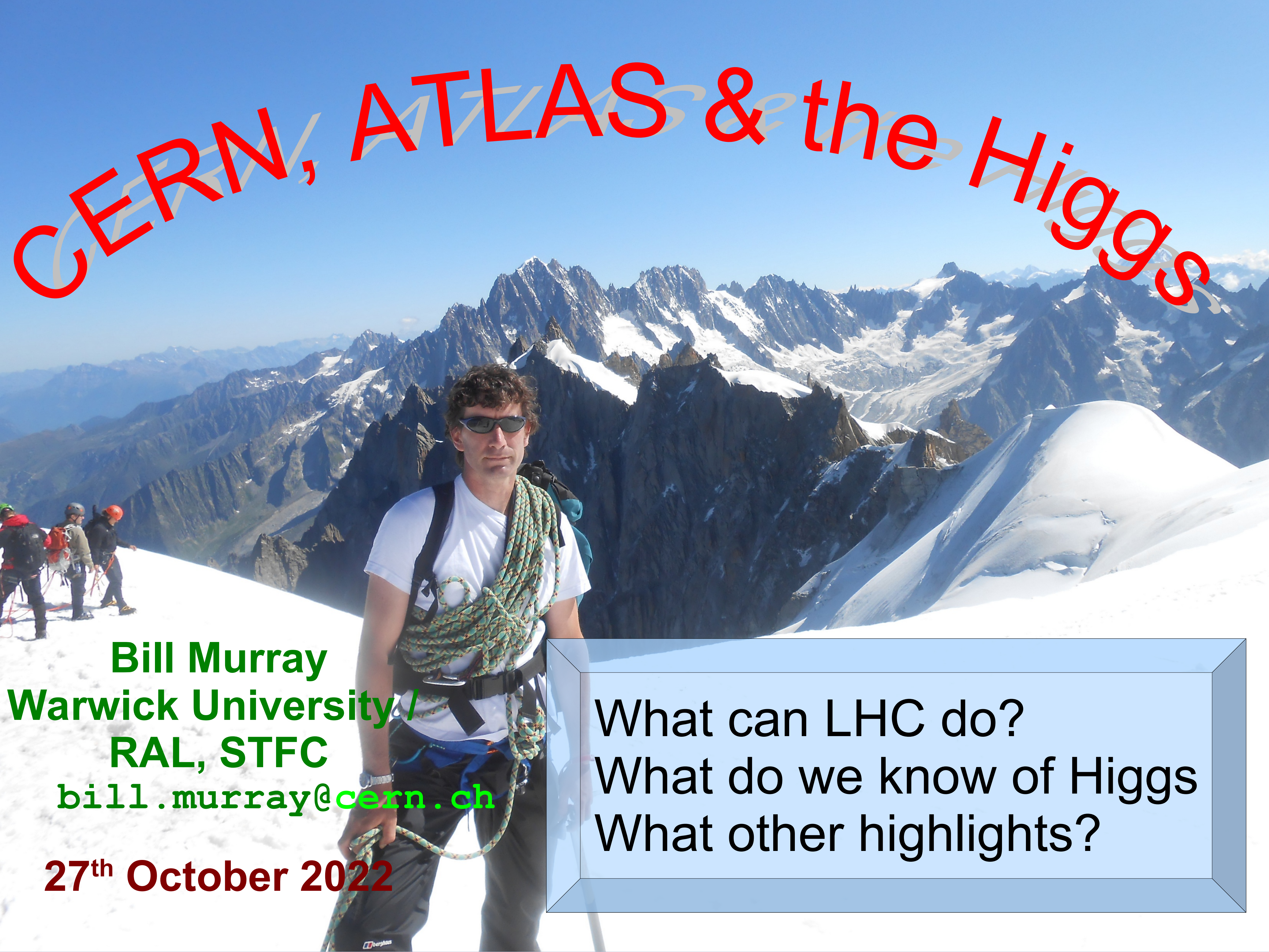


CERN, ATLAS & the Higgs

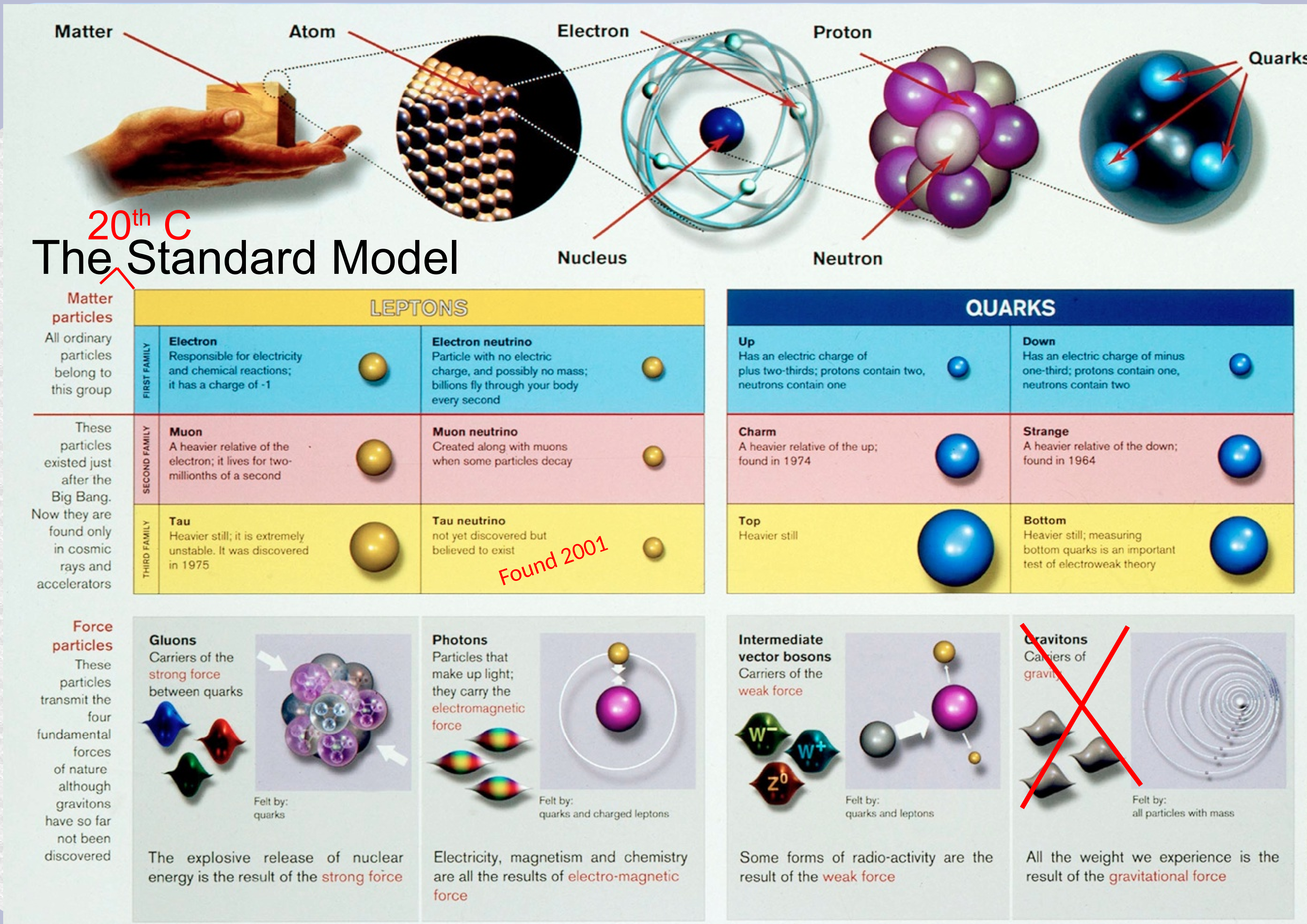
Bill Murray
Warwick University / RAL, STFC
bill.murray@cern.ch

27th October 2022

What can LHC do?
What do we know of Higgs
What other highlights?

Science and Technology Facilities Council

WARWICK THE UNIVERSITY OF WARWICK




Matter
Atom
Electron
Proton
Quarks
Nucleus
Neutron
The Standard Model
No Higgs!
Matter particles
All ordinary particles belong to this group
These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators
LEPTONS
QUARKS
FIRST FAMILY
SECOND FAMILY
THIRD FAMILY
Electron
Responsible for electricity and chemical reactions; it has a charge of -1
Electron neutrino
Particle with no electric
Up
Has an electric charge of plus two-thirds; protons contain two, neutrons contain one
Down
Has an electric charge of minus one-third; protons contain one, neutrons contain two
Muon
A heavier relative of the electron; it lives for two-millionths of a second
Strange
A heavier relative of the down; found in 1964
Tau
Heavier still; it is extremely unstable. It was discovered in 1975
Tau neutrino
not yet discovered but believed to exist
Found 2001
Heavier still
Bottom
Heavier still; measuring bottom quarks is an important test of electroweak theory
Force particles
These particles transmit the four fundamental forces of nature although gravitons have so far not been discovered
Gluons
Carriers of the strong force between quarks
Felt by: quarks
The explosive release of nuclear energy is the result of the strong force
Photons
Particles that make up light; they carry the electromagnetic force
Felt by: quarks and charged leptons
Electricity, magnetism and chemistry are all the results of electro-magnetic force
Intermediate vector bosons
Carriers of the weak force
W⁻
W⁺
Z⁰
Felt by: quarks and leptons
Some forms of radio-activity are the result of the weak force
Felt by: all particles with mass
All the weight we experience is the result of the gravitational force
GRAPHICS: PETER CROWTHER

Open Questions

- Mass (Philosophy or science?)
  - Why do particle have the masses they do?
- Gravity
  - there is no gravity in the Standard Model
- Neutrino Mass
  - Neutrinos have mass – but how? We do not know
- Dark matter
  - Most matter in the Universe is something unknown
- Dark energy
  - An unknown force accelerates the Universe expansion
- Matter-antimatter asymmetry
  - Where did the antimatter go after the big bang?
- The naturalness problem
  - I will explain this later

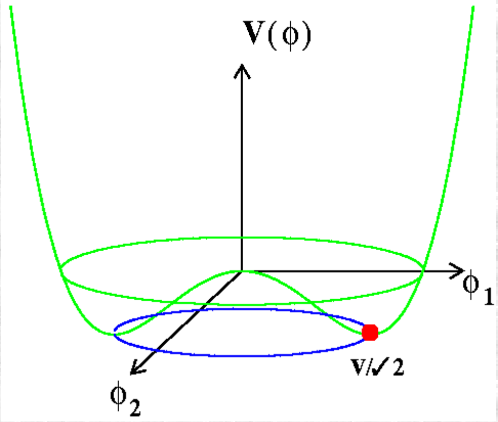
Mass: Higgs idea

- One problem was, the maths said all the particles should weigh nothing
  - That is not true
- But it is hard to change the equations, add mass
  - a mass term violates 'gauge symmetry'
- Peter Higgs et al, in 1964, had an idea.....

What is Higgs' mechanism?

- Doublet of SU(2)$_L$, $\Phi=(\Phi_1,\Phi_2)$
- Potential respects SU(2)$_L$
  But Vacuum does not!

$$V(\Phi) = \frac{\lambda}{3!}\left\{\overline{\Phi}\Phi - v^2/2\right\}^2$$



Fermions:

Interact with Higgs field slows them down → generates mass

Bosons:

SU(2)$_L$ interact, gain mass

U(1)$_\gamma$ and SU(3)$_c$ do not, massless

3 degrees of freedom in Boson masses
4th becomes fundamental scalar

- Go to PX430

Higgs' idea of mass

- Think of a fish tank:

Science and Technology Facilities Council

WARWICK
THE UNIVERSITY OF WARWICK

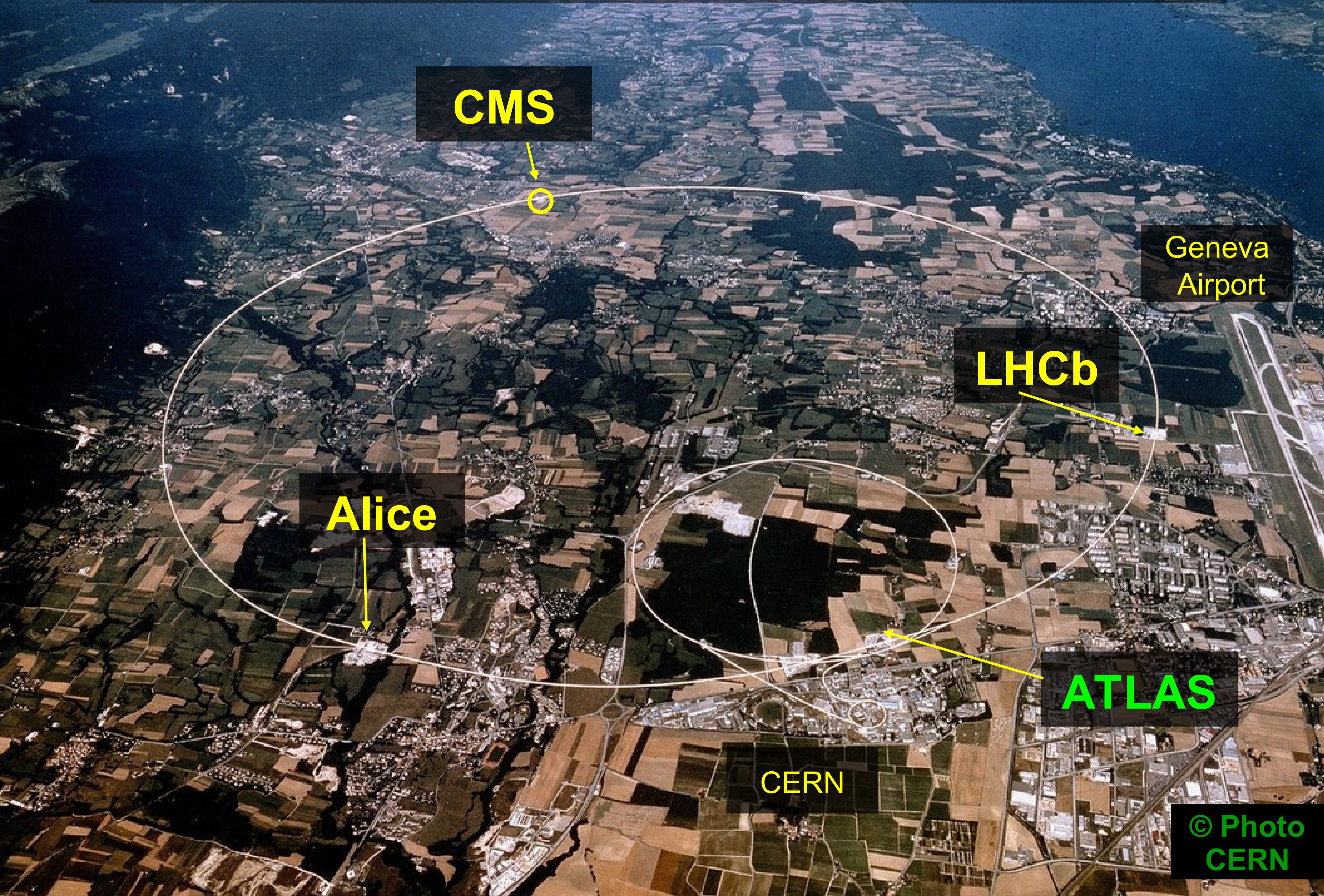
Empty the tank

- The fish will call this an empty tank
- but it still has water in it

Higgs theory

- Maybe the same applies to us?
- What if empty space is actually full of stuff
  - A field of weak charge everywhere
    - It slows you down moving through it
    - And we feel that drag as mass
  - If we could get outside then we would be massless
    - But we cannot.
- How do we know if its true?
  - If we kick the 'water' (or Higgs field) we should make it ripple
  - The ripple is called the Higgs boson
- But how do we kick the Higgs field?
  - Build the LHC!

A huge accelerator: CERN's LHC



LHC operation

- LHC accelerates protons to 6.8 TeV (6800 GeV)
  - Tevatron (previous accelerator) got to 1000 GeV
  - 1eV is the energy an electron gets from a 1V battery
  - 1 GeV is the energy required to make a proton ($E=mc^2$)
  - Speed is 0.99999998c
- They circle the 27km tunnel 11,000 times / second
- The pass the accelerating cavities a million time in only 100 seconds
  - Increasing their energy is not really the problem
- Making the bending them is the tough job
  - Consider the lateral acceleration…. 10^{17}G
  - 8.3Tesla magnets
  - 12000 amps in a wire, coiled ~80 times
    - This is superconducting, or I^2R losses would be huge

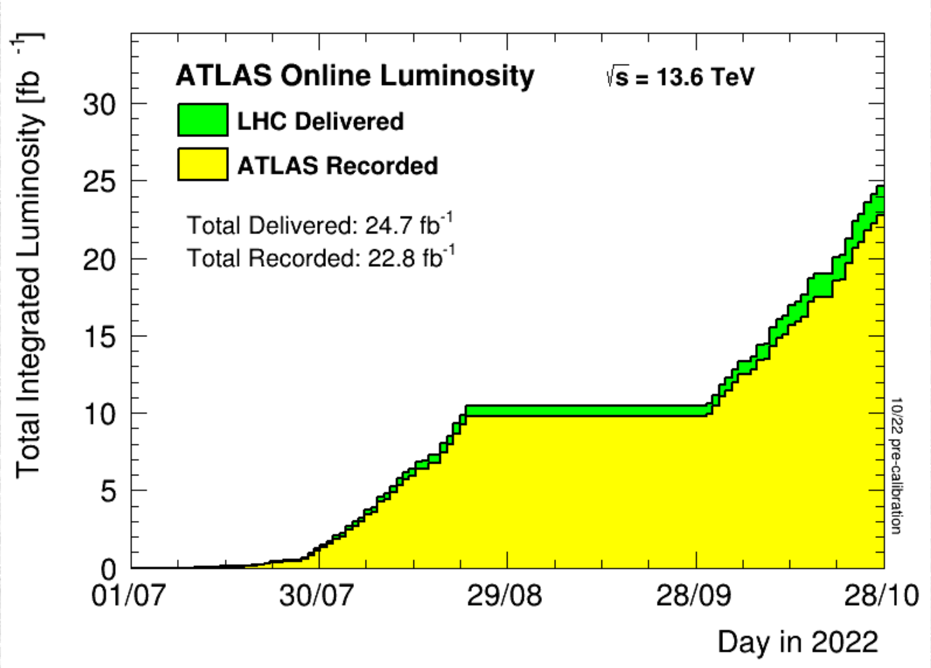
LHC: A tool to address them

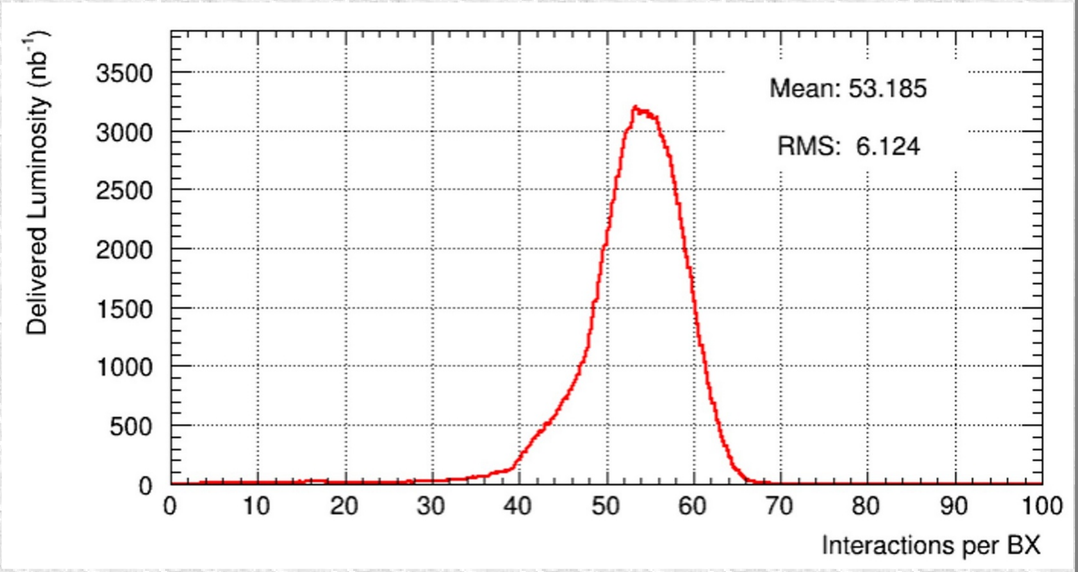
- Collides protons at 6.8 TeV on 6.8 TeV
  - c/f Tevatron, previous record, of 1 TeV on 1 TeV
- At a luminosity (measure of collision rate) 2 10^{34}cm^{-2}s^{-1}
  - Against the Tevatron's 4 10^{32}cm^{-2}s^{-1}: 50 times more
  - With 50 collisions each time the beams cross
- Together creating amazing numbers of new particles:
  - Thirty billion W bosons
  - Ten billion Z bosons
  - A hundred million top quark pairs
  - seven million Higgs bosons
- This allows detailed measurements of their properties
  - And searches for any new particles
- But lost in10000000000000000 proton-proton collisions
  - The `trigger' is vital – and I will skip it

ATLAS detector

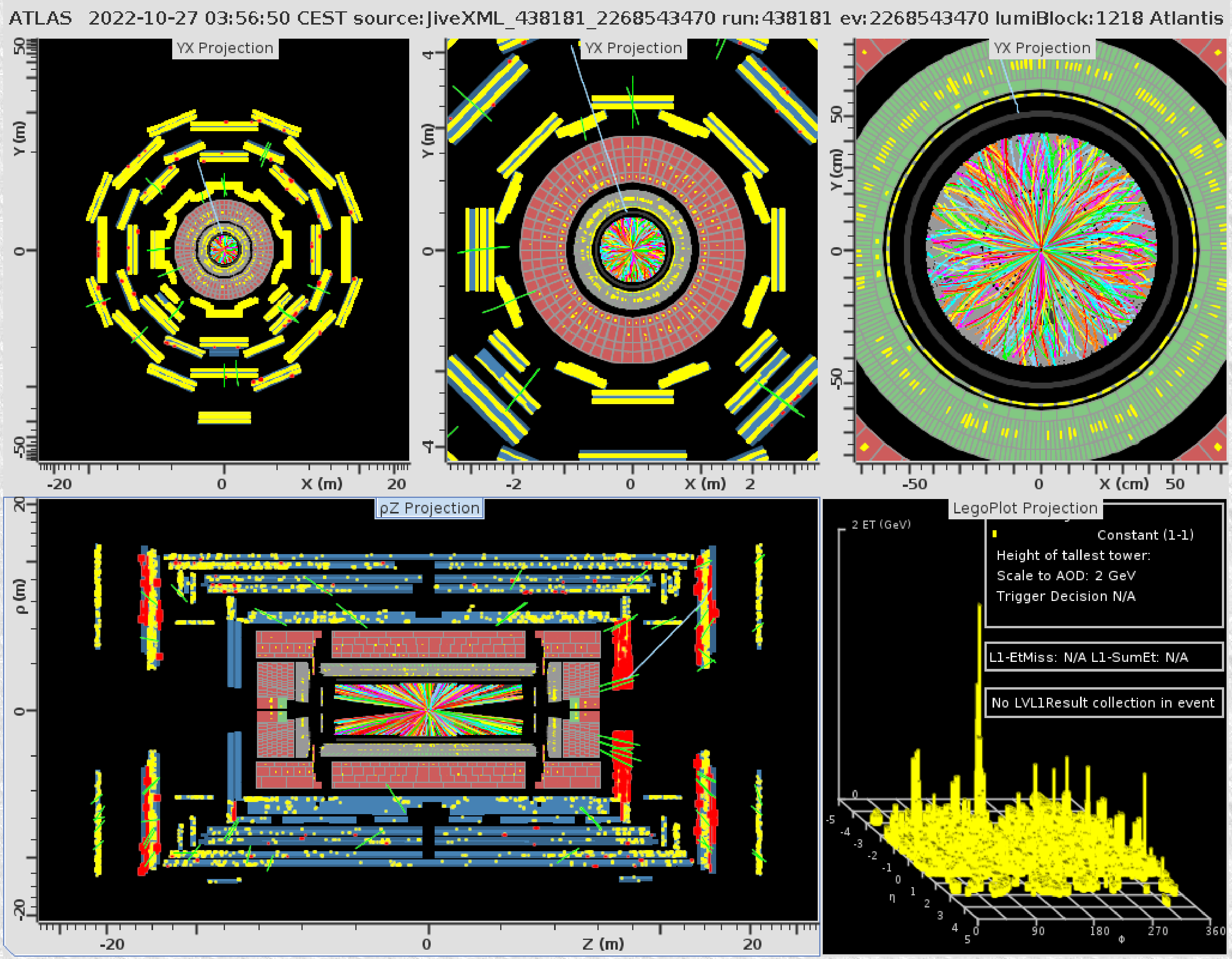
LHC & ATLAS status

- LHC performing well: many records broken this year
  - Beam energy: 6.8 TeV
  - Max charge per bunch: 1.38×10^{11}
  - Max beam charge: 3.33×10^{14}: 359 Megajoules (melt 16 tons lead)
  - Lumi in a fill: $0.776 fb^{-1}$
  - Lumi in a day: $1.134 fb^{-1}$
- $22.8 fb^{-1}$ recorded in Run 3; but with huge pileup



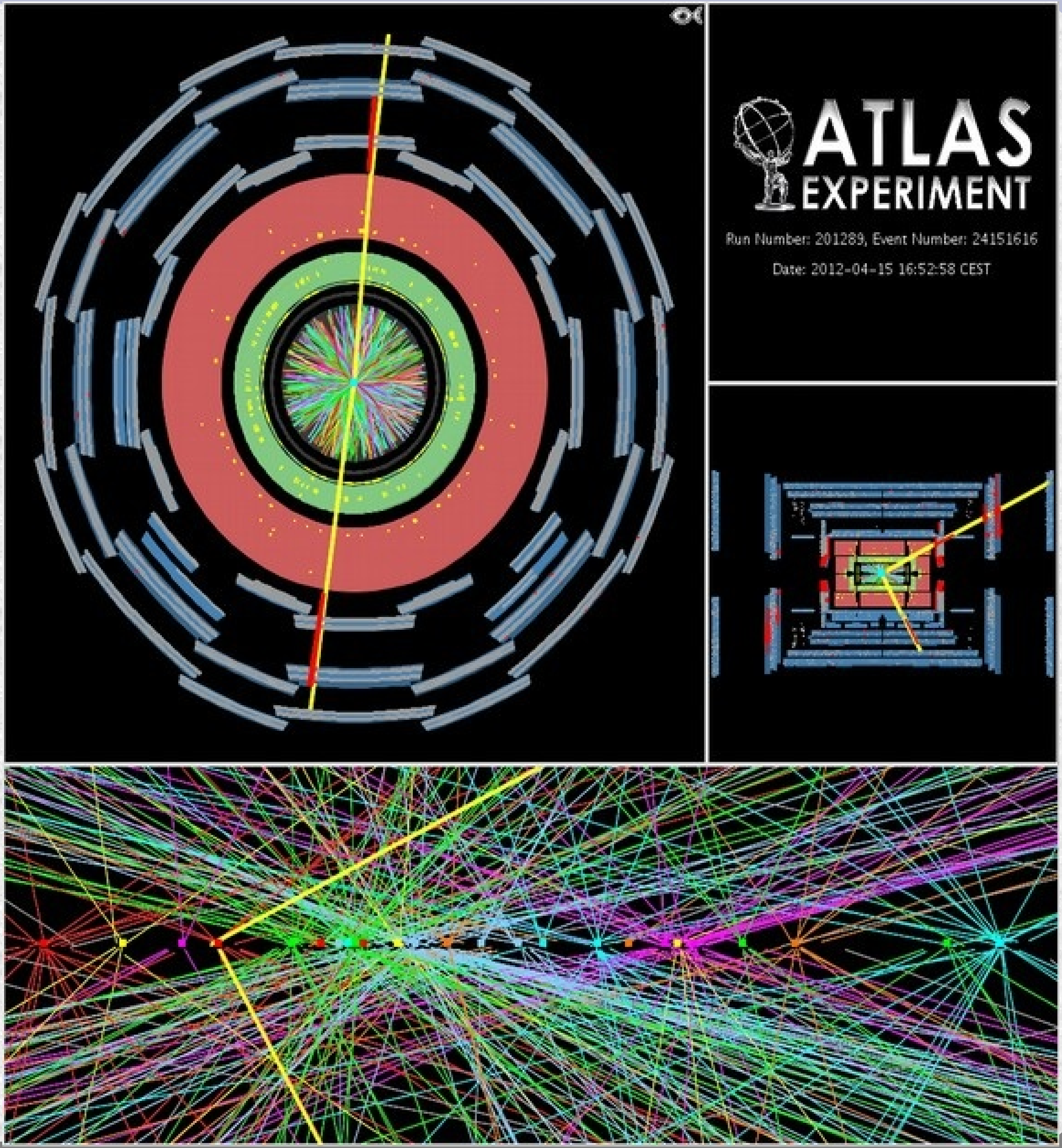


A collision recorded this morning

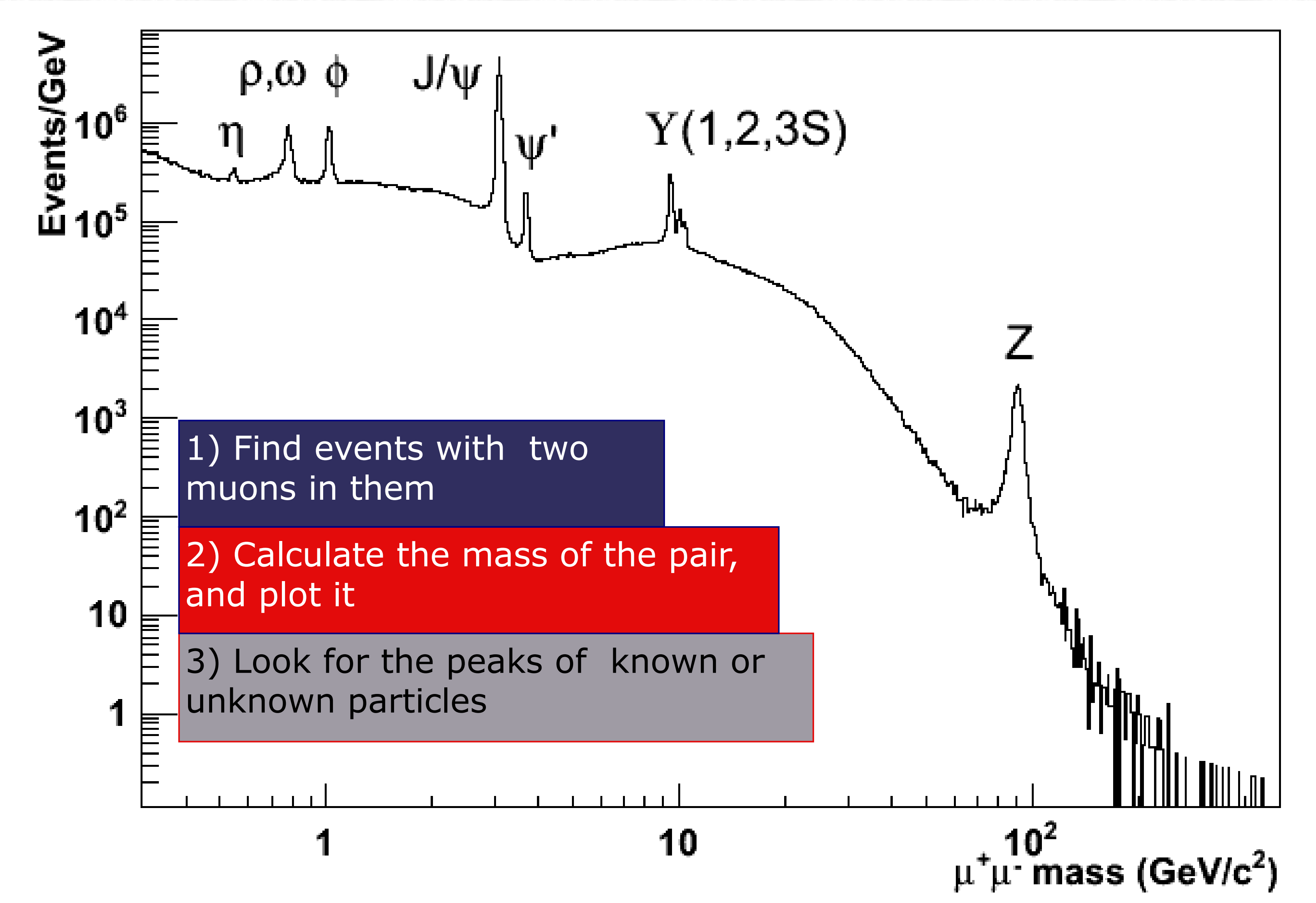


Here is an event with 2 muons

- Most particles are stopped at the green calorimeter
- Muons get right to the outside
  - Two are seen here
  - They are heavy copies of electrons
- They both come from the same collision
  - Are they connected?



Hunting for mass bumps



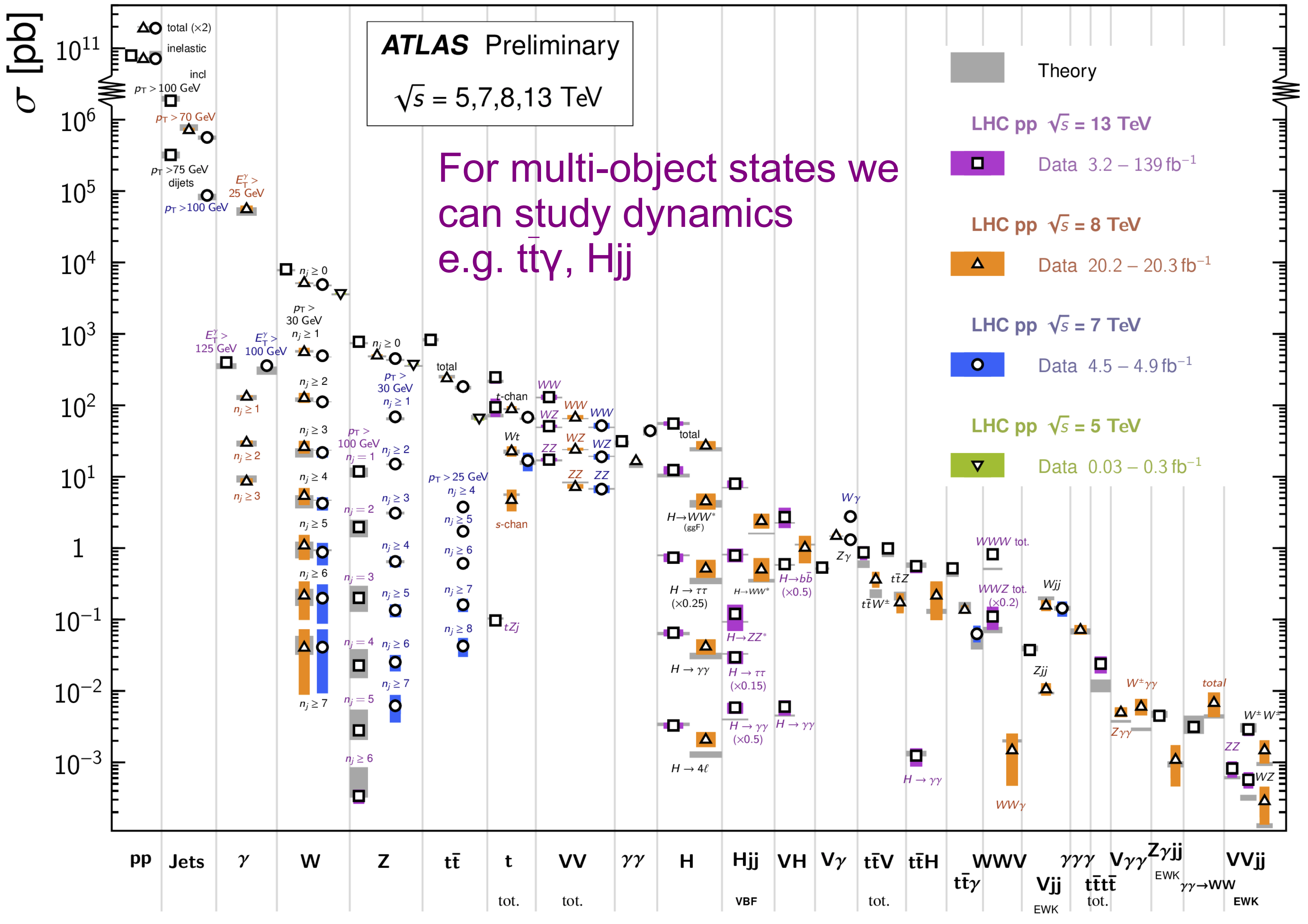
1) Find events with two muons in them

2) Calculate the mass of the pair, and plot it

3) Look for the peaks of known or unknown particles

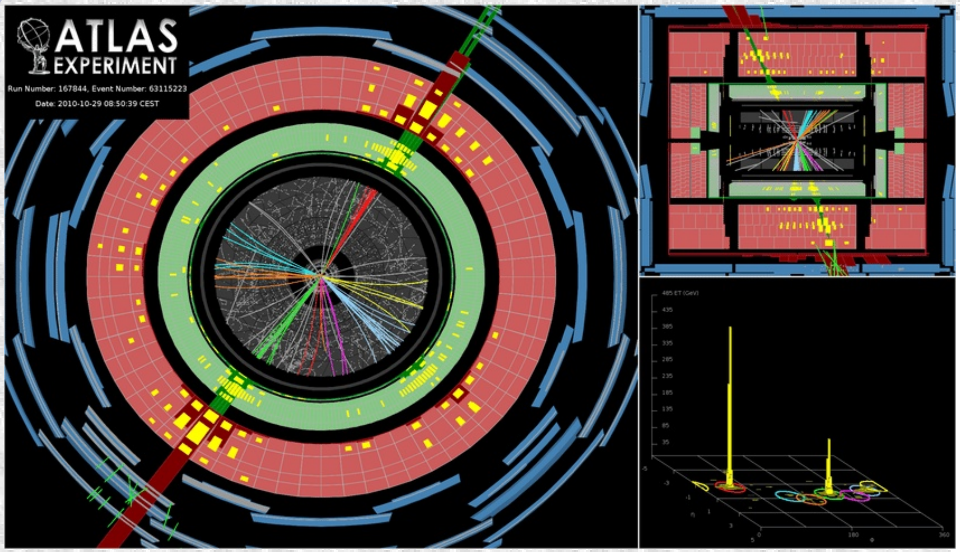
Standard Model Production Cross Section Measurements

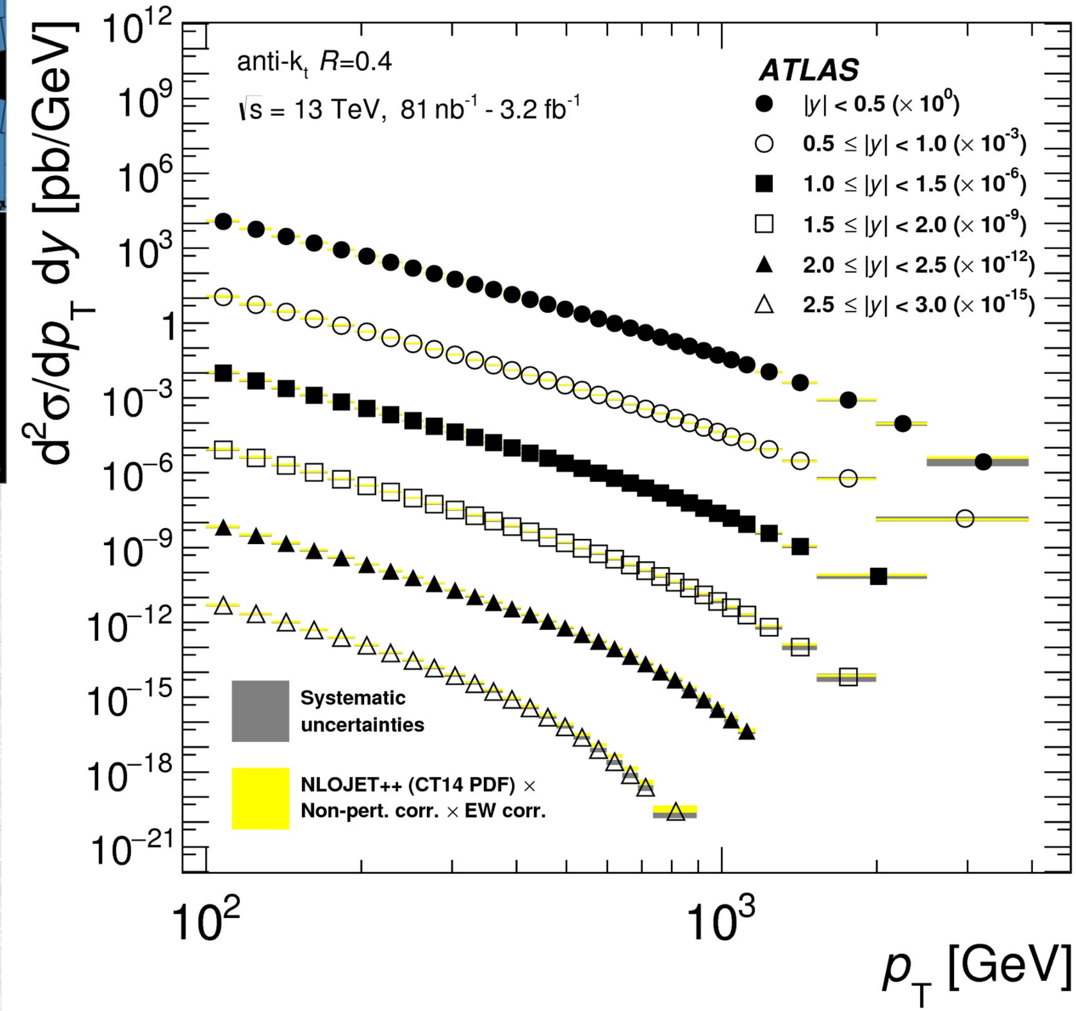
Status: February 2022



For multi-object states we can study dynamics e.g. $t\bar{t}\gamma$, Hjj

Jets: a spray of hadrons

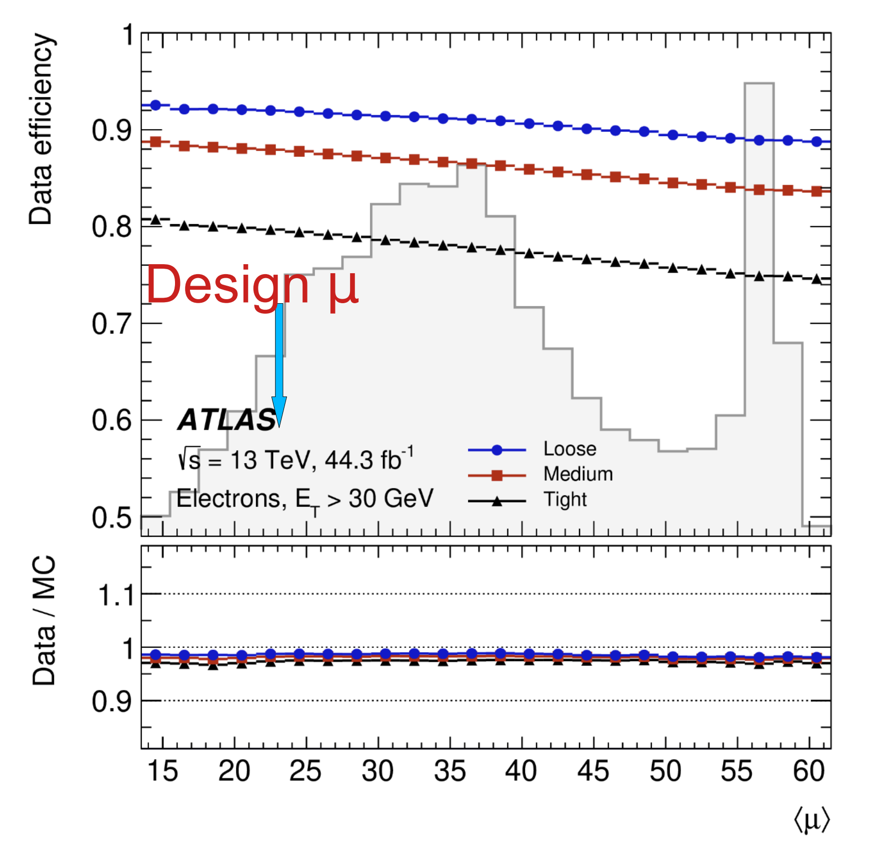


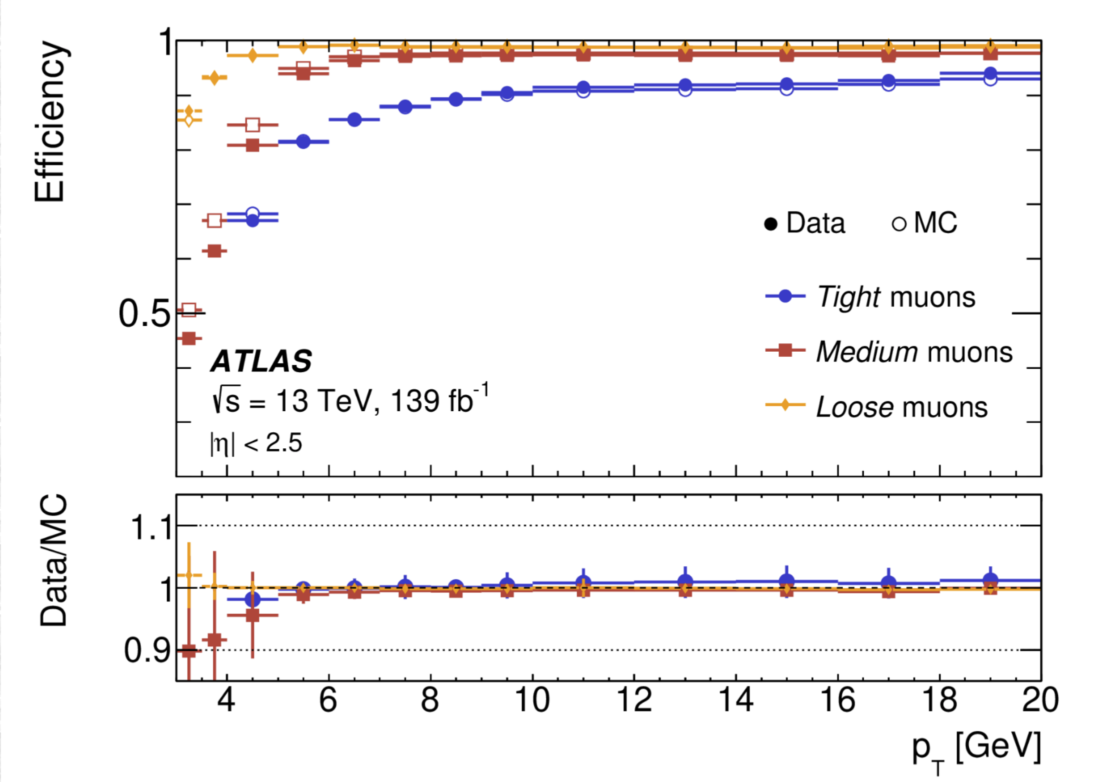


- Two partons scatter, but there are no free quarks
  - Instead $\pi^\pm$, π , K, p, n
  - Tricky to measure well
- A very common process
  - High momentum ones are less likely.

Performance and modelling

- Efficiency reasonable; limited pileup impact
- Measured in data using $Z \to l^+l^-$



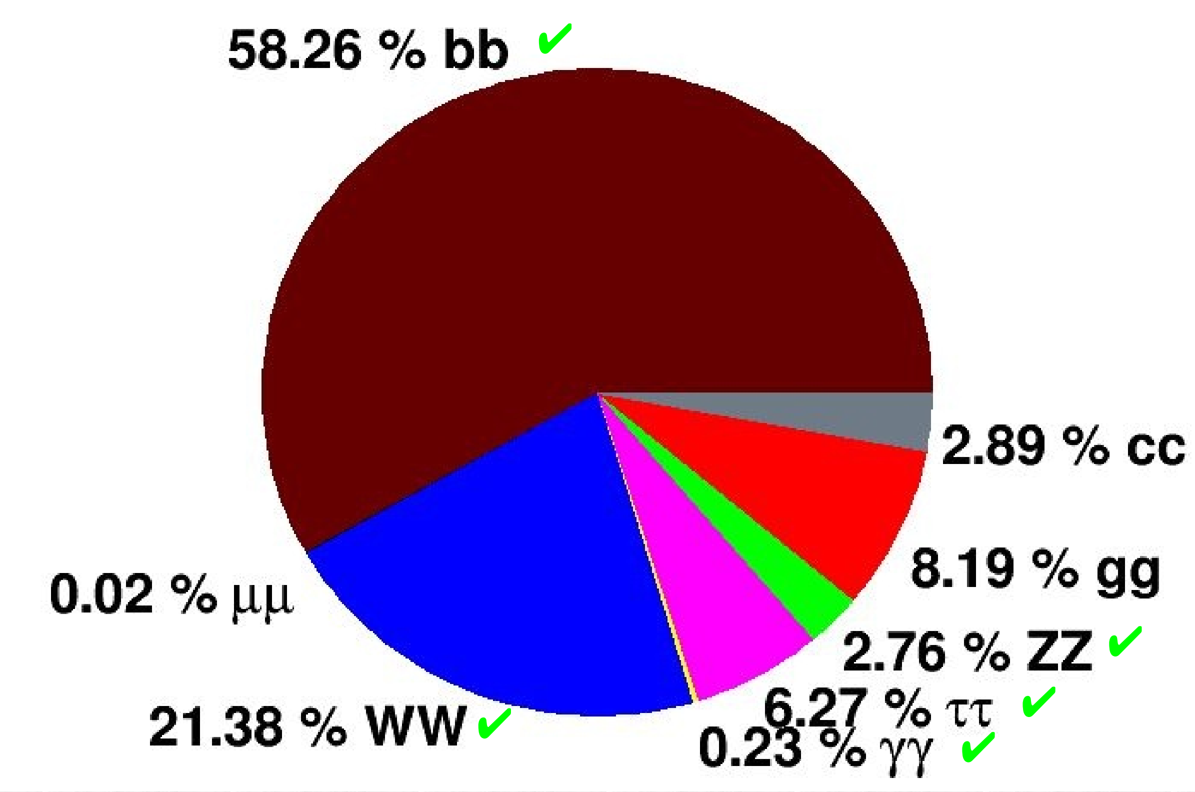


- Simulation model predicts the data well
  - Correction factors measured in data are used; generally close to 1

Higgs boson: 10 years on

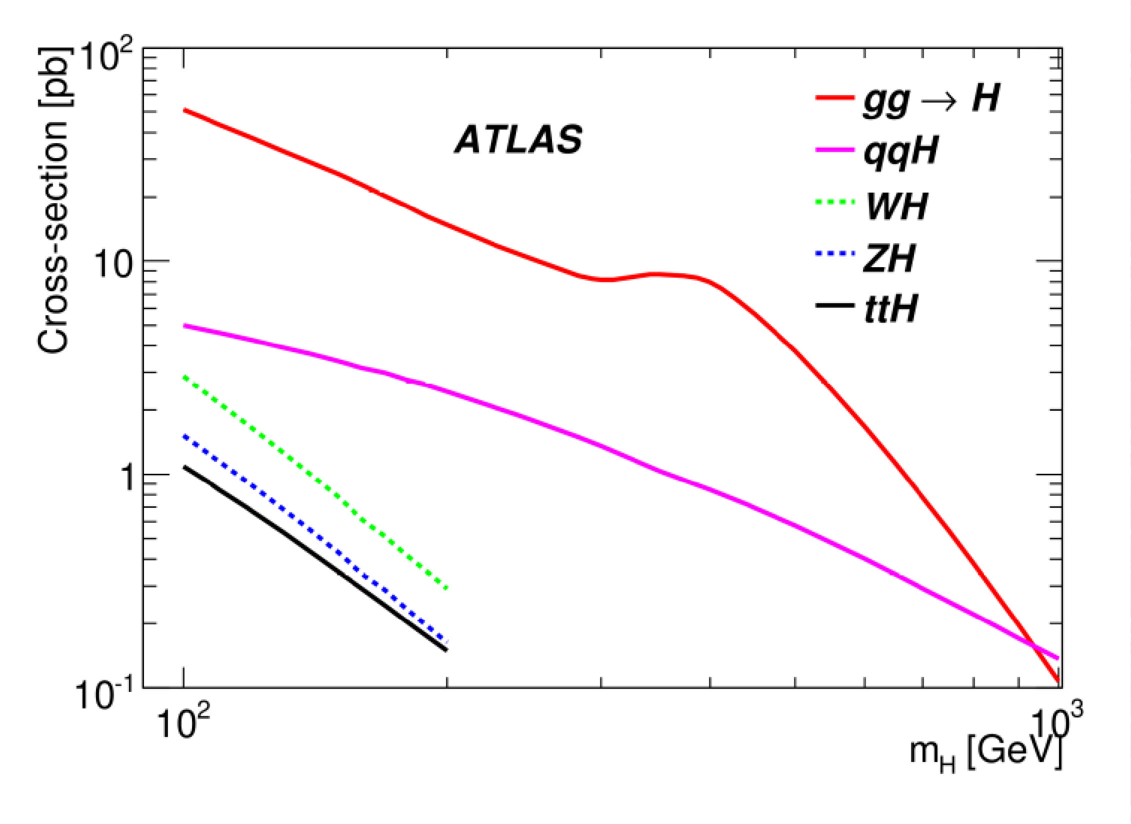
- The defining discovery of the LHC
- Decays to ZZ, $\gamma\gamma$, WW, $\tau\tau$, bb: all observed at 5σ
- Same for ggH, VBF, VH and ttH production

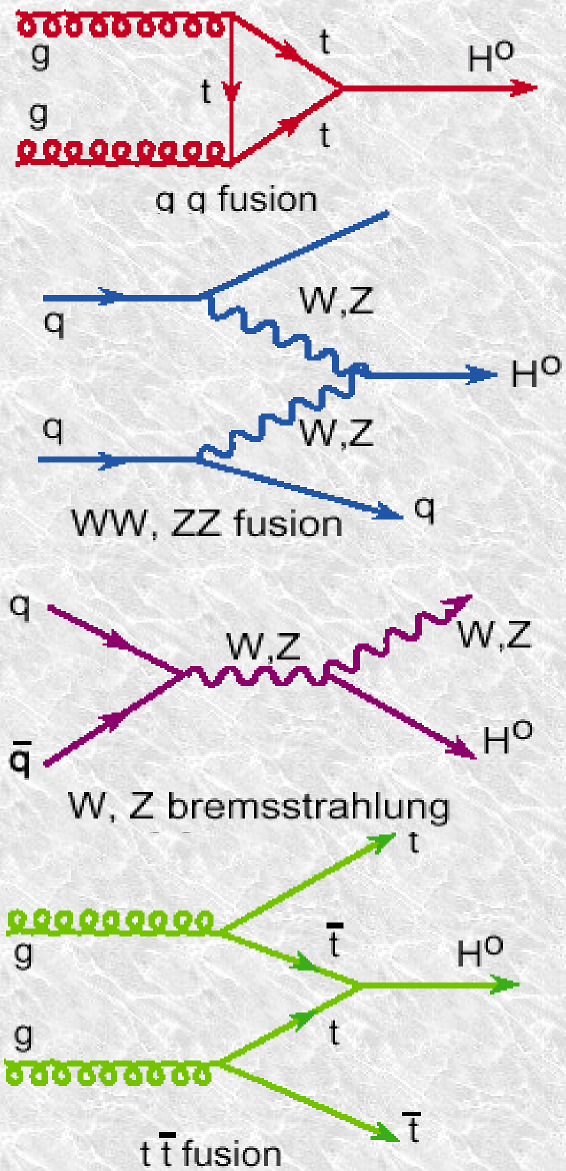
Higgs BRs



Higgs production

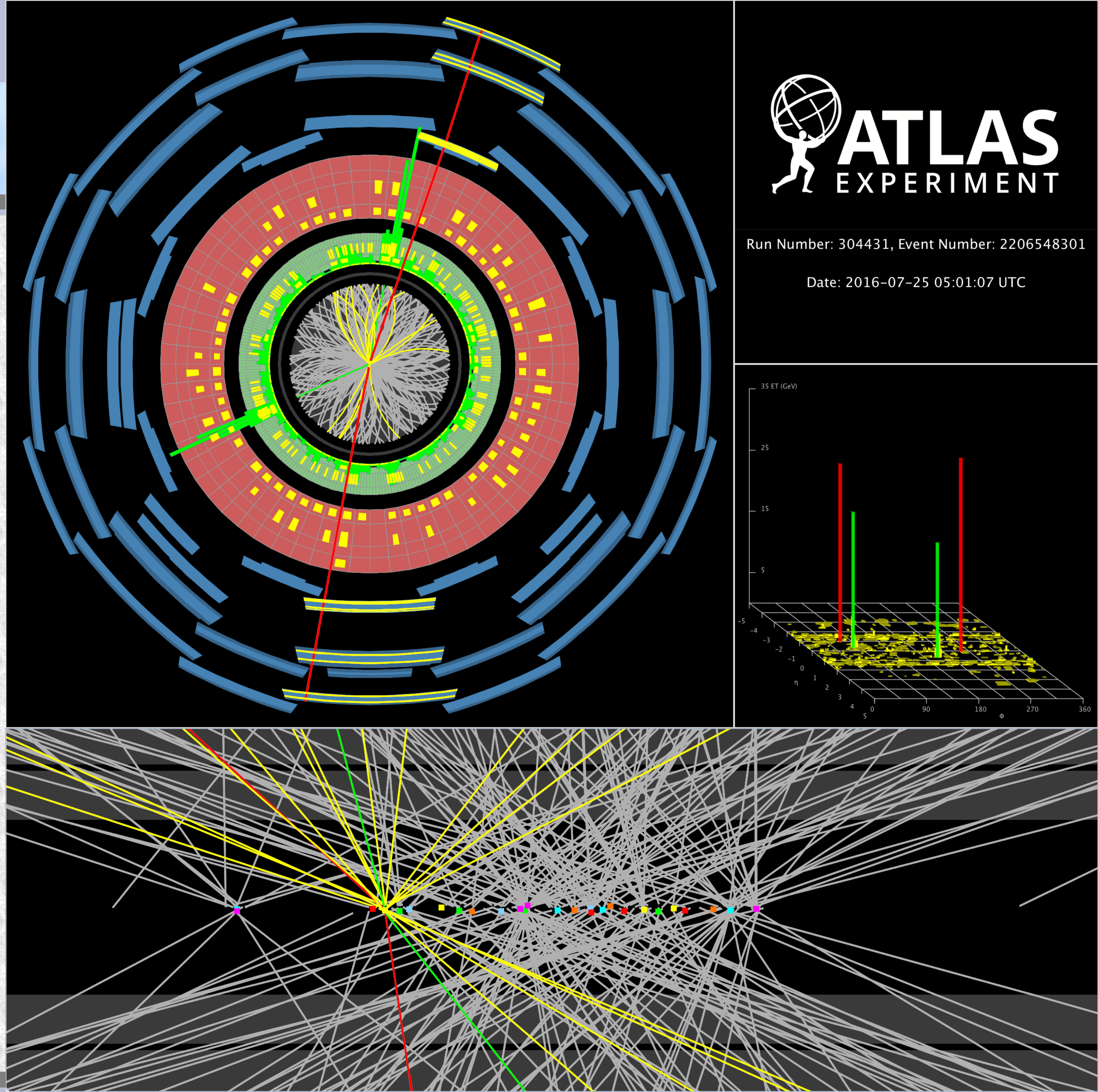
- Higgs interacts with mass
  - Quarks in proton are light
  - So typically make W,Z or t
    - Higgs produced from them





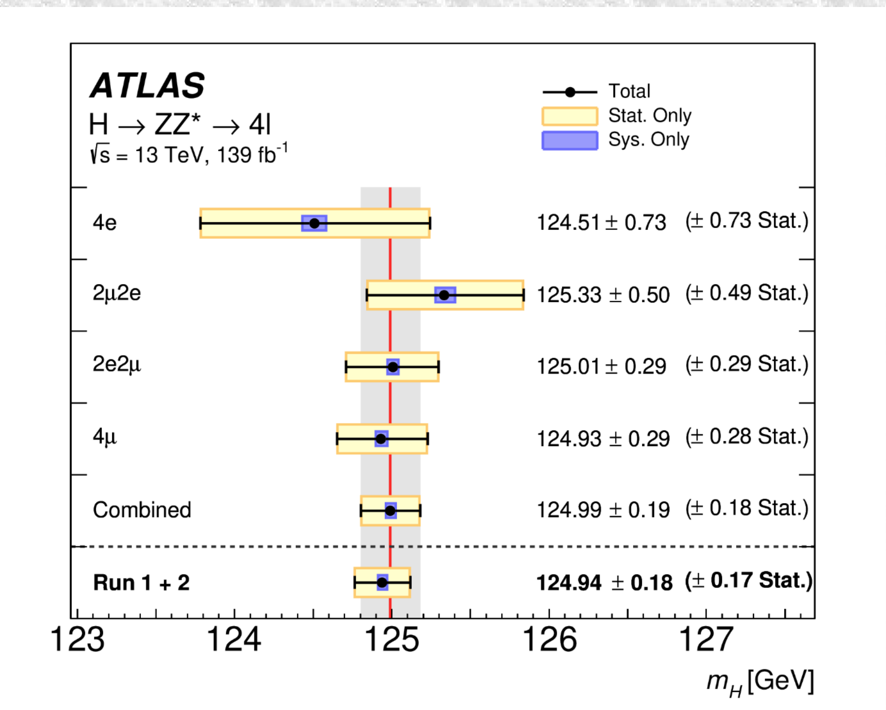
Science and Technology Facilities Council

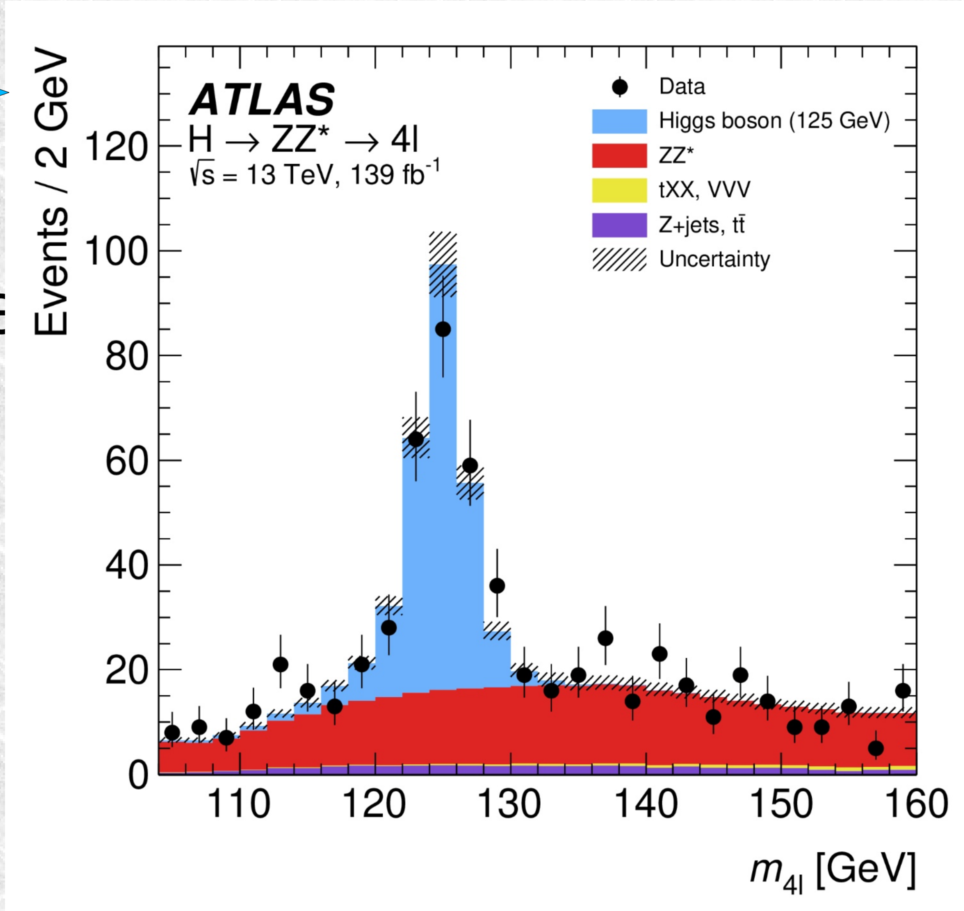
$H \to ZZ$
$\to llll$



H to ZZ & mass HIGG-2020-07

- Clean ZZ mode used for much
  - Fig is from mass paper
- M_H=124.94±0.19GeV
  - Stat dominated
  - 28 MeV unc. from μ p_T scale
    - (Run 2)

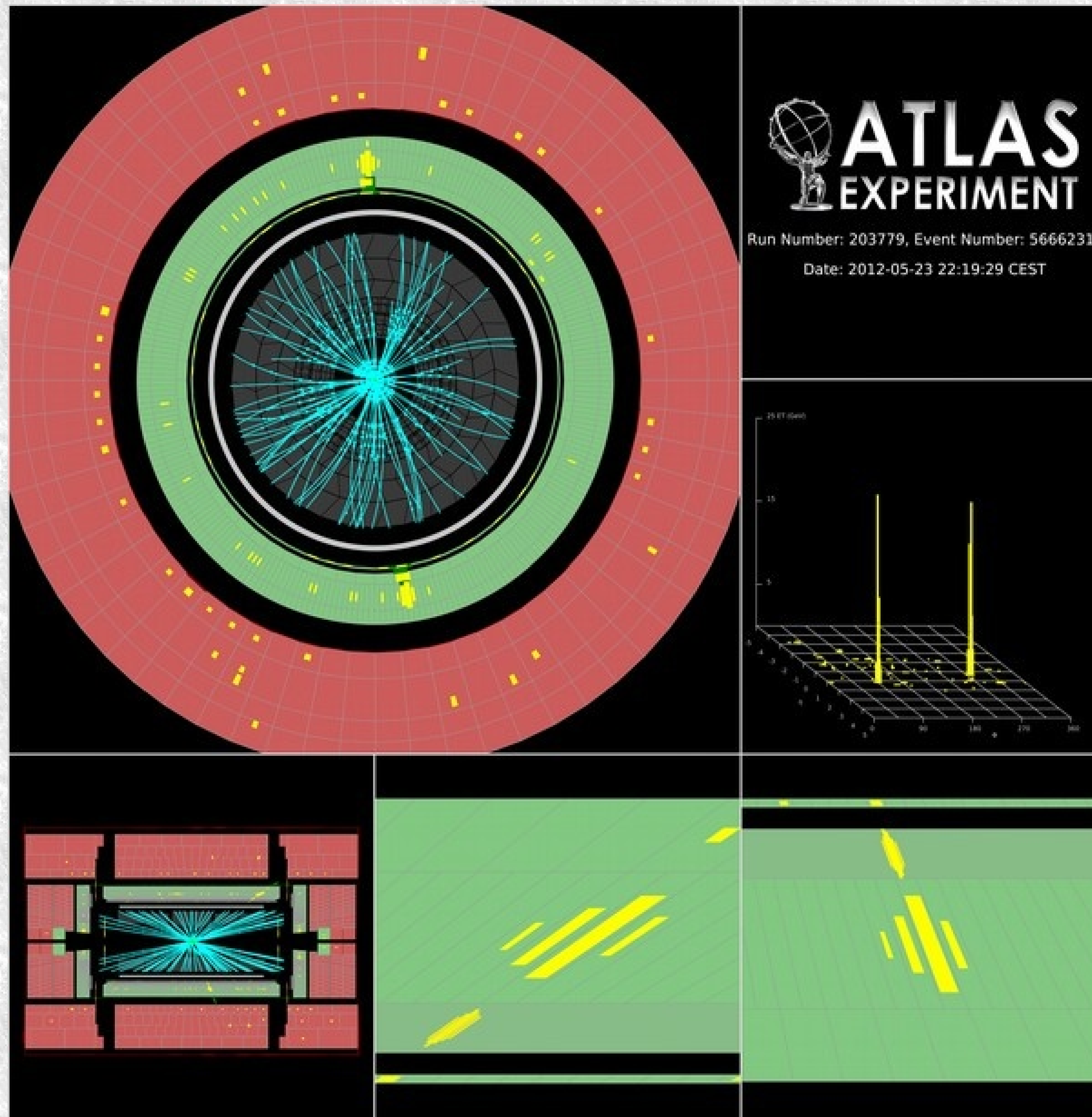




- 0.15% from single channel
  - More to come (H→γγ)

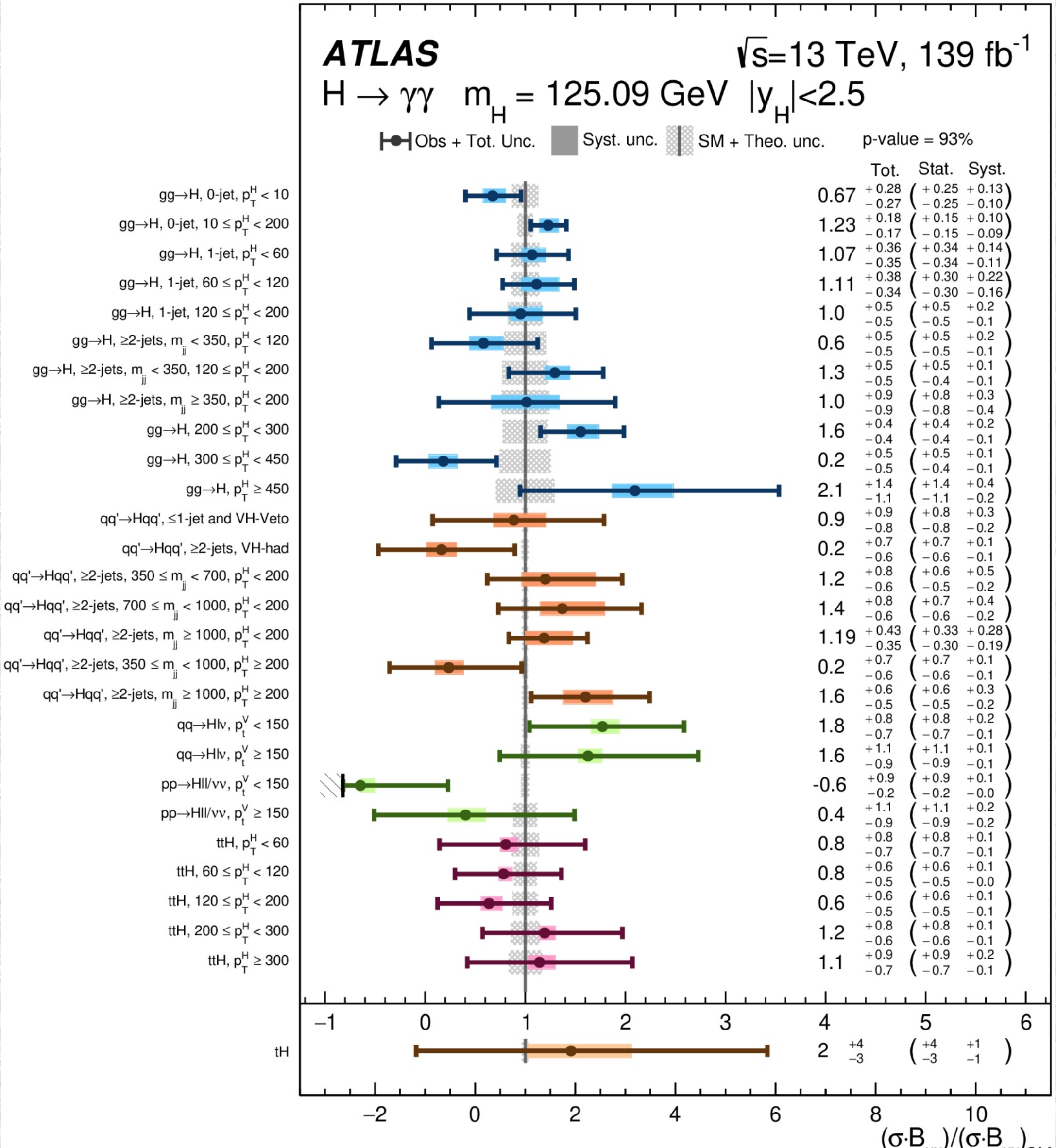
H→γ γ

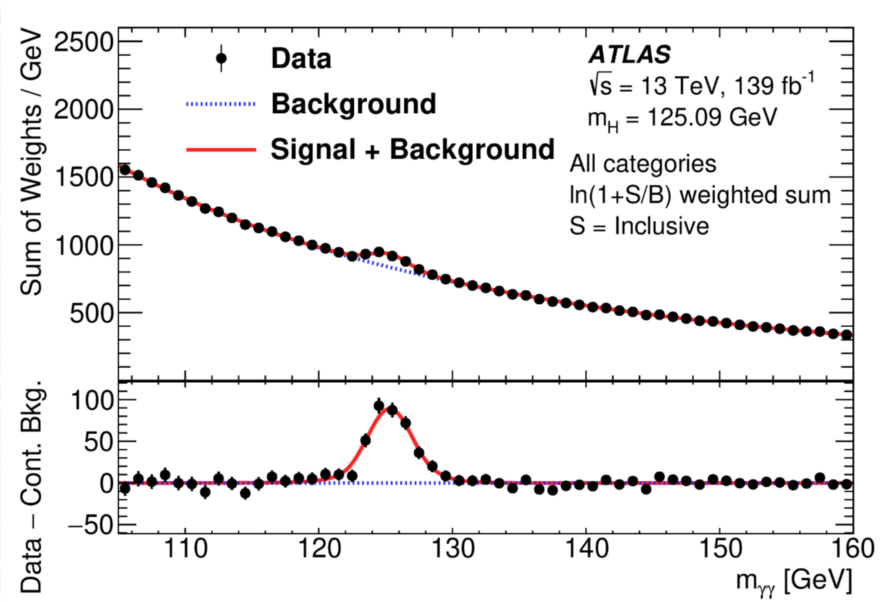
- Not a common decay
  - But 10x ZZ
  - 2 per 1000 Higgs
  - Measure photon energy/direction
    - Extract γγ mass
- Photon is neutral, so no track
- But a cluster of energy in 'ECAL'
- But photons are light – lots of light comes out of collisions



H to γγ

HIGG-2020-16

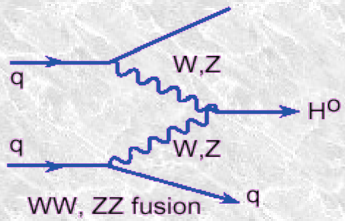


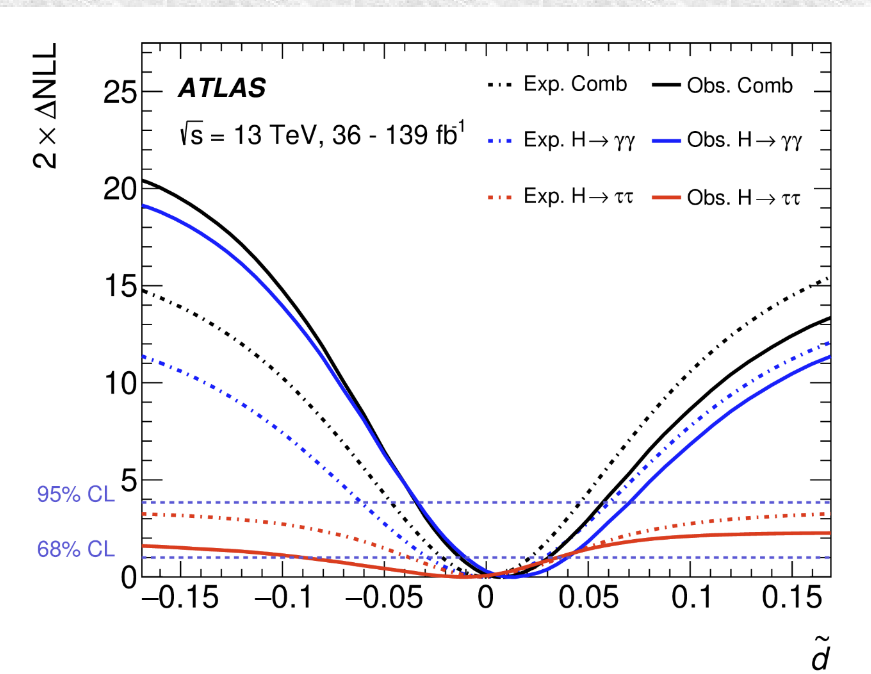


- Thousands of events
  - Allows probing many production modes
  - ggF, VBF, VH, ttH
- Overall $\mu=1.04^{+0.10}_{-0.09}$

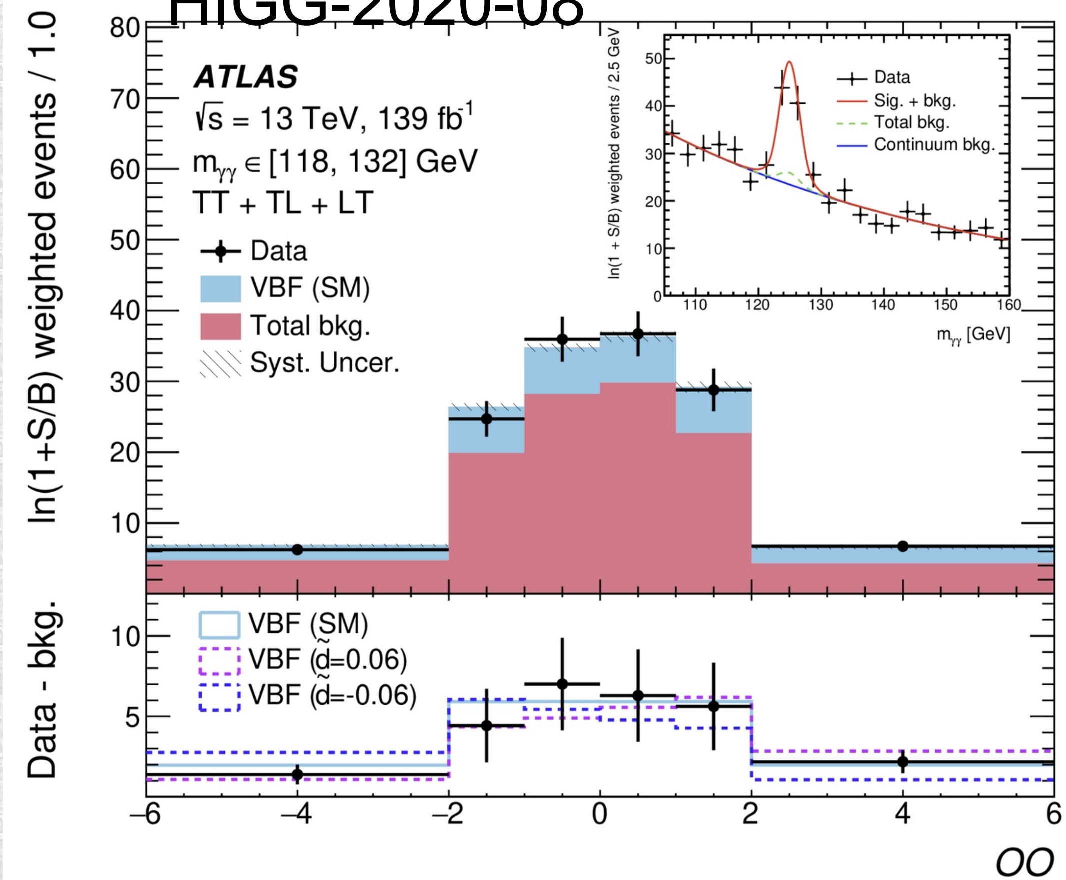
CP violation: H to γγ VBF

- Could explain matter-antimatter asymmetry
- Use angle between recoil jets in VBF
- Construct "optimal observable"
- Test for coupling "$\tilde{d}$"





HIGG-2020-08



Results (combined with similar $H\rightarrow\tau\tau$):

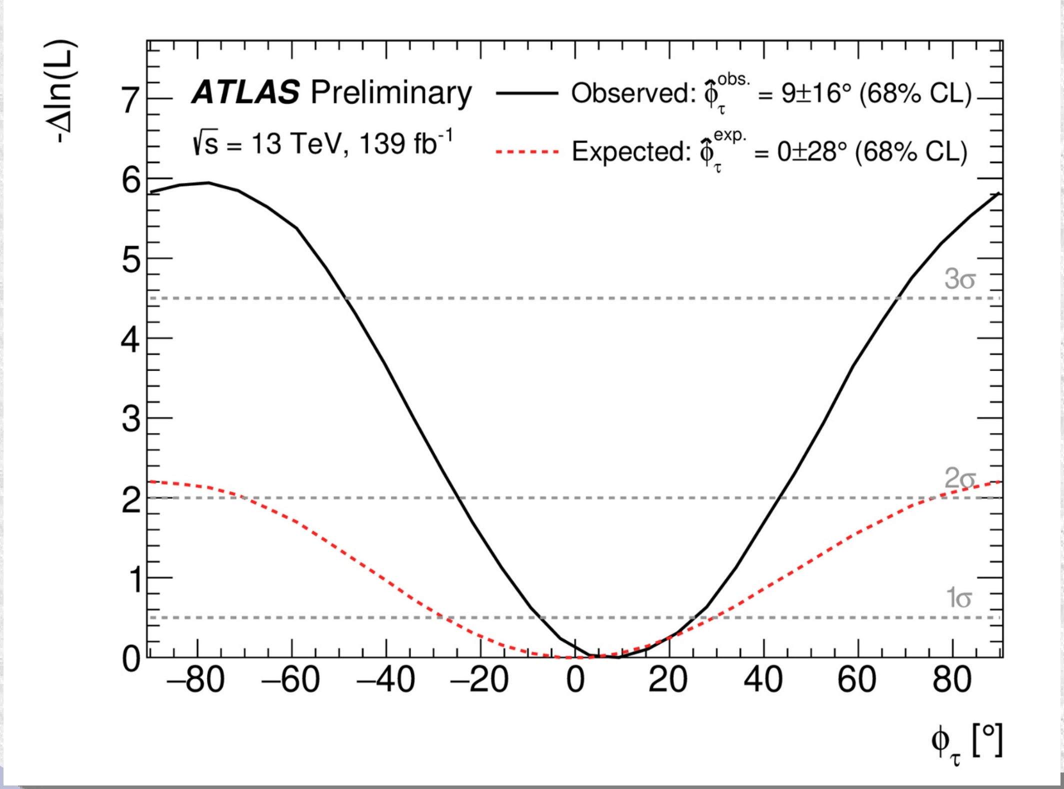
$-0.012 < \tilde{d} < 0.030$ (68%)

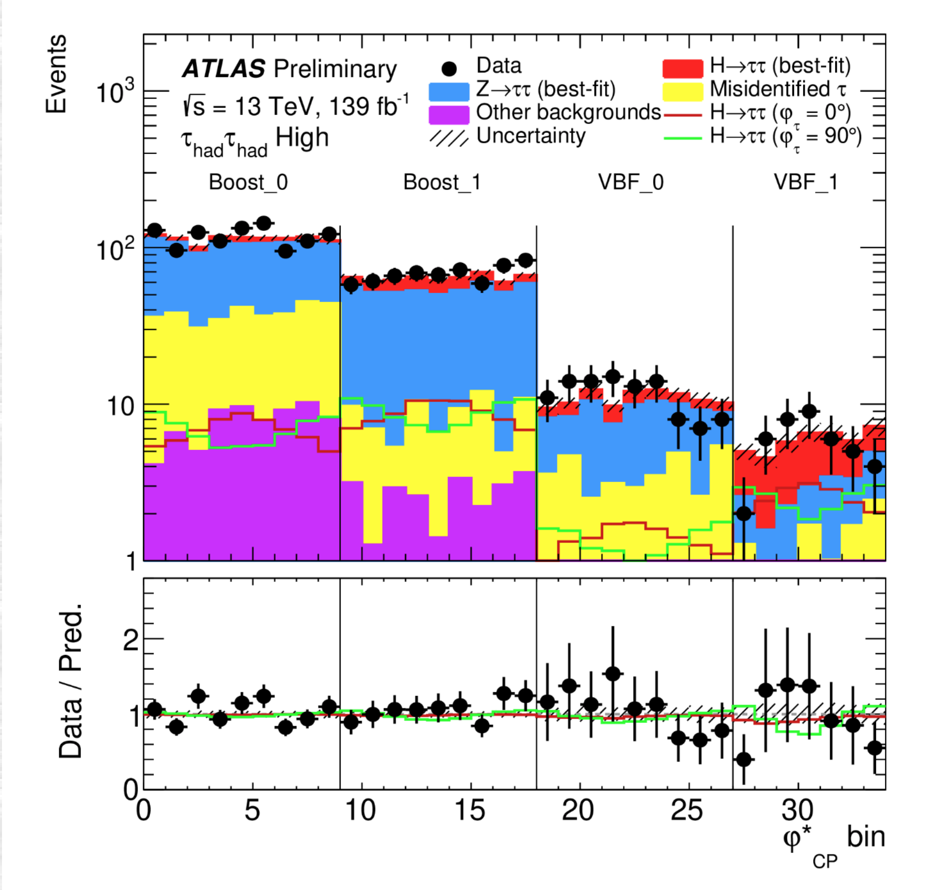
No sign of CP violation in H-VV coupling

H to ττ decay

ATLAS-CONF-2022-032

- Tau decays and allows study of its CP with fermions
  - Constrains mixing phase as 9±16°



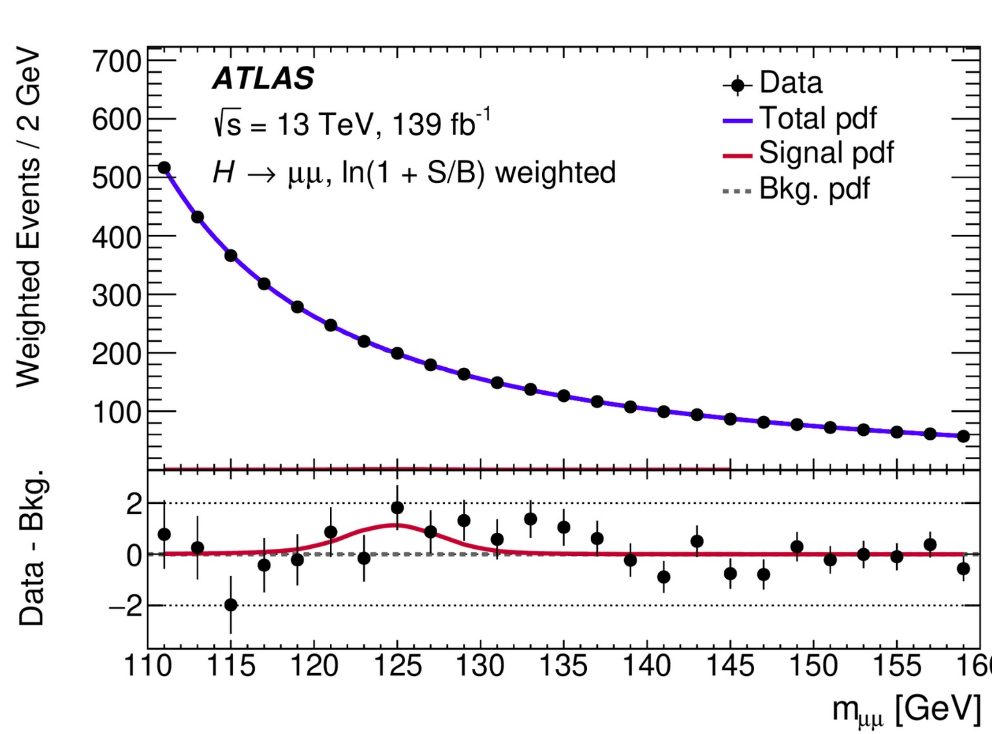


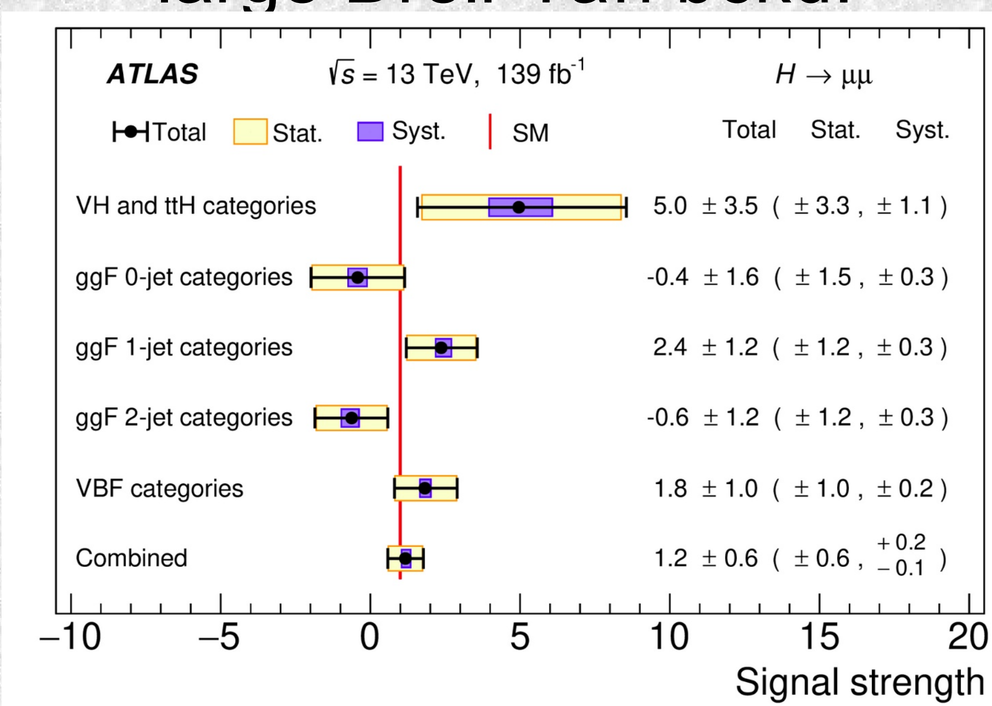
- Data gave unusually good error

H to μμ

Phys. Lett. B 812 (2021) 135980

- ‘Simple’ bump hunt
- 20 categories of p_T, eta, VBF. VH, ttH
- Approach like γγ, but:
  - 10 times lower rate
  - large Drell-Yan bckd.



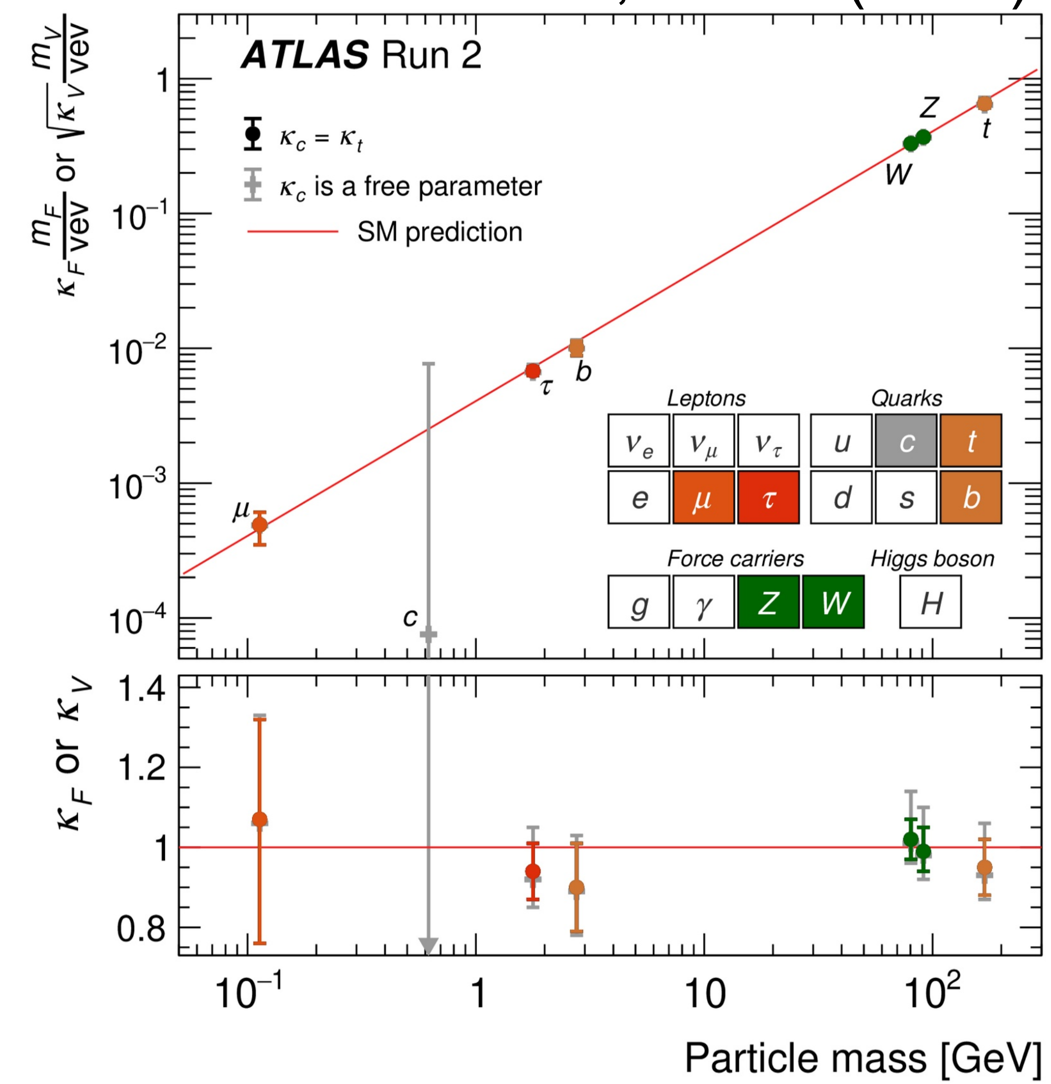


- Significance: 2σ obs (1.7σ exp. SM)
  - Statistics dominated
  - 2nd generation in sight!

Interactions with all particles?

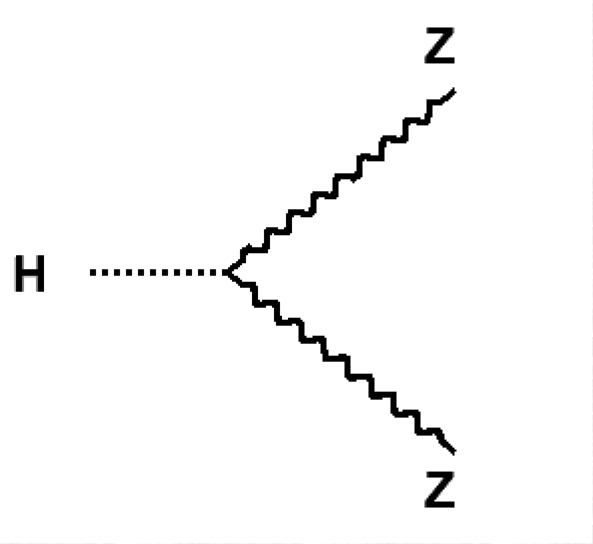
- Interaction should scale with mass
- Confirmed for vector bosons and all 3rd generation fermions
  - Save ν_τ!
- 2nd generation fermions now being constrained too

Nature 607, 52–59 (2022)



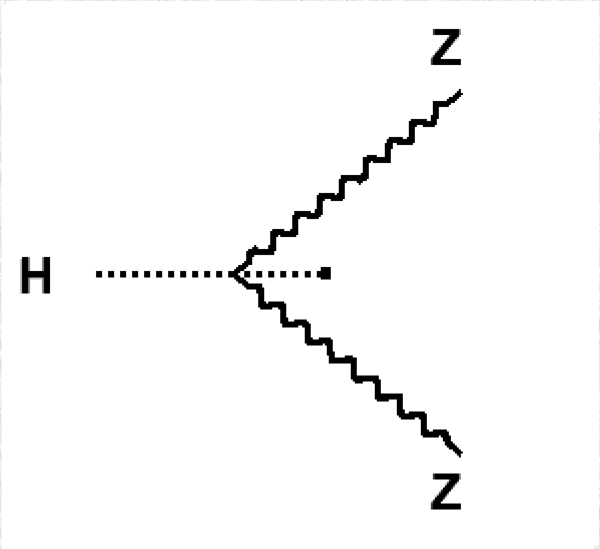
Evidence: H to ZZ

- The measured HZZ rate is about 10xH$\gamma\gamma$
  - After allowing for Z→ll Br
  - And 2 $m_Z > m_H$!
  - So HZZ must be a strong interaction
- The Z interacts with weak charge
- ZZH vertex shows the H must be weak charged
  - But Z is neutral (Charge and weak charge)
  - So in H→ZZ where does the charge go?



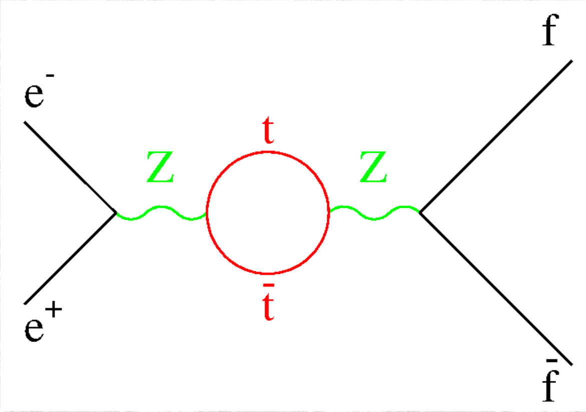
Evidence: H to ZZ

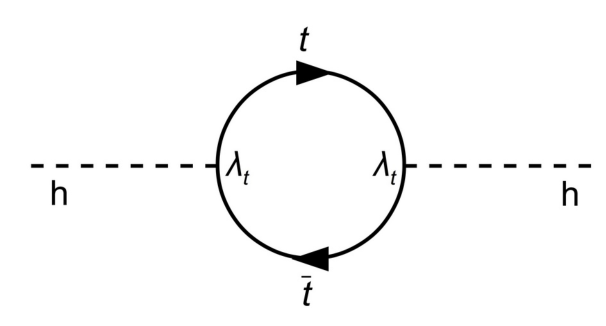
- The measured HZZ rate is about 10x$H\gamma\gamma$
  - After allowing for $Z \to ll$ Br
  - So HZZ must be a strong interaction
- The Z interacts with weak charge
- ZZH vertex shows the H must be weak charged
  - But Z is neutral (Charge and weak charge)
  - So in $H \to ZZ$ where does the charge go?
- It is really a 4-point coupling
  - One leg 'grounded' in the vacuum
- The ZZ decay needs vacuum help
  - With a (weak) charge!
- The apparent 3 point couplings come from $\partial_\mu \phi \partial_\mu \phi$ expanded about v
- There IS a field



A tale of two top loops

- Z and Higgs bosons are neutral and interact with top quarks
  - They can split (Uncertainty) into a tt pair and reform again
  - This changes measured properties
- Precise measurements of Z bosons at LEP (etc.) in 1990s predicted m_t=173±12 GeV
  - C/f 173±1 GeV from measurement
- Conclusion: Loops are real and work as we expect



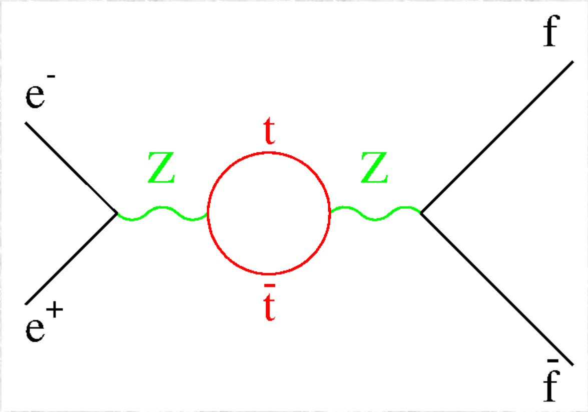


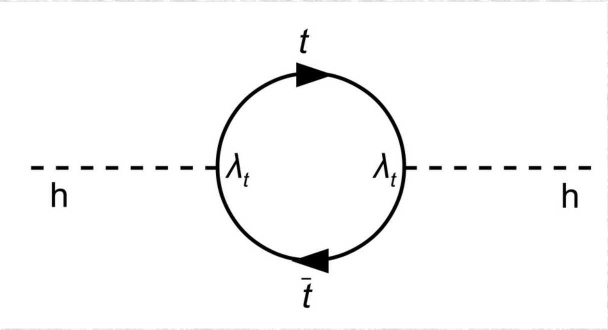
A tale of two top loops

- Higgs boson properties are also changed by top loop
  - But maths is different because H is spin 0, Z spin 1
- Effect is to correct measured mass to be

$$M^2_{H,meas} = M^2_{H,bare} + p^2_{max}/c^2$$

- p_{max} is the highest momentum allowed before theory changes
  - e.g. scale of Gravity? ~ 10^{18} GeV
- So the fact we see 125GeV says our theory stops around 125GeV!



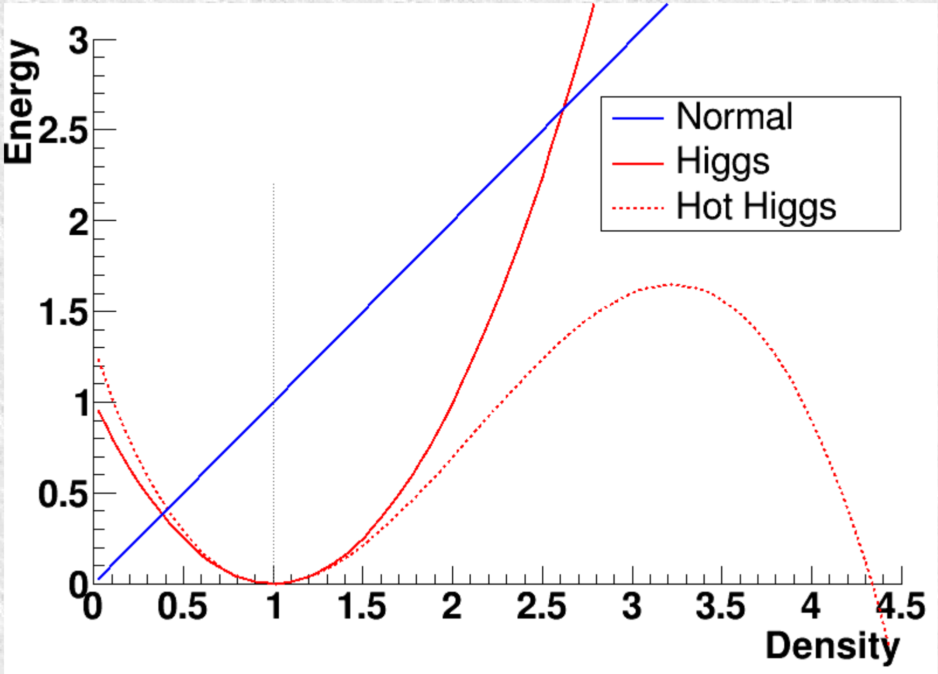


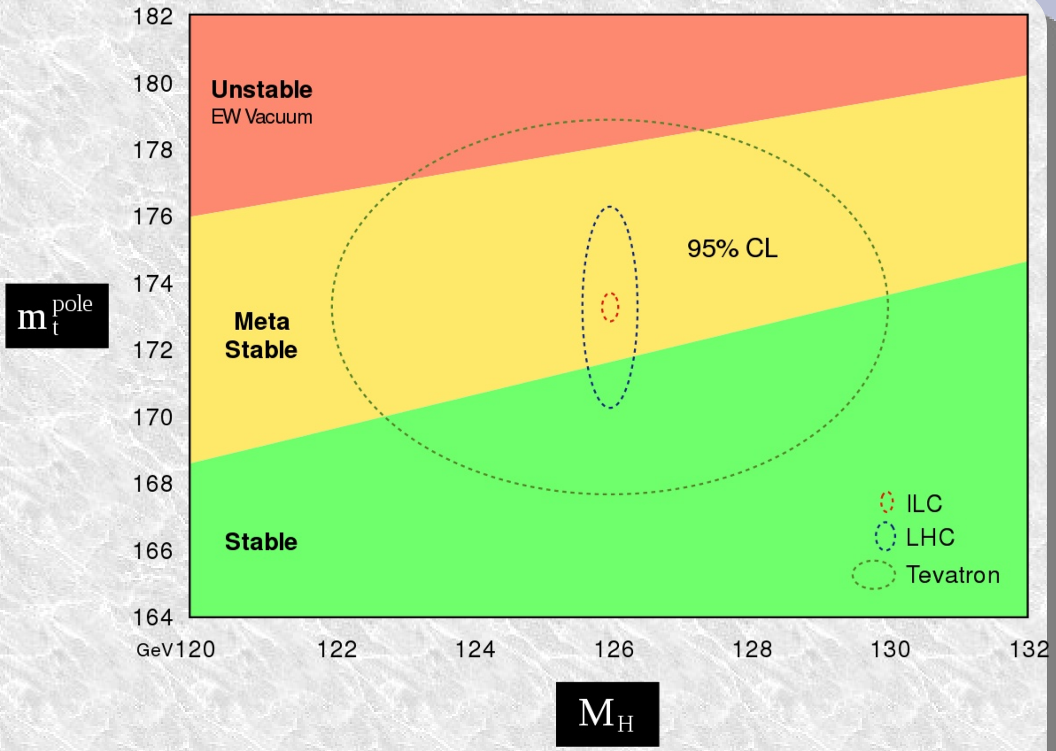
Naturalness

- This *suggests* something is missing with a mass near the Higgs boson mass
- Supersymmetry would fix this with a top-partner the ‘stop’
    - And it has a dark matter candidate too...
- But there are many other ideas

- This makes us very enthusiastic about the high-energy LHC data
  - Huge amounts are piling in
  - Anything might be round the next corner….

Is Higgs potential stable?





- Current estimates suggest vacuum is unstable
  - A deeper Higgs potential may exist
  - If it ‘tunnels’ into it…..that would be bad
- But it depends upon the top quark mass
  - If that is low we may be safe!

How bad?

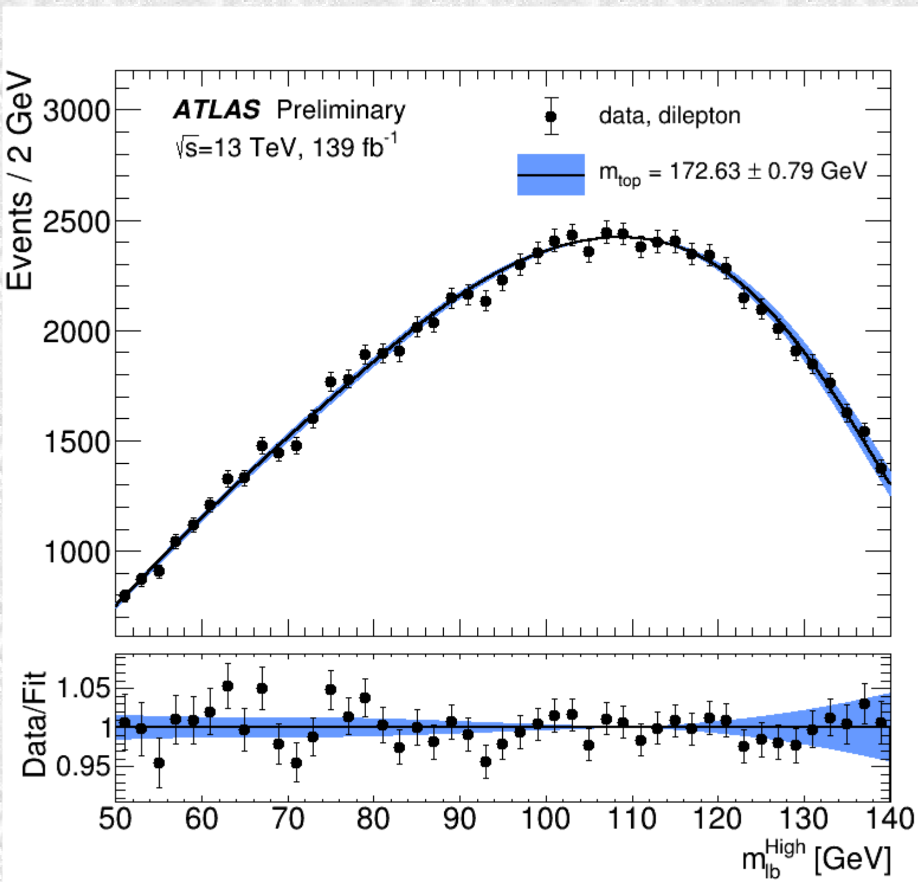
- If that happens anywhere in the Universe a ball of super-dense state will expand at the speed of light.
  - And destroy all it touches
- But: the expected lifetime is >>>> the universe lifetime

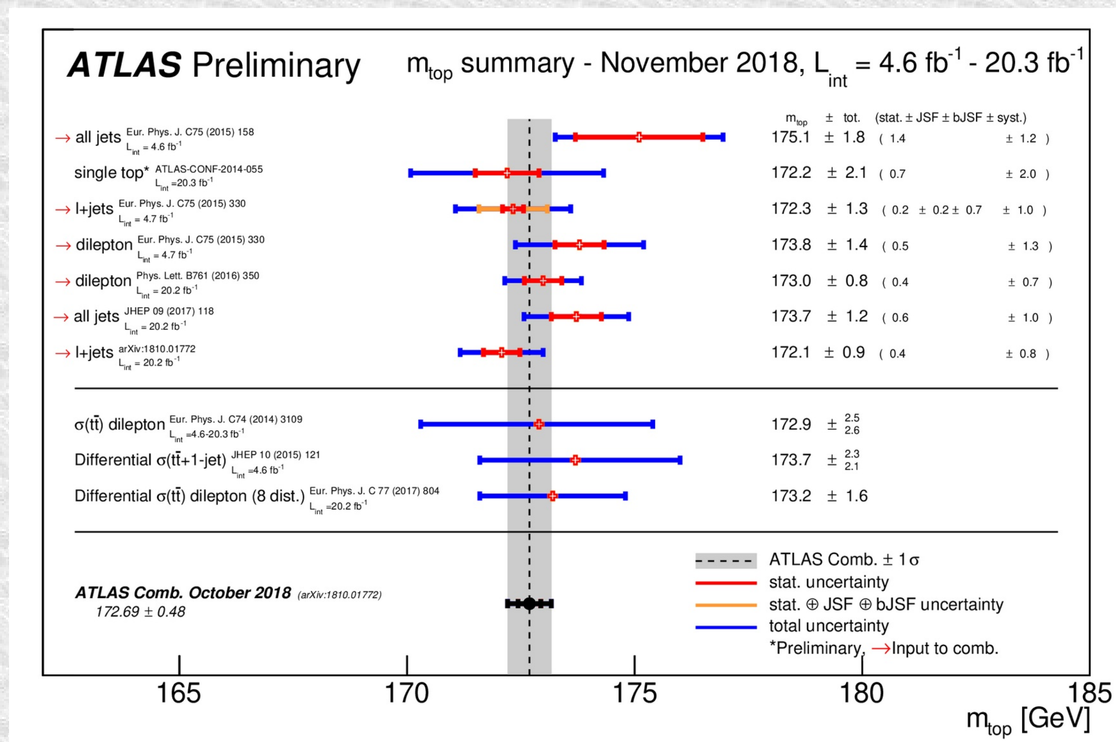
- Also, it seems likely the Big Bang would have set it off
- So probably our equations miss something?
- Or perhaps the top mass is lower than about 172 GeV?

Run 2 Top mass in llbb ATLAS-CONF-2022-058

New

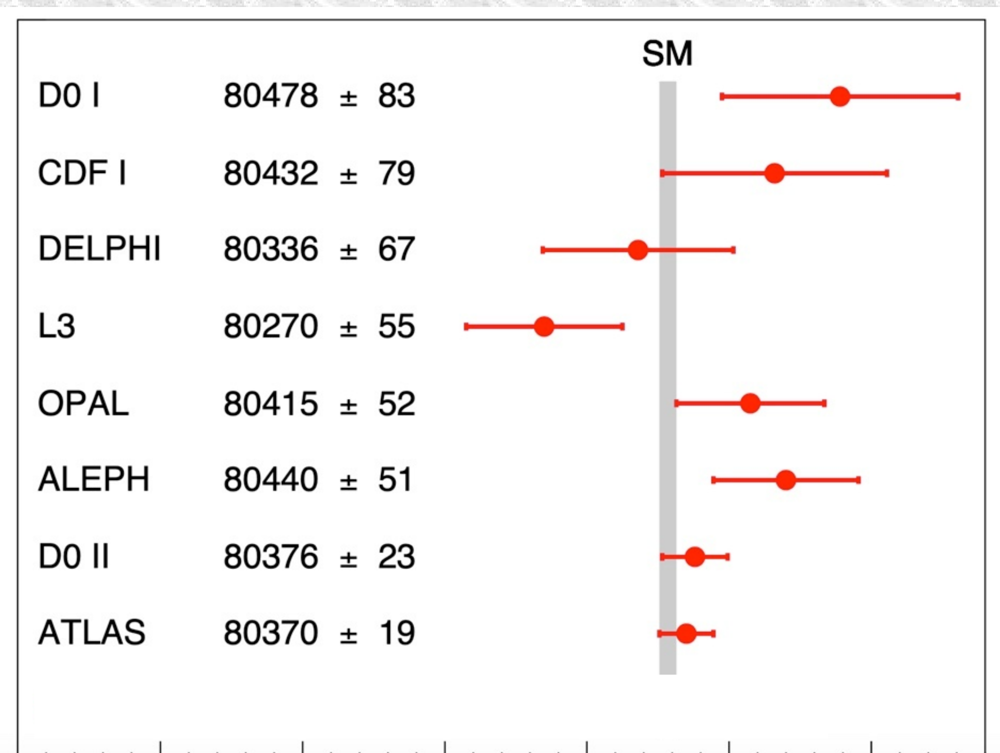
- m_{top}=172.63 ± 0.20 (stat) ± 0.67 (syst) ±0.37 (recoil) GeV
  - Recoil uncertainty (Brooks and Skands) new
- Matches 172.69 ± 0.48 GeV ATLAS Run 1 combination
  & 36fb^{-1} 13 TeV 174.41± 0.39 (stat) ± 0.66 (syst) ±0.25 (recoil) GeV ll
- c/f 171.77 ± 0.38 GeV recent CMS

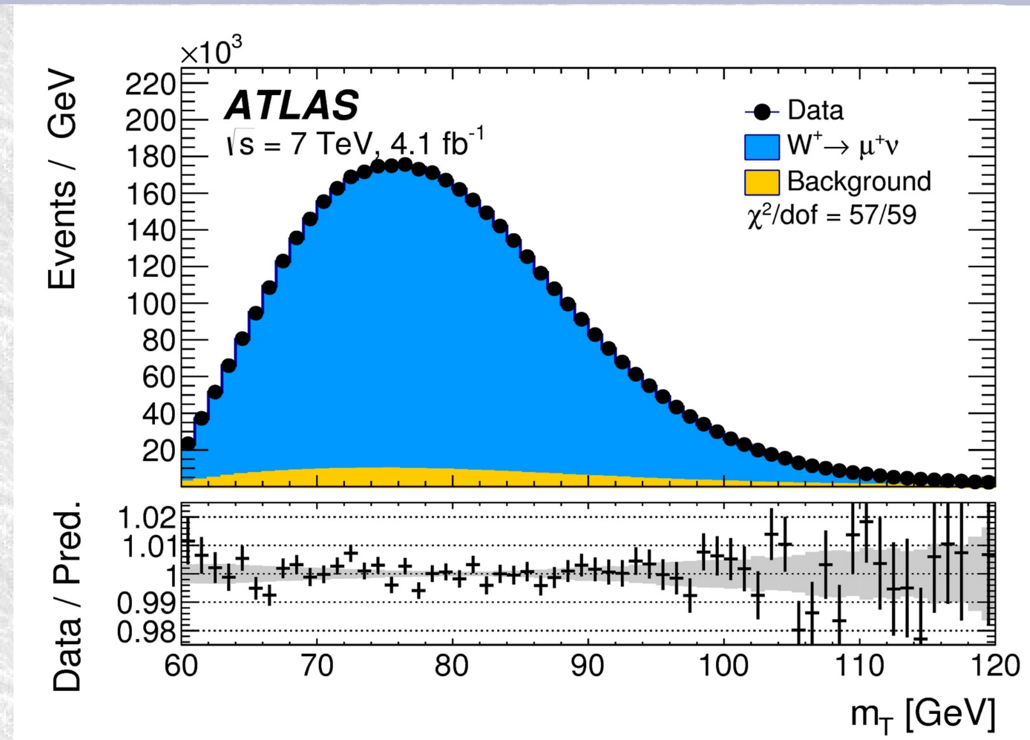




The W boson mass

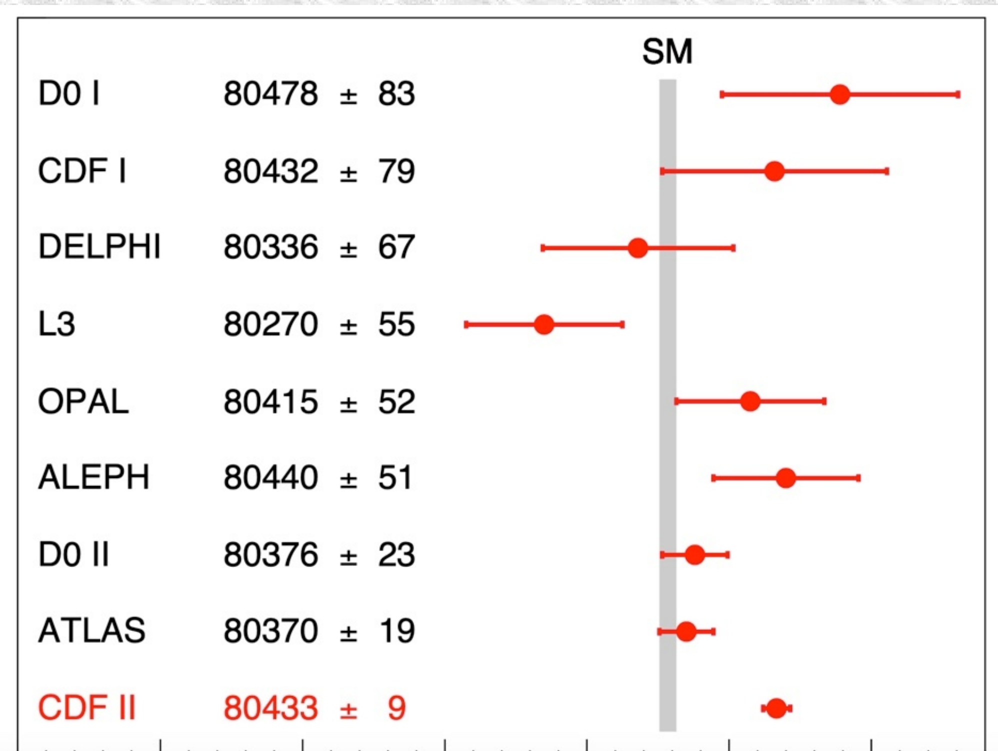
- Use W→μν / eν decays
  - Measurement hard with neutrino, but lots of W
  - Gave worlds best result!
  - Matching SM predictions

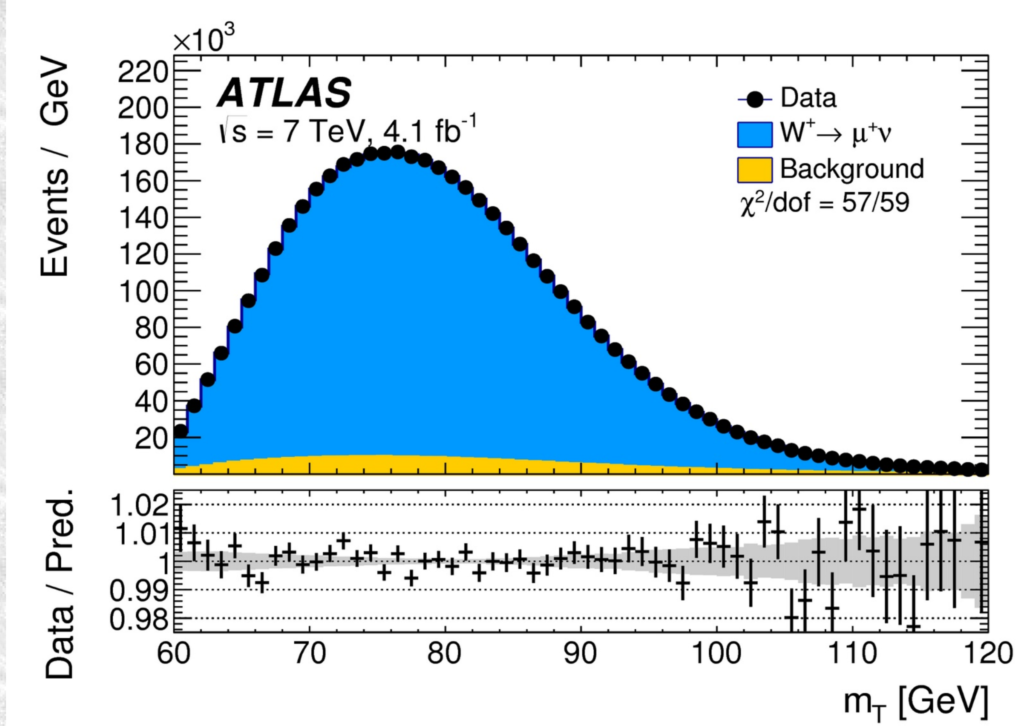




The W boson mass

- Use W→μν / eν decays
  - Measurement hard with neutrino, but lots of W
  - Gave worlds best result!
  - Matching SM





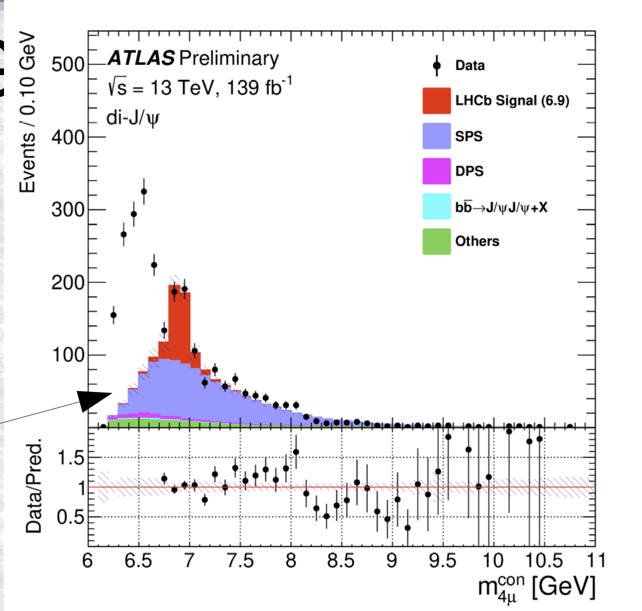
- But in April CDF (from US TeVatron) released new measurement
  - Twice as precise
  - 7σ from SM; 3σ from us

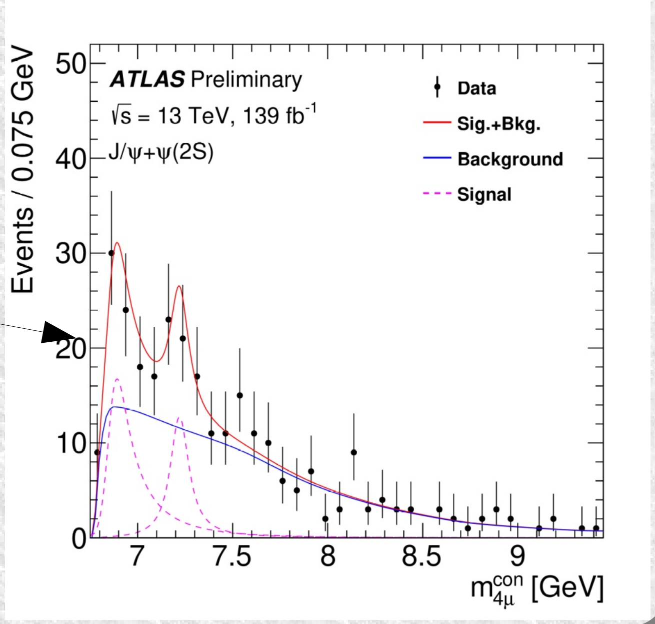
Some other cute physics

Di charmonium in 4μ states

ATLAS-CONF-2022-040

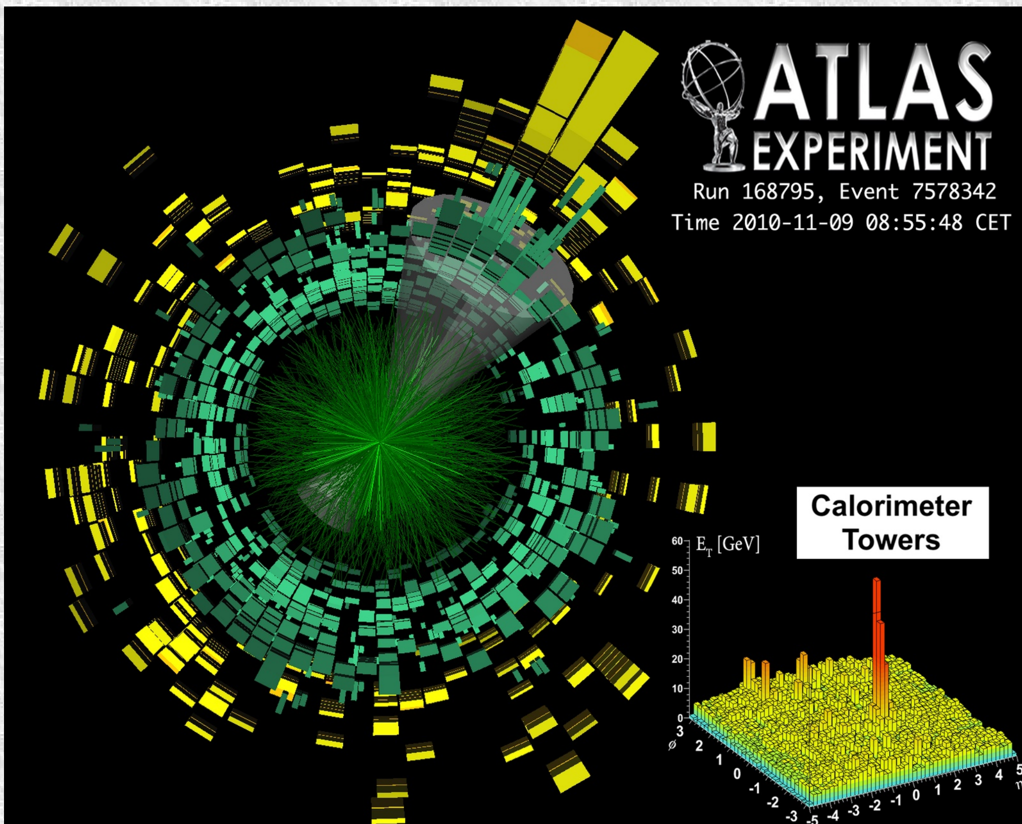
- Find prompt 4μ events, p_T>3,3,4,4G
  - J/ψ+J/ψ or J/ψ+ψ(2s)
  - ΔR<0.25 between charmonia
- J/ψ+J/ψ Analysis:
  - Single PS Background from MC
  - Excesses for mass below 7.5 GeV
    - 6.9 GeV peak seen also by LHCb
    - Broad lower mass structure best fitted with two more peaks, detail unclear
- J/ψ+ψ(2s) also show a 6.9 GeV peak
  - bump at 7.2 GeV
  - Also seen by LHCb & CMS in ψψ

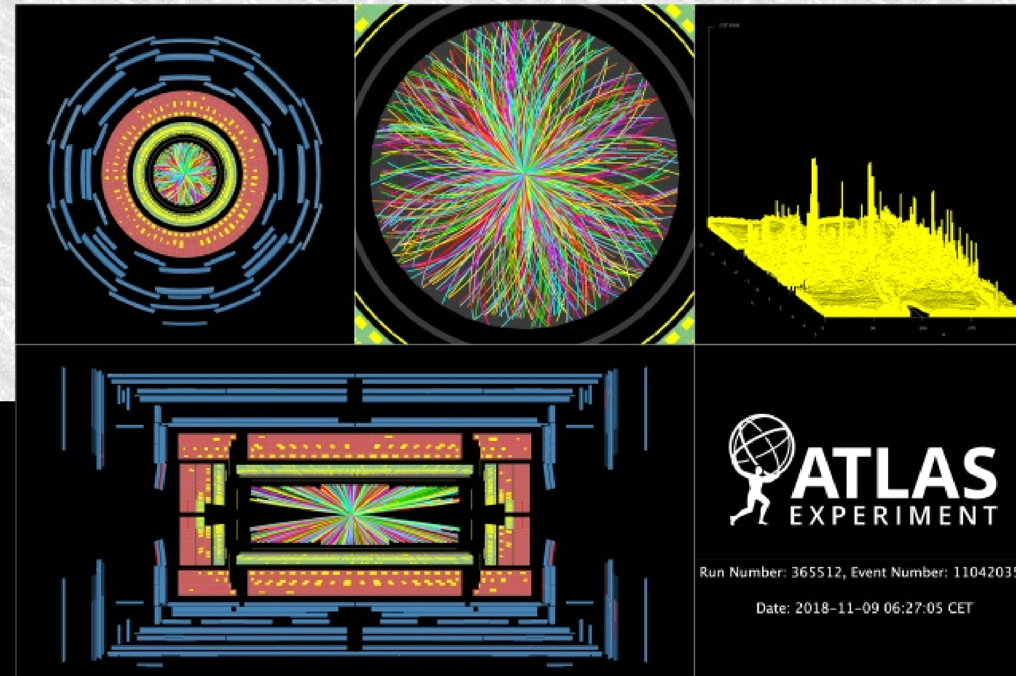




PbPb collisions

- Typically spend 1 month each year colliding heavy ions
- 208 nuclei on 208



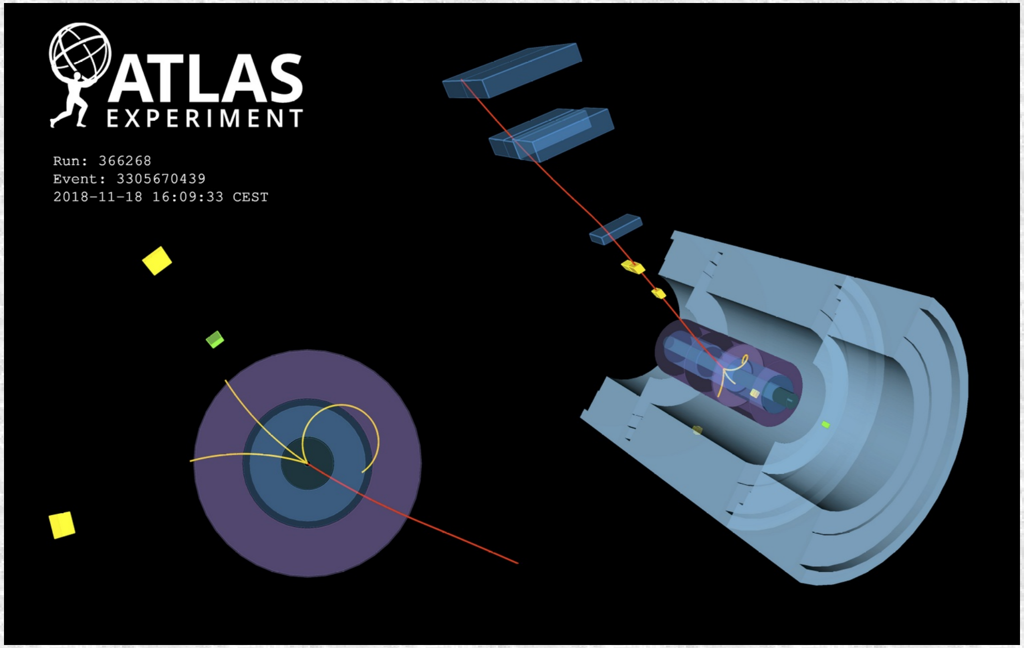


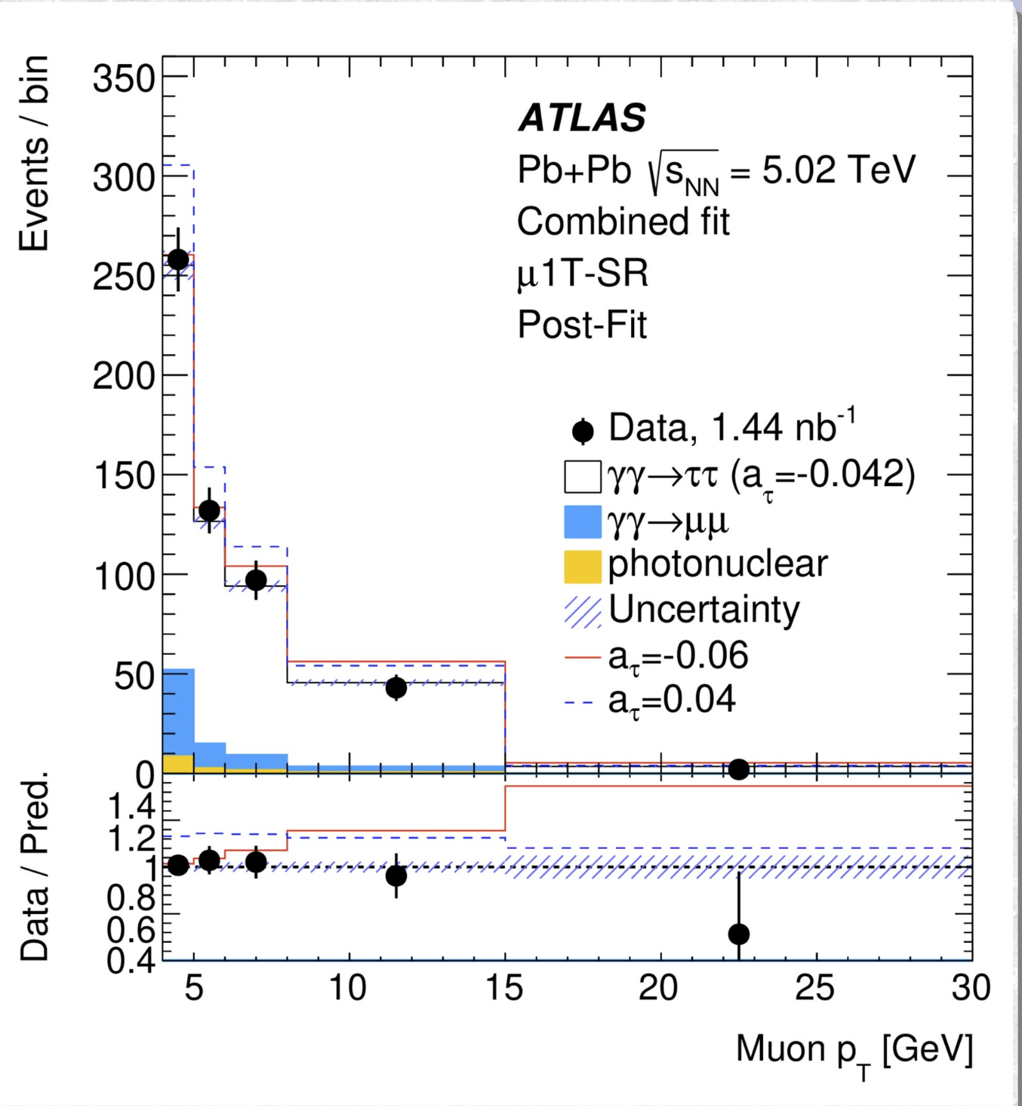
- Found a weird phenomenon: jet quenching
  - One jet fails to make it through the quark-gluon plasma

Weirder still PbPb: $\gamma\gamma \rightarrow \tau\tau$

STDM-2019-19

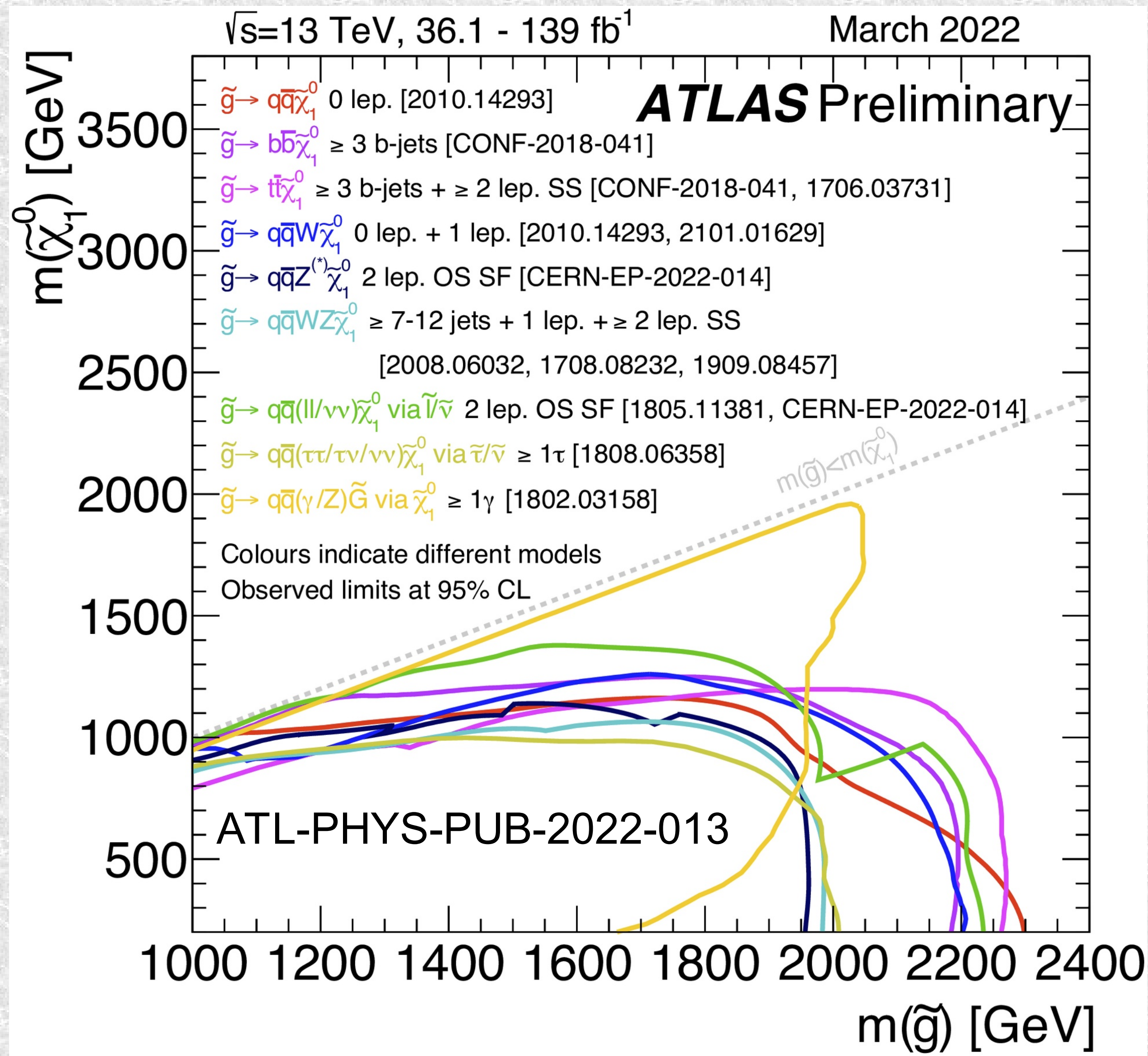
- PbPb ultraperipheral collisions provide intense EM fields
  - Allows clean $\gamma\gamma \rightarrow \tau\tau$
  - Constrain tau g-2





Supersymmetry: no discovery

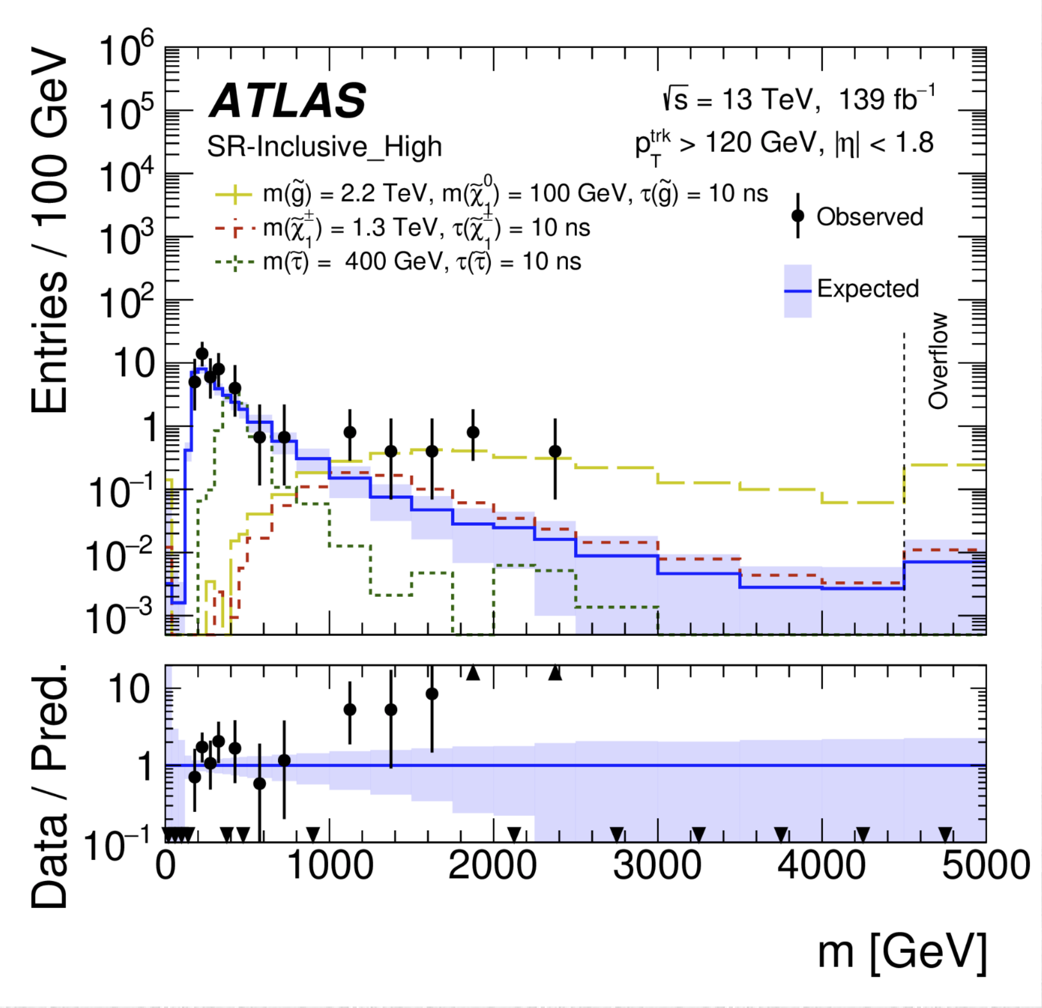
- Most searches turn up nothing
- But a lot was pinned on SUSY
- It could solve many questions
  - Like dark matter
- But many simplified models with a neutralino below 1 TeV and a gluino below 2 TeV are excluded



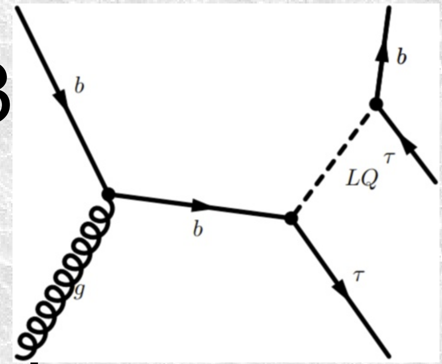
Long lived SUSY

SUSY-2018-42

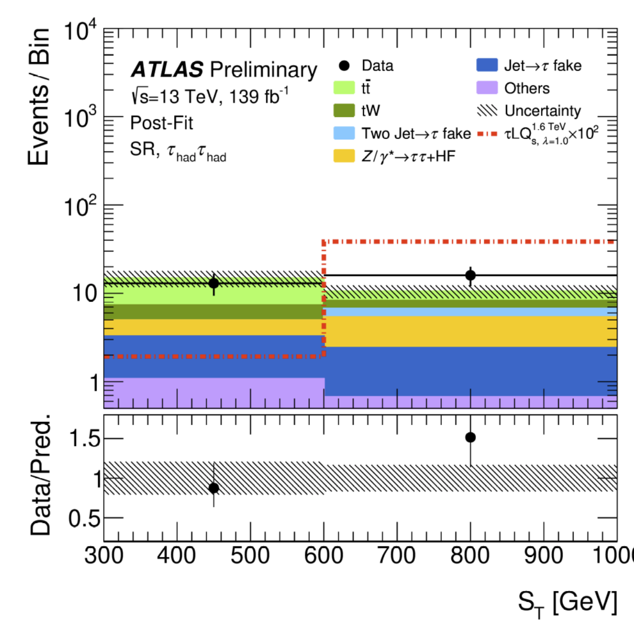
- Search for less simple SUSY scenarios
- e.g. Massive long-lived particles which are slow
  - Highly ionising
- Look for high MET events with high-p_T tracks
  - $dE/dx > 2.4\ MeVg^{-1}cm^2$
- Small excess seen
  - 3.6σ for 1.4 TeV signal
  - But not confirmed by timing in calo./muons

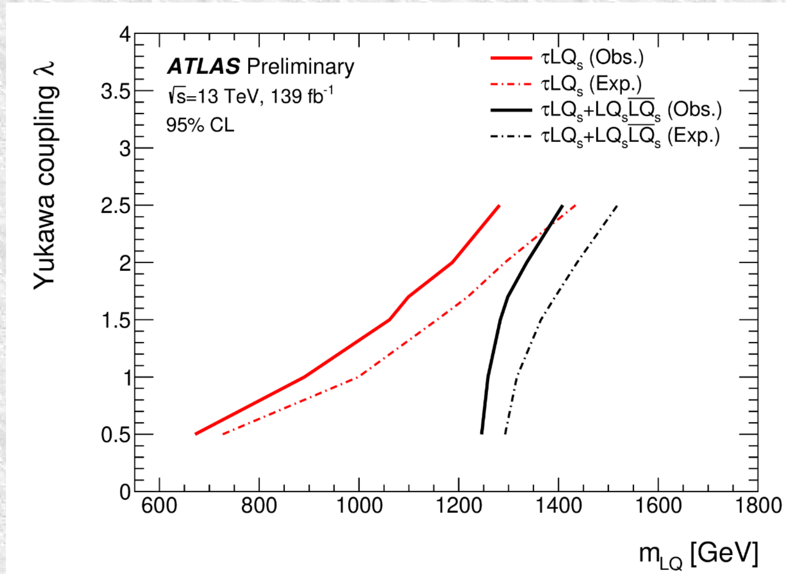


Scalar leptoquark in bττ ATLAS-CONF-2022-037



- Model assumes q=4/3
- Inspired by LFV hints from b decays
- Taus sought in lep-had and had-had configurations
  - Later dominates, show right.
- No evidence for signal
  - Single or pair produced
  - Combined: leptoquarks below 1.26 TeV excluded for a Yukawa coupling of 1
- Broad programme
  - see ATL-PHYS-PUB-2022-012

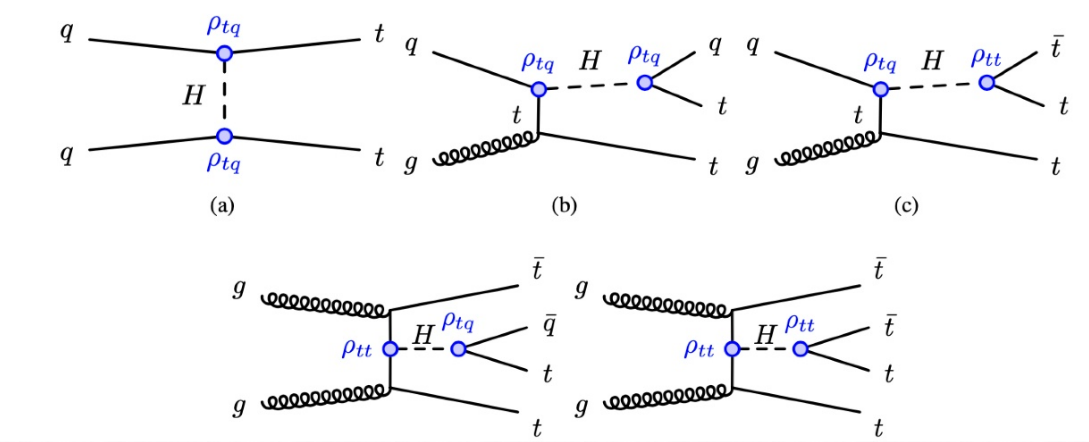


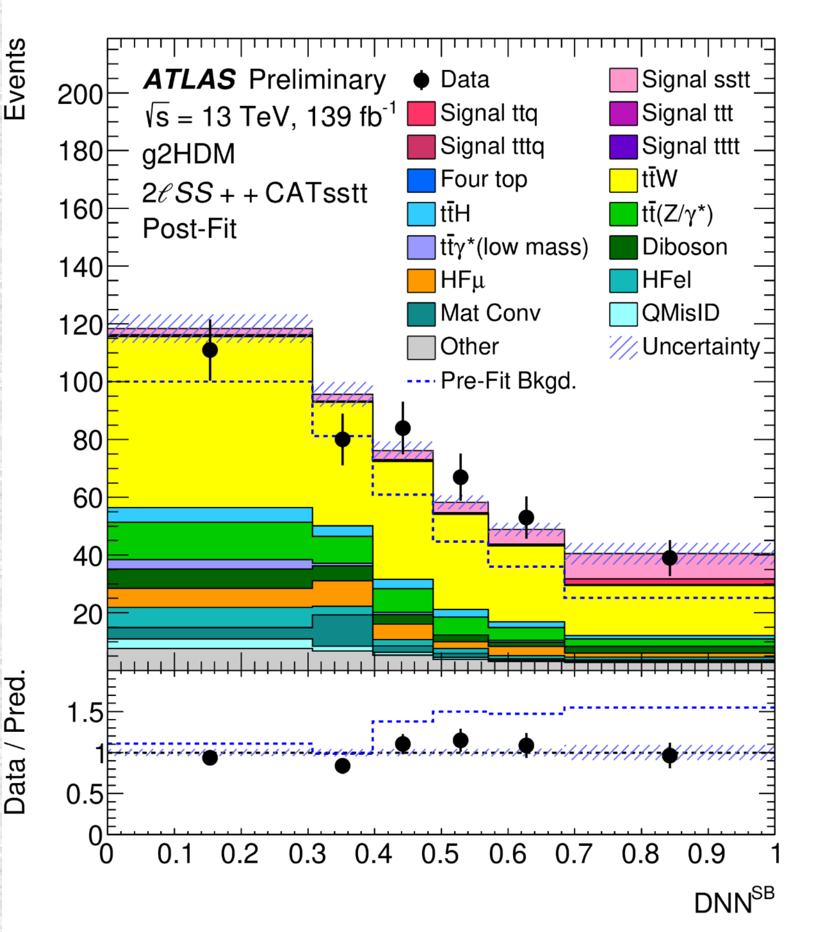


Generic 2HDM

ATLAS-CONF-2022-039

- Allows flavour violation
  - e.g. 3rd generation uu→tt !!





- Scan ρ_{tt}, ρ_{tc}, ρ_{tu} couplings
- and heavy Higgs masses 200 GeV < m_H < 1000 GeV
- largest deviation 2.8σ local
  - ρ_{tt}=0.32, ρ_{tc}=0.05, ρ_{tu}=0.85
  - m_H=1000

Science and Technology Facilities Council

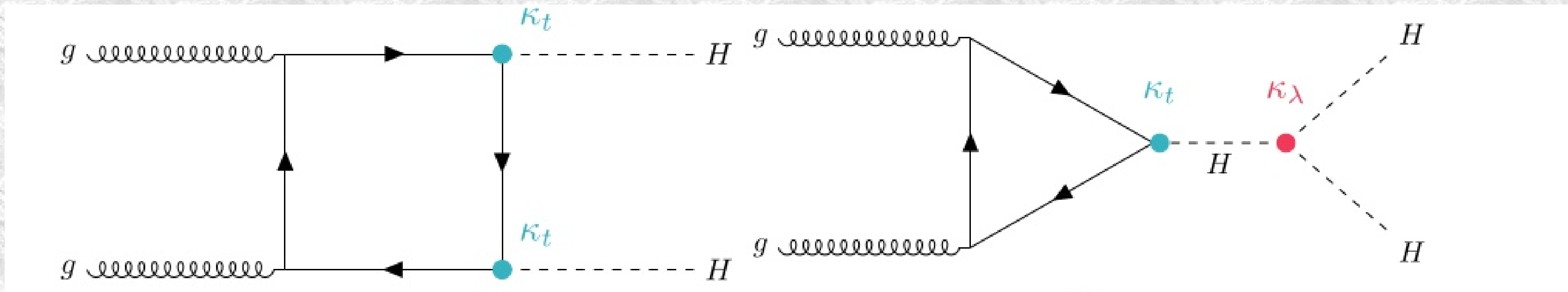
WARWICK THE UNIVERSITY OF WARWICK

What about the Higgs field?

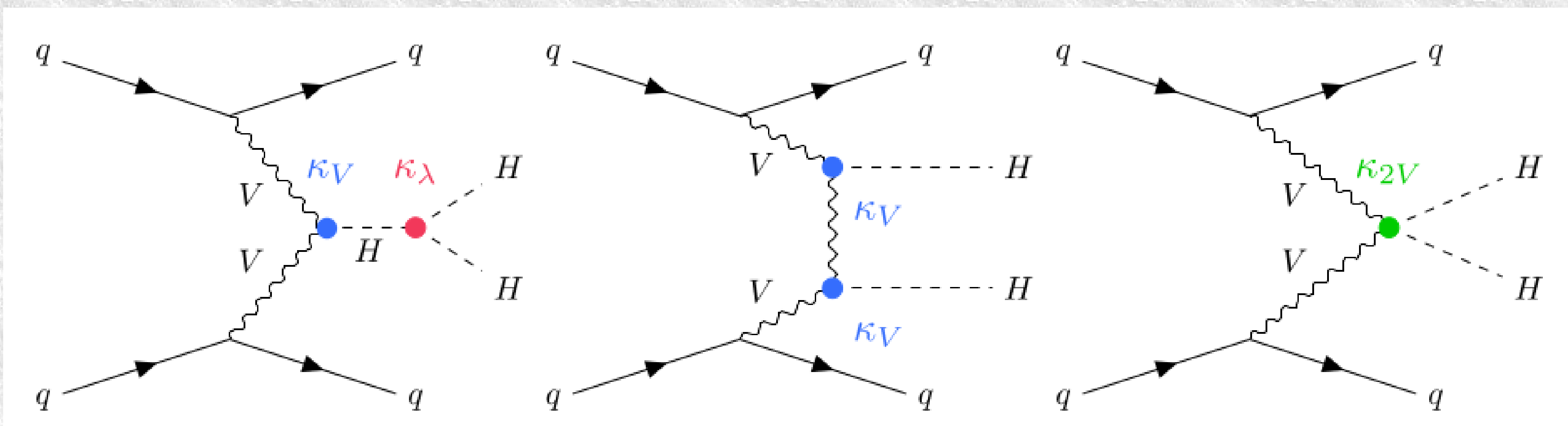
- The Higgs mechanism needs the field filling space
  - Unlike light, you turn it off and it is still there
  - ~2 Higgs bosons / fm^3
- The density of the field is cosmologically ridiculous
  - It is 120 orders of magnitude larger than dark energy – and the opposite sign
  - Remember: we don't have a quantum theory of gravity
- So do we really expect you to believe its there?
- We should measure the self-coupling of the Higgs
  - This is what generates the field.
  - We might learn something from studying events with two Higgs bosons at once
    - But that will be a very hard road to follow...

Di-Higgs production

- ggF



- VBF

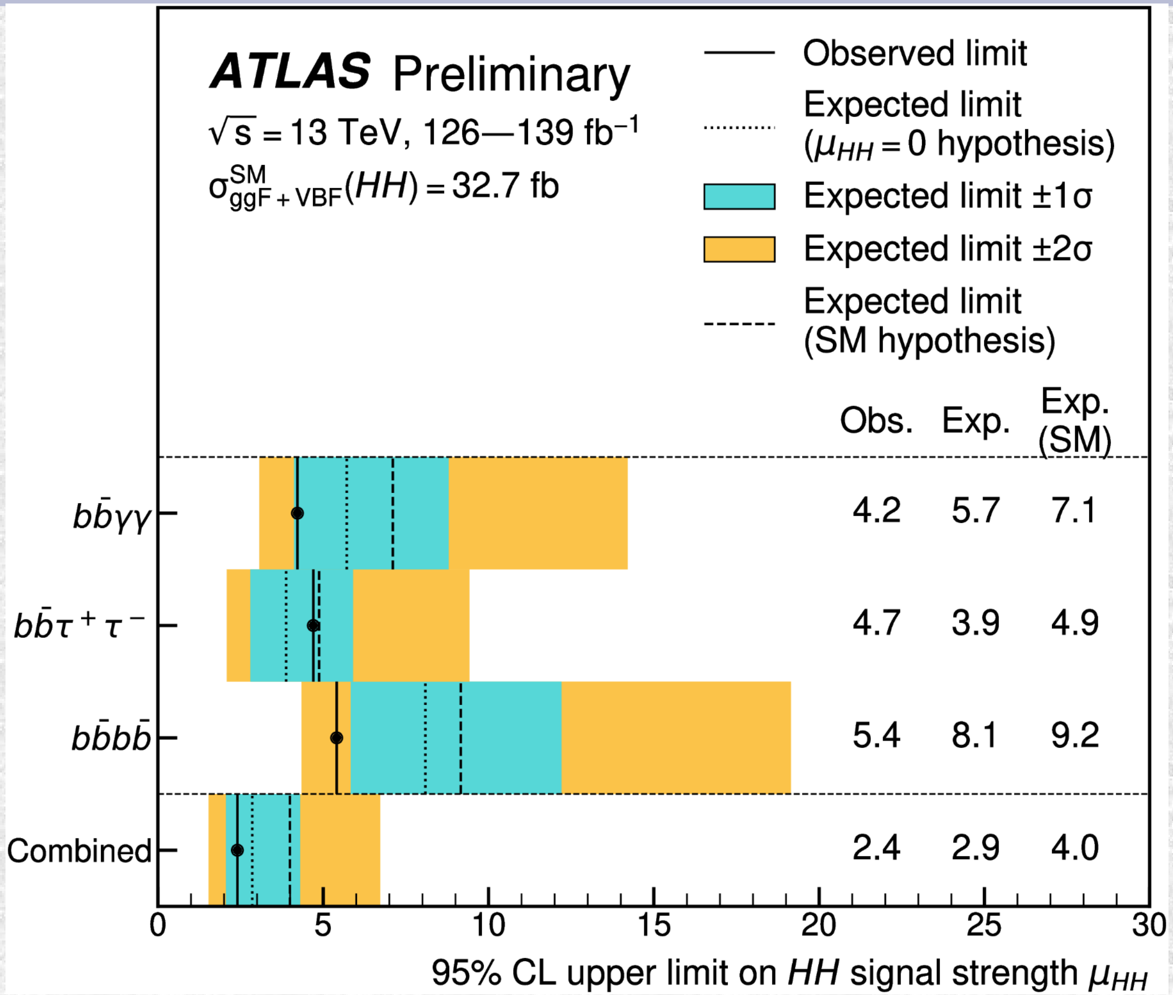


- Interference between paths destructive for both
- κ_λ scales coupling, SM=1. Affects both modes,
  - Interplay with κ_t in ggF, κ_V and κ_{2V} in VBF

  m(HH) spectrum depends on κ_λ, κ_{2V}

Combined HH

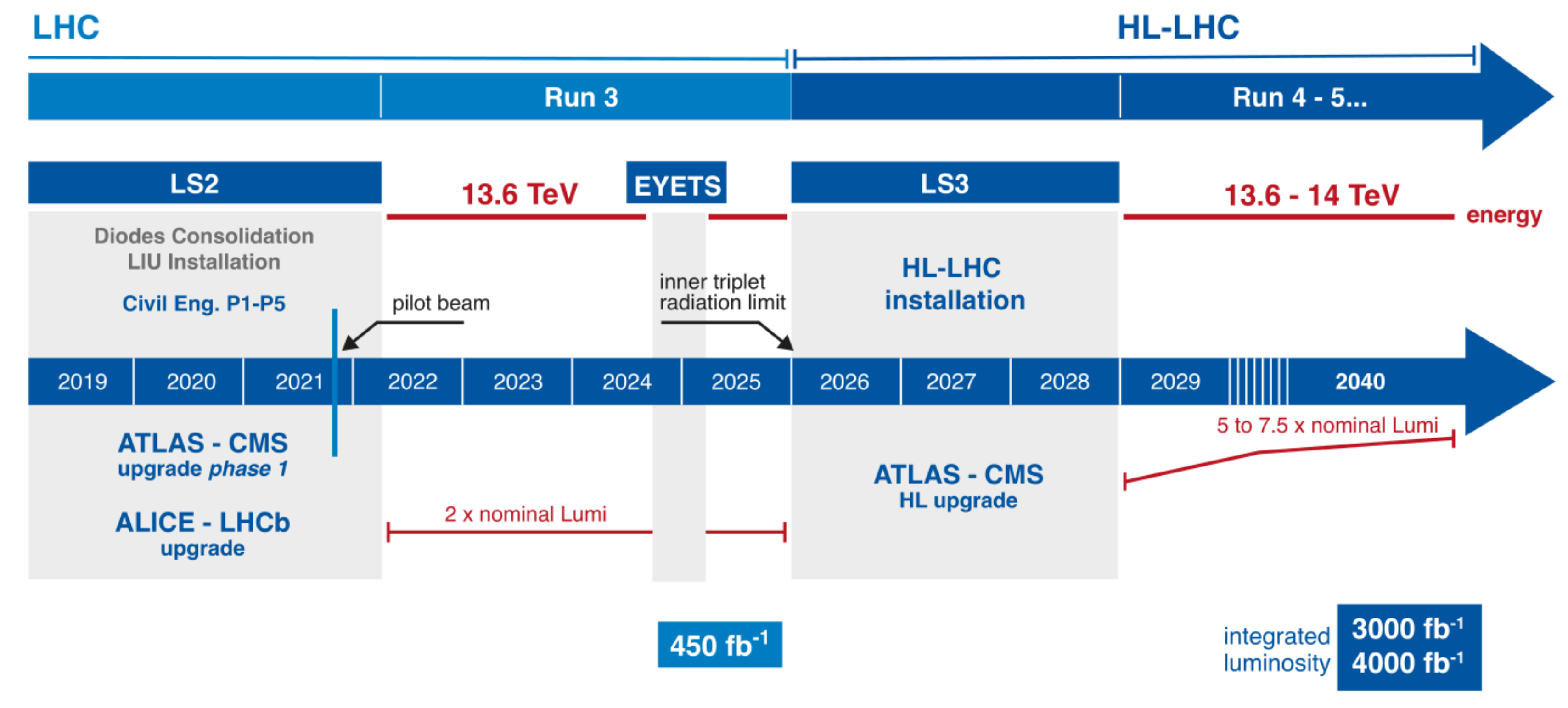
ATLAS-CONF-2022-050



- Limit on HH production at 2.4 x SM strength
  - c/f 2.9 expected (no HH) or 4.0 (SM)

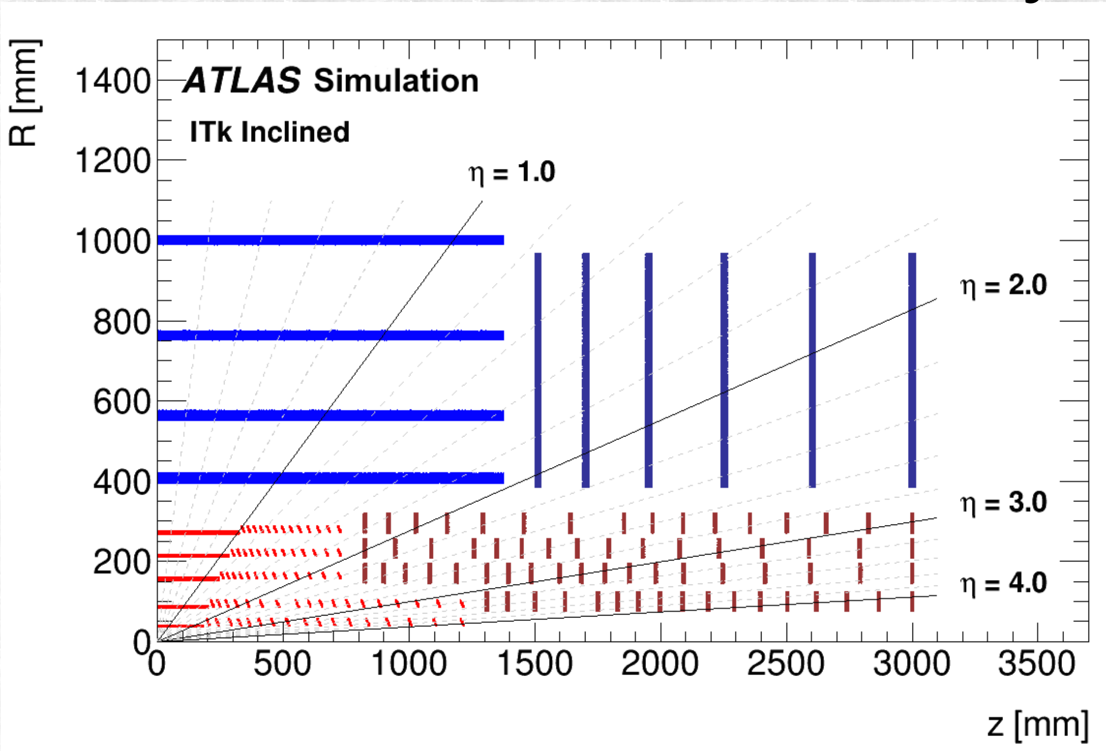
The future

- ATLAS is using 139fb^{-1} @ 13TeV for most results
- Run 3 may bring 300fb^{-1} @ 13.6 TeV
- HL-LHC will bring an order of magnitude more



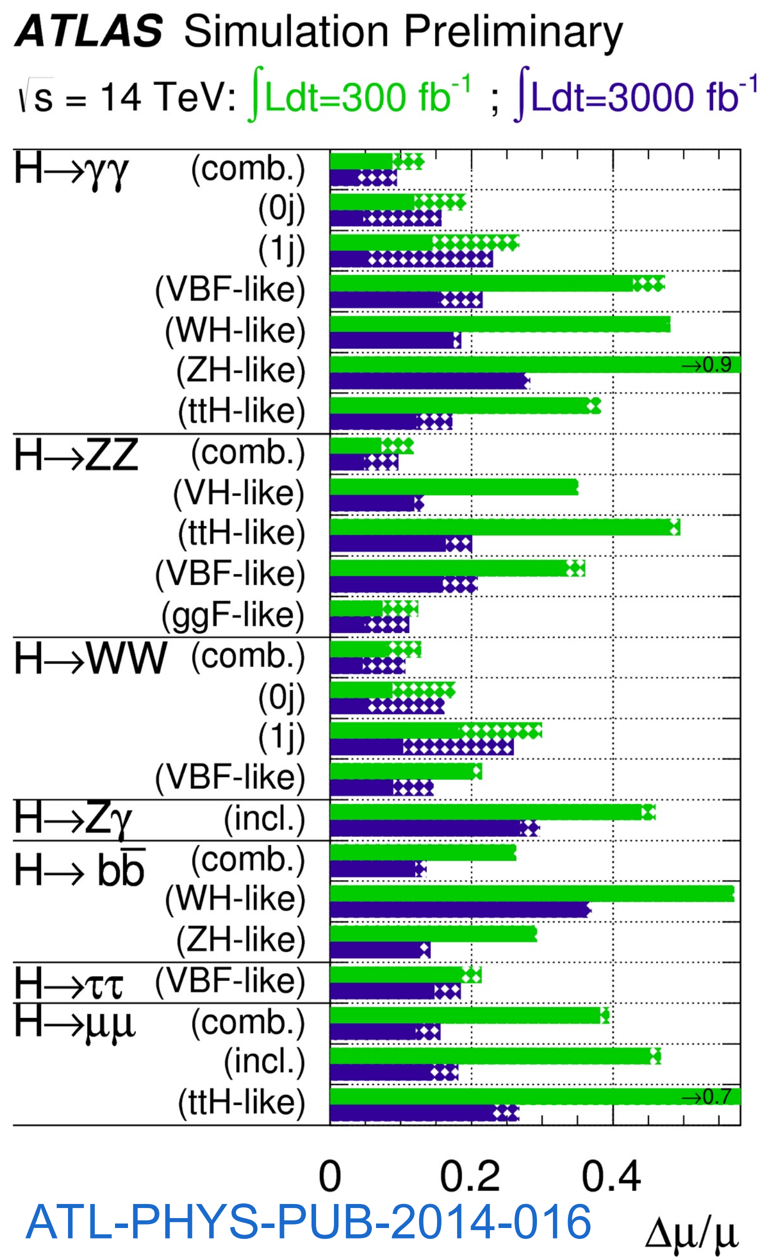
Upgrade Example: Inner tracker

- Tracker rebuild to handle radiation & tracks density
- ITk features
  - All silicon (fast) layout
    - 5 pixel, 4 strip
  - Higher granularity
    - Reduced occupancy
  - Improved radiation handling
  - Extended coverage
    - $|\eta|$ limit 2.5 → 4



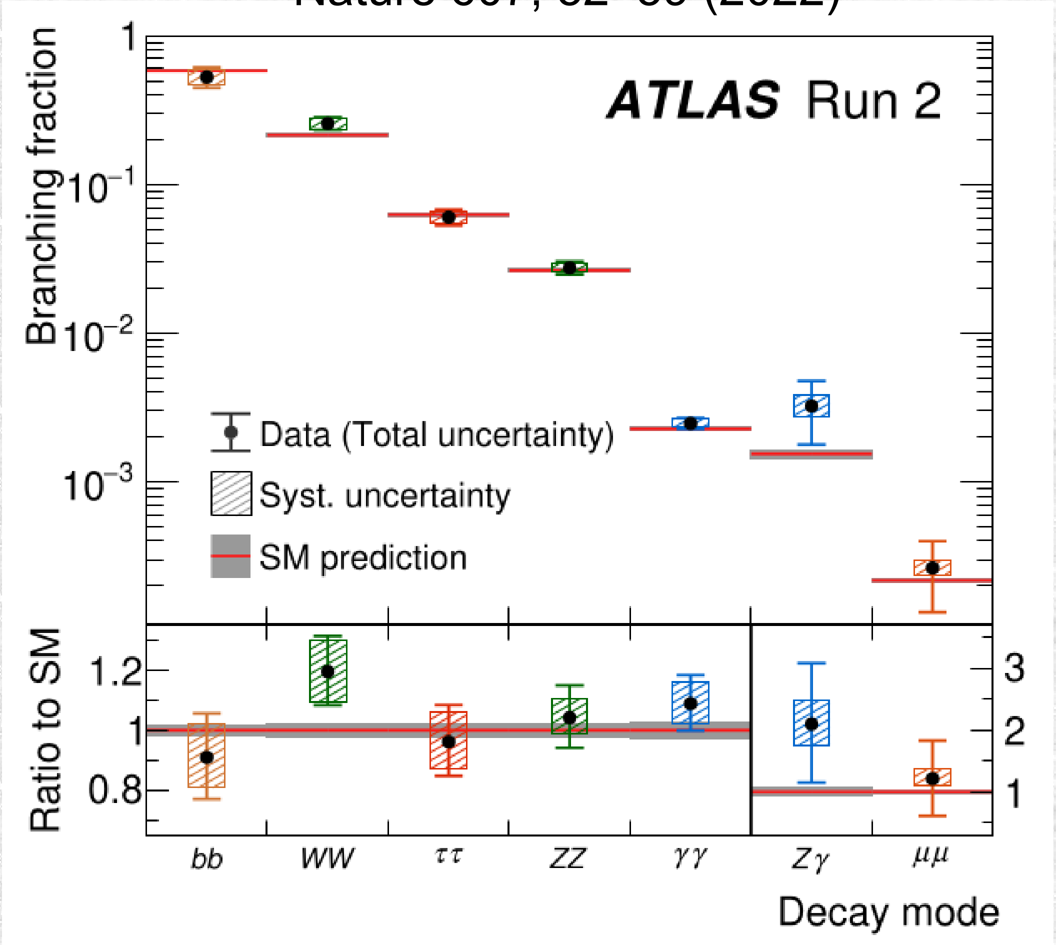
- Maintains or improves performance despite pileup
- The build schedule is tight but doable for 2029

Expectations: exceeded



ATL-PHYS-PUB-2014-016

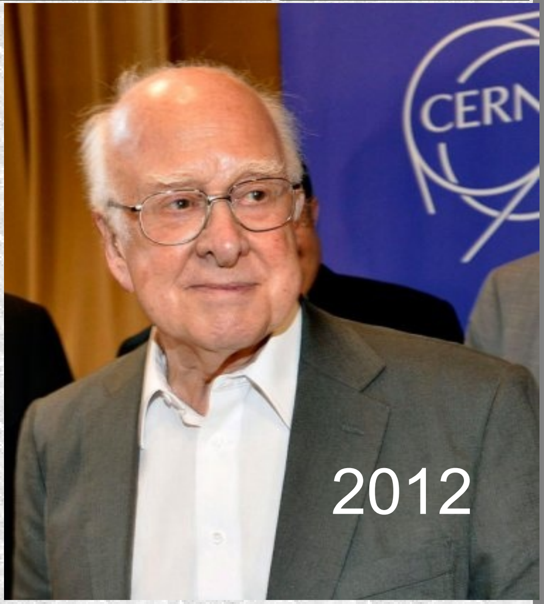
Nature 607, 52–59 (2022)



- Run 2 results are comparable to 2014 HL-LHC expectations

What comes next?

- We have found a Higgs boson
- This confirms a 'Higgs Field' filling space
  - Unlike light, you turn it off and it persists
  - But it is much denser than lead...
- This is something radically new
  - It is not like matter, not like a force
    - Newton, 1704, described world as these
  - It is a Higgs field, something new.
- Now we need to understand it
- LHC is producing large amounts of high energy (13+TeV) data
  - maybe we will find something else too!



Outlook

- Broad Physics programme
- Over 1000 papers published
  - With many more to come from Run 2
  - While Run 3 data is already on us
- No one knows what discoveries they will bring
  - But diHiggs sensitivity is approaching fast
- ATLAS is a friendly Titan…
  - Ready to gather more Golden Apples

The complete theory:

- We have maths that describes particles and forces

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial \mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu +$$

$$-\frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2} |\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

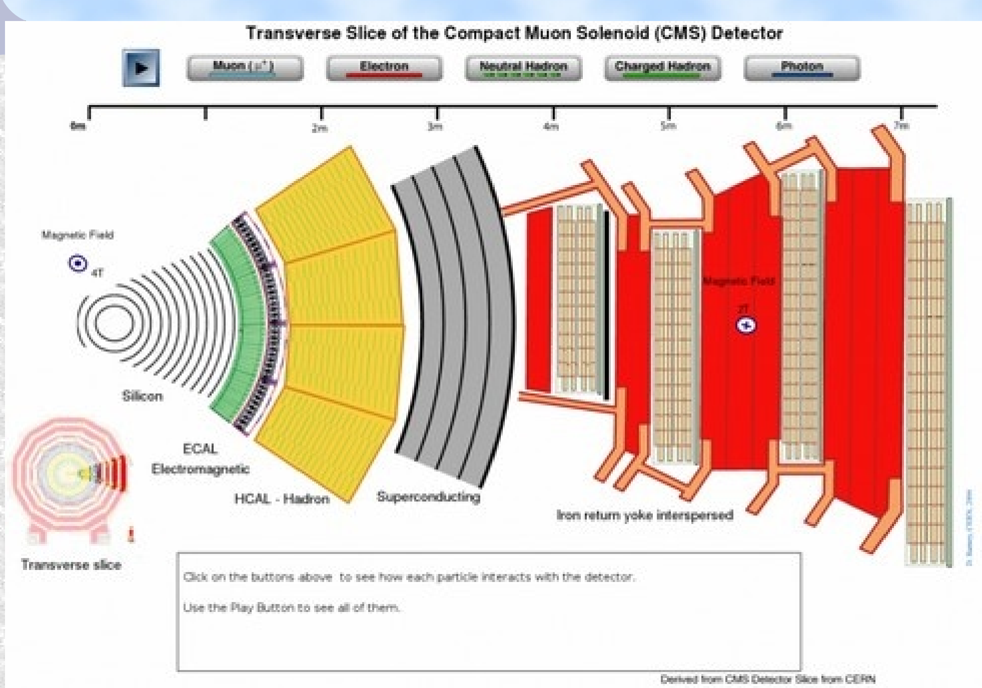
$$-\frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

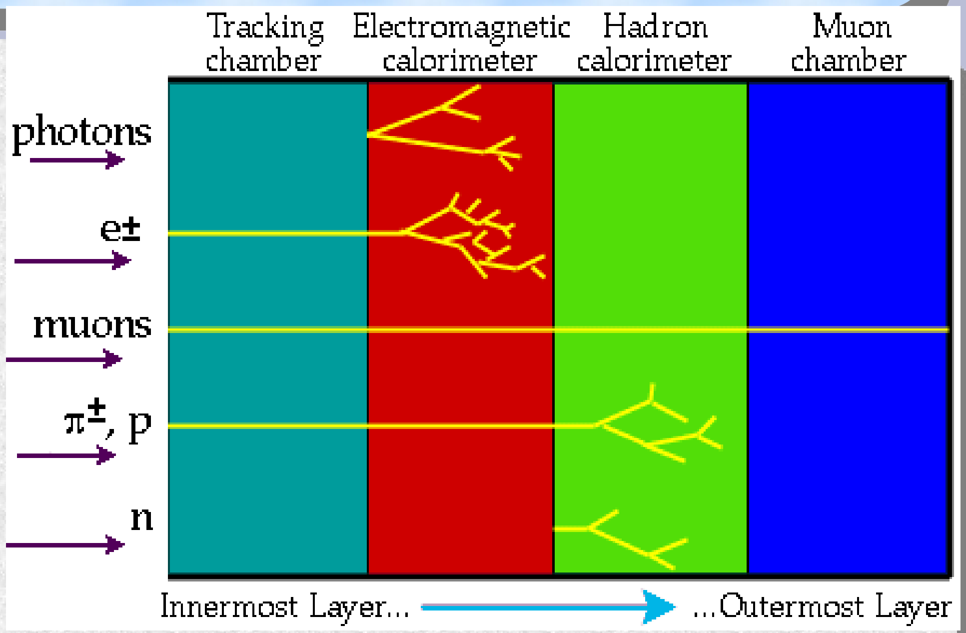
$$-\frac{1}{2} M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W} \eta^3 - \frac{g'^2 M_\eta^2}{32 M_W} \eta^4 + |M_W W_\mu^+ + \frac{g}{2} \eta W_\mu^+|^2 +$$

$$+\frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

- But we cannot discuss that here

Particle identification

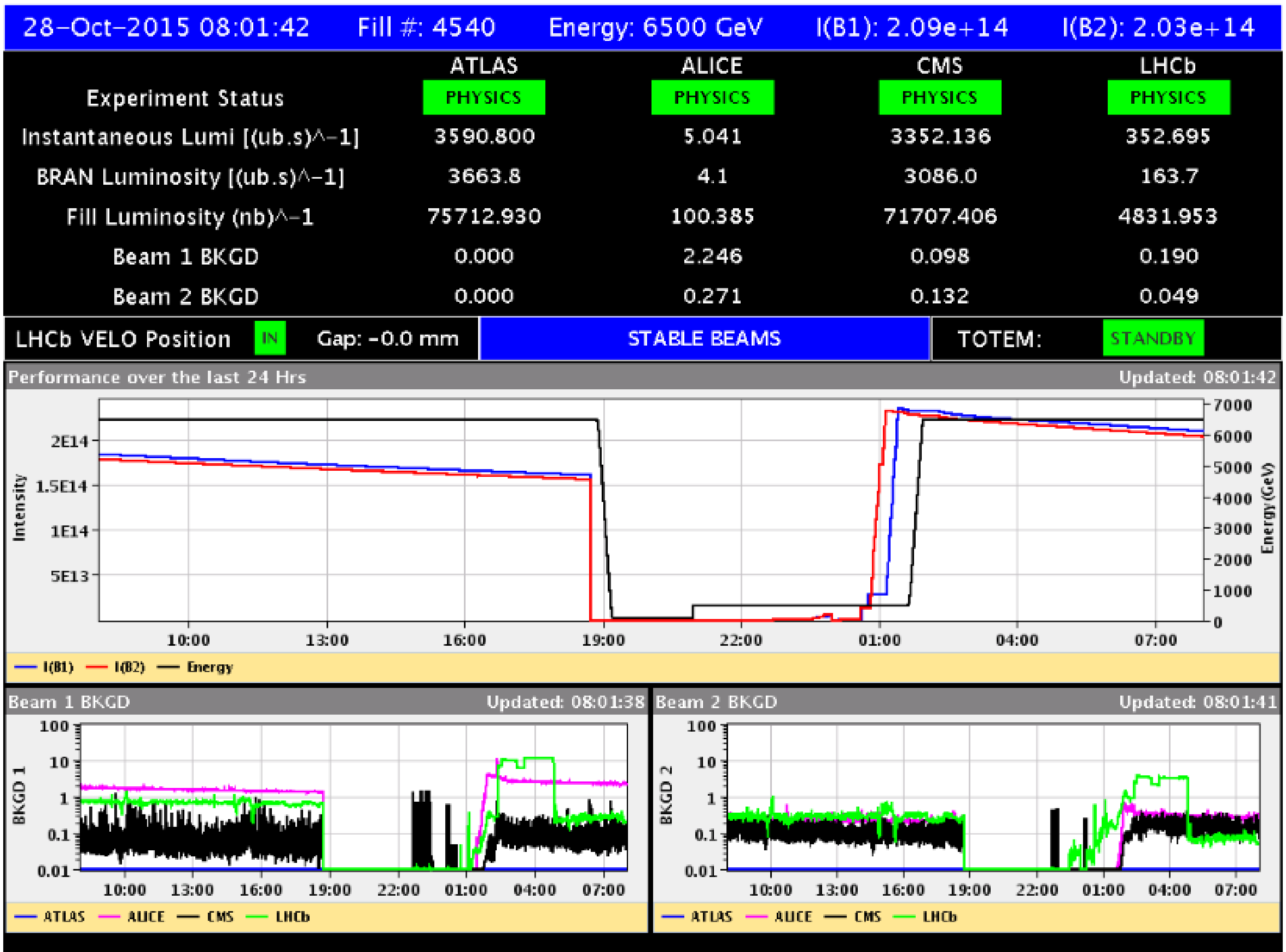




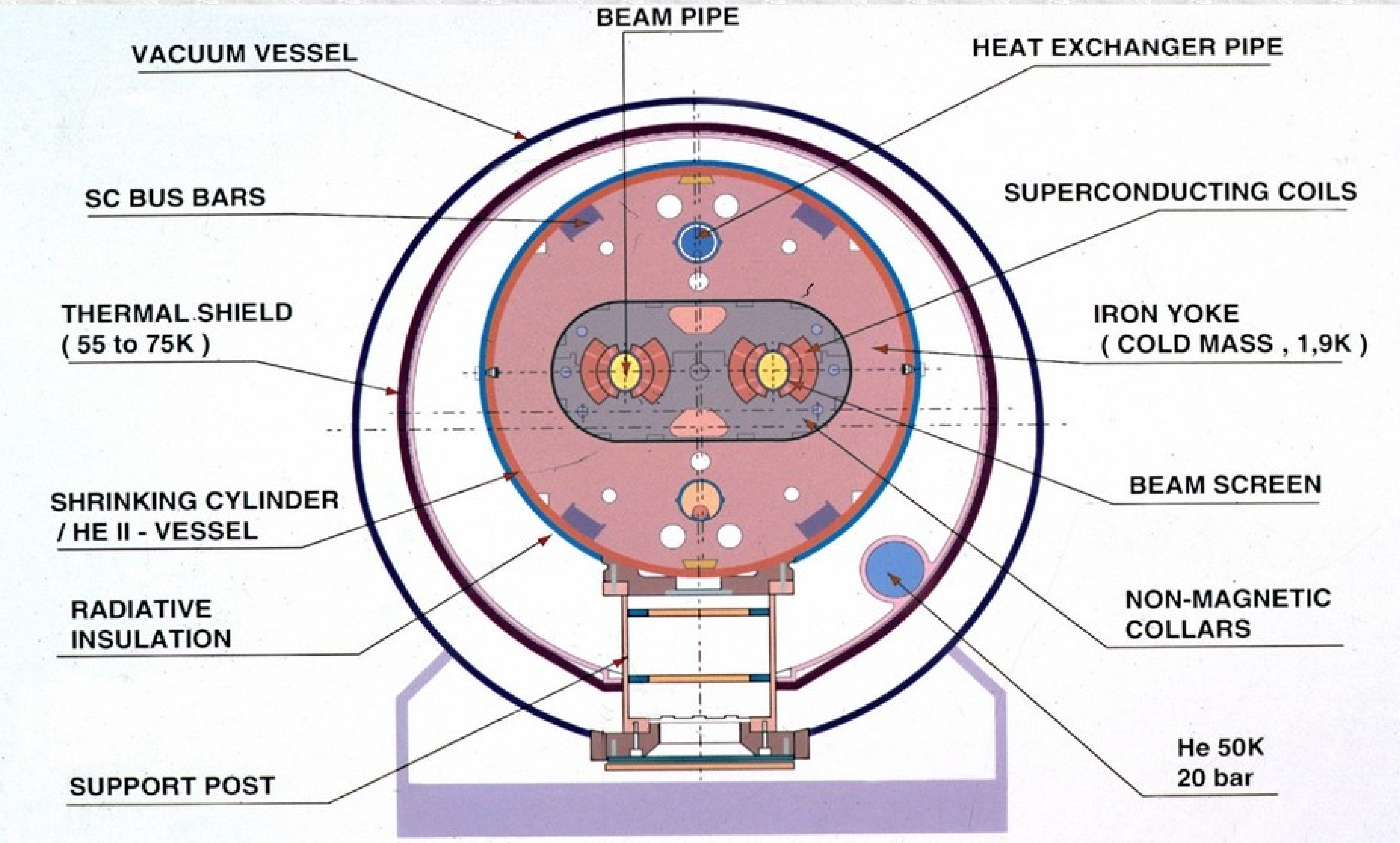
Look at me! I'm a neutrino

- Reconstruct long-lived particles in the detector
  - Basically only a few types: photons(γ), e^-, μ^-, p^+, π^+, n, ν
  - Can identify type by interaction pattern in the detector
  - Measure the momentum by bending in magnetic field
- Electrons, muons and photons especially useful
  - There are none in a proton so their presence is suggestive
  - We can measure their energy very well

LHC running


28-Oct-2015 08:01:42
Fill #: 4540
Energy: 6500 GeV
I(B1): 2.09e+14
I(B2): 2.03e+14
ATLAS
ALICE
CMS
LHCb
Experiment Status
PHYSICS
PHYSICS
PHYSICS
PHYSICS
Instantaneous Lumi [(ub.s)^-1] 3590.800 5.041 3352.136 352.695
BRAN Luminosity [(ub.s)^-1] 3663.8 4.1 3086.0 163.7
Fill Luminosity (nb)^-1 75712.930 100.385 71707.406 4831.953
Beam 1 BKGD 0.000 2.246 0.098 0.190
Beam 2 BKGD 0.000 0.271 0.132 0.049
LHCb VELO Position
IN
Gap: -0.0 mm
STABLE BEAMS
TOTEM:
STANDBY
Performance over the last 24 Hrs
Updated: 08:01:42
Intensity
Energy (GeV)
I(B1)
I(B2)
Energy
Beam 1 BKGD
Updated: 08:01:38
BKGD 1
Beam 2 BKGD
Updated: 08:01:41
BKGD 2
ATLAS
ALICE
CMS
LHCb

LHC magnets



Cross Section of LHC Dipole

The 4 big detectors

- LHC has 4 points where the beams cross
- ATLAS
  - Designed to see what happens at the highest energy
  - 'General Purpose' – ready for anything
    - e.g. Higgs, Supersymmetry, dark matter, black holes
- CMS
  – Similar to ATLAS. 2 experiments check each other
- LHCb
  - Studies b quarks, for matter-antimatter differences
  - LHC energy & luminosity means lots of particles
- ALICE
  - Studies the quark gluon plasma
  - A soup of free quarks when two lead nuclei collide
  - LHC switches to Pb+Pb for last few weeks of year

The Higgs self-interaction

- The Brout-Englert-Higgs theory replaces a mass term ($m\varphi^2$) by a two-term piece ($-m\varphi^2+\varphi^4$)
- Φ is the field density
- The field-energy, or action, has a minimum away from zero
- It is this that means the Universe sits in a high Higgs density state