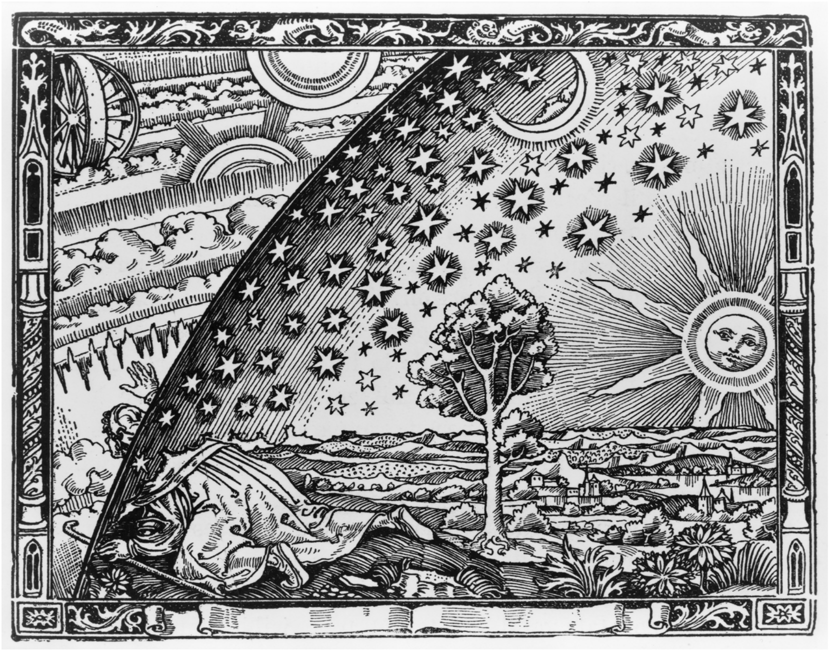
Beyond the Standard Model

Hamburg International Summer School
14 – 25 July 2025



Katharina Behr

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

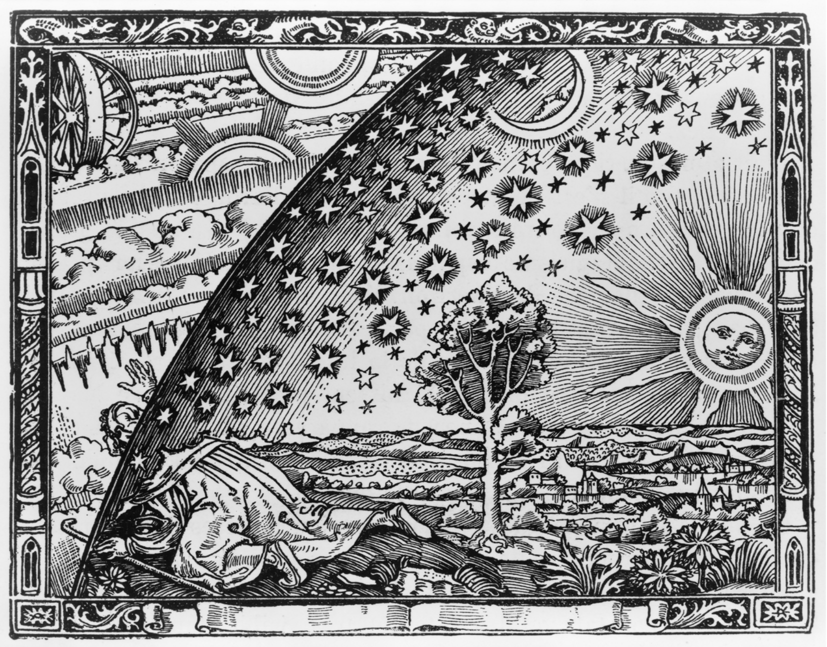
ATLAS EXPERIMENT

DESY.

Outline

> **Part 1:**
  - What motivates us to look beyond the Standard Model?
  - Experimental techniques

> **Part 2**:
  - Example: dark matter
    - WIMP searches at the LHC
    - Axion detectors at DESY
  - Outlook: the future of the LHC and beyond



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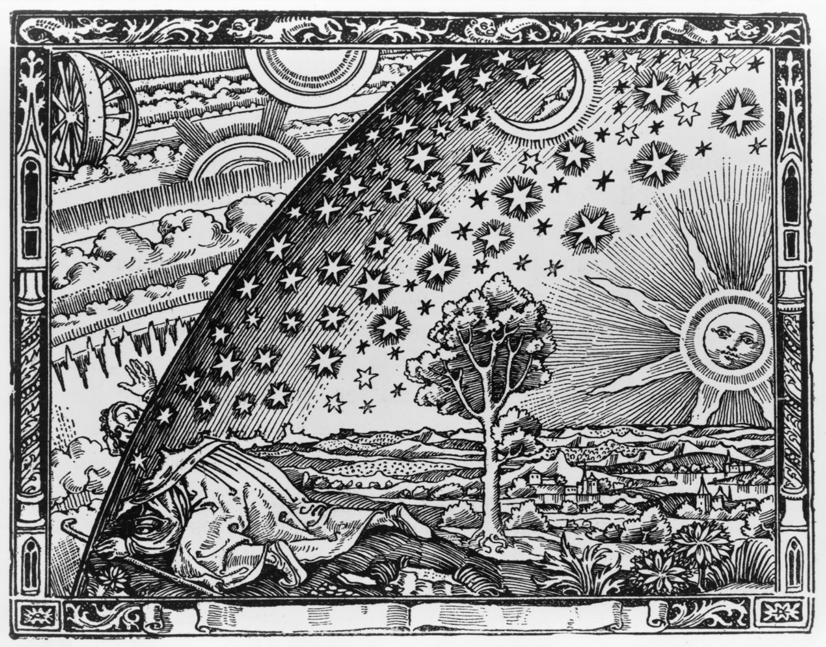
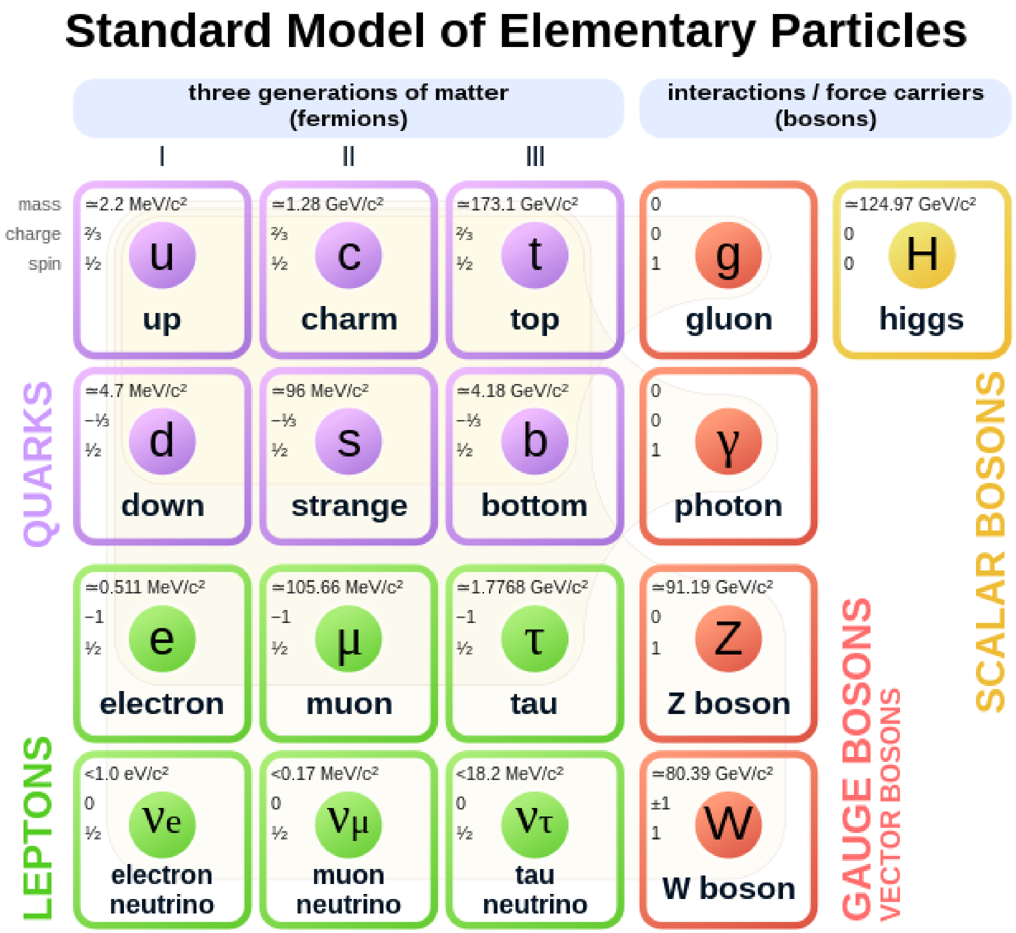


The Standard Model in 2025

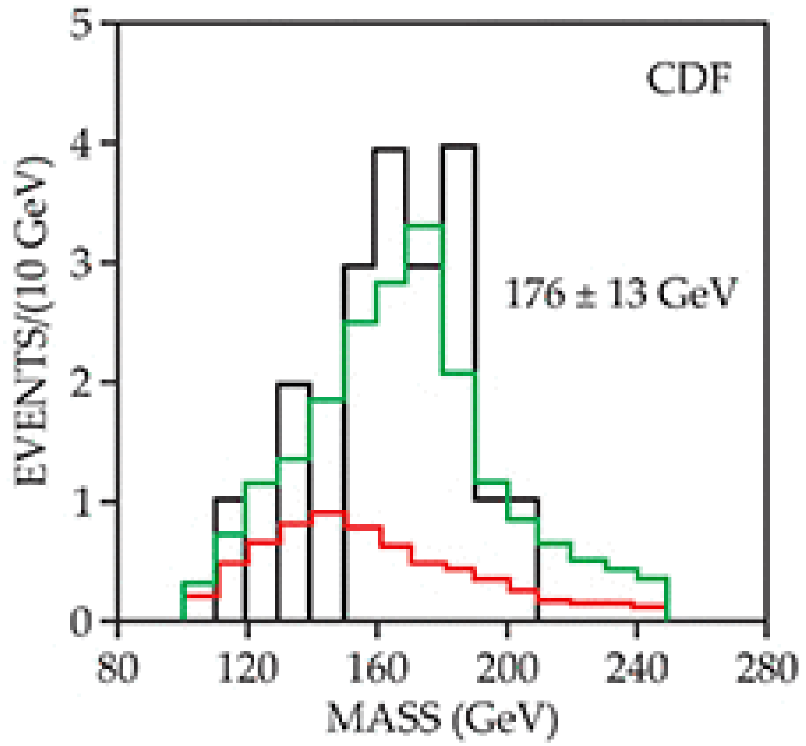


A success story: particle predictions (1)

> Example: Top quark

- Predicted in 1973 to explain observed CP violations in kaon decays
- Observed at Tevatron (Fermilab, U.S.) in 1995
  - First mass estimate: 176 ± 13 GeV
  - Predicted before discovery to be > 160 GeV

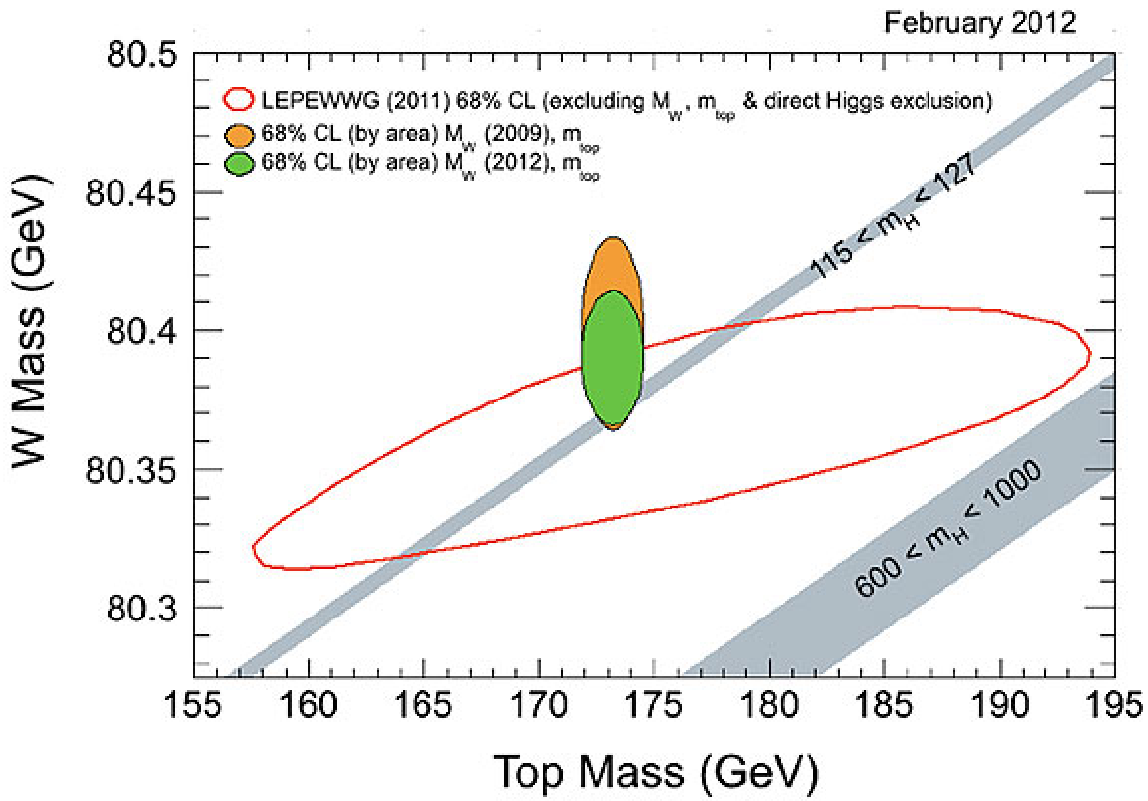
- Top quark mass now known at precision of < 1 GeV
  - M_{TOP} = 172.76 ± 0.3 GeV (PDG, 2019)



A success story: particle predictions (2)

> Example: Higgs boson

- Predicted in 1964 by Brout, Englert, Higgs
- Discovered in July 2012 at LHC (CERN)
- Mass of 125 GeV
  - Within range previously predicted by SM

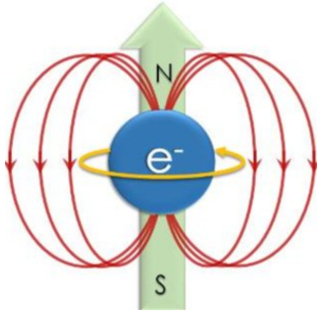


A success story: precision tests (1)

> Example: magnetic moment of the electron

– Intrinsic quantity arising from electron spin

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



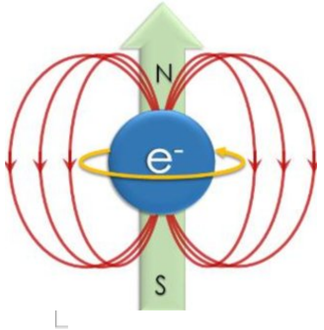
– Depends on *g*-factor

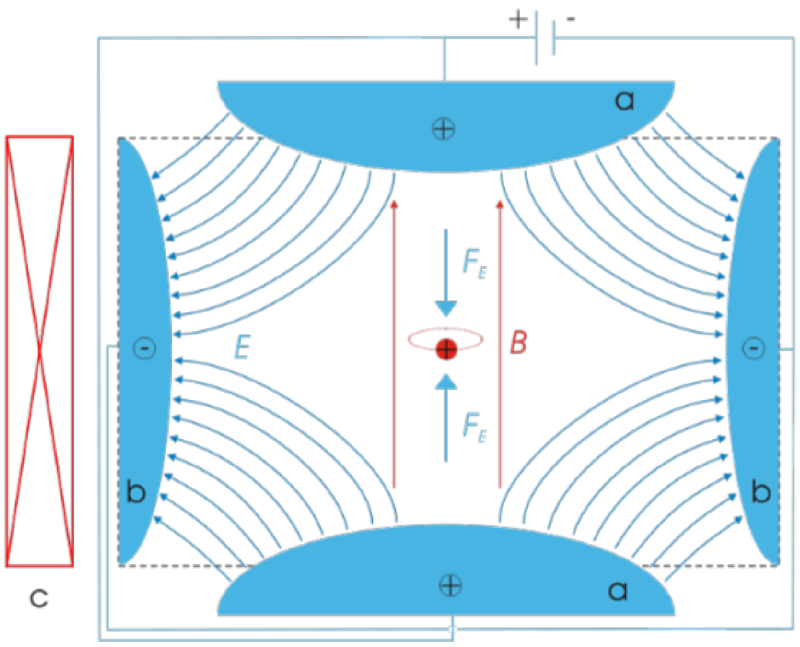
- Classic quantum mechanics for a point-like Dirac particle: $g = 2$
- Quantum field theory → loop quantum corrections: $g \neq 2$

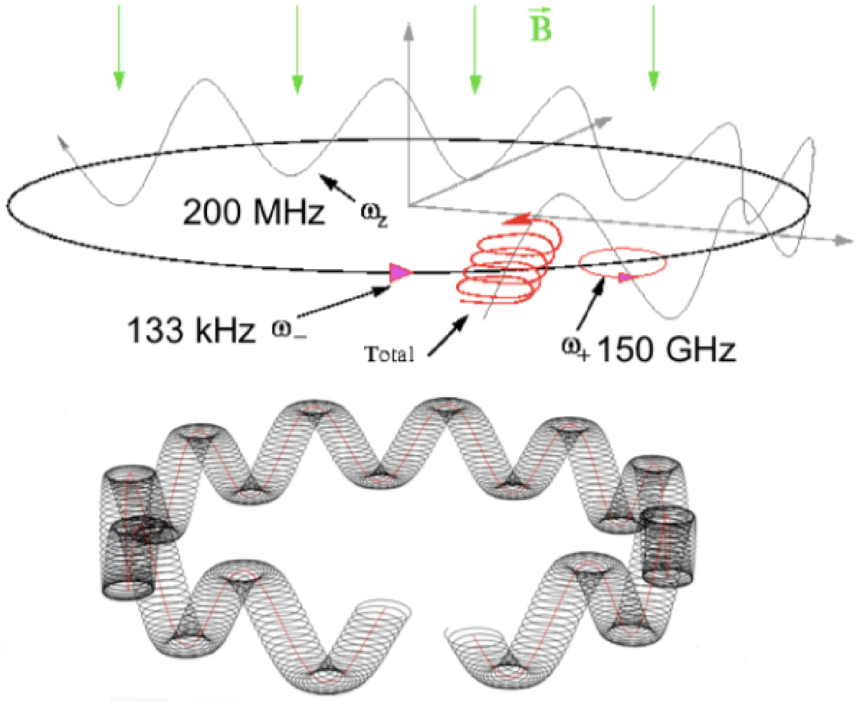
A success story: precision tests (1)

> Example: magnetic moment of the electron

- Measurement using a single electron in a Penning trap
- Comparison of cyclotron and precession frequencies





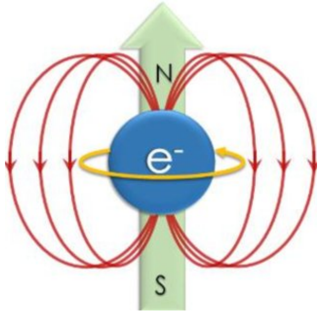


A success story: precision tests (1)

> Example: magnetic moment of the electron

– Results from latest Harvard measurement [Hanneke et al, PRL 100 (2008) 120801]

- Using a one-electron quantum cyclotron



$$\boxed{\begin{aligned} g/2 &= 1.001\ 159\ 652\ 180\ 73\ (28) \quad [0.28\ \text{ppt}]\ \ (\text{measured}) \\ g(\alpha)/2 &= 1.001\ 159\ 652\ 177\ 60\ (520) \quad [5.2\ \text{ppt}]\ \ (\text{predicted}) \end{aligned}}$$

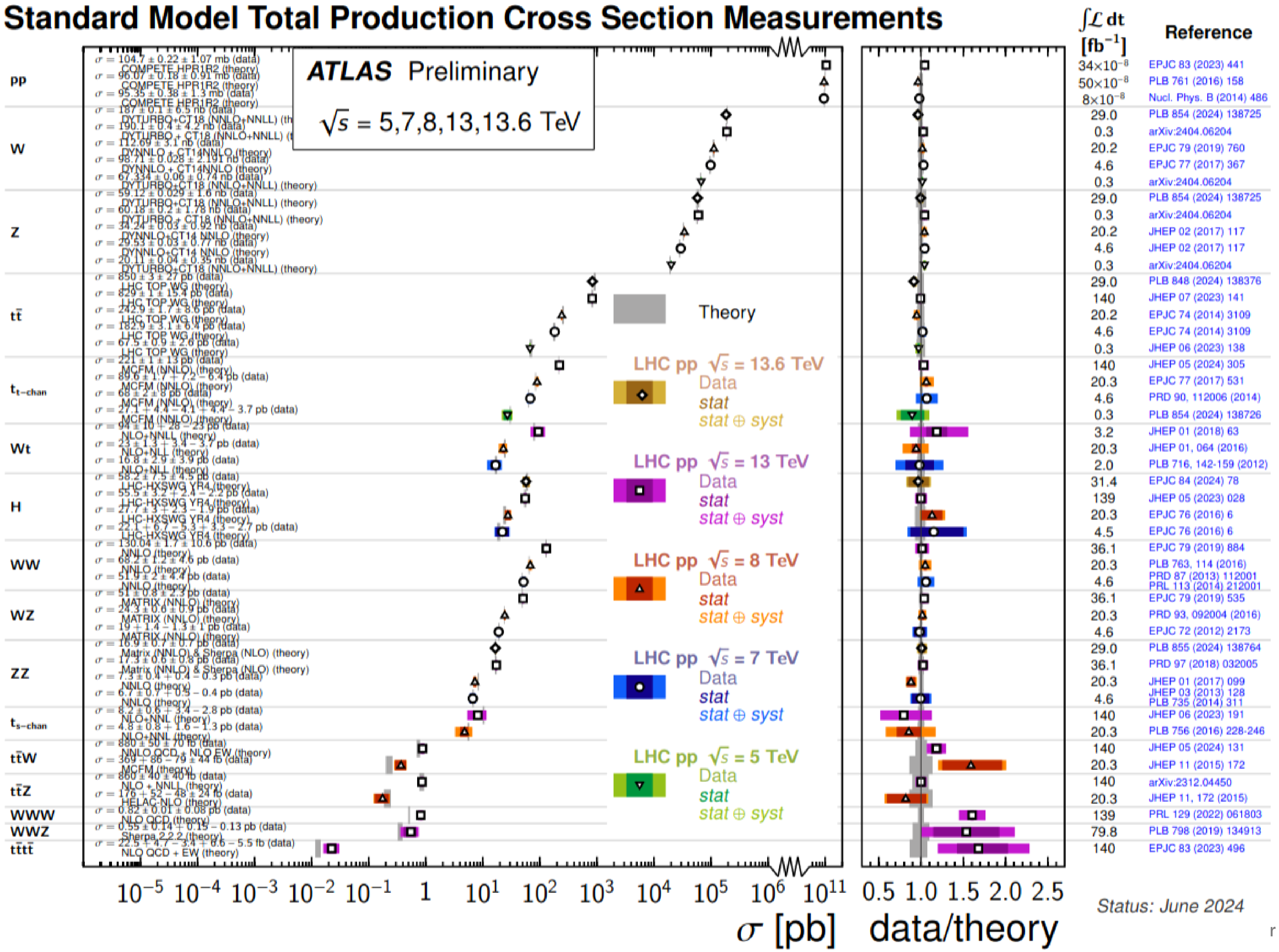
– Measured value agrees with SM prediction at precision better than 1 part per billion

– Note that calculated value depends on α, which is taken from other measurements

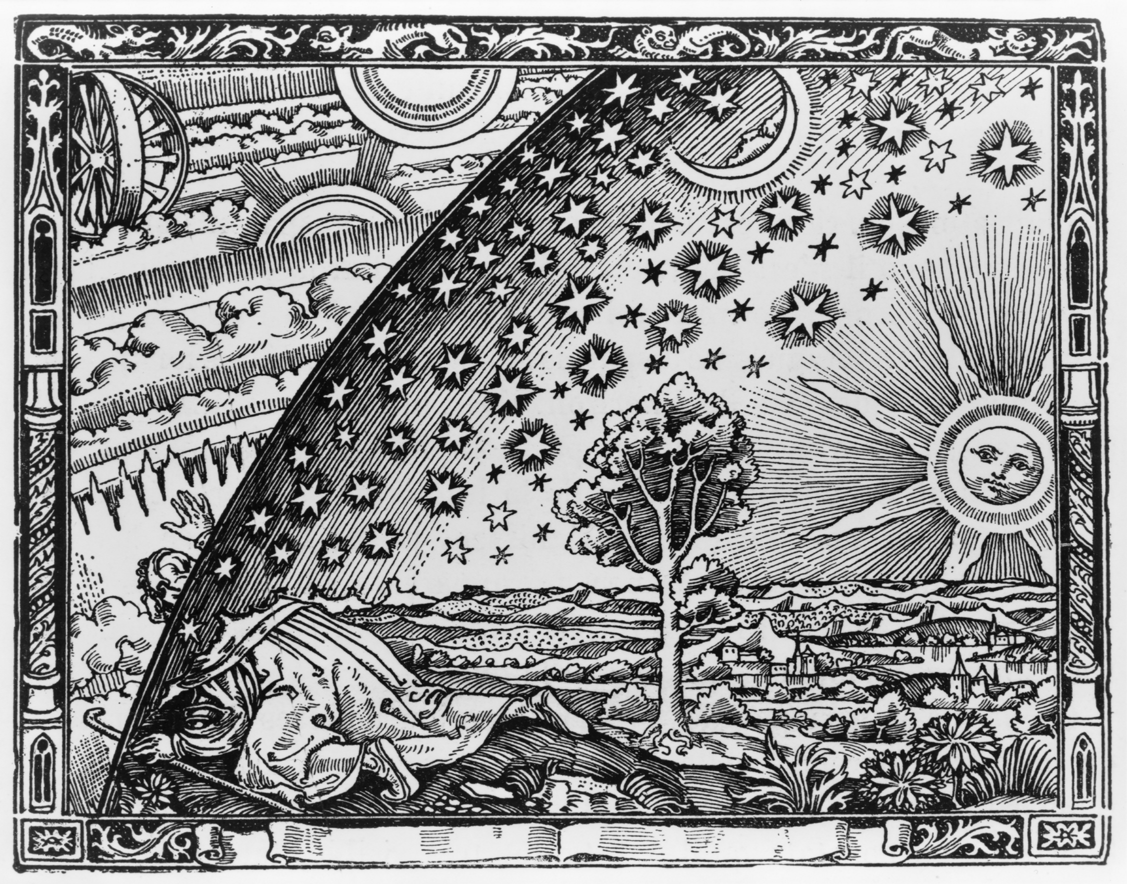
- Can also use g/2 measurement as input to extract α

A success story: precision tests (2)

- Production cross-sections of common and rare processes
  - Measure how often a certain reaction occurs in the LHC’s proton-proton collisions
  - Compare to the rates calculated via the SM


Standard Model Total Production Cross Section Measurements
ATLAS Preliminary
√s = 5,7,8,13,13.6 TeV
pp
W
Z
tt̄
t_t-chan
Wt
H
WW
WZ
ZZ
t_s-chan
tt̄W
tt̄Z
WWW
WWZ
tt̄tt̄
Theory
LHC pp √s = 13.6 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 5 TeV
Data
stat
stat ⊕ syst
σ [pb]
data/theory
∫ℒ dt [fb⁻¹]
Reference
Status: June 2024

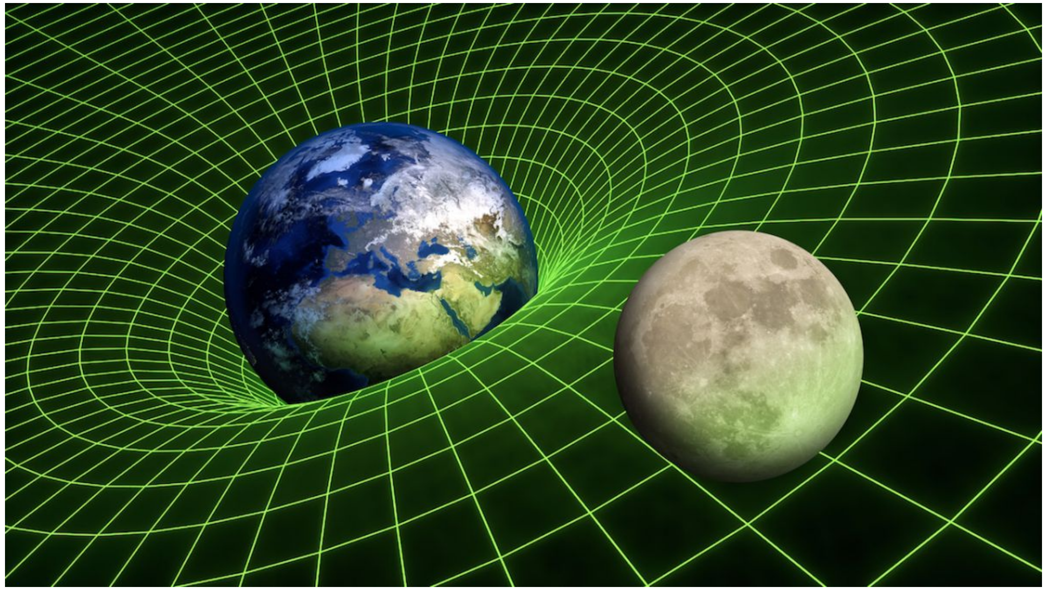
Why look beyond the SM?

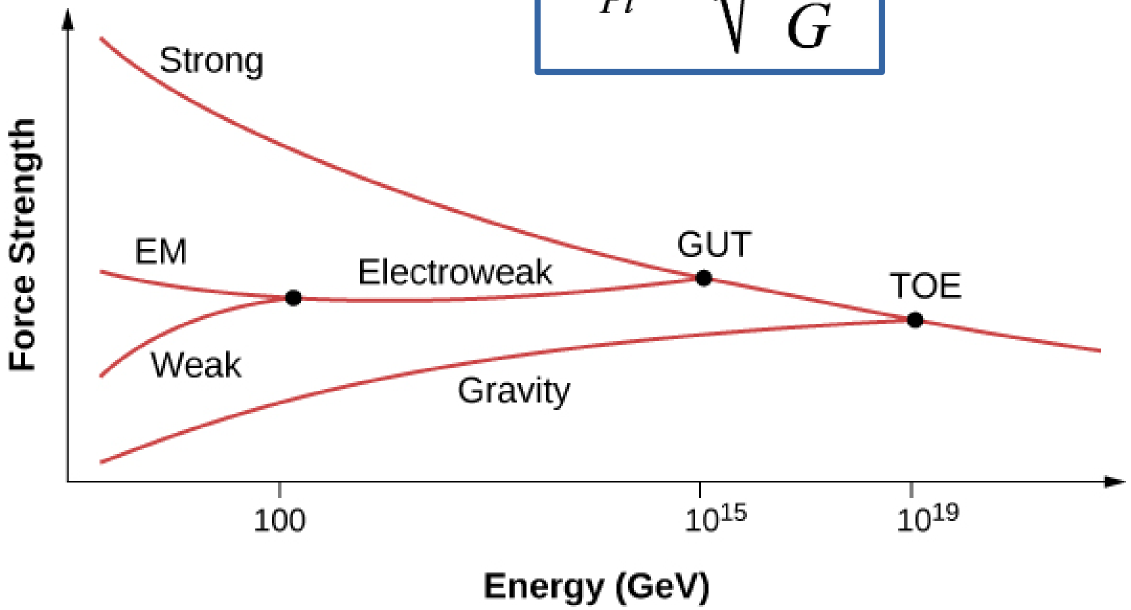


Missing pieces: gravity

> 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

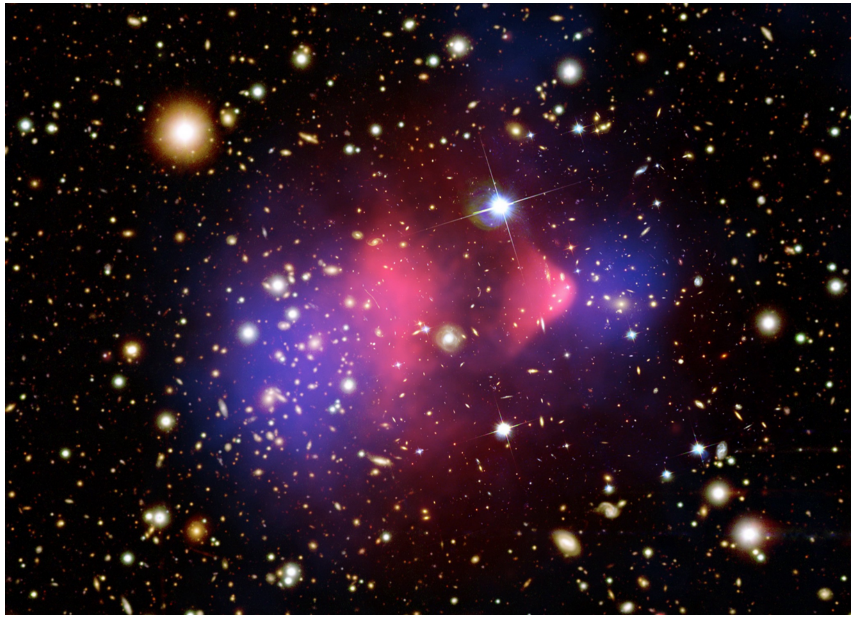
$$m_{Pl} = \sqrt{\frac{\hbar \cdot c}{G}}$$

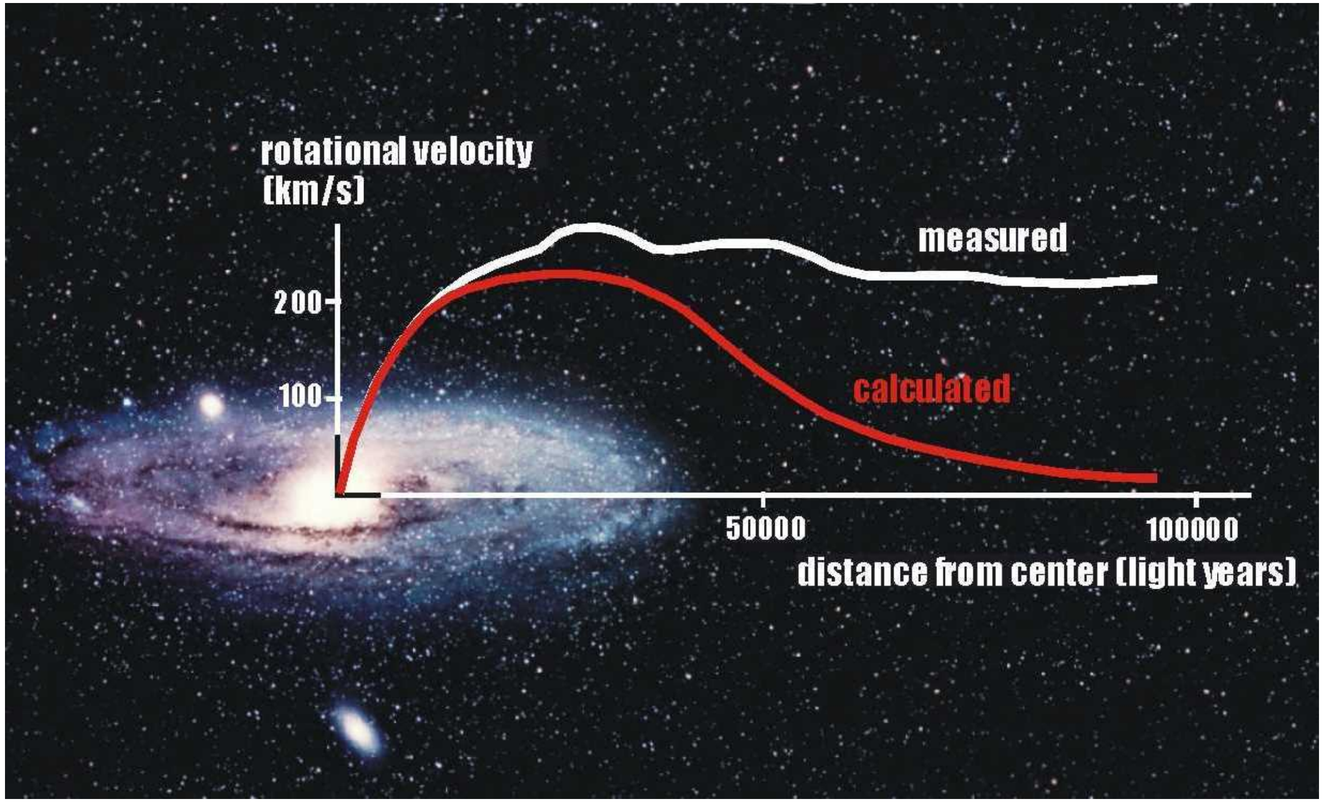




Missing pieces: dark matter

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

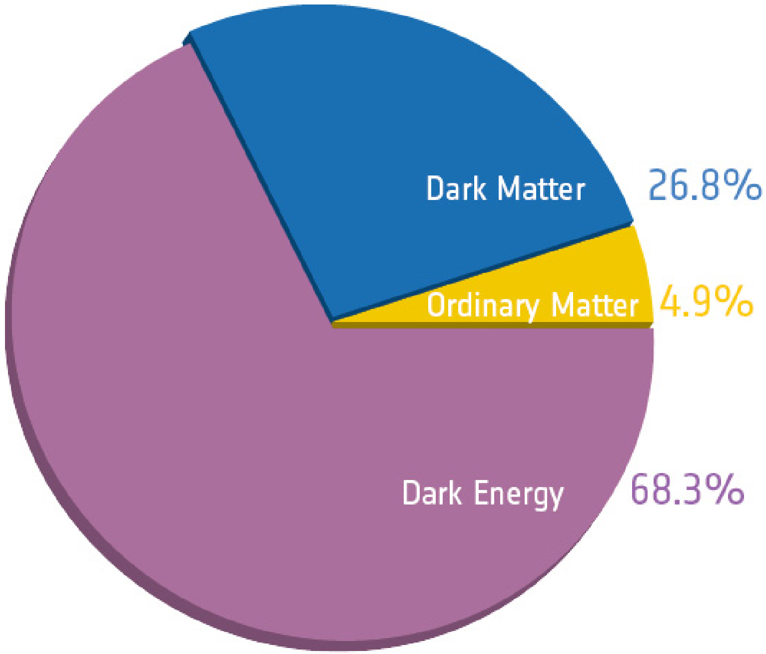


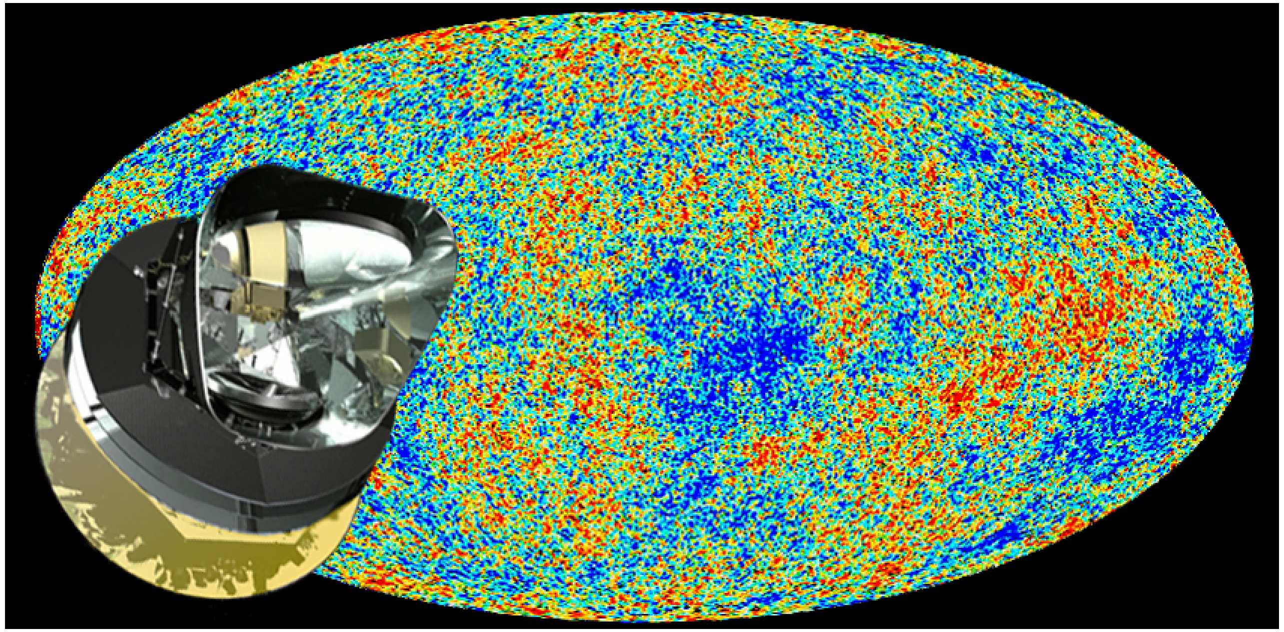


Missing pieces: dark matter & dark energy

> 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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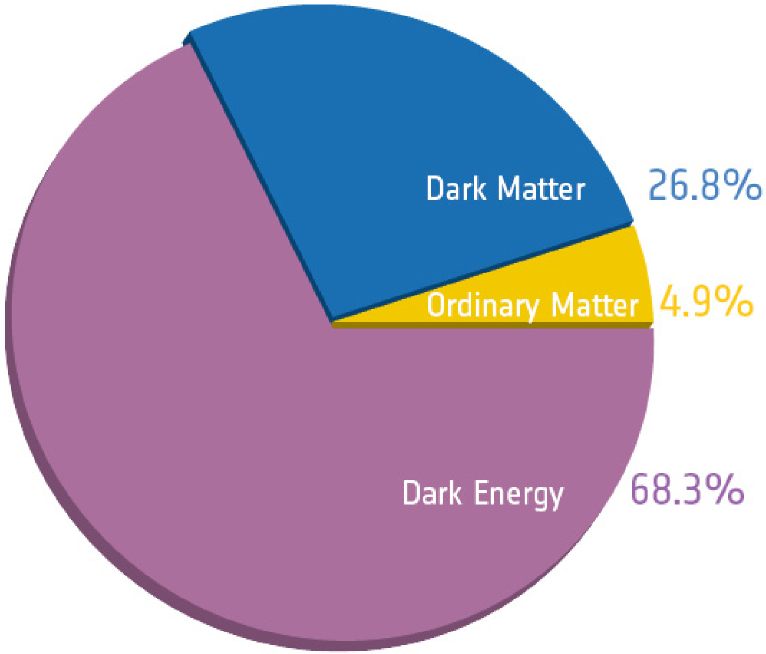
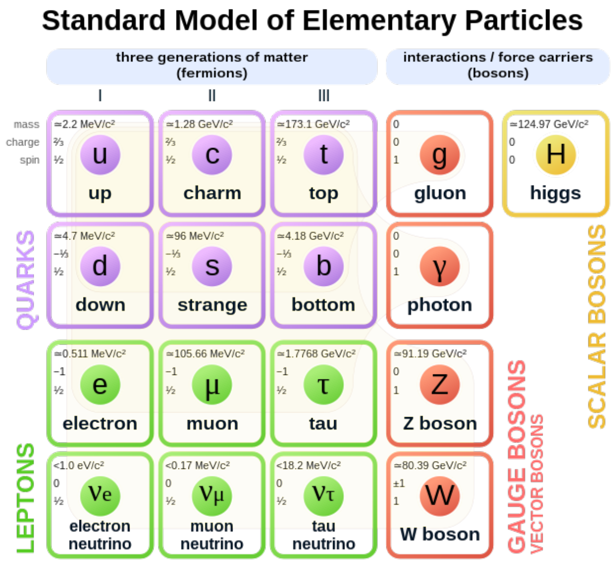
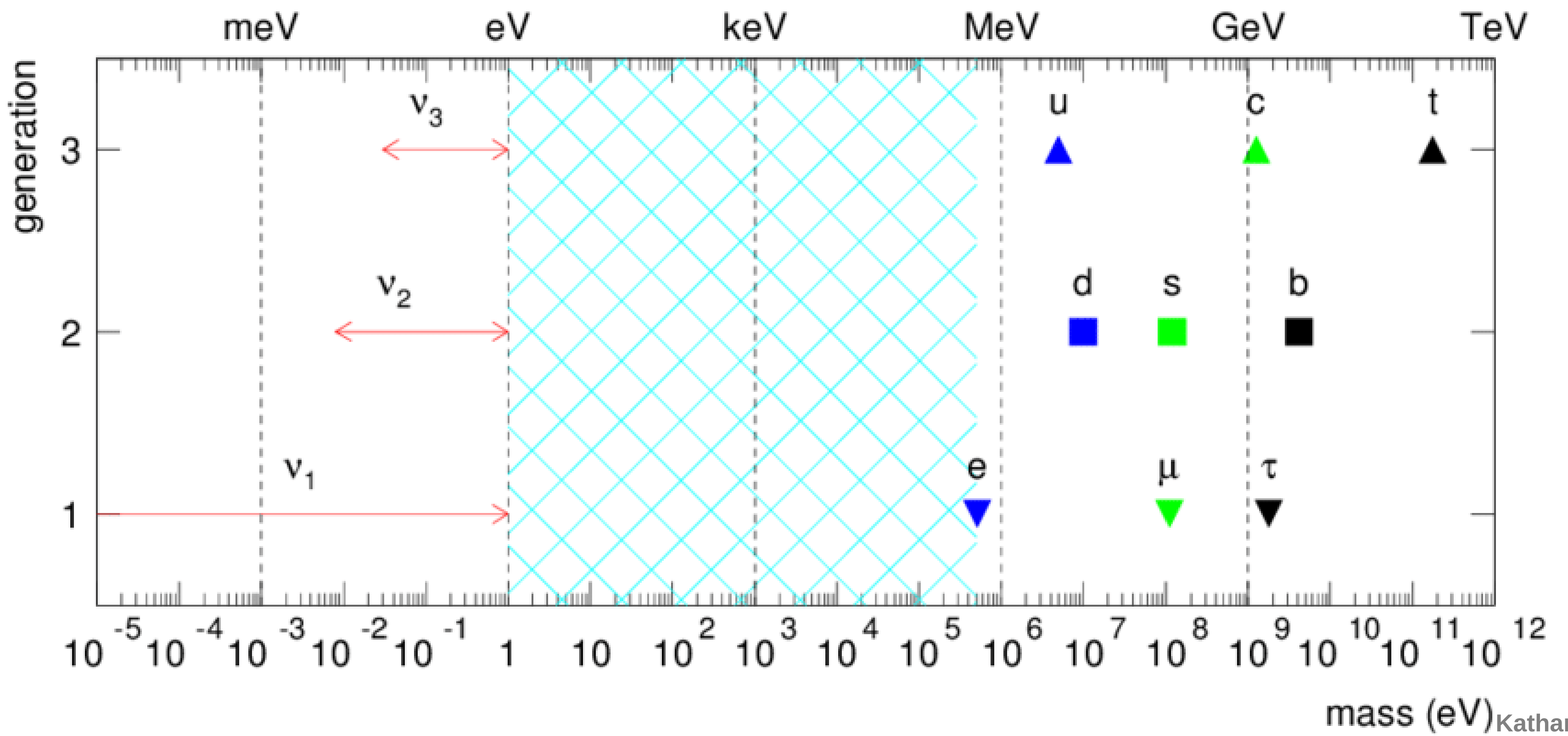


SM describes only 5% of matter-energy content of the Universe



Conceptual issues within the SM

> 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?



The strong CP problem (1)

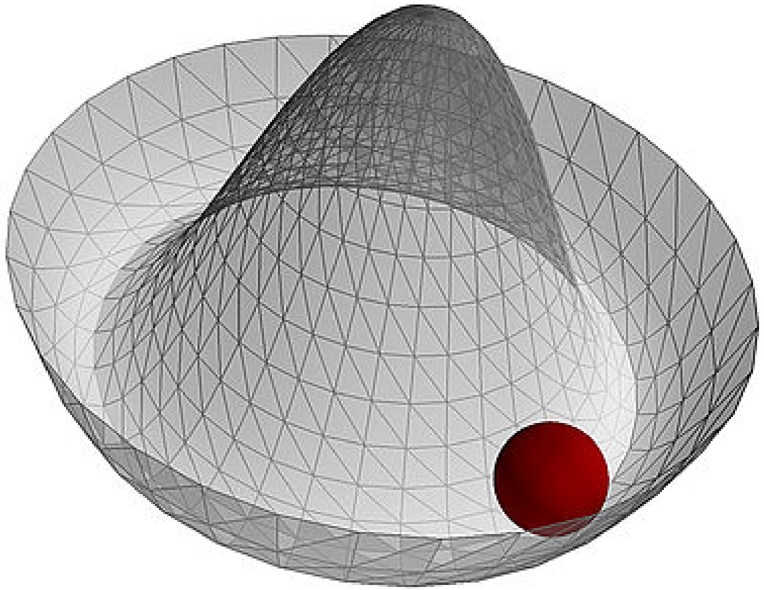
- QCD Lagrangian for massive quarks contains a CP violating term
- Amount of CP violation depends on parameter θ^*, which can take values in [0,1]

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

- θ* = 0 indicates extreme fine-tuning

The strong CP problem (2)

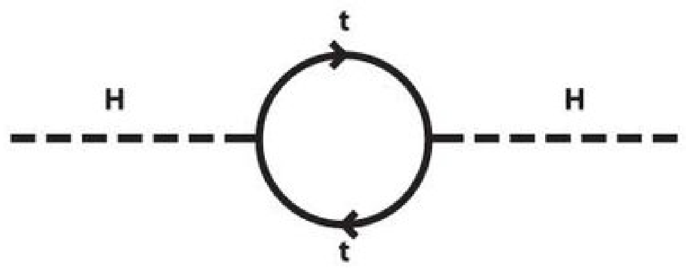
- Possible solution via the Peccei-Quinn mechanism
- Relate θ^* to a new physical field with a global chiral U(1) symmetry
- Field has tilted Mexican hat potential
- Spontaneous breaking of U(1) → pseudo-Goldstone boson: axion
- VEV of axion field leads to $\theta^* = 0$
  - No fine tuning!
- Axion also 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 $O(10^{19}\ \mathrm{GeV})$
  - 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
  - …

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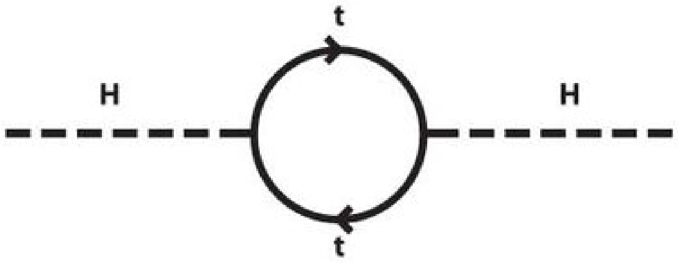

- No BSM physics → SM valid up to Planck scale O(10^{18} GeV)
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- BSM solutions:
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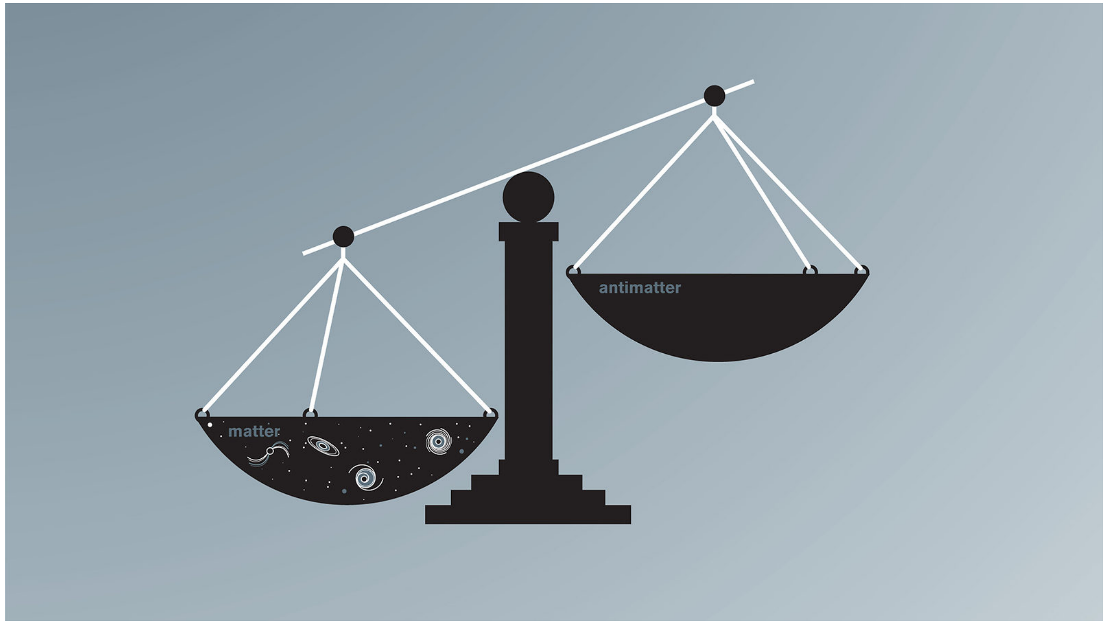
Matter-antimatter imbalance

- 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



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

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> What caused this imbalance?

> **Sakharov conditions**

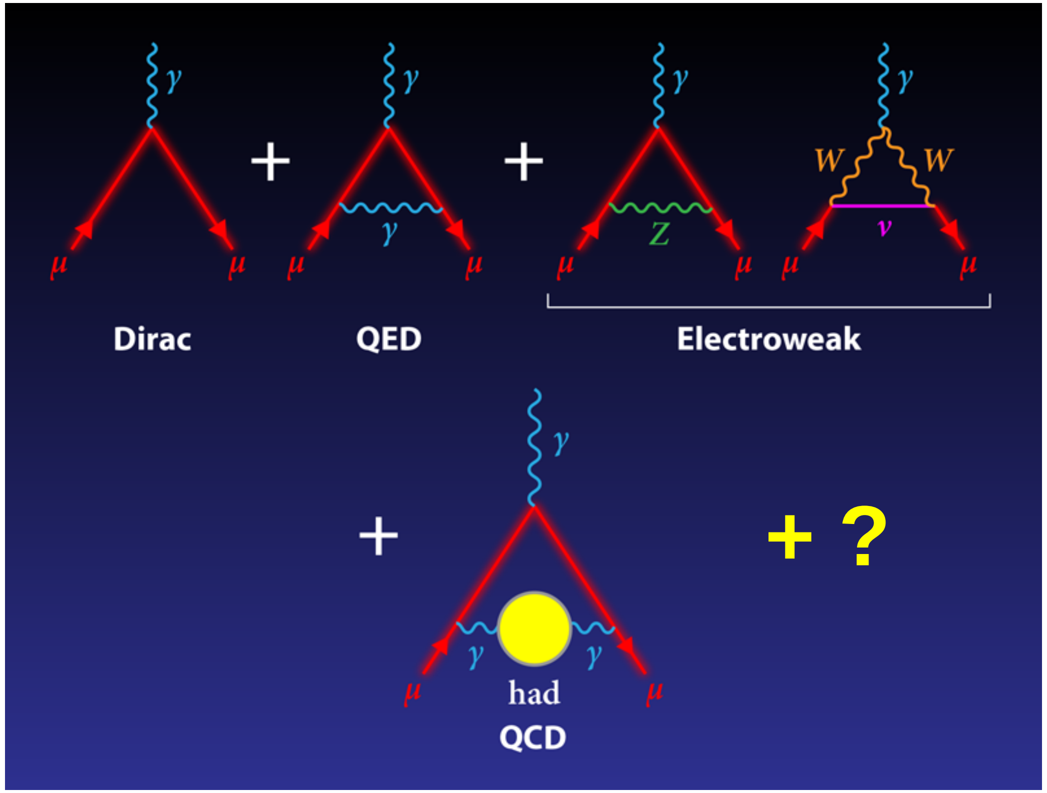
1. Baryon number violating processes
2. C and CP violation
3. Processes out of thermal equilibrium

- 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

Muon g-2 (1)

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

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

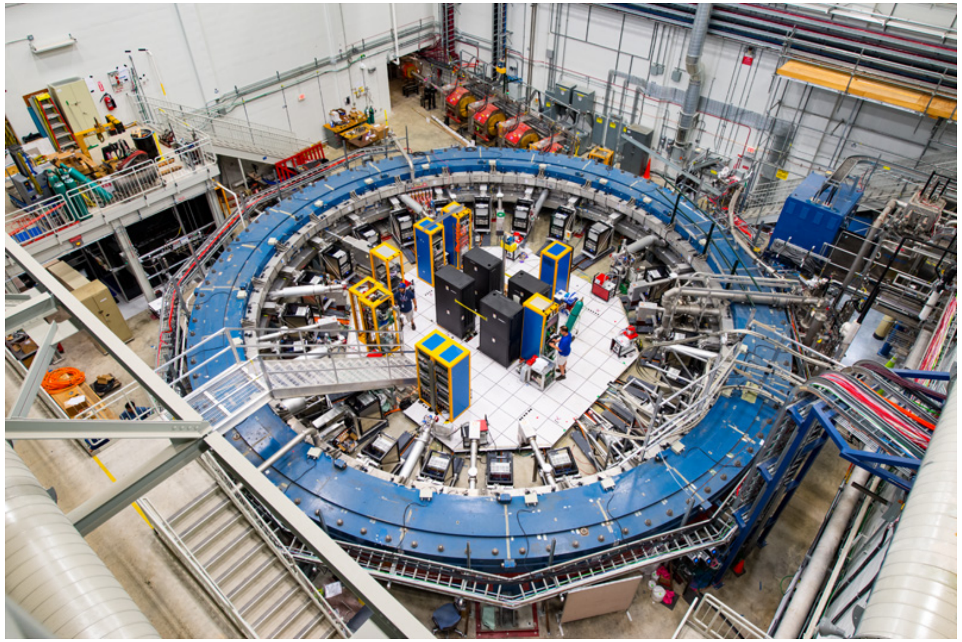


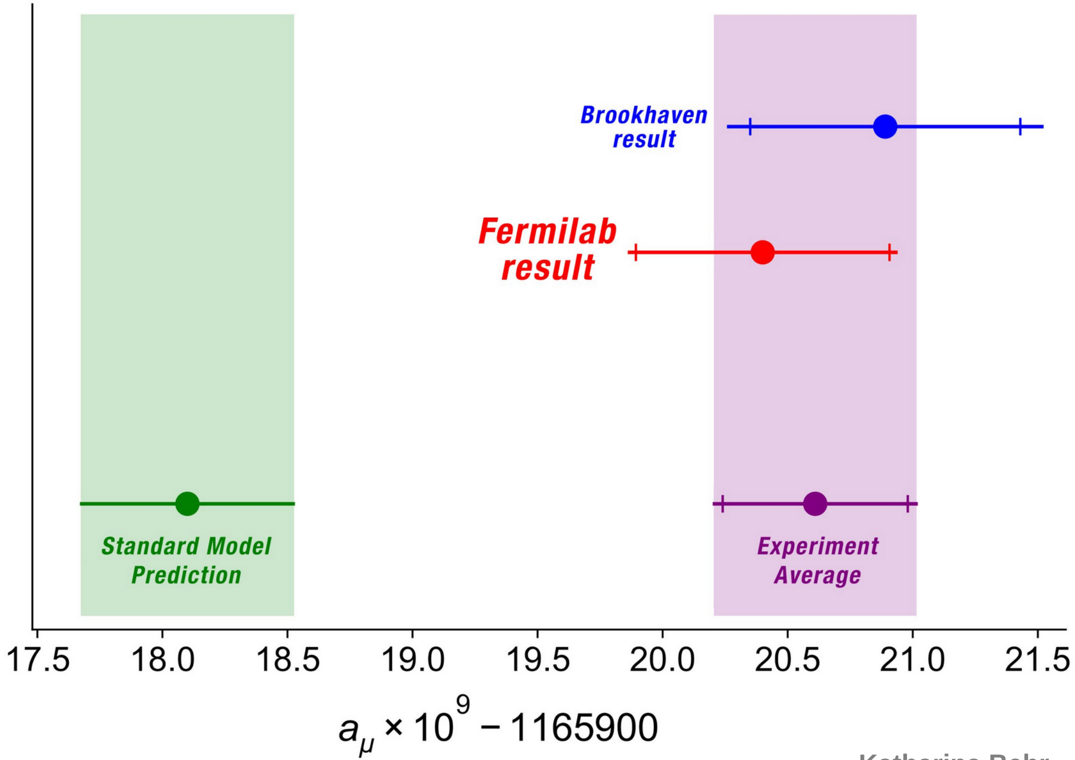
- Loop quantum corrections: $g \neq 2$
- Anomalous magnetic moment: $a = (g\text{-}2)/2$

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

Muon g-2 (2)

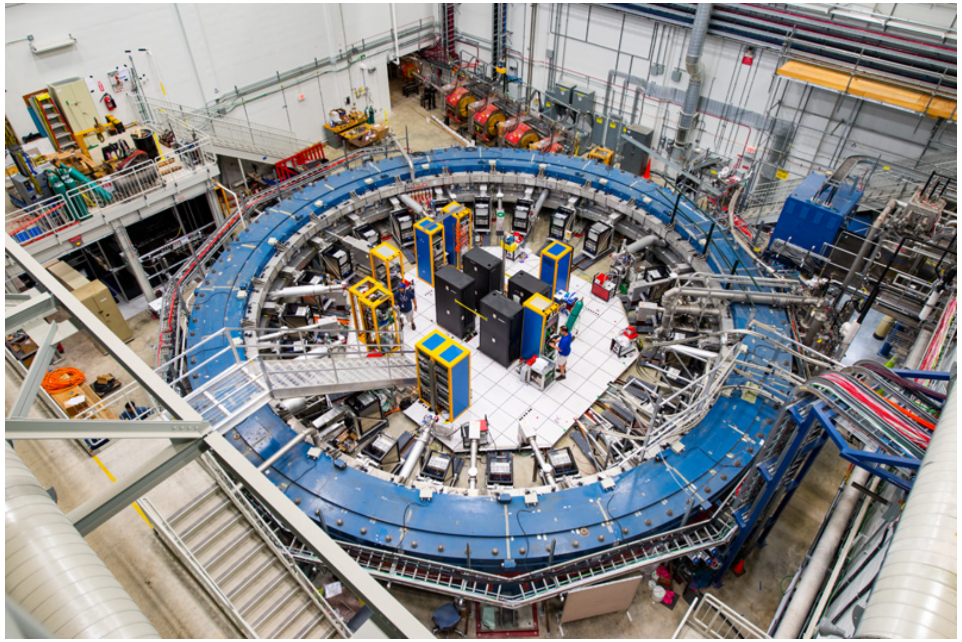
- Storage ring with polarised muons in magnetic field → measure precession frequency
- Measurements at BNL (2004) first revealed tension with SM of 2.6σ significance
- Subsequent measurements at Fermilab (2021) yielded combined significance of 4.2σ

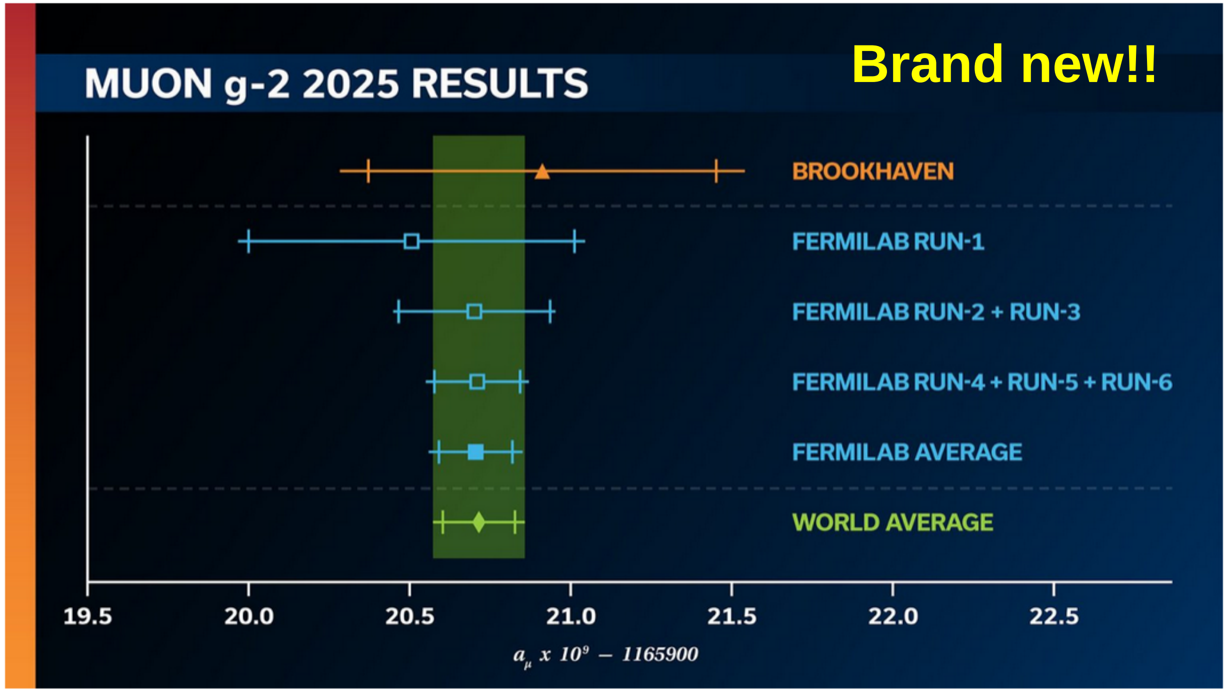




Muon g-2 (3)

- Storage ring with polarised muons in magnetic field → measure precession frequency
- Measurements at BNL (2004) first revealed tension with SM of 2.6σ significance
- Subsequent measurements at Fermilab (2021) yielded combined significance of 4.2σ
- Most precise measurement of muon g-2 to date: 127 parts-per-billion precision!

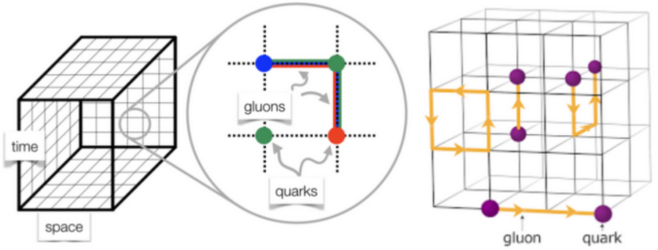




Credit: Muon g-2 collaboration

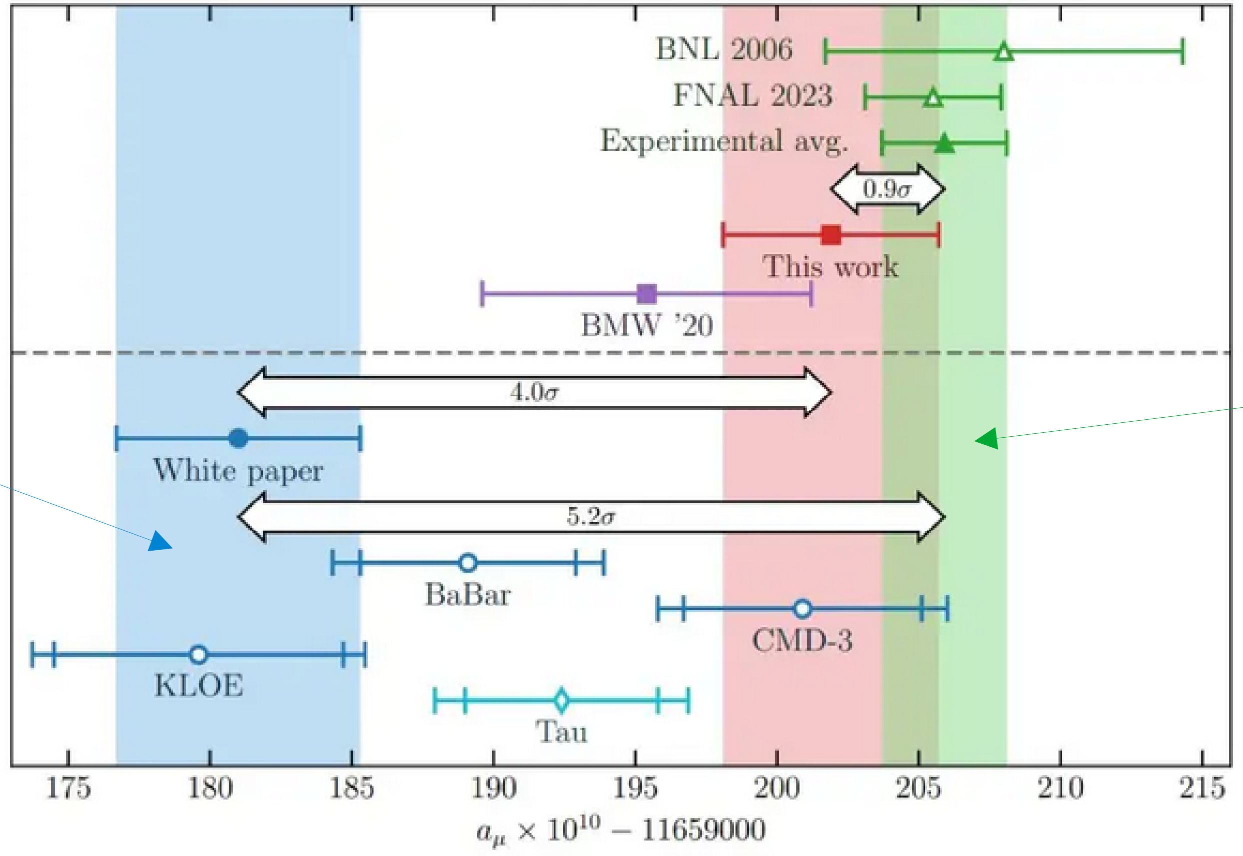
Muon g-2 (4)

- Meanwhile on the theory front: new SM calculations based on Lattice QCD
- **Significantly reduced tension** between SM predictions and experimental results



Credit: Ed van Bruggen/edryd

Conventional calculations



Experimental results

Credit: A. Boccaletti et al., arXiv:2407.10913, 2024

Flavour anomalies

> Tension with SM predictions in various precision measurements of B-meson decays

> Possible violation of Lepton Flavour Universality (LFU)

– LFU: SM interactions same for all lepton flavours

– Only differences due to different lepton masses

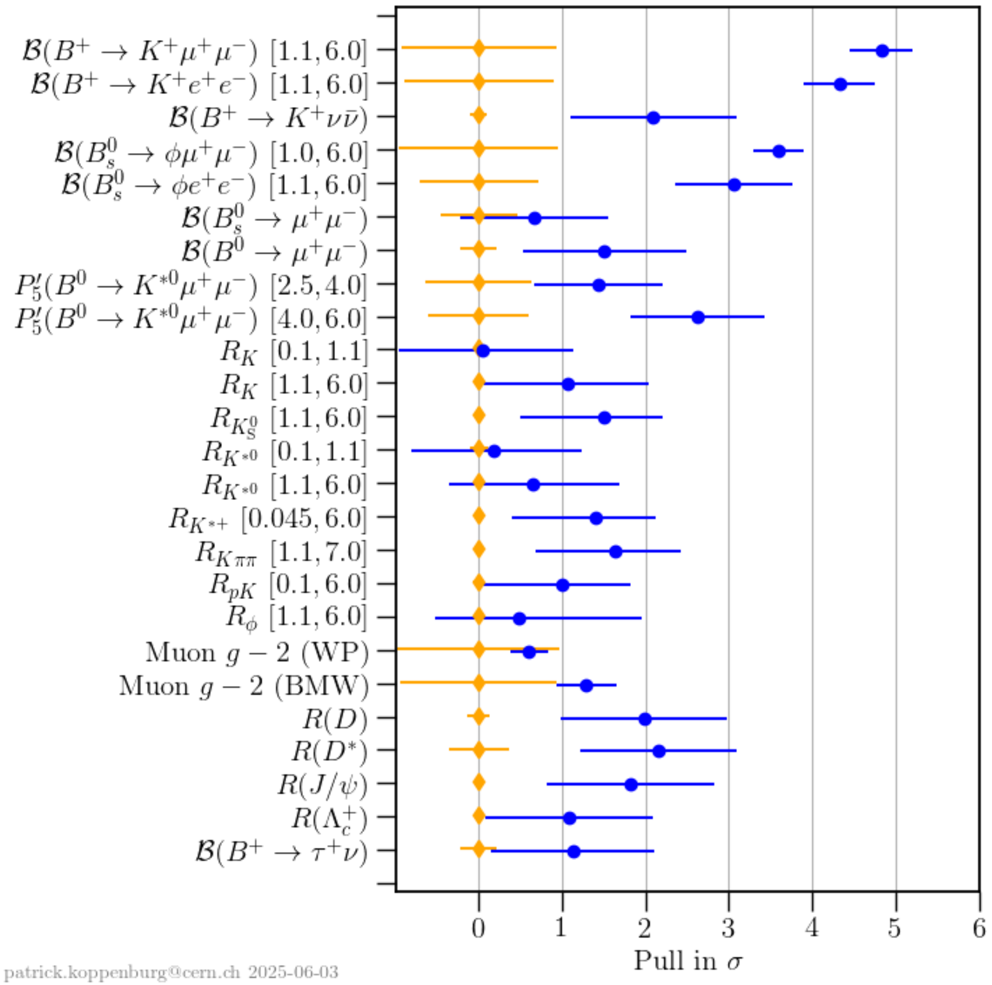
> In general two types of processes:

– b → s l^+l^- (neutral currents): μ vs. e

– b → c lν (charged currents): τ vs. μ/e

> In different experiments since 2013:

– BarBar, Belle, LHCb



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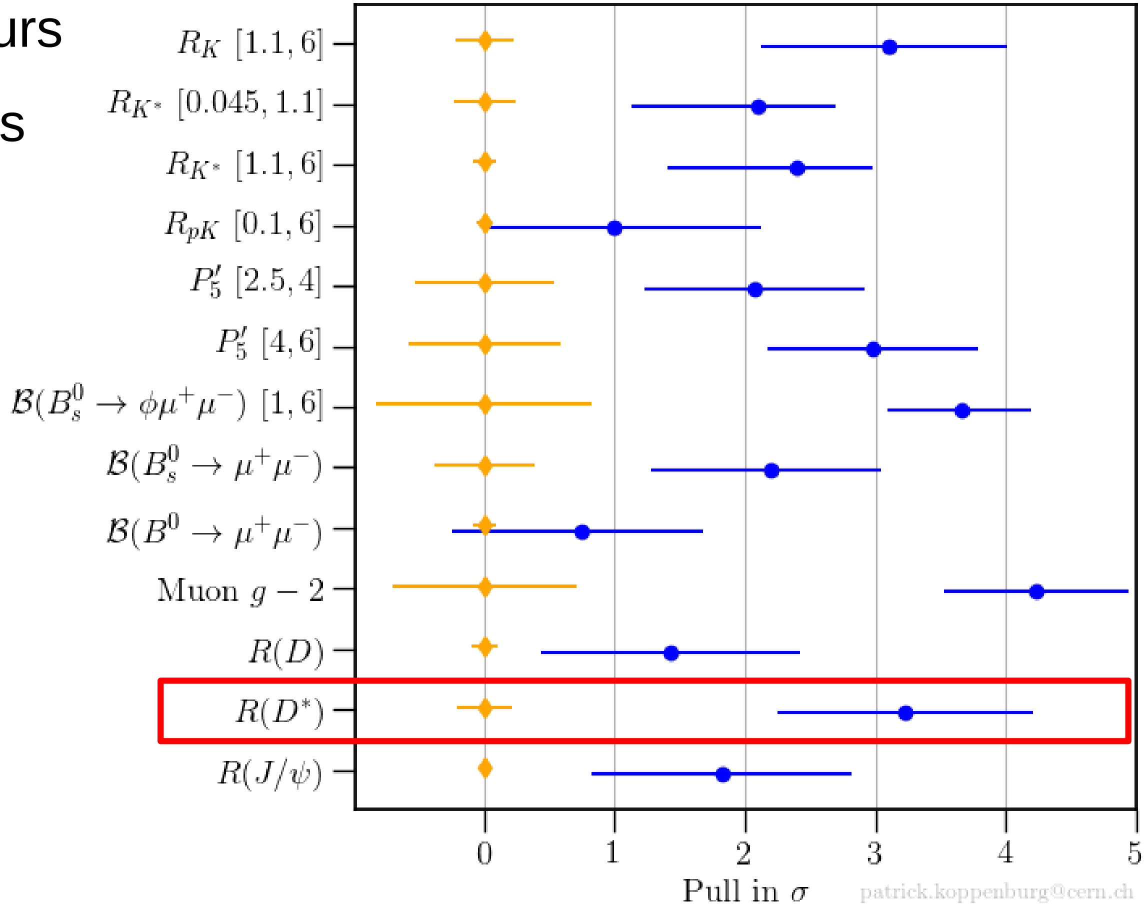


Flavour anomalies: R_{D^*}

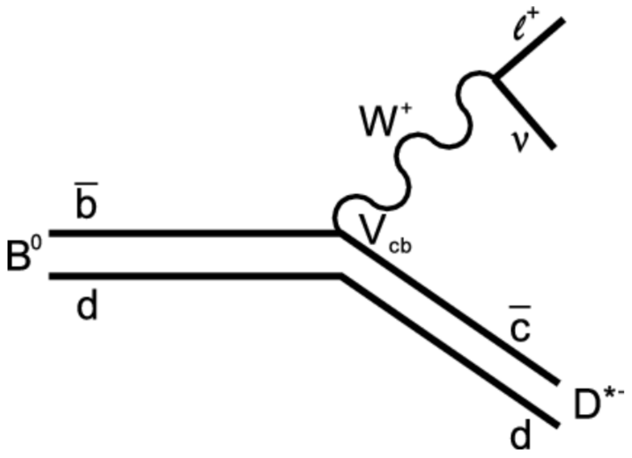
> SM prediction: $R_{D^*} = 1$

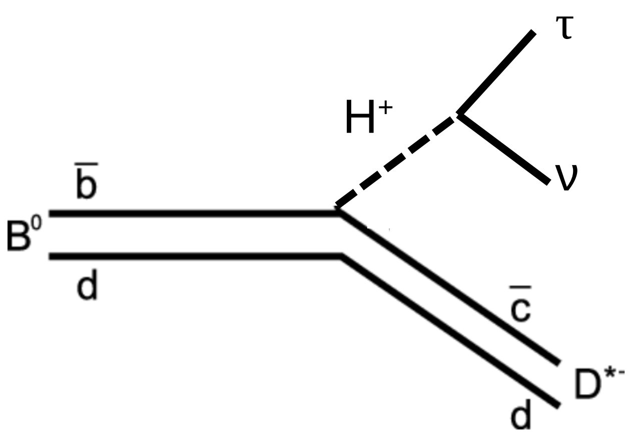
> Measurement deviates by > 3σ

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D^* \ell^- \bar{\nu}_\ell)} \quad \text{where } \ell = e \text{ or } \mu$$

> Anomalies could be due to presence of new particles (leptoquarks, charged Higgs bosons, …)

- Heavy charged Higgs bosons couple preferentially to heavier leptons





Many questions. Many possible answers!

Open questions in the SM:

Unification of all forces?

Gravity?

Hierarchy problem?

Nature of DM?

Matter-antimatter imbalance?

Strong CP problem?

Flavour anomalies?

Muon g-2?

...

Beyond SM theories:

Composite Higgs

Axions

Leptoquarks

Extended Higgs sector

Supersymmetry

Extra dimensions

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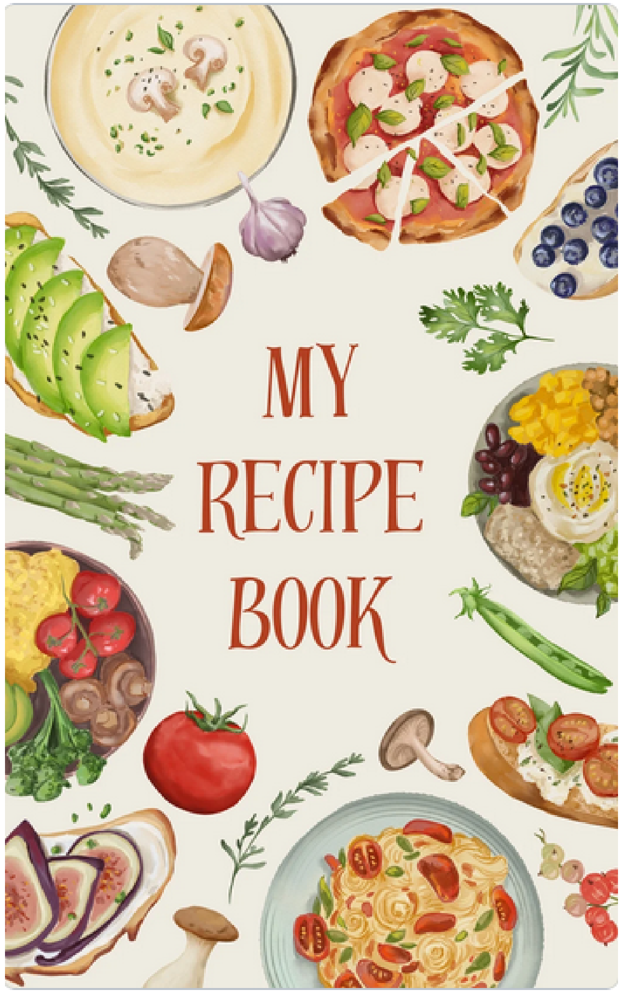
See Higgs 3 lecture on BSM Higgs

Experimental Techniques

Basic recipe for collider searches

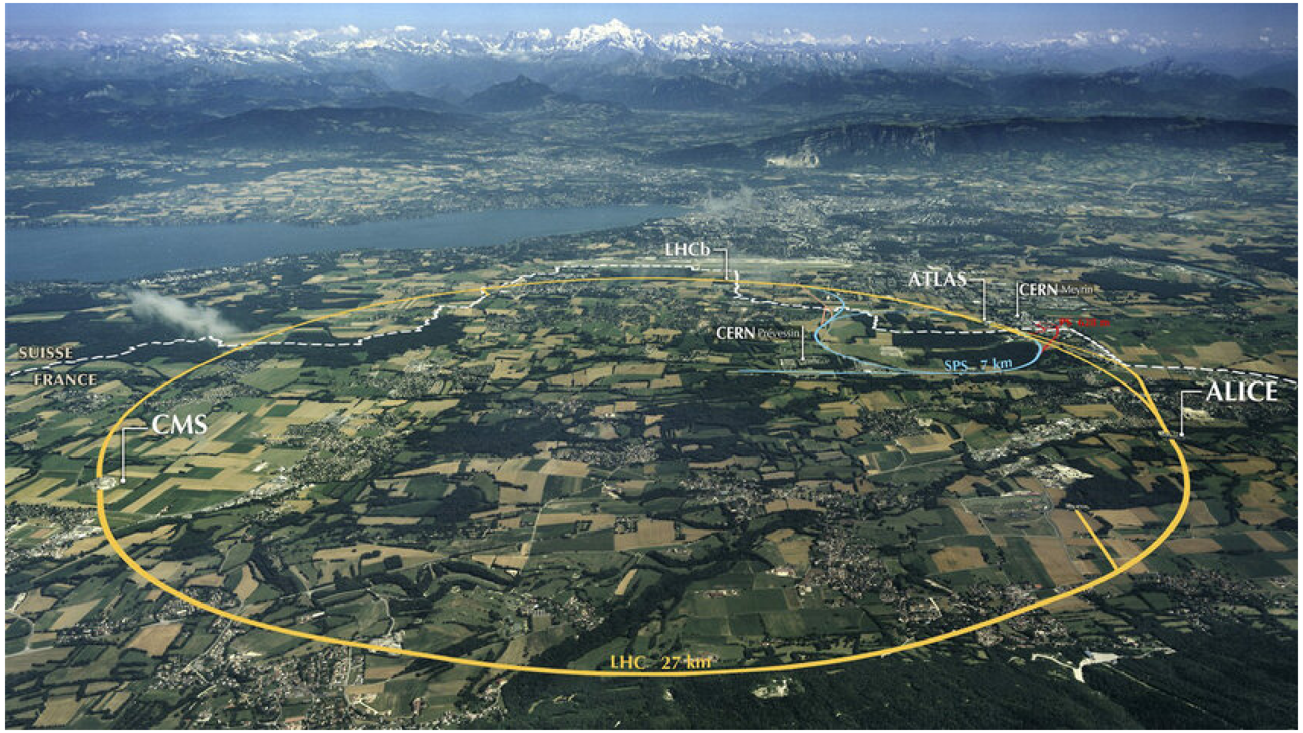
> Many ingredients needed
> Simple recipe common to most searches
> Refined by each individual analysis team



Ingredient 1: a particle collider

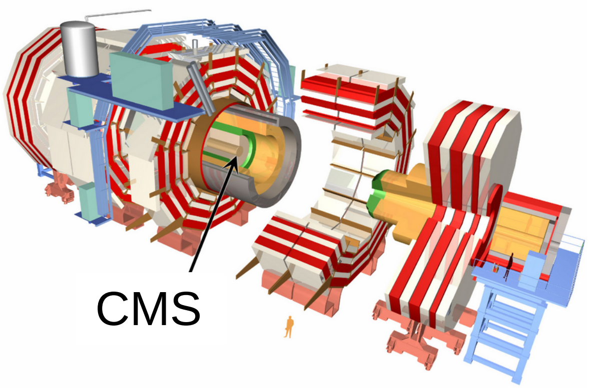
> LHC – a discovery machine!

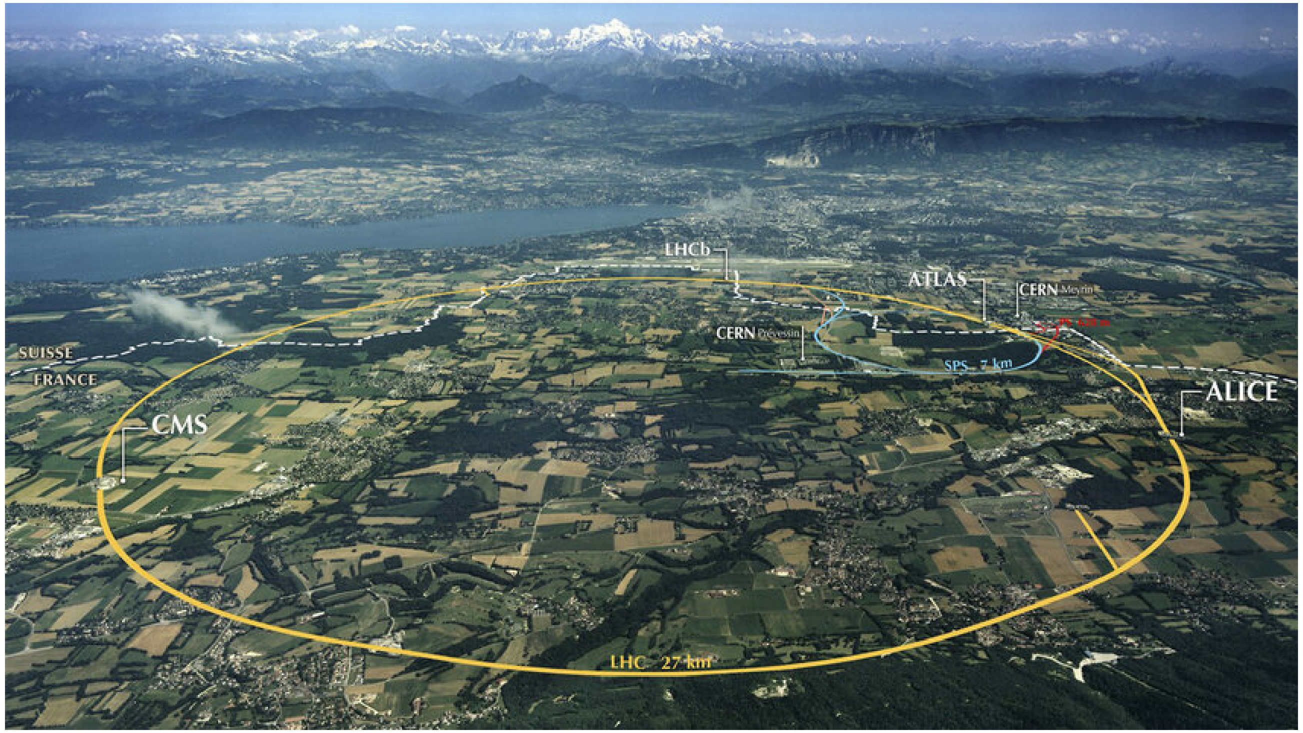
- Highest centre-of-mass energies reached in a lab to date (14 TeV)
- Hadron collider: different partonic initial states and effective centre-of-mass energies

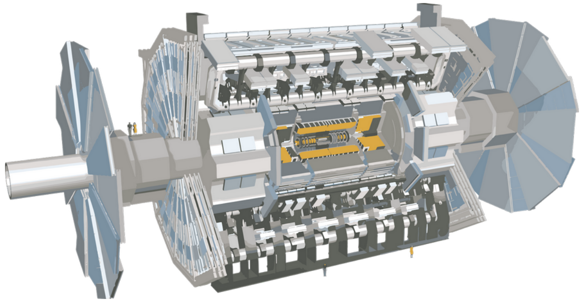


Ingredient 2: detectors

- ATLAS, CMS – two general-purpose detectors capable of capturing Higgs-boson decay products
- LHCb, ALICE, … specialised detectors for heavy-flavour and heavy-ion physics, respectively
    - Also capable of searching for certain types of new phenomena


CMS



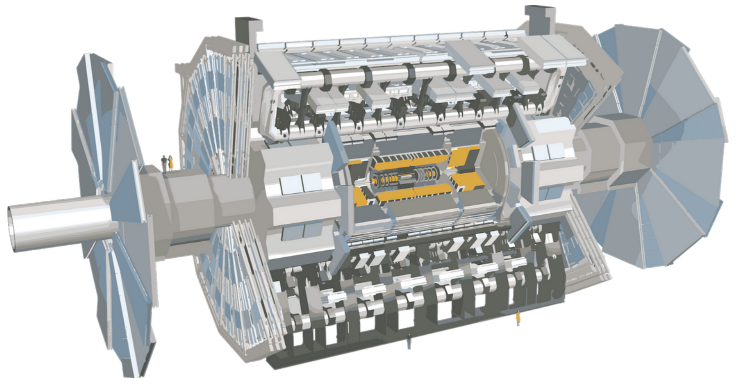
ATLAS


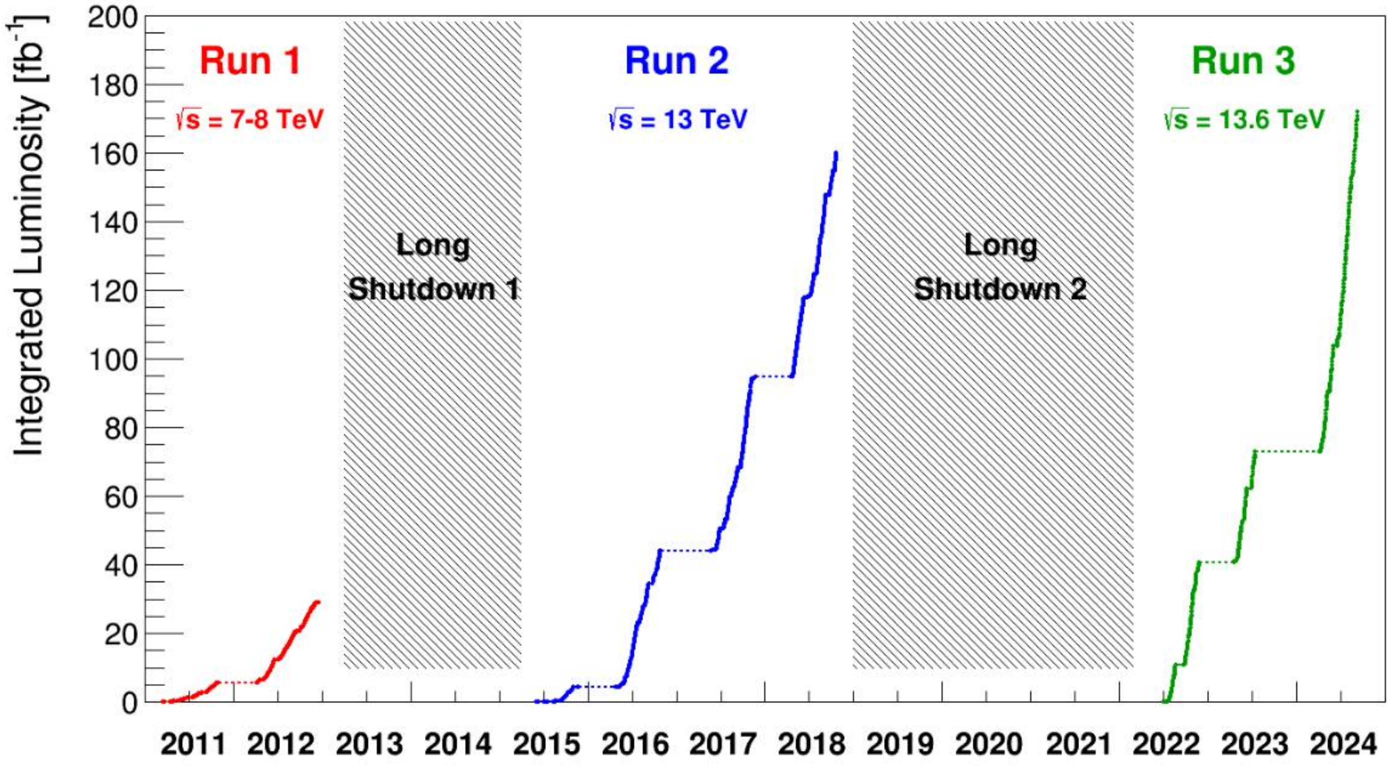
Ingredient 3: data

> Collect detector data during LHC periods of operation (runs)

> Focus here on proton-proton collisions

> Three runs at different centre of mass energies





Ingredient 3: data and simulation

> **Detector data**

- Real data taken with a detector
- Different datasets for different LHC operation periods
- Mix of various different processes

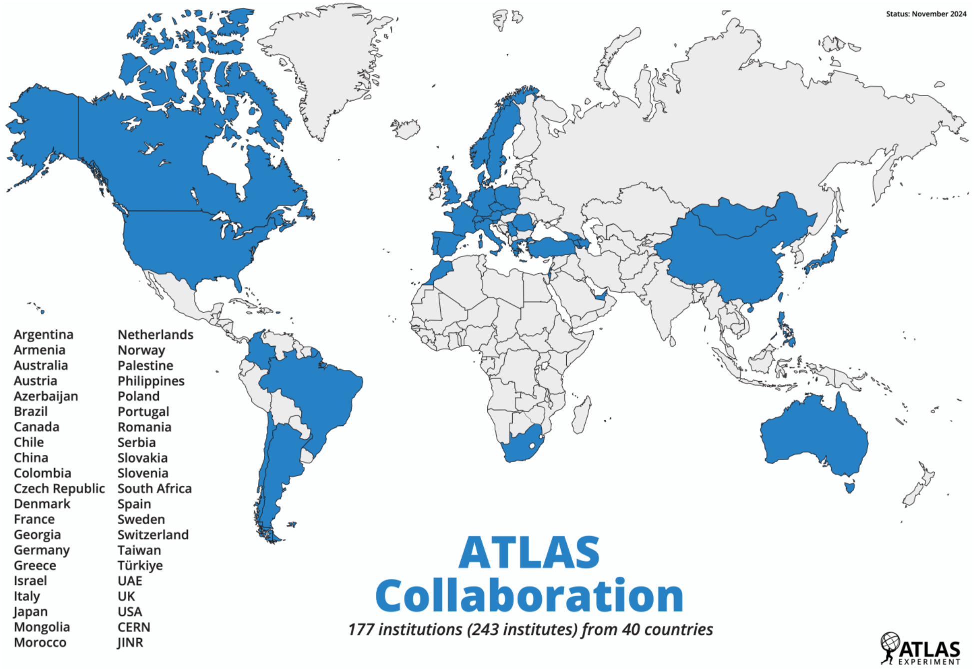
> **MC simulation**

- Generate well-defined process
  - SM or BSM expectation
  - Typically just one process per sample
- All “truth” information accessible
- Need to be careful to simulate realistic detector conditions

See Juergen’s MC lecture

Ingredient 4: collaborations

- Large international collaborations for each detector
- Hundreds to thousands of scientists, engineers, technicians who
  - Operate the detector
  - Reconstruct and calibrate the detector data
  - Provide and operate computing and simulation tools
  - Perform the data analysis

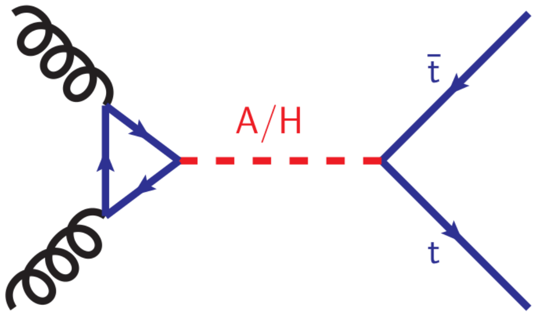


Basic recipe: search concept

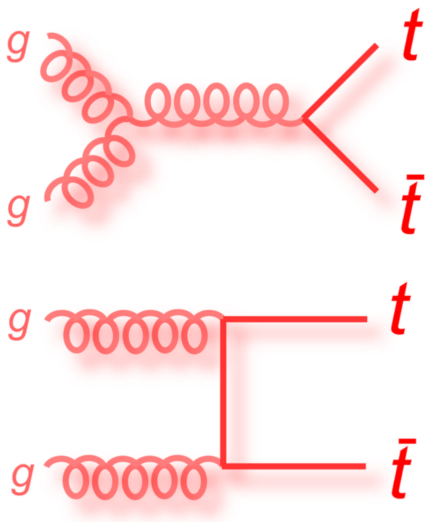
> Search for a specific signal “S” in a data sample composed of a potential signal and background “B”

> Typically S << B

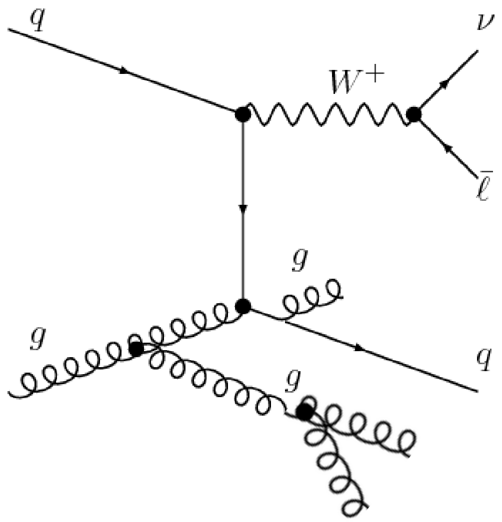
Signal
Heavy Higgs boson
decaying to ttbar



SM ttbar production
Irreducible background

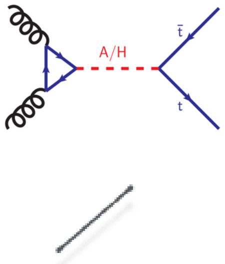


SM W+jets production
Reducible background



How to find a needle in a haystack?

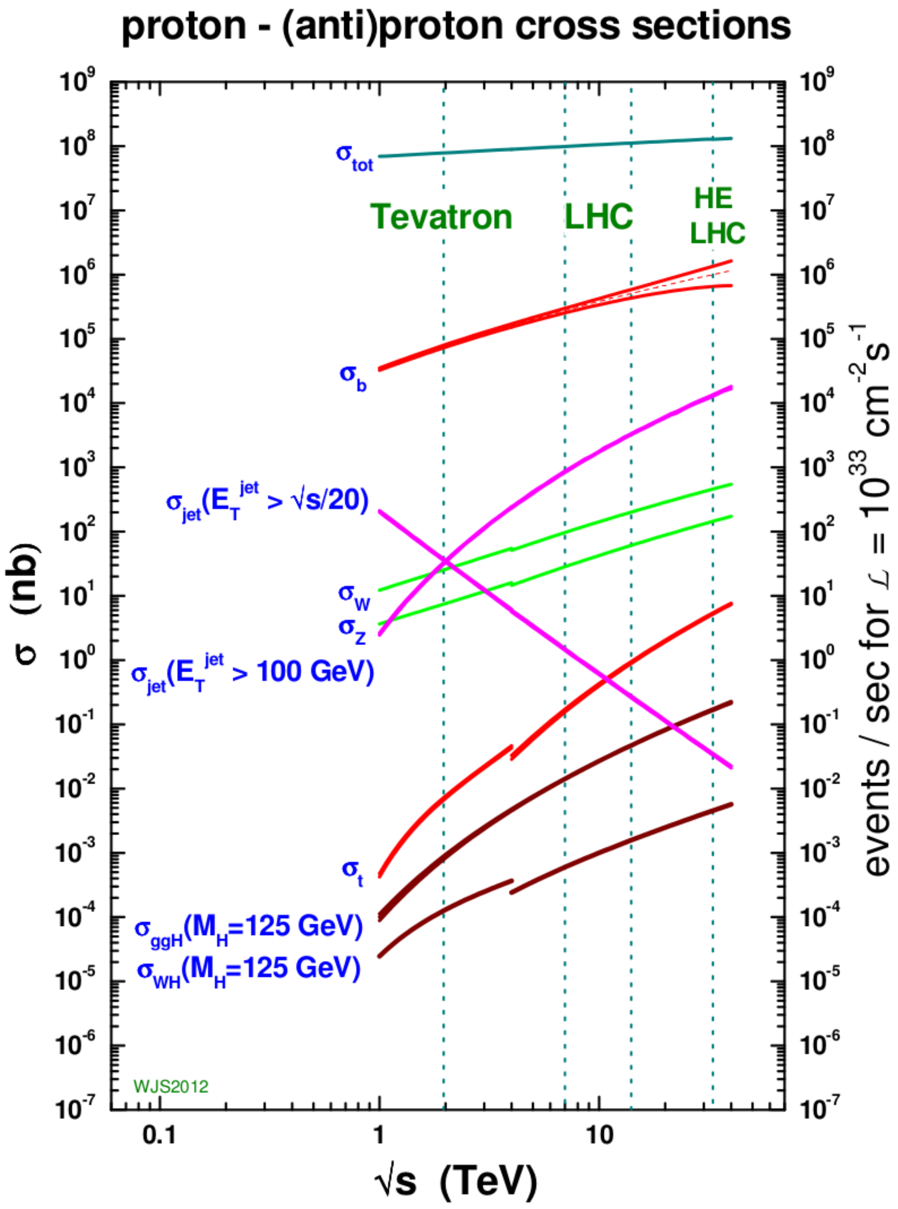
- Typically S << B
- Isolate small signal from huge dataset



Signal
(a.k.a. the needle)

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

T.G. McCarthy



How to find a needle in a haystack?

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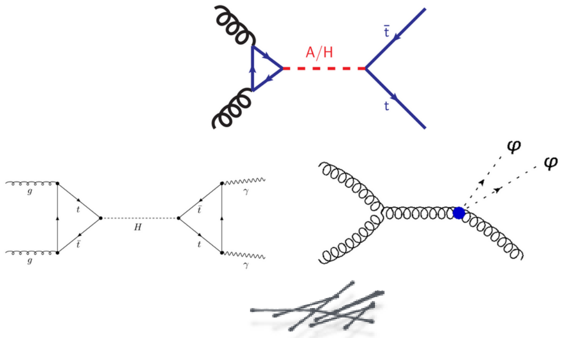
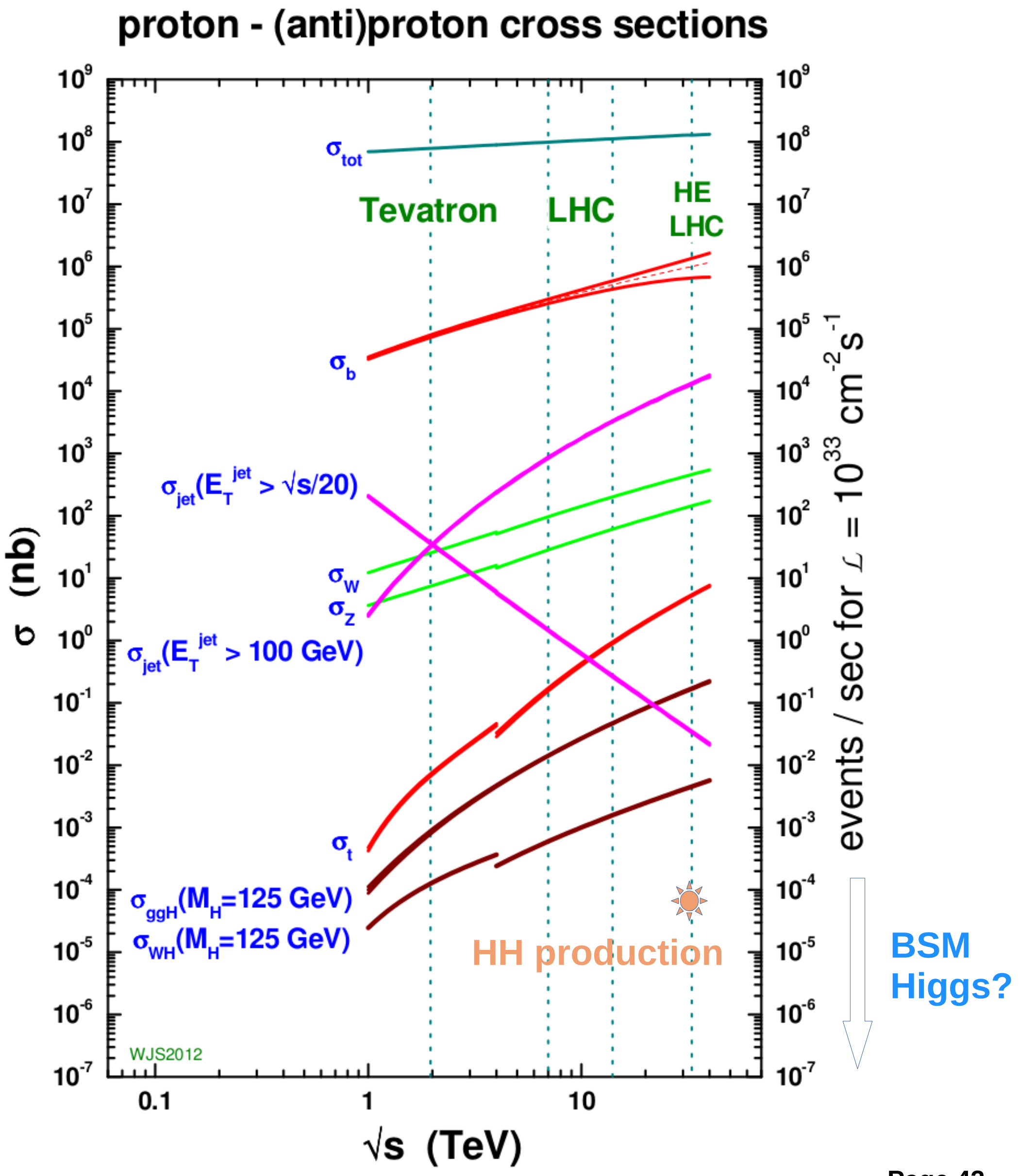


Signal
(several needles)

Backgrounds
(several different types of haystacks)
(will all be blended together into a big mess)

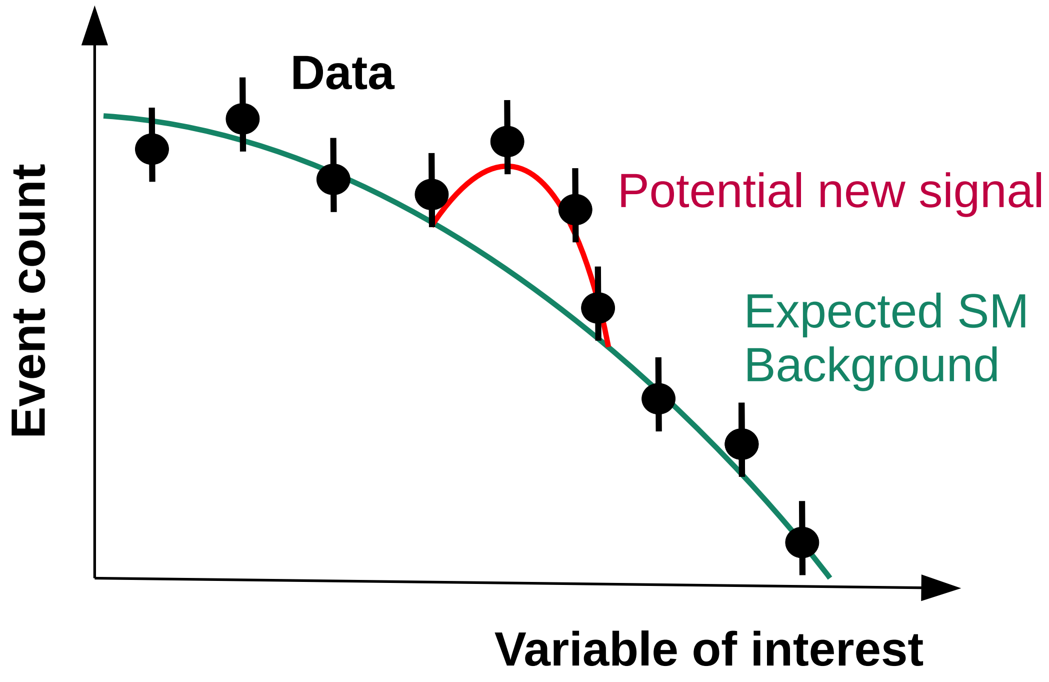
T.G. McCarthy



What type of signal are we looking for?

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

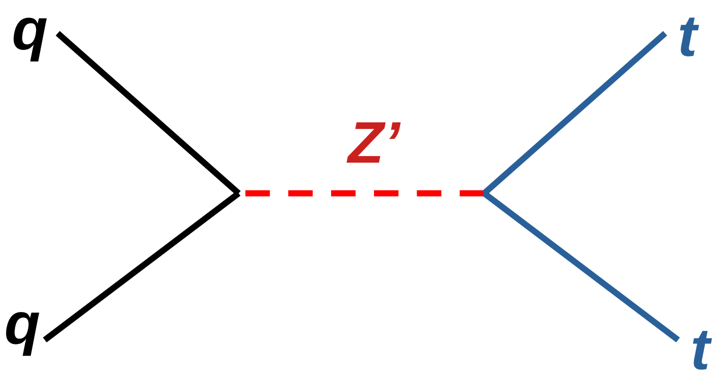
> Different search strategies
  - Cut-and-count method
  - Bump hunt
  - Tail hunt
  - ...

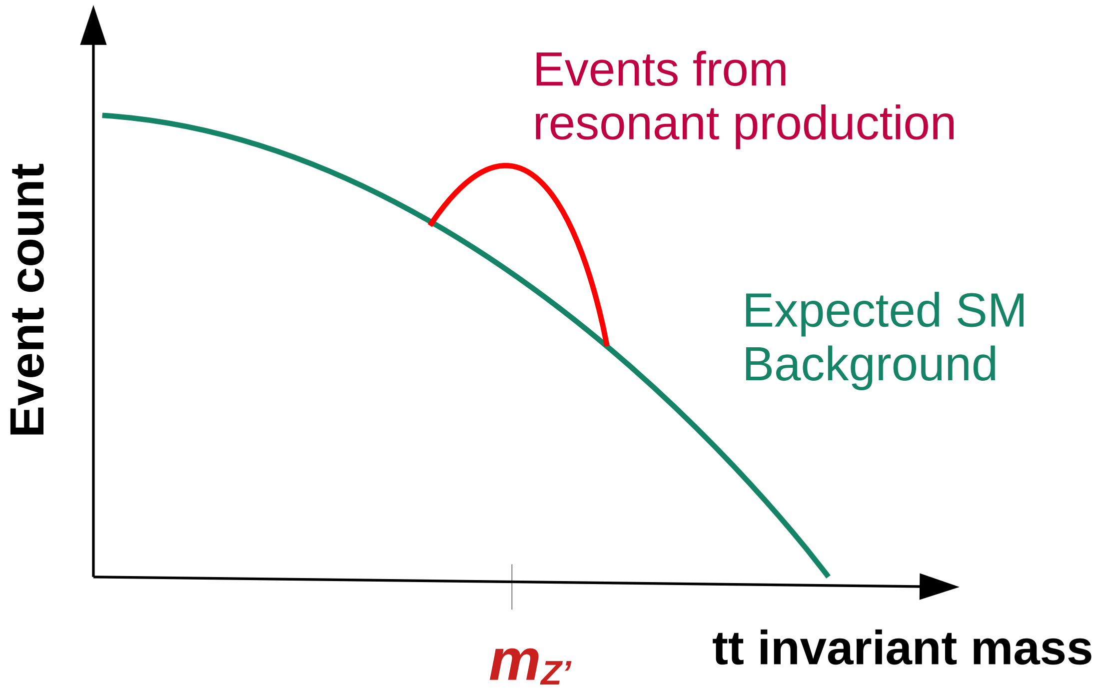


> Each comes with its own set of advantages/disadvantages!

Bump Hunting

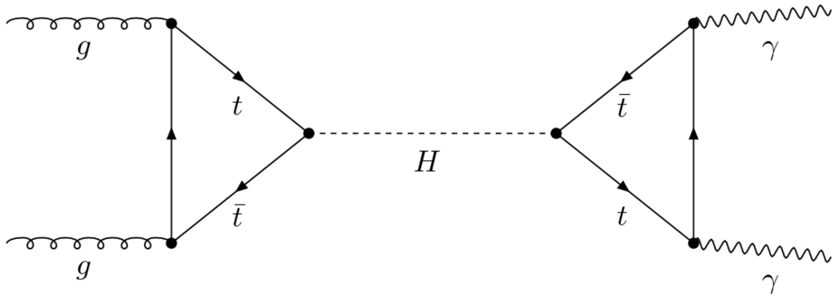
- Search for a localised deviation in the distribution of a variable of interest
  - Typically: invariant mass

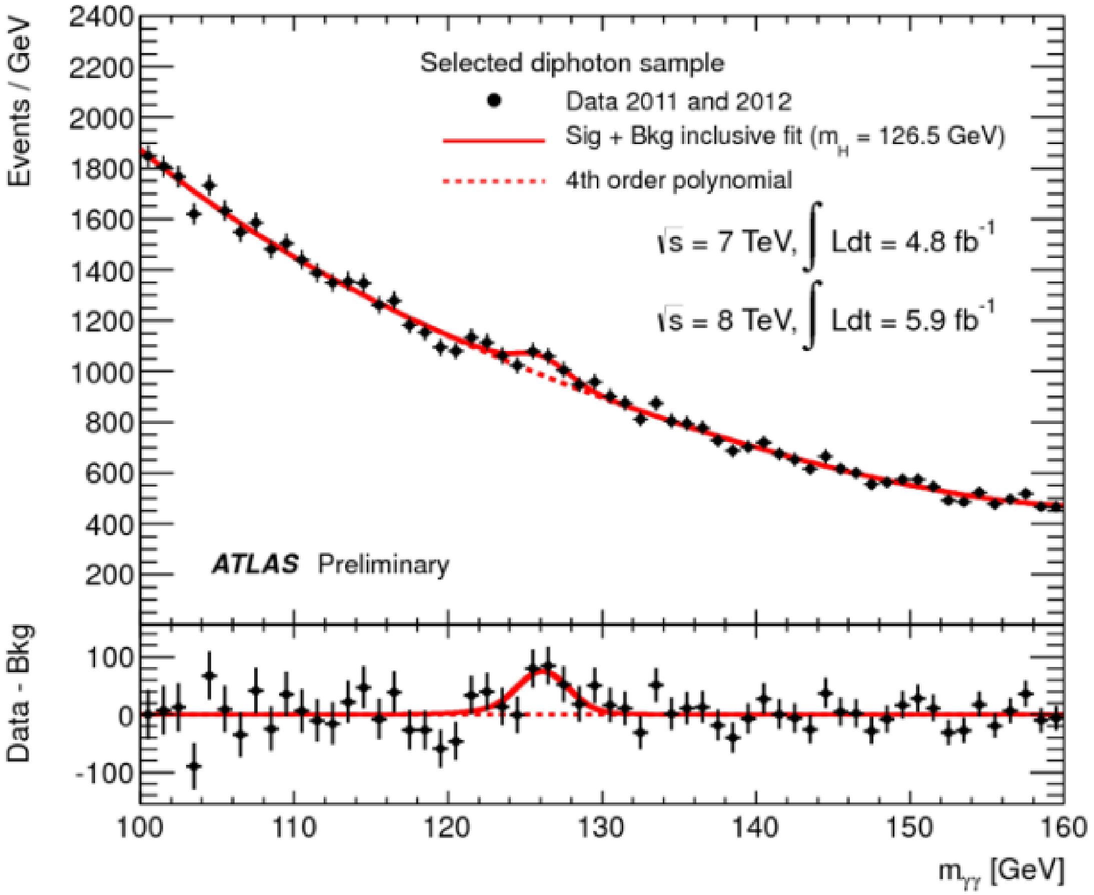




Bump Hunting

- 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)



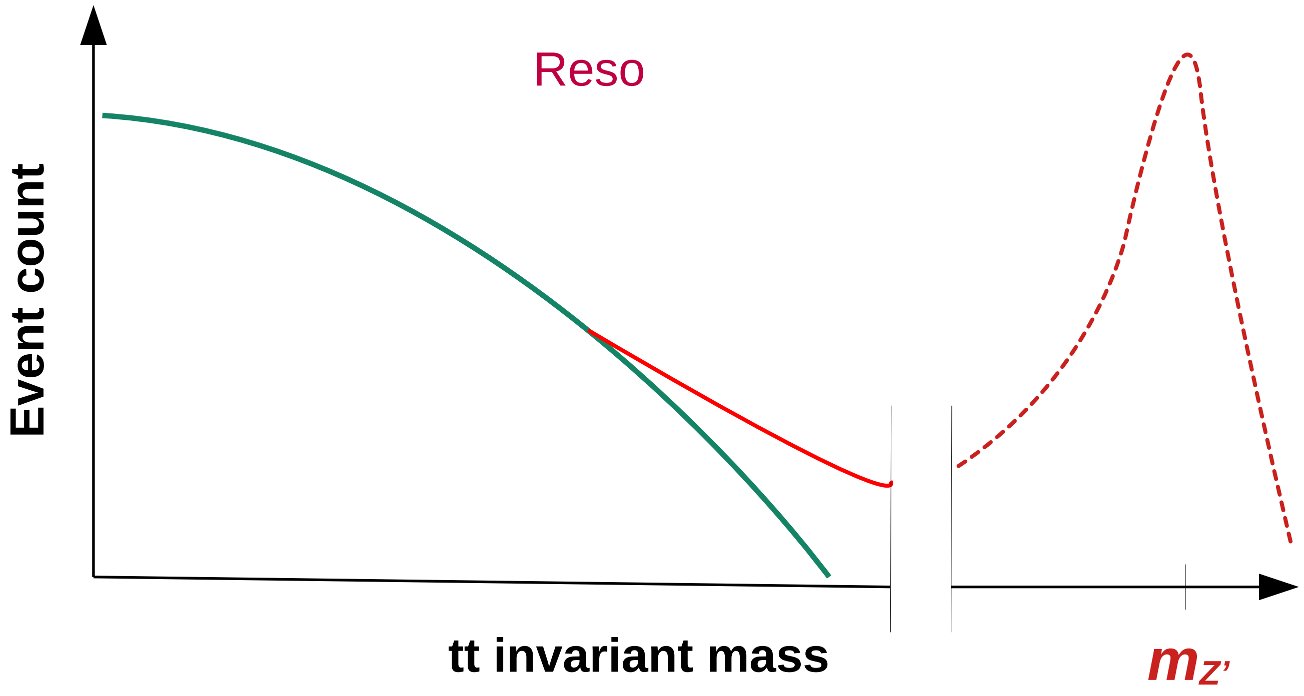


Tail Hunting

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

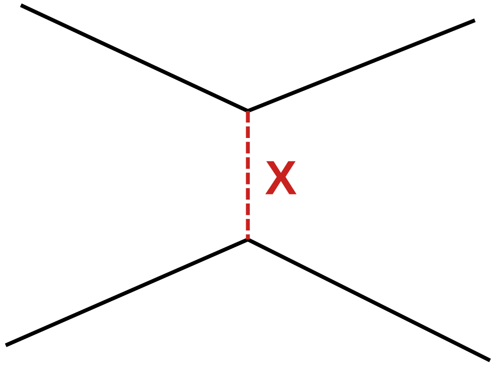
> Typical examples:

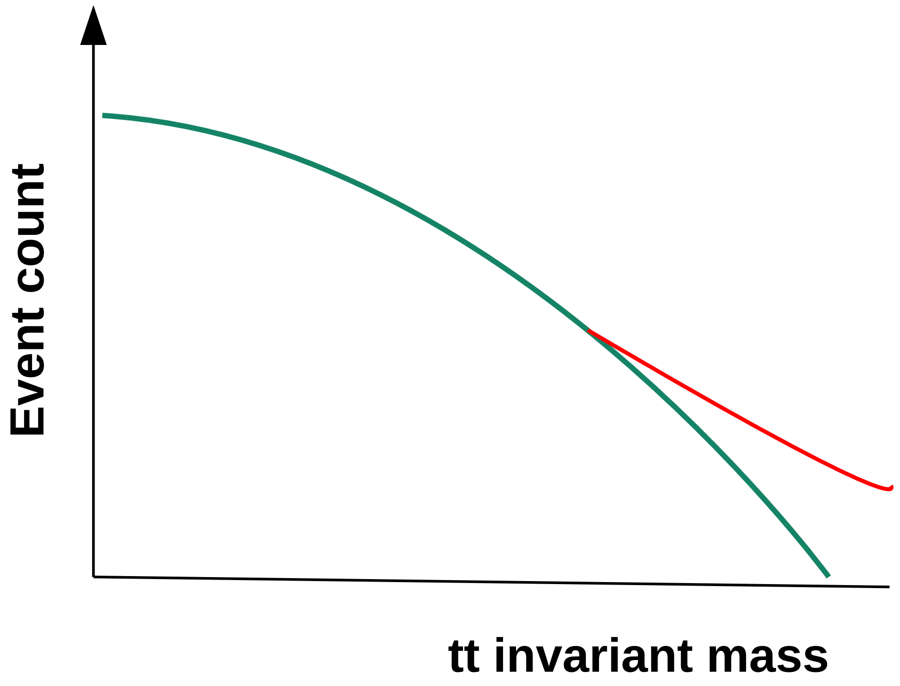
  – Resonances beyond reach of the LHC



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 processes
    (t-channel, radiation, ...)

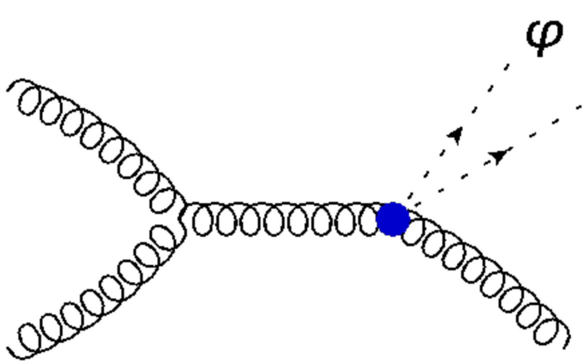




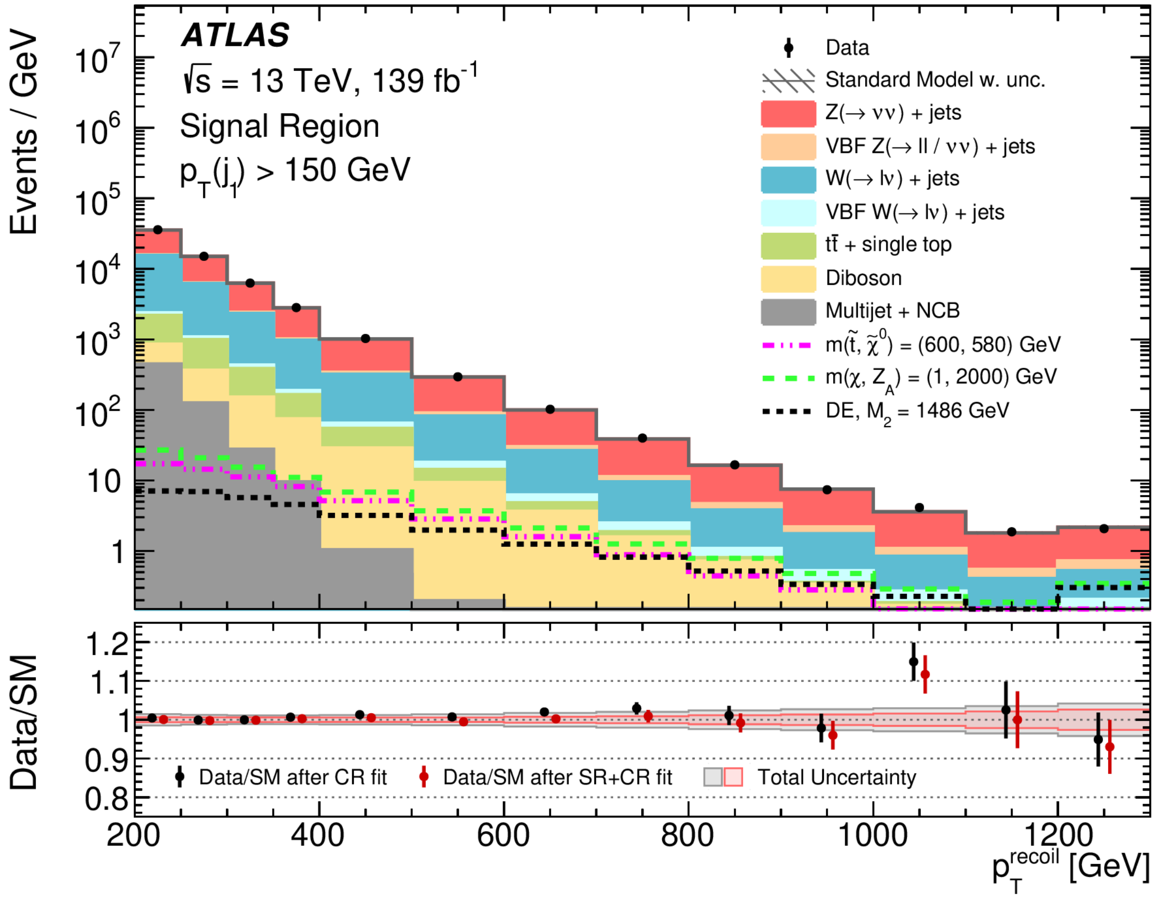
Tail Hunting

- 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

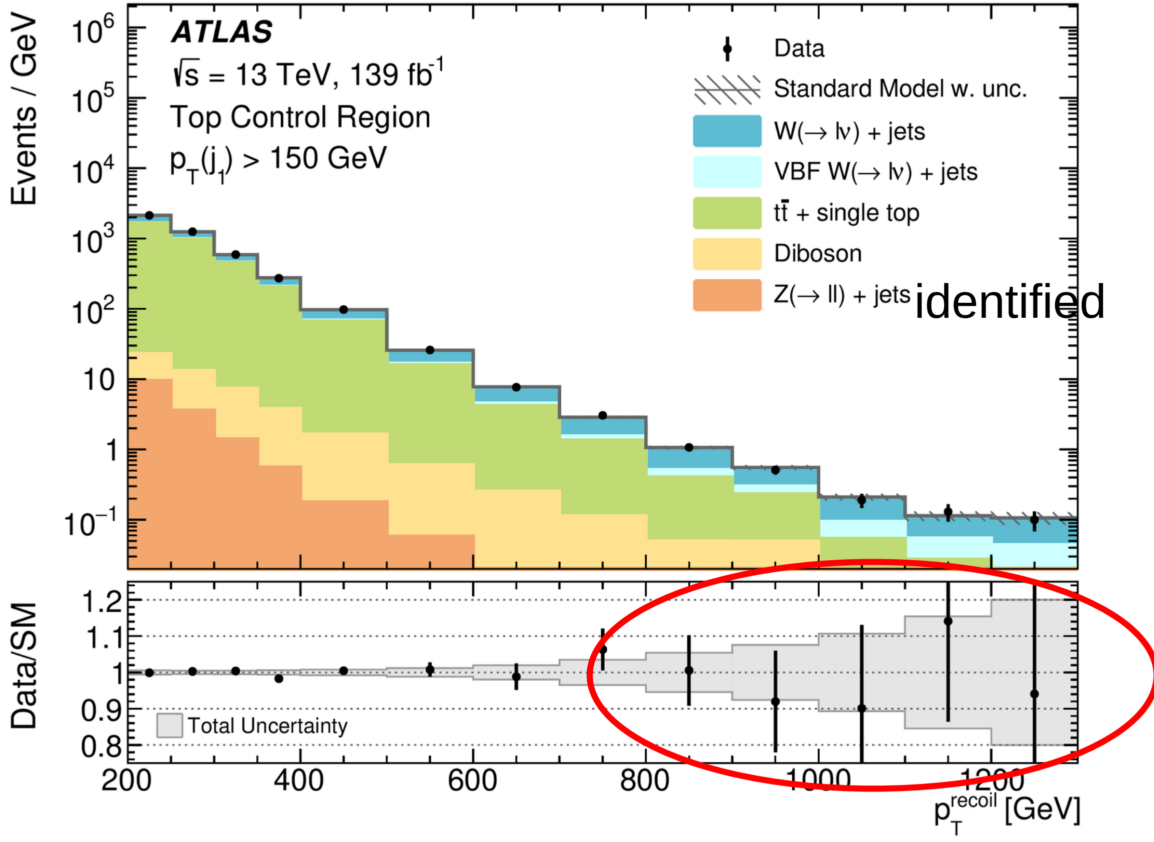


Recoiling gluon, leading to single visible jet



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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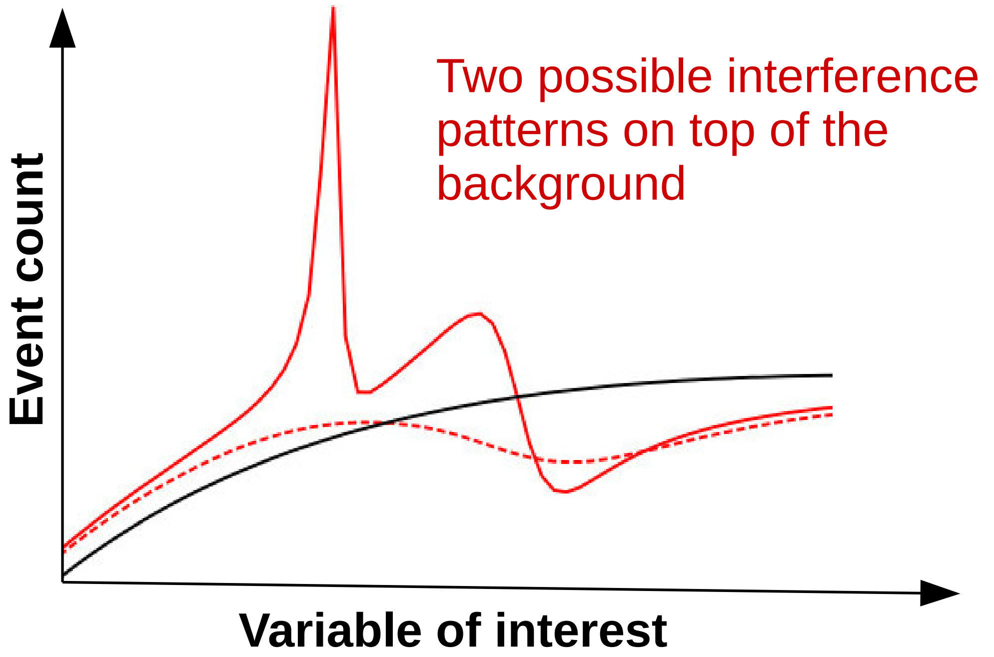
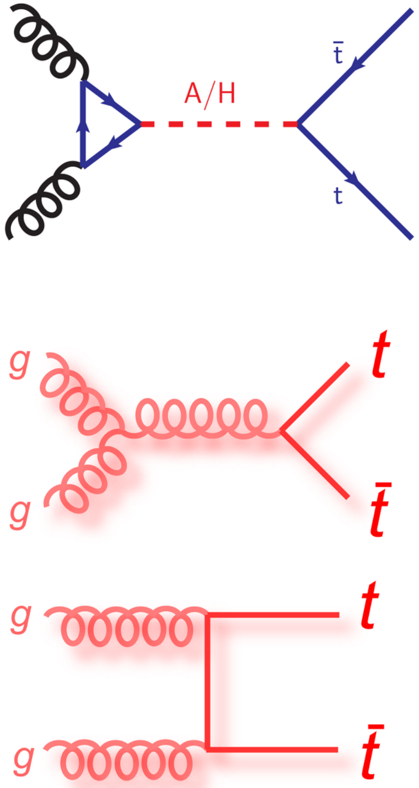
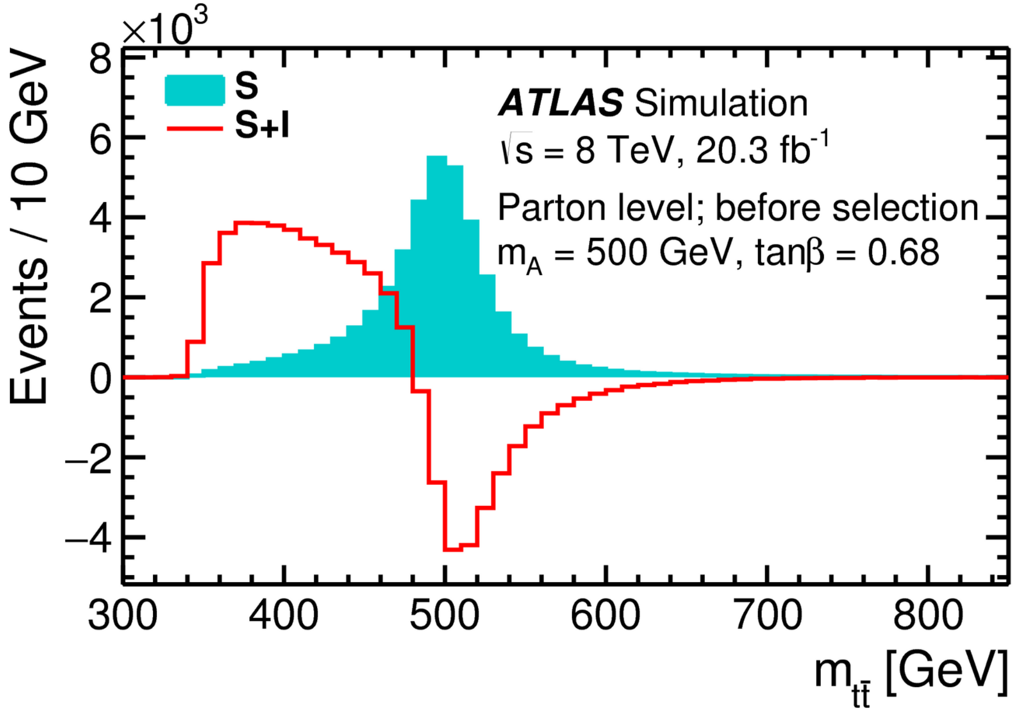


Interference searches

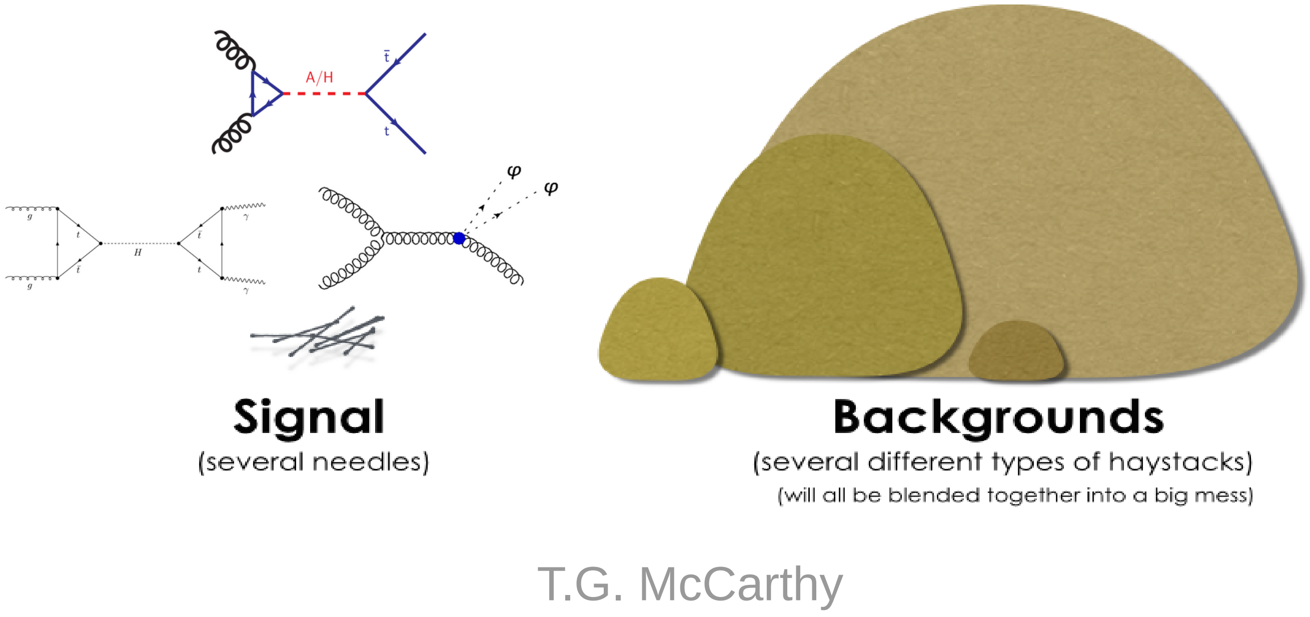
- Prominent example: decay of a heavy Higgs boson A/H to a top-antitop quark pair
- Cutting-edge experimental techniques needed: statistical treatment, high-resolution reconstruction, ...

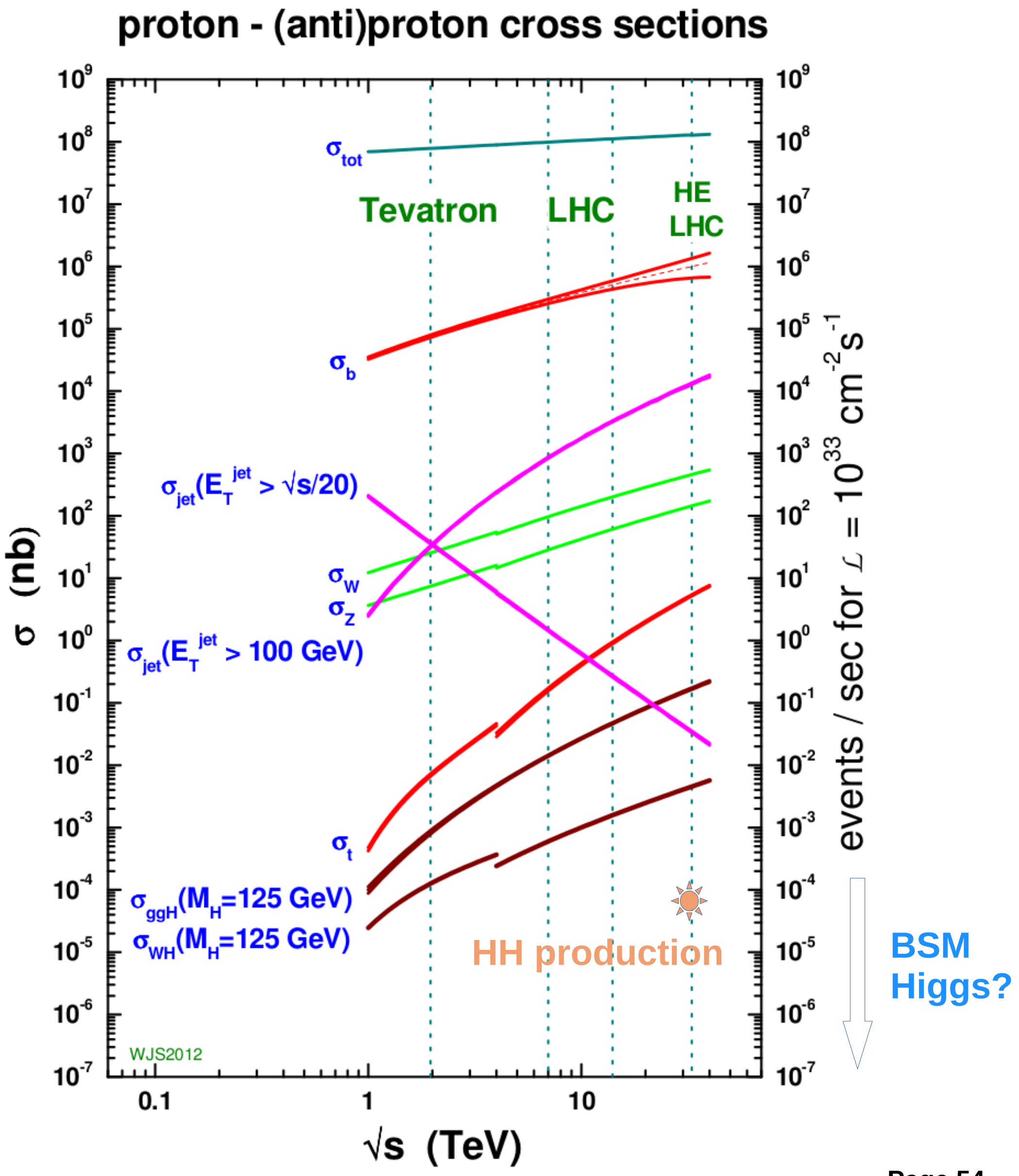




Back to our haystack...

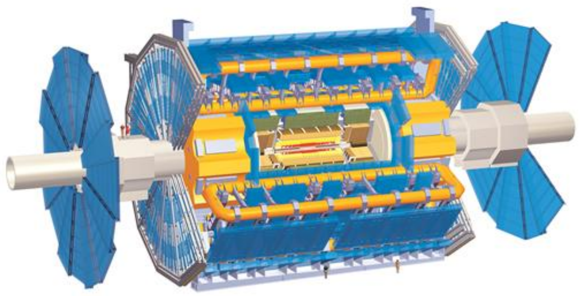
> Need to isolate signal from background, no matter what the signal type

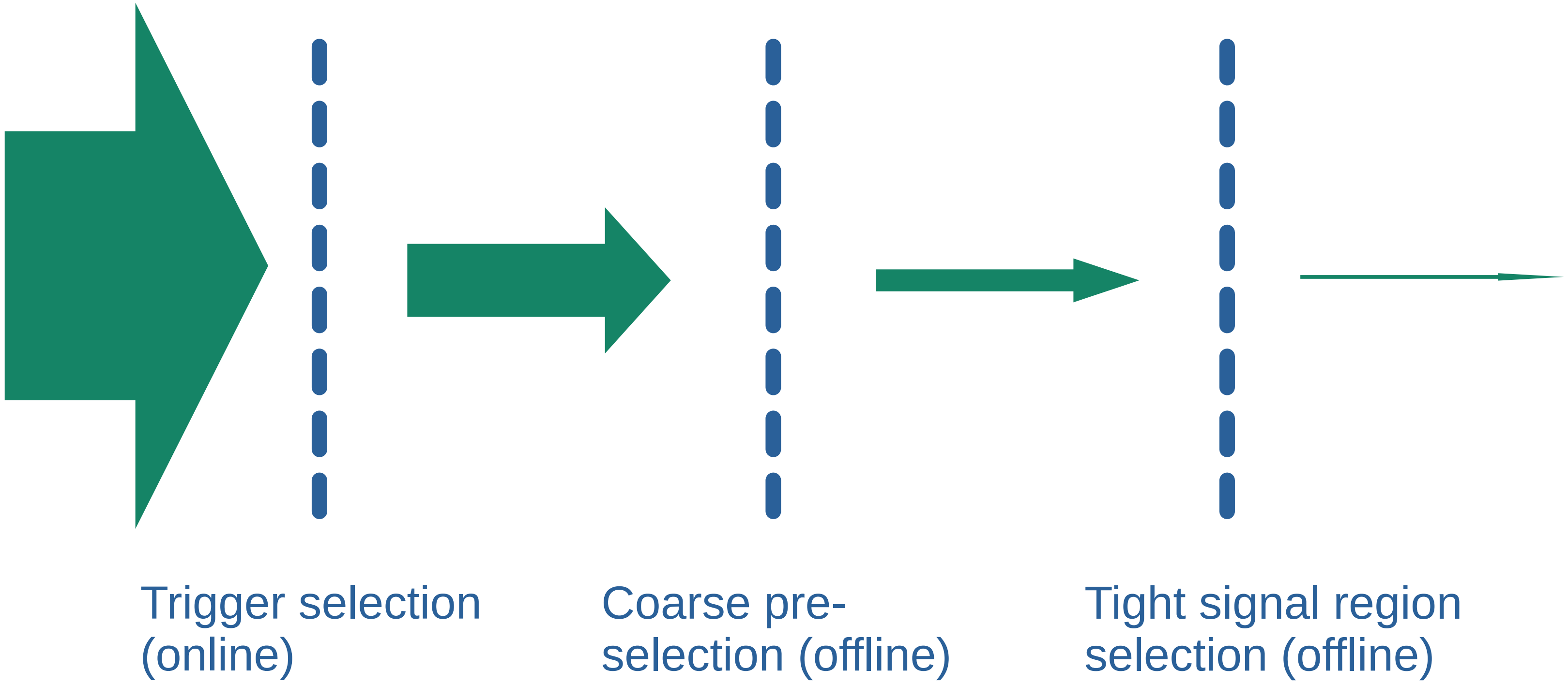




Recipe step 1: collect the data

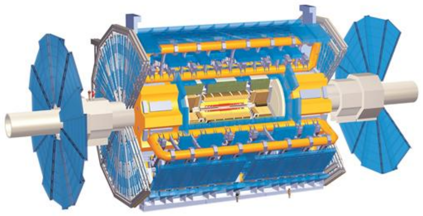
- LHC collision rate: 40 MHz of collision events
- Typical event size (raw detector data): 1.6 MB
- Petabytes of data, most of it not very interesting (known physics, low-energy collisions)





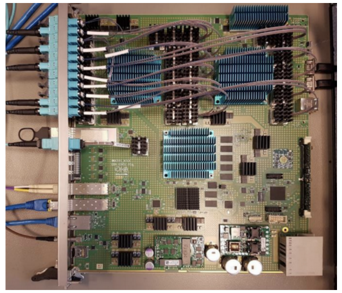
Recipe step 1: collect the data with triggers

LHC collisions



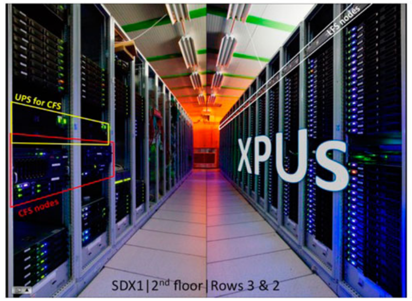
40 MHz

L1 hardware trigger



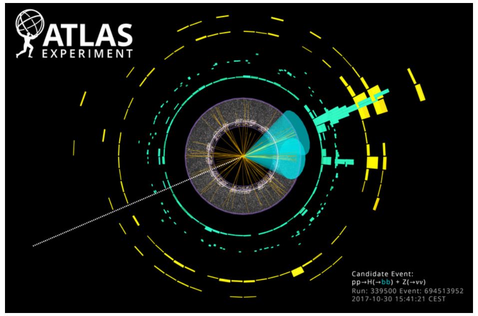
1 kHz

HLT software trigger



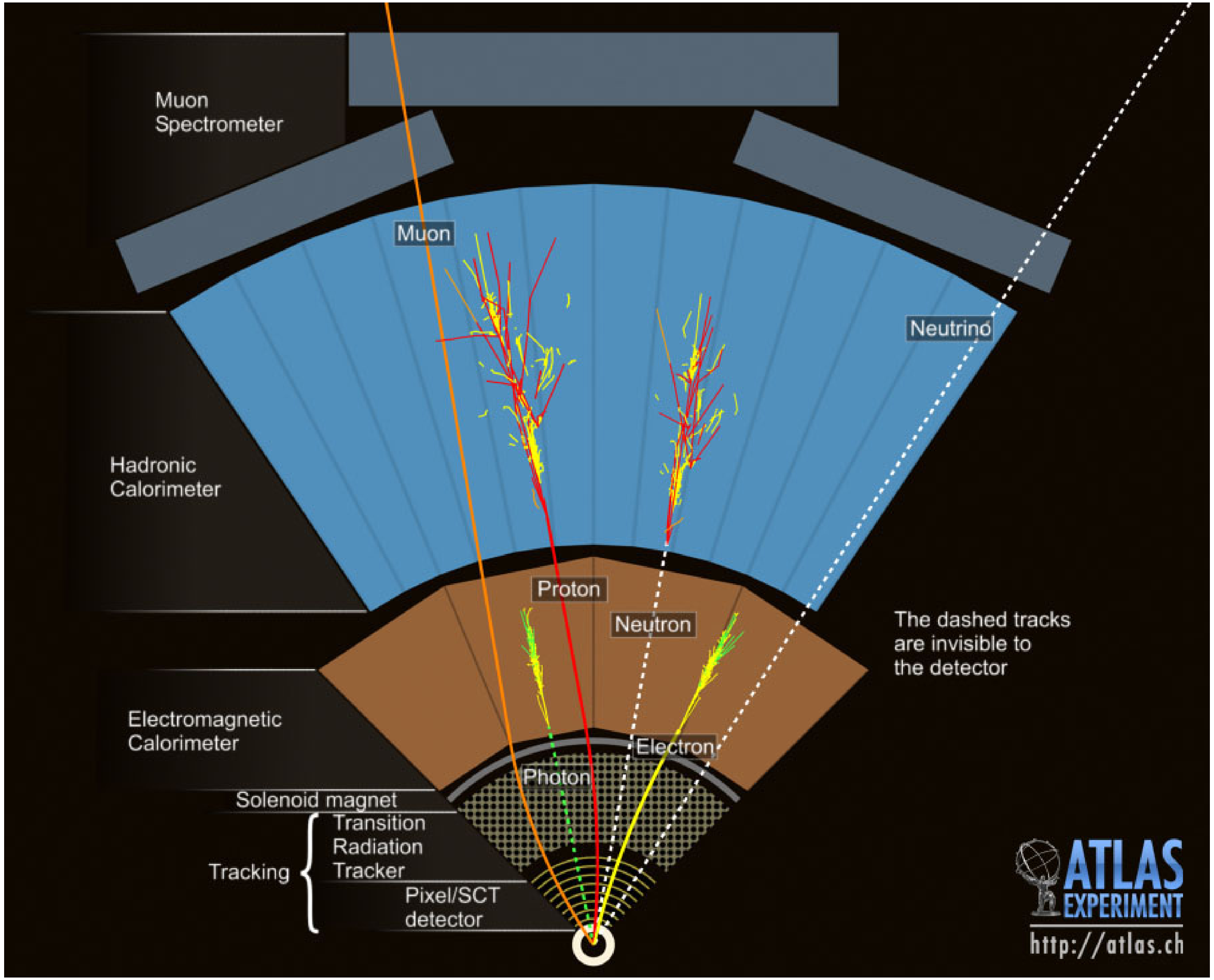
1 kHz

Offline reconstruction and analysis



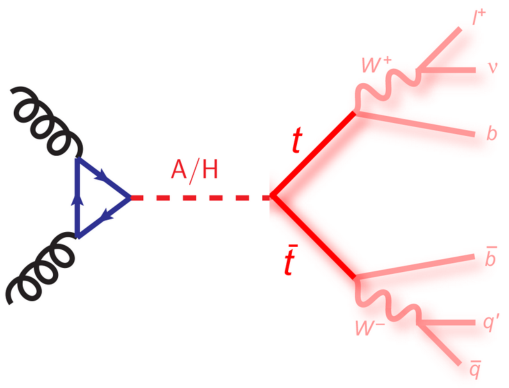
- Triggers = event filters based on fast pattern recognition algorithms
- Both hardware (L1) and software (HLT) based algorithms
- HLT algorithms a slightly simplified version of full offline reconstruction algorithms
- Both standard triggers (e.g. single-electron triggers) and triggers optimised for unusual signature.
- Careful optimisation of trigger algorithms crucial: If you don't trigger on a signature, its events are lost!

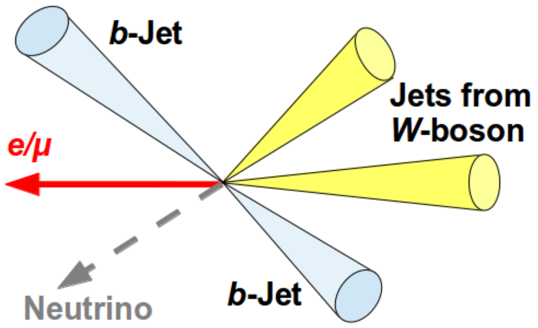
Recipe step 2: reconstruct and identify the particles

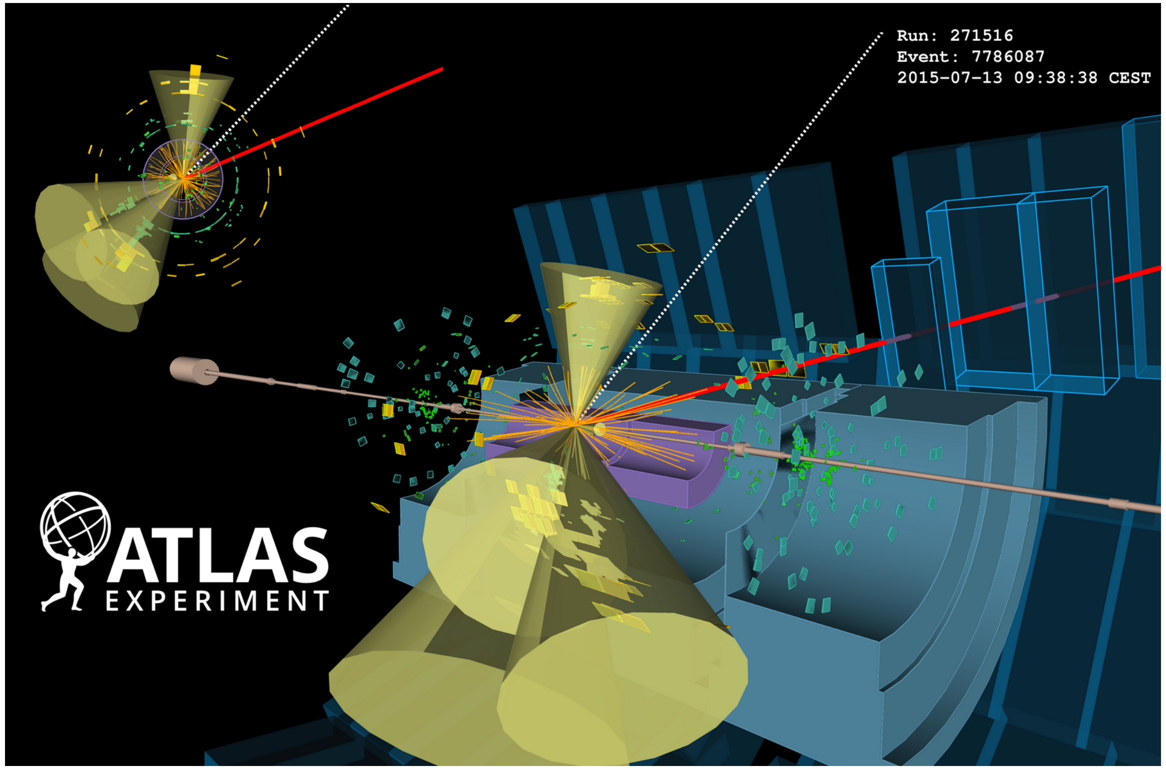


Recipe step 2: reconstruct and identify the particles

> Example: top-antitop quark production with one hadronic, one leptonic top-quark decay

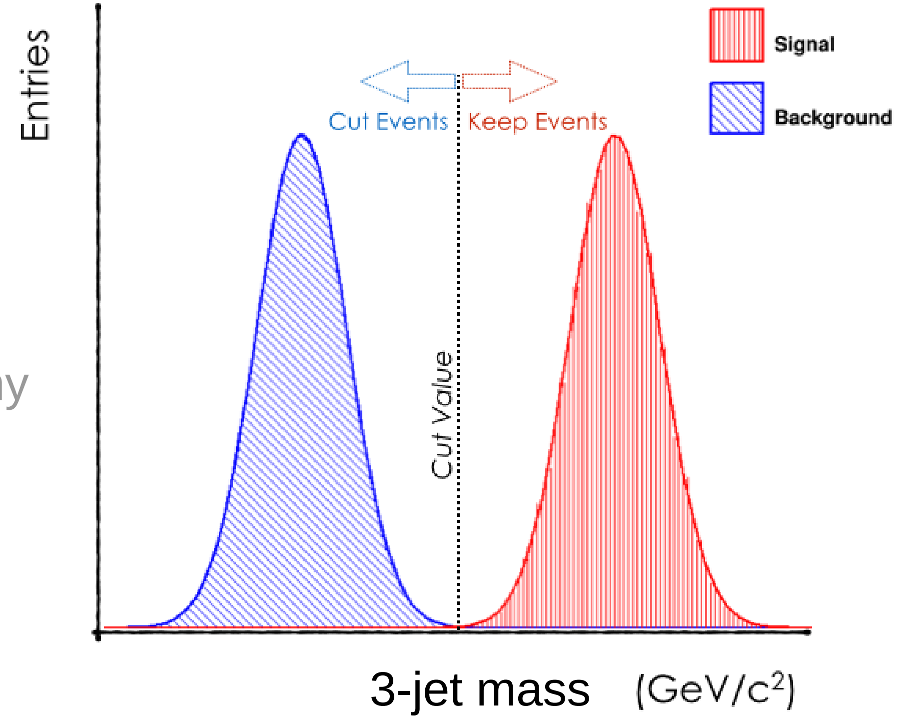






Recipe step 3: define selection criteria

- 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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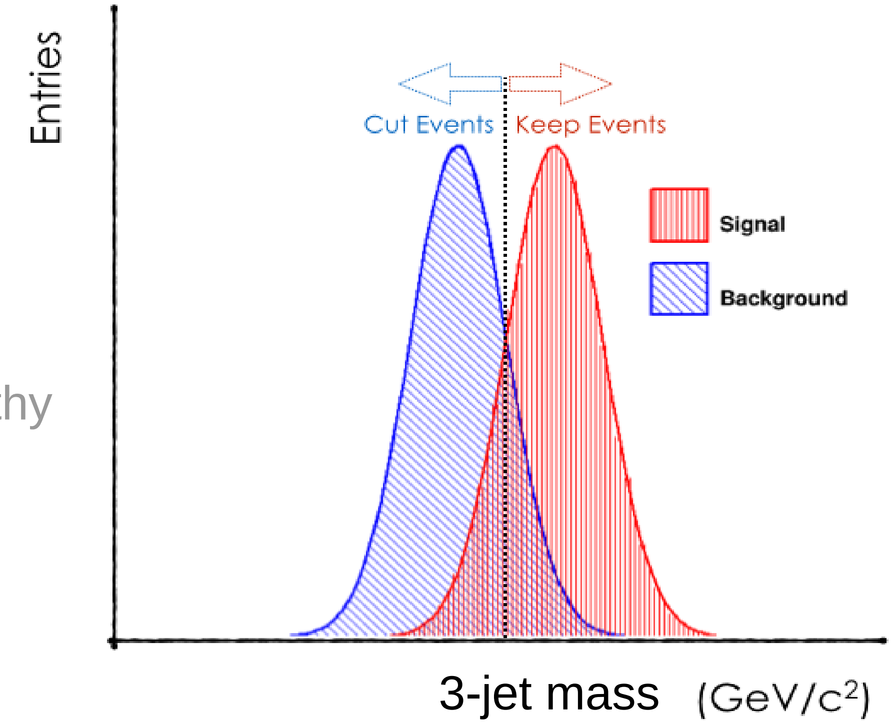
T.G. McCarthy



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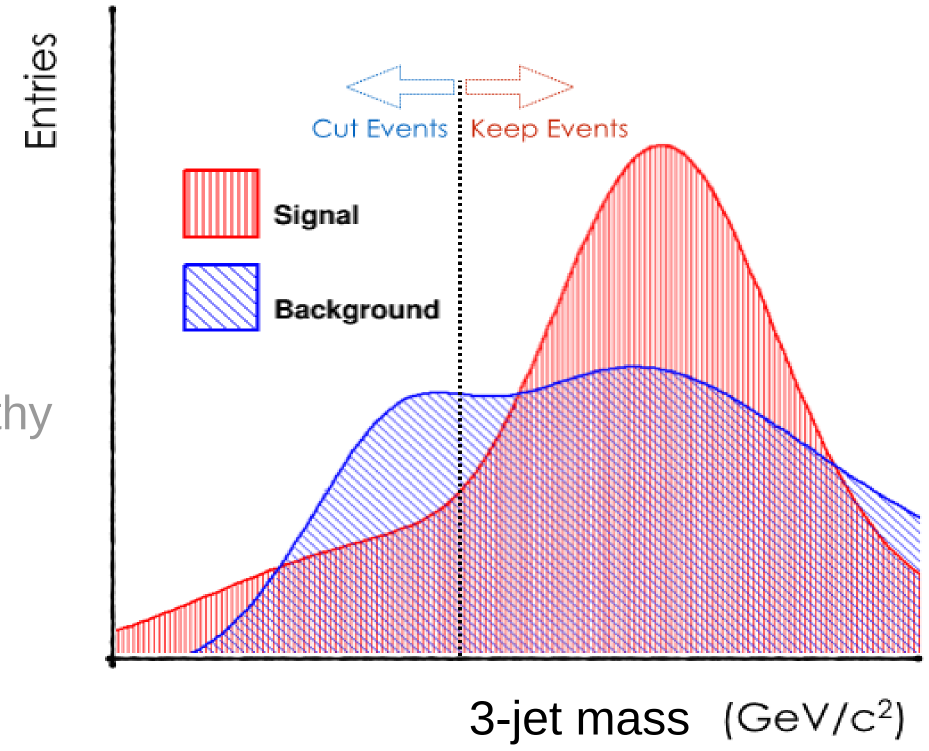

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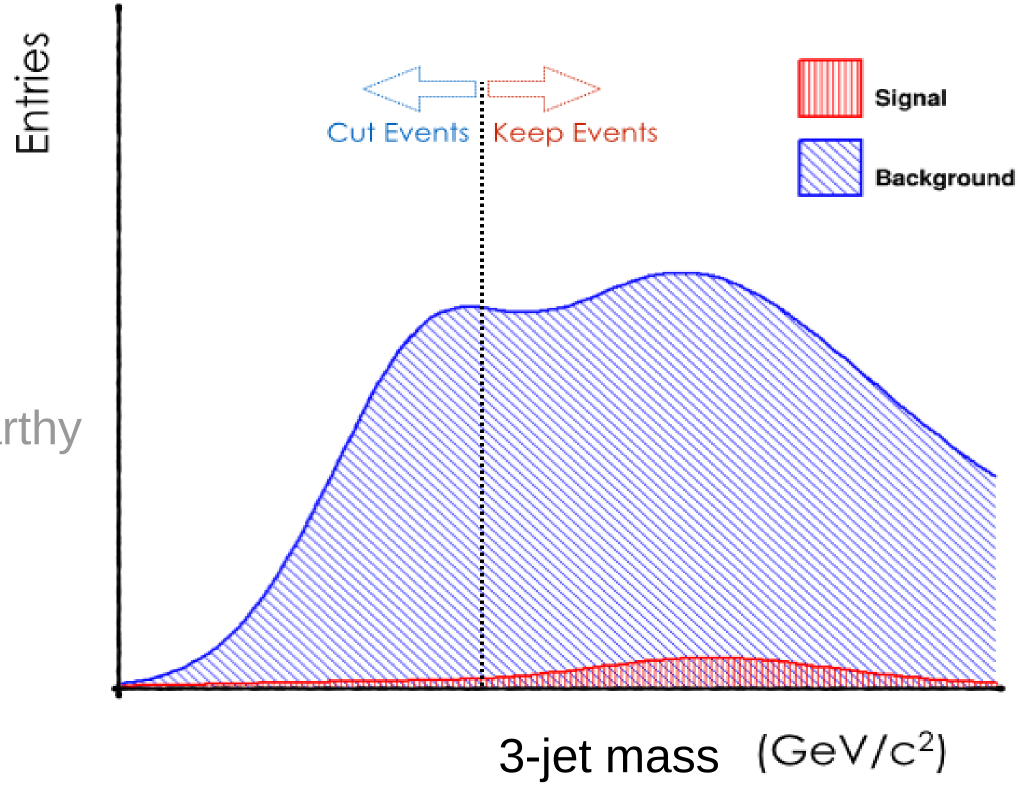

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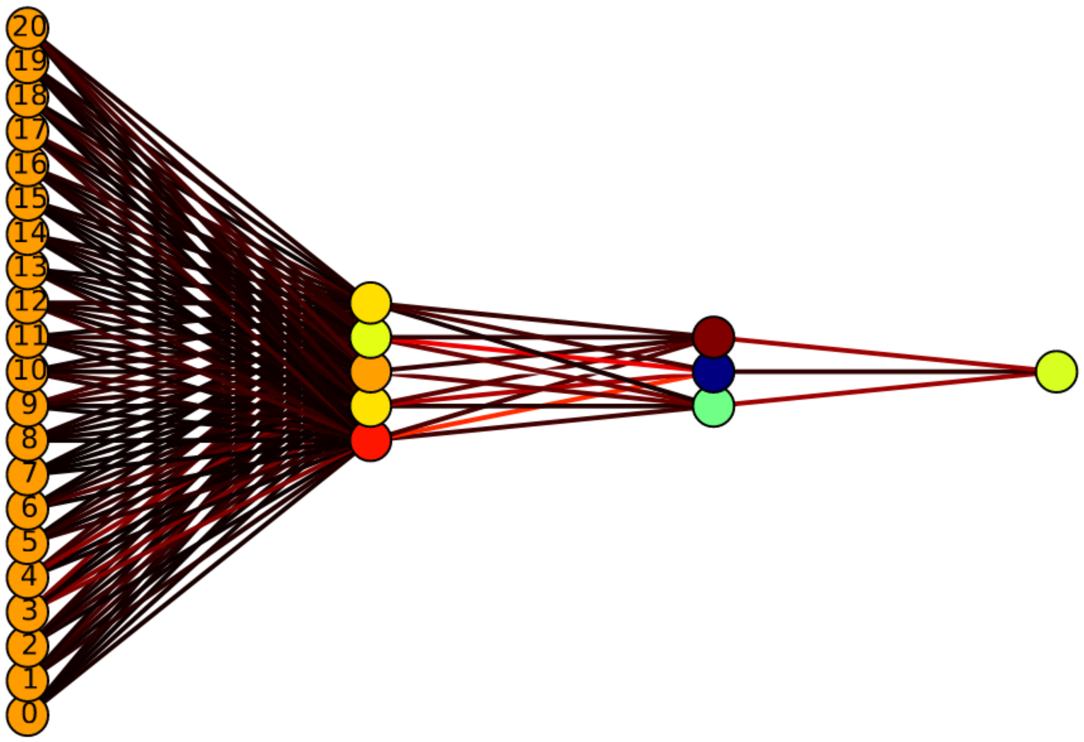
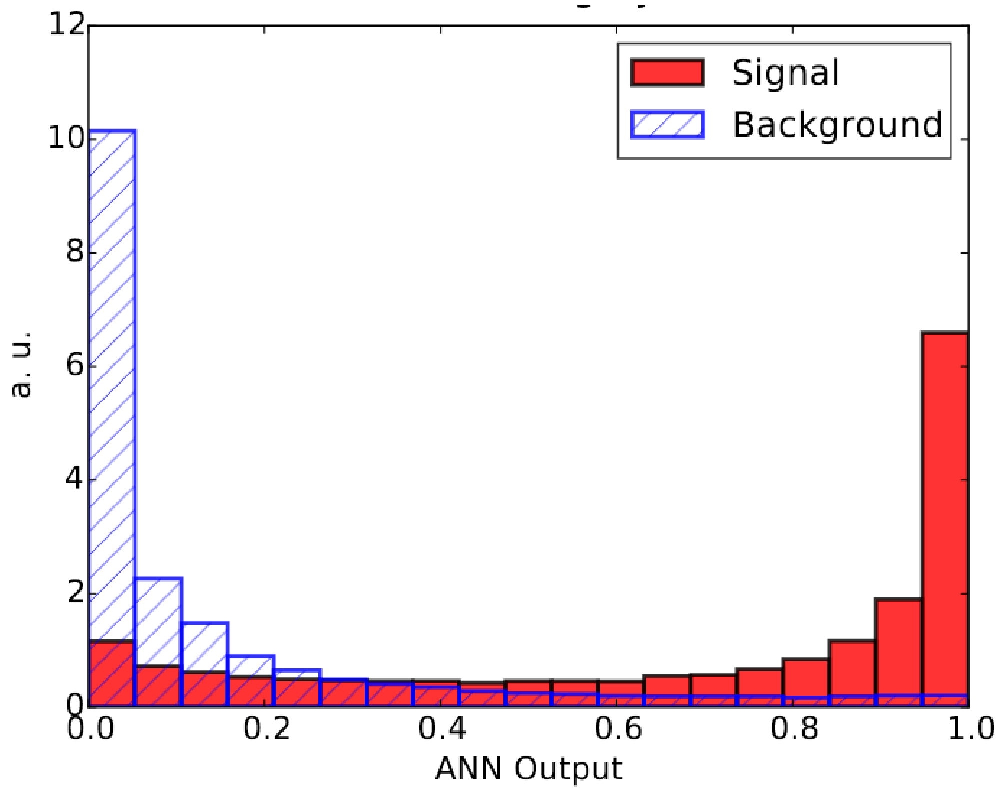
Recipe step 3: define selection criteria

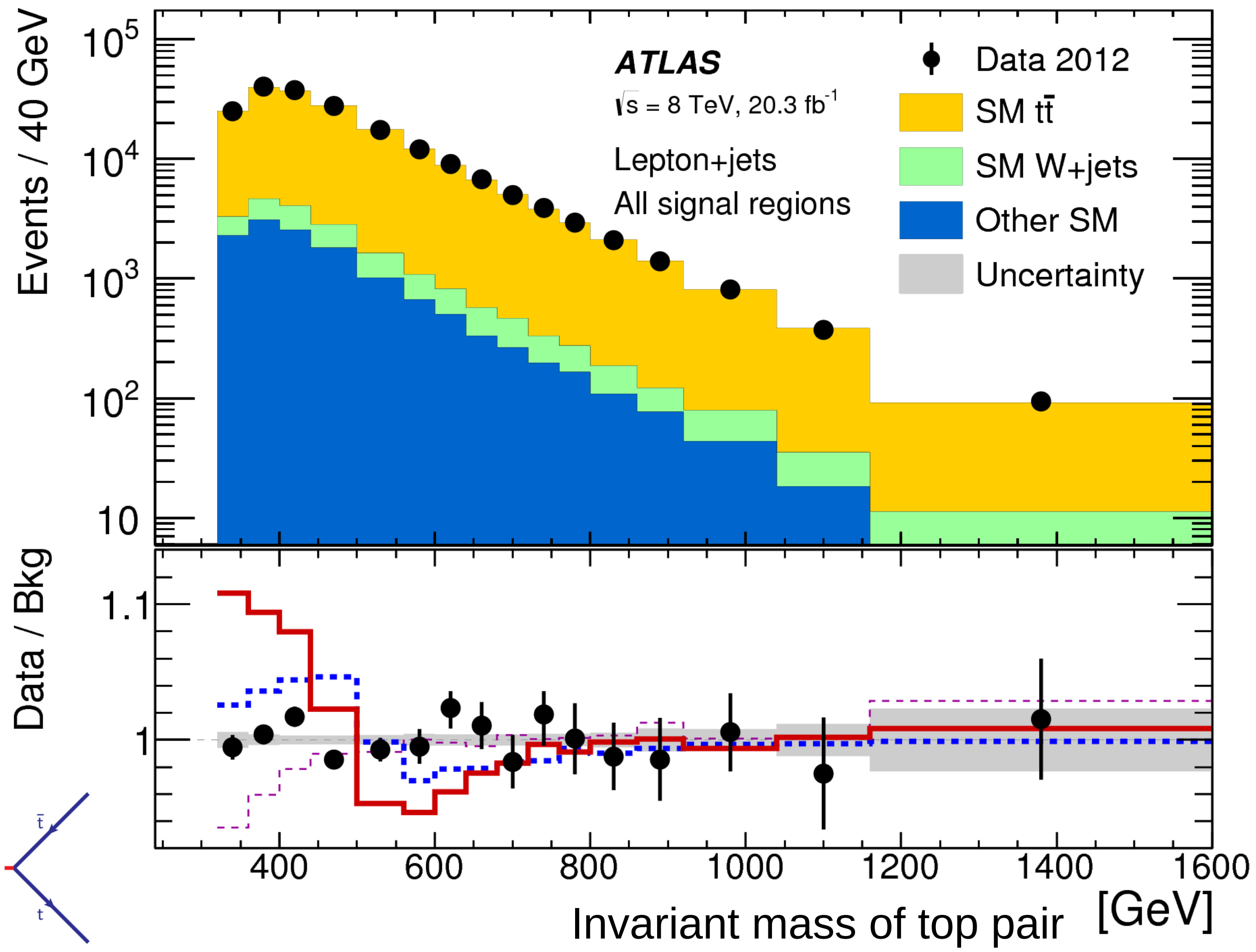
> Can refine signal regions using machine-learning algorithms
  - Exploit small differences in various kinematic variables
  - Exploit correlations between variables

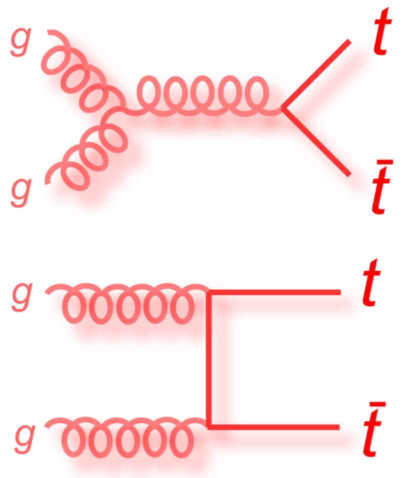
See Gregor's ML lectures

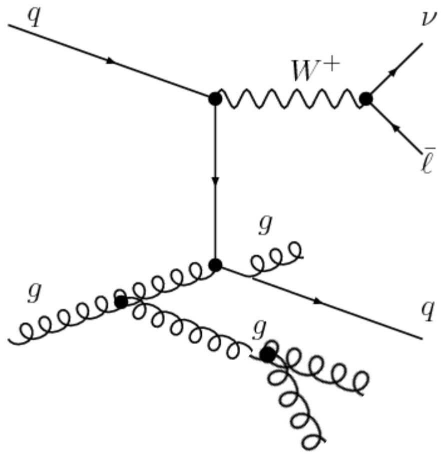


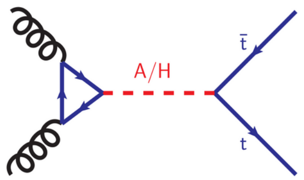


A final signal region





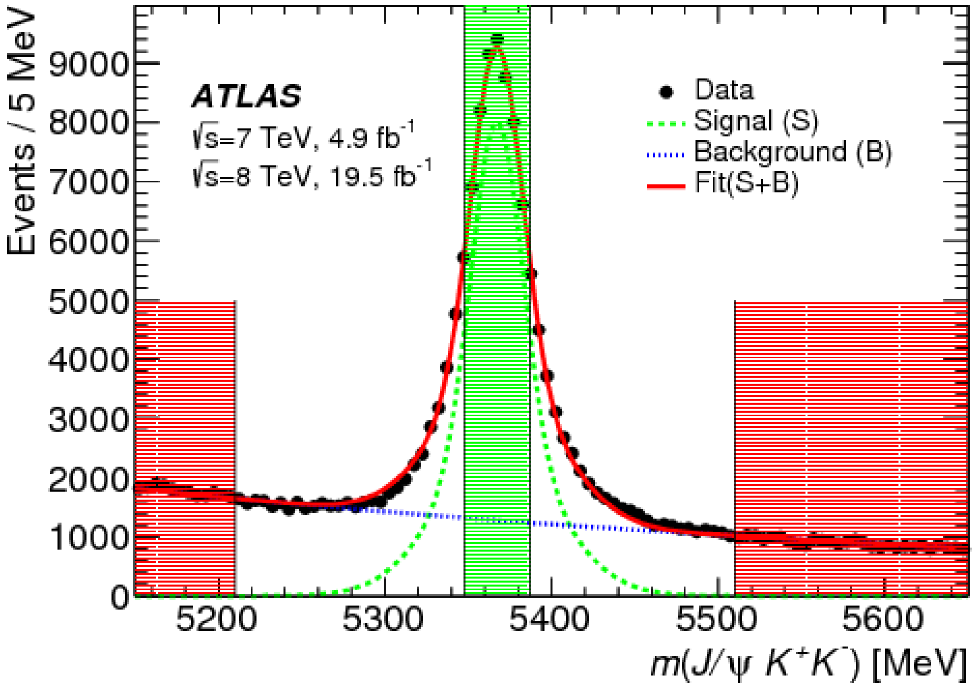




Recipe step 4: estimate backgrounds

> Monte Carlo simulation is one option for well-known (=calculated) processes
  - Check validity in signal-depleted control regions and derive corrections if needed

> Data-driven estimates needed in some cases
  – 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
    - …

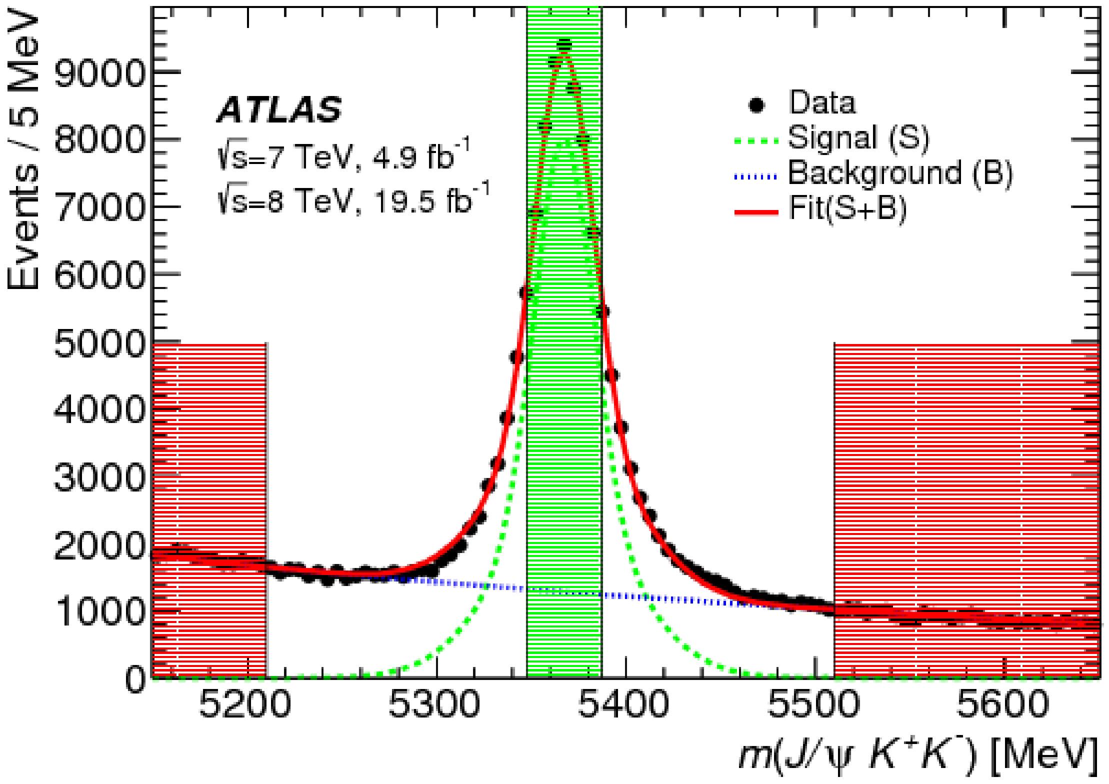


Recipe step 4: sidebands

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

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

> Extrapolate to signal region

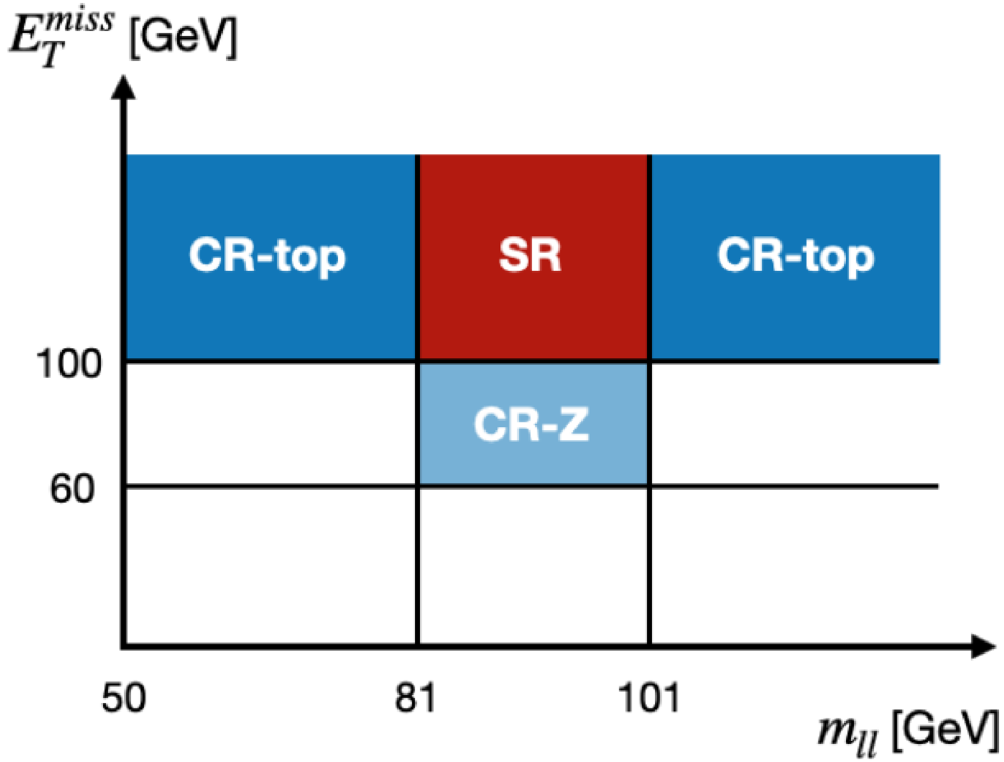


Recipe step 4: control regions

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

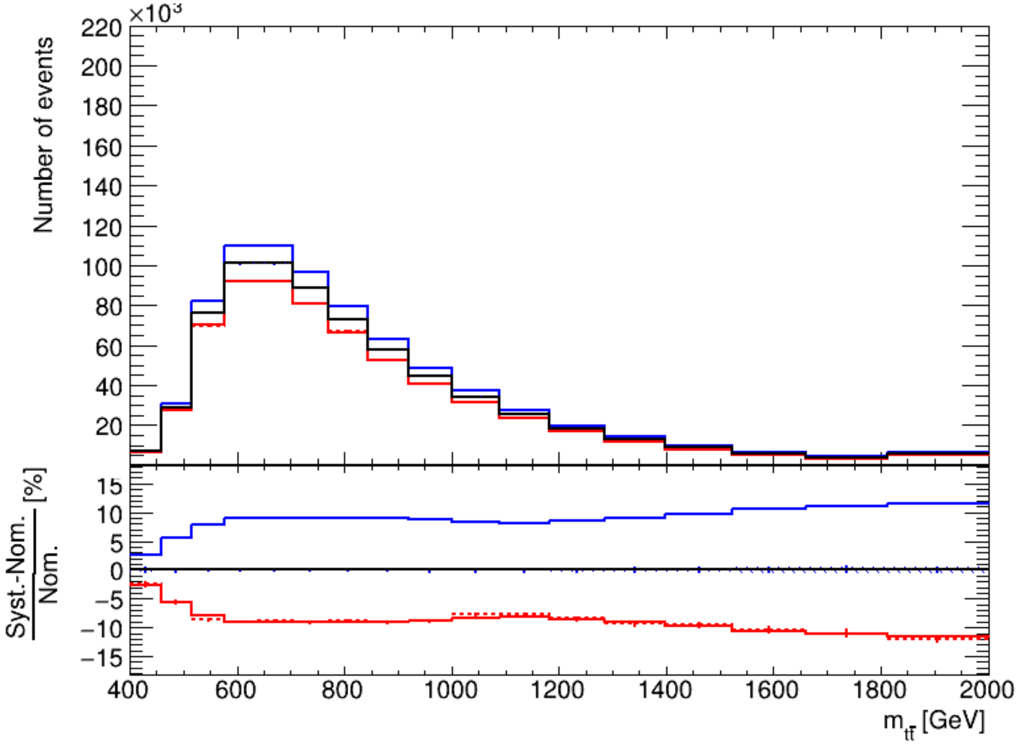
- Must be carefully designed to
  - Be signal depleted
  - Be enriched in background of interest
  - Close enough to SR to avoid biases
  - ...

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



Recipe step 5: estimate systematic uncertainties

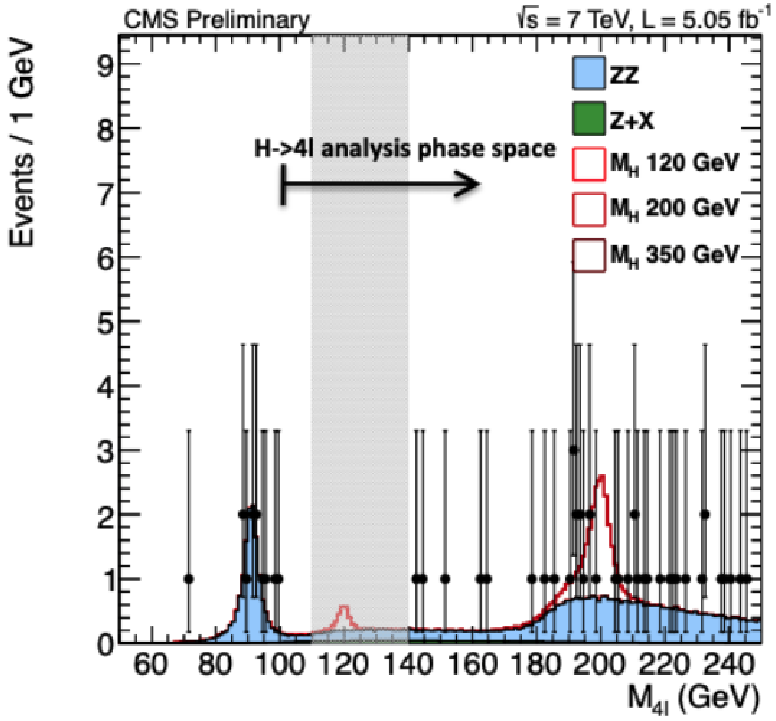
- Various different sources:
  - Modeling uncertainties, e.g. unknown higher-order corrections
  - Experimental uncertainties, e.g. uncertainties on electron energy measurement
- Propagate to final spectrum
- Uncertainties degrade sensitivity to signal



Recipe step 6: unblind

> Signal region(s) blinded until analysis strategy finalised

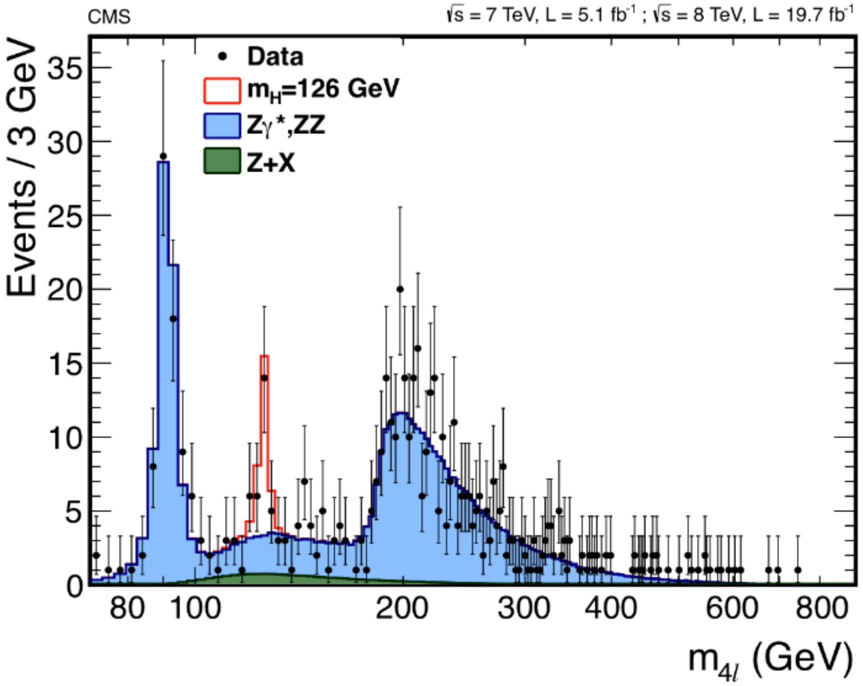
- That is: not allowed to look at the data in the signal regions
- Optimise strategy based on MC simulation and control region data only



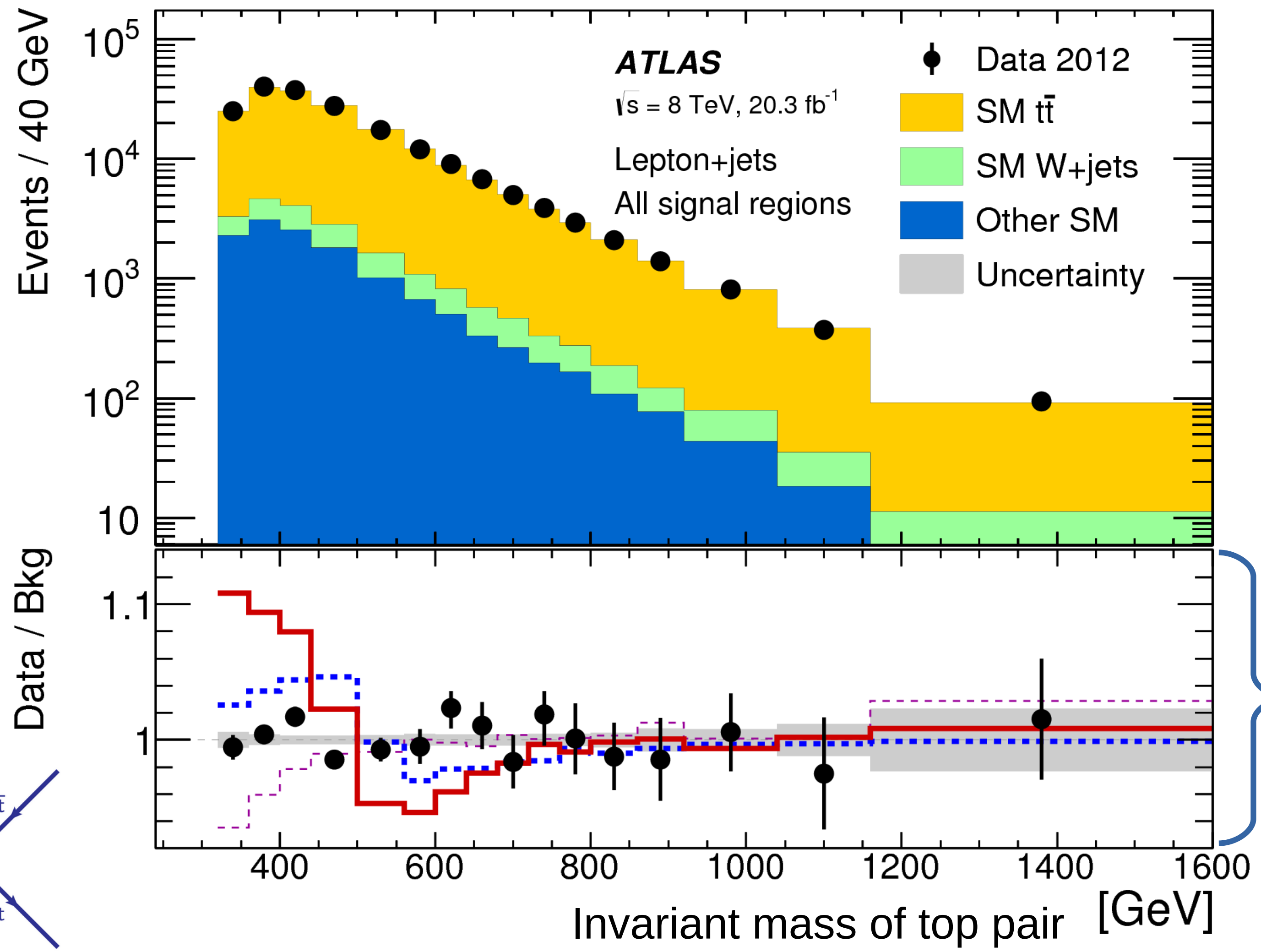
Recipe step 6: unblind

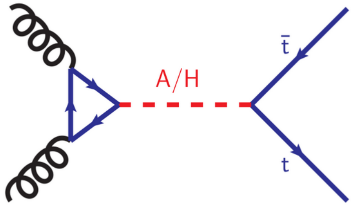
> Signal region(s) blinded until analysis strategy finalised
  - That is: not allowed to look at the data in the signal regions
  - Optimise strategy based on MC simulation and control region data only

> Unblind once strategy is solid and “frozen”



A final signal region



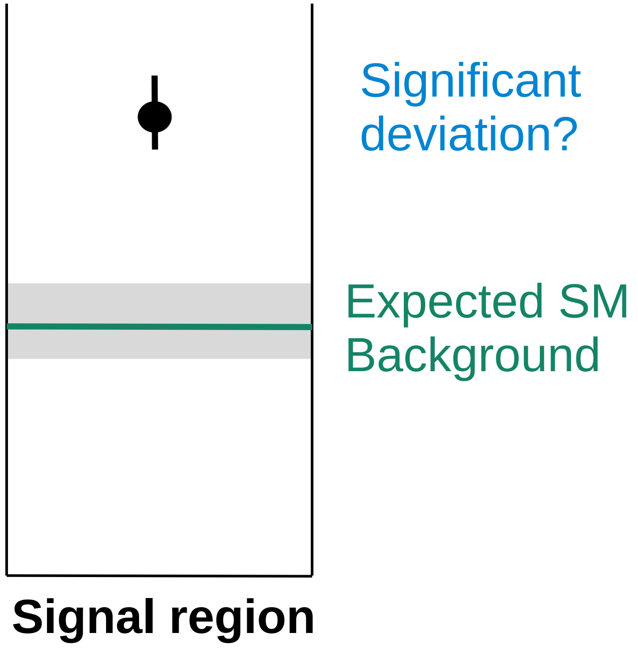


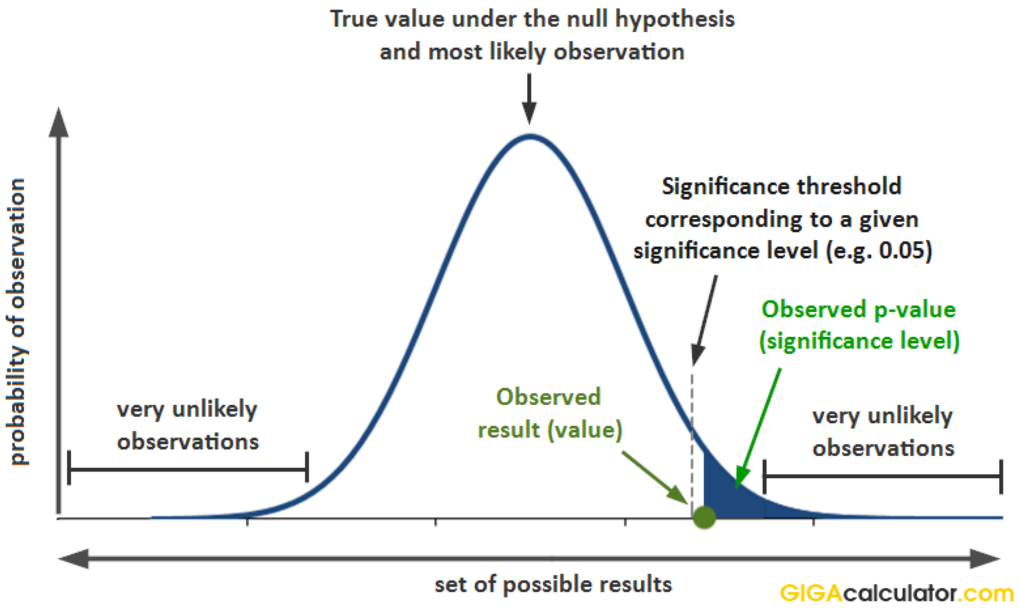
Need to quantify agreement between data and SM prediction

Recipe step 7: statistical data analysis

> Two consecutive statistical tests in BSM searches:
  - Quantify agreement between data and SM prediction (*"Any interesting deviation?"*)
  - Quantify (dis)agreement between data and BSM hypothesis (*"limit setting"*)

> Based on profile likelihood fit of SM prediction to data (prediction can vary within uncertainties)



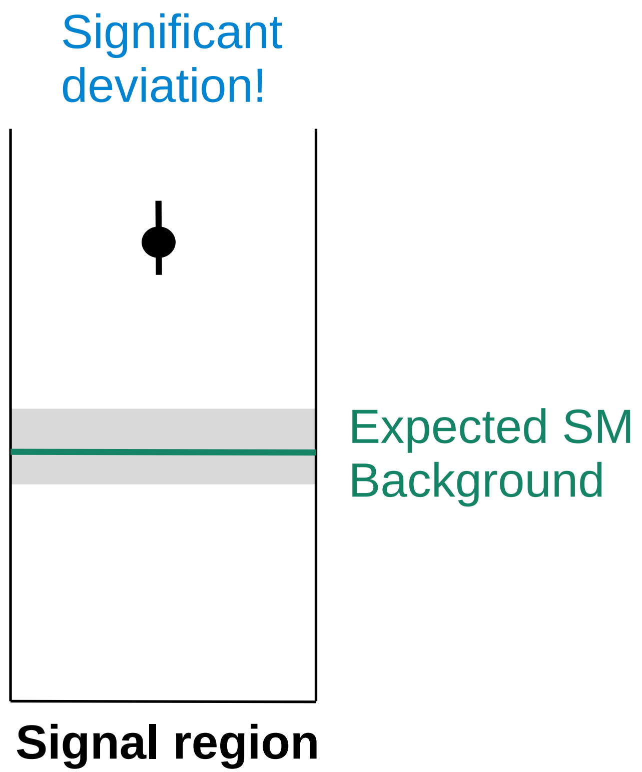


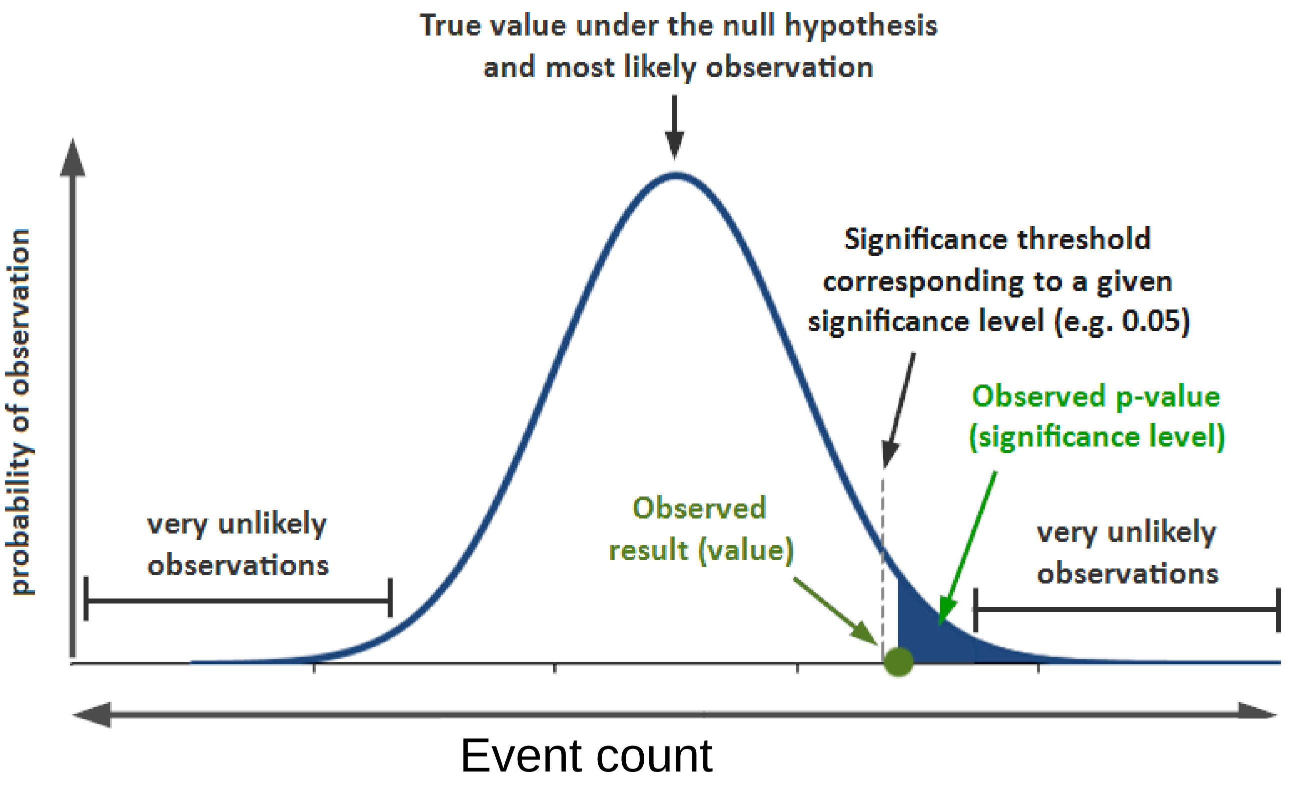
Quantify agreement with SM prediction

> 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





Quantify agreement with SM prediction

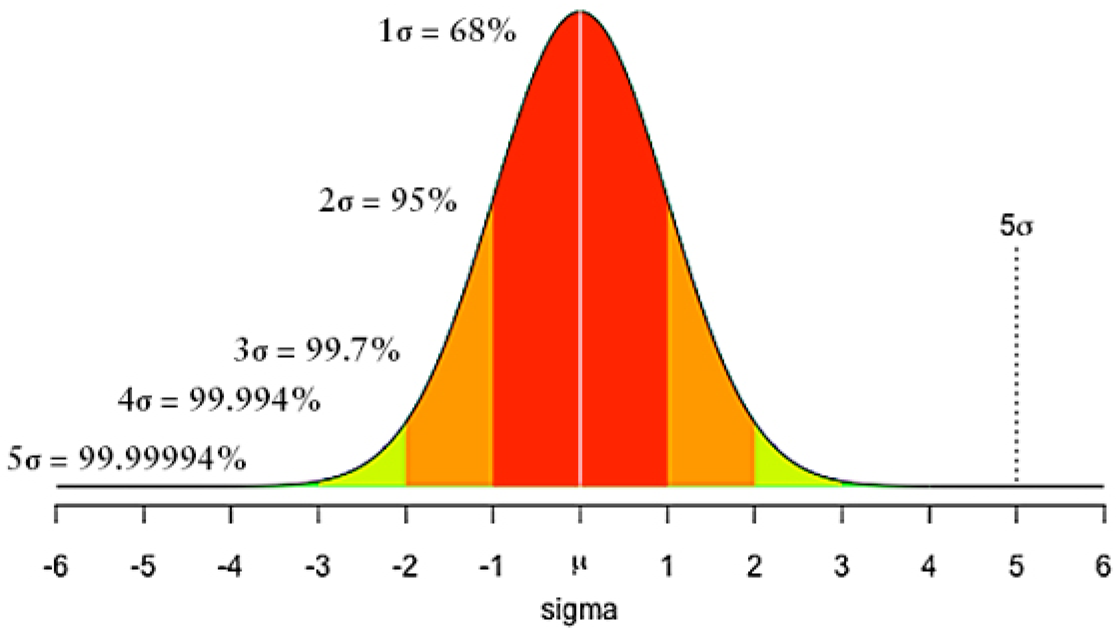
> Null hypothesis H_0: SM only, no BSM

> **p-value**: probability that H_0 produces deviation at least as extreme as the one observed

> Or quote **significance** instead:

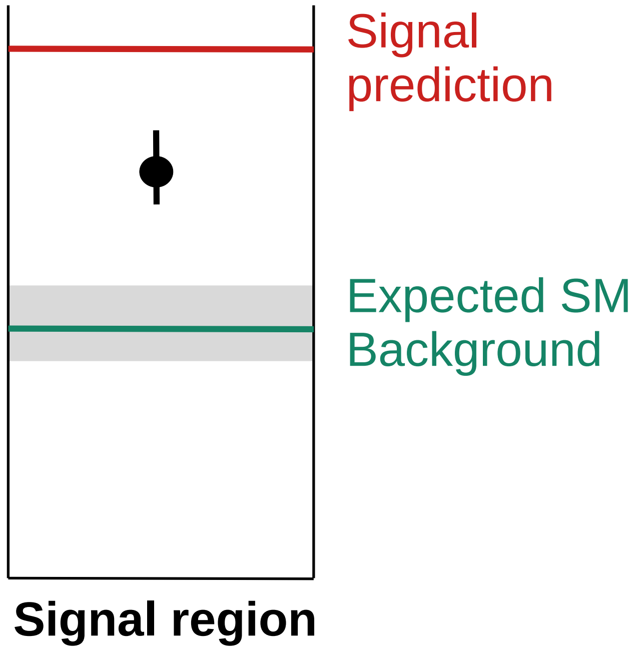
$$\boxed{Z = \Phi^{-1}(1 - p),}$$

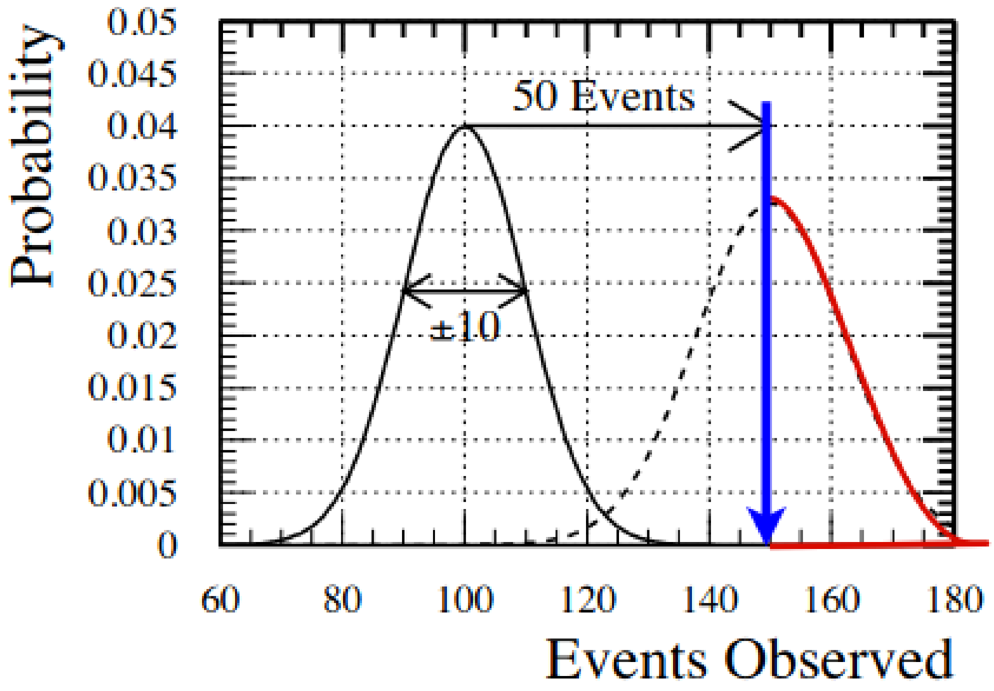
> where Φ^{-1} is inverse of cumulative Gaussian



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)

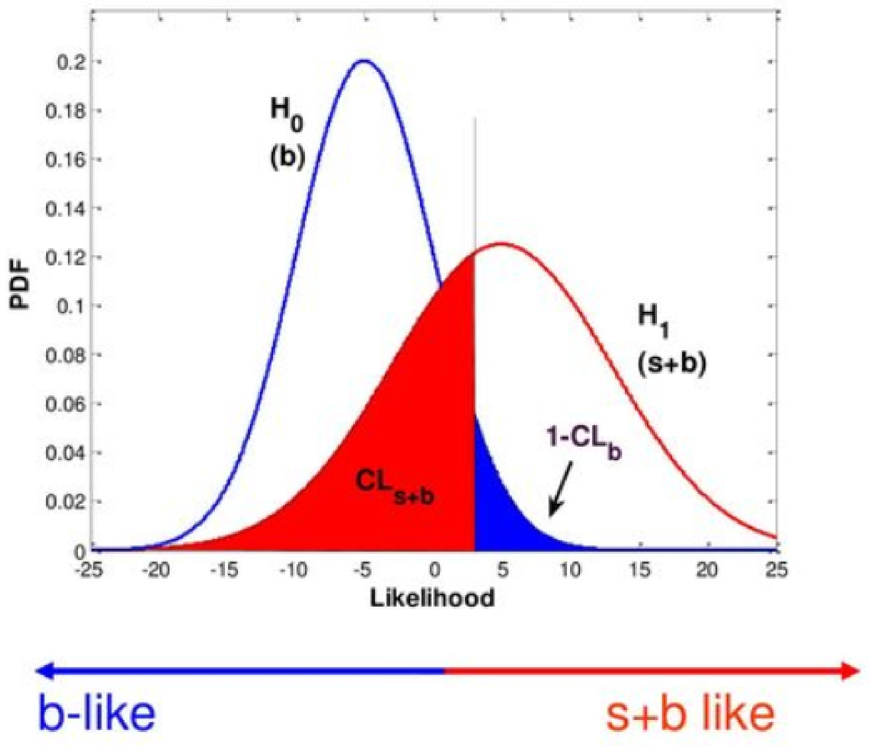




Quantify agreement with BSM hypothesis H_1

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

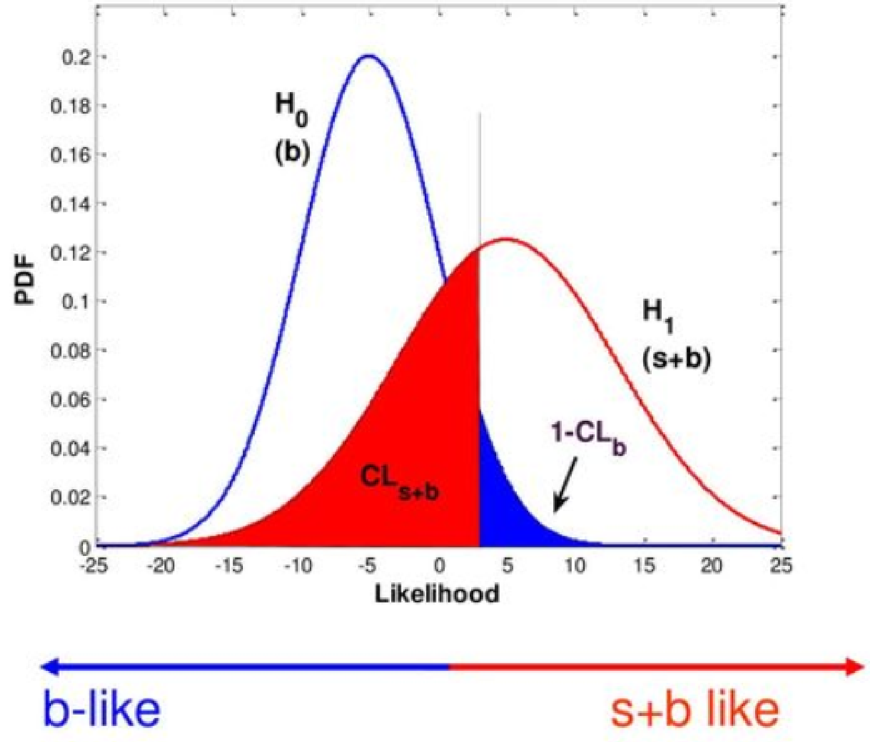
$$L(D|\mu,\boldsymbol{\theta}) = \underbrace{\prod_{j=1}^{M}\prod_{i=1}^{N}\mathrm{Pois}(n_{i,j}|\mu,\boldsymbol{\theta})}_{\text{Poisson terms}} \cdot \underbrace{\prod_{\mathrm{NP}} f(\theta^{(\mathrm{NP})})}_{\text{Constraint terms}}$$



Further reading:
Lecture by G. Cowan [link]

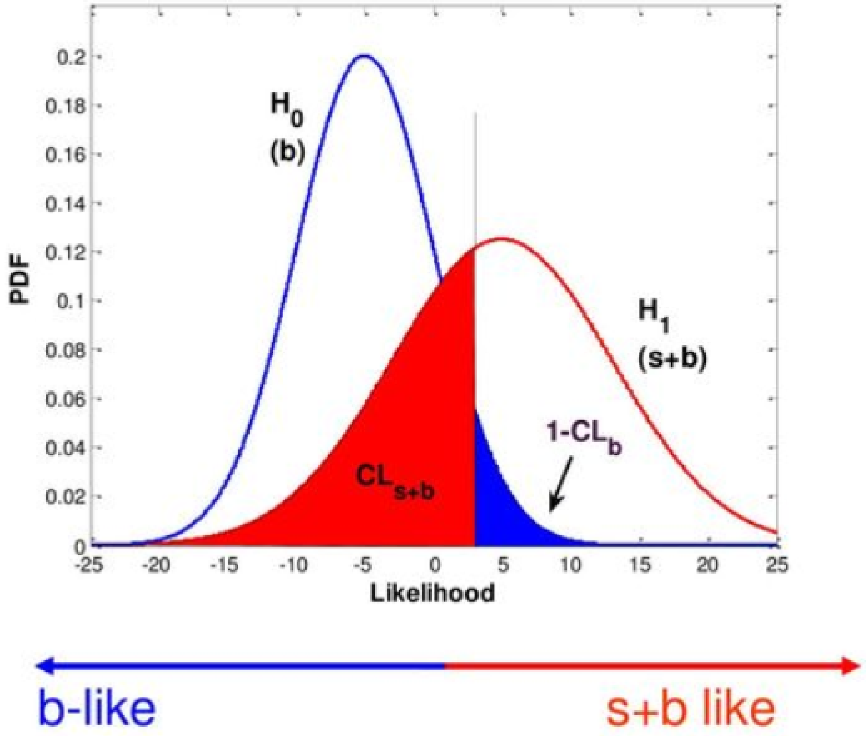
Quantify agreement with BSM hypothesis H_1

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



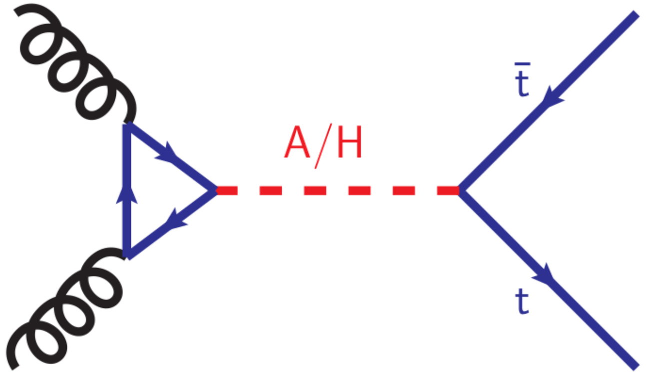
Quantify agreement with BSM hypothesis H_1

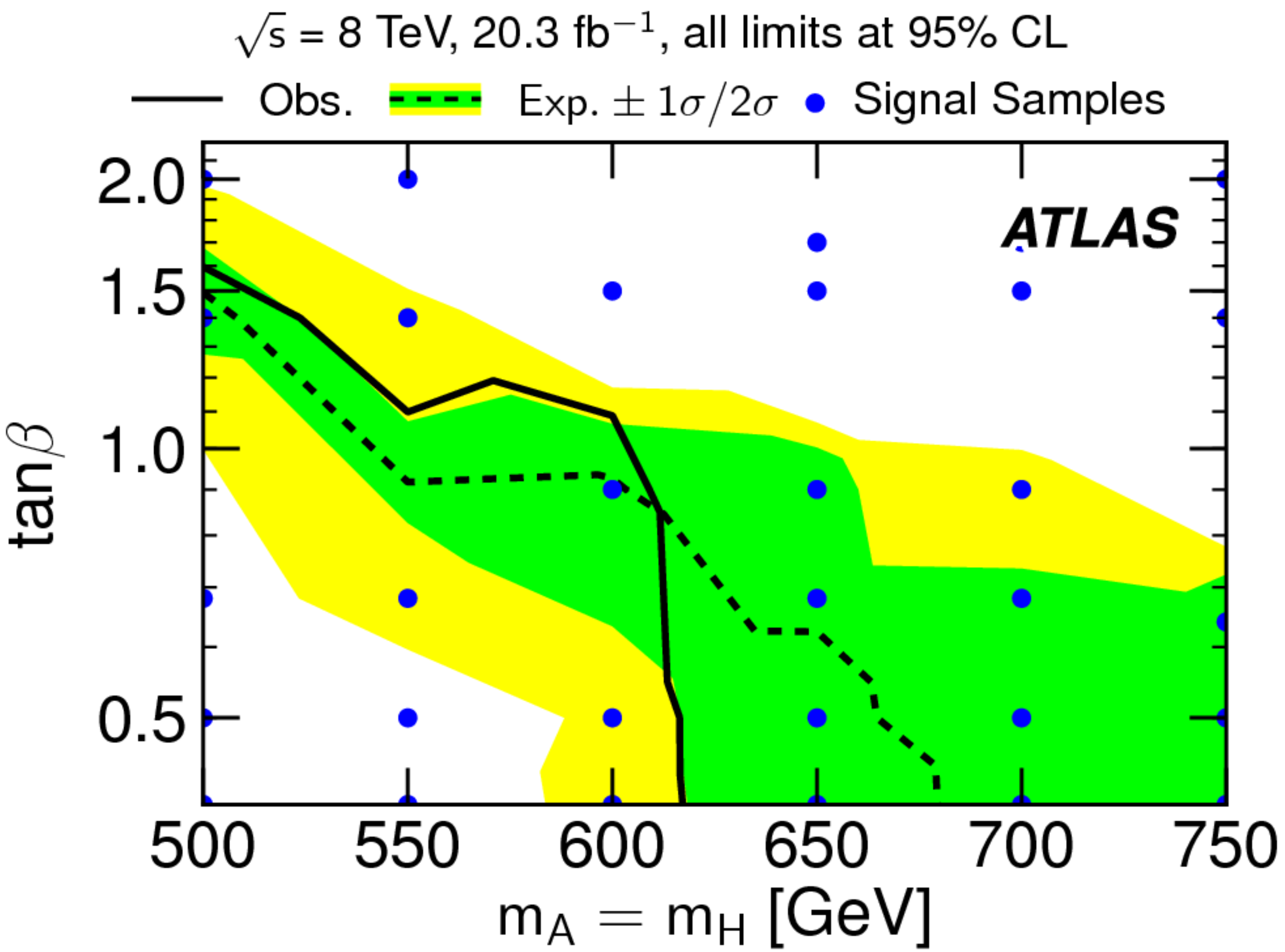
- Problem:
  - Danger to falsely reject H_1 even if separation between H_1 and H_0 is poor, i.e. sensitivity to H_1 is low
- Solution:
  - $CL(s) = CL(s+b)/[1-CL(b)]$
- Confidence level
  - H_1 excluded at 95% CL if $CL(s) < 0.05$



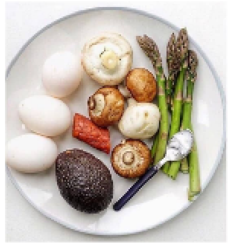
A final result

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



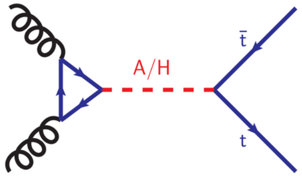


Search recipe summary

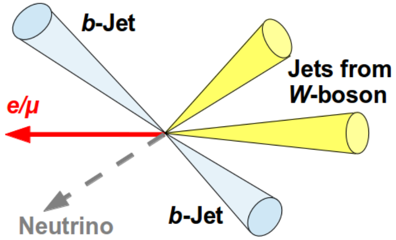


Ingredients

> Pick and study a signal of interest (MC simulation)



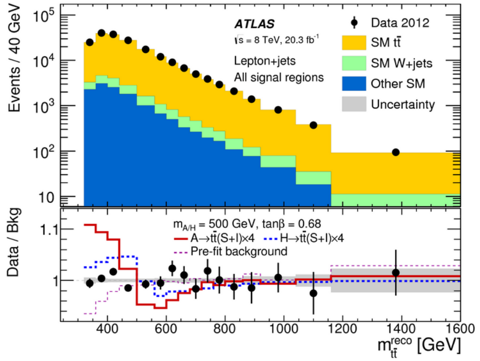
> Select subset of events enriched in signal (signal region)



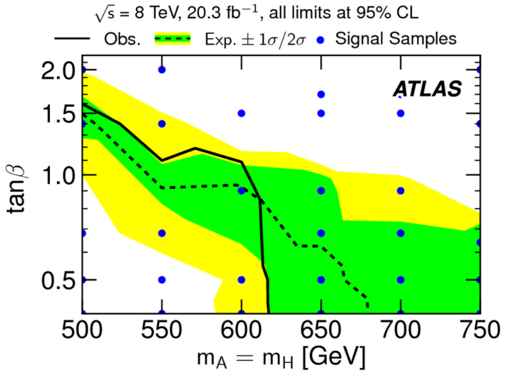
Recipe steps

> Estimate backgrounds and systematic uncertainties

- Often via control regions enriched in background



> Test agreement between SM prediction and data



Finished meal

Discovery!

Characterise signal …
and open the champagne

Null result

Derive constraints on
BSM models

Credit: J. Alimena

BONUS SLIDES

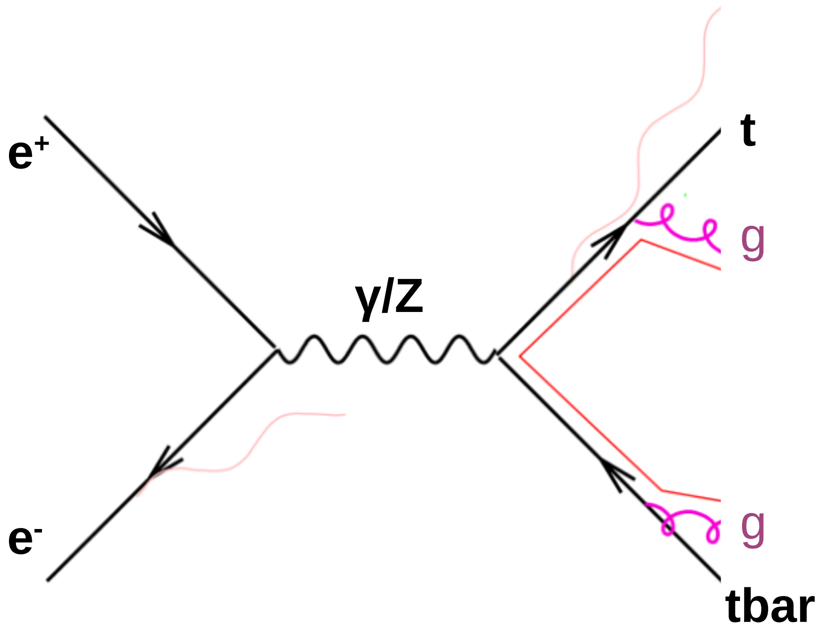
Event simulation

- 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

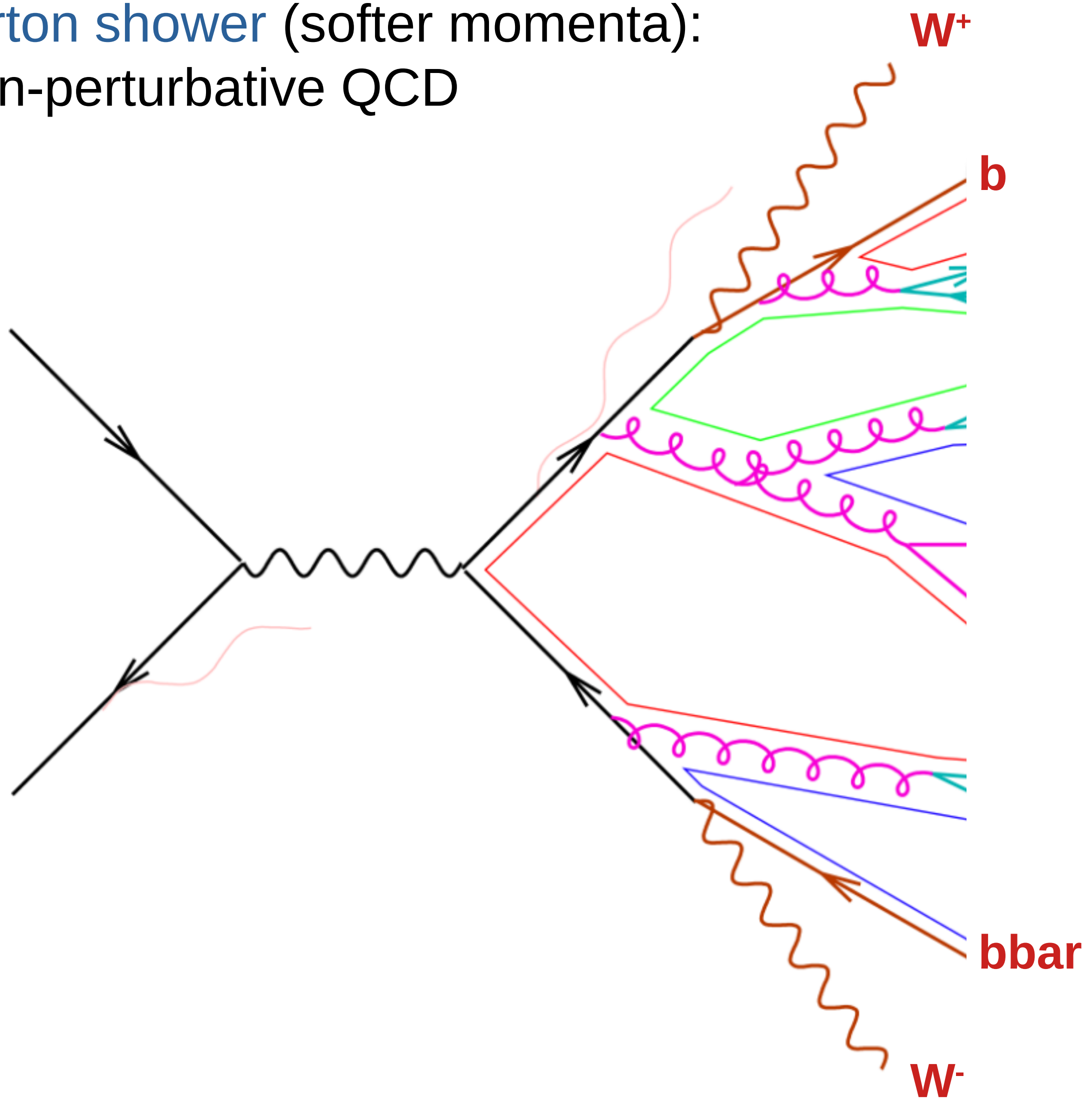
> Hard processes (large momentum transfers): perturbative QCD

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



Simulation step by step

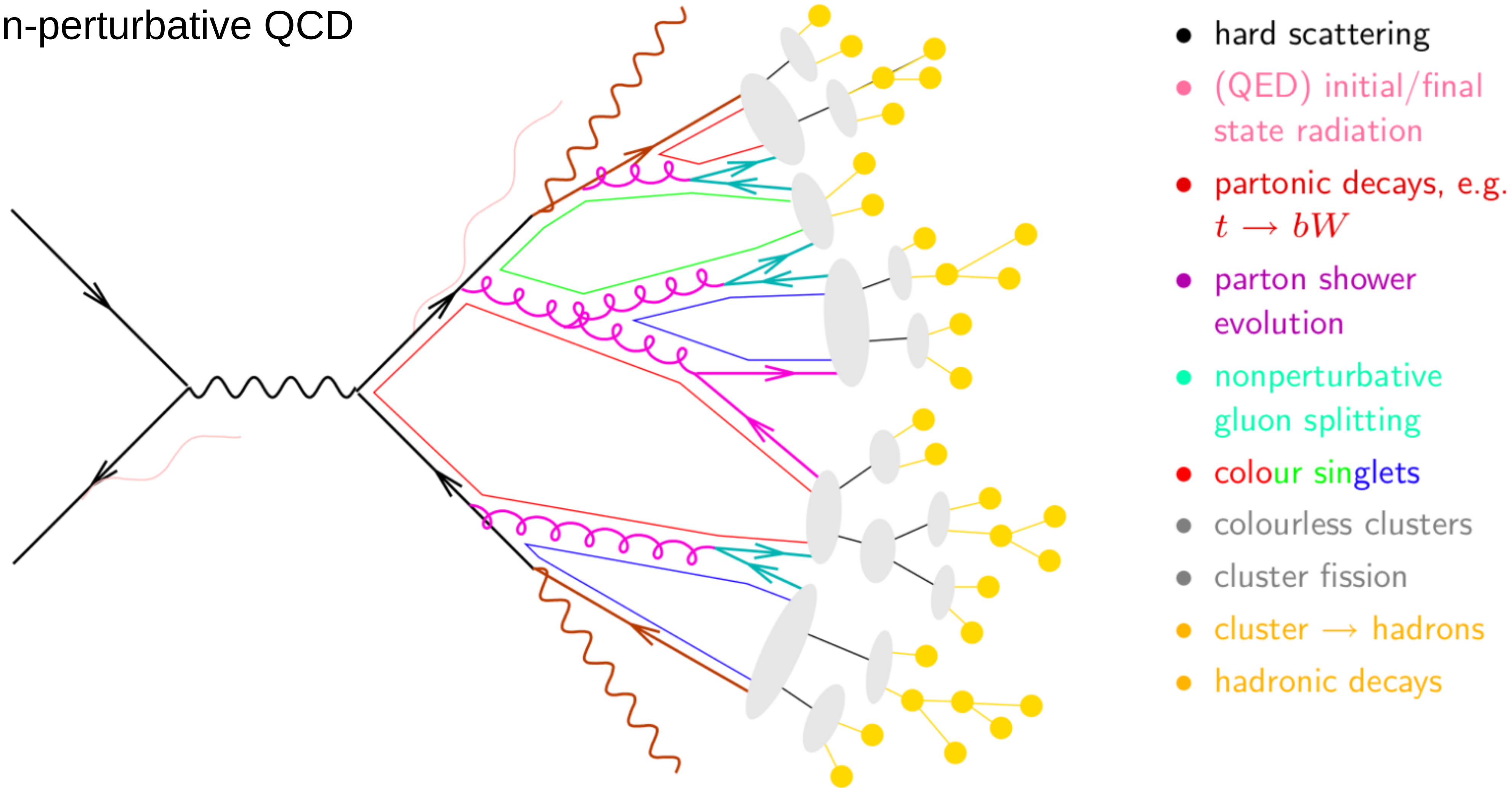
> Parton shower (softer momenta):
  non-perturbative QCD



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \longrightarrow bW$
- 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!

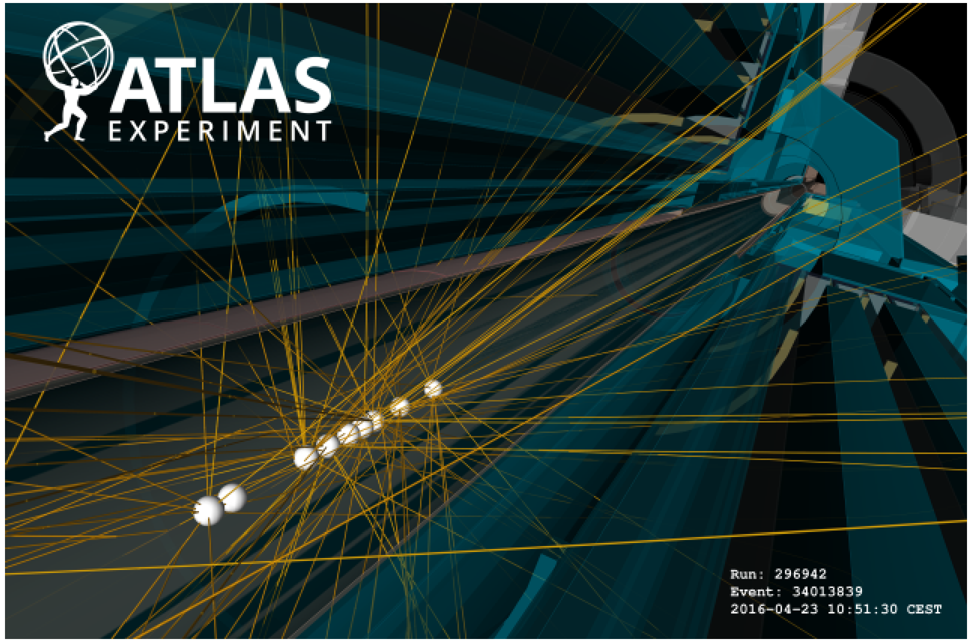
Think outside the (black)box!

*“[…] 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, …
> 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]

Further aspects

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

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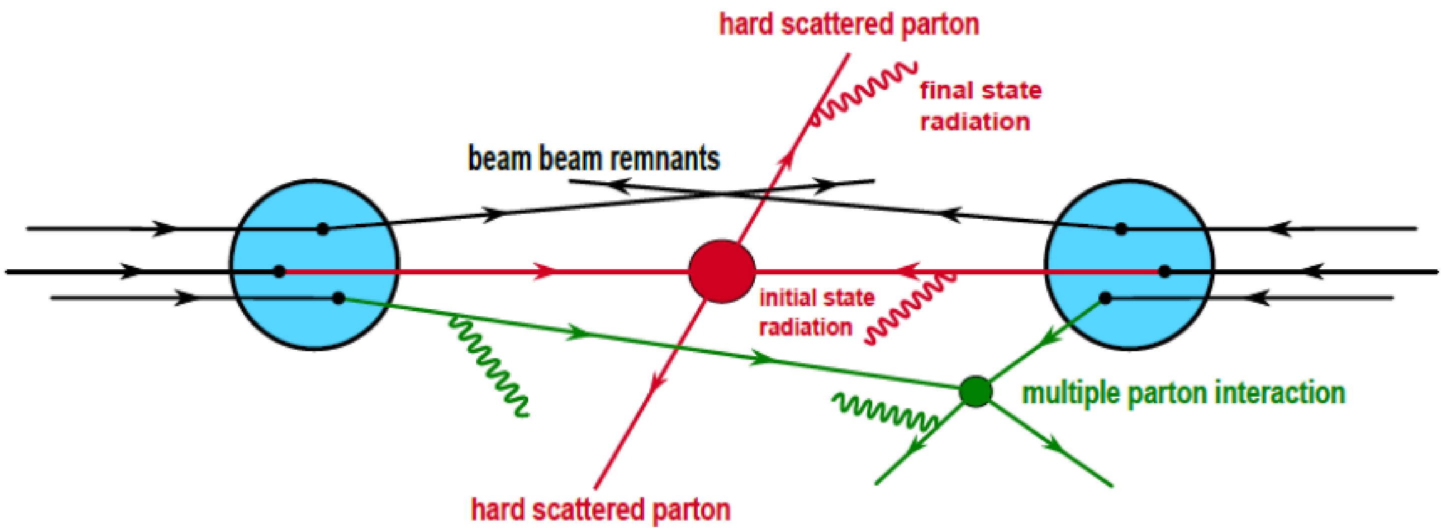
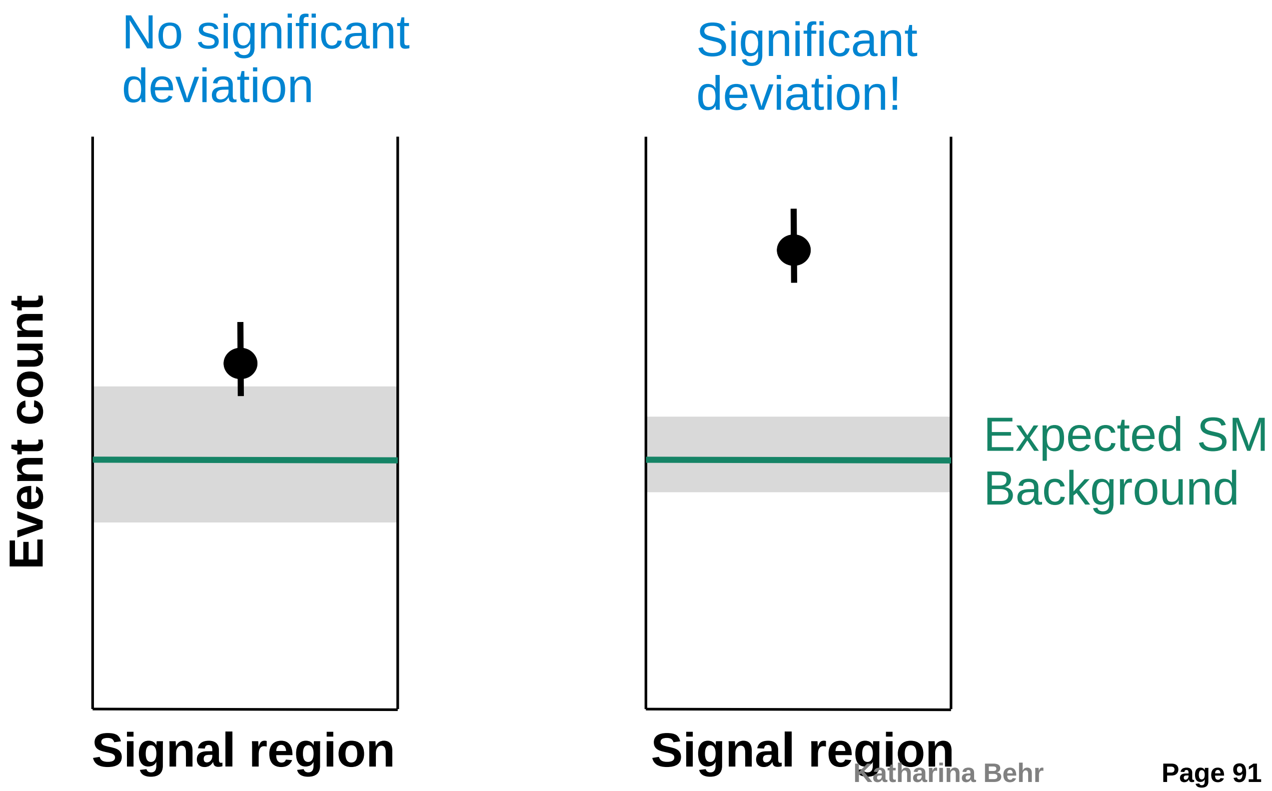


Cut-and-count method

- 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)



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> **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