Searching for new physics in high-mass ditau events at ATLAS

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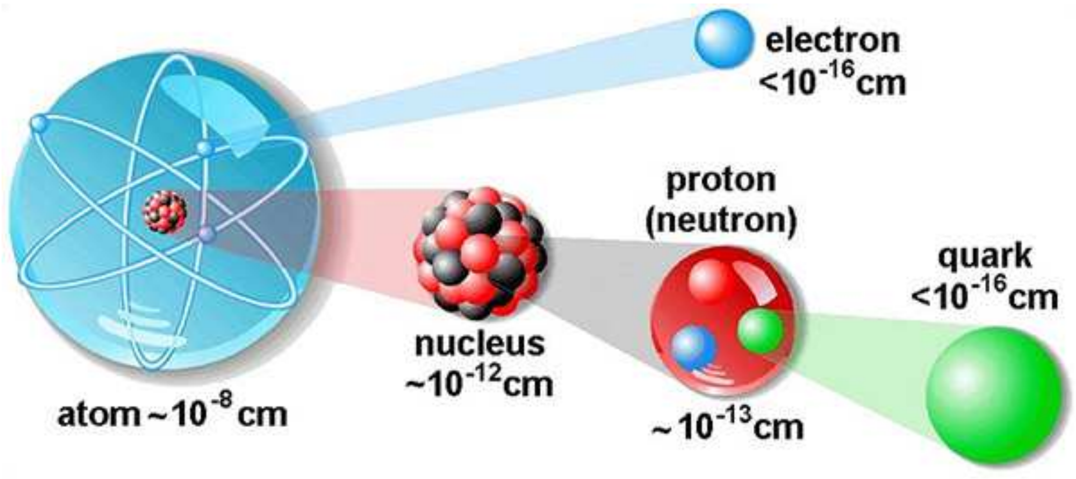
Outline

1. Introduction
   Standard Model, LHC, ATLAS
2. TRT commissioning
   threshold calibration, hit efficiency
3. Tau performance
   reconstruction, cut-based ID, pile-up robustness
4. SM $Z \rightarrow \tau\tau$
   selection design, observation, cross section
5. $Z' \rightarrow \tau\tau$
   fake factor method, exclusion

Particle Physics

Fundamental questions
of particle physics:

1. ***What is matter?***
2. ***How does it interact?***



Four fundamental forces at low energies:

1. Gravity	- very weak, no complete quantum theory
2. Electromagnetism	- binds atoms, chemistry
3. Strong force	- nuclear range, binds nuclei
4. Weak force	- nuclear range, radioactivity, solar fusion

Standard Model

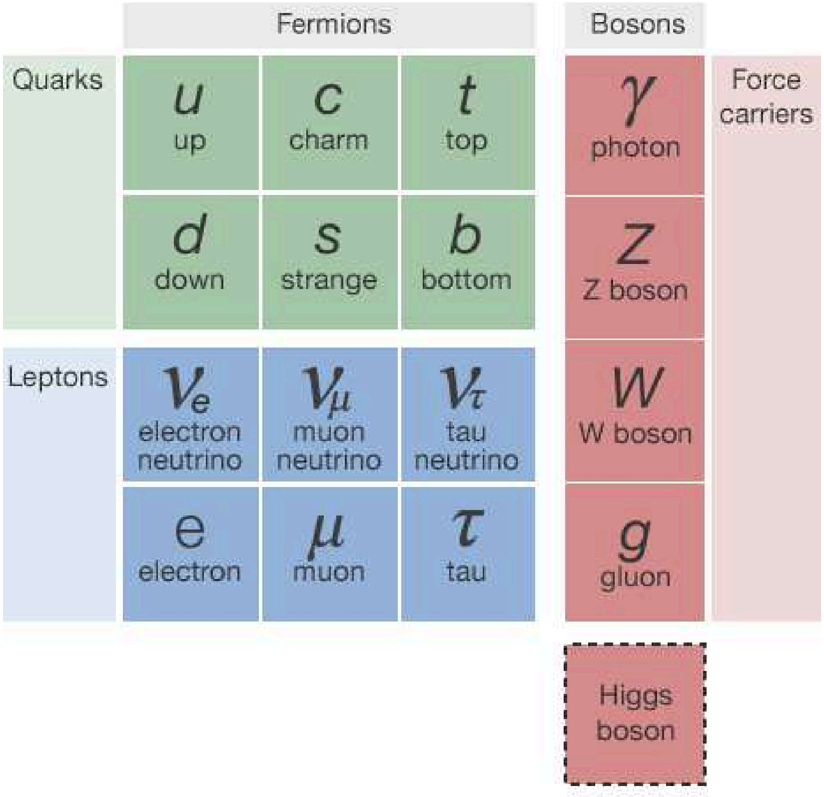
- In QFT, ***fields*** are actually what is fundamental, and particles are localized excitations in the fields.
- ***Gauge symmetries*** determine the character of the forces between fermion fields through gauge bosons.
- The SM gauge group is

$$\mathbf{SU(3)_C} \times \underbrace{\mathbf{SU(2)_L} \times \mathbf{U(1)_Y}}$$

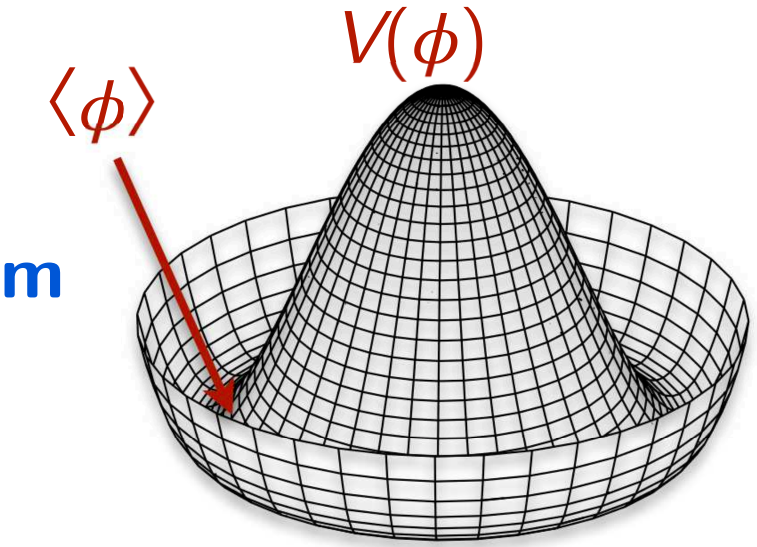
$\Downarrow$ **Strong force**

$\Downarrow$ **Higgs mechanism**

EM + weak forces



	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	



July 4, 2012
CERN announces the discovery of a new particle by ATLAS and CMS, consistent with the Higgs boson

The New York Times

Late Edition

NEW YORK, THURSDAY, JULY 5, 2012

$2.50

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

Physicists Find Elusive Particle Seen as Key to Universe

July 5 cover of the New York Times:
Physicists Find Elusive Particle Seen as Key to the Universe

Why the Standard Model?

- Why the **gauge group** $SU(3)_C \times SU(2)_L \times U(1)_Y$?
- Why are there **3 generations** of quarks and leptons?
- Why are lepton and hadron charges quantized in the same units? Why the existing **hypercharges**?

$$Q_{\mathrm{EM}} = T_{3\mathrm{L}} + Y/2$$

Is it because...

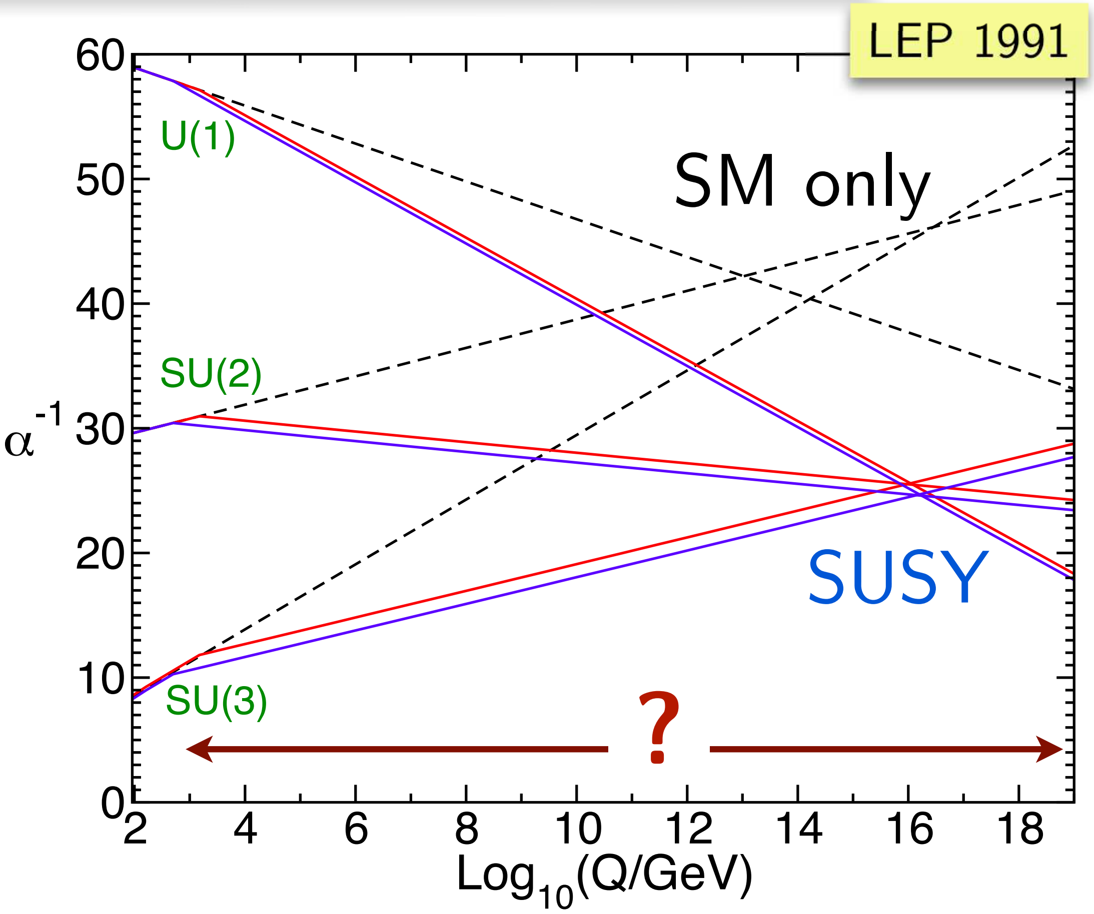
- ***the gauge group of Nature is actually bigger?***
- ***and the SM is the product of a larger symmetry breaking process than just electroweak symmetry breaking?***
- $SO(10) \rightarrow SU(5) \times U(1)$ Georgi-Glashow
  $SO(10) \rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R$ Pati-Salam

