Standard Model physics with taus in the final states in ATLAS

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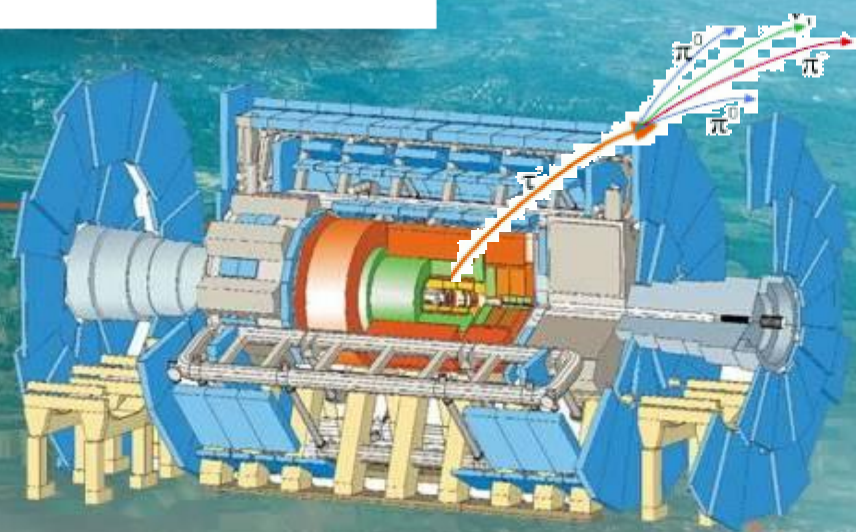

Cracow Epiphany Conference
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Why are we interested in τ leptons?

- τ leptons play an important role in the ATLAS physics program as they provide an important signature in searches for the Standard Model Higgs boson and new phenomena in a wide range of theoretical models

see talks by: Philipp Fleischmann
Juan Antonio Valls Ferrer
Tuan Vu Anh
Michiru Kaneda

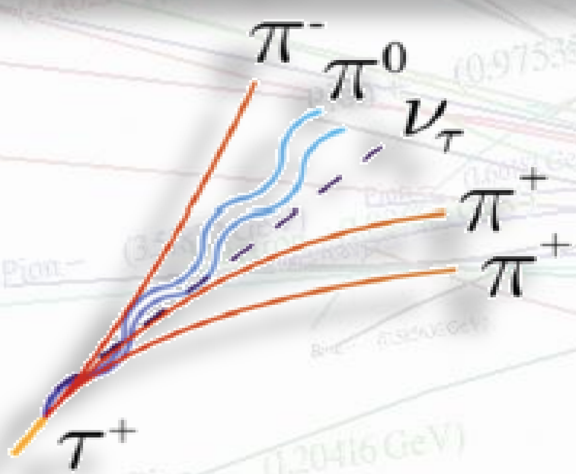
- Standard Model processes with τ in final states are
  - interesting themselves as measured for the first time at so high energy
  - important as they are backgrounds for new physics searches
  - the key to understand τ reconstruction/identification performance of the detector

- This talk covers
  - W/Z/$t\bar{t}$ cross section measurements with τ leptons
  - estimation of τ identification efficiency with $W\to\tau\nu$ and $Z\to\tau\tau$ events
  - τ polarization studies with $W\to\tau\nu$ process

Results for p+p at $\sqrt{s}$ = 7 TeV

Properties of τ leptons

- Mass: 1.777 GeV/c2
  heaviest lepton
- cτ: ~87μm
  short lifetime
- Weak decays



Since leptonic τ decays are difficult to distinguish from prompt e/μ, the τ identification algorithms deal only with the visible part (without the neutrino) of the hadronic τ decay modes.

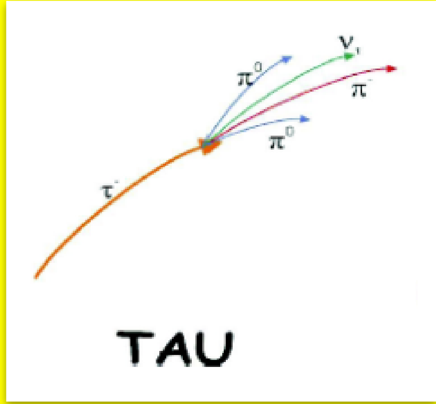
Most important decay modes

Decay Mode	Branching Fraction
Leptonic modes	**~35%**
$\tau^\pm \rightarrow e^\pm \nu_e \nu_\tau$	18%
$\tau^\pm \rightarrow \mu^\pm \nu_\mu \nu_\tau$	17%
Hadronic modes	**~65%**
1 prong (1 charged particle)	**46%**
$\tau^\pm \rightarrow \pi^\pm \nu_\tau$	11%
$\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$	26%
$\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \nu_\tau$	9%
3 prong (3 charged particles)	**14%**
$\tau^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp \nu_\tau$	9%
$\tau^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp \pi^0 \nu_\tau$	5%

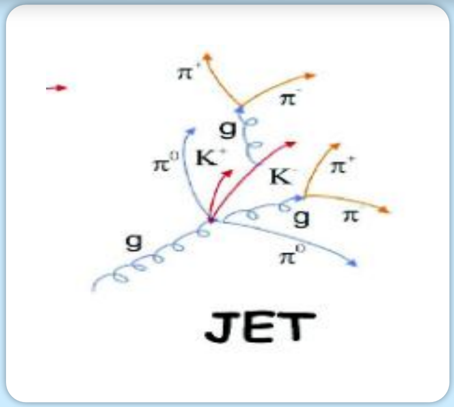
Main sources of fake taus

QCD jets

Main challenge: separate out a clean sample of τ leptons from the overwhelming QCD jet rate!



- narrow, collimated
- 1 or 3 tracks
- small invariant mass of decay products
- have secondary vertex



- wide
- can have many tracks
- large invariant mass of decay products
- come directly from primary vertex

- Electrons
- Muons

Electrons and muons can also be misidentified as 1-prong τ candidates.
Separate algorithms are developed in order to reject them.

Two steps to find τ candidates

Reconstruction

- Building of a τ candidate starts from reconstructed jets
- Tracks satisfying dedicated selection are associated to τ candidates
  - additional algorithm is used to find the primary vertex from which τ originates and tracks are selected with respect to it
    - smaller degradation due to pile-up
- Final energy of τ candidates is obtained using dedicated MC-based calibration
- Identification variables are calculated from the tracking and calorimetric information

Identification

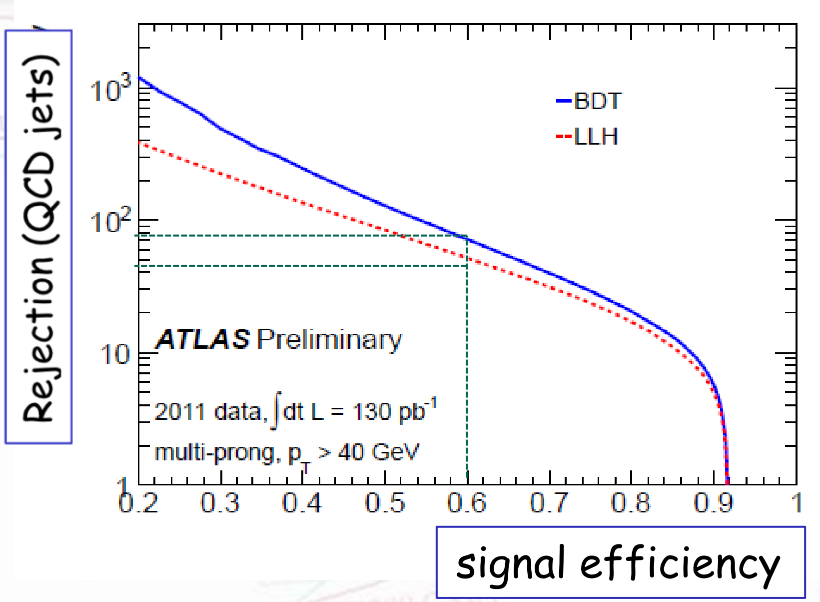
- Aimed to distinguish between QCD jets/electrons/muons and τ leptons
- Variables based on τ decay properties are combined into various (multivariate) discriminants to reject fake τ candidates
- Cut on the output of the discriminants is used to select a sample of τ candidates with the desired level of background rejection and signal efficiency

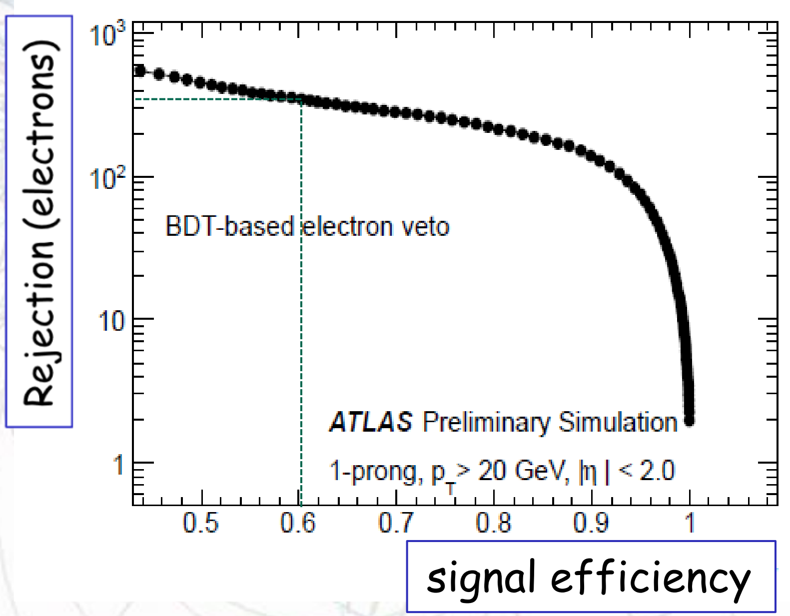
τ identification methods

ATLAS-CONF-2012-142

- Two algorithms used to identify hadronic τ's and reject QCD jets: boosted decision trees (BDT) and a log-likelihood (LLH) .
- Threshold on their values is calculated as a function of $p_T(\tau)$, wrt number of vertices reconstructed in the event and separately for one-prong and multi-prong τ candidates
- The cut-based/BDT algorithms used to reject electrons and muons faking τ candidates

Rejection= (# of reconstructed τ candidates)/ (# of reconstructed τ candidates passing identification)



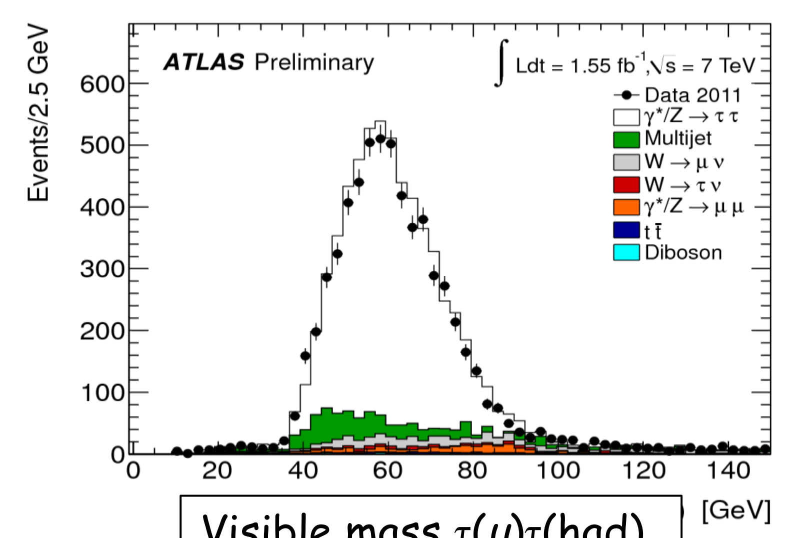


For τ efficiency of 96% ~55% of muons misidentified as τ candidates are rejected (wrt τ identification, electron veto and overlap removal with identified muons)

$Z \rightarrow \tau\tau$ cross section measurement

ATLAS-CONF-2012-006

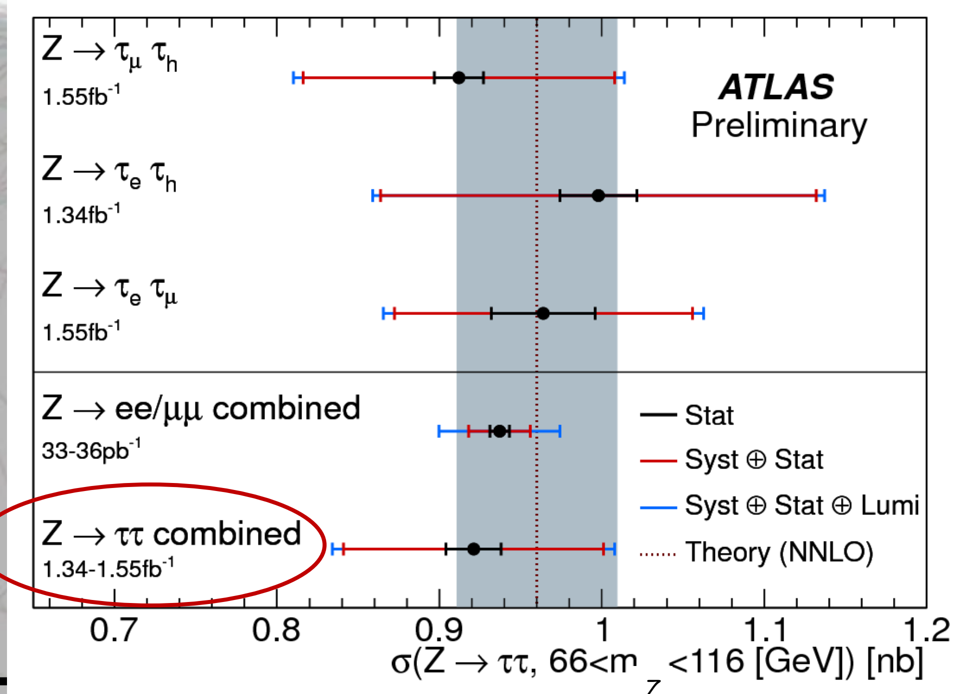
- Performed on ~1.5 fb^{-1} of 2011 data
- 3 final states: $\tau(e)\tau(had)$, $\tau(\mu)\tau(had)$, $\tau(e)\tau(\mu)$
- Triggers:
  - isolated muon for $\tau(\mu)\tau(had)$ and $\tau(e)\tau(\mu)$
  - combined τ and electron for $\tau(e)\tau(had)$
- Background estimation
  - QCD, W,Z->ll (l=e,μ): main backgrounds - partially or fully data driven
  - $t\bar{t}$, dibosons: MC
- Dominant systematics: energy scale 8%, electron 6% and τ 5% identification



Visible mass $\tau(\mu)\tau(had)$

$\sigma(Z\rightarrow\tau\tau, 66<m_Z<116$ GeV$) =$
$0.92\pm0.02(stat) \pm0.08(syst) \pm0.03(lumi)$ nb

