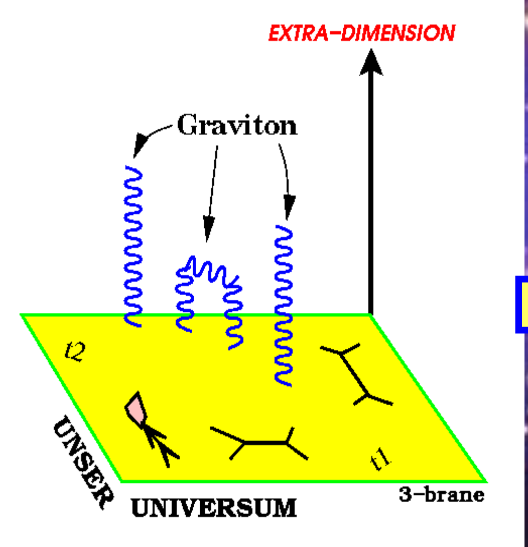


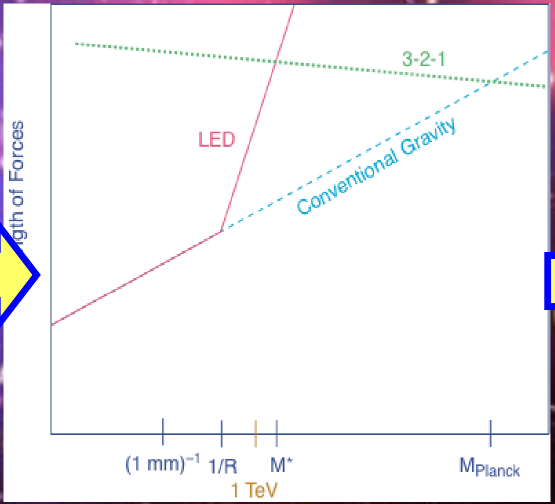
Extra Space Dimensions

Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV}$$

$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV}$$





The Gravitational force becomes strong!

New Planck scale is larger than 3 TeV

Extra Space Dimensions

Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246\ \text{GeV}$$

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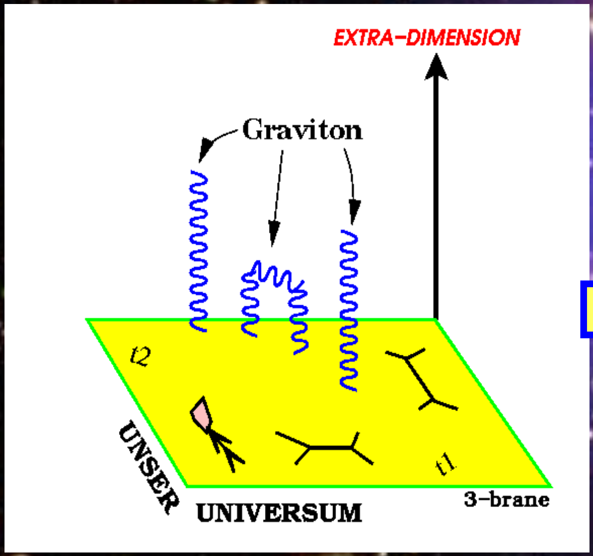
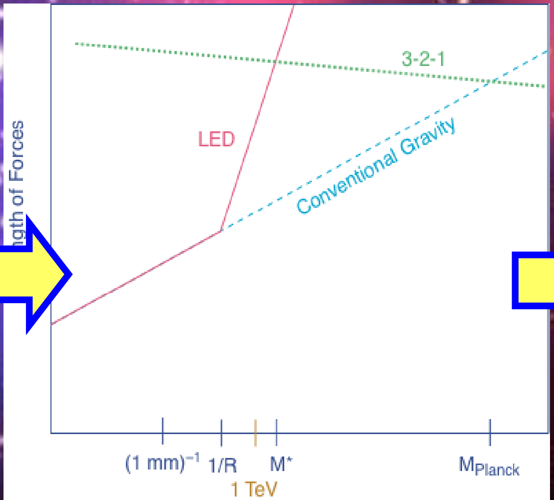
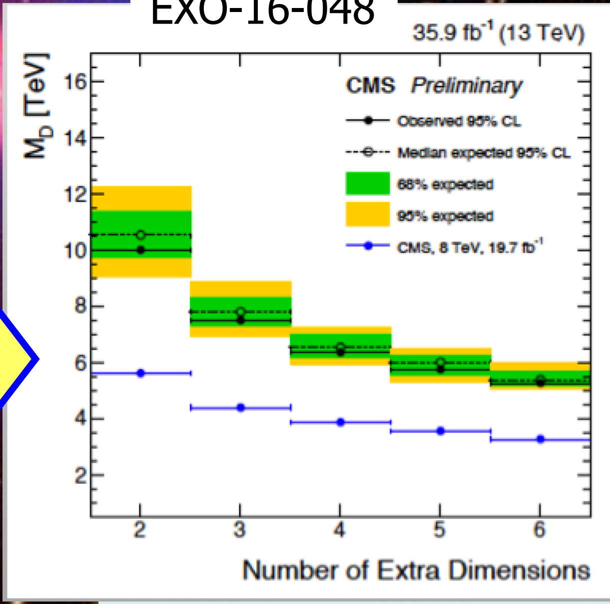




EXO-16-048

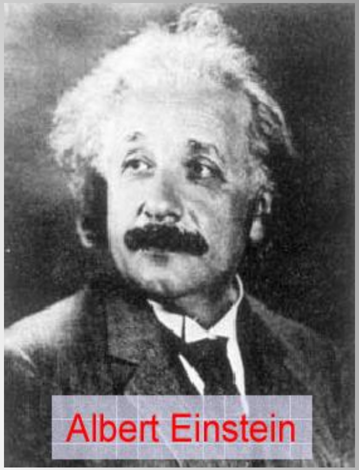


The Gravitational force can become strong!

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

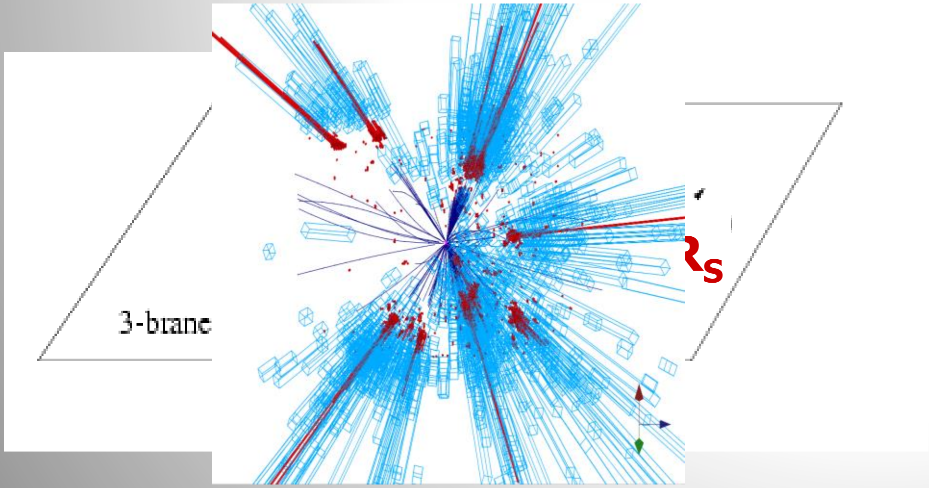
Quantum Black Holes at the LHC?

Black Holes are a direct prediction of Einstein’s general theory on relativity

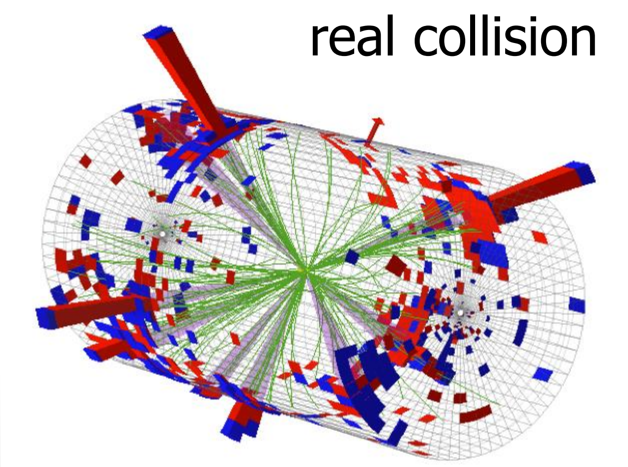


If the Planck scale is in ~TeV region:
can expect Quantum Black Hole production

Quantum Black Holes are harmless for the environment: they will decay within less than 10^{-27} seconds ⇒ SAFE!



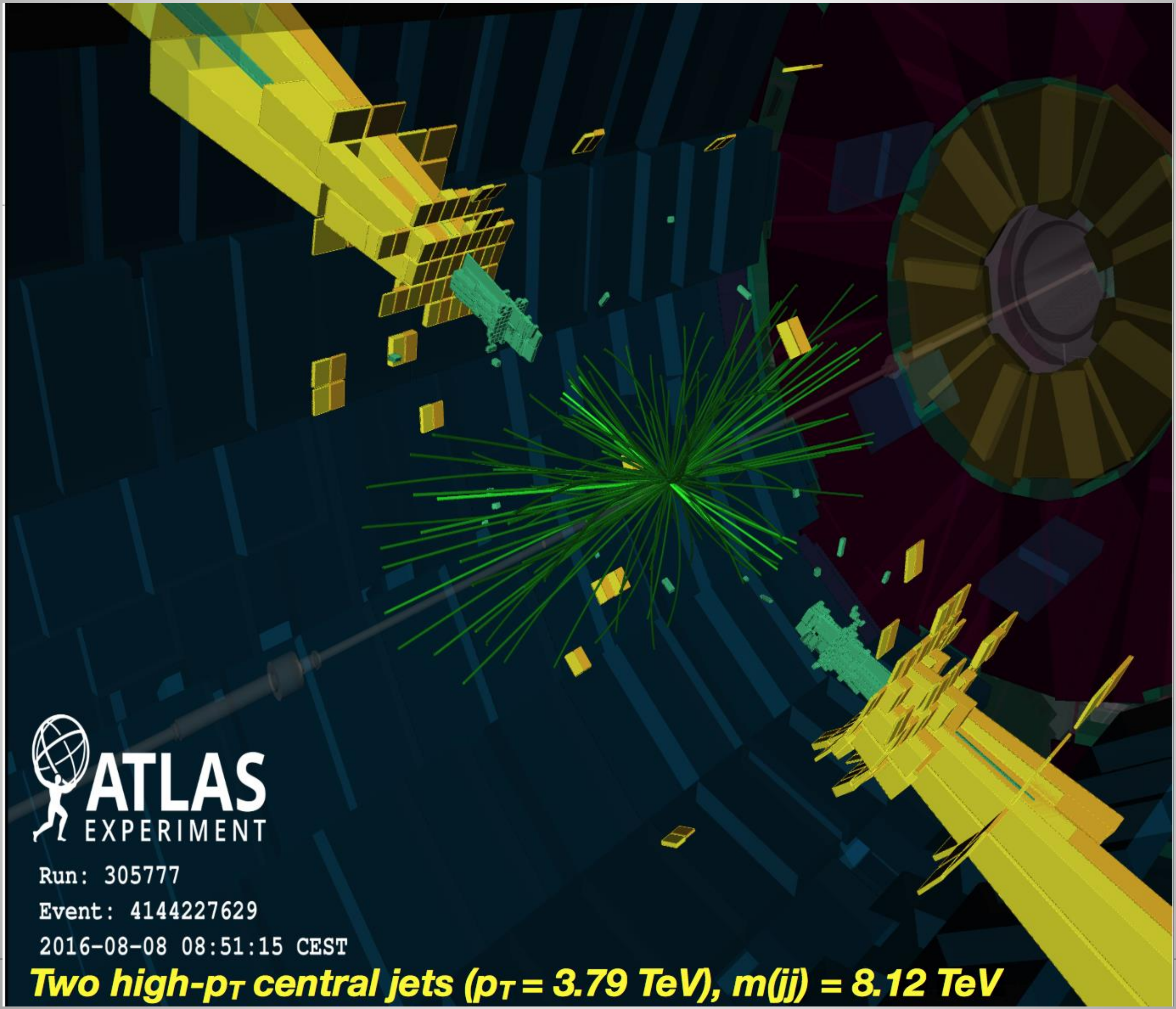
Simulation of a Quantum Black Hole event



