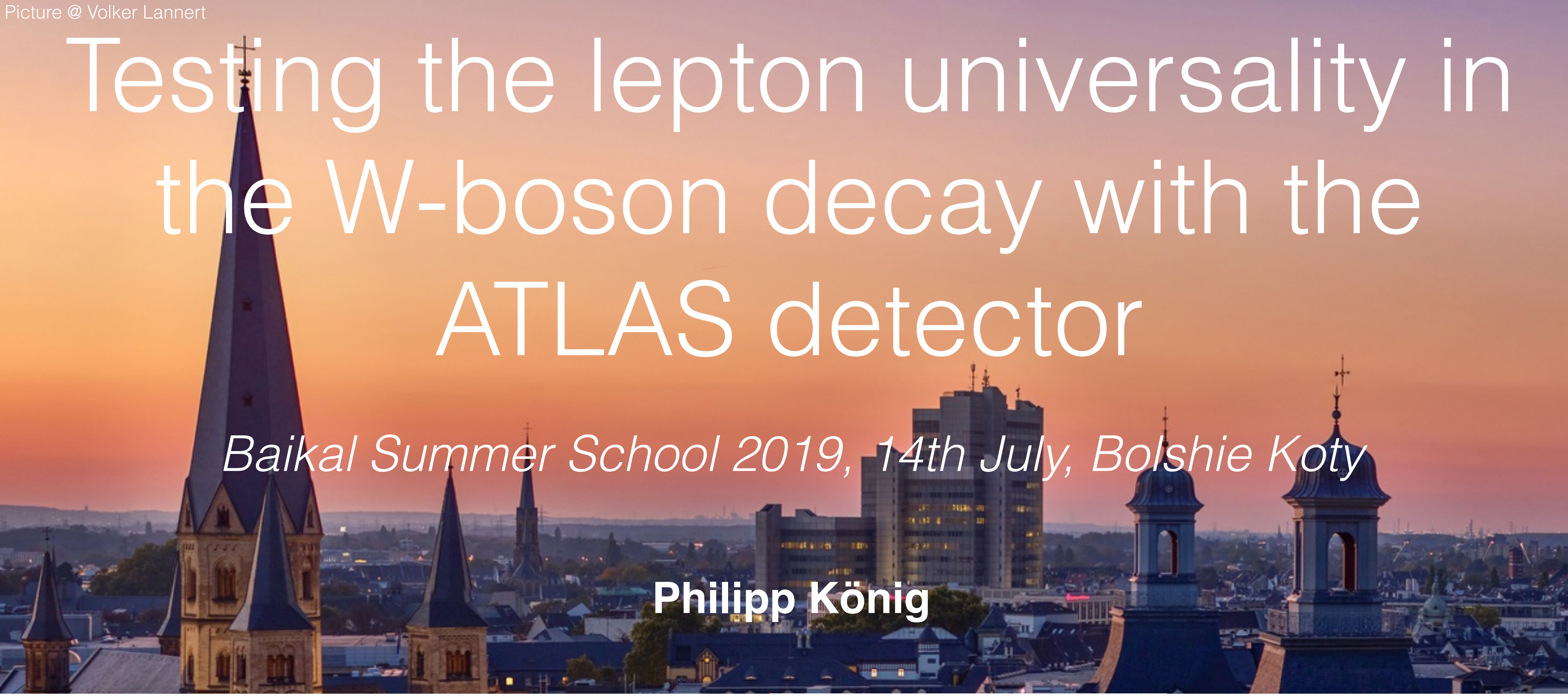

Picture @ Volker Lannert

Testing the lepton universality in the W-boson decay with the ATLAS detector

Baikal Summer School 2019, 14th July, Bolshie Koty

Philipp König

ATLAS EXPERIMENT

bcgs
Bonn-Cologne Graduate School of Physics and Astronomy

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

UNIVERSITÄT BONN

BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC

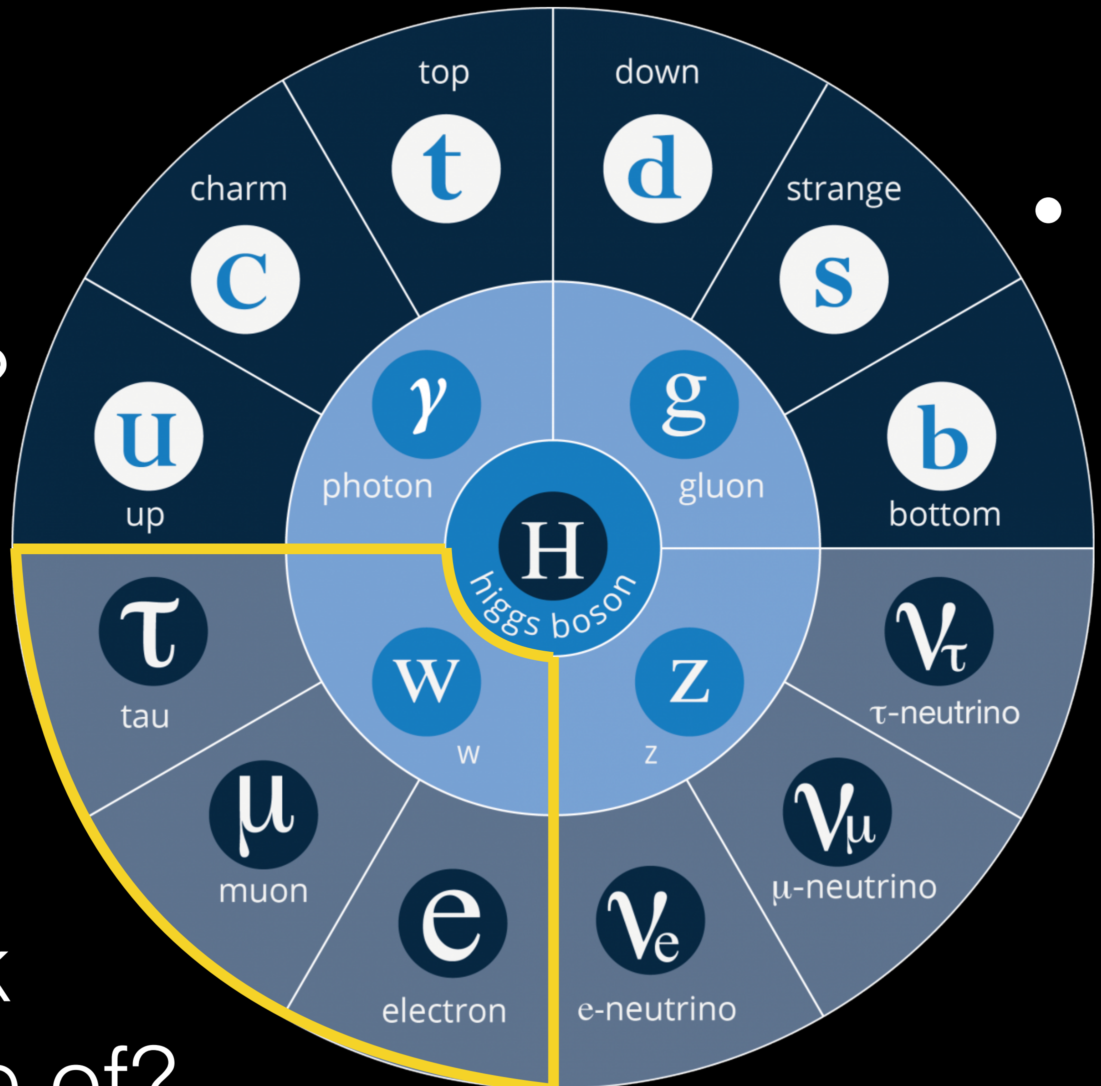
FSP 103 ATLAS

Picture @ Volker Lannert

Picture @ Alexander Gerst, ESA

Open Questions of the Standard Model

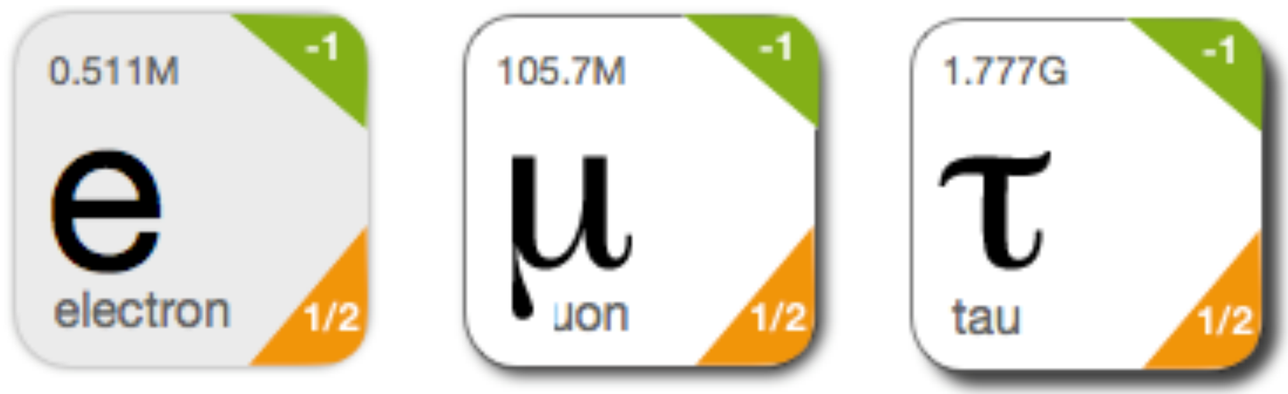
- Why is there more matter than anti-matter?
- How can we describe gravity?
- What is dark matter made of?



➡ Precision measurements of the SM are interesting approach to search for BSM physics

Source: https://atlas.cern/discover/physics

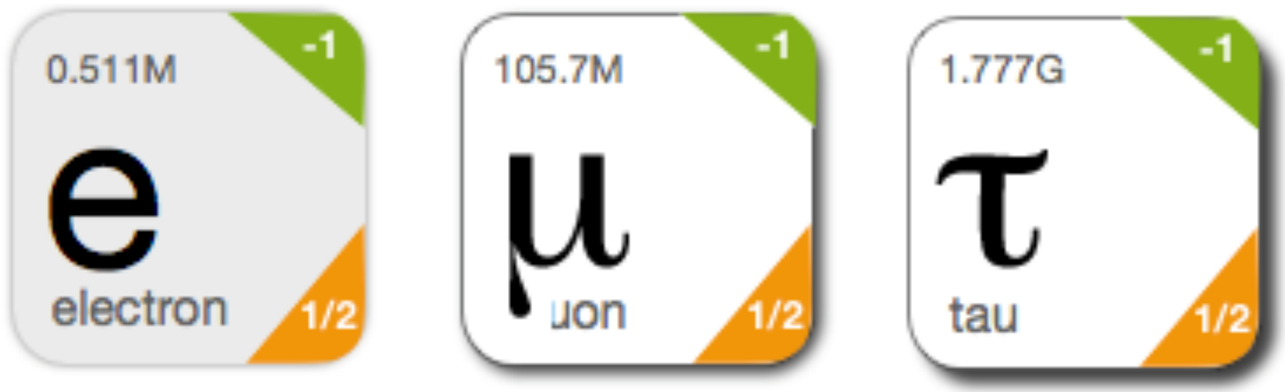
Lepton Universality



- Electroweak interaction preserves lepton universality in the SM
- Higgs mechanism breaks lepton universality by different couplings to leptons (depending on the mass)
- Is there an additional mechanism for lepton universality breaking?

Source: http://united-states.cern/physics/standard-model-and-beyond

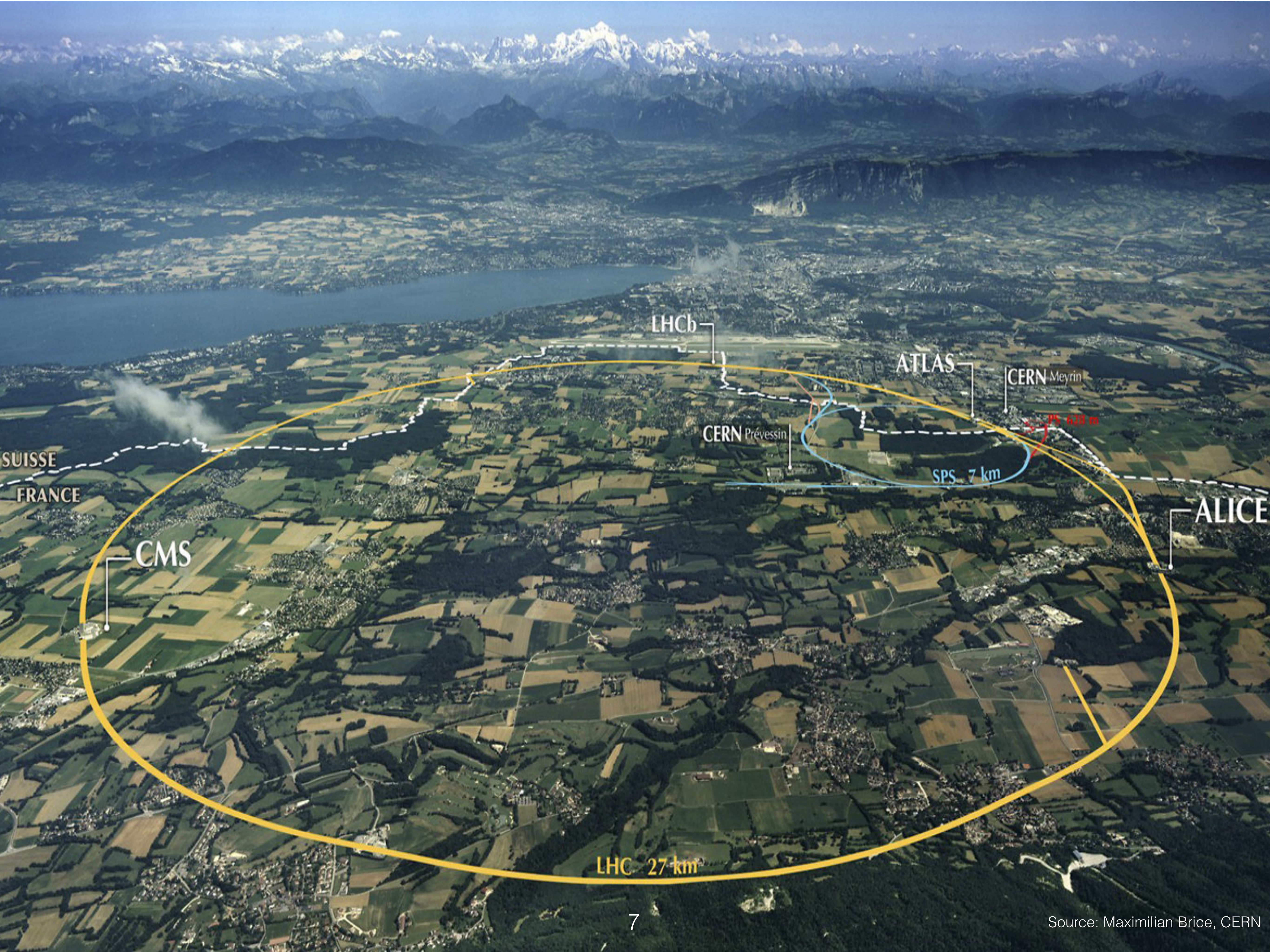
Lepton Universality



W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	(MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40189
$\mu^+\nu$		(10.63 ± 0.15) %		40189
$\tau^+\nu$		(11.38 ± 0.21) %		40170

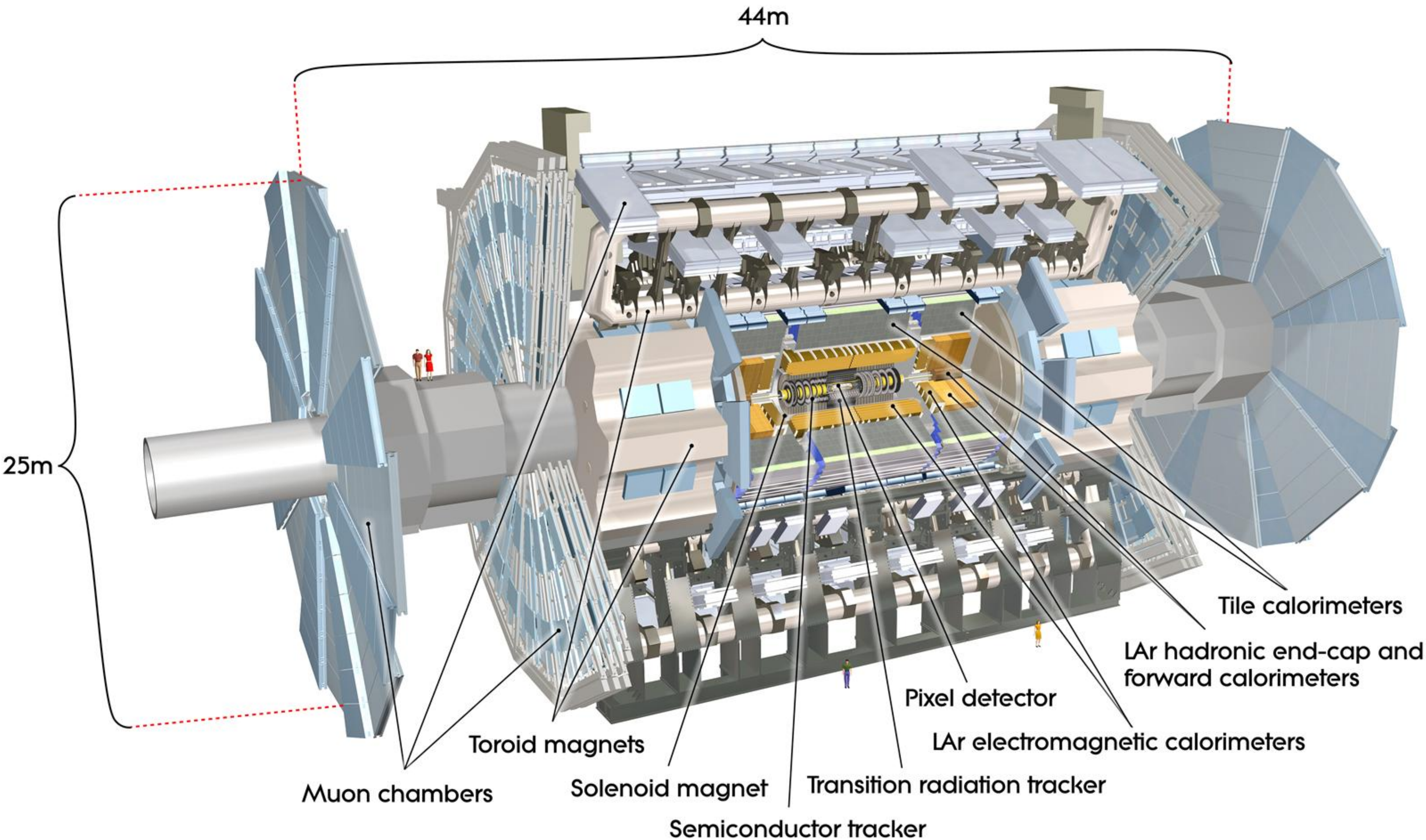
- No experimentally observed violation of lepton universality
- 2 sigma effect seen by LHCb
  - $\mathscr{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathscr{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$ (arXiv:1506.08614)
  - $B^0 \to K^{*0}\ell^+\ell^-$ (arXiv:1705.05802)

