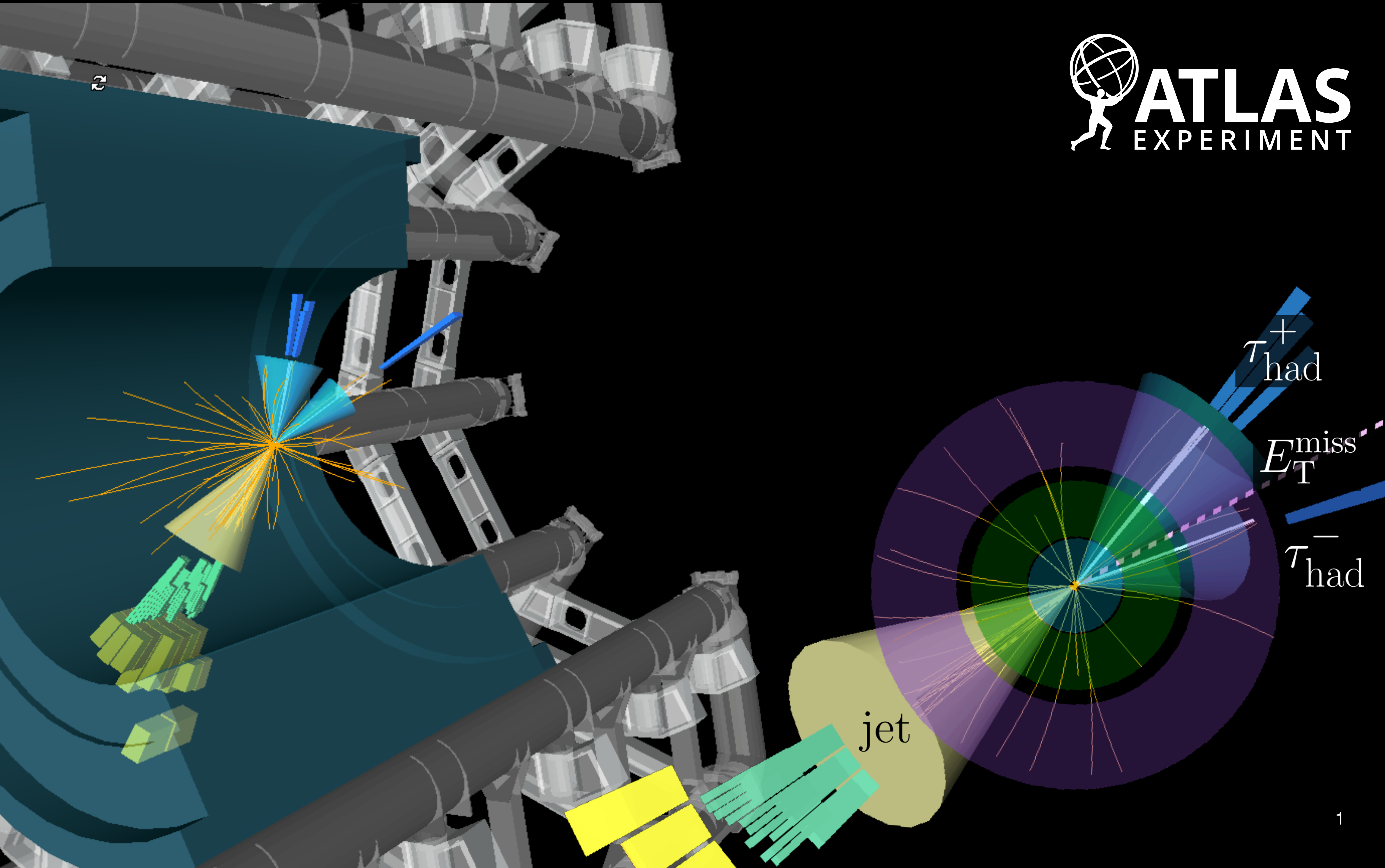
What can we learn with taus at the LHC?

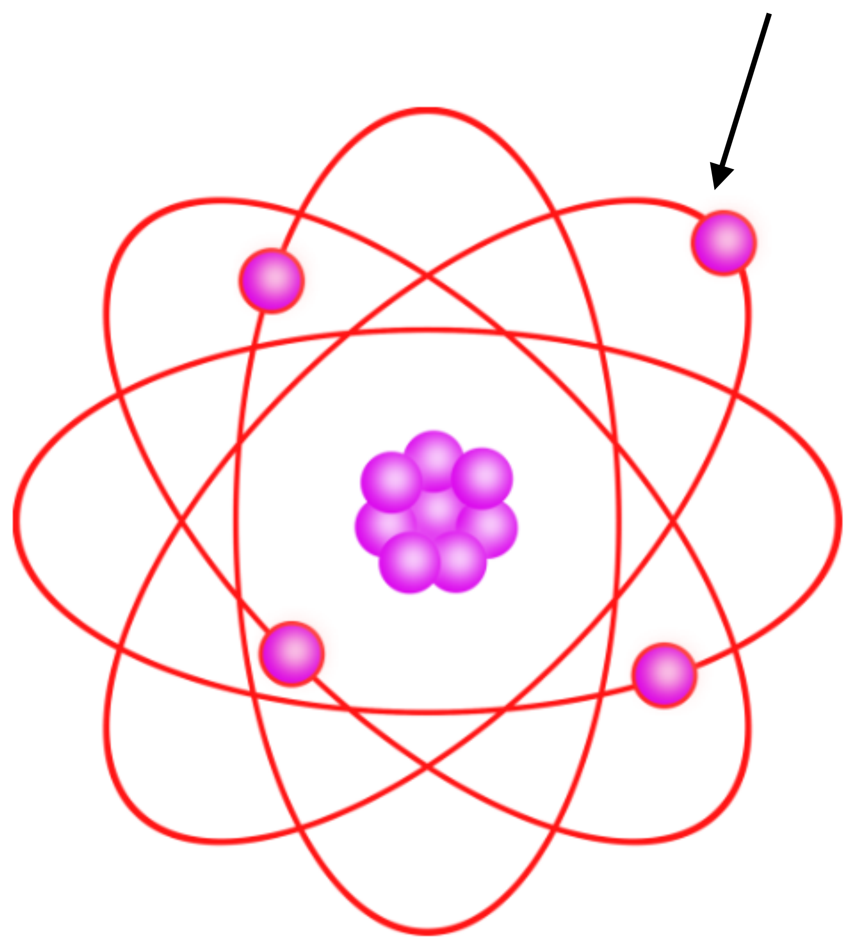
Quentin Buat (University of Washington) — Feb 1st, 2023

ATLAS EXPERIMENT



The electron …

- Discovered in 1891
- Elementary stable particle
- Most accurate and verified predictions in Physics are about the electron

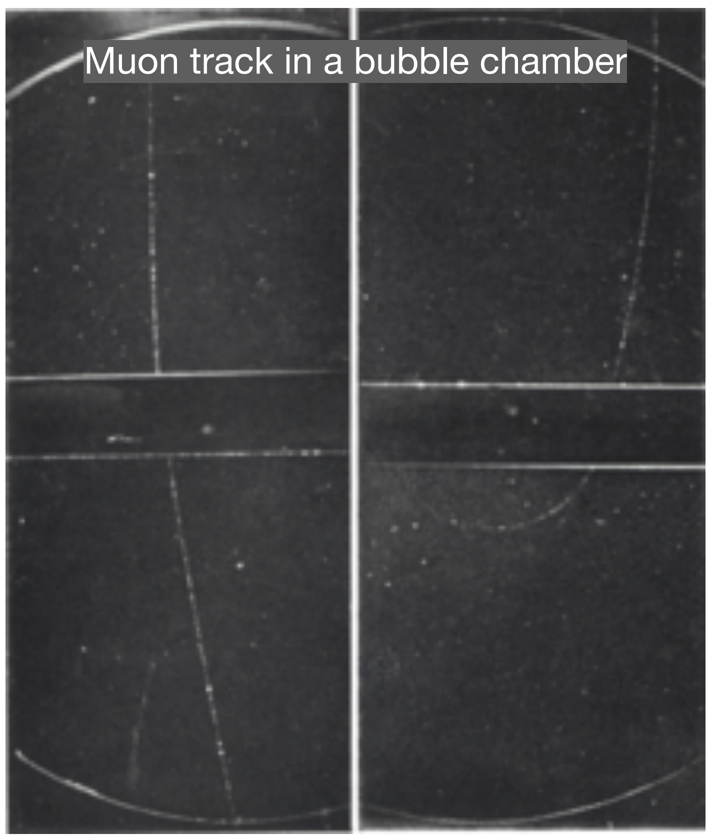


Is a particle we use extensively in our daily life

Has two cousins

From greek for ‘The third one’

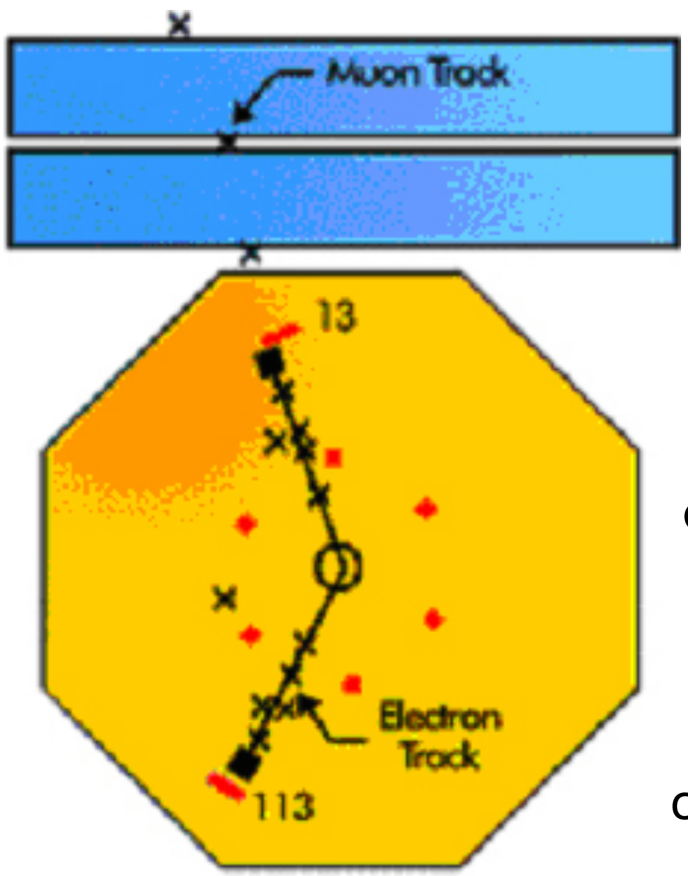
The Muon



Anderson and Neddermeyer, 1936

‘Who ordered that!?’, I.I. Rabi

The Tau (lepton)



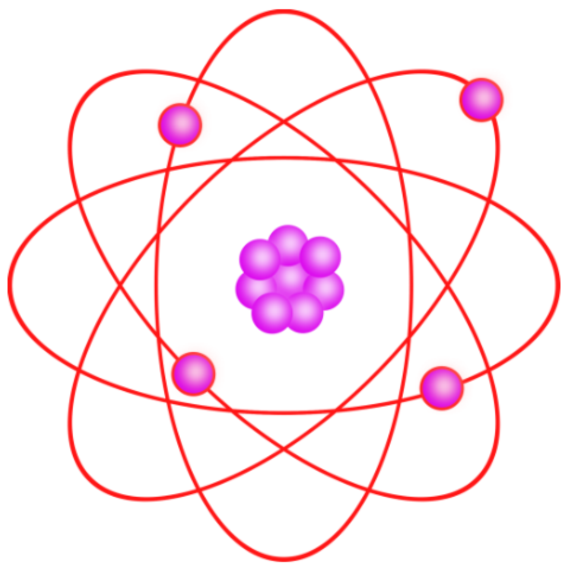
Perl et al., 1975

A tau lepton produced at SLAC with the SPEAR e+e- 3 GeV collider

Momentum conservation allows to infer presence of the tau lepton

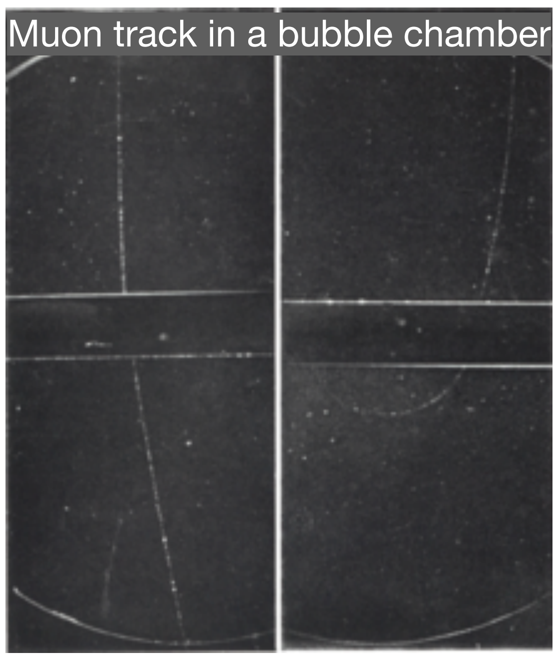
Lepton Flavour Universality

Electron



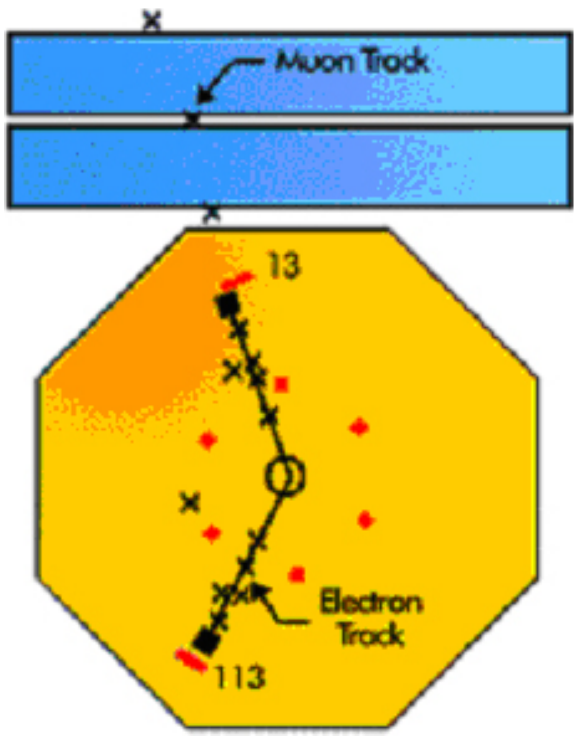
J.J Thompson, 1891

Muon



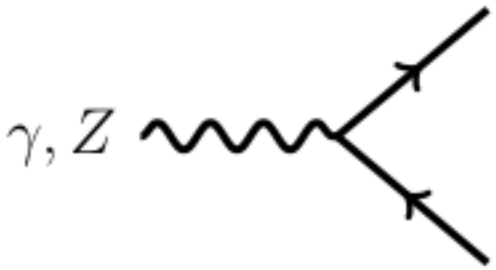
Anderson and Neddermeyer, 1936

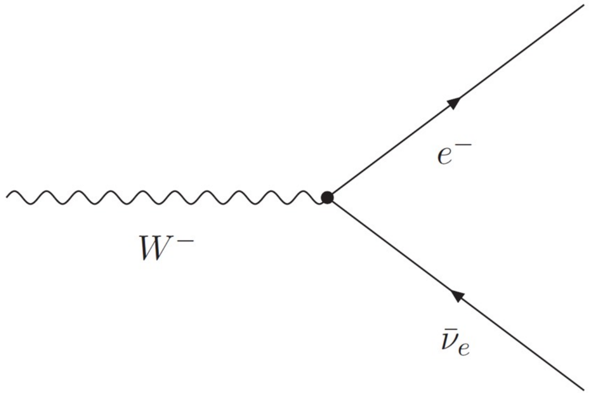
Tau



Perl et al., 1975

Interactions with gauge bosons are the same for the three charged leptons



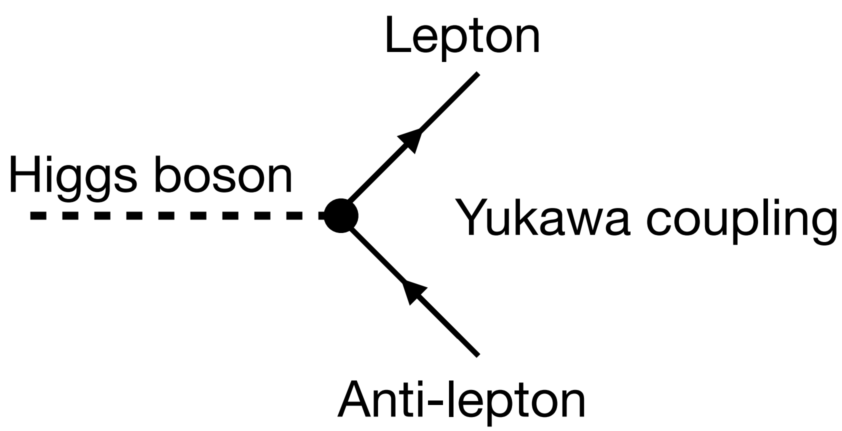


The electron, the muon and the tau lepton seem to fundamentally be the same except…

Yukawa Interactions

[Credit: PhD Comics]

- For their masses!
  - And therefore their couplings to the Higgs boson

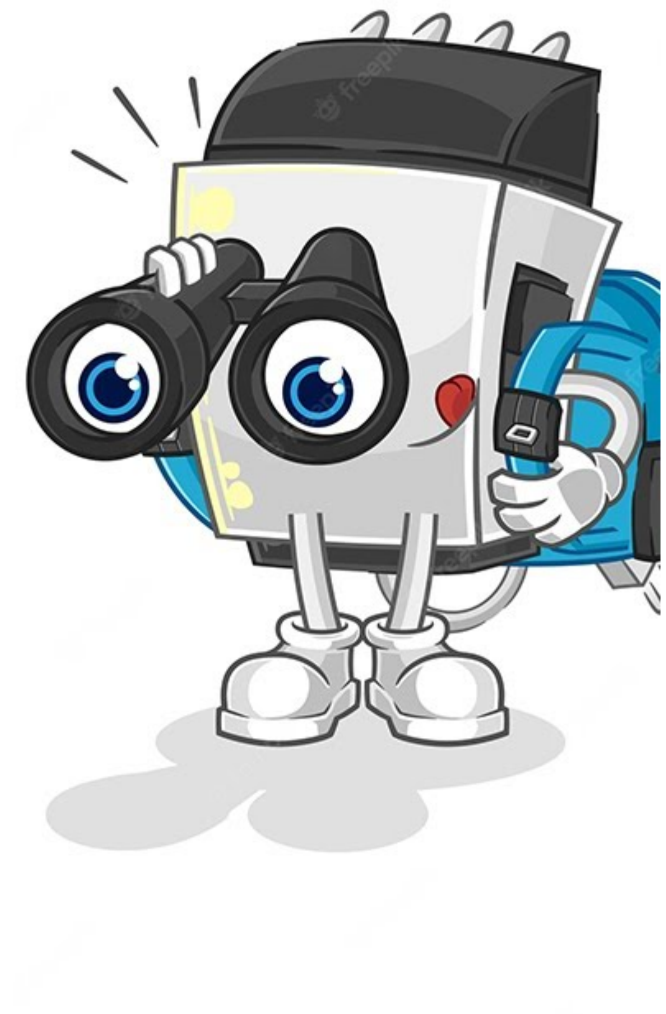


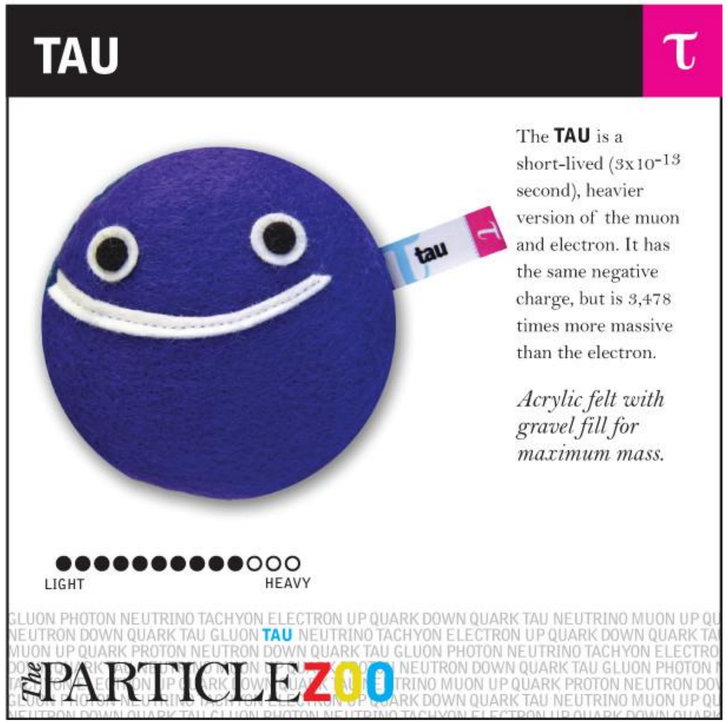
	Electron	Muon	Tau
Mass	511 keV	106 MeV	1.7 GeV
~Number of Higgs decays in ATLAS	0.03	2000	500,000
Couples to the Higgs boson?	?	Hints that yes, to be settled soon	**Yes!**

Discovery of the Higgs-tau coupling:
Direct evidence of interactions between a scalar boson and fermions

What can we learn with taus at the LHC?

- Finding them in data
- Higgs measurements
- Studying them
- Future prospects



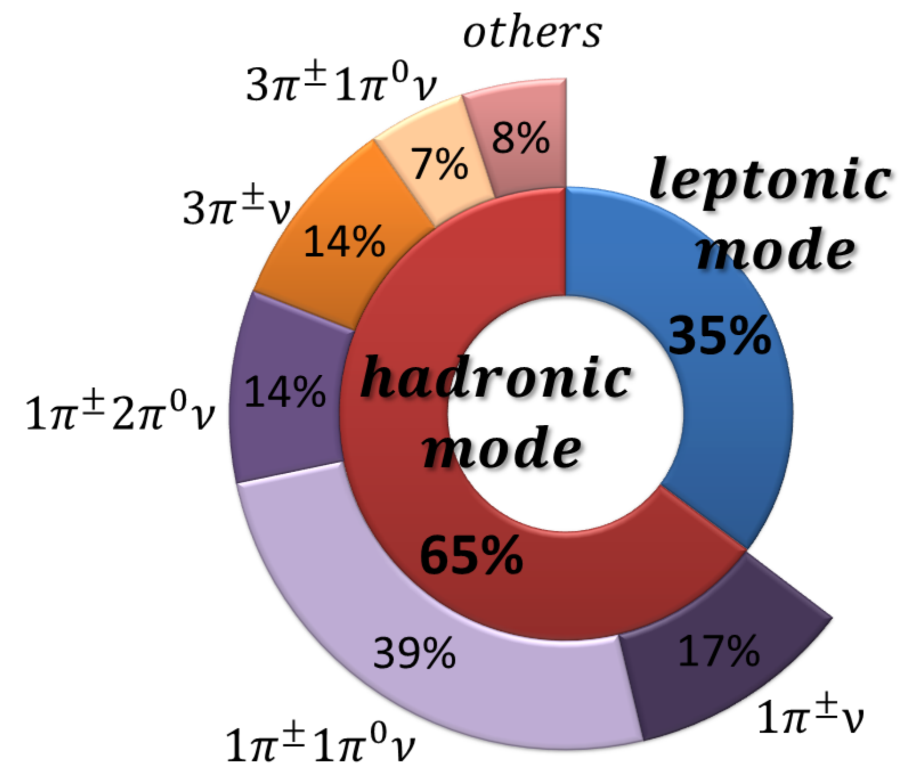


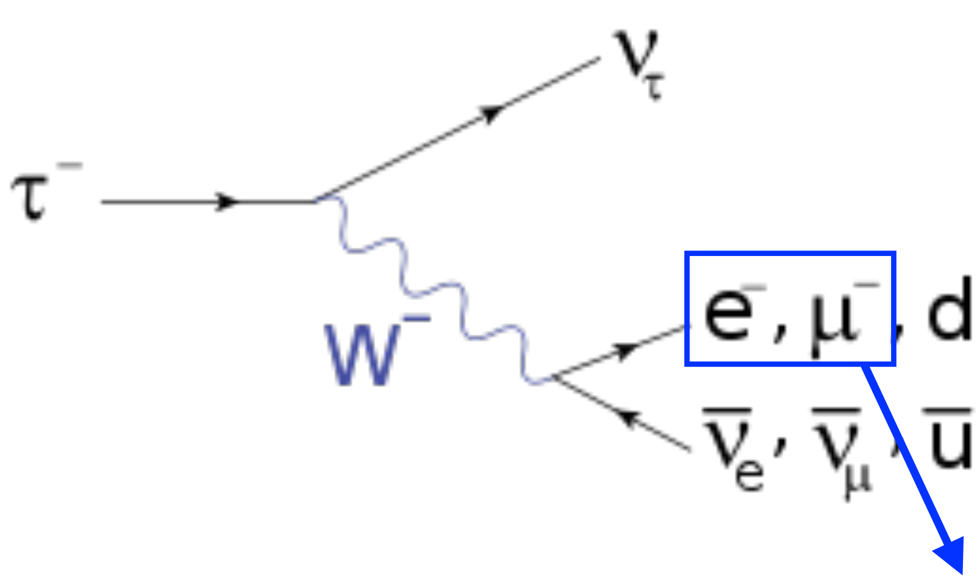
Detecting Tau Leptons at the LHC

Tau Lepton Decays

- Mass: 1.7 GeV
- Mean lifetime: 0.29 ps
- Proper decay length: 87 μm
- First active layer of ATLAS is at 33mm

Main decay modes





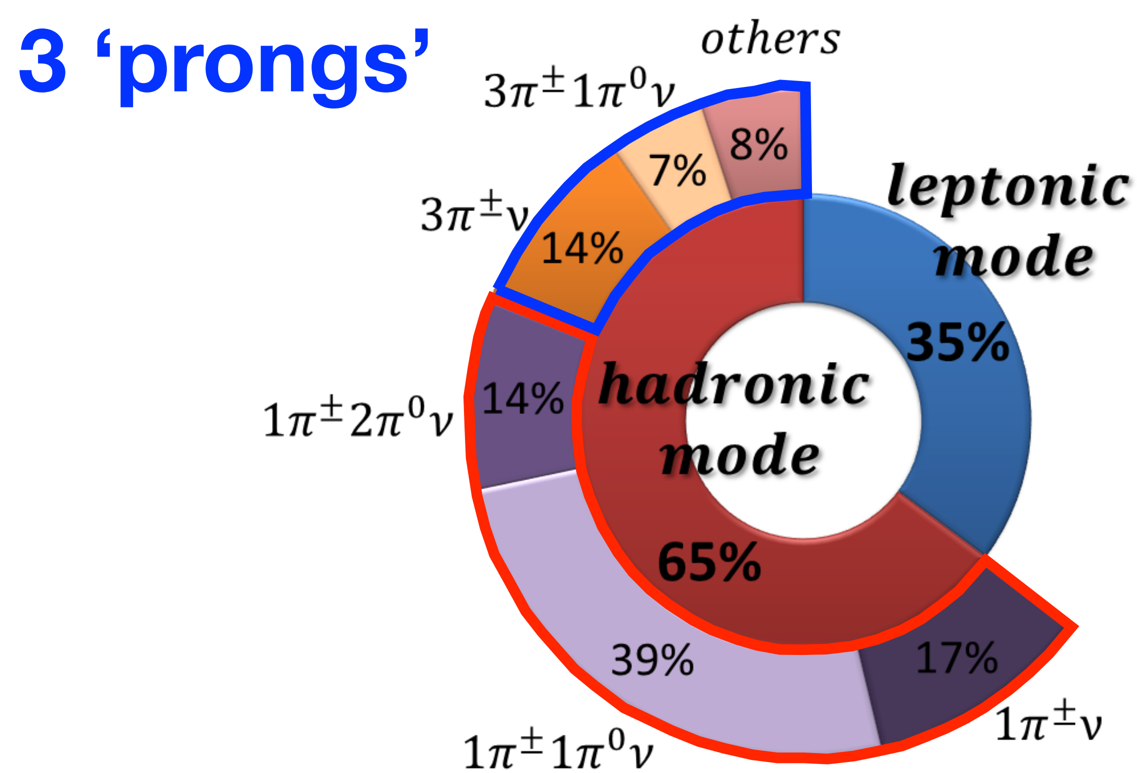
Experimentally similar to prompt electrons or muons

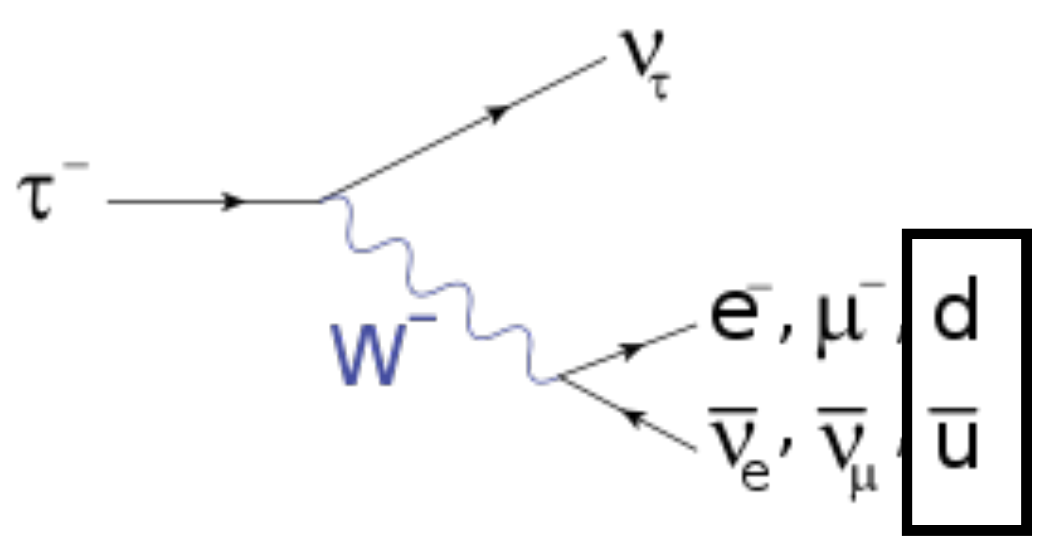
Detecting Tau Leptons at the LHC

Why the hadronic decays?

- Branching fraction = 65%
- Only one neutrino
- Multi-body visible decays carry a lot of information about the parent particle

Main decay modes





1 'prong' = 1 π^+

Hadronisation → set of π^+ and π^0

87% of the H→ττ decays involve a hadronically-decaying tau lepton

The LHC

Collisions Data

- Hadron collider, started collecting data in 2010
- The dataset:
  - p-p collisions at $\sqrt{s}$= 5, 7, 8, **13**, 13.6 TeV
  - Collisions with Pb and other heavy ions

27km ring at the border of France and Switzerland

The LHC

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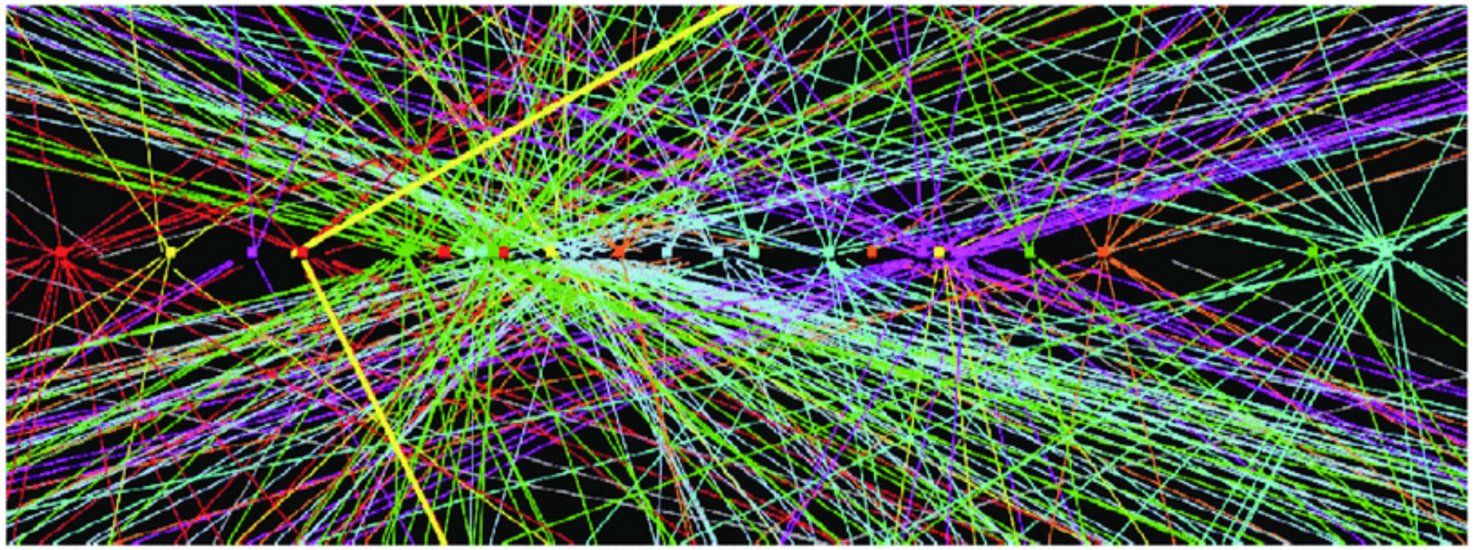
  - Collisions with Pb and other heavy ions
- p-p collisions Run2 dataset
  - $\sqrt{s}$ = **13** TeV
  - ~10^{11} protons per bunch

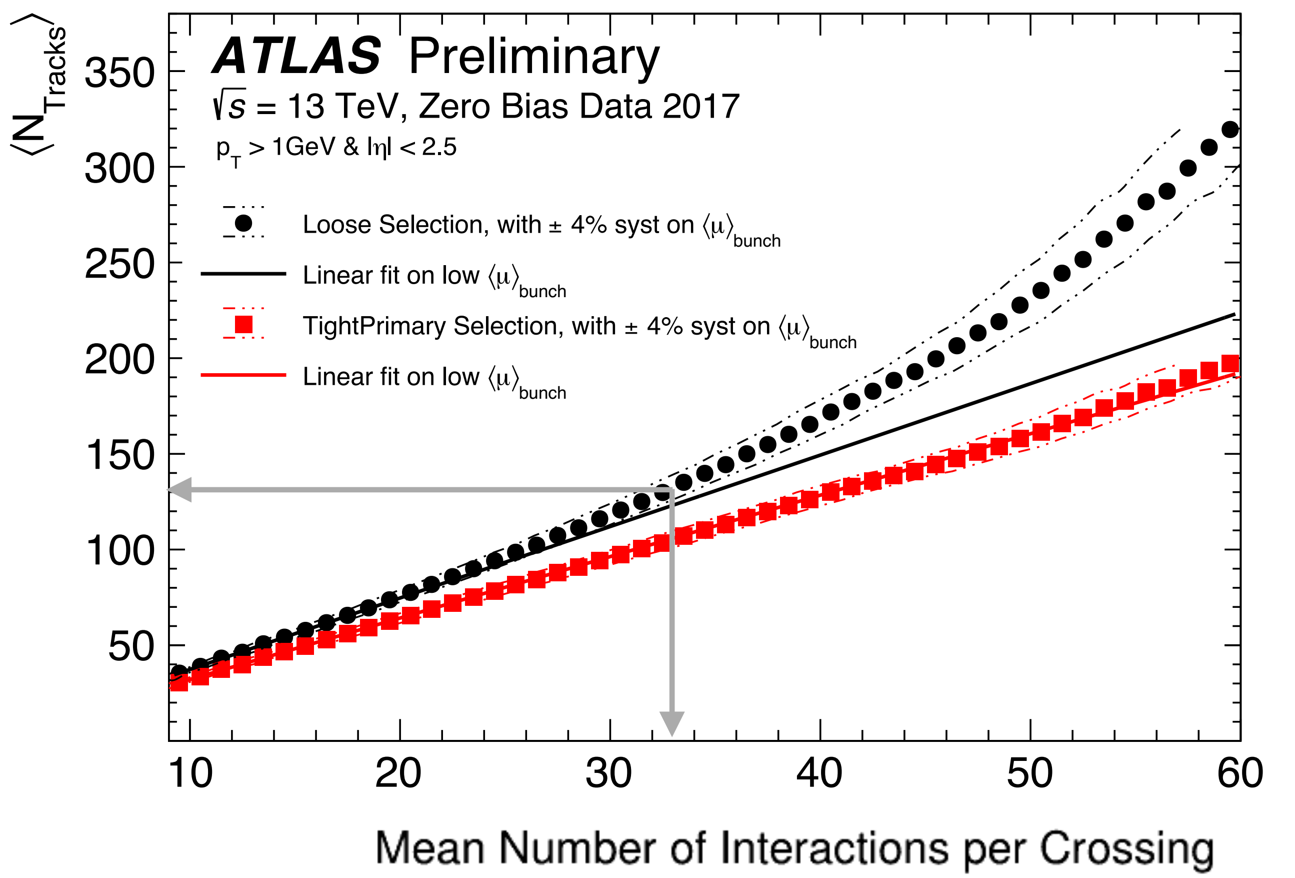


Tracks reconstructed in ATLAS during a typical Run2 data event

The LHC

Collisions Data

- Hadron collider, started collecting data in 2010
- The dataset:
  - p-p collisions at $\sqrt{s}$= 5, 7, 8, **13**, 13.6 TeV
  - Collisions with Pb and other heavy ions
- p-p collisions Run2 dataset
  - $\sqrt{s}$= **13** TeV
  - ~10^{11} protons per bunch
  - Expect in average about 140 charged particles in the detector



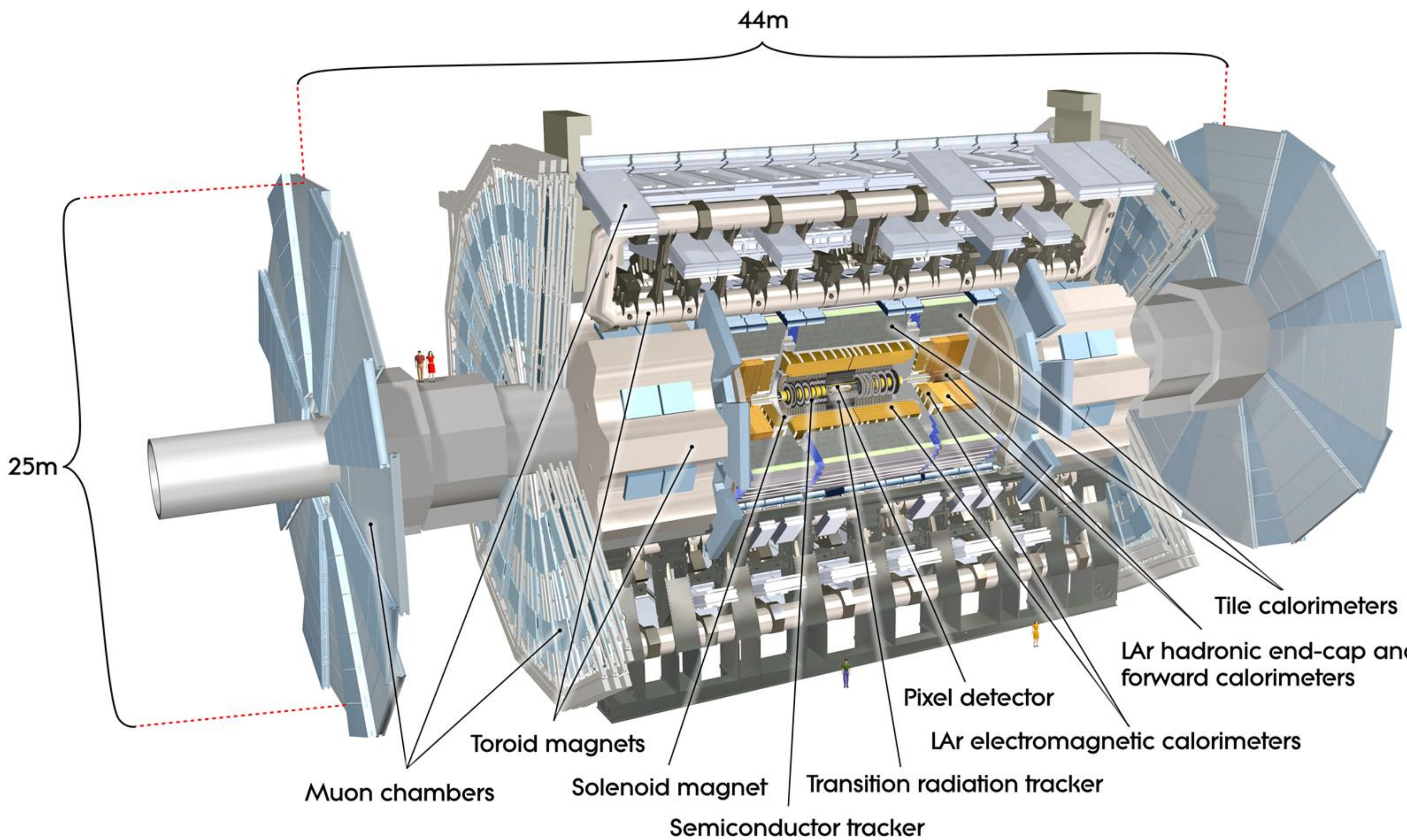
The ATLAS Detector

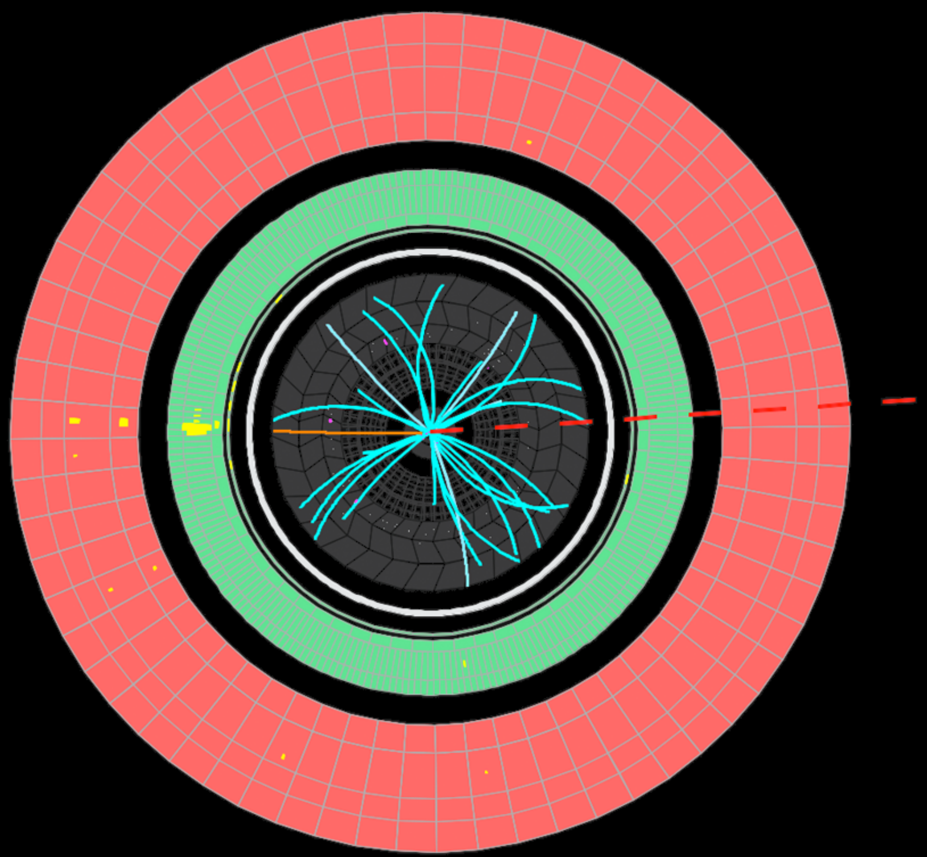
Reconstructing High Energy Physics Data Events

1. Collect information from the detector

2. Use it to measure relevant quantities (momentum, position, …)

NB: I'm focusing on tau leptons but similar approaches are pursued for electrons, muons and jets

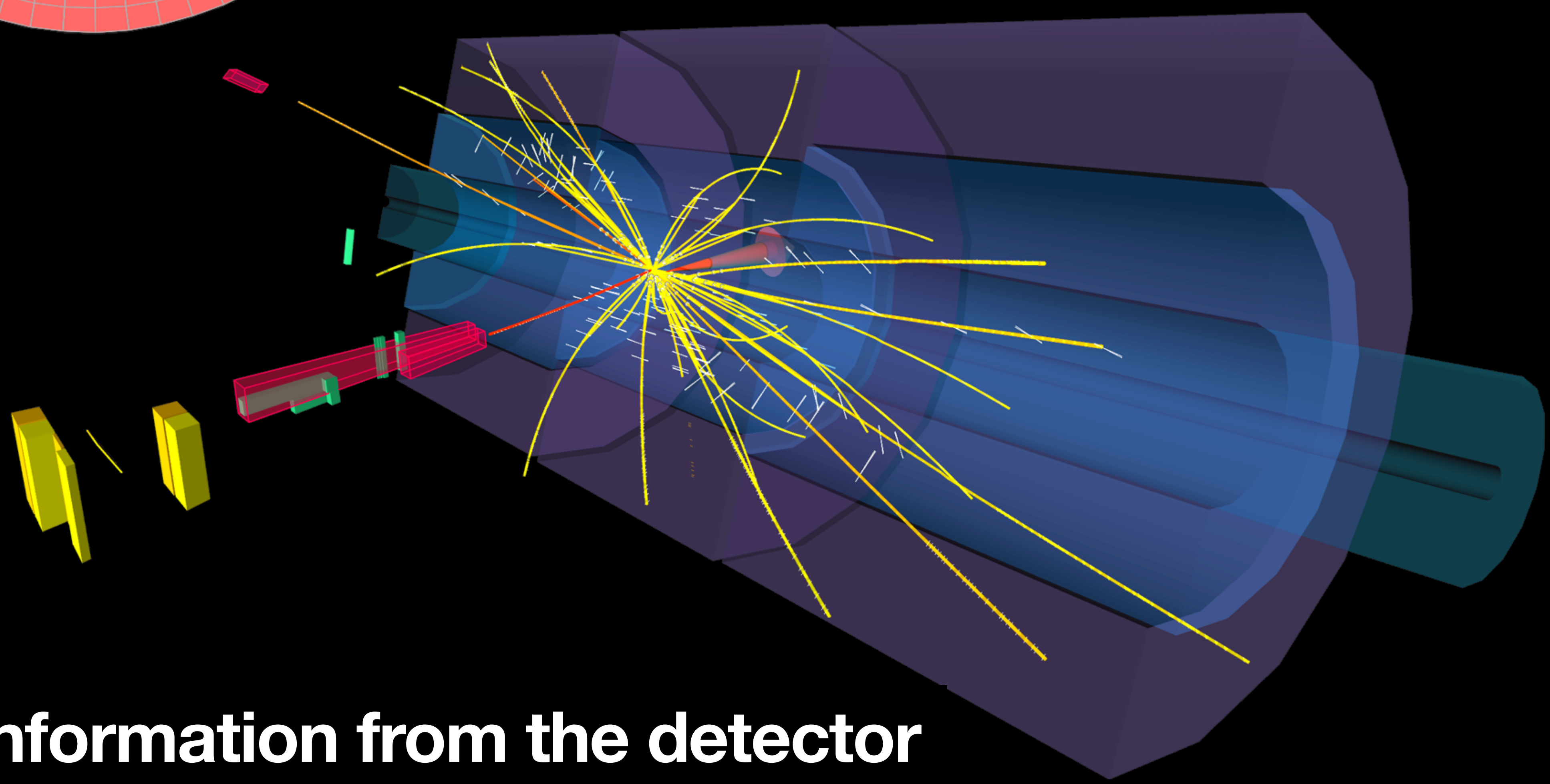




ATLAS EXPERIMENT

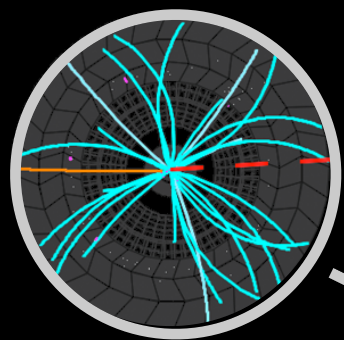
Run 155697, Event 6769403
Time 2010-05-24, 17:38 CEST

$W \to \tau\nu$ candidate in 7 TeV collisions

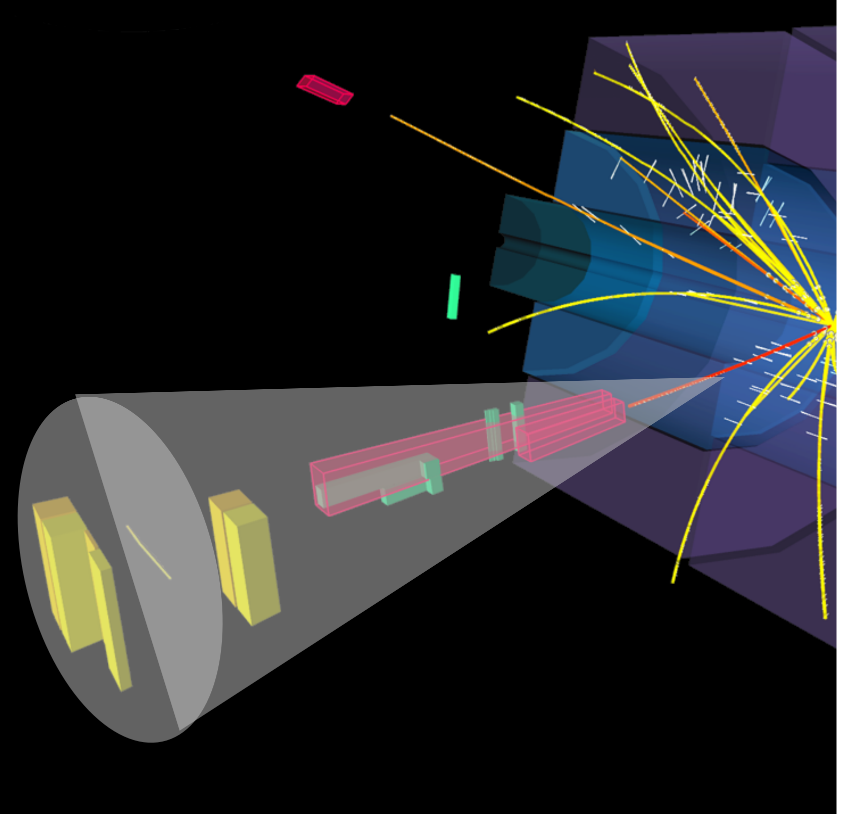


Collect information from the detector

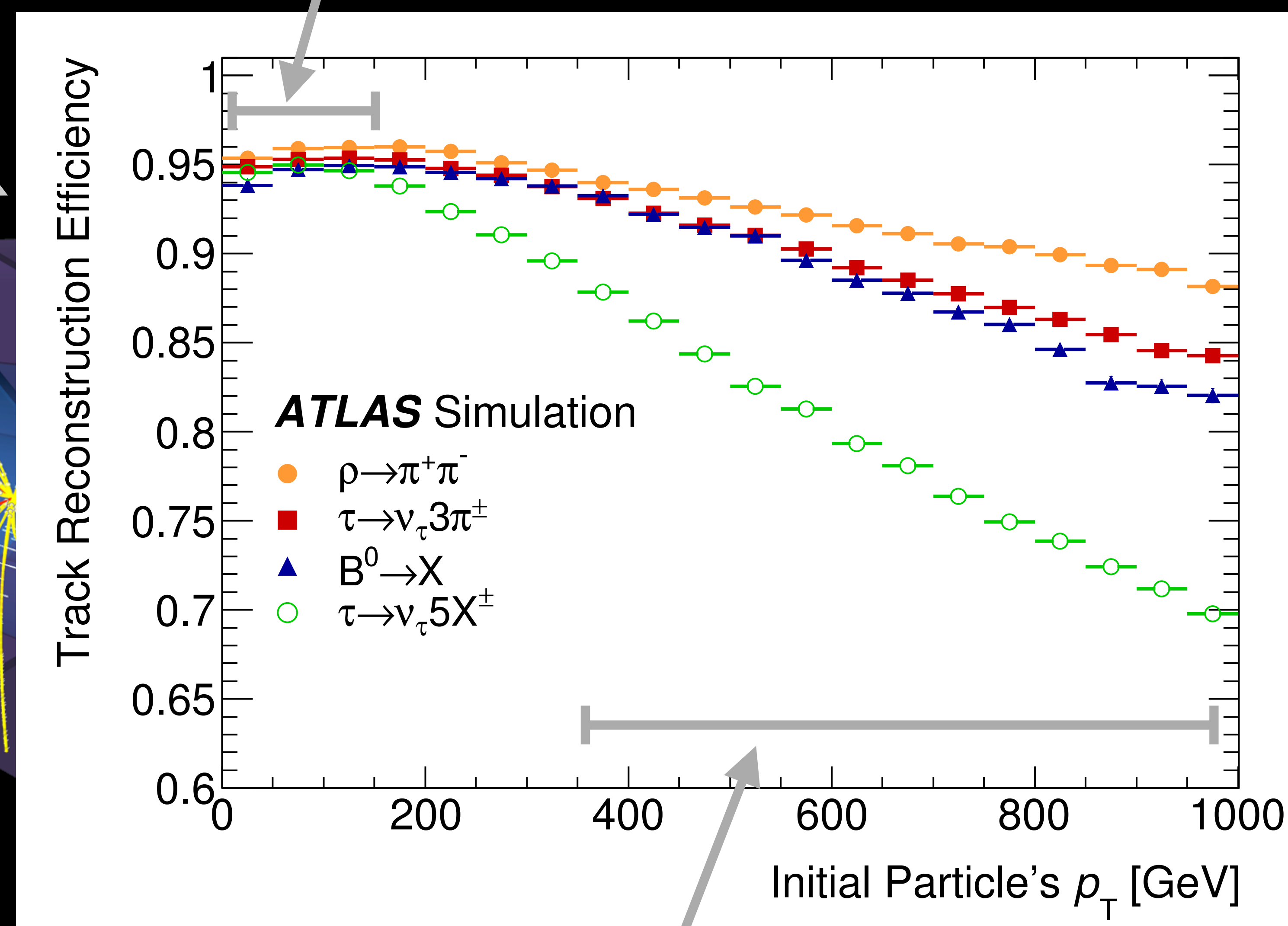
Charged particles in the tracker



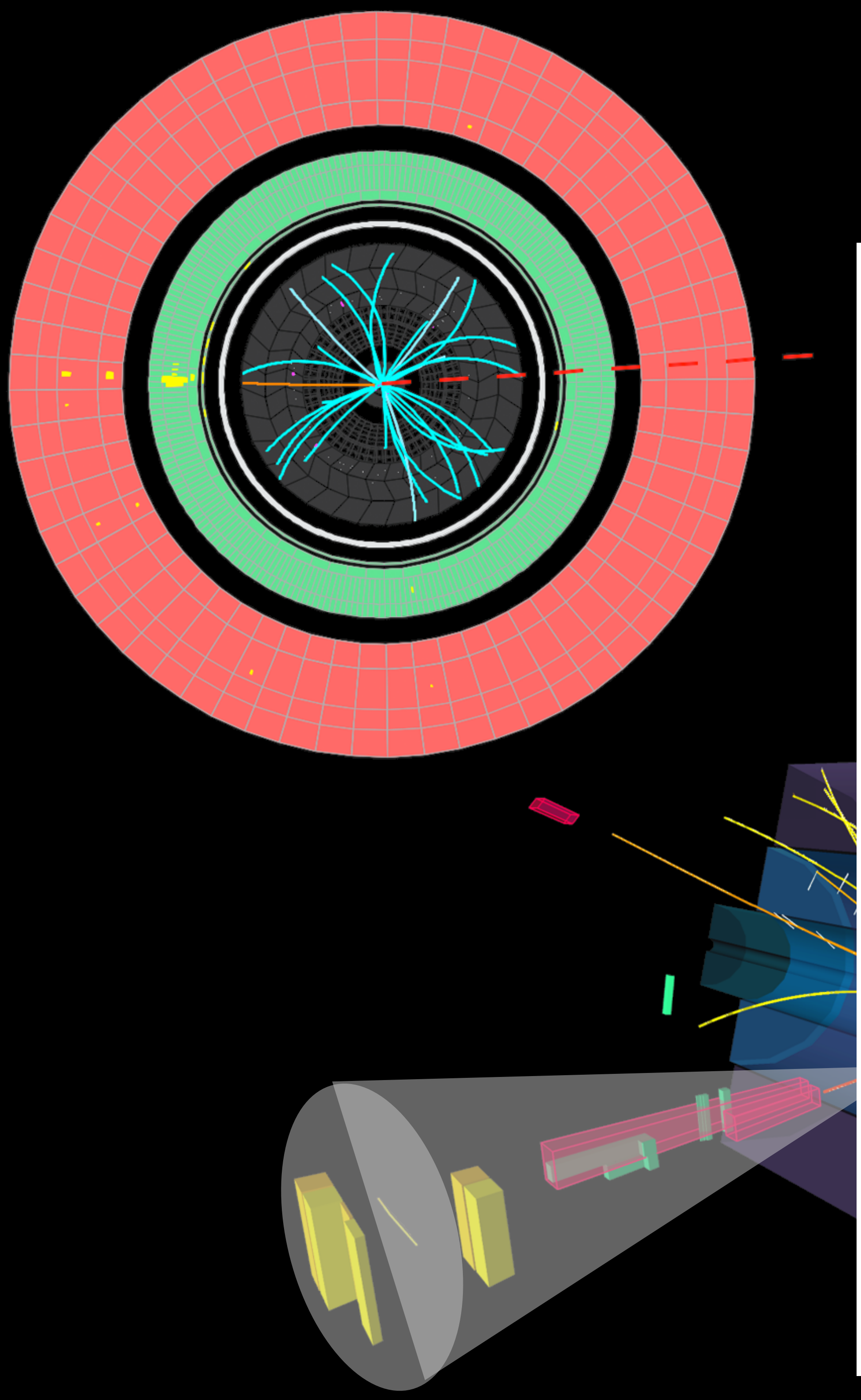
Pattern recognition algorithm connecting hits



Hadronic interactions in the tracking material (5% loss)



High p_T: Silicon hits merging (tracks too collimated)



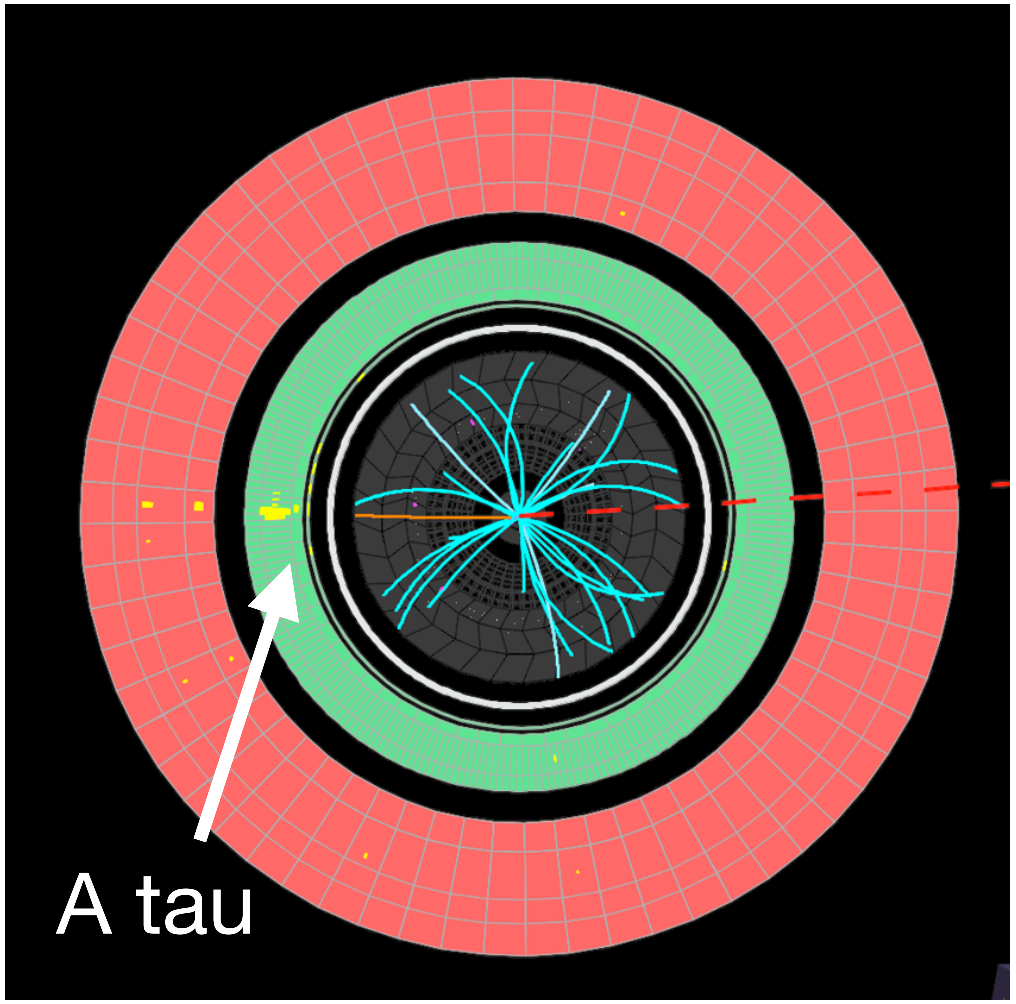
At this point we identified:

- An energy deposit in the calorimeters
- Tracks (charged particles)
- We connected them together

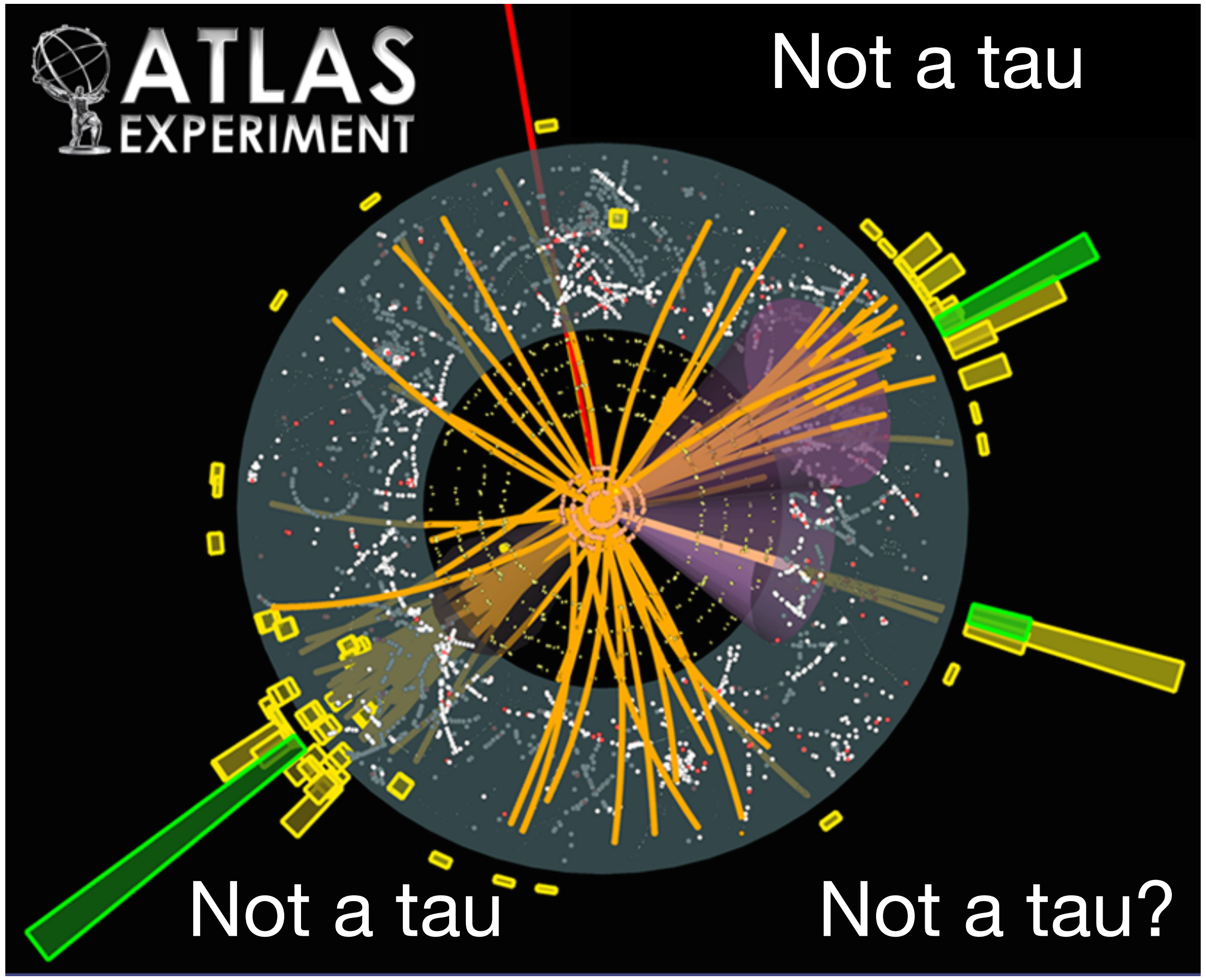
Can we see tau leptons?

The Large Hadron Collider

Event I've hand-picked



Typical LHC collision event



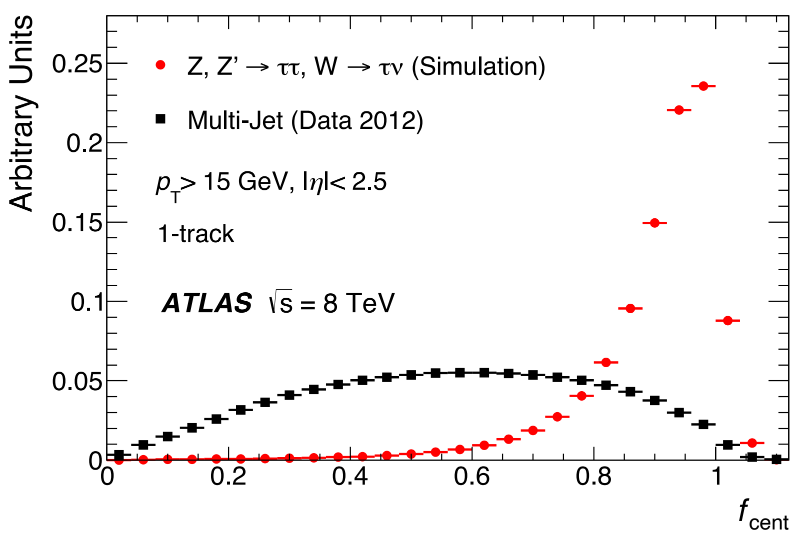
Is there a tau lepton in there?

Hard to tell… and not only because event displays are hard to interpret

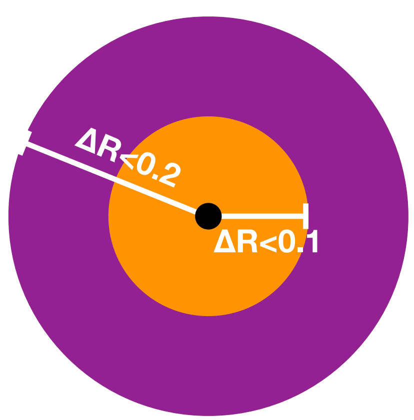
Harvest the information collected by the detectors

Developing ‘expert’ features

With the calorimeters

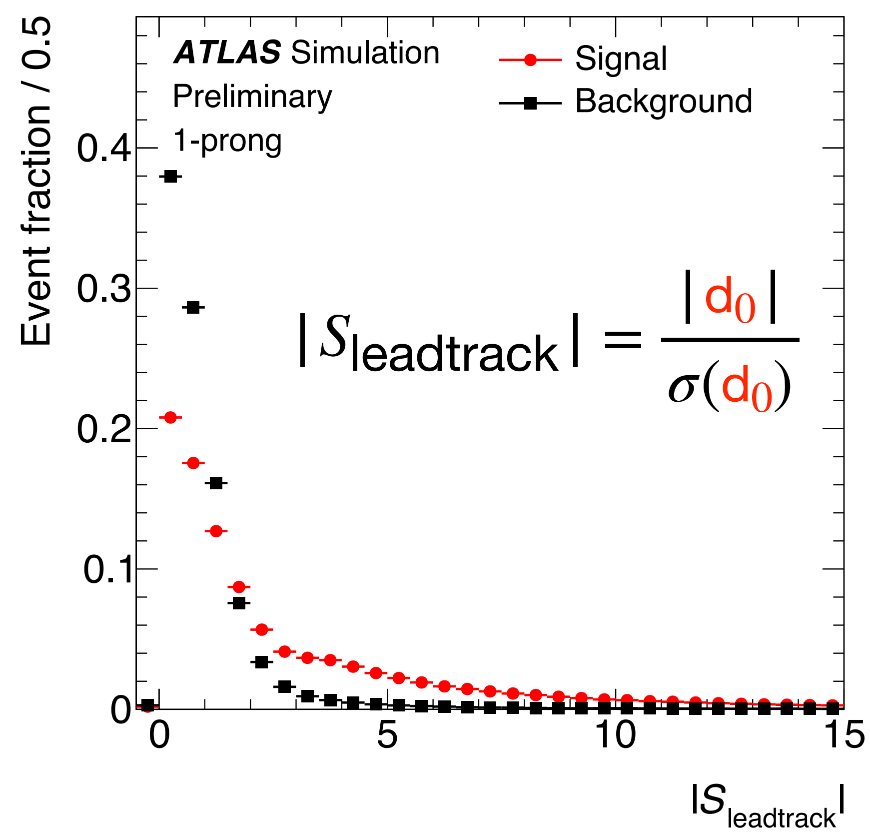


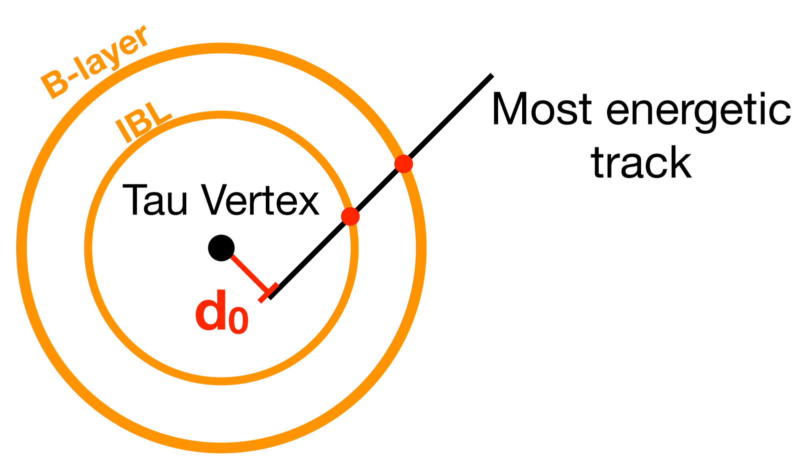
$$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$$



Energy ratio in the tau cone

With the tracker



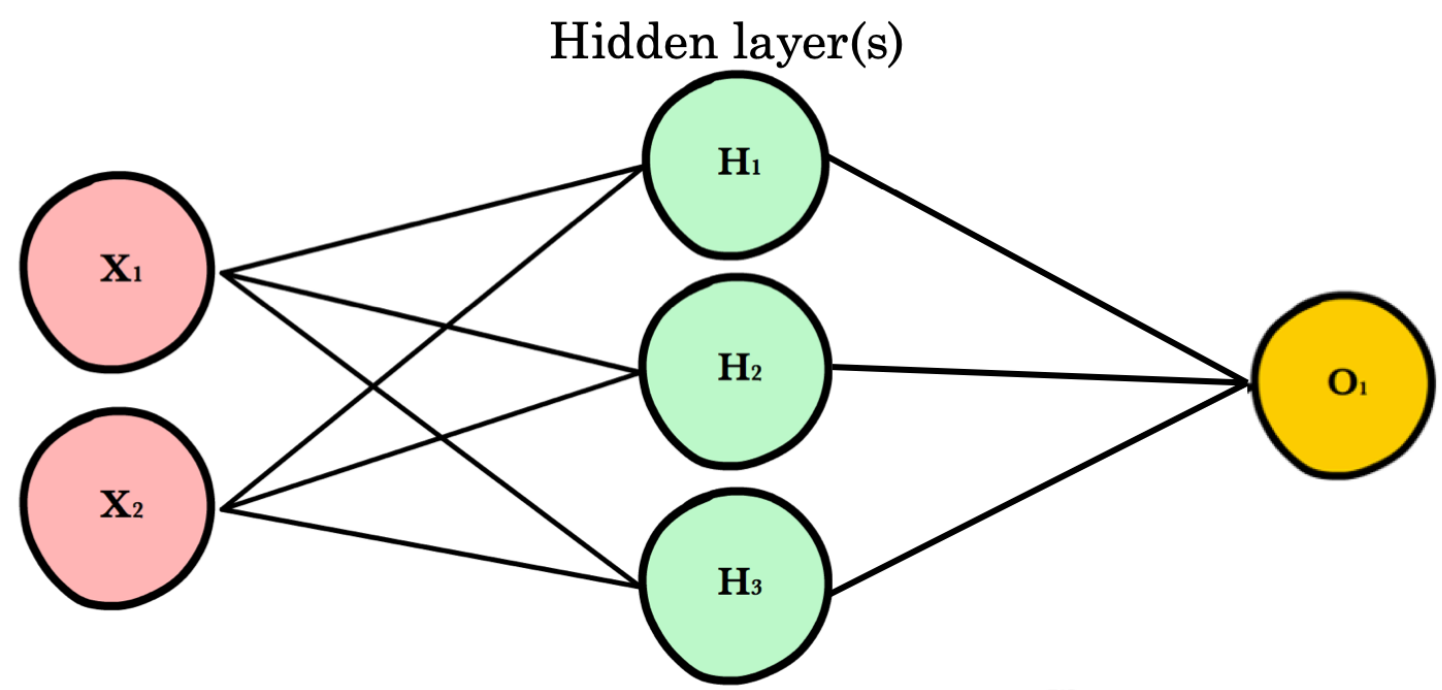


Track displacement

and combining the two detectors

Leveraging Deep-learning techniques

- Neural networks to design sophisticated model to extract as much as possible from the data



Source: ML Glossary, Forwardpropogation

Neural networks can approximate any function*

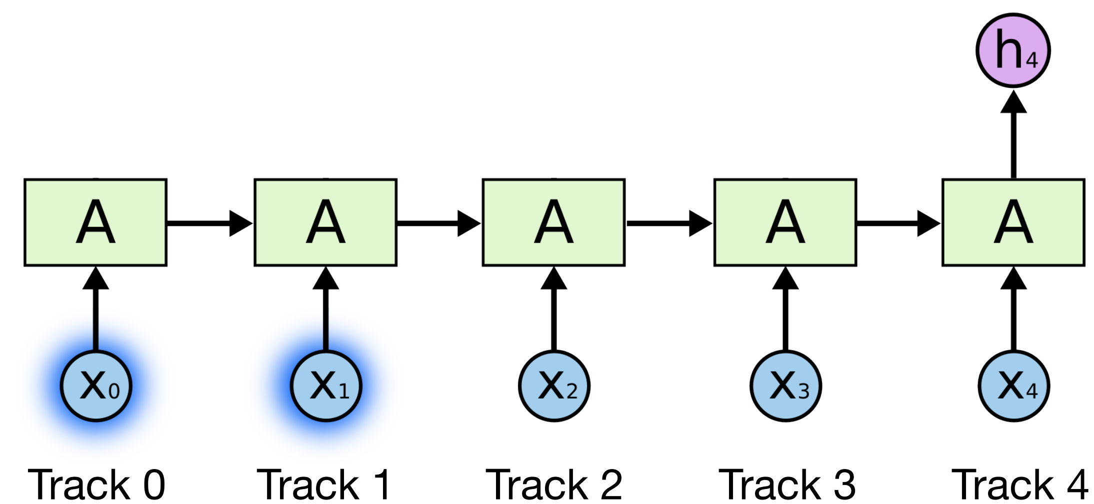
Powered by computing developments (GPUs)

* with the caveat you may need an infinite amount of nodes

Leveraging Deep-learning techniques

- Use information from tracks and clusters:
  - 4-vectors
  - shape and position characteristics
- Use a network architecture adequate to the problem:
  - Recurrent neural network
  - Correlate track-to-track (cluster-to-cluster) features for track (cluster) pair combinations

Output keeps some memory of all the tracks

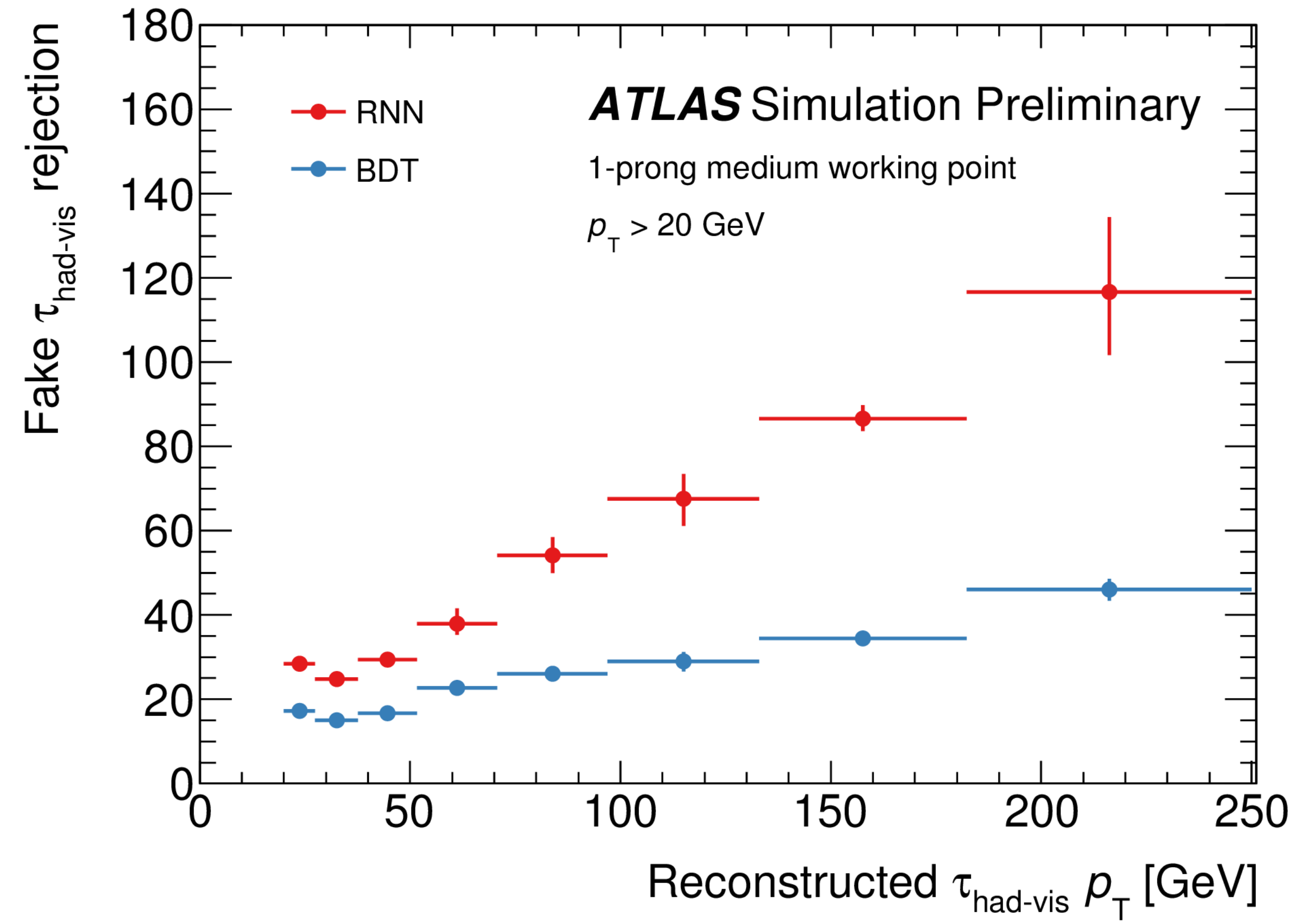


Hidden cell A gets updated sequentially after each element of the sequence

When data is organized as sequences (i.e. set of particles), make the hidden layer aware of this structure

Leveraging Deep-learning techniques

- Previous technique (BDT):
  - Only uses expert features
- Recurrent Neural Network (RNN):
  - Expert features
  - Also include individual tracks and clusters from the tau cone
  - Outperforms the previous technique over the entire kinematic regime

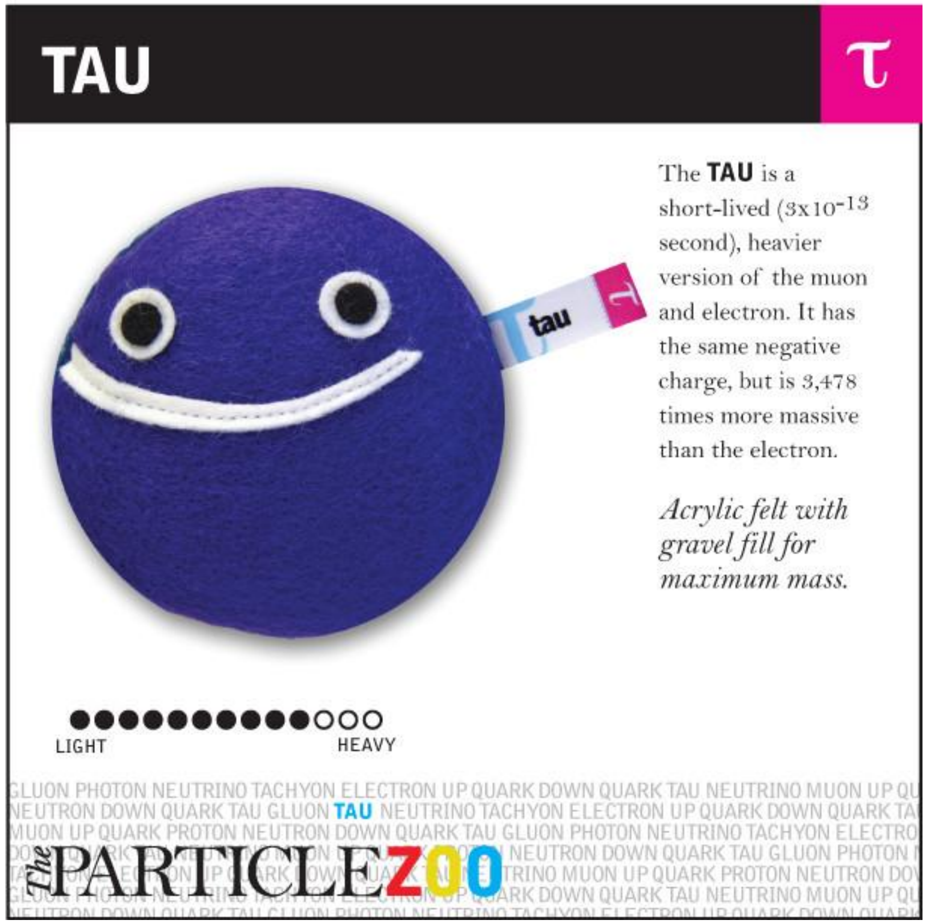


Typical rejection achieved

1 jet every 35 (240) gets mislabeled as 1-(3-)prong tau lepton

Leveraging deep learning techniques

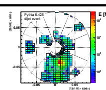
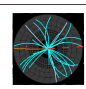
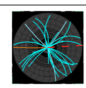
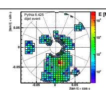
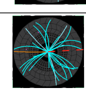
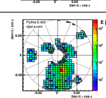
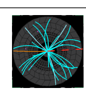
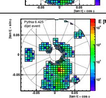
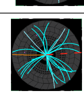
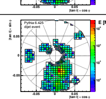
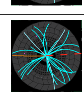
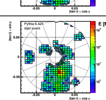
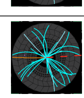
- By exploiting the full granularity of the ATLAS detector, we can build powerful discriminating variables to characterise the tau leptons
- Deep learning techniques bring a sizeable boost of performance
    - Decisive for the success of the measurement program!



Leveraging Deep-learning techniques

for many tasks…

Full list of algorithms used in ATLAS…

Step	Features			Algorithm type	Task
	Clusters and cells	Tracks	Expert features		
Seeding				Clustering + Anti-k_T	Identify the region of interest to collect tracks and clusters coming from a tau lepton
Track classification				Multiclass RNN	Label every track in the tau cone $\pi^\pm$, $e^\pm$, pile-up, fake
Vertex determination			$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$	Binary NN + expert variable ranking	Picks the most likely vertex the tau lepton decays originate from
Substructure			$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$	Binary BDT + clustering	Identify $\pi^\pm$ and π^0, assign the cell energies and determine the pions four-momenta
Tau Energy Scale			$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$	BRT	Calibrate the visible four-momentum of the tau lepton
Tau ID			$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$	Two binary RNNs	Score how likely a candidate is a tau lepton or a jet
Tau Decay Mode			$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$	Multiclass RNN	Label every tau lepton with a number of $\pi^\pm$ and a number of π^0
Electron veto			$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$	Two binary RNNs	Score how likely a candidate is a tau lepton or an electron

… Need to be retuning for each data-taking

ATLAS PUB Note

ATL-PHYS-PUB-2022-044

15th September 2022

Reconstruction, Identification, and Calibration of hadronically decaying tau leptons with the ATLAS detector for the LHC Run 3 and reprocessed Run 2 data

Most recent update

➡ Ongoing work to build a more holistic approach

What can we learn with taus at the LHC?

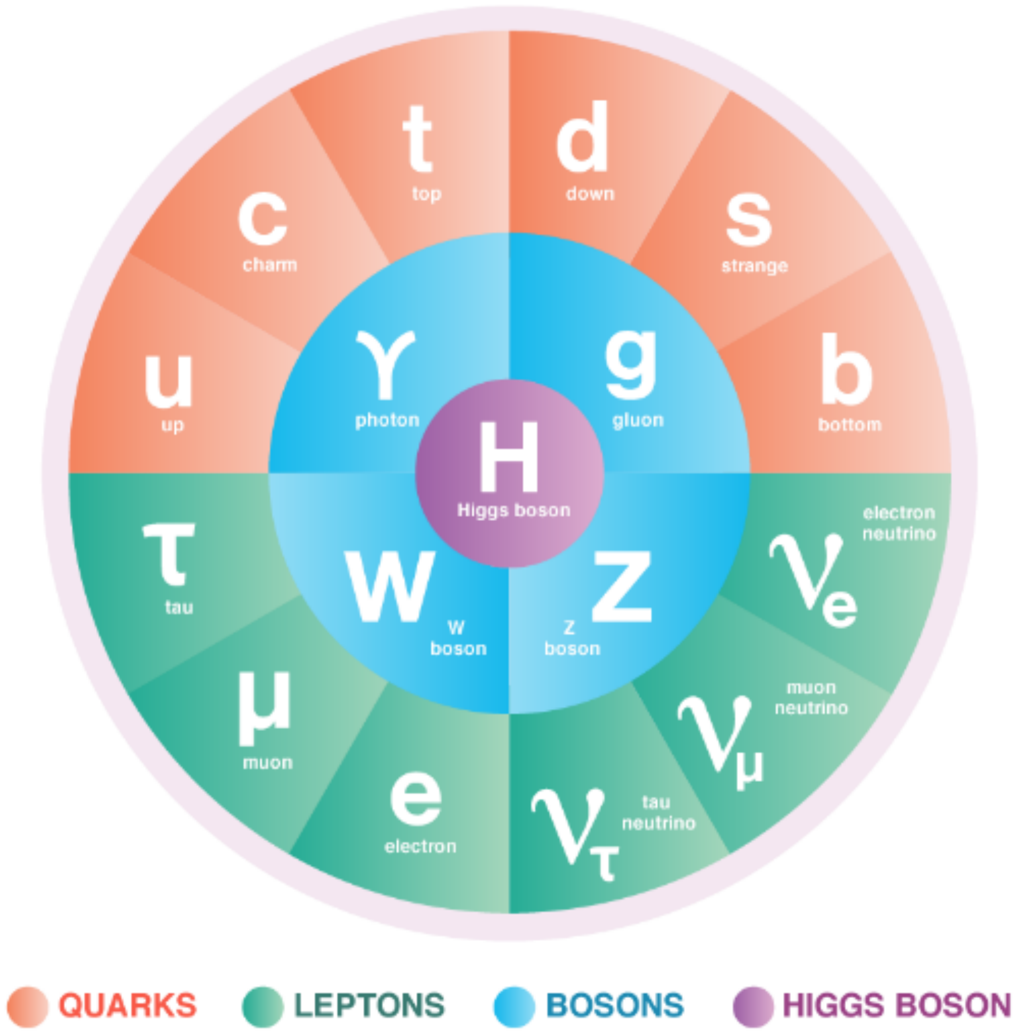
- Finding them in data
- **Higgs measurements**
- Studying them
- Future prospects

[Credit: PhD Comics]

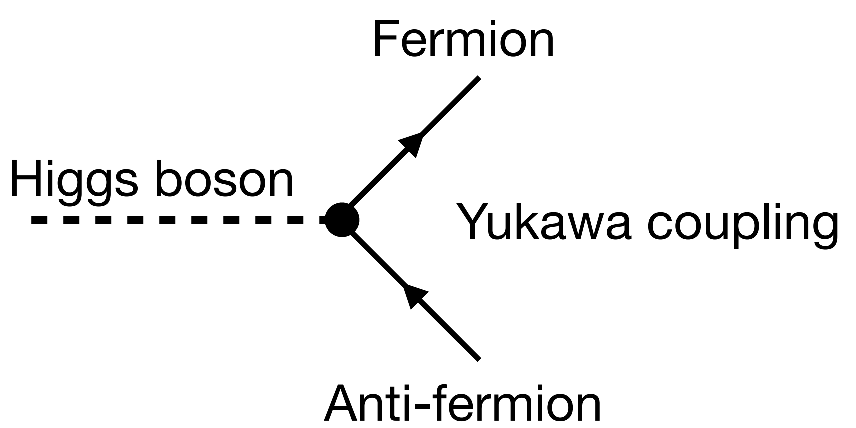
The Higgs boson

A scalar particle to complete the model

- Standard Model:
  - Elementary building blocks of matter and the interactions that govern them
- Higgs boson:
  - Only elementary scalar particle
  - Cornerstone of the standard model
- Scalar couplings to fermions is a new type of interaction



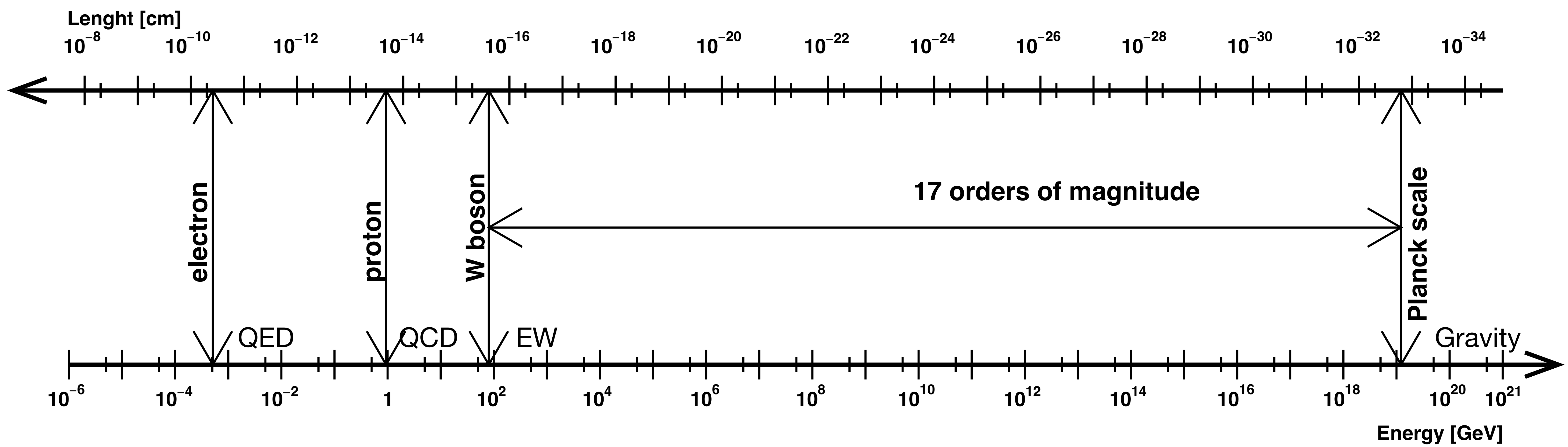
Elementary particles



The Higgs boson

is a great tool to search for BSM effects

[Credit: PhD Comics]



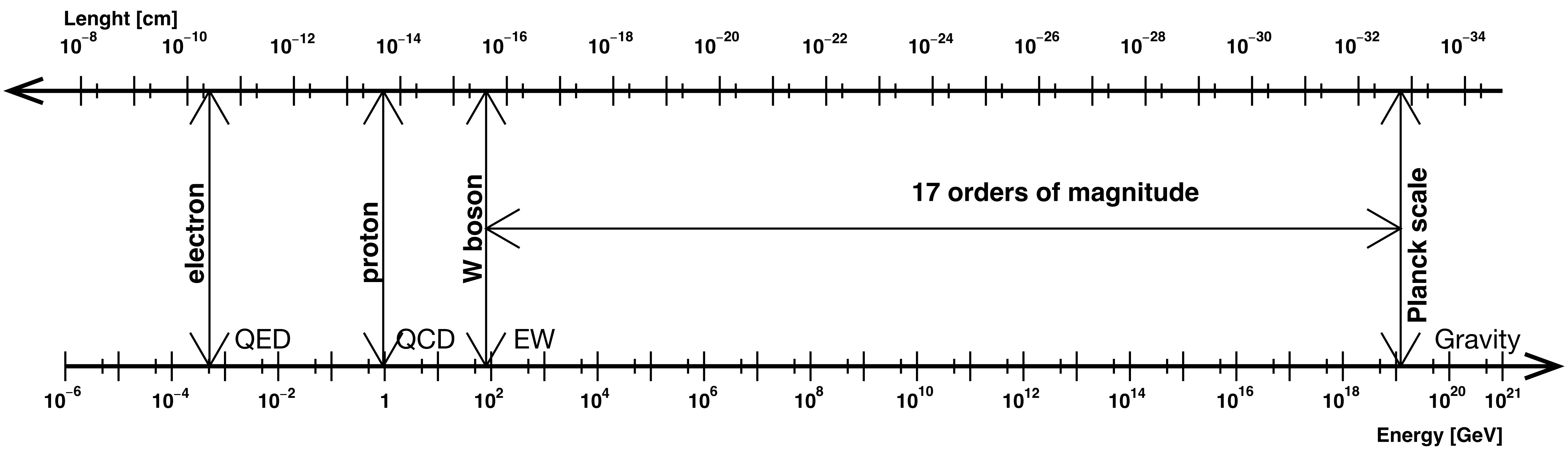
Known forces in Nature and their associated energy scale

- Standard Model: m_H has been determined → fully constrained theory
- Each Higgs measurement tests the model’s validity at higher energy scales through quantum corrections

The Higgs boson

is a great tool to search for BSM effects

[Credit: PhD Comics]



Known forces in Nature and their associated energy scale

Each measurement probes the presence of new physics beyond the EW scale

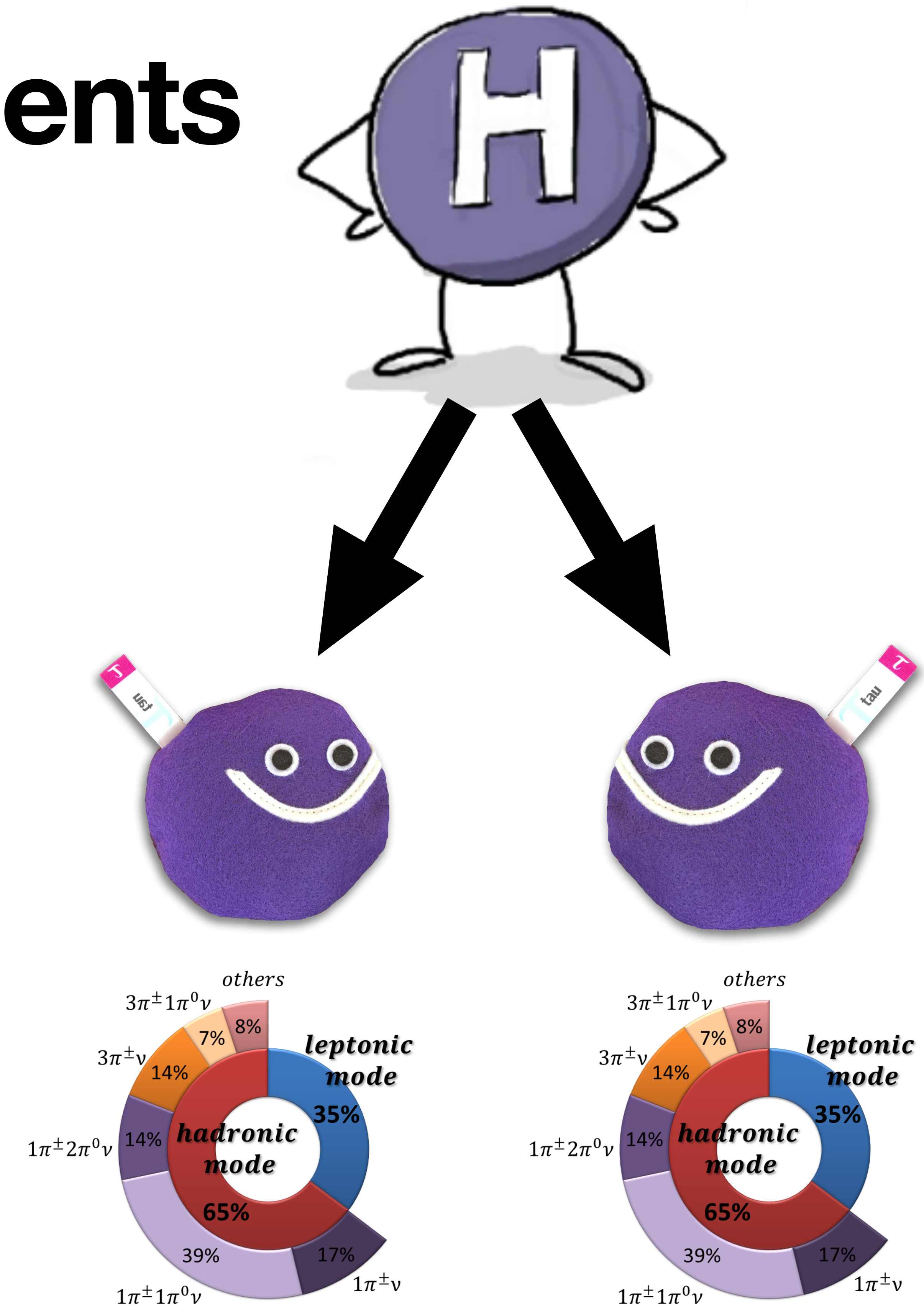
Higgs coupling Precision (%)	Probed Energy Scale
10	1-2 TeV
1	> 10 TeV

M. Peskin et al, Snowmass Summary Chapter

$H \to \tau\tau$ measurements

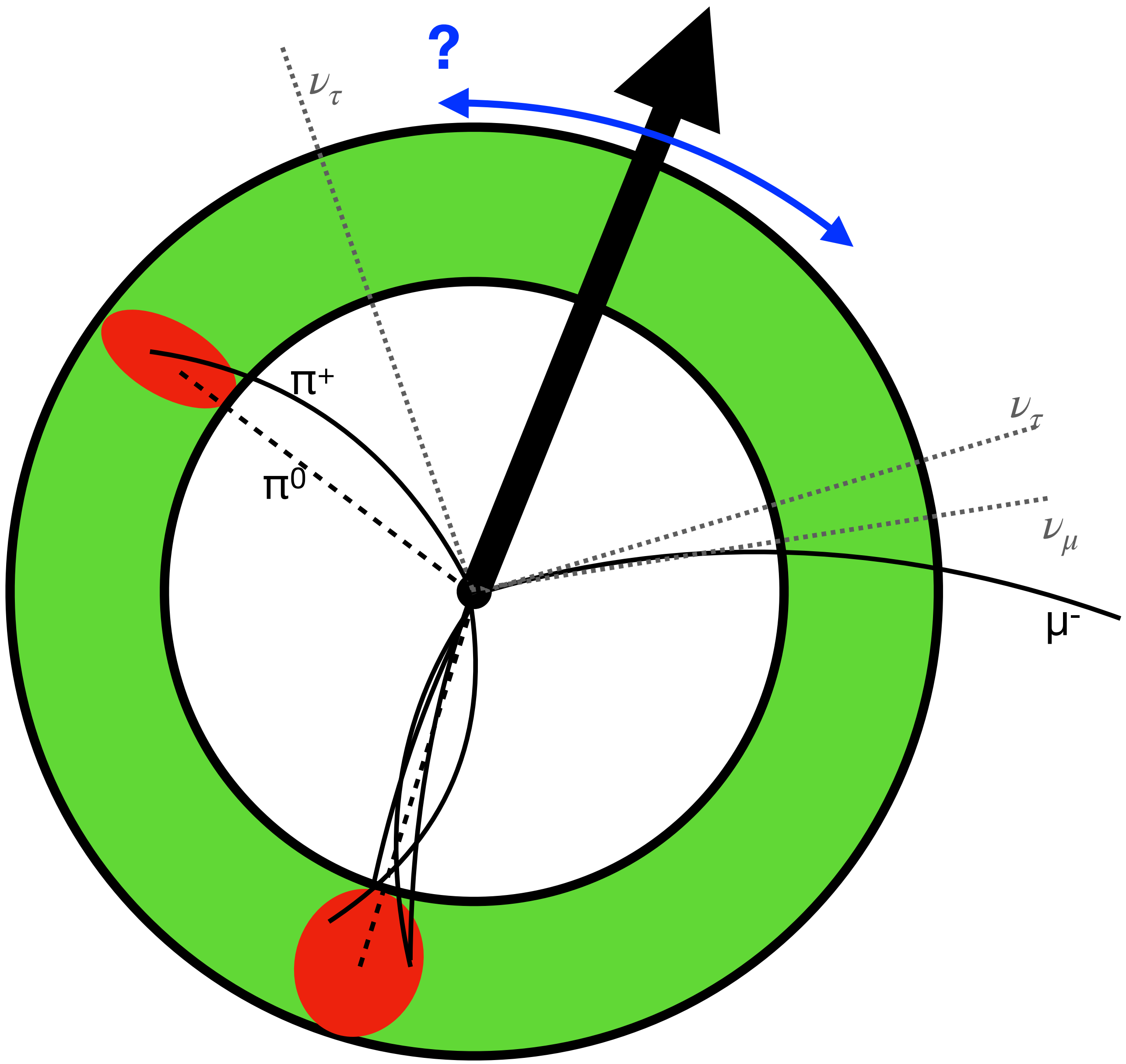
Data Analysis Workflow

1. Collect events with targeted final states
    - One electron and one muon
    - One lepton and one hadronic tau
    - Two hadronic taus
2. **Reconstruct the Higgs candidate from the visible decay products**

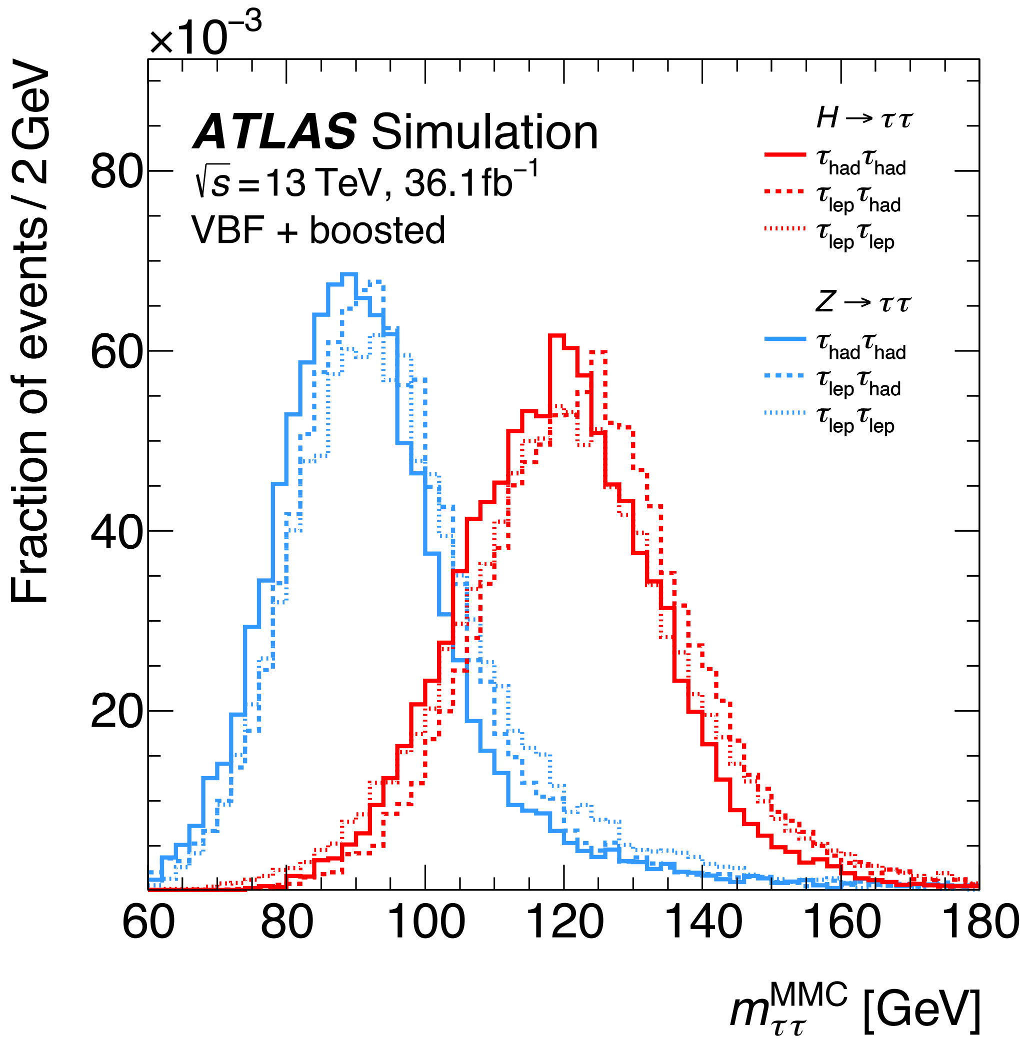


Estimate the Higgs 4-vector

Data Analysis Key Feature



Probabilistic estimate of the Higgs 4-vector for each event



LHC: momentum conservation in the transverse plane

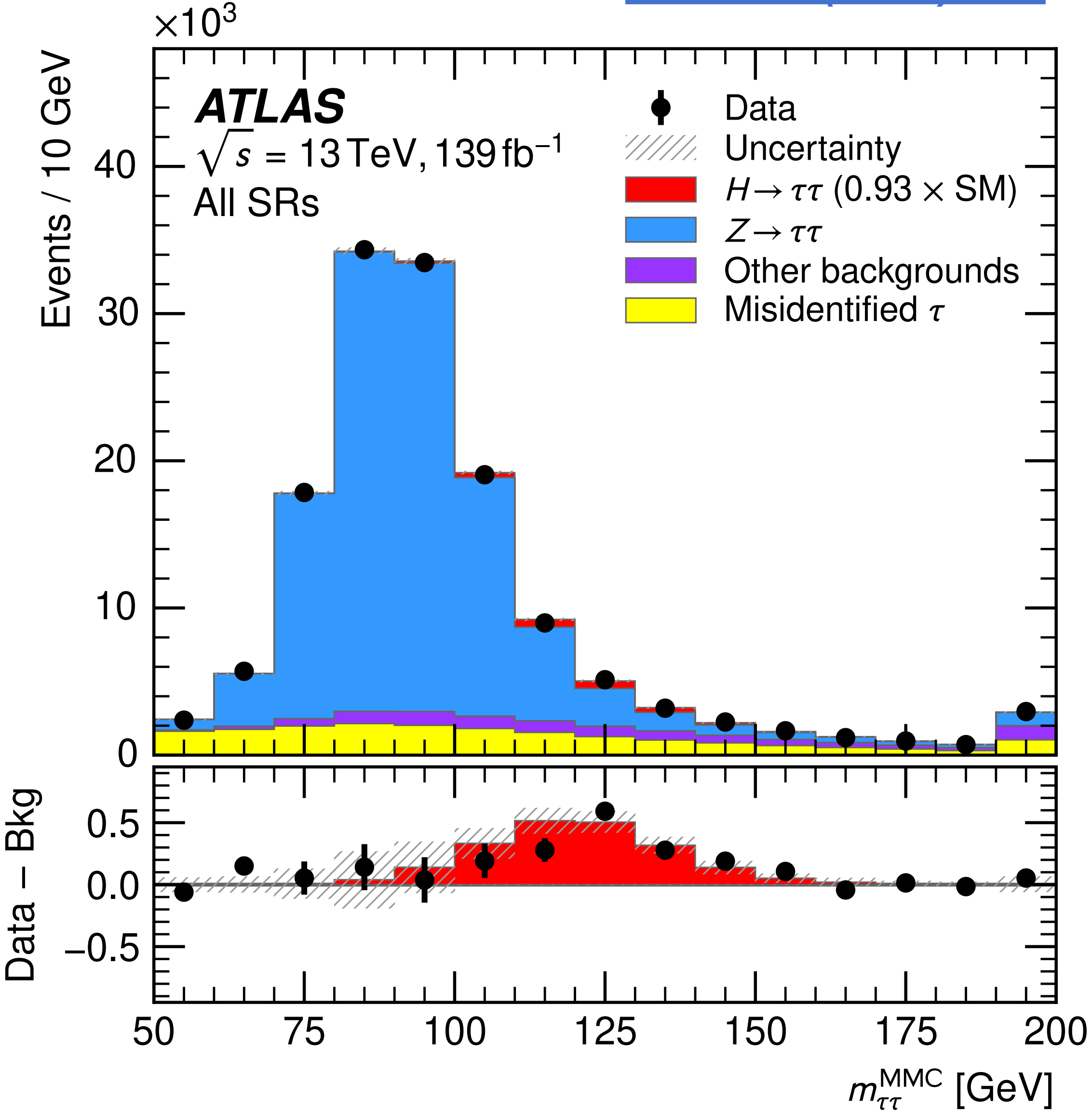
$H \to \tau\tau$ measurements

Data Analysis Workflow

1. Collect events with targeted final states
   - One electron and one muon
   - One lepton and one hadronic tau
   - Two hadronic taus
2. Reconstruct the Higgs candidate from the visible decay products
3. **Precisely estimate the background expectations**

After topologic cuts and tau quality criteria are applied: $Z \to \tau^+\tau^-$ events are the dominant remaining background

JHEP 08 (2022) 175

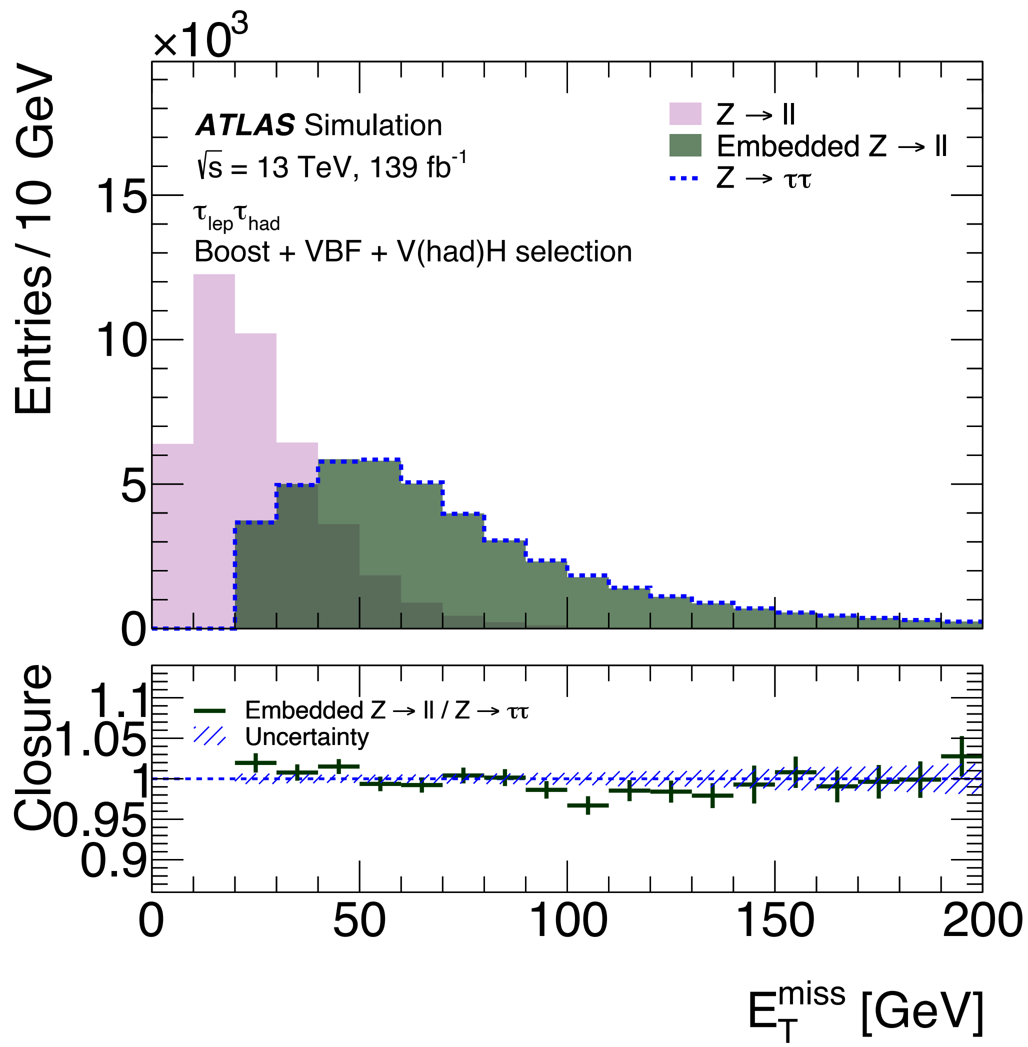


Per event estimator of the mass of the Higgs boson

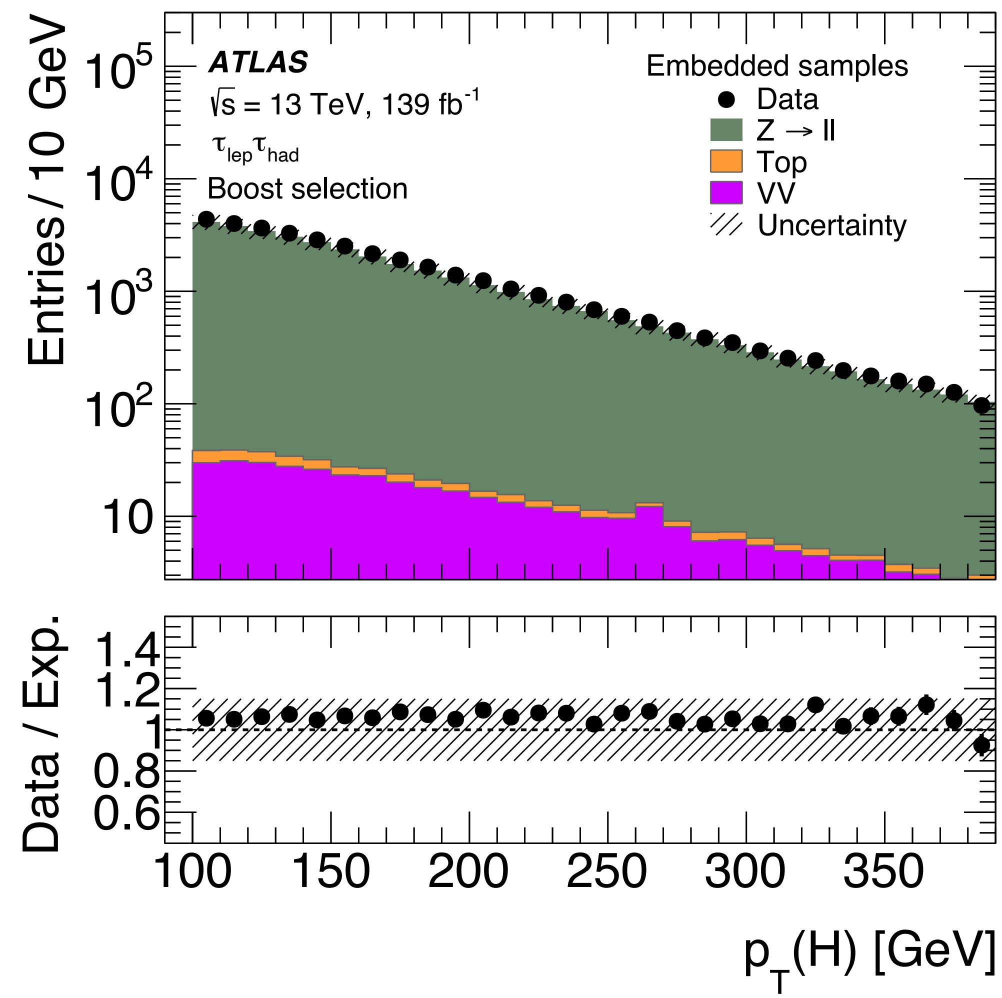
Embedding procedure

Data Analysis Key Features

- Model $Z \to \tau^+\tau^-$ with large and clean samples of $Z \to \ell^+\ell^-$ events
- Remove light leptons, add tau lepton decays, recompute the kinematics of the entire event



Emulate presence of missing energy in $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events

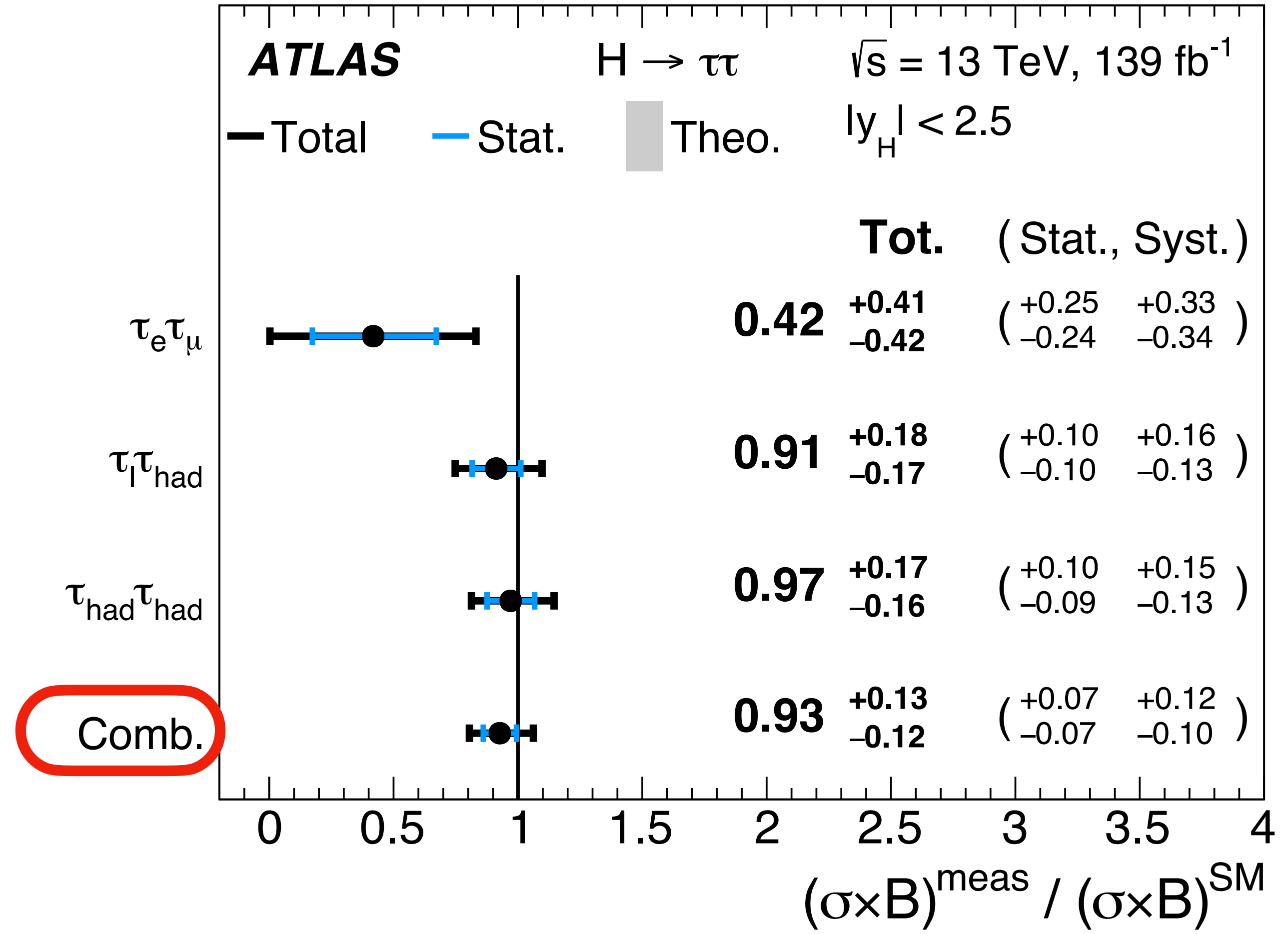


Verify simulations in the phase space of the analysis

$H \to \tau\tau$ measurements

Results

1. Collect events with targeted final states
    - One electron and one muon
    - One lepton and one hadronic tau
    - Two hadronic taus
2. Reconstruct the Higgs candidate from the visible decay products
3. Precisely estimate the background expectations
4. **Extract the parameters of interest using a templated fit of the Higgs boson mass estimator**



Achieved a precision of 13%

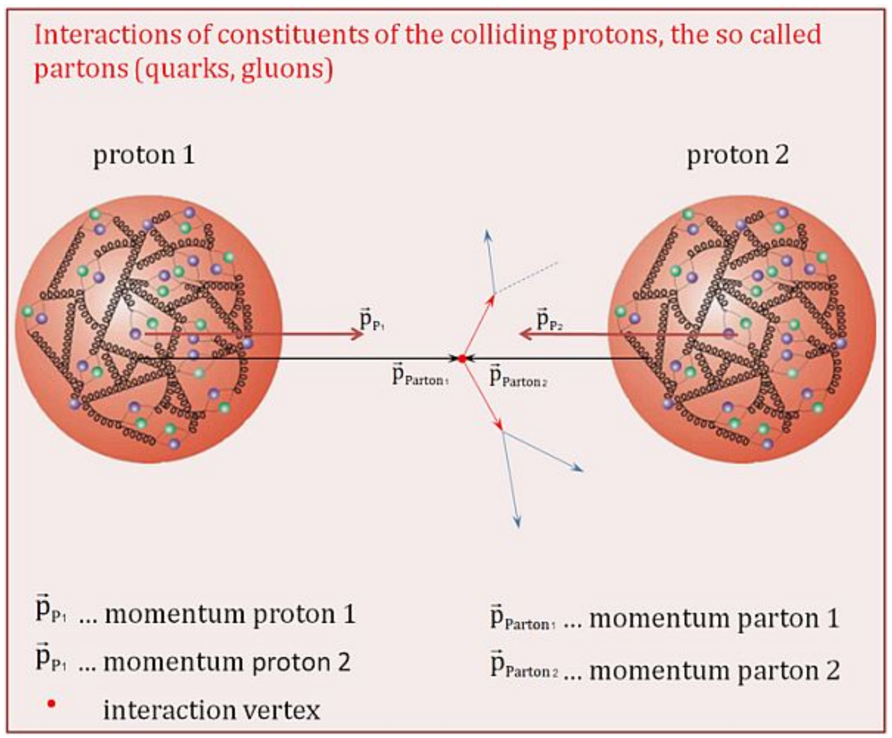
Extremely robust measurement with excellent statistical compatibility across final states

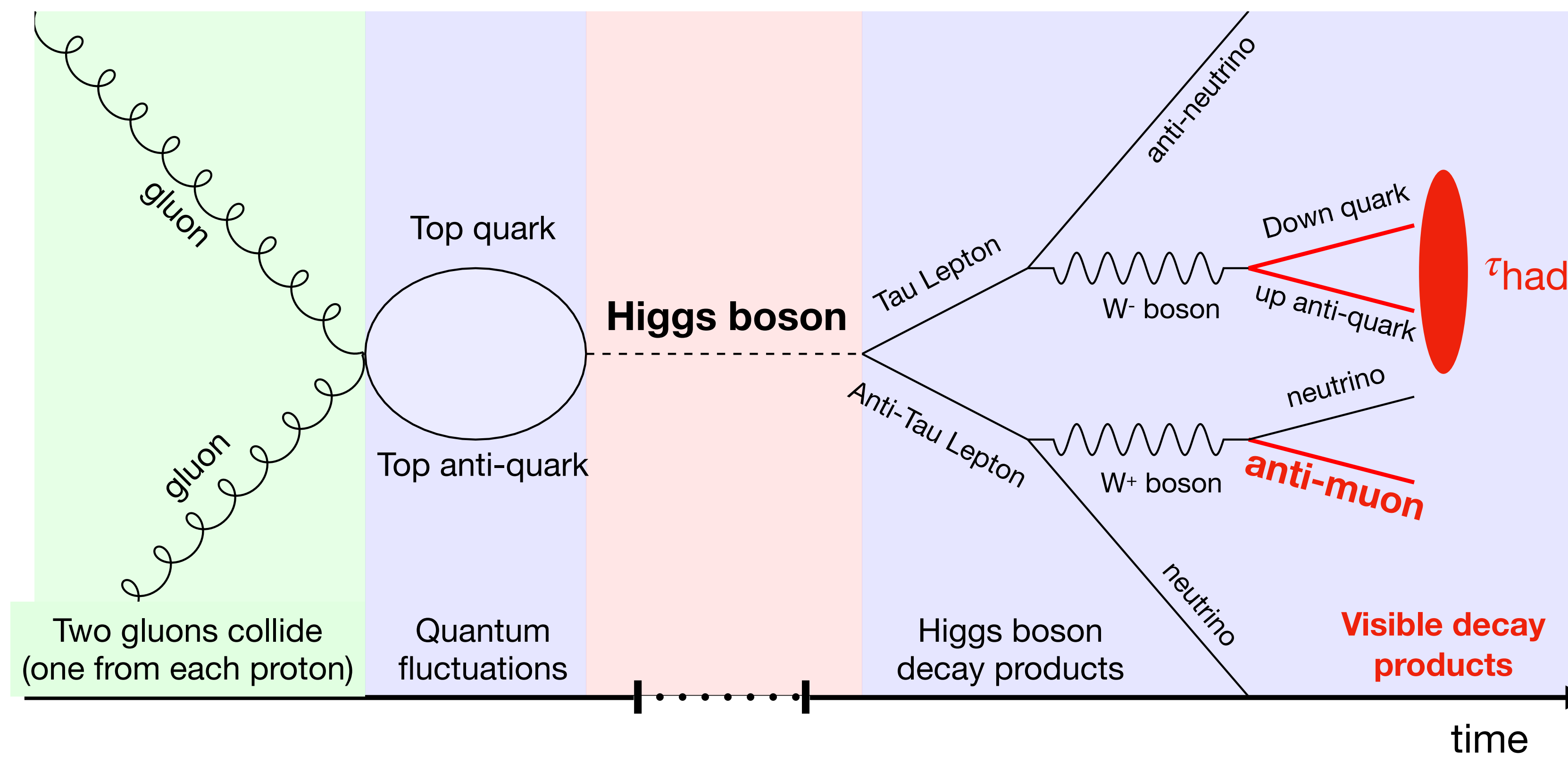
$p_{SM} = 58\%$

Higgs boson measurements

At the LHC

Only the product of production and decay couplings can be measured



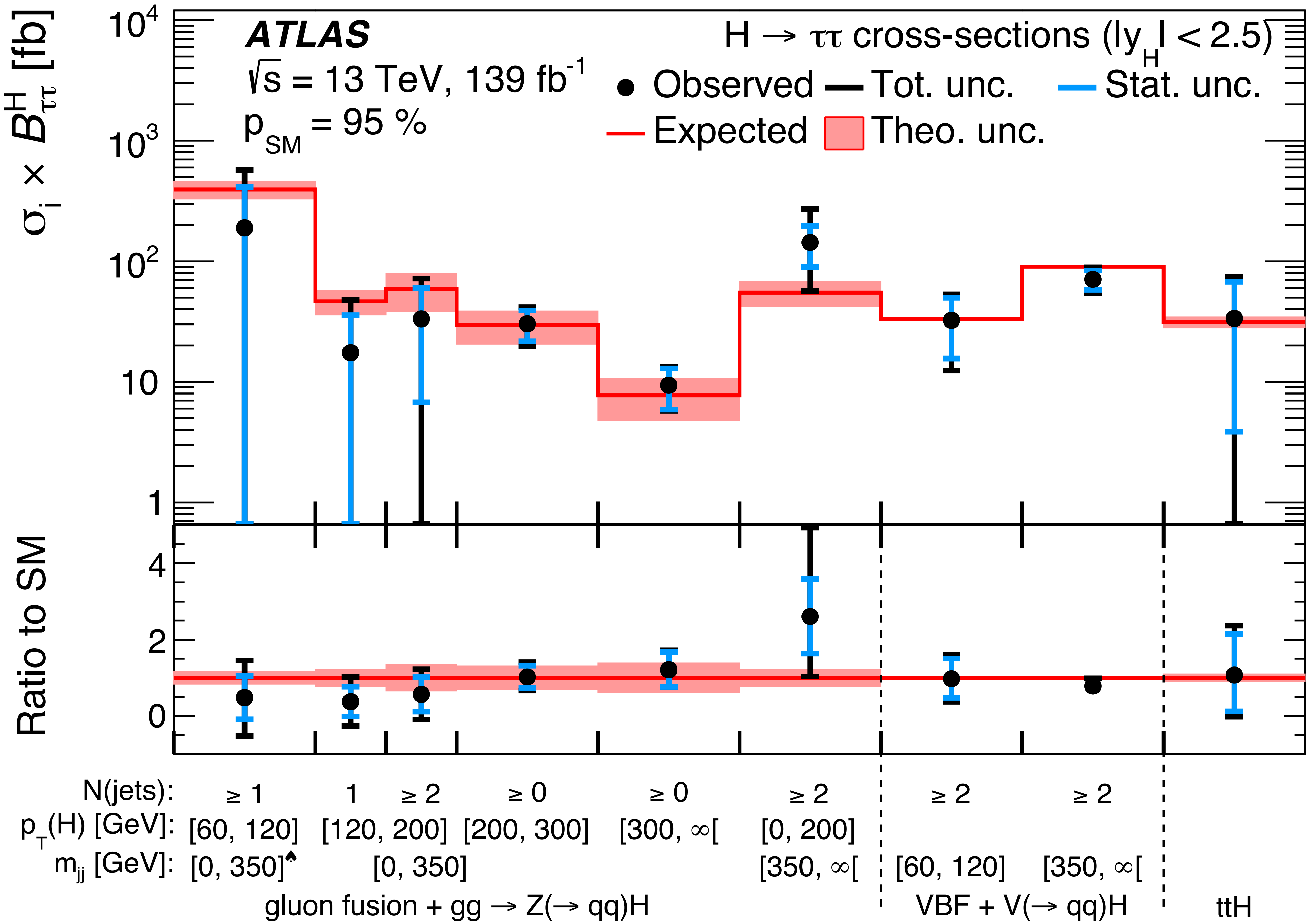


$$\approx (Y_t \cdot Y_\tau)^2$$

We study as many production and decay modes as possible
as they offer complimentary sensitivities

Results

Cross-section measurements in the STXS framework

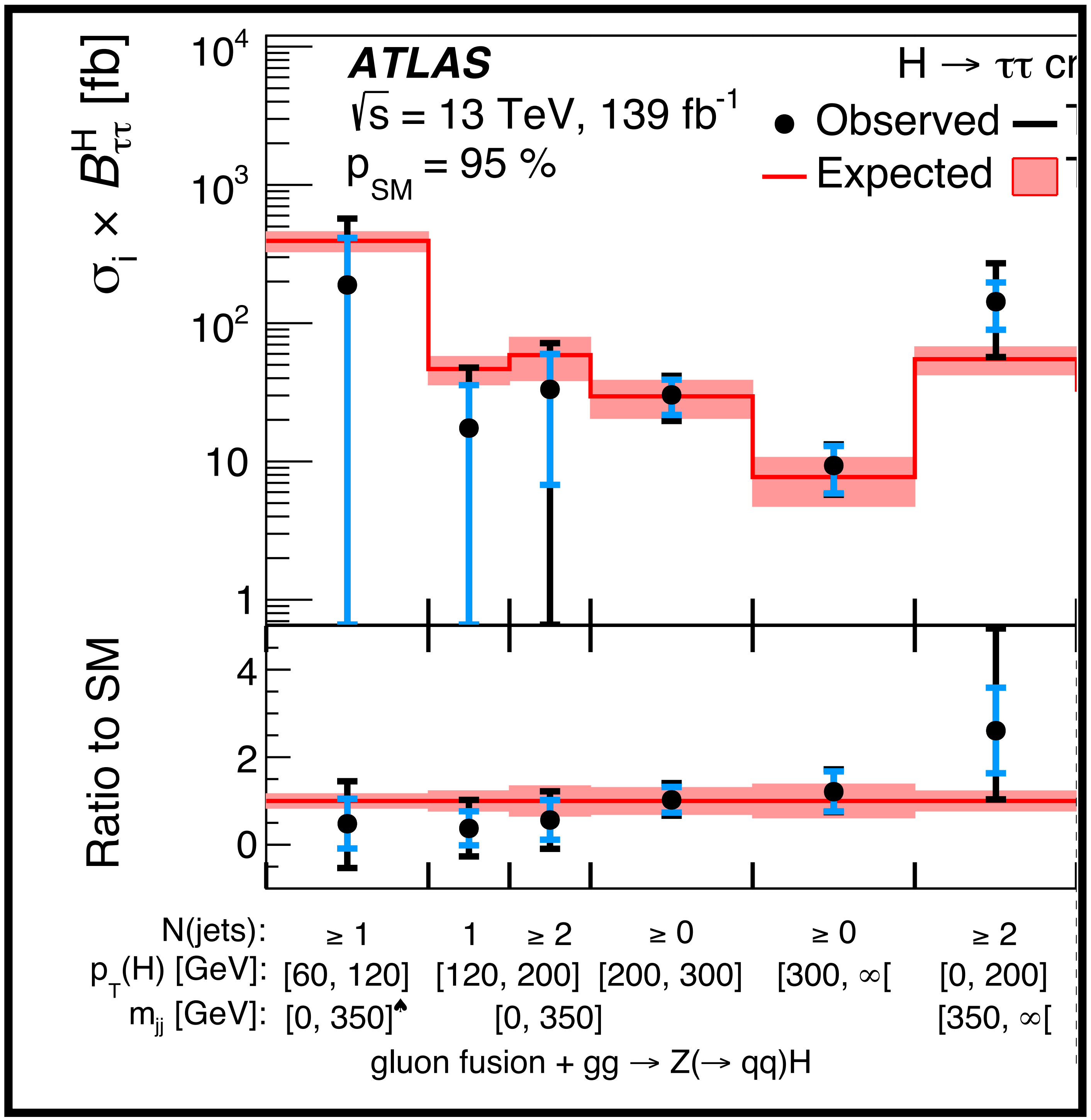


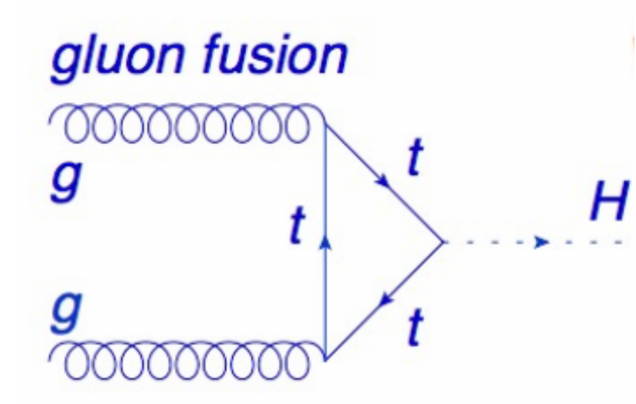
Explore kinematics of the Higgs boson in the four main production modes

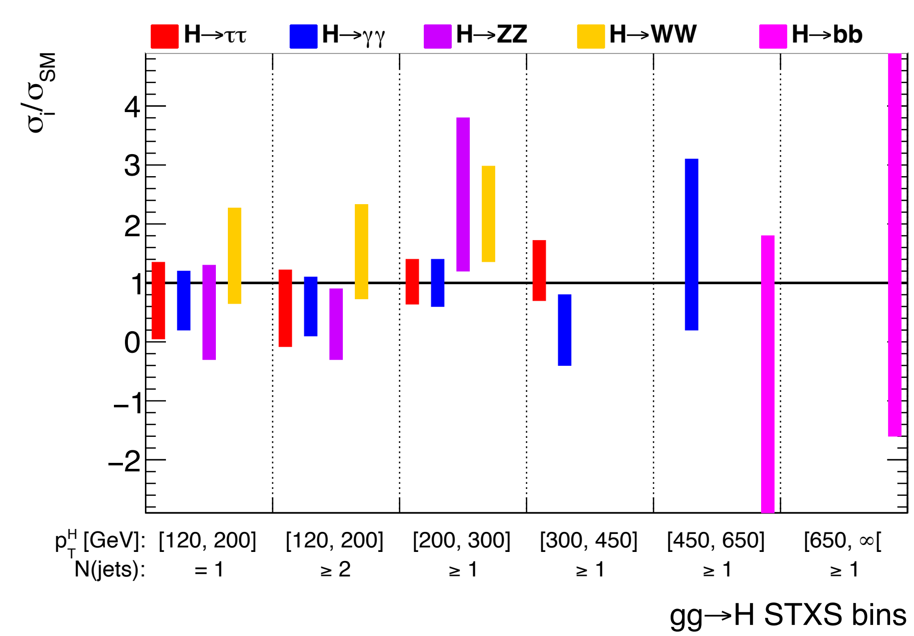
Enhance sensitivity to new physics by studying events with high momentum transfer

Results

Cross-section measurements in the STXS framework





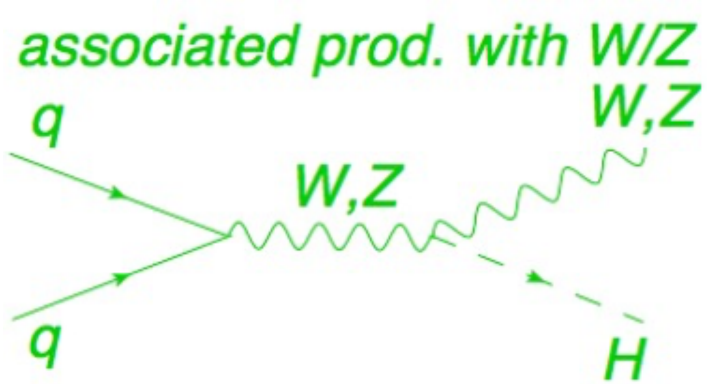


Most sensitive channel for $200 < p_T(H) < 450$
(around the Top quark loop threshold)

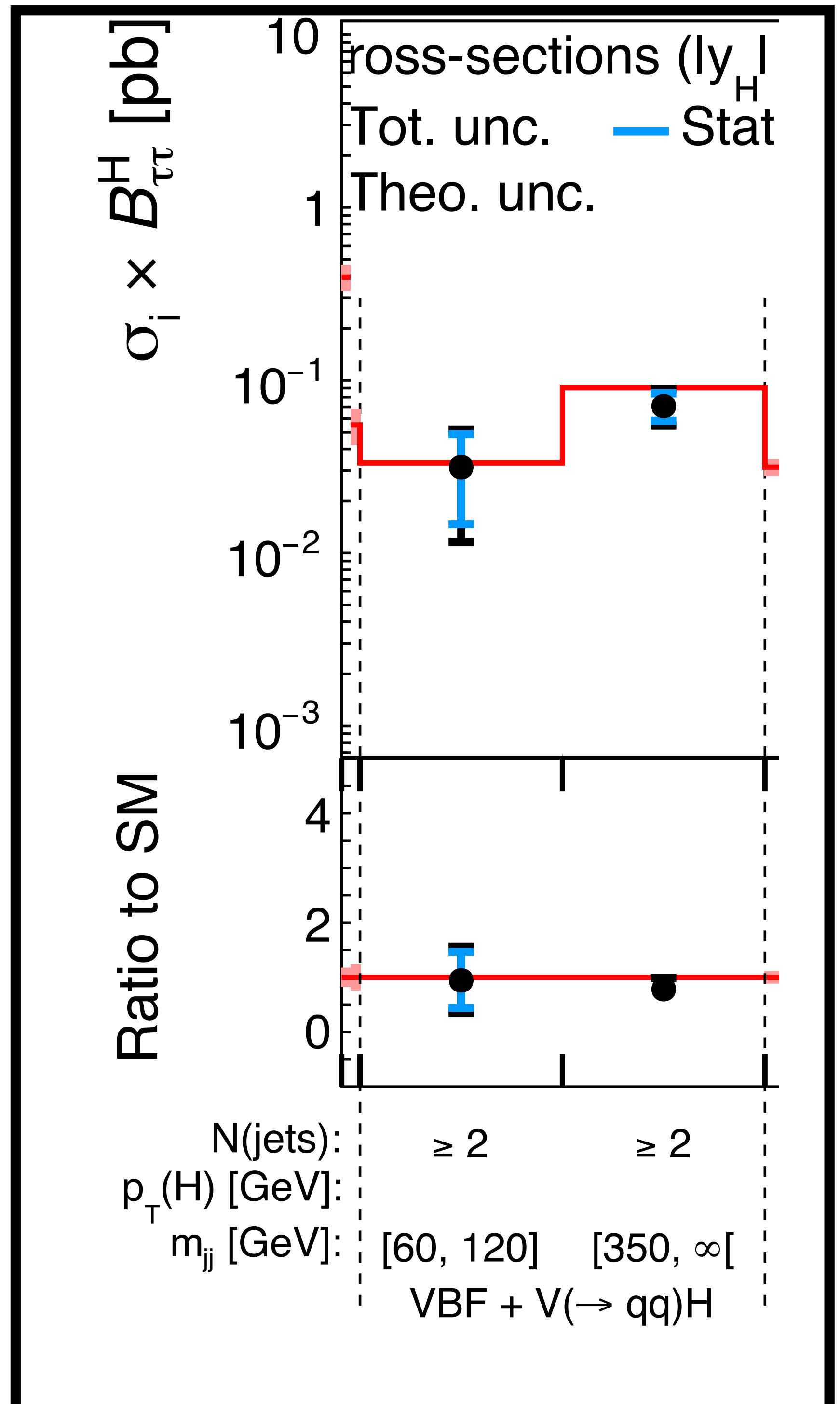
Ongoing effort to extend the measurement to higher $p_T(H)$

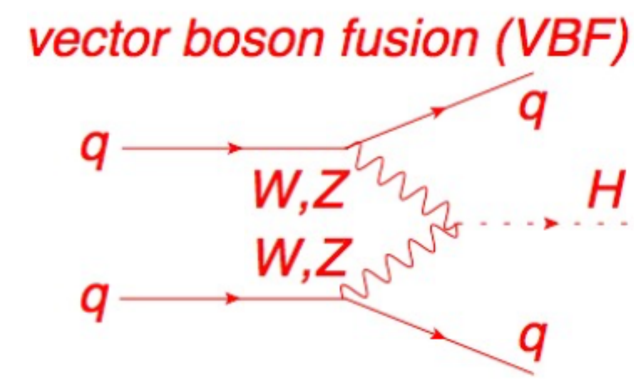
Results

Cross-section measurements in the STXS framework



First measurement dedicated to the V(had) final state



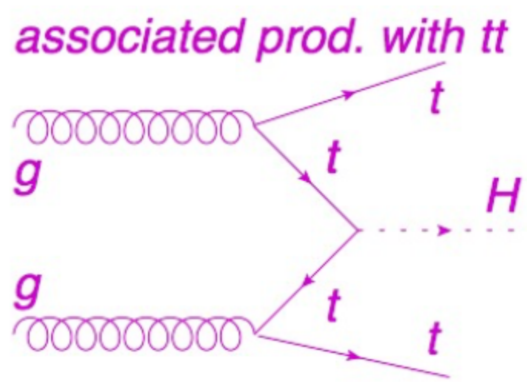


VBF with $m_{jj} > 350$ GeV is the most sensitive phase of the analysis

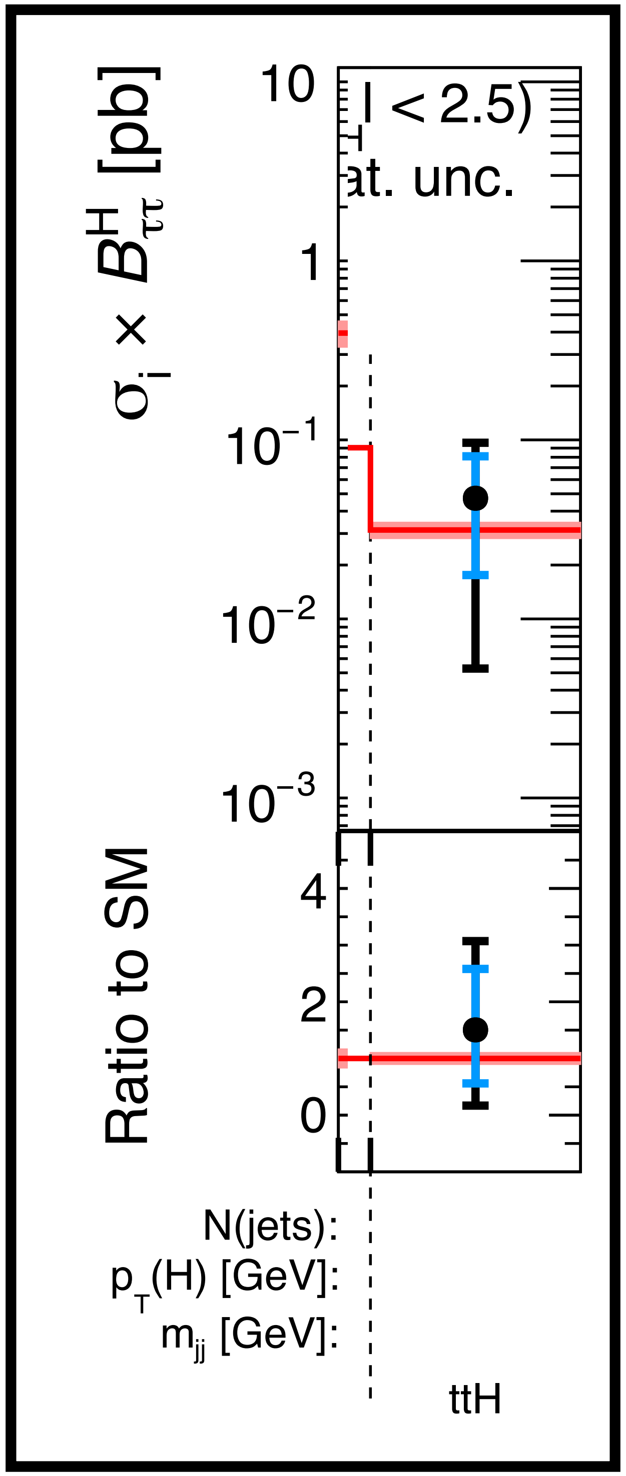
Ongoing effort to extend the measurement to study the Higgs production versus m_{jj}

Results

Cross-section measurements in the STXS framework



$t\bar{t}(0\ell)H(\tau_{\mathrm{had}}\tau_{\mathrm{had}})$



New channel explored

Fully hadronic final state offers the opportunity to measure $p_T(H)$ in the ttH production mode

$H \rightarrow \tau\tau$ measurements

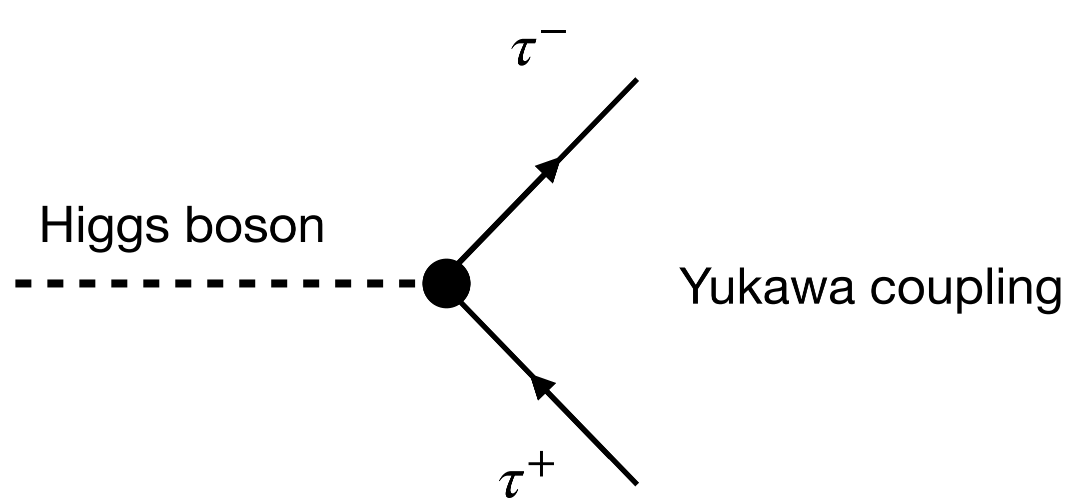
Summary

1. $\sigma(\text{pp} \rightarrow H \rightarrow \tau^+\tau^-)$ measured with 13% precision

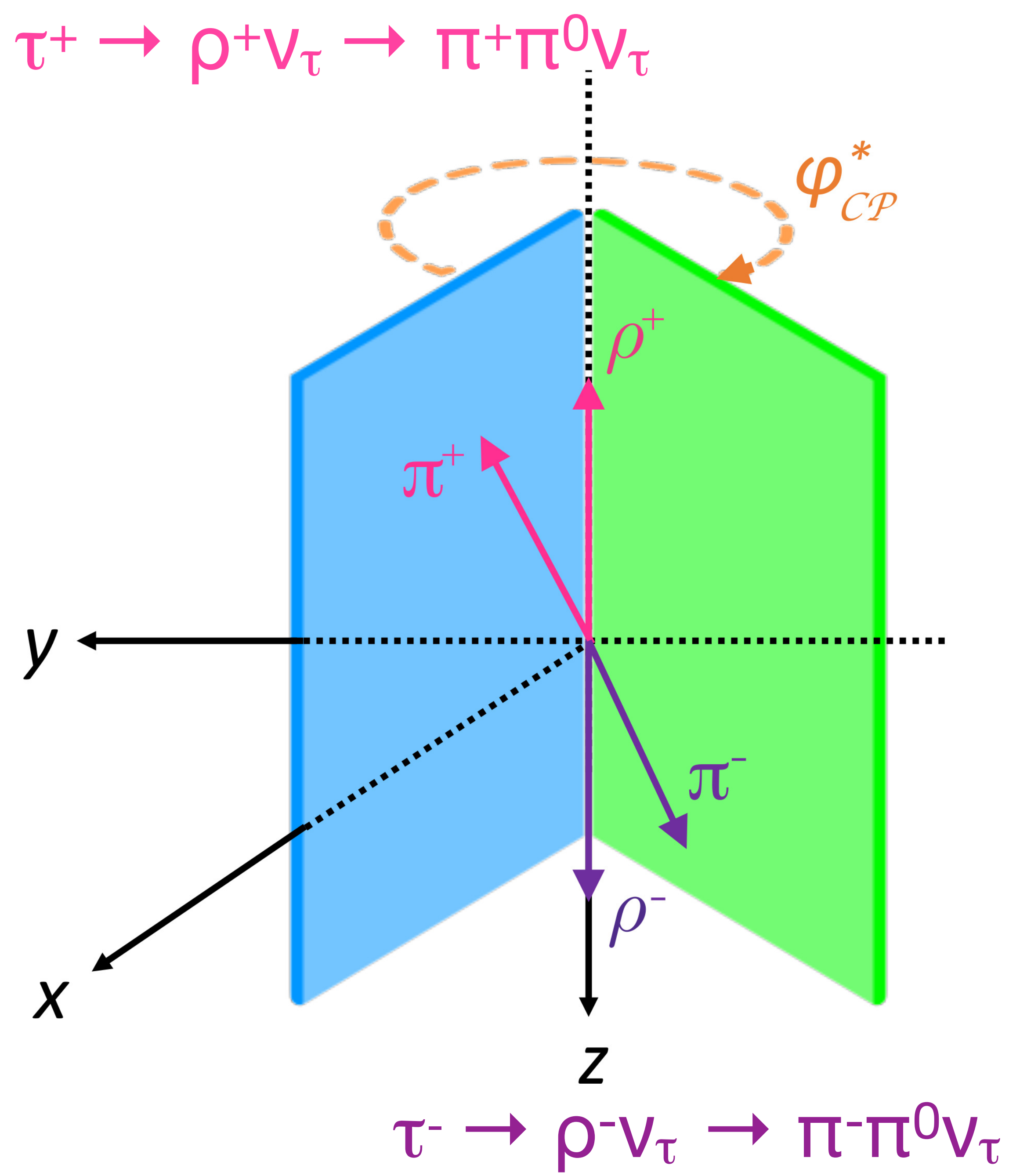
2. Probe the four dominant production modes

3. Comprehensive exploration of the kinematic properties of the Higgs boson

- What else can we tell about the $H \rightarrow \tau^+\tau^-$ vertex?



CP properties of $H \to \tau\tau$ vertex



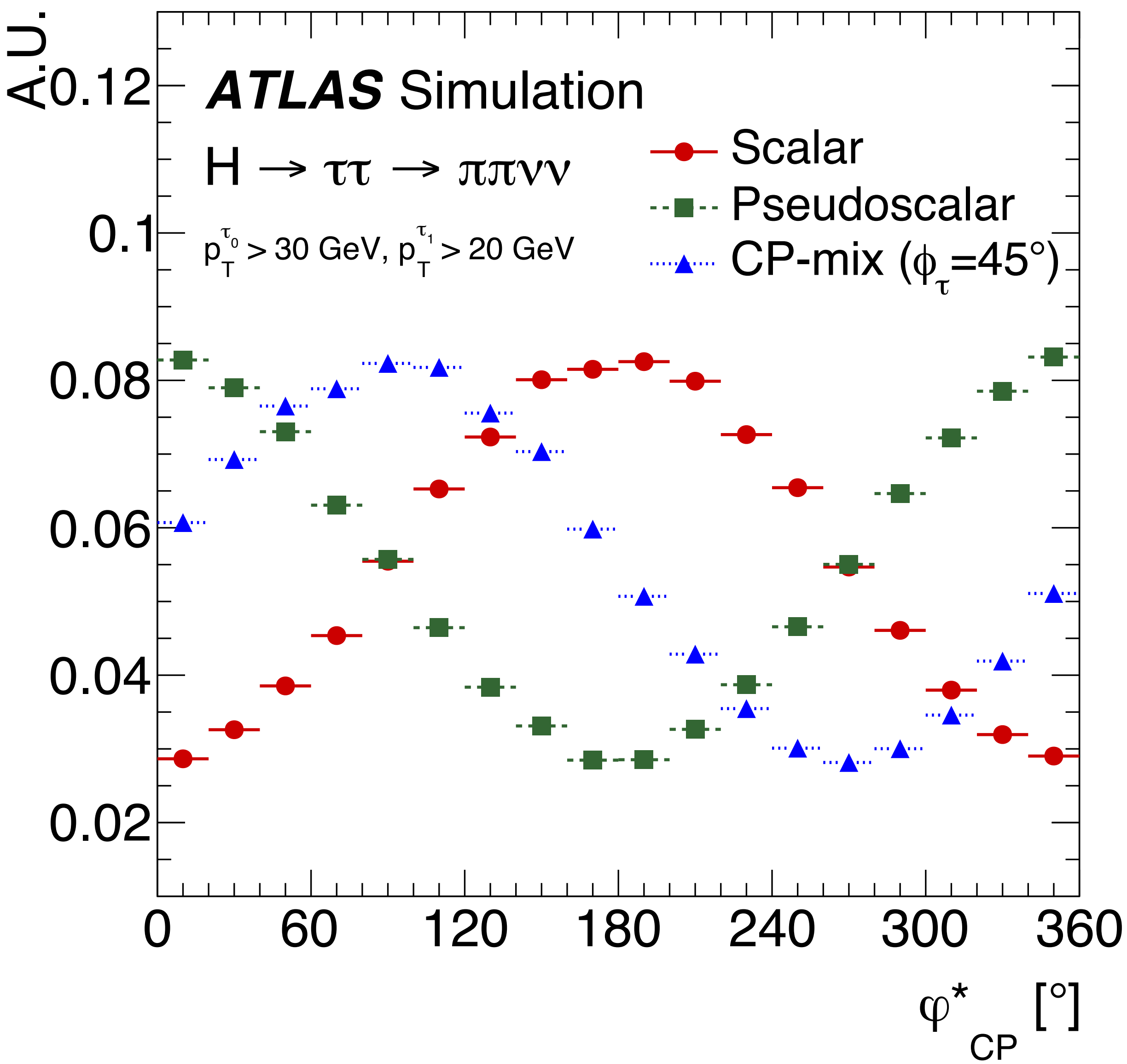
ϕ^*_{CP} is sensitivity to the Higgs CP properties through the tau polarizations

CP properties of $H \rightarrow \tau\tau$ vertex

Scalar → CP-even (SM)

Pseudo-scalar → CP-odd

CP-mix → Mixture of two states



CP properties of $H \to \tau\tau$ vertex

Scalar → CP-even (SM)

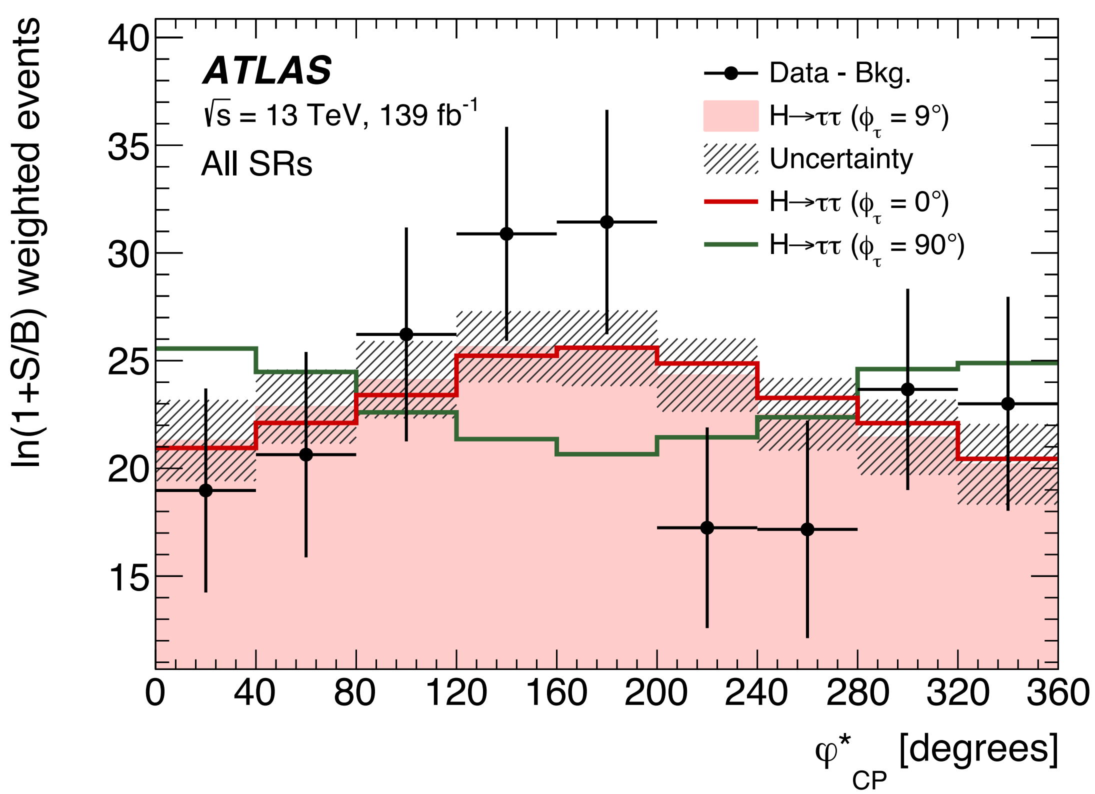
Pseudo-scalar → CP-odd

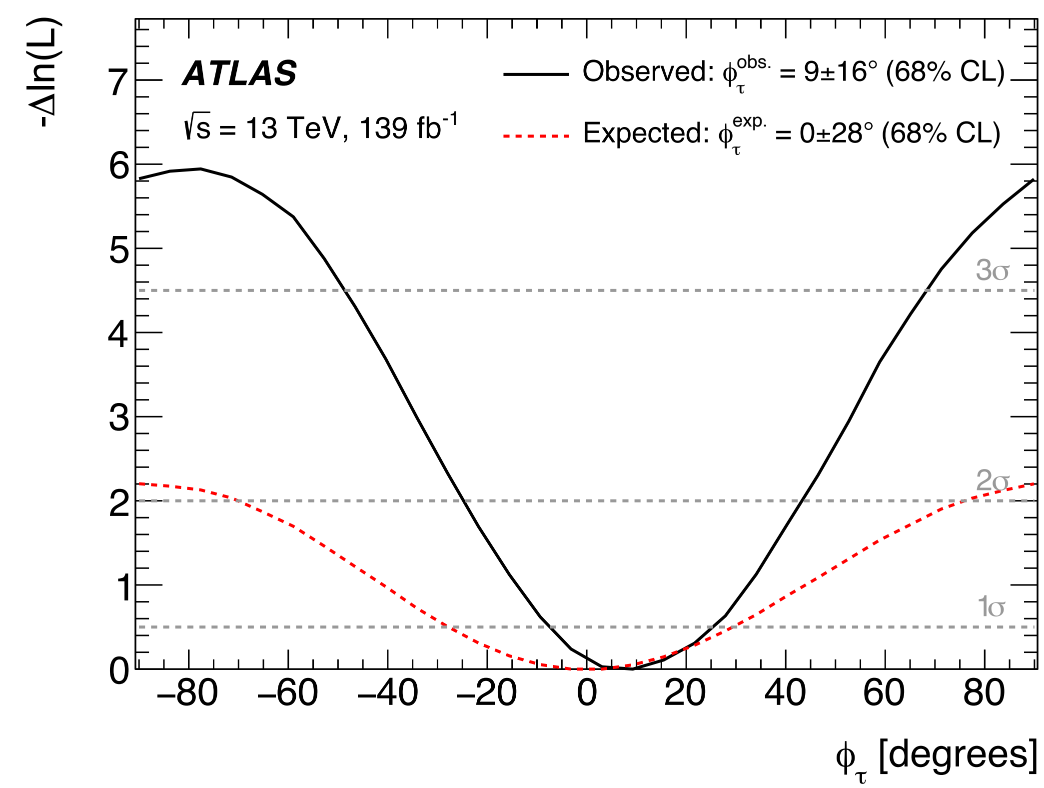
CP-mix → Mixture of two states

Measure the allowed amount of CP-odd mixture: $\phi_\tau = 9 \pm 16°$

CP-odd hypothesis rejected at 3.4σ confidence level

arXiv:2212.05833





$H \to \tau\tau$ measurements

Summary

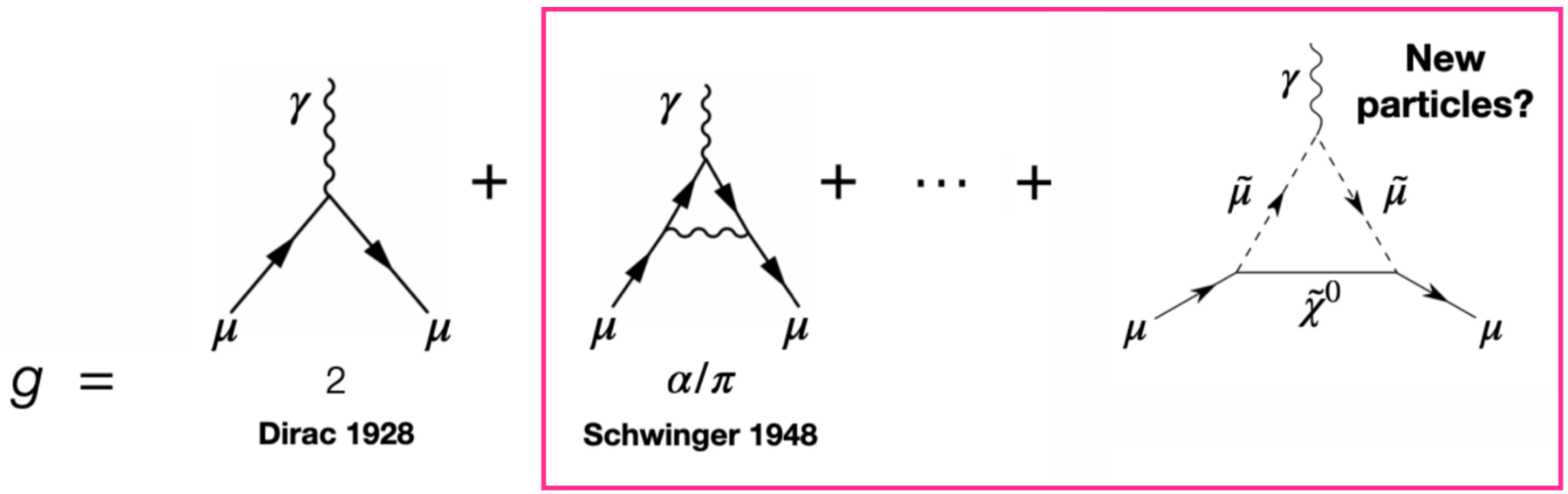
1. σ(pp $\to H \to \tau^+\tau^-$) measured with 13% precision
2. Probe the four dominant production modes
3. Comprehensive exploration of the kinematic properties of the Higgs boson
4. CP-odd (pseudo-scalar) hypothesis rejected in the $H \to \tau^+\tau^-$ vertex but still room for a mixture of scalar/pseudo-scalar states

What can we learn with taus at the LHC?

- Finding them in data
- Higgs measurements
- **Studying them**
- Future prospects

Anomalous magnetic dipole moment

- Charged particle with a spin have an intrinsic magnetic moment
- For spin 1/2 particles: $\mu = \text{g} \times q/2m \times S$



In many BSM models, couplings of new particle is enhanced for heavier leptons

Typical enhancement of ~300 for taus over muons

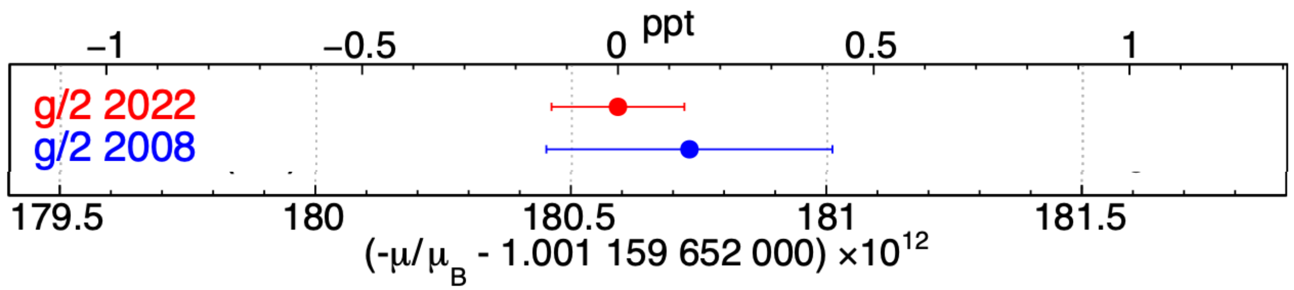
Anomalous magnetic moment: $a = \dfrac{(g-2)}{2}$

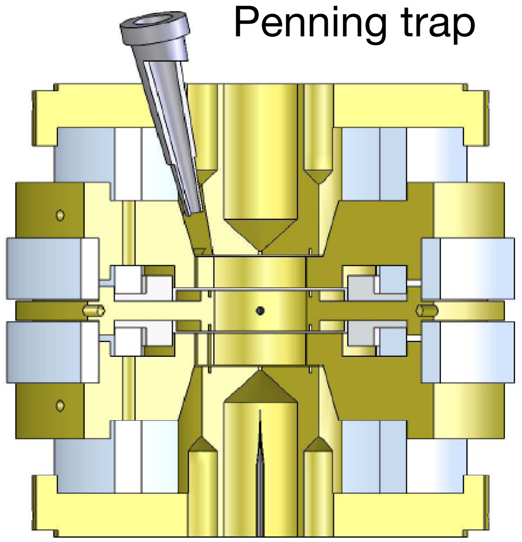
Measurements for the electron and the muon

PDG: $(g-2)/2 = (1159.65218076 \pm 0.00000028)\times 10^{-6}$

Most accurate and verified prediction in Physics

Electron

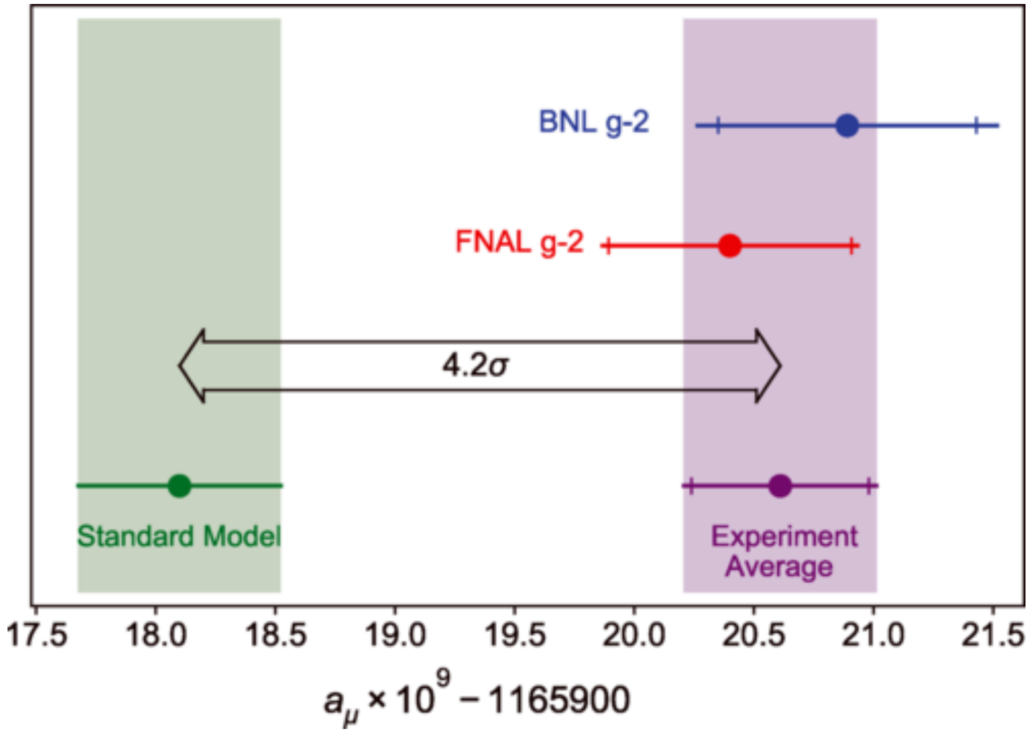




Muon

Muon g-2 experiment at Fermilab

Measure muon precession in a magnetic field



So, what about the tau lepton?

Tau Lepton Measurement

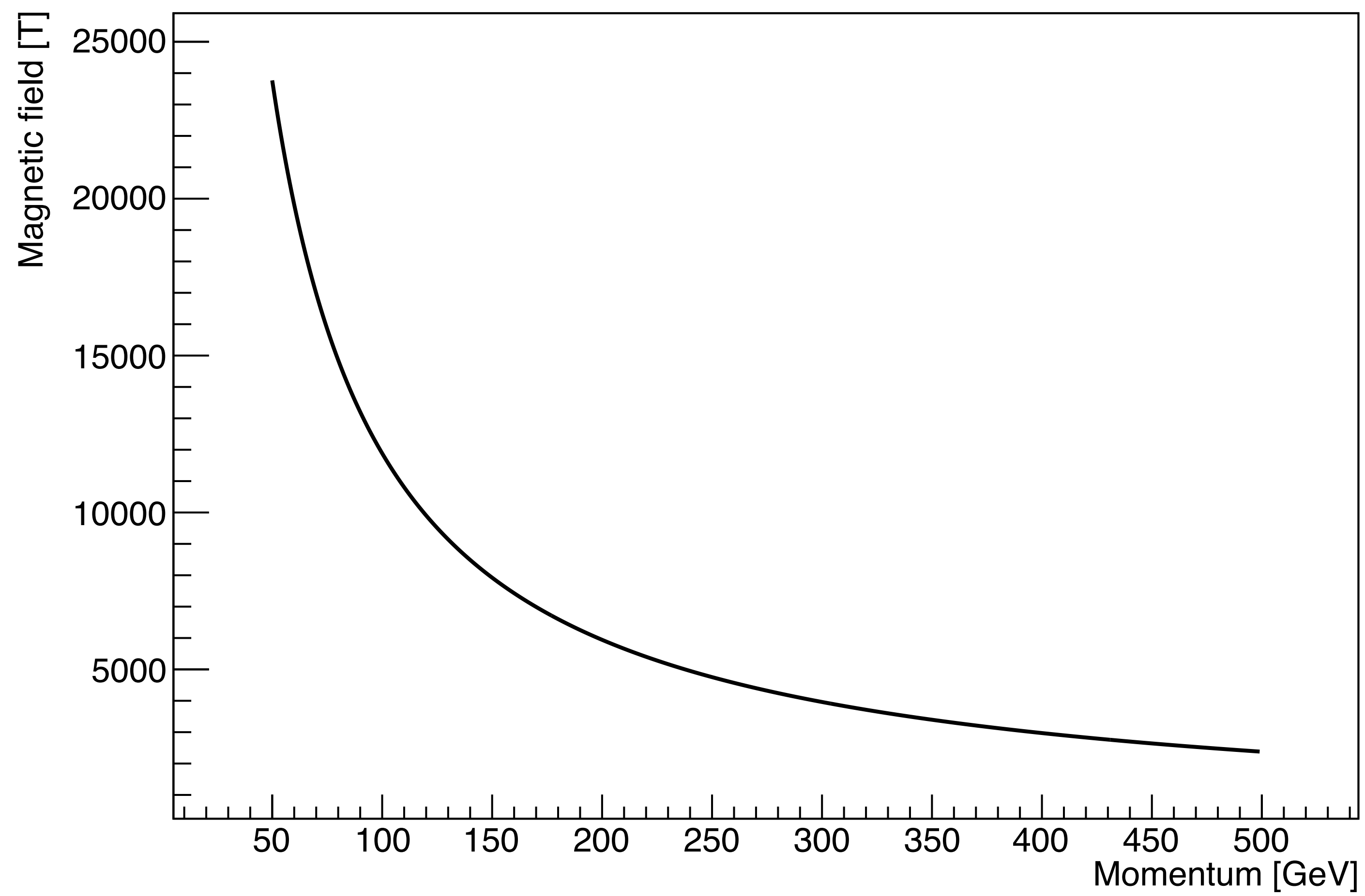
Constraining tau g-2

Trap them?

Bend them?

Tau mean lifetime = 0.29 ps

Magnetic field to bend a tau lepton with a 5° angle

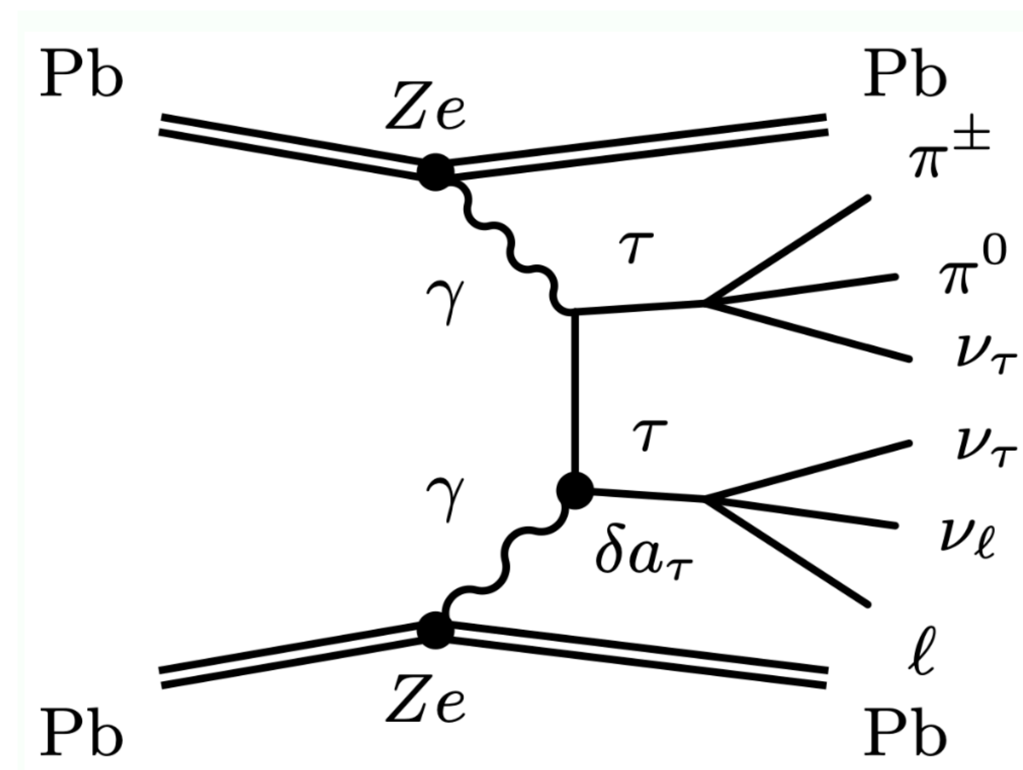


Use collider data!

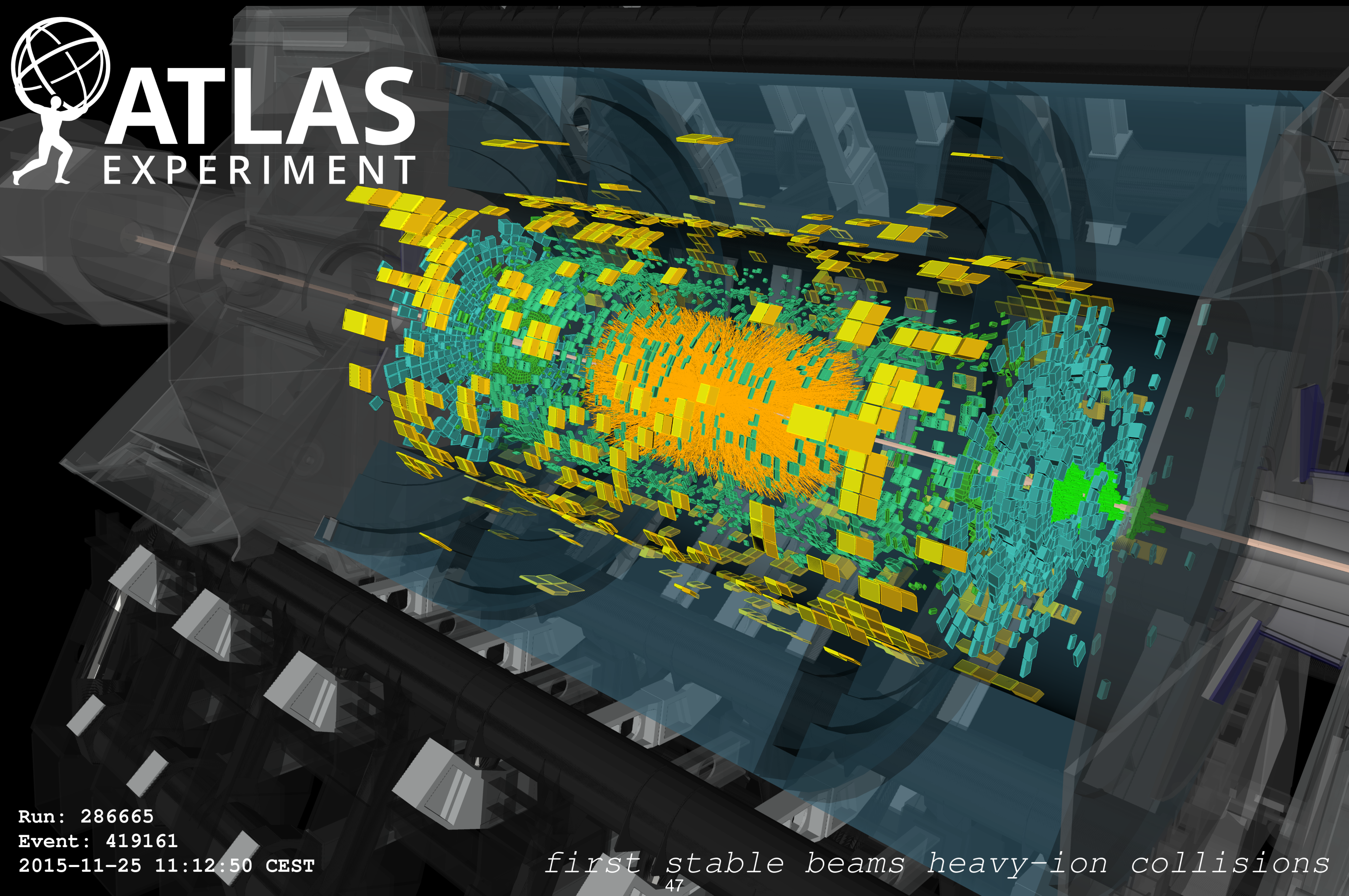
Tau Lepton Measurement

Constraining tau g-2

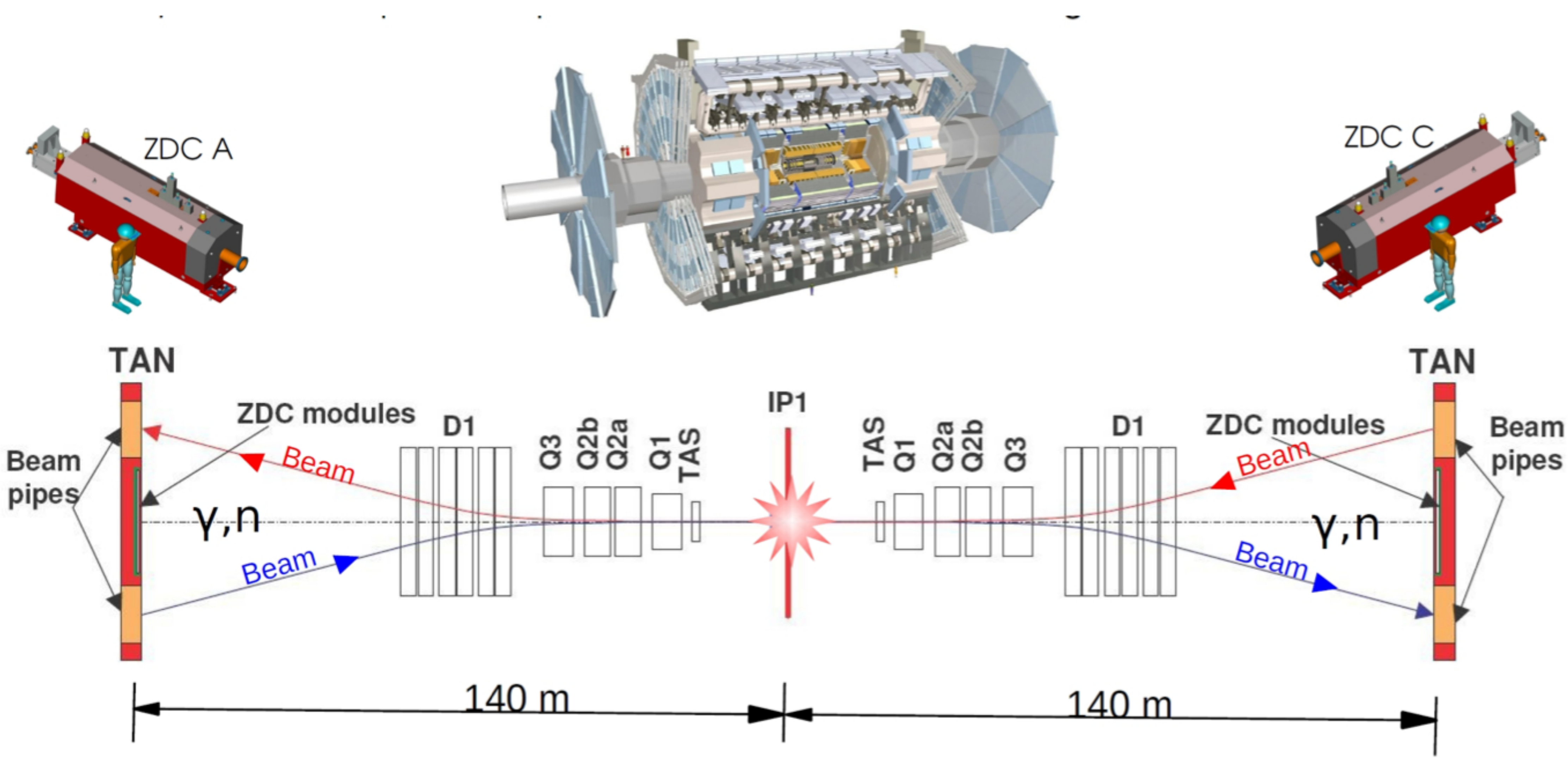
- At the LHC: Photon collisions from Pb-Pb
- Z^4 cross-section enhancement
- Important to get events with near-zero photon virtuality
  - Collect tau decays with lowest possible momentum



A typical Pb-Pb collision event



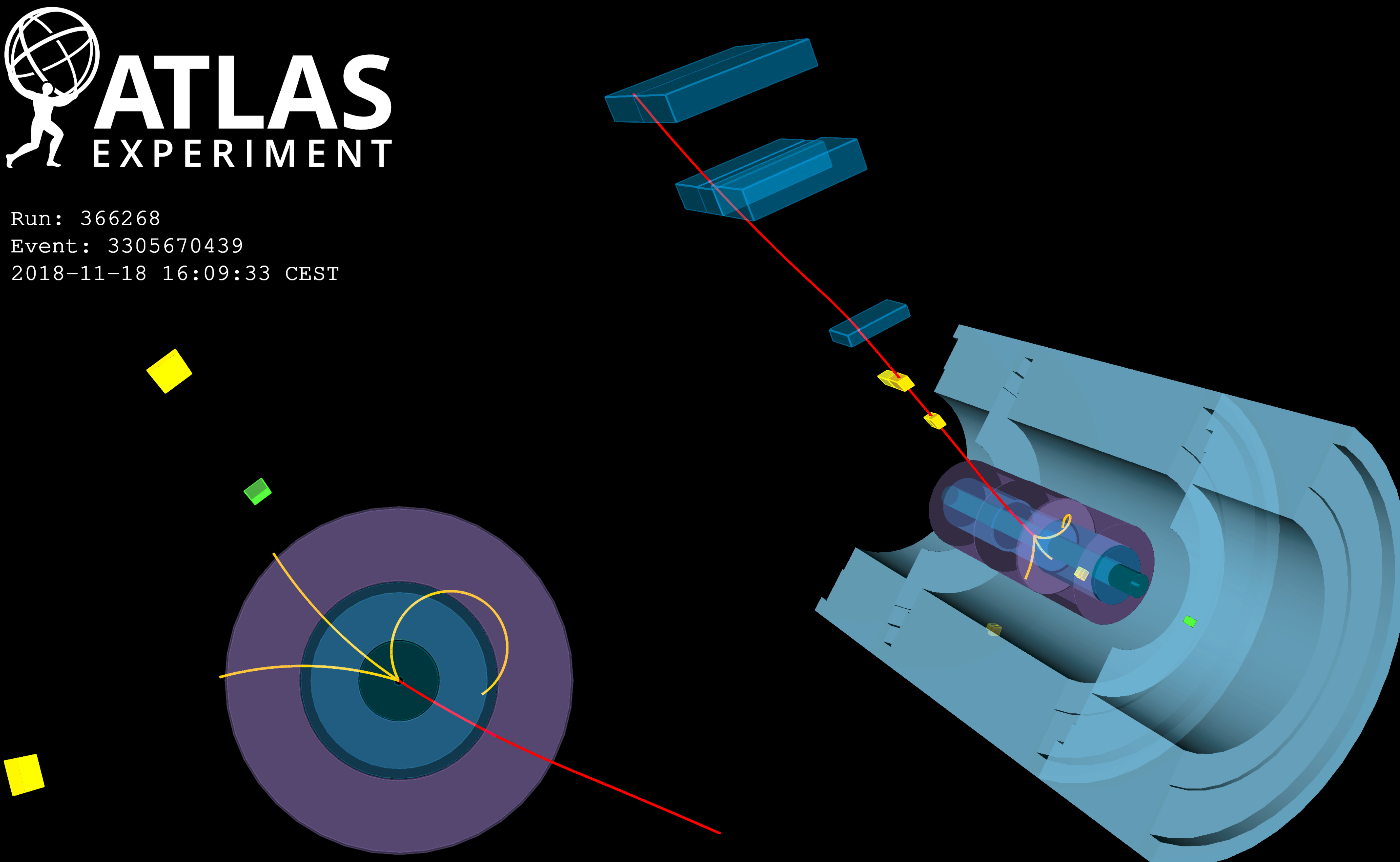
Zero Degree Calorimeters



Detect neutral particles emitted by the interacting nuclei to suppress events where at least one nuclei broke up

➡ select very clean ultra peripheral collisions

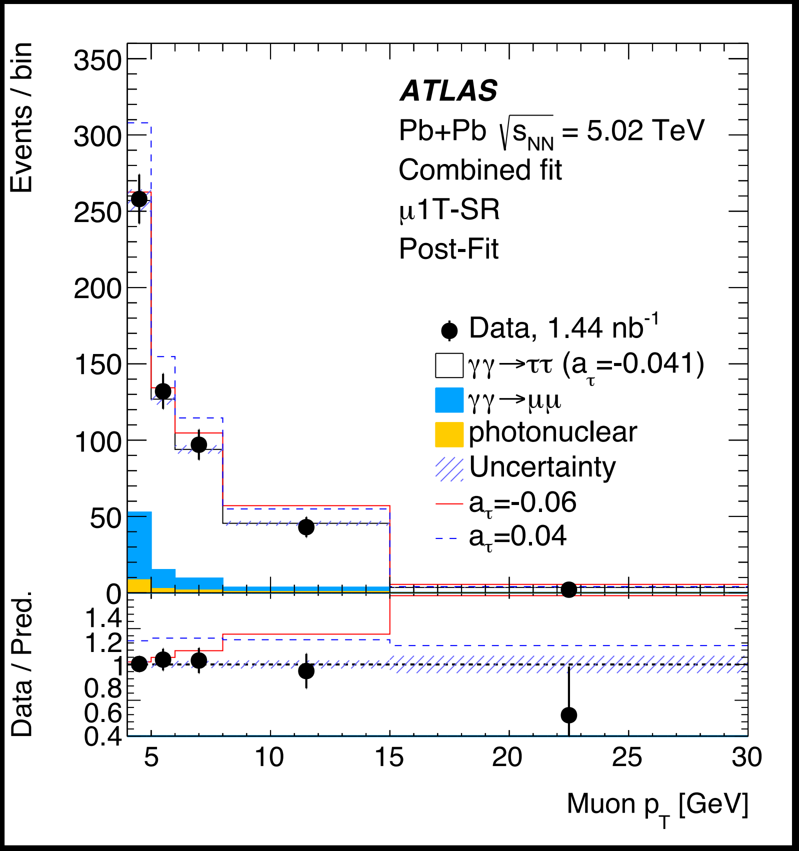
$\gamma\gamma \rightarrow \tau\tau$ event in Pb-Pb collisions



arXiv:2204.13478

Tau Lepton Measurement

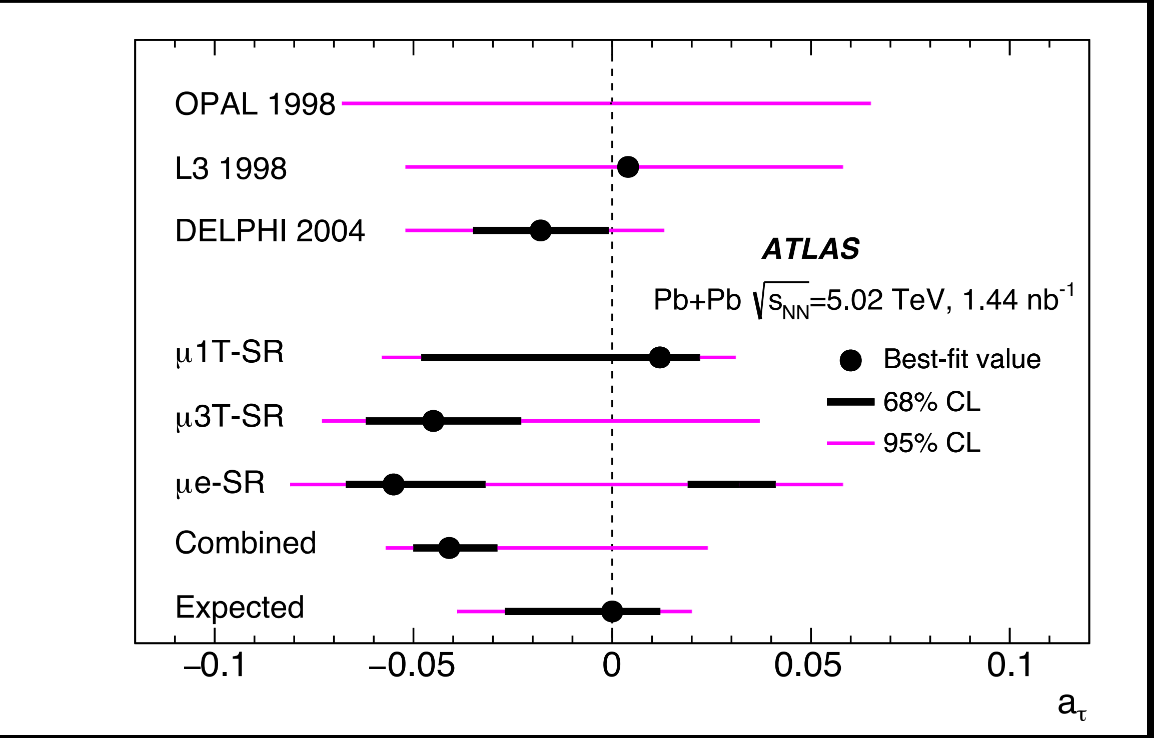
Constraining tau g-2



Template fit of the muon p_T

- Analysis strategy: measure muon p_T as handle between a_τ hypotheses
- Observation of the $\gamma\gamma \rightarrow \tau\tau$ process in PbPb collisions
- Similar sensitivity to DELPHI (most precise measurement to date)

$$a_\tau = -0.041(-0.058 < a_\tau < 0.025 @ 95\% CL)$$



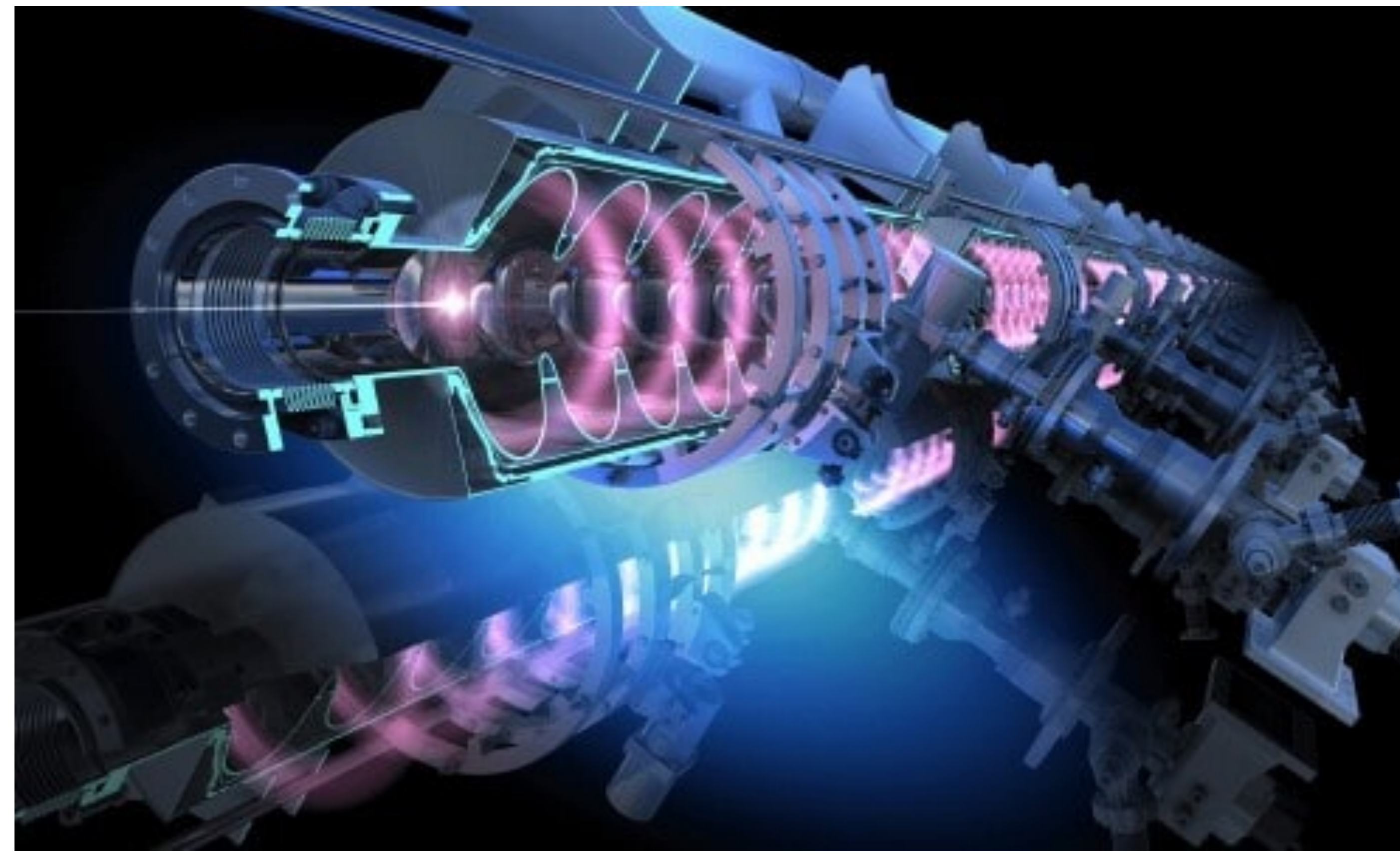
Lepton g-2 measurements

Summary

- **Electron**: measured with a precision of 10^{-9}, outstanding success of the SM
- **Muon**: measured with a precision of 10^{-8}, intriguing discrepancy with the SM predictions ($>4\sigma$)
- **Tau**: still largely unconstrained, new measurement strategy at the LHC on track to reach precision of the first quantum correction with more data
- In many BSM models, new particles couple more strongly to tau than electron or muon

What can we learn with taus at the LHC?

- Finding them in data
- Higgs measurements
- Studying them
- **Future prospects**



More Data!

LHC Run3 has started

- $\sqrt{s}$= 13.6 TeV
- Will triple the size of the pp collisions dataset
- Several upgrades to the detector systems, software and computing

The third run of the Large Hadron Collider has successfully started

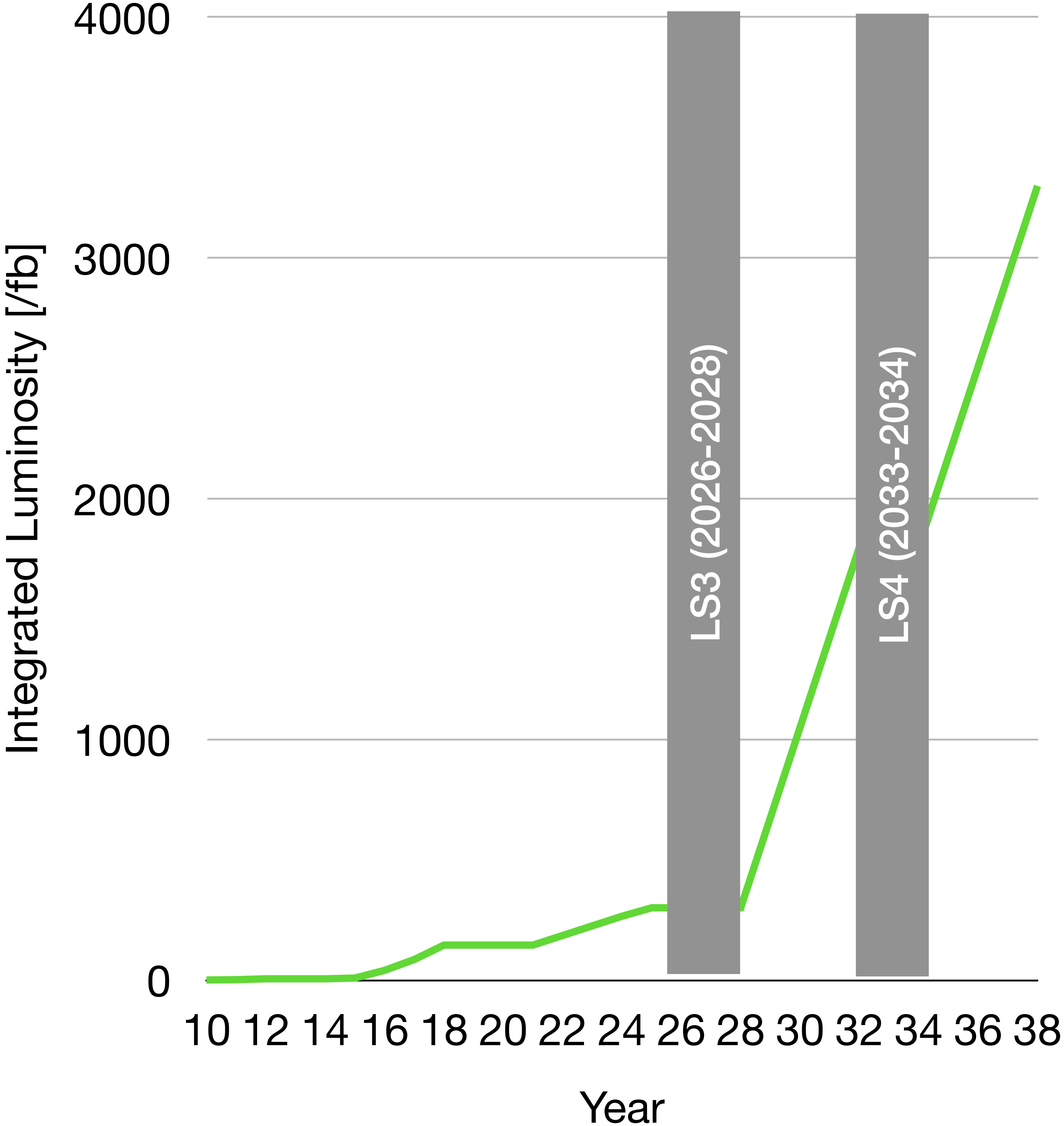
A round of applause broke out in the CERN Control Centre on 5 July at 4.47 p.m. CEST when the Large Hadron Collider (LHC) detectors started recording high-energy collisions at the unprecedented energy of 13.6 TeV

5 JULY, 2022

Celebrations at the CERN control centre (CCC) to mark the start of LHC Run 3 (Image: CERN)

HL-LHC

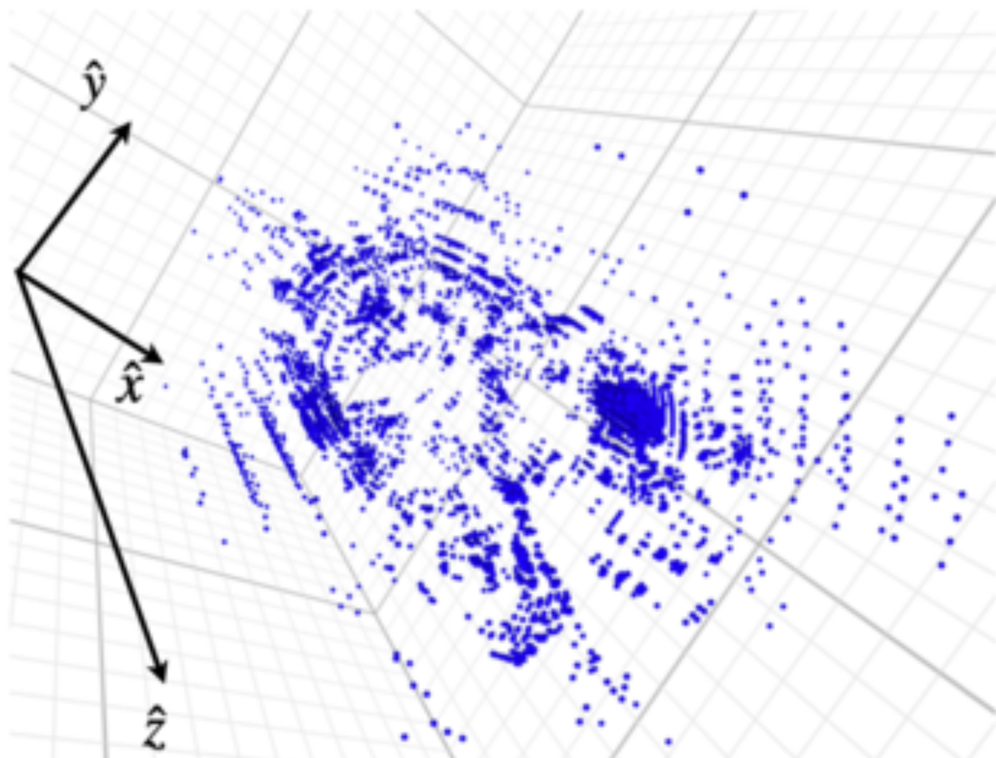
- Build a very large dataset: 20x larger than now
  - Enable searches and measurements for rare processes (Higgs self coupling)
  - Explore the Higgs sector as precisely as possible
- Very harsh data-taking condition: pileup increase by ~6
  - Important detector upgrade: tracker, trigger system, timing detector, …
  - **Deployment of powerful ML algorithms**

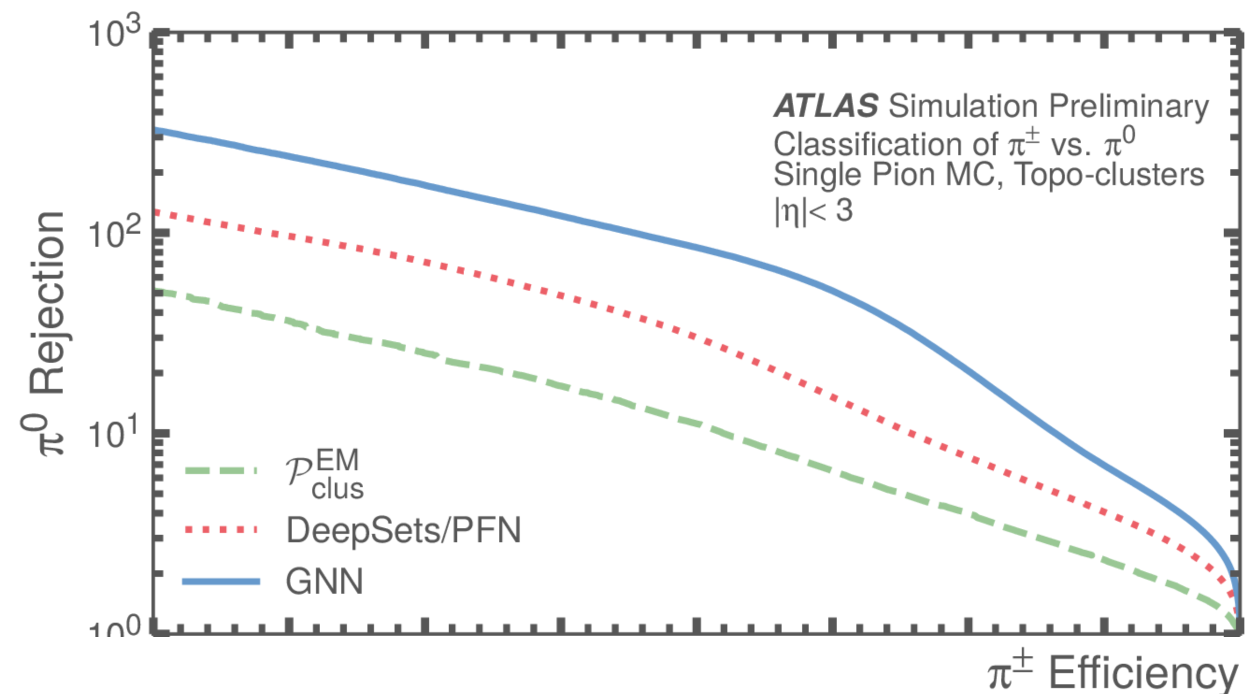


HL-LHC Event Reconstruction

Computer vision approach

- Feed Neural Network with detector hits and output fully calibrated and identified object





Latest ATLAS study to distinguish π^+ and π^0

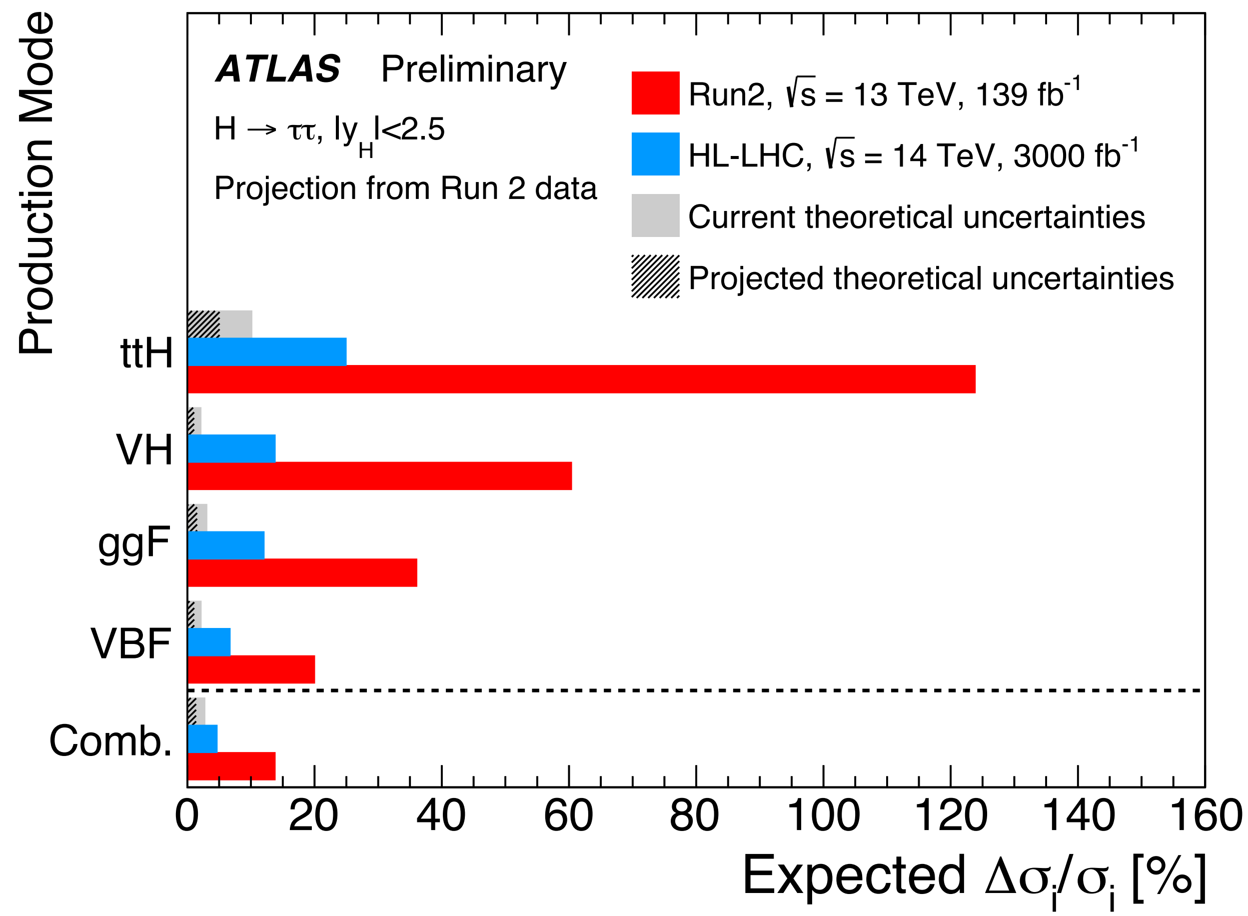
- Advantages:
  - Enable more powerful algorithms thanks to deeper connection between each detector hit
  - Extremely well suited for the computing infrastructure planned for HL-LHC

HL-LHC

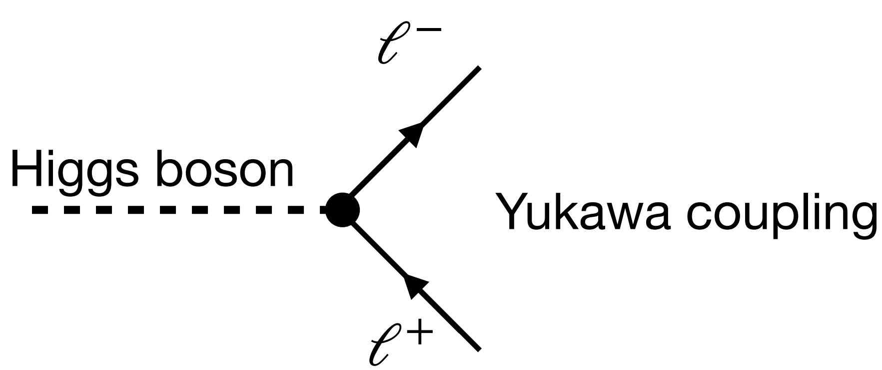
Exciting Prospects for Higgs boson measurements

Tau Yukawa expected to be measured with a precision of 2%

Will probe for BSM effect at an energy scale of O(10 TeV)



Future colliders



	Electron	Muon	Tau
Mass	511 keV	106 MeV	1.7 GeV
Measurement outlook	Intriguing idea at the FCC-ee with a dedicated run at $\sqrt{(s)}=m_H$	<0.5%	<0.5%
		Constraint new Physics well above 10 TeV	

Conclusion

- Higgs boson measurements
    - Powerful tool to explore above the TeV scale
- Tau leptons play a key role in the program
    - Yukawa couplings and production modes
- Detecting them is hard…
    - But rewarding!
- Tau lepton g-2 is still largely unconstrained
    - On track to measure it at the LHC!