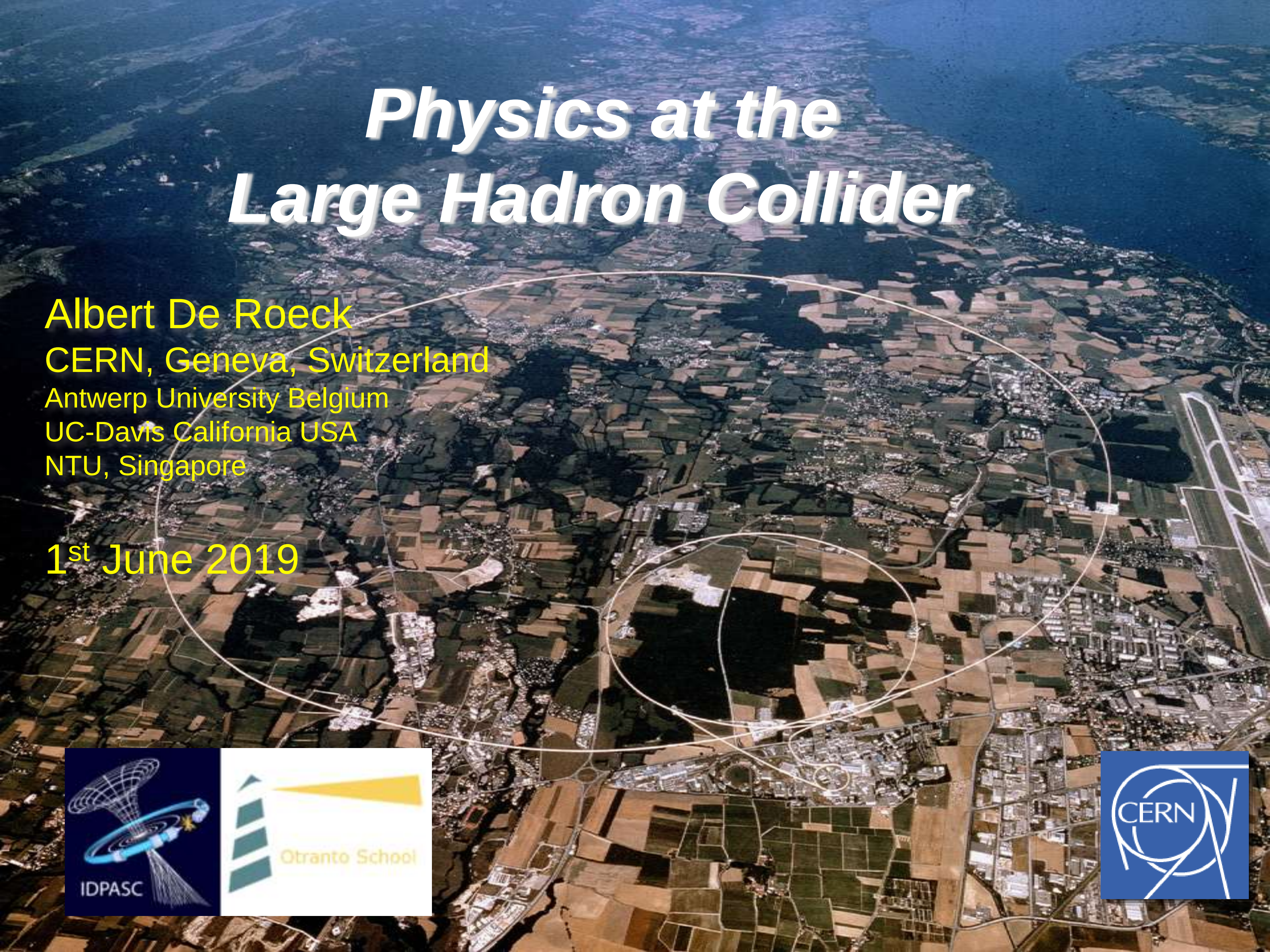


Physics at the Large Hadron Collider

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

1st June 2019

IDPASC

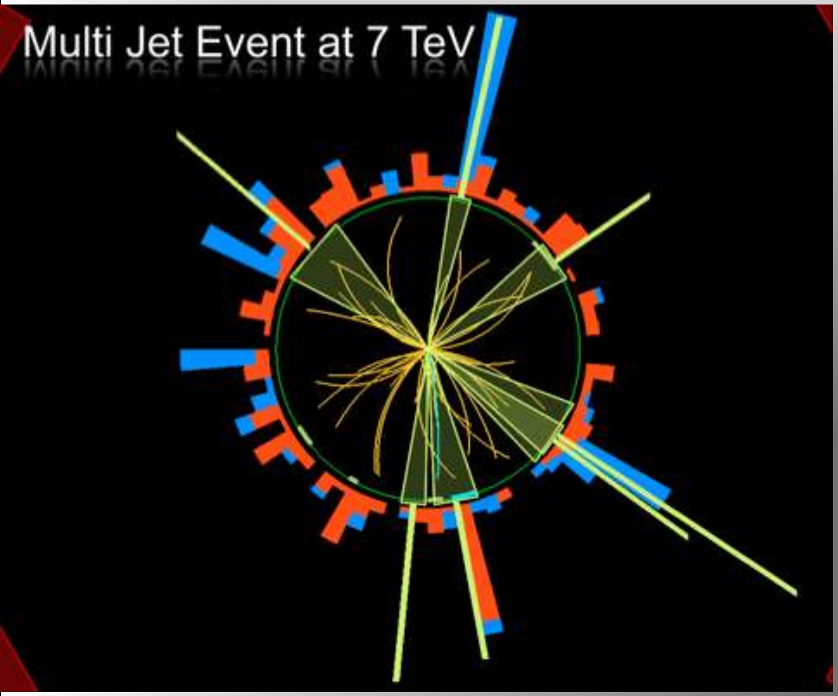
Otranto School

CERN

Lecture Plan

Overview of the 2 lectures in the next days

- Lecture 1: Introduction to Experimental Techniques at the LHC & Measurements and test of the Standard Model
- Lecture 2: The Higgs boson and Searches beyond the Standard Model, and a short outlook to the future at the LHC

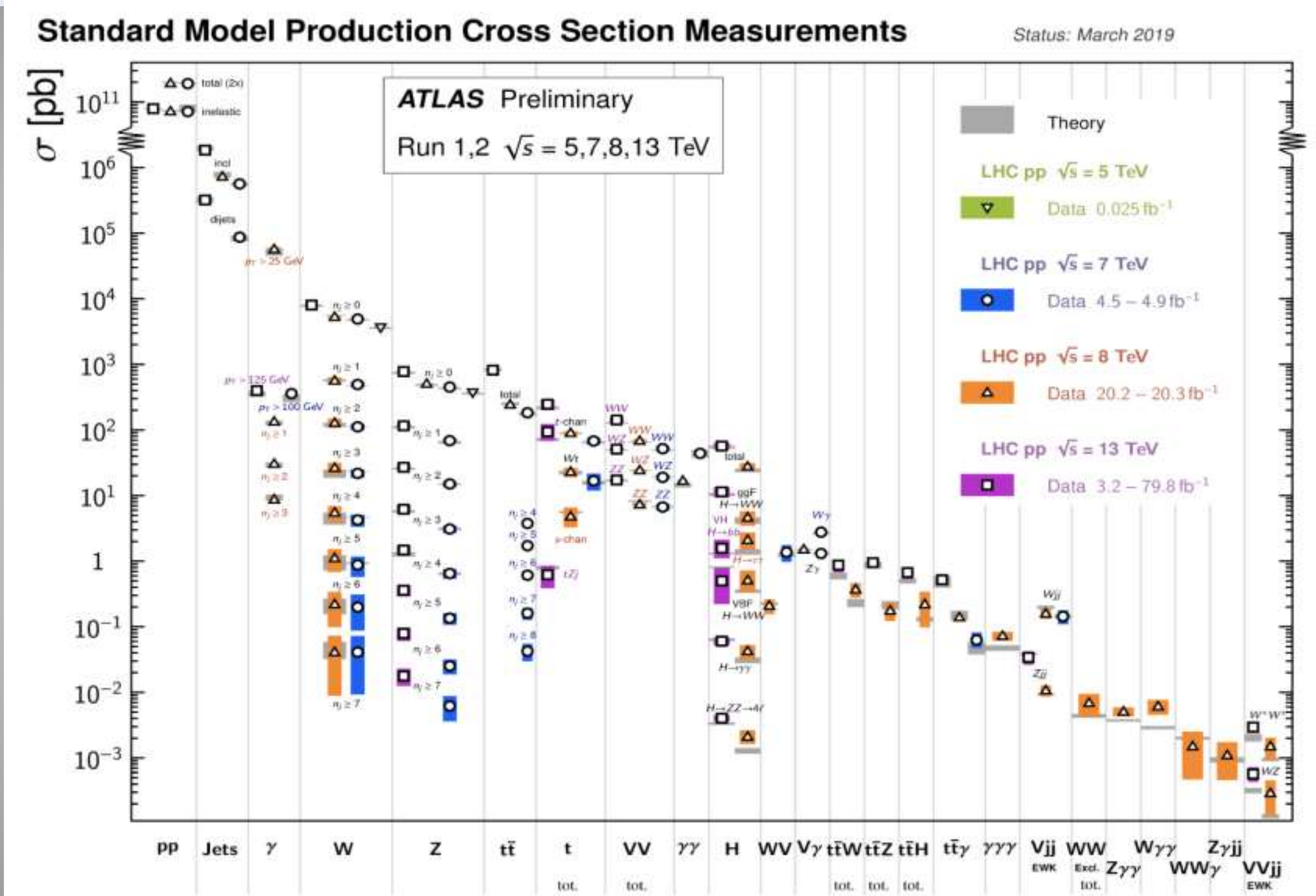


Outline Lecture I

- The Higgs: new physics or Standard Model
- Searching for Supersymmetry
- Searching for Dark Matter
- New Searches
- Outlook
- Summary

Disclaimer:
ATLAS & CMS have very similar results
Typically one chosen for illustration

Summary: Cross Sections 7/8/13 TeV



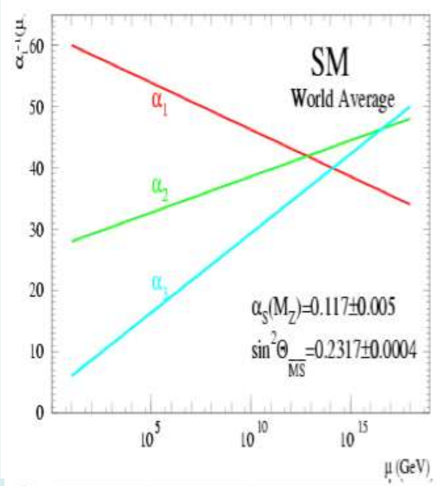
All measurements in good agreement with the Standard Model predictions!!

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

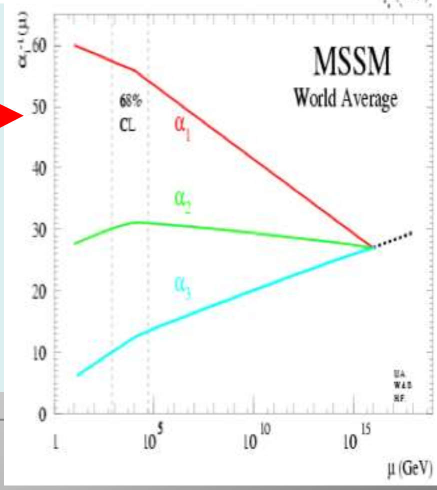
Discover physics beyond the Standard Model

Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy? 19 parameters!
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy



Most popular extensions since 2000

- Supersymmetry
- Extra space dimensions

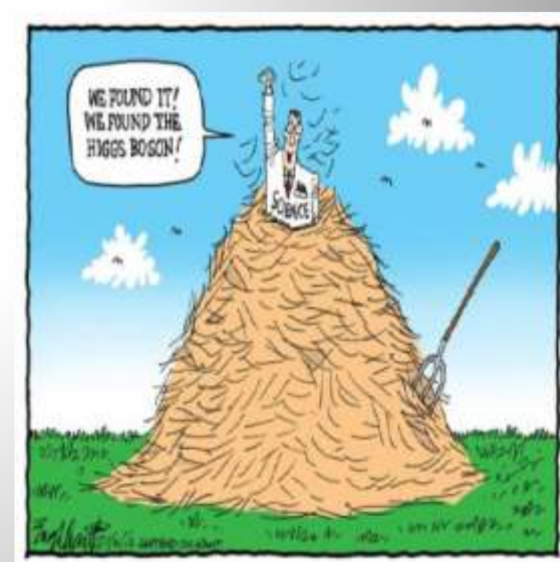


Many other ideas: More symmetry and gauge bosons, composite Higgs models, L-R symmetry, quark & lepton substructure, Little Higgs models, Technicolor, Hidden Valleys, 4th generation…

Higgsless models "disfavoured" these days

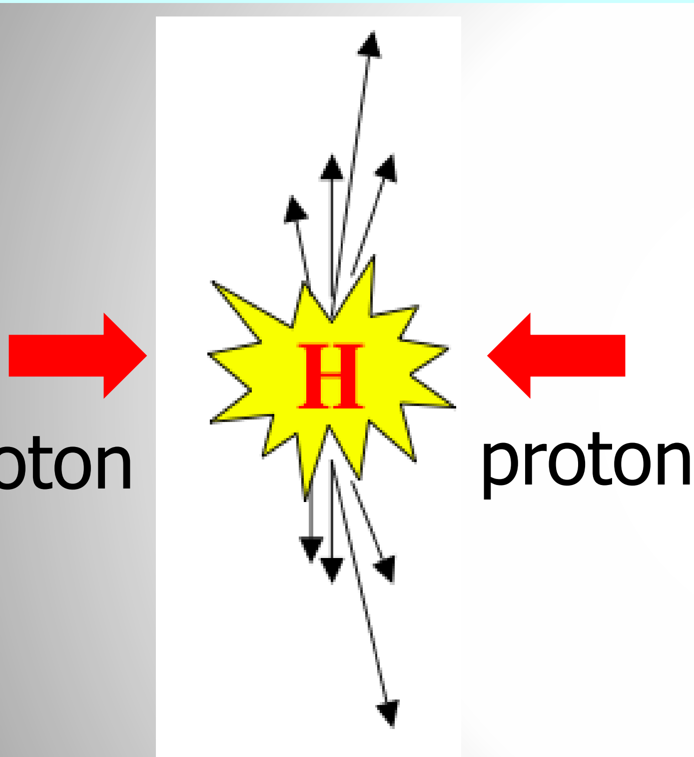
Higgs

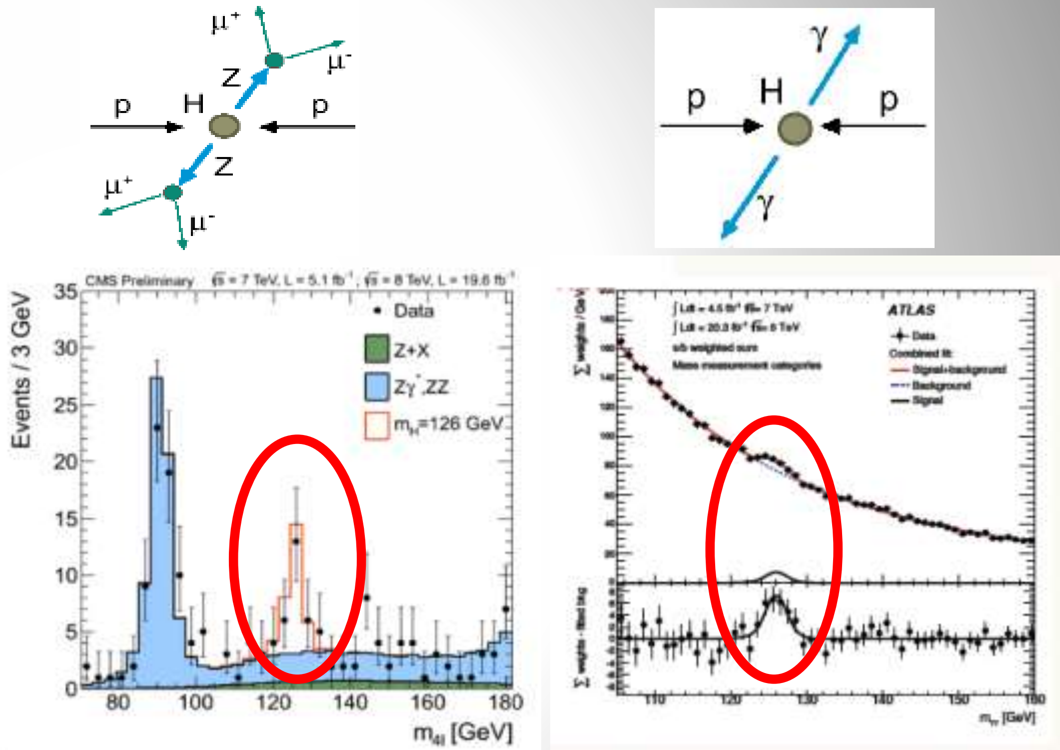
The party 7 years ago



2012: A Milestone in Particle Physics

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





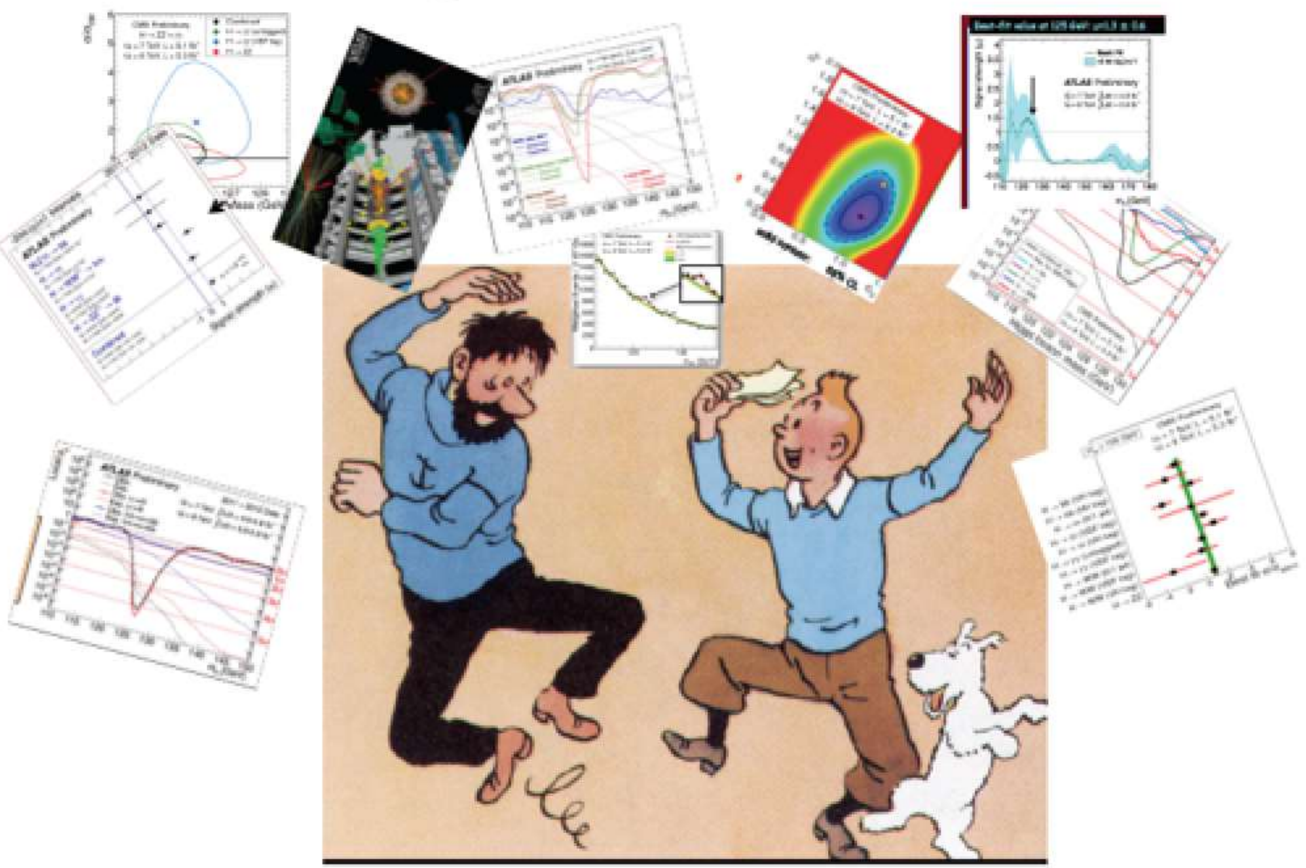
The mass of the Higgs particle is $m_H = 125.09 \pm 0.24 \;\text{GeV}$ following the Run-1 ATLAS+CMS combination arXiv:1503.07589

The Theorist and Experimentalists

The party in 2012!

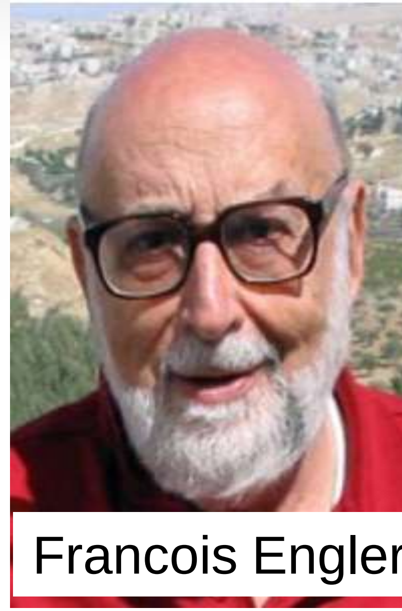
A. Pomarol ICHEP2012

Not everybody at the party
eg higgsless models…



But careful about resurrections, Higgs imposters…

Tuesday 8 October 2013



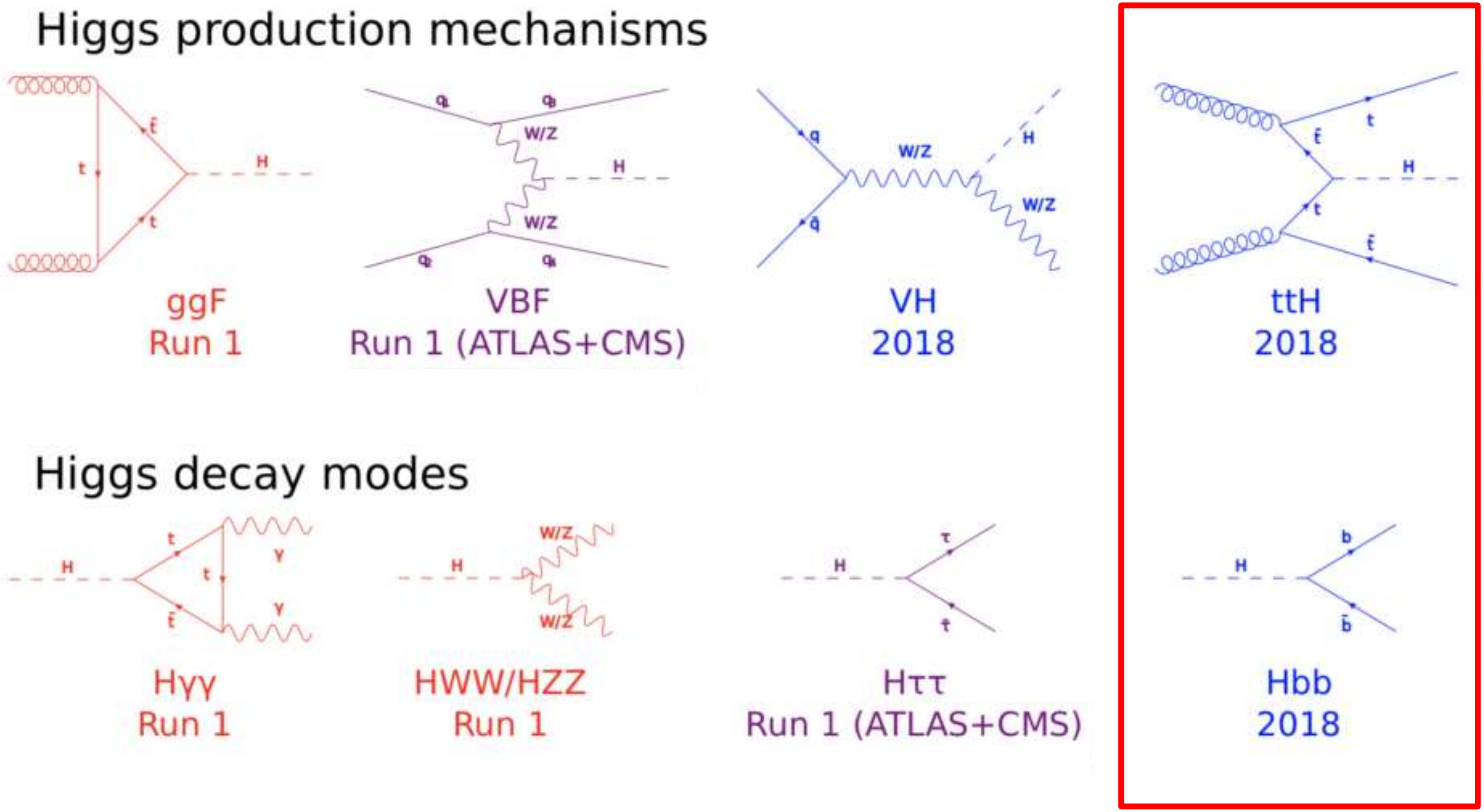
Francois Englert

Peter Higgs

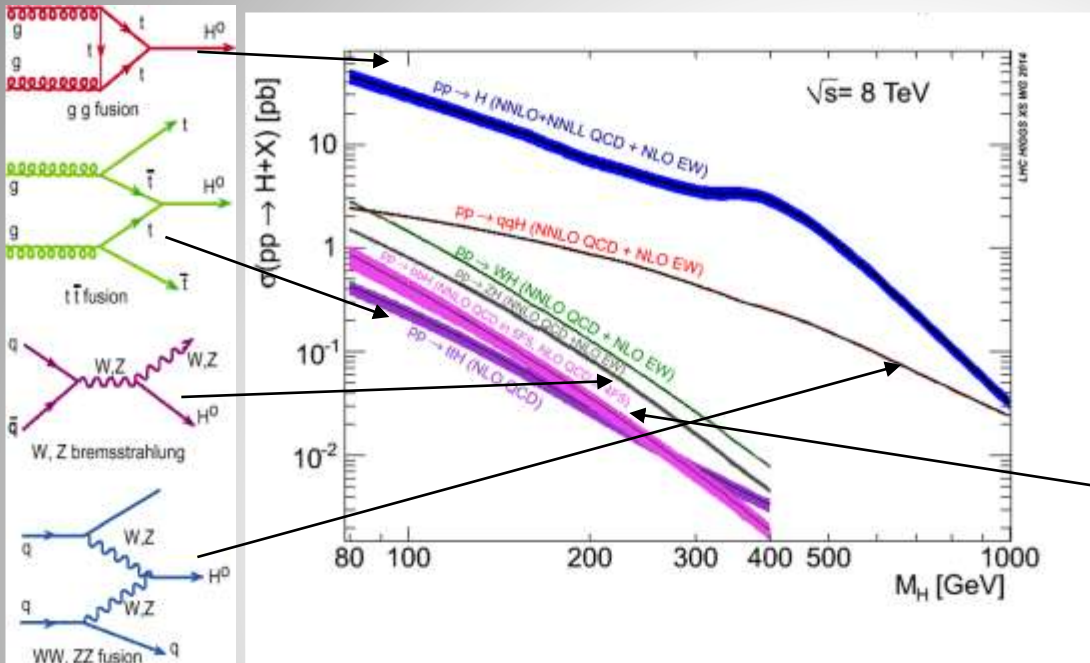
Congratulations!!!!

Higgs Production and Decay

Not observed in run-1



Higgs Production & Decay



Processes

- •Gluon fusion
- •Vector Boson Fusion
- •W/Z associated prod.
- •Top associated prod
- •B-quark associated prod?