Black holes with mass
Below 9 TeV are excluded

Black Holes Hunters at the LHC…

Dijet Resonance Searches @13TeV



Run: 305777

Event: 4144227629

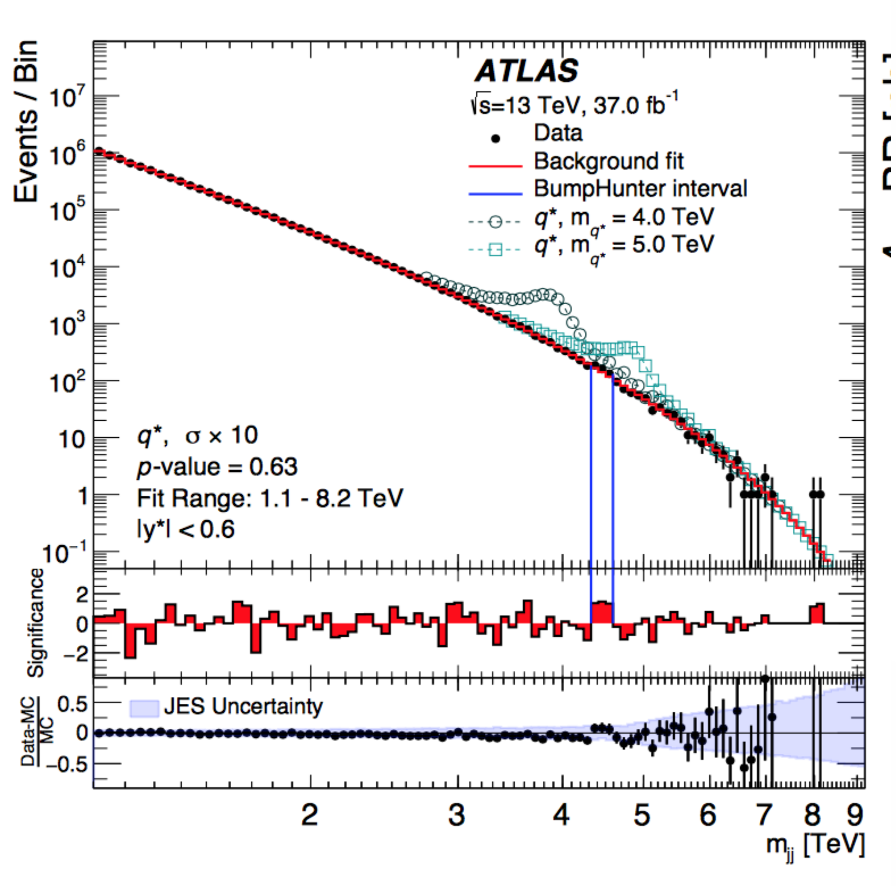
2016-08-08 08:51:15 CEST

Two high-p_T central jets ($p_T = 3.79$ TeV), m(jj) = 8.12 TeV

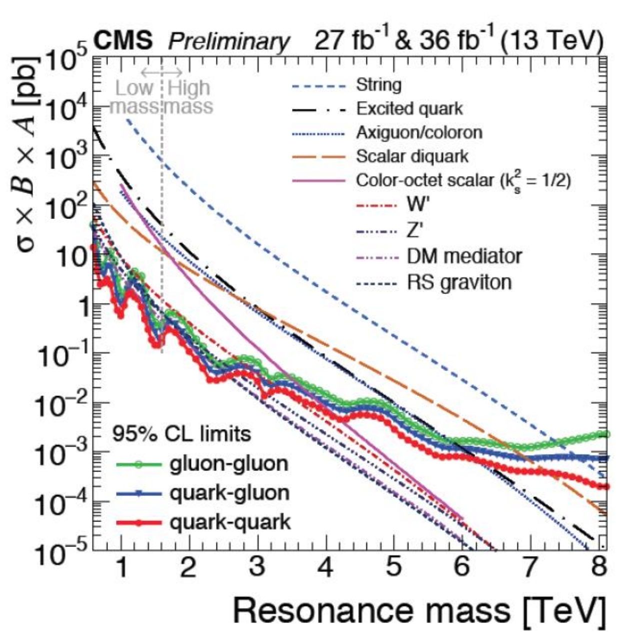
Dijet Resonance Searches @13TeV

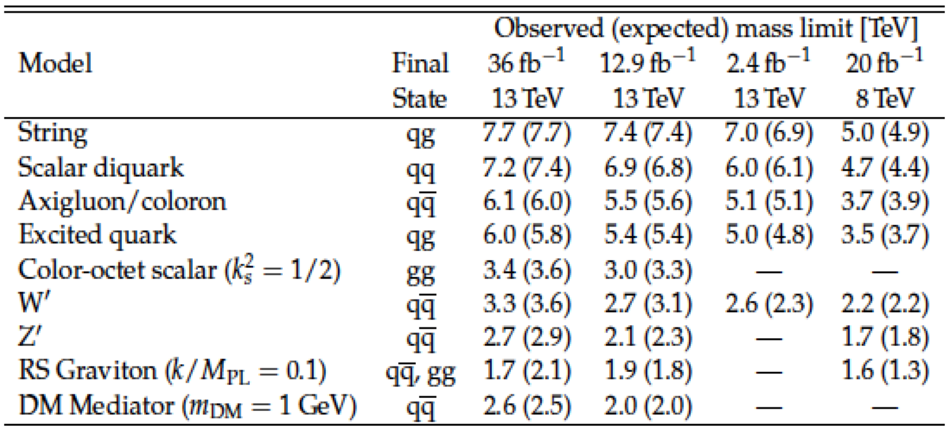
arXiv:1703.09127

Background: QCD smooth shape fit



EXO-16-056

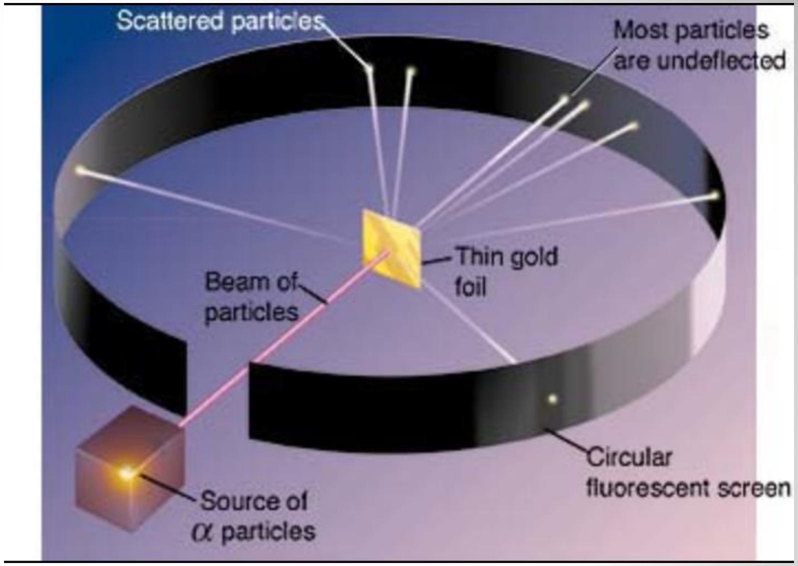


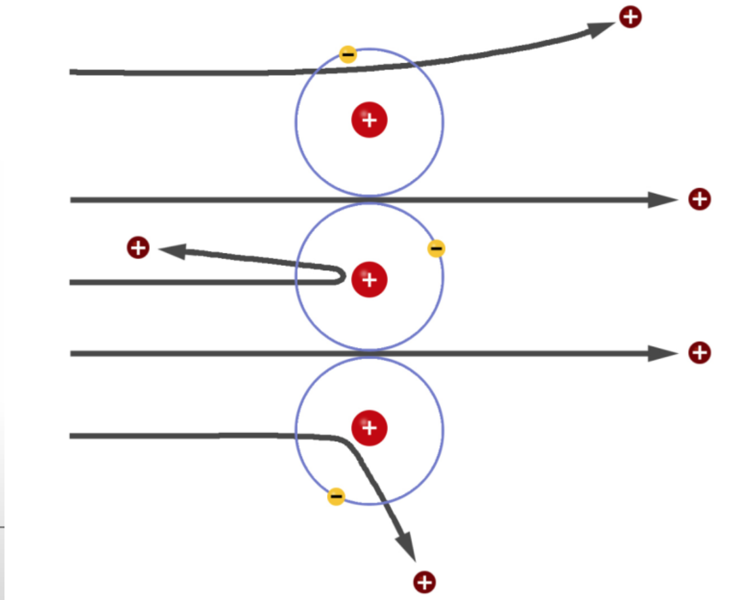


Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.7 (7.7)	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	7.2 (7.4)	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	6.0 (5.8)	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.0 (3.3)	—	—
W′	$q\bar{q}$	3.3 (3.6)	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.7 (2.9)	2.1 (2.3)	—	1.7 (1.8)
RS Graviton ($k/M_{\mathrm{PL}} = 0.1$)	$q\bar{q}$, gg	1.7 (2.1)	1.9 (1.8)	—	1.6 (1.3)
DM Mediator ($m_{\mathrm{DM}} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.0 (2.0)	—	—

36 fb^{-1} limits from 13 TeV between 1.7 and 7.7 TeV, dependent on model

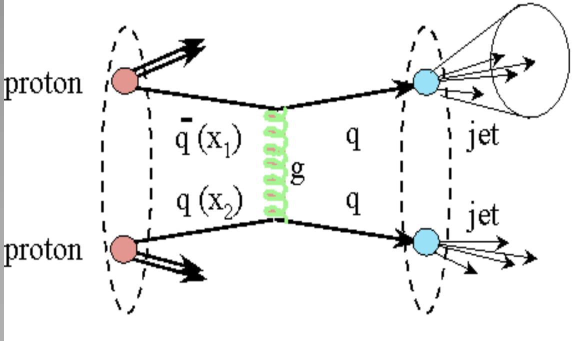
Are Quarks Elementary Particles?

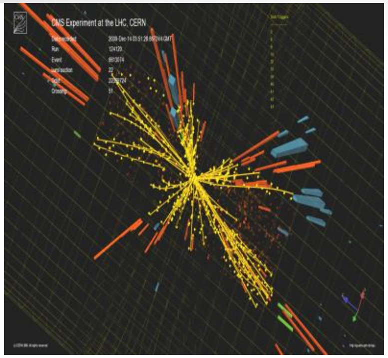


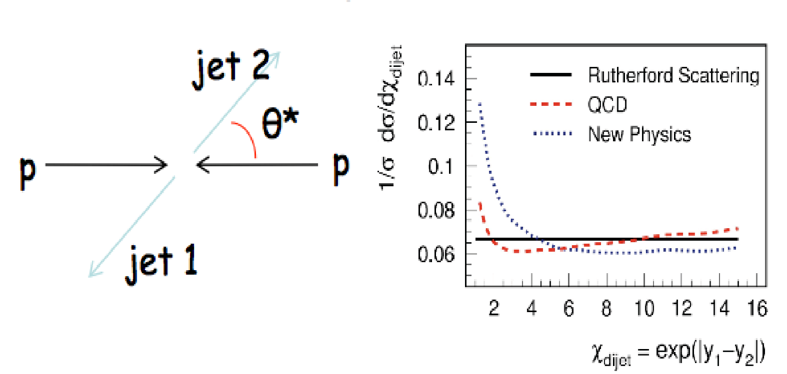


Rutherford experiment:
Unexpected backscattering of α-particles:
Evidence for the structure of atoms !! (1911)

Are Quarks Elementary Particles?

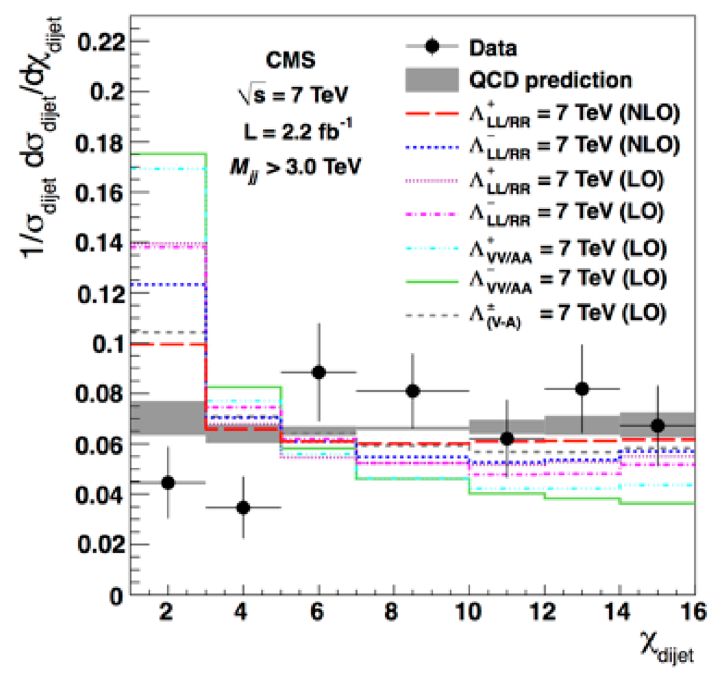


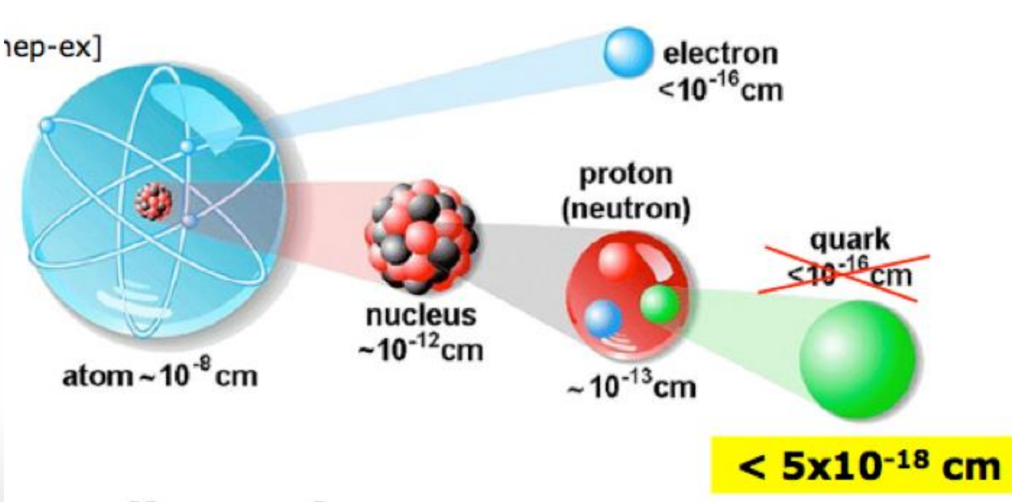




Measurement of the production angle of the jet with respect to the beam

-> High Energy Rutherford Experiment





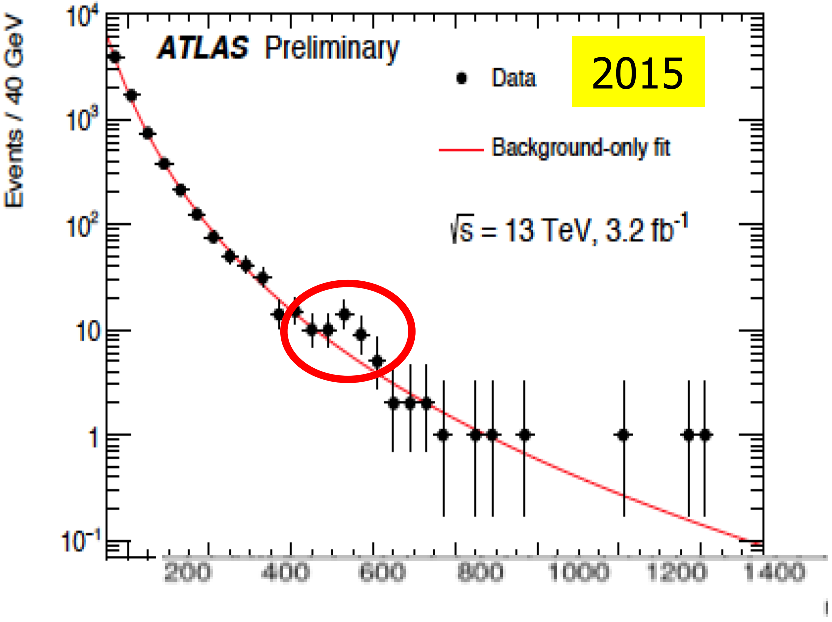
Quarks remain elementary particles after these first results