Source: http://united-states.cern/physics/standard-model-and-beyond,
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)



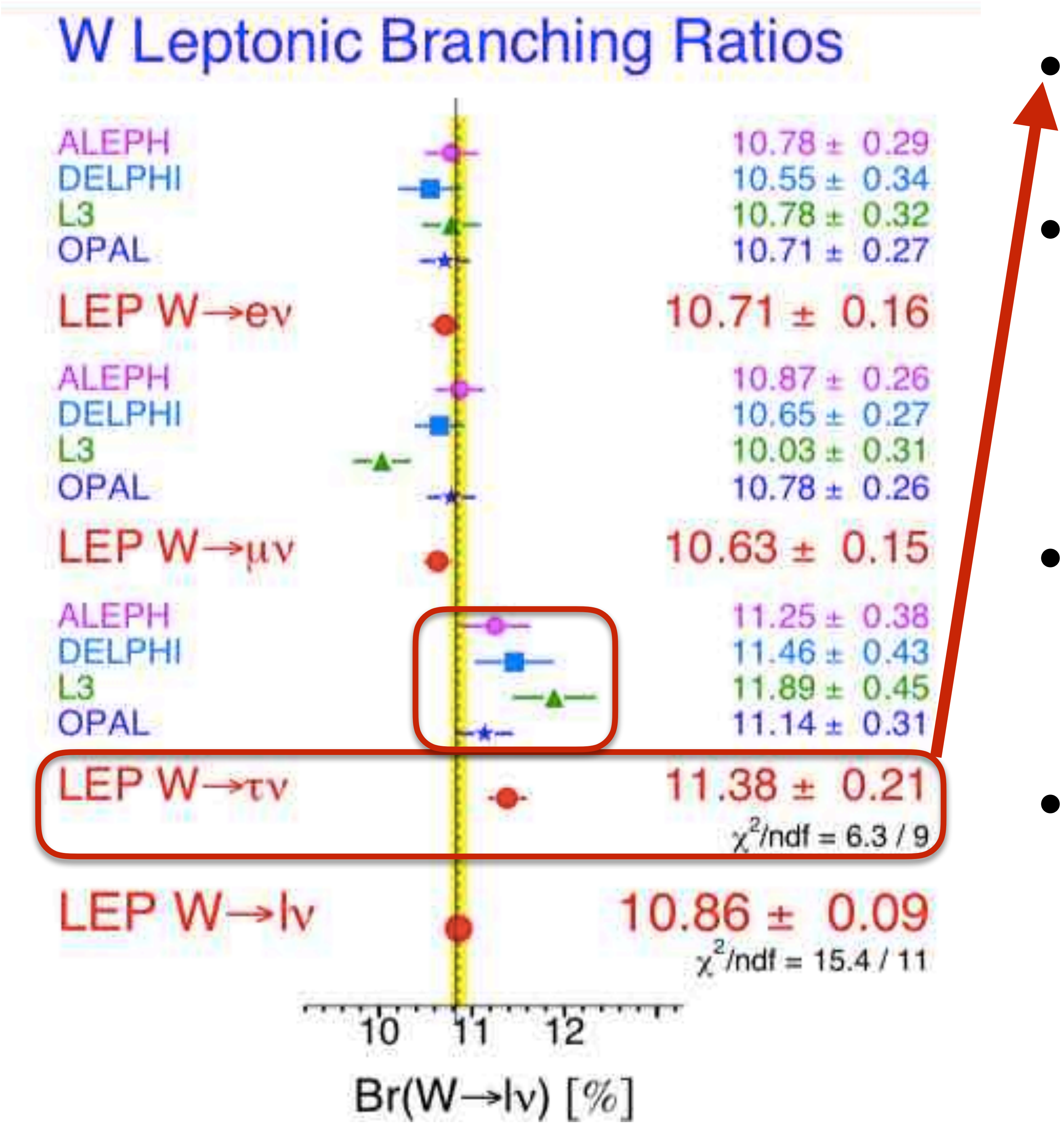
Source: Maximilian Brice, CERN

The ATLAS Detector



Source: https://atlas.cern/discover/detector

Motivation

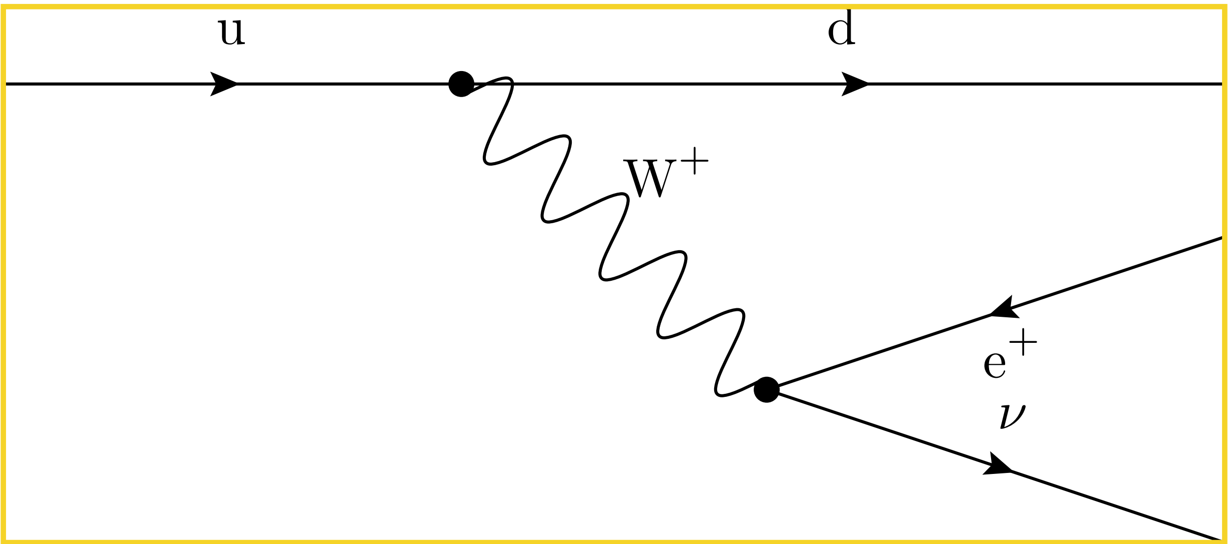


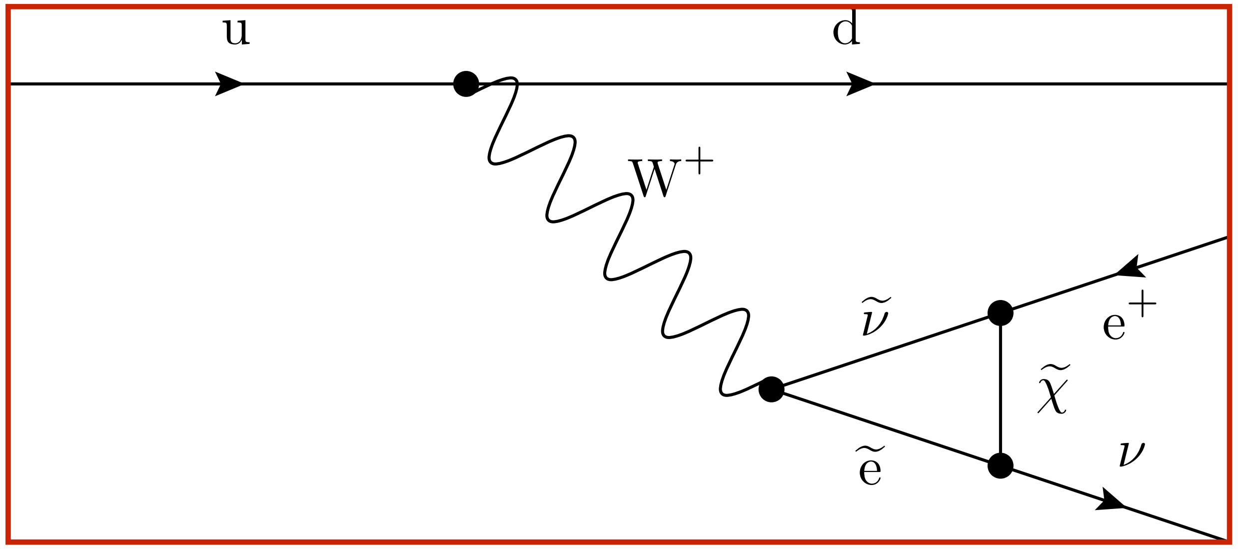
- 2 sigma discrepancy
- Excellent possibility to test SM and lepton universality
- Indicator for BSM physics
- Parameter of Interest (POI):

$$\mathrm{BR}(W \to \tau\nu_\tau)/\mathrm{BR}(W \to \mu\nu_\mu)$$

Source:arXiv:hep-ex/0511027

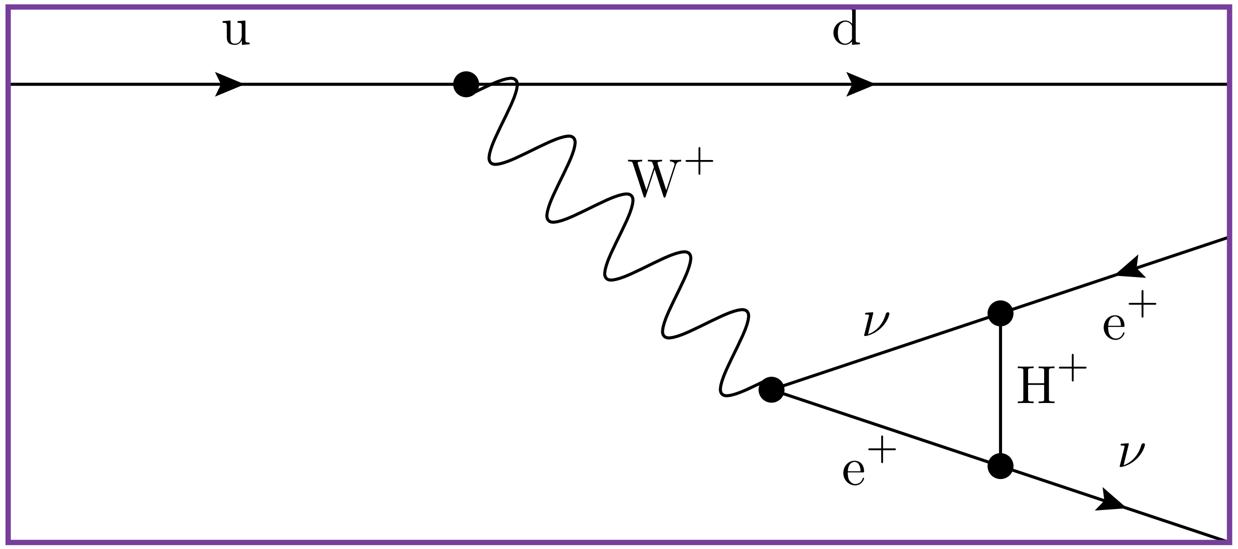
W-Boson Decay





- SM decay into positron and neutrino

- Additional loops with
  - SUSY
  - Charged Higgs



W-Mass Measurement

- Starting point: W-mass measurement with the ATLAS detector at 7 TeV (arXiv:1701.07240)

➡ Very similar analysis

Measurement of the *W*-boson mass in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector

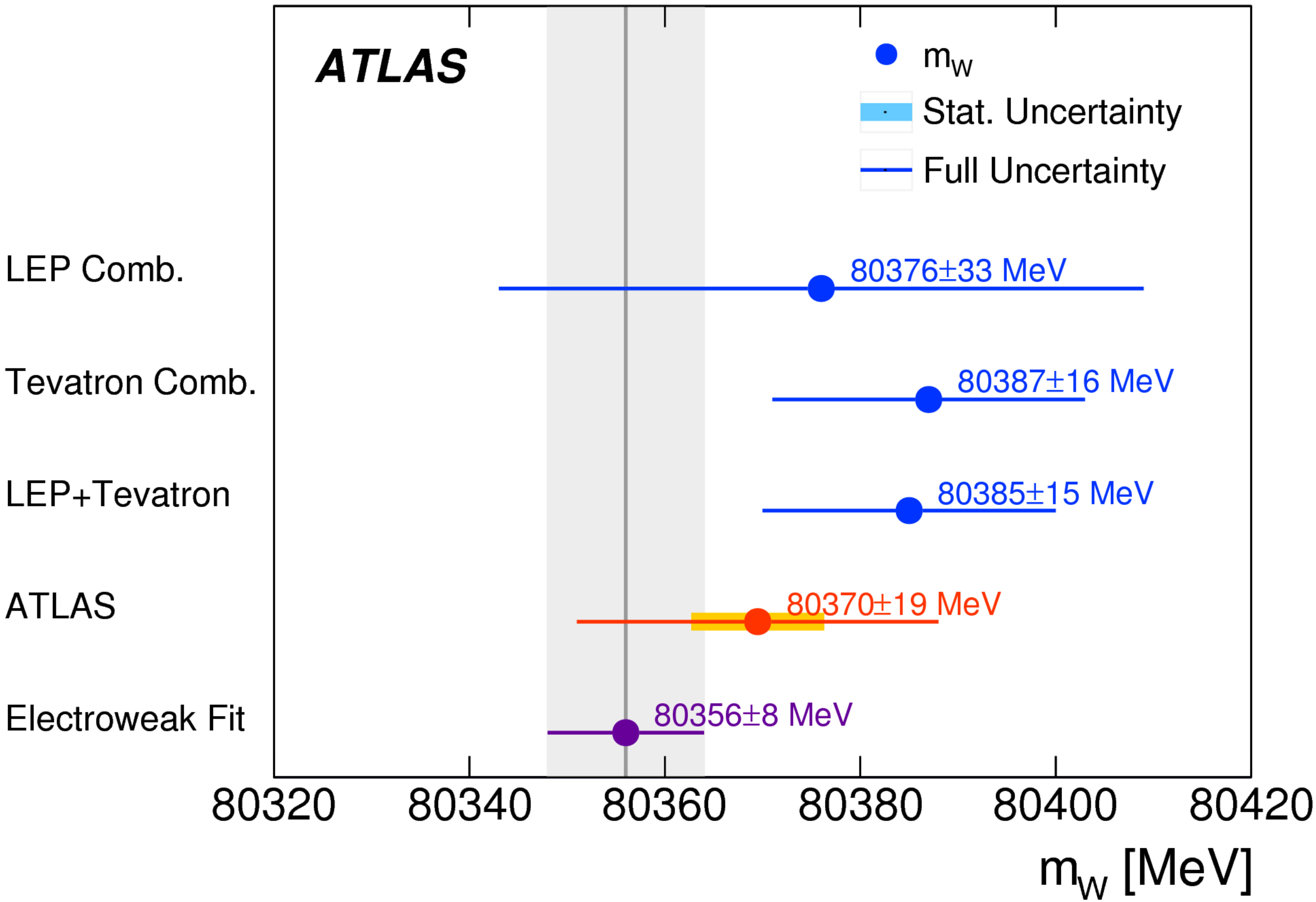
The ATLAS Collaboration

A measurement of the mass of the W boson is presented based on proton–proton collision data recorded in 2011 at a centre-of-mass energy of 7 TeV with the ATLAS detector at the LHC, and corresponding to 4.6 fb^{-1} of integrated luminosity. The selected data sample consists of 7.8×10^6 candidates in the $W \to \mu\nu$ channel and 5.9×10^6 candidates in the $W \to e\nu$ channel. The W-boson mass is obtained from template fits to the reconstructed distributions of the charged lepton transverse momentum and of the W boson transverse mass in the electron and muon decay channels, yielding

$$\begin{aligned} m_W &= 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV} \\ &= 80370 \pm 19\ \text{MeV}, \end{aligned}$$