Theoretical expectation:
0.96 ± 0.05 nb at NNLO



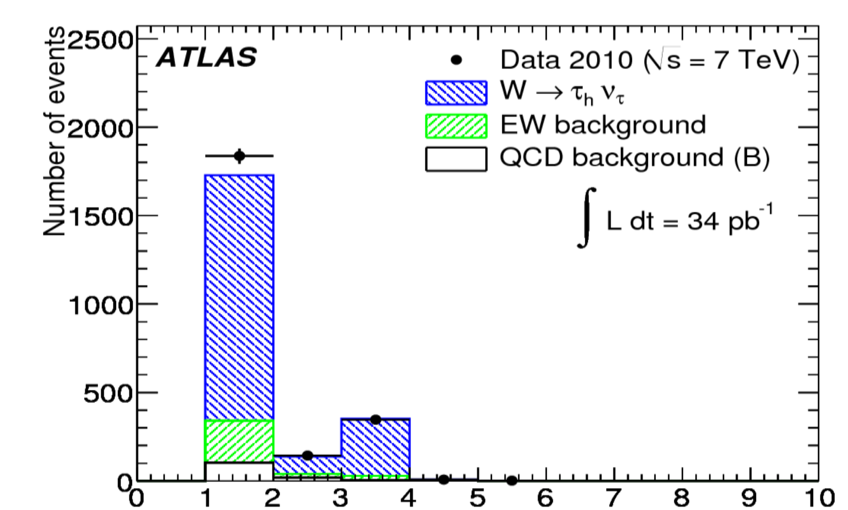
W → τν cross section measurement

Phys.Lett. B706 (2012)

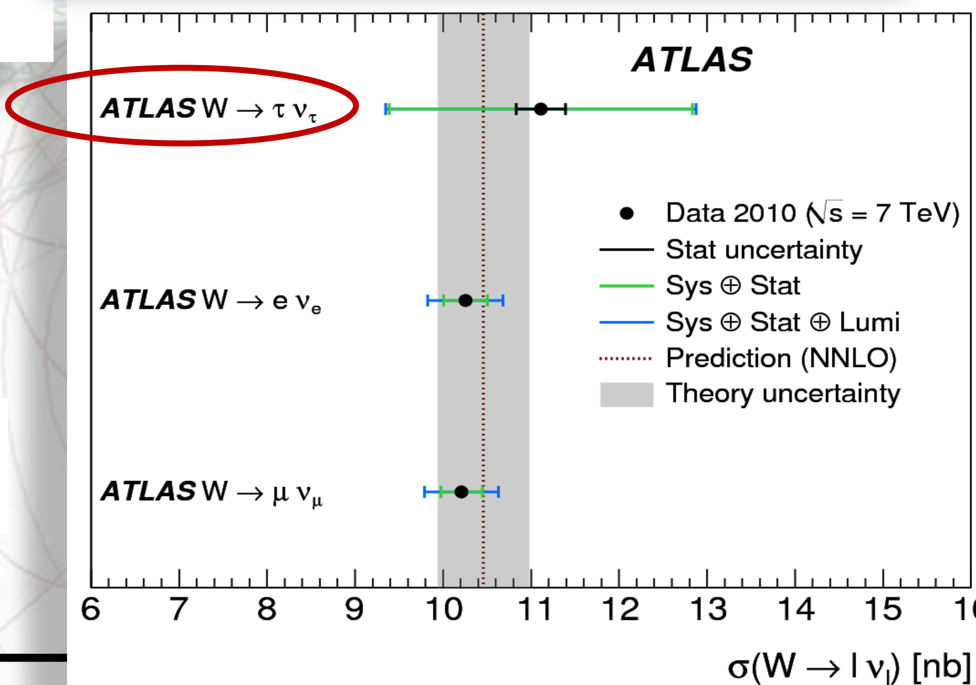
- Performed on 34 pb^{-1} of 2010 data
- Only hadronic τ final state
- Challenging: lack of additional lepton like in $Z \to \tau\tau$ process to select signal
- Combined $\tau + E_T^{miss}$ trigger
- Background estimation
  - QCD data driven
  - EW from MC
- Dominant systematics: energy scale: 8%, trigger efficiency 7%, τ identification efficiency 10.3%

$\sigma(W \to \tau\nu)$ =
$11.1 \pm 0.3(stat) \pm 1.7(syst) \pm 0.4(lumi)$ nb

Theoretical expectation:
10.46 ± 0.52 nb at NNLO



Number of τ candidate tracks



τ identification efficiency measurement

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- Three τ efficiency measurements in data with tag-and-probe method:
  - two using Z-> τ(μ)τ(had) events, tag: muon passing single muon trigger
  - one using W-> τ(had)ν events, tag: event passes E_T^{miss} trigger

- Probe: hadronically decaying τ

- τ efficiency = fraction of probes passing τ identification

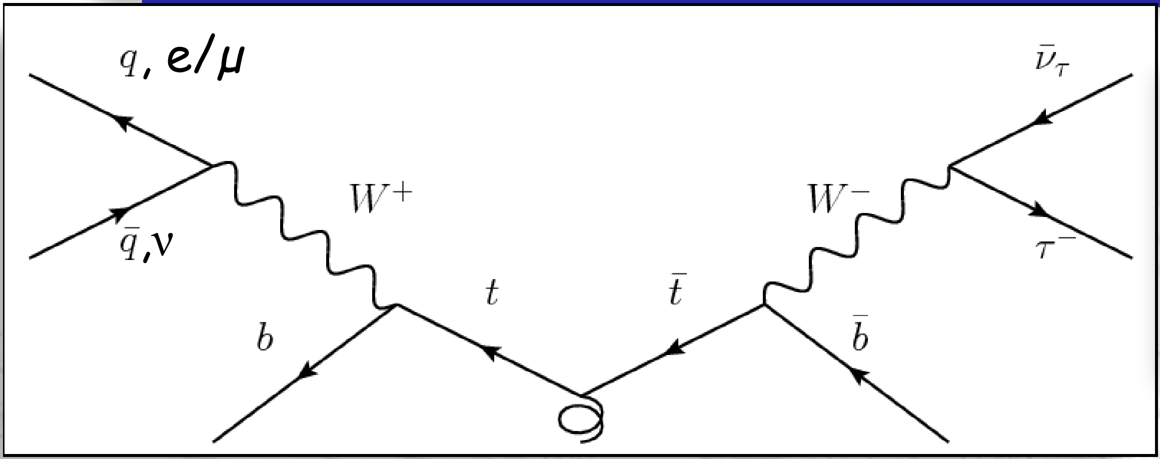
- Fraction of real and misidentified τ candidates is estimated from the fit of the track multiplicity distribution of the probe τ or from a two-dimensional side-band extrapolation

- τ efficiency data/MC scale factors consistent with 1

τ identification	τ efficiency (data)	data/MC scale factor
BDT *loose*	0.73 ± 0.03(stat) ± 0.04(syst)	0.96 ± 0.04(stat) ± 0.05(syst)
BDT *medium*	0.59 ± 0.02(stat) ± 0.03(syst)	0.93 ± 0.04(stat) ± 0.04(syst)
BDT *tight*	0.37 ± 0.01(stat) ± 0.01(syst)	0.99 ± 0.04(stat) ± 0.03(syst)
LLH *loose*	0.79 ± 0.05(stat) ± 0.04(syst)	0.93 ± 0.06(stat) ± 0.05(syst)
LLH *medium*	0.70 ± 0.03(stat) ± 0.03(syst)	0.97 ± 0.04(stat) ± 0.05(syst)
LLH *tight*	0.46 ± 0.02(stat) ± 0.03(syst)	0.96 ± 0.05(stat) ± 0.06(syst)

from W-> τ(had)ν events

Measurement of $t\bar{t}$ production cross section



Top quark pairs are produced in abundance at the LHC

- makes it possible to study experimentally challenging decay channels and topologies

- $t\bar{t}$ cross section measurement in the final state with τ leptons
  - makes it possible to probe flavor dependent effects in top quark decays
  - important to complete a high-precision measurement of the top-decay branching ratio under the SM
  - relevant to searches for new physics processes, in particular for $H^\pm$ production in top quark decays or RPV SUSY → enhancement in the $t\bar{t}$ cross section
- Two final states studied
  - hadronically decaying τ and jets, **$t\bar{t}$ → [bτ(had)][bqq]**, ~10% of all $t\bar{t}$ decays
    - analyzed data: 1.67 fb^{-1}

arXiv:1211.7205, submitted to EPJC

  - hadronically decaying τ and lepton, **$t\bar{t}$ → [bτ(had)][be/μν]**, ~5% of all $t\bar{t}$ decays
    - analyzed data: 2.05 fb^{-1}

Phys. Lett. B 717 (2012)

$t\bar{t}$ cross section: τ(had) + jets final state

arXiv:1211.7205, submitted to EPJC

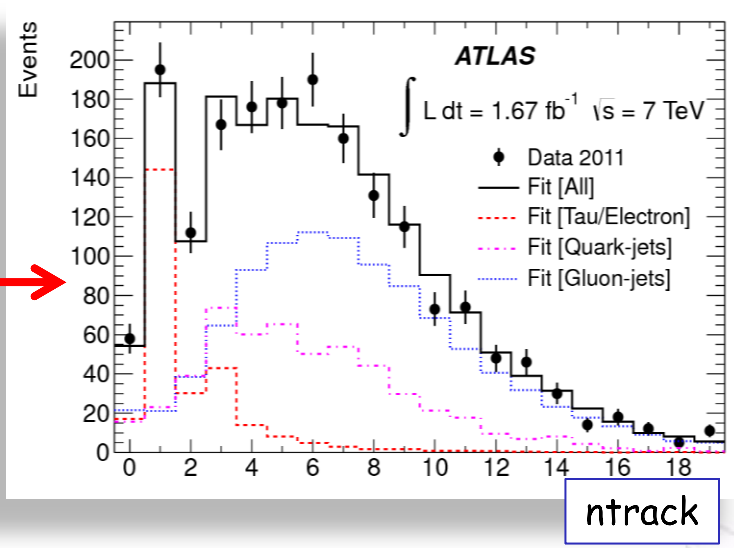
b-jet trigger: at least 4 jets with 2 identified as b-jets

Dominant backgrounds: QCD multijets, top-pairs with different final state or wrong τ candidate

Method: number of charged tracks associated to a jet (**ntrack**) is used to separate τ and backgrounds

- can be used as a cross-check/calibration to standard τ identification

- Fit **ntrack** to extract number of τ and electron events
  - **ntrack** shapes estimated from data for the main backgrounds: QCD multijets (Gluon-jets) and $t\bar{t}$ with quark- jets misidentified as τ (Quark-jets)
- Subtract remaining, small EW backgrounds (W+jets, single top) using MC predictions
- Number of τ events obtained by using the expected ratio (from MC) of τ's and electrons passing the selection in the $t\bar{t}$ sample



Systematics: ISR/FSR modeling 15%, event generator 11%, b-tagging efficiency 9%

$\sigma(t\bar{t})$ = 194 ±18(stat) ±46(syst) pb

Theoretical expectation: **167** $^{+17}_{-18}$ pb

Hathor 1.2 M. Aliev et al., Comput. Phys. Commun. 182, 1034 (2011)

$t\bar{t}$ cross section: τ(had) + leptons final state

Phys. Lett. B 717 (2012)

Two final states considered:

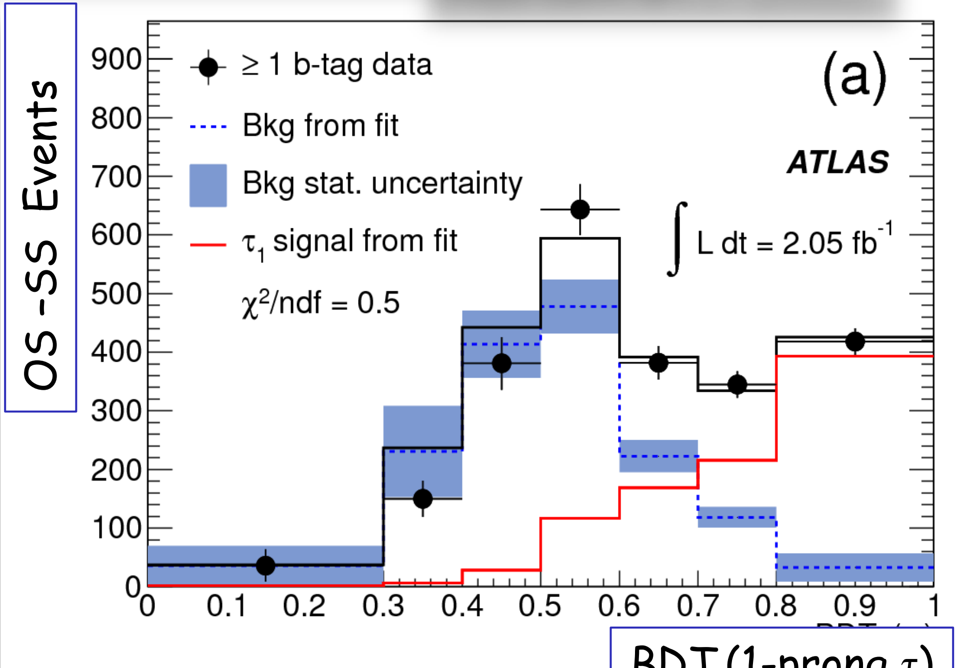
- $e + \tau$ selected with single-electron trigger
- $\mu + \tau$ selected by single-muon trigger

At least one jet identified as b-jet required

Main background: $t\bar{t} \rightarrow e/\mu$ + jets

Method: τ identification BDT algorithm is used

- Focus on **OS-SS** events: charges of e/μ and τ with opposite sign – same sign
  - OS-SS -> to cancel the contribution from charge-symmetric gluon-fakes (QCD)



BDT (1-prong τ)

- Number of τ leptons (signal) is extracted by fitting distribution of **OS-SS BDT** output with signal (MC) and background templates (data driven)
- Results combined for 1-prong and multi-prong τ candidates and for e and μ final states

Systematics: b-tag ~8%, ISR/FSR ~4%, τ identification ~3%

$\sigma(t\bar{t})$ = 186±13(stat) ±20(syst) ±7(lumi) pb

Theoretical expectation: **164** $^{+11}_{-16}$ pb

Hathor 1.2 M. Aliev et al., Comput. Phys. Commun. 182, 1034 (2011)

τ polarization

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

τ polarization (Pτ) is a measure of the asymmetry of the cross section for left-handed and right-handed τ's

Process	Pτ
$W^- \to \tau\nu$	-1
$Z \to \tau\tau$	-0.15
$H \to \tau\tau$	0
MSSM $H^- \to \tau\nu$	+1

• Ability to measure τ polarization allows for
  - tests of Standard Model predictions
  - constraints on new models, for example Z′ and W′ degree of parity violation varies between models
  - rejection of irreducible background (W from $H^\pm$)

• Angular distribution of the τ decay products depends on the spin orientation of τ lepton
  - hadronic τ decays are particularly useful due to presence of only one neutrino

• Observable: **charged asymmetry** **Υ** -> ρ meson polarization analyzer

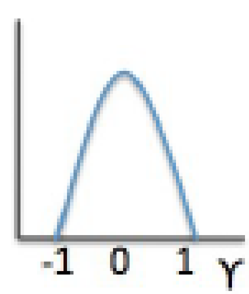
$BR(\tau \to \rho\nu \to \pi^\pm\pi^0\nu)$ ~25%

Track pt

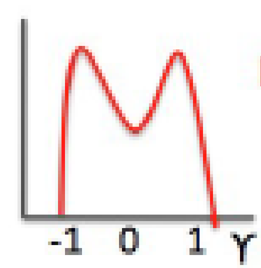
Pi0 energy : difference between tau and track pt

$$\frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T} \approx 2\frac{p_T^{trk}}{p_T} - 1 = \Upsilon.$$

Tau pt



transversely polarized ρ favored by τ_L



longitudinally polarized ρ favored by τ_R

Measurement of τ polarization

Eur.Phys.J. C72 (2012) 2062

- Studied with $W \to \tau\nu$ events and with 24 pb^{-1} of data
- **First measurement of τ polarization at hadron colliders and at $Q^2 = m_W^2$**
- The charged asymmetry is measured in all of the decay modes to a single charged meson
- Event selection and background estimation as for $W \to \tau\nu$ cross section measurement

- τ polarization measured from fit of the observed charged asymmetry distribution to linear combination of templates prepared with the left-handed and right-handed τ MC samples (+ QCD multijet data)

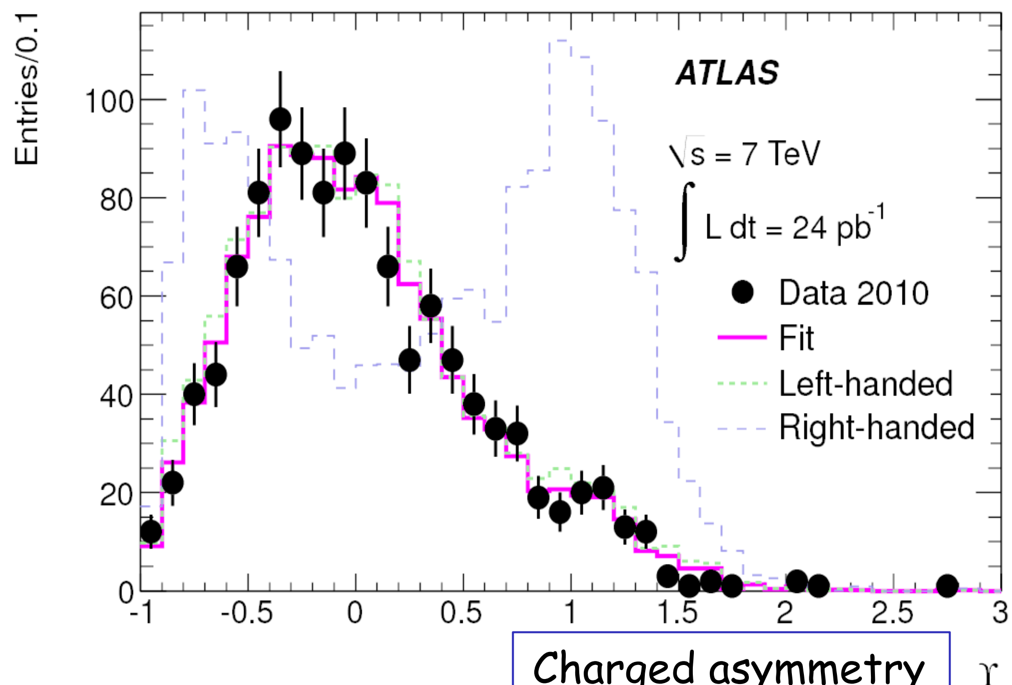
Measured value

$$P_\tau = -1.06 \pm 0.04\ (stat)\ ^{+0.05}_{-0.07}\ (syst).$$

P_τ lies in [-1, -0.91] with 95% probability

Dominant systematics: energy scale, modeling the signal templates

TauSpinner, Z. Czyczula et al., arXiv:1201.0117



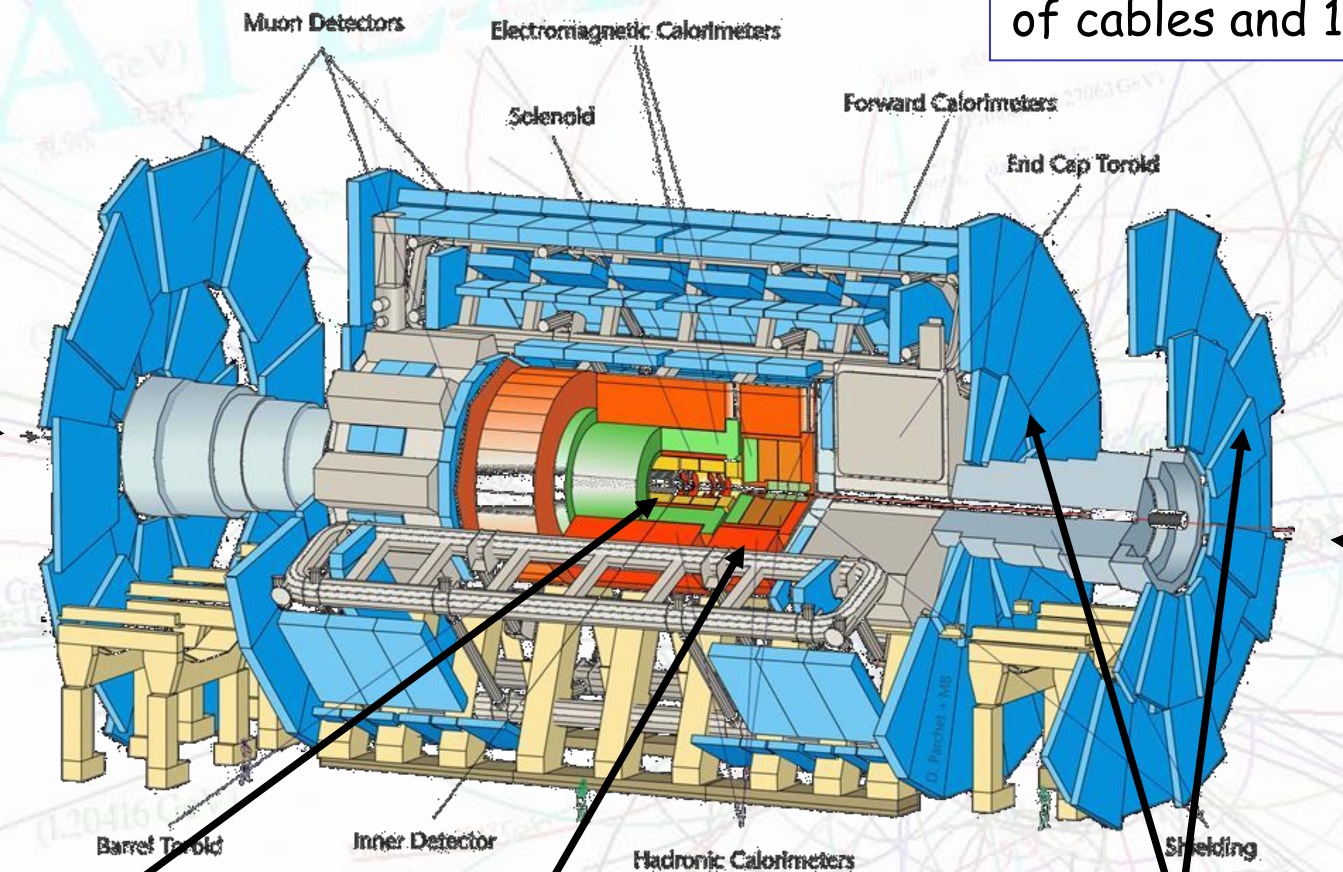
Summary

- ATLAS has an extensive physics program with τ leptons
- Large variety of τ Standard Model physics analyses being held in ATLAS
- τ reconstruction and identification well understood
- Measured cross section of $W/Z/t\bar{t}$ in good agreement with theory NNLO predictions
- Standard Model channels provide a tool for τ identification measurements
- Performed the first measurement of τ polarization at hadron collider and the first direct measurement of helicity structure at $Q^2 = m_W^2$
  - small statistical and systematic uncertainties of the measurement demonstrate the method potential

Additional slides for curious kids

ATLAS – A Toroidal LHC ApparatuS

25m diameter, 46m long, weighing 7000T, with 3000km of cables and 10^8 channels



Tracking ($|\eta|<2.5$, B=2T):
- Silicon pixels and strips
- Transition Radiation Tracker

$\sigma/P_T=0.05\% \, P_T + 1\%$
(2%@20GeV)
$\sigma(d0)$=15 um@20 GeV

Calorimetry ($|\eta|<5$)
EM : Pb-LAr
HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

EM : $\sigma(E)/E = 10\%/\sqrt{E} + 0.7\%$

Hadron : $\sigma(E)/E = 50\%/\sqrt{E} + 3\% \; (\eta < 3)$

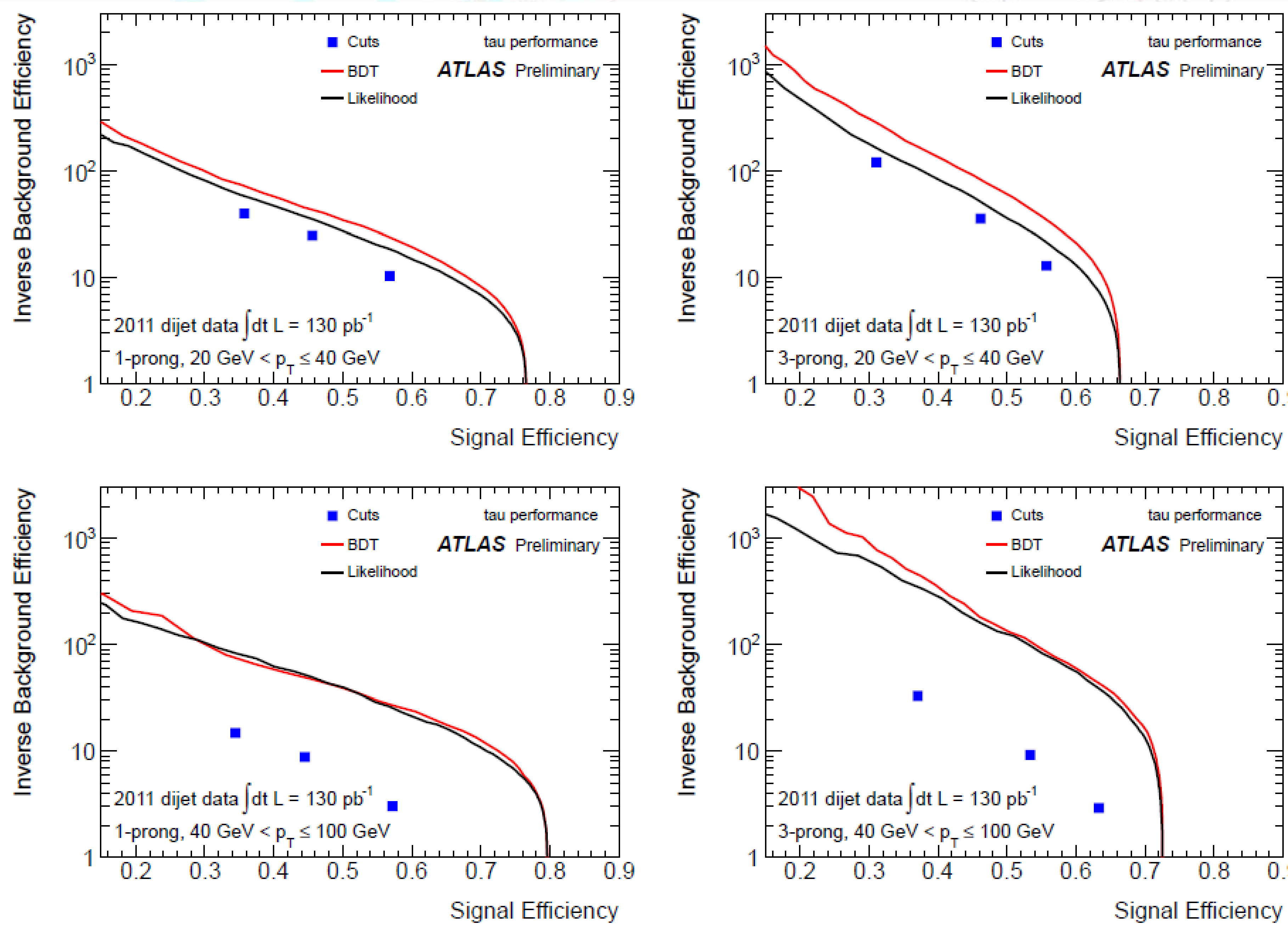
$\sigma(E)/E = 100\%/\sqrt{E} + 10\% \; (\eta > 3)$

Muon spectrometer ($|\eta|<2.7$, B=4T max)
Toroid magnet system with precision and trigger chambers

σ/P_T=2-10%

τ identification methods

ATLAS-CONF-2011-152

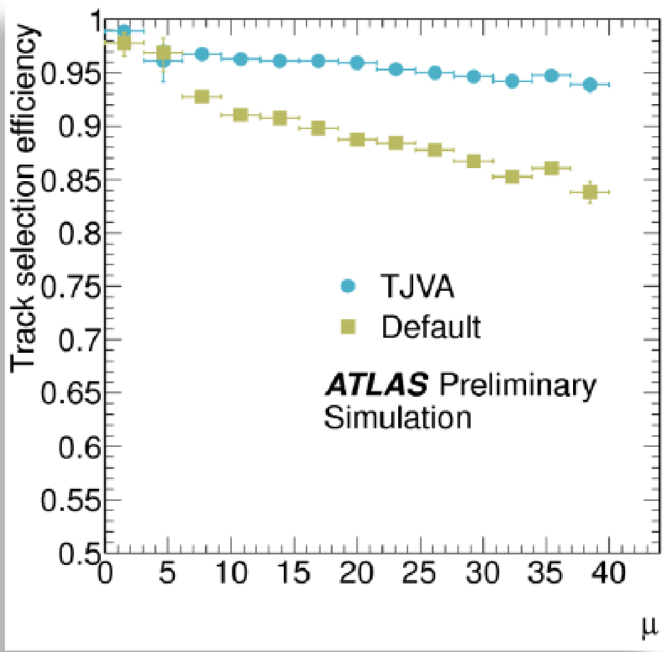


Tau Jet Vertex Association (TJVA)

- For each tau candidate a vertex candidate with the highest Jet Vertex Fraction (f_{JVF}) is found and used as a primary vertex

$$f_{\mathrm{JVF}}(\mathrm{jet}|\mathrm{vtx}) = \frac{\sum p_T^{\mathrm{trk|vtx}}}{\sum p_T^{\mathrm{trk}}}$$

- Track selection is done with respect to it
- With Tau Jet Vertex Association (TJVA), tau candidate track multiplicity is less sensitive to pile-up and a smaller degradation in efficiency is observed as pile-up increases

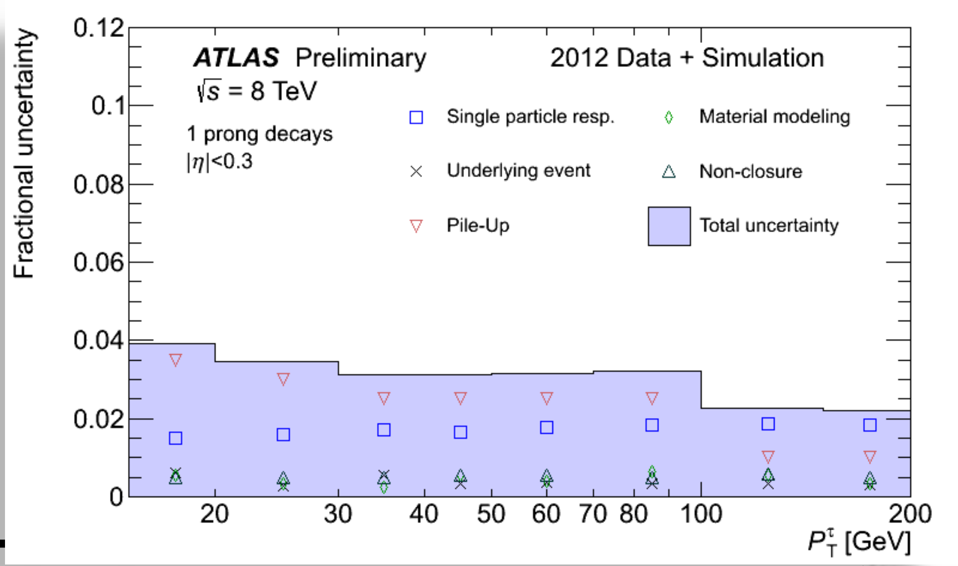


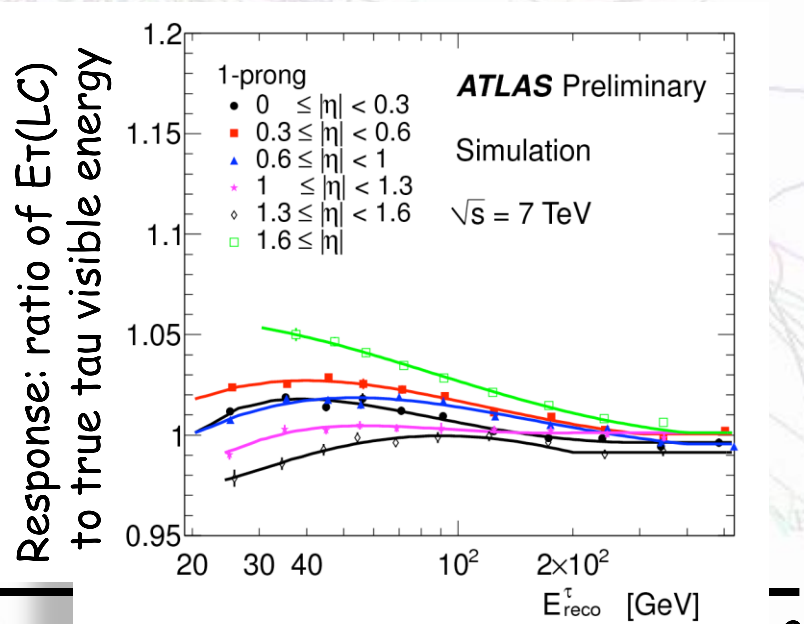
Track selection efficiency with respect to the average number of pile up interactions in Z->tautau MC, 3-prongs.

Tau Energy Scale

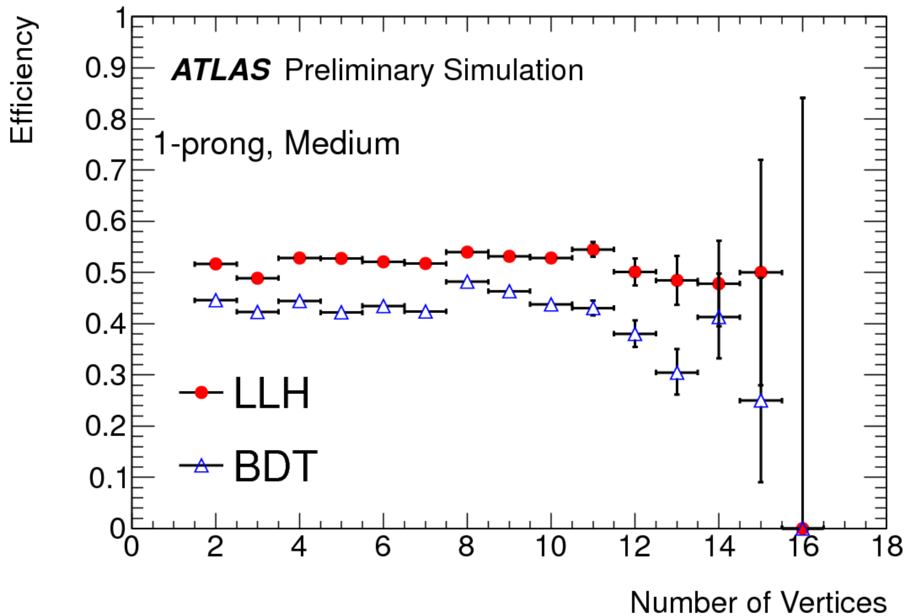
- Topological clusters calibrated using local hadron calibraton (LC)
- LC accounts for
  - Non-compensation of calorimeters
  - Energy deposited outside the reconstructed cluster
  - Dead material
- LC weights derived from MC
- Additional corrections applied to restore true tau energy value (TES)
- Uncertainty on TES
  - 3 - 5% depending on eta and prong of tau
- Reduced uncertainty due to inclusion of
  - particle responses from isolated single hadrons and combined test beam data instead of MC samples

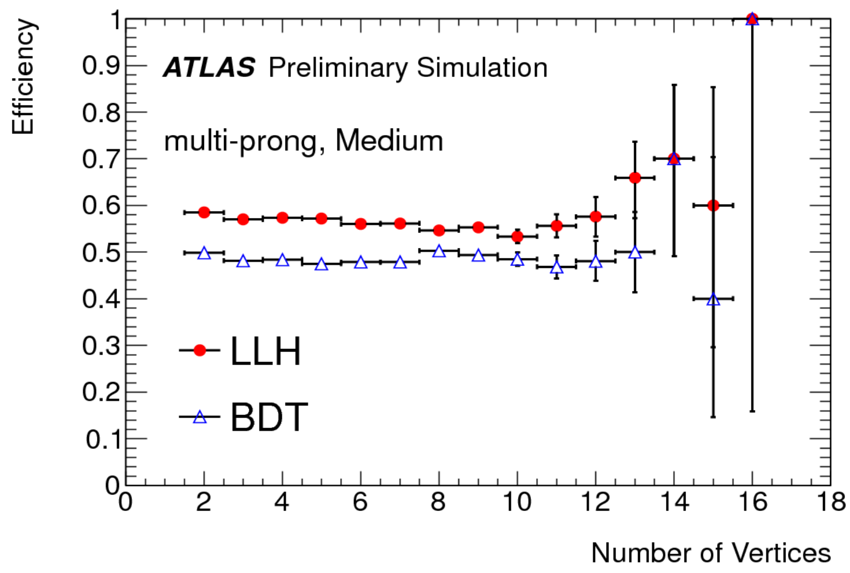
ATLAS-CONF-2012-064



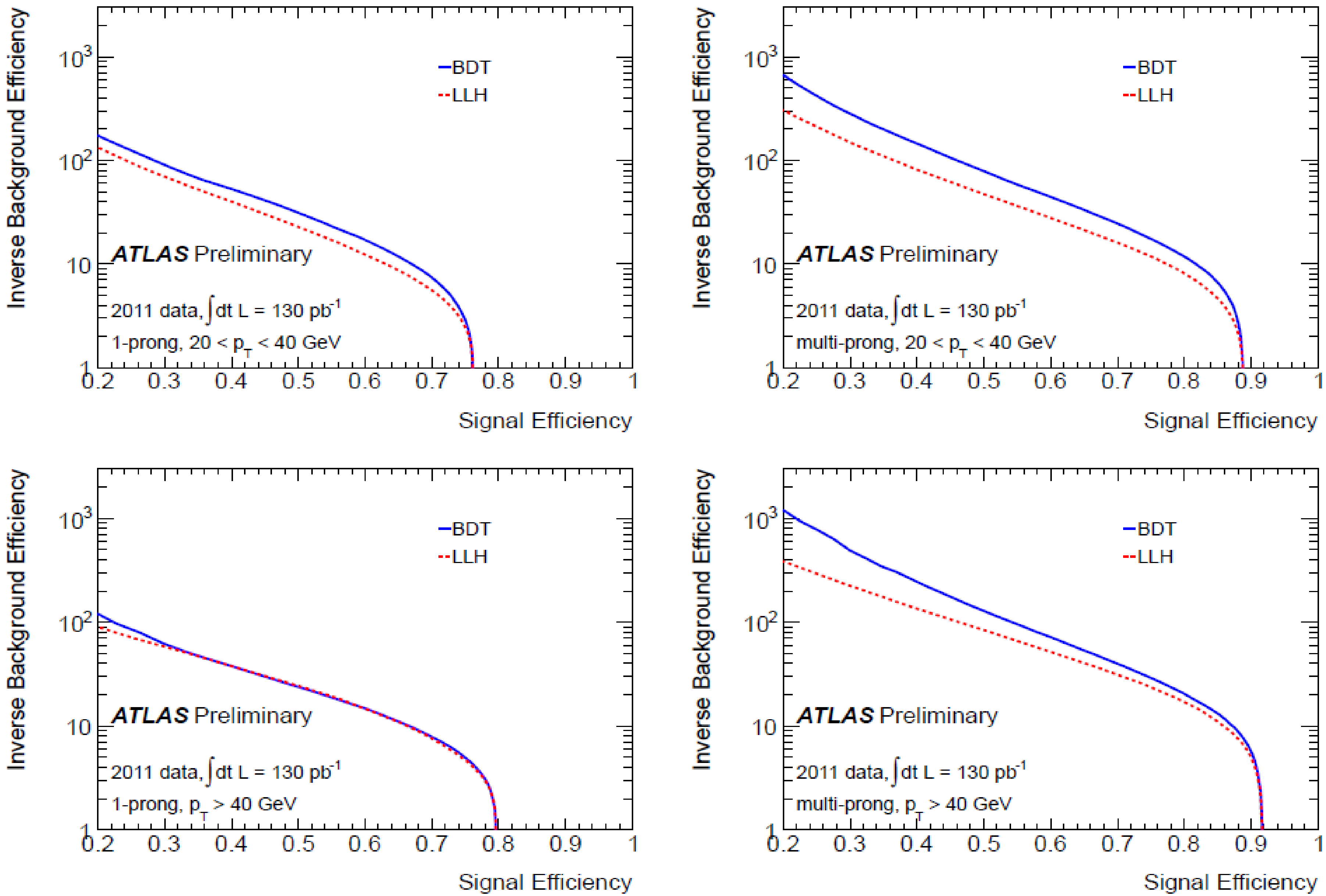


Tau Identification

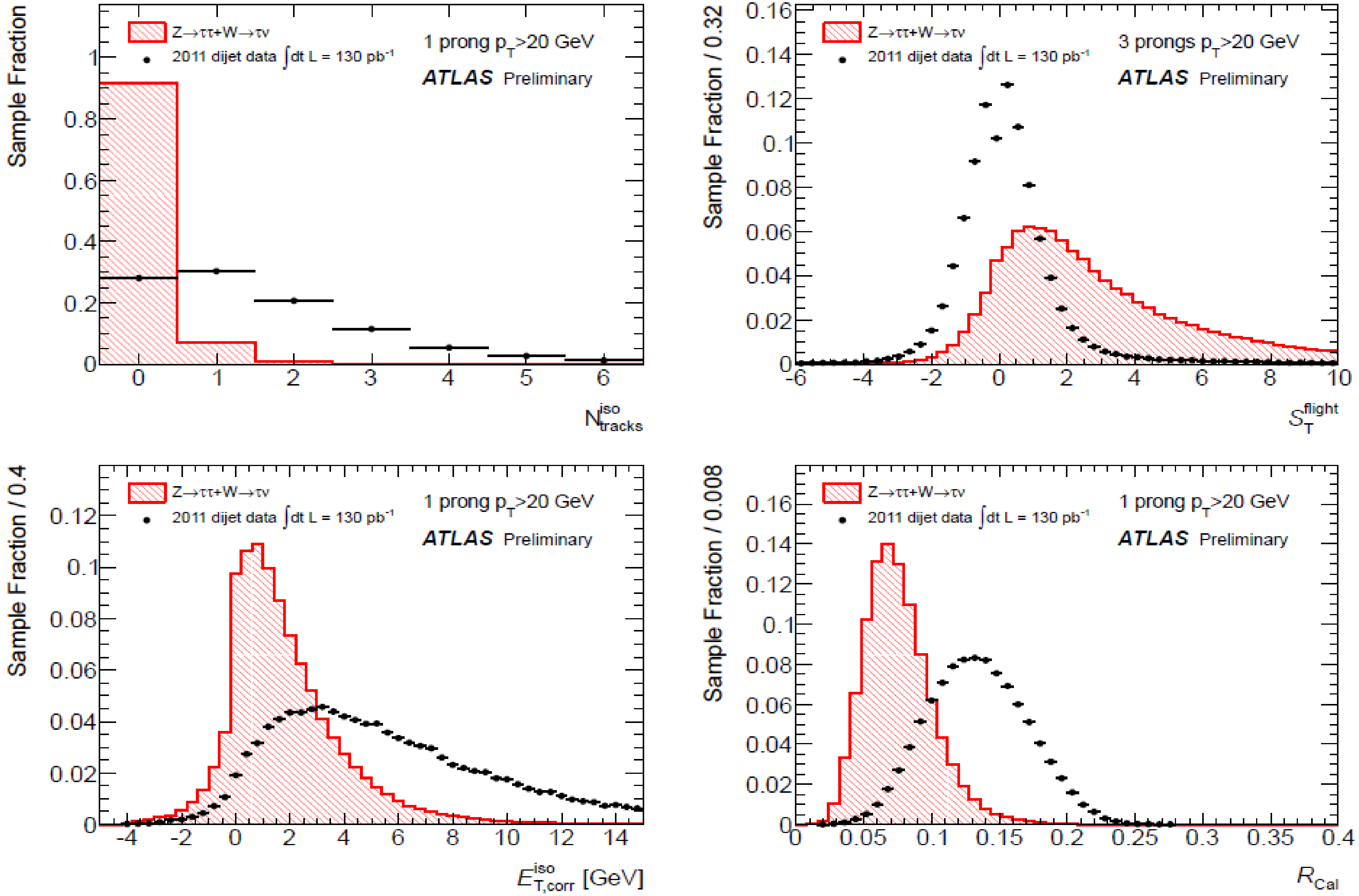




Tau Identification



Tau Identification Variables (against QCD jets) (1)



Tau Identification Variables (against QCD jets) (2)