# New Results from the LHC

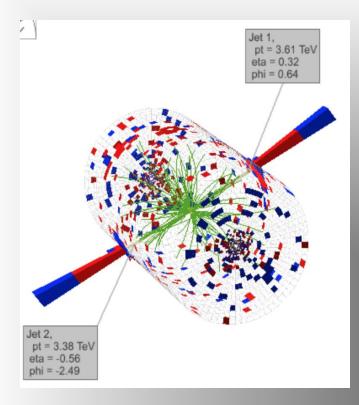
Albert De Roeck CERN, Geneva, Switzerland Antwerp University Belgium UC-Davis California USA NTU, Singapore

4<sup>th</sup> September 2

#### Corfu Summer Institute

18th Hellenic School and Workshops on Elementary Particle Physics and Gravity Corfu, Greece 2018





#### Bird-eyes view on new results Mostly from CMS and ATLAS...

Details in the specific talks at this conference

# Outline

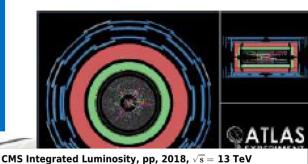
- Introduction
- Physics results
  - •The Standard Model
  - The Higgs particle
    Searches for New Physics & Dark Matter
  - •New opportunities at the LHC?
  - Summary/Outlook

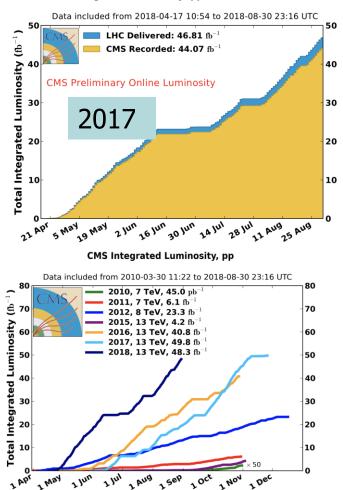
#### LHC experiments are back in business at a new record energy 13 TeV

#### 3<sup>rd</sup> June 2015 Run-2 starts



2010-2012: Run-1 at 7/8 TeV CM energy
Collected ~ 25 fb<sup>-1</sup>
2015-2018: Run-2 at 13 TeV CM Energy
Collected so far at 13 TeV:~ 130 fb<sup>-1</sup>
Expected by end of 2018: ~ 150+ fb<sup>-1</sup>





Date (UTC)

#### It Started (first attempt) in September 2008!

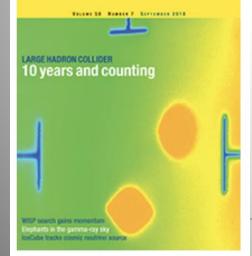


#### The day the world switched on to particle physics

When the Large Hadron Collider circulated its first protons 10 years ago, it made headlines around the globe. What was it that drove one of the biggest media events science has ever seen, and is the LHC still able to capture the public imagination?

#### CERNCOURIER

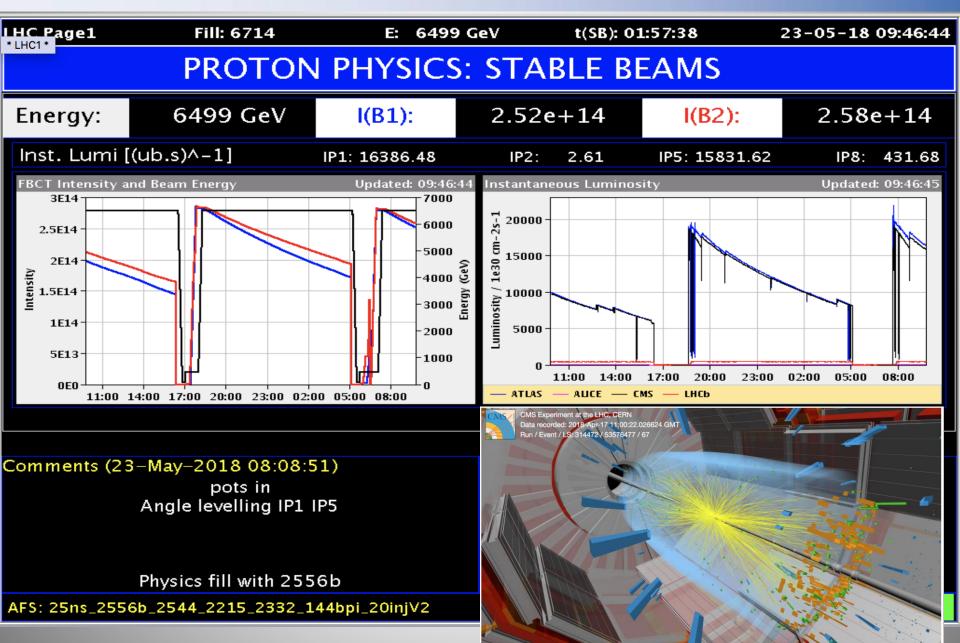
#### Available since yesterday: Cern Courier September 2018



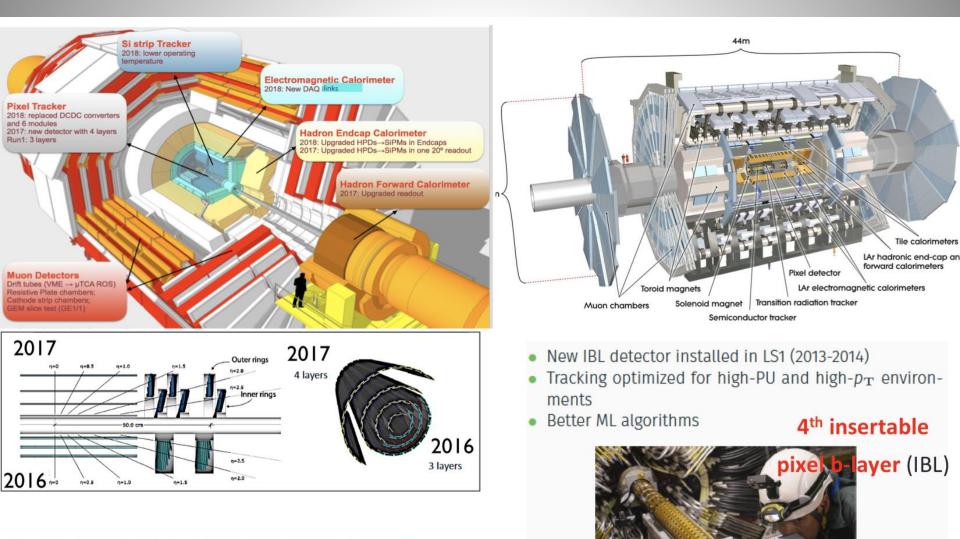


Top: scenes from first-beam day in the ATLAS (left) and CMS control rooms. Although there were no collisions that day, the experiments were able to record "splash" events – whereby protons strike a collimator and spray secondary particles into the detectors.

### LHC Operation 2018: Going Very Well!!



### ATLAS & CMS Experiments in 2018/17



Large impact on b-tagging performance

N. De Filippis

### **Detector Status**

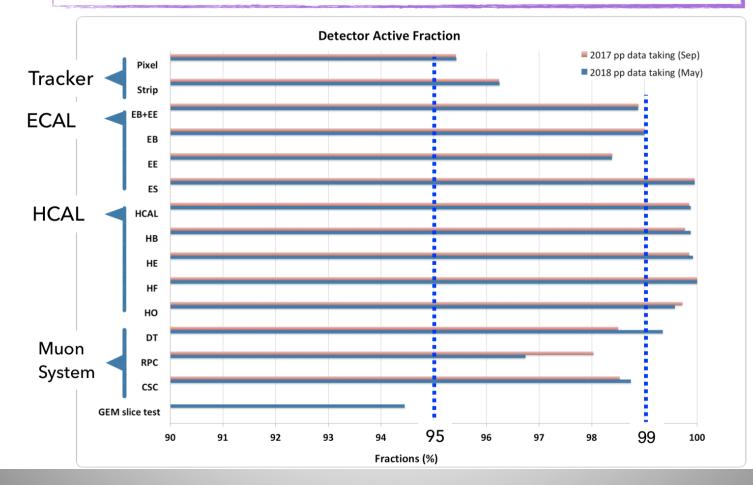
#### Example CMS



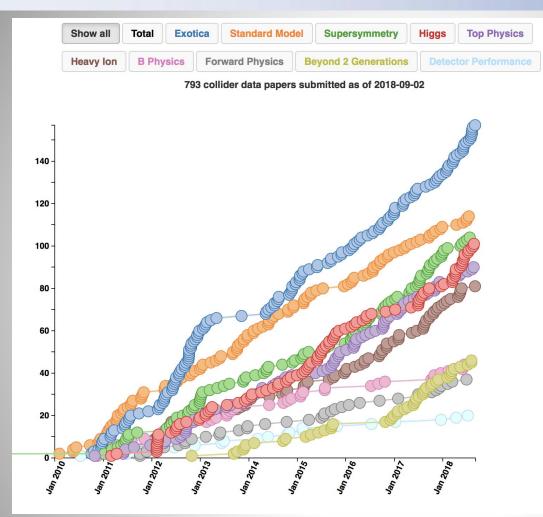
#### **CMS** Detector Status



Fractions of active channels high and stable since many years



# LHC Publications: Example CMS

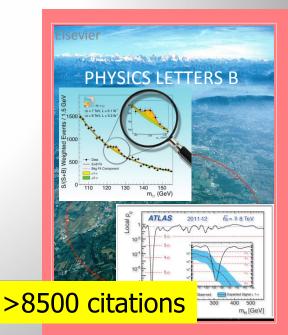


http://cms-results.web.cern.ch/cmsresults/public-results/publications-vs-time/

#### Similar for ATLAS

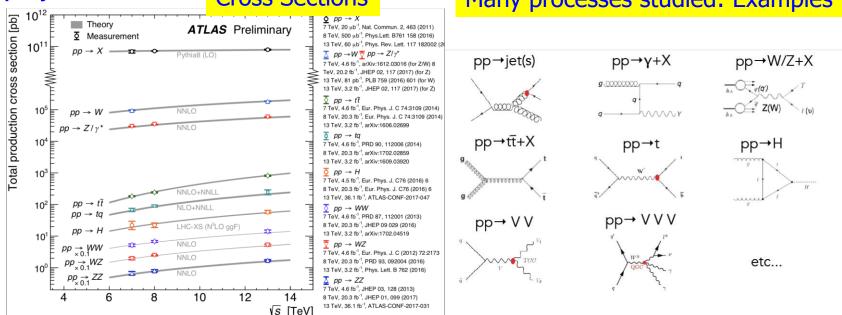
~ 800 publications on pp (and pPb/PbPb) physics since 1/2010

About 100 papers on Higgs studies!! Paper 16 was the discovery paper!



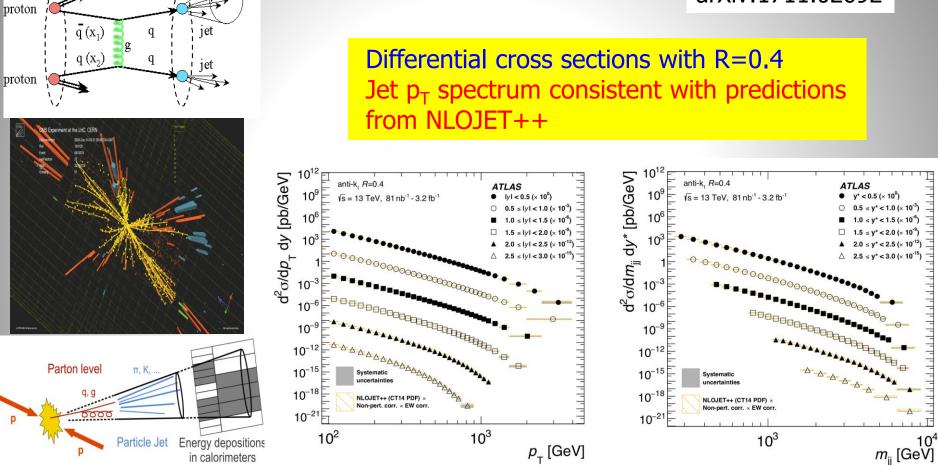
### **Standard Model Measurements**

- Standard Model measurements forms an important part of the physics program of the LHC!!
- Precision measurements allow test for a wide range of SM predictions, and extract fundamental parameters (eg  $\alpha_s$ )
  - Requires matching precision at theory prediction side
- Important to understand backgrounds for searches for new physics
   Cross Sections
   Many processes studied: Examples



### **Inclusive Jet Production (13 TeV)**

arXiv:1711.02692



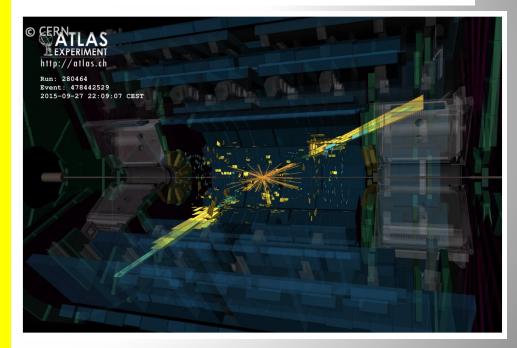
Agreement with NLO calculations over the full range, up to and beyond 2 TeV  $p_T$  jets... QCD predictions work well...

### **Jet Studies**

#### Plenty of studies with jets!

**Examples of studies/results**  Azimuthal correlations Multi-jet production Jet substructure and boosted jet analyses Forward jet production Strong coupling constant  $\alpha_{s}$  determination PDF sensitivity and extraction

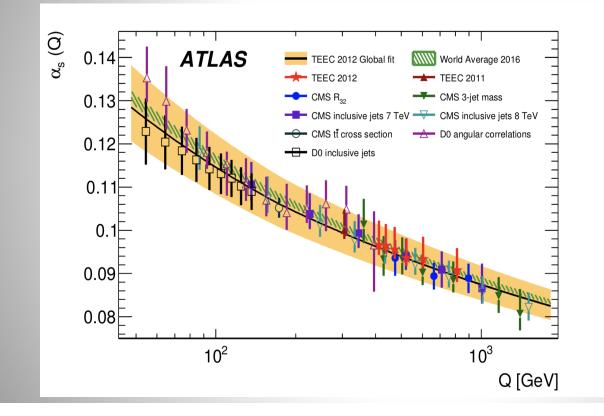
#### Dijet invariant mass = 7.9 TeV



The highest mass ATLAS dijet event recorded in 2015

### **Determination of alpha\_s**

Many ways to extract alpha\_s : 3/2 jet ratios, inclusive jets, tt-cross section. Here: transverse energy-energy correlations and associated asymmetries in multi-jet events. Select events with 2 leading jets with total H<sub>T</sub> > 800 GeV