1974

- e.g. Pati-Salam SO(10): $Q_{\mathrm{EM}} = T_{3\mathrm{L}} + T_{3\mathrm{R}} + 1/2(B-L)$

Running of the couplings

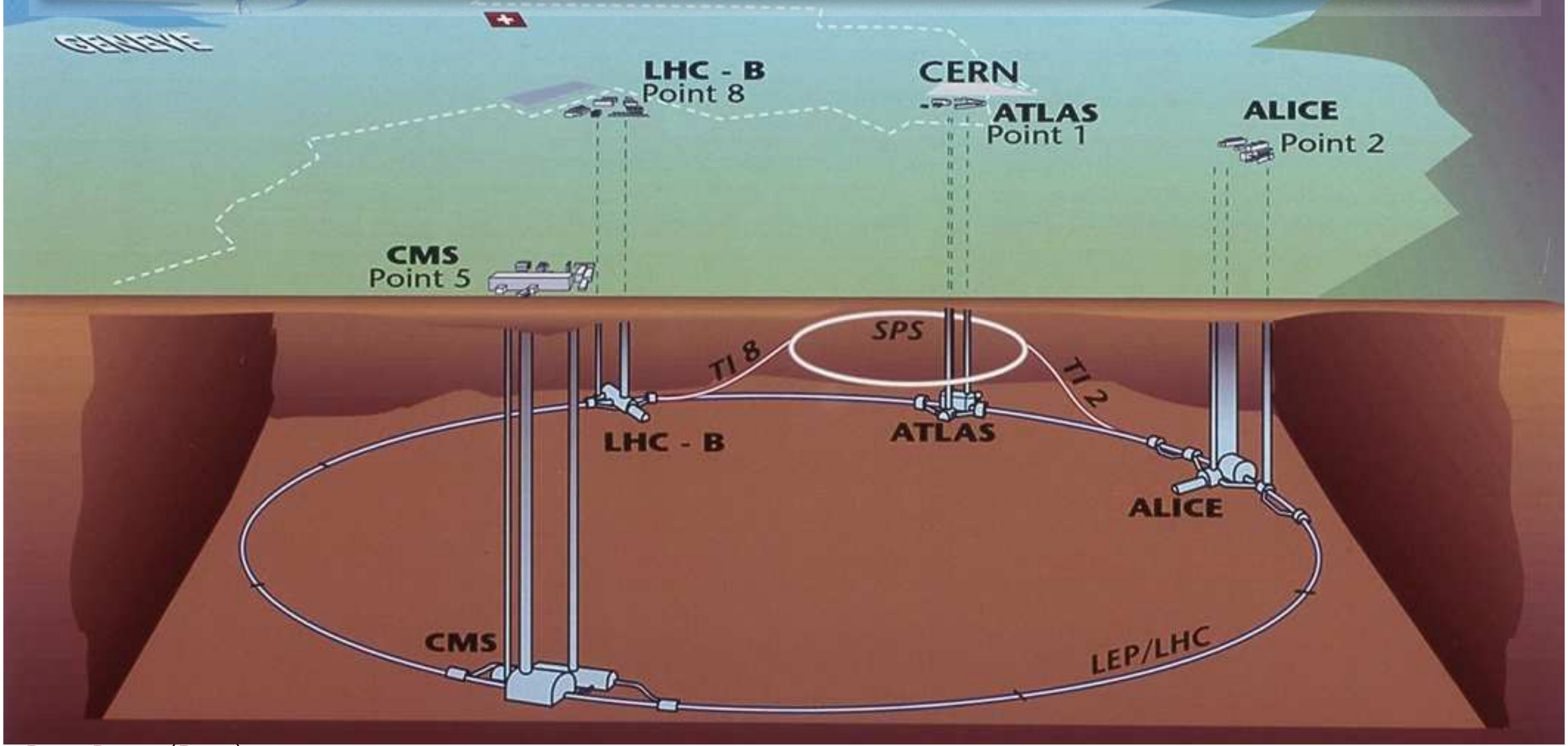
- After precision measurements of the SM couplings at LEP, one could run the couplings according to the RGEs to higher energies.
- The SM ***couplings apparently converge***, motivating the possibility of **grand unification** (GUTs).
- Moreover, the unification seems to require **Supersymmetry**, but the extrapolation is over 10^{14} orders, and ***we need more experimental clues***.



- ***Z’* bosons occur in theories with additional U(1) symmetries.**
- **Best limits on *Z’→ee/μμ* are** **$M > 2.86$ TeV ATLAS [ATLAS-CONF-2013-017]**
  $M > 2.96$ TeV CMS [CMS-PAS-EXO-12-061]
- **Important to test the couplings to all lepton flavors.**

Overall view of the LHC experiments.

- 27 km circumference
- 1232 dipoles: 15 m , 8.3 T
- 100 tons liquid He, 1.9 K
- p-p collisions at $\sqrt{s} = $ 7-8 TeV
- inst. luminosity = 10^{32}-10^{34} cm^{-2}s^{-1}
- 10^{11} protons / bunch
- 1000 bunches/ beam
- 20 MHz , 50 ns bunch spacing
- 1-40 interactions / crossing
- 0.5 × 10^{9} interactions / sec



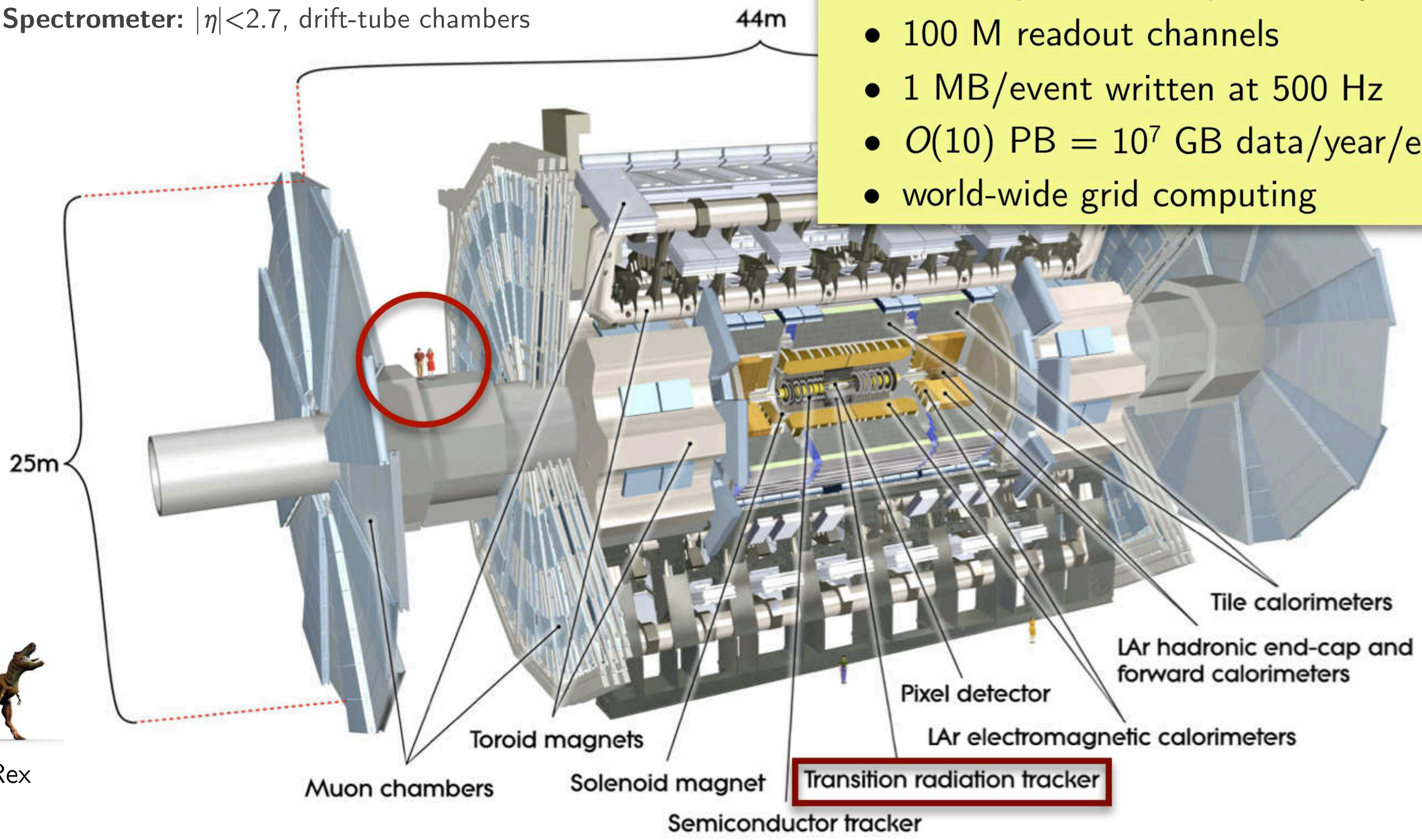
ATLAS Detector

Both ATLAS and CMS have:

- 3000 scientists, 170+ institutions
- tracking, calorimetry, muon spec.
- 100 M readout channels
- 1 MB/event written at 500 Hz
- $\mathcal{O}(10)$ PB = 10^7 GB data/year/exp.
- world-wide grid computing

