One Ring to Rule them All, One Ring to Find them

Reinhild Yvonne Peters

The University of Manchester

MANCHESTER 1824

European Research Council
Established by the European Commission

One Ring to Rule ~~them~~ All, One Ring to Find ~~them~~

Out the SM

New Physics

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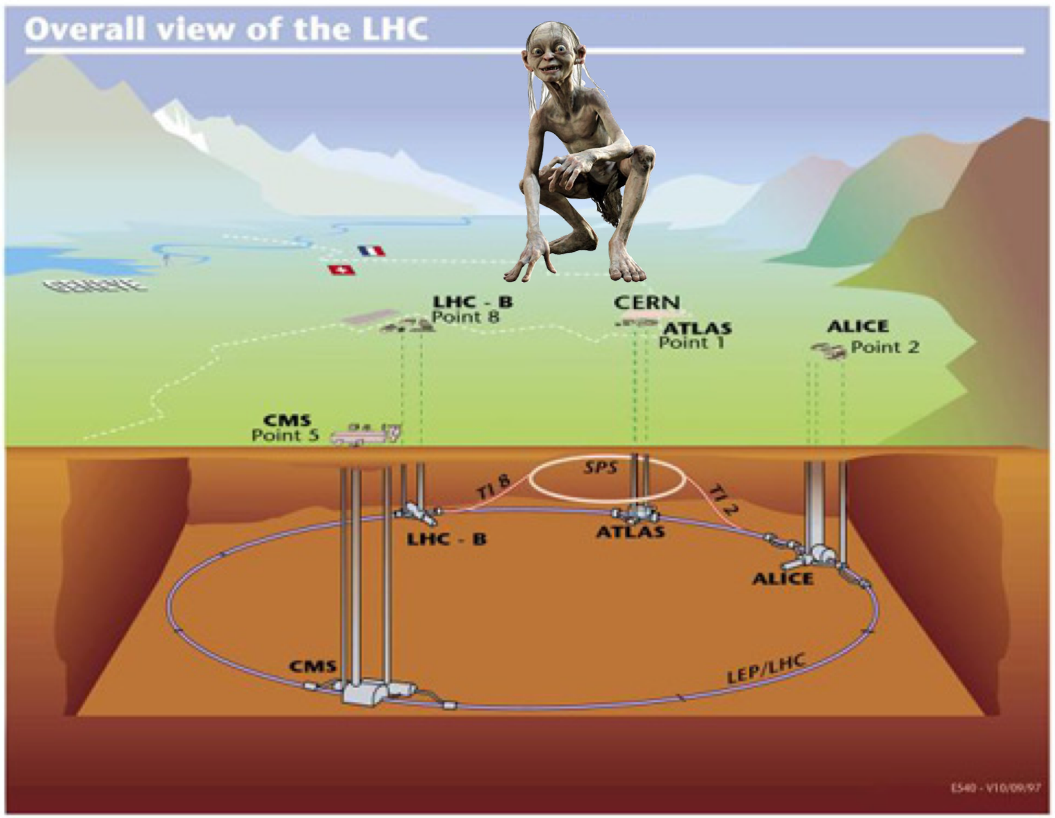
The LHC

- LHC: 13 TeV Proton-Proton collisions (2011: 7 TeV; 2012: 8 TeV)
  - Start: 2009
  - Energies like 10^{-13} - 10^{-14} seconds after big-bang!



- Some LHC key data:
  - 27km ring
  - ~100m underneath surface
  - 1232 dipole magnets to keep protons in their orbit
    - Further magnets for focusing
  - Magnets get cooled to 1.9 Kelvin (-271.25 Celsius) → the LHC is the coolest ring in the universe!

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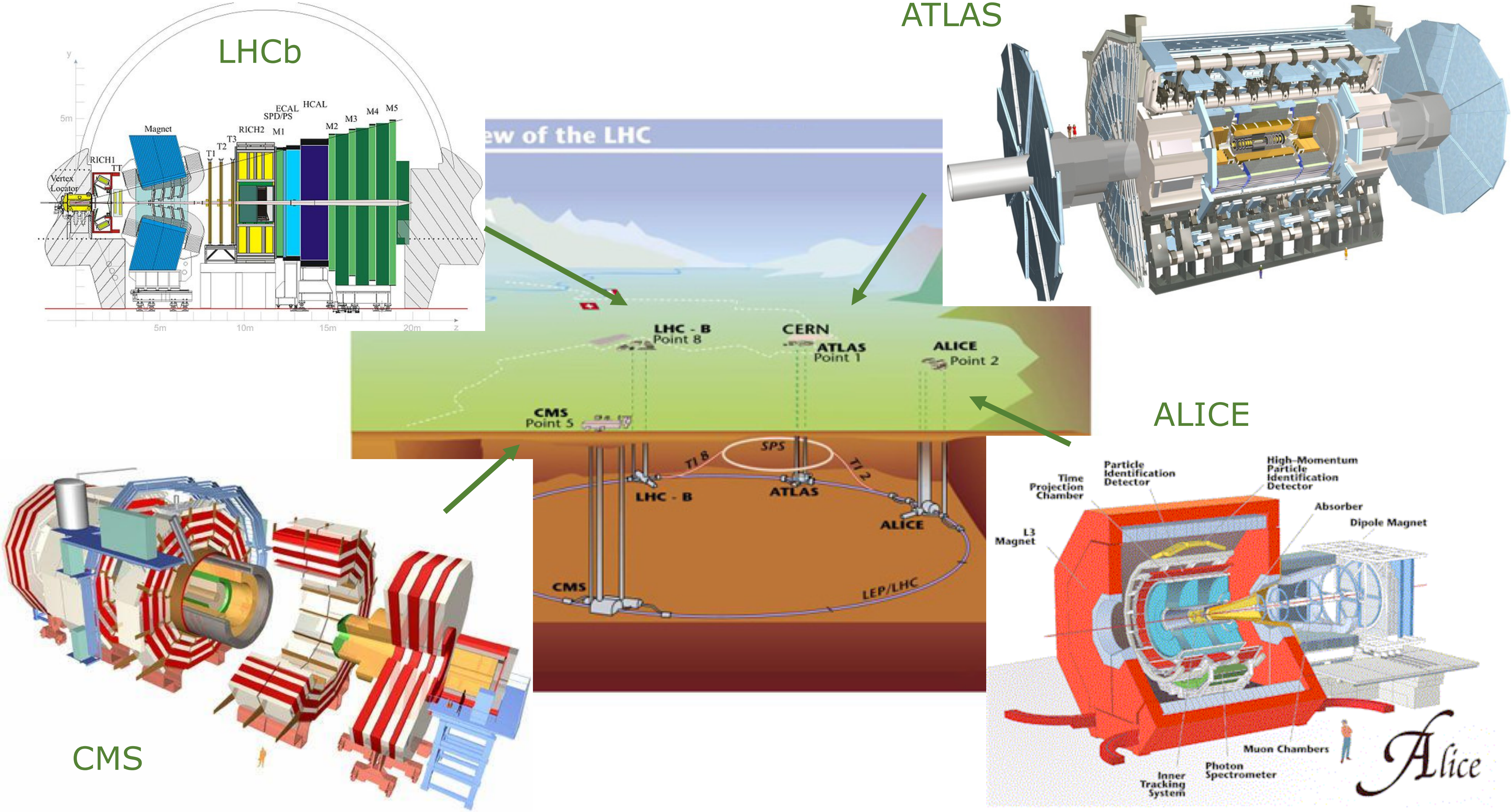
The “Main” LHC Experiments



LHC Experiments

- ATLAS & CMS: general purpose detectors
- LHCb: forward spectrometer → focused on b & c physics
- ALICE: study heavy ion interactions → quark-gluon plasma

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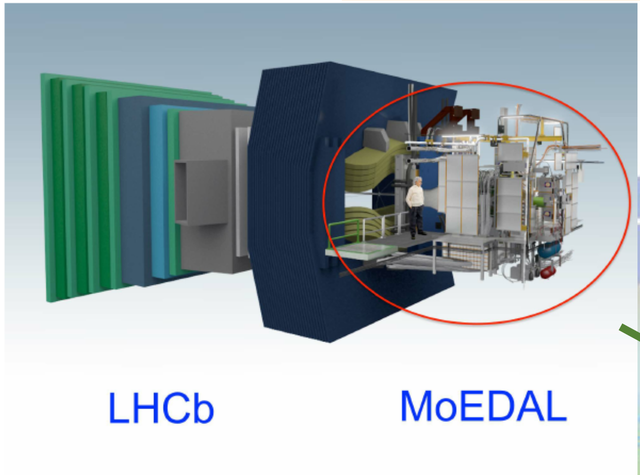
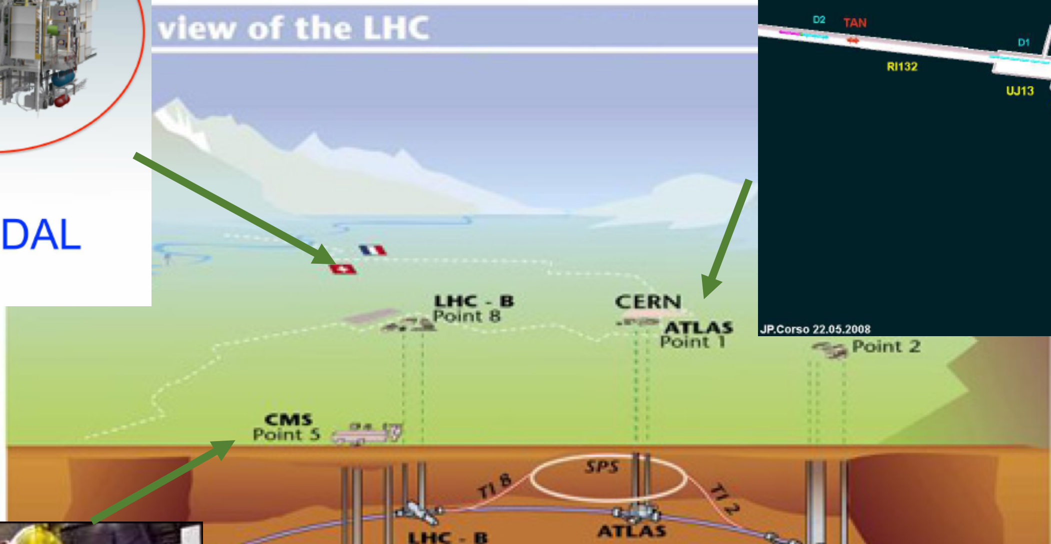
- Smaller experiments:
  - Totem: forward detectors (around CMS)
  - LHCf: forward detector (around ATLAS)
    → both for forward physics
  - MoEDAL: near LHCb
    - Search for magnetic monopoles

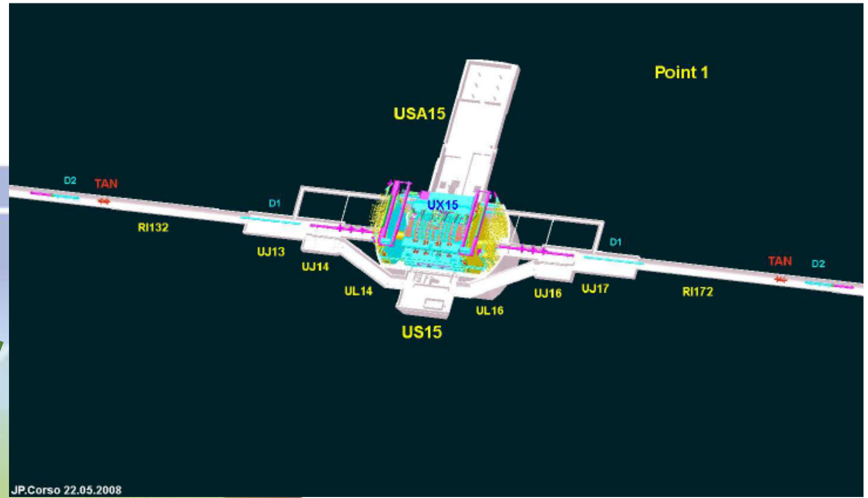
The Other Experiments

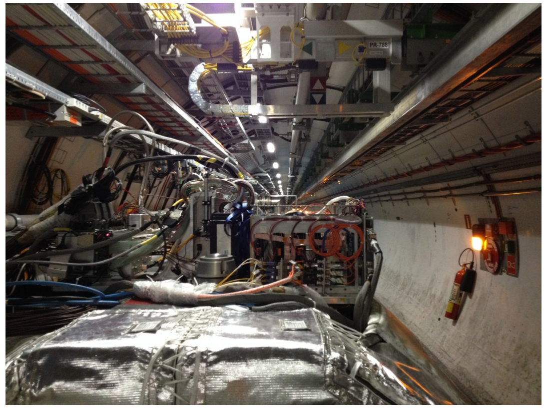


MoEDAL

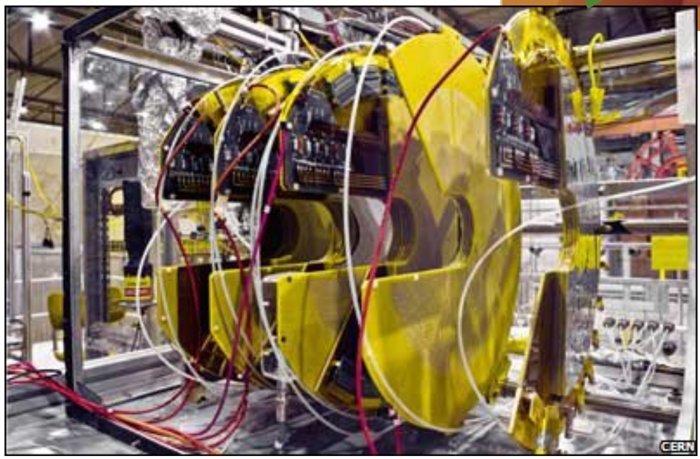
LHCf

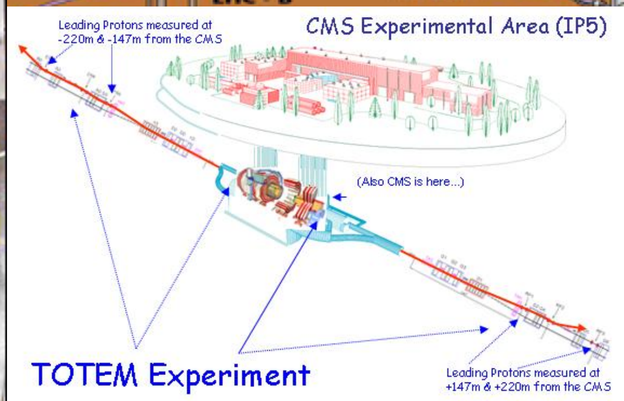






TOTEM





All Experiments

- ATLAS & CMS: general purpose detectors
- LHCb: forward spectrometer → focused on b & c physics
- ALICE: study heavy ion interactions → quark-gluon plasma
- Smaller experiments:
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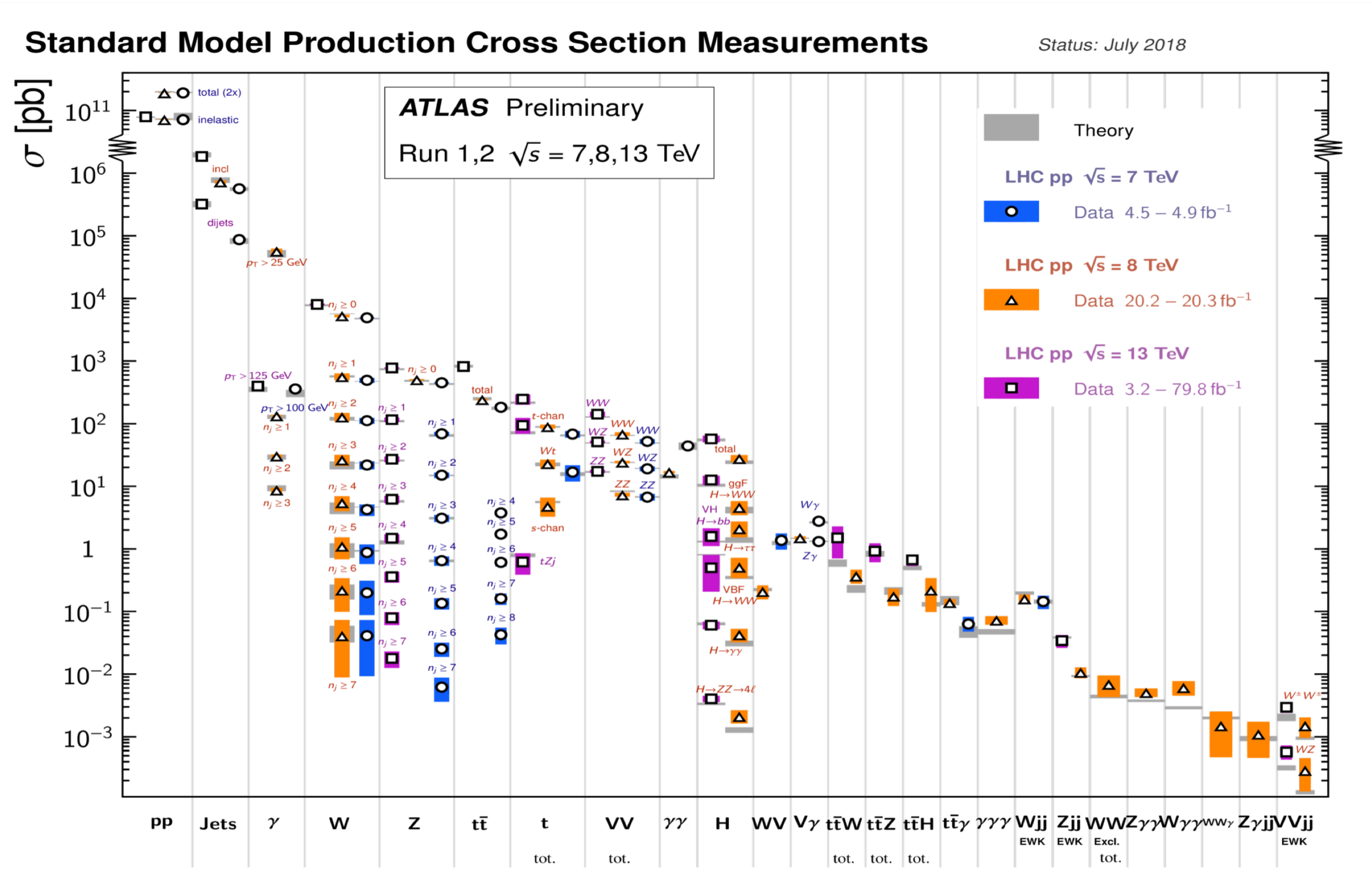
- All quite interesting (definitely LHC is not just the Higgs!)
  - This talk: focused on ATLAS (& implicitly CMS)

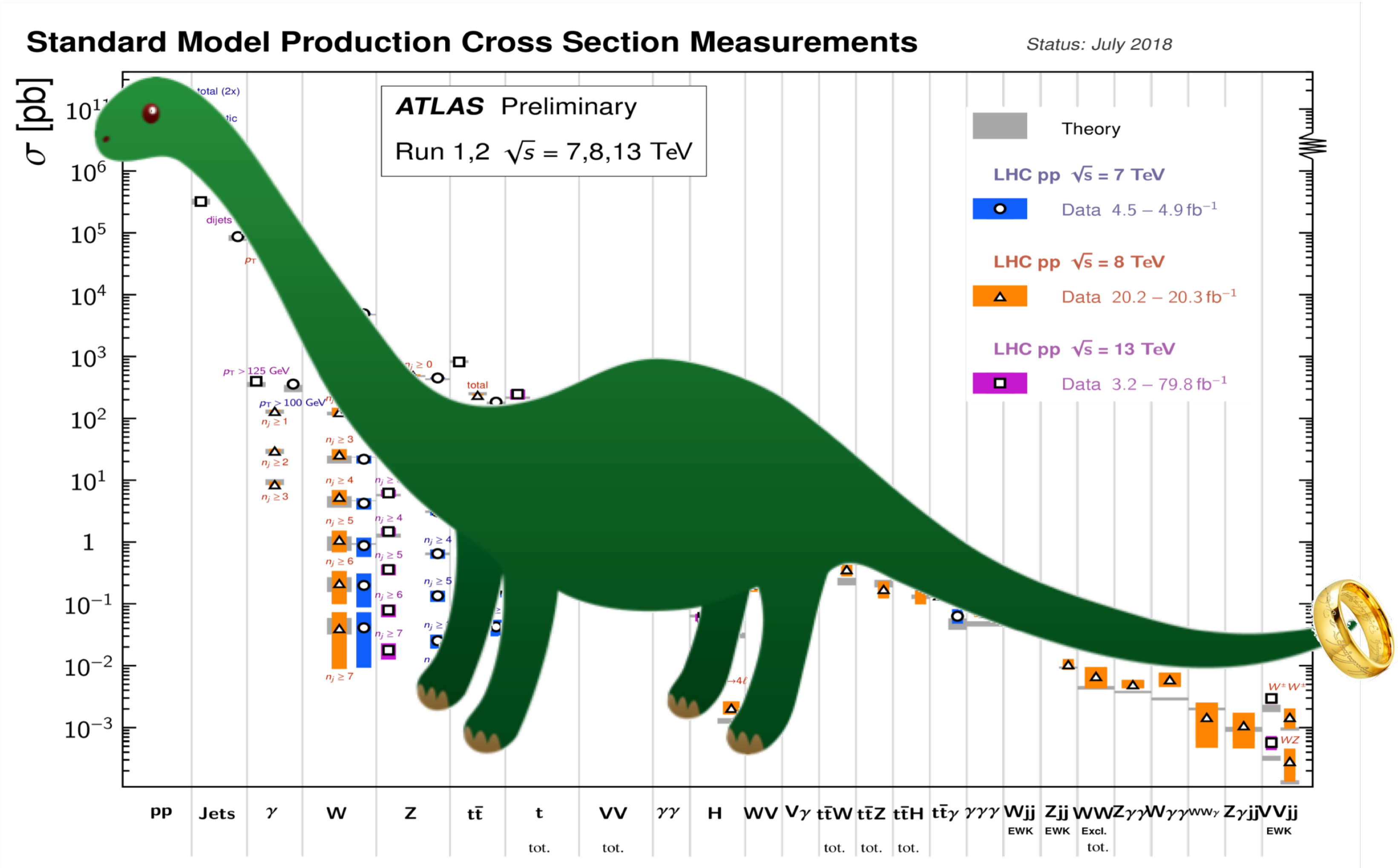
What to do at ATLAS & CMS?

- Measure and Search!



What to do at ATLAS & CMS?

- Measure and Search and dig out the dino's tail



The Precious

- The Higgs
  - Discovery of the Higgs in 2012
  - Completing the SM of particle physics

Higgs boson-like particle discovery claimed at LHC

COMMENTS (1665)

By Paul Rincon
Science editor, BBC News website, Geneva

The moment when Cern director Rolf Heuer confirmed the Higgs results

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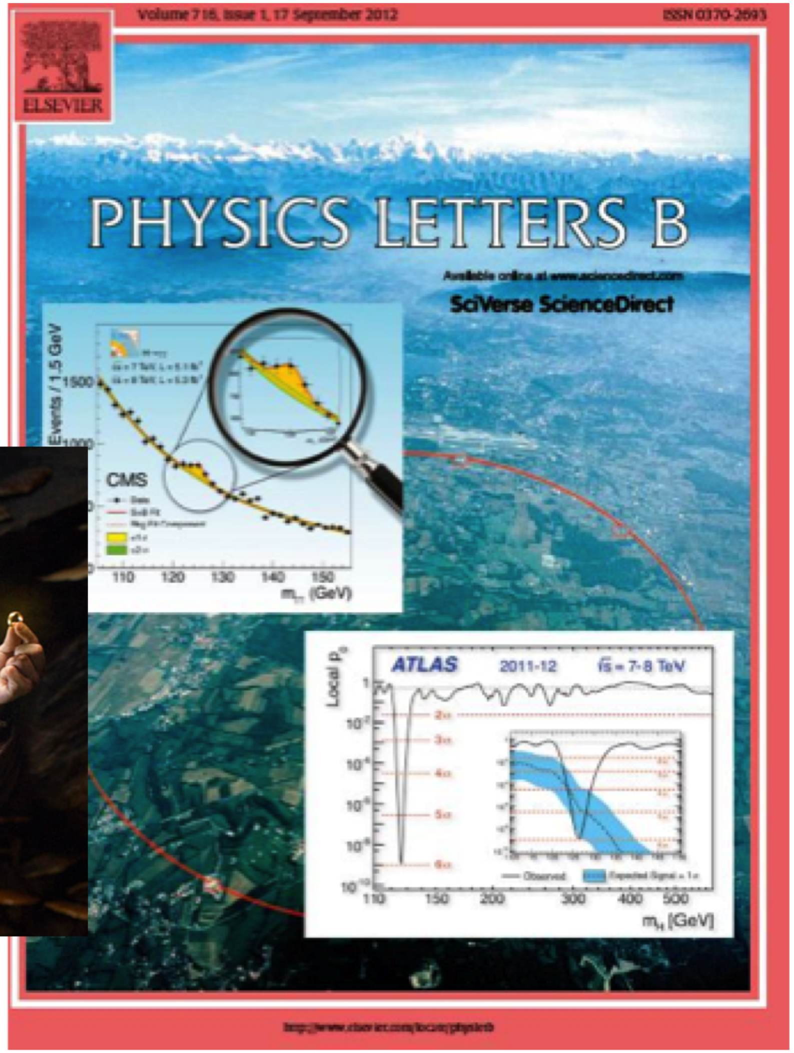

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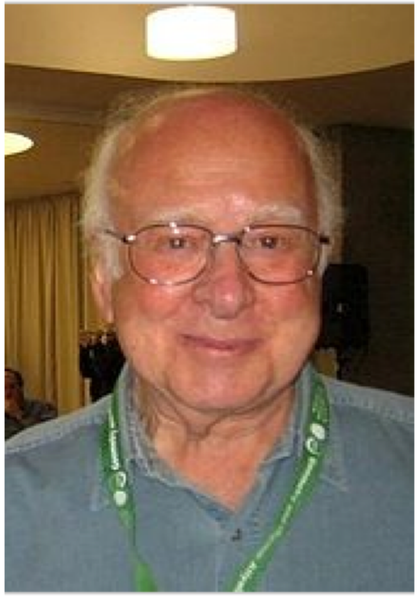

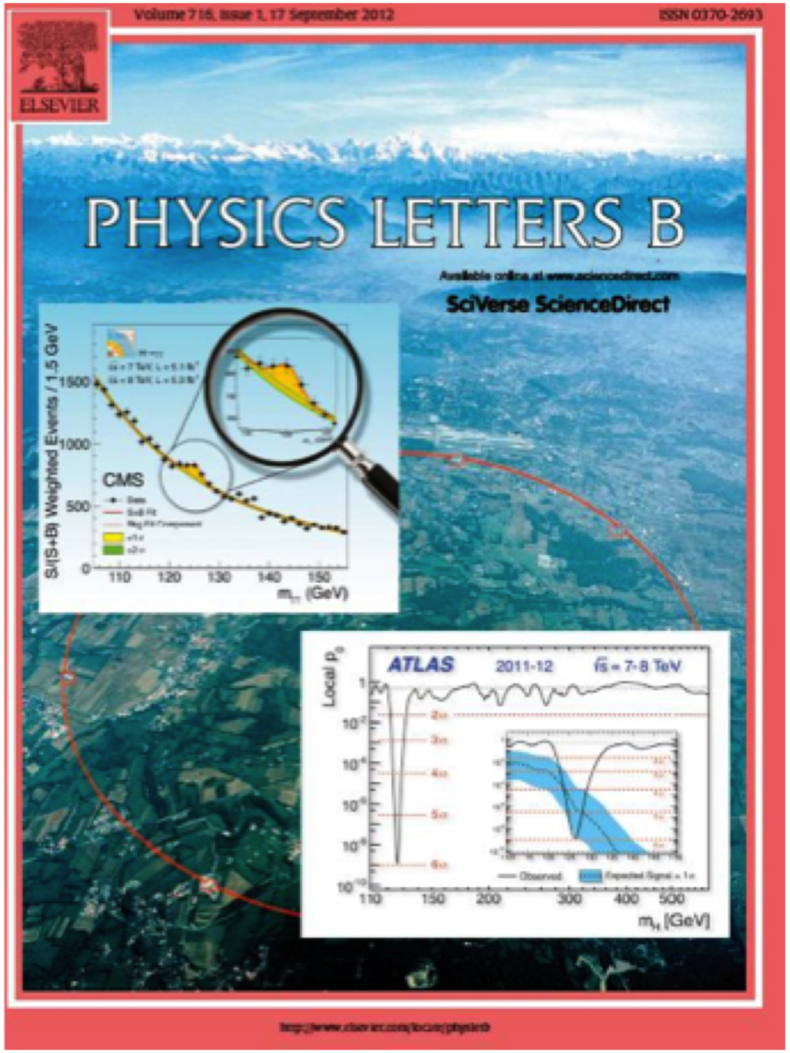

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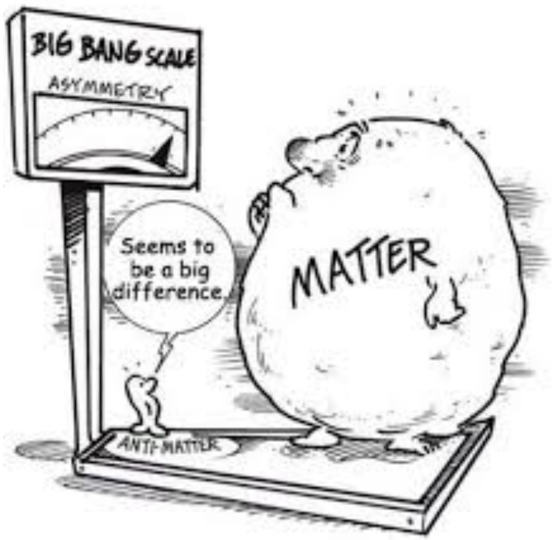
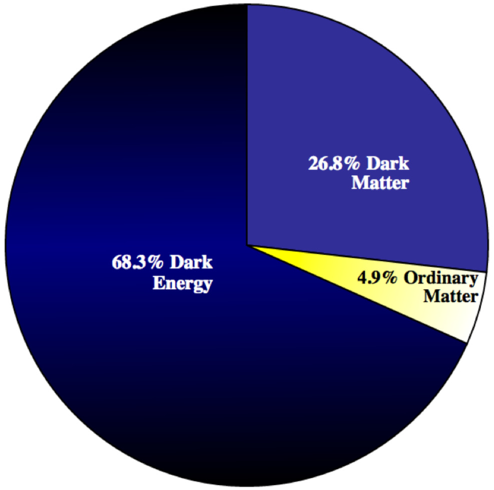
Why not stop there?

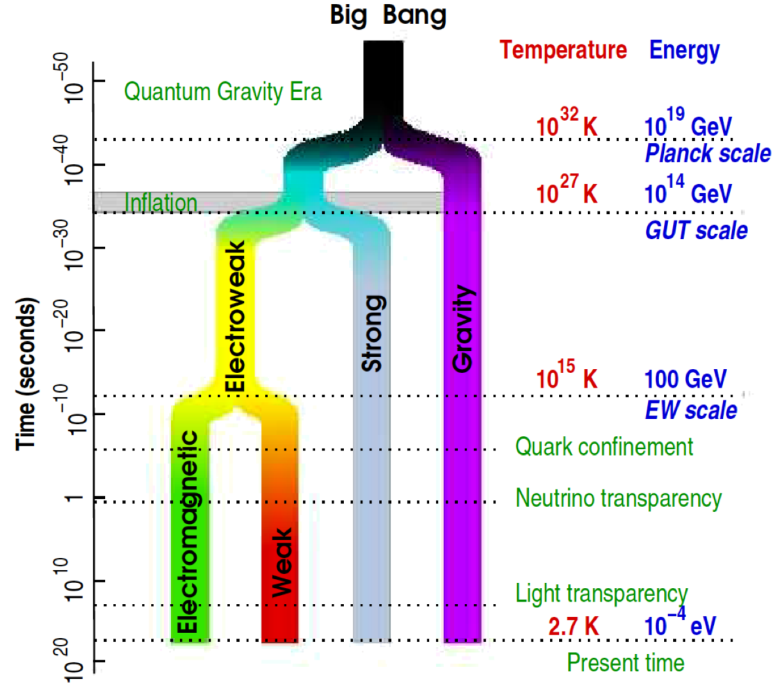
Matter-antimatter asymmetry



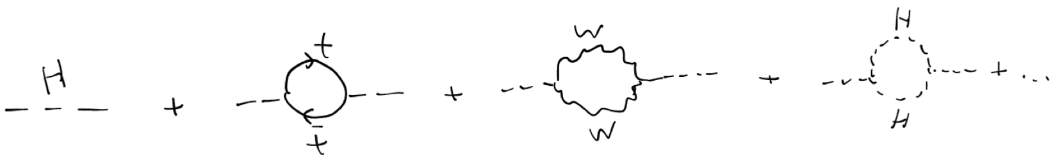


Dark matter
Dark energy

Unification of forces?



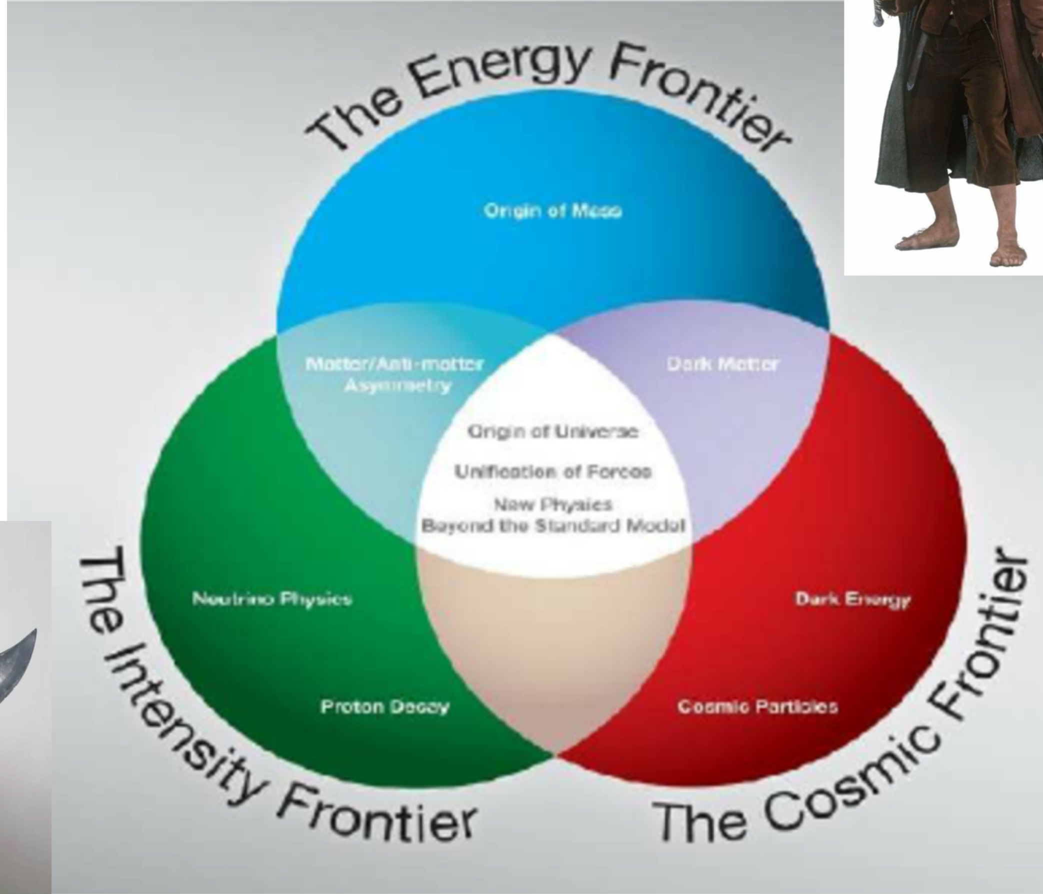
Hierarchy problem

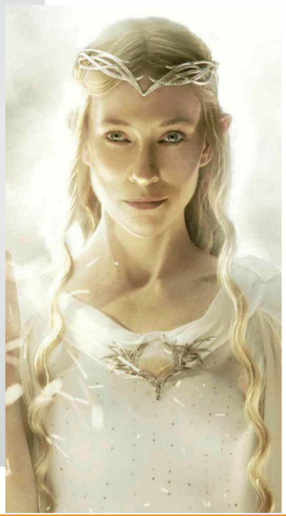


- Many open questions the SM can not answer
  - We know there must be something more…something….

The Frontiers

- Several frontiers to look
  - LHC: at the Energy Frontier



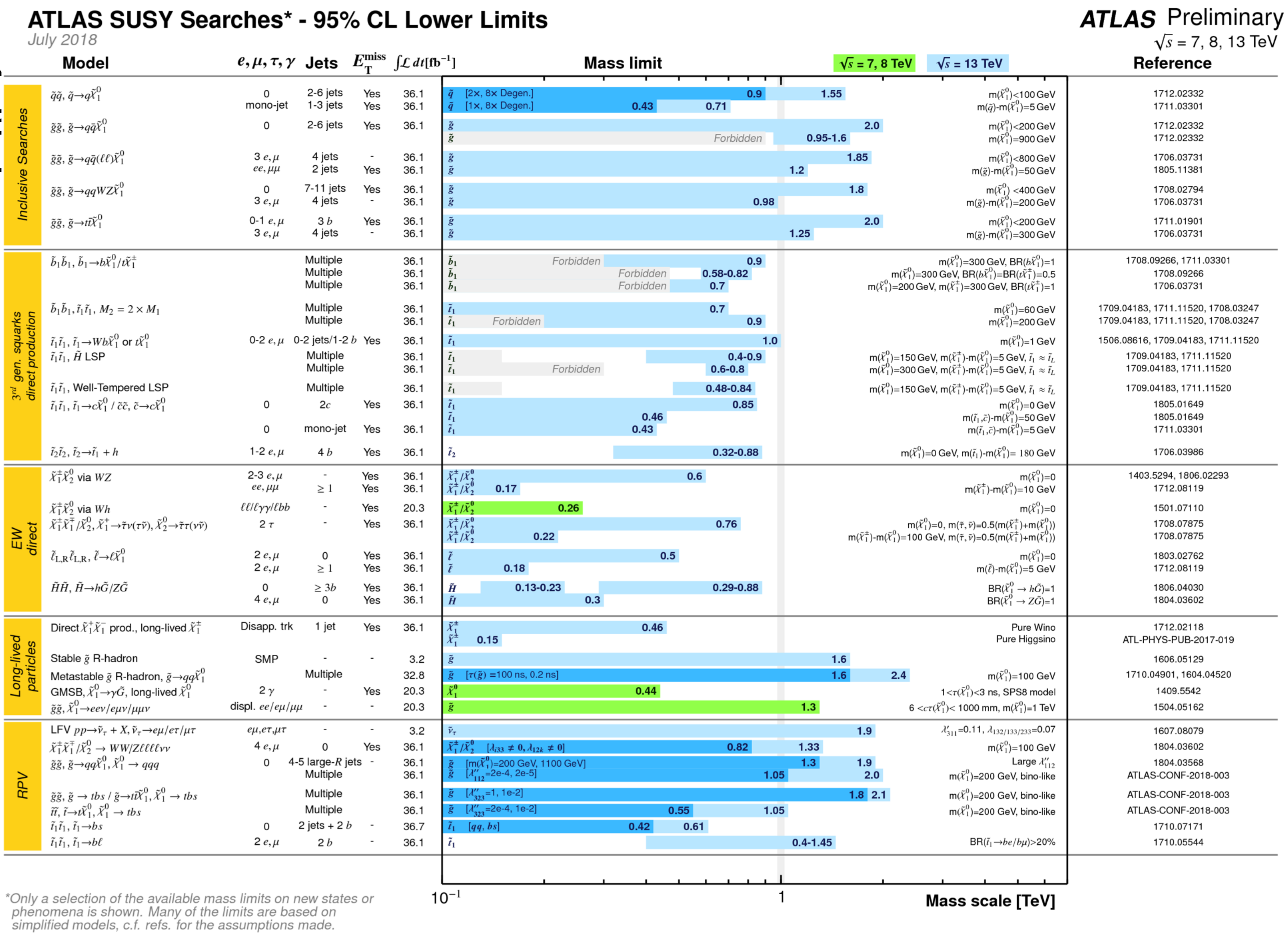


The Way forward

- Direct searches:
  - Take your favorite model
  - Design analysis around it
  - Look for deviation from background

The Way forward

- Direct searches:
  - Take you
  - Design a
  - Look for



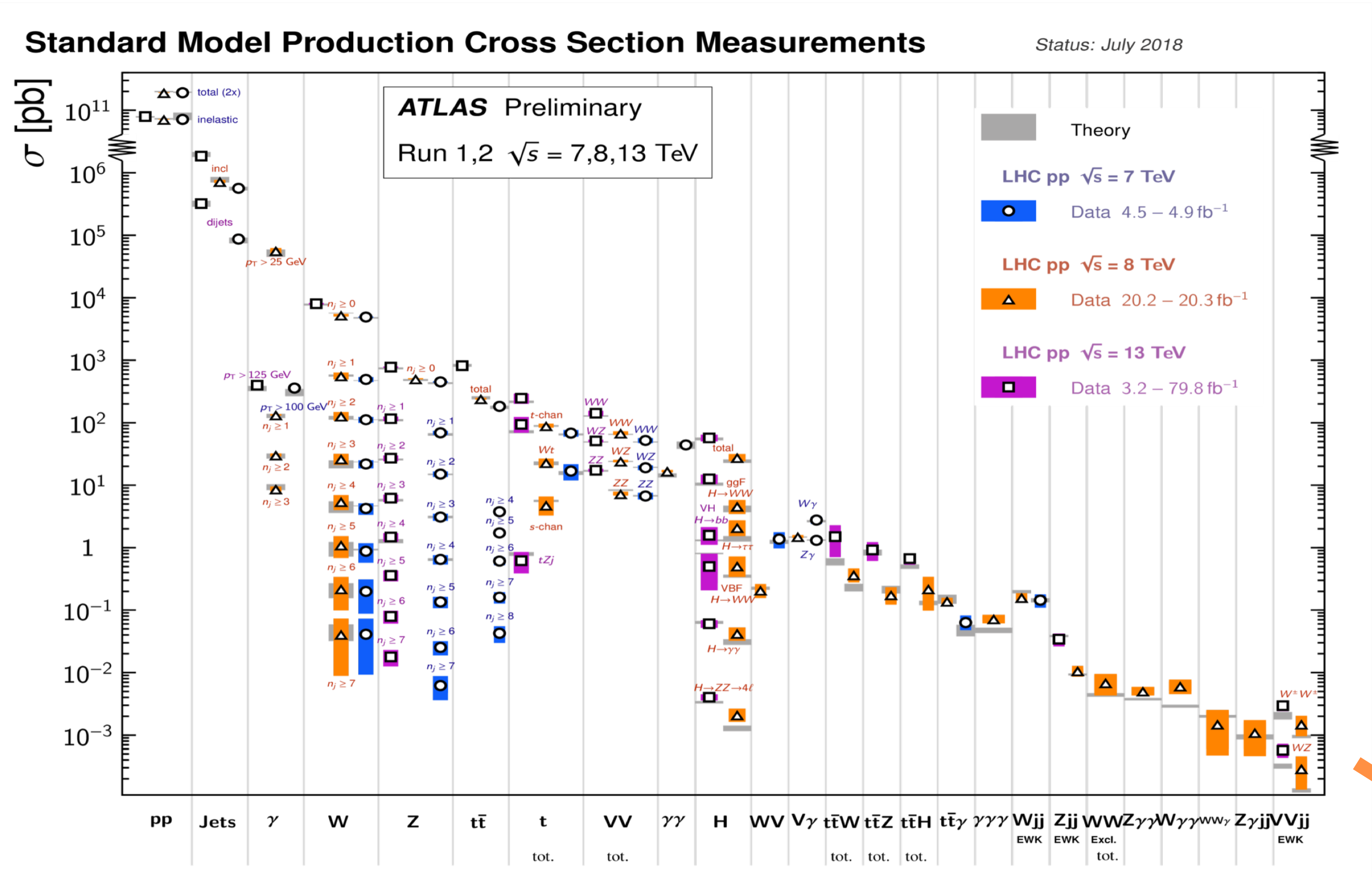
The Way forward

- Direct searches:
  - Take your favorite model
  - Design analysis around it
  - Look for deviation from background

- Indirect searches:
  - Perform precision measurements
  - Compare to prediction and look for deviation
  - Interpretation in terms of new physics, as model-independent as possible

Indirect Searches

- Usually: start with inclusive cross section of next-lowest process



Differential distributions

- Next step: properties and differential distributions
- Differential distributions:
  - Test of higher-order QCD
  - Generic test of the SM → test for new physics
  - Also: tune Monte Carlo
    - Reduction of systematic uncertainties for many analyses
    - Due to large amount of data: many analyses are limited by systematic uncertainties!
- Main challenge:
  - 1. What observables are useful?
  - 2. Make distributions comparable to theory calculations
    - Correct detector effects
    - Which are the “true” particles?

Particle versus Parton

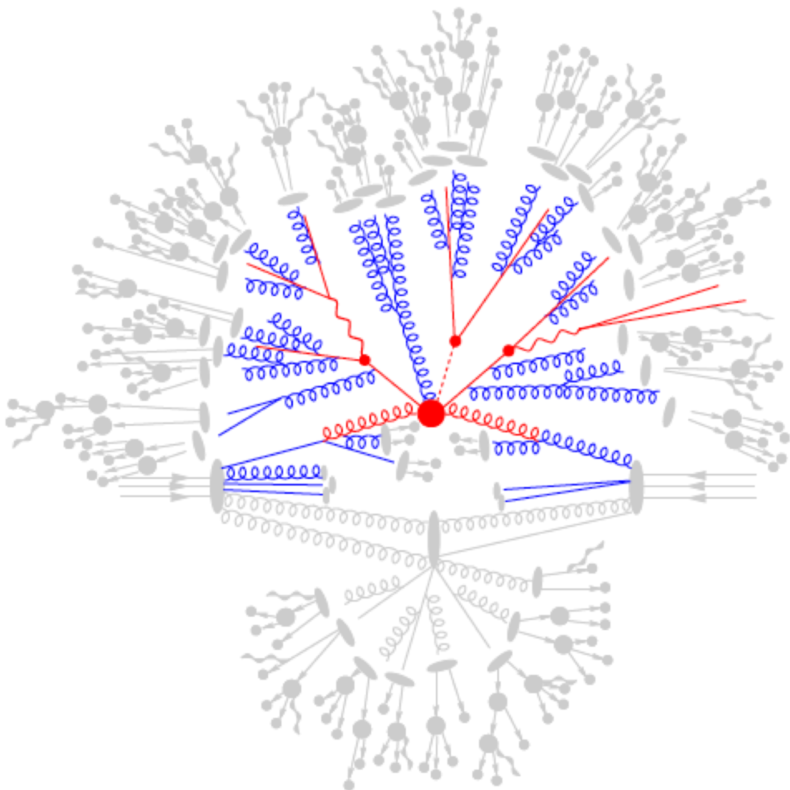
- General issue: Parton versus particle level

MC generator dependencies

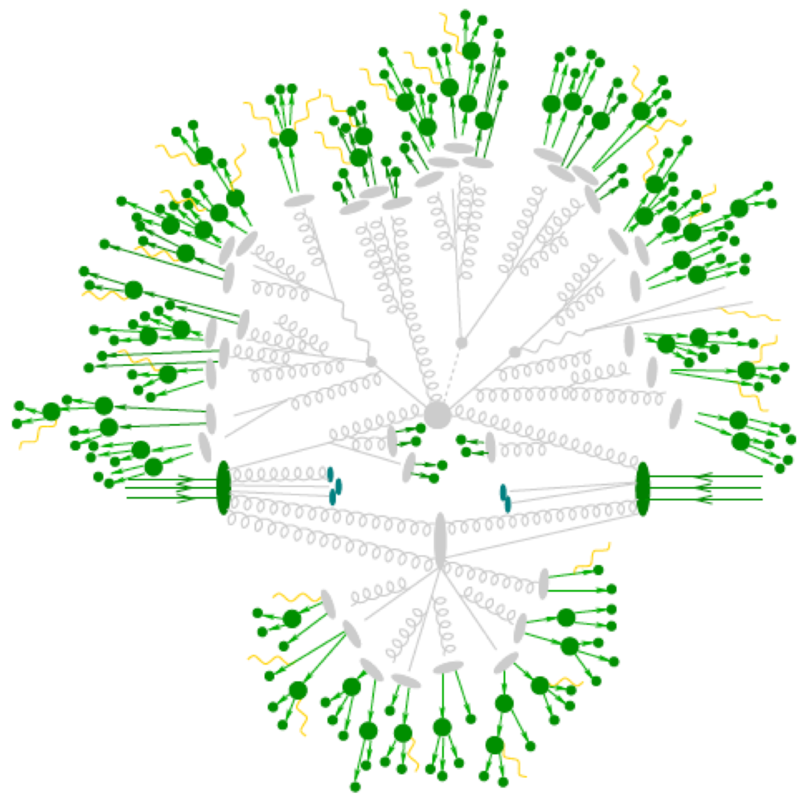
Stable particles

Particle versus Parton

- General issue: Parton versus particle level



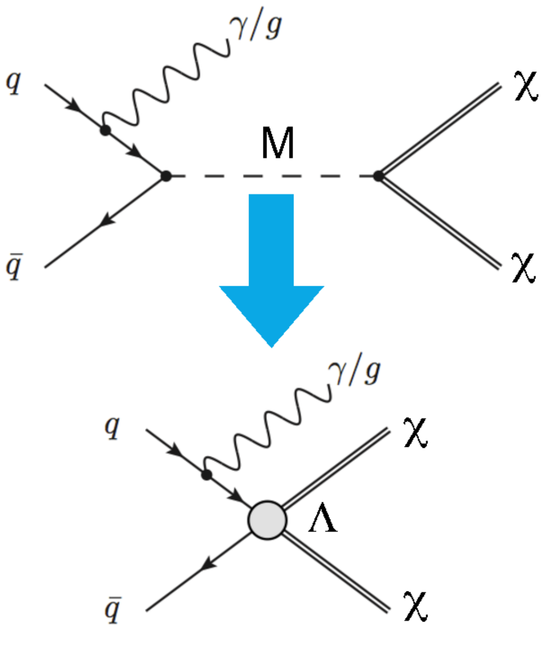
MC generator dependencies



Stable particles

Interpretations

- Interpretation for new physics can be done with specific models
  - For example: 2HDM, Susy…
- Interpretation can also be done with EFT
  - Effective field theory
  - Idea: parametrize new physics as effective coupling



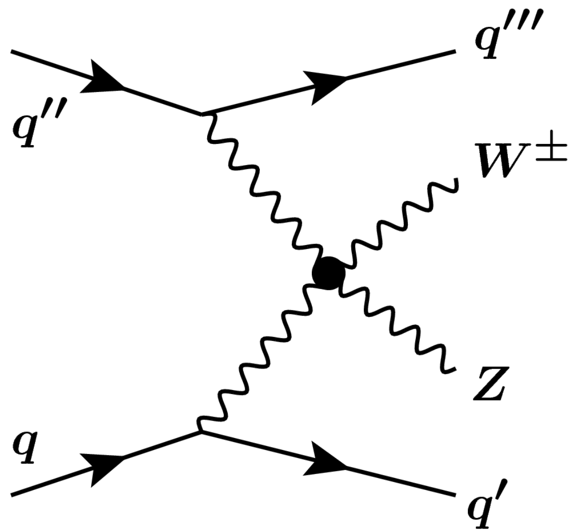
Examples

- Three examples
  - Interesting analyses from ATLAS (similar from CMS)
- A new observation: VBS

- The smart one: Higgs Width
- The fellowship of the heavy dudes: $t\bar{t}H$

Example Analysis 1: VBS

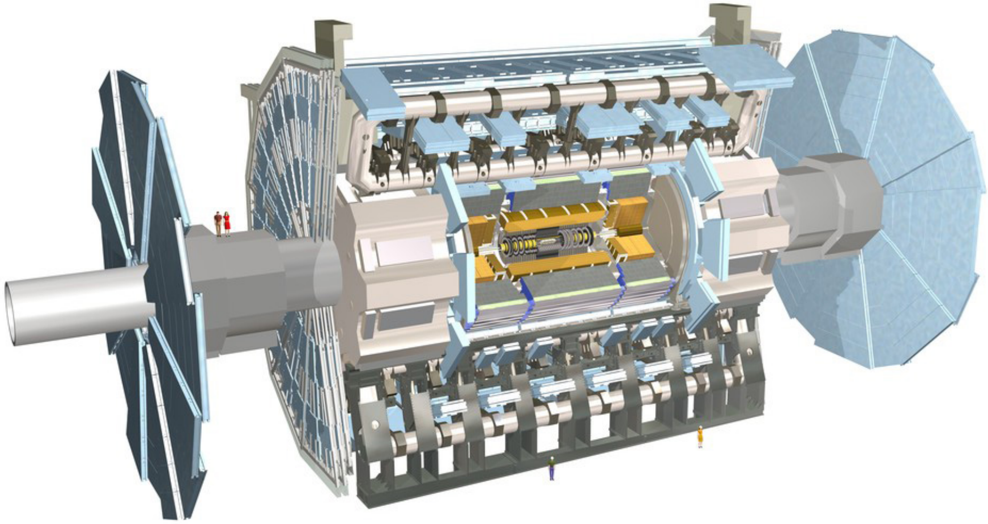
- Use the LHC as "Weak boson collider"
  - Vector boson scattering VV -> VV:
    key process to probe gauge symmetry of EW theory
    - New physics can alter couplings



- New results on VBS
- Example: Recent observation of electroweak WZjj
  - challenging analysis: electroweak VVjj can not be studied separately from other VVjj processes (that include strong interaction)

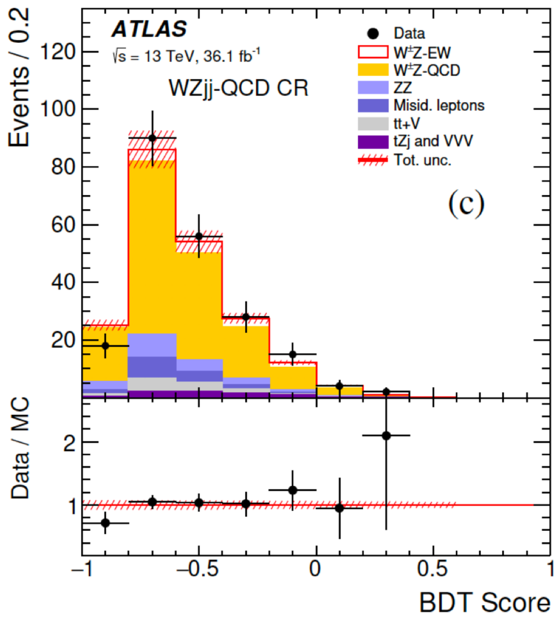
VBS

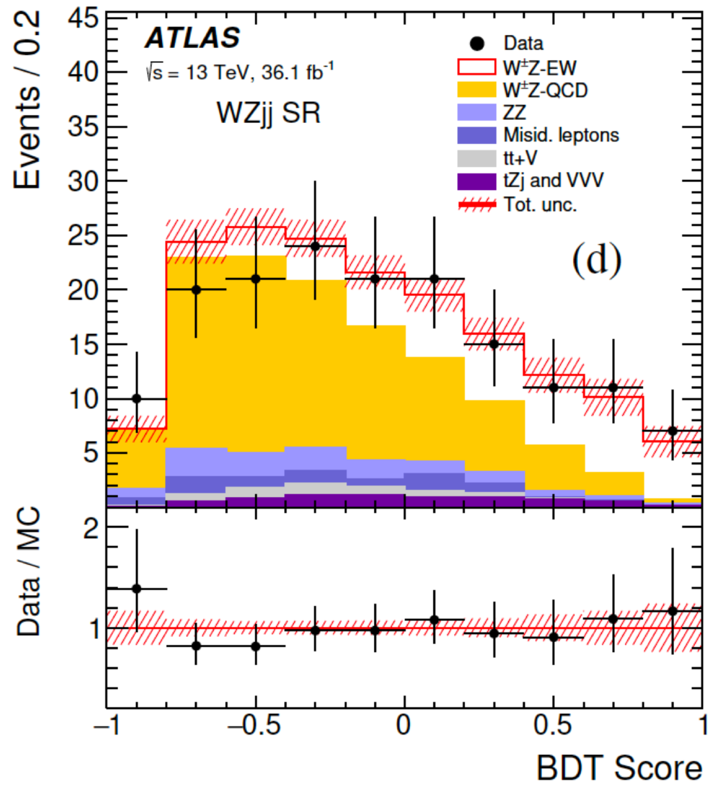
- Measurement done as fiducial cross section
  - Defining cuts on particle level close to detector acceptance
- Advantage: don’t make assumption about extrapolation beyond measurable phase space!



VBS

- Main background: WZjj QCD background
  - Important to model it well! Usually: define control region dominated by this background
- Train Boosted Decision Trees to distinguish signal from background
  - combining sensitive variables into one big discriminator





VBS

- Fiducial cross section extracted using BDT score
  - Many systematic uncertainties important
  - Treated as "nuisance parameter" -> allows data to constrain big systematics

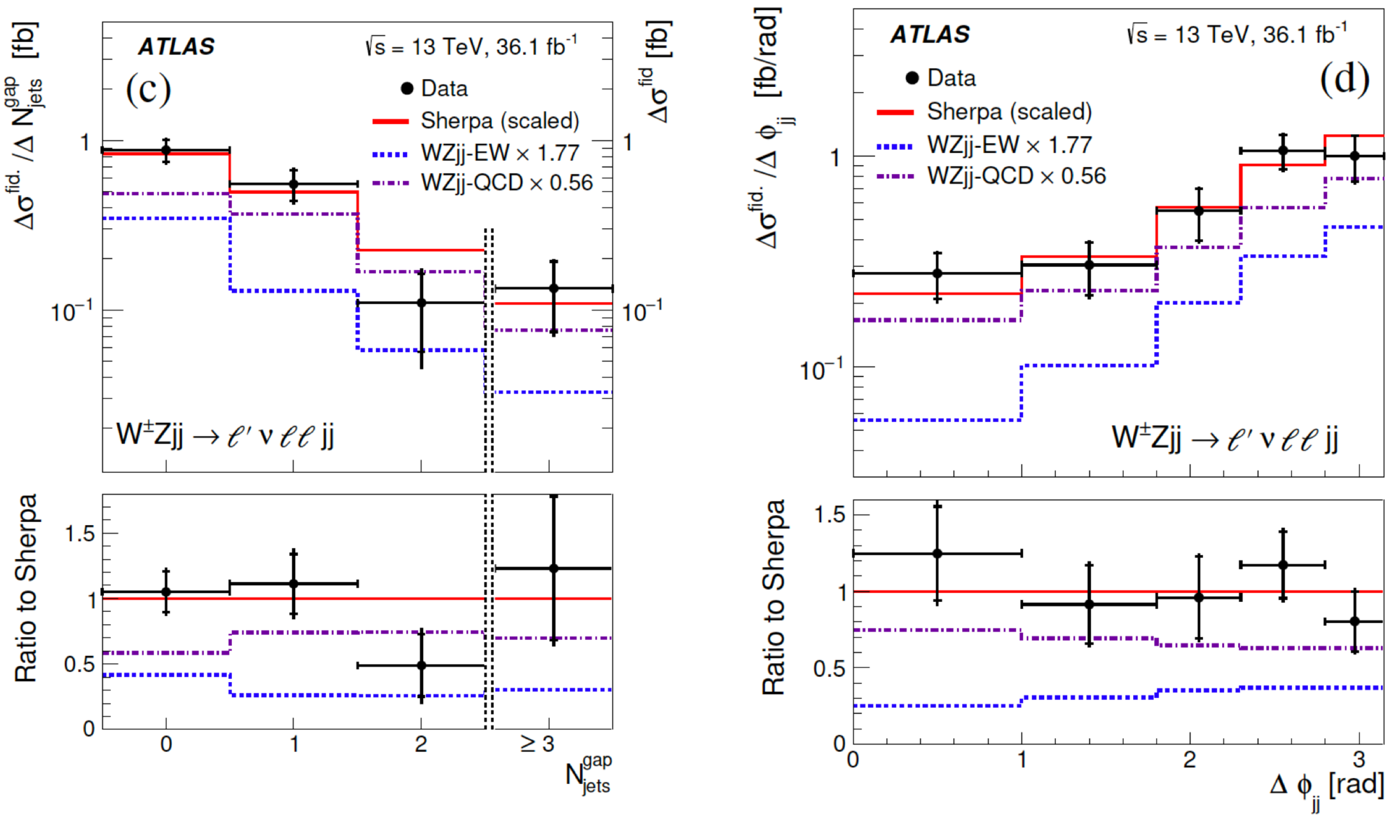
Source	Uncertainty [%]
$WZjj$–EW theory modelling	4.8
$WZjj$–QCD theory modelling	5.2
$WZjj$–EW and $WZjj$–QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.7

- WZjj electroweak fiducial cross section:

$$\sigma^{\text{fid.}}_{WZjj-\text{EW}} = 0.57\,^{+0.14}_{-0.13}\,(\text{stat.})\,^{+0.05}_{-0.04}\,(\text{exp. syst.})\,^{+0.05}_{-0.04}\,(\text{mod. syst.})\,^{+0.01}_{-0.01}\,(\text{lumi.})\text{ fb} = 0.57\,^{+0.16}_{-0.14}\text{ fb},$$

VBS: Differential

- Also differential distributions of WZjj performed
  - Various variables
  - Unfolding required



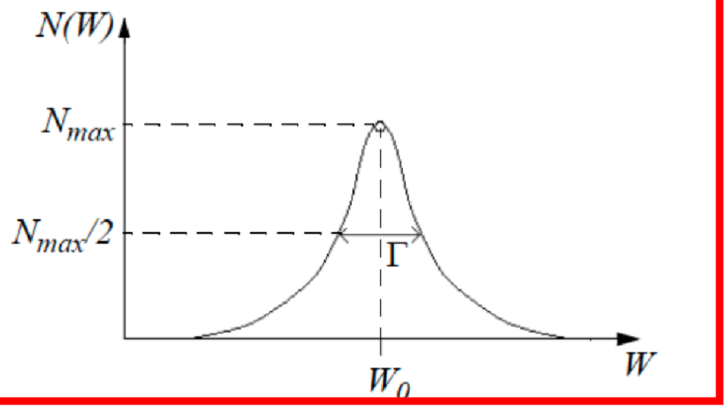
arxiv:1812.09740 (2018)

- Unfolded distributions: directly comparable to predictions
  - Can be used to test new physics models, or test MC tuning/modeling

Example 2: Higgs Width

- Total Higgs width: important quantity!
  - Any hidden decays? Dark matter?
- Issue: can not measure total Higgs width at LHC
  - Higgs width much smaller than detector resolution: Γ_{SM}~4.1 MeV
  - Cross sections: Higgs coupling and width can not be determined independently

$$N(W) = \frac{K}{(W - W_0)^2 + \Gamma^2/4}$$



- Solution (until we have lepton colliders?!):
  - Use off-shell Higgs boson production!

Higgs Width

- Cross sections (κ: coupling relative to SM prediction)
  - Off-shell:

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

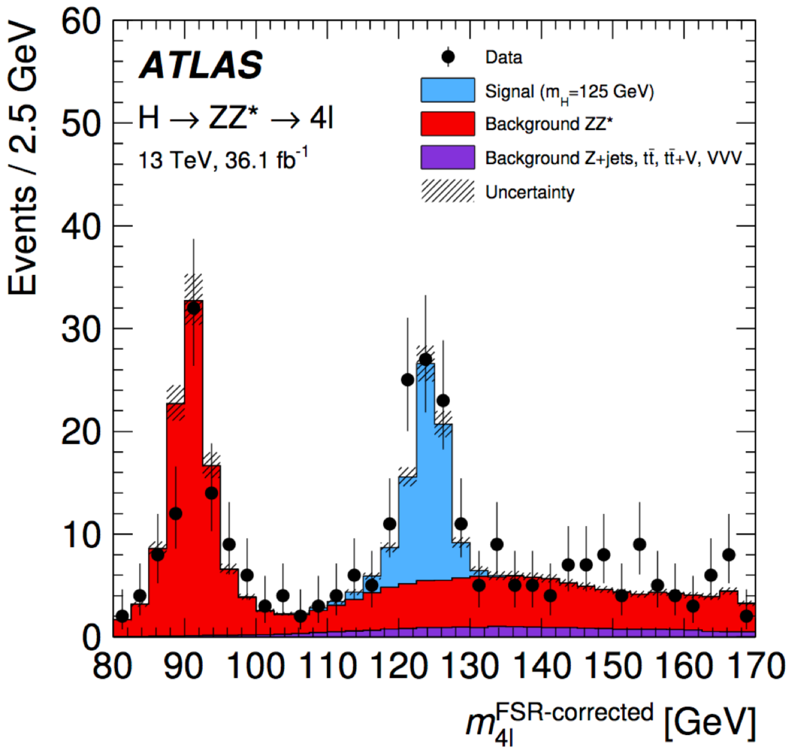
  - On-shell:

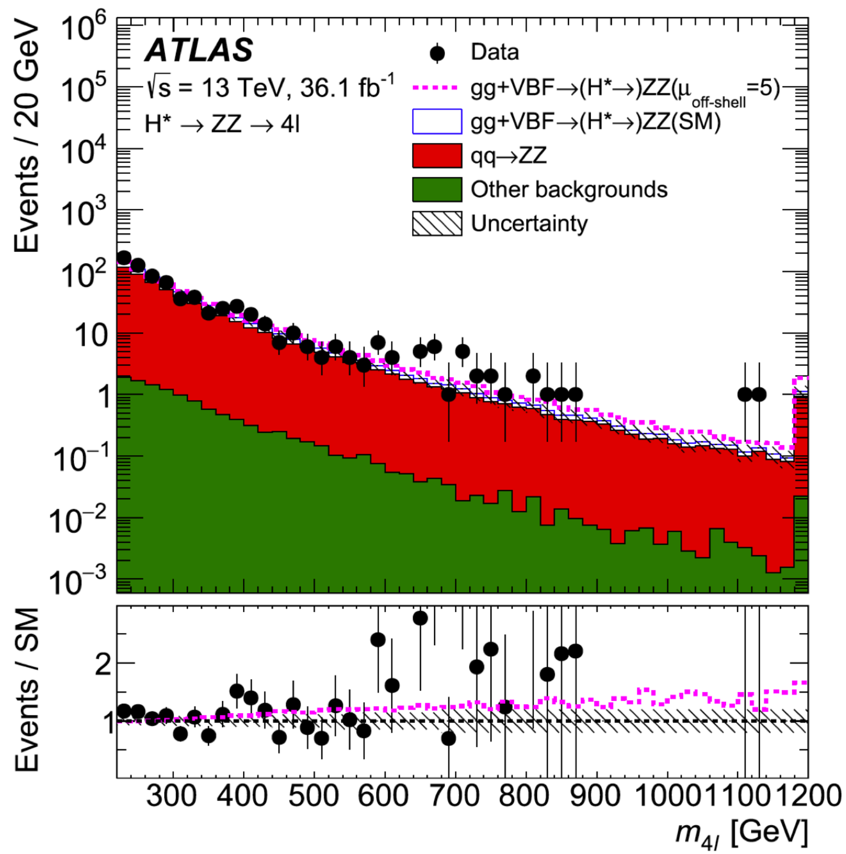
$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

- Ratio off/on shell: direct information about Higgs width!

Higgs Width

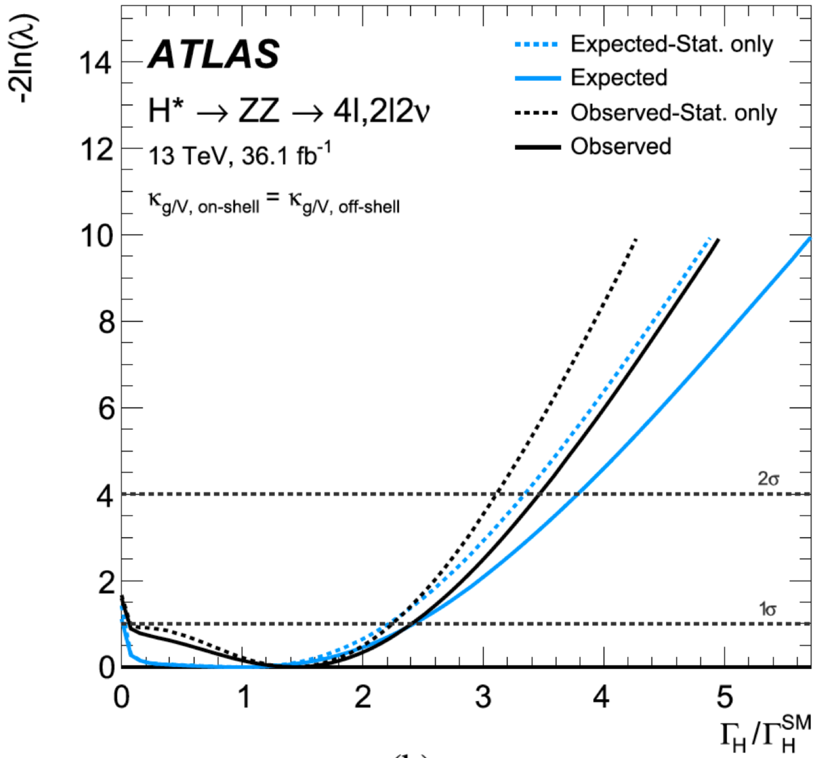
- Perform 4 lepton analysis
  - Similar analyses for on and off shell version





Higgs width

- Limits on Higgs width:
  observed 95% CL upper limit on Higgs boson width of 14.4 MeV

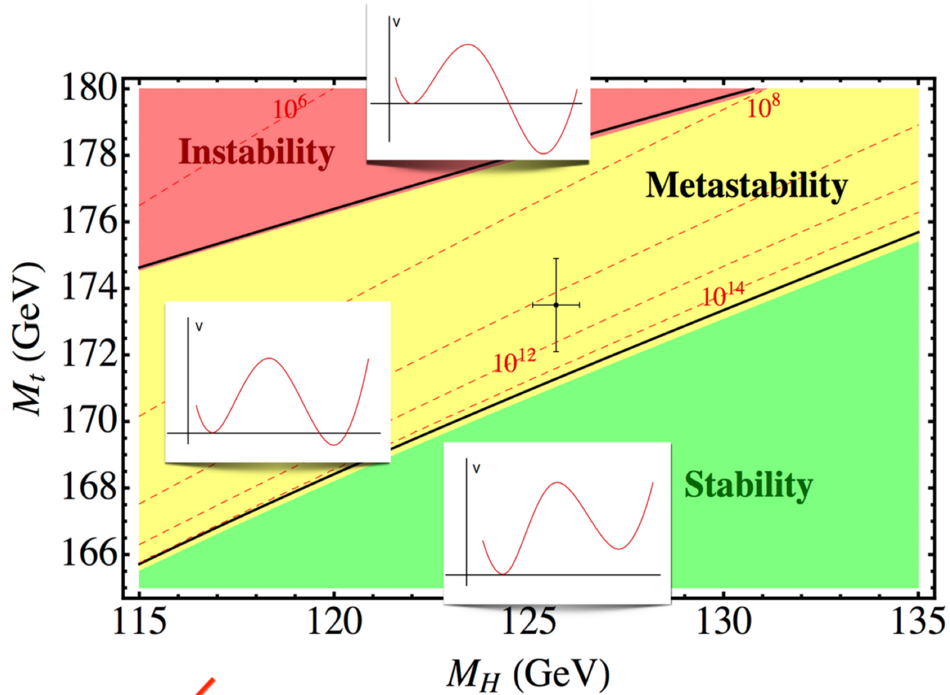


(b)

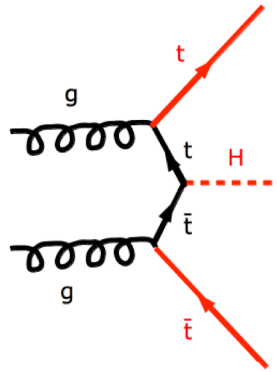
PLB 786, 233 (2018)

Example 3: $t\bar{t}H$

- Top and Higgs: Heaviest known elementary fermion and boson!
  - Top-Higgs Yukawa coupling: predicted to be ~1 in the SM
    → special role of top quark in electroweak symmetry breaking?
    → window to new physics?
    → metastable universe?

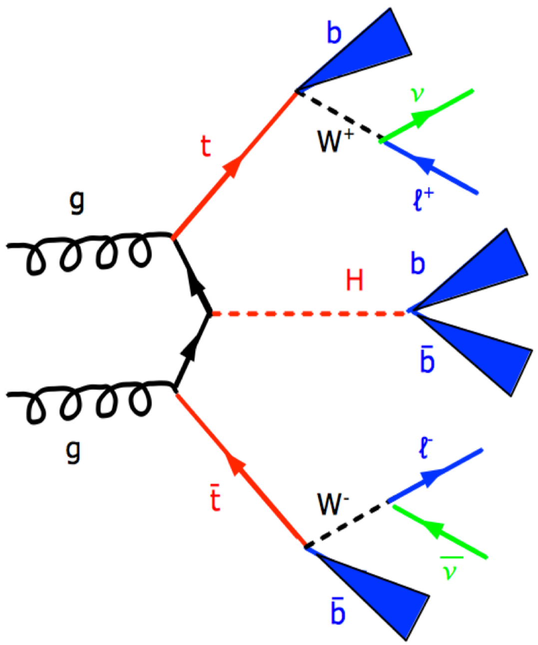


- Measuring top-Higgs Yukawa coupling directly: important! (indirectly: in H→γγ and gg→H)
  - Main channel: $t\bar{t}H$



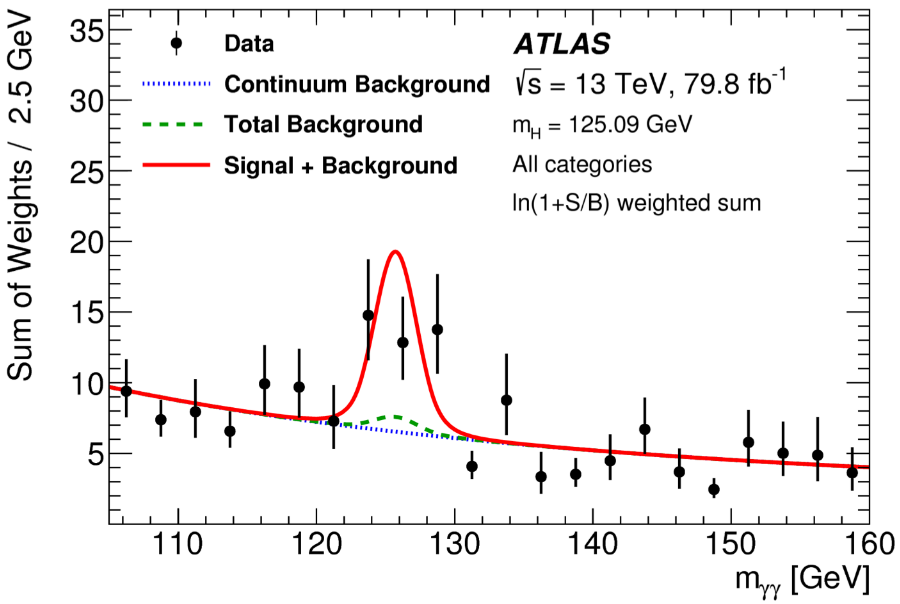
The Top and the Higgs

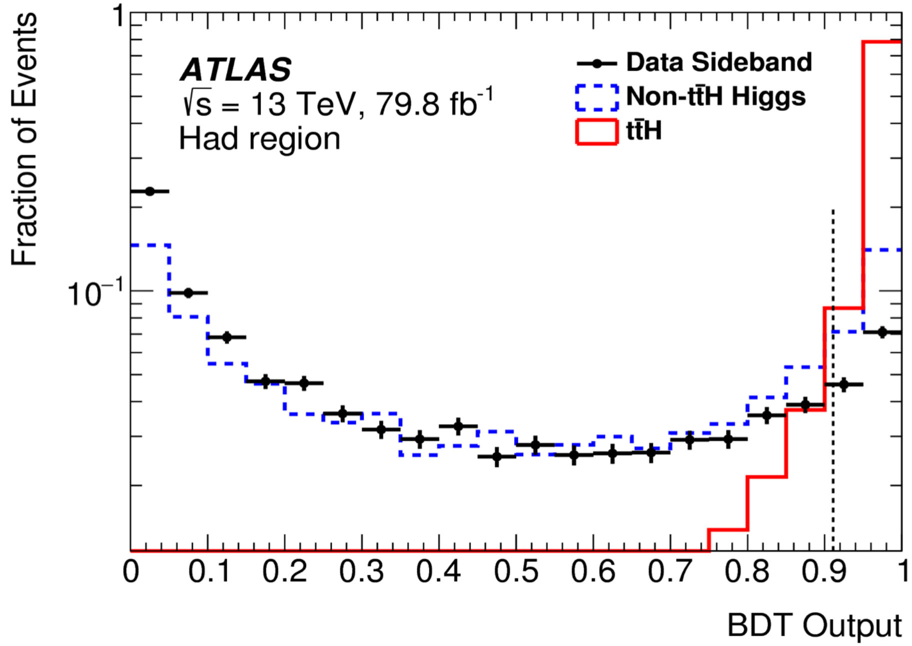
- Last year: First observation of $t\bar{t}H$!
  (first by CMS, then ATLAS; similar strategies, concentrating on ATLAS here)
  - Combination of multiple channels:
    - Higgs decay to $b\bar{b}$, WW*, $\tau^+\tau^-$, $\gamma\gamma$, ZZ*
    - Hadronic and/or leptonic top decays used



Diphoton Channel

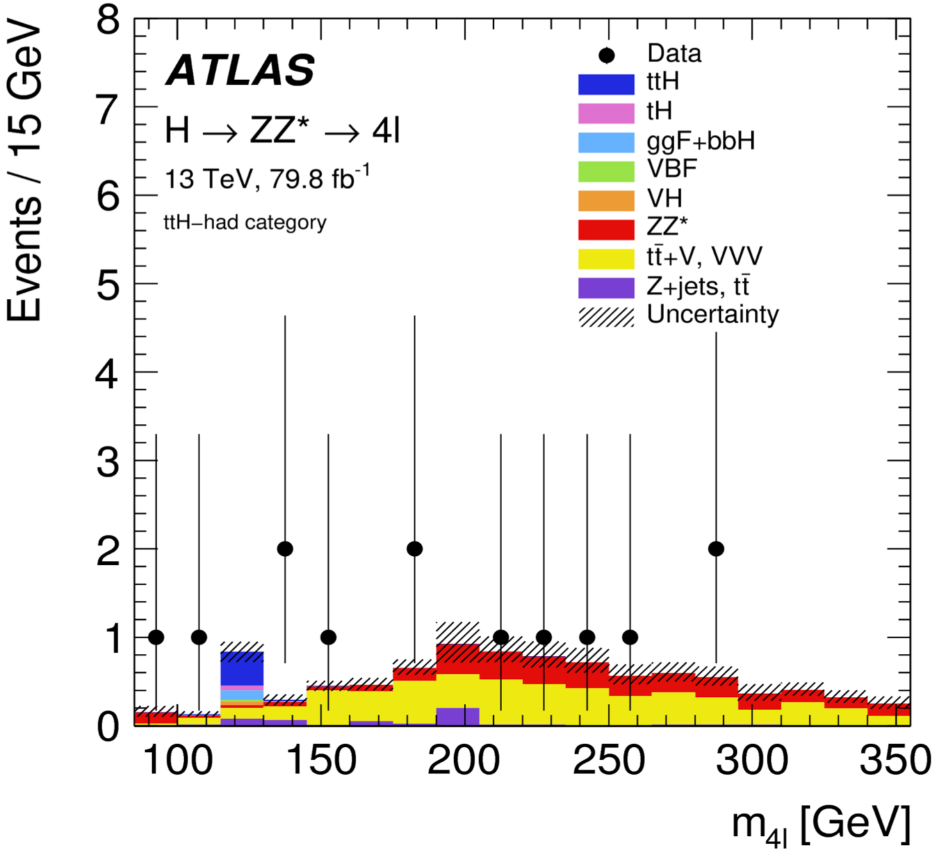
- Define two regions: hadronic top decays or events with at least one charged lepton
  - $m_{\gamma\gamma}$: has to be between 105 and 160GeV
- For each region: train BDTs





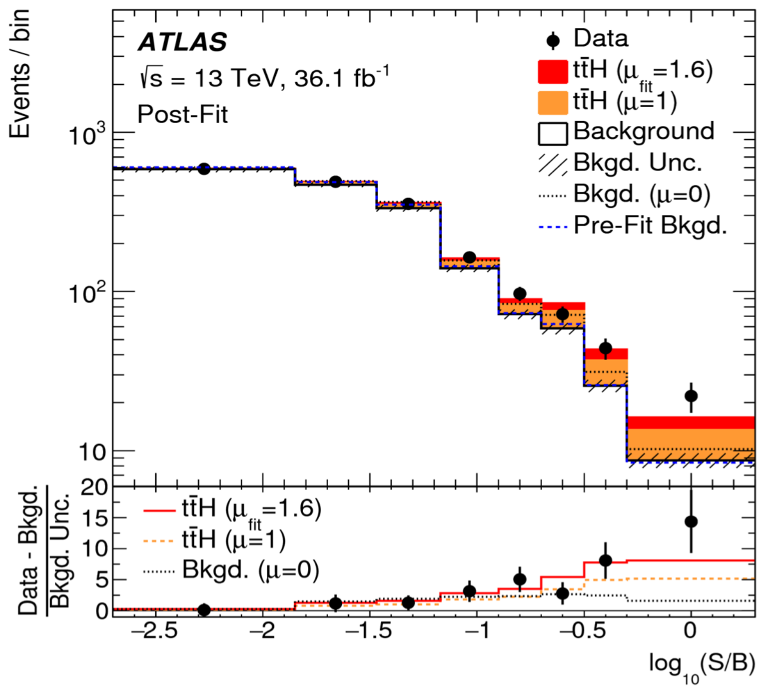
ZZ Channel

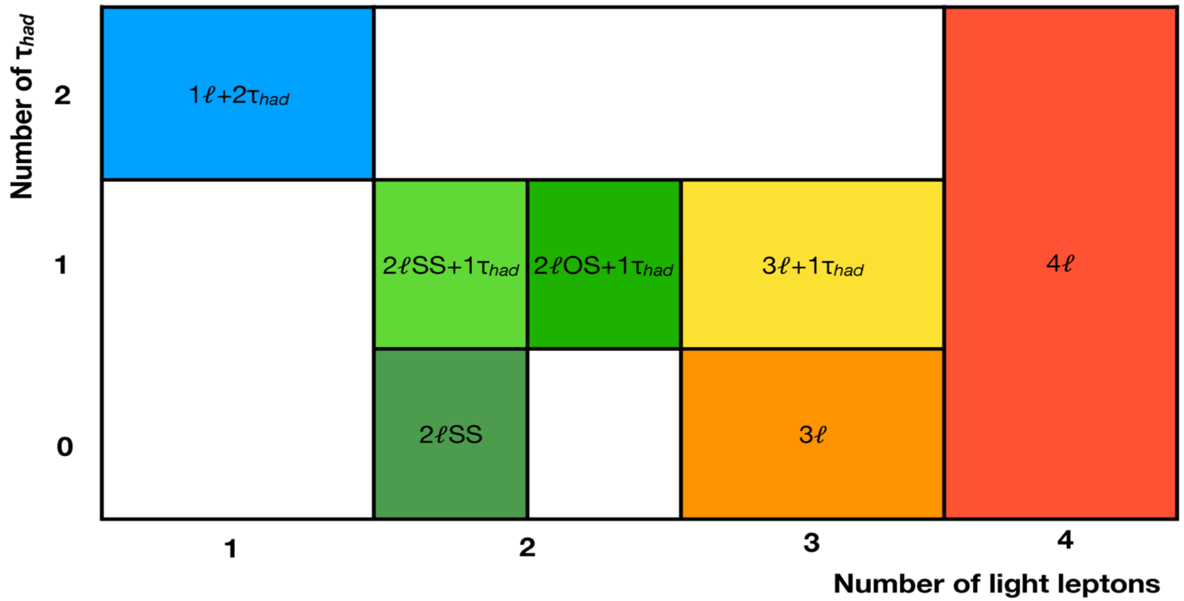
- Use events with at least 4 isolated charged leptons
  - Two regions: hadronic (both tops decay hadronically) and leptonic (at least one top decays leptonically)
  - BDT used on hadronic region



Multilepton Channel

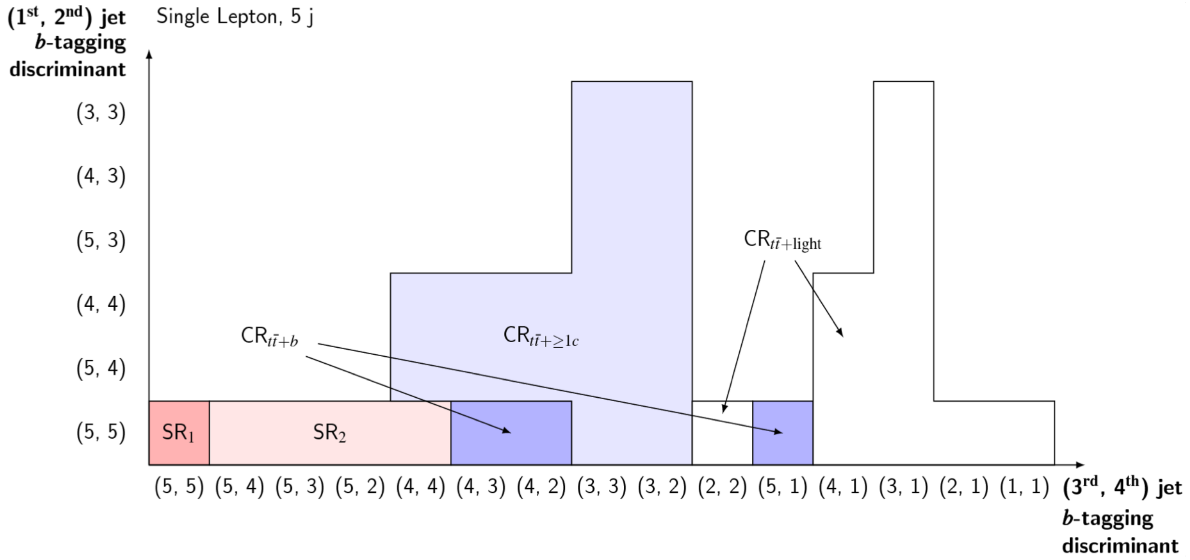
- Includes H→WW (&ZZ) and H→ττ decays
- Many channels considered
  - Some use BDTs

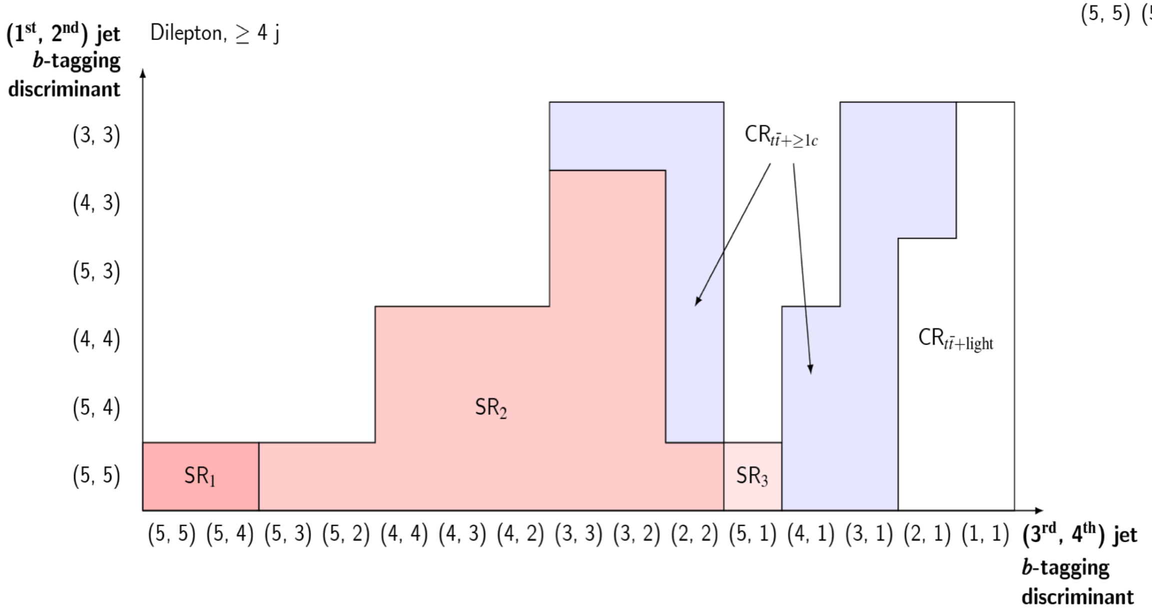




H → $b\bar{b}$ Channel

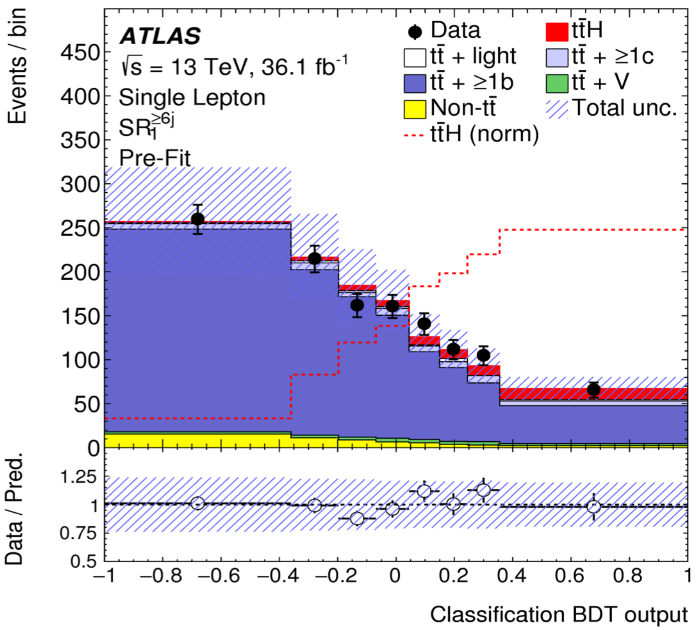
- Semileptonic and dileptonic channels considered
  - Separation in many different control and signal regions
- Very challenging analysis
  - Modeling of background $t\bar{t}b\bar{b}$

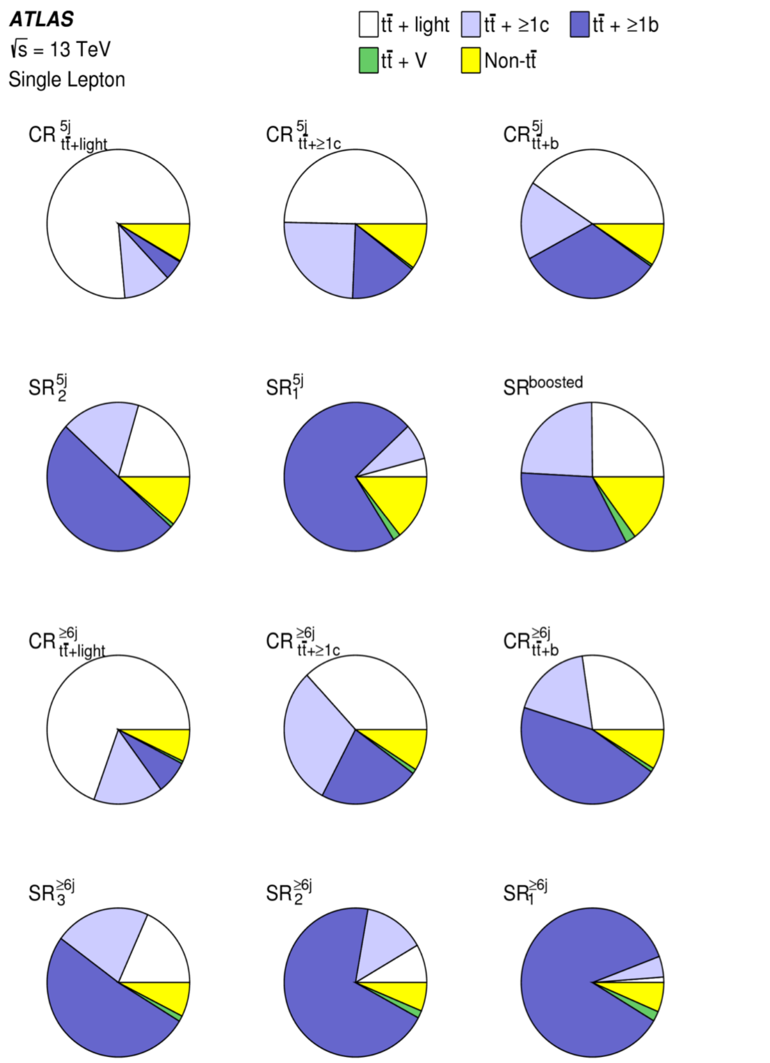




Semileptonic

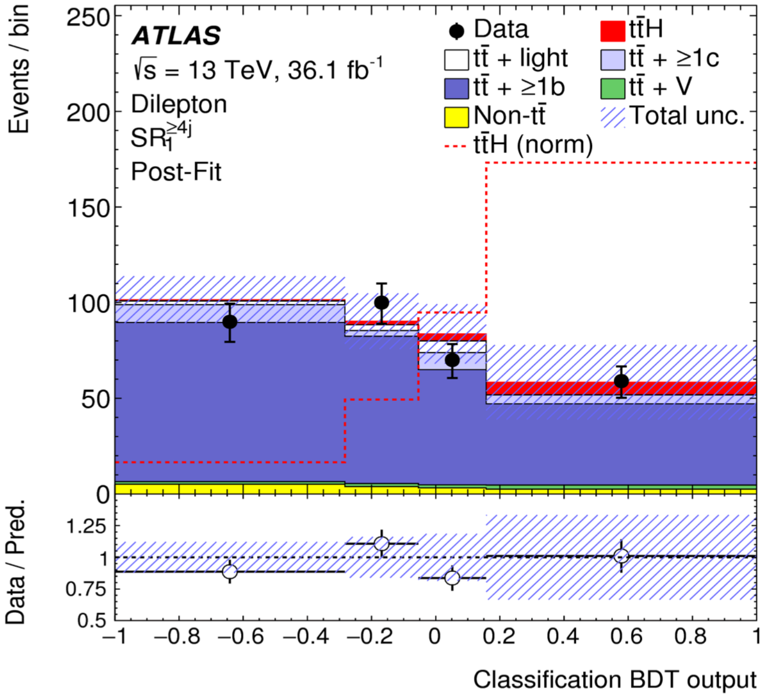
- BDTs used enhancing significance
  - Reconstruction of event done with "reconstruction BDT" → access to variables using full events
- Fits including control regions → improves control over backgrounds

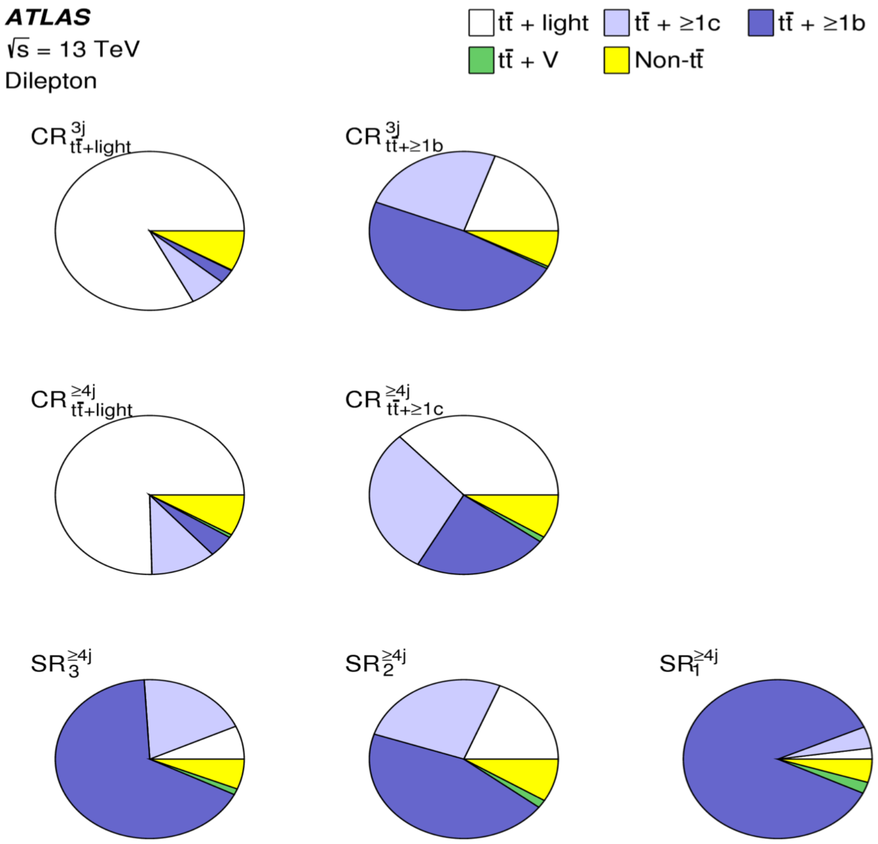




Dileptonic

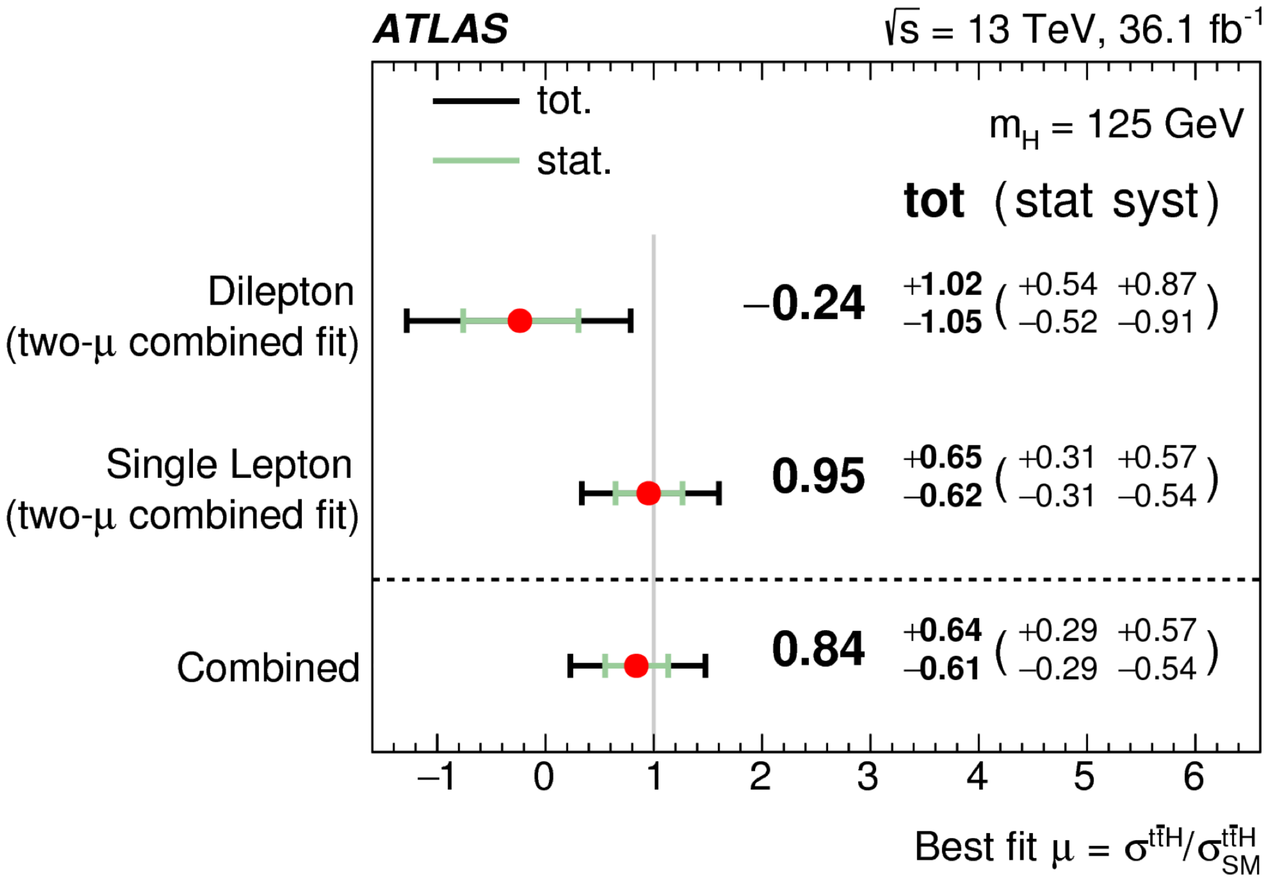
- Similar strategy as in semileptonic channel
  - Reconstruction of full event information more challenging due to two neutrinos





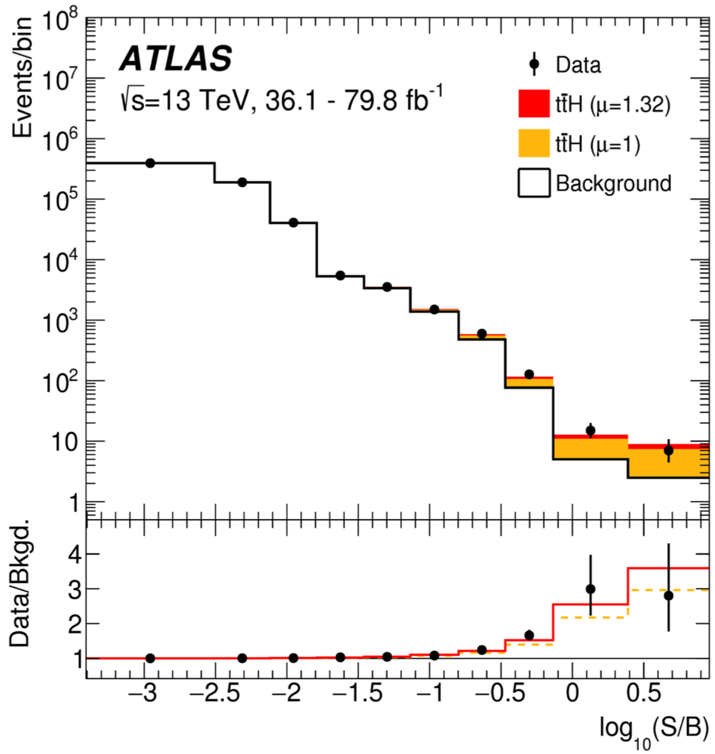
$t\bar{t}H$, $H\to b\bar{b}$ Results

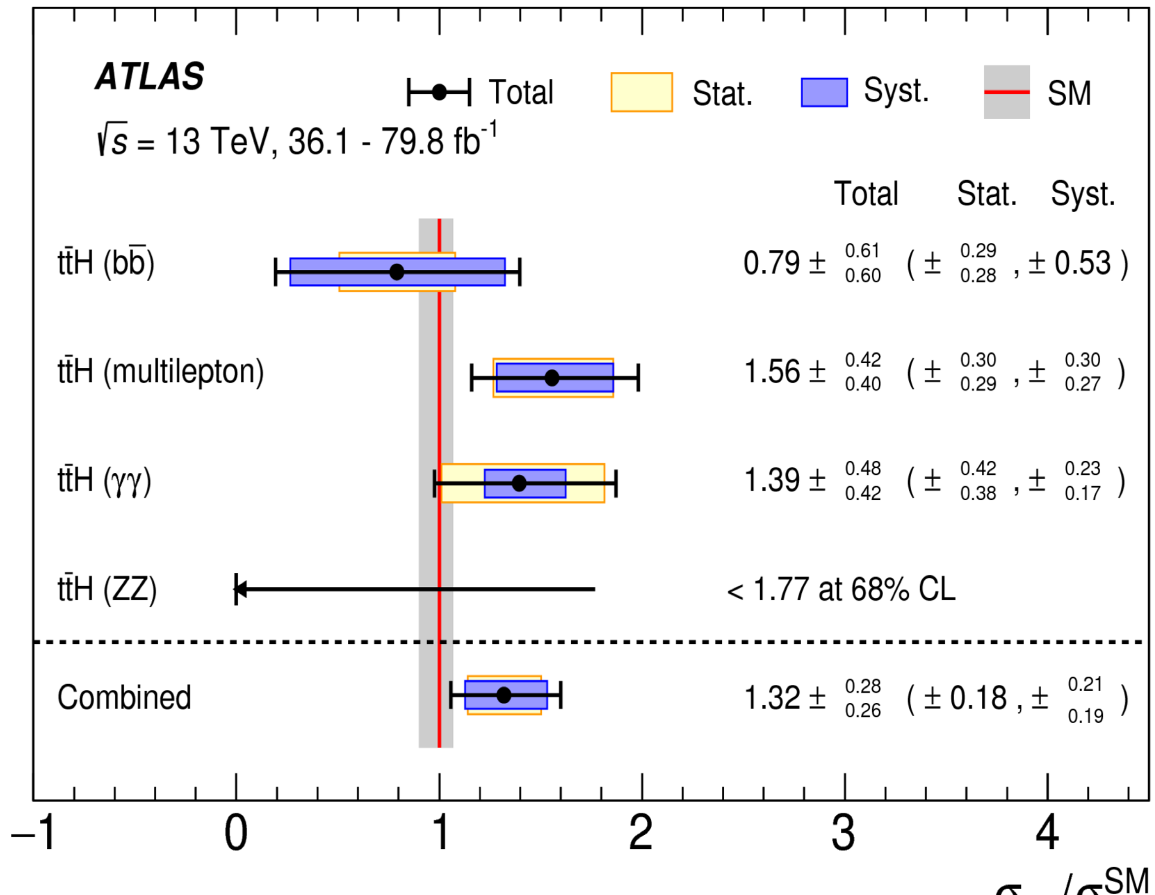
- Results already dominated by systematic uncertainties
  $\to$ background modeling of $t\bar{t}b\bar{b}$ a main factor



Combination

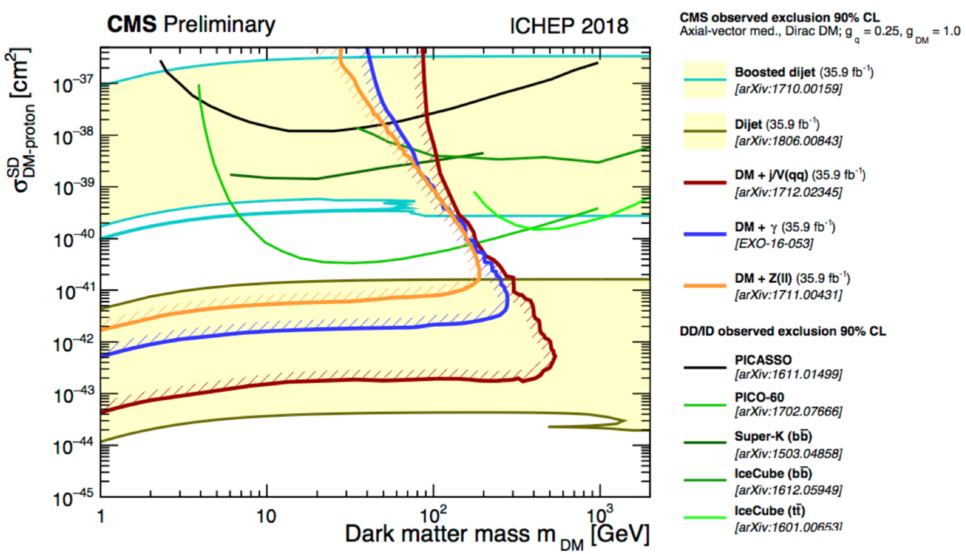
- Combination of all channels: Observation of $t\bar{t}H$!
  - Observed significance of 5.8σ

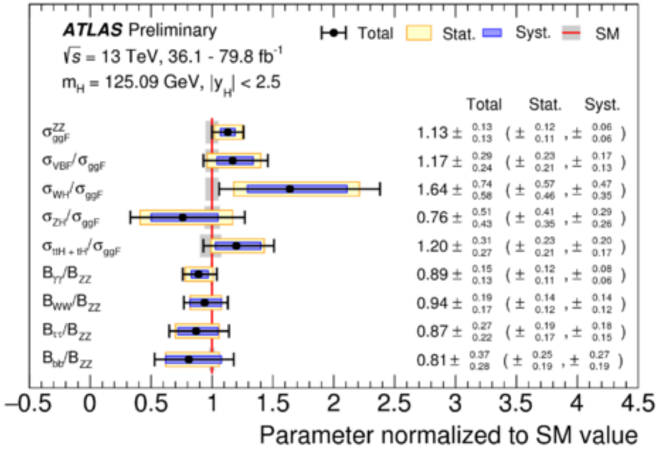


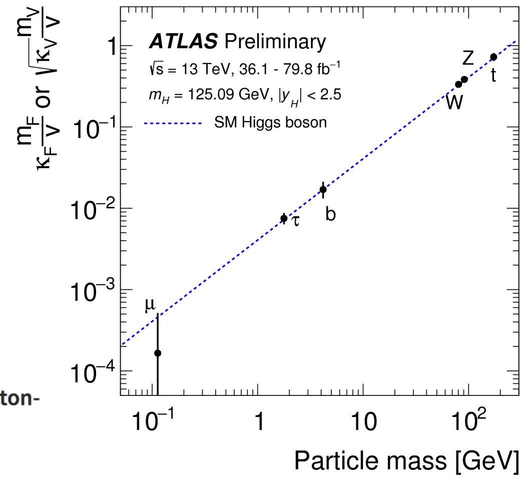


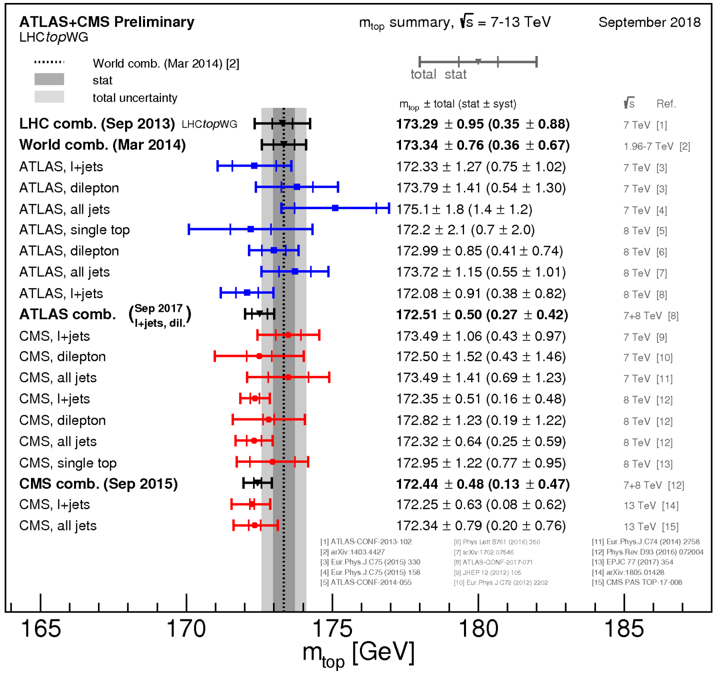
PLB 784, 73 (2018)

Many more Results







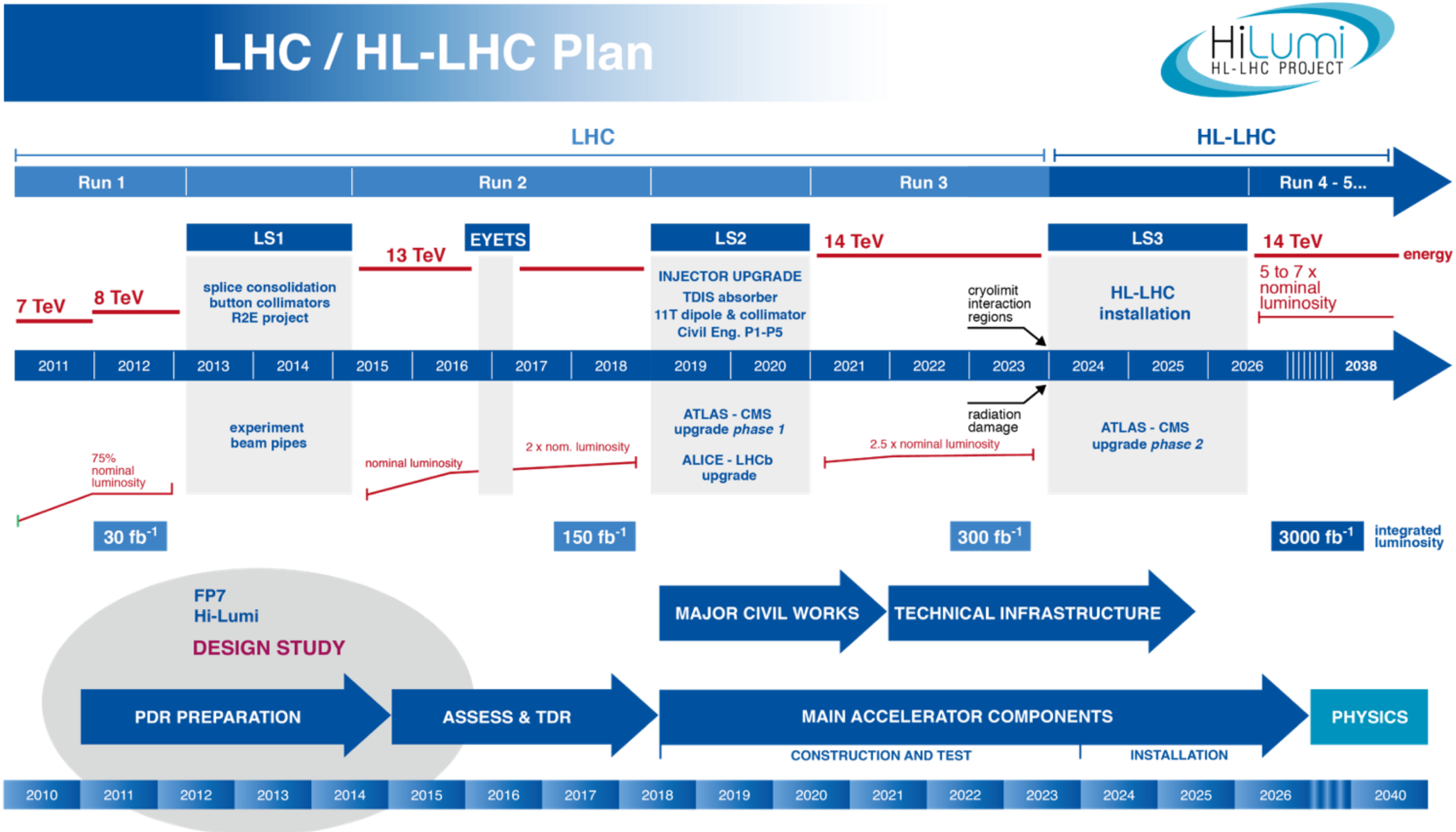


Odd gluon compounds may be lurking in protons

Precision results from the TOTEM experiment provide further explanation on proton-proton interactions at high energies

9 FEBRUARY, 2018 | By Iva Raynova

Future



LHC / HL-LHC Plan
HiLumi
HL-LHC PROJECT
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2038
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
radiation
damage
ATLAS - CMS
upgrade phase 2
75%
nominal
luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity
FP7
Hi-Lumi
DESIGN STUDY
MAJOR CIVIL WORKS
TECHNICAL INFRASTRUCTURE
PDR PREPARATION
ASSESS & TDR
MAIN ACCELERATOR COMPONENTS
PHYSICS
CONSTRUCTION AND TEST
INSTALLATION
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2040

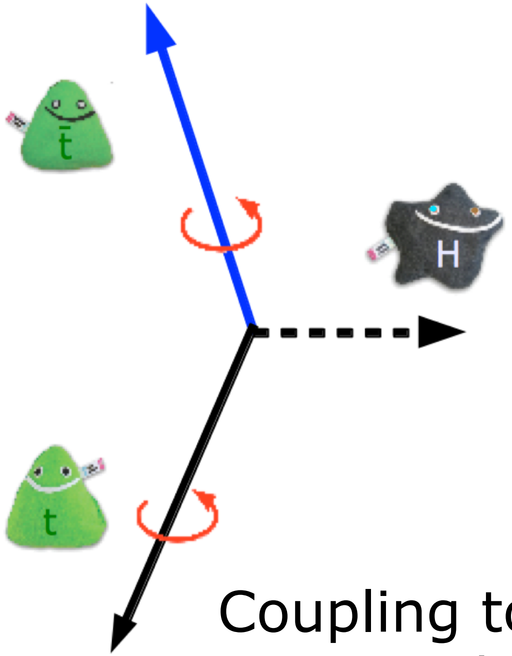
Future

- Probe production modes not yet assessible
  - For example 4top production, maybe di-Higgs?
- Get smarter on methods
  - Reduce systematic uncertainties; increase sensitivity
- Understand modeling
  - Tuning!
- Probe properties not yet accessible
  - My favorite: top-Higgs coupling: Any CP-odd contributions?
- Direct interaction of theorists+experimentalists essential

My person favorite (Future)

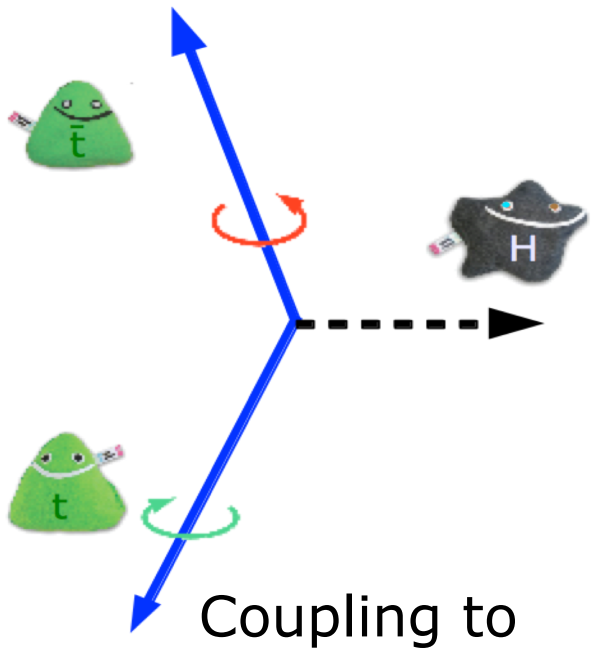
- Look for CP odd top-Higgs couplings
- CP violation required for Sakharov conditions
  → mixing with CP odd necessary
  → CP odd component in Higgs sector?

CP odd:



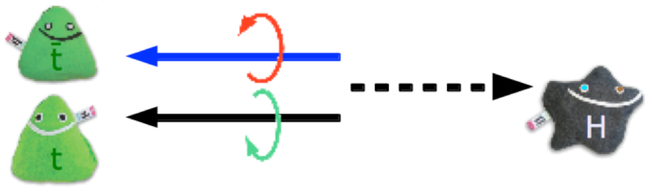
Coupling to
opposite helicity $t\bar{t}$

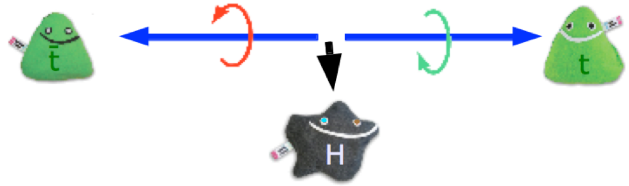
CP even:

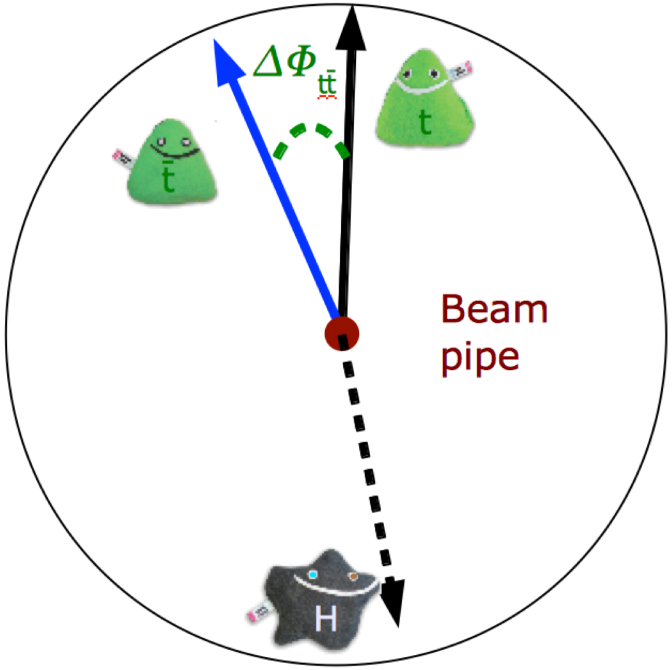


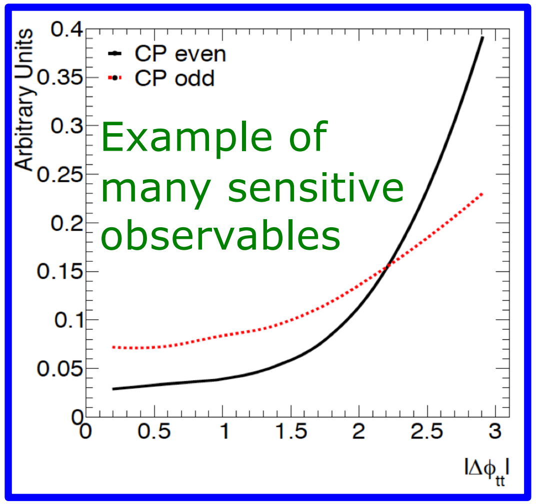
Coupling to
same helicity $t\bar{t}$

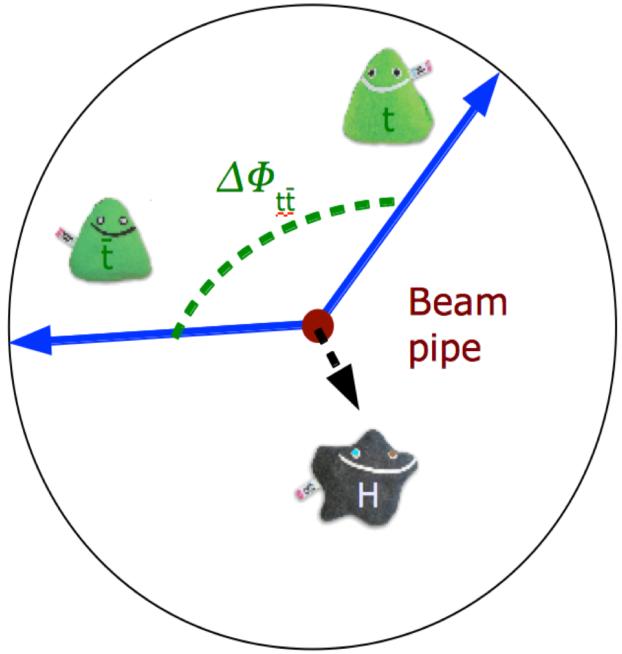
Odd versus even Higgs







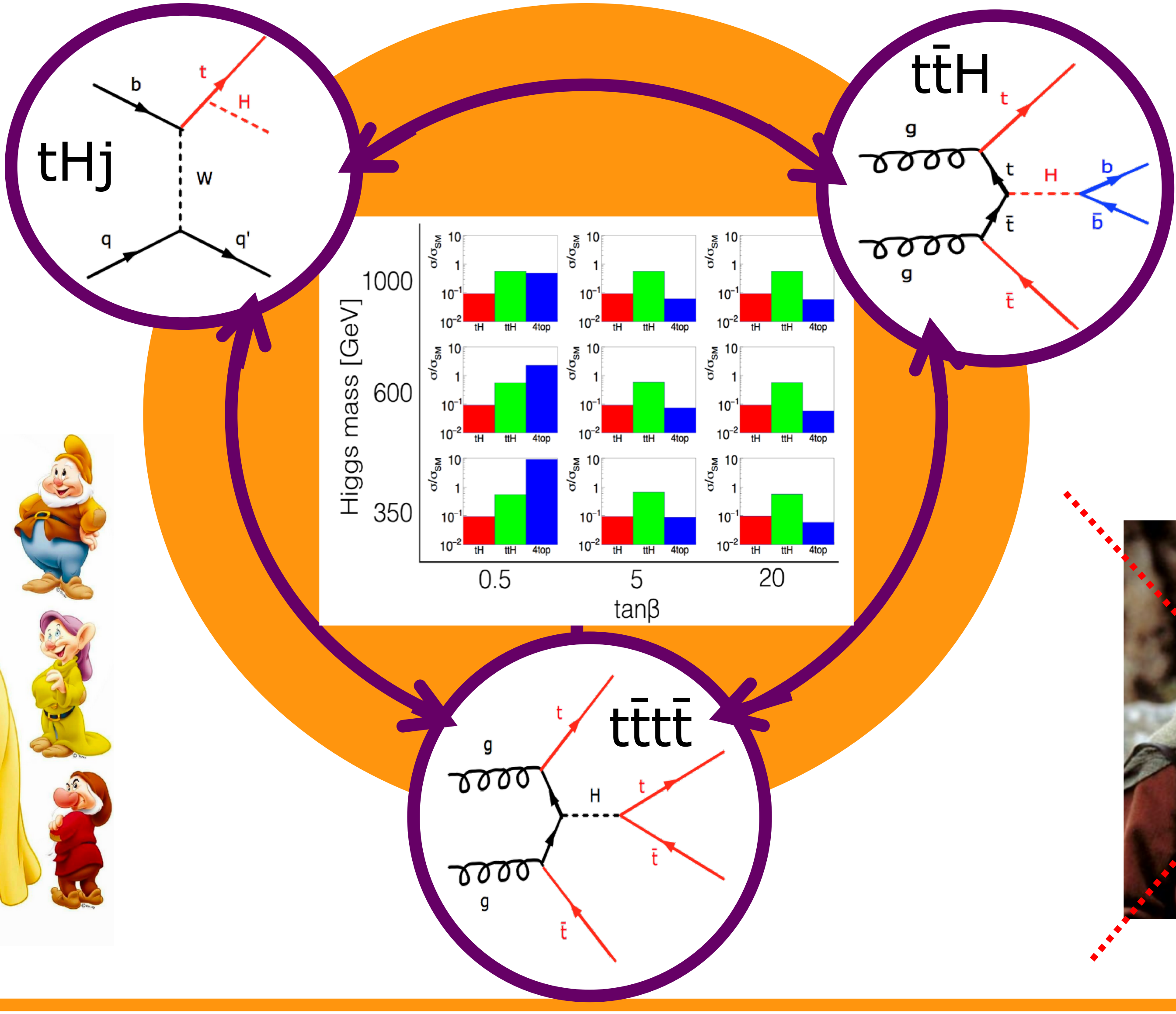




Coupling to
opposite helicity $t\bar{t}$

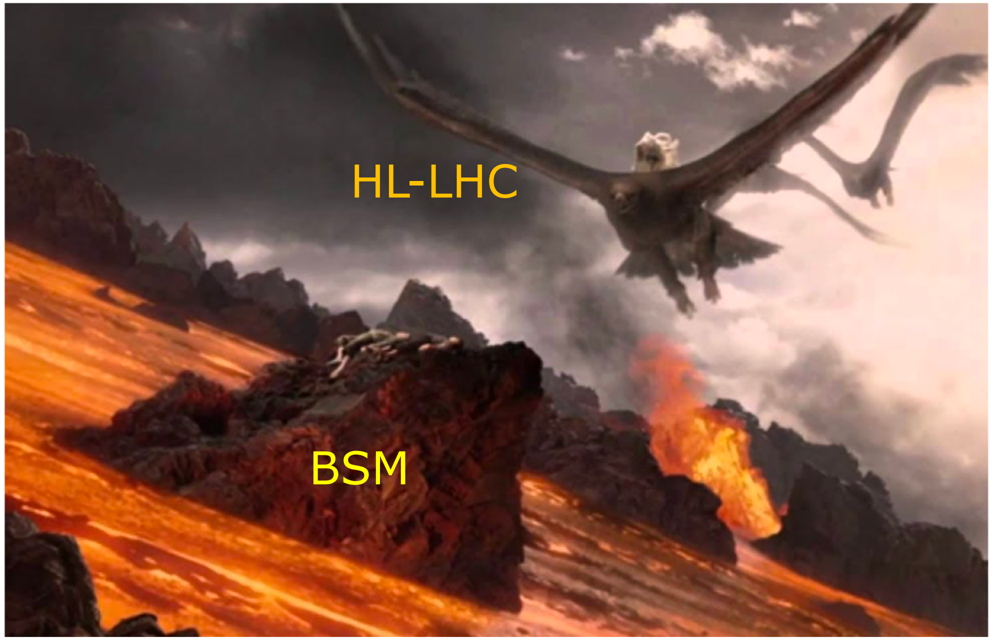
Coupling to
same helicity $t\bar{t}$

The Higgs And The 7 Tops



Summary

- LHC: fysics phun on the hunt for new physics
  - More data
  - Highest energy frontier
- Drive towards more precision measurements on main experiments

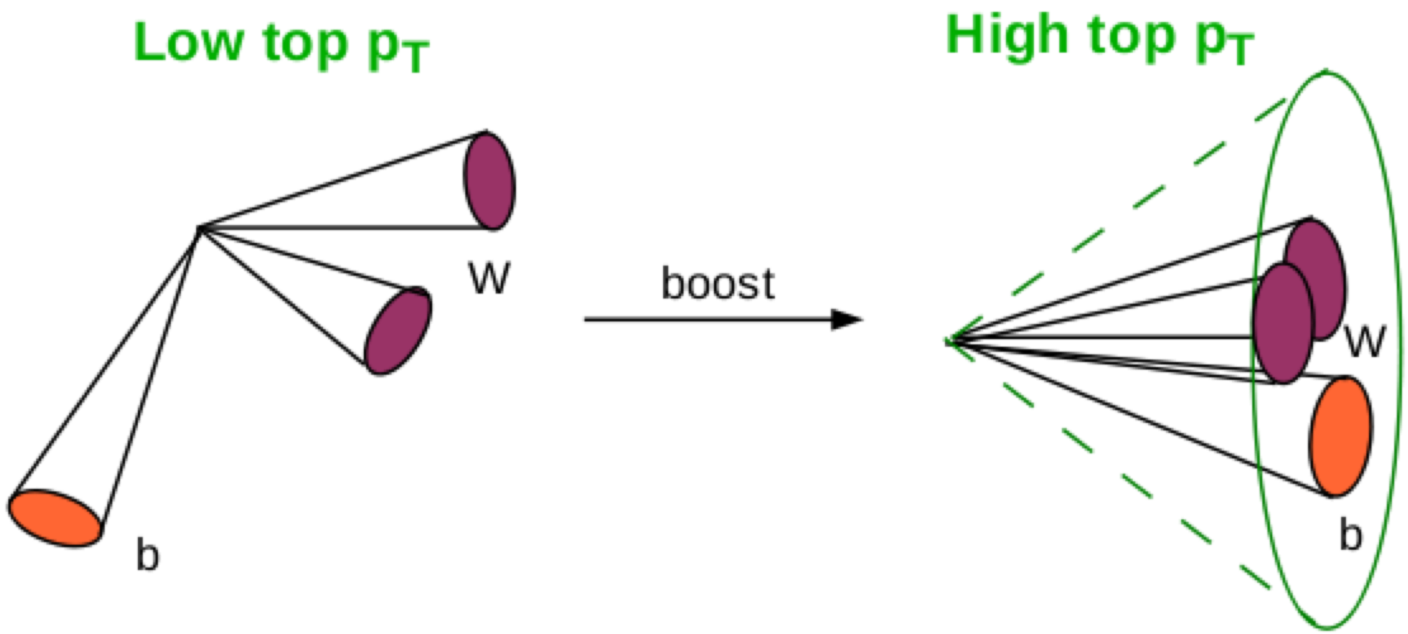


Backup

Boosting algorithms

Boosting algorithms important

- Higher collision energy → more events can be boosted
- Production of heavy particles → decay products can be boosted → results in boosted regimes



To Higgs or not to Higgs?

Loads of progress in the last years (for example on couplings
→ figure from July this year)

Interaction with gauge bosons:

$H \to ZZ^*$ ATLAS-CONF-2018-018

Well established in run-1

$H \to WW^*$ ATLAS-CONF-2018-004

6.3 (5.2) σ obs (exp) (run-2 only)

Yukawa coupling to fermions:

Top-quark: ttH **80 fb^{-1}**

6.3σ (5.1σ) obs (exp) arXiv:1806.00425

Beauty-quark $H \to bb$: **80 fb^{-1}** New

5.4σ (5.5σ) obs (exp) ATLAS-CONF-2018-036

Tau-lepton: $H \to \tau\tau$

6.4σ (5.4σ) obs (exp) ATLAS-CONF-2018-021

Muon $H \to \mu\mu$: **80 fb^{-1}** New

$\sigma_{limit}/\sigma_{SM}$<2.1 (obs) ATLAS-CONF-2018-026

Charm-quark: $H \to cc$:

$\sigma_{limit}/\sigma_{SM}$<104 (obs) PRL 120 (2018) 211802