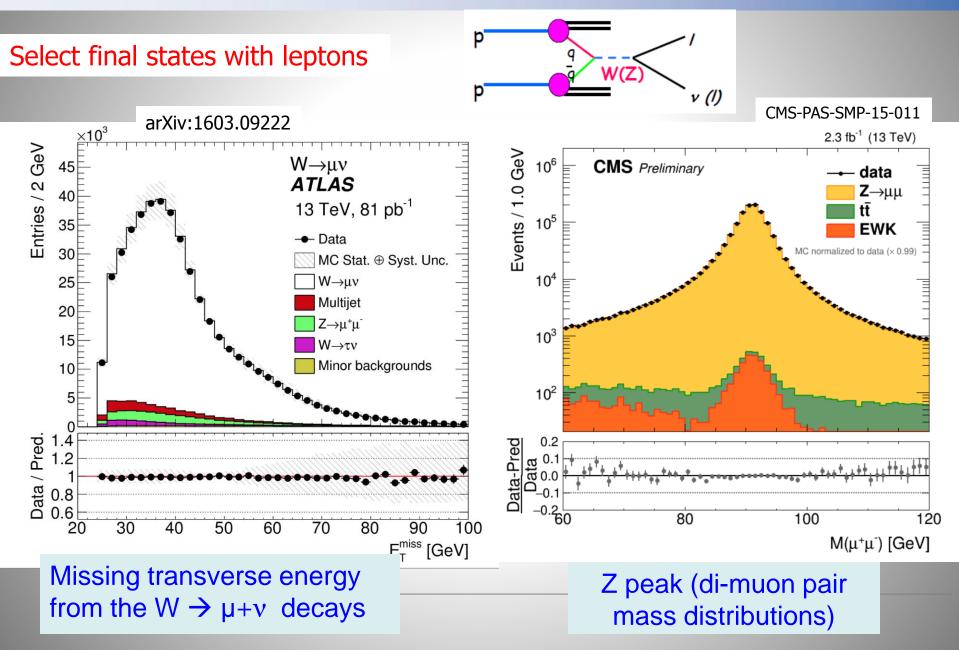


8 TeV analysis
NLO extractions
Theory uncert. dominate

ATEEC is the difference between the forward and backward TEEC

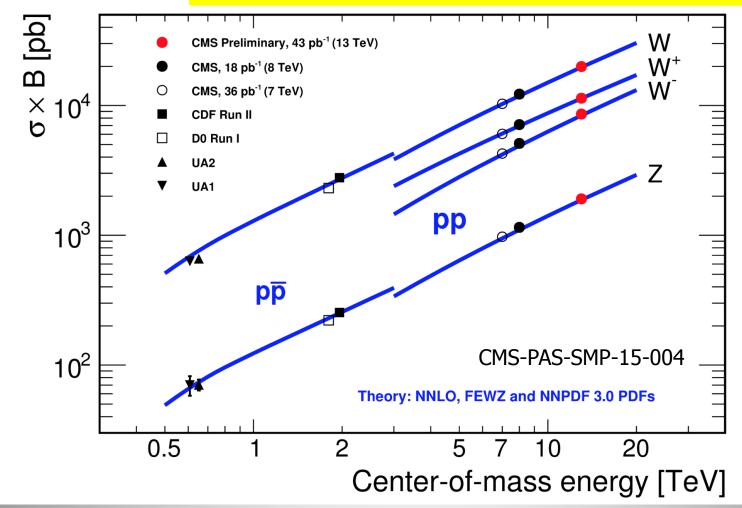
 $\alpha_{\rm s}(m_Z) = 0.1162 \pm 0.0011 \text{ (exp.)} {}^{+0.0076}_{-0.0061} \text{ (scale)} \pm 0.0018 \text{ (PDF)} \pm 0.0003 \text{ (NP)}, \text{ TEECs}$  $\alpha_{\rm s}(m_Z) = 0.1196 \pm 0.0013 \text{ (exp.)} {}^{+0.0061}_{-0.0013} \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0004 \text{ (NP)}, \text{ ATEECs}$ 

#### W and Z Boson Production



### W and Z Boson Production

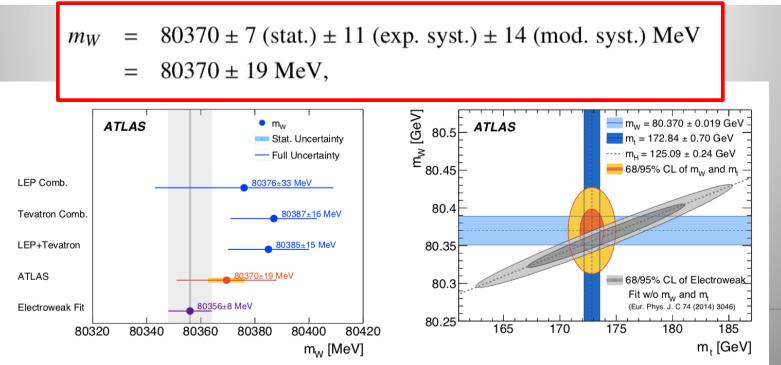
Measurements at 7/8/13 TeV with a precision of 3-4% ->dominated by the luminosity uncertainty!



Many detailed EWK studies possible –and done-- with the large Z,W samples

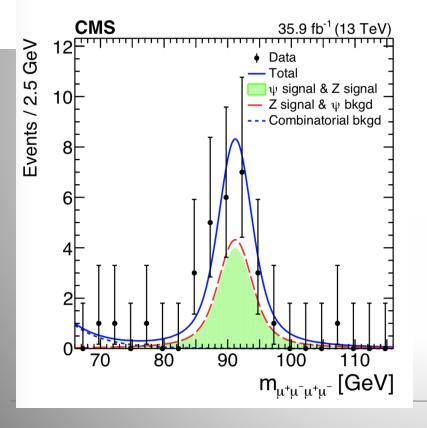
### **W-Mass Determination**

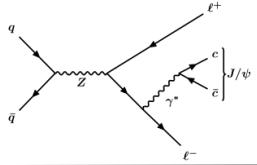
- Measurement based on 7 TeV data (4.6 fb<sup>-1</sup>). It takes time to get the systematic uncertainties under control for precision!!
- Included ~14.10<sup>6</sup> W leptonically decaying W candidates
- Technique uses template fits to the W  $p_T$  and  $m_T$  predictions
- Calibration of energy scale, recoil response and efficiency studies using the large Z sample. Modelling of helicity effects constrained by W and Z data. arXiv:1701.07240



#### **Rare Processes**

- Large Z samples at the LHC allow for study of rare Z decays (eg not observed at LEP): Z-> 2 leptons +  $J/\psi$
- SM expected Branching Ratio 6.7-7.7x10<sup>-7</sup>
- Observed 24 events -> Branching Ratio 8x10<sup>-7</sup>





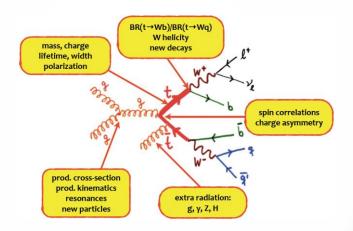
arXiv:1806.04213

Further:

 $\frac{\mathcal{B}(Z \to J/\psi \,\ell^+ \ell^-)}{\mathcal{B}(Z \to \mu^+ \mu^- \mu^+ \mu^-)} = 0.67 \pm 0.18 \,(\text{stat}) \pm 0.05 \,(\text{syst})$ 

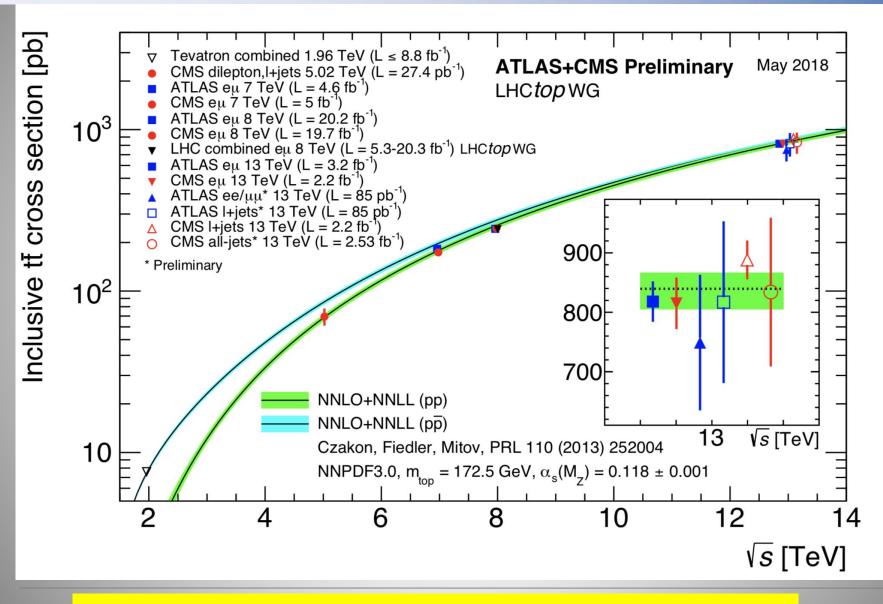
This is the rarest Z decay channel observed up to date. Background for rare Higgs decays

### **Top Production**



 The heaviest known elementary particle: ~173 GeV
 Coupling to the Higgs ~1 → Special role in EWK symmetry breaking? LHC is a top factory with ~5.10<sup>6</sup> produced tt-pairs (run-1) ~3.10<sup>7</sup> produced tt-pairs (2016)

### **Top Quark Cross Sections**



Good agreement with the SM predictions up to the 13 TeV

### **Top Mass Determination**

ATLAS+CMS Preliminary LHCtopWG	$m_{top}$ summary, $\sqrt{s} = 7-13 \text{ TeV}$	September 2017
World Comb. Mar 2014, [7] stat	total stat	
total uncertainty	m <sub>top</sub> ± total (stat ± syst)	s Ref.
ATLAS, I+jets (*)	172.31 ± 1.55 (0.75 ± 1.35)	7 TeV [1]
ATLAS, dilepton (*)	173.09 ± 1.63 (0.64 ± 1.50)	7 TeV [2]
CMS, I+jets	173.49 ± 1.06 (0.43 ± 0.97)	7 TeV [3]
CMS, dilepton	172.50 ± 1.52 (0.43 ± 1.46)	7 TeV [4]
CMS, all jets	173.49 ± 1.41 (0.69 ± 1.23)	7 TeV [5]
LHC comb. (Sep 2013) LHC top WG	173.29 ± 0.95 (0.35 ± 0.88)	7 TeV [6]
World comb. (Mar 2014)	173.34 ± 0.76 (0.36 ± 0.67)	1.96-7 TeV [7]
ATLAS, I+jets	172.33 ± 1.27 (0.75 ± 1.02)	7 TeV [8]
ATLAS, dilepton	173.79 ± 1.41 (0.54 ± 1.30)	7 TeV [8]
ATLAS, all jets	= 175.1 ± 1.8 (1.4 ± 1.2)	7 TeV [9]
ATLAS, single top	172.2 ± 2.1 (0.7 ± 2.0)	8 TeV [10]
ATLAS, dilepton	172.99 ± 0.85 (0.41± 0.74)	8 TeV [11]
ATLAS, all jets	173.72 ± 1.15 (0.55 ± 1.01)	8 TeV [12]
ATLAS, I+jets	172.08 ± 0.91 (0.38 ± 0.82)	8 TeV [13]
ATLAS comb. ( <sup>Sep 2017</sup> ) H <del>▼H</del>	172.51 ± 0.50 (0.27 ± 0.42)	7+8 TeV [13]
CMS, I+jets	172.35 ± 0.51 (0.16 ± 0.48)	8 TeV [14]
CMS, dilepton	172.82 ± 1.23 (0.19 ± 1.22)	8 TeV [14]
CMS, all jets	172.32 ± 0.64 (0.25 ± 0.59)	8 TeV [14]
CMS, single top	172.95 ± 1.22 (0.77 ± 0.95)	8 TeV [15]
CMS comb. (Sep 2015) ⊢ <del>▼</del> ⊢	172.44 ± 0.48 (0.13 ± 0.47)	7+8 TeV [14]
(*) Superseded by results	172.25 ± 0.63 (0.08 ± 0.62)           ITAS-CONF-2013-046         [7] arXiv:1403.4427           BLAS-CONF-2013-047         [8] Eur-Phys.1C75 (2015) 330           JHEP 12 (2012) 105         [8] Eur-Phys.1C75 (2015) 138           Eur-Phys.LC72 (2012) 2202         [10] ATLAS-CONF-2014-055           Eur.Phys.LC74 (2014) 2758         [11] Phys.Left.B761 (2016) 550           ATLAS-CONF-2014-051-102         [12] arXiv:11202.74564	13 TeV [16] [13] ATLAS-CONF-2017-071 [14] Phys.Rev.D93 (2016) 072004 [15] EPUC 77 (2017) 354 [16] CMS-PAS-TOP-17-007
	75 180 <sub>op</sub> [GeV]	185

Steady improvements over the last years in Run-1

Precision reached now ~0.3%

# Hadronization model uncertainties one of the main limitations

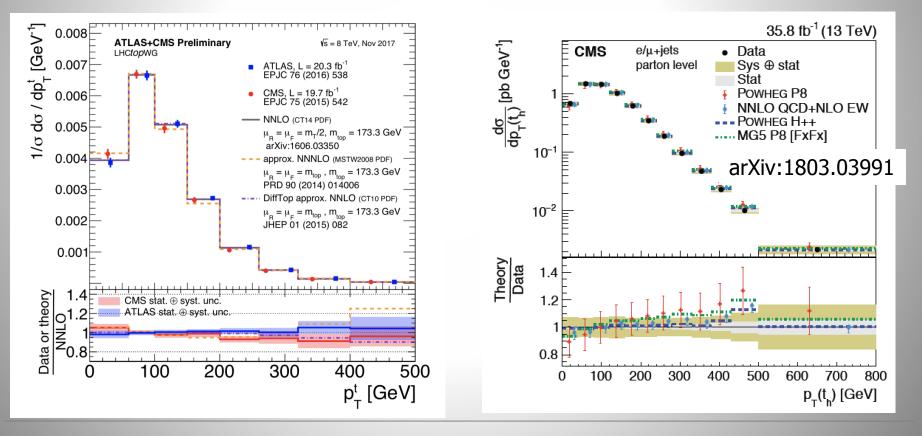
Several alternative methods have been and are being explored using  $J/\psi$ , secondary vertices,... This is not the final word yet

#### Experiment combination under way

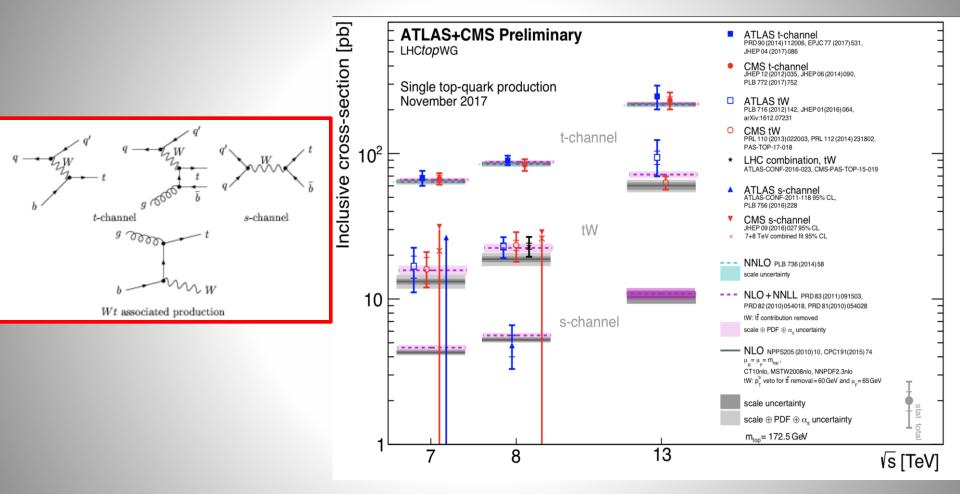
Note: the average value LHC somewhat lower than Tevatron one:  $174.34 \pm 0.64$  GeV

### **Top Differential Cross Sections**

#### Run-1 showed a difference in the p<sub>T</sub> spectrum of the top in data compared to ME+PS predictions. Better agreement achieved with recent NNLO calculations!

