A mono-τ search with the ATLAS Detector in pp-collisions at $\sqrt{s} = 13\ TeV$

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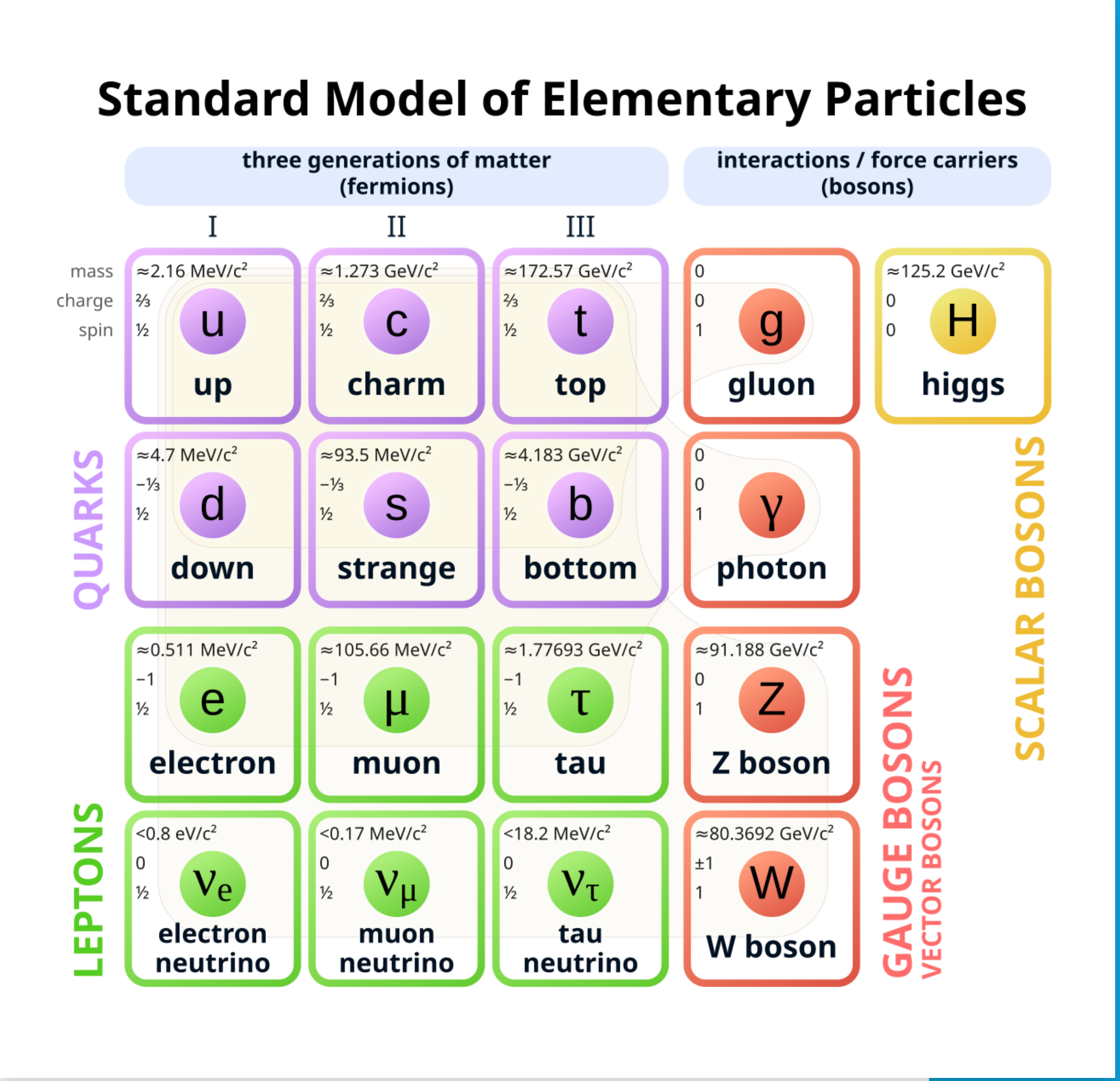
The Standard Model

- **Standard Model (SM)**
  Theoretical framework
  - Matter particles
  - Interactions

- **Experimentally** verified at great extend

- **Shortcomings**
  - Gravity ?
  - Massive neutrinos ?
  - Hierarchy problem ?
  - Matter/Antimatter asymmetry ?
  - Experimental discrepancies ?

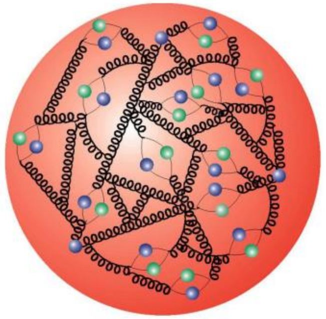


SM Symmetry

QCD **ElectroWeak**

$$SU(3) \times SU(2) \times U(1)$$

Quarks/gluons
Confinement
Hadrons (p : uud)

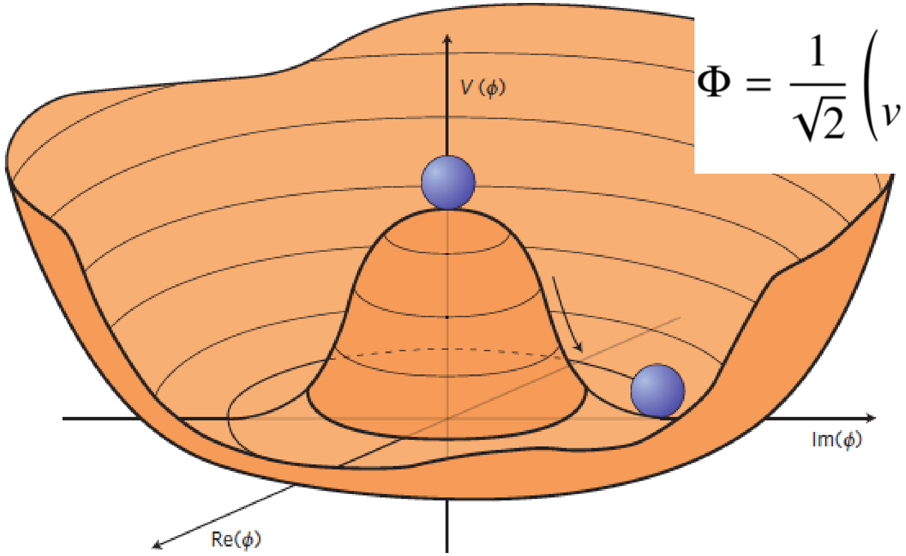


Spontaneous Symmetry Breaking

$$U_Q(1)$$

Electromagnetic Interactions (γ)
Massive gauge bosons
Massive fermions
Higgs Boson

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda |\phi^\dagger \phi|^2$$



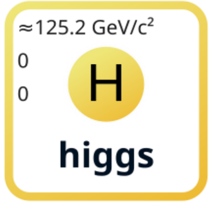
$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$m_{W^\pm} = \frac{gv}{2}$$

$$m_f = \frac{y_f v}{\sqrt{2}}$$

$$m_Z = \frac{m_W}{\cos \theta_W}$$

$$\cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}}$$



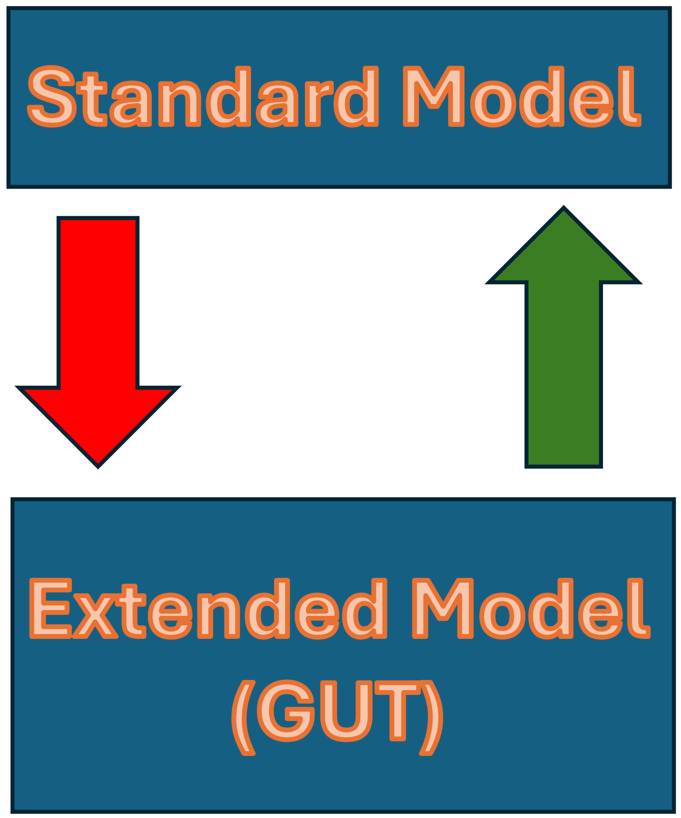
Extension of the SM

New theories can be built either by:

- **Standard Model Extension**
- **Breaking of Larger Symmetries (GUT)**

Example:
Left-Right Symmetric Models (Parity violation, right-handed neutrinos)

String Theories/GUTs with SO(10)



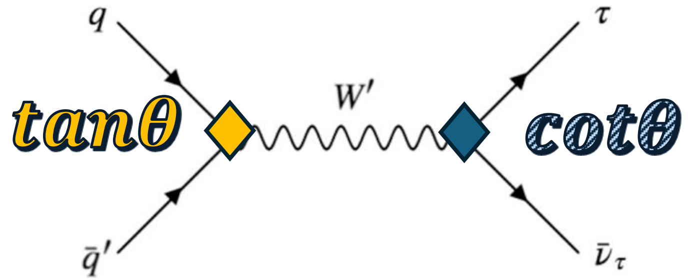
W' models

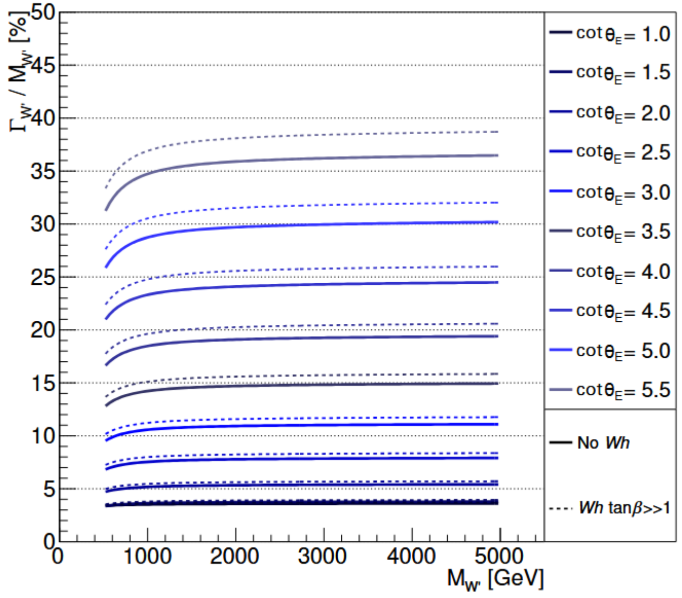
- **Emergence of W'**
  - Through breaking of Extended Symmetry
  - Depending on t
- **Sequential Standard Model**
  - Benchmark model
  - Same couplings as the SM W
- **Non-Universal Gauge Interaction Models (NUGIM)**
  - Couplings can vary between generations
  - Motivated by fermion mass-hierarchy, D-mesons ratio discrepancy

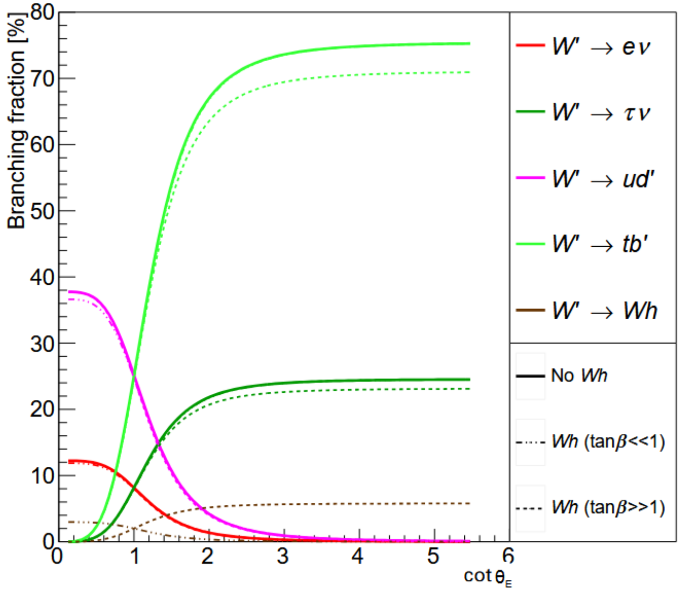
$$SU_1(2) \times SU_2(2) \times U(1)$$

$$\Downarrow$$

$$SU_L(2) \times U(1)$$



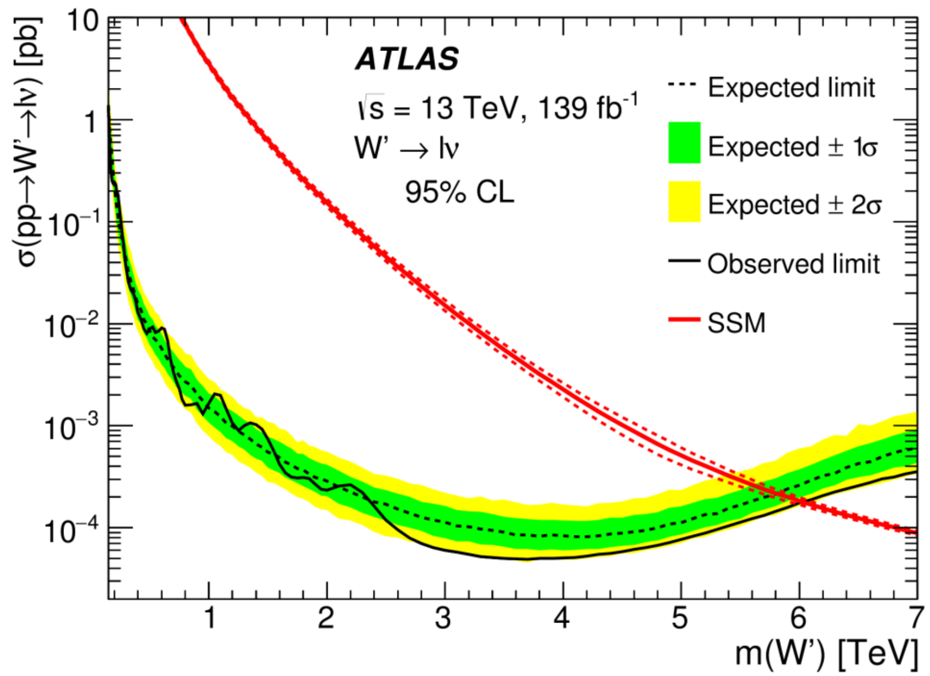


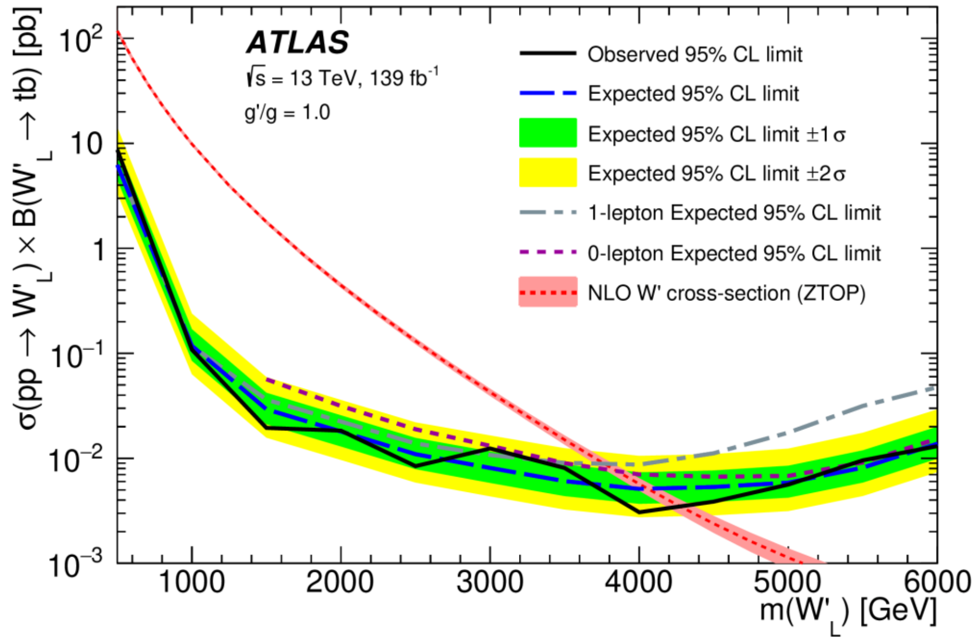


Experimental Searches

- **Resonance is unobserved**

- **Direct Searches**
  - Performed by ATLAS/CMS
  - Leptonic excluded <6 TeV @95% CL
  - tb excluded <4.2 TeV @95% CL
- **Indirect Searches**
  - Involve precision measurements/deviation of SM parameters





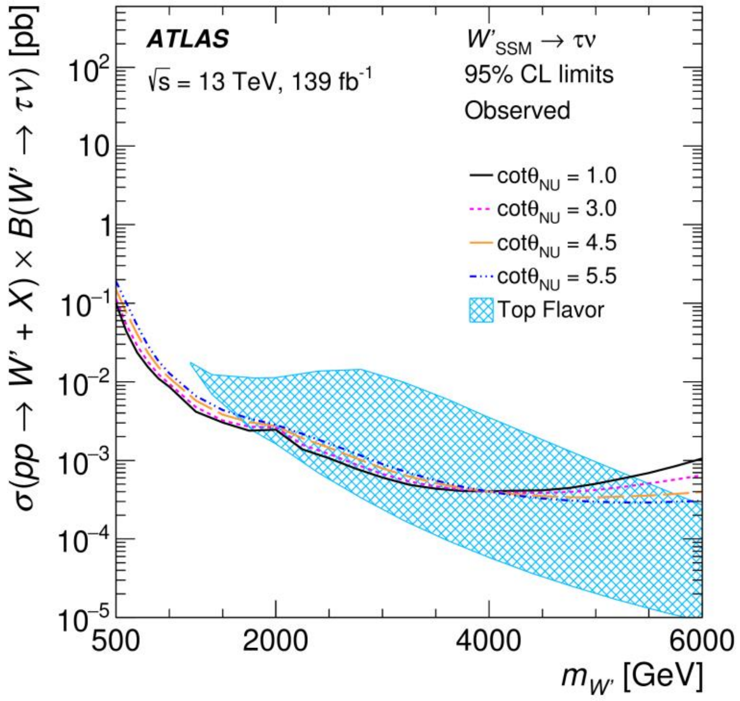
Motivations

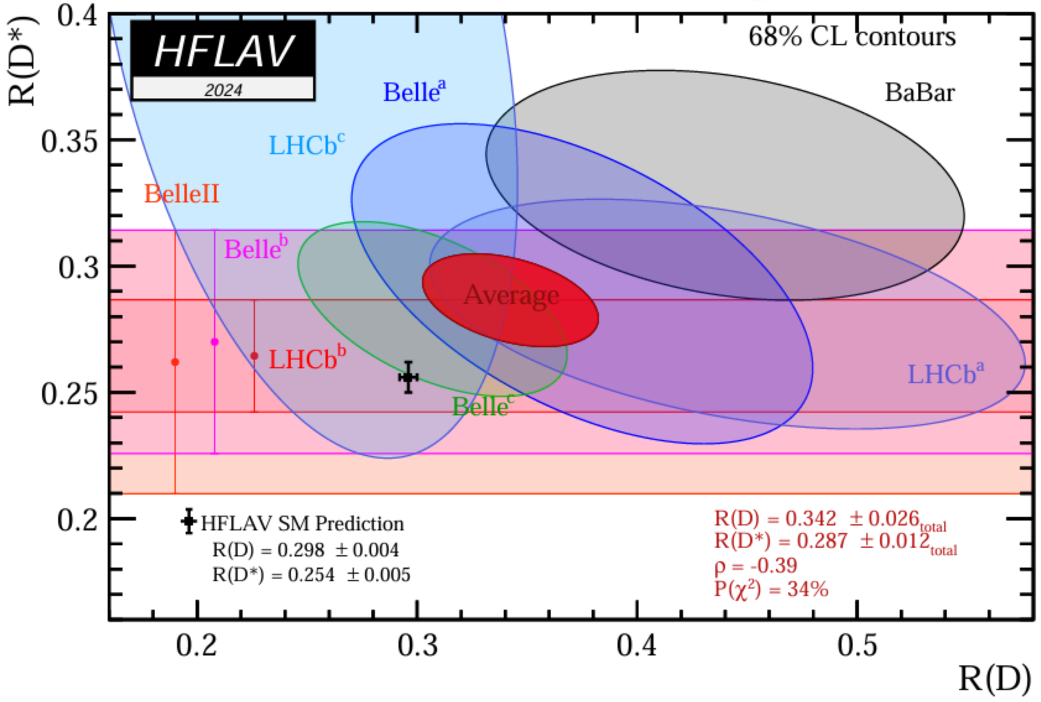
Why τ?

Hierarchy of fermion masses among generations (1^{st} / 2^{nd} << 3^{rd})

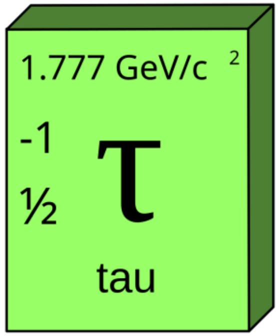
Consistent deviation in key SM parameters

Complementarity – New probes



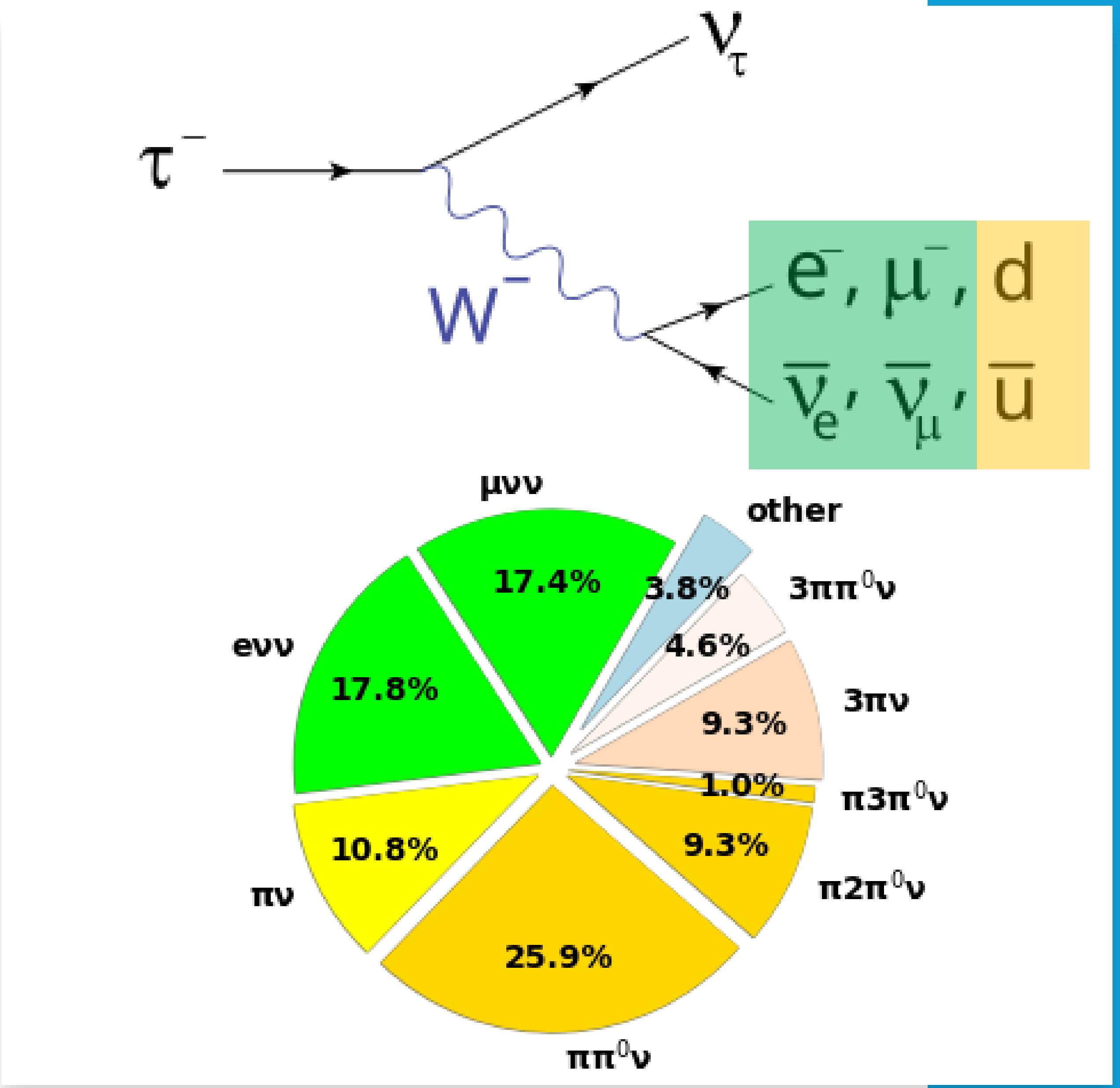


The tau lepton



- **Tau leptons** :
  - 3rd generation lepton
  - Mean lifetime: 290 ps (87 μm)
  - Most massive lepton → decays weakly to both **leptons (35%)** and **hadrons (65%)**

- Hadronic decays:
  1/**3**- charged mesons → "**prongs**"
  and variety of neutral mesons



The Large Hadron Collider

- Ultimately: 27 km “Ring”
- Accelerates protons at highest energies of 6.5 TeV (99.9999991% c)
- Collisions occur at various points → Detectors built

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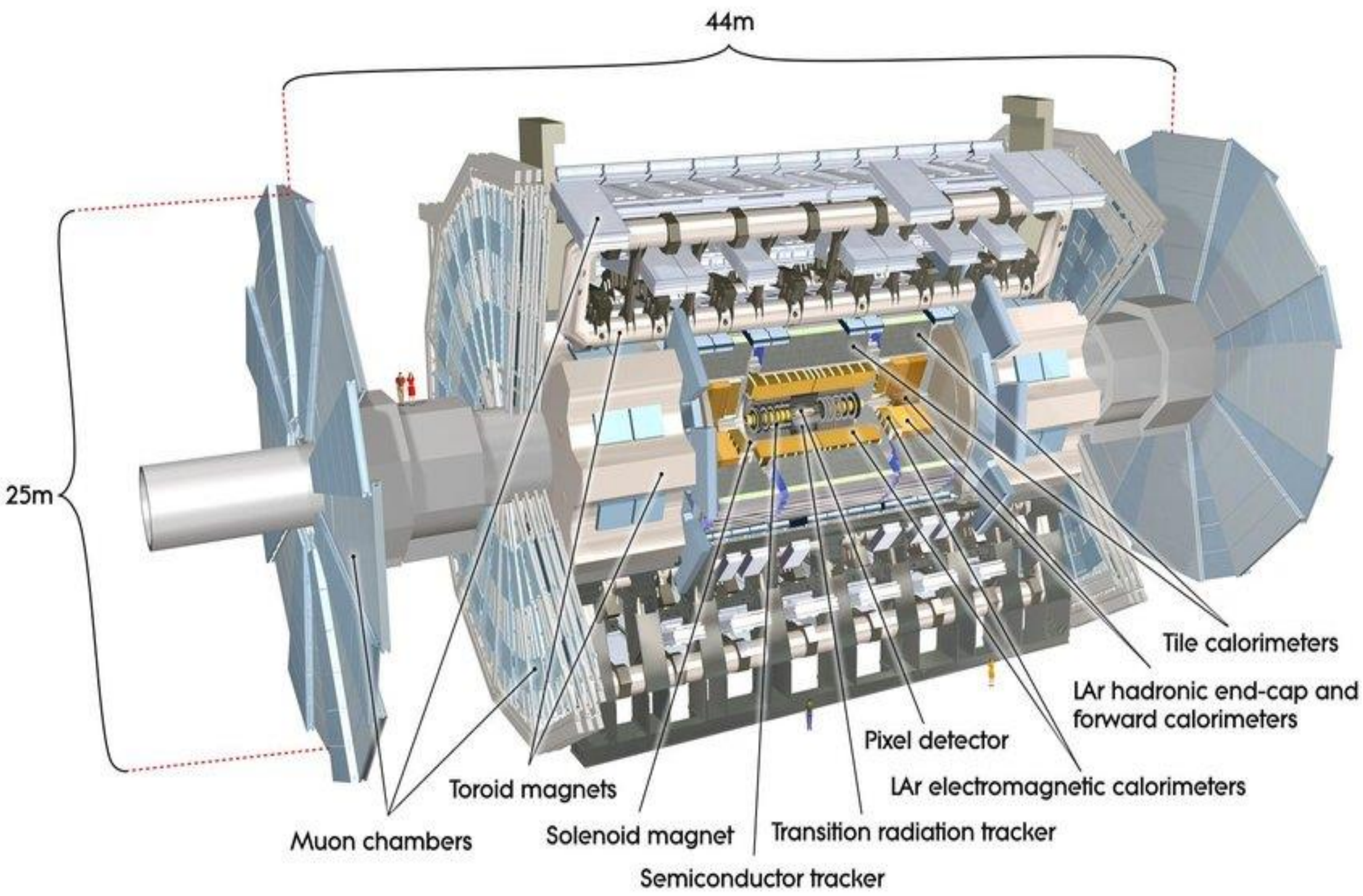
ATLAS Detector

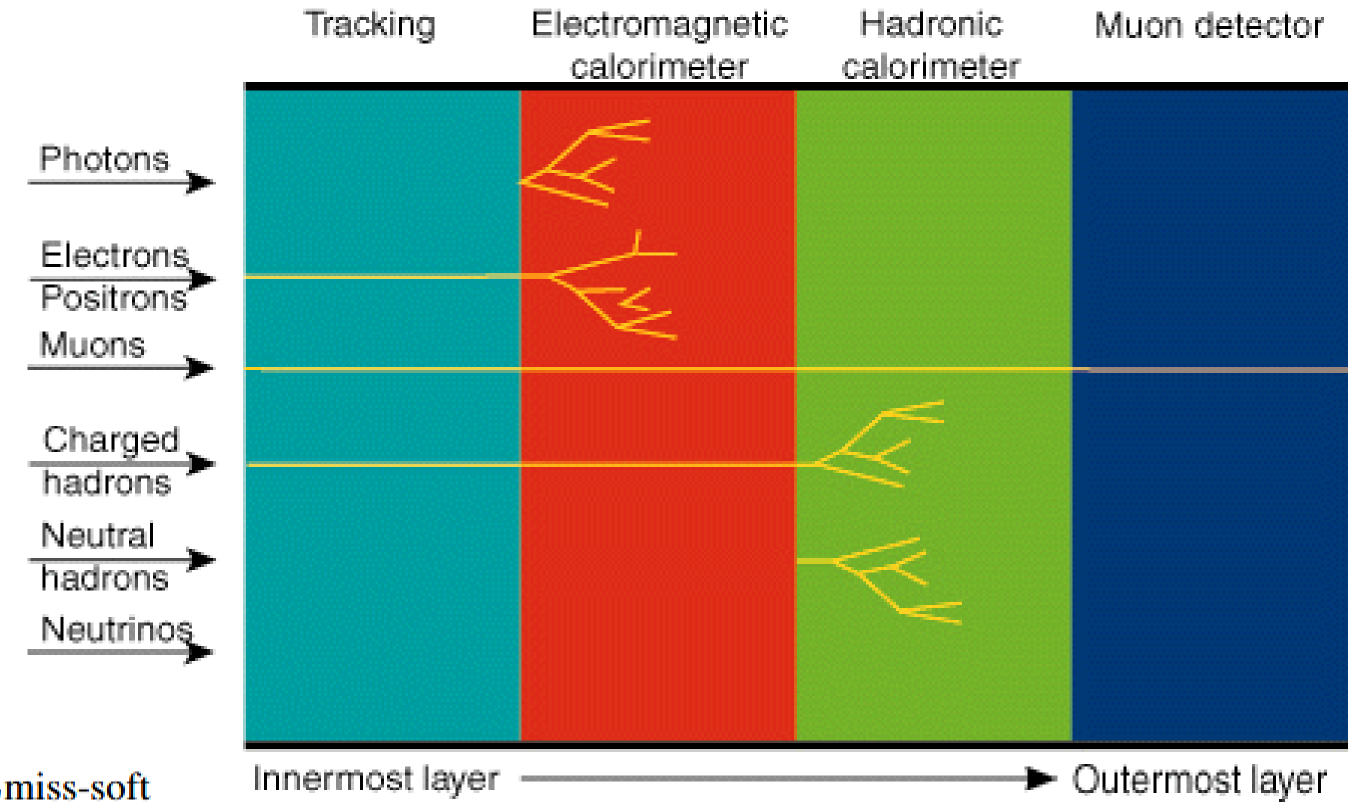
- General purpose detector
- Cylindrical symmetry, radially many layers
- Detect and record outputs of collisions
- Reconstruct particles (“physics objects”)



ATLAS Detector

- General purpose detector
- Cylindrical symmetry, radially many layers
- Detect and record outputs of collisions
- **Reconstruct particles ("physics objects")**
- Missing Transverse Energy:

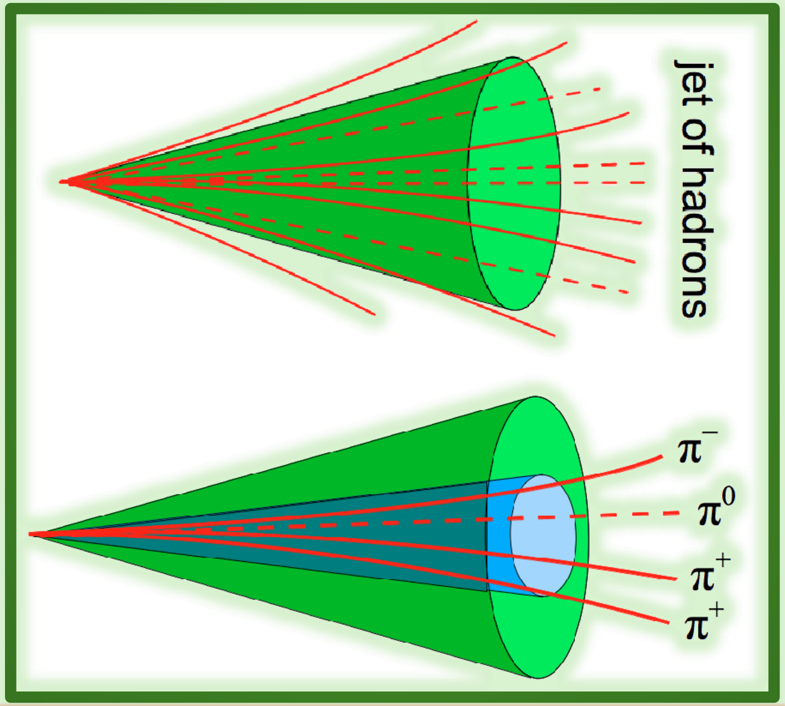
$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss-e}} + E_{x(y)}^{\text{miss-}\mu} + E_{x(y)}^{\text{miss-}\tau} + E_{x(y)}^{\text{miss-jet}} + E_{x(y)}^{\text{miss-soft}}$$

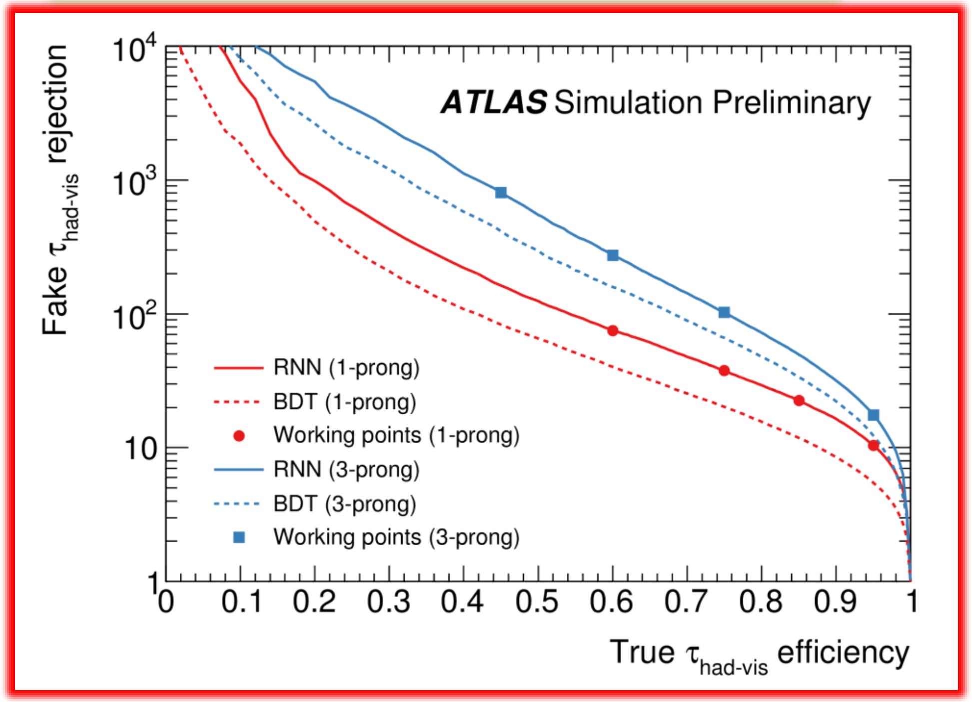


Tau Reconstruction & Identification

- **Tau reconstruction** seeded by jets
- Key elements: collimated deposits, low track multiplicities
- Still large background from QCD processes at ATLAS
- **Tau identification** using Recurrent Neural Networks (jets) and Boosted Decision Trees (electrons)

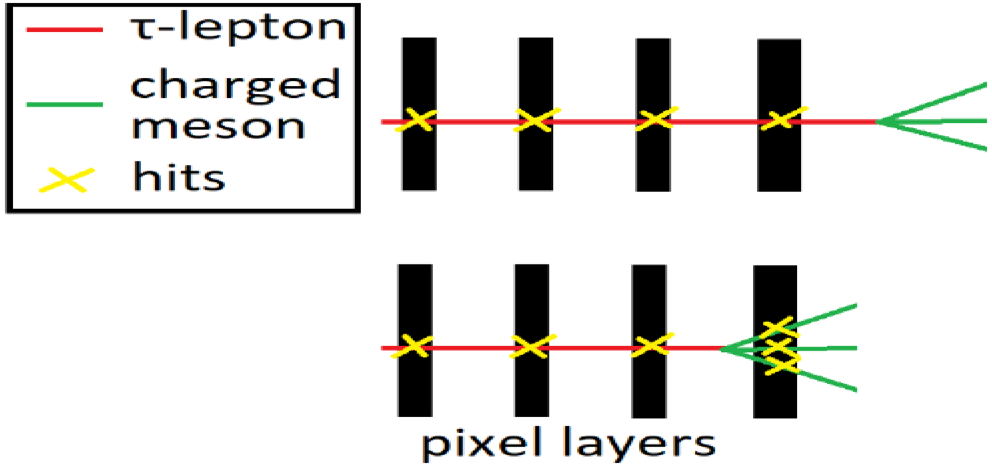
Define “Working Points” based on signal efficiency (e.g. “VeryLoose” → 95%)

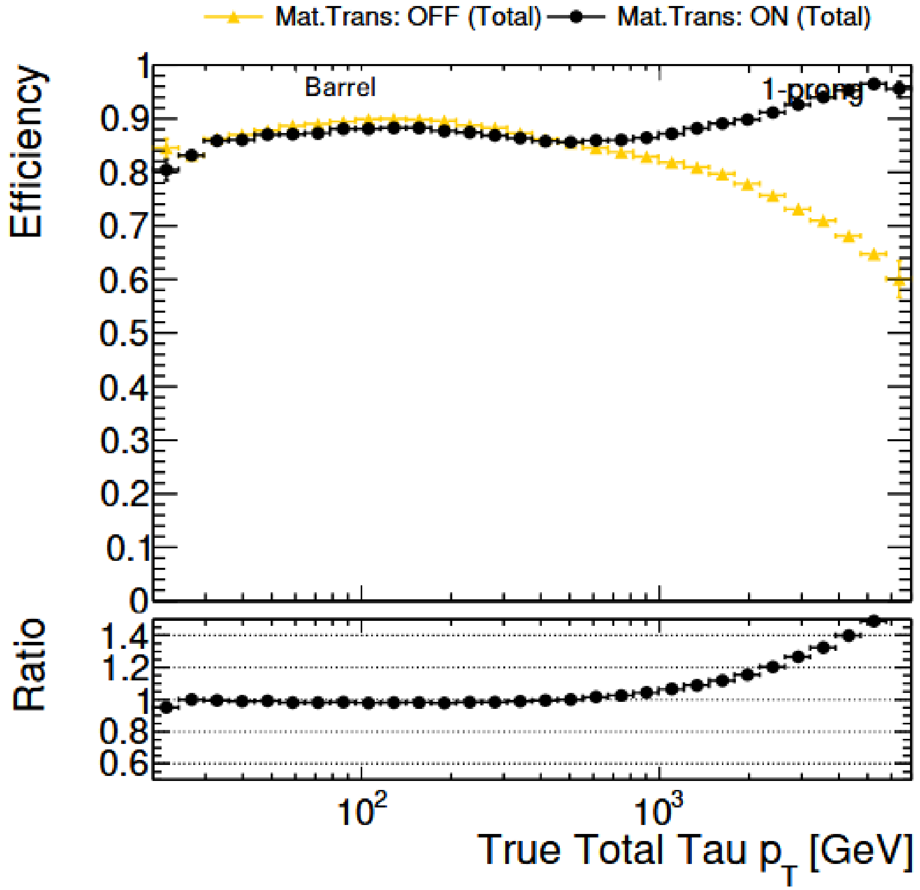




Highly-boosted τ decays

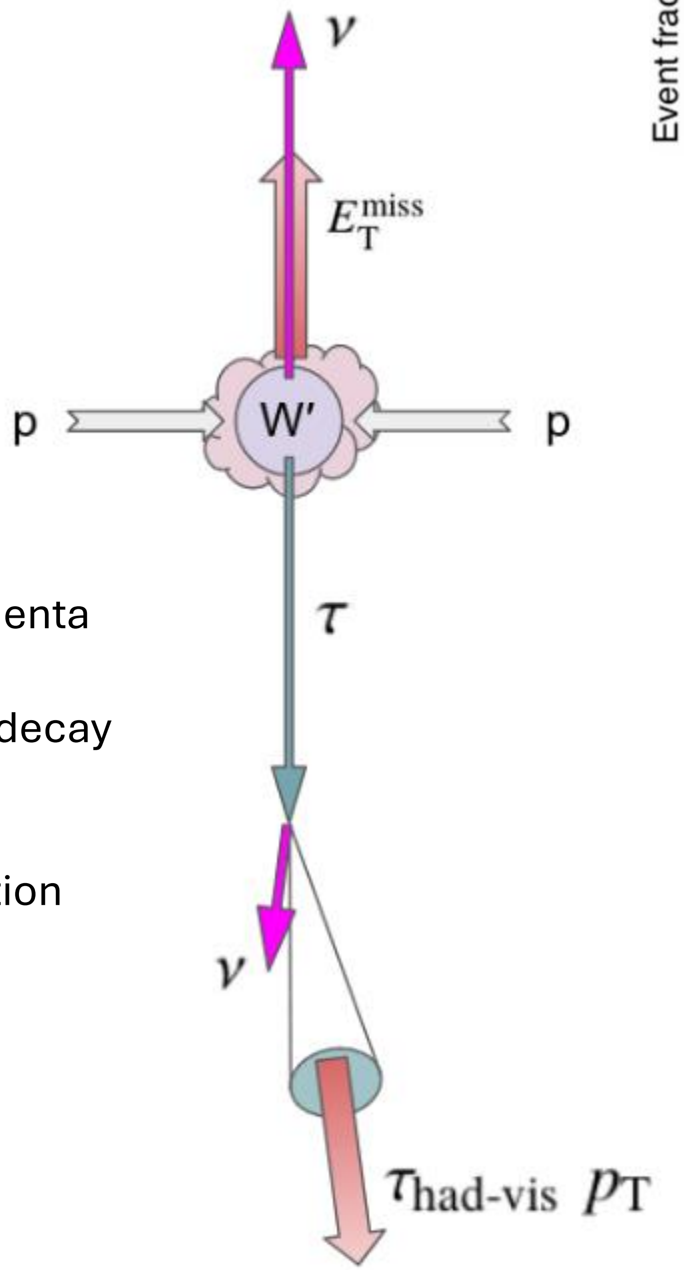
- **Challenge**:
  - Highly boosted tau can have significant lifetime and decay within detector.
  - Tau hits were not propagated in detector **simulation**
- Possible discrepancy with **data**
- Correct simulation with weights

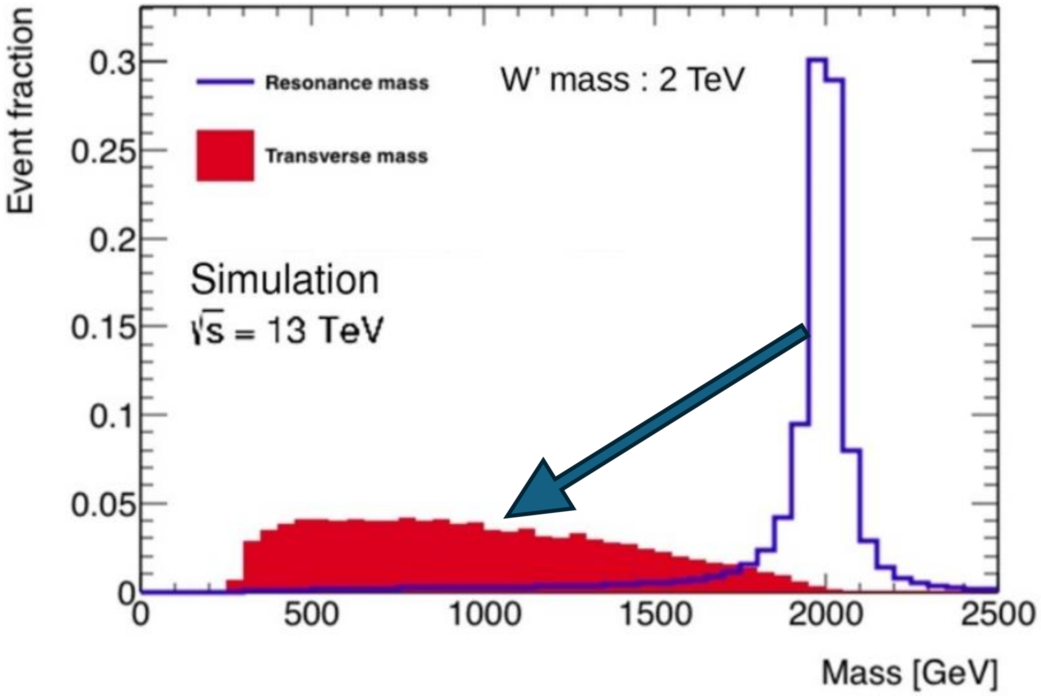




Event Topology

- W' produced almost at rest
- $\tau\ \nu$ back-to-back with balanced momenta
- The same for the products of the tau decay and missing transverse energy
- Mass = Energy → "mass" reconstruction from measuring energies





$$m_T = \sqrt{2E_T^{miss} p_T^{\tau_{had\text{-}vis}} \left[1 - \cos \Delta\phi(\tau_{had\text{-}vis}, E_T^{miss})\right]}$$

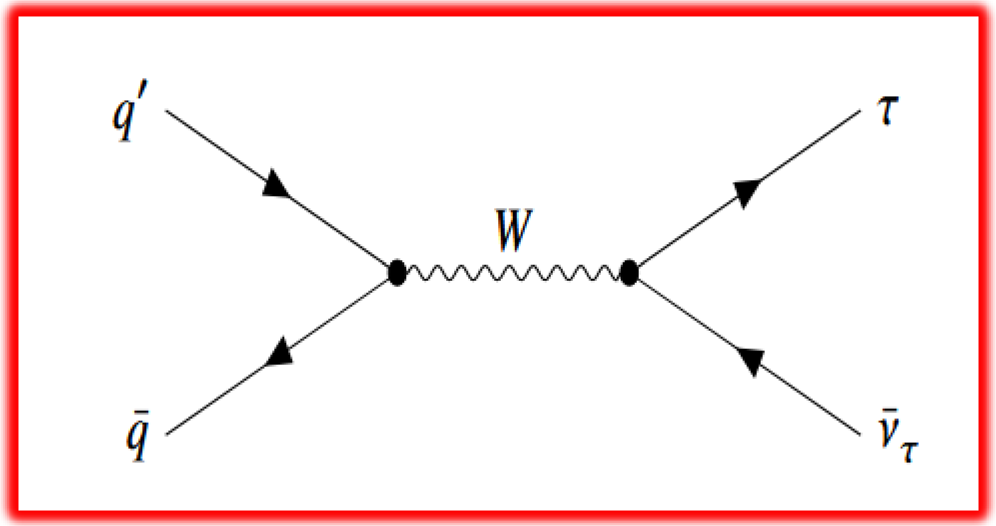
Backgrounds

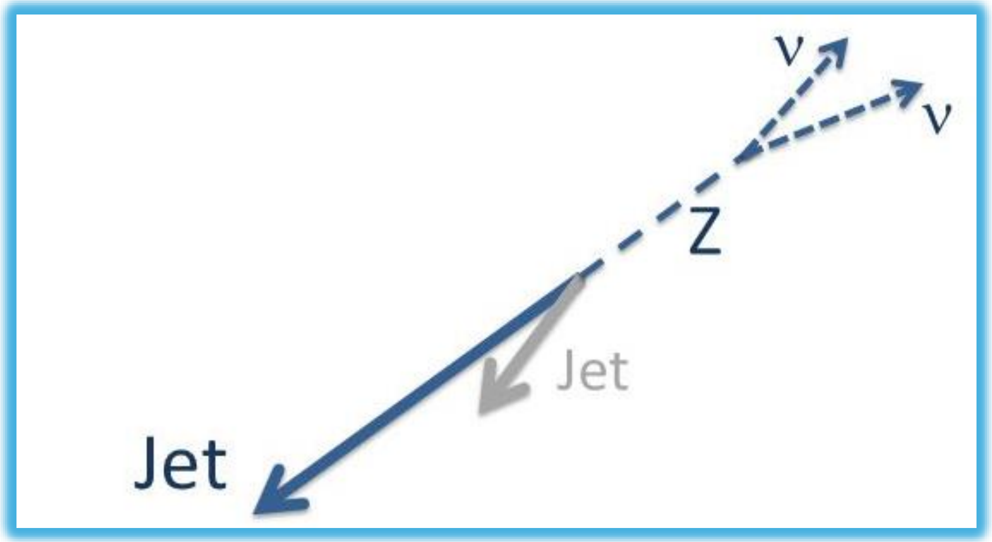
- **Backgrounds : similar signature as signal in detector**

  irreducible: $W \to \tau\nu$

  subdominant: $t\bar{t} + tX$, diboson (WW , ZZ, ZW)

- Methods to study:
  - **Real τ in final state**: Simulation (Monte Carlo)
  - **Jets misidentified as τ** : Data-driven method ("fake factor method")





Fake Factor Method

Fake factor method established method for fake tau background

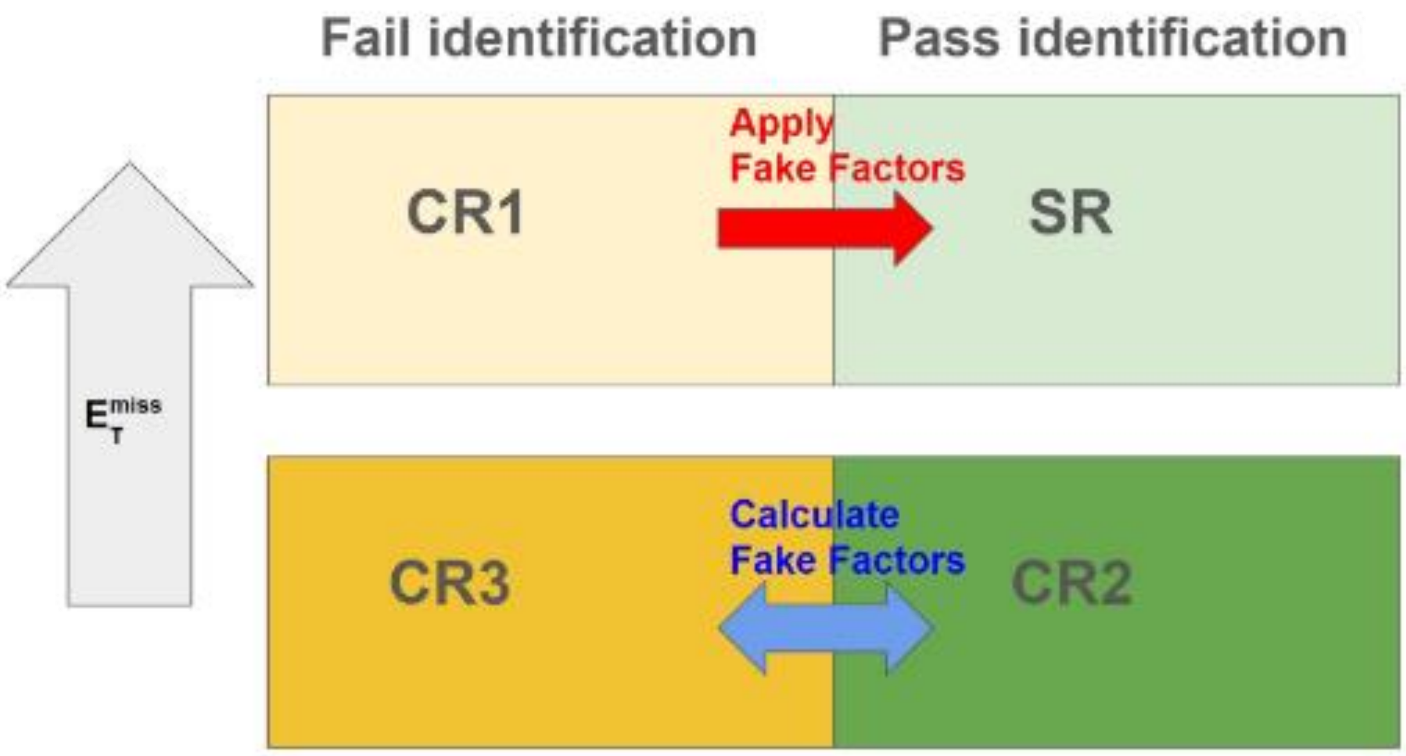
Define CR rich in jets → Calculate Fake Factor F from jets in data passing tau identification

Apply fake factor to Signal Region failing identification

This gives the expected jets passing the identification in SR

Systematics associated with applicability of fake factor due to differences in CRs

$$N_{jet}^{SR} = F \times CR1$$



$$F = \frac{N_{jet}^{CR2}}{N_{jet}^{CR3}}$$

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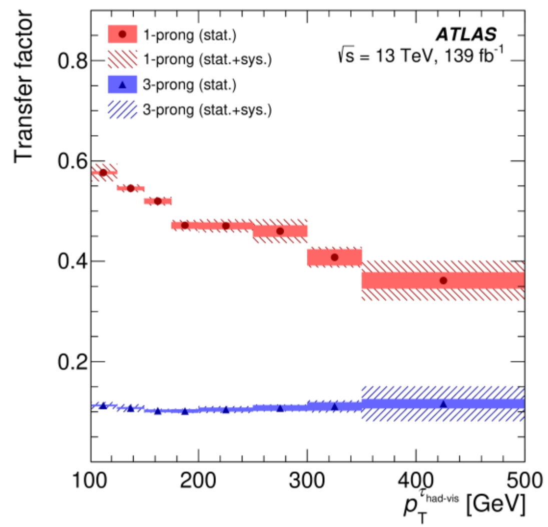
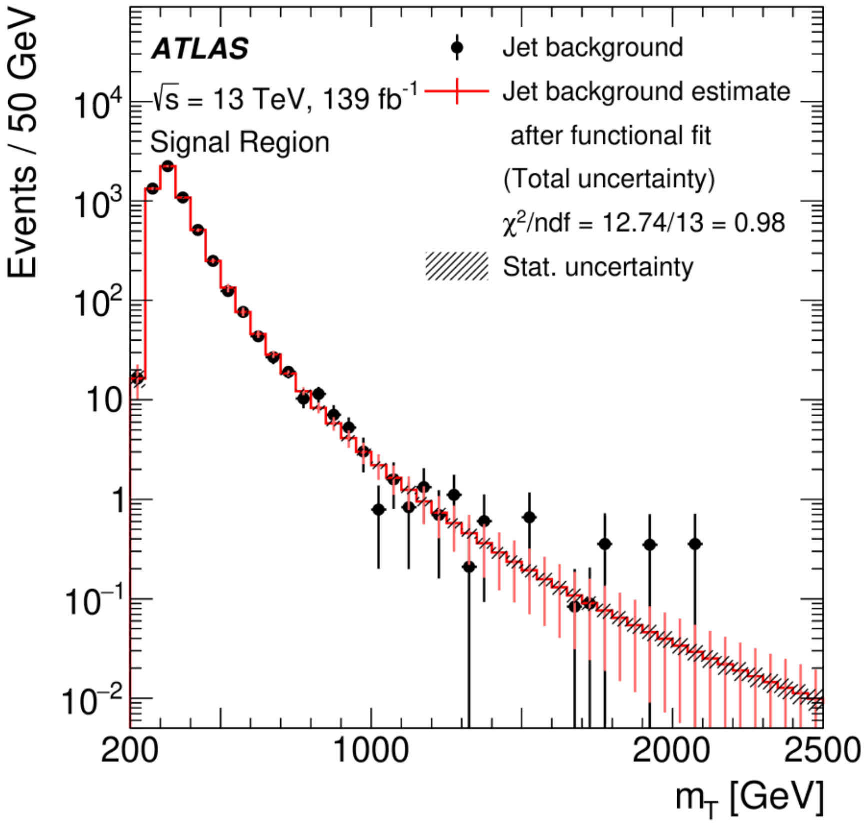
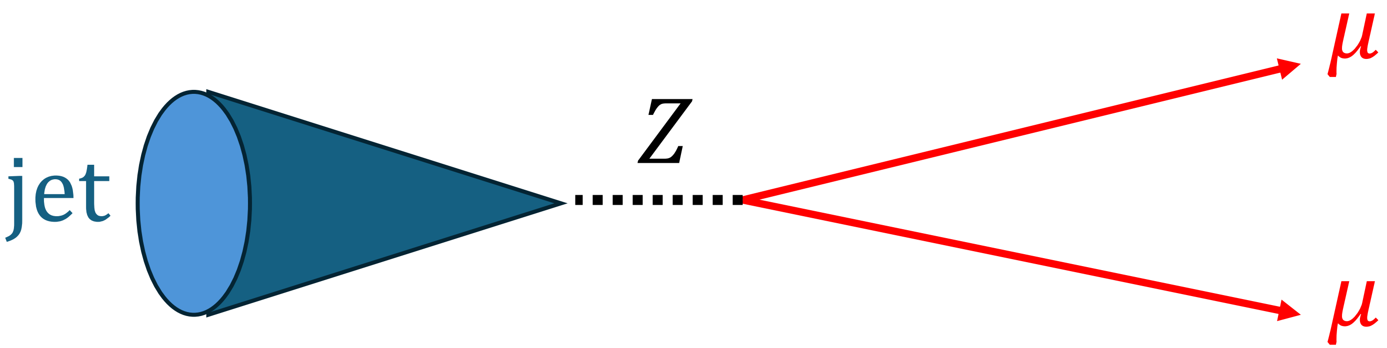




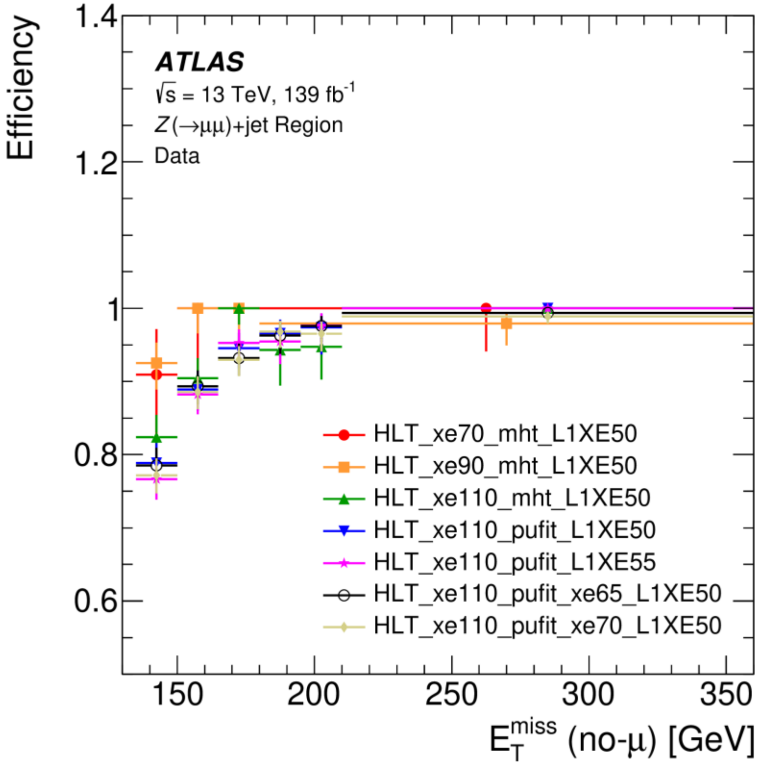
Trigger Calibration

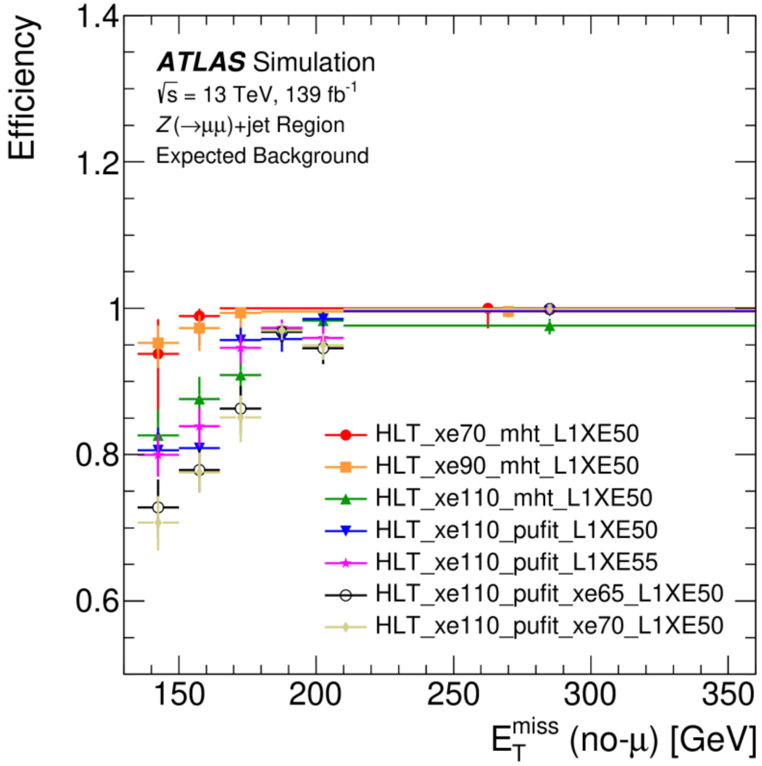


- **E_T^{miss}-trigger calibration**: dependent on topology

- Measured efficiencies in data/MC using muons (invisible at E_T^{miss}-trigger)

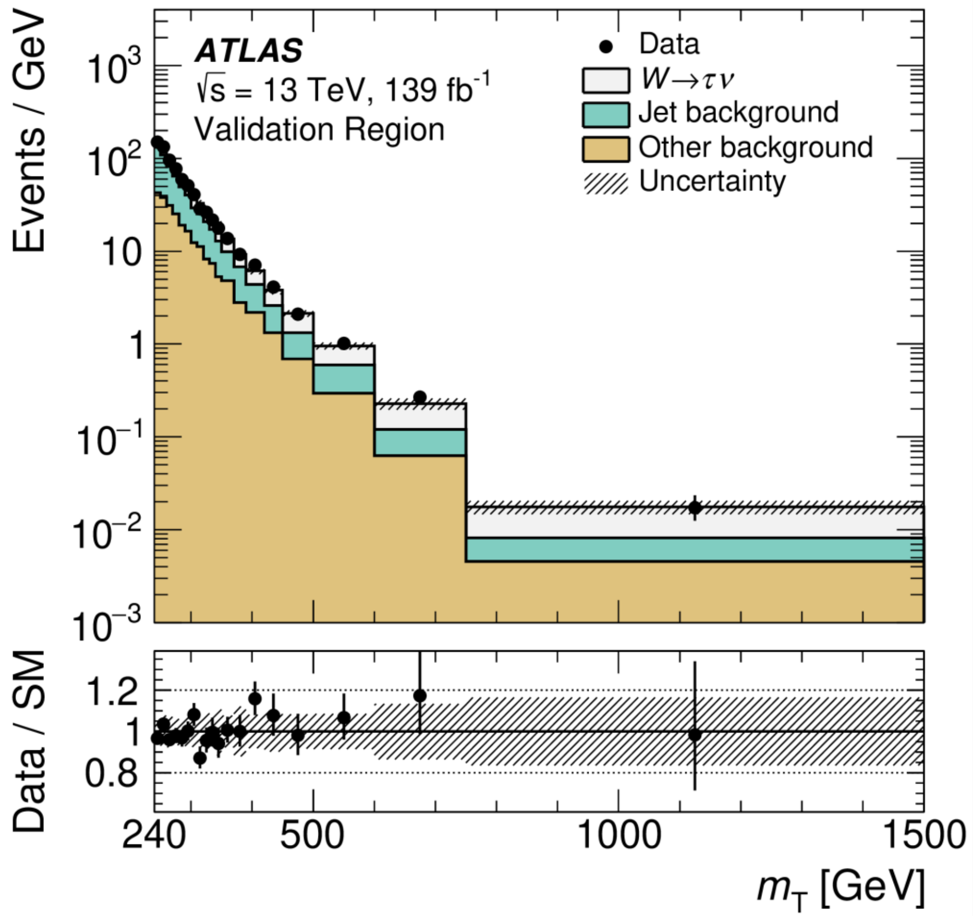
- Used $Z(\rightarrow \mu\mu) + jet$, $W(\rightarrow \mu\nu) + jet$ and $t\bar{t}$ events with similar topology as SR





Validation of Background

- Want to check new/unseen regions- Do we trust our expectations?
- Validation of background estimation was performed on data in singal-free region
- Achieved by reverting selection on balanced momenta
- **Good agreement** was observed, adding credibility to background estimation



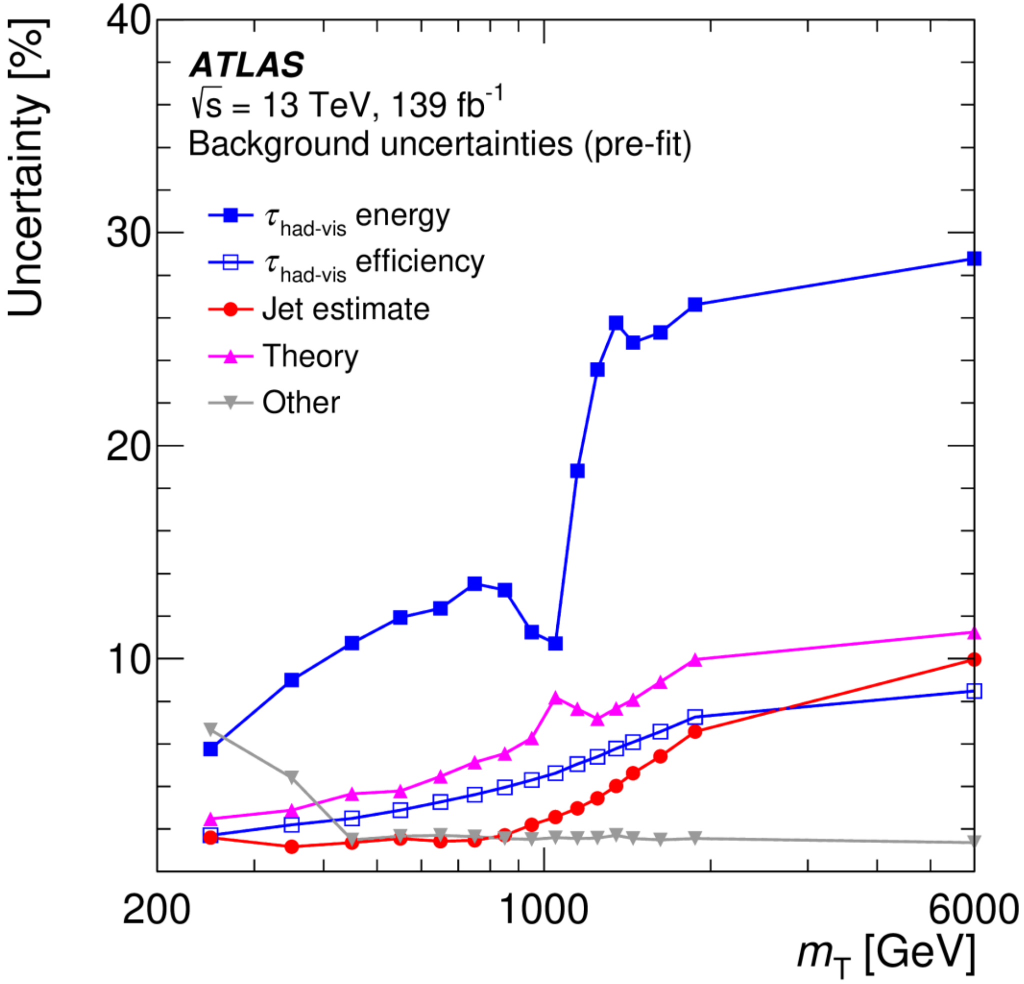
Statistical Model

- Interested in determining signal strength $\mu = \frac{\sigma_{obs}}{\sigma_{SSM}}$ in a

$$N_{exp} = b + \mu s$$

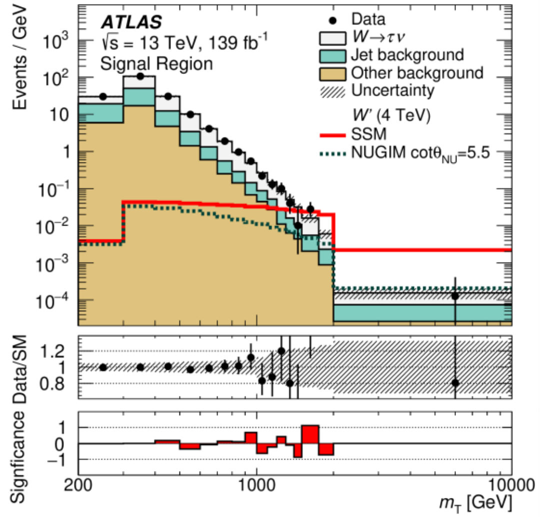
- Profile Likelihood fit performed in data comparing B-only and B+S hypotheses

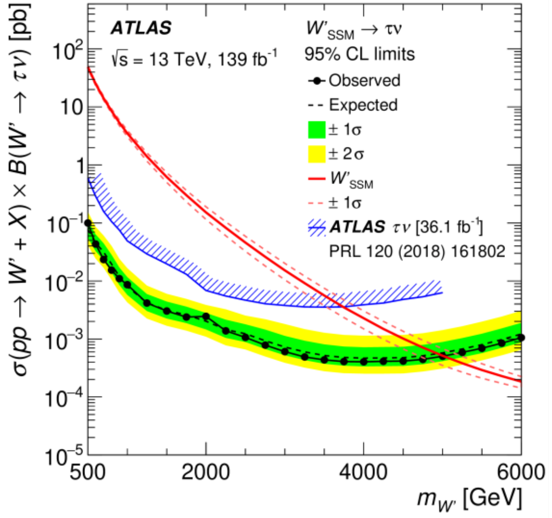
- Systematic uncertainties propagated as nuisance parameters



Exclusion Limits in SSM

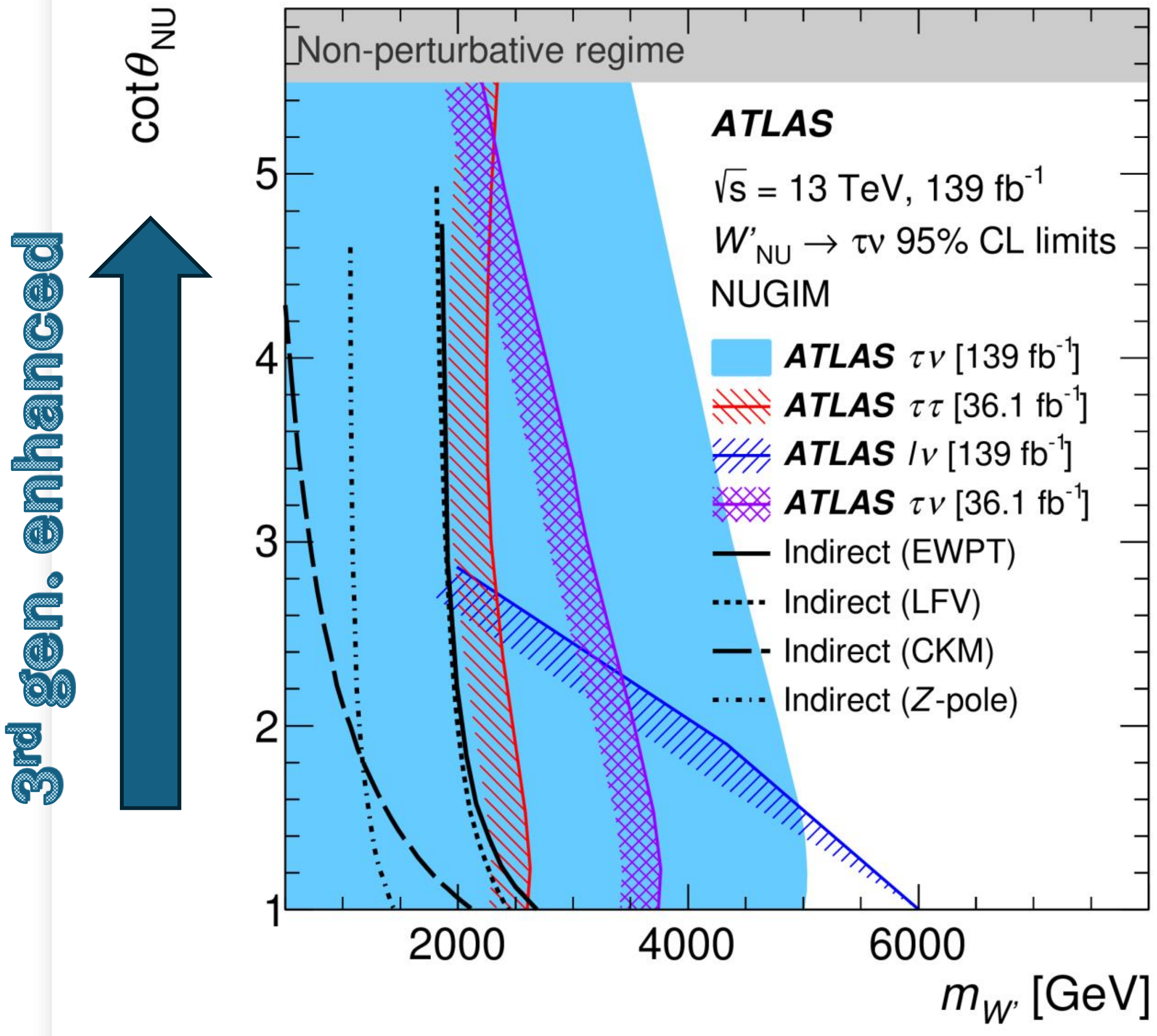
- Excess is determined via significant deviation in data from expectation
- No excess observed → Derive upper limits on possible $\sigma(pp \rightarrow W' + X) \cdot Br(W' \rightarrow \tau\nu)$
- SSM excluded at 95% CL up to 5 TeV





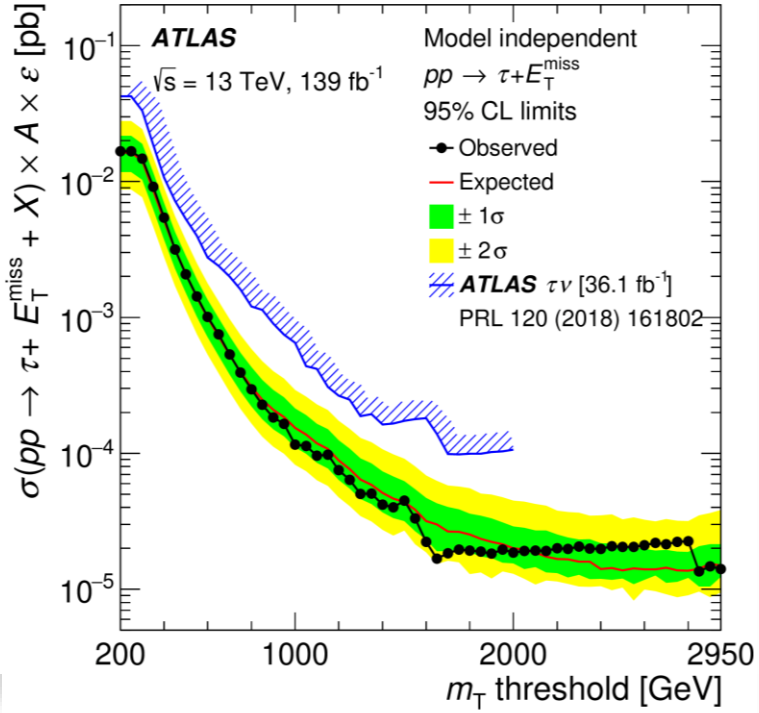
Exclusion Limits in NUGIM

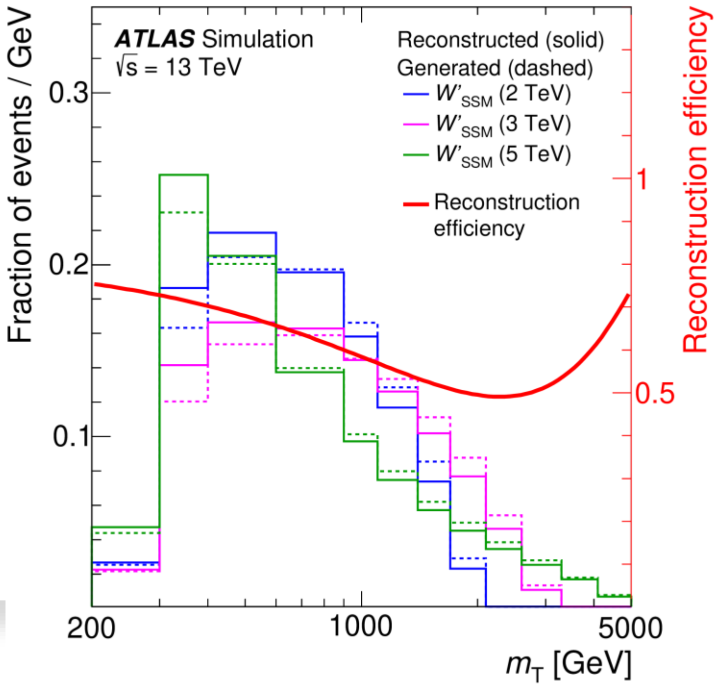
- Excess is determined via significant deviation in data from expectation
- No excess observed → Derive upper limits on possible $\sigma(pp \to W' + X) \cdot Br(W' \to \tau\nu)$
- NUGIM excluded 3.3-5 TeV



Exclusion Limits Model Indipendent

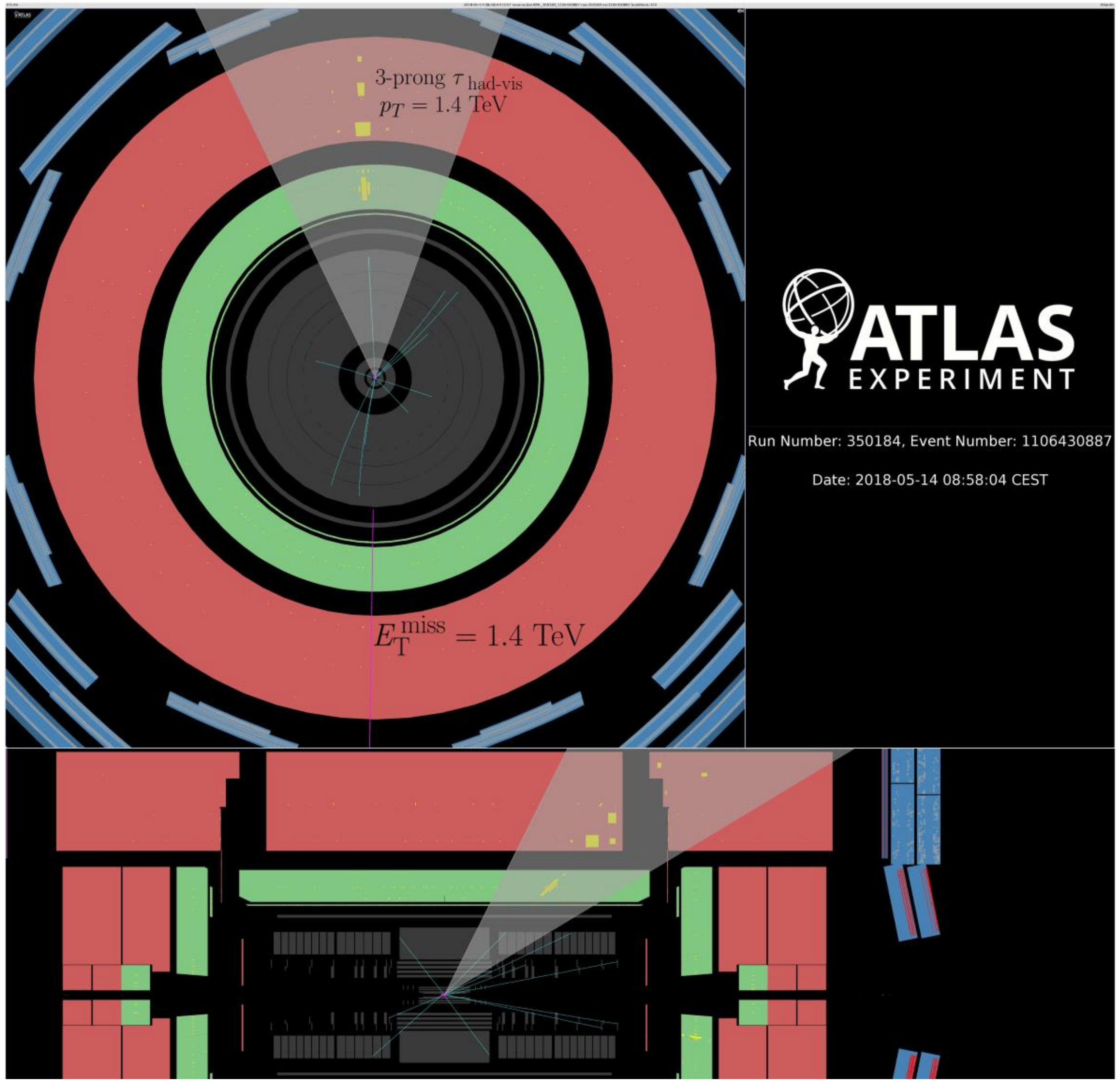
- Other models may predict different signal m_T shapes resulting in $\tau + E_T^{miss}$
- Limits provided for model independent searches with thresholds on m_T
- Also prescriptions derived on simulation for correcting detector effects





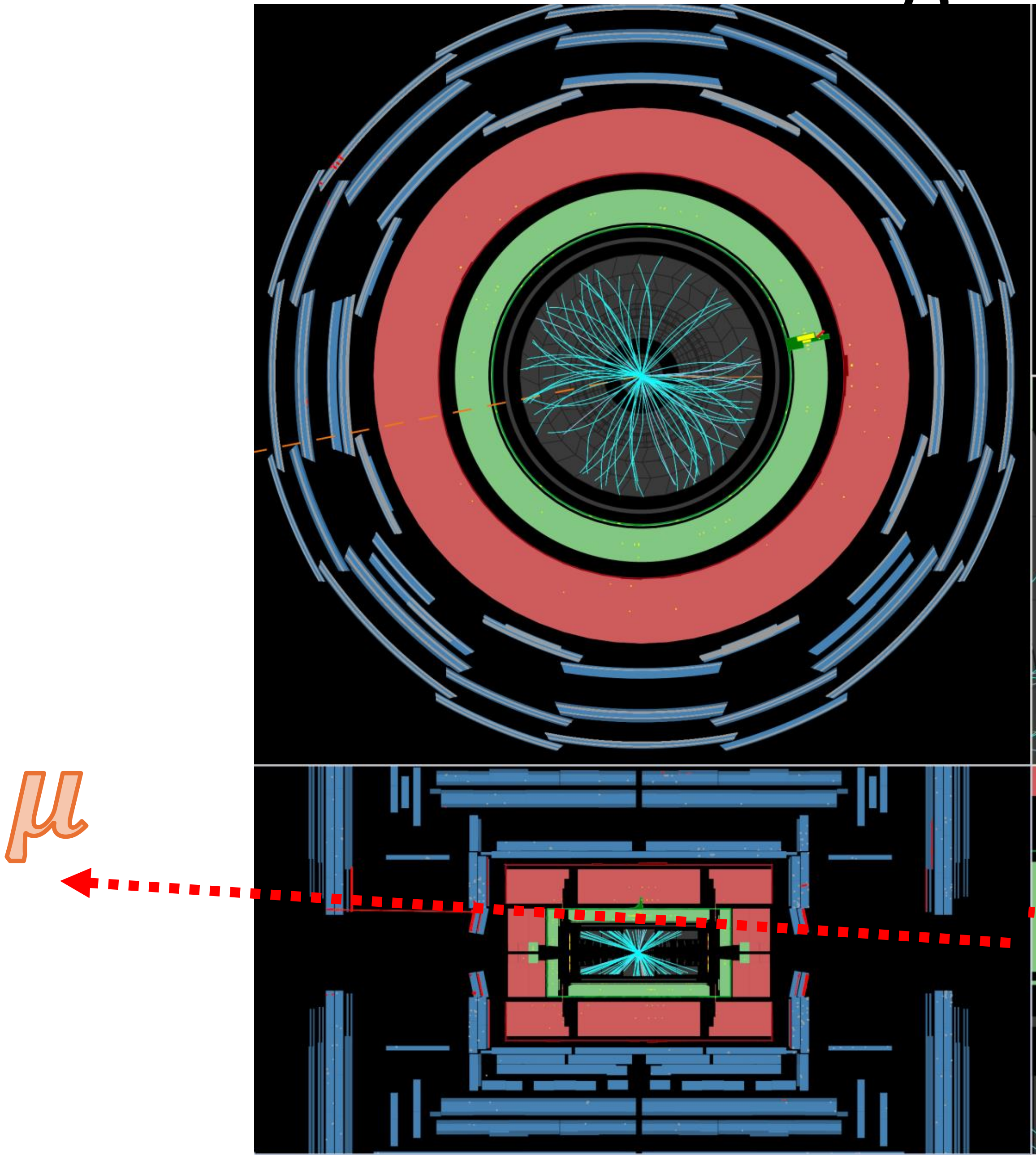
Conclusions

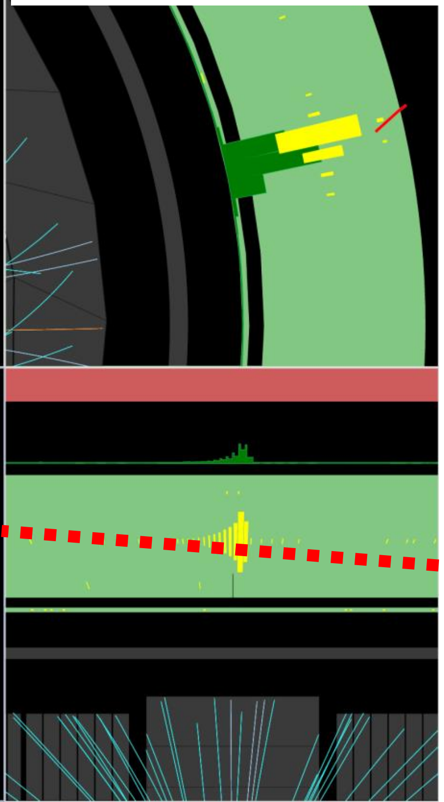
- **A search performed for high-mass resonances decaying to a τν**
- **No significant excess over expectation observed → upper limits on cross sections were derived**
- **Studied SSM, NUGIM**
- **Derived model-independent limits for theory reinterpretation**
- **Currently most stringent limits on this channel**
- **An exciting future ahead...**

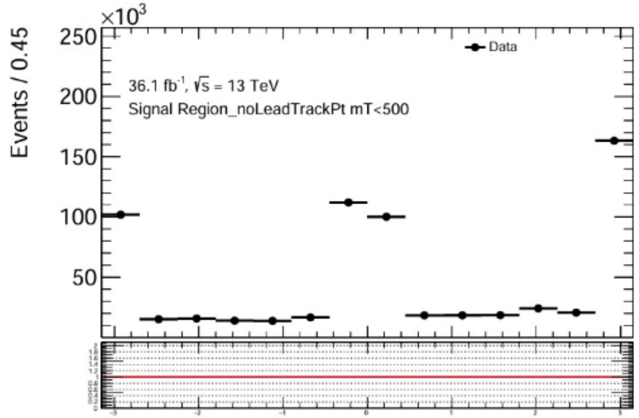


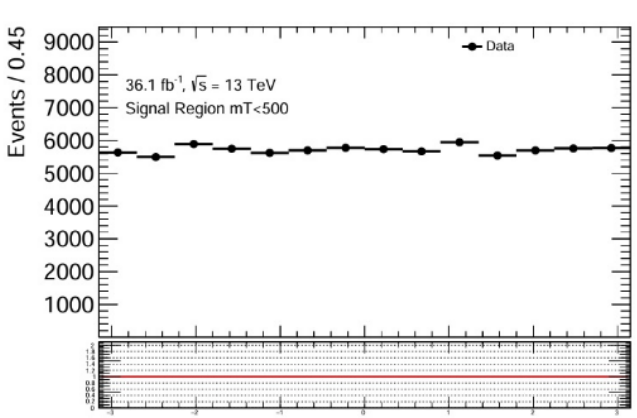
Many Thanks

Non-Collisional Background







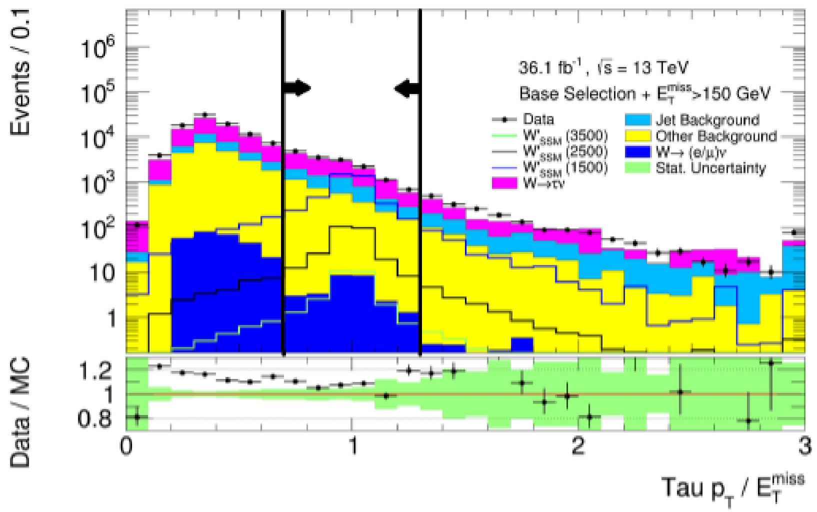


Event Selection

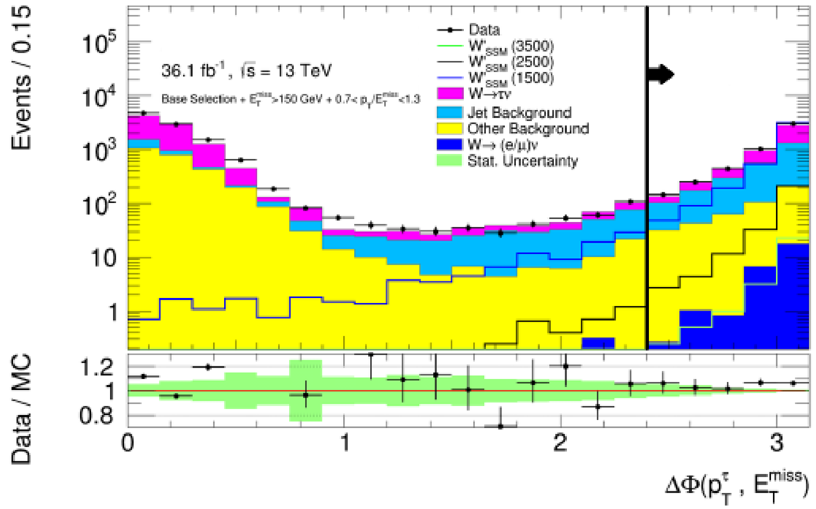
	Preselection
$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	70, 90, 110 GeV
Event cleaning	applied
$\tau_{\text{had-vis}}$ tracks	1 or 3
$\tau_{\text{had-vis}}$ charge	± 1
$\tau_{\text{had-vis}}$-p_{T}	> 30 GeV
$\tau_{\text{had-vis}}$ $p_{\mathrm{T}}^{\text{leadTrack}}$	> 10 GeV
Lepton veto	applied
$\Delta\phi$	> 2.4 rad

Region requirements

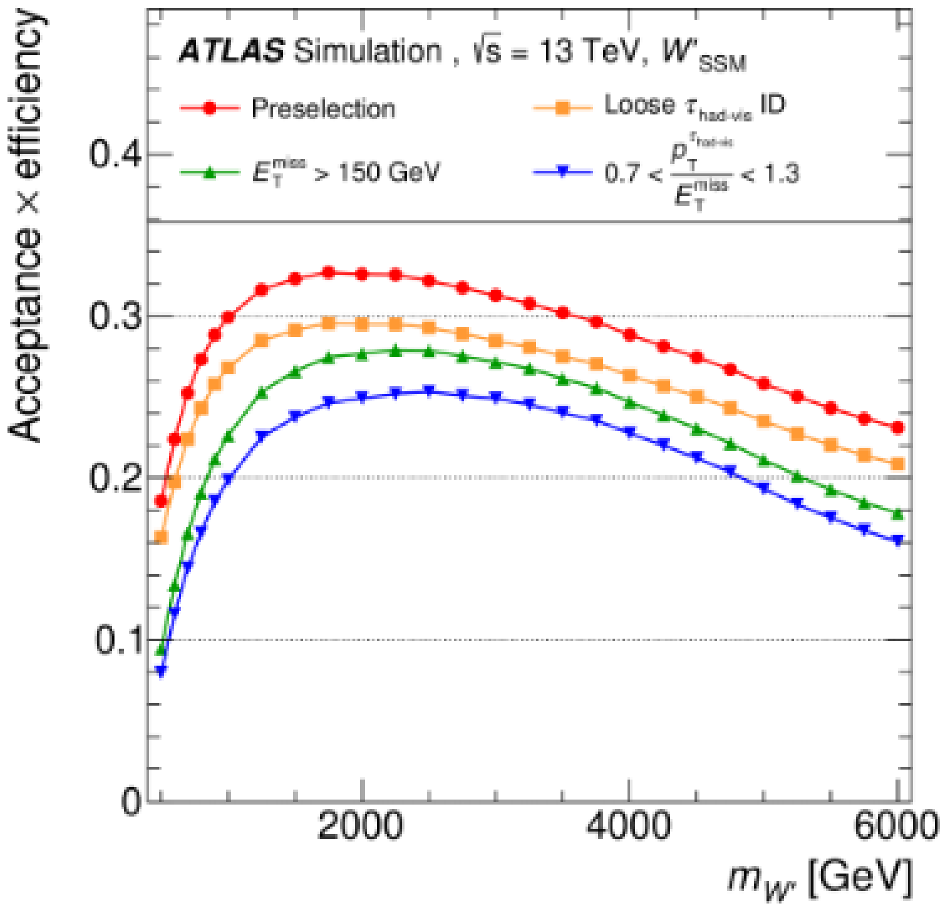
	SR	CR1	CR2	CR3	VR
τ-lepton identification	L	VL\L	L	VL\L	L
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 150 GeV	< 100 GeV	< 100 GeV	> 150 GeV
$\tau_{\text{had-vis}}$-p_{T} / $E_{\mathrm{T}}^{\mathrm{miss}}$	$\in [0.7, 1.3]$	$\in [0.7, 1.3]$	$\cdots$	$\cdots$	< 0.7
m_{T}	$\cdots$	$\cdots$	$\cdots$	$\cdots$	> 240 GeV

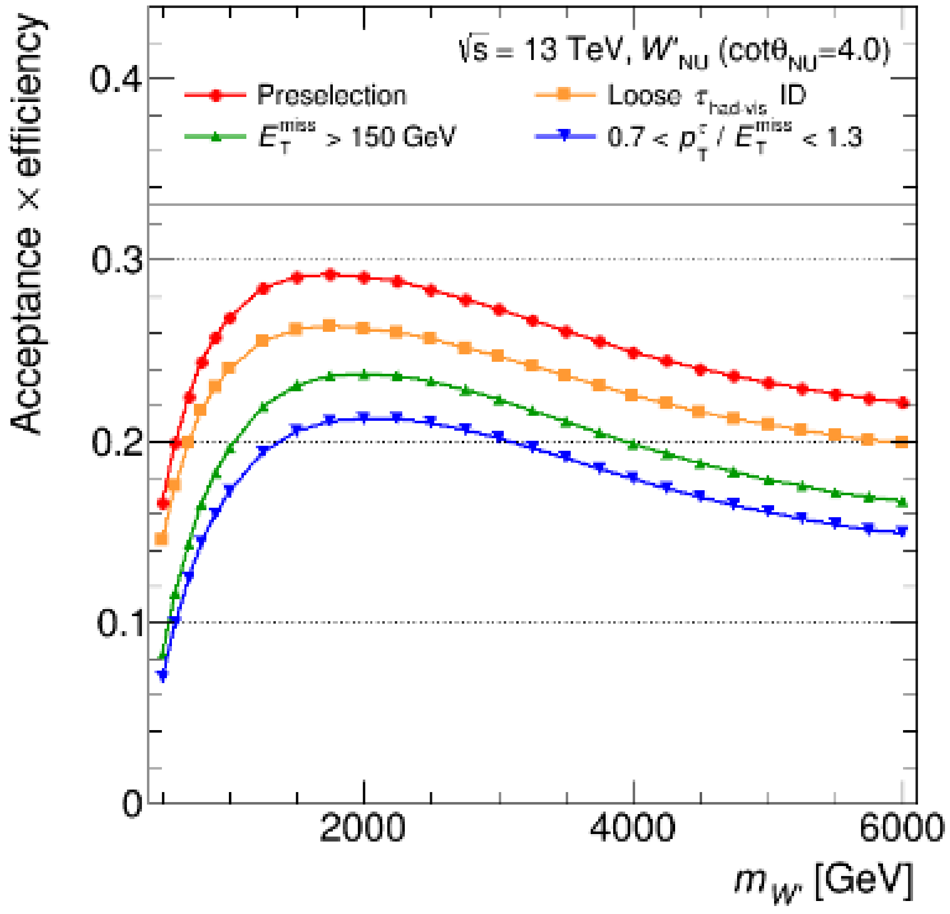


(a)



Acceptance


ATLAS Simulation , √s = 13 TeV, W'SSM
Preselection
Loose τhad-vis ID
E_T^miss > 150 GeV
0.7 < p_T^τhad-vis / E_T^miss < 1.3
Acceptance × efficiency
0
0.1
0.2
0.3
0.4
2000
4000
6000
m_W' [GeV]


√s = 13 TeV, W'NU (cotθNU=4.0)
Preselection
Loose τhad-vis ID
E_T^miss > 150 GeV
0.7 < p_T^τ / E_T^miss < 1.3
Acceptance × efficiency
0
0.1
0.2
0.3
0.4
2000
4000
6000
m_W' [GeV]

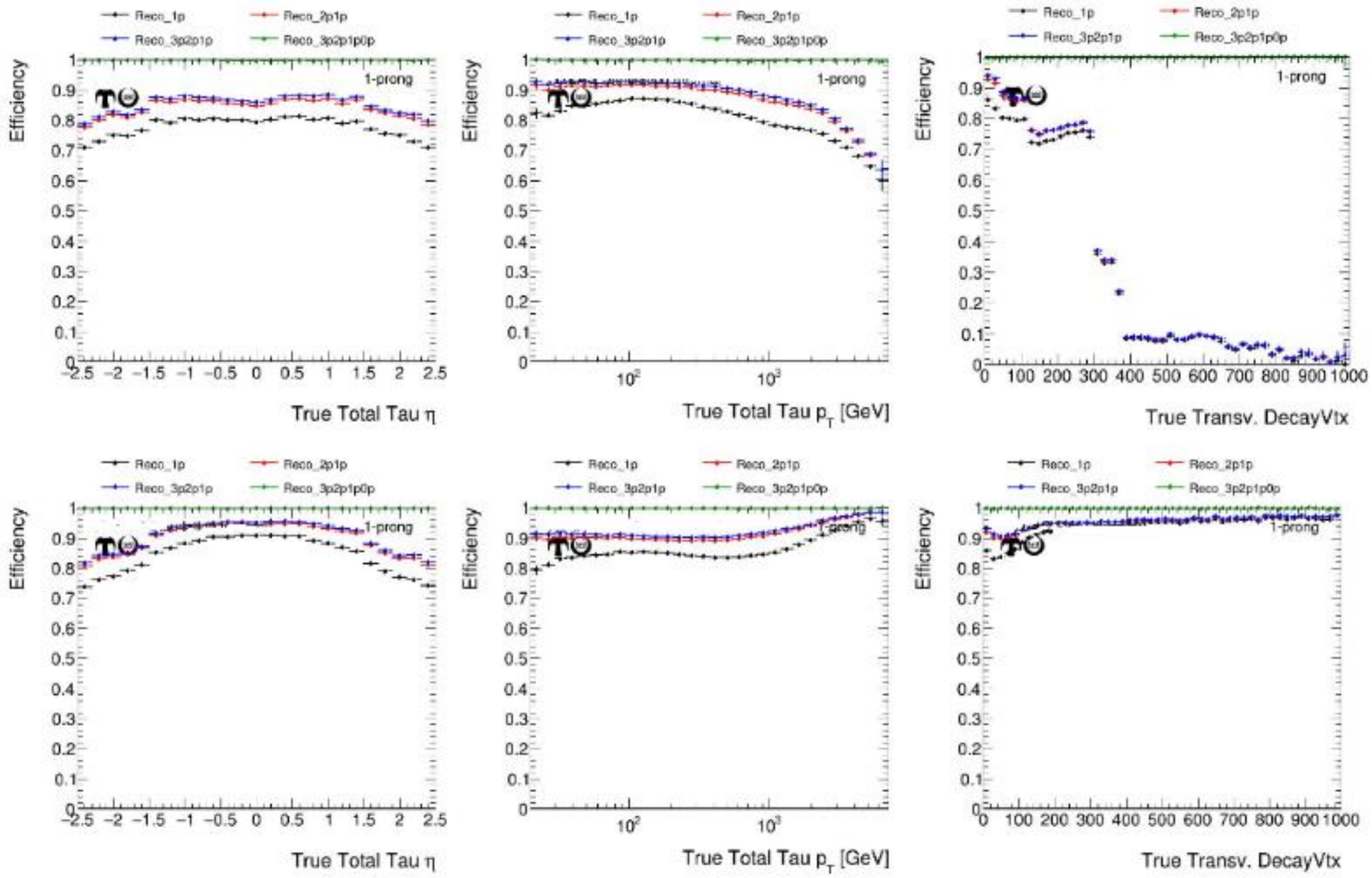
Trigger

Baseline	
Feature	Criterion
Trigger	Lowest-unprescaled single muon trigger
Muon p_T	$p_T^{\text{lead-}\mu} > 30(55)$ GeV
Event Cleaning	EC_LooseBad + Detector cleaning + Dead Tile Module cleaning
BadJet Cleaning	TightBad
eVeto and BadMuon veto	$N_{\mu-\text{bad}} + N_{e-\text{loose}} = 0$
Tau Multiplicity	$N_\tau \geq 1$
Tau Charge	$\lvert q\rvert = 1$ if (1||3)-tracks else $\lvert q\rvert \leq 2$
Tau Identification	Very Loose
Back-to-Back topology	$\Delta\phi(\tau, E_T^{\text{miss}}) > 2.4$
Z Region	
Number of muons	$N_{\mu-\text{loose}} = 2$
Oppositely charged muons	$q_{0-\mu} q_{1-\mu} < 0$
Invariant Mass window	$m_{\mu\mu} \in [66.6,\ 116.6]$ GeV
W Region	
Number of muons	$N_{\mu-\text{loose}} = 1$
Transverse Mass requirement	$m_T(\mu, E_T^{\text{miss}}) > 50$ GeV
B-veto	$N_{b\text{-jets}} = 0$
top Region	
Number of muons	$N_{\mu-\text{loose}} = 1$
Transverse Mass requirement	$m_T(\mu, E_T^{\text{miss}}) > 50$ GeV
B-tag	$N_{b\text{-jets}} > 0$

Boosted taus (true 1 track)

Simulation

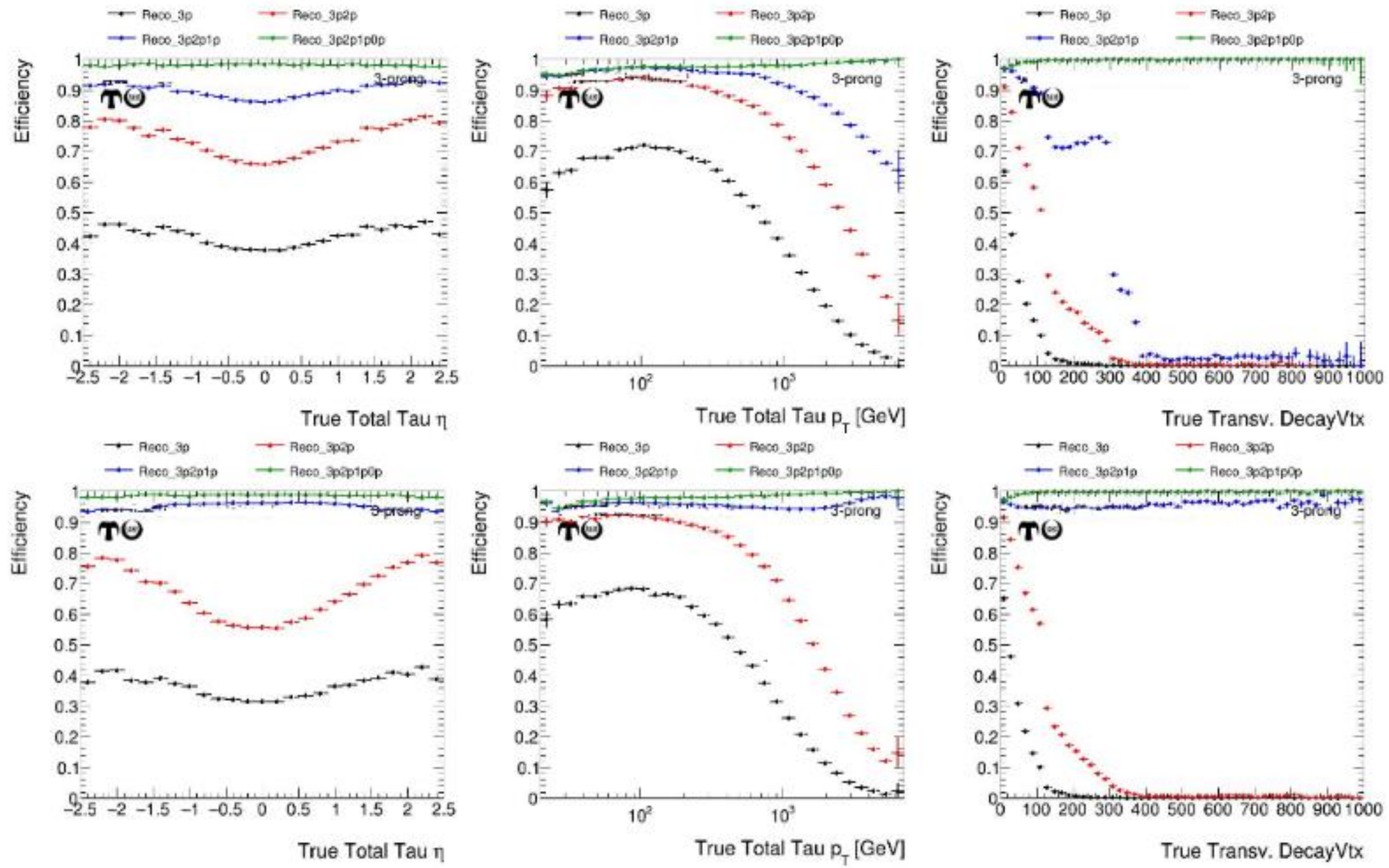
“Data”



Boosted taus (true 1 track)

Simulation

"Data"



Signal

$$B(m_{\tau\nu}; M) = \frac{1.0}{(m_{\tau\nu}^2 - M^2)^2 + (m_{\tau\nu}^2\Gamma(M)/M)^2} \; ,$$

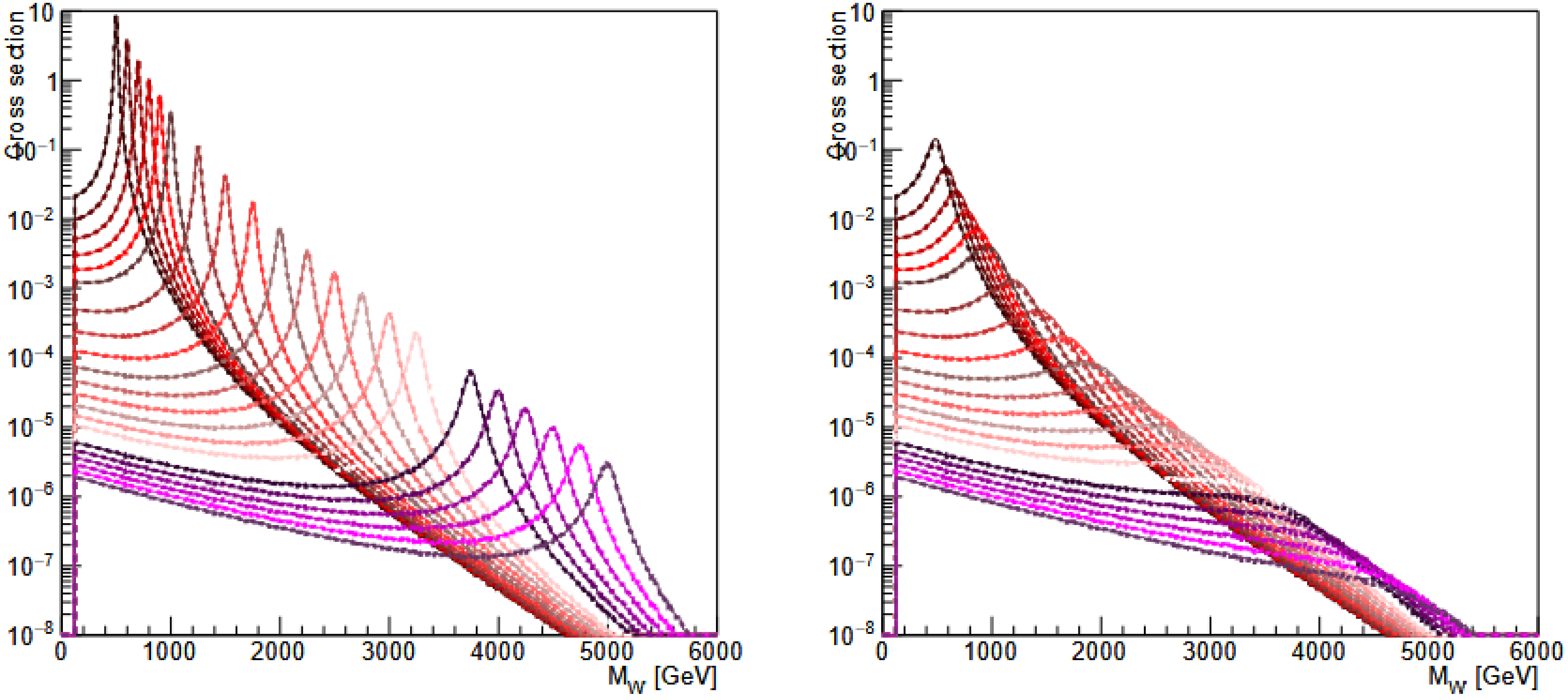
$$\Gamma_{W'} = 2\Gamma_{W'\to e\nu} + 1\Gamma_{W'\to\tau\nu} + 2N_c\Gamma_{W'\to ud'} + 1N_c\Gamma_{W'\to tb'} + \Gamma_{W'\to Wh}$$

$$\Gamma_{W'\to e\nu} = \frac{m_{W'}g_W^2}{48\pi}t^2$$

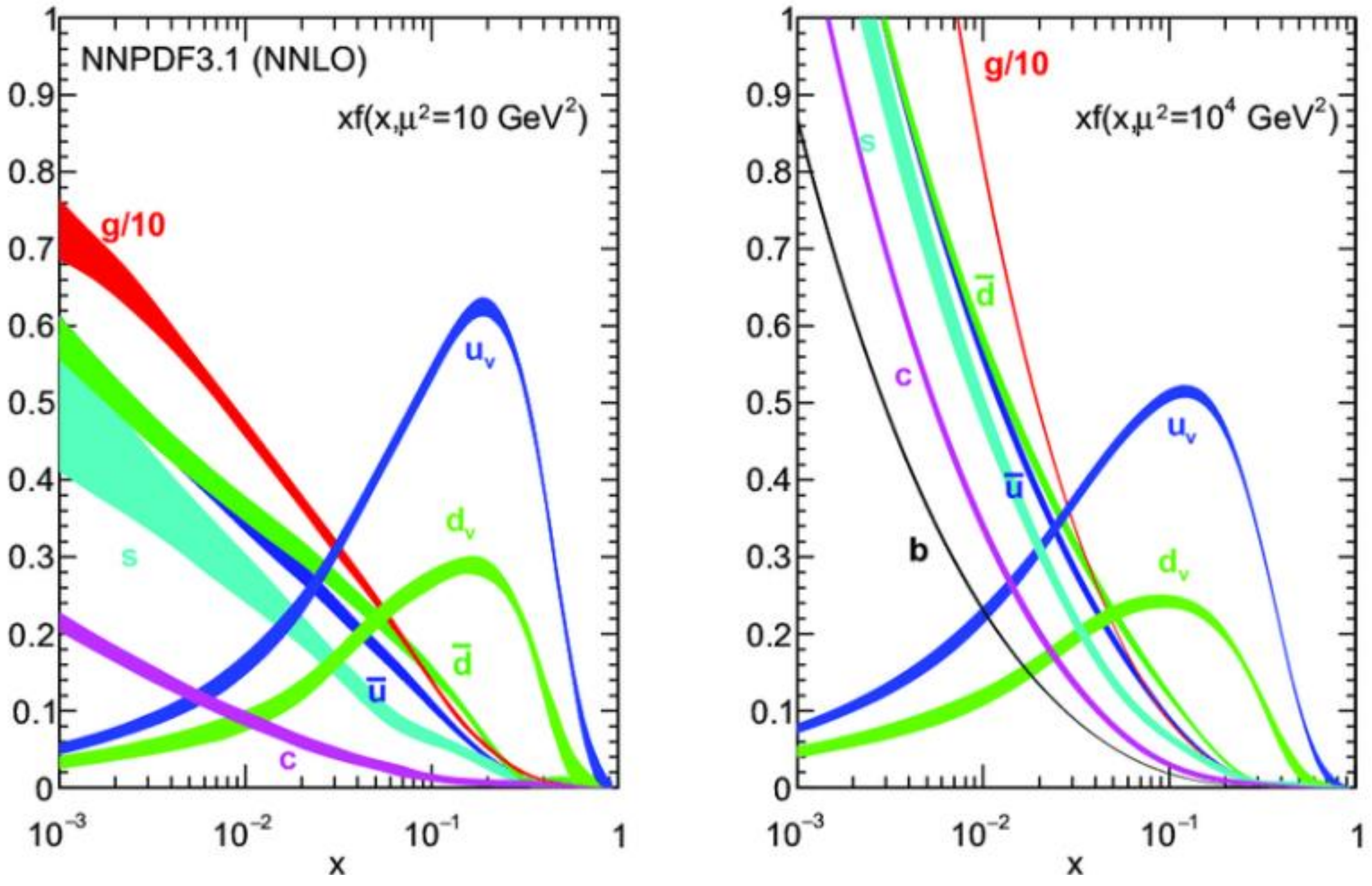
$$\Gamma_{W'\to\tau\nu} = \frac{m_{W'}g_W^2}{48\pi}\frac{1}{t^2}$$

$$\Gamma_{W'\to ud'} = \frac{m_{W'}g_W^2}{48\pi}t^2\left(1+\frac{\alpha_s}{\pi}\right)$$

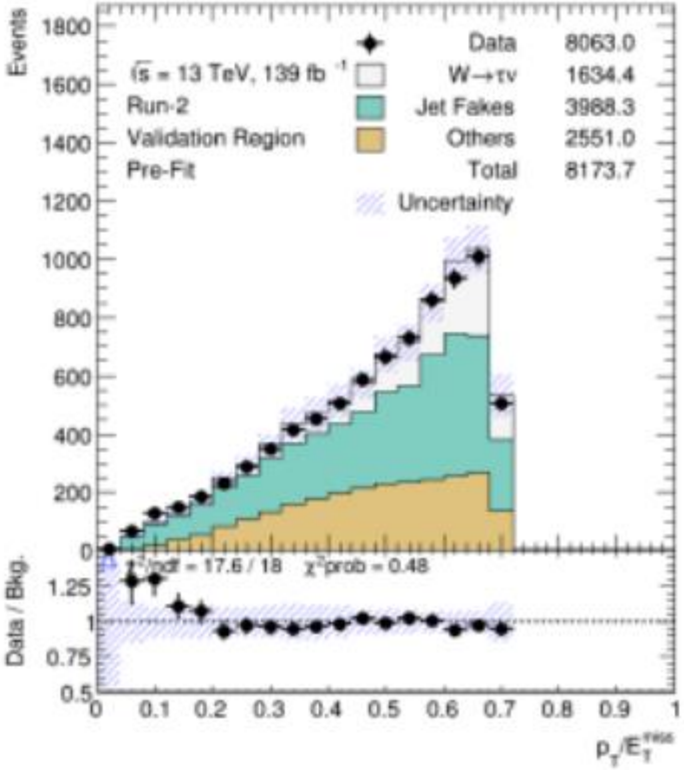
$$\Gamma_{W'\to tb'} = \frac{m_{W'}g_W^2}{48\pi}\frac{1}{t^2}\left(1+\frac{\alpha_s}{\pi}\right)\cdot C_t(B)$$



Proton Structure



VR



Events
√s = 13 TeV, 139 fb⁻¹
Run-2
Validation Region
Pre-Fit
Data 8063.0
W→τν 1634.4
Jet Fakes 3988.3
Others 2551.0
Total 8173.7
Uncertainty
χ²/ndf = 17.6 / 18 χ²prob = 0.48
Data / Bkg.
p_T/E_T^miss

Statistics

$$CL_s = \frac{CL_{s+b}}{CL_b} \equiv \frac{p_{s+b}}{1 - p_b}$$

where

- $p_{s+b} = \int_{q_\mu^{\text{obs}}}^{\infty} f(q_\mu \mid \mu, \hat{\theta}_\mu)$ is the p-value for the signal-plus-background hypothesis.
- $p_b = \int_{-\infty}^{q_0^{\text{obs}}} f(q_0 \mid \mu = 0, \hat{\theta}_0)$ the p-value for the background-only hypothesis.