New Results from the LHC

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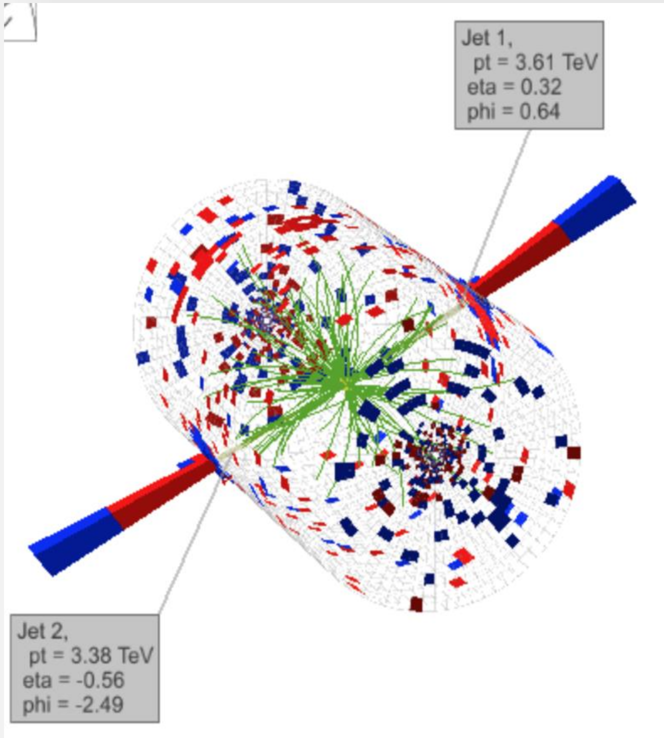
Outline



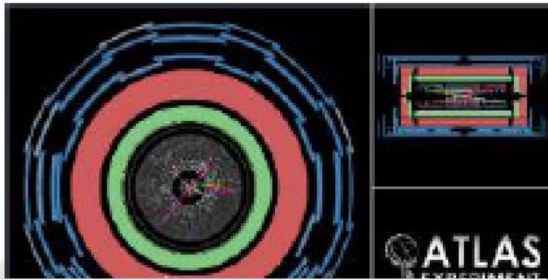
Bird-eyes view on new results
Mostly from CMS and ATLAS…

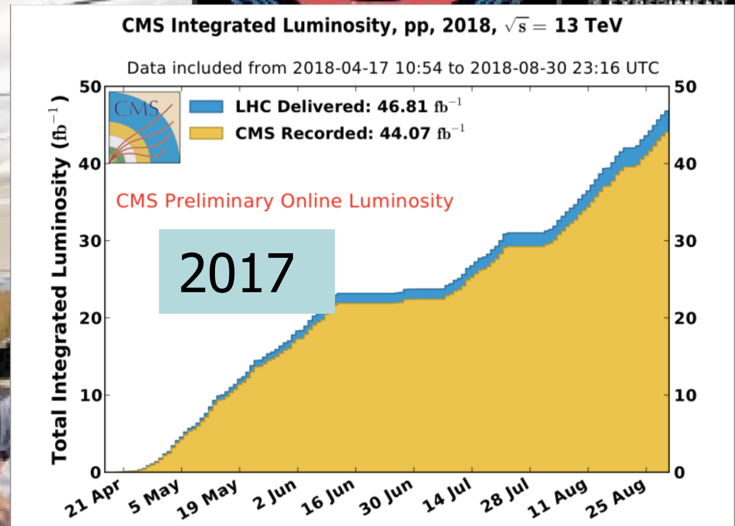
Details in the specific talks at this conference

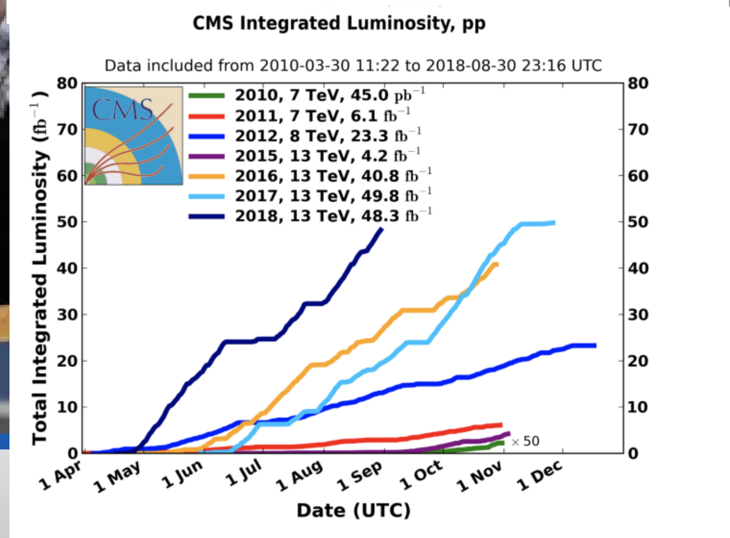
- Introduction
- Physics results
  - The Standard Model
  - The Higgs particle
  - Searches for New Physics & Dark Matter
  - New opportunities at the LHC?
  - Summary/Outlook

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

3rd June 2015 Run-2 starts





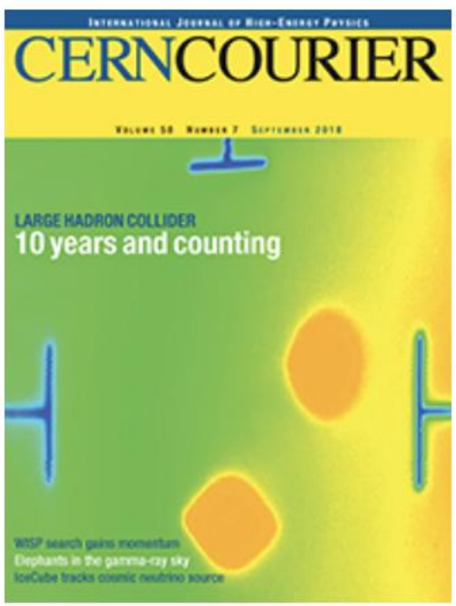


- 2010-2012: Run-1 at 7/8 TeV CM energy
  - Collected ~ 25 fb^{-1}
- 2015-2018: Run-2 at 13 TeV CM Energy
  - Collected so far at 13 TeV:~ 130 fb^{-1}
  - Expected by end of 2018: ~ 150+ fb^{-1}

It Started (first attempt) in September 2008!

The day the world switched on to particle physics

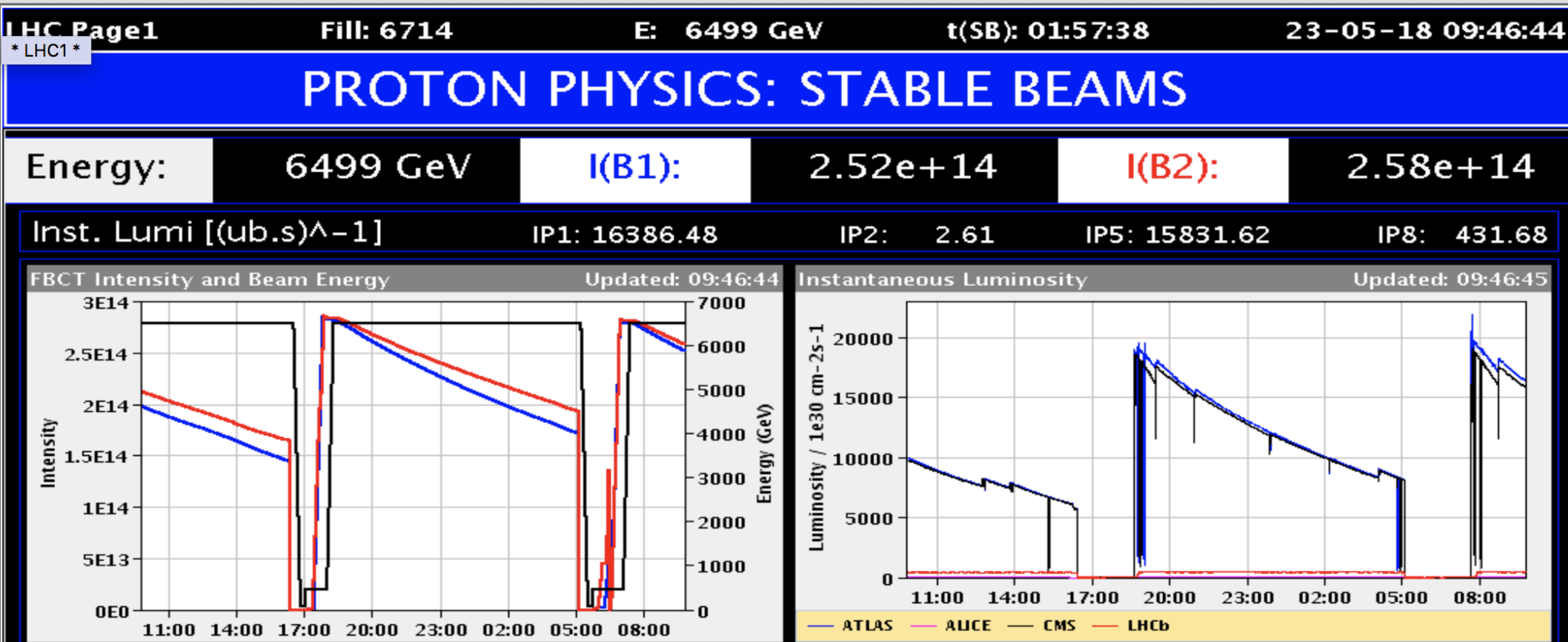
When the Large Hadron Collider circulated its first protons 10 years ago, it made headlines around the globe.
What was it that drove one of the biggest media events science has ever seen, and is the LHC still able to capture the public imagination?

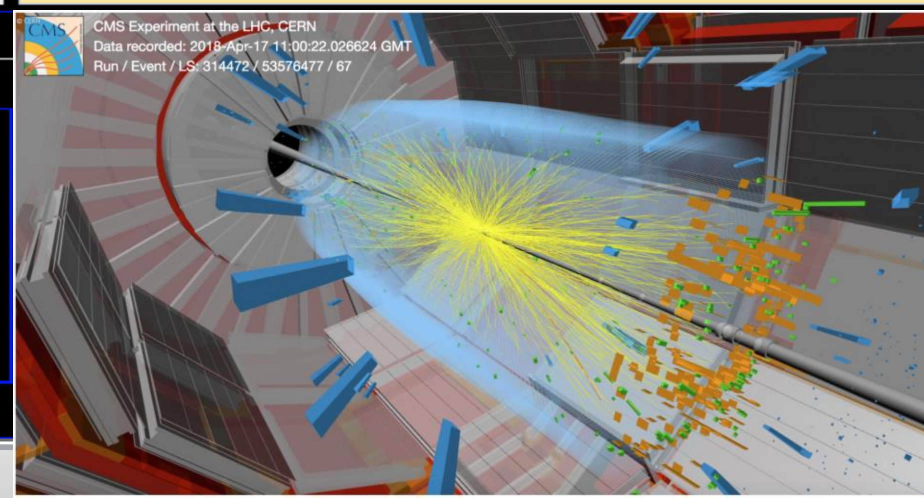


Available since yesterday: Cern Courier September 2018

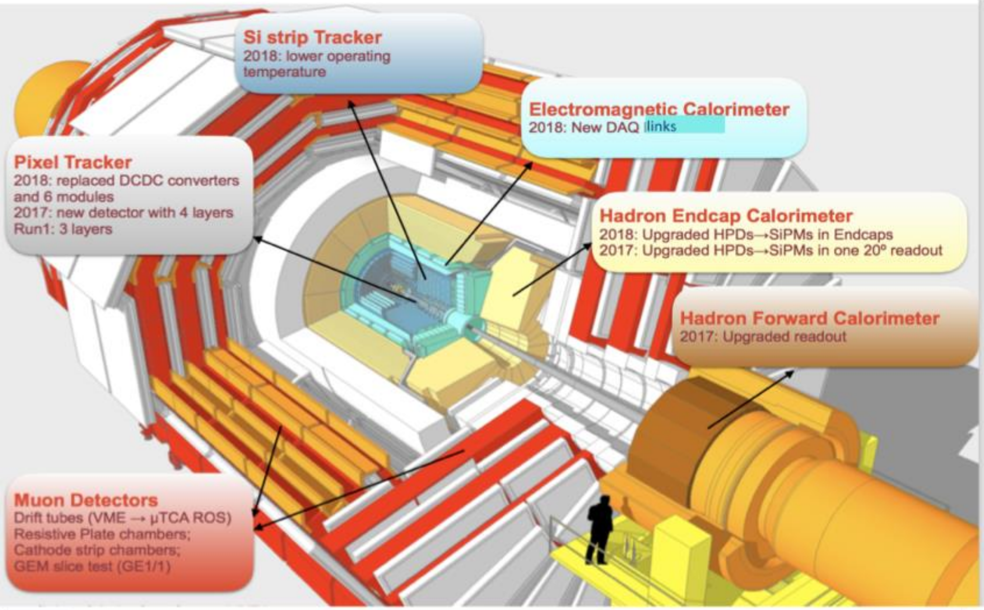
Top: scenes from first-beam day in the ATLAS (left) and CMS control rooms. Although there were no collisions that day, the experiments were able to record "splash" events – whereby protons strike a collimator and spray secondary particles into the detectors.

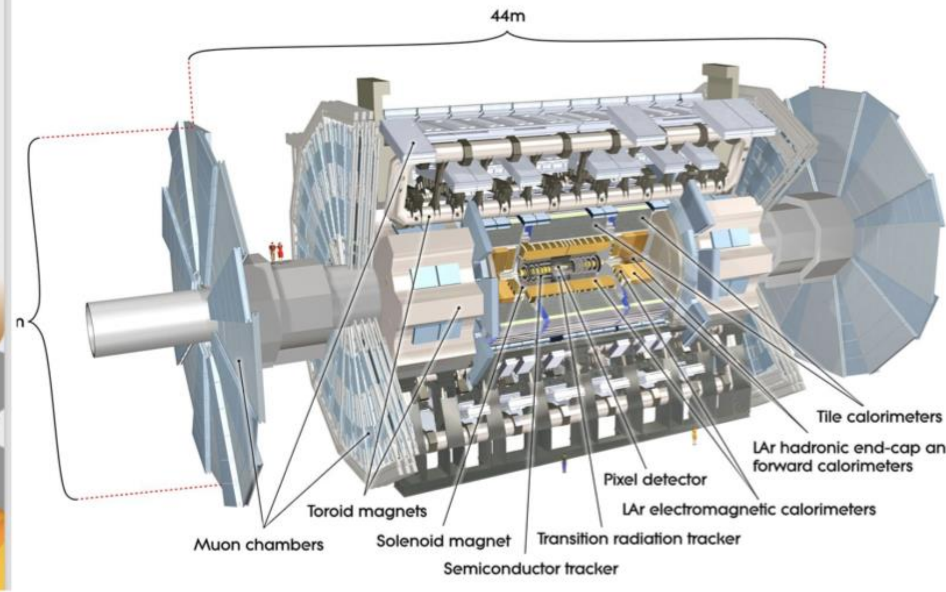
LHC Operation 2018: Going Very Well!!

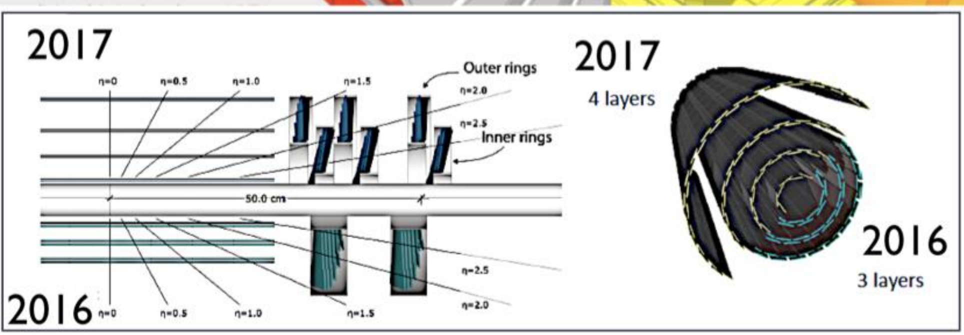




ATLAS & CMS Experiments in 2018/17







- New IBL detector installed in LS1 (2013-2014)
- Tracking optimized for high-PU and high-p_T environments
- Better ML algorithms

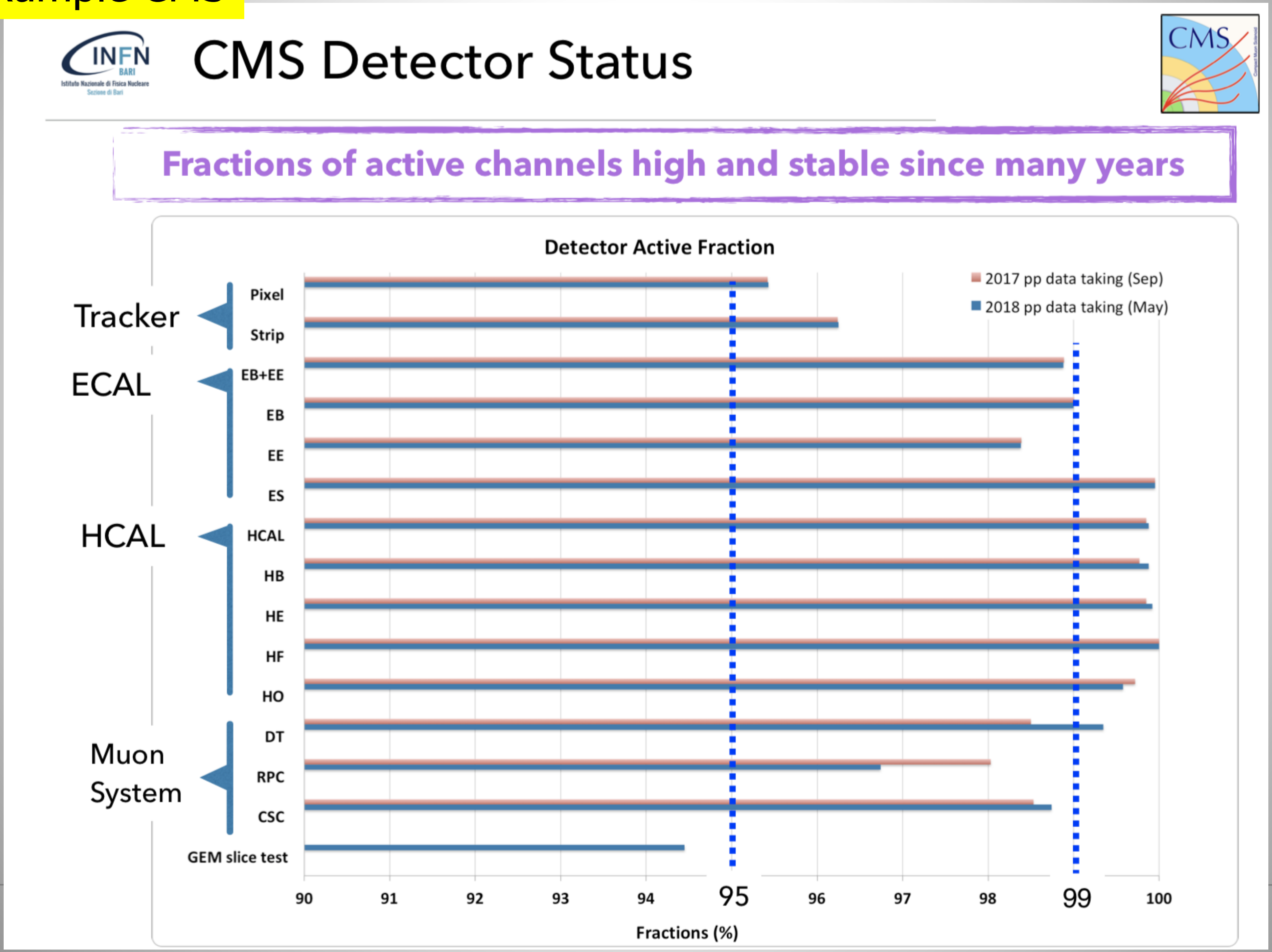
4th insertable pixel b-layer (IBL)

Large impact on b-tagging performance

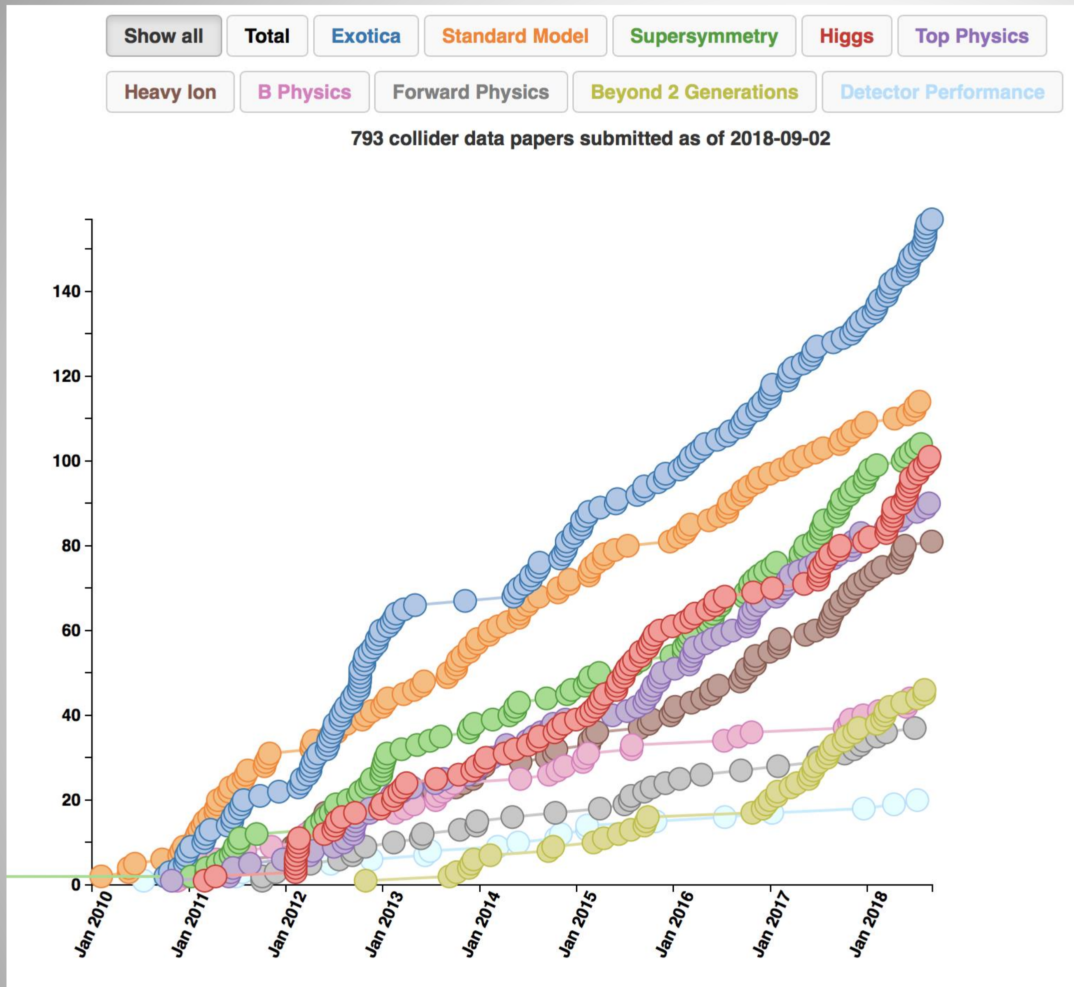
N. De Filippis

Detector Status

Example CMS



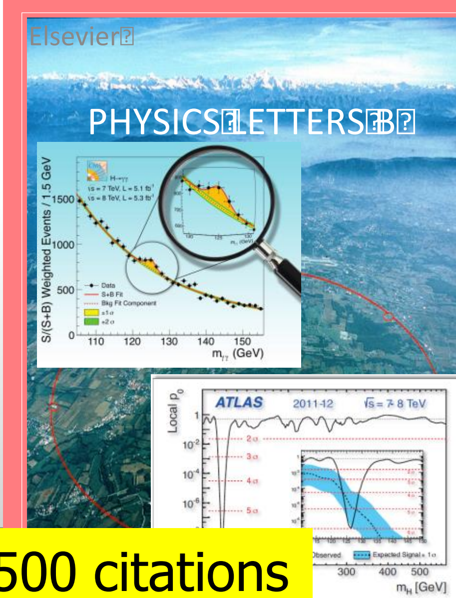
LHC Publications: Example CMS



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

About 100 papers on Higgs studies!!

Paper 16 was the discovery paper!



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

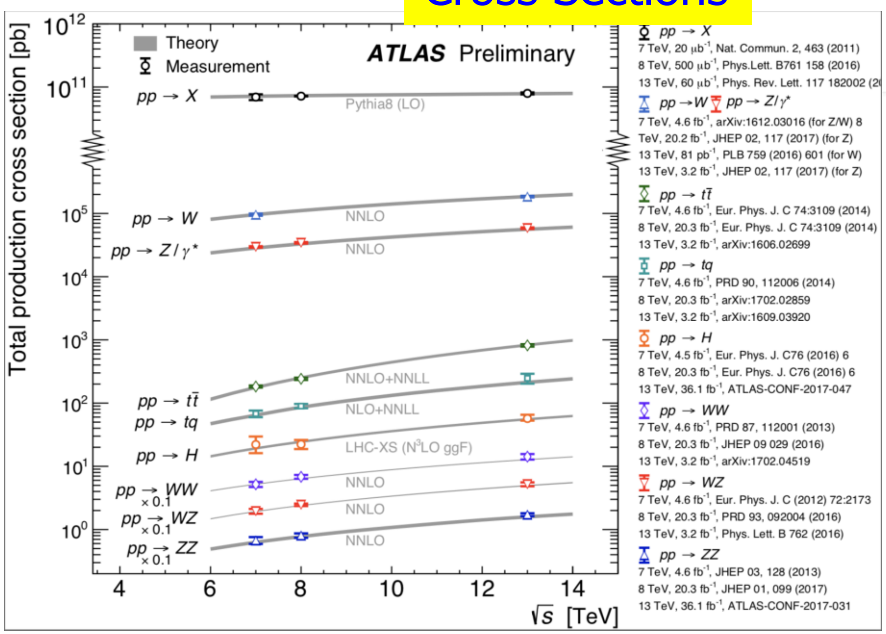
>8500 citations

Similar for ATLAS

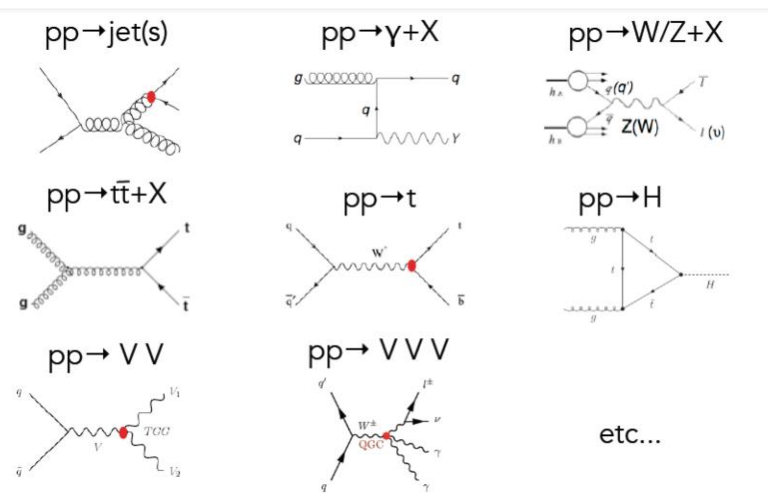
Standard Model Measurements

- 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 α_s)
  - Requires matching precision at theory prediction side
- Important to understand backgrounds for searches for new physics

Cross Sections

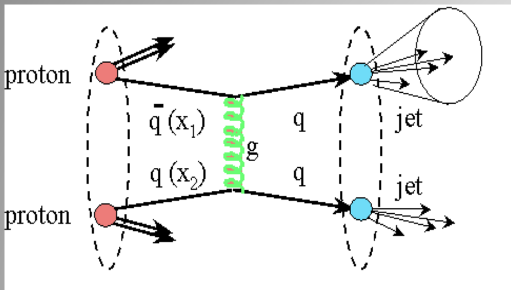


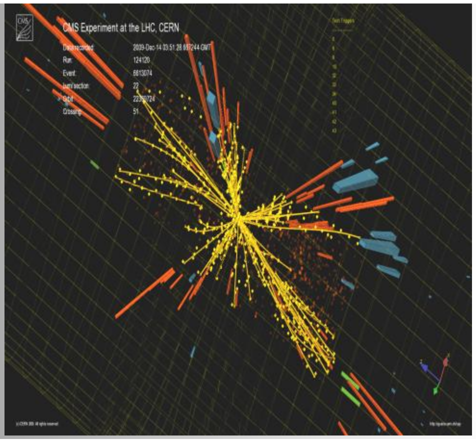
Many processes studied: Examples

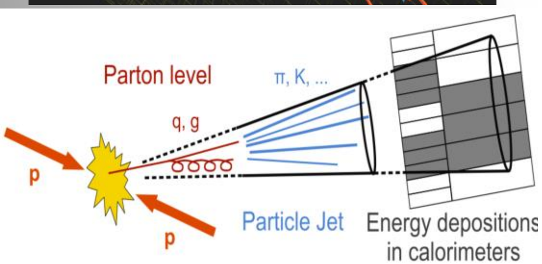


Inclusive Jet Production (13 TeV)

arXiv:1711.02692

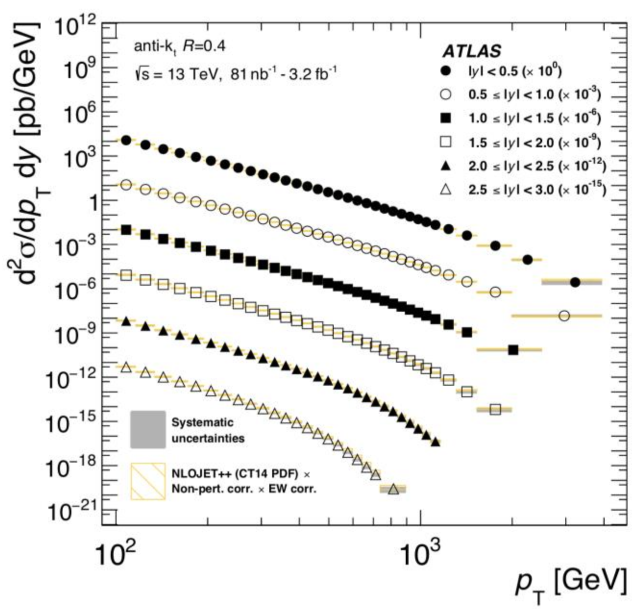


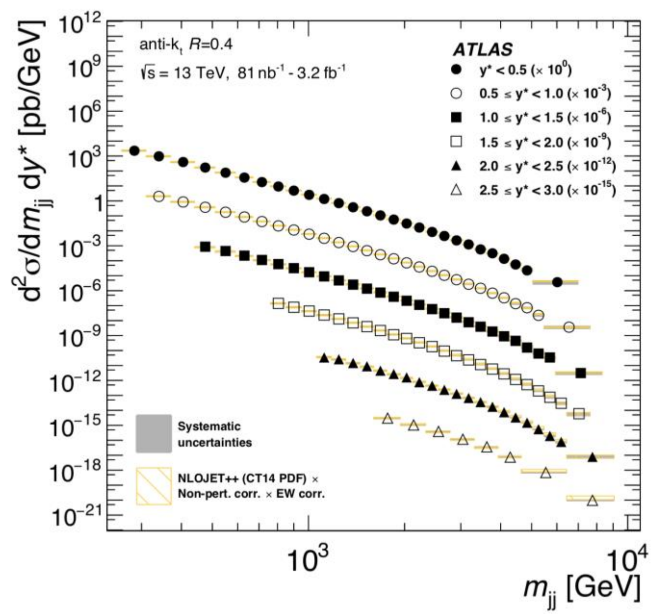




Differential cross sections with R=0.4

Jet p_T spectrum consistent with predictions from NLOJET++





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

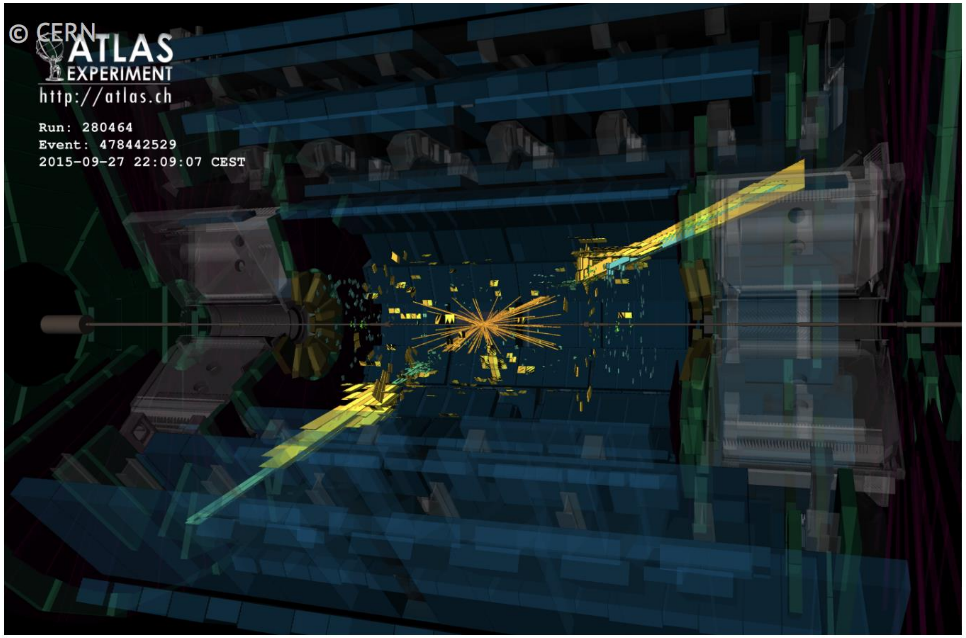
Jet Studies

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 α_s determination
- PDF sensitivity and extraction

⑤

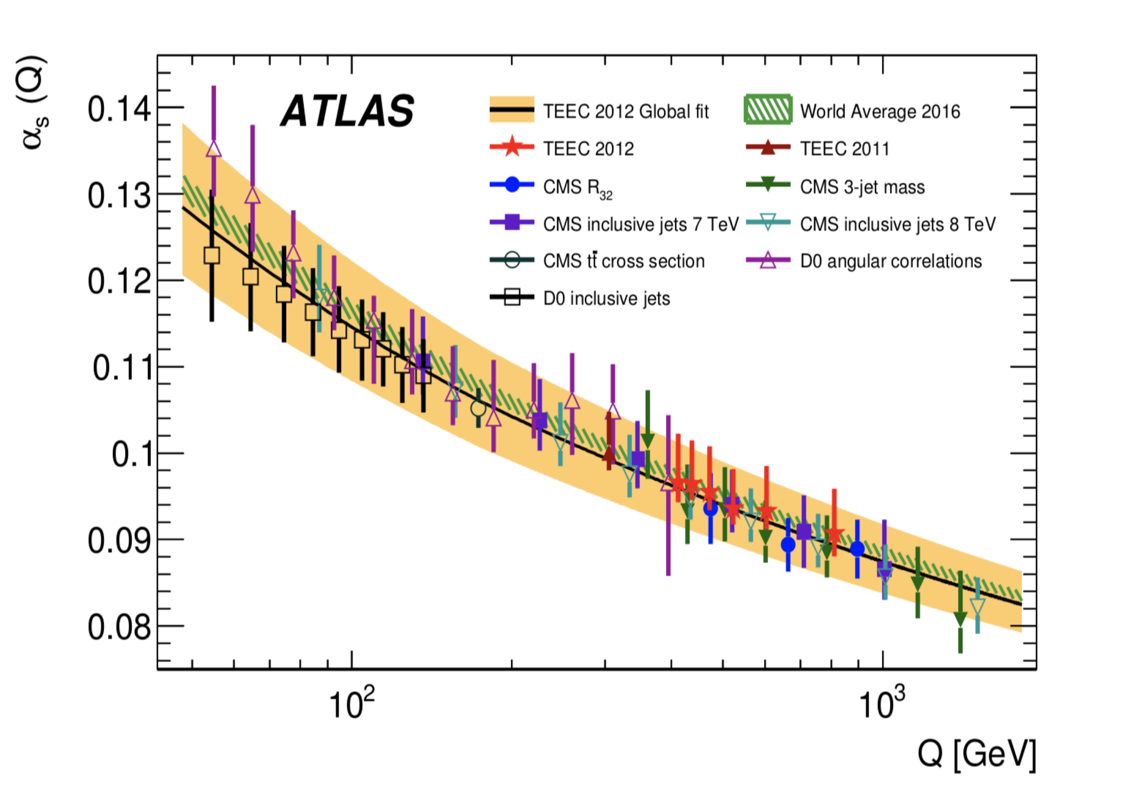
Dijet invariant mass = 7.9 TeV



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_T> 800 GeV



arXiv:1707.02562

- 8 TeV analysis
- NLO extractions
- Theory uncert. dominate

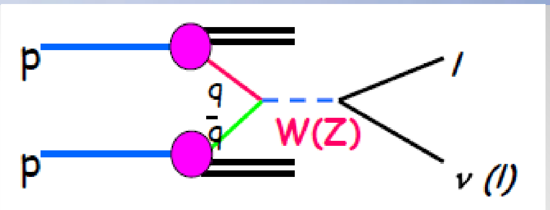
ATEEC is the difference between the forward and backward TEEC

$$\alpha_s(m_Z) = 0.1162 \pm 0.0011\ (\text{exp.})\ ^{+0.0076}_{-0.0061}\ (\text{scale}) \pm 0.0018\ (\text{PDF}) \pm 0.0003\ (\text{NP}),$$ TEECs

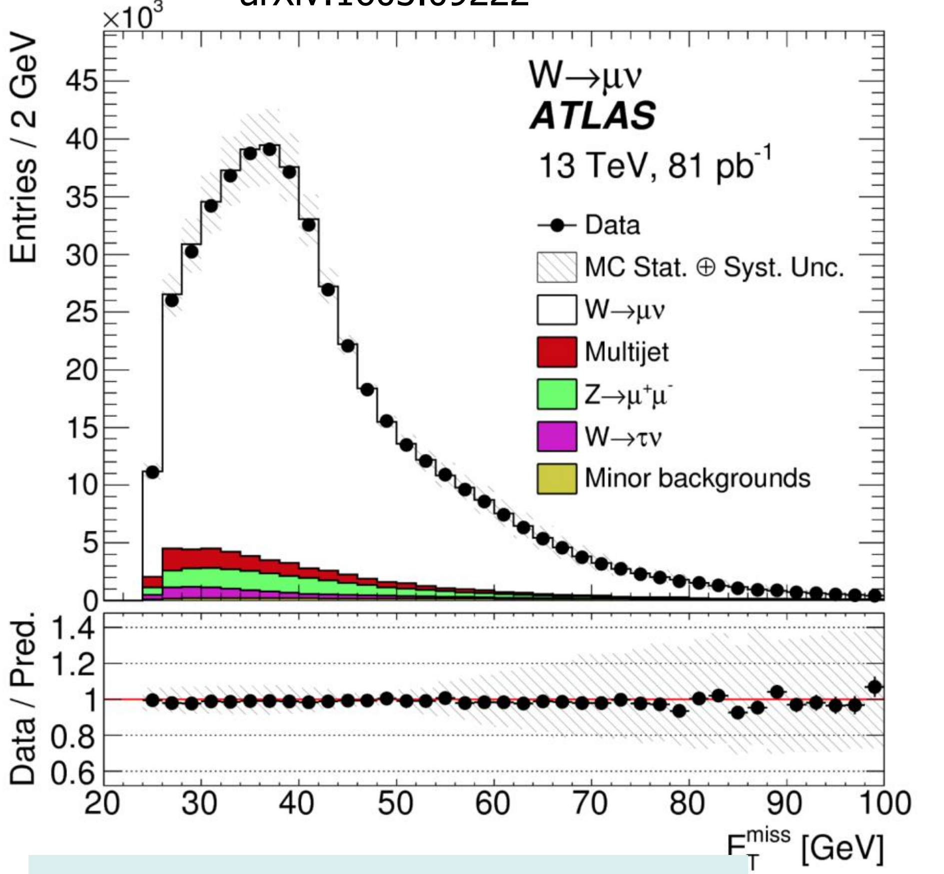
$$\alpha_s(m_Z) = 0.1196 \pm 0.0013\ (\text{exp.})\ ^{+0.0061}_{-0.0013}\ (\text{scale}) \pm 0.0017\ (\text{PDF}) \pm 0.0004\ (\text{NP}),$$ ATEECs

W and Z Boson Production

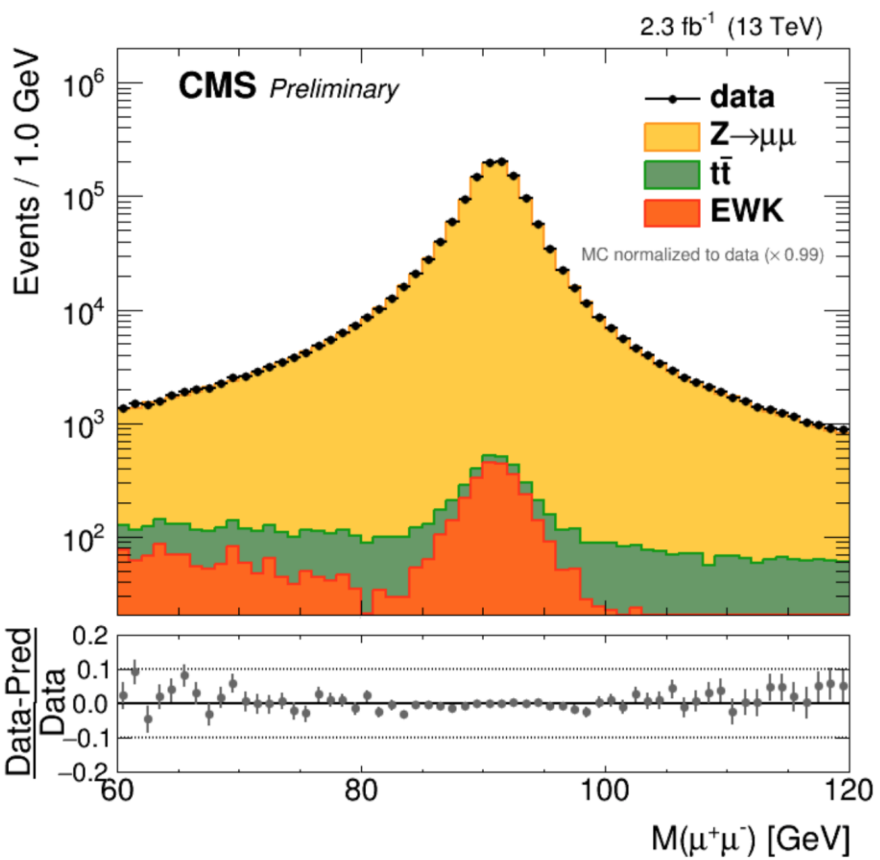
Select final states with leptons



arXiv:1603.09222



CMS-PAS-SMP-15-011

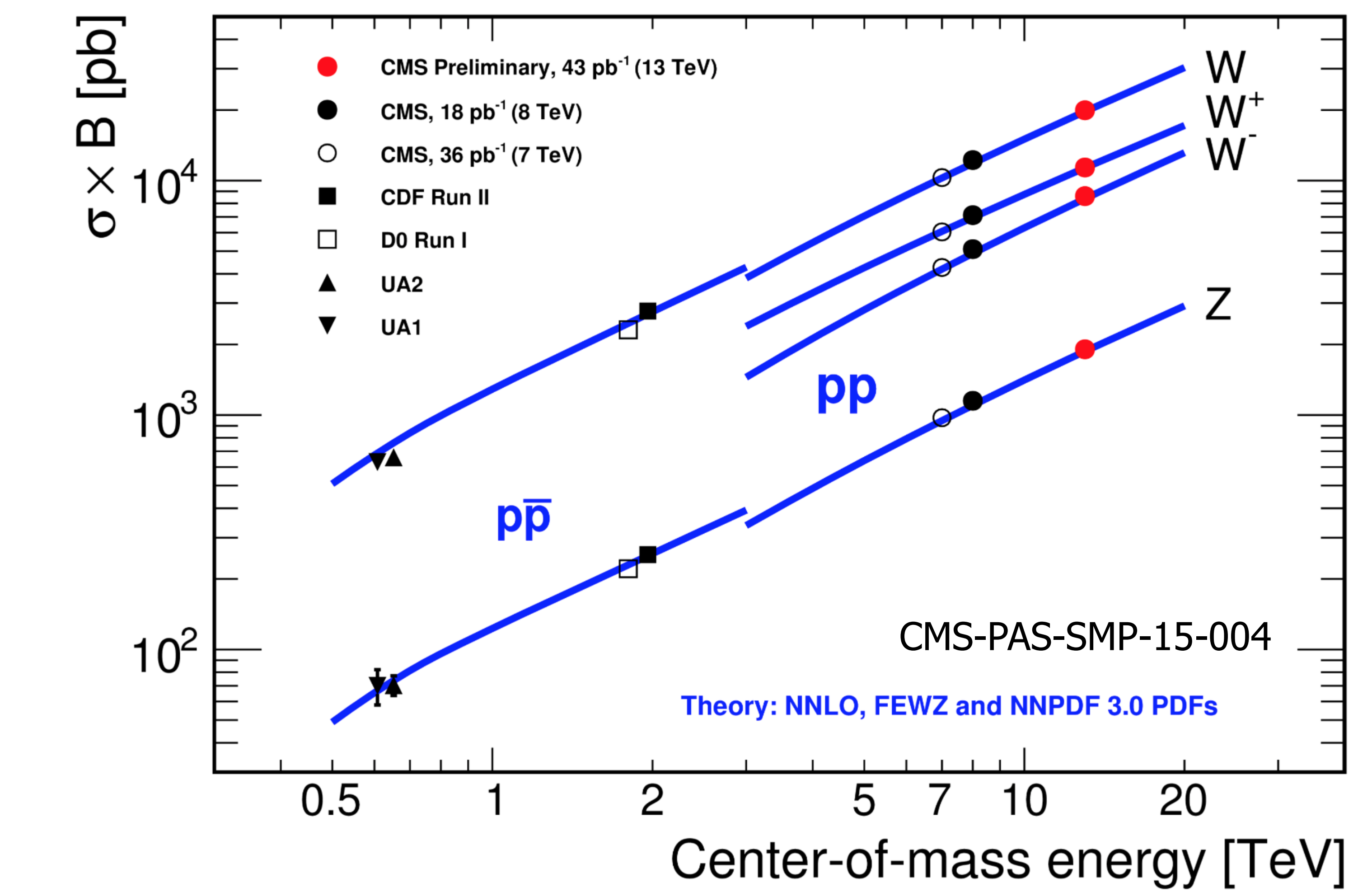


Missing transverse energy from the W → μ+ν decays

Z peak (di-muon pair mass distributions)

W and Z Boson Production

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



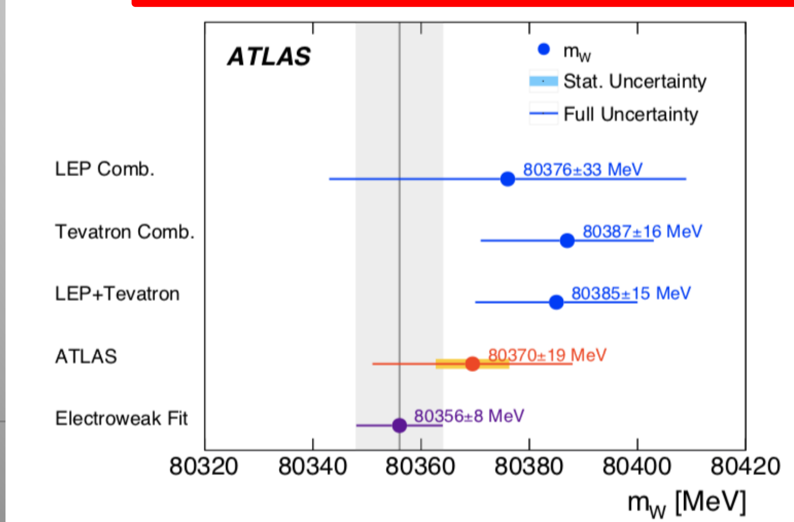
Many detailed EWK studies possible –and done-- with the large Z,W samples

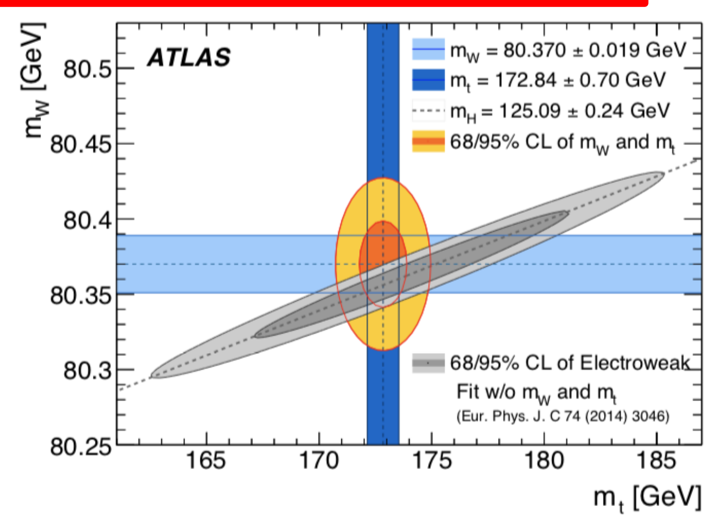
W-Mass Determination

- Measurement based on 7 TeV data (4.6 fb^{-1}). It takes time to get the systematic uncertainties under control for precision!!
- Included ~14.10^6 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

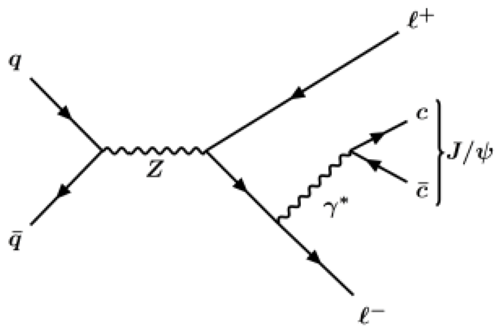
$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} = 80370 \pm 19\ \text{MeV},$$

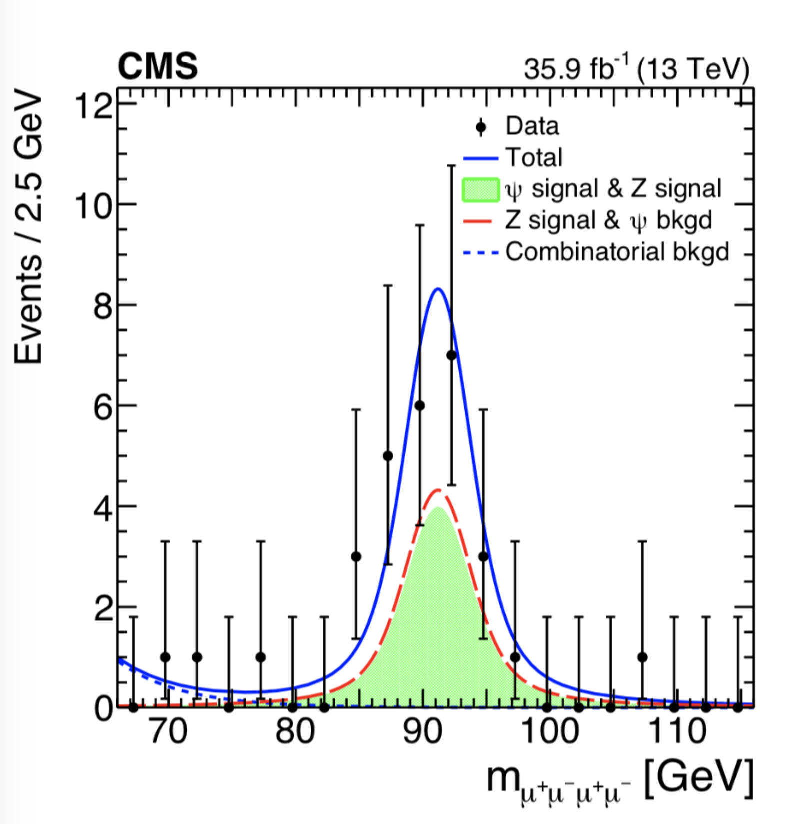




Rare Processes

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





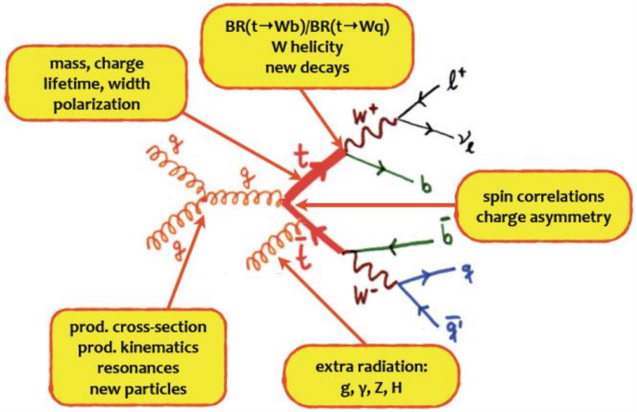
arXiv:1806.04213

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

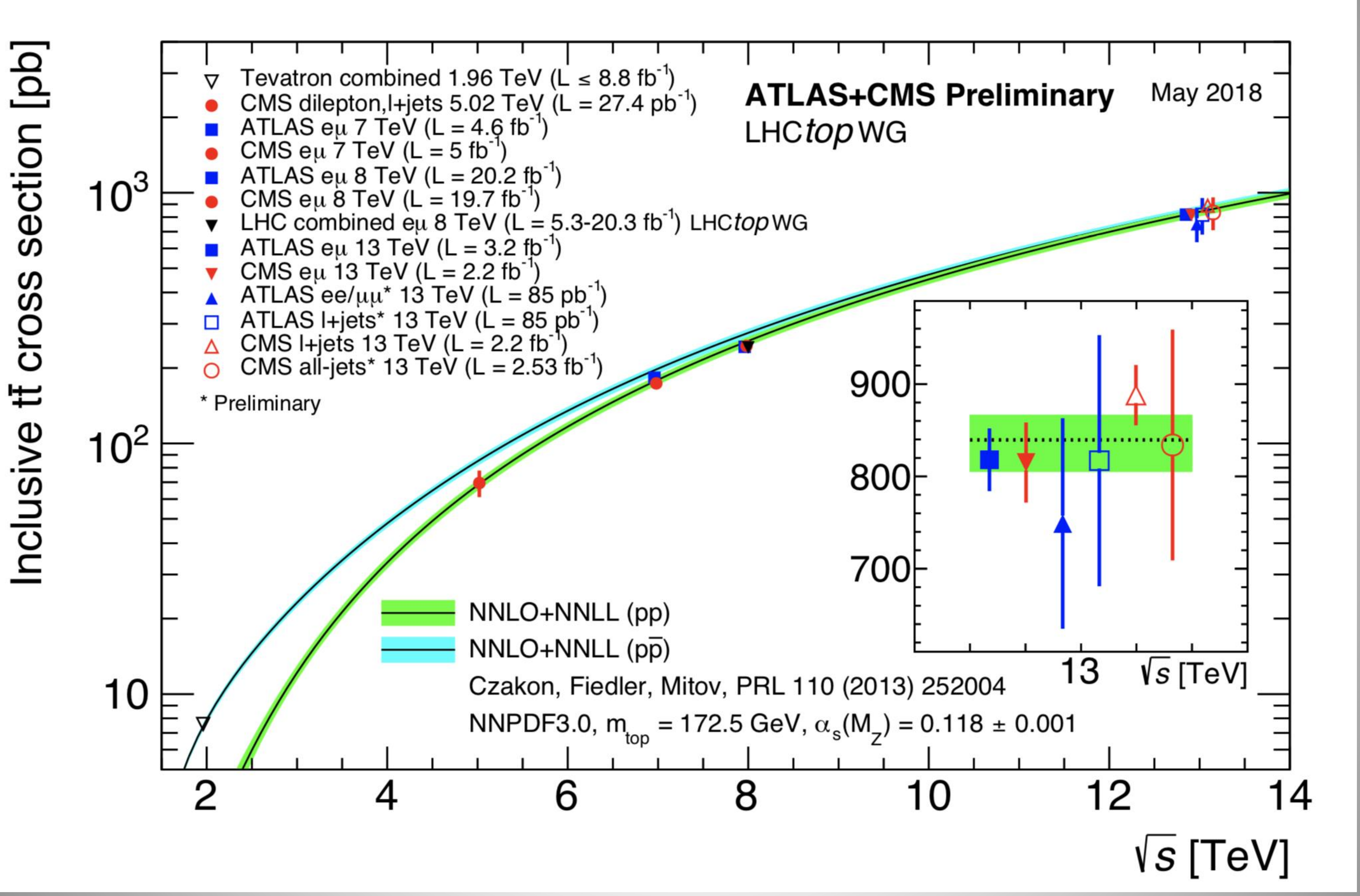


- The heaviest known elementary particle: ~173 GeV
- Coupling to the Higgs ~1 → Special role in EWK symmetry breaking?

LHC is a top factory with ~5.10^6 produced tt-pairs (run-1)

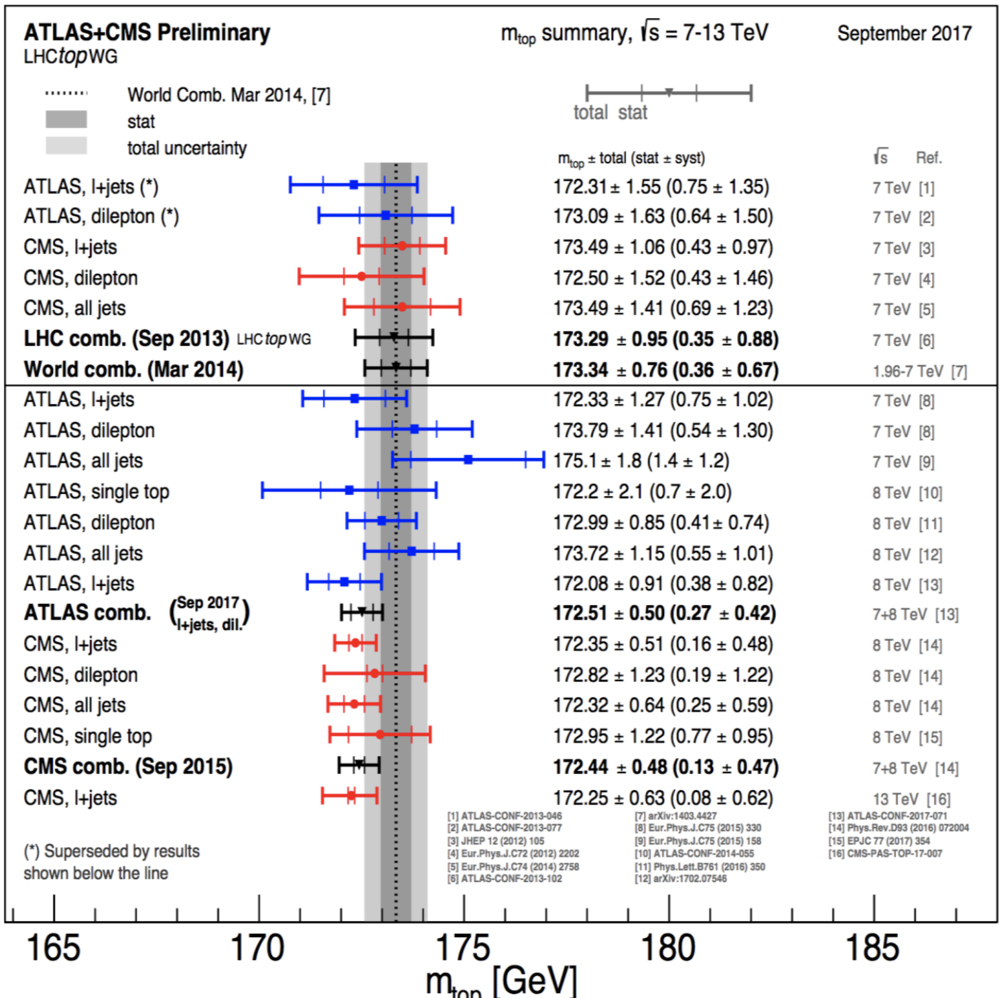
~3.10^7 produced tt-pairs (2016)

Top Quark Cross Sections



Good agreement with the SM predictions up to the 13 TeV

Top Mass Determination



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/ψ, secondary vertices,…
This is not the final word yet

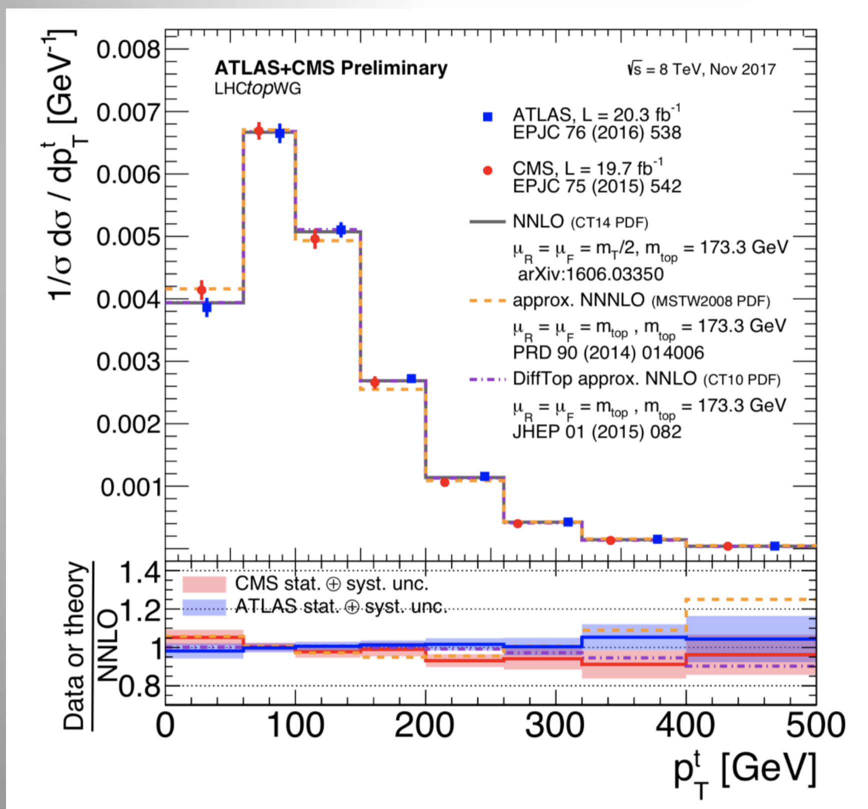
Experiment combination under way

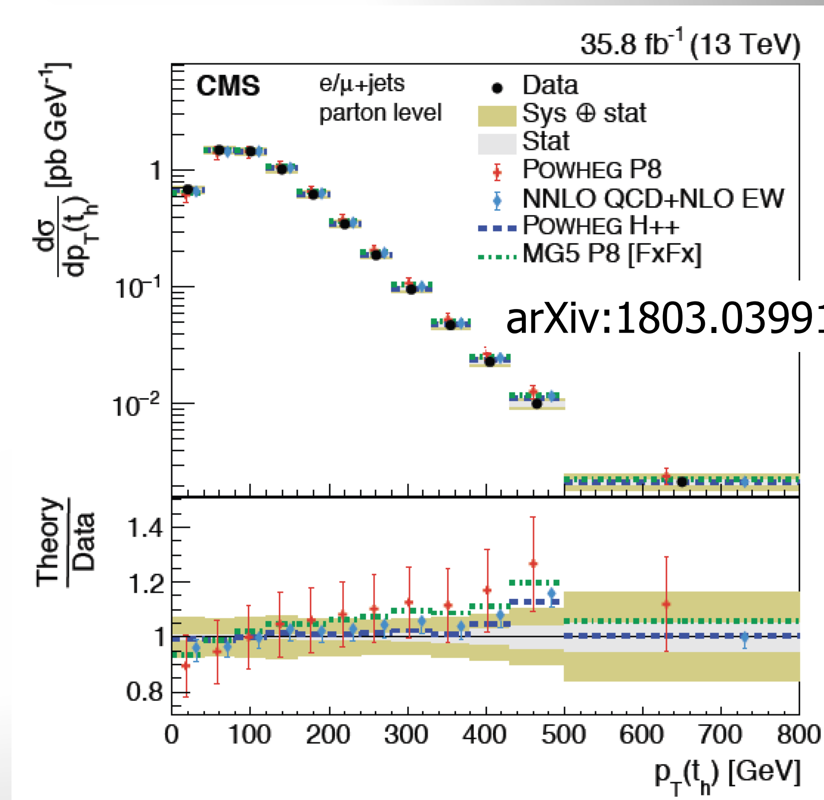
Note: the average value LHC somewhat lower than Tevatron one: 174.34 ± 0.64 GeV

Top Differential Cross Sections

Run-1 showed a difference in the p_T spectrum of the top in data compared to ME+PS predictions.

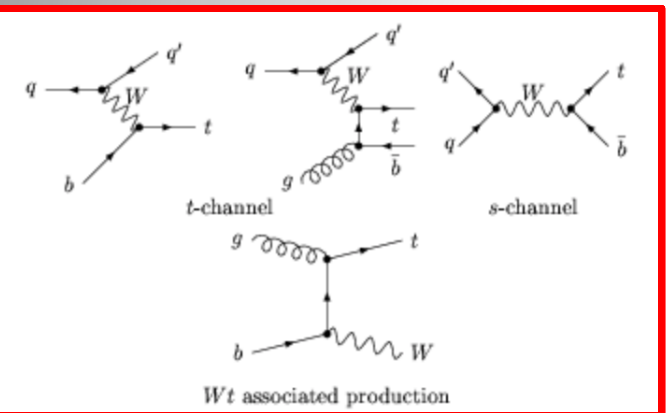
Better agreement achieved with recent NNLO calculations!

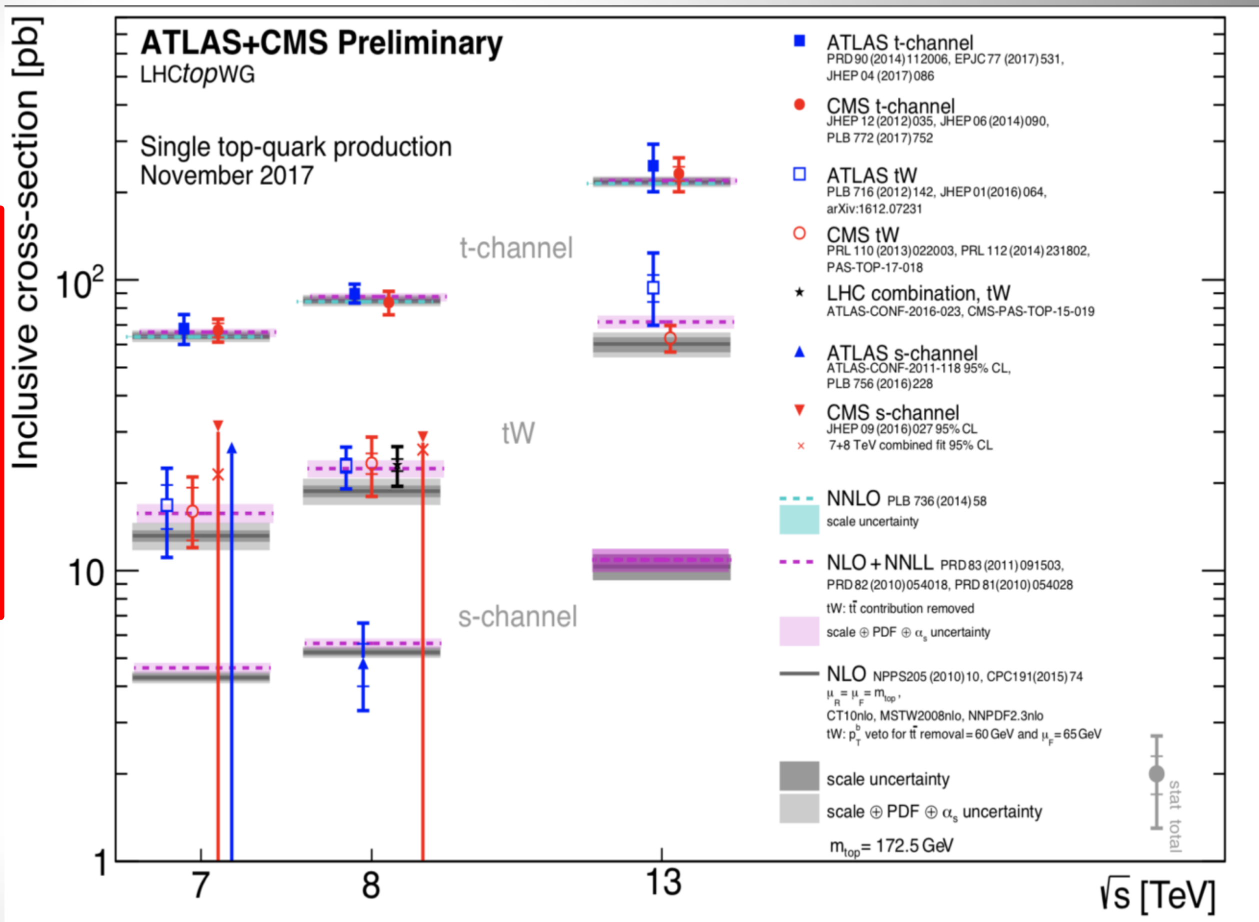




arXiv:1803.03991

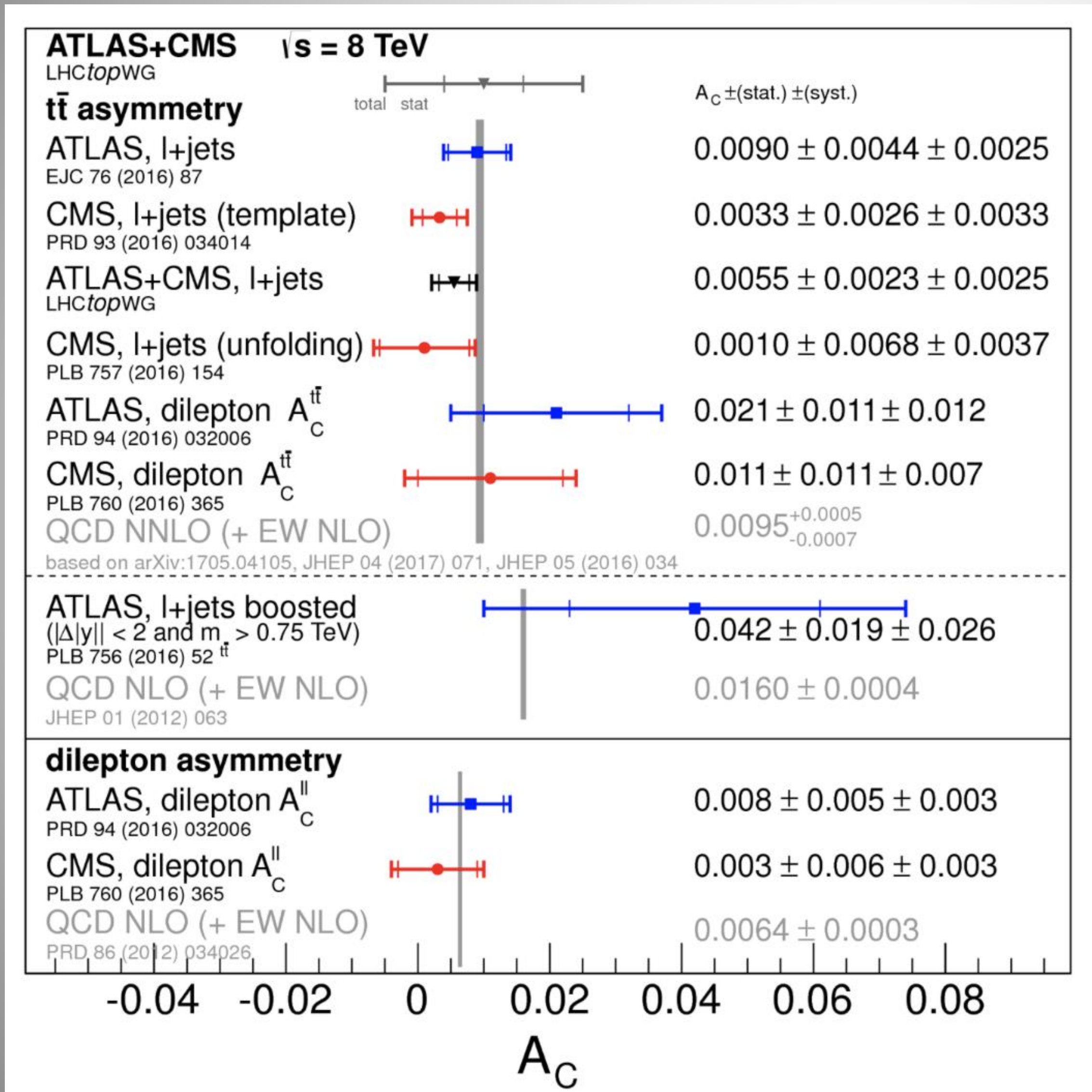
Single Top Production





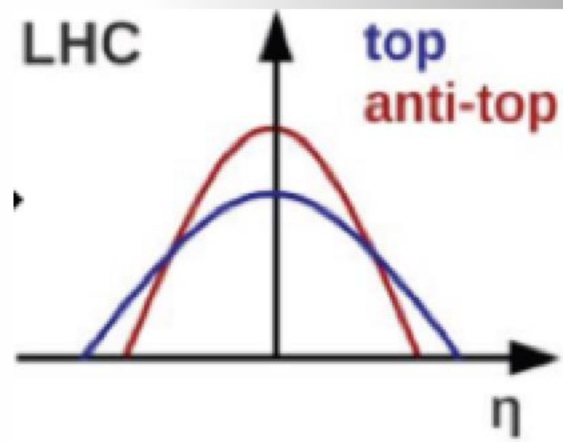
Most single top processes have been studied in run-1 and run-2 by CMS and ATLAS.

Top Charge Asymmetry



$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}.$$

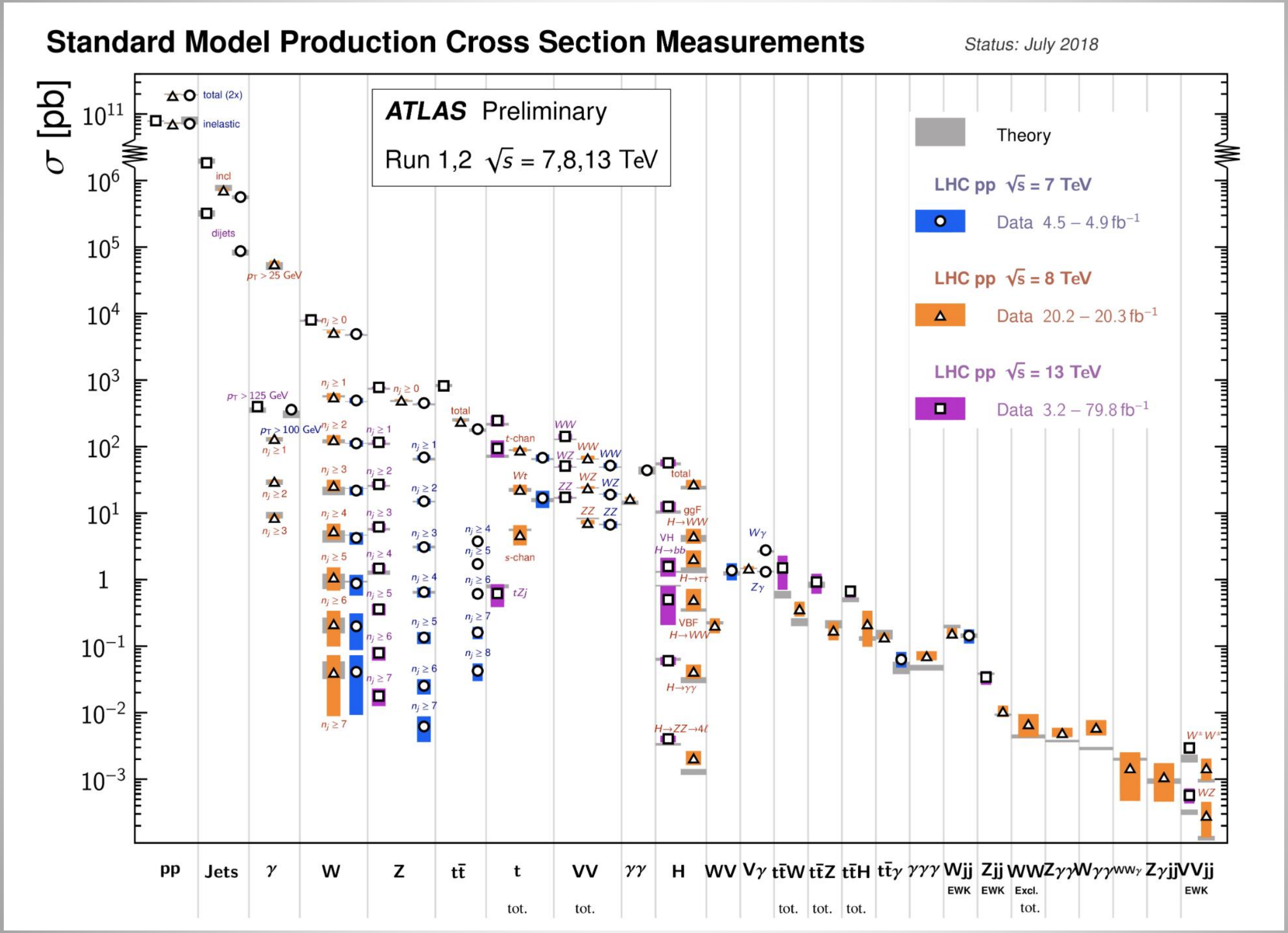
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



This was a hot topic a few years ago. ☺

No worries at present …

Summary: Cross Sections 7/8/13 TeV

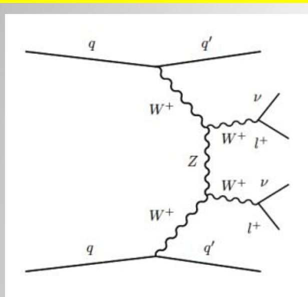


All measurements in good agreement with the Standard Model predictions!!

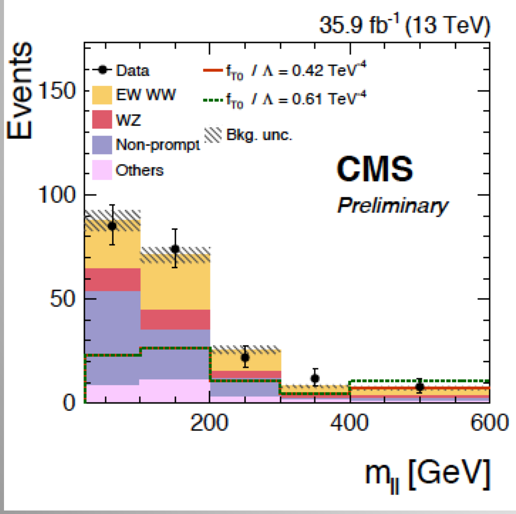
Measurements of New SM Processes at LHC

Examples

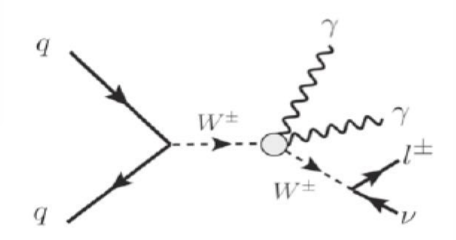
EWK WWjj production



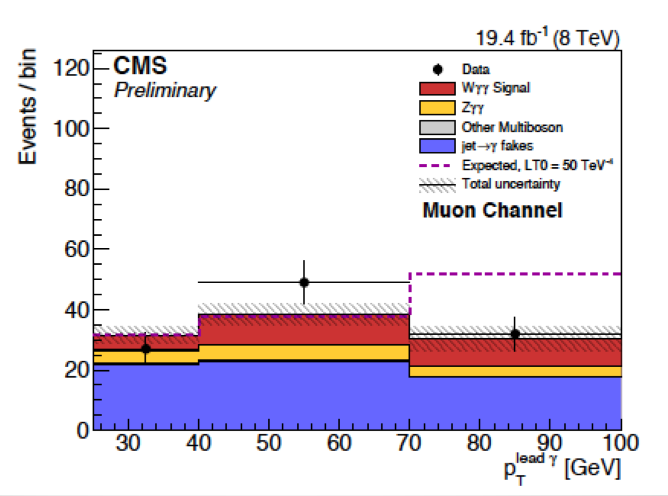
arXiv:1709.05822



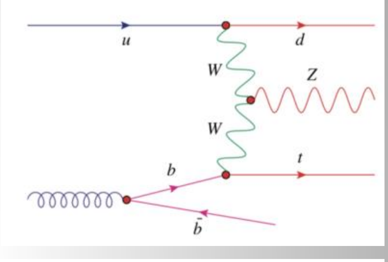
Wγγ production



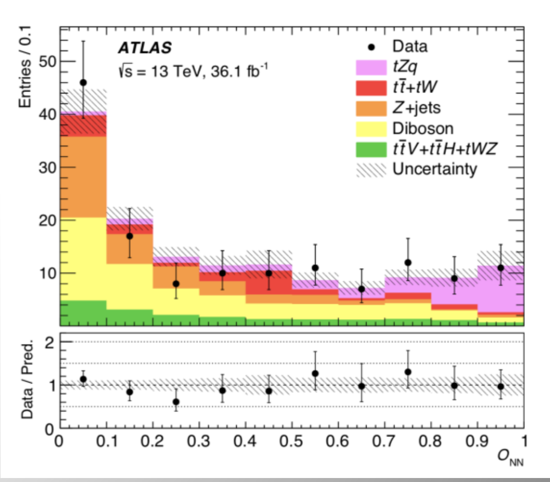
arXiv:1704.00366



tZ production



arXiv:1710.03659

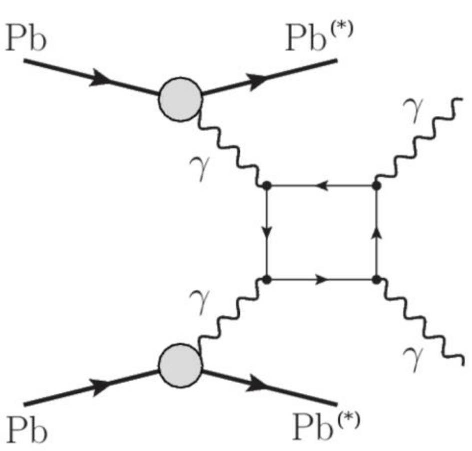


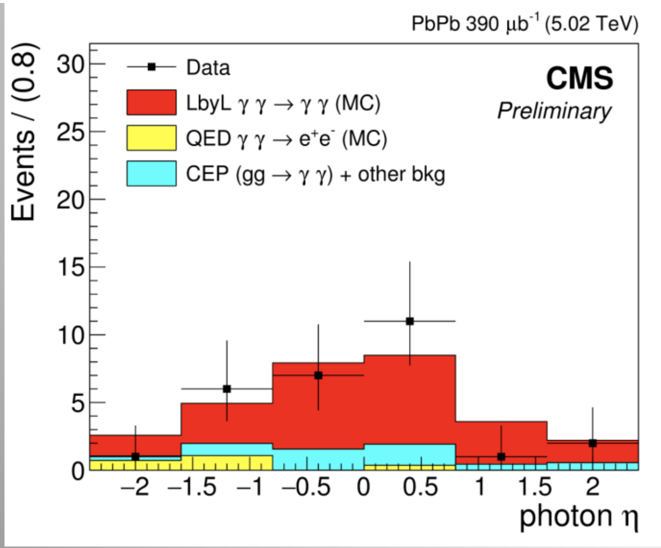
Many other processes eg in top sector: ttW, ttγγ, ttbb,…

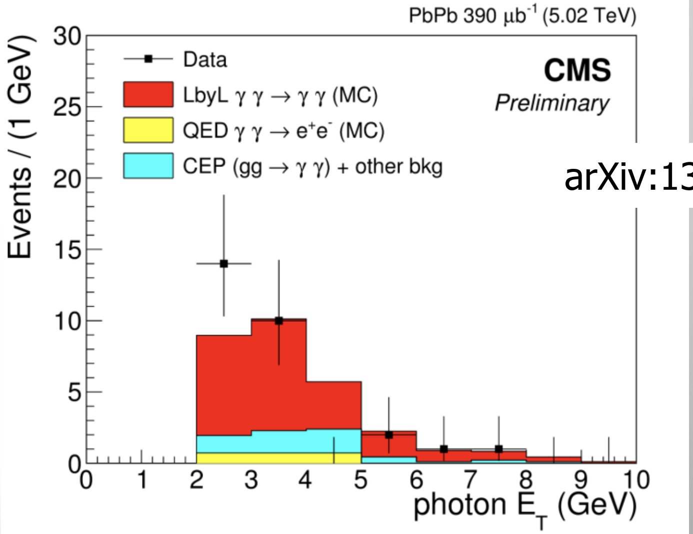
Light-by-light Scattering

- 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

CMS-FSQ-16-012





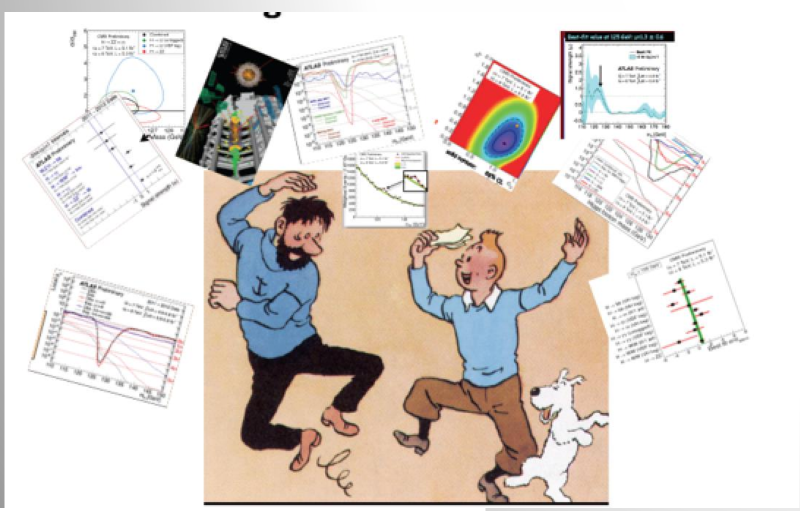


arXiv:1305.7142

$$\sigma_{\rm fid}(\gamma\gamma \to \gamma\gamma) = 122 \pm 46\,(\text{stat}) \pm 29\,(\text{syst}) \pm 4\,(\text{th})\,\text{nb},$$

TH $$\sigma_{\rm fid}(\gamma\gamma \to \gamma\gamma) = 138 \pm 14\,\text{nb}.$$

Higgs

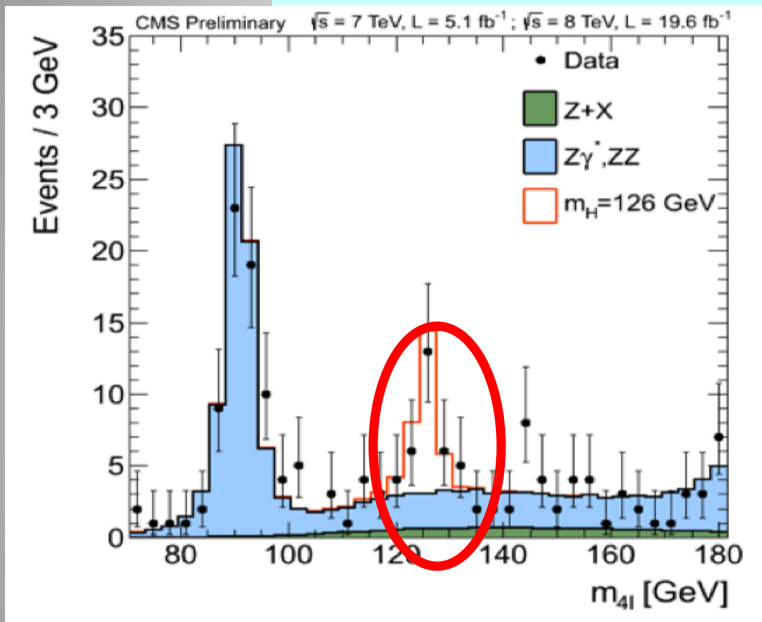


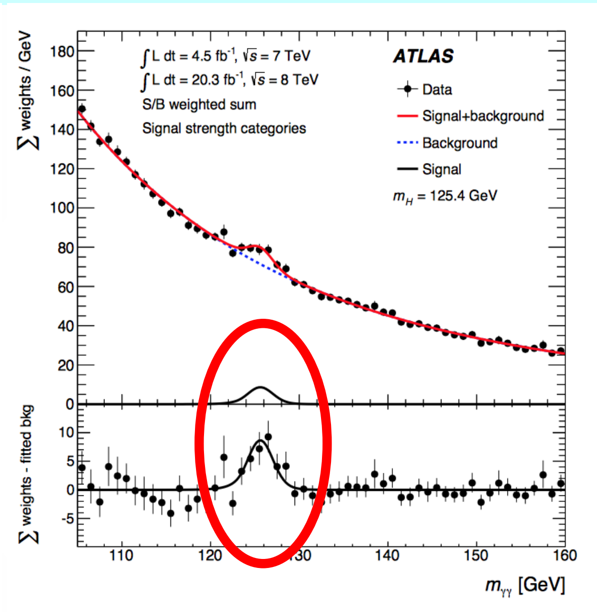
The party 6 years ago

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





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

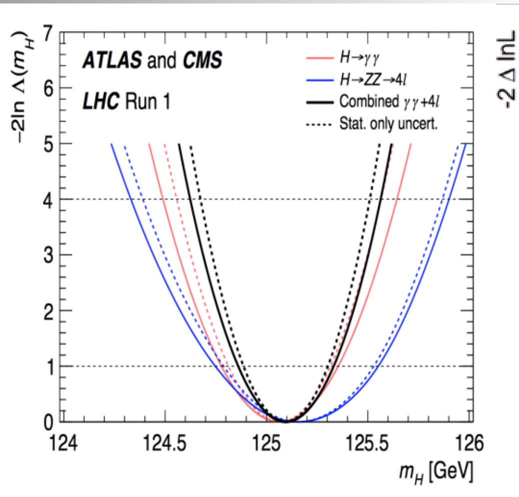
	ggF	VBF	VH	ttH
H-> gamgam				
H-> ZZ				
H->WW				
H-> bb				
H-> tau tau				
H-> Zgamma				
H-> mumu				
H-> invisible				

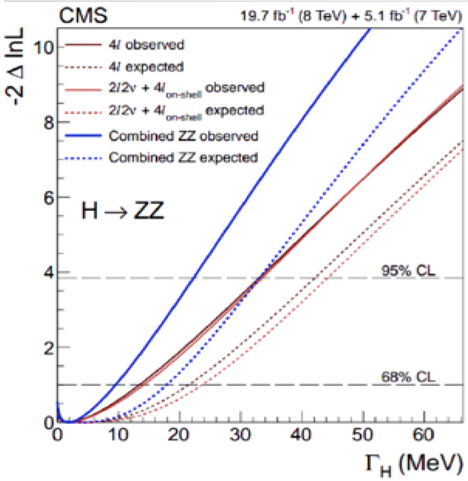
Results released

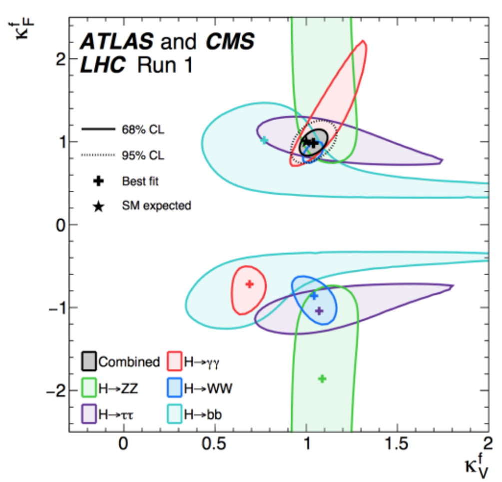
In progress

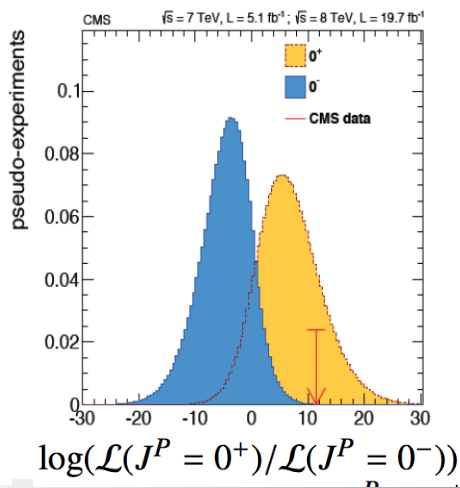
Brief Higgs Summary from Run-1

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









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

Width
< 24 MeV
(95%CL)

Couplings are within ~20% of the SM values

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

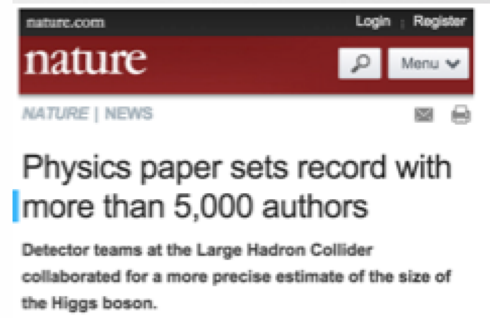
We continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, heavier Higgses, charged Higgses…

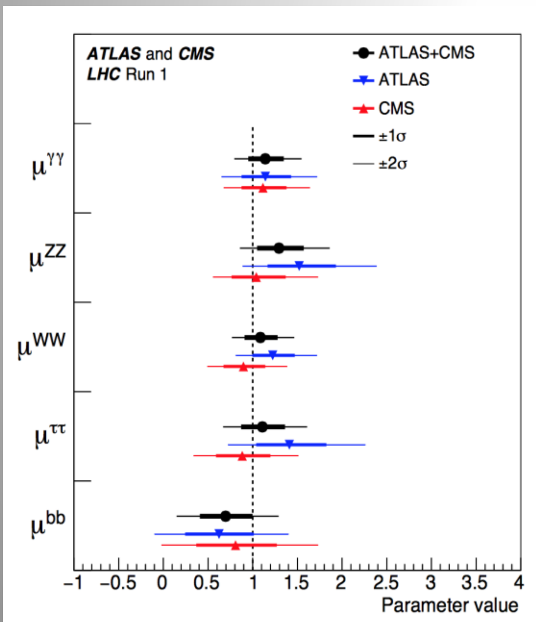
Higgs: ATLAS+CMS Combination

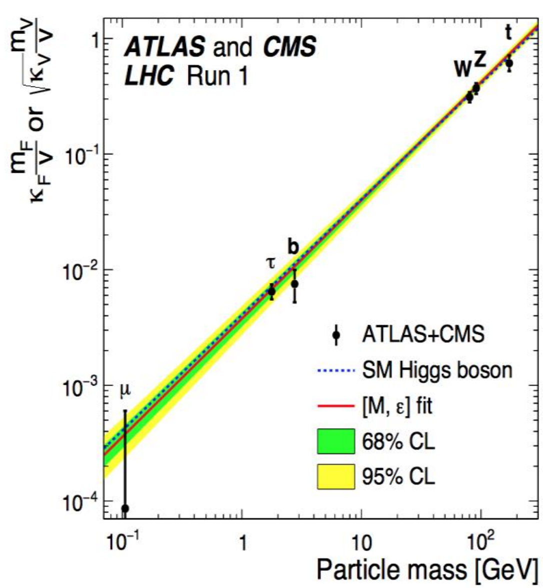
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

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:

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

Narrowing Down on the Higgs Width

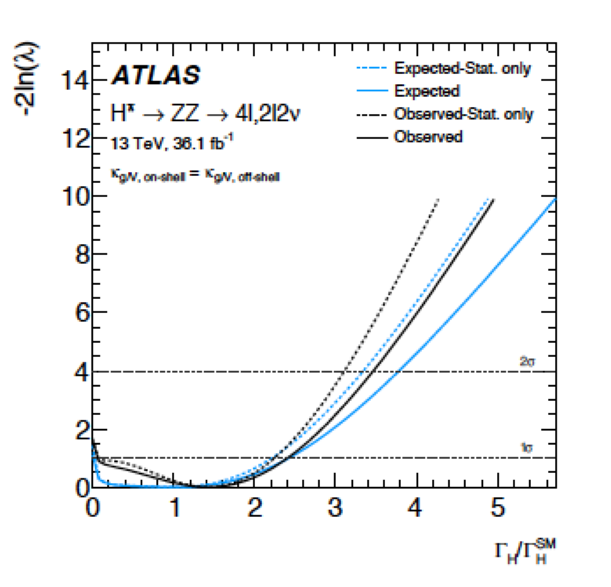
arXiv:1808.01191

- New estimation on the Higgs Width of the Higgs 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 2ν with H mass above 220 (250) GeV

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}},$$

$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}},$$

		Observed	Expected		
			Median	$\pm 1\ \sigma$	$\pm 2\ \sigma$
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \to 2\ell 2\nu$ 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]
$\Gamma_H/\Gamma_H^{\text{SM}}$	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]

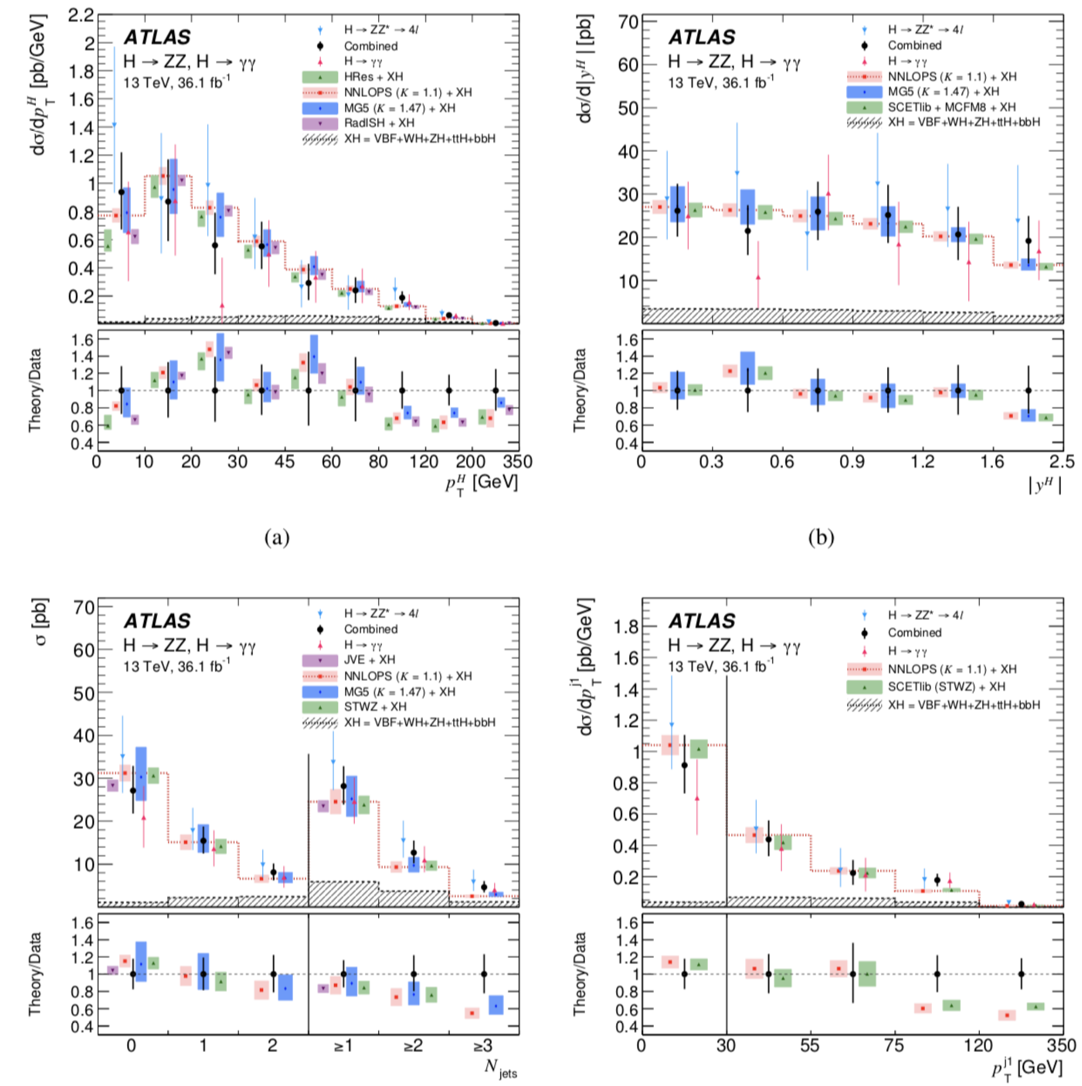


-> Higgs total width limit < 14.4 MeV obs. (15.2 MeV exp.)

Higgs Results @ 13 TeV

Higgs kinematics differential distributions

arXiv:1805.10197



H→γγ and
H→ZZ→4 leptons

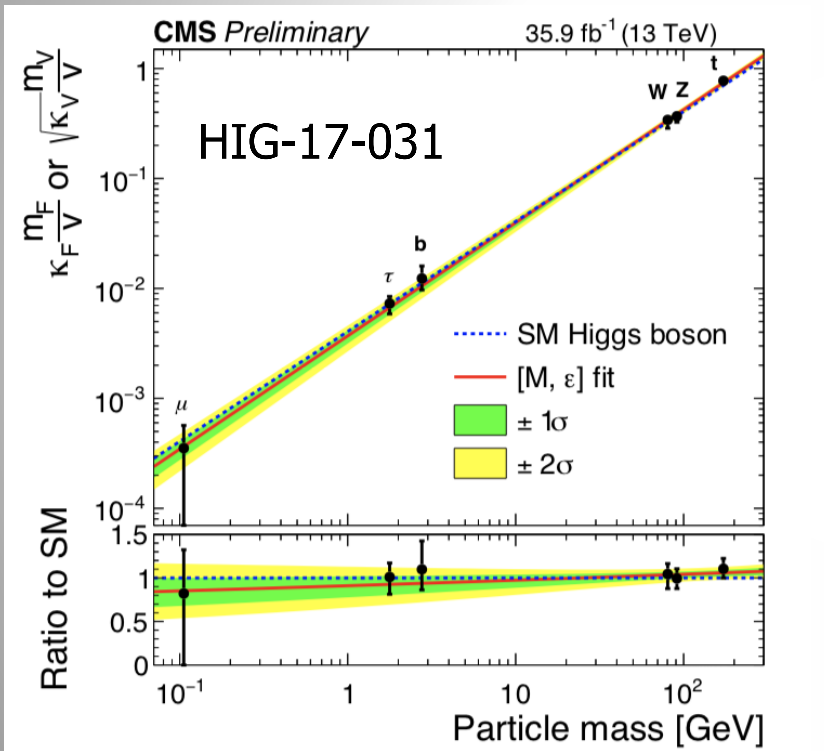
Total Higgs cross section

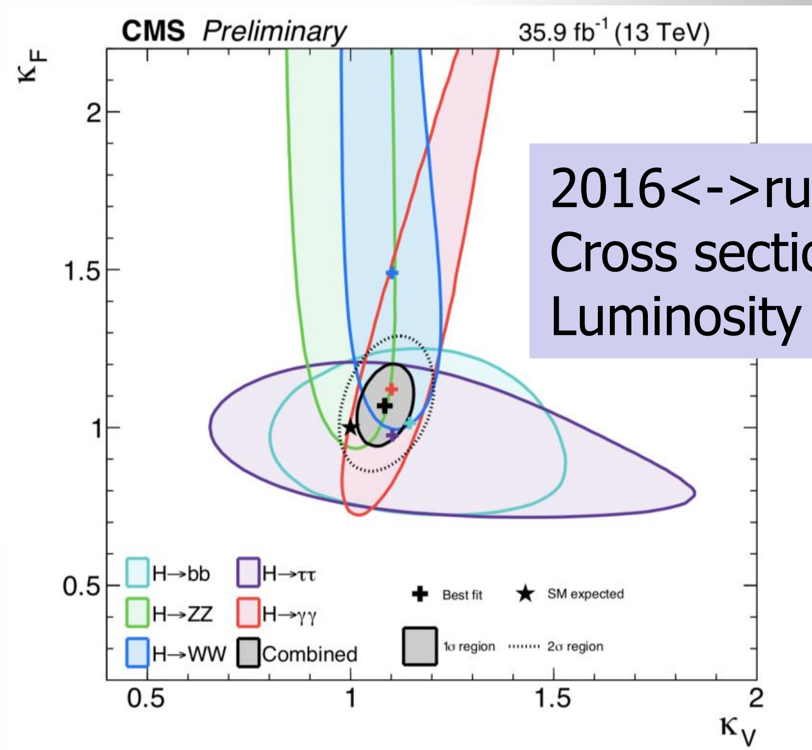
$$57.0^{+6.0}_{-5.9}\ \text{(stat.)}\ ^{+4.0}_{-3.3}\ \text{(syst.) pb}$$

Results in agreement with the Standard Model

Higgs Results @ 13 TeV

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





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

Results in agreement with the Standard Model

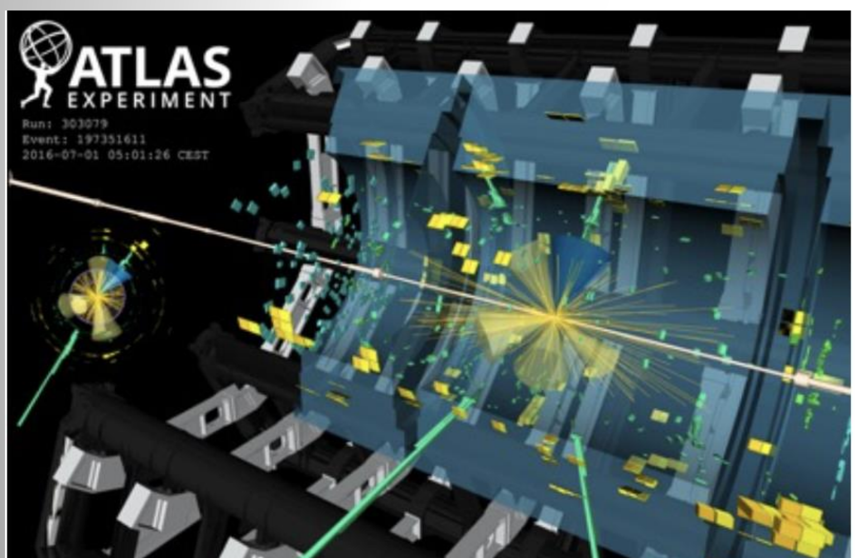
$$\mu = 1.17^{+0.10}_{-0.10}$$
$$= 1.17^{+0.06}_{-0.06}\,(\text{stat.})\ ^{+0.06}_{-0.05}\,(\text{sig. th.})\ ^{+0.06}_{-0.06}\,(\text{other sys.}),$$

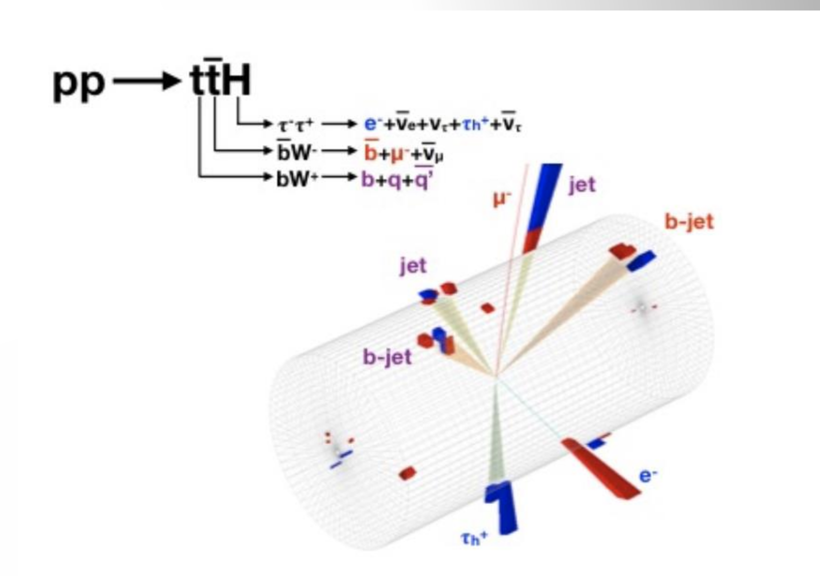
A lot happened recently…

CERN Press Release 4/6/2018

The Higgs boson reveals its affinity for the top quark

04 Jun 2018



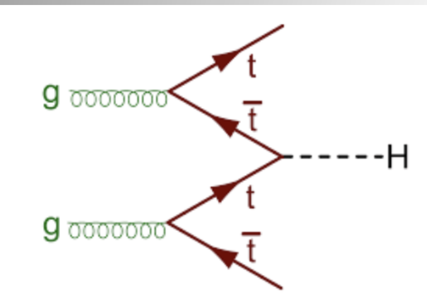


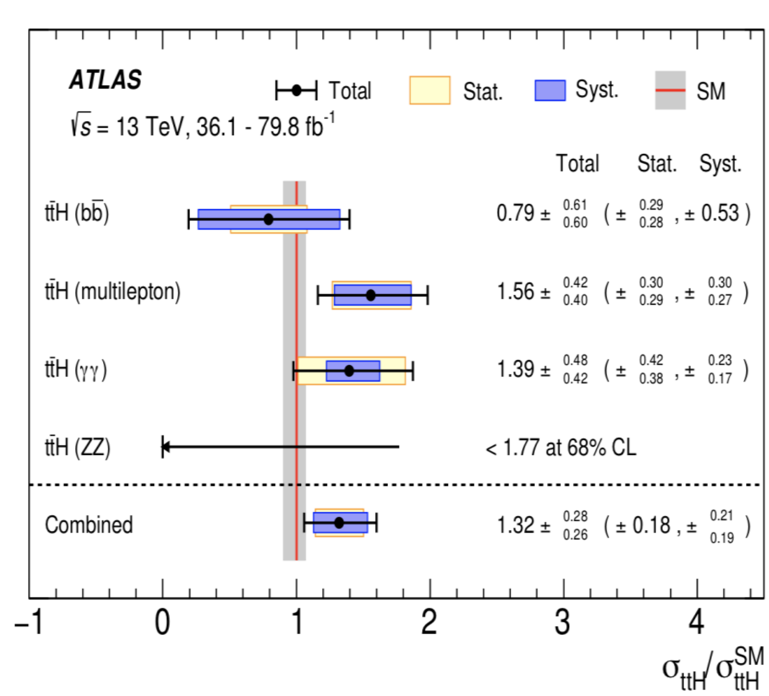
Higgs Results @ 13 TeV

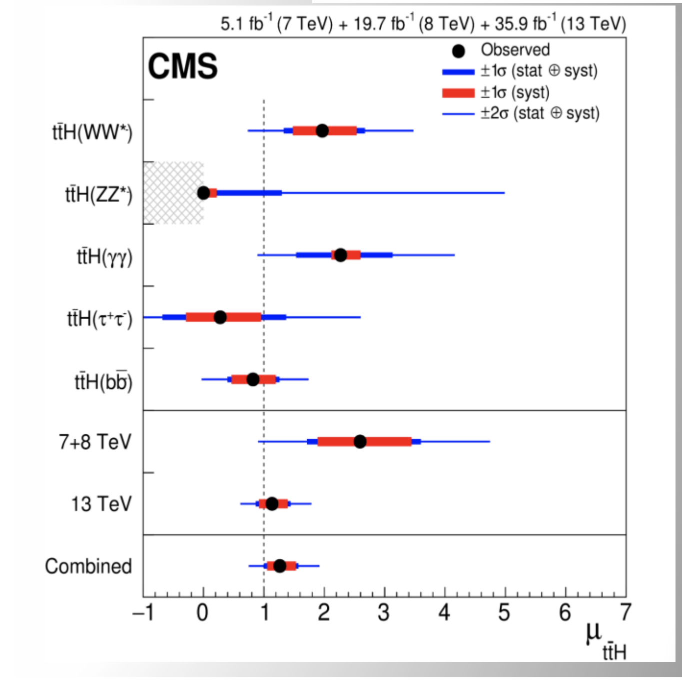
ttH production: Combination of all Higgs decay channels and combination with the 7/8 TeV data of Run-1

arXiv:1804.0261

arXiv:1806.0425







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!

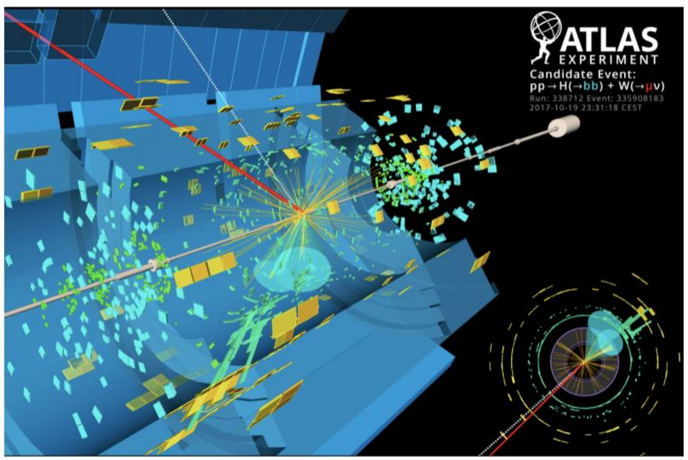
Results in agreement with the Standard Model

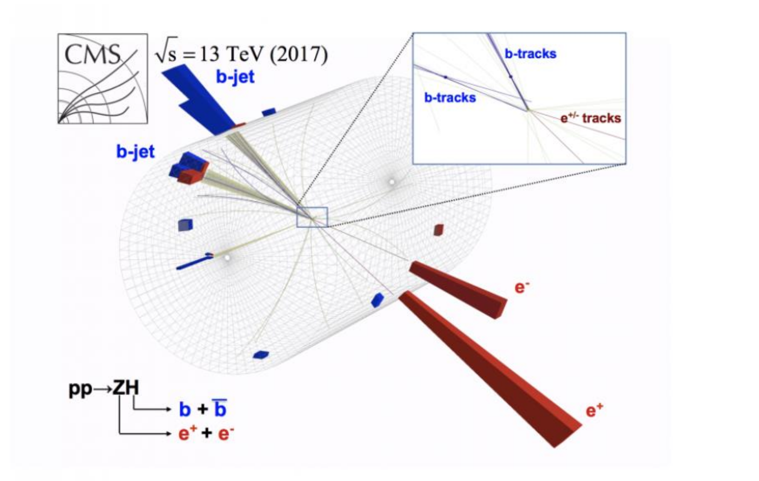
A lot happened recently…

CERN Press Release 28/8/2018

Long-sought decay of Higgs boson observed

28 Aug 2018

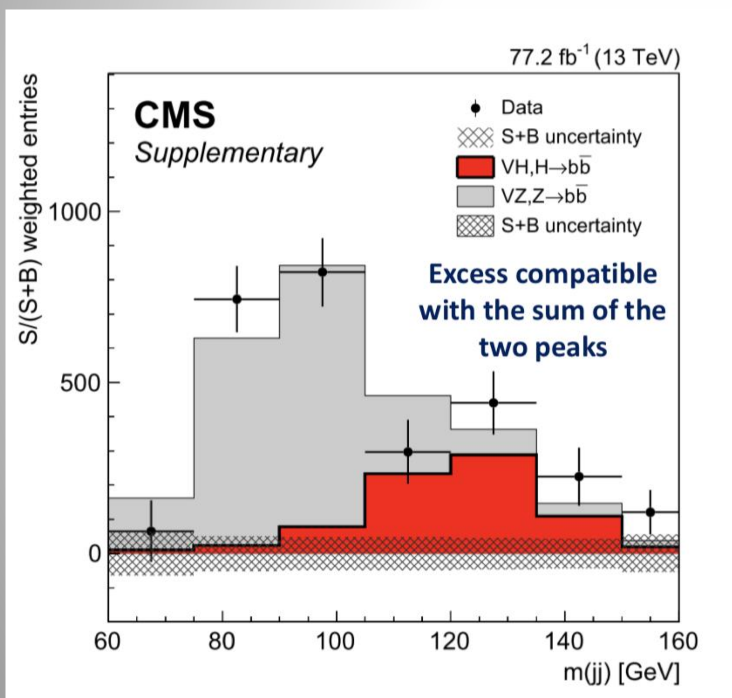


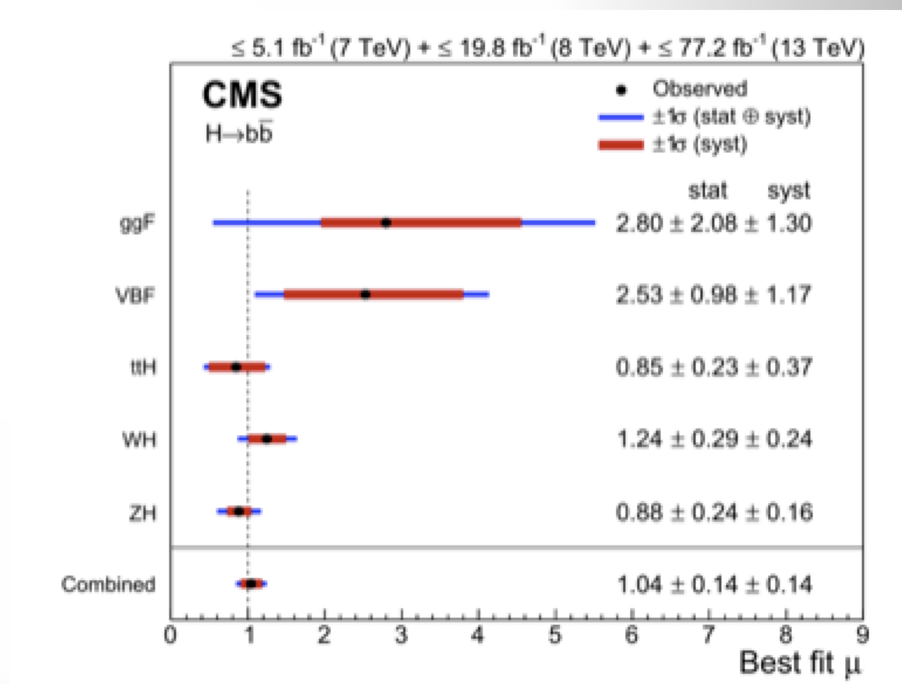


Higgs to bb Decay

- 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

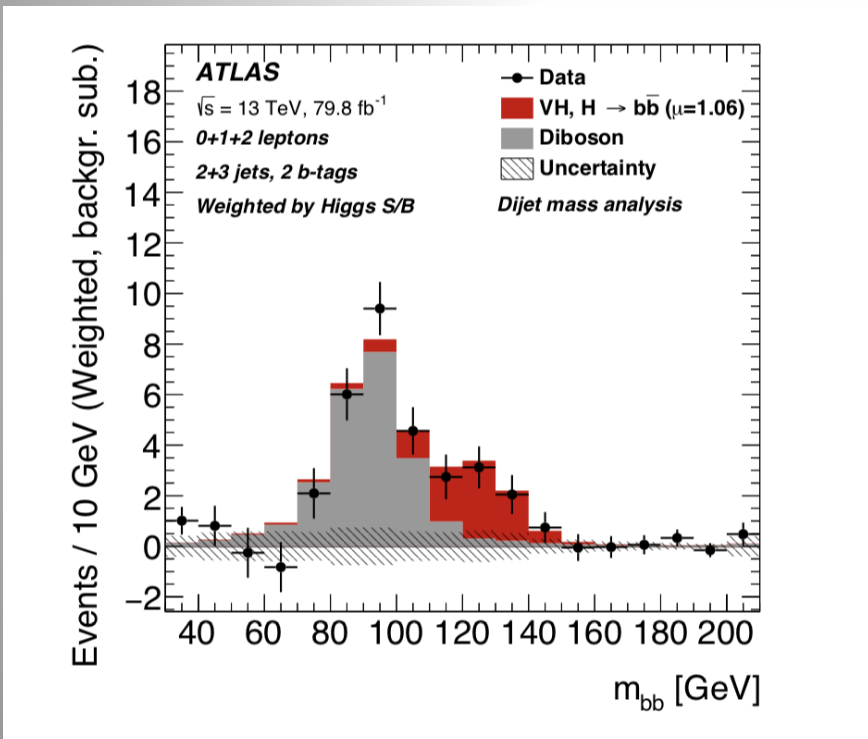


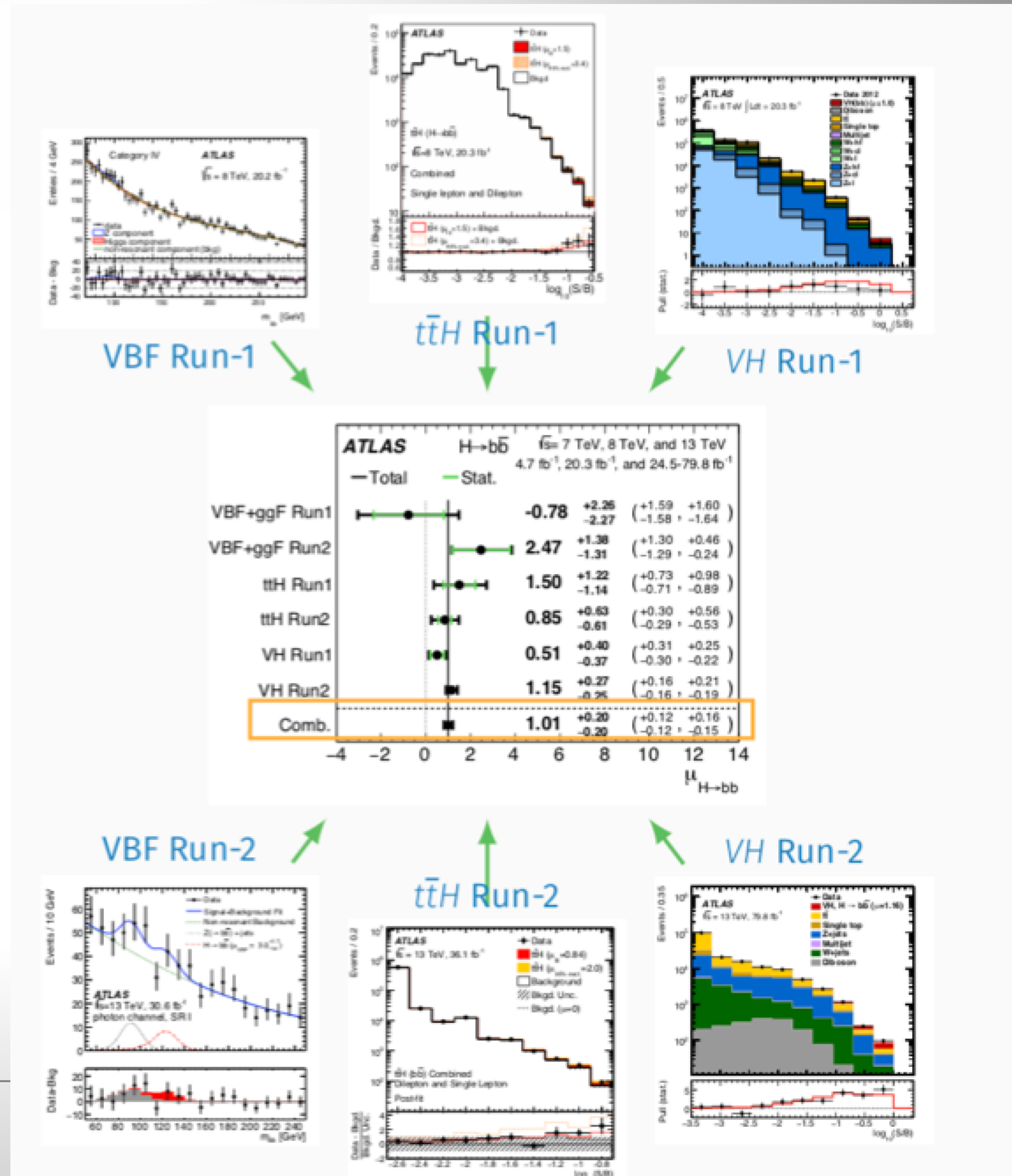


Excellent agreement with the Standard model… again…

Higgs to bb Decay

arXiv:1808.08238





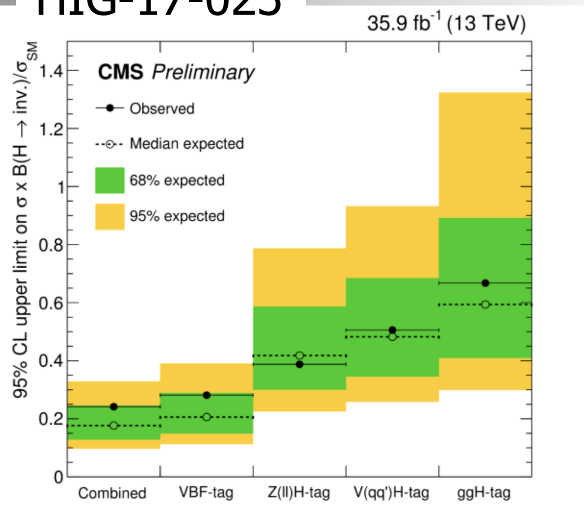
Same here!!

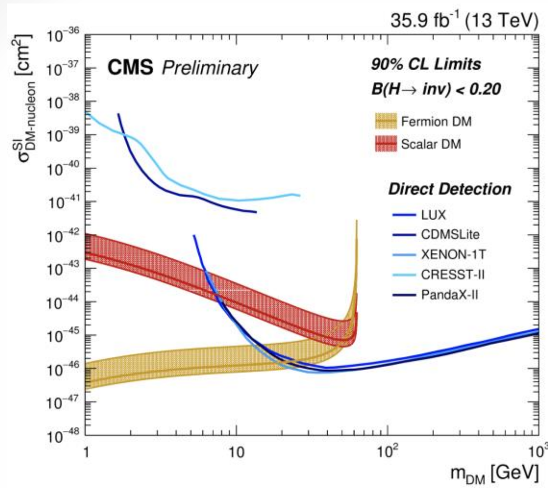
More Higgs Studies…

arXiv:1802.04329

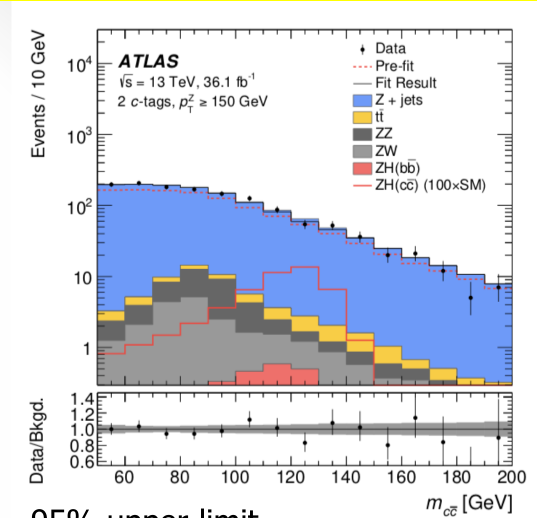
Higgs decay to invisible

HIG-17-023





Higgs decay to charm search



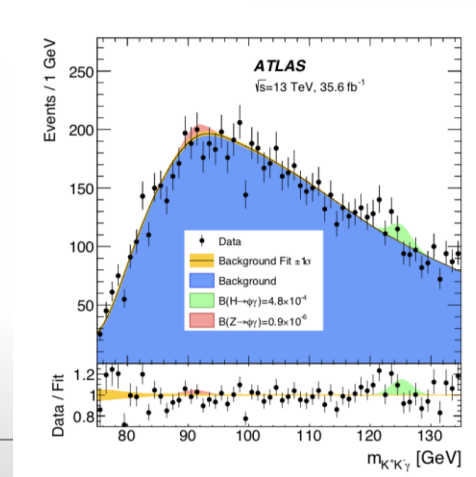
95% upper limit

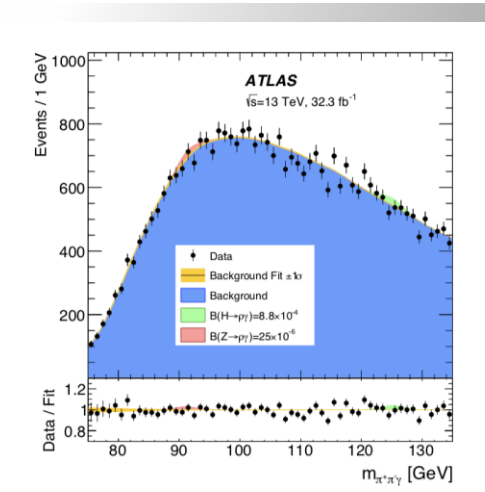
$\sigma(pp \to ZH) \times \mathcal{B}(H \to c\bar{c})$ is 2.7 $(3.9^{+2.1}_{-1.1})$ pb

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

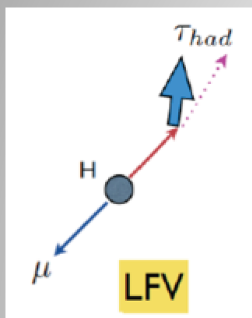


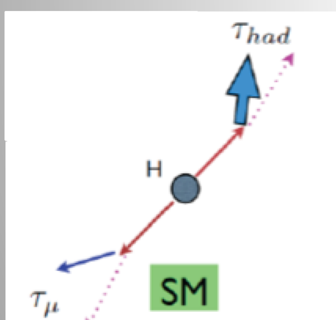


Search for LFV Decays: H →μτ

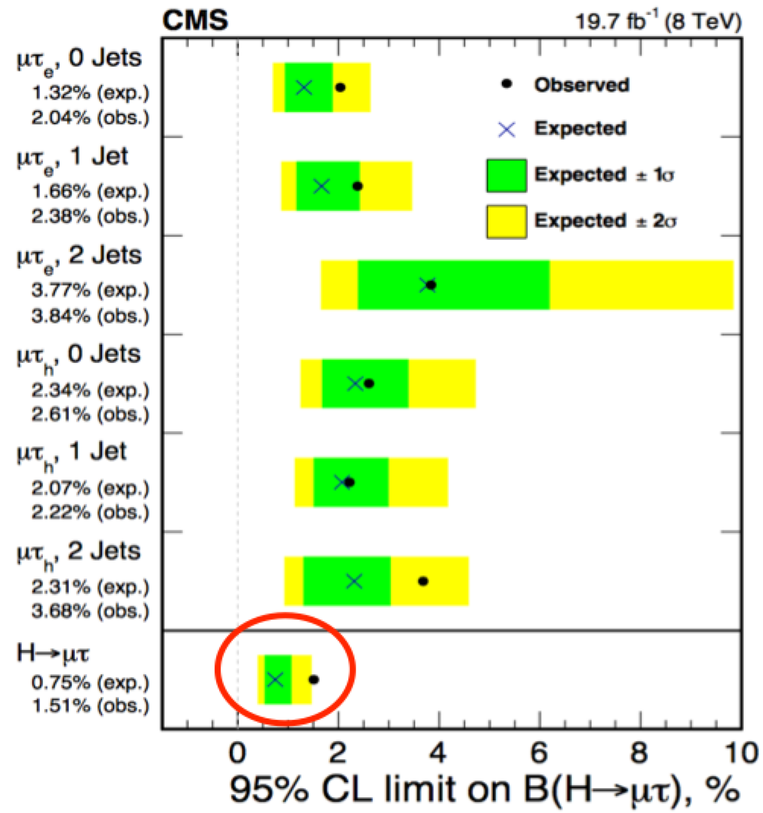
arXiv:1502.07400

Recall: Results from the 8 TeV





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

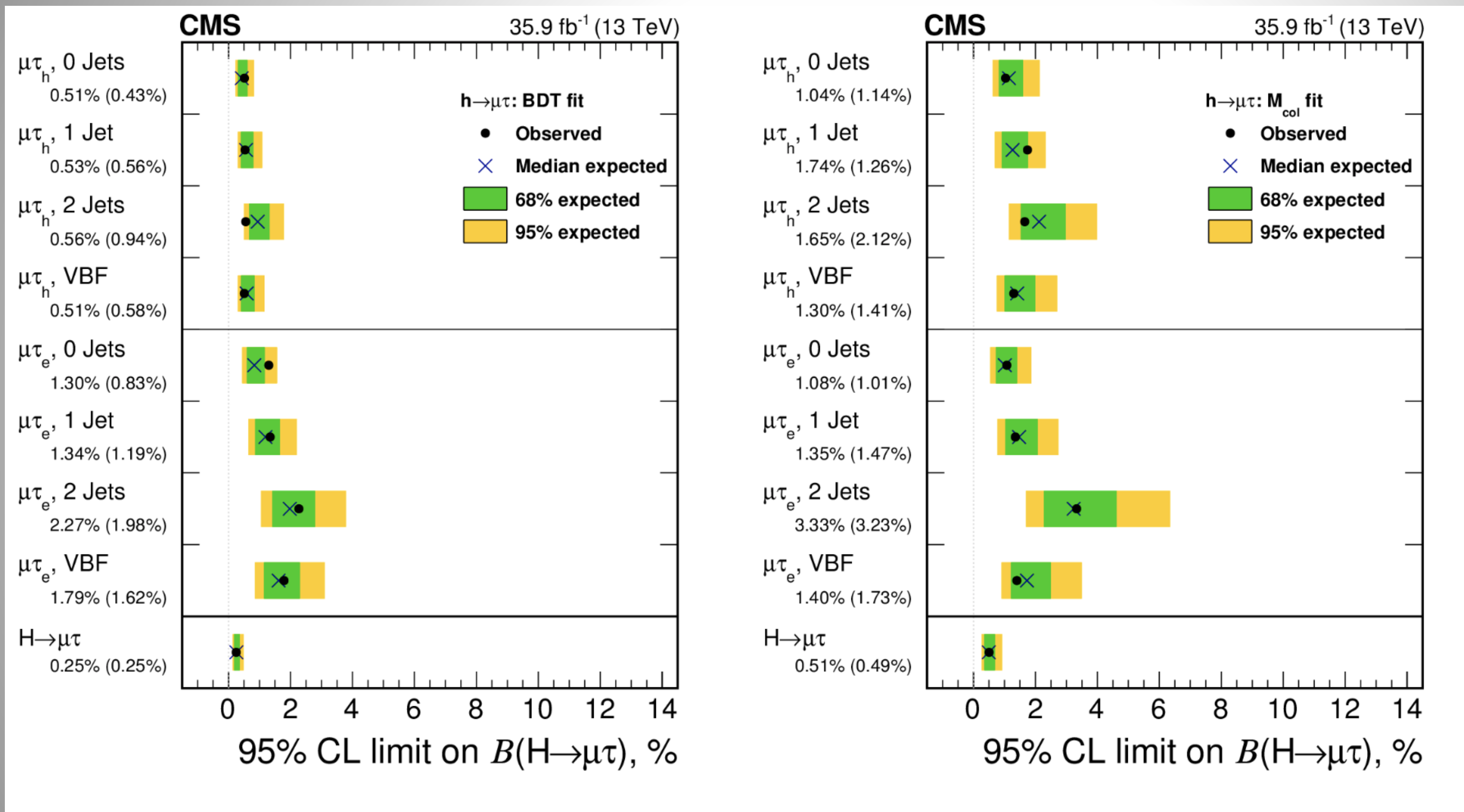


Mild excess giving a 2.4σ effect in Run-1… What about 2016 data?

Search for LFV Decays: H →μτ, eτ

The 2016 data does NOT show an excess

arXiv:1712.07173



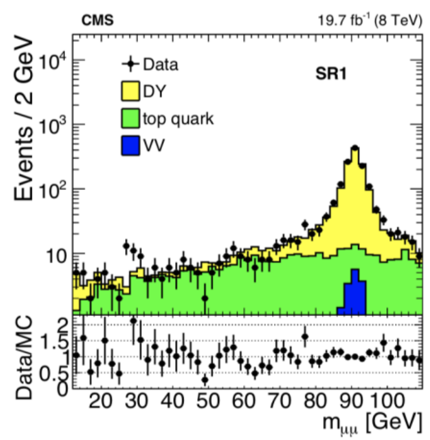
☹ It would Have been Nice…

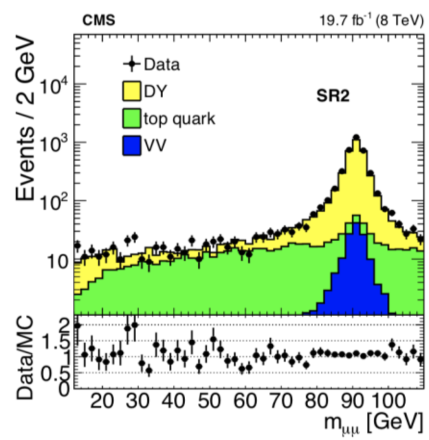
	Observed (expected) limits (%)		Best fit branching fraction (%)	
	BDT fit	M_{col} fit	BDT fit	M_{col} fit
$H \to \mu\tau$	<0.25 (0.25)%	<0.51 (0.49) %	0.00 ± 0.12 %	0.02 ± 0.20 %
$H \to e\tau$	<0.61 (0.37) %	<0.72 (0.56) %	0.30 ± 0.18 %	0.23 ± 0.24 %

Search for New Resonances

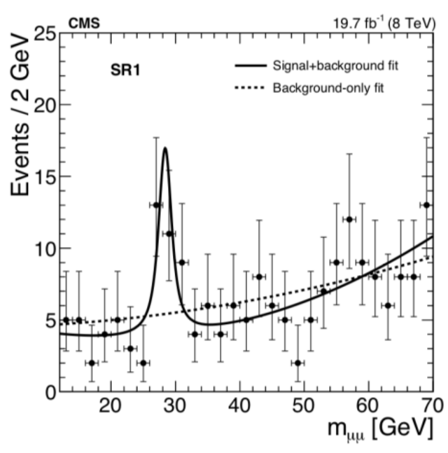
arXiv:1808.01890

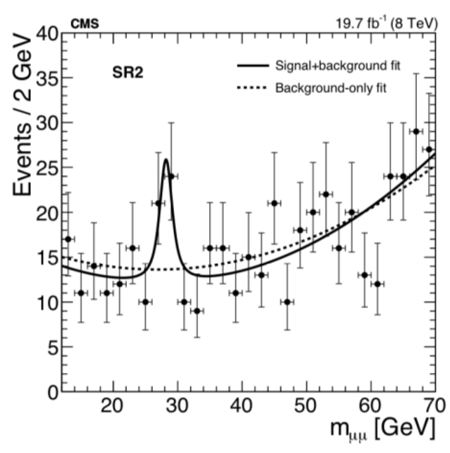
NMSSM Higgs inspired search in mass range 12-70 GeV
-Search for bump in muon pair mass spectrum with associated b-jets
-SR1: 2 muons + one central and one forward jets ($|\eta|$ >2.4), at least 1 b
-SR2: 2 muons + 2 central and no forward jets, at least 1 b





8 TeV Data





Both regions are independent

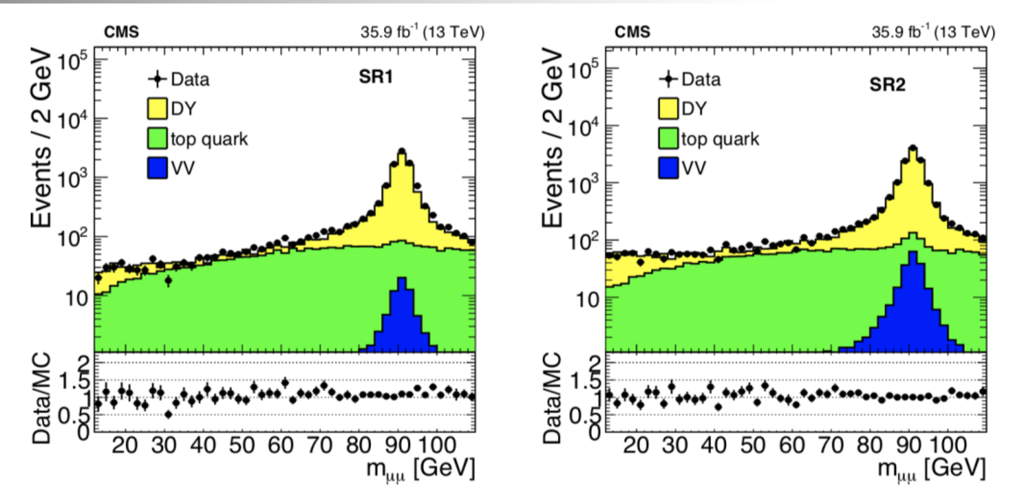
Excess seen in the both regions around 28 GeV

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

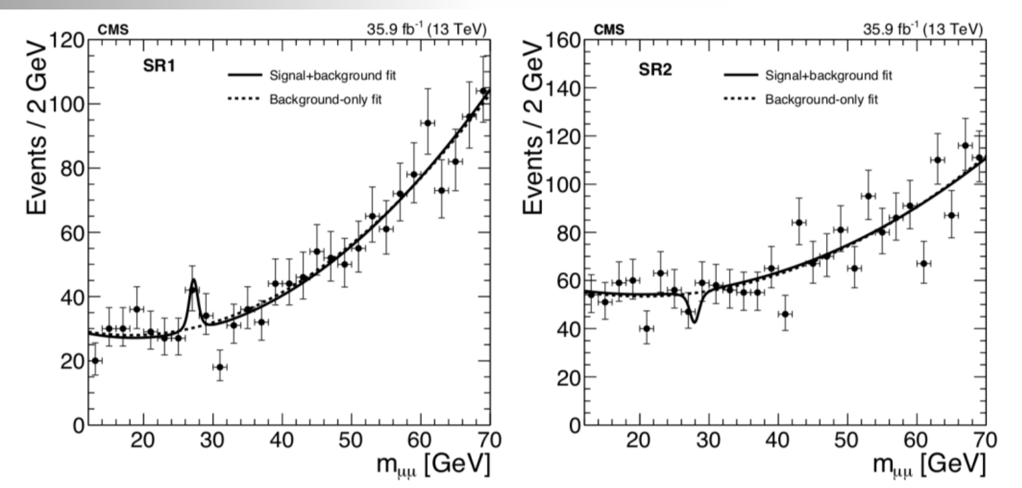
Search for New Resonances

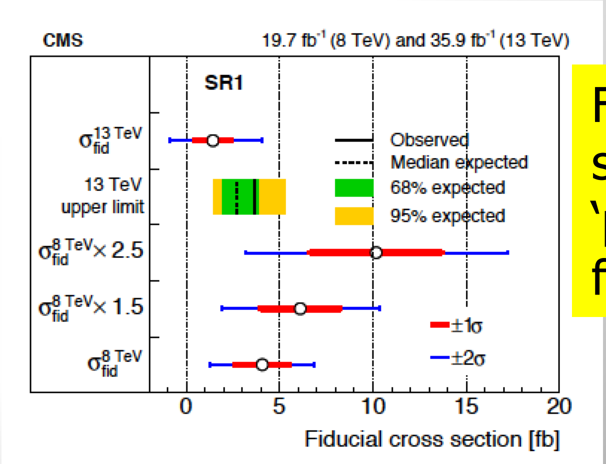
13 TeV Data

....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? ☺

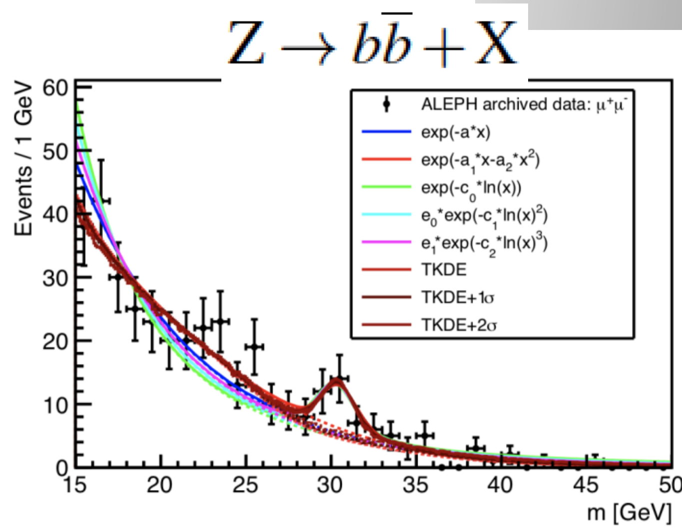
Search for New Resonances

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

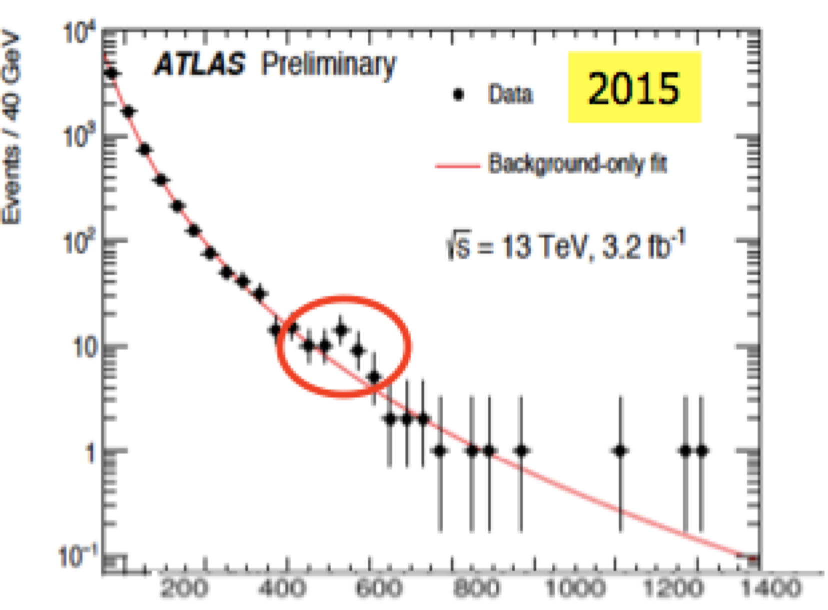
How to Become an Ambulance Chaser?

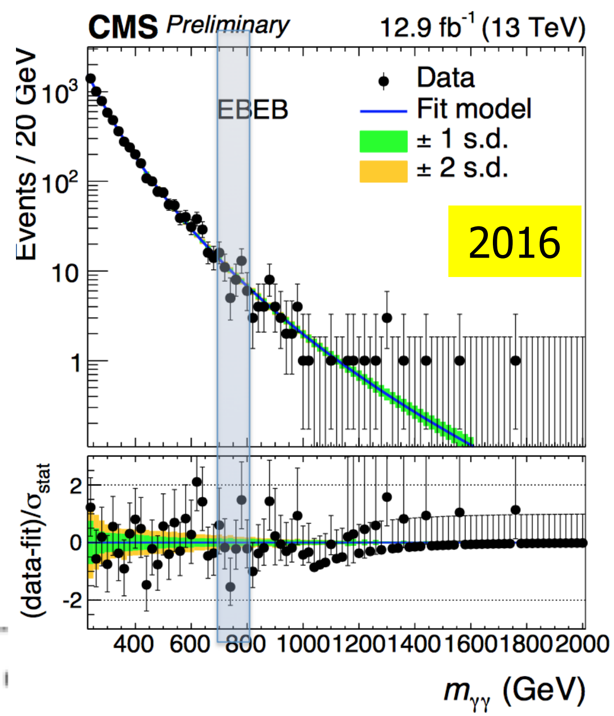
Remember the 750 GeV bump in CMS and ATLAS??
-> End of 2015/early 2016

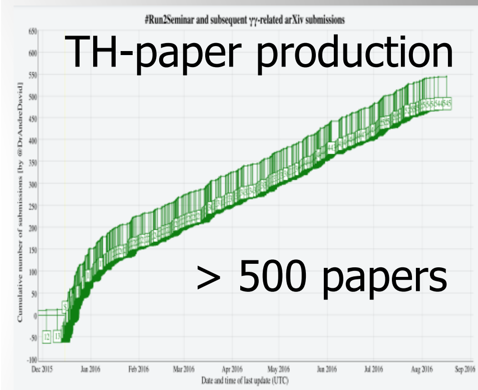
A New Particle at 750 GeV: X → γγ ?

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

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





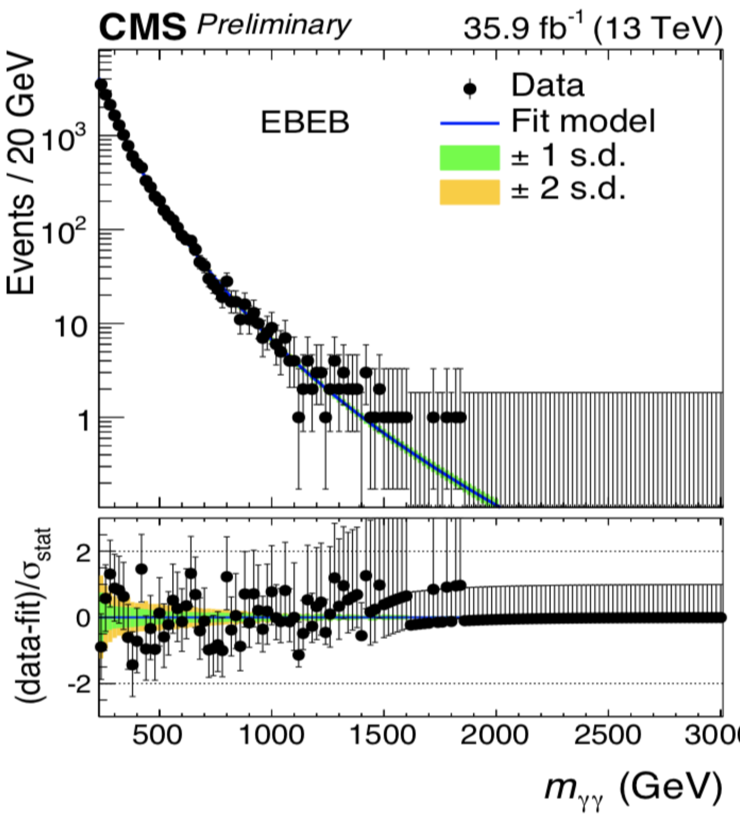


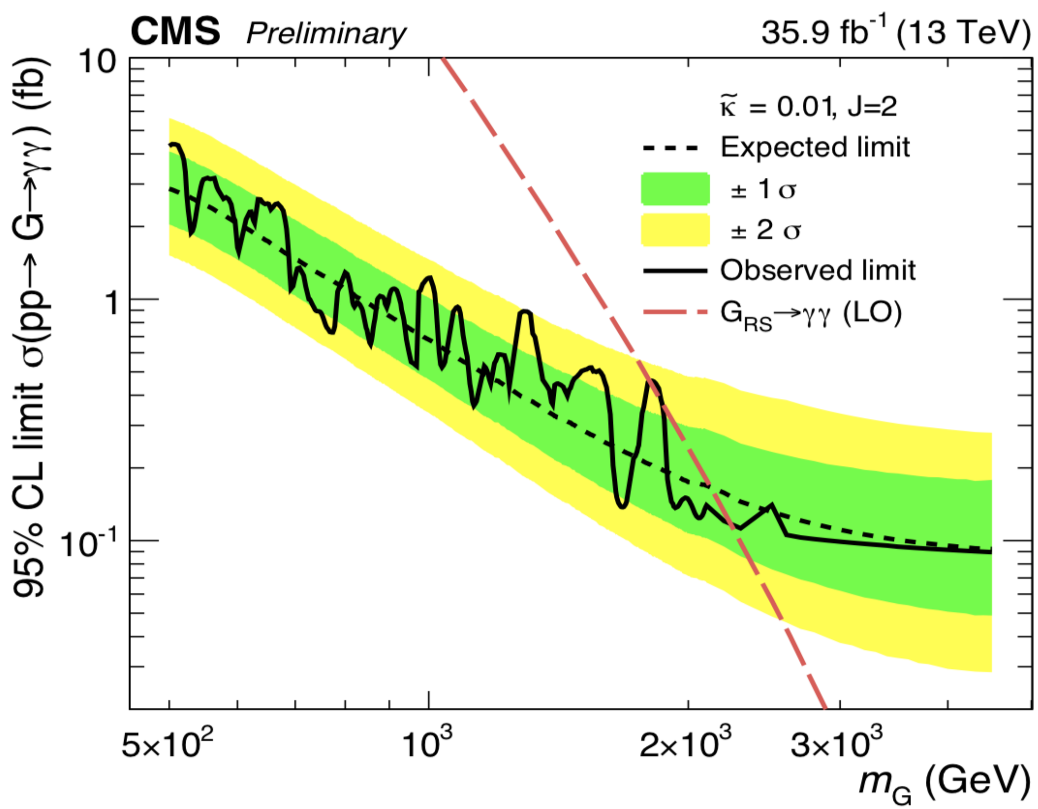
2015: Statistical fluctuation? A new resonance? ???
2015 data: CMS: 3.4 σ ! ATLAS up to 3.9 σ !! (local significances)
2016 data: 13 fb^{-1} CMS and ATLAS Nada!!

Search for a Di-photon Resonance

EXO-17-017

The search with the full 2016 data





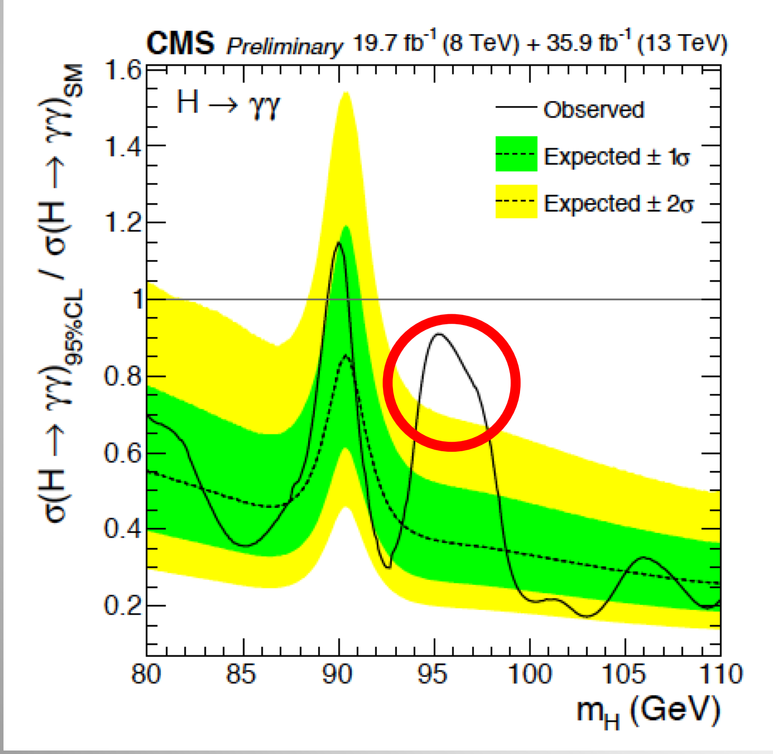
2016 data: Full statistics CMS ... nothing special

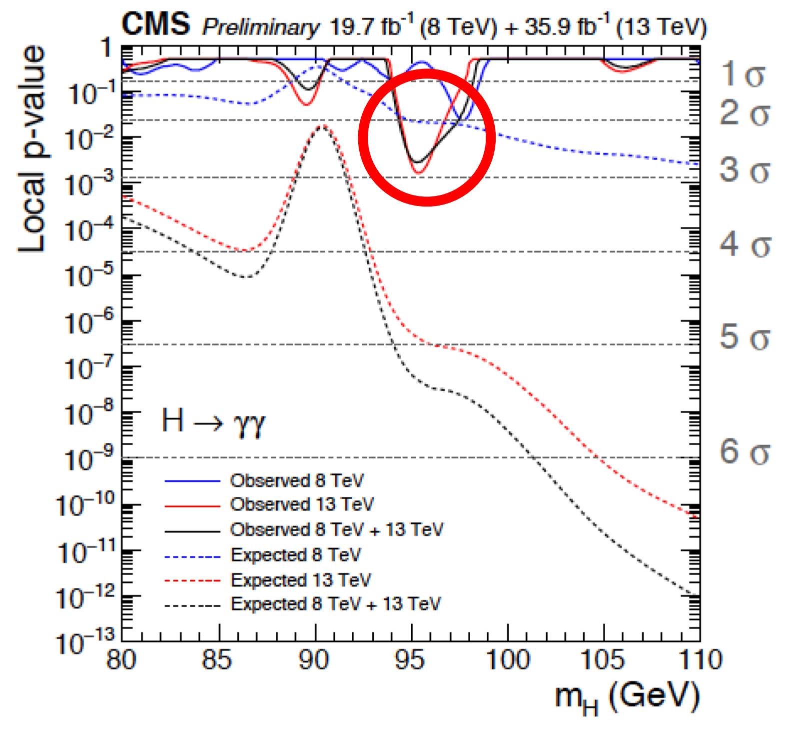
Is 96 GeV the New 750 GeV (?)

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

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

CMS-HIG-17-013

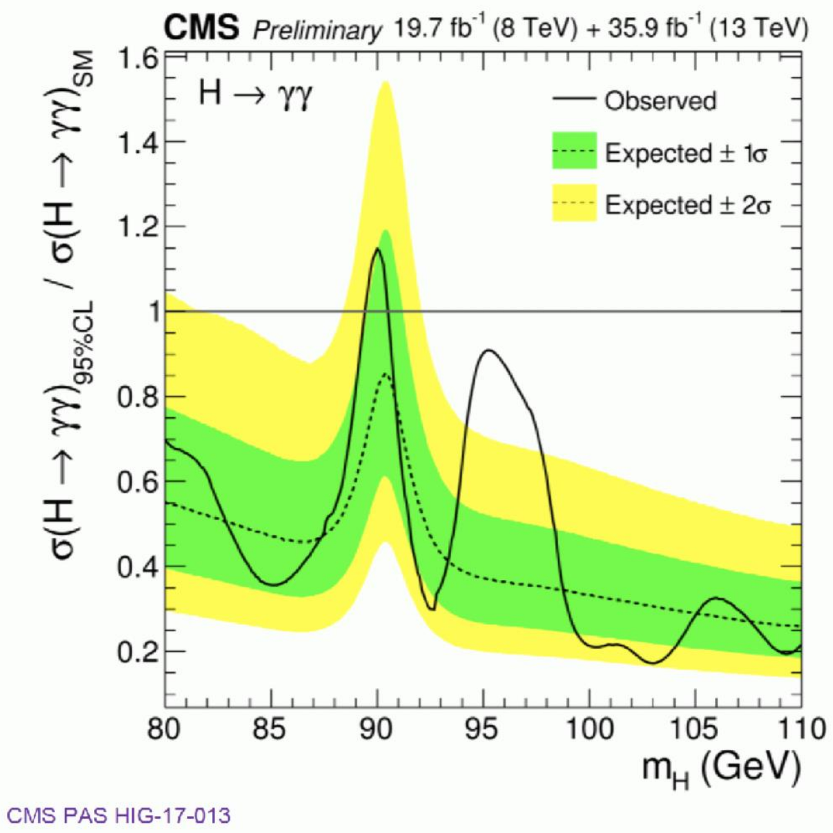




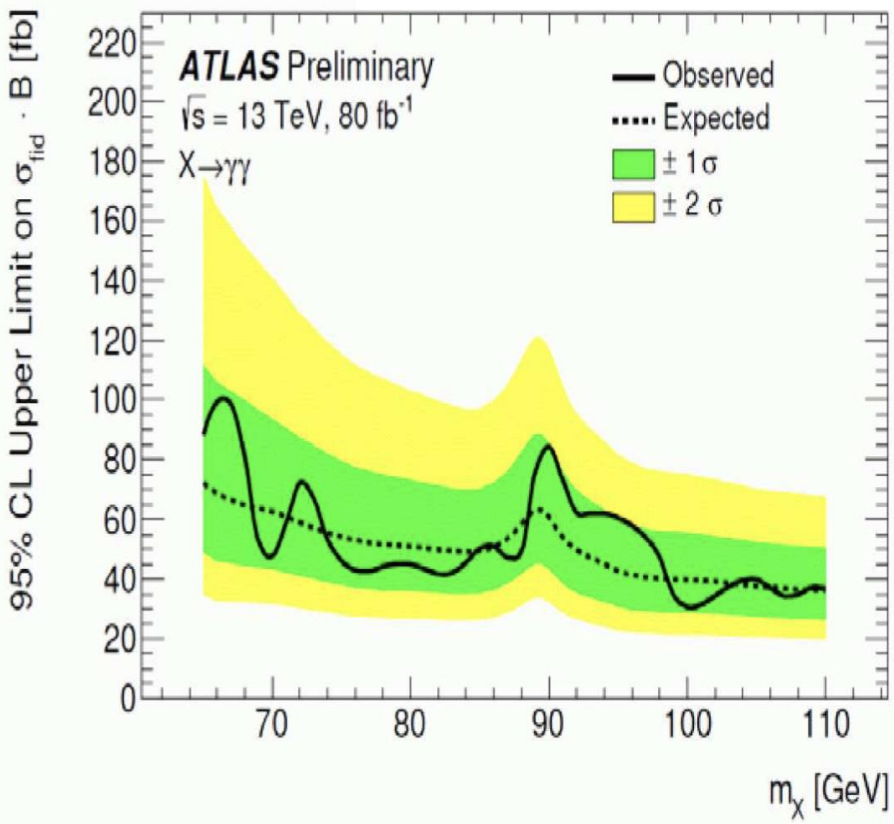
So far seen only in CMS. Waiting for the ATLAS data to be released… ☺ !!

Is 96 GeV the New 750 GeV (?)

CMS-HIG-17-013



ATLAS-CONF-2018-025

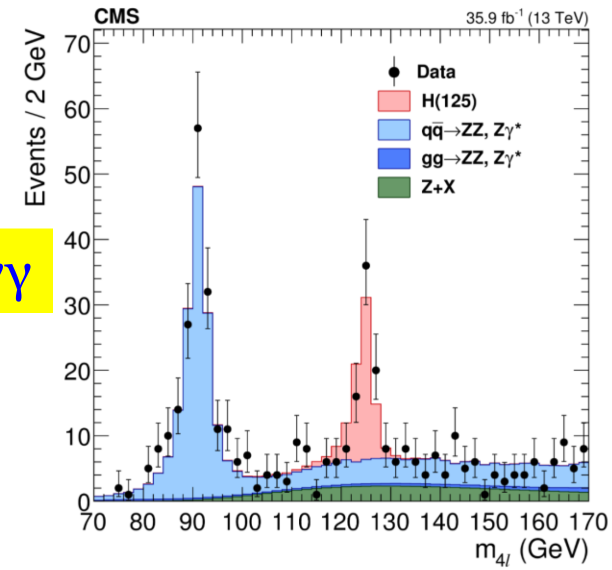


Probably not… ATLAS does not confirm the same size of effect…
Let’s see with more data…

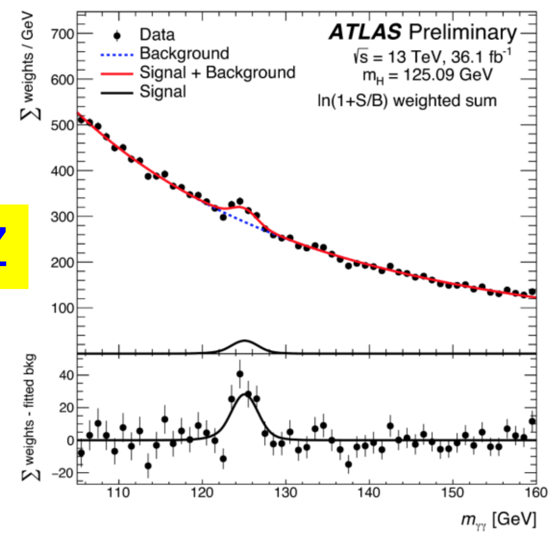
Higgs @ 13 TeV in Run 2

- Higgs particle is still there ! ☺

H→ γγ



H→ ZZ



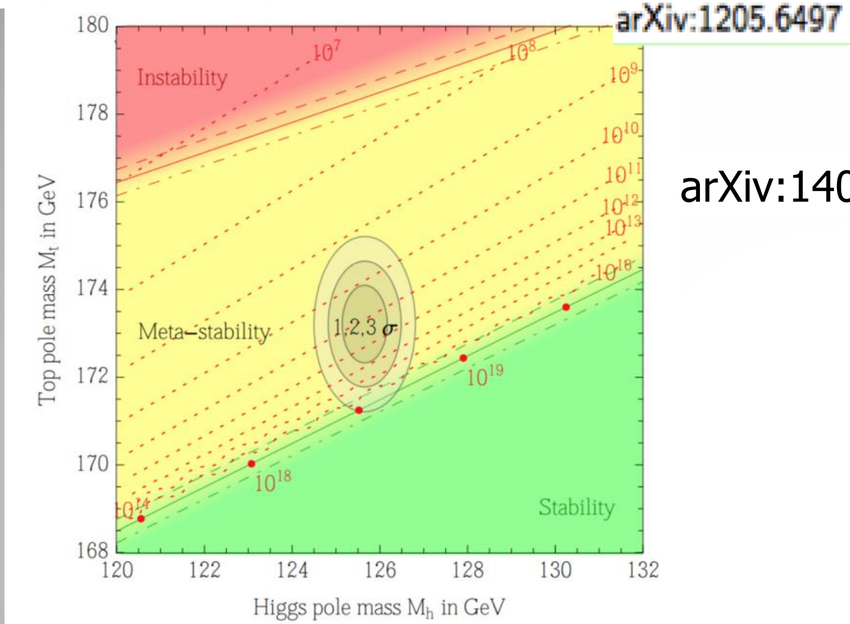
- The mild deviations seen in Run-1 seem to be gone ☹
- Observation of H→bb in the associated production channel
- Direct observation of ttH production
- No deviations from Standard Model Higgs expectations yet!!

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

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

Physics Beyond the Standard Model?

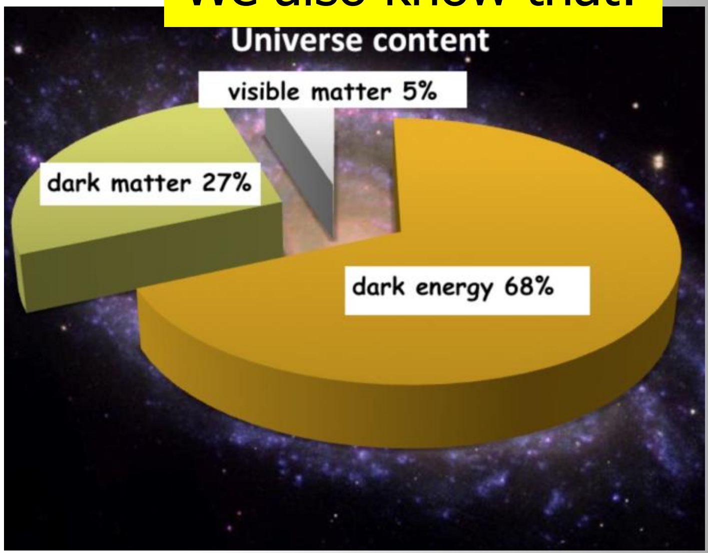
Important SM parameter → stability of EW vacuum



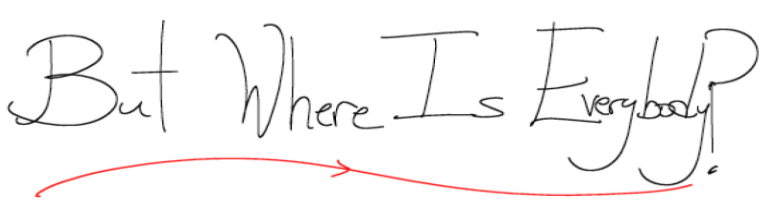
arXiv:1403.6535

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

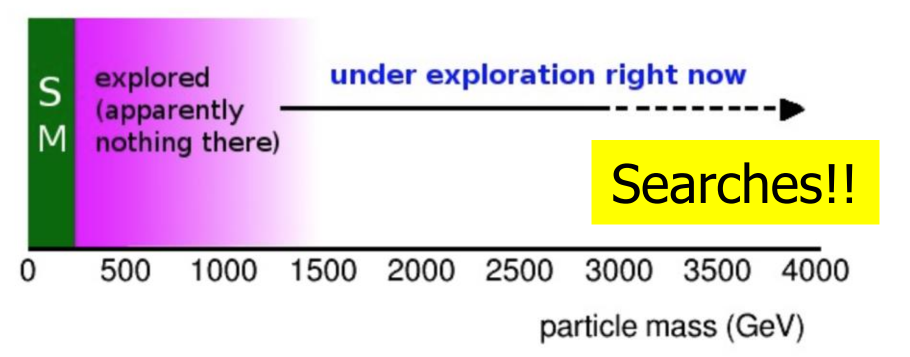
We also know that:



New Physics inevitable?
But at which scale/energy?



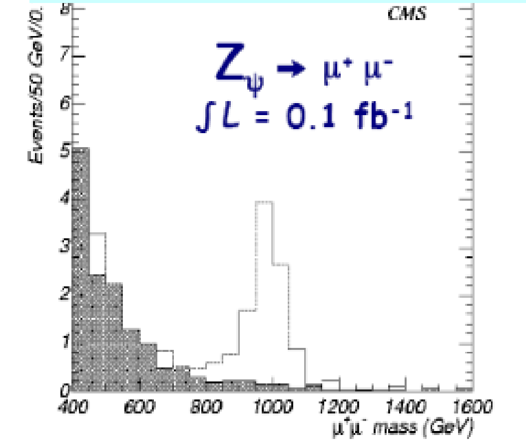
N. Arkani-Hamed



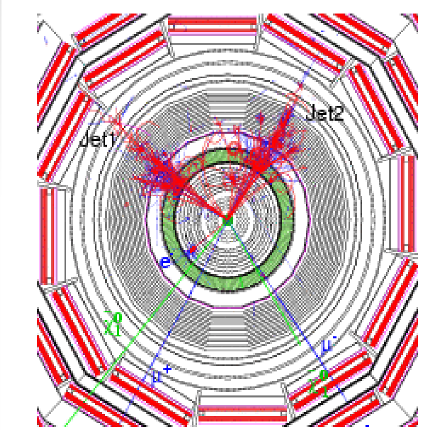
Searches for BSM Physics

New Physics?

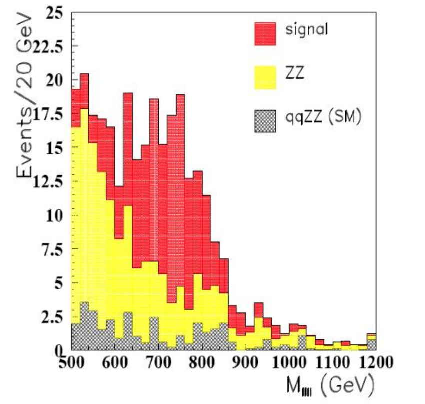
New Gauge Bosons?



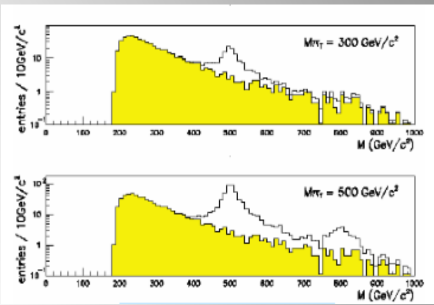
Supersymmetry



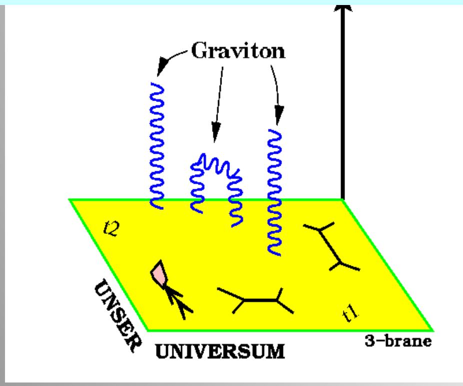
ZZ/WW resonances?



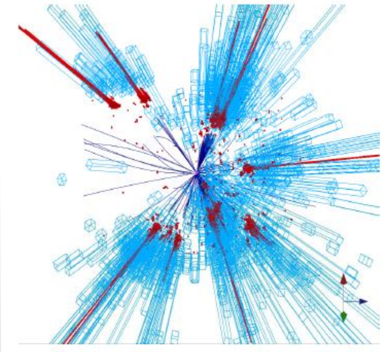
Technicolor?



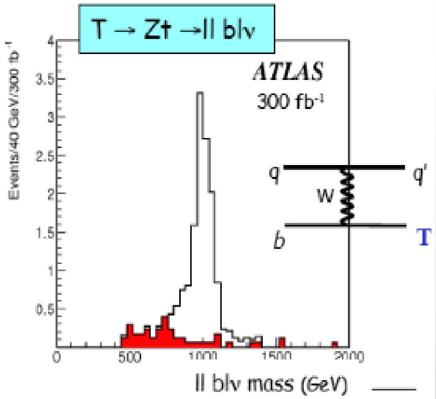
Extra Dimensions?



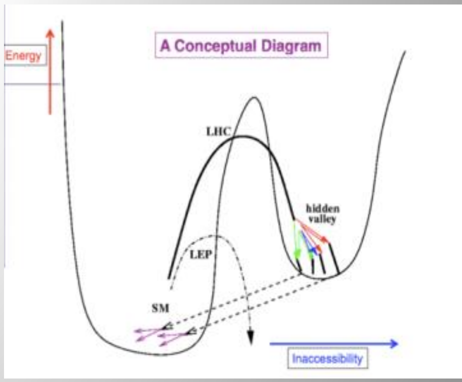
Black Holes???



Little Higgs?

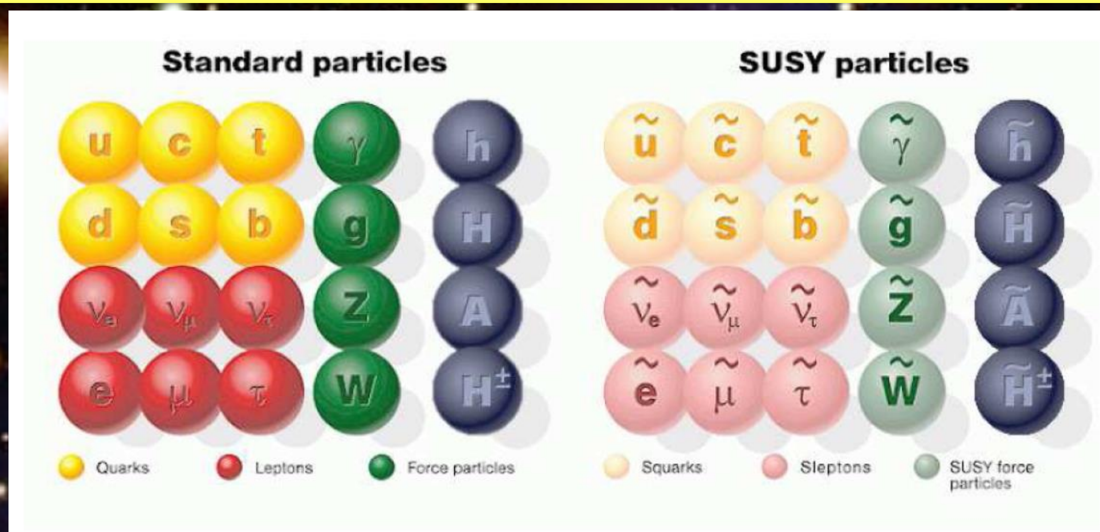


Hidden Valleys?



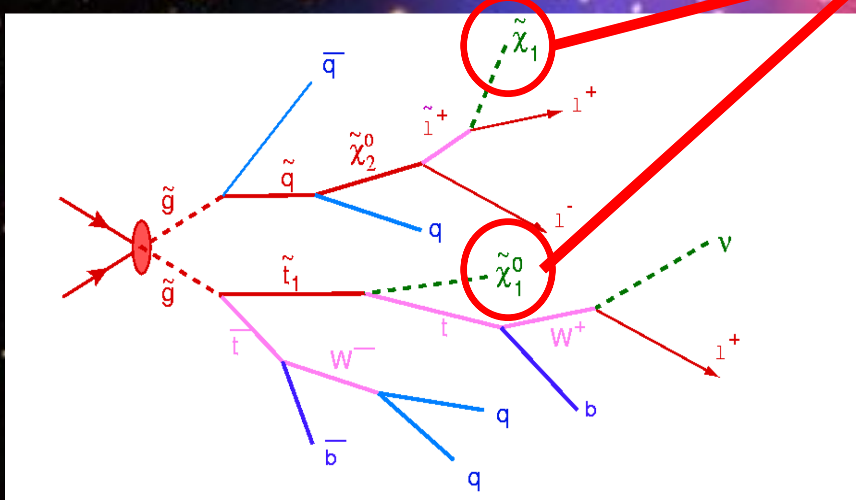
What stabelizes the Higgs Mass? Many ideas, not all popular any more
A large variety of possible signals. We have to be ready for that

Supersymmetry: a new symmetry in Nature?

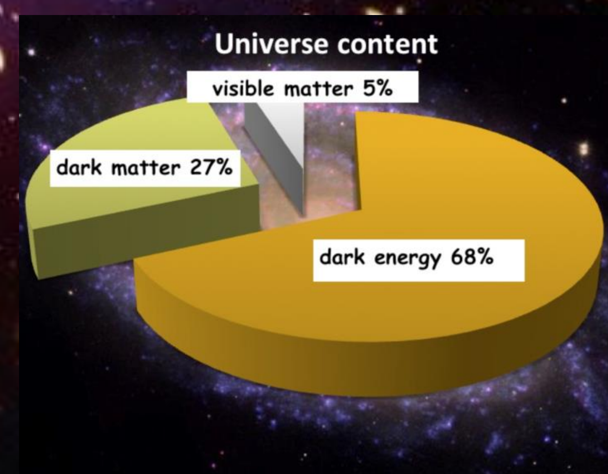


Candidate particles for Dark Matter

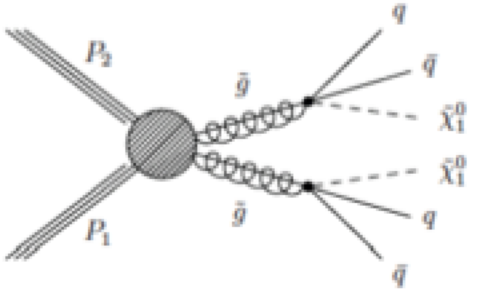
$\Rightarrow$ Produce Dark Matter in the lab

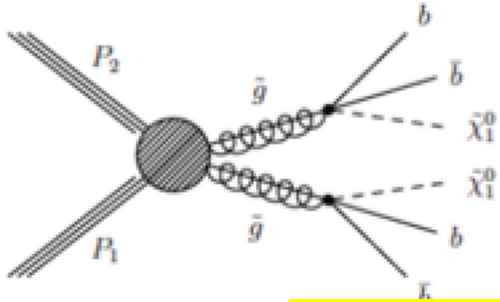


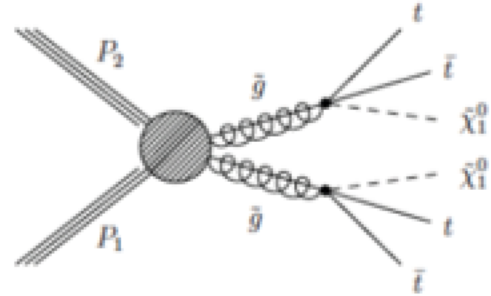
SUSY particle production at the LHC



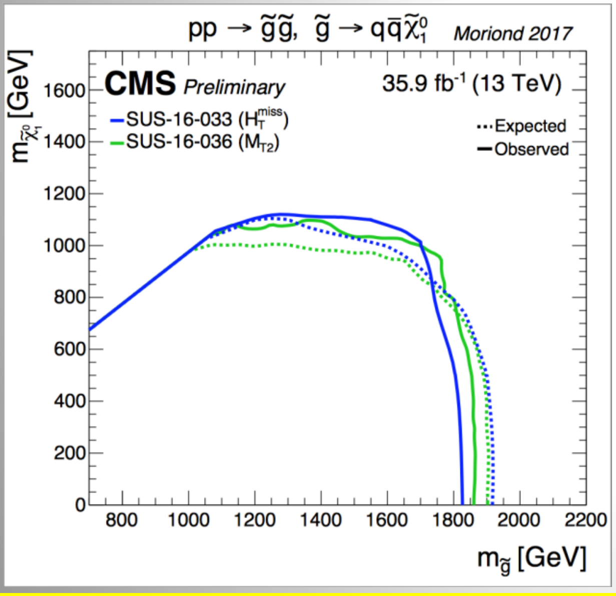
Supersymmetry: Gluinos

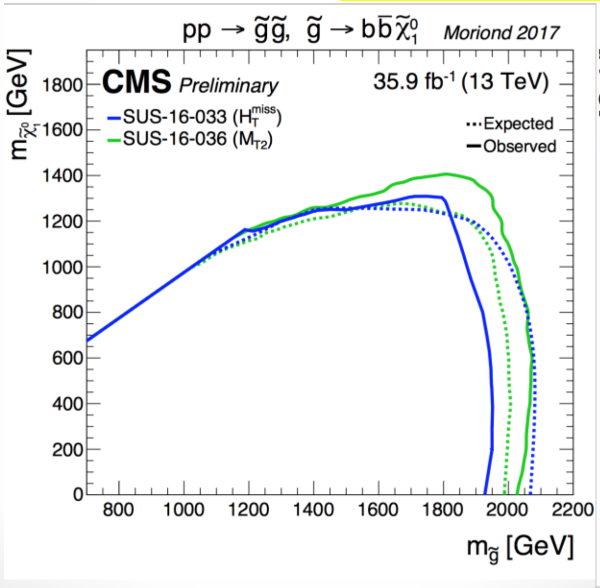


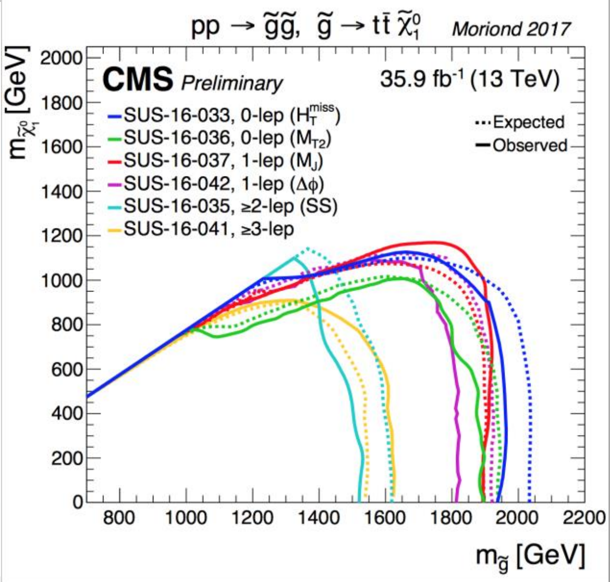




Interpretation in simplified models (SMS)







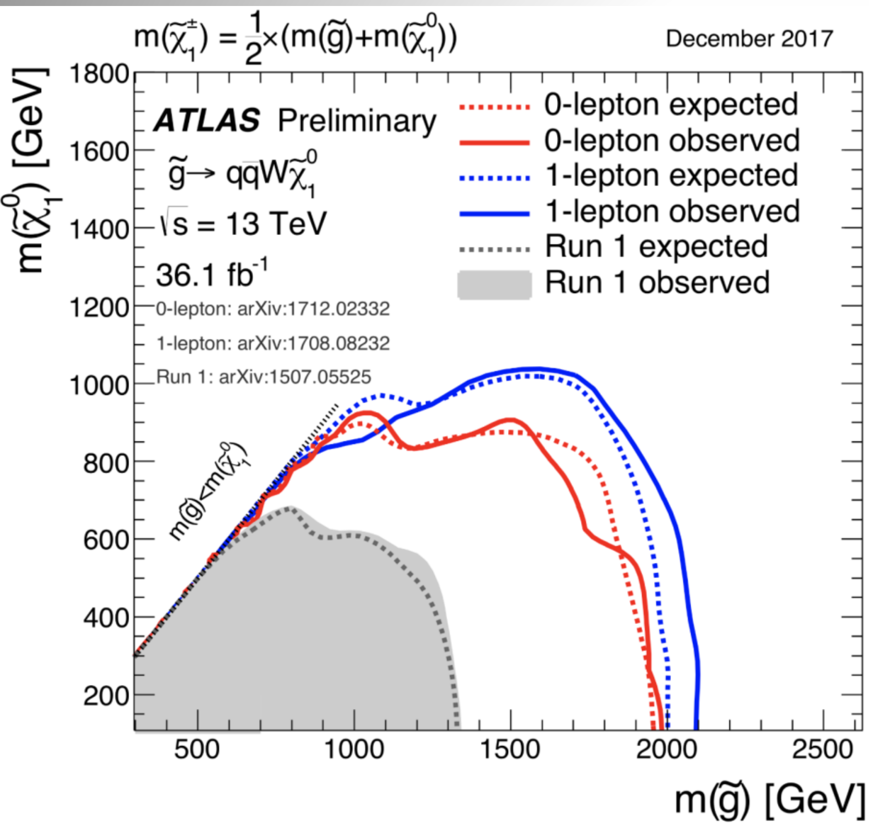
No significant signal to date

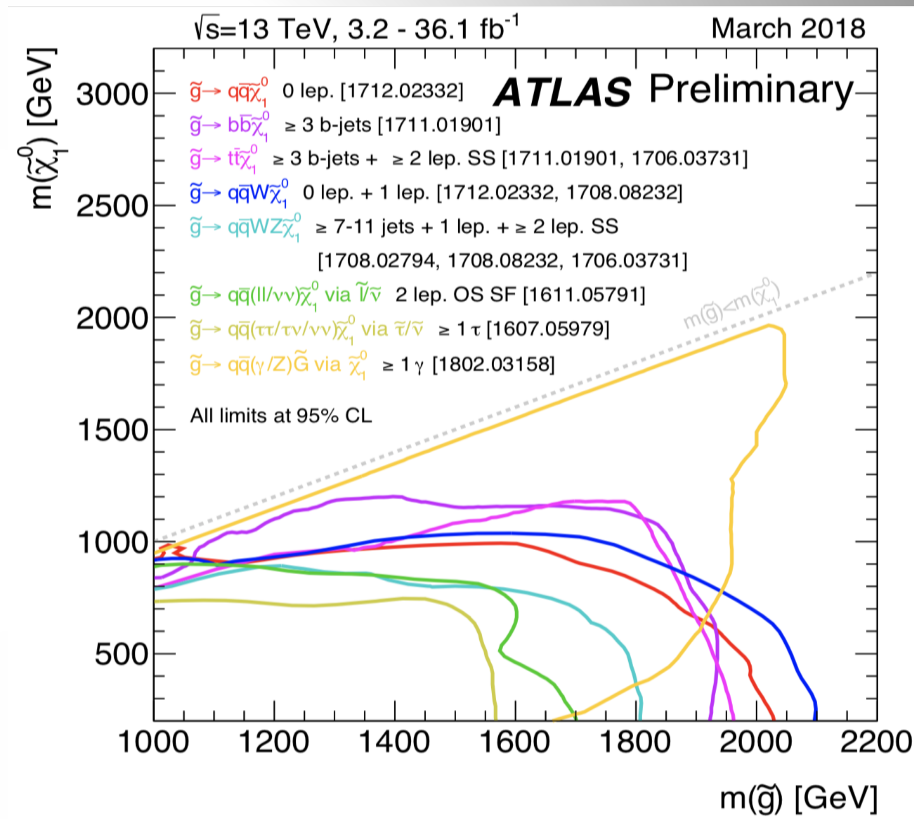
Within the context of the SMS:

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.



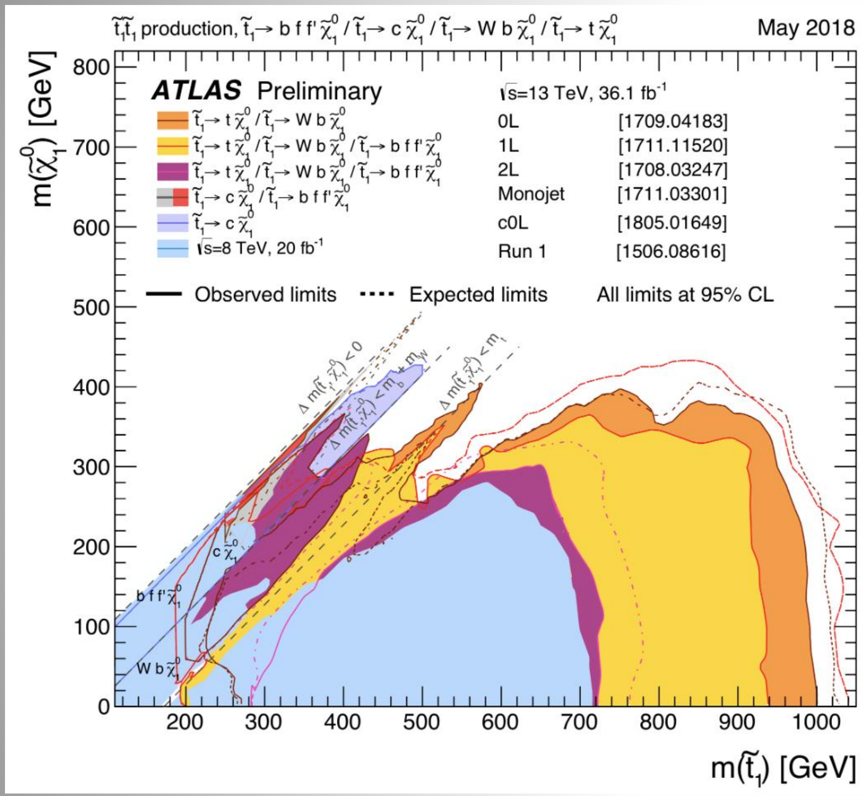


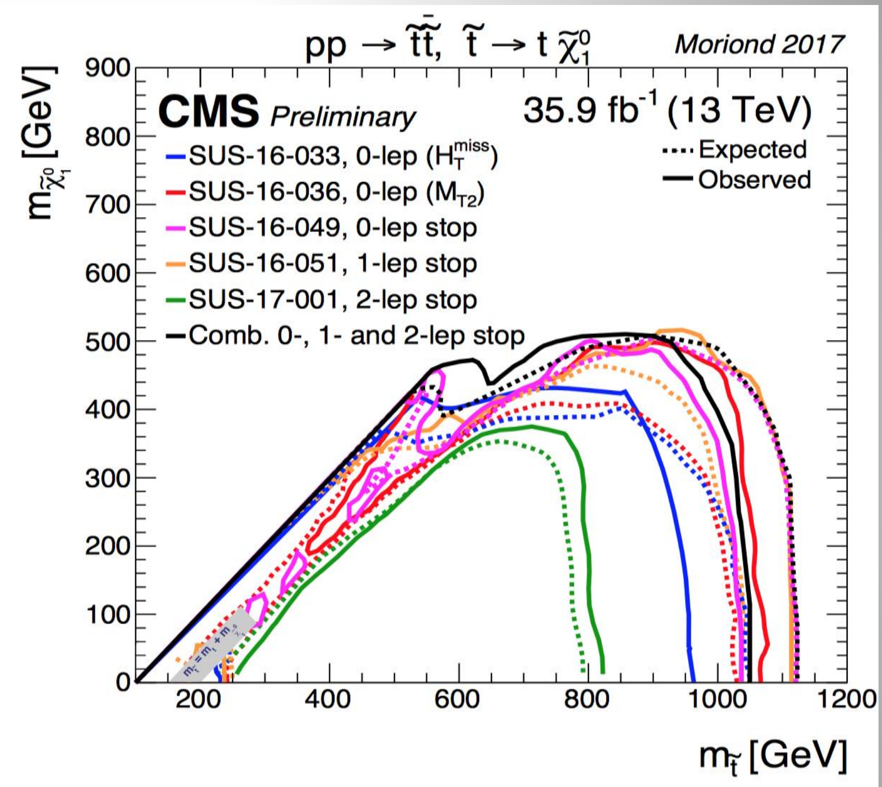
No significant signal to date

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:

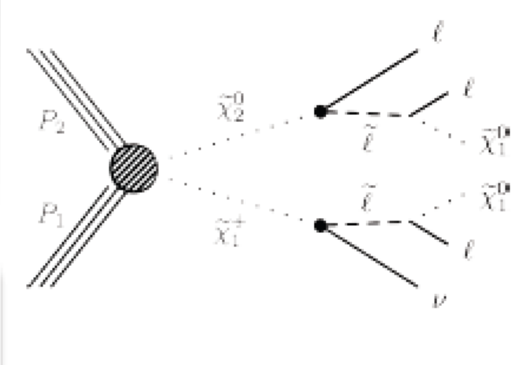
Exclude with masses up to 1100 GeV for neutralino masses up to 500 GeV

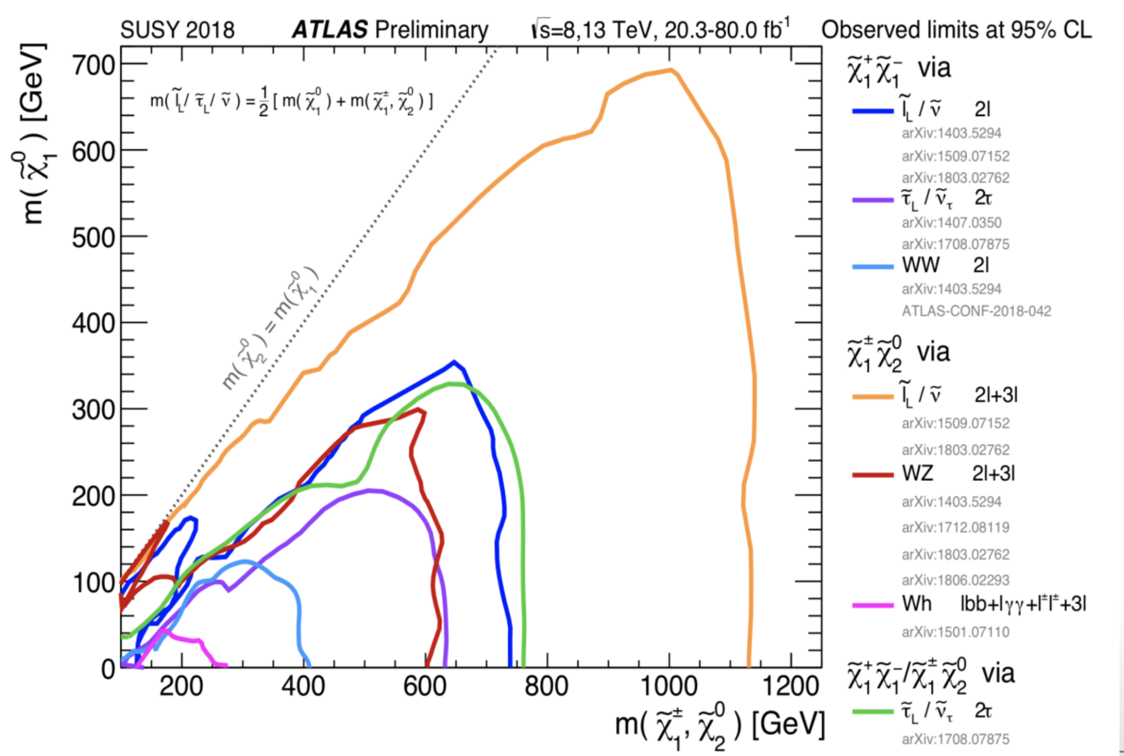
Sensitivity is ~ 200-400 GeV better than Run-1 reach & gaps being covered

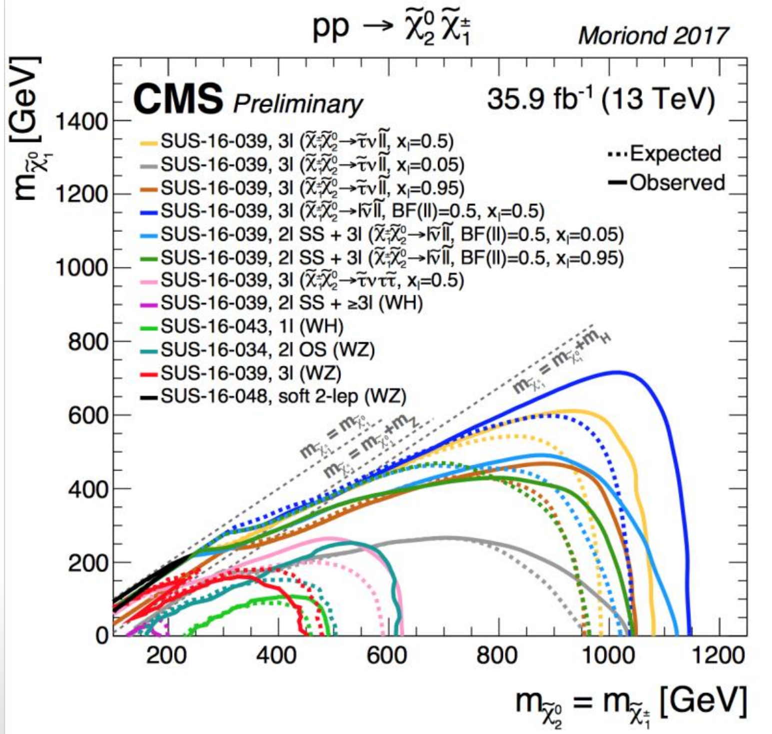
Is this getting critical for Natural Models??

Chargino and Neutralino Production

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





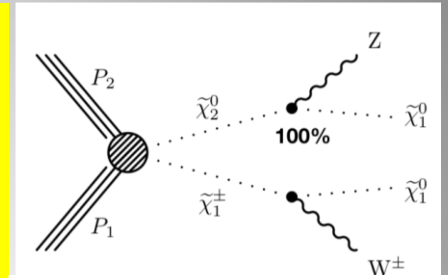


Exclude masses up to 1100 GeV for neutralino masses up to 700 GeV

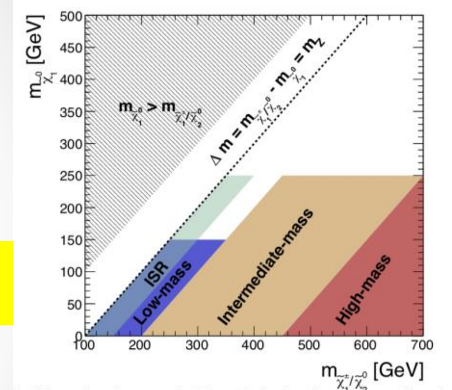
Chargino and Neutralino Production

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

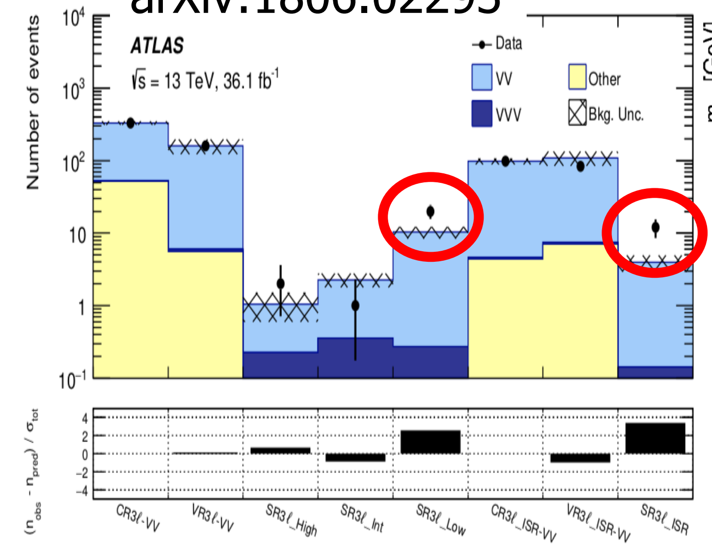


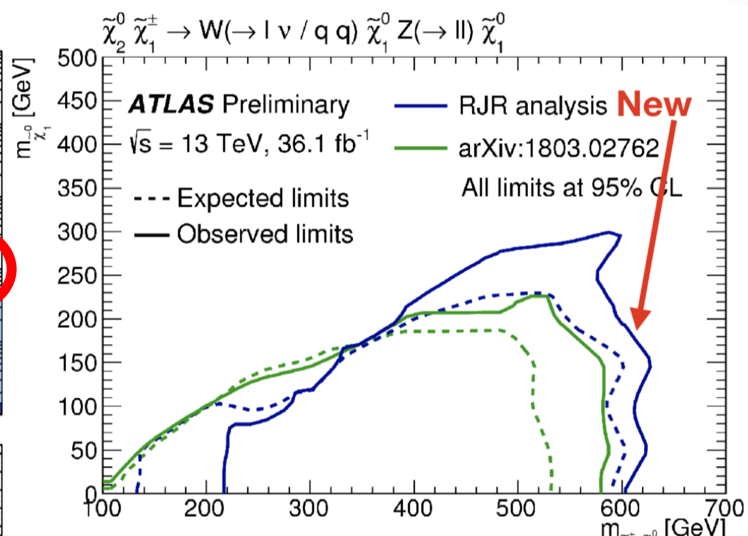
Signal region	SR3ℓ_Low	SR3ℓ_ISR	SR2ℓ_Low	SR2ℓ_ISR
Total observed events	20	12	19	11
Total background events	10 ± 2	3.9 ± 1.0	8.4 ± 5.8	$2.7^{+2.8}_{-2.7}$



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

arXiv:1806.02293





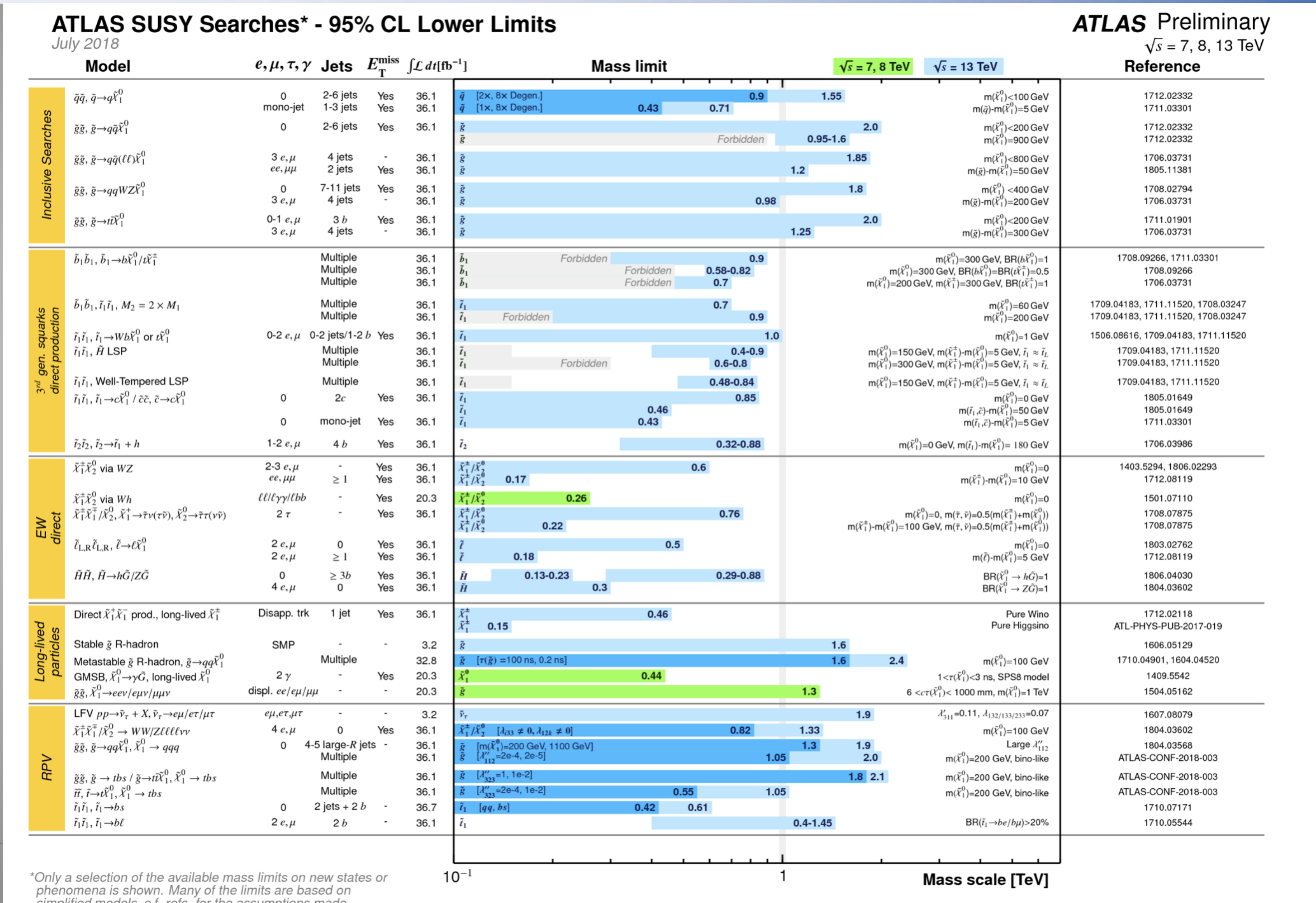
Conventional 2L/3L

Compatible with previous studies?

To be watched…

But "3σ"s have come and gone..

The SUSY SEARCH Chart So Far…



SUSY (as seen outside HEP…)

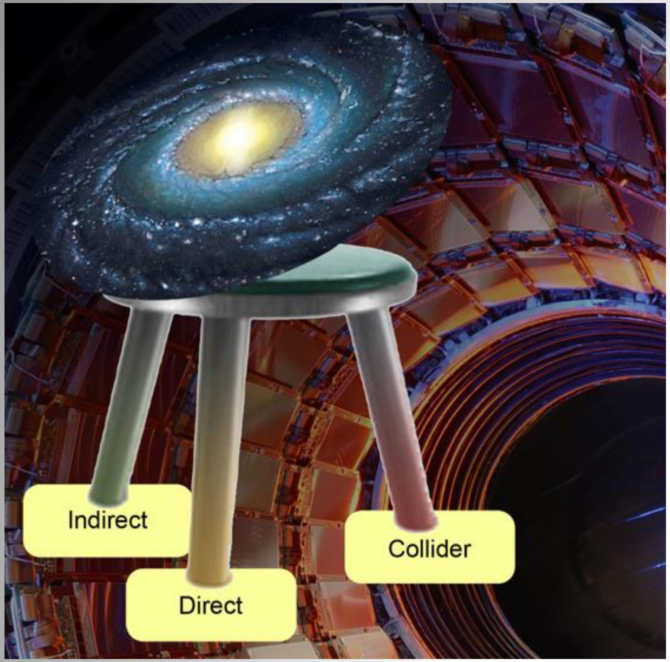
November '16 ago on the web page of The Economist (!?!):

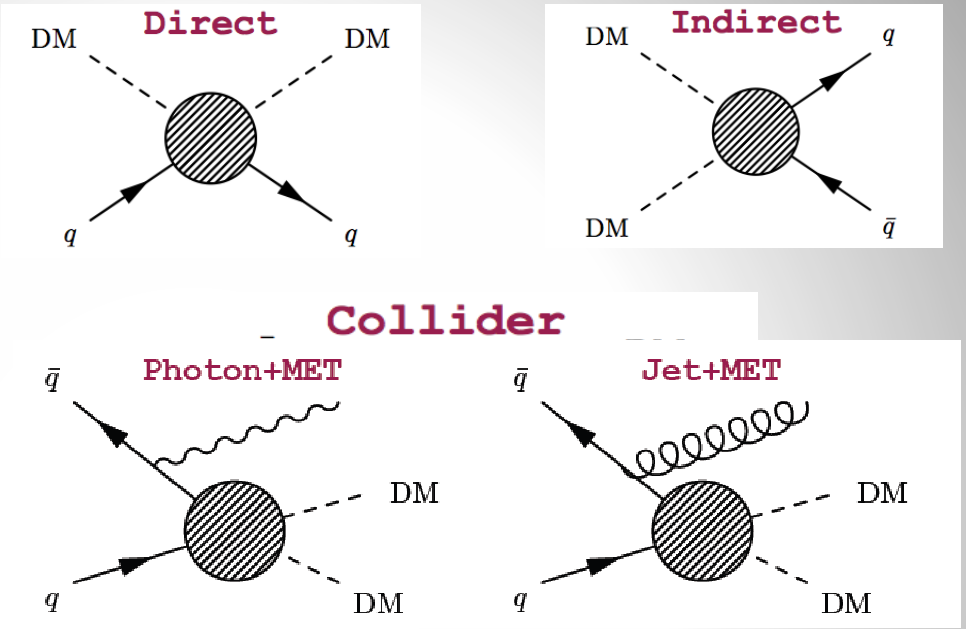
Supersymmetry is a beautiful idea. But no evidence supports it

But not giving up as yet!!!

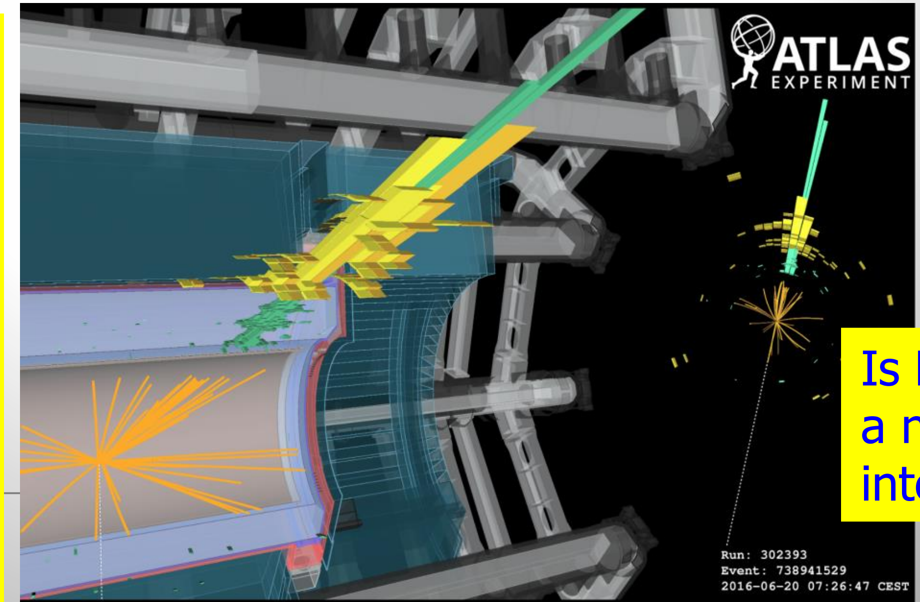
http://www.economist.com/news/science-and-technology/21709946-supersymmetry-beautiful-idea-there-still-no-evidence-support-it

Dark Matter Searches at the LHC





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



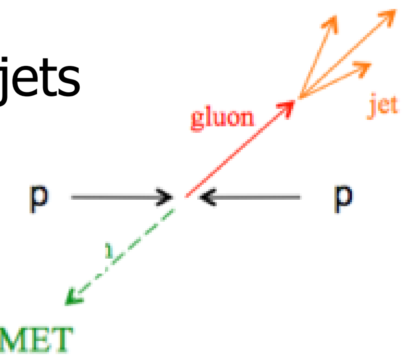
Is Dark Matter a new weakly interacting particle?

Mono-object Searches in CMS

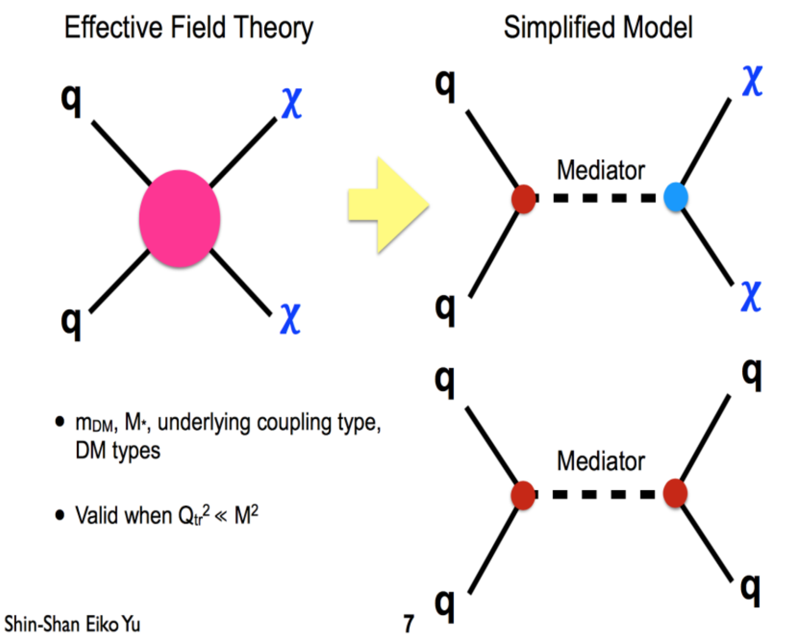
- Mono-jets: Generally the most powerful
- Mono-photons: First used for dark matter Searches
- Mono-Ws: Distinguish dark matter couplings to u- and d-type of quarks
- Mono-Zs: Clean signature
- Mono-Tops: Couplings to tops
- Mono-Higgs: Higgs-portals
- Higgs Decays?

Are Dark Matter weakly interacting massive particles (WIMPs?)

Example Monojets



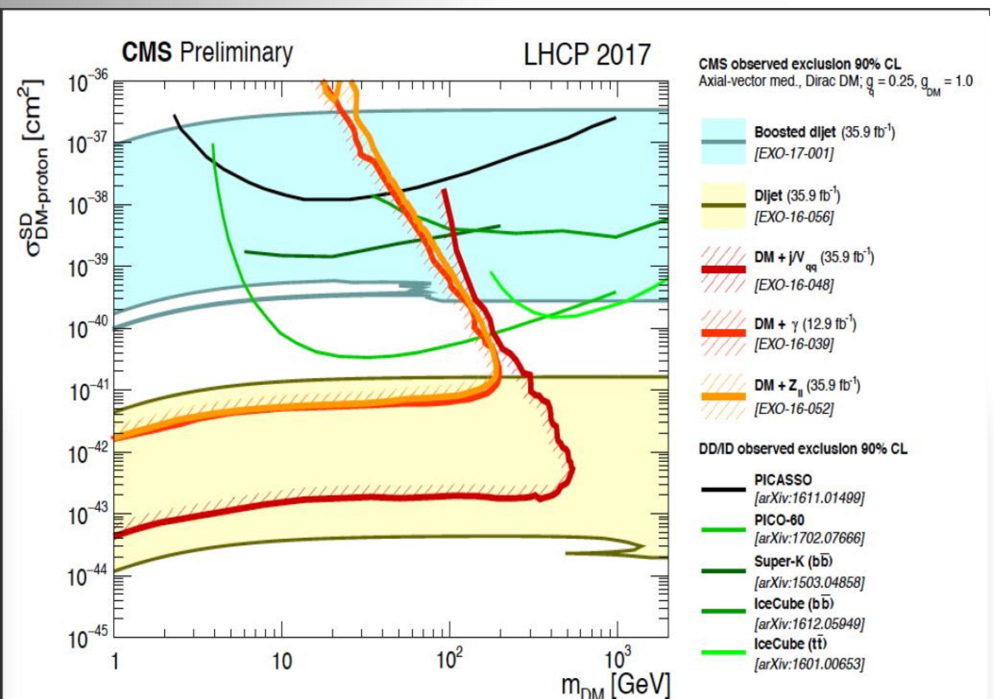
Dark Matter?



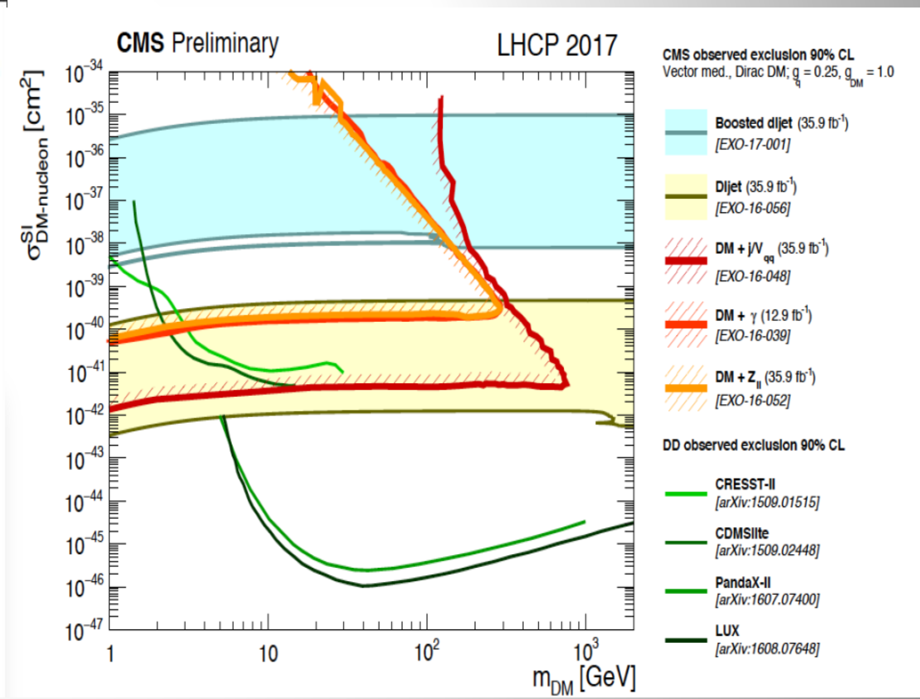
Comparison with Direct Detection

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

Axial-vector mediator and
Spin-dependent direct limits



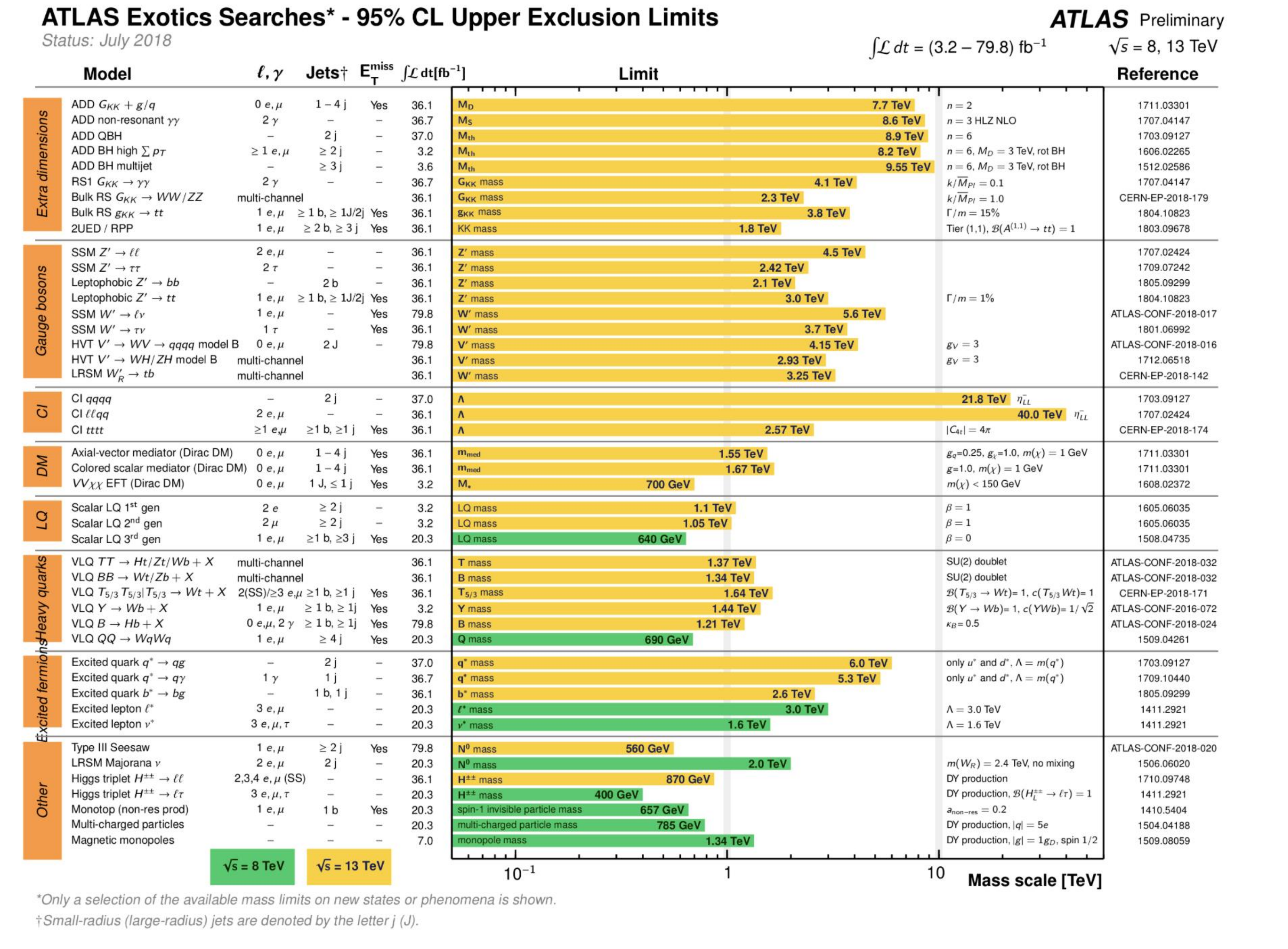
Vector mediator and
Spin-independent direct limits



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

90% CL limits

Exotica Searches: Limits



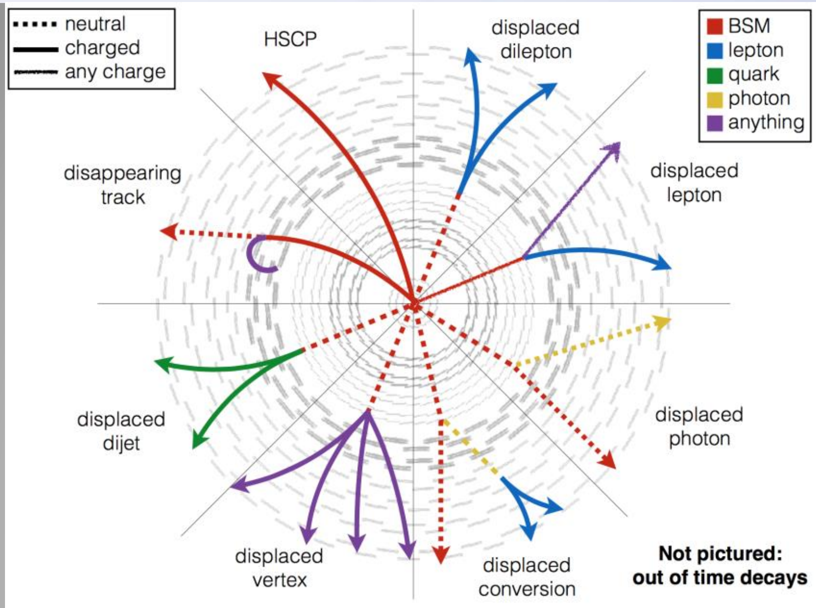
Are we leaving no stone unturned?

- 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?

Leave no stone unturned!!

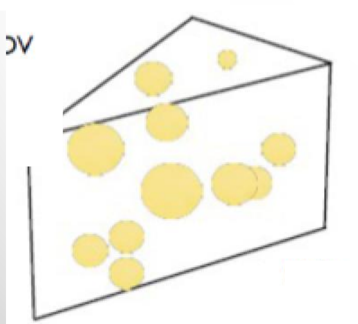
Searches for Long Lived Particles

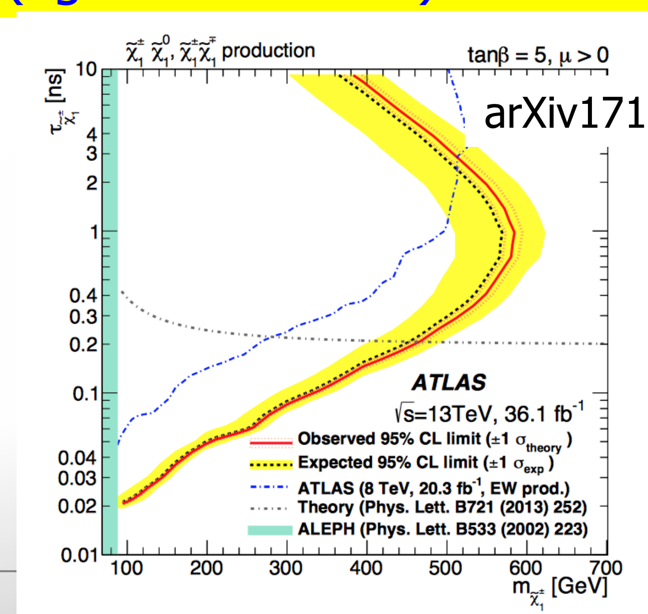


Increasing interest and effort:
Look for unusual signals in the detector from long-lived particles

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

Present coverage?





arXiv1712.02118

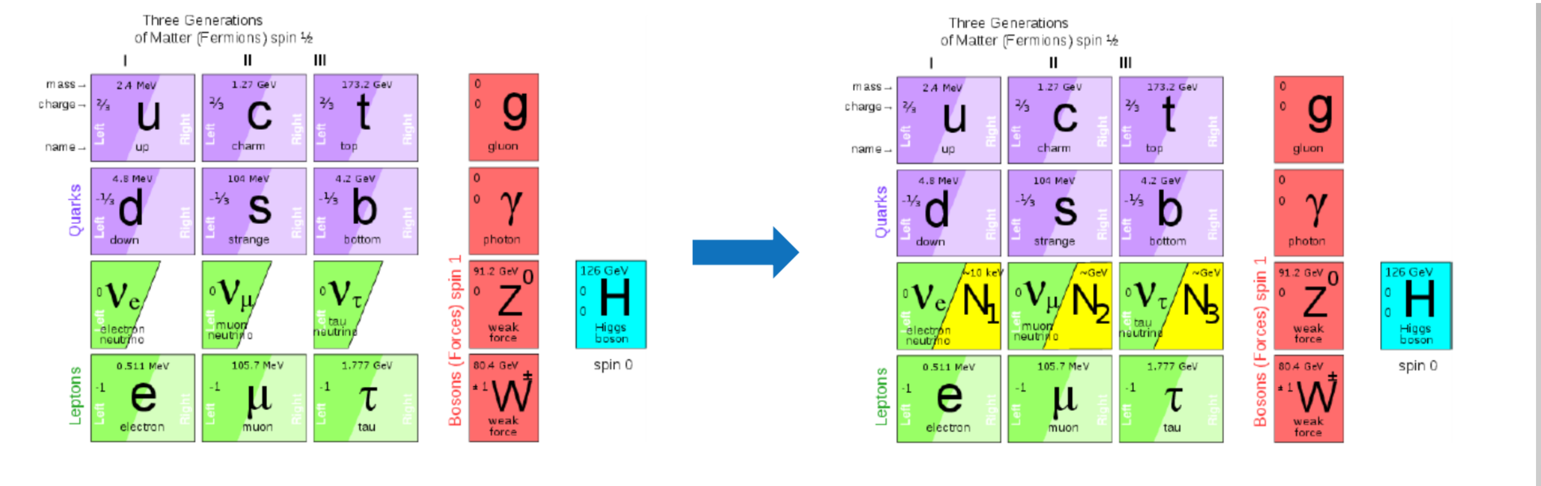
LHC-wide organized study ->
https://indico.cern.ch/e/LHC_LLP_October_2017

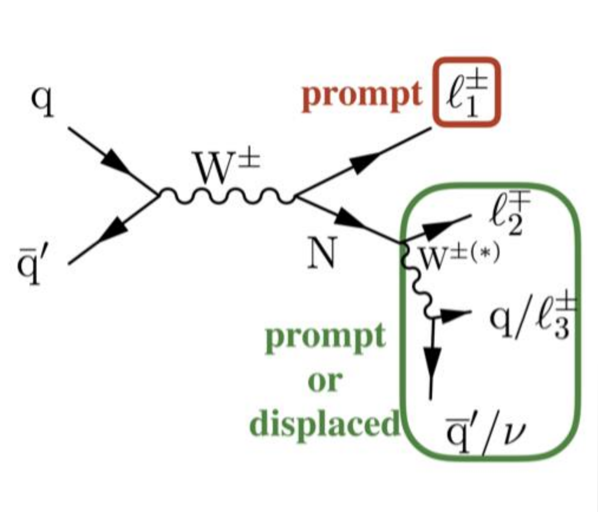
A White Paper in preparation!

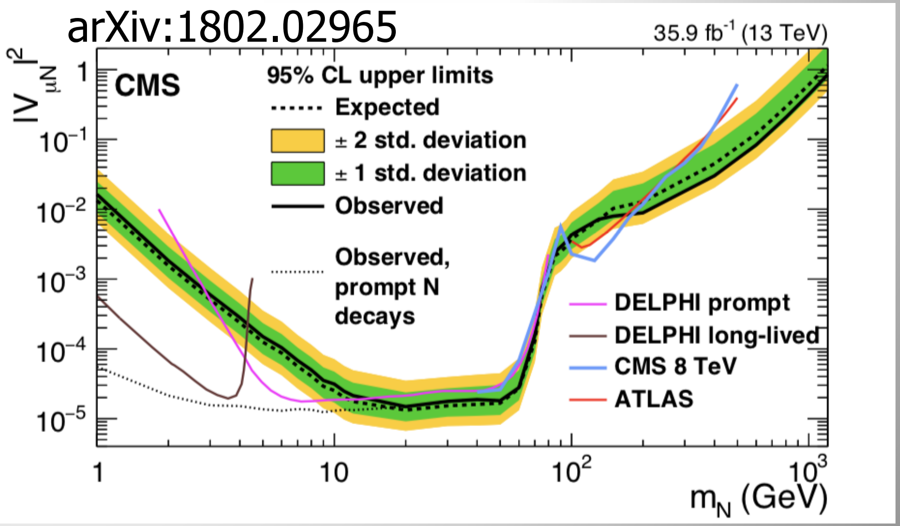
Search for Heavy Neutral Leptons

Neutrino portal: νMSM (Neutrino Minimal Standard Model)

Minimal extension of the SM fermion sector by Right Handed HNLs: N1, N2, N3.

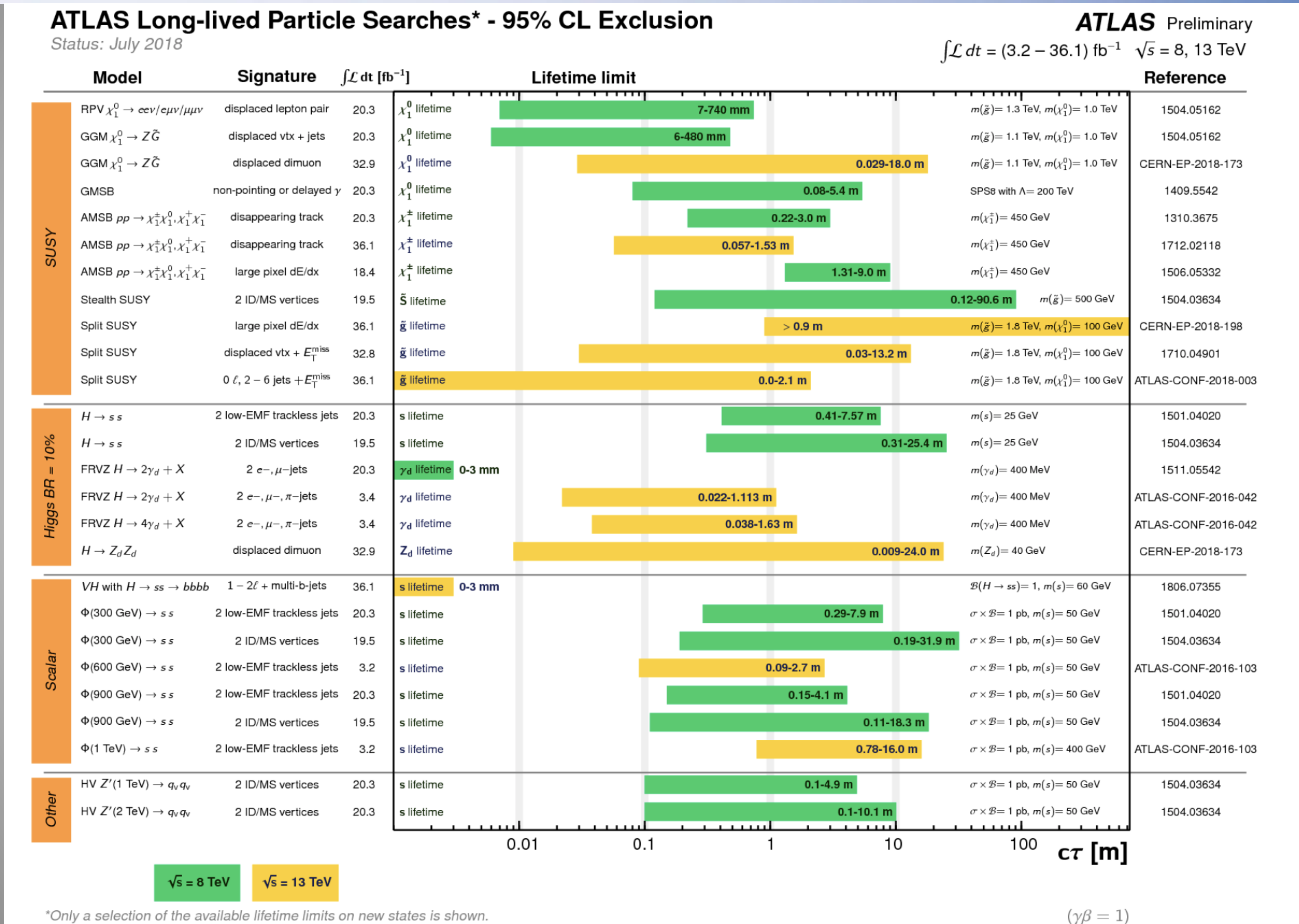






-> HNL hunting also focus of the SHIP experiment proposal

Long Lived Particle Searches

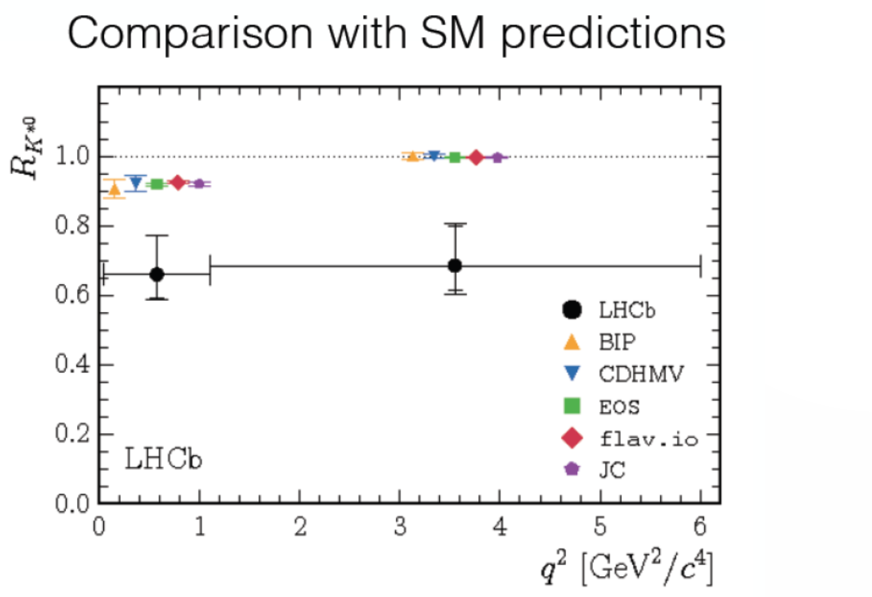


LHCb: Test of Lepton Universality

A puzzling results from the LHCb experiment…

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

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



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^{10} b-pairs by the end of run2!!

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

2.1 - 2.3 σ

2.4 - 2.5 σ

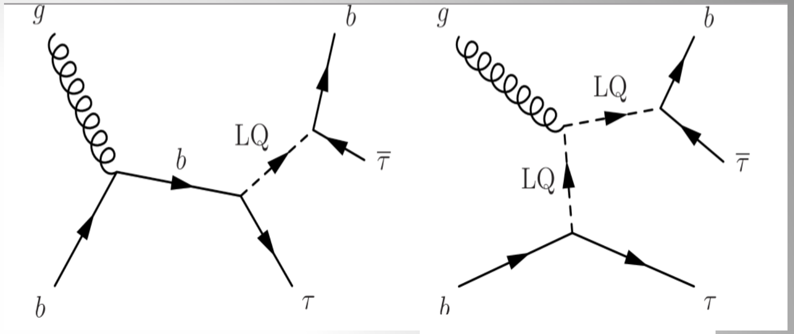
?

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

?

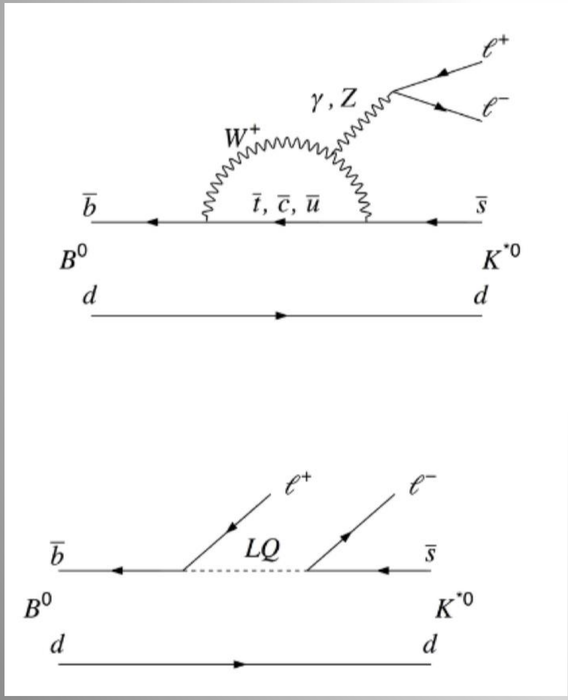
Third Generation Leptoquarks

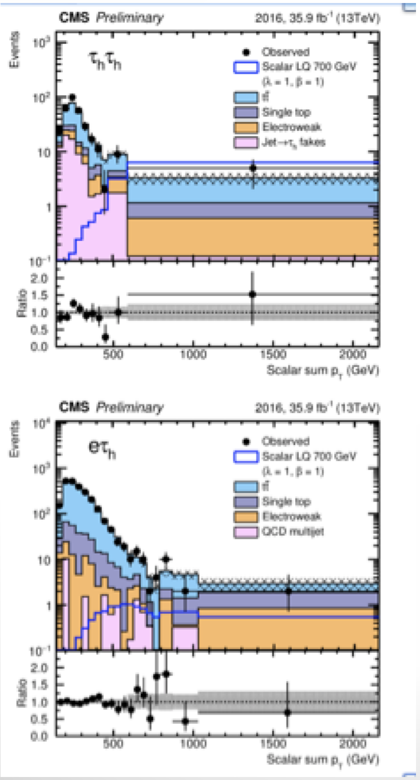
Candidate explanation: Leptoquarks with couplings to second/third generation.
-> Check in ATLAS and CMS

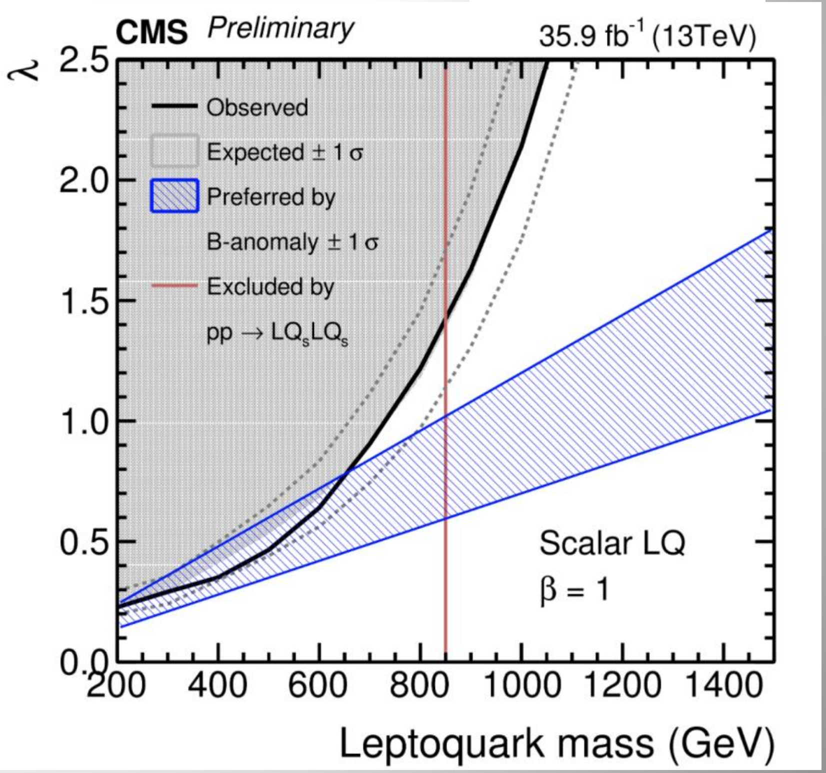


EXO-17-029

Example search in the tau-b final state



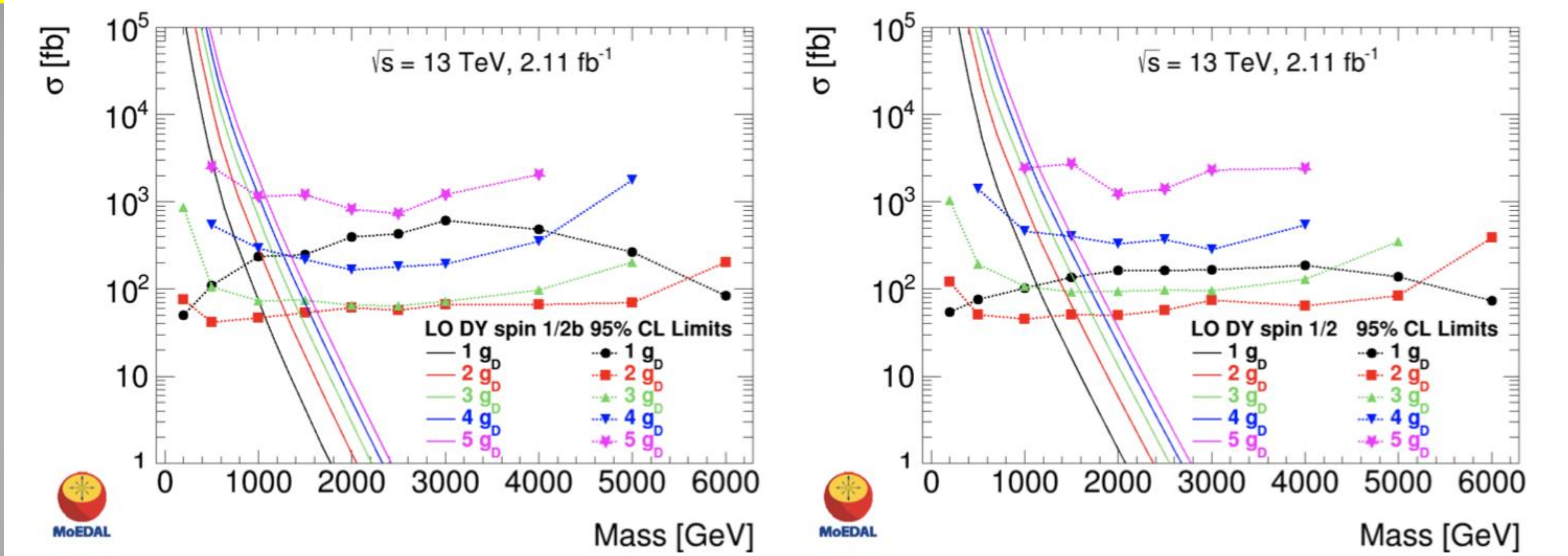


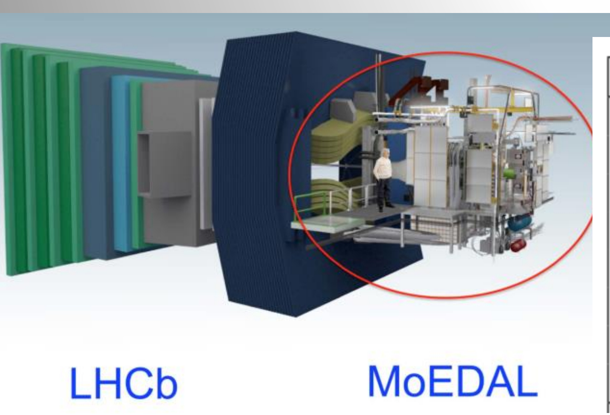


Blue region is preferred by the B-anomalies…

Monopole Searches: MoEDAL @ 13TeV

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



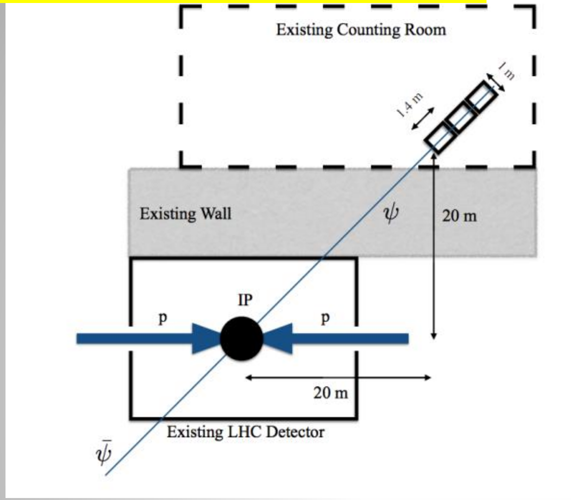


Mass limits [GeV]	$1g_D$	$2g_D$	$3g_D$	$4g_D$	$5g_D$
MoEDAL 13 TeV (2016 exposure)					
DY spin-0	600	1000	1080	950	690
DY spin-$\frac{1}{2}$	1110	1540	1600	1400	–
DY spin-1	1110	1640	1790	1710	1570
DY spin-0 β-dep.	490	880	960	890	690
DY spin-$\frac{1}{2}$ β-dep.	850	1300	1380	1250	1070
DY spin-1 β-dep.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

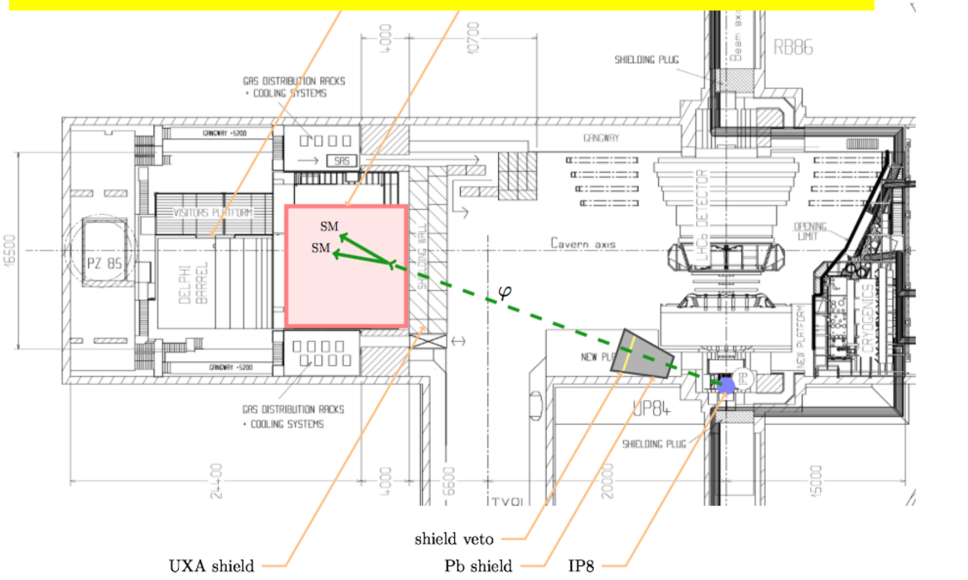
- Limits for different monopole charges
- First monopole search result @LHC at 13 TeV No signal (yet)..

Possible New Experiments @LHC

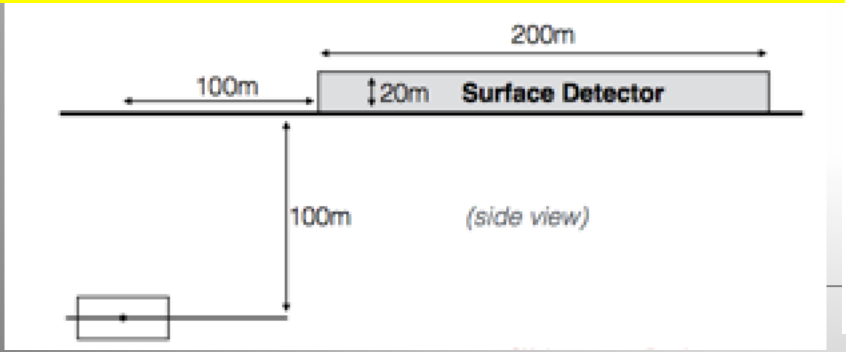
MilliQan: searches for millicharged particles



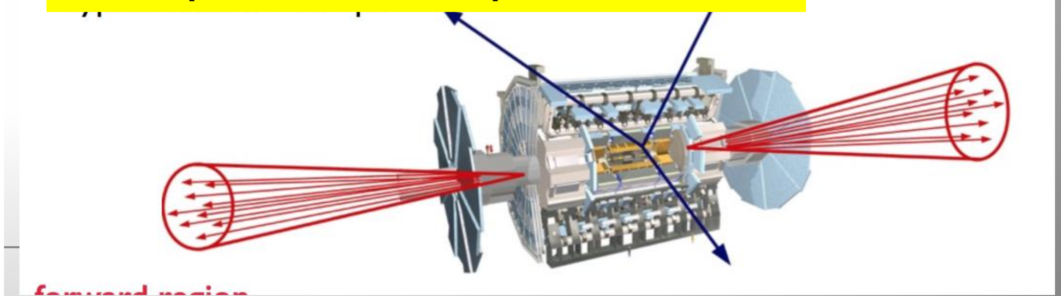
CODEX-b: searches for long lived weakly interacting neutral particles



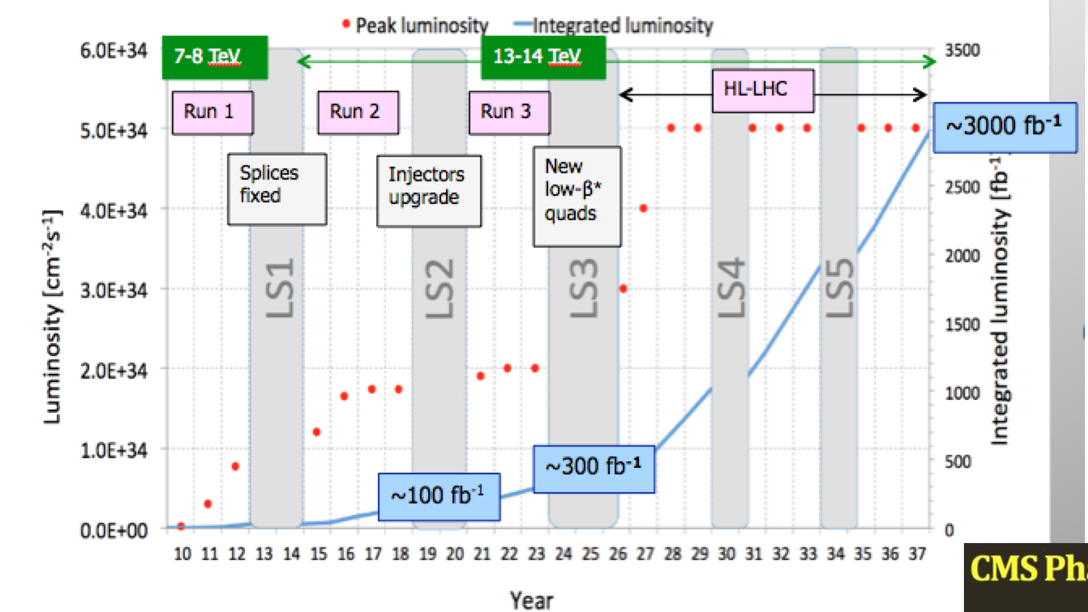
MATHUSLA: searches for long lived weakly interacting neutral particles



FASER: searches for long lived dark photons-like particles



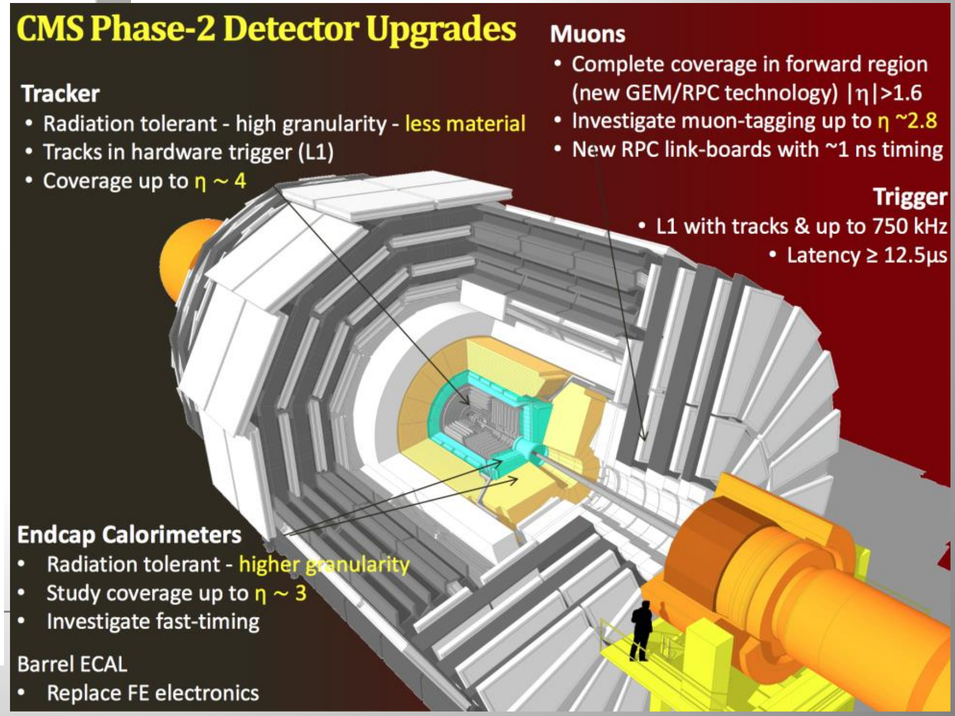
LHC Outlook and Plans



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

Approved LHC program to collect 3000 fb^{-1} in total with the LHC (HL-LHC)

Maximize the reach for searches and for precision measurements (eg Higgs)



LHC will run till ~2037

Only 4-5% of the collisions delivered so far…

Then a high energy LHC (28 TeV)?

Summary

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

  There are a number of 3-sigma effects, as always, but… ☺
- Dark Matter and Long Lived Particle searches are being explored in a systematic way. White paper on LLPs to appear.
- First results from the 2017 data are being released.
- New physics in the flavour sector? New TH paradigms?
- The LHC is continuing to explore the Terascale.
  much data to look forward to: it takes on significa
  to show the way!! Collected >130 fb^{-1}@ 13 TeV s

And hopefully one day soon now:

The Future

-2018: plan for 70 fb^{-1}

-2021-2023: plan for 300 fb^{-1}

- >2016 High Luminosity upgrade: collect 3000 fb^{-1} 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 $W\gamma\gamma$, 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 $Z\gamma$, $\mu\mu$, cc, light quark couplings…?
- Data taking is continuing !!
- Theorists: watch the precision of the data!! ☺