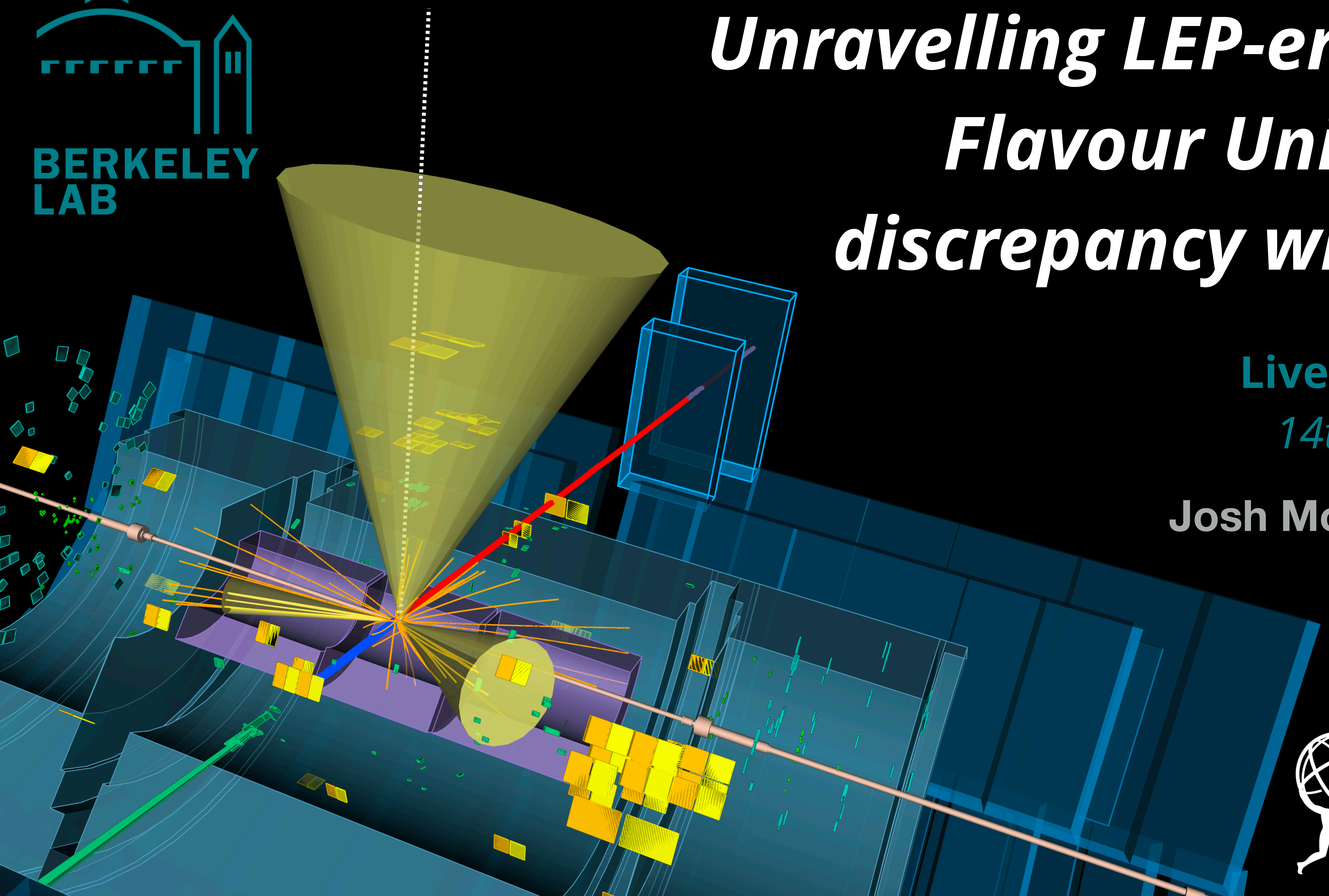
BERKELEY LAB

Unravelling LEP-era Lepton Flavour Universality discrepancy with ATLAS



Liverpool Seminar

14th October 2020

Josh McFayden (LBNL)

@JoshMcFayden
cern.ch/mcfayden

ATLAS EXPERIMENT

Introduction

I will present a recent ATLAS result using the full √s=13 TeV Run 2 dataset:

- *Test of the universality of τ and μ lepton couplings in W boson decays from $t\bar{t}$ events at √s=13 TeV*

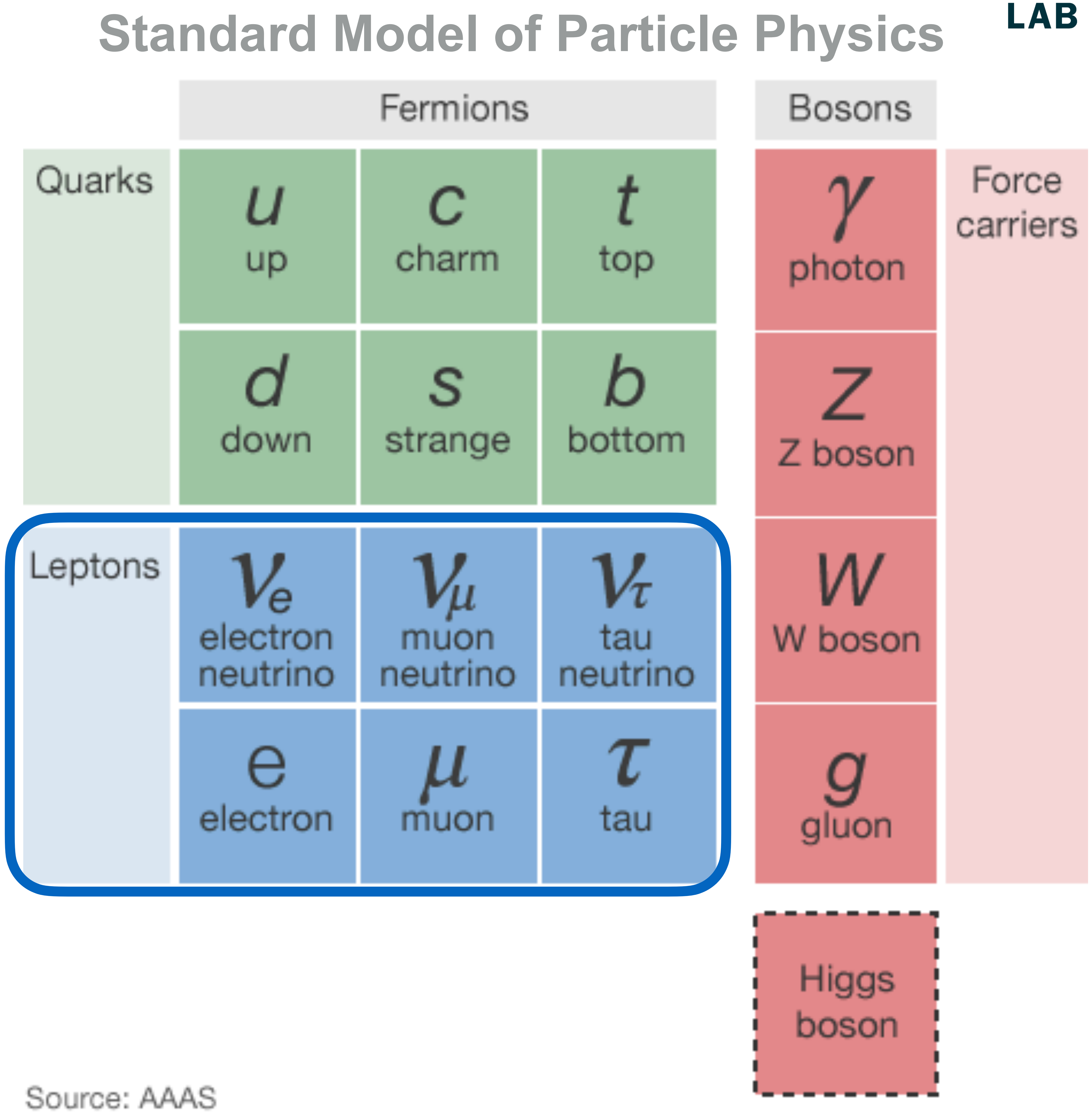
[arXiv:2007.14040]

Submitted to Nature Physics

A new probe in the very active field of **Lepton Flavour Universality**.

Lepton Flavour Universality

- Leptons are among the lightest fundamental particles.



Source: AAAS

Lepton Flavour Universality

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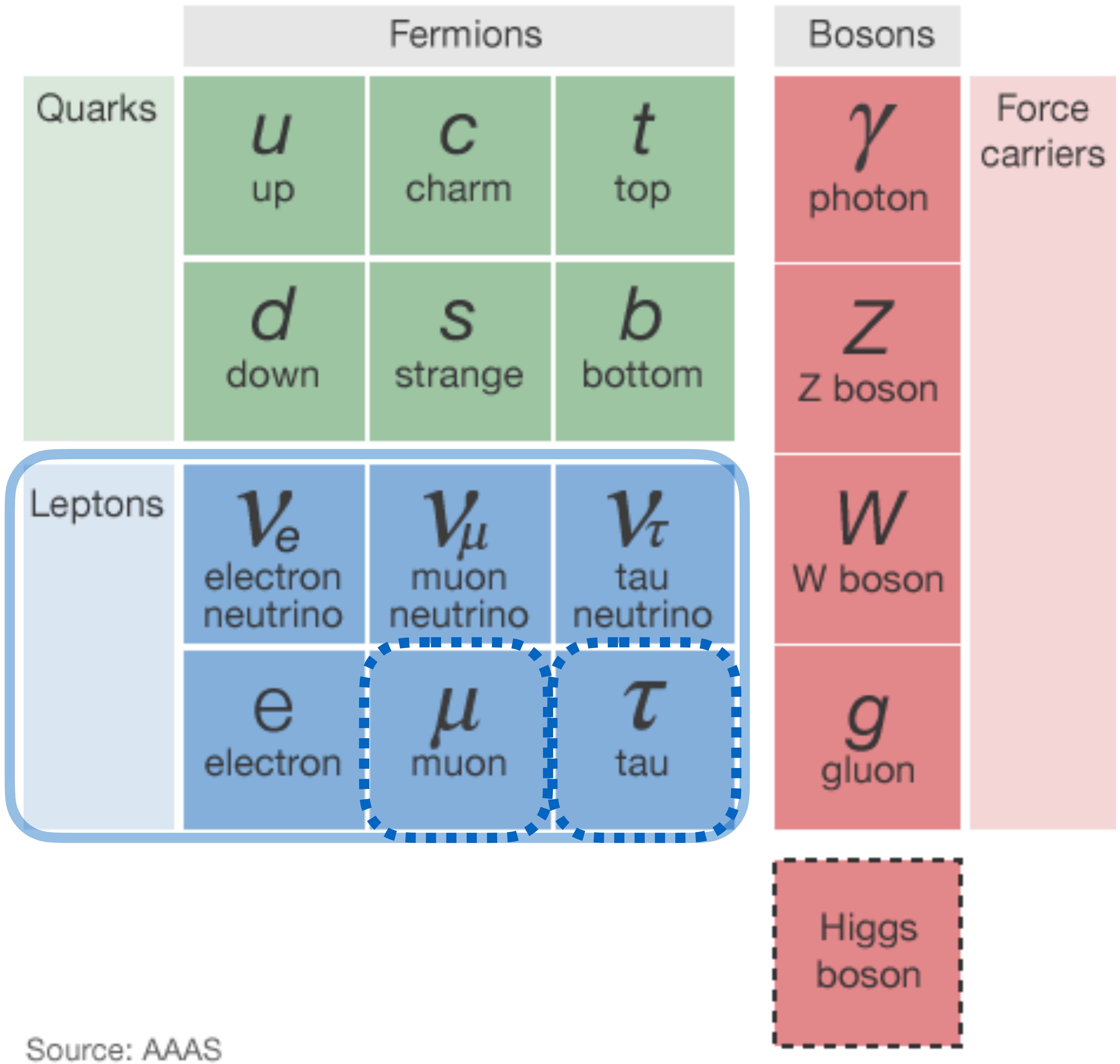
  - This new ATLAS measurement focusses on the **muon** and **tau** leptons.

Standard Model of Particle Physics



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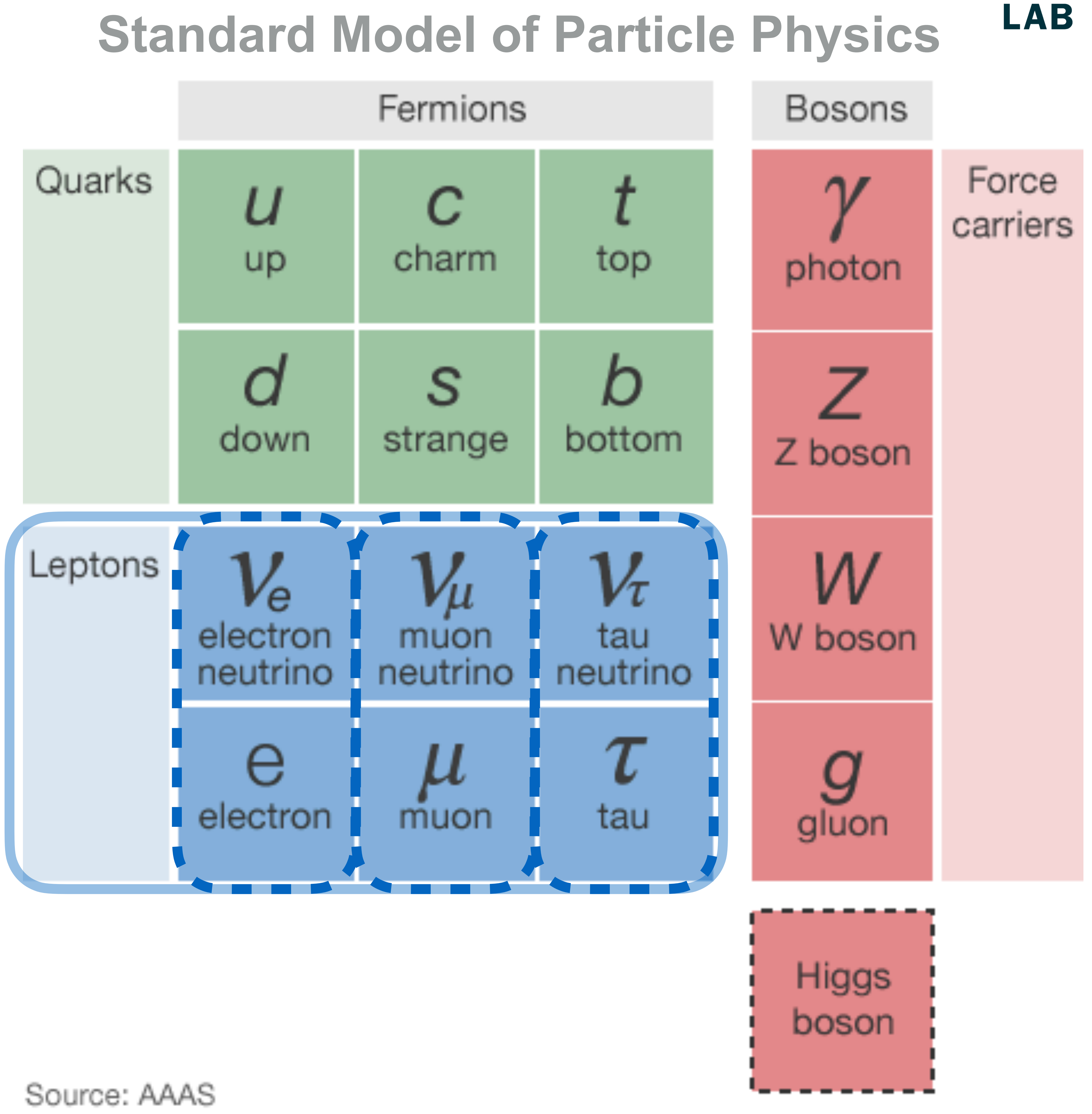
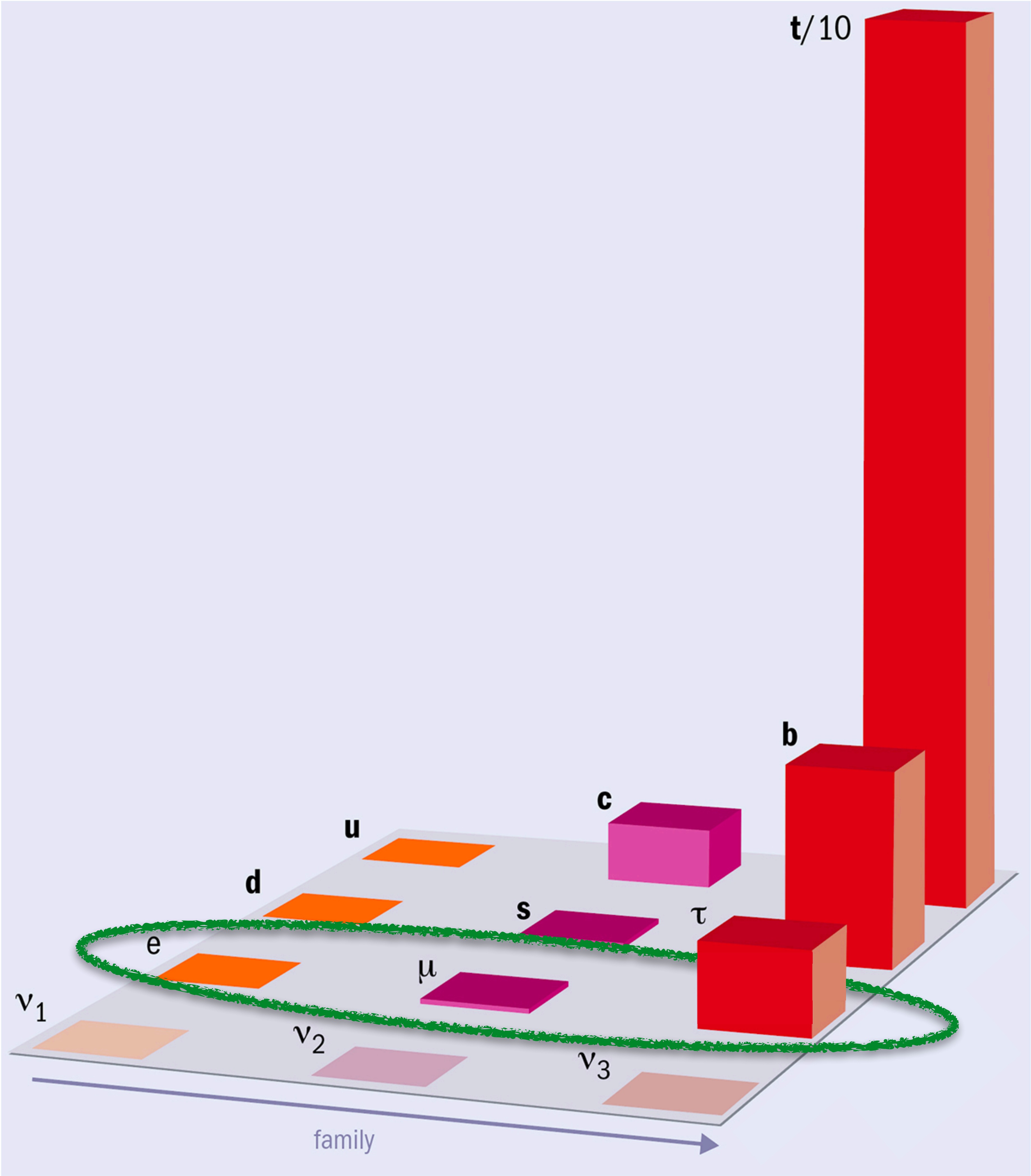
Lepton **Flavour** Universality

- Leptons are among the lightest fundamental particles.
  - This new ATLAS measurement focusses on the **muon** and **tau** leptons.
- These belong to two of the three **flavours** of the lepton family.



Lepton Flavour **Universality**

- The heart of the concept of Lepton Flavour **Universality** is:
  - According to the Standard Model (SM) each *flavour* of *lepton* only differ in their **mass**.



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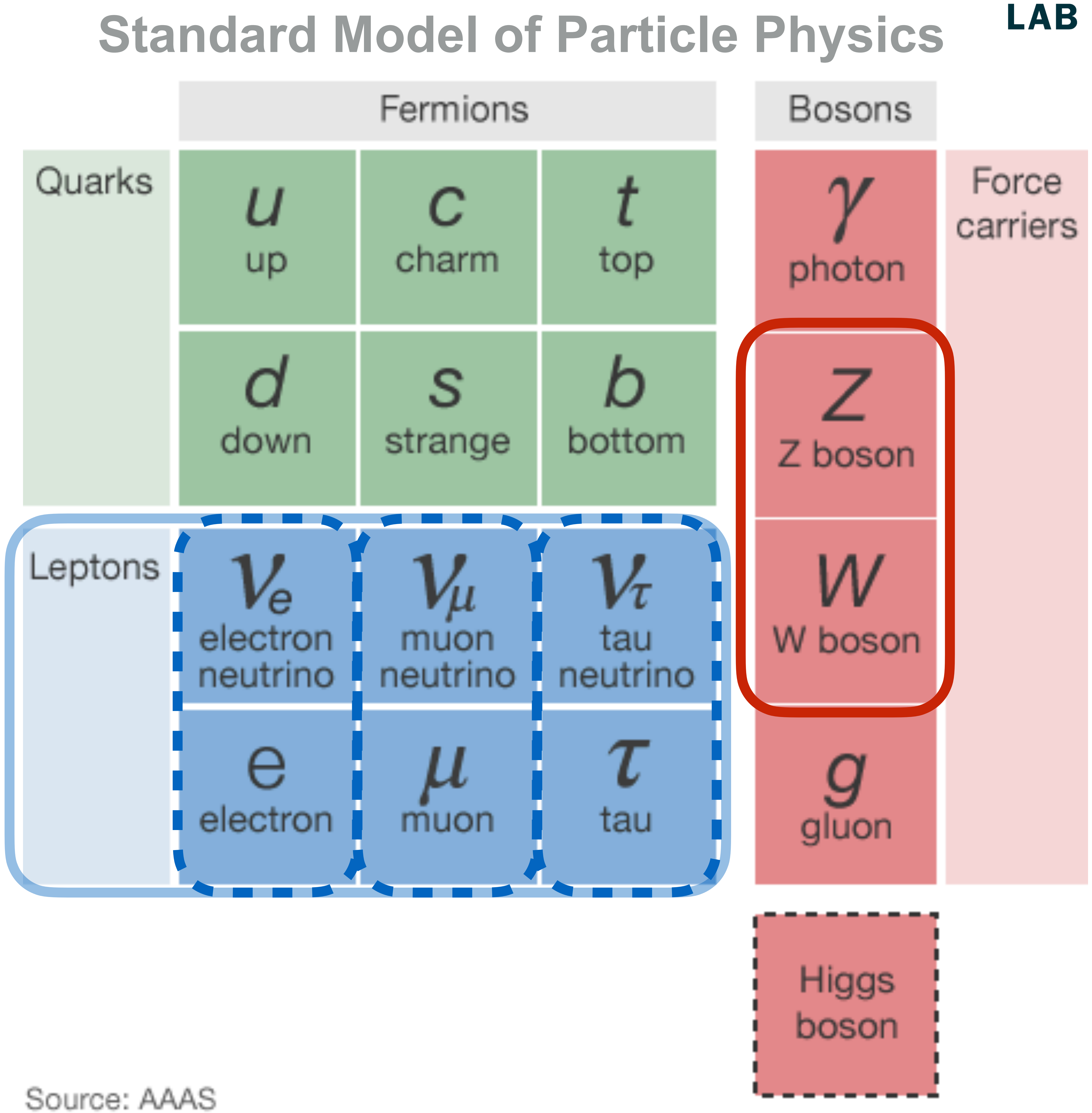

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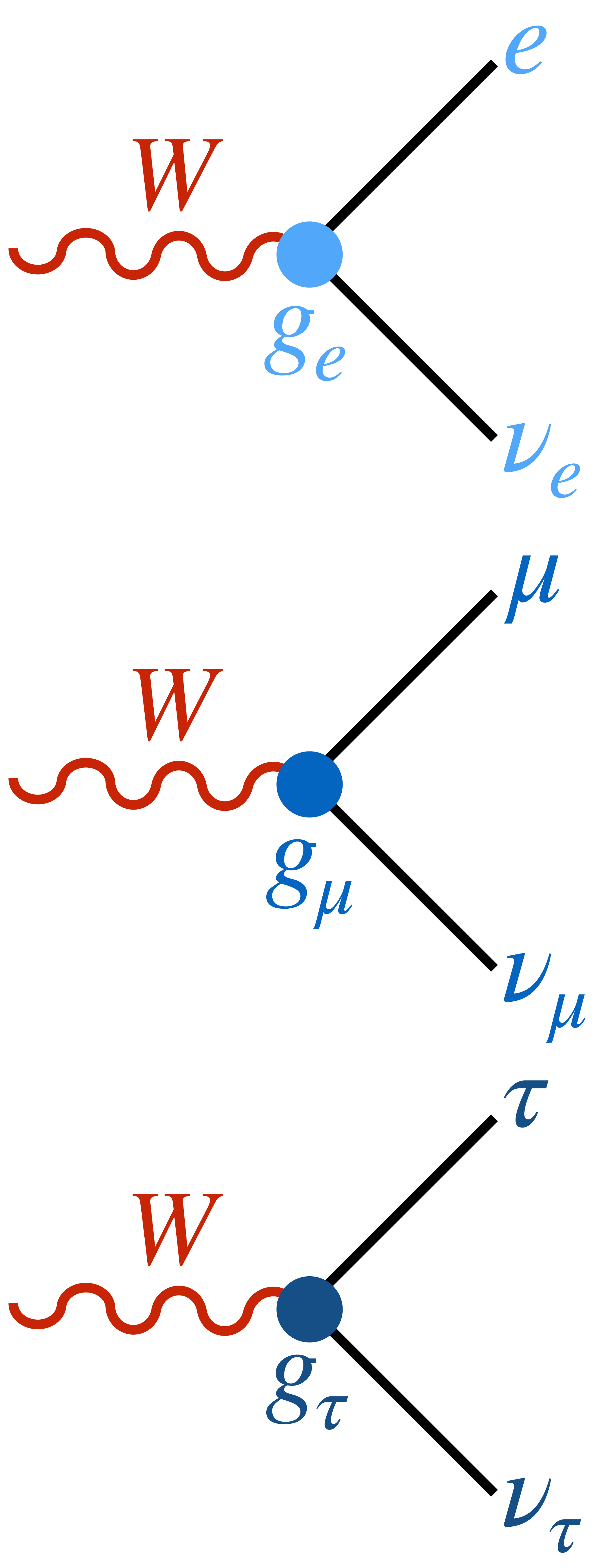
$$g_\ell = g_e = g_\mu = g_\tau$$



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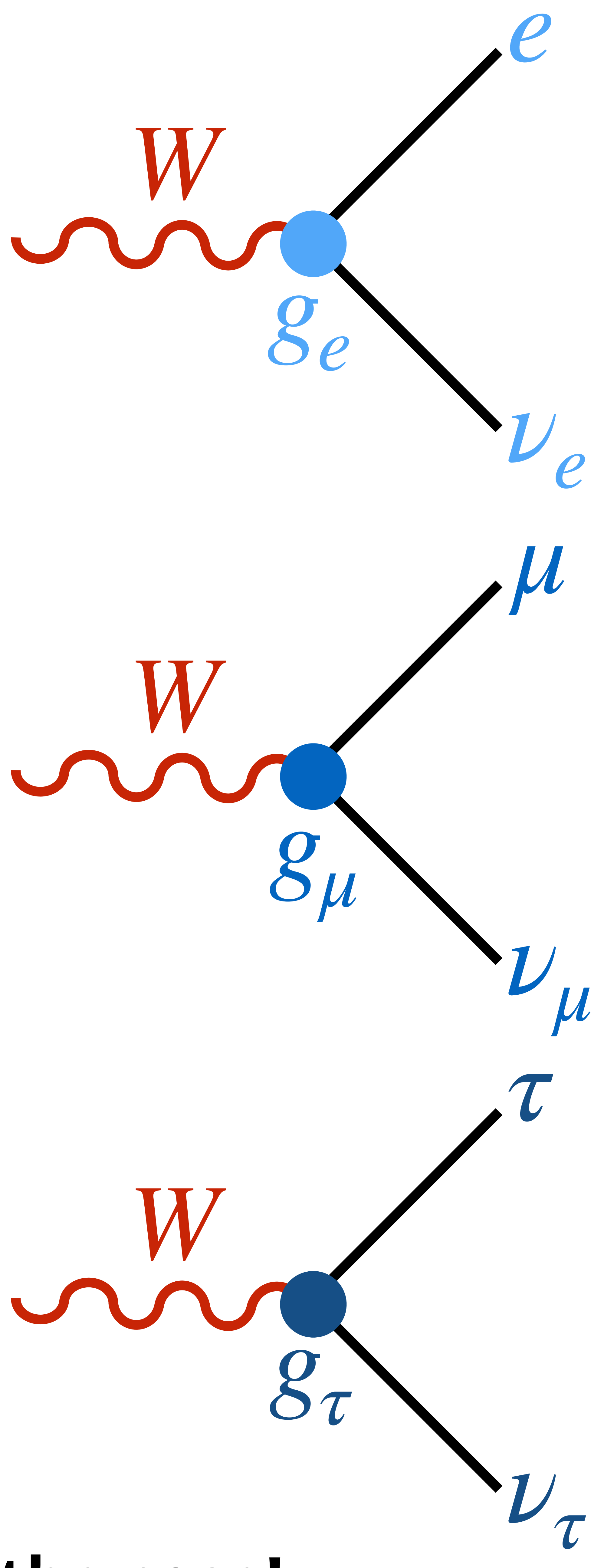

- **But this is an assumption - it's not guaranteed to be the case!**

Lepton Flavour **Universality**

- CERN Courier article referring to the **muon** discovery:

'Who ever ordered that?'