Numbers taken from the LHC Higgs Cross Section WG

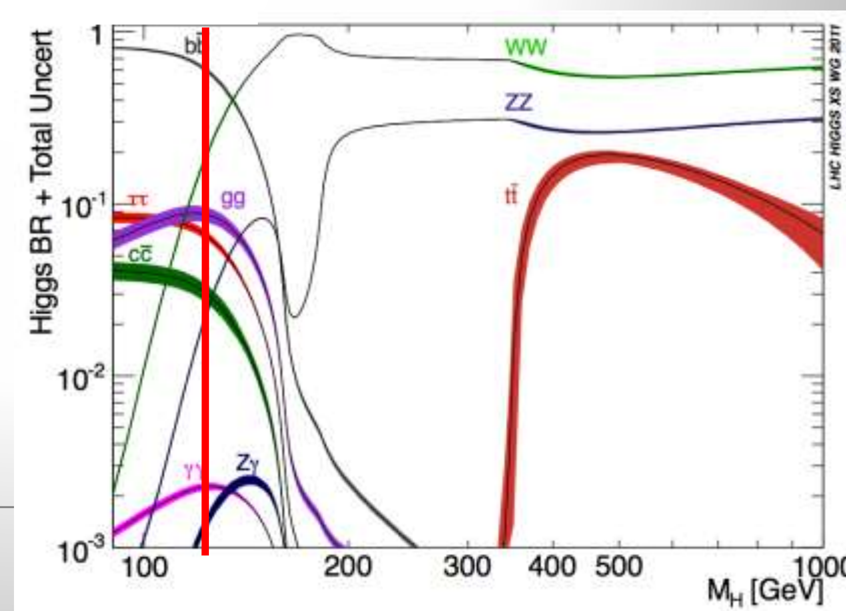
See CERN yellow reports:

YR1: Inclusive cross sections

YR2: Differential cross sections

YR3: Properties

YR4: Deciphering the nature of the Higgs sector



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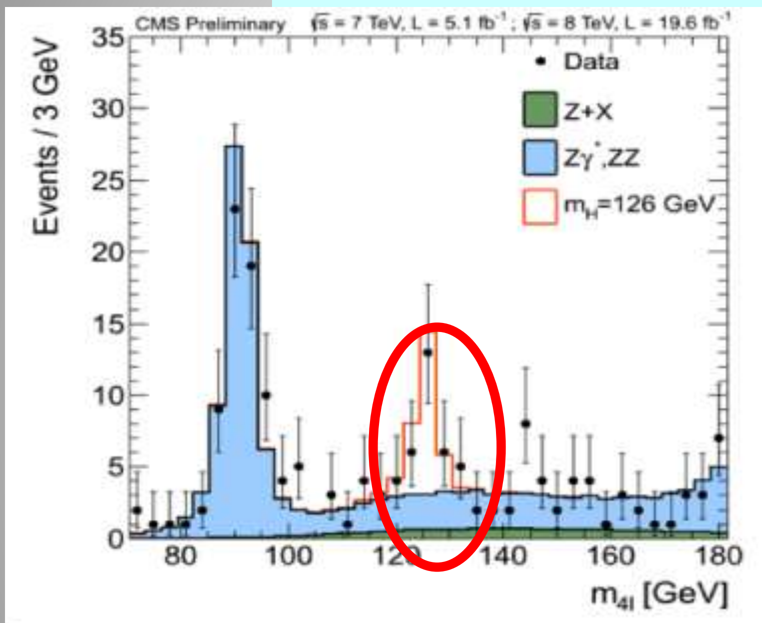
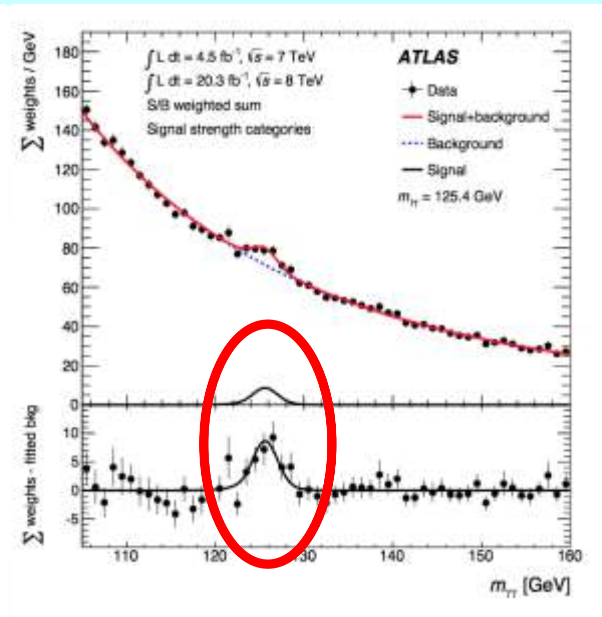




2014: Higgs Boson well established.

Most accessible channels studied

- Observation in WW, ZZ and γγ channels
- tau tau at the limit
- bb and ttH not observed in Run-1

2018

	ggF	VBF	VH	ttH
H-> gamgam	Results released	Results released	Results released	Results released
H-> ZZ	Results released	Results released	Results released	Results released
H->WW	Results released	Results released	Results released	Results released
H-> bb	Results released	Results released	Results released	Results released
H-> tau tau	Results released	Results released	Results released	Results released
H-> Zgamma	Results released	Results released		
H-> mumu	Results released	Results released	Results released	
H-> invisible	Results released	Results released	Results released	In progress

Results released (green)

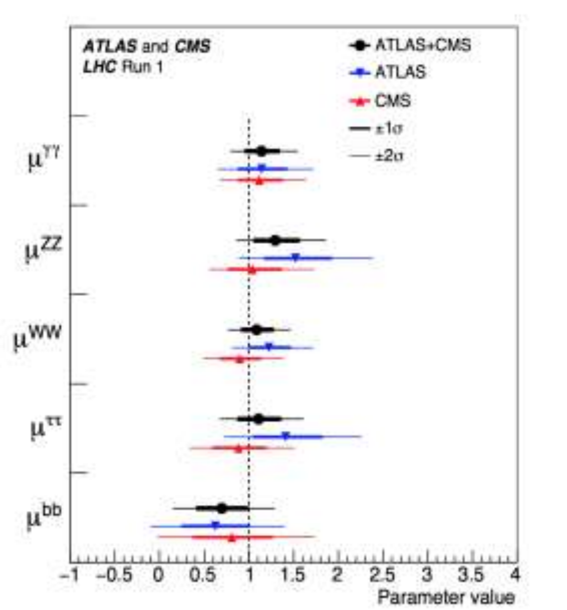
In progress (yellow)

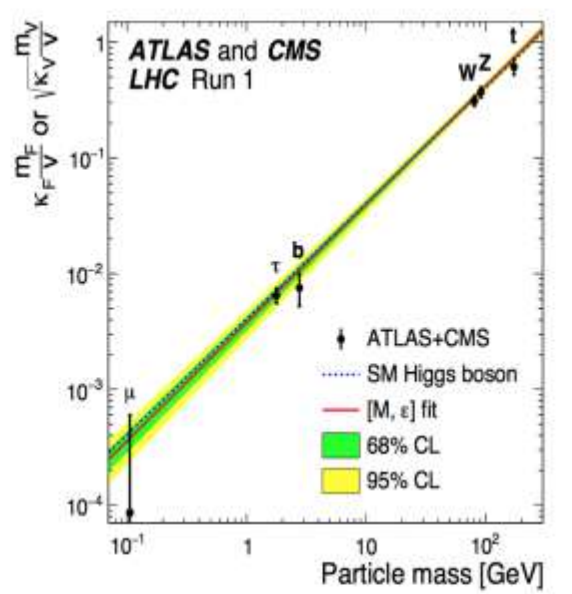
Higgs: ATLAS+CMS Combination

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!!





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

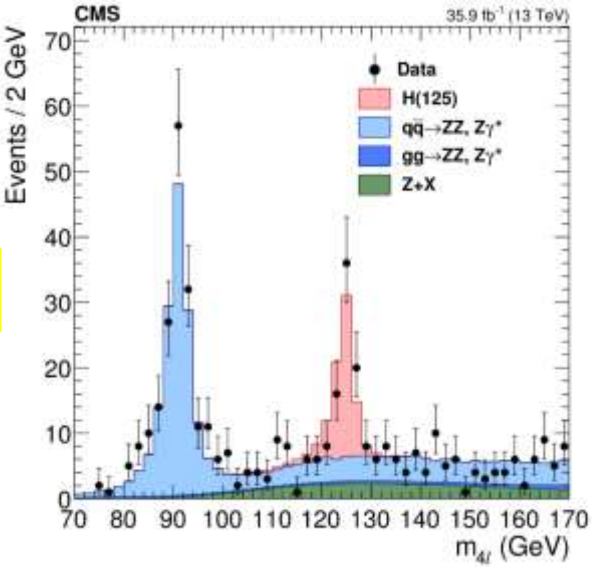
Signal strength/SM:

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

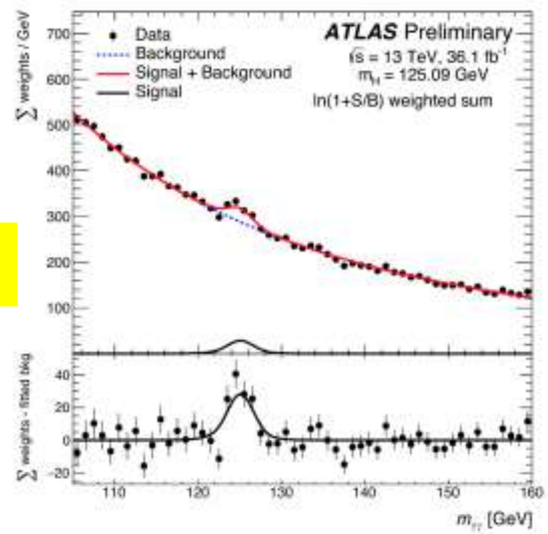
Higgs @ 13 TeV in Run 2

- Higgs particle is still there ! ☺

H→ ZZ



H→ γγ



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

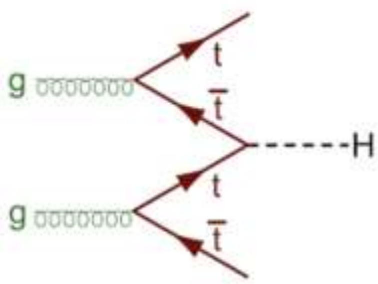
The Higgs Boson is still very much Standard Model-like!

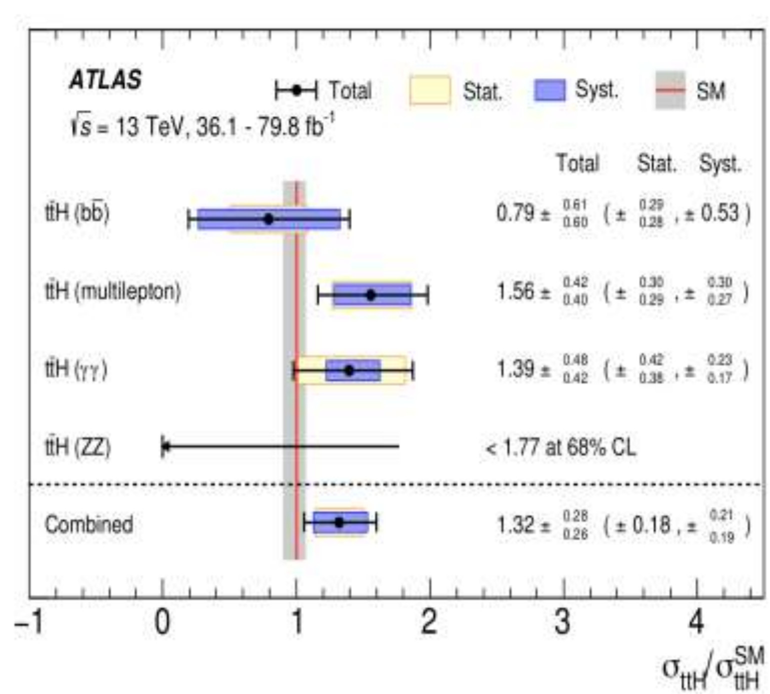
$$\mu = 1.17^{+0.10}_{-0.10}$$

Higgs ttH Production

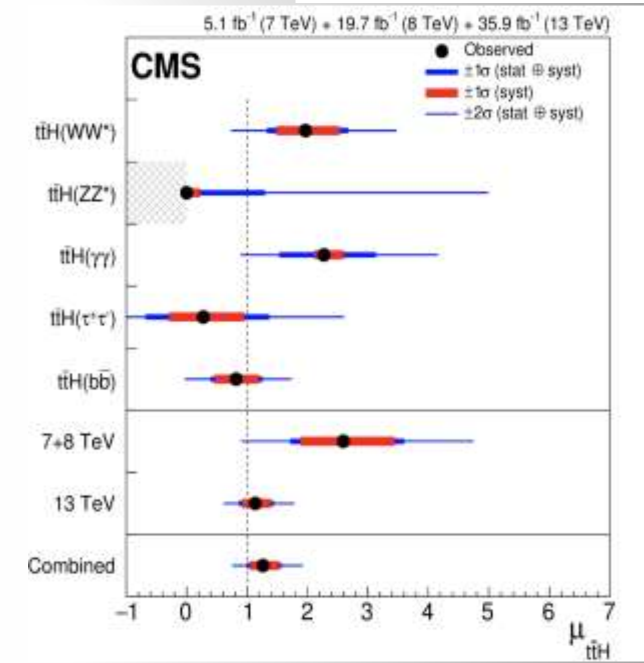
ttH production: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1

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

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

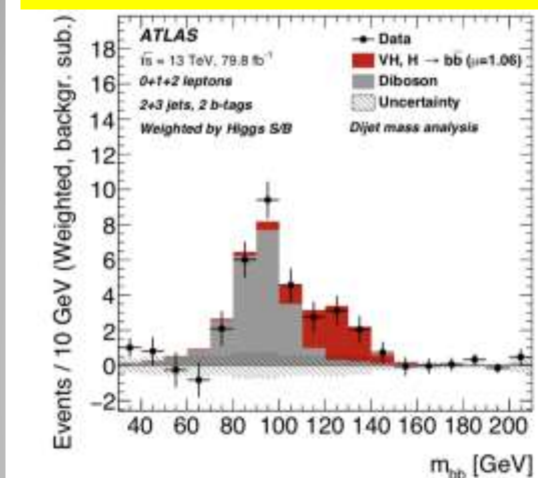
Significance = 5.9σ (exp 4.2σ)

Observation of ttH!

Results in agreement with the Standard Model

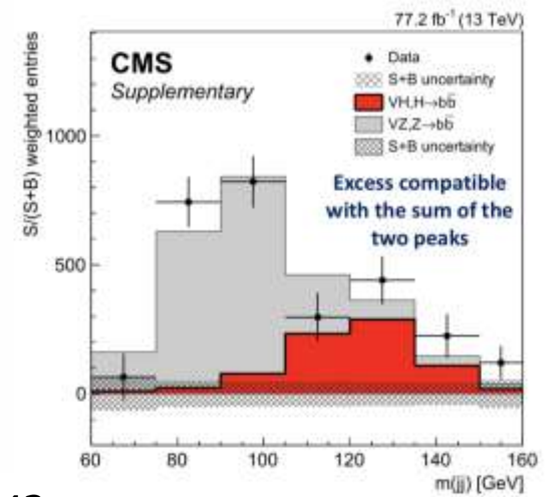
Higgs to bb Decay

H->bb decay: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1

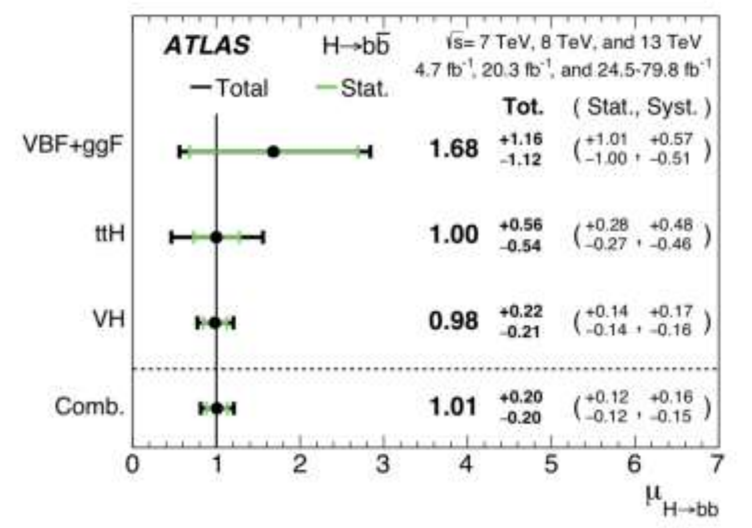


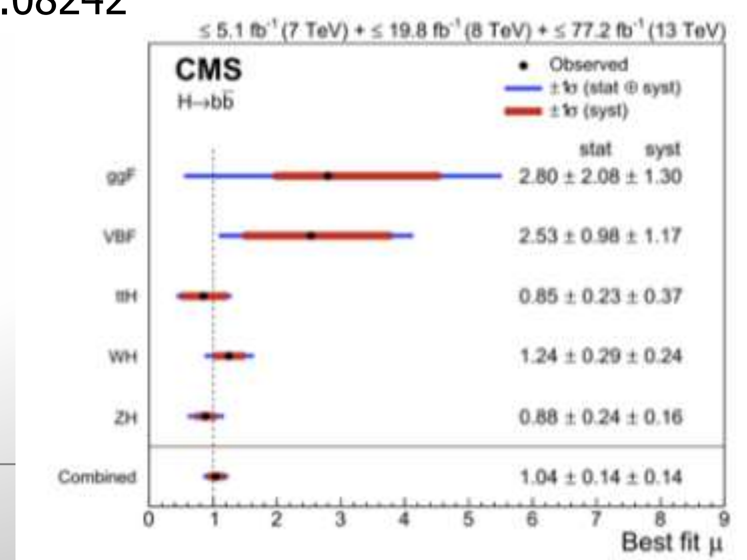
arXiv:1808.08238

H->bb observed with more than 5σ in both experiments



arXiv:1808.08242



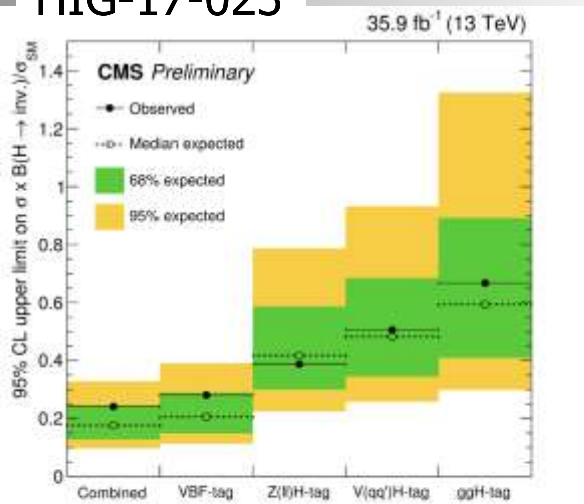


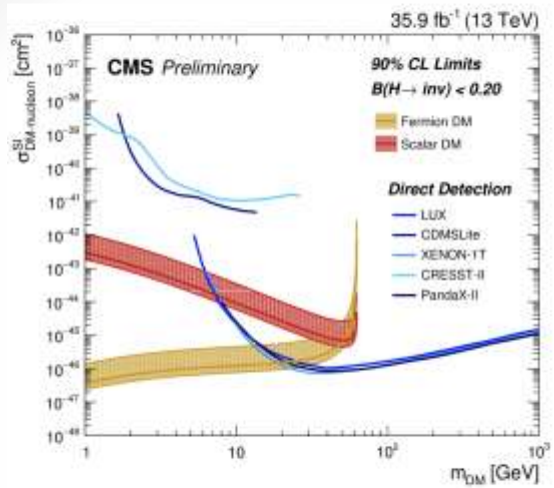
More Higgs Studies…

arXiv:1802.04329

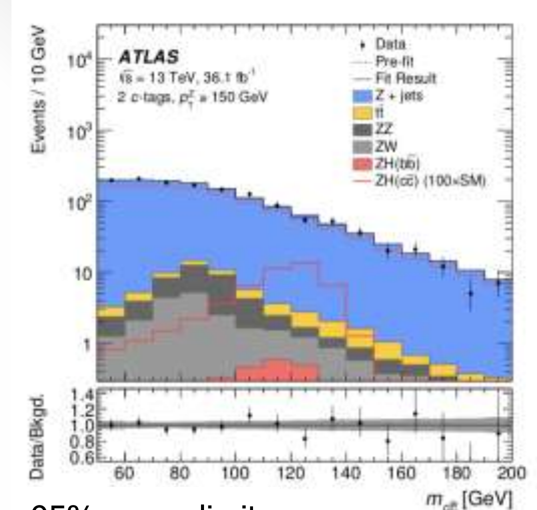
Higgs decay to invisible

HIG-17-023





Higgs decay to charm search



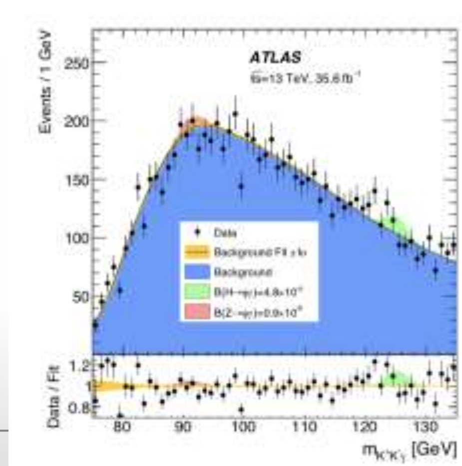
95% upper limit

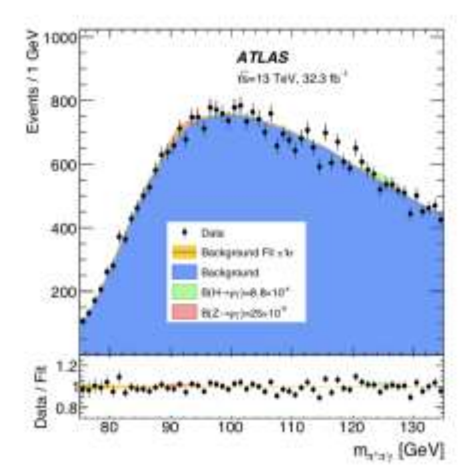
$\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ is 2.7 $(3.9^{+2.1}_{-1.1})$ pb

Higgs decay to ργ and ϕγ search

arXiv:1712.02758

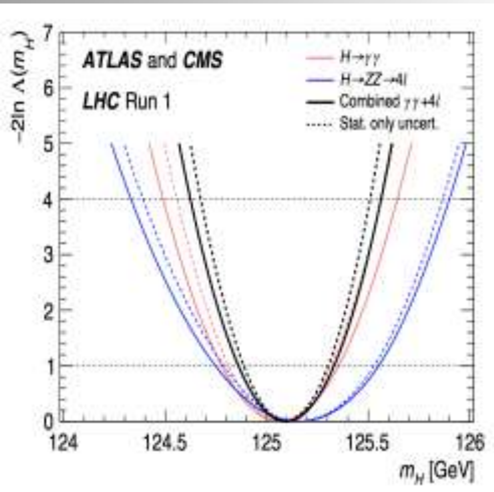
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)\,[\,10^{-4}\,]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)\,[\,10^{-6}\,]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)\,[\,10^{-4}\,]$	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)\,[\,10^{-6}\,]$	33^{+13}_{-9}	25

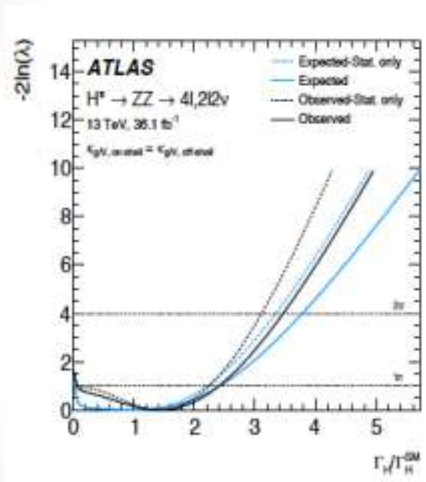


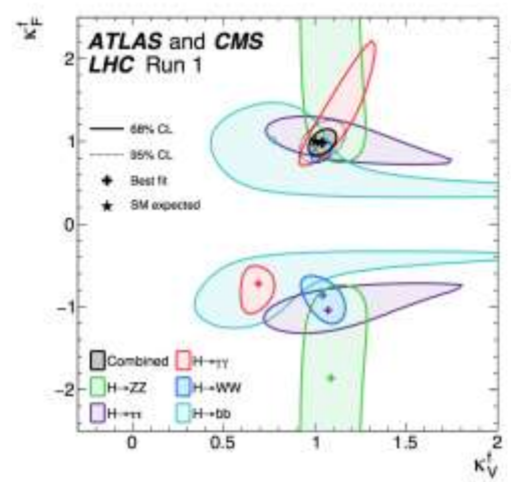


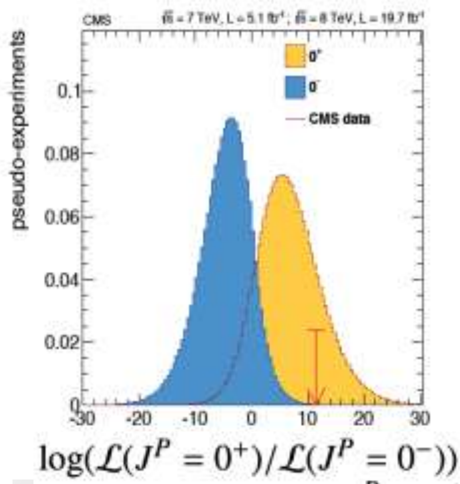
Brief Higgs Summary (so far)

We know already a lot on this brand New Higgs particle!!









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

Width
< 14 MeV
(95%CL)

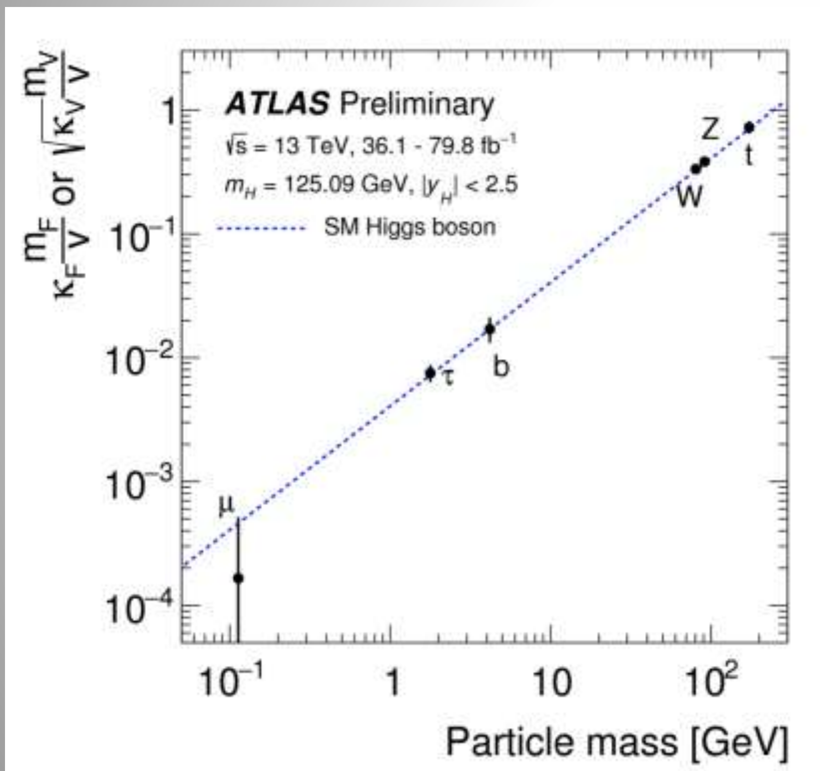
Couplings are
within ~10-20%
of the SM values

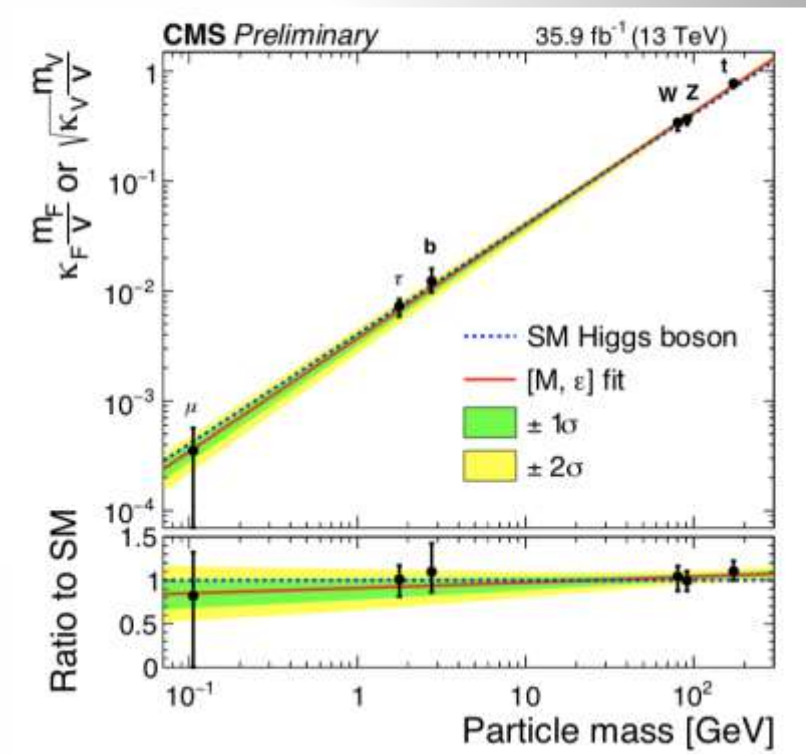
Spin =
$0^{+(+)}$ preferred
over 0^{-},1,2

We continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, heavier Higgses, charged Higgses…

Brief Higgs Summary (so far)

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





ATLAS-CONF-2018-031

CMS: arXiv:1809.10733

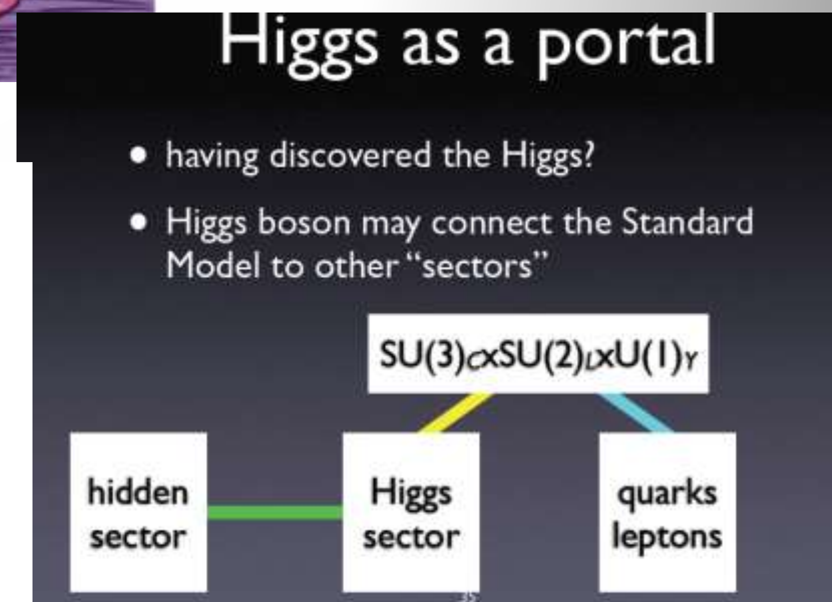
Results in agreement with the Standard Model

$$\mu = 1.13^{+0.09}_{-0.08}$$

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

The Future: Studying the Higgs…

- More LHC Data 2021-2023
- LHC upgrade ! 2026-2036
- Experiment upgrades!!
- Other/new machines?
  -> see later

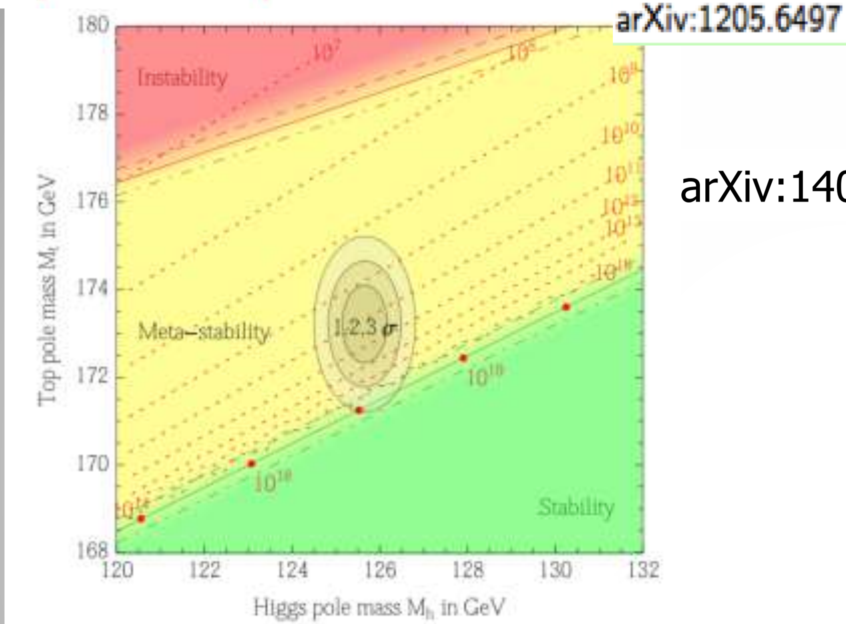


Many questions are still unanswered:

- What explain a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- What is the origin of neutrino masses?
- …

Physics Beyond the Standard Model?

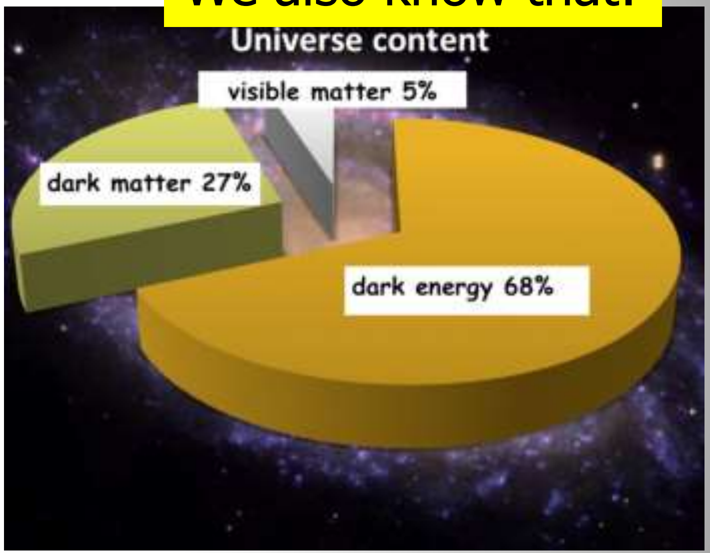
Important SM parameter → stability of EW vacuum



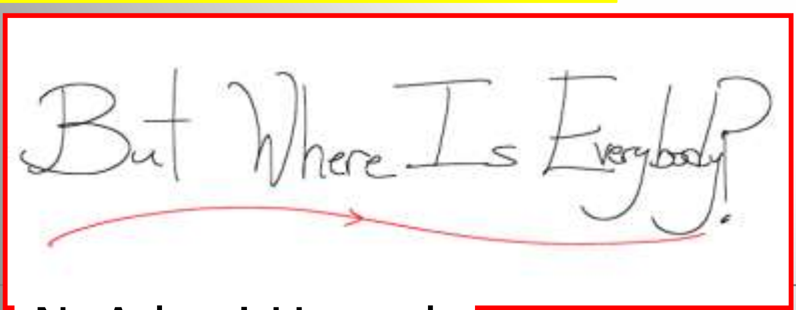
arXiv:1403.6535

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

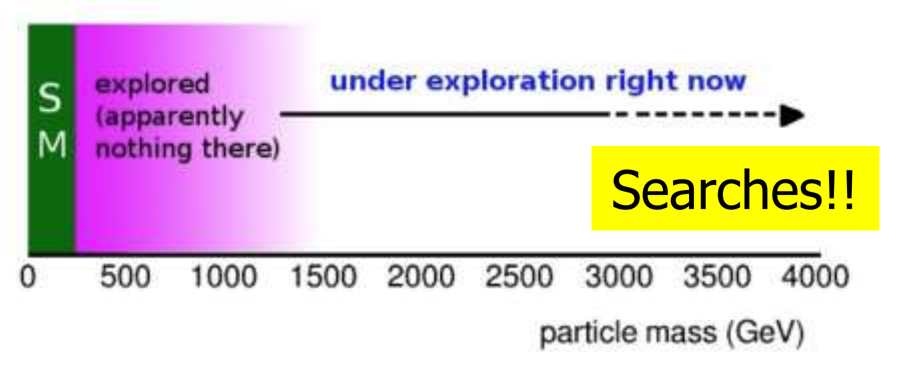
We also know that:



New Physics inevitable?
But at which scale/energy?



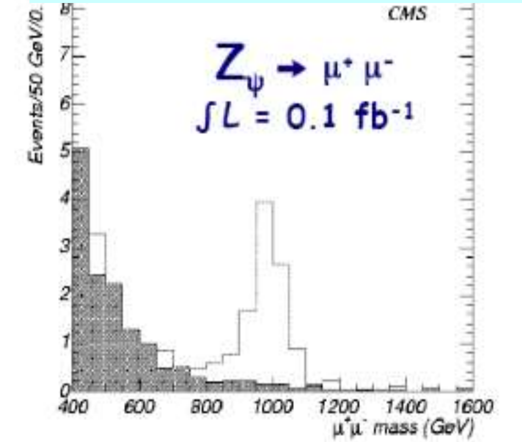
N. Arkani-Hamed



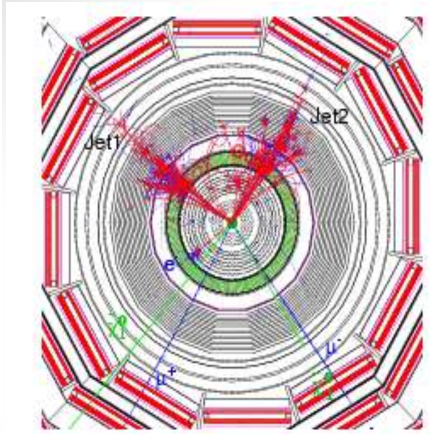
Searches!!

New Physics?

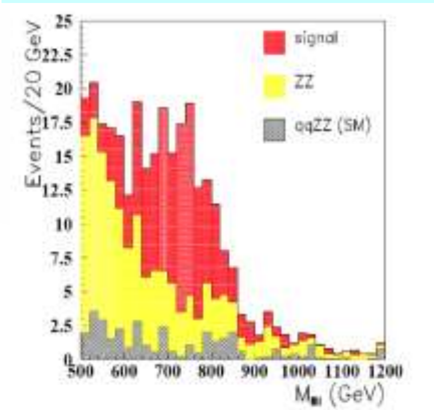
New Gauge Bosons?



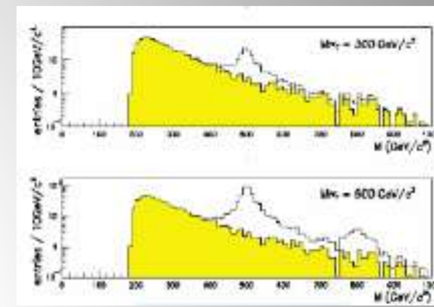
Supersymmetry



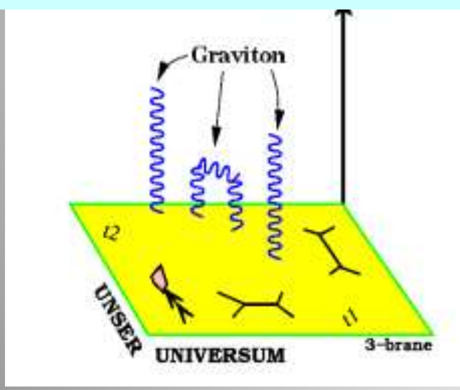
ZZ/WW resonances?



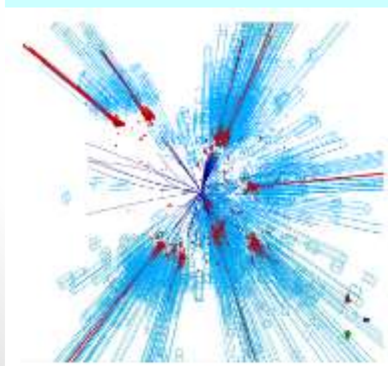
Technicolor?



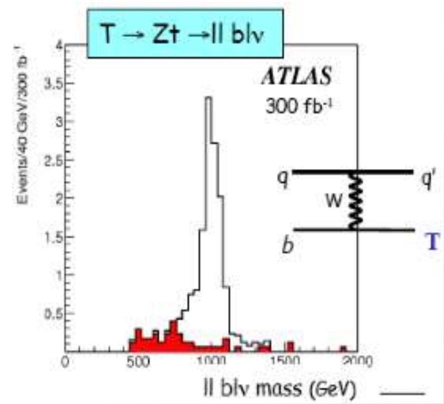
Extra Dimensions?



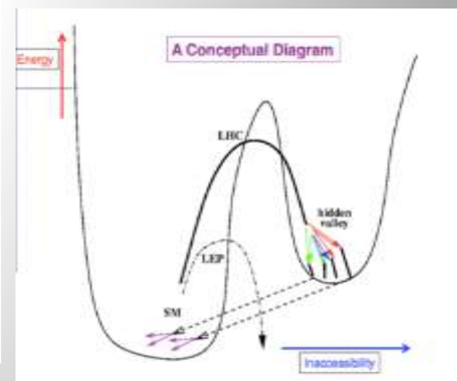
Black Holes???



Little Higgs?



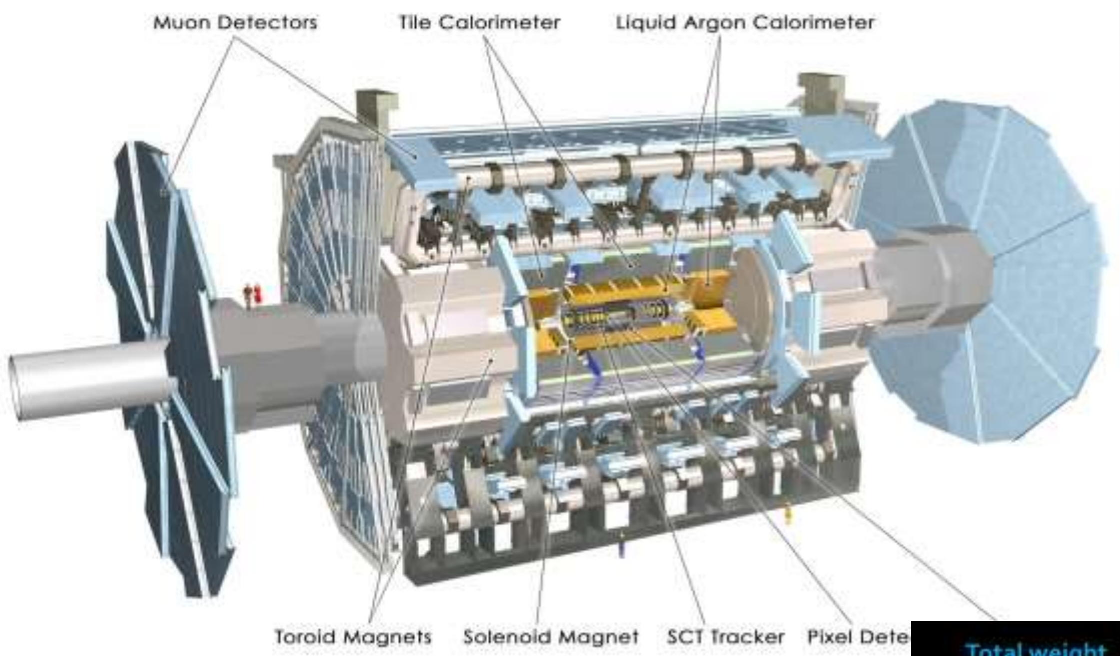
Hidden Valleys?



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

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

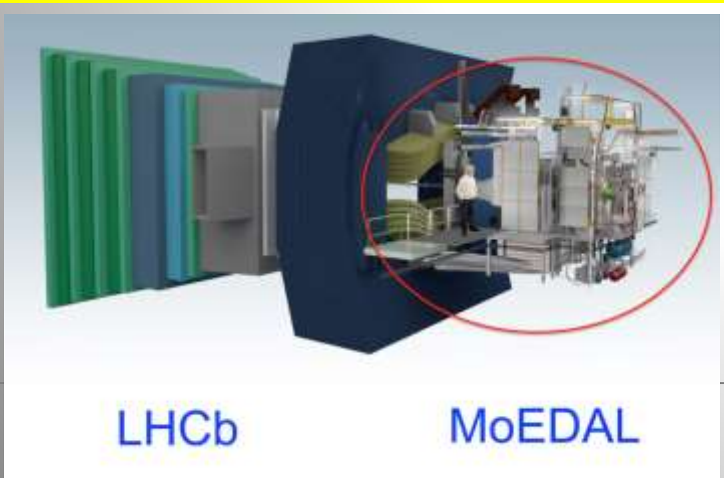
New Physics Hunters @ the LHC

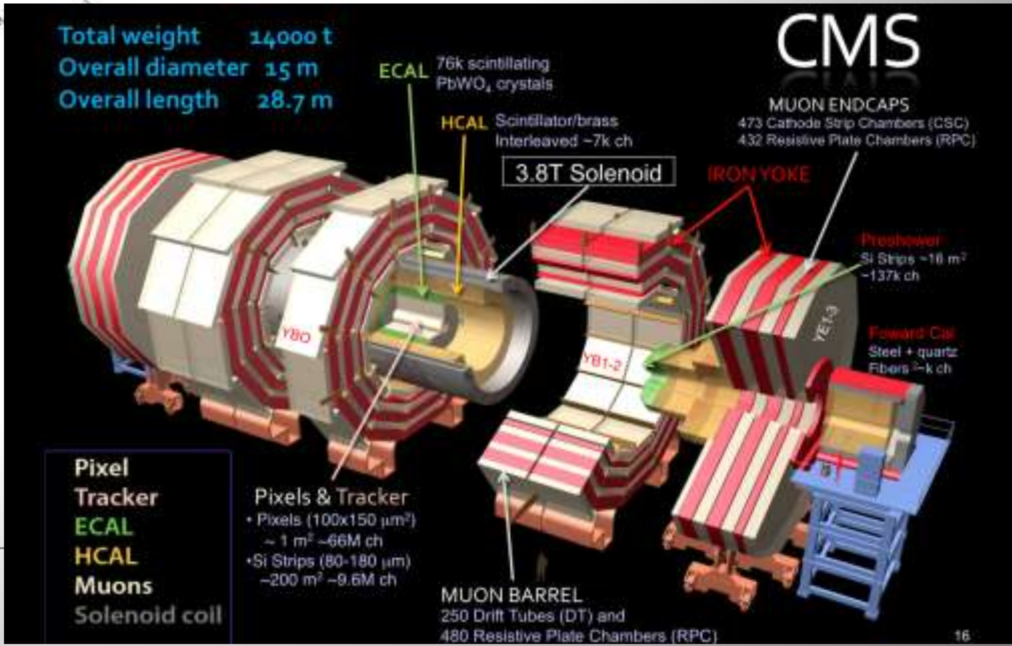


The ATLAS experiment

The CMS experiment

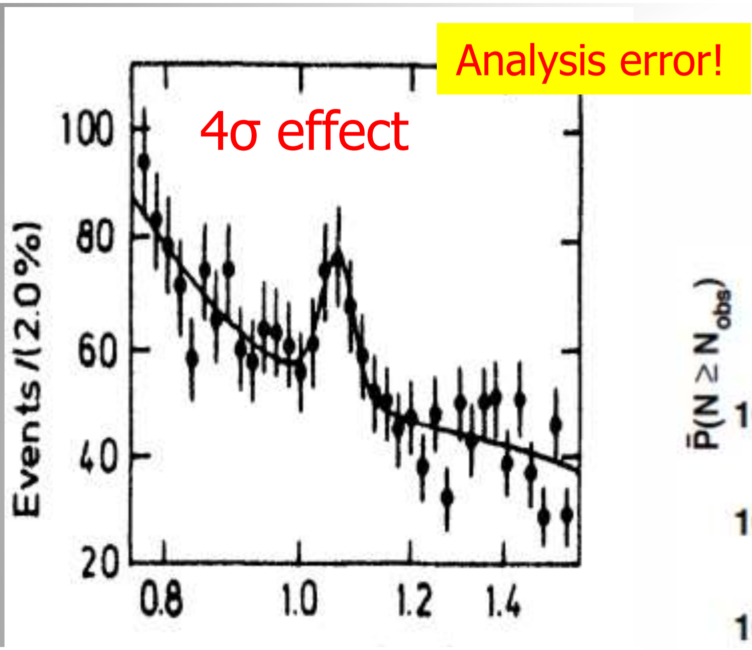
…And also LHCb and MoEDAL



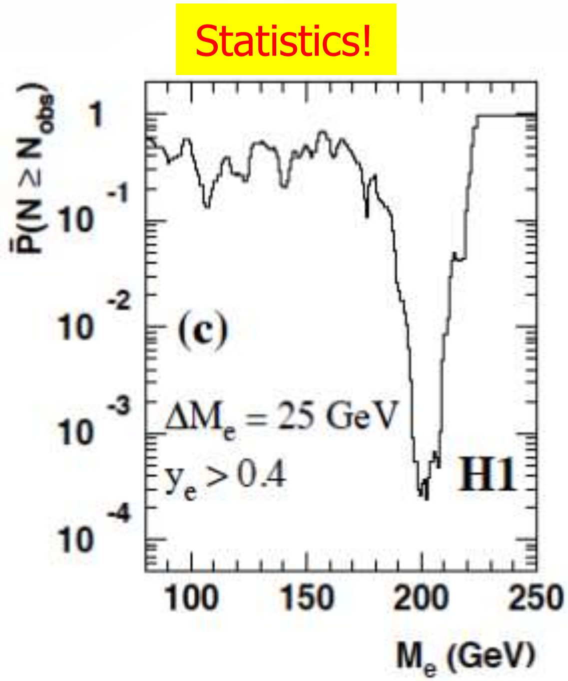


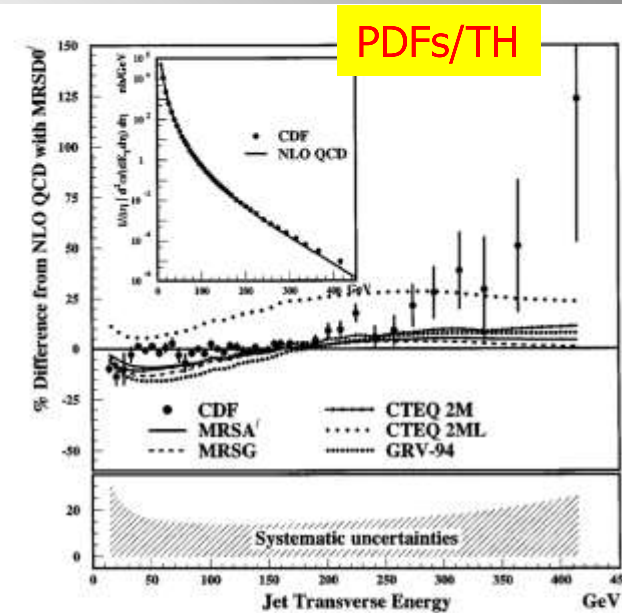
Careful with “Discoveries”!

EVIDENCE FOR A MASSIVE STATE IN THE RADIATIVE DECAYS OF THE UPSILON



Is the X(8.31 GeV) the Higgs particle? A lot of excitement summer 1984





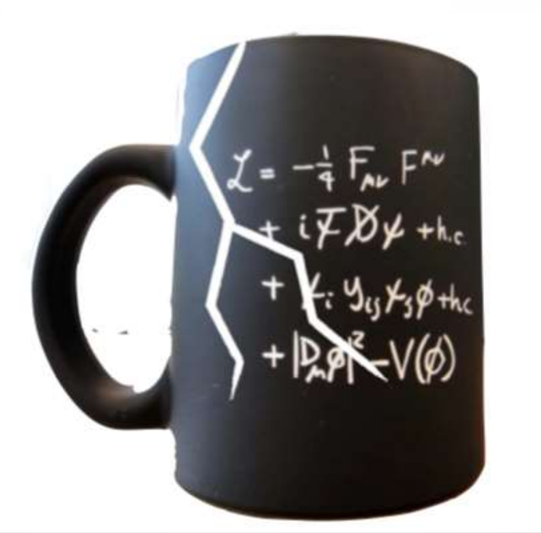
Excess in inclusive jet analysis: substructure?

NON of these were actual discoveries!!

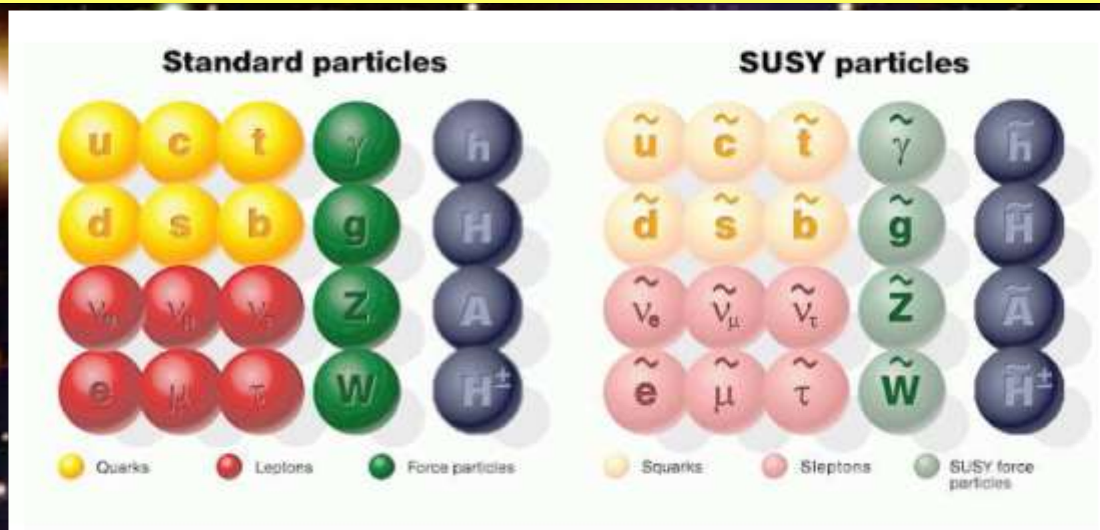
Excess of events at high Q^2 in ep DIS at HERA, mainly in H1:

- 7 events found with an electron-quark mass of ~200 GeV, expected ~1 event
- 4 events found with expected 2 events in ZEUS -> Leptoquarks?

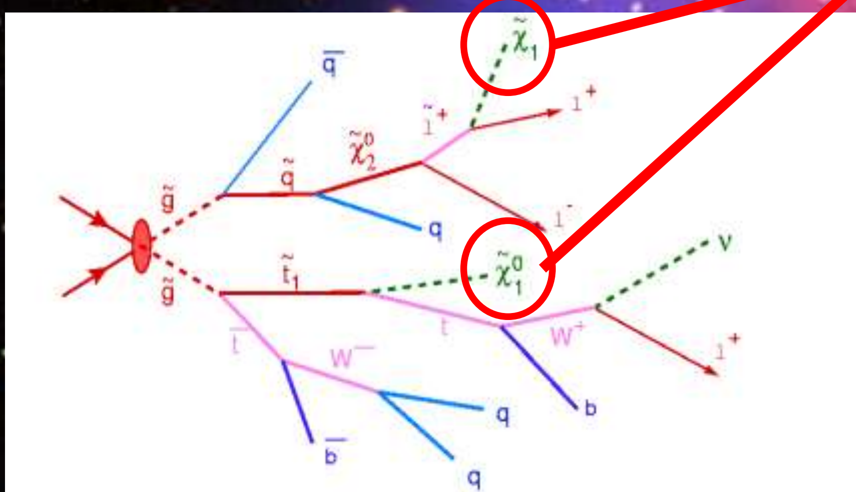
Searches for BSM Physics



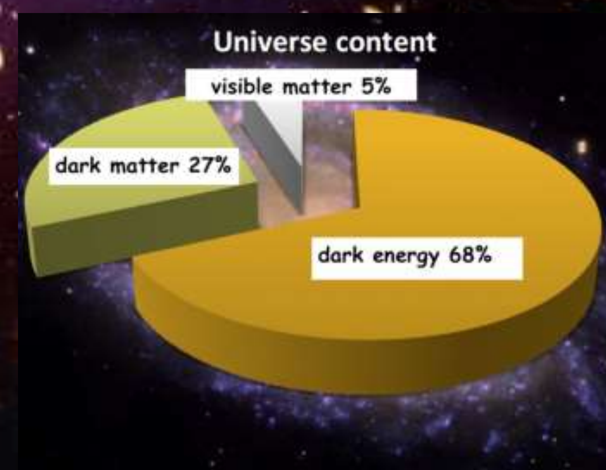
Supersymmetry: a new symmetry in Nature?



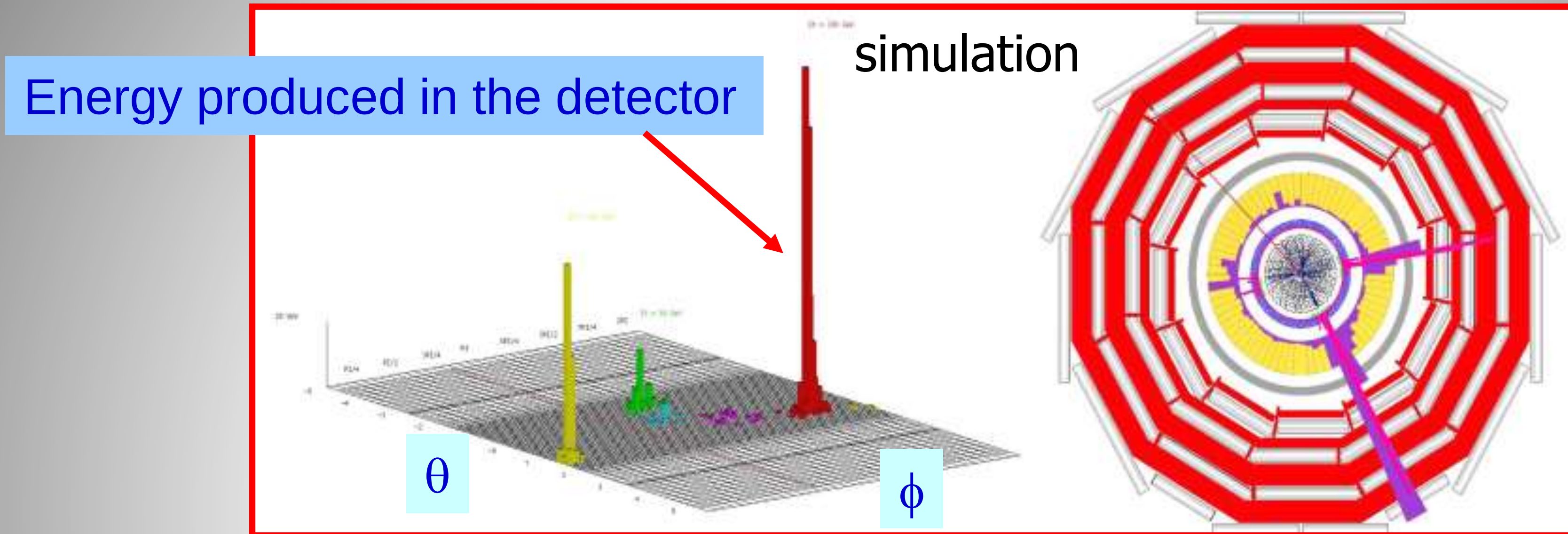
Candidate particles for Dark Matter
⇒ Produce Dark Matter in the lab

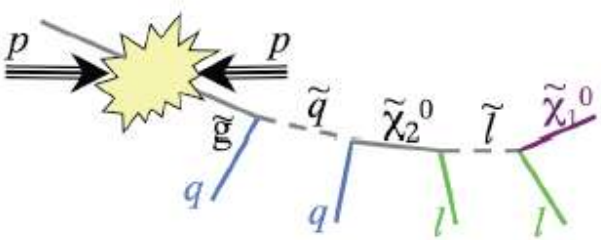


SUSY particle production at the LHC



Detecting Supersymmetric Particles

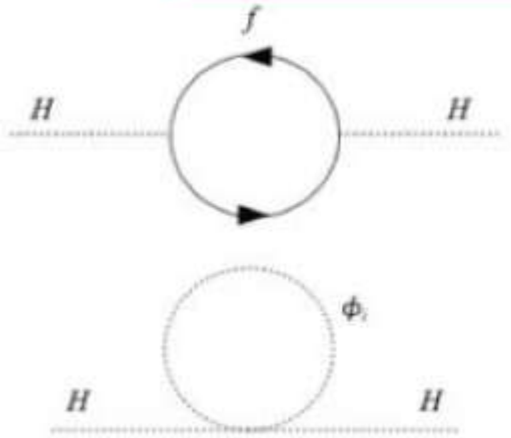




Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

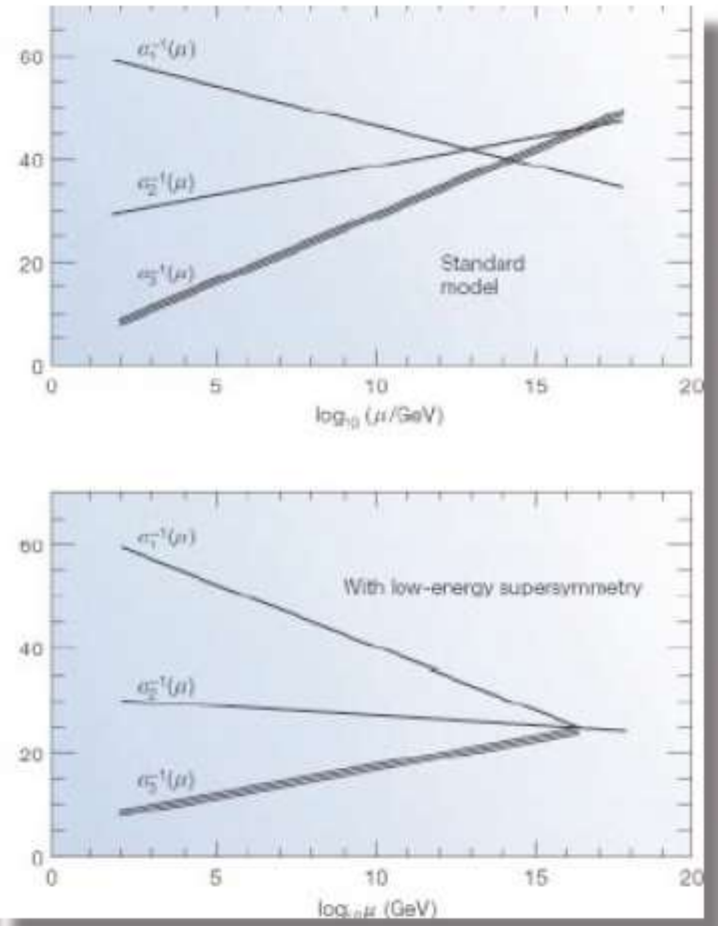
➡ Very prominent signatures in CMS and ATLAS

Why SUSY is good for you!!

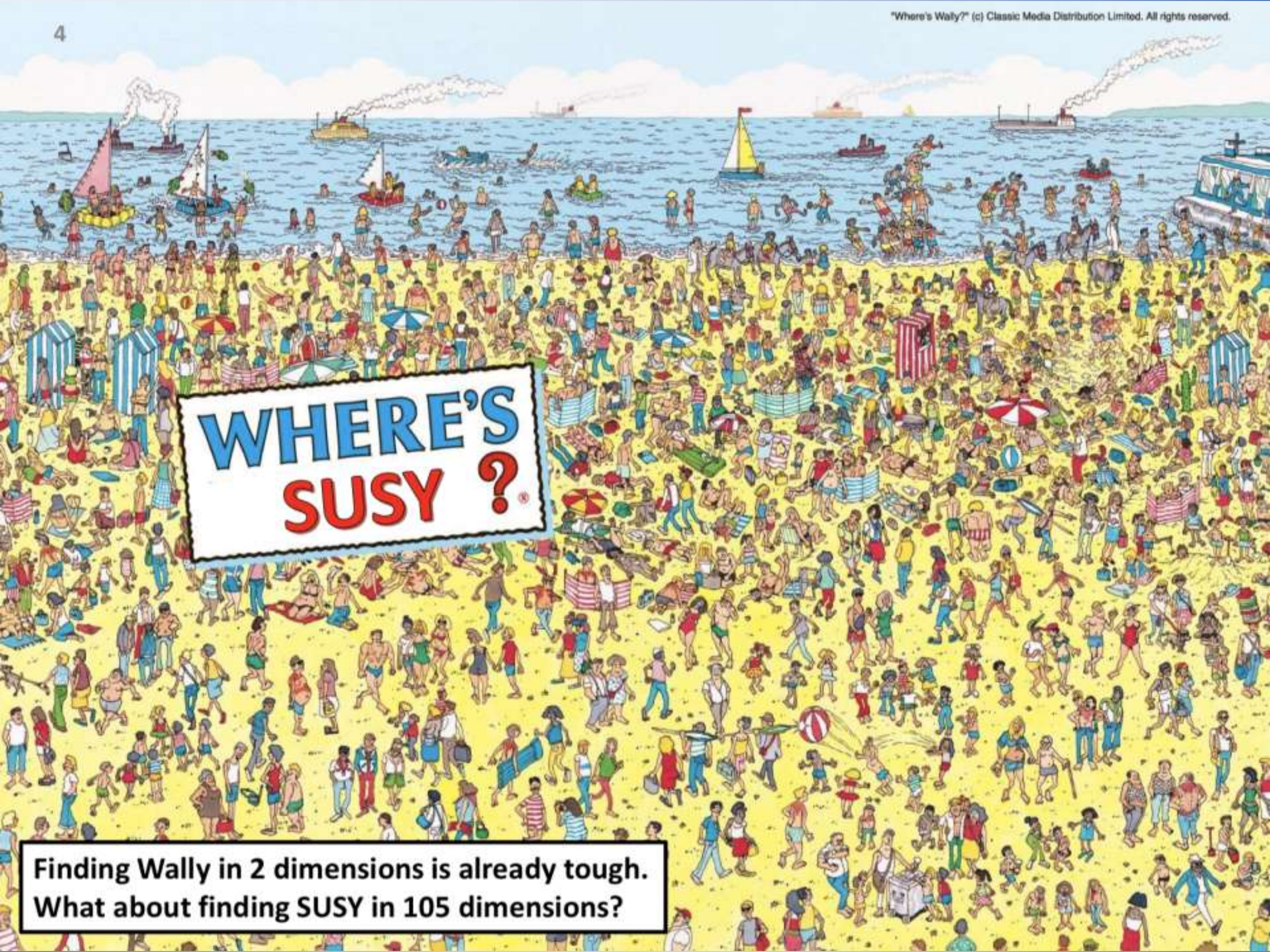


$$\Delta M_H^2 \sim \frac{\lambda_f^2}{4\pi^2}[(m_f^2 - m_S^2)\log(\frac{\Lambda}{m_S})]$$

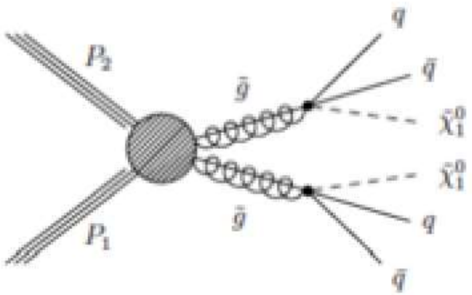
- Elegant solution to the hierarchy problem (i.e., why the Higgs mass is not at the Planck scale)
- Gauge unification

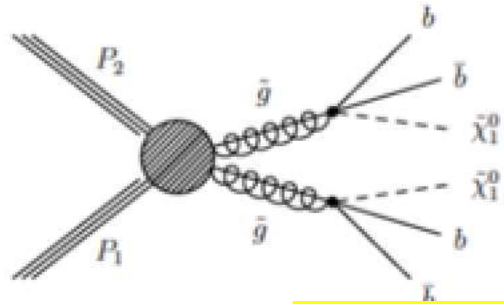


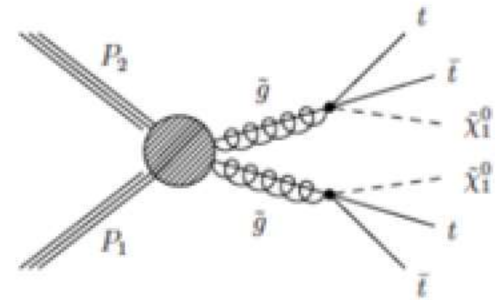
- Dark matter candidate with the right abundance


WHERE'S
SUSY ?
Finding Wally in 2 dimensions is already tough.
What about finding SUSY in 105 dimensions?

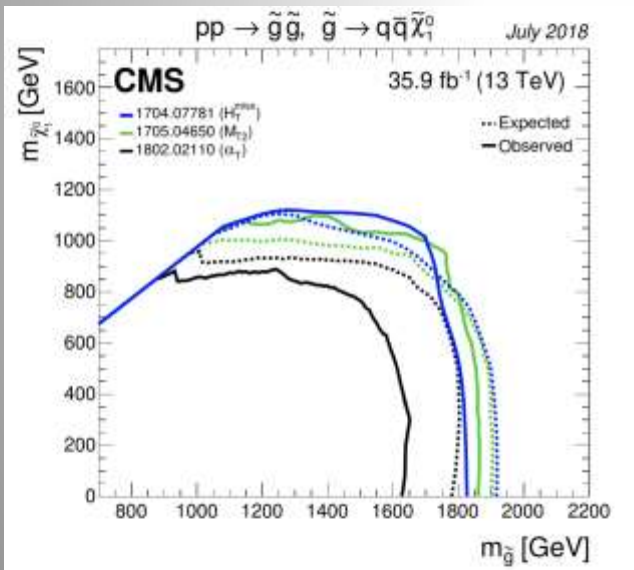
Supersymmetry: Gluinos

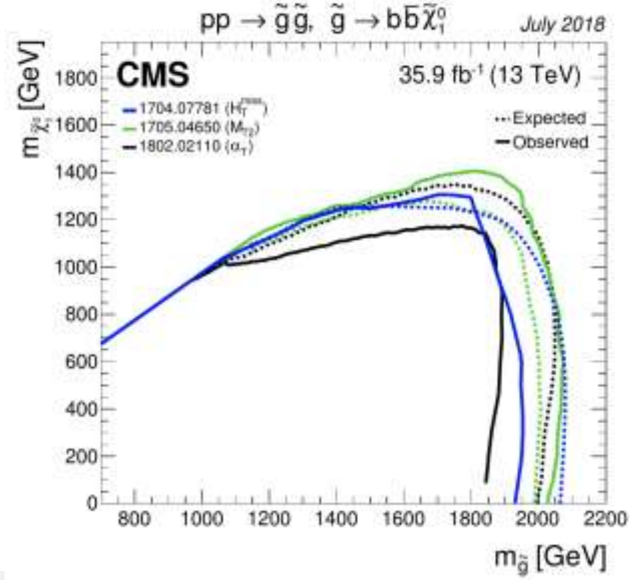


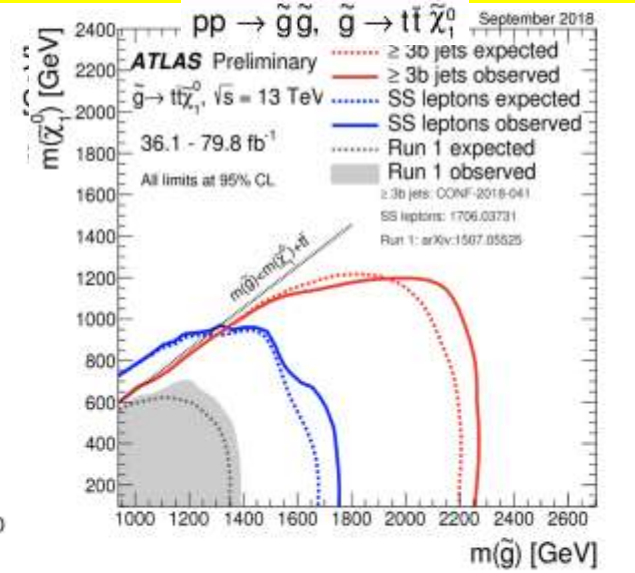




Interpretation in simplified models (SMS)







No significant signal to date

Within the context of the SMS:

Exclude with gluino masses ~ 2200 GeV for neutralino masses up to 800 GeV

What is really needed from SUSY?

End 2011: Revision!

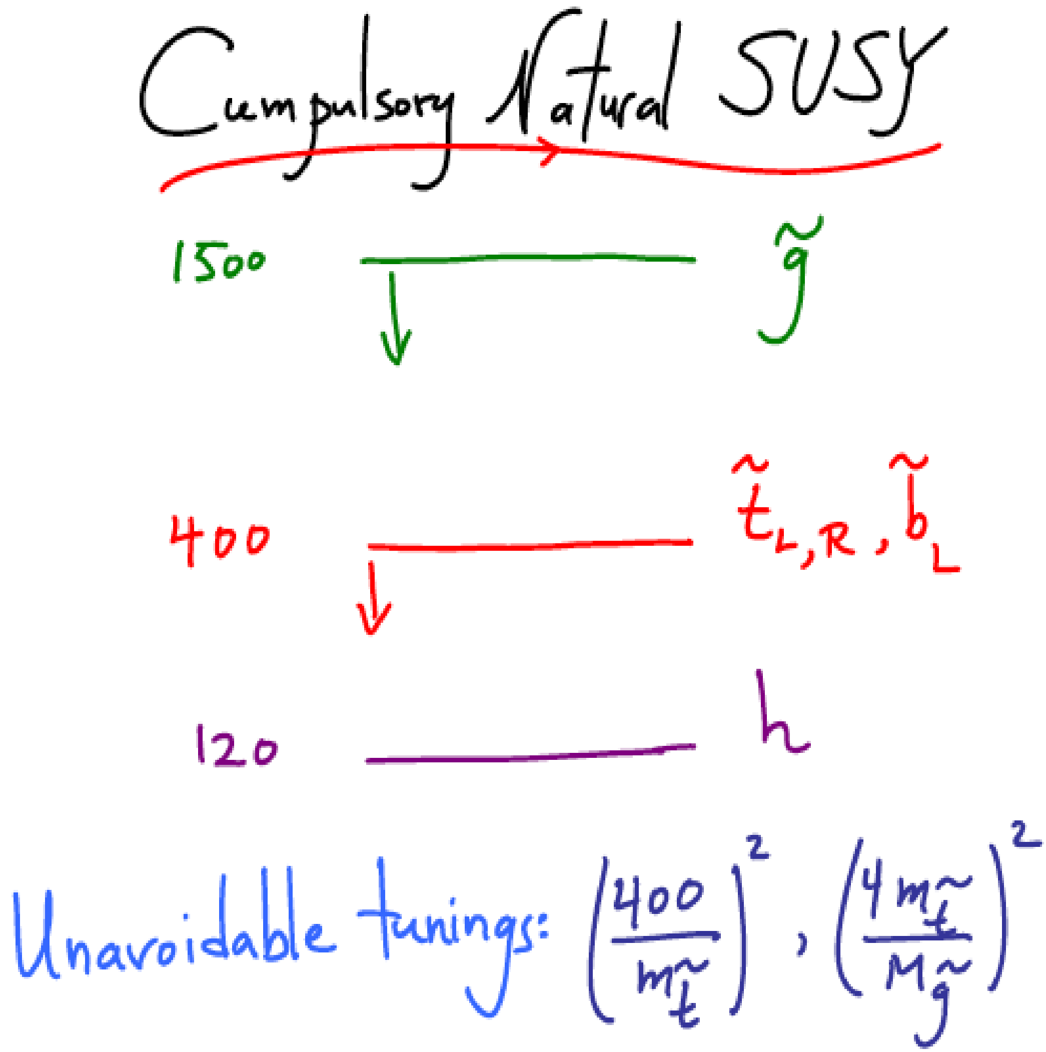
N. Arkani-Ahmed
CERN Nov 2011

Papucci, Ruderman, Weiler arXiv:1110.6926

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

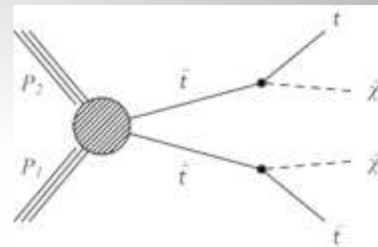
Moving away from constrained SUSY models to 'natural' models

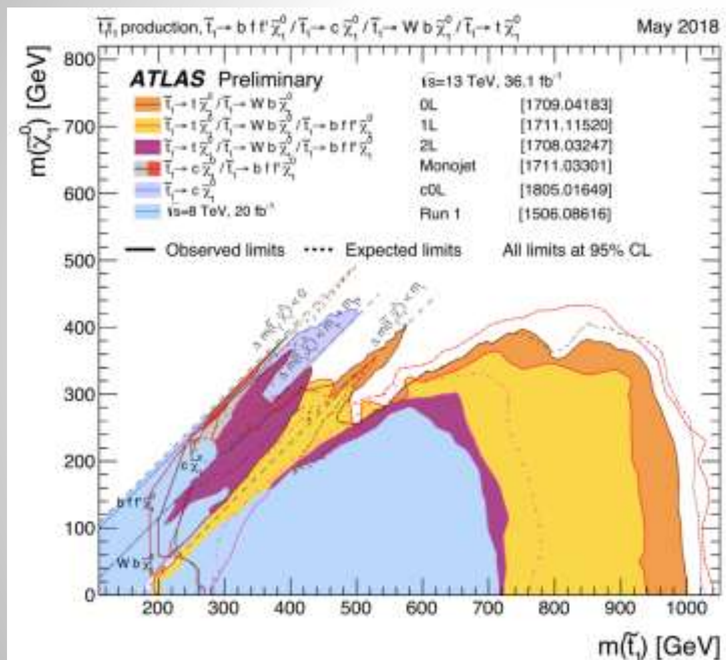
Natural SUSY survived LHC so far, but we are getting close to push it to its limits!

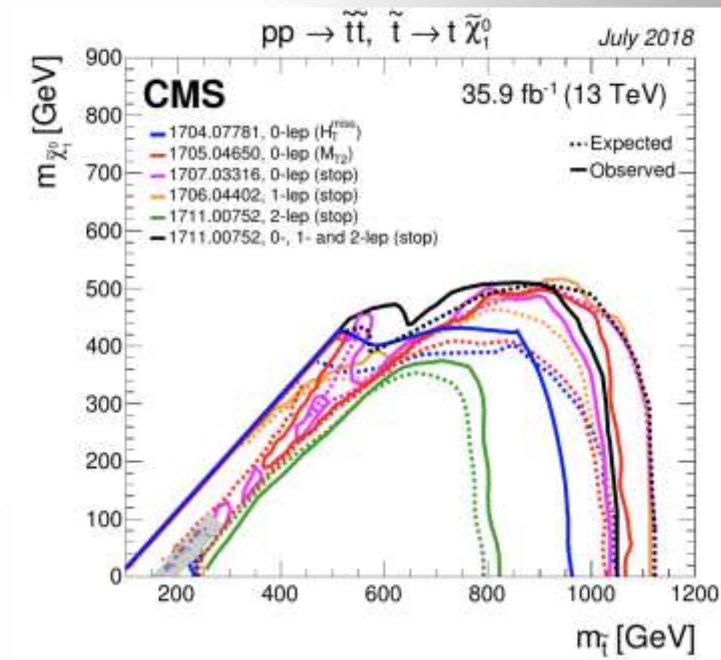


Top Squark Search Summaries

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



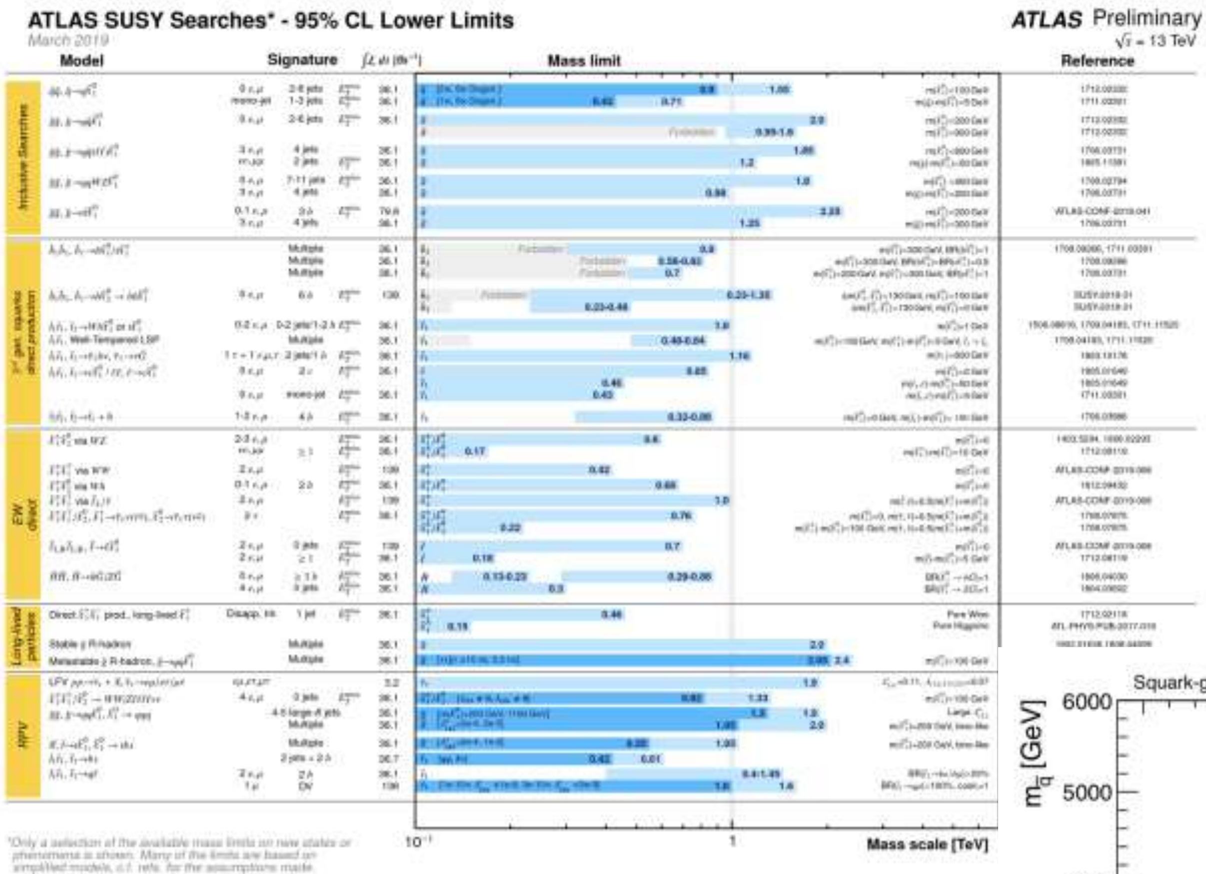




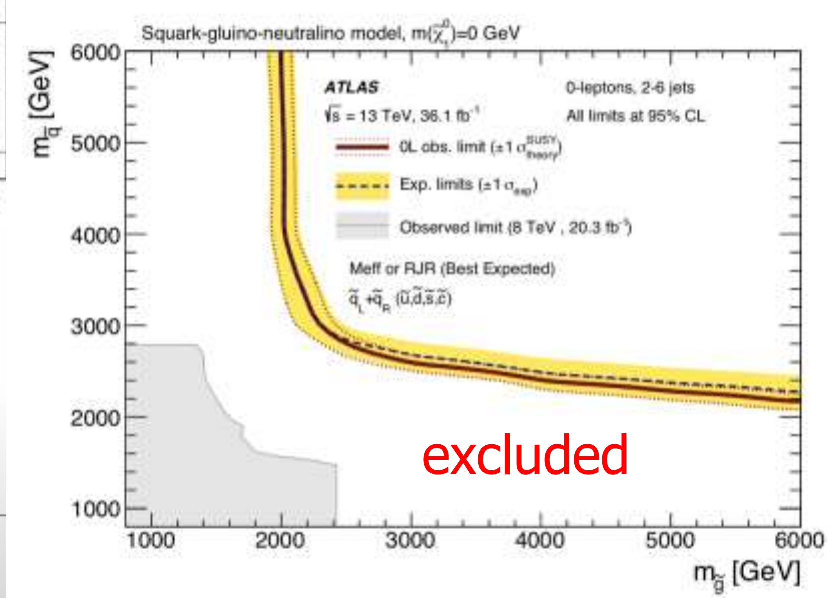
Within the context of the SMS:
Exclude with masses up to 1100 GeV for neutralino masses up to 500 GeV

Is this getting critical for Natural Models??

The SUSY SEARCH Chart So Far…



Limits from individual analyses



Excluded squark and gluino mass region

SUSY (as seen from outside HEP…)

November '16 reported by The Economist (!?!):

But not giving up as yet!!!
So far 2016 data analysed

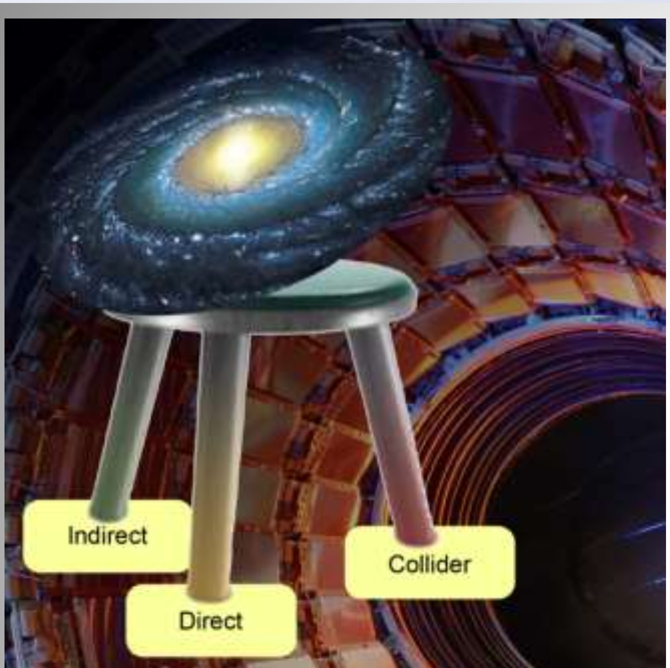
Keep the party ready..

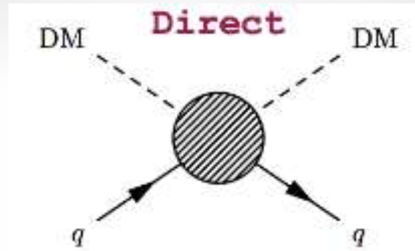
2017+2018 (4x more data) is coming !!

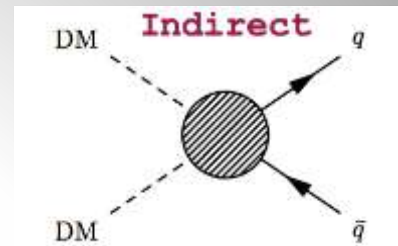
http://www.economist.com/news/science-and-technology/21709946-supersymmetry-beautiful-idea-there-still-no-evidence-support-it

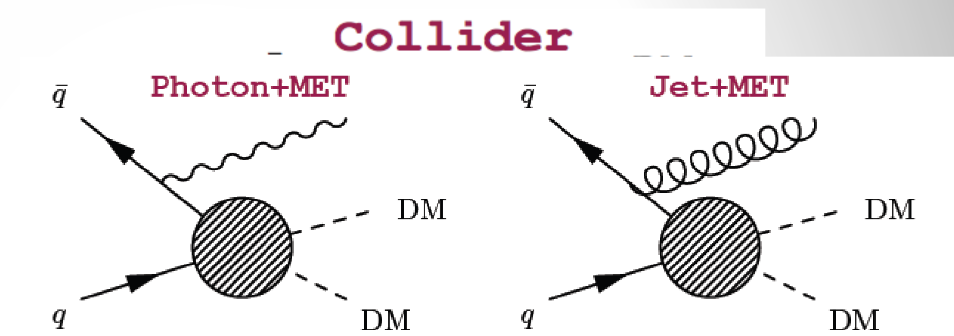
J. Ellis

Dark Matter Searches at the LHC

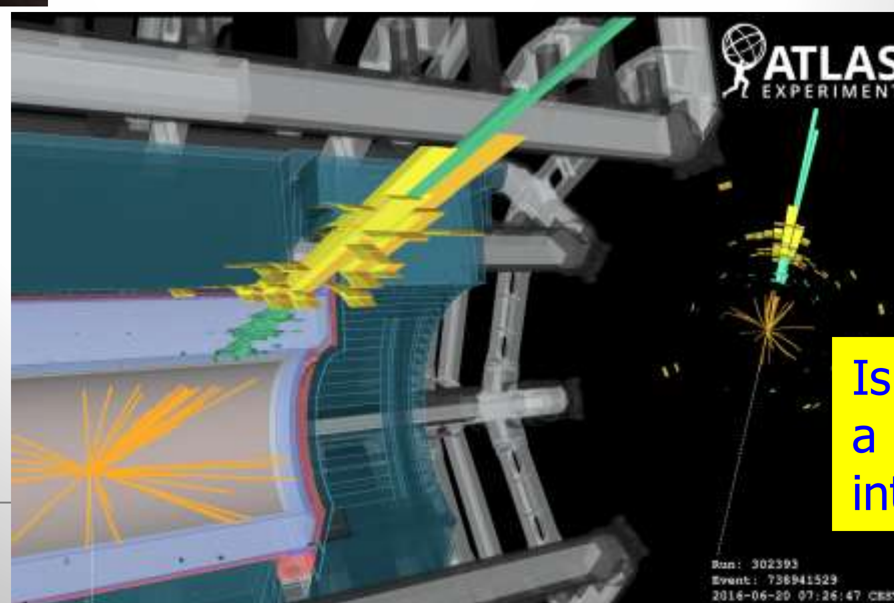






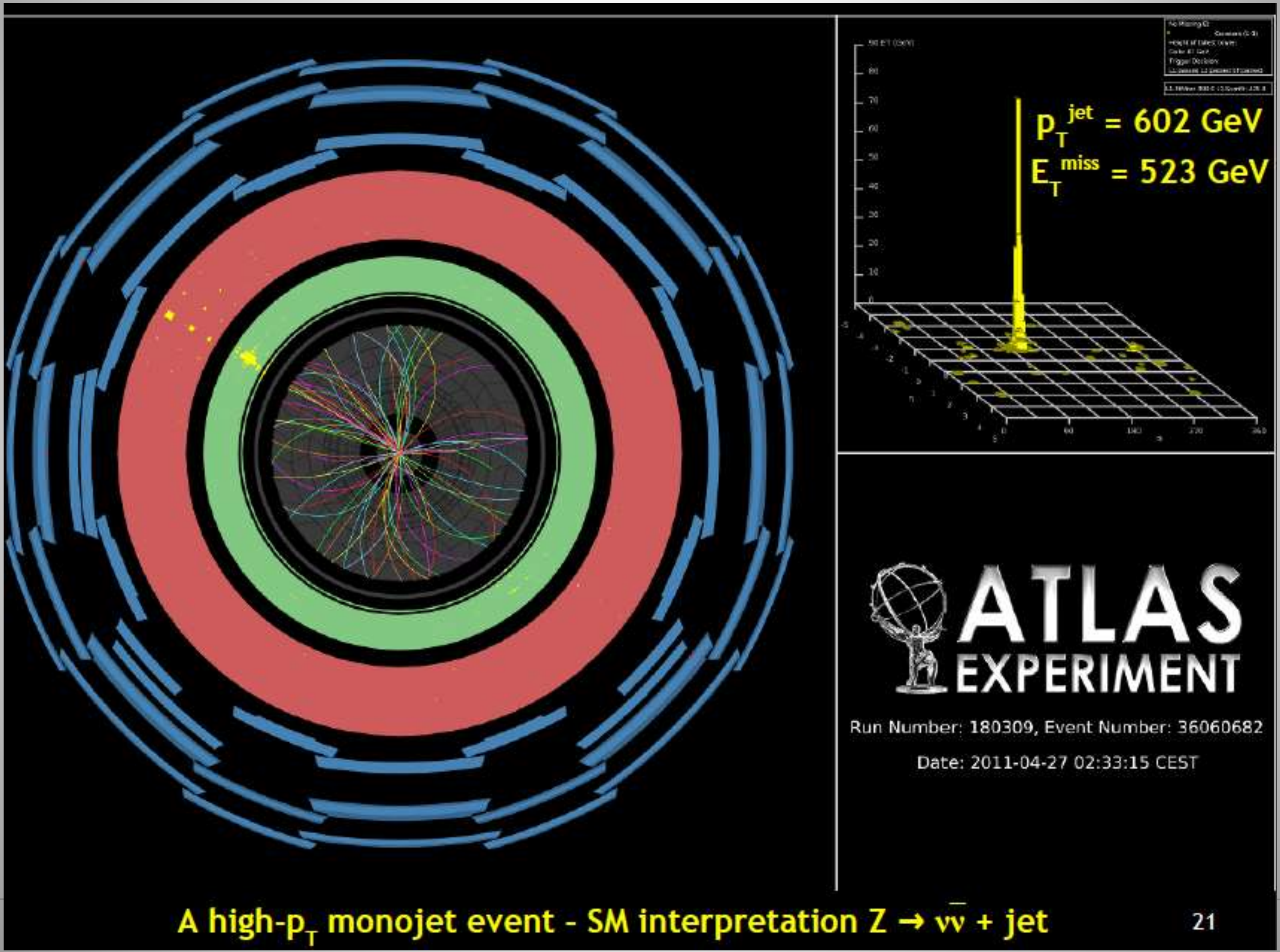


- Identifying Dark Matter is one of the most important questions in physics today!
- It is likely a new as yet undetected particle
- Can it be produced at the LHC?



Is Dark Matter a new weakly interacting particle?

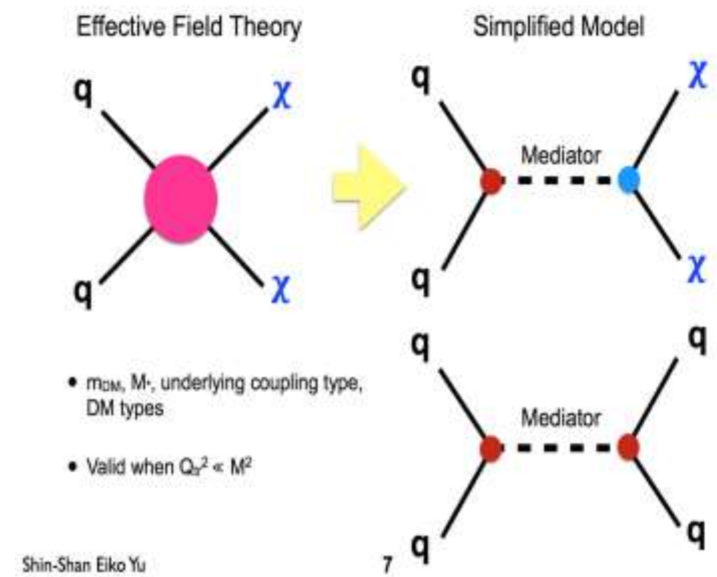
A High p_T Mono-jet event



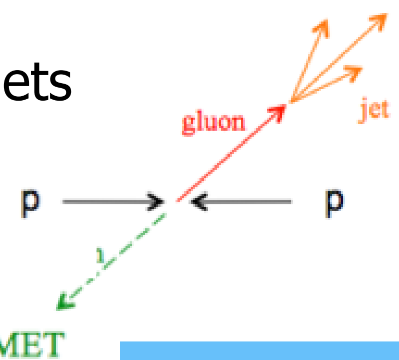
Mono-object Searches in CMS

- 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



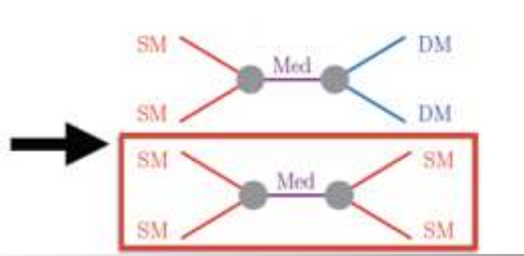
Dark Matter?

Now: **LHC Dark Matter Working Group**

http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc

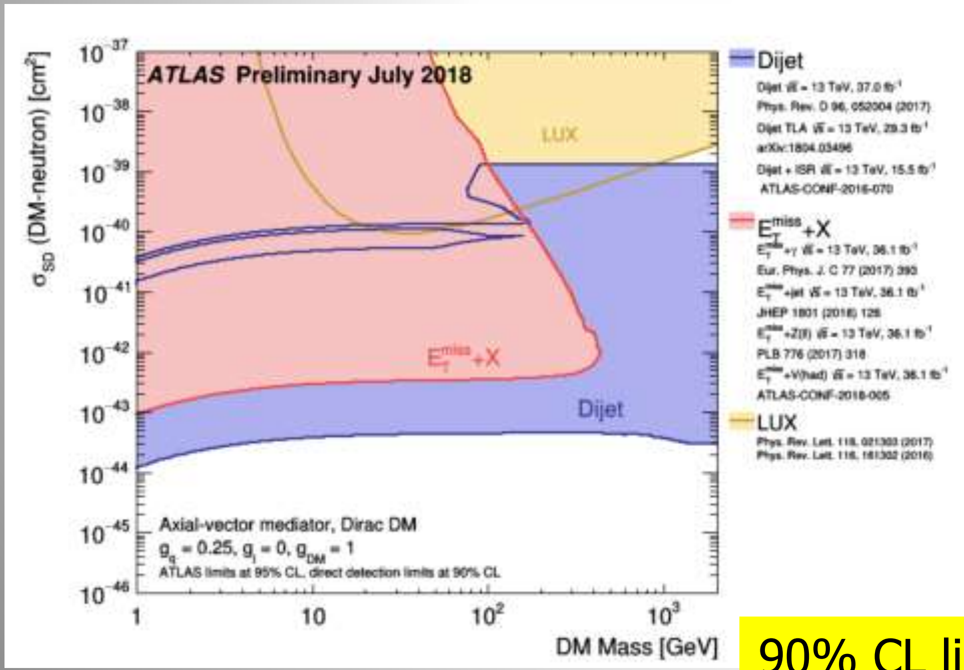
Comparison with Direct Detection

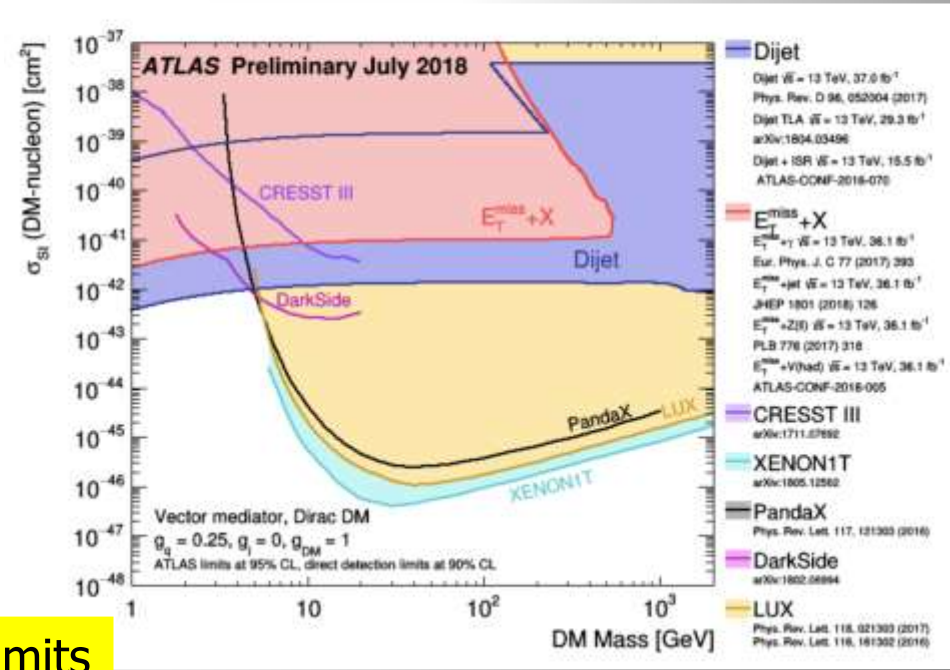
No signal seen in any of the "mono"-signals so far
Extend limits by search for the mediator



Axial-vector mediator and
Spin-dependent direct limits

Vector mediator and
Spin-independent direct limits





90% CL limits

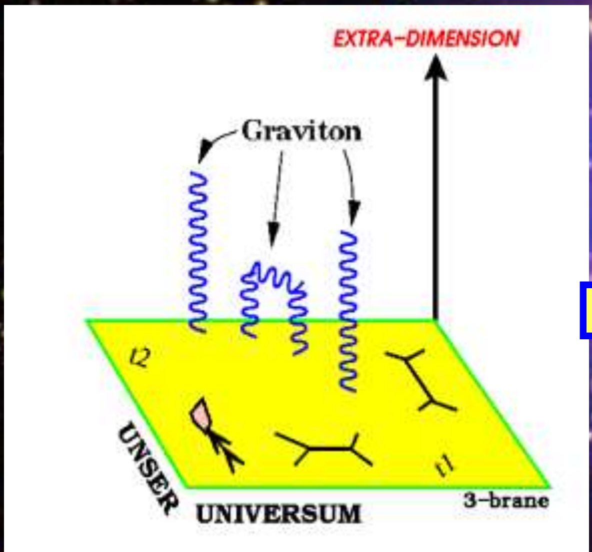
Mono-jet/V & Dijet searches are typically the most sensitive ones

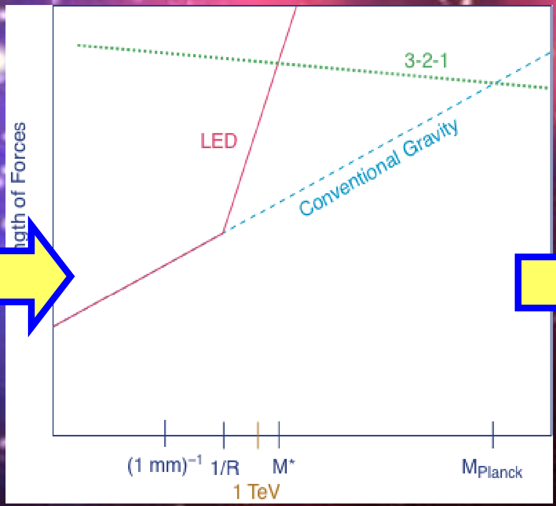
Extra Space Dimensions

Problem:

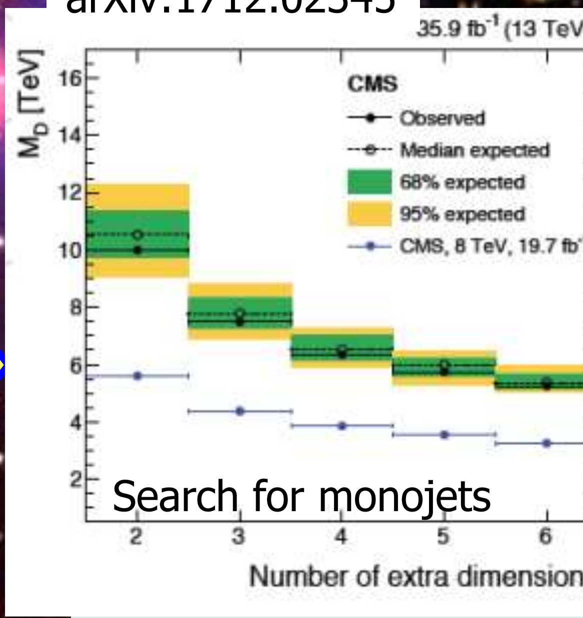
$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV}$$

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





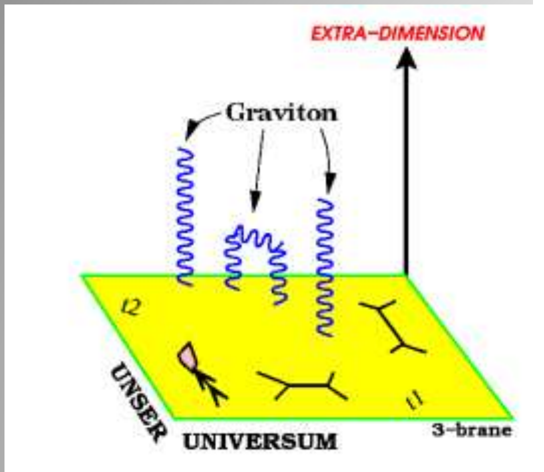
arXiv:1712.02345



The Gravitational force can become strong!

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

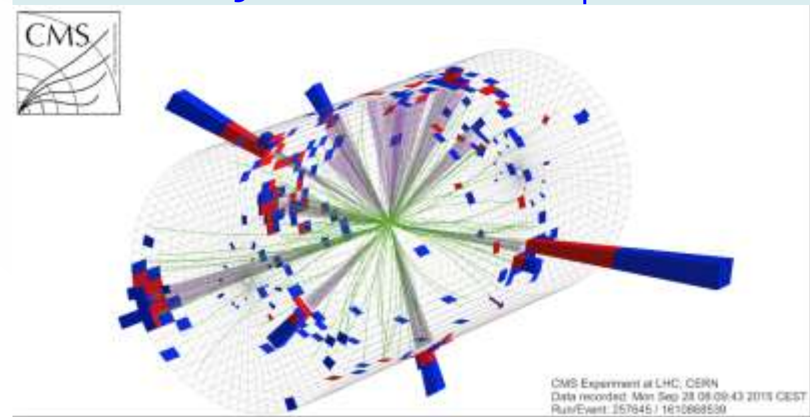
Search for Micro Black Holes



Extra Dimensions!

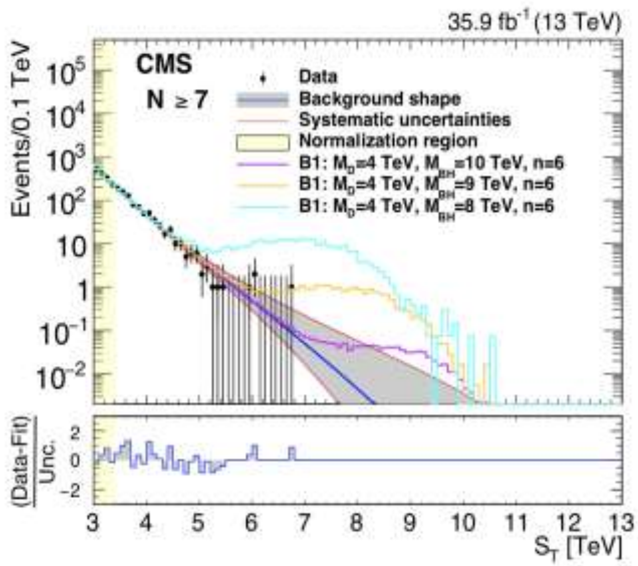
Planck scale
a few TeV?

2015: 12 jet event with S_T=5.4 TeV

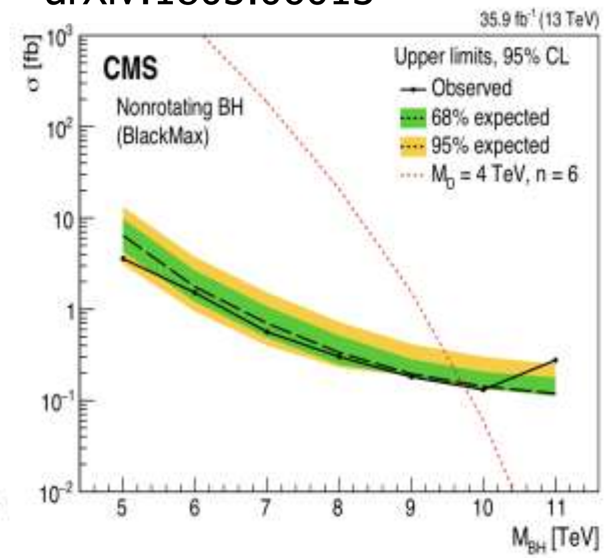


Look for the decay producs of an evaporating black hole

-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

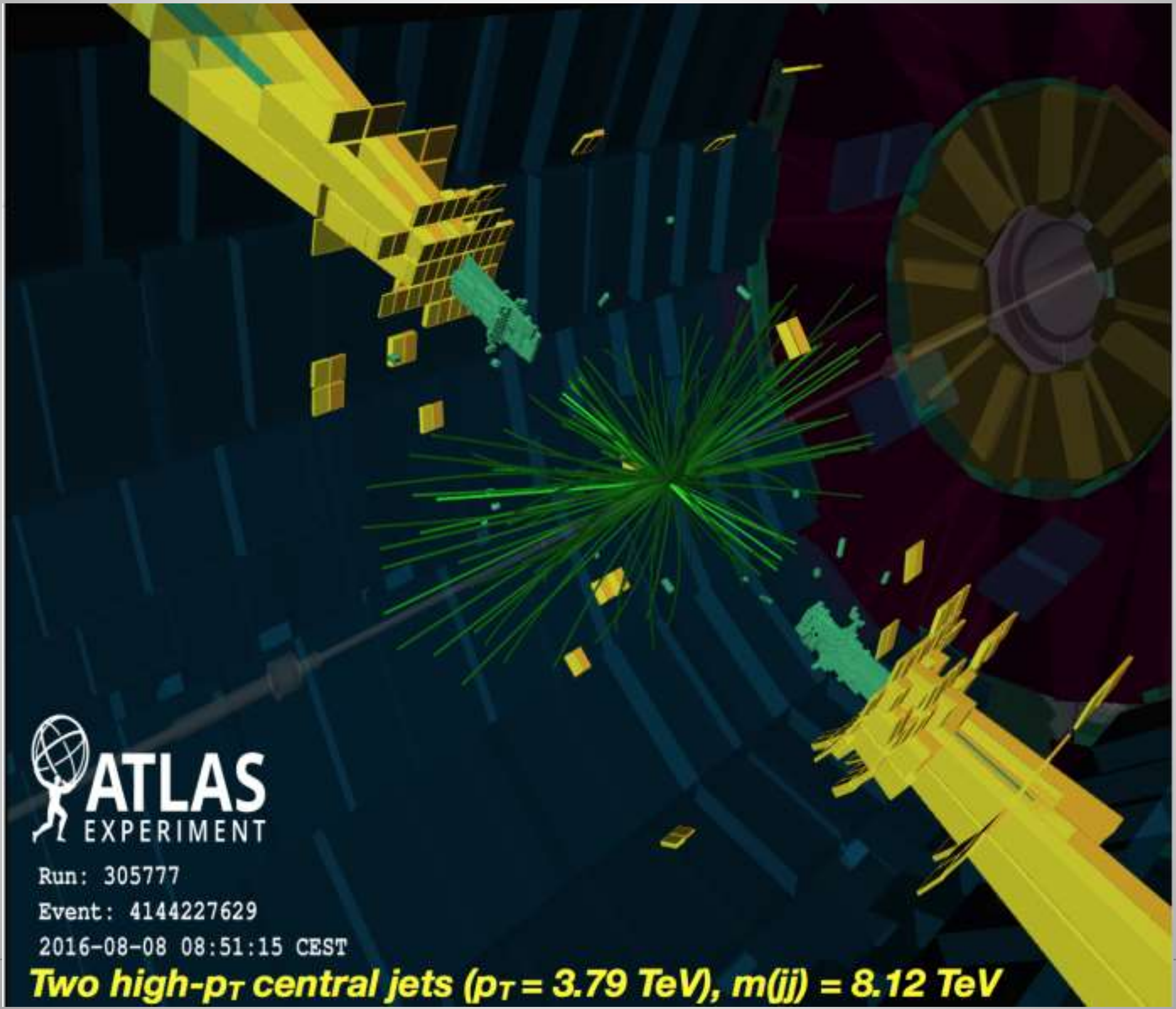


arXiv:1805.06013



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

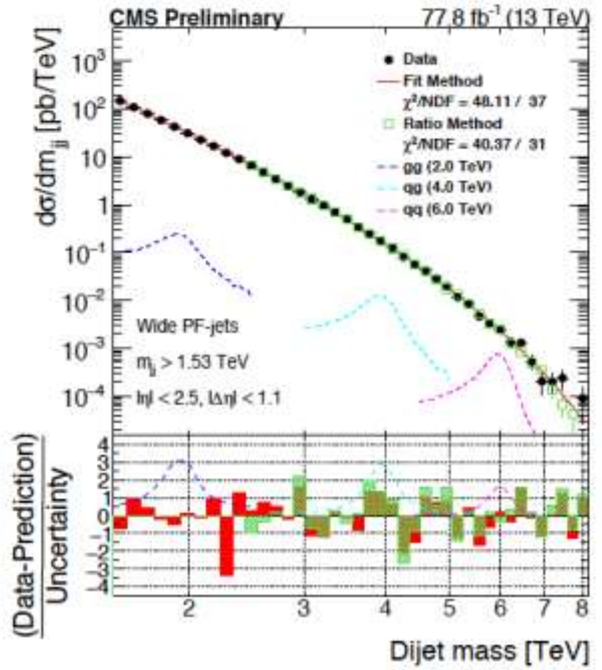
Dijet Resonance Searches @13TeV

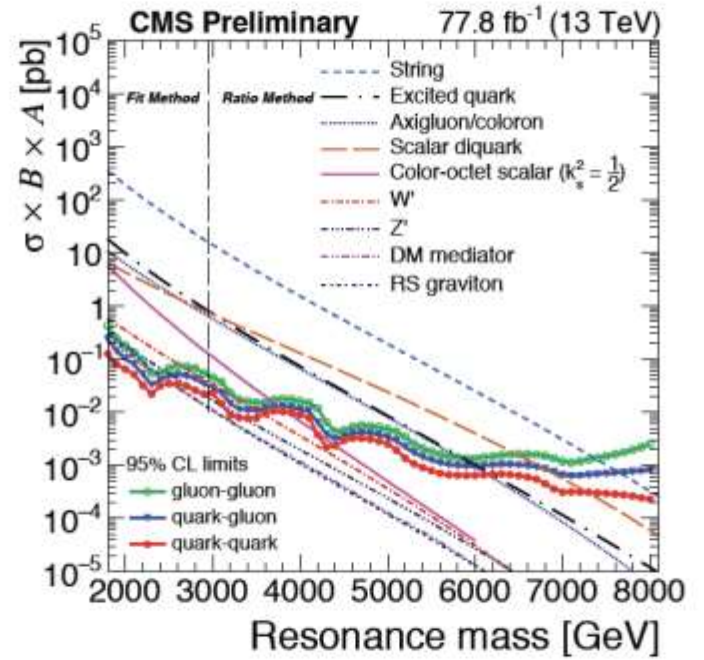


Search for Di-jet Resonances

Search for dijet resonances based on 2016+2017 data sample

PAS EXO-17-026



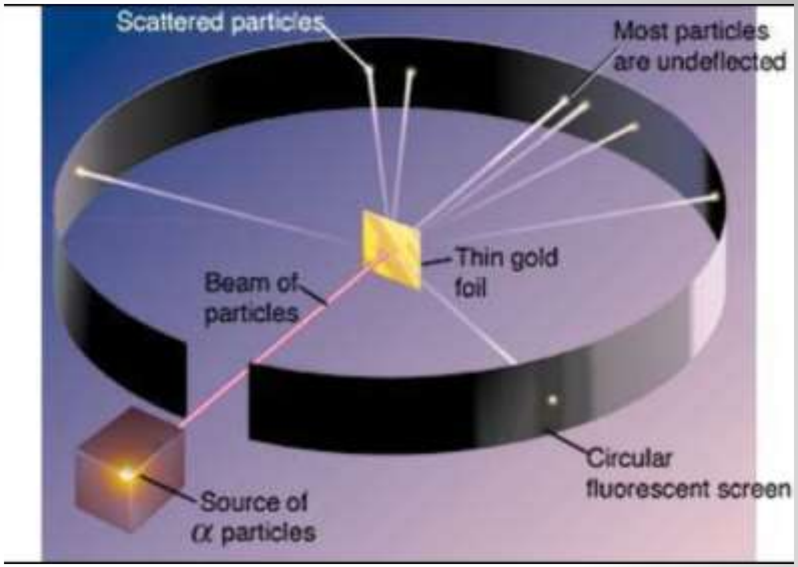


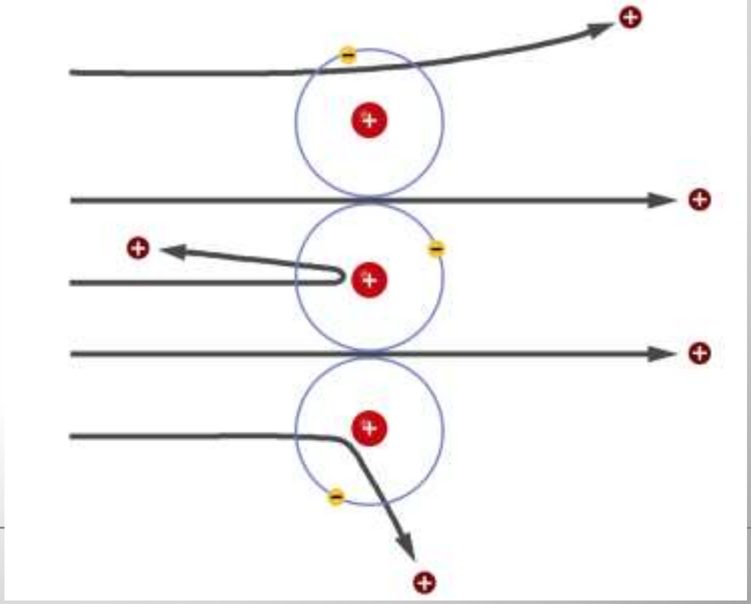
Slow increase in mass reach of ~ few 100 GeV

More Luminosity -> test smaller couplings

Model	Final State	Observed (expected) mass limit [TeV] 36 fb^{-1} 13 TeV	77.8 fb^{-1} 13 TeV
String	qg	7.7 (7.7)	7.6 (7.9)
Scalar diquark	qq	7.2 (7.4)	7.3 (7.5)
Axigluon/coloron	$q\bar{q}$	6.1 (6.0)	6.2 (6.3)
Excited quark	qg	6.0 (5.8)	6.0 (6.0)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.4 (3.6)	3.7 (3.8)
W′	$q\bar{q}$	3.3 (3.6)	3.6 (3.8)
Z′	$q\bar{q}$	2.7 (2.9)	2.9 (3.1)
RS graviton ($k/M_{PL} = 0.1$)	$q\bar{q}$, gg	1.8 (2.3)	2.4 (2.4)
DM mediator ($m_{DM} = 1$ GeV)	$q\bar{q}$	2.6 (2.5)	2.5 (2.8)

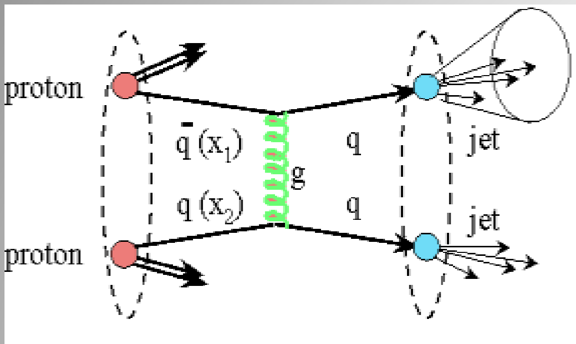
Are Quarks Elementary Particles?