Magnets: 2T solenoid, 4T toroid barrel and end-caps

Muon Spectrometer: $|\eta|<2.7$, drift-tube chambers



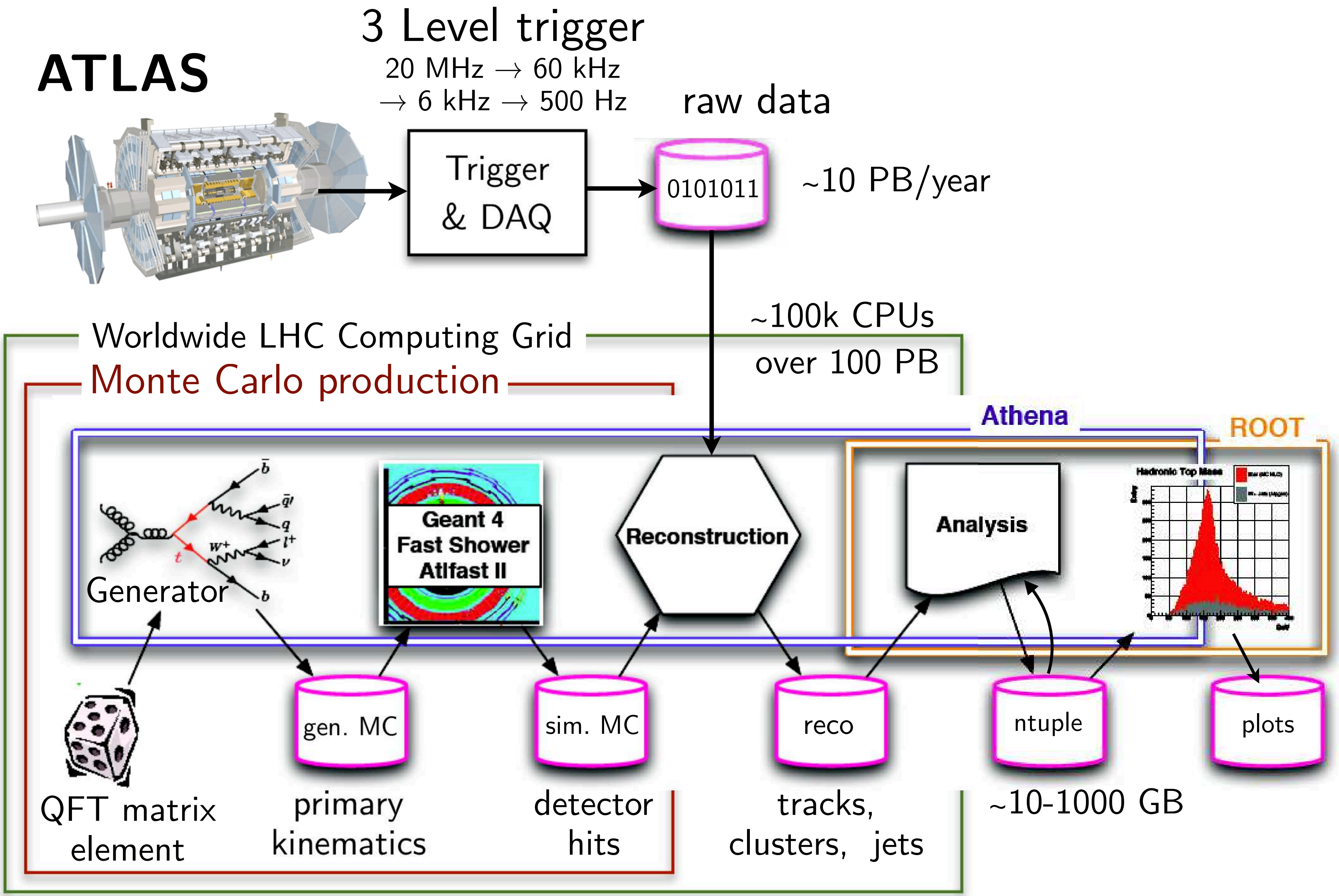
T.Rex

Tracking: $|\eta|<2.5$, B=2T, precise tracking and vertexing, Si pixels, strips, and TRT straws, TR electron ID

Electromagnetic Calorimeter: $|\eta|<3.2$, 3+1 layers corrugated layers of lead and LAr

Hadronic Calorimeter: $|\eta|<5$, Central: iron/scintillator tiles, Forward: copper/tungsten-LAr