Source:arXiv:1701.07240

Results from W-Mass Measurement



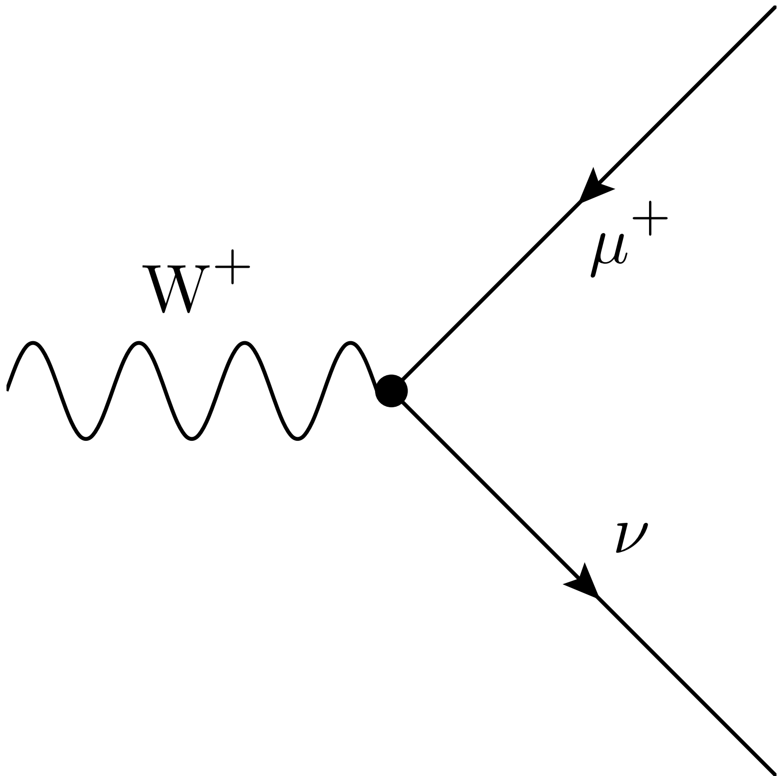
Source:arXiv:1701.07240

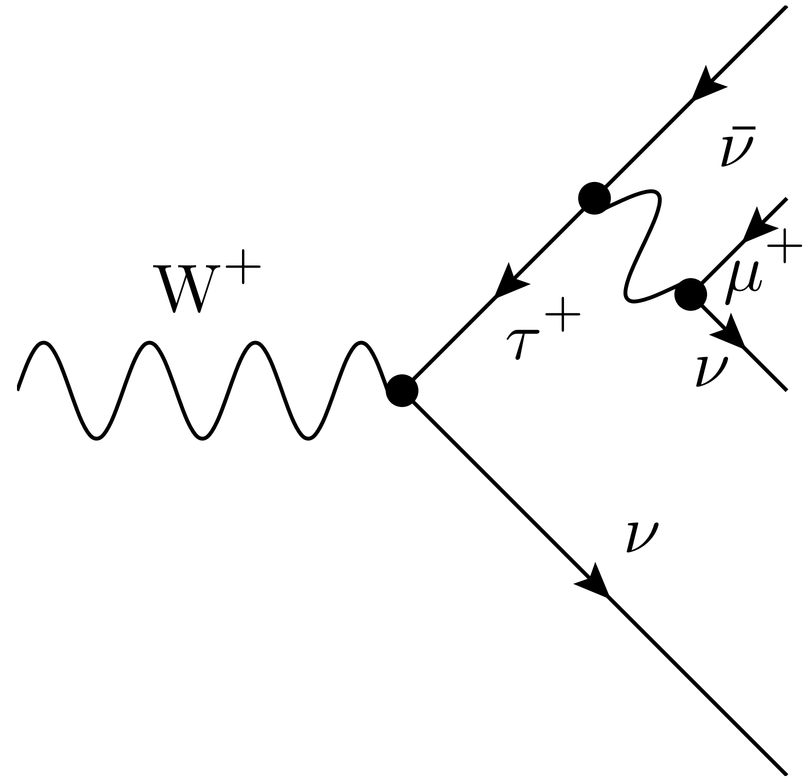
Event Selection of W-Mass Measurement

Cut Stage	Electron Channel	Muon Channel
Trigger	Single electron trigger (20/22 GeV)	Single muon trigger (18 GeV)
Signal cuts	Exactly one well reconstructed electron/muon	
	$p_{\mathrm{T}}^{l} > 30\,\mathrm{GeV}$	
	$p_{\mathrm{T}}^{W} < 30\,\mathrm{GeV}$	
	$m_{\mathrm{T}}^{W} > 60\,\mathrm{GeV}$	
	$p_{\mathrm{T}}^{\mathrm{miss}} > 30\,\mathrm{GeV}$	

Source:arXiv:1701.07240

Measurement of the Ratio of the Branching Ratios

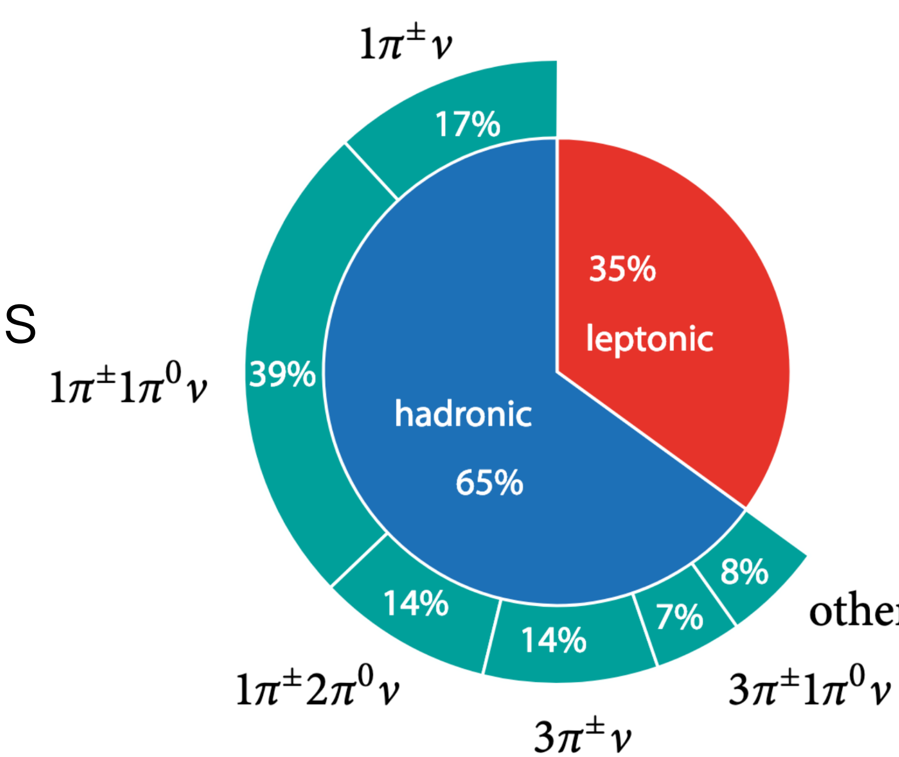




~11%

~11%x17.4%

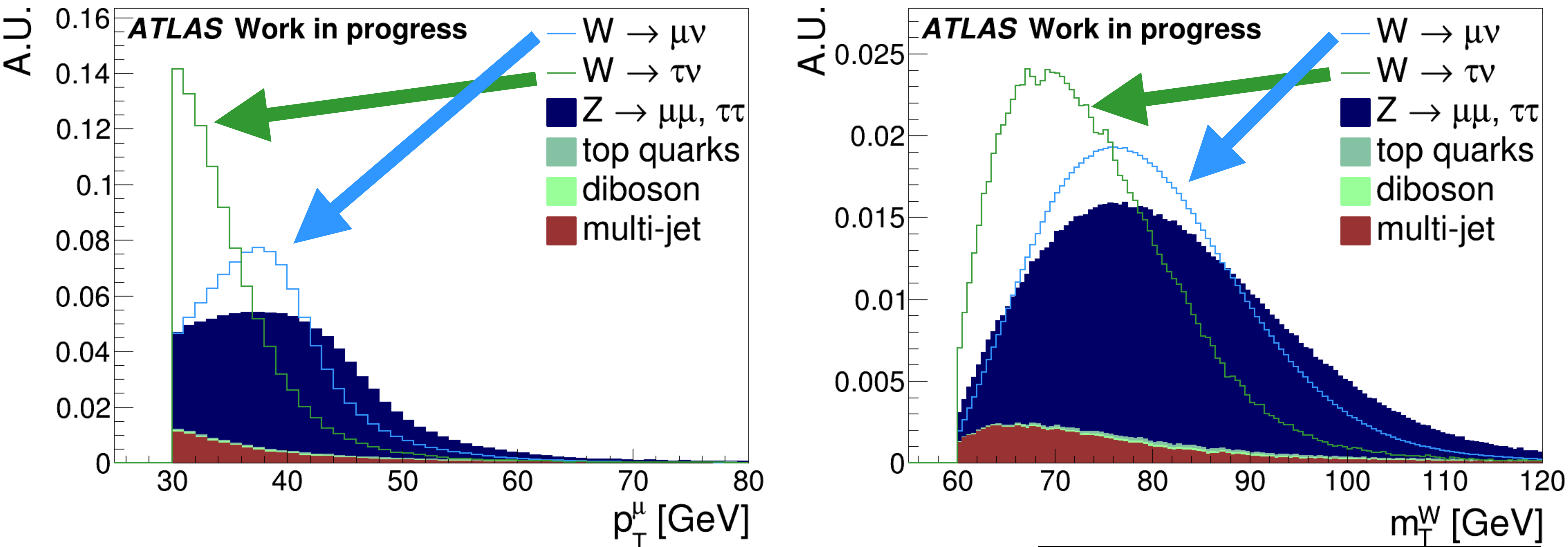
- Select lepton final state due to
  - high trigger efficiency
  - cancellation of many systematic uncertainties



- Parameter of Interest (POI):

$$R_{\tau\mu}^{SIG} = \mathscr{B}(W \to \tau\nu_\tau)/\mathscr{B}(W \to \mu\nu_\mu)$$

Interesting Variables

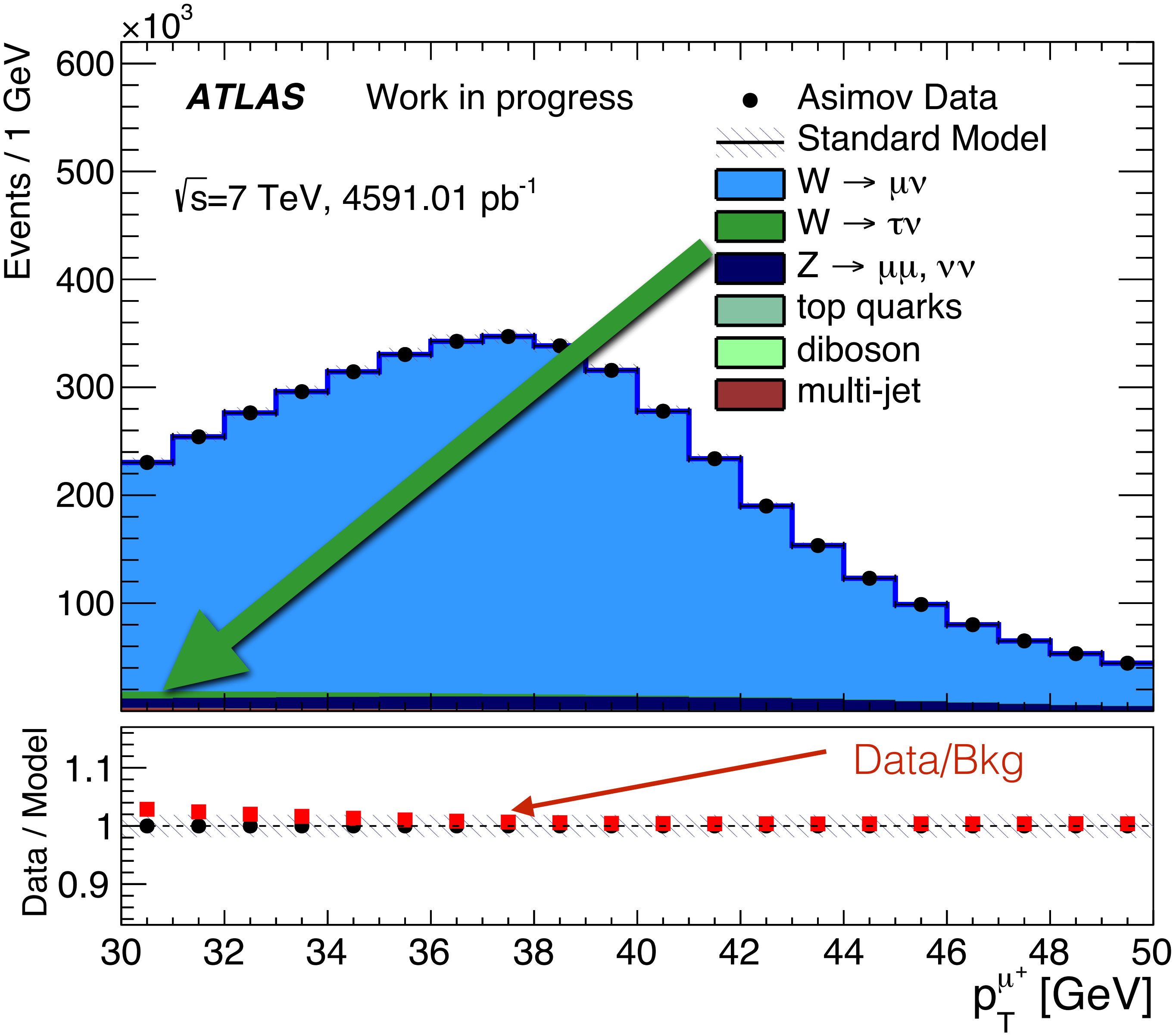


$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{l} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \Delta\phi(p_{\mathrm{T}}^{l}, p_{\mathrm{T}}^{\mathrm{miss}}))}$$

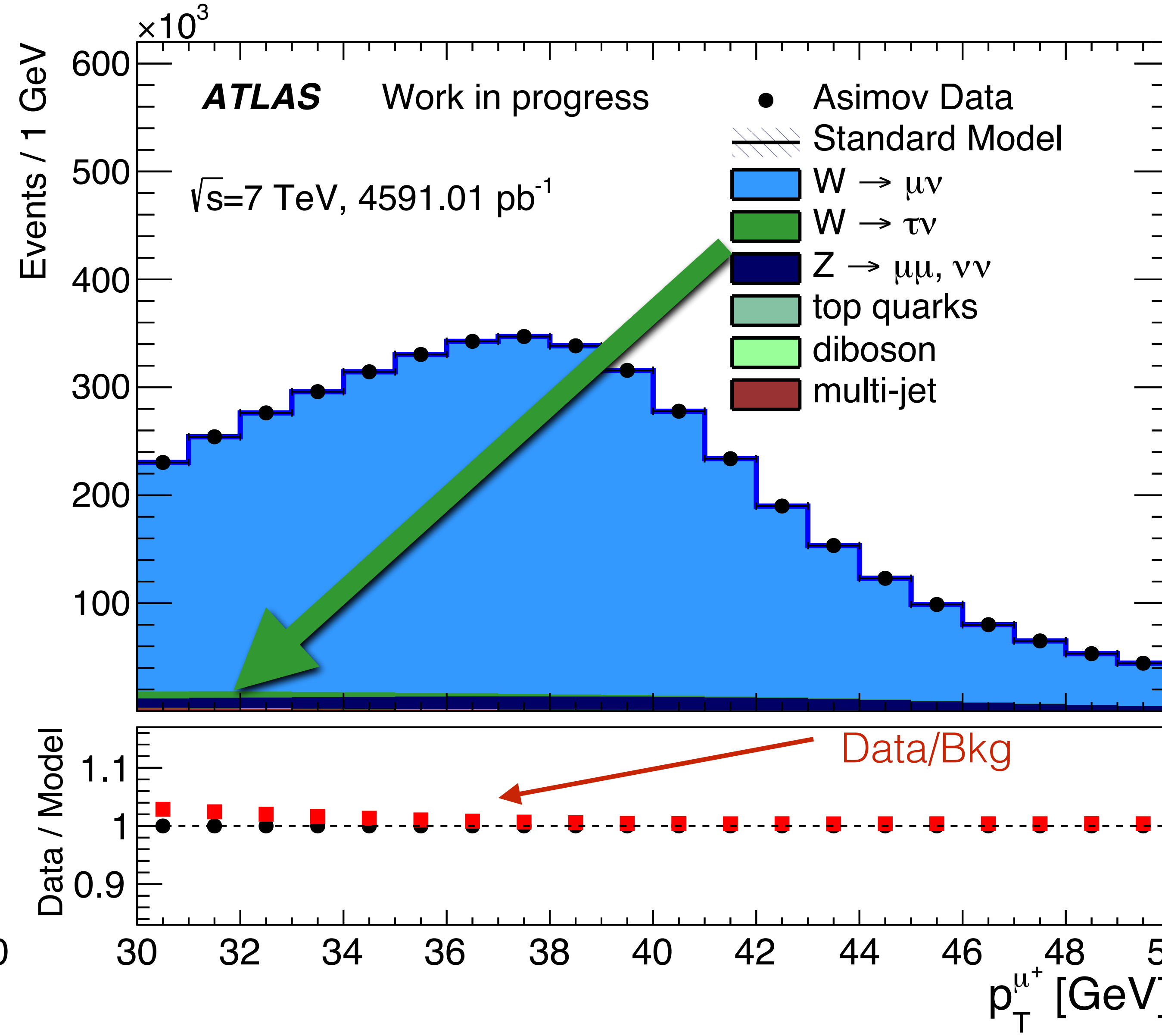
- Shape difference between tau and muon signal as large as possible
- Difference is coming from additional neutrino in tau process

Results for Fitting pT

before fit



after fit



- Agreement between data and MC is 1 as Asimov Data (sum of all samples) was used as Data
- One scale factor ($R_{\tau\mu}^{SIG}$) is 100% correlated with the branching ratio itself