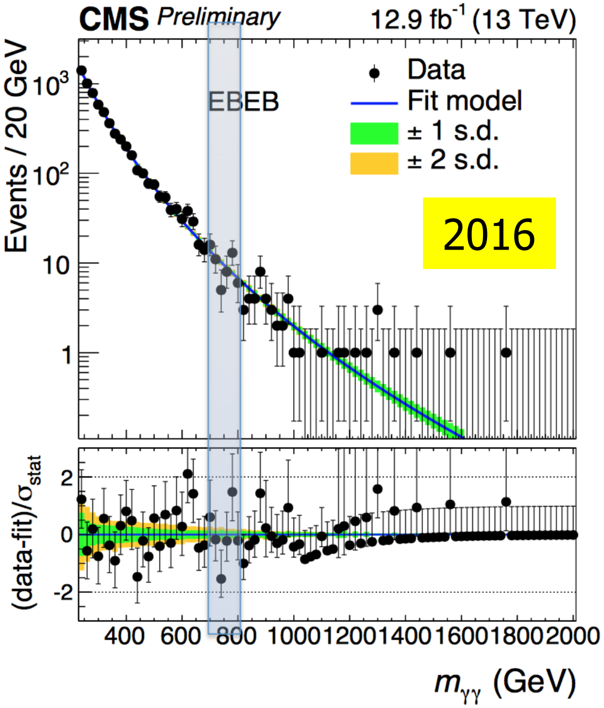
A New Particle at 750 GeV: X → $\gamma\gamma$?

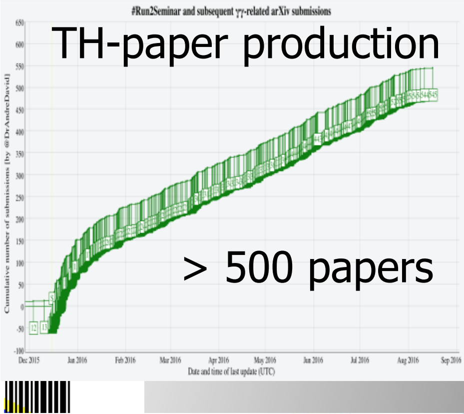
Excitement in December 2015

->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







TH-paper production

> 500 papers

2015: Statistical fluctuation? A new resonance? ???

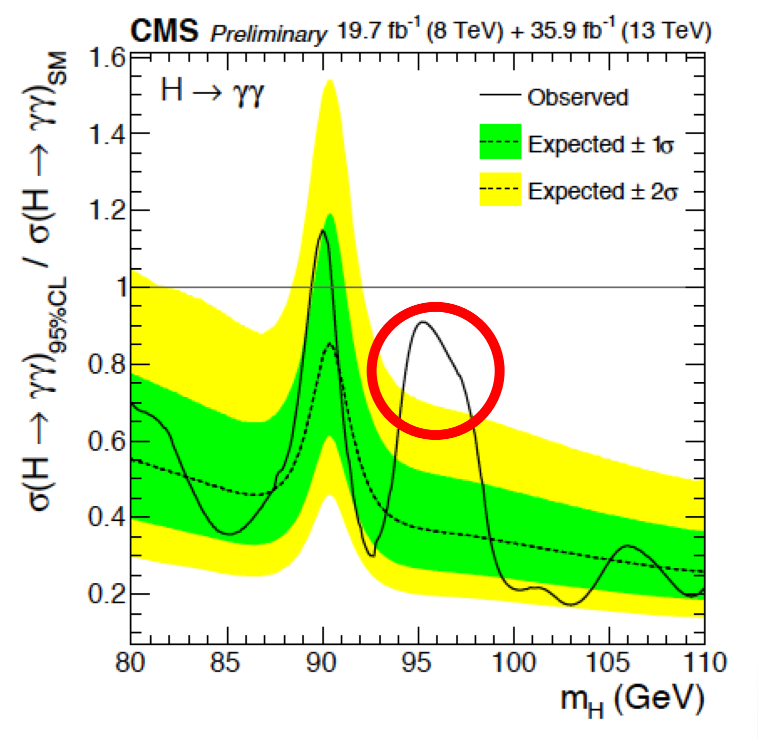
2015 data: CMS: 3.4 σ ! ATLAS up to 3.9 σ !! (local significances)

2016 data: CMS and ATLAS Nada!!

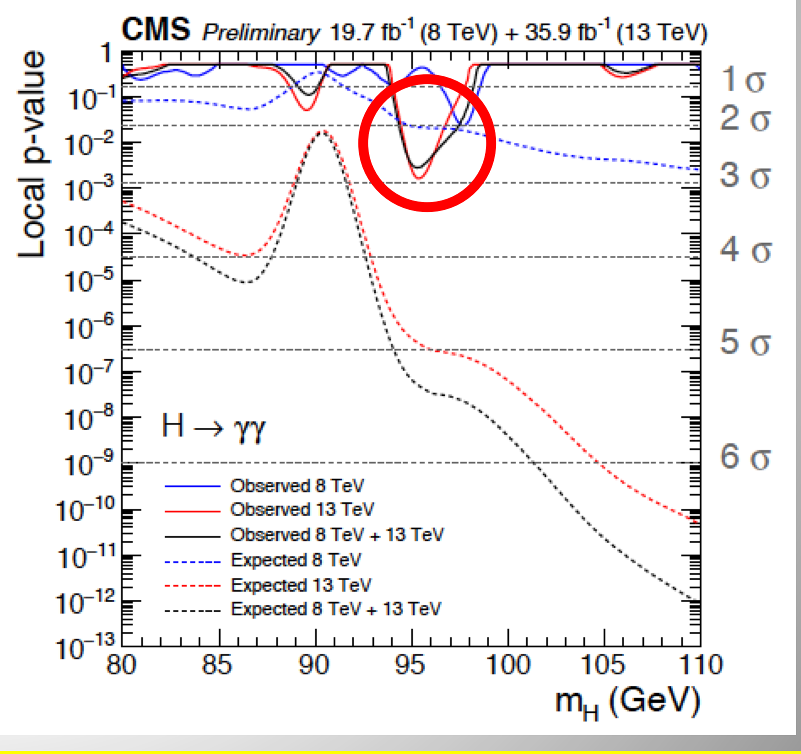
Is 96 GeV the New 750 GeV (?)

A new result released this 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

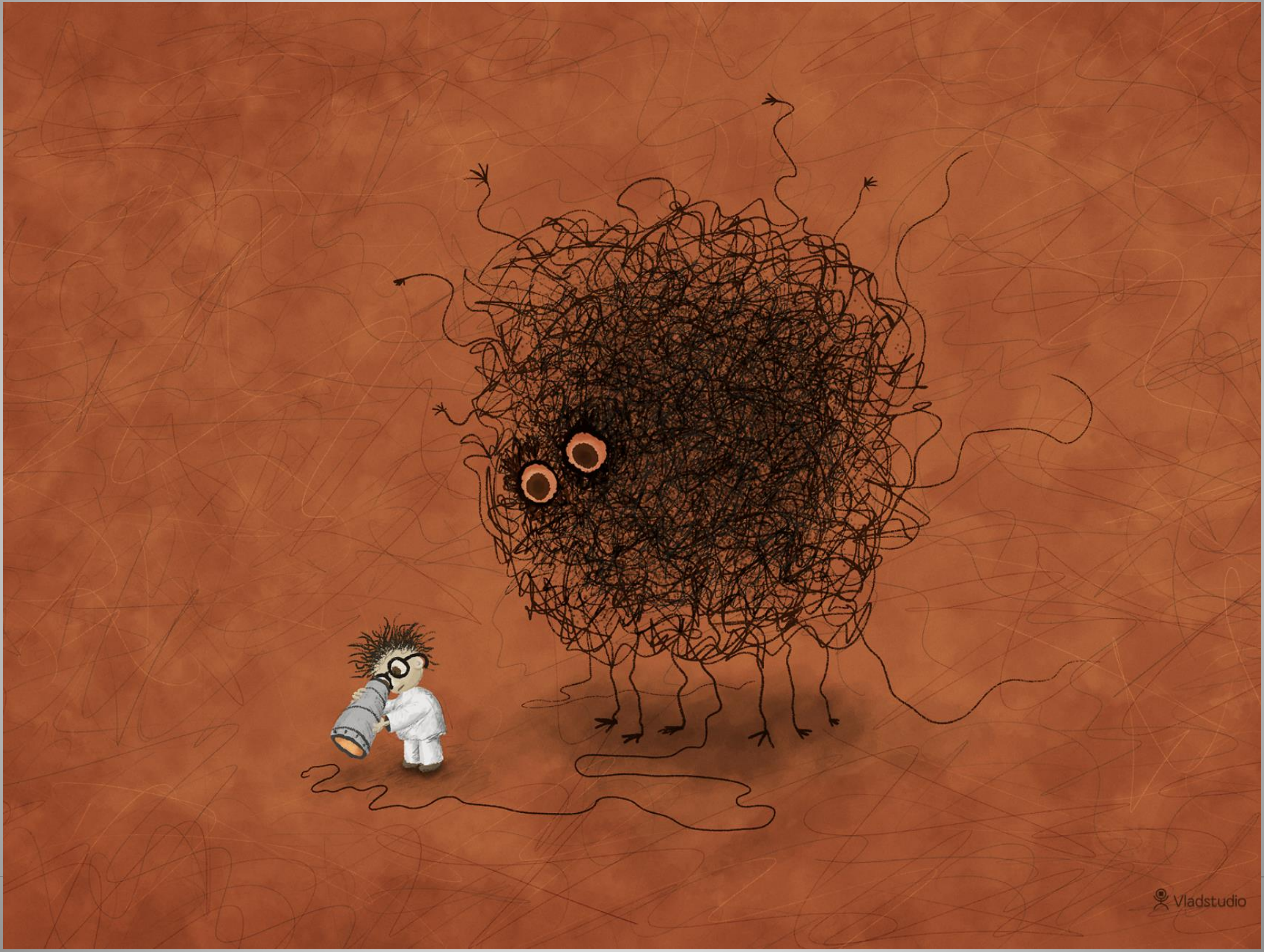


CMS-HIG-17-013

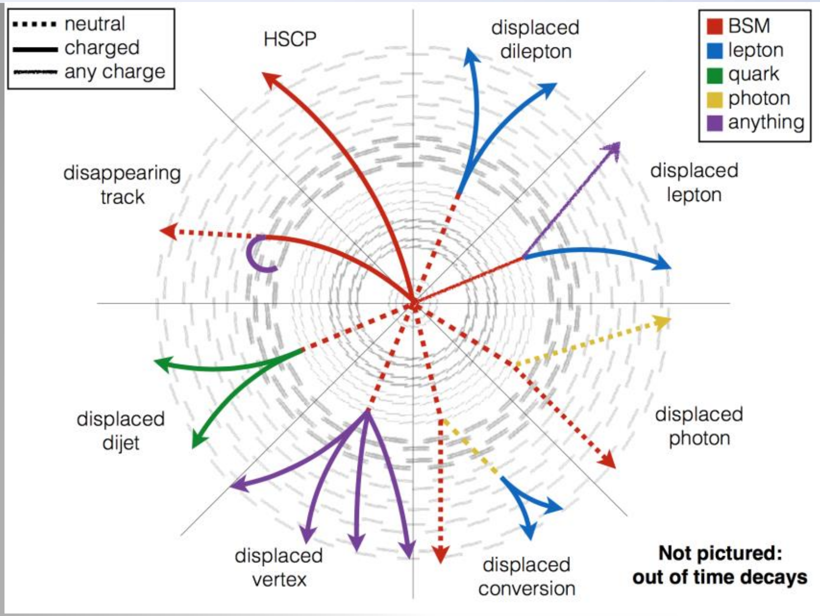


So far seen only in CMS. Waiting for the ATLAS data to be released… ☺ !!

Are we Looking at the Right Place?