It is a lepton subject only to the types of force called the electromagnetic and the weak . Its intrinsic angular momentum or spin is 1/2. In all these properties it is identical to the electron . The mystery of the muon stems from the belief that the mass of a particle is a consequence of the interactions it undergoes . In this respect , the muon and the electron , as far as we know , are identical — they are subject to the same interactions. Where then does the difference in mass stem from ?

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Lepton Flavour **Universality**

- When the muon was first discovered there was significant experimental work on the problem of *"how does the muon differ from the electron"*
- It was suggested that the muon *“might have a special interaction with hadrons not possessed by the electron"*

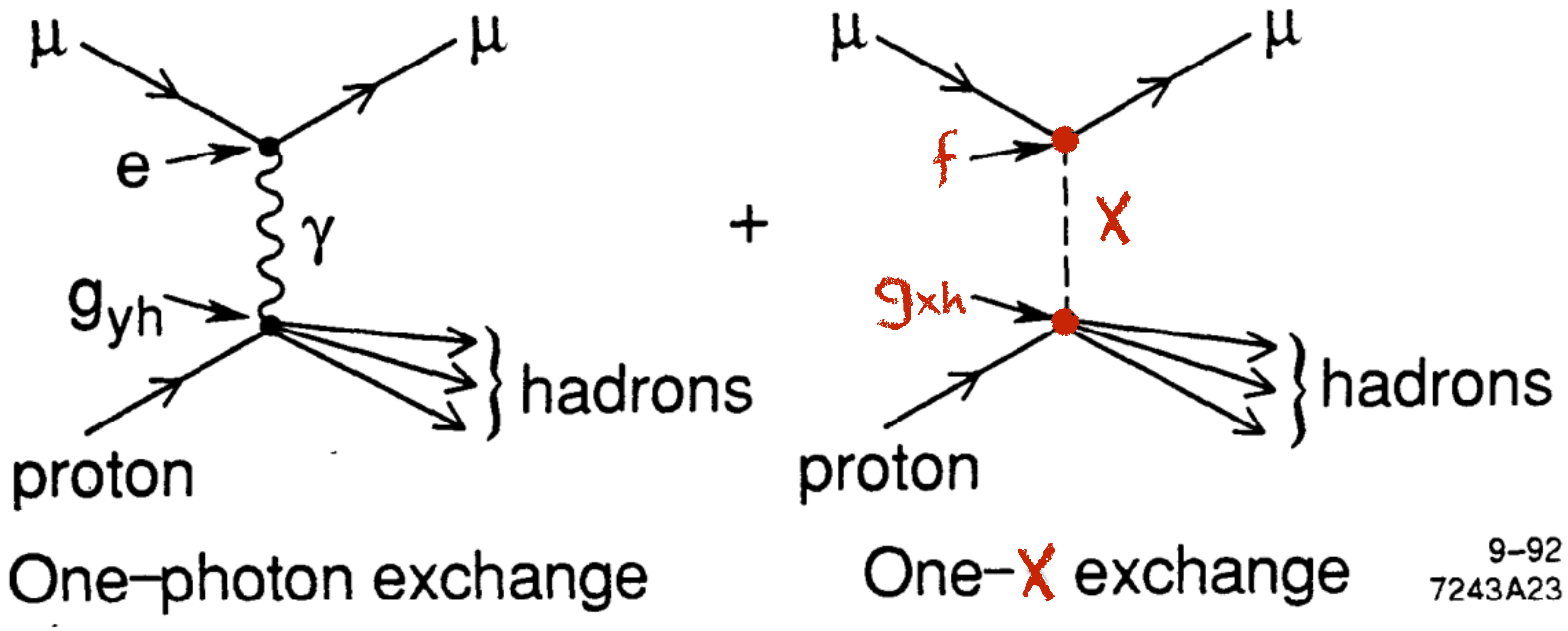


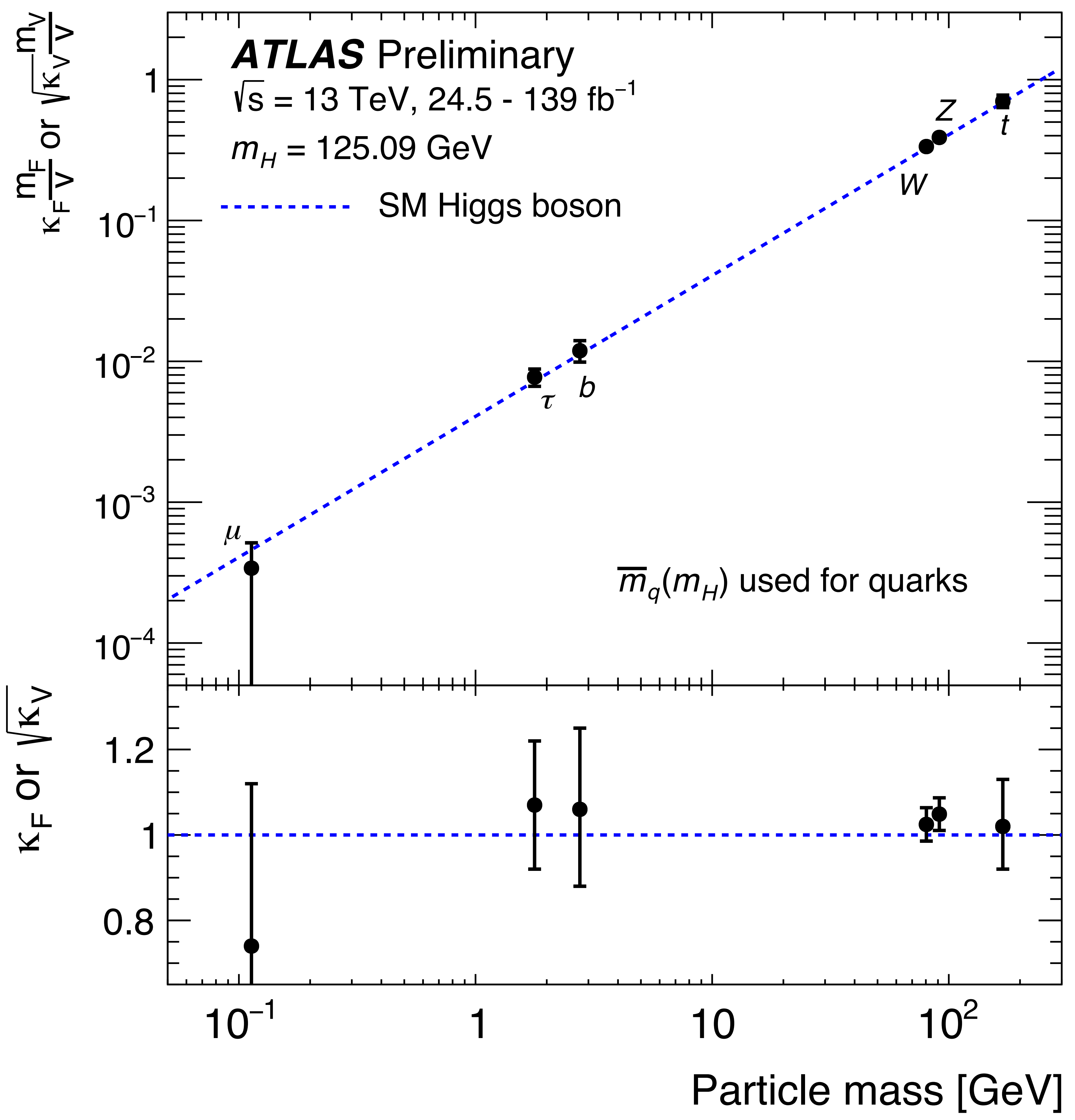
Fig. 1. From Perl (1971): the interaction of a muon with hadrons through exchange of a particle X, an example of the speculation that the muon has a special interaction with hadrons that is not possessed by the electron.

Lepton Flavour **Universality**

- Today it is well understood that the lepton masses originate from the Higgs Mechanism.

- The universality of lepton couplings with the electroweak bosons is still an assumption of the Standard Model.

  - Despite very precise measurements that support this assumption some **tensions** have also been observed…

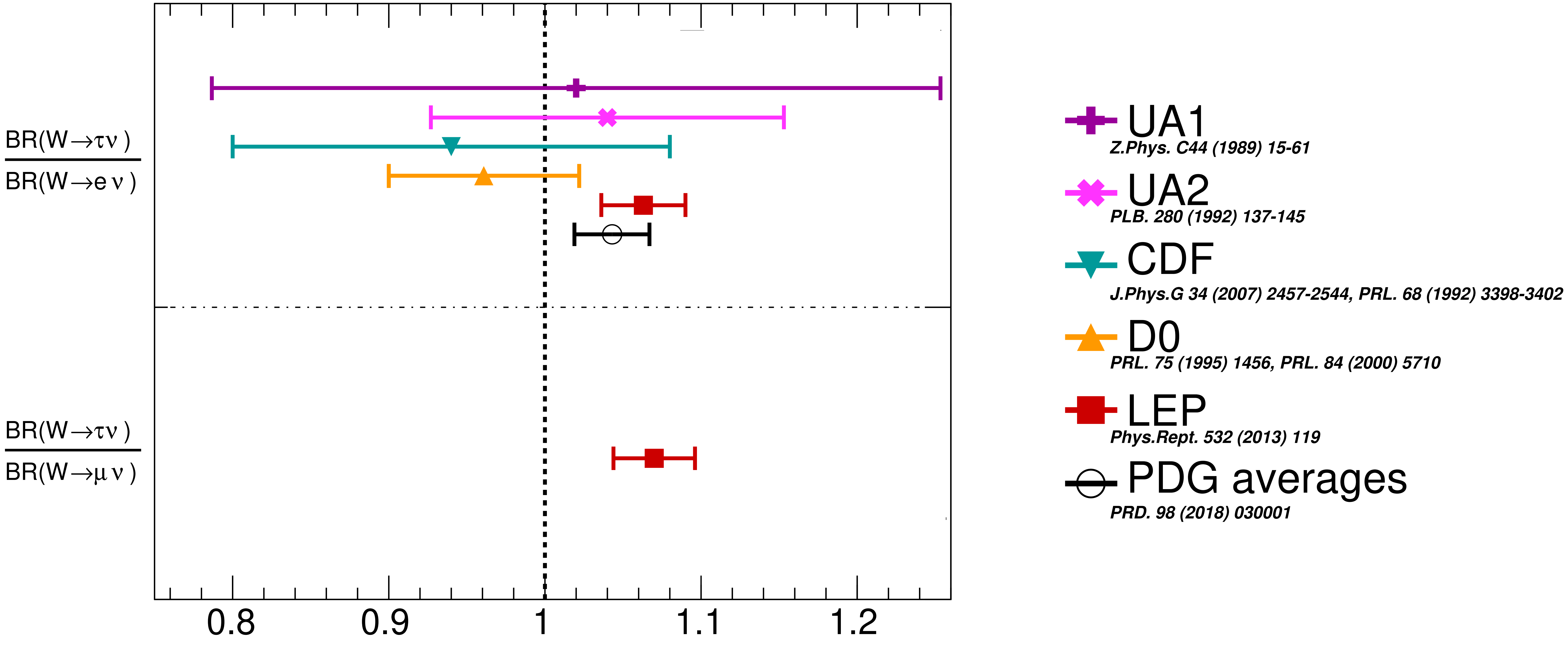


Tension in LEP measurements

- The branching ratios of W→eν,μν are precisely known.
  - Measured most precisely at LEP in the WW final state.

- However the uncertainties on τ measurements are still reasonably large making this interesting to pursue.

- There is also some **tension with the SM in the τ measurements**:
  - In particular in the **ratios of branching ratios**.



Tension in LEP measurements

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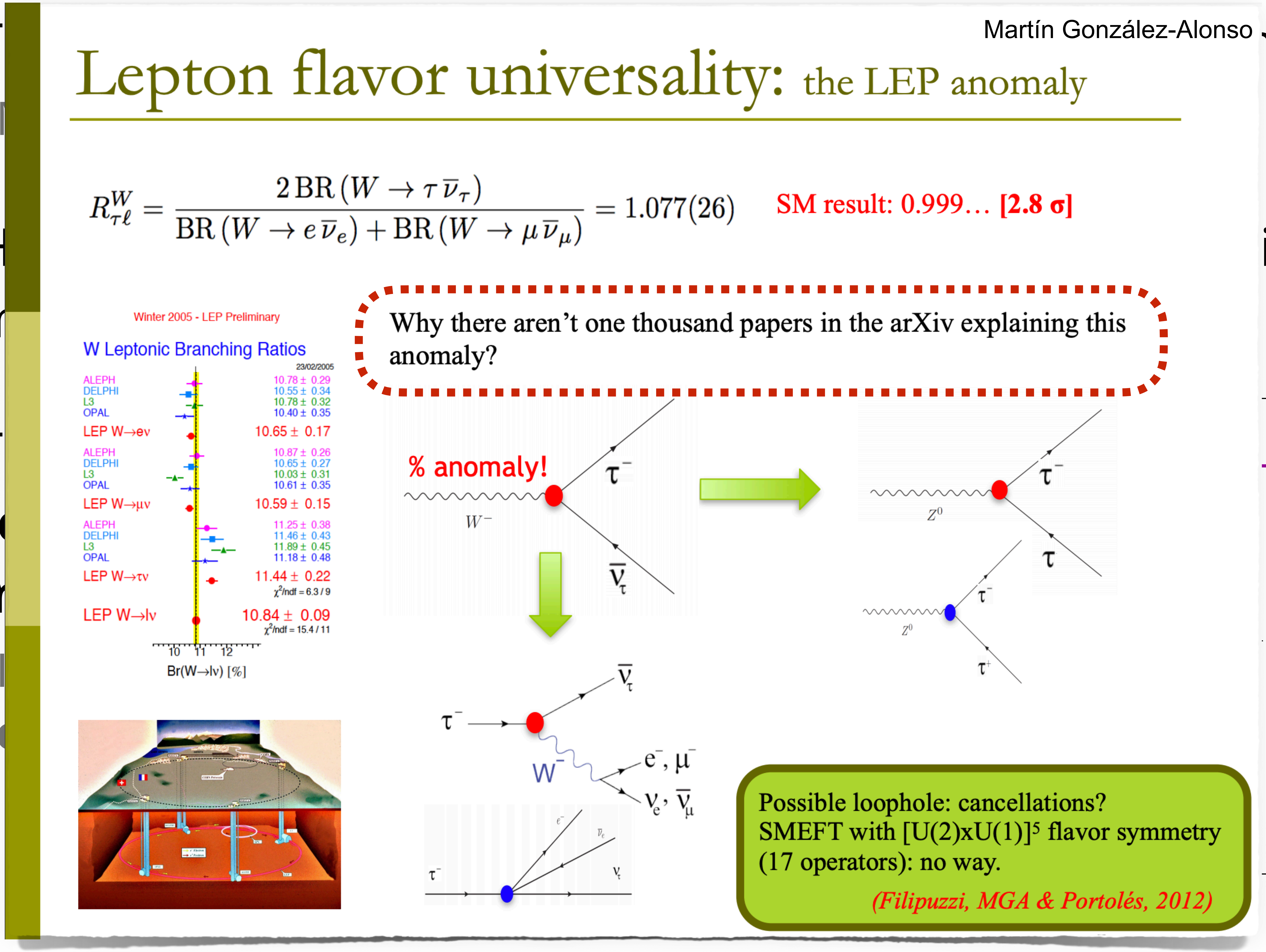
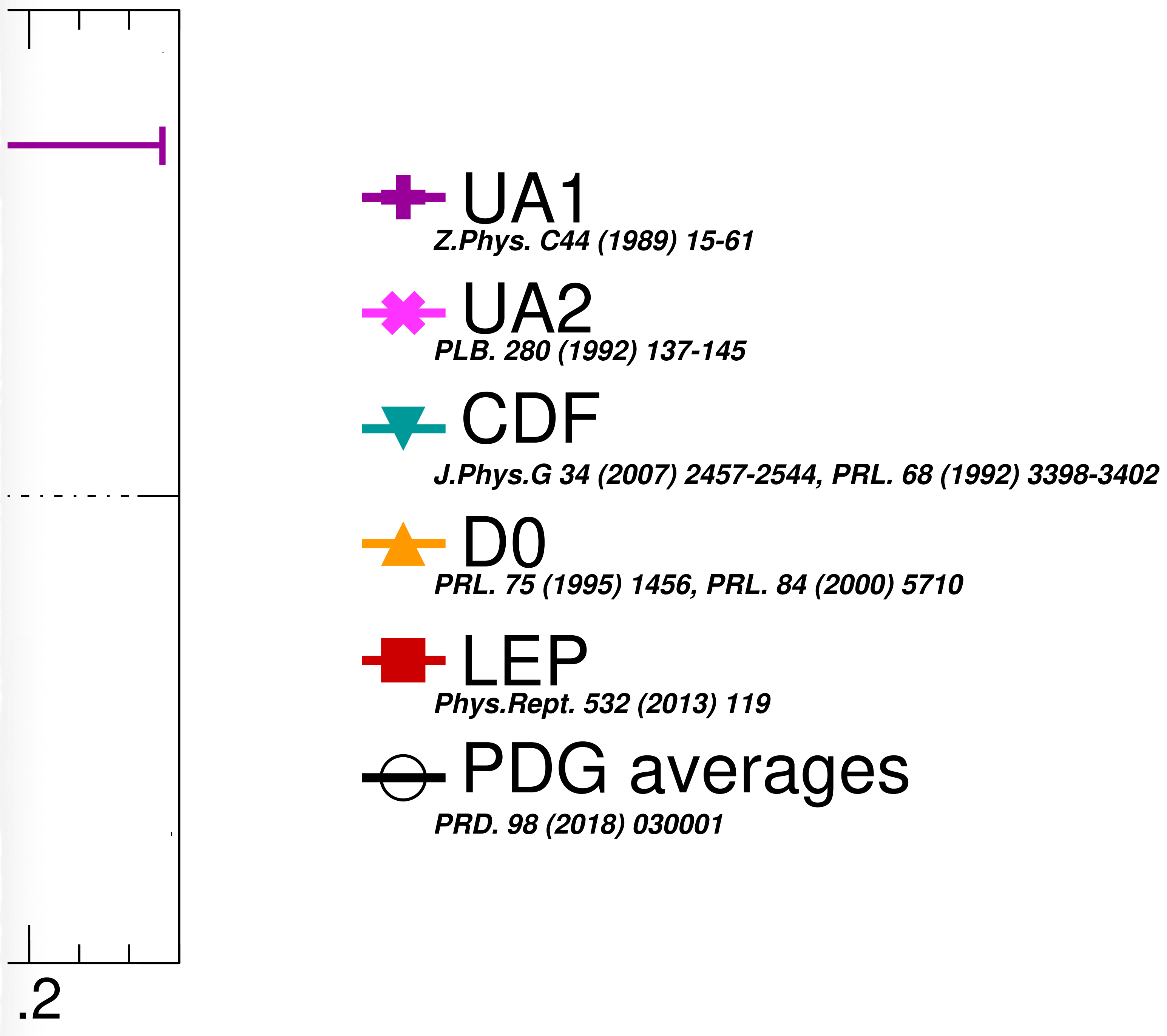
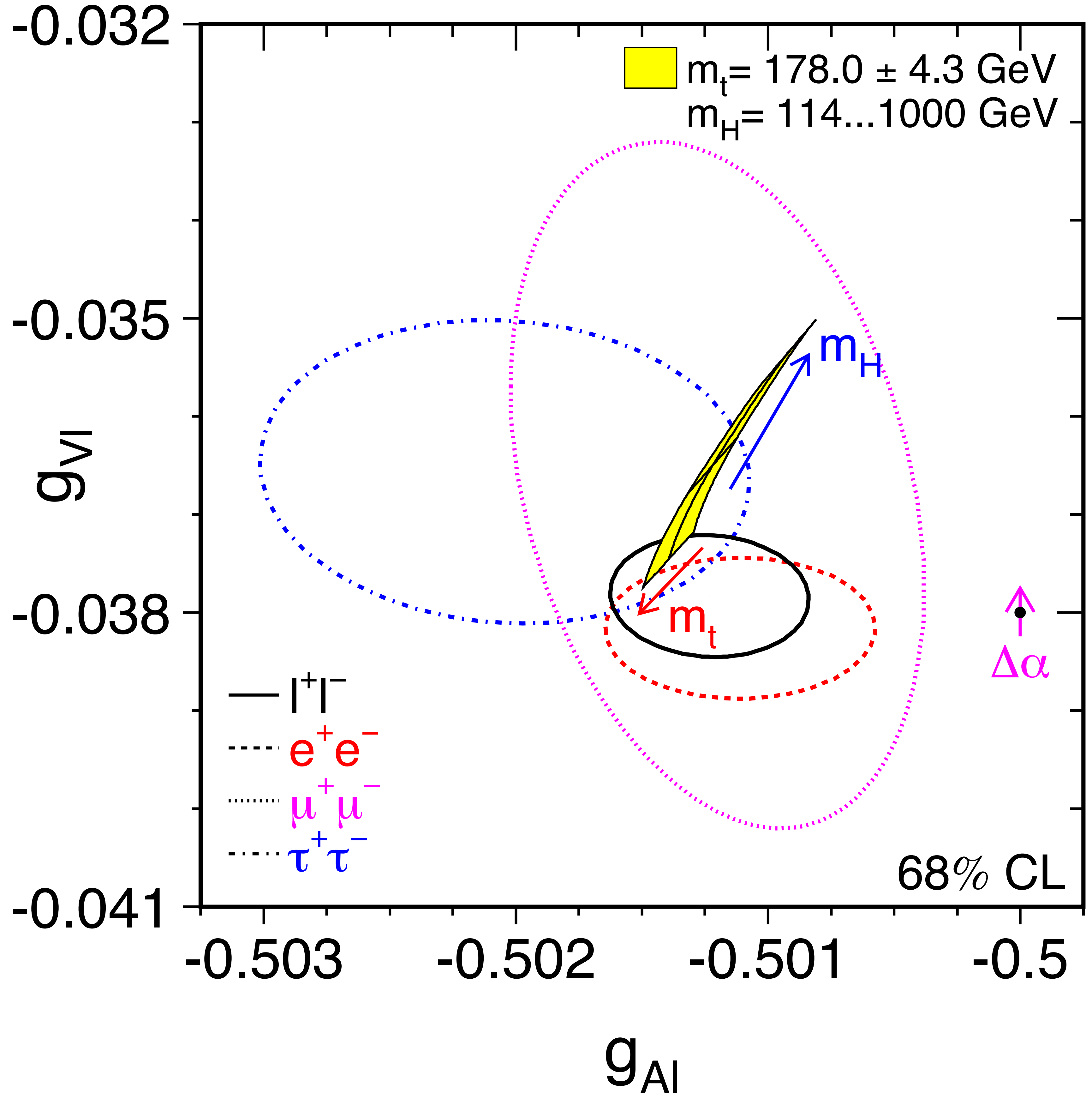




Precision electroweak measurements

- Charged current:
  - Low-energy measurements of the τ lifetime and branching fractions give a very precise test of lepton flavour universality:
    - $g_\tau / g_\mu = 0.9999 \pm 0.0014$.
- Neutral current:
  - The vector and axial vector couplings between leptons and the Z are also known precisely from Z-pole measurements at LEP and SLD
    - Per-mil level for g_{Al},
    - Between per-mil and percent for g_{Vl}.

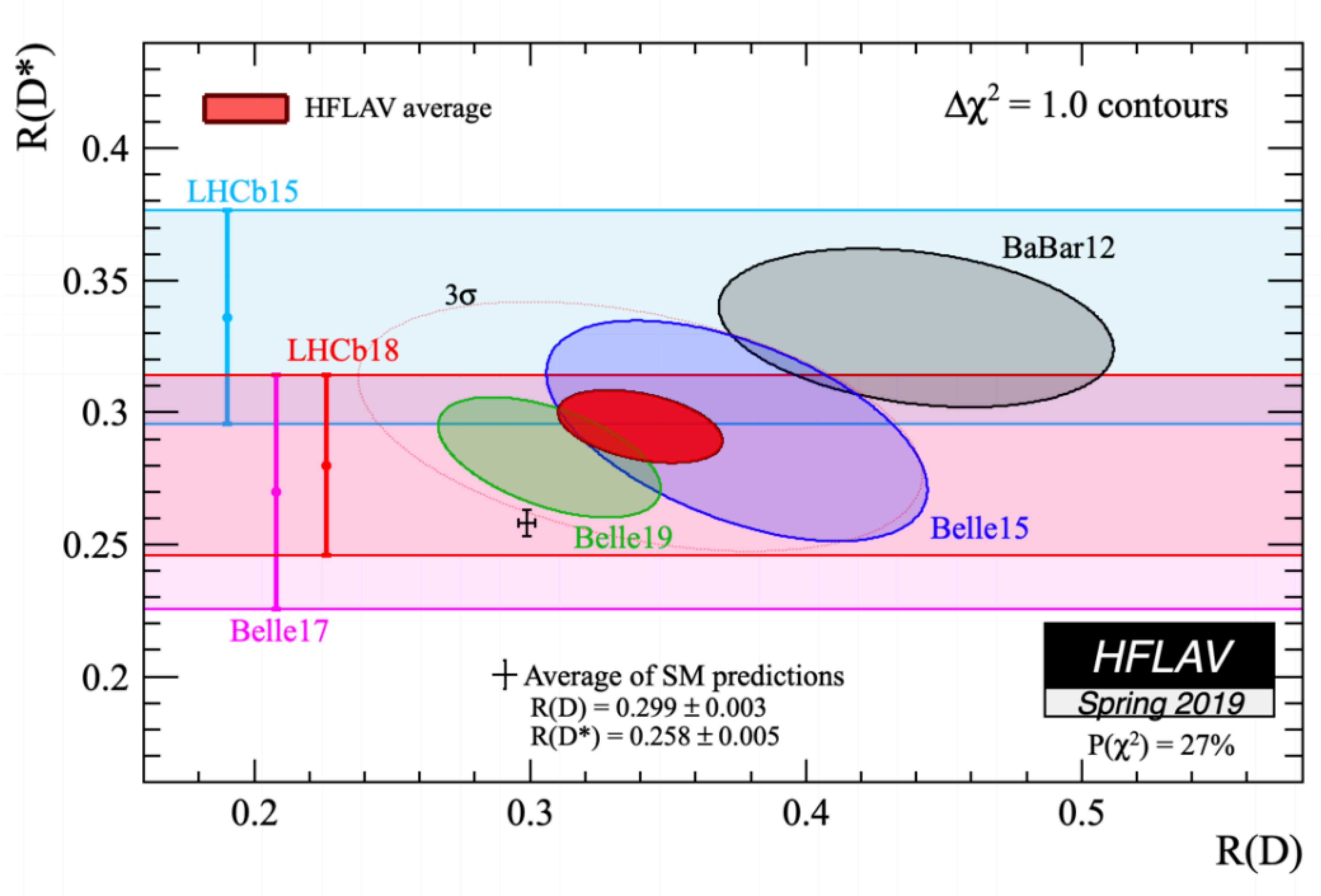


Tension in B-decay measurements

- B-factories and LHCb have also recently seen discrepancies in their tests of lepton universality from B decays involving τ leptons:
  - Specifically **R(D$^{(*)}$)**:

$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\mu\nu)}$$

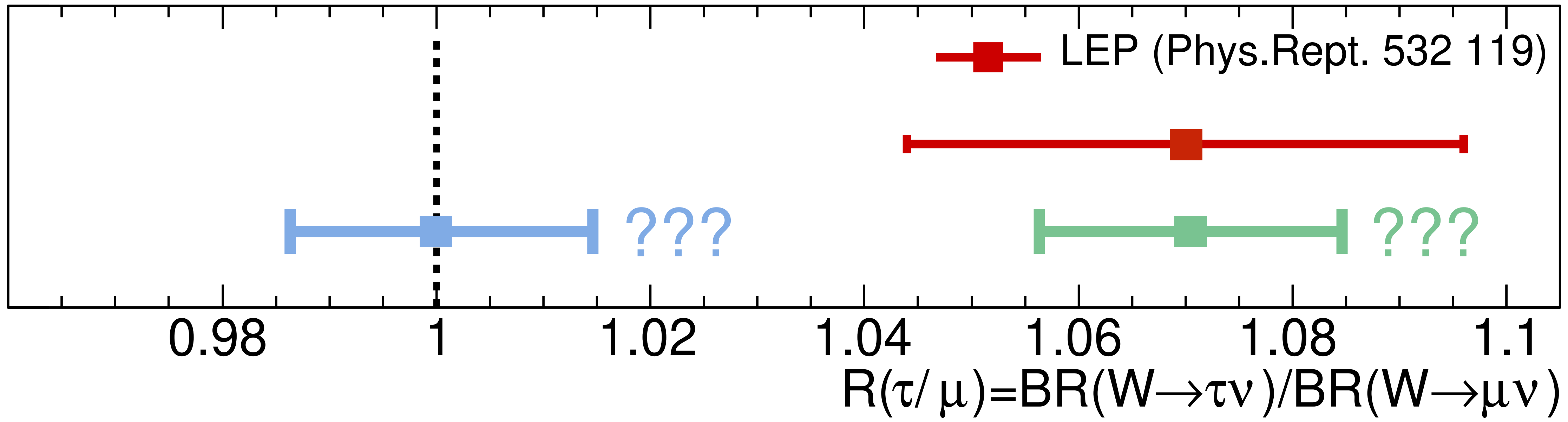
- Latest average shows 3.1σ discrepancy with the SM:



- However, these measurements probe a rather different phase-space:
  - Sensitivity to different mass range.

Analysis strategy

- To conclusively prove either that the LEP **discrepancy is real** or that it was a **fluctuation**, a **precision of at least 1–2%** is required.
  - Confirmation of the LEP measurement with this level of precision would correspond to an unambiguous **discovery of beyond the Standard Model physics**!



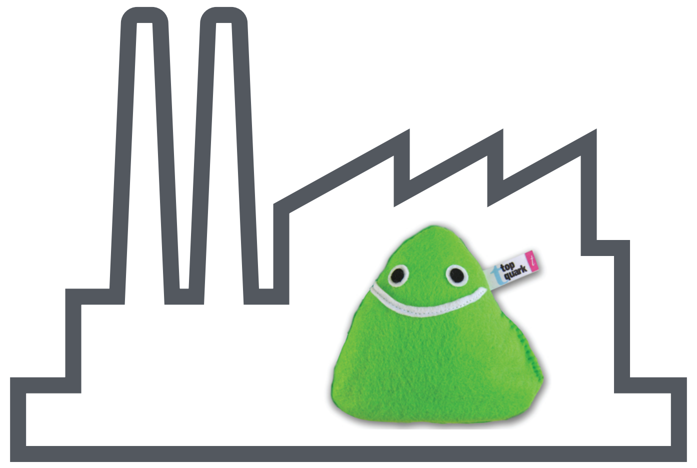
- This level of precision not previously thought possible at a hadron collider
  - Large backgrounds and kinematic biases due to e.g. the trigger selection.

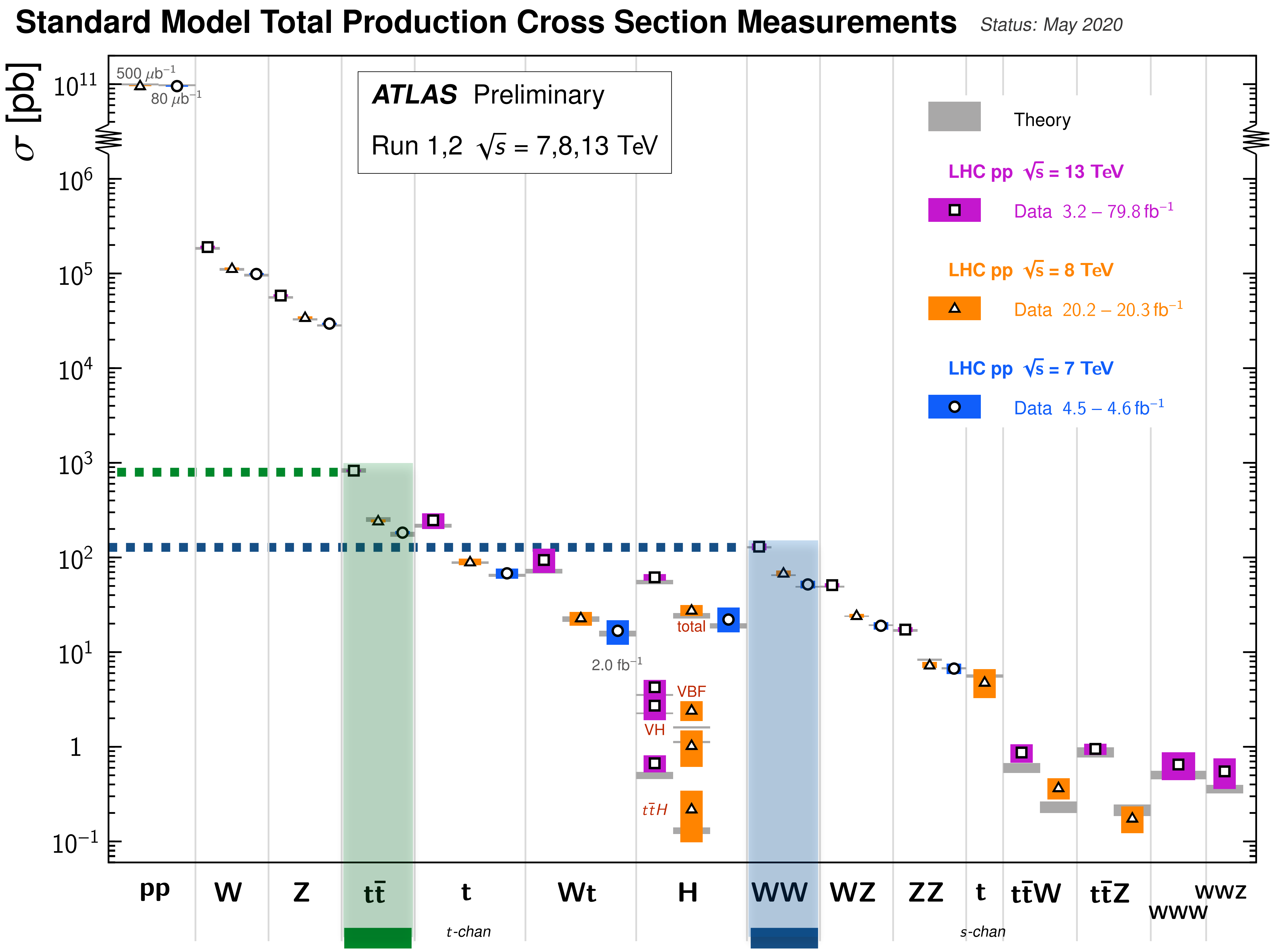
- **How to obtain a large unbiased sample muons and taus from W decays?**

Analysis strategy

- Achieved in this measurement by using **top quark pair** events.

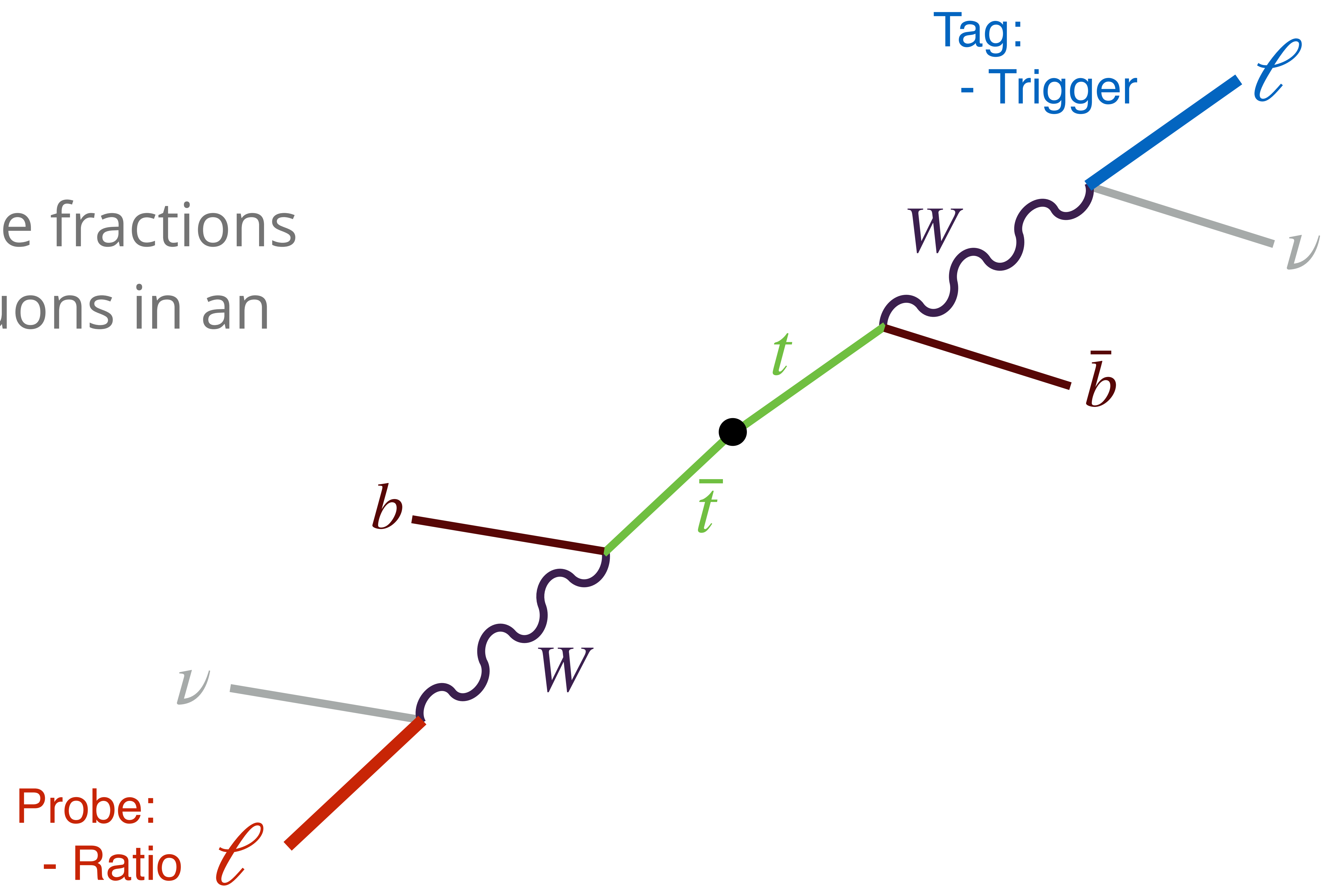
- The LHC is a top quark factory
  - Over 100 million **top quark pairs** produced in the latest run.
    - This is a huge sample of **W-boson pairs**
    - Order of magnitude more than from **WW production**





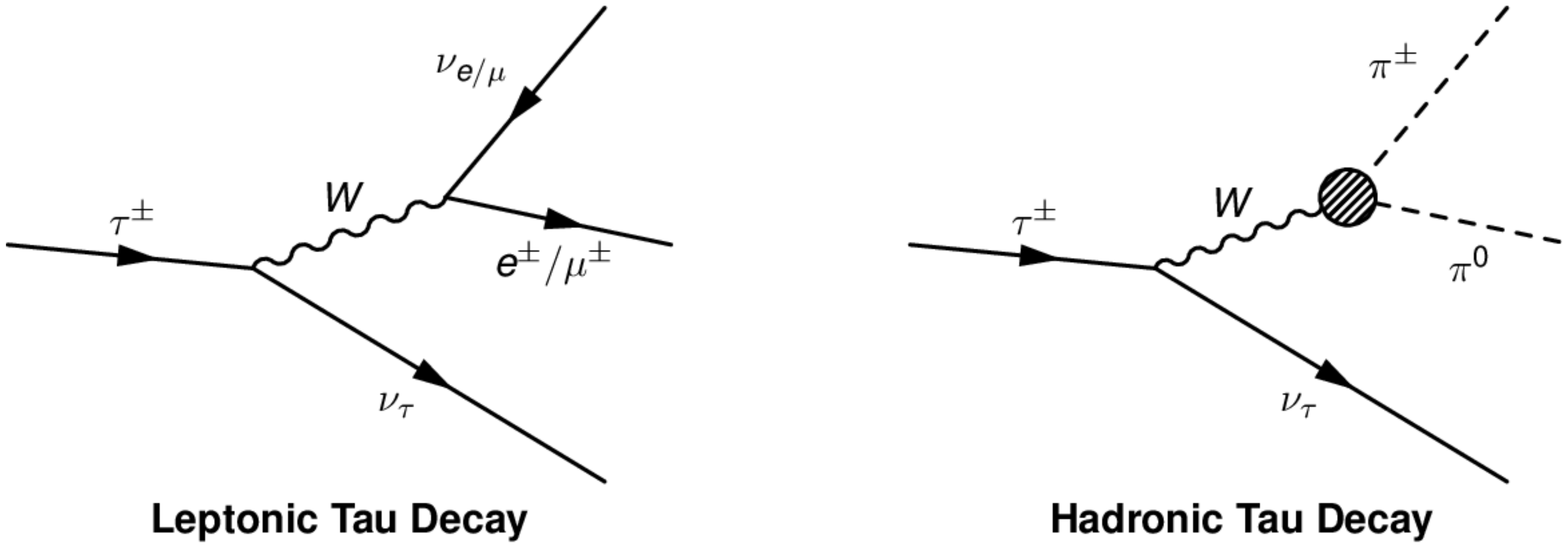
Analysis strategy

- These W pairs are exploited in a **tag**-**and**-**probe** approach:
  - One W is used to select events
  - The other is used to measure the fractions of decays to tau-leptons and muons in an unbiased way.



Analysis strategy

- The analysis focuses on leptonic ($\tau \to \mu\nu_\mu\nu_\tau$) decays
  - Hadronic τ decays are more complicated to reconstruct and come with larger uncertainties.

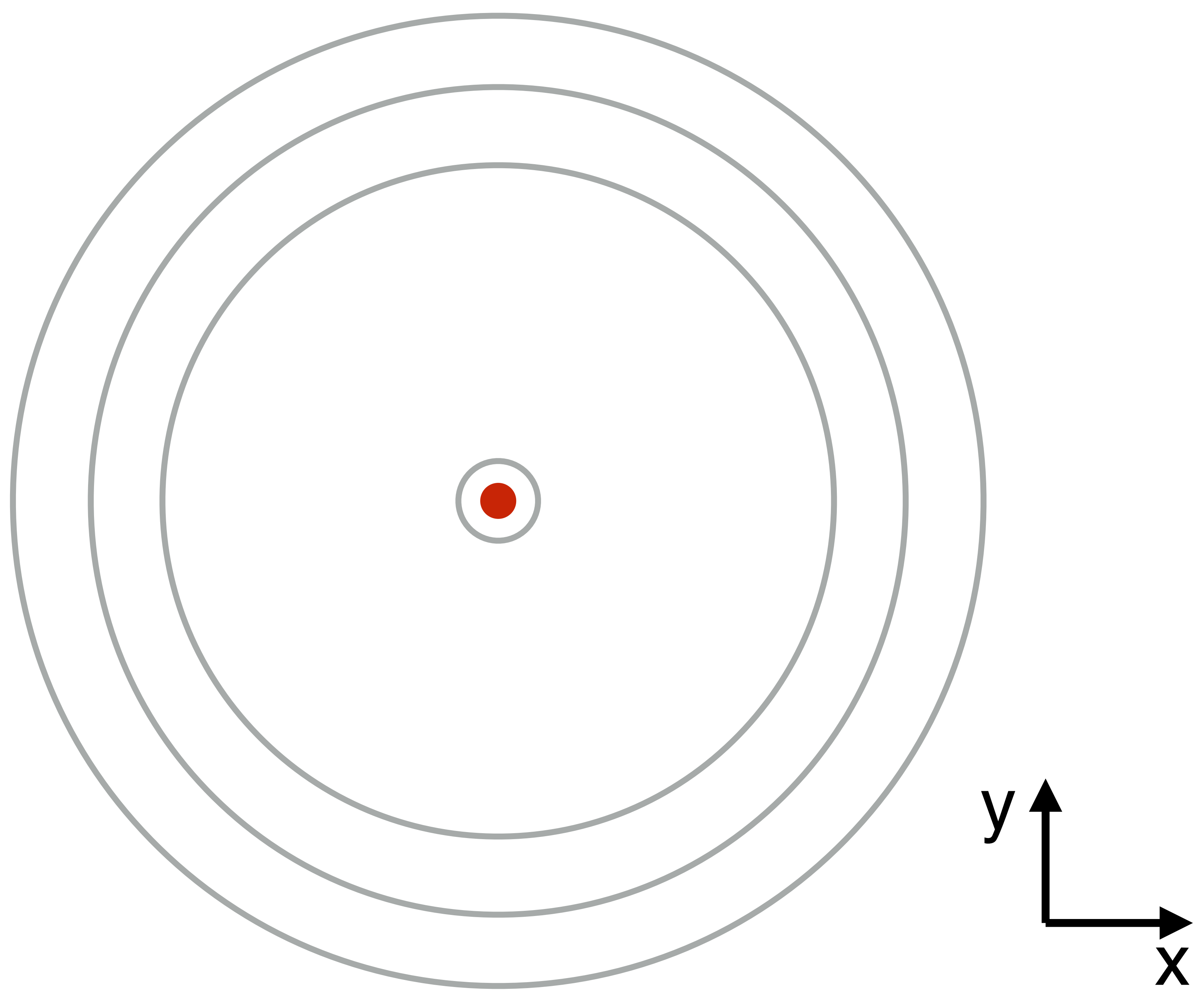


  - BR($\tau \to \mu\nu_\mu\nu_\tau$) is well known (17.39 ± 0.04 %) so we can extrapolate:

$$\frac{\mathrm{BR}(W \to \tau(\to \mu\nu\nu)\nu)}{\mathrm{BR}(W \to \mu\nu)} \to \frac{\mathrm{BR}(W \to \tau\nu)}{\mathrm{BR}(W \to \mu\nu)} = R(\tau/\mu)$$

Analysis strategy

- Need to separate **muons from tau decays** and **muons direct from W decay**.
- Use precise muon reconstruction to exploit the **lifetime of the tau** and its **lower momentum** decay products by:
  - Transverse impact parameter: $|d_0^{\mu}|$.
  - Muon transverse momentum: p_T^{μ}.



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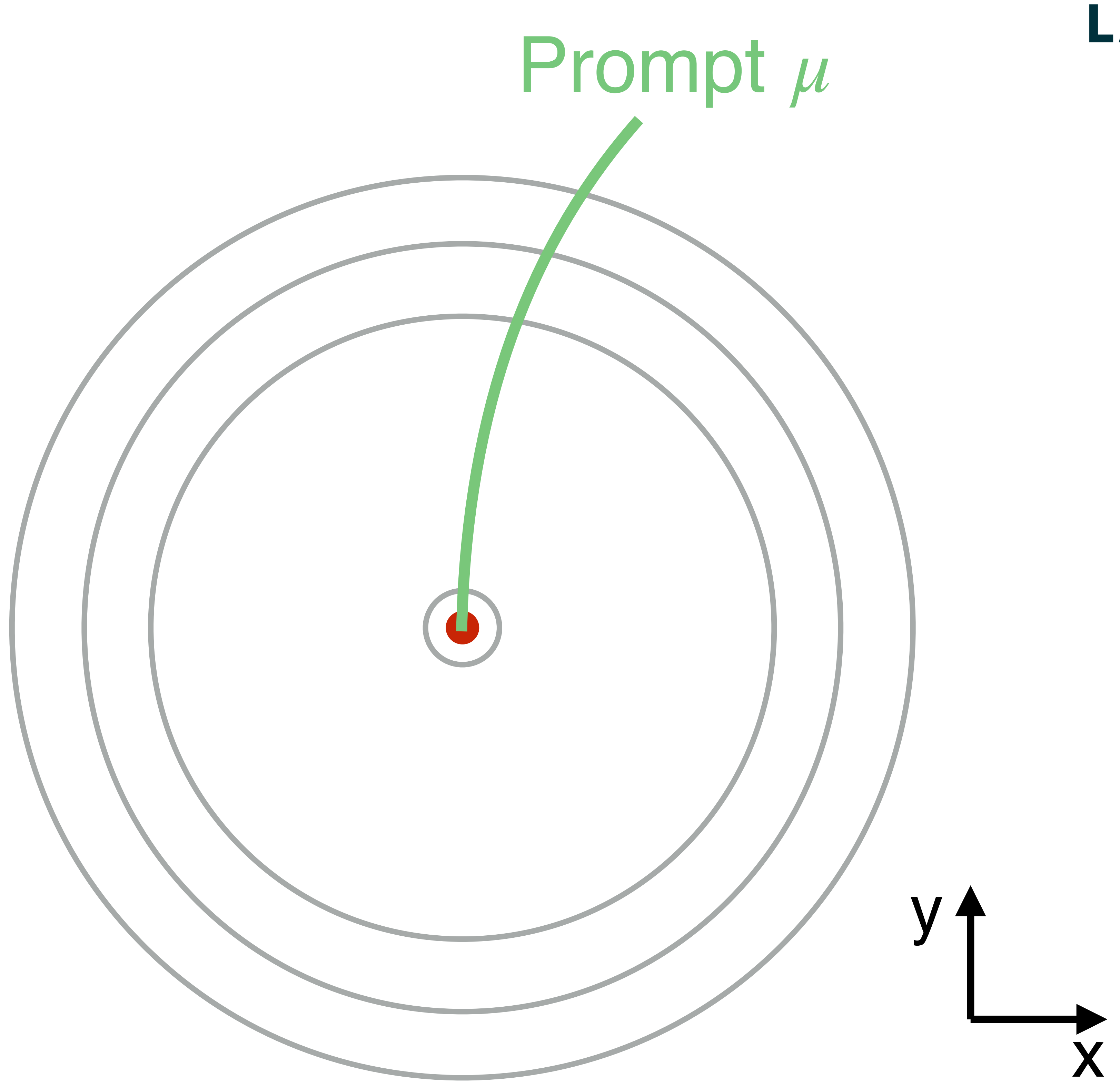

- **Prompt μ** are produced at the **beam line**.

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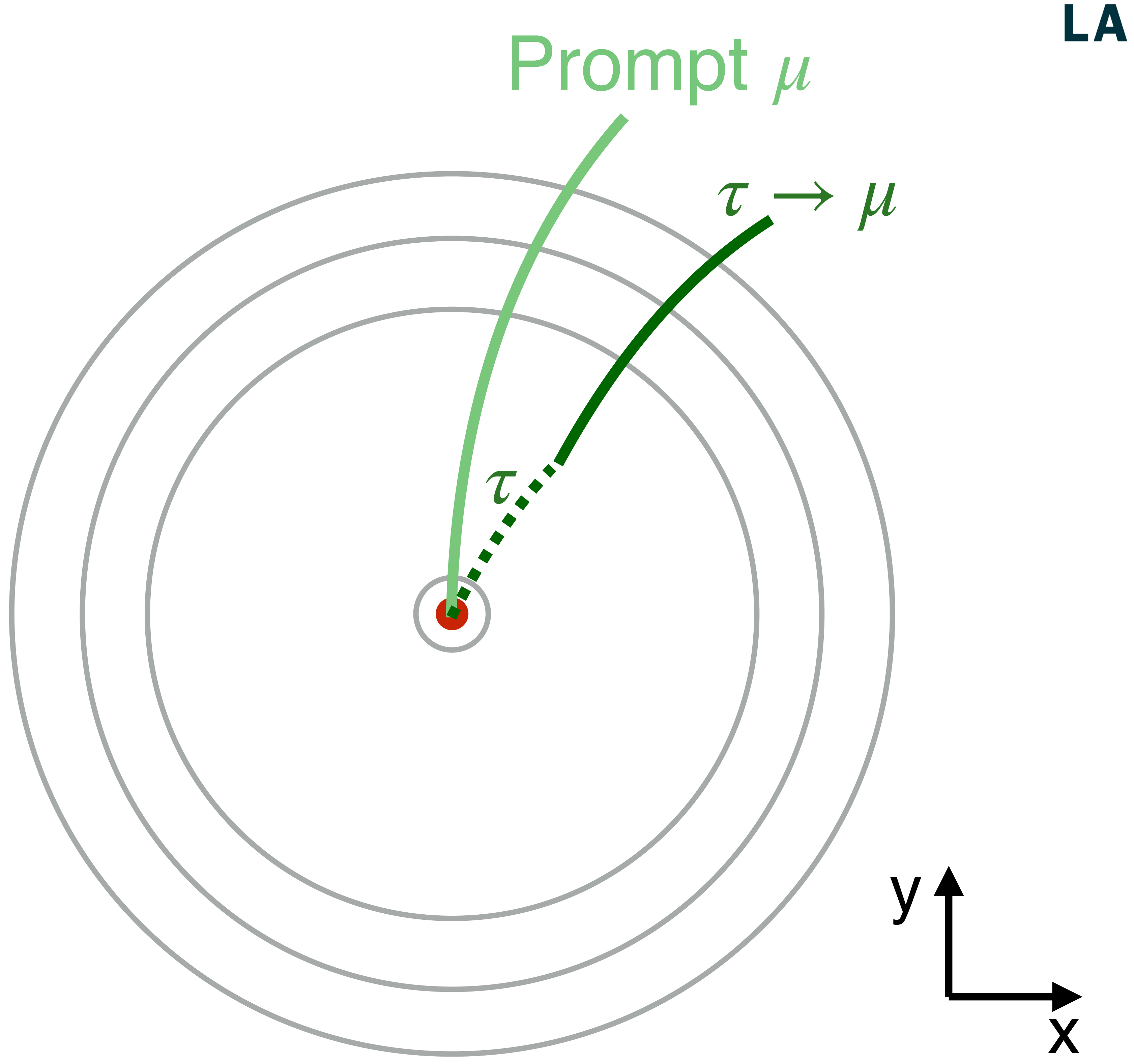

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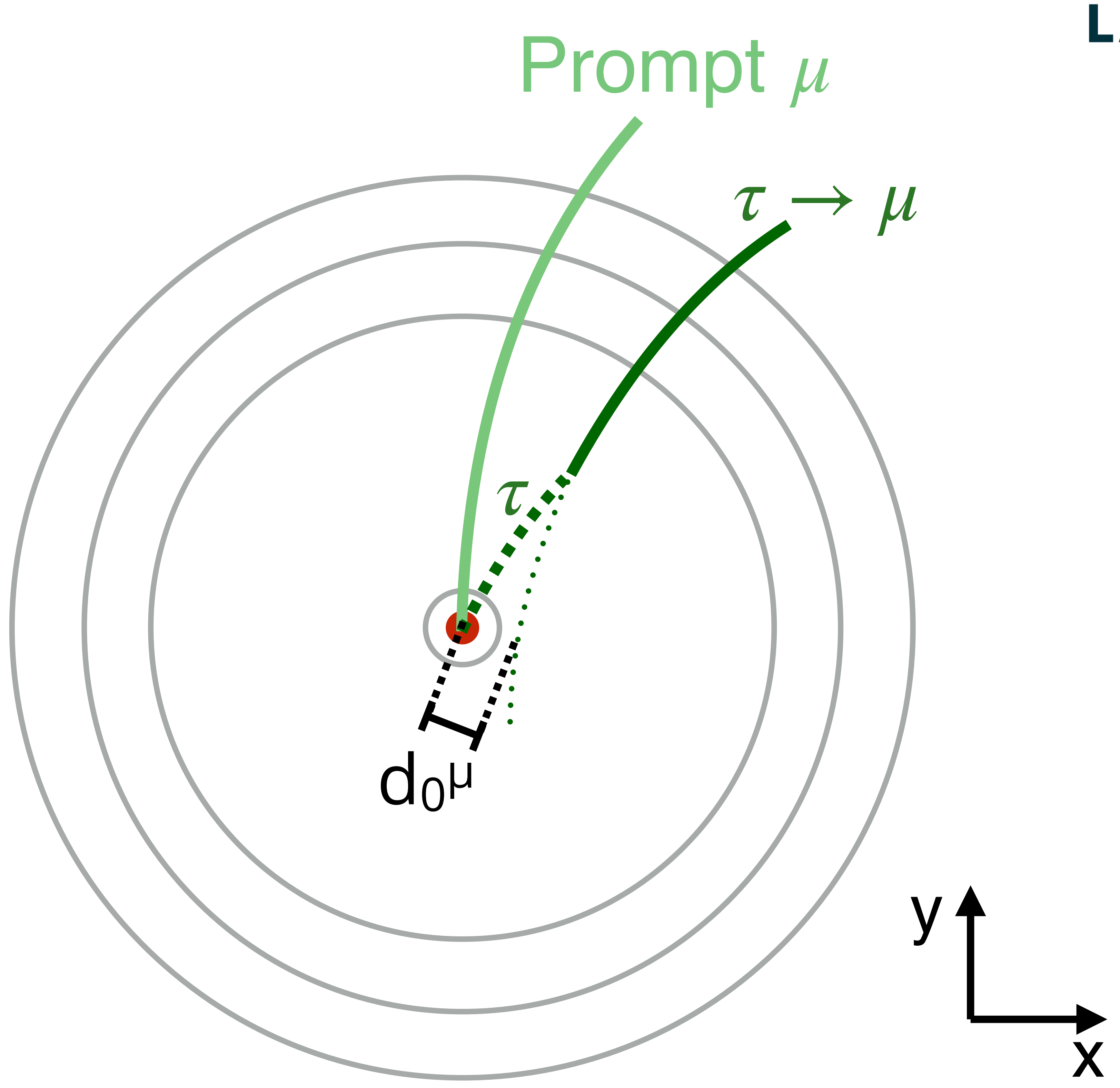

- **Prompt μ** are produced at the **beam line**.
- The **τ** flies ~2 mm from before decaying.
- d_0^μ = closest approach to the beam line:
  → 0 for **Prompt μ**
  → ~0.1 mm for **τ→μ**

Analysis strategy

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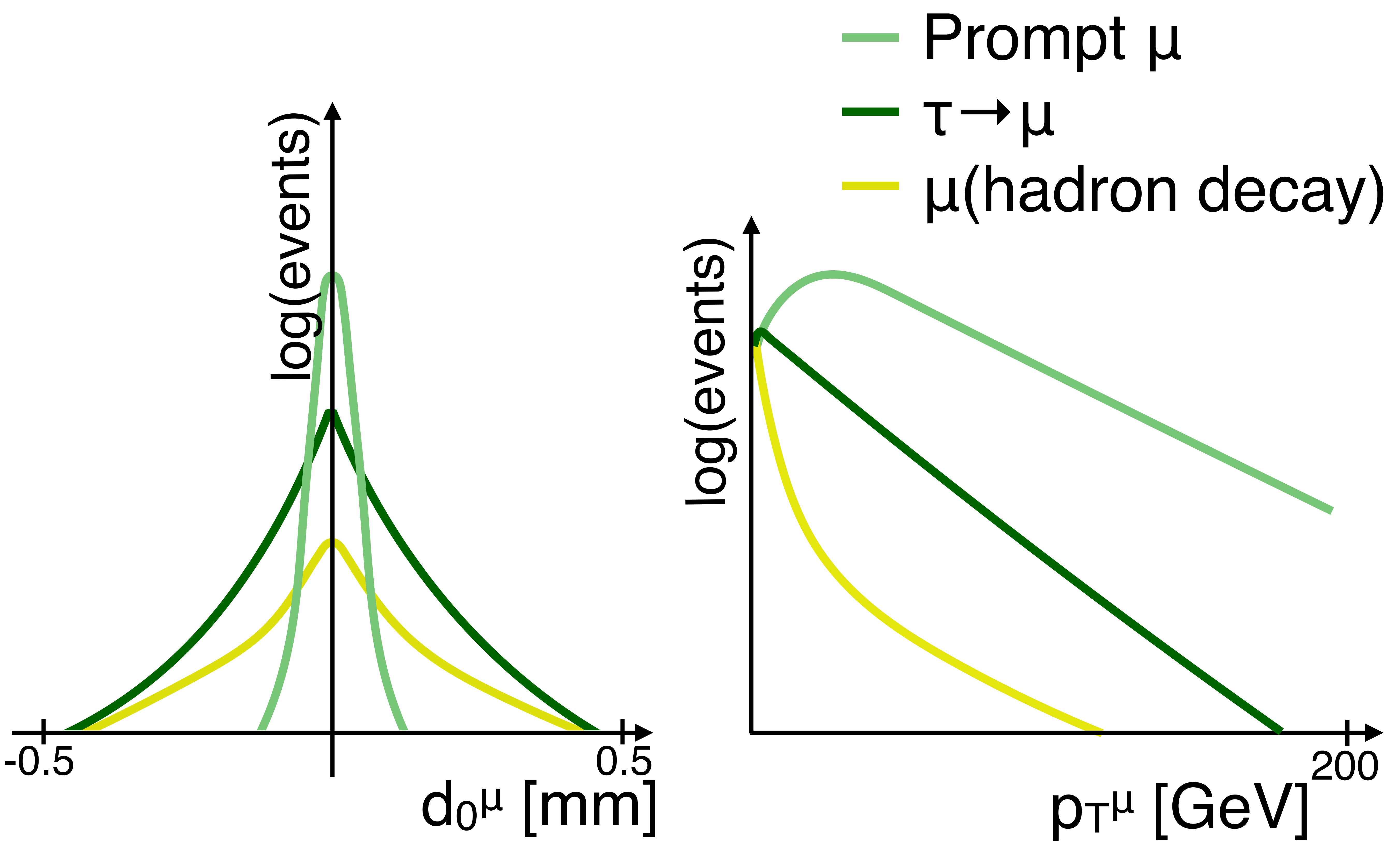
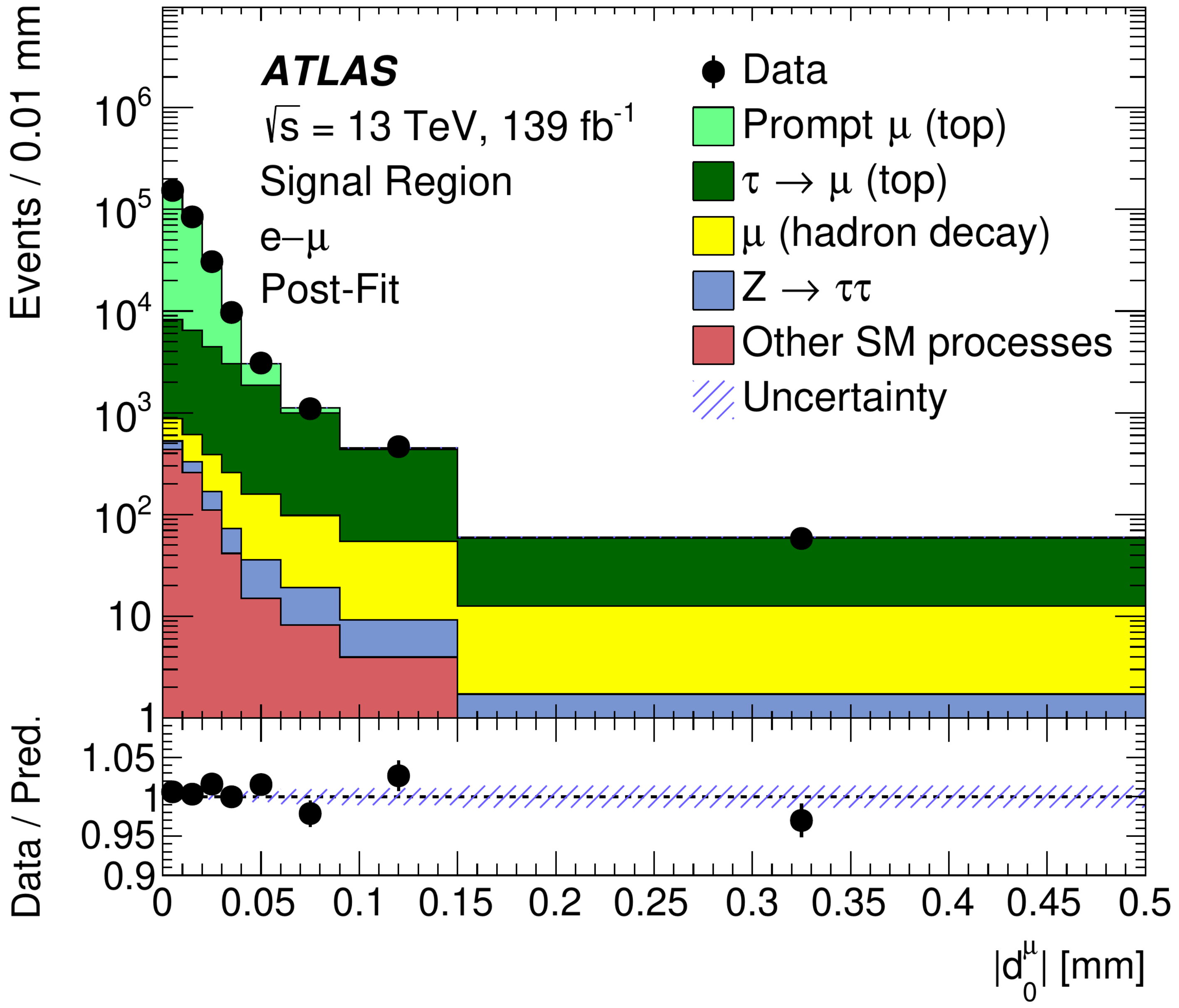


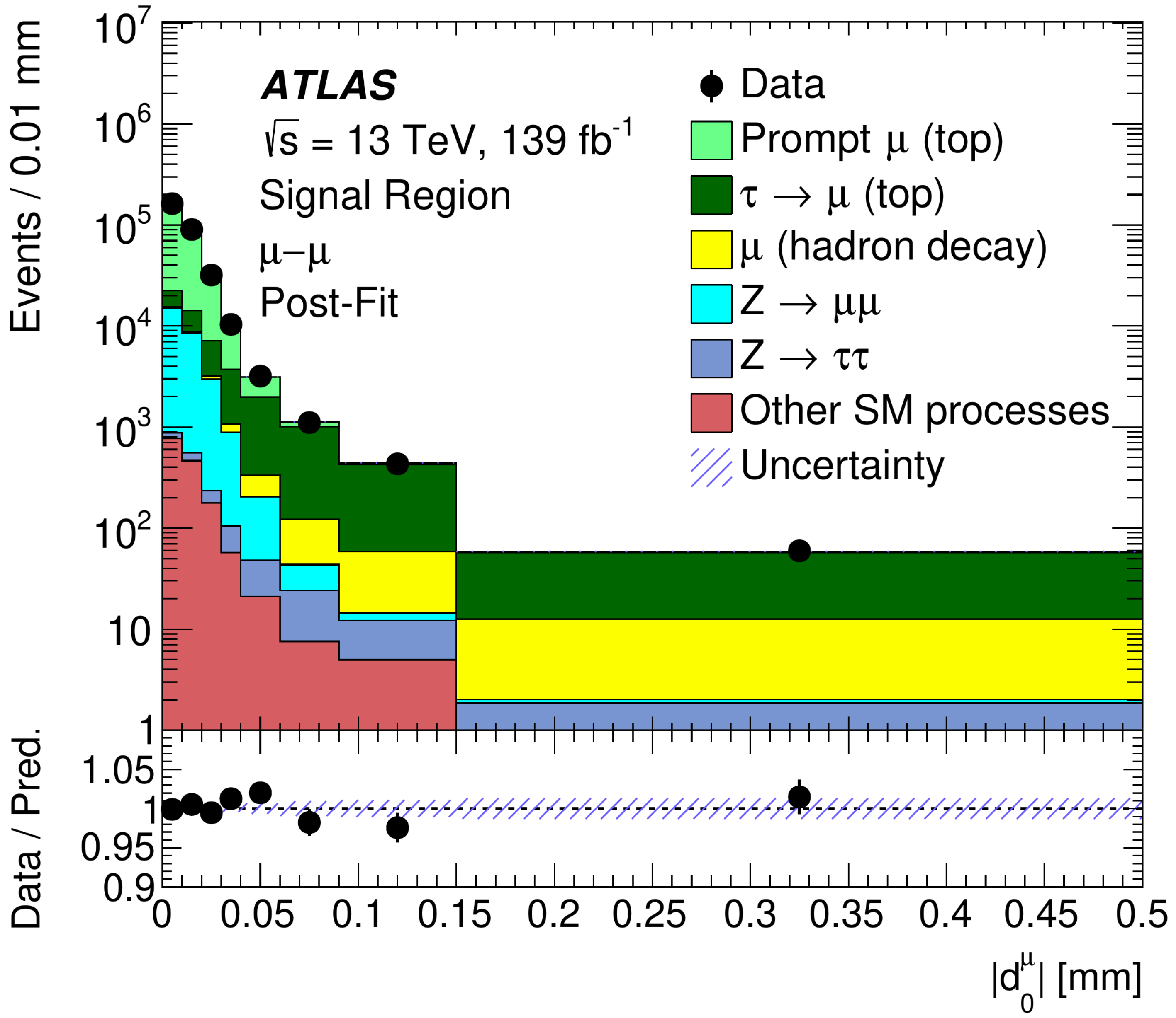
Analysis strategy

- Require standard di-lepton $t\bar{t}$ selection:
  - 2 opposite-charge leptons, 2-b-tagged jets, Z veto.
- Select tag lepton (e,μ) with single lepton triggers
- Select probe muon with p_T > 5 GeV.

- **Main backgrounds:**
  - **Muons from (b- & c-)hadron decays**.
  - Significant **Z →μμ** contribution in μμ channel.

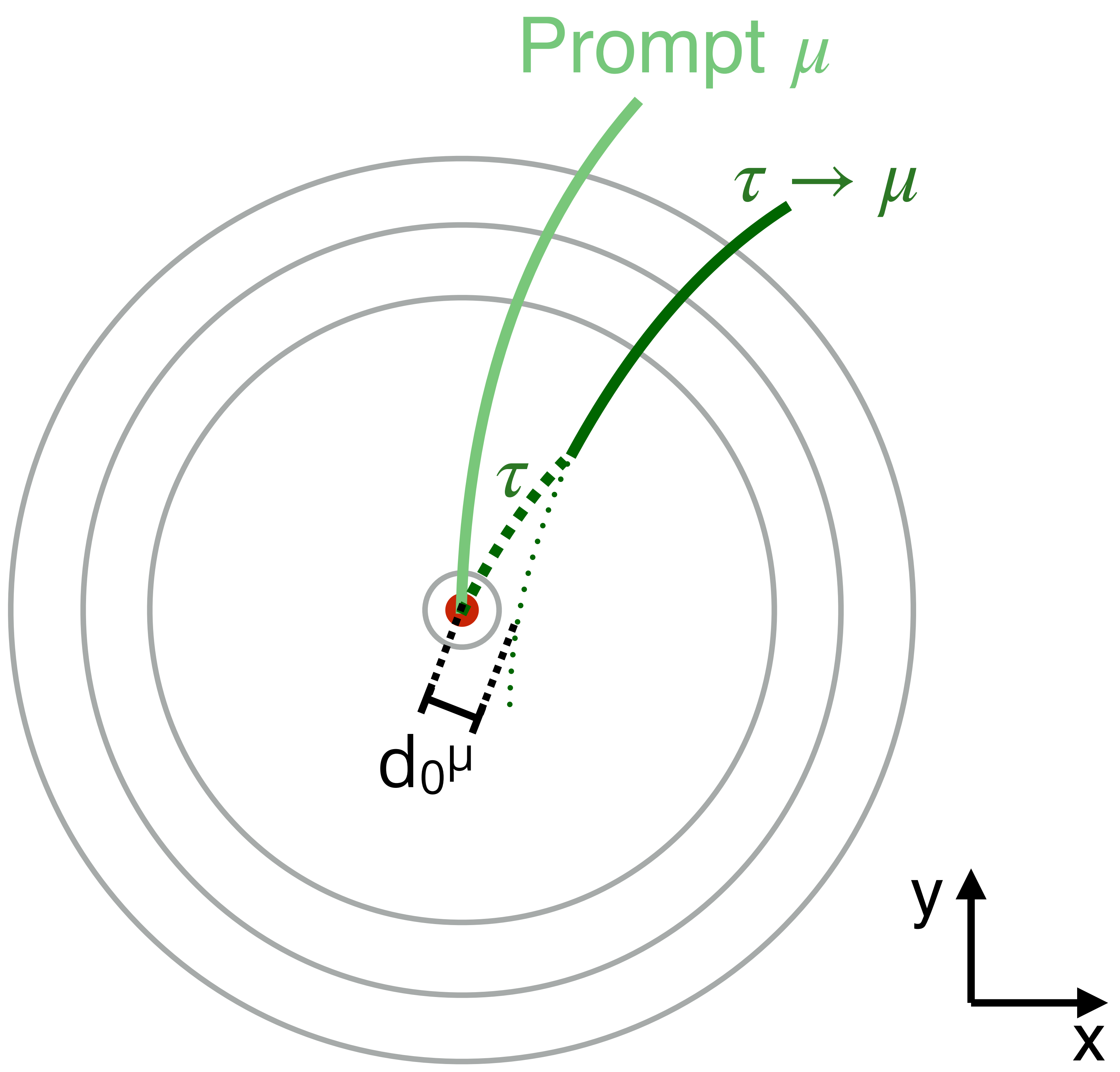
- Perform a **2D fit** of the probe muon **$|d_0^\mu|$** and **p_T^μ**:
  - Extract **R(τ/μ)** and the rate of $t\bar{t}$ events.
  - **μ(hadron decay)** background drops quickly in p_T^μ so the 2D fit has regions with different sensitivity.





Impact parameter definition

- The transverse impact parameter, **$|d_0^\mu|$**, is vital for the analysis:
  - The distance of closest approach of muon tracks in the transverse plane.
  - Defined with respect to the beam line:
    - This definition is most process-independent.
  - Allows data driven methods to determine $|d_0^\mu|$ shape and apply corrections.



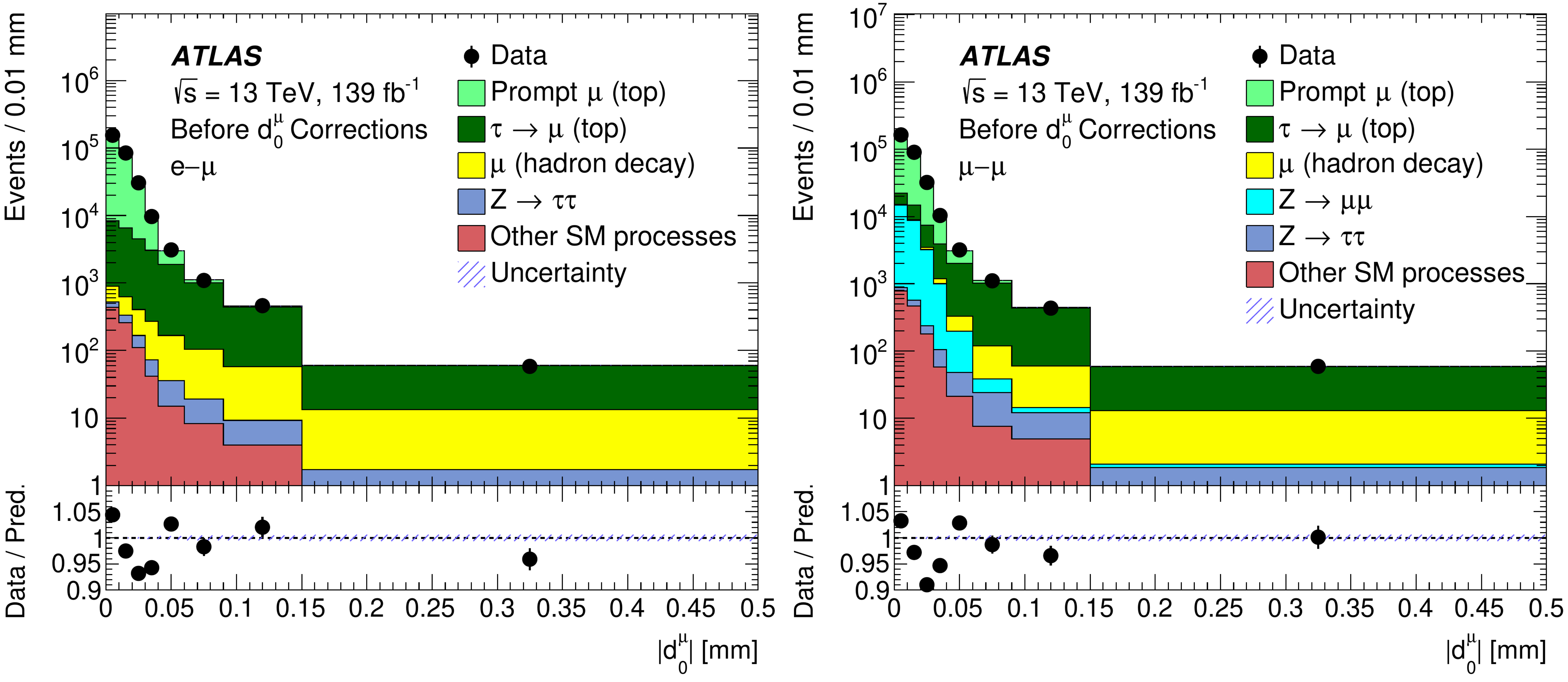
- Corrections applied:
  - $|d_0^\mu|$ distributions for prompt muons taken from $Z \rightarrow \mu^+\mu^-$ events in data.
  - Resolution measured in data using the same region.
    - Used to smear the MC to match the resolution in data
  - The uncertainties on these methods are the most important for the analysis.

Impact parameter corrections

- $|d_0^\mu|$ distribution for **prompt muons** is taken from $Z\rightarrow\mu^+\mu^-$ data.
  - Determined in 33 kinematic bins in p_T^μ and $|\eta^\mu|$.
- Selection:
  - Opposite-charge same-flavour leptons
  - No b-tagged jets
  - $85 < m(\mu^+\mu^-) < 100$ GeV
  - **>99.9% Z purity**
- Procedure:
  - Obtain distribution in data in each kinematic bin.
  - Subtract small backgrounds using MC.
  - Normalise $|d_0^\mu|$ shape to the yield in each kinematic bin in SR.

Before

Imperfect modelling of beamspot size, material and alignment.



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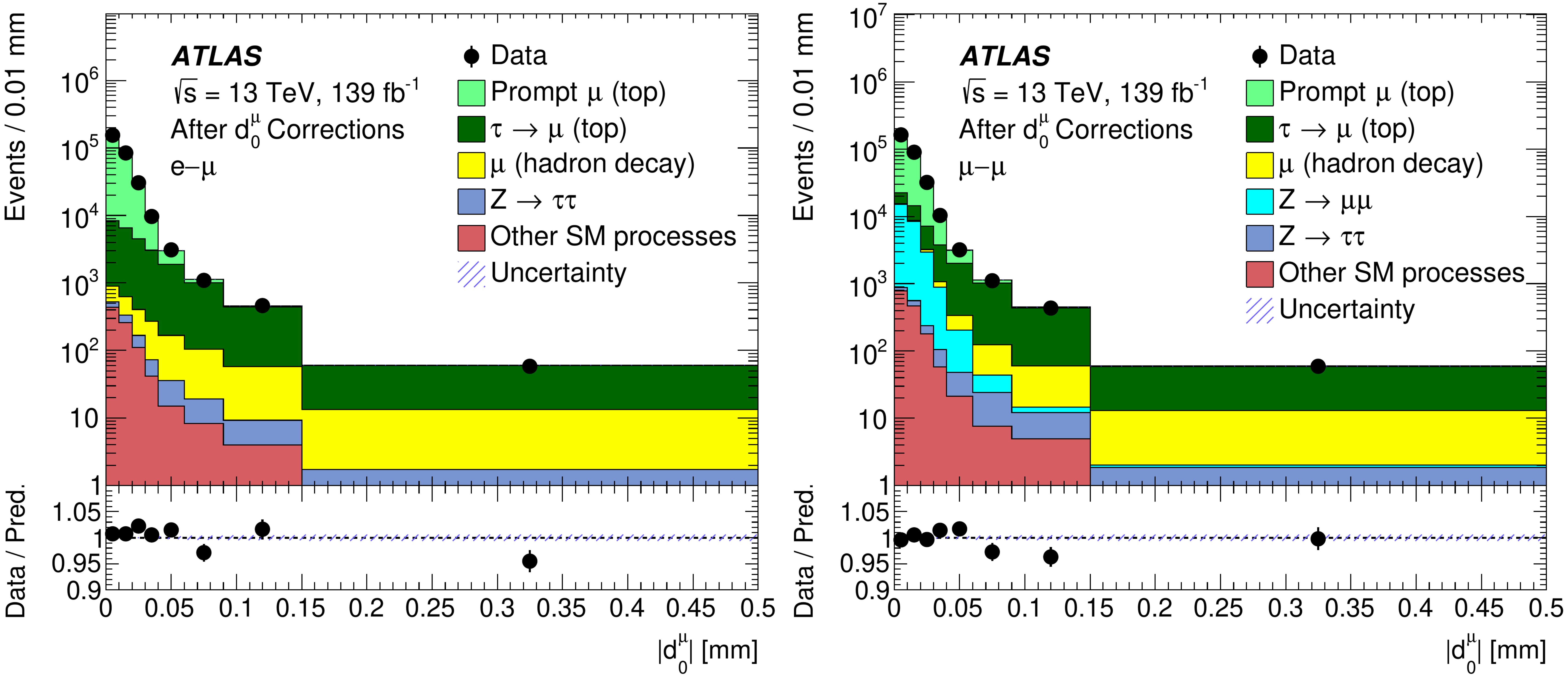
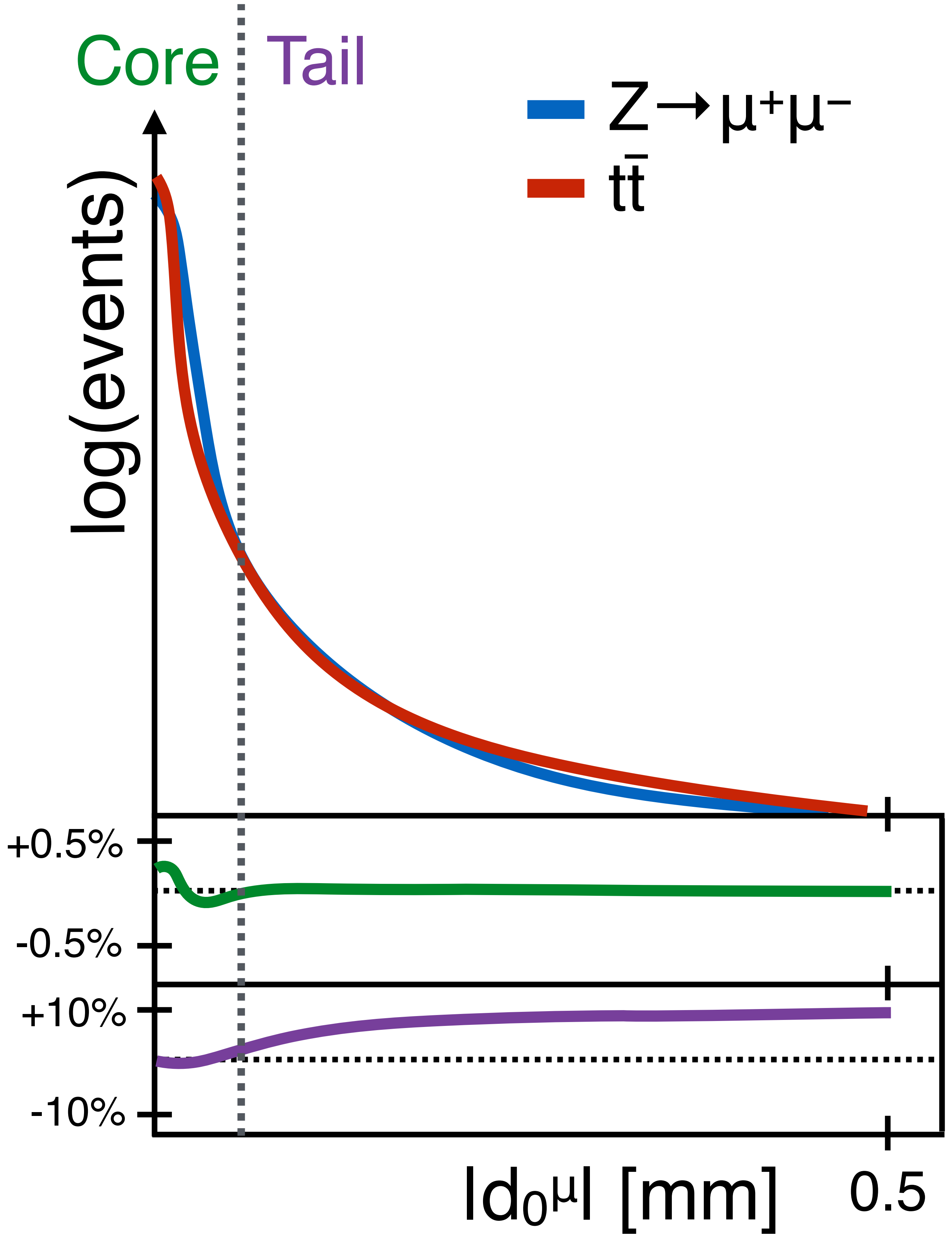


Pre-fit (only normalisation corrections applied)

Impact parameter corrections

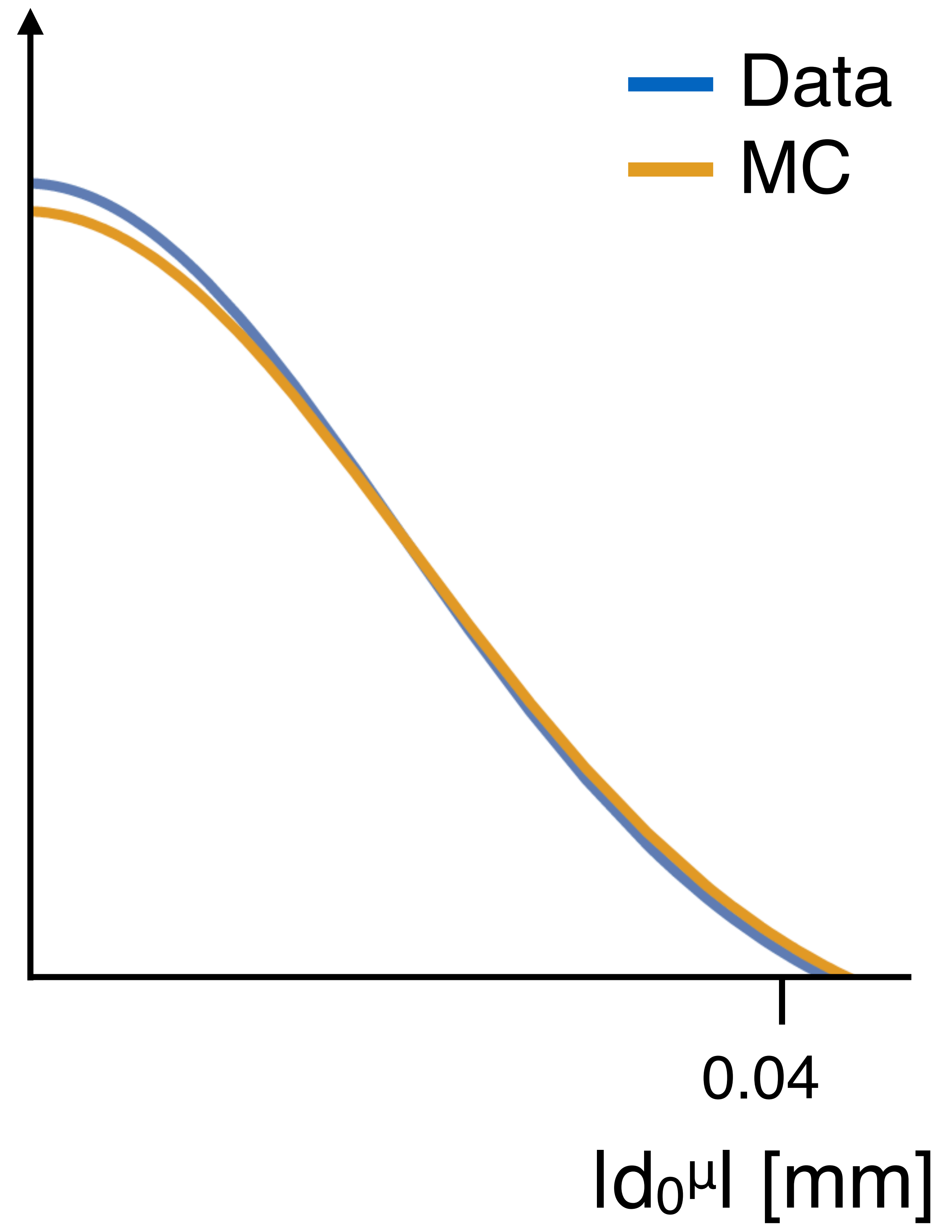
- The systematic uncertainty on the $|d_0^\mu|$ distributions derived from data comes from the **extrapolation** from a **$Z \rightarrow \mu^+\mu^-$** to **$t\bar{t}$** final state
  - Small biases from differing hadronic environment and the finite p_T^μ and $|\eta^\mu|$ binning.
- The uncertainty is derived from non-closure in MC:
  - Get ratio of $t\bar{t}$ and $Z \rightarrow \mu^+\mu^-$ **in simulation** in each bin.
  - **Rescale the data distribution to get uncertainty:**
    - The **core** of the $|d_0^\mu|$ resolution,
    - The **tail** of $|d_0^\mu|$.



Impact parameter corrections

- Using the same calibration region we also correct the resolution of $|d_0^\mu|$ for the non-prompt contributions:
  muons from tau decays and **muons from hadron decays**.

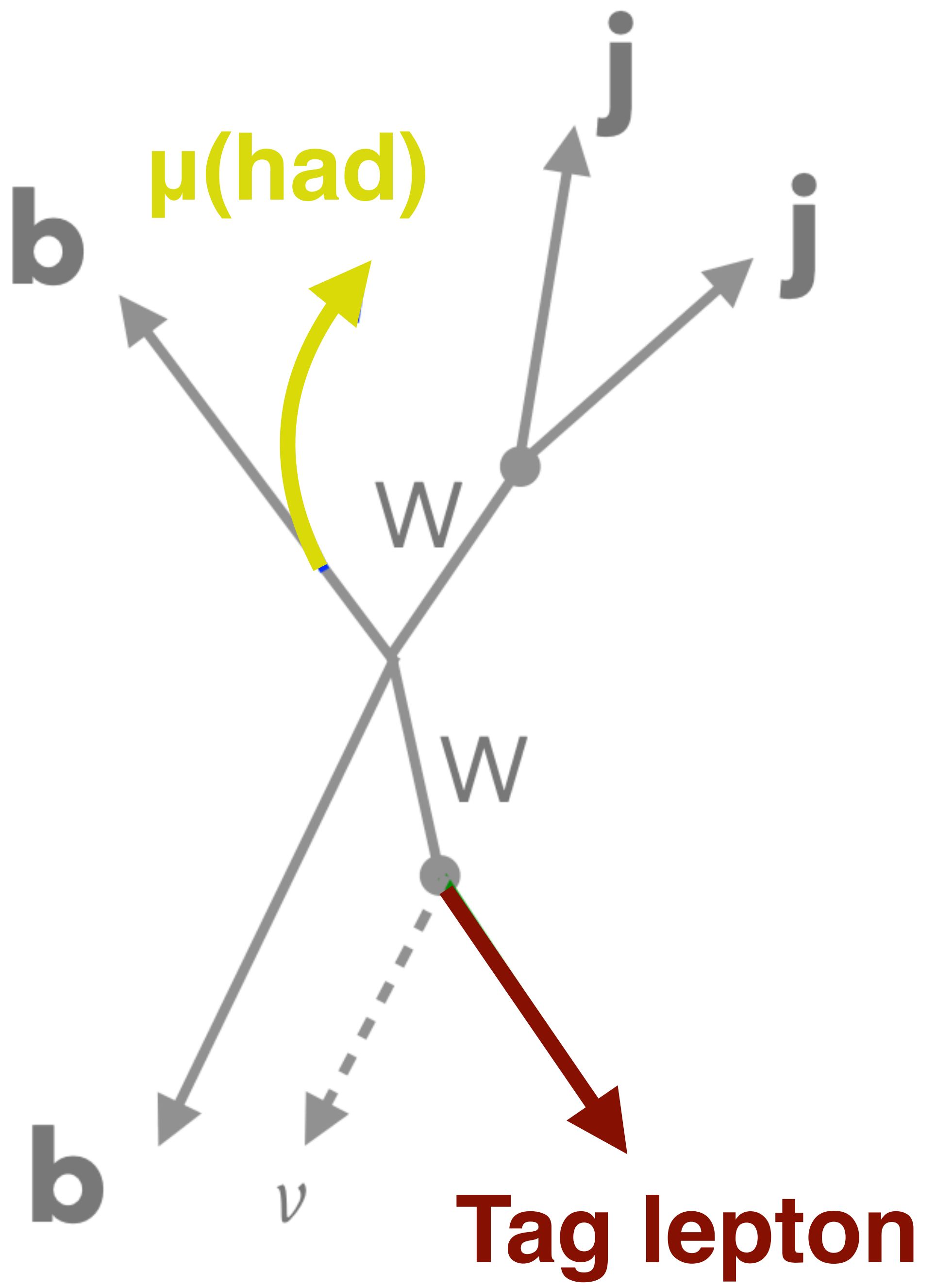
- The Gaussian core of the $|d_0^\mu|$ resolution is estimated in **data** and **MC**:
  - Fit $|d_0^\mu|$ (for $|d_0^\mu| < 0.02$ mm)
    - For $p_T \sim 20$ GeV the resolution is ~14 μm.
  - Corrections are applied to the MC to account for differences in resolution between data and MC.



- Data/MC modelling after smearing is checked in a $Z \rightarrow \tau\tau$ validation region.
- The associated uncertainty is half size of correction.

Muons from hadron decays

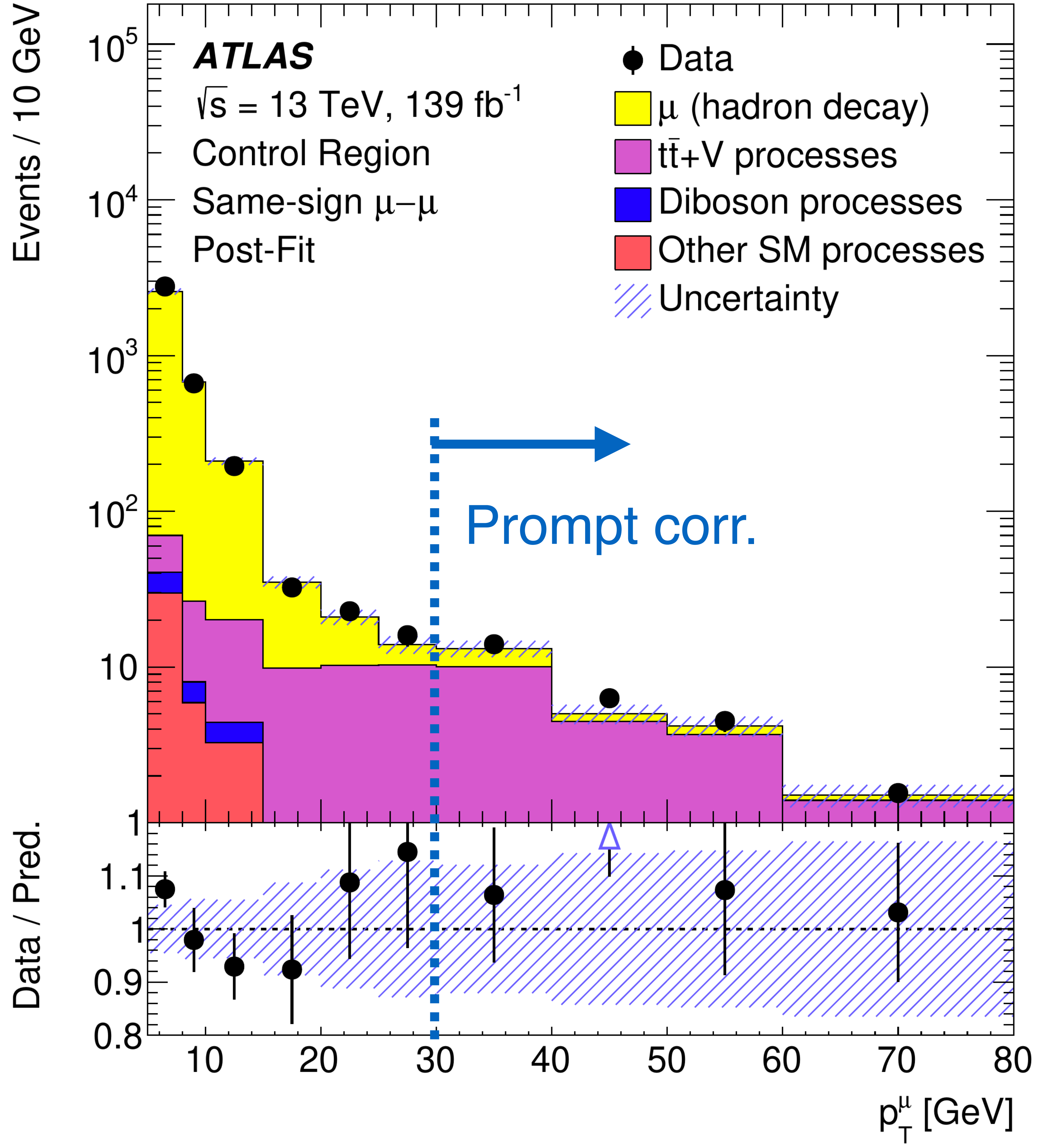
- The most significant **background** at high $|d_0^\mu|$ is from **b- and c-hadron decays**.
  - This contribution comes primarily from semi-leptonic $t\bar{t}$ events.
  - Largest source from b-hadron decays with a significant component also from c-hadrons.



- **Normalisation** corrected to match data using a **same-sign control regions**
  - One region is defined for each of tag-lepton channels (eμ and μμ)
  - High purity of this background is obtained.
    - b-hadron backgrounds contributes equally to same-sign (SS) and opposite-sign (OS) selections.
    - c-hadron contribution is not equal in SS and OS, but has a significant component in both.

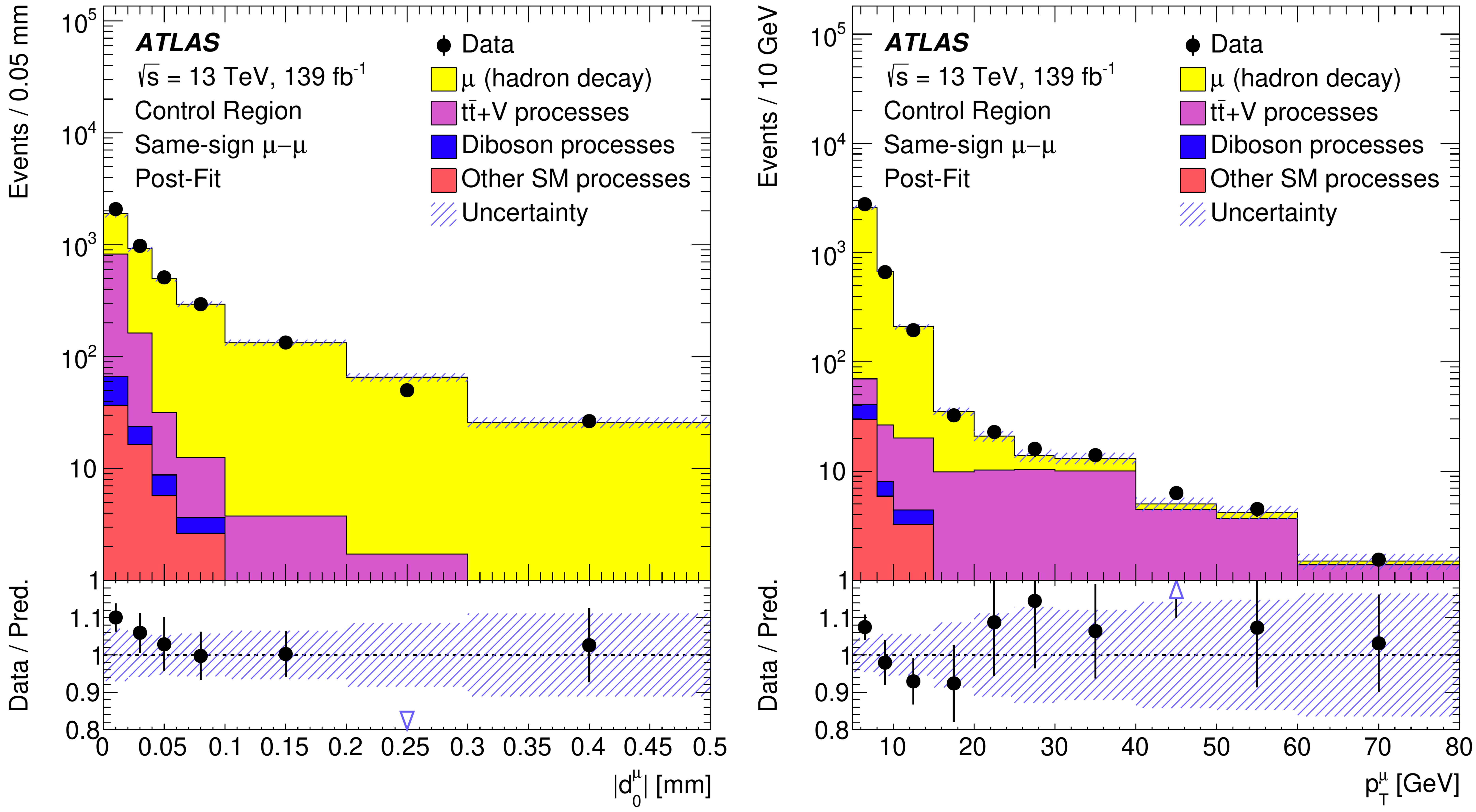
Muons from hadron decays

- **Normalisation** from **same-sign control region**.
  - **Prompt contributions** corrected in high-p_T region.
  - **Normalisation correction factor**
    - Take SS rate in data (subtracting corrected prompt)
    - Divide by SS rate in MC.
- Simulation used for:
  - Extrapolation from SS to OS,
  - $|d_0^\mu|$ distribution shape.



Control region | μ(hadron decay)

- The normalisation factors are:
  - **NF(μ-μ) = 1.37**
  - NF(e-μ) = 1.39
- The data agrees well with simulation within uncertainties in the control region.
- This gives confidence that the distributions of p_T^{μ} and $|d_0^{\mu}|$ in the SR are well modelled.



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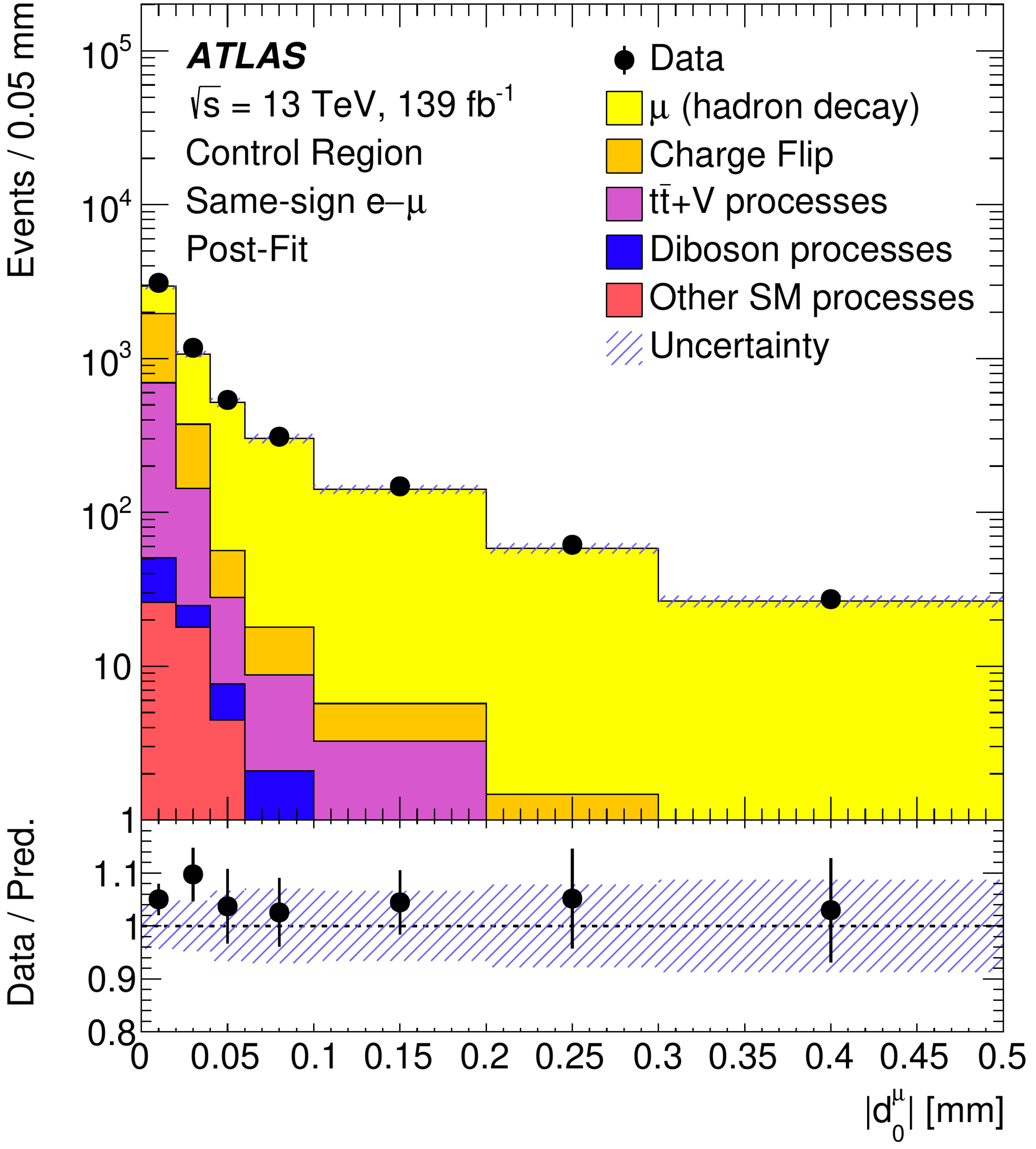
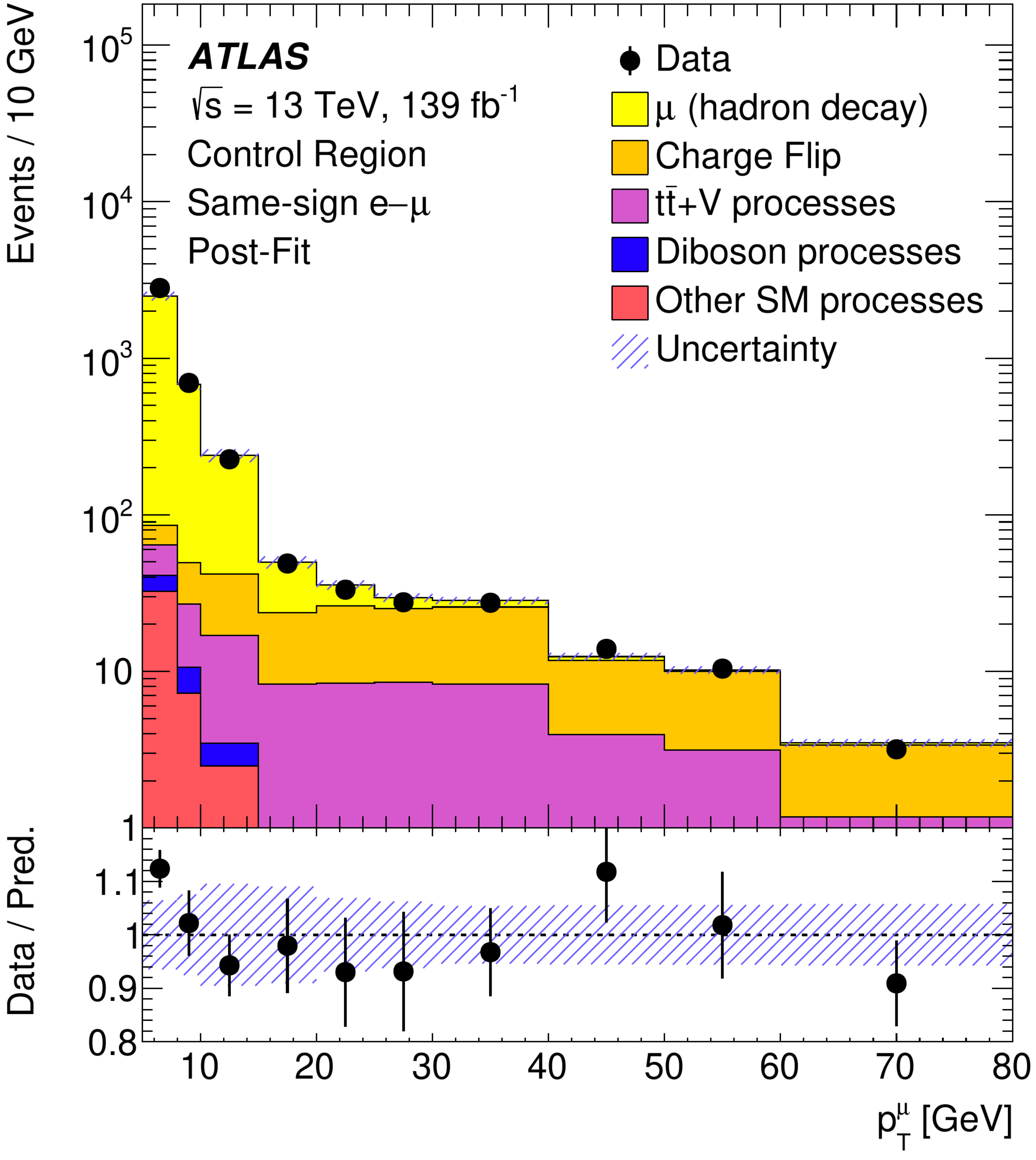




Charge-flip important in eμ channel
- Taken from MC and normalised at high p_T

Muon from hadron decay background

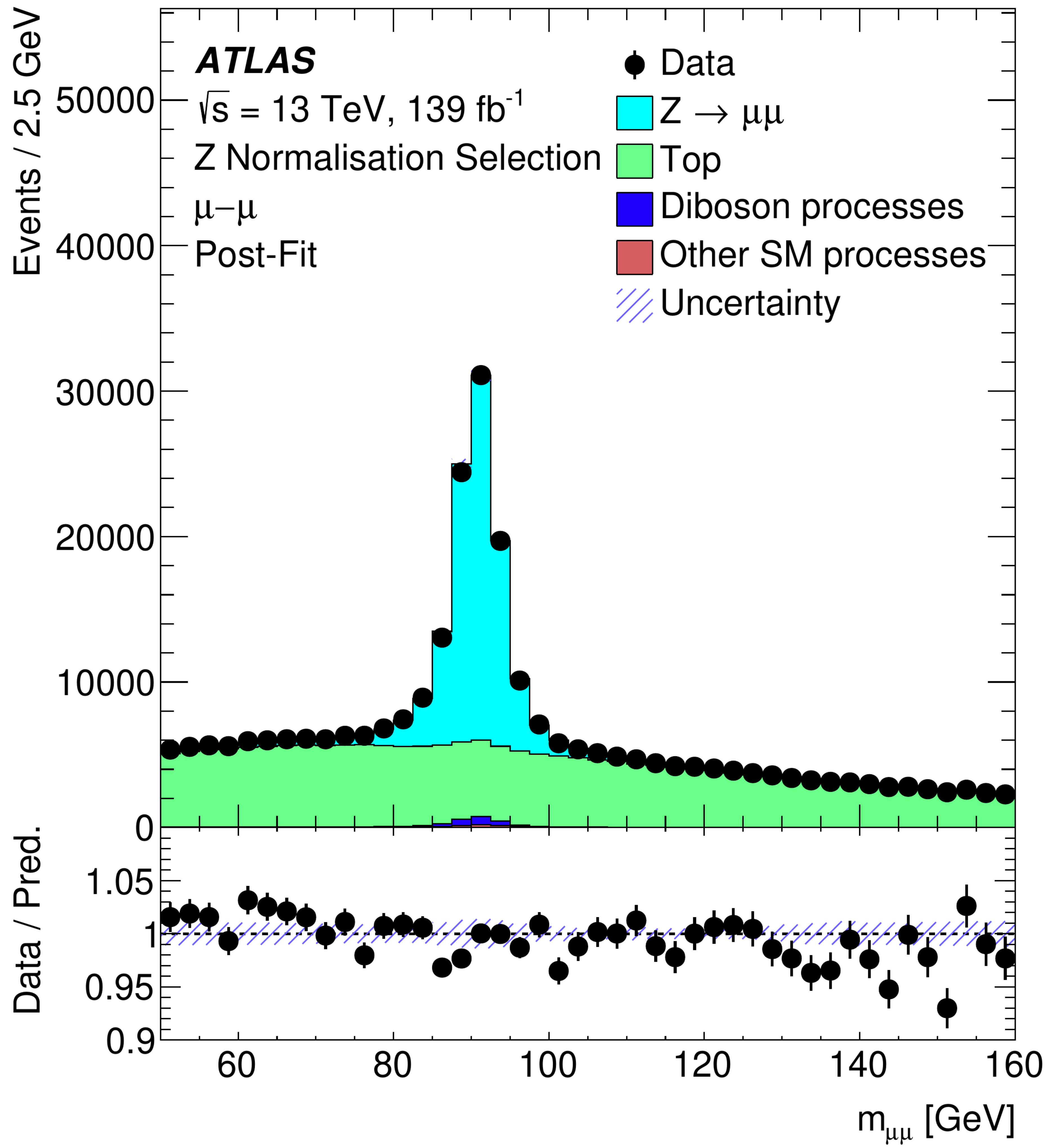
- Uncertainties on the **normalisation** come from three components
  - Limited size of the SS control region: eμ = 4% μμ = 4%
  - MC modelling: eμ = 8% μμ = 3%
  - Subtracted prompt p_T cut: eμ = 1.0% μμ = 1.3%

- Uncertainties are also derived to account for effects that can change the **shape** of $|d_0^\mu|$:
  - These come from the choice of MC generator - more details later…

- The modelling is cross-checked in a fakes-dominated region that is a subset of the signal region and good agreement in data is observed.

Z background normalisation

- In the μμ-channel there is a residual contribution from the **$Z \rightarrow \mu^+\mu^- + b\bar{b}$ background**.
- Normalisation obtained from data
  - Selection identical to signal region without the Z-veto.
- The $m_{\mu\mu}$ distribution is fitted from 50 - 140 GeV.
  - Breit-Wigner⊕Gaussian used for the $Z \rightarrow \mu\mu$ resonance
  - 3rd-order Chebychev polynomial used for background.
    - Other functions are tested to provide a systematic uncertainty.
- Normalisation factor found to be **1.36 ± 0.01**



Reconstruction uncertainties

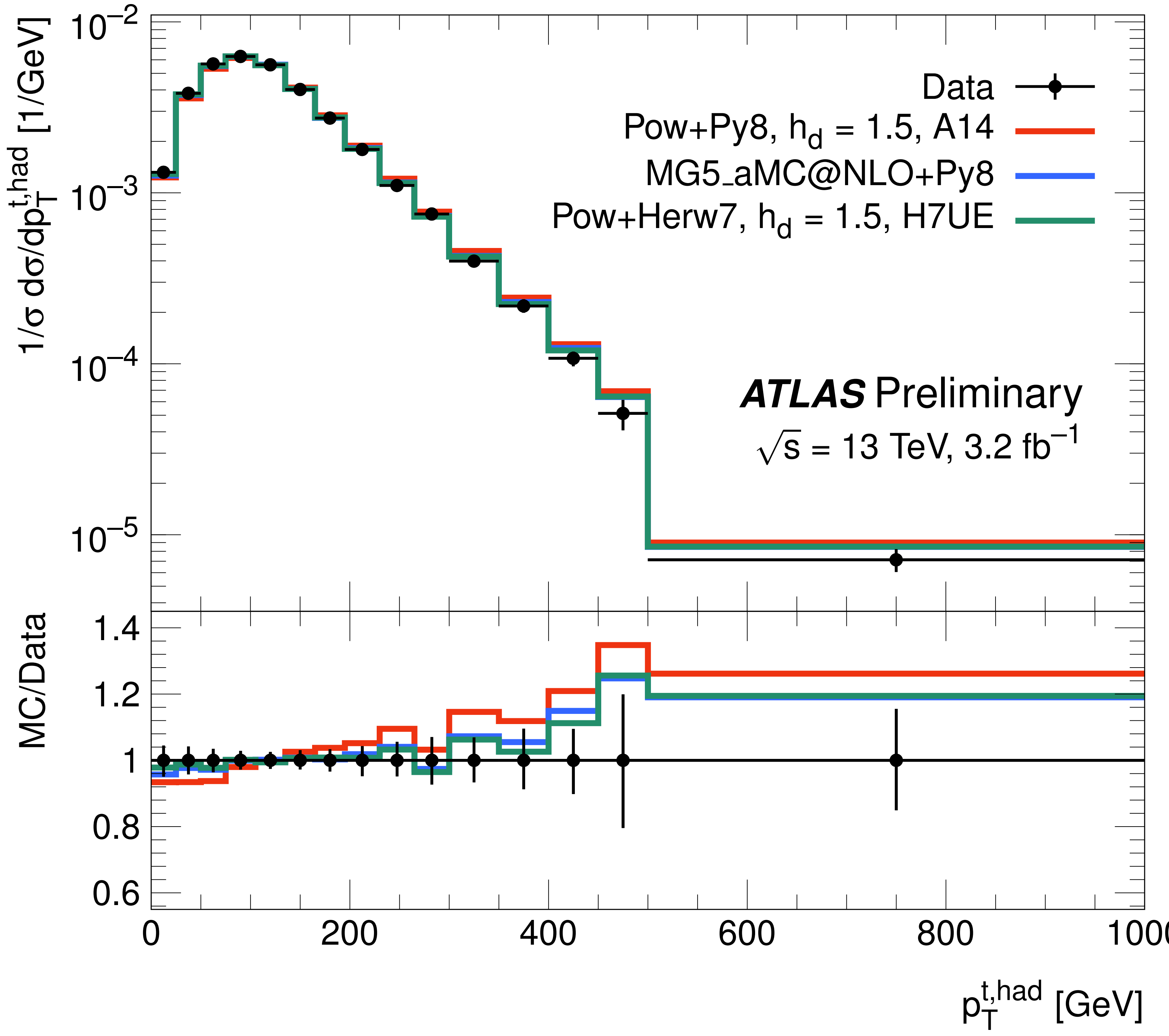
- Precise **muon reconstruction** is a cornerstone of the measurement.
  - Uncertainties on efficiencies corrections are most important.
  - Measured in data and simulation using a *tag* and *probe* method.
  - *Scale factors* correct MC to data: these depend on p_T.
    - Affect the **prompt μ** and **τ→μ** differently resulting in impact on ***R*(τ/μ)**.
    - **Muon isolation** and **low p_T muon identification** scale factors most important.

- The **pile-up** modelling is also important.
  - Simulated events reweighted to different <μ> to provide an uncertainty.
    - Impact on **R(τ/μ)** is mostly due to the residual effect on p_T^μ modelling.

Modelling uncertainties

- MC generator uncertainties important for $\mathbf{p_T^\mu}$ and $\mathbf{|d_0^\mu|}$ modelling.
  - To improve the modelling of p_T^μ, the simulated $t\bar{t}$ events are reweighed in $p_T(t)$ to NNLO in QCD.

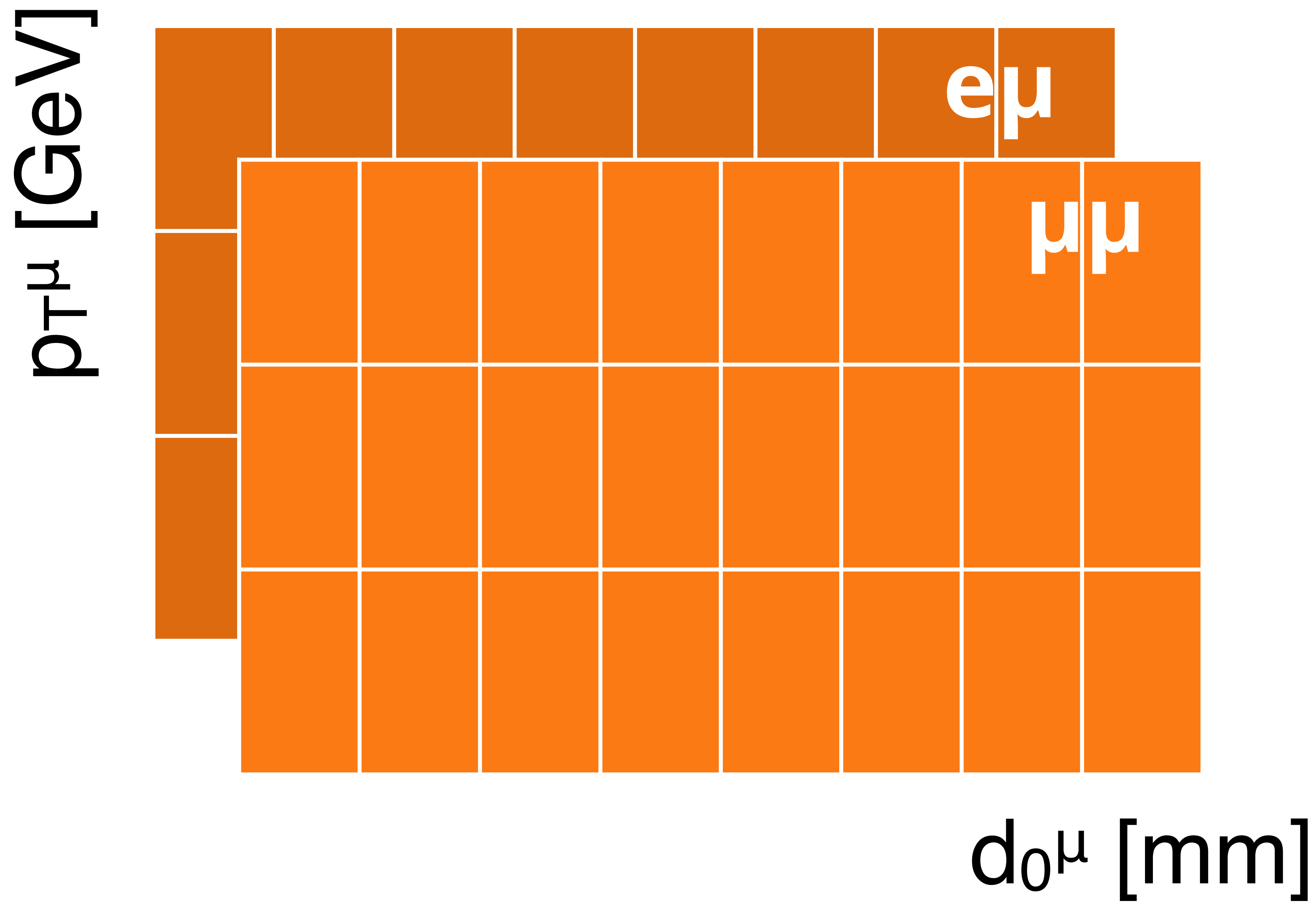
[ATL-PHYS-PUB-2018-009]



- Different generator components varied:
  - **Amount of initial (final) state radiation**,
  - **Factorisation and renormalisation scales**,
  - **Powheg h_{damp} parameter**,
  - **NNLO $p_T(t)$ reweighting**,
  - **Parton shower and hadronisation**
    - For **prompt μ** and **τ→μ** uncertainty is separated into 4 components:
      - Low p_T^μ, middle p_T^μ, high p_T^μ (norm.) and high p_T^μ (shape).

Fit model

- R(τ/μ) is extracted from a profile likelihood fit performed in 2D with:
  - Three bins in p_T^μ = [5, 10, 20, 250] GeV,
  - Eight bins in $|d_0^\mu|$ = [0, 0.01, 0.02, 0.03, 0.04, 0.06, 0.09, 0.15, 0.5] mm,
  - In two channels, **eμ** and **μμ**,
    - 48 bins in total



- Two parameters are freely floating: R(τ/μ) and $k(t\bar{t})$
  - $k(t\bar{t})$ is a constant scaling factor applied to prompt μ and τ→μ, $t\bar{t}$ and Wt components
  - R(τ/μ) only affects the τ-muon components.
- Uncertainties are correlated between the prompt μ and τ→μ components
  - Many only affect the overall event selection and tag-lepton requirements
  - These **cancel out in the ratio** to have minimal impact on R(τ/μ).
  - This includes uncertainties related to jet reconstruction, flavour tagging and trigger efficiencies.

Results | Data/MC post-fit (eμ)

- Excellent agreement between data and the expectation is observed after the fit to data.
  - The two highest p_T^μ bins have the largest sensitivity to R(τ/μ).
  - The lowest p_T^μ bin helps to understand the μ(hadron decay) background modelling.

Results | Data/MC post-fit (μμ)

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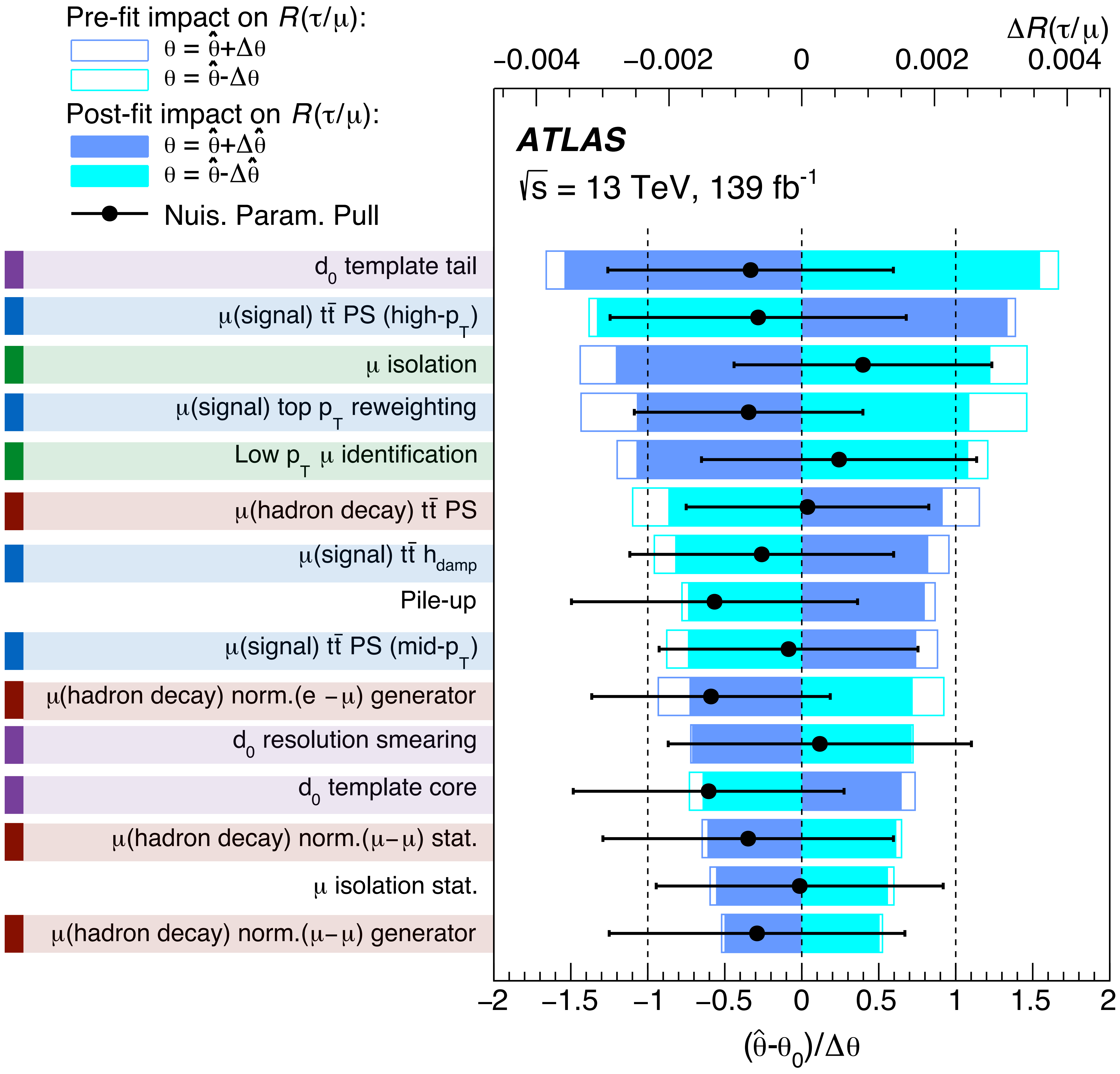
  - The lowest p_T^μ bin helps to understand the μ(hadron decay) background modelling.

Results | Impact of uncertainties

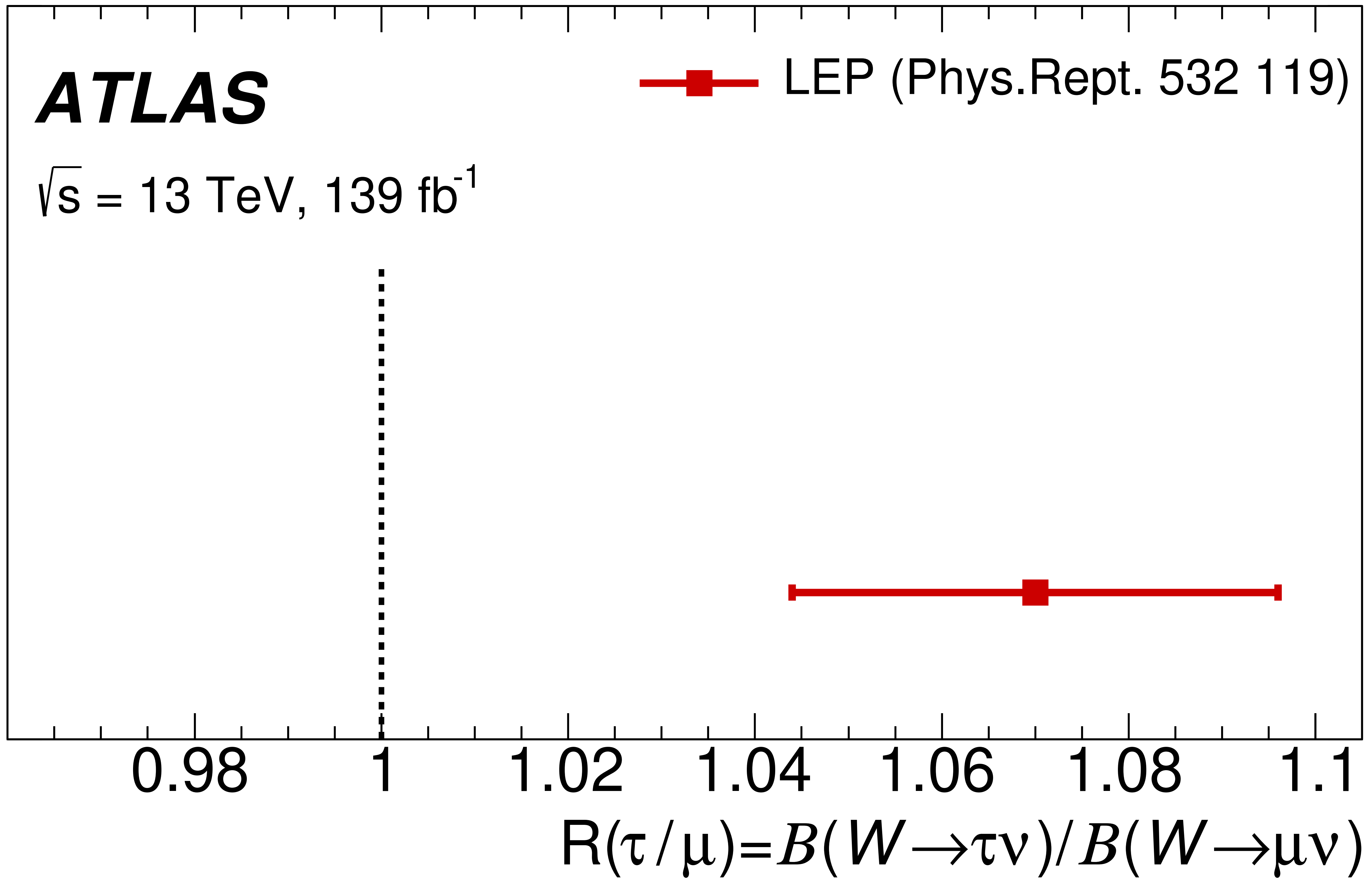
- The total uncertainty is dominated by systematics with a non-negligible statistical component:
  - Uncertainty on BR($\tau \rightarrow \mu\nu_\mu\nu_\tau$) is ~negligible.

Uncertainty group	$\Delta R(\tau/\mu)$
Data statistics	0.007
Systematics total	0.011
- Data-driven backgrounds	0.005
- Theory	0.006
- Instrumental	0.007
- Normalisation factors	<0.001
- Limited MC statistics	0.002
- $BR(W \rightarrow \tau\nu \rightarrow \mu\nu\nu\nu)$	0.002
Total uncertainty	0.013

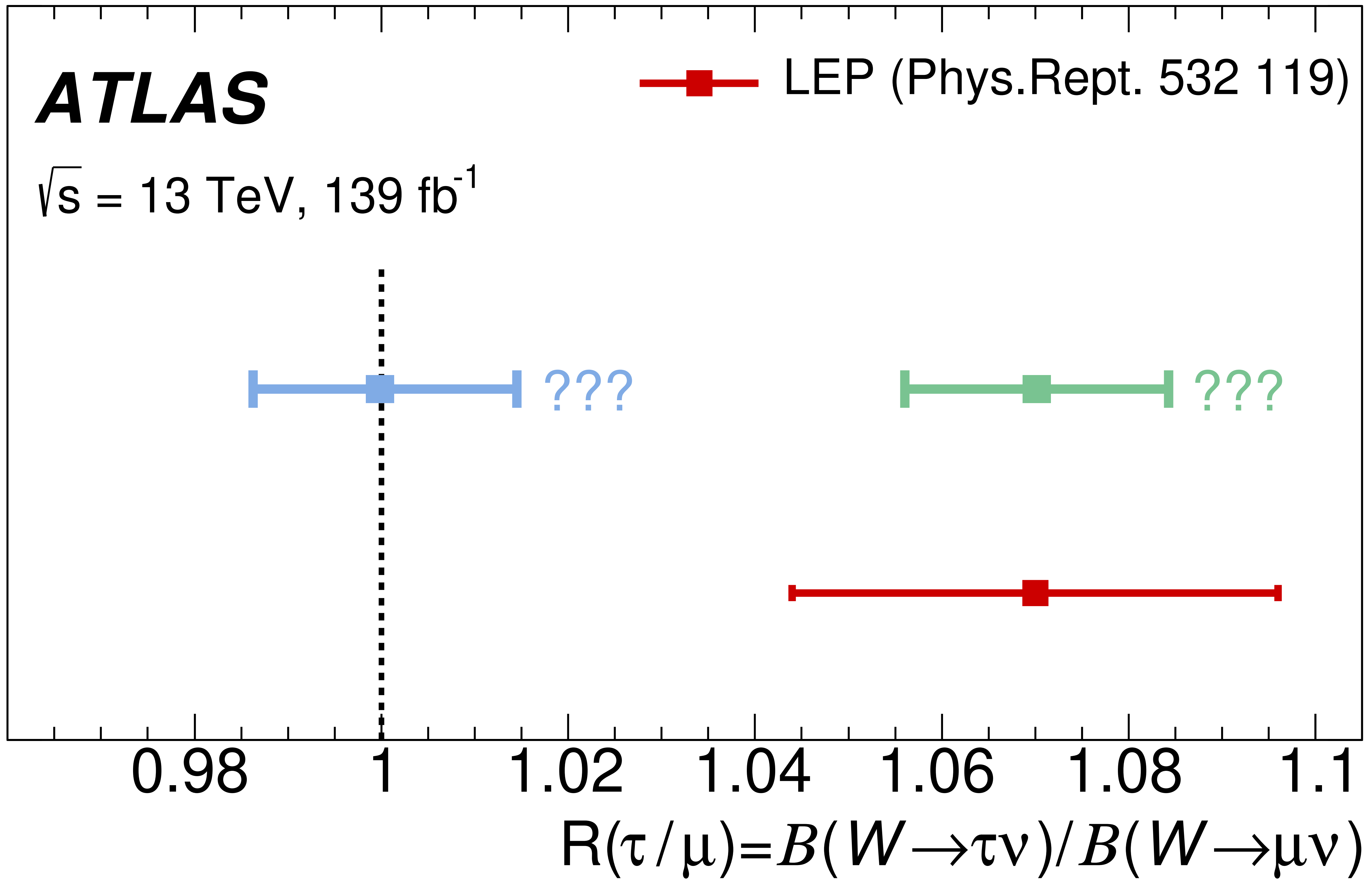


- Dominant uncertainties come from:
  - **Modelling of $|d_0^\mu|$ distributions from data**
  - **$t\bar{t}$ modelling of signal**
  - **$t\bar{t}$ modelling of μ(hadron decays)**
  - **Muon reconstruction efficiencies.**

Results


ATLAS
√s = 13 TeV, 139 fb-1
LEP (Phys.Rept. 532 119)
0.98
1
1.02
1.04
1.06
1.08
1.1
R(τ/μ)=B(W→τν)/B(W→μν)

Results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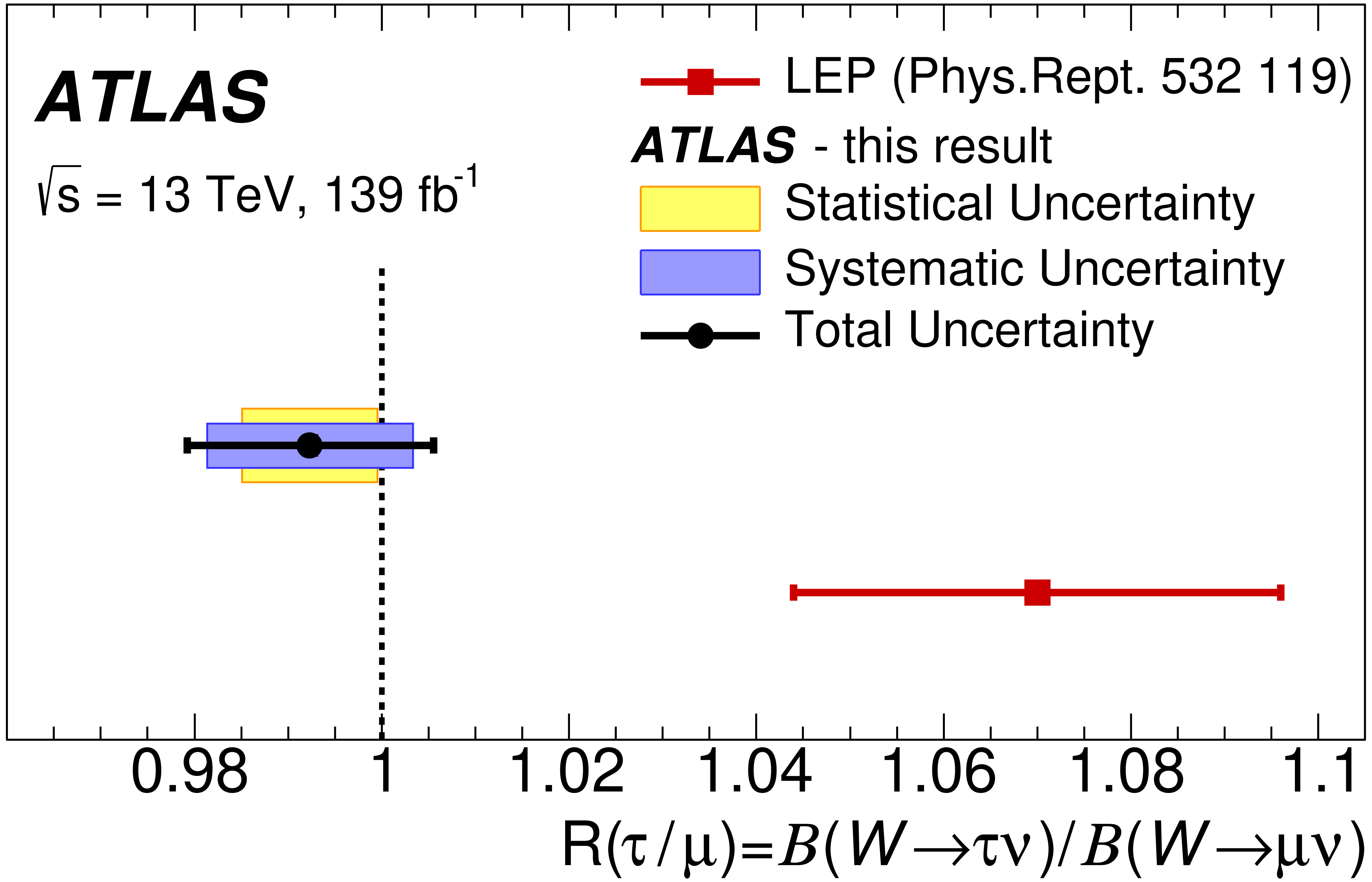
???
???
0.98
1
1.02
1.04
1.06
1.08
1.1
$R(\tau/\mu) = B(W\to\tau\nu)/B(W\to\mu\nu)$

Results

- The measured value is:

$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat}) \pm 0.011\ (\text{syst})\ ]$$

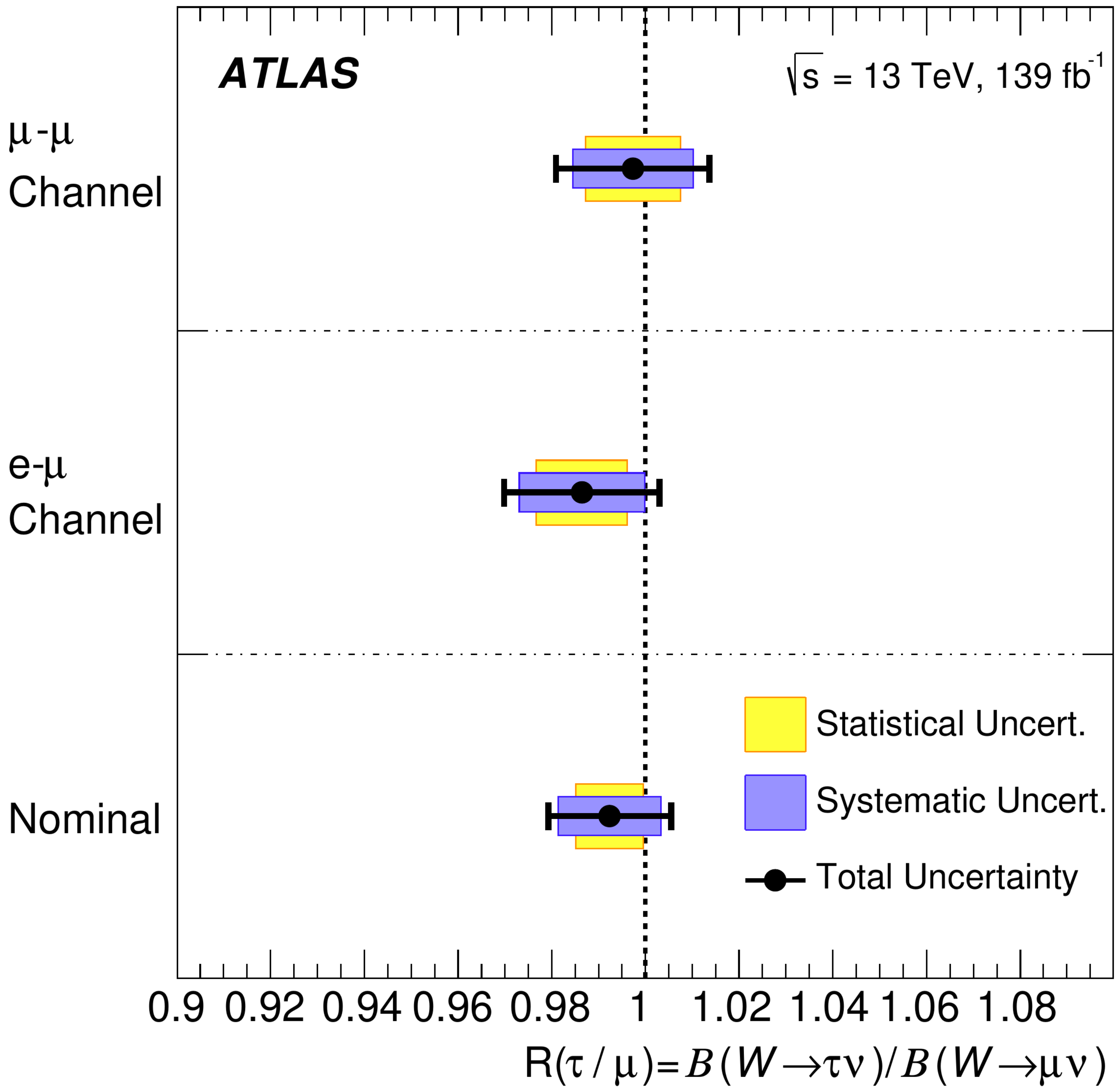
  - **In very good agreement with the Standard Model!**
  - This forms the **most precise measurement** of this ratio to date.
    - Almost twice the precision of the combination of **LEP results**.



Consistency checks

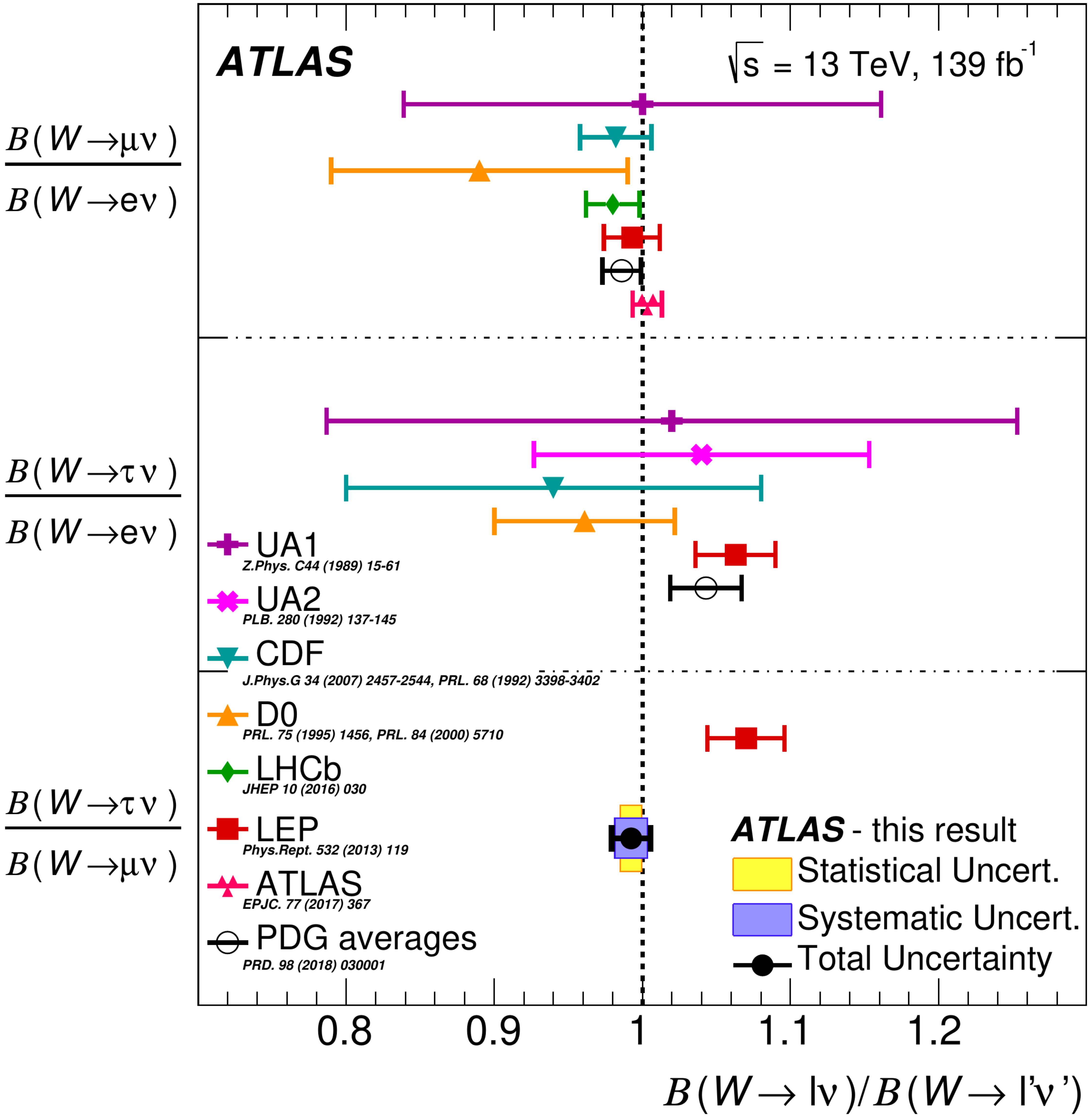
- Consistency of the result was observed when performing the in several different scenarios:
  - Subsets of the data (2015-16, 2017, 2018),
  - eμ and μμ channels,
  - Individual p_T^μ bins,
  - Separately for each lepton charge.

- This all gives confidence in the robustness of the result.



Summary

- A new technique exploiting ATLAS's huge Run 2 dataset and excellent muon reconstruction sheds new light on an old discrepancy.
  - Yet another example of the impressive high **precision measurements** possible at the LHC!



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- A 5σ deviation might have been more fun…

  …but this is still a(nother) beautiful confirmation of the Standard Model!

Résonaances

Particle Physics Blog

Saturday, 1 August 2020

Death of a forgotten anomaly

Anomalies come with a big splash, but often go down quietly. A recent ATLAS measurement, just posted on arXiv, killed a long-standing and by now almost forgotten anomaly from the LEP collider. LEP was an electron-positron collider operating some time in the late Holocene. Its most important legacy is the very precise measurements of the interaction strength between the Z boson and matter, which to this day are unmatched in accuracy. In the second stage of the experiment, called LEP-2, the collision energy was gradually raised to about 200 GeV, so that pairs of W bosons could be produced. The experiment was able to measure the branching fractions for W decays into electrons, muons, and tau leptons. These are precisely predicted by the Standard Model: they should be equal to 10.8%, independently of the flavor of the lepton (up to a very small correction due to the lepton masses). However, LEP-2 found

$$Br(W \to \tau\nu)/Br(W \to e\nu) = 1.070 \pm 0.029, \quad Br(W \to \tau\nu)/Br(W \to \mu\nu) = 1.076 \pm 0.028.$$

While the decays to electrons and muons conformed very well to the Standard Model predictions, there was a 2.8 sigma excess in the tau channel. The question was whether it was simply a statistical fluctuation or new physics violating the Standard Model's sacred principle of *lepton flavor universality*. The ratio $Br(W \to \tau\nu)/Br(W \to e\nu)$ was later measured at the Tevatron, without finding any excess, however the errors were larger. More recently, there have been hints of large lepton flavor universality violation in B-meson decays, so it was not completely crazy to think that the LEP-2 excess was a part of the same story.

Summary

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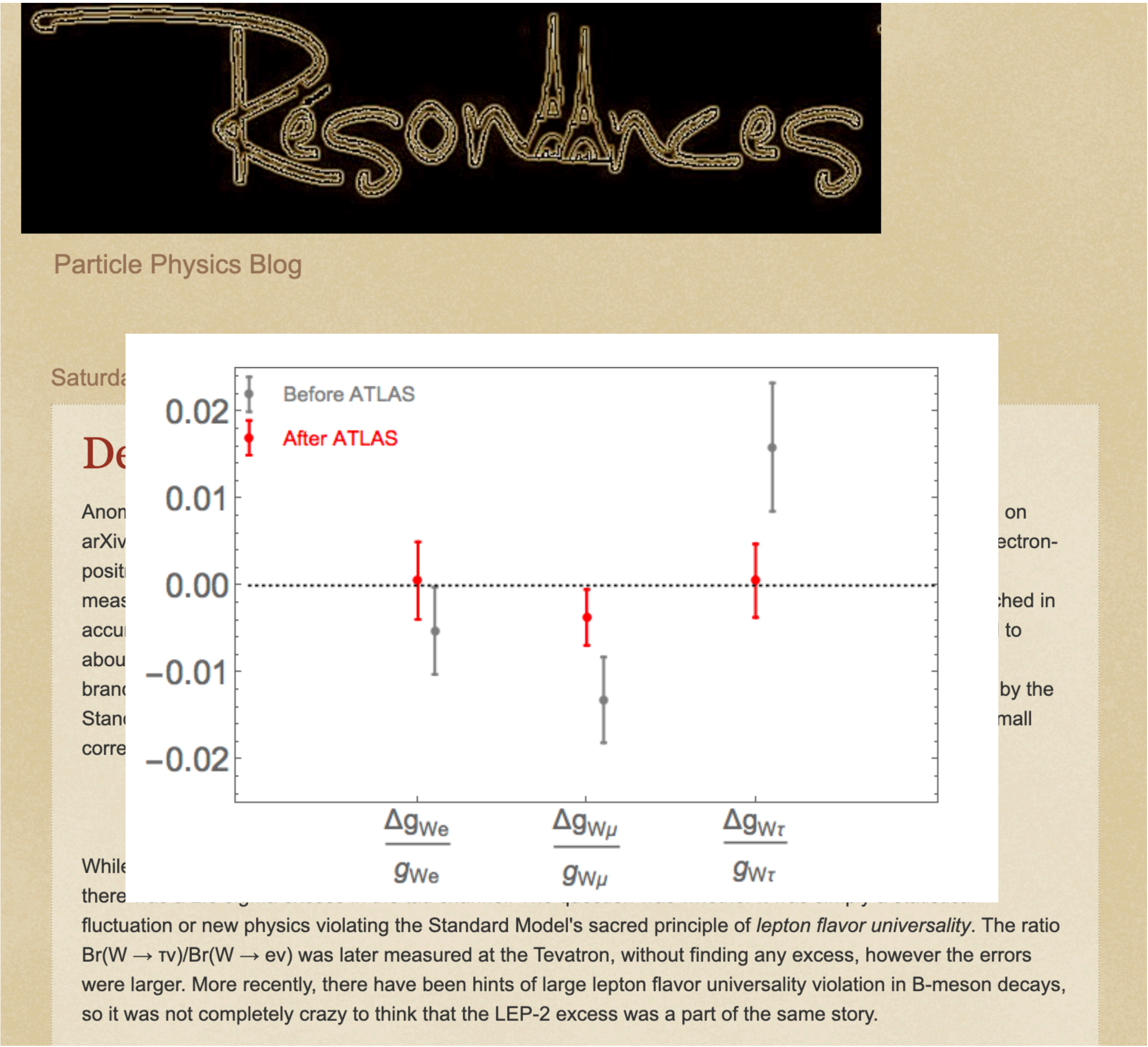

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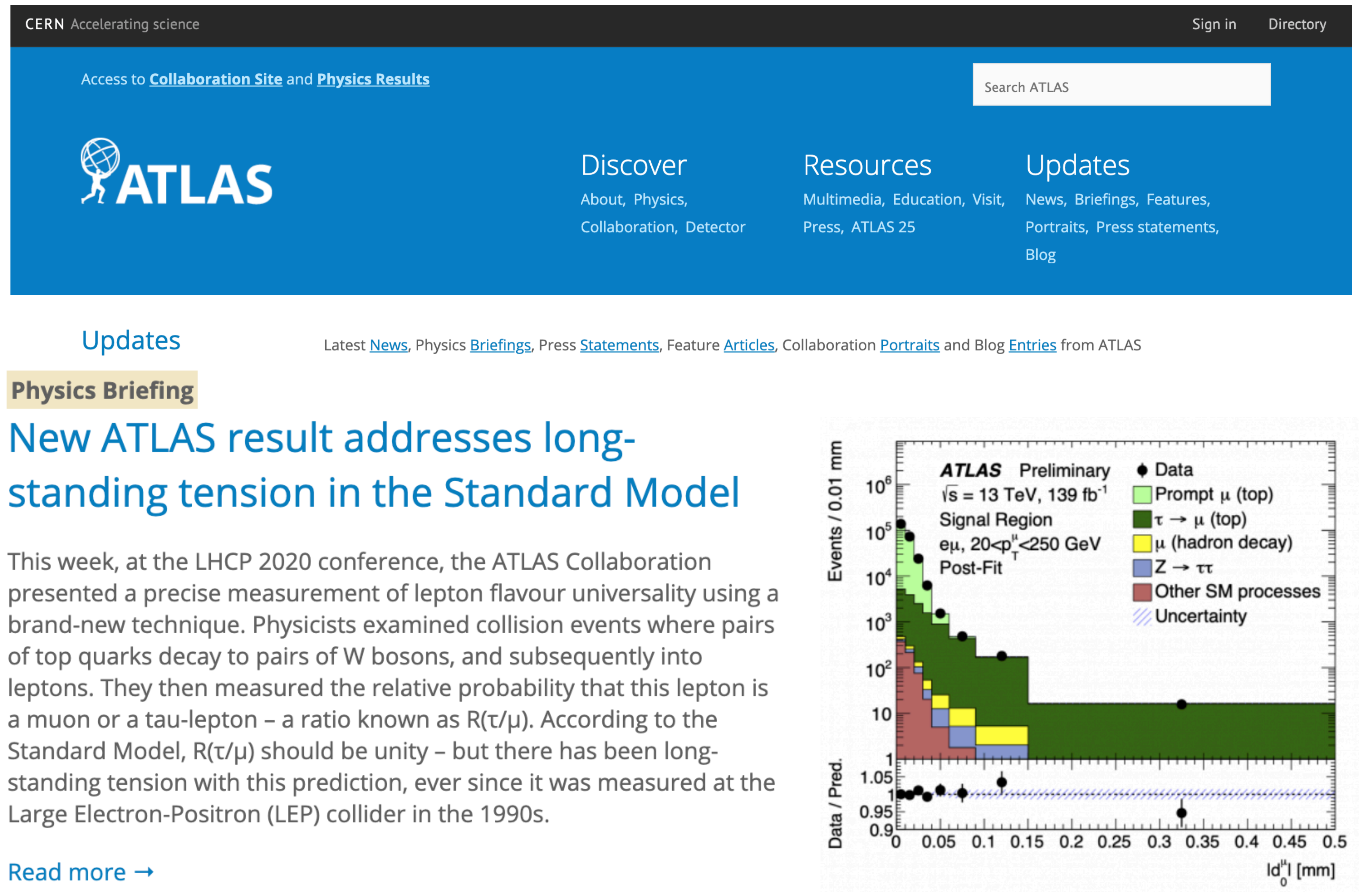

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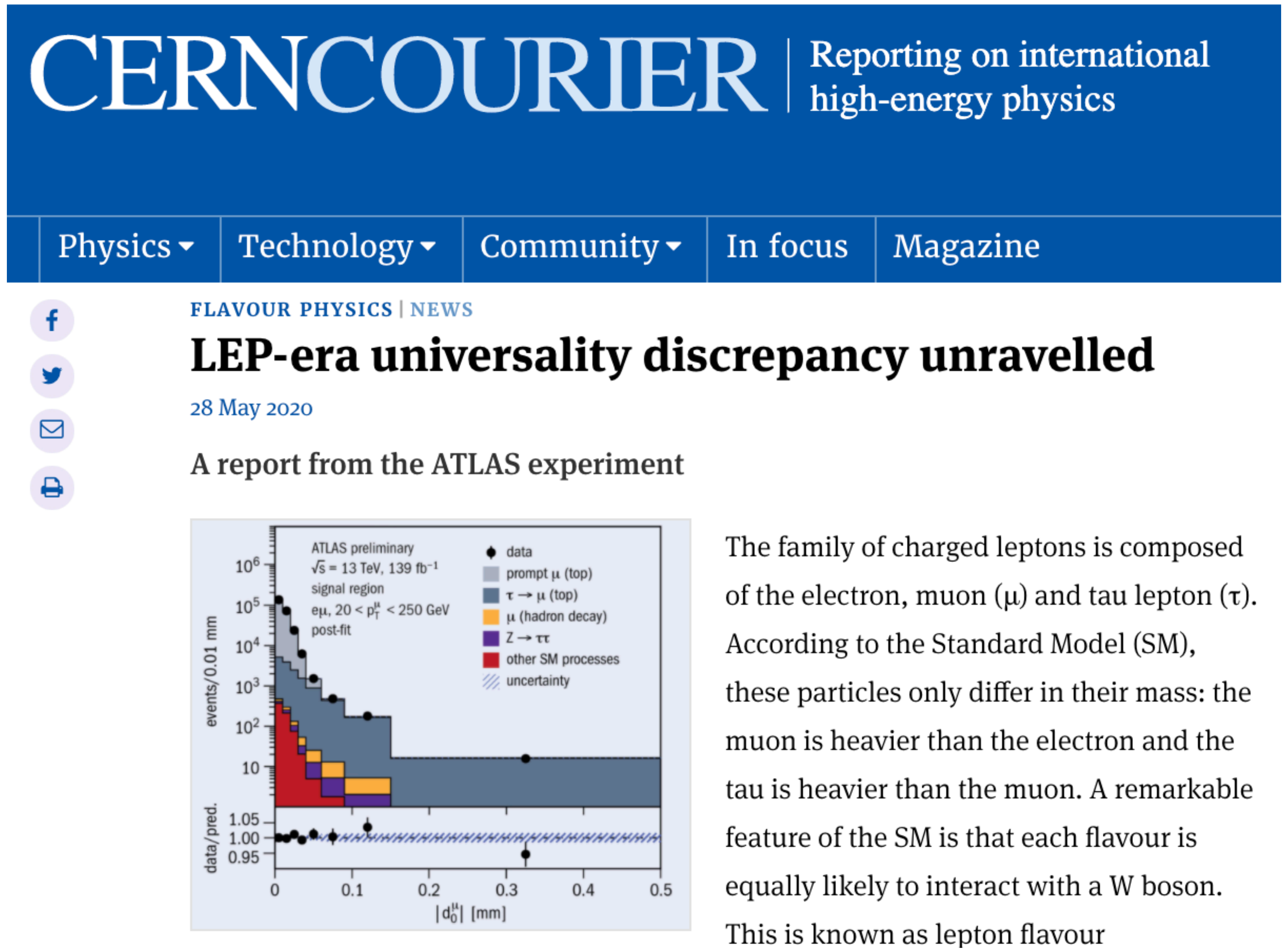
Updates — Latest News, Physics Briefings, Press Statements, Feature Articles, Collaboration Portraits and Blog Entries from ATLAS

Physics Briefing

New ATLAS result addresses long-standing tension in the Standard Model

This week, at the LHCP 2020 conference, the ATLAS Collaboration presented a precise measurement of lepton flavour universality using a brand-new technique. Physicists examined collision events where pairs of top quarks decay to pairs of W bosons, and subsequently into leptons. They then measured the relative probability that this lepton is a muon or a tau-lepton – a ratio known as R(τ/μ). According to the Standard Model, R(τ/μ) should be unity – but there has been long-standing tension with this prediction, ever since it was measured at the Large Electron-Positron (LEP) collider in the 1990s.

Read more →



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FLAVOUR PHYSICS | NEWS

LEP-era universality discrepancy unravelled

28 May 2020

A report from the ATLAS experiment

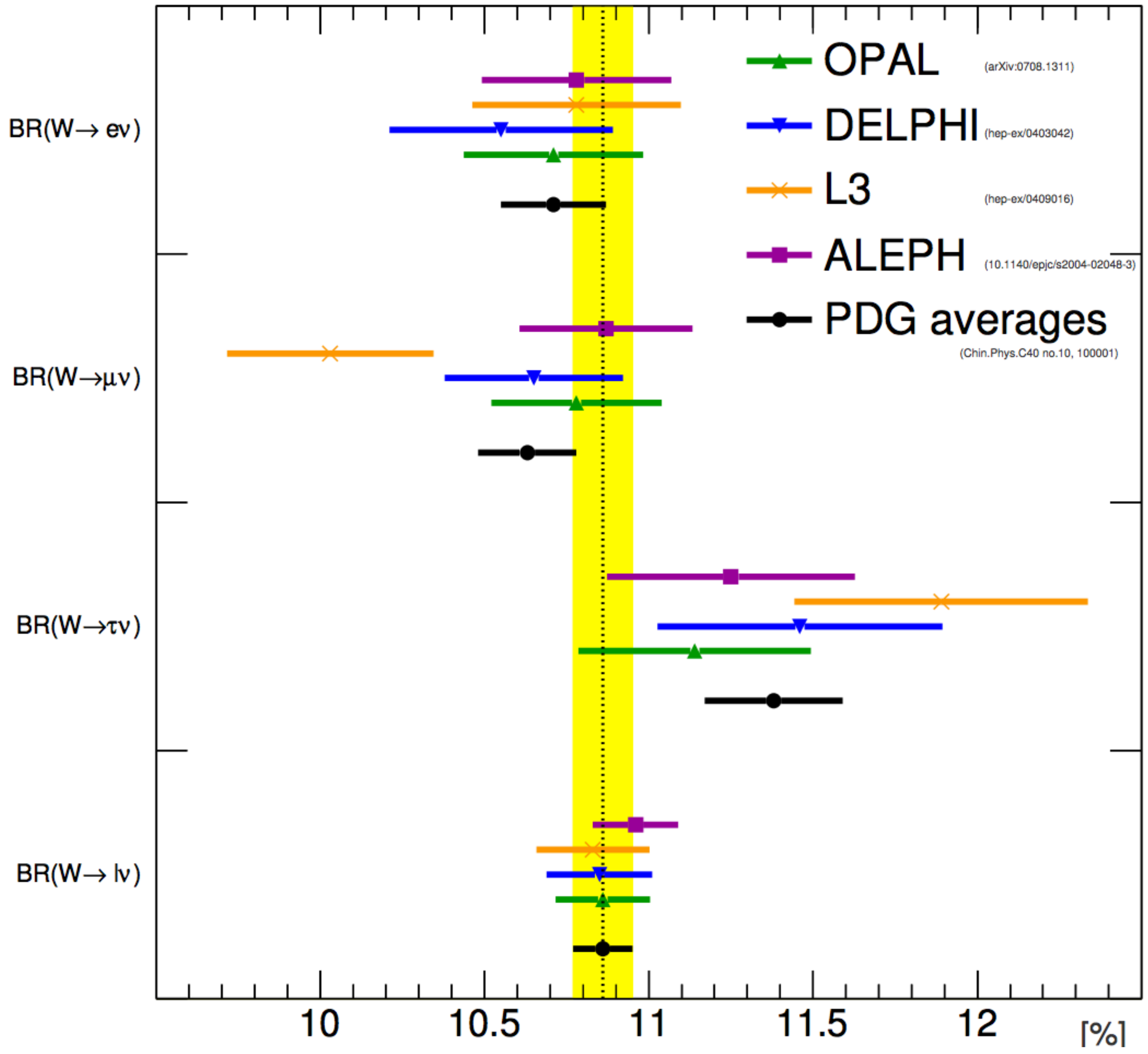
The family of charged leptons is composed of the electron, muon (μ) and tau lepton (τ). According to the Standard Model (SM), these particles only differ in their mass: the muon is heavier than the electron and the tau is heavier than the muon. A remarkable feature of the SM is that each flavour is equally likely to interact with a W boson. This is known as lepton flavour

Thanks for your attention!

Back-ups

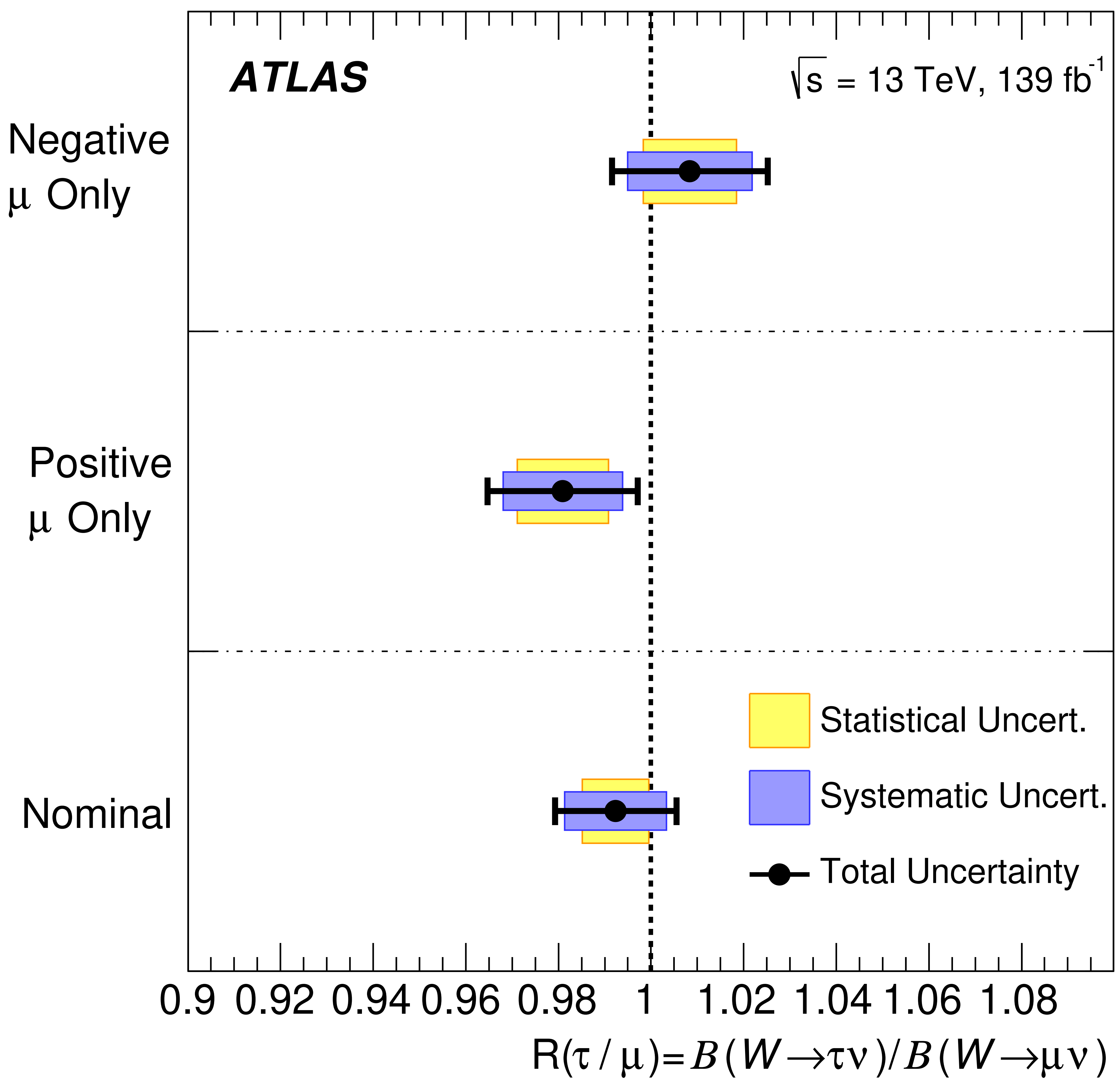
Individual BR measurements

- The individual W→ℓν branching ratio measurements:



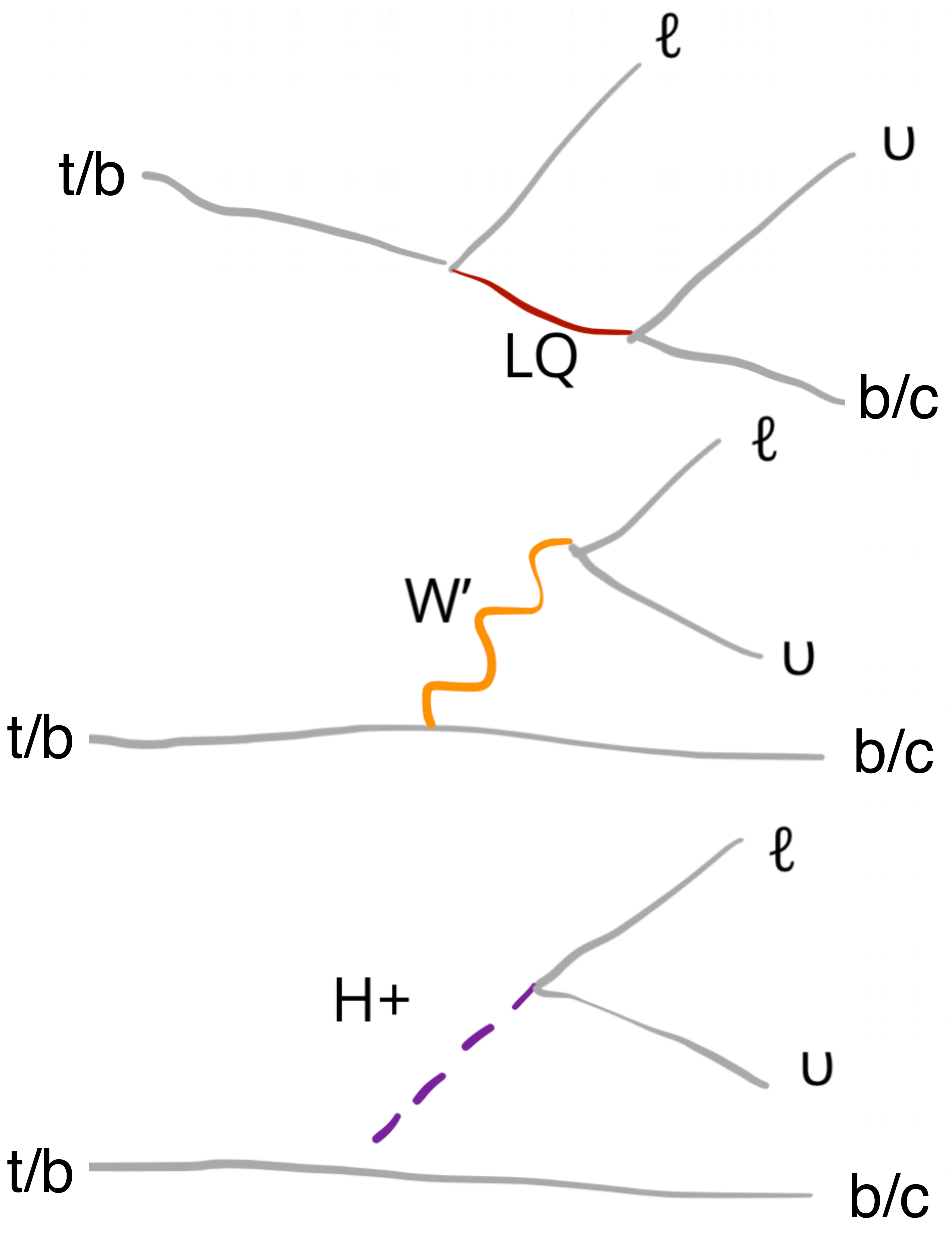
Cross-checks

- Lepton charge cross-checks



Possible interpretations

- The kinds of BSM models that could modify the measured couplings are:
  - Leptoquarks
  - W’
  - Charged Higgs



Results | Data/MC pre-fit - eμ

- Pre-fit distributions in the signal regions.
  - After application of data-driven corrections to the d_0 modelling.
  - Data-driven normalisation factors are applied.

Results | Data/MC post-fit - eμ

- Post-fit distributions in the signal regions.
  - After application of data-driven corrections to the d_0 modelling.
  - Data-driven normalisation factors are applied.
  - NP pulls and constraints from the fit applied.

Results | Data/MC pre-fit - μμ

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  - Data-driven normalisation factors are applied.
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Muons from hadron decays

- The most significant **background** at high $|d_0^\mu|$ from **b- and c-hadron decays**.
- **Normalisation** from **same-sign control region**.
  - **Prompt contributions** corrected in high-p_T region.
  - **Normalisation correction factor**
    - Take SS rate in data (subtracting corrected prompt)
    - Divide by SS rate in MC.
- Simulation used for:
  - Extrapolation from SS to OS,
  - $|d_0^\mu|$ distribution shape.

$$N_{\text{data}}^{\text{OS},\mu(\text{had})} = R N_{\text{MC}}^{OS,\mu(\text{had})}$$

$$R = \frac{N_{\text{data}}^{\text{SS}} - S N_{\text{MC}}^{\text{SS,non}-\mu(\text{had})}}{N_{\text{MC}}^{\text{SS},\mu(\text{had})}}$$

$$S = \left[\frac{N_{\text{data}}^{\text{SS}} - N_{\text{MC}}^{\text{SS},\mu(\text{had})}}{N_{\text{MC}}^{\text{SS},\mu(\text{had})}}\right]_{p_T>30\text{ GeV}}$$

Object details

- Baseline muons
  - Required to satisfy the medium identification criteria.
  - Isolation
    - Sum of the transverse momentum of other tracks within a cone of 0.3 in ΔR / $p_T < 0.04$
    - Sum of calorimeter deposits within a cone of $\Delta R < 0.2$ / $p_T < 0.15$
  - $|\eta| < 2.5$
  - Required to be close to primary vertex
    - Distance of closest approach in r-z plane of less than 0.3 mm
    - Transverse impact parameter with respect to the beamline, $|d0| < 0.5$ mm

- Tag muons
  - $p_T > 27.3$ GeV to pass the trigger thresholds
- Probe muons
  - $p_T > 5$ GeV

Optimisation

Variables considered in optimisation:

- N b-jets and working point
- 3rd lepton veto
- Z-mass window criteria
- η criteria of probe leptons.
- z0 probe lepton - reject “fake" leptons from pile-up
- Muon Momentum Balance Significance: targets decays in flight of pi± and K±.
  - the compatibility of the ID and MS muon tracks
- Track Isolation of Probe lepton: targets “fake" leptons from heavy flavour decays
  - ptcone, etcone, on top of gradient iso.
- ΔR(l, jet): targets “fake" leptons from heavy flavour decays.
- ΔR(l, b-jet): targets “fake" leptons from heavy flavour decays.

Why not use d_0 significance?

- Using d_0 significance introduces additional complication
  - Need to control both d_0 and its uncertainty.
  - More complicated that then data-driven template method we use.

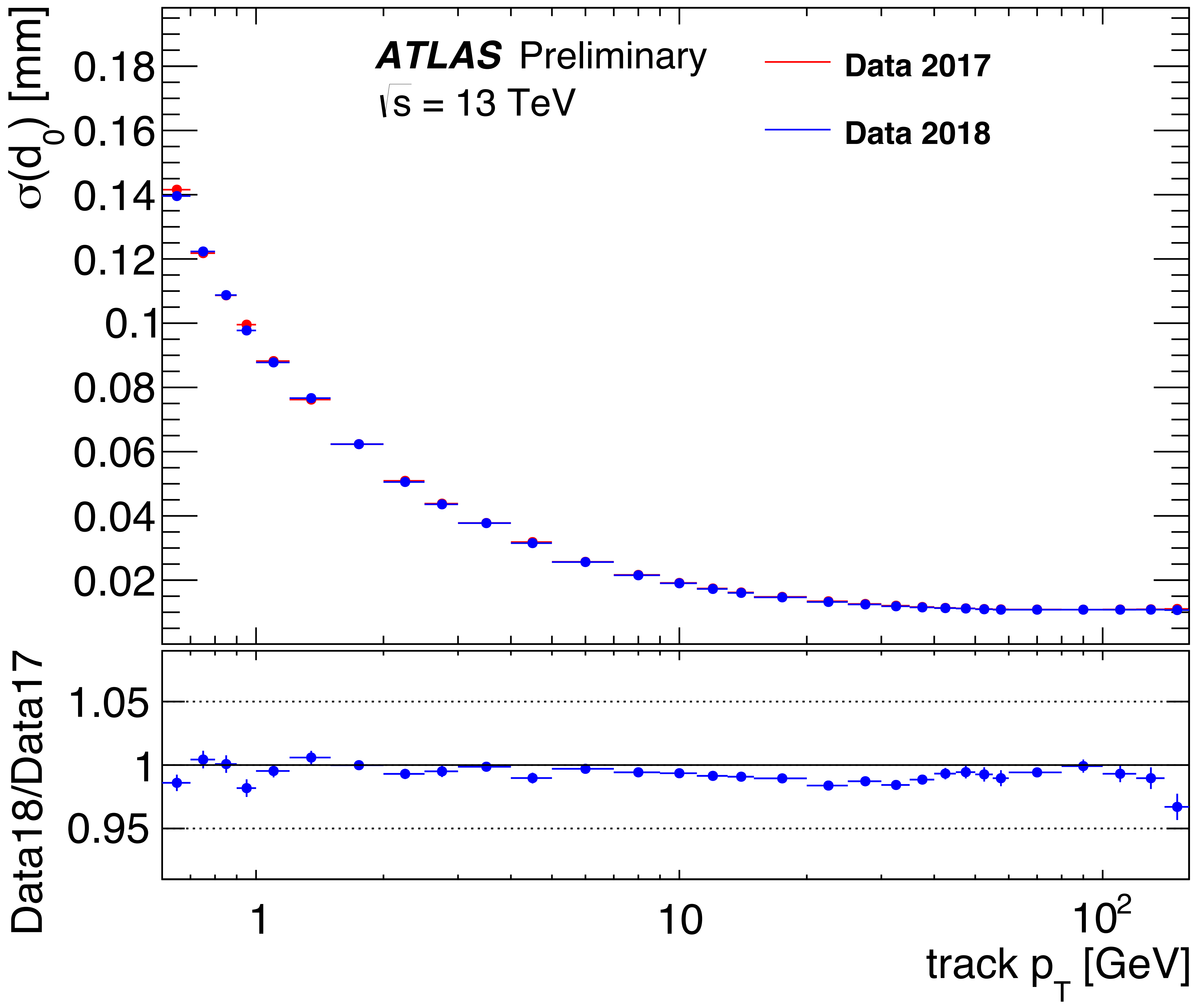
- Even though d_0 significance is more stable in different kinematic bins, both d_0 and $\sigma(d_0)$ do vary
  - The consistency between data and MC is more complicated for d_0 significance

- We checked the two variables are very close in final analysis precision.
  - Given this and the additional complications we used d0

Impact parameter definition

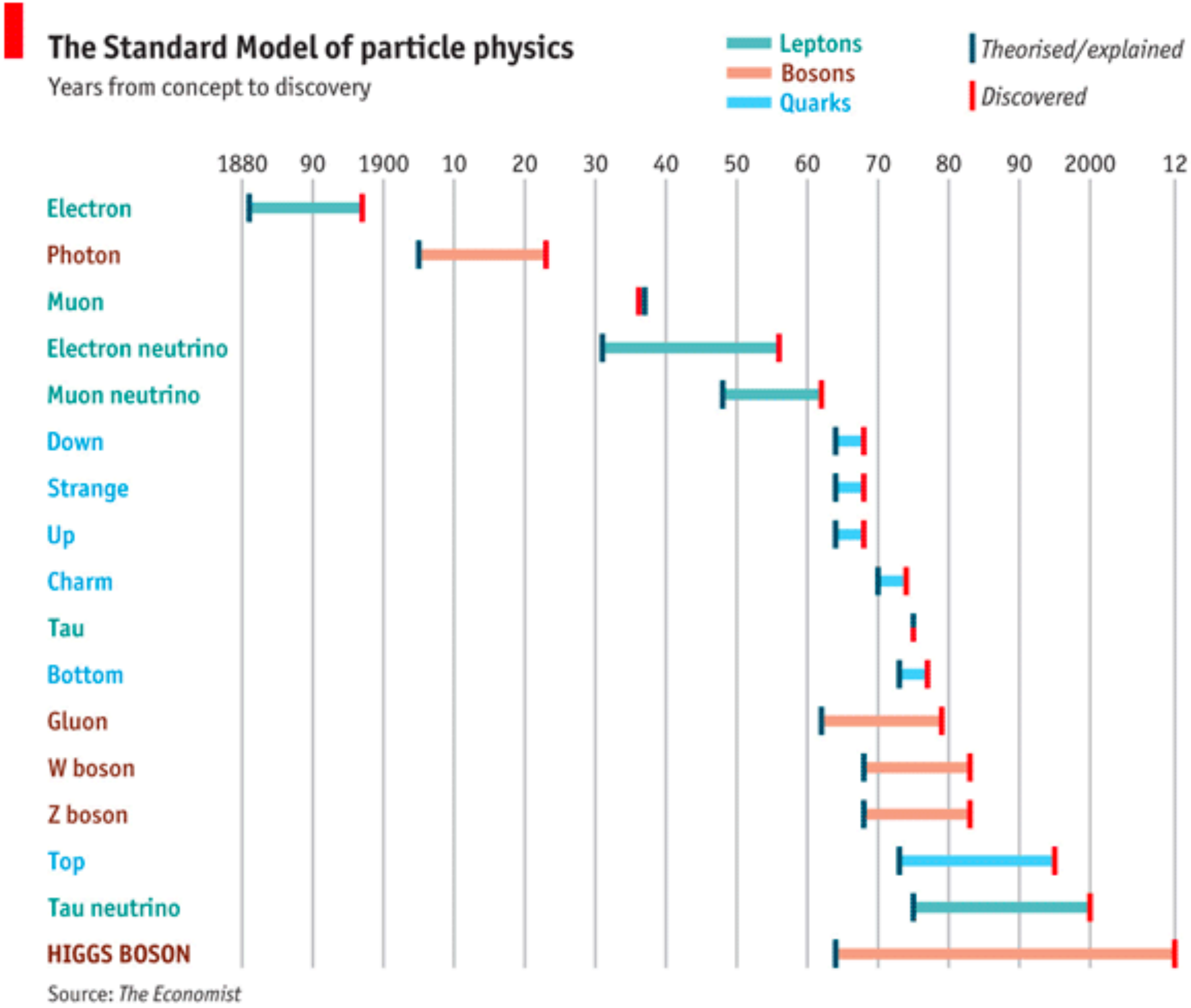
- The transverse impact parameter, **$|d_0^\mu|$**, is vital for the analysis:
  - The distance of closest approach of muon tracks in the transverse plane.
  - Defined with respect to the beam line:
    - This definition is most process-independent.
  - Allows data driven methods to determine $|d_0^\mu|$ shape.

[IDTR-2018-008]

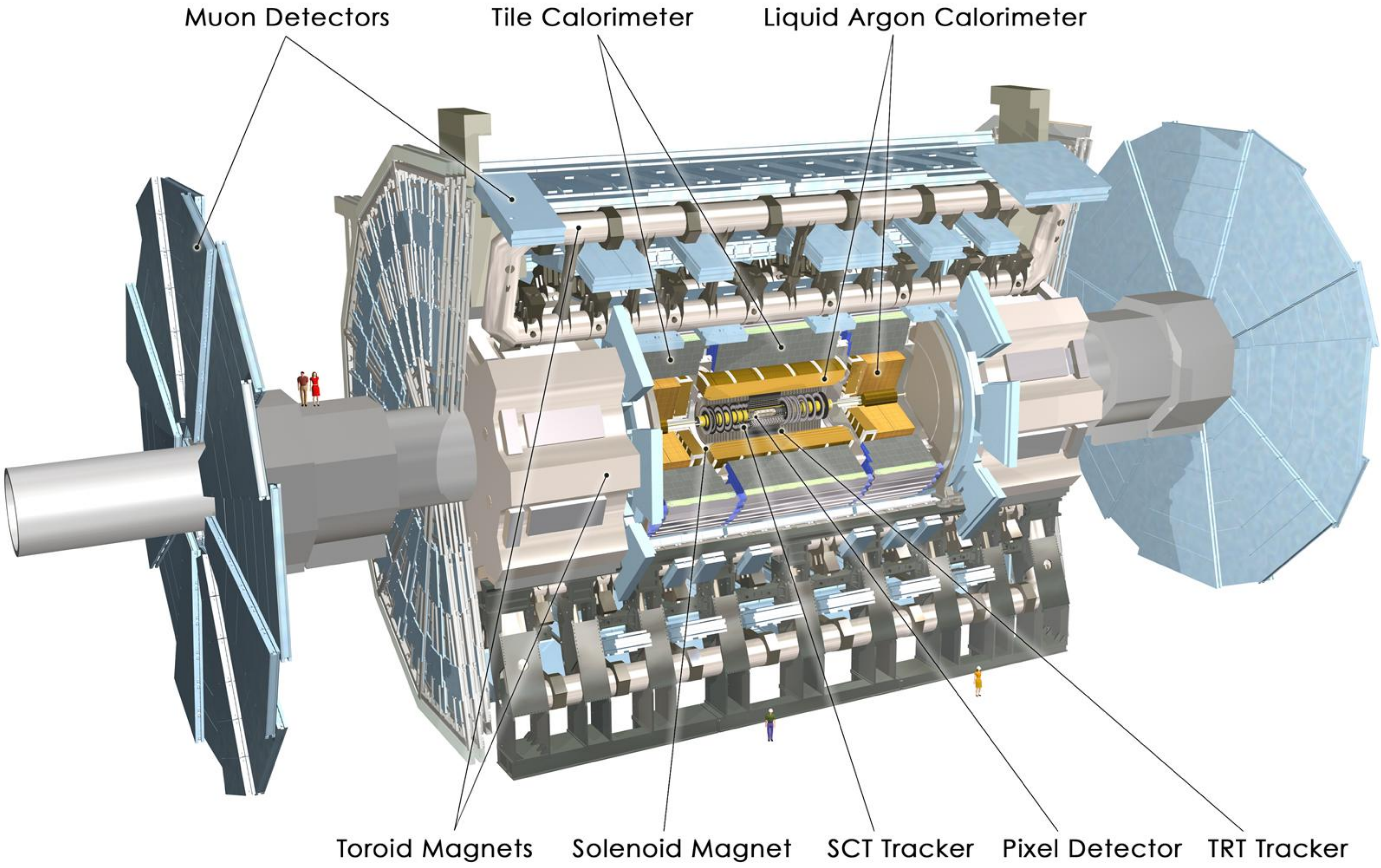


- Corrections applied:
  - $|d_0^\mu|$ distributions for prompt muons taken from $Z \to l^+l^-$ events in data.
  - Resolution measured in data using the same data.
    - Used to smear the MC to match the resolution in data
  - The uncertainties on these methods are the most important for the analysis.

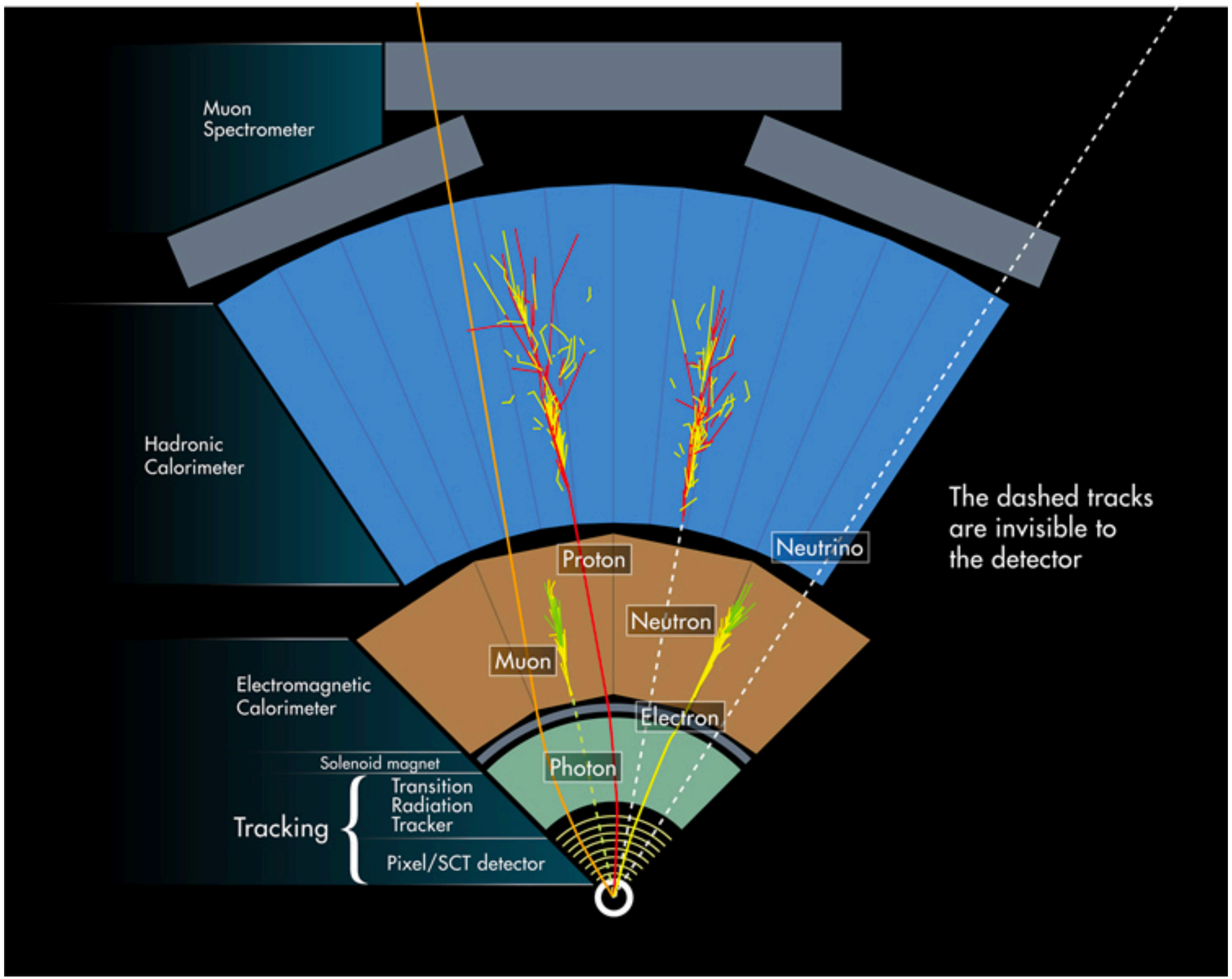
From concept to discovery



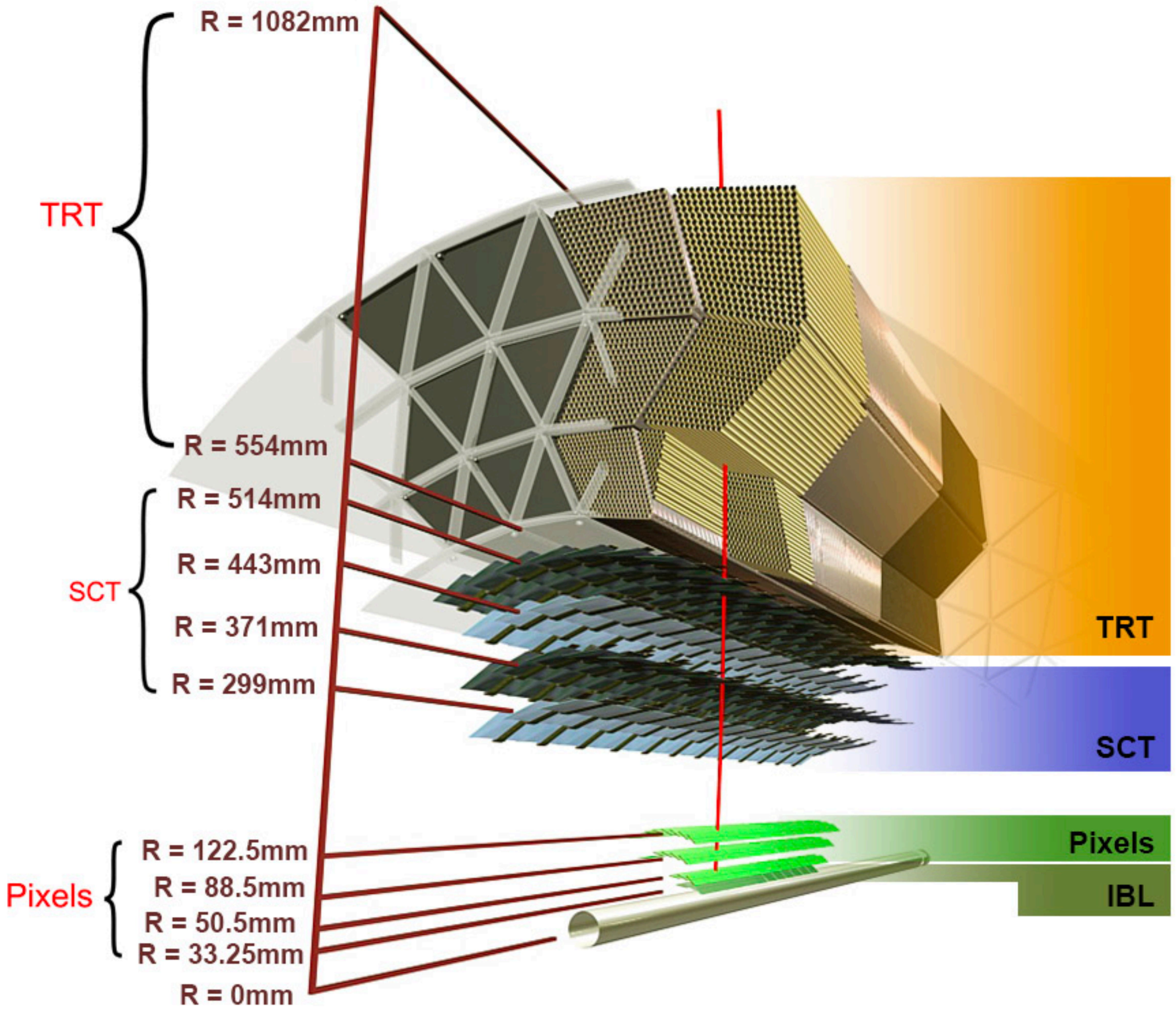
ATLAS | Detector



ATLAS | Detector particle ID



ATLAS | Inner Detector



Using hadronic taus

- A self-calibrating, double-ratio method to test tau lepton universality in W boson decays at the LHC

[1910.11783]

- R(bbWW):
  - defined such that uncertainties from lepton ID, b-tagging, trigger, ~cancel
  - Sensitive to τ_{had} identification uncertainties
- R(Z):
  - ~same sensitivity to uncertainties to R(bbWW), in particular from TauID
- R(WZ):
  - Uncertainties from τ_{had} ID ~cancel in R(WZ).

$$R(bbWW) \equiv \frac{N(tt \to bb\ell\tau_{\rm had})}{N(tt \to bbe\mu)},$$

$$R(Z) \equiv \frac{N(Z \to \tau\tau \to \ell\tau_{\rm had})}{N(Z \to \tau\tau \to e\mu)},$$

$$R(WZ) \equiv \frac{R(bbWW)}{R(Z)}$$

$$\equiv \frac{N(tt \to bb\ell\tau_{\rm had}) \times N(Z \to \tau\tau \to e\mu)}{N(tt \to bbe\mu) \times N(Z \to \tau\tau \to \ell\tau_{\rm had})}$$

Theoretical origin of LFU

- LFU is related to the very structure of the SM
  - based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
    - corresponding to strong and electroweak interactions

- There are three main features relevant for LFU:
  - Fermion fields are organised in three generations with the same gauge charge assignments leading to the same structure of couplings in all three generations (universality).
  - The Higgs mechanism for the breakdown of the electroweak gauge symmetry does not affect the universality of the gauge couplings (including electromagnetism).
  - The only difference between the three families comes from the Yukawa interaction between the Higgs field and the fermion fields.