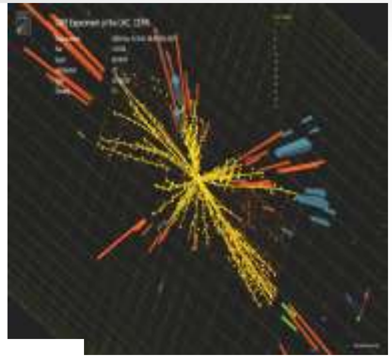


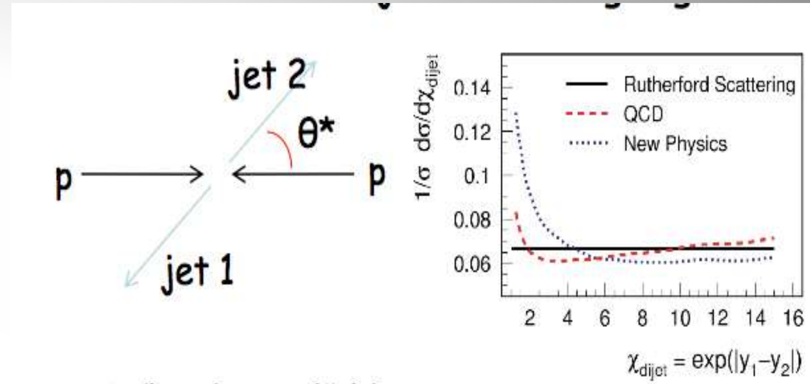


Rutherford experiment:
Unexpected backscattering of α-particles:
Evidence for the structure of atoms !! (1911)

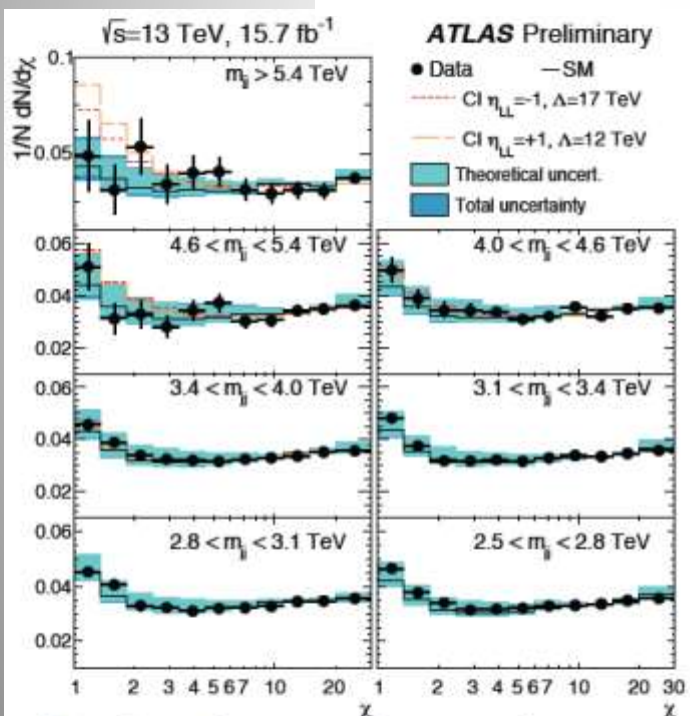
Are Quarks Elementary Particles?



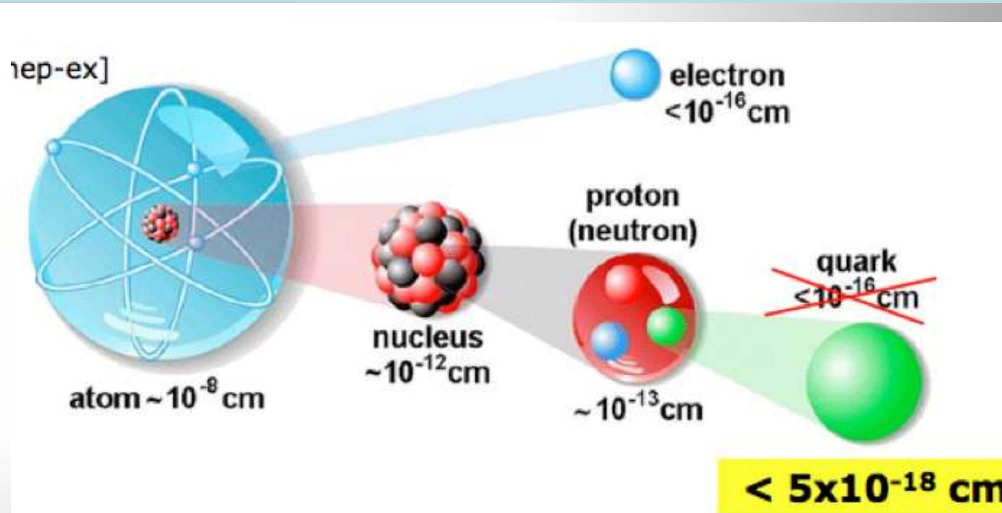




CONF-2016-069



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

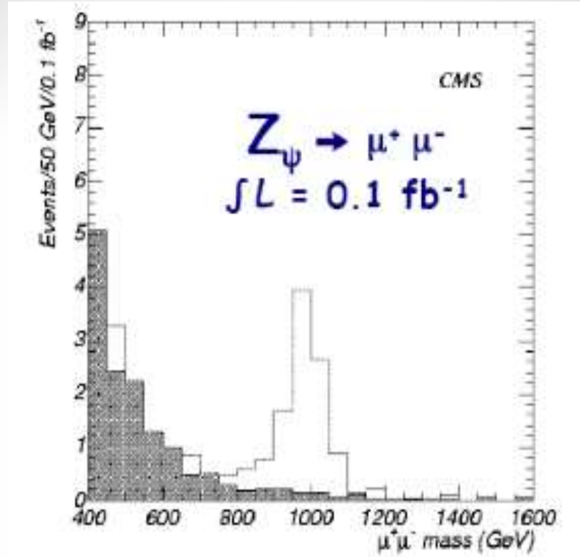
E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

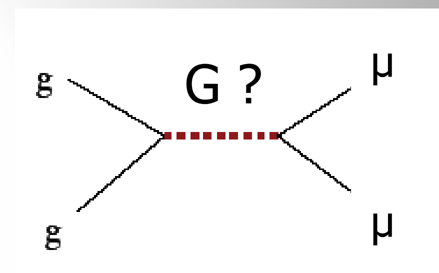
A peak!!

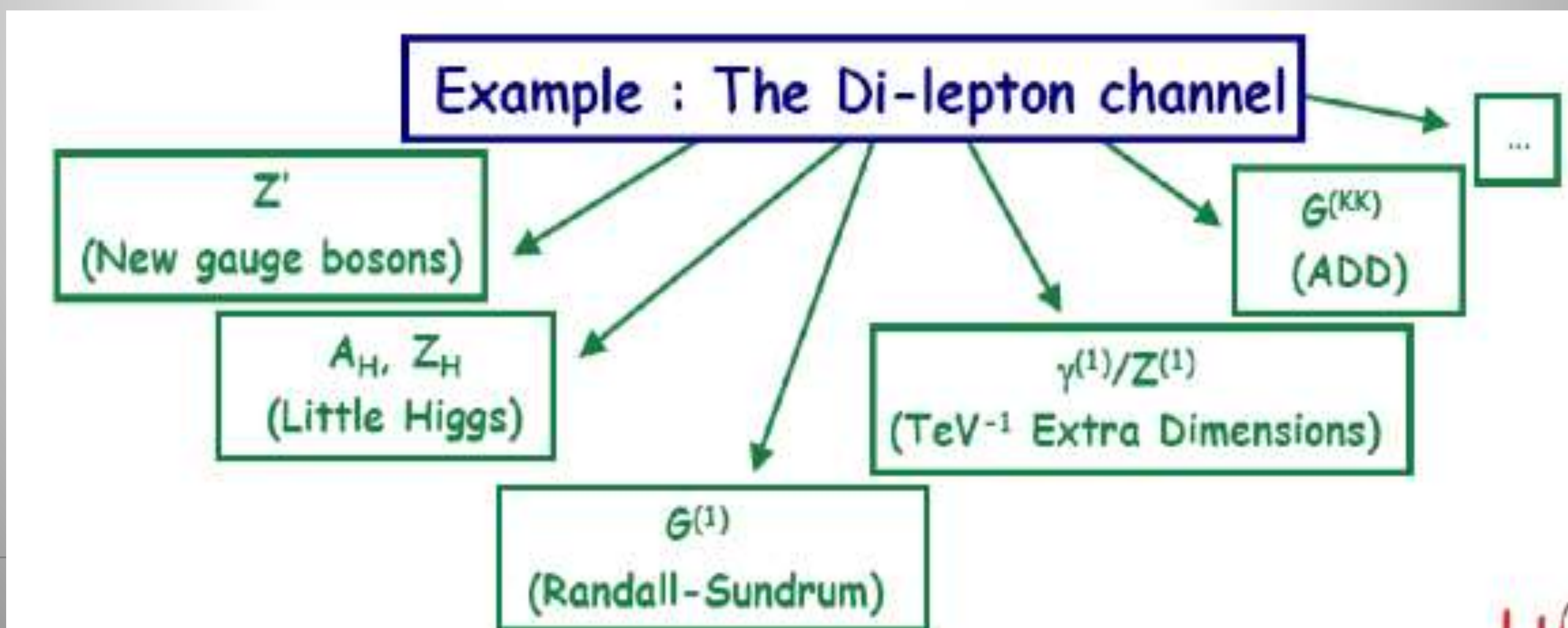
A new particle!!

A discovery!!



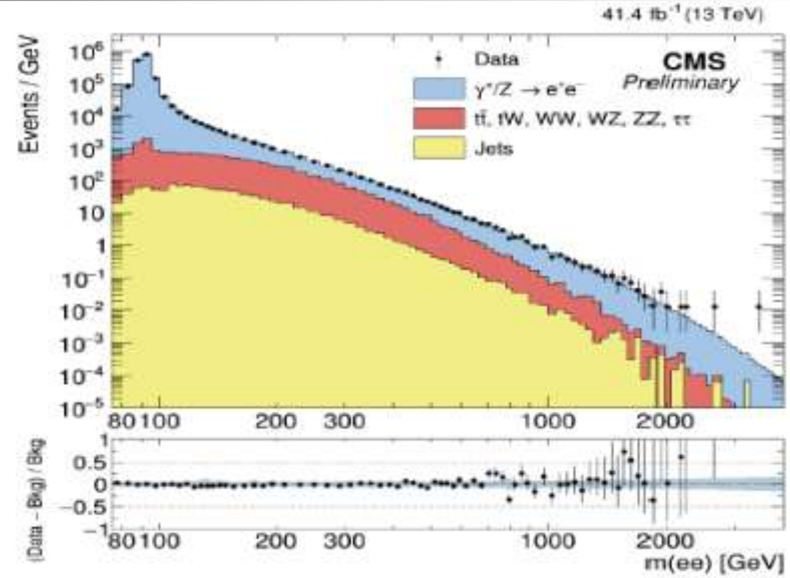
Example
pp→μμ +X



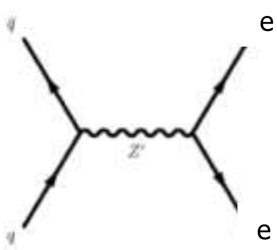


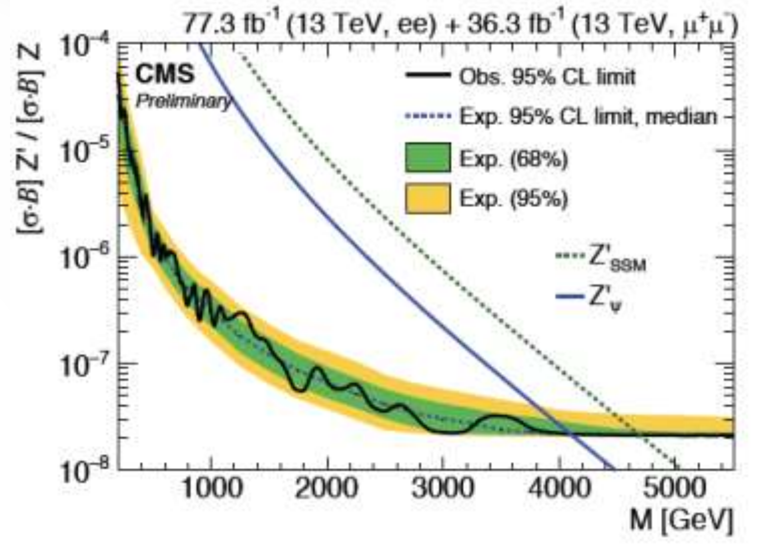
Lepton+MET/Dilepton Searches

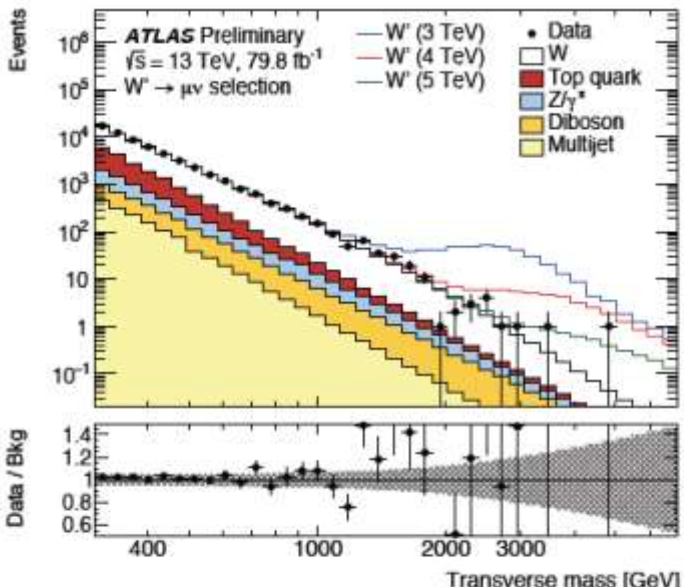
Search for dilepton resonances (Z'…) or lepton+MET (W'…) searches



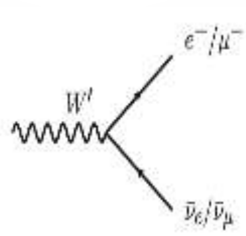
EXO-18-006







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})

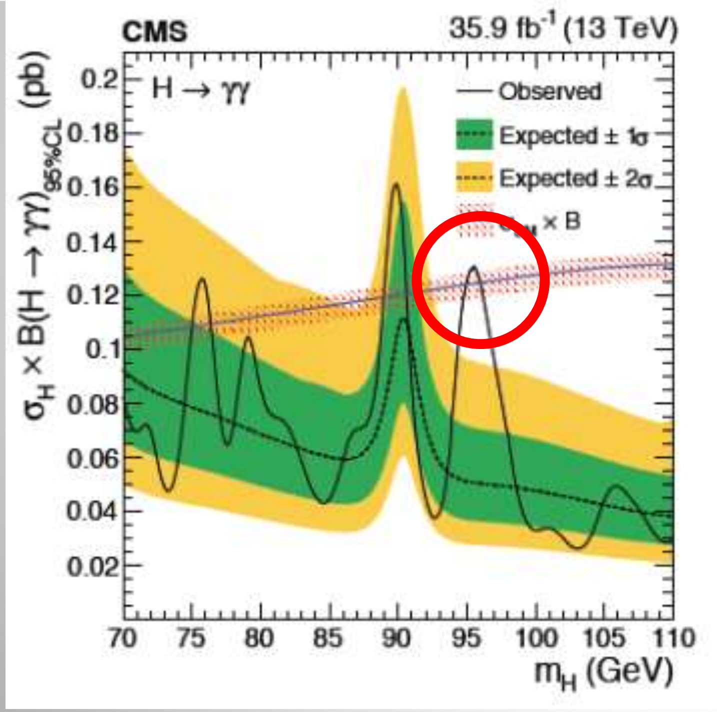
Do we see any deviations???

Low Mass Diphoton Spectrum

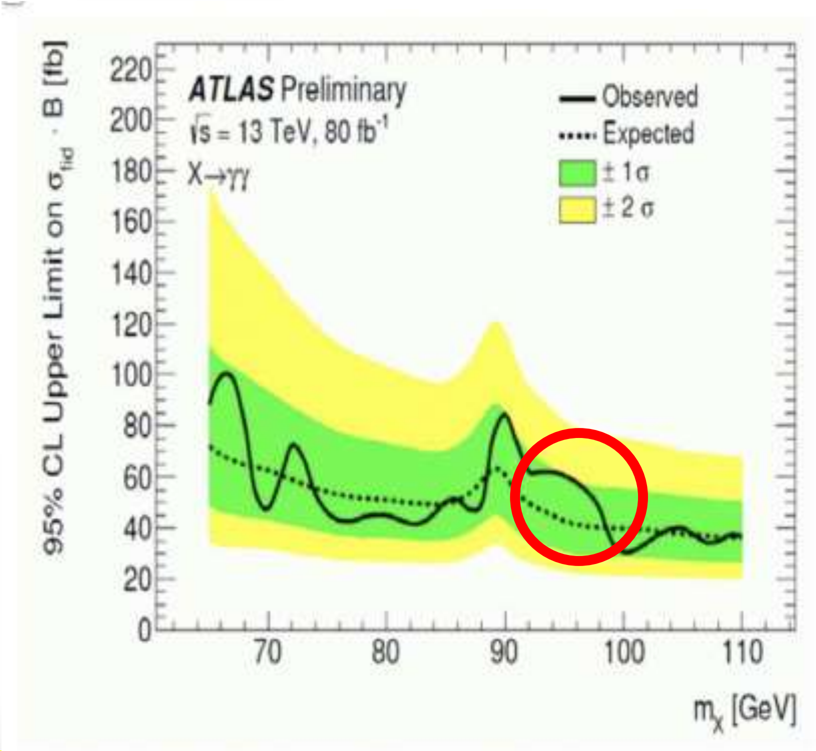
A search for X->γγ at low mass

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 local excess at 95.3 GeV

CMS-HIG-17-013



ATLAS-CONF-2018-025



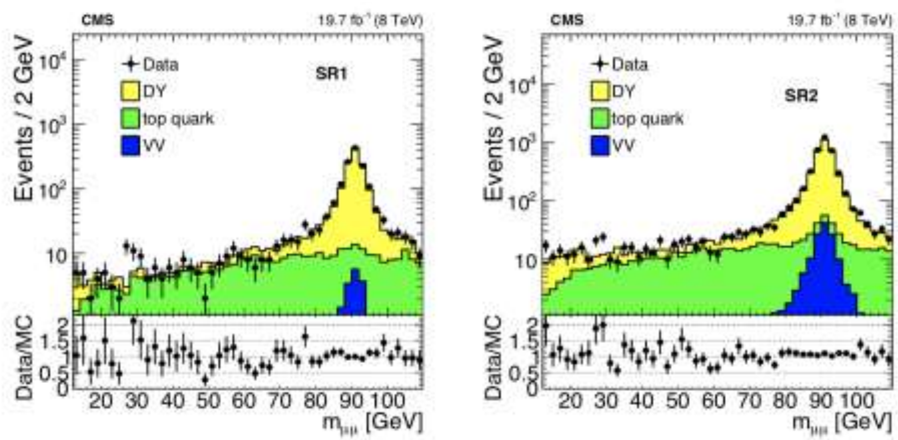
Probably not ☹ … ATLAS does not see the same size of effect…
Let's see with more data in future…

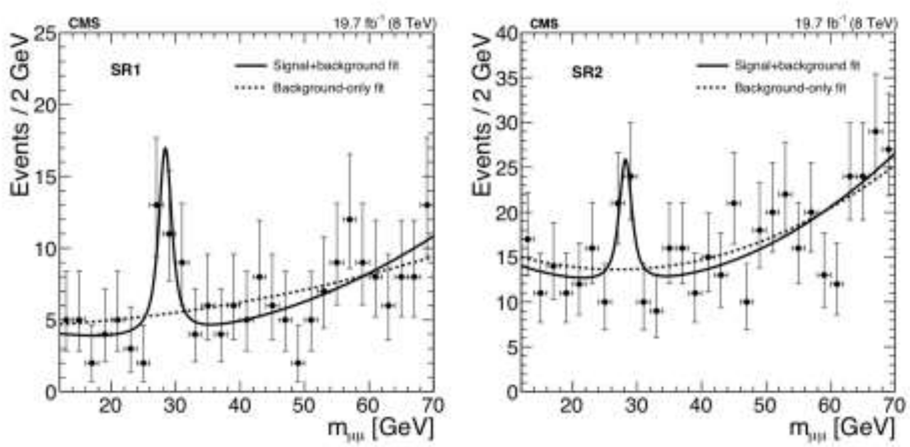
Search for New Resonances

arXiv:1808.01890

NMSSM Higgs inspired search in mass range 12-70 GeV
- Search for bump in muon pair mass spectrum with associated b-jets
- SR1: 2 muons + one central and one forward jets ($|\eta| > 2.4$), at least 1 b
- SR2: 2 muons + 2 central and no forward jets, at least 1 b

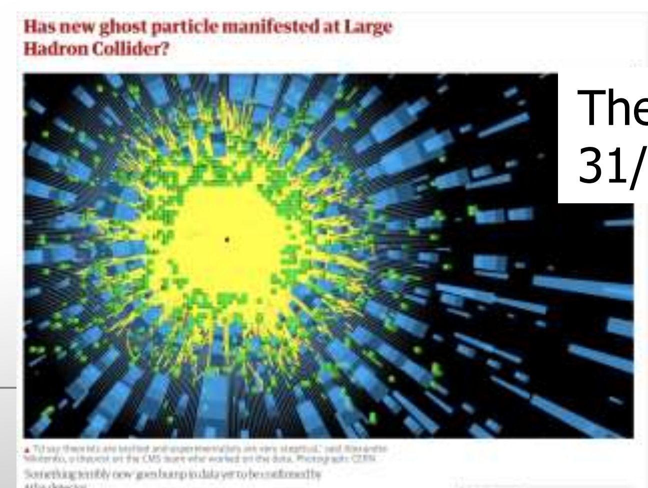
8 TeV Data





Both regions are independent
Excess seen in the both regions around 28 GeV

SR1: 4.2σ local significance
(~3.0σ global sign.)
SR2: 2.9σ local significance

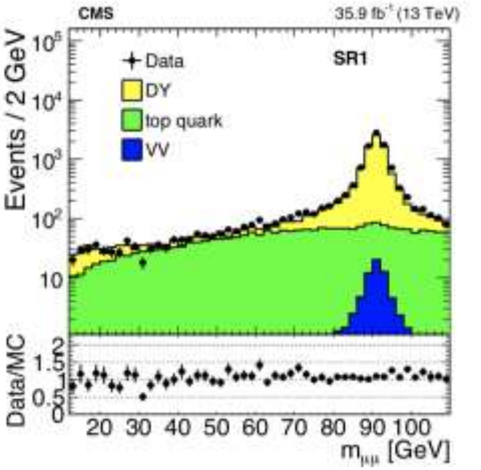


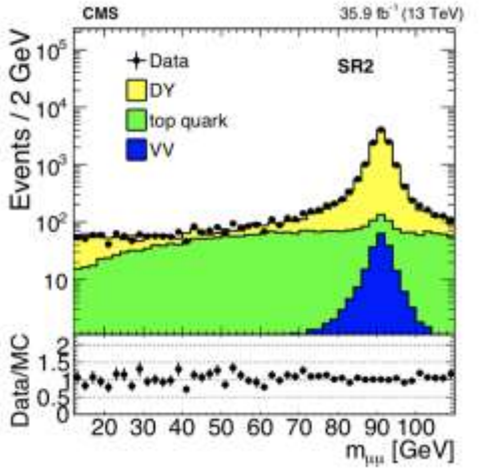
The Guardian
31/10/2018

Search for New Resonances

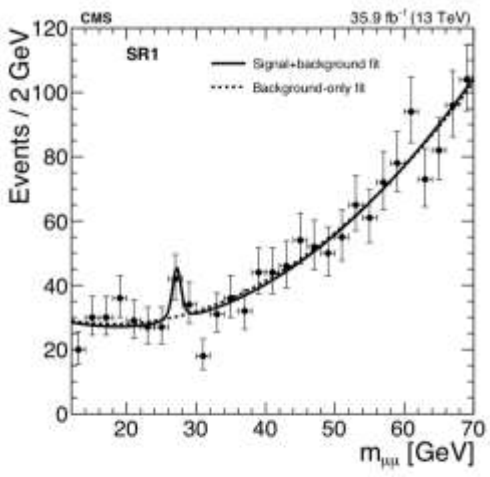
13 TeV Data

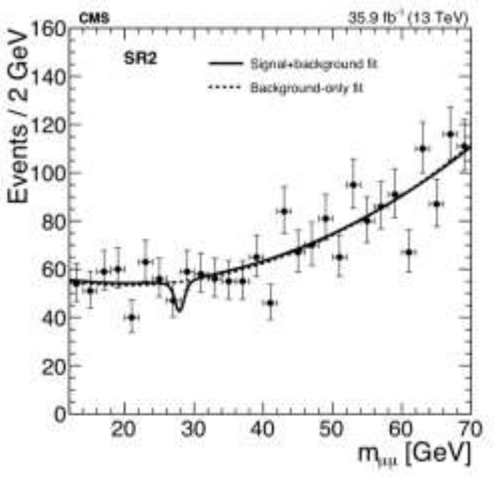
....No significant deviation..