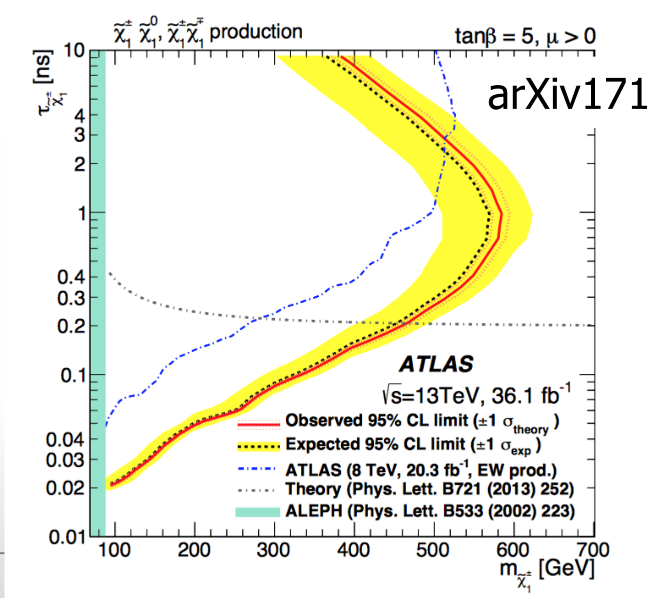


Searches for Long Lived Particles



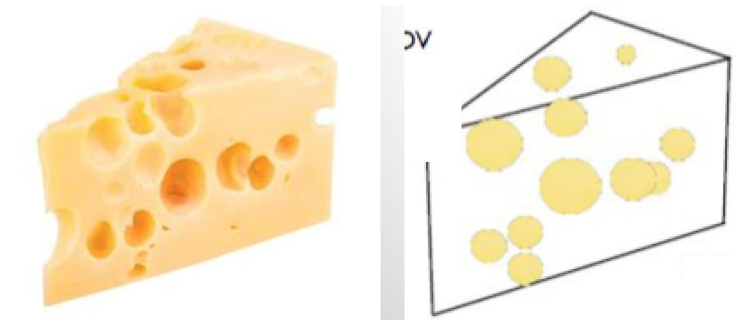
Increasing interest and effort: Look for unusual signals in the detector from long-lived particles

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



arXiv1712.02118

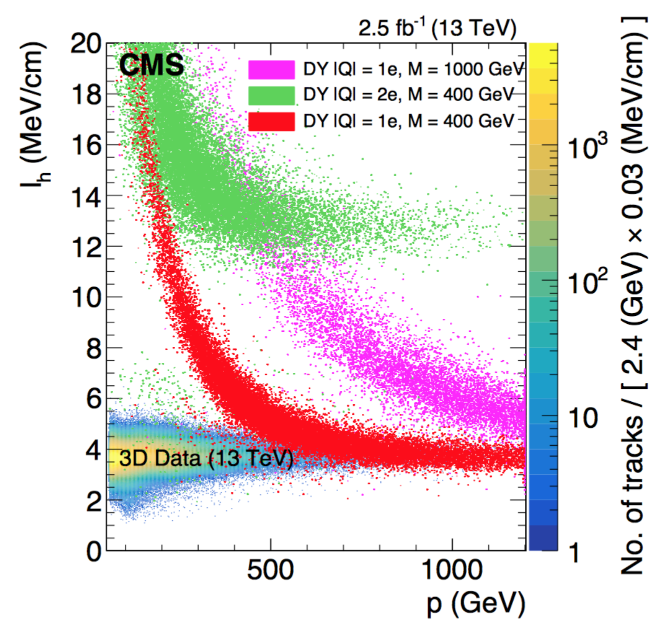
Present coverage?



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

A White Paper in preparation!

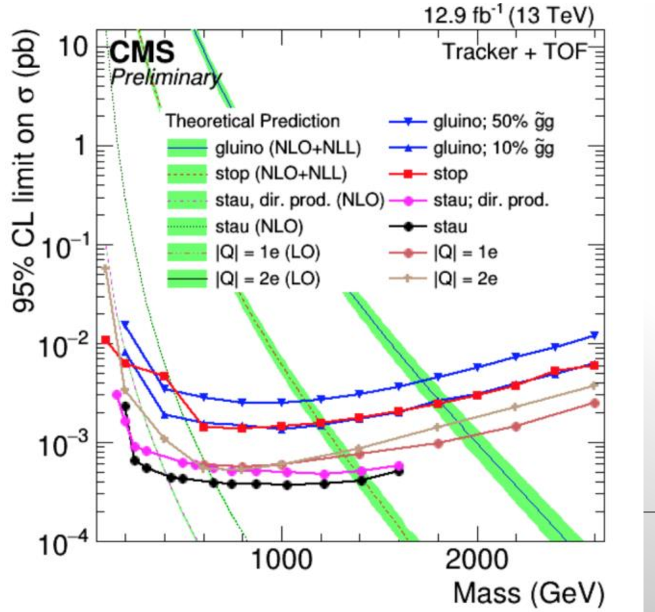
Heavy Stable Ionizing Particles

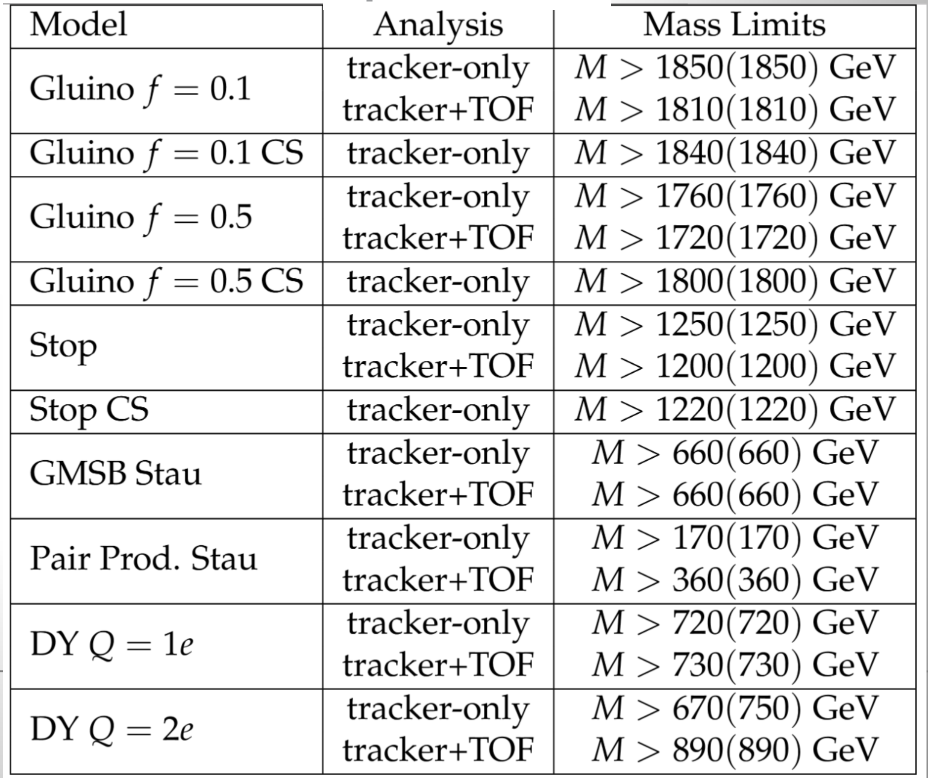


Detection techniques used for (multiple/fractional) heavy stable charge particles

- Abnormal energy loss (de/dx)
- Slower than speed of light (lowβ) via time of flight measurements with the muon system

Time of flight $\frac{1}{\beta} = 1 + \frac{c\delta_t}{L}$ EXO-16-036





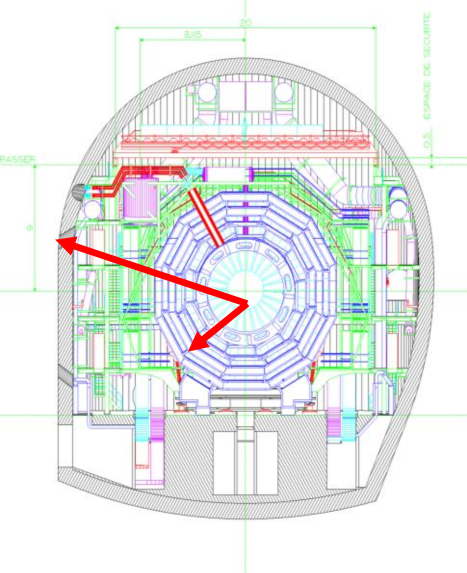
Model	Analysis	Mass Limits
Gluino $f = 0.1$	tracker-only tracker+TOF	$M > 1850(1850)$ GeV $M > 1810(1810)$ GeV
Gluino $f = 0.1$ CS	tracker-only	$M > 1840(1840)$ GeV
Gluino $f = 0.5$	tracker-only tracker+TOF	$M > 1760(1760)$ GeV $M > 1720(1720)$ GeV
Gluino $f = 0.5$ CS	tracker-only	$M > 1800(1800)$ GeV
Stop	tracker-only tracker+TOF	$M > 1250(1250)$ GeV $M > 1200(1200)$ GeV
Stop CS	tracker-only	$M > 1220(1220)$ GeV
GMSB Stau	tracker-only tracker+TOF	$M > 660(660)$ GeV $M > 660(660)$ GeV
Pair Prod. Stau	tracker-only tracker+TOF	$M > 170(170)$ GeV $M > 360(360)$ GeV
DY $Q = 1e$	tracker-only tracker+TOF	$M > 720(720)$ GeV $M > 730(730)$ GeV
DY $Q = 2e$	tracker-only tracker+TOF	$M > 670(750)$ GeV $M > 890(890)$ GeV

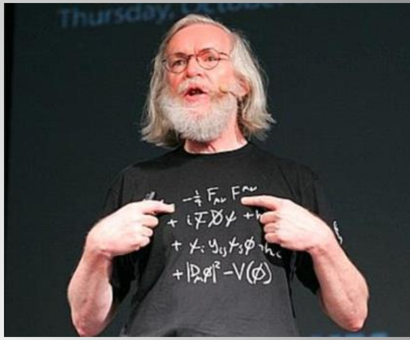
Searches for Exotic Long Lived Particles

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

⇒Challenges to the experiments!





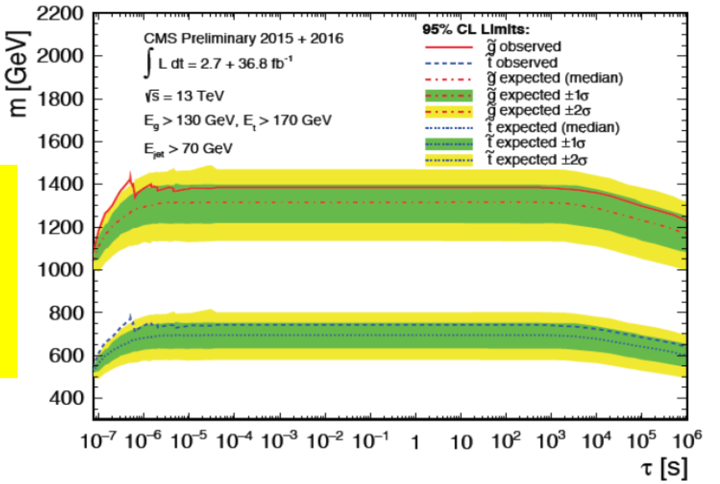
EG:ADR, J. Ellis et al. hep-ph/0508198

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

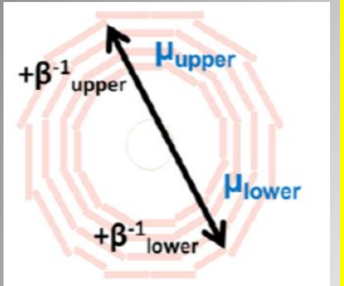
Analysis searching for “decays” in calorimeter

Limits on M_{stop} ~744 GeV and M_{gluino} ~1385 GeV 95% CL for lifetimes from 10 μsec to 1000s

EXO-16-004



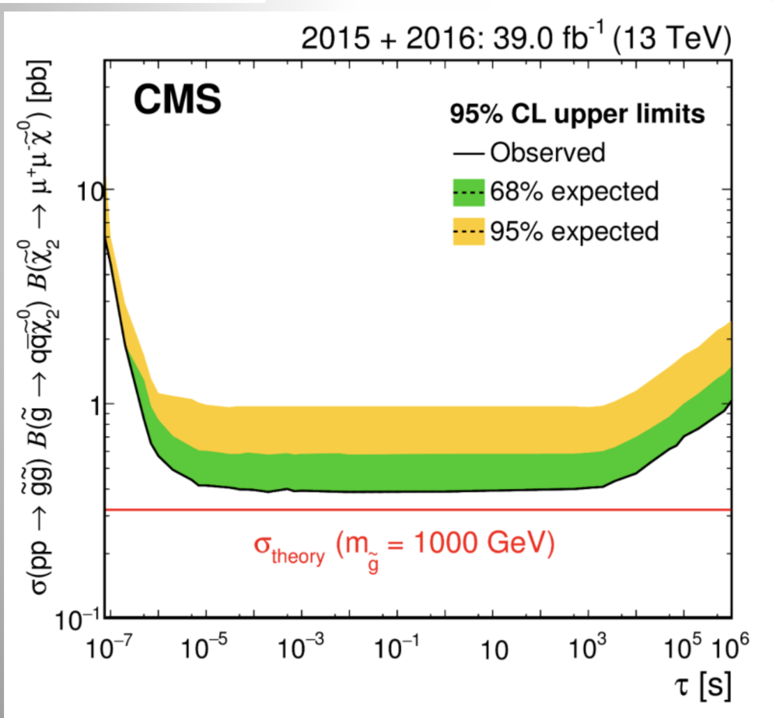
Search for Stopped Long Lived Particles

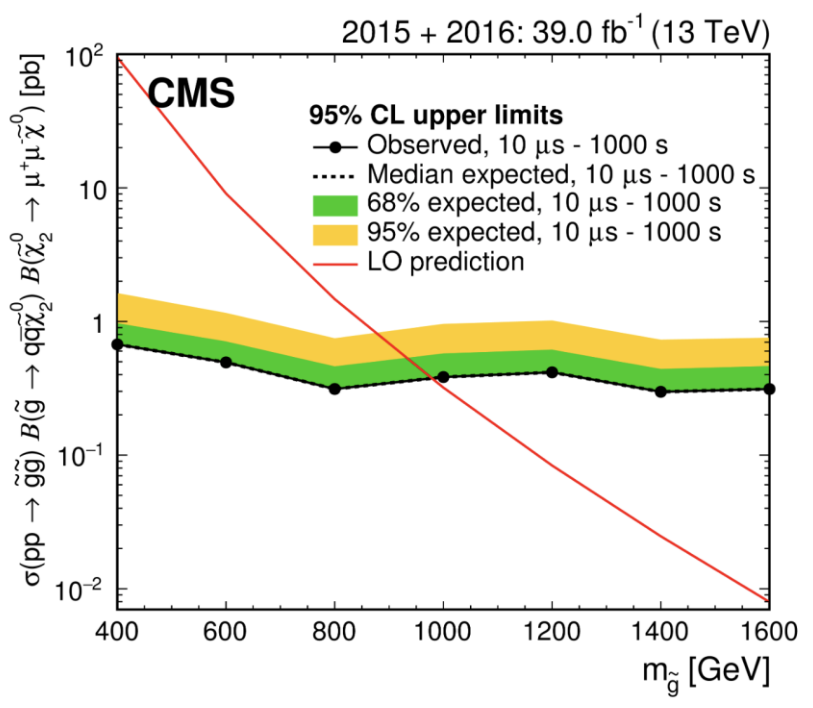


- Search for long lived particles that stop in the detector and decay into jets after some time, non-coincident with pp collisions
- 744 hours trigger lifetime in 2015/16 included in this search.
- Searches for long lived gluinos with delayed muons
- No events observed in 2015/16.

arXiv:1801.00359

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

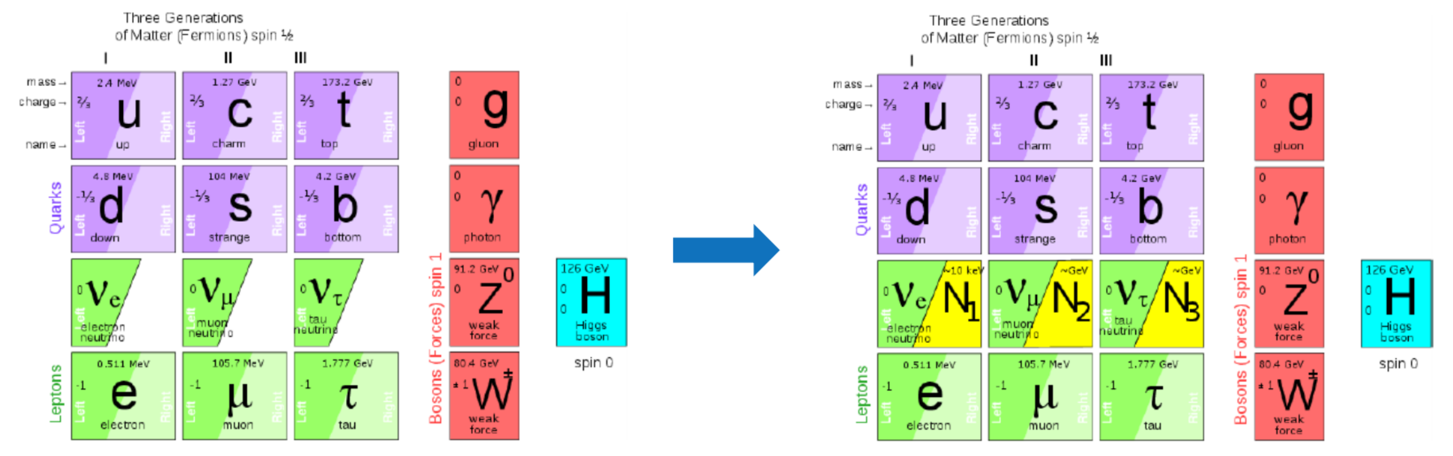


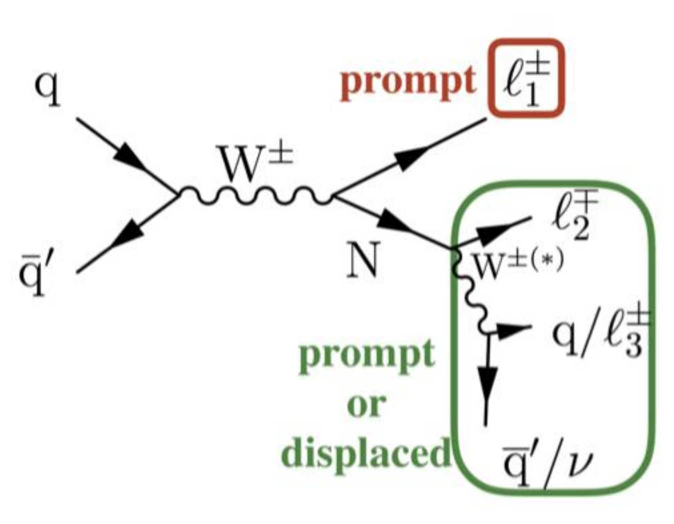


Limits on 400<M_{gluino}<970 GeV 95%CL for lifetimes from 10 μsec to 1000s

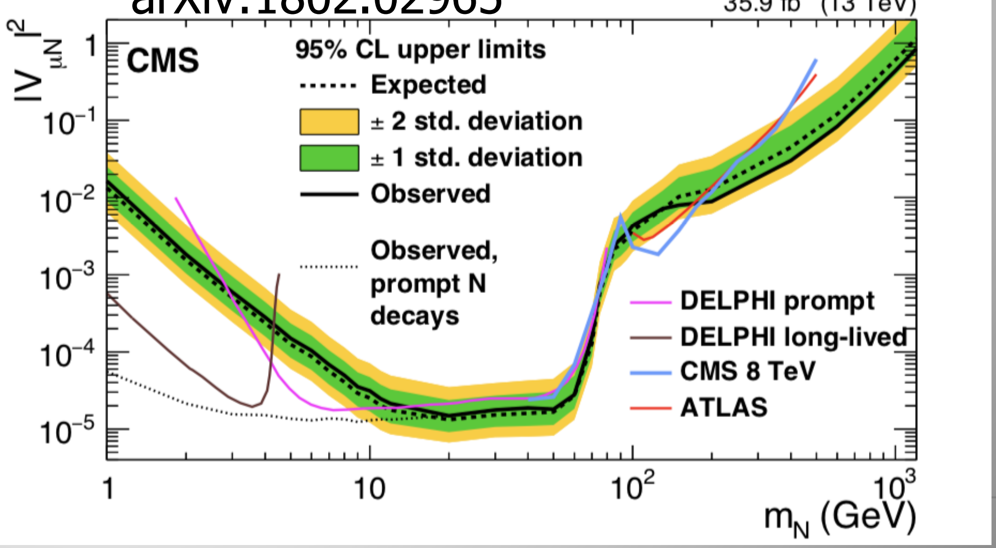
Search for Heavy Neutral Leptons

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

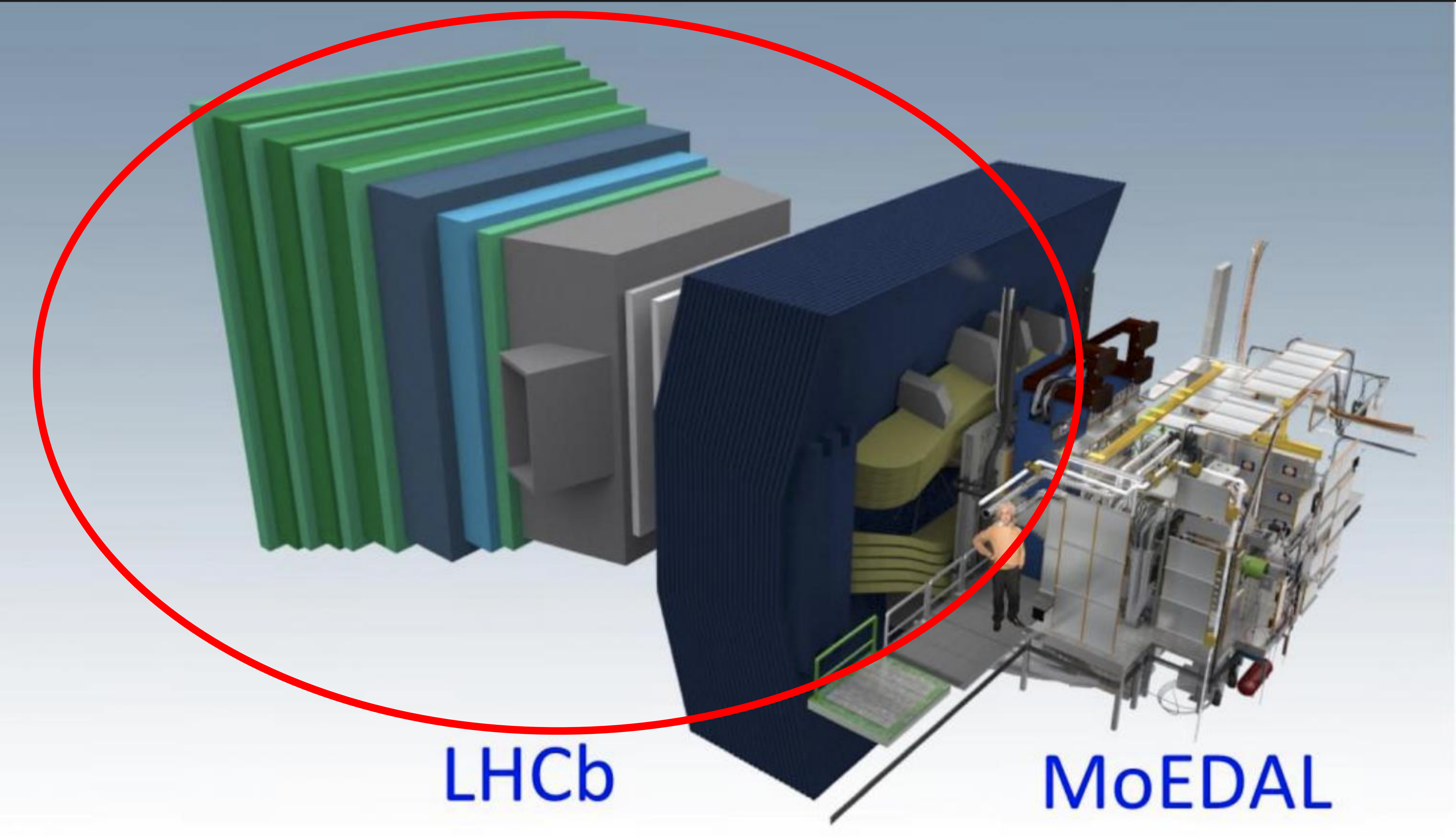




arXiv:1802.02965



The LHCb Experiment



Recent Measurement of $B_{s(d)}$-> μμ

arXiv:1703.05747

- Recent LHCb analysis based on Run 1 and Run 2 data (3+1.4 fb^{-1})
- First observation from a single experiment with a significance of 7.8 σ

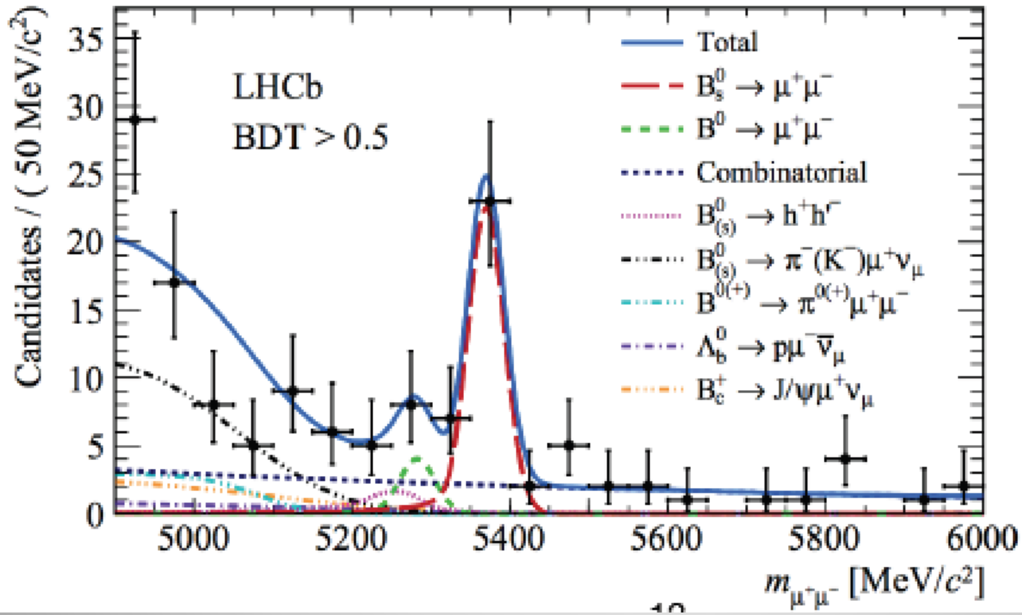
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad (\;\; 20\%)$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

$$\mathcal{B}_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

Bobeth et al.
PRL 112 (2014) 101801

- Consistent with SM expectation at current level of precision



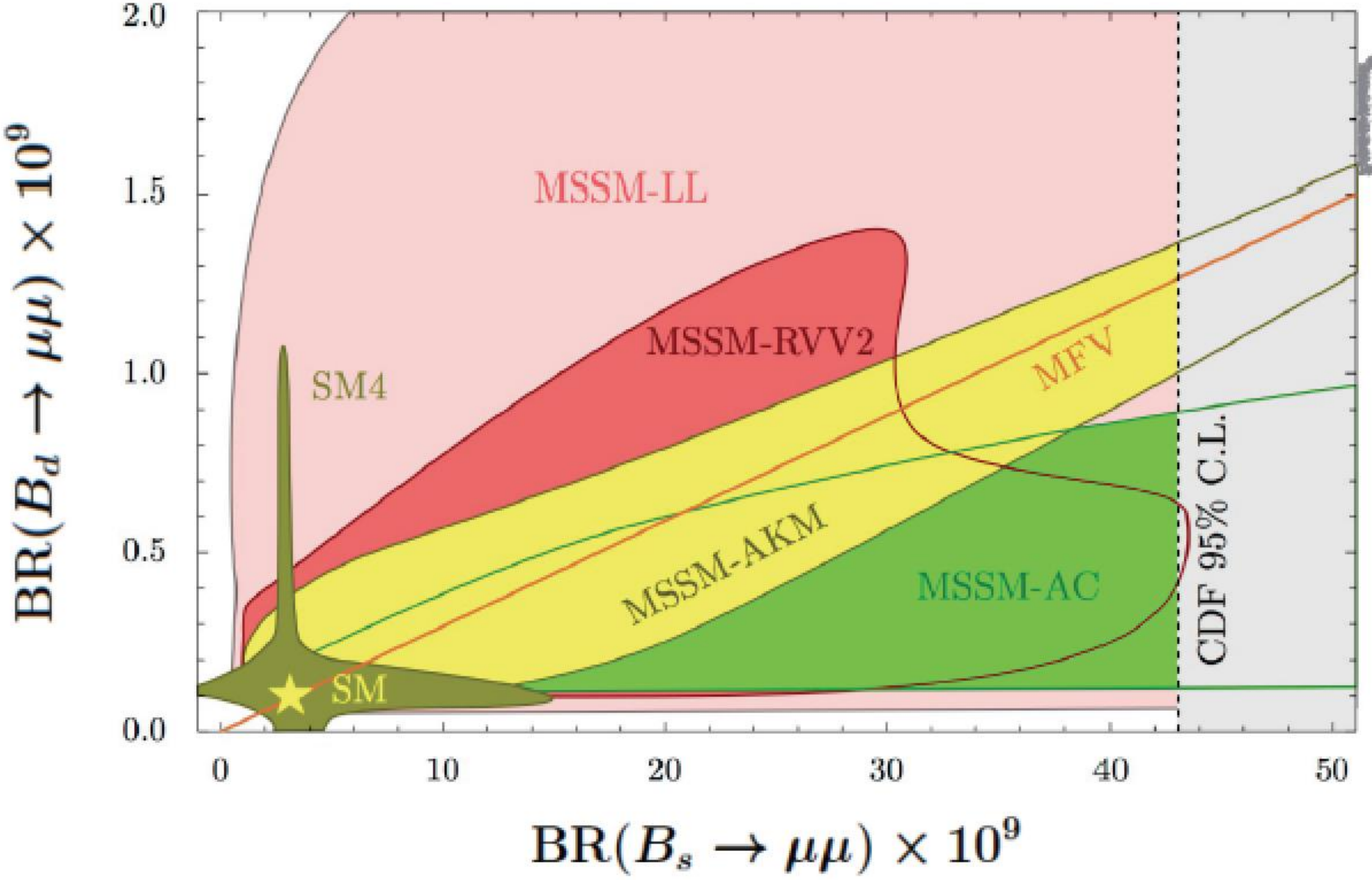
PRL 118 (2017) 191801

Implication for New Physics searches!

Measurement of B_s-> μμ

- Sizeable effects expected in many MSSM models

Straub, arXiv:1107.0266

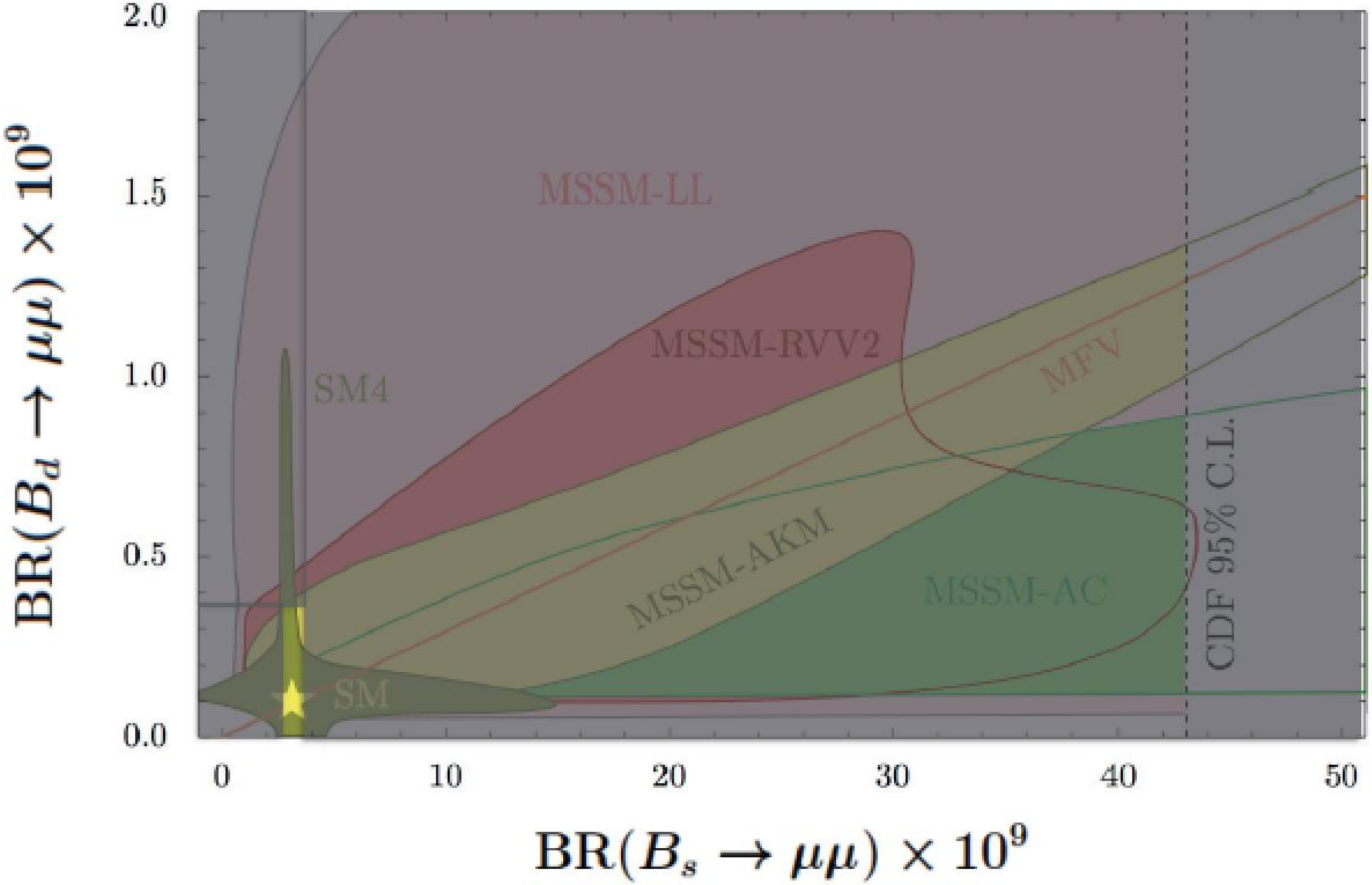


Pre-LHC

Measurement of B_s-> μμ

- Sizeable effects expected in many MSSM models

Straub, arXiv:1107.0266



Now

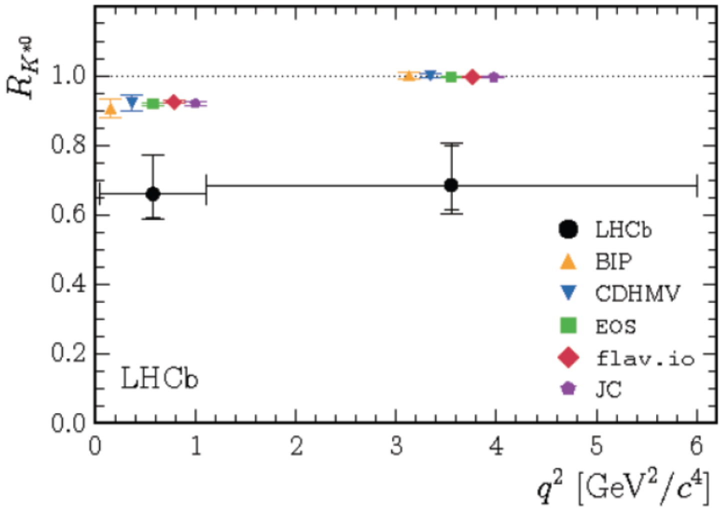
LHCb: Test of Lepton Universality

A puzzling results from the LHCb experiment…

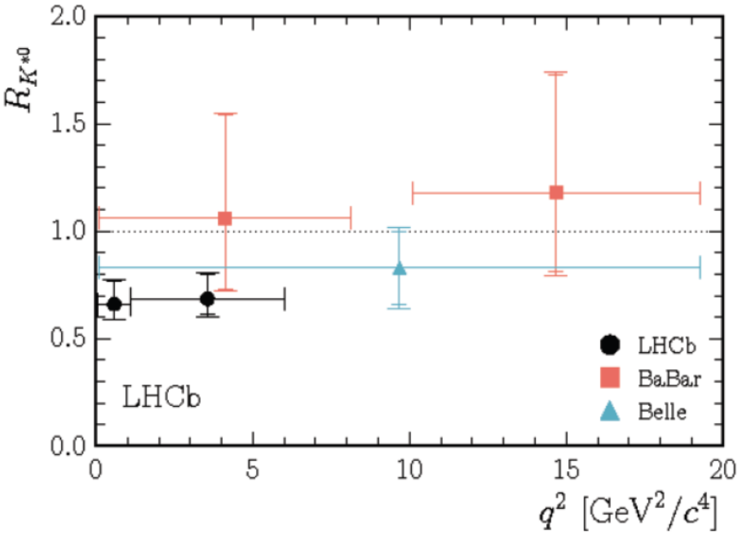
Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to He^+e^-$ $H = K, K^*, \phi, \ldots$

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

Comparison with SM predictions



Comparison with BaBar & Belle

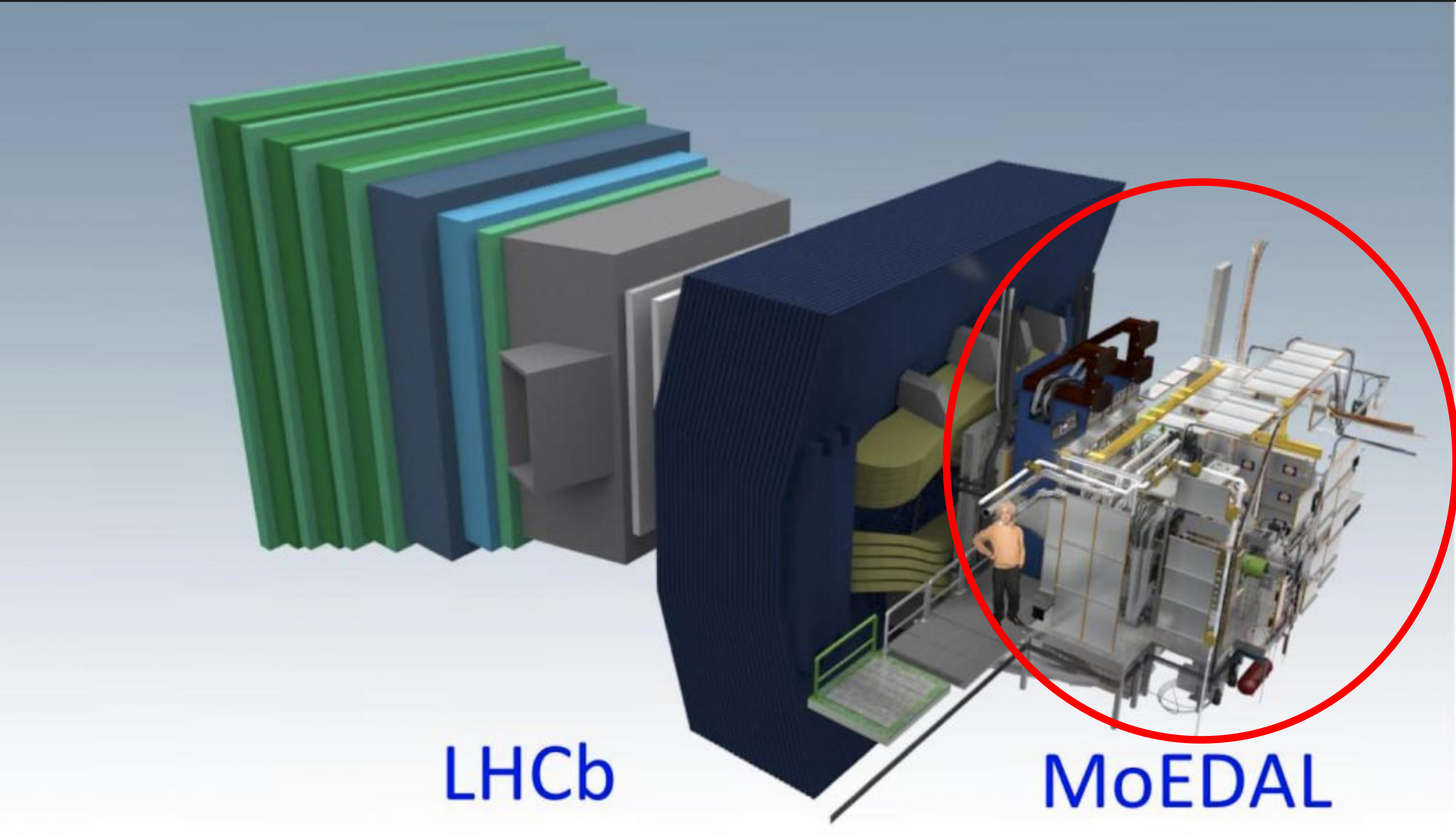


$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\,\text{GeV}^2 \end{cases}$$

2.1 - 2.3 σ
2.4 - 2.5 σ

?