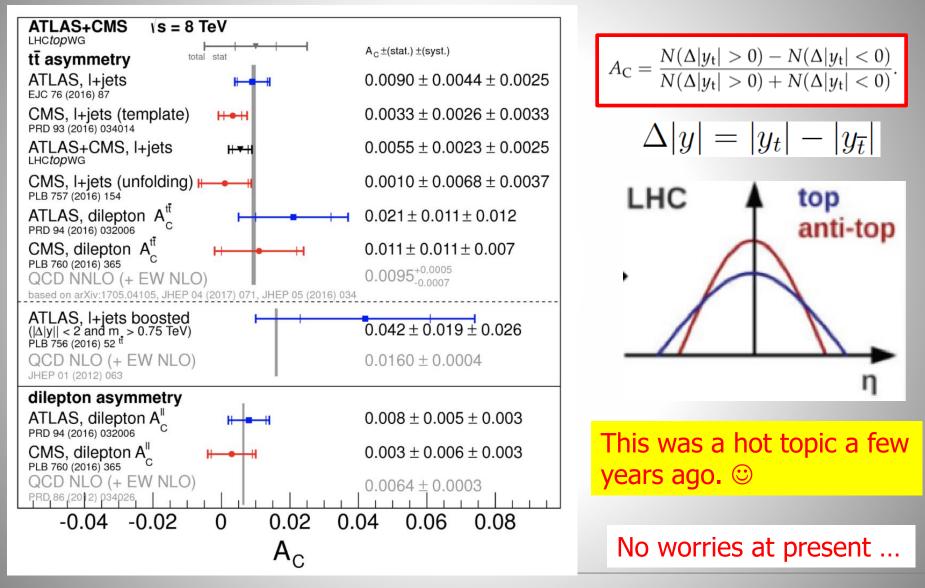


### **Single Top Production**

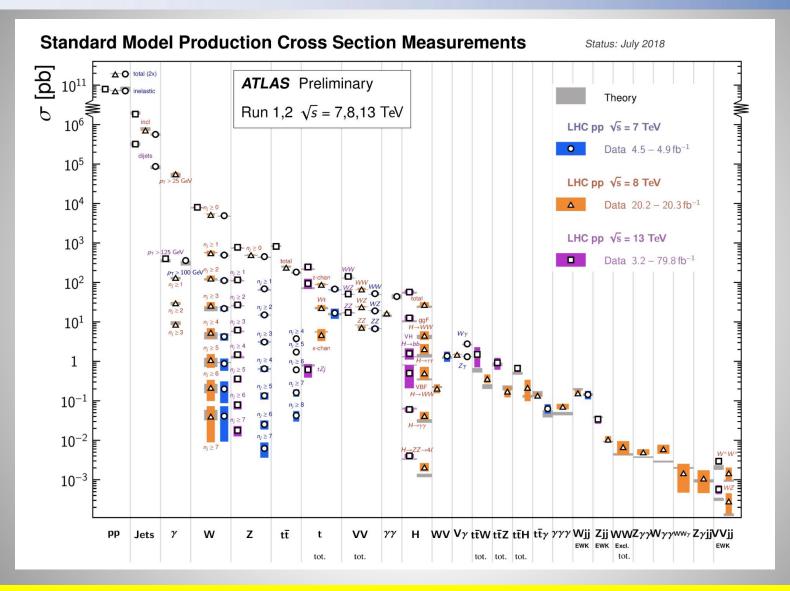


Most single top processes have been studied in run-1 and run-2 by CMS and ATLAS.

# **Top Charge Asymmetry**



# Summary: Cross Sections 7/8/13 TeV



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

#### **Measurements of New SM Processes at LHC**

#### **Examples**

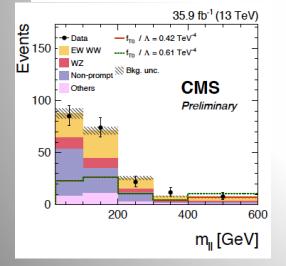
#### EWK WWjj production

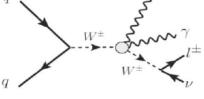


#### tZ production

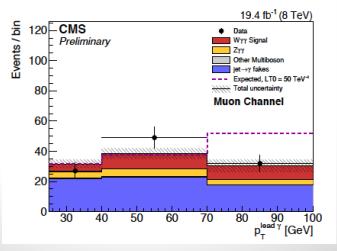


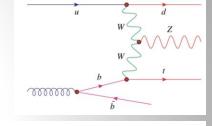
arXiv:1709.05822



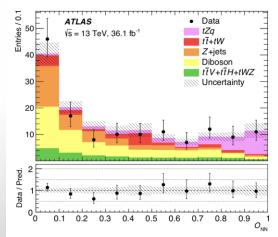


arXiv:1704.00366





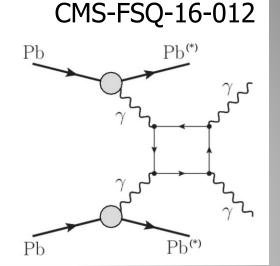
#### arXiv:1710.03659

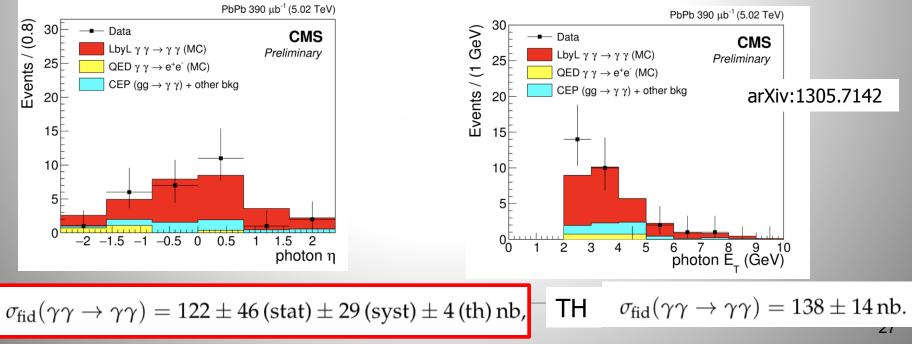


Many other processes eg in top sector: ttW, ttyy, ttbb,...

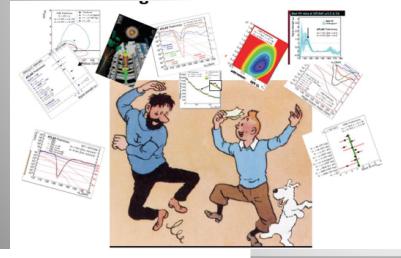
# **Light-by-light Scattering**

- Select ultra-peripheral collisions in PbPb
- Exclusive 2-photon final state selection
- Small acoplanarity (< 0.01)
- Small diphoton  $p_T$  (< 1 GeV)
- 14 events found, 3.8 background events est.
- Similar to ATLAS result: arXiv:1702.01625





# Higgs



#### The party 6 years ago



CERN 🤣 @CERN Happy 5th anniversary, #HiggsBoson! It's been 5 years since we announced your discovery: cern.ch/go/gm97 #HiggsStories

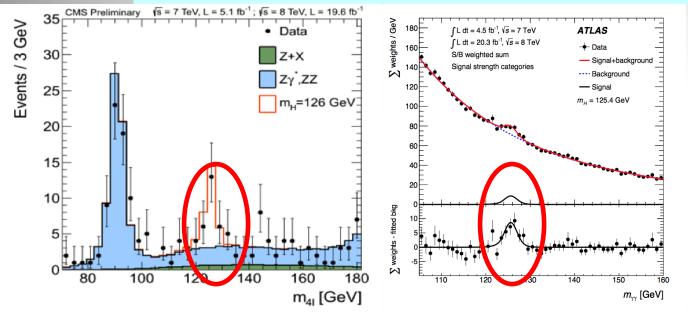


**1**2 13 428 9 566

What happened since?

# **2012: A Milestone in Particle Physics**

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



	ggF	VBF	VH	ttH
H-> gamgam				
H-> ZZ				
H->WW				
H-> bb	_			
H-> tau tau				
H-> Zgamma				
H-> mumu				
H-> invisible	_			

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

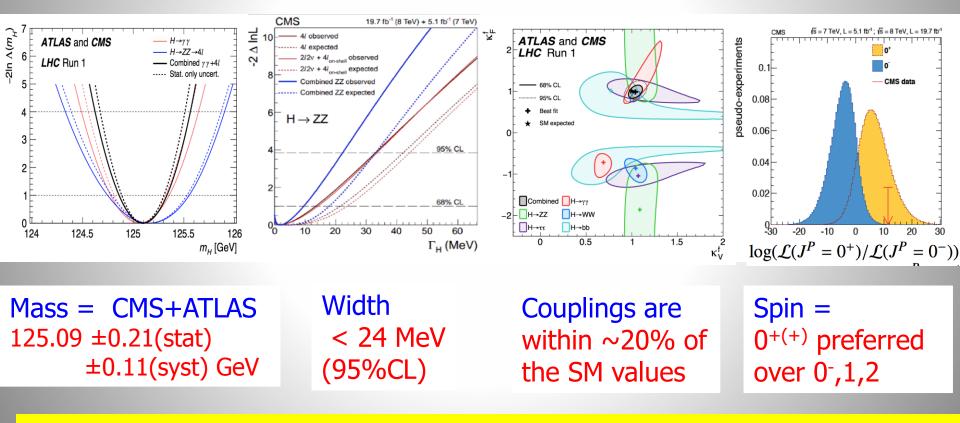
**Results released** 

In progress

2018

# **Brief Higgs Summary from Run-1**

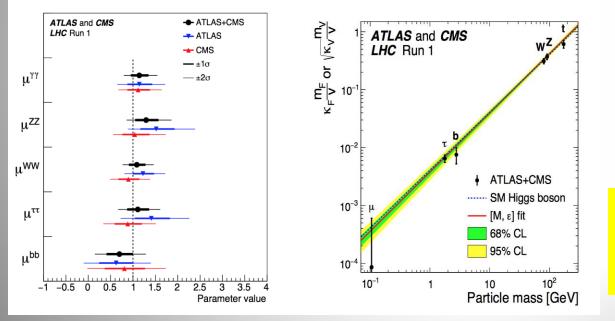
#### We know already a lot on this brand New Higgs particle!!



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

# **Higgs: ATLAS+CMS Combination**

Production process	Measured significance $(\sigma)$	Expected significance $(\sigma)$
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		
$H \rightarrow \tau \tau$	5.5	5.0
$H \rightarrow bb$	2.6	3.7



#### The Run-1 Higgs Legacy!

arXiv:1606.02266 / JHEP 1608 (2016) 045 5153 authors!!



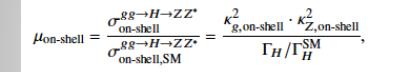
The newly found boson has properties as expected for a Standard Model Higgs

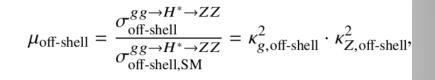
Signal strength/SM:

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

# **Narrowing Down on the Higgs Width**

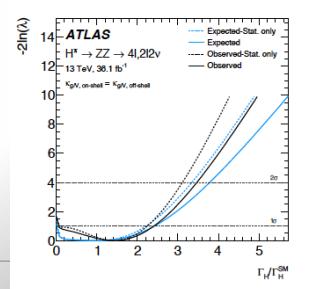
- New estimation on the Higgs Width of the Higgs arXiv:1808.01191
   based on comparing the off-shell and on-shell signal strength
- SM width at 125 GeV is 4.1 MeV
- Off-shell channels: H-> ZZ 4leptons and H->ZZ-> 2l 2v with H mass above 220 (250) GeV





		Observed		Expected		
		Observed	Median	$\pm 1 \sigma$	$\pm 2 \sigma$	
	$ZZ \rightarrow 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]	
$\mu_{ ext{off-shell}}$	$ZZ \rightarrow 2\ell 2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]	
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]	
$\Gamma_H/\Gamma_H^{ m SM}$	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]	
$R_{gg}$	Combined	4.3	4.1	[3.3, 5.6]	[2.7, 8.2]	

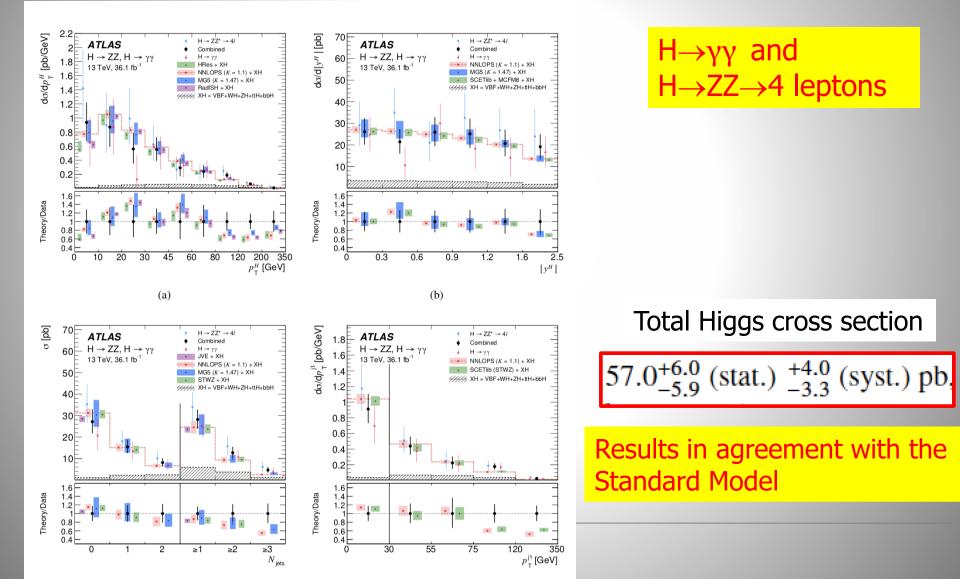
-> Higgs total width limit < 14.4 MeV obs. (15.2 MeV exp.)



# Higgs Results @ 13 TeV

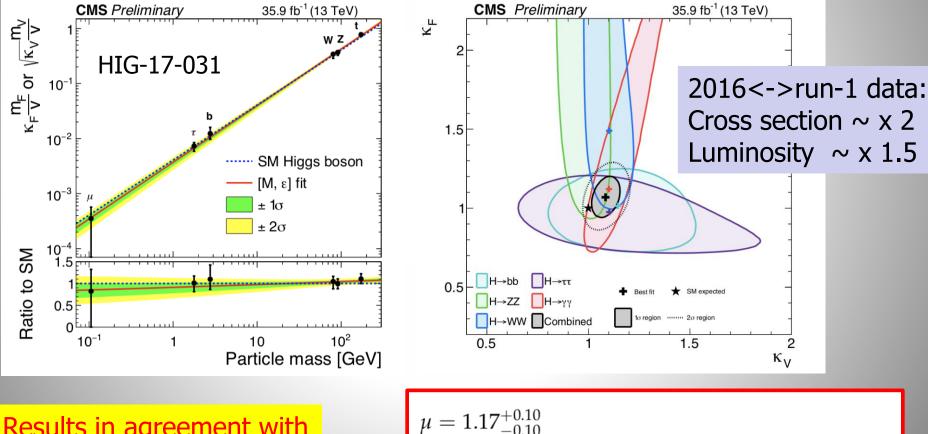
#### Higgs kinematics differential distributions

#### arXiv:1805.10197



# Higgs Results @ 13 TeV

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



 $= 1.17^{+0.06}_{-0.06}$  (stat.)  $^{+0.06}_{-0.05}$  (sig. th.)  $^{+0.06}_{-0.06}$  (other sys.)

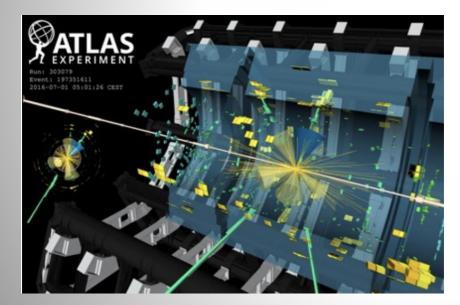
Results in agreement with the Standard Model

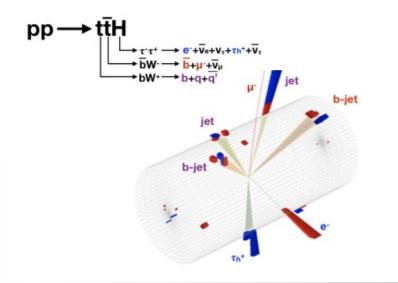
### A lot happened recently...

#### CERN Press Release 4/6/2018

# The Higgs boson reveals its affinity for the top quark

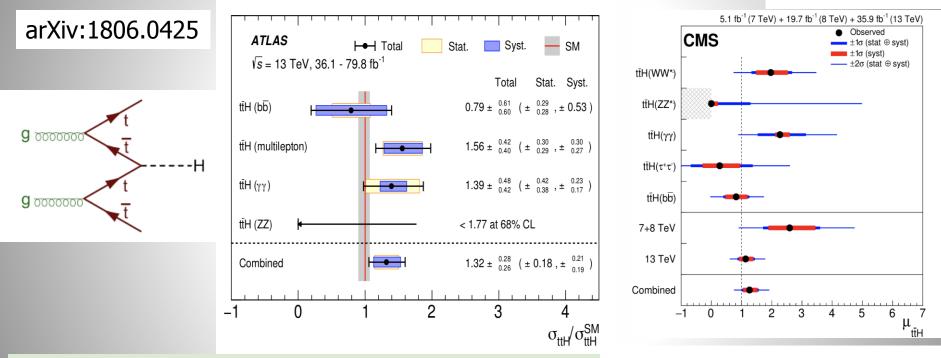
04 Jun 2018





# Higgs Results @ 13 TeV

#### ttH production: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1 arXiv:1804.0261



7+8+13 TeV data

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

Significance =  $5.9\sigma$  (exp 4.2 $\sigma$ )

**Observation of ttH production with:** 

- -- Run-2 alone: 5.8 σ significance (4.9 σ expected)
- -- Run-1 and Run-2 combined: 6.3  $\sigma$  significance (5.1  $\sigma$  expected)

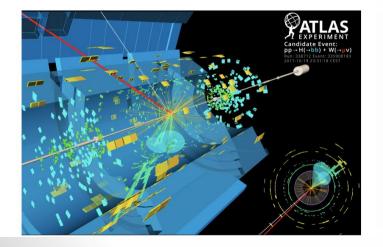
#### Observation of ttH! Results in agreement with the Standard Model

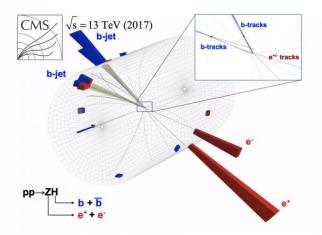
### A lot happened recently...

CERN Press Release 28/8/2018

#### Long-sought decay of Higgs boson observed

28 Aug 2018

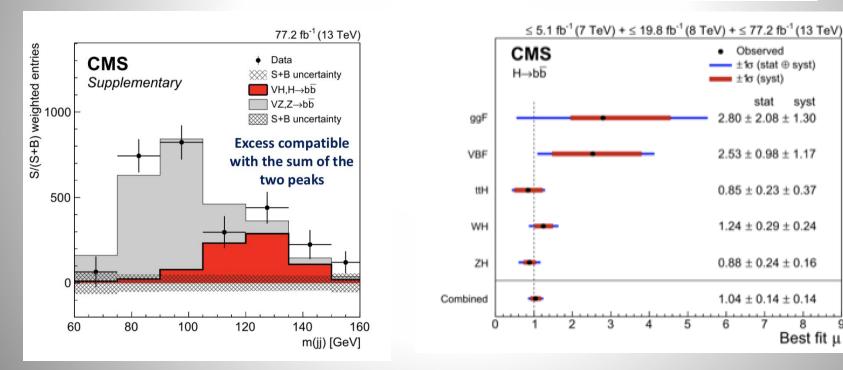




### **Higgs to bb Decay**

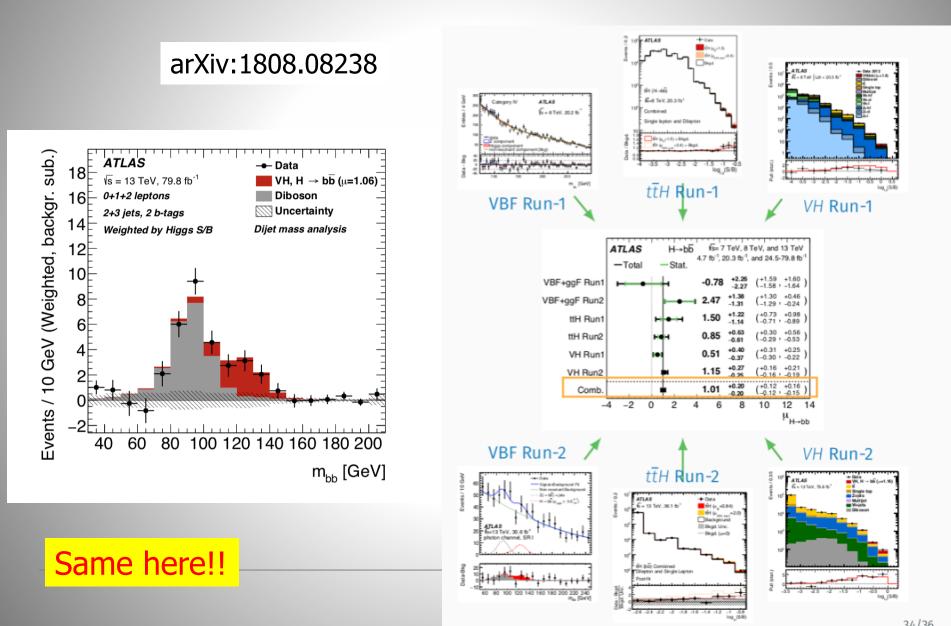
- Combination of CMS H→bb measurements : VH, boosted ggH, VBF, ttH
- Measured signal strength is μ = 1.04 ± 0.20

#### Significance 5.5σ expected **5.6σ observed**



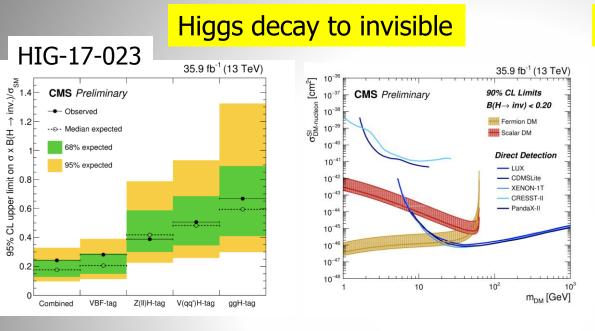
Excellent agreement with the Standard model... again...

# **Higgs to bb Decay**

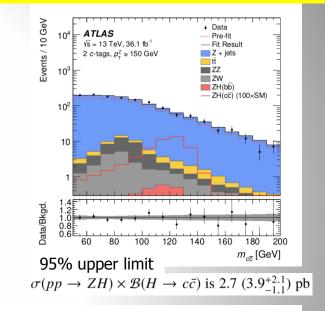


# More Higgs Studies...

#### arXiv:1802.04329



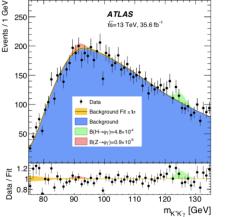
#### Higgs decay to charm search

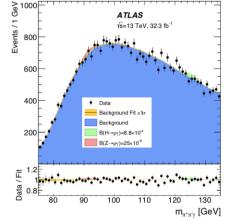


#### Higgs decay to $\rho\gamma$ and $\phi\gamma$ search

#### arXiv:1712.02758

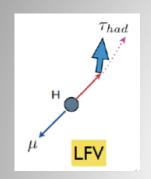
Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}\left(H  ightarrow \phi \gamma ight)\left[  ight. 10^{-4}  ight.  ight]$	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}\left(Z  o \phi \gamma  ight) \left[  ight. 10^{-6}  ight.  ight]$	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}\left(H ightarrow ho\gamma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

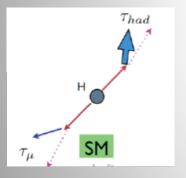




# Search for LFV Decays: $H \rightarrow \mu \tau$

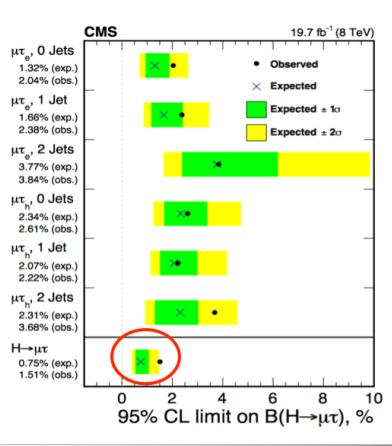
#### arXiv:1502.07400





### Recall: Results from the 8 TeV

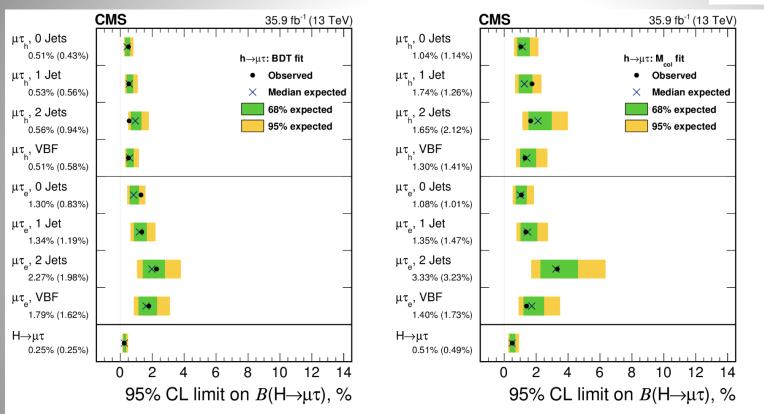
- Comparable sensitivity
   from all channels
- $\mathcal{B}(\mathrm{H} 
  ightarrow \mu au) < 1.51\%$  at 95%
- Large improvement of previous limits
  - Background-only p-value of 0.010 (2.4  $\sigma$ ) - Best fit  $\mathcal{B}(H \rightarrow \mu \tau) = (0.84^{+0.39}_{-0.37})\%.$



Mild excess giving a 2.4 $\sigma$  effect in Run-1... What about 2016 data?

# Search for LFV Decays: $H \rightarrow \mu \tau$ , $e\tau$

### The 2016 data does NOT show an excess



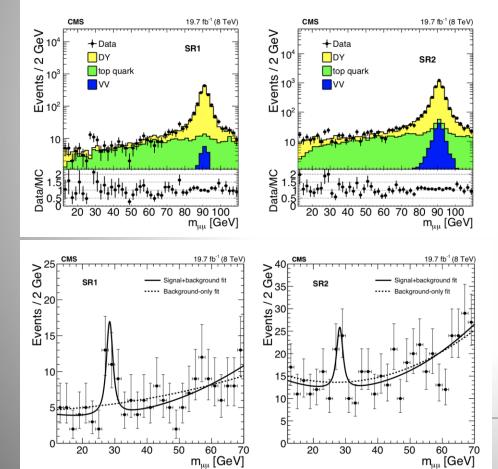
It wouldHave beenNice...

		Observed (expe	ected) limits (%)	Best fit branch	ing fraction (%)
		BDT fit	$M_{\rm col}$ fit	BDT fit	$M_{\rm col}$ fit
$H \rightarrow p$	ıτ	<0.25 (0.25)%	<0.51 (0.49) %	$0.00 \pm 0.12$ %	$0.02 \pm 0.20$ %
$H \rightarrow \epsilon$	$e\tau$	<0.61 (0.37) %	<0.72 (0.56) %	$0.30 \pm 0.18~\%$	$0.23 \pm 0.24$ %

#### arXiv:1712.07173

### **Search for New Resonances**

NMSSM Higgs inspired search in mass range 12-70 GeVarXiv:1808.01890-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

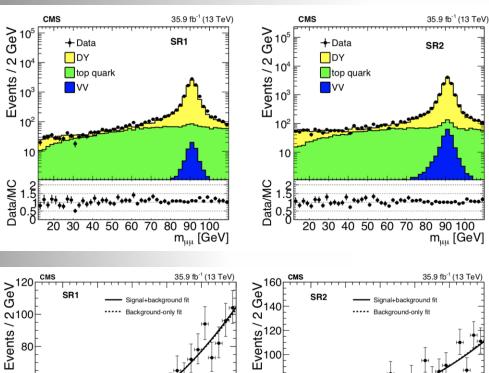
Excess seen in the both regions around 28 GeV

SR1:  $4.2\sigma$  local significance (~3.0 $\sigma$  global sign.) SR2:  $2.9\sigma$  local significance

### **Search for New Resonances**

m<sub>uu</sub> [GeV]

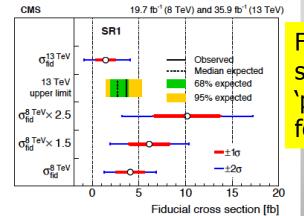
70

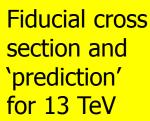


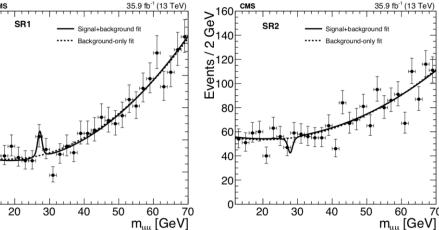
#### 13 TeV Data

#### ....No significant deviation..

$\sqrt{s}$ (TeV)	8	3	13		
Event category	SR1	SR2	SR1	SR2	
Local significance (s.d.)	4.2	2.9	2.0	1.4 deficit	
Ns	$22.0\pm7.6$	$22.8\pm9.5$	$14.5\pm9.3$	$-14.9\pm10.1$	
N <sub>S</sub> observed upper limit at 95% CL	40.4	44.7	36.9	32.2	
N <sub>S</sub> expected upper limit at 95% CL	18.3	27.6	27.6	35.6	
ε <sup>reco</sup>	0.27 =	± 0.01	$0.28\pm0.01$		
Integrated luminosity, $\mathcal{L}$ (fb <sup>-1</sup> )	19.7	$\pm 0.5$	$35.9 \pm 0.9$		
$\sigma_{\rm fid}$ (fb)	$4.1\pm1.4$	$4.2\pm1.7$	$1.4\pm0.9$	$-1.5\pm1.0$	
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	







80

60

40

20

#### Are the 13 TeV data a killjoy? <sup>(C)</sup>

### **Search for New Resonances**

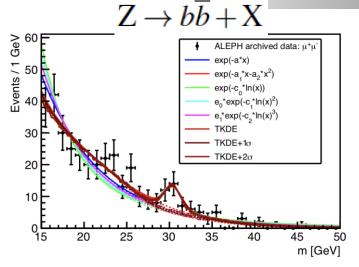
If the effect in the 8 TeV data is real =>

- What makes it 'invisible' at 13 TeV? Some possibilities include:
  - effect of the jet veto in SR2 (pile-up?)
  - kinematics / acceptance (depends on the model)

-Unclear what it is (too large rate for eg bbA or AA production) - A new scalar, also affecting g-2? (see arXiv:1808.02431)

-Anything like that reported before?

- Maybe... see A. Heister, using public ALEPH data arXiv:1609.06536/unpublished
- -Next: More 13 TeV data to come Other experiments can have a look, especially @ 8 TeV



### How to Become an Ambulance Chaser?



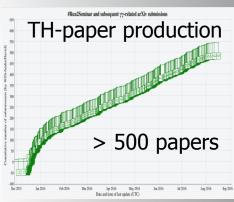
#### Remember the 750 GeV bump in CMS and ATLAS?? -> End of 2015/early 2016

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

#### 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 **CMS** Preliminary 12.9 fb<sup>-1</sup> (13 TeV) > 5010<sup>3</sup> Data EBEB Fit model Events / 20 6 ATLAS Preliminary 2015 ± 1 s.d. Data ± 2 s.d. SVents Background-only fit 2016 10 Vs = 13 TeV, 3.2 fb<sup>-1</sup> data-fit)/σ<sub>stat</sub> 101 400 600 800 100012001400160018002000 1400  $m_{\gamma\gamma}$  (GeV)





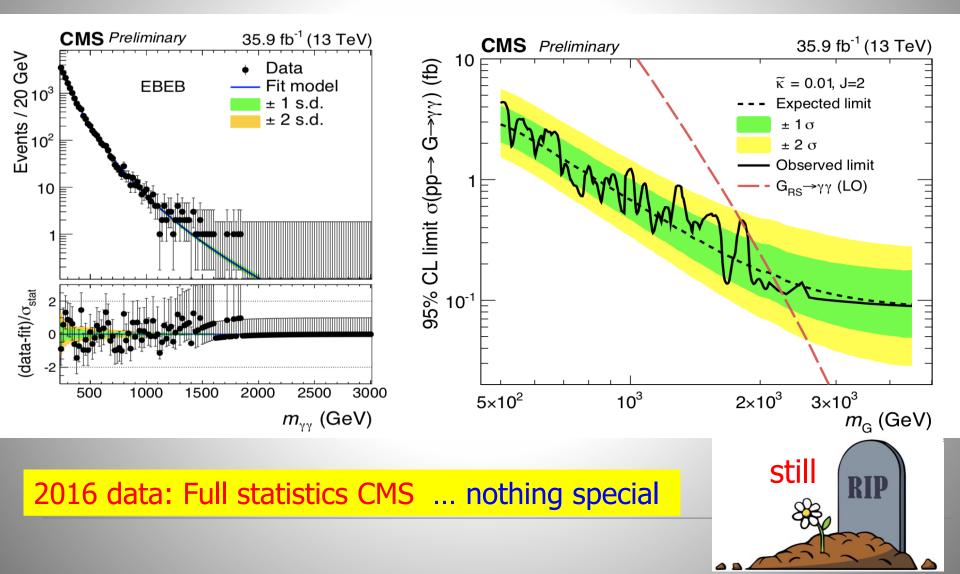


**2015: Statistical fluctuation? A new resonance? ???** 2015 data: CMS: 3.4  $\sigma$  ! ATLAS up to 3.9  $\sigma$  !! (local significances) 2016 data: 13 fb<sup>-1</sup> CMS and ATLAS **Nada**!!

### **Search for a Di-photon Resonance**

EXO-17-017

#### The search with the full 2016 data

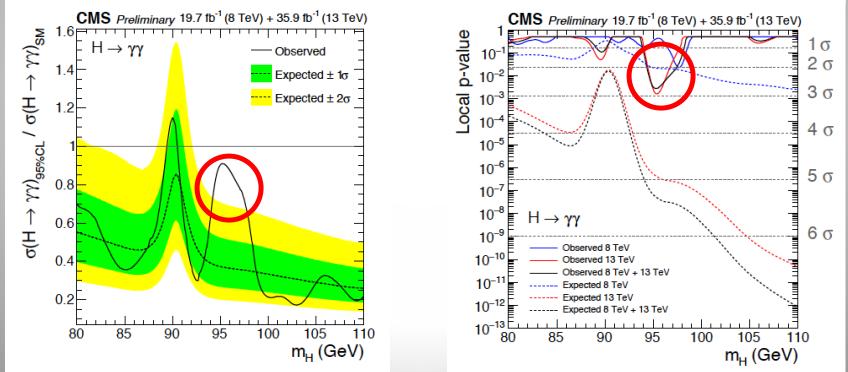


### Is 96 GeV the New 750 GeV (?)

August 2017: A search for X-> $\gamma\gamma$  at low mass

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

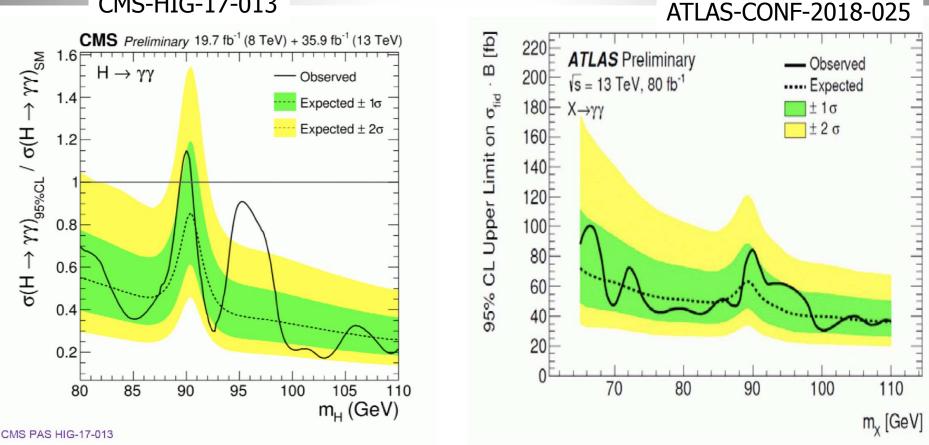
CMS-HIG-17-013



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

## Is 96 GeV the New 750 GeV (?)

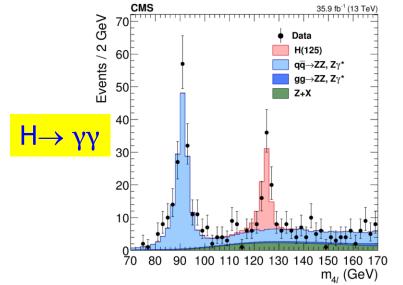
CMS-HIG-17-013

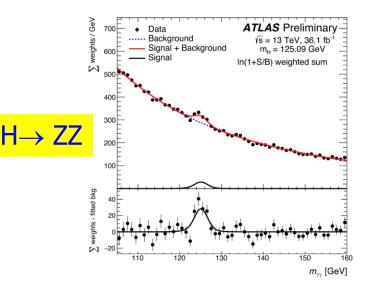


Probably not... ATLAS does not confirm the same size of effect... Let's see with more data...

# Higgs @ 13 TeV in Run 2

### • Higgs particle is still there ! ③



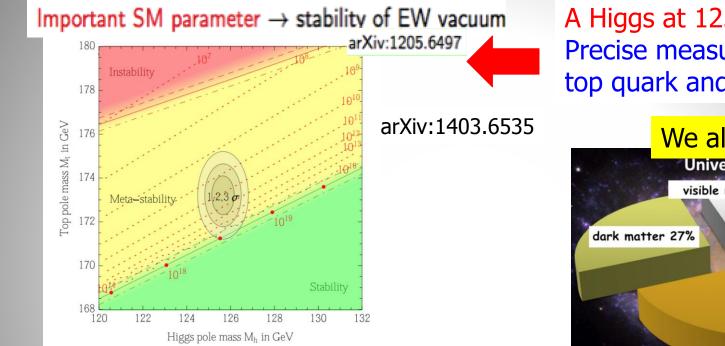


- The mild deviations seen in Run-1 seem to be gone ⊗
- Observation of H→bb in the associated production channel
- Direct observation of ttH production
- No deviations from Standard Model Higgs expectations yet!!
   The Higgs Boson is still yery

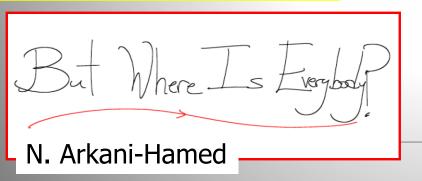
The Higgs Boson is still very much Standard Model-like!

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

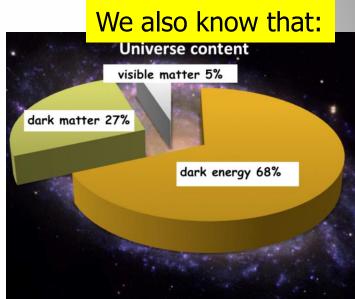
### **Physics Beyond the Standard Model?**

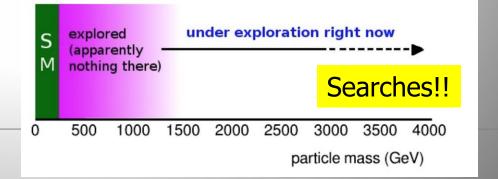


#### New Physics inevitable? But at which scale/energy?



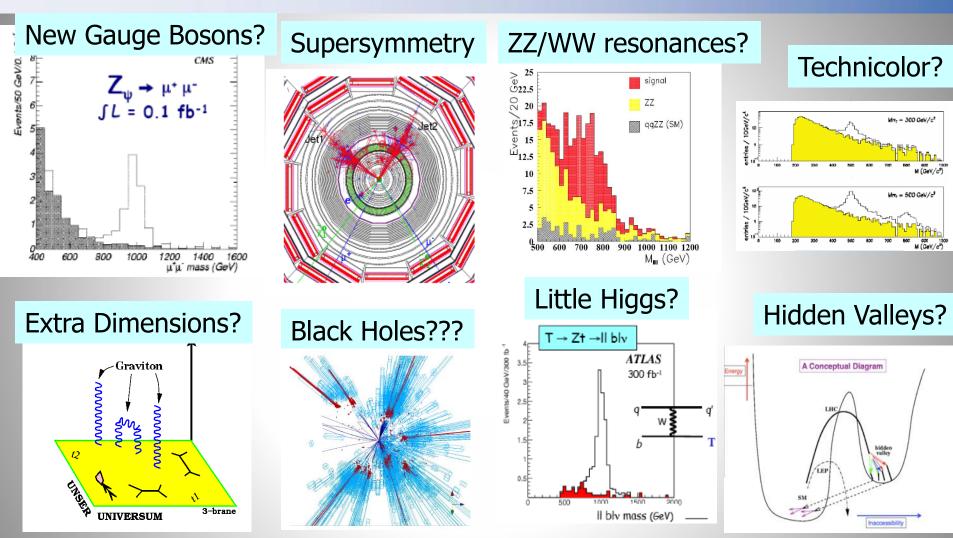
A Higgs at 125 GeV Precise measurements of the top quark and the Higgs mass





### **Searches for BSM Physics**

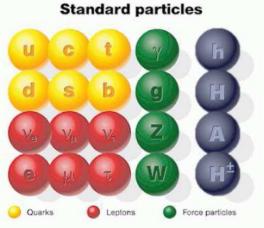
### **New Physics?**

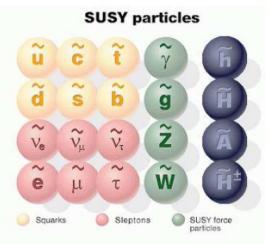


What stabelizes the Higgs Mass? Many ideas, not all popular any more A large variety of possible signals. We have to be ready for that

### Supersymmetry: a new symmetry in Nature?

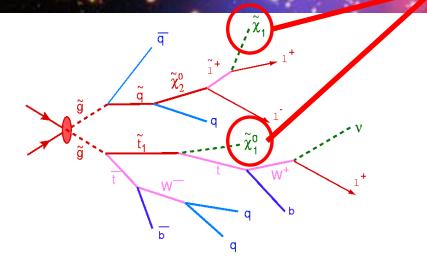




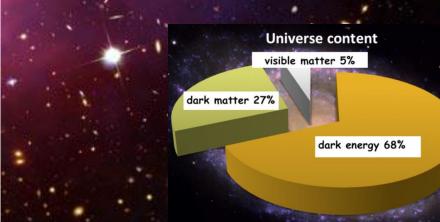




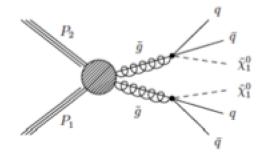
# Candidate particles for Dark Matter $\Rightarrow$ Produce Dark Matter in the lab

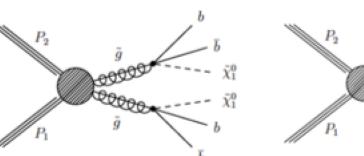


SUSY particle production at the LHC

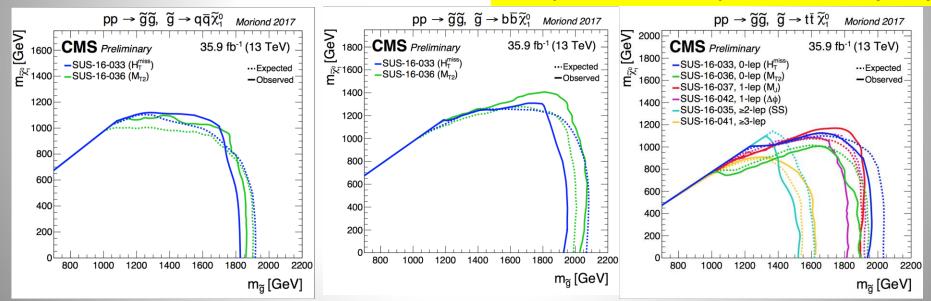


### **Supersymmetry: Gluinos**





#### Interpretation in simplified models (SMS)

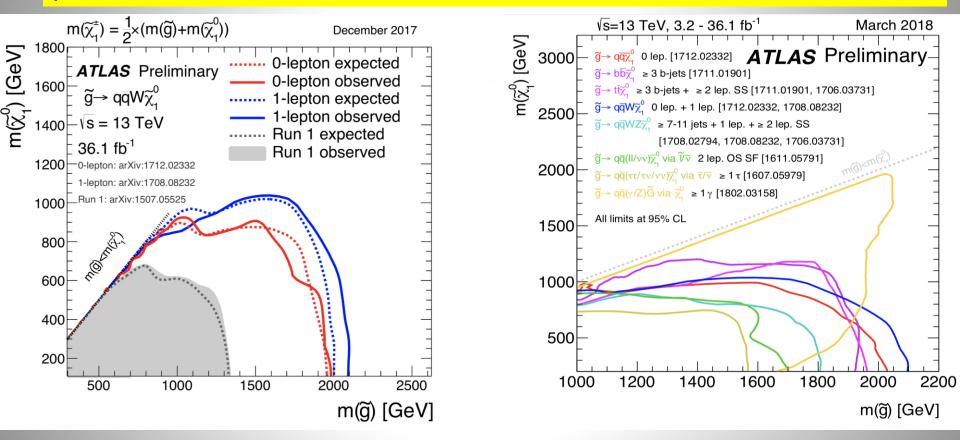


No significant signal to date

Within the context of the SMS: Exclude with gluino masses ~ 2100 GeV for neutralino masses up to 800 GeV

# **Supersymmetry: Gluinos**

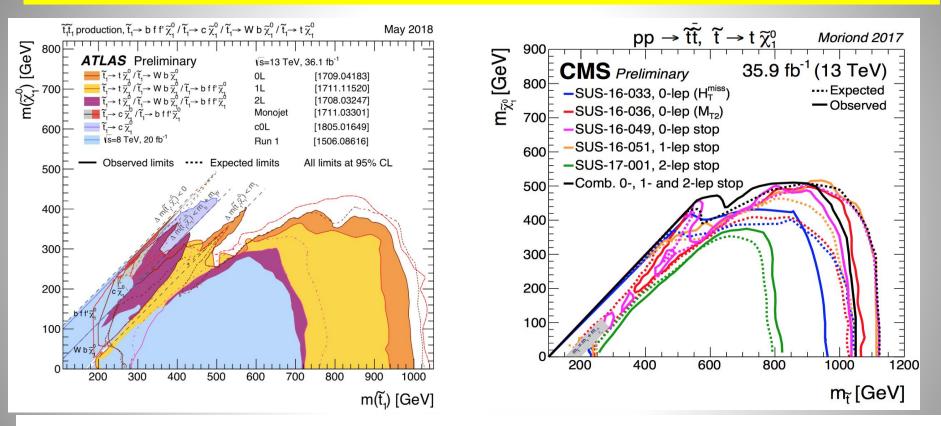
Gluino production with decay chains with direct decay to the lightest SUSY particle or via cascade chains.



No significant signal to date Within the context of the SMS: Exclude with gluino masses ~ 2000 GeV

# **Top Squark Search Summaries**

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



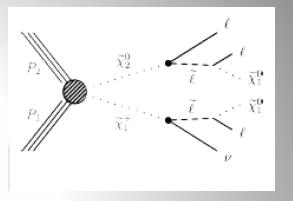
Within the context of the SMS: Exclude with masses up to 1100 GeV for neutralino masses up to 500 GeV Sensitivity is ~ 200-400 GeV better than Run-1 reach & gaps being covered

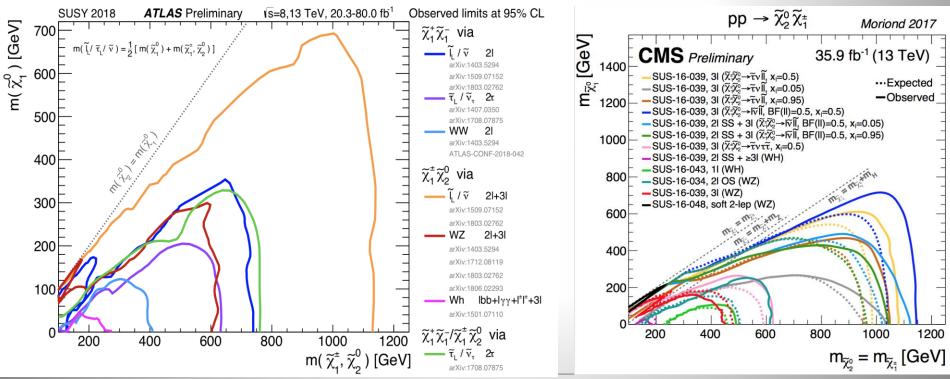
Is this getting critical for Natural Models??

# **Chargino and Neutralino Production**

Direct production of "electro-weakino pairs

- Decays via sleptons /sneutrinos
- •Using benchmarks to illustrate different scenarios
- •Multilepton searches (incl. taus)





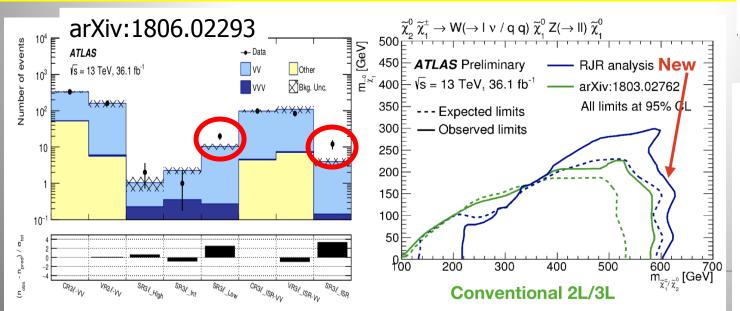
Exclude masses up to 1100 GeV for neutralino masses up to 700 GeV

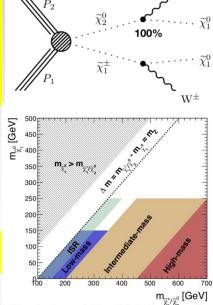
# **Chargino and Neutralino Production**

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

Signal region	SR3ℓ_Low	SR3ℓ_ISR	$SR2\ell\_Low$	SR2ℓ_ISR
Total observed events	20	12	19	11
Total background events	$10 \pm 2$	3.9 ± 1.0	$8.4 \pm 5.8$	$2.7^{+2.8}_{-2.7}$

#### Excess observed in 4 low $\Delta M$ regions ranging from 1.5 $\sigma$ ->3 $\sigma$





Compatible with previous studies? To be watched... But "3σ"s have

come and gone..

### The SUSY SEARCH Chart So Far...

#### ATLAS SUSY Searches\* - 95% CL Lower Limits

ATLAS Preliminary

J	uly 2018										$\sqrt{s} = 7, 8, 13 \text{ TeV}$
	Model	$e, \mu, \tau, \gamma$	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	∫£ dt[fb	0-1]	Mass limit		$\sqrt{s} = 7, 8 \text{ Te}$	$\sqrt{s} = 13 \text{ TeV}$	Reference
Ñ	$\tilde{q}\tilde{q},\tilde{q}{ ightarrow}q\tilde{\chi}_{1}^{0}$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	<ul> <li><i>q̃</i> [2x, 8x Degen.]</li> <li><i>q̃</i> [1x, 8x Degen.]</li> </ul>	0.43	0.9 0.71	1.55	$m(\tilde{\chi}_{1}^{0}) < 100 \text{ GeV} \ m(\tilde{q}) - m(\tilde{\chi}_{1}^{0}) = 5 \text{ GeV}$	1712.02332 1711.03301
arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0	2-6 jets	Yes	36.1	ğ ğ		Forbidden	2.0 0.95-1.6	${ m m}({ ilde {\chi}}_1^0){<}200{ m GeV}\ { m m}({ ilde {\chi}}_1^0){=}900{ m GeV}$	1712.02332 1712.02332
'e Se	$\tilde{g}\tilde{g},  \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ ee,μμ	4 jets 2 jets	- Yes	36.1 36.1	ĩg ĩg			1.85 1.2	$m(\tilde{\chi}_{1}^{0}) < 800 \text{ GeV} \ m(\tilde{g}) - m(\tilde{\chi}_{1}^{0}) = 50 \text{ GeV}$	1706.03731 1805.11381
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 З <i>е</i> , µ	7-11 jets 4 jets	Yes -	36.1 36.1	Ĩ Ŝ		0.98	1.8	$m({ ilde \chi}_1^0)$ <400 GeV $m({ ilde g})$ - $m({ ilde \chi}_1^0)$ =200 GeV	1708.02794 1706.03731
Ę	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 e,μ 3 e,μ	3 <i>b</i> 4 jets	Yes	36.1 36.1	20 00°			2.0 1.25	$m(\tilde{\chi}_{1}^{0}) < 200 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_{1}^{0}) = 300 \text{ GeV}$	1711.01901 1706.03731
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$		Multiple Multiple Multiple		36.1 36.1 36.1		Forbidden Forbidden Forbidden	0.9 0.58-0.82 0.7	$m(\tilde{\chi}_1^0)=20$	$\begin{array}{c} m(\tilde{\chi}_{1}^{0}){=}300~\text{GeV},~BR(b\tilde{\chi}_{1}^{0}){=}1\\ 1){=}300~\text{GeV},~BR(b\tilde{\chi}_{1}^{0}){=}BR(t\tilde{\chi}_{1}^{1}){=}0.5\\ 0~\text{GeV},~m(\tilde{\chi}_{1}^{1}){=}300~\text{GeV},~BR(t\tilde{\chi}_{1}^{1}){=}1 \end{array}$	1708.09266, 1711.03301 1708.09266 1706.03731
tion	$\tilde{b}_1\tilde{b}_1,\tilde{\iota}_1\tilde{\iota}_1,M_2=2\times M_1$		Multiple Multiple		36.1 36.1			0.7		$\mathfrak{m}( ilde{\chi}_1^0)$ =60 GeV $\mathfrak{m}( ilde{\chi}_1^0)$ =200 GeV	1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247
3 <sup>rd</sup> gen. squarks direct production	$ \begin{split} \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 &\rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0 \\ \tilde{t}_1 \tilde{t}_1, \tilde{H} \text{ LSP} \end{split} $	0-2 <i>e</i> , <i>µ</i>	0-2 jets/1-2 Multiple Multiple	b Yes	36.1 36.1 36.1	$\tilde{\iota}_1$ $\tilde{\iota}_1$ $\tilde{\iota}_1$ $\tilde{\iota}_1$	Forbidden	1.0 0.4-0.9 0.6-0.8	$m(\tilde{\chi}_1^0)=1$	$m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ 50 GeV, $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$ , $\tilde{r}_{1} \approx \tilde{r}_{L}$ 50 GeV, $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$ , $\tilde{r}_{1} \approx \tilde{r}_{L}$	1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520 1709.04183, 1711.11520
3 <sup>rd</sup> g direc	$\tilde{t}_1 \tilde{t}_1$ , Well-Tempered LSP		Multiple		36.1	ĩ <sub>1</sub>		0.48-0.84	$m(\tilde{\chi}_1^0)=1$	50 GeV, m( $\tilde{\chi}_1^{\pm}$ )-m( $\tilde{\chi}_1^{0}$ )=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	2 <i>c</i> mono-jet	Yes Yes	36.1 36.1	$\tilde{\iota}_1$ $\tilde{\iota}_1$ $\tilde{\iota}_1$	0.46 0.43	0.85		$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ $m(\tilde{\iota}_1, \tilde{c})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$ $m(\tilde{\iota}_1, \tilde{c})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1805.01649 1805.01649 1711.03301
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 <i>e</i> , <i>µ</i>	4 <i>b</i>	Yes	36.1	ĩ <sub>2</sub>		0.32-0.88	m	$(\tilde{\chi}_{1}^{0})=0 \text{ GeV}, m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=180 \text{ GeV}$	1706.03986
	$ ilde{\chi}_1^{\pm}  ilde{\chi}_2^0$ via $WZ$	2-3 e,μ ee,μμ	- ≥ 1	Yes Yes	36.1 36.1	$ \begin{array}{ccc} \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} \ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} \end{array} & \textbf{0.17} \end{array} $		0.6		$m(\tilde{\chi}_1^{\circ})=0$ $m(\tilde{\chi}_1^{\circ})-m(\tilde{\chi}_1^{\circ})=10~\mathrm{GeV}$	1403.5294, 1806.02293 1712.08119
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via $Wh$	<i>ℓℓ/ℓγγ/ℓbb</i>	-	Yes	20.3	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.26			$m(\bar{\chi}_1^0)=0$	1501.07110
EW direct	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_{2}^{0} \rightarrow \tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1			0.76	$m(\tilde{\chi}_1^{\pm})$ - $m(\tilde{\chi}_1^0)$ =	$ m(\tilde{\chi}_{1}^{0}) = 0, \ m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{\pm}) + m(\tilde{\chi}_{1}^{0})) 100 \ \text{GeV}, \ m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{\pm}) + m(\tilde{\chi}_{1}^{0})) $	1708.07875 1708.07875
0	$\iota_{\mathrm{L},\mathrm{R}}\iota_{\mathrm{L},\mathrm{R}},\iota\to\iota_{\mathrm{A}}$	2 e,μ 2 e,μ	$0 \ge 1$	Yes Yes	36.1 36.1	<i>ℓ̃</i> <i>ℓ̃</i> 0.18	0.9			${f m}( ilde{\chi}_1^0)=0 \ {f m}( ilde{\chi}_1^0)=5 \ {f GeV}$	1803.02762 1712.08119
	$\tilde{H}\tilde{H},\tilde{H}{ ightarrow}h\tilde{G}/Z\tilde{G}$	0 4 <i>e</i> ,μ	$\geq 3b$	Yes Yes	36.1 36.1	<u>Й</u> 0.13-0.2 <u>Й</u>	0.3	0.29-0.88		$ \begin{array}{l} BR(\tilde{\chi}^0_1 \to h\tilde{G}) = 1 \\ BR(\tilde{\chi}^0_1 \to Z\tilde{G}) = 1 \end{array} $	1806.04030 1804.03602
pa	$Direct\tilde{\chi}_1^*\tilde{\chi}_1^-prod.,long-lived\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm}  $ 0.15	0.46			Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
Long-lived particles	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	ĝ			1.6		1606.05129
ong	Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ , long-lived $\tilde{\chi}_1^0$	2 ~	Multiple	Vee	32.8	$\tilde{g} = [\tau(\tilde{g}) = 100 \text{ ns}, 0.2 \text{ ns}]$	6] 0.44		1.6 2.4	( 1)	1710.04901, 1604.04520 1409.5542
1	GMSB, $\chi_1^- \rightarrow \gamma G$ , long-lived $\chi_1^-$ $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow eev/e\mu v/\mu\mu v$	2 γ displ. <i>ee/eµ/μ</i>	- μ -	Yes	20.3 20.3	$\frac{\chi_1}{\tilde{g}}$	0.44		1.3	$1 < \tau(\tilde{\chi}_1^0) < 3 \text{ ns, SPS8 model}$ $6 < c\tau(\tilde{\chi}_1^0) < 1000 \text{ mm, m}(\tilde{\chi}_1^0) = 1 \text{ TeV}$	1409.5542
_	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	εμ,ετ,μτ	-		3.2	ν <sub>τ</sub>			1.9	$\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$	1607.08079
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 e, µ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0  [\lambda_{i33} \neq 0, \lambda_{12k} \neq$	0]	0.82	1.33	$m(\tilde{\chi}_1^0)=100 \text{ GeV}$	1804.03602
>	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}^0_1, \tilde{\chi}^0_1 \rightarrow qqq$		-5 large- <i>R</i> je Multiple	ets -	36.1 36.1	$\tilde{g} = [m(\tilde{\chi}_1^0) = 200 \text{ GeV}, 110 \\ \tilde{g} = [\lambda''_{112} = 2e-4, 2e-5]$		1.0	1.3 1.9 5 2.0	Large $\lambda_{112}''$ m $(\tilde{\chi}_1^0)$ =200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003
RPV	$\tilde{g}\tilde{g}, \tilde{g} \to tbs / \tilde{g} \to tt\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g} = [\lambda_{323}'' = 1, 1e-2]$			1.8 2.1	$m(\tilde{\chi}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$		Multiple		36.1	$\tilde{g}$ [ $\lambda''_{323}$ =2e-4, 1e-2]		0.55 1.0	5	m( $\tilde{\chi}_1^0$ )=200 GeV, bino-like	ATLAS-CONF-2018-003
	$ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs  \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b\ell $	0 2 <i>e</i> ,μ	2 jets + 2 <i>l</i> 2 <i>b</i>	- b	36.7 36.1	$\tilde{t}_1  [qq, bs]$ $\tilde{t}_1$	0.42	0.61	0.4-1.45	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$	1710.07171 1710.05544
			20								
									I		J
*Only	a selection of the available mas	ss limits on	new state	es or	1	<b>0</b> <sup>-1</sup>			1	Mass scale [TeV]	

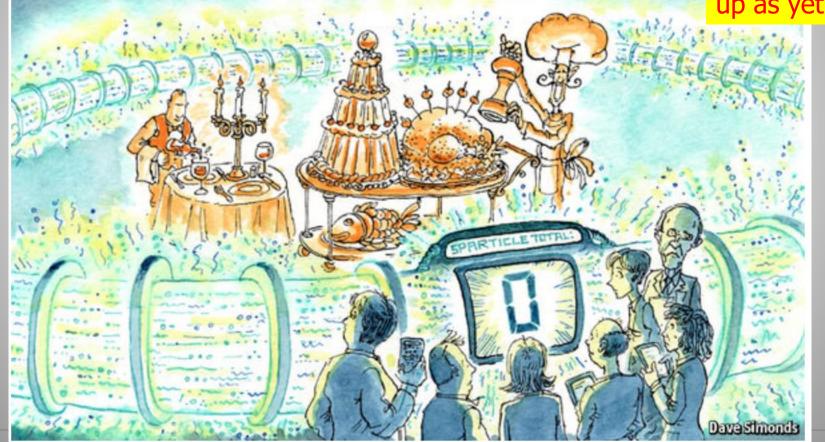
\*Only a selection of the available mass limits on new states or phénomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# SUSY (as seen outside HEP...)

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

Supersymmetry is a beautiful idea. But no evidence supports it

But not giving up as yet!!!

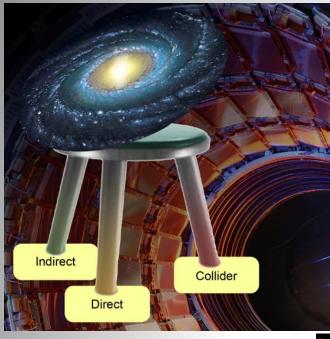


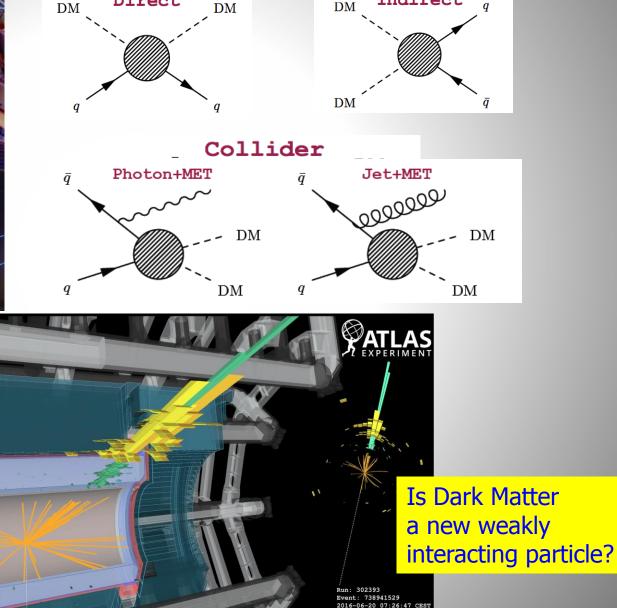
http://www.economist.com/news/science-and-technology/21709946-supersymmetry-beautiful-idea-there-still-no-evidence-support-it

### **Dark Matter Searches at the LHC**

Direct

DM





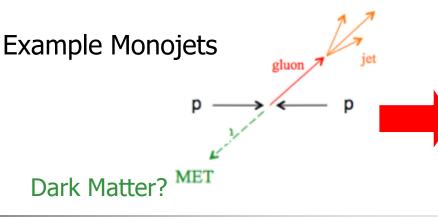
Indirect

DM

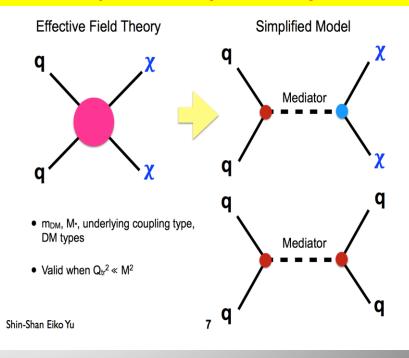
 Identifying Dark Matter is one of the most important questions in physics today! •It is likely a new as yet undetected particle •Can it be produced at the LHC?

# **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 dtype 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?)

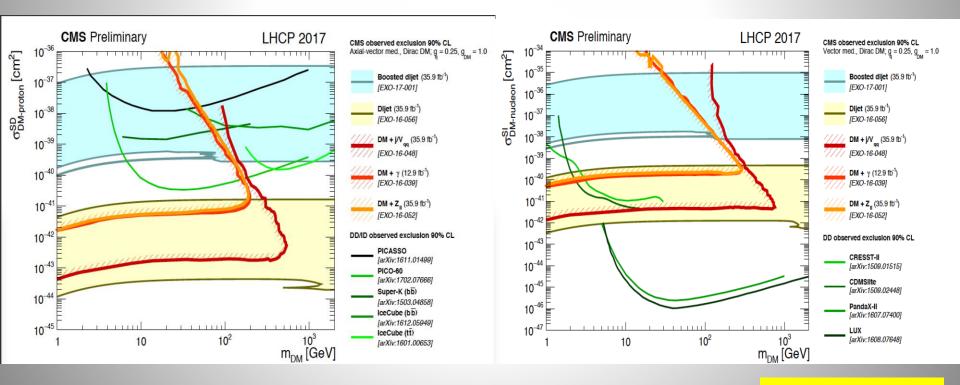


## **Comparison with Direct Detection**

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

#### Axial-vector mediator and Spin-dependent direct limits

#### Vector mediator and Spin-independent direct limits



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

90% CL limits

### **Exotica Searches: Limits**

#### ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

Sta	atus: July 2018						$\int \mathcal{L} dt = ($	3.2 – 79.8) fb <sup>-1</sup>	$\sqrt{s} = 8, 13 \text{ TeV}$
	Model	<i>ℓ</i> ,γ	Jets†	$\mathbf{E}_{\mathbf{T}}^{\mathrm{miss}}$	∫£ dt[fb		5		Reference
Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\gamma\gamma$ ADD QBH ADD BH high $\sum p_T$ ADD BH multijet RS1 $G_{KK} \rightarrow \gamma\gamma$ Bulk RS $G_{KK} \rightarrow WW/ZZ$ Bulk RS $g_{KK} \rightarrow tt$ 2UED / RPP		$1 - 4j$ $-$ $2j$ $\geq 2j$ $\geq 3j$ $-$ $1$ $\geq 1 b, \geq 1J/$ $\geq 2 b, \geq 3$		36.1 36.7 37.0 3.2 3.6 36.7 36.1 36.1 36.1	М <sub>D</sub> M <sub>5</sub> M <sub>4</sub> M <sub>5</sub> M <sub>4</sub> M <sub>5</sub> M <sub>4</sub> M <sub>5</sub> M <sub>4</sub> M <sub>5</sub> M <sub>4</sub> M <sub>5</sub> M <sub>5</sub> M <sub>4</sub> M <sub>5</sub> M <sub>5</sub> M <sub>4</sub> M <sub>5</sub> M <sub>5</sub>		$\begin{split} n &= 2\\ n &= 3 \text{ HLZ NLO}\\ n &= 6\\ n &= 6, M_D = 3 \text{ TeV, rot BH}\\ n &= 6, M_D = 3 \text{ TeV, rot BH}\\ k/\overline{M}_{PI} &= 0.1\\ k/\overline{M}_{PI} &= 1.0\\ \Gamma/m &= 15\%\\ \text{ Tier } (1,1), \mathcal{B}(A^{(1,1)} \rightarrow tt) = 1 \end{split}$	1711.03301 1707.04147 1703.09127 1606.02265 1512.02586 1707.04147 CERN-EP-2018-179 1804.10823 1803.09678
Gauge bosons	$\begin{array}{l} \text{SSM } Z' \to \ell\ell \\ \text{SSM } Z' \to \tau\tau \\ \text{Leptophobic } Z' \to bb \\ \text{Leptophobic } Z' \to tt \\ \text{SSM } W' \to \ell\nu \\ \text{SSM } W' \to \tau\nu \\ \text{HVT } V' \to WV \to qqqq \text{ mode} \\ \text{HVT } V' \to WH/ZH \text{ model B} \\ \text{LRSM } W'_R \to tb \end{array}$	1 e,μ 1 τ elB 0 e,μ		- 2j Yes Yes Yes -	36.1 36.1 36.1 79.8 36.1 79.8 36.1 36.1 36.1	Z' mass         4.5 T           Z' mass         2.42 TeV           Z' mass         2.1 TeV           Z' mass         3.0 TeV           W' mass         3.7 TeV           V' mass         4.15 TeV           V' mass         2.93 TeV           W' mass         3.25 TeV	i.6 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$	1707.02424 1709.07242 1805.09299 1804.10823 ATLAS-CONF-2018-017 1801.06992 ATLAS-CONF-2018-016 1712.06518 CERN-EP-2018-142
CI	Cl qqqq Cl ℓℓqq Cl tttt	_ 2 e,μ ≥1 e,μ	2 j _ ≥1 b, ≥1 j	– – Yes	37.0 36.1 36.1	Λ Λ Λ Λ Λ 2.57 TeV		<b>21.8 TeV</b> $\eta_{LL}^-$ <b>40.0 TeV</b> $\eta_{LL}^-$ $ C_{4t}  = 4\pi$	1703.09127 1707.02424 CERN-EP-2018-174
MQ	Axial-vector mediator (Dirac D Colored scalar mediator (Dirac $VV_{\chi\chi}$ EFT (Dirac DM)		$\begin{array}{c} 1-4 \ j \\ 1-4 \ j \\ 1 \ J, \leq 1 \ j \end{array}$	Yes Yes Yes	36.1 36.1 3.2	m <sub>med</sub> 1.55 TeV           m <sub>med</sub> 1.67 TeV           M,         700 GeV		$\begin{split} g_q = 0.25,  g_\chi = 1.0,  m(\chi) &= 1 \text{ GeV} \\ g = 1.0,  m(\chi) &= 1 \text{ GeV} \\ m(\chi) < 150 \text{ GeV} \end{split}$	1711.03301 1711.03301 1608.02372
ΓØ	Scalar LQ 1 <sup>st</sup> gen Scalar LQ 2 <sup>nd</sup> gen Scalar LQ 3 <sup>rd</sup> gen	2 e 2 μ 1 e,μ	≥ 2 j ≥ 2 j ≥1 b, ≥3 j	- Yes	3.2 3.2 20.3	LQ mass         1.1 TeV           LQ mass         1.05 TeV           LQ mass         640 GeV		$\begin{array}{l} \beta = 1 \\ \beta = 1 \\ \beta = 0 \end{array}$	1605.06035 1605.06035 1508.04735
Excited fermionsHeavy quarks	$ \begin{array}{l} VLQ \ TT \rightarrow Ht/Zt/Wb + X \\ VLQ \ BB \rightarrow Wt/Zb + X \\ VLQ \ BT_{5/3} \ T_{5/3} \ T_{$		l u ≥1 b, ≥1 j ≥ 1 b, ≥ 1	Yes	36.1 36.1 36.1 3.2 79.8 20.3	T mass         1.37 TeV           B mass         1.34 TeV           T <sub>5/3</sub> mass         1.64 TeV           Y mass         1.44 TeV           B mass         1.21 TeV           Q mass         690 GeV		SU(2) doublet SU(2) doublet $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ $\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$ $\kappa_B = 0.5$	ATLAS-CONF-2018-032 ATLAS-CONF-2018-032 CERN-EP-2018-171 ATLAS-CONF-2016-072 ATLAS-CONF-2018-024 1509.04261
xcited fermior	Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow q\gamma$ Excited quark $b^* \rightarrow bg$ Excited lepton $\ell^*$ Excited lepton $\gamma^*$	- 1 γ - 3 e, μ 3 e, μ, τ	2 j 1 j 1 b, 1 j -		37.0 36.7 36.1 20.3 20.3		6.0 TeV 3 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 1709.10440 1805.09299 1411.2921 1411.2921
Other	Type III Seesaw LRSM Majorana $\nu$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \ell$ Higgs triplet $H^{\pm\pm} \rightarrow \ell \tau$ Monotop (non-res prod) Multi-charged particles Magnetic monopoles	$     \begin{array}{r}       1 e, \mu \\       2 e, \mu \\       2,3,4 e, \mu (SS \\       3 e, \mu, \tau \\       1 e, \mu \\       - \\       - \\       \hline       \sqrt{s} = 8 \text{ TeV}     \end{array} $	≥ 2 j 2 j 5) - 1 b - - -	Yes   Yes  	79.8 20.3 36.1 20.3 20.3 20.3 7.0	Nº mass         560 GeV           Nº mass         2.0 TeV           H±* mass         870 GeV           H±* mass         400 GeV           spin-1 invisible particle mass         657 GeV           motiopole mass         785 GeV		$m(W_R) = 2.4$ TeV, no mixing DY production DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$ $a_{non-res} = 0.2$ DY production, $ q  = 5e$ DY production, $ g  = 1g_D$ , spin 1/2	ATLAS-CONF-2018-020 1506.06020 1710.09748 1411.2921 1410.5404 1504.04188 1509.08059
	_		10-11			10 <sup>-1</sup> 1	1	<sup>0</sup> Mass scale [TeV]	

\*Only a selection of the available mass limits on new states or phenomena is shown. †Small-radius (large-radius) jets are denoted by the letter j (J).

## Are we leaving no stone unturned?

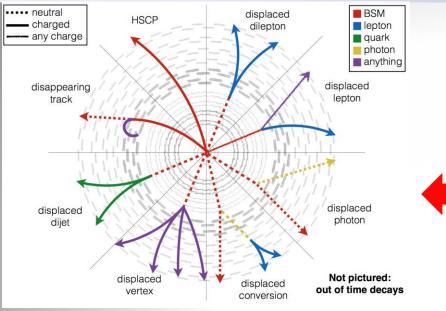
- The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics (higher mass, lower couplings)
- But if we still do not see more than a 2 sigma at the end of run-III, the HL-LHC will be likely mostly a precision physics machine, searching for subtle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

Are we looking at the right place?



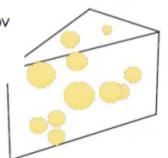


# **Searches for Long Lived Particles**



#### Present coverage?

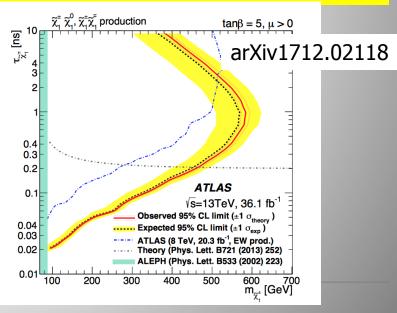




LHC-wide organized study -> https://indico.cern.ch/e/LHC\_LLP\_October\_2017 A White Paper in preparation!

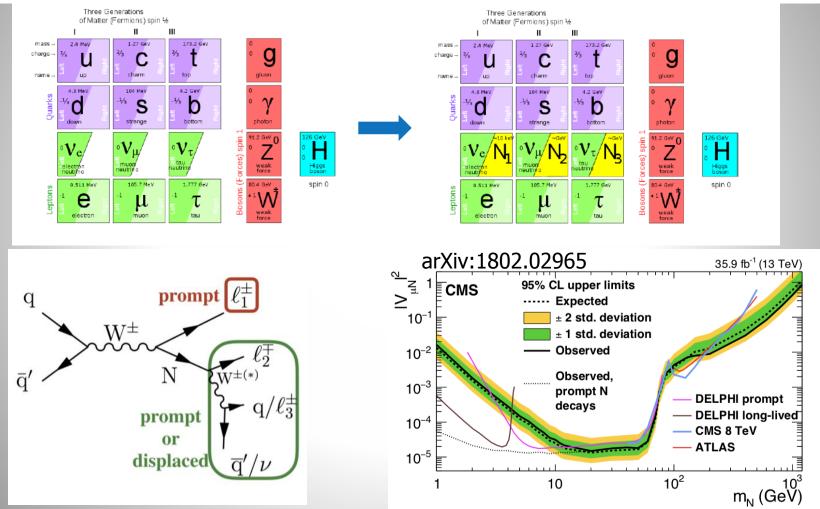
Increasing interest and effort: Look for unusual signals in the detector from long-lived particles

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



### **Search for Heavy Neutral Leptons**

#### Neutrino portal: vMSM (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

### **Long Lived Particle Searches**

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

Status: July 2018

ATLAS Preliminary

 $\int \mathcal{L} dt = (3.2 - 36.1) \text{ fb}^{-1} \sqrt{s} = 8, 13 \text{ TeV}$ 

	Model	Signature	∫£ dt [fb	-1]	Lifetime limit		JZ ur = (0.2 00.1) 10	Reference
	$\operatorname{RPV} \chi_1^0 \to eev/e\mu v/\mu\mu v$	displaced lepton pair	20.3	$\chi_1^0$ lifetime		7-740 mm	$m( ilde{g}){=}$ 1.3 TeV, $m(\chi_1^0){=}$ 1.0 TeV	1504.05162
	$\operatorname{GGM} \chi^0_1 \to Z \tilde{G}$	displaced vtx + jets	20.3	$\chi_1^0$ lifetime		6-480 mm	$m({ ilde g}){=}$ 1.1 TeV, $m(\chi_1^0){=}$ 1.0 TeV	1504.05162
	$\operatorname{GGM} \chi^0_1 \to Z \tilde{G}$	displaced dimuon	32.9	$\chi_1^0$ lifetime		0.029-18.0 m	$m({ ilde g}){=}$ 1.1 TeV, $m(\chi_1^0){=}$ 1.0 TeV	CERN-EP-2018-173
	GMSB	non-pointing or delayed	y 20.3	$\chi_1^0$ lifetime		0.08-5.4 m	SPS8 with $\Lambda{=}200~\text{TeV}$	1409.5542
	AMSB $pp \rightarrow \chi_1^{\pm} \chi_1^0, \chi_1^{+} \chi_1^{-}$	disappearing track	20.3	$\chi_1^{\pm}$ lifetime		0.22-3.0 m	$m(\chi_1^{\pm})=$ 450 GeV	1310.3675
SUSY	AMSB $pp \rightarrow \chi_1^{\pm} \chi_1^0, \chi_1^+ \chi_1^-$	disappearing track	36.1	$\chi_1^{\pm}$ lifetime	_	0.057-1.53 m	$m(\chi_1^{\pm})=$ 450 GeV	1712.02118
S	AMSB $\rho p \rightarrow \chi_1^{\pm} \chi_1^0, \chi_1^+ \chi_1^-$	large pixel dE/dx	18.4	$\chi_1^{\pm}$ lifetime		1.31-9.0 m	$m(\chi_1^{\pm})=$ 450 GeV	1506.05332
	Stealth SUSY	2 ID/MS vertices	19.5	<b>Š</b> lifetime			<b>0.12-90.6 m</b> $m(\tilde{g}) = 500 \text{ GeV}$	1504.03634
	Split SUSY	large pixel dE/dx	36.1	<b>ğ</b> lifetime		> 0.9 m	$m(\tilde{g}) = 1.8 \text{ TeV}, m(\chi_1^0) = 100 \text{ GeV}$	CERN-EP-2018-198
	Split SUSY	displaced vtx + $E_{T}^{miss}$	32.8	ĝ lifetime		0.03-13.2 m	$m(\tilde{g}) = 1.8 \text{ TeV}, \ m(\chi_1^0) = 100 \text{ GeV}$	1710.04901
	Split SUSY	0 $\ell$ , 2 – 6 jets + $E_{T}^{miss}$	36.1	ĝ lifetime		0.0-2.1 m	$m({{ ilde g}})=$ 1.8 TeV, $m(\chi_1^0)=$ 100 GeV	ATLAS-CONF-2018-003
	$H \rightarrow s s$	2 low-EMF trackless jets	20.3	s lifetime		0.41-7.57 m	<i>m</i> ( <i>s</i> )= 25 GeV	1501.04020
%0	$H \rightarrow s s$	2 ID/MS vertices	19.5	s lifetime		0.31-25.4	m (s)= 25 GeV	1504.03634
= 10%	FRVZ $H  ightarrow 2\gamma_d + X$	2 <i>e−</i> , <i>µ−</i> jets	20.3	γ <sub>d</sub> lifetime 0-3 mm			$m(\gamma_d) = 400 \text{ MeV}$	1511.05542
Higgs BR	FRVZ $H  ightarrow 2\gamma_d + X$	2 <i>e</i> -, <i>μ</i> -, <i>π</i> -jets	3.4	γd lifetime		0.022-1.113 m	$m(\gamma_d) = 400 \text{ MeV}$	ATLAS-CONF-2016-042
Higg	FRVZ $H  ightarrow 4 \gamma_d + X$	2 <i>e</i> -, <i>μ</i> -, <i>π</i> -jets	3.4	$\gamma_{\rm d}$ lifetime		0.038-1.63 m	$m(\gamma_d) = 400 \text{ MeV}$	ATLAS-CONF-2016-042
	$H \rightarrow Z_d Z_d$	displaced dimuon	32.9	Z <sub>d</sub> lifetime		0.009-24.0	$m \qquad m(Z_d) = 40 \text{ GeV}$	CERN-EP-2018-173
	$VH$ with $H \rightarrow ss \rightarrow bbbb$	$1-2\ell$ + multi-b-jets	36.1	s lifetime 0-3 mm			$\mathcal{B}(H \rightarrow ss) = 1, m(s) = 60 \text{ GeV}$	1806.07355
	$\Phi(300 \text{ GeV}) \rightarrow s s$	2 low-EMF trackless jets	20.3	s lifetime		0.29-7.9 m	$\sigma \times \mathcal{B} = 1 \text{ pb, } m(s) = 50 \text{ GeV}$	1501.04020
	$\Phi(300 \text{ GeV}) \rightarrow s s$	2 ID/MS vertices	19.5	s lifetime		0.19-31	<b>.9 m</b> $\sigma \times \mathcal{B} = 1$ pb, $m(s) = 50$ GeV	1504.03634
Scalar	$\Phi(600 \text{ GeV}) \rightarrow s s$	2 low-EMF trackless jets	3.2	s lifetime		0.09-2.7 m	$\sigma \times \mathcal{B} = 1 \text{ pb, } m(s) = 50 \text{ GeV}$	ATLAS-CONF-2016-103
S	$\Phi(900 \text{ GeV}) \rightarrow s s$	2 low-EMF trackless jets	20.3	s lifetime		0.15-4.1 m	$\sigma \times \mathcal{B} = 1 \text{ pb}, m(s) = 50 \text{ GeV}$	1501.04020
	$\Phi(900 \text{ GeV}) \rightarrow s s$	2 ID/MS vertices	19.5	s lifetime		0.11-18.3 m	$\sigma \times \mathcal{B} = 1 \text{ pb}, m(s) = 50 \text{ GeV}$	1504.03634
	$\Phi(1 \; \text{TeV}) \to \textit{s} \; \textit{s}$	2 low-EMF trackless jets	3.2	s lifetime		0.78-16.0 m	$\sigma \times \mathcal{B} = 1 \text{ pb, } m(s) = 400 \text{ GeV}$	ATLAS-CONF-2016-103
-	${\rm HV} \; Z'({\rm 1 \; TeV}) \rightarrow q_{\rm v} q_{\rm v}$	2 ID/MS vertices	20.3	s lifetime		0.1-4.9 m	$\sigma \times \mathcal{B} = 1 \text{ pb, } m(s) = 50 \text{ GeV}$	1504.03634
Other	${\rm HV}\; Z'({\rm 2\;TeV}) \to q_{\rm V} q_{\rm V}$	2 ID/MS vertices	20.3	s lifetime		0.1-10.1 m	$\sigma  imes \mathcal{B} = 1$ pb, $m(s) = 50$ GeV	1504.03634
	√s = 8 ⊺	<b>TeV</b> √s = 13 TeV		0.	01 0		<sup>100</sup> cτ [m]	

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

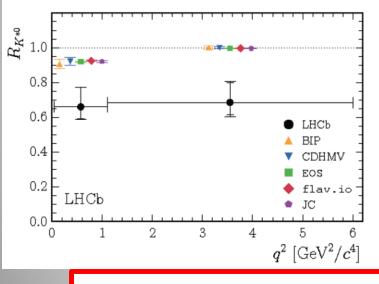
 $(\gamma\beta = 1)$ 

# LHCb: Test of Lepton Universality

### A puzzling results from the LHCb experiment...

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

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



Comparison with SM predictions

If confirmed independent checks will become very important. BelleII? (in a few years form now)

CMS has installed a special trigger to collect an unbiased b-sample which is active since 2018 -> Expect 10<sup>10</sup> b-pairs by the end of run2!!

 $R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07} \,(\text{stat}) \pm 0.03 \,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \,\text{GeV}^2 & 2.1 - 2.3 \,\sigma \\ 0.69^{+0.11}_{-0.07} \,(\text{stat}) \pm 0.05 \,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0 \,\text{GeV}^2 & 2.4 - 2.5 \,\sigma \end{cases}$   $Also: R_{D^{(*)}}^{\tau/\ell} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$ 

### **Third Generation Leptoquarks**

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

 $B^0$ 

#### Example search in the tau-b final state EXO-17-029 CMS Preliminary 2016, 35.9 fb<sup>-1</sup> (13TeV) **CMS** Preliminary 35.9 fb<sup>-1</sup> (13TeV) 2.5 ب Scalar LQ 700 Gel 0. = 1.8 = 10Single top Observed Expected $\pm 1 \sigma$ Y,Z S 2.0 Whanny Preferred by B-anomaly $\pm 1 \sigma$ $\overline{t}, \overline{c}, \overline{u}$ $\overline{h}$ Excluded by 1.5 æ 1.0 $K^{*0}$ $B^0$ $pp \rightarrow LQ_sLQ_s$ Scalar sum p., (GeV) CMS Preliminary 2016, 35.9 fb<sup>-1</sup> (13TeV) 1.0 Scalar LQ 700 GeV 0 = 1, B = 1Electrowea QCD multije 0.5 Scalar LQ $\beta = 1$ LO K<sup>\*0</sup> 0.0L 200 2.0 800 1000 1200 1400 400 600 Leptoquark mass (GeV) Scalar sum p<sub>y</sub> (GeV)

Blue region is preferred by the B-anomalies...

LQ

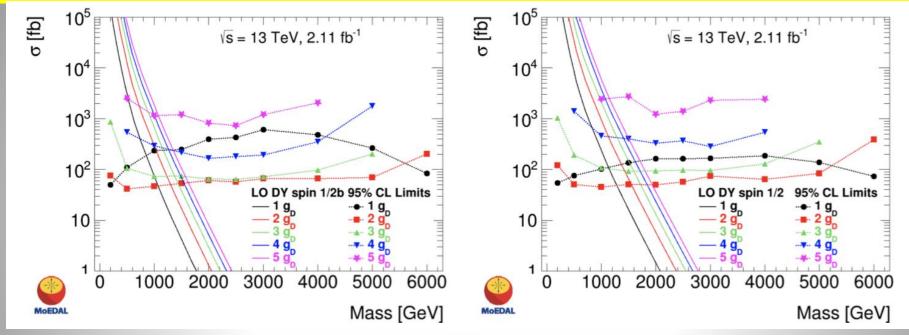
h

LQ

LO

### 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<sup>-1</sup>) arXiv:1712.09849



•Limits for different
monopole charges

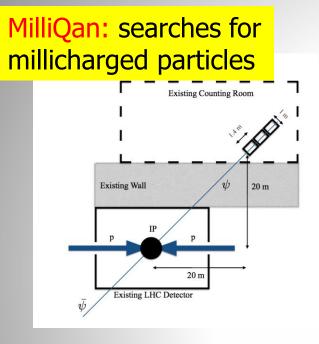
•First monopole search result @LHC at 13 TeV No signal (yet)..

Mass limits [GeV]	$1g_{\rm D}$	$2g_{\rm D}$	$3g_{\rm D}$	$4g_{\rm D}$	$5g_{\rm D}$
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 $\beta$ -dep.	490	880	960	890	690
DY spin- $\frac{1}{2}\beta$ -dep.	850	1300	1380	1250	1070
DY spin-1 $\beta$ -dep.	930	1450	1620	1600	1460
ALTERATION IT					
	MoEDAL 13 TeV (2016 exposure) DY spin-0 DY spin- $\frac{1}{2}$ DY spin-1 DY spin-0 $\beta$ -dep. DY spin- $\frac{1}{2}\beta$ -dep.	MoEDAL 13 TeV         (2016 exposure)         DY spin-0       600         DY spin-1       1110         DY spin-0 $\beta$ -dep.         490       DY spin-1         DY spin-1 $\beta$ -dep.         850	MoEDAL 13 TeV       0       0         (2016 exposure)       0       0         DY spin-0       600       1000         DY spin-12       1110       1540         DY spin-1       1110       1640         DY spin-0 $\beta$ -dep.       490       880         DY spin-1       2       1300       1300	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c c c c c c c c c c c c c c c c c c $

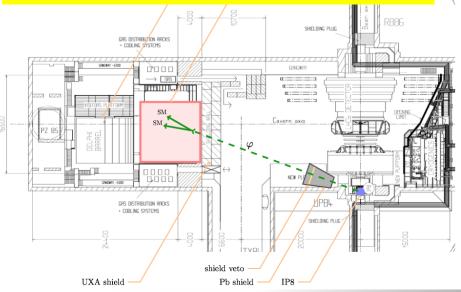
**LHCb** 

**MoEDAL** 

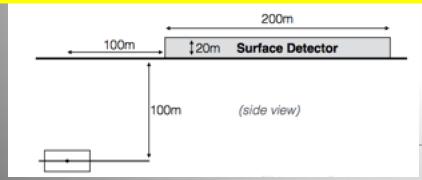
# **Possible New Experiments @LHC**



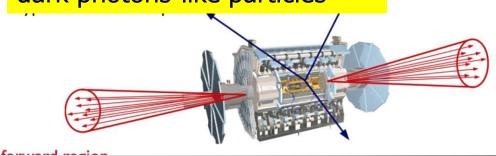
CODEX-b: searches for long lived weakly interacting neutral particles



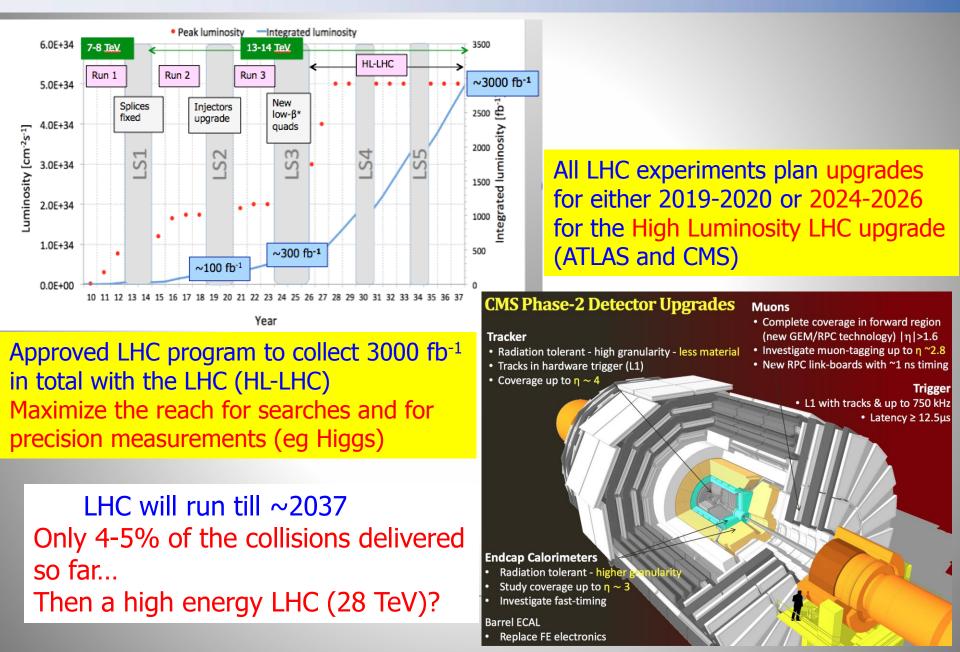
# MATHUSLA: searches for long lived weakly interacting neutral particles



# FASER: searches for long lived dark photons-like particles



### LHC Outlook and Plans



### Summary

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

There are a number of 3-sigma effects, as always, but... ©

- Dark Matter and Long Lived Particle searches are being explored in a systematic way. White paper on LLPs to appear.
- First results from the 2017 data are being released.
- New physics in the flavour sector? New TH paradiams?
- The LHC is continuing to explore the Terascale. much data to look forward to: it takes on significa to show the way!! Collected >130 fb<sup>-1</sup>@ 13 TeV solution
   And hopefully one day soon now:



**The Future** 



-2018: plan for 70 fb<sup>-1</sup> -2021-2023: plan for 300 fb<sup>-1</sup> - >2016 High Luminosity upgrade: collect 3000 fb<sup>-1</sup> by ~ 2035

# Summary

- The data of Run-1 allowed for many precise measurements of Standard Model processes, eg on the top quark, EWK and in QCD.
- Electroweak measurements in agreement with the data in general. New process measured eg  $W_{YY}$ , EWK WWjj...
- The LHC is a top-factory. Very detailed study of the top quarks ongoing. No surprises yet!
- The Higgs particle at 125 GeV shows no deviation from its Standard Model expectations (yet?). Now more precise coupling measurements and combined fits, differential distributions studies, as well as searches for rare processes Zγ, μμ, cc, light quark couplings...?
- Data taking is continuing !!
- Theorists: watch the precision of the data!! ③