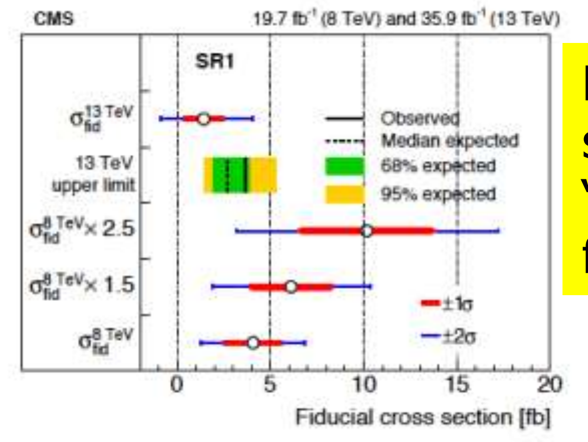




$\sqrt{s}$ (TeV)	8		13	
Event category	SR1	SR2	SR1	SR2
Local significance (s.d.)	4.2	2.9	2.0	1.4 deficit
N_S	22.0 ± 7.6	22.8 ± 9.5	14.5 ± 9.3	-14.9 ± 10.1
N_S observed upper limit at 95% CL	40.4	44.7	36.9	32.2
N_S expected upper limit at 95% CL	18.3	27.6	27.6	35.6
ε^{reco}	0.27 ± 0.01		0.28 ± 0.01	
Integrated luminosity, $\mathcal{L}$ (fb^{-1})	19.7 ± 0.5		35.9 ± 0.9	
σ_{fid} (fb)	4.1 ± 1.4	4.2 ± 1.7	1.4 ± 0.9	-1.5 ± 1.0
Observed upper limit at 95% CL (fb)	7.6	8.4	3.7	3.2
Expected upper limit at 95% CL (fb)	3.4	5.2	2.7	3.5







Fiducial cross section and 'prediction' for 13 TeV

Are the 13 TeV data a killjoy? ☺

ATLAS results @ 8 TeV?...

LHCb: Tests of Lepton Universality

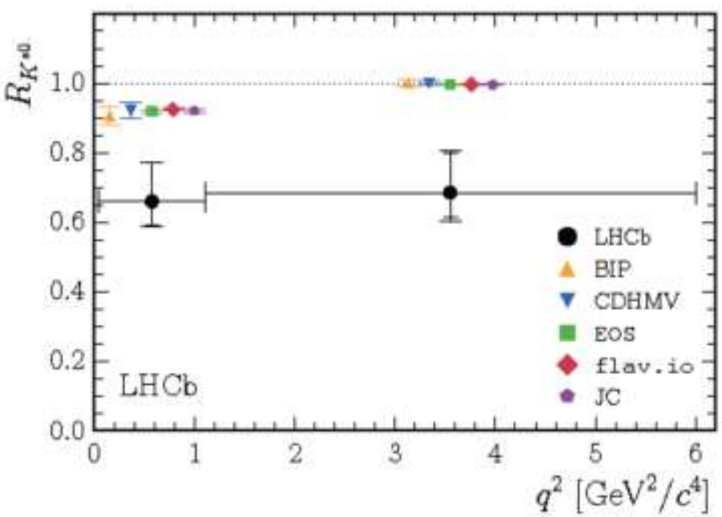
A few puzzling results from the LHCb experiment…

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



If confirmed, independent checks will become very important.
Belle II? ->in a few years form now

CMS has installed a special trigger to collect an unbiased b-sample which is active since 2018
-> about 10^{10} b-pairs collected during 2018 via parked data stream

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

2.1 - 2.3 σ
2.4 - 2.5 σ

?

LHCb Update eagerly awaited ☺ !!!

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

?

Updates from Moriond March '19

R_K result with 2011 to 2016 data LHCb-Paper-2019-009

LHCb Imperial College London

Using 2011 and 2012 LHCb data, R_K was:

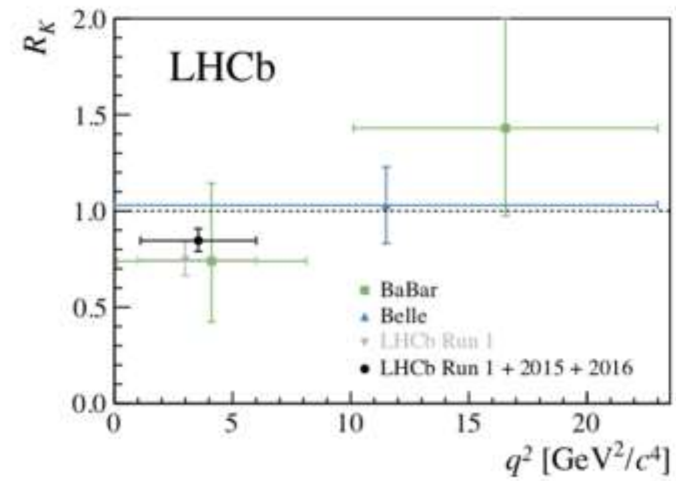
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.}),$$

$\sim 2.6\,\sigma$ from SM (PRL113(2014)151601).

Adding 2015 and 2016 data, R_K becomes:

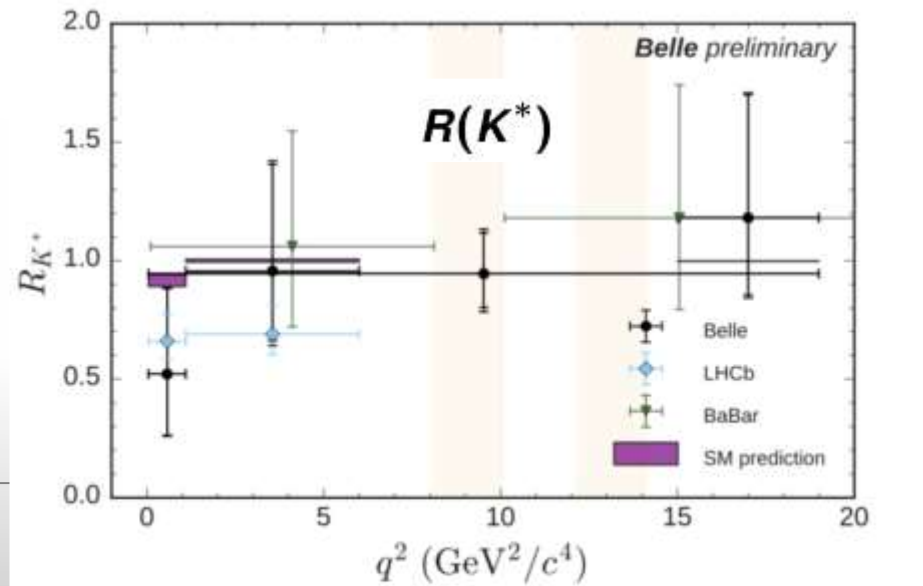
$$\mathbf{R_K = 0.846\ ^{+0.060}_{-0.054}(\text{stat.})\ ^{+0.016}_{-0.014}(\text{syst.})}$$

$\sim$ **2.5 σ** from SM.



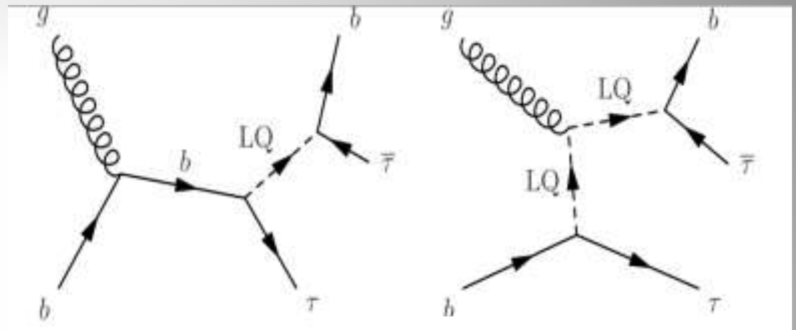
Updates presented at the Moriond winter conference:
- LHCb (R_K)
- Belle (R_{K*})

Effect did NOT become more significant ☹



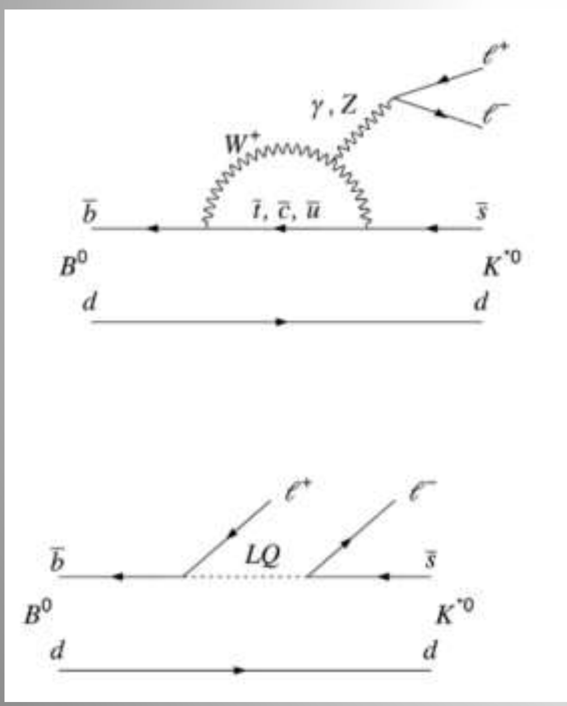
Third Generation Leptoquarks

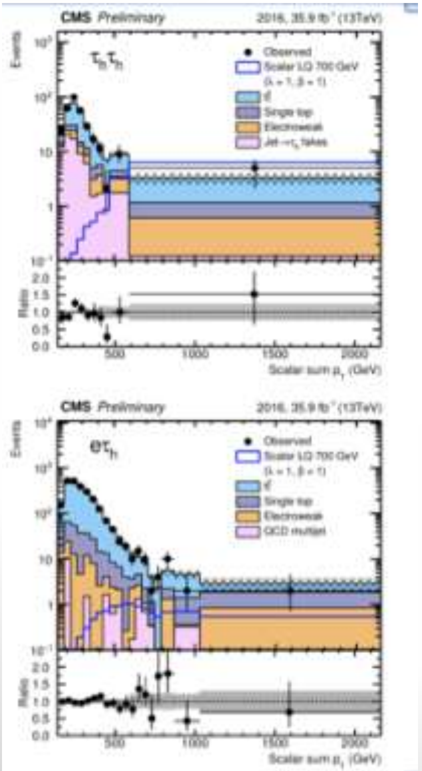
Candidate explanation: Leptoquarks with couplings to second/third generation.
-> Check in ATLAS and CMS

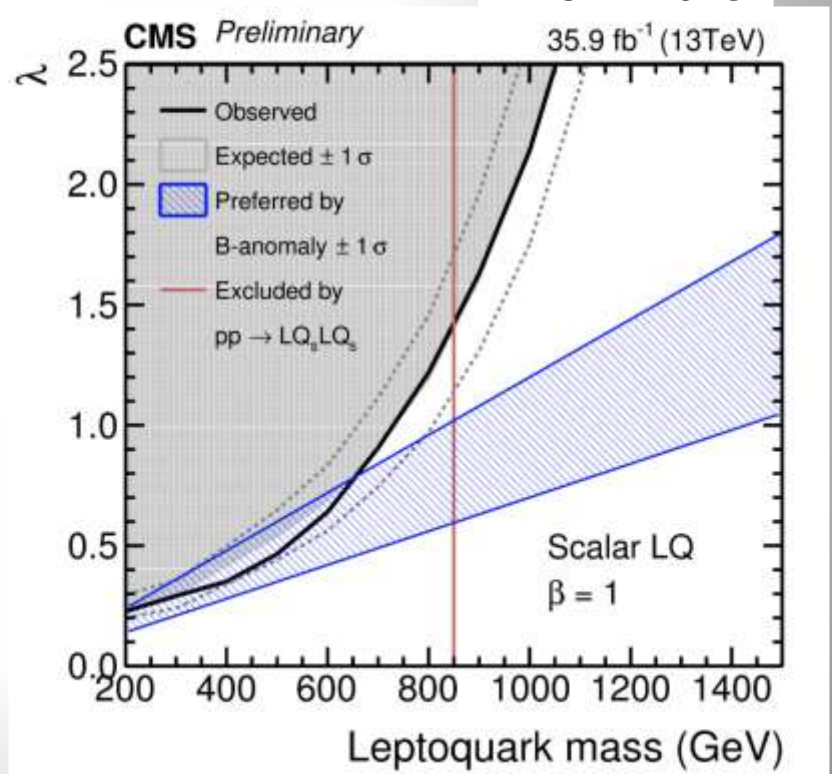


Example search in the tau-b final state

EXO-17-029







Blue region is preferred by the B-anomalies…

Exotica Searches: Limits

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

Status: March 2019

$\int \mathcal{L}\, dt = (3.2 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ 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	7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09127
	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	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW/ZZ \to qqqq$	0 e, μ	2 J	–	139	G_{KK} mass	2.8 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2019-003
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	Z' mass	3.0 TeV	$\Gamma/m = 1\%$	1804.10823
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	79.8	W' mass	5.6 TeV		ATLAS-CONF-2018-017
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass	3.7 TeV		1801.06992
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass	4.4 TeV	$g_V = 3$	ATLAS-CONF-2019-003
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass	2.93 TeV	$g_V = 3$	1712.06518
	LRSM $W'_R \to tb$	multi-channel			36.1	W' mass	3.25 TeV		1807.10473
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η^-_{LL}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ	40.0 TeV	η^-_{LL}	1707.02424
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi)$ = 1 GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 − 4 j	Yes	36.1	m_{med}	1.67 TeV	g=1.0, $m(\chi)$ = 1 GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_*	700 GeV	$m(\chi)$ < 150 GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1[st] gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass	1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2[nd] gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass	1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3[rd] gen	2 τ	2 b	–	36.1	LQ^u_3 mass	1.03 TeV	$\mathcal{B}(LQ^u_3 \to b\tau) = 1$	1902.08103
	Scalar LQ 3[rd] gen	0-1 e, μ	2 b	Yes	36.1	LQ^d_3 mass	970 GeV	$\mathcal{B}(LQ^d_3 \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass	1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass	1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	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	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2019-007
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass	2.6 TeV		1805.09299
	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	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass	560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H^{\pm\pm}_L \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

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

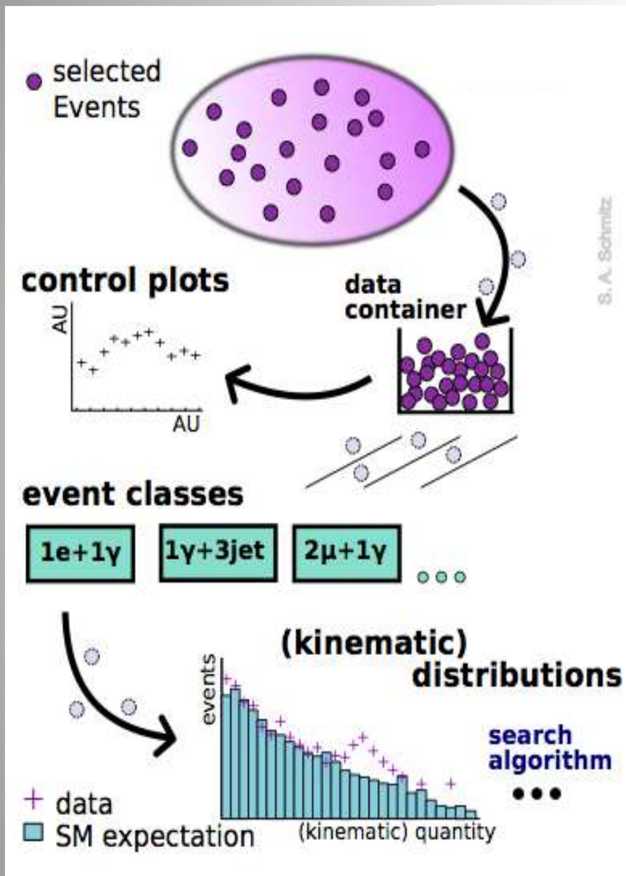
Legend: $\sqrt{s}$ = 8 TeV; $\sqrt{s}$ = 13 TeV partial data; $\sqrt{s}$ = 13 TeV full data

*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).

A Global View! Generic Searches

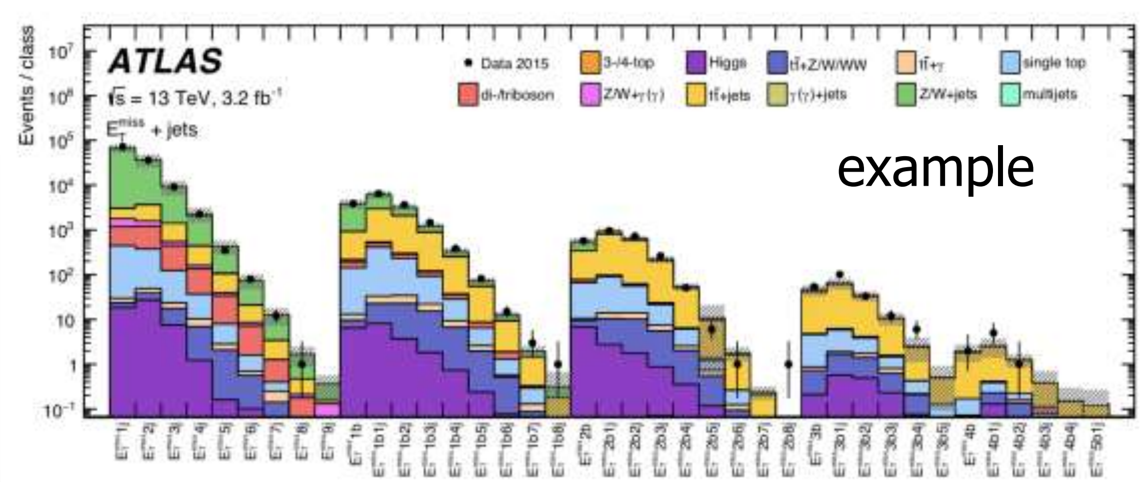
arXiv:1807.07447



Model independent search

- Divide events into exclusive classes
- Study deviations from SM predictions in a statistical way

Object	jet	b-jet	electron	muon	photon	E_T^{miss}
Label	j	b	e	μ	γ	E_T^{miss}
p_T (min) [GeV]	60	60	25	25	50	200



2.5 fb^{-1}/13 TeV (>700 classes)
→Checking for bumps in invariant and effective mass of objects

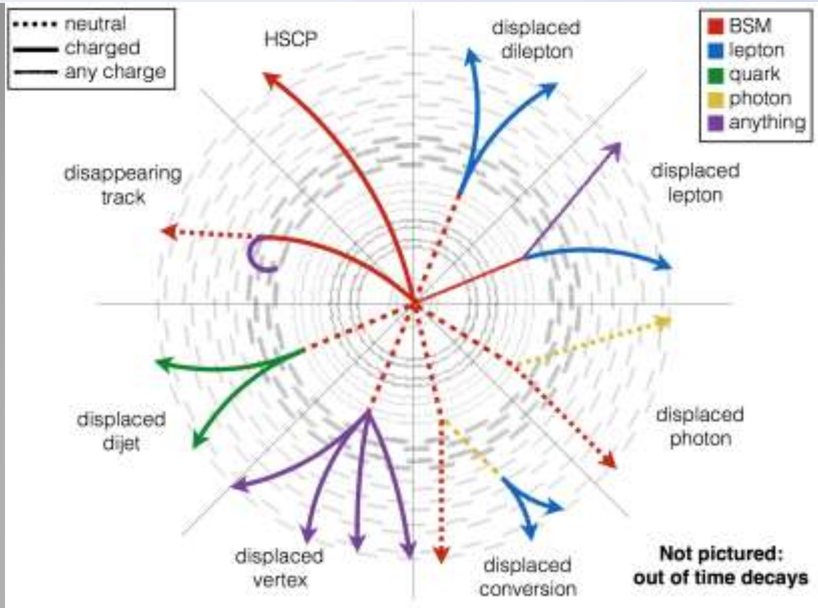
No significant deviation found

Beyond what is expected from statistics

Are we leaving no stone unturned?

- The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics (higher mass, lower couplings)
- But if we still do not see more than a 2 sigma at the end of run-3, the HL-LHC will be likely mostly a precision physics machine, searching for subtle deviations
- Are we looking at the right place? Time for more effort in thinking of complementary searches?

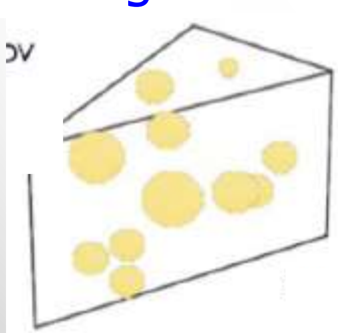
Searches for Long Lived Particles

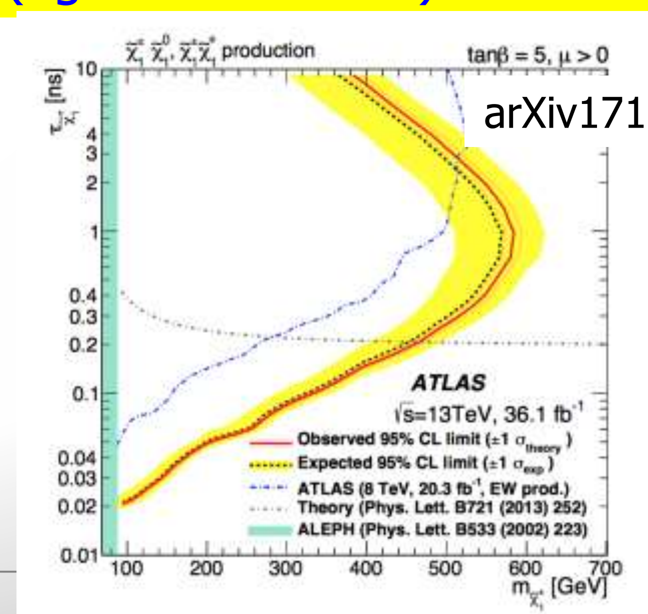


Increasing interest and effort:
Look for unusual signals in the detector from long-lived particles

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

Present coverage?



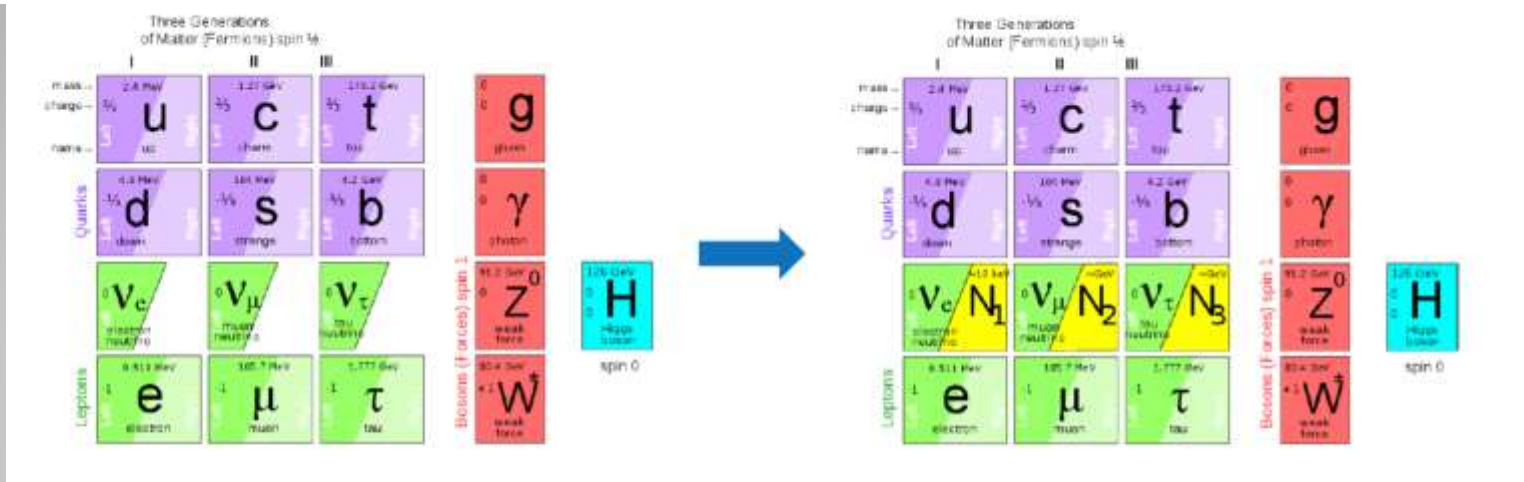


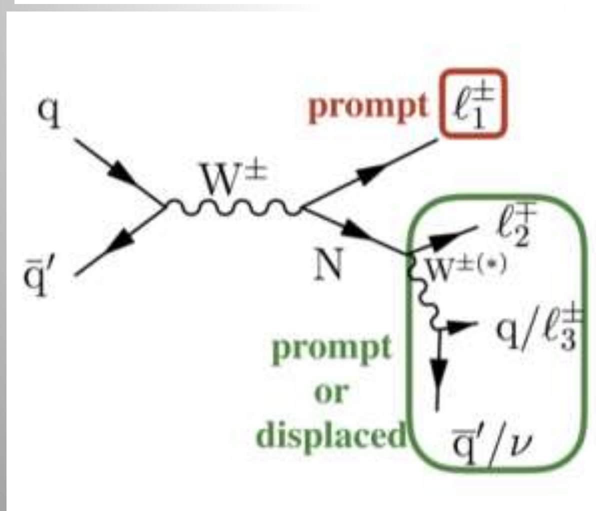
arXiv1712.02118

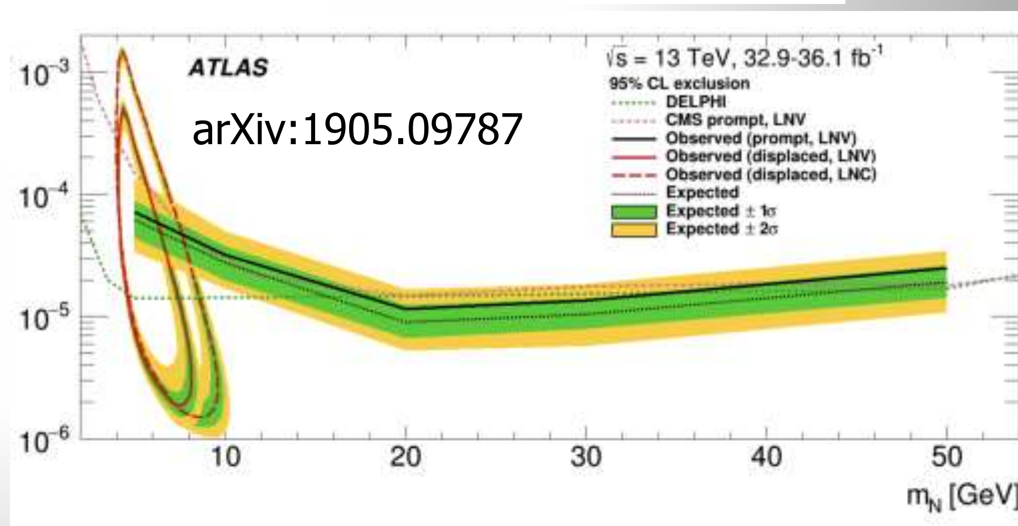
LHC-wide organized study ->
https://indico.cern.ch/e/LHC_LLP_October_2017

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.