The MoEDAL Experiment



Magnetic Monopoles

Magnetic Monopoles to explain the quantization of electric charge (Dirac ‘31)

$$g = \frac{q_m}{e} = \frac{n}{2\alpha_\mathrm{e}} = n \cdot g_\mathrm{D} \approx n \cdot 68.5$$

g_D is the Dirac unit magnetic charge

$$\nabla . \mathrm{E} = 4\pi \rho_e$$

$$\nabla . \mathrm{B} = 4\pi \rho_m$$

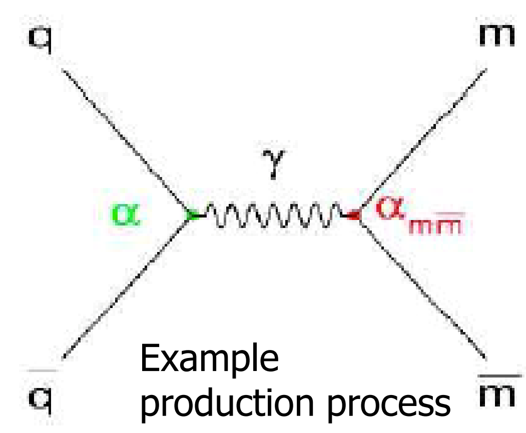
$$-\nabla \times \mathrm{E} = \frac{1}{c}\frac{\partial \mathrm{B}}{\partial t} + \frac{4\pi}{c}\mathrm{j_m}$$

$$\nabla \times \mathrm{B} = \frac{1}{c}\frac{\partial \mathrm{E}}{\partial t} + \frac{4\pi}{c}\mathrm{j_e}$$

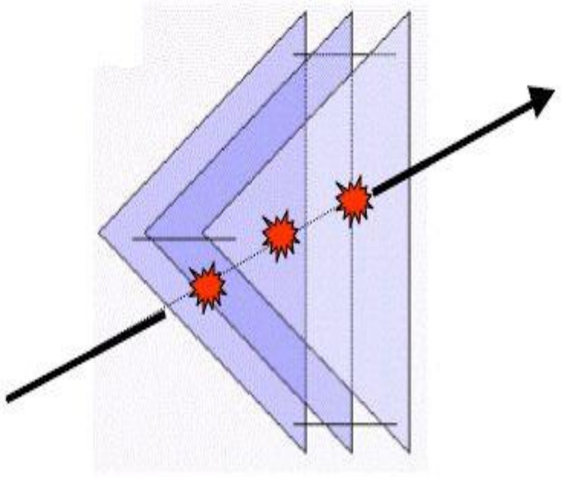
$$\mathrm{F} = q_e\left(\mathrm{E} + \frac{\mathrm{v}}{c} \times \mathrm{B}\right) + q_m\left(\mathrm{B} - \frac{\mathrm{v}}{c} \times \mathrm{E}\right)$$

- Symmetrizes Maxwell equations!
- Dirac: Charge quantization consequence of angular momentum quantization in the presence of monopole
- ‘t Hooft, Polyakov: GUT monopoles
- Cho-Maison: Electroweak monopoles in the TeV range. Recent discussion: Elis et al.:arXiv:1602.01745

Collider signature: pair production of very highly ionizing particles!



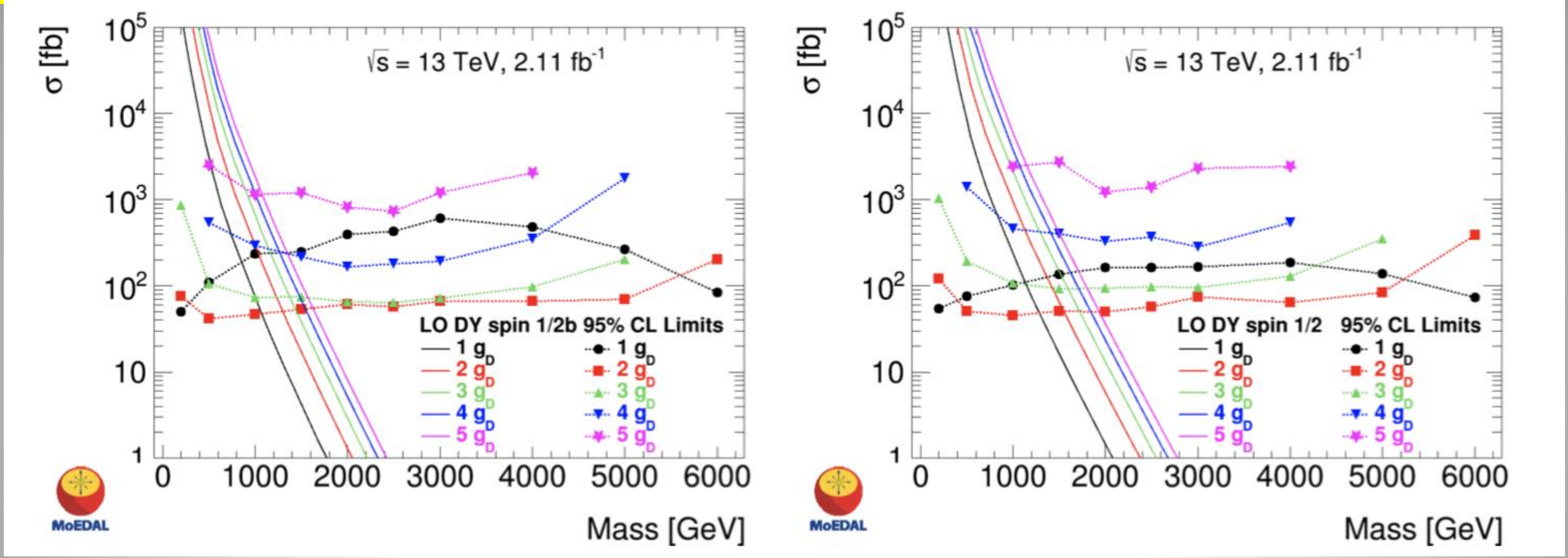
Example production process

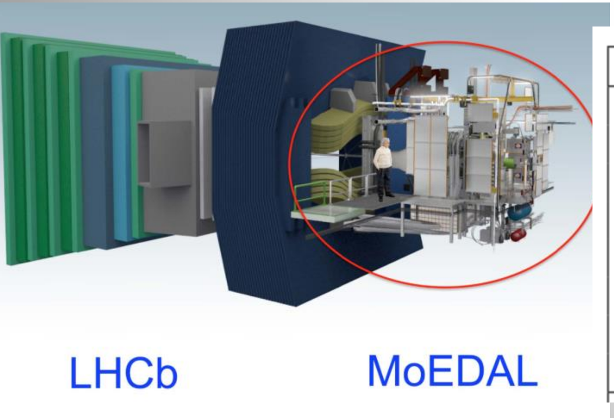


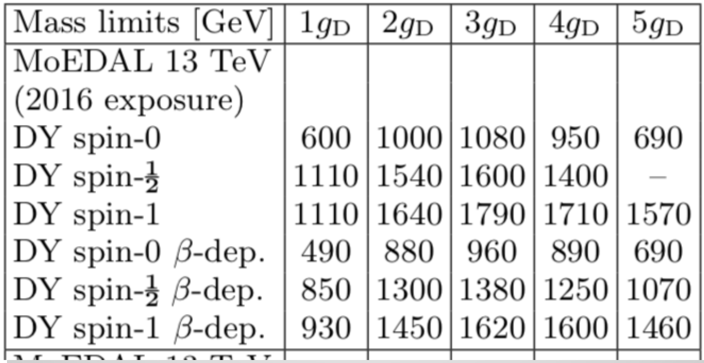
Monopoles will ‘burn’ through the plastic sheets of the experiment or get trapped in the dense material of the trapping detector

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

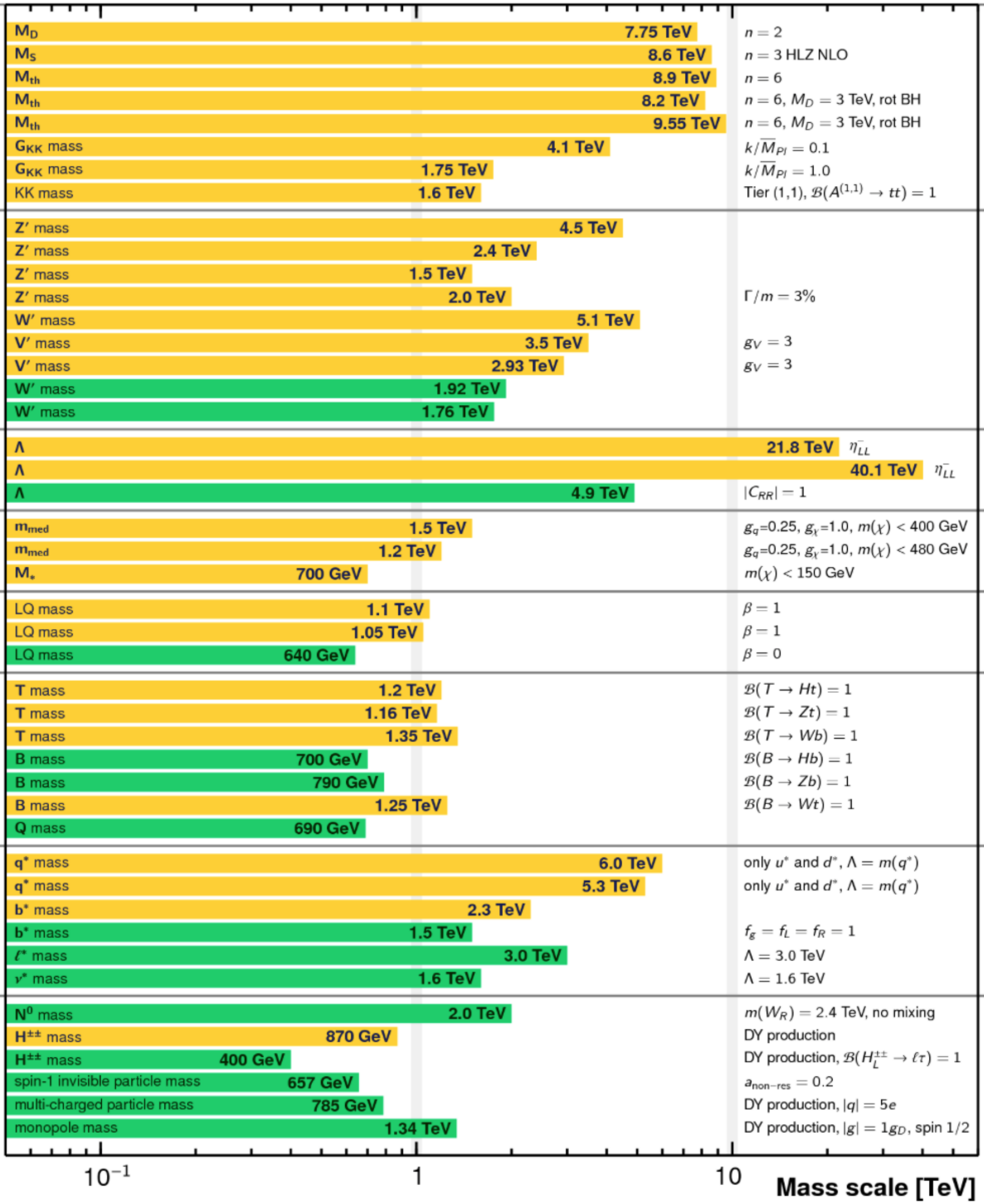
- First monopole search result @LHC at 13 TeV No signal yet..

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

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



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0\ e, \mu$	1 – 4 j	Yes	36.1	🟨 M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	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 $\sum p_T$	$\geq 1\ e, \mu$	≥ 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 $G_{KK} \to \gamma\gamma$	$2\ \gamma$	–	–	36.7	🟨 G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\ e, \mu$	1 J	Yes	36.1	🟨 G_{KK} mass 1.75 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1\ e, \mu$	≥ 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 $Z' \to \ell\ell$	$2\ e, \mu$	–	–	36.1	🟨 Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	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 $Z' \to tt$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	3.2	🟨 Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	36.1	🟨 W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	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 $W'_R \to tb$	$1\ e, \mu$	2 b, 0-1 j	Yes	20.3	🟩 W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	$0\ e, \mu$	≥ 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 $\ell\ell qq$	$2\ e, \mu$	–	–	36.1	🟨 Λ 40.1 TeV	η^-_{LL}	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/$\geq$3 e, μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0\ e, \mu$	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)	$0\ e, \mu, 1\ \gamma$	≤ 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)	$0\ e, \mu$	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	$2\ \mu$	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	$1\ e, \mu$	$\geq$1 b, $\geq$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 $TT \to Zt + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	36.1	🟨 T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	$1\ e, \mu$	≥ 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/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	36.1	🟨 B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	$1\ e, \mu$	≥ 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 $q^* \to q\gamma$	$1\ \gamma$	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^*	$3\ e, \mu$	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e, \mu, \tau$	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	$2\ e, \mu$	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 $H^{\pm\pm} \to \ell\tau$	$3\ e, \mu, \tau$	–	–	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)	$1\ e, \mu$	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

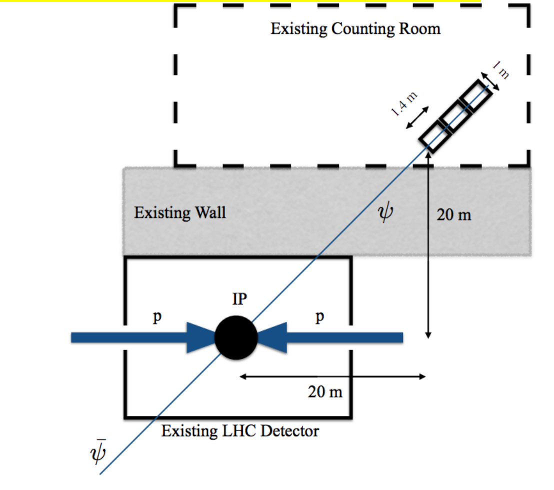
🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

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

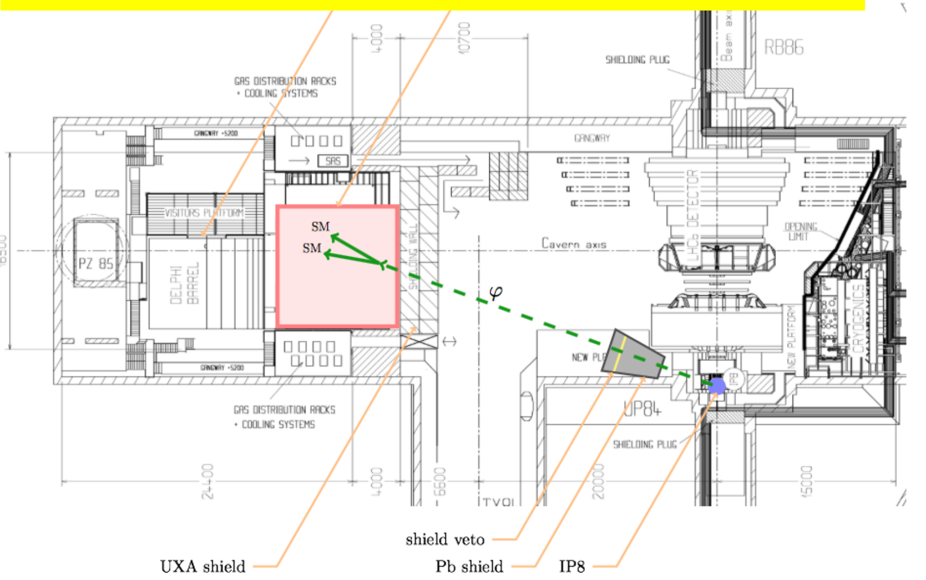
†Small-radius (large-radius) jets are denoted by the letter j (J).