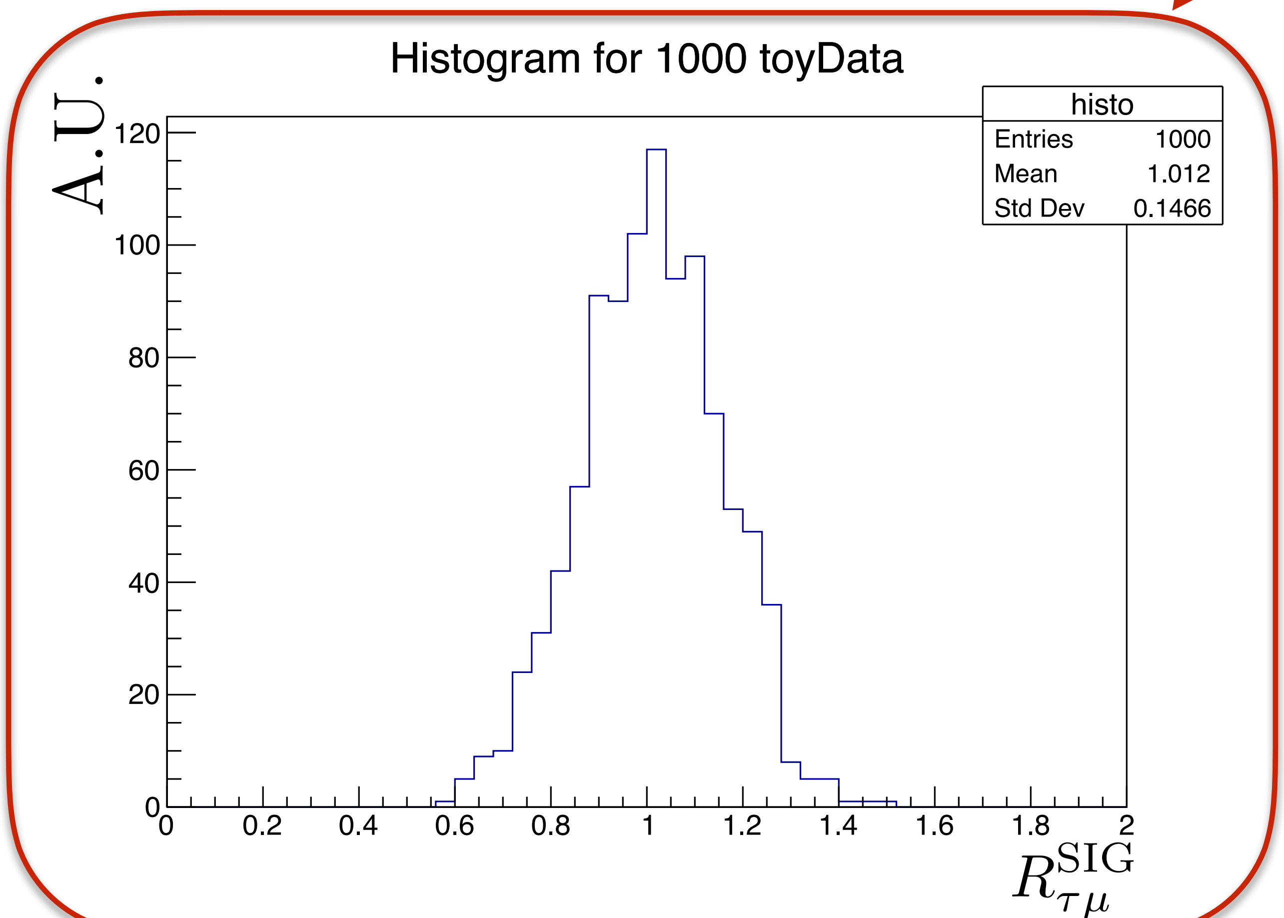
Fit Results for pT

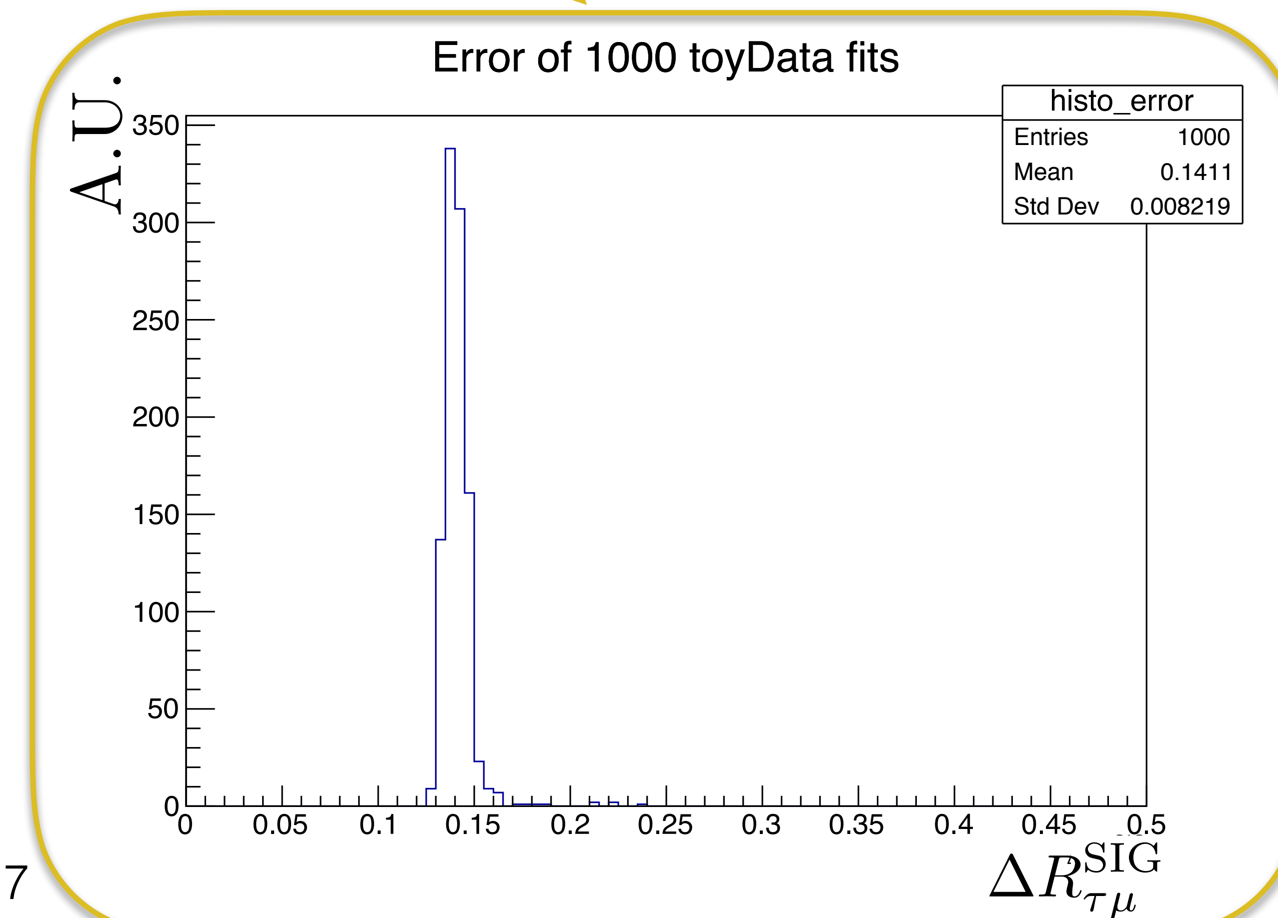
Asimov Data

Parameter	initial value and error	fitted value and error
Rtaumu_SIG	1.00 ± 0.000100	1.00 ± 0.143262

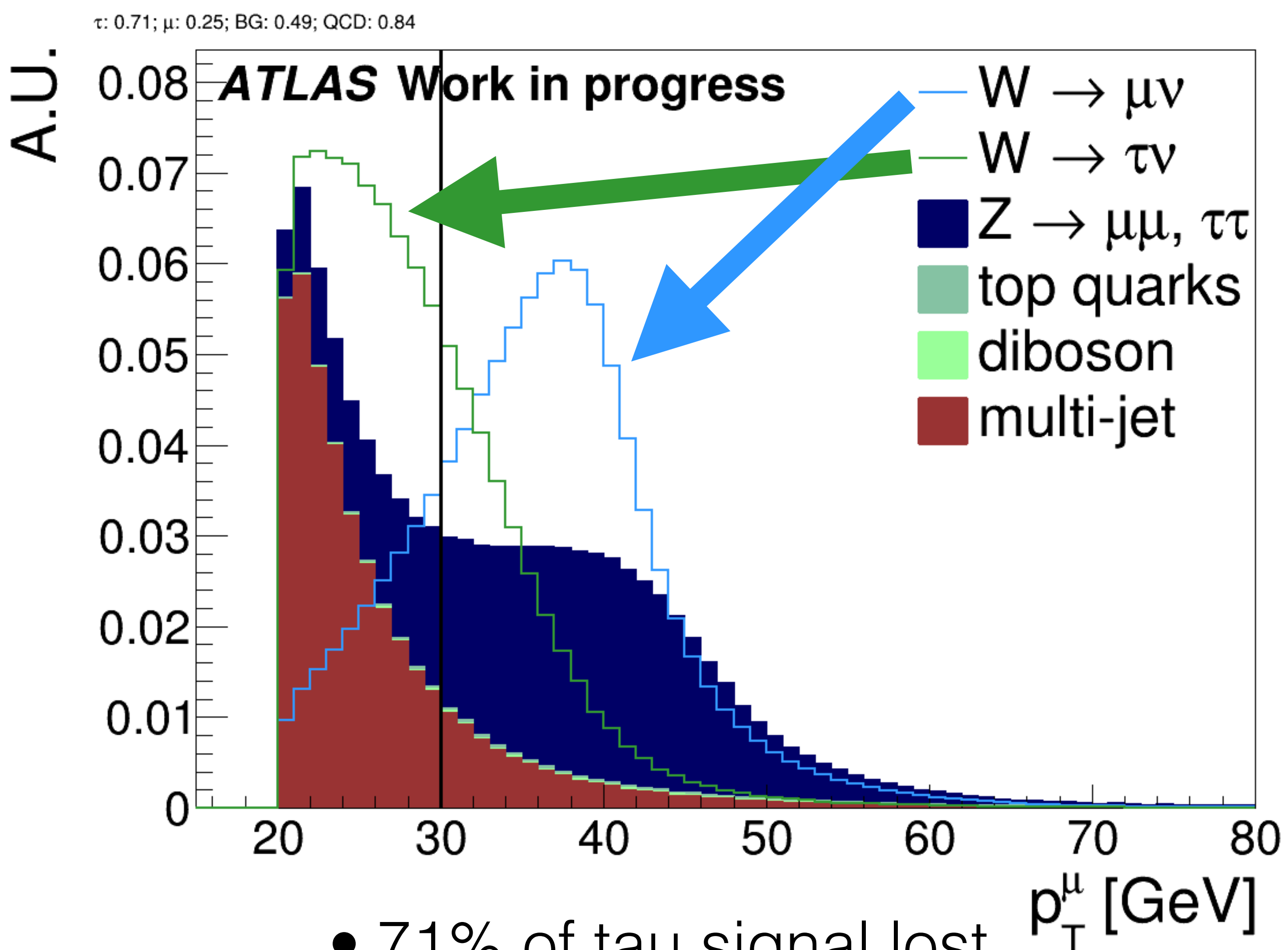
Parameter	initial value and error	fitted value and error
Rtaumu_SIG	1.00 ± 0.000100	1.00 ± 0.047772

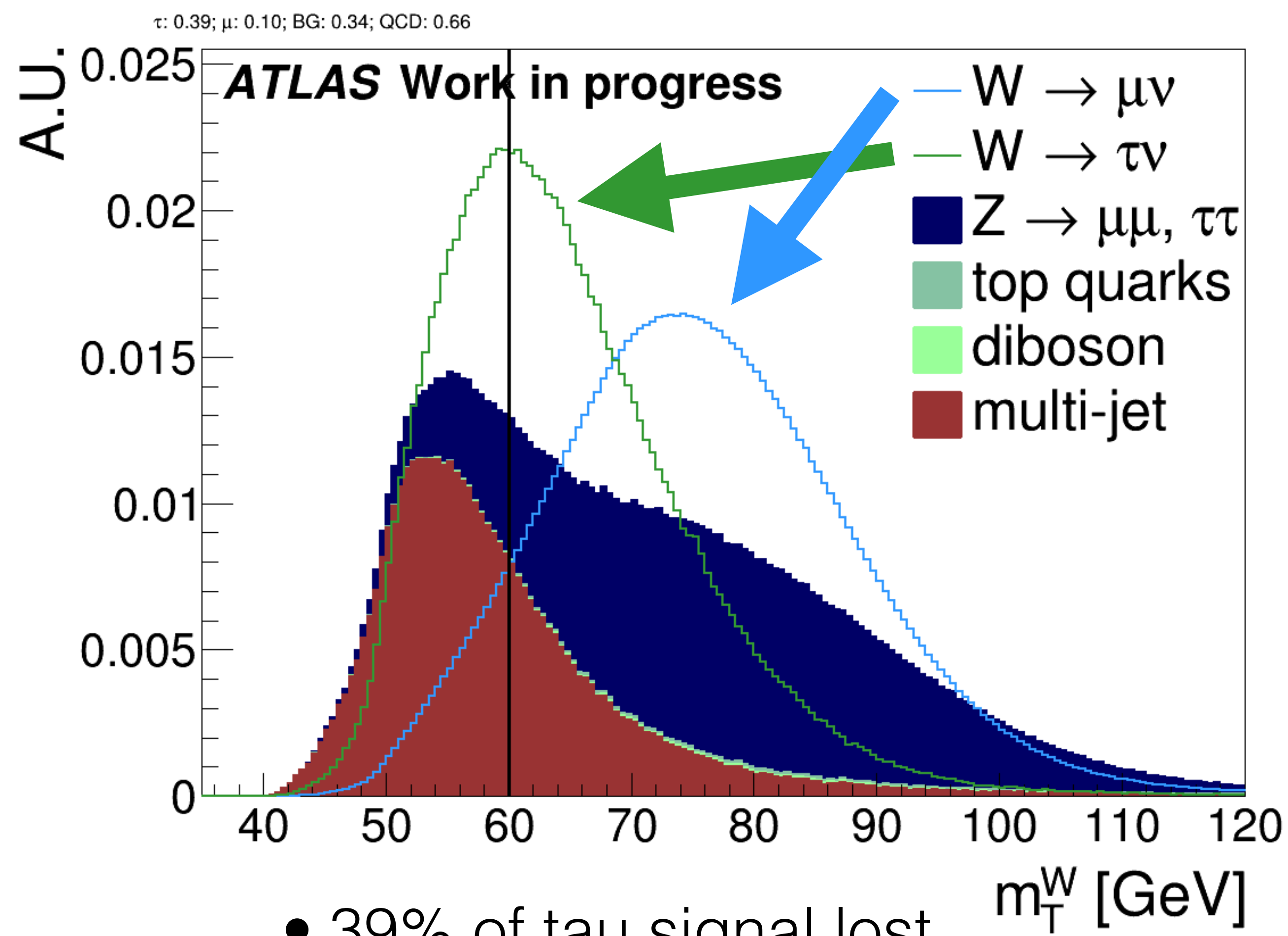
- Error on branching ratio relatively high (~14.3%)
- Statistical error is 4.8%
- Error is confirmed by Toy Data
- Error is rather stable for different pull factors





Relax Cuts





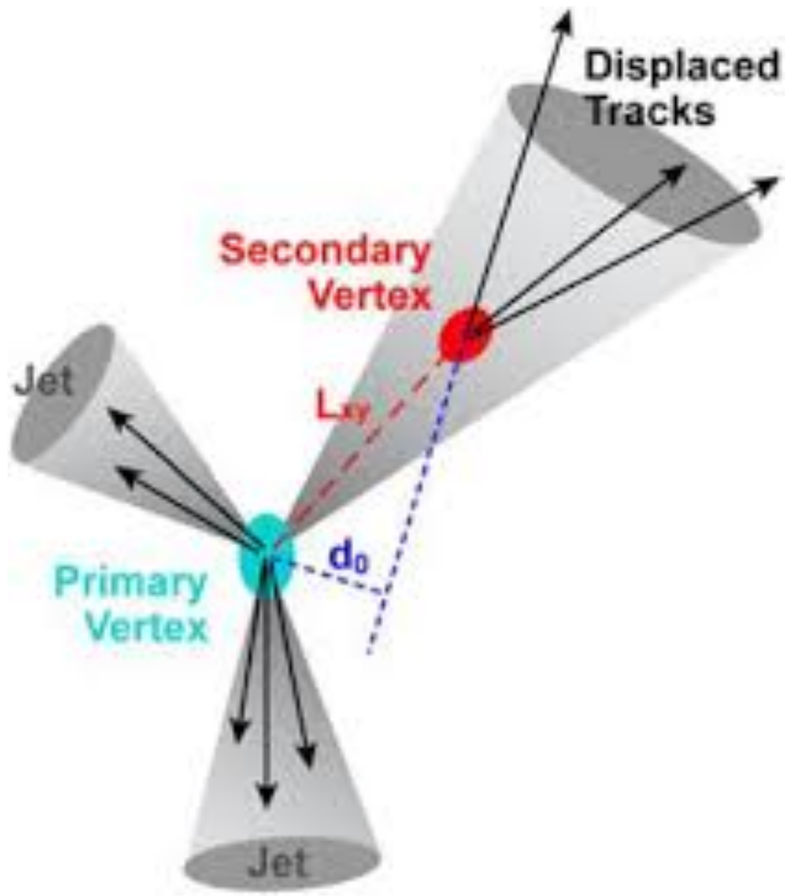
- 71% of tau signal lost
- 39% of tau signal lost

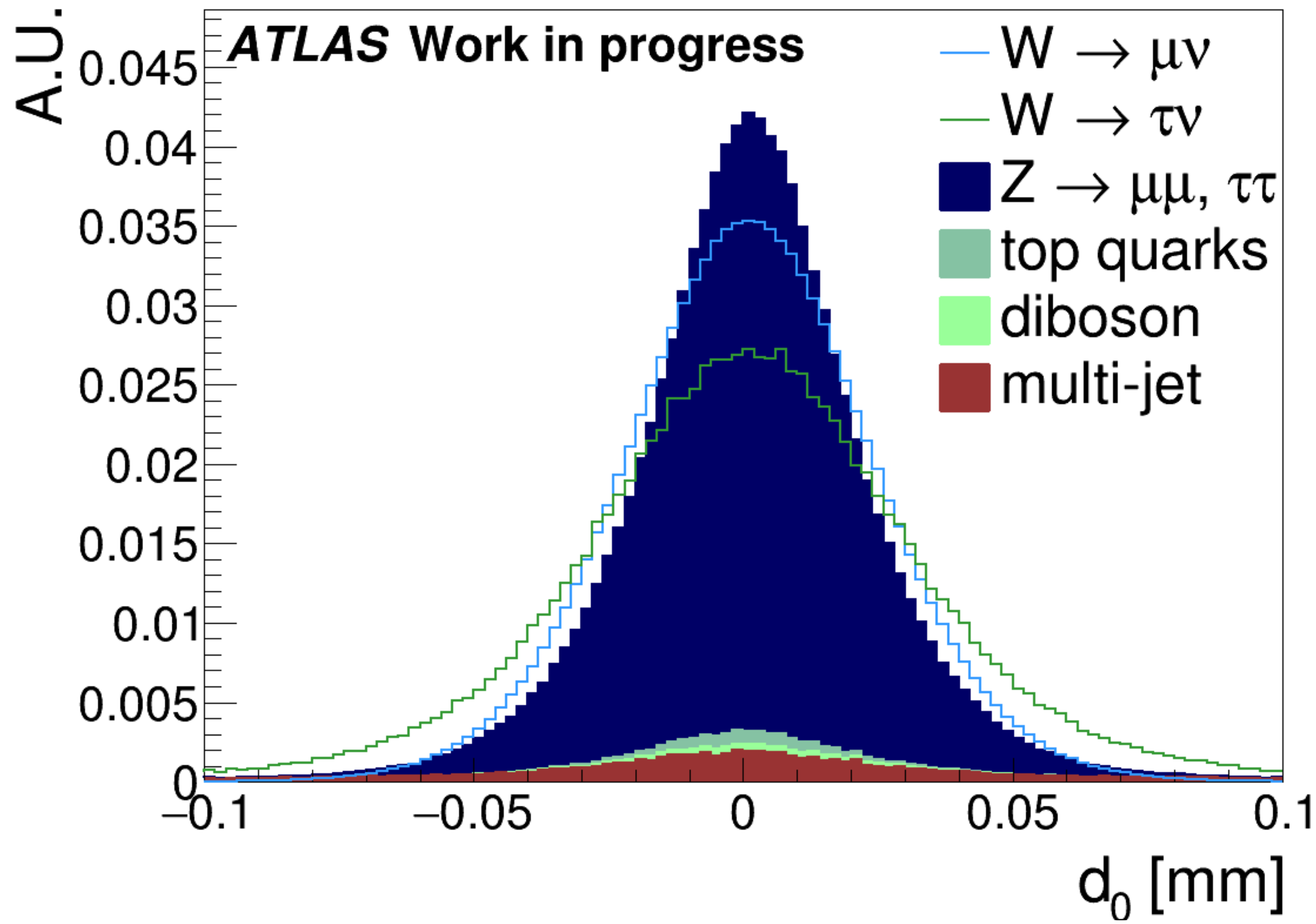
p_T : 30 GeV, m_T^W : 60 GeV → p_T : 20 GeV, m_T^W : 40 GeV

14.3% (4.8% stat) → 10.4% (2.4% stat)

➡ Need to further reduce the uncertainties

Vertexing



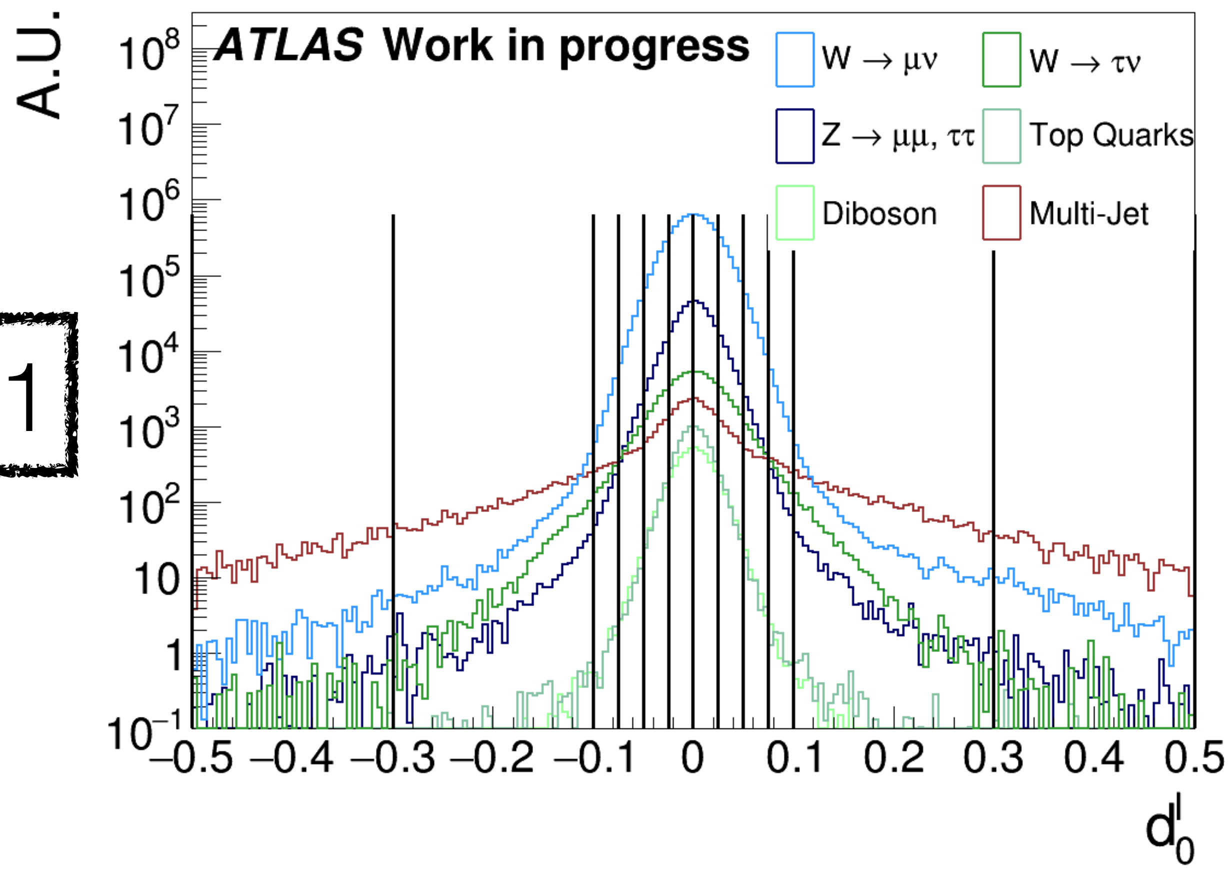


- Visible shape difference due to lifetime of tau lepton (decays after 87μm)
- Completely independent from kinematic quantities
- Needs to be explored in detail
- 2D Histogram unrolled in one dimension (due to technical limits of HistFitter)

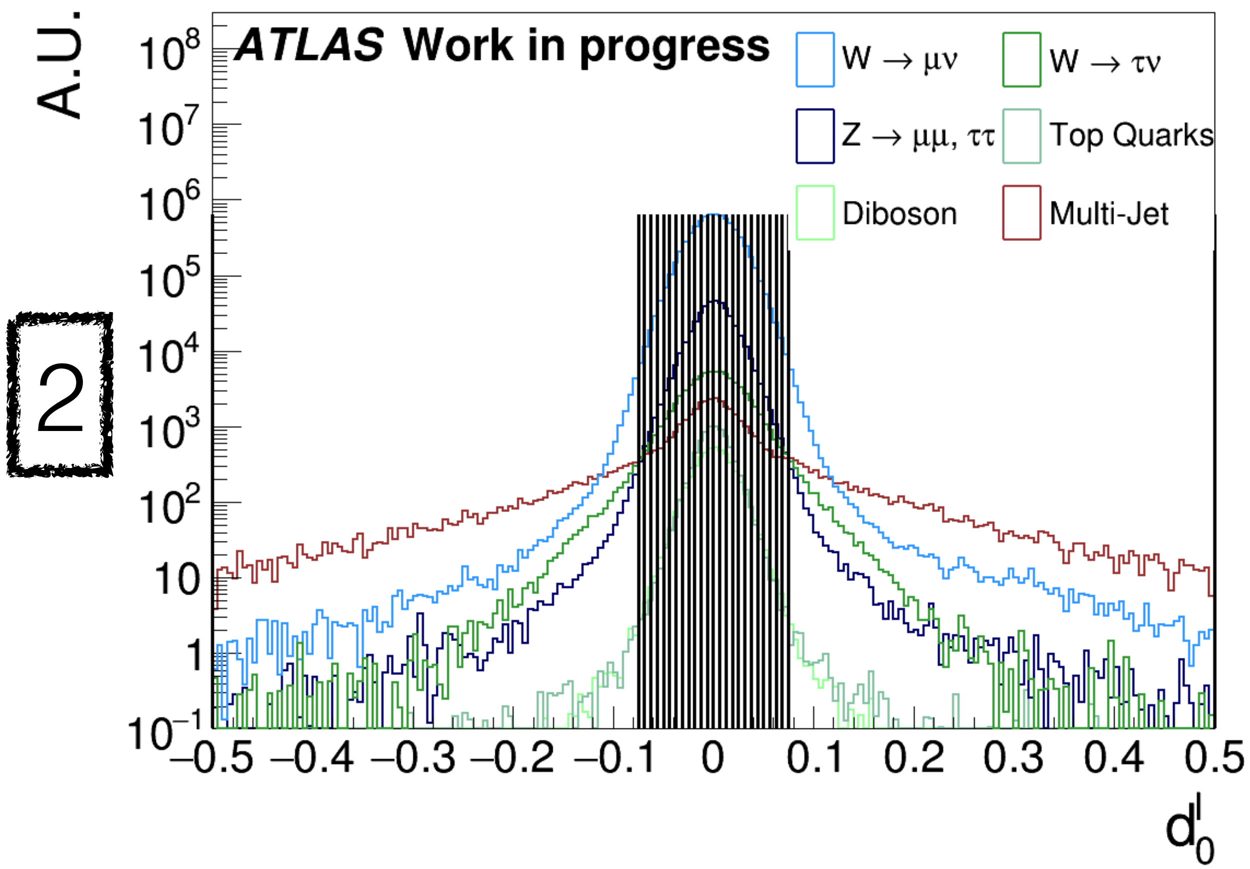
Source: http://atlas.kek.jp/sub/documents/jps201409/18pSK-6.pdf

2D Fit

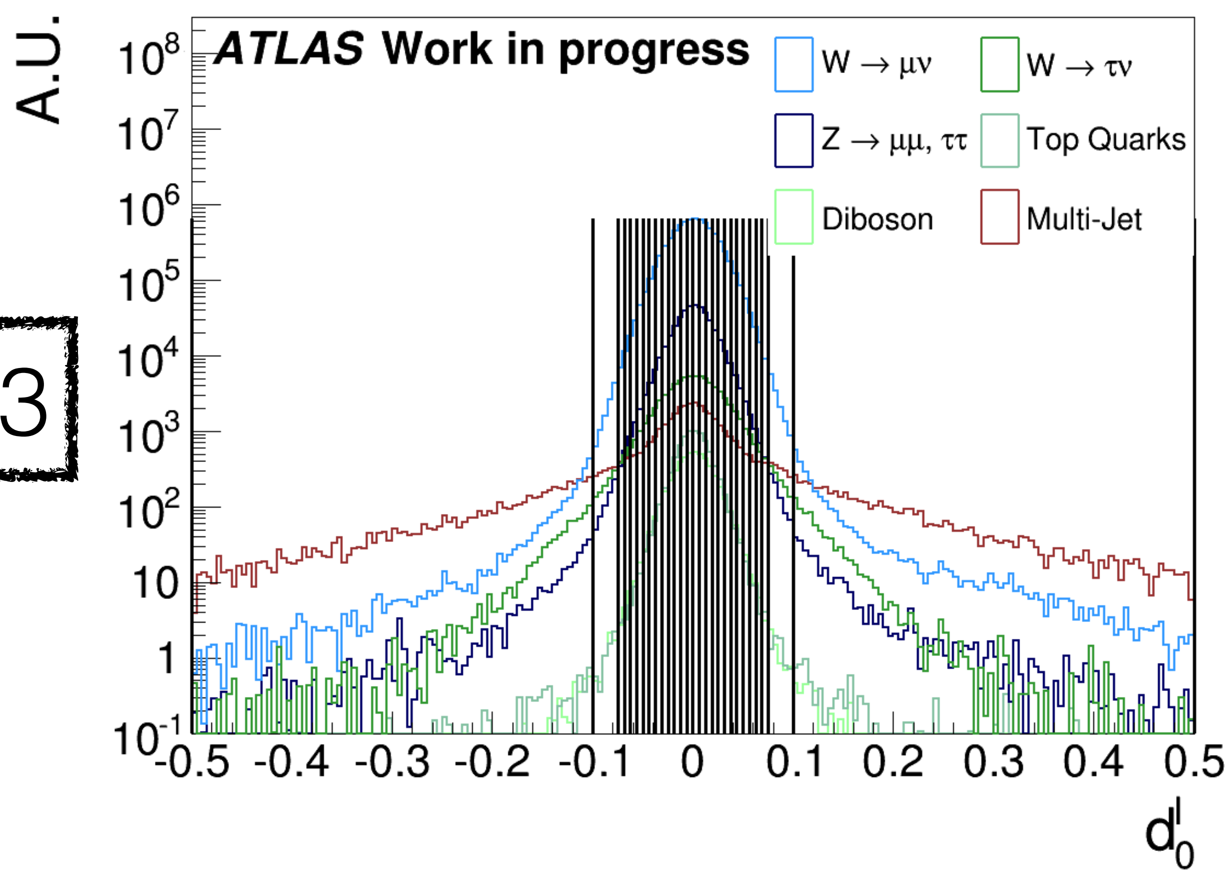
1



2



3



- 3 different binning configurations in d0

2D Fit

	Muons	Electrons	Combined
1D Fit	4.8 %	5.4 %	3.6 %
Binning 1	2.5 %	4.3 %	2.2 %
Binning 2	2.9 %	4.3 %	2.4 %
Binning 3			2.1 %
Relaxed Cuts Binning 3	0.6 %	1.2 %	0.5 %

- numbers provided by Hannah Schmitz

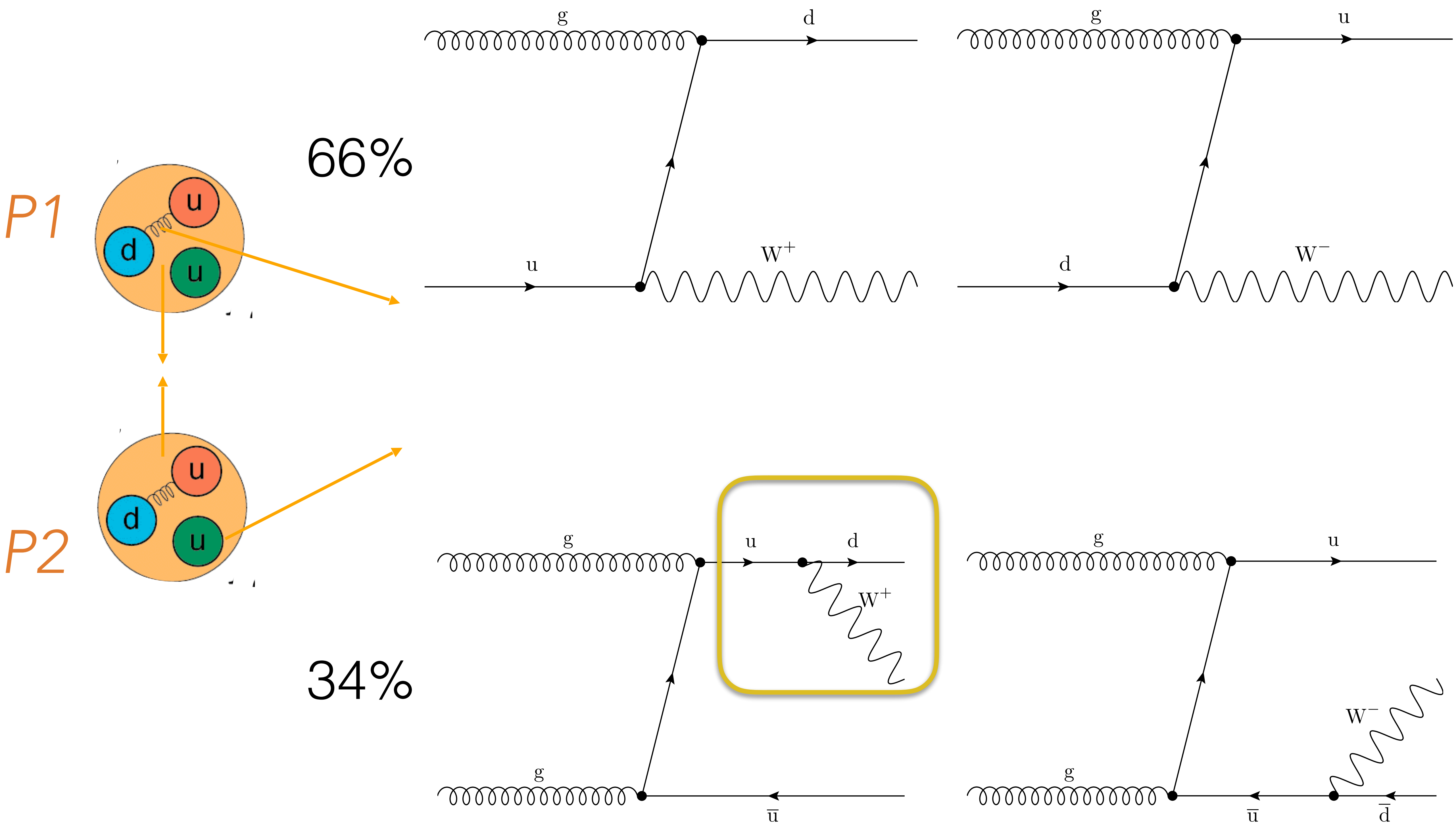
Summary and Outlook

- Precision measurement of the lepton universality is excellent possibility to test the SM and an indicator for BSM physics
- Analysis based on W-Mass measurement from ATLAS at 7 TeV
  - ➡ Joint the re-analysis effort for even better precision
- Fully consistent setup and a fully functional fit including all systematics for muons
- Relaxed cuts and/or adding d0 improve the sensitivity of the branching ratio measurement
- Include electron channel with all systematics to the fit
- Work on vertexing