Data flow and reconstruction



ATLAS

3 Level trigger

20 MHz → 60 kHz
→ 6 kHz → 500 Hz

Trigger
& DAQ

raw data

0101011

~10 PB/year

~100k CPUs
over 100 PB

Worldwide LHC Computing Grid

Monte Carlo production

Athena

ROOT

Generator

Geant 4
Fast Shower
Atlfast II

Reconstruction

Analysis

gen. MC

sim. MC

reco

ntuple

plots

QFT matrix
element

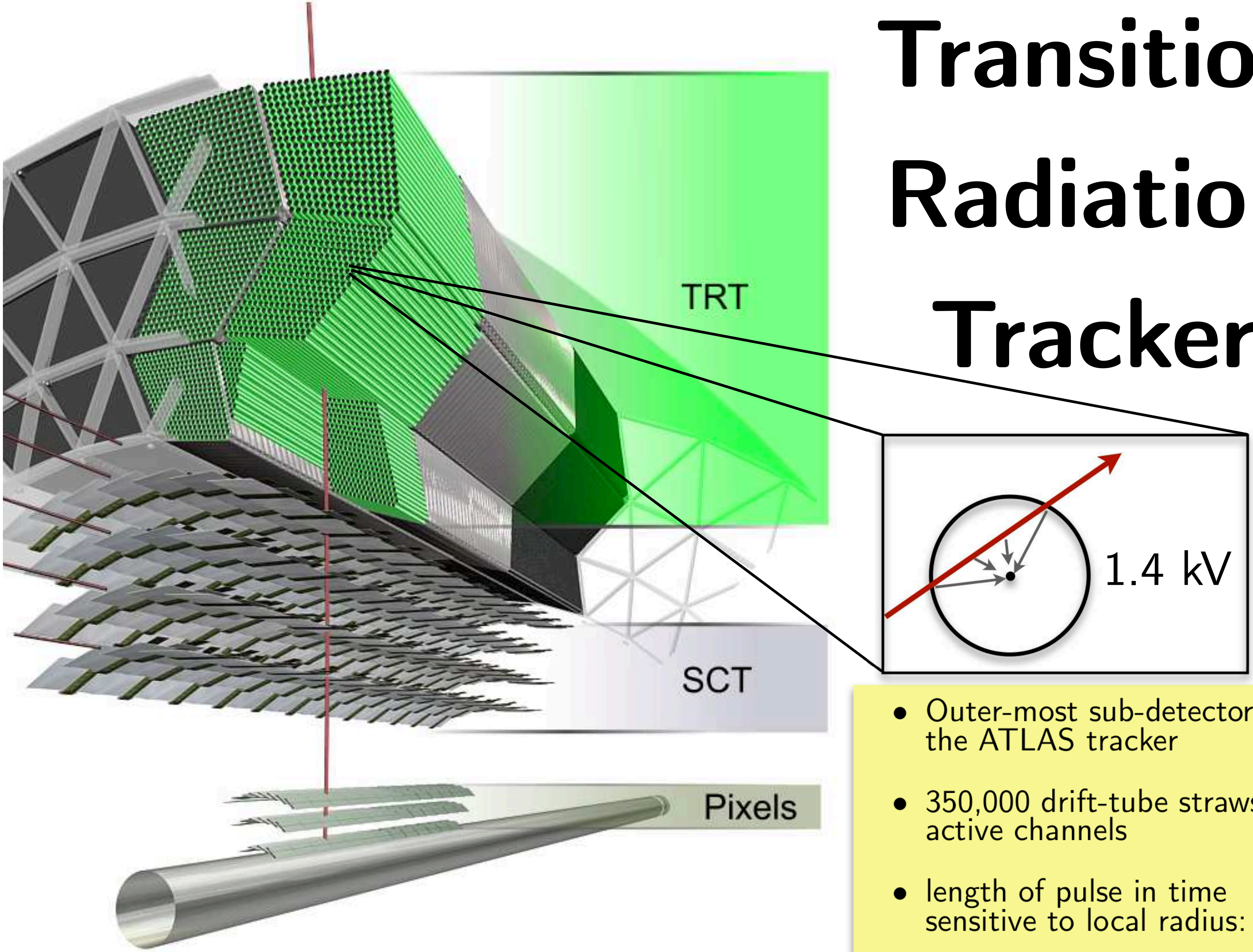
primary
kinematics

detector
hits

tracks,
clusters, jets

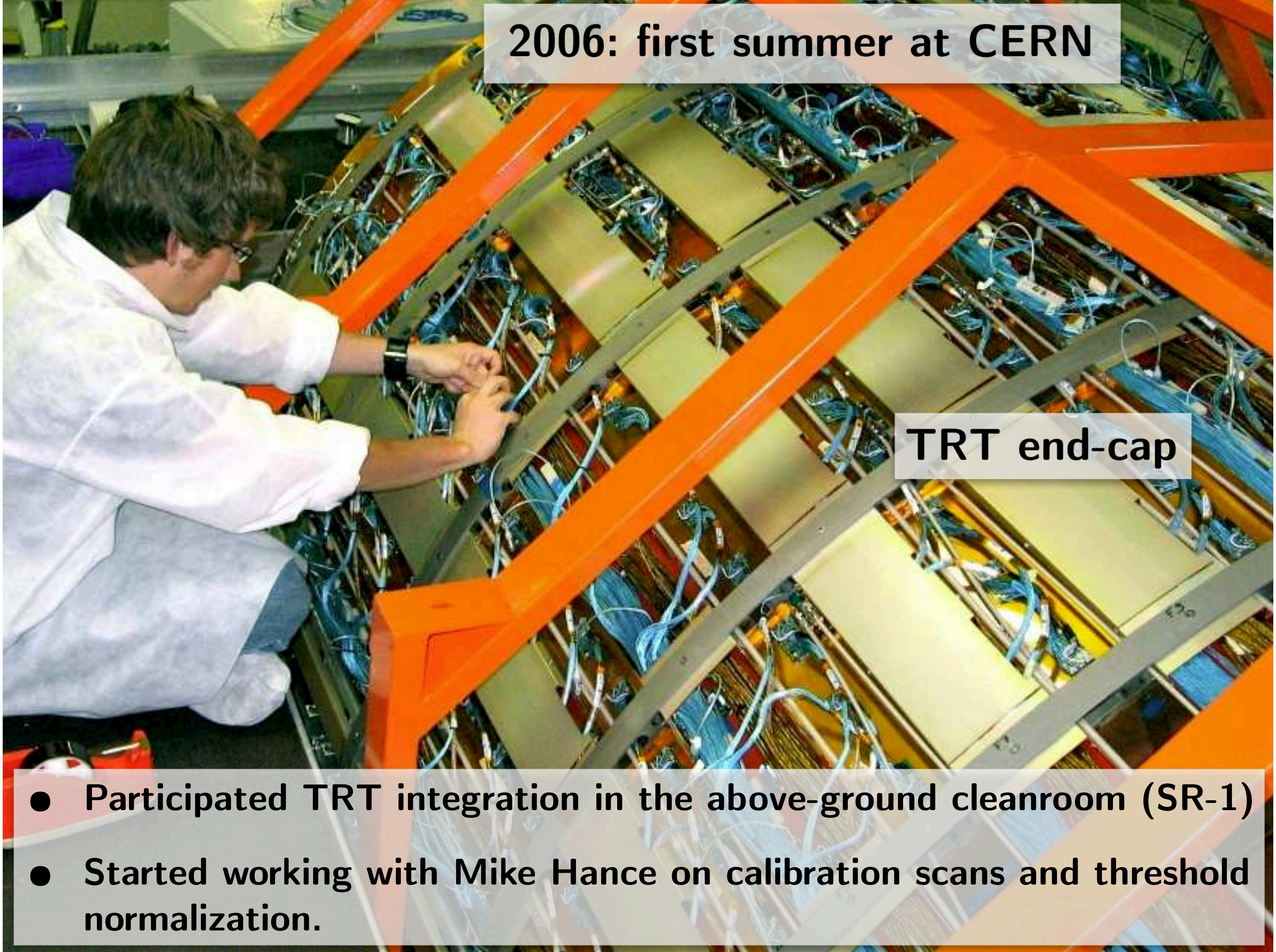
~10-1000 GB

Transition Radiation Tracker



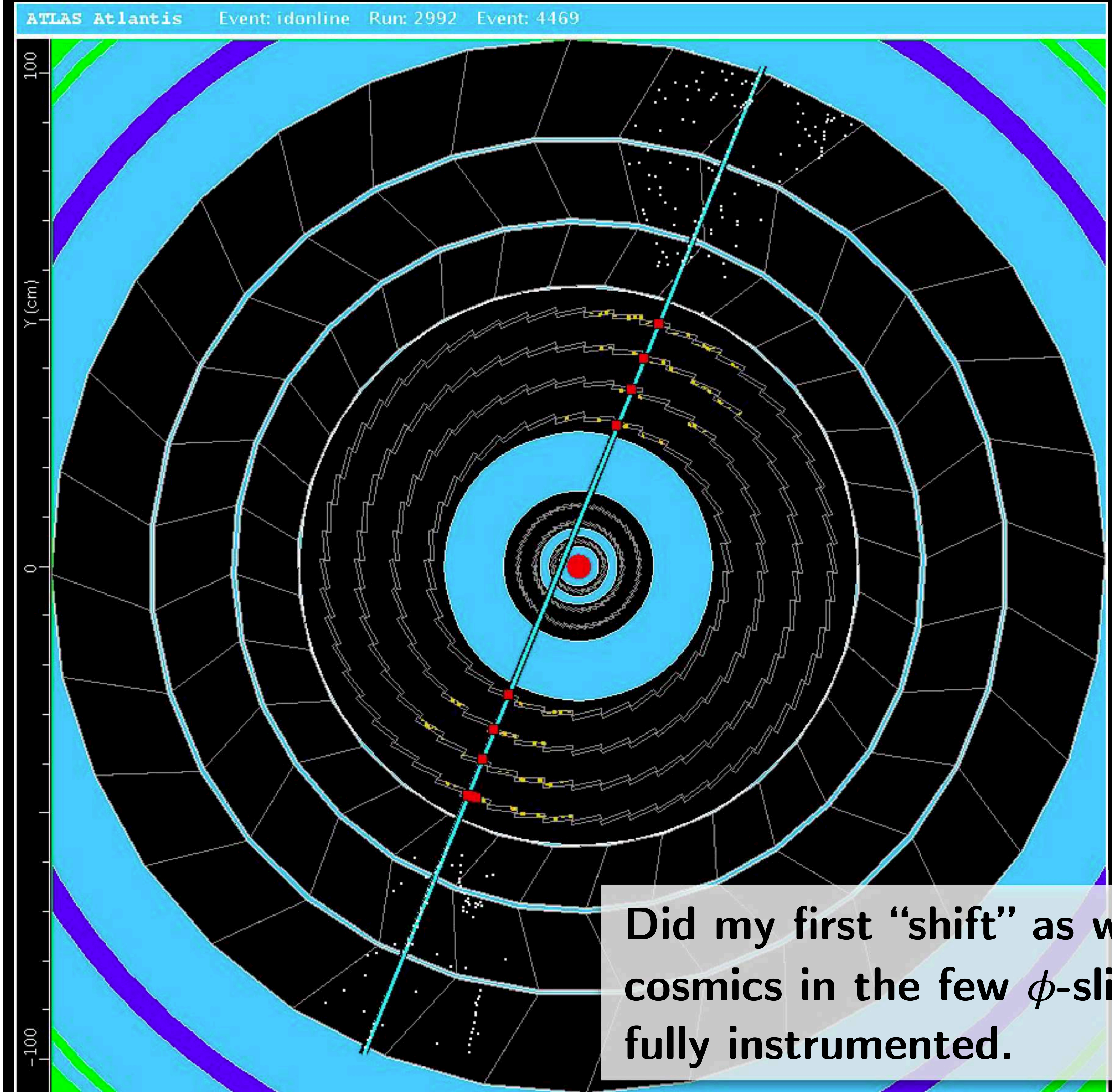
- Outer-most sub-detector of the ATLAS tracker
- 350,000 drift-tube straws = active channels
- length of pulse in time sensitive to local radius: $R(t)$
- 120 μm resolution

2006: first summer at CERN



TRT end-cap

- Participated TRT integration in the above-ground cleanroom (SR-1)
- Started working with Mike Hance on calibration scans and threshold normalization.

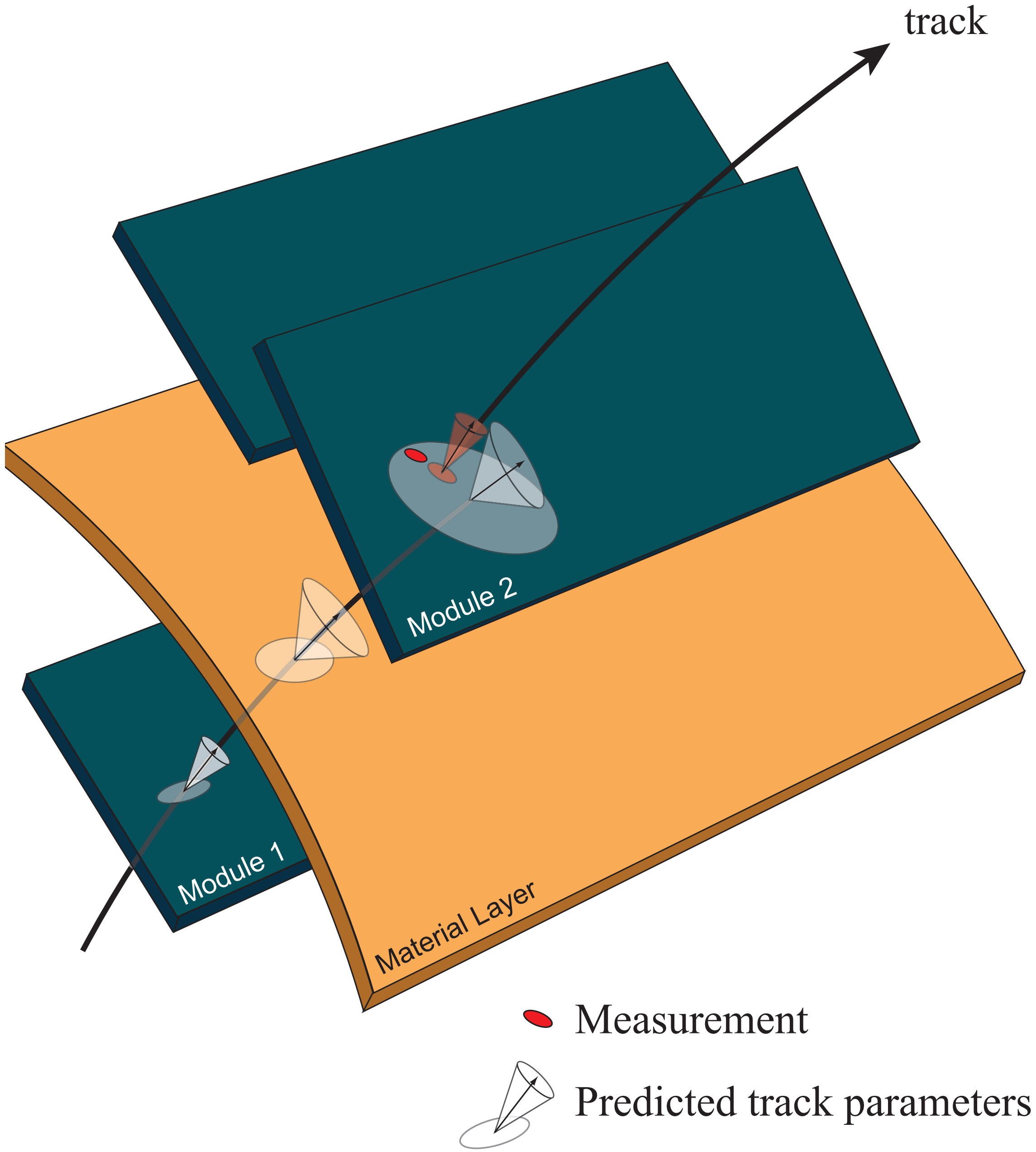


2006

Did my first "shift" as we saw the first cosmics in the few ϕ-slices that were fully instrumented.

TRT hit efficiency

‘09-’10

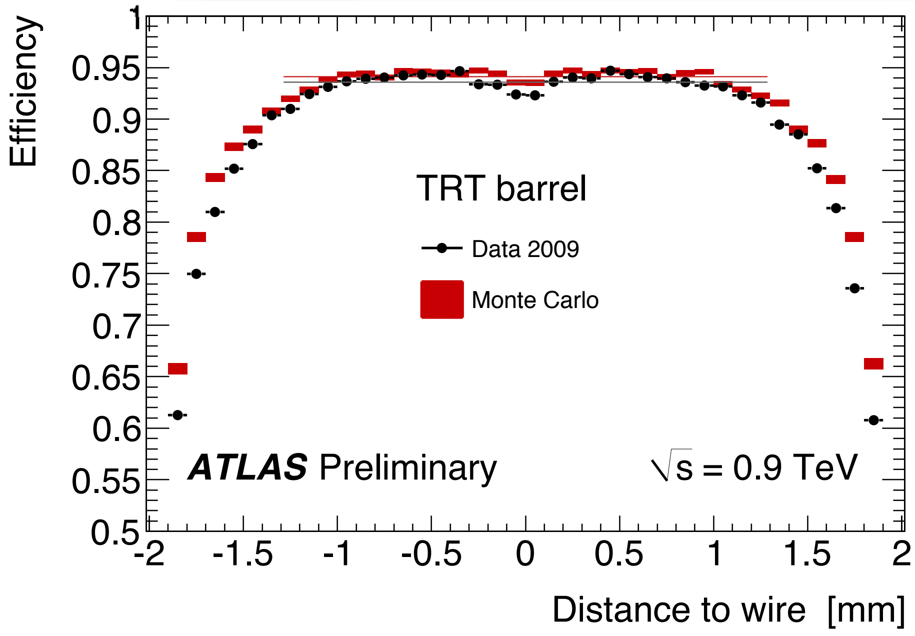


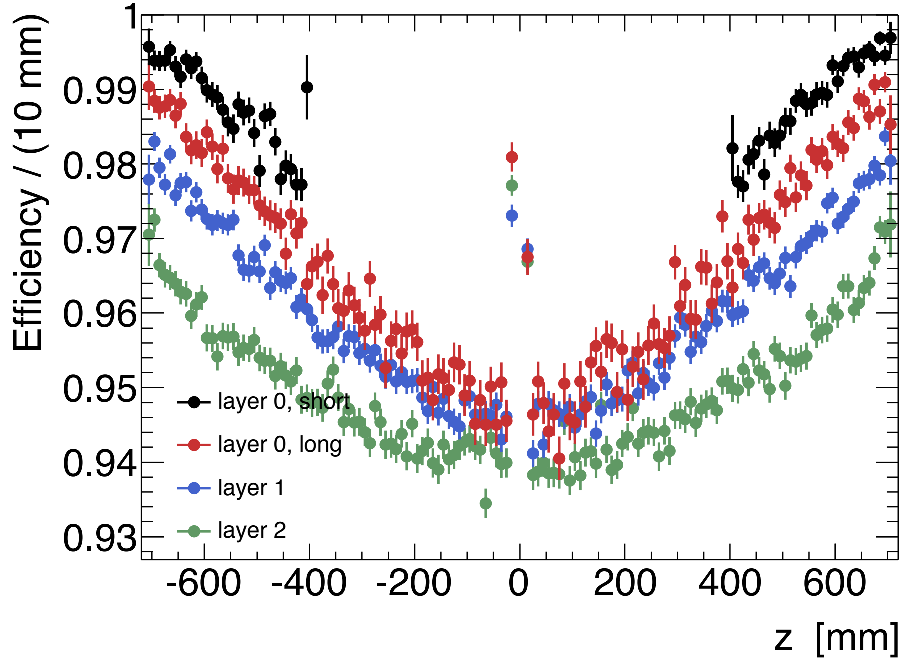
- $\varepsilon(x) = \dfrac{n_{\mathrm{hits}}(x)}{n_{\mathrm{hits}}(x) + n_{\mathrm{holes}}(x)}$
- ***Hits*** are easy to count directly from the data.
- ***Holes*** are counted by extrapolating along a track to determine which straws were crossed.
- ***Extrapolation tools*** use a detailed description of detector material to stochastically model bremsstrahlung and multiple scattering.

[ATL-SOFT-PUB-2007-005, ATL-COM-INDET-2011-088]

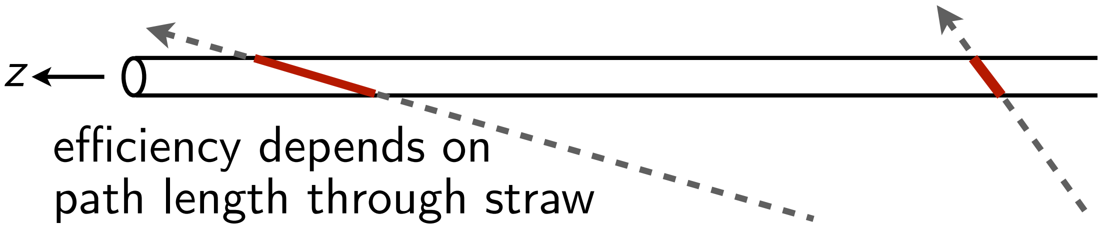
TRT hit efficiency

‘09-’10





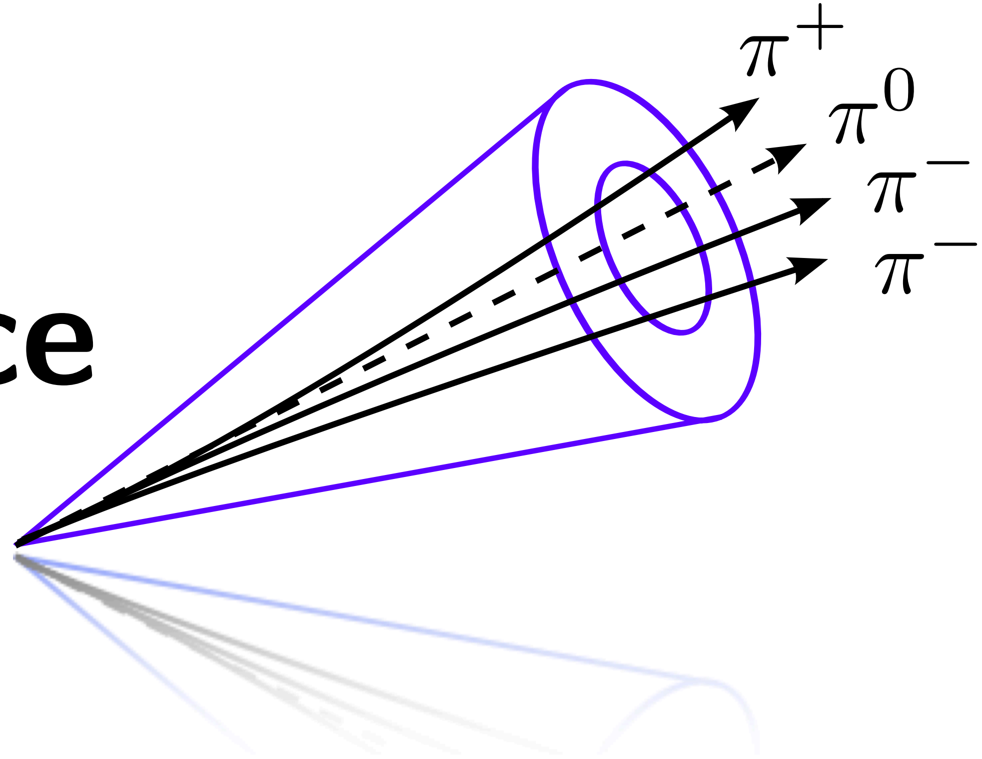
- I wrote an algorithm that uses extrapolator tools to calculate the TRT straw-hit efficiency.
- Gives an important data/MC comparison to test the TRT digitization, the step in the MC production where the response detector and electronics are simulated.
- ***Published in the first JHEP paper*** documenting the ATLAS detector performance with the first 900 GeV collision from 2009.



efficiency depends on path length through straw

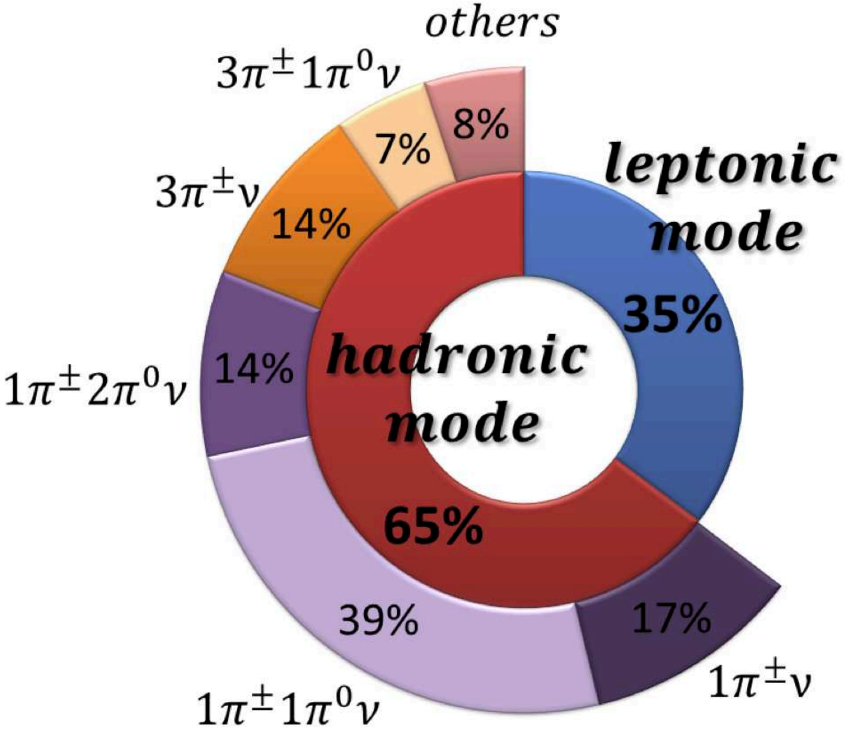
[J. High Energy Phys. 09 (2010) 056 arXiv:1005.5254]