Possible New Experiments @LHC

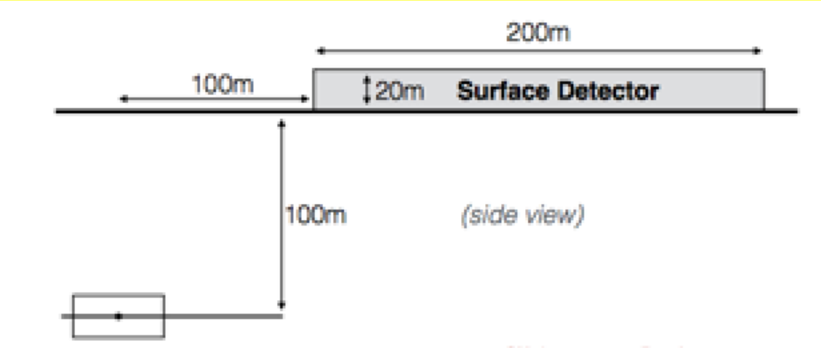
MilliQan: searches for millicharged particles



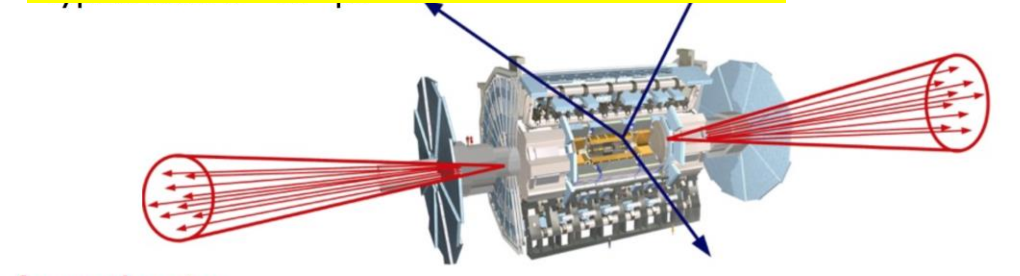
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles

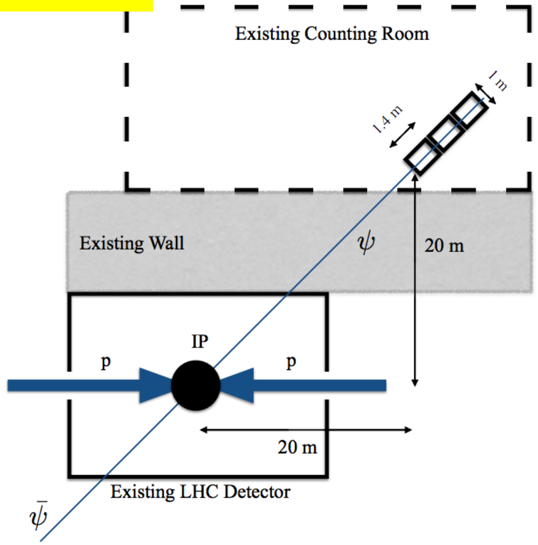


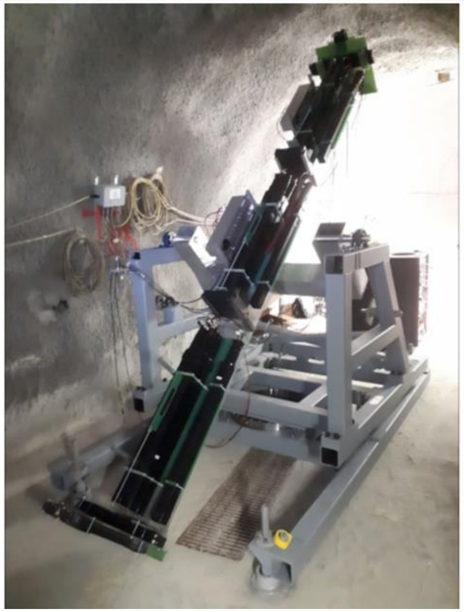
FASER: searches for long lived dark photons-like particles



Possible New Experiments @LHC

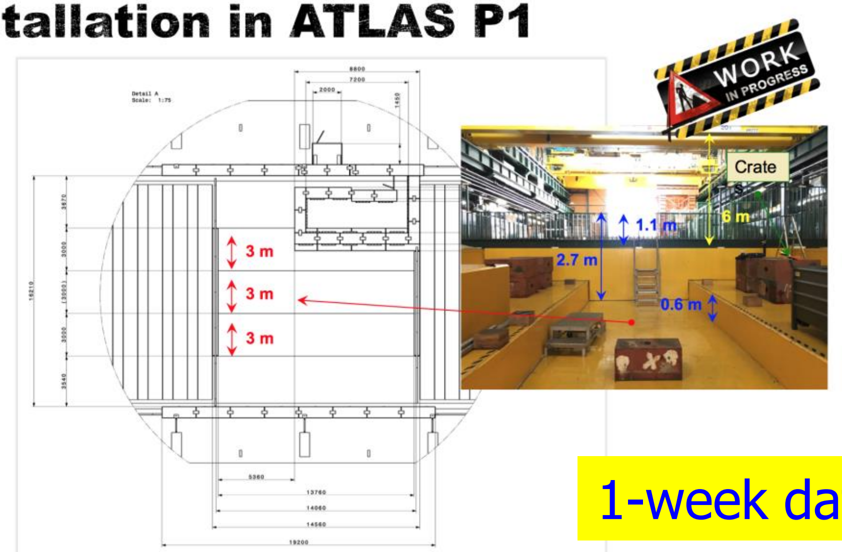
MilliQan





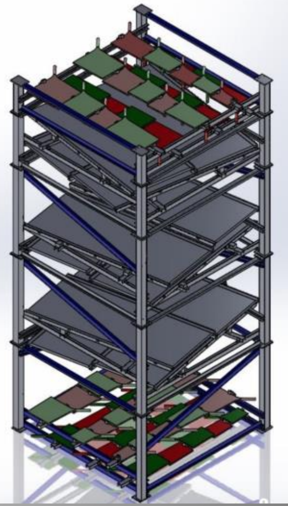
- September 2017: Installation of a 1% demonstrator.
- Collected ~ 27 fb^{-1} mostly for technical tests

Installation in ATLAS P1



MATHUSLA **Test Stand**

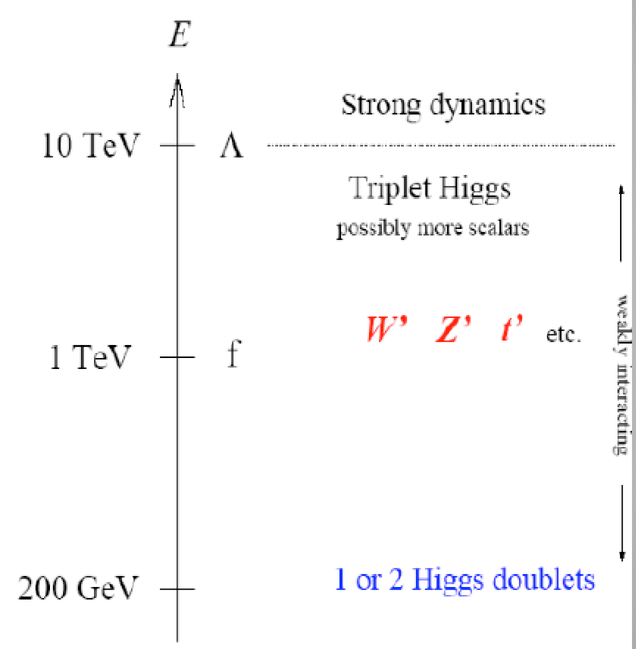
- Two scintillator layers
- Three layers of 4 RPCs each, two in x-coordinate and two in y-coordinate
- 5 m tall, 2.5 m by 2.8 m surface area
- ~1.5 ns resolution for scintillators, ~1 ns resolution for RPCs
- TDC and ADC information for each scintillator
- RPCs have readout system from ARGO which includes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



1-week data taken in November

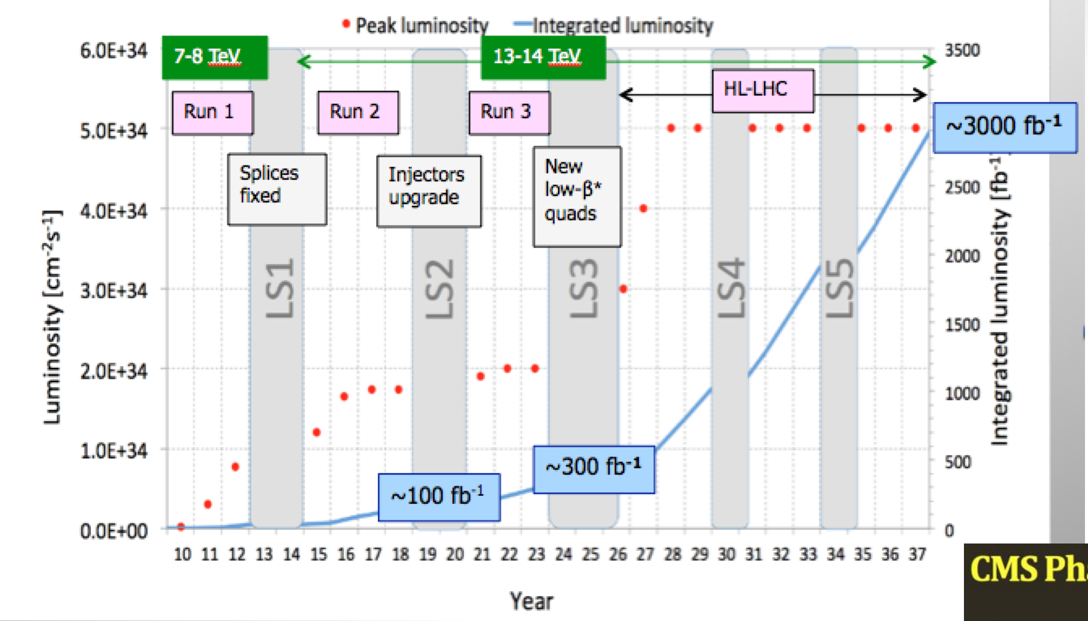
Many Other New Physics Ideas…

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - leptoquarks
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….



Have to keep our eyes open for all possibilities: Food for many PhD theses!! And Discoveries!!!

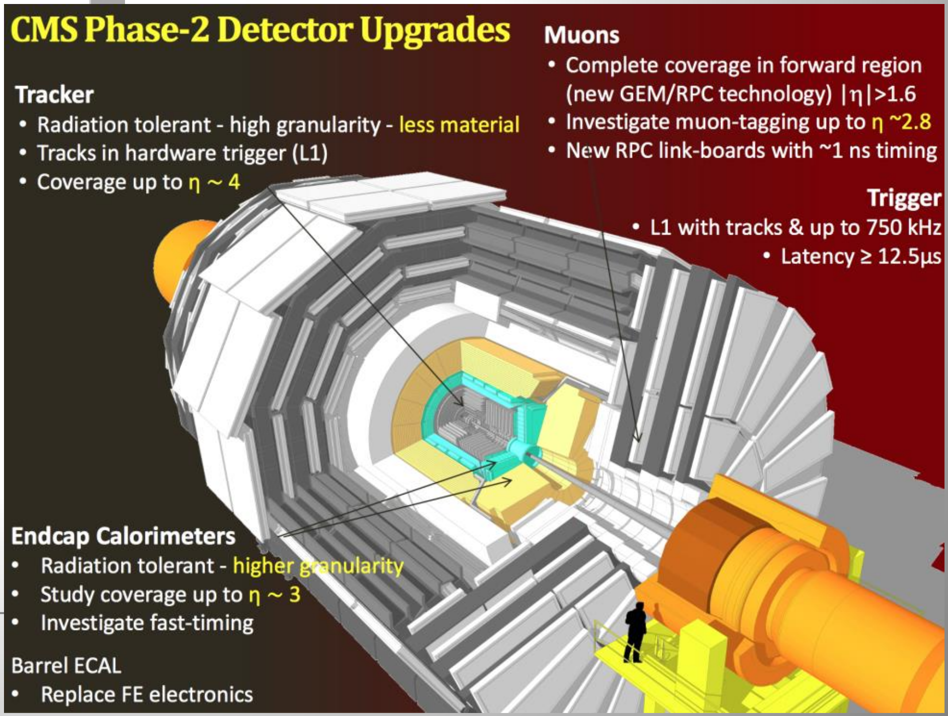
LHC Outlook and Plans



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)?



CMS Phase-2 Detector Upgrades

Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Complete coverage in forward region (new GEM/RPC technology) |η|>1.6
- Investigate muon-tagging up to η ~2.8
- New RPC link-boards with ~1 ns timing

Trigger
- L1 with tracks & up to 750 kHz
- Latency ≥ 12.5μs

Endcap Calorimeters
- Radiation tolerant - higher granularity
- Study coverage up to η ~ 3
- Investigate fast-timing

Barrel ECAL
- Replace FE electronics

Summary

- Standard Model measurements @ 13 TeV show no surprise. E.g. W/Z and top cross sections according to expectations
- New Higgs measurements at 13 TeV. So far the Higgs is very consistent with Standard Model expectations.
- No sign of new physics in the first 13 TeV data… This starts to cut into the 'preferred regions' for a large number of models, like SUSY.
- Dark Matter and Long Lived Particle searches are being explored in a more systematic way
- New physics in the flavour sector? New paradigms in TH?
- 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: