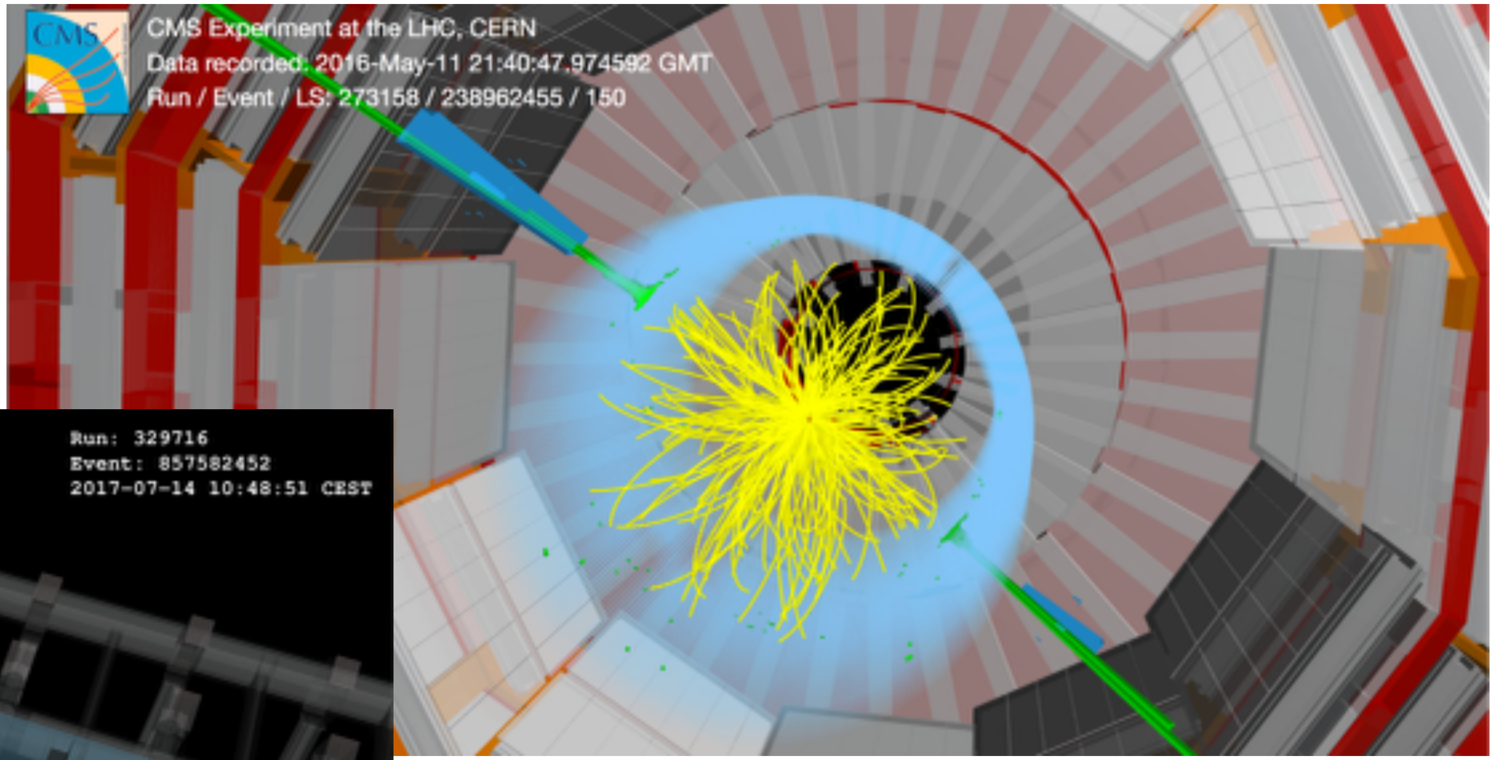
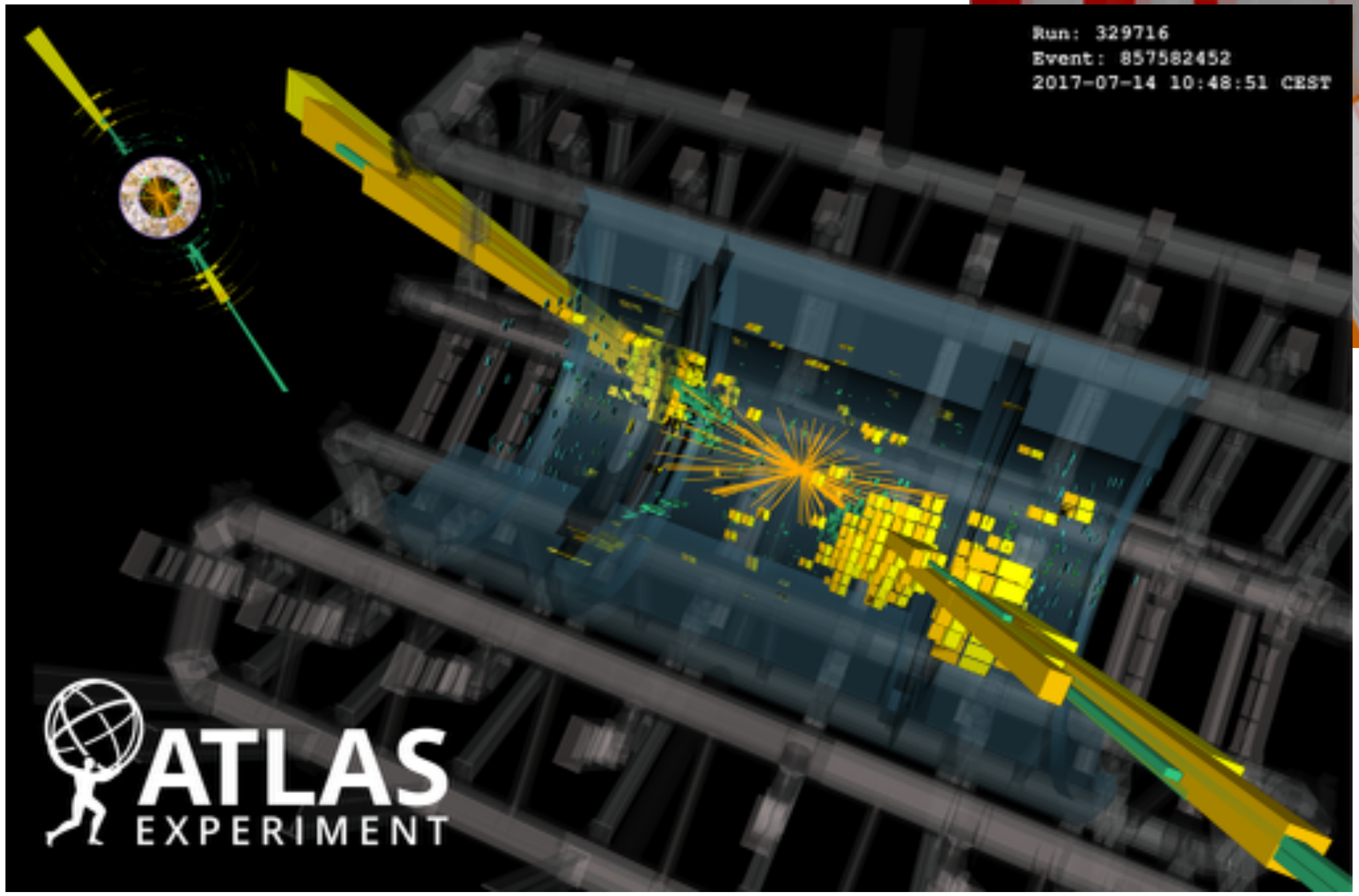
LHC: Status and Results

$m_{jj} = 9.3\text{TeV}$!



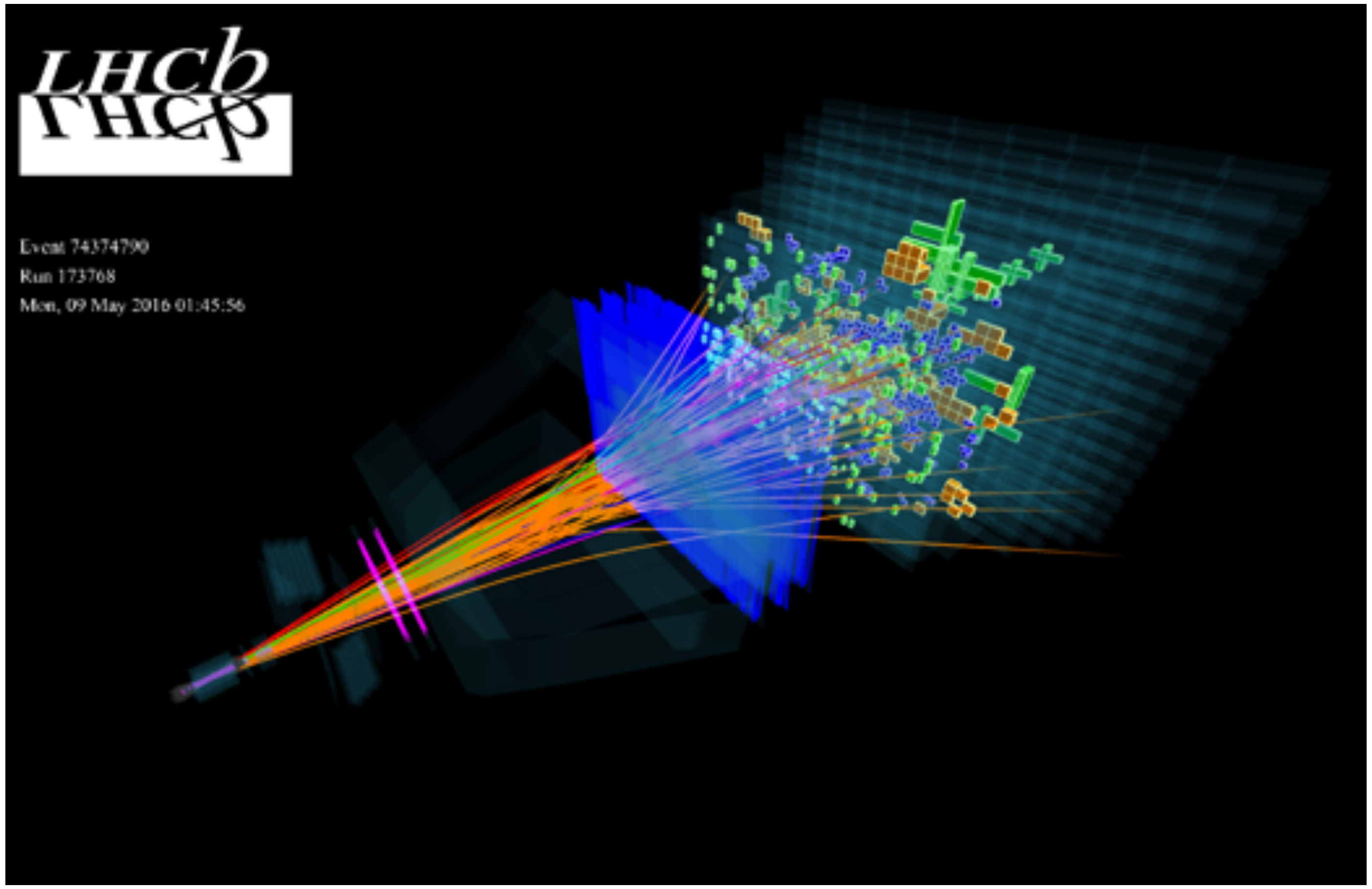


$m_{jj} = 7.7\text{TeV}$!

Dave Newbold, U. Bristol
IPPP Annual Theory Meeting

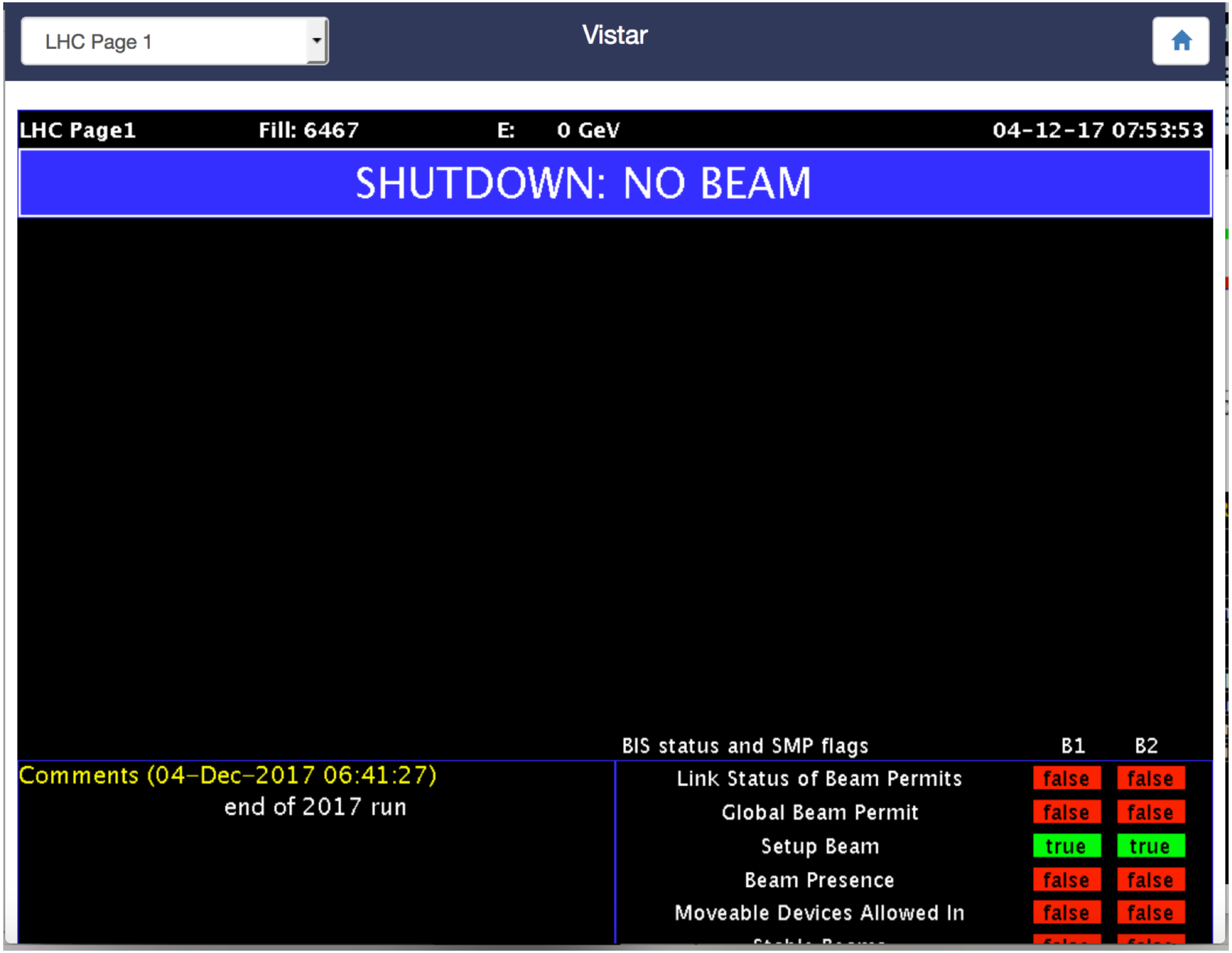
Outline

- Outline:
  - LHC status
  - The experimental challenge
  - Higgs physics
  - Standard Model (briefly)
  - SUSY & Dark Matter
  - Flavour (super-briefly)
  - LHC upgrades
  - The future



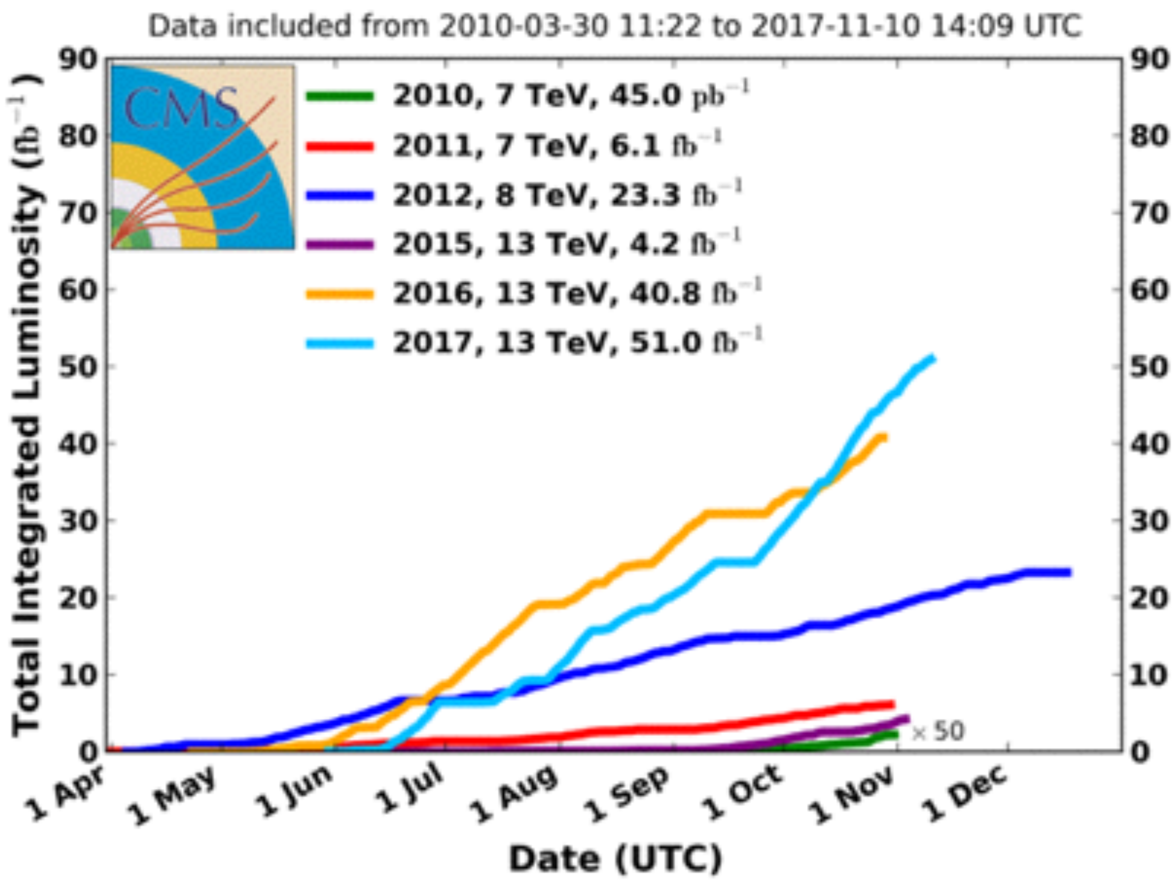
- Executive summary:
  - The Higgs is still there, but no signs of new physics yet…
  - … though a few developing hints, and some new places to look
  - … but only 3% of the final dataset collected!
  - Life is hard for experimentalists, and getting harder
  - Lots of new ideas in play – keep thinking!

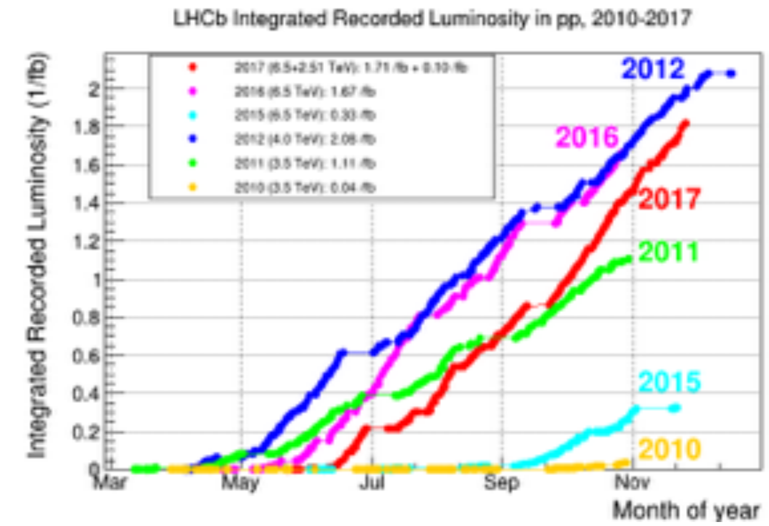
Current LHC Status: OFF

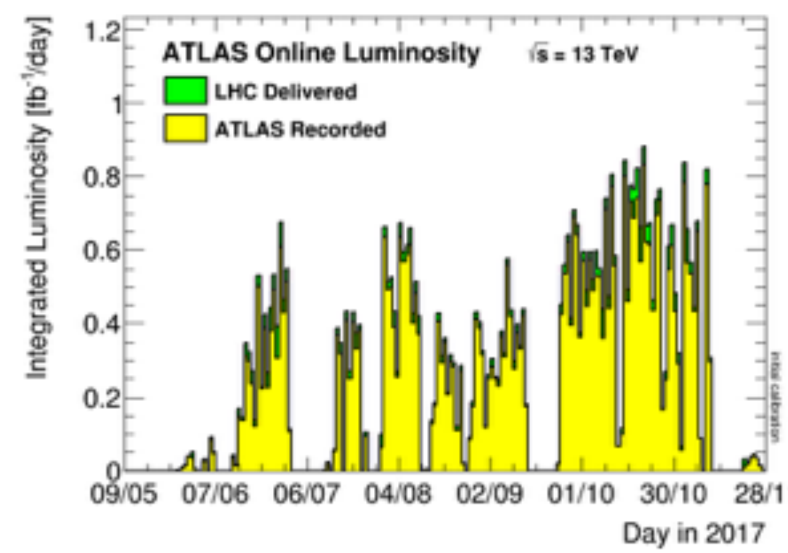


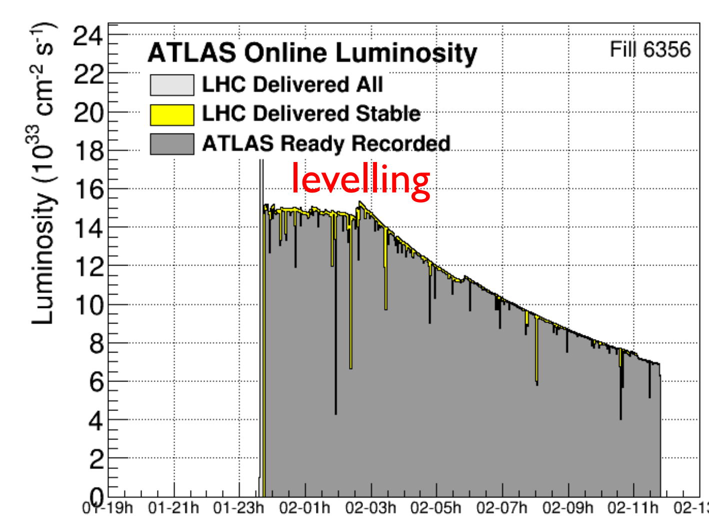
LHC Performance

100 / fb per GPD achieved!



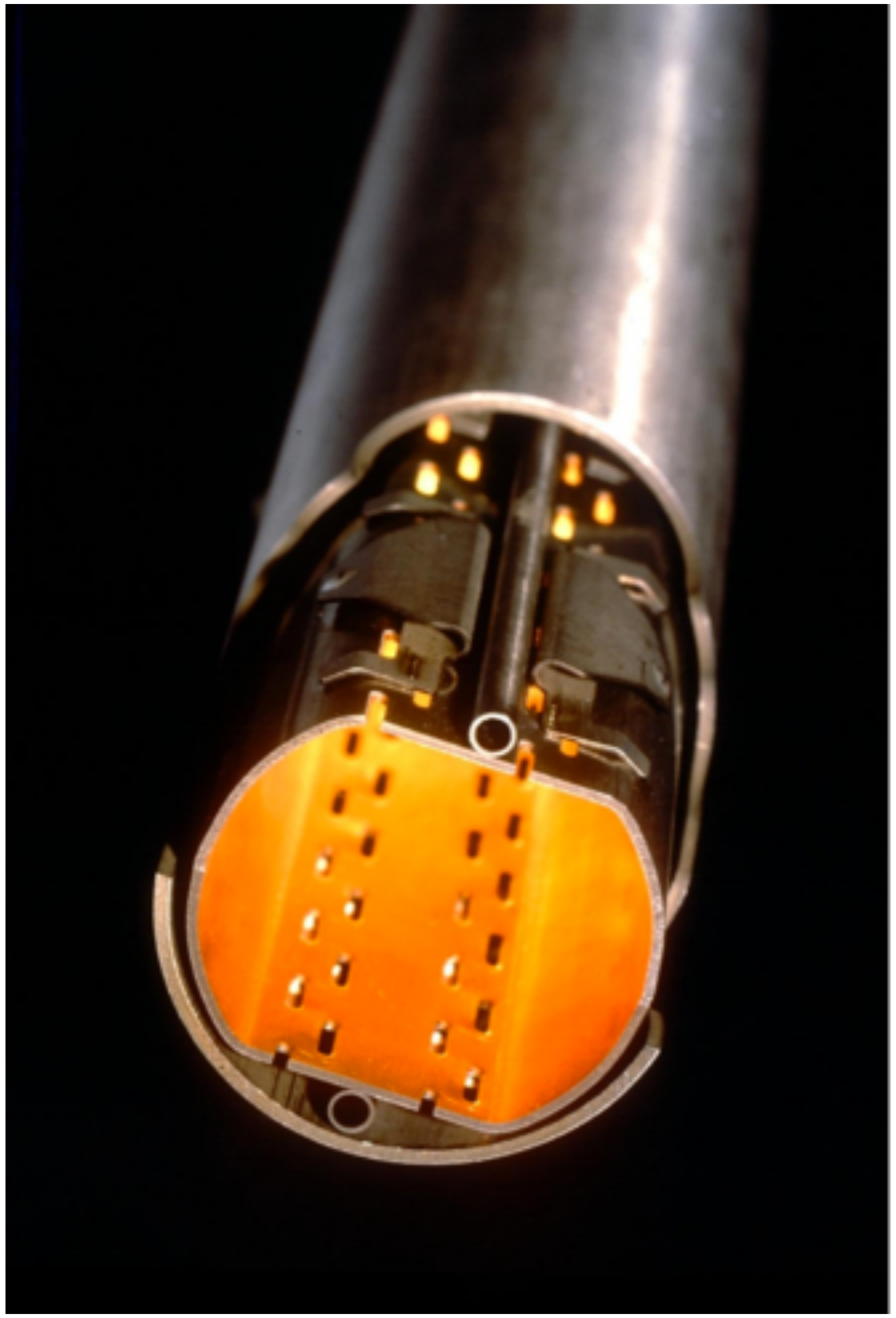


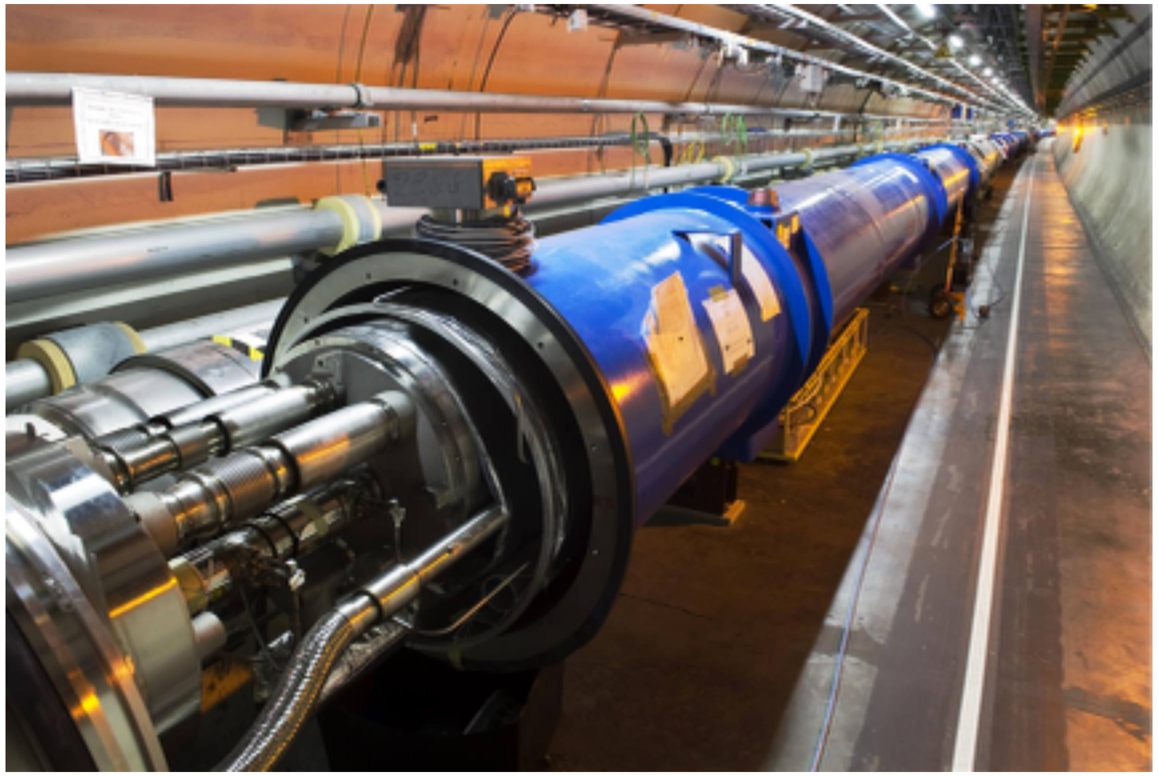




- We are in 13TeV 'production physics': luminosity is all!
  - Though not everything has been smooth…

Operational Challenges in 2017



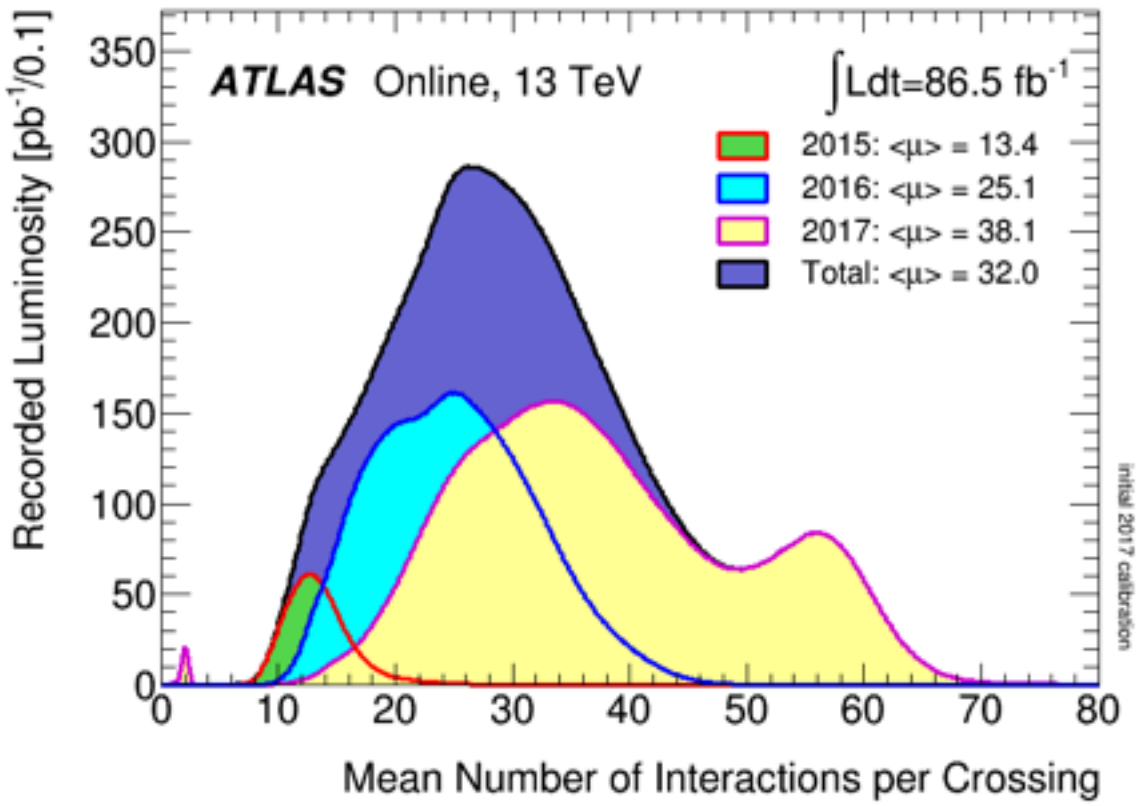


- Snow at 16L2: ‘flakes’ of frozen magnetic N_2, O_2

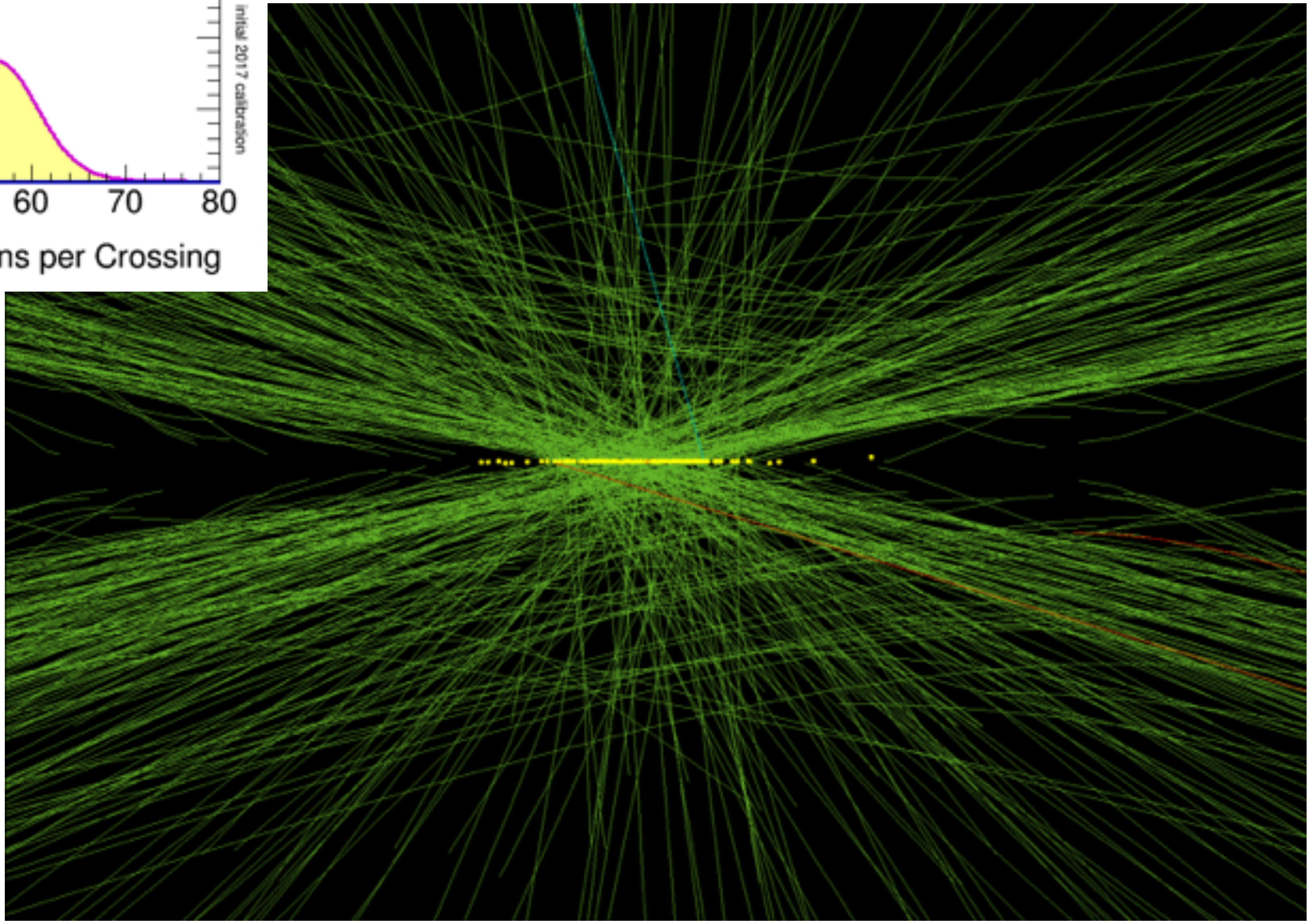
Physics Challenges at the LHC

- Some generalisations about LHC physics
- The 'energy frontier': CMS and ATLAS
  - Physics is 'dirty', deal with inclusive channels
    - Often, events are not even fully reconstructed (MET…)
  - Most things are invisible beneath huge QCD background
    - Both correlated (light quark jets swamp everything) and uncorrelated (pile-up)
  - Statistics is everything, since detector systematics are 'irreducible'
    - All systematics estimates and controls need to be data-driven
    - As event sample grows, find rarer-but-cleaner ways to access physics
- The 'precision frontier': LHCb
  - Physics is 'clean', usually deal with exclusive channels
  - Flavour ID is possible, everything is (mostly) reconstructed
  - QCD is your friend (b cross-section) and your enemy (QCD pollution)
  - Statistics are sacrificed for experimental precision

Pile-Up

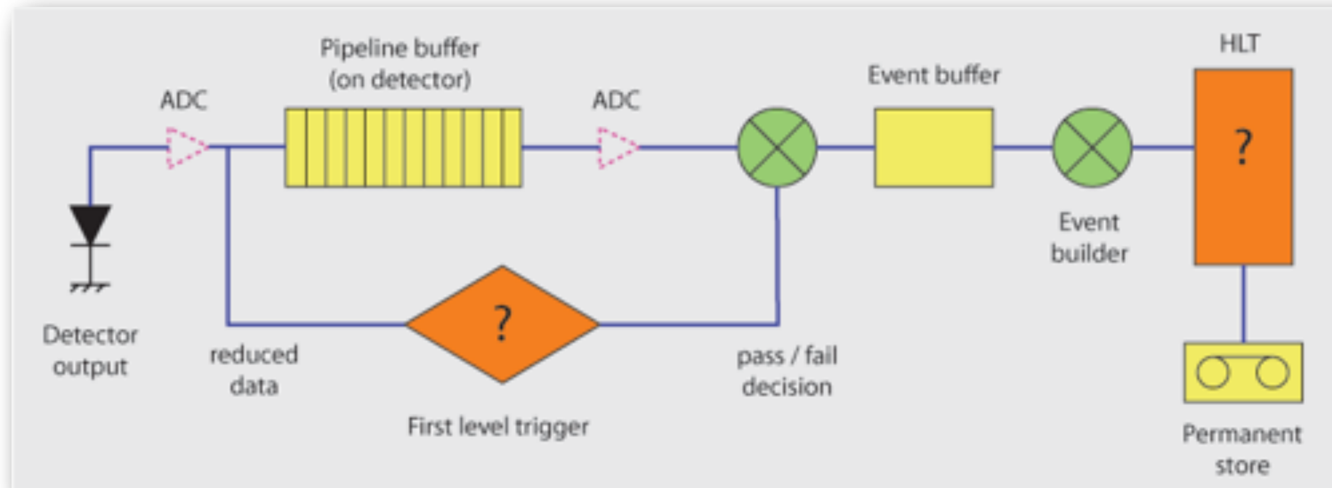


$n_{PV}=78$



Q: How Long Does an LHC Analysis Take?

- "Far too long; years and years" — A. Theorist
- A: About 1μs
  - All events for offline analysis must pass the trigger



- How the trigger works:
  - Can't use tracking data
  - Reduce calo / muon data in spatial and E or p resolution
  - Stir for no more than ~μs in real time (data is waiting on detector)
  - Allow ~100kHz - 1MHz of crossings to pass, data is read out
  - Then throw away most of the rest in HLT: rate to storage: O(100Hz)
- What you can't have
  - Anything needing tracks: displaced vertex, flavour tag, etc
  - Vertex association; electron/photon ID; invariant mass; complex event shape vars
- Triggering is the #1 problem at LHC, and getting harder
  - Though there are new ideas; more on this later

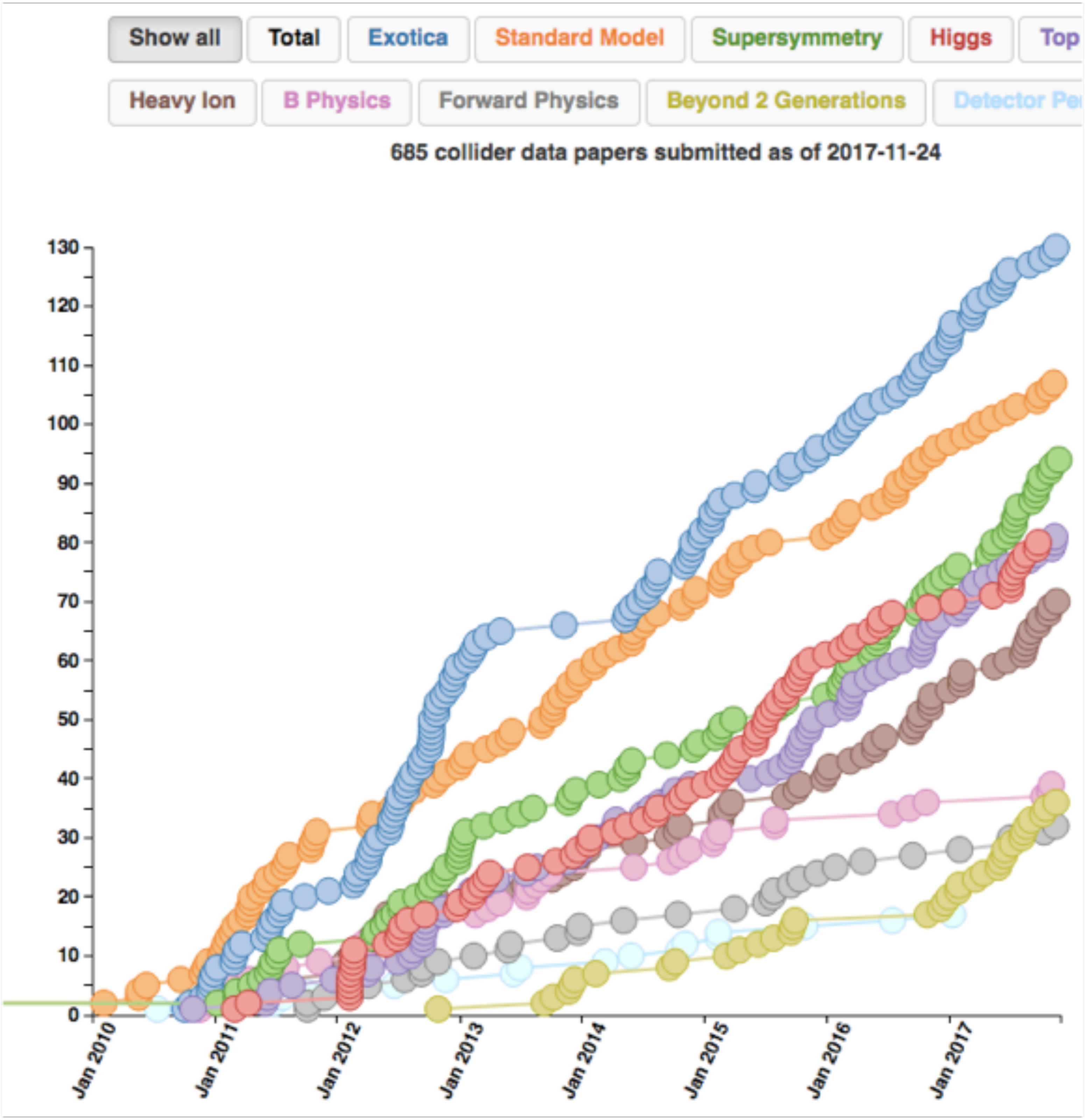
The Challenge of Presentation

- Experimentalists' problems
  - Models are often complex with large-dimensional parameter space (classic example: SUSY)
  - Experiments integrate over phase space, badly
  - Phenomenology can wildly from point to point
  - What do we actually measure? Depends who you ask!

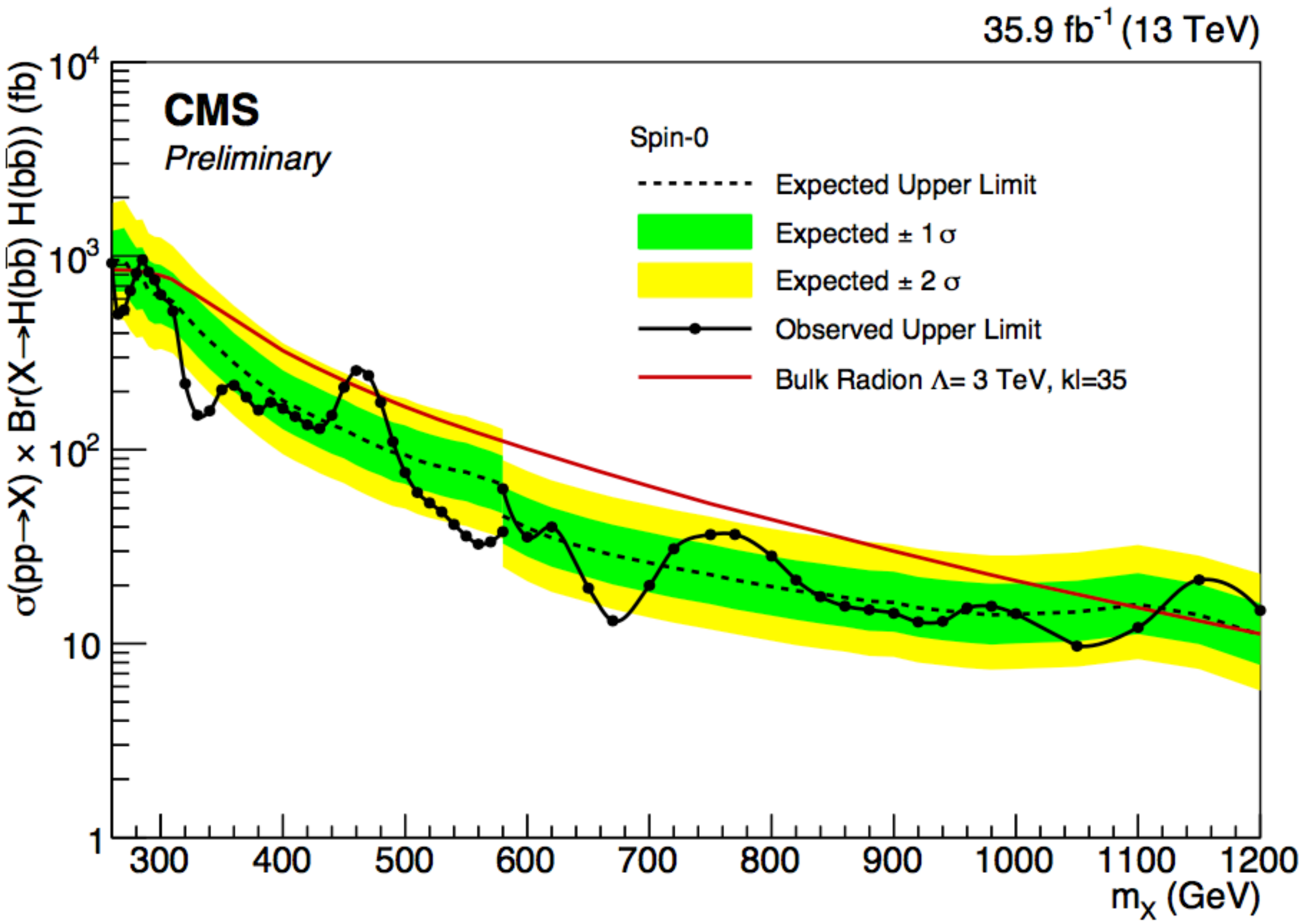
- Presentation of results
  - Back in 2012 it was easy ("five sigma", mass limits, etc)
  - More difficult now to report progress without being misinterpreted / misunderstood
  - What does a 'two sigma observation' mean anyway?
  - When to publish and when not to?

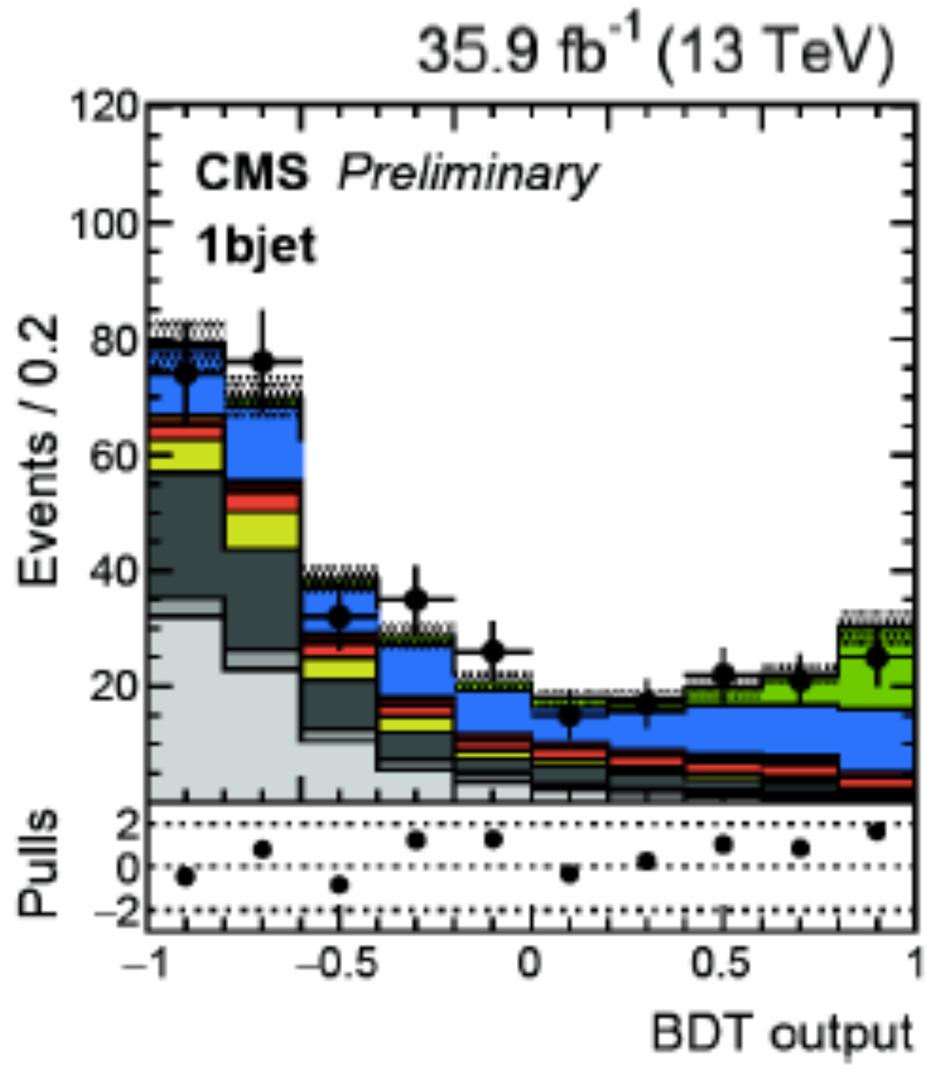
- Theorists' problems
  - What the hell do all these plots actually mean?
  - Insufficient information to allow proper interpretation
  - Hard to see the big picture in a sea of information / opinion

No Shortage of Results



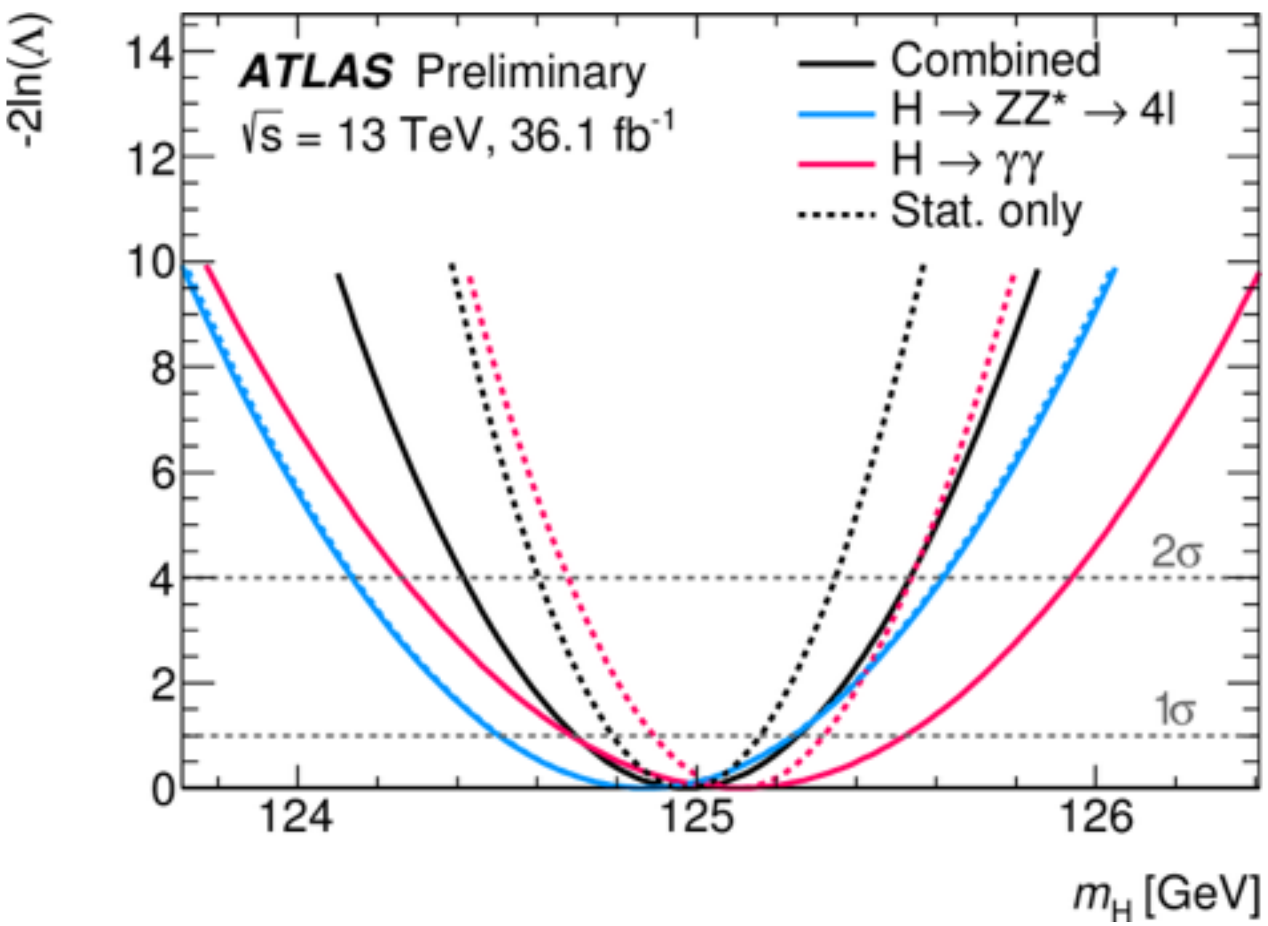
The Anatomy of a Plot

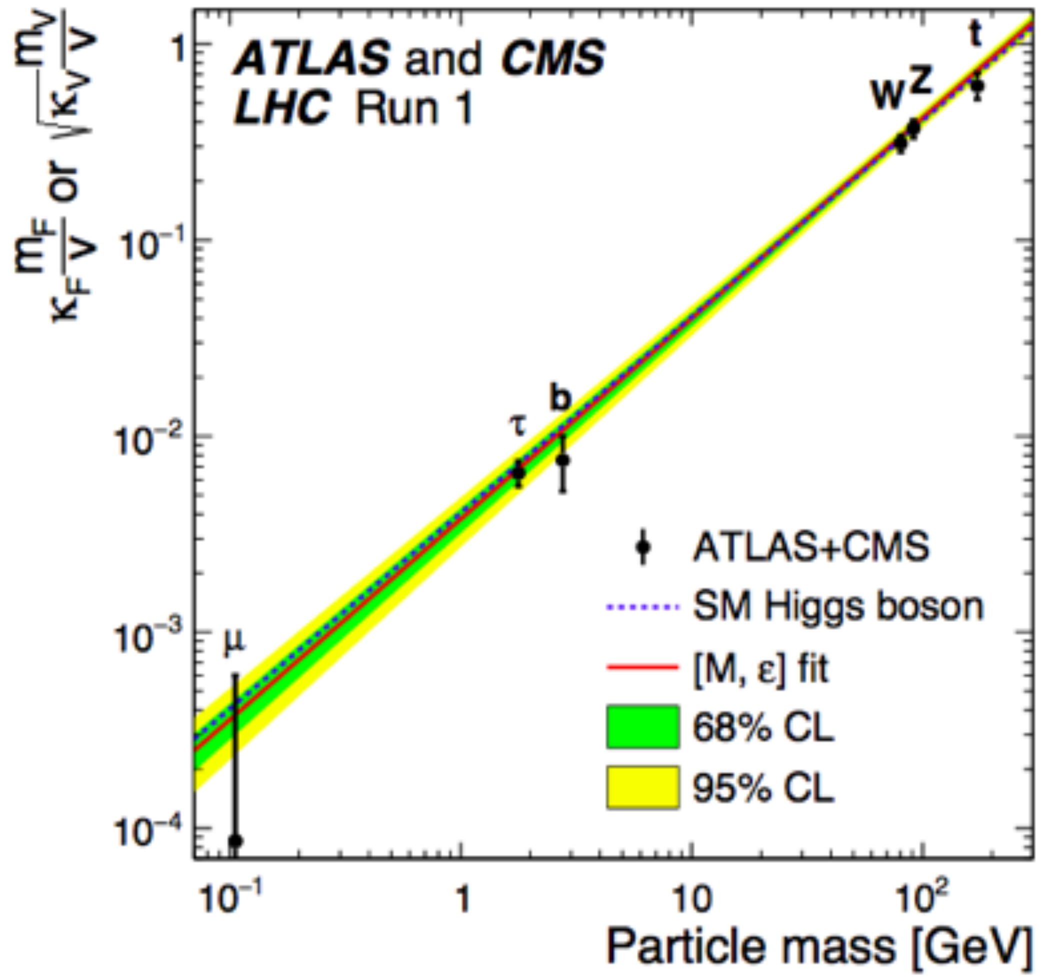




- ‘Brazil’ plots giving way to more complex beasts…
  - Note that the points on these plots are *all correlated*
  - When people talk about ‘global’ significance, they are talking about *within that analysis*
  - Many analyses ‘interpret’ the same events – and background estimates are correlated!
  - Combination between experiments is a subtle art
  - “If your result needs a statistician, you should design a better experiment” — Rutherford

Higgs Physics

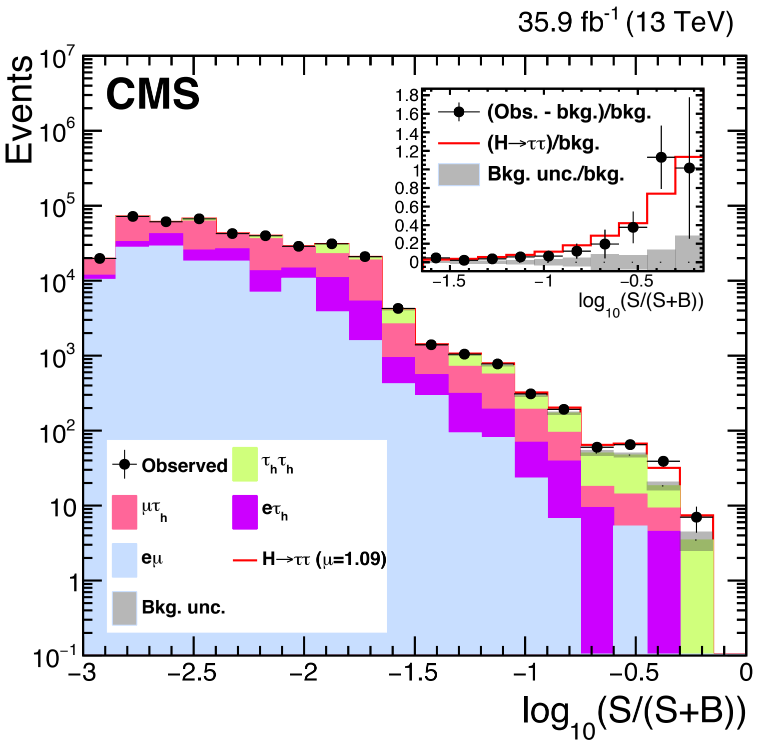


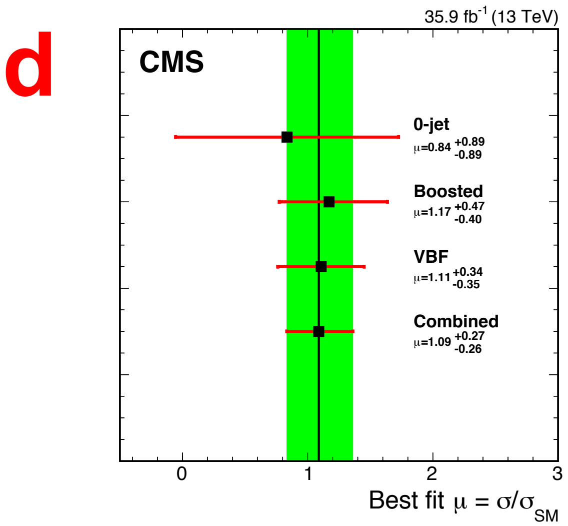


- It's still there… so what is it?
- Detailed measurements of couplings (and more) will tell us
  - Thanks to Paris Sphicas for beautiful summary slides…

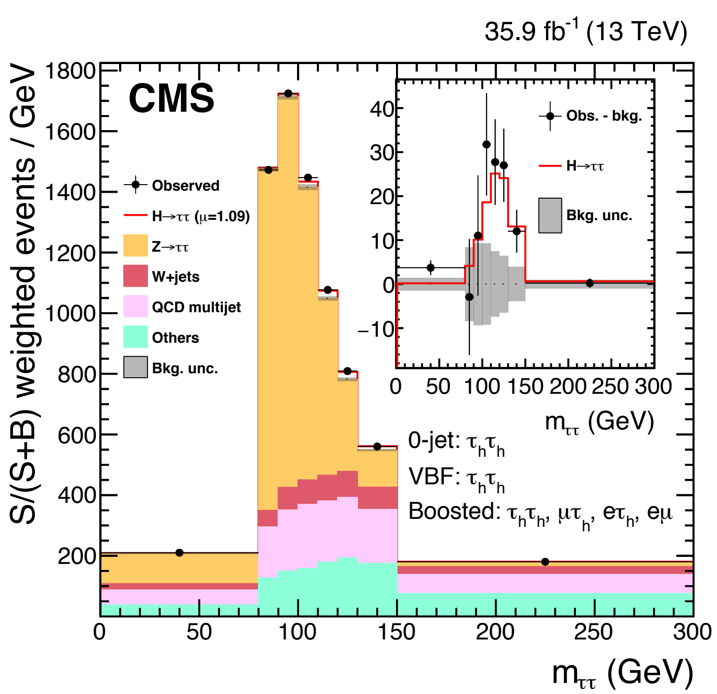
3rd Generation Fermions

$H \rightarrow \tau\tau$: established



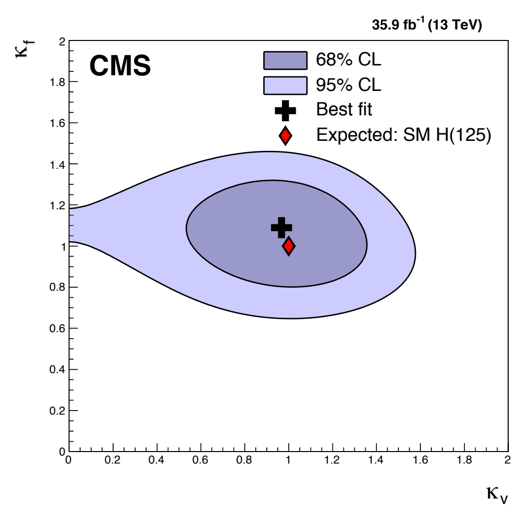


$$\mu = 1.09^{+0.27}_{-0.26} \quad (4.9\sigma)$$

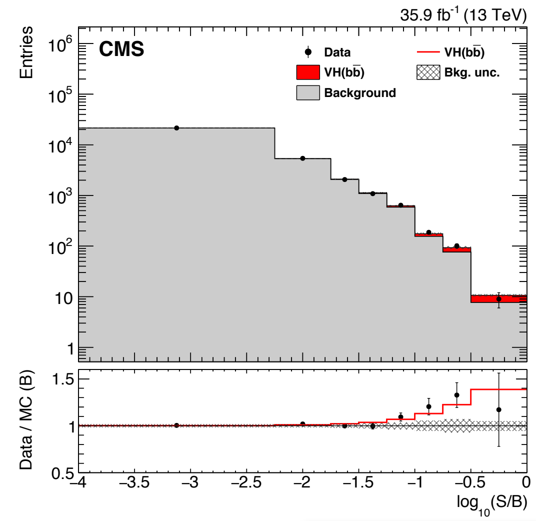


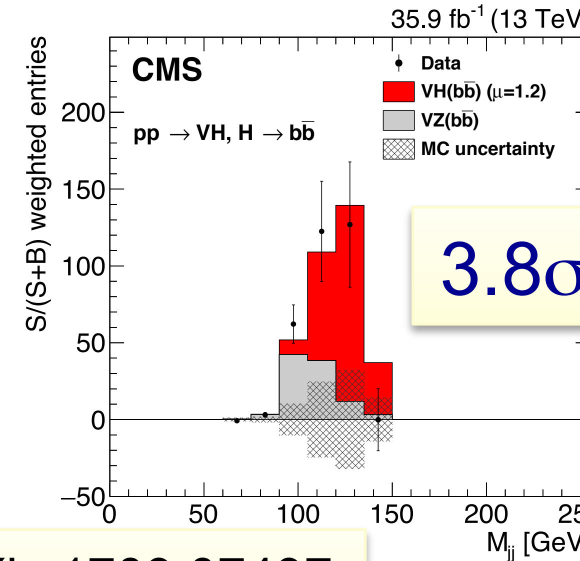
Comb. 7+8+13 TeV:

$$\mu = 0.98 \pm 0.18 \quad (5.9\sigma)$$



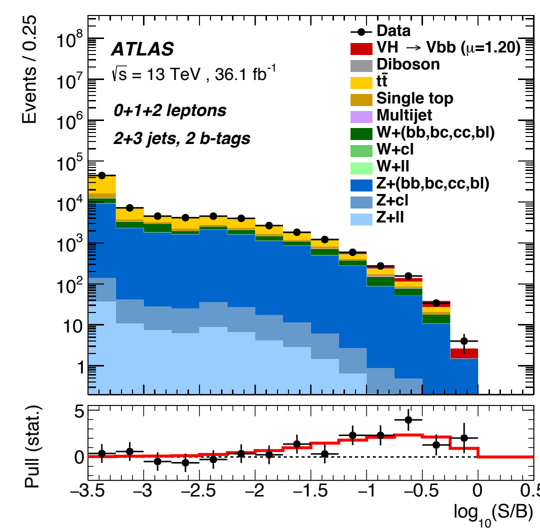
$H \rightarrow bb$: evidence ($>3\sigma$)

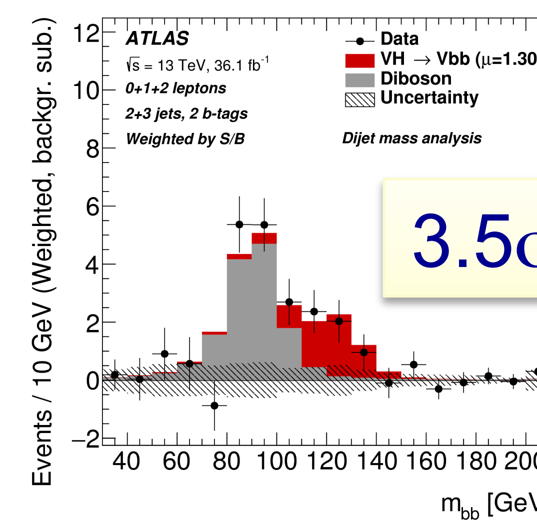




3.8σ

CMS arXiv:1709.07497





3.5σ

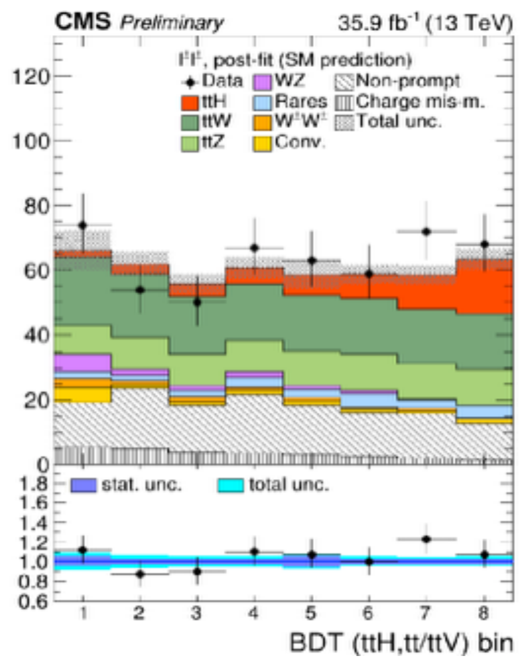
ATLAS arXiv:1708.03299

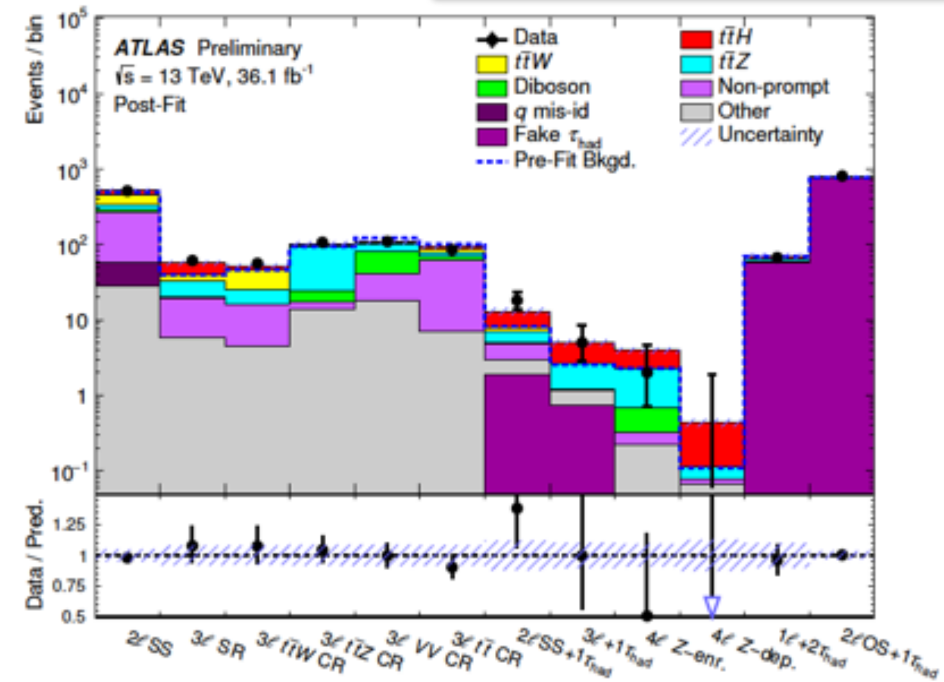
Top

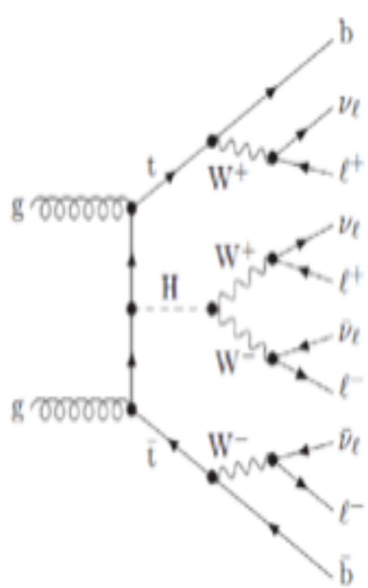
- **Coupling to the top quark (special: $y_t \approx 1$)**

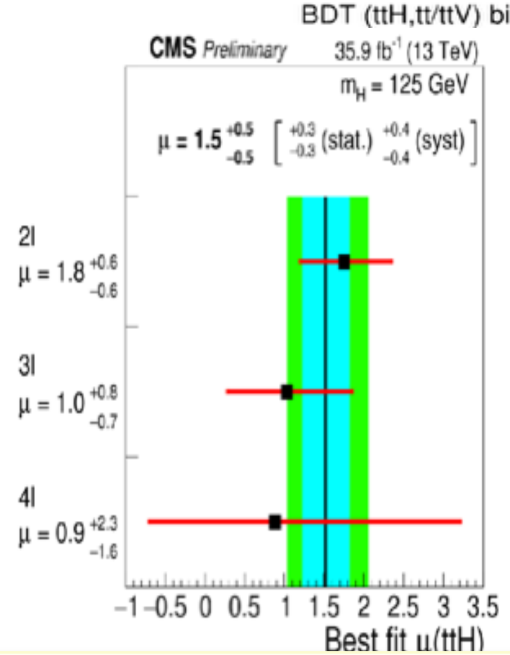
H-t coupling: ttH production elusive (~1% of ggH)

Most recently: update (ATLAS)

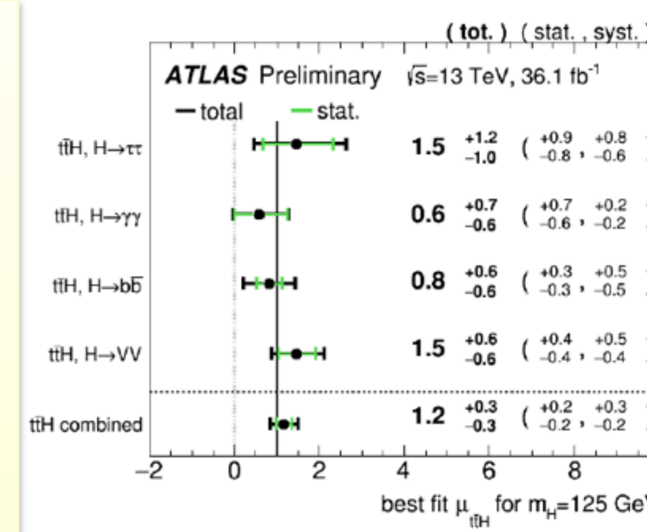








Combination of four channels (ATLAS)
Obs: 4.2 σ;
Exp: 3.8 σ



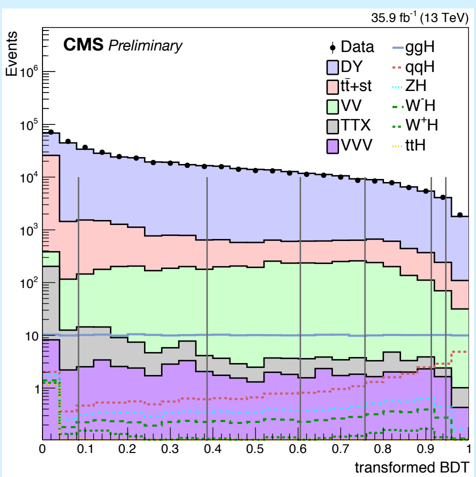
Main channels:
H→bb & H→WW;

@EPS: CMS: 3.3 σ (2.5 exp)

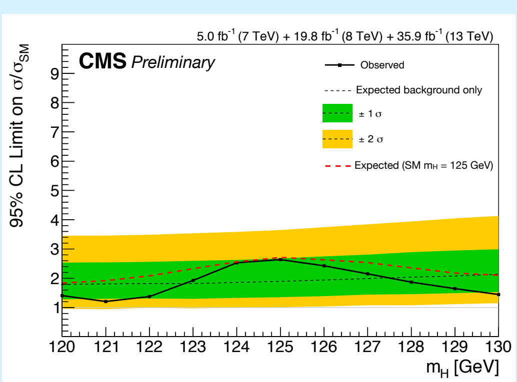
2nd Generation Fermions

H→μμ within LHC reach; now only a question of when

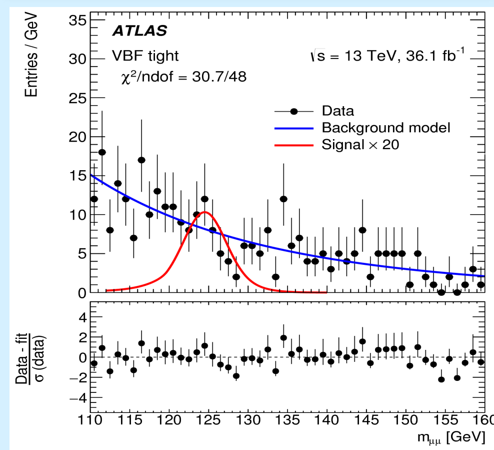
Huge DY bkg



CMS-HIG-17-019



ATLAS 1705.04582

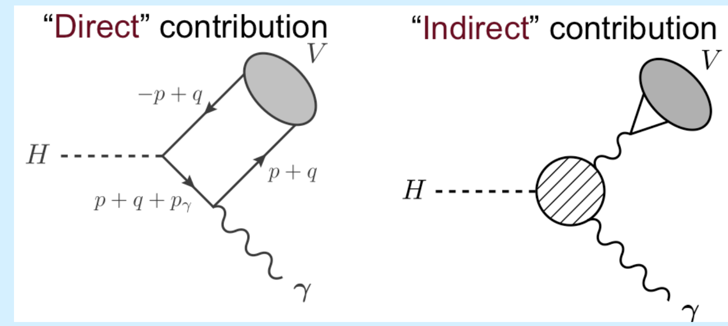


$\mu < 2.8$ (2.9 exp)

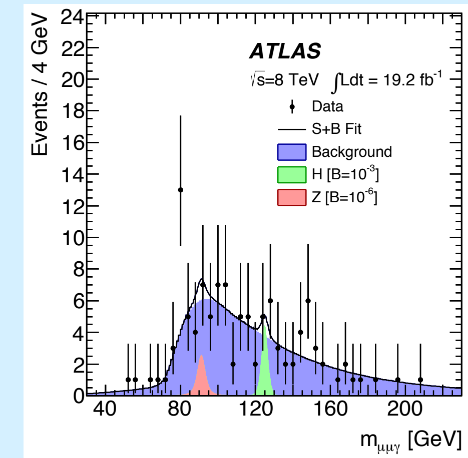
$\mu<2.64$ (1.89 exp)
Sig: 0.98σ (1.09σ)
$\mu=0.9+1.0-0.9$

0.3ab^{-1}: 2.3σ/expt

H–c coupling: H→J/ψγ

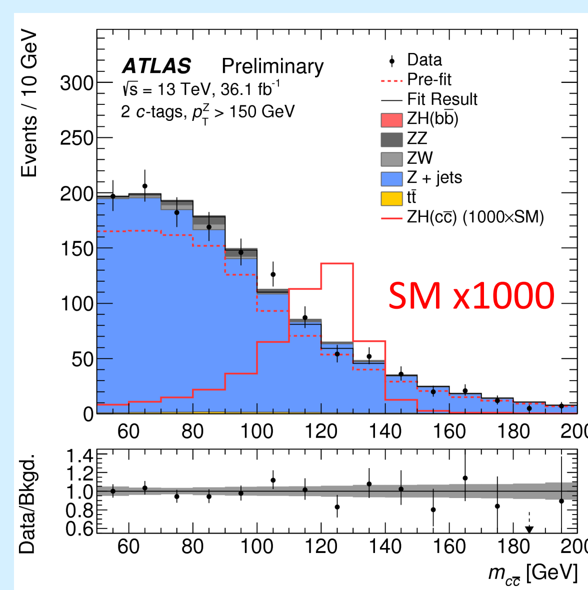


$$\left|(11.9 \pm 0.2) - (1.04 \pm 0.14)\kappa_c\right|^2 \times 10^{-10}\ \text{GeV}$$



arXiv:1501.03276

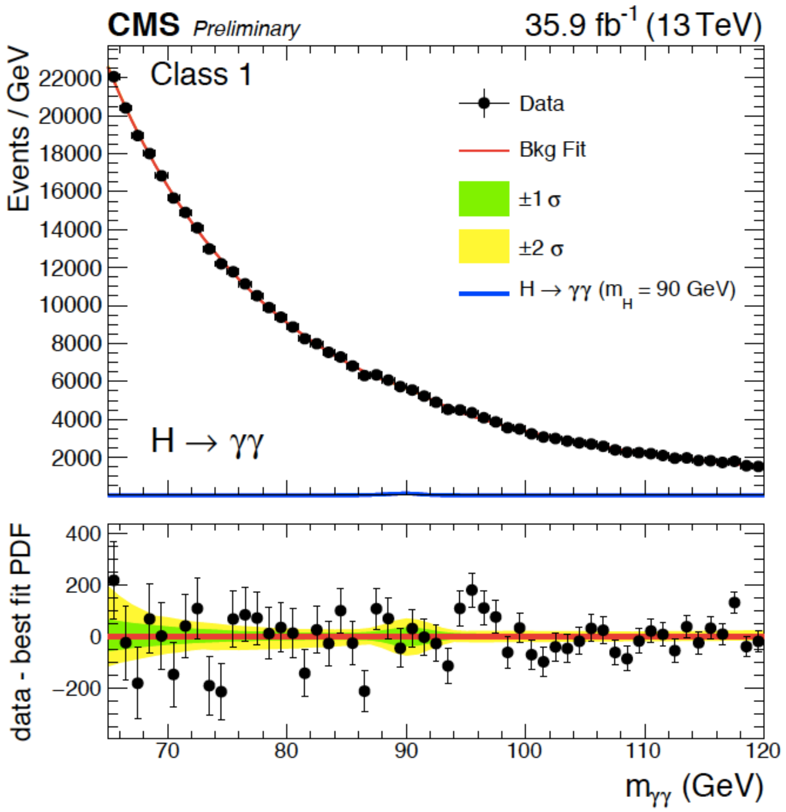
H–c coupling: H→cc (jets)

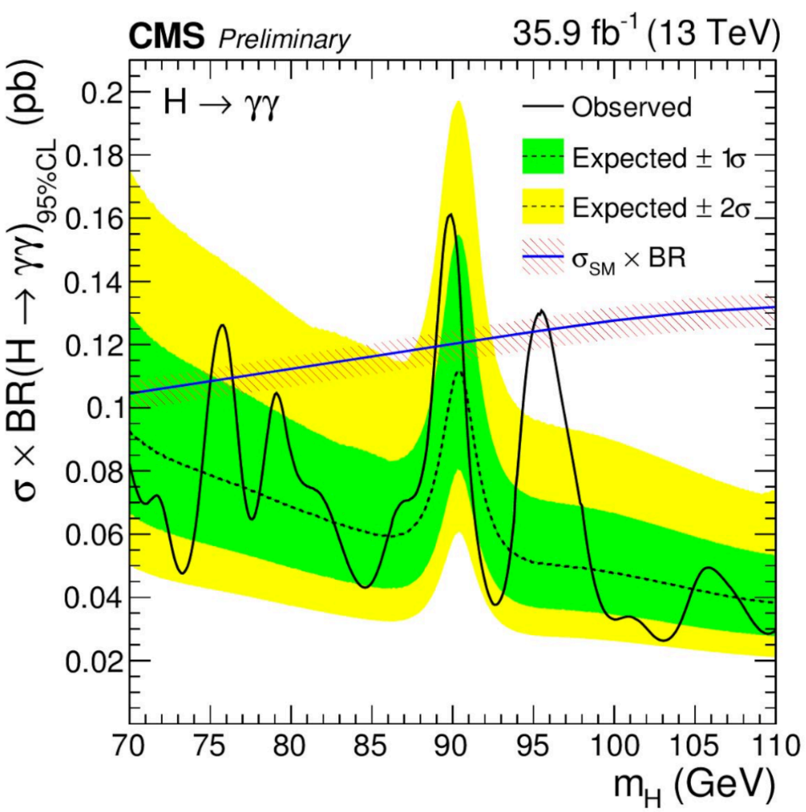


ATLAS-CONF-2017-078

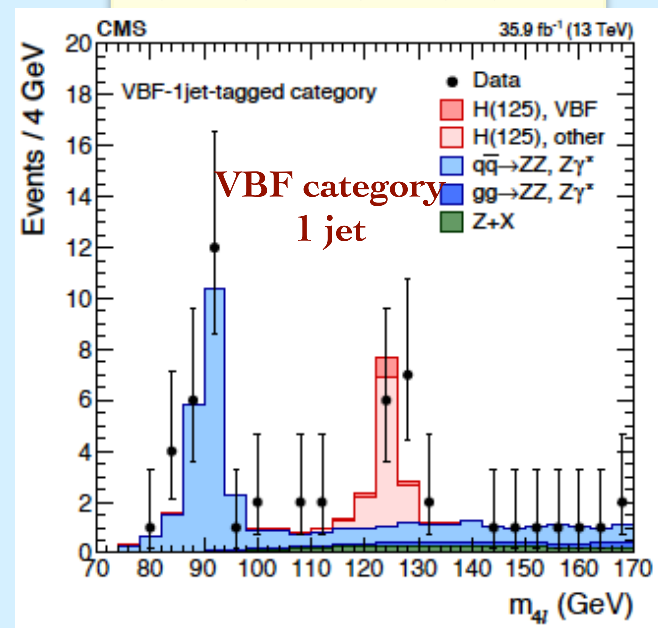
$\sigma(VH)B(H\to cc)$ <2.7pb (3.9pb exp)
SM: 25.5 fb (~10^2 times smaller)

Exploiting Increasing Stats

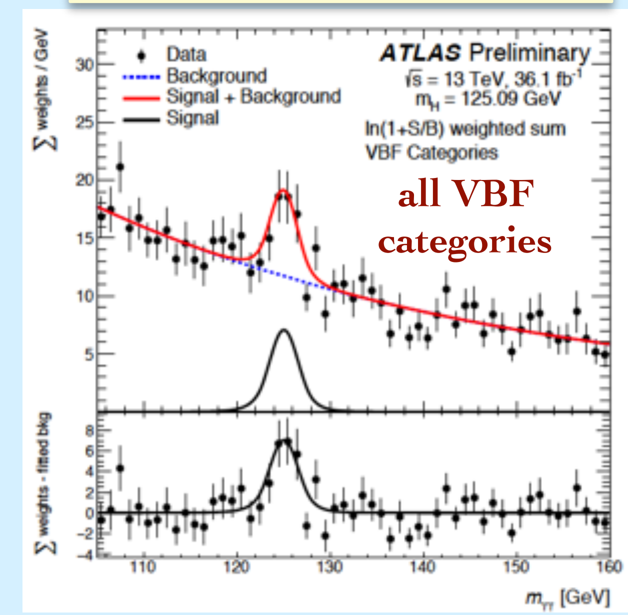




CMS-HIG-16-041



ATLAS 1708.03299

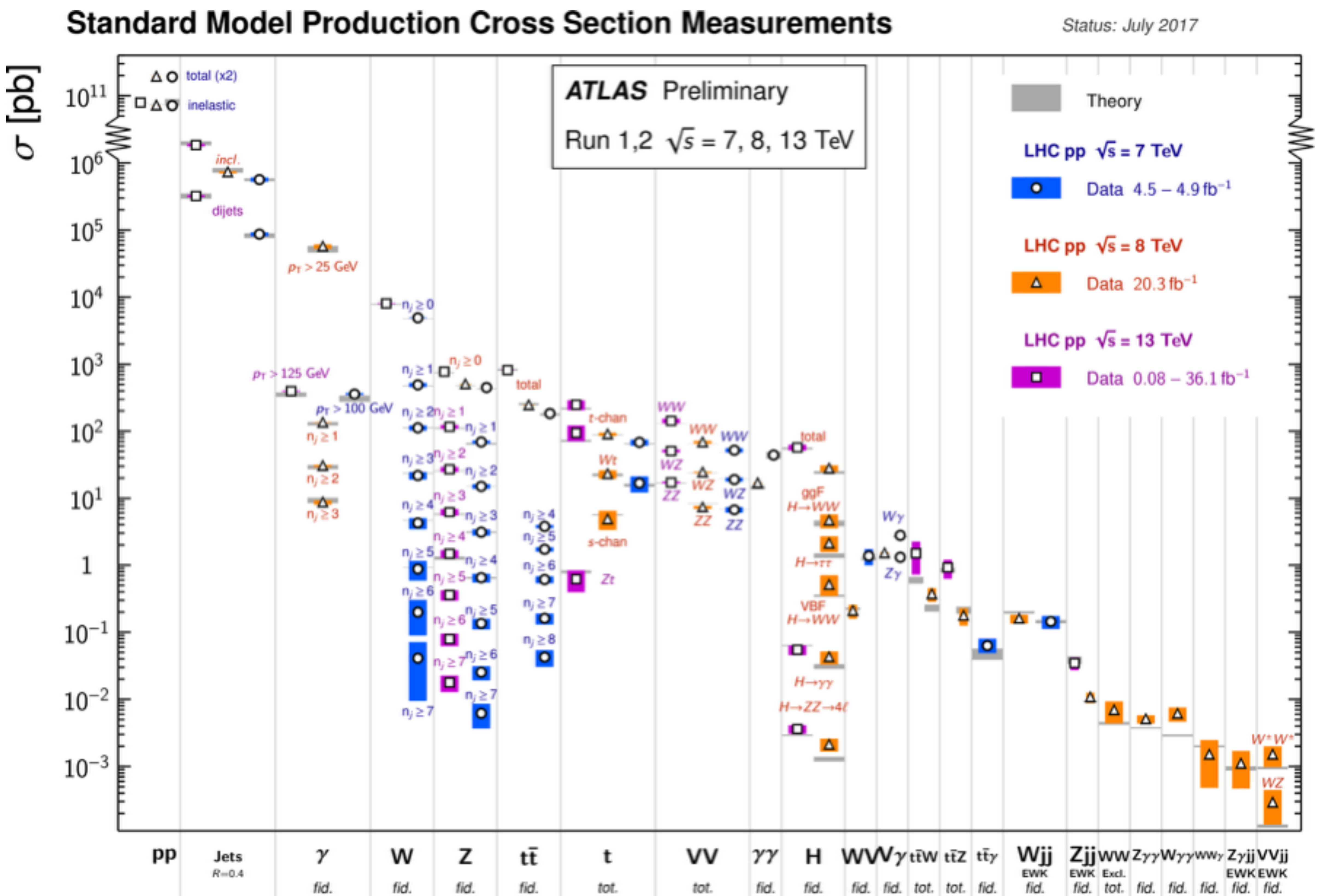


σ/σ_{SM}=1.2±0.2

VBF clearly seen

- Exclusive VBF production now in play
  - Future potential for H width measurement
- ‘Gaps’ in low mass Higgs search fill up
  - Mainly due to trigger algorithm improvements

Standard Model

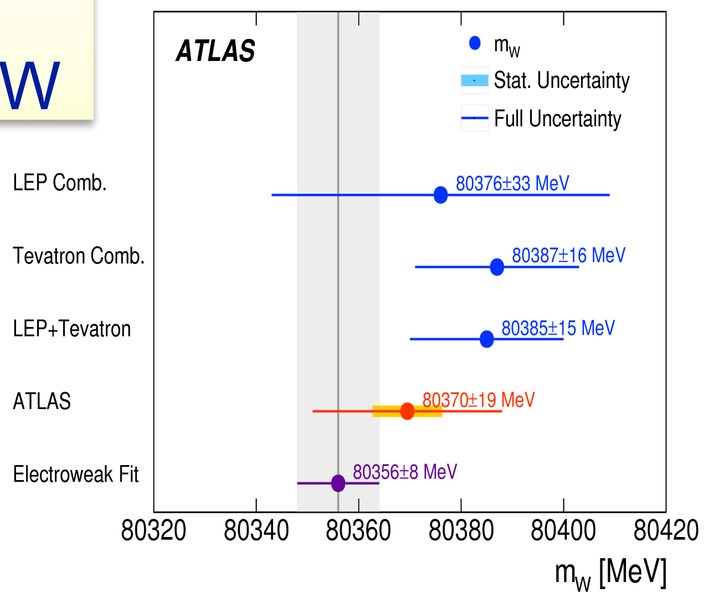


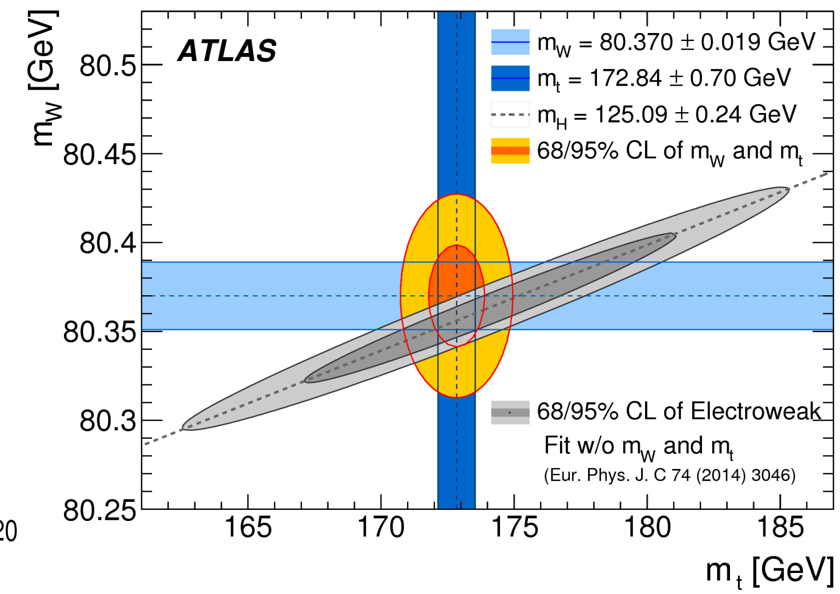
 IPPP Annual Meeting, 20th Dec 2017 Dave.Newbold@cern.ch

Rutherford Appleton Laboratory · University of BRISTOL

Standard Model 'Precision' Measurements

m_W





So what next?
Theory errors:

$M_W = 80.358 \pm 0.008$ GeV

$M_t = 177.0 + 2.3 - 2.4$ GeV

$\Delta m_t^{exp} < \Delta m_t^{the}$

→ Experiment: more work on m_W needed!

m_t

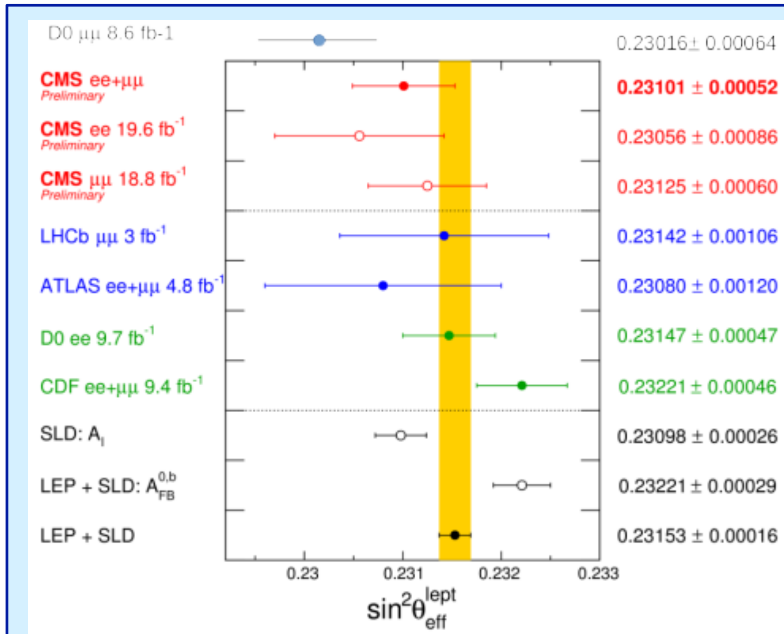
ATLAS and CMS in good agreement:

- $m_t^{\text{ATLAS}} = 172.84 \pm 0.70$ GeV
- $m_t^{\text{CMS}} = 172.44 \pm 0.48$ GeV

Some tension with Tevatron average:

$m_t^{\text{Tev}} = 174.30 \pm 0.65$ GeV

Caveat:
m^{pole} vs "m^{MC}" &
$O(\Lambda_{QCD})$ effects



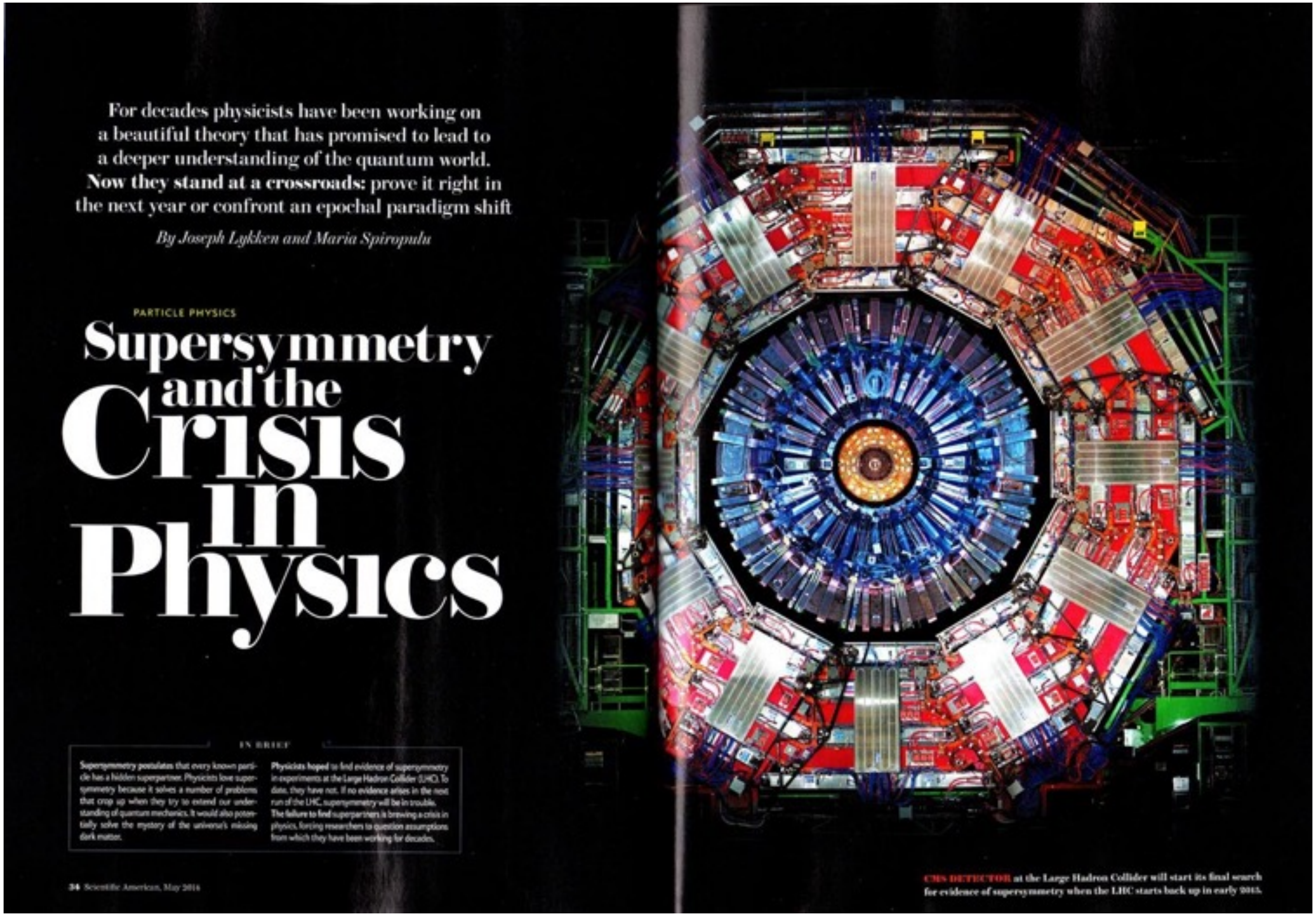
$\pm\ 0.00052$

$\sin^2\theta_W$

No match, but surprisingly good (and no discrep…)

± 0.00016

SUSY


For decades physicists have been working on a beautiful theory that has promised to lead to a deeper understanding of the quantum world. **Now they stand at a crossroads:** prove it right in the next year or confront an epochal paradigm shift

By Joseph Lykken and Maria Spiropulu

PARTICLE PHYSICS

Supersymmetry and the Crisis in Physics

IN BRIEF

Supersymmetry postulates that every known particle has a hidden superpartner. Physicists love supersymmetry because it solves a number of problems that crop up when they try to extend our understanding of quantum mechanics. It would also potentially solve the mystery of the universe's missing dark matter.

Physicists hoped to find evidence of supersymmetry in experiments at the Large Hadron Collider (LHC). To date, they have not. If no evidence arises in the next run of the LHC, supersymmetry will be in trouble. **The failure to find** superpartners is brewing a crisis in physics, forcing researchers to question assumptions from which they have been working for decades.

34 Scientific American, May 2014

CMS DETECTOR at the Large Hadron Collider will start its final search for evidence of supersymmetry when the LHC starts back up in early 2015.

Published 2014…

- SUSY was meant to be easy… what happened?

A Lesson from History

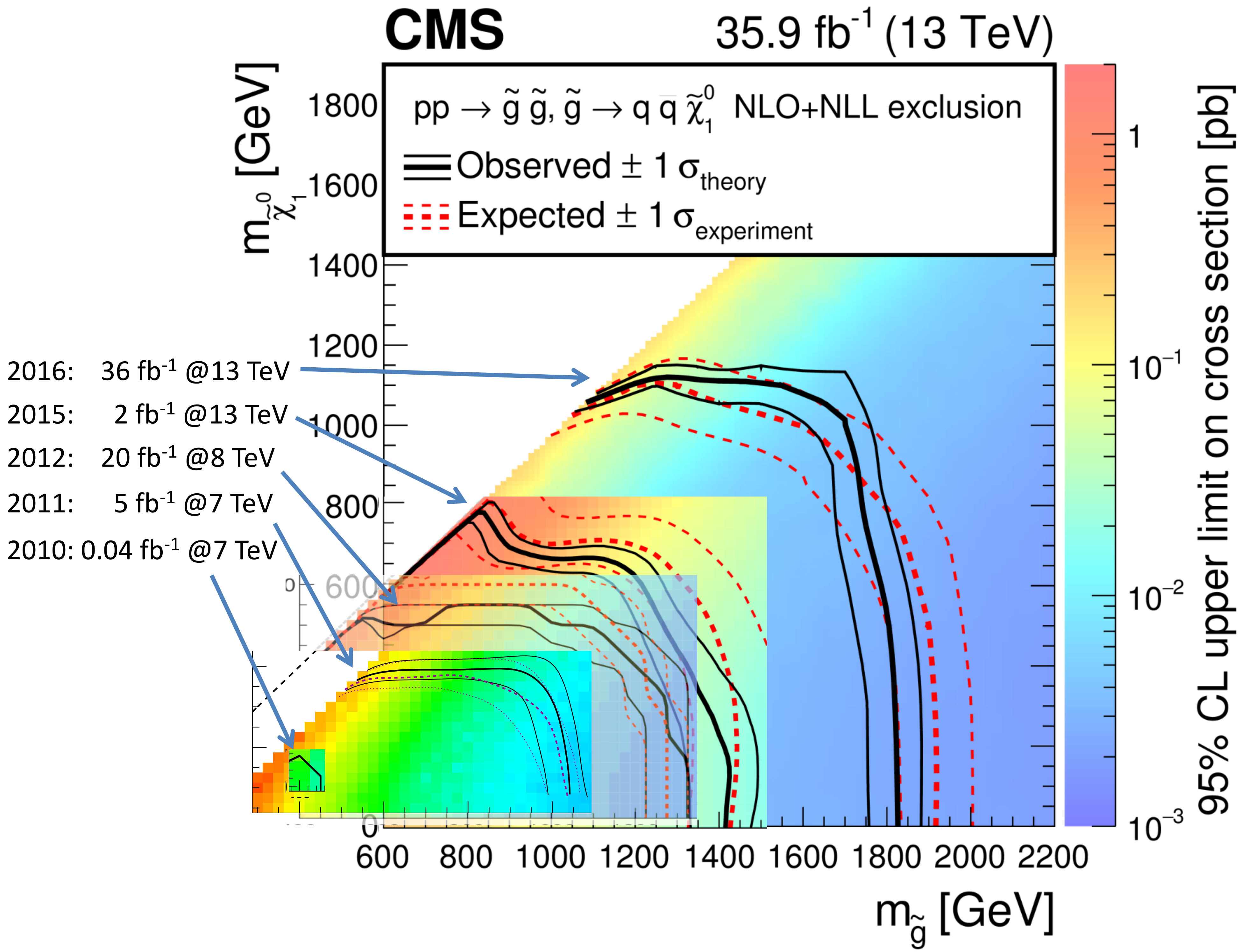
Yes & No	Yes	No	Abstain
Marius Gaudesius	MAKEENKO	G. 't Hooft *)	Neuberger
	Stelle	Z. Komargodski	Kirnan
	SHIH	A. JENKINS	Jutta Geth
	D.O'Connell	P.H. Damgaard	
	Emil Bjerrum-Bohr	Alexander Kolberg	
	Klaus SPLITTORFF	Savvas Nesseris	
	[illegible]	Simon BADGER	
	Gianluca Grignani	KOSTYA ZAREMBO	
	[illegible] (WARNER)	Alberto Guffanti	
	Oliver Schlotterer	Holger Bech Nielsen	
	Yang Zhang	S. Caron-Huot	
	Hidehiko Shimada	Henrik [illegible]	
	[illegible]	Song He	
	Thomas Søndergaard	Kasper Larsen	

(See over.)

*) But both sides will claim victory

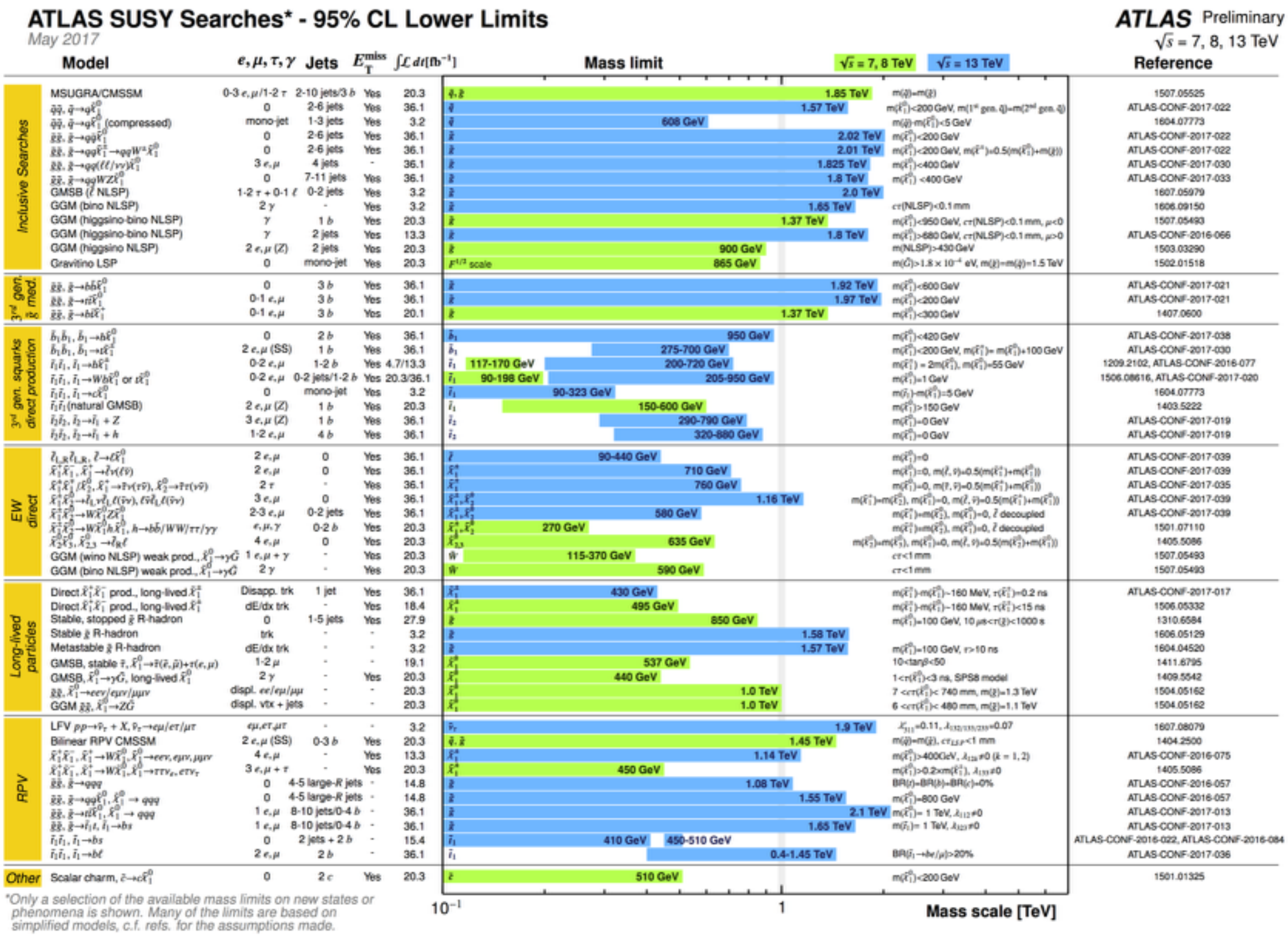
- Bet: SUSY discovery by 2016
  - (an amazingly poor choice of date)

Where are We?



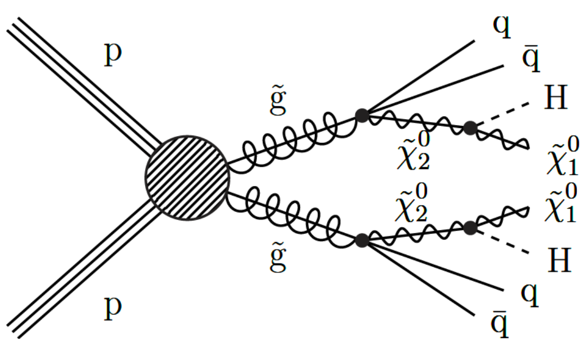
- ‘Classic’ CMS gluino mass limits for each run

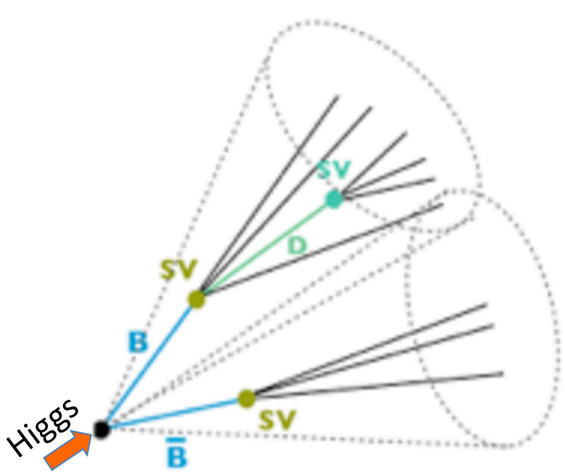
No Stone Unturned

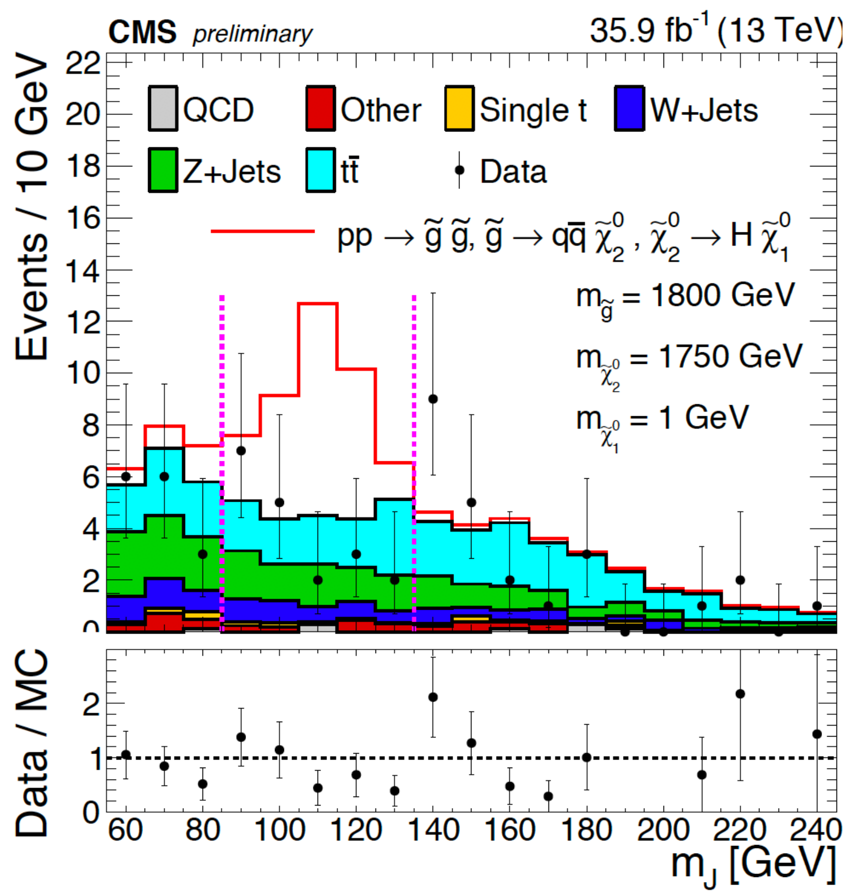


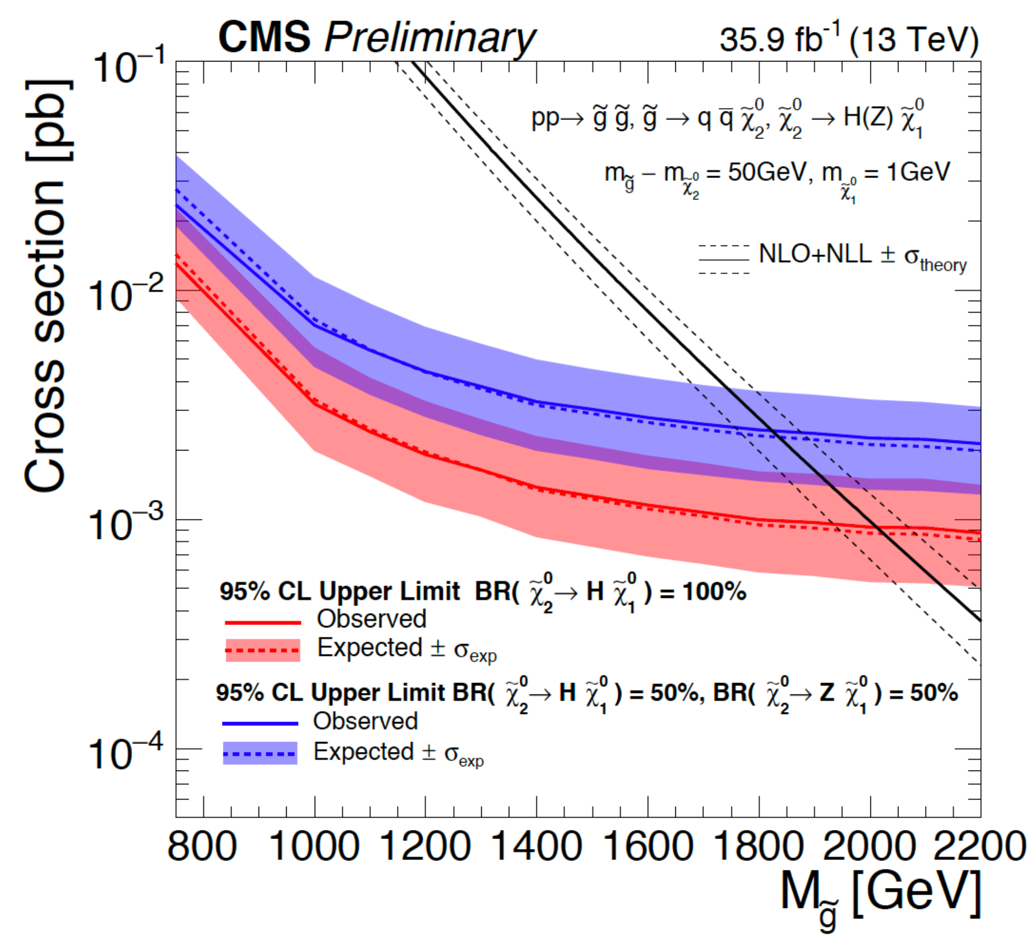
Corners and Cracks

- Possible ways forward:
  - Wait and see; perhaps with ‘more advanced’ reconstruction techniques
  - New signatures: long-lived particles; boosted final states
  - Hard-to-see places: compressed spectra; R-parity violating SUSY
  - Electroweak-produced SUSY
- Theory input surely needed here, more than anywhere

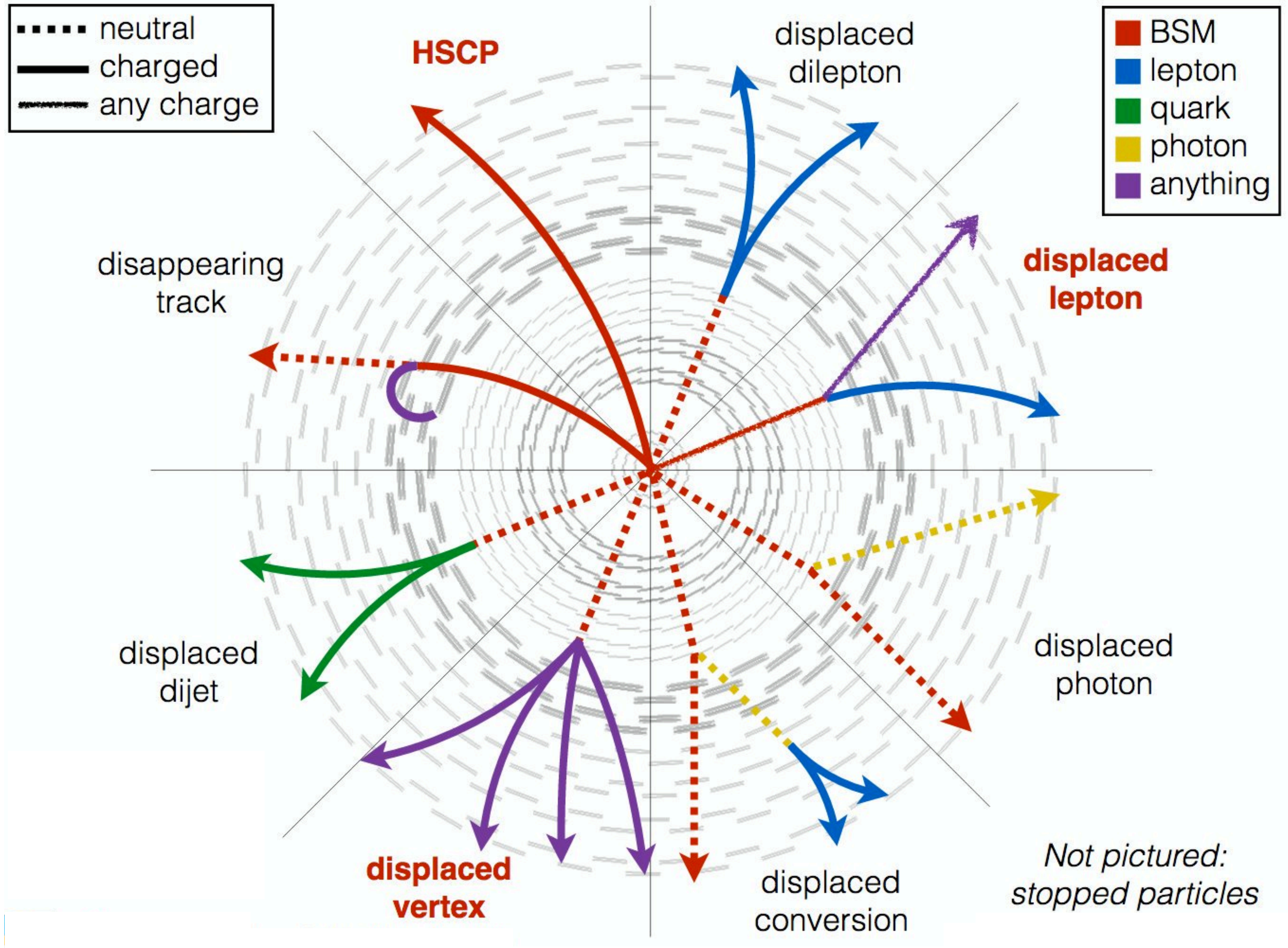






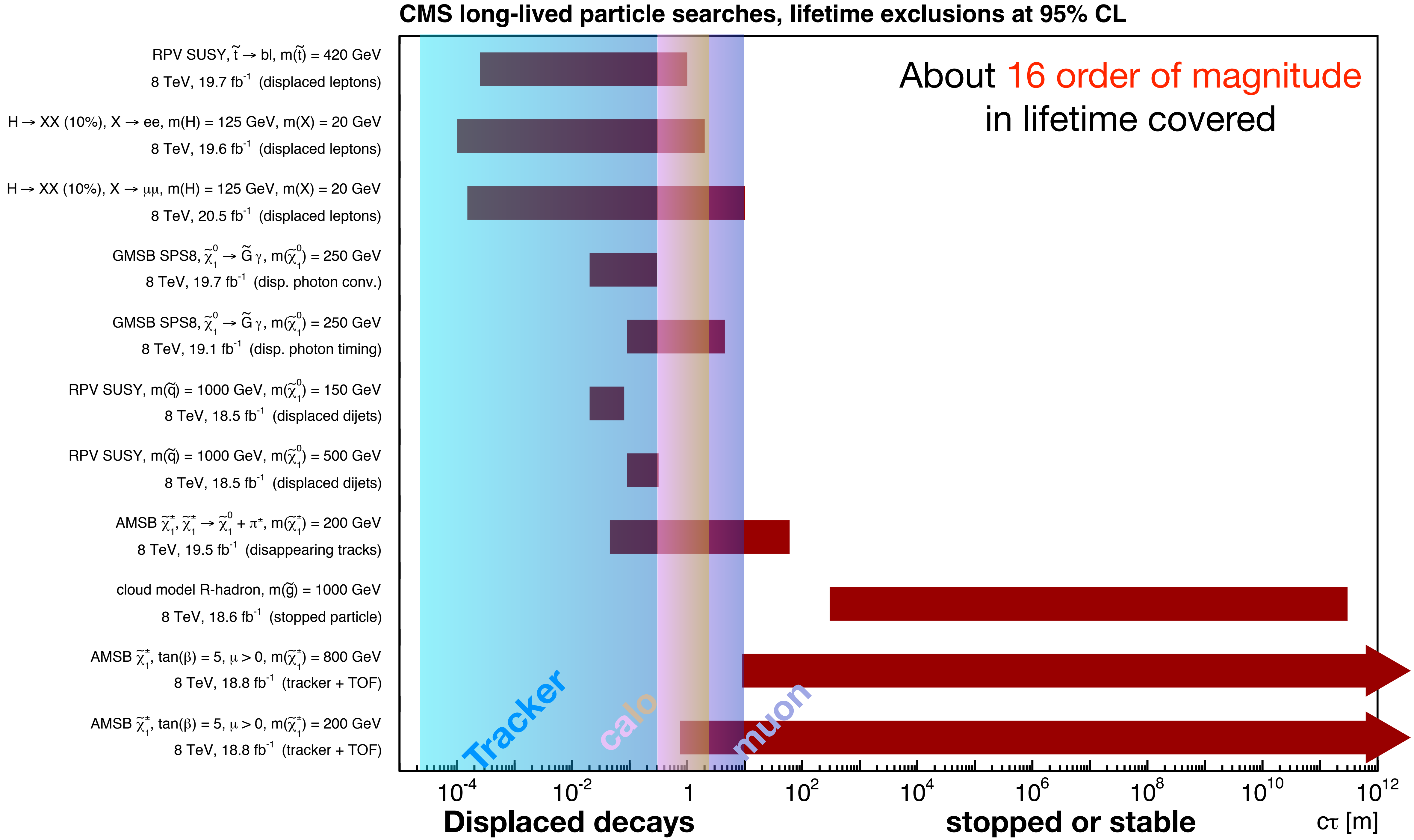


Long-Lived Particles



- *Generic* phenomenology for small couplings, small Δm
- Constraints on LLP parameter space from cosmology

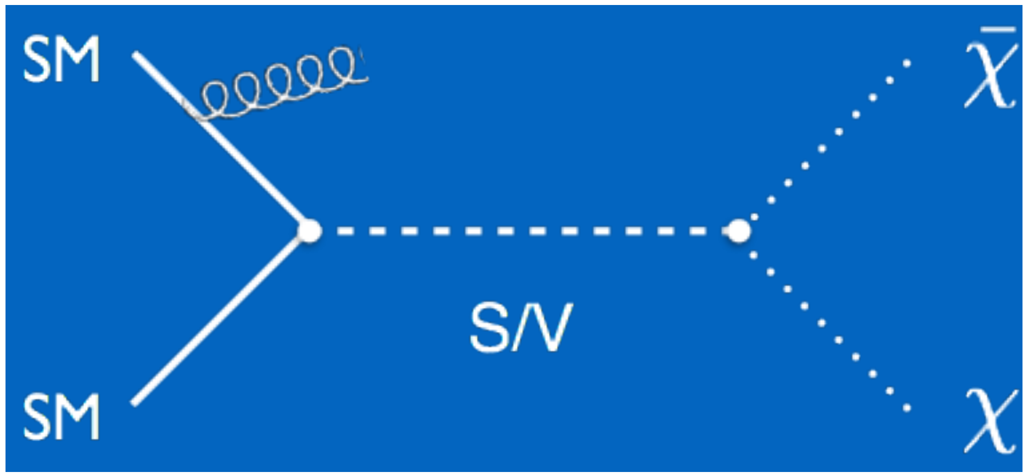
Long-Lived Particles



- For an up-to-date summary of all results -> SUSY17

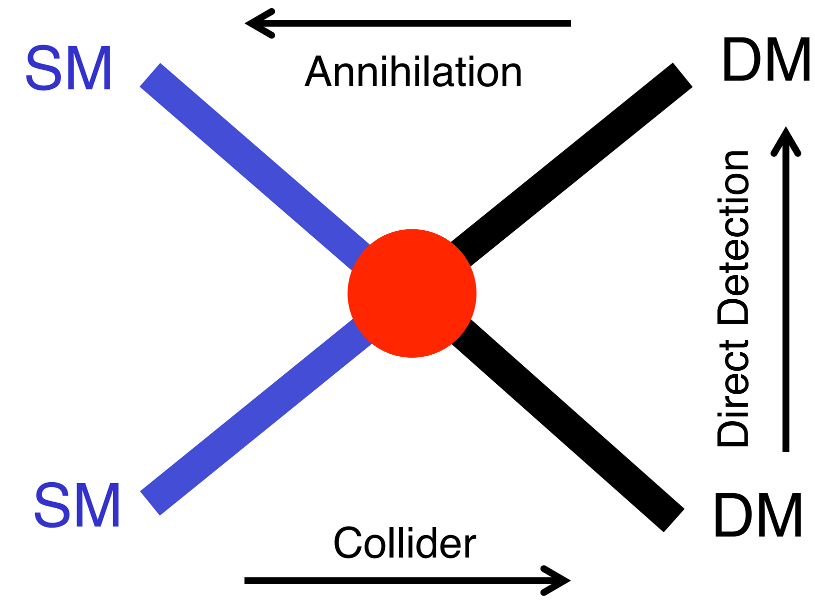
A Different Perspective: Generic DM

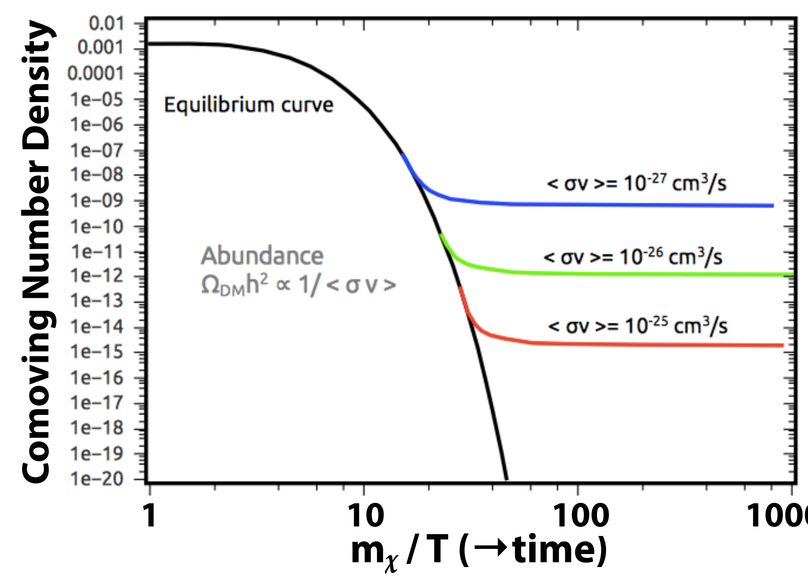
- Typically parameterized by 5 parameters:



  - mass of DM particle, m_χ
  - mass and width of mediator particle, m_{med}, Γ_{med}
  - coupling of mediator to SM sector, g_q
  - coupling of mediator to DM sector, g_χ

- A/A-V: $g_q = 0.25$, $g_\chi = 1$
- S/P-S: $g_q = 1$, $g_\chi = 1$





- Parameterise DM (i.e. WIMP) production via simplified models
- Allows comparison with direct detection / cosmology
  - Thanks to Henning Flaecher for beautiful summary slides

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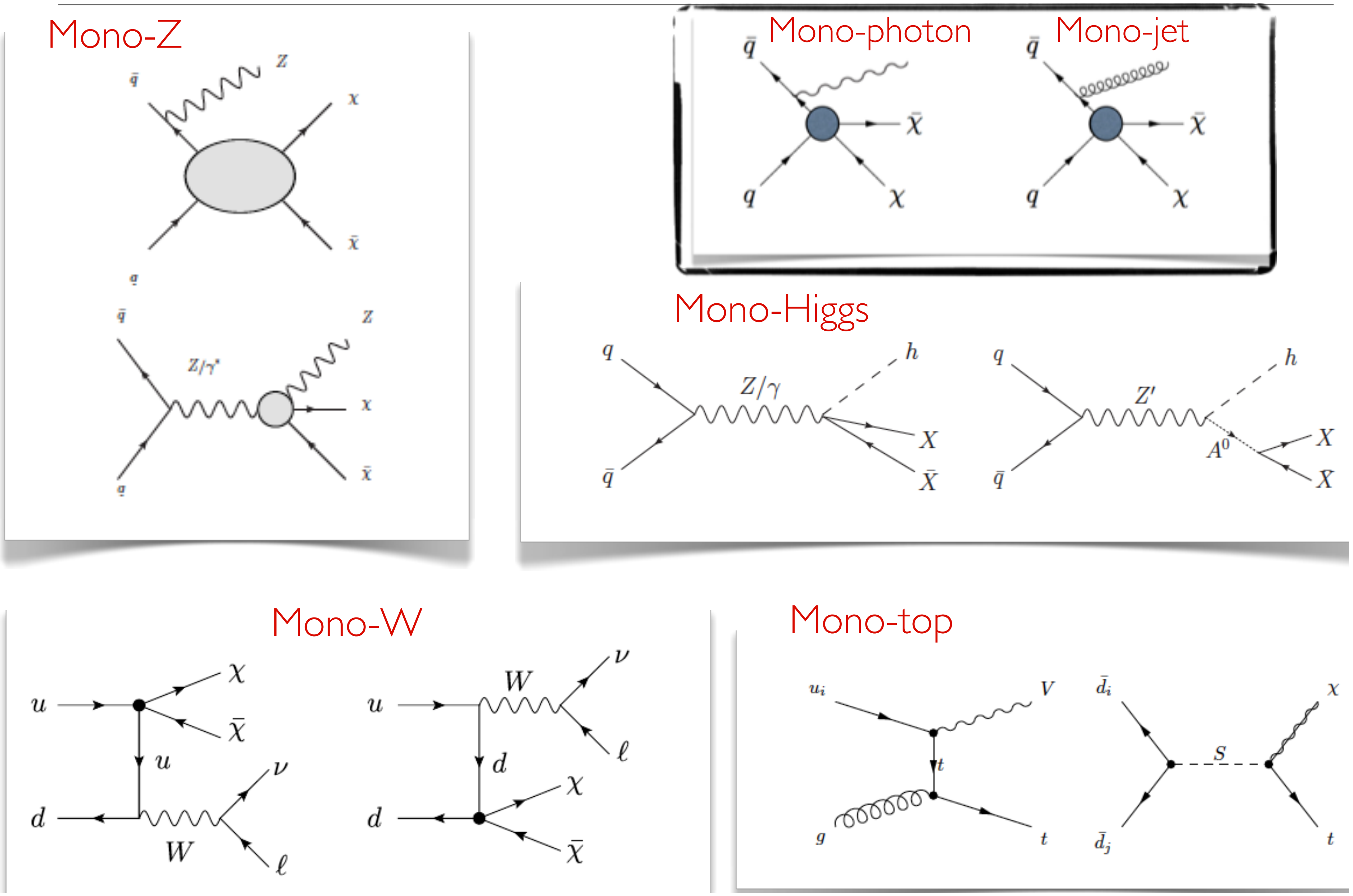
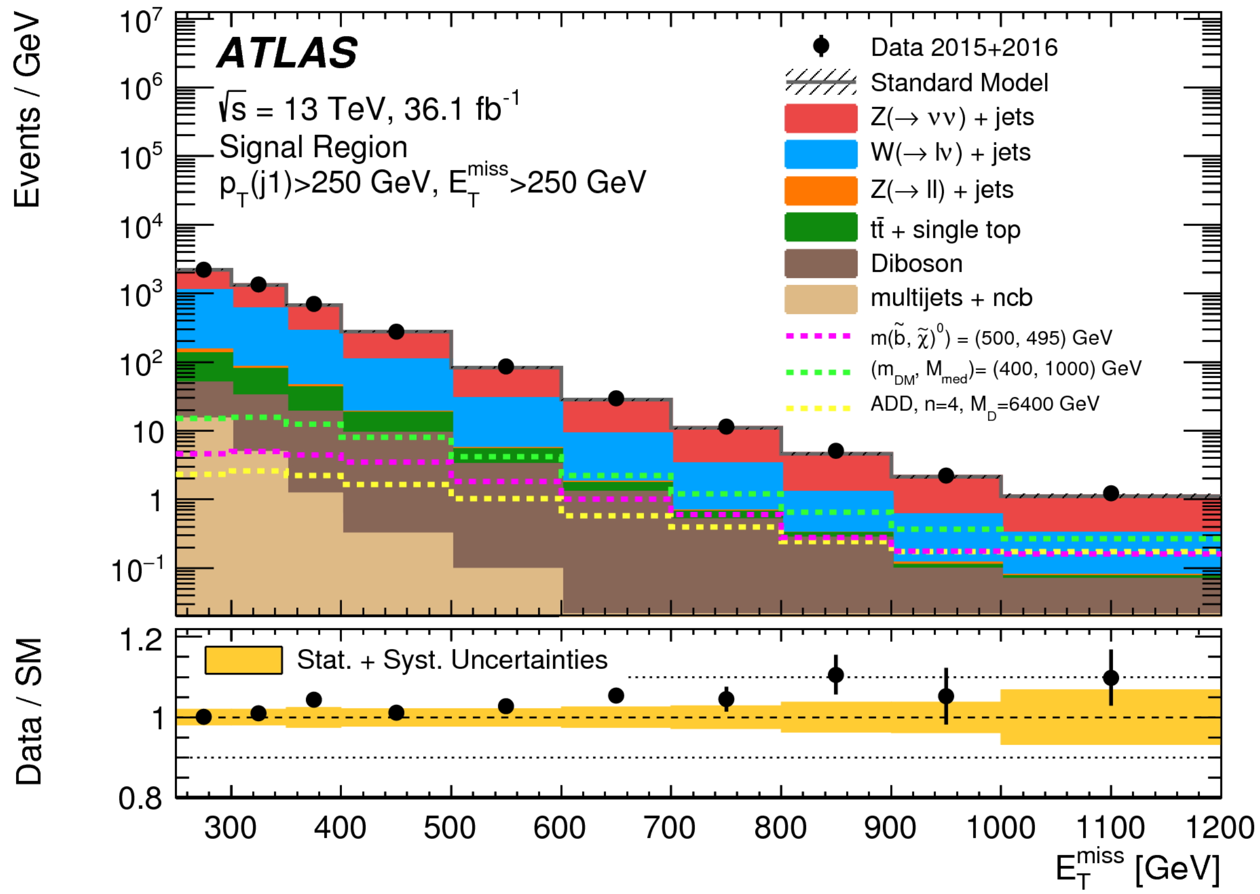
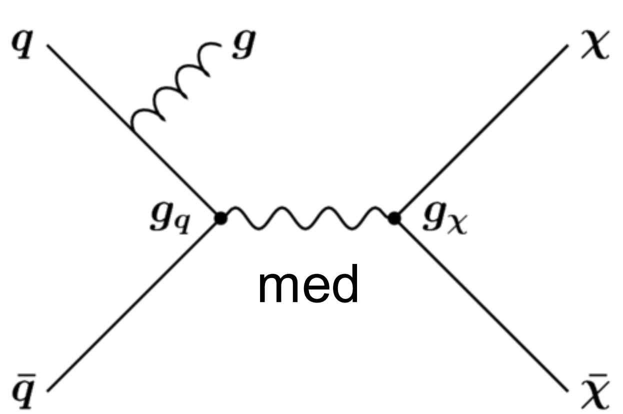
Monomania!

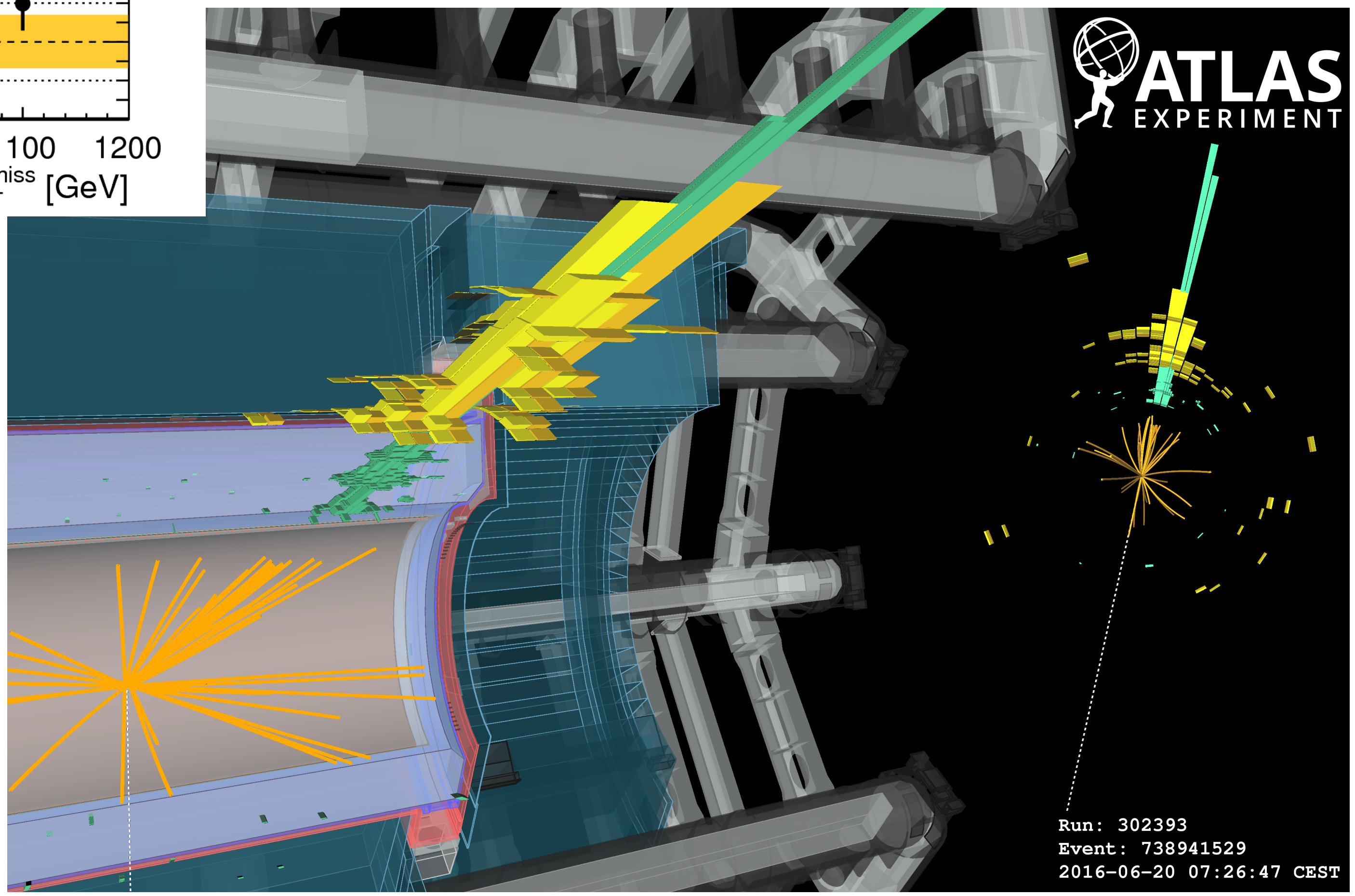


- Trigger on ‘ISR’ system recoiling against DM system
- Complements searches in full UV-complete models, e.g. SUSY

Monomania

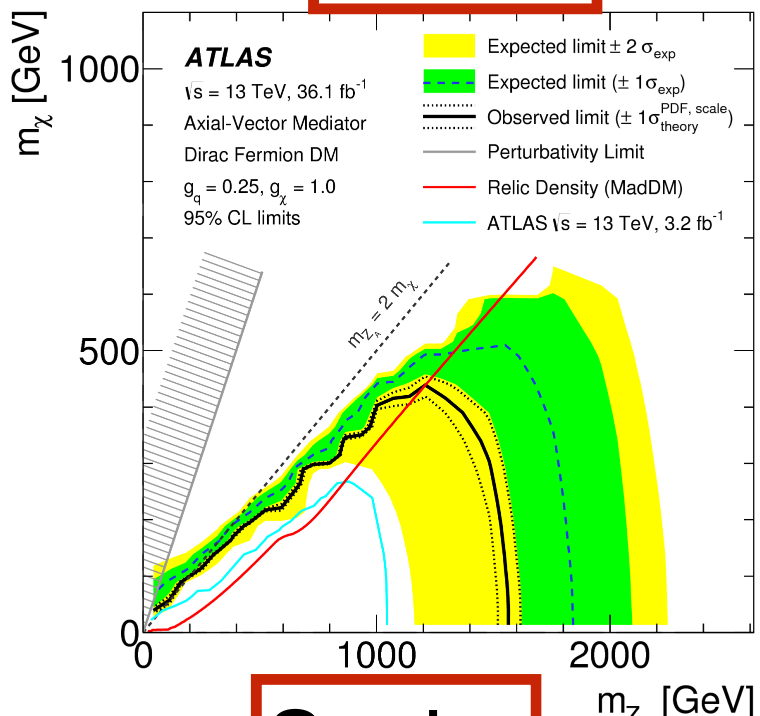

ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Signal Region
p_T(j1)>250 GeV, E_T^{miss}>250 GeV
Data 2015+2016
Standard Model
Z(→ νν) + jets
W(→ lν) + jets
Z(→ ll) + jets
tt̄ + single top
Diboson
multijets + ncb
m(b̃, χ̃⁰) = (500, 495) GeV
(m_DM, M_med)= (400, 1000) GeV
ADD, n=4, M_D=6400 GeV
Stat. + Syst. Uncertainties
Events / GeV
Data / SM
E_T^{miss} [GeV]


q
g
χ
g_q
g_χ
med
q̄
χ̄

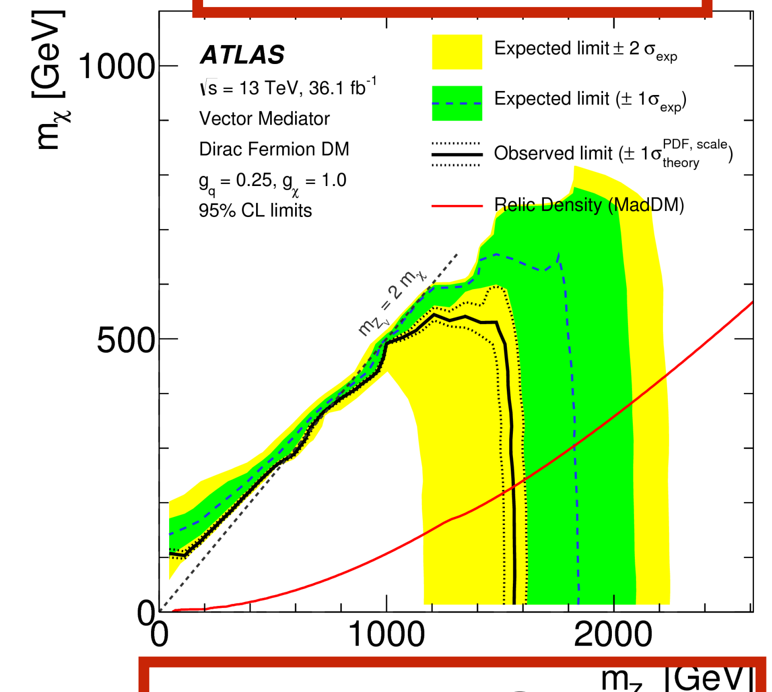

ATLAS
EXPERIMENT
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

Interpretation

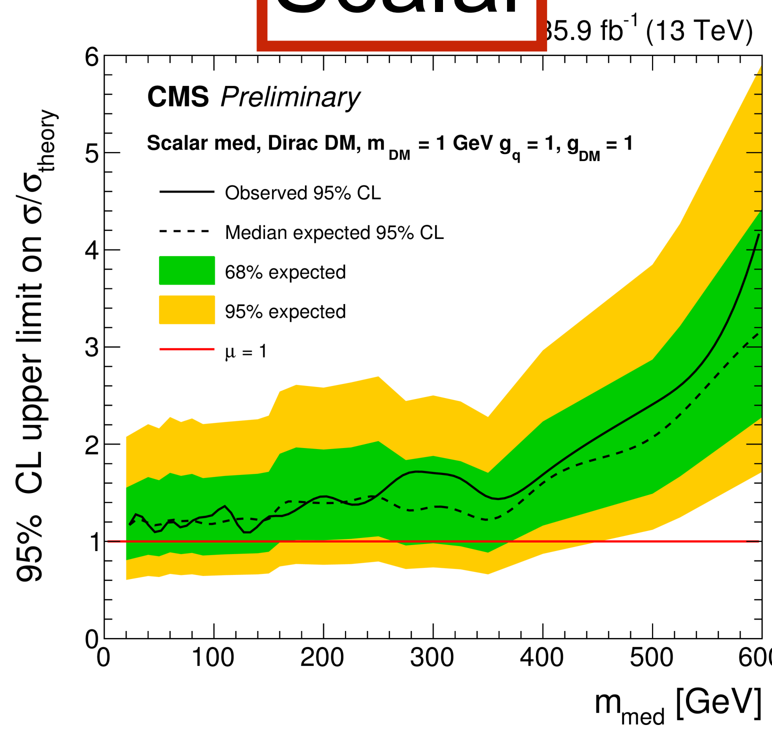
Vector



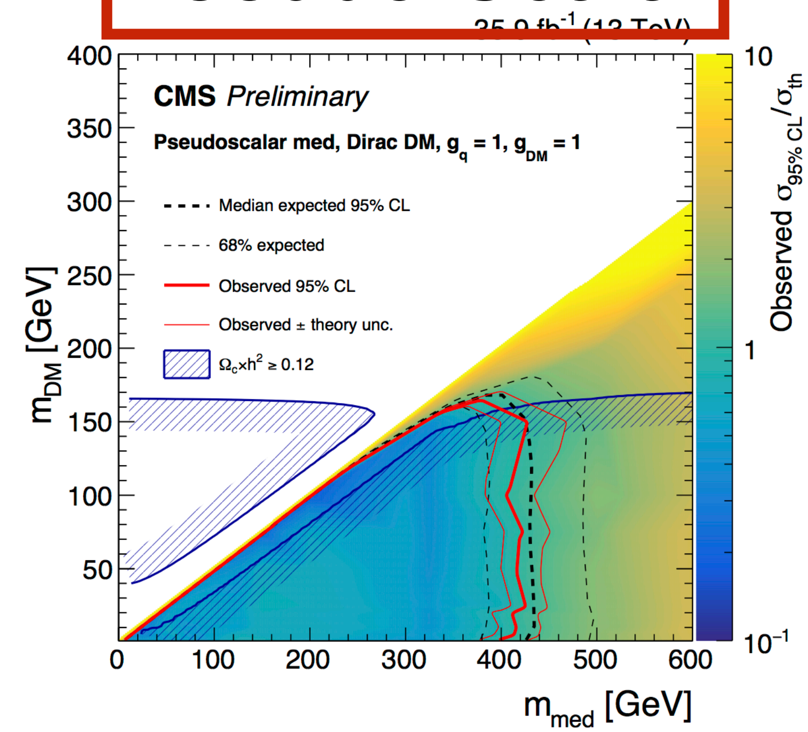
Axial-Vector



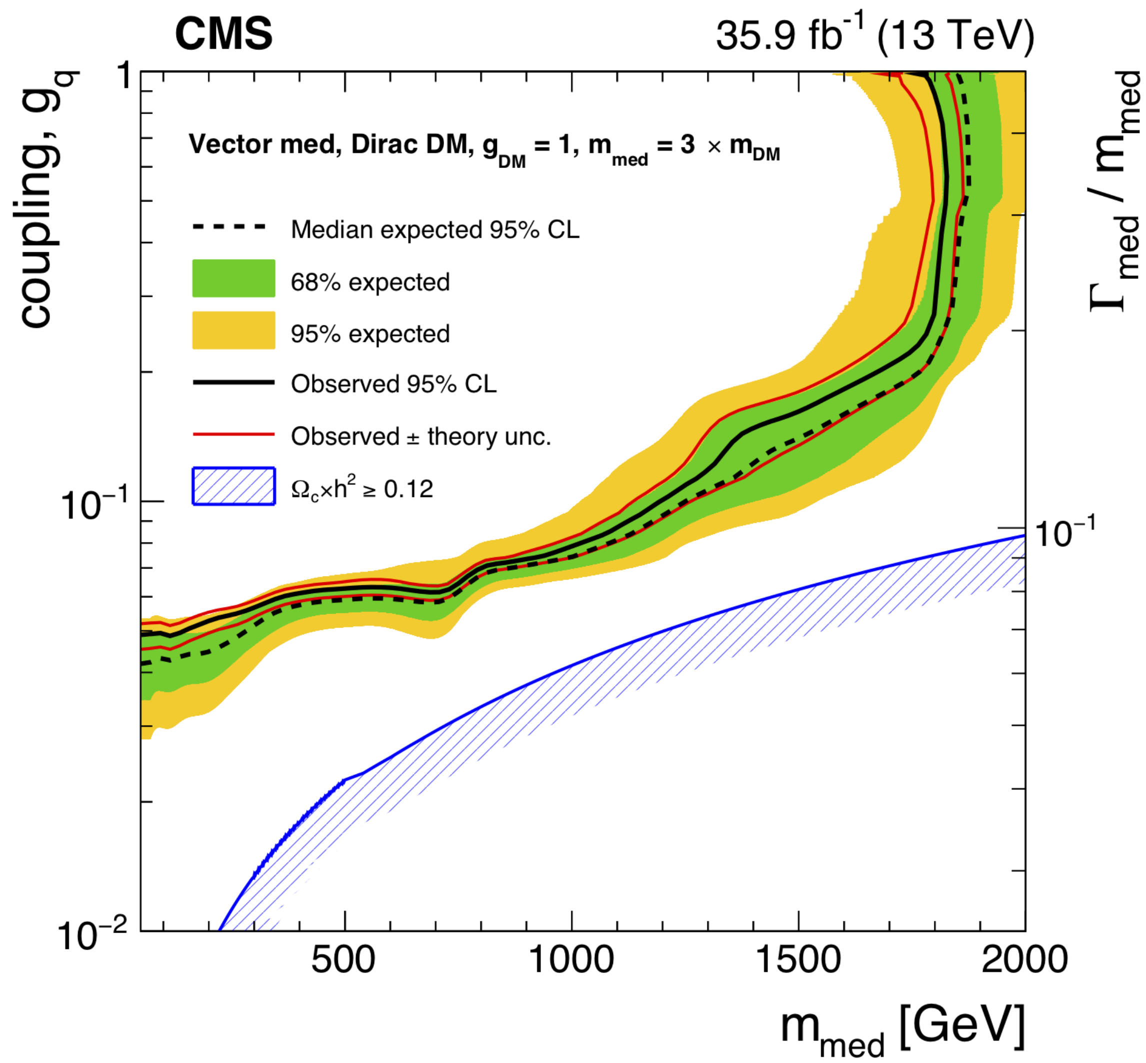
Scalar

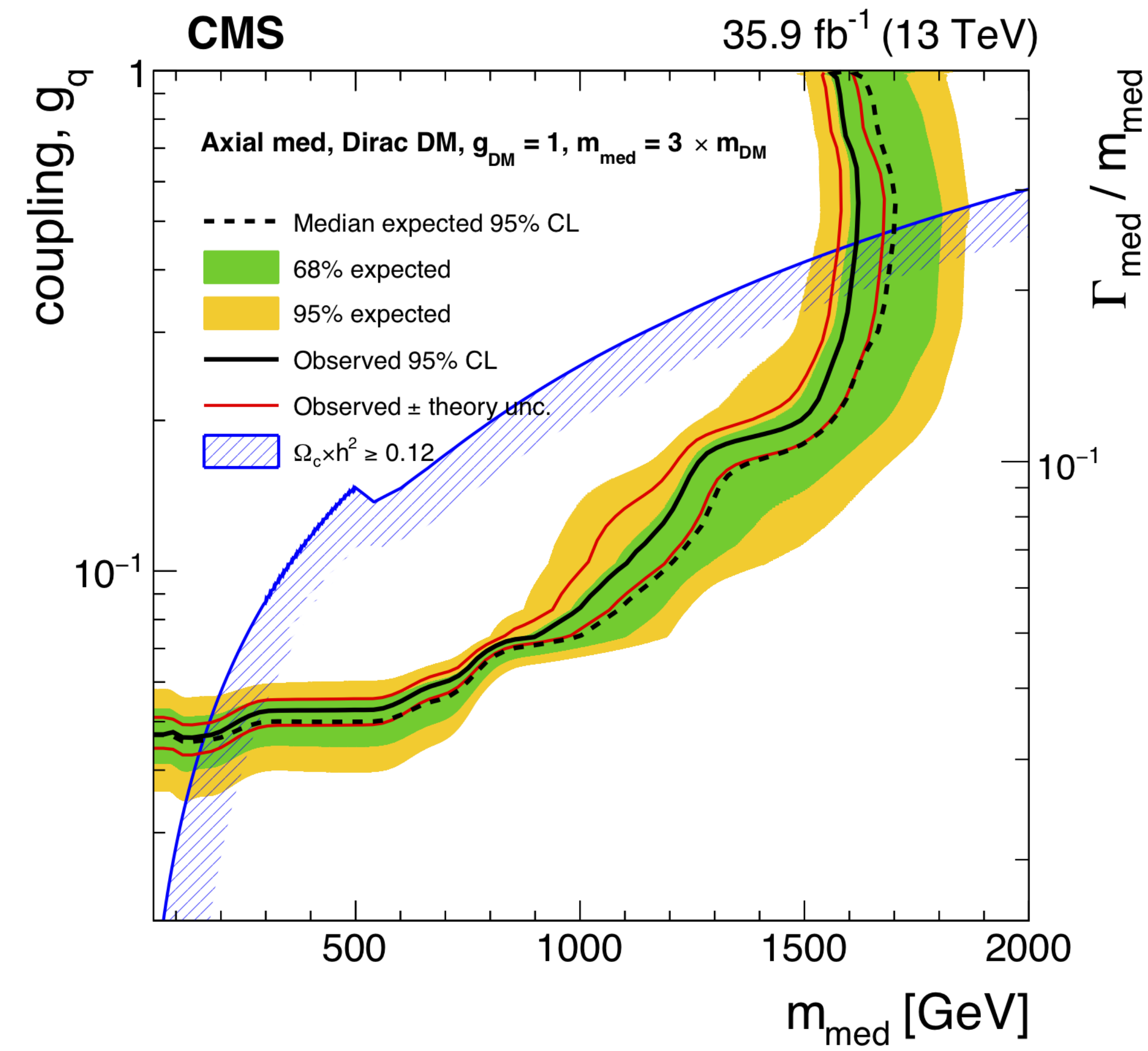


Pseudo-Scalar



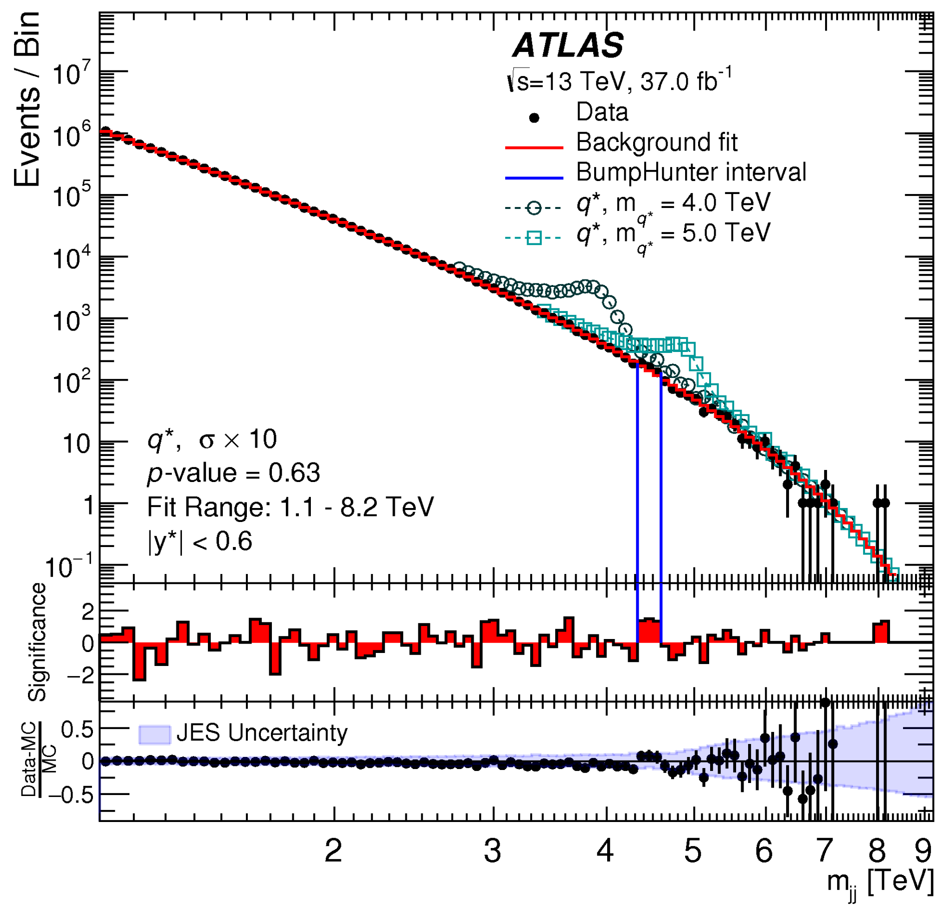
Interpretation



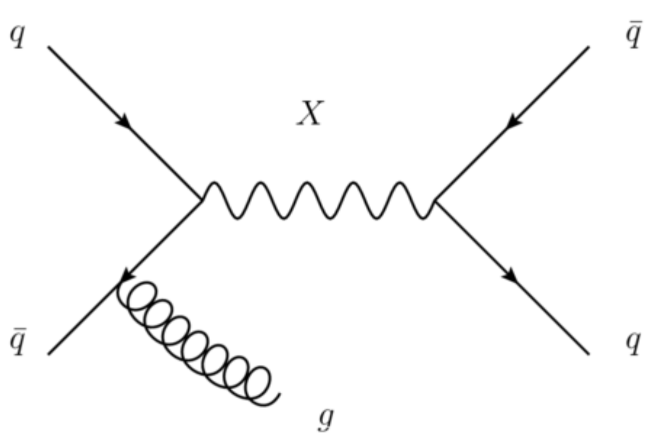


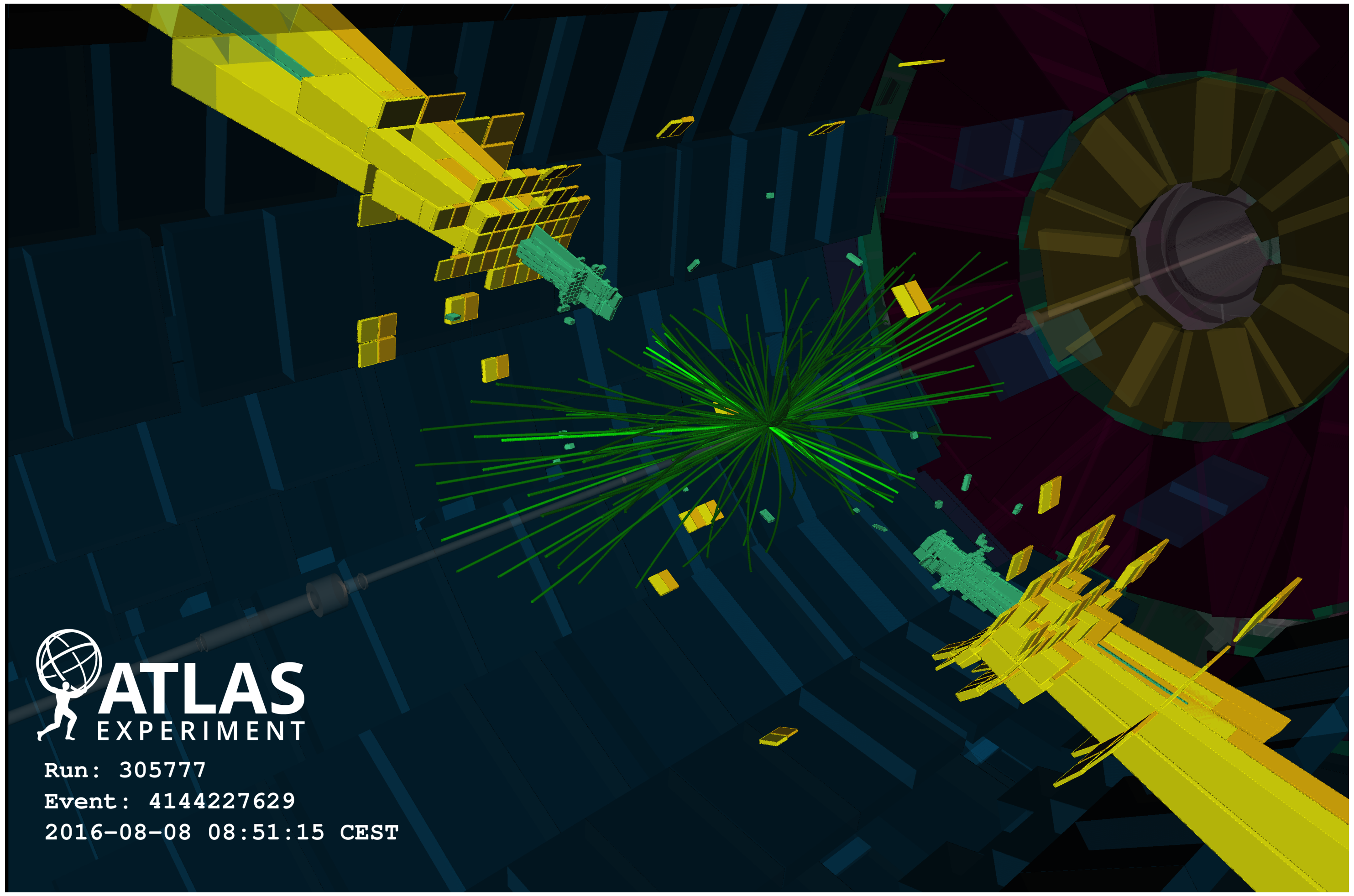
- Observations incompatible with relic density limits
  - For particular (and narrow) ranges of couplings
  - More to come with increased statistics

Mediator Searches

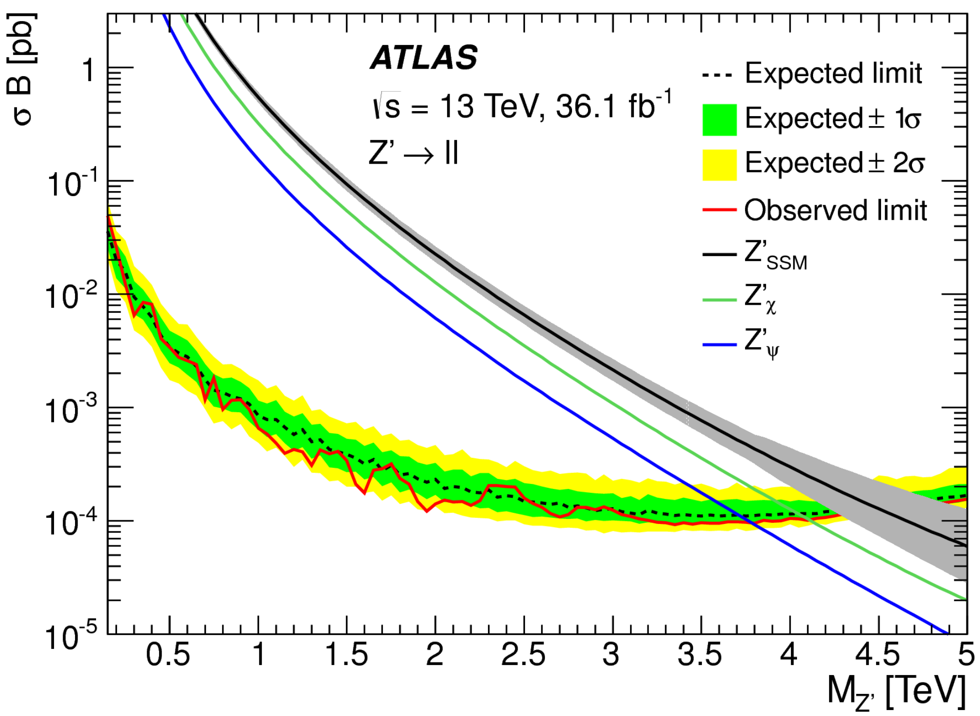


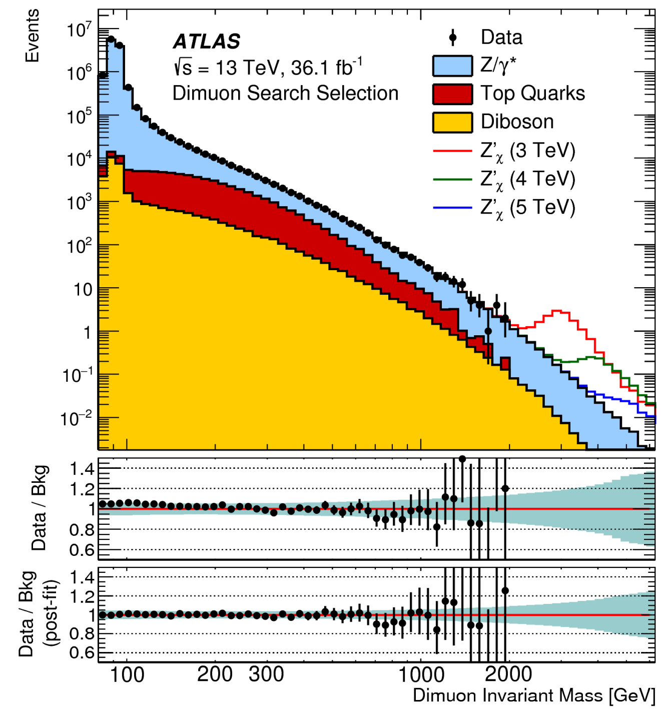
- Low-mass mediators swamped by QCD
  - Use clever analysis-in-trigger techniques: 'data scouting'
  - Trigger on high-p_T ISR, look for jet substructure in recoil system

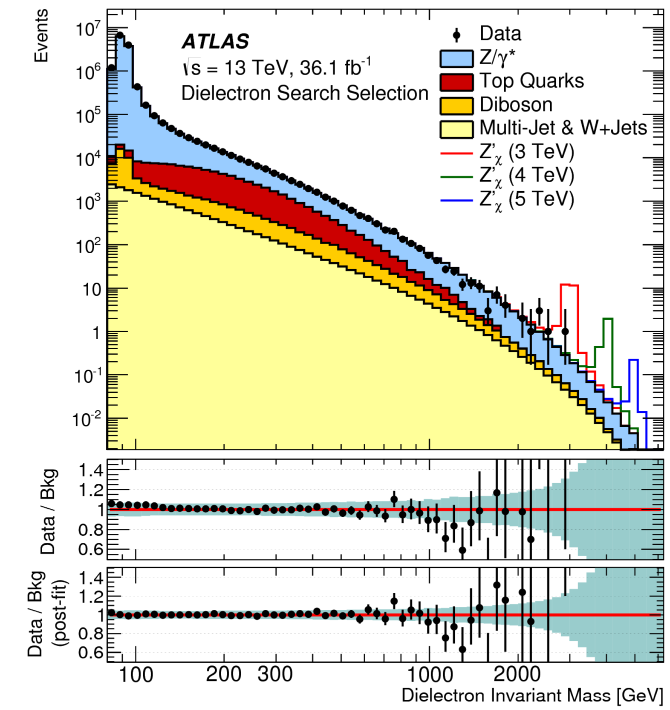




An Old Favourite…

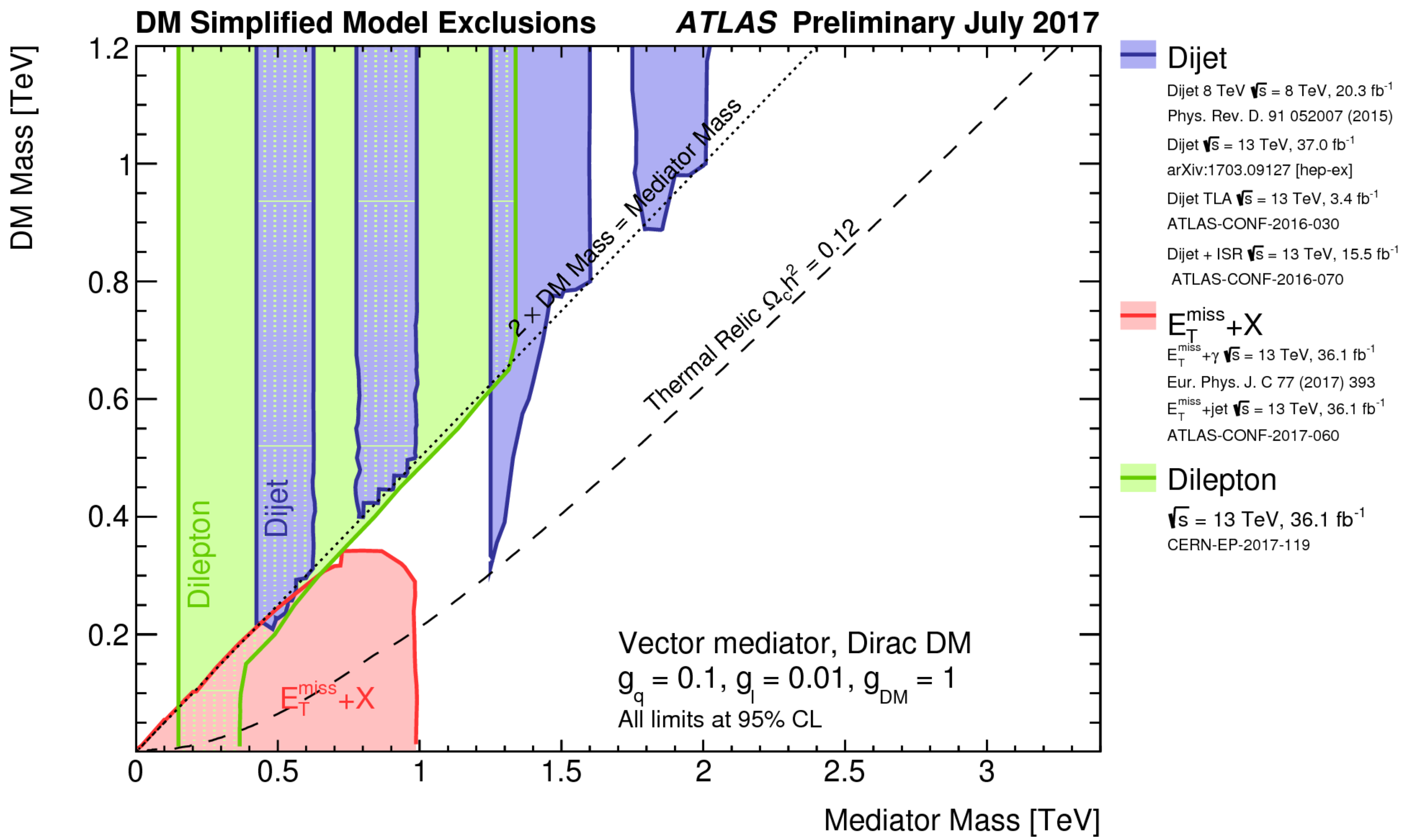






- Classic Z' hunt now interpreted as DM mediator search
  - Signal: same flavour, opposite charge dilepton
  - Control: opposite flavour / same charge dilepton
  - Main background DY production (well-modelled)
  - Current (model-dependent) limits from CMS and ATLAS around 4.5 TeV

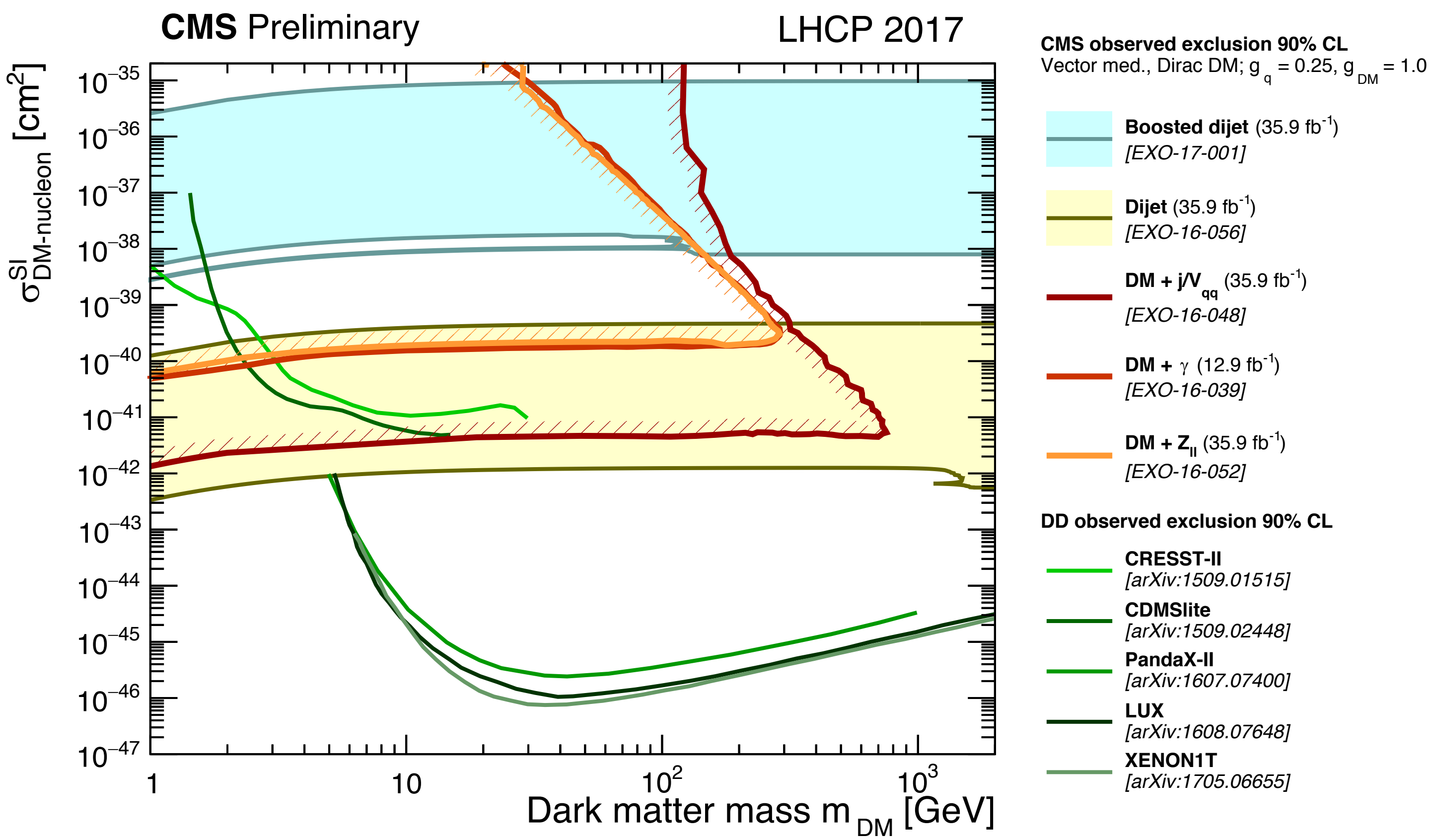
The Grand Picture



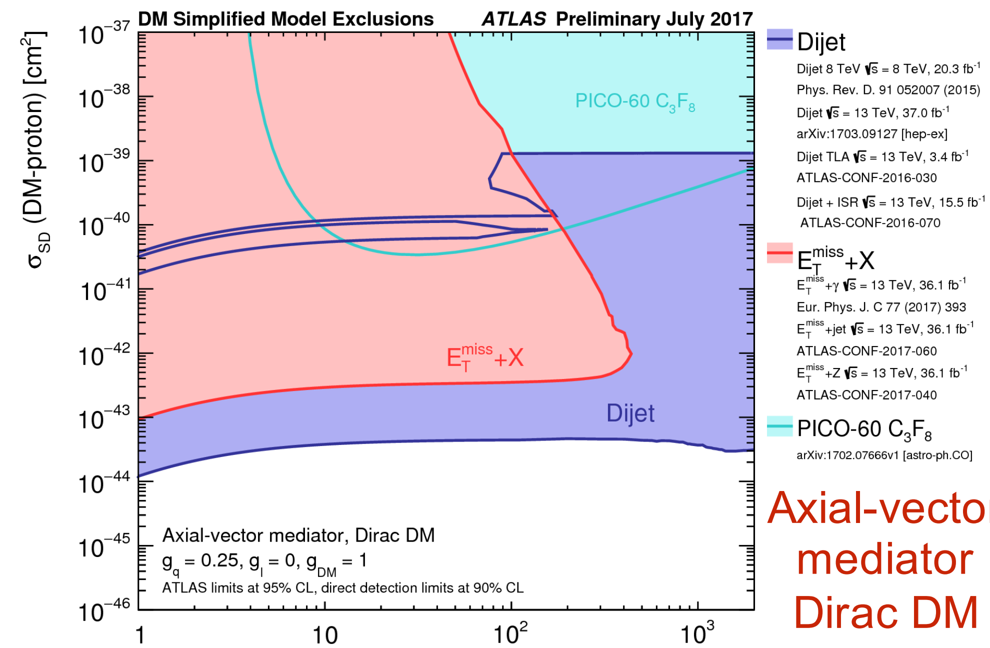
- Vertical structures are mediator searches
- Exclusion areas strongly depend on coupling assumptions
- Much weaker constraints on scalar and pseudo scalar mediators…

Comparison with Direct Direction

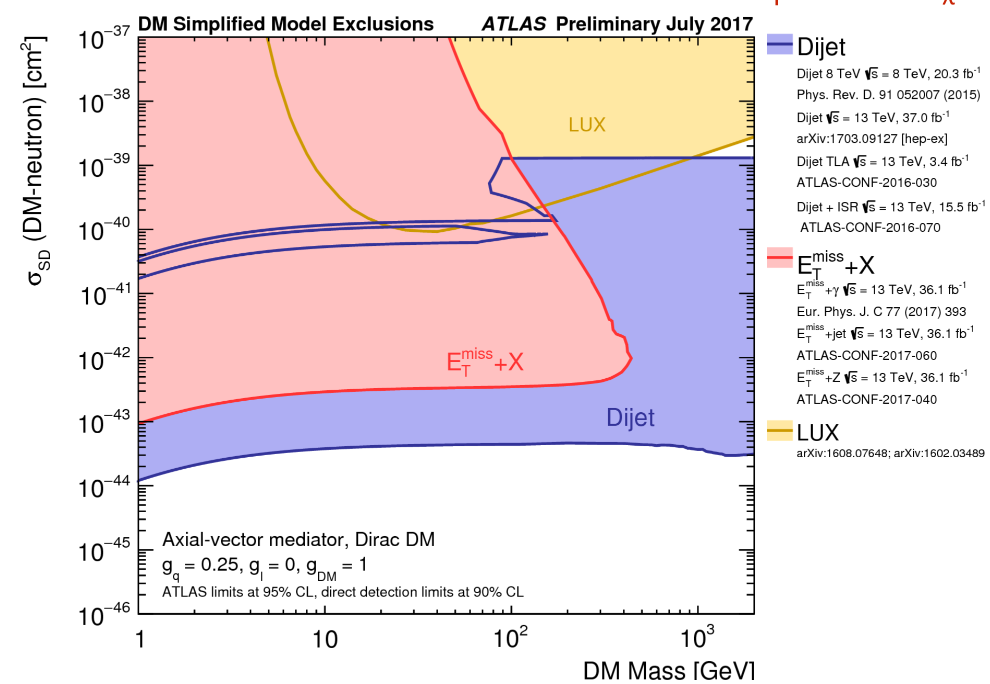
Spin-independent



Spin-dependent

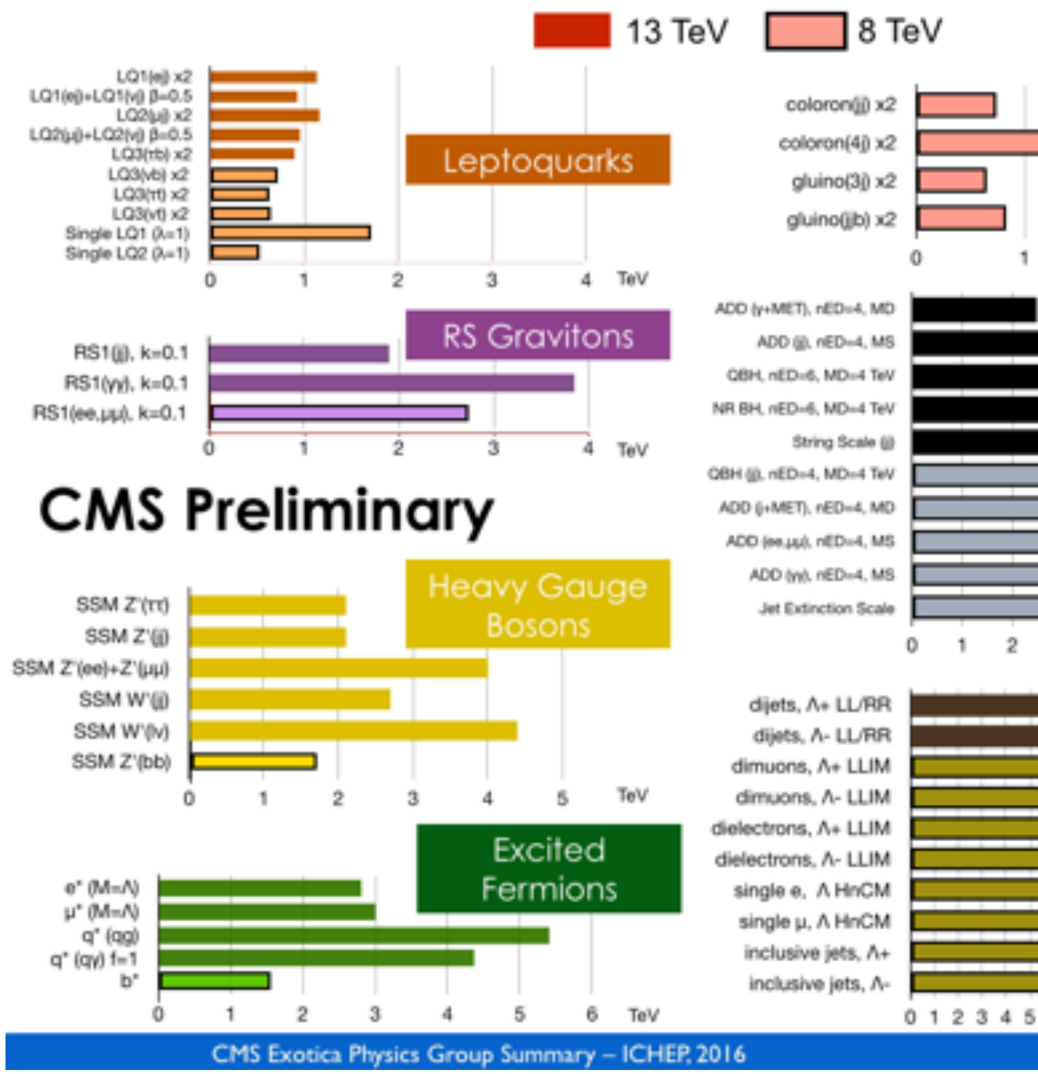


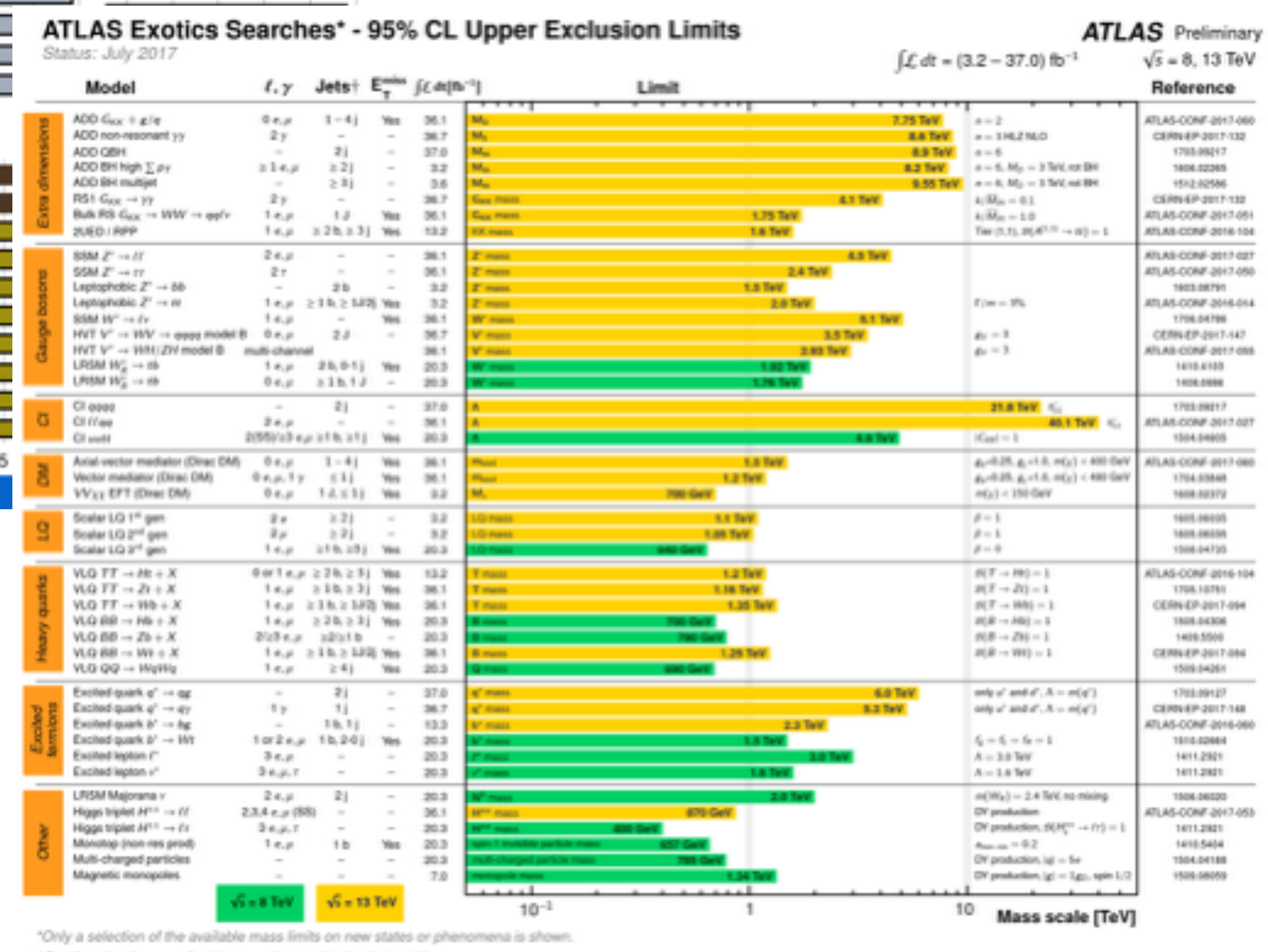
Axial-vector mediator Dirac DM g_q=0.25, g_χ = 1



- Collider and DD searches are clearly complementary
  - Collider competitive at low DM masses, pseudoscalar mediator (hard)
  - Watch this space…

Exotica: Nothing to See Here





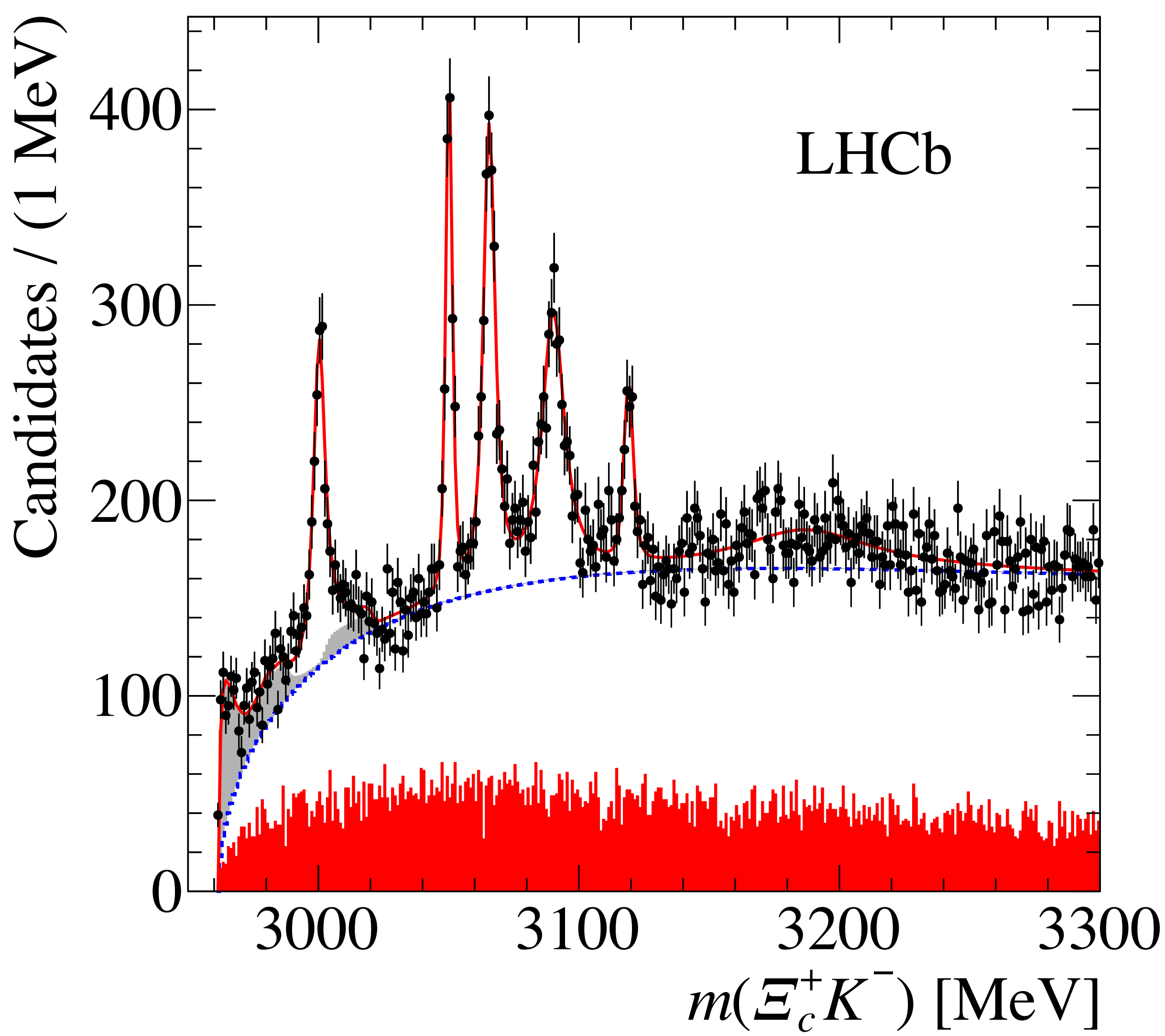
- Still looking!
- Now trying to close gaps in parameter coverage

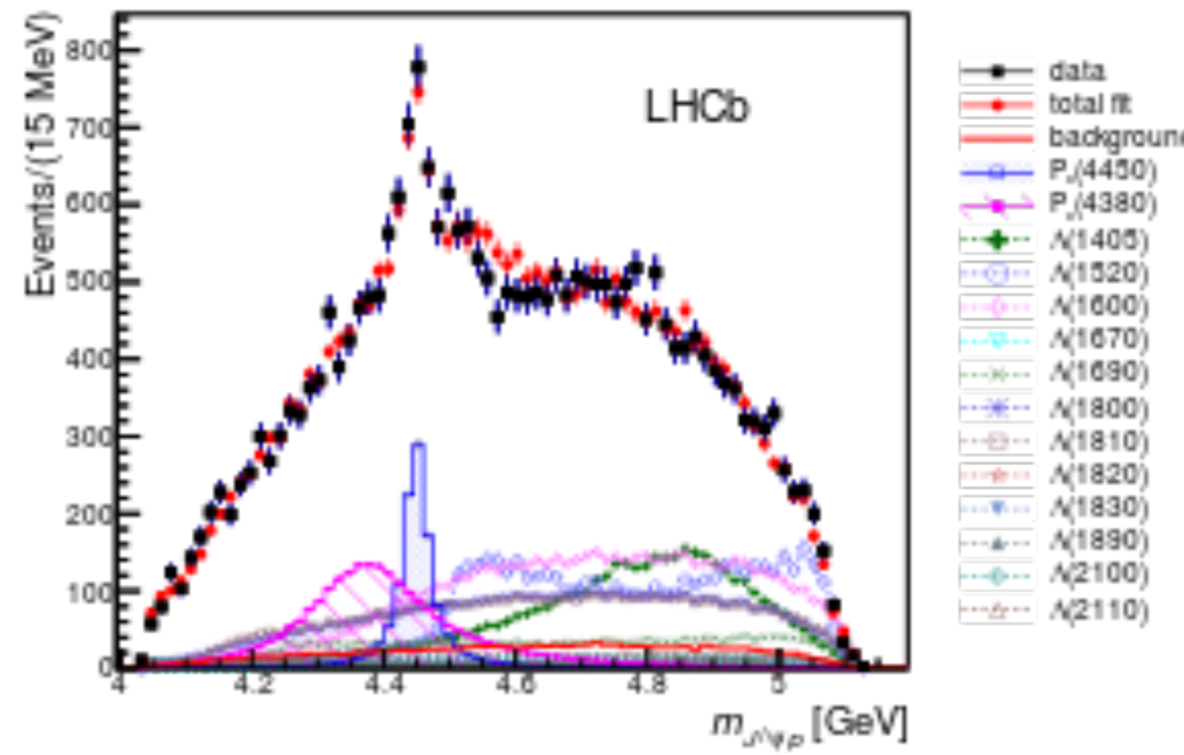
LHCb: Lumps and Bumps

Pentaquark!

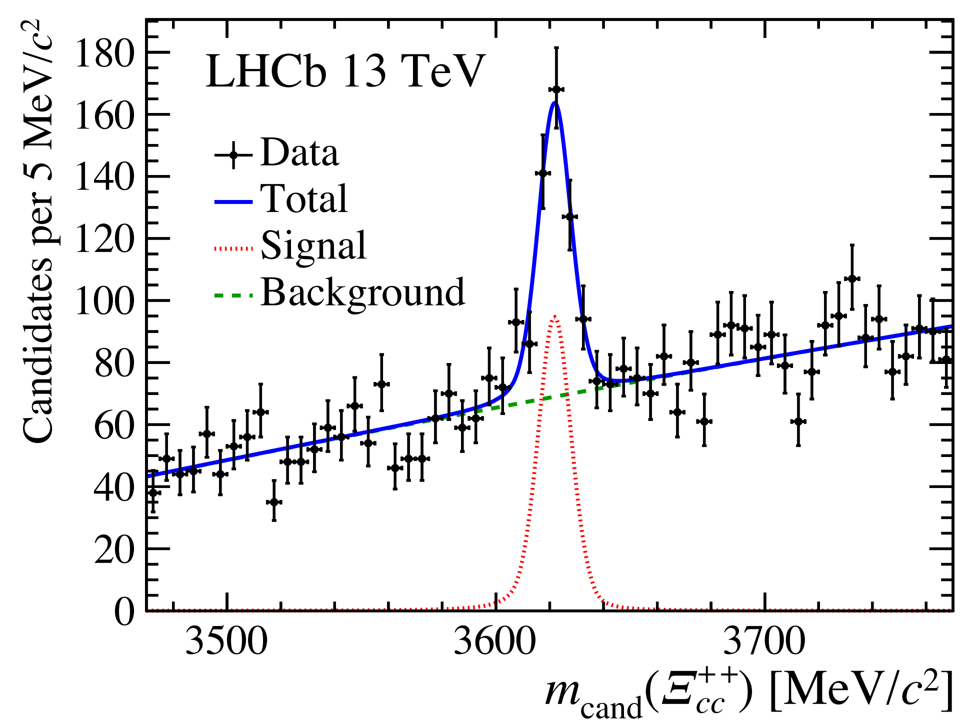
Excited Ω_c states

Phys. Rev. Lett. **118**, 182001





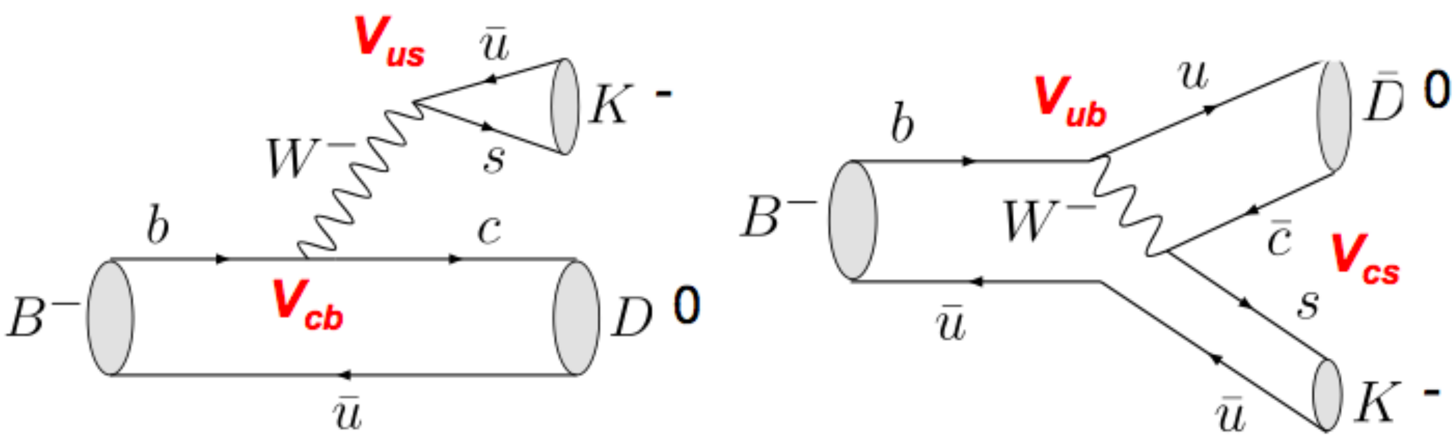
Phys. Rev. Lett. 119, 112001 (2017)



Ξ_{cc}

- All consistent with theory

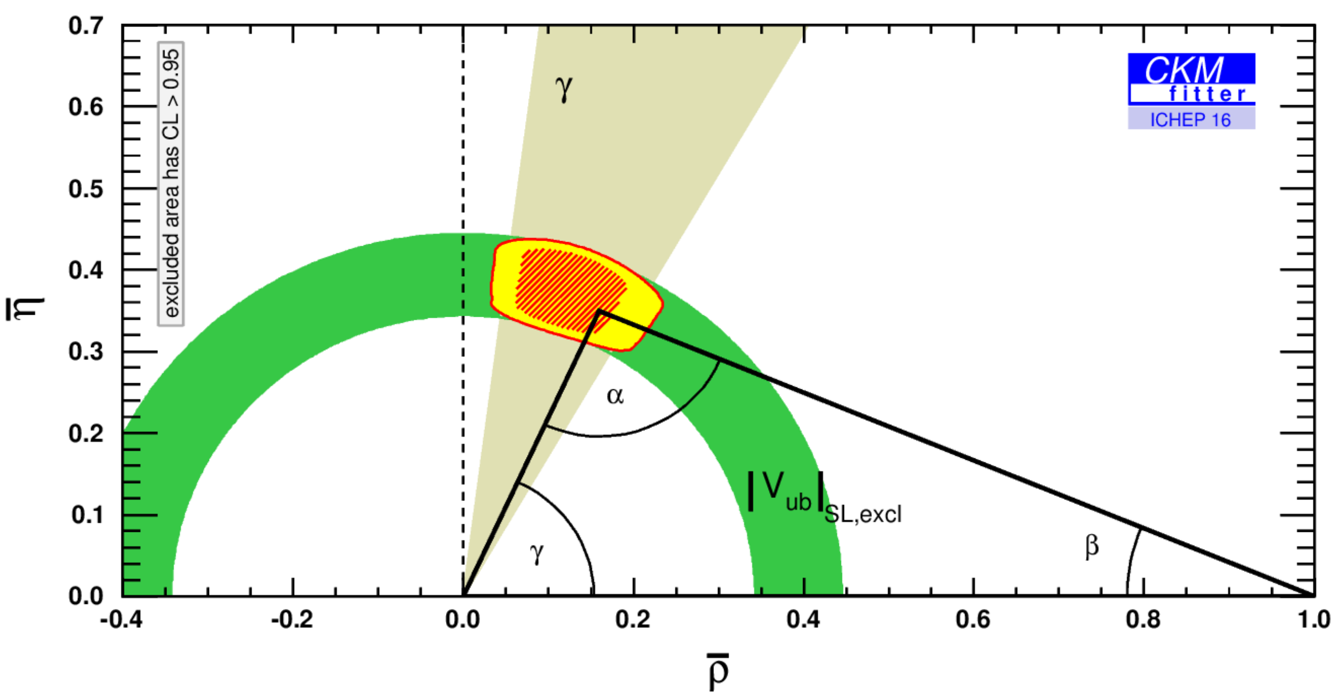
Flavour: CKM

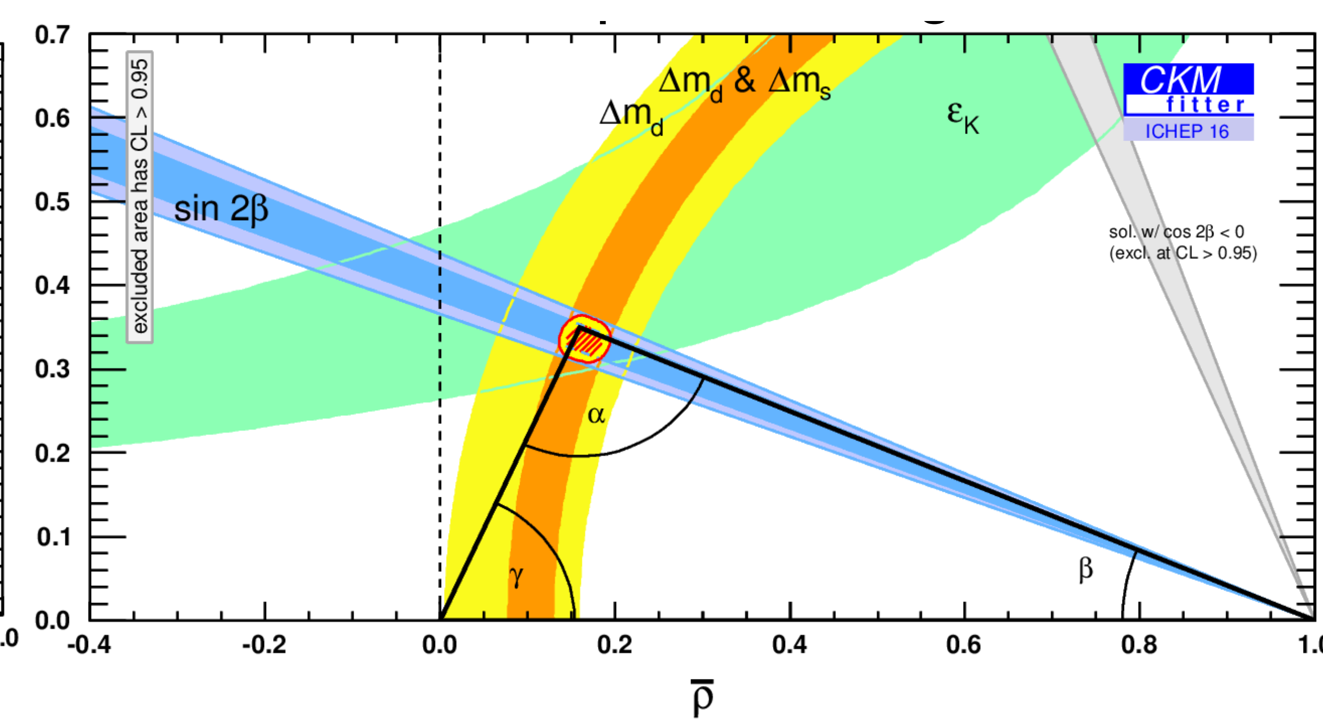


*traditionally; LQCD progress enabling new complementary methods

“Largely trees”*

“Largely loops” -> NP

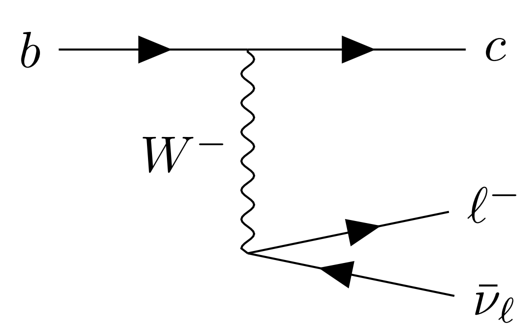


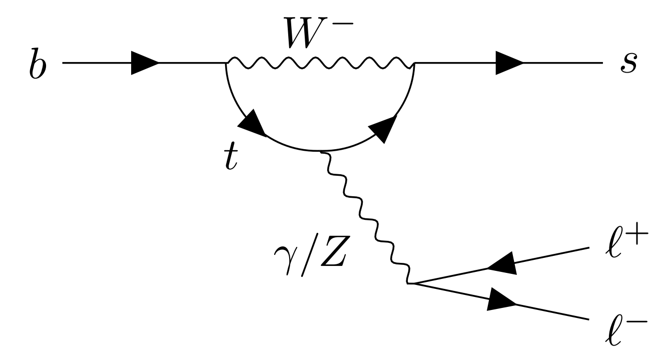


- Tests of CKM unitarity sensitive to O(100TeV) scale physics
- All about gamma now… tough measurements

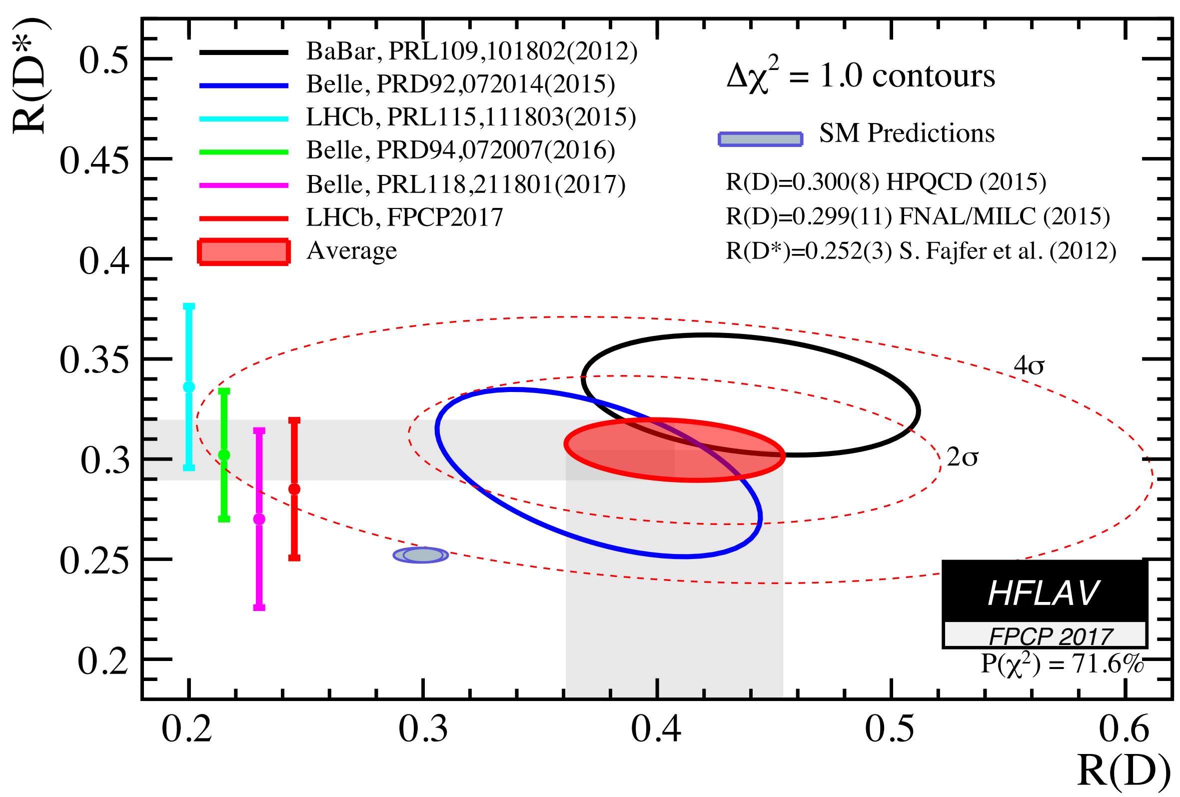
$$\boxed{\gamma = (76.8\,^{+5.1}_{-5.7})^\circ}$$

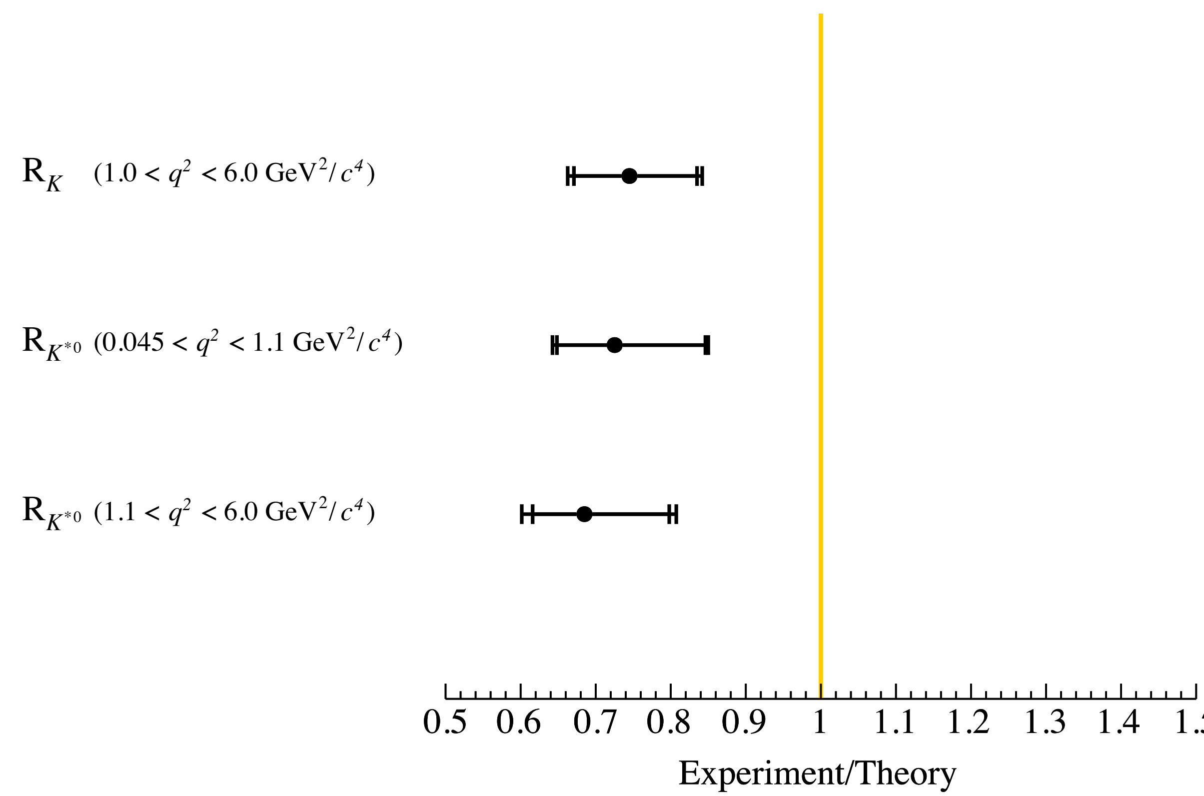
Flavour: Lepton Universality Violation





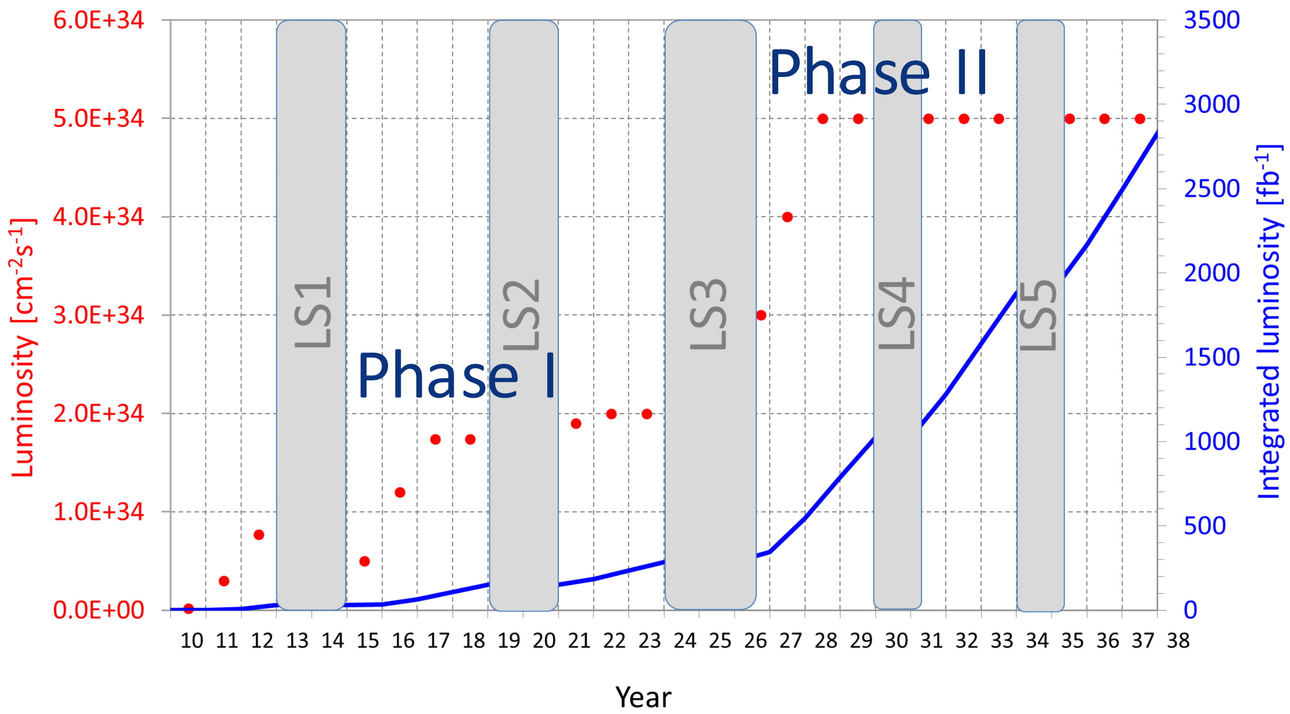
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)} \qquad R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

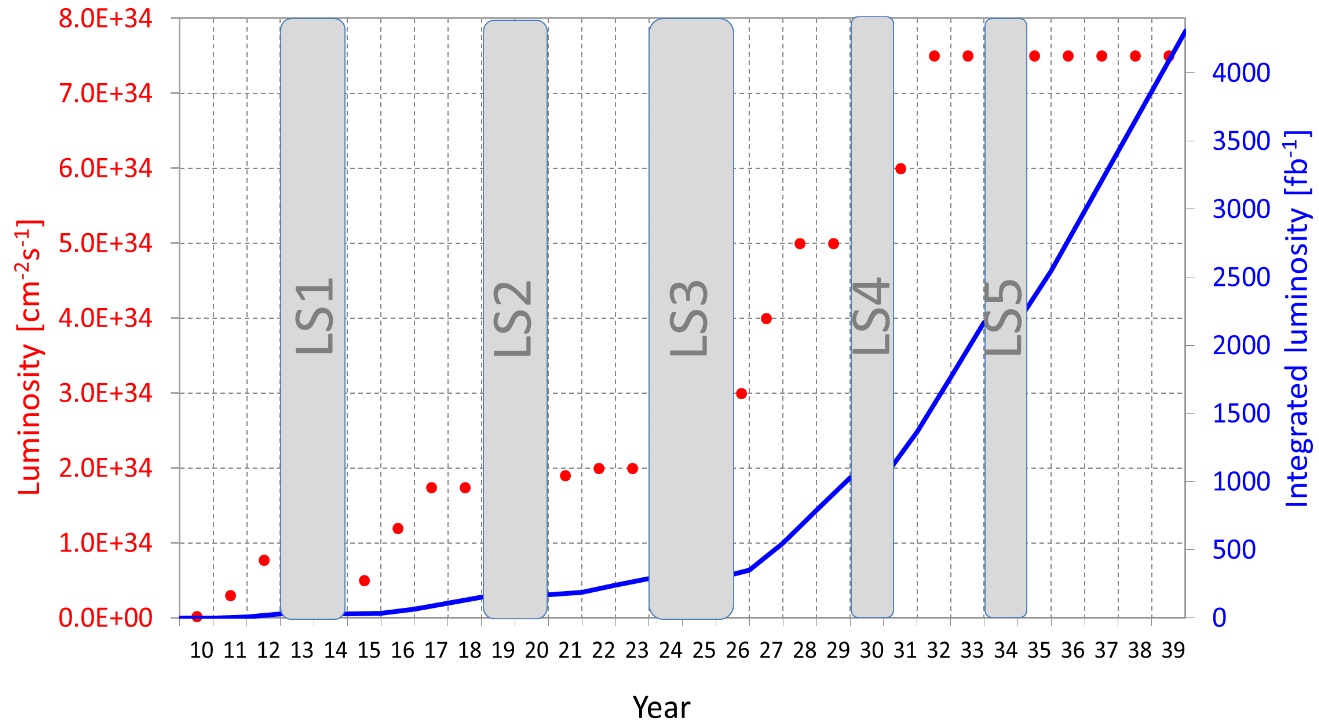




- 4σ tension with the SM prediction (assuming it stays put)
- Hard to explain with any single (heavy) source of interference…

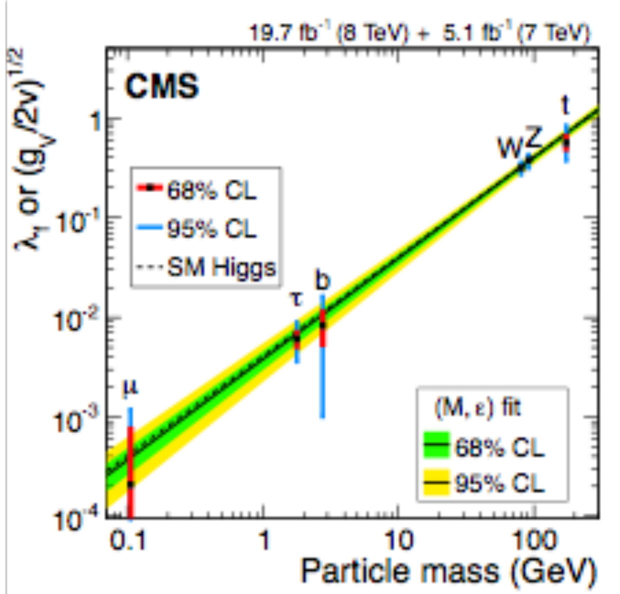
LHC Upgrades

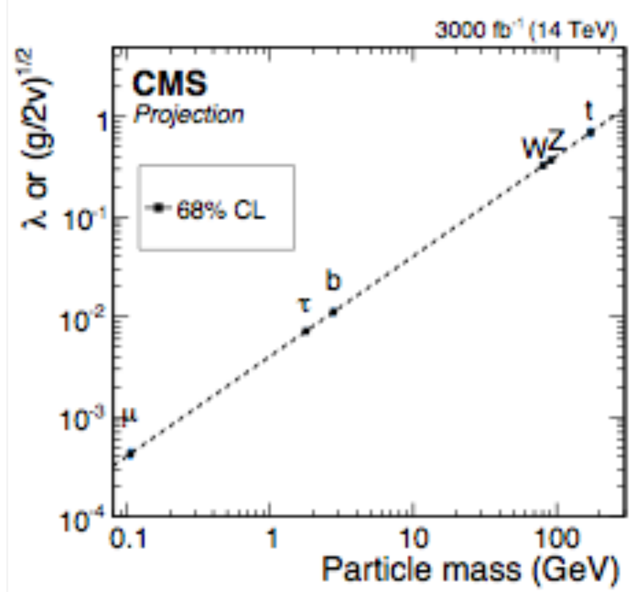


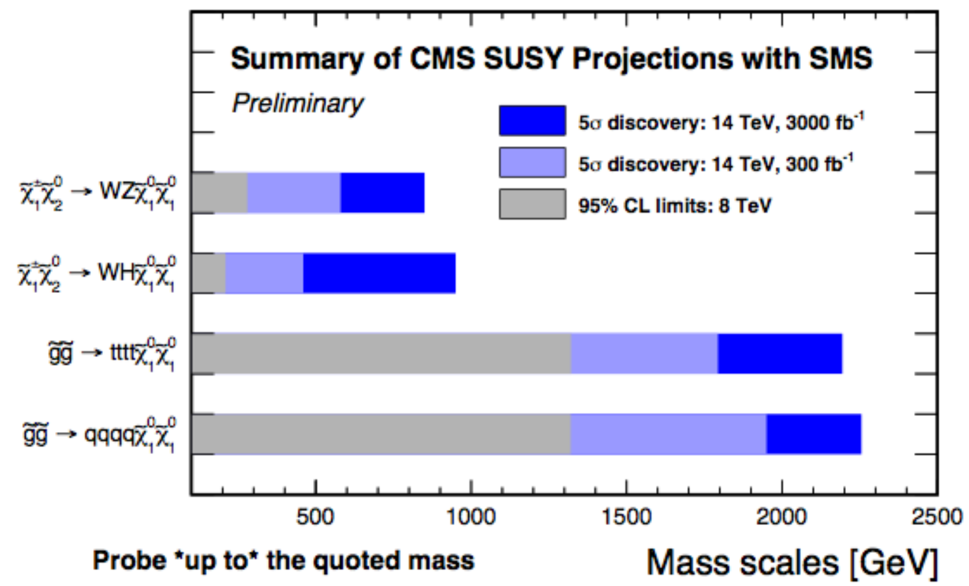


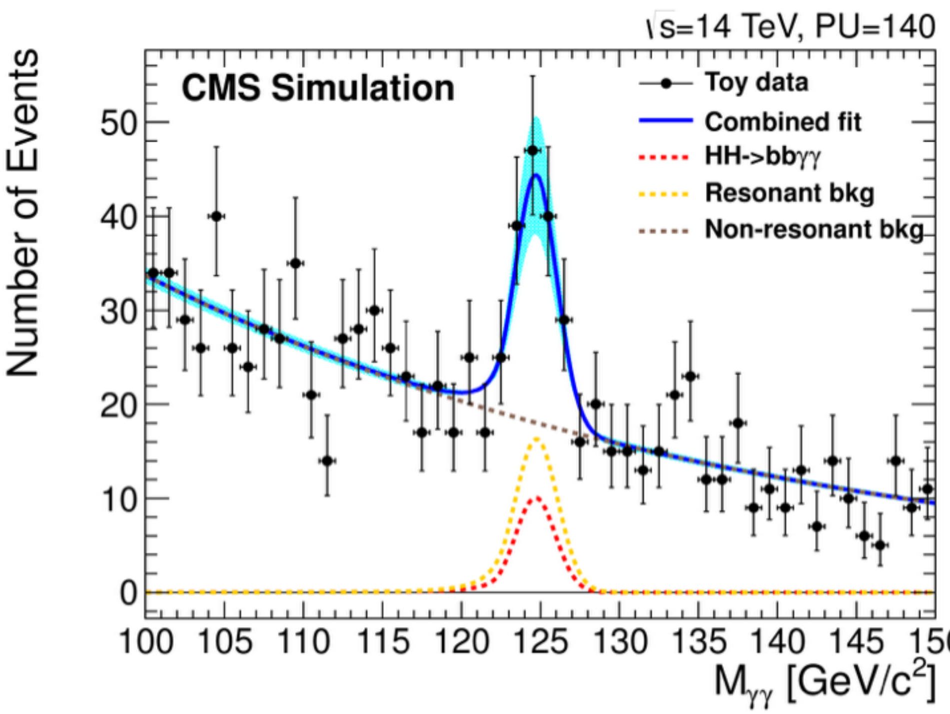
- Push LHC to ultimate limit of 5 - 10 times design luminosity
  - Requires upgrades to many parts of CERN infrastructure during LS2, 3, 4
  - Highest instantaneous luminosity may not be the best physics option
    - 7.5E+34 implies 200 overlapping events per crossing; may not be handleable by detectors
    - Levelled scenario provides less integrated lumi, but constant running conditions
- Detector upgrade strategy
  - Upgraded detectors must have *better* performance than the originals
  - As in original detectors, we will push the technological envelope — hard
  - Should not forget that lifetime of 'new' detectors will be as long as the originals

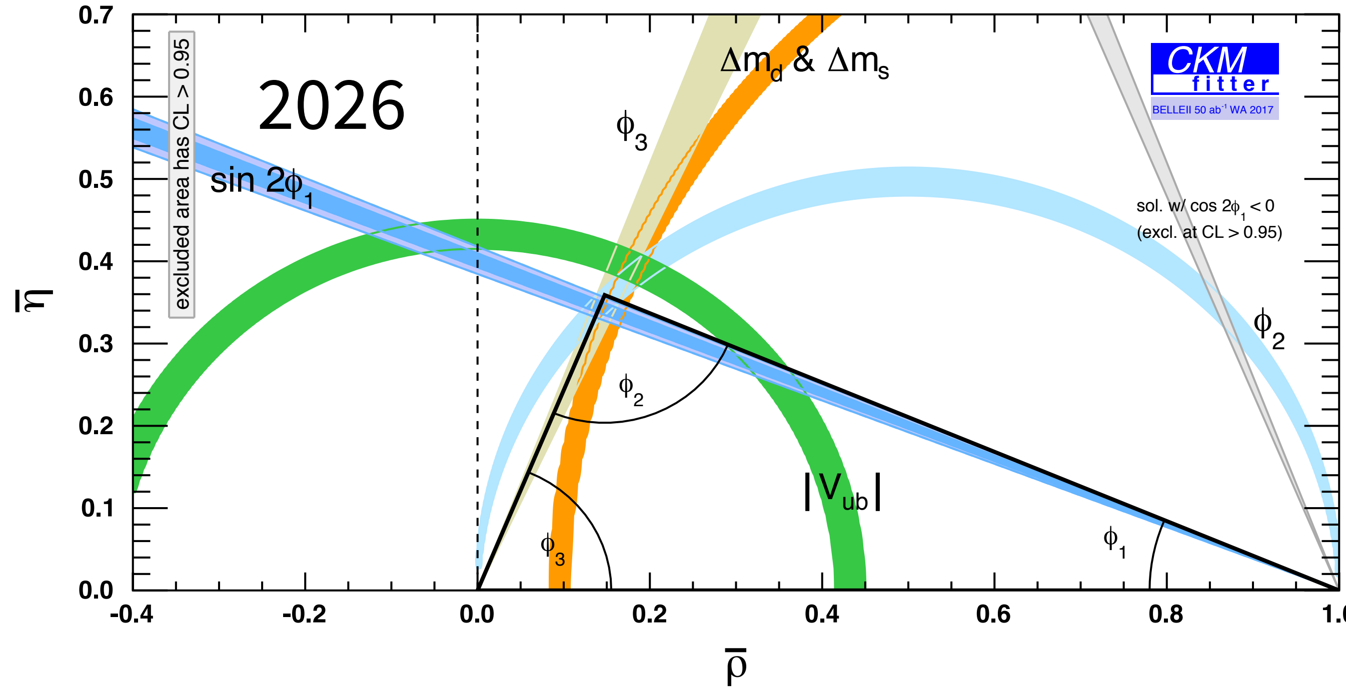
Long-Term LHC Physics











- Precision H physics; HH coupling; increased mass limits
- What we need is more data — but not at any price

Science & Technology Facilities Council Rutherford Appleton Laboratory
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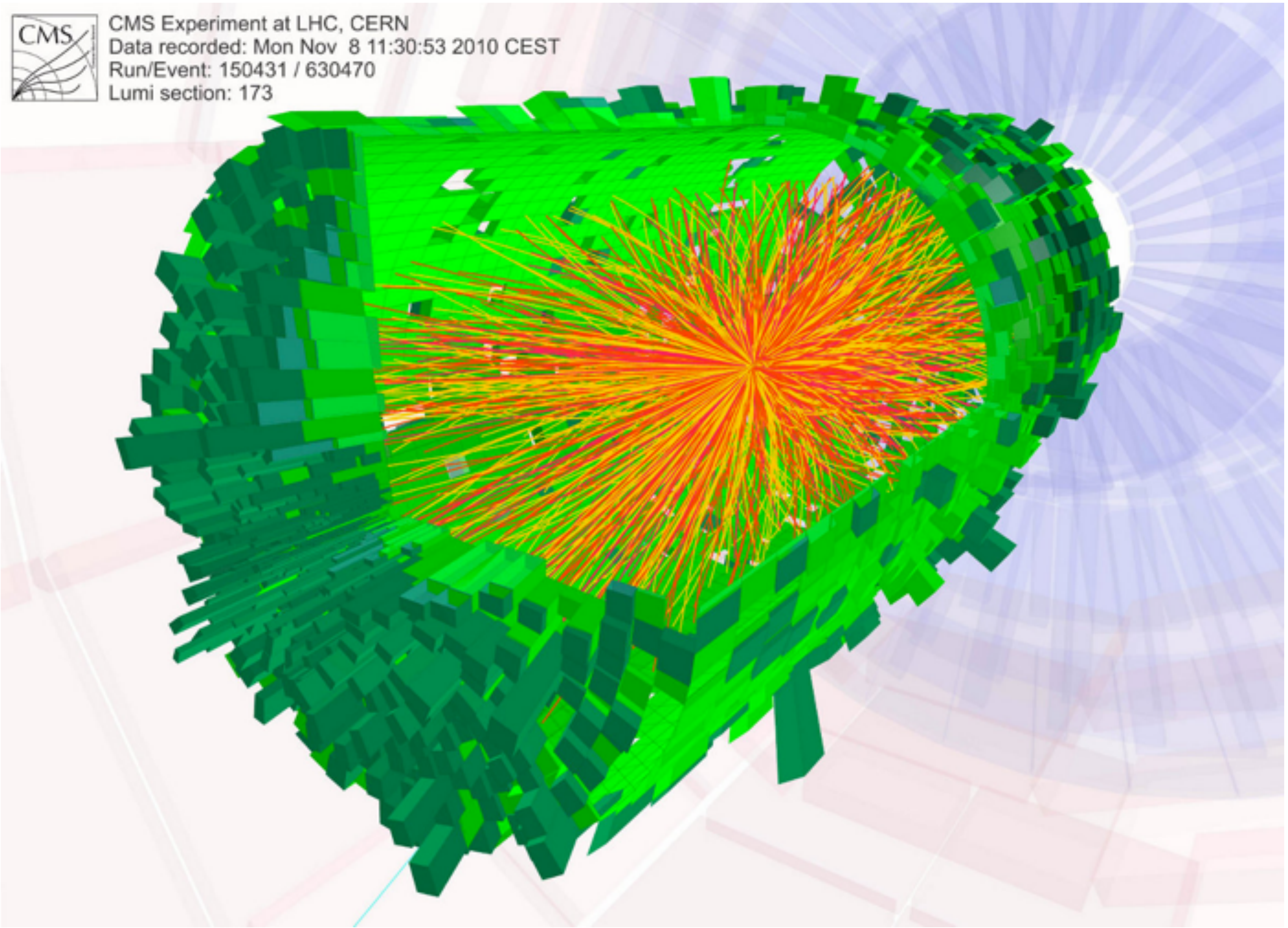
The Environment



$\langle n_{PV} \rangle = 140$

- HI experience with high-occupancy (but low-rate) conditions
  - Key challenges for Phase-2 are data rates, long-term detector behaviour

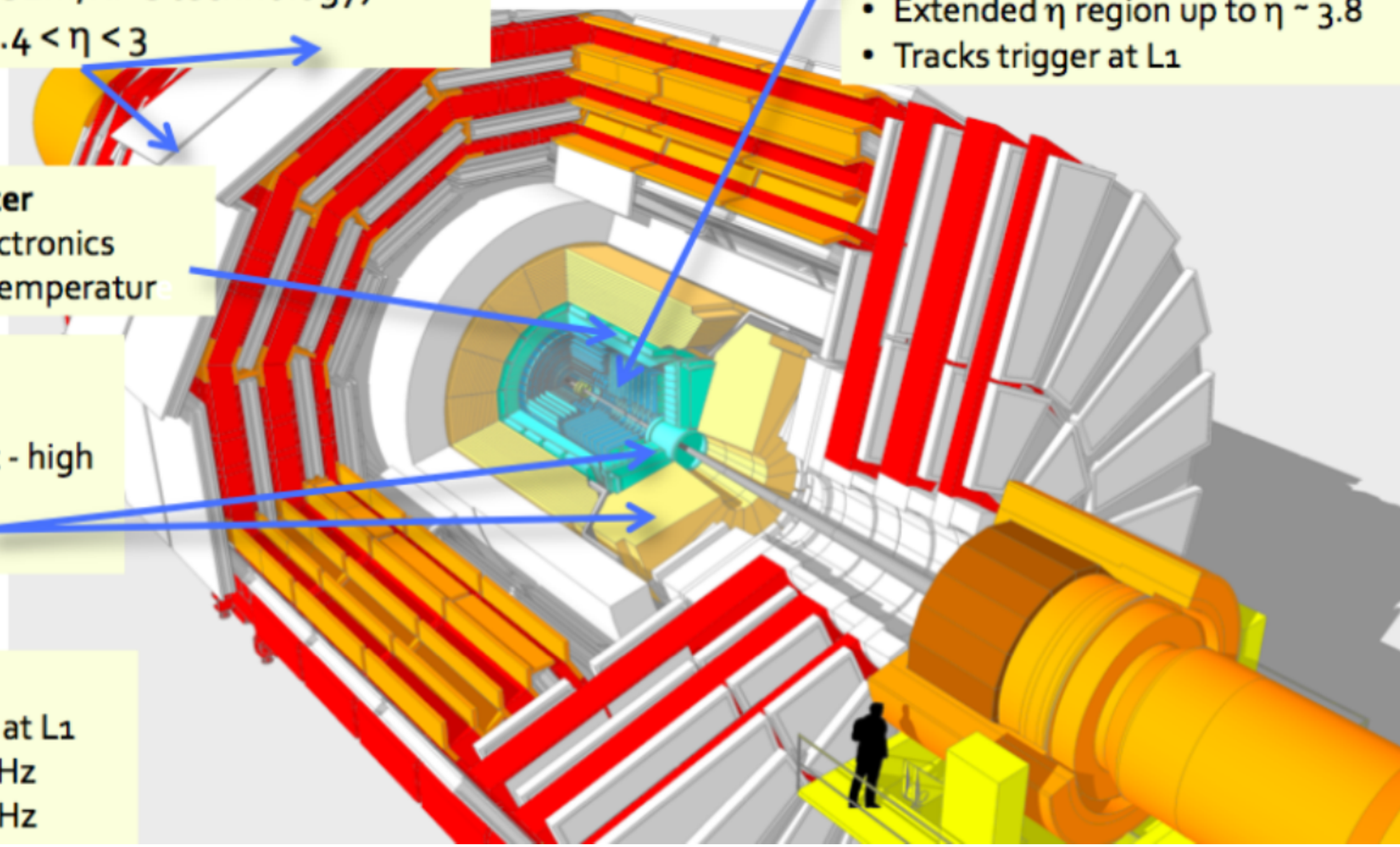
Some Themes

- Basic improvements
  - Denser environment: increased granularity everywhere
  - More particle flux: increased rad hardness
  - Complete new tracking systems for CMS and ATLAS
- Improved triggering and data-handling
  - Data rates increasing by 1.5 orders of magnitude
  - CMS: put tracks into L1 trigger: ultimate flexibility, but very hard
  - ATLAS: improve fast tracking at L2, much higher L1 trigger rate
- Completely new detector techniques
  - Precision timing layers, to triangulate position of overlapping vertices
  - CMS: 'particle flow' reconstruction on the detector: HGC endcap calo
- Status of approval
  - CMS / ATLAS upgrade ~250MCHF each (LHCb also has ambitions)
  - LHCC approval just starting now; construction kicks off in 2019

CMS Upgrade

Muon System
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$ (new GEM/RPC technology)
- Muon-tagging $2.4 < \eta < 3$

Replace Tracker
- Radiation tolerant - higher granularity - less material -better p_T resolution
- Extended η region up to η ~ 3.8
- Tracks trigger at L1

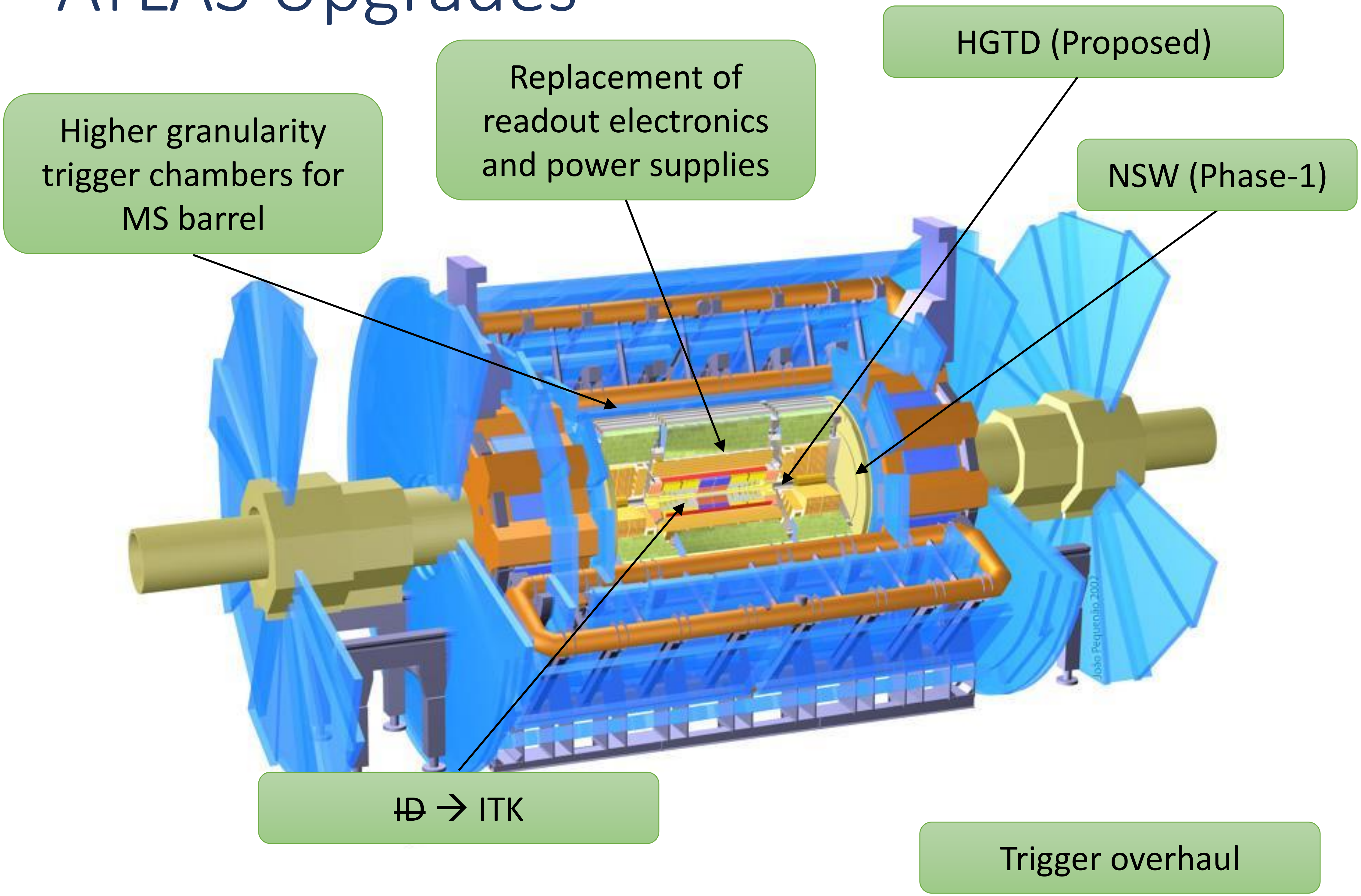


Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature

Replace endcap Calorimeters
- Radiation tolerant - high granularity
- 3D capability

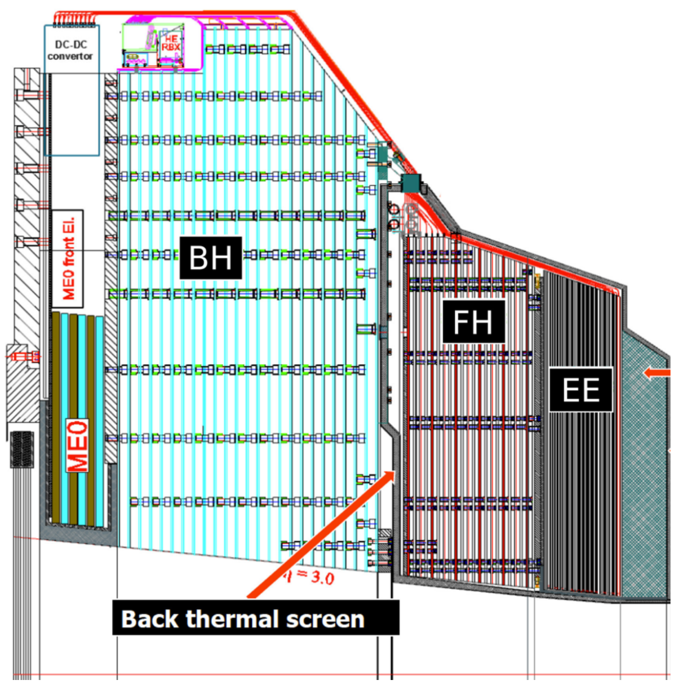
Trigger/HLT/DAQ
- Track information at L1
- L1-Trigger ~ 750 kHz
- HLT output ~7.5 kHz

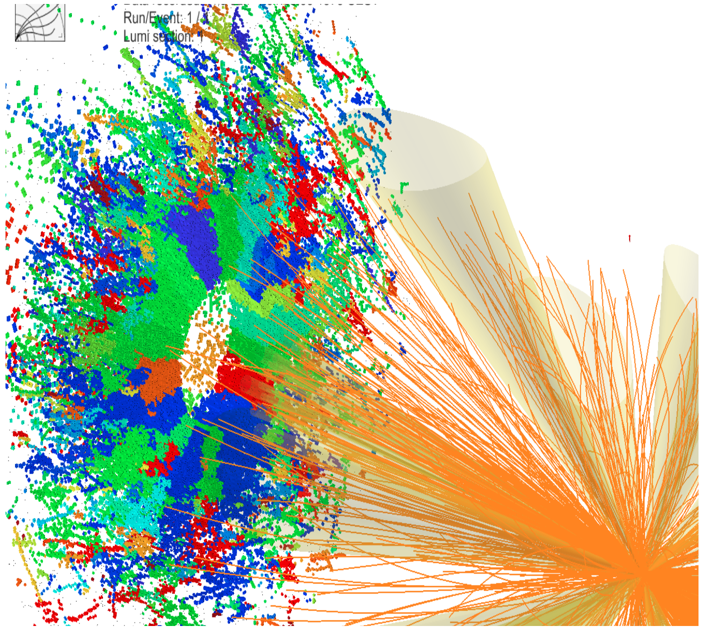
ATLAS Upgrades



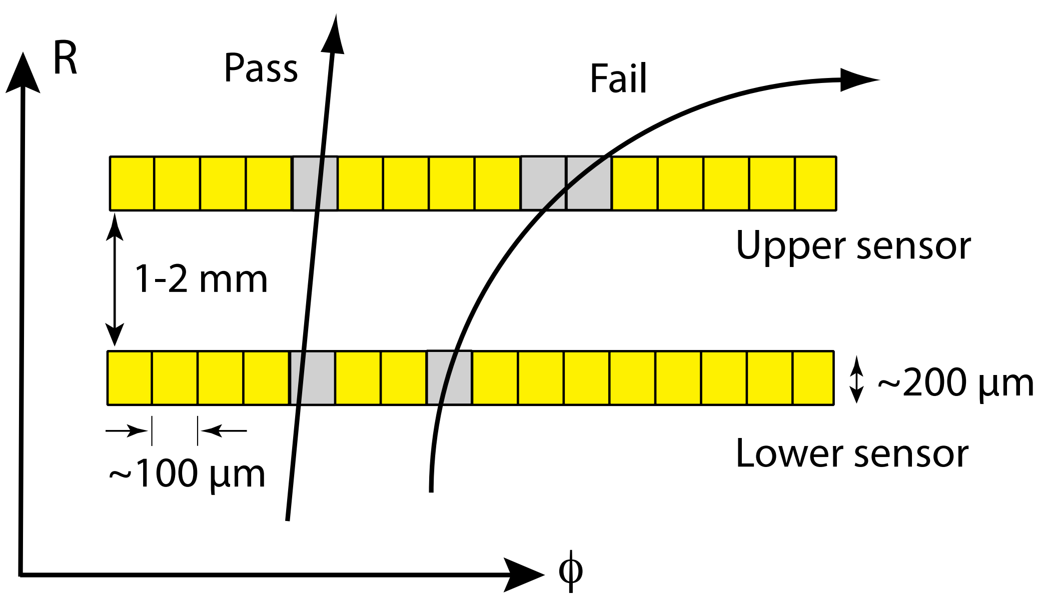
CMS UK Highlights

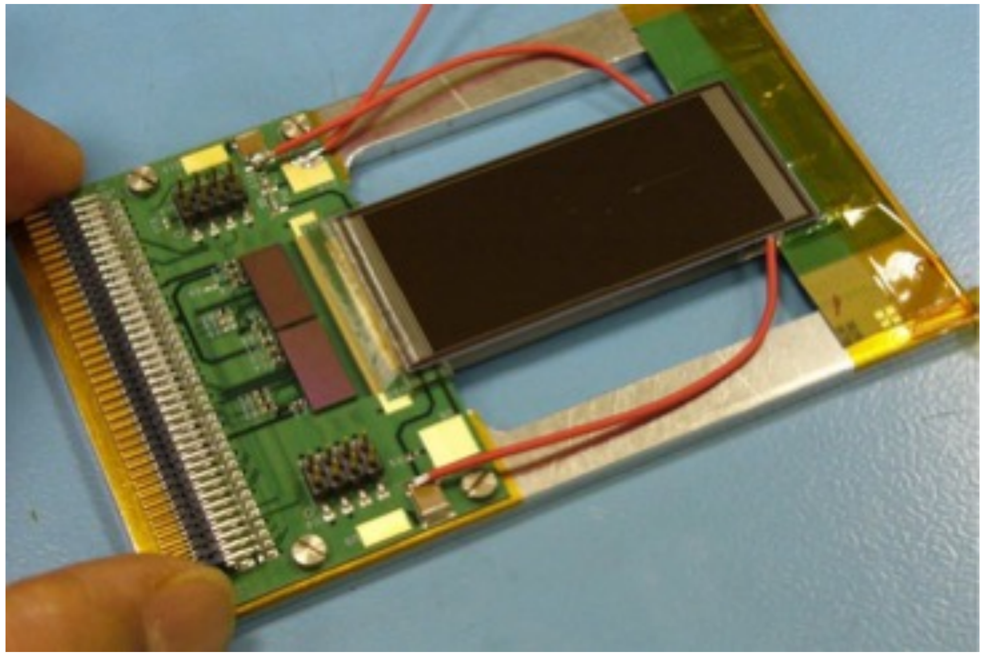
Calo



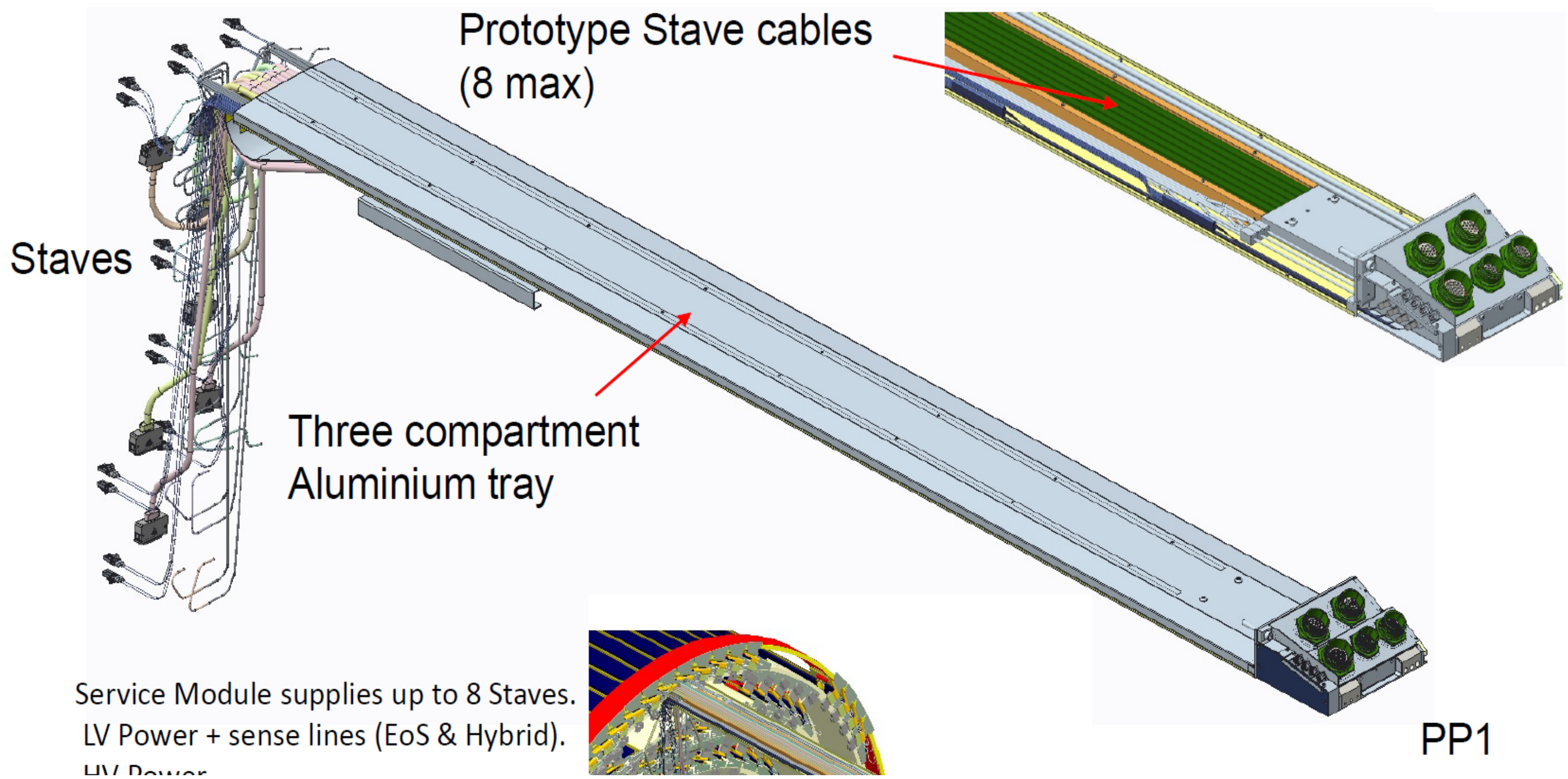


Tracking

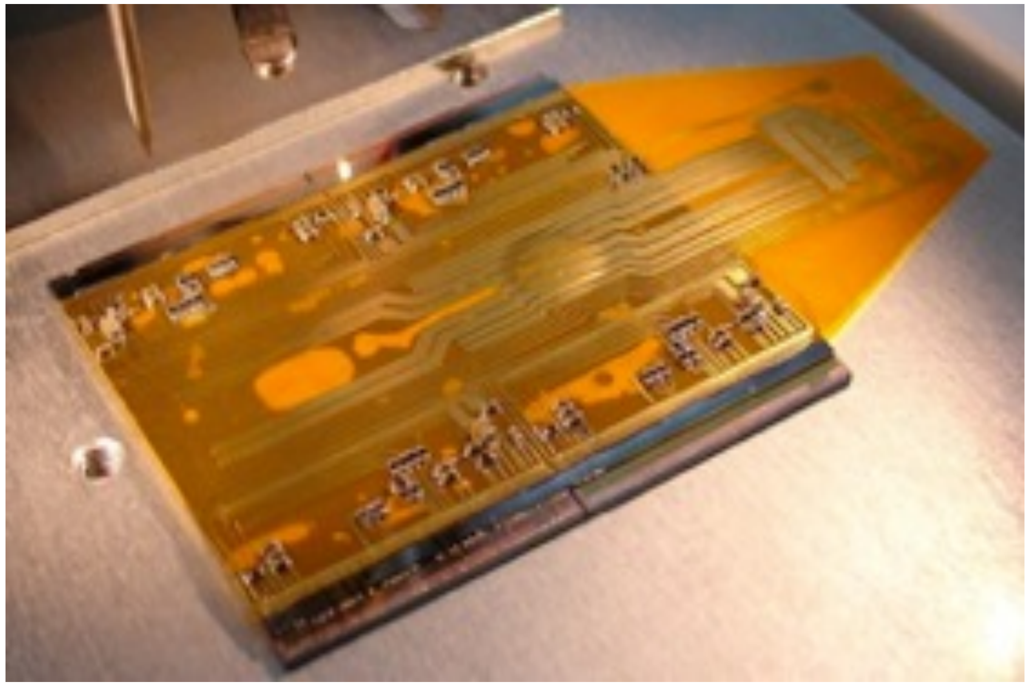




ATLAS UK Highlights



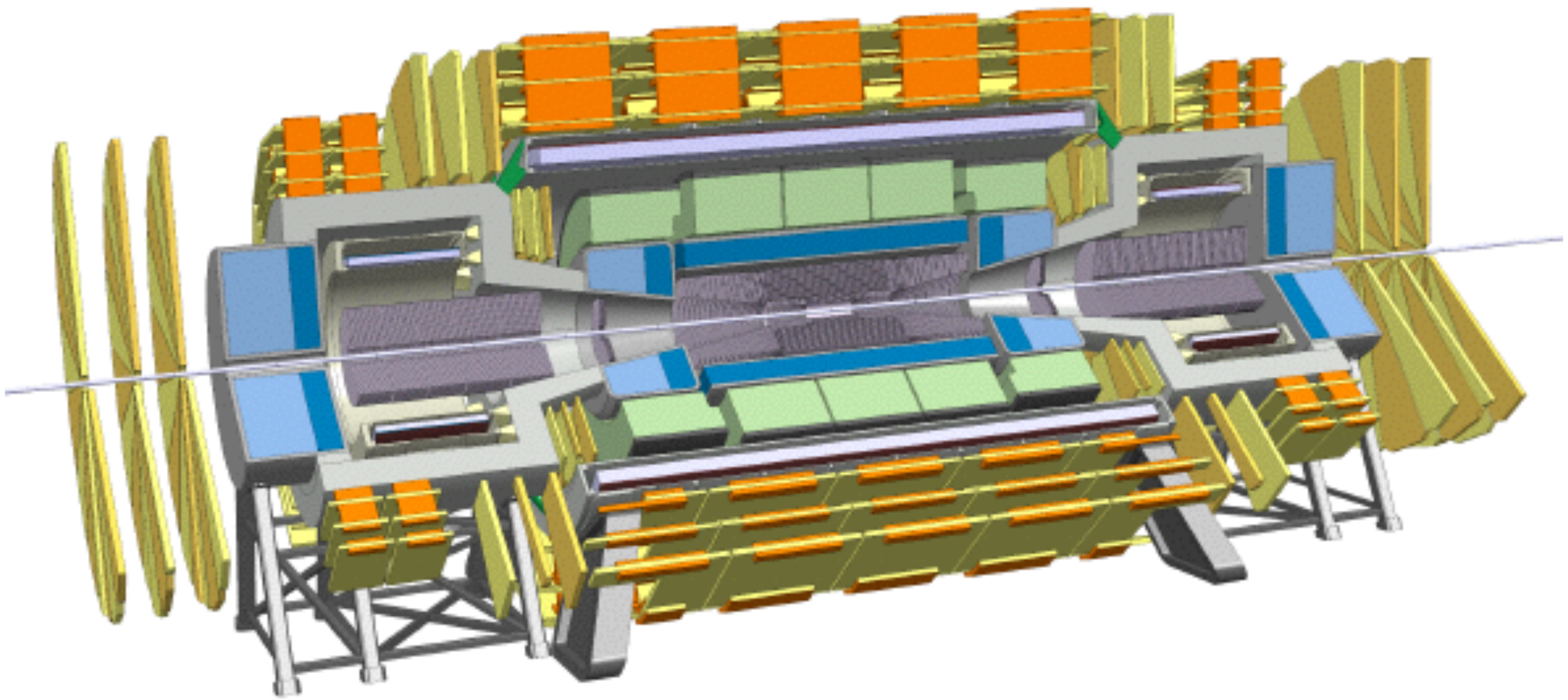
Prototype stave design - ITK

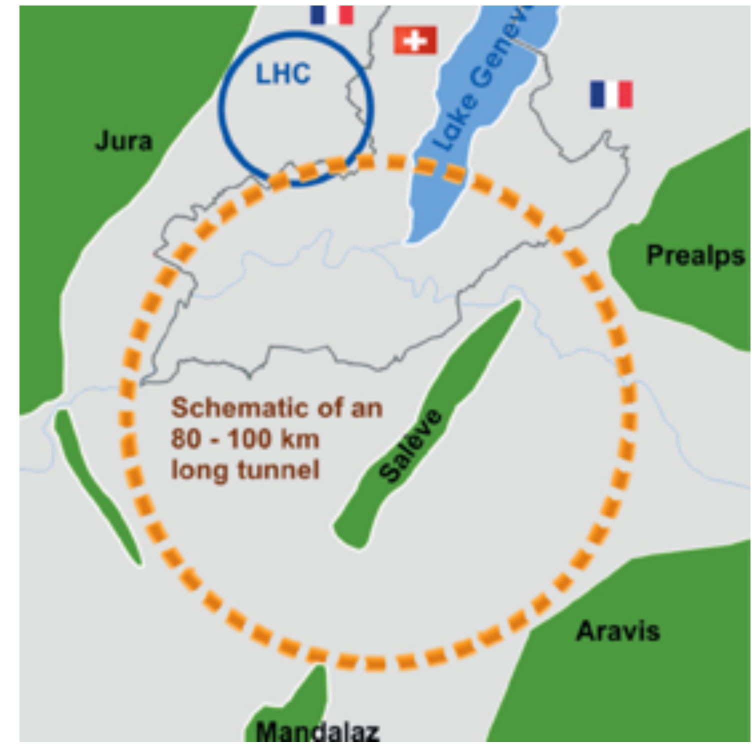


Prototype tracker module

EFEX L1 trigger upgrade card

The Far Future (2035++)





- FCC-hh design study due to report in 2018
  - 100TeV, 100km machine, 16T dipoles (similiar tech to an HE-LHC)
  - Detectors will be 'technologically challenging' — much R&D needed
- Physics
  - Discovery 40TeV q*/Z', 10TeV gluino; few % on Higgs self-coupling
  - Of course, we expect to be doing *new* and more exciting physics by 2035++
- Plea for help from phenomenologists — physics case and data selection
  - It is not at all obvious how or on what to trigger at such a machine!

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Summary

- LHC alive, well, and hard at work
  - Machine performance continues to improve -> 'production mode'
  - Experimental programme progressing, but things are getting harder…
- Physics programme
  - No signs of new physics yet — patience and care required now
  - Several tensions with SM in the flavour section; more to come here
  - Higgs physics entering the precision era
  - NP searches at GPDs finding new ways to probe into cracks and corners
- Long term future
  - We have only 3% of the 3/ab dataset!
  - New era of experiment construction for HL-LHC coming soon — busy times
  - A new machine, new backgrounds, new problems, but physics in 2026
- Interaction between experiment and theory
  - Clearly in rude health, thank you!
  - The 'hard thinking starts here' – new ideas please!