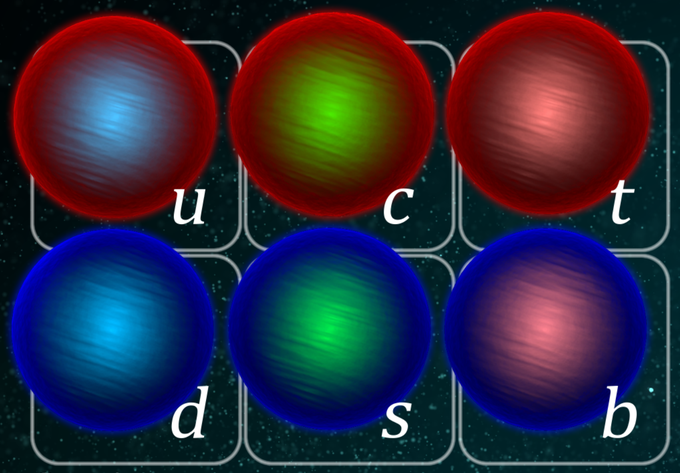
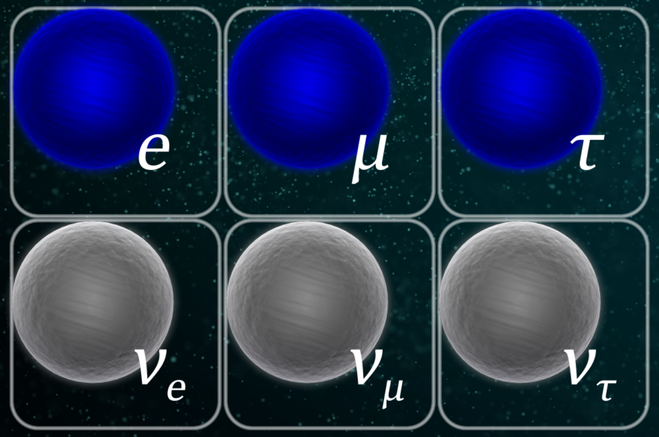
Model-Independent Measurements

Monica Dunford - KIP Heidelberg

The genesis to any measurement is the question itself

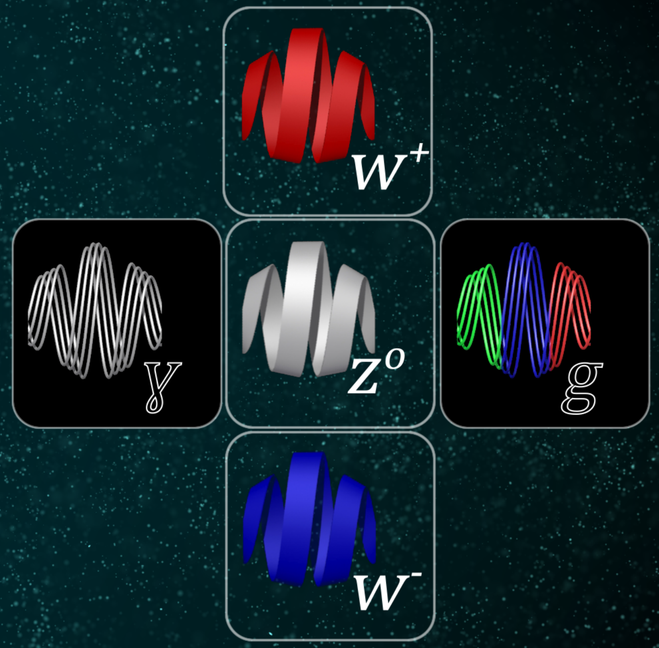


Quarks



Leptons


Higgs boson

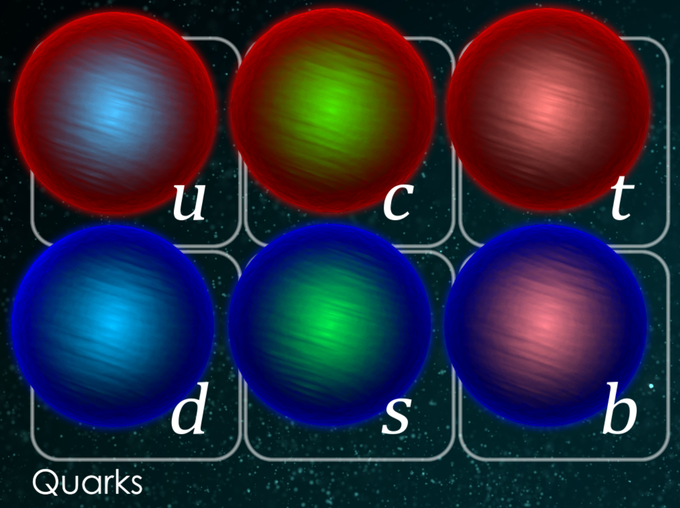


Forces

ACCELERATING SCIENCE

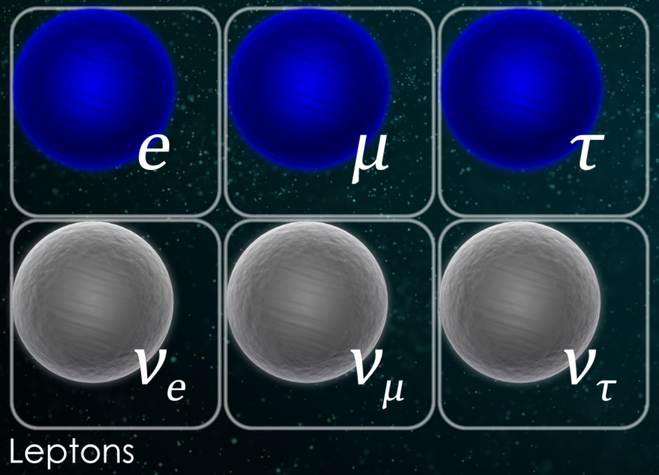
The genesis to any measurement is the question itself

Mass hierarchy



CP Violation

Additional particles?



Composite Higgs?

Who breaks electroweak symmetry?

Why is θ_{13} so small?

Majorana vs. Dirac

Why is neutrino mixing so large?

Dark energy?

Dark matter?

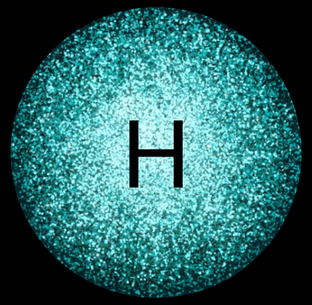
Gravity?

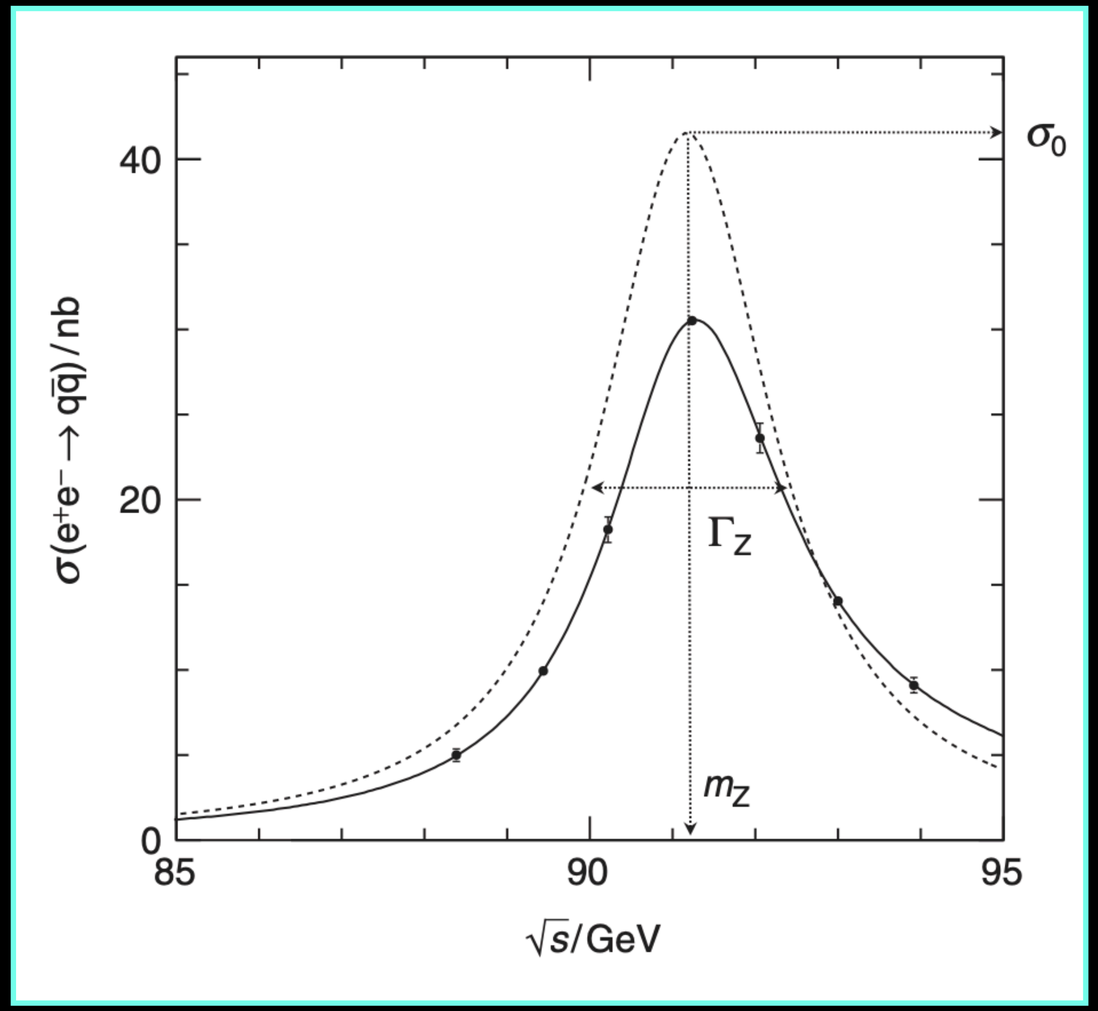
Unified forces?

Theories beyond the Standard Model?


Is dark matter just modified gravity?
What is dark matter?
Or something else like primordial blackholes?
Is it a particle?
How is it distributed?
Is it heavy and fast or light and slow?
Is the Earth in a dark matter deficit?
Dark matter is massive. How does it gets its mass?
What role does dark mater play in galaxy formation?
Each of these questions are important and the measurements to answer them are completely different
Building those measurements, both experimentally and theoretically, is where all the fun is

Dark matter has mass. How?

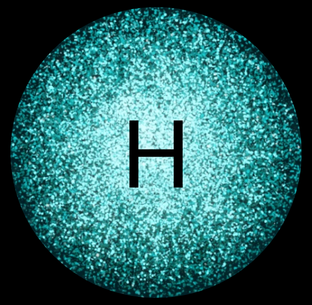




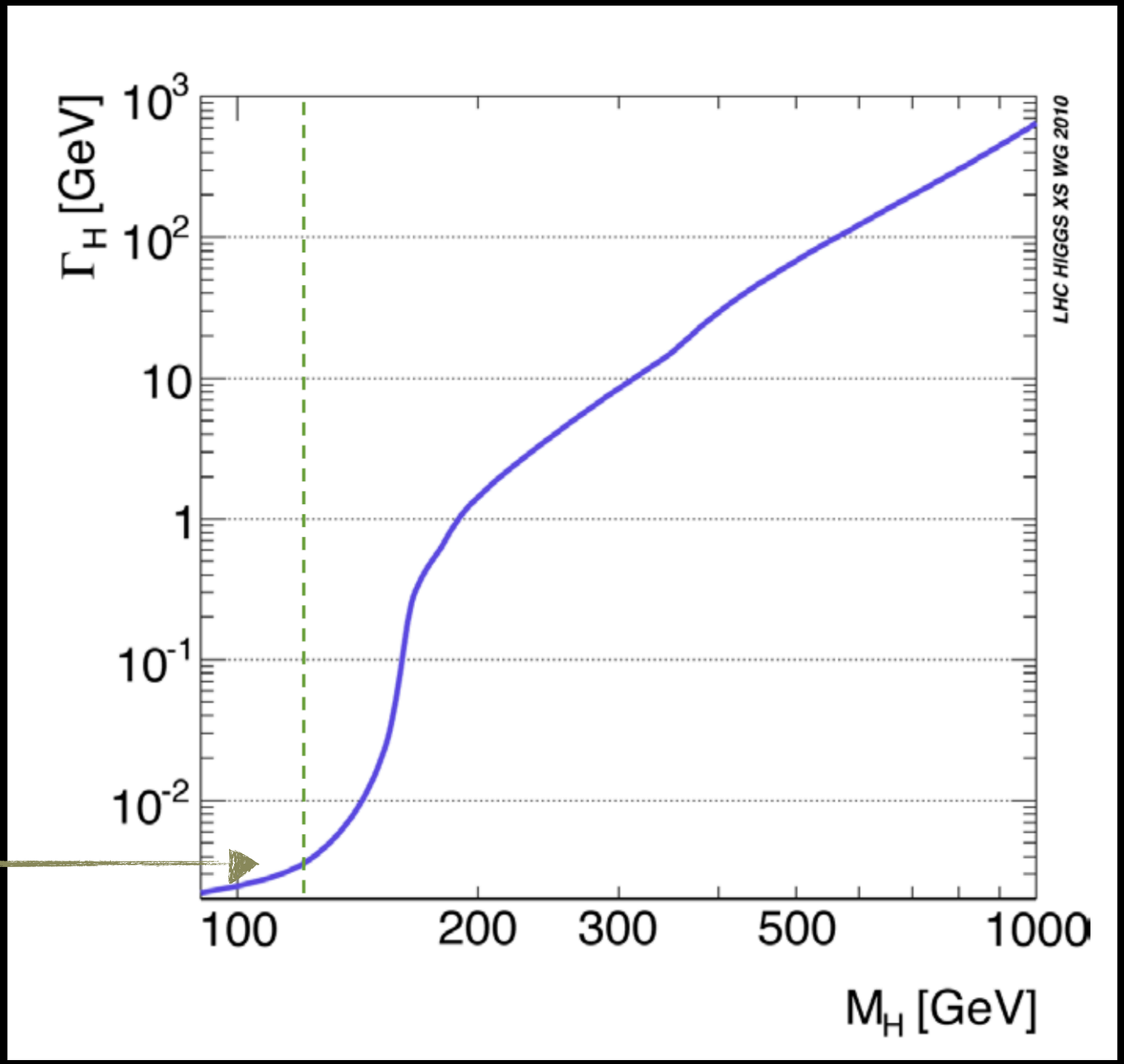
$$\sigma^0(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}.$$

$$\Gamma_Z = 3\Gamma_{\ell\ell} + \Gamma_{\text{hadrons}} + N_\nu\Gamma_{\nu\nu}.$$

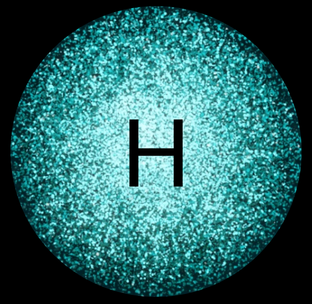
Dark matter has mass. How?



- Prediction 4.07 MeV



Dark matter has mass. How?



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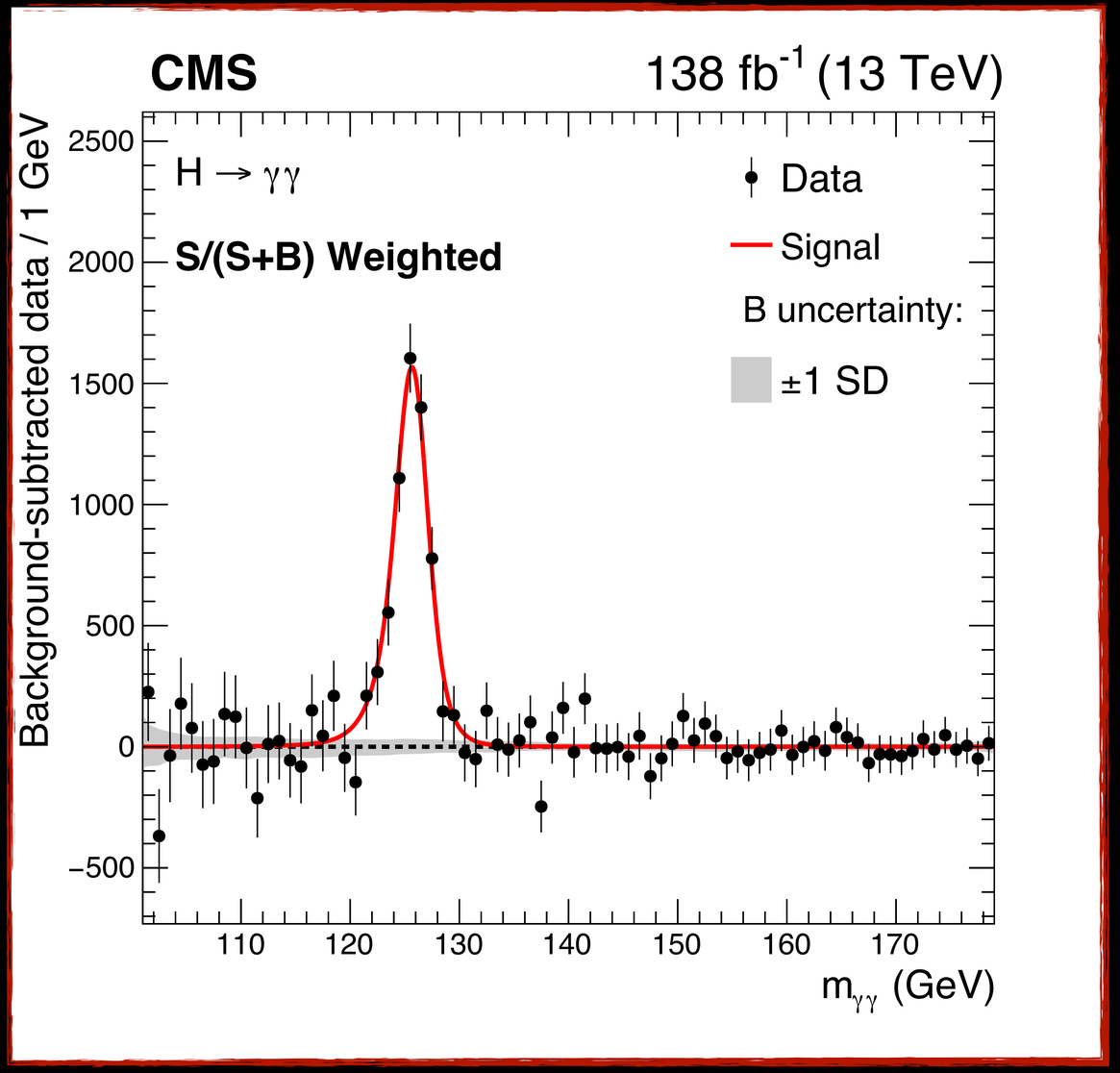
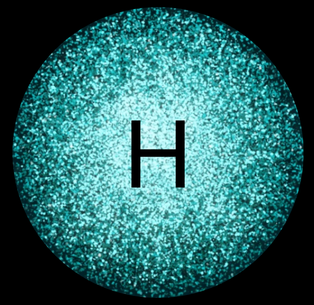


This is the detector's resolution
Game over (?)

D… mass. How?



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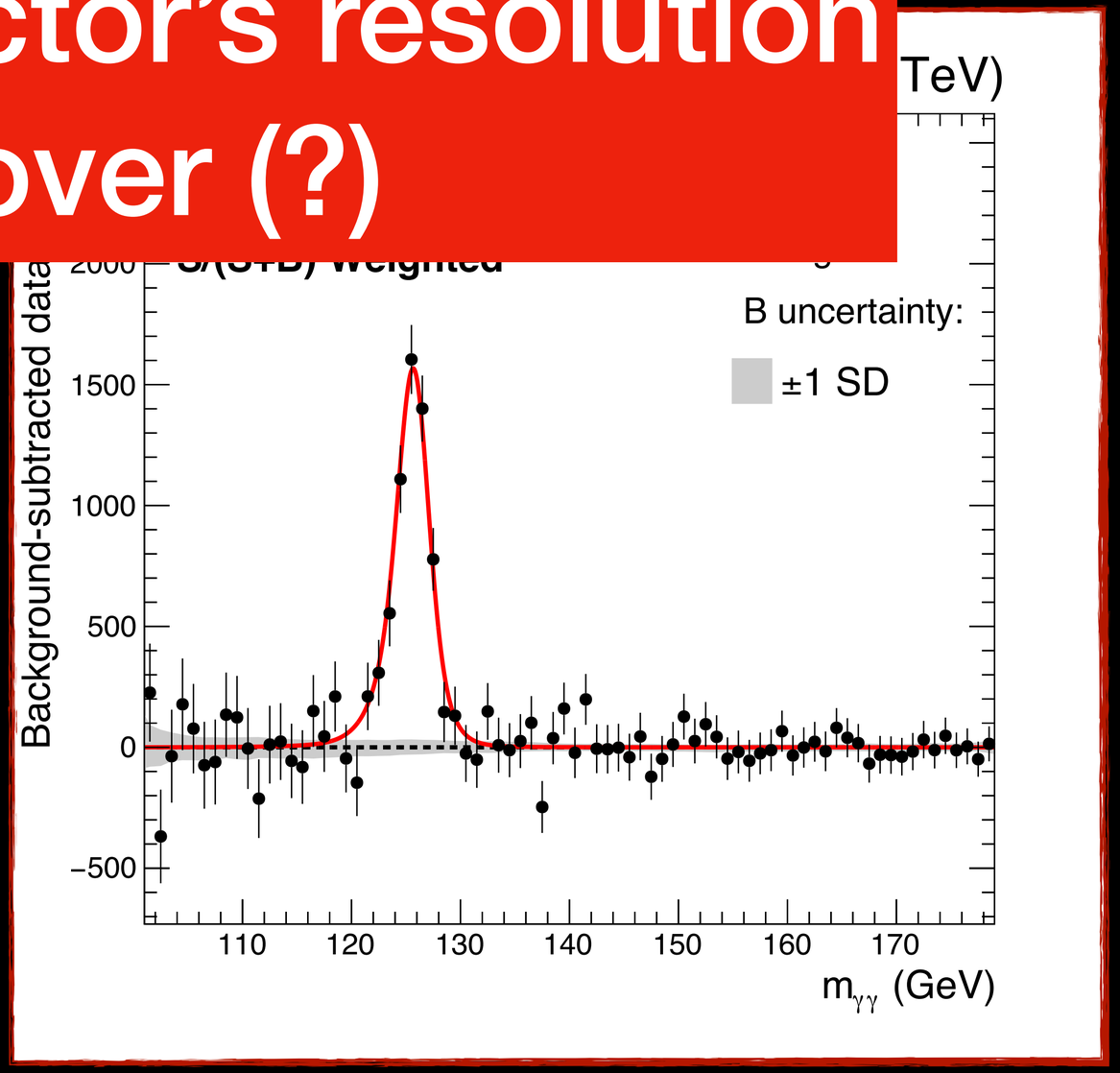
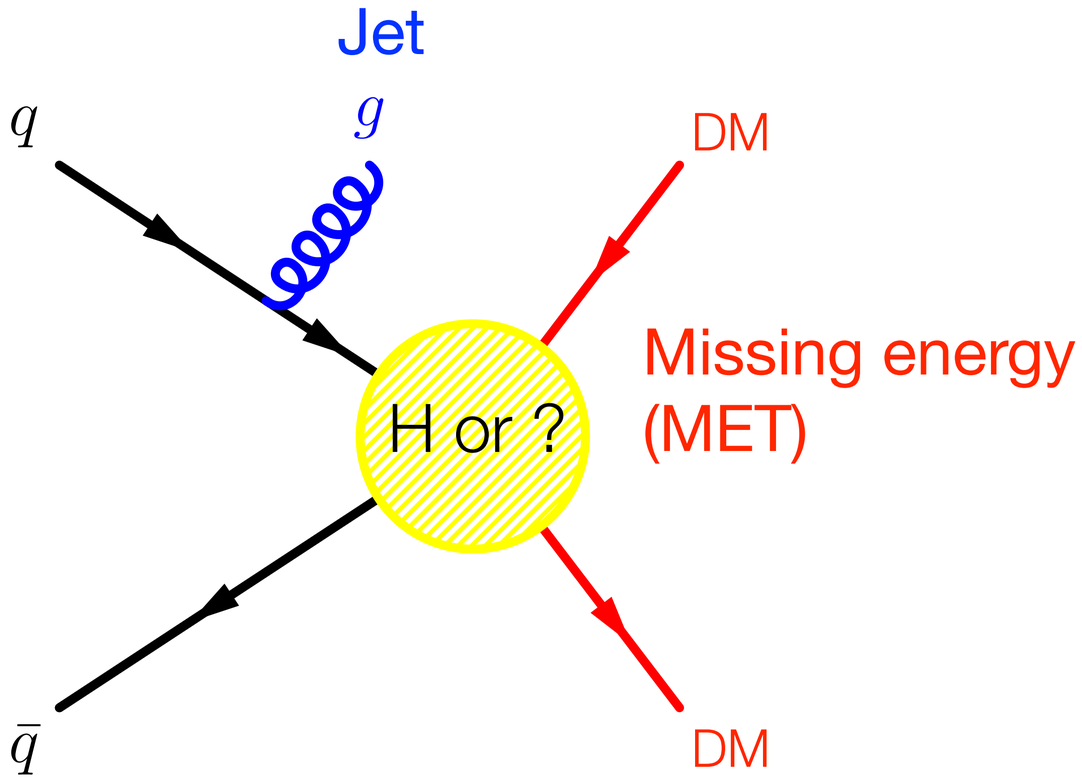
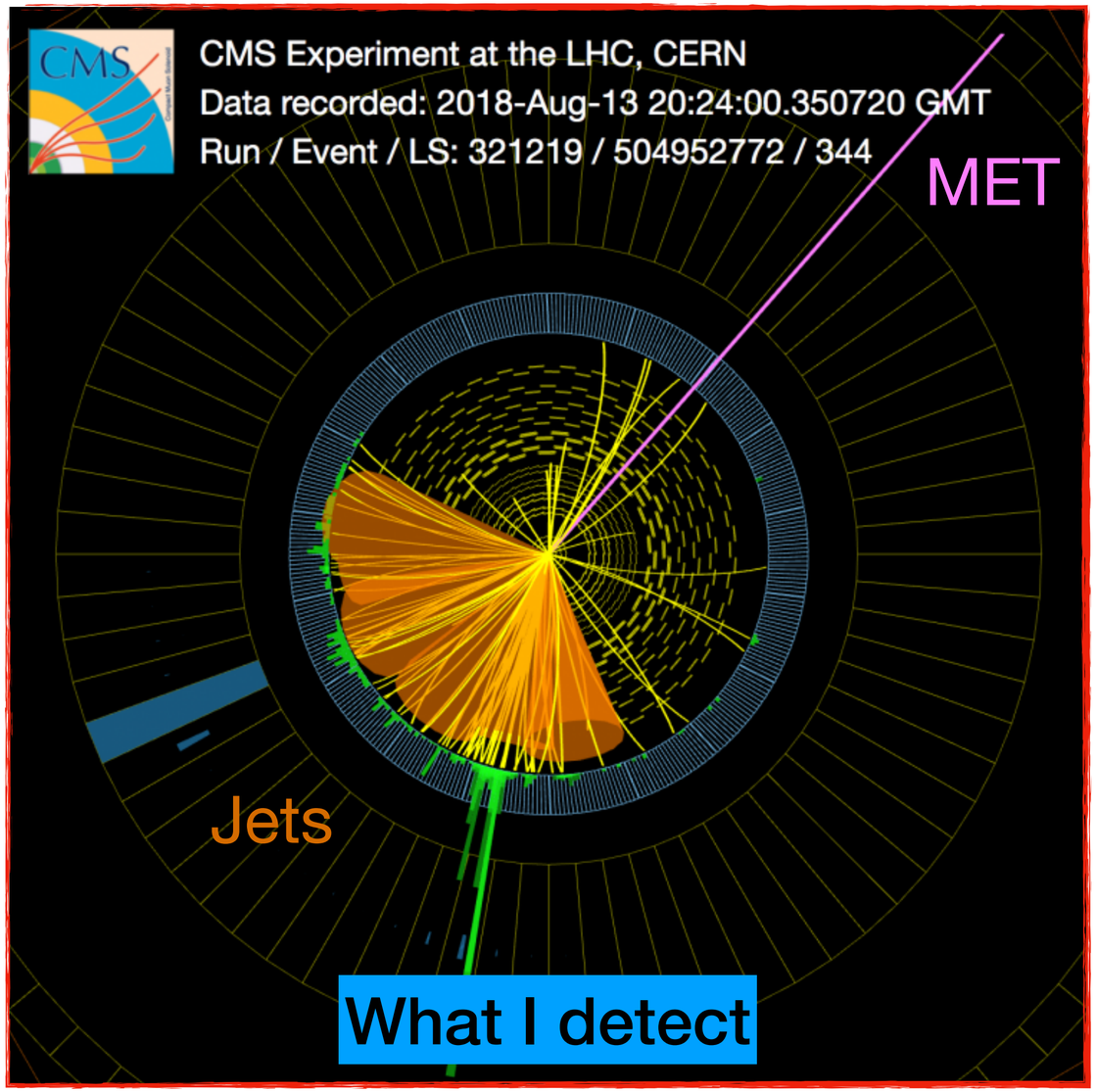


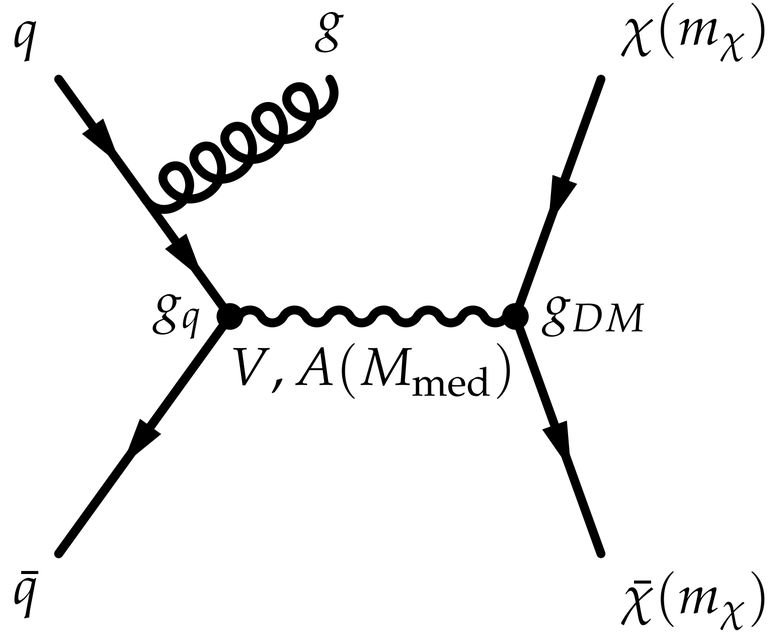
Back to the drawing board

- Search for a Higgs boson (or anything else) decaying to dark matter
- Dark matter doesn't interact (i.e. don't detect it)
- See only its 'shadow'. Detect it via missing transverse energy



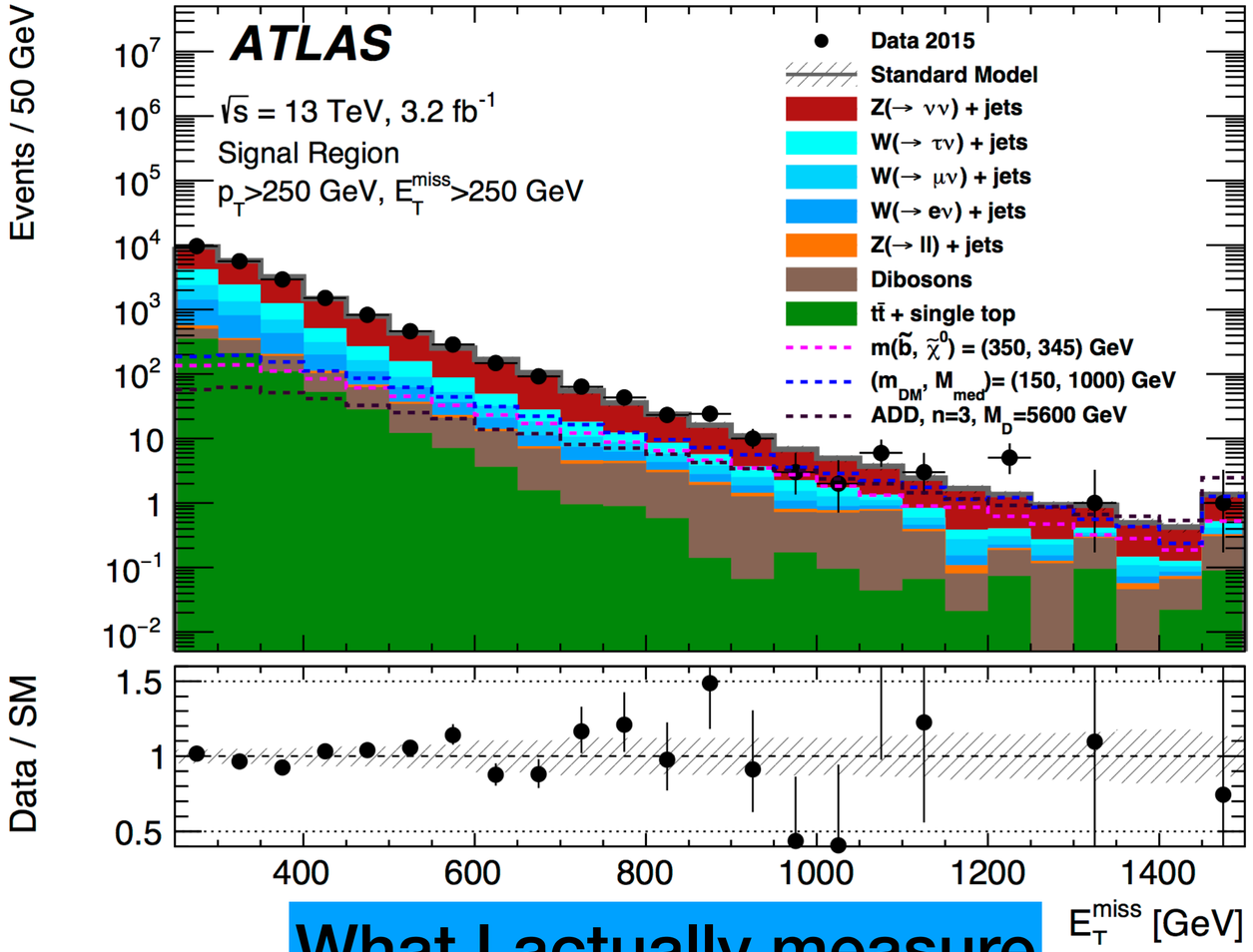
Detecting dark matter



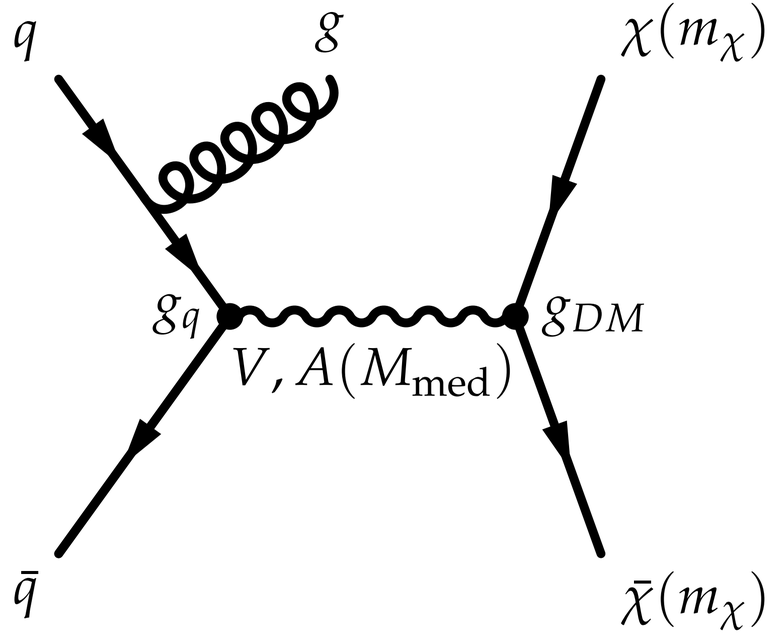


What I want to measure

Dark matter and the Higgs



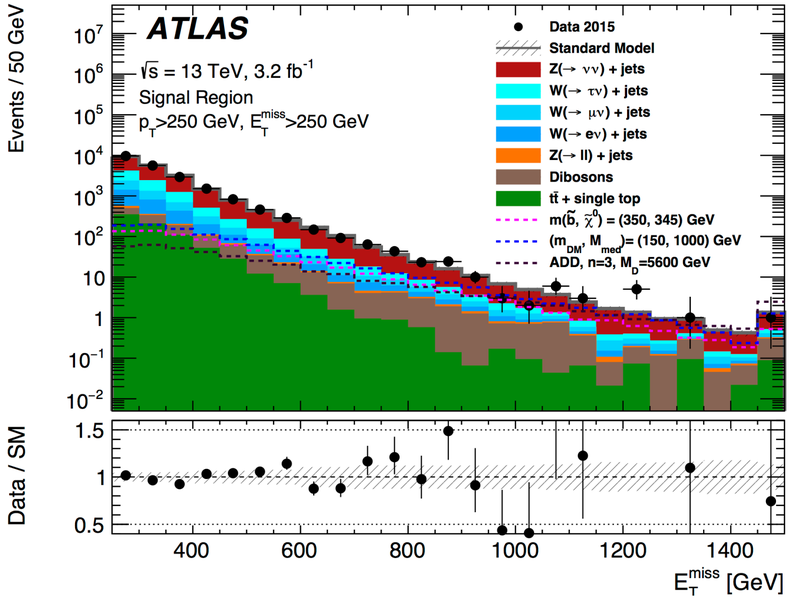
What I actually measure



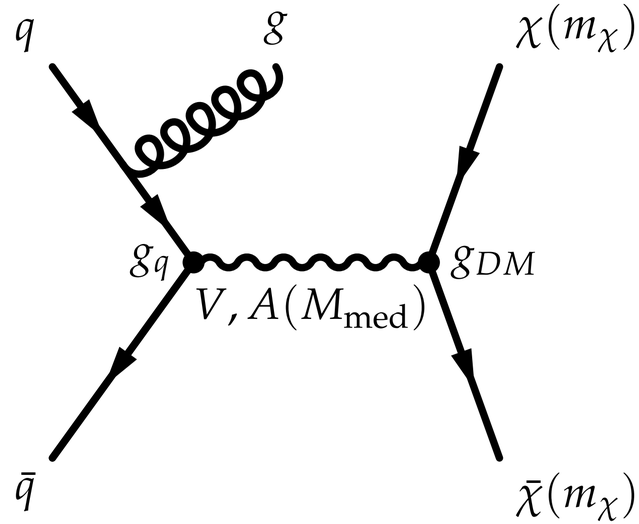
What I want to measure

How do these actually connect?

Number of events



Cross section or couplings

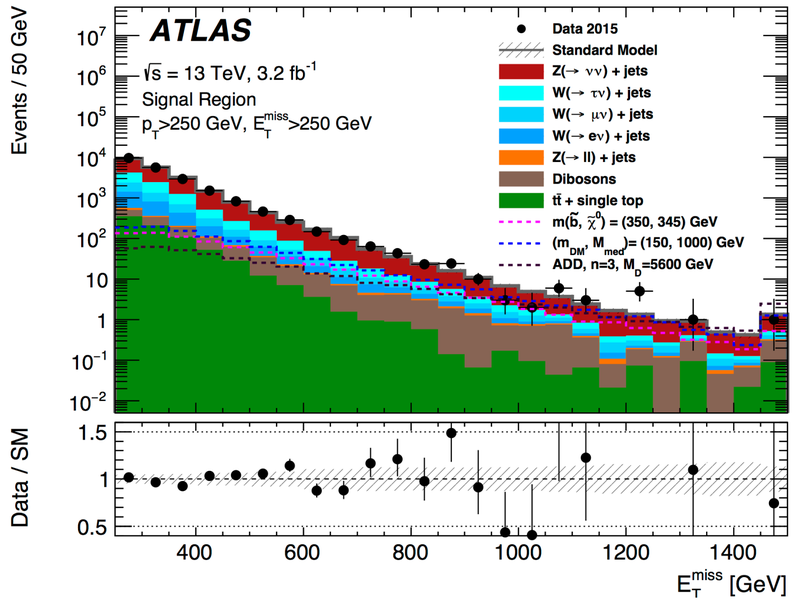


What I actually measure

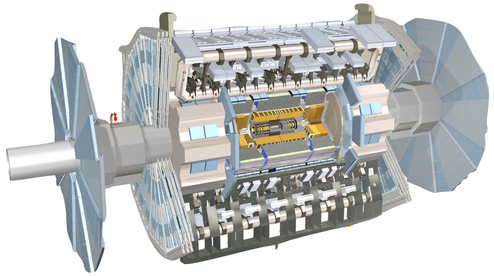
What I want to measure

How do these actually connect?

Number of events



Detector effects

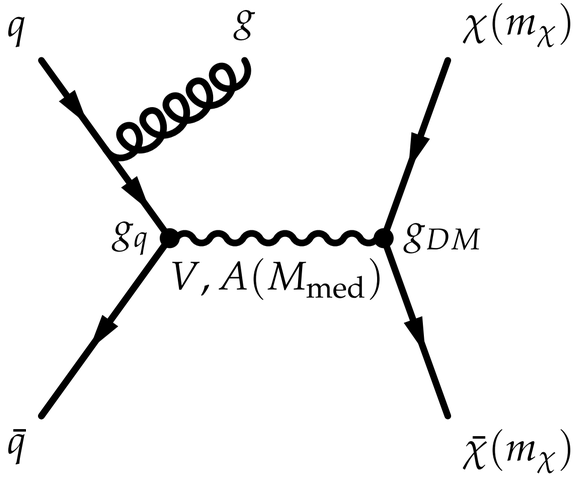


Calibration
Finite resolution
Finite coverage
Non-perfect efficiencies
Measurement uncertainties

Final state particle definition
Like lifetime cut (10ps)
Pre/post hadronization
Fiducial selection

Phase space/particle definition

Cross section or couplings



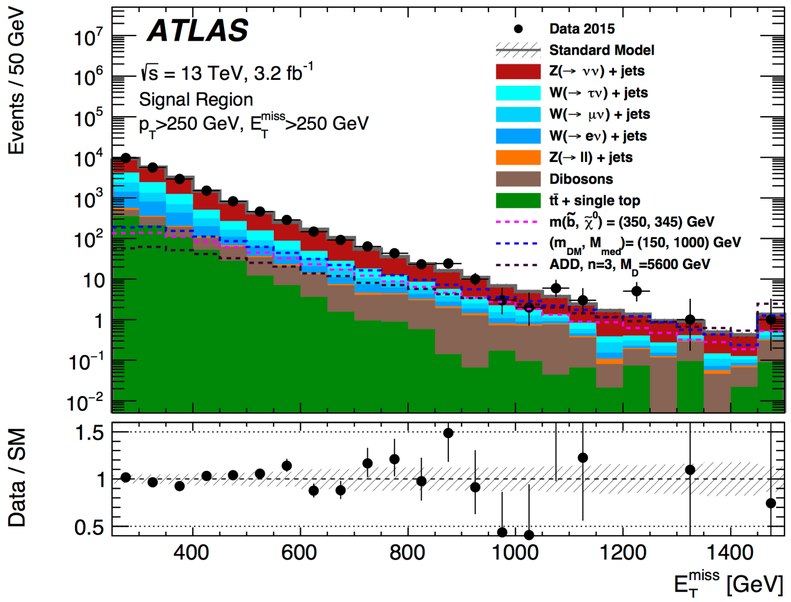
What I actually measure

What I want to measure

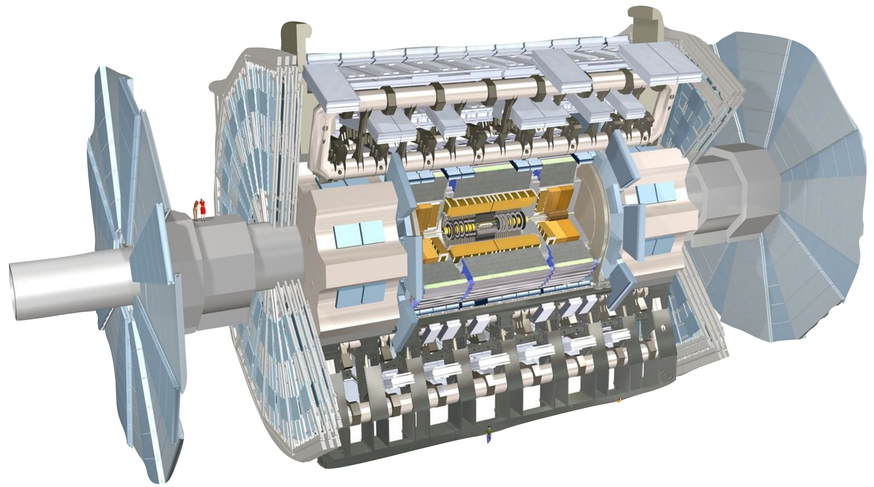
How do these actually connect?

Use a MC + Simulation …

Number of events

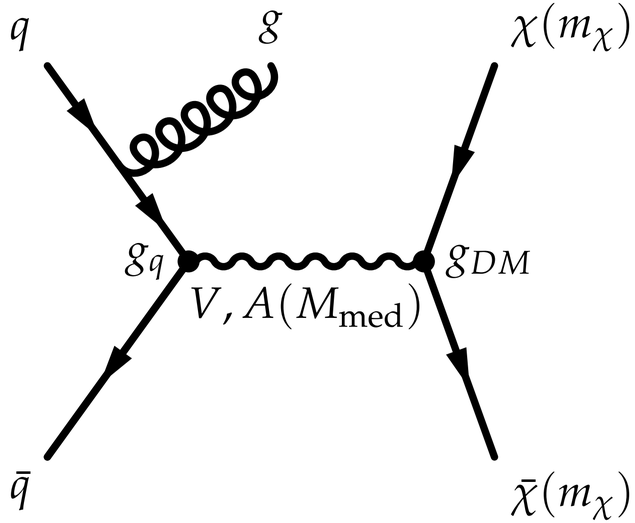


To correct for all detector effect (i.e unfolding)



To predict the data

Cross section or couplings



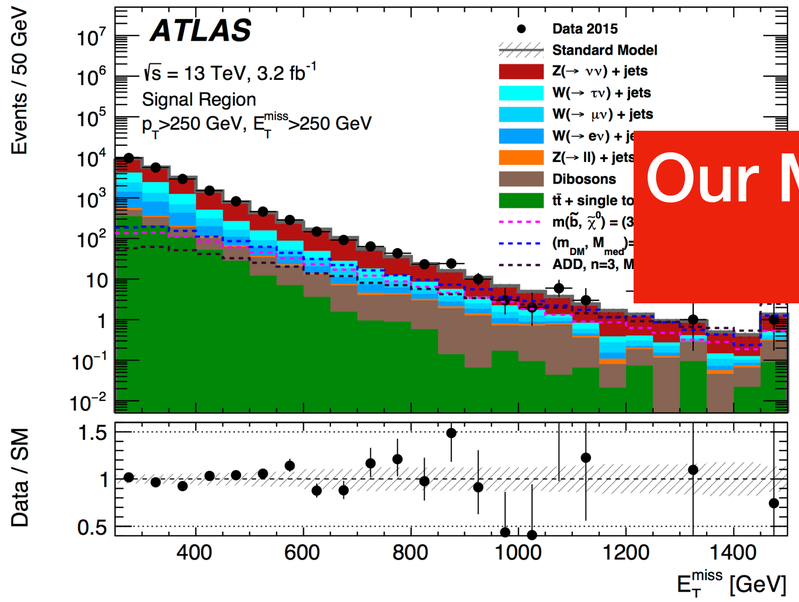
How do these actually connect?

Use a MC + Simulation …

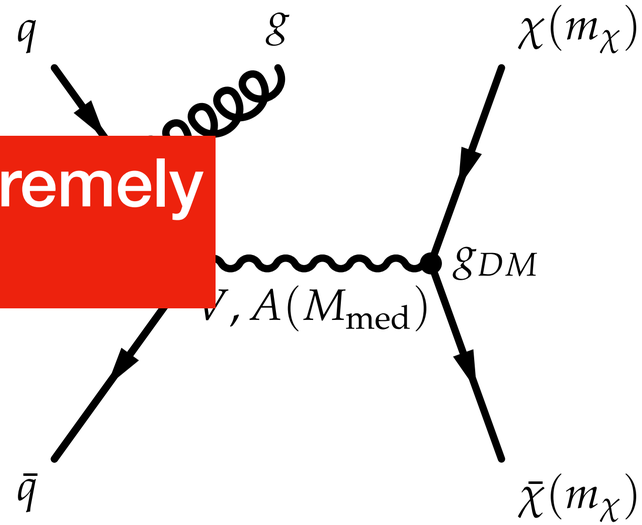
Number of events

Cross section or couplings

To correct for all detector effect (i.e unfolding)



Our Monte Carlo and simulation are extremely powerful and unique tools!



To predict the data

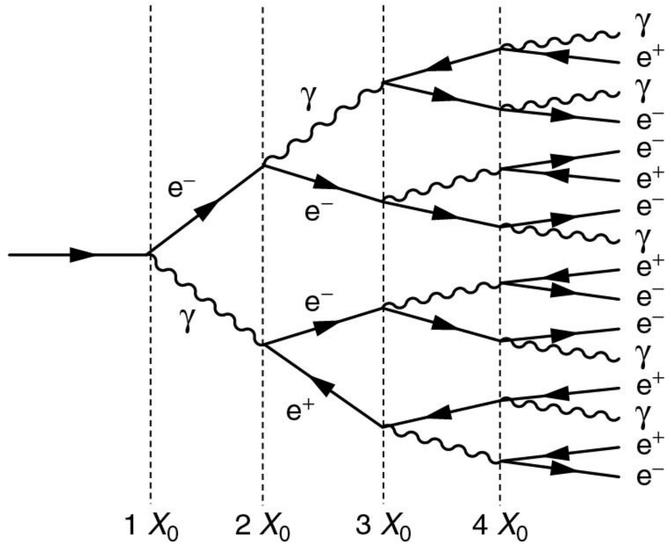
Designing a measurement

Designing a measurement - some key ingredients

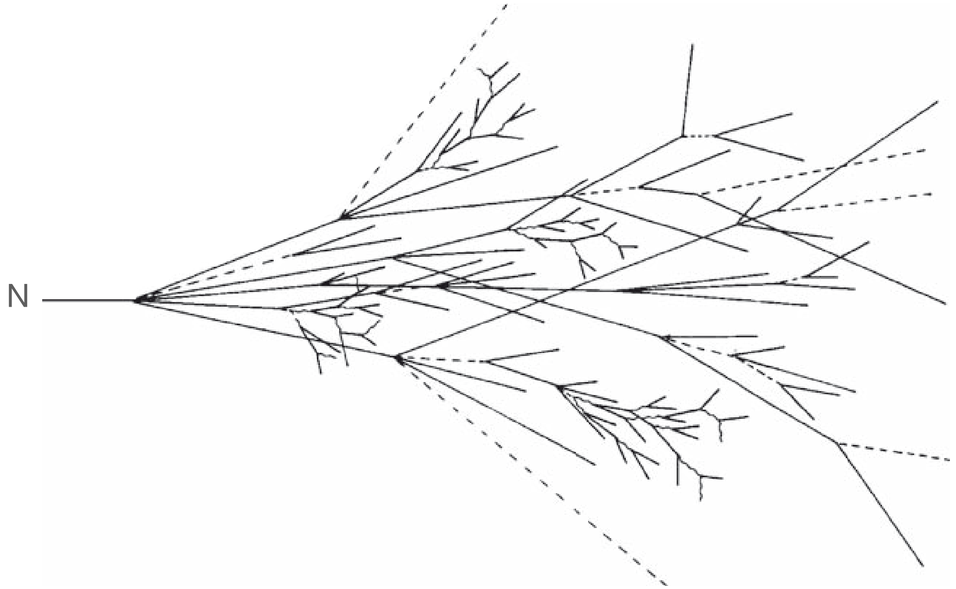
- What is the final state and how precisely can you reconstruct it? Is it precise enough for your question?
- How large is the signal (what you want to measure/find) compared to backgrounds with the same final state (other processes that are in your way)?
- What will be the dominate uncertainty? Can it be controlled or constrained?

A brief aside… Experimentally not all particles are equal

- Muons, electrons, photons are most precise, hadrons less so
- Comes down to how particles lose energy



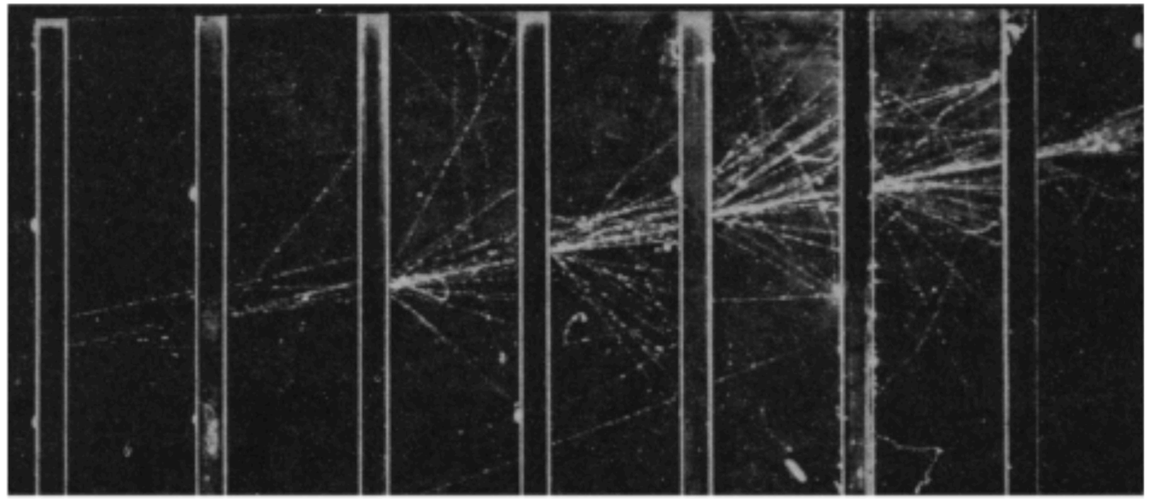
EM shower - many interactions, fluctuations are small (i.e. EM showers look similar)



Hadronic shower - energy loss via strong interaction and ionisation. Final state varies, large shower-to-shower variations

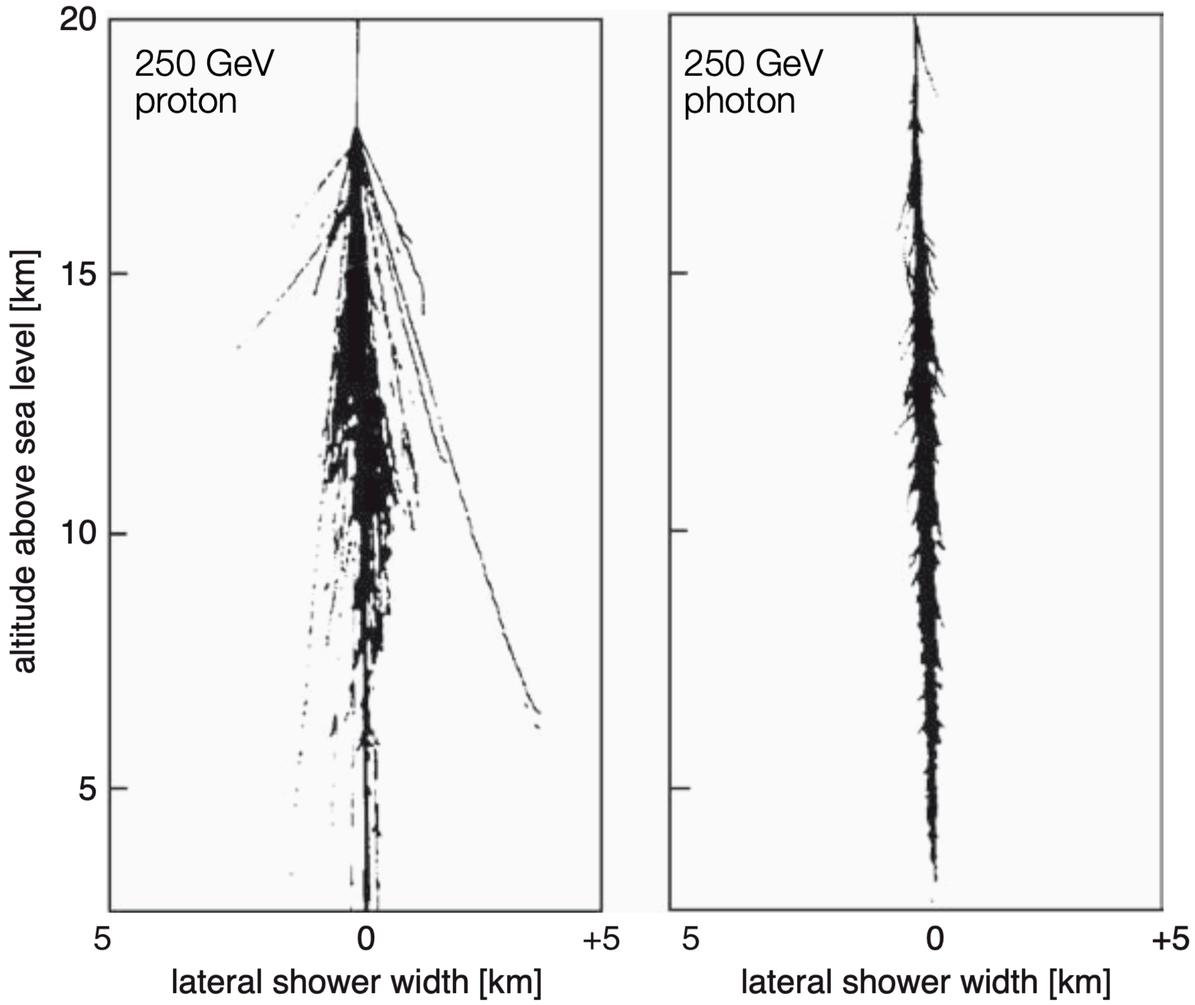
A brief aside… Experimentally not all particles are equal

- Some examples



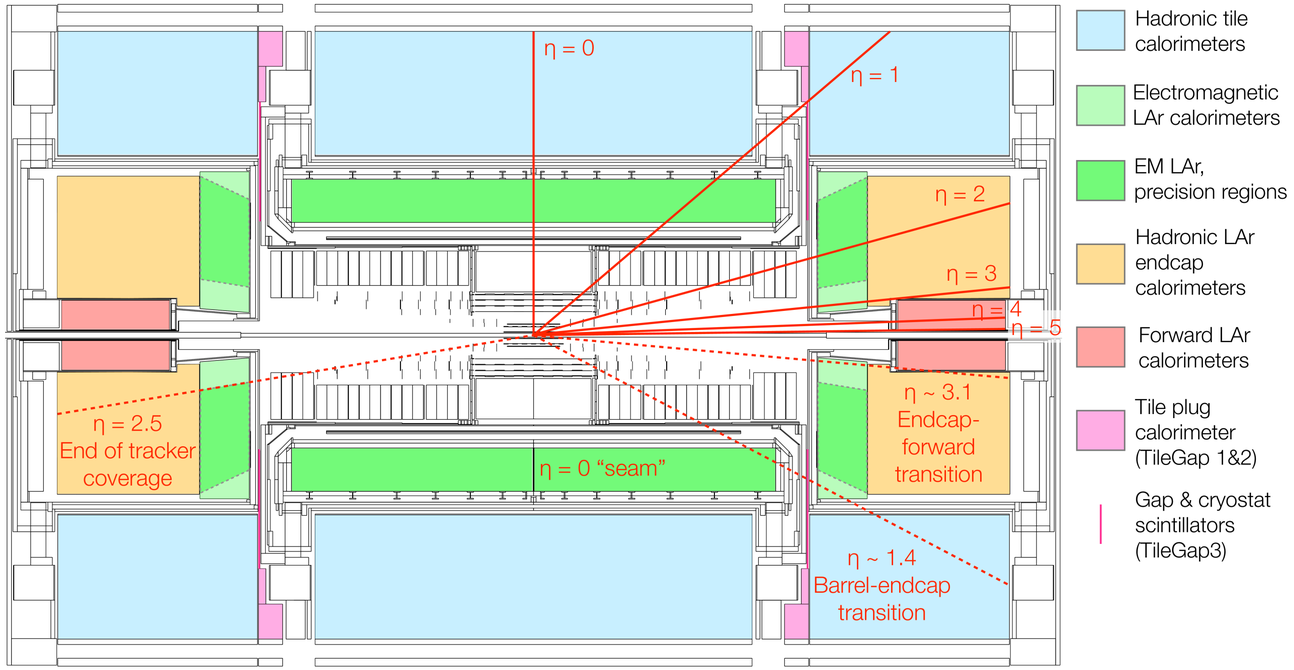
EM shower in a sampling calorimeter

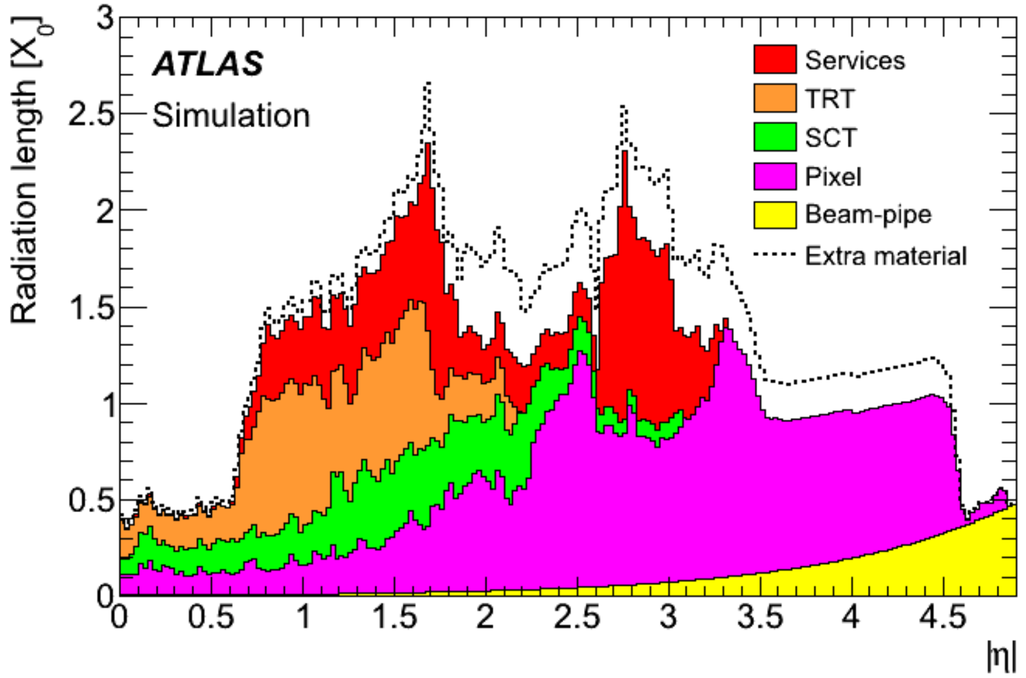
Air shower simulation



Detector corrections

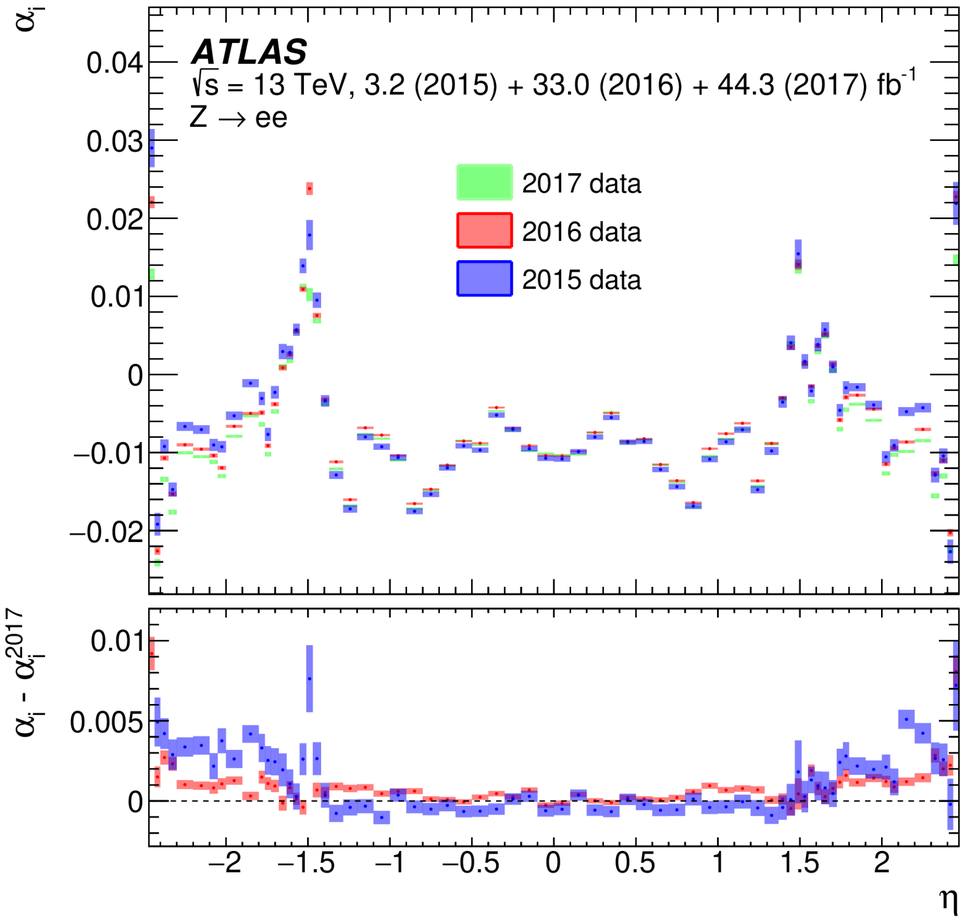
- Must account and correct for many effects - like pile-up, different detector technologies, material budget

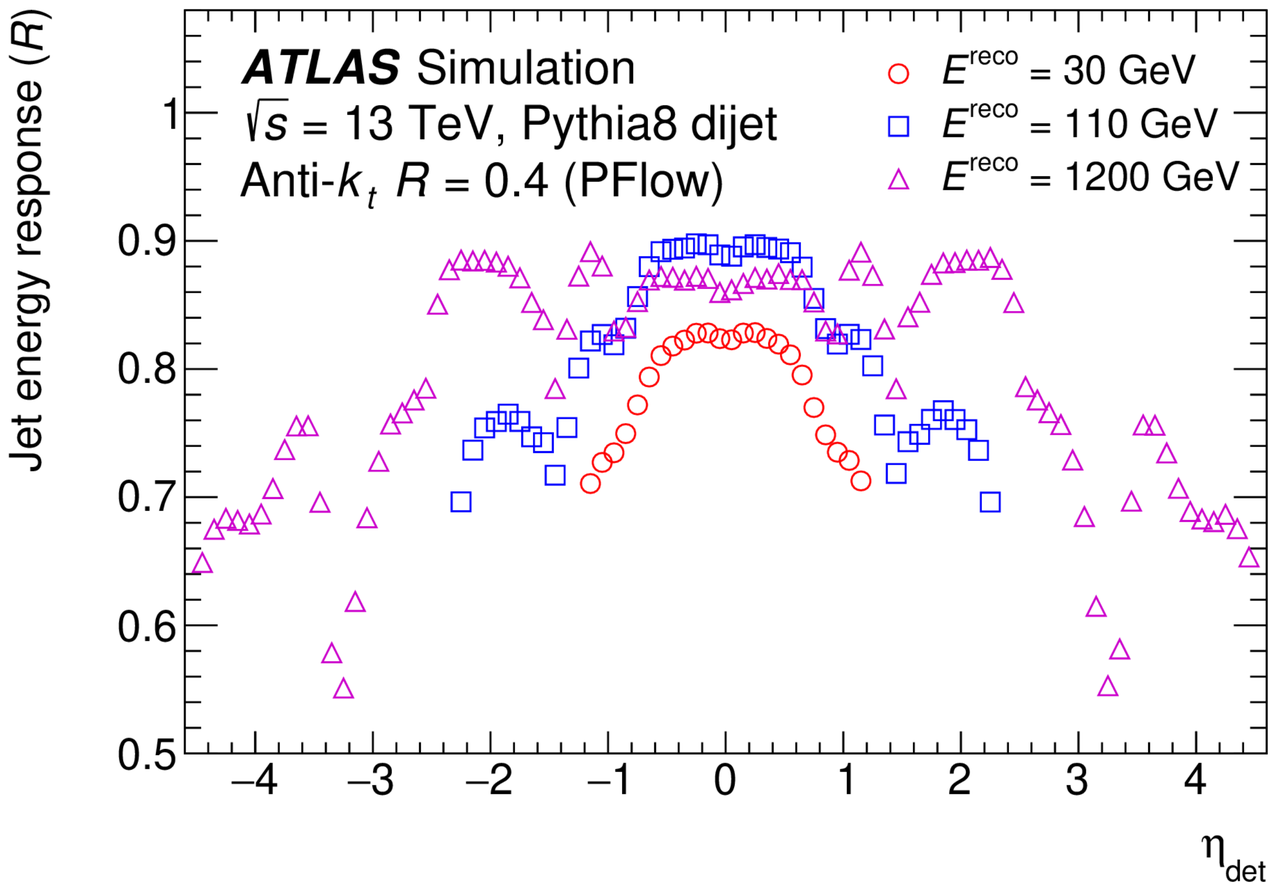




Detector corrections

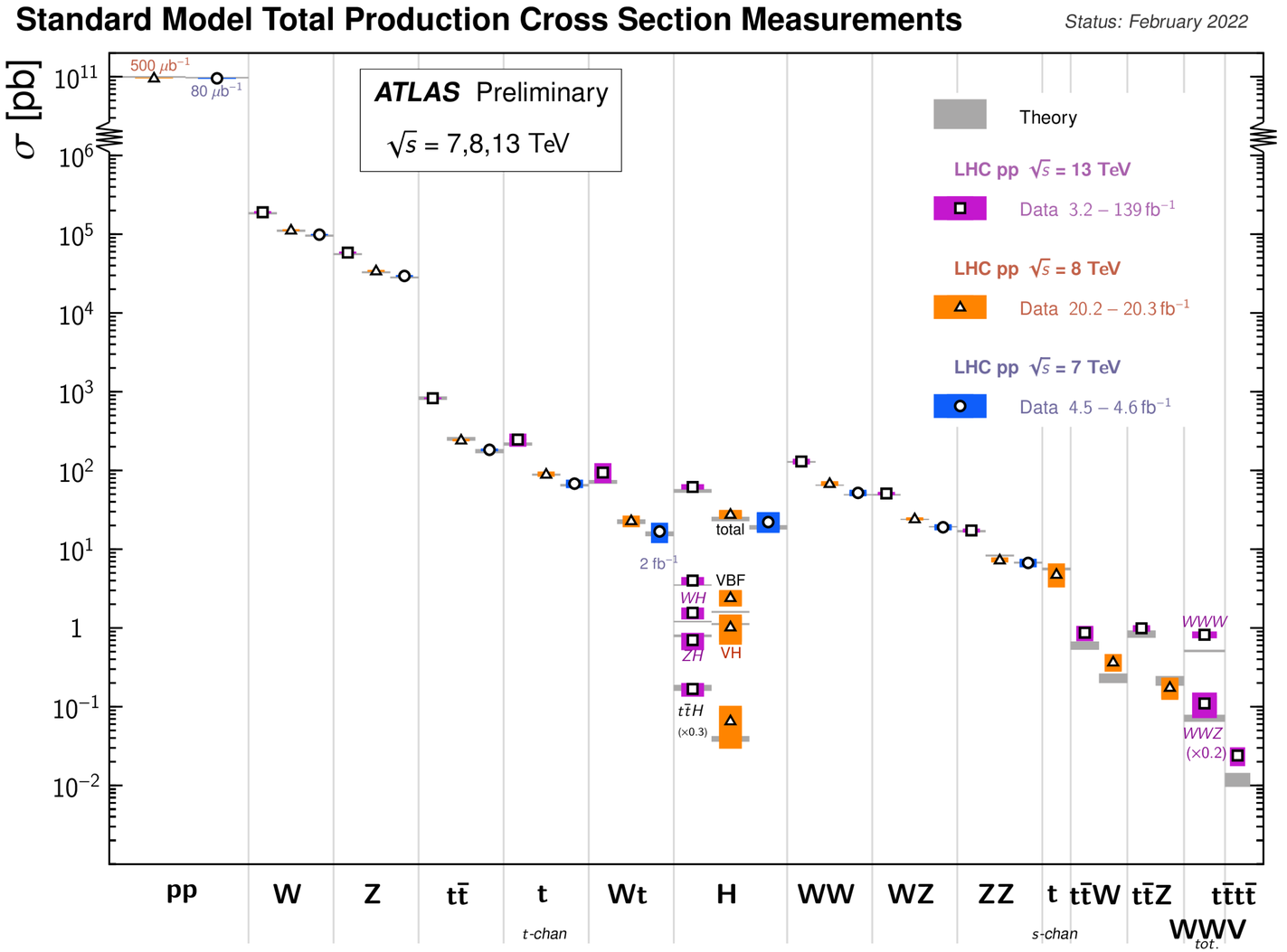
- Often have strong η dependence, some corrections can be large





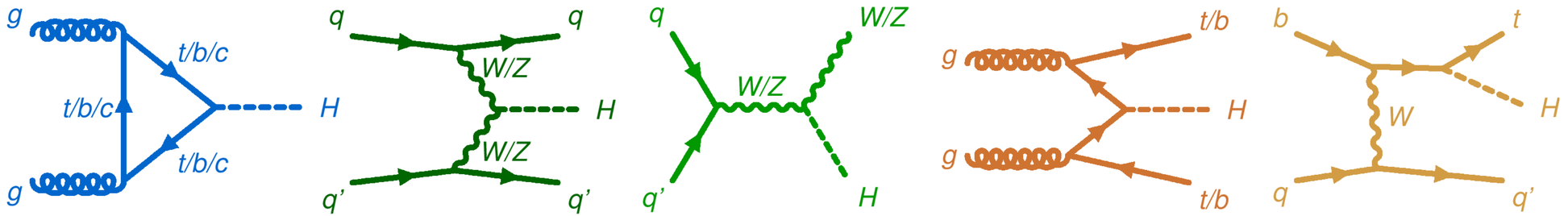
A brief aside… Theoretically not all particles are equal

- QCD dominates (i.e. we produce a lot of jets)
- For the W/Z decays to hadrons dominate
- For Higgs, decays to b-quarks and taus dominate



As a general rule - A Higgs example

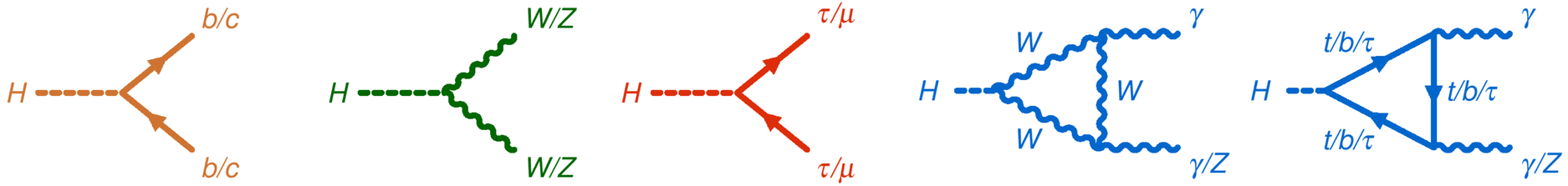
Production



Probability

More → Less

Decay



As a general rule - A Higgs example

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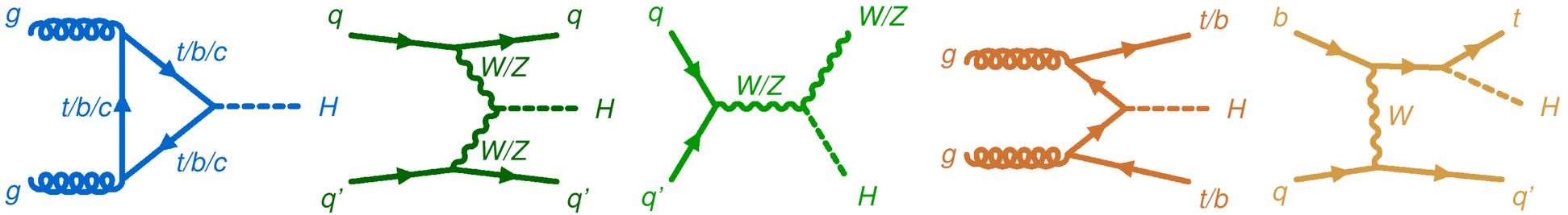


Probability

More

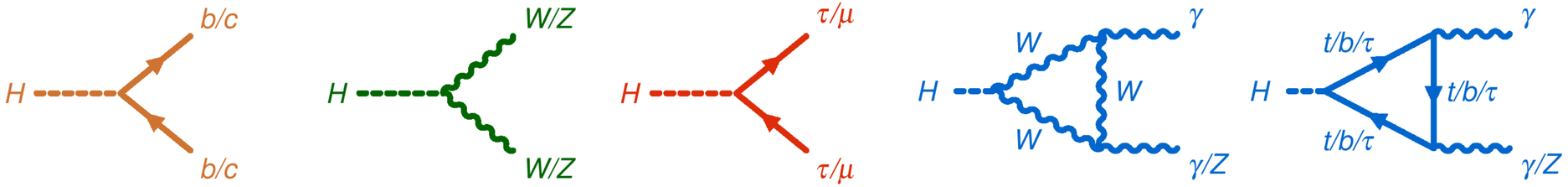
Less

Experimentally

Harder

Easier

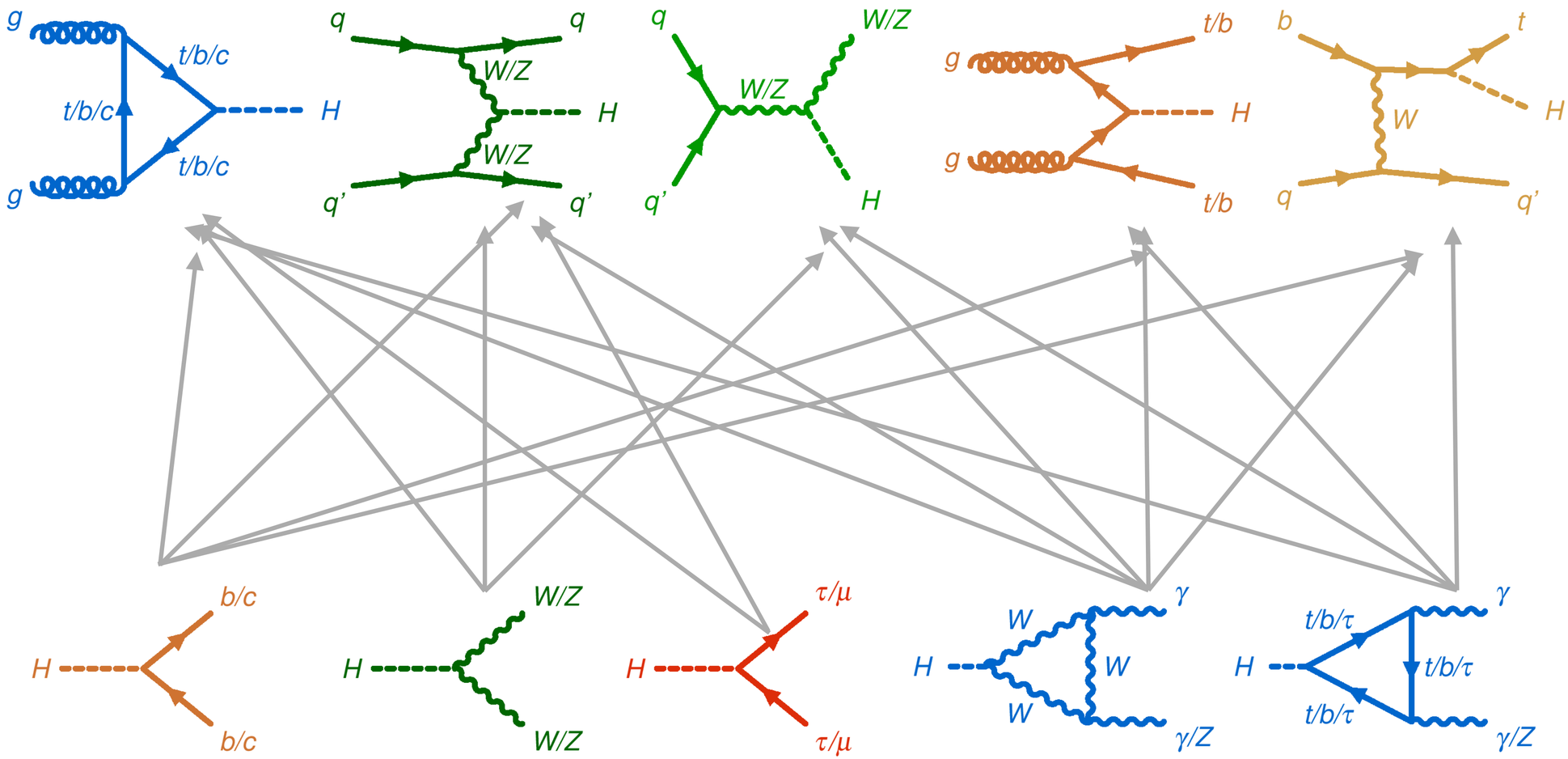
Decay



In practice - measure them all

Production

Decay



In practice - measure them all

Production

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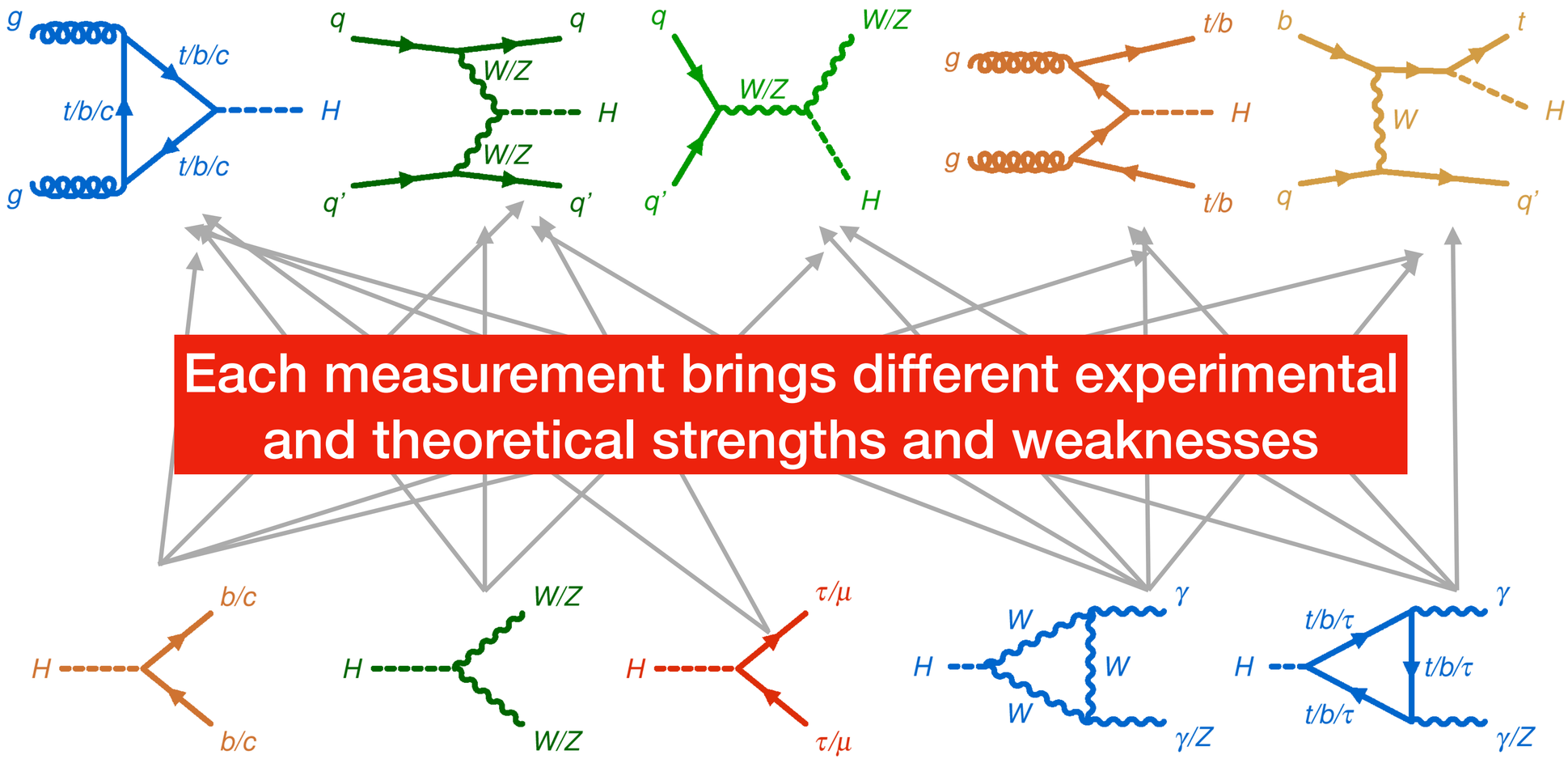
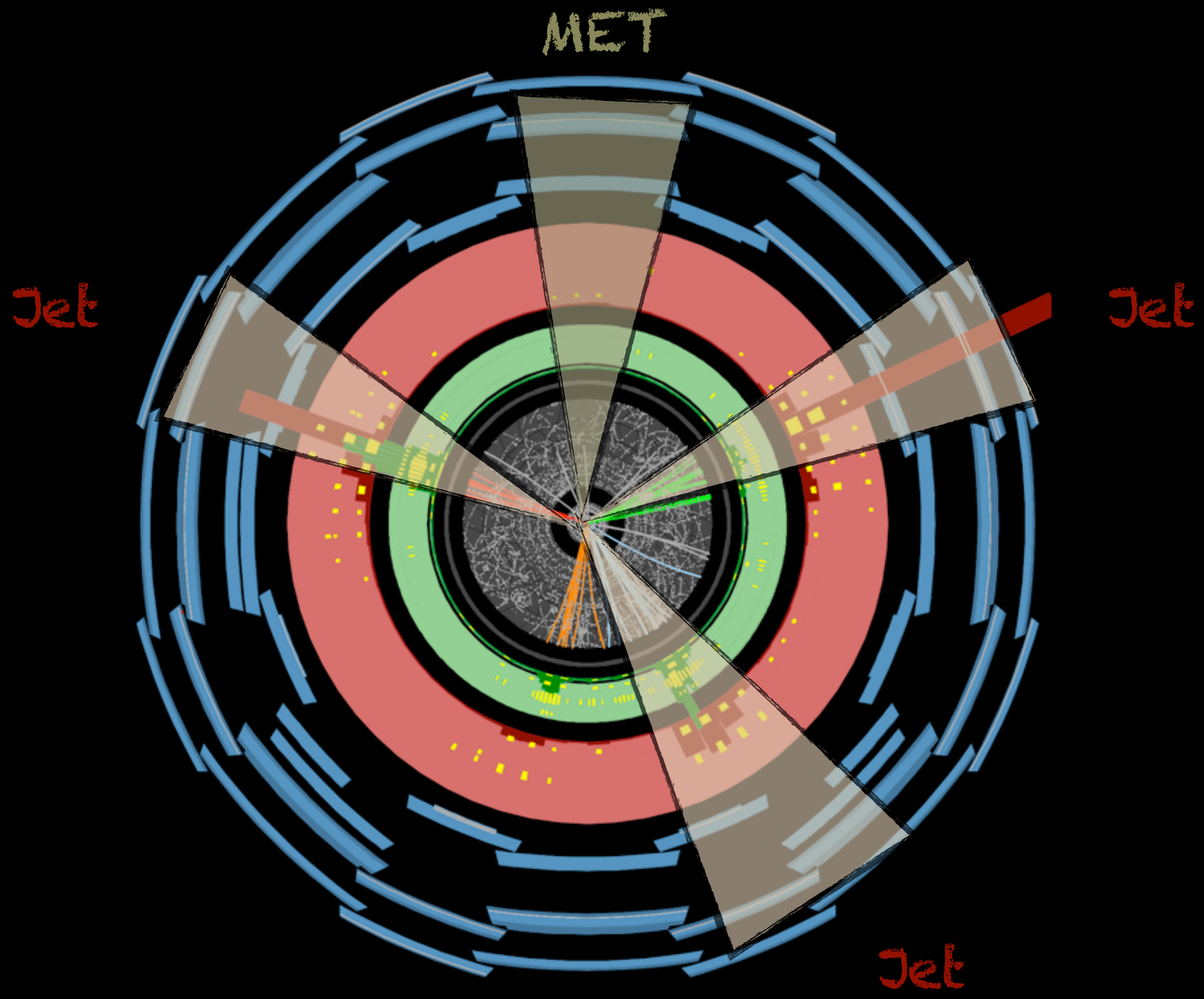


Each measurement brings different experimental and theoretical strengths and weaknesses

- How precisely can you reconstruct the final state? Is it precise enough?



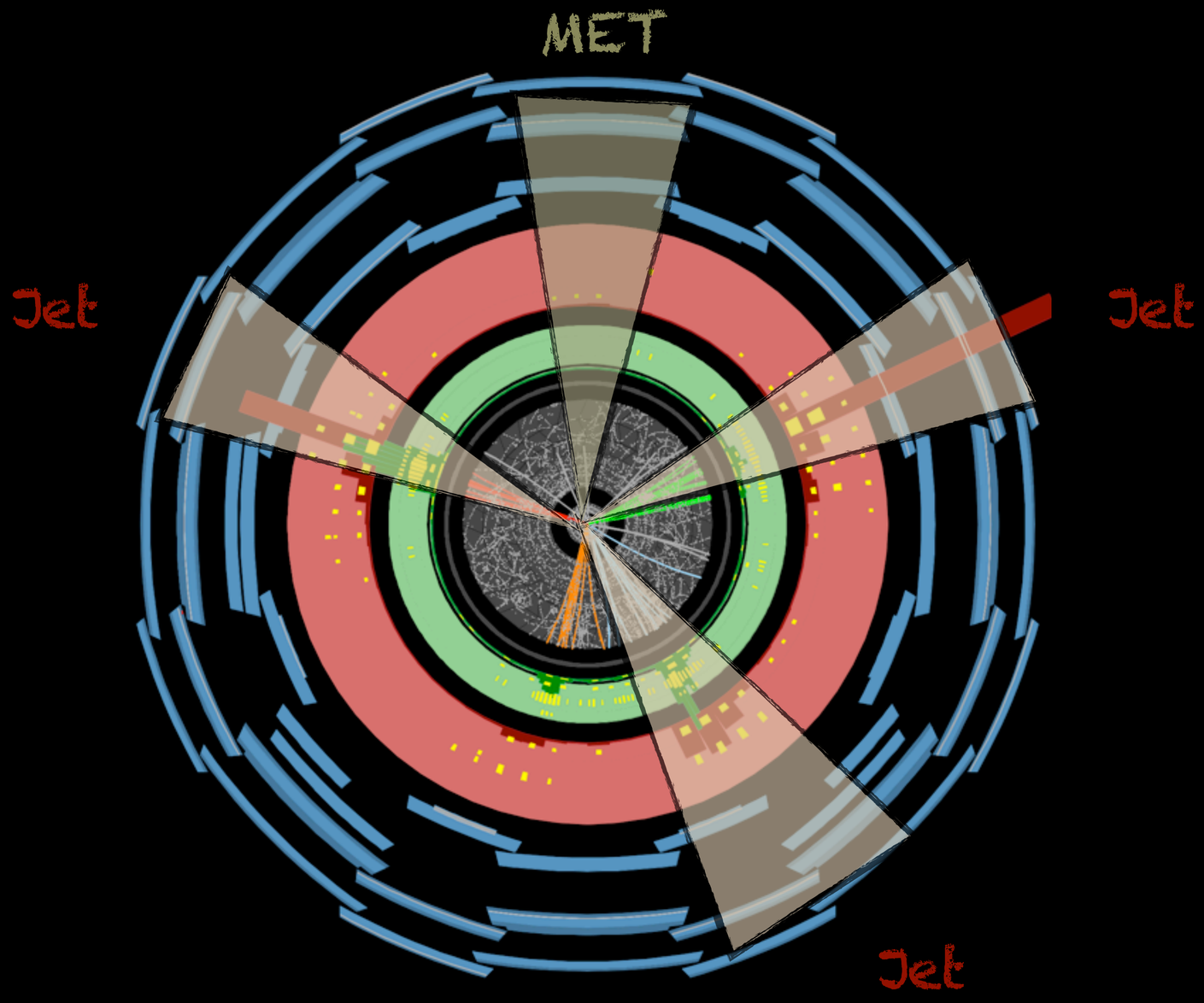
Energy_{xy} DM = Energy_{xy} before - Energy_{xy} Jets

- How precisely can you reconstruct the final state? Is it precise enough?

Missing energy is the weakest link

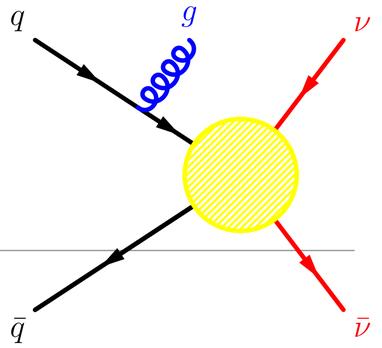
Relies on measuring everything else

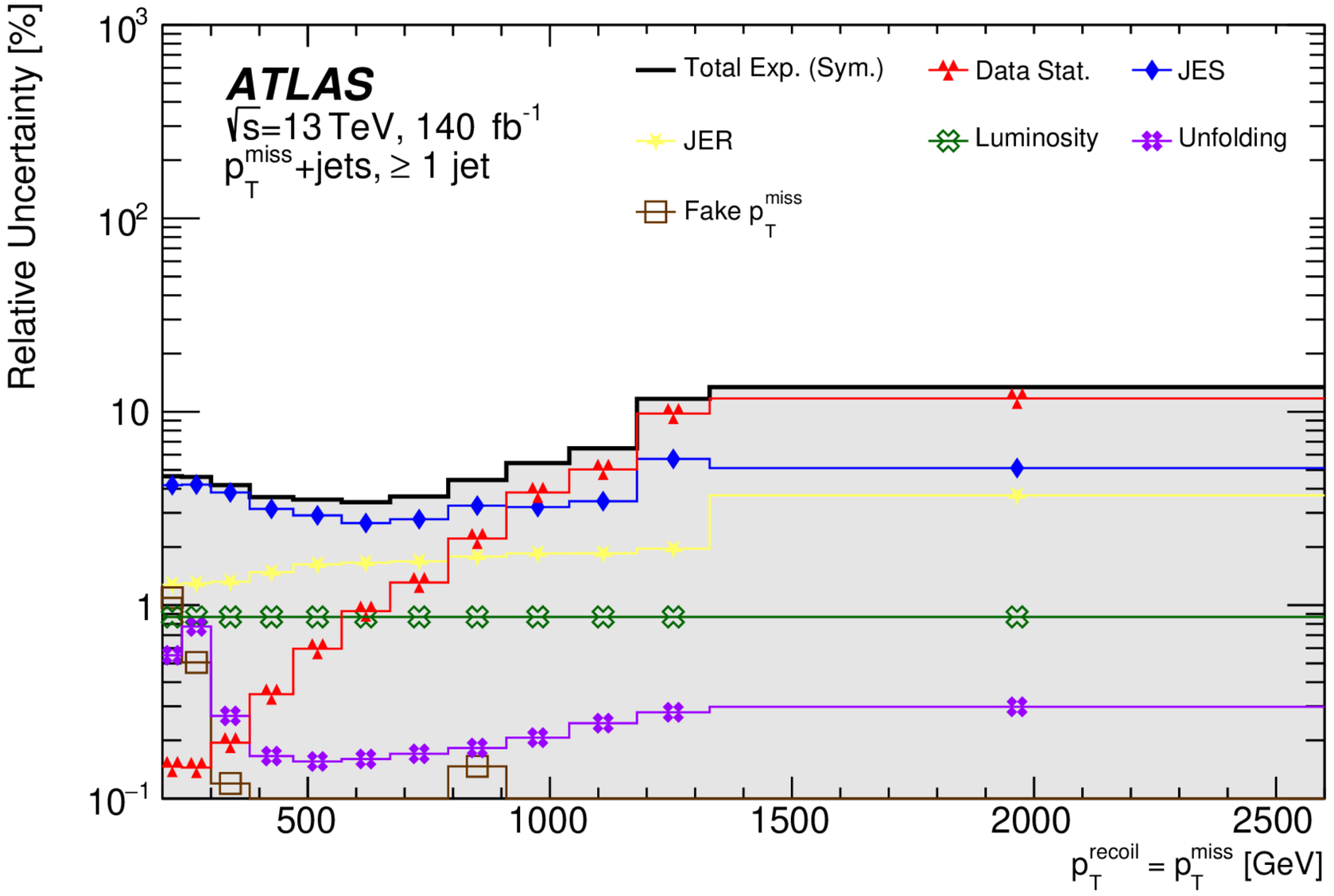
The **detector resolution** of each other object and **the uncertainty** on the measurement of each other object is propagated to the determination of missing energy



Energy_{xy} DM = - Energy_{xy} Jets

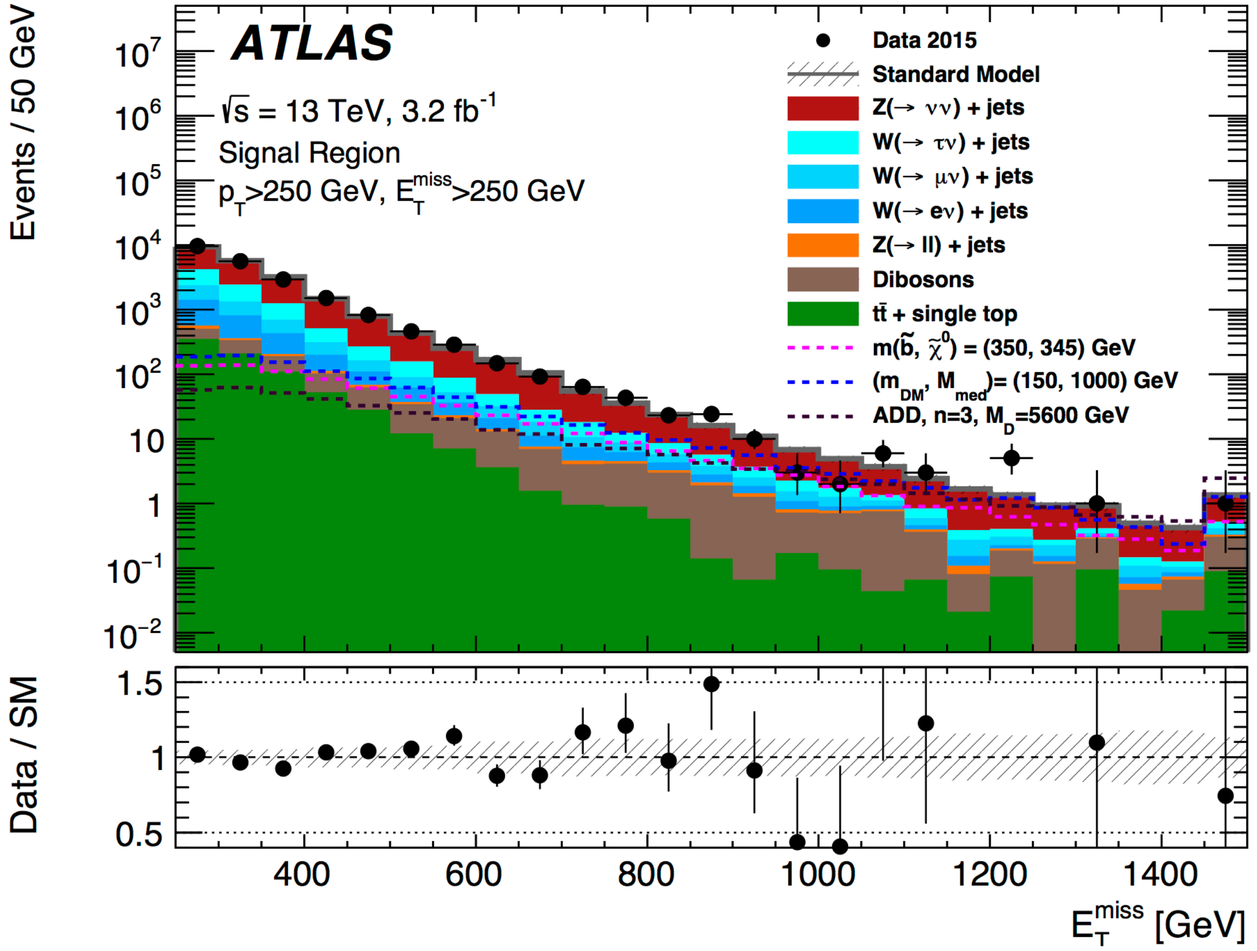
Reconstructing the final state





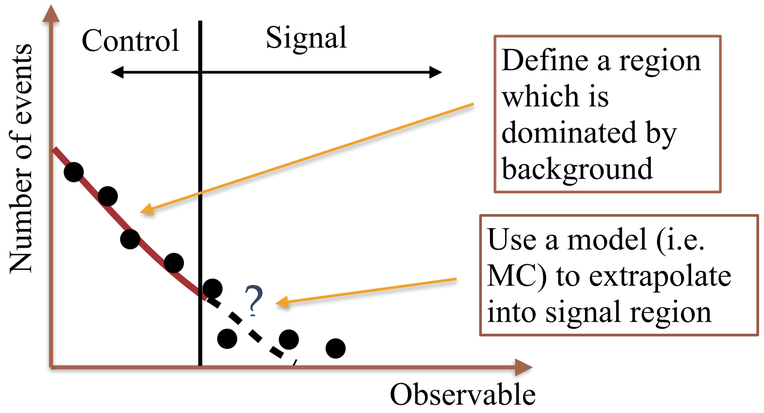
Backgrounds

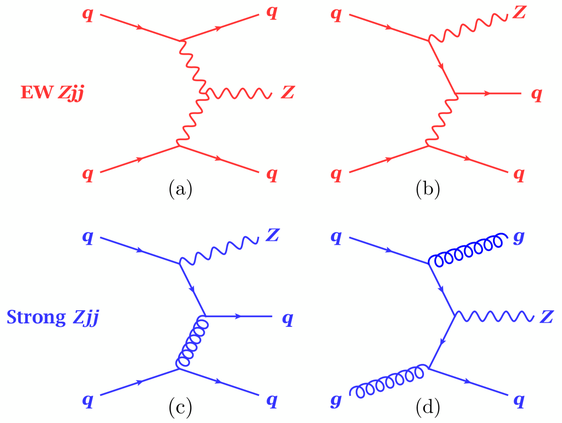
- How large is the signal compared to backgrounds with the same final state?
- Three main types of backgrounds
  - Backgrounds from the same final state (i.e. Z to neutrinos + jets)
  - Backgrounds where an object was outside the acceptance or not reconstructed (i.e W decays to leptons)
  - Backgrounds due to misconstruction (i.e. multijet production)

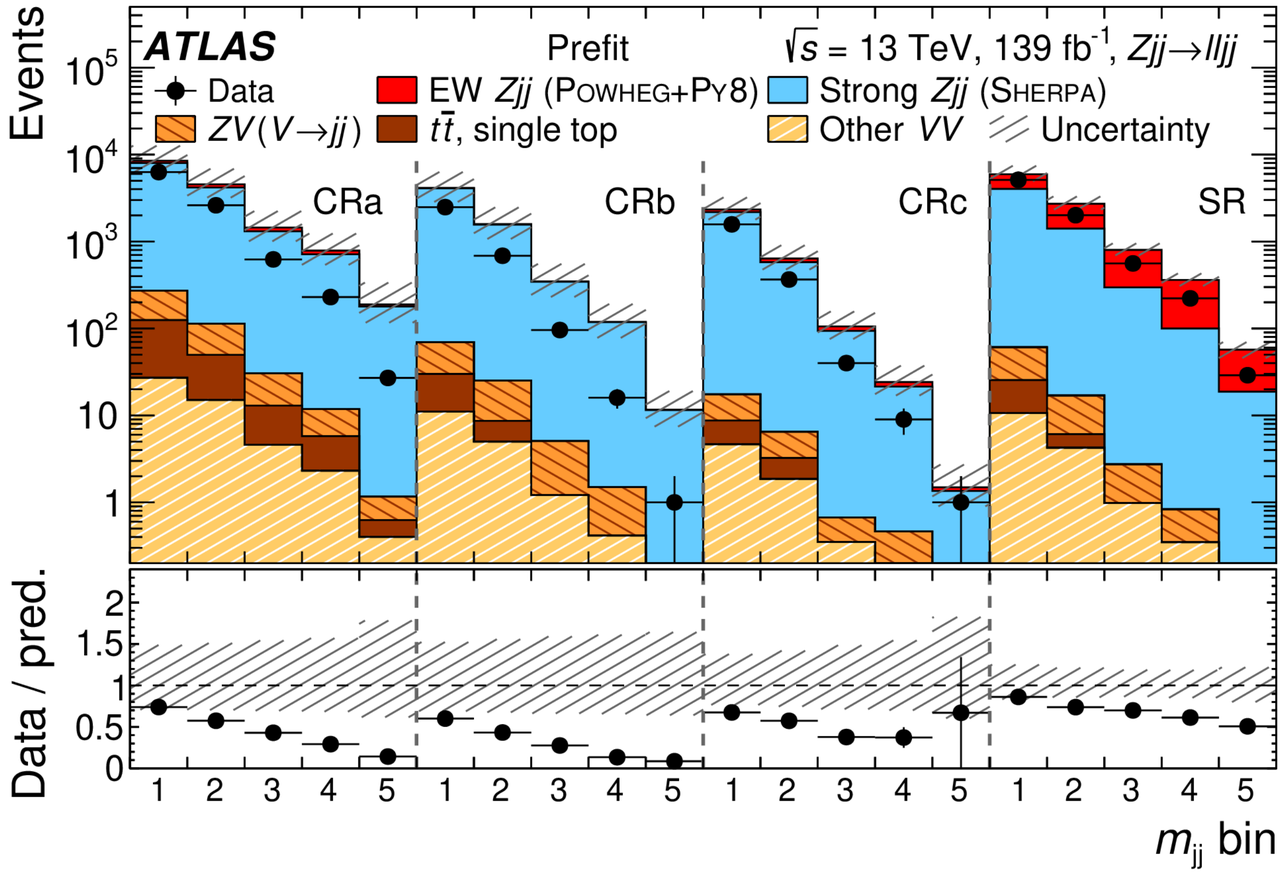


Uncertainties

- What will be the dominate uncertainty? Can it be controlled or constrained?







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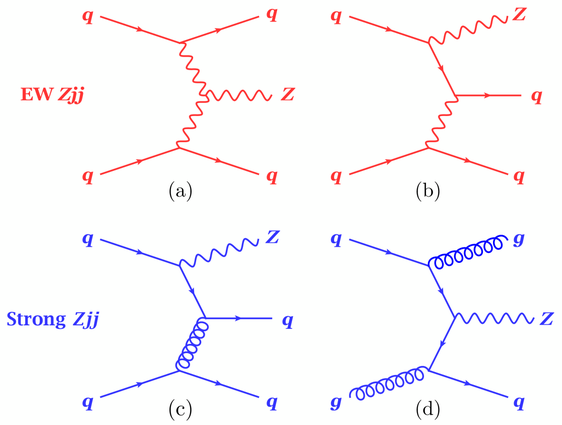
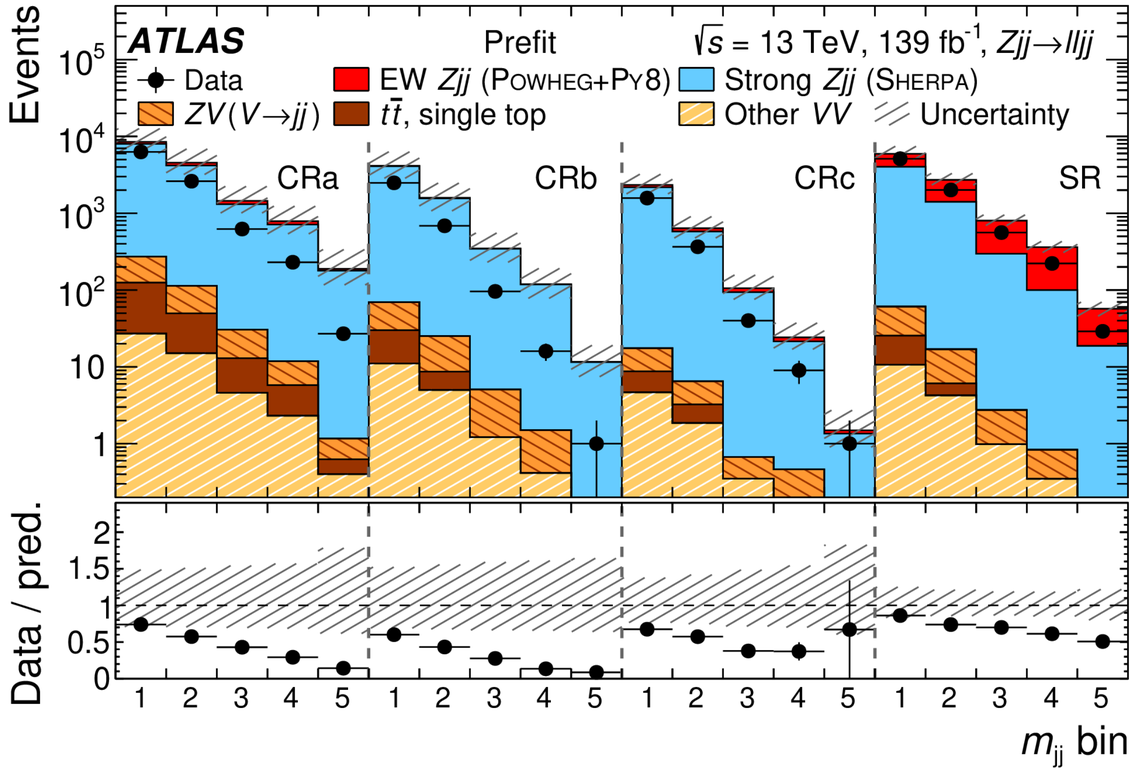
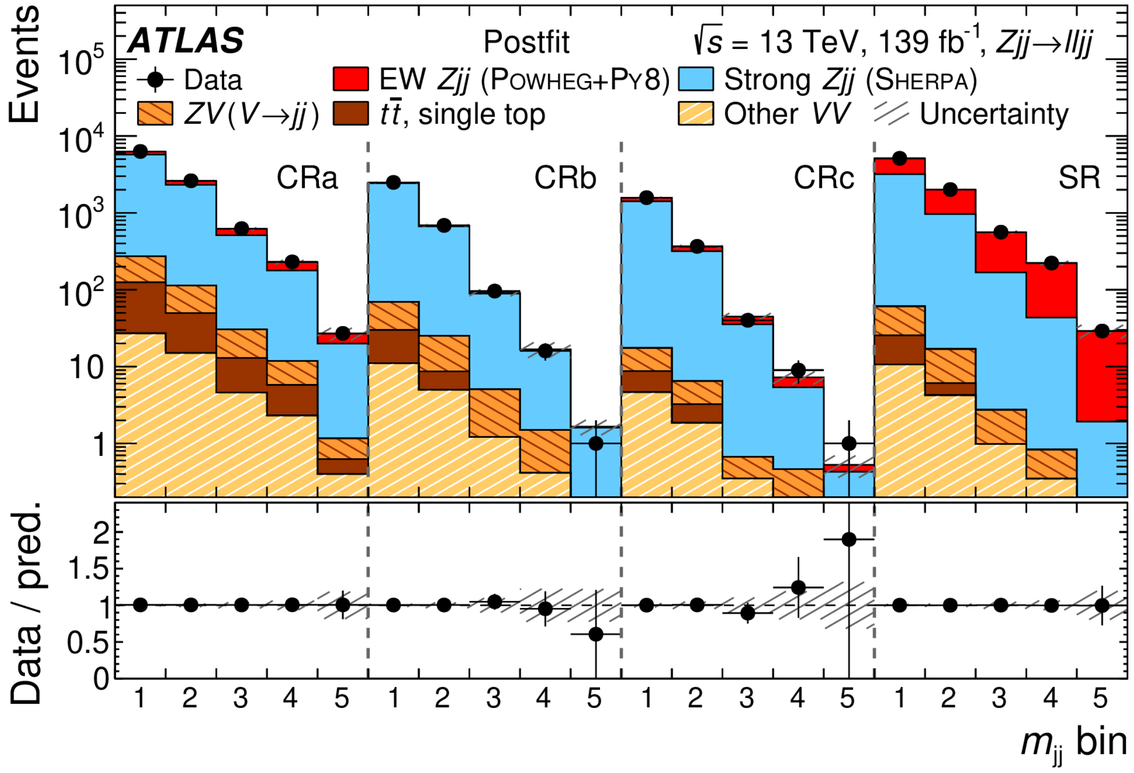
- What will be the dominate uncertainty? Can it be controlled or constrained?



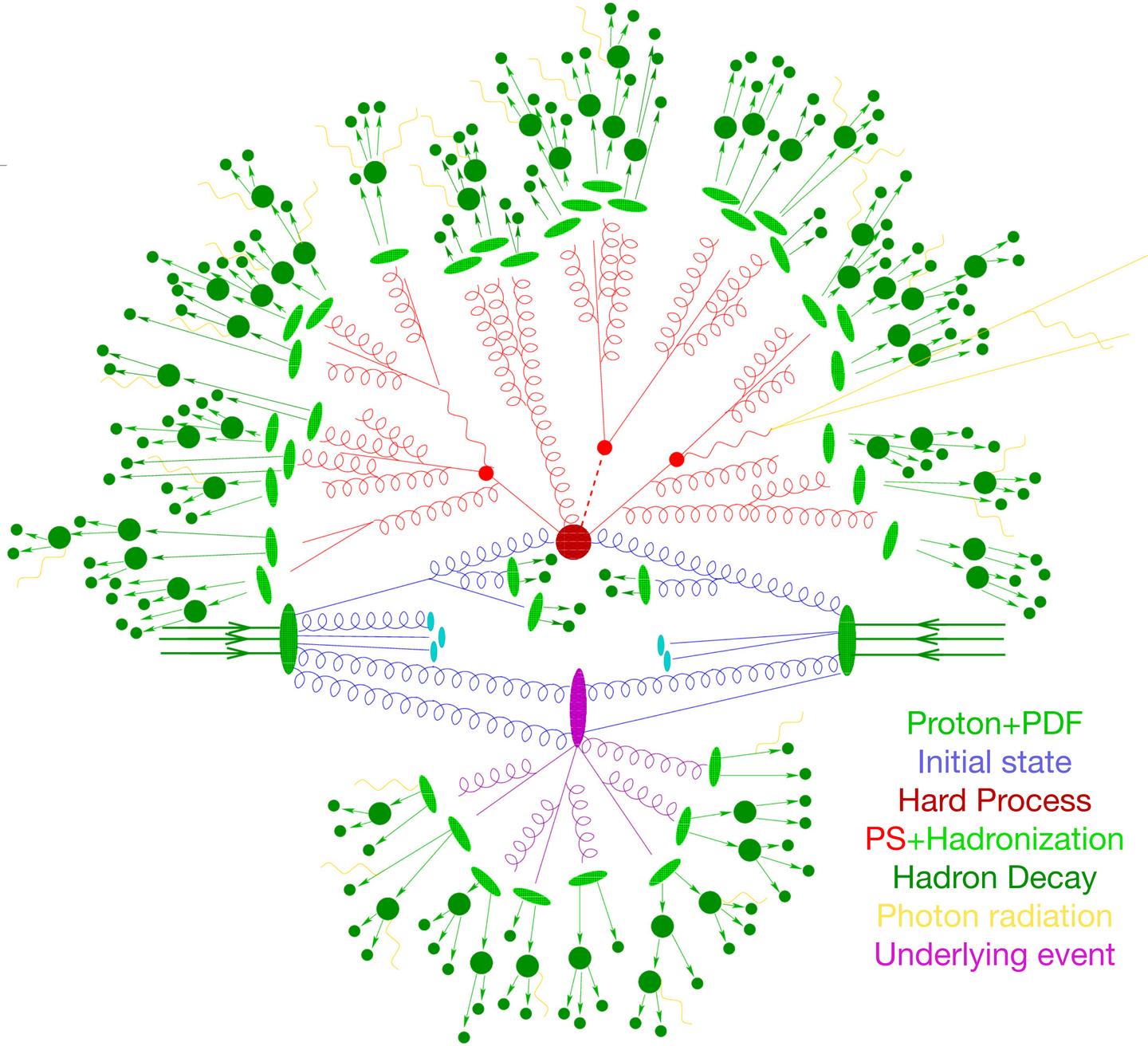




Defining the phase space

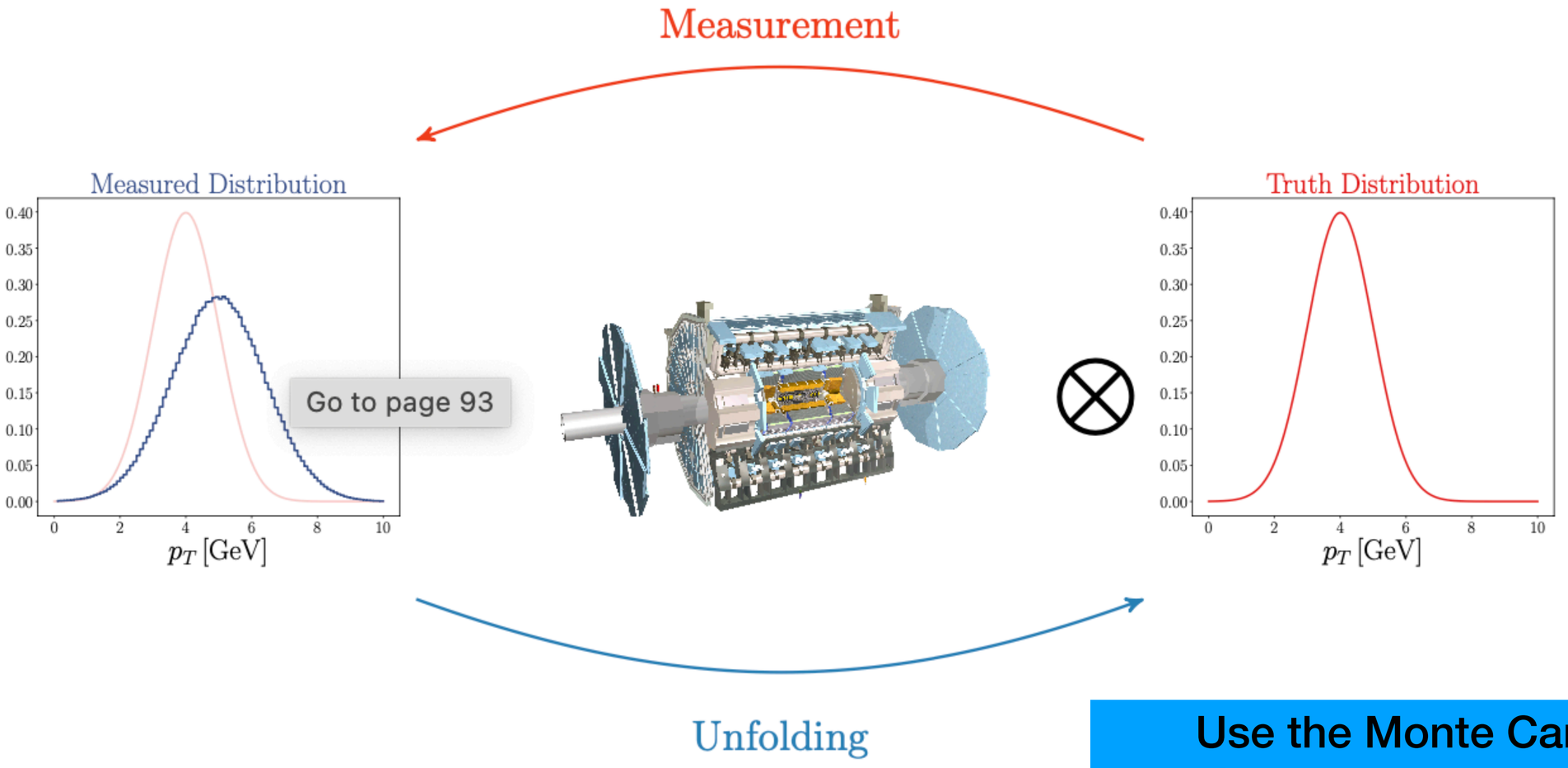
Defining the phase space

- The detector has a certain kinematic region (i.e. it's not a 4π detector and it can't measure pT = 0)
- Fiducial phase space is a criteria applied to final state 'truth' particles



Unfolding - Correcting for detector effects

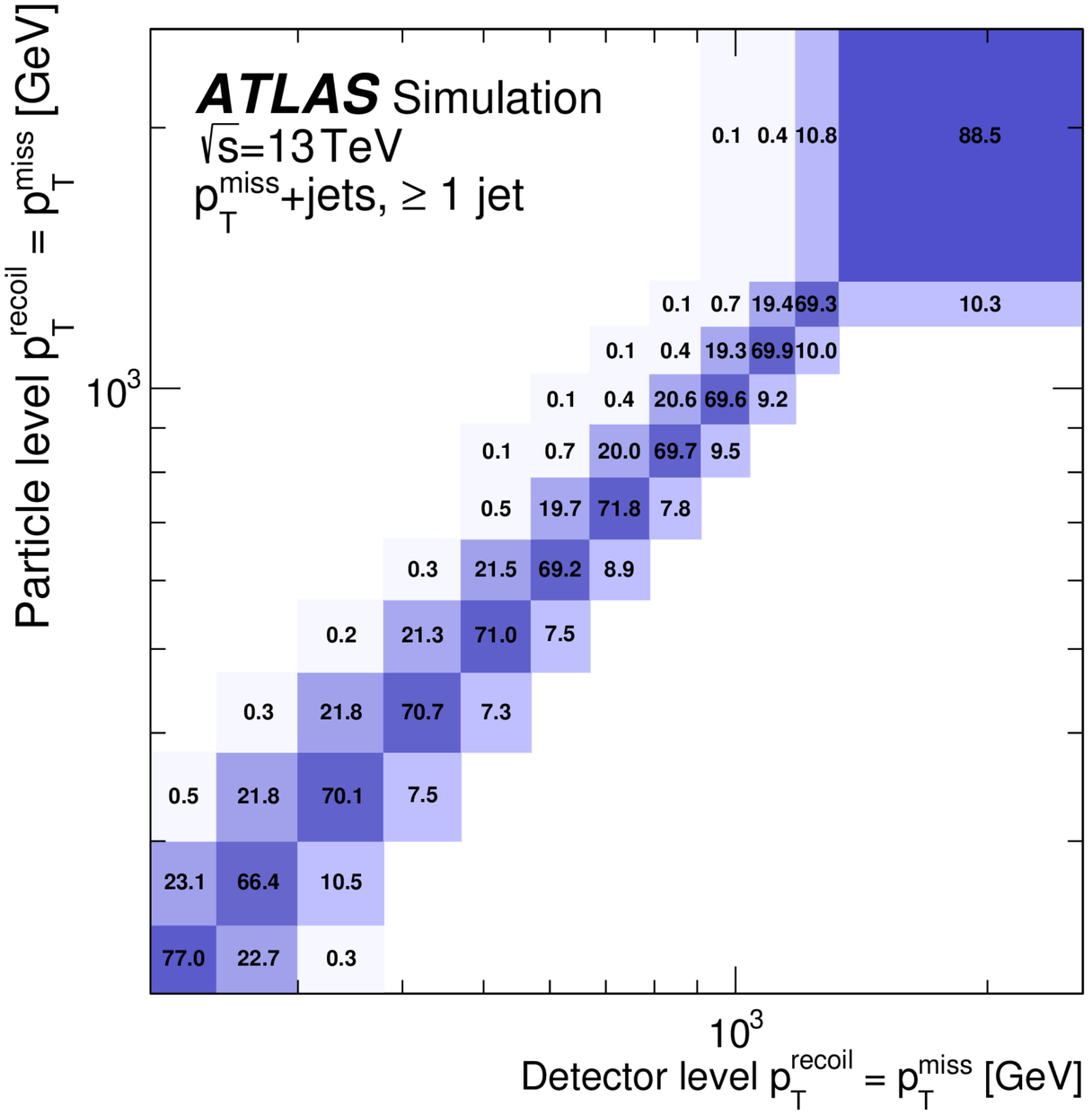
Unfolding - the basics



Use the Monte Carlo/ Simulation to unfold

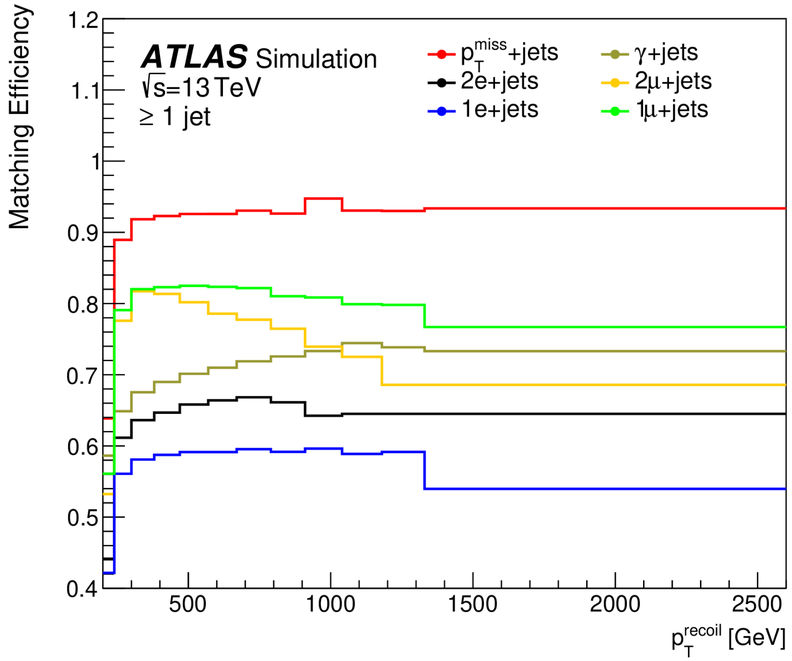
Unfolding - the basics

- Migration matrix - maps truth to reconstructed object
  - Fewer migrations is better



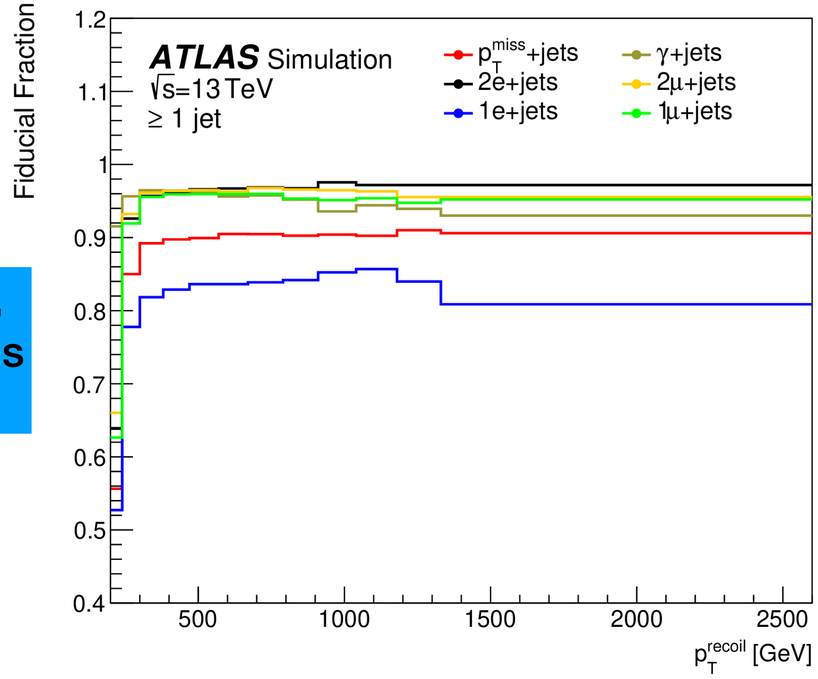
Unfolding - the basics

- Additional corrections for
  - Events in truth phase that are not at detector level (matching efficiency)
  - Events at detector-level but in truth the phase space (shows as the fiducial fraction, fraction where an event is in both)
  - Closer to 1.0 is better

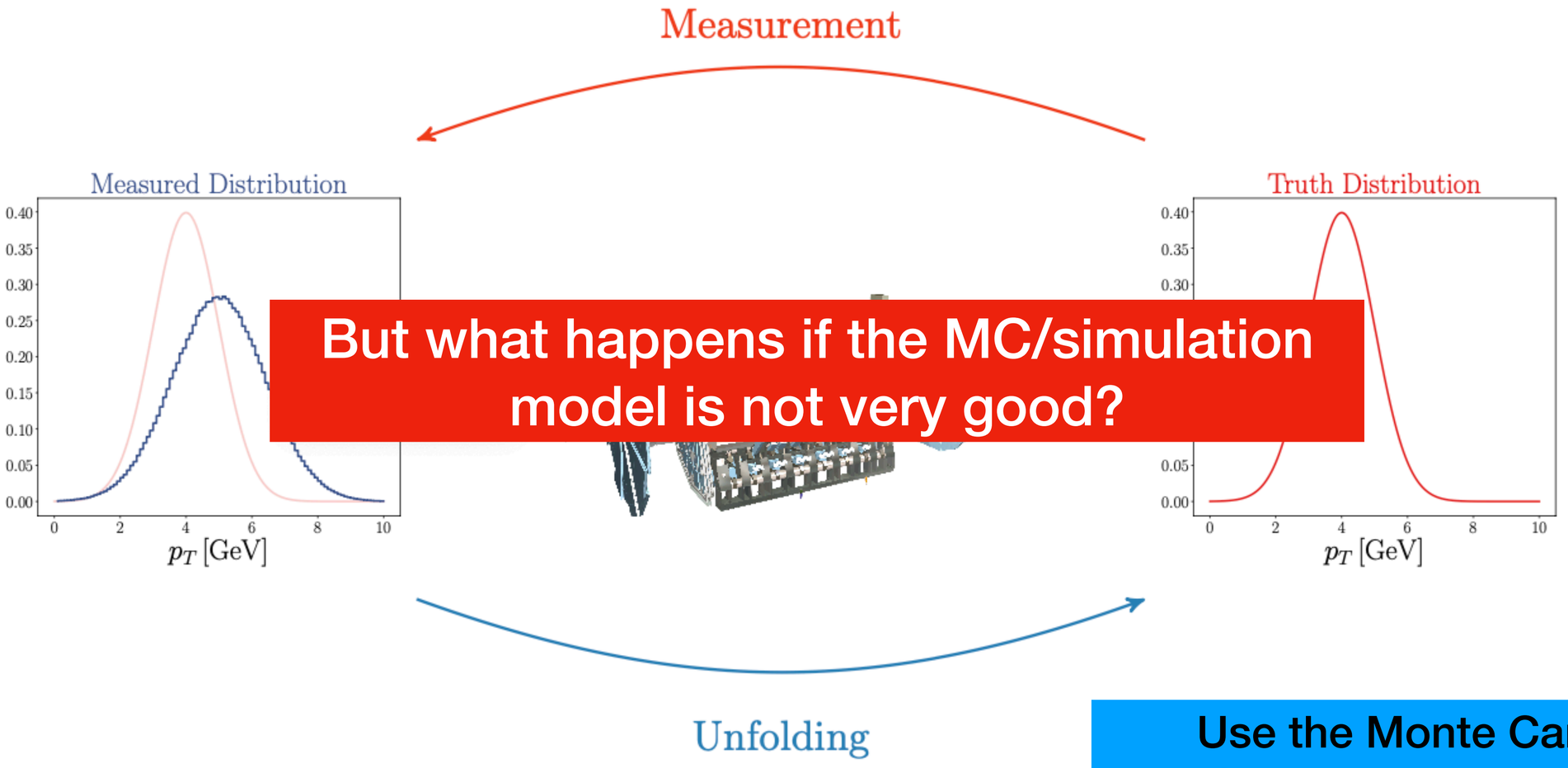


A poor choice of phase space definition can affect this

Poor choice of binning, poor detector resolutions can affect this



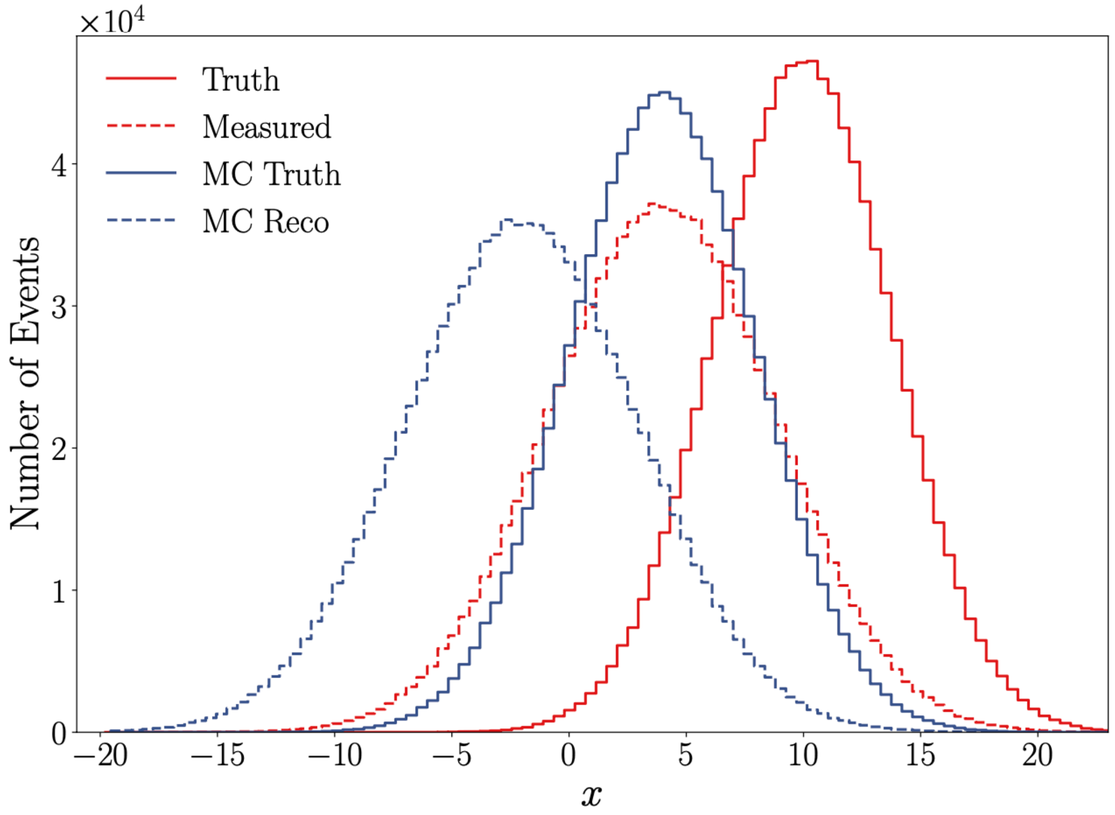
Unfolding - the basics



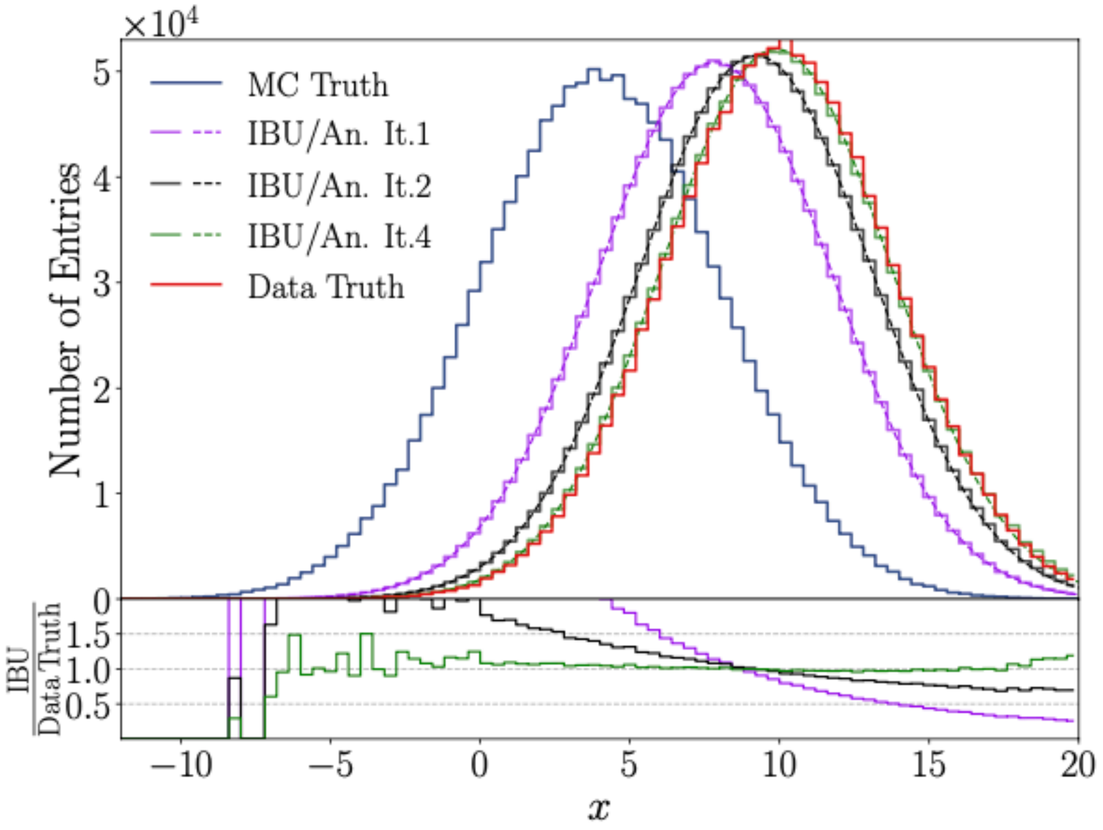
But what happens if the MC/simulation model is not very good?

Use the Monte Carlo/ Simulation to unfold

A poor MC/simulation model example



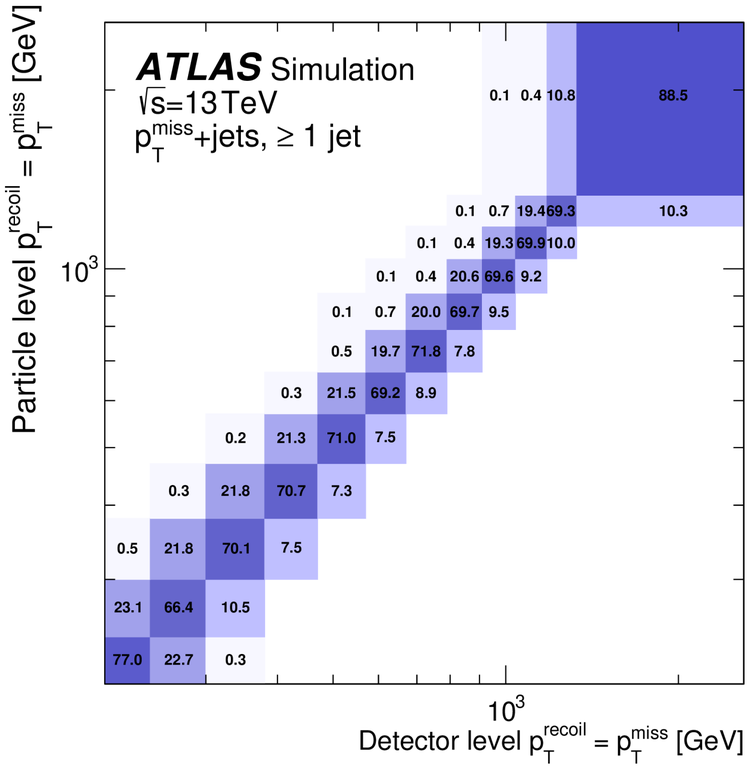
A toy example of a poor model

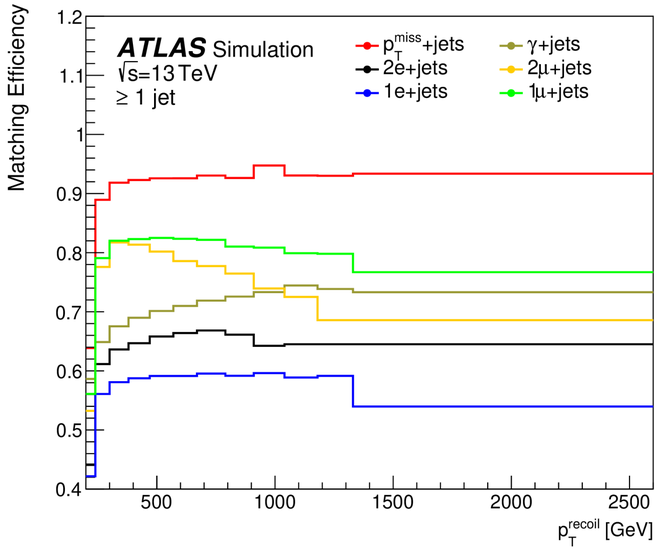


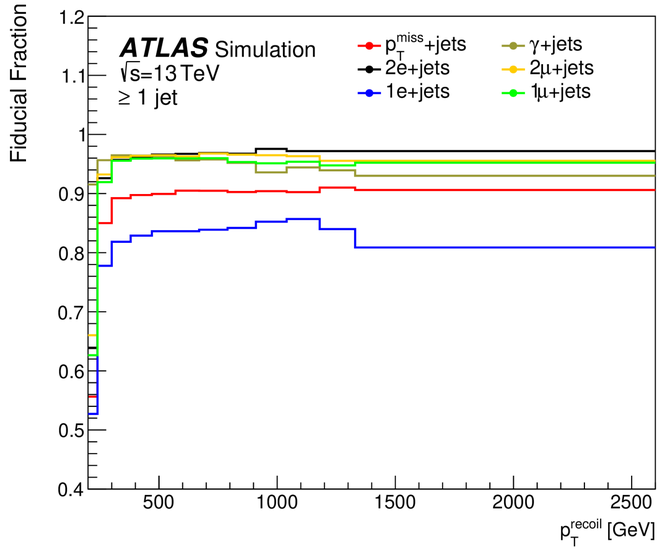
To avoid model dependences on the measure, do an iterative approach

A word of caution

- We use iterative unfolding to reduce dependencies on the underlying model





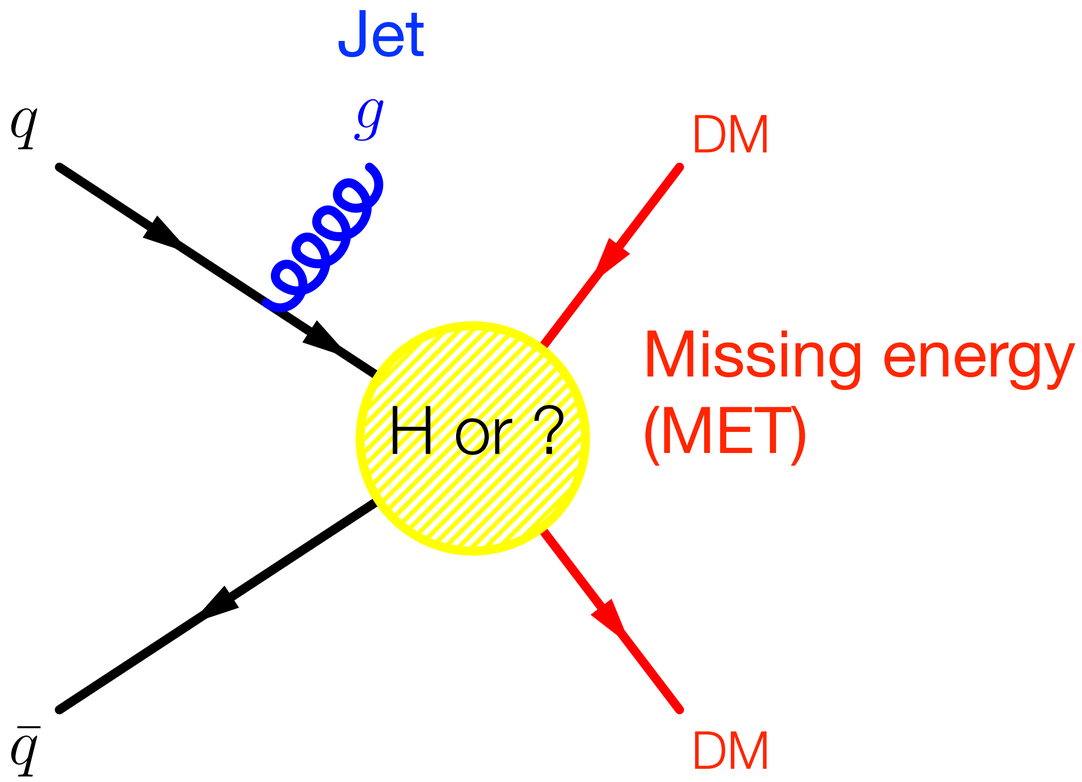


Iterations largely improve the migration matrix

These are more susceptible to model dependencies and therefore the optimal phase space and measurement definition for the question at hand is critical

A real example with all the pieces in place

My question - Does DM couple to the Higgs?



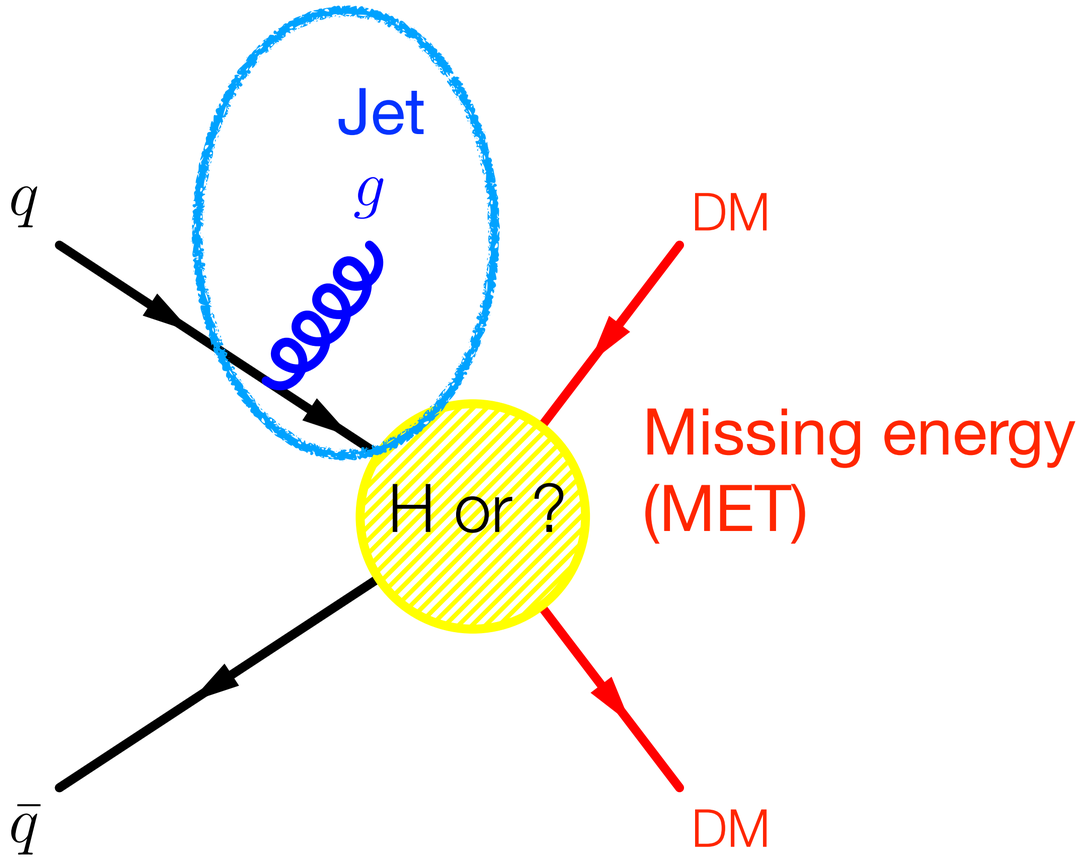
A real example with all the pieces in place

My question - Does DM couple to the Higgs?

My measurement - **the process will be rare — Focus on jets (high cross section)**

Backgrounds will be large — Will measure them via control regions

Jets are imprecise — Will reduce the uncertainties via a ratio



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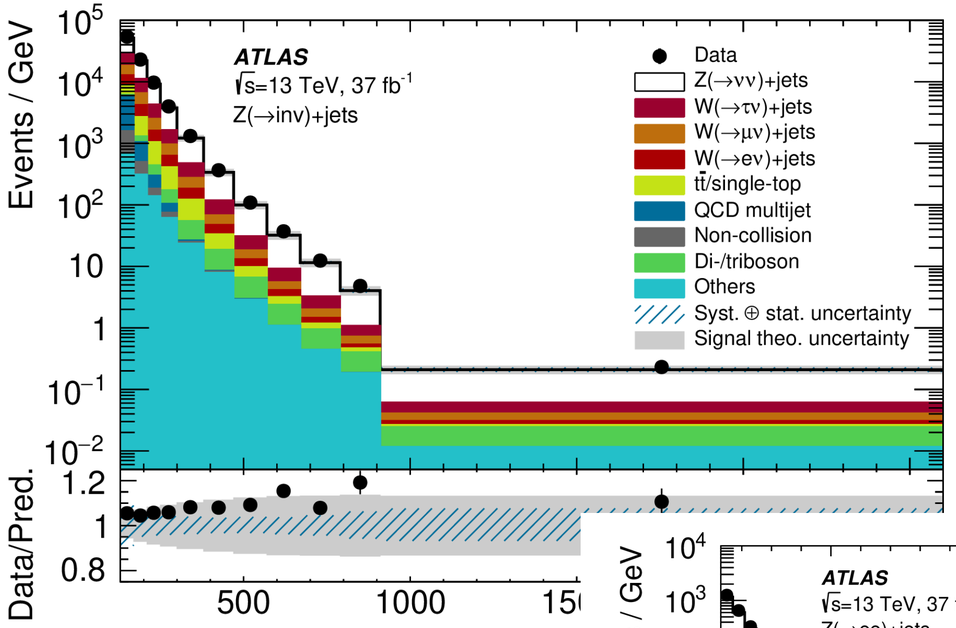
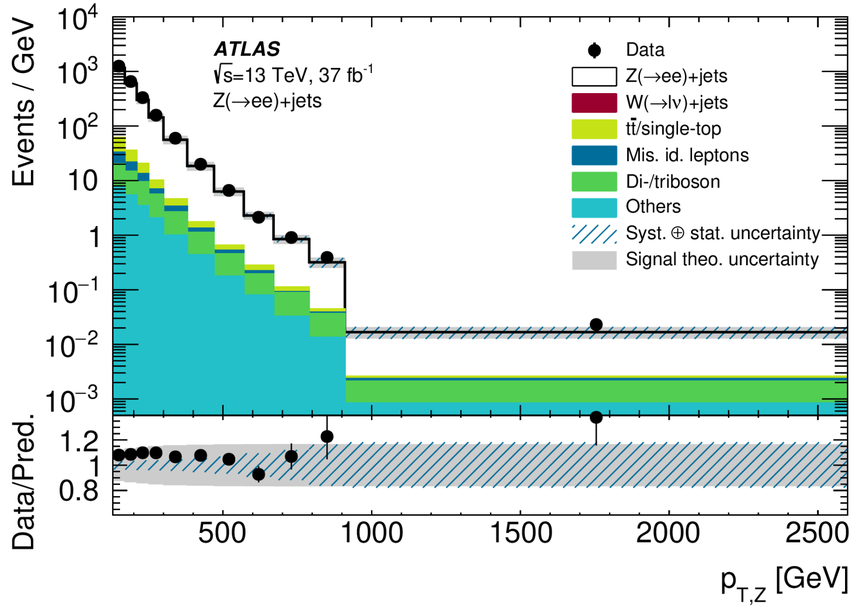


What I want to measure

Background enhanced (control region), rely on theory to extrapolate to my signal region



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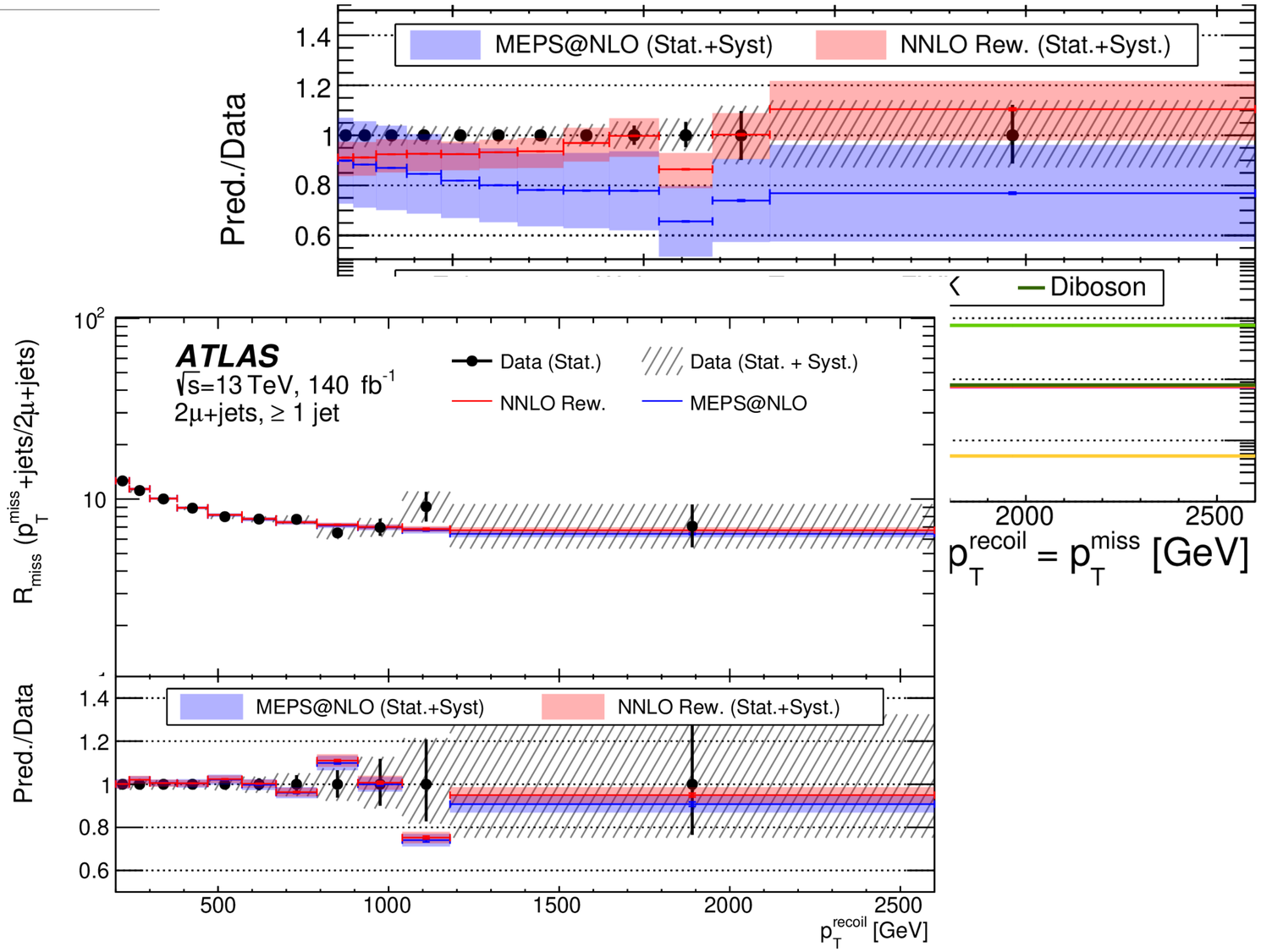
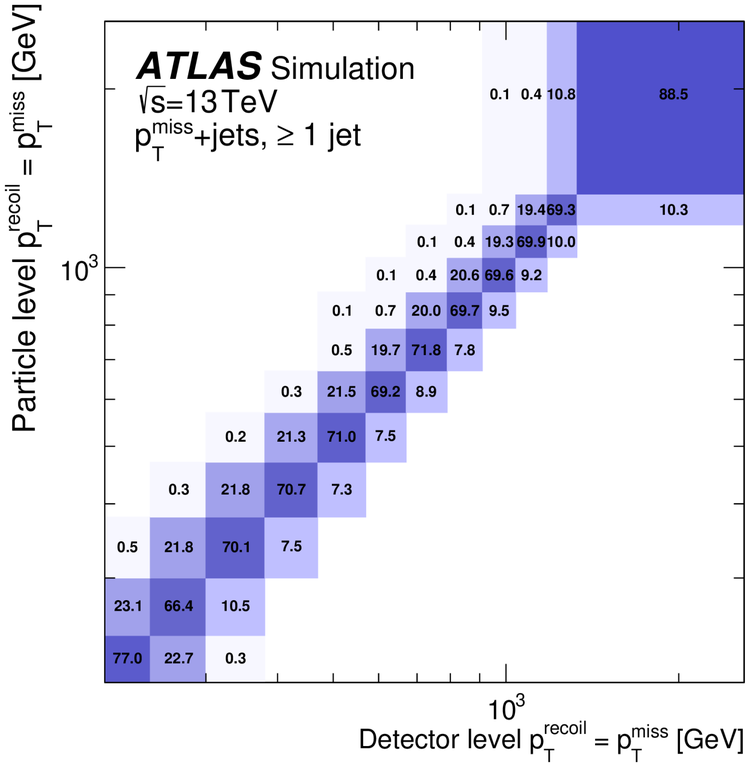
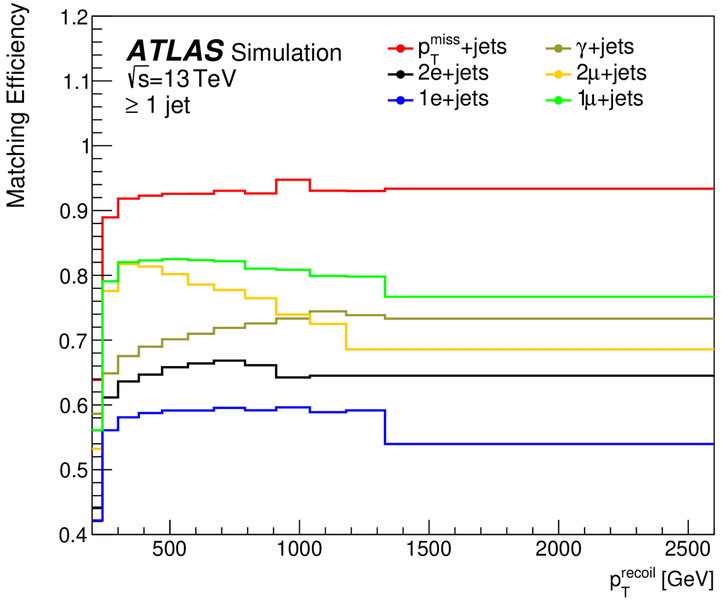
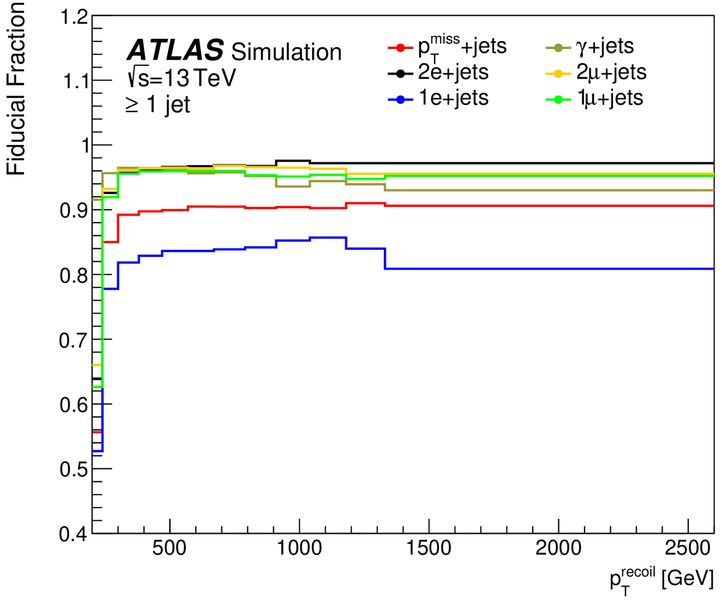


A real example with all the pieces in place

My phase space





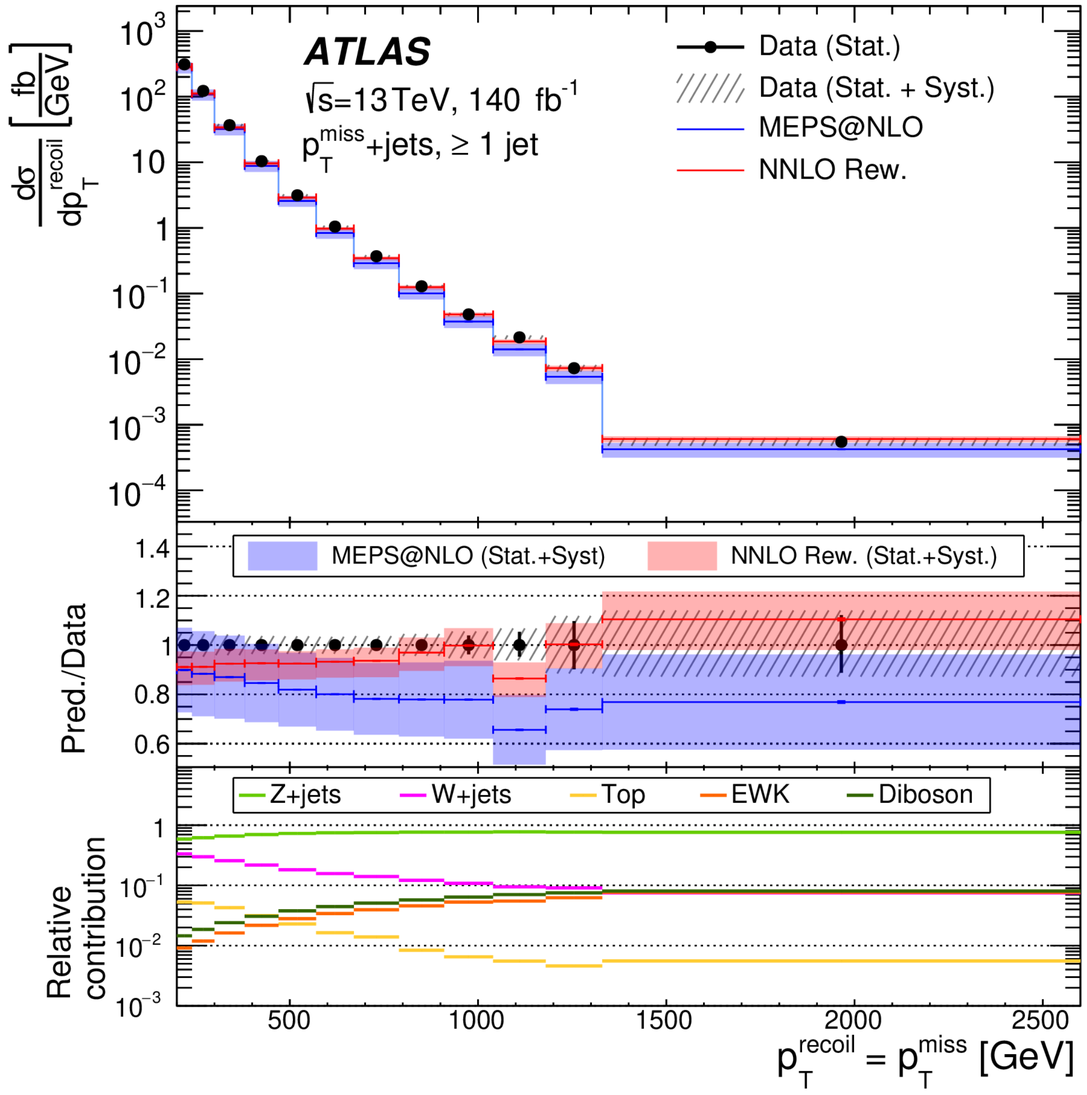


A real example with all the pieces in place

My phase space

My results

Fully corrected! Usable by anyone with a theory

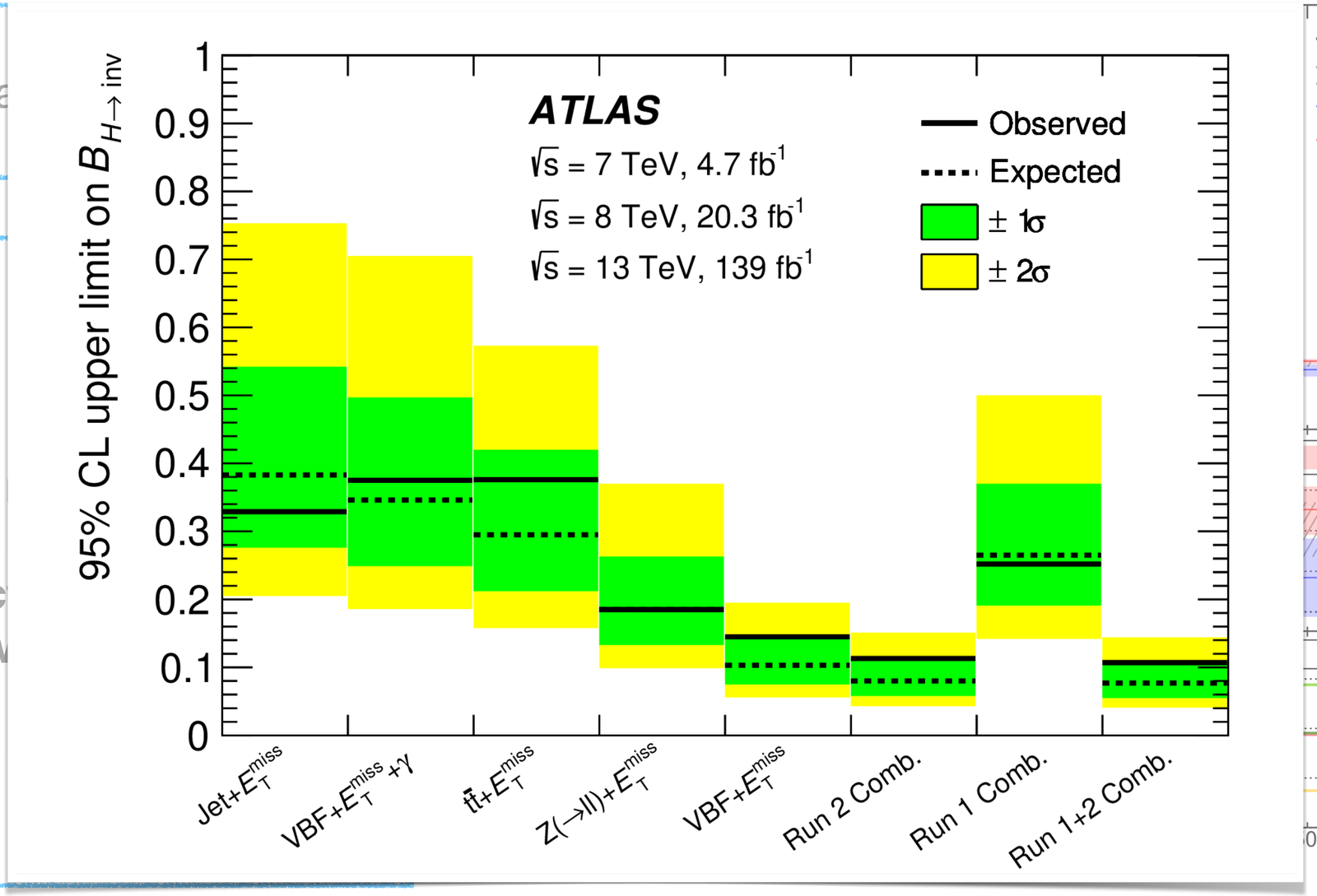


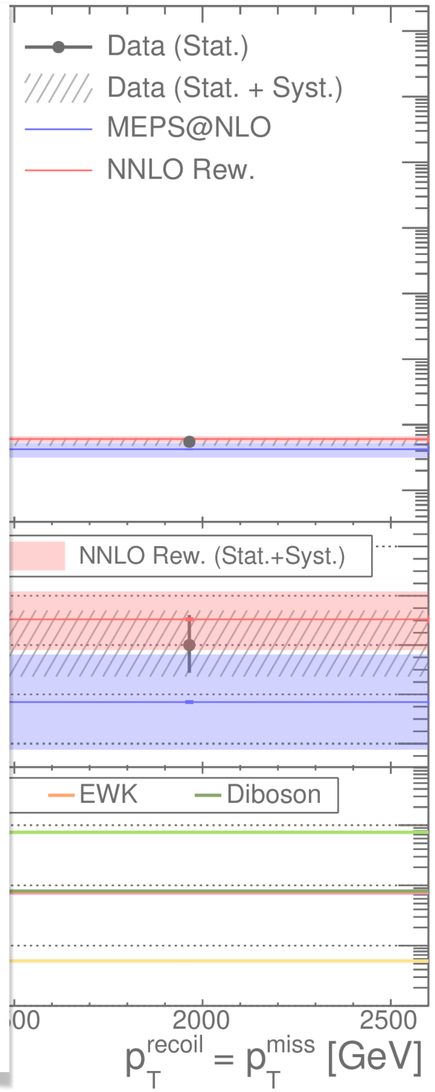
A real example with all the pieces in place

My pha

My

Fully correc
anyone w

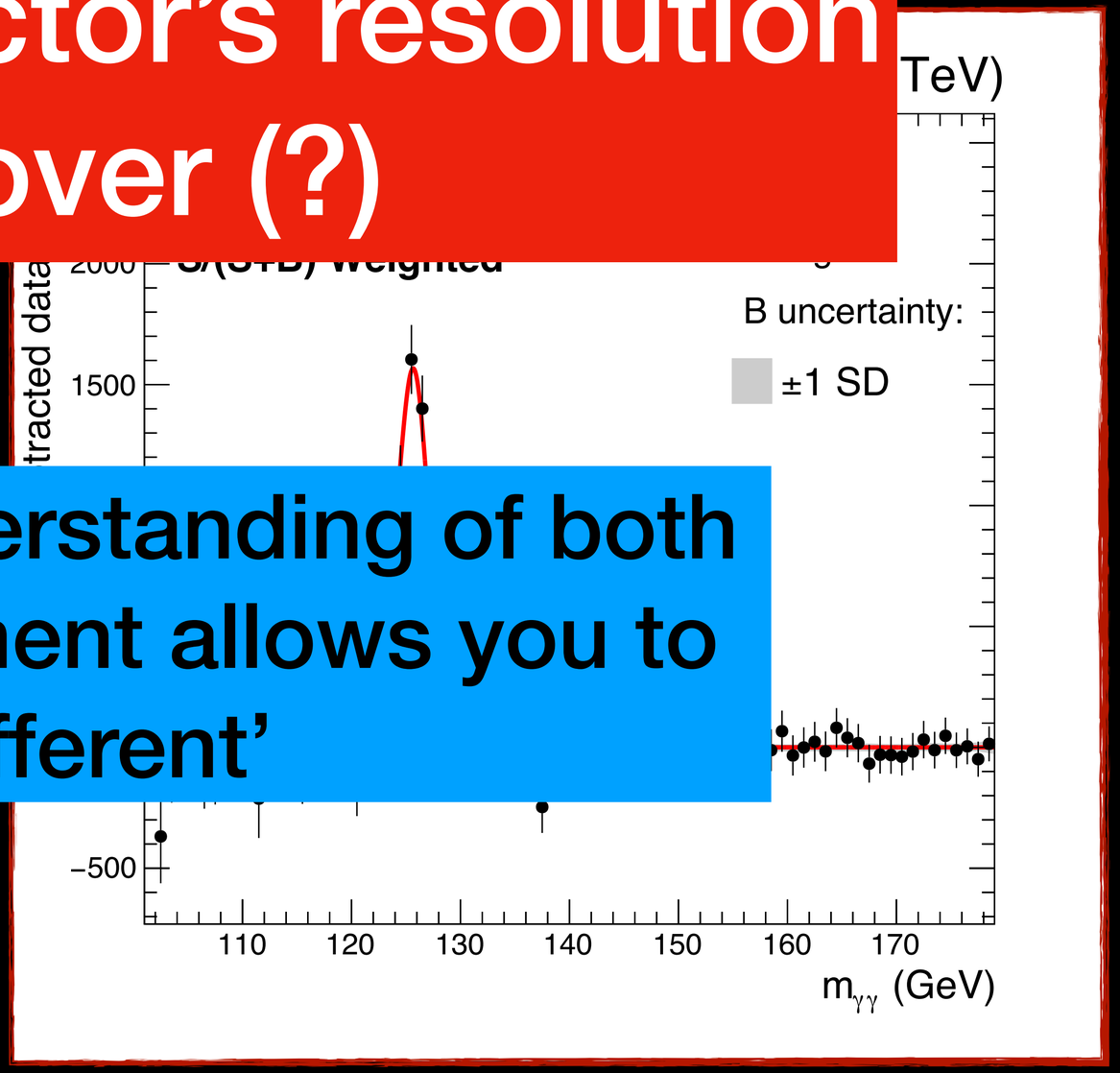




This is the detector's resolution
Game over (?)

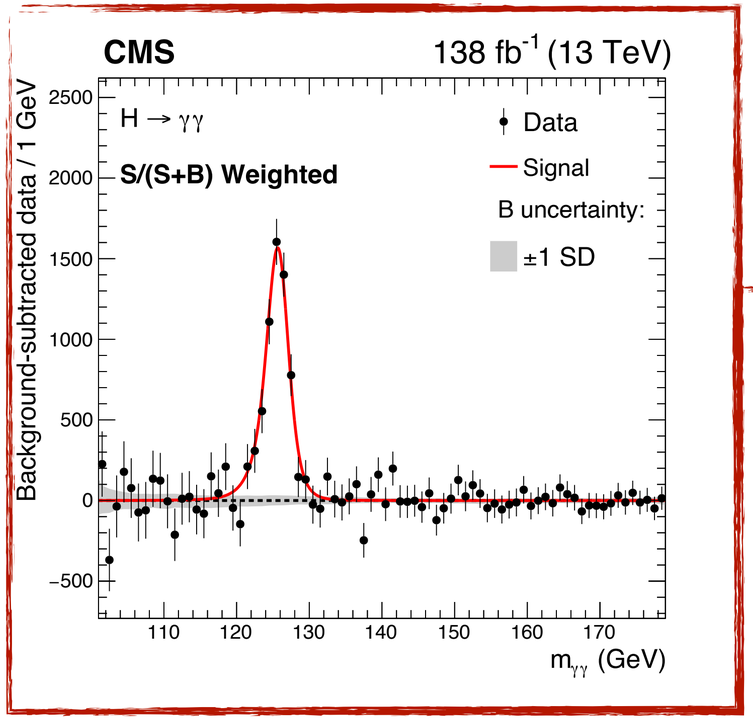
D
mass. How?

- Prediction 4.07 MeV



Having a good understanding of both theory and experiment allows you to 'think different'

An impossible width



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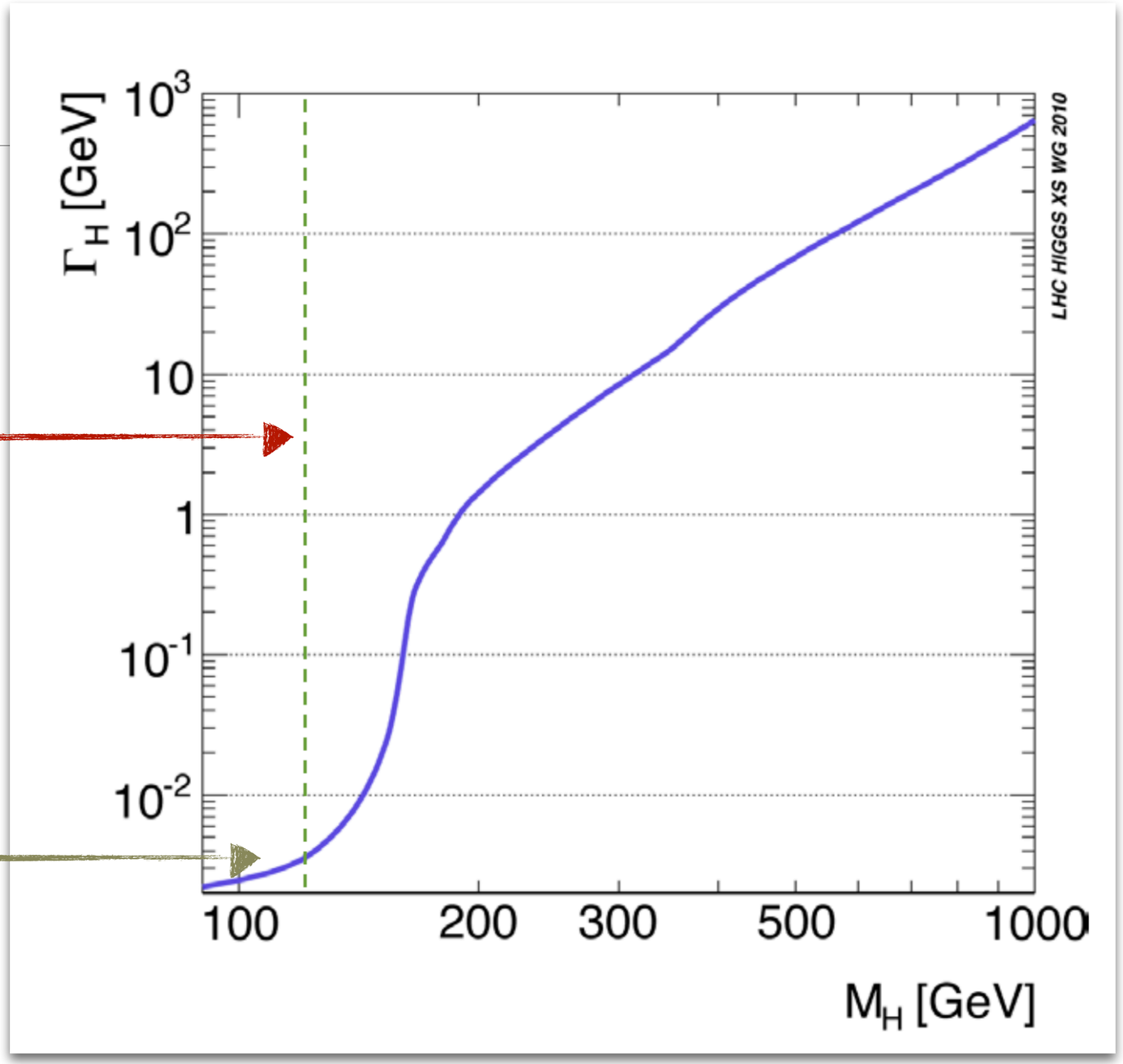
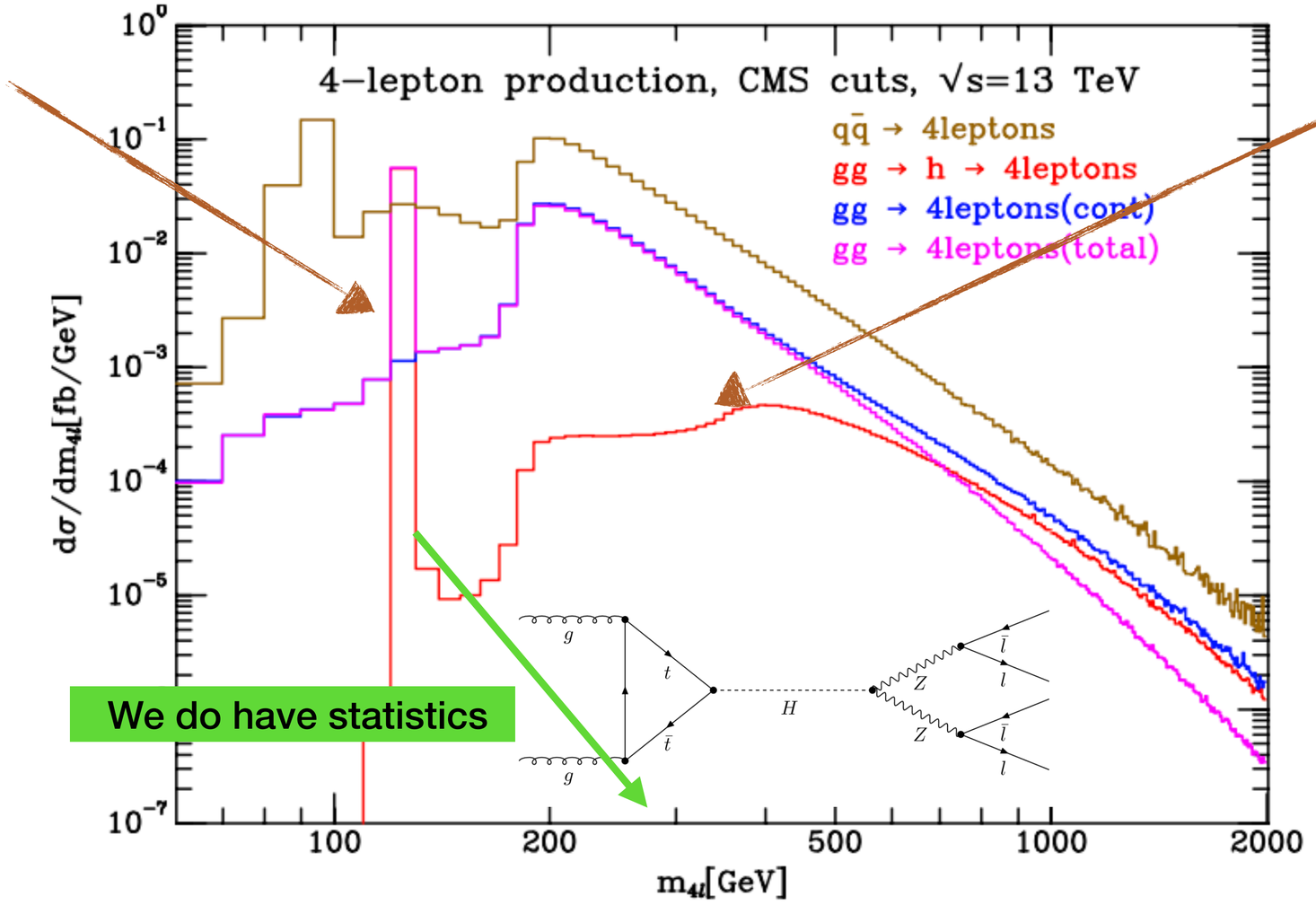


Particle vs. Propagator

On-shell

Off-shell



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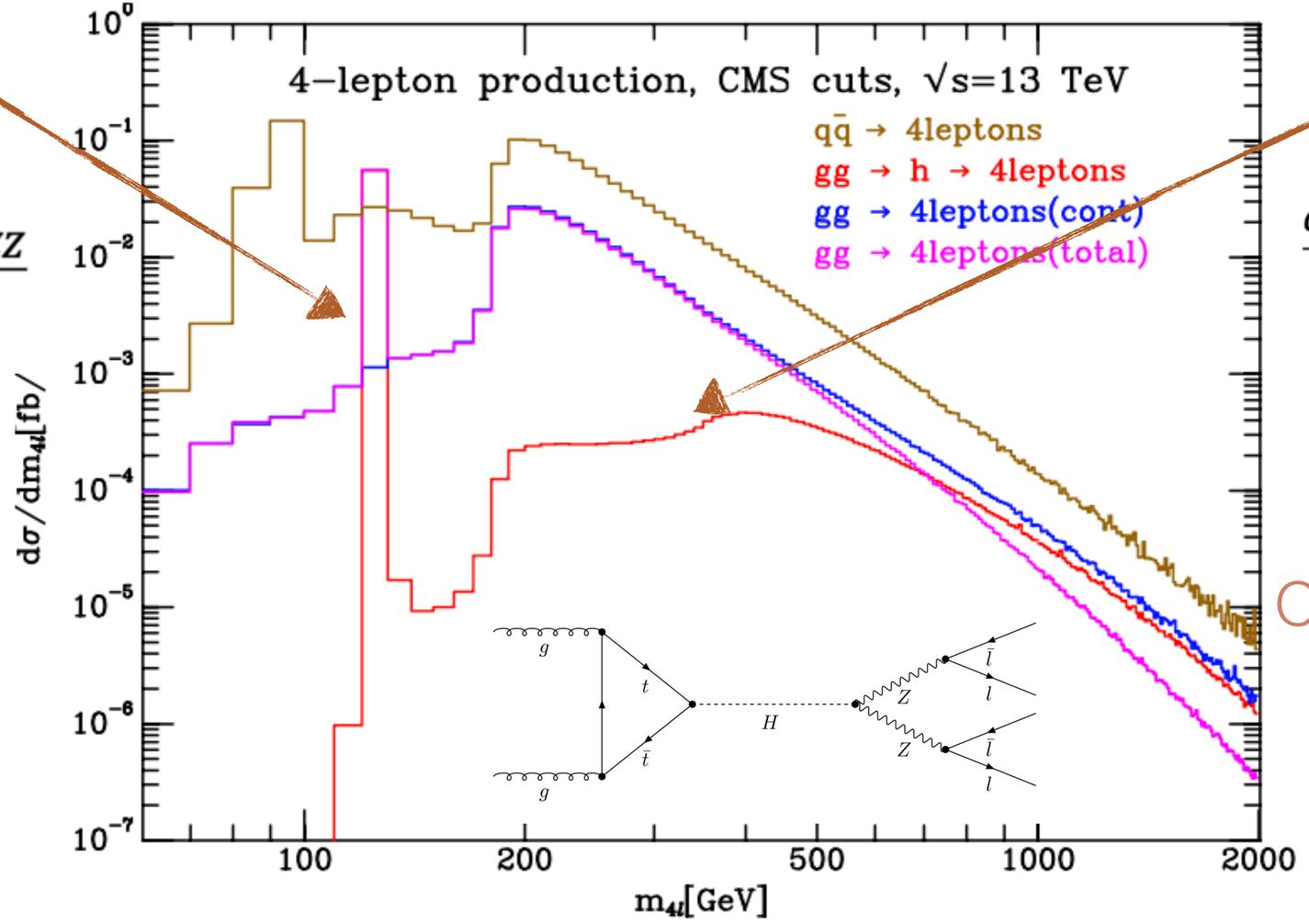
Particle vs. Propagator

On-shell

$$\sigma^{pp\to H\to ZZ}_{\text{on-shell}} \propto \frac{g^2_{Hgg} g^2_{HZZ}}{m_H \Gamma_H}$$

Width dependence



Off-shell

$$\frac{d\sigma^{pp\to H\to ZZ}_{\text{off-shell}}}{dm_{ZZ}} \propto \frac{g^2_{Hgg} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2}$$

Coupling, mass dependence

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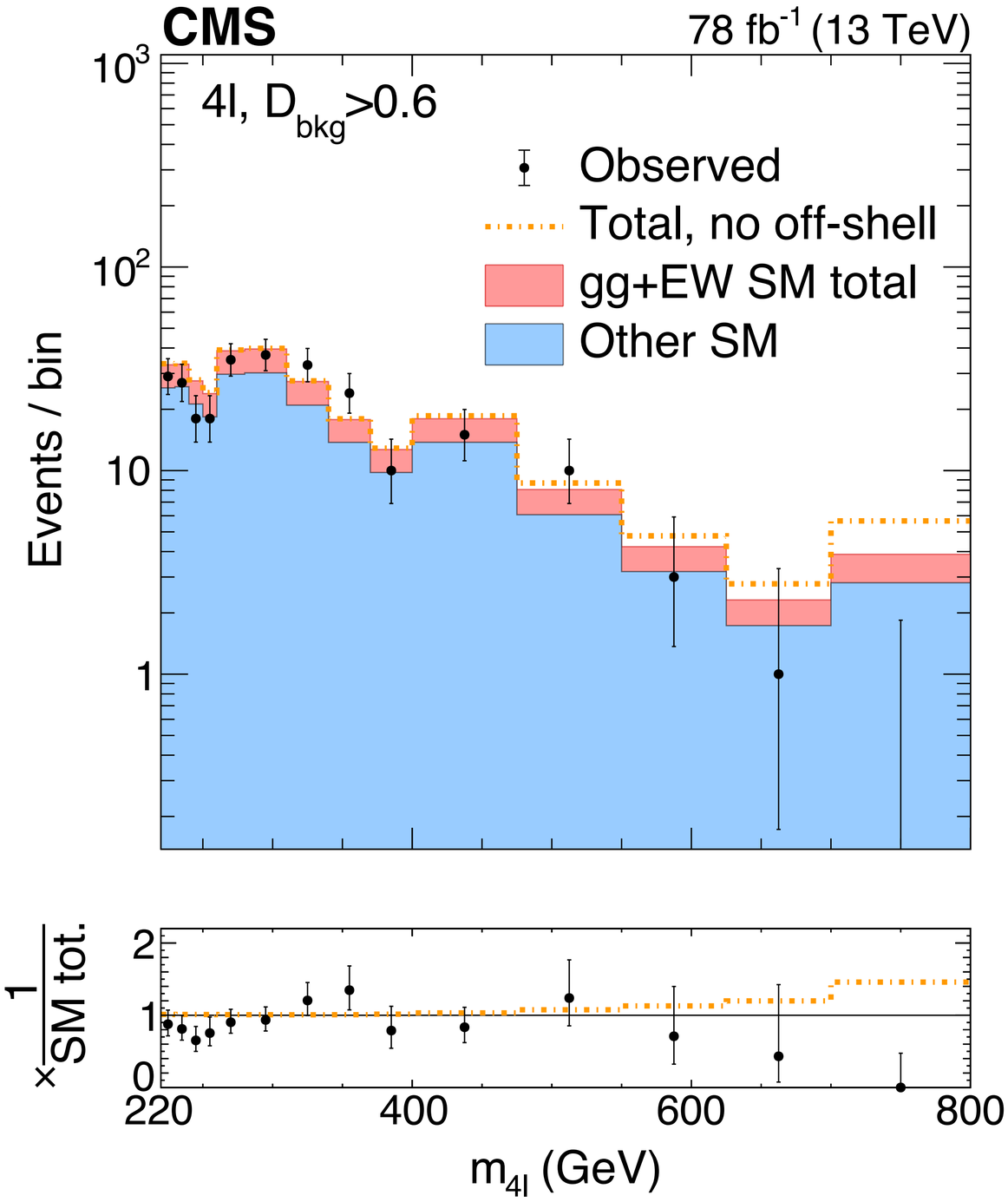
Fitting it all together

- [enter here… a huge amount of measurement fanciness]
- Fit 117 categories together in both on-shell and off-shell to extract the width



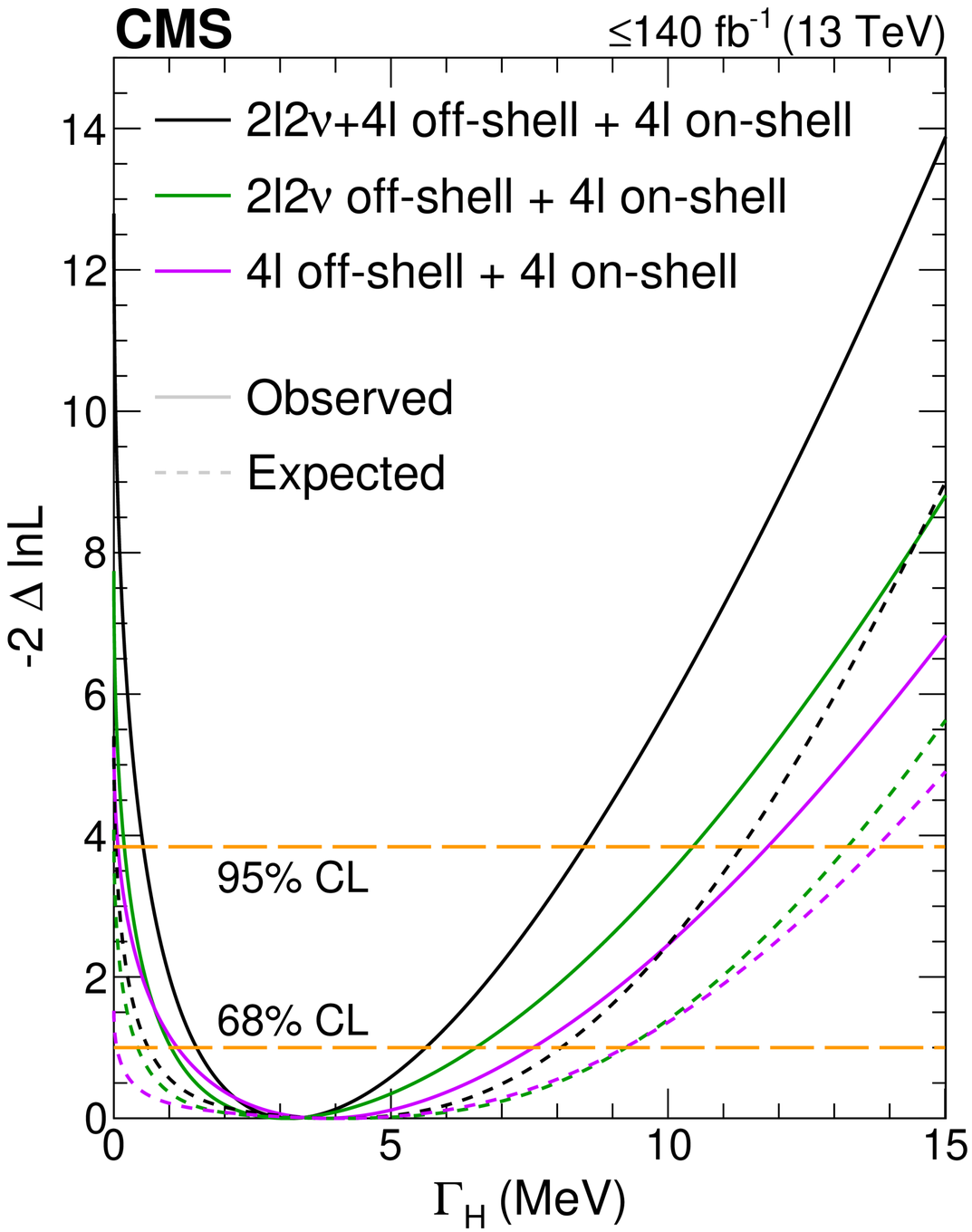
Obtaining the width

CMS

$$\Gamma = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

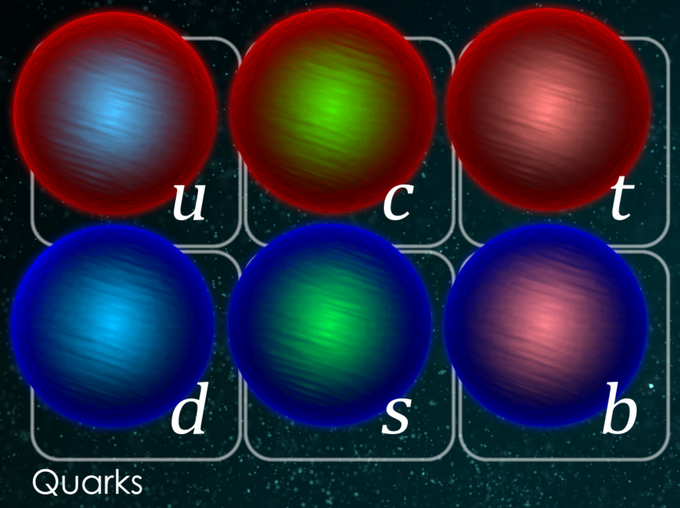
ATLAS

$$\Gamma = 4.6^{+2.6}_{-2.5}\ \text{MeV}$$



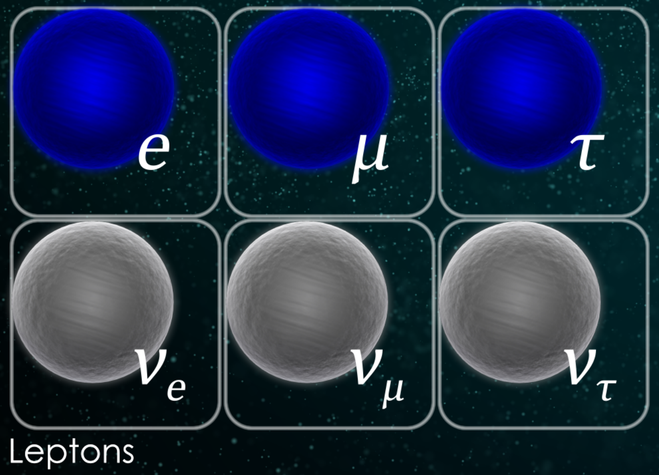
The genesis to any measurement is the question itself

Mass hierarchy



CP Violation

Additional particles?



Composite Higgs?

Who breaks electroweak symmetry?

Why is θ_{13} so small?

Majorana vs. Dirac

Why is neutrino mixing so large?

Dark energy?

Dark matter?

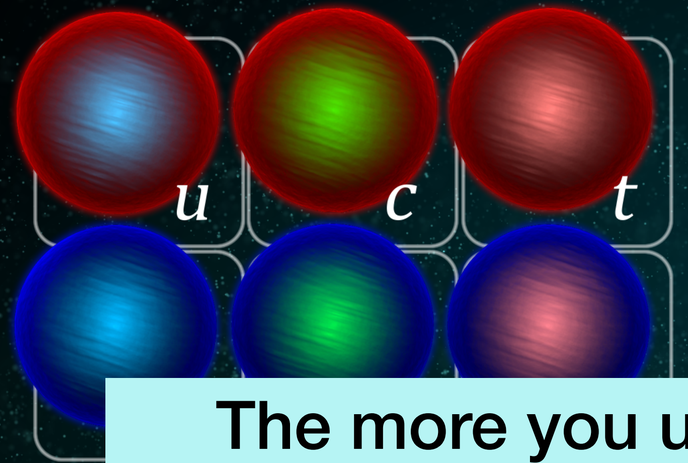
Gravity?

Unified forces?

Theories beyond the Standard Model?

The genesis to any measurement is the question itself

Mass hierarchy



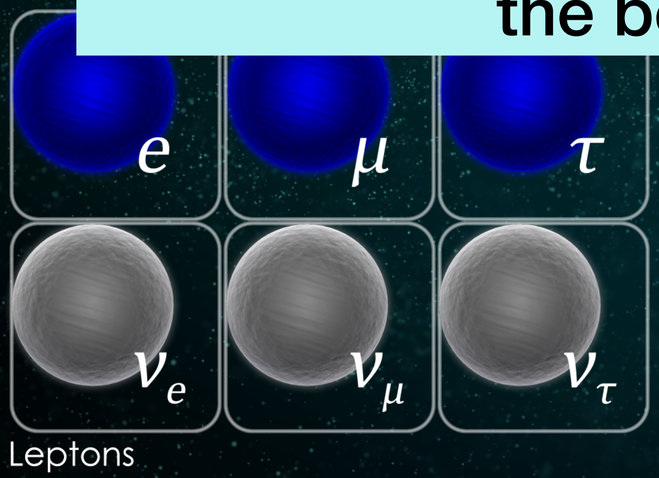
Dark energy?

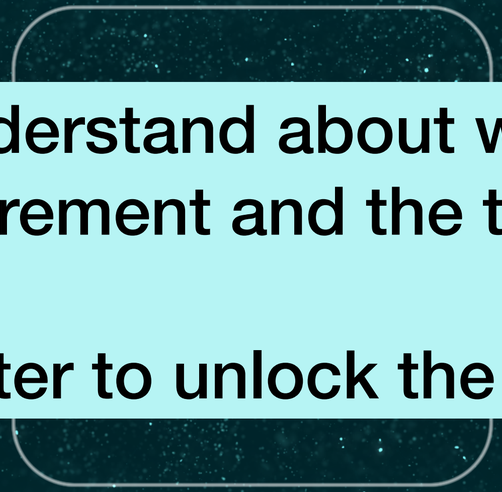
Dark matter?

Additional pa

The more you understand about what goes into the experimental measurement and the theory estimations —

the better to unlock the answer





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Extras