Standard Model Physics at Colliders

day 2!

TRISEP 2025 // 19-20 May 2025

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Data acquisition

Triggering and readout

We can't save all 30 MHz of interactions to disk for future study: how do we choose?

Balance needs of experiment with readout limitations:

- Detector electronics limit the amount of data we can pull off each detector
- Limit on the total data rate (8 GB/s) out of the detector
- Limit on the amount of data we can store, even on **tape**
- Limit on the amount of data we can **reconstruct**
- Limit on the amount of time we can take to decide if we want to keep an event

ATLAS & CMS use a **two-level trigger system:**

Hardware
ASIC & FPGA
Coarse, fast decision

100 kHz →

Software
Reconstruction with early rejection
Fine-grained decision

Choosing which events to select

How do we choose which 100 kHz of events to send to the software trigger, and which 3 kHz of events to save to disk?

Most events are selected with **generic triggers** that cover most use cases:

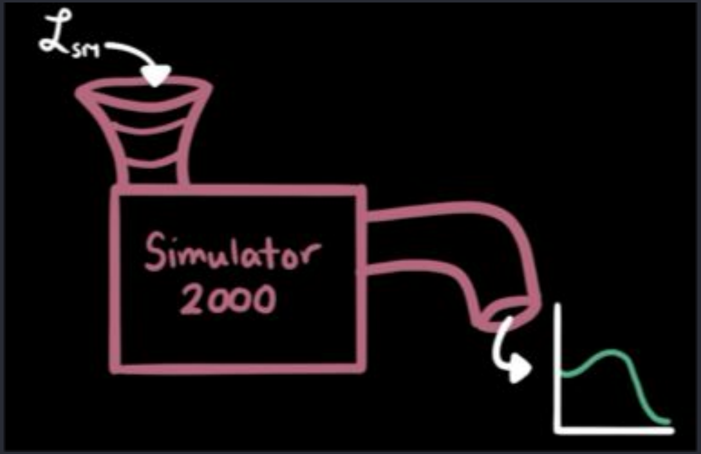
- Electron, muon, photon, tau, jet, and *b*-jet triggers with p_T thresholds
- MET triggers
- Multi-object triggers with lower p_T thresholds

Special triggers are generally implemented for processes that wouldn't be selected by the above (very relevant for searches!):

- Invariant mass selections targeting specific resonances
- Selections tuned for very close-by objects
- Dedicated triggers for long-lived particles
- … your favourite trigger here… as long as it's low rate!

Simulating interactions

In order to compare data with simulation, we need the simulation to **match how we select data**



Event generators tell us what **truth particles** we expect from a process, both from the **hard scatter** and the proton breakup

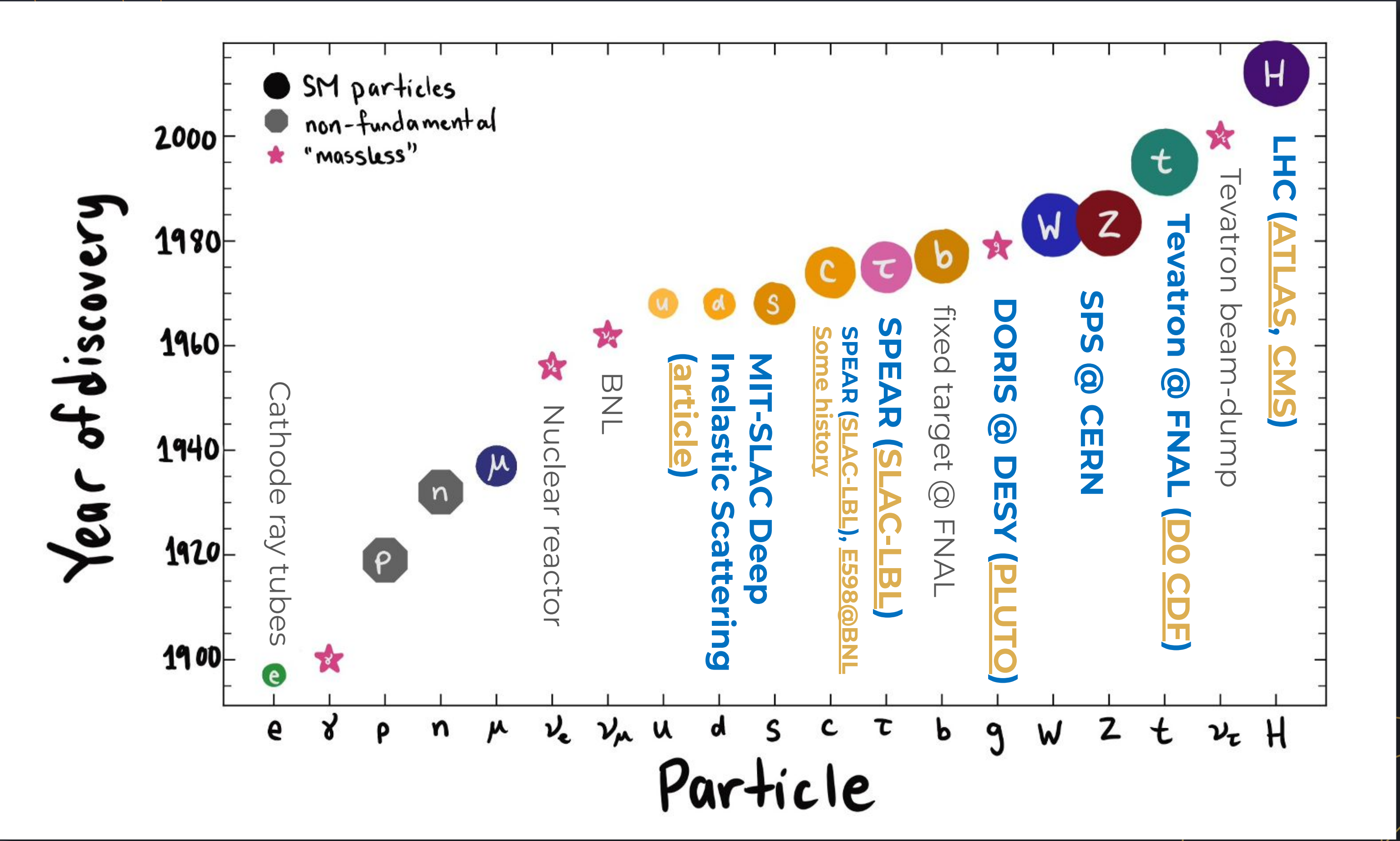
- e.g. Madgraph, Pythia, Sherpa, Herwig, Powheg
- Take parton distribution functions as input
- Pileup is not included!

Geant4 tells us how these particles interact with the detector

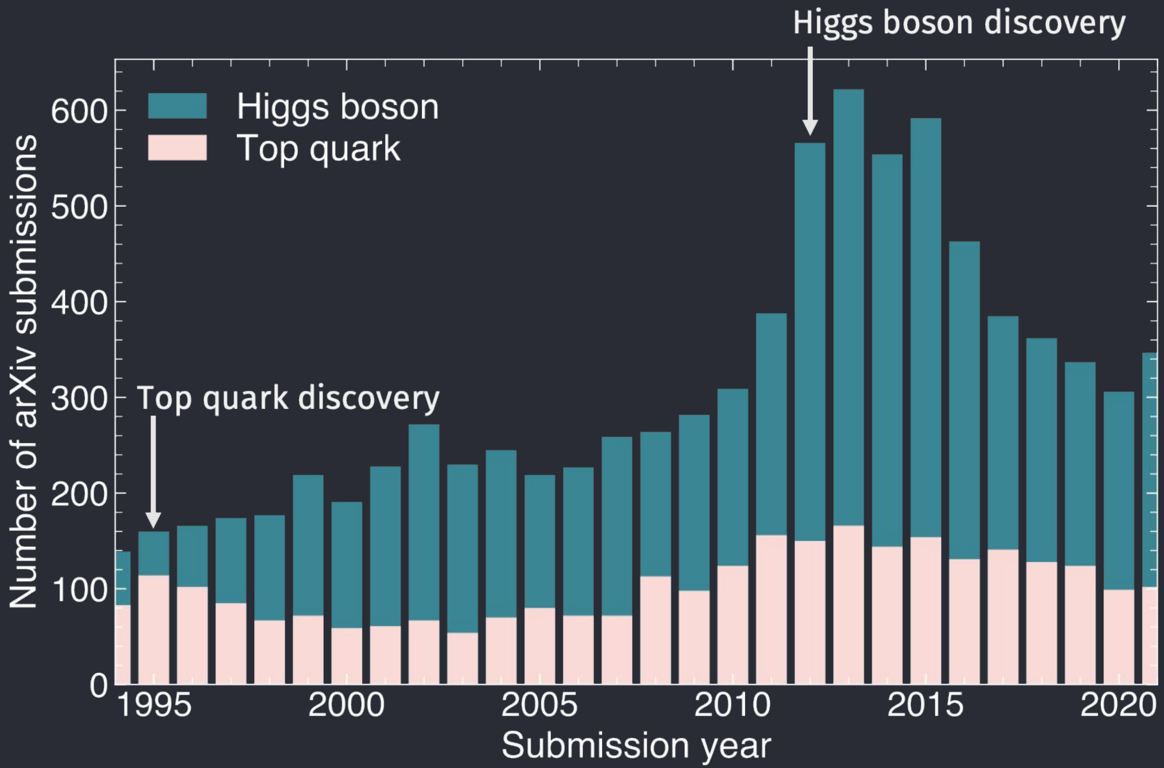
Every selection requirement we make in an analysis needs to be applied to both data and simulation (no truth selections allowed!)

Standard model measurements

Timeline of particle discoveries



Discovery is just the start



*histograms are not stacked

What counts as a measurement?

Observing new **particles** or **interactions**

Measuring particle properties (mass, spin, width, couplings, branching ratios)

Measuring SM properties (e.g. strong coupling constant)

Measuring both **inclusive cross-sections** of SM processes

Measuring **differential cross-sections** of SM processes, including:

- Kinematic variables
- Angular distributions and correlations
- Properties of interactions, e.g. polarization

Testing hypotheses of the SM (e.g. lepton universality)

Cross-section measurements

We want to extract the cross-section from

$$N^{\text{obs}}_{\text{signal}} = L_{\text{int.}} \sigma C A$$

nb: The cross-section here should include the full process being measured, e.g. not just "pp → H", but "pp → H → WW → eνμν"

C = correction factor, which corrects **truth** to **reconstruction** (try this out!)
A = acceptance, which takes you from the region you want to measure your cross-section in (the "fiducial region") to the full process.

In practice, we can lump these together into the **efficiency = N_{reco} / N_{truth}**

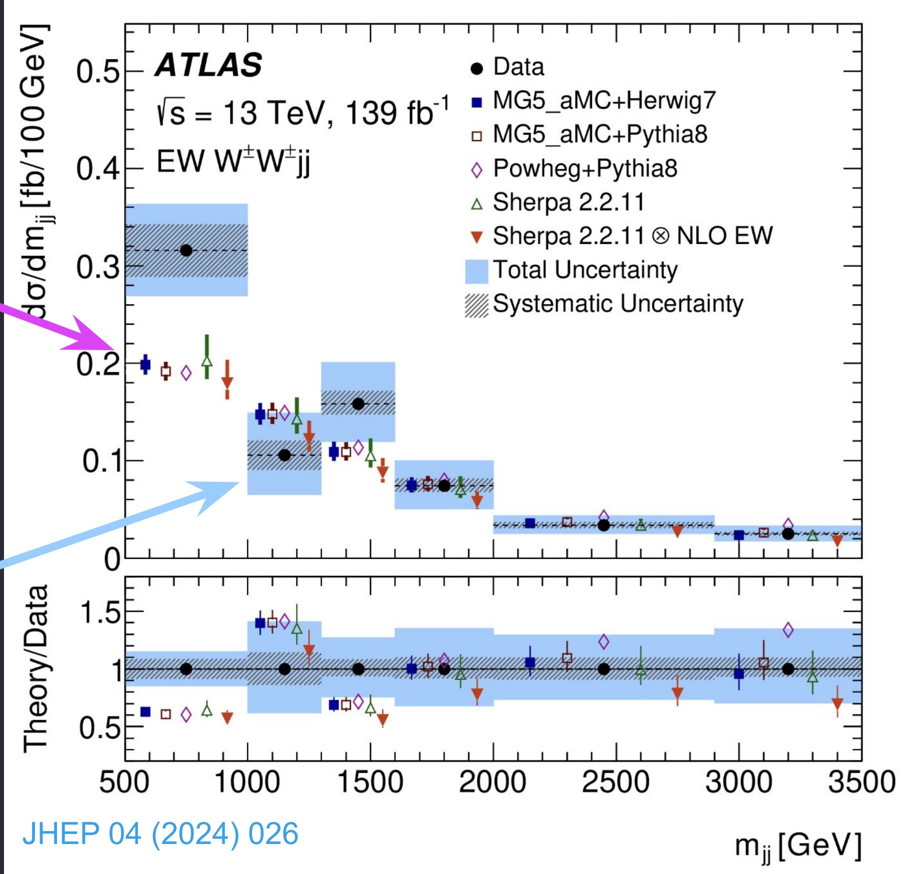
Calculating the efficiency allows us to **undo detector effects**: **unfold** the data back to something "independent" of the experimental apparatus

Unfolded measurements are easier for theorists to compare their results to: they don't need to simulate the detector (hard!)

An unfolded distribution

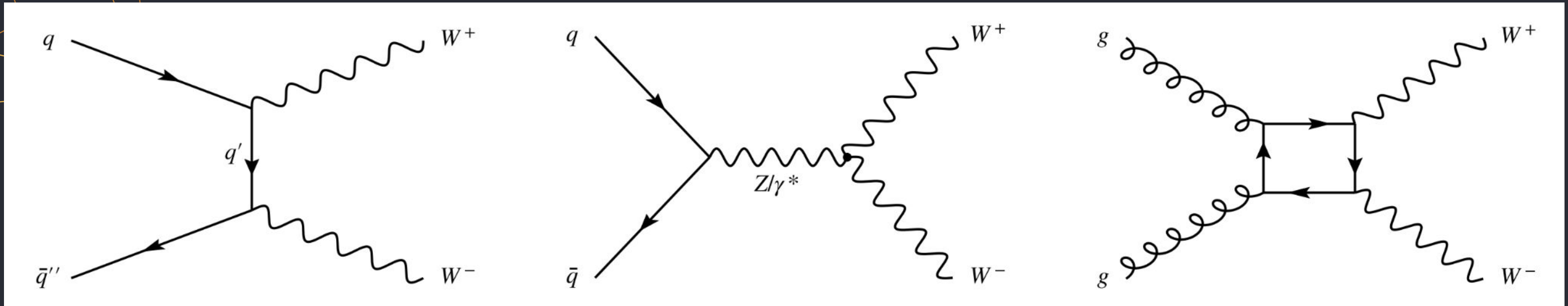
Predictions from different event generators, with modelling uncertainties - no detector simulation, just truth

Unfolded data - what distribution a generator would have to give to match what we see in the actual recorded collision events

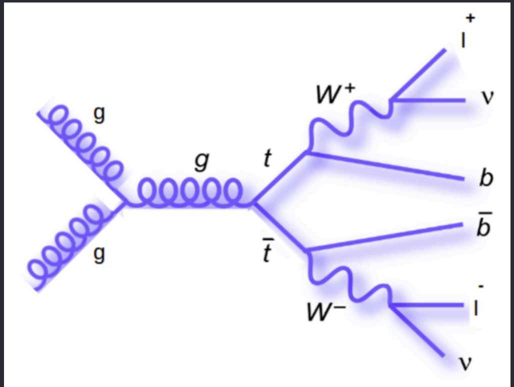


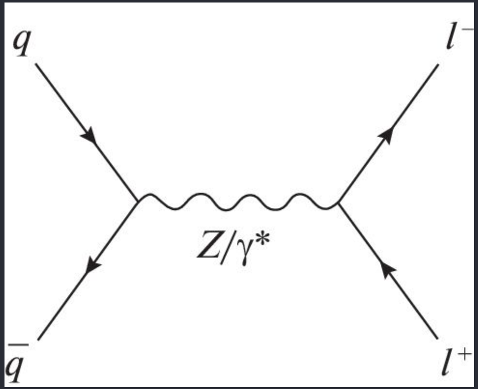
Cross-section measurements – W^+W^-

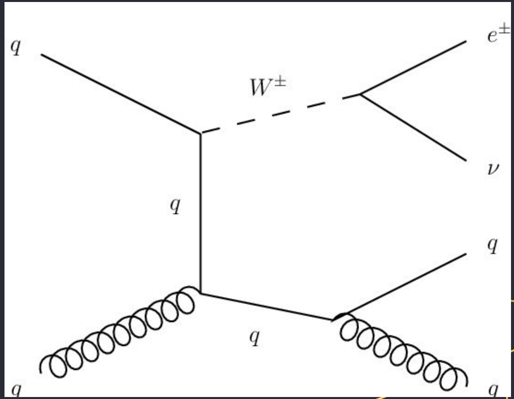
STDM-2020-16



Backgrounds:







Cross-section measurements – W^+W^-

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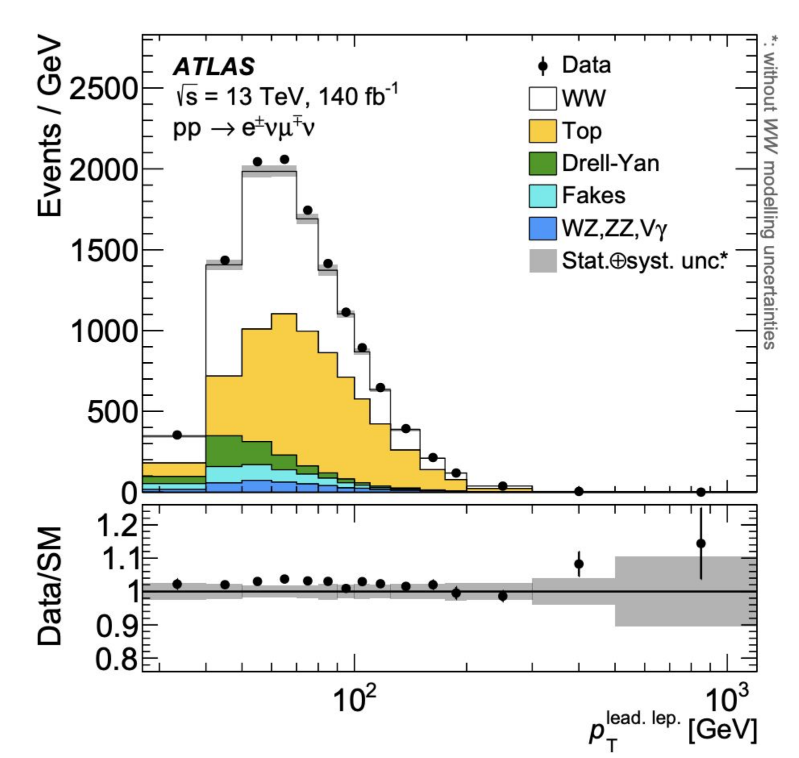
Table 2: Summary of the object and event selection criteria.

	Requirement	Criteria
Electron	p_T	> 27 GeV
	$\|\eta\|$	$\in [0, 1.37) \cup (1.52, 2.47)$
	Identification	`TightLH` working point
	Isolation	`Gradient`
	Impact parameters	$\|d_0/\sigma_{d_0}\| < 5$; $\|z_0 \cdot \sin\theta\| < 0.5$ mm
Muon	p_T	> 27 GeV
	$\|\eta\|$	< 2.5
	Identification	`Medium` working point
	Isolation	`Tight_FixedRad`
	Impact parameters	$\|d_0/\sigma_{d_0}\| < 3$; $\|z_0 \cdot \sin\theta\| < 0.5$ mm
b-jets	p_T	> 20 GeV
	$\|\eta\|$	< 2.5
	Pile-up suppression	jet-vertex tagger [90] for $p_T < 60$ GeV and $\|\eta\| < 2.4$
	b-tagging	DL1r, 85% efficiency working point
Jets	p_T	> 30 GeV
	$\|\eta\|$	< 4.5
	Pile-up suppression	jet-vertex tagger [90] for $p_T < 60$ GeV and $\|\eta\| < 2.4$
Event	Leptons	1 electron and 1 muon of opposite electric charge; no additional lepton with $p_T > 10$ GeV, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
	Number of b-jets	0
	$m_{e\mu}$	> 85 GeV



Cross-section measurements – unfolding

There are a few ways to **unfold** a result, including:

1. **Bin-by-bin unfolding**: Calculate and apply an efficiency correction for each bin
   (misses bin migrations!)

2. **Matrix inversion:** calculate a **response matrix** M_{ij} that tells you what fraction of true events in bin *j* are reconstructed in each bin *i* of the reconstructed distribution. Inverting the matrix will take reco →truth!

   $$N^{\text{reco}}_{i,\text{signal}} = M_{ij} N^{\text{truth}}_{j,\text{signal}} \Rightarrow N^{\text{truth}}_{i,\text{signal}} = M^{-1}_{ij} N^{\text{reco}}_{j,\text{signal}}$$

   reconstructed events that don't pass truth selection must be considered background!
   underflow and overflow must either be accounted for in the histograms/matrix OR be considered background

3. **Bayesian iterative method**: more complicated but often used, see:
   arXiv:1010.0632, epjconf_conf2017_11008

Cross-section measurements – W^+W^-

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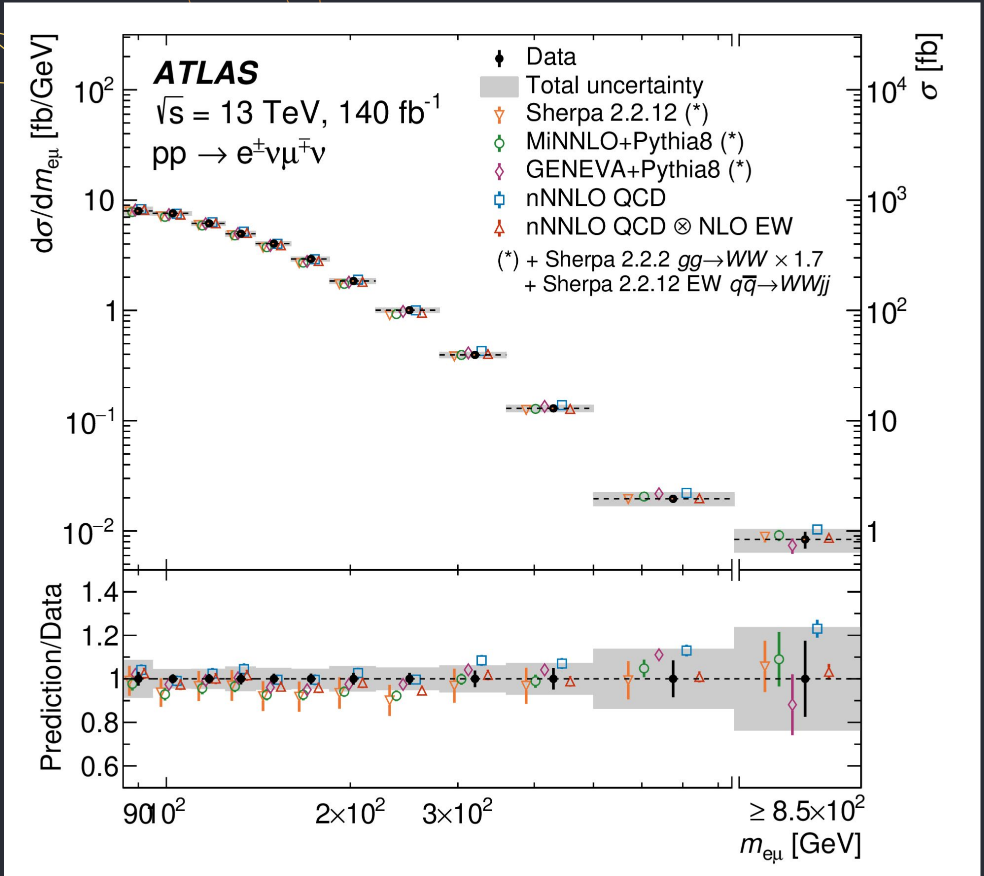


Overall this is excellent agreement between prediction and data

Results can be used to constrain BSM particles and theories

Multiboson interactions

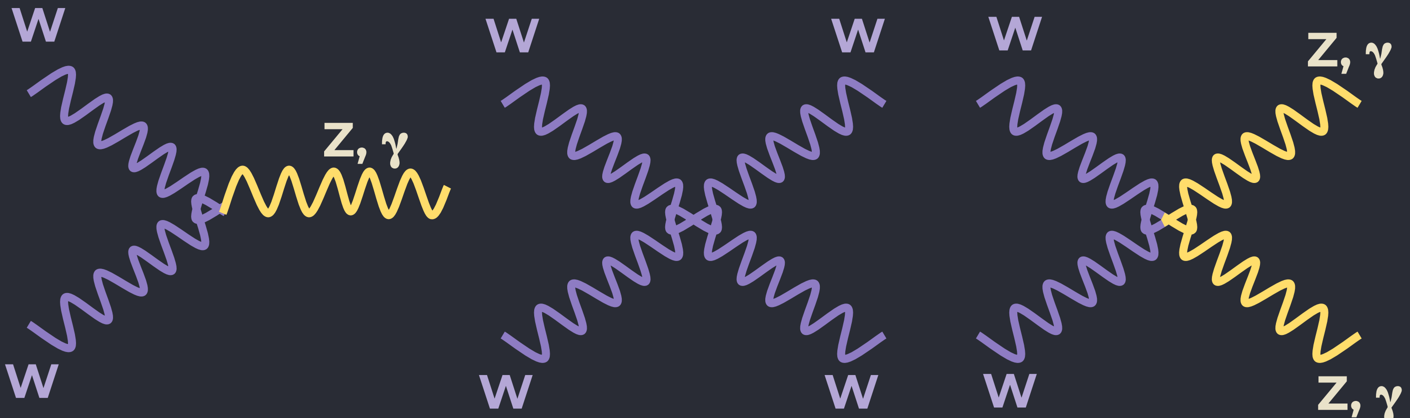
Factor of g^2 **suppresses** this interaction in the SM: interactions with QGCs are **rare processes**

Triple gauge couplings

$$\mathcal{L}_{EW,WZA} = ig\cos\theta_W[(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu)\partial^\mu Z^\nu + W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu]$$
$$+ ig\sin\theta_W[(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu)\partial^\mu A^\nu + W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu]$$

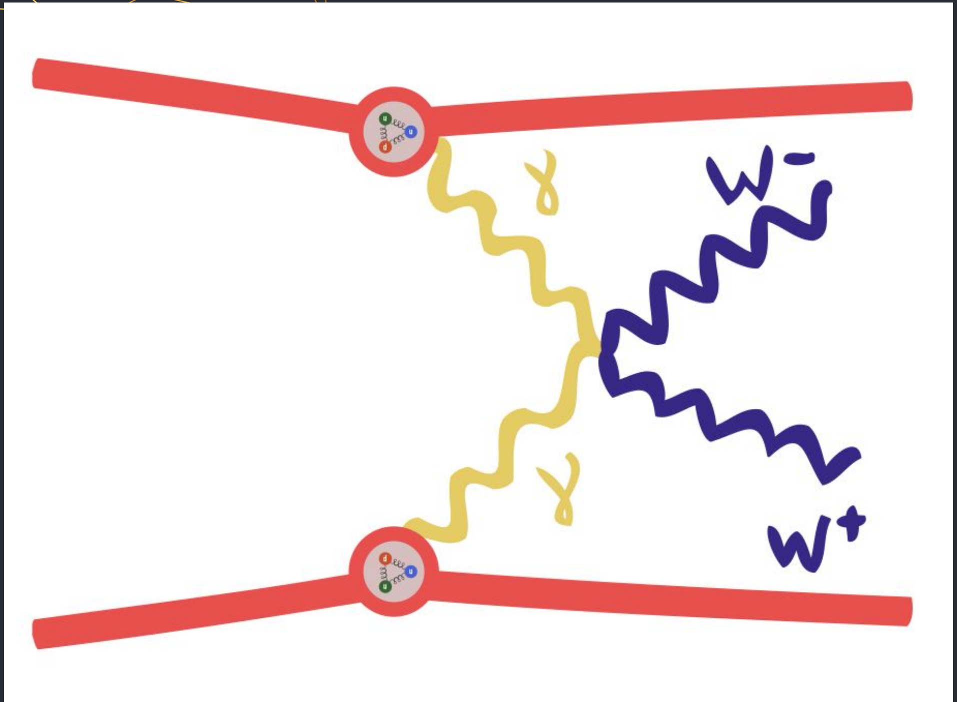
Quartic gauge couplings!

$$+ g^2\cos^2\theta_W(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu}Z_\nu Z^\nu)$$
$$+ g^2\sin^2\theta_W(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu}A_\nu A^\nu)$$
$$+ g^2\sin\theta_W\cos\theta_W[W^+_\mu W^-_\nu(Z^\mu A^\nu + Z^\nu A^\mu) - 2W^+_\mu W^{-\mu}Z_\nu A^\nu)]$$
$$+ \frac{1}{2}g^2(W^+_\mu W^-_\nu)(W^{+\mu}W^{-\nu} - W^{+\nu}W^{-\mu})$$



NO ALL NEUTRAL VERTICES!

LHC as a photon collider

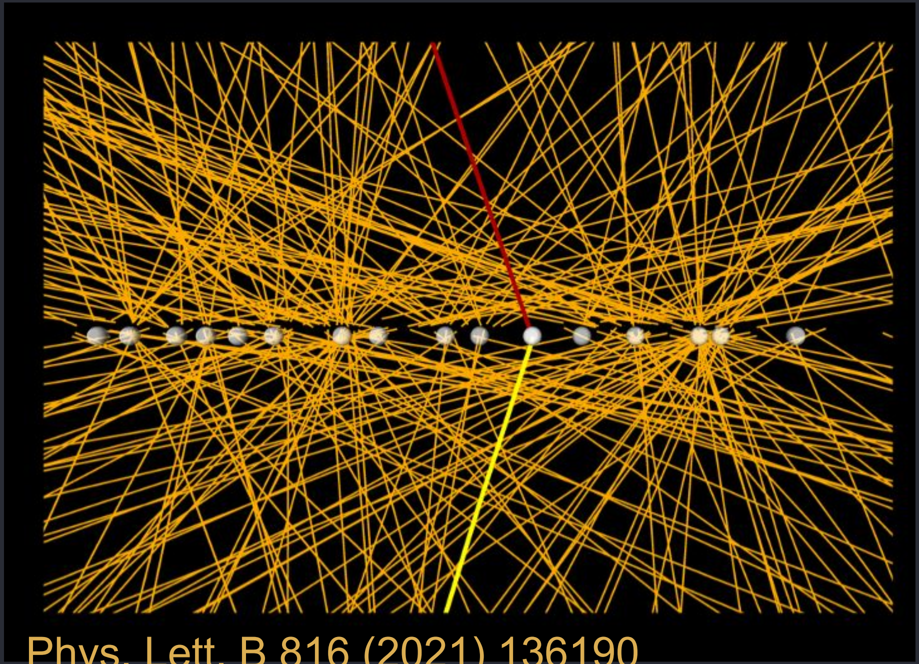


- **Protons** (and ions!) can radiate photons

- If photons are radiated from both beams, the photons can interact inelastically, while the protons themselves stay intact