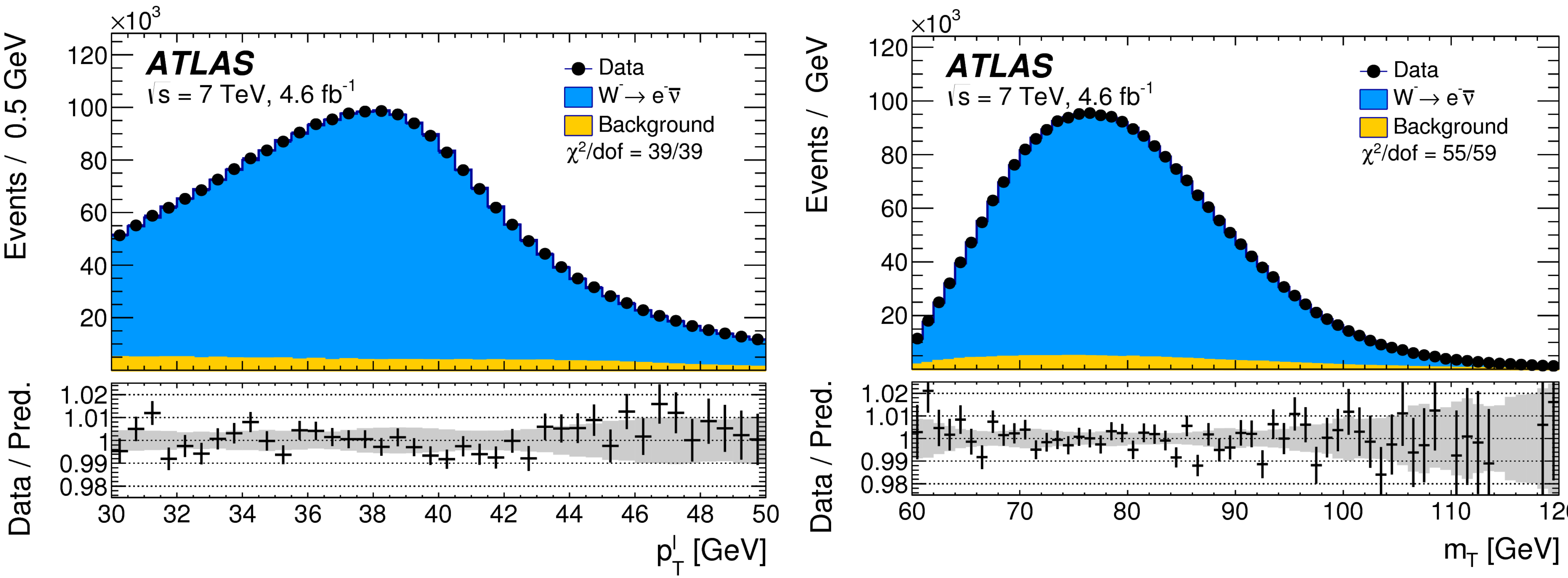
The End

Backup

Production of W-Bosons at the LHC



Results from W-Mass Measurement

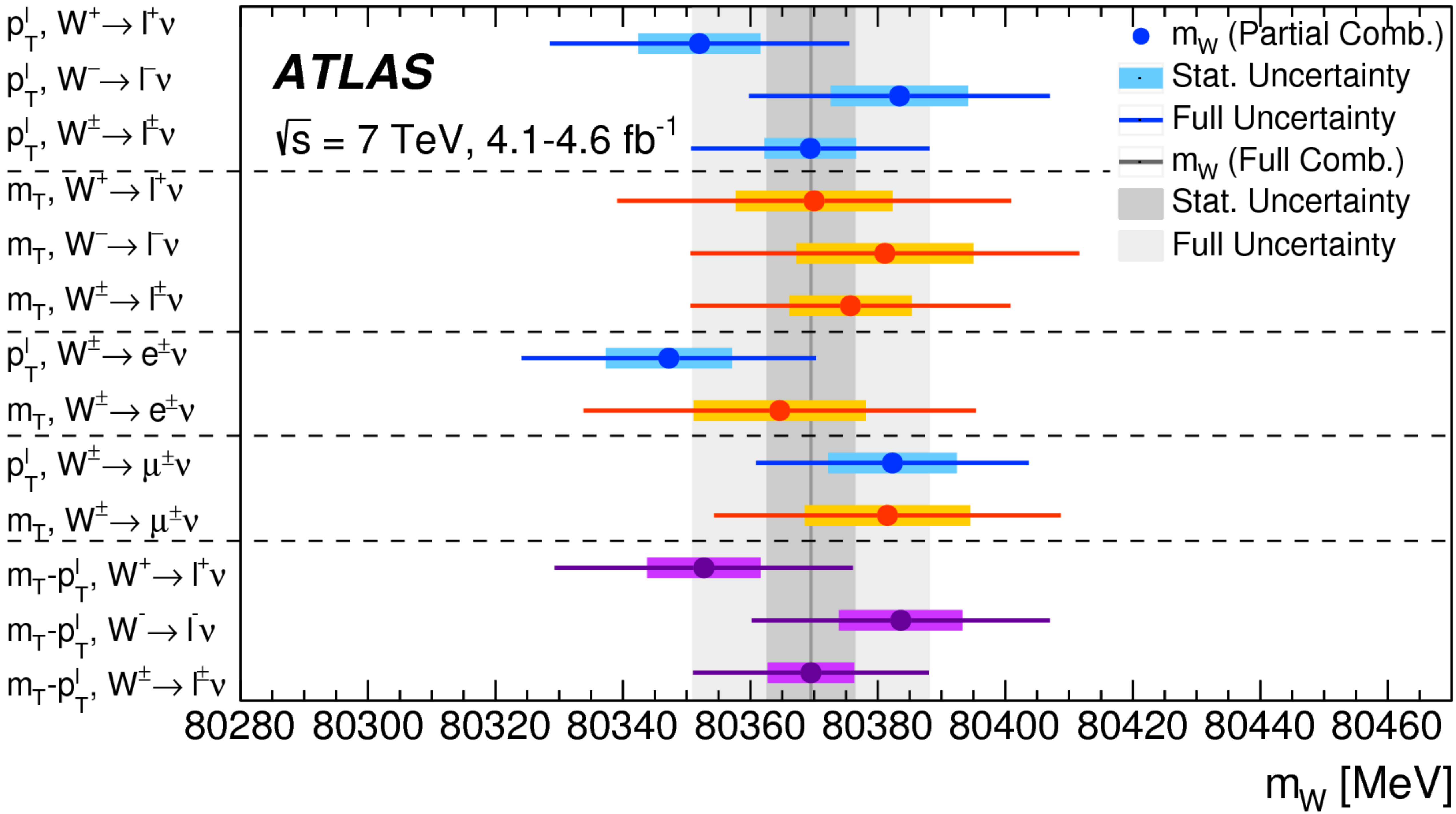


$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{l} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \Delta\phi(p_{\mathrm{T}}^{l}, p_{\mathrm{T}}^{\mathrm{miss}}))}$$

- MC template fit for different masses in pT or mT
- Fitted positive and negative leptons separately

Source:arXiv:1701.07240

Results from W-Mass Measurement



Source:arXiv:1701.07240

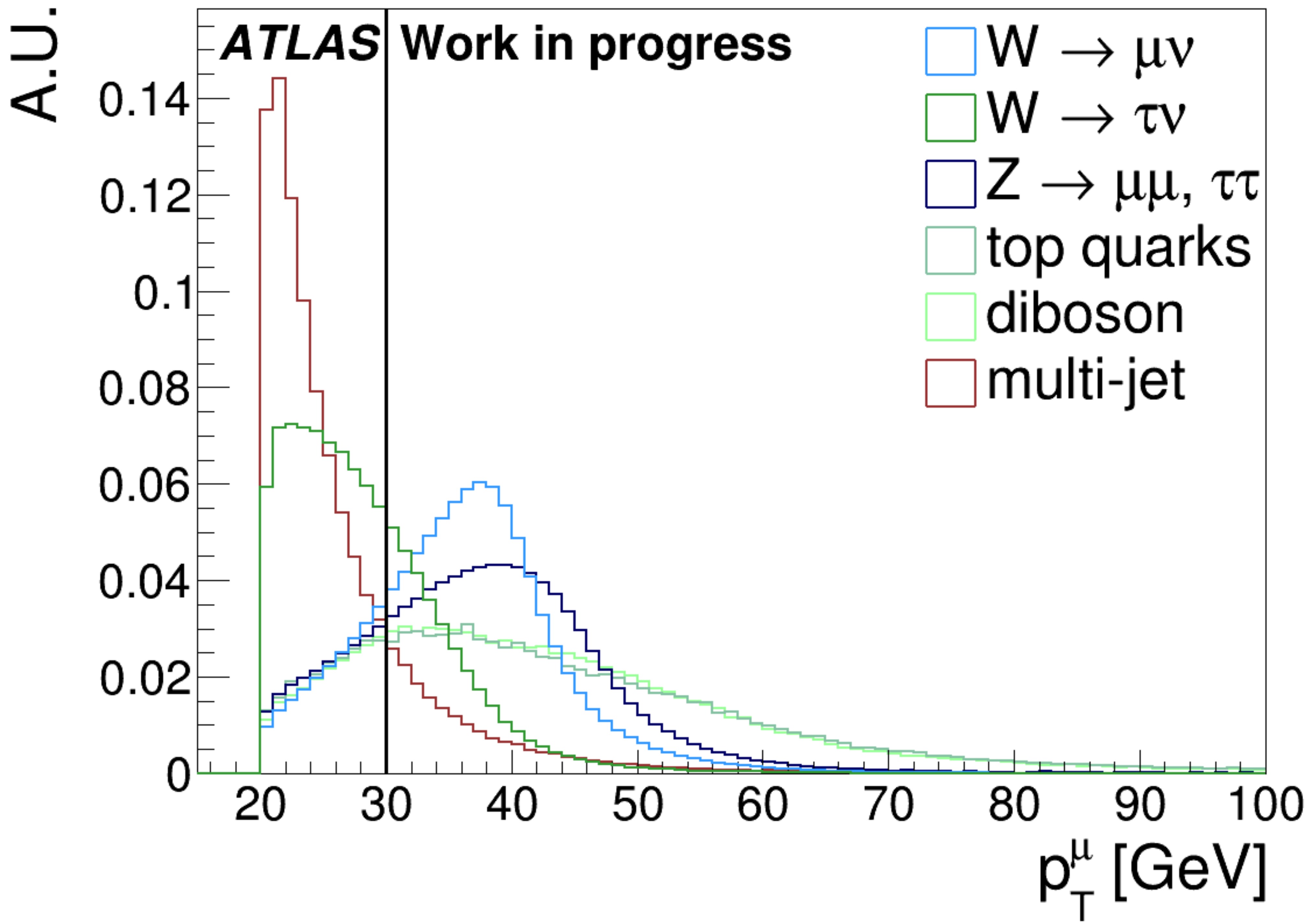
Introduction to fit setup

- implemented histogram-based fit in HistFitter
- multi-bin fit of $p_{\mathrm{T}}^{\mu^+}$ in 20 bins from 30 to 50 GeV
- H_data != mu_tau*H_tau + mu_mu*H_mu + mu_B*H_B + syst

  = mu_mu*Rtaumu*H_tau + mu_mu*H_mu + mu_mu*Rbkgmu*H_B + syst

  = **mu_mu***(**Rtaumu***H_tau + H_mu + **Rbkgmu***H_B) + syst
- so we have **one overall normalisation** scale factor and **two „branching ratio“** scale factors
- used AsimovData (so summed up background without smearing, fit should not pull the branching ratio)

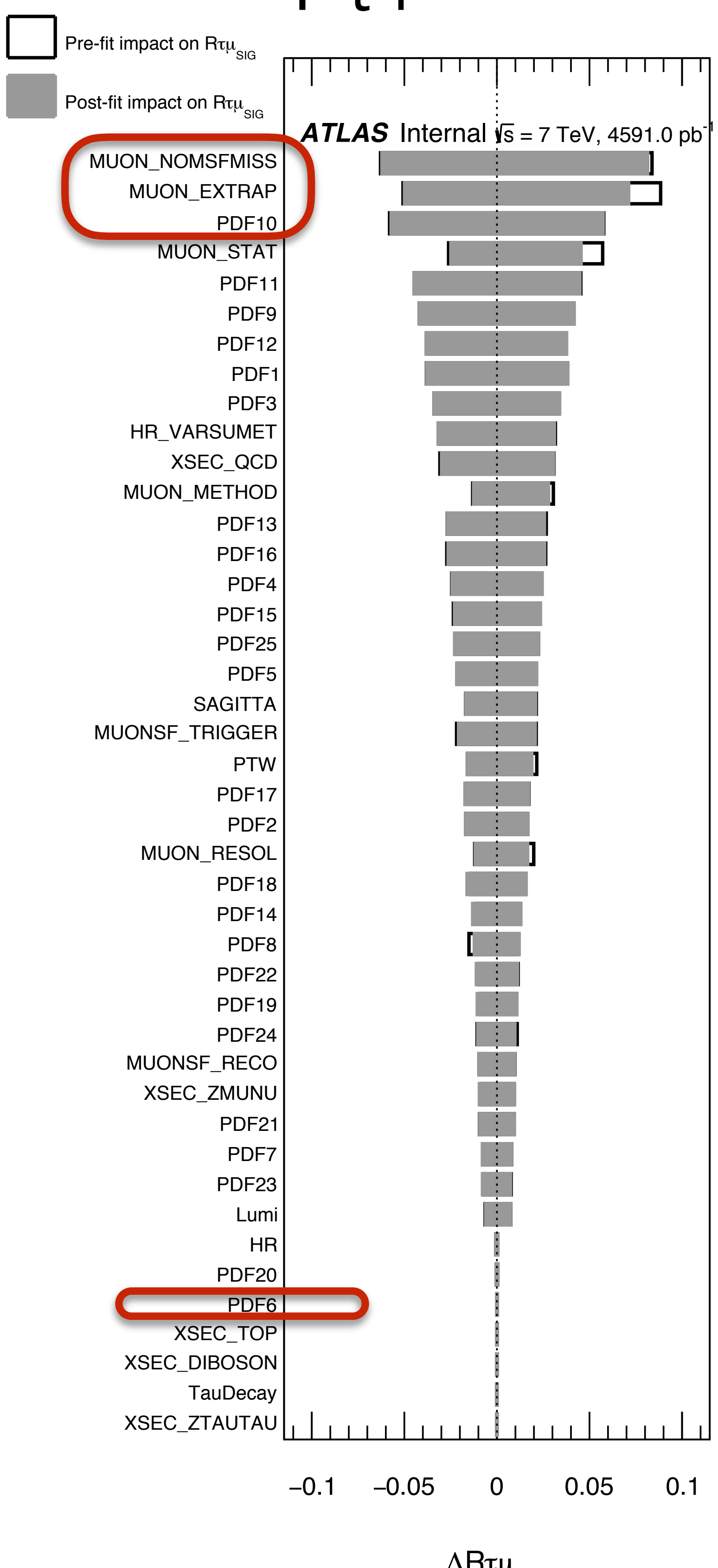
Relax Cuts



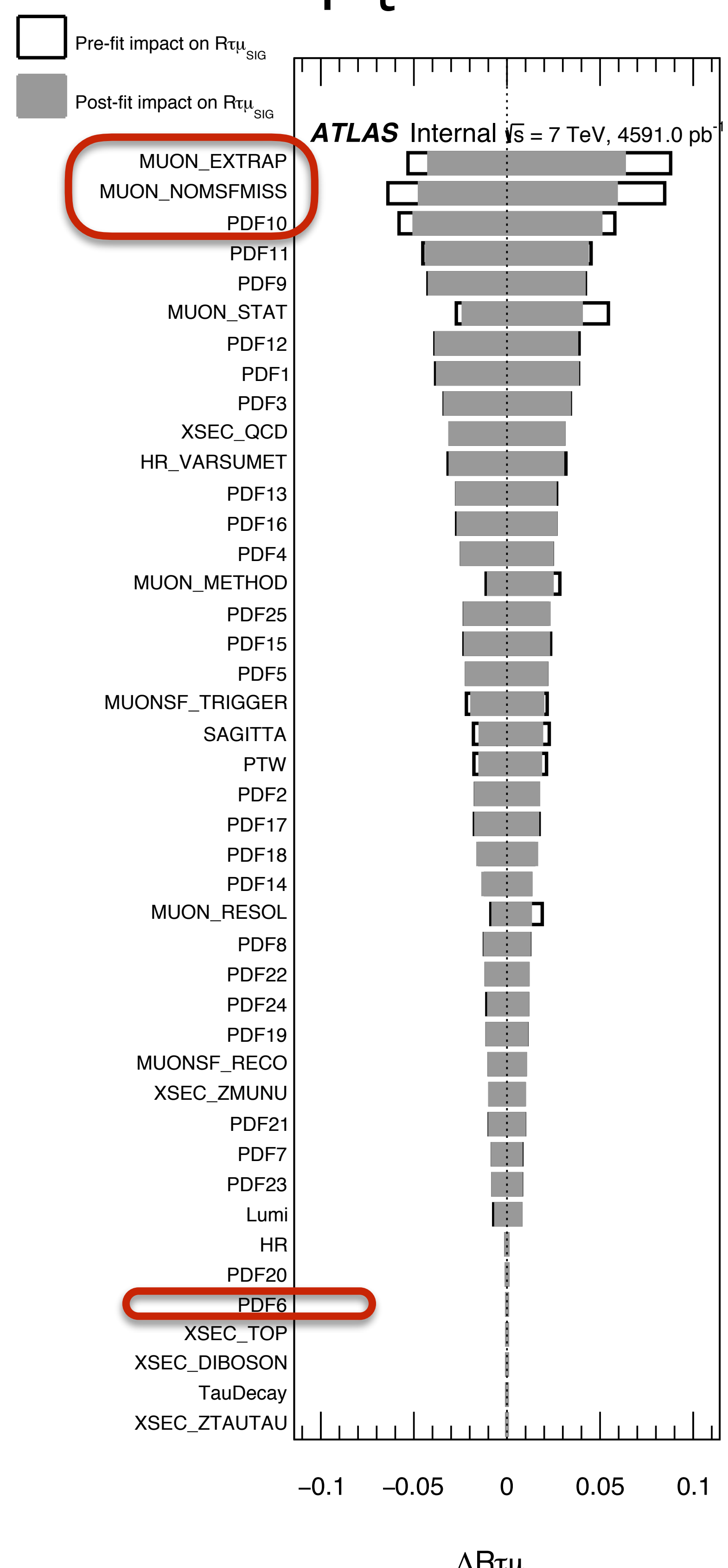
A.U.
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ATLAS Work in progress
W → μν
W → τν
Z → μμ, ττ
top quarks
diboson
multi-jet
20
30
40
50
60
70
80
90
100
p$_T^\mu$ [GeV]

Ranking plots

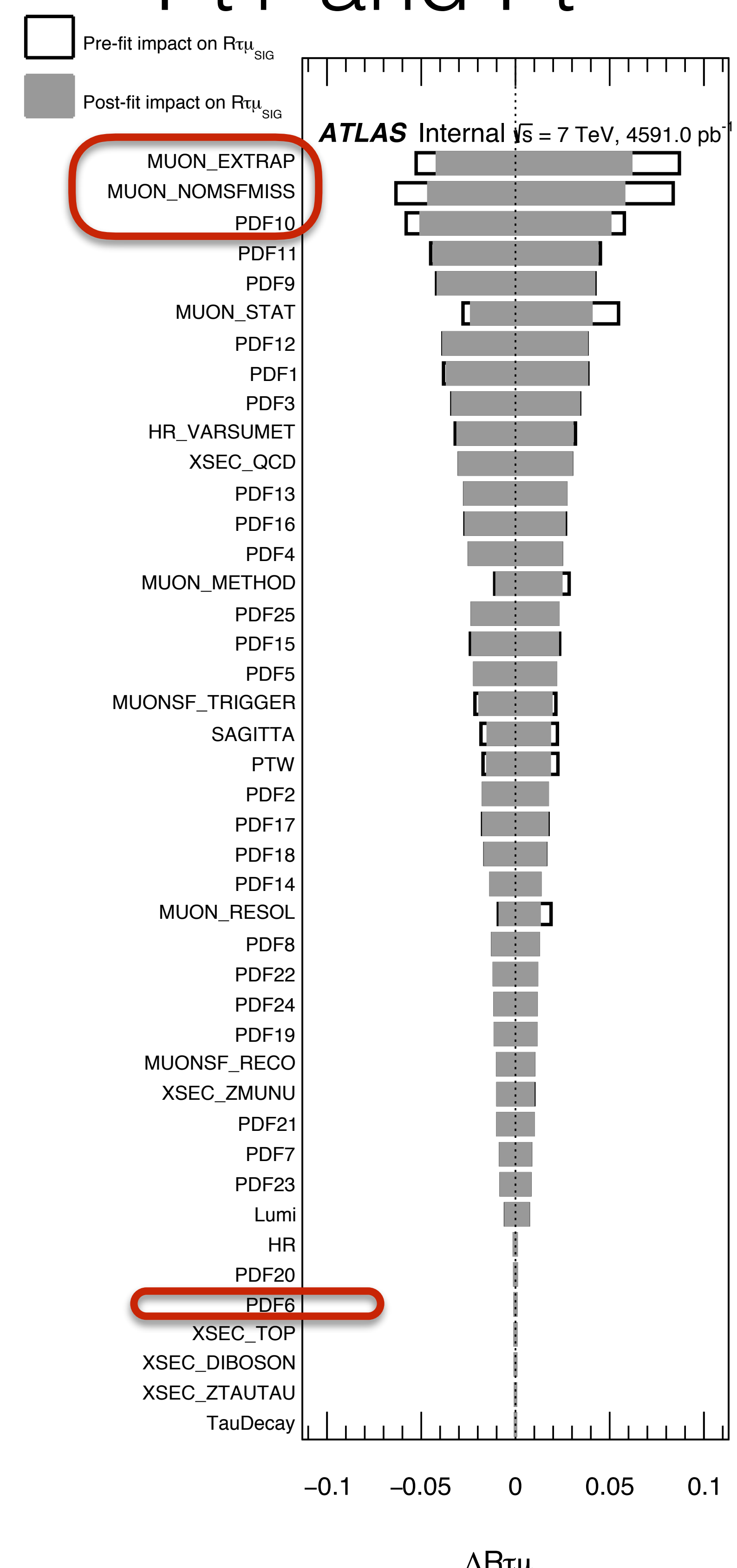
Pt+



Pt-

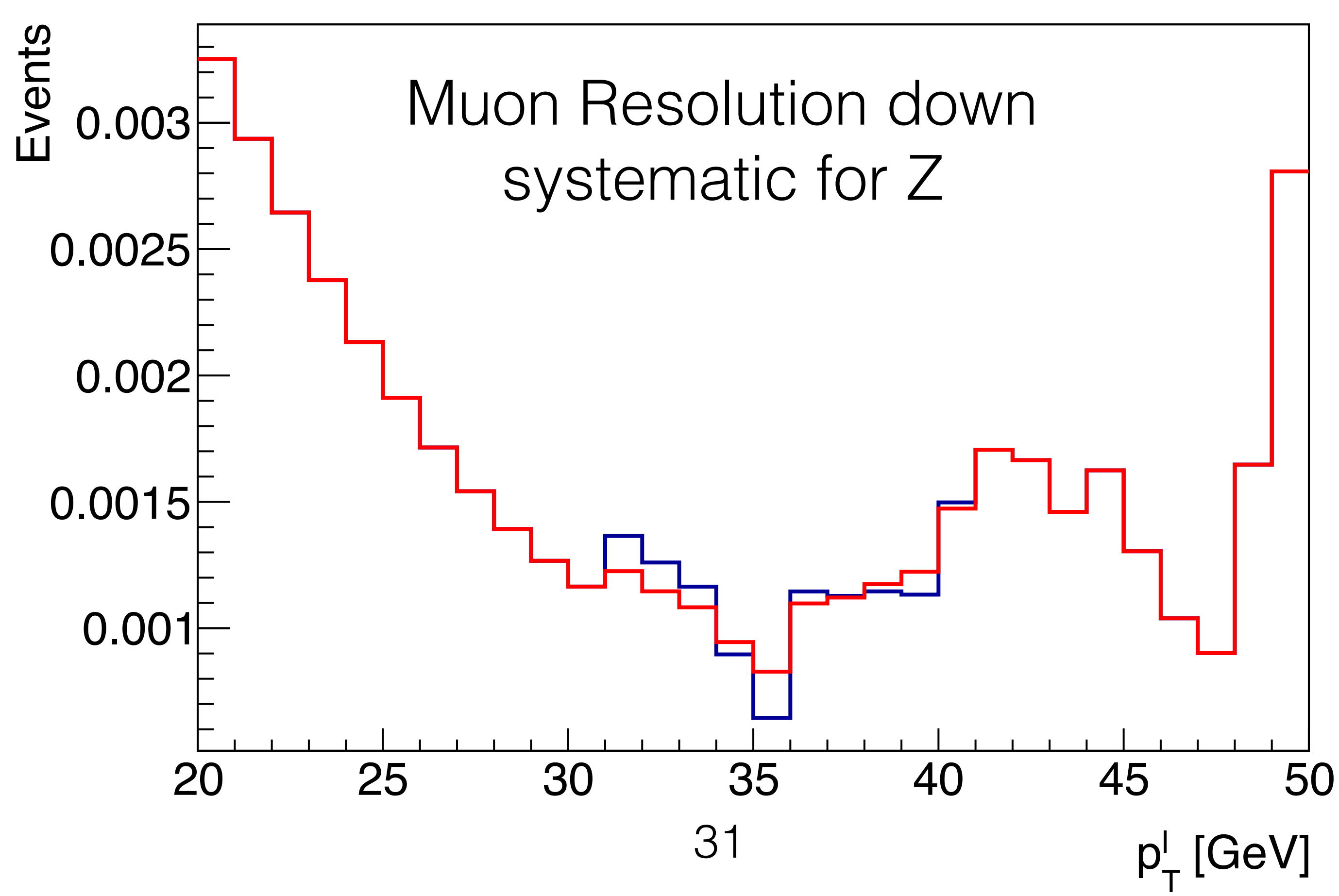


Pt+ and Pt-



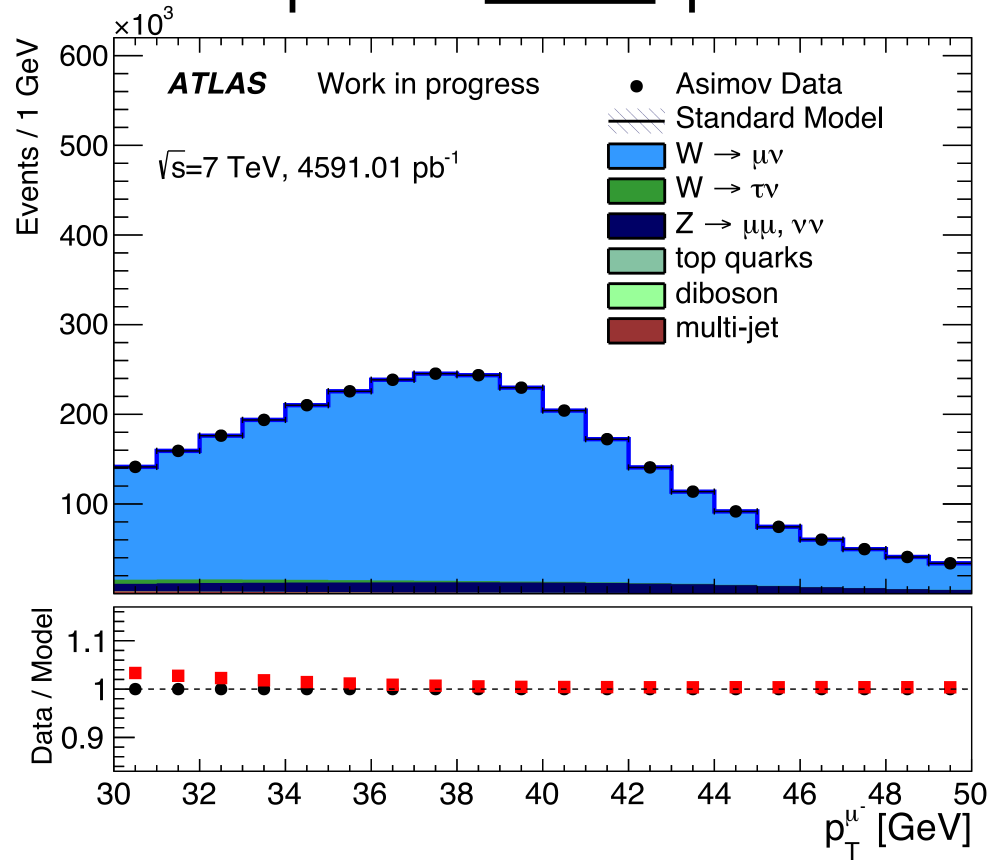
Extrapolated systematic uncertainties

- Fitted polynomial function 2nd order to the first half of the histogram
- 1st approach: Take fit function as systematic unc. for pT values < 30 GeV
- 2nd approach: Re-evaluate the systematics in the range between 30-40 GeV by taking the mean of the old systematic and the fit function



Results with more Statistics

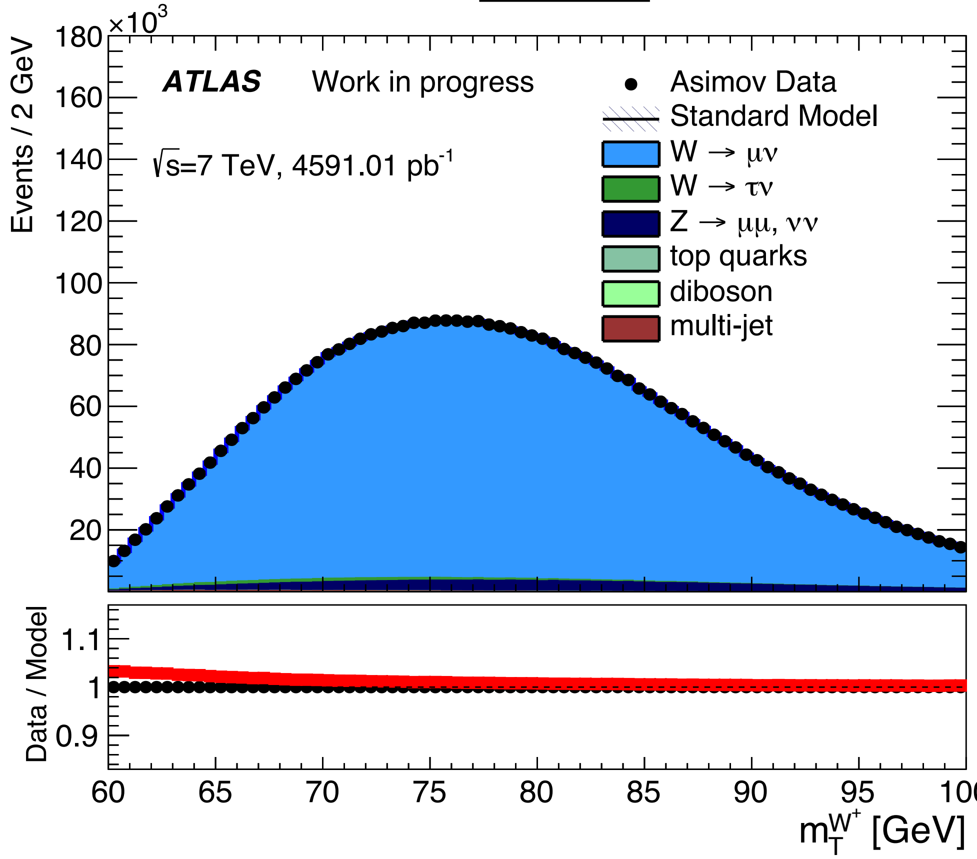
pT+ **and** pT-



Parameter	initial value and error	fitted value and error
Rtaumu_SIG	1.00 ± 0.000100	1.00 ± 0.143262

- Error on POI is 14.3%
- Statistical error is 4.8%

mT+ **and** mT-



Parameter	initial value and error	fitted value and error
Rtaumu_SIG	1.00 ± 0.000100	1.00 ± 0.173735

- Error on POI is 17.4%
- Statistical error is 5.8%

Maximum Likelihood

Idea: Maximize $\log L(\mu)$ in all bins [2]

$$-\log L(\mu) = (\mu S + B) + \log n! - \sum_{e=1}^{n} \log(\mu S f_s(x_e) + B f_B(x_e))$$

- Attention: The used Likelihoods depend on normalization factors and statistical uncertainties

[2] Source [2]

Maximum Likelihood

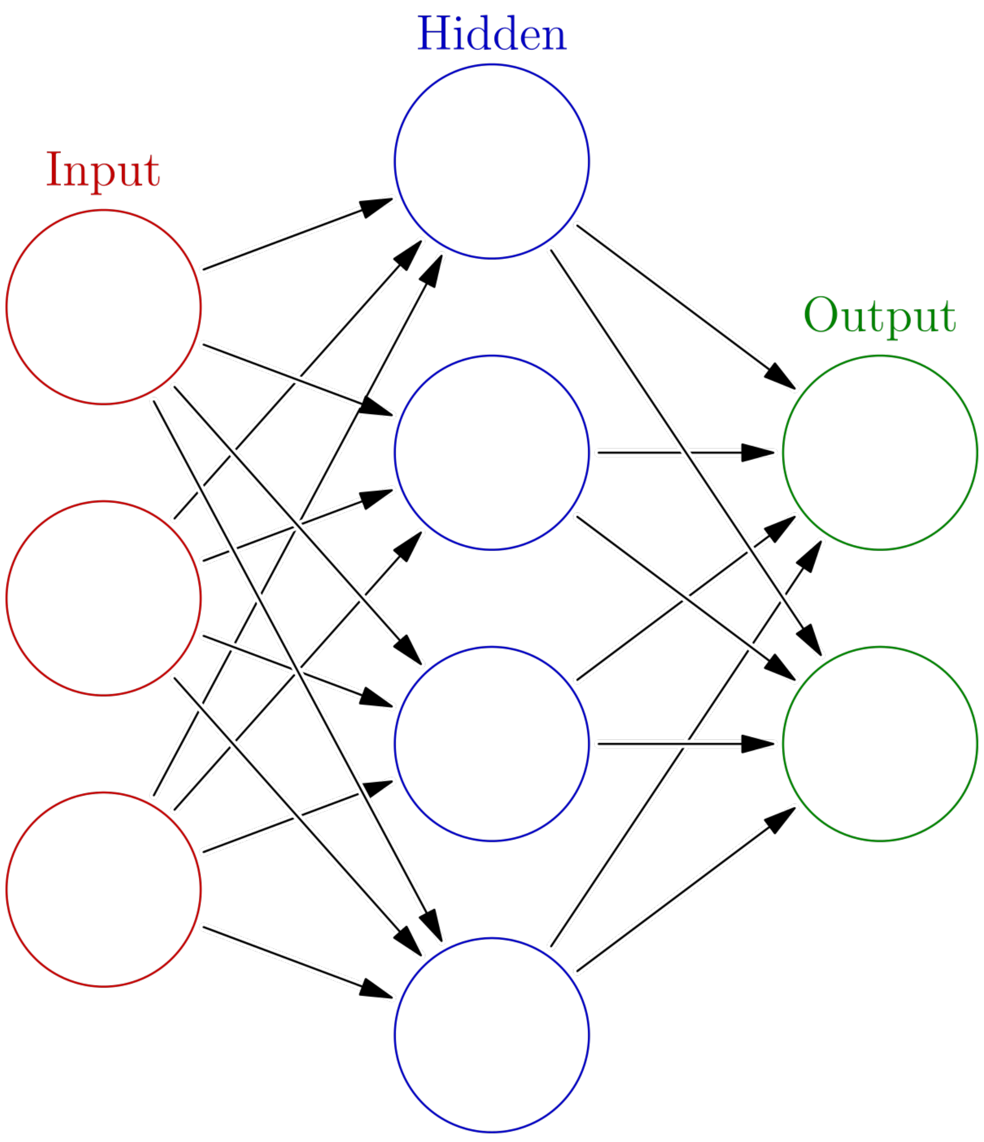
Idea [1]: Find probability model for receiving n events in the data where the variable e has a value x_e

$$P(x_1 \dots x_n|\mu) = \mathrm{Pois}(n|\mu S + B) \prod_{e=1}^{n} \Big(\frac{\mu S \cdot f_S(x_e) + B \cdot f_B(x_e)}{\mu S + B} \Big)$$

S: number of signal events
B: number of background events
$f_S(x)$ and $f_B(x)$: signal and background shape
μ: signal strength

[1] Source [2]

Neural Network

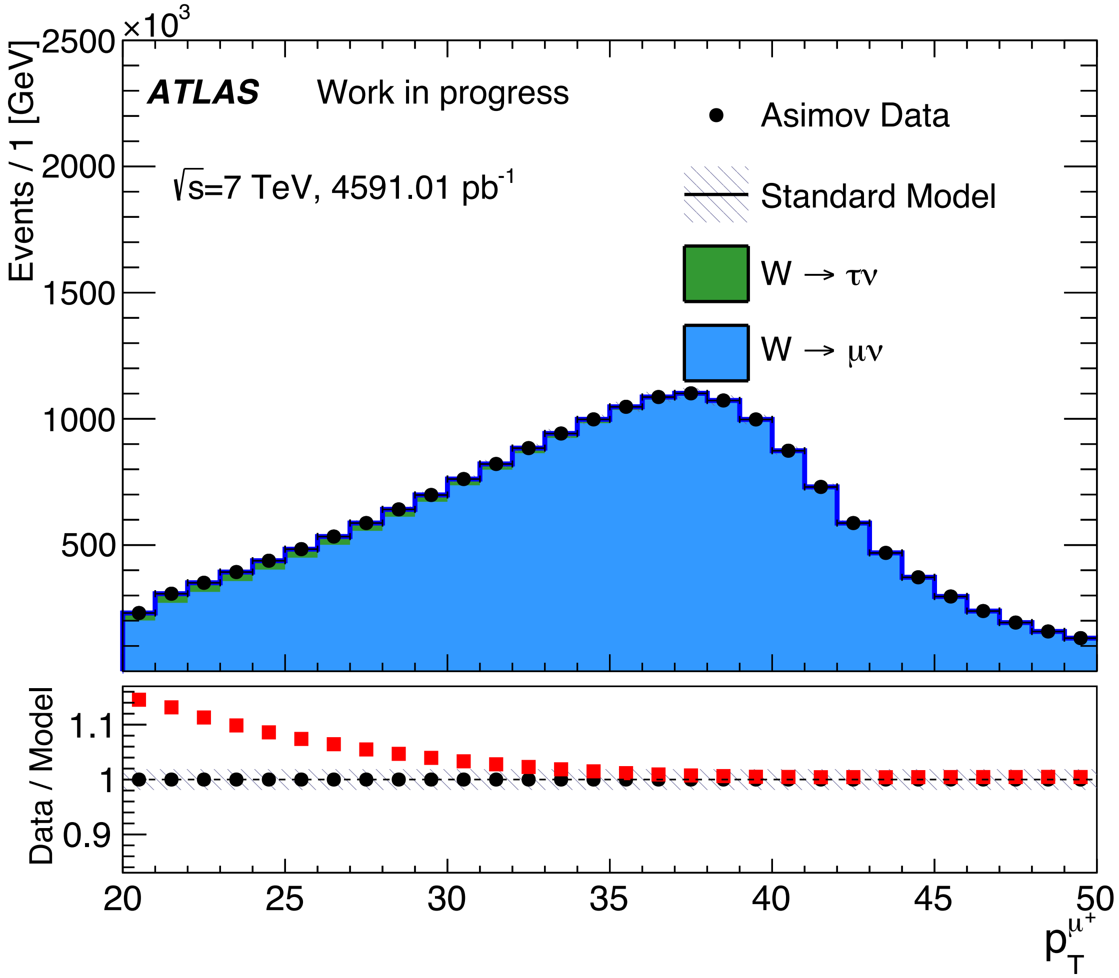


- 1 hidden layer with 50 nodes
- 14 input variables
- Desired output should be 0 for muons and 1 for taus

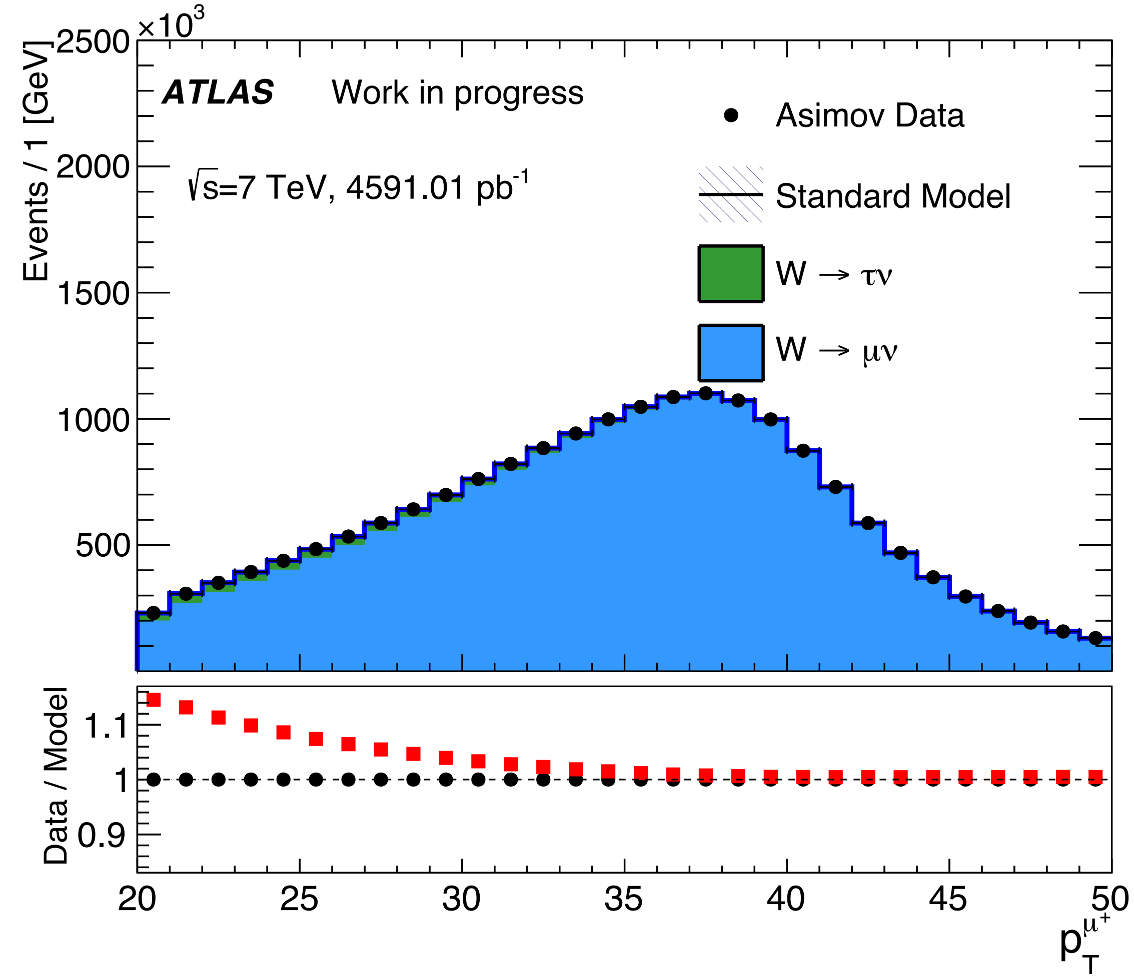
Source:arXiv:1701.07240

Pt of positive muons

before fit



after fit

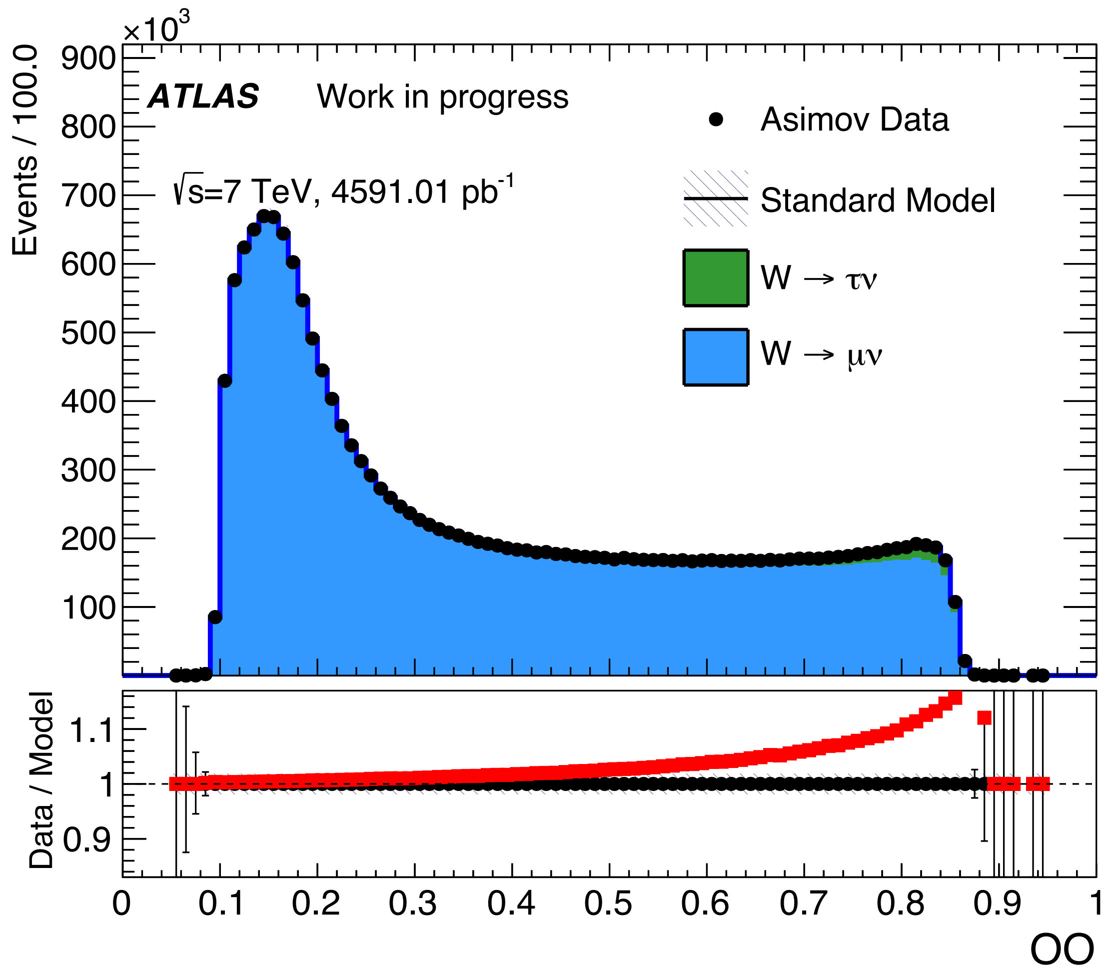


Parameter	initial value and error	fitted value and error
alpha_Lumi	0.00 ± 1.000000	0.00 ± 0.999991
mu_SIG	1.00 ± 0.000100	1.00 ± 0.019008
Rtaumu_SIG	1.00 ± 0.000100	1.00 ± 0.007869

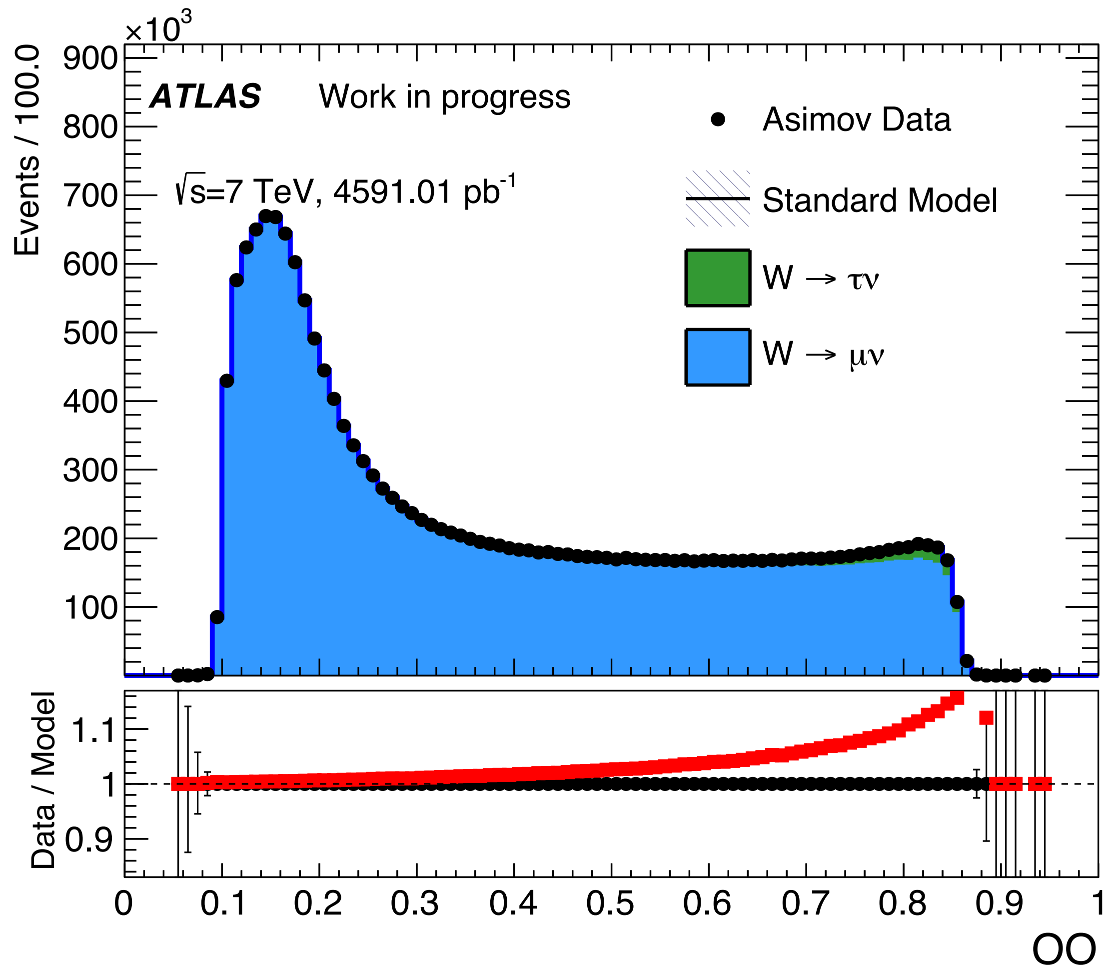
Table: Floating fit parameters for the analysis involving signal region SR, before (left) and after (right) the background-only fit. The quoted fit errors come from HESSE.

Neural Network with 14 Input Observables

before fit



after fit



Parameter	initial value and error	fitted value and error
alpha_Lumi	0.00 ± 1.000000	0.00 ± 1.000007
mu_SIG	1.00 ± 0.000100	1.00 ± 0.019009
Rtaumu_SIG	1.00 ± 0.000100	1.00 ± 0.007528

Table: Floating fit parameters for the analysis involving signal region SR, before (left) and after (right) the background-only fit. The quoted fit errors come from HESSE.