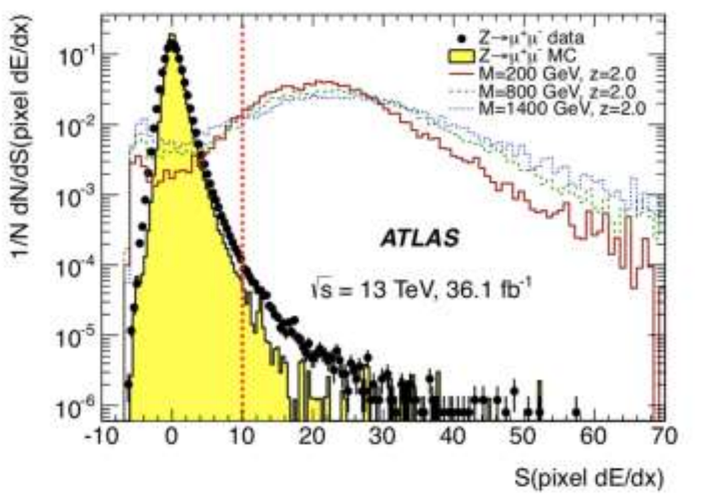




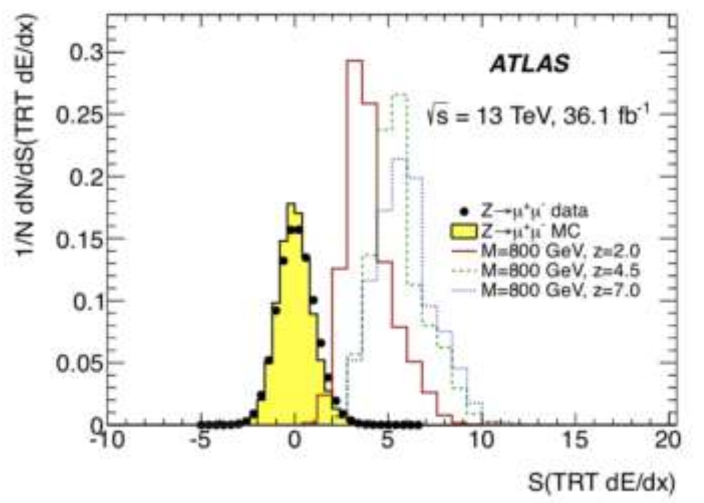
-> HNL hunting also focus of the SHIP experiment proposal

Multi Charged Particles

Pixel tracker

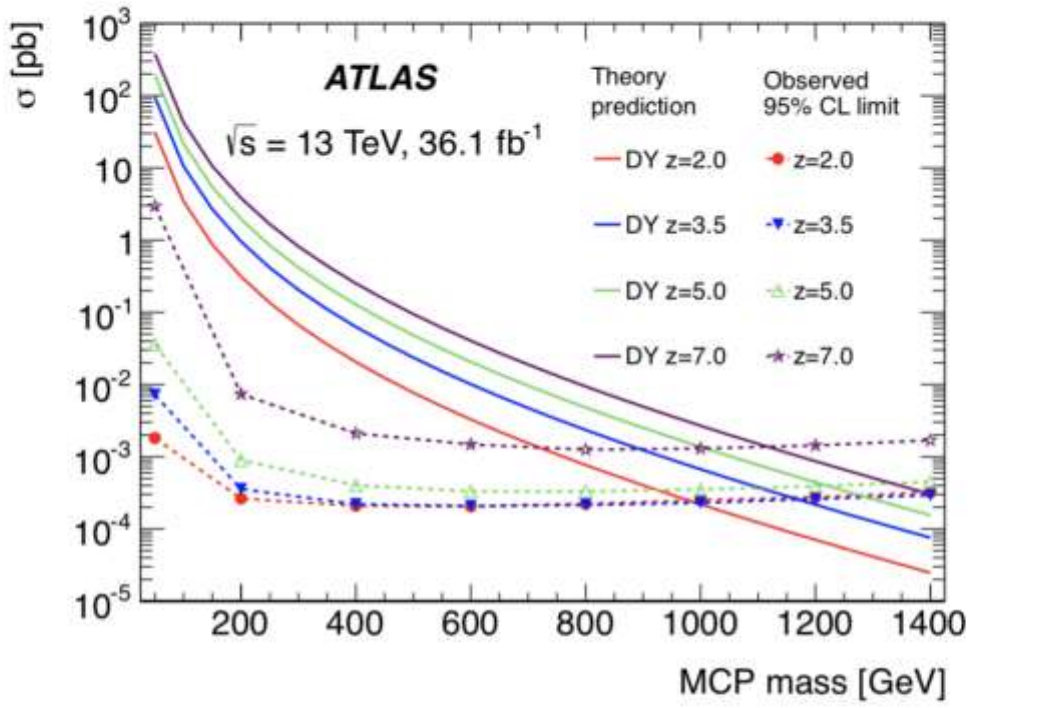


TRT tracker



Use central tracker and de/dx measurement to search for particles with electric charges of 2e to 7e

arXiv:1812.03673



Exclusion between 50 GeV and 980-1220 GeV

LHC Community White Paper

Web page: https://indico.cern.ch/event/649760

Searches for long-lived particles at the LHC: Second workshop of the LHC LLP Community

17 Oct 2017, 16:00 → 20 Oct 2017, 18:00 Europe/Zurich

Giambiagi Lecture Hall (ICTP, Trieste, Italy)

Albert De Roeck (CERN), Bobby Samir Acharya (Abdus Salam Int. Cent. Theor. Phys. (IT)), Brian Shuve (SLAC National Accelerator Laboratory), James Beacham (Ohio State University (US)), Xabier Cid Vidal (Universidade de Santiago de Compostela)

Next workshop: 27-29 May 2019 CERN

White paper — chapter statuses and roundtable
[draft here (18 Oct)]

- Simplifed models — First draft done!
- Experimental coverage — First draft essentially done!
- Triggers, upgrades, HL- / HE-LHC opportunities
  — First draft in progress
  —> discussion today [live doc!]
- Re-interpretations / recommendations
  — First draft imminent!
- Backgrounds — First draft imminent!
- Dark showers
  — First draft (summarizing status and advertising for

White Paper being finalized

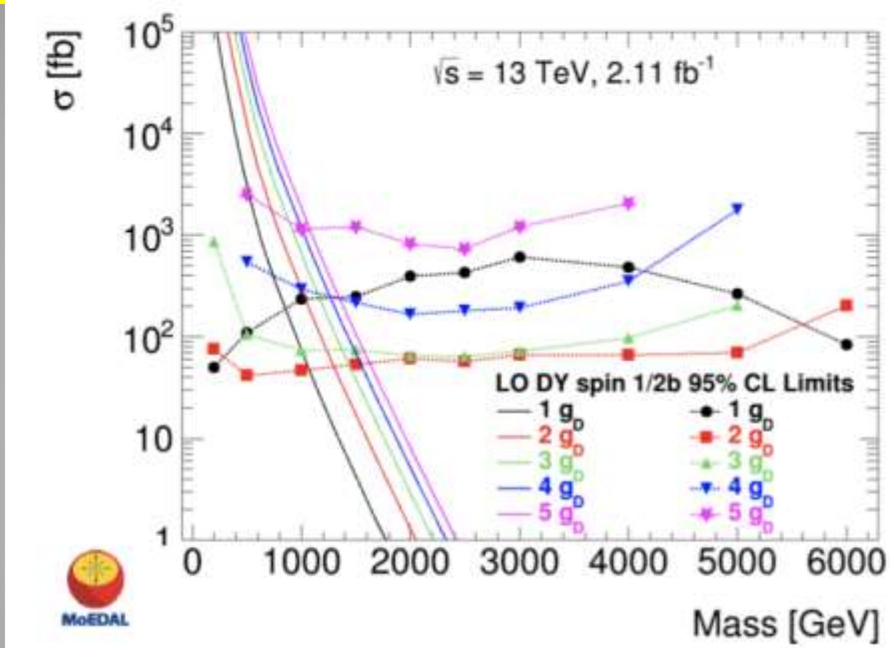
Input from ATLAS, CMS, LHCb, proposed specialized experiments and theory

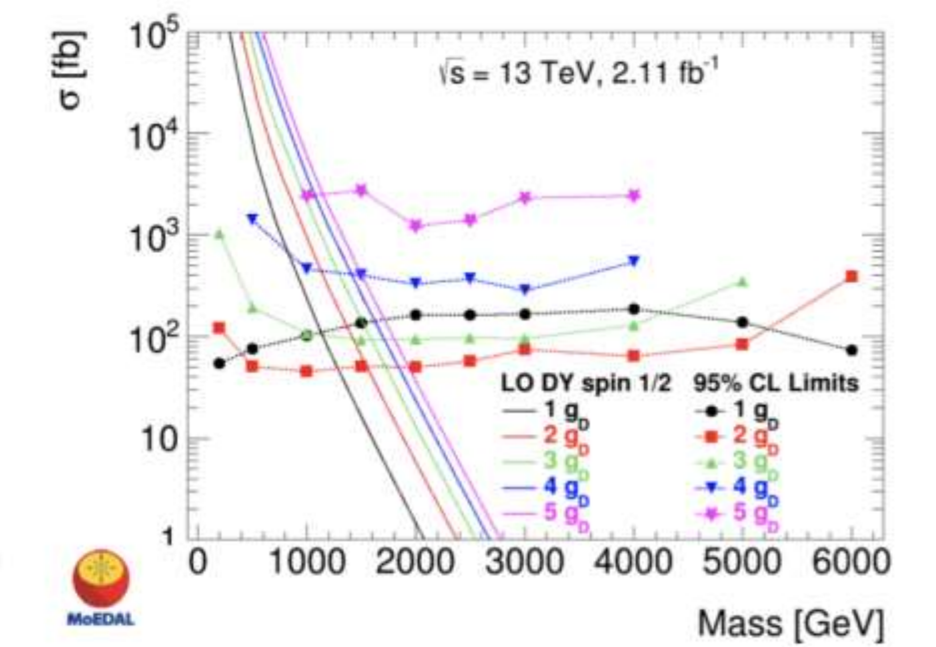
Completed March 2019
(~ 300 pages)

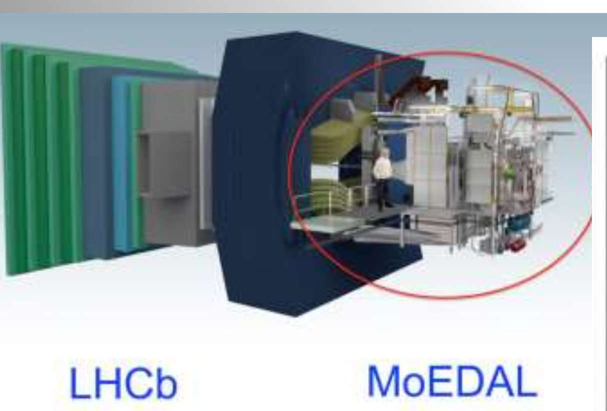
arXiv:1903.04497

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







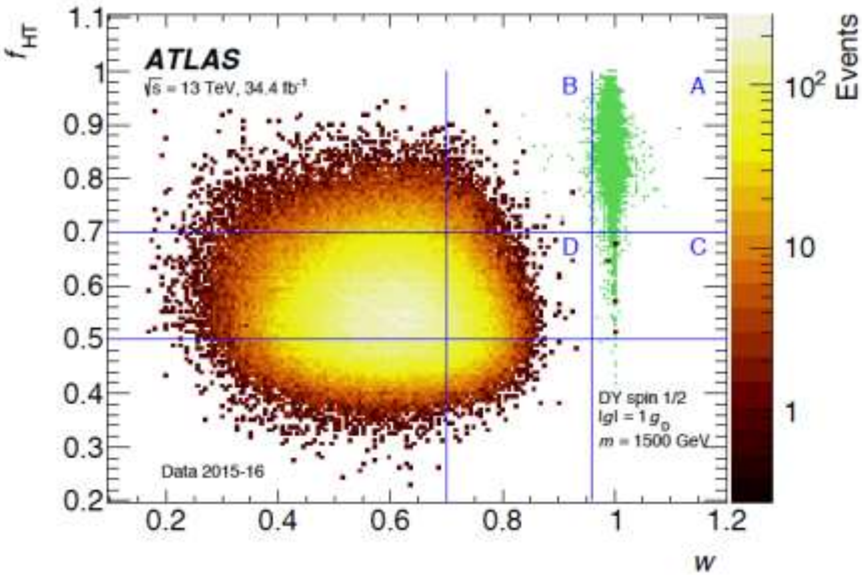
Mass limits [GeV]	$1g_D$	$2g_D$	$3g_D$	$4g_D$	$5g_D$
MoEDAL 13 TeV (2016 exposure)					
DY spin-0	600	1000	1080	950	690
DY spin-$\frac{1}{2}$	1110	1540	1600	1400	–
DY spin-1	1110	1640	1790	1710	1570
DY spin-0 β-dep.	490	880	960	890	690
DY spin-$\frac{1}{2}$ β-dep.	850	1300	1380	1250	1070
DY spin-1 β-dep.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

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

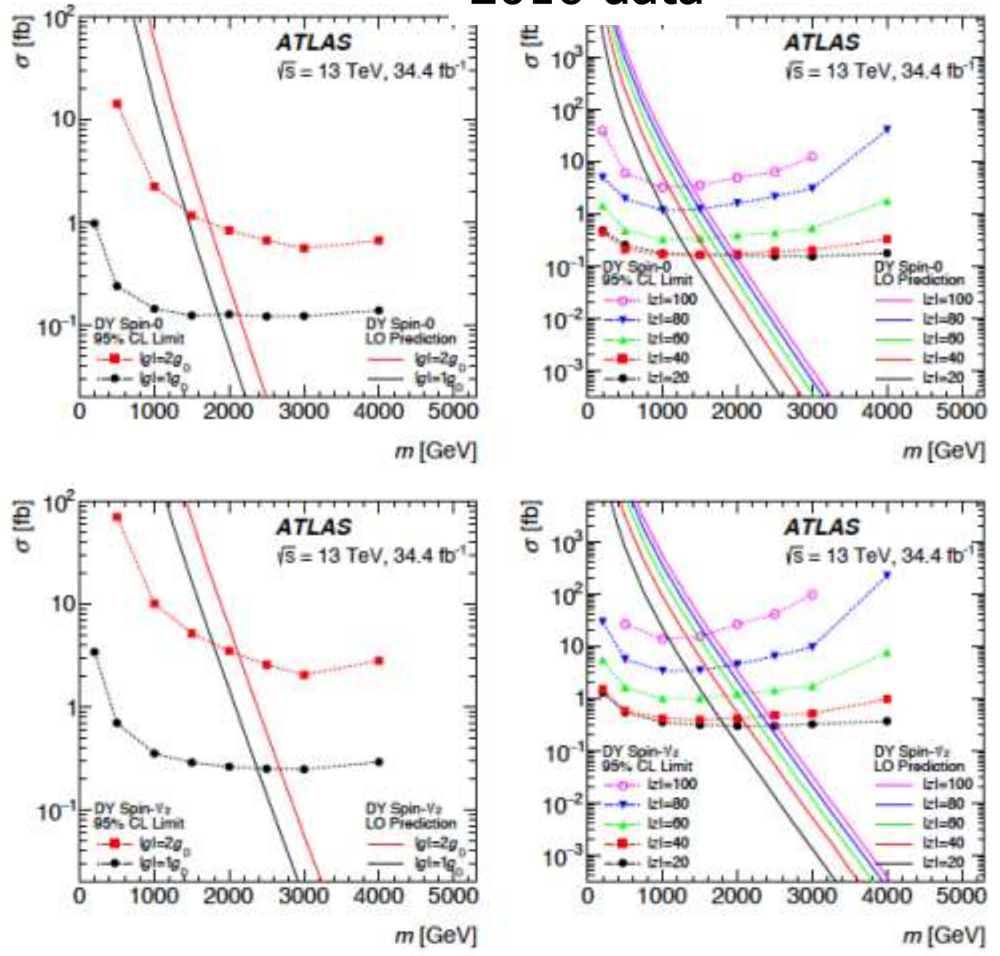
New: ATLAS Monopole Search

arXiv:1903.08491

Use high ionization in the transition radiation tracker and pencil-like energy deposit in the ECAL



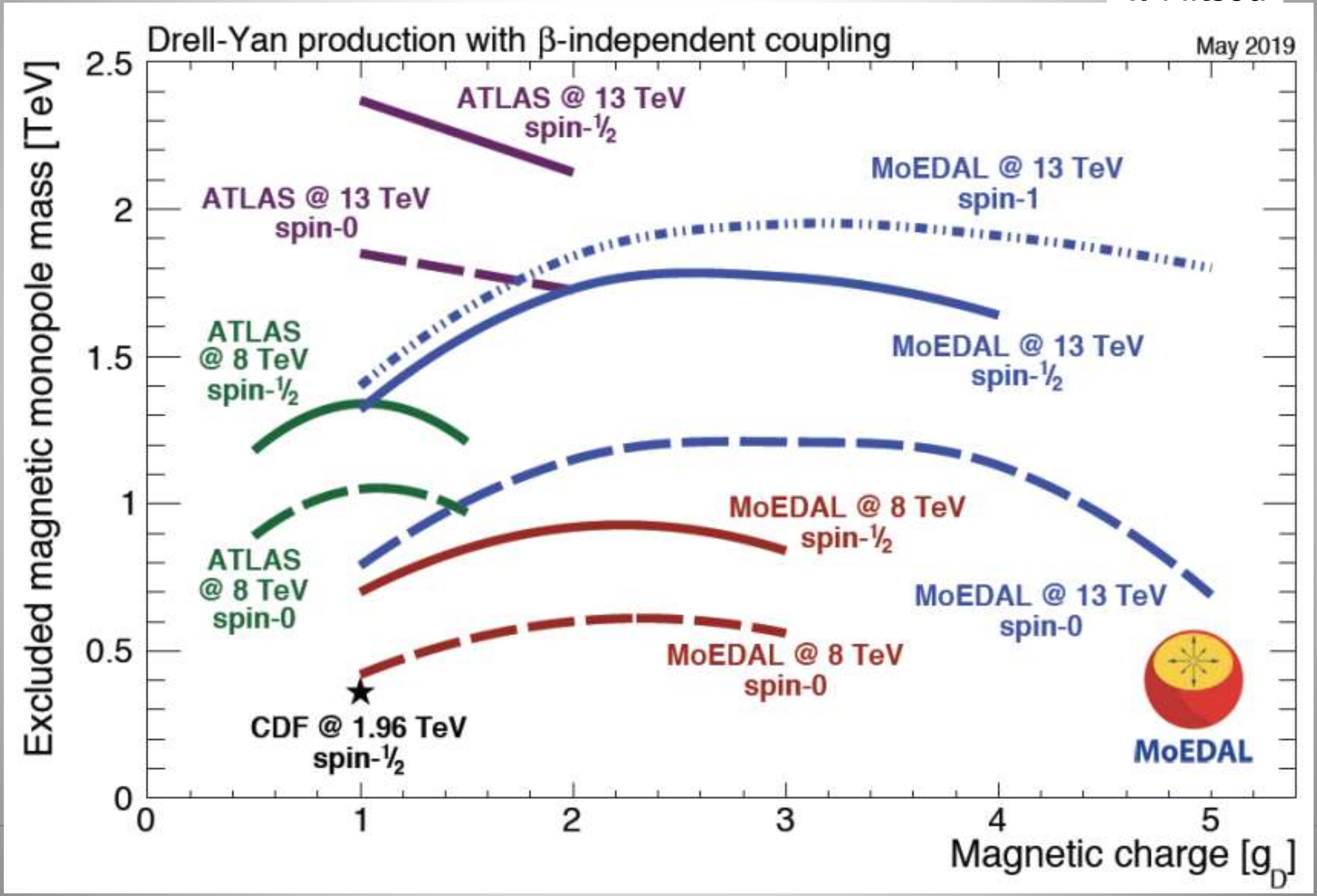
2016 data



Results interpreted via Drell-Yan production for Dirac charges 1 and 2

LHC Monopole Searches

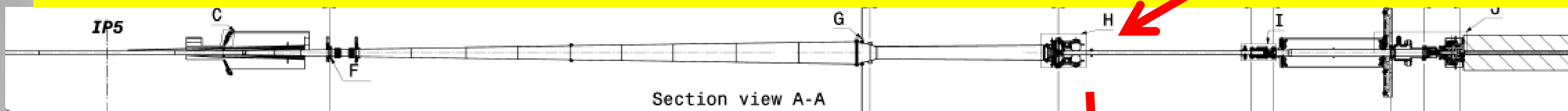
V. Mitsou



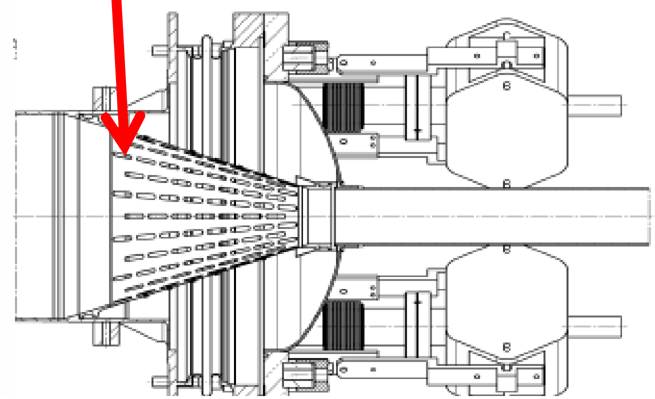
Monopoles Stopped in the Beampipe

ADR et al., Eur. Phys .J. C72 (2012) 2212

Test performed with pieces of material from the LHC from 18 m away from the interaction region



$|g| \geq 4g_D$

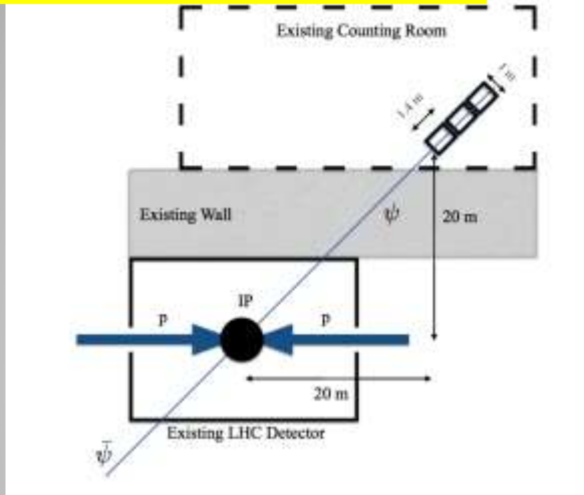


Faulty connecting "fingers" were removed and scanned in a SQUID in Zurich

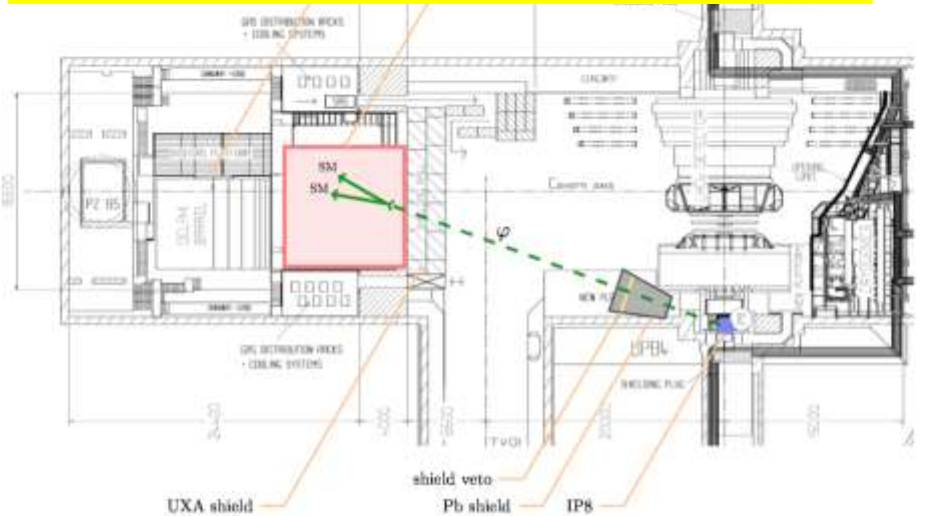
Want to use the 2012 CMS beampipe! MoEDAL officially got it since 18/2/2019!!
A beampipe analysis effort has been put into place in MoEDAL
-> The analysis preparation effort is starting now

Proposals for New Experiments @LHC

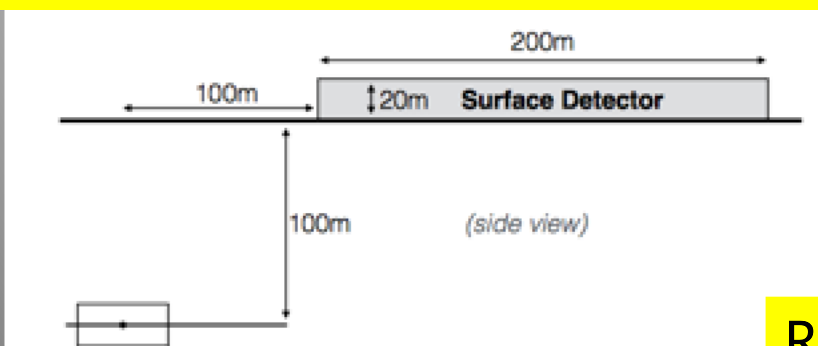
MilliQan: searches for millicharged particles



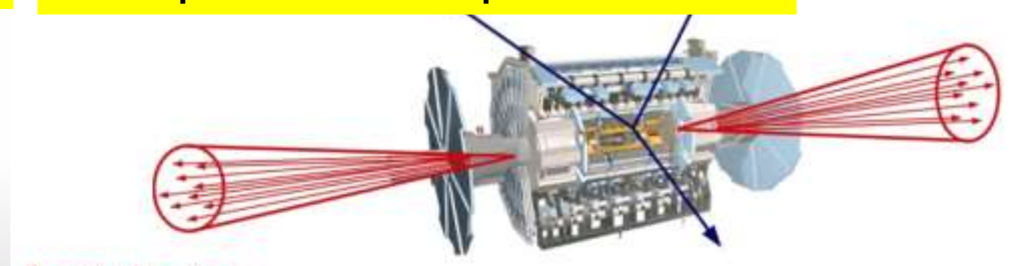
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles

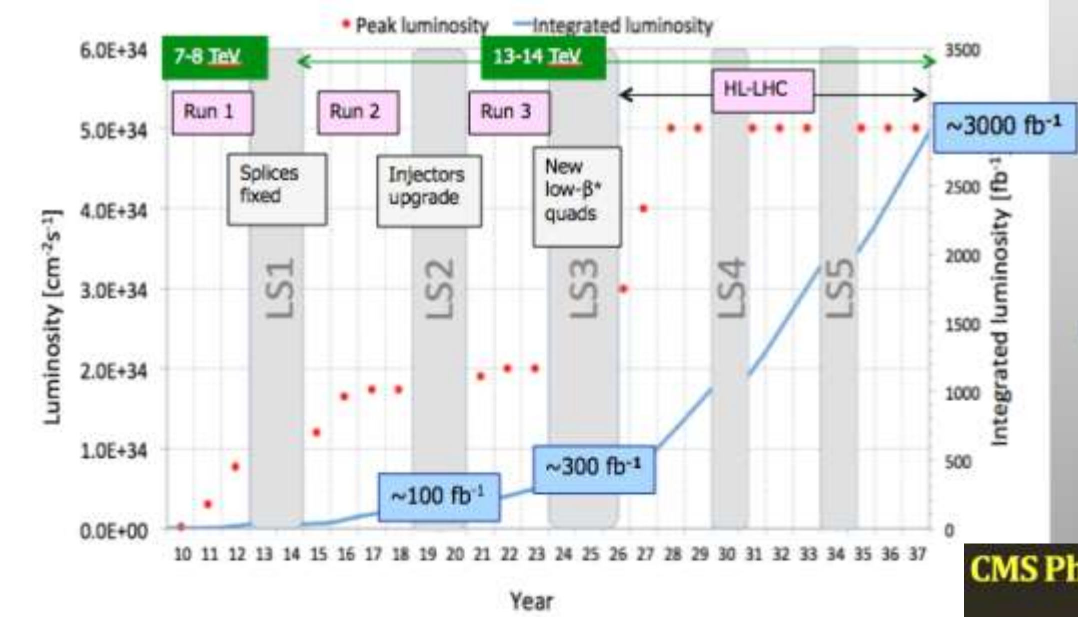


FASER: searches for long lived dark photons-like particles



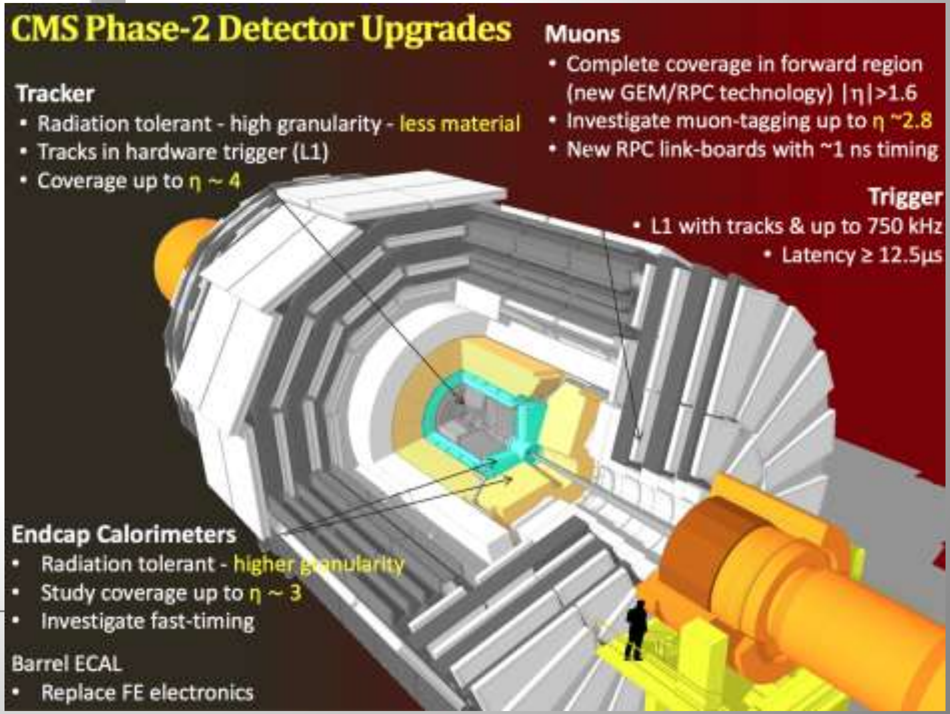
Recent also AL3X (re-use of ALICE for LLP)…

LHC Outlook and Plans



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

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 ~5% of the collisions delivered so far…
Then a high energy LHC (28 TeV)?
This option is discussed @ CERN..

Summary

- Measurements of Standard Model processes show good agreement with predictions. Precise measurements require precise calculations.
- New Higgs measurements at 13 TeV. So far the Higgs is very consistent with Standard Model expectations. All main decay and production channels now observed
- 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 few 3-sigma effects…
- Dark Matter and lonmg lived particle searches are being explored in a systematic way.
- New physics in the flavour sector? New TH para
- The LHC is continuing to explore the Terascale.
significant deviation to show the way!! Collected
13 TeV . …And hopefully one day soon now: