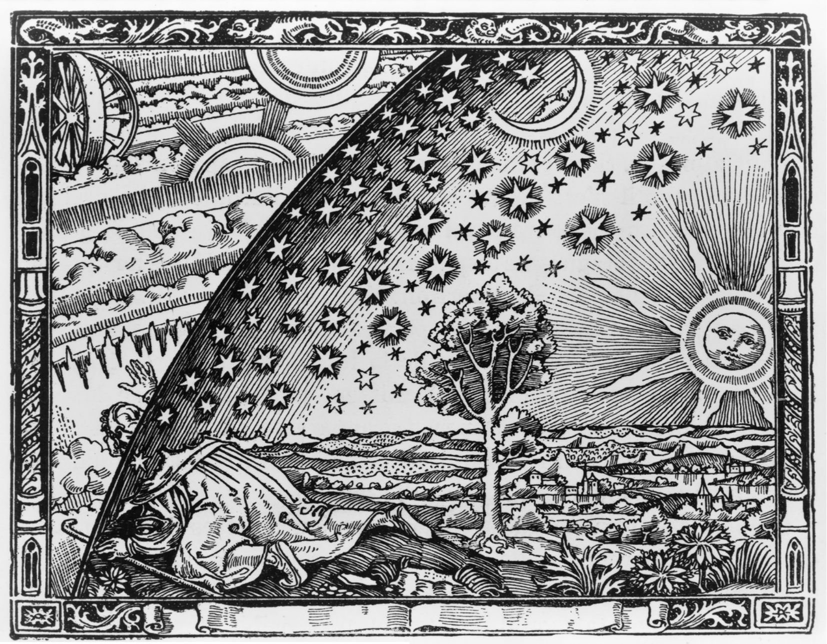
To the Higgs and beyond

Hamburg International Summer School
14 – 25 July 2025

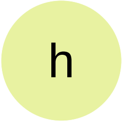


Katharina Behr

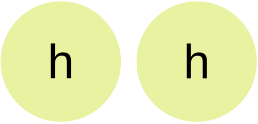
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
ATLAS EXPERIMENT
DESY.

Outline

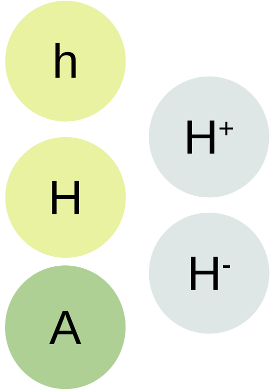
- **Part 1: The vacuum is not empty**
  - The Higgs boson in the Standard Model
  - Characterization of the Higgs boson since its discovery

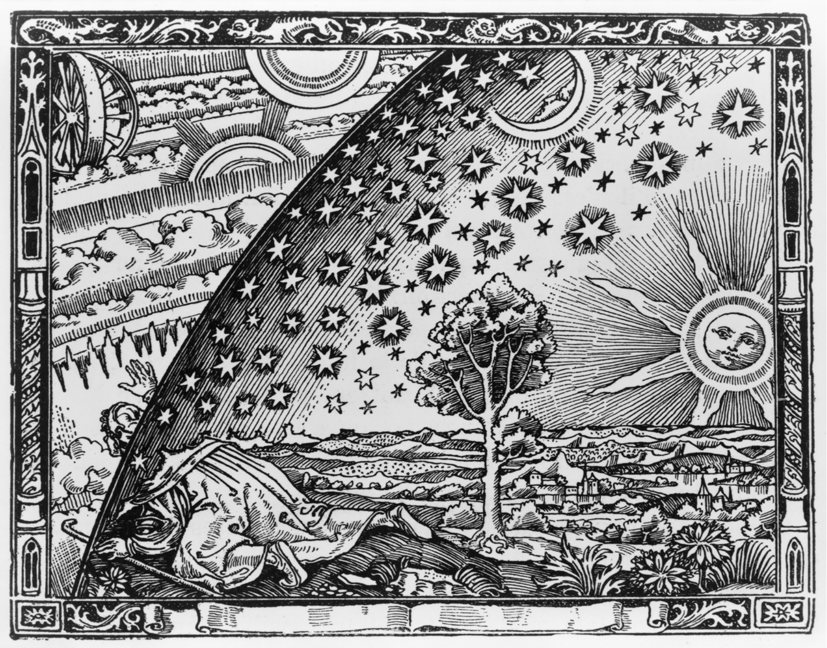


- **Part 2: What is the fingerprint of the vacuum?**
  - Unravelling the Higgs potential
  - Higgs boson pair production
  - Extra: Triple Higgs production
  - Outlook: the future of the LHC and beyond



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





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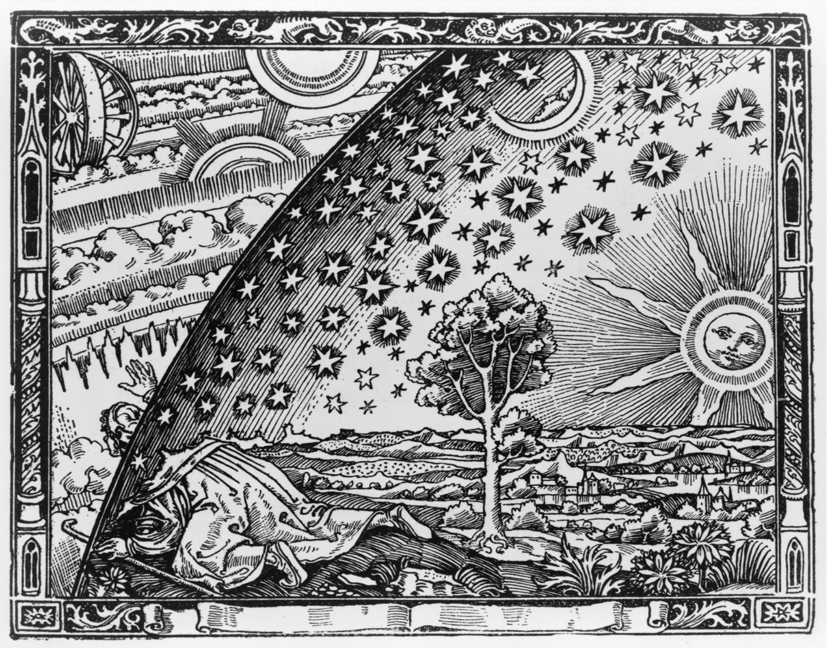
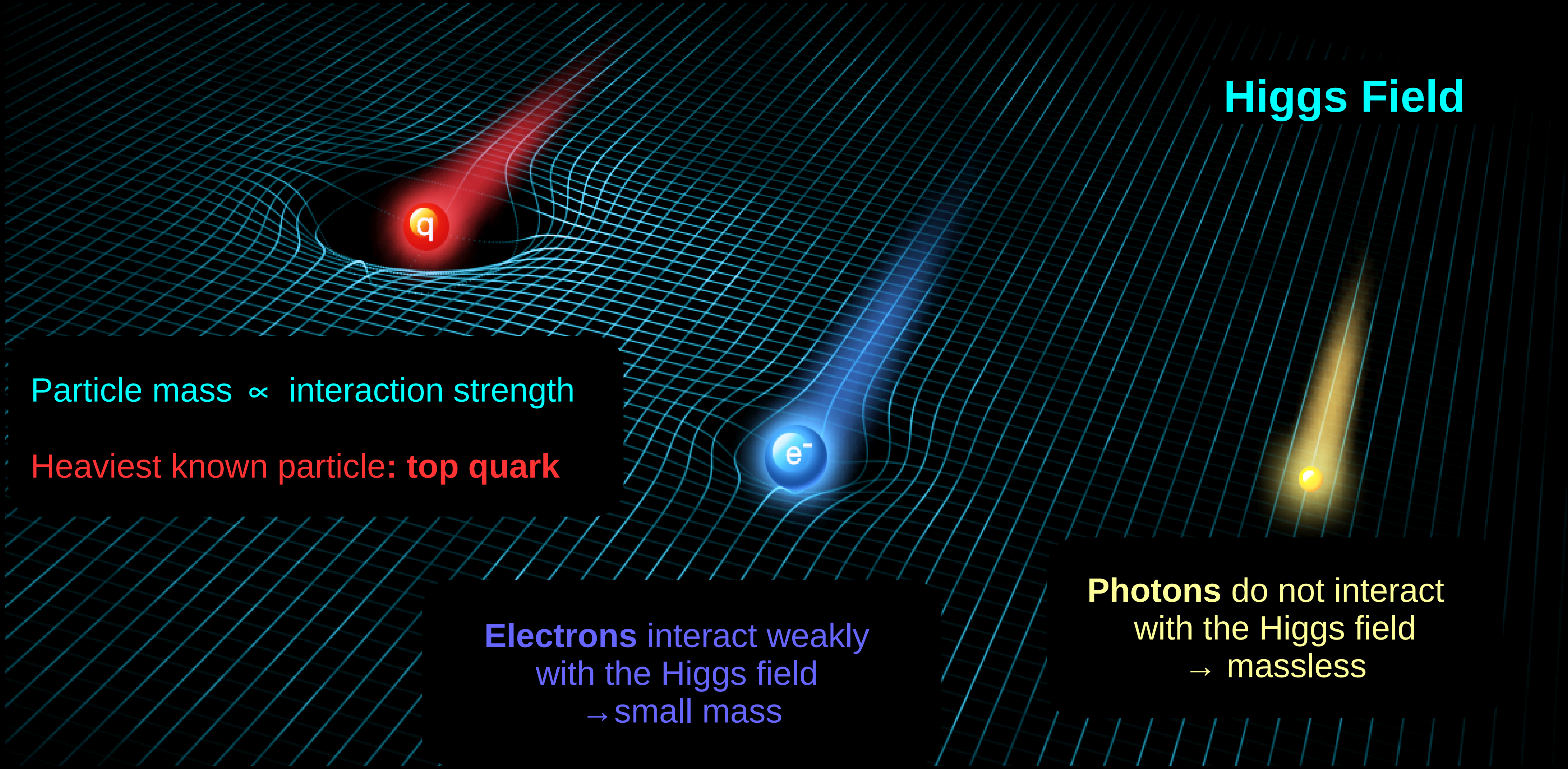
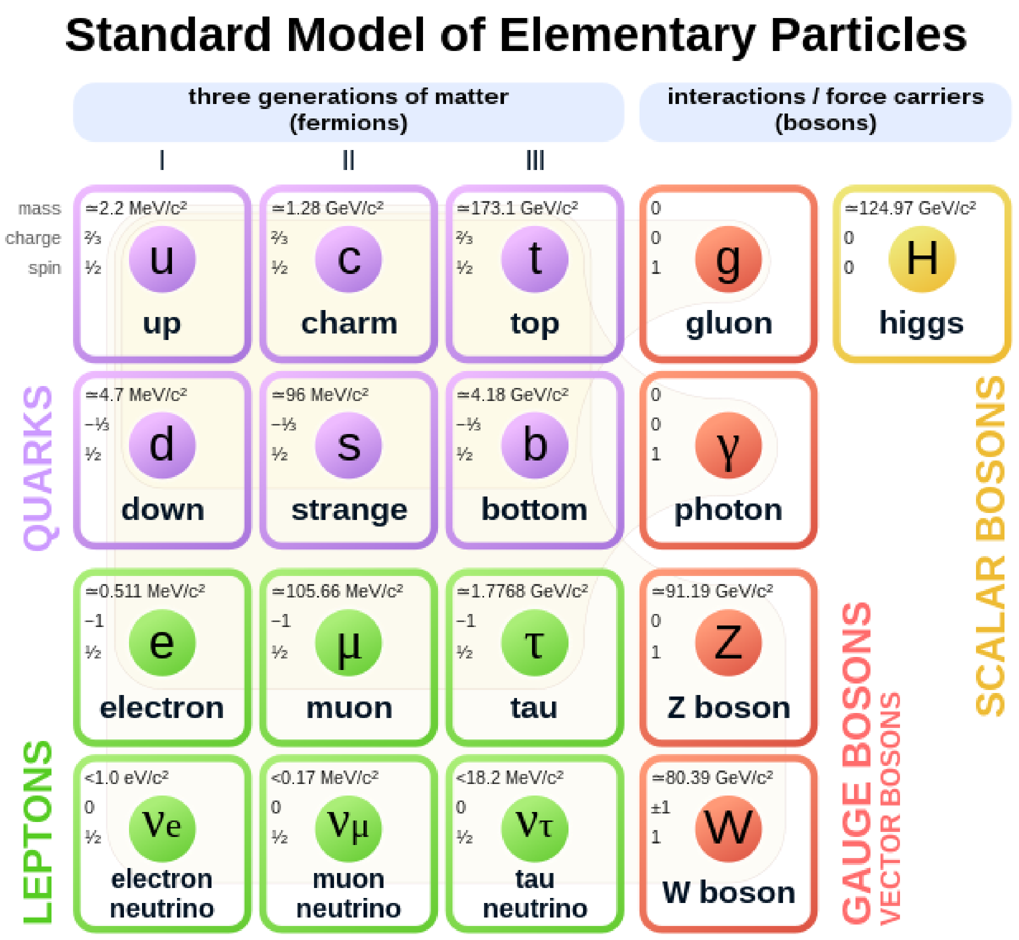


What is the vacuum?



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

Why do we need a Higgs field?



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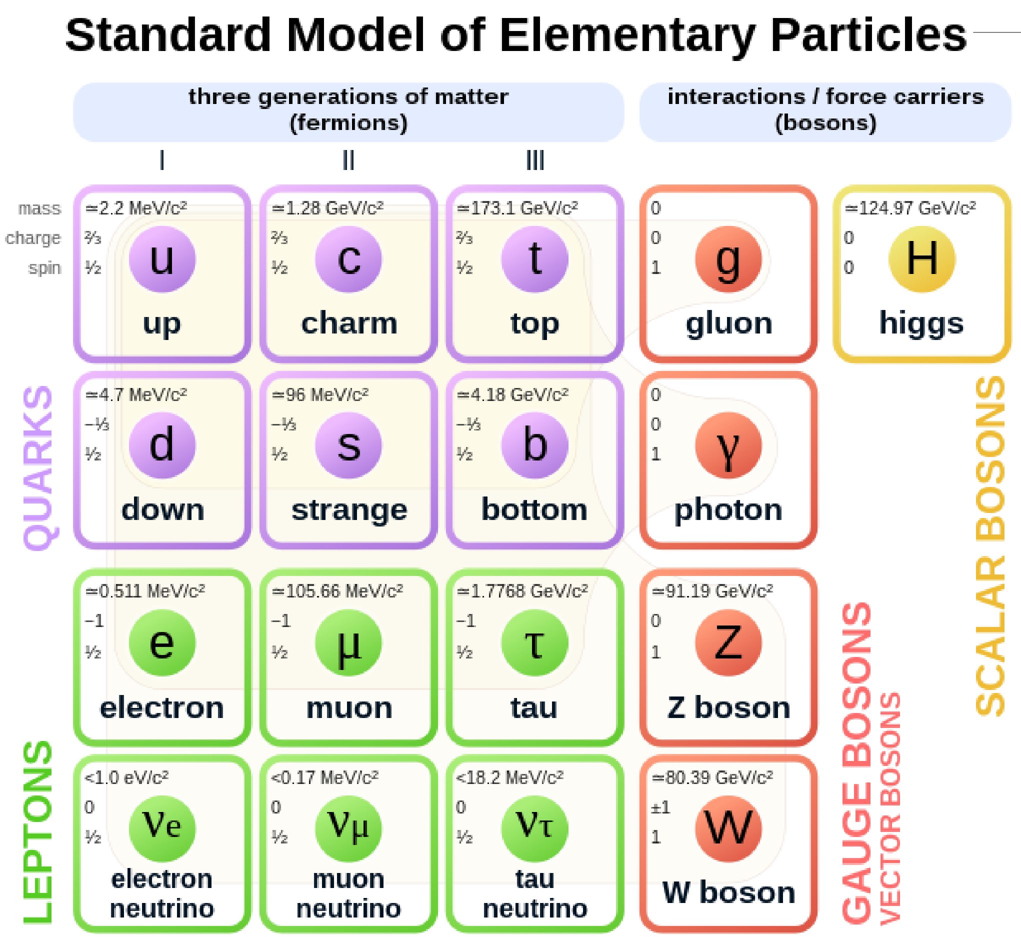


Gauge theory:

$SU(3)_C \times SU(2)_L \times U(1)_Y$

strong force

electroweak force

Each gauge group represents a symmetry of the Standard Model

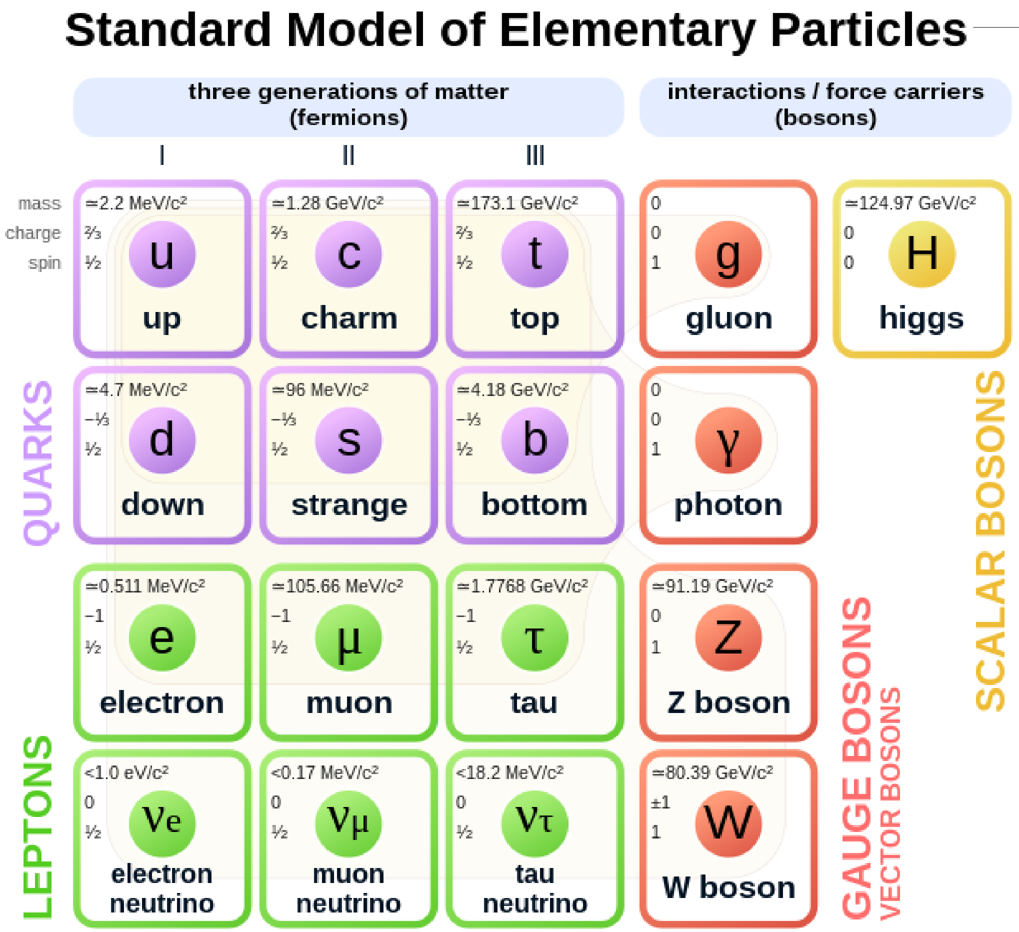
Noether' theorem

Each symmetry corresponds to a conserved charge

E.g. colour charge for the strong force

Why do we need a Higgs field?

Caveat:
Assumes massless gauge bosons!



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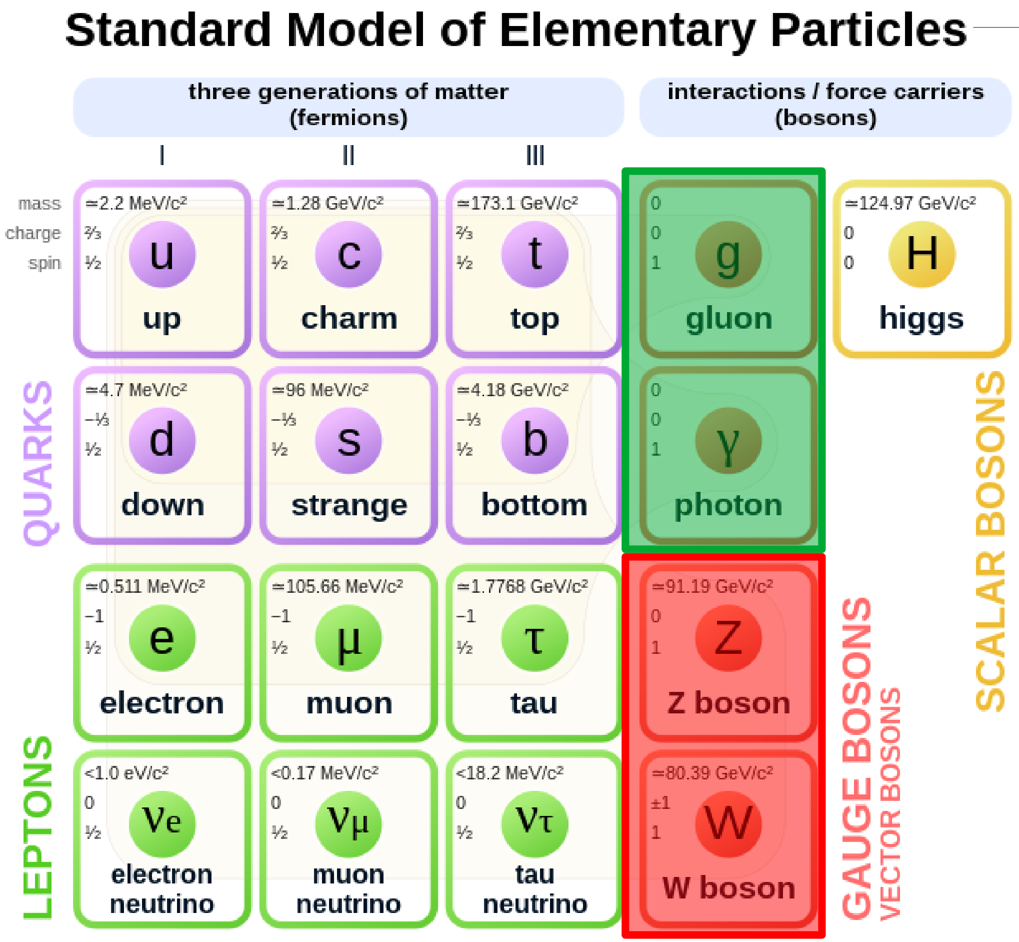
Massless: g, y

Very massive: W, Z



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How can we make gauge bosons massive?

> 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

Mass 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

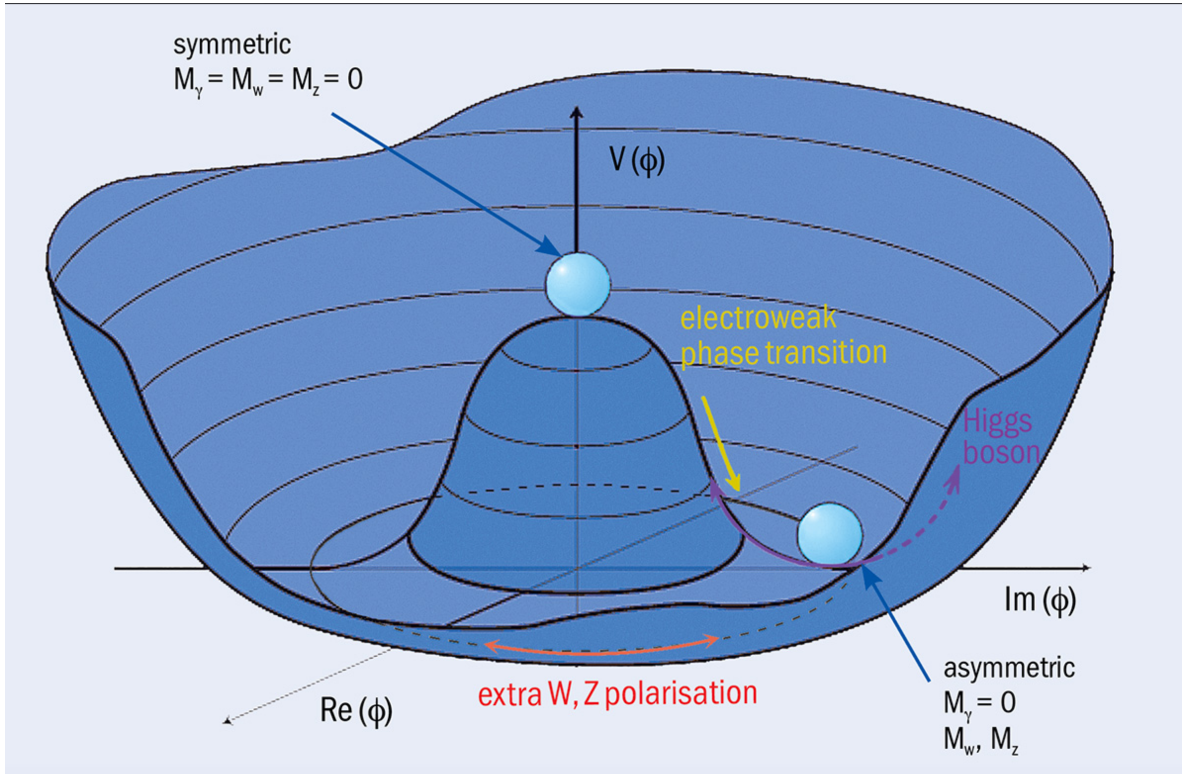
$$A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \eta(x)$$

The (Brout-Englert-) Higgs mechanism: idea

- Add a new scalar field ϕ to the SM: Higgs field
- Trick: this field has a Mexican hat potential
  - Potential as a whole is symmetric under gauge transformation
  - Its ground state(s) are not
- Spontaneous symmetry breaking!
- Dynamically generates W and Z boson masses

Gauge transformation

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



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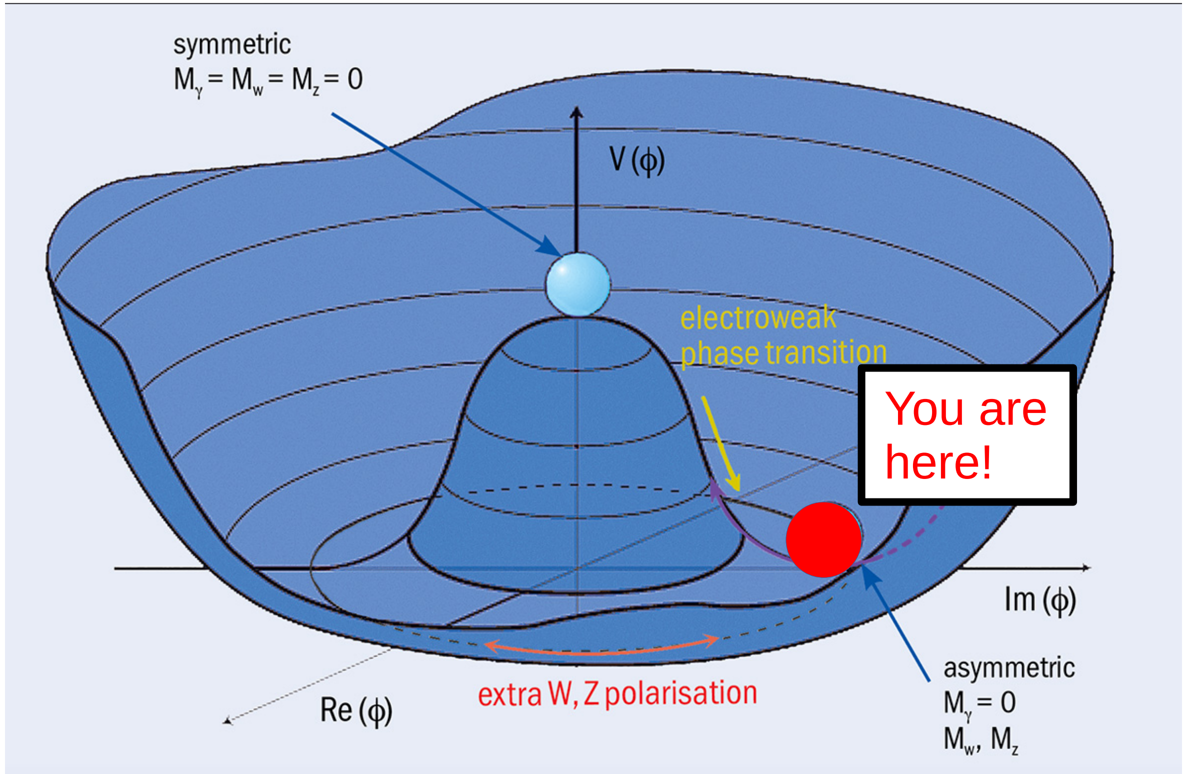

The (Brout-Englert-) Higgs mechanism: Lagrangian

> Extend Lagrangian by Higgs kinetic and potential terms:

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

Kinetic term

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

Potential term

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

Invariant under gauge transformation:

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x),$$
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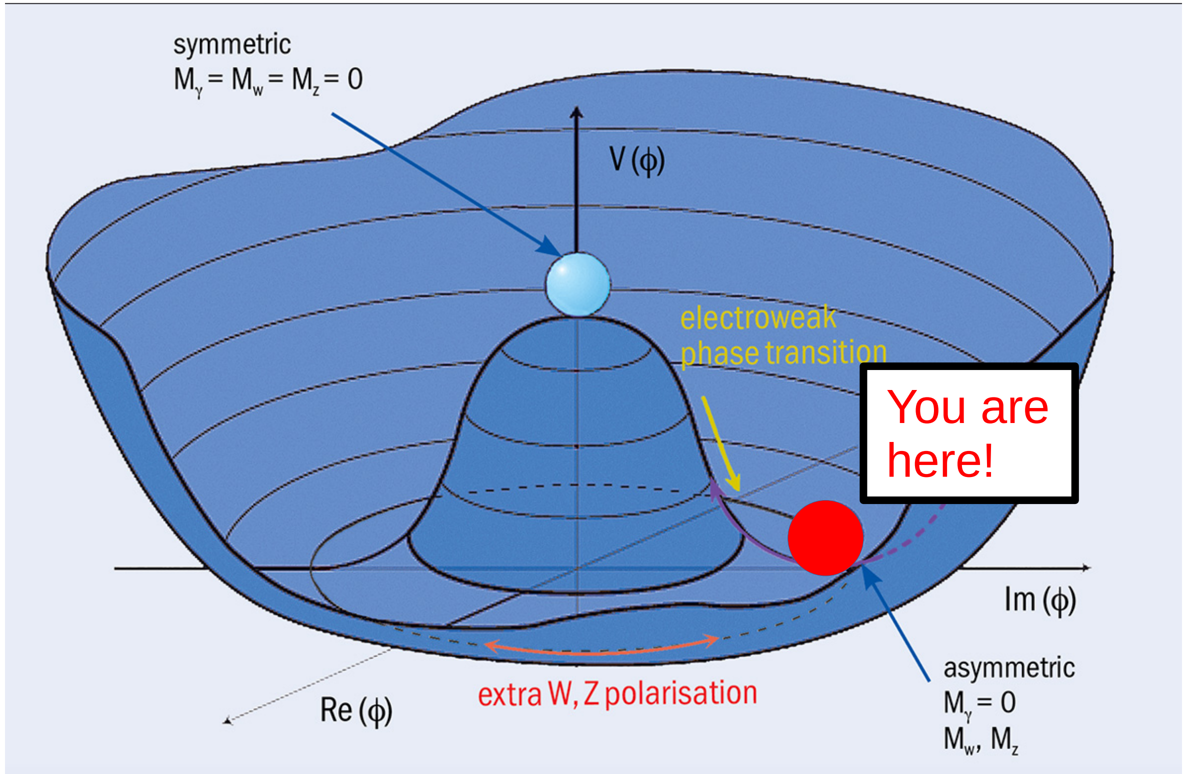

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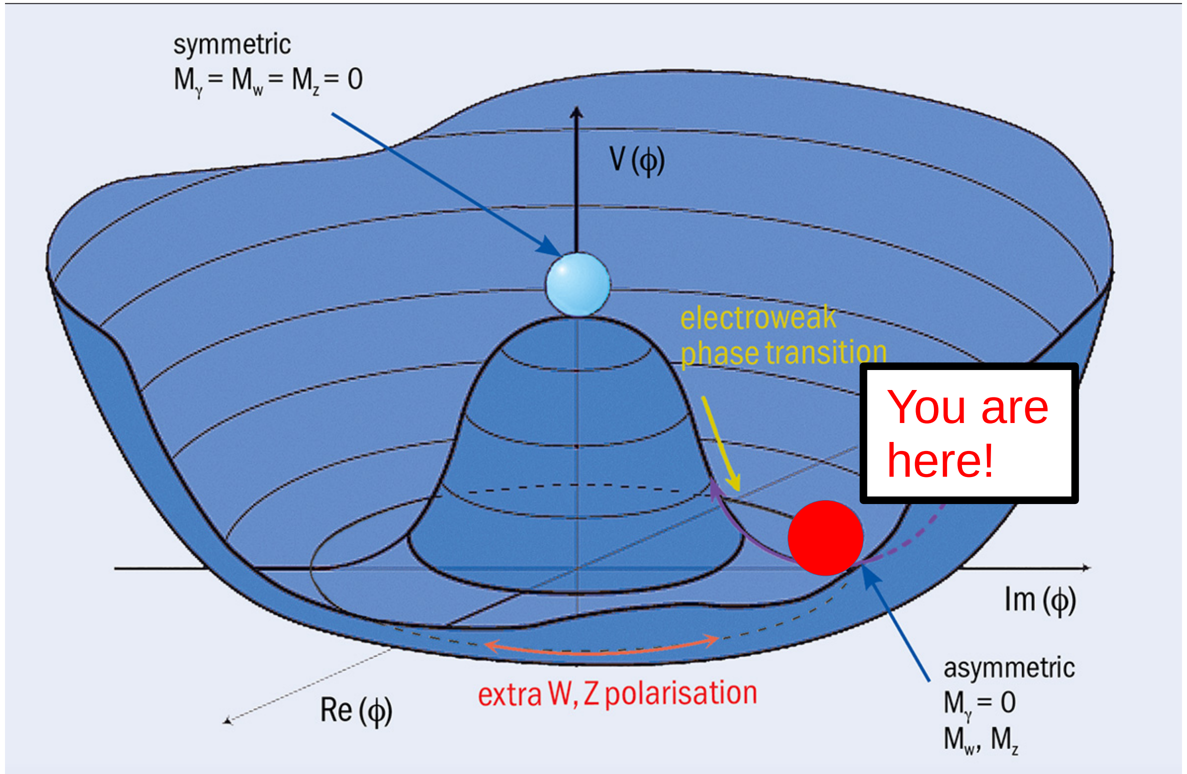
$$\phi(x) \to e^{ie\eta(x)} \phi(x).$$

> Here for simplicity: complex scalar field (2 degrees of freedom)

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

> In fact: complex iso-spin doublet (4 degrees of freedom)

$$\Phi = \sqrt{\frac{1}{2}} \begin{pmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{pmatrix} = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$$



Spontaneous symmetry breaking

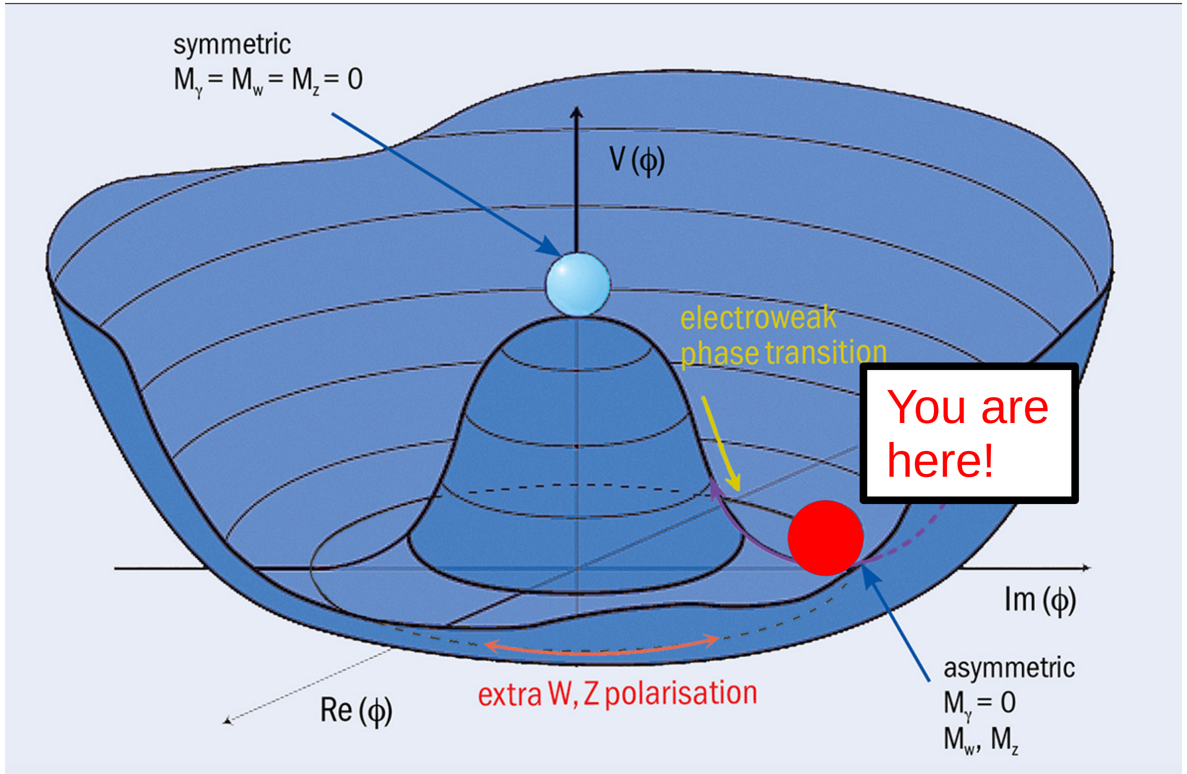
> Ground state(s) with non-zero vacuum expectation value

$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Vacuum expectation value

> v determined by EW precision measurements

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



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Vacuum expectation value

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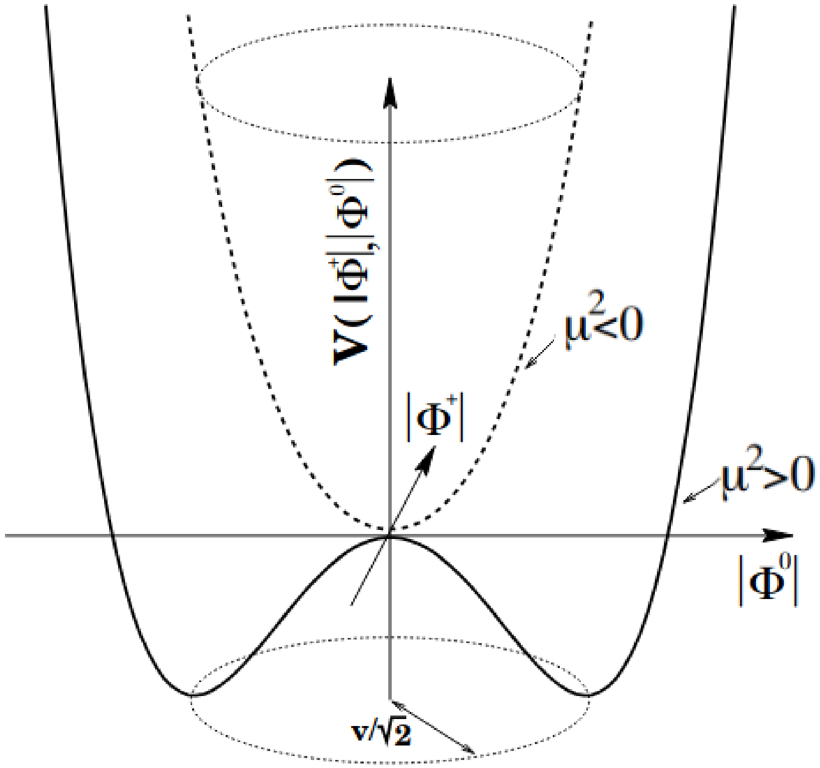


> v determined by EW precision measurements

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

> “Distance” of ground-state from zero: $v = \sqrt{\frac{\mu^2}{\lambda}}$.

How does this relate to physical quantities?

- Expand around the EW vacuum (minimum)

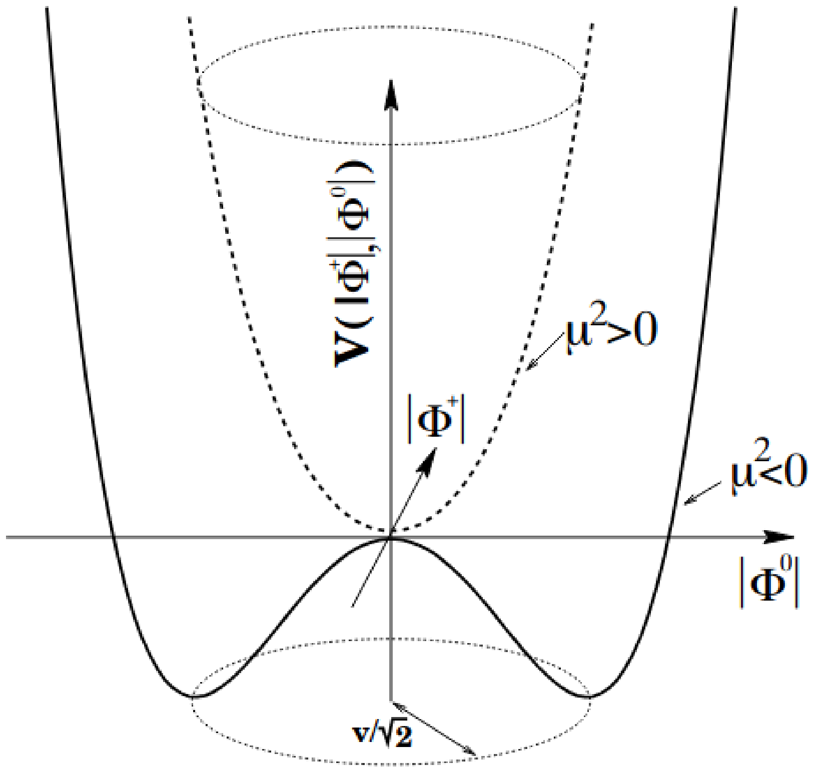
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

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

- Reparameterise in terms of Higgs mass m_h and v

$$\lambda = \frac{m_h^2}{2v^2}. \qquad v = \sqrt{\frac{\mu^2}{\lambda}}.$$

- Only free parameter of Higgs mechanism: m_h



Gauge boson mass!

> Rewrite original Lagrangian after symmetry breaking and expansion

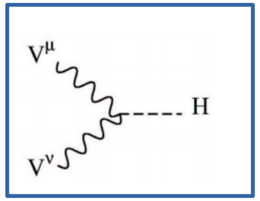
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^\dagger (D^\mu\phi) - V(\phi)$$

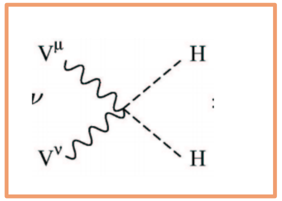
One degree of freedom field ϕ:
absorbed into this mass term*

Second degree of freedom:
yields the Higgs field

Mass term!

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu h)^2 + \underbrace{\frac{1}{2}e^2v^2A_\mu A^\mu}_{\text{Gauge boson mass term}} + e^2vhA_\mu A^\mu + \frac{1}{2}e^2h^2A_\mu A^\mu - V(h)$$





*For experts: This degree of freedom would show up as a massless scalar “Goldstone” boson if we had not expanded around the minimum.

The full Higgs Lagrangian

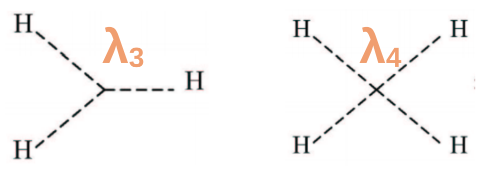
> Expanding around the vacuum expectation value

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

$$+ \frac{2M_W^2}{v} h W_\mu^+ W^{\mu -} + \frac{M_Z^2}{v} h Z_\mu Z^\mu + \frac{M_W^2}{v^2} h^2 W_\mu^+ W^{\mu -} + \frac{M_Z^2}{2v^2} h^2 Z_\mu Z^\mu$$

The full Higgs Lagrangian

- 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

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> 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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The full Higgs Lagrangian

> 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

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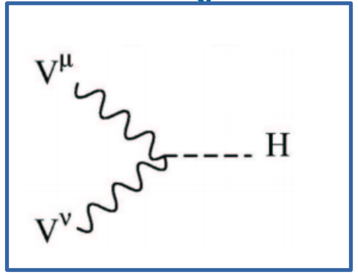
Single Higgs to boson couplings
→ more on this later!



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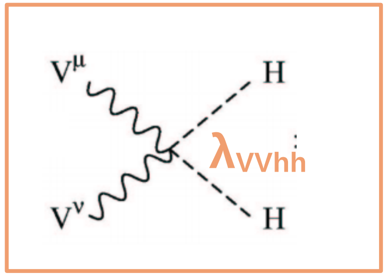


Di-Higgs to di-boson coupling (not observed yet)

→ Tomorrow's lecture!

What about Fermion masses?

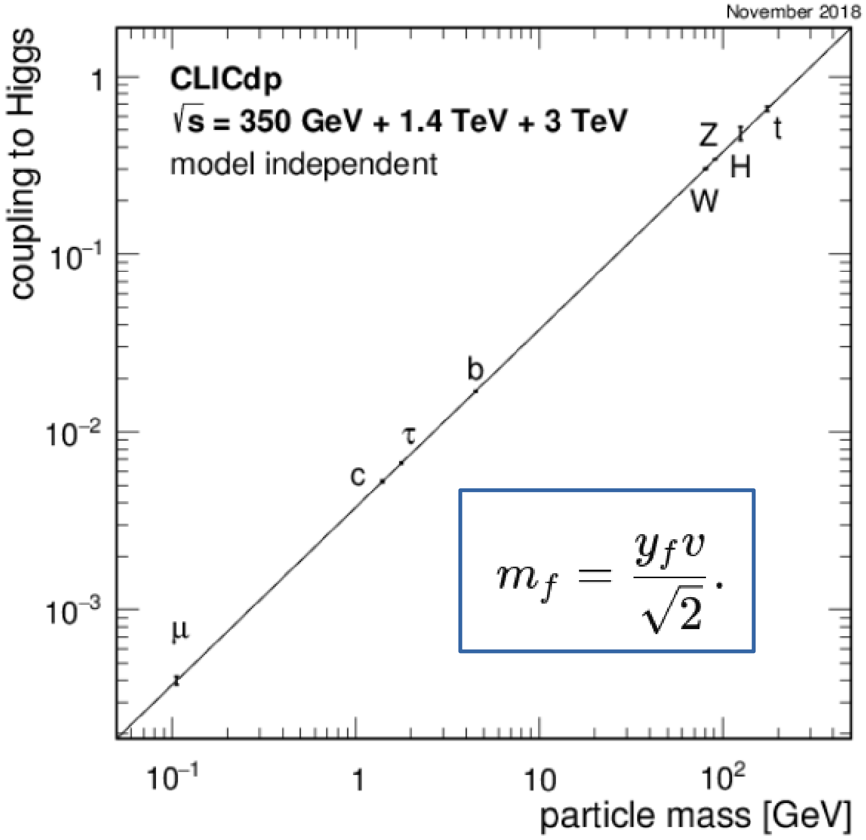
- Ad-hoc assumption: Yukawa-coupling of the Higgs field to fermions

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

- Rewrite after EWSB:

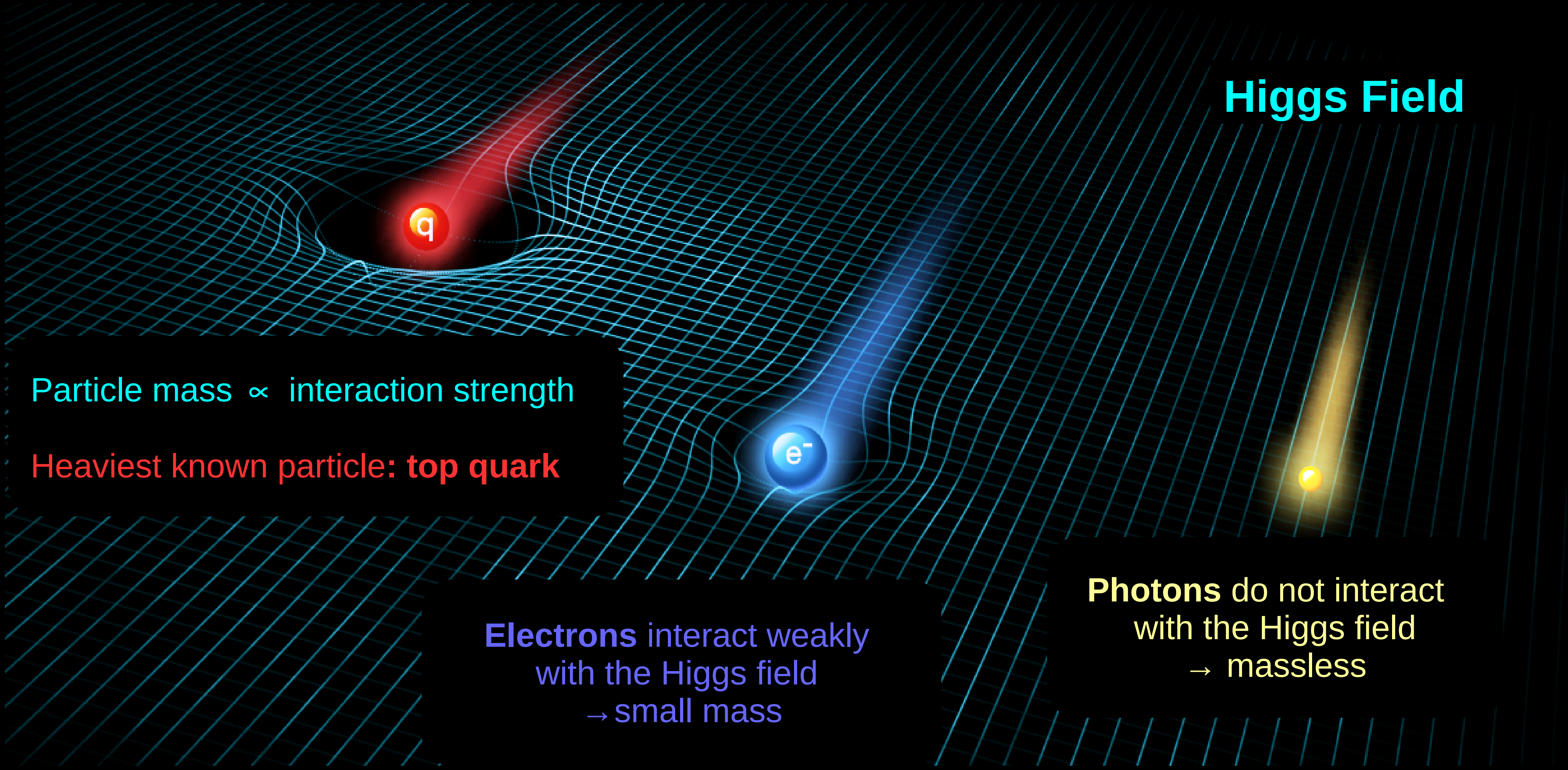
$$\mathcal{L}_{\text{Yukawa}} = -m_f \bar{\psi}\psi - \frac{m_f}{v}\bar{\psi}\psi h$$

- Fermion coupling y_f to Higgs field proportional to fermion mass



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

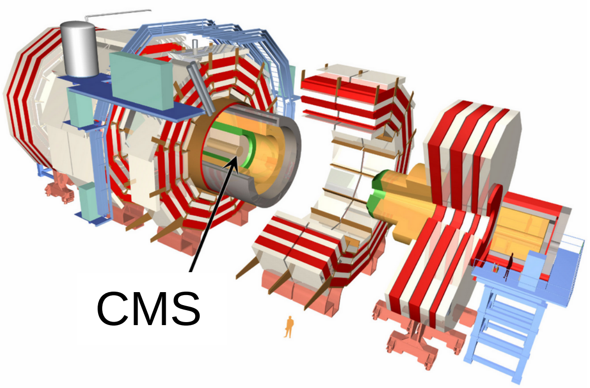
Note: y-axis different for different particle types



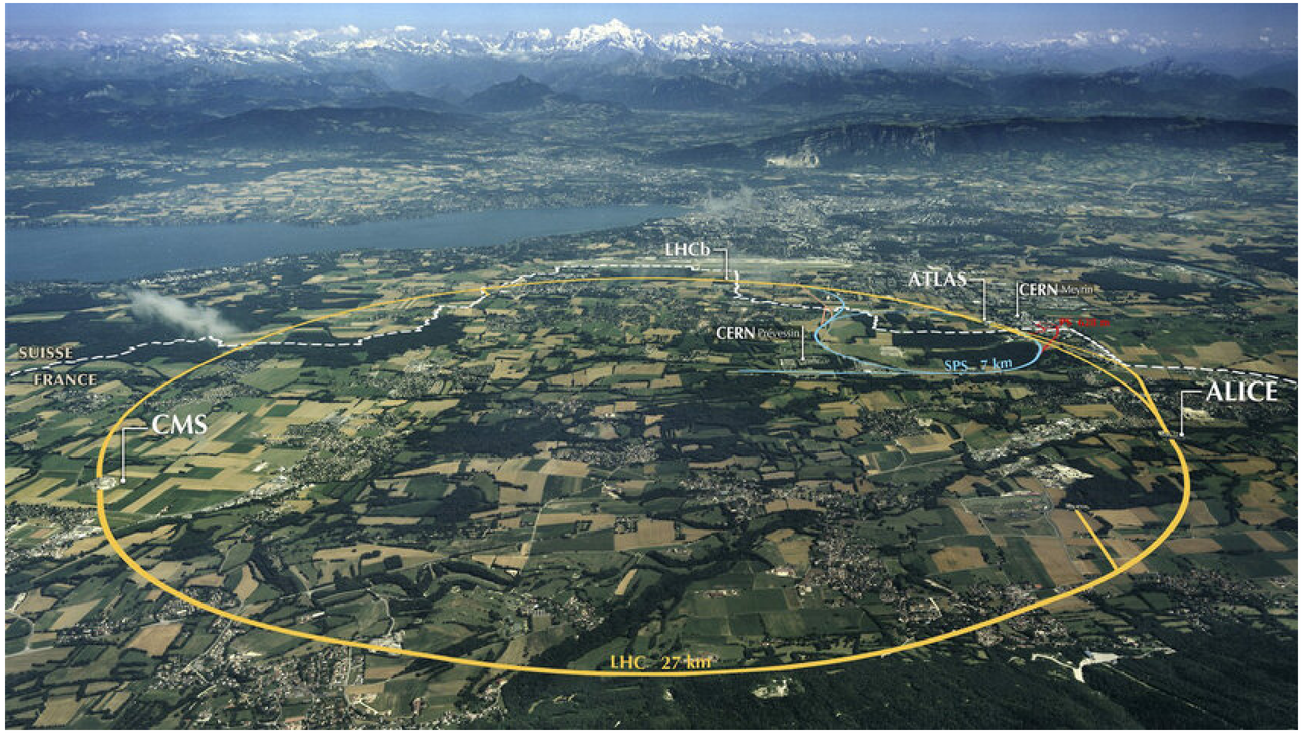
Artistic view of the Higgs field.
Image credit: beyondsciencetv.com

Probing the vacuum with the world's largest microscope

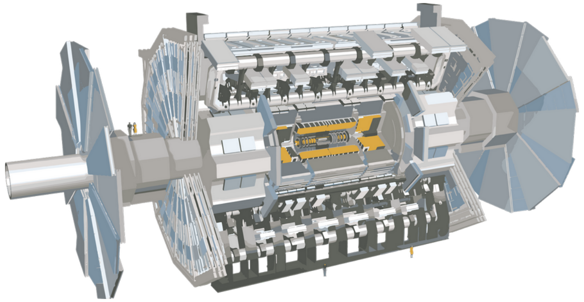
- LHC - the only place in the world capable of producing Higgs bosons.
- ATLAS, CMS – two general-purpose detectors capable of capturing Higgs-boson decay products



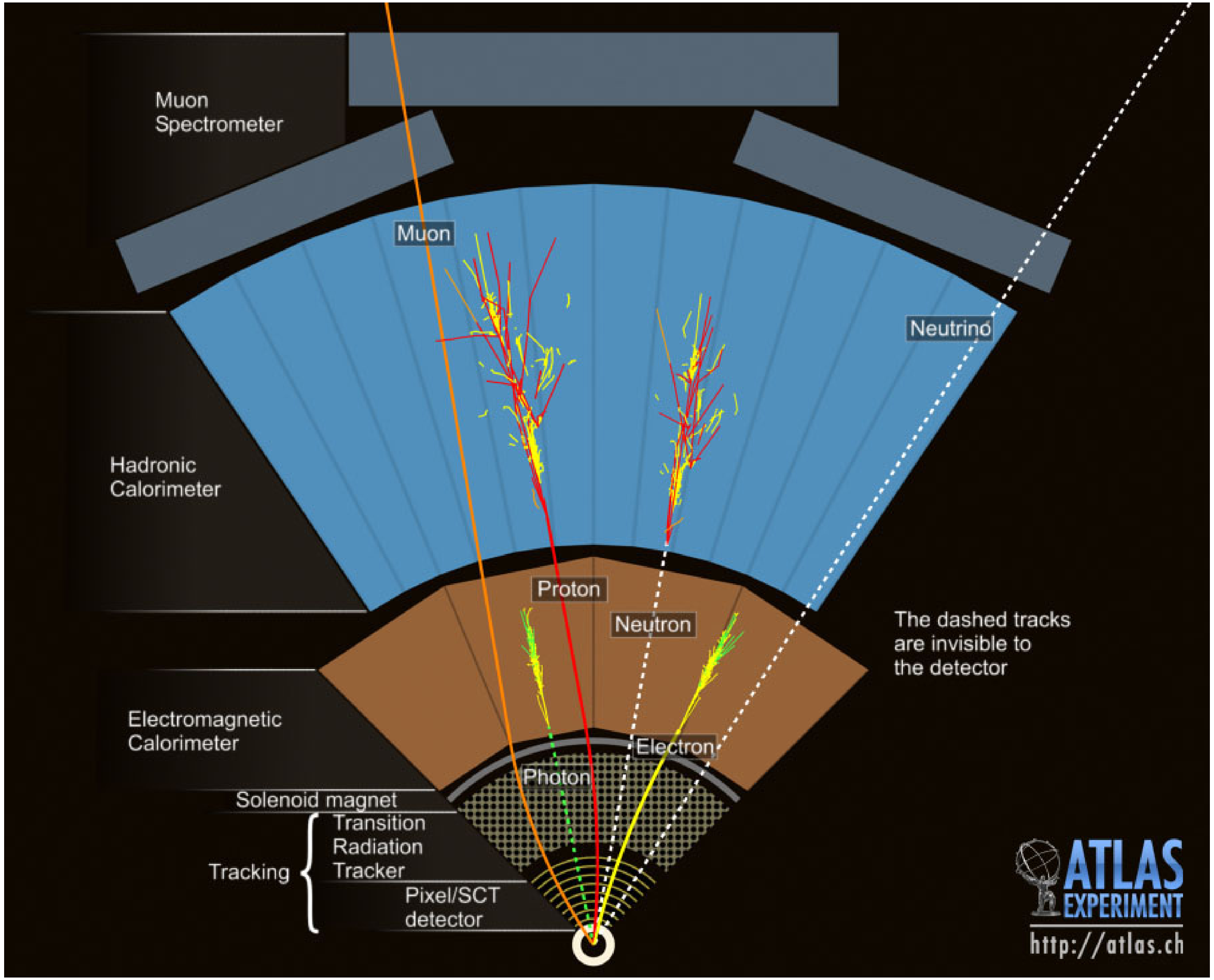
CMS



ATLAS



A closer look at the ATLAS detector

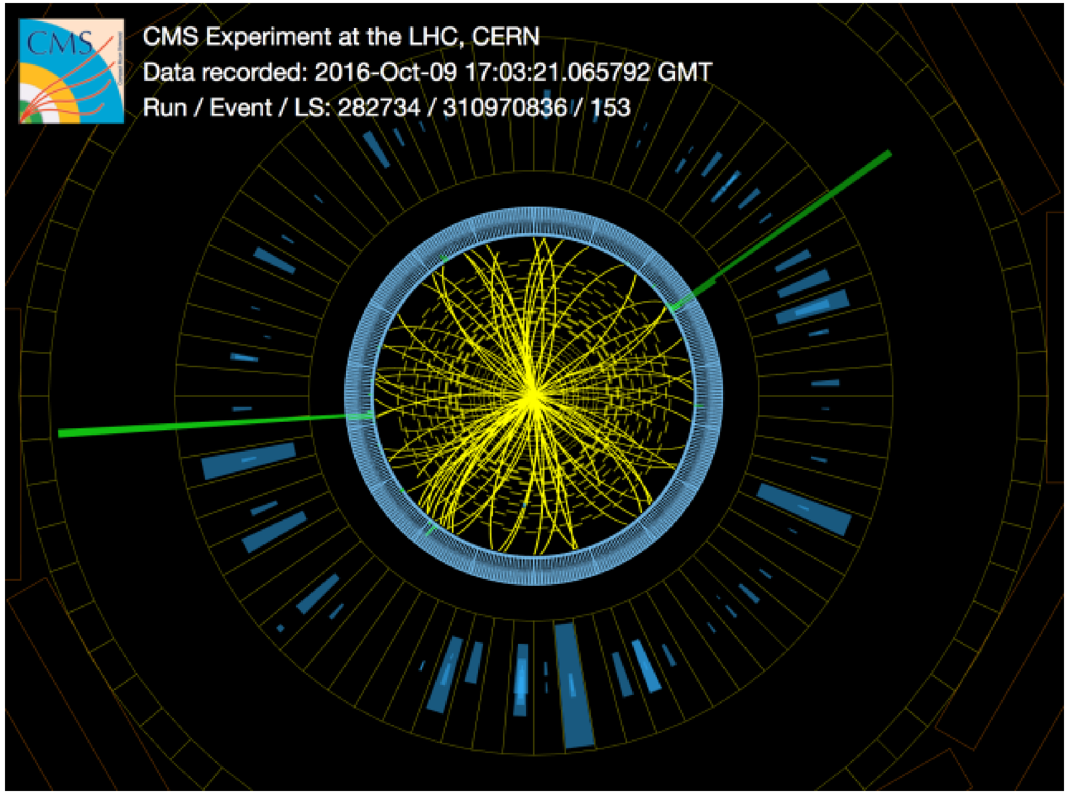


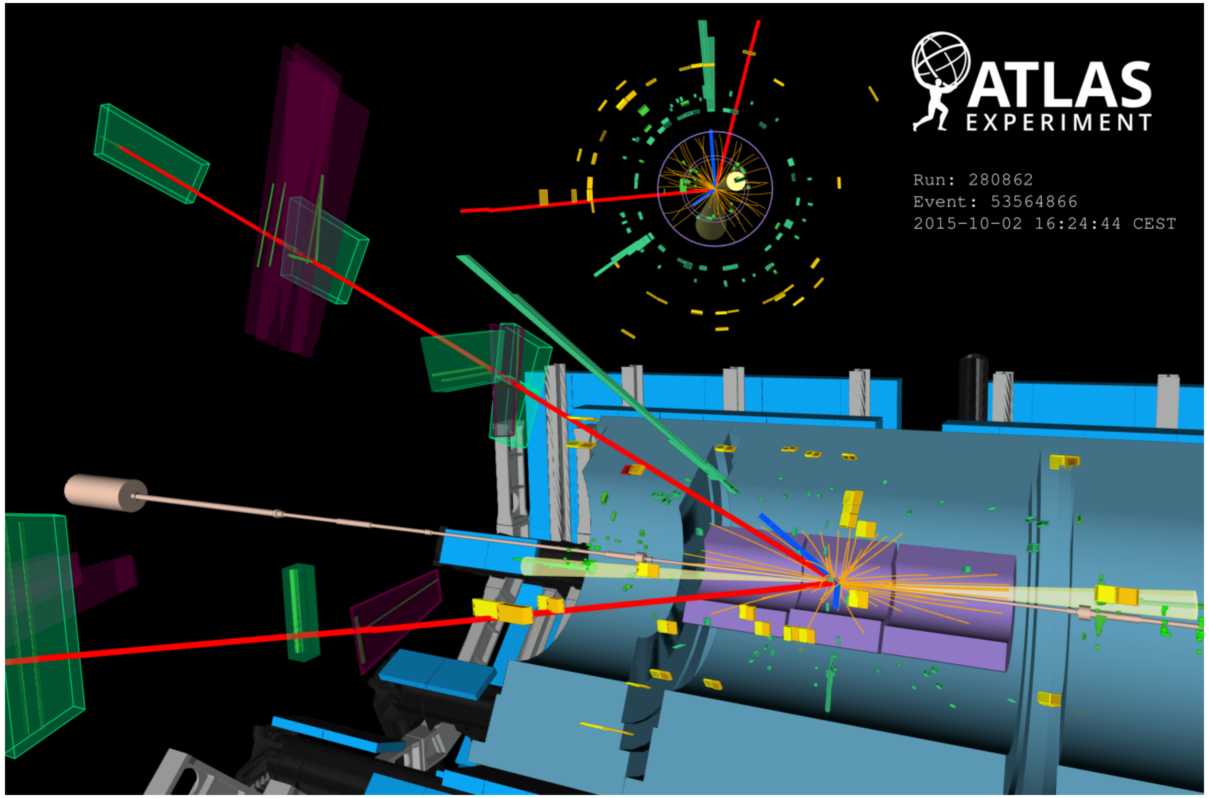
The discovery of a Higgs boson in 2012

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

> Two "golden" Higgs boson decay channels:

- h → γγ
- h → ZZ* → 4l





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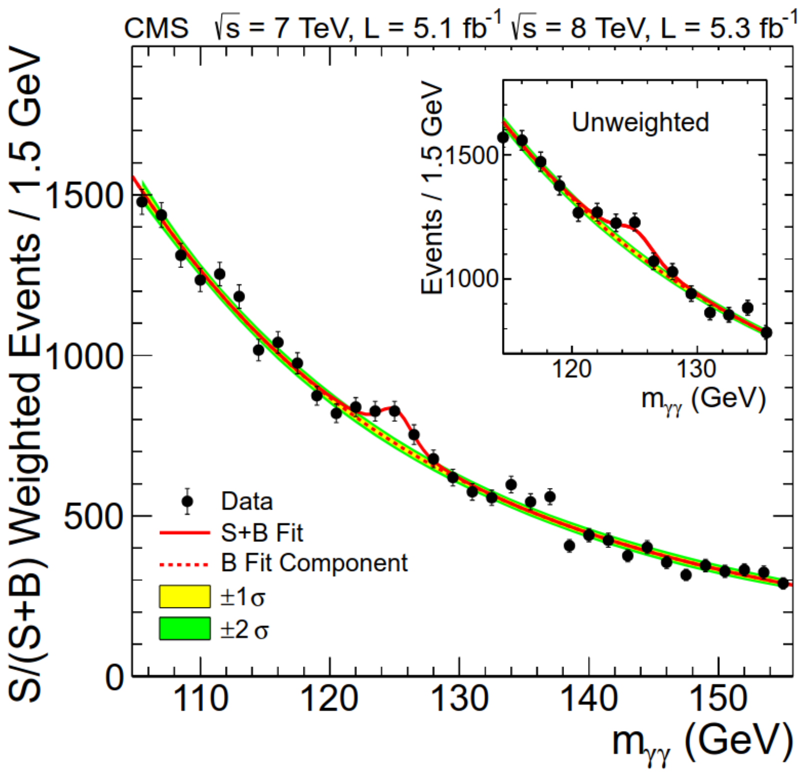
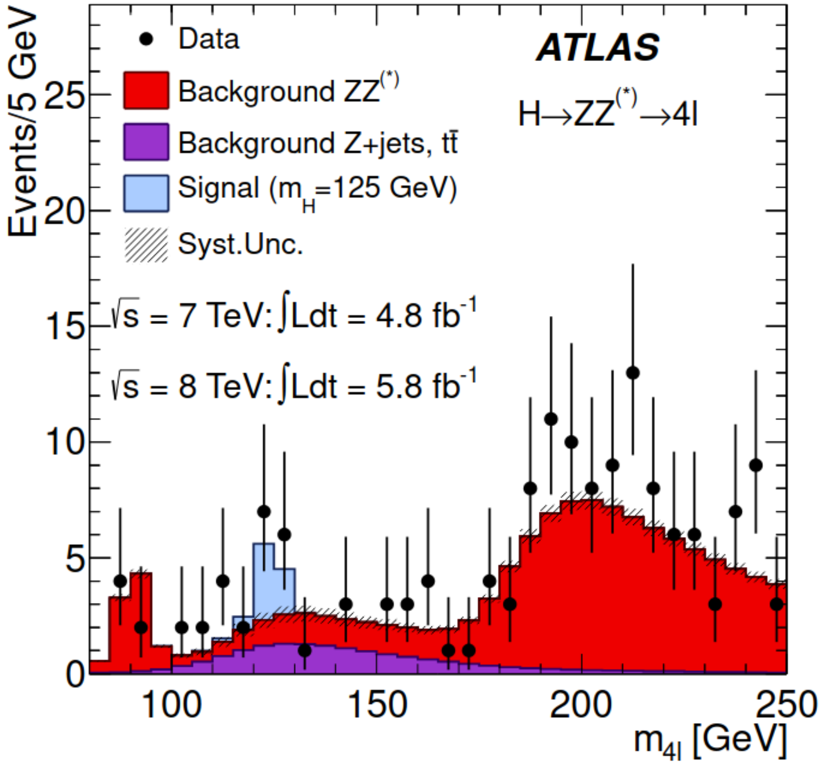
Observation in γγ channel

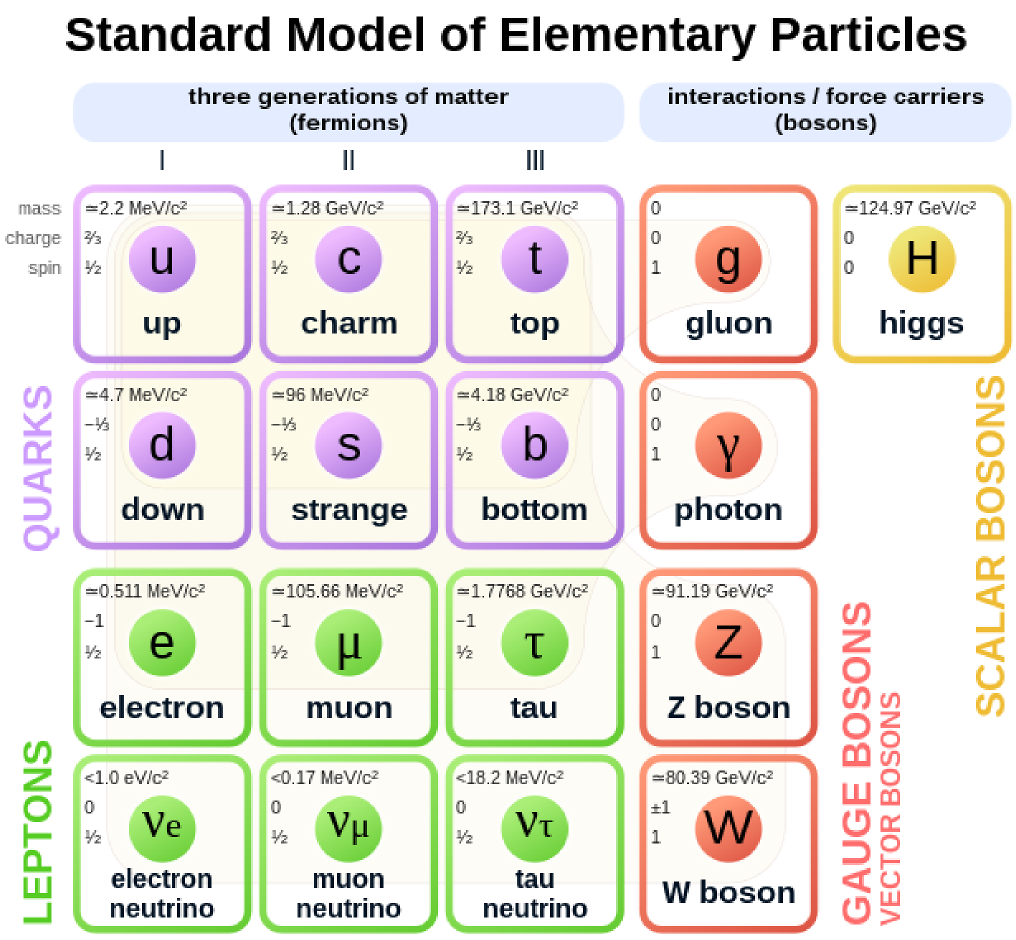


Observation in 4l channel



The discovery of a Higgs boson in 2012

The Standard Model of Particle Physics in 2025



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

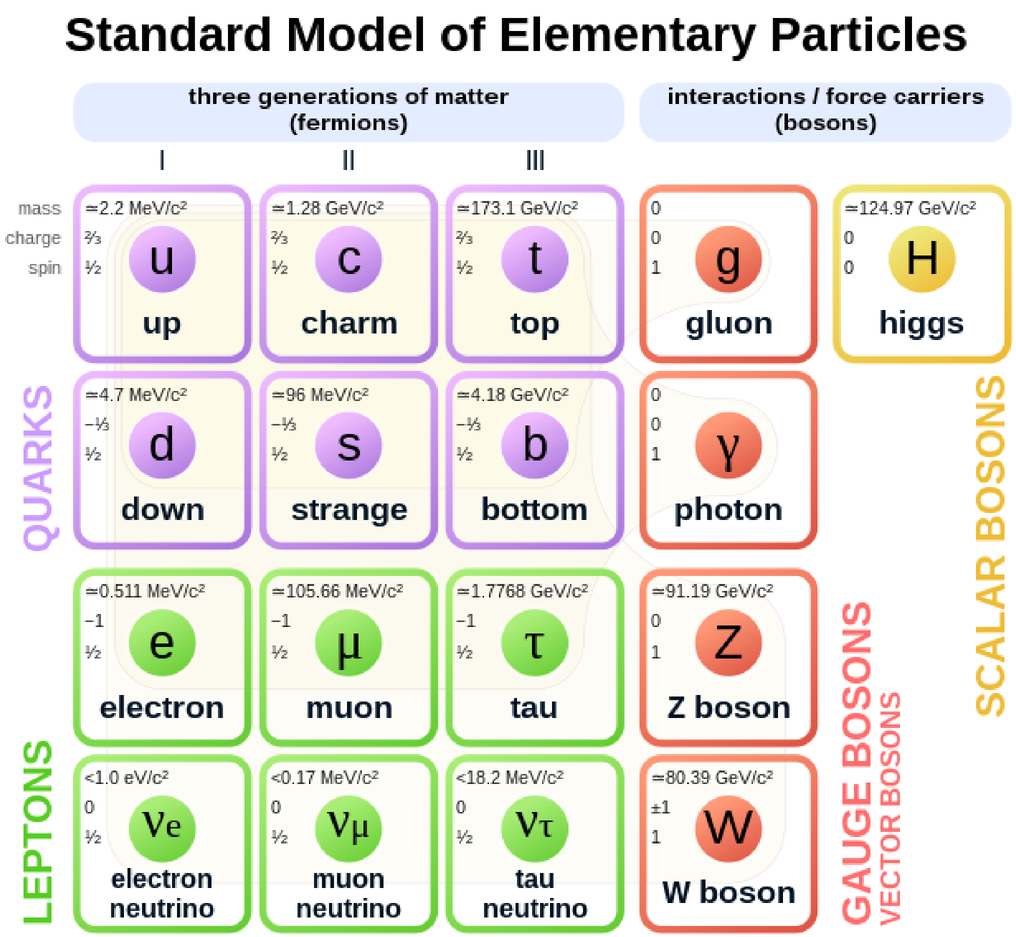
> Higgs coupling: the higher the mass, the stronger the coupling

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

> Higgs production and decay modes:

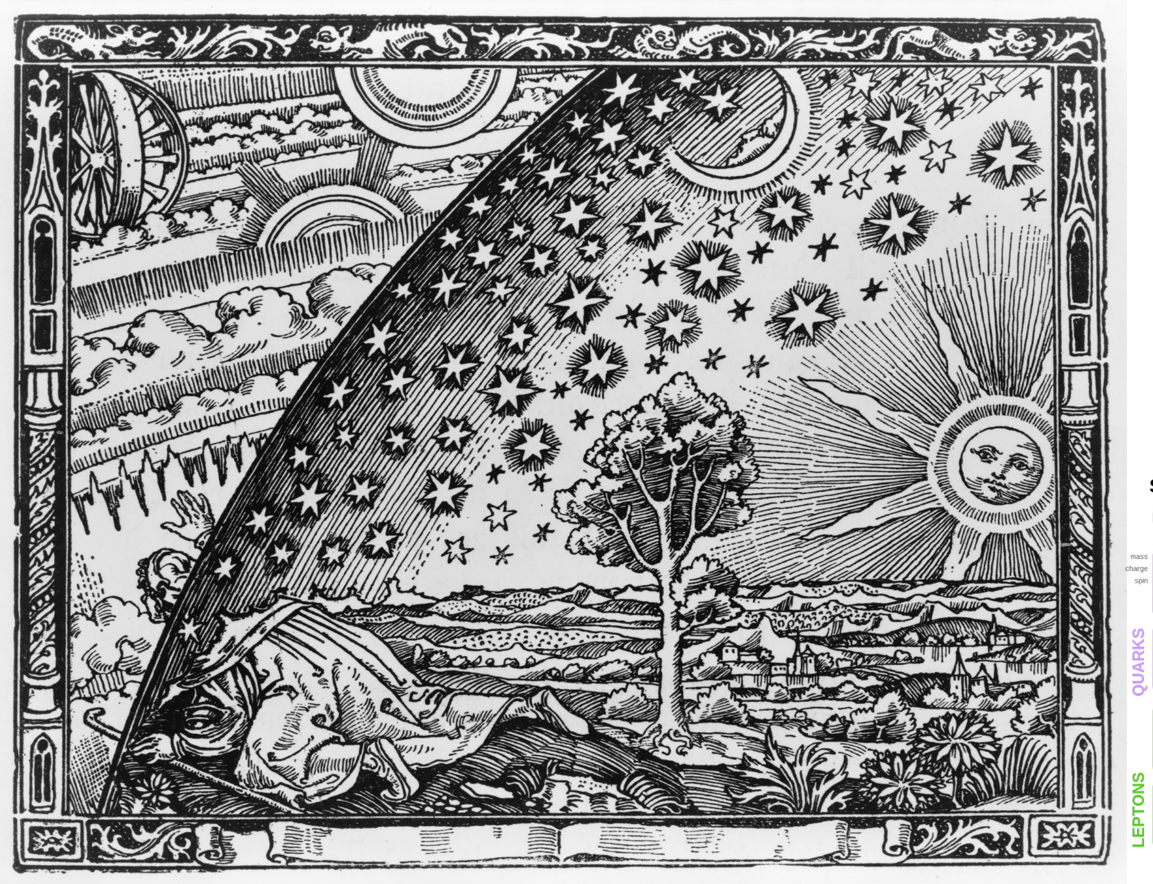
- Fully determined by above properties
- Closure tests: check if measured values agree with predictions

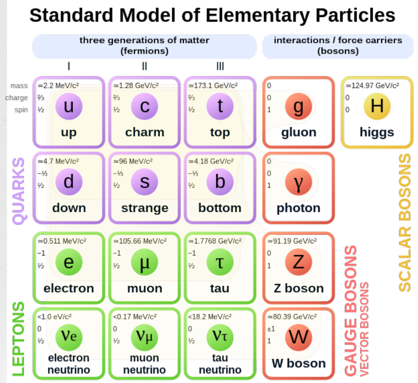
We want to scrutinise this new puzzle piece!



Why is this interesting?

We know the SM is not a complete theory!

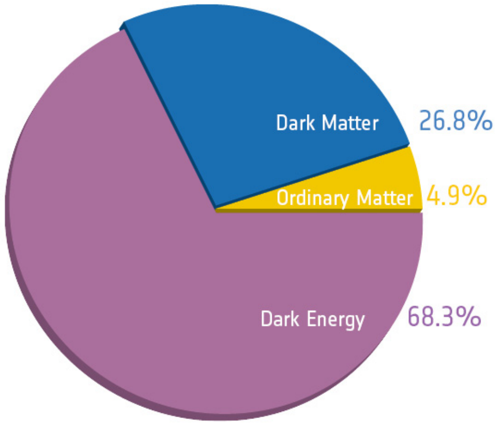




Many open questions remain after the Higgs discovery

> Hierarchy problem: small observed Higgs mass not compatible with "SM-only" scenario
  - Scalar field not protected from loop corrections at higher scales
  - Should drive Higgs mass up to Planck scale

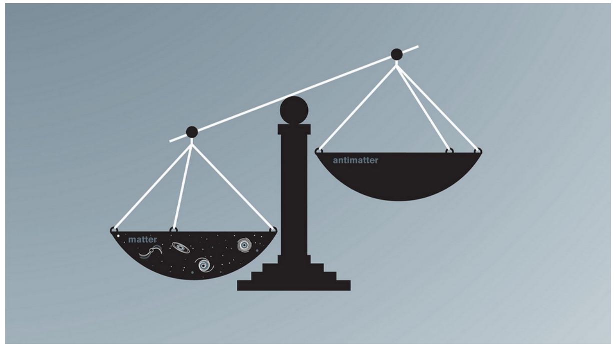
> Dark matter: makes up 85% of matter in the universe
  - Particle nature unknown



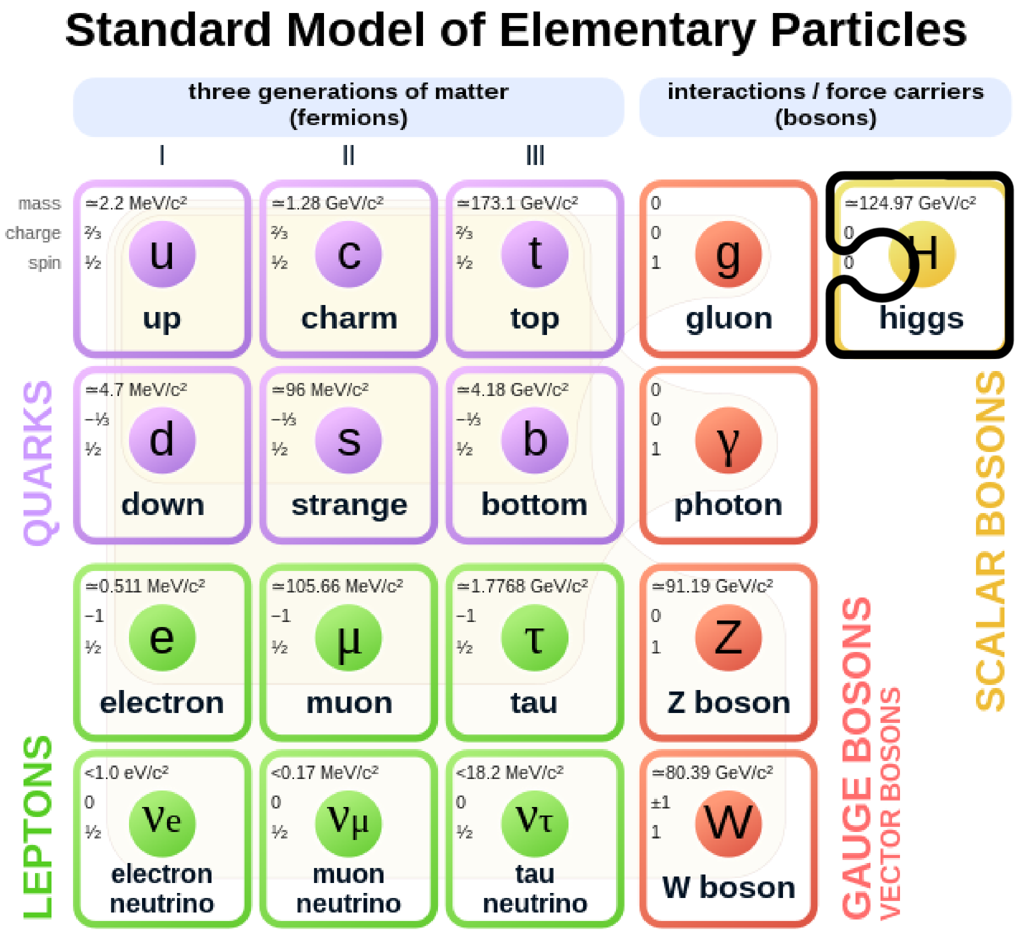
> Matter-antimatter asymmetry: where is all the antimatter?
  - Equal amounts of matter and antimatter should have been created at the Big Bang

> ...

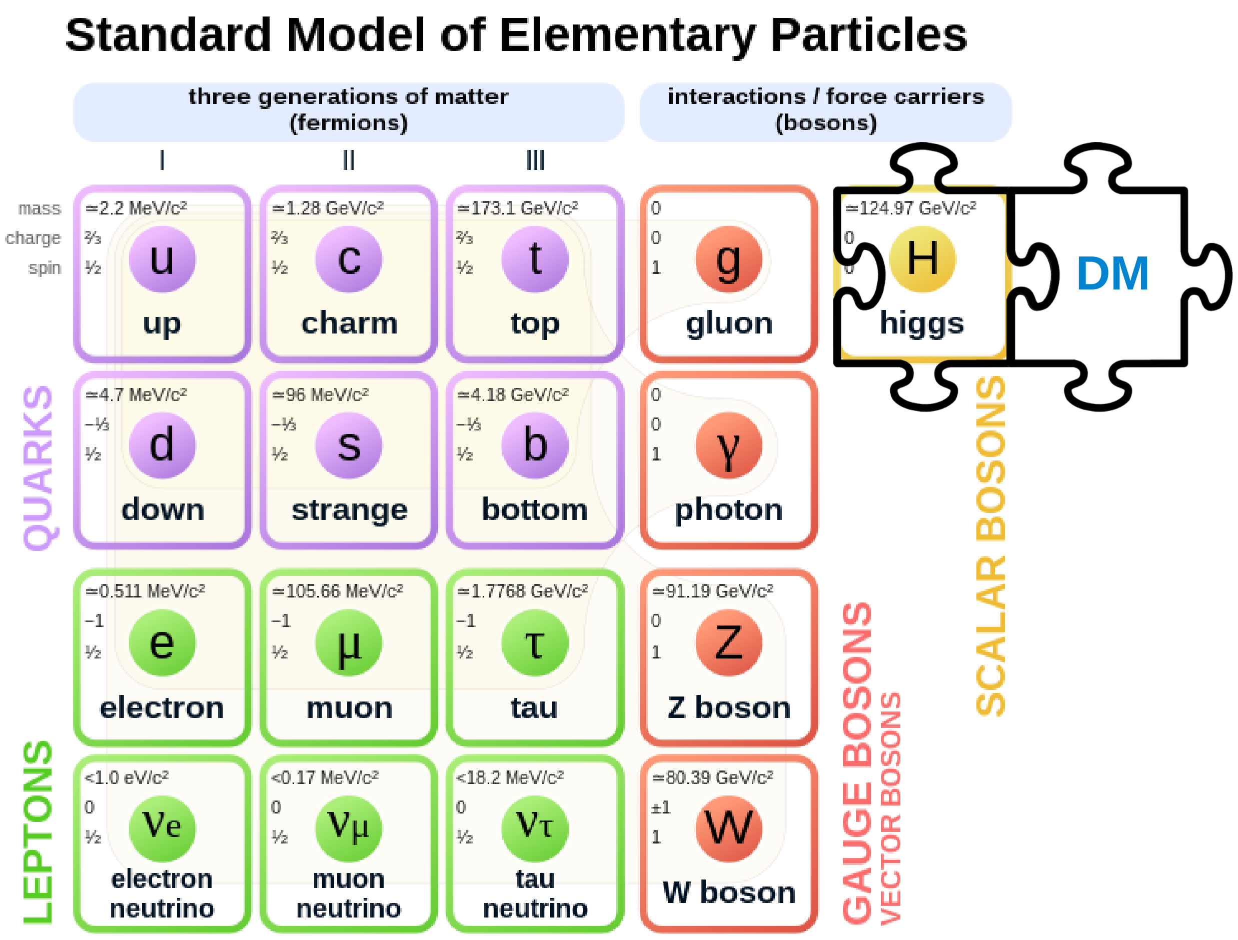
More in BSM lectures!



Is the Higgs boson just the last missing piece in the SM...



… or can it point us toward phenomena beyond the SM?



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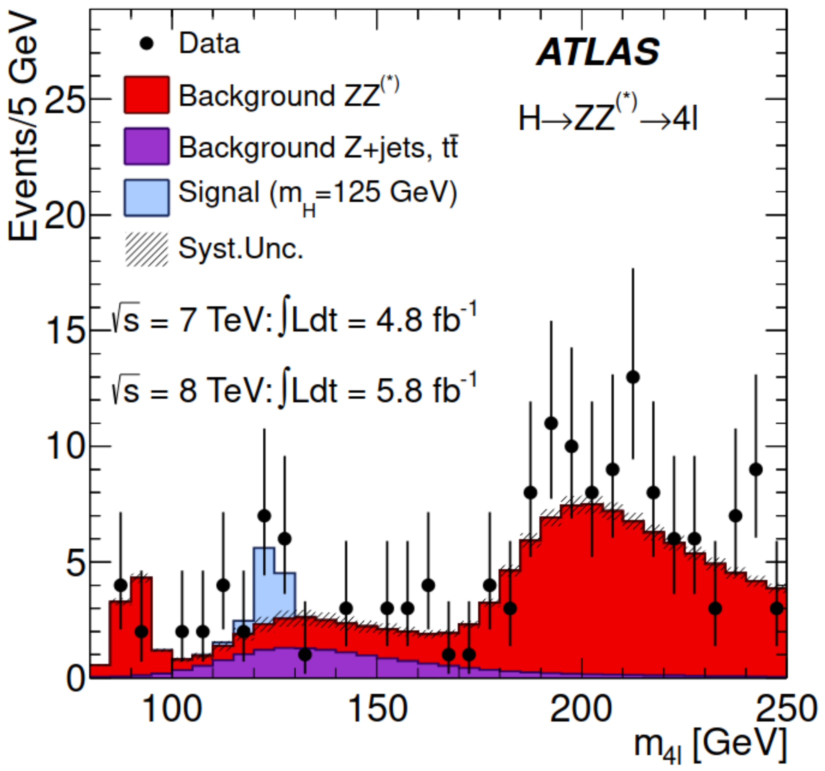
- Higgs coupling: the higher the mass, the stronger the coupling
  - fermion coupling ~ fermion mass
  - boson coupling ~ (boson mass)^2
- Higgs production and decay modes:
  - Fully determined by above properties
  - Closure tests: check if measured values agree with predictions

Characterising the Higgs boson

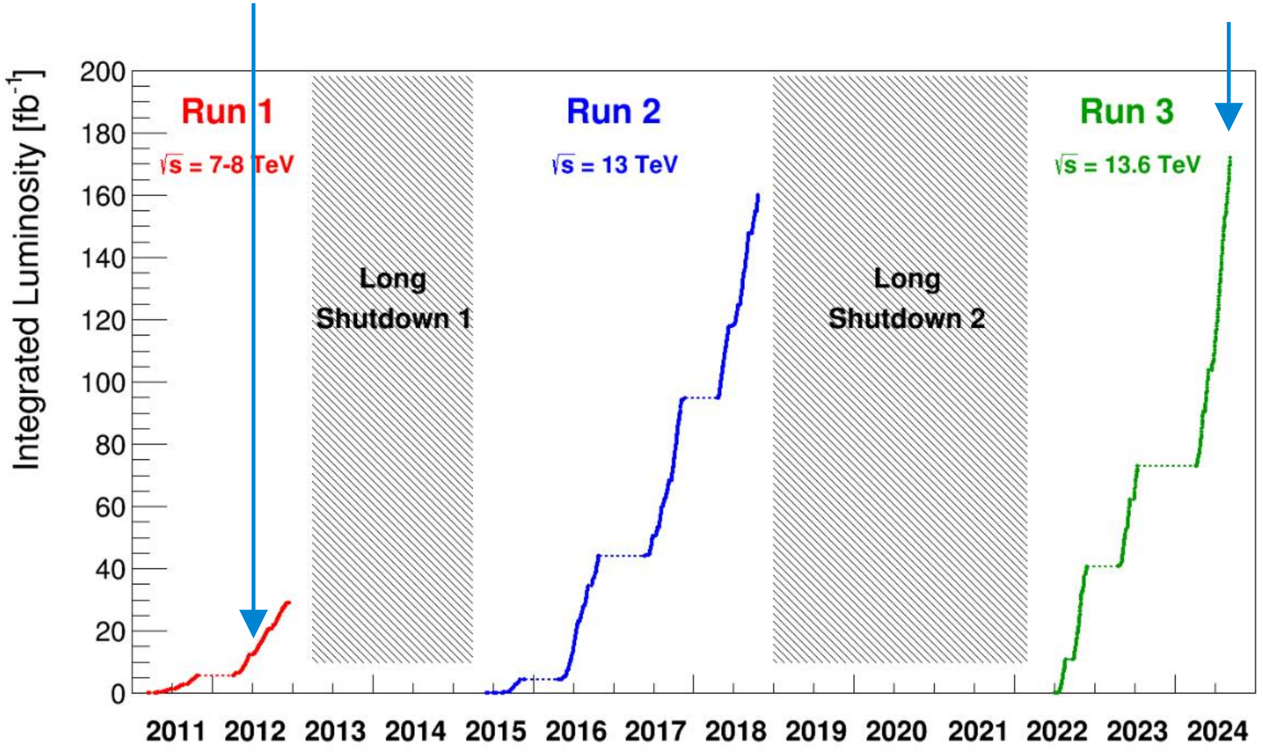
- Discovery based on only a fraction of LHC Run-1 data: ~10 fb^{-1} of data at $\sqrt{s}$ = 7 TeV and 8 TeV
- Much more data taken since then
- Tremendous progress in our understanding of the first fundamental spin-0 particle observed in nature

Observation in 4l channel



Higgs discovery

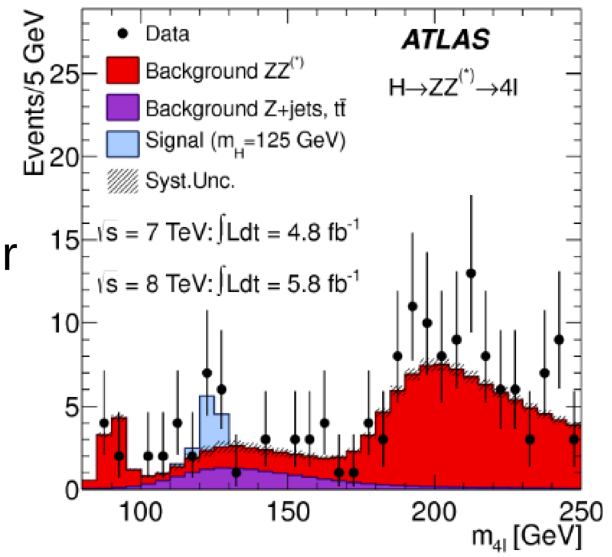
Today

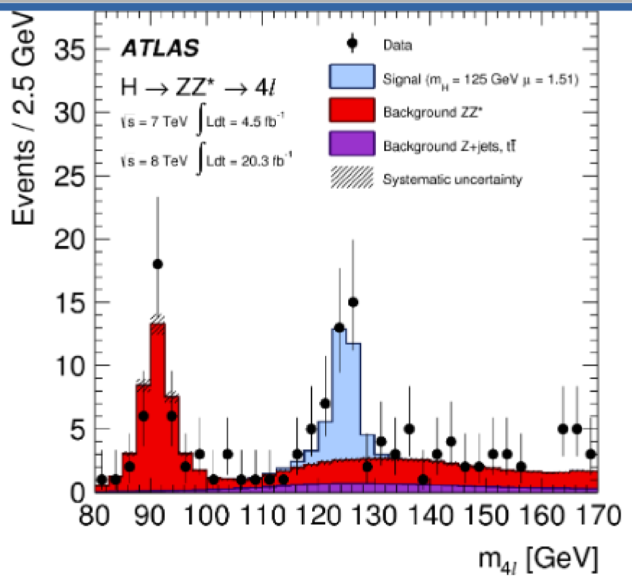


From discovery to characterisation

Run 1

Summer 2012

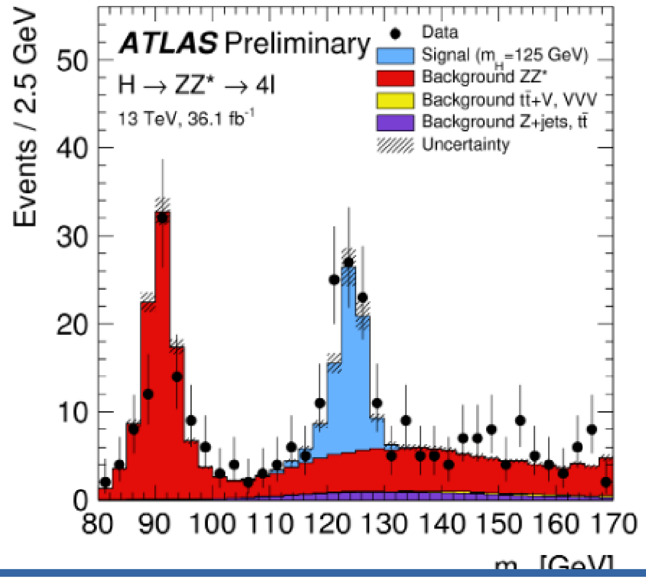


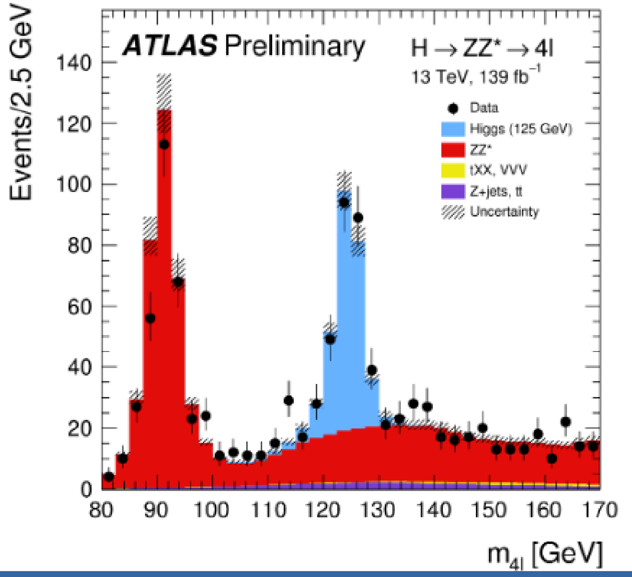


Winter 2012

Run 2

2016





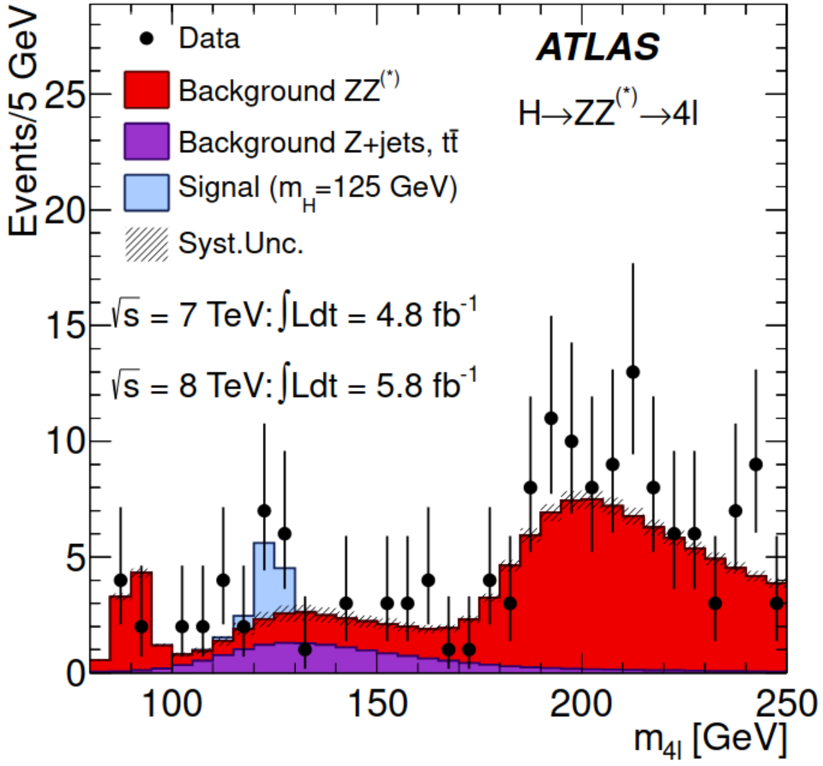
2018

Run 3
on-going...

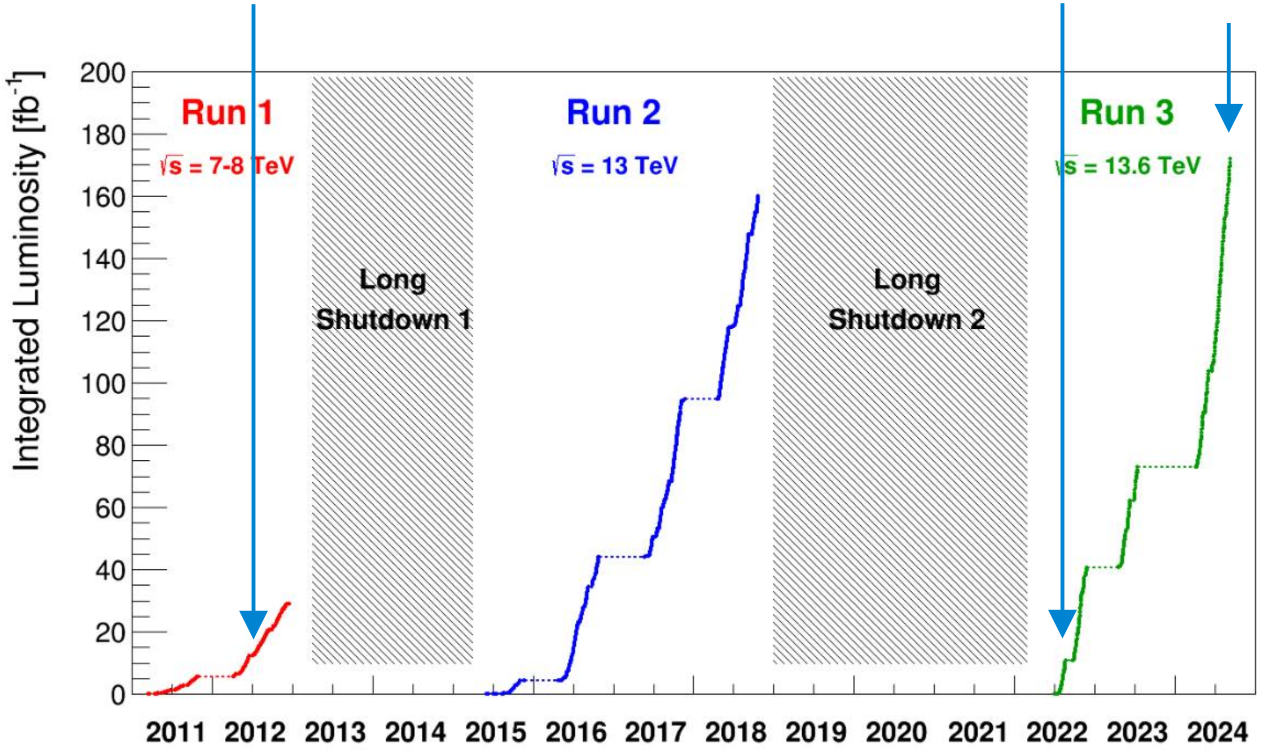
Characterising the Higgs boson

- 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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> Higgs production and decay modes:

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

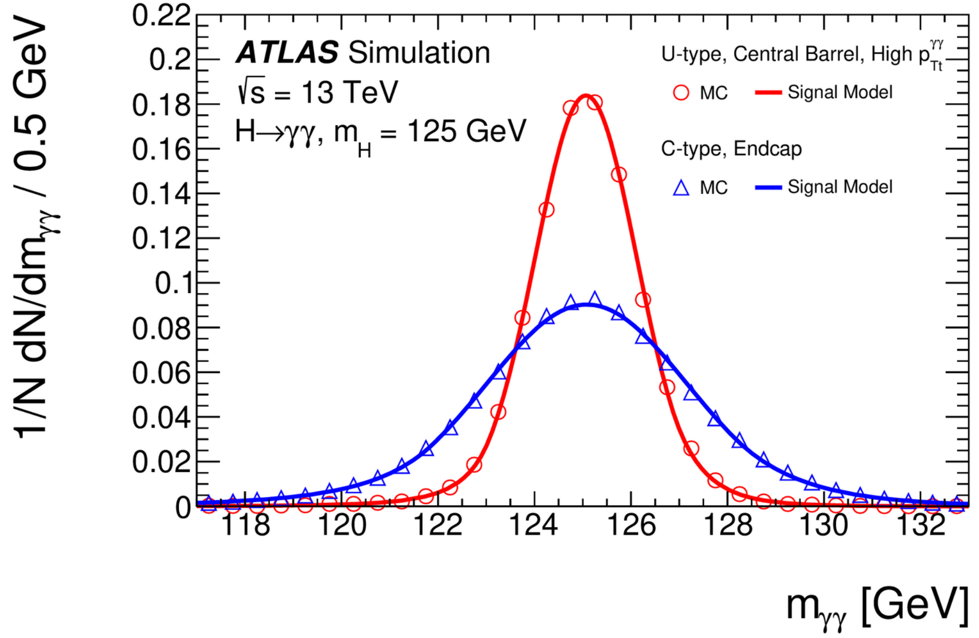
Measuring the Higgs boson mass

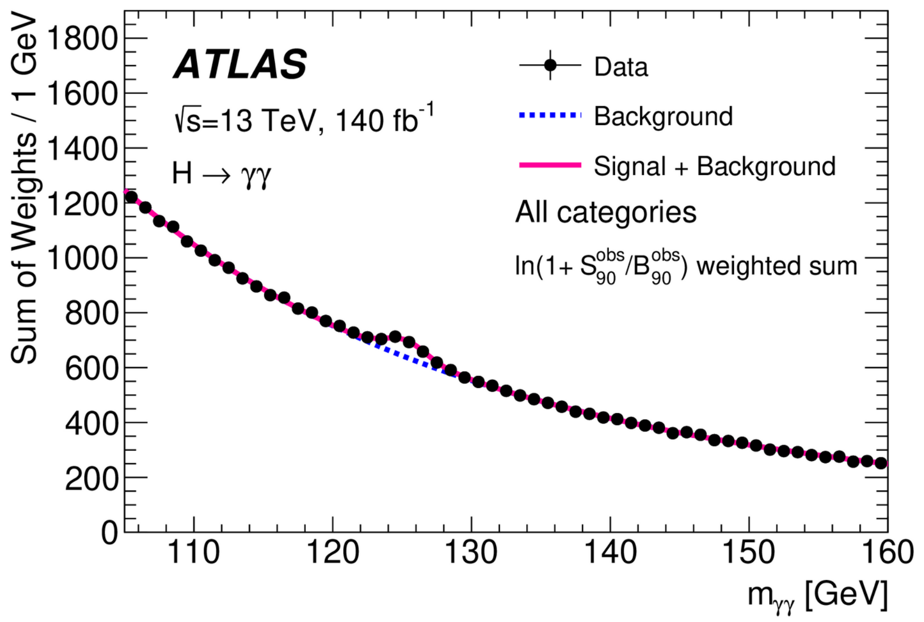
> Golden decay modes *h → γγ* and *h → ZZ* → 4ℓ* most suitable

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

> Example: *h → γγ*

- 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





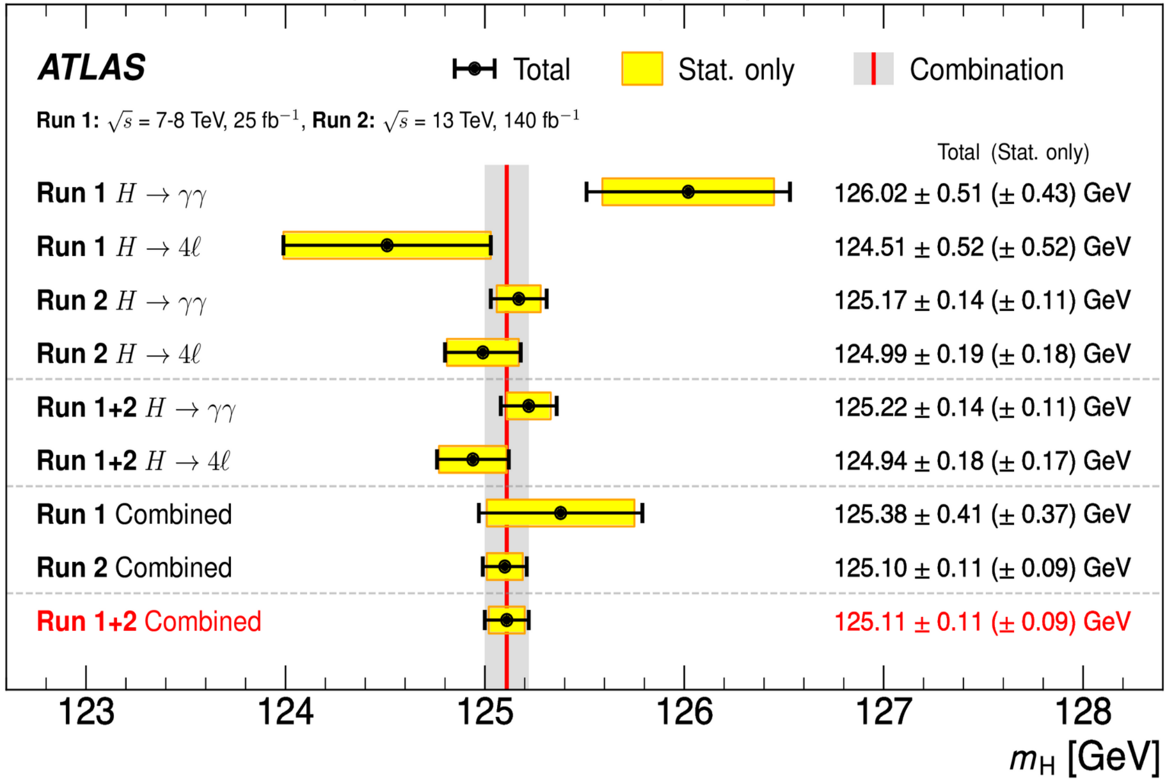
Measuring the Higgs boson mass

- Golden decay modes *h→γγ* and *h → ZZ* → 4ℓ* 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!

Phys. Rev. Lett. 131 (2023) 251802

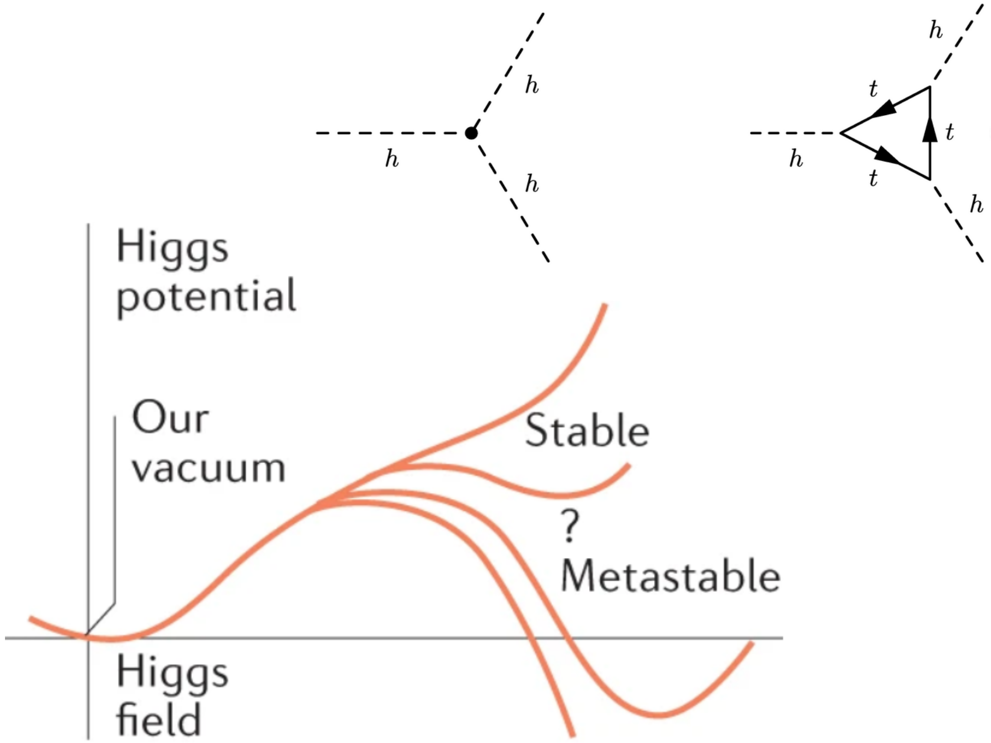


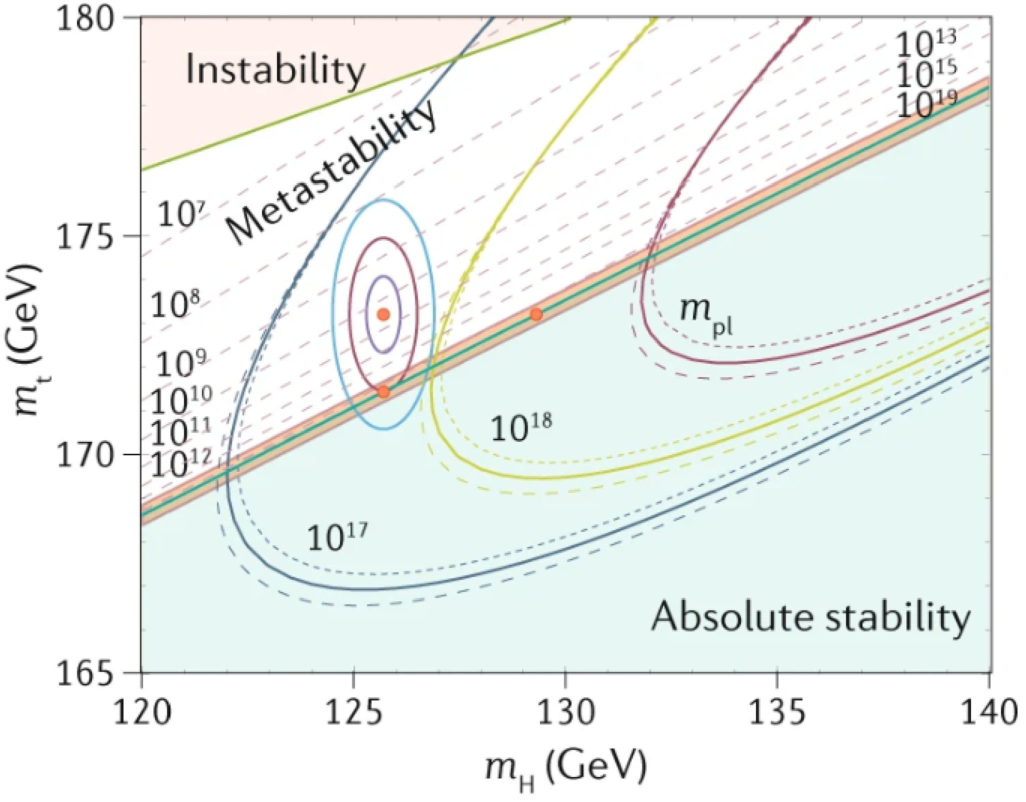
Cosmological implications of the Higgs boson mass

> Higgs mass at a remarkable value:

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

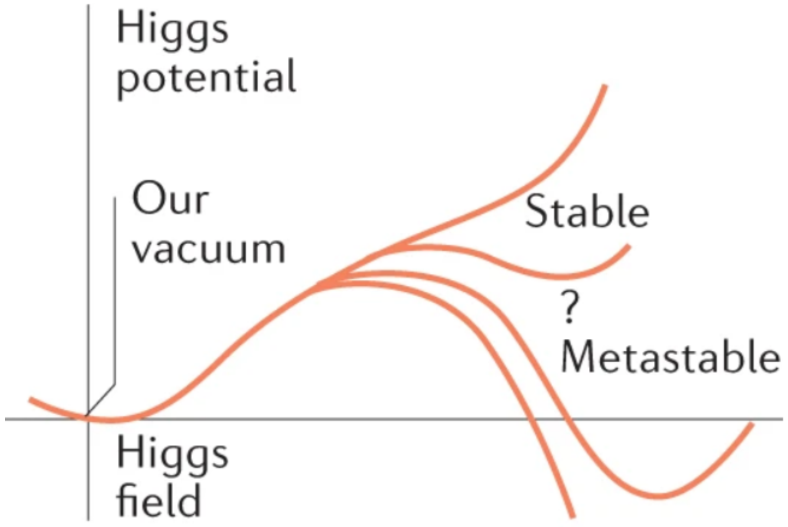
- Running trilinear coupling at high energies with large contributions from top loops
- Negative self-couplings possible at large energies → metastability!

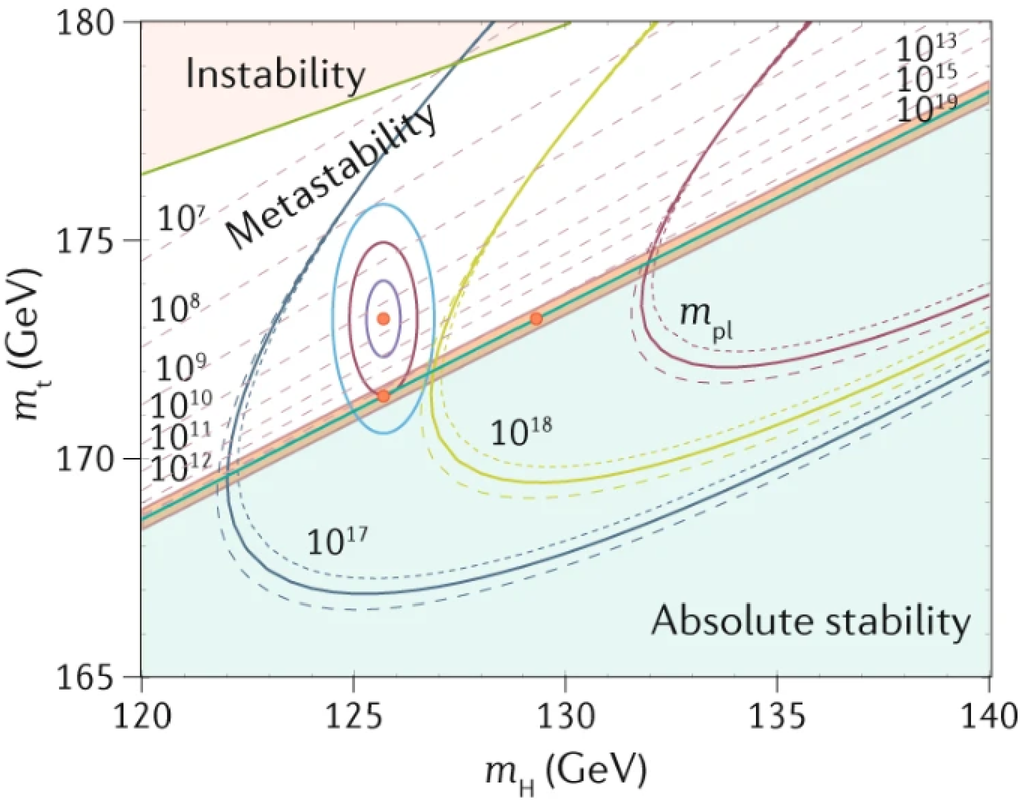




Cosmological implications of the Higgs boson mass

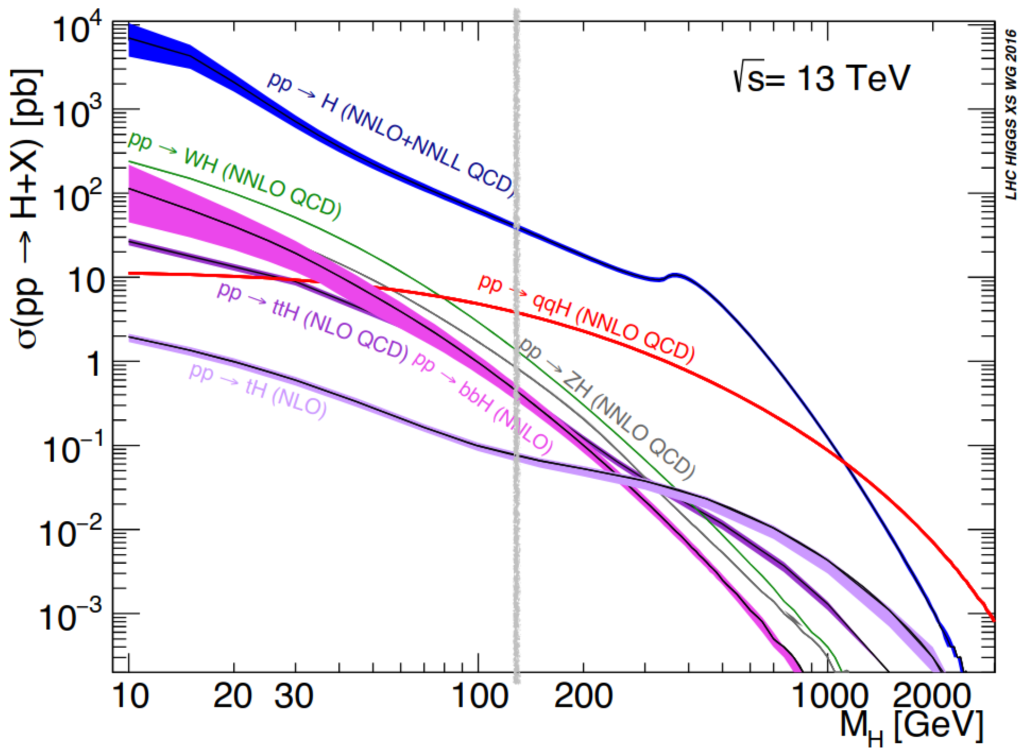
- BSM physics to stabilise vacuum during inflation?
- Non-minimal coupling of Higgs with gravity?
  - Possibly detectable impact primordial gravitational wave spectrum

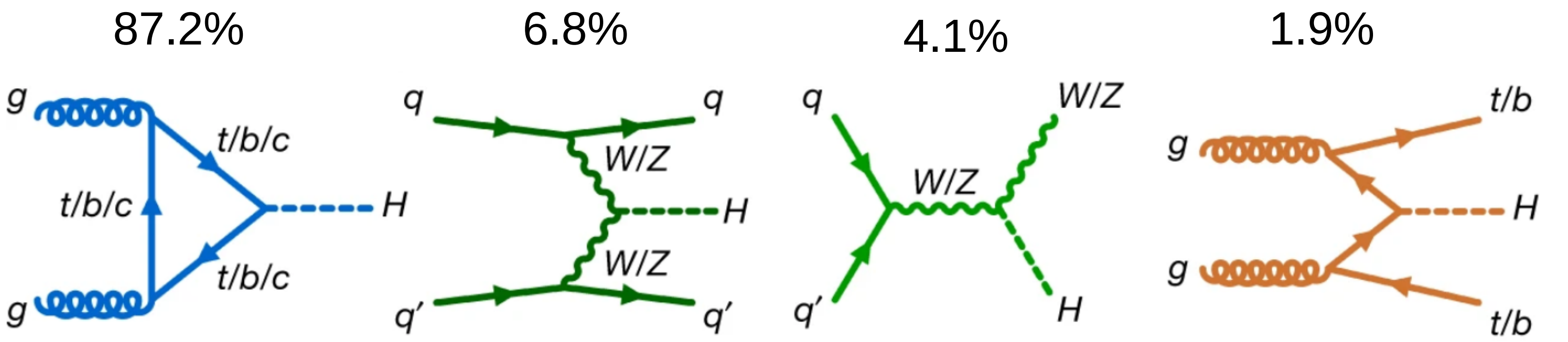




Implication of the Higgs boson mass for production and decay

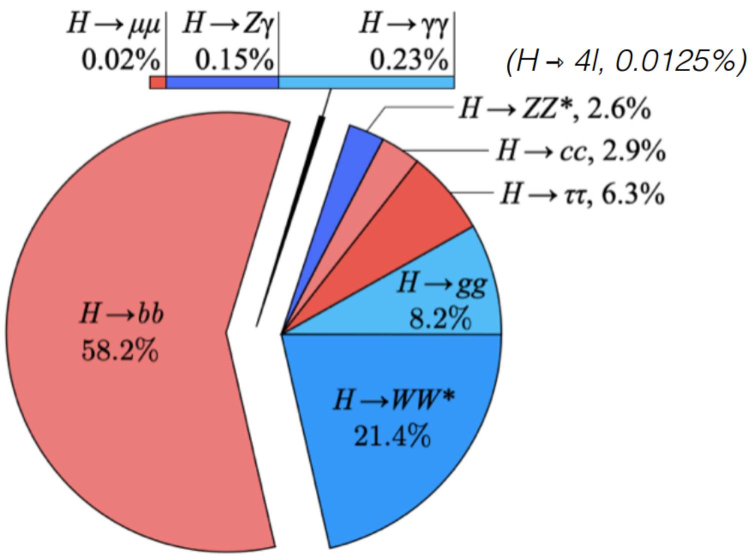
- Production rates fixed for a given value of m_h
- Dominant production mode: gluon fusion

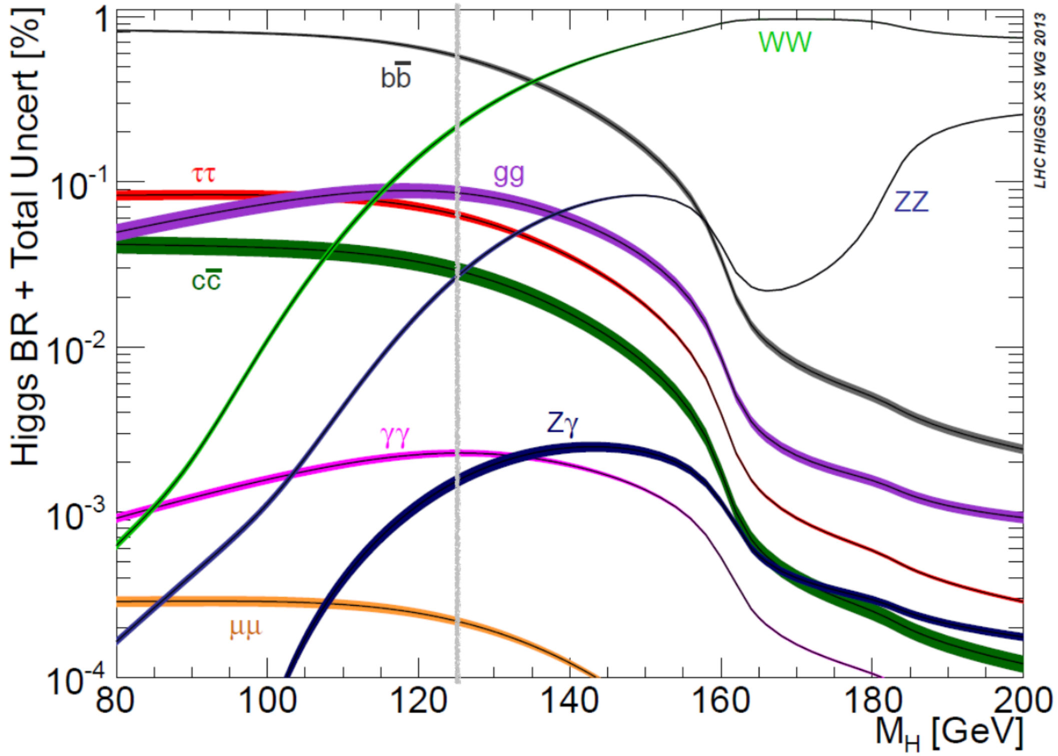


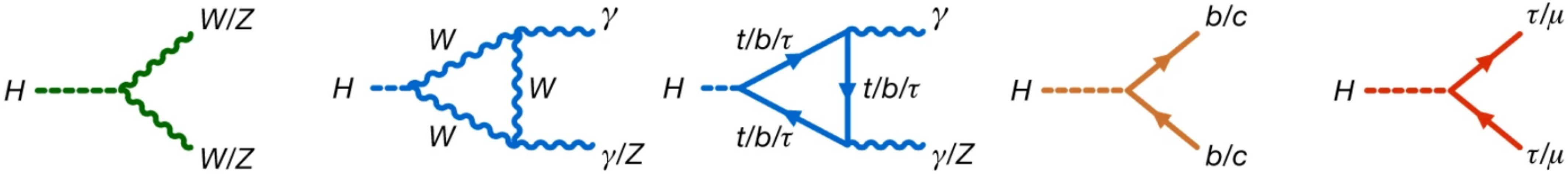


Implication of the Higgs boson mass for production and decay

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







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- fermion coupling ~ fermion mass
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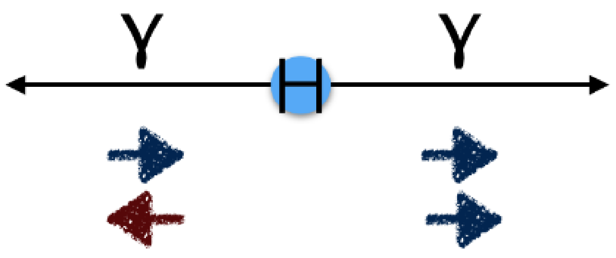
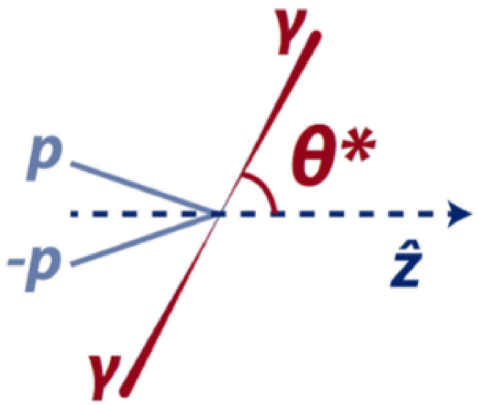
> Higgs production and decay modes:

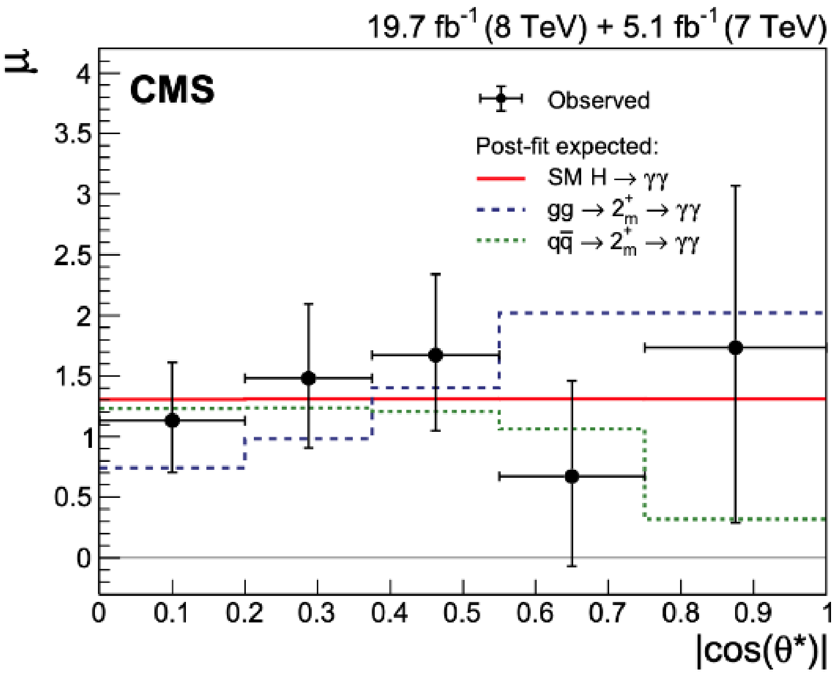
- Fully determined by above properties
- Closure tests: check if measured values agree with predictions

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



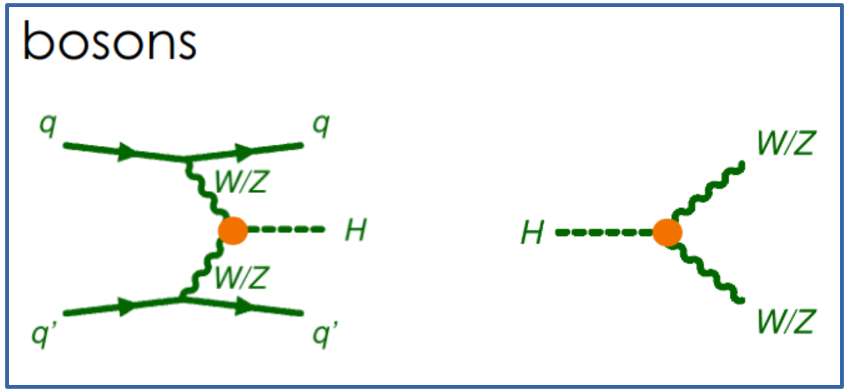


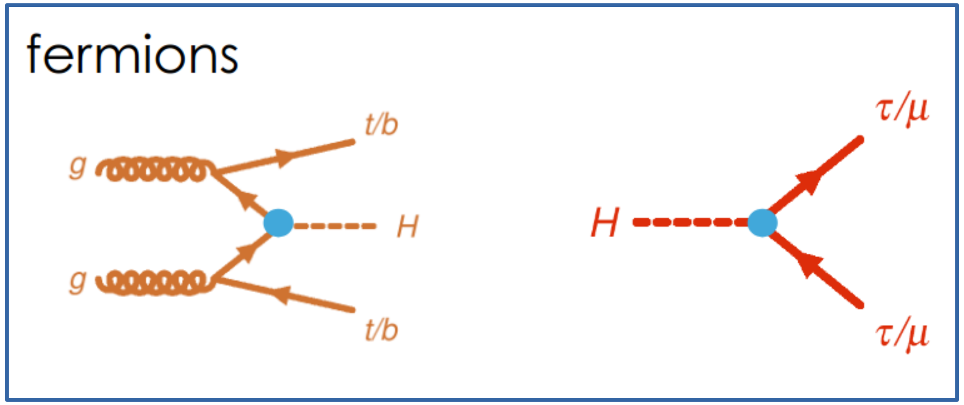


Higgs CP properties

> Measure CP properties of Higgs couplings to different SM particles

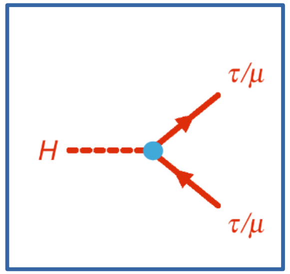
> Separately for bosons and fermions



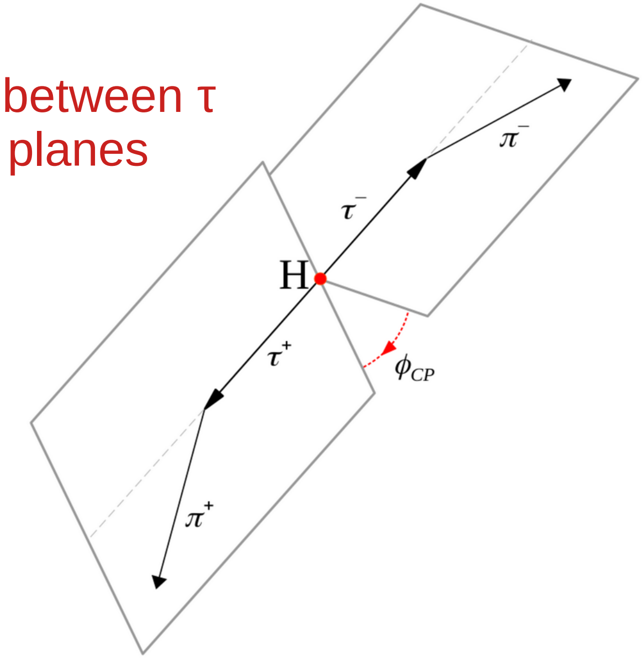


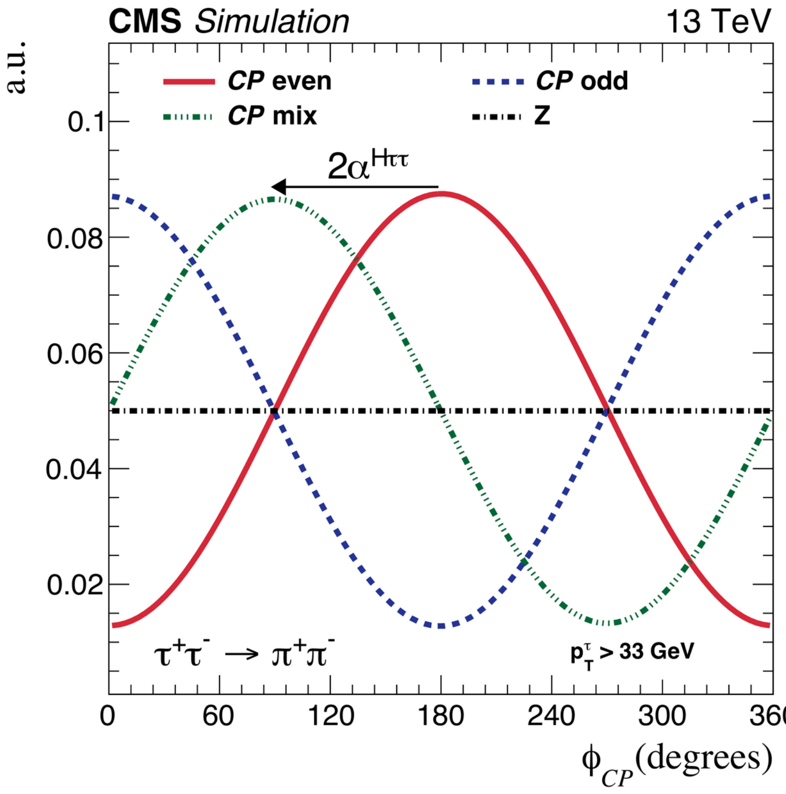
Example: CP properties of decay to τ leptons

- 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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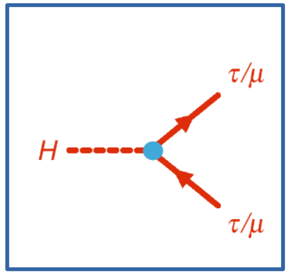

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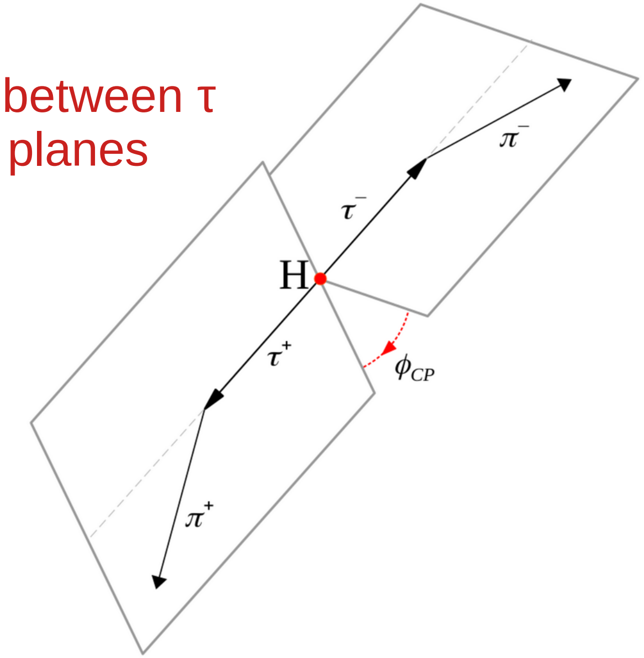

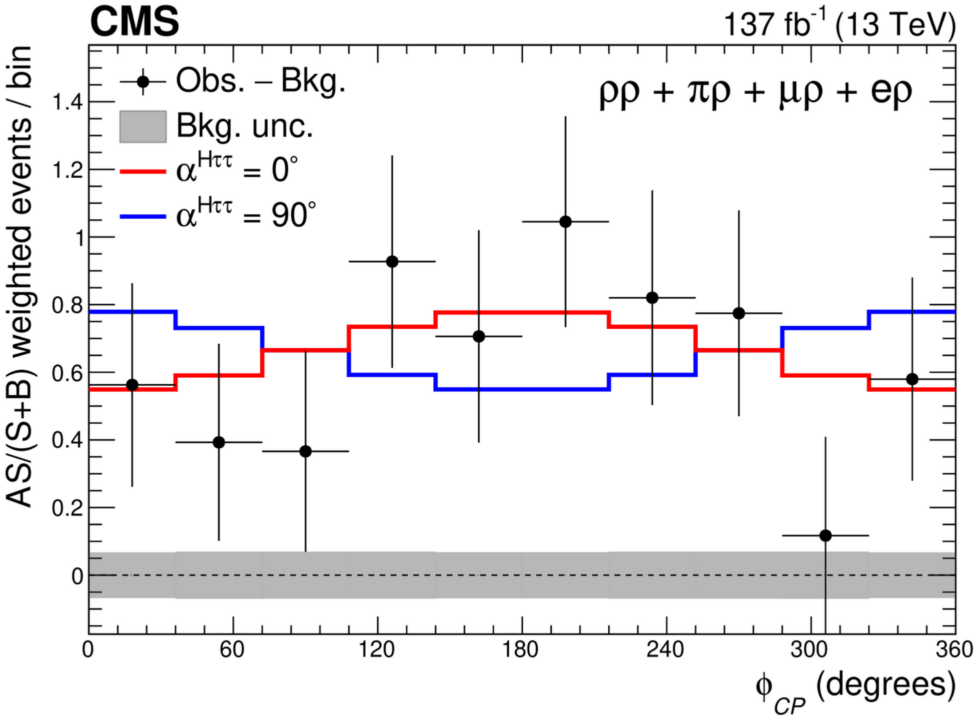

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> Measure CP properties of Higgs couplings to different SM particles

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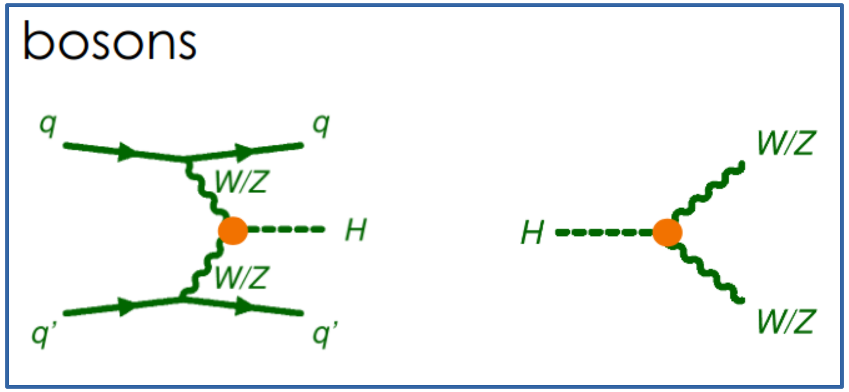

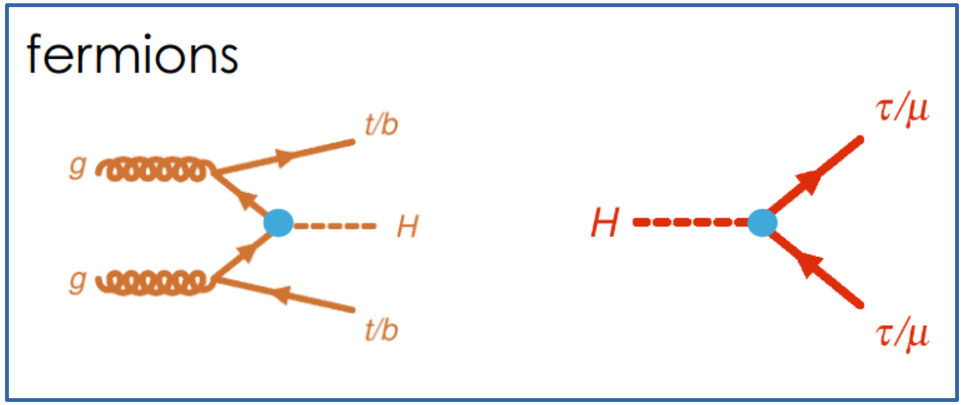

> **Results:**

- 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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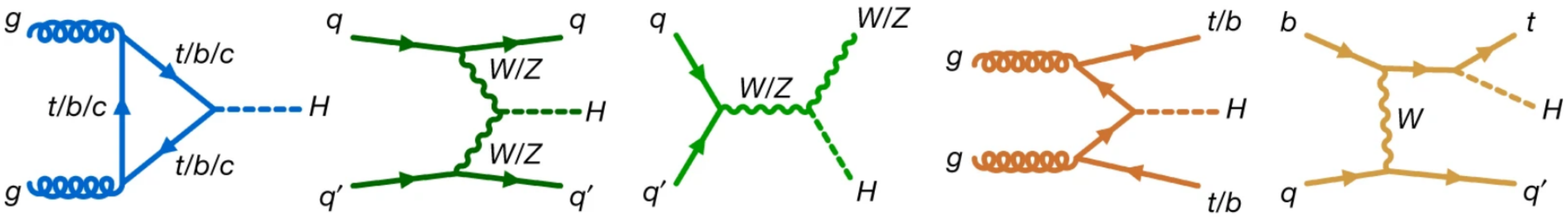
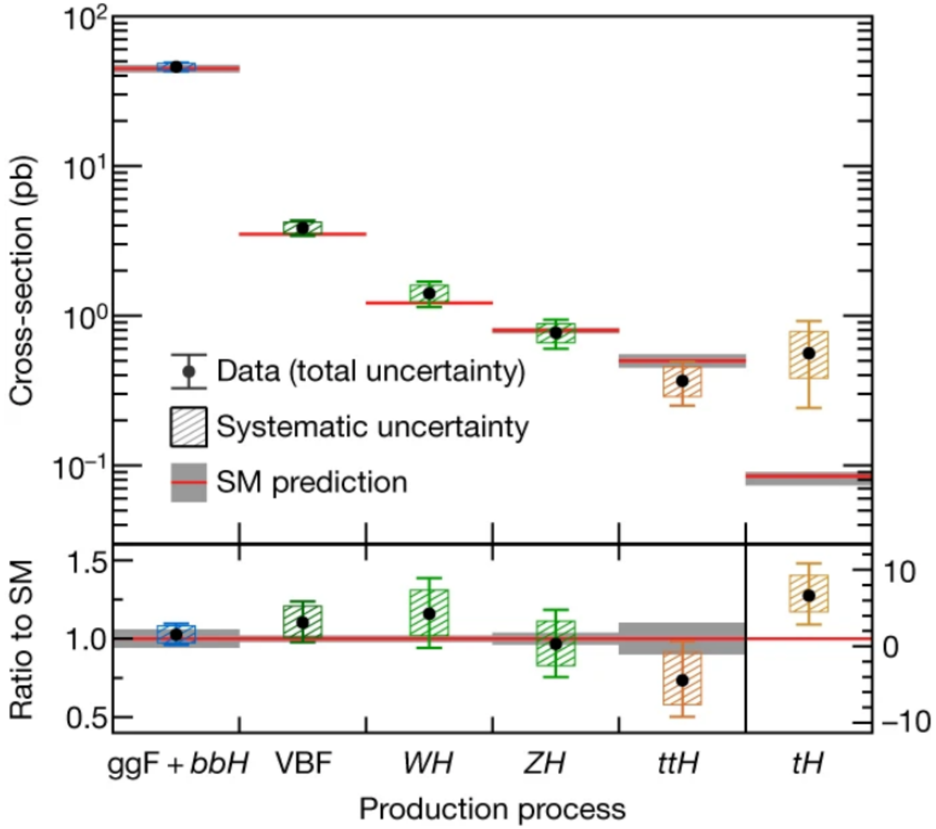
Higgs boson production measurements



- 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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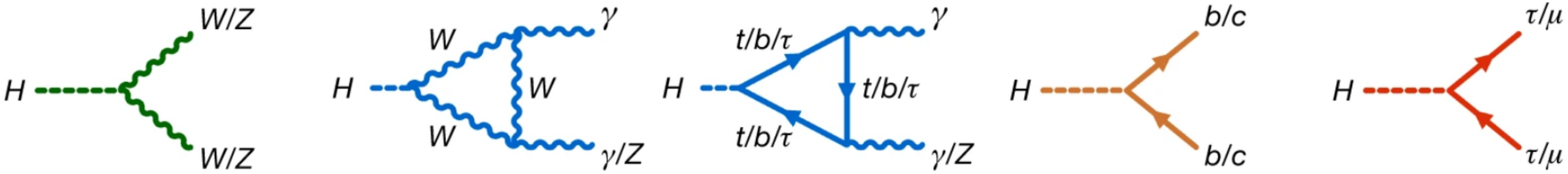
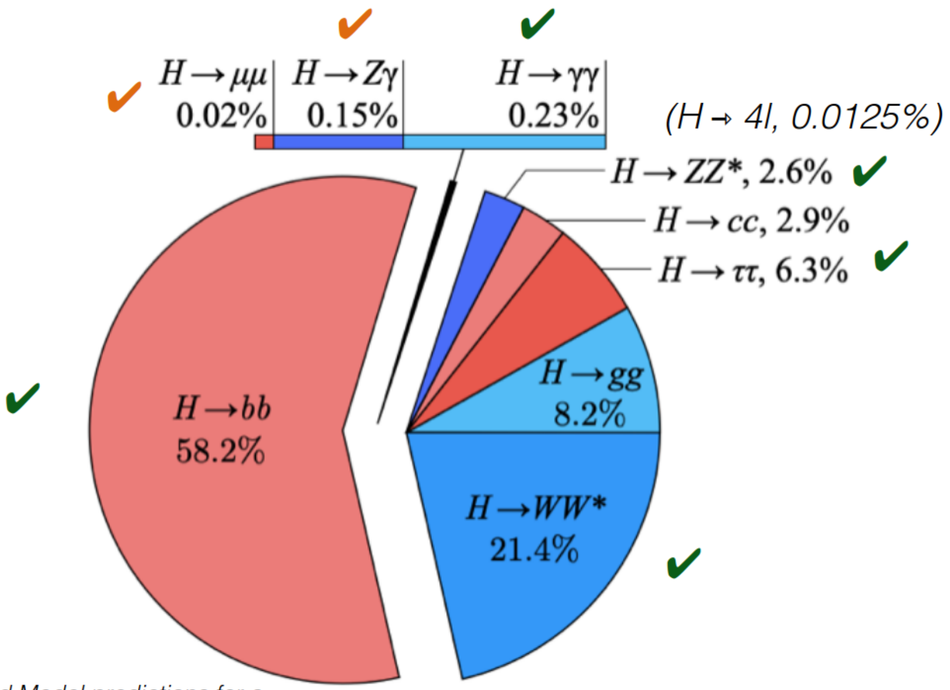


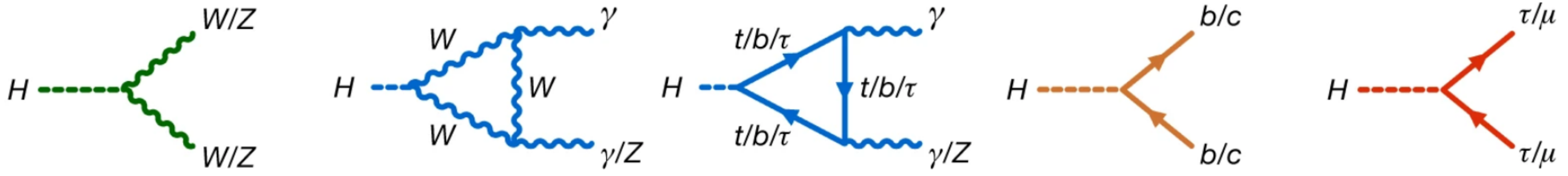


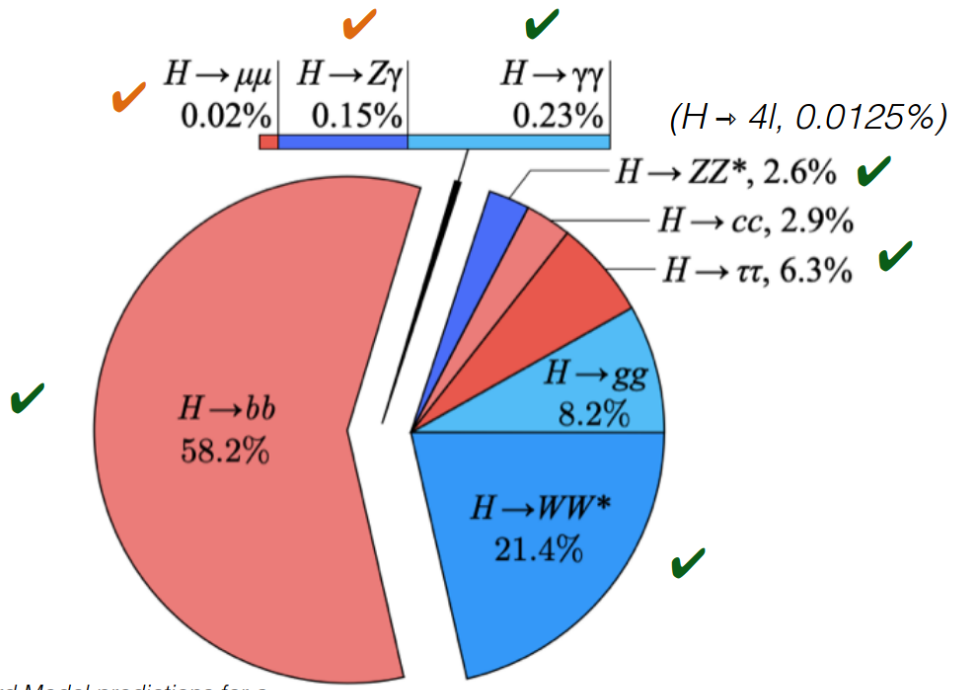
(Standard Model predictions for a Higgs boson with mass 125 GeV)

> 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





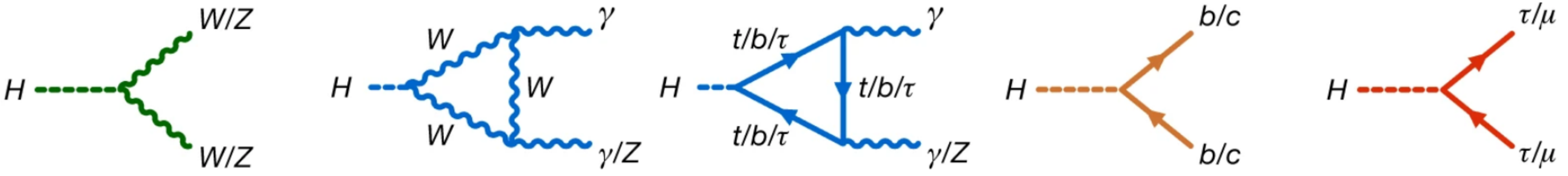
(Standard Model predictions for a Higgs boson with mass 125 GeV)

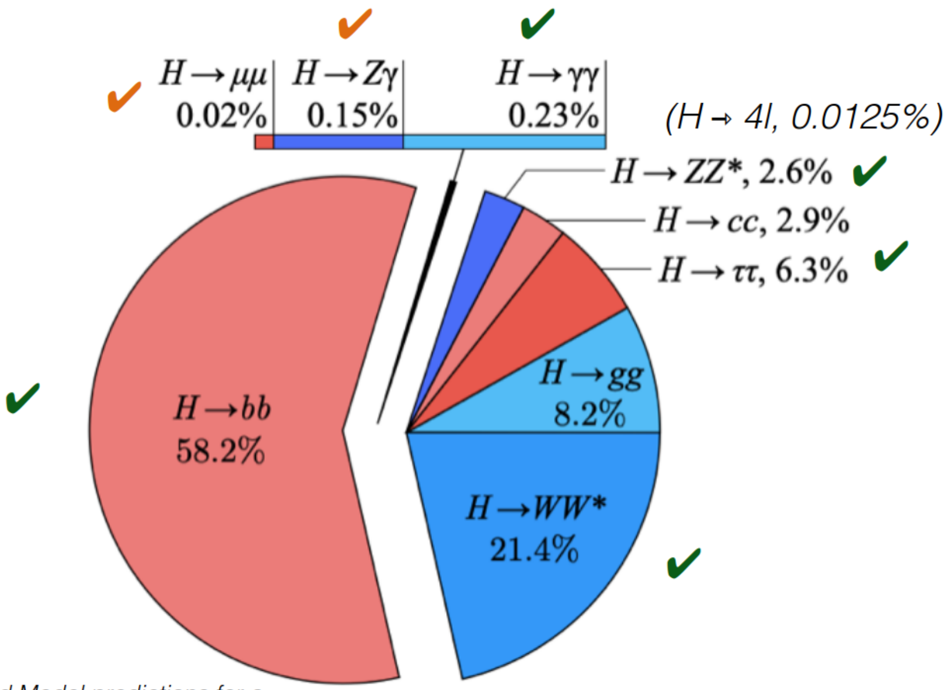
> Discover each decay mode with >5σ
  - Can make use of all production modes

> 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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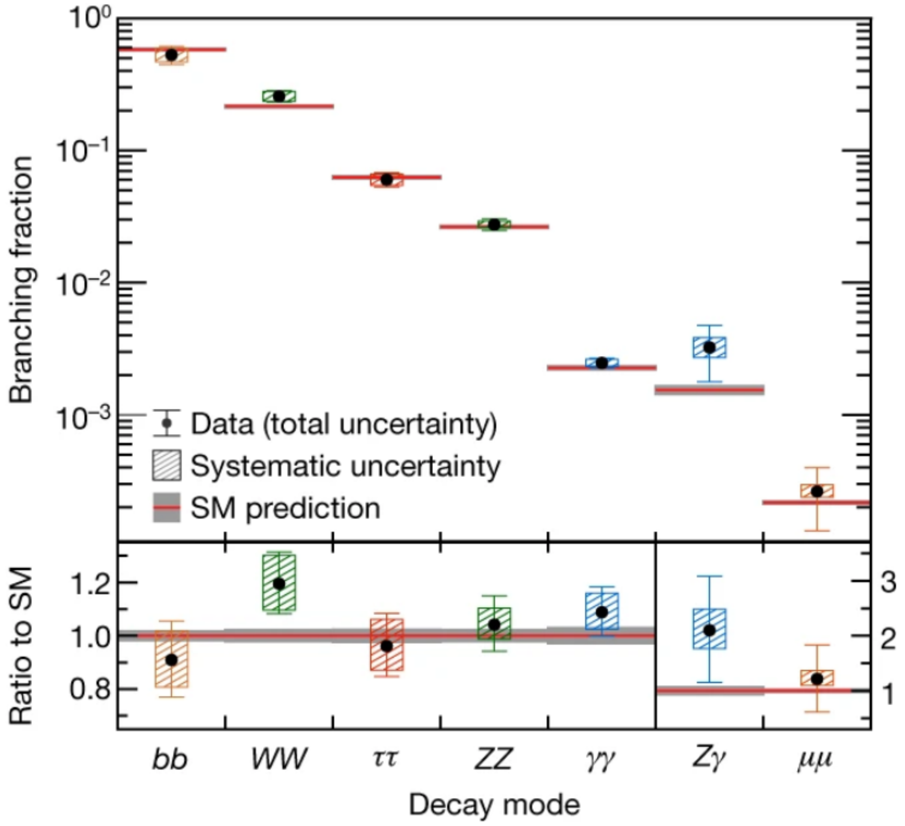
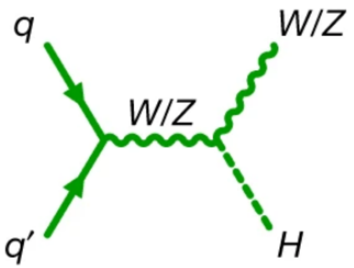


Example: discovery of *h* → *bb* (2018)

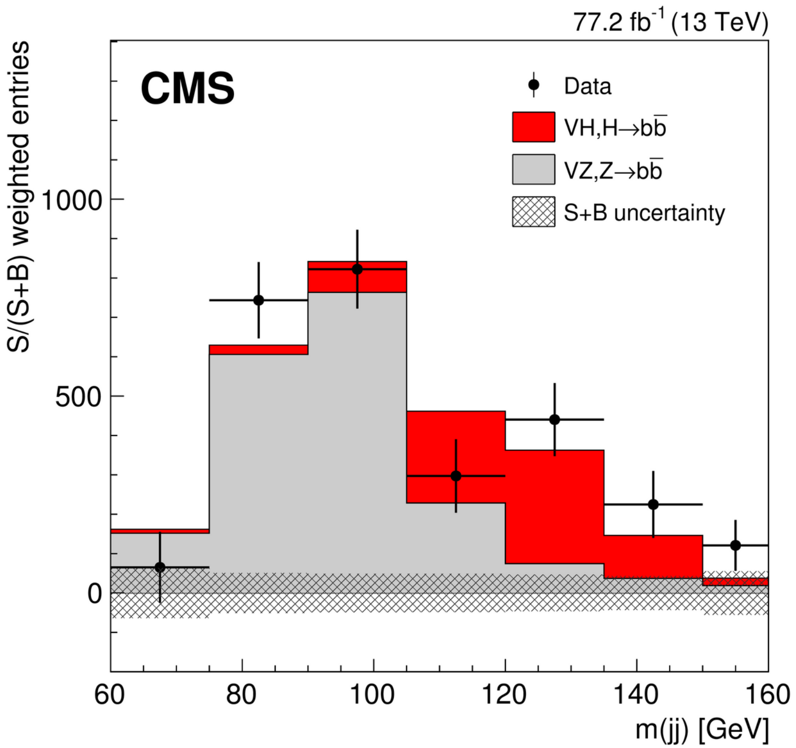


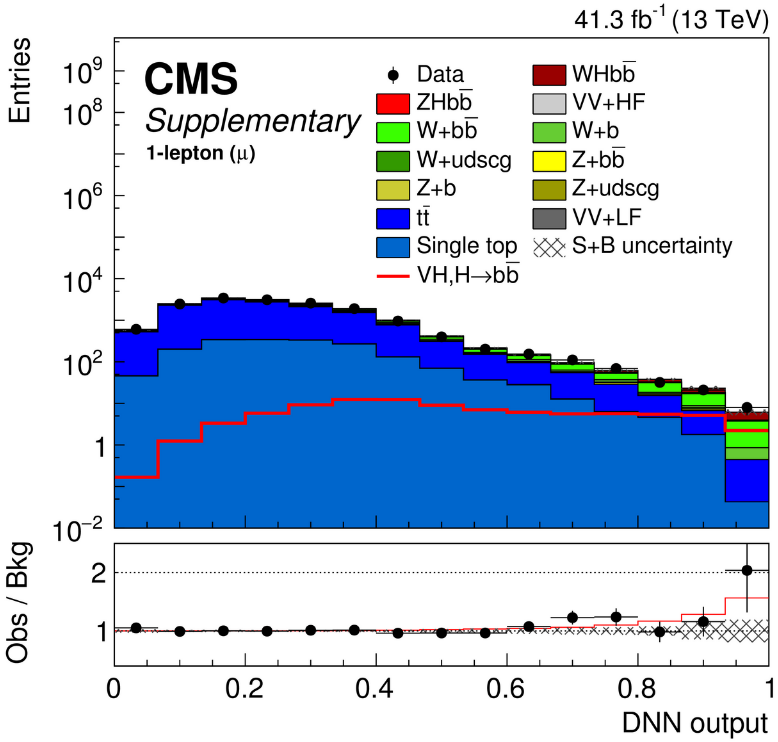
> Latest decay mode to fermions to be discovered, despite largest branching ratio
  - Important because it probes couplings to third generation down-type fermion

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

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

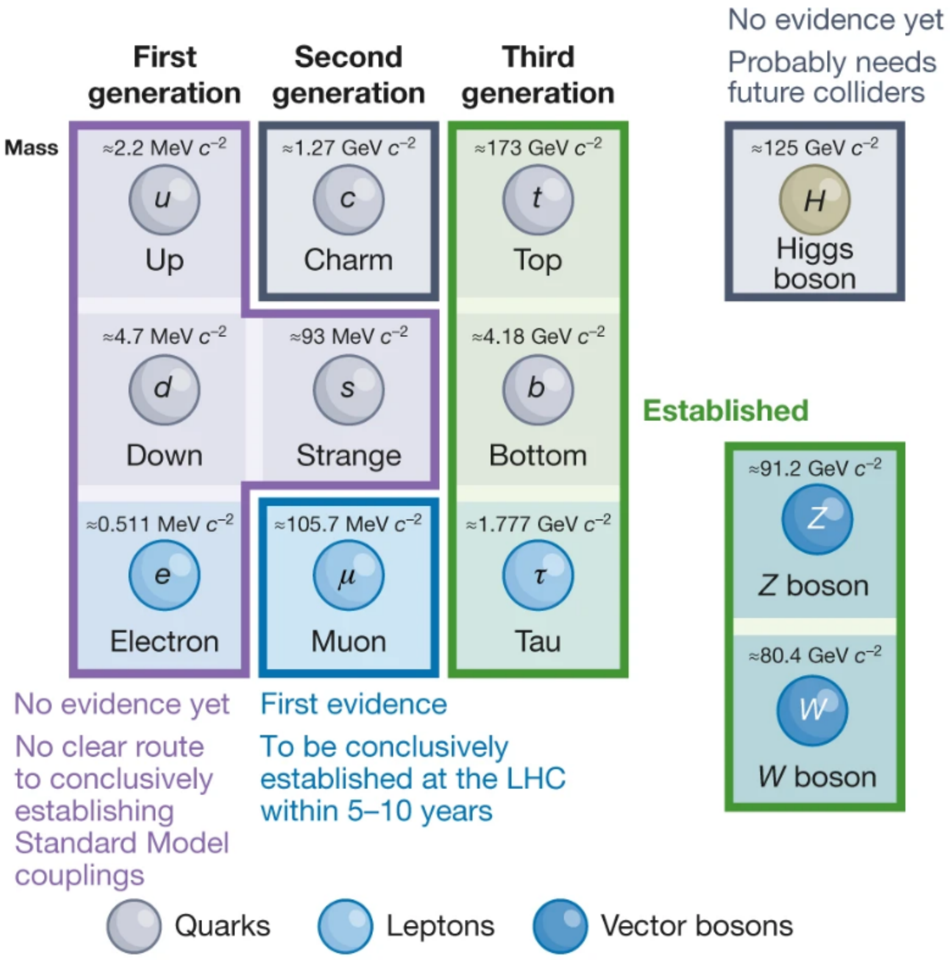
> Background still challengingly large → extensive use of ML (deep neural nets)

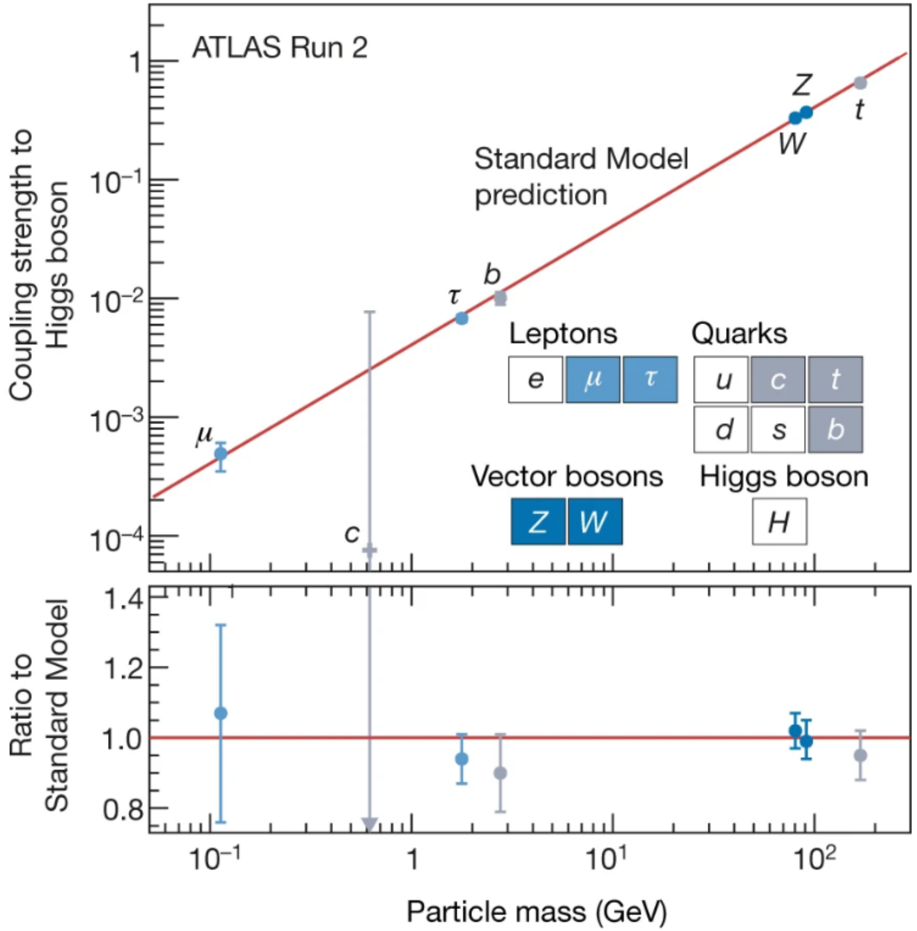




Higgs boson decay summary

> 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

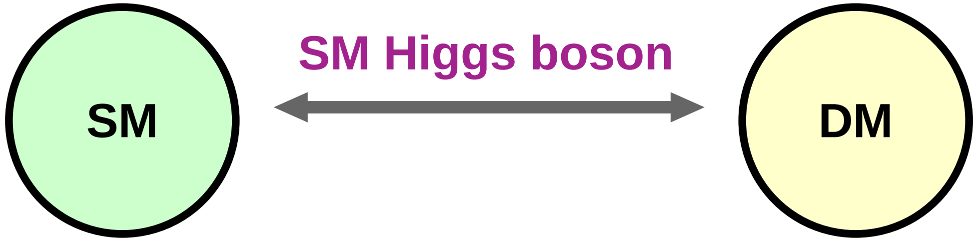
Quiz question:
Can you think of another possibility how the Higgs boson can decay invisibly in the SM?

Invisible decays of the Higgs boson

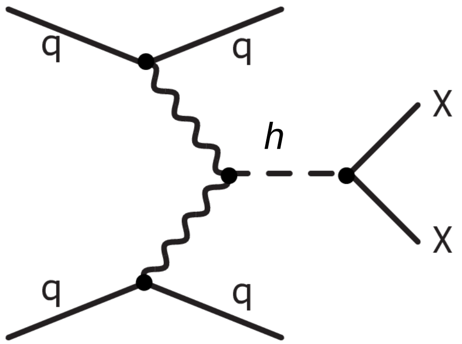
- Higgs boson does not couple directly to neutrinos in the SM
- Invisible decays in the SM: $h \rightarrow ZZ^* \rightarrow 4\nu$
- Tiny branching ratio: $BR(h \rightarrow inv) = 0.1\%$

Invisible decays of the Higgs boson

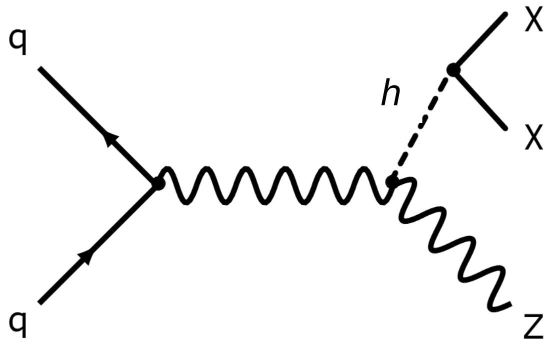
- Higgs boson does not couple directly to neutrinos in the SM
- Invisible decays in the SM: $h \to ZZ^* \to 4\nu$
- Tiny branching ratio: $BR(h \to inv) = 0.1\%$
- Could be significantly increased if the Higgs boson is a portal to DM → direct decays to DM!



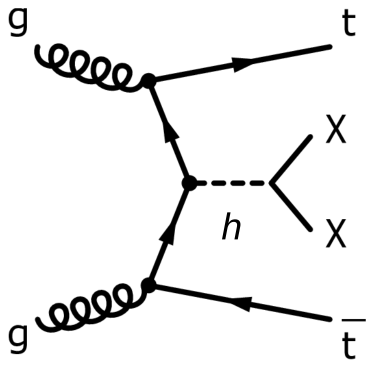
Production modes in h→inv searches



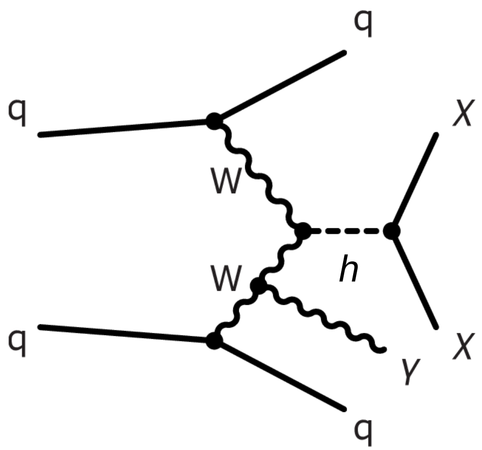
Vector-boson fusion (VBF)



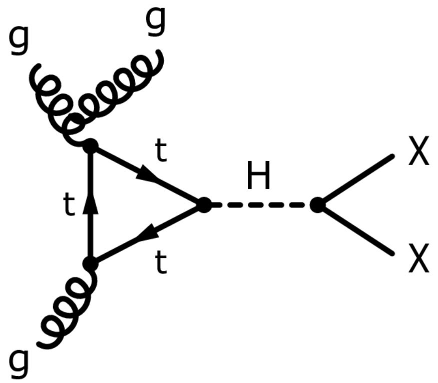
Higgs strahlung (Zh)



Top-quark associated (tth)

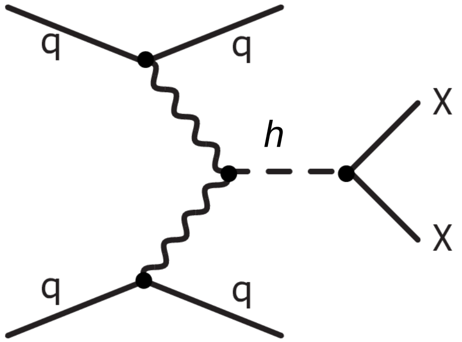


VBF + photon

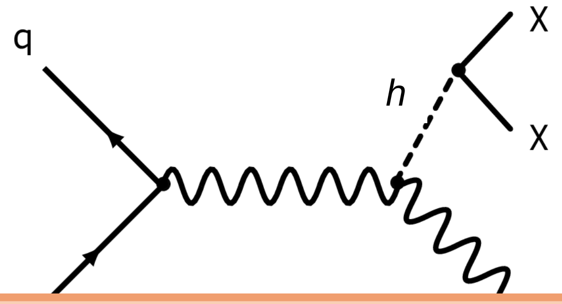


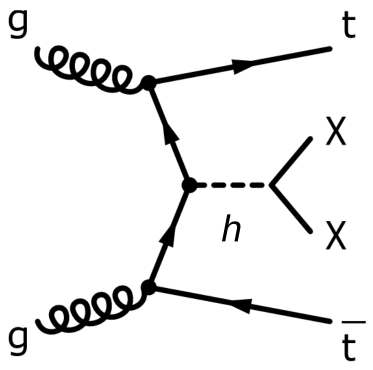
Gluon fusion

Production modes in h→inv searches



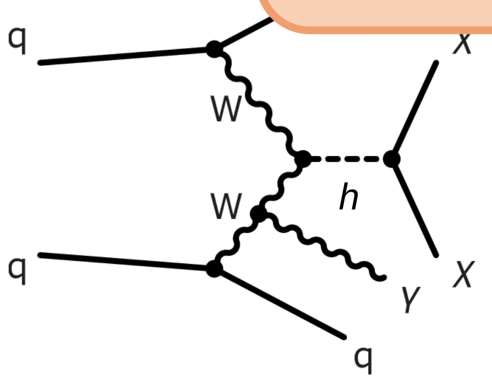
Vector-boson fusion (VBF)



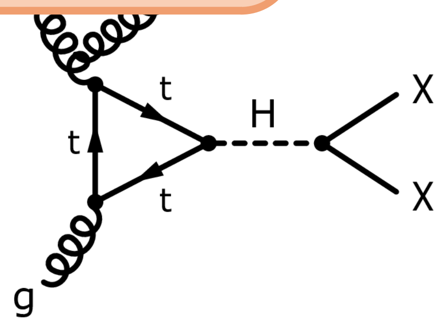


Top-quark associated (tth)

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

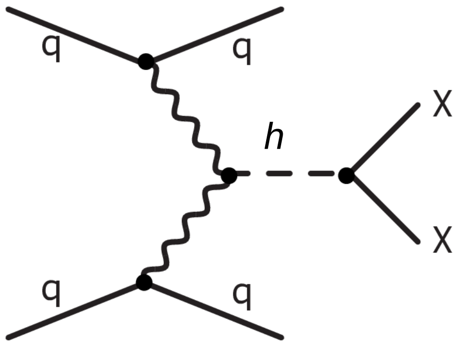


VBF + photon

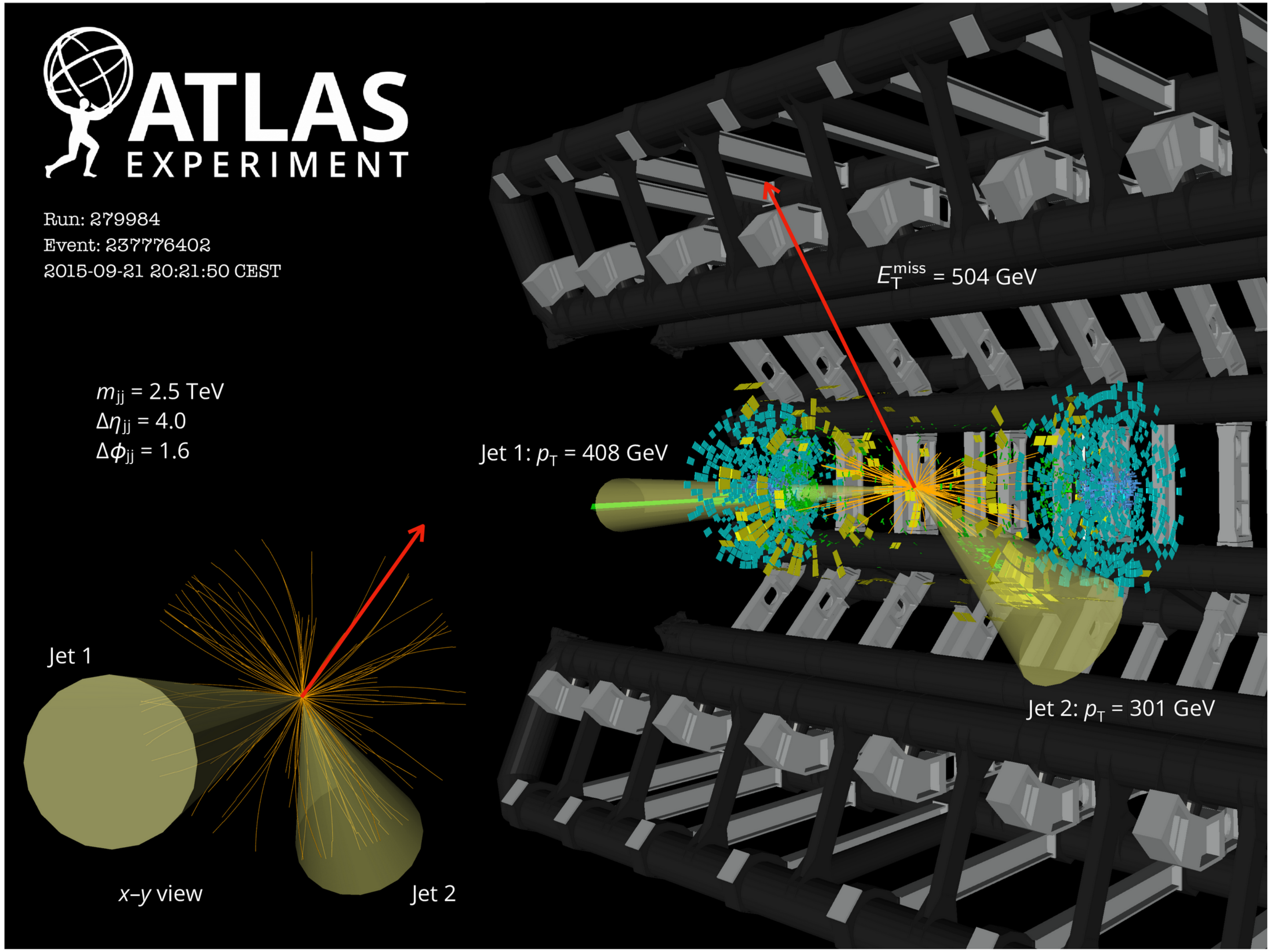


Gluon fusion

Vector-boson fusion production of h → inv



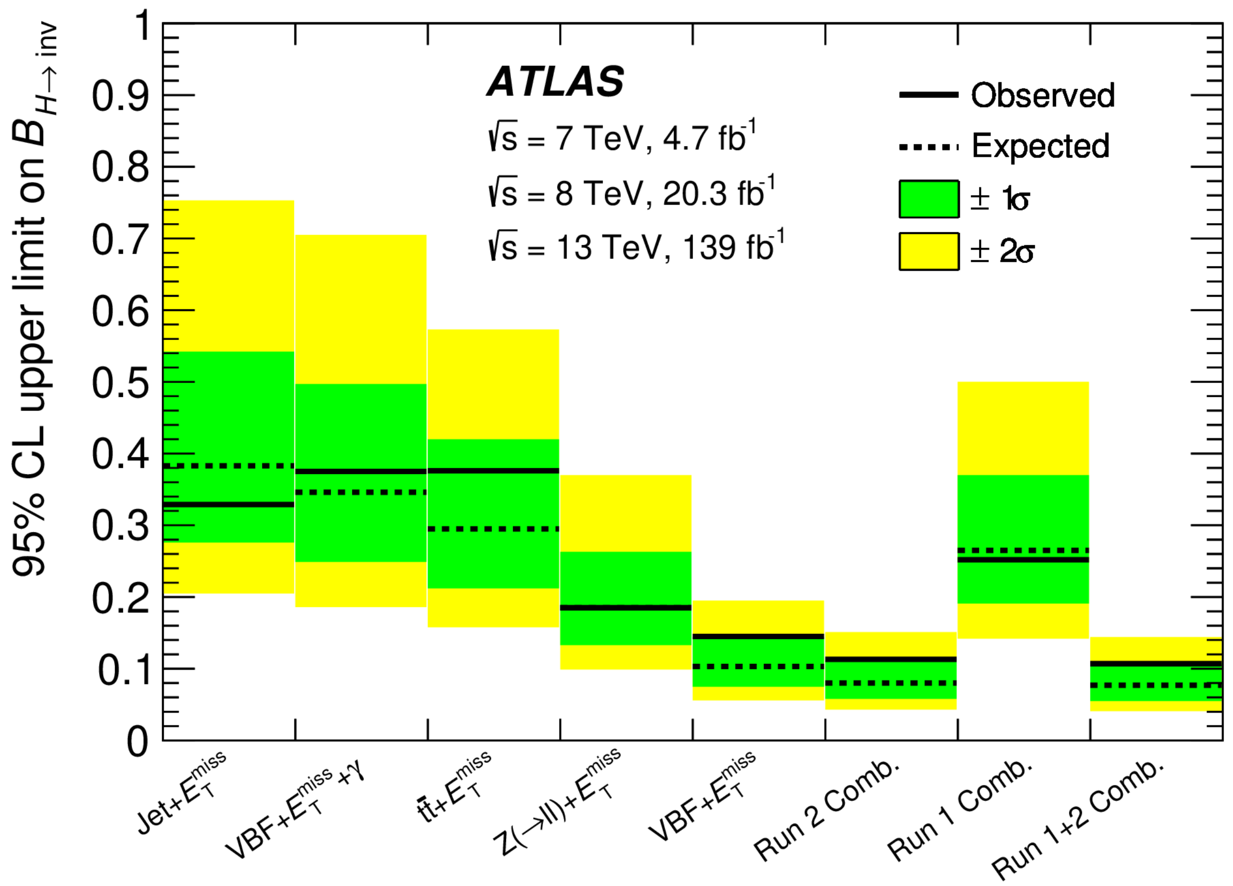
Vector-boson fusion (VBF)



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 ($0.077^{+0.030}_{-0.022}$)

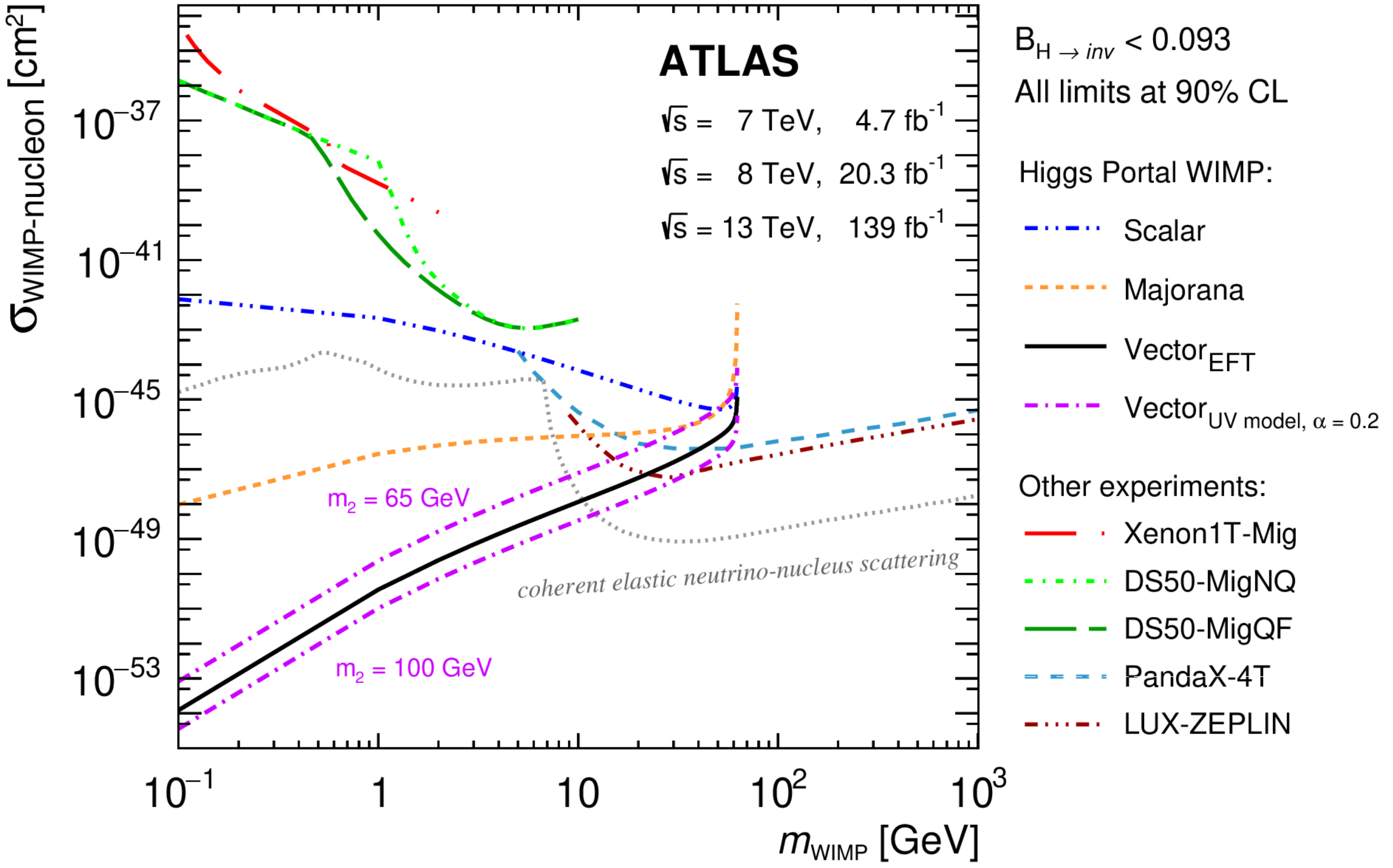
at 95% CL

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

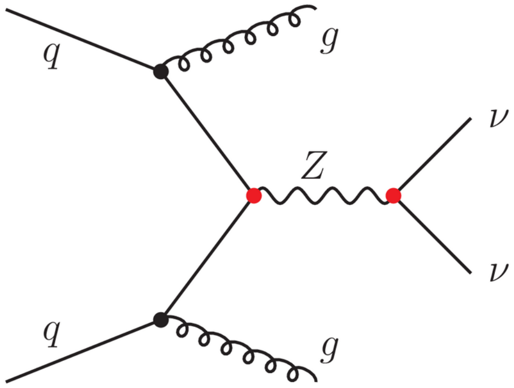
- Next lecture!

BONUS SLIDES

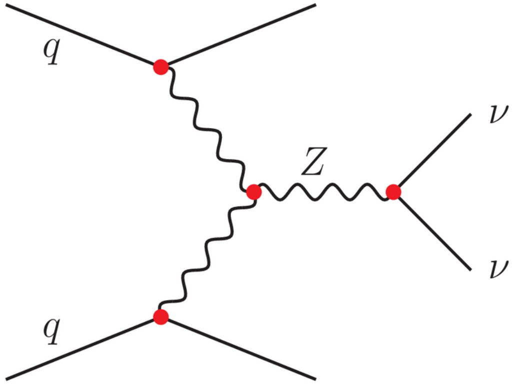
Vector-boson fusion production of h → inv

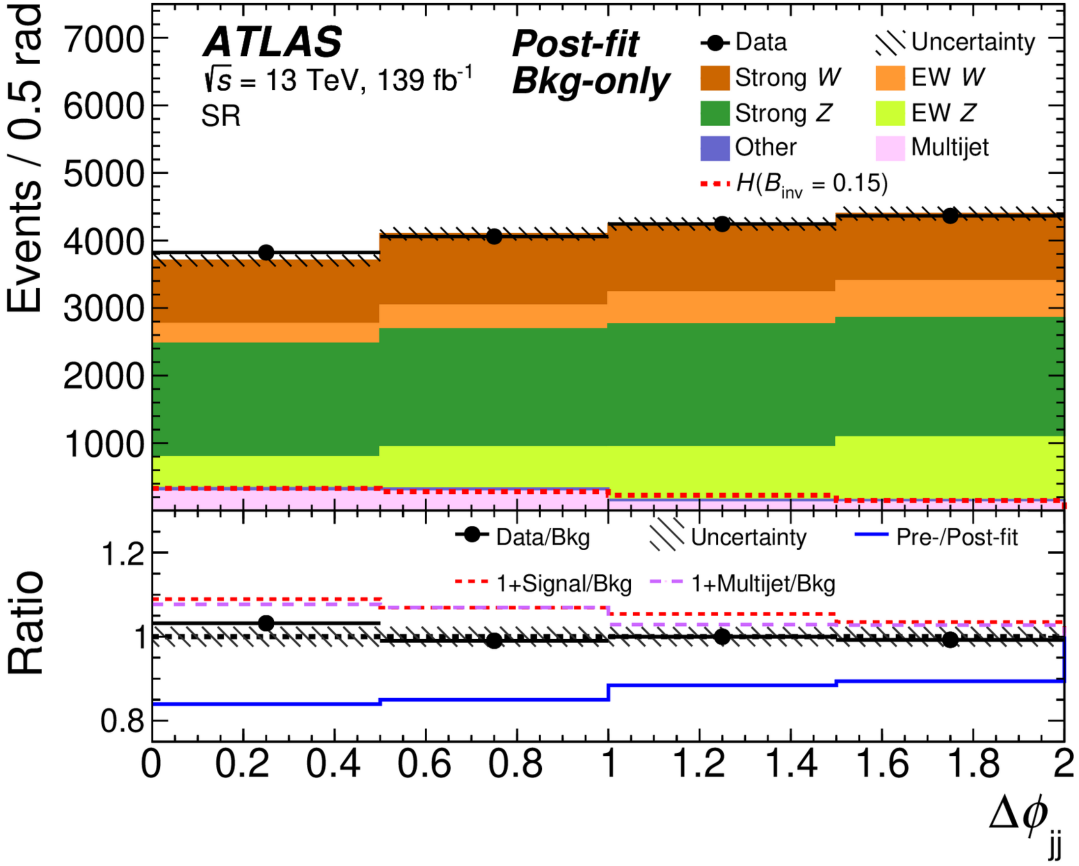
- Main background from Z(νν)+jets production
- Further background from W(lν)+jets production where lepton was not correctly identified
- Both processes poorly modelled in simulation → data-driven estimate

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)

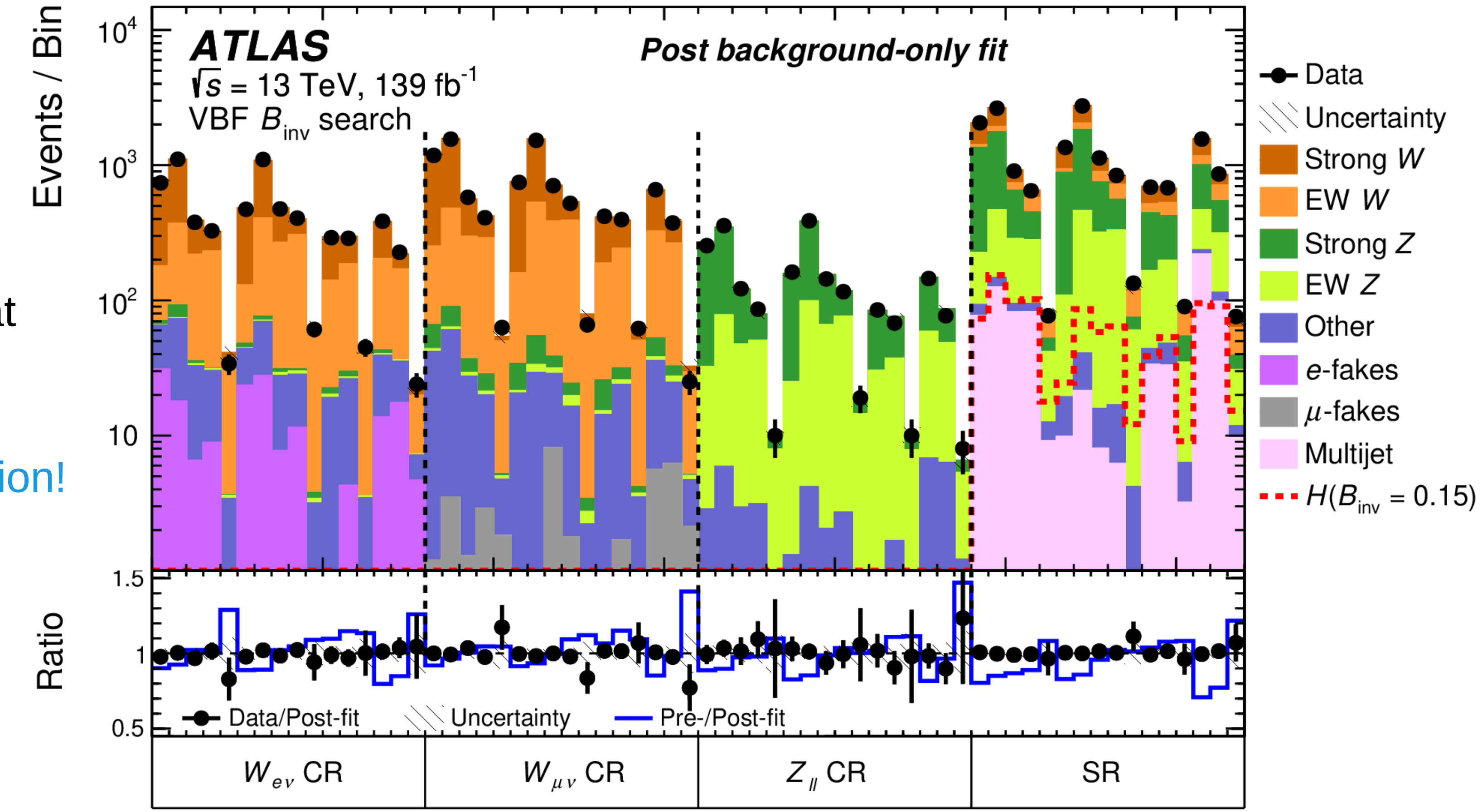
> Problem: low statistical power of Z(ll) CR

> Trick: use W(lν) CR in addition

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

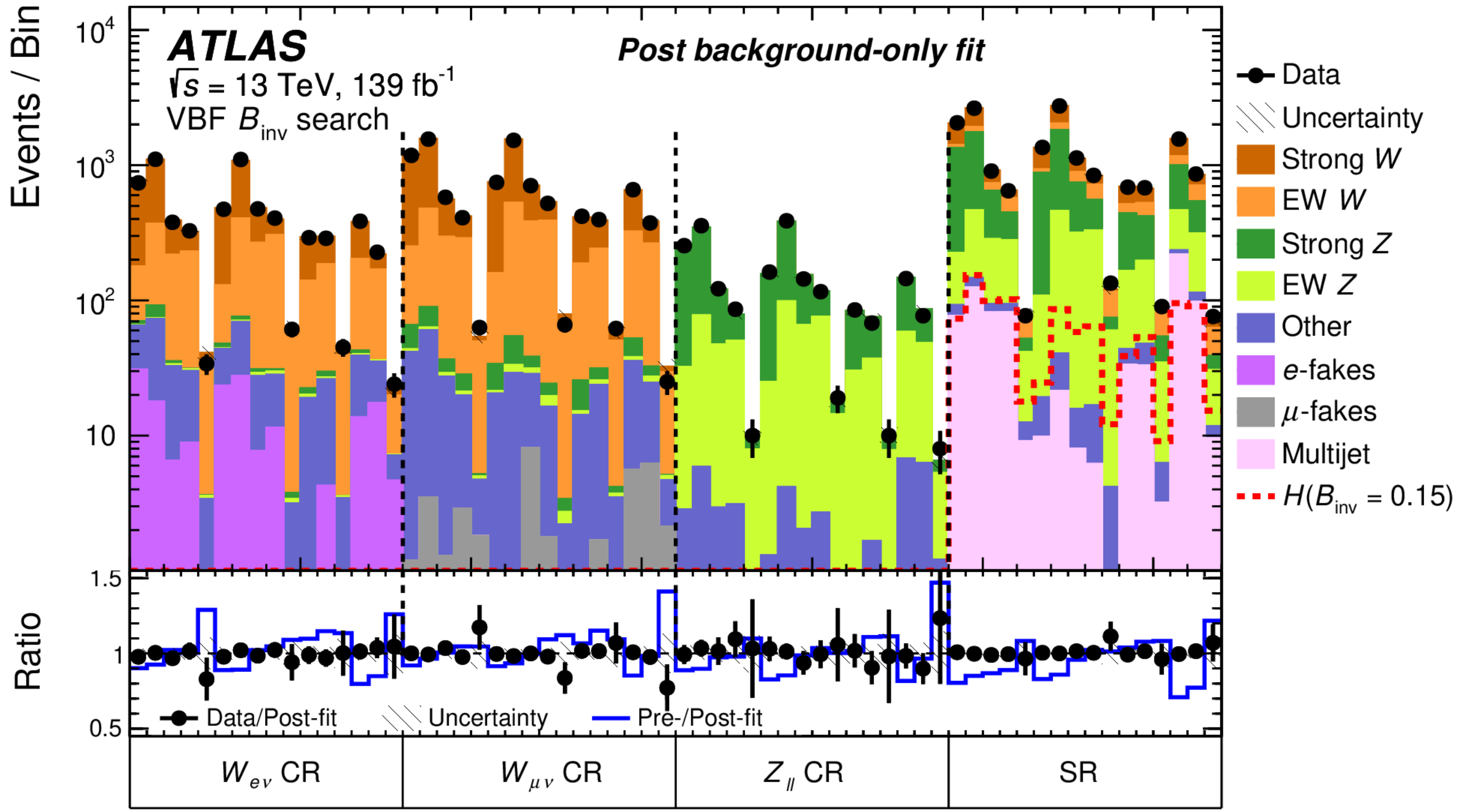
> Provided by dedicated calculation at NLO-QCD + NLO-EW precision derived in the phase of the search

> Fruitful theory-experiment cooperation!



Vector-boson fusion production of h → inv

> BR(h → 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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  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

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

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

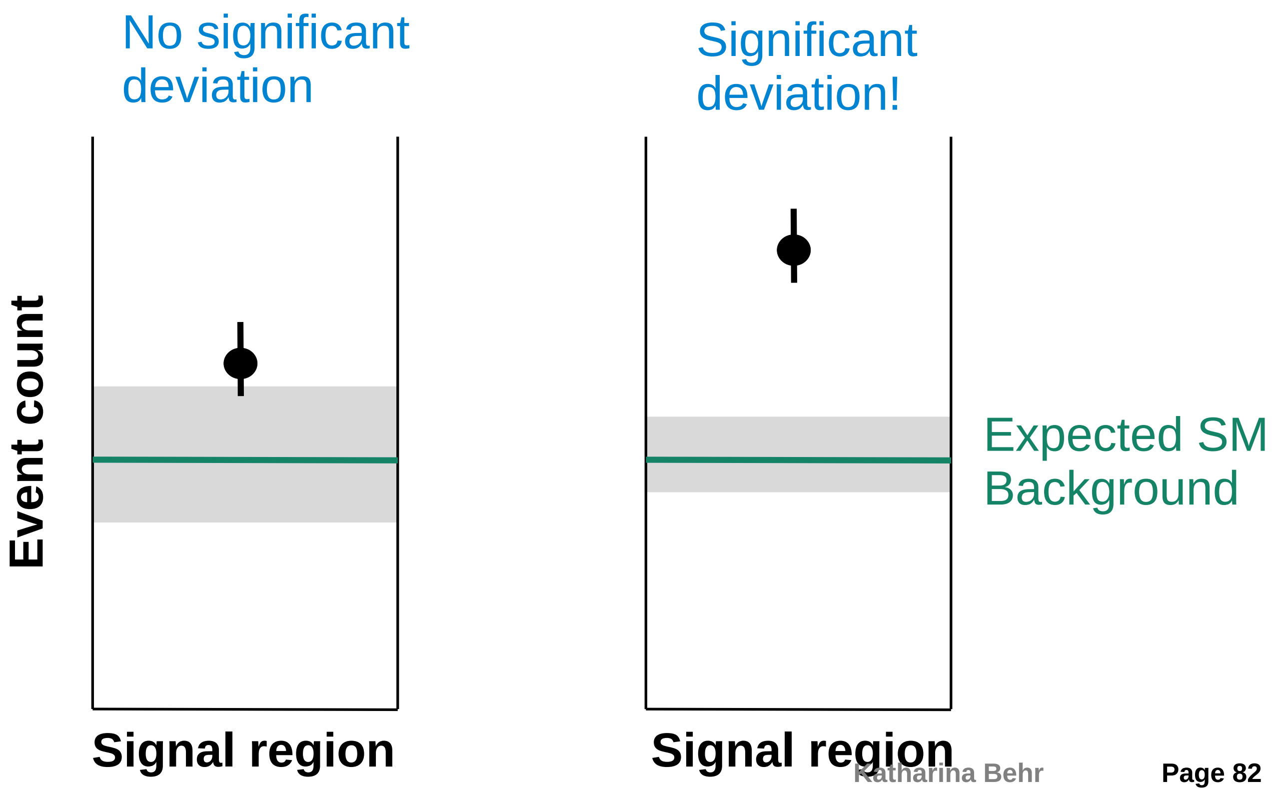
- Strong CP violation in SM QCD (6 massive quarks) via equivalent phase θ^*
- Would imply non-zero neutron electric dipole moment: $d_N = (5.2\ 10^{-16}\ e\ \text{cm})\ \theta^*$
- Measurements constrain dipole moment to $|d_N| < 10^{-26}\ e$ cm → $\theta^* < 10^{-10}$ → fine-tuning!

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

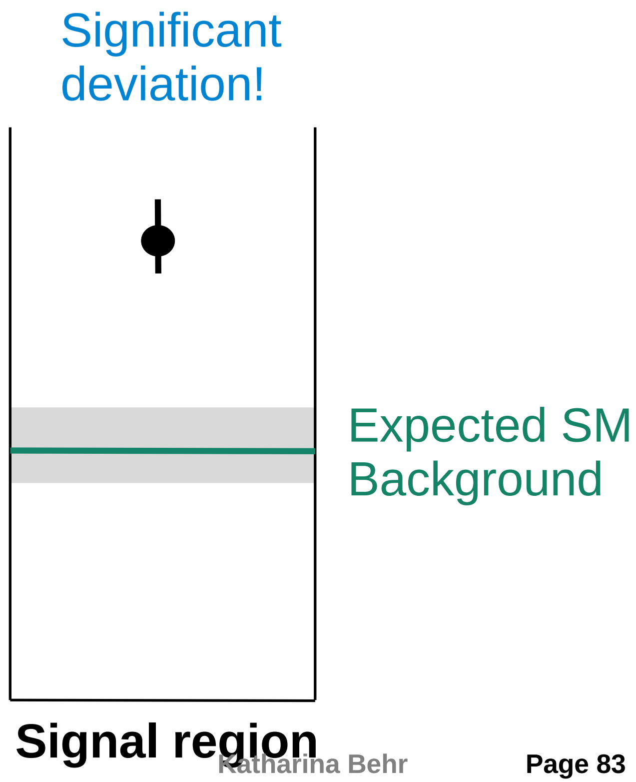
> Calculate significance of deviation from SM prediction (accounting for uncertainties)



Cut-and-count method

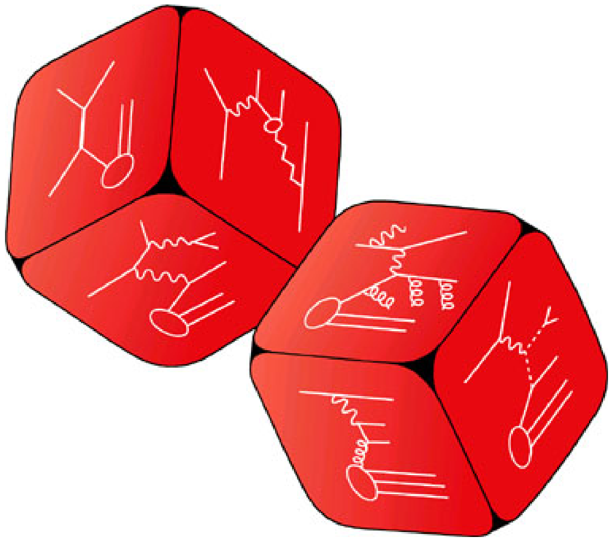
- Select (**cut**) events that you expect to be consistent with signal (signal region)
- **Count** data events in signal region and compare with number of expected SM events
- Calculate significance of deviation from SM prediction (accounting for uncertainties)

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



Monte Carlo event generators in a nutshell

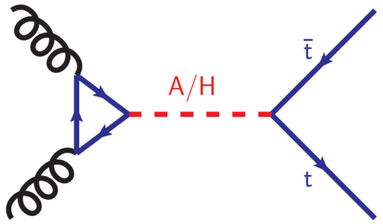
- Quantum nature of elementary particle interactions: non-deterministic
  - Given initial state can lead to different final states with different probabilities
- **Idea:**
  - Calculate probability distribution for a given process (or sub-processes)
  - Random sampling to generate events with particle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



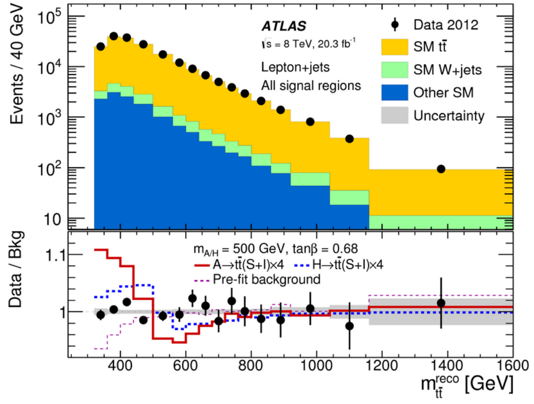
Experimental Techniques

Experimental analysis step by step

- Pick and study a signal of interest

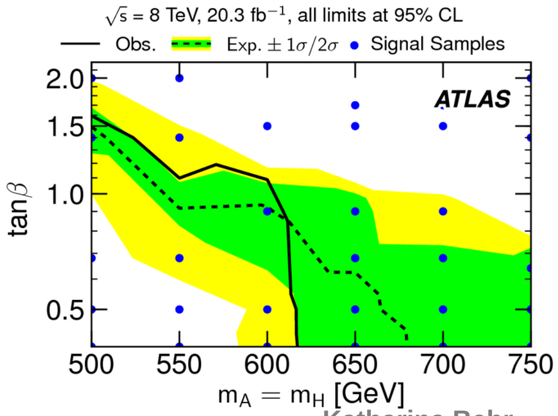


- Select subset of events enriched in signal (signal region)



- Estimate backgrounds and systematic uncertainties

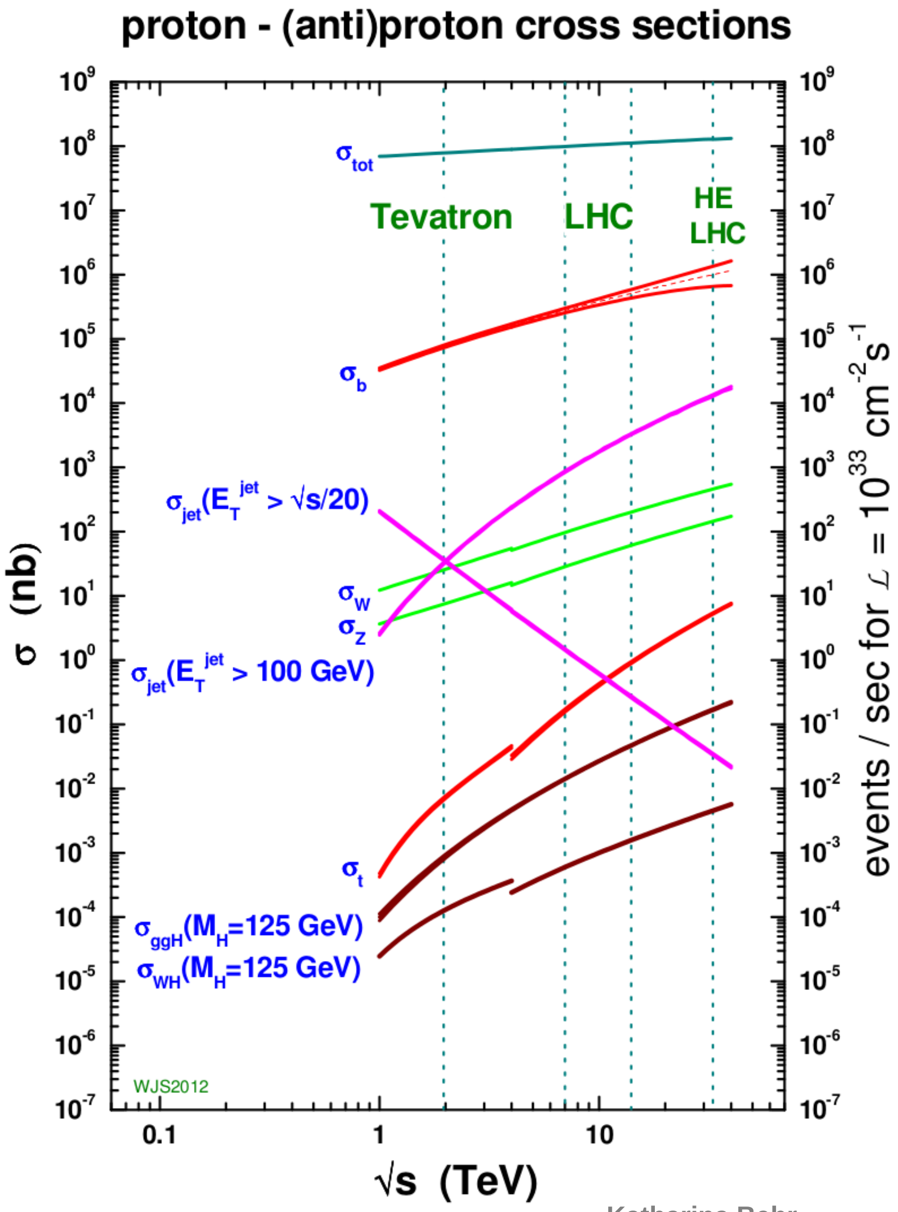
- Test agreement between SM prediction and data



How to search for BSM signals?

> Isolate small signal from huge dataset

T.G. McCarthy



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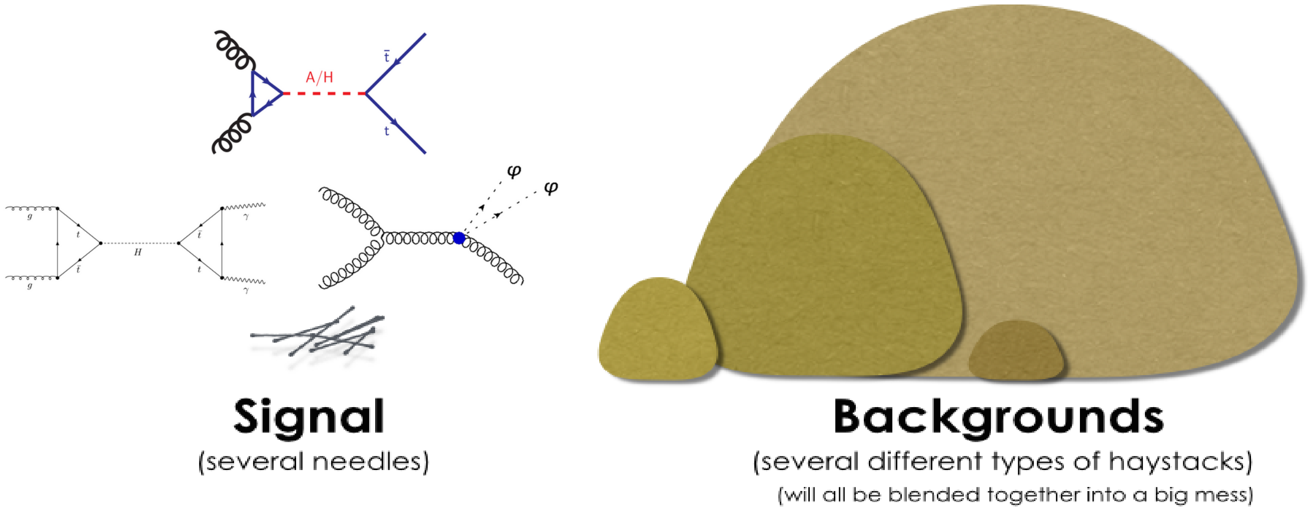
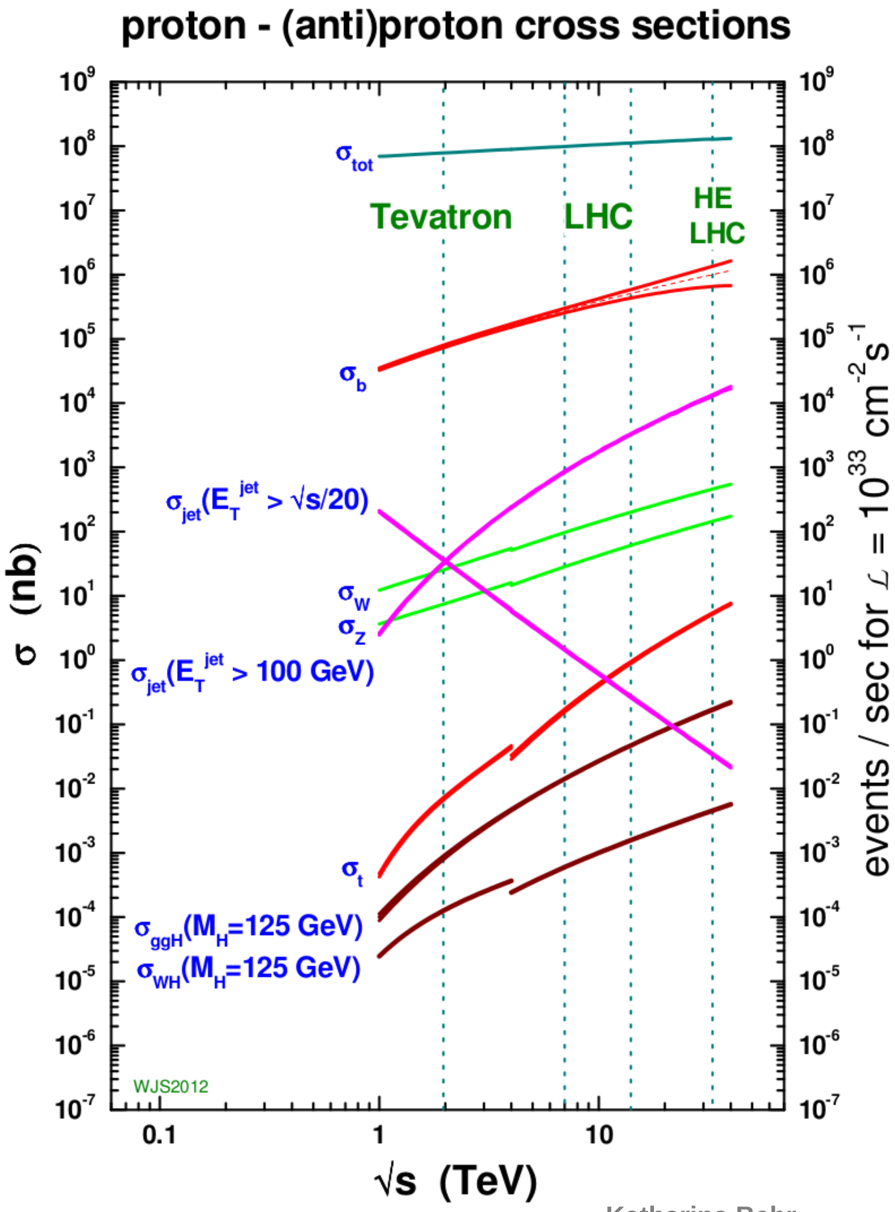
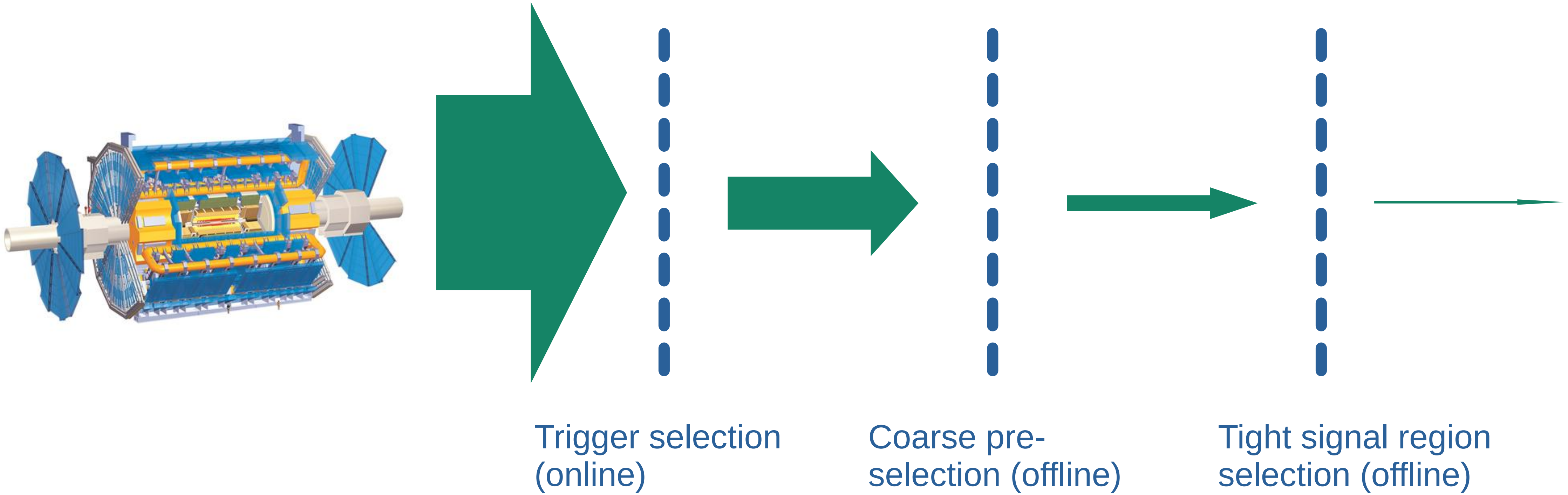


T.G. McCarthy



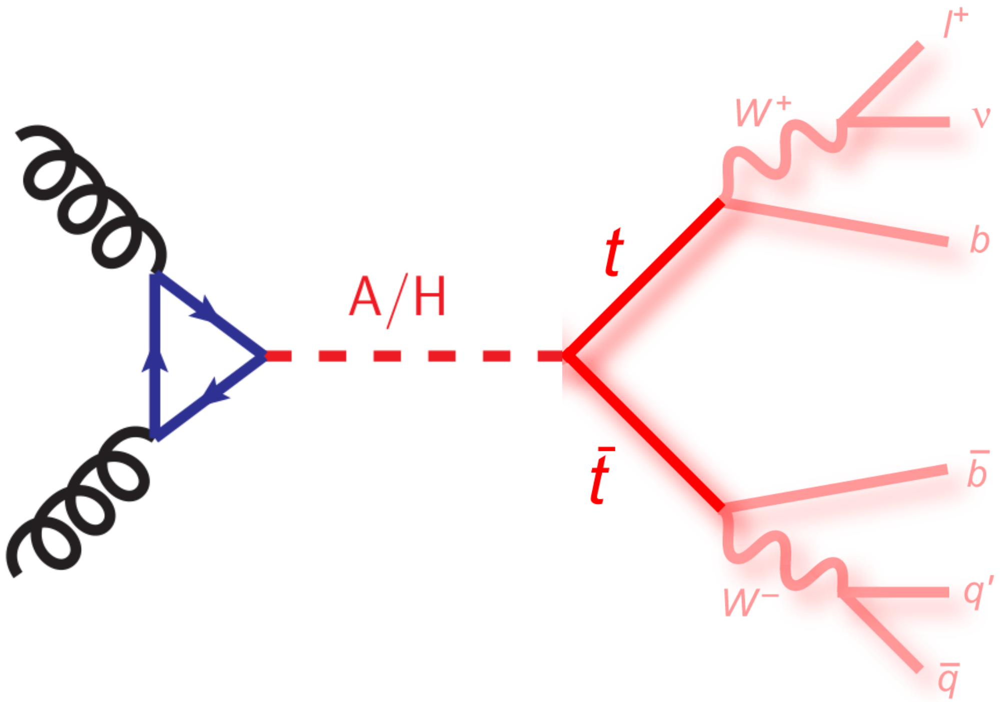
Select signal-like events

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



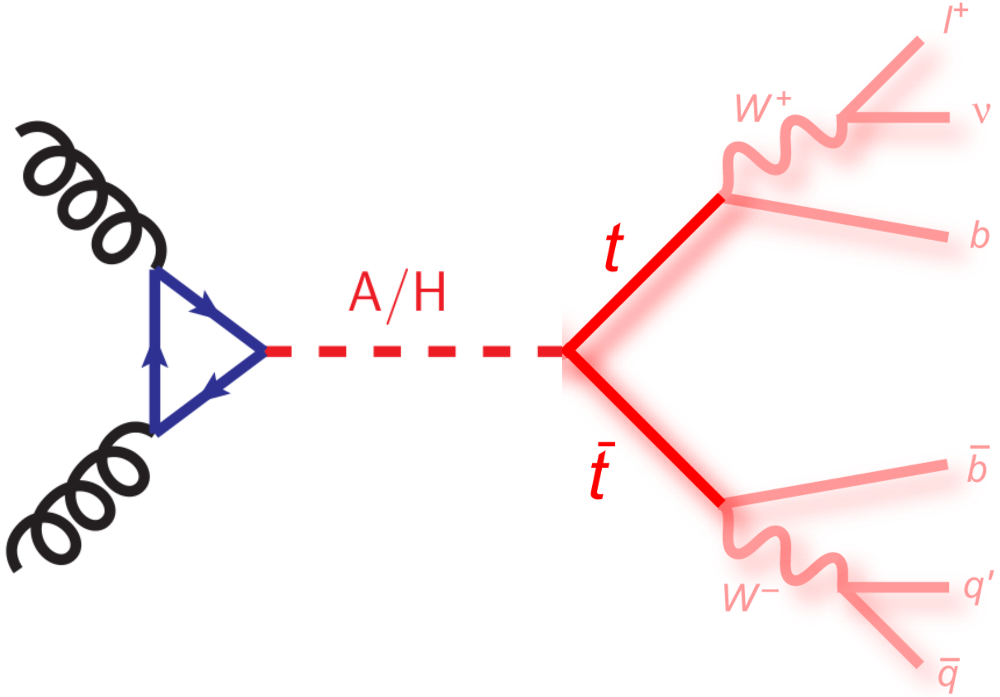
Exercise

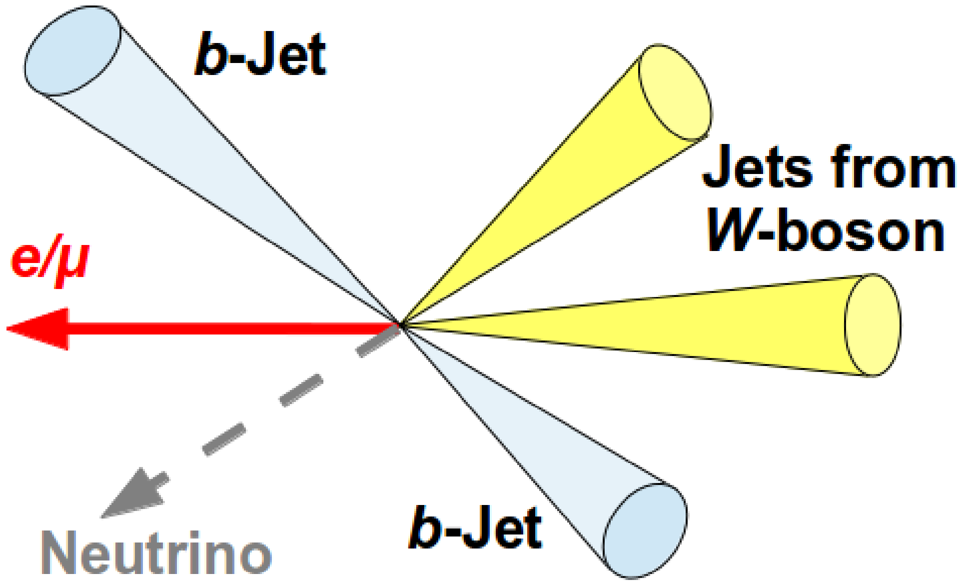
- Define a signal region for semi-leptonic ttbar decay
- For simplicity assume that charged lepton is an electron or muon



Exercise

> Define a signal region for semi-leptonic ttbar decay



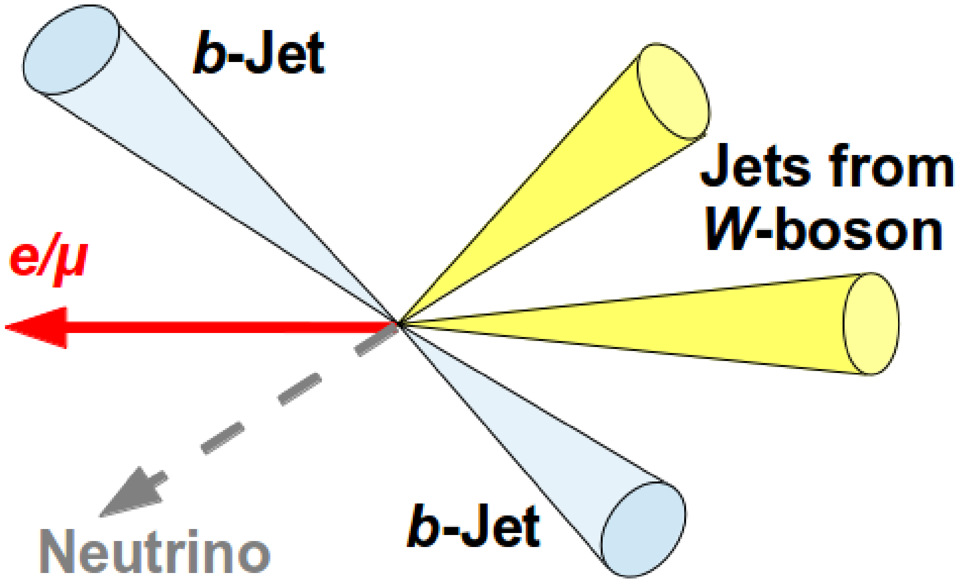


Exercise: Solution

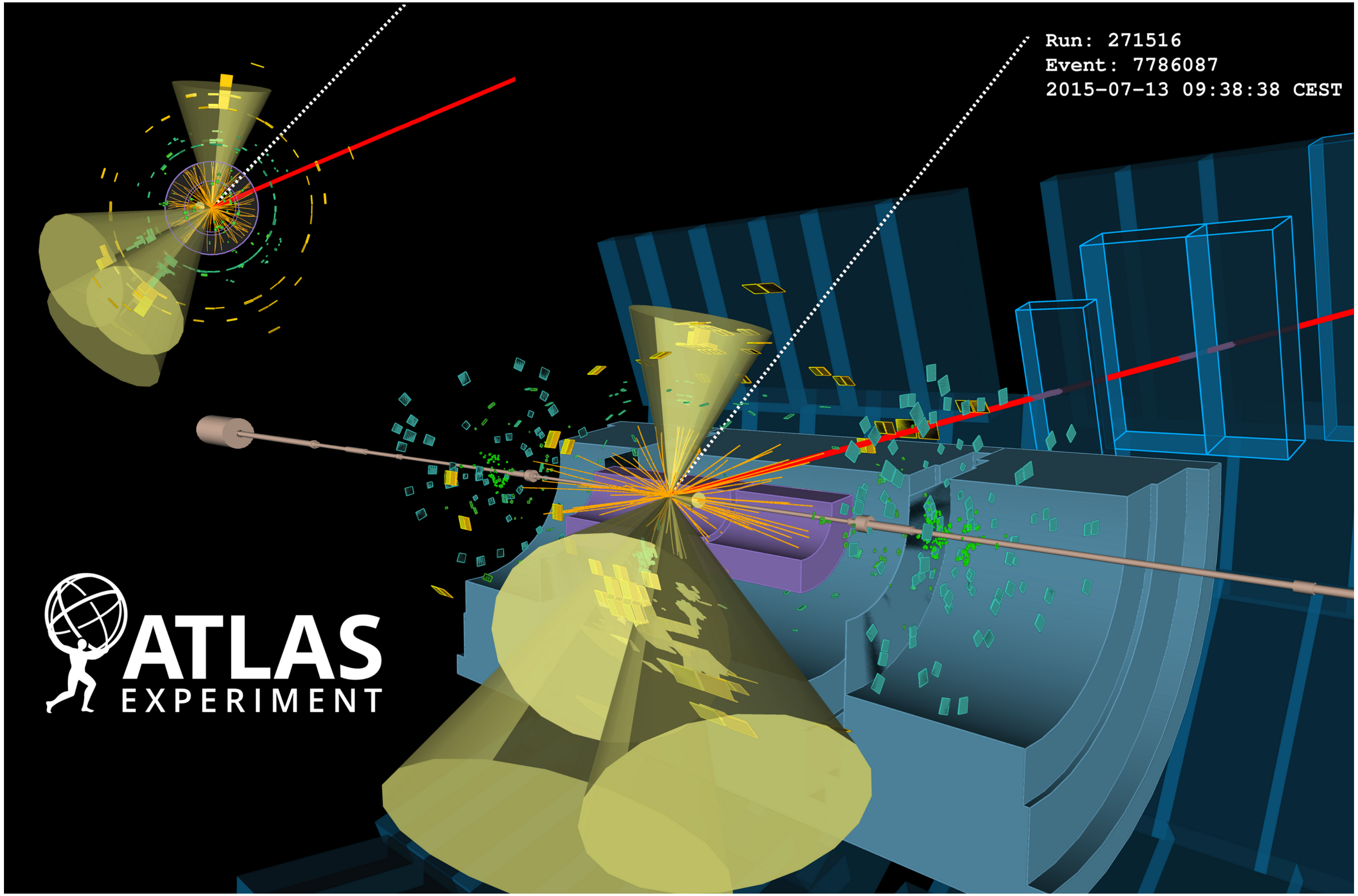
- Exactly 1 electron or muon
- Missing energy (from the neutrino)
- At least 4 jets

- Bonus 1: 2 jets identified as b-jets

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

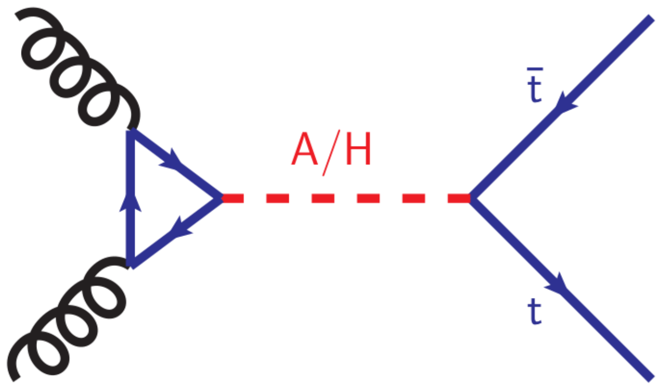


Exercise: Solution

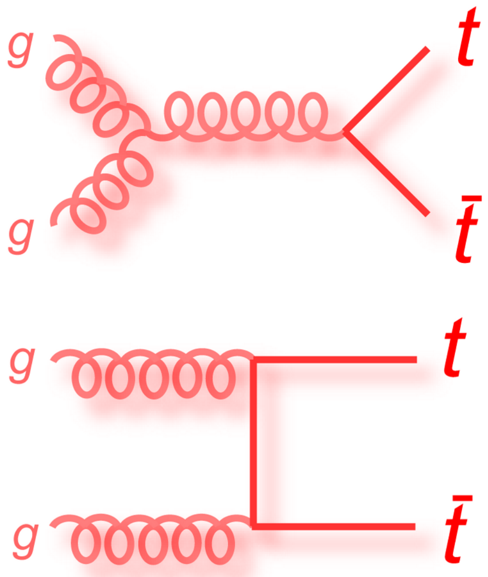


Signal vs backgrounds

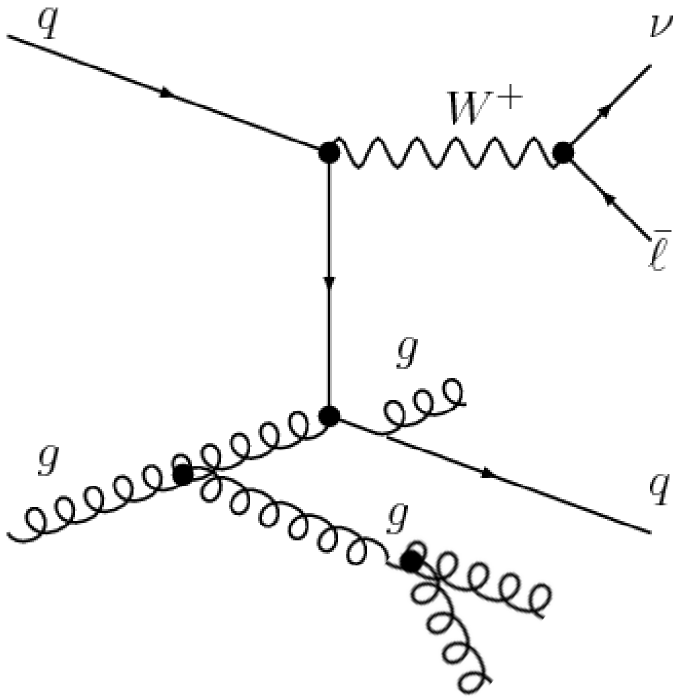
Signal



SM ttbar production
Irreducible background

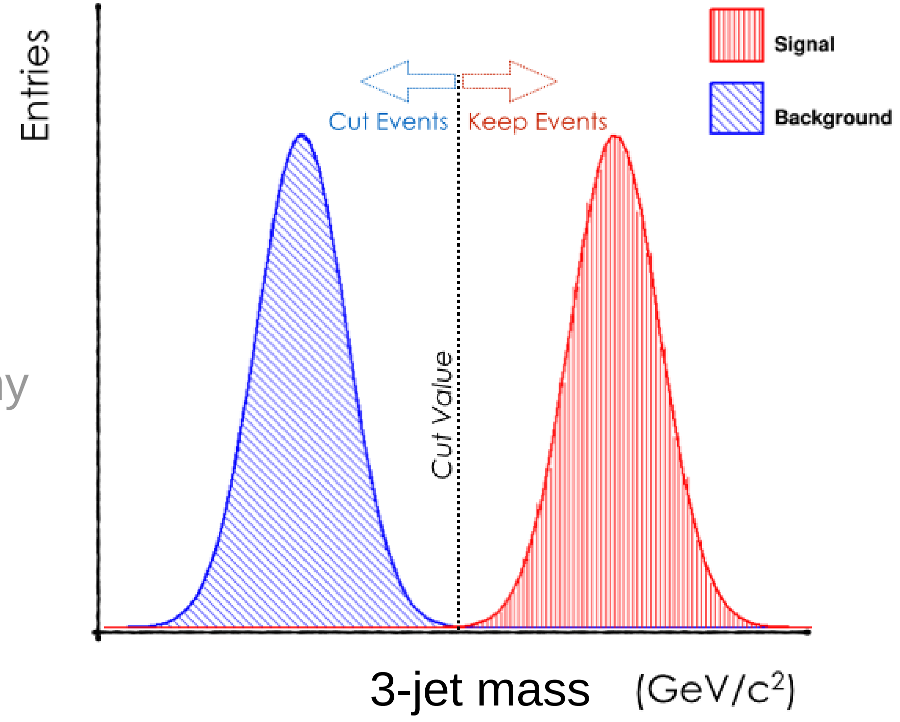


SM W+jets production
Reducible background



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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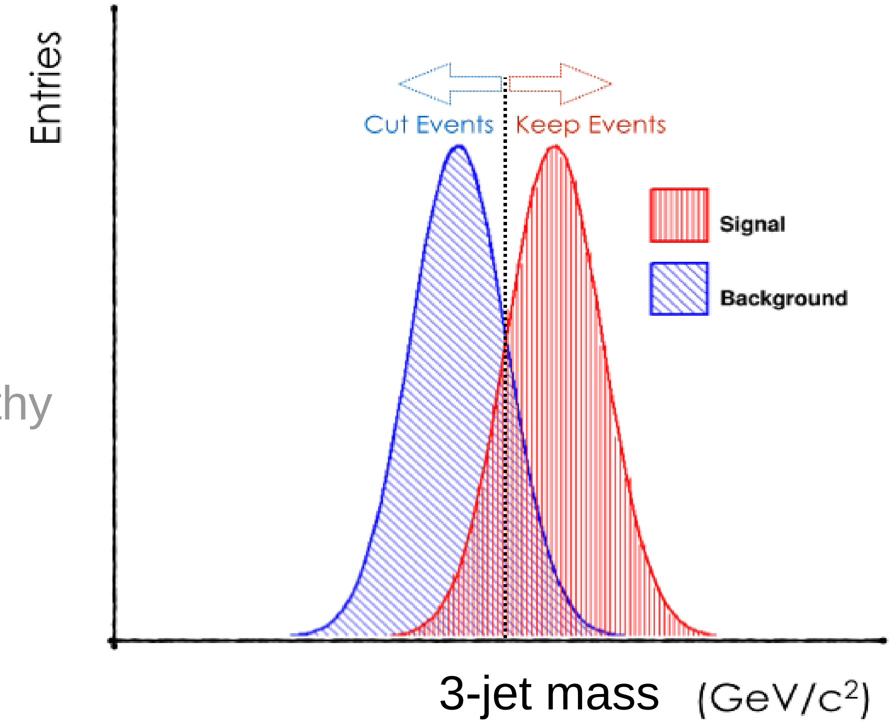

T.G. McCarthy

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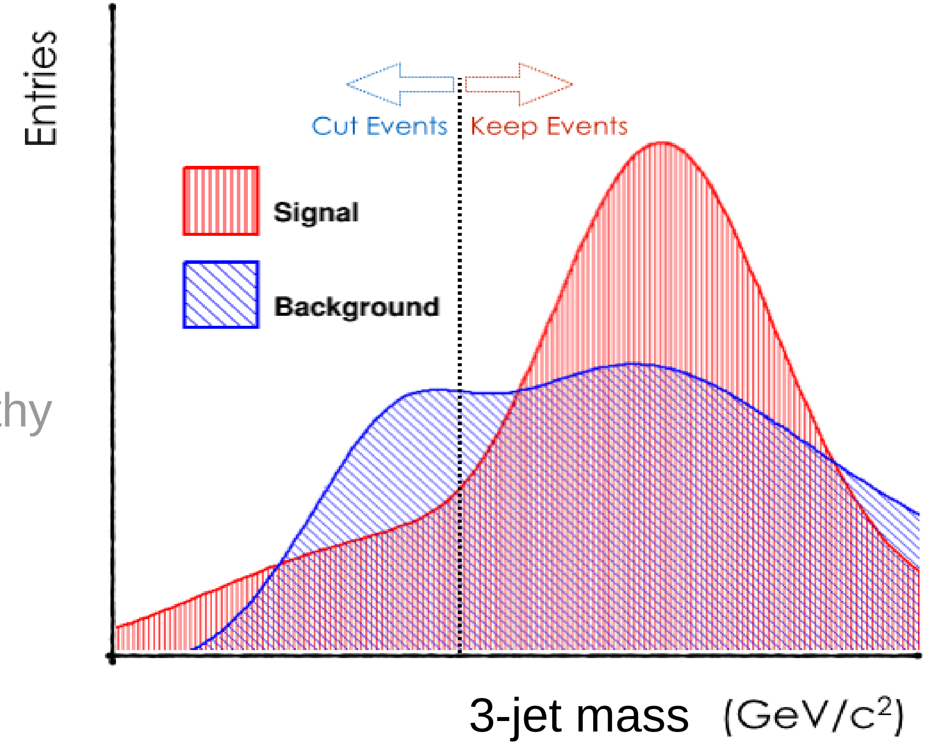

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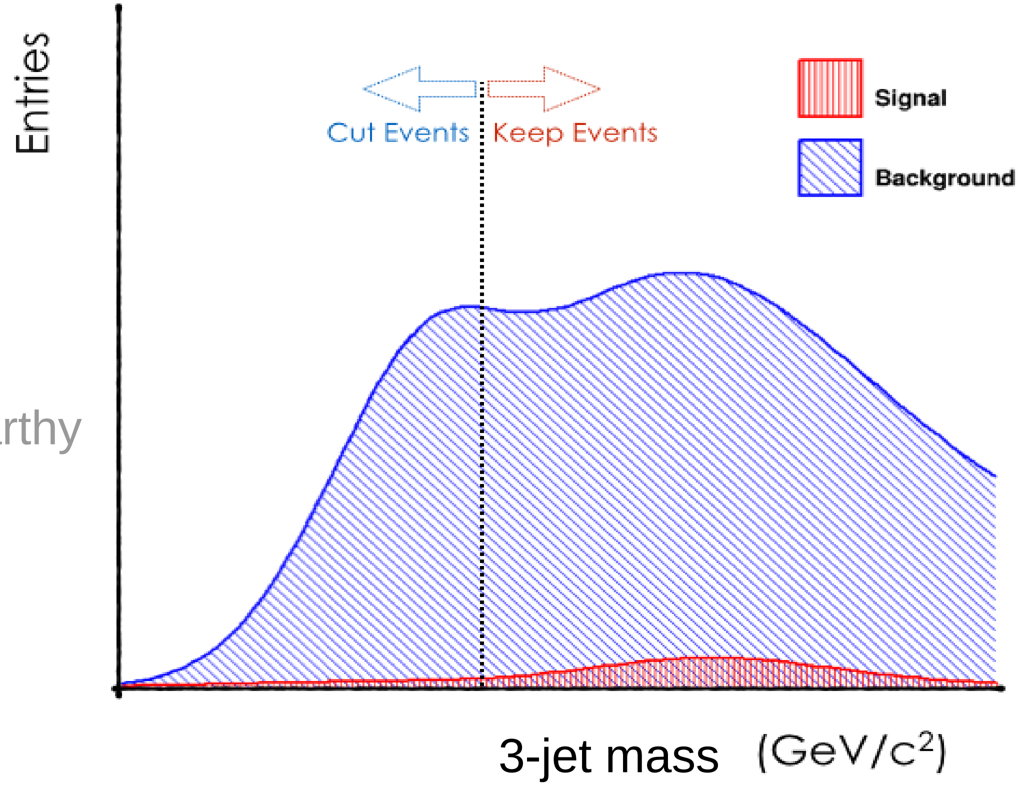

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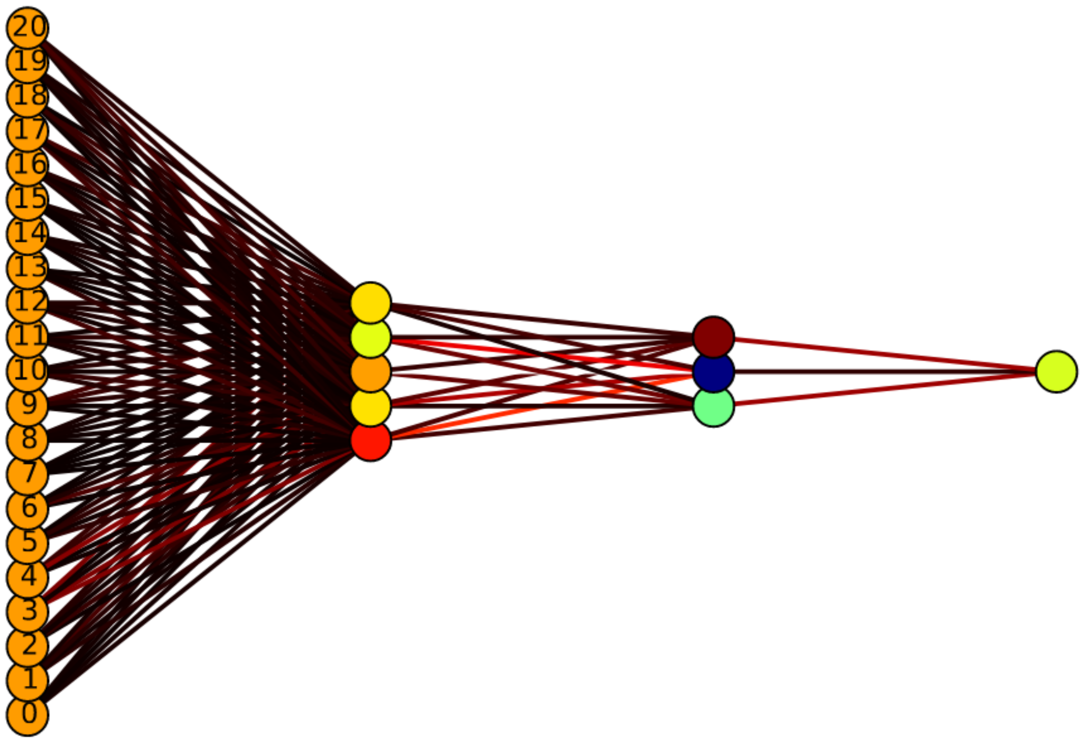
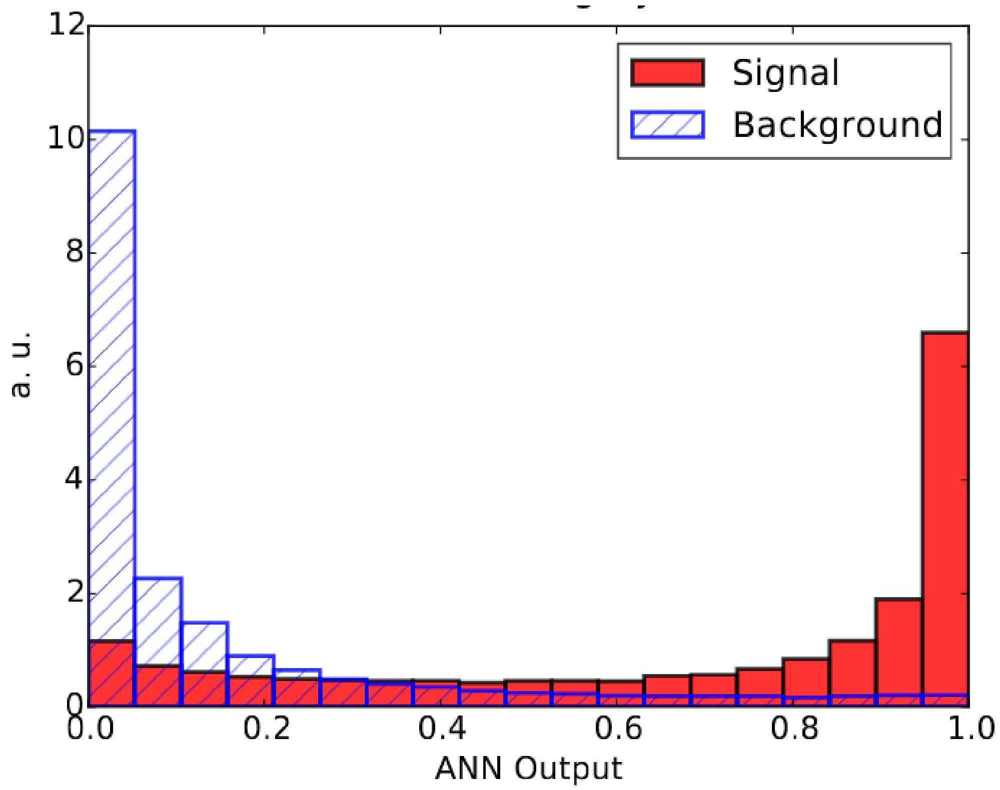
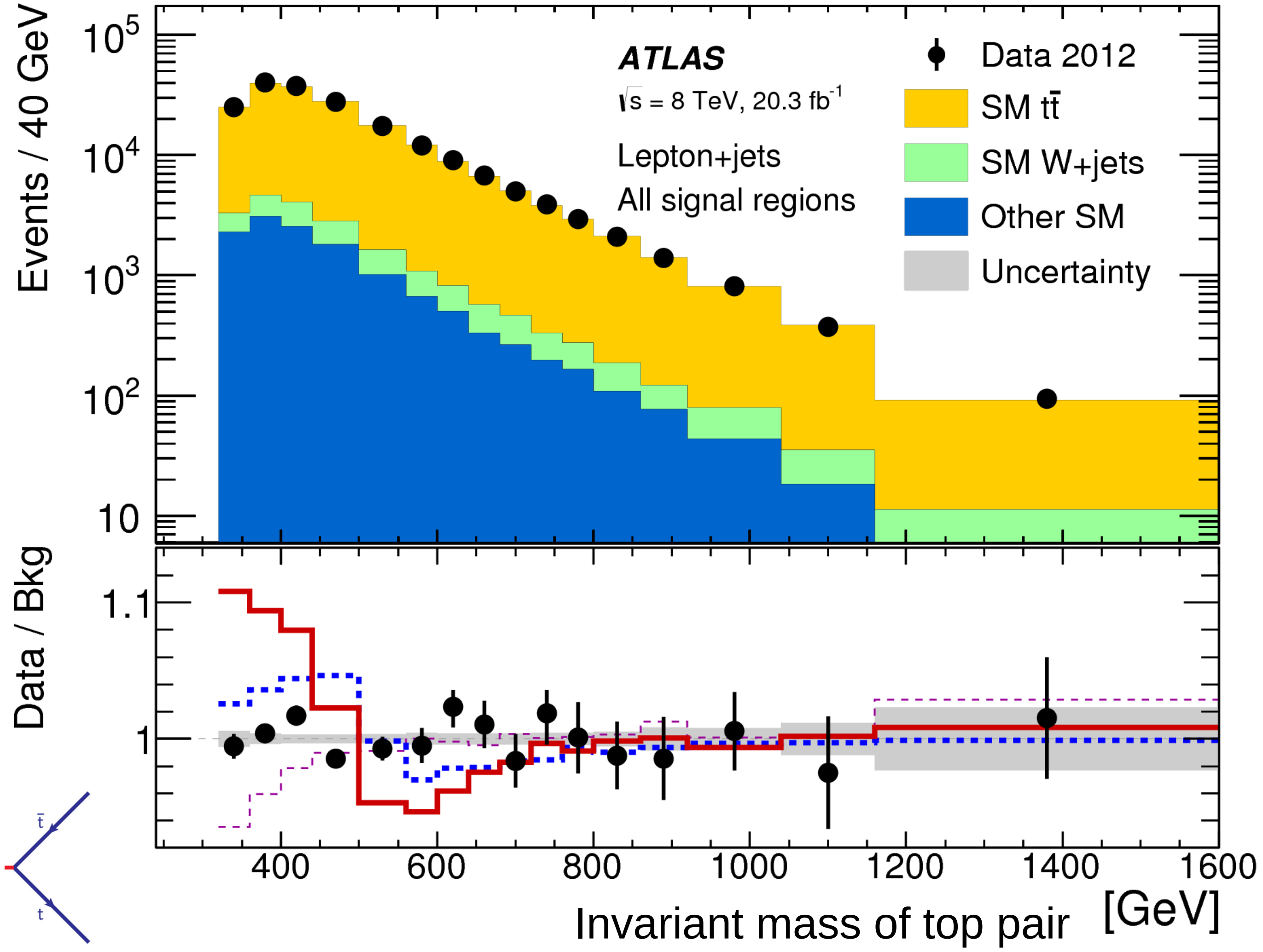
Signal region definition

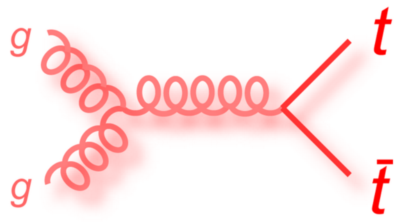
> Can refine signal regions using machine-learning algorithms
  - Exploit small differences in various kinematic variables
  - Exploit correlations

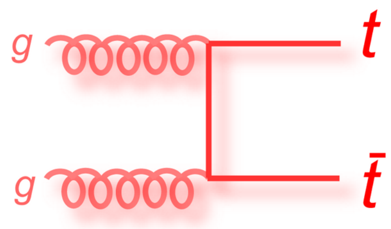


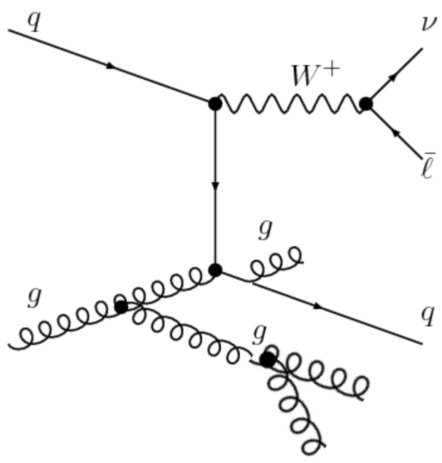


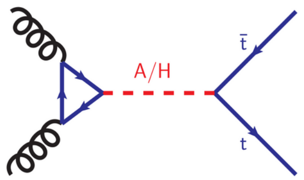
A final signal region











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)

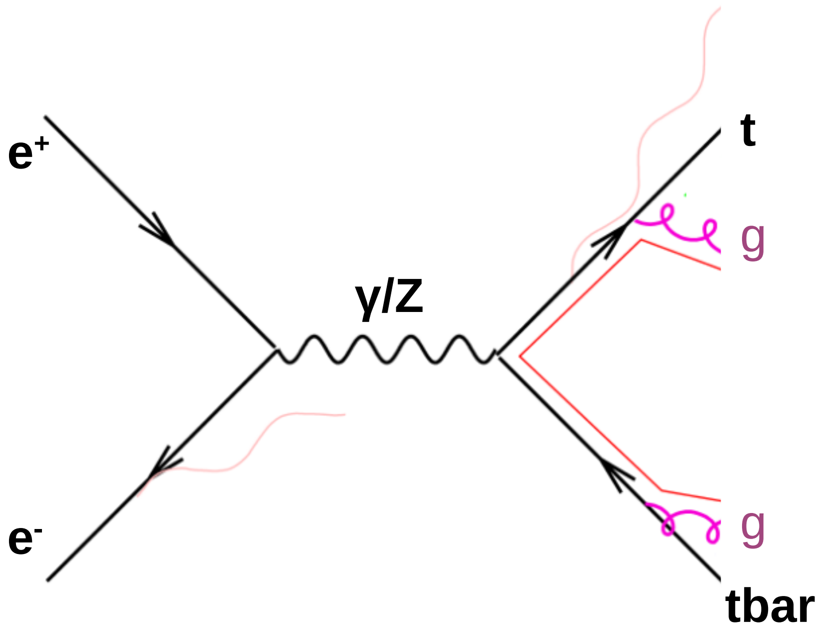
> Estimate systematic uncertainties
  - Create different background predictions within experimental uncertainties
  - E.g. top mass known with ±1 GeV uncertainty

    → Simulate top quark pair production for m_{top}(central) and m_{top}(central)±1 GeV

Simulation step by step

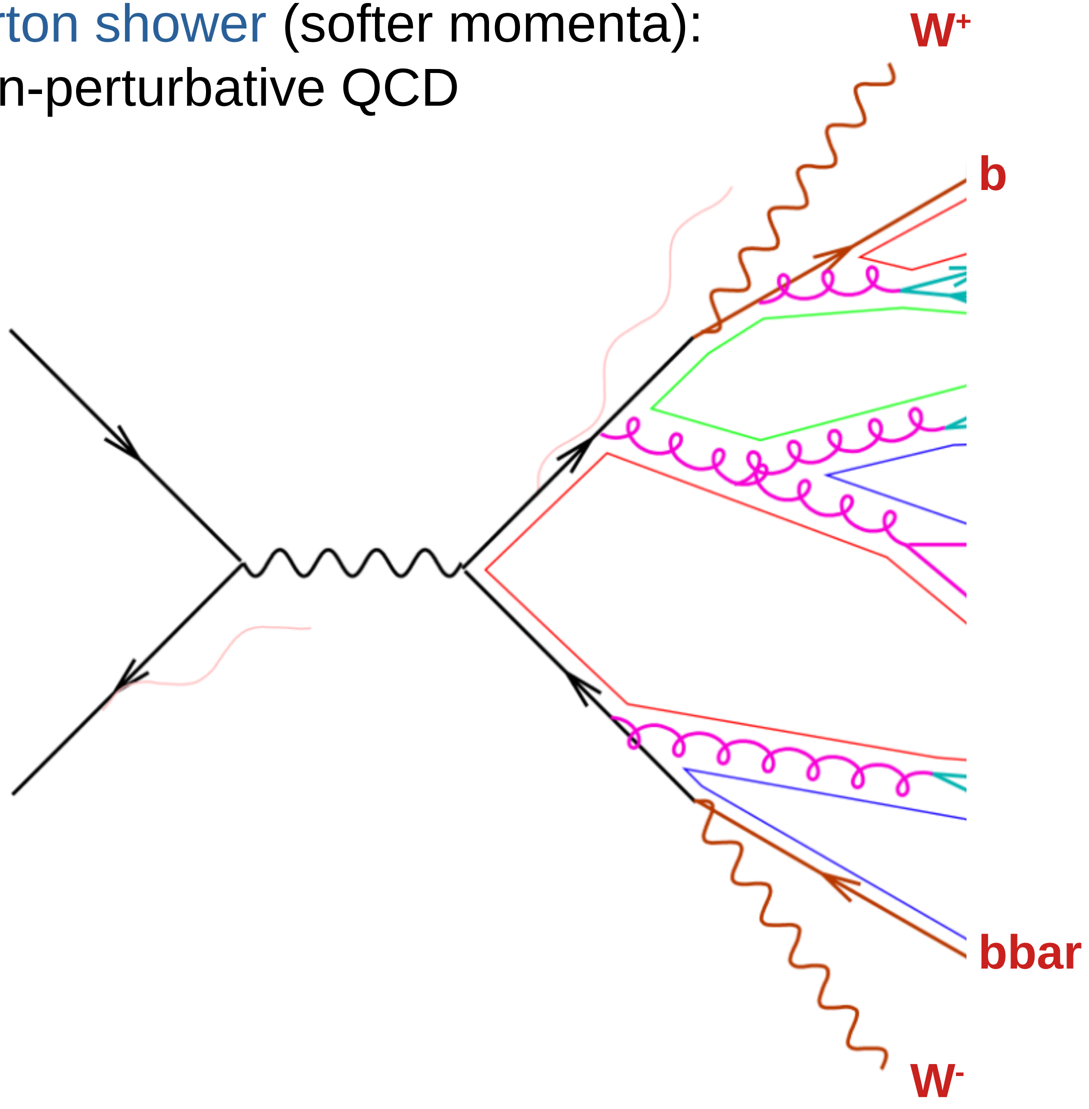
> Hard processes (large momentum transfers): perturbative QCD

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



Simulation step by step

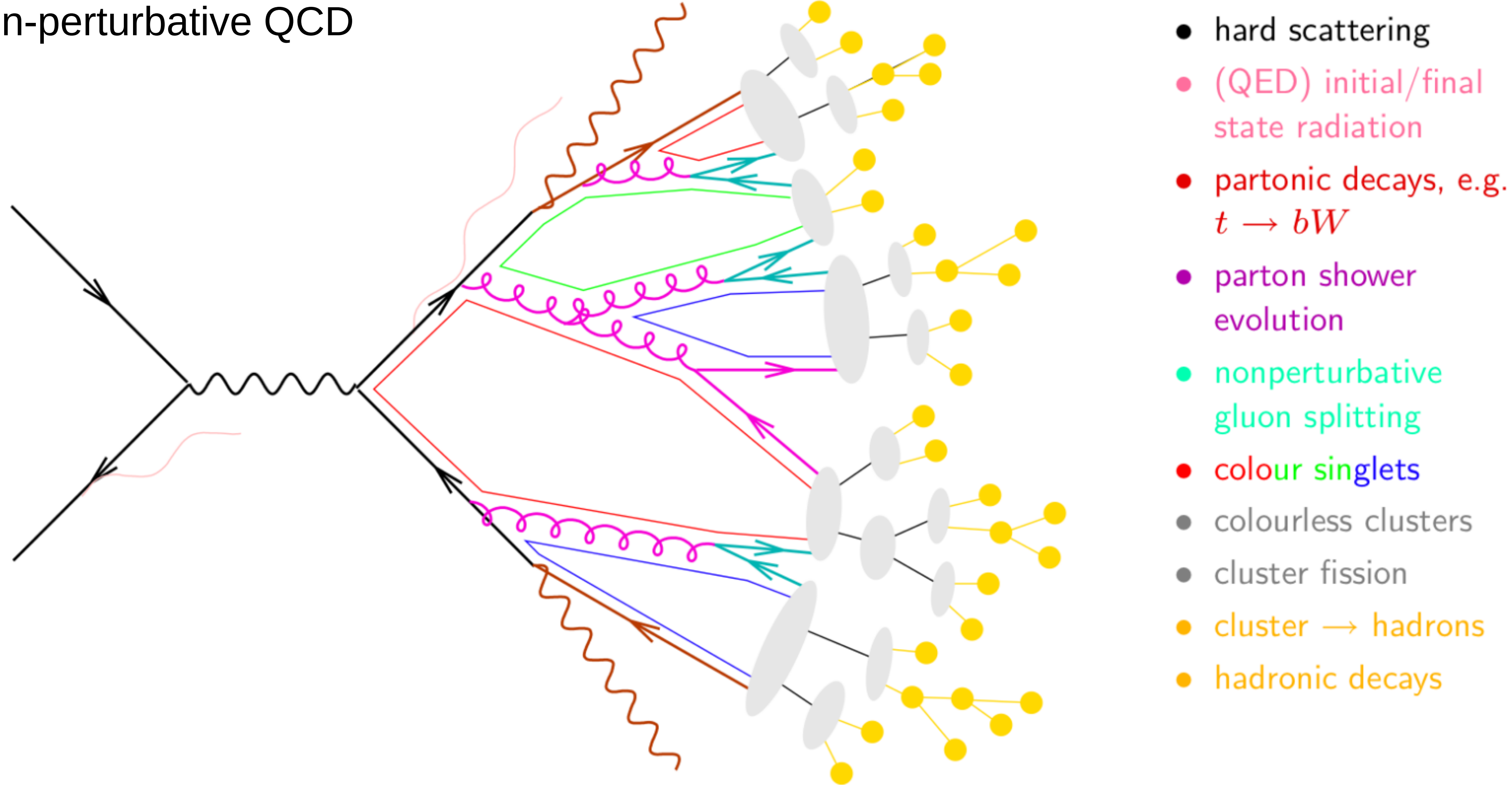
> Parton shower (softer momenta): non-perturbative QCD



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

Simulation step by step

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



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!****"*

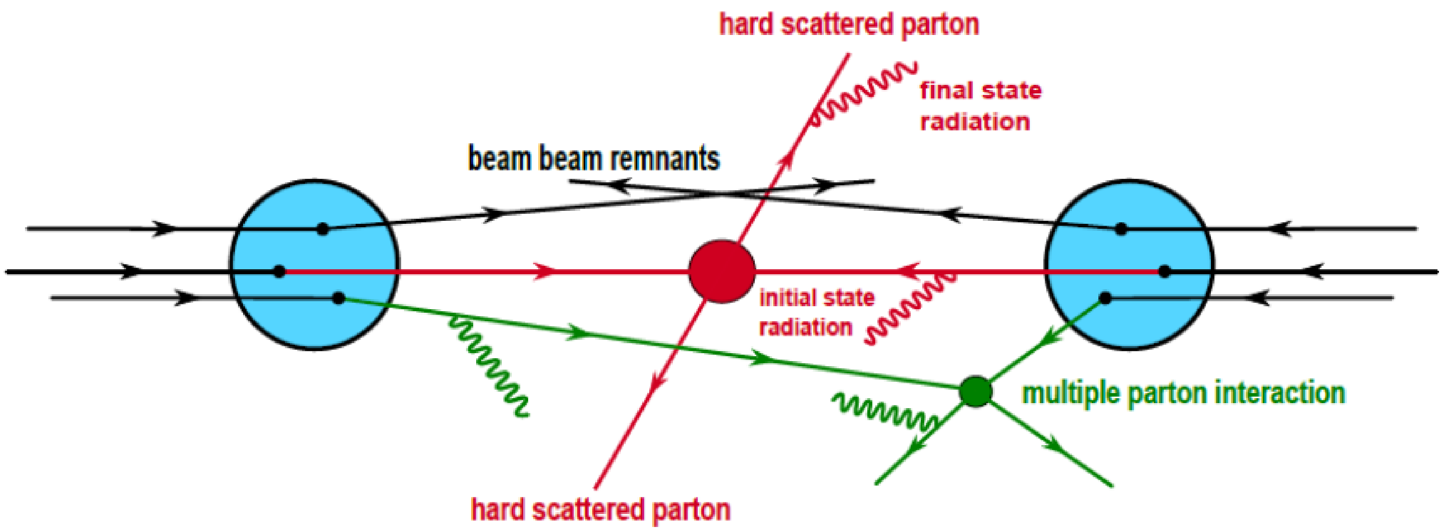
From the manual of the Pythia5 MC generator

Further aspects

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

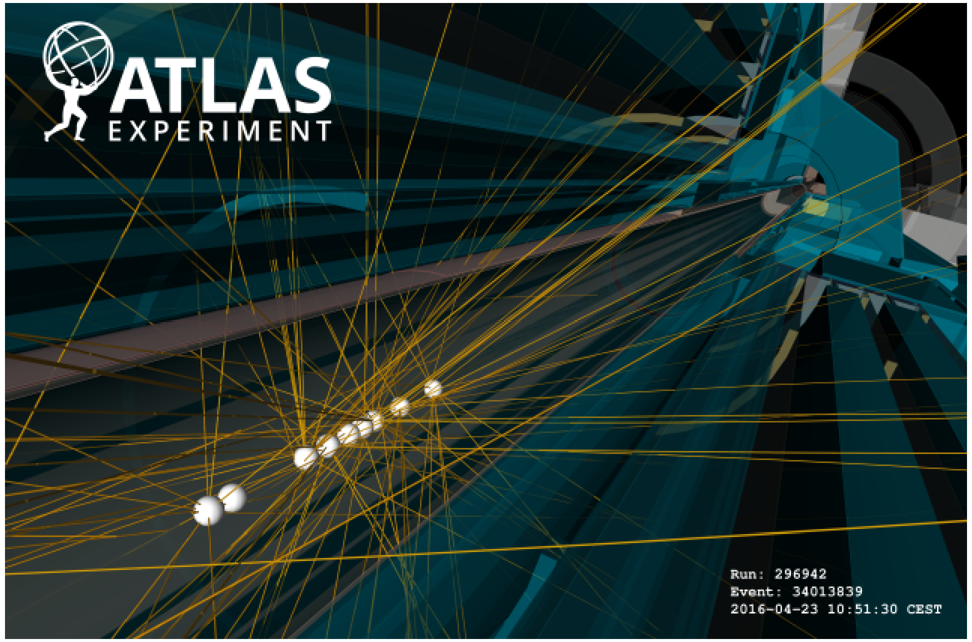
Further aspects

- 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

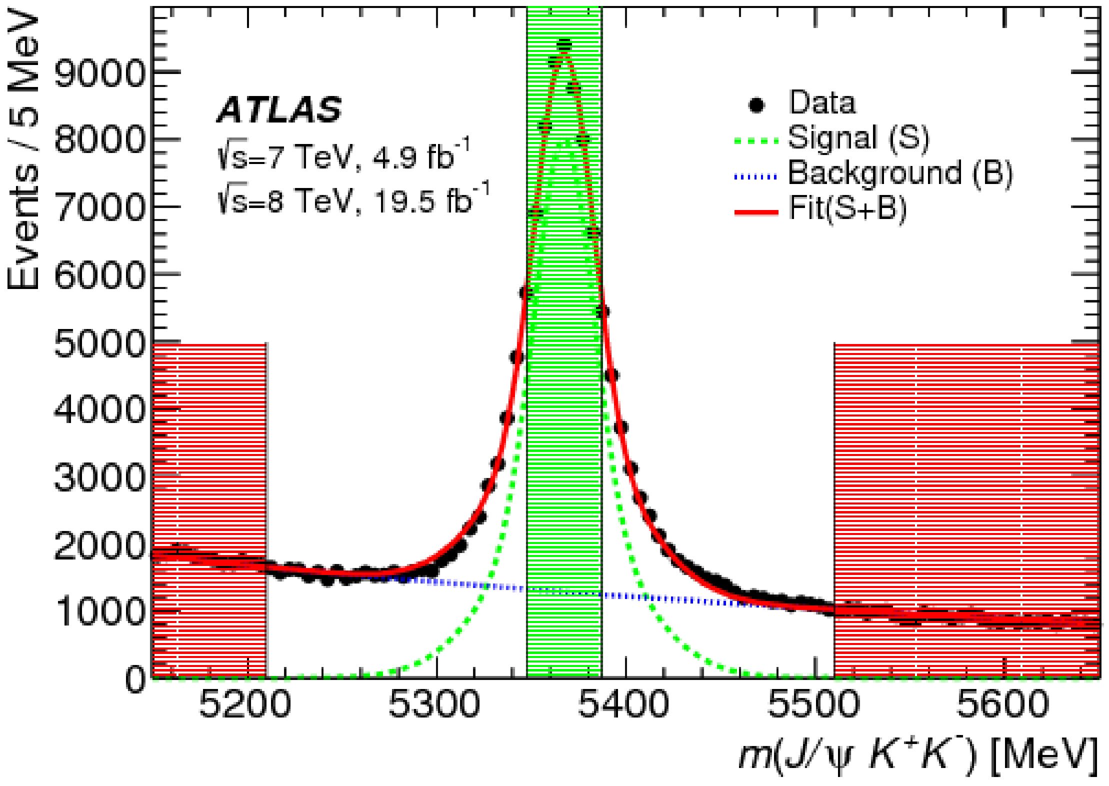
- Simulation not always feasible for estimating background processes
  - Instrumental backgrounds (related to detector effects)
    - Jets with high EM component faking electrons
    - Backgrounds from detector noise
    - …
  - Processes with large cross-section that would require large MC statistics
    - 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

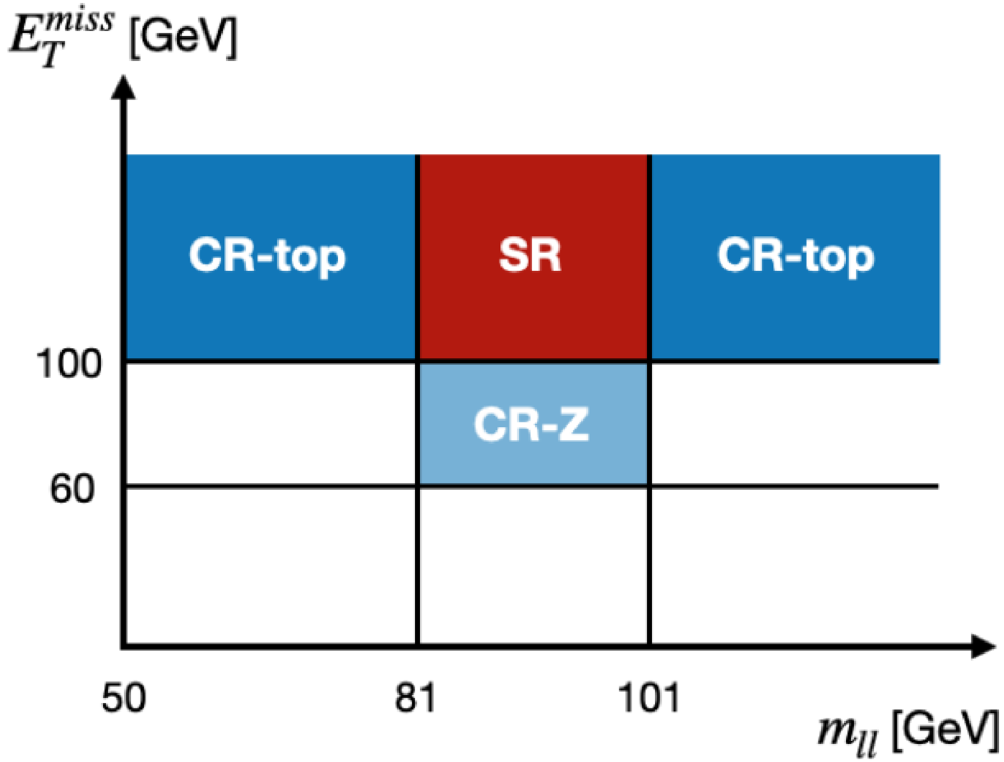


Control Regions

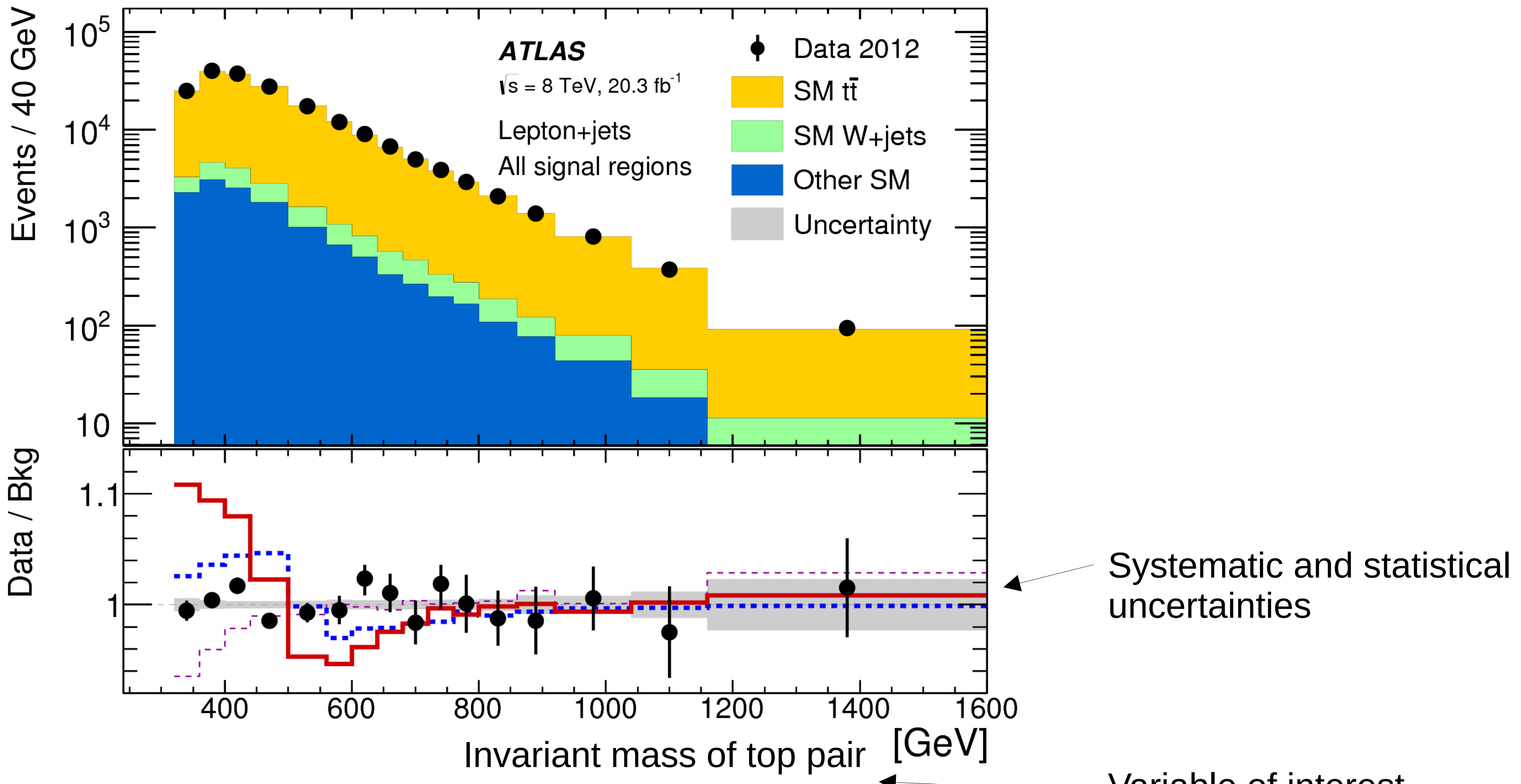
> Same idea as with sidebands but using a modified selection to define a control region
  - Orthogonal to signal region, signal depleted

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

Signal signature: Z(→ll) + E_T^{miss} + bbar

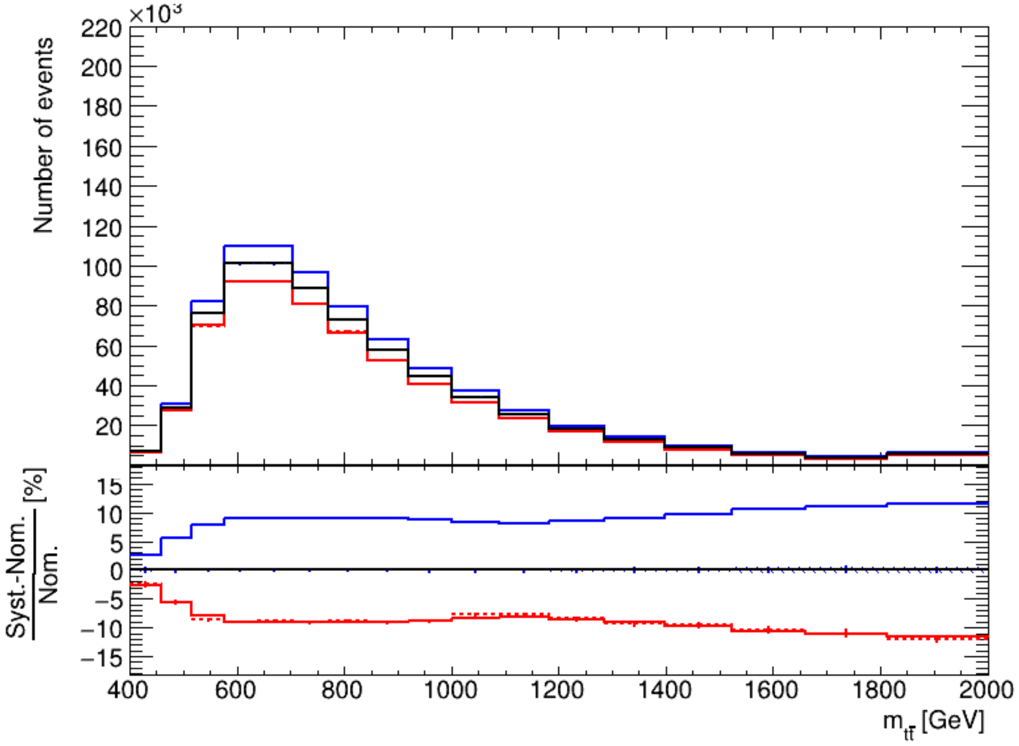


A final signal region



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



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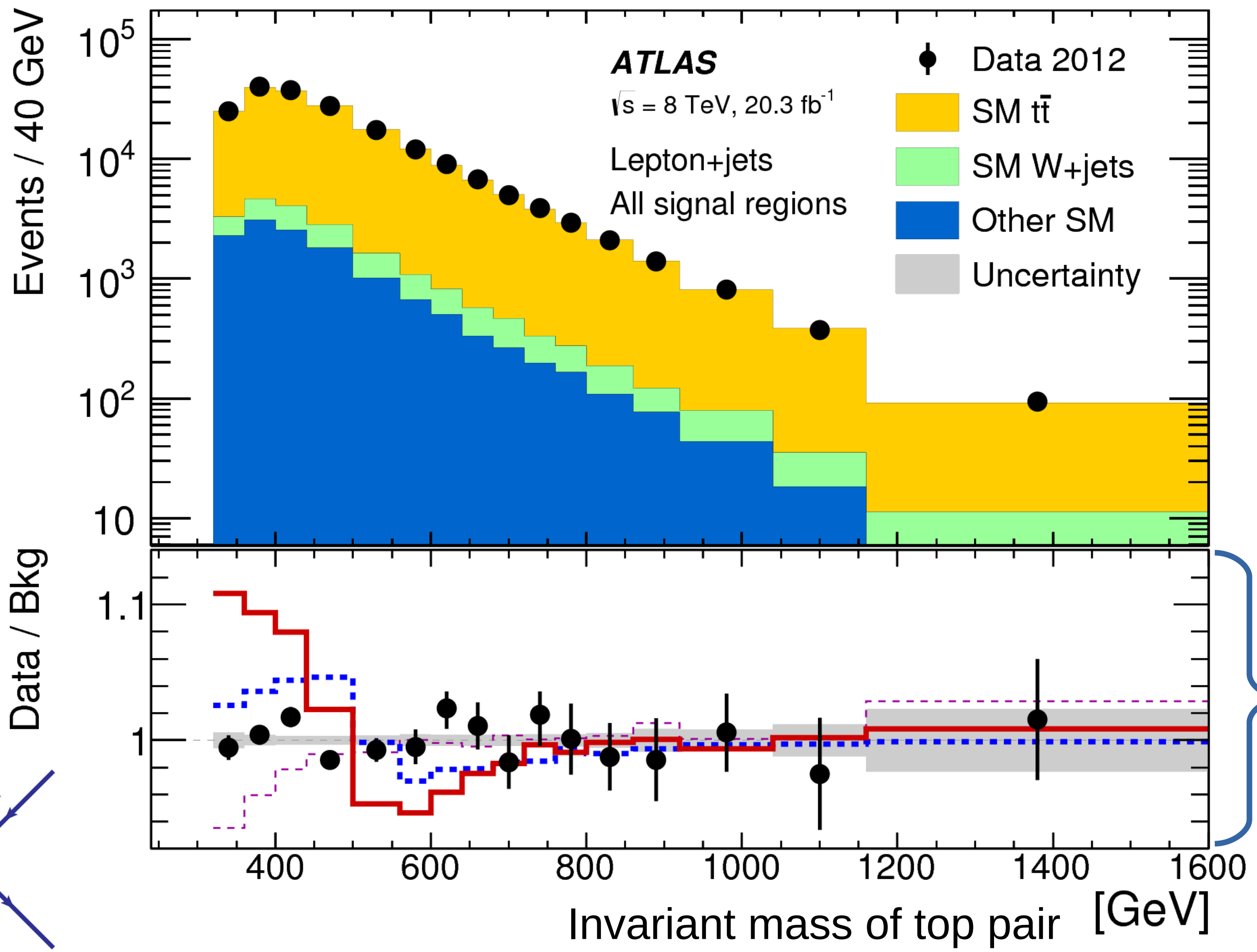
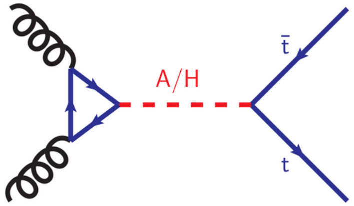


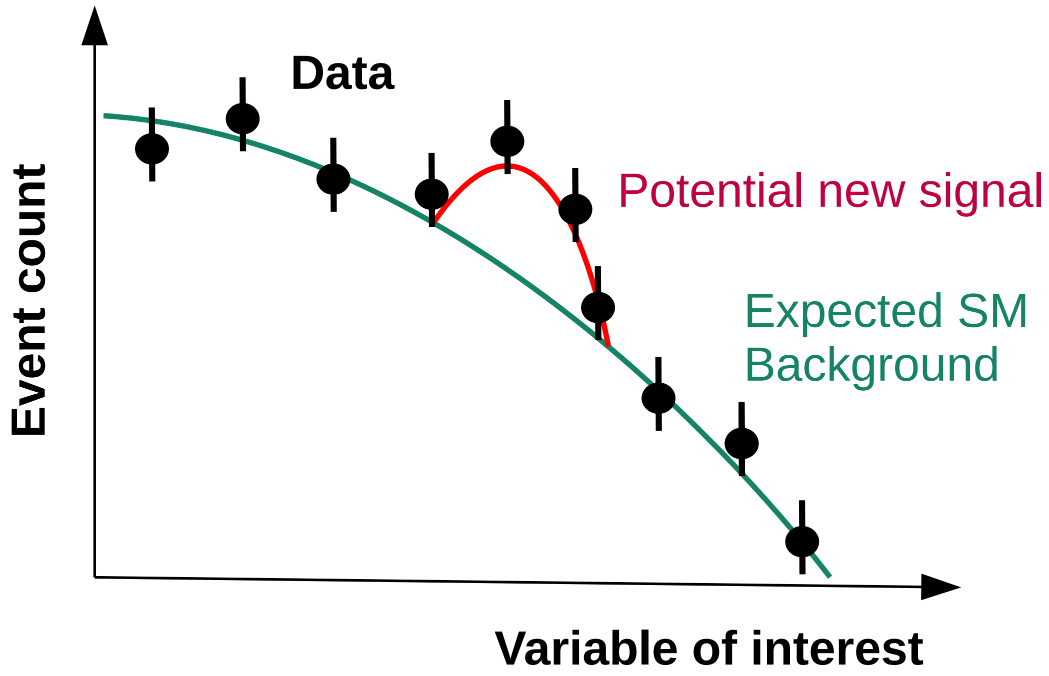


What type of deviation are we looking for?

What are we looking for?

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

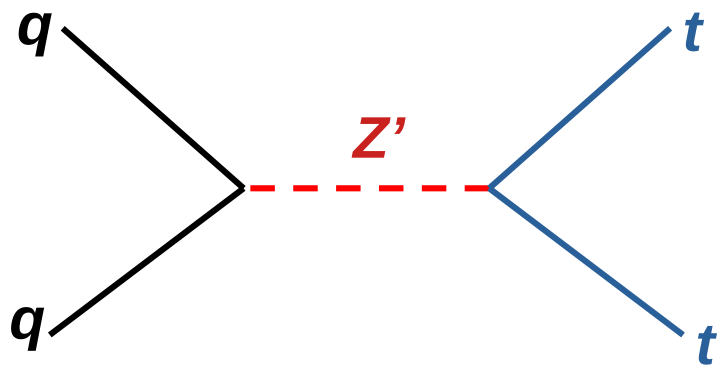
- Different search strategies
  - Cut-and-count method
  - Bump hunt
  - Tail hunt
  - ...

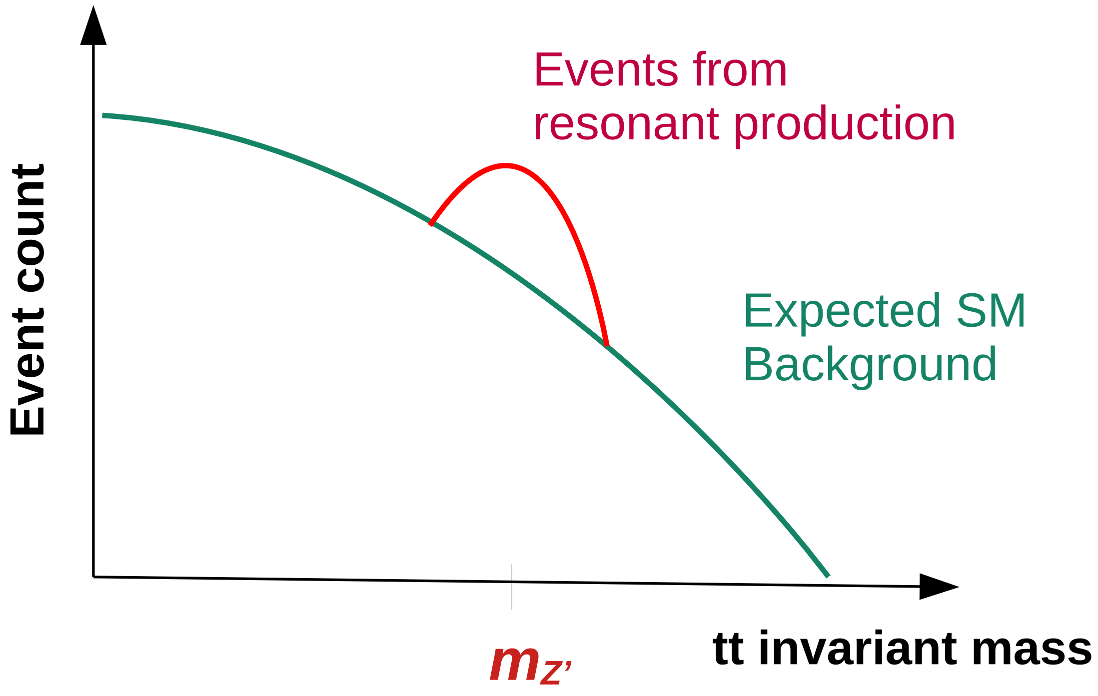


- Each comes with its own set of advantages/disadvantages!

Bump Hunting

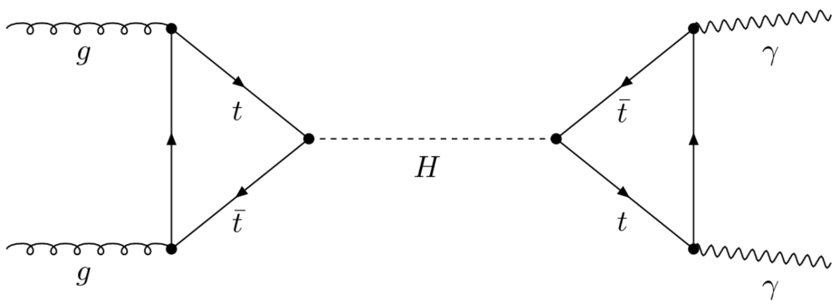
> Search for a localised deviation in the distribution of a variable of interest
  - Typically: invariant mass

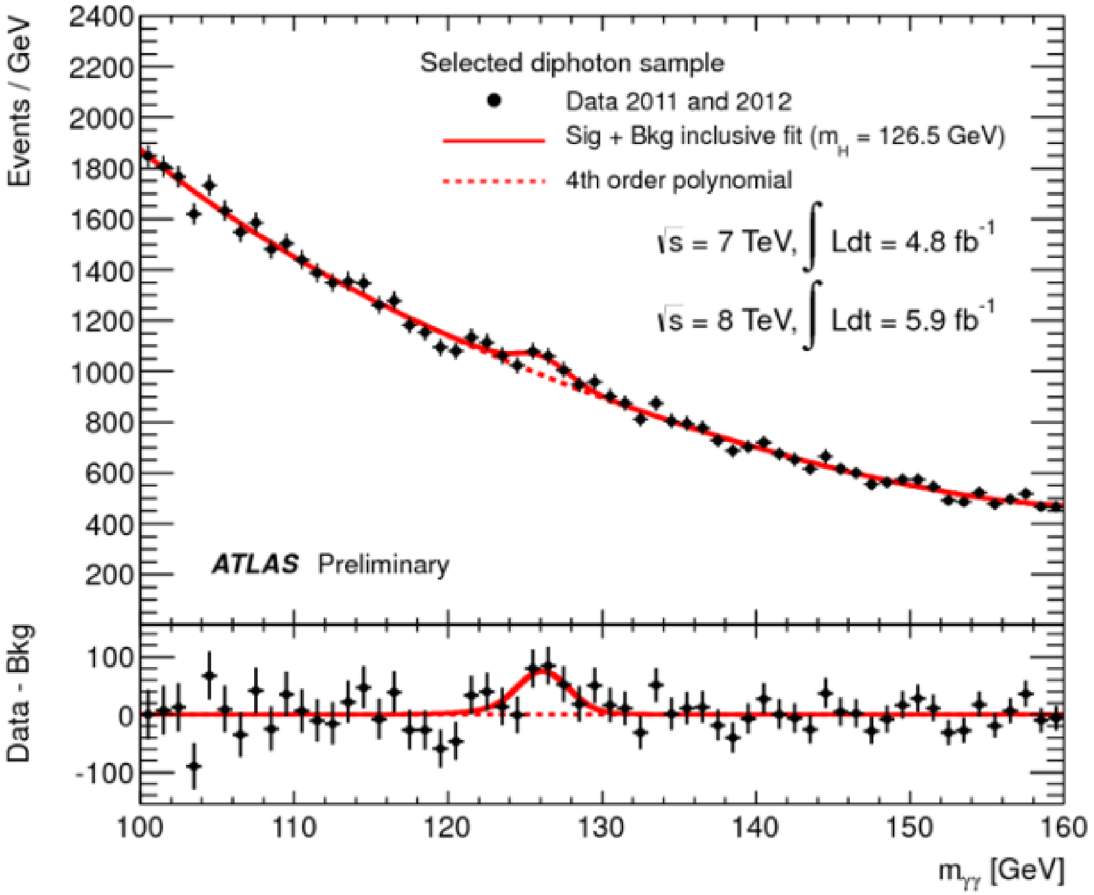




Bump Hunting

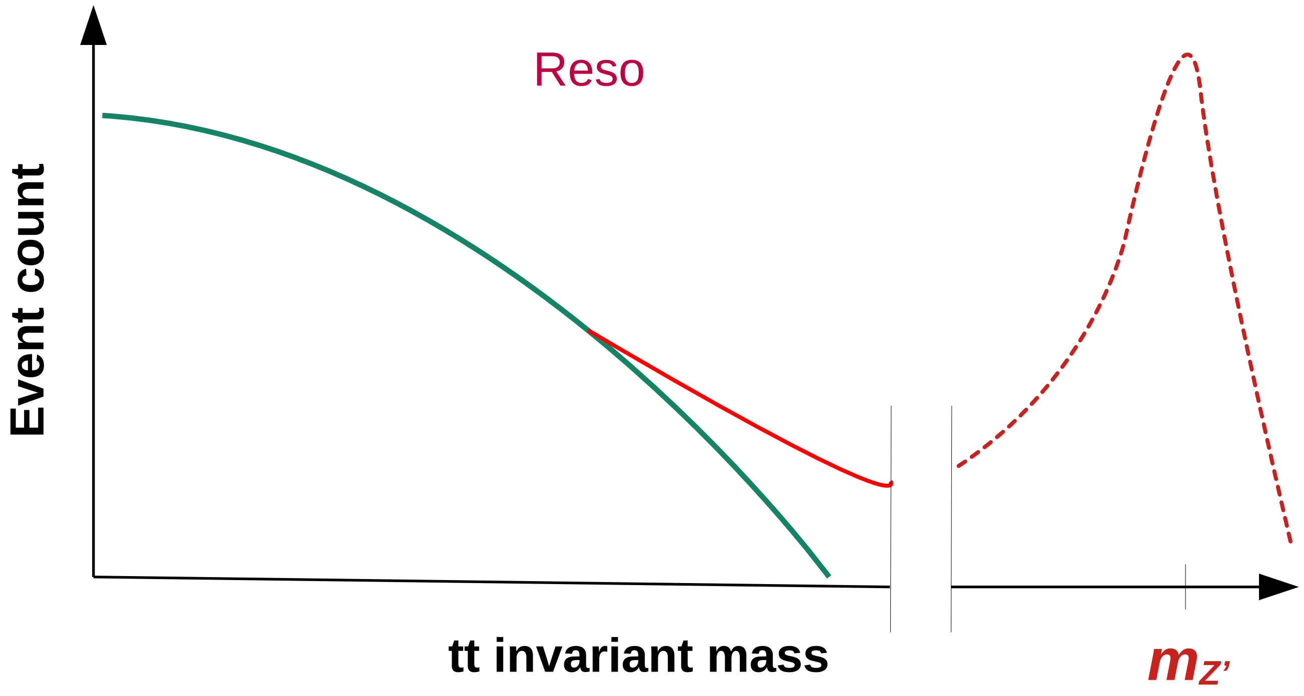
- Search for a localised deviation in the distribution of a variable of interest
  - Typically: invariant mass
- Most recent successful example:
  - Higgs boson discovery (2012, CERN)





Tail Hunting

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

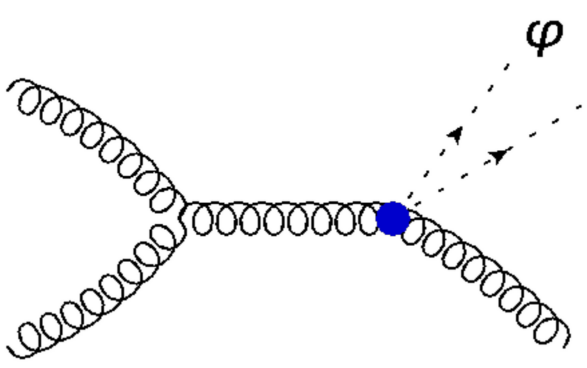


Tail Hunting

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

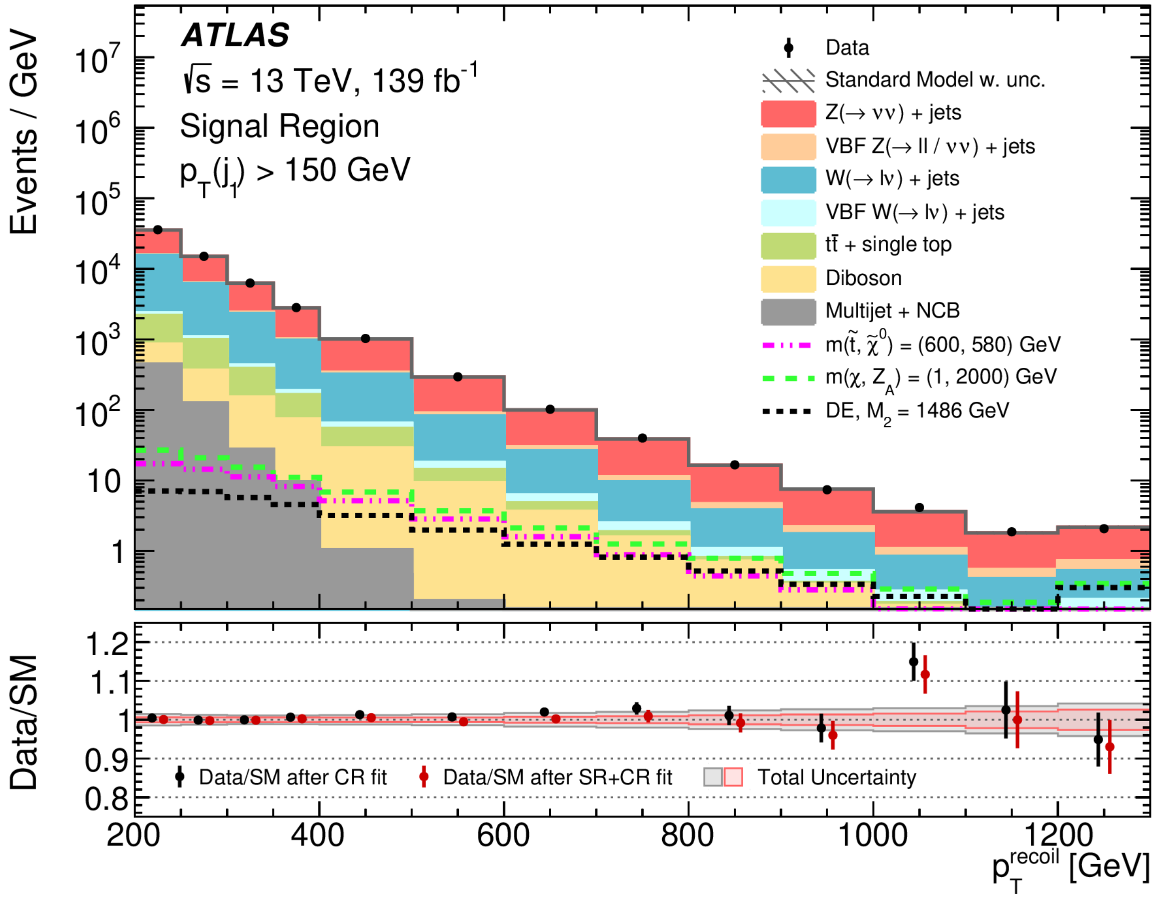
> Typical examples:

- 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:

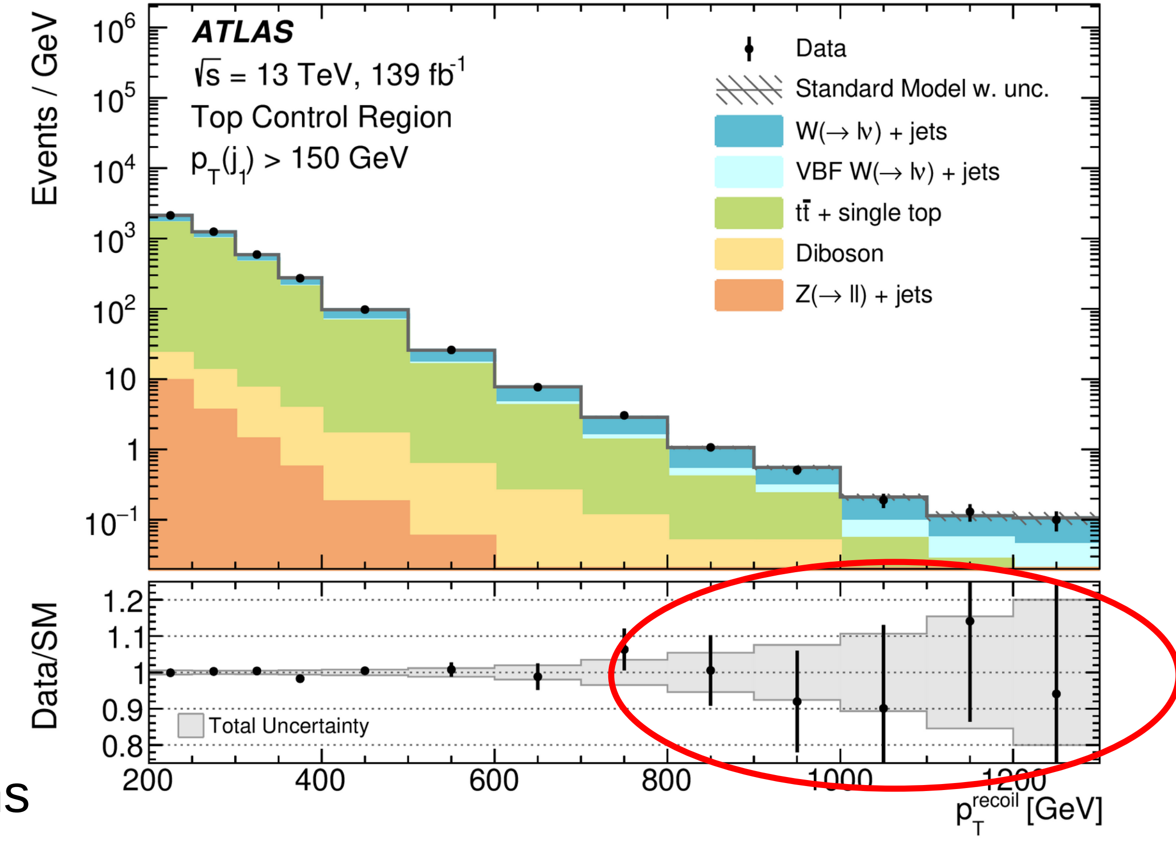
- Resonances beyond reach of the LHC
- Non-resonant production of new particles

> **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?

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- 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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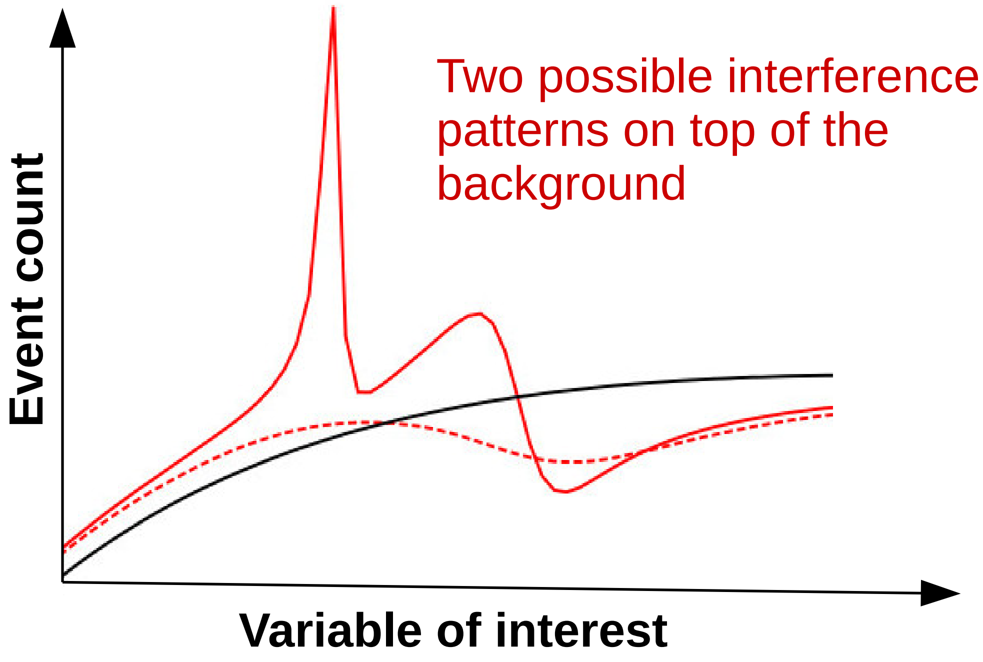
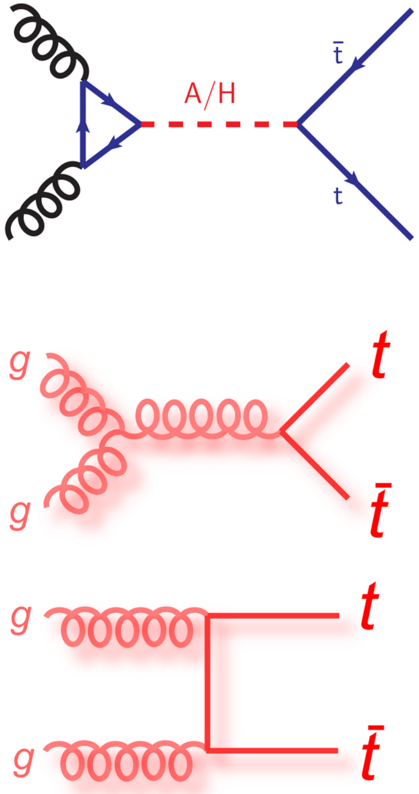
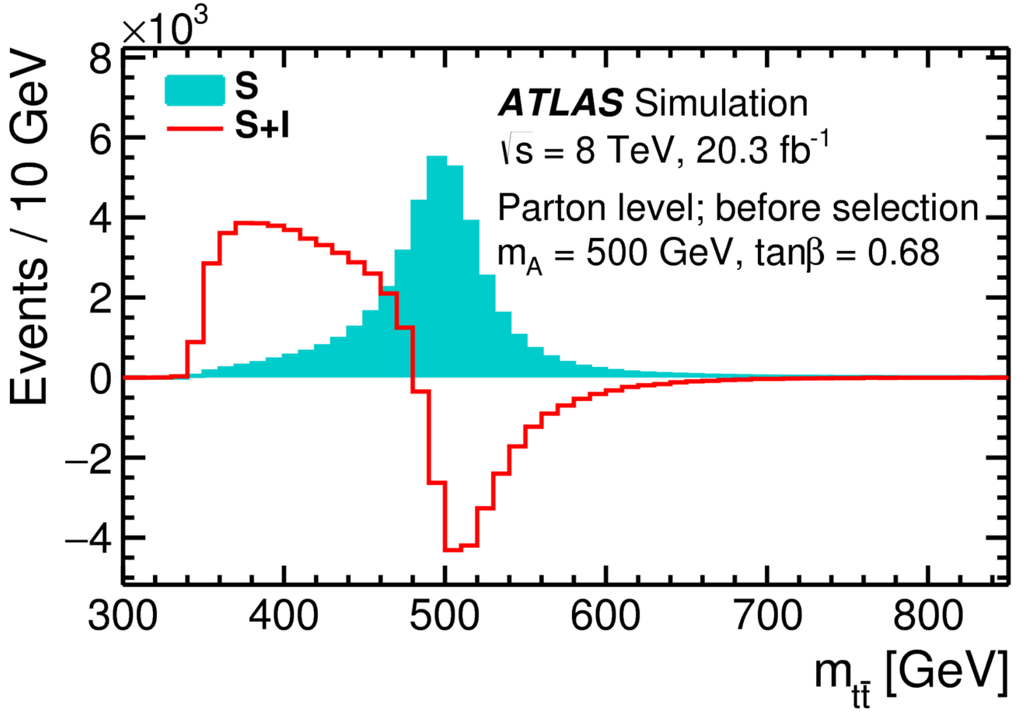


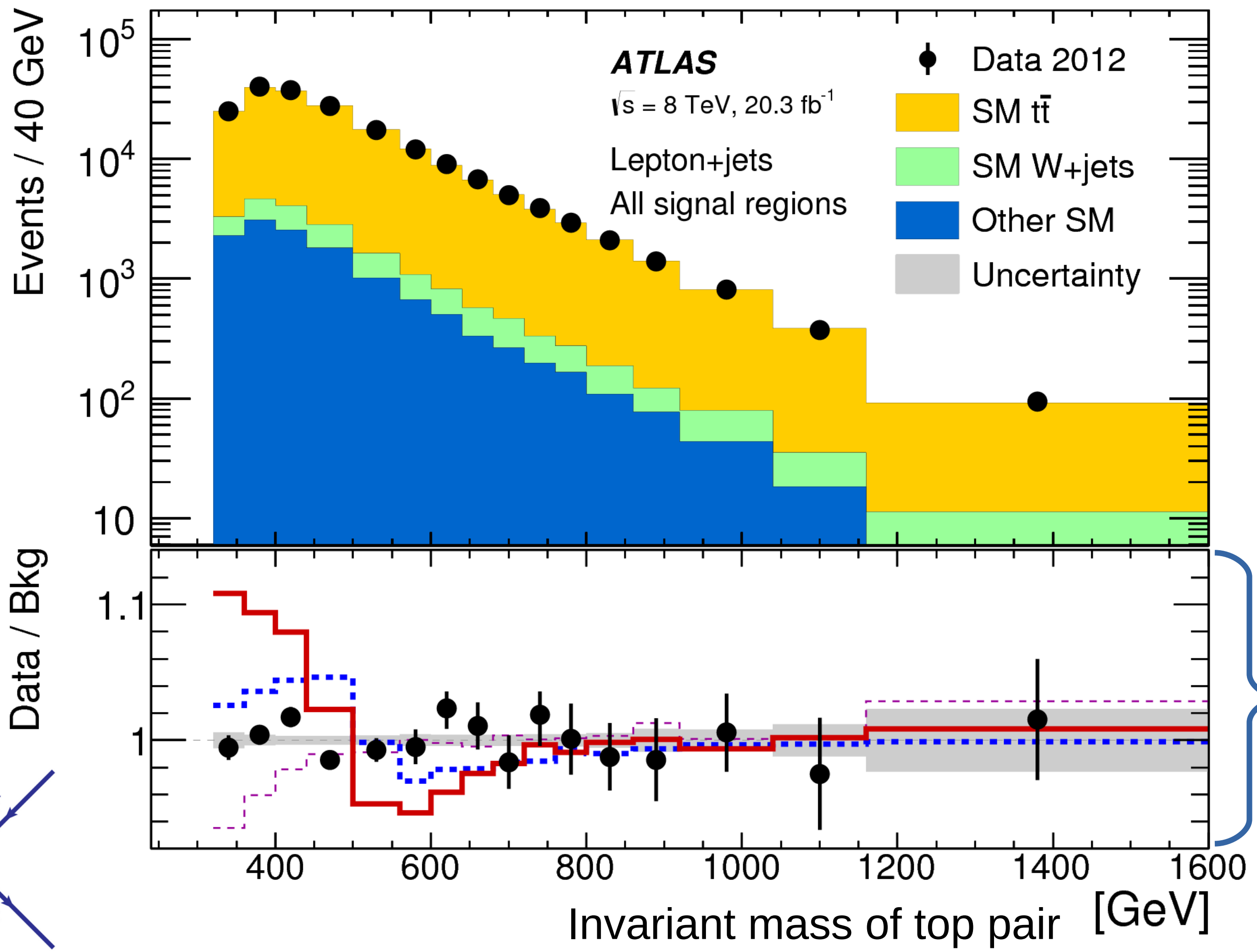
Beyond Bump Hunts

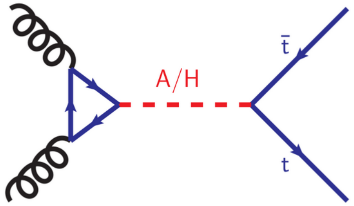
- Prominent example: decay of a heavy Higgs boson A/H to a top-antitop quark pair
- Need cutting edge methods → on-going research @ DESY





A final signal region





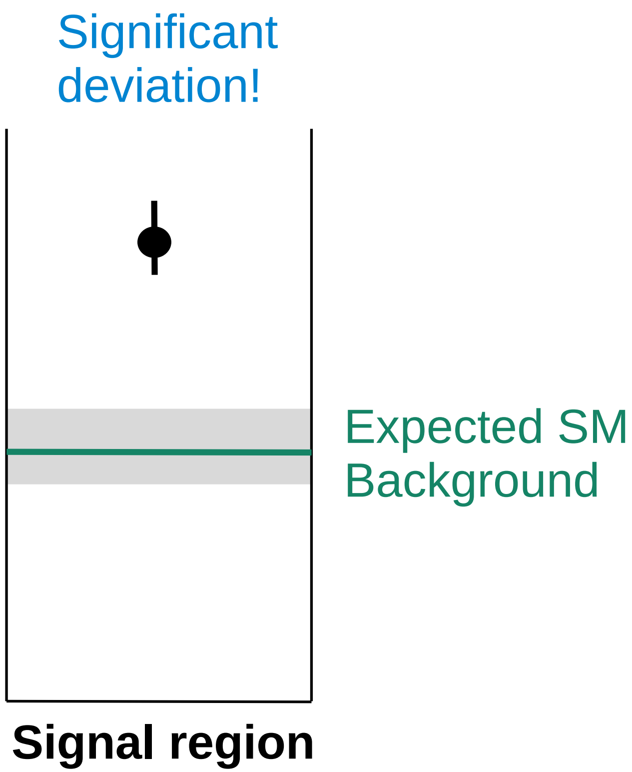
Need to quantify agreement between data and SM prediction

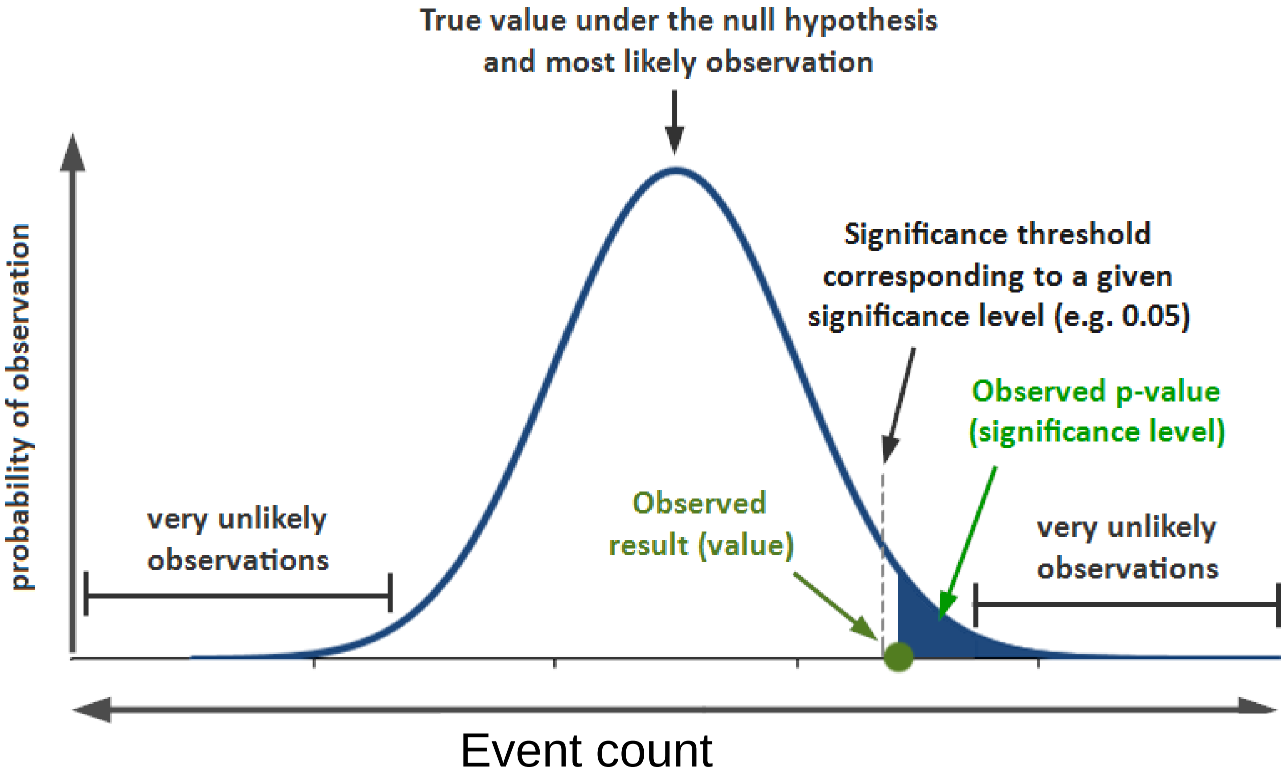
Statistical analysis

> 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



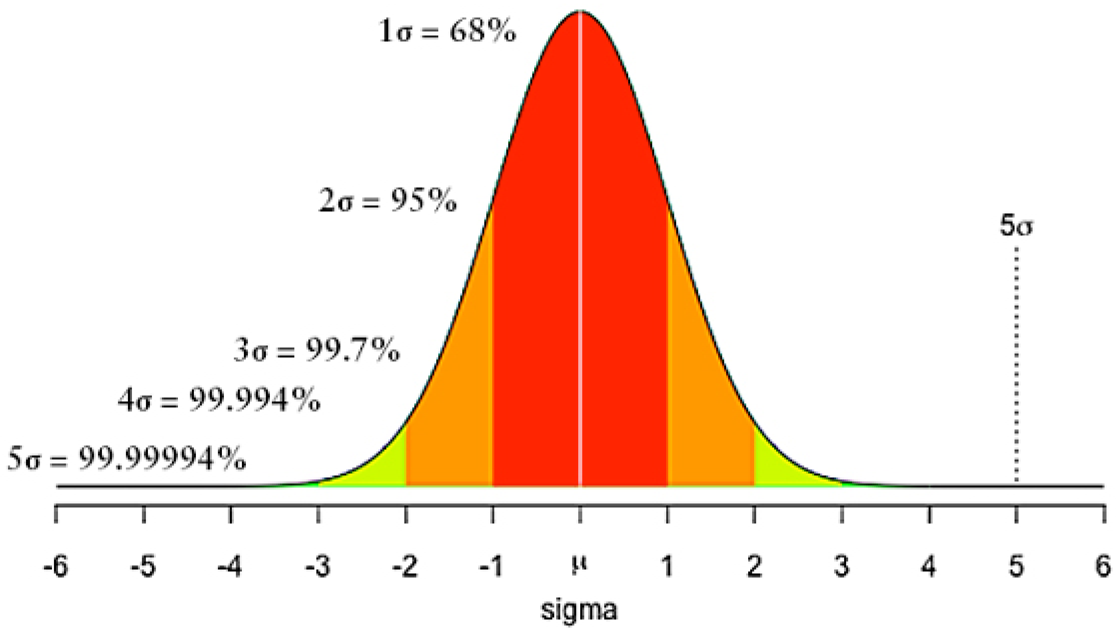


Step 1: quantify agreement with SM prediction

- 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:

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

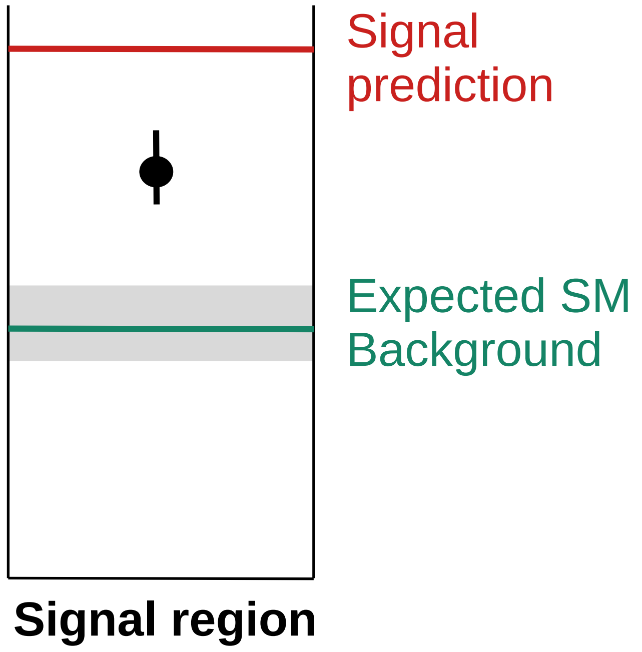
- where Φ^{-1} is inverse of cumulative Gaussian

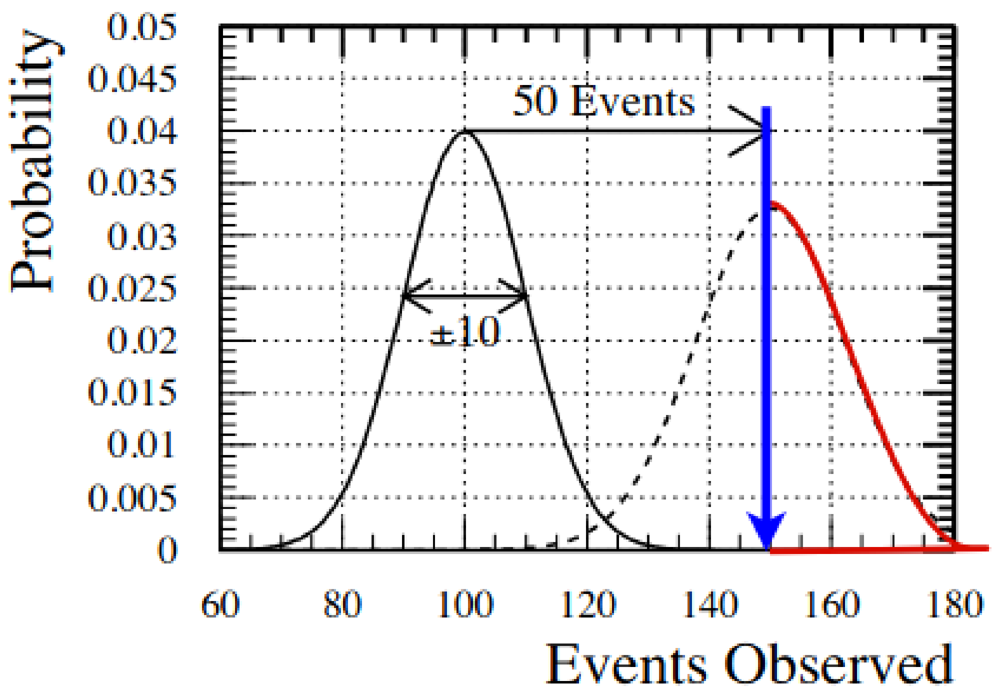


Step 2: Quantify agreement with BSM hypothesis H_1

> 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)

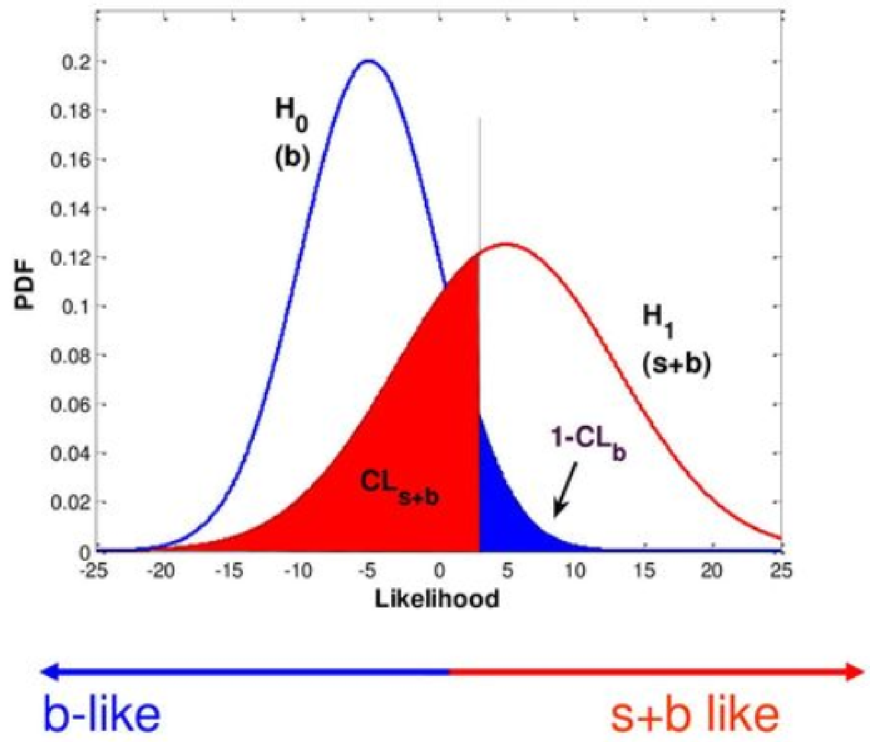




Step 2: Quantify agreement with BSM hypothesis H_1

- Usually, setup is more complicated: many bins, many signal regions
- Construct a likelihood function that quantifies data/MC agreement in all bins

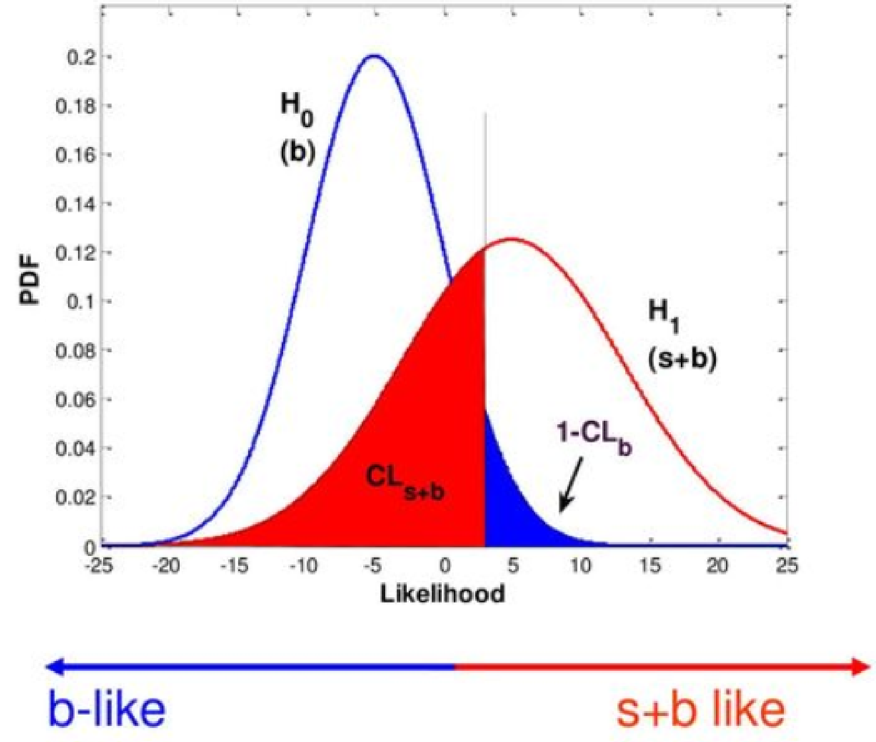
$$L(D|\mu,\boldsymbol{\theta}) = \underbrace{\prod_{j=1}^{M}\prod_{i=1}^{N} \mathrm{Pois}(n_{i,j}|\mu,\boldsymbol{\theta})}_{\text{Poisson terms}} \cdot \underbrace{\prod_{\mathrm{NP}} f(\theta^{(\mathrm{NP})})}_{\text{Constraint terms}}$$



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:

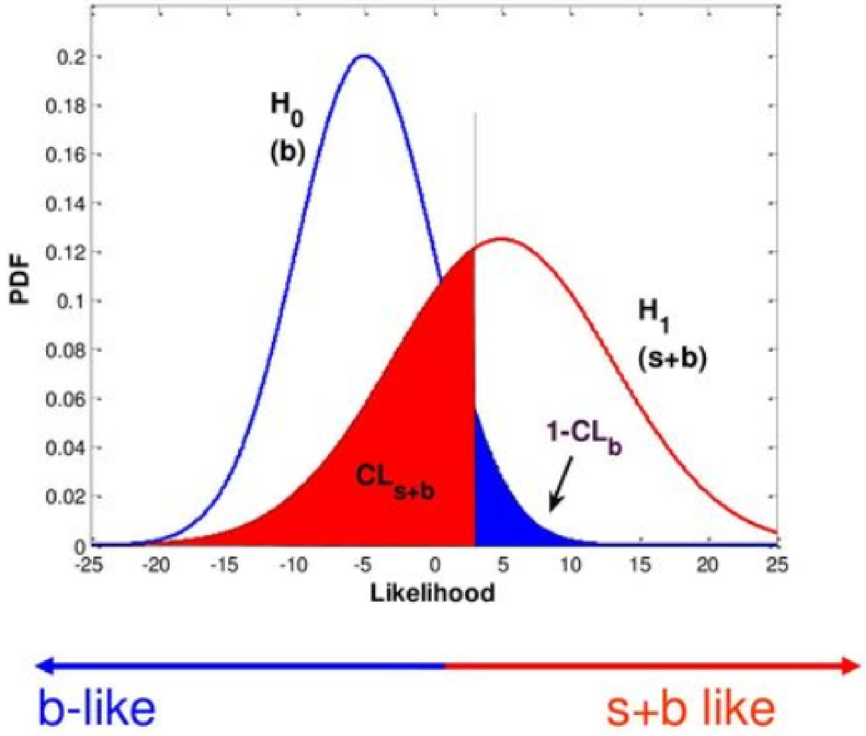
– Danger to falsely reject H_1 even if separation between H_1 and H_0 is poor, i.e. sensitivity to H_1 is low

> Solution:

– CL(s) = CL(s+b)/[1-CL(b)]

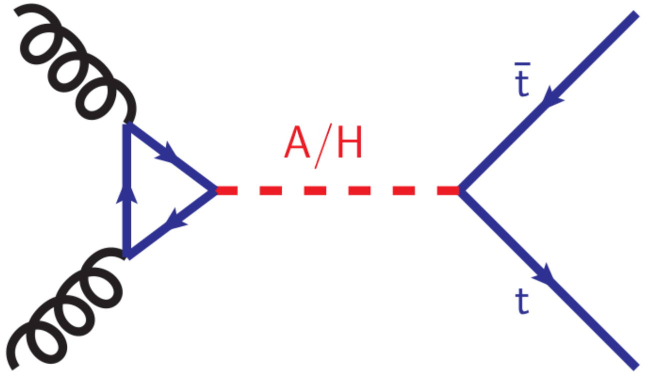
> Confidence level

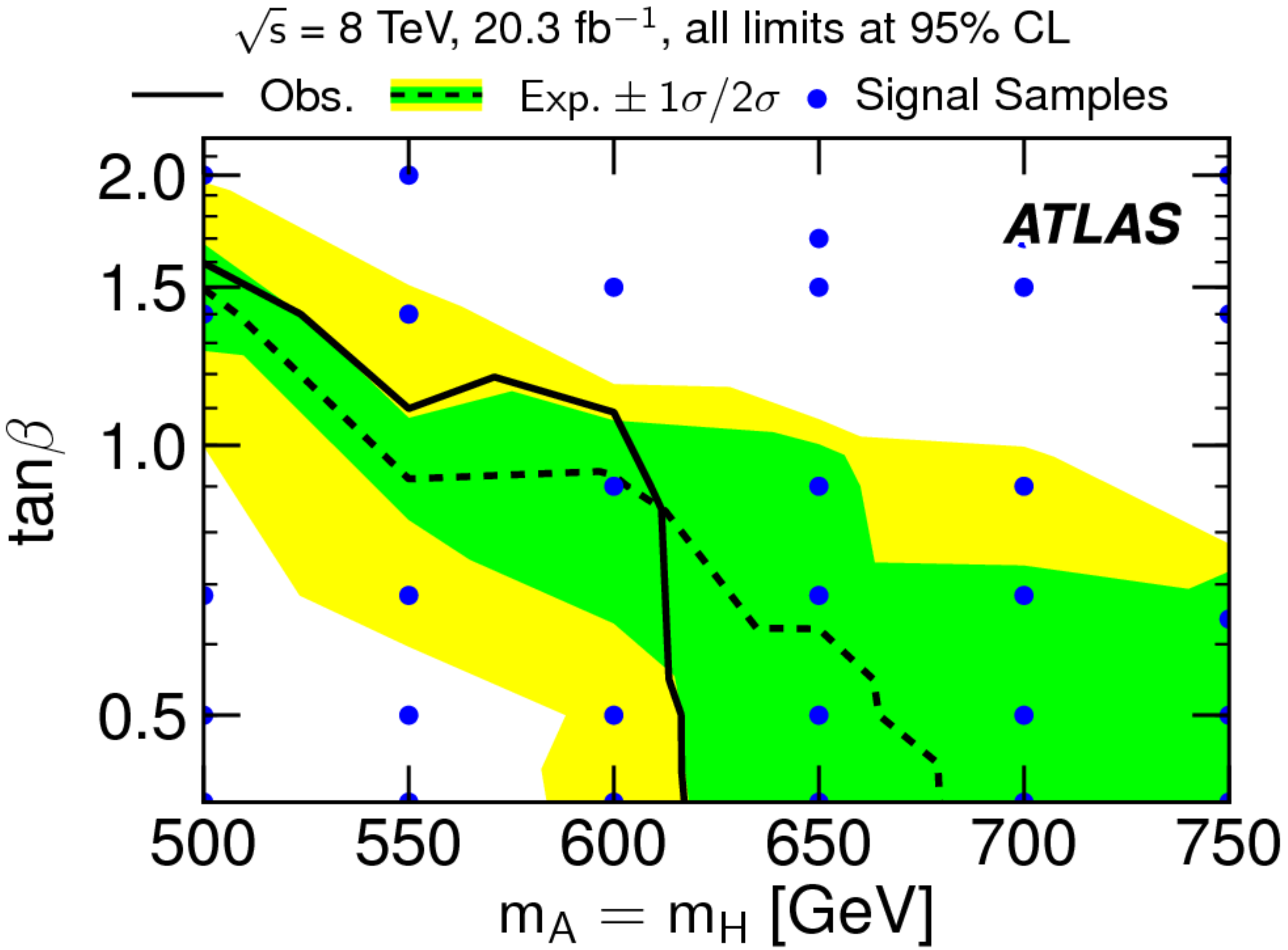
– H_1 excluded at 95% CL if CL(s) < 0.05



A final result

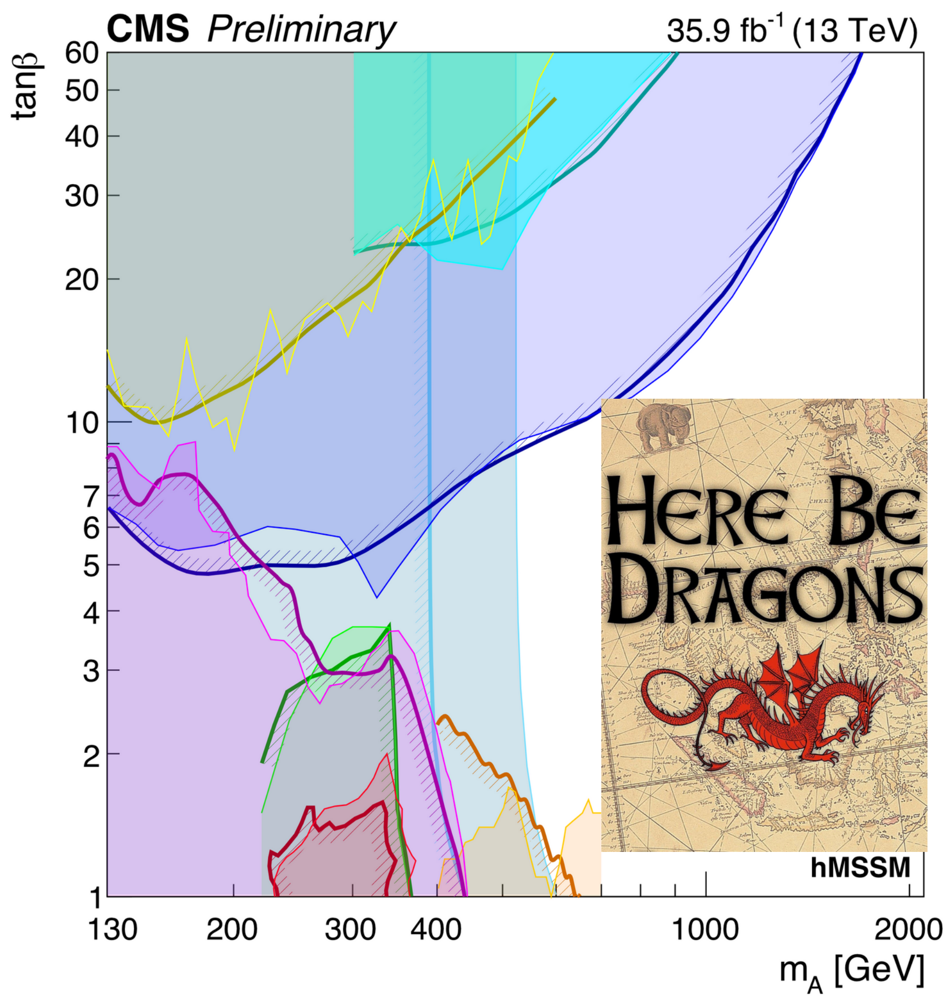
- The famous “Brazilian” plot, showing observed and expected exclusion limits with error bands





Where do we stand?

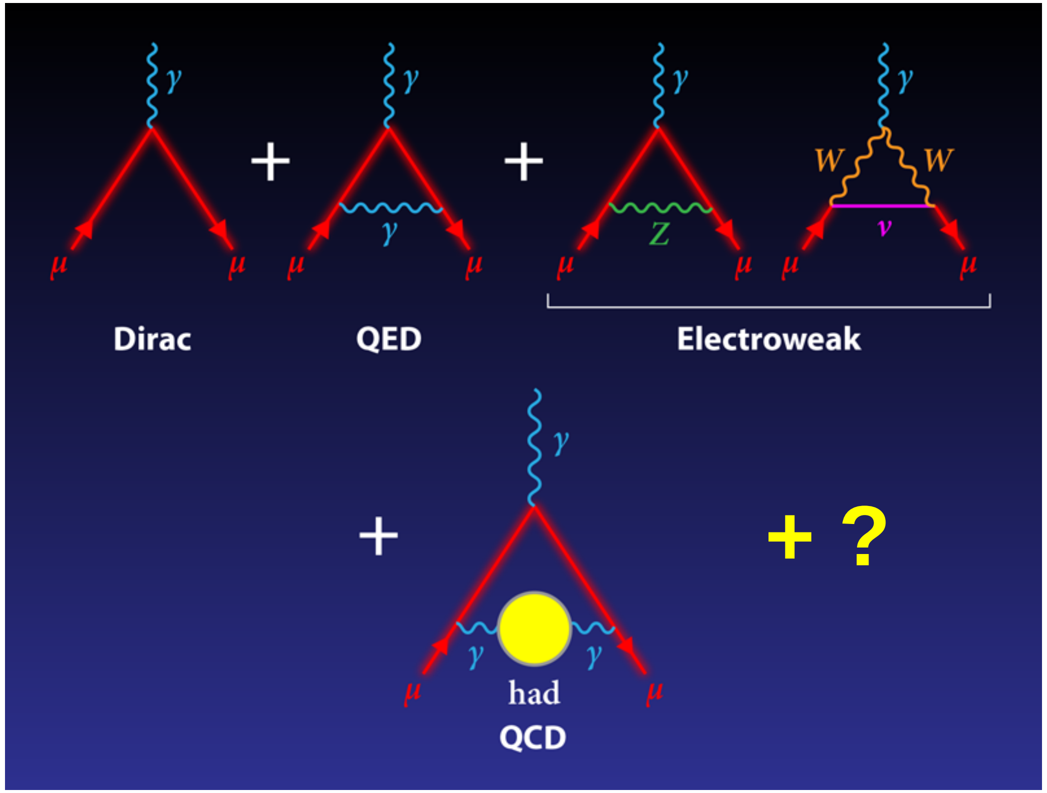
- No significant (5σ) deviation from the SM observed so far.
- Results constrain BSM models…
- … and point to uncharted territory!



Muon g-2 (1)

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

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



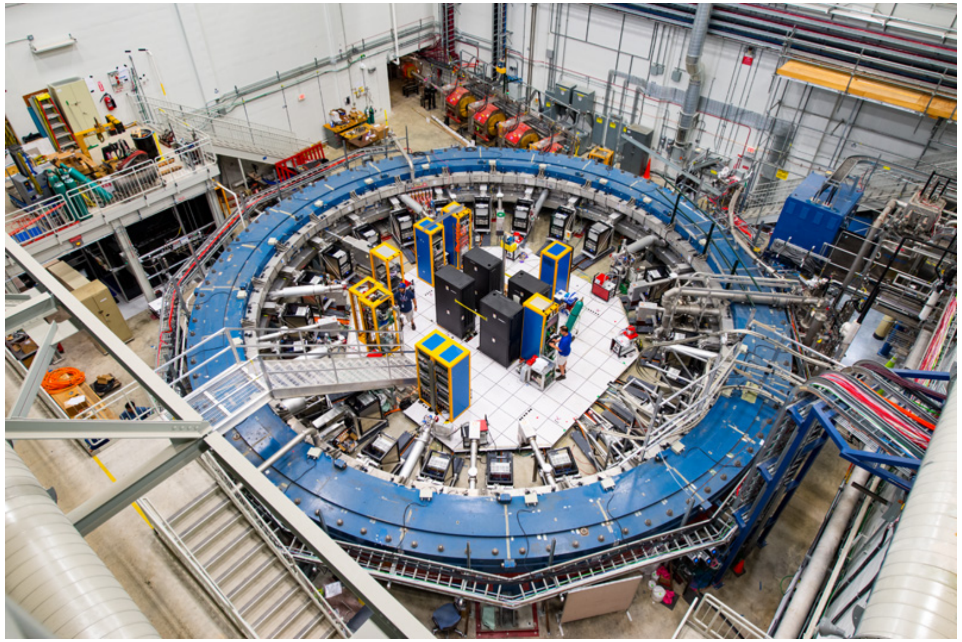
> Loop quantum corrections: $g \neq 2$

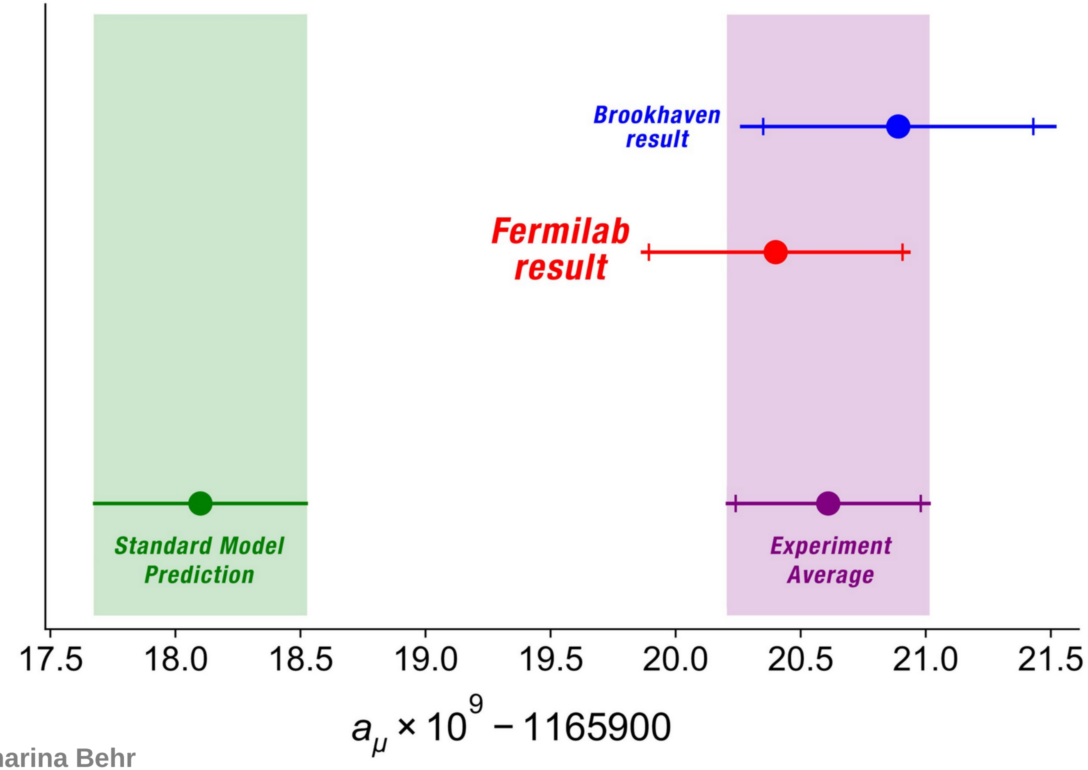
> Anomalous magnetic moment: $a = (g-2)/2$

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

Muon g-2 (2)

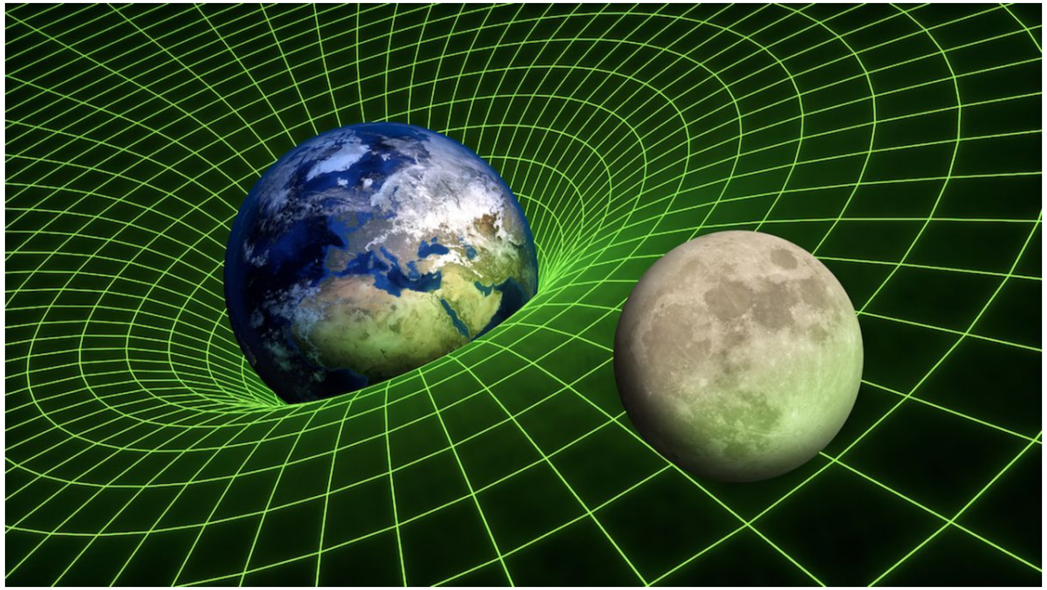
- Storage ring with polarised muons in magnetic field → measure precession frequency
- Measurements at BNL (2004) first revealed tension with SM of 2.6σ significance
- Confirmed by new Fermilab measurement (2021) at 4.2σ combined significance
  - More data is being taken and analysed



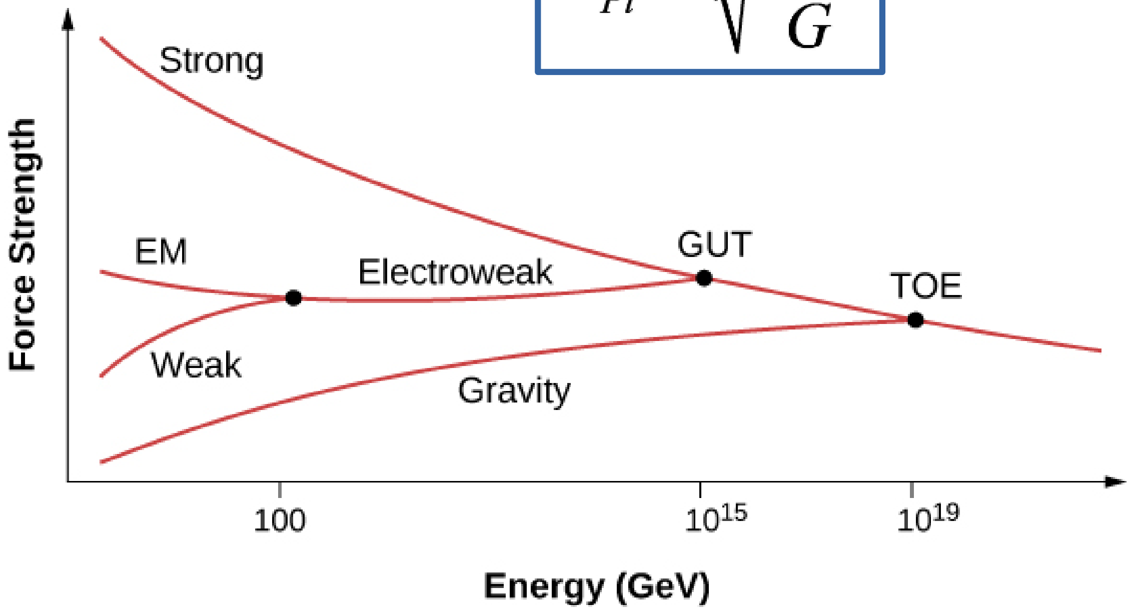


Missing pieces: gravity

> 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

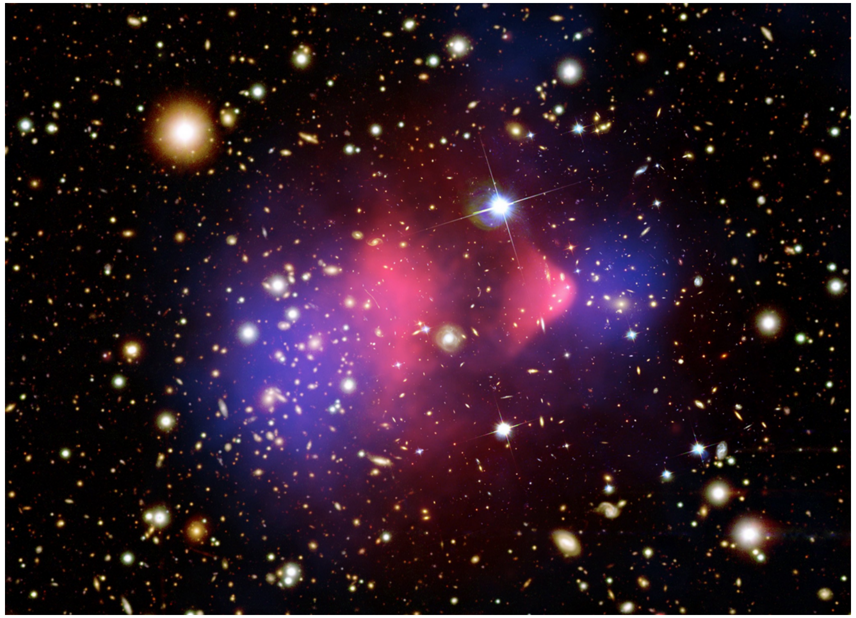


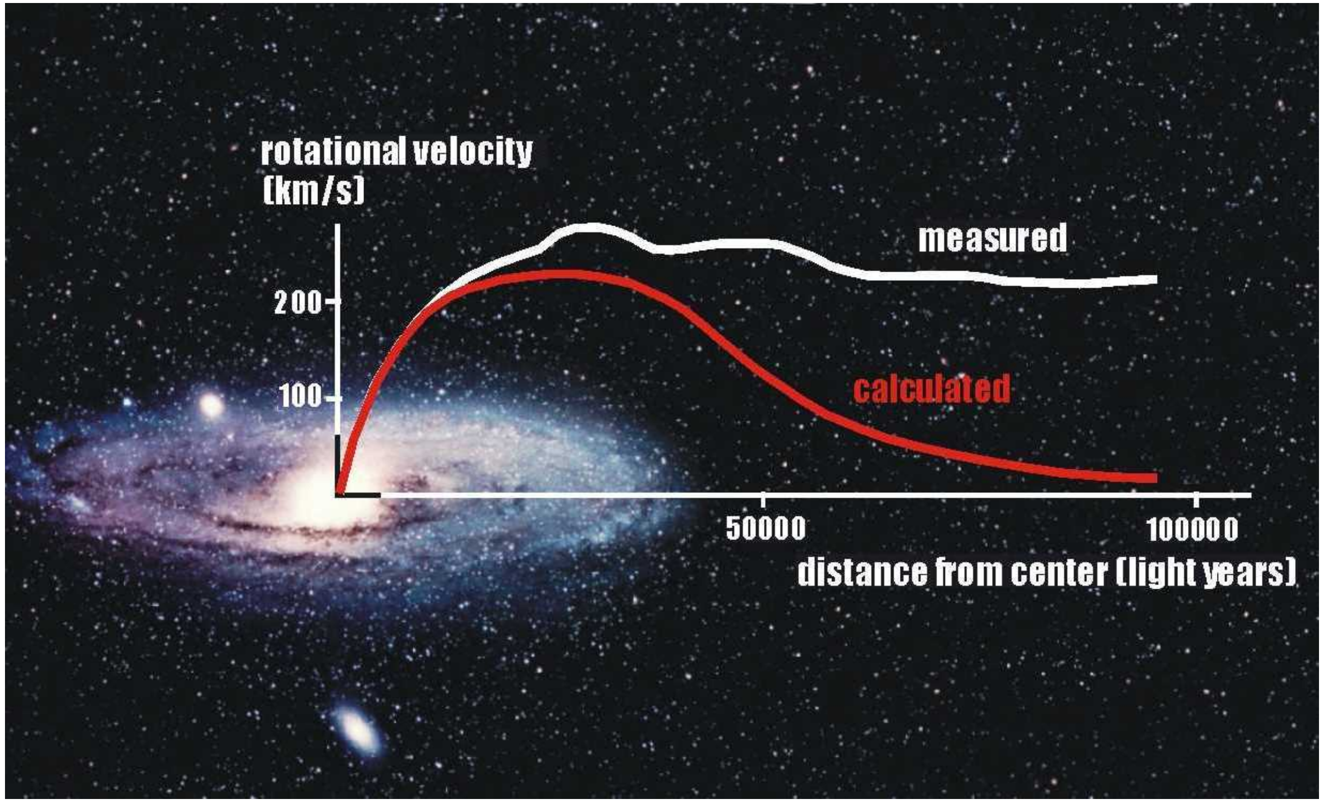
$$m_{Pl} = \sqrt{\frac{\hbar \cdot c}{G}}$$



Missing pieces: dark matter

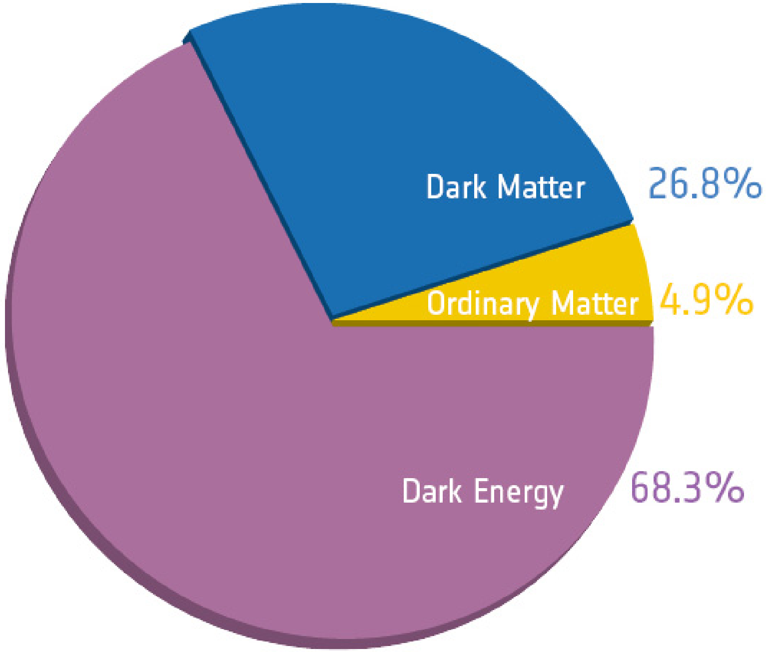
- Various sources of astrophysical evidence for existence of DM
  - Galactic rotation curves
  - Motion of galactic clusters
  - Gravitational lensing
  - ...

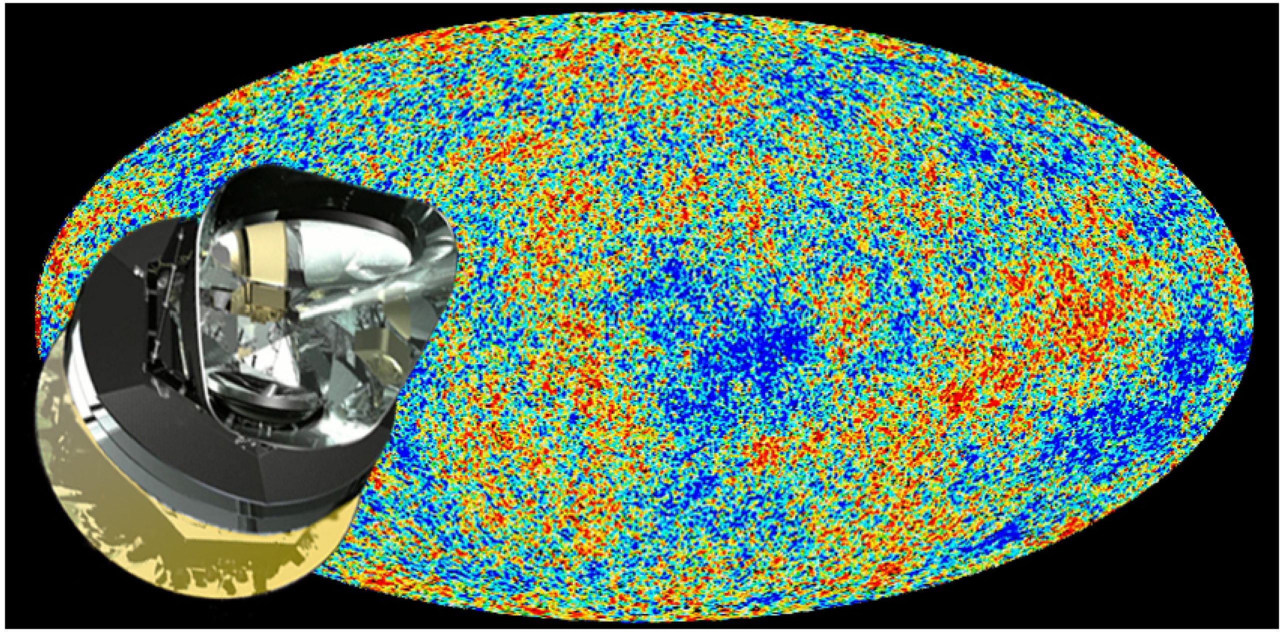




Missing pieces: dark matter and dark energy

- 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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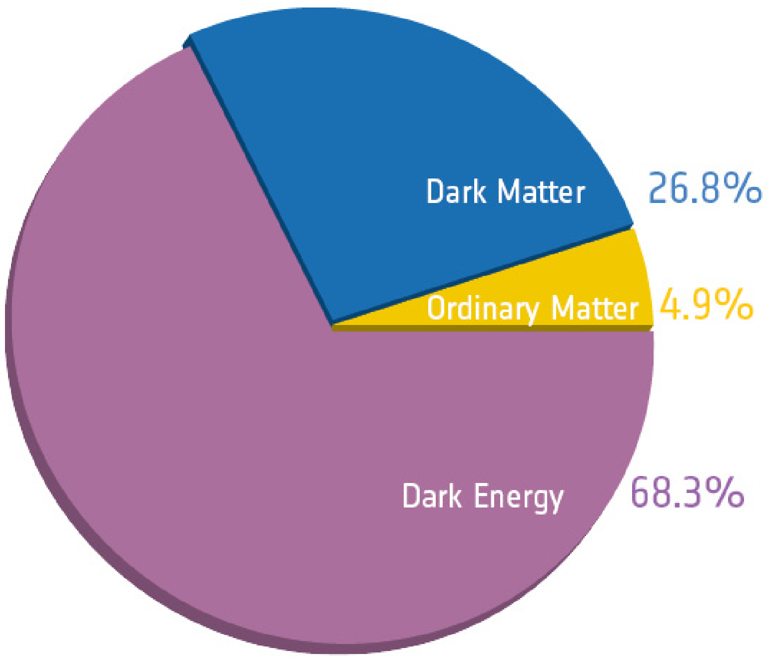
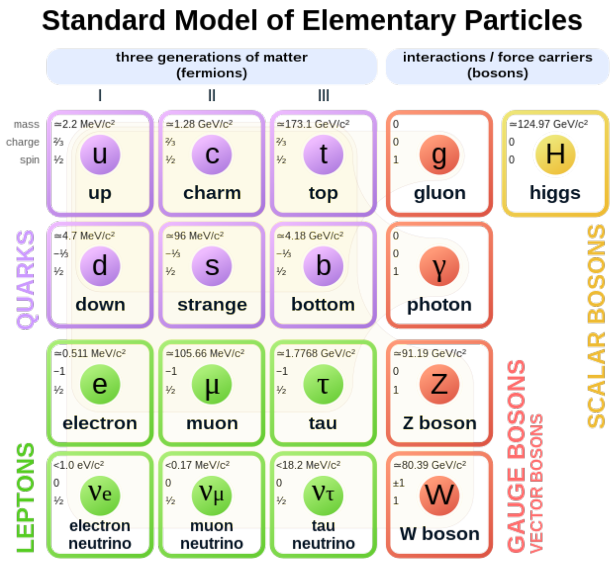


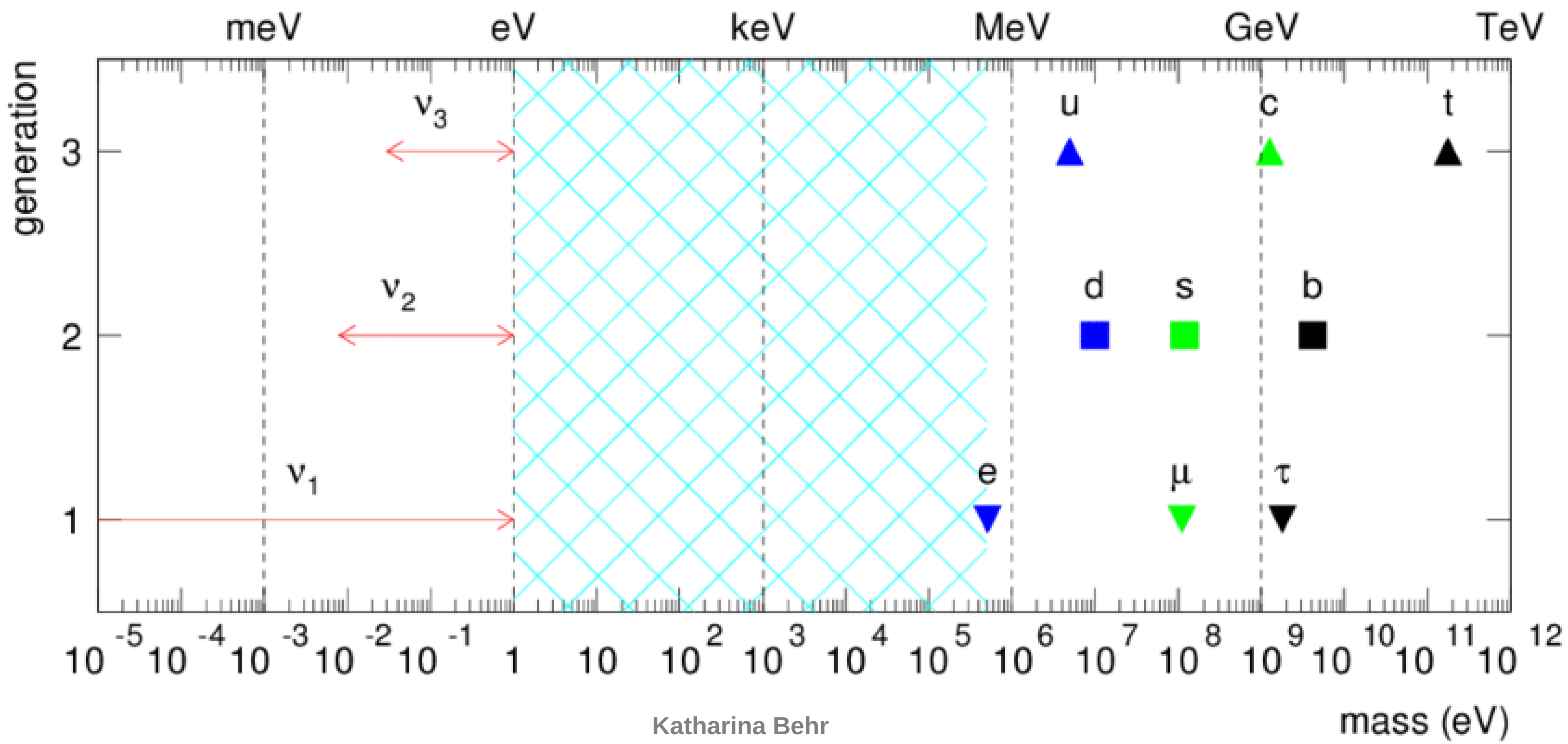
SM describes only 5% of matter-energy content of the Universe



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

Matter-antimatter imbalance

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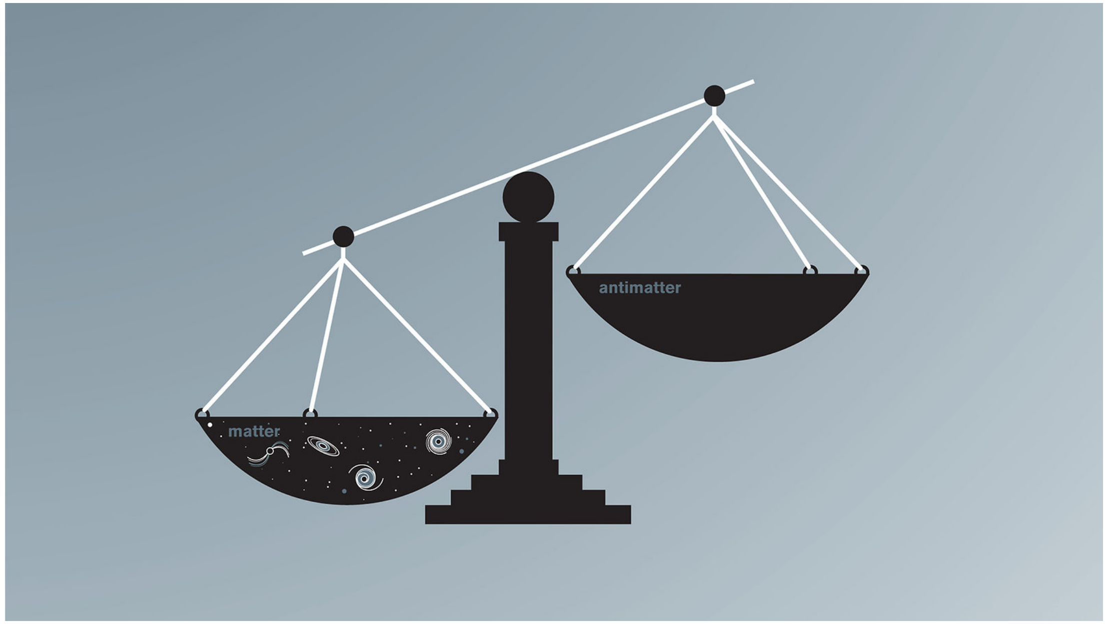


Excellent review of Sakharov conditions by D. Perepelitska [link]

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 $|d_N| < 10^{-26}\ e$ 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

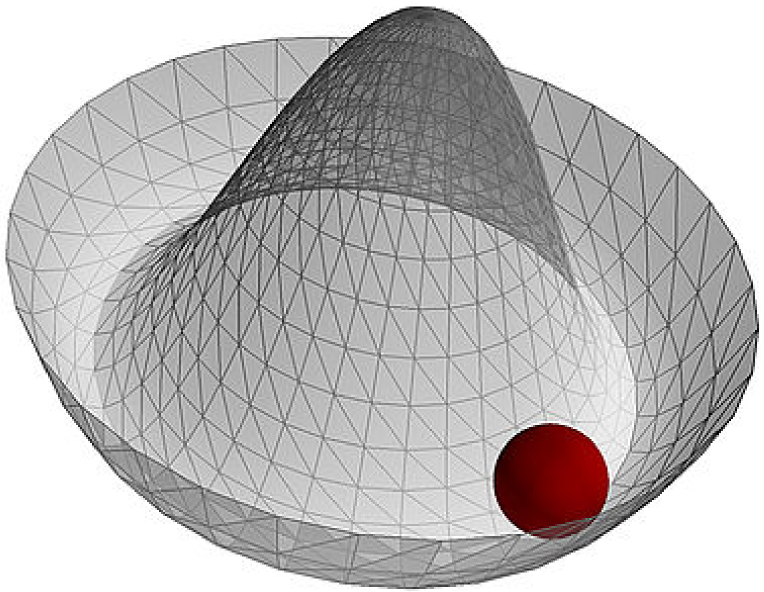
> Field has tilted Mexican hat potential

> Spontaneous breaking of U(1) $\rightarrow$ pseudo-Goldstone boson: axion

> VEV of axion field leads to $\theta^* = 0$

  – No fine tuning!

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

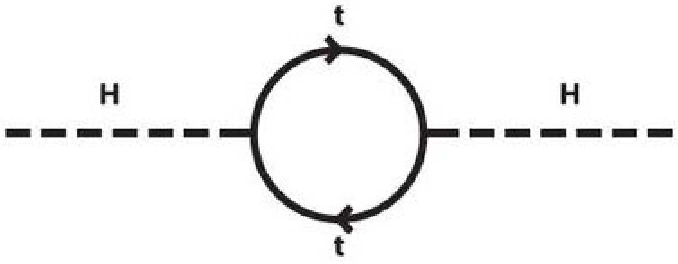


Credit: U Wuppertal

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

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^{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
  - …