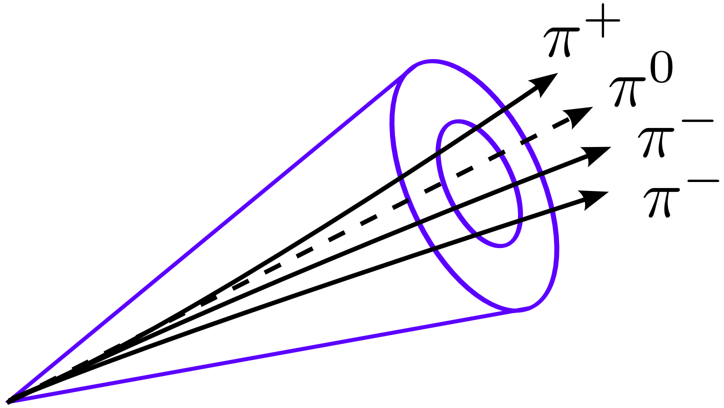
Tau performance

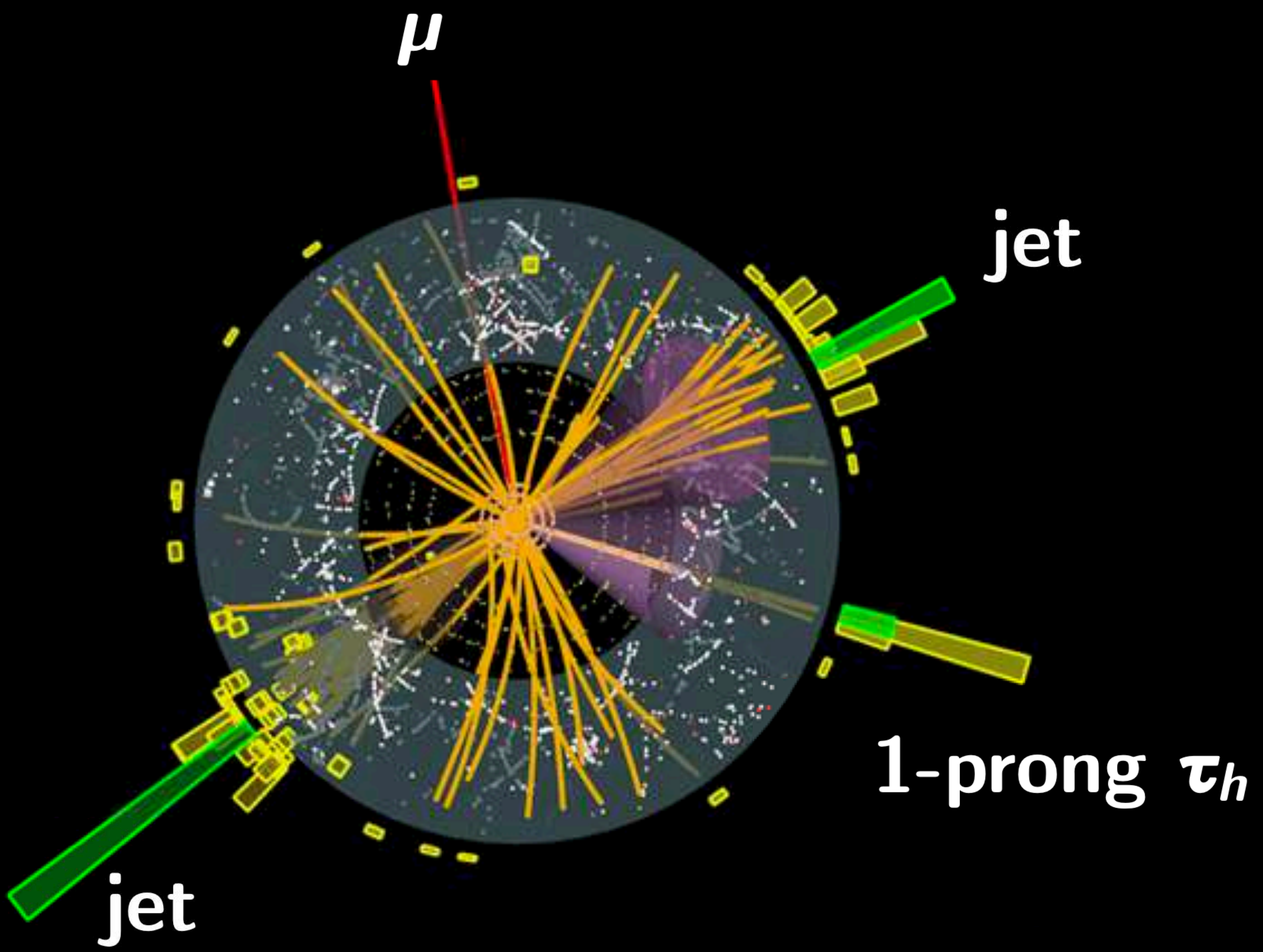


What's a tau?

- Only lepton massive enough to decay hadronically (1.8 GeV).
- 65% hadronic
  50% 1-prong, 15% 3-prong.
- Decay in beam pipe: cτ ≈ 87 μm.
- **Signature:** narrow jet with 1 or 3 tracks, possibly additional EM clusters.
- **Challenge:** large multijet background at hadron colliders.
- **Importance:** can have preferred coupling to new physics:
  SM $H\to\tau\tau$, $H^+\to\tau^+\nu$, $Z'\to\tau\tau$,
  high-tanβ **SUSY**,...

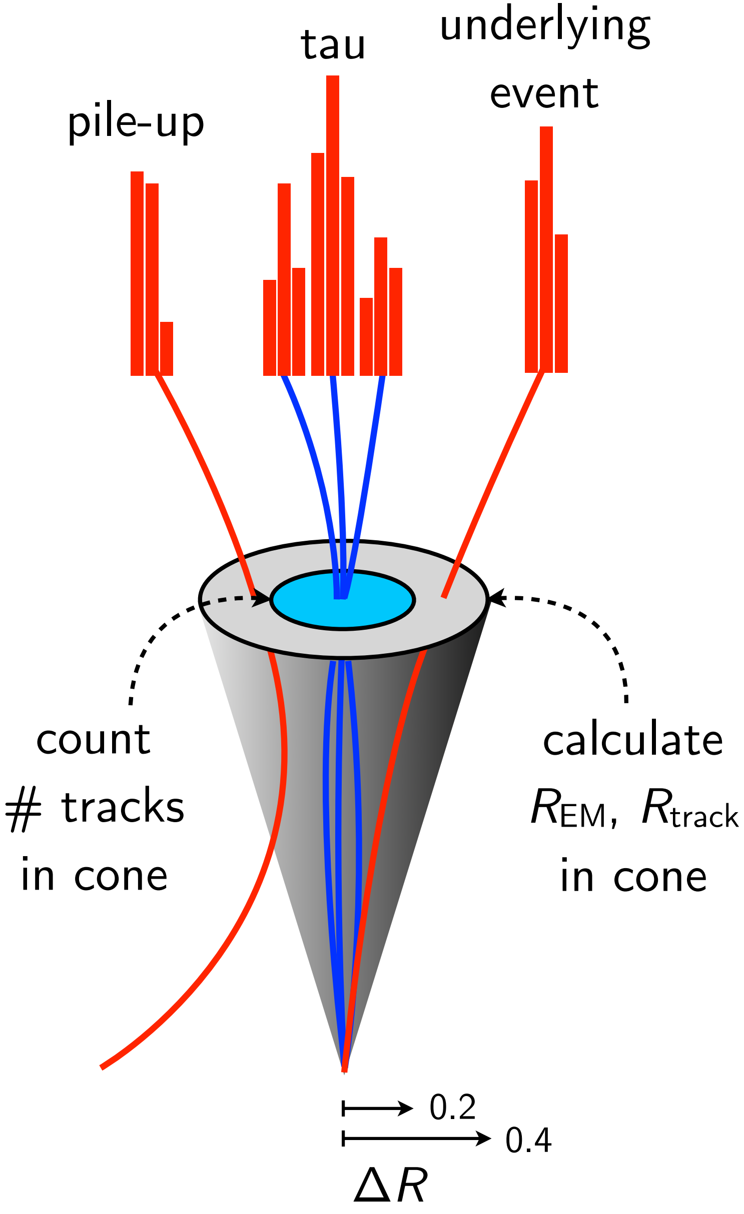





μ
jet
1-prong τ_h
jet

Tau reconstruction

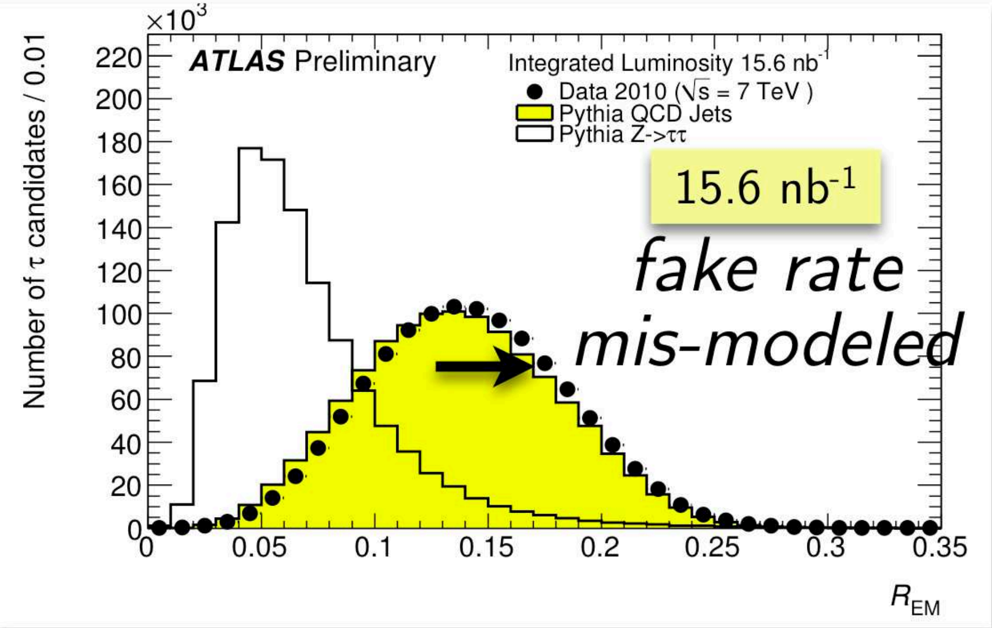
1. **Seeded by anti-k_t jets** (R=0.4) of 3-D topological calorimeter clusters.
2. **Define the four-momentum** as the jet-axis with a tau-specific calibration.
3. **Associate tracks** with the jet that are consistent with the chosen vertex.
4. **Calculate discriminating variables** from the combined calorimeter and tracking information, later used to identify hadronic tau decays with BDT and likelihood based discriminants.



Cut-based tau ID

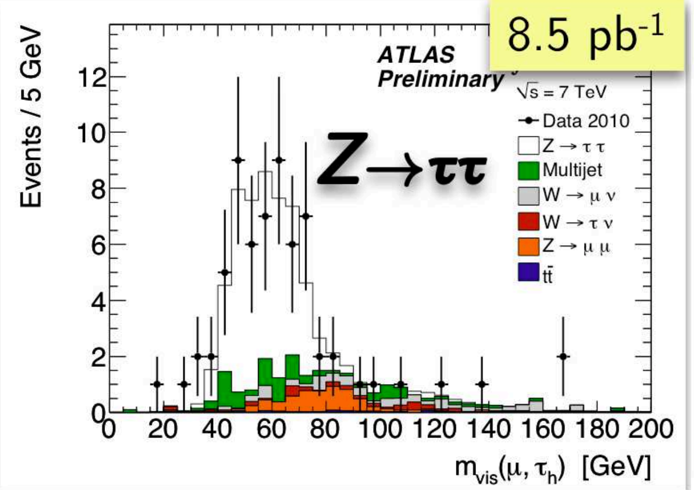
2010

- My timing with the development of tau reconstruction software and the arrival of first collision data allowed me to contribute to the ***first data/MC comparisons*** of tau ID variables and ***develop the first cut-based ID*** used with ATLAS data.
- Prefers narrow calorimeter deposits and closely associated tracks.
- Used in the ***first observation*** of $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$.



15.6 nb^{-1}

fake rate mis-modeled



8.5 pb^{-1}

$Z \rightarrow \tau\tau$

Safe Cut Variables

① $R_{\mathrm{EM}} = \frac{\sum \Delta R \, E_{\mathrm{T}}}{\sum E_{\mathrm{T}}}$, summed over cells from the first 3 layers of the EM calorimeter within $\Delta R < 0.4$.

② $R_{\mathrm{track}} = \frac{\sum \Delta R \, p_{\mathrm{T}}}{\sum p_{\mathrm{T}}}$, summed over tracks associated to the tau within $\Delta R < 0.2$.

③ $f_{\mathrm{trk,1}} = \frac{p_{\mathrm{T}}(\mathrm{lead\ track})}{p_{\mathrm{T}}(\tau_{\mathrm{h}})}$, the transverse momentum fraction of the leading track.

[ATLAS-CONF-2010-012, ATLAS-CONF-2010-059, ATLAS-CONF-2010-086, ATLAS-CONF-2011-010]

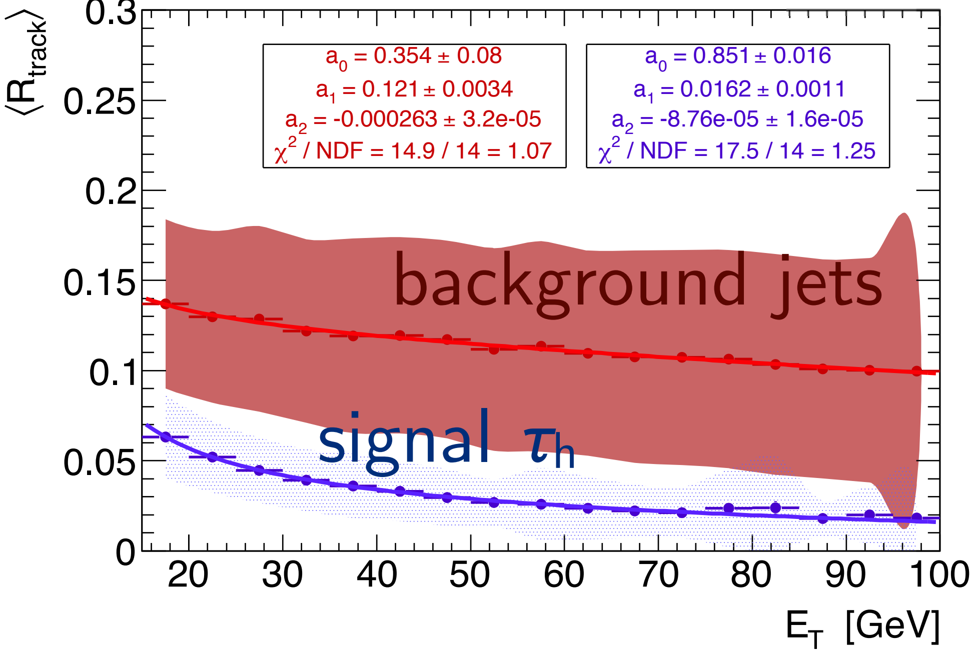
E_{T}-parametrized ID

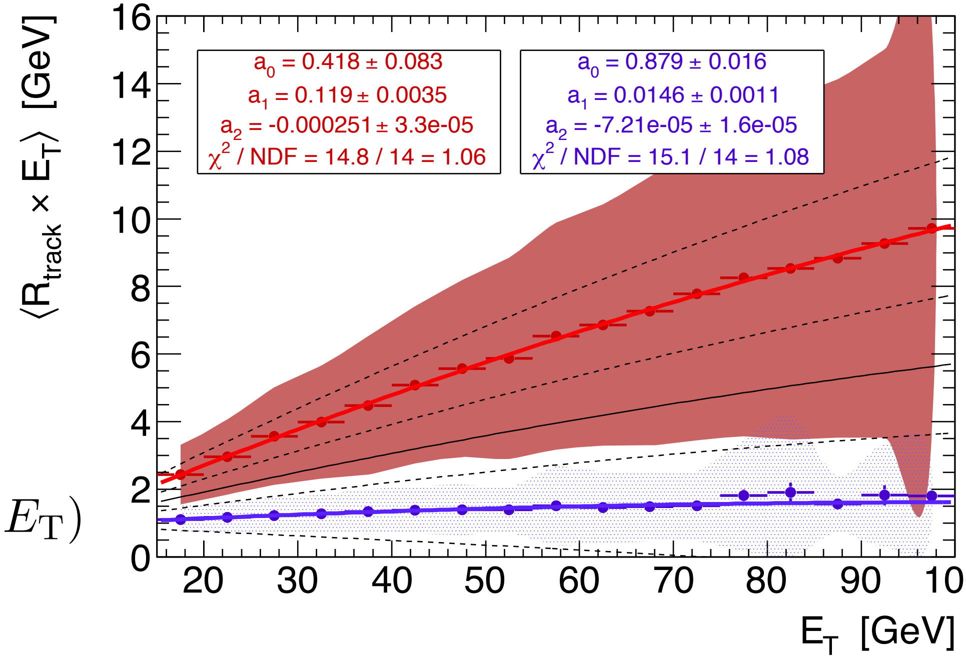
2010

- Lorentz boost implies R should collimate as

$$R(E_{\mathrm{T}}) \propto \frac{1}{E_{\mathrm{T}}}$$

- Multiplying by E_{T} flattens out E_{T}-dependence.
- Example plots here are for 3-prong, but the π^0s of 1-prong taus also collimate.
- Construct a smooth family of curves between the signal and background that have efficiency that is approximately flat in E_{T}.



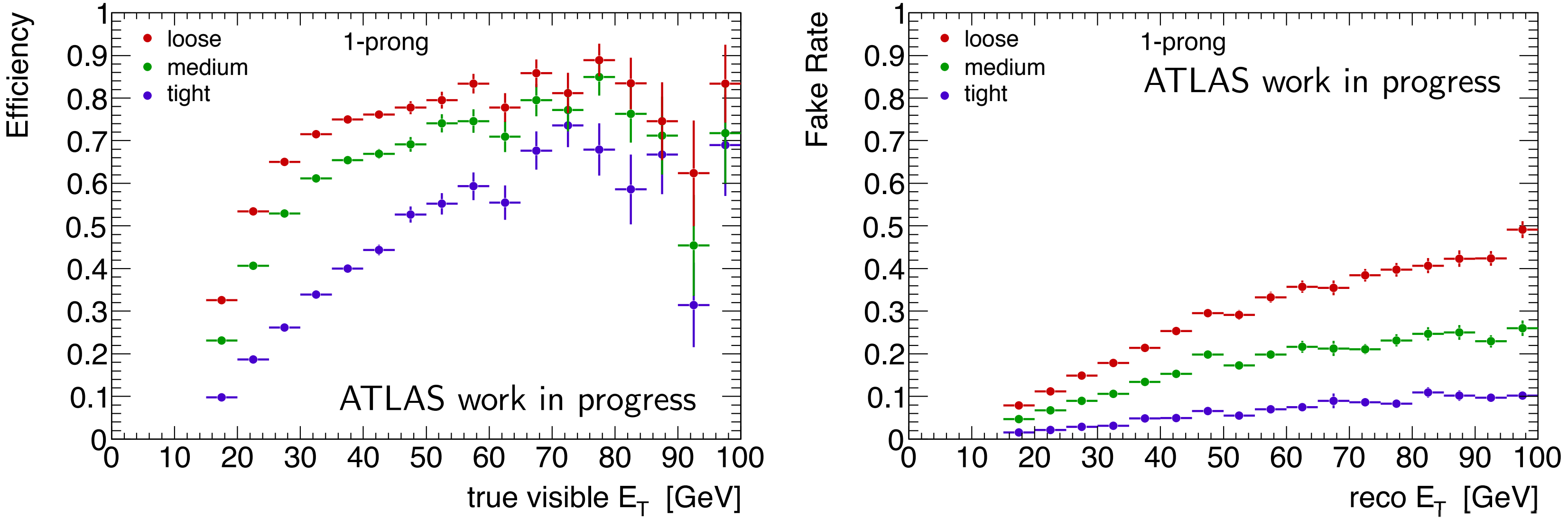


$$R_{\mathrm{cut}}(E_{\mathrm{T}};x_{\mathrm{cut}})\,E_{\mathrm{T}} = (1-x_{\mathrm{cut}})\,f_{\mathrm{sig}}(E_{\mathrm{T}}) + \;x_{\mathrm{cut}}\,f_{\mathrm{bkg}}(E_{\mathrm{T}})$$

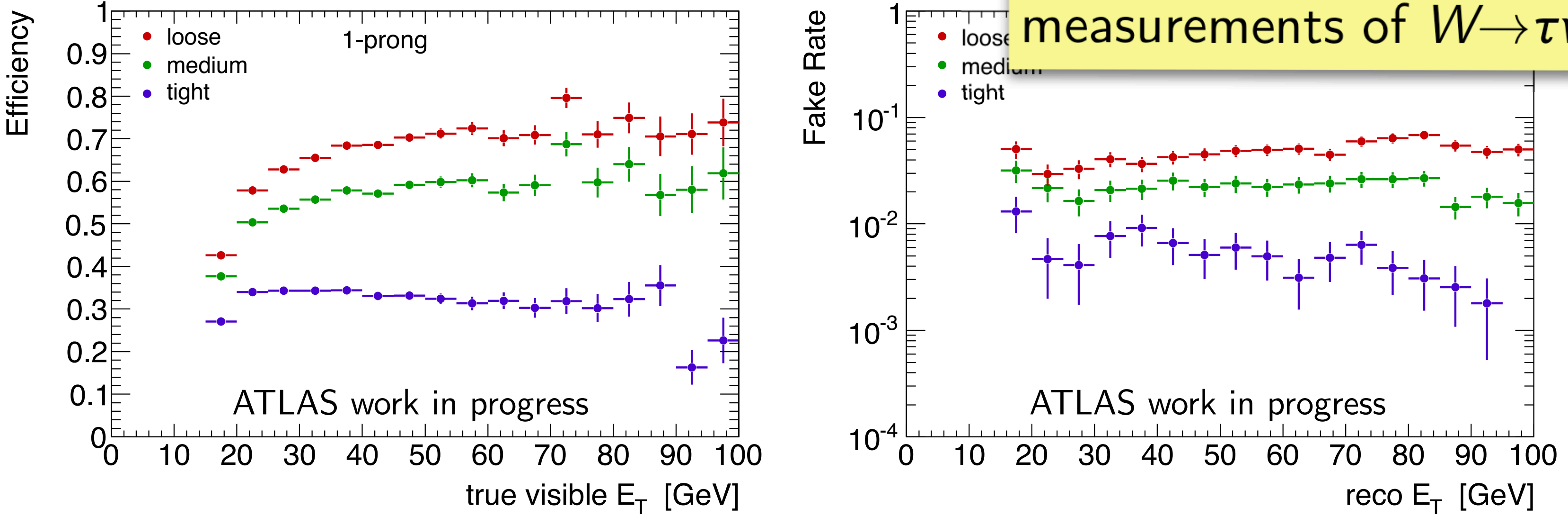
Efficiency / Rejection

2010

Simple cuts

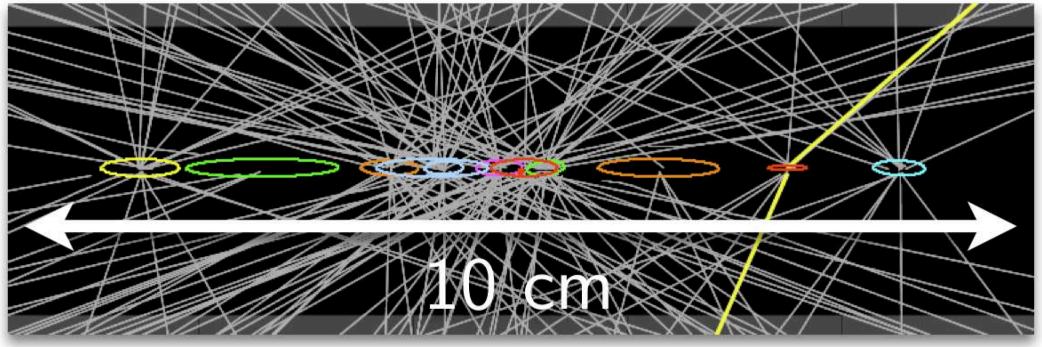


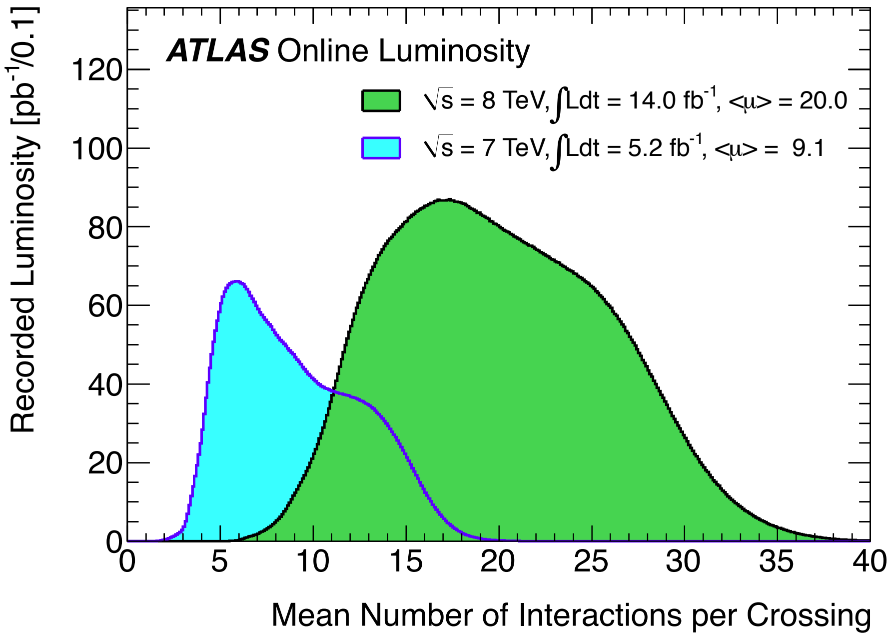
E_T-parametrized cuts



used for first ATLAS cross section measurements of $W\to\tau\nu$ and $Z\to\tau\tau$

Pile-up





- 1-40 pile-up interactions / crossing

- The additional tracks and clusters from pile-up are especially challenging for tau identification, which discriminates hadronic tau decays from jets with isolation-related track and calorimeter quantities.

- Efforts in 2011-2012 involved re-defining or adding corrections to identification variables to be more robust against the increasing pile-up.

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults]

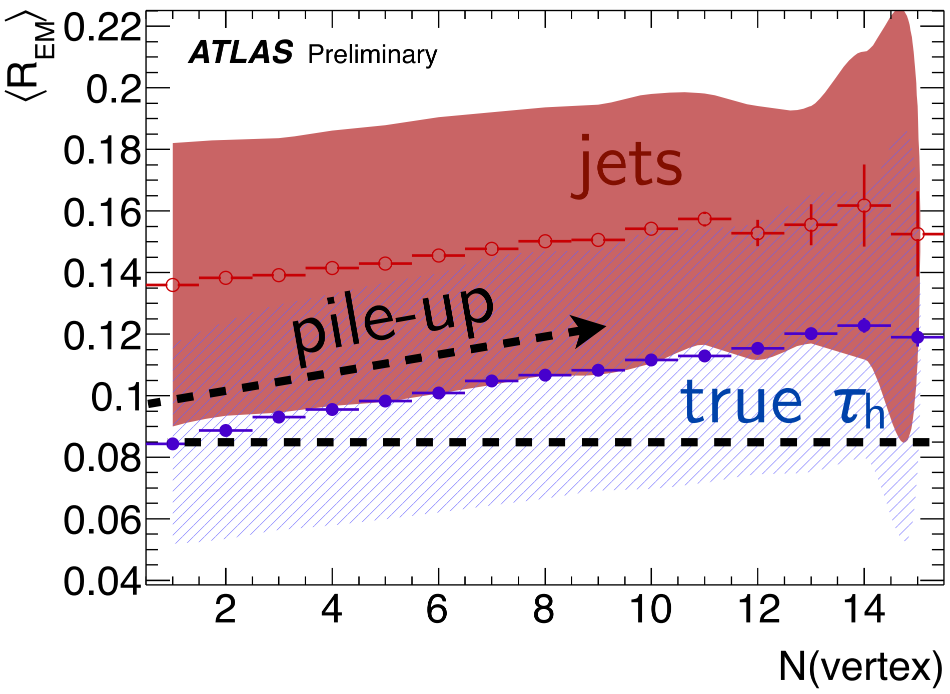
Identification and pile-up

