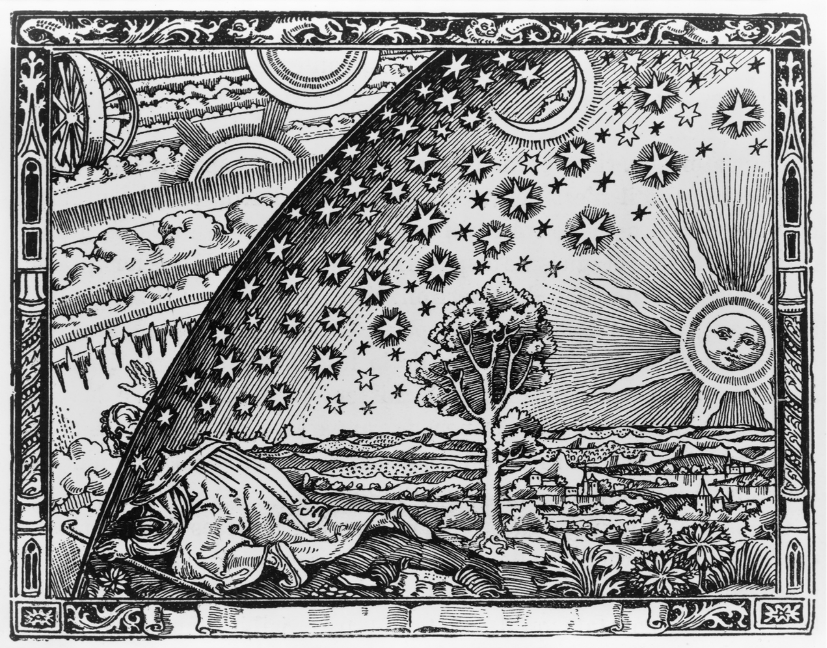
To the Higgs and beyond

Quantum Universe Days
17 – 19 February 2025



Katharina Behr

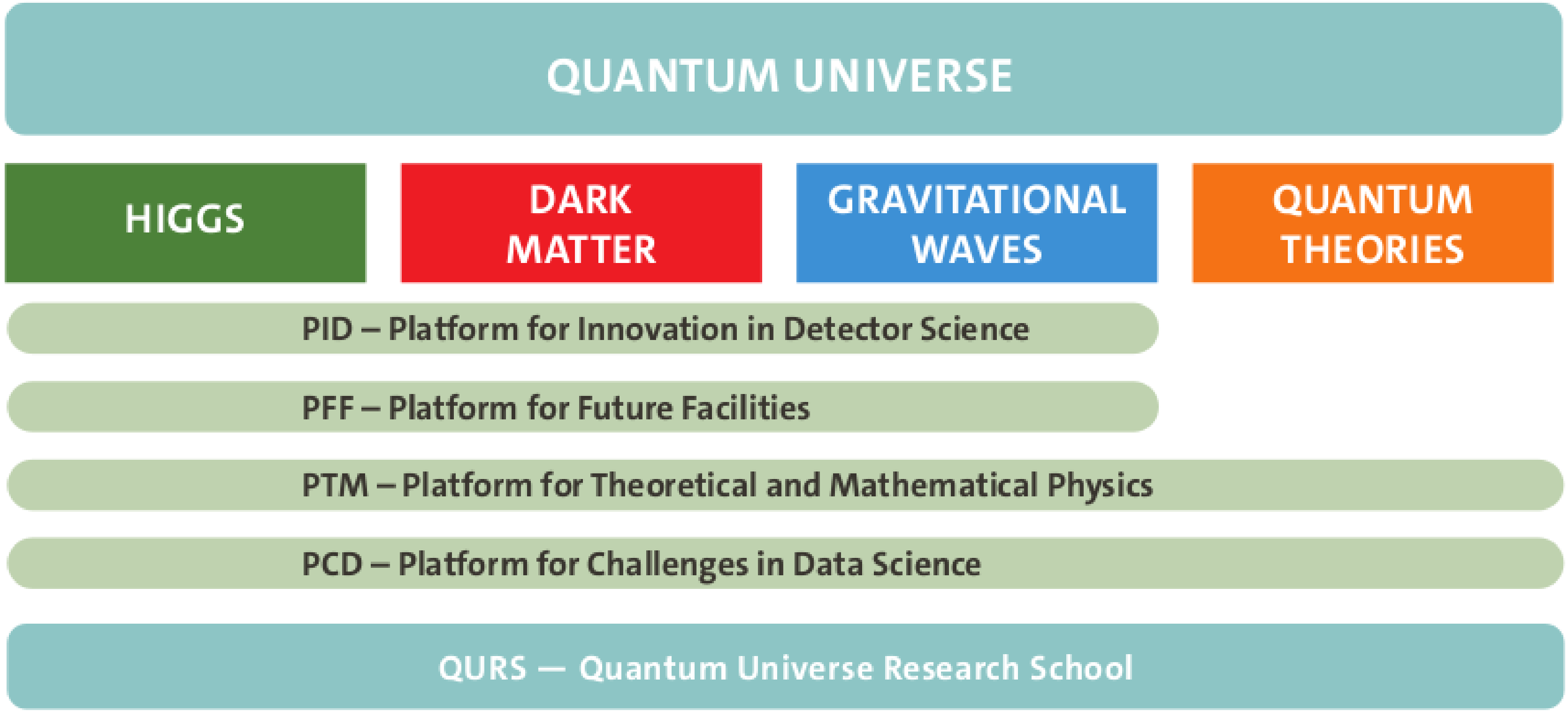
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ATLAS EXPERIMENT

DESY.

Higgs within Quantum Universe

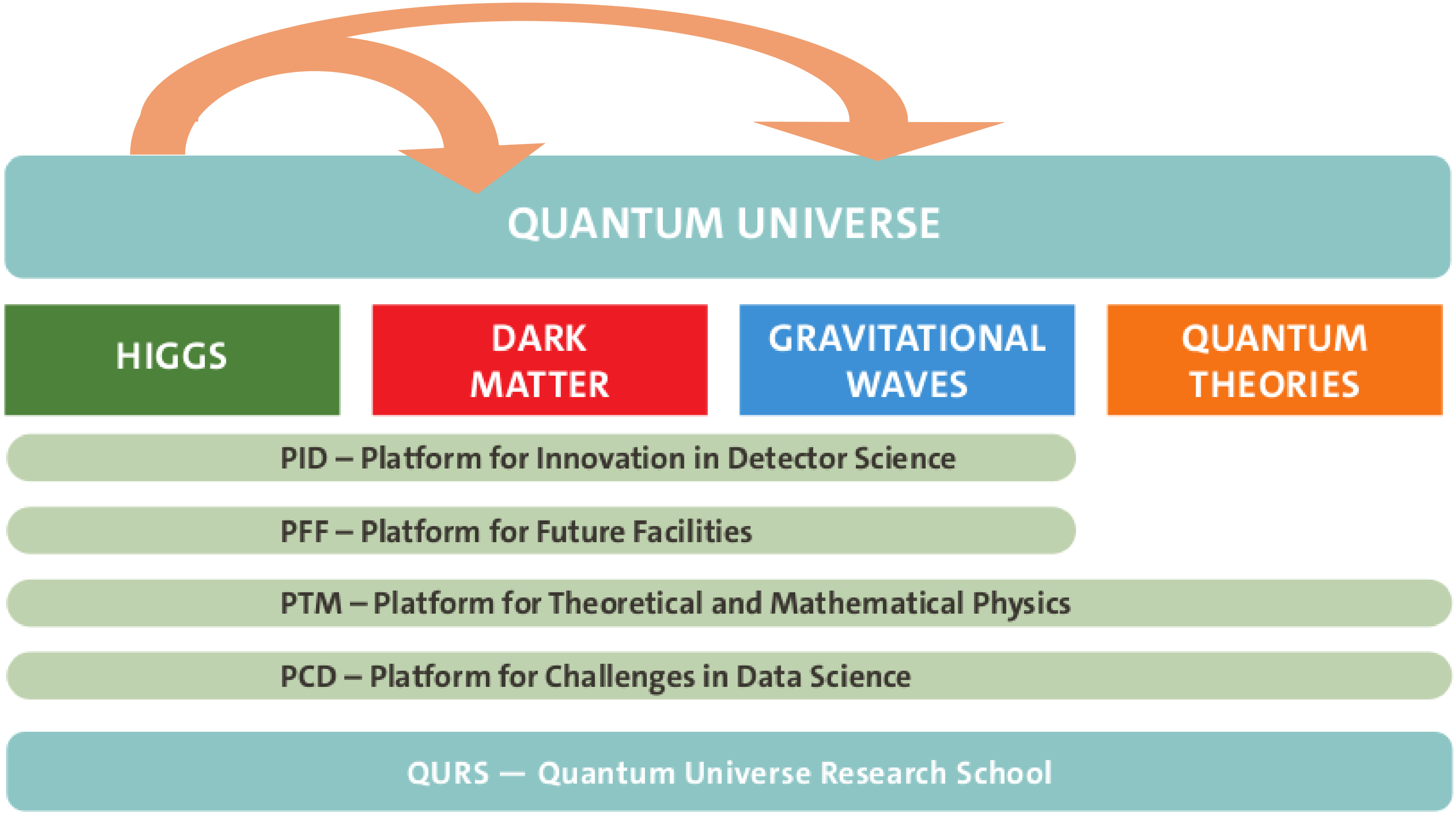
> Integral part of QU research activities



Higgs within Quantum Universe

> Strong connections with other pillars

- Will cover some of these here. See also DM and Advanced Higgs lectures.



Outline

- **Part 1: The vacuum is not empty**
  - The Higgs boson in the Standard Model
  - Characterization of the Higgs boson since its discovery

h

- **Part 2: What is the fingerprint of the vacuum?**
  - Unravelling the Higgs potential
  - Higgs boson pair production
  - Extra: Triple Higgs production
  - Outlook: the future of the LHC and beyond

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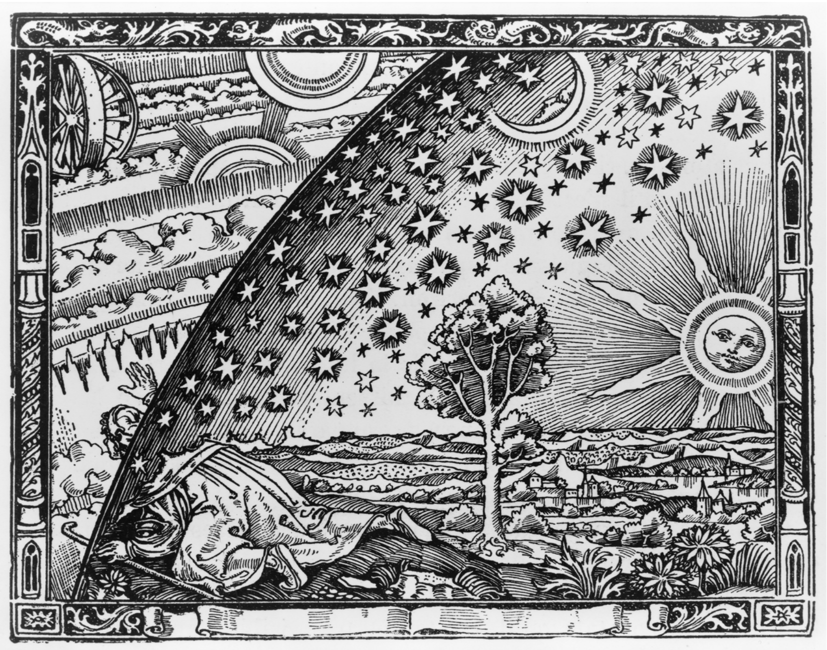
- **Part 3: Is there even more to the vacuum?**
  - Extended Higgs sectors
  - Extra: news from the ttbar threshold
  - Long-lived particles and the Higgs

h H A H^+ H^-



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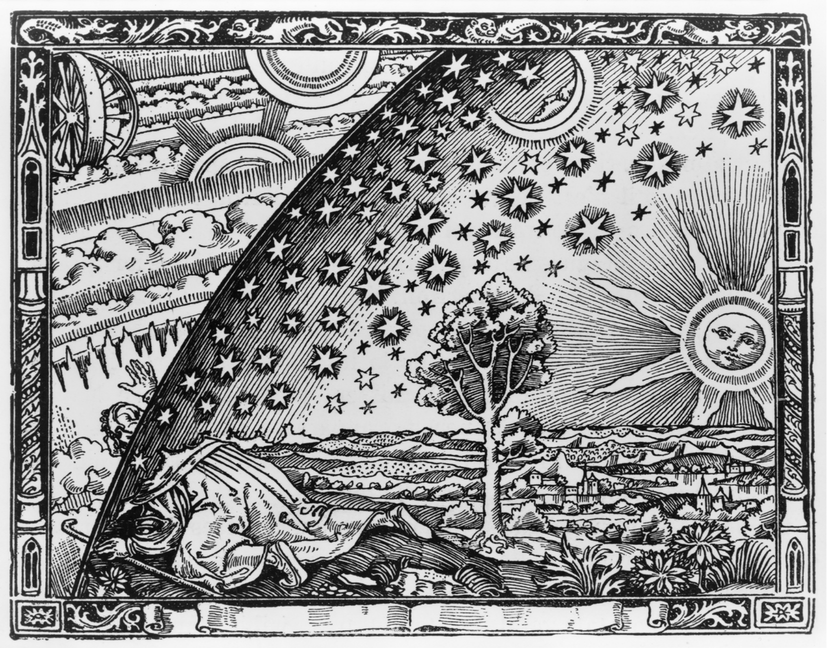
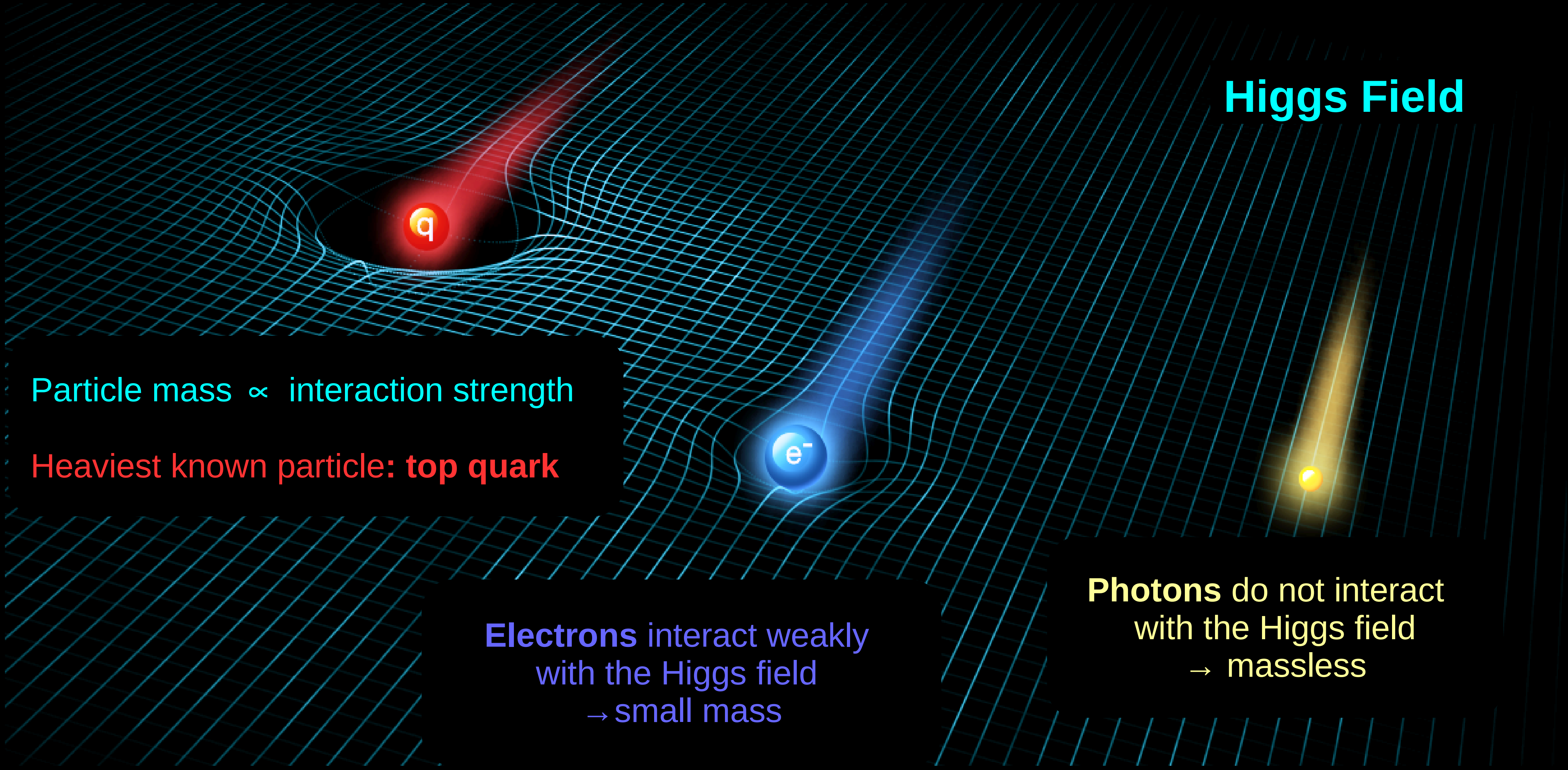


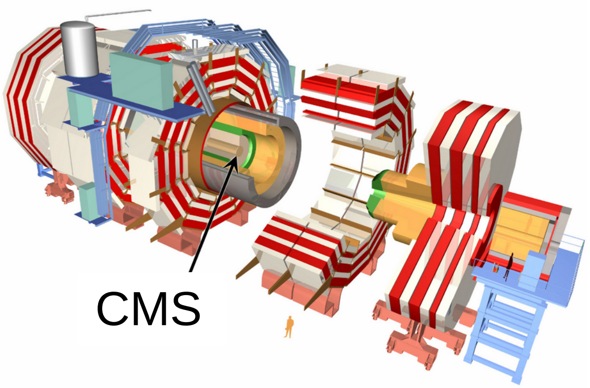


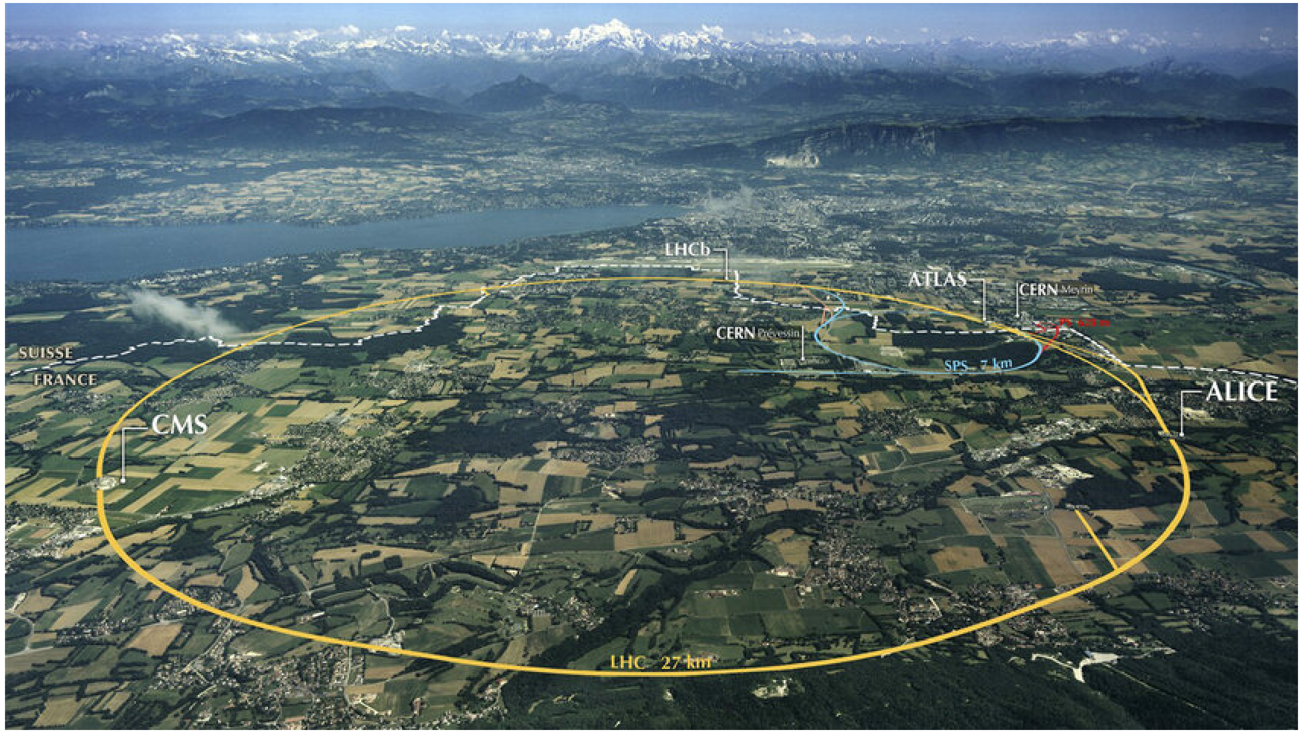
Artistic view of the Higgs field.
Image credit: beyondsciencetv.com

Probing the vacuum with the world’s largest microscope

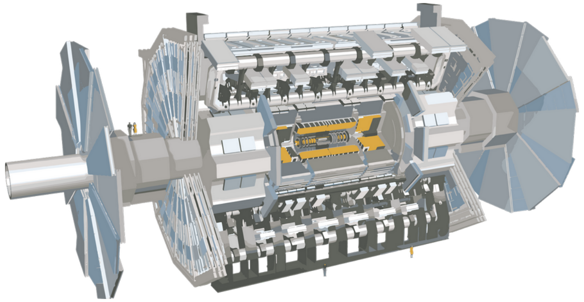
> LHC - the only place in the world capable of producing Higgs bosons.

> ATLAS, CMS – two general-purpose detectors capable of capturing Higgs-boson decay products

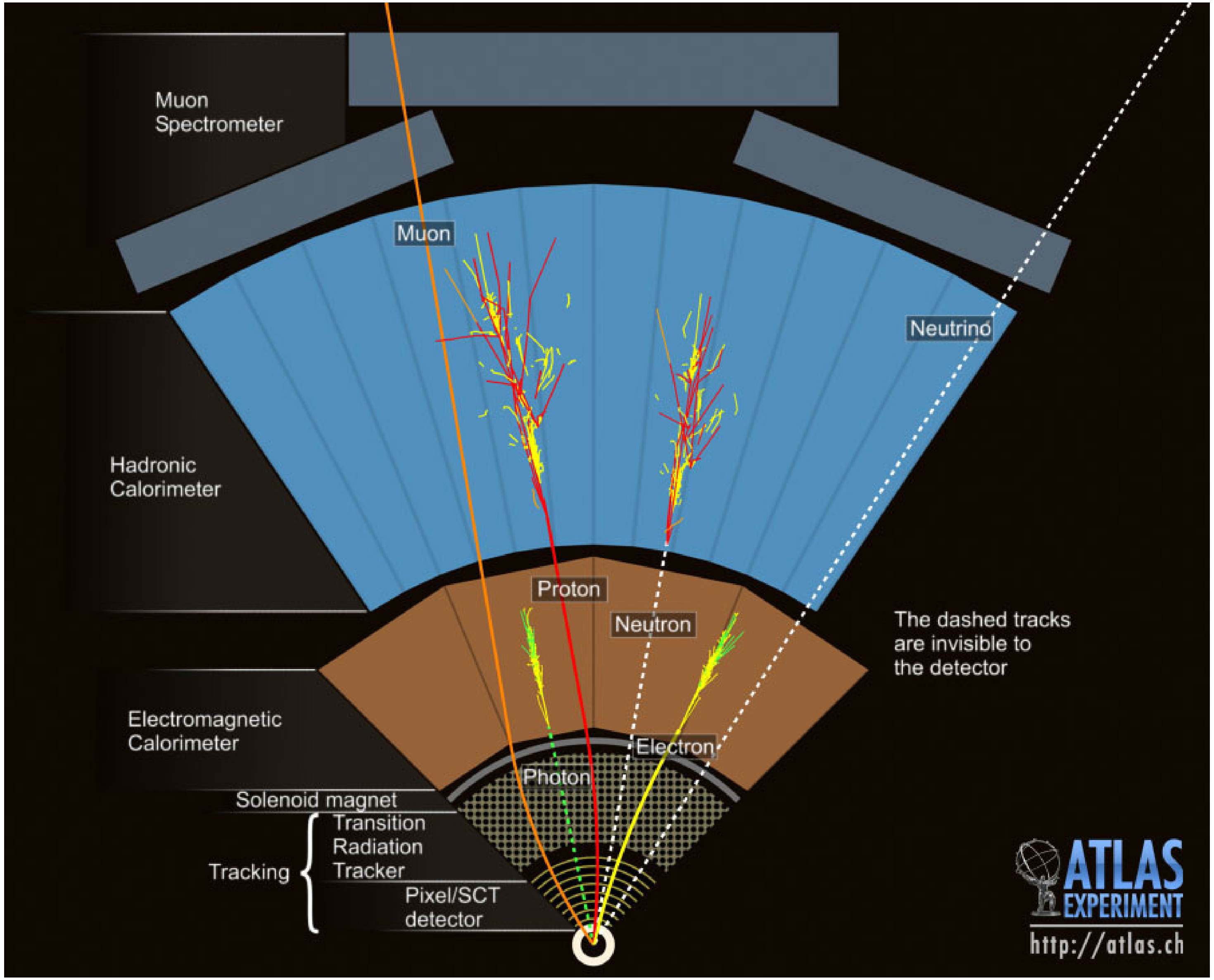




ATLAS



A closer look at the ATLAS detector

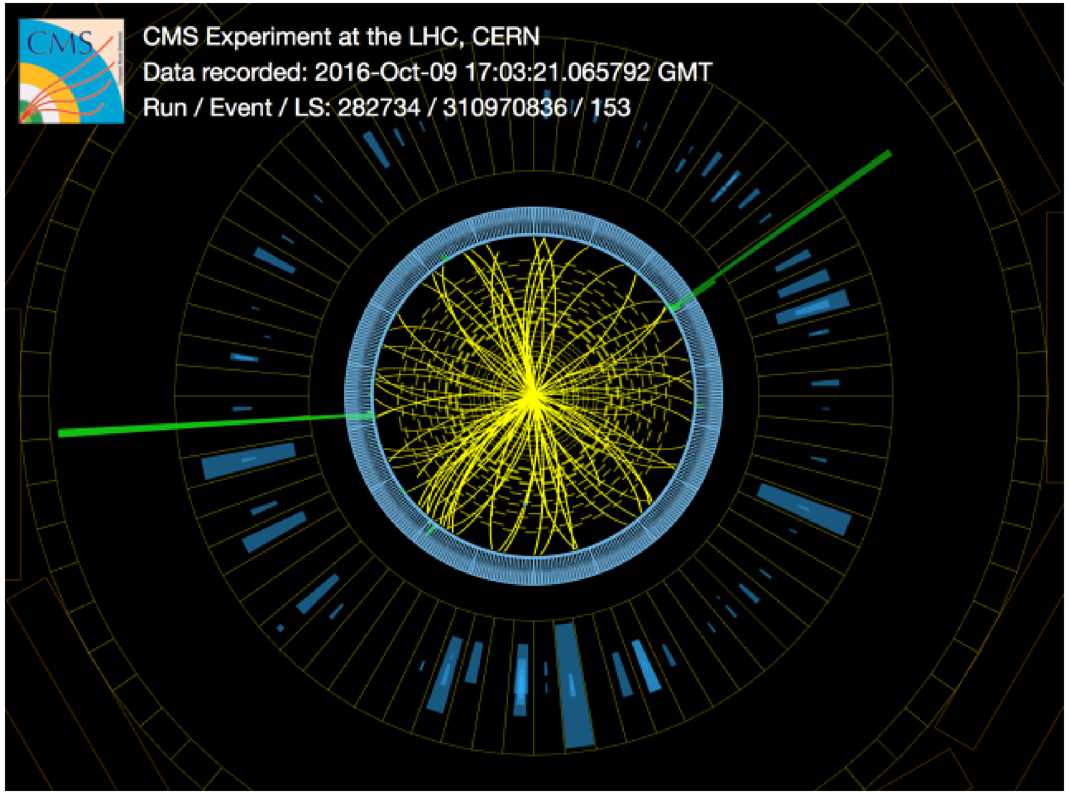


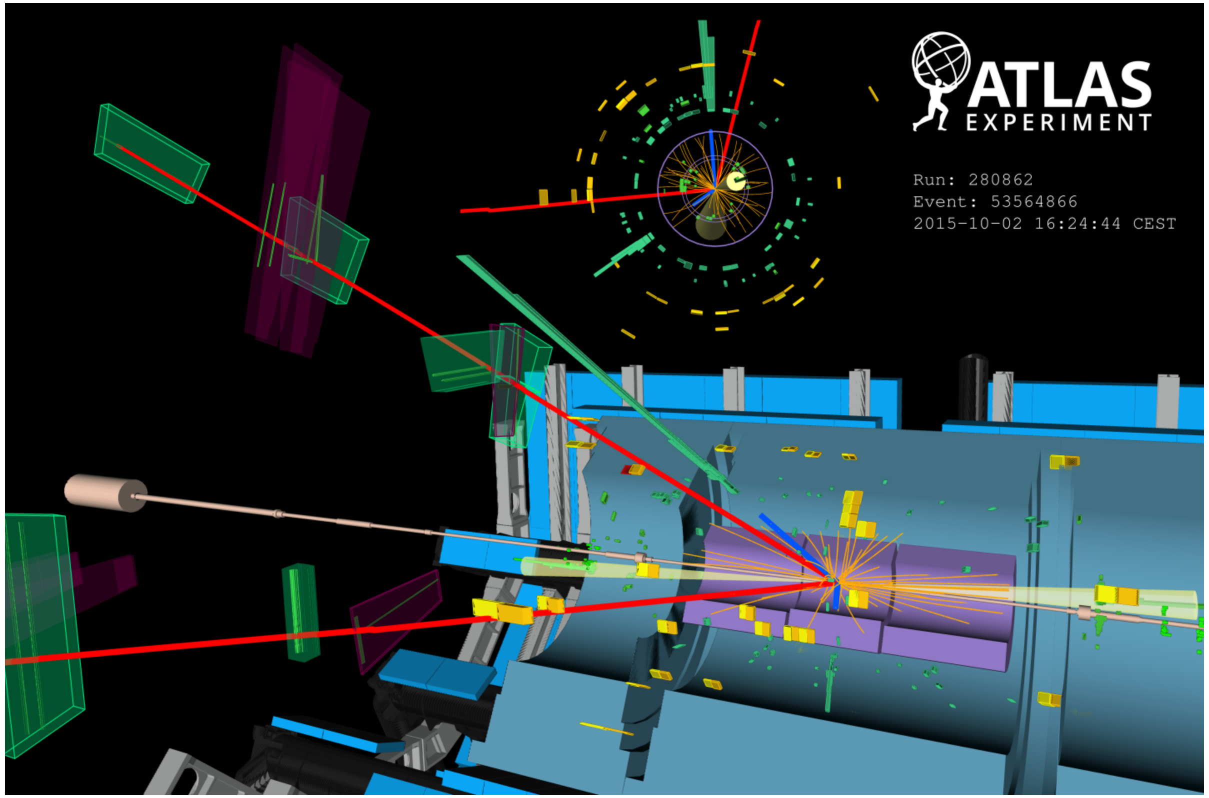
The discovery of a Higgs boson in 2012

> Higgs boson not stable → decays at the beam interaction point into stable particles

> Two "golden" Higgs boson decay channels:

- $h \rightarrow \gamma\gamma$
- $h \rightarrow ZZ^* \rightarrow 4l$





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- h → γγ
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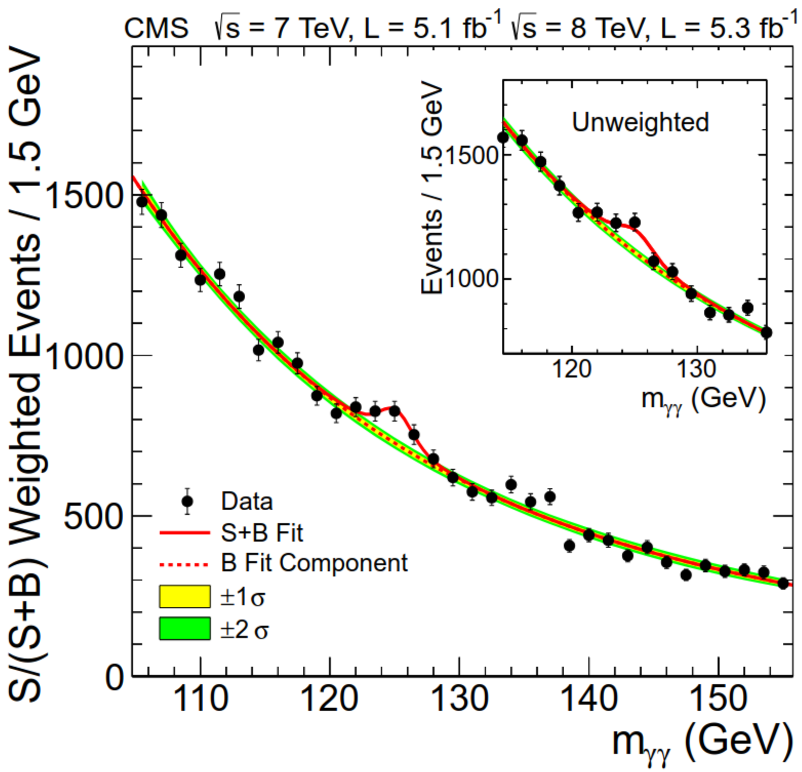
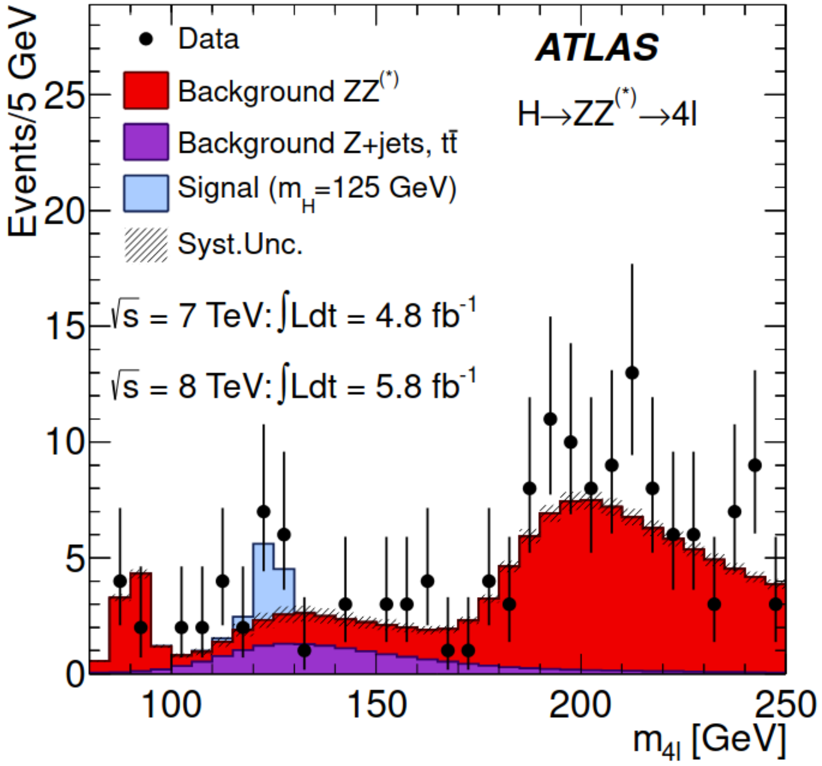
Observation in γγ channel

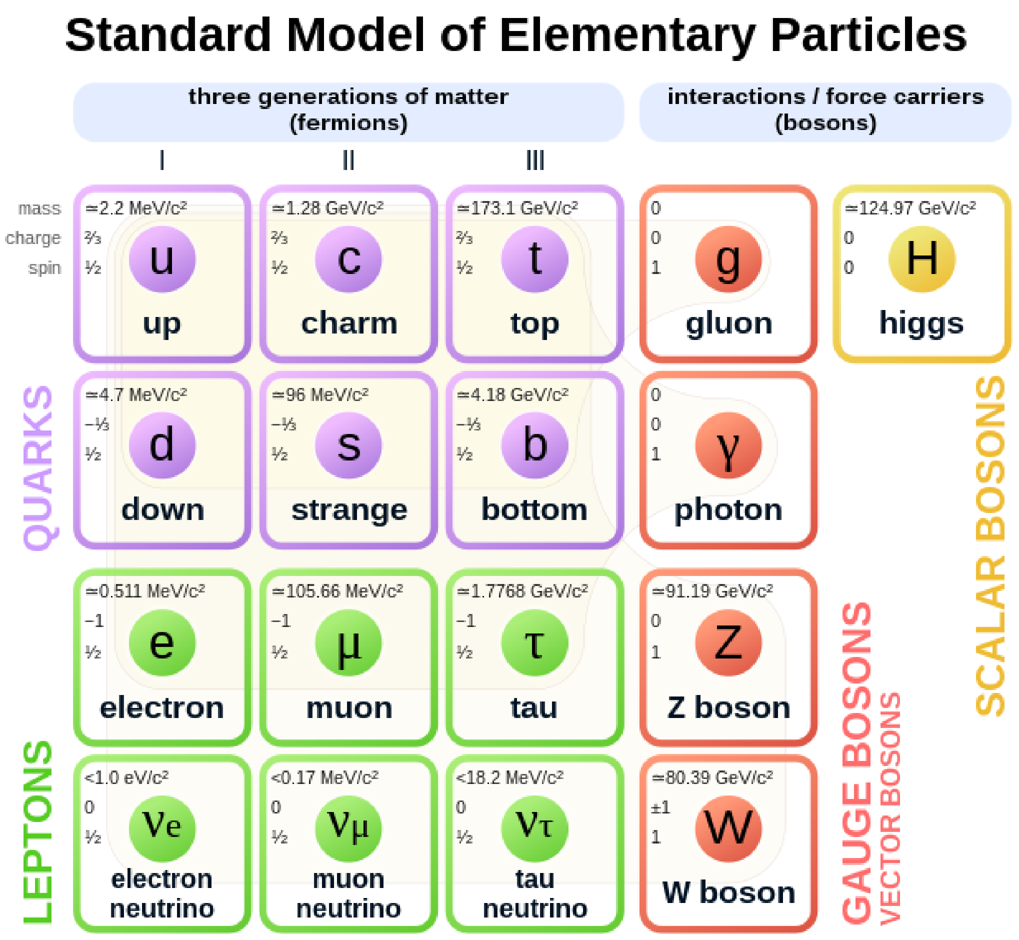


Observation in 4l channel



The discovery of a Higgs boson in 2012

The Standard Model of Particle Physics in 2025



Recap: BEH mechanism of the SM (1)

- Unification of electromagnetic and weak interactions by Glashow, Salam, Weinberg
- *SU(2) x U(1)* gauge theory that assumes massless gauge bosons

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- Unification of electromagnetic and weak interactions by Glashow, Salam, Weinberg
- *SU(2) x U(1)* gauge theory that assumes massless gauge bosons
- Example: *U(1)* theory with field A_μ

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu,$$

Kinetic term

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Invariant under
gauge transformation

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x)$$

Not invariant under
gauge transformation

$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x)$$

Recap: BEH mechanism of the SM (2)

- Unification of electromagnetic and weak interactions by Glashow, Salam, Weinberg
- *SU(2) x U(1)* gauge theory that assumes massless gauge bosons
- But: *W* and *Z* gauge bosons are massive!
- Need to generate mass dynamically → Higgs mechanism!

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi)$$

Kinetic term

$$D_\mu = \partial_\mu - ieA_\mu$$

Potential term

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

Lagrangian invariant under:

$$A_\mu(x) \to A_\mu(x) - \partial_\mu\eta(x),$$
$$\phi(x) \to e^{ie\eta(x)}\phi(x).$$

Recap: The Higgs Potential (1)

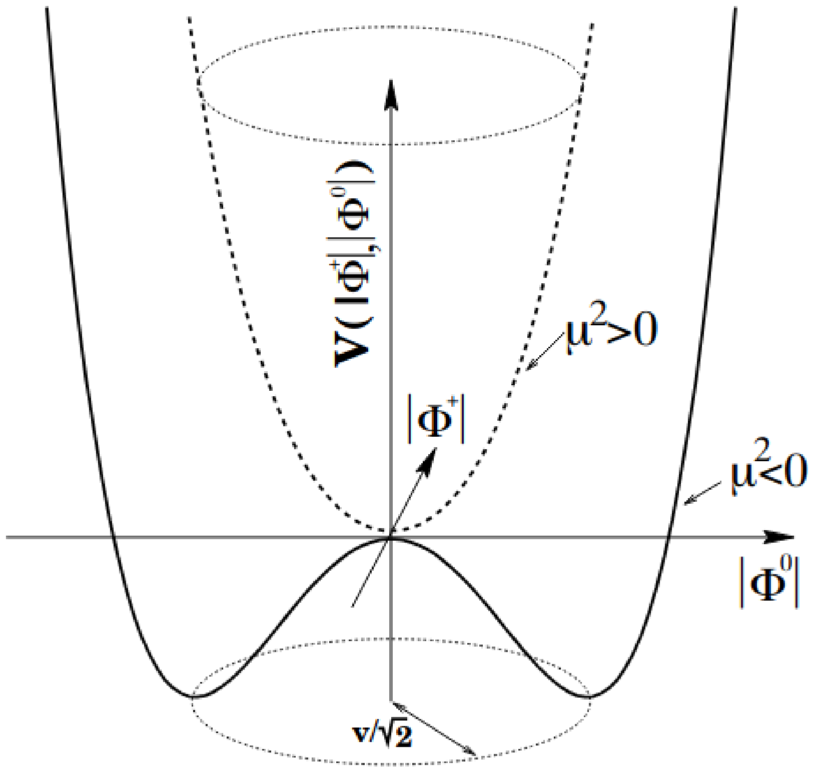
- Potential for complex doublet field
- Parameters μ and λ
- Spontaneous symmetry breaking for $\mu^2 < 0$

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad v = \sqrt{\frac{\mu^2}{\lambda}}.$$

Vacuum expectation value

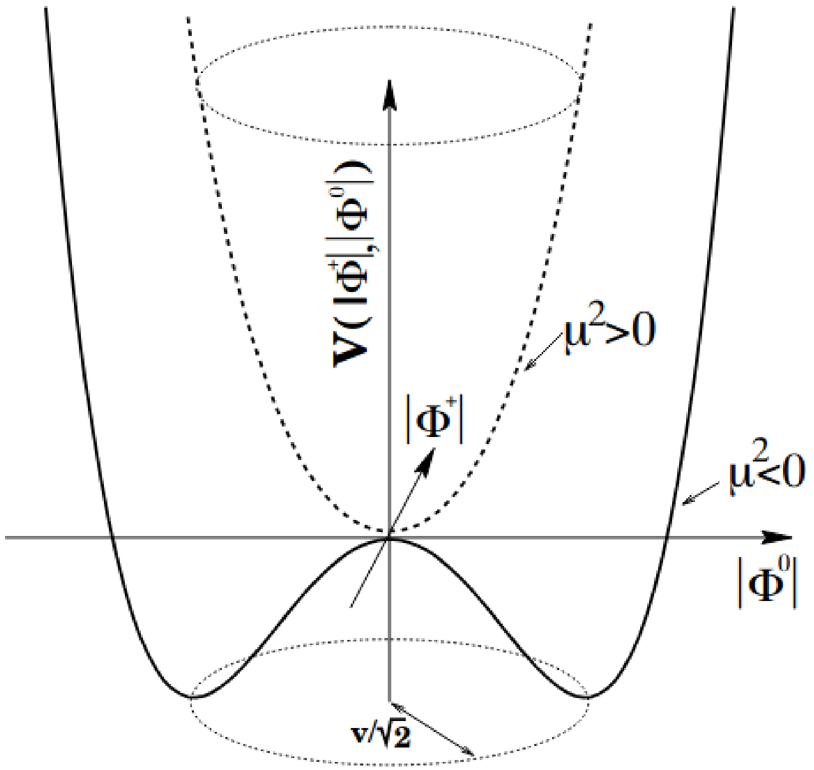


Recap: The Higgs Potential (2)

- Expand around the EW vacuum (minimum)
- Reparameterise in terms of Higgs mass m_h and *v*

$$\lambda = \frac{m_h^2}{2v^2}$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + \underbrace{\frac{m_h^2}{2v}}_{\lambda_3} h^3 + \underbrace{\frac{m_h^2}{8v^2}}_{\lambda_4} h^4$$



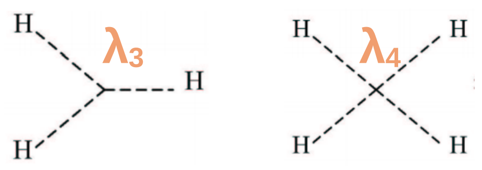
- Value of v determined by EW precision measurements

$$v = \sqrt{\frac{1}{\sqrt{2}G_F}} \approx 246 \text{ GeV}.$$

- Only free parameter of Higgs mechanism: m_h

Recap: Higgs coupling to weak gauge bosons

> Three degrees of freedom "eaten" by boson fields during EWSB → *W* and *Z* masses



Trilinear and quartic self-couplings (determine shape of potential)

→ Tomorrow's lecture!

Higgs potential

$$\mathcal{L}_{\text{Higgs}} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{m_h^2}{2v}h^3 - \frac{m_h^2}{8v^2}h^4 + M_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2}M_Z^2 Z_\mu Z^\mu$$

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Recap: Higgs coupling to weak gauge bosons

> Three degrees of freedom “eaten” by boson fields during EWSB → *W* and *Z* masses

$$M_W^2 = \frac{1}{4} g^2 v^2$$

W mass term

$$\mathcal{L}_{\text{Higgs}} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \frac{m_h^2}{2v} h^3 - \frac{m_h^2}{8v^2} h^4 + M_W^2 W_\mu^+ W^{\mu-} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu$$

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Recap: Higgs coupling to weak gauge bosons

> Three degrees of freedom "eaten" by boson fields during EWSB → *W* and *Z* masses

$$M_Z^2 = \frac{1}{4}(g^2 + g'^2)v^2$$

Z mass term

$$\mathcal{L}_{\text{Higgs}} = \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \frac{m_h^2}{2v}h^3 - \frac{m_h^2}{8v^2}h^4 + M_W^2 W_\mu^+ W^{\mu -} + \frac{1}{2}M_Z^2 Z_\mu Z^\mu$$

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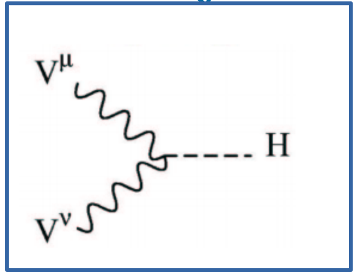
Single Higgs to boson couplings
→ more on this later!



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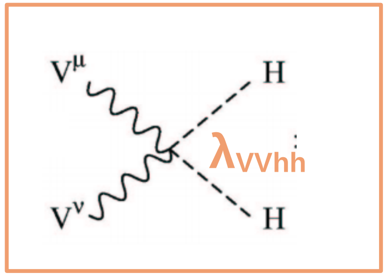


Di-Higgs to di-boson coupling (not observed yet)

→ Tomorrow's lecture!

Recap: Higgs couplings to fermions

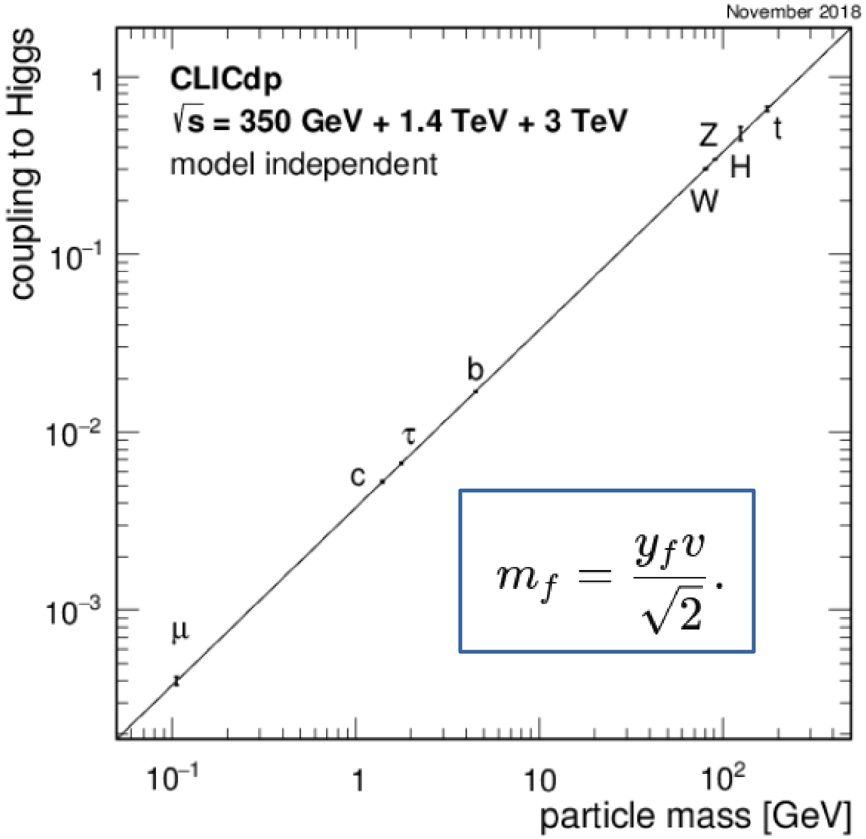
> Ad-hoc assumption: Yukawa-coupling of the Higgs field to fermions

$$\mathcal{L}_{\text{Yukawa}} = -y_f \left(\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \phi^\dagger \psi_L\right)$$

> Rewrite after EWSB:

$$\mathcal{L}_{\text{Yukawa}} = -m_f \bar{\psi}\psi - \frac{m_f}{v} \bar{\psi}\psi h$$

> Fermion coupling y_f to Higgs field proportional to fermion mass



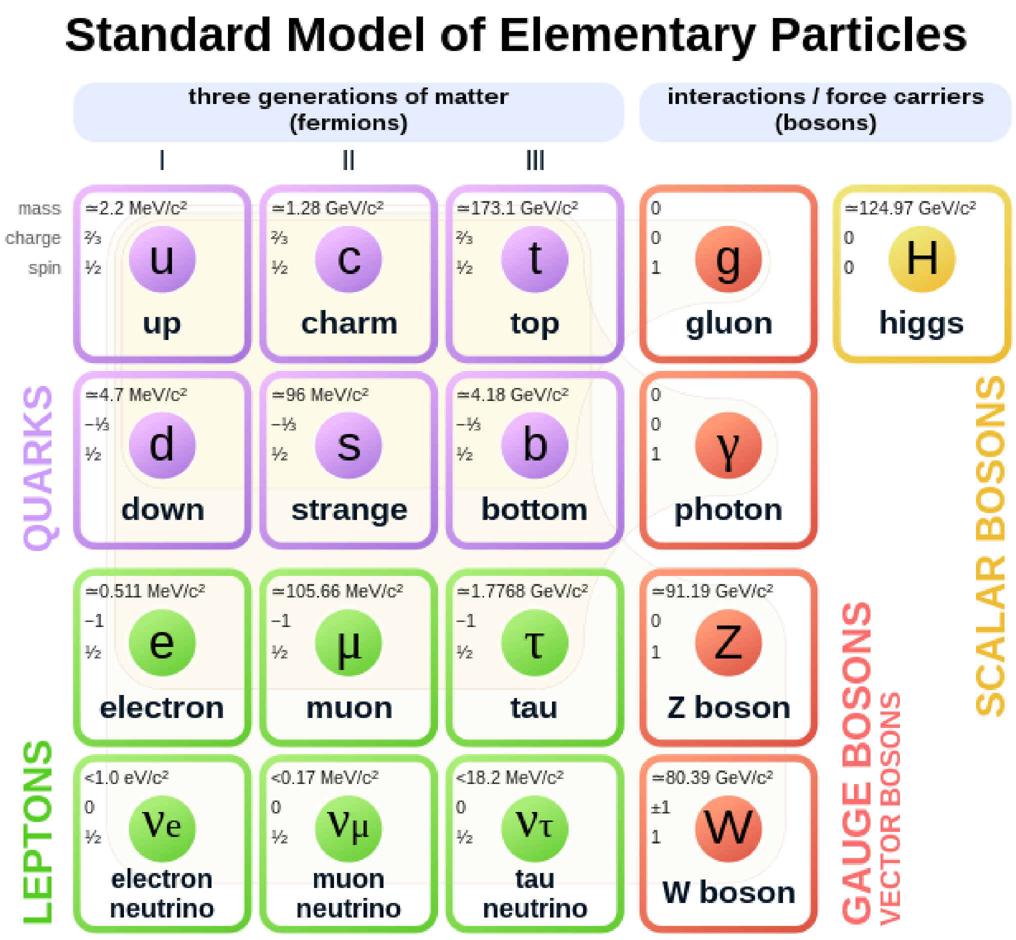
$$m_f = \frac{y_f v}{\sqrt{2}}.$$

Note: y-axis different for different particle types

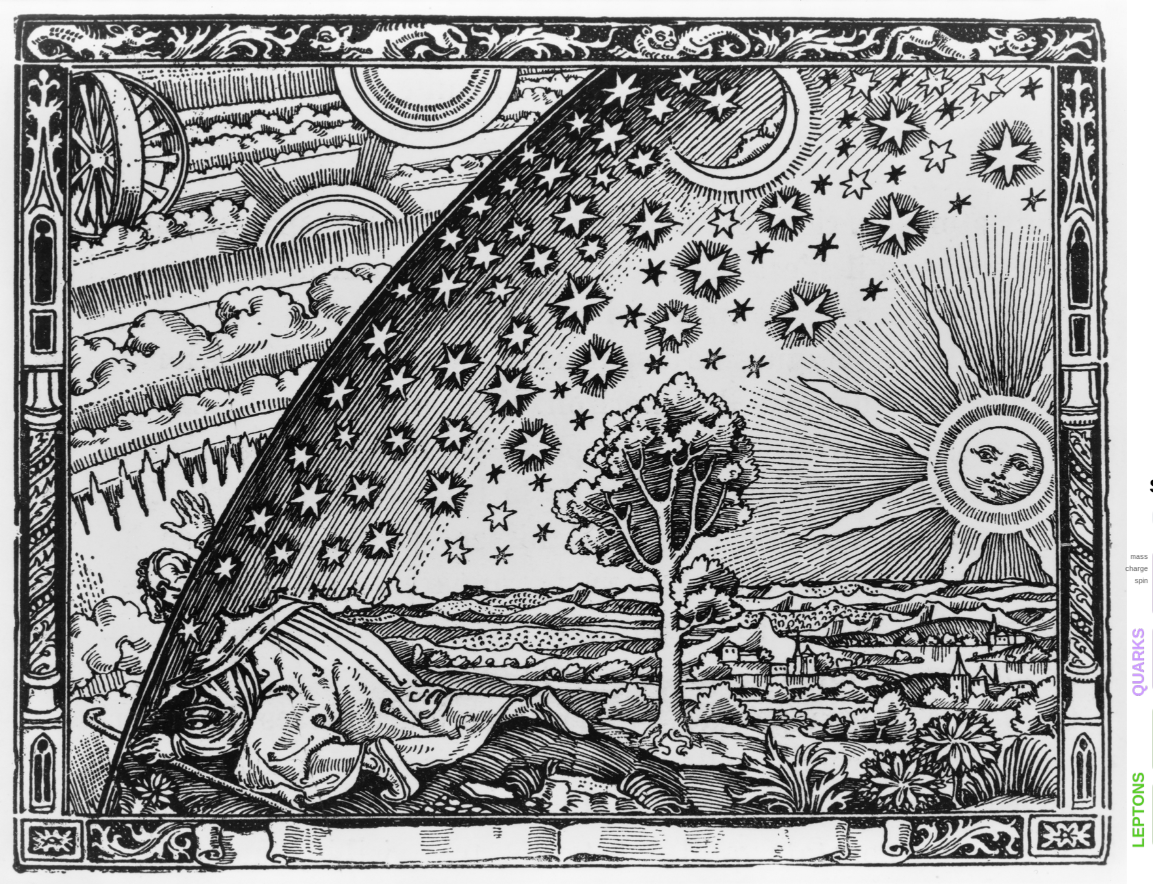
SM predictions for the Higgs boson

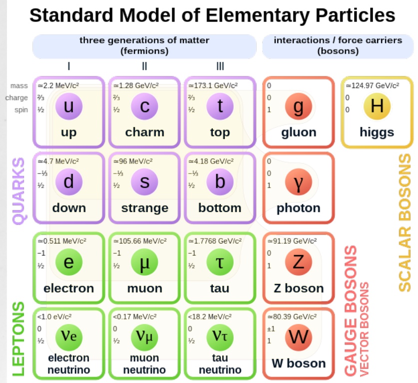
- Higgs mass: Higgs is massive and its mass m_h a *free parameter* of the SM.
- Higgs CP properties: a scalar (CP-even) state
- Higgs coupling: the higher the mass, the stronger the coupling
  - fermion coupling ~ fermion mass
  - boson coupling ~ (boson mass)^2
- Higgs production and decay modes:
  - Fully determined by above properties
  - Closure tests: check if measured values agree with predictions

The Standard Model of Particle Physics in 2025



Why look beyond the SM?

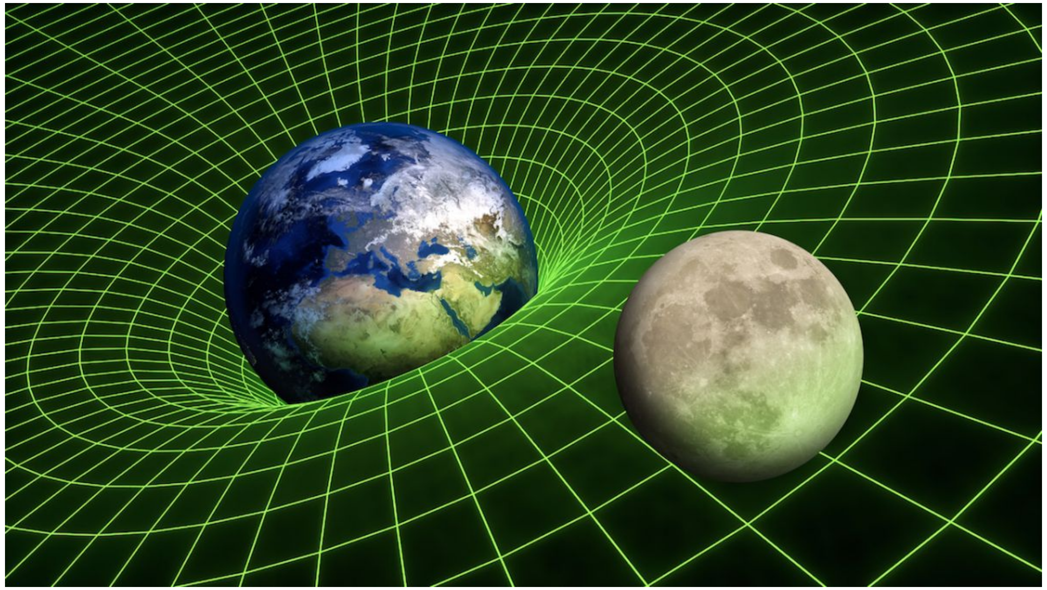


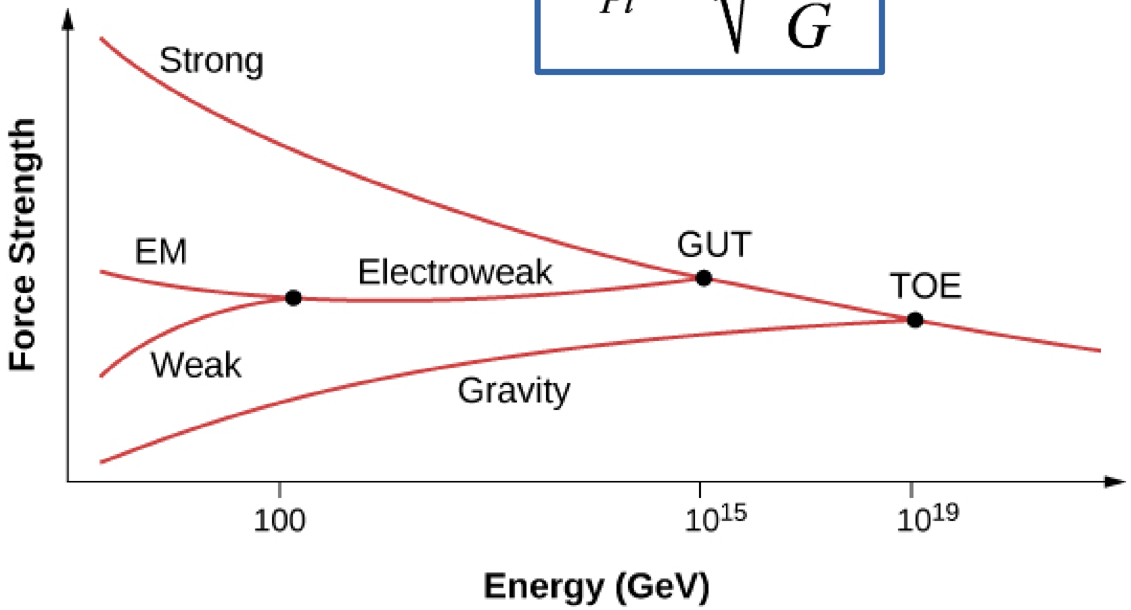


Missing pieces: gravity

- Gravity not described by SM
  - Various approaches to describe gravity with a quantum field theory have failed
  - Theory of Everything: SM + General Relativity
  - Unification at Planck scale 10^{19} GeV
    - Electroweak force and gravity are of the same order

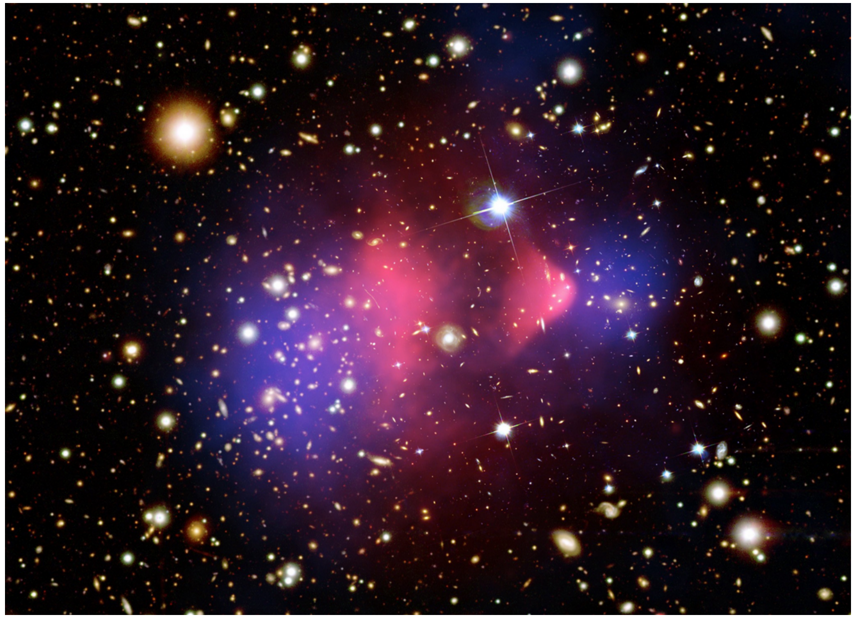
$$m_{Pl} = \sqrt{\frac{\hbar \cdot c}{G}}$$

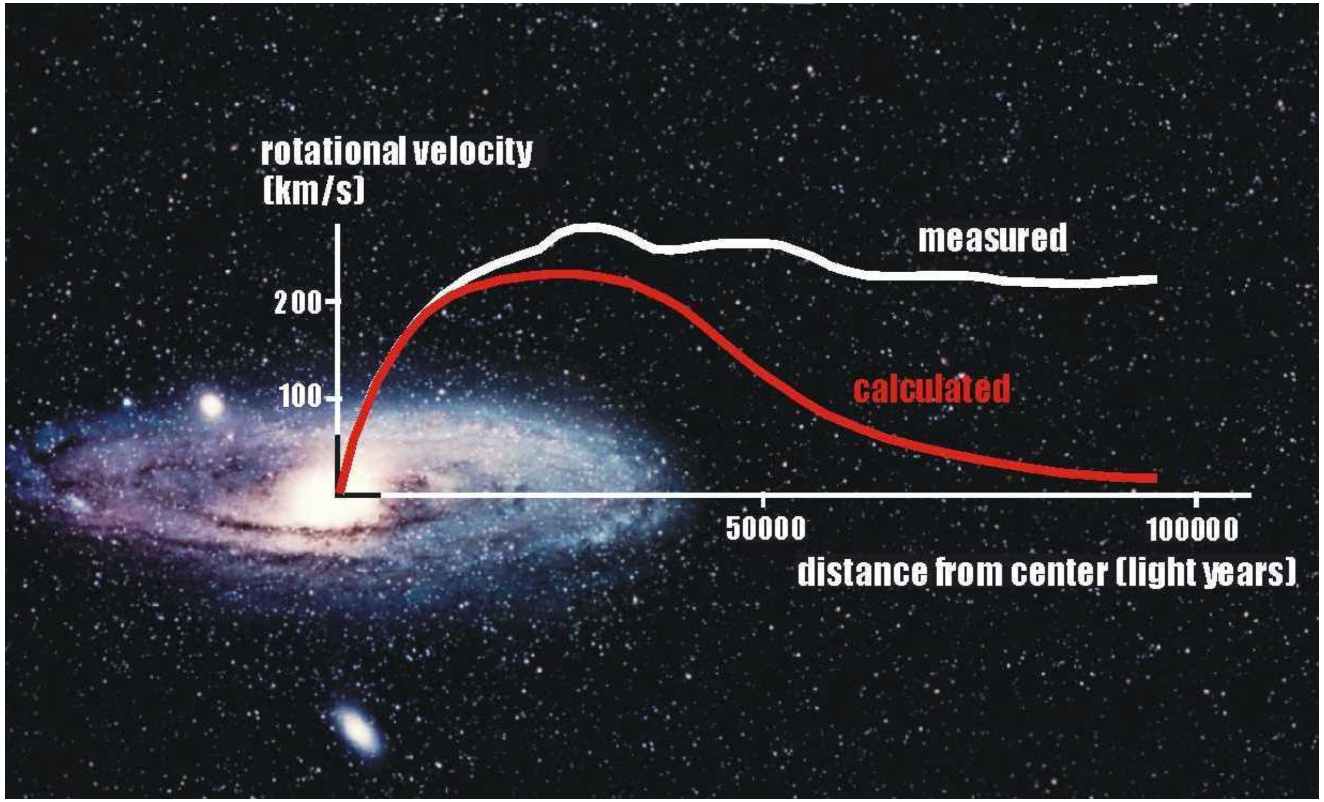




Missing pieces: dark matter

- Various sources of astrophysical evidence for existence of DM
  - Galactic rotation curves
  - Motion of galactic clusters
  - Gravitational lensing
  - ...

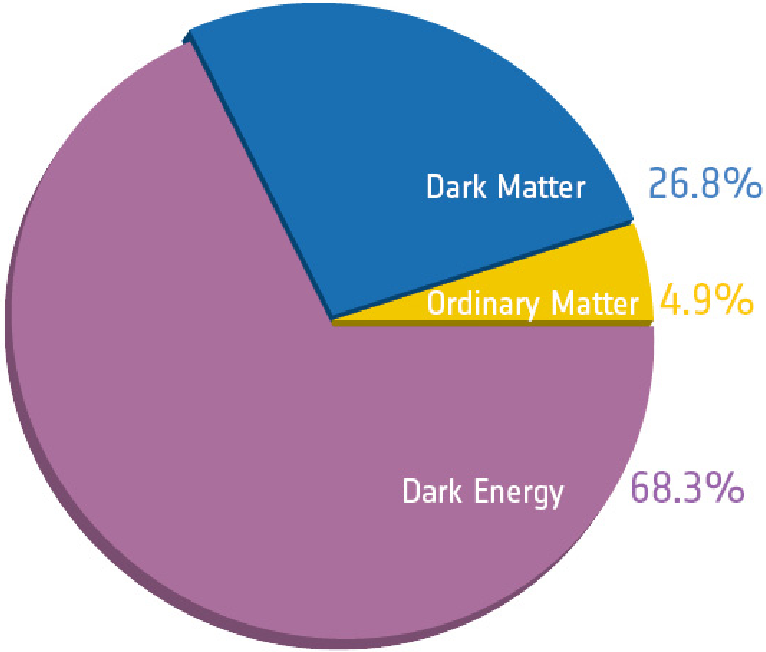


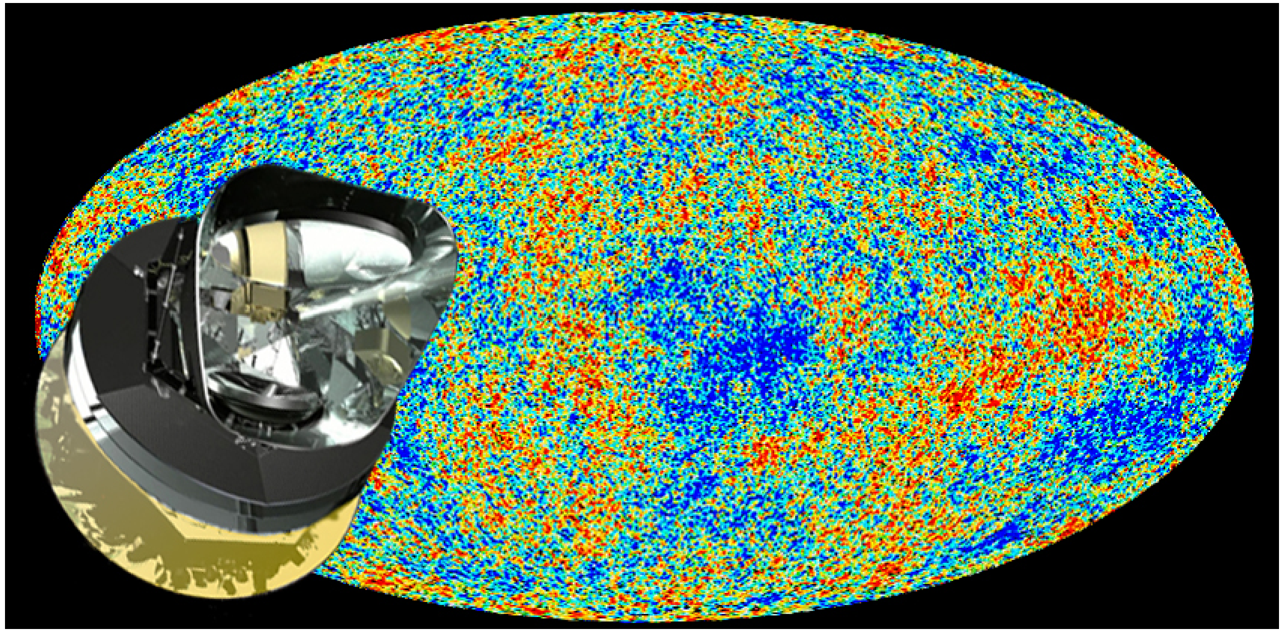


Missing pieces: dark matter and dark energy

> No candidates for dark matter (DM) or dark energy (DE)

- DM and DE content determined from CMB as measured by Planck satellite





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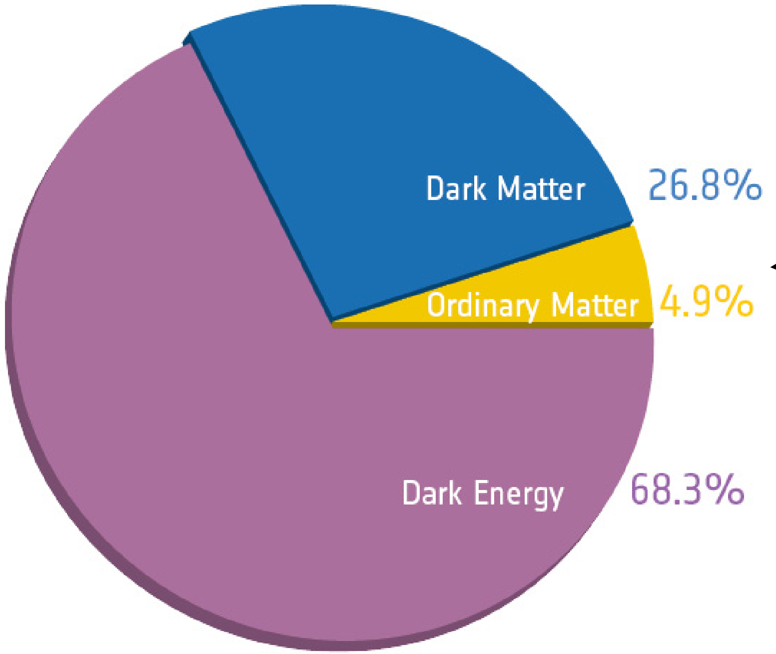
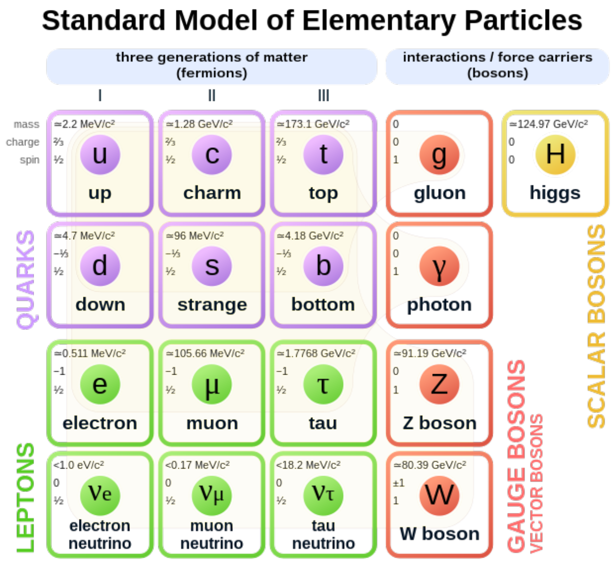


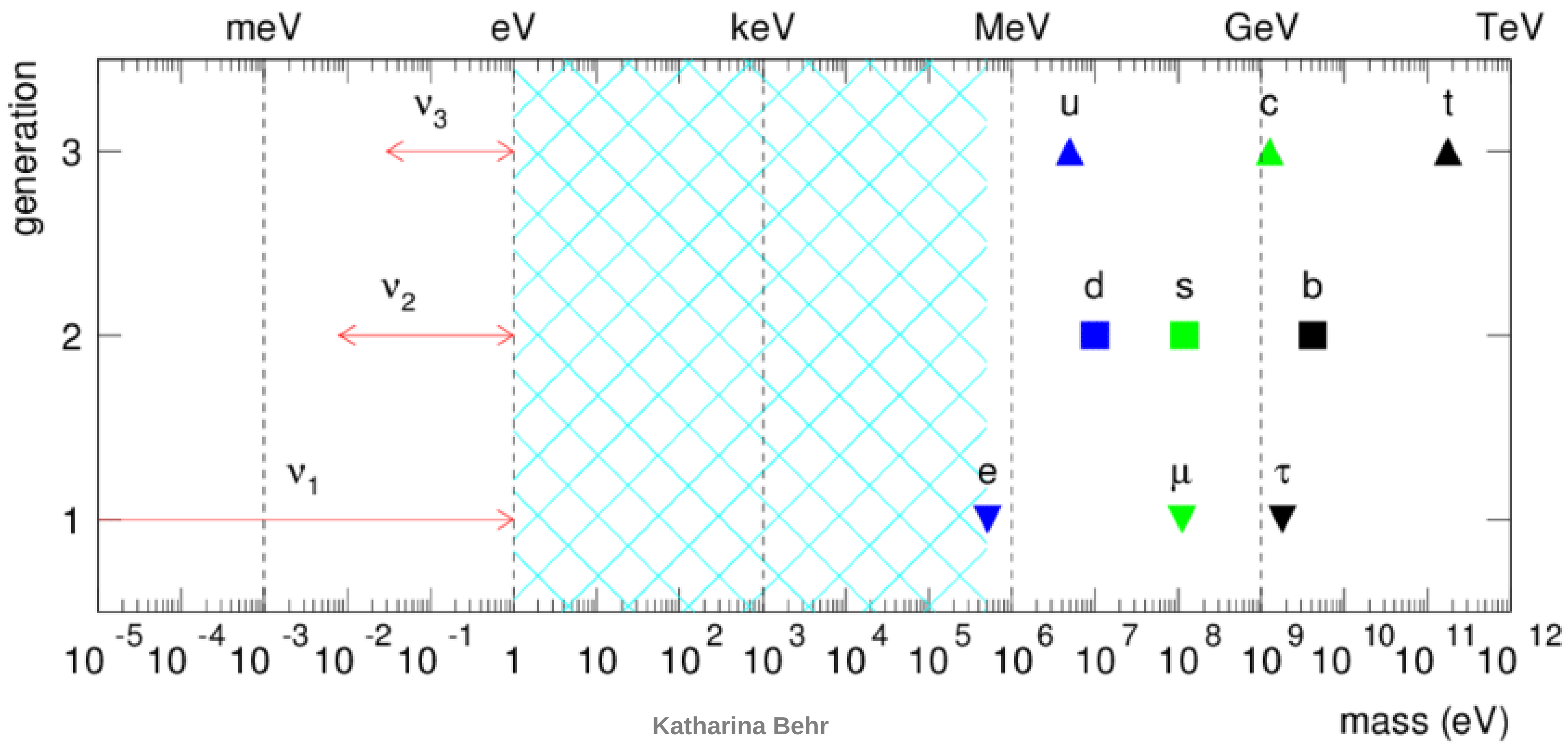
SM describes only 5% of matter-energy content of the Universe



Conceptual issues within the Standard Model

> Many assumptions introduced ad-hoc, without underlying theory motivation

- 26 free parameters, including all fermion masses
- Why three lepton and quark generations?
- Why do the fermion masses differ by at least 12 orders of magnitude?



Matter-antimatter imbalance

- Equal amounts of matter and antimatter created in the Big Bang (B=0)
- Observable universe completely dominated by matter (B>0)
- What caused this imbalance?

- **Sakharov conditions**
  1. Baryon number violating processes
  2. C and CP violation
  3. Processes out of thermal equilibrium

- CP violation observed in the SM
  - Kaon and B-meson system
  - Not sufficiently large to explain imbalance
- Need additional sources of CP violation!
  - E.g. from neutrino sector
  - E.g. from extended Higgs sector models

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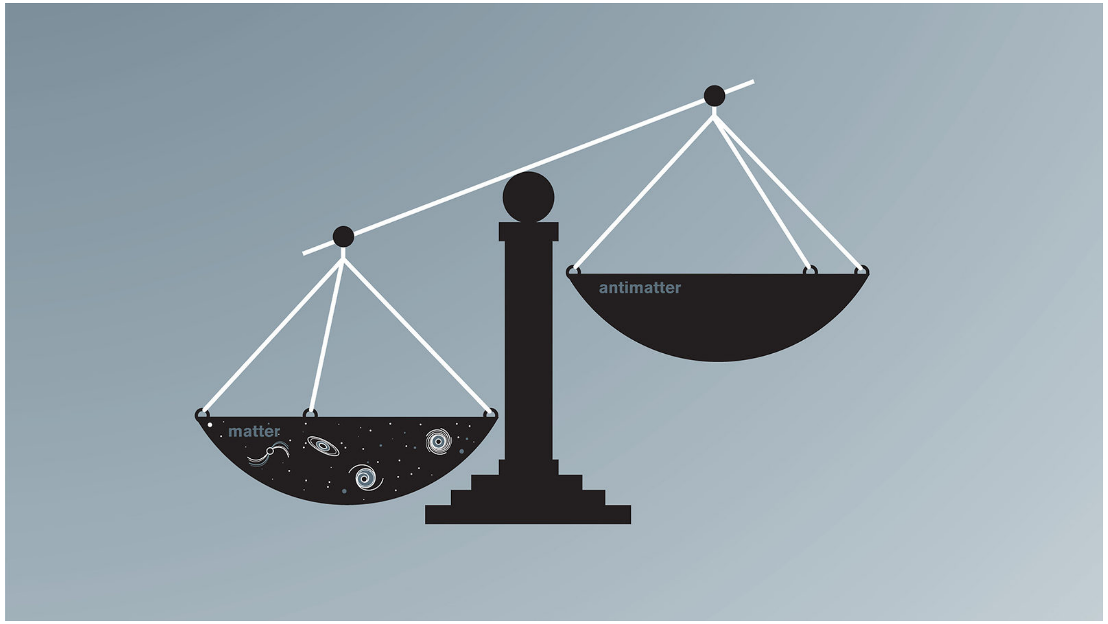


Excellent review of Sakharov conditions by D. Perepelitska [link]

The strong CP problem (1)

- QCD Lagrangian for massive quarks contains a CP violating term
- Amount of CP violation depends on parameter θ^*, which can take values in [0,1]

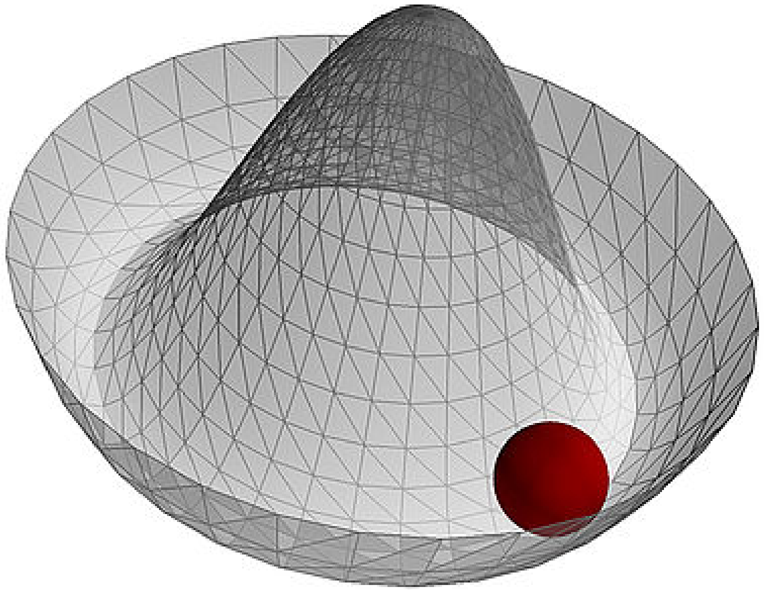
- Strong CP violation → non-zero neutron electric dipole moment: $d_N = (5.2\ 10^{-16}\ e\ \text{cm})\ \theta^*$
- Measured from Larmor precession of neutron spin in antiparallel and parallel E and M fields
- Measurements constrain dipole moment to $|d_N| < 10^{-26}\ e\ \text{cm}$ → $\theta^* < 10^{-10}$

- $\theta^* = 0$ indicates extreme fine-tuning

The strong CP problem (2)

- Possible solution via the Peccei-Quinn mechanism
- Relate θ^* to a new physical field with a global chiral U(1) symmetry
- Field has tilted Mexican hat potential
- Spontaneous breaking of U(1) → pseudo-Goldstone boson: axion
- VEV of axion field leads to $\theta^* = 0$
  - No fine tuning!

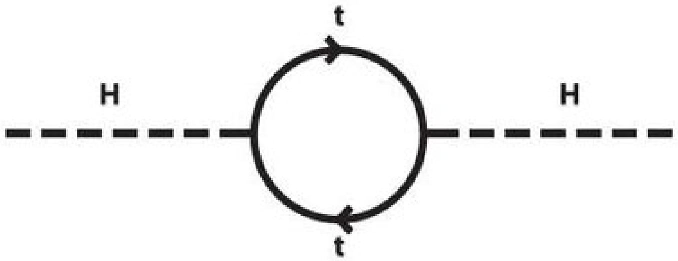
- Axion also a dark matter candidate (see later).



Credit: U Wuppertal

The hierarchy problem

- SM contains an elementary scalar particle (Higgs)
  - Vulnerable to quantum loop corrections of arbitrary high scales



- No BSM physics → SM valid up to Planck scale O(10^{19} GeV)
  - Higgs mass should be 16 orders of magnitude larger than the measured 125 GeV

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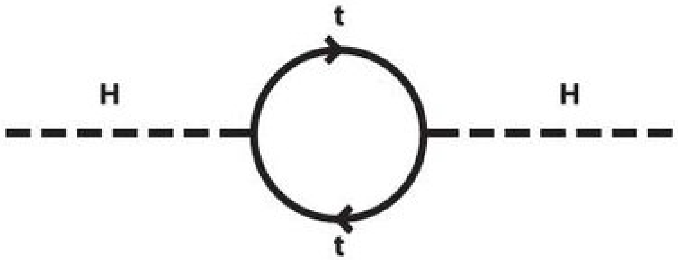
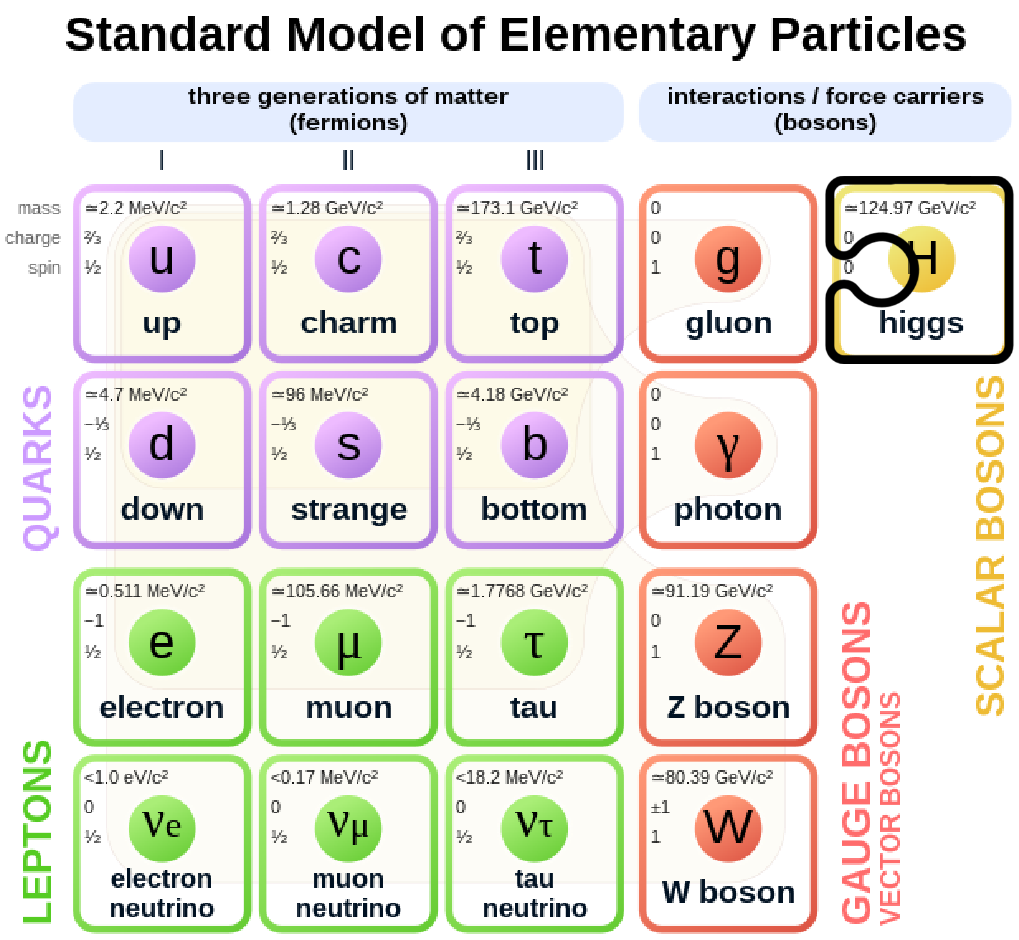
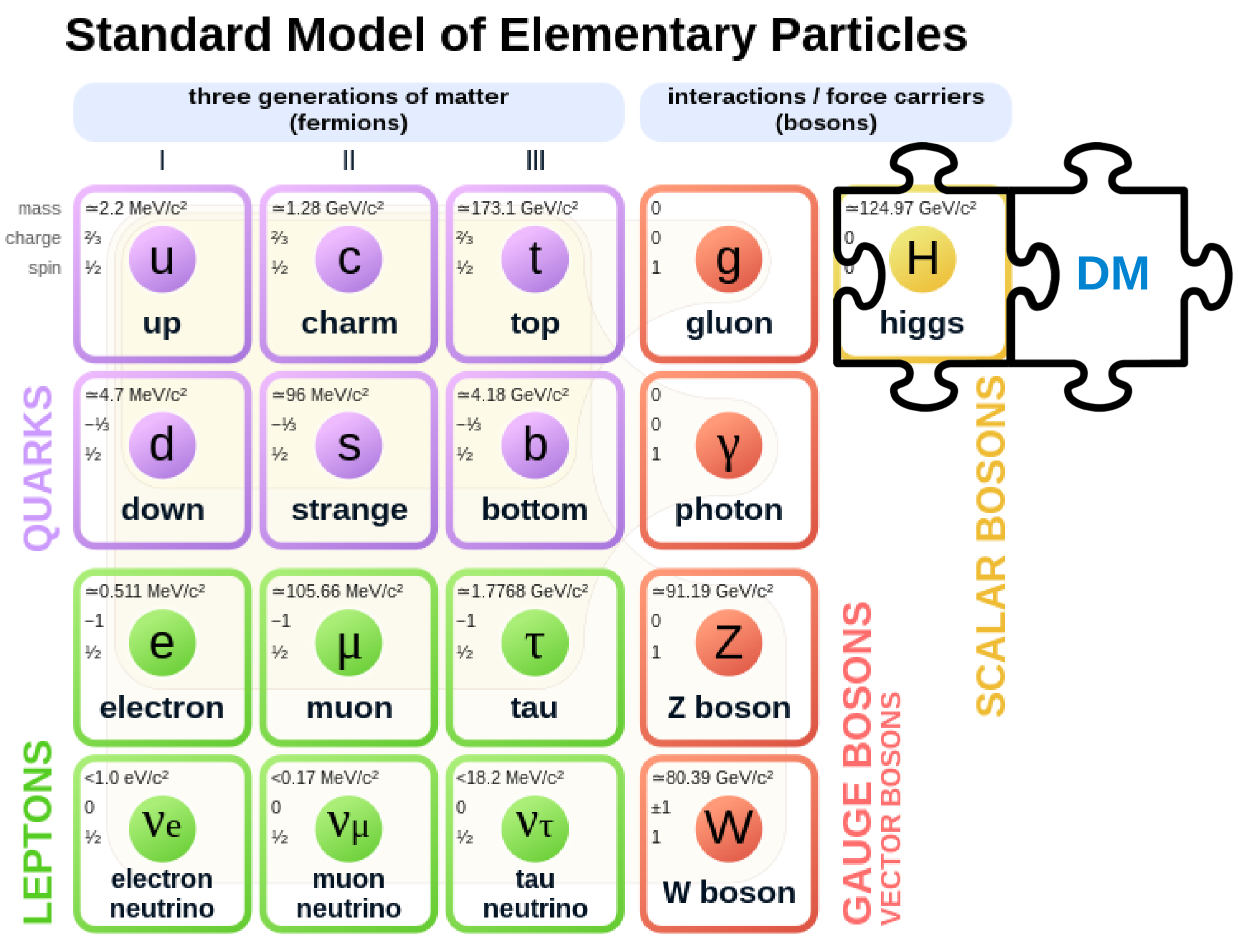


- No BSM physics → SM valid up to Planck scale O(10^{18} GeV)
  - Higgs mass should be 16 orders of magnitude larger than the measured 125 GeV
- BSM solutions:
  - Supersymmetry: additional loops to cancel divergent loops
  - Extra dimensions
  - Composite Higgs models
  - …

Can the Higgs boson point us toward phenomena beyond the SM?



Can the Higgs boson point us toward phenomena beyond the SM?



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> Higgs mass: Higgs is massive and its mass m_h a *free parameter* of the SM.

> Higgs CP properties: a scalar (CP-even) state

> Higgs coupling: the higher the mass, the stronger the coupling

- fermion coupling ~ fermion mass
- boson coupling ~ (boson mass)^2

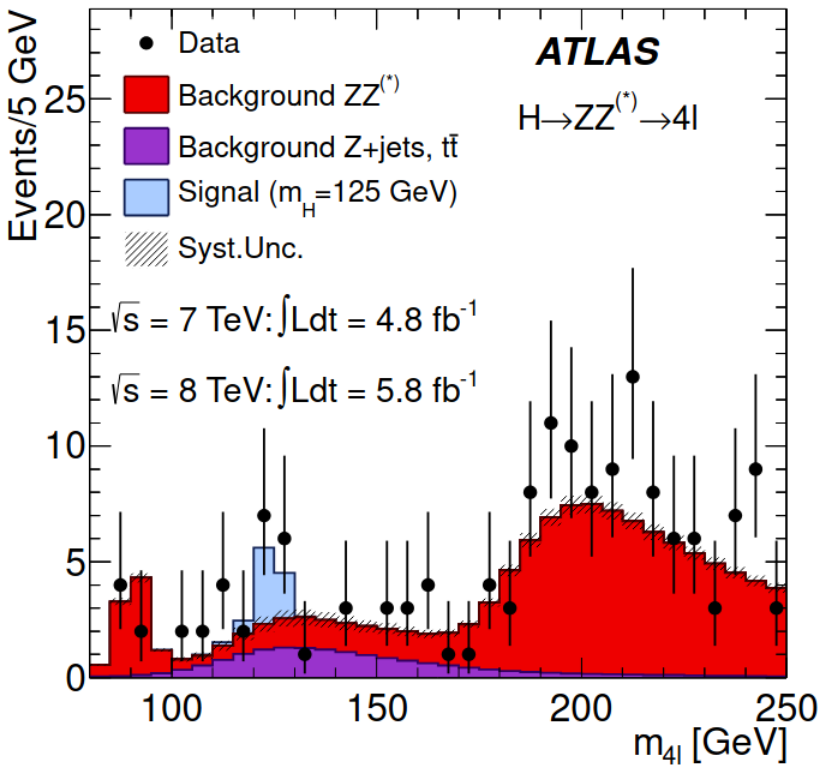
> Higgs production and decay modes:

- Fully determined by above properties
- Closure tests: check if measured values agree with predictions

Characterising the Higgs boson

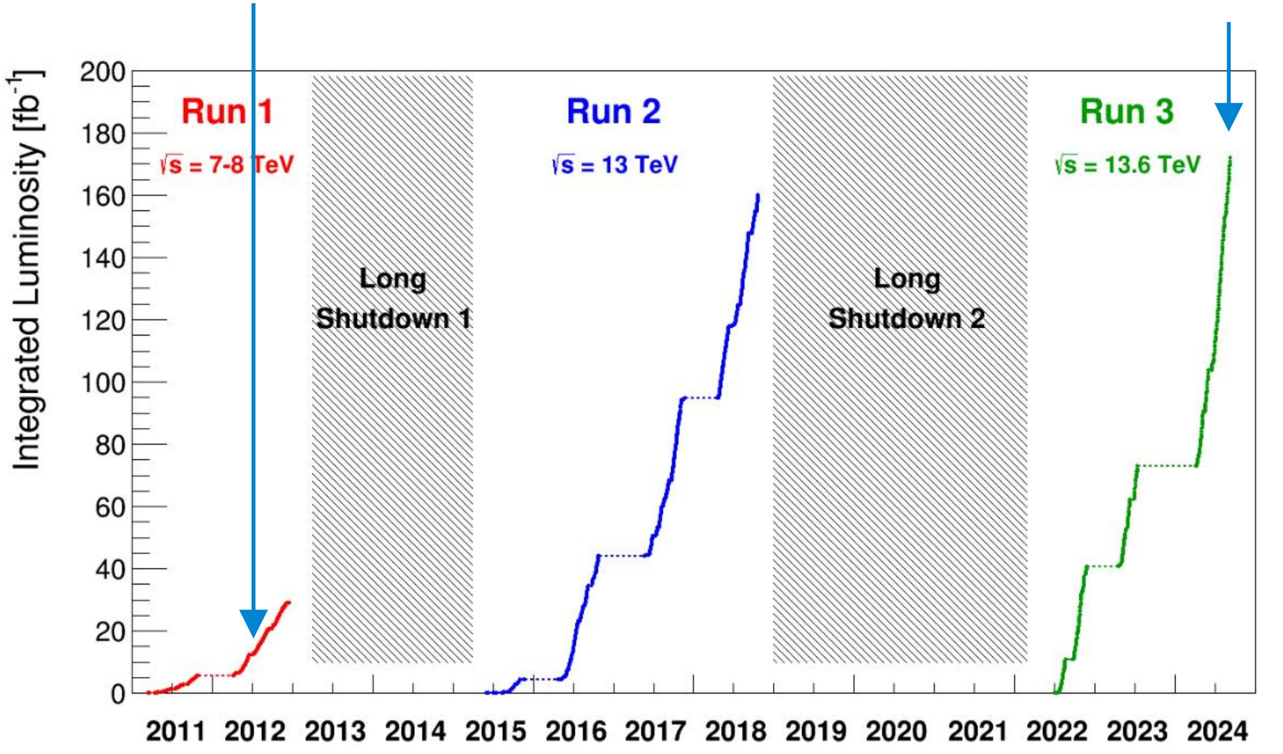
- Discovery based on only a fraction of LHC Run-1 data: ~10 fb^{-1} of data at $\sqrt{s}$ = 7 TeV and 8 TeV
- Much more data taken since then
- Tremendous progress in our understanding of the first fundamental spin-0 particle observed in nature

Observation in *4ℓ channel*



Higgs discovery

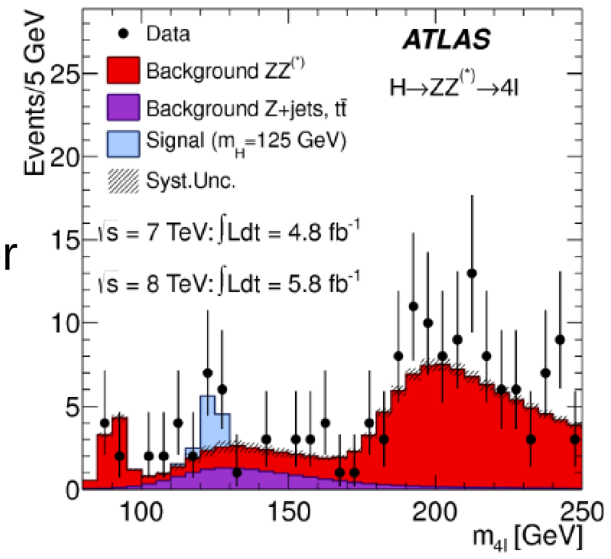
Today

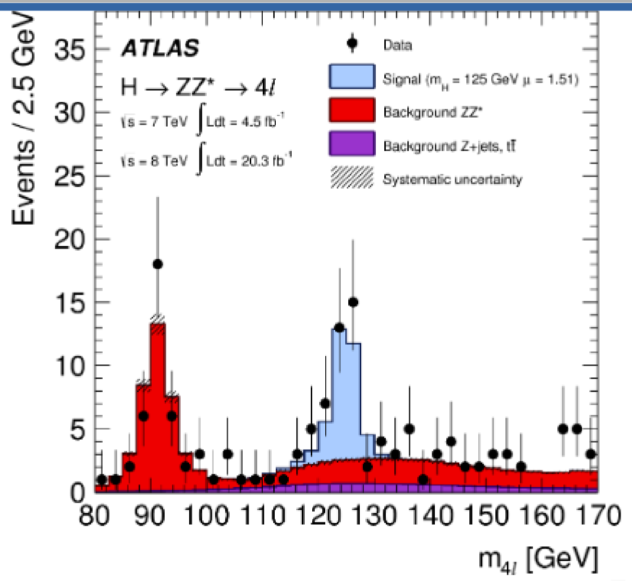


From discovery to characterisation

Run 1

Summer 2012

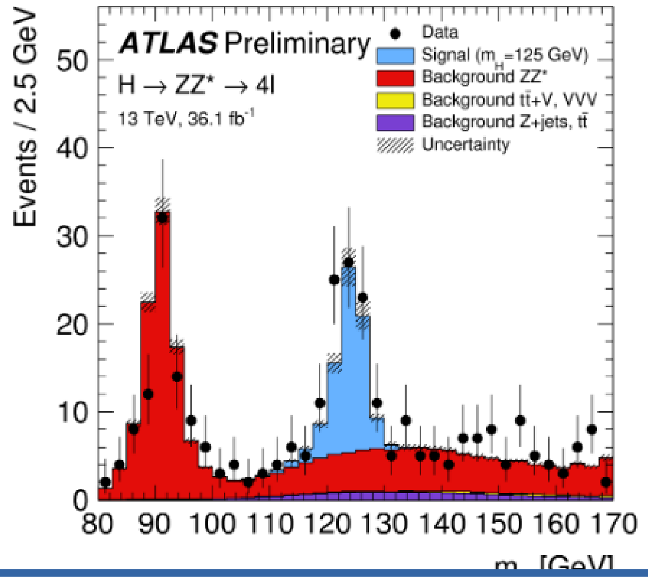


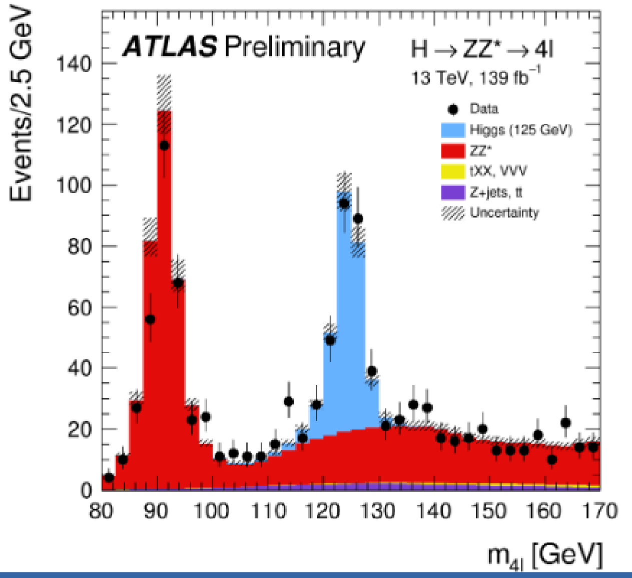


Winter 2012

Run 2

2016





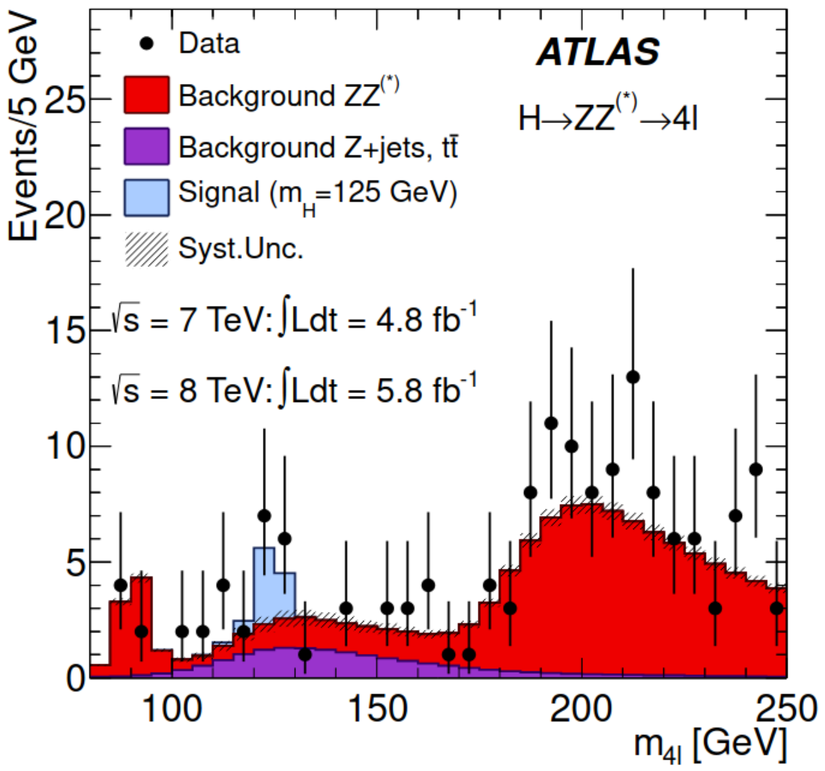
2018

Run 3
on-going...

Characterising the Higgs boson

- Comprehensive summary of Higgs property measurements published in Nature in 2022 (Higgs@10)
- Even more progress made since, e.g. on mass precision

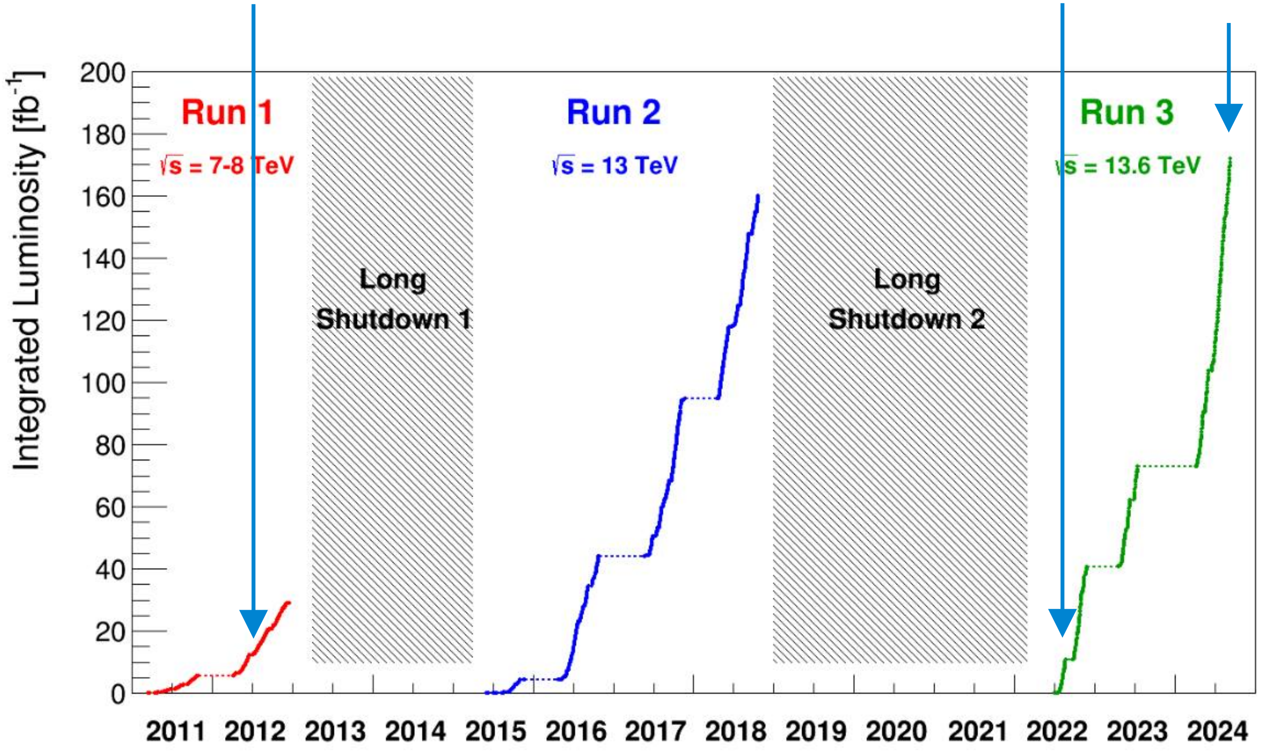
Observation in 4l channel



Higgs discovery

Higgs@10

Today



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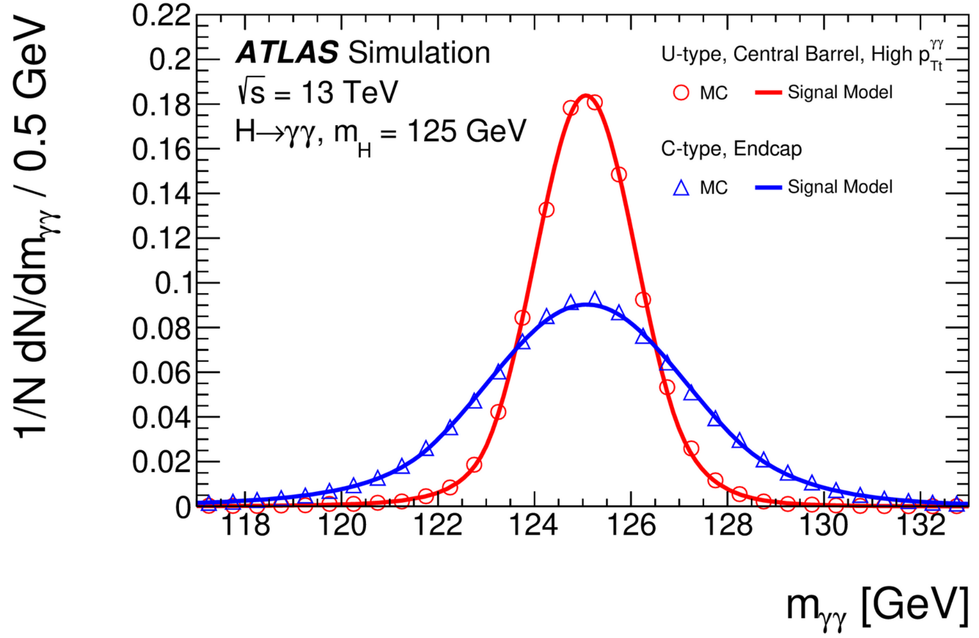
Measuring the Higgs boson mass

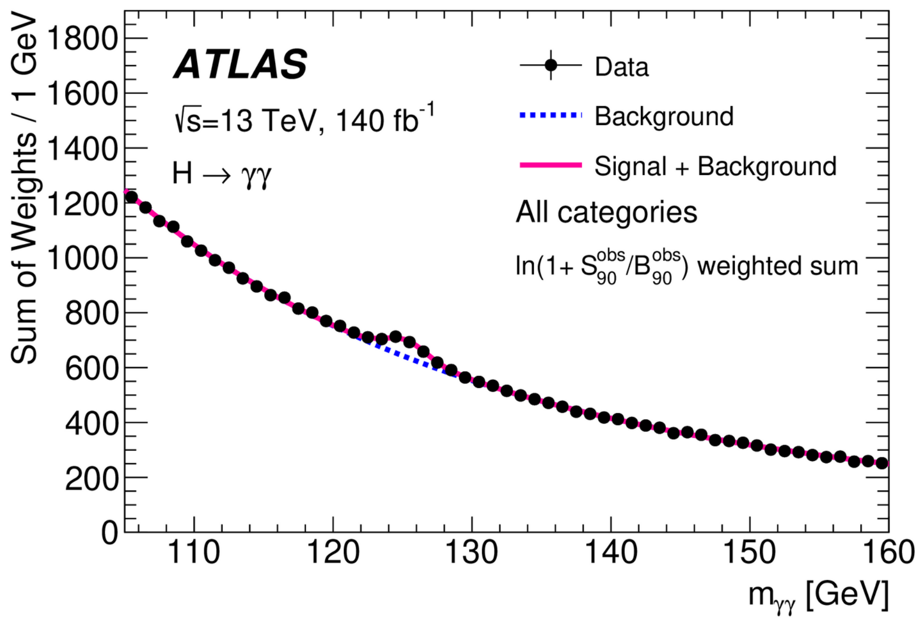
> Golden decay modes $h \to \gamma\gamma$ and $h \to ZZ^* \to 4\ell$ most suitable

> Excellent mass resolution → clear mass peak above a continuum background

> Example: $h \to \gamma\gamma$

- Require precise measurement of photon energy and direction in electromagnetic calorimeters
- Functional fit to data: double-sided Chrystal Ball + second-order polynomial
- Separately for photons in barrel and endcap regions





Measuring the Higgs boson mass

- Golden decay modes $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ^* \rightarrow 4\ell$ most suitable
- Excellent mass resolution → clear mass peak above a continuum background
- Statistical combination of both channels (Run 1 + Run 2)

ATLAS Run-2 combination:
m_h = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) GeV
= 125.11 ± 0.11 GeV

< 1 permille accuracy!

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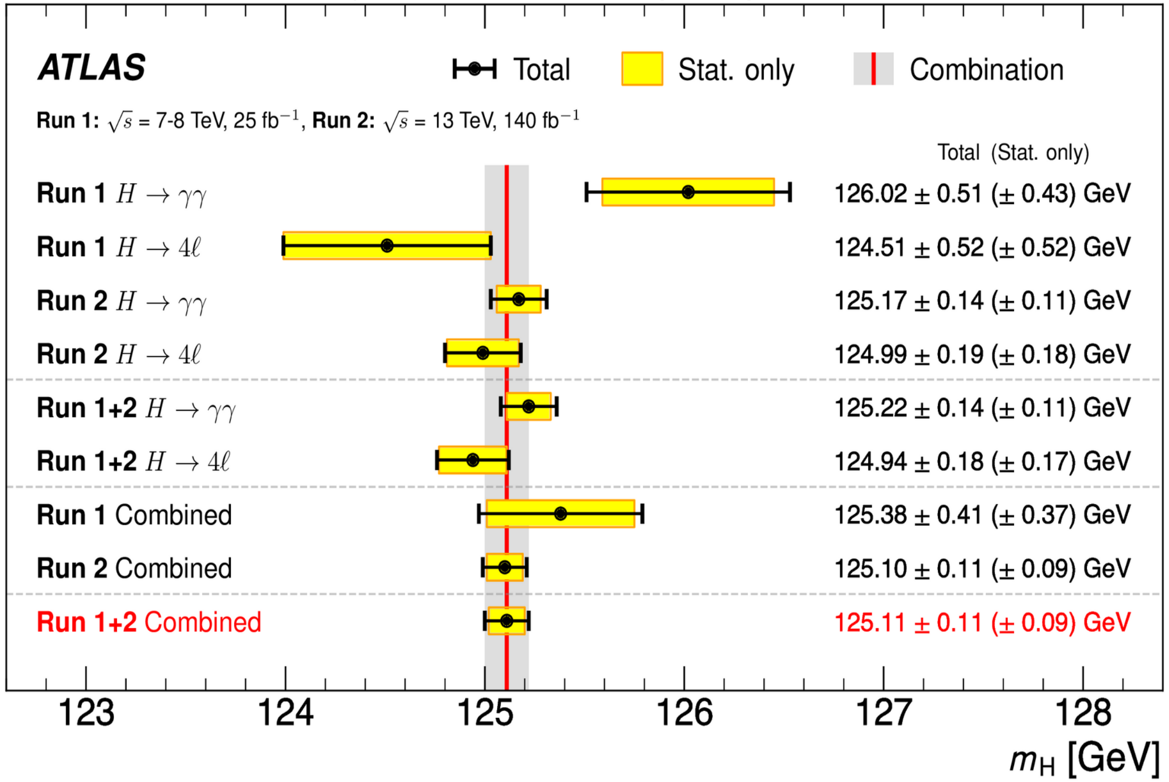
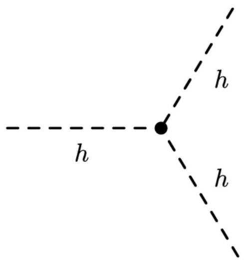


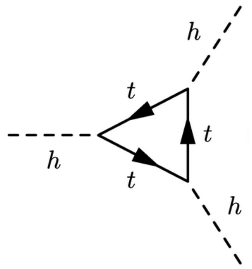
Cosmological implications of the Higgs boson mass

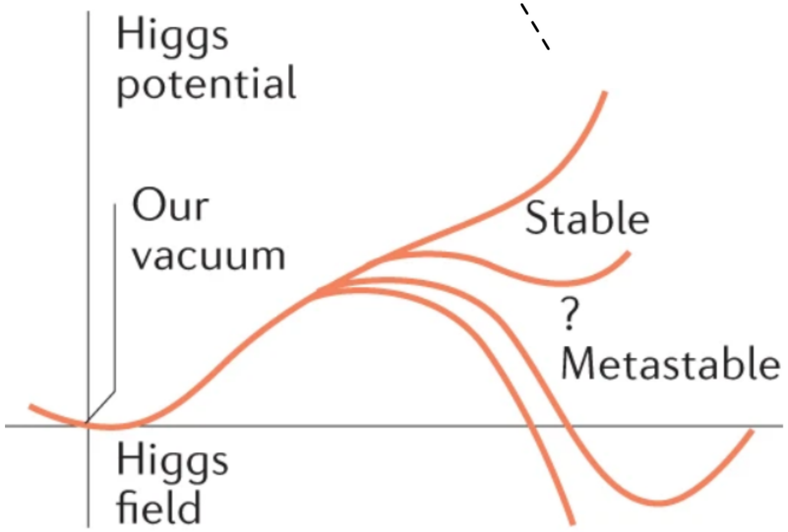
> Higgs mass at a remarkable value:

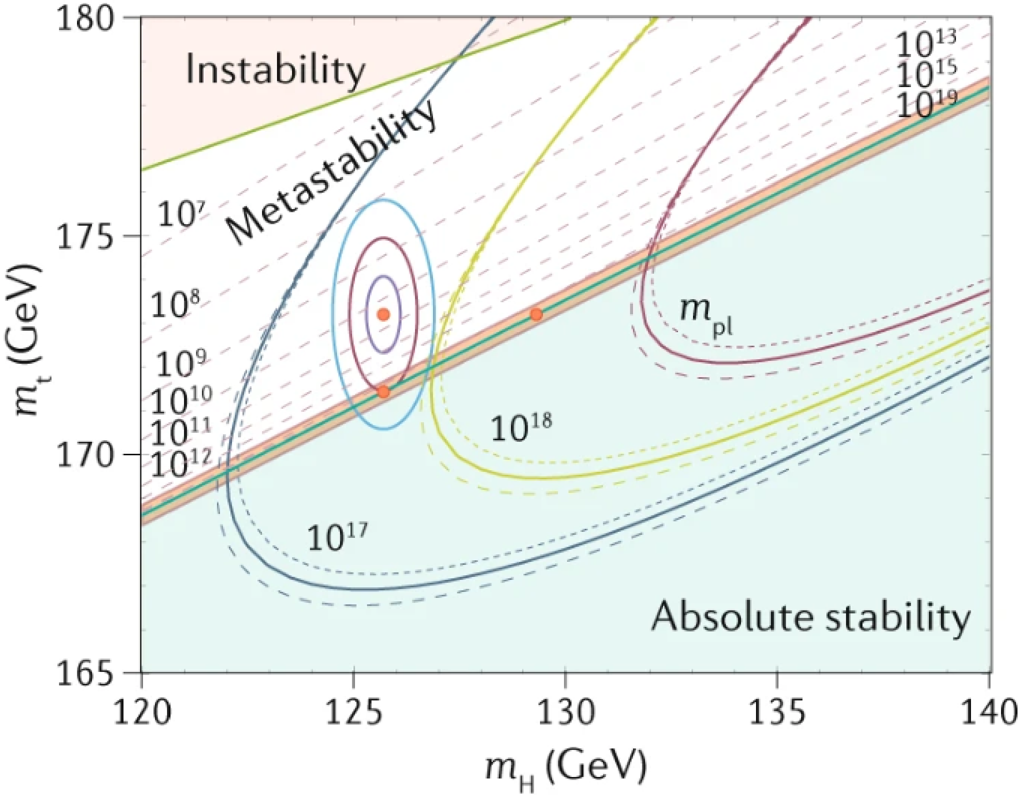
> SM vacuum close to border between stable and metastable at high energies given measured m_{top}

- Running trilinear coupling at high energies with large contributions from top loops
- Negative self-couplings possible at large energies → metastability!



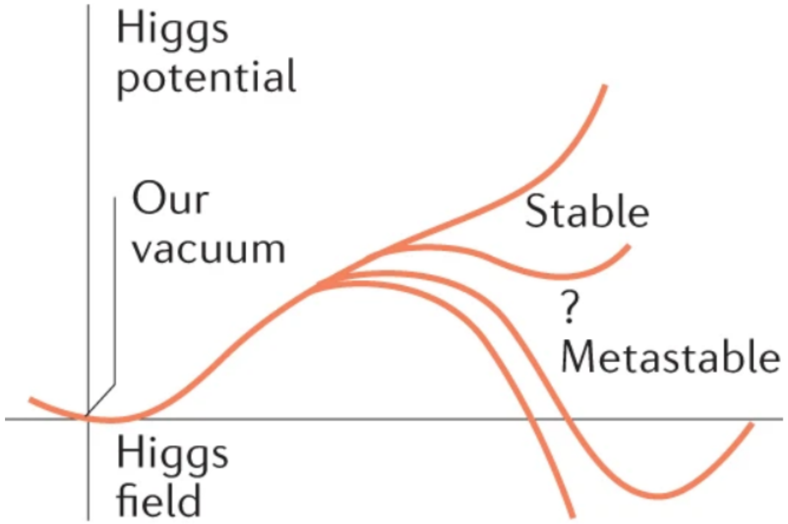


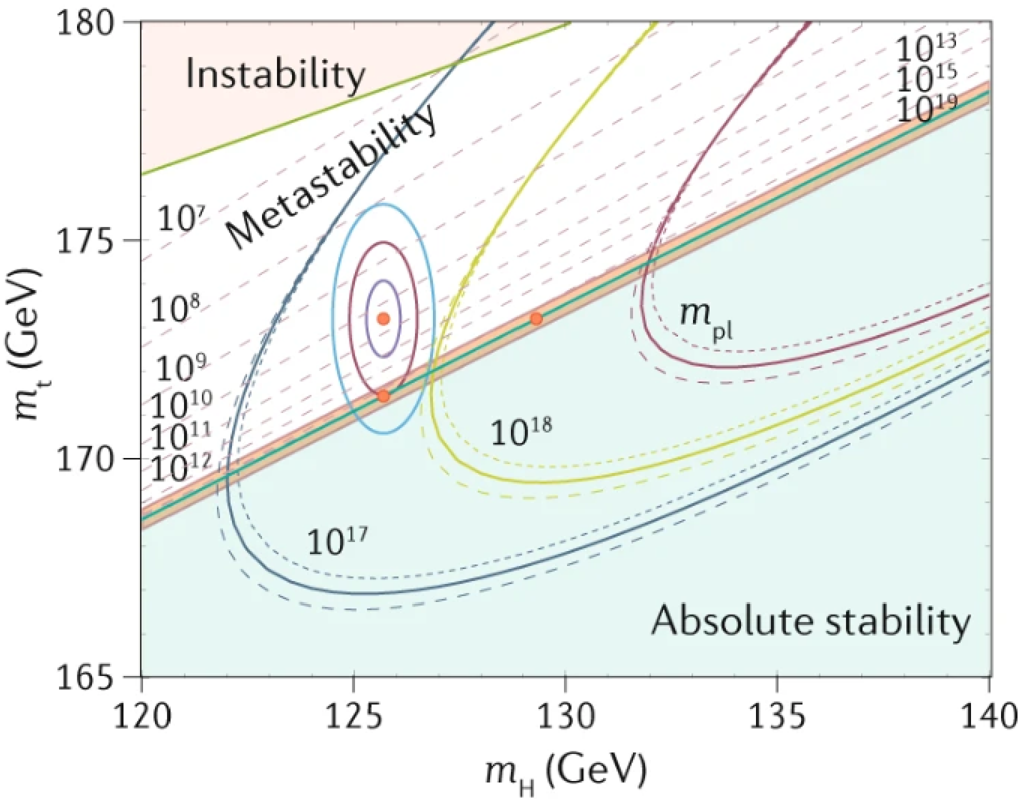




Cosmological implications of the Higgs boson mass

- BSM physics to stabilise vacuum during inflation?
- Non-minimal coupling of Higgs with gravity?
  - Possibly detectable impact primordial gravitational wave spectrum

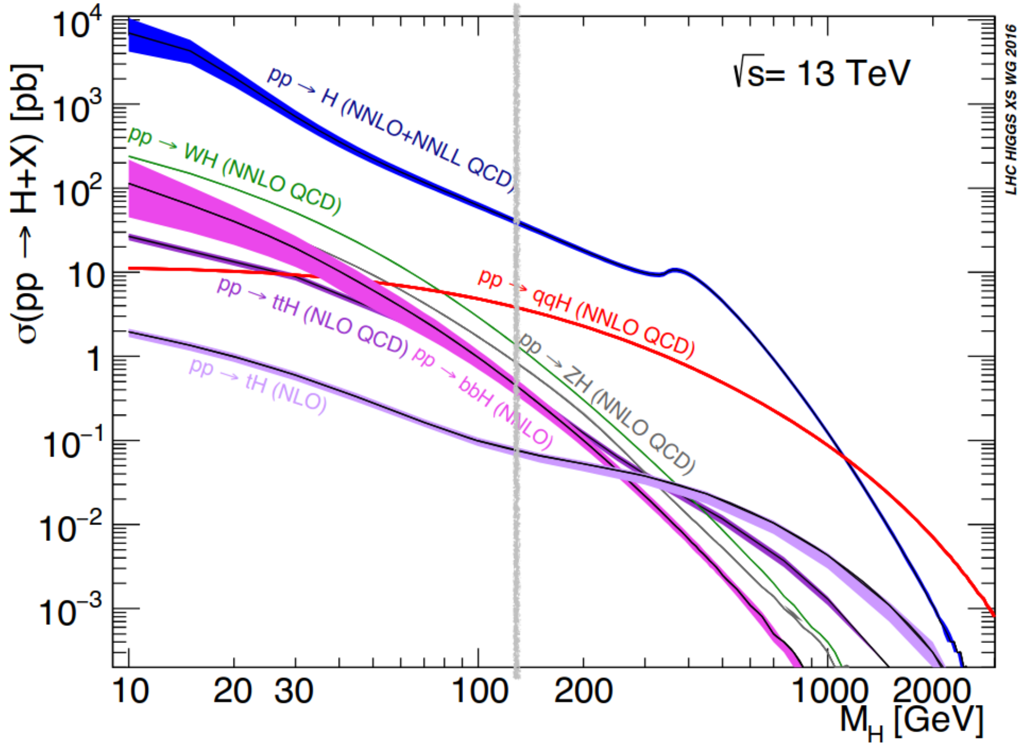


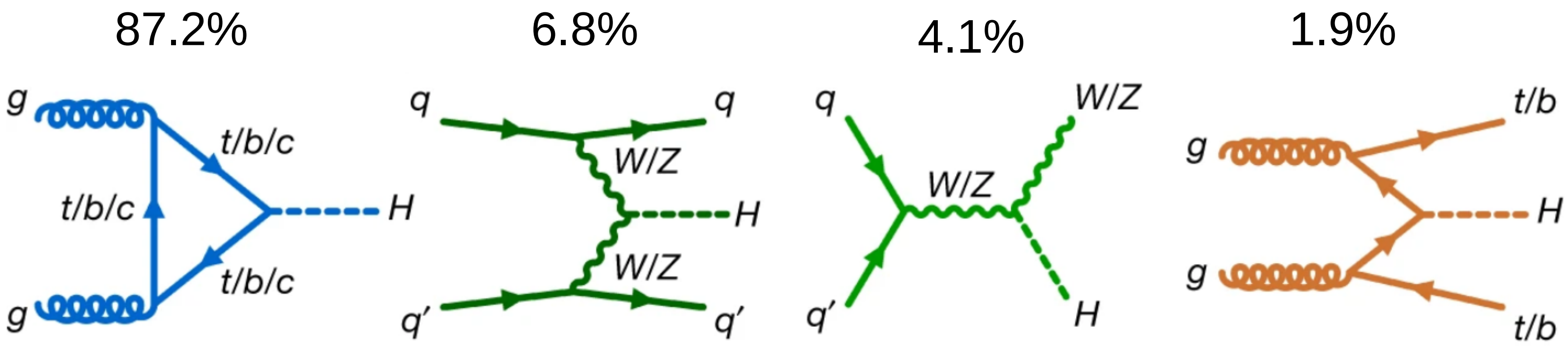


Implication of the Higgs boson mass for production and decay

> Production rates fixed for a given value of m_h

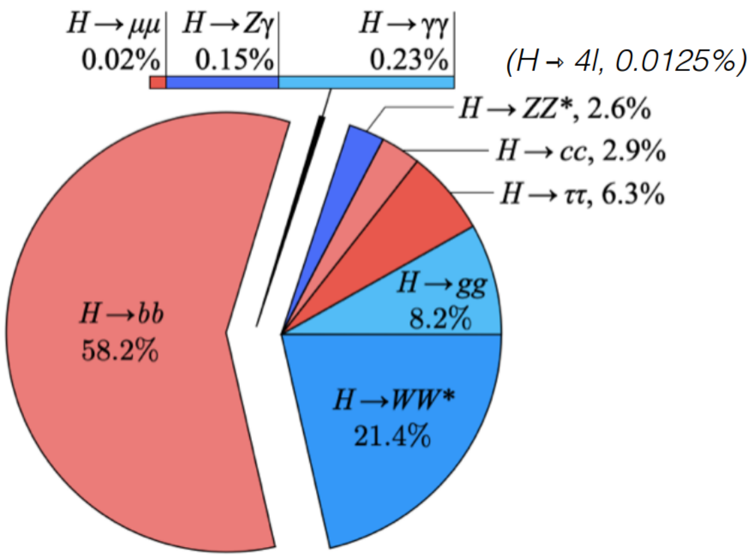
> Dominant production mode: gluon fusion

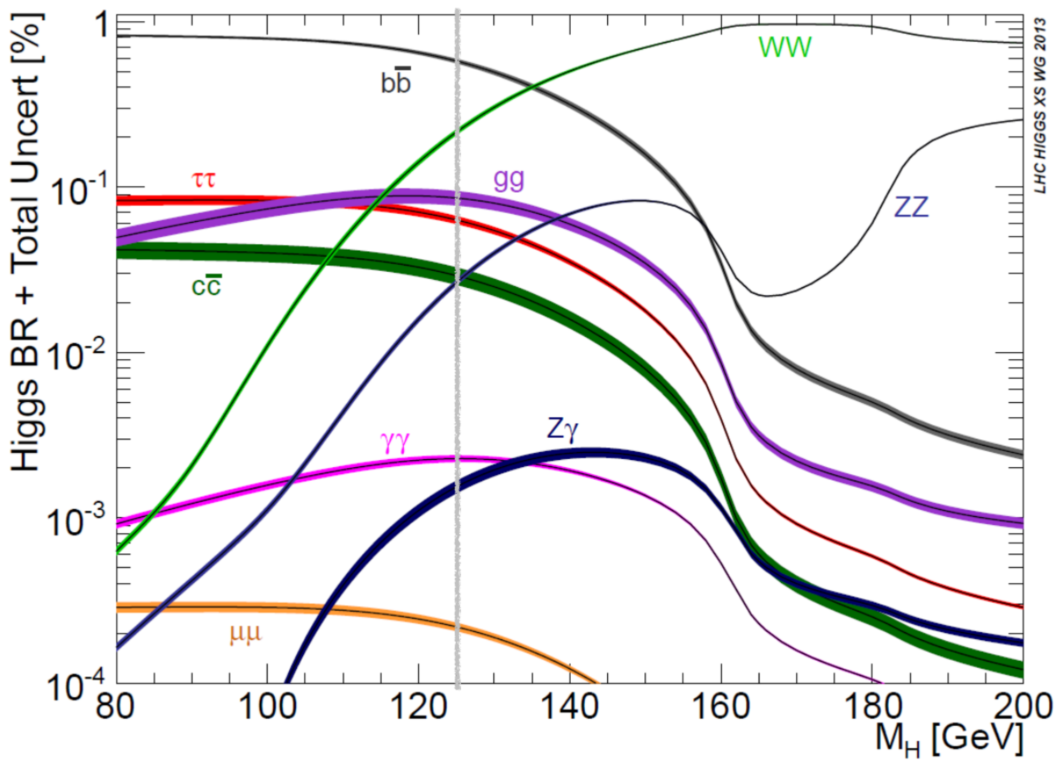


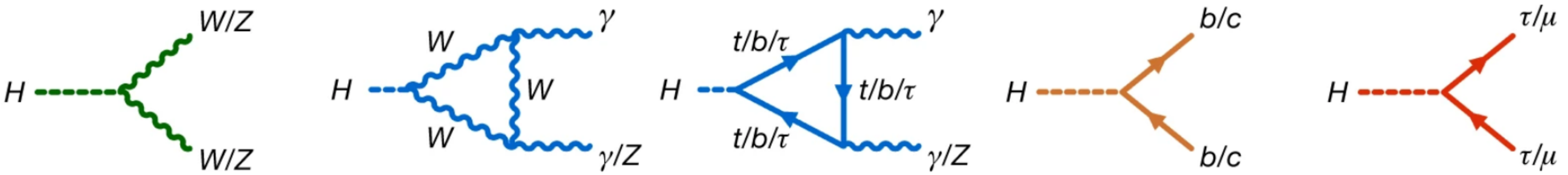


Implication of the Higgs boson mass for production and decay

- Decay rates fixed for a given value of m_a
- Assuming SM Yukawa couplings
- Dominant decay mode: h → bb







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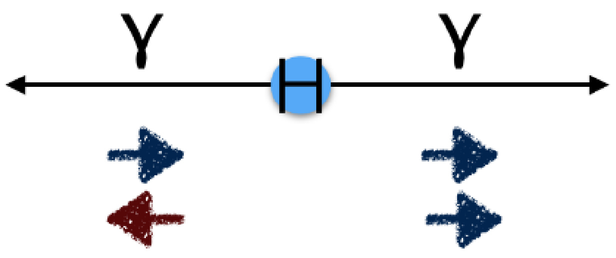
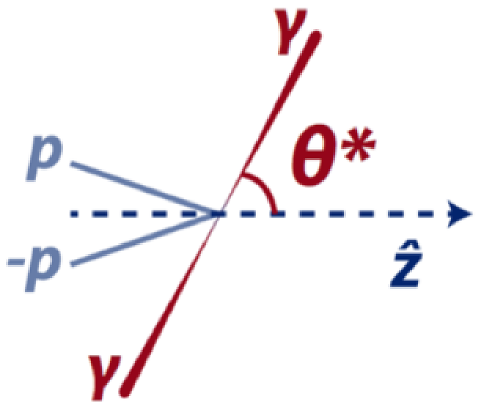
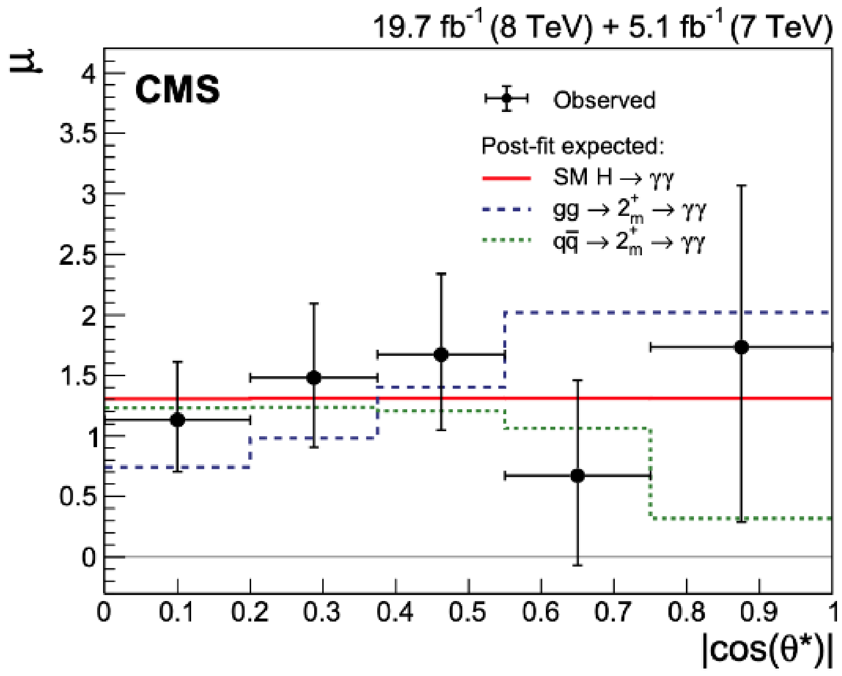
Higgs boson spin

- Spin 1 excluded by the fact that Higgs decays into photons
  - Landau-Yang theorem:
    - Spin-1 particle (J_z = 0, ±1) cannot decay into two identical massless spin-1 particles (J_z = ±1)
    - Direct consequence of angular momentum conservation and Bose symmetry
- Spin 2 excluded for a number of different tensor structures (~ 99.9%)
- Spin 0 as predicted for the SM Higgs

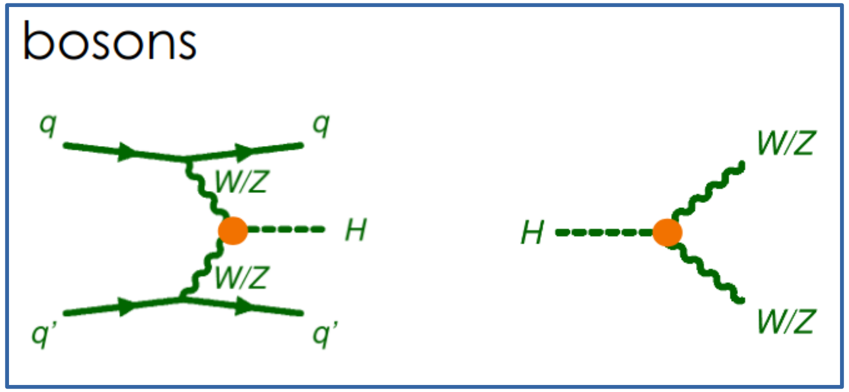


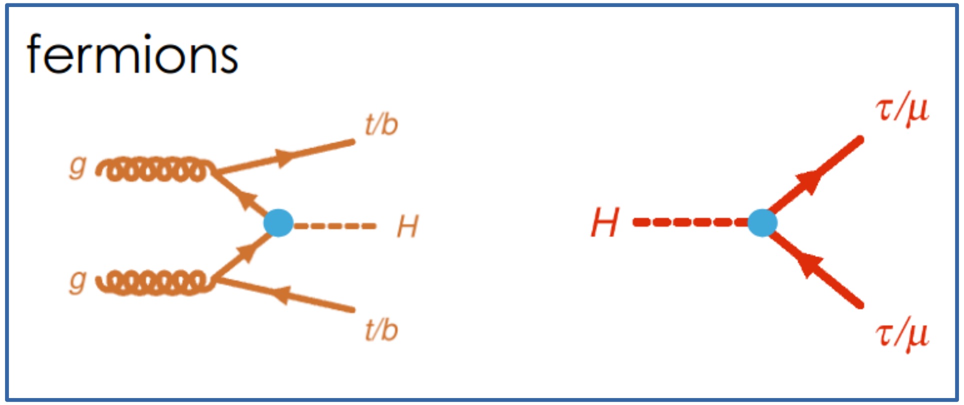




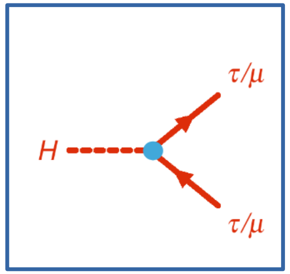
Higgs CP properties

- Measure CP properties of Higgs couplings to different SM particles
- Separately for bosons and fermions



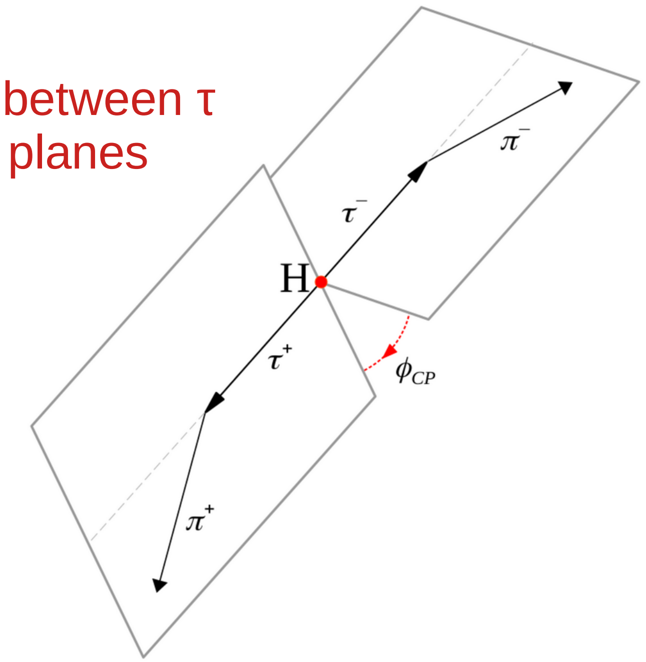


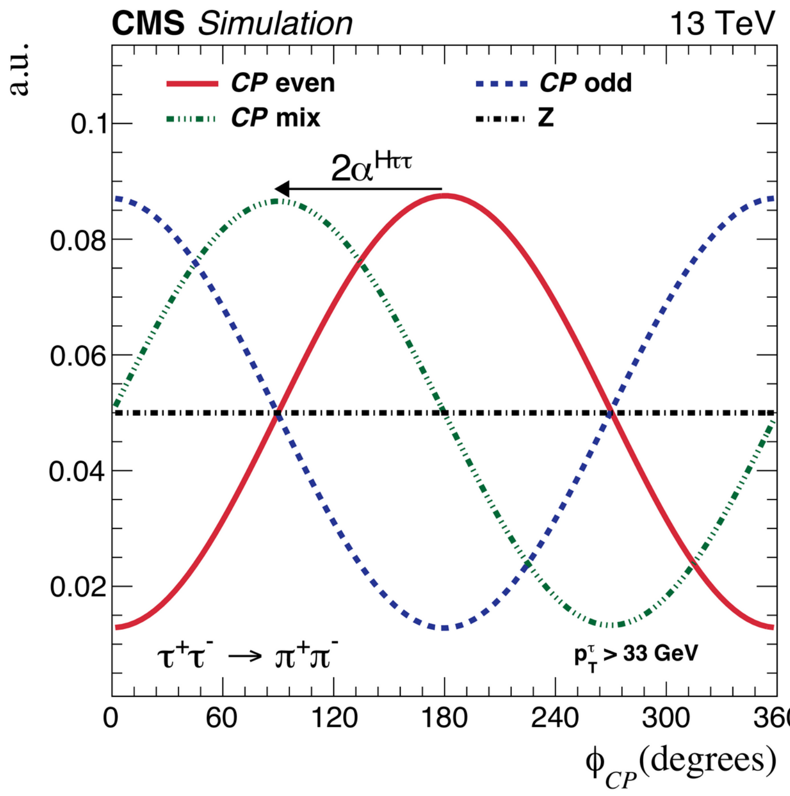
Example: CP properties of decay to τ leptons



- Idea: Higgs CP state determines correlations between τ-lepton spins
- Spin information about τ leptons from angle between τ leptons and visible decay product (e.g. $\pi^{\pm}$)
- Angle ϕ^{CP} sensitive to Higgs CP state

Angle between τ decay planes





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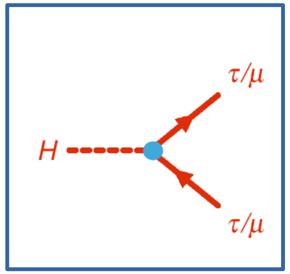

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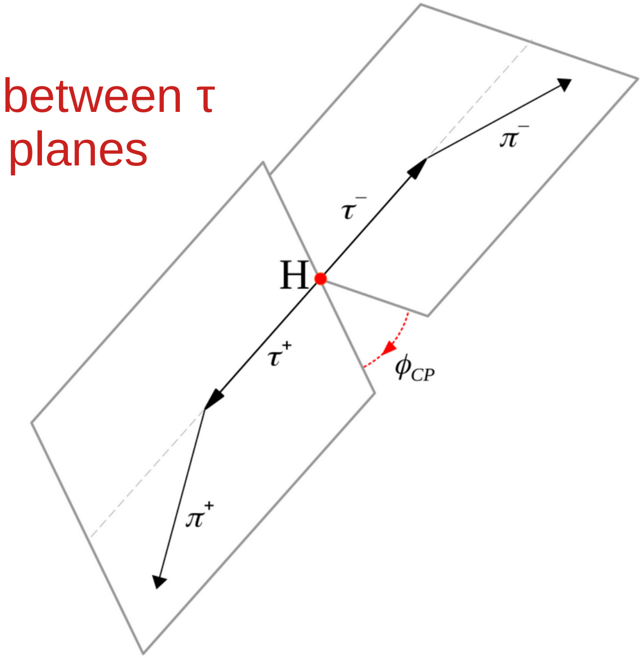

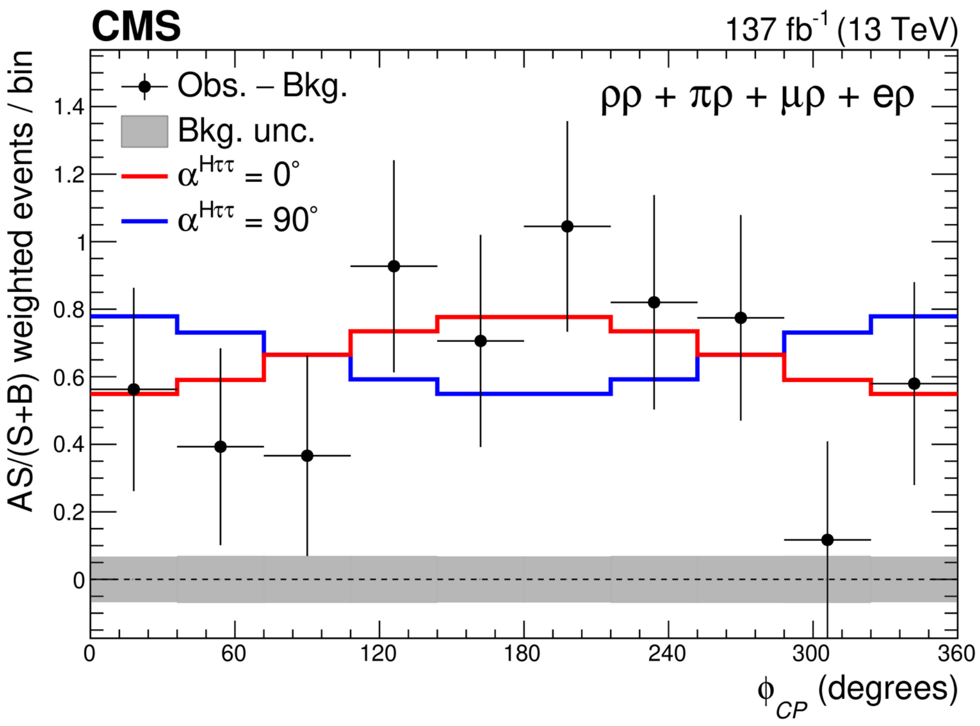

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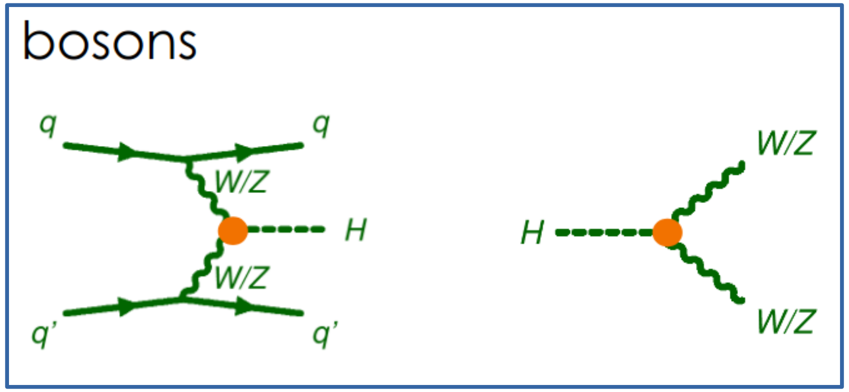

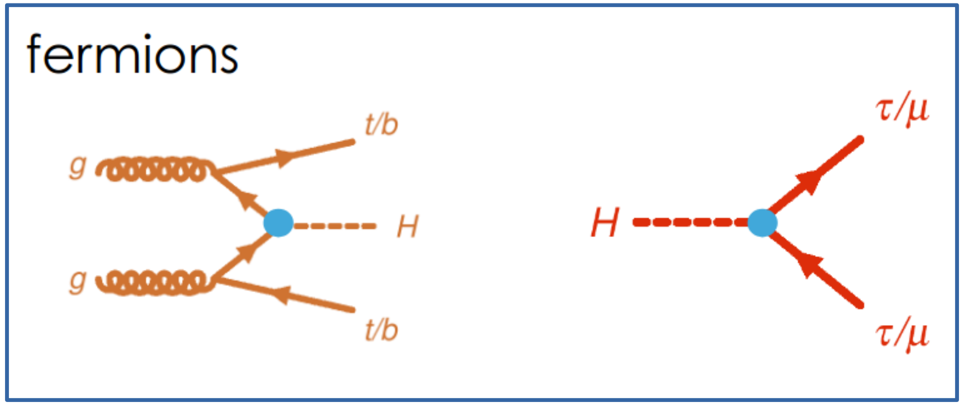

- **Results:**
  - Pure CP odd Higgs coupling to bosons excluded at > 99.9% (ATLAS, CMS)
  - Pure CP even Higgs coupling to fermions excluded with > 3 sigma
  - Admixtures (CP even and CP odd couplings) still possible

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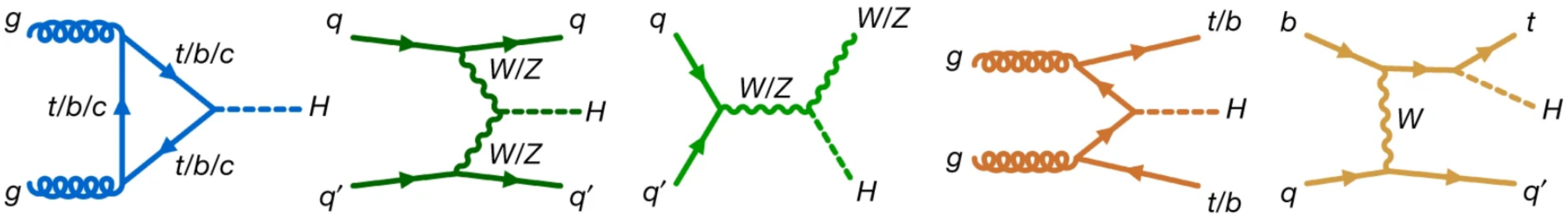
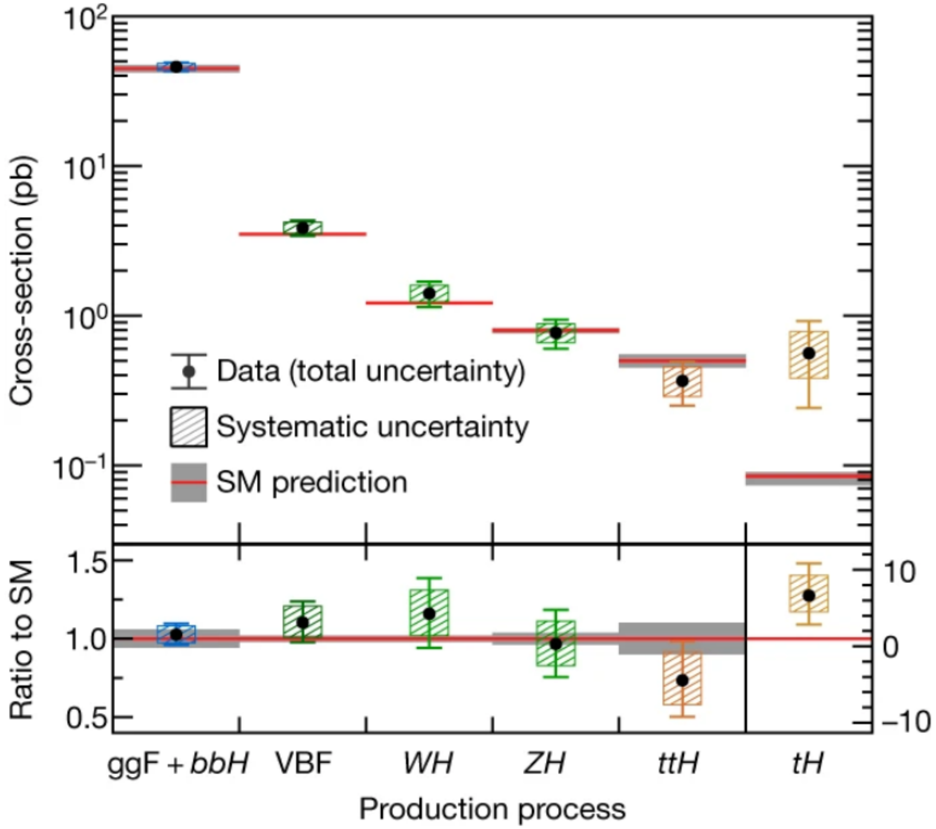
Higgs boson production measurements



> Each has a particular final state in addition to the Higgs decay
  - VBF: 2 forward jets
  - VH: 2 leptons from vector boson
  - ttH: two top quarks

> Consider different possible Higgs decays to enhance sensitivity



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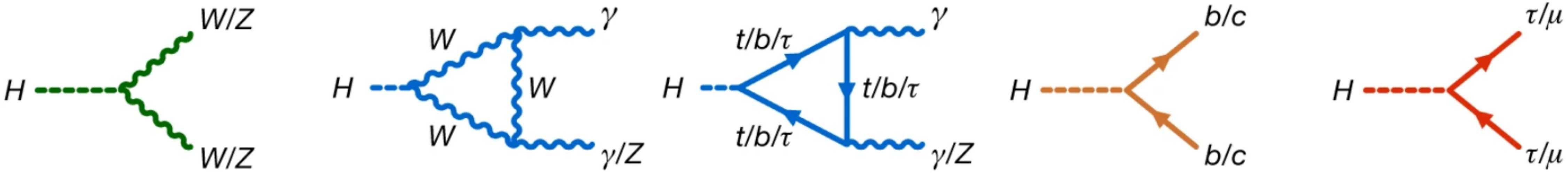
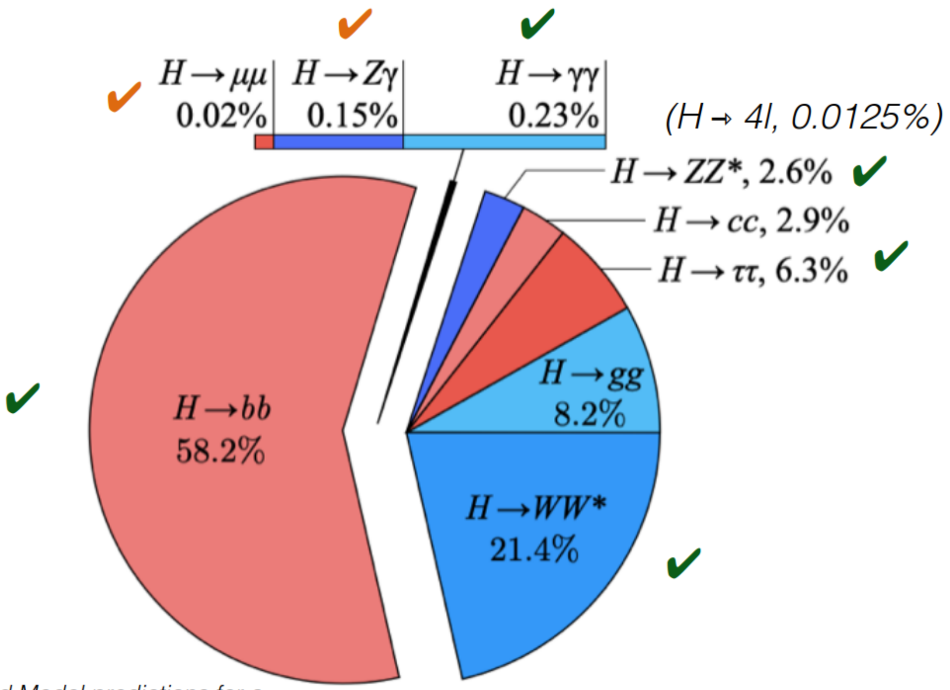
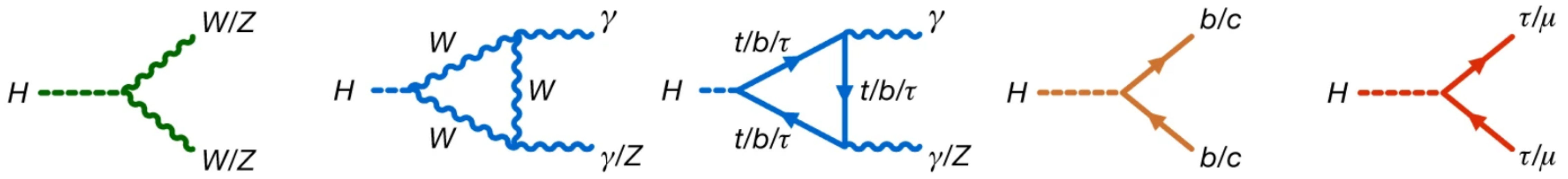


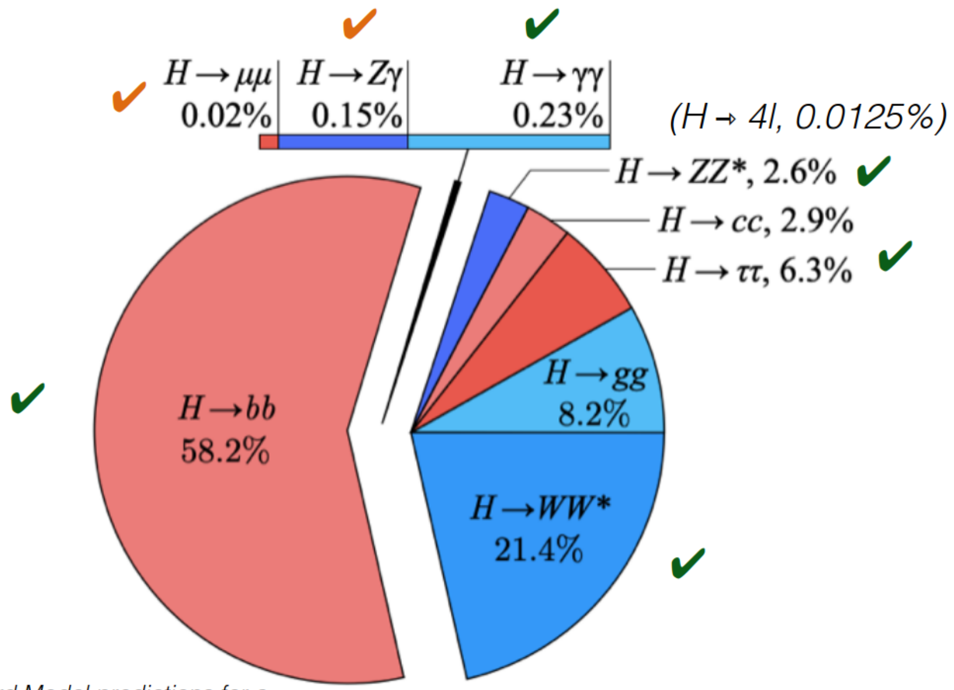


(Standard Model predictions for a Higgs boson with mass 125 GeV)

- Discover each decay mode with >5σ
  - Can make use of all production modes
- Measure as precisely as possible and compare with SM predictions

Higgs boson decay measurements



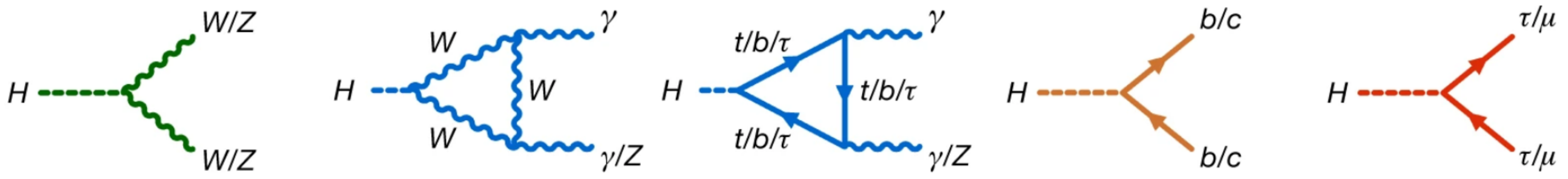


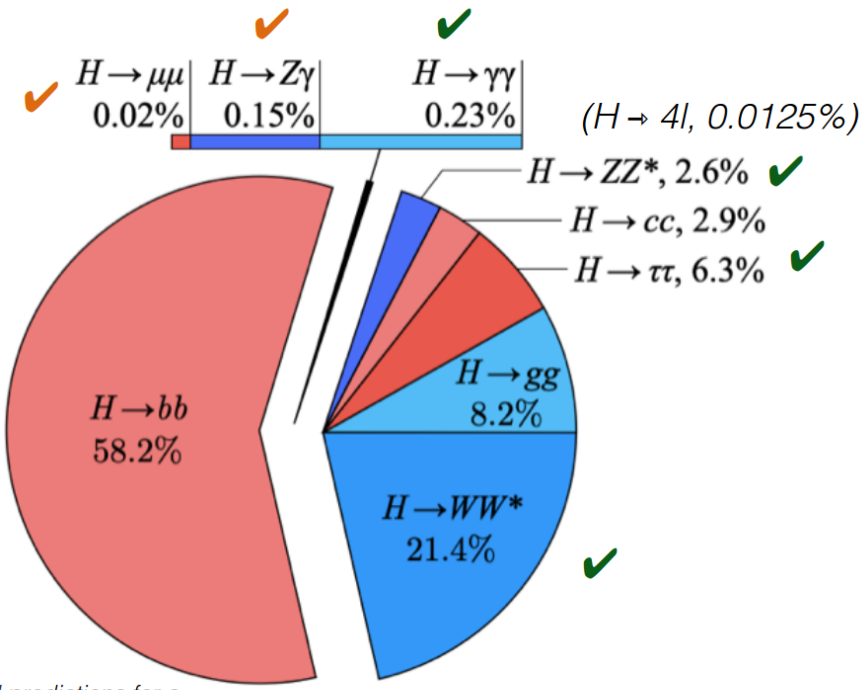
(Standard Model predictions for a Higgs boson with mass 125 GeV)

> Discover each decay mode with >5σ
  - Can make use of all production modes
> Measure as precisely as possible and compare with SM predictions

Quiz question:
Which of the observed decay modes (green tick marks) was discovered last?

Higgs boson decay measurements





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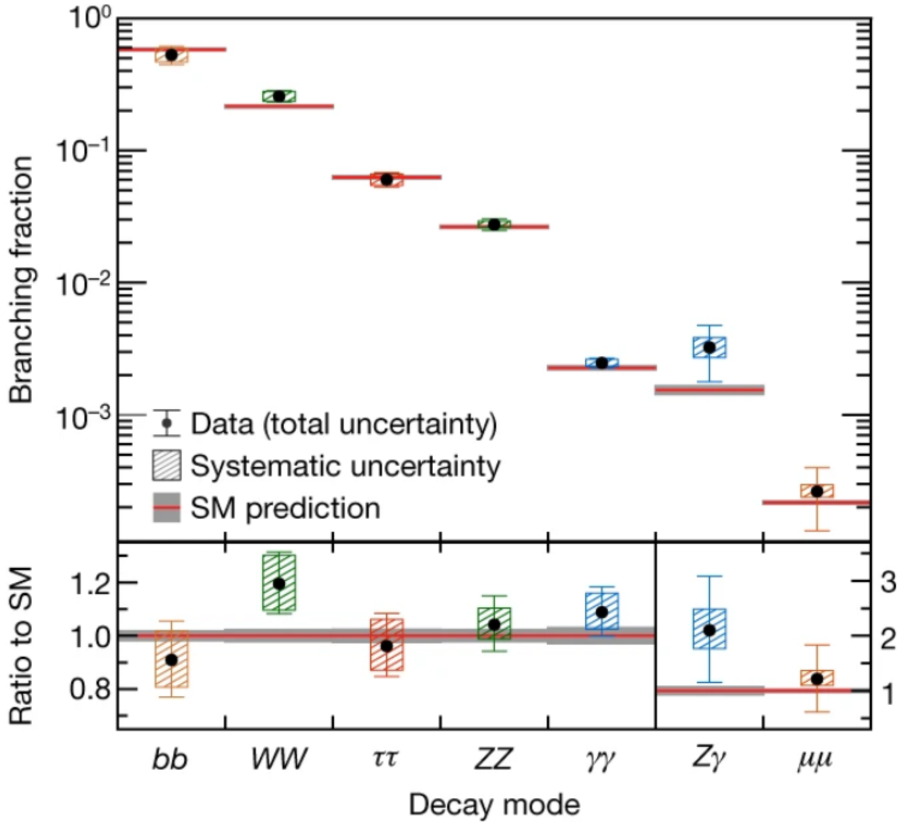


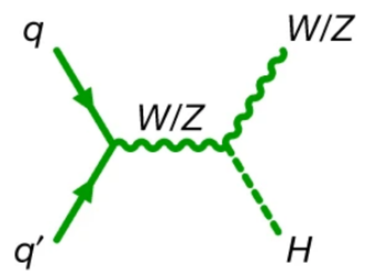
Example: discovery of *h* → *bb* (2018)

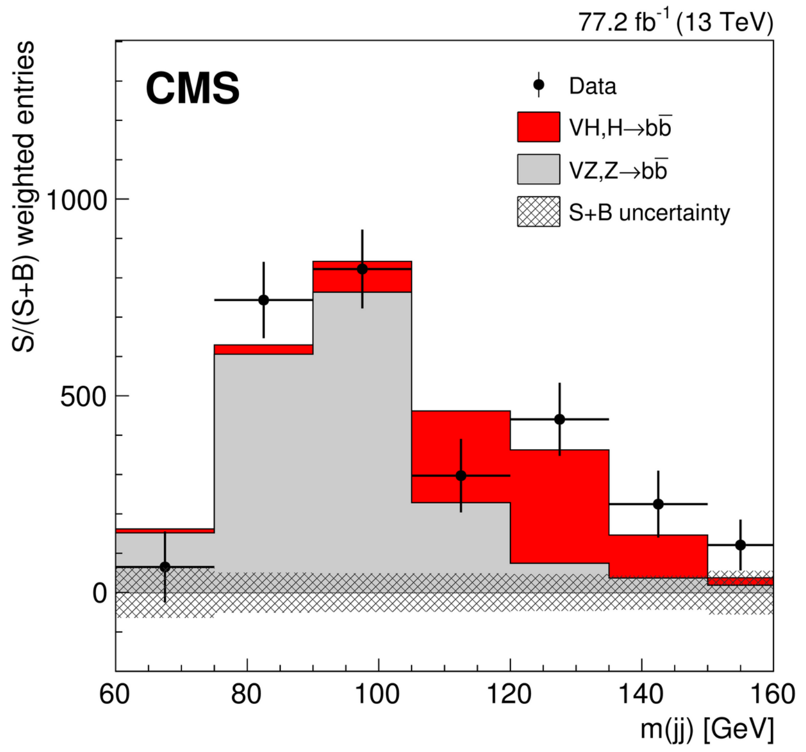
> Latest decay mode to fermions to be discovered, despite largest branching ratio
  - Important because it probes couplings to third generation down-type fermion

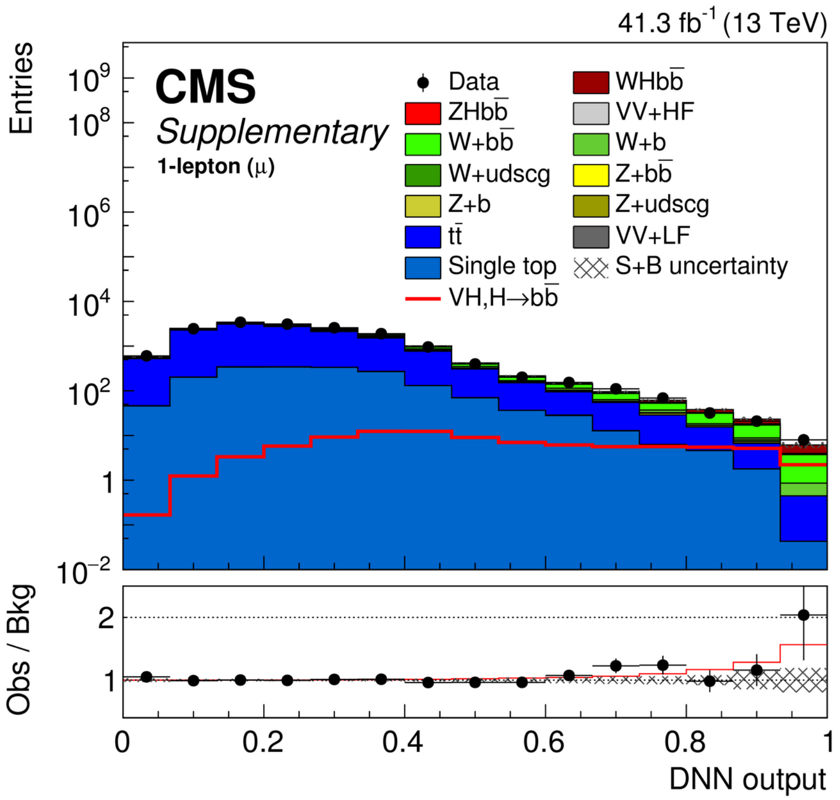
> Challenge: hadronic final state at LHC → large background from QCD multijet production

> Target Zh, Wh production with leptonically decaying boson to suppress QCD background

> Background still challengingly large → extensive use of ML (deep neural nets)

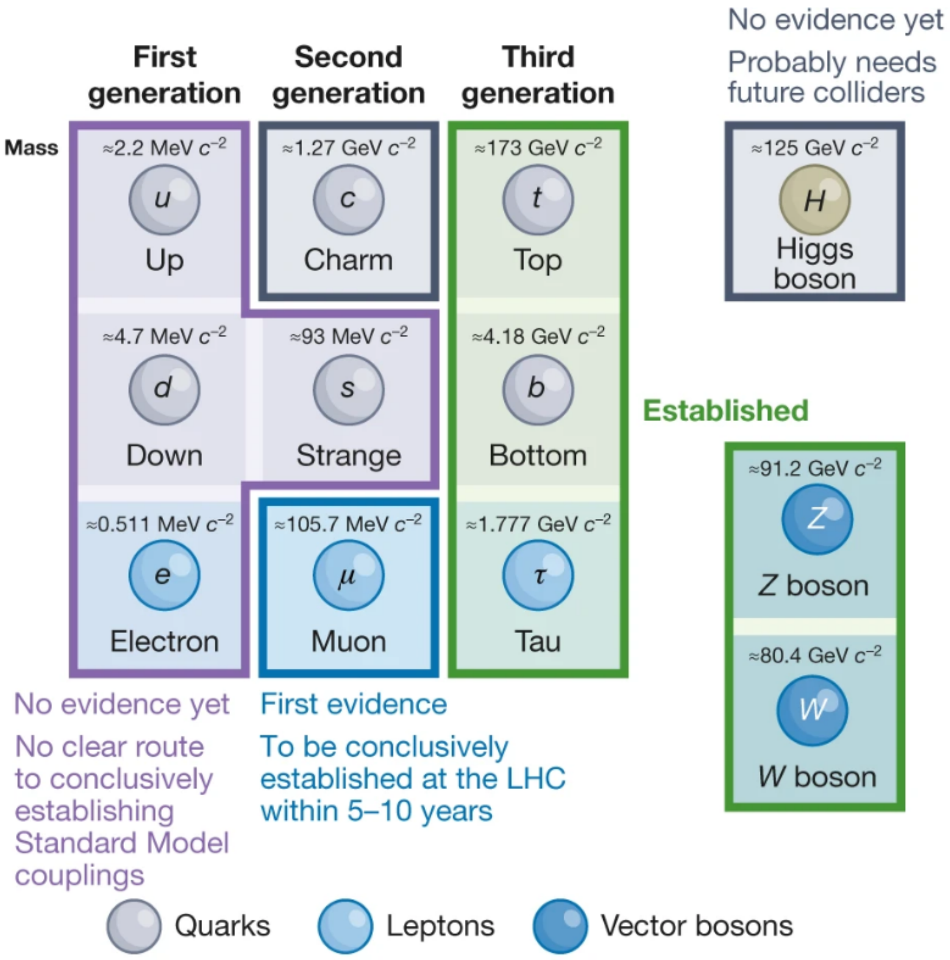


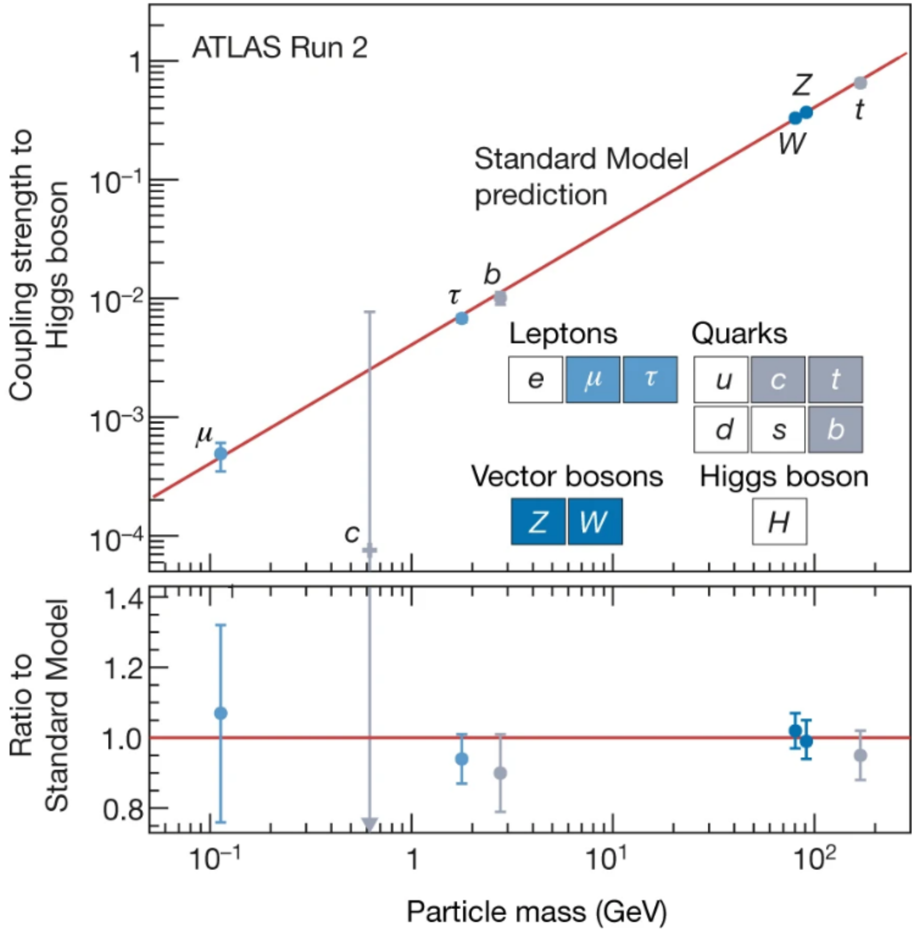




Higgs boson decay summary

> Good agreement with the SM prediction… within current precision





Invisible decays of the Higgs boson

> Higgs boson does not couple directly to neutrinos in the SM

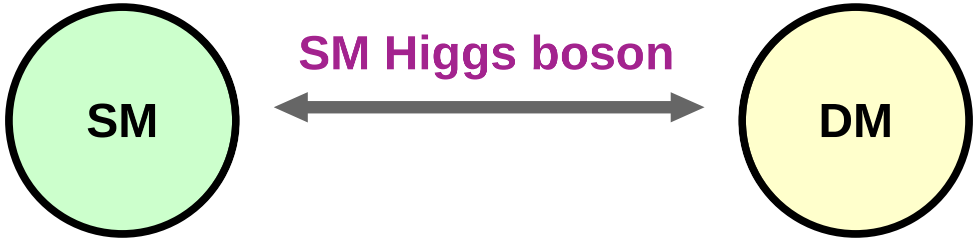
Quiz question:
Can you think of another possibility how the Higgs boson can decay invisibly in the SM?

Invisible decays of the Higgs boson

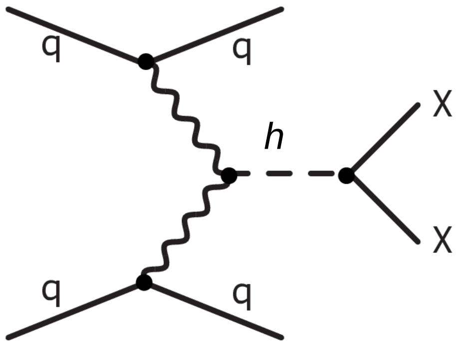
> Higgs boson does not couple directly to neutrinos in the SM
> Invisible decays in the SM: $h \rightarrow ZZ^* \rightarrow 4\nu$
> Tiny branching ratio: $BR(h \rightarrow inv) = 0.1\%$

Invisible decays of the Higgs boson

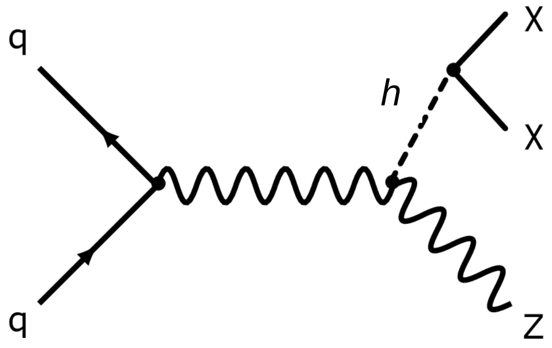
- Higgs boson does not couple directly to neutrinos in the SM
- Invisible decays in the SM: $h \rightarrow ZZ^* \rightarrow 4\nu$
- Tiny branching ratio: $BR(h \rightarrow inv) = 0.1\%$
- Could be significantly increased if the Higgs boson is a portal to DM → direct decays to DM!



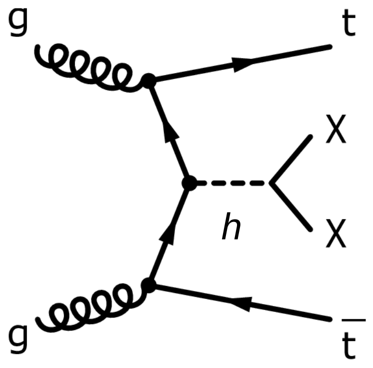
Production modes in h→inv searches



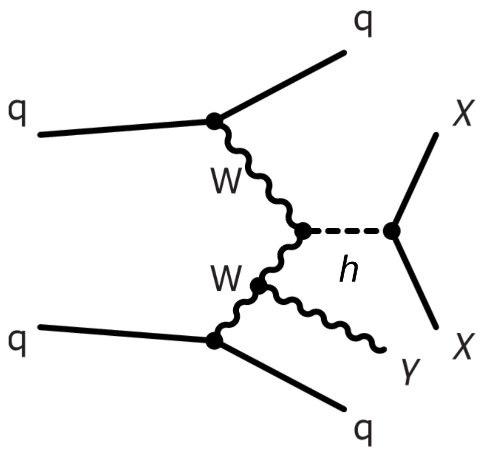
Vector-boson fusion (VBF)



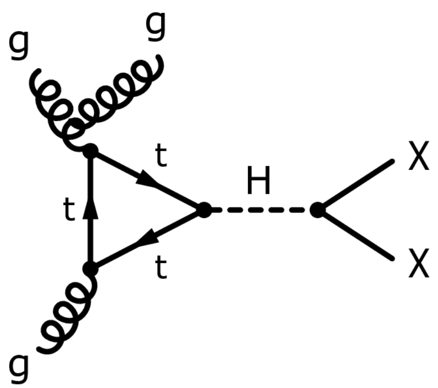
Higgs strahlung (Zh)



Top-quark associated (tth)

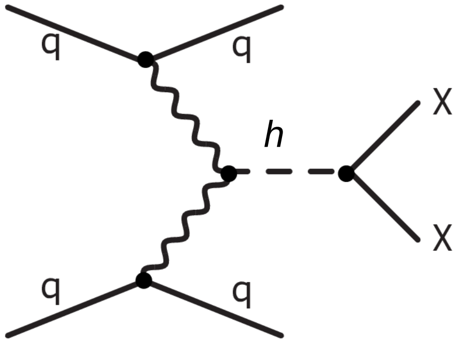


VBF + photon

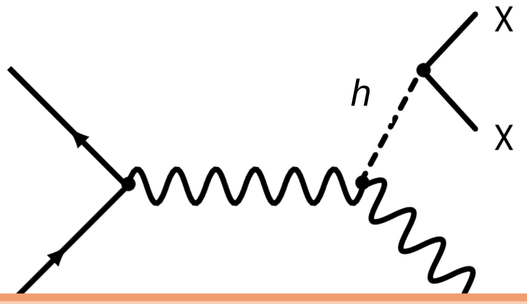


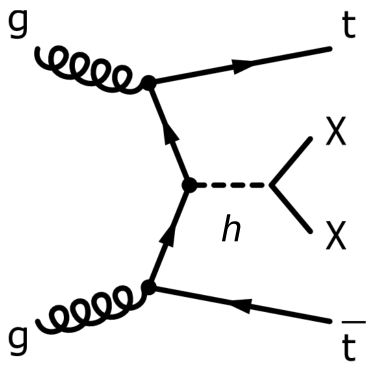
Gluon fusion

Production modes in h→inv searches



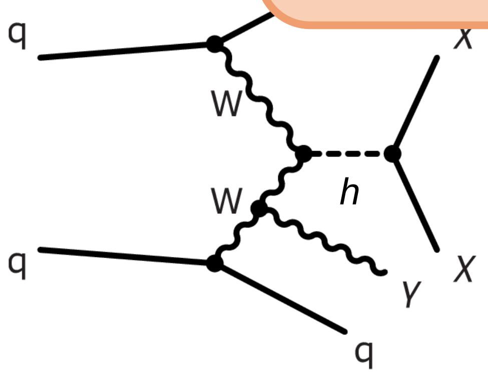
Vector-boson fusion (VBF)



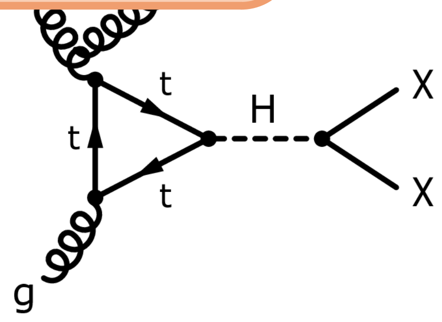


Top-quark associated (tth)

Quiz question:
Which production mode do you expect to be most sensitive to h→ inv decays?

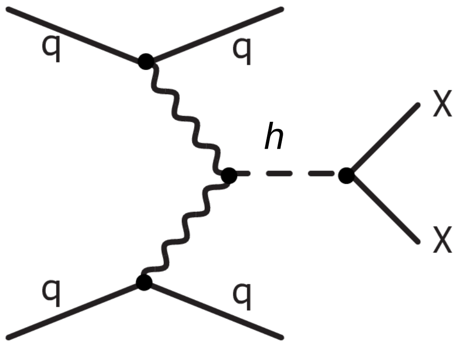


VBF + photon

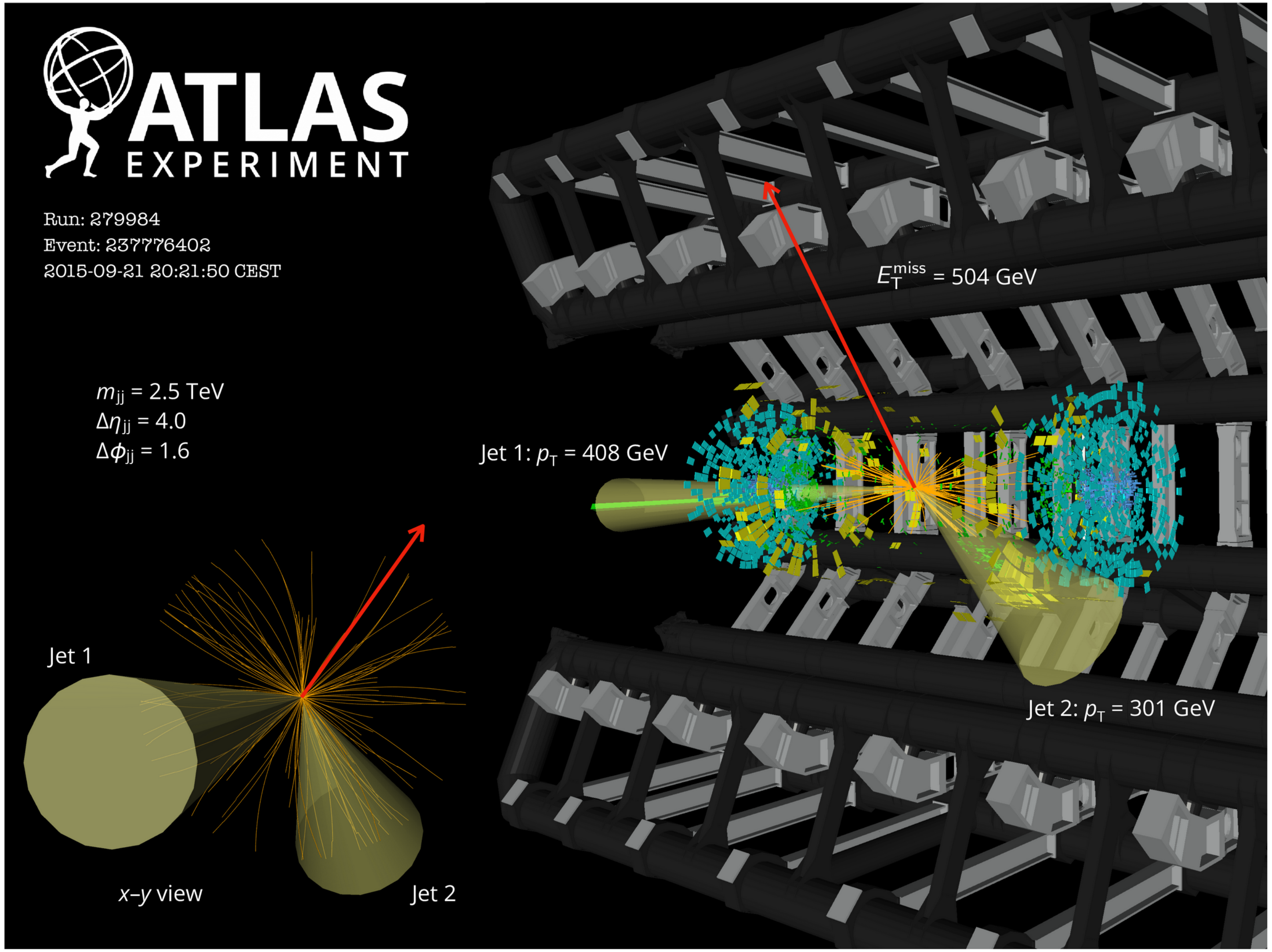


Gluon fusion

Vector-boson fusion production of h → inv



Vector-boson fusion (VBF)

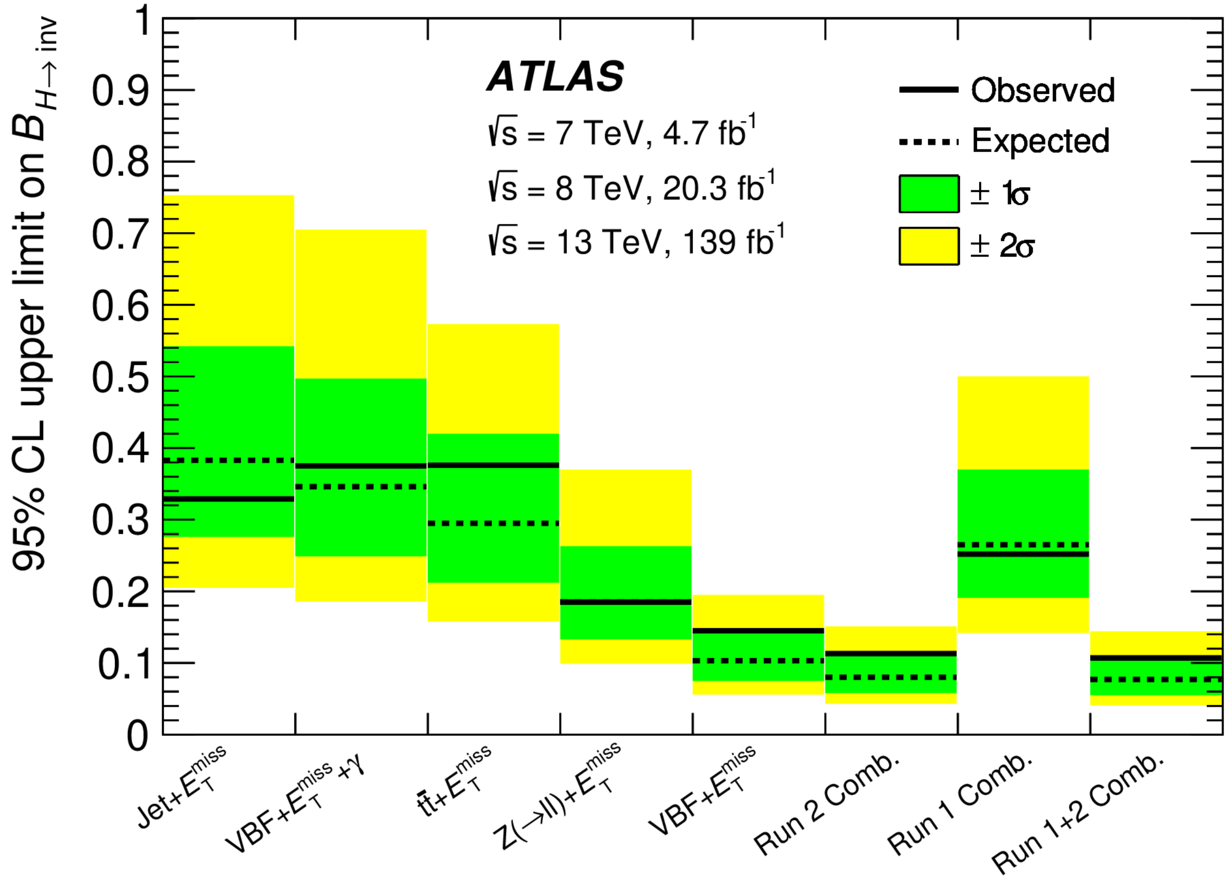


Statistical combination of h → inv searches

Phys. Lett. B 842 (2023) 137963

> Combine results from different production modes for optimal sensitivity

> Additionally: results on at $\sqrt{s}$ = 7 and 8 TeV data included in previous Run-1 combination



BR(h → inv) < 0.107 ($0.077^{+0.030}_{-0.022}$)

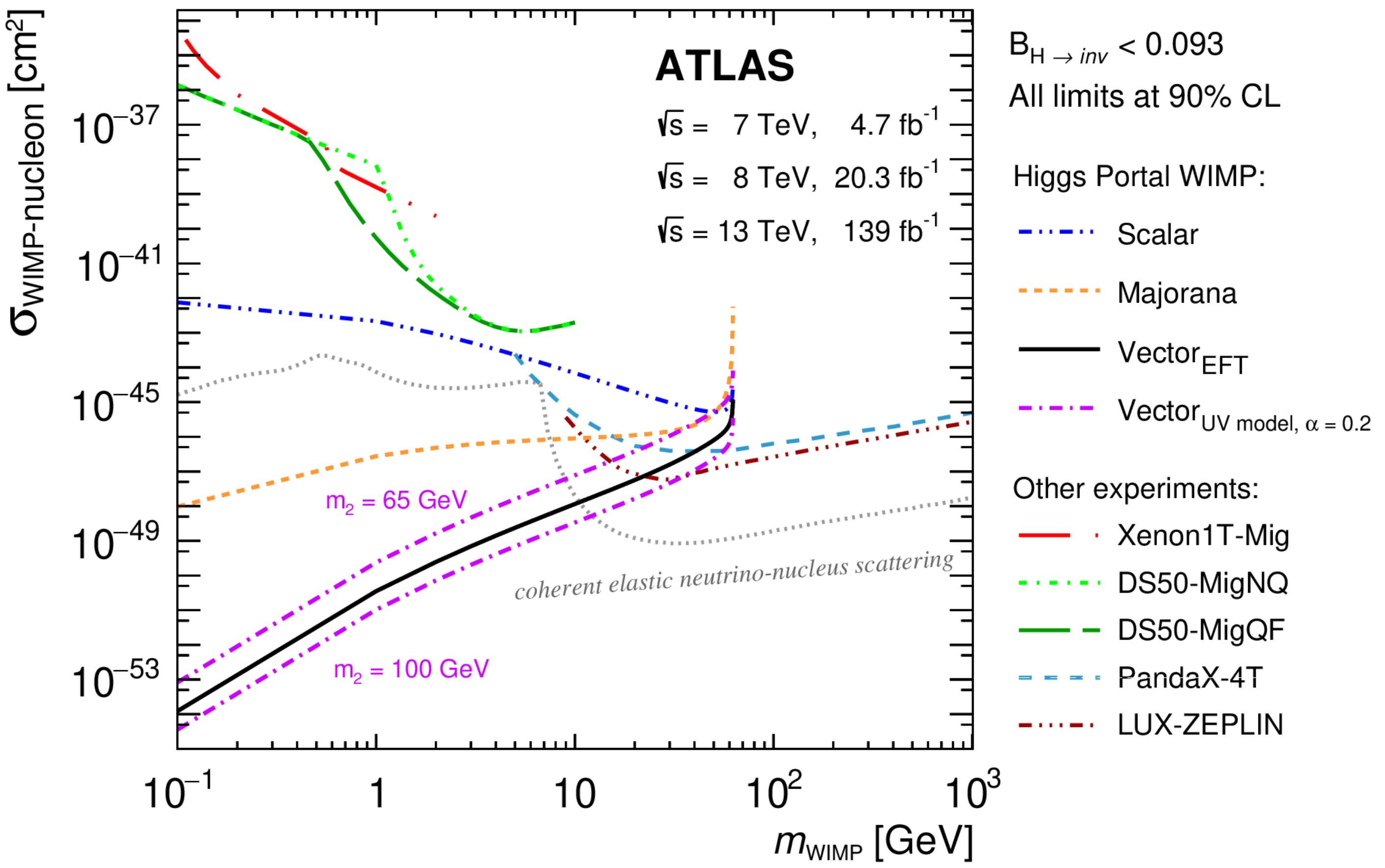
at 95% CL

Statistical combination of h → inv searches

Phys. Lett. B 842 (2023) 137963

> Interpretation in different Higgs Portal WIMP models (Scalar, Majorana, Vector)

> Complementary constraints to direct detection results for WIMP masses < 0.5 Higgs mass



Higgs Part 1: Summary

> Discovery of a Higgs boson by the ATLAS and CMS collaborations at the LHC in 2012

> Significant progress in characterising the new particle:

- Mass measured to be ~125 GeV with < 1 permille precision
- Measured Higgs boson properties, like spin, cross sections and decay branching ratios
- So far, all results consistent with SM predictions within current precision

> Key missing piece of information: full shape of the Higgs potential

- Tomorrow's lecture!

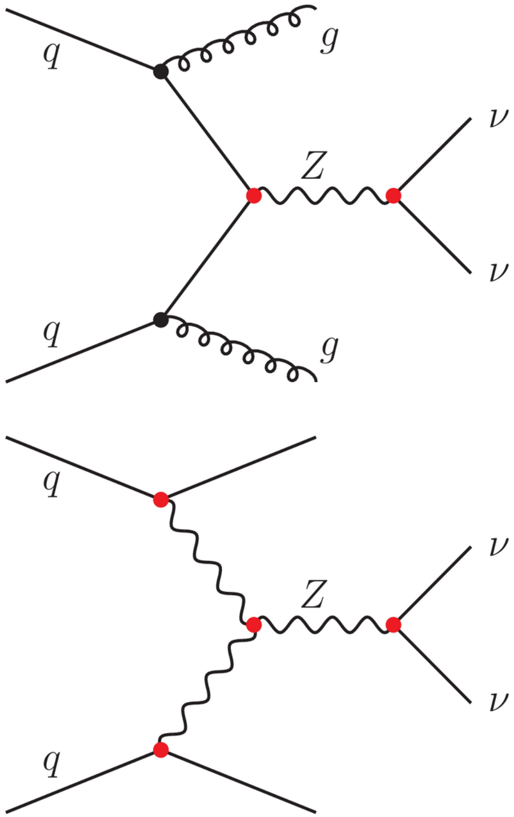
BONUS SLIDES

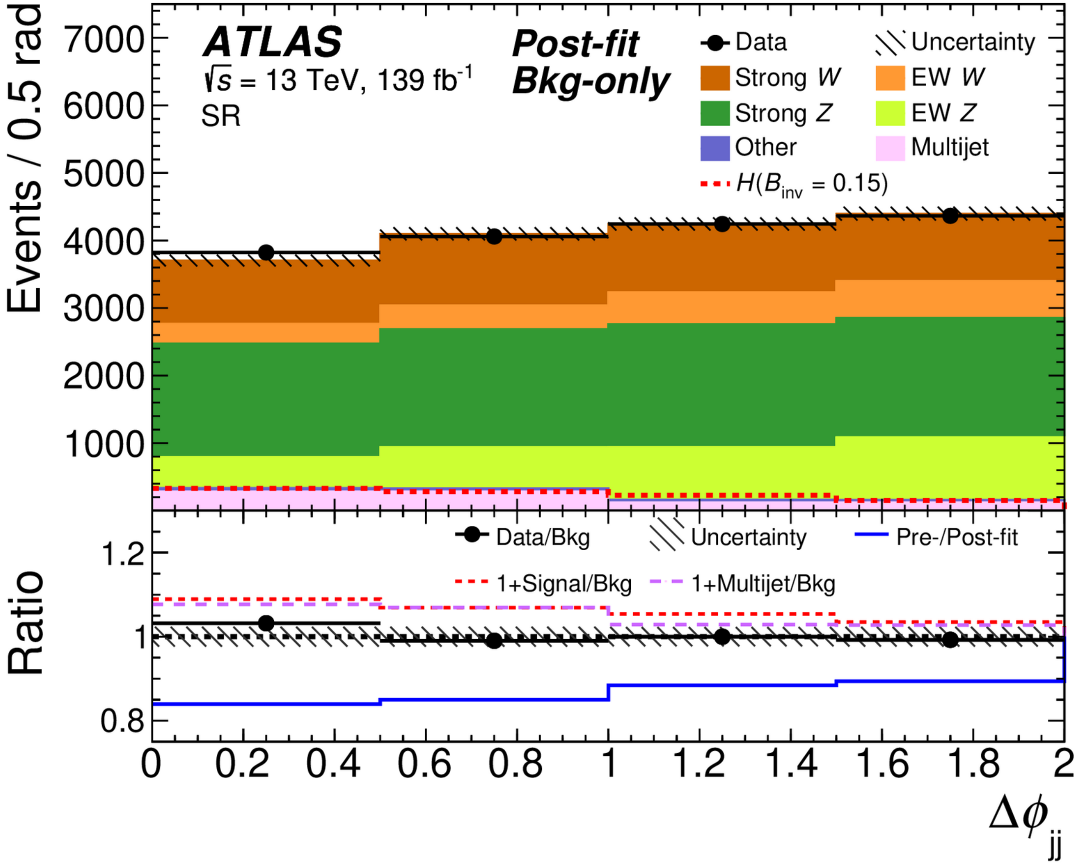
Vector-boson fusion production of h → inv

- Main background from Z(νν)+jets production
- Further background from W(lν)+jets production where lepton was not correctly identified
- Both processes poorly modelled in simulation → data-driven estimate

Strong *Z*

EW *Z*





Vector-boson fusion production of h → inv

> Combined fit to various signal-enriched regions and regions enriched in Z+jets and W+jets

> Use Z(ll)+jets events to estimate Z(νν)+jets background (same production mode, same kinematics)

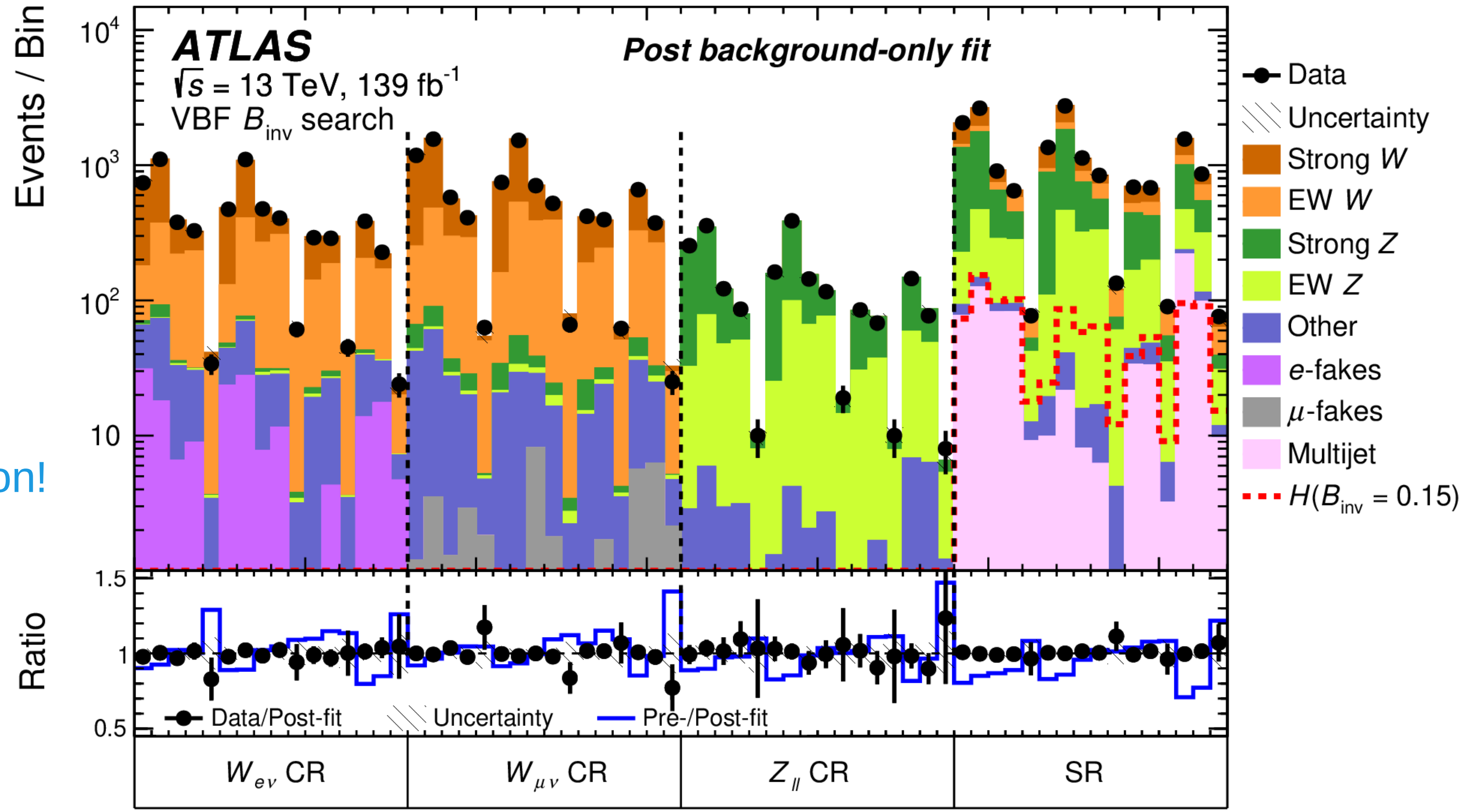
> Problem: low statistical power of Z(ll) CR

> Trick: use W(lν) CR in addition

> Requires accurate estimate of ratio of + jets and + jets cross sections

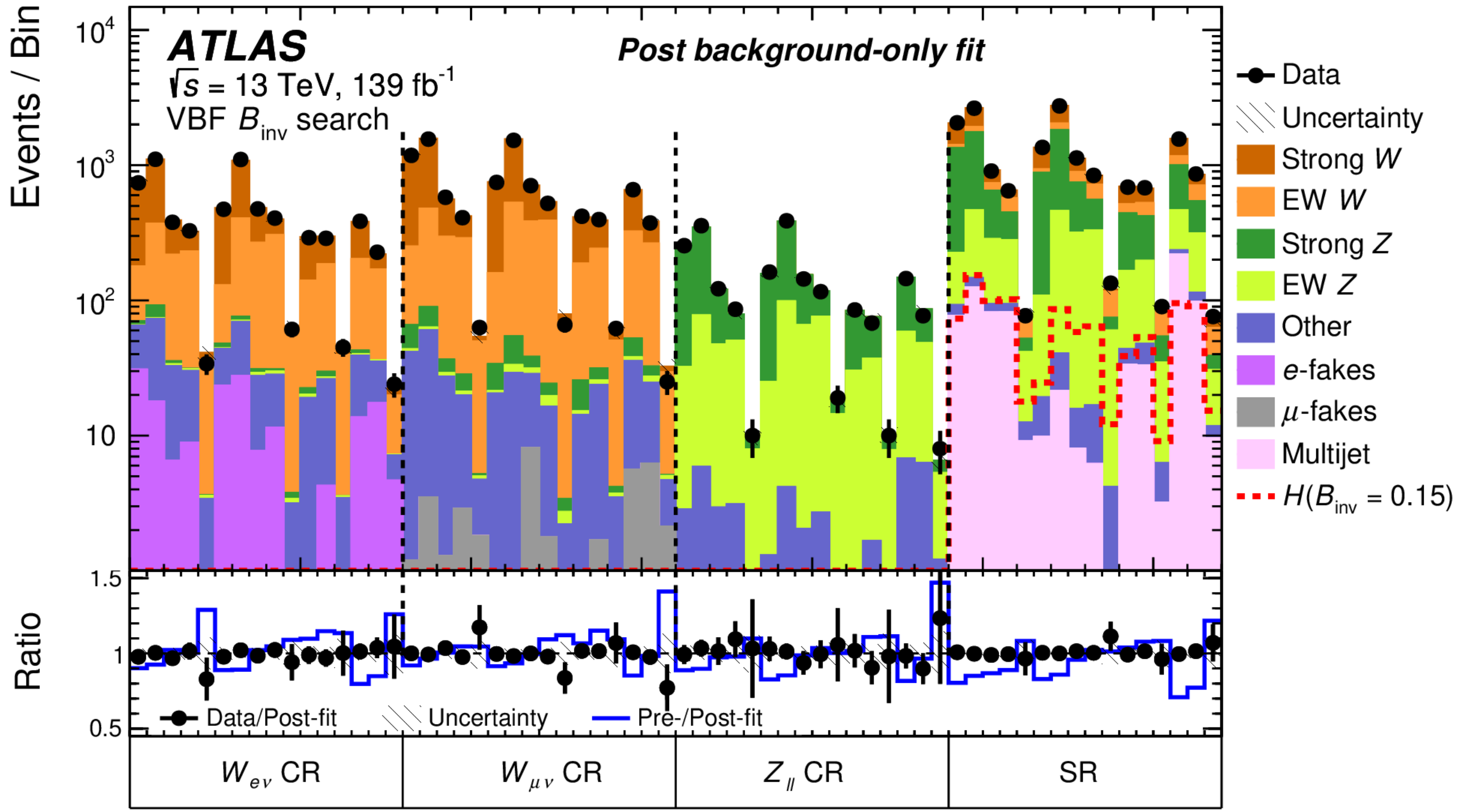
> Provided by dedicated calculation at NLO-QCD + NLO-EW precision derived in the phase of the search

> Fruitful theory-experiment cooperation!



Vector-boson fusion production of h → inv

> $BR(h \to inv) < 14.5\%$ observed ($10.3\%^{+4.1\%}_{-2.8\%}$ expected) at 95% CL



The LHC today

- LHC Page 1: https://op-webtools.web.cern.ch/vistar/vistars.php
- Collisions at new record energy of 13.6 TeV started on 5th July!

Matter-antimatter imbalance

> Equal amounts of matter and antimatter created in the Big Bang (B=0)

> Observable universe completely dominated by matter (B>0)

> What caused this imbalance?

> **Sakharov conditions**

1. Baryon number violating processes
2. C and CP violation
3. Processes out of thermal equilibrium

- Possible in the SM and BSM models
  - E.g. supersymmetry
- Not observed yet
  - Proton decay would be the smoking gun

Matter-antimatter imbalance

- Equal amounts of matter and antimatter created in the Big Bang (B=0)
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- **Sakharov conditions**

  1. Baryon number violating processes
  2. C and CP violation
  3. Processes out of thermal equilibrium

Conditions met in SM e.g. during EWSB

The strong CP problem (1)

- QCD can in principle violate CP (assuming all quarks are massive)
- Example of a Yang-Mills theory with a single massive quark

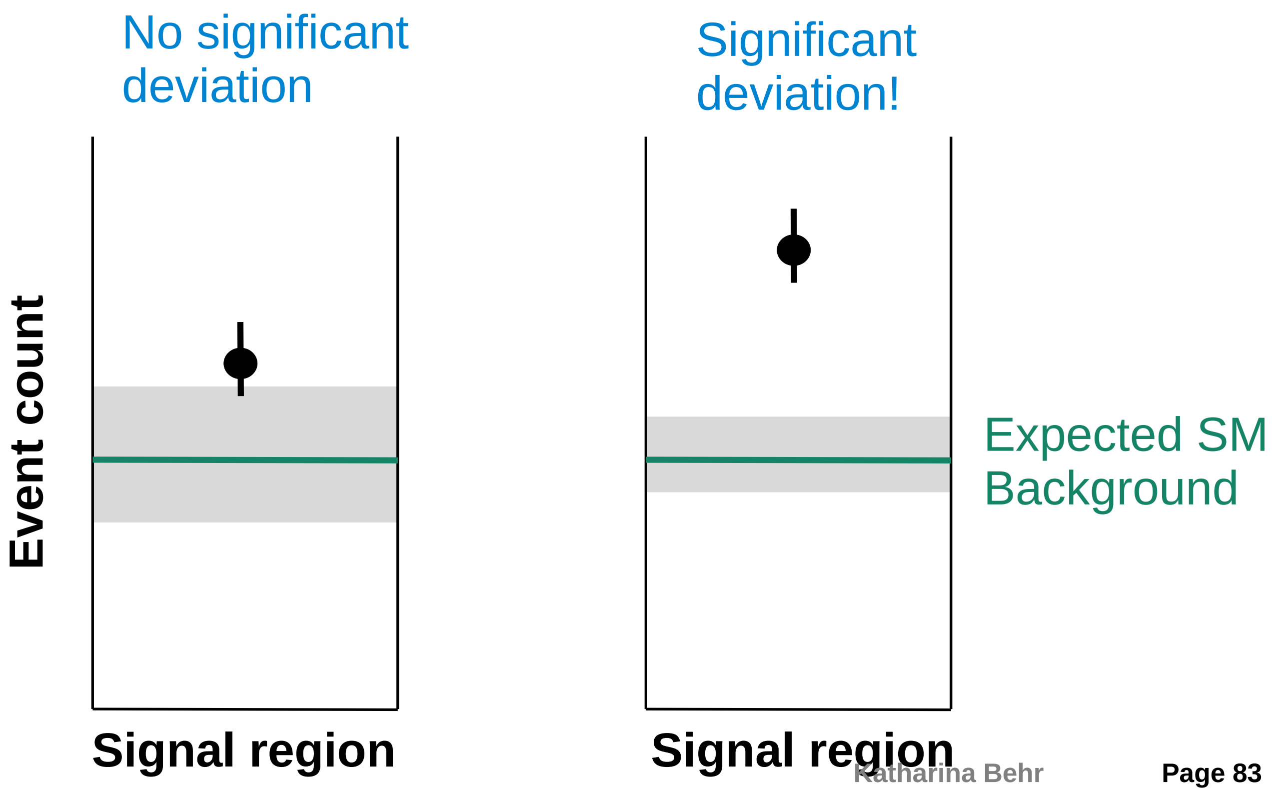
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{\theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}} + \bar{\psi}(i\gamma^\mu D_\mu - \boxed{me^{i\theta'\gamma_5}})\psi.$$

Potentially CP violating, unless $\theta = -\theta'$
→ fine-tuning!

- Strong CP violation in SM QCD (6 massive quarks) via equivalent phase θ^*
- Would imply non-zero neutron electric dipole moment: $d_N = (5.2\ 10^{-16}\ e\ \text{cm})\ \theta^*$
- Measurements constrain dipole moment to $|d_N| < 10^{-26}\ e$ cm → $\theta^* < 10^{-10}$ → fine-tuning!

Cut-and-count method

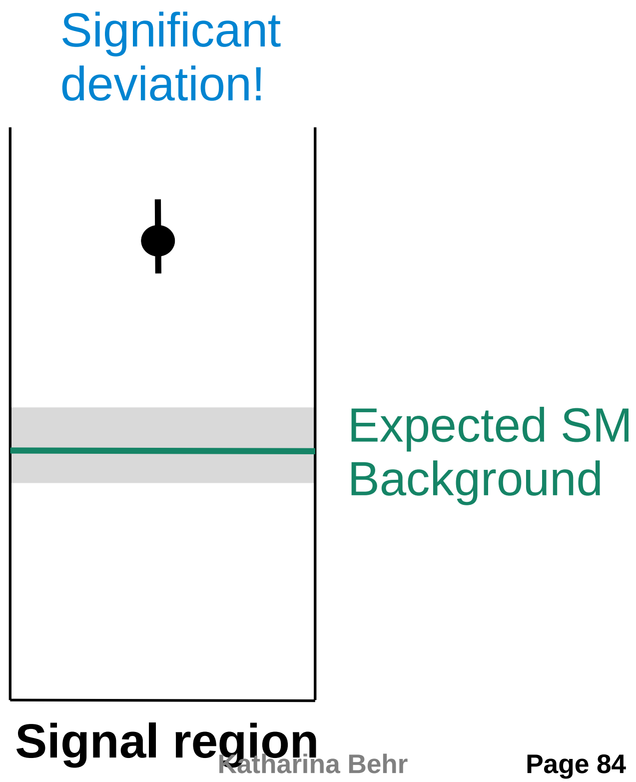
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)



Cut-and-count method

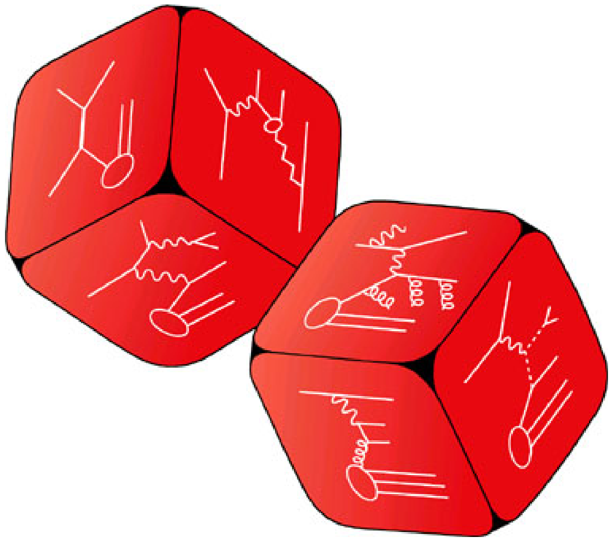
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)

- **Advantage**: suited for low-stat regions, model agnostic
- **Disadvantage**: single bin → vulnerable to fluctuations → less sensitive



Monte Carlo event generators in a nutshell

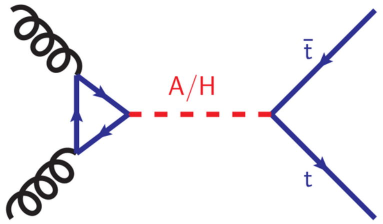
- Quantum nature of elementary particle interactions: non-deterministic
  - Given initial state can lead to different final states with different probabilities
- **Idea:**
  - Calculate probability distribution for a given process (or sub-processes)
  - Random sampling to generate events with particle kinematics according to these distributions



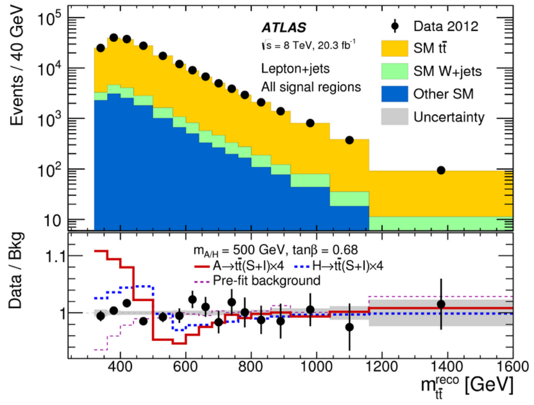
Experimental Techniques

Experimental analysis step by step

> Pick and study a signal of interest

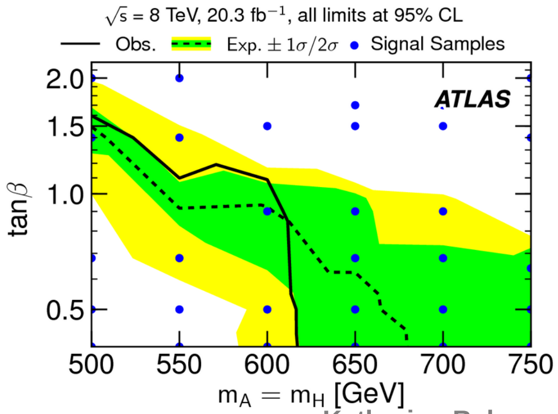


> Select subset of events enriched in signal (signal region)



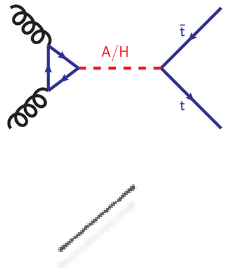
> Estimate backgrounds and systematic uncertainties

> Test agreement between SM prediction and data



How to search for BSM signals?

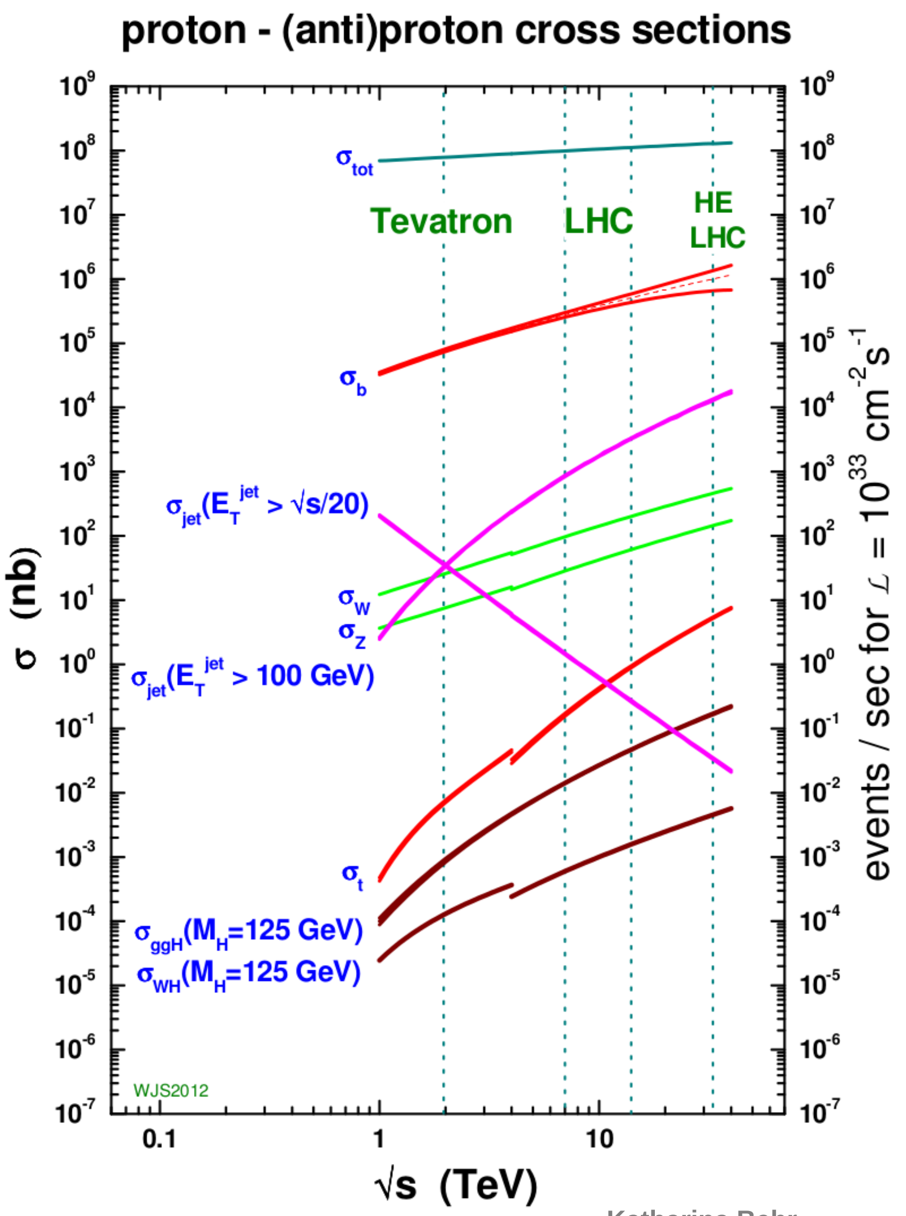
> Isolate small signal from huge dataset



Signal
(a.k.a. the needle)

Background
(a.k.a. the haystack)
(...it's meant to be a haystack)

T.G. McCarthy



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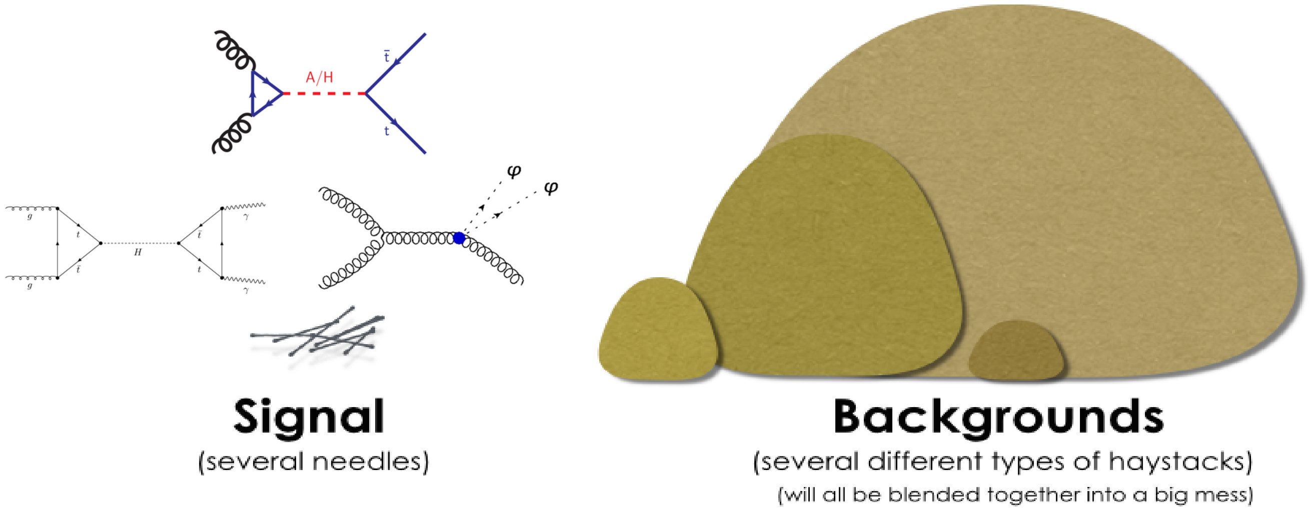
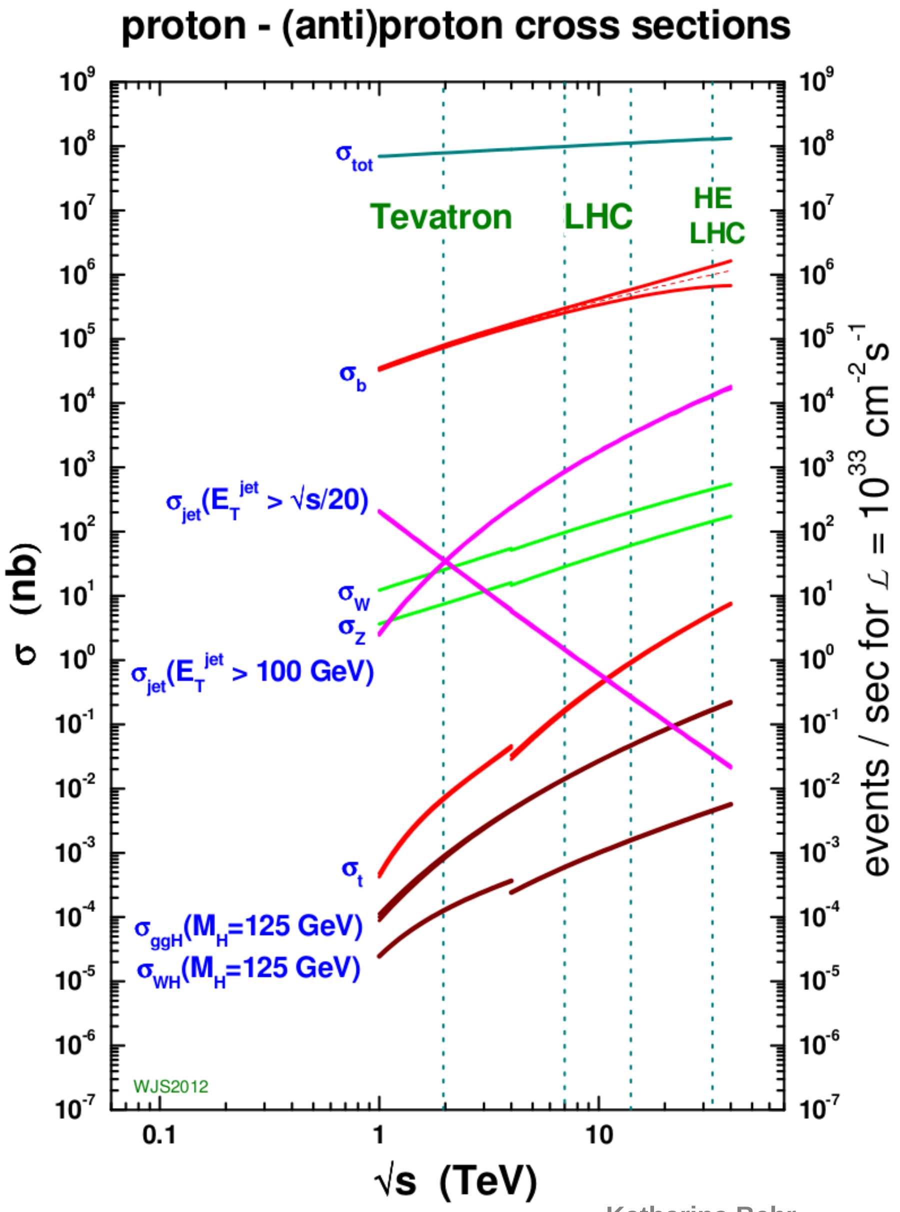
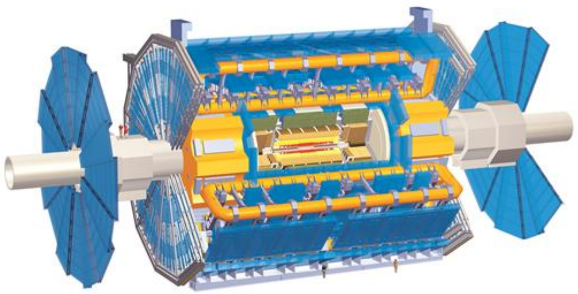


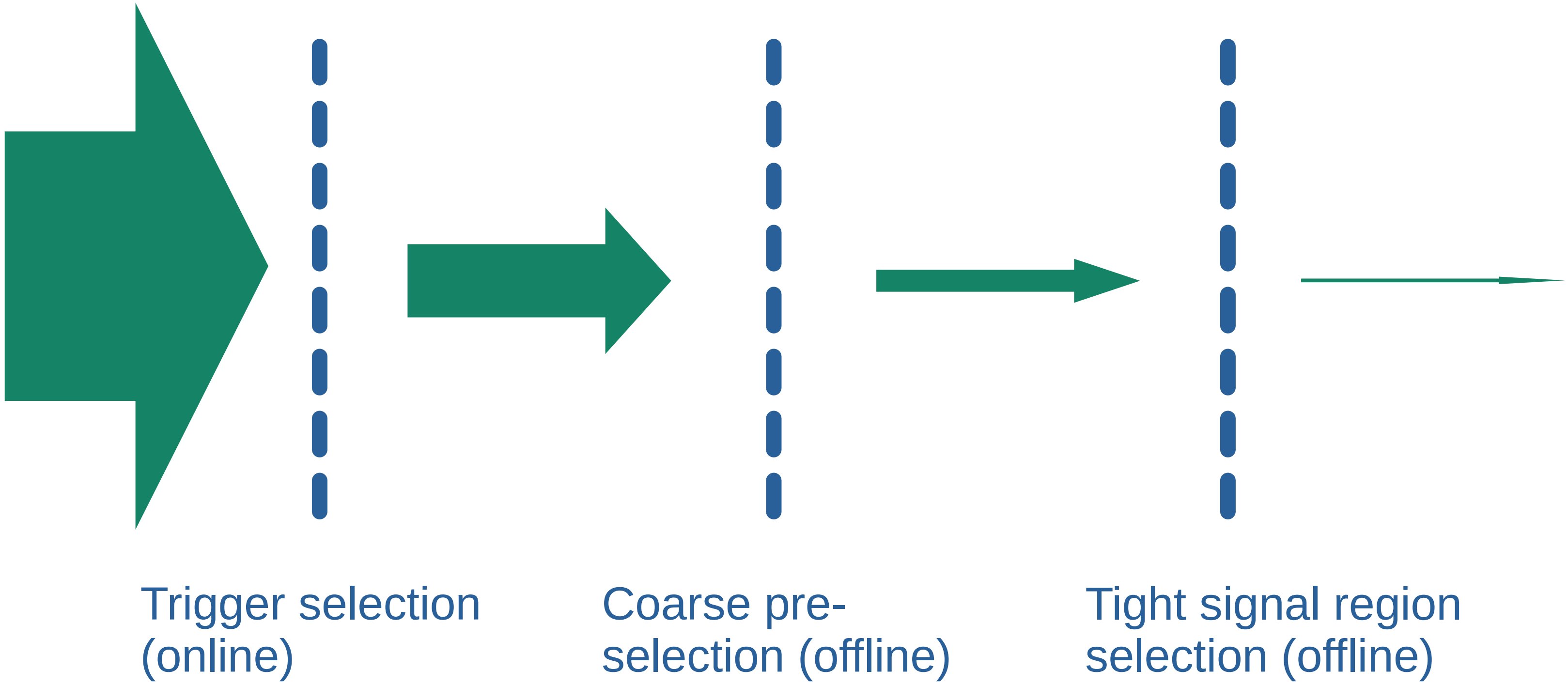
T.G. McCarthy



Select signal-like events

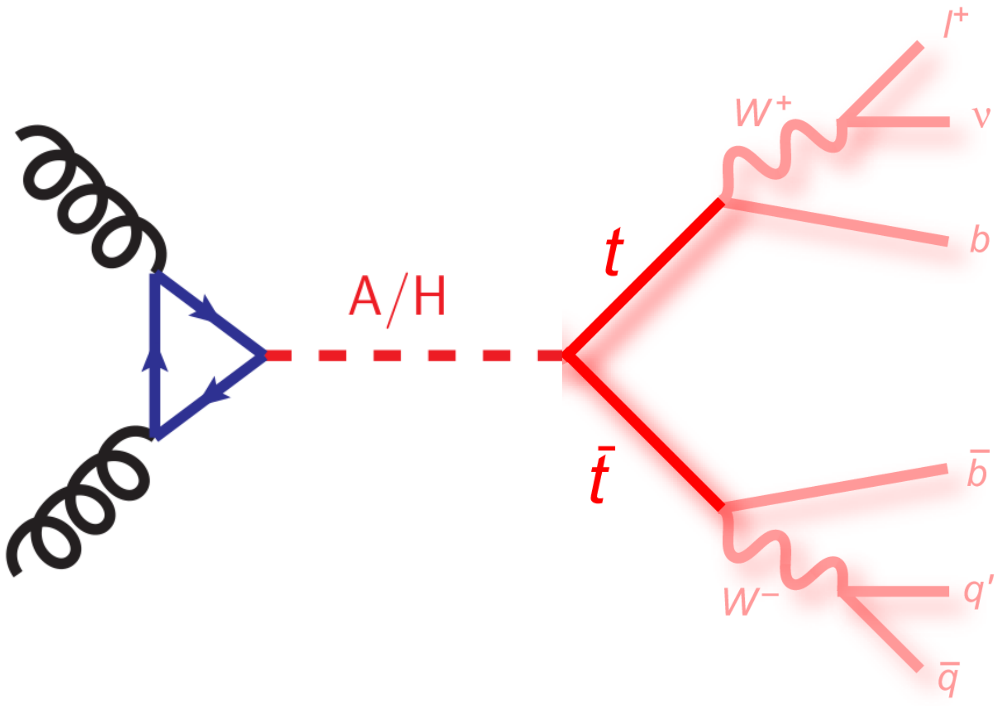
- Define criteria that characterise chosen signal in detector
- Apply selection criteria to reduce background
- Signal-enriched region (signal region)





Exercise

- Define a signal region for semi-leptonic ttbar decay
- For simplicity assume that charged lepton is an electron or muon



Exercise

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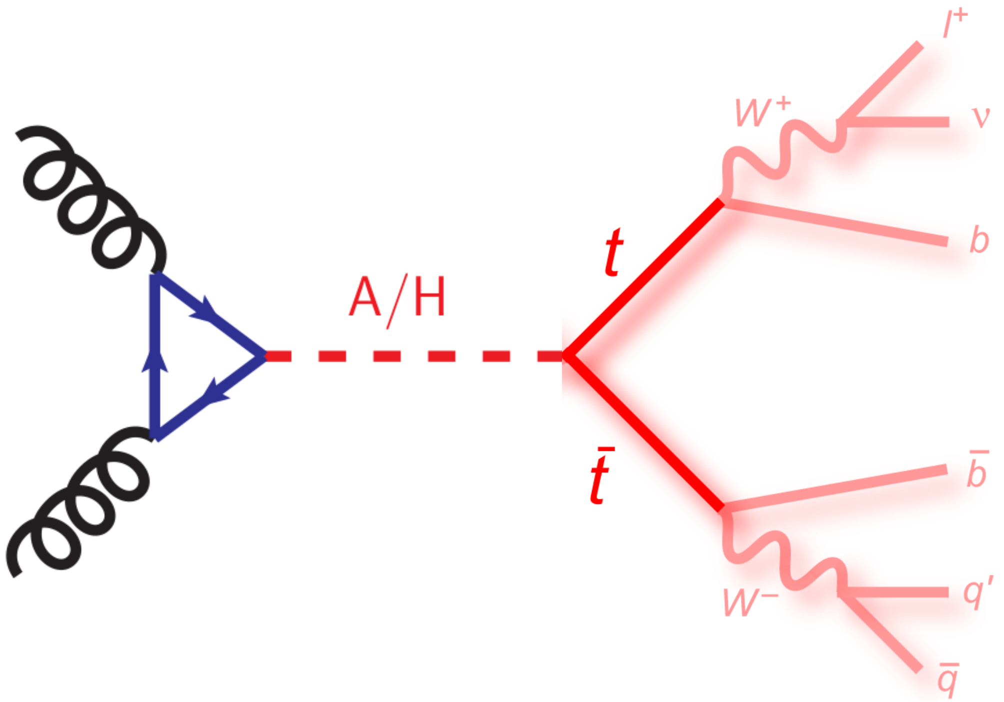
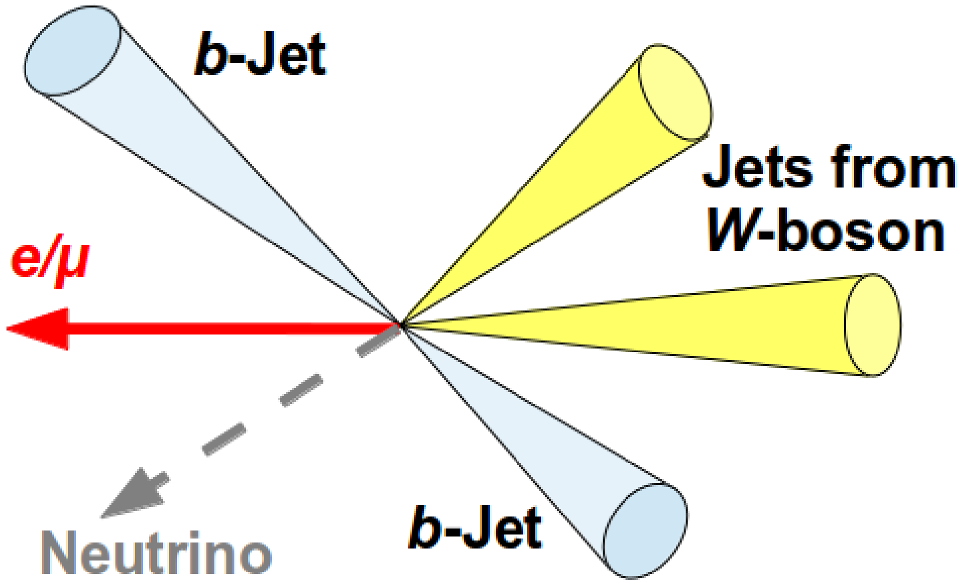


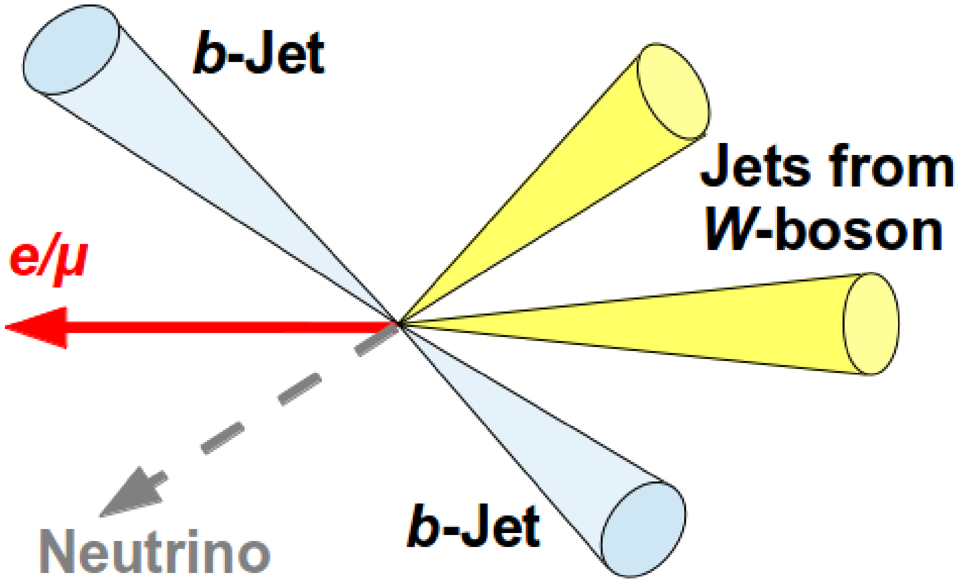


Exercise: Solution

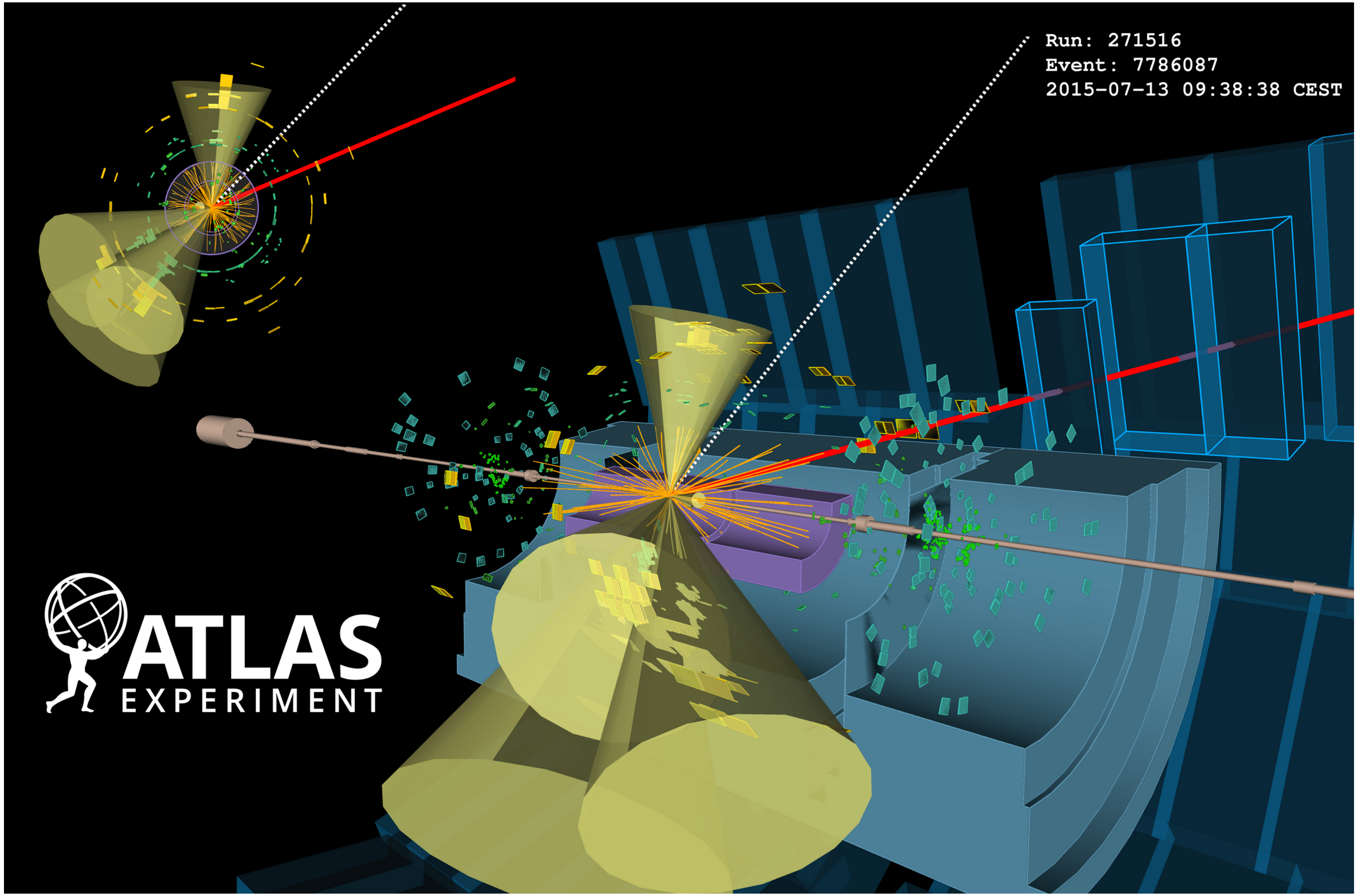
- Exactly 1 electron or muon
- Missing energy (from the neutrino)
- At least 4 jets

- Bonus 1: 2 jets identified as b-jets

- Bonus 2:
  - Combined mass of 2 jets = W mass
  - Combined mass of 3 jets = top mass

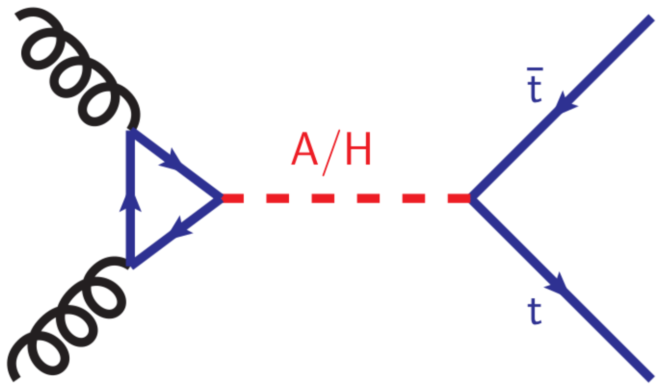


Exercise: Solution

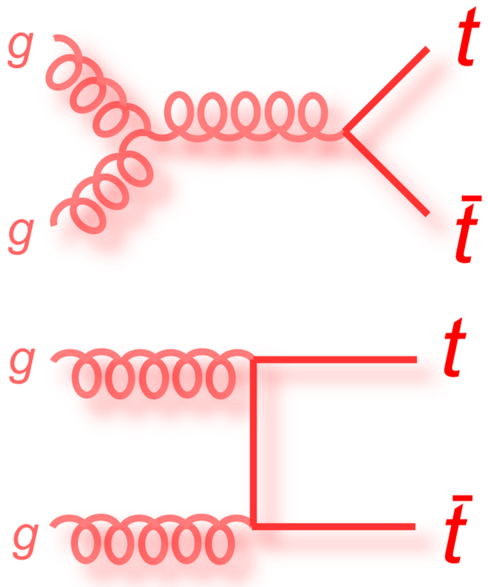


Signal vs backgrounds

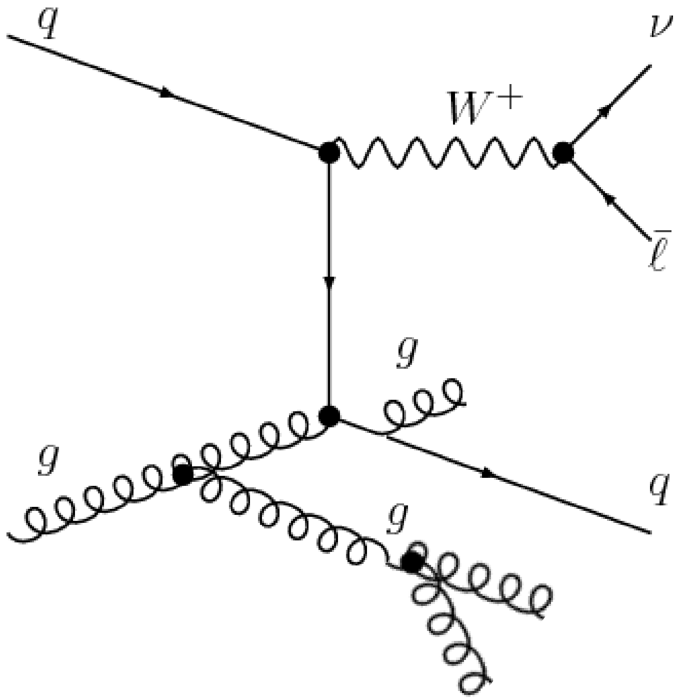
Signal



SM ttbar production
Irreducible background



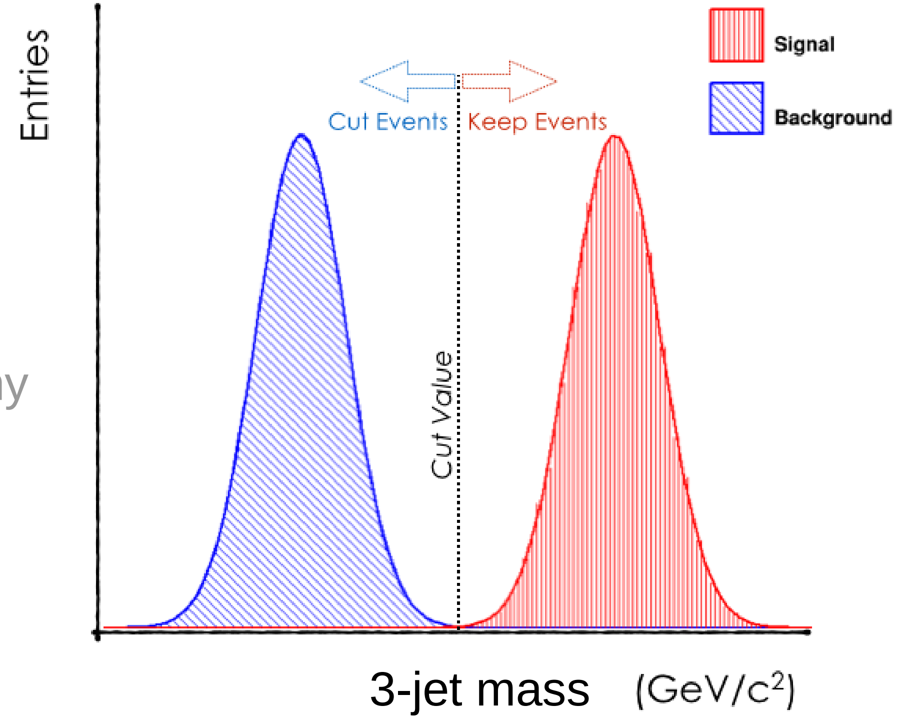
SM W+jets production
Reducible background



Signal region definition

> Apply selection criteria (cuts) to reduce background
> Signal-enriched region (signal region)
> Additional cuts based on differences in kinematic distributions

T.G. McCarthy



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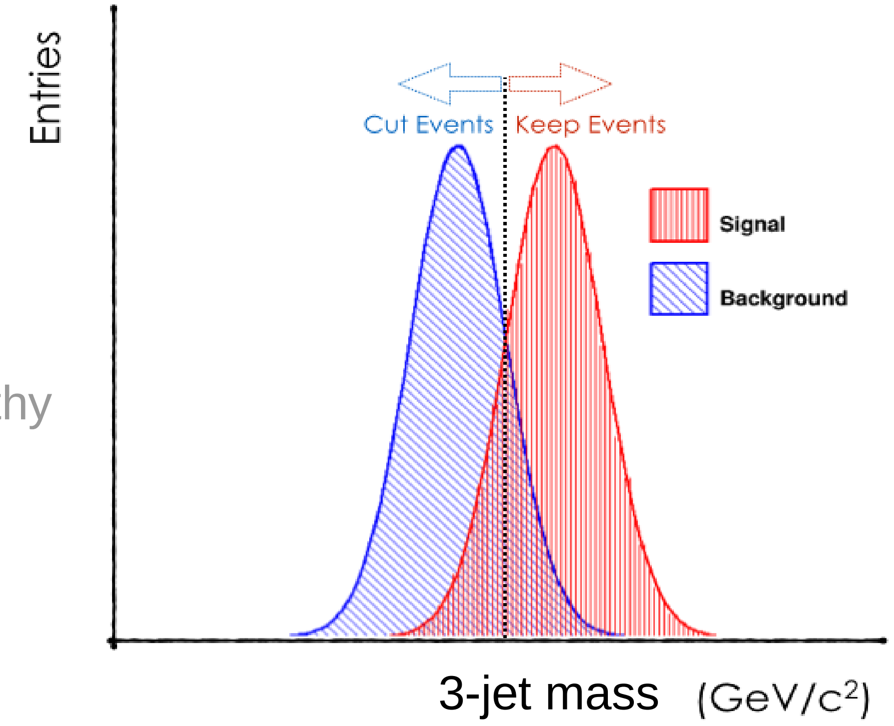

T.G. McCarthy

Signal region definition

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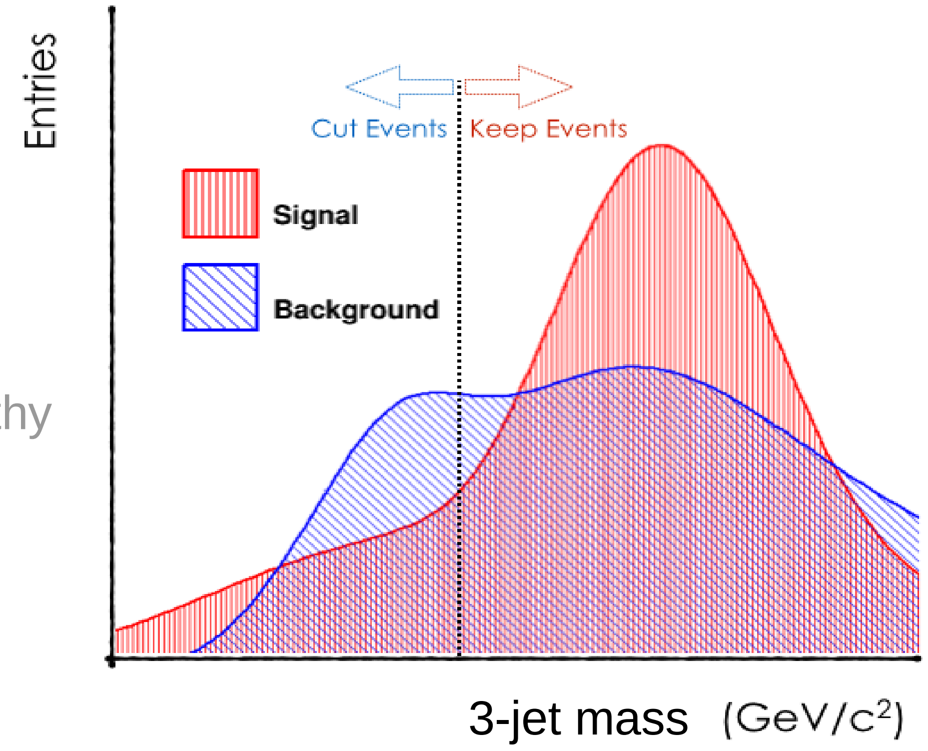

T.G. McCarthy

Signal region definition

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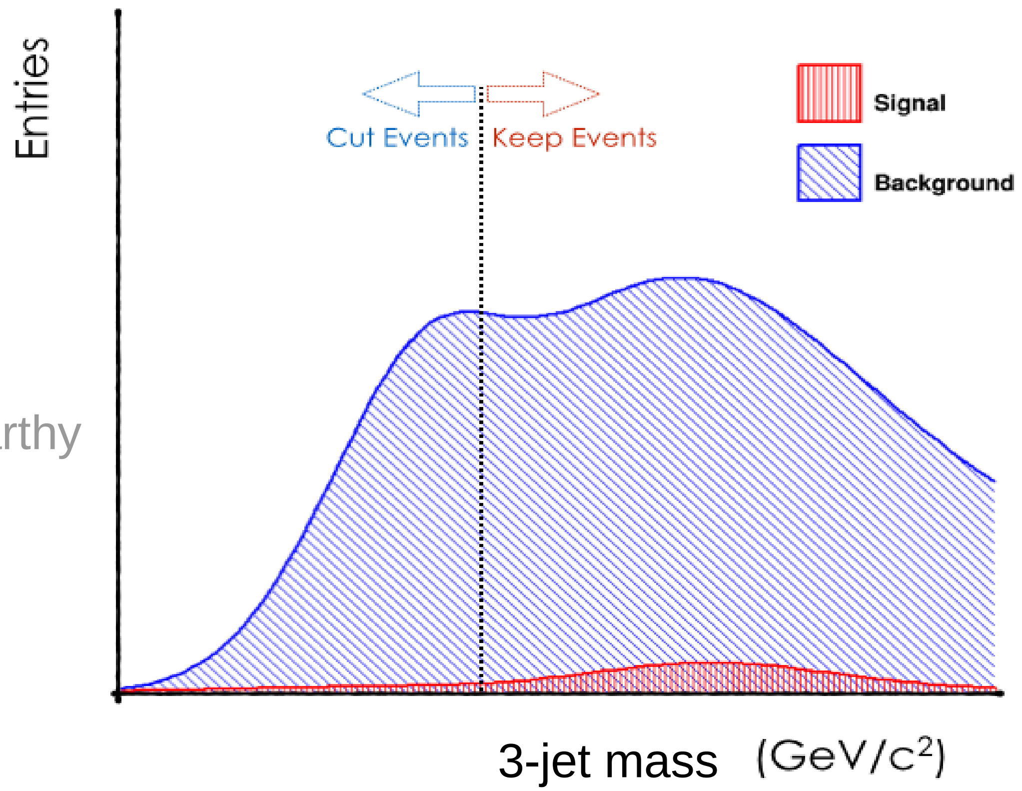

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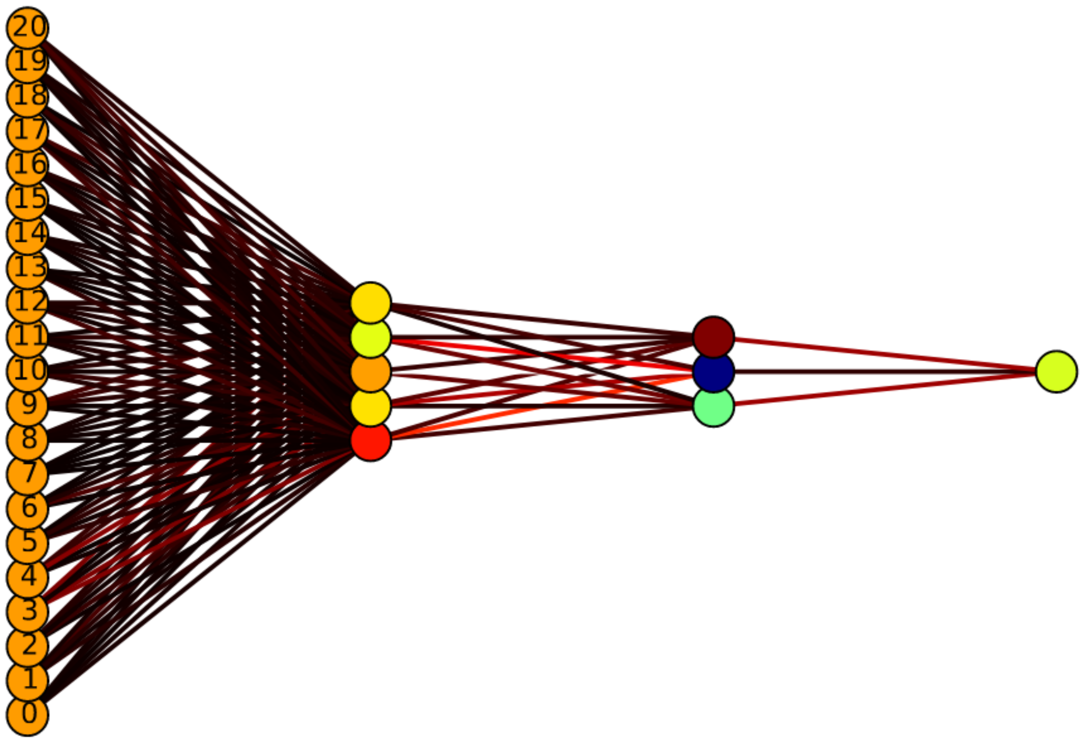
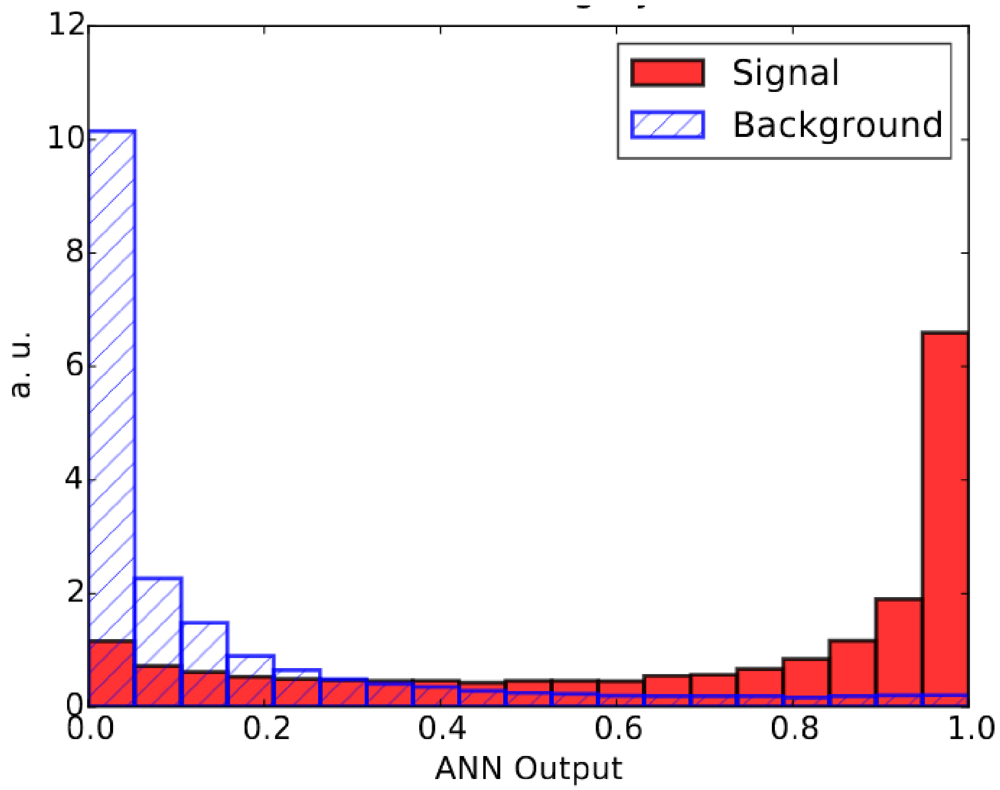
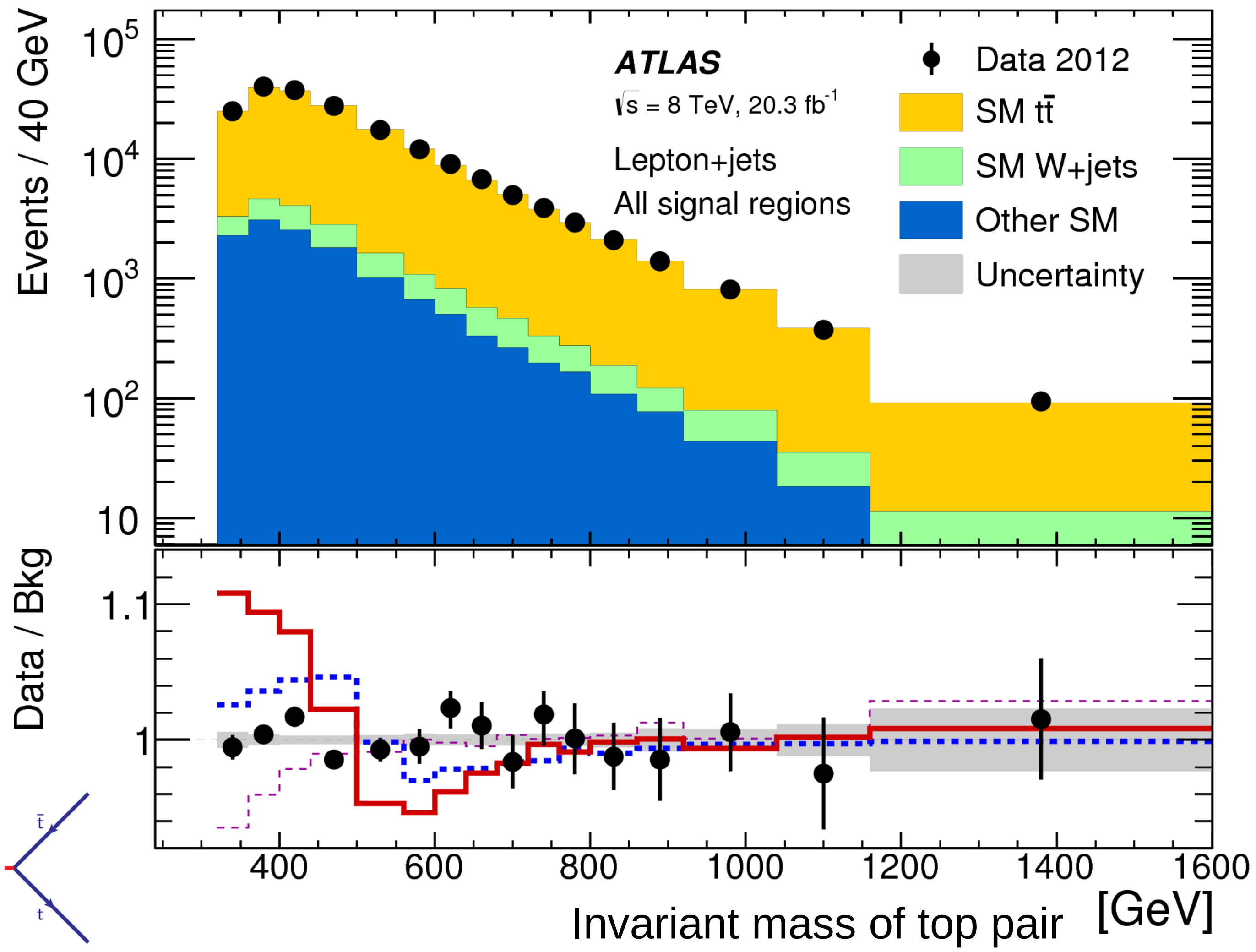
Signal region definition

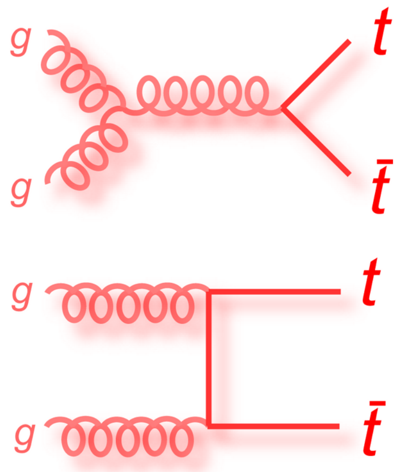
> Can refine signal regions using machine-learning algorithms
  - Exploit small differences in various kinematic variables
  - Exploit correlations

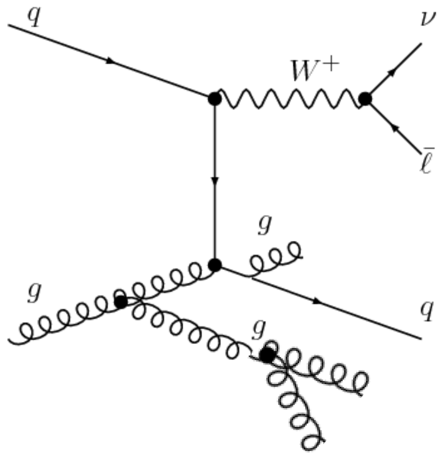


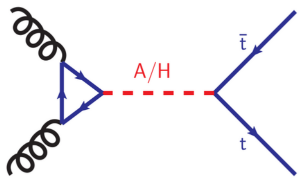


A final signal region







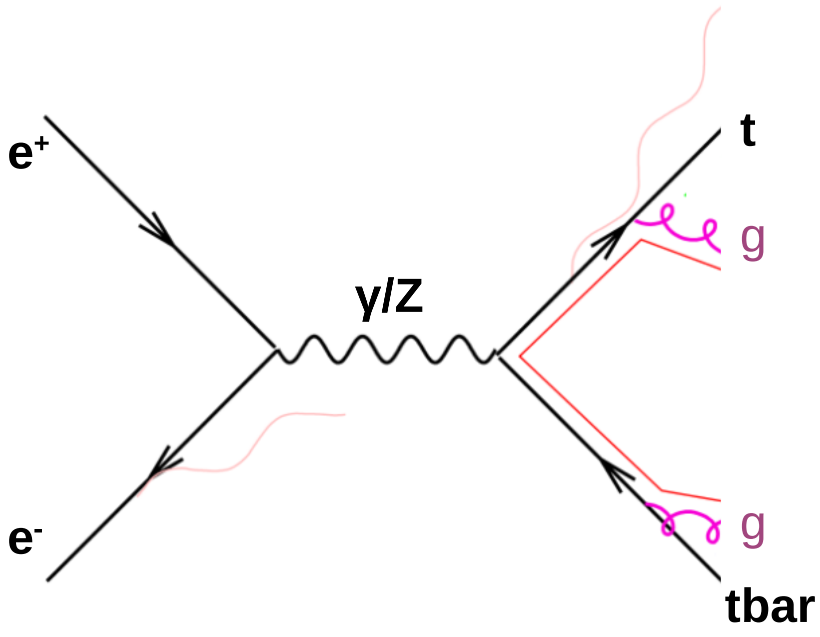


Event simulation

- Simulate possible signals based on theoretical models
  - Optimise sensitivity of searches
- Simulate background processes
  - Compare predictions to data and look for deviations
  - Some background processes can be simulated very accurately…
  - … others not (see data-driven estimates later)
- Estimate systematic uncertainties
  - Create different background predictions within experimental uncertainties
  - E.g. top mass known with ±1 GeV uncertainty
    - → Simulate top quark pair production for m_{top}(central) and m_{top}(central)±1 GeV

Simulation step by step

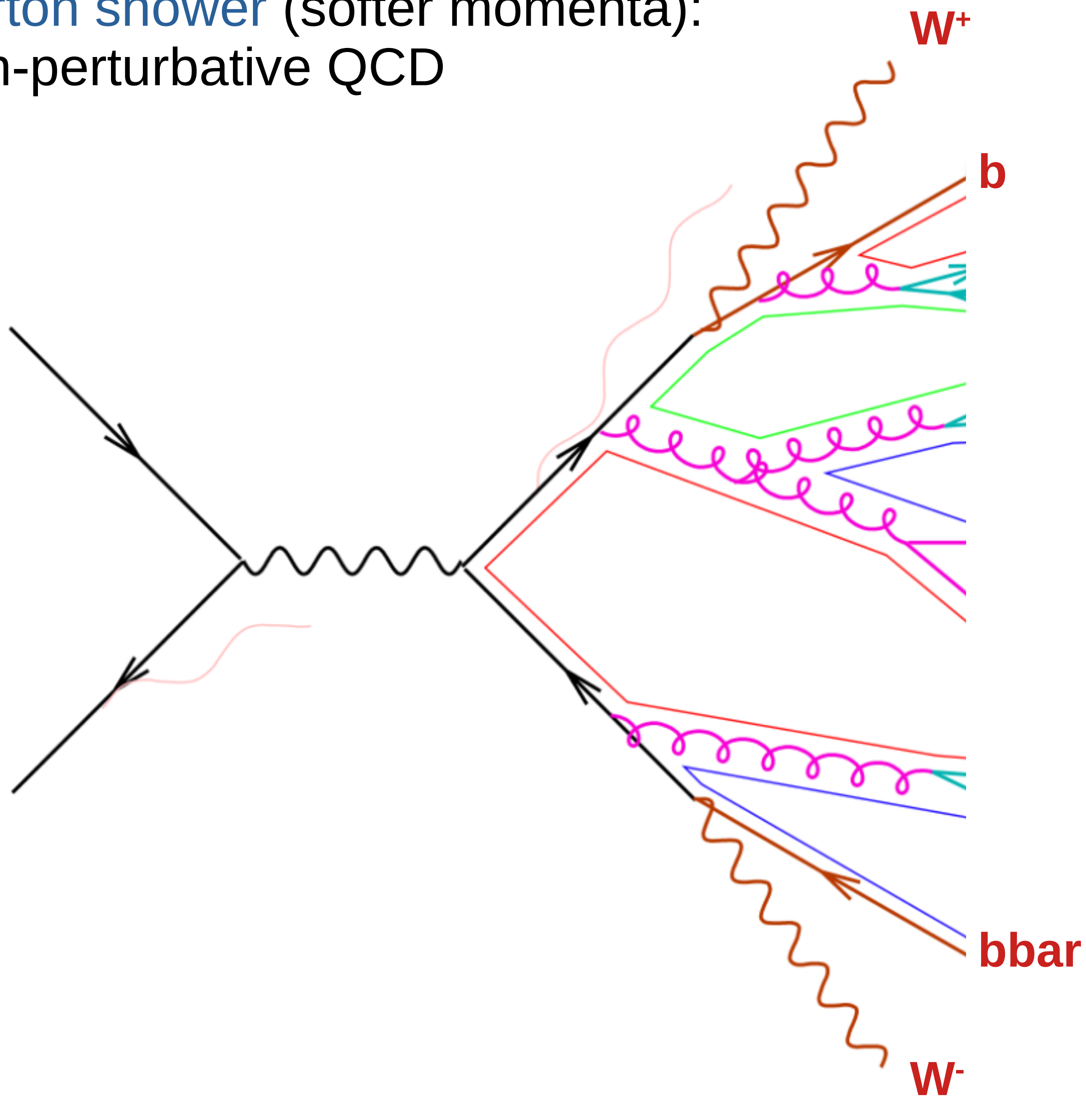
> Hard processes (large momentum transfers): perturbative QCD



- hard scattering
- (QED) initial/final state radiation

Simulation step by step

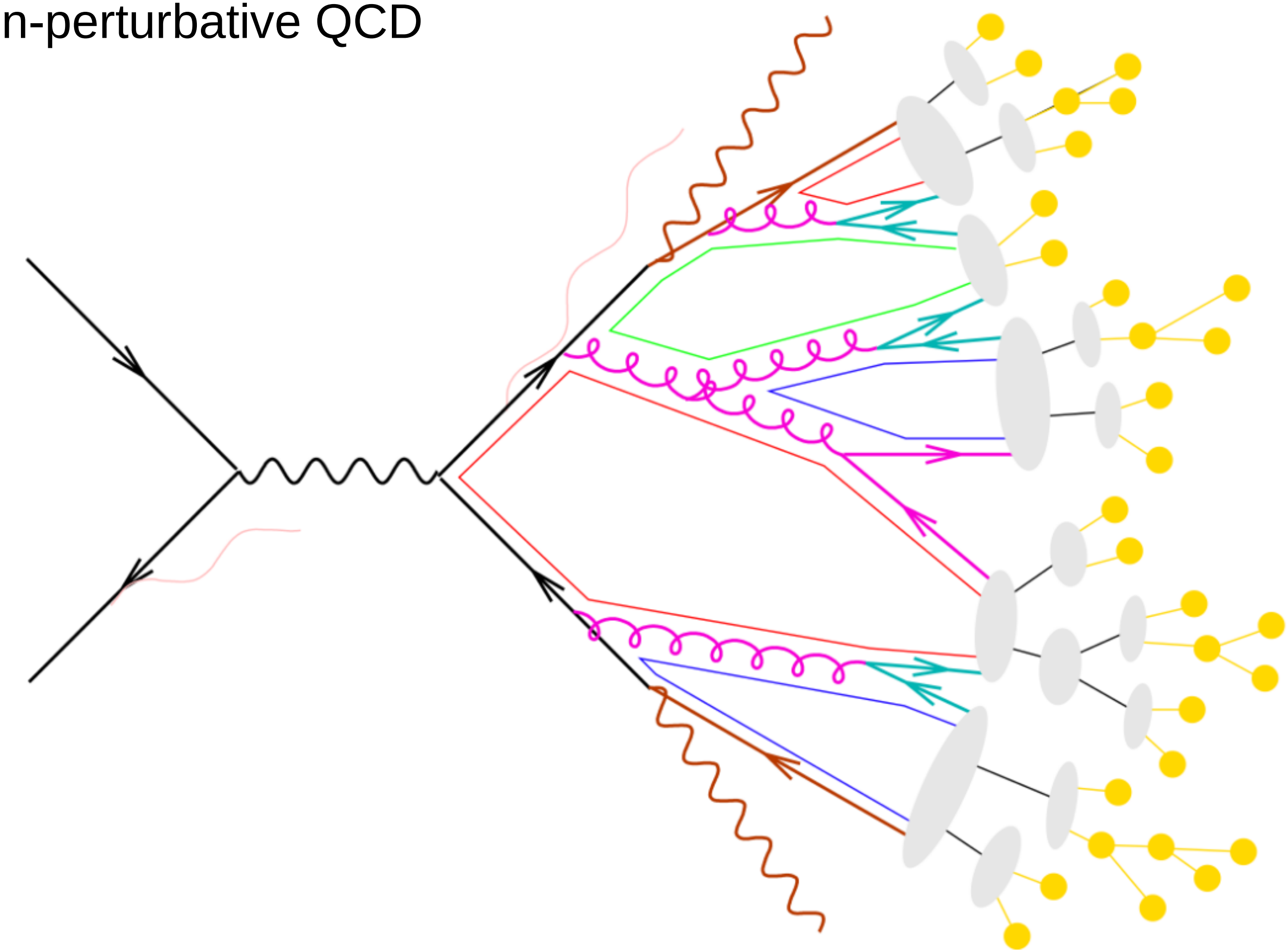
> Parton shower (softer momenta): non-perturbative QCD



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting

Simulation step by step

> Hadronisation (soft, low energy): non-perturbative QCD



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

Think outside the (black)box!

> Many different event generators available for HEP/LHC

- Choice depends on process, required precision, …
  - E.g. matrix-element generators: MadGraph, Powheg
  - E.g. matrix-element + parton-shower generators: Pythia, Herwig
- Important to understand differences and subtleties to not treat them as blackboxes!

Think outside the (black)box!

“[…] remember that the programs ***do not represent a dead collection of established truths****, but rather one of many possible approaches to the problem of multiparticle production in high-energy physics, at the frontline of current research.* ***Be critical!****”*

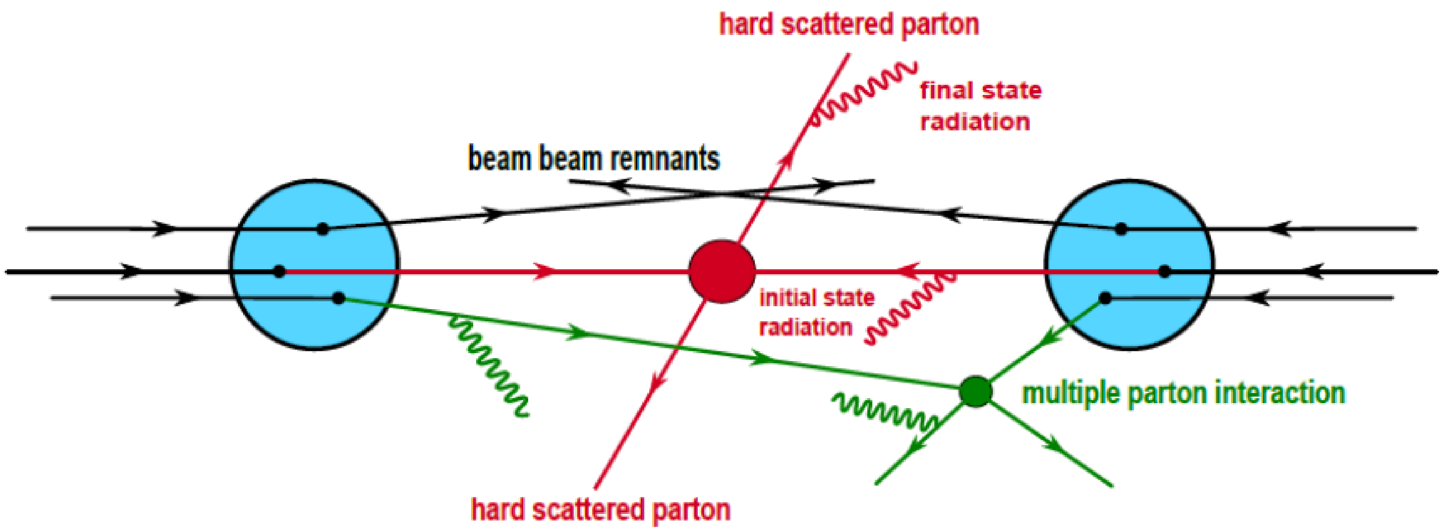
From the manual of the Pythia5 MC generator

Further aspects

> Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, ...

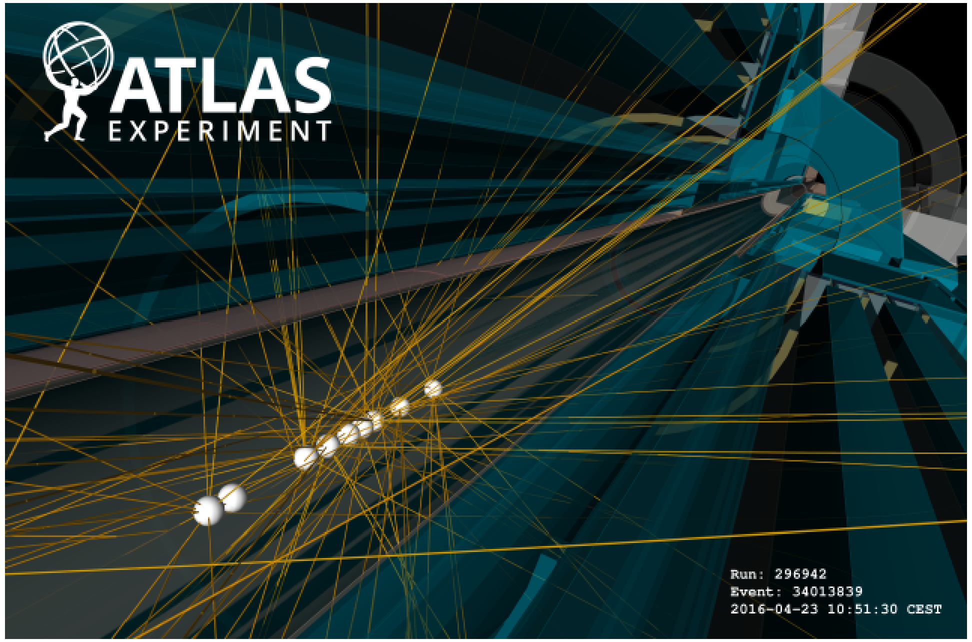
Further aspects

- Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, …
- Specifically for hadron colliders (LHC, Tevatron, …):
  - **Underlying Event**: simulate interactions of additional partons within same two protons



Further aspects

- Simulate interactions of (collider) stable particle with detector material
  - Geant4, Delphes, …
- Specifically for hadron colliders (LHC, Tevatron, …):
  - **Underlying Event**: simulate interactions of additional partons within same two protons
  - **Pile-up**: simulate interactions of additional protons in the same bunch crossing



- Further reading:

  lecture by M. Seymour and M. Marx [link]

Estimating background processes from data

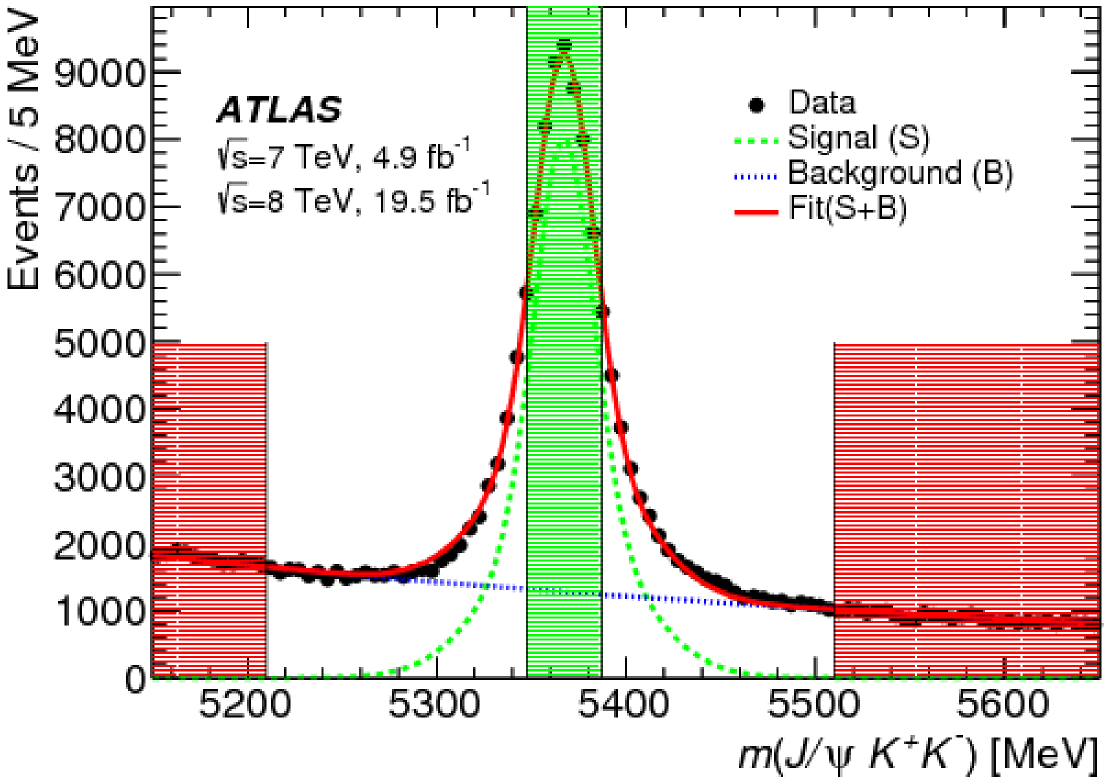
- Simulation not always feasible for estimating background processes
  - Instrumental backgrounds (related to detector effects)
    - Jets with high EM component faking electrons
    - Backgrounds from detector noise
    - …
  - Processes with large cross-section that would require large MC statistics
    - Mostly multijets at the LHC
  - Known modeling limitations
    - Missing higher-order processes
    - …
- Use fully data-driven estimates or data-driven corrections

Sidebands

> Assume known signal region (= location in the spectrum)

> Fit background in sidebands (= adjoining parts of the spectrum, signal depleted)

> Extrapolate to signal region

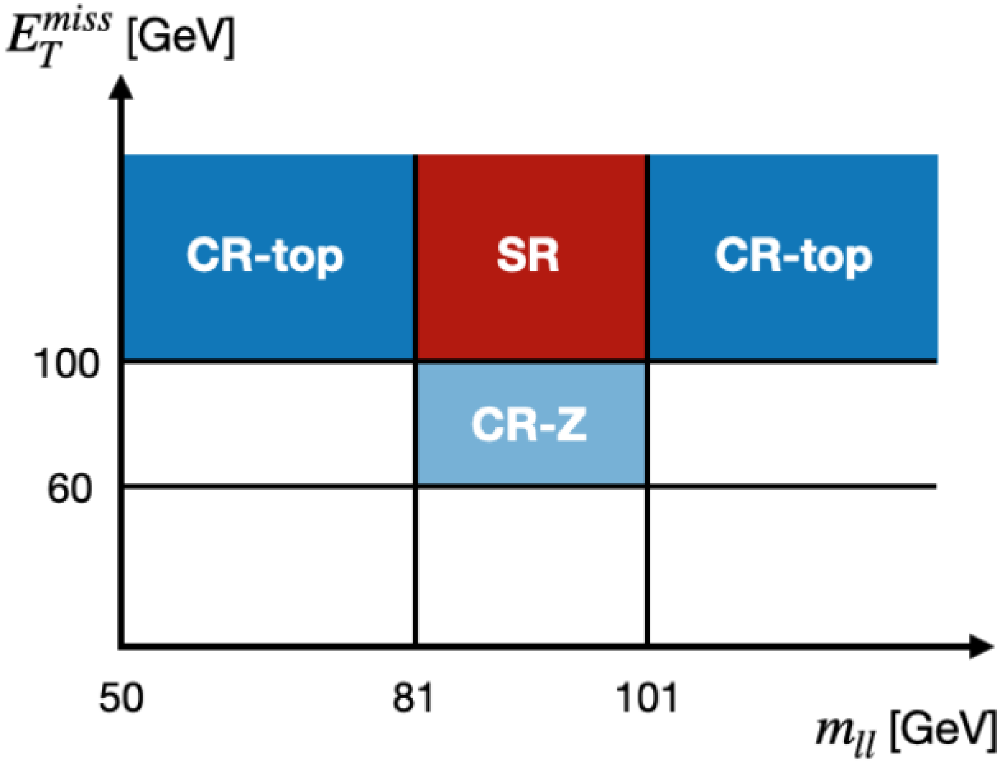


Control Regions

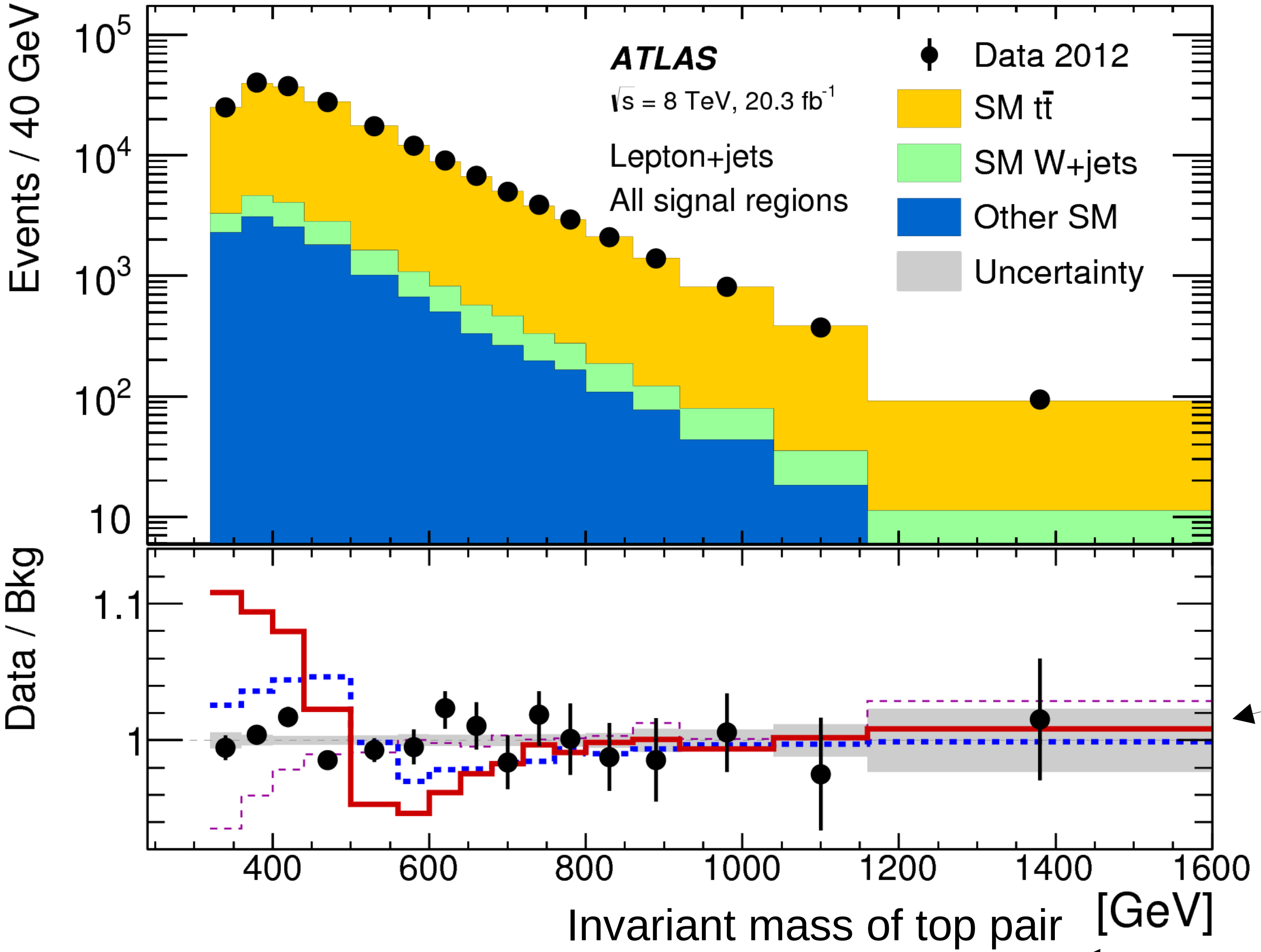
> Same idea as with sidebands but using a modified selection to define a control region
  - Orthogonal to signal region, signal depleted

Signal signature: $Z(\rightarrow ll) + E_T^{miss}$ + bbar

> Must be carefully designed to
  - Be signal depleted
  - Be enriched in background of interest
  - Close enough to SR to avoid biases
  - ...



A final signal region

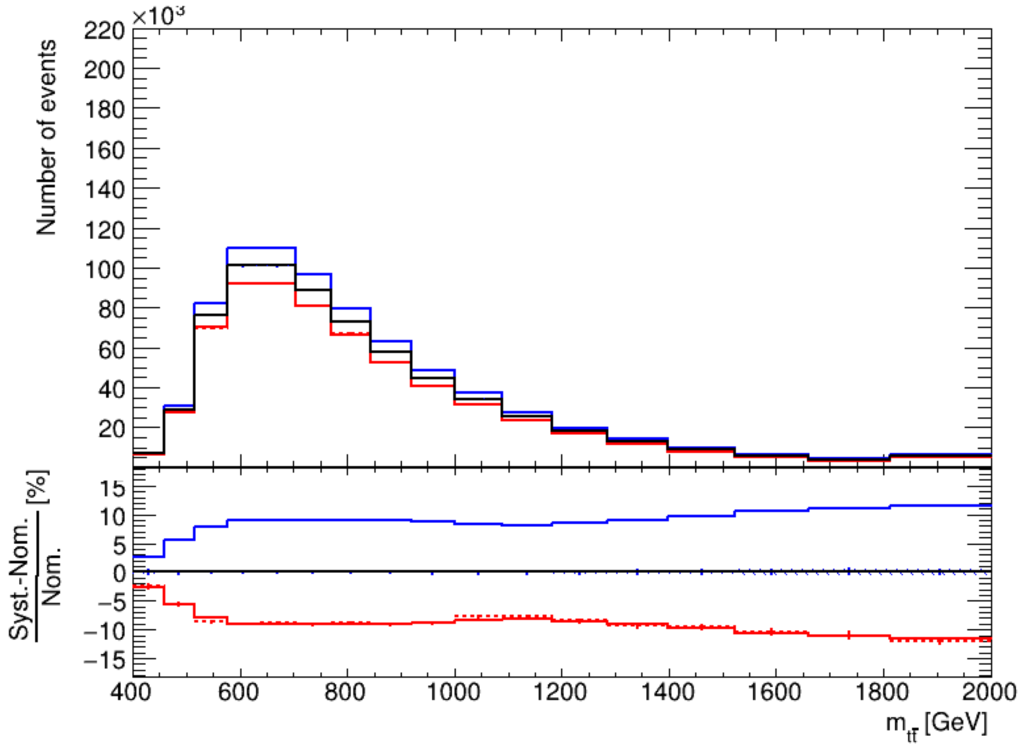


Systematic and statistical uncertainties

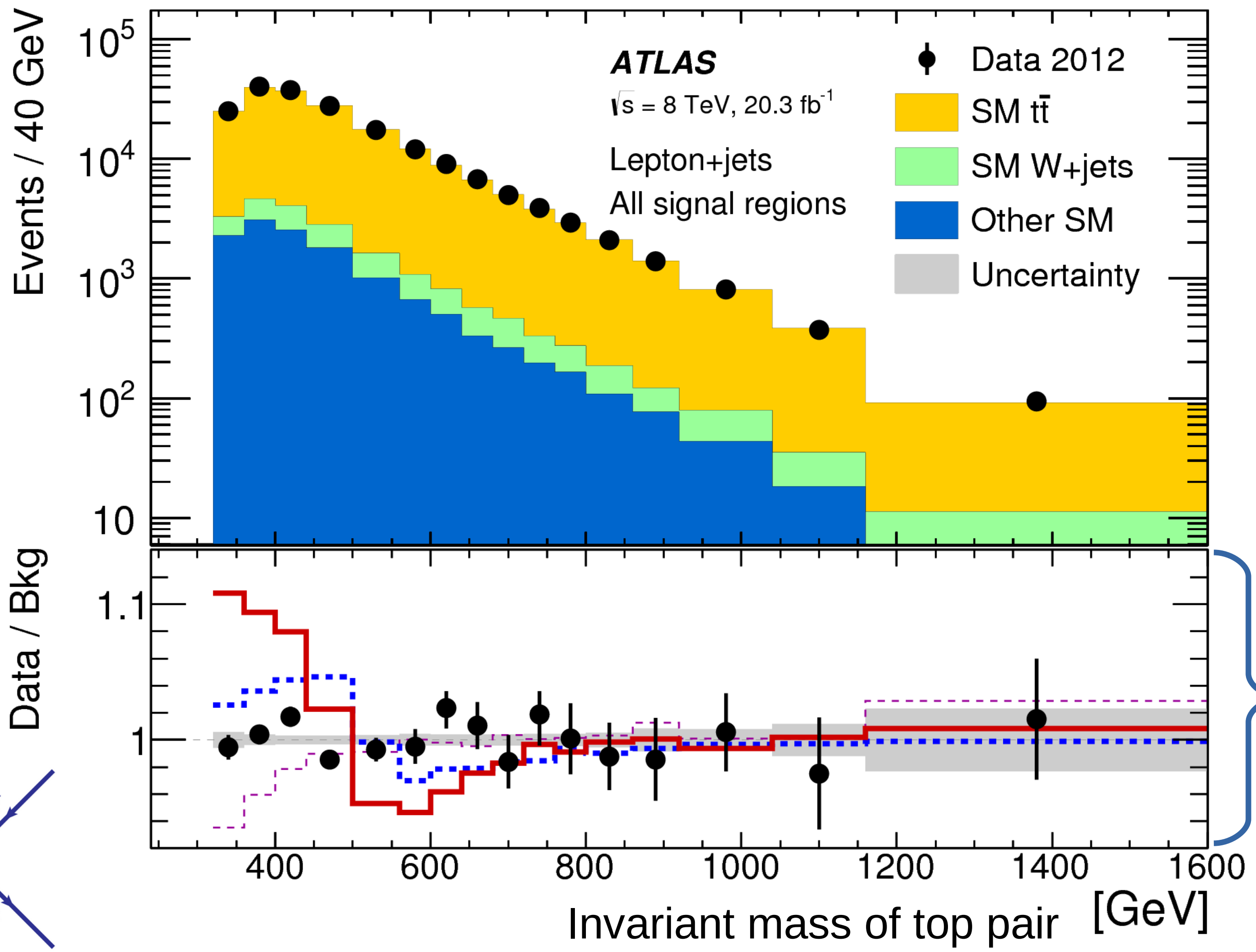
Variable of interest

Systematic uncertainties

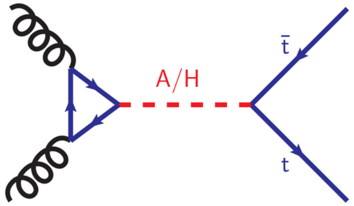
- Various different sources:
  - Modeling uncertainties, e.g. unknown higher-order corrections
  - Experimental uncertainties, e.g. uncertainties on electron energy measurement
- Propagate to final spectrum
- Uncertainties degrade sensitivity to signal



A final signal region



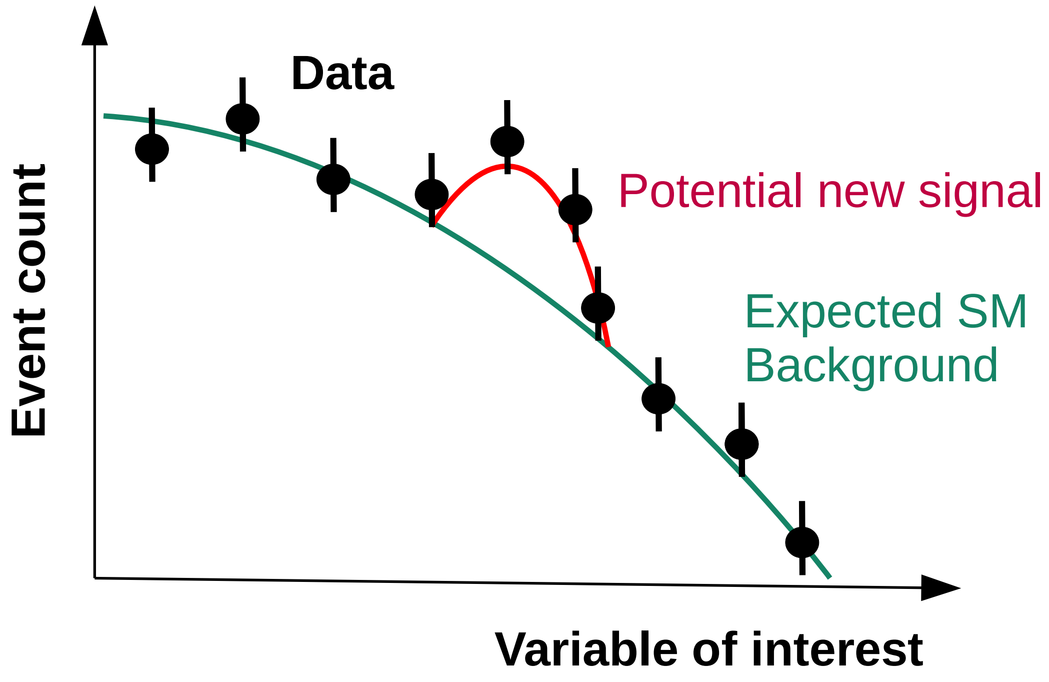
What type of deviation are we looking for?



What are we looking for?

> Most generally put: we search for a significant deviation from the SM prediction

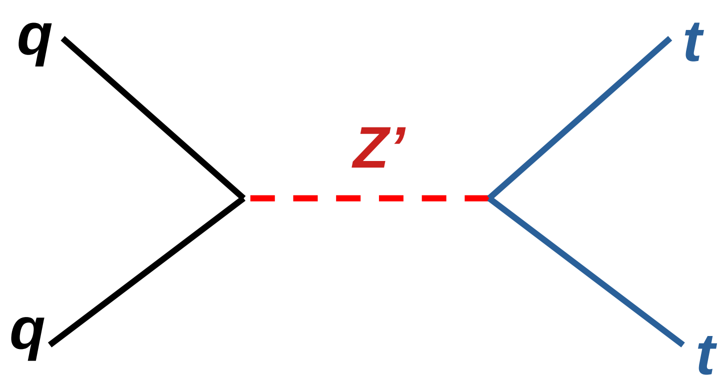
> Different search strategies
  - Cut-and-count method
  - Bump hunt
  - Tail hunt
  - ...

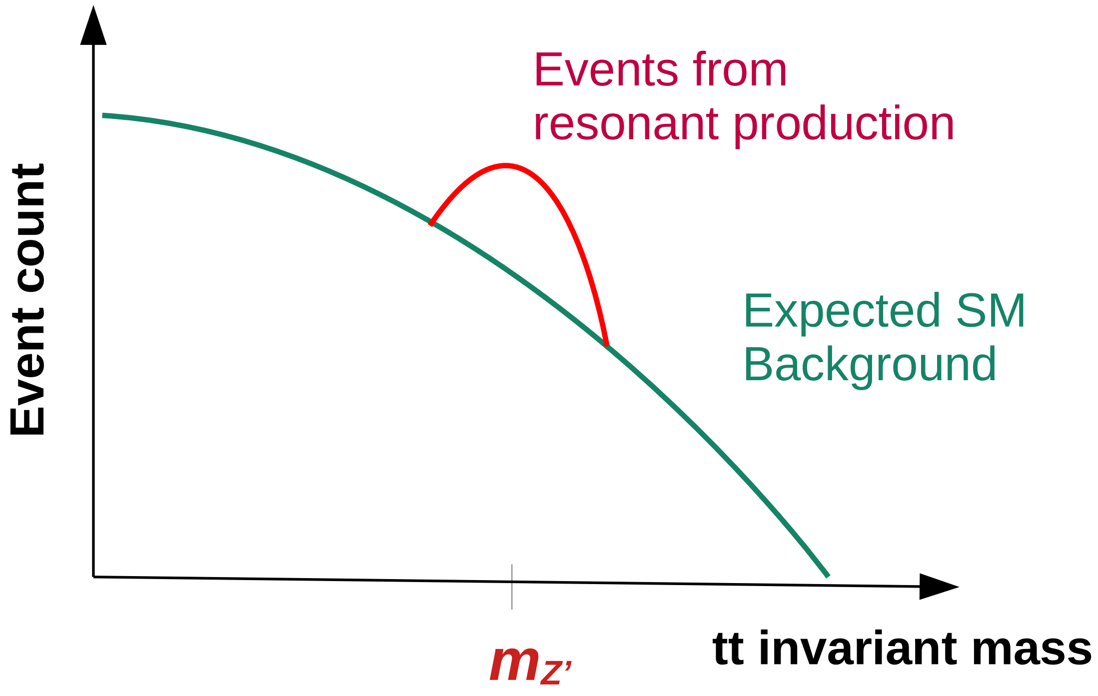


> Each comes with its own set of advantages/disadvantages!

Bump Hunting

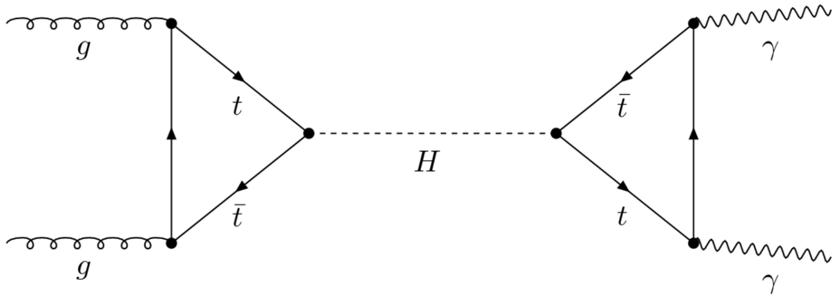
> Search for a localised deviation in the distribution of a variable of interest
  - Typically: invariant mass

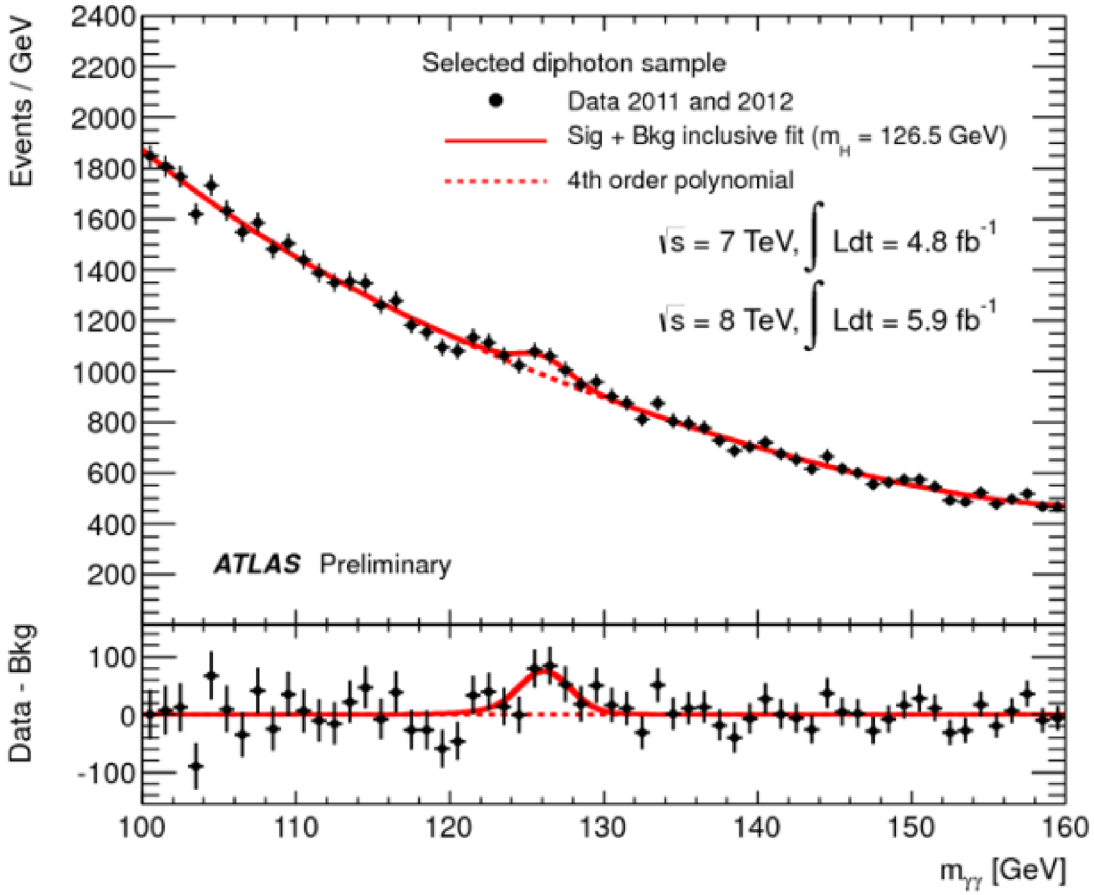




Bump Hunting

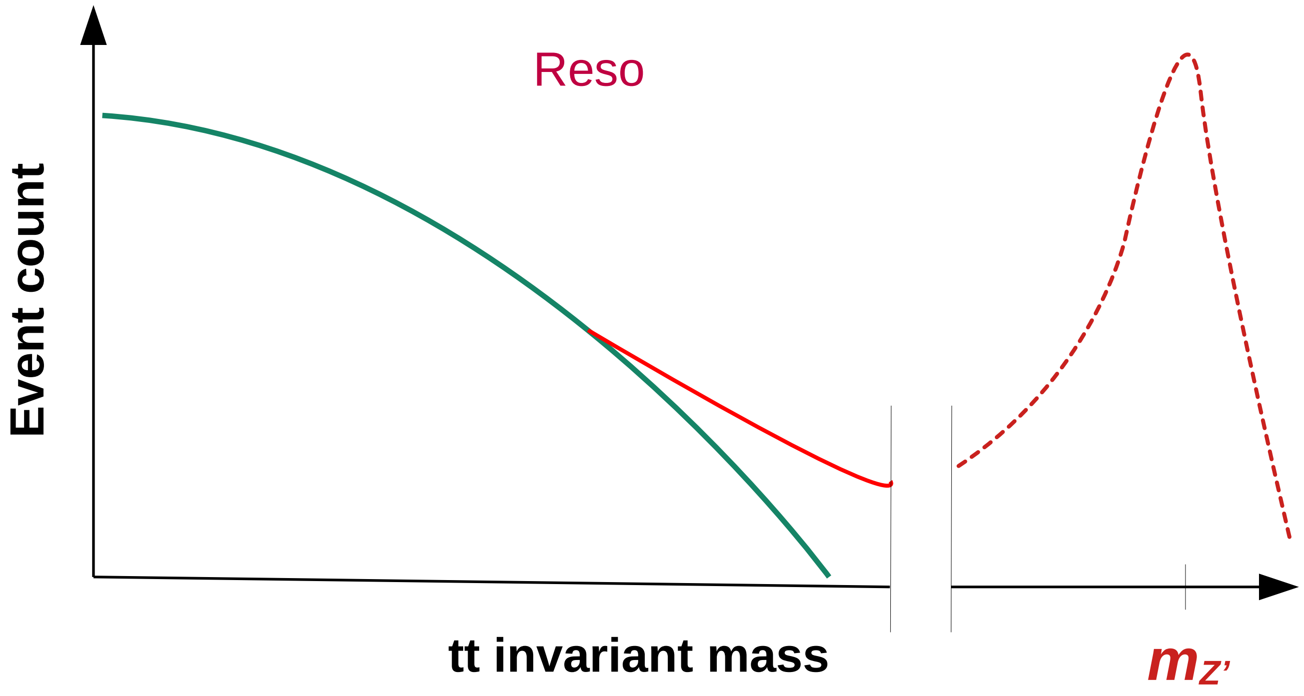
> Search for a localised deviation in the distribution of a variable of interest
  – Typically: invariant mass
> Most recent successful example:
  – Higgs boson discovery (2012, CERN)





Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest
> Typical examples:
  – Resonances beyond reach of the LHC



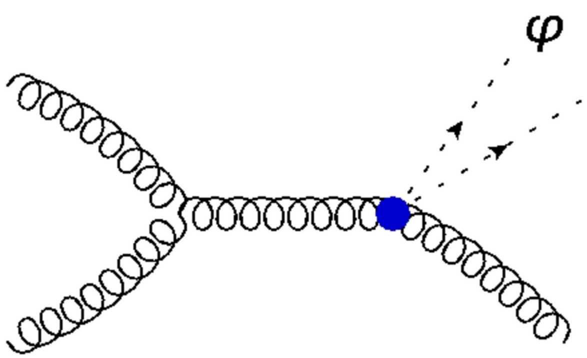
Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest

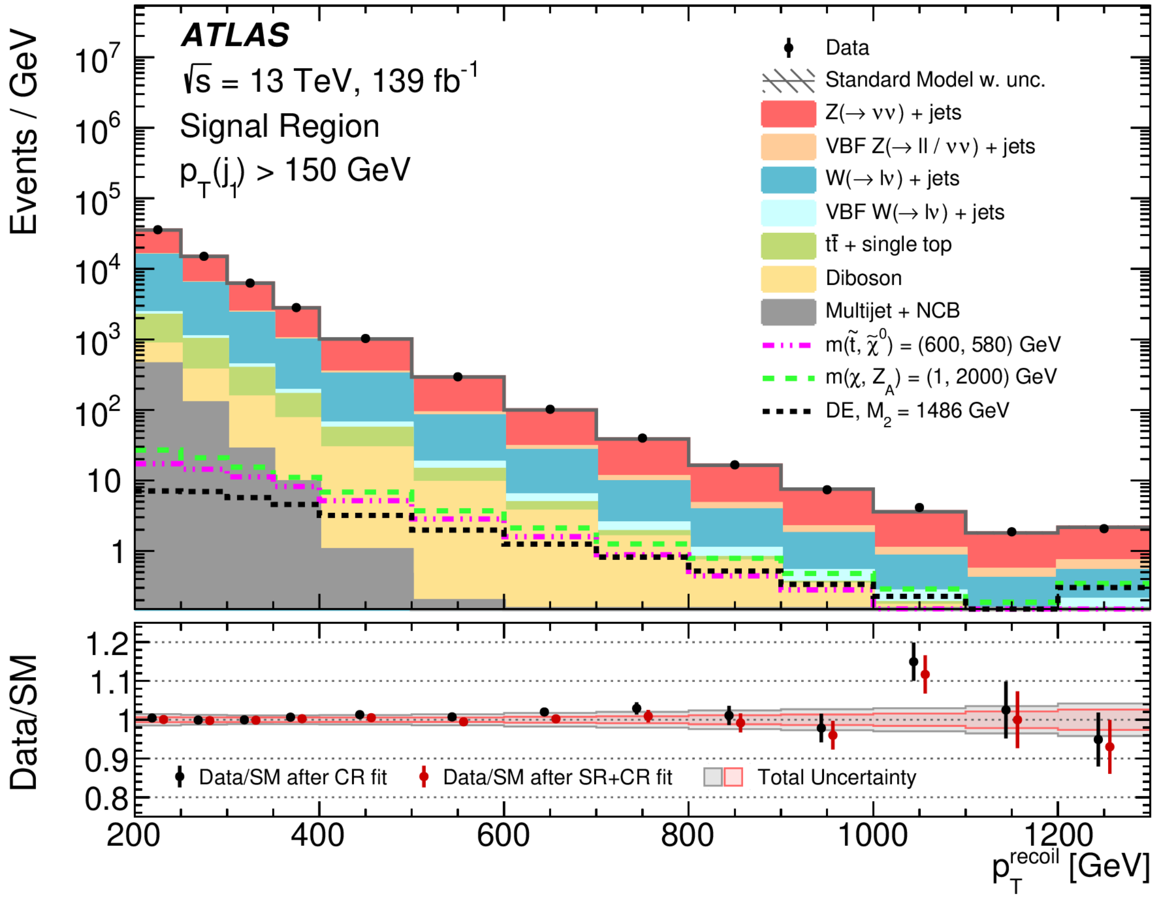
> Typical examples:

- Resonances beyond reach of the LHC
- Non-resonant production of new particles
  - E.g. dark matter or dark energy

Non-interacting scalar dark energy particles, → missing energy



Recoiling gluon, leading to single visible jet



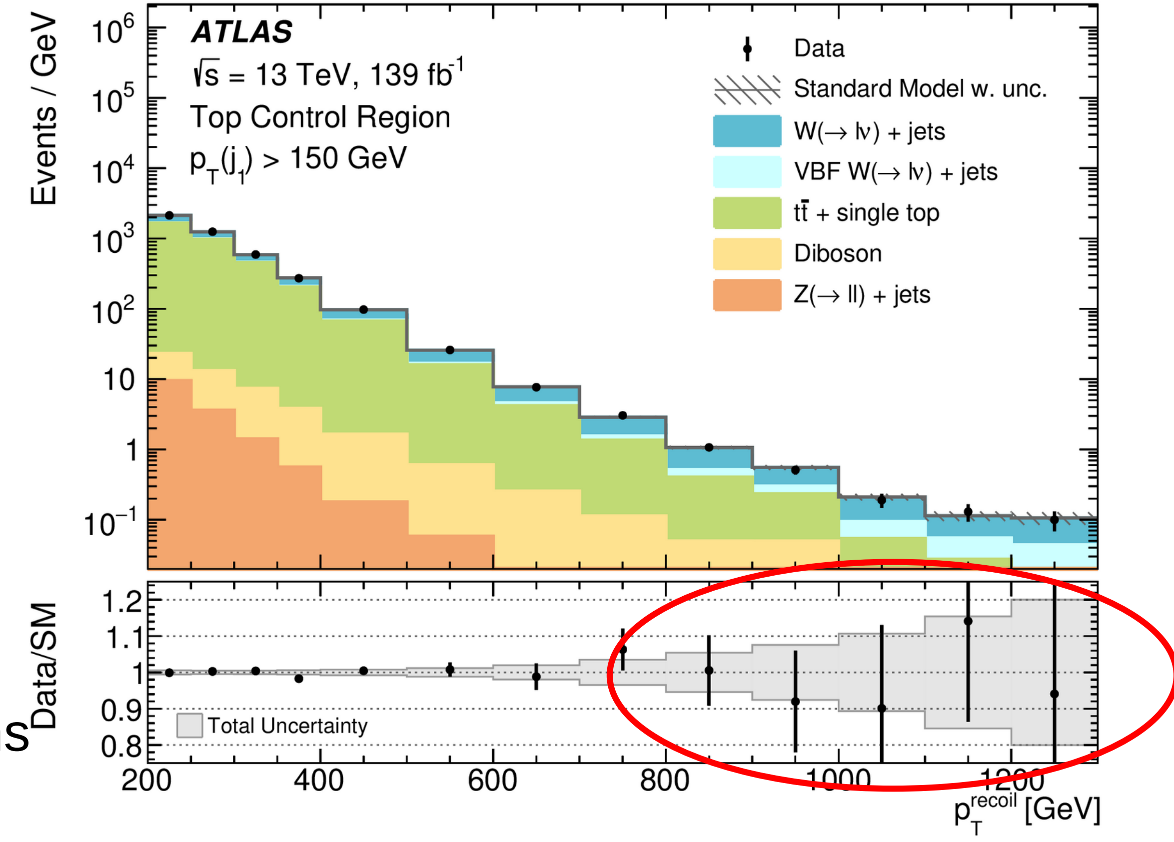
Tail Hunting

> Search for a tail enhancement in the distribution of a variable of interest

> Typical examples:
  - Resonances beyond reach of the LHC
  - Non-resonant production of new particles

> **Advantages**:
  - Sensitive to processes that cannot be identified by bump hunts

> **Disadvantages**:
  - Tails of distributions suffer from low statistics
  - Often sizeable systematic uncertainties
    - E.g. due to missing higher-order calculations



What if new particles are less obvious to spot?

> Bump hunt assumes “signal sitting on top of background”: **S** **+** **B** = $|s|^2 + |b|^2$

What if new particles are less obvious to spot?

- Bump hunt assumes “signal sitting on top of background”: **S + B** = $|s|^2 + |b|^2$
- Quantum mechanics: two processes with same initial and same final state will interfere!
  - $|s + b|^2 = |s|^2 + 2\,\mathrm{Re}(s\,b) + |b|^2$ = **S + I + B** → **Interference!!**

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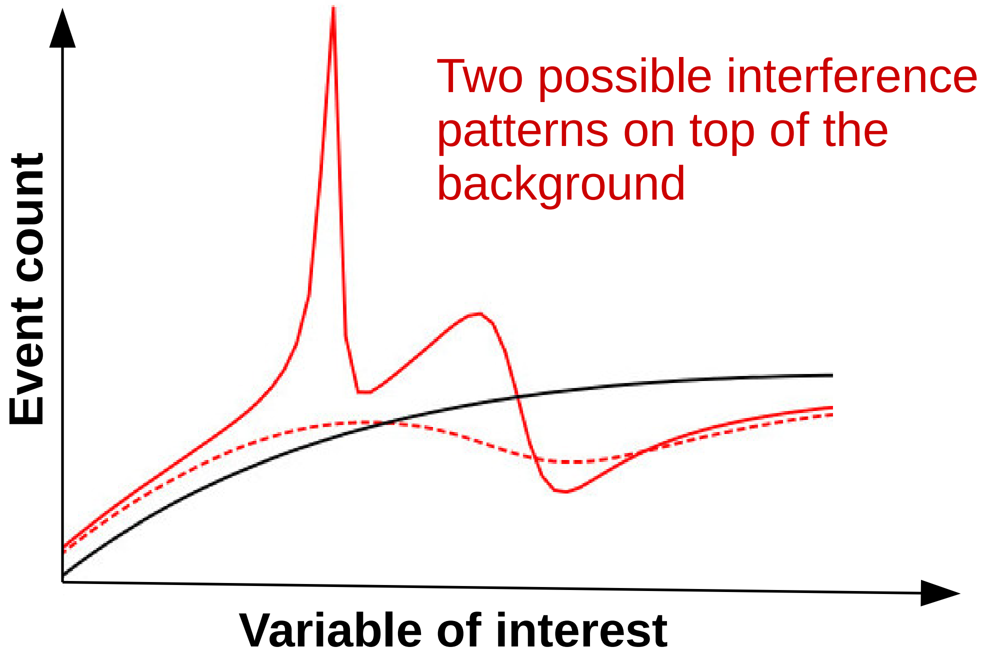
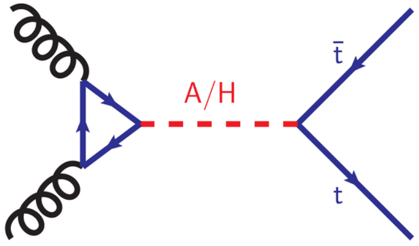
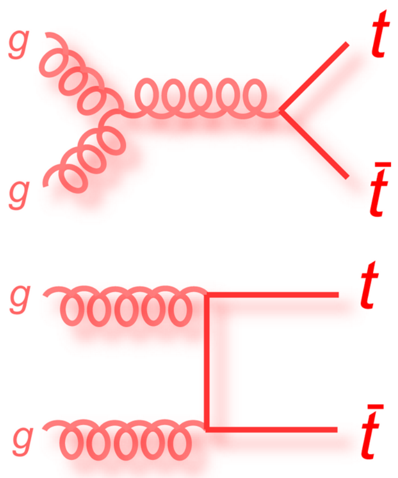


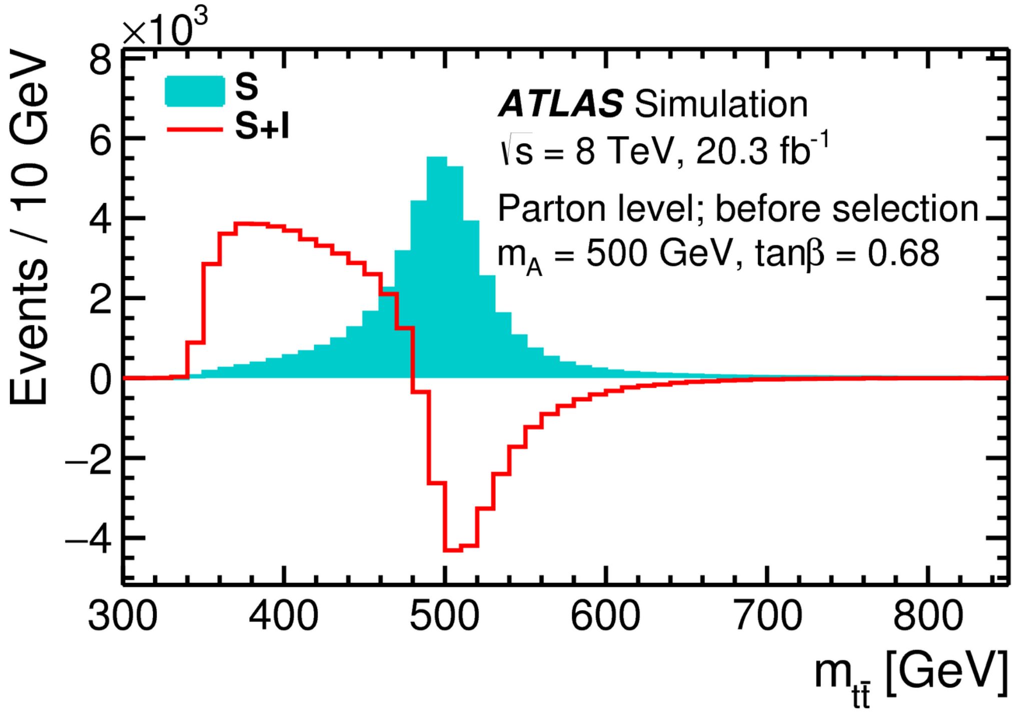
Beyond Bump Hunts

> Prominent example: decay of a heavy Higgs boson A/H to a top-antitop quark pair

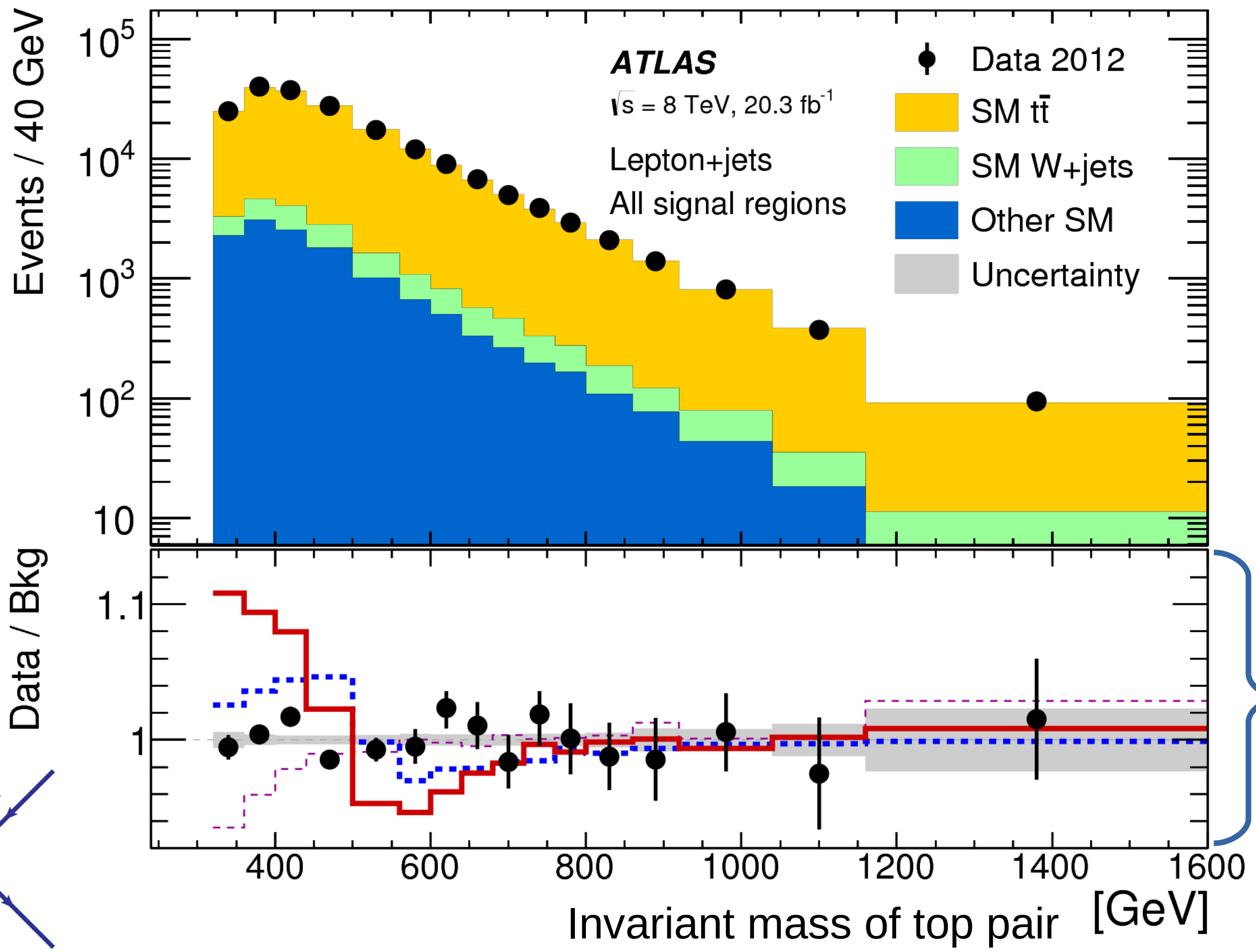
> Need cutting edge methods → on-going research @ DESY



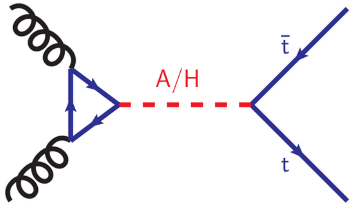




A final signal region



Need to quantify agreement between data and SM prediction



Statistical analysis

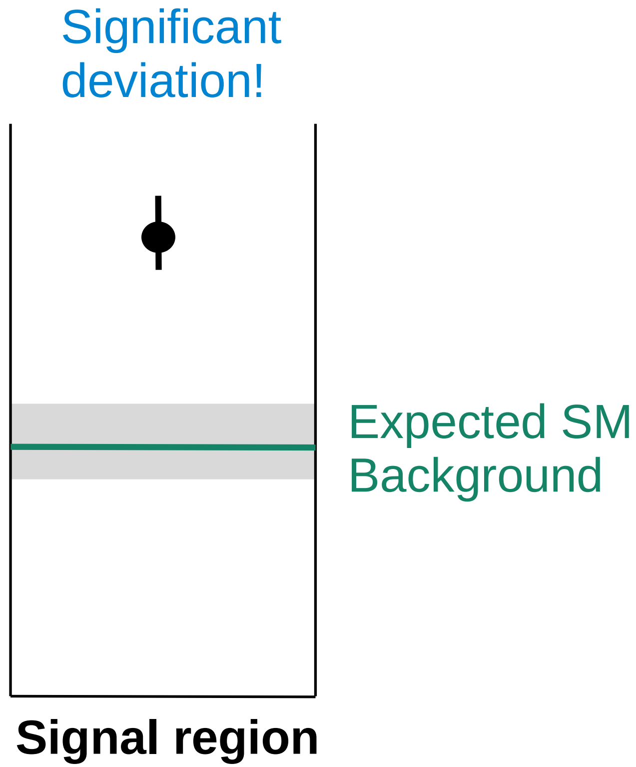
> Two statistical analysis stages in BSM searches:

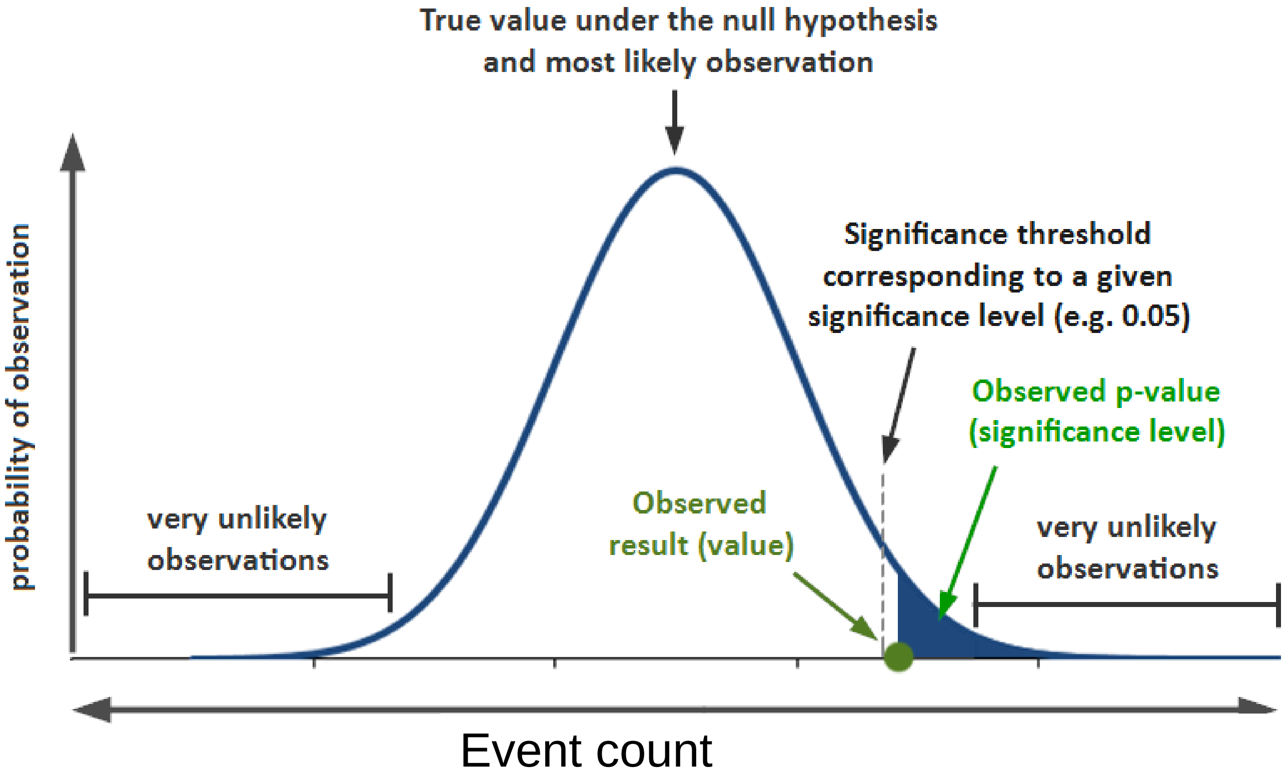
  – Quantify agreement between data and SM prediction (*“Any interesting deviation?”*)

  – Quantify (dis)agreement between data and BSM hypothesis (*“limit setting”*)

Step 1: quantify agreement with SM prediction

- Null hypothesis H_0: SM only, no BSM
- **p-value**: probability that H_0 produces deviation at least as extreme as the one observed
- Simple example: cut-and-count



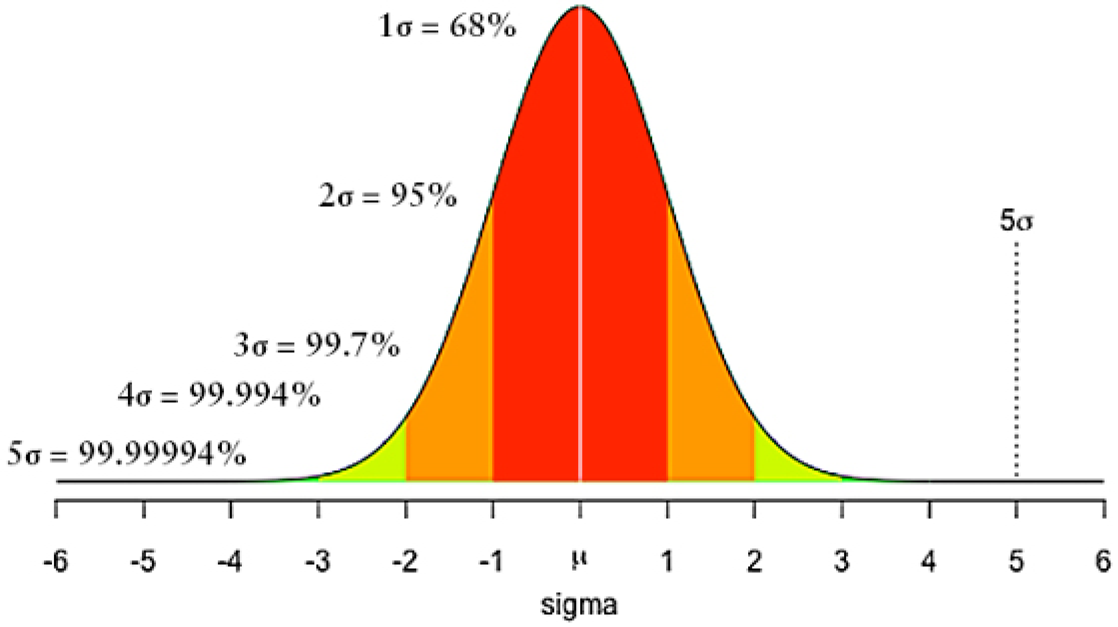


Step 1: quantify agreement with SM prediction

- Null hypothesis H_0: SM only, no BSM
- **p-value**: probability that H_0 produces deviation at least as extreme as the one observed
- Or quote **significance** instead:

$$Z = \Phi^{-1}(1 - p),$$

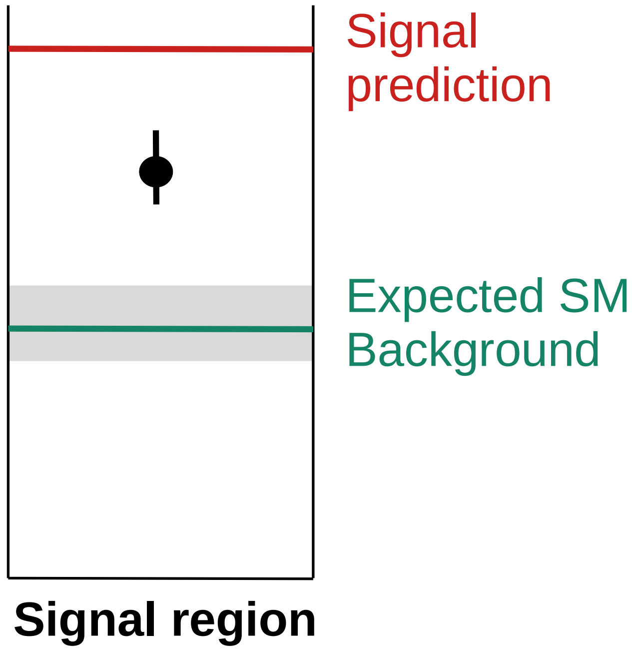
- where Φ^{-1} is inverse of cumulative Gaussian

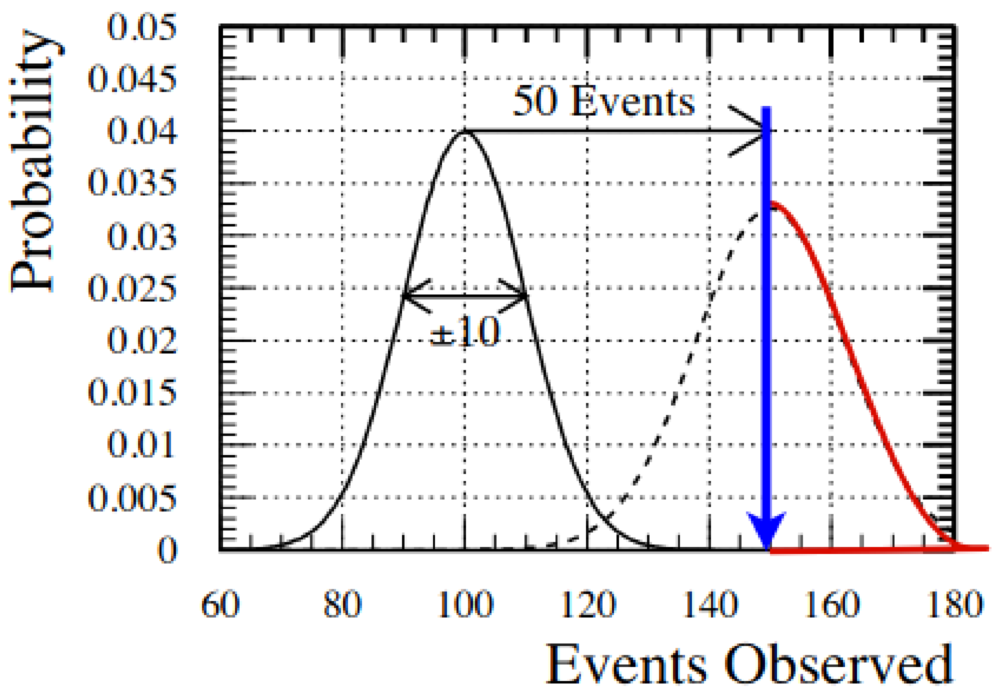


Step 2: Quantify agreement with BSM hypothesis H_1

> If excess was found: test agreement with BSM … and open the champagne ;)

> If no excess was found: test degree to which H_1 is excluded by data (limit setting)



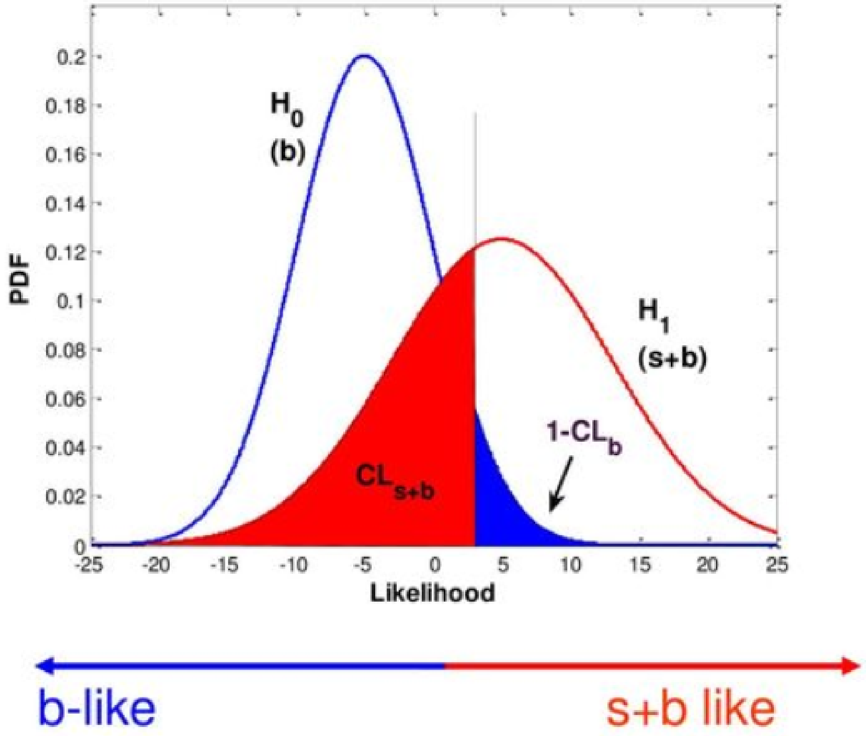


Step 2: Quantify agreement with BSM hypothesis H_1

> Usually, setup is more complicated: many bins, many signal regions

> Construct a likelihood function that quantifies data/MC agreement in all bins

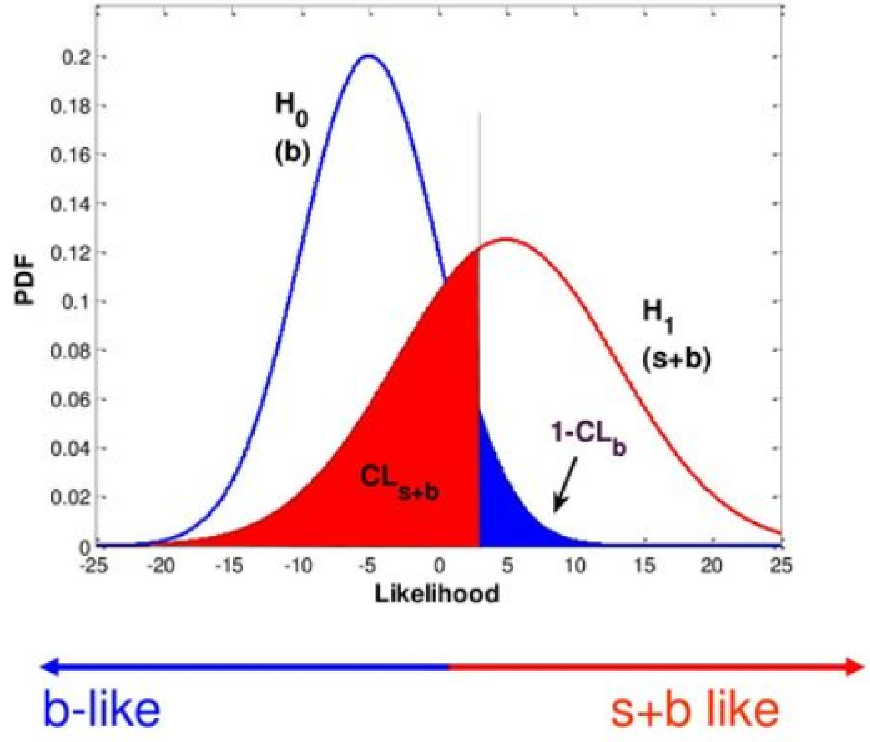
$$L(D|\mu,\boldsymbol{\theta}) = \underbrace{\prod_{j=1}^{M}\prod_{i=1}^{N}\mathrm{Pois}(n_{i,j}|\mu,\boldsymbol{\theta})}_{\text{Poisson terms}} \cdot \underbrace{\prod_{\mathrm{NP}} f(\theta^{(\mathrm{NP})})}_{\text{Constraint terms}}$$



Further reading:
Lecture by G. Cowan [link]

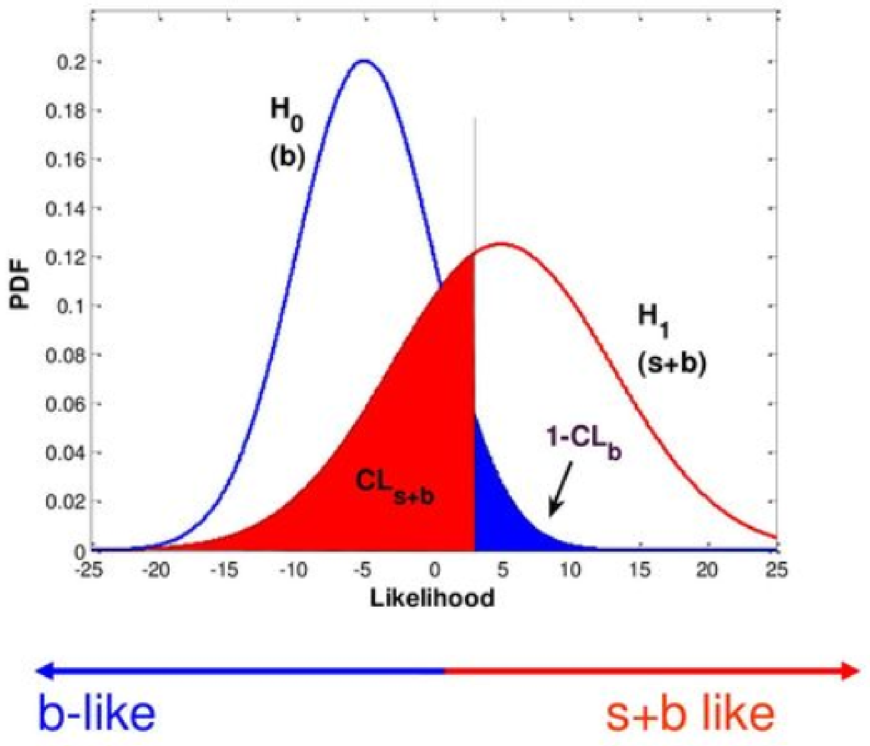
Step 2: Quantify agreement with BSM hypothesis H_1

- CL(s+b) – probability to falsely reject signal because it is too similar to background
- Confidence level
  - H_1 excluded at 95% CL if $CL(s+b) < 0.05$



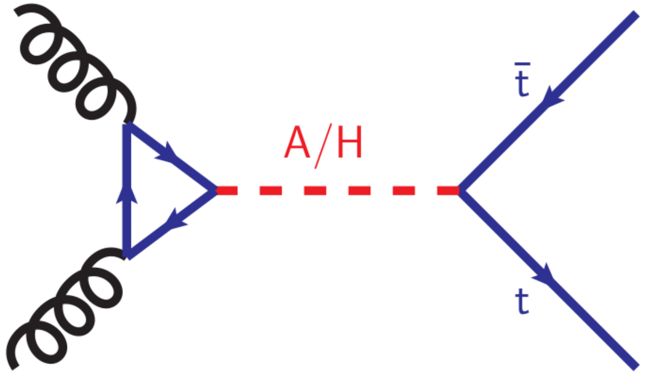
Step 2: Quantify agreement with BSM hypothesis H_1

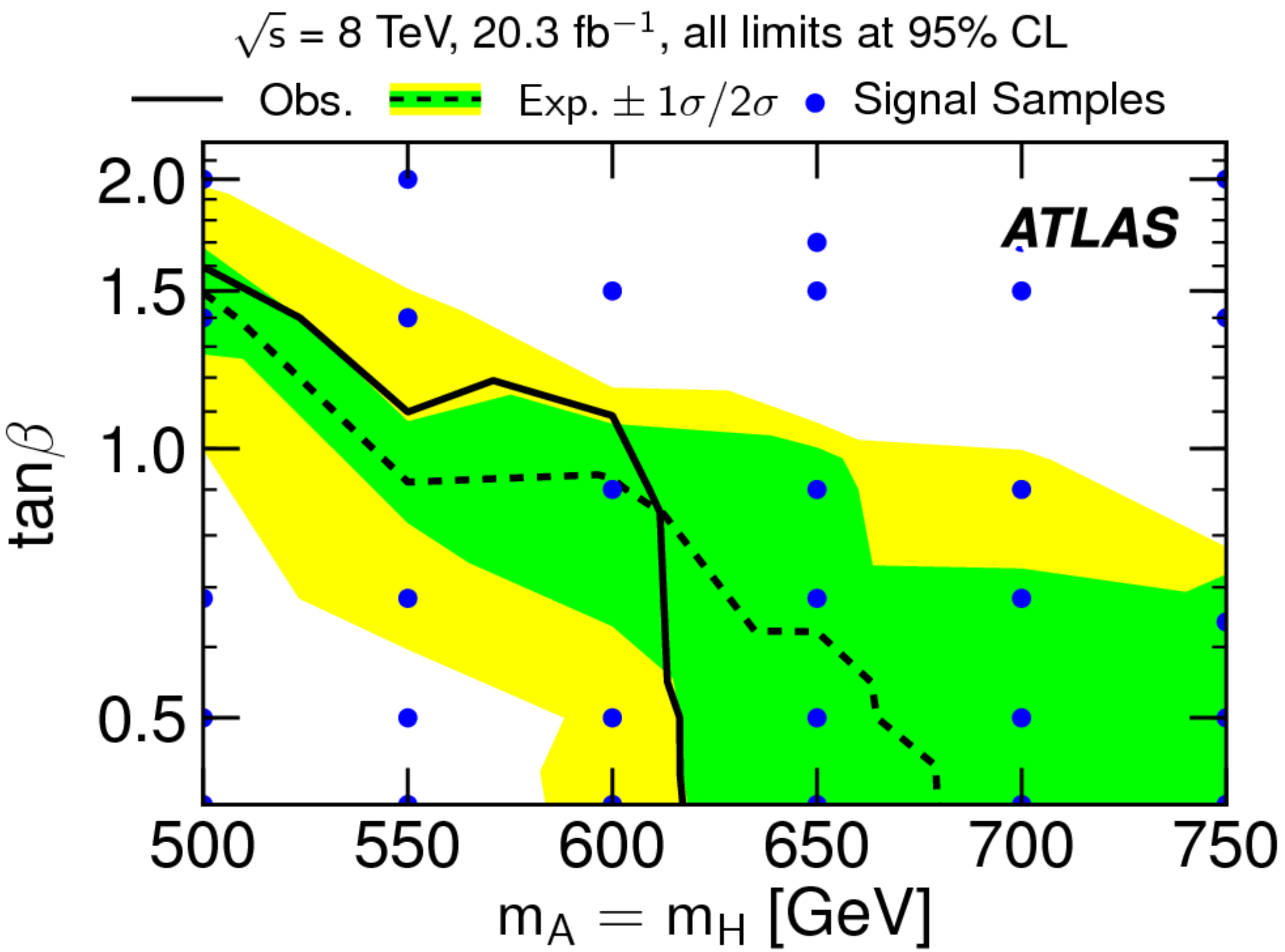
- Problem:
  - Danger to falsely reject H_1 even if separation between H_1 and H_0 is poor, i.e. sensitivity to H_1 is low
- Solution:
  - CL(s) = CL(s+b)/[1-CL(b)]
- Confidence level
  - H_1 excluded at 95% CL if CL(s) < 0.05



A final result

- The famous “Brazilian” plot, showing observed and expected exclusion limits with error bands



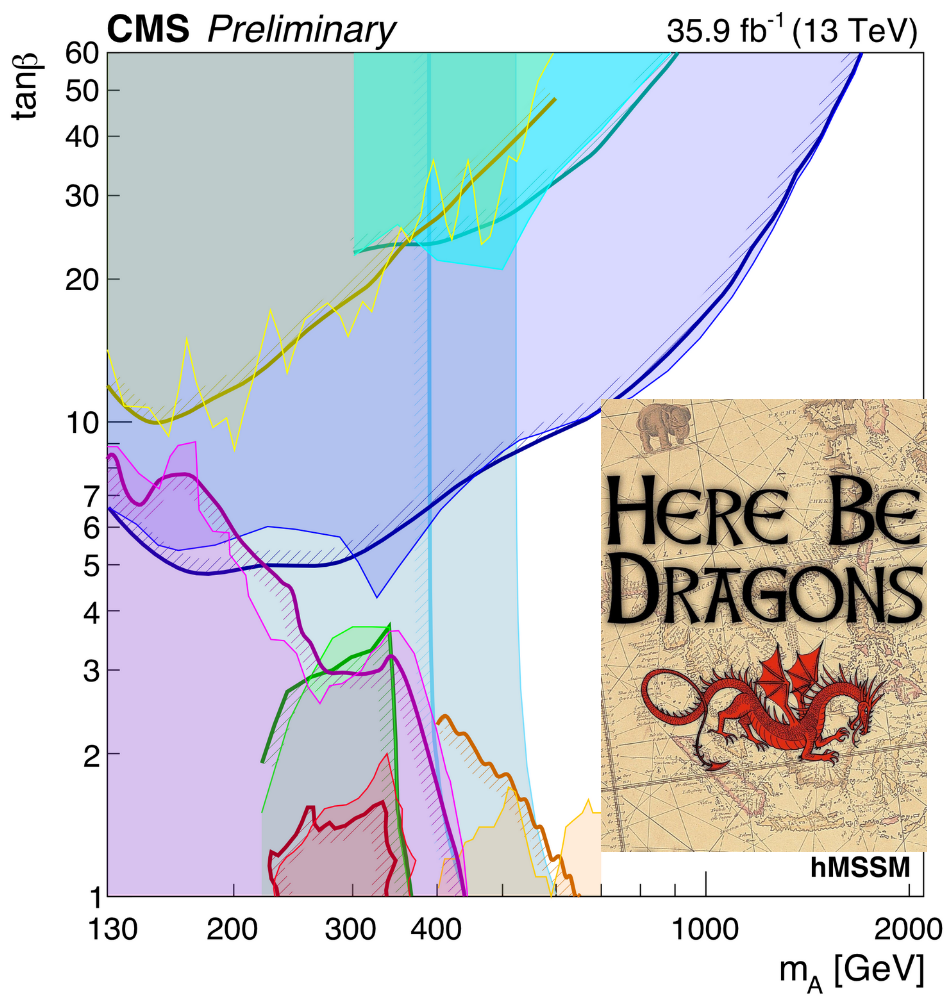


Where do we stand?

> No significant (5σ) deviation from the SM observed so far.

> Results constrain BSM models…

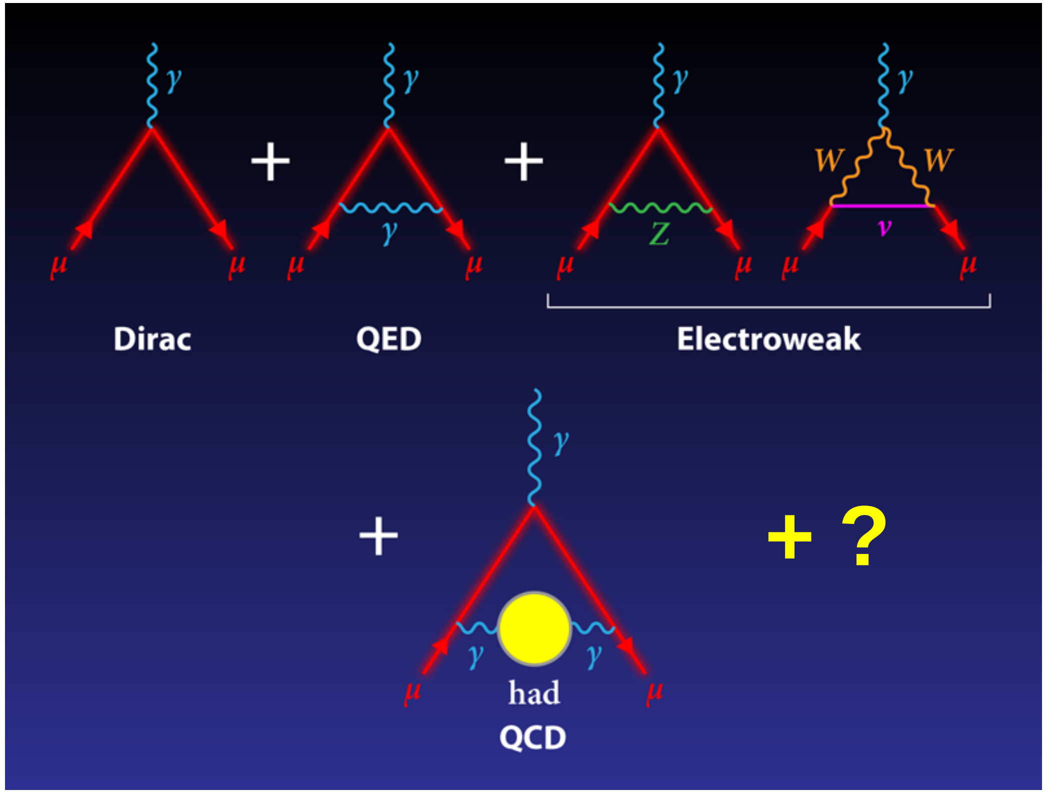
> … and point to uncharted territory!



Muon g-2 (1)

> Anomalous magnetic moment of the muon in analogy to that of the electron

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$



> Loop quantum corrections: $g \neq 2$

> Anomalous magnetic moment: $a = (g-2)/2$

> Sensitive to large range of possible quantum corrections, including possible BSM contributions

Muon g-2 (2)

- Storage ring with polarised muons in magnetic field → measure precession frequency
- Measurements at BNL (2004) first revealed tension with SM of 2.6σ significance
- Confirmed by new Fermilab measurement (2021) at 4.2σ combined significance
  - More data is being taken and analysed