LHC as a photon collider

Find the vertex with **only leptons** - no tracks from proton breakup

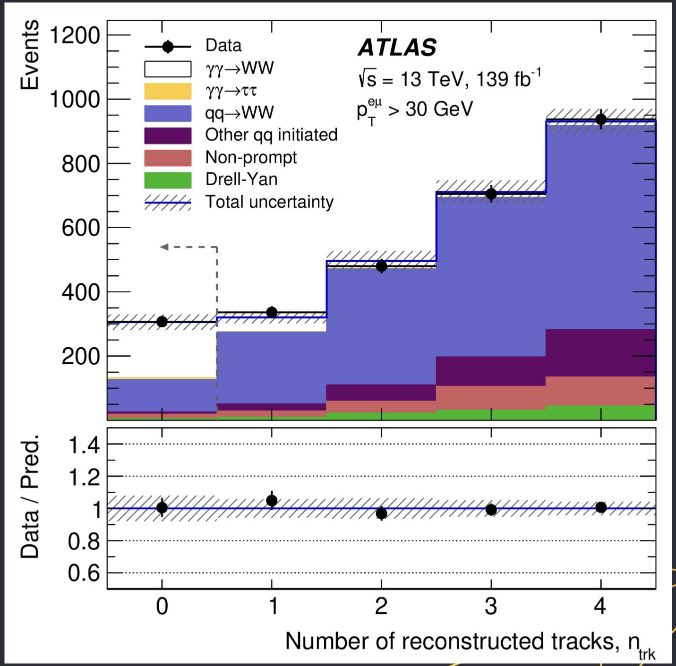


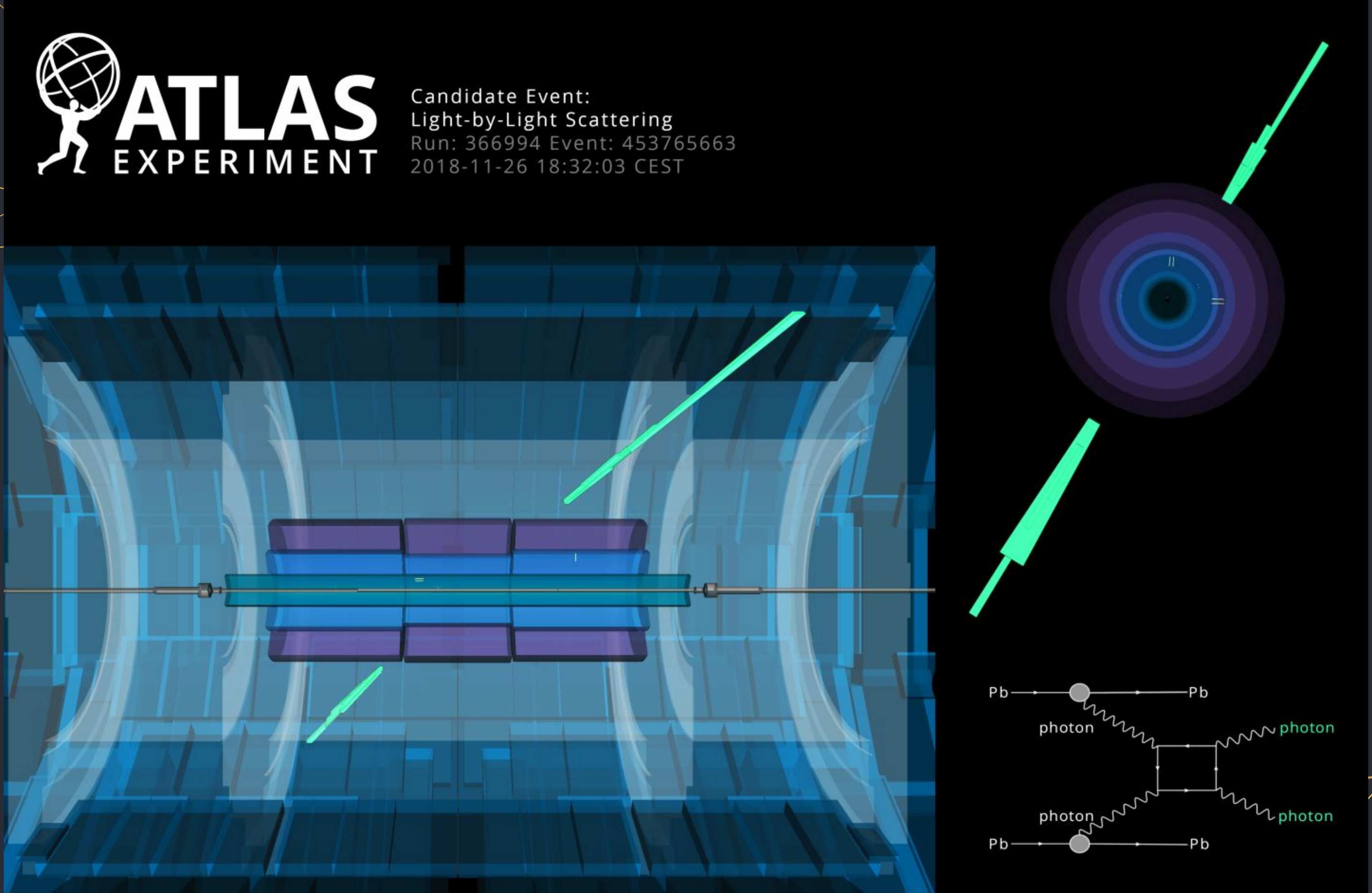
[Phys. Lett. B 816 (2021) 136190](#)

Observed significance: 8.4σ

Fiducial cross-section of $\gamma\gamma \rightarrow WW$:

3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb




Candidate Event:
Light-by-Light Scattering
Run: 366994 Event: 453765663
2018-11-26 18:32:03 CEST
Pb
Pb
photon
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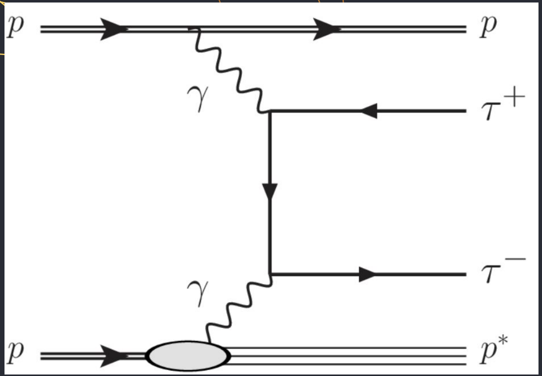
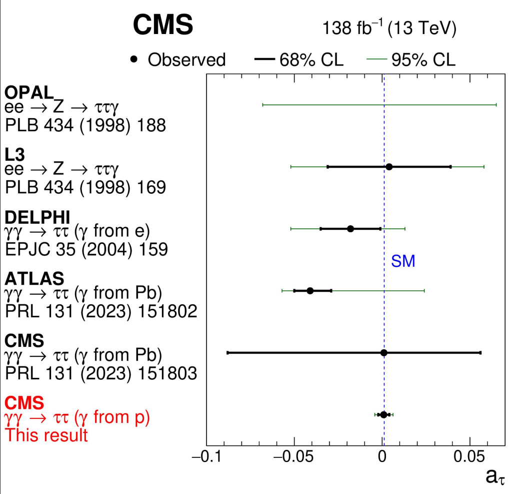
[Rep. Prog. Phys. 87 (2024) 107801]

Tau anomalous magnetic moment



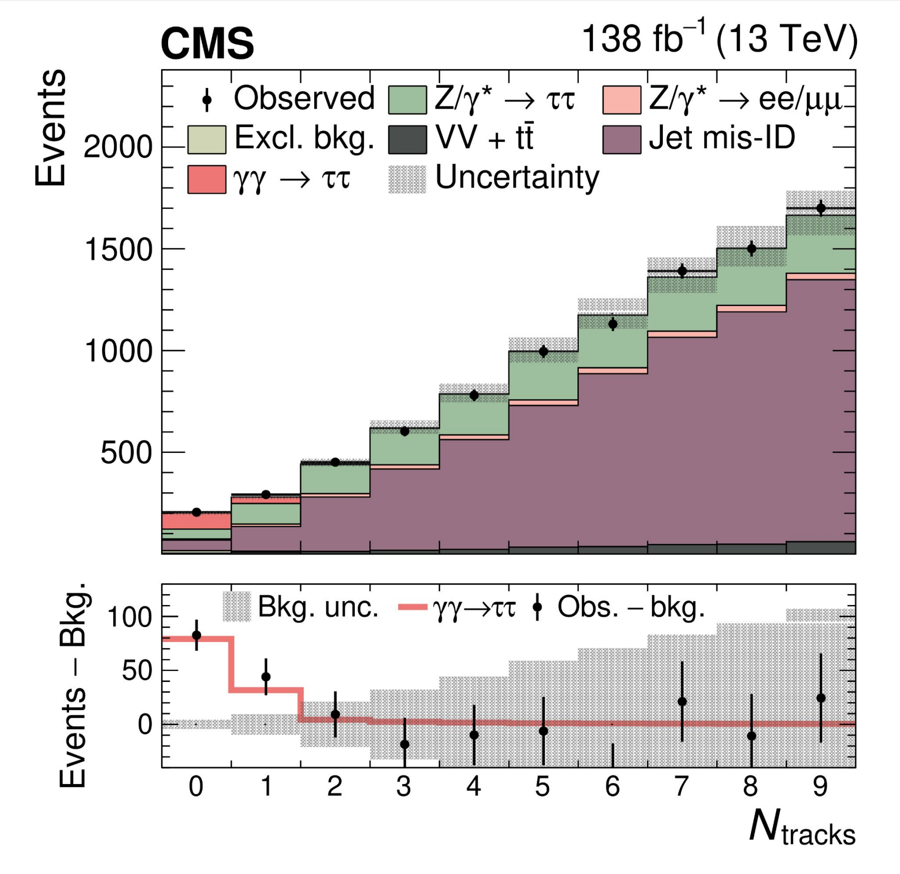


Taus decay to…

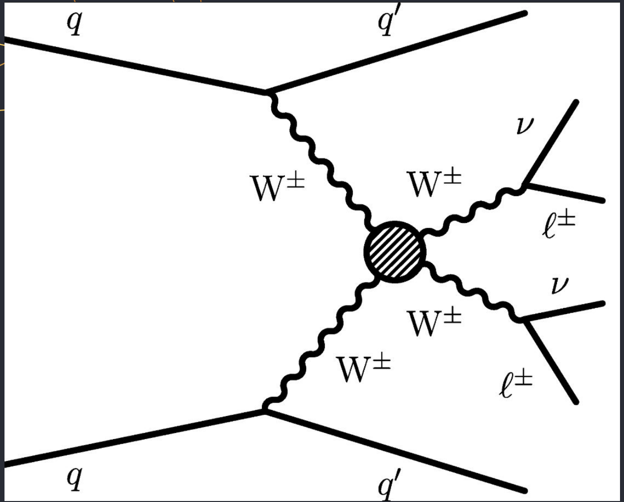
"Easy" to ID:
17%: $\mu\nu_\mu\nu_\tau$
18%: $e\nu_e\nu_\tau$

Hard to ID:
65%: hadronically, usually with at least one charged pion and one neutral pion

Cross-section depends
On the value of the magnetic moment of the tau ("tau g-2")!

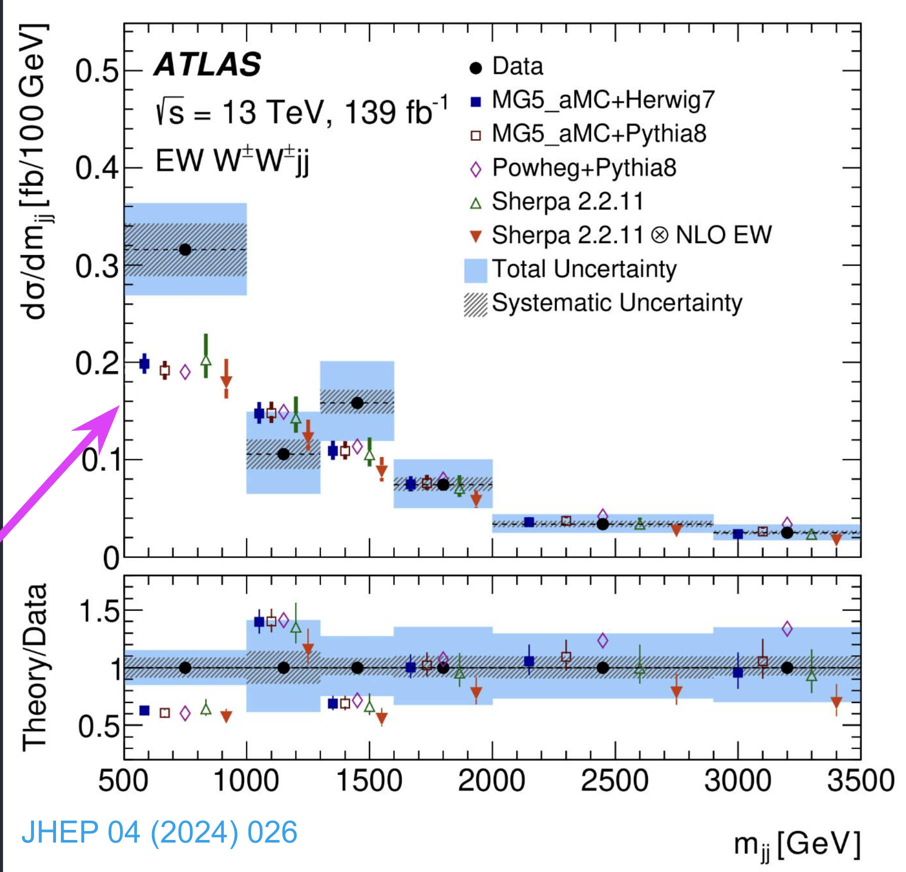


(Not just any) unfolded distribution



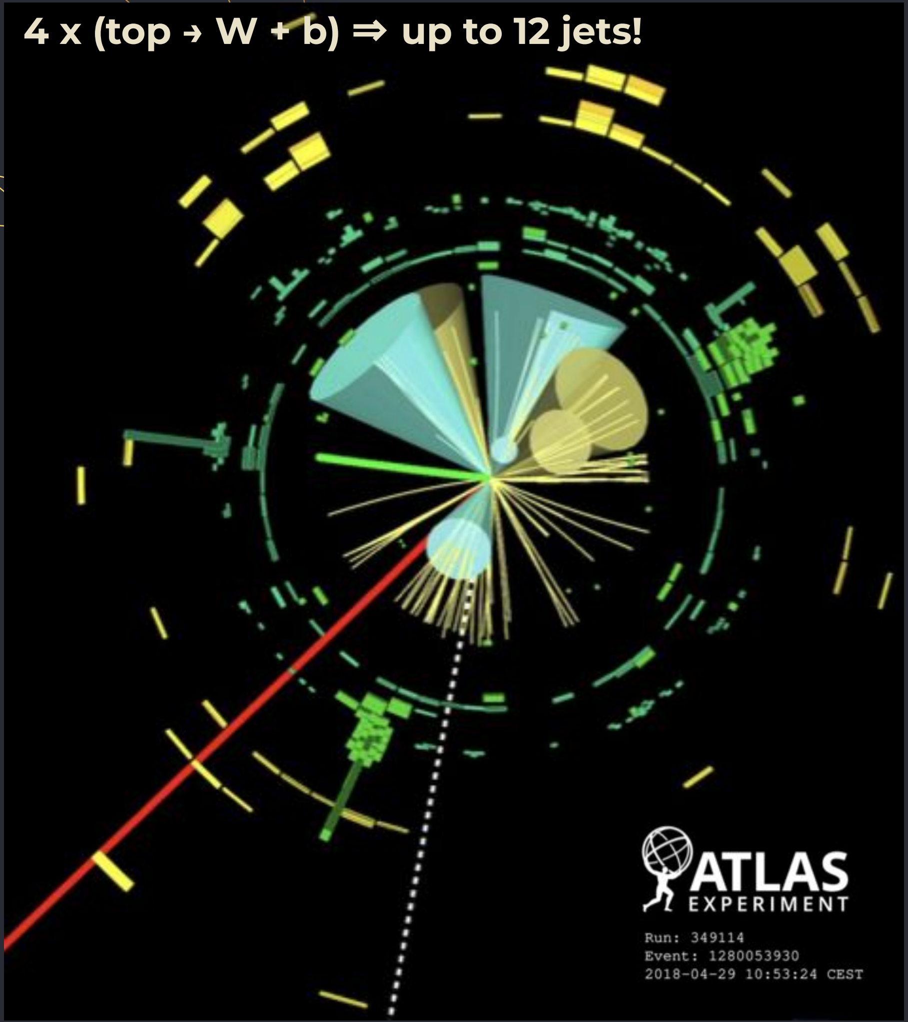
Rare process ⇒ smaller BSM effects are needed to visibly modify the result

...is that what we see here?

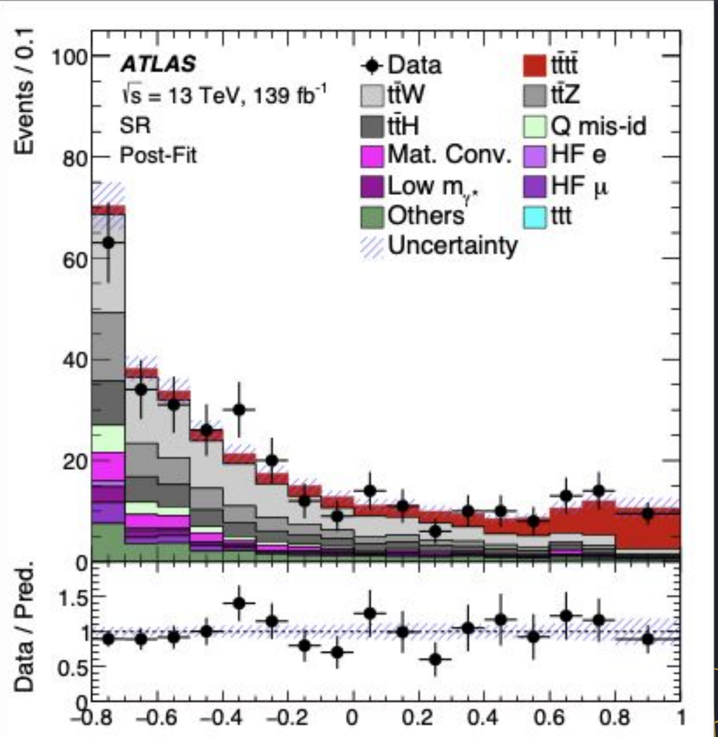


JHEP 04 (2024) 026

Four top-quark production



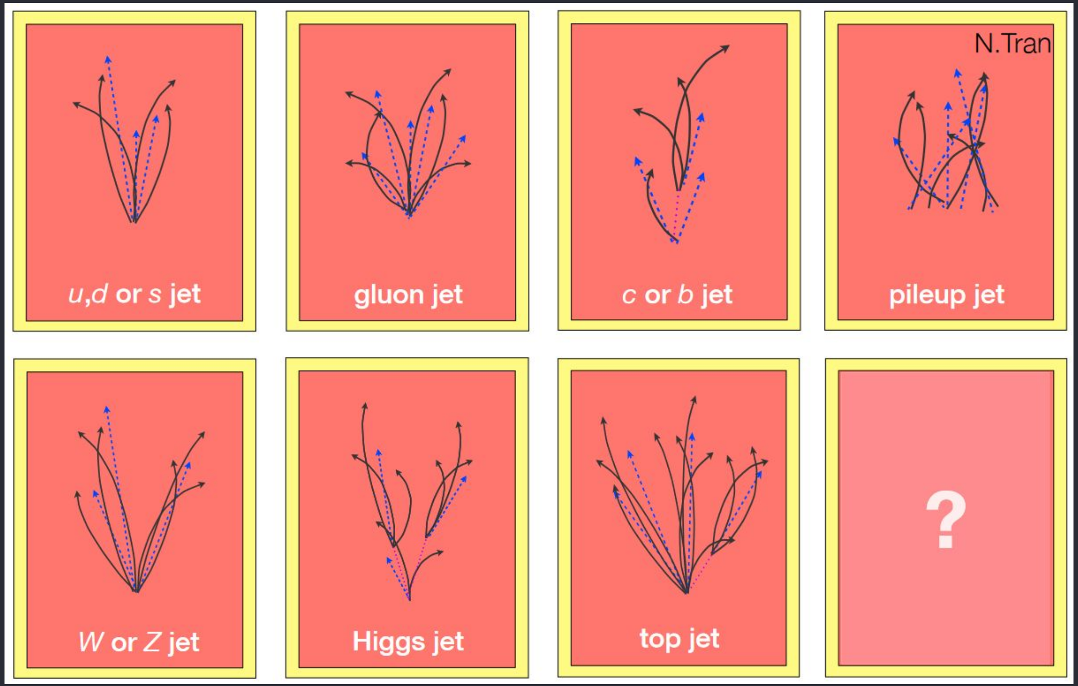
Observed significance of 4.3σ (expected 2.4σ)



Eur. Phys. J. C 80 (2020) 1085

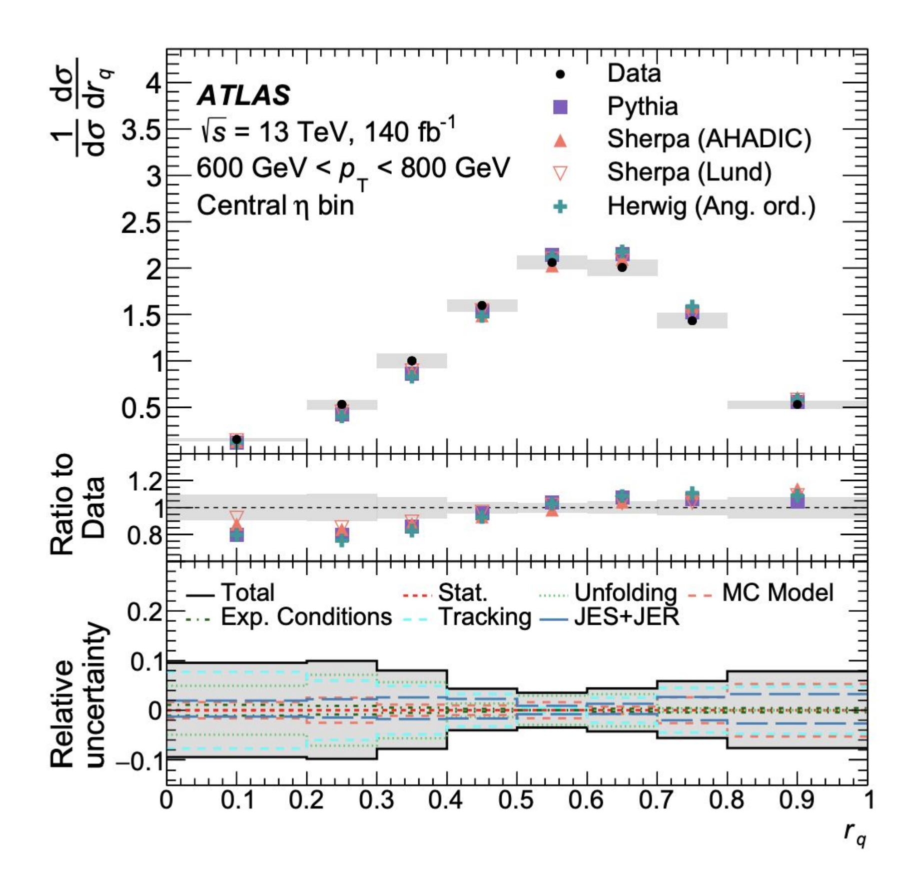
QCD (is complicated!)

In many analyses, we use **jet substructure** to help classify jets, e.g. quark vs gluon jets, or jets from W → qq' vs a single q/g



Distinguishing these relies on our ability to accurately simulate the fragmentation and hadronization of each type of jet

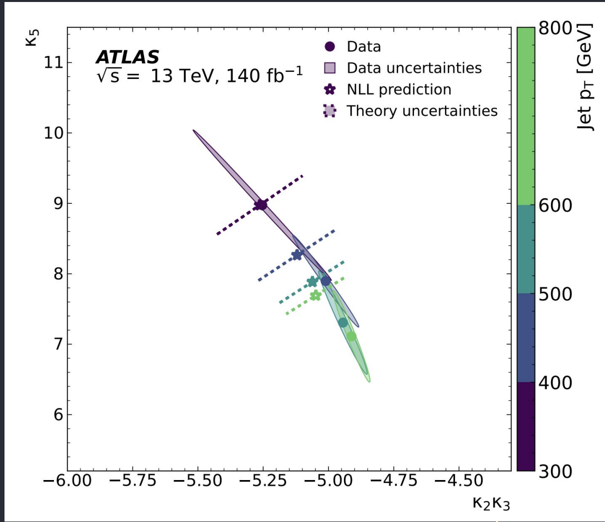
QCD – Properties of tracks in jets



r_q = fraction of a jet's transverse momentum carried by **charged particles**

Moments of the r_q distribution the encode **correlations** in the hadronization process

Provides inputs to theoretical calculations of jet substructure!

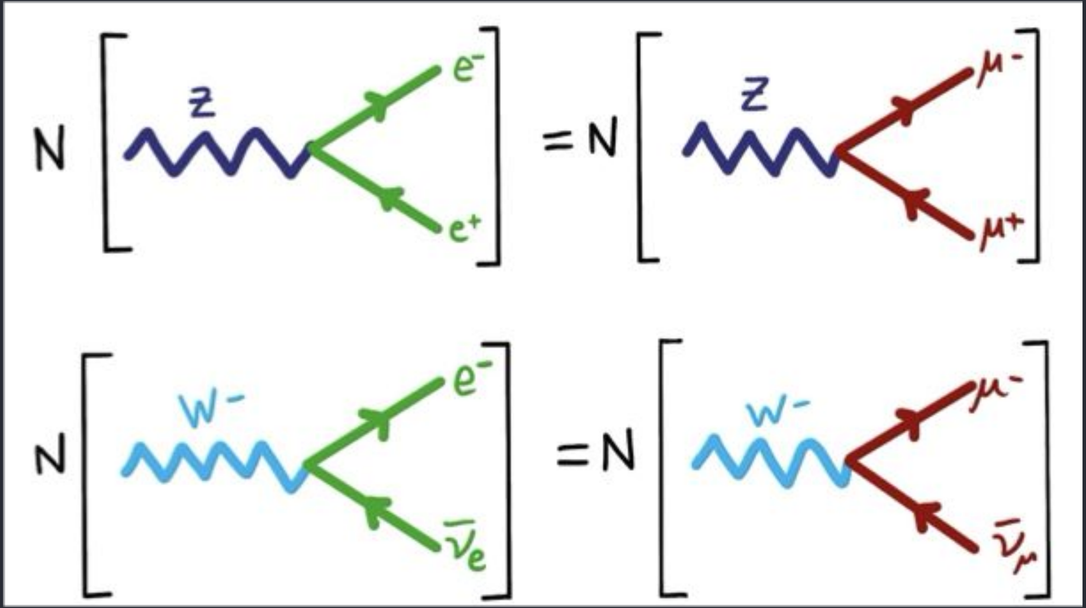


Kappas = non-trivial coefficients of moments

Flavour physics

Roughly: a subfield of particle physics that studies processes that depend on quark and lepton flavour

In the Standard Model, gauge boson decays exhibit
lepton-flavour universality

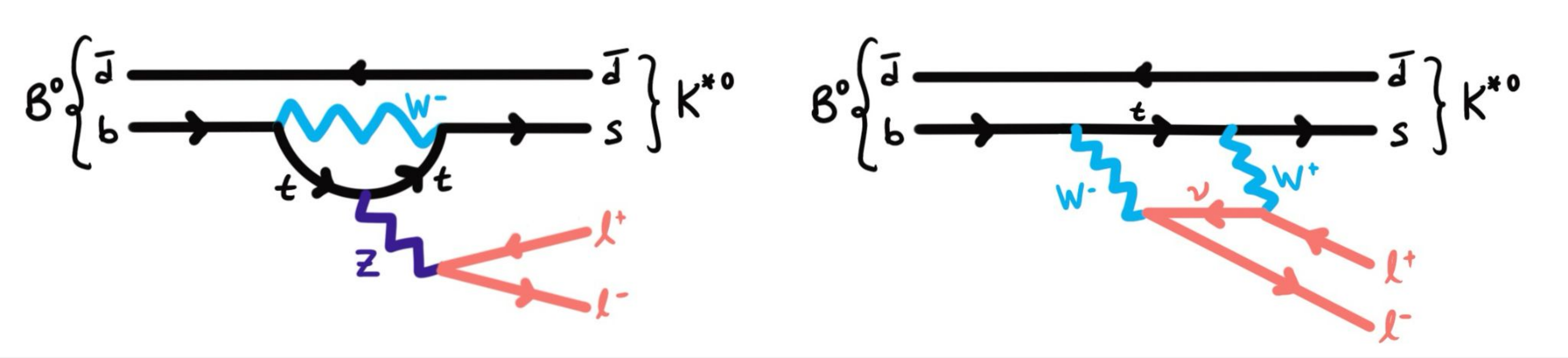


both theoretically predicted and well-measured experimentally

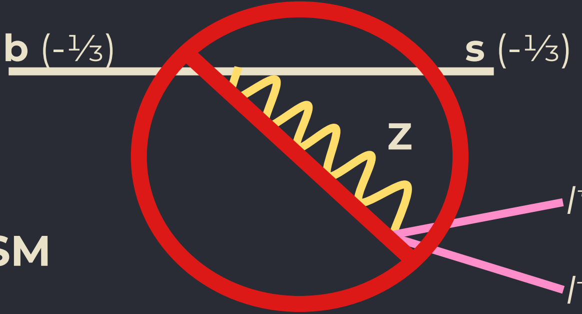
minimal differences do appear from kinematic effects due to $m_{el} < m_{muon}$

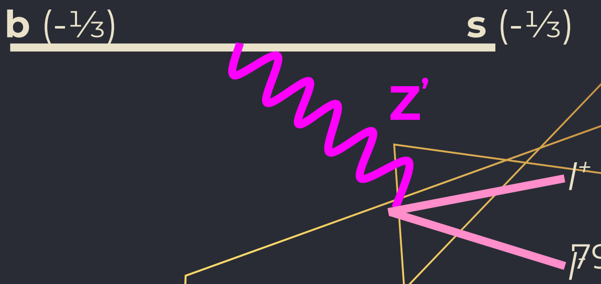
Lepton flavour universality

B-mesons are an ideal place to look for deviations from universality because some of their decays are very **rare** e.g. the flavour changing process $b \rightarrow sl^+l^-$:



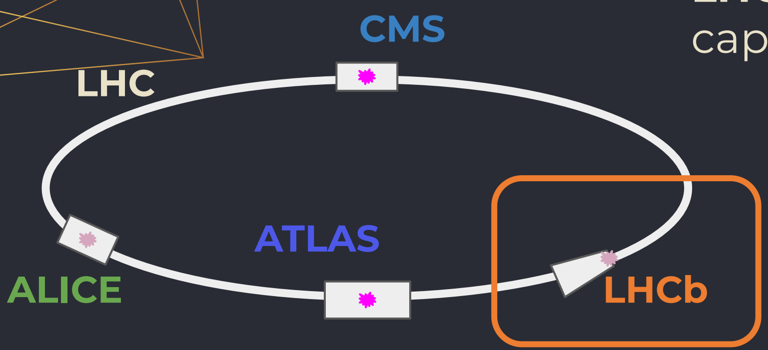
Rare because this is a **flavour-changing neutral current:** overall, **no change in quark charge** – this is **not possible at tree-level in the SM**





B-physics experiments

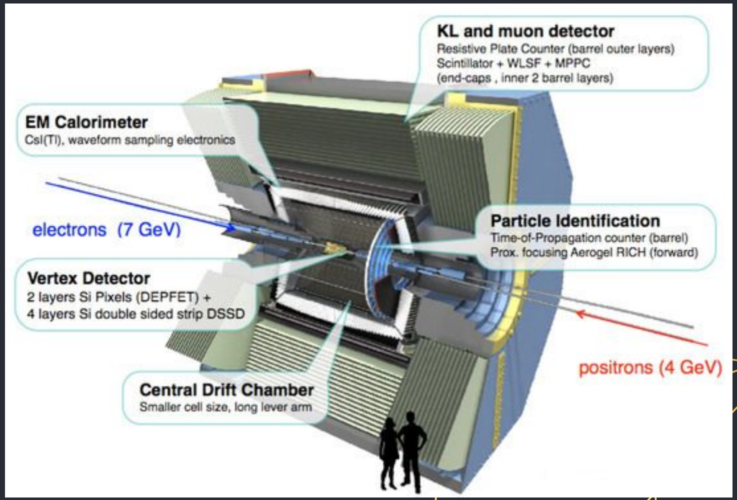
LHCb detector is designed specifically to capture *b*-hadron decays



LHC levels luminosity much lower to reduce pileup, enabling cleaner secondary vertex finding (identification of hadron decay vertices!)

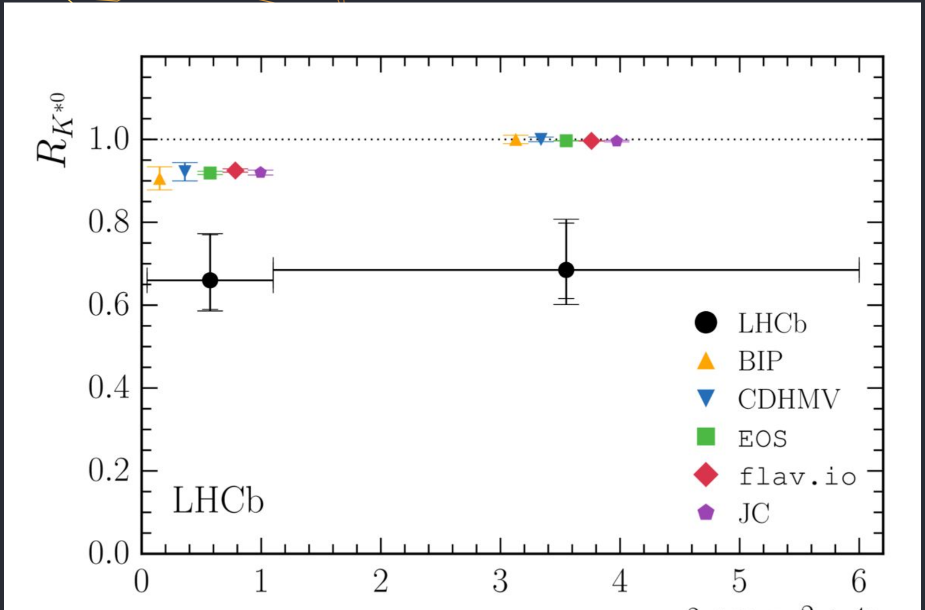
Belle II @ SuperKEKB is a dedicated experiment in Japan

- SuperKEKB is an e+e- collider
- Runs at √s = 10.58 GeV (Υ(4s) resonance)
  - Υ(4s) → B$\bar{B}$ > 96% of the time!
- **Huge** luminosity, "physics" data taking since 2019

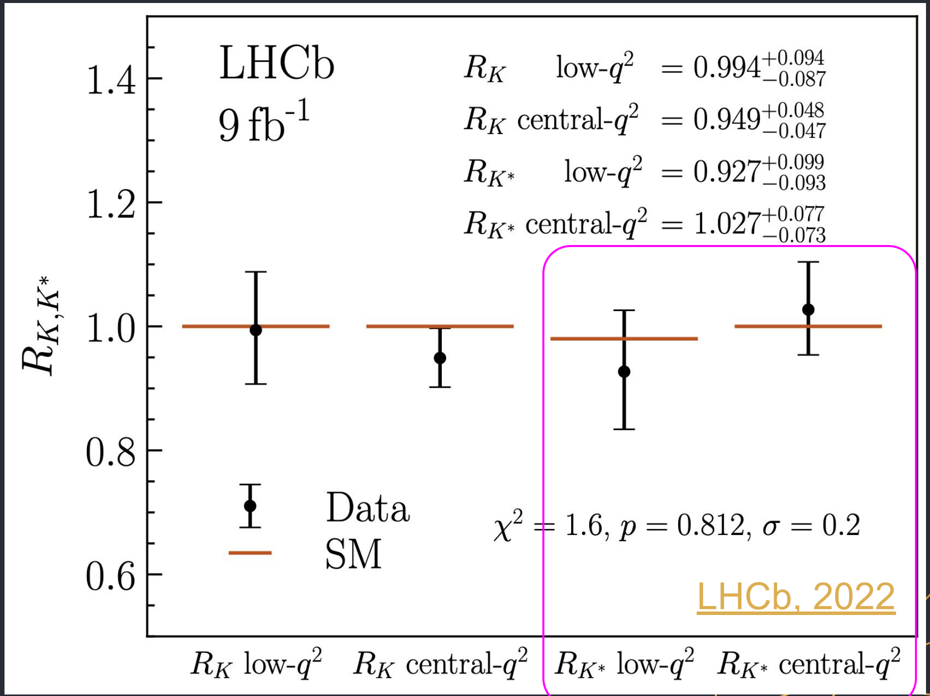


Some recent history on LFU

Measure the ratio of B-decays to electrons vs muons in $B^0_d \to K^{*0} l^+ l^-$



[LHCb, 2017]

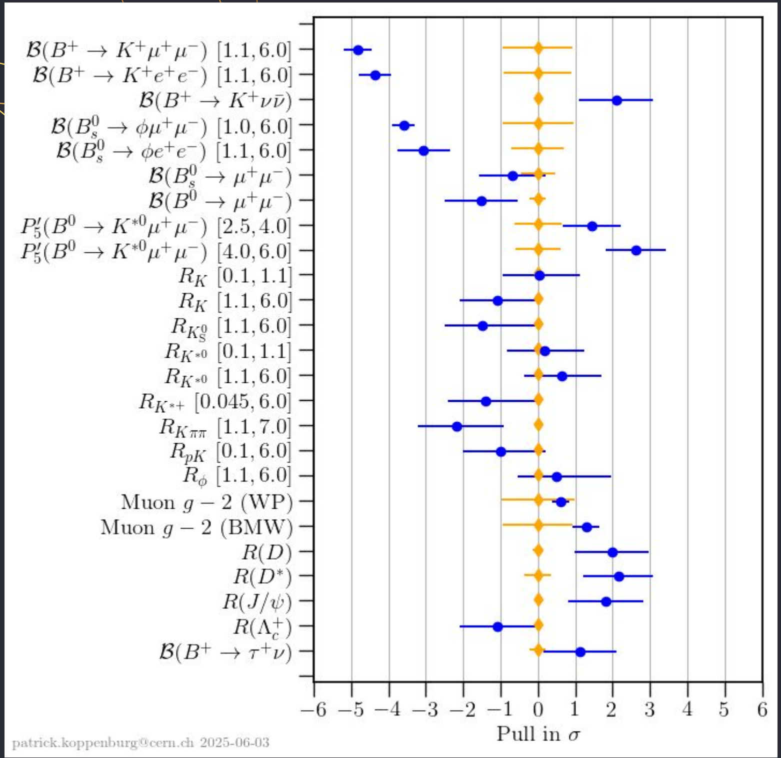


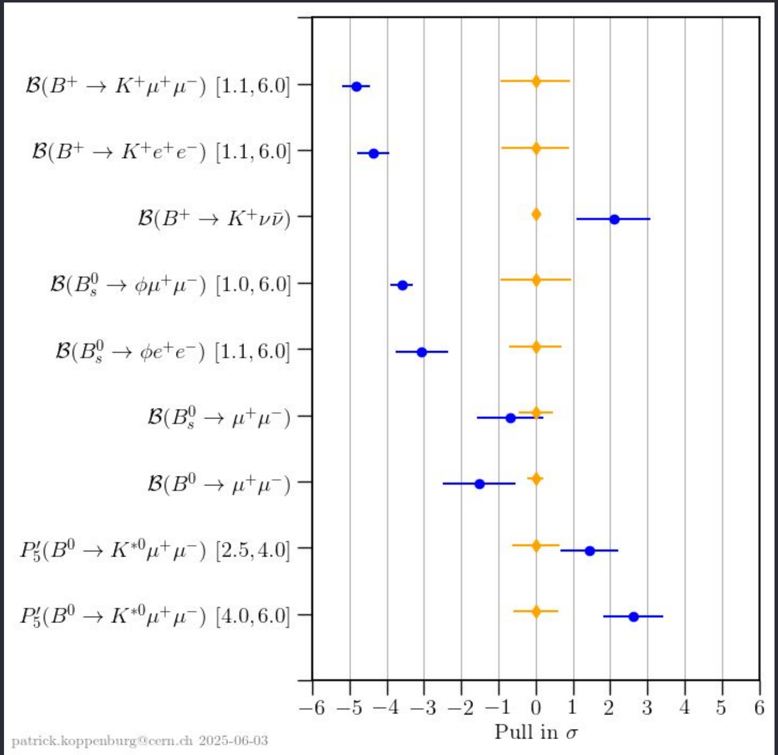
[LHCb, 2022]

Discrepancy has vanished with more data :(

Flavour anomalies

https://www.koppenburg.ch/anomalies.html



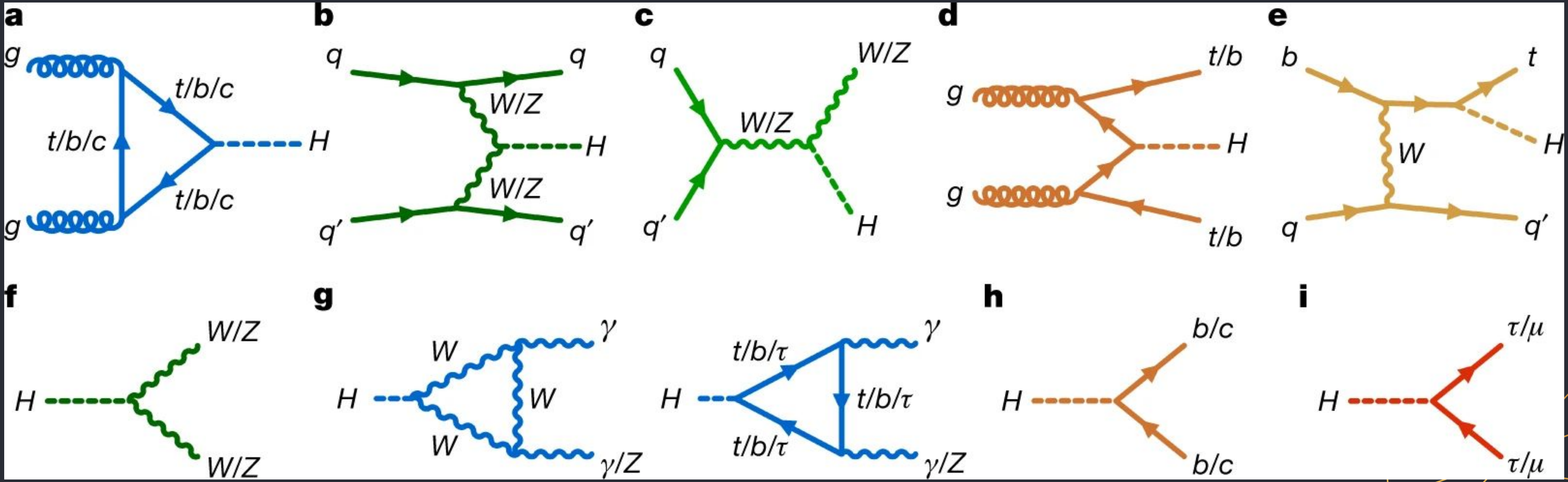


Most of these results are LHCb and Belle/Belle II - shown are combinations.
New physics? Or pointing to a need to improve our simulations…

Studies of the Higgs boson

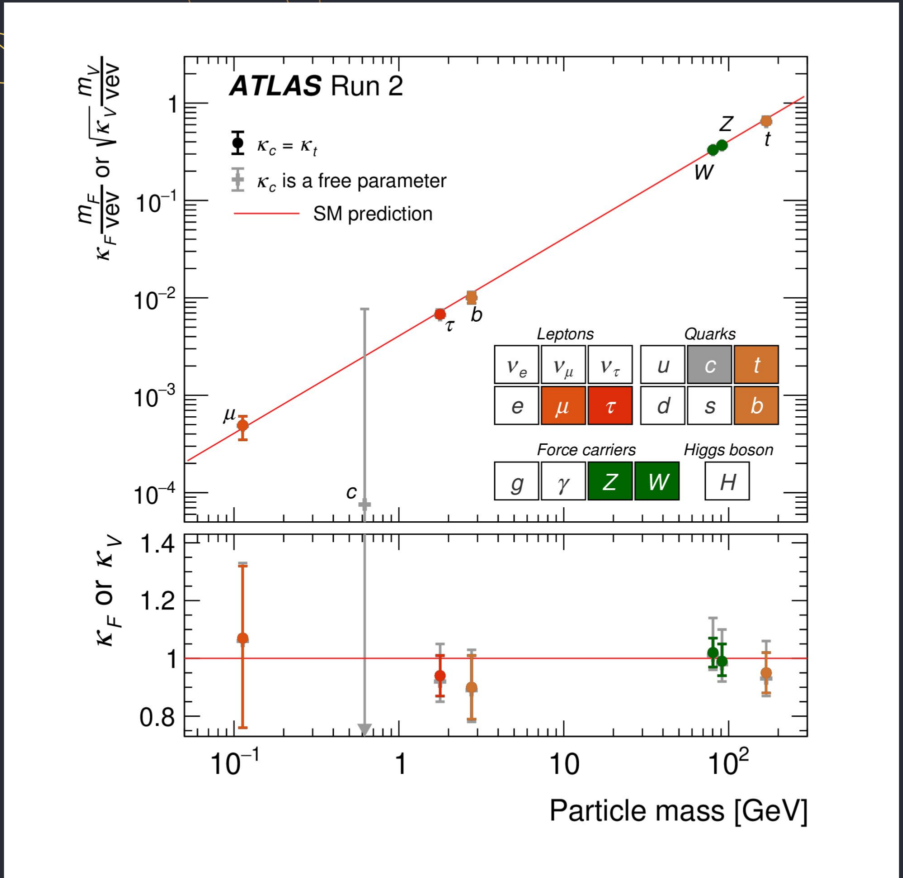
Overview paper: Detailed map of Higgs 10 years after discovery

Post-discovery, we need to measure **everything** about the Higgs boson: how it's produced and how it decays (couplings), spin, mass...



Higgs boson couplings

Overview paper: Detailed map of Higgs 10 years after discovery



Very hard for small mass particles!

Some we can measure via decay

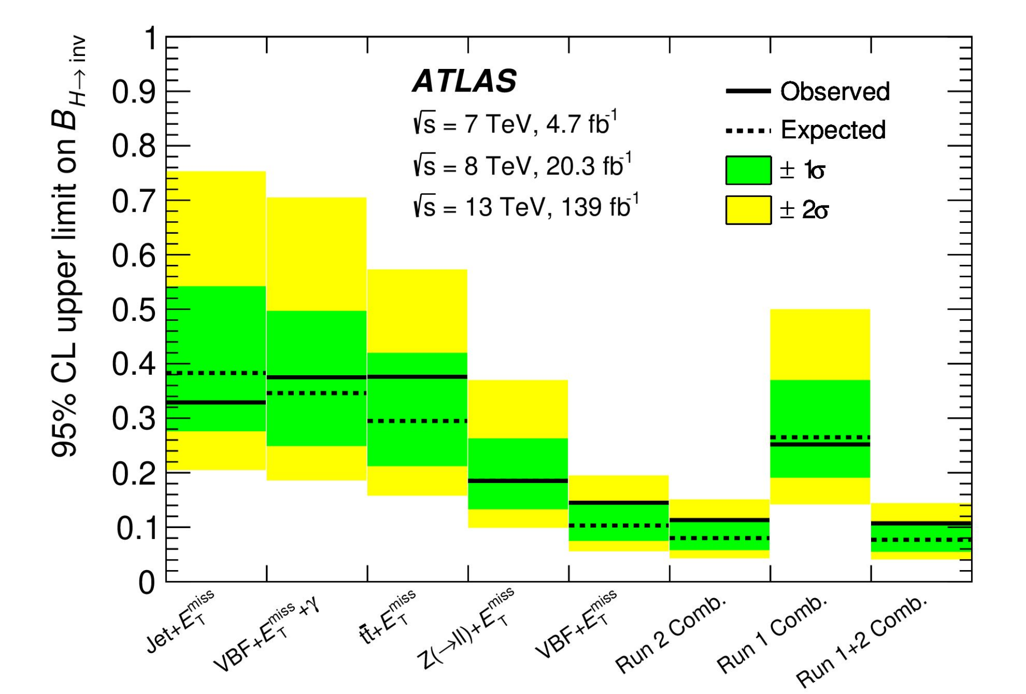
Some via production

And some with both!

Phys. Lett. B 842 (2023) 137963

Higgs boson ⟶ invisible particles

The Standard Model predicts 0.1% of Higgs boson decays will be to “invisible particles” (neutrinos)



0.1% is currently too small to measure (below our sensitivity)

We set **limits** on the maximum branching ratio that the data allows for Higgs boson decays to invisible particles

Current limit is 0.107 (10.7%)

Uncertainties

Statistical vs systematic uncertainties

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Uncertainty source	Effect
Total uncertainty	3.1%
Statistical uncertainty	1.1%
Top modelling	1.6%
Fake-lepton background	1.5%
Flavour tagging	0.7%
Other background	0.9%
Signal modelling	1.0%
Jet calibration	0.6%
Luminosity	0.8%
Other systematic uncertainties	0.9%

Uncertainties due to the size of the dataset: if this is largest, the analysis is **statistically-limited**

(you should **never** be limited by simulation statistics: that's just a sign you need more events!)

Systematic uncertainties and theoretical modelling uncertainties:

- Sometimes combined into "systematic uncertainties"
- Sometimes due to limited number of data events in control regions
- Usually kept separate in cross-section results in case theory calculations improve!

Excellent notes, arXiv:020702
Summarized in slides

Systematic uncertainties vs effects

Systematic effects is a general category which includes effects such as background, scanning efficiency, energy resolution, variation of counter efficiency with beam position, and energy, dead time, etc. The uncertainty in the estimation of such a systematic effect is called a systematic error.

Jay Orear

Excellent notes, arXiv:020702
Summarized in slides

Systematic uncertainties vs effects

(and **never** systematic error – an error is something you fix!)

> Systematic effects is a general category which includes effects such as background, scanning efficiency, energy resolution, variation of counter efficiency with beam position, and energy, dead time, etc. The uncertainty in the estimation of such a systematic effect is called a systematic ~~error.~~ **uncertainty**
>
> Jay Orear

Systematic uncertainties are **not:**

- Uncertainties to add "just in case", e.g. you have two methods to measure a background that are different but in statistical agreement. No uncertainty necessary!
- Uncertainties to add if two methods *disagree*: **find out why they disagree and choose the correct one!**
- "Just in case" uncertainties because you're not confident in your results
- But you'll see all of these happening in collider experiments anyways

Some words to live by (print & post by your desk!)

So finally:

1. Thou shalt never say ‘systematic error’ when thou meanest ‘systematic effect’ or ‘systematic mistake’.
2. Thou shalt know at all times whether what thou performest is a check for a mistake or an evaluation of an uncertainty.
3. Thou shalt not incorporate successful check results into thy total systematic error and make thereby a shield to hide thy dodgy result.
4. Thou shalt not incorporate failed check results unless thou art truly at thy wits’ end.
5. Thou shalt not add uncertainties on uncertainties in quadrature. If they are larger than chickenfeed thou shalt generate more Monte Carlo until they shrink to become so.
6. Thou shalt say what thou doest, and thou shalt be able to justify it out of thine own mouth; not the mouth of thy supervisor, nor thy colleague who did the analysis last time, nor thy local statistics guru, nor thy mate down the pub.

Do these, and thou shalt flourish, and thine analysis likewise.

Modelling ("theoretical") uncertainties

If we want to compare a measurement to data we need to understand how well our simulation is doing!

1. Uncertainties due to uncertainties in the parton distribution functions
   Both from the PDF itself **and** comparing to the outcome of other PDFs

2. Uncertainties due to the choice QCD parameters in the MC generation (the renormalization and factorization scale)
   We usually vary these each up and down by a factor of two and see how the result changes

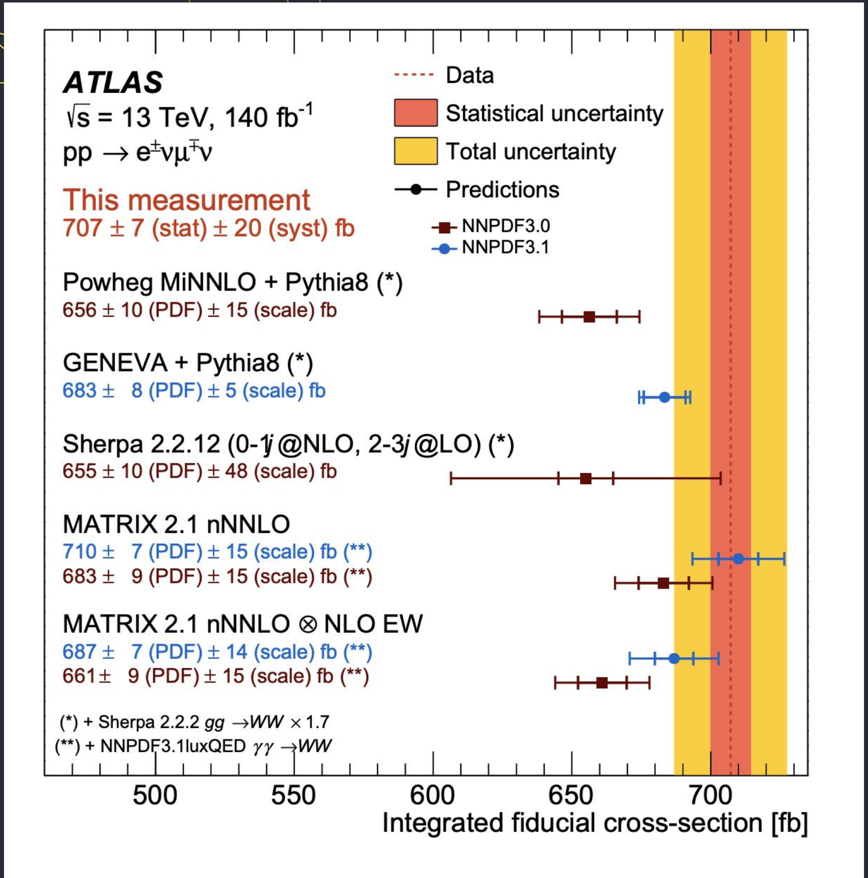
3. Uncertainties due to the choice of parton showering model
   Can compare different event generators, or vary the parameters from 2. in the parton showering (or both!)

4. Uncertainties due to the choice of the strong coupling constant, α_s
   Vary α_s to understand how this affects the result

5. Some processes will have other parameters with uncertainties

Modelling ("theoretical") uncertainties

STDM-2020-16



Uncertainties on predictions are reported separately

Dominant effect is generally from the **renormalization and factorization scales**

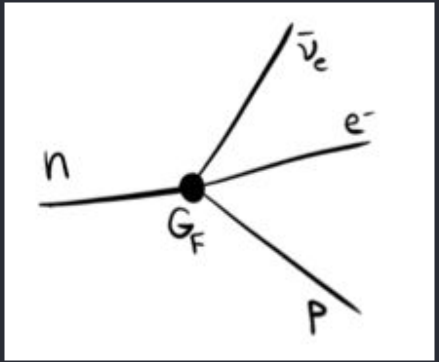
Other processes will have different sensitivity to these uncertainties

Effective field theories

Quantifying agreement with the SM

Measurements of the SM can tell us if there is space for effects from **BSM particles**
Effective field theories (EFTs) provide a framework to quantify effects from **heavy particles** out of reach of direct searches

A historical example:



At energies well below the W or Z mass, we can write electroweak interactions as an **effective** interaction

Cross-section $\sigma \sim G_F^2\, E_{CM}^2$

Worked for many 4-fermion interactions!
But, at when E_{CM} → few hundred GeV, this theory **breaks the unitarity bound**

⇒ **the W boson is needed to restore unitarity**

Standard Model Effective Field Theory

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_j \frac{c_{d6,j}}{\Lambda^2} \mathcal{O}_{j,\text{dim-6}} + \sum_k \frac{c_{d8,k}}{\Lambda^4} \mathcal{O}_{k,\text{dim-8}}$$

- Parametrize **all** possible higher order deviations from the SM as an expansion in a cutoff scale **$1/\Lambda$**

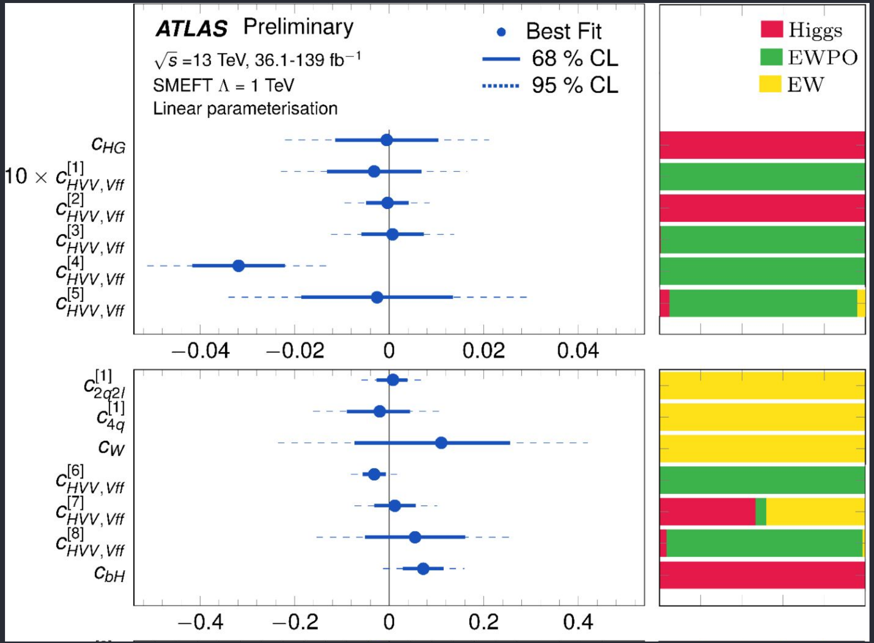
  Λ: energy scale below which the EFT is valid. Above this, the EFT approximation no longer makes sense

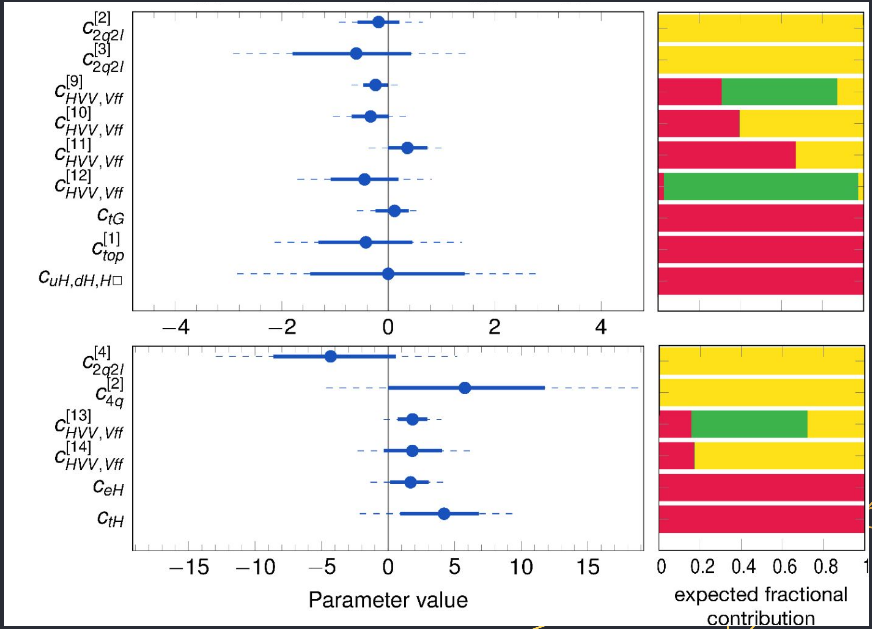
If there is some **new particle** that affects our processes, it could show up as a non-zero contribution in one of these terms!

Caveat: does not parameterize ***all BSM models*** *– just those with* ***heavy particles*** *that modify SM interactions*

SMEFT results

Best results when we look simultaneously in all of the measurements we have for how big an EFT term coefficient (Wilson coefficient) could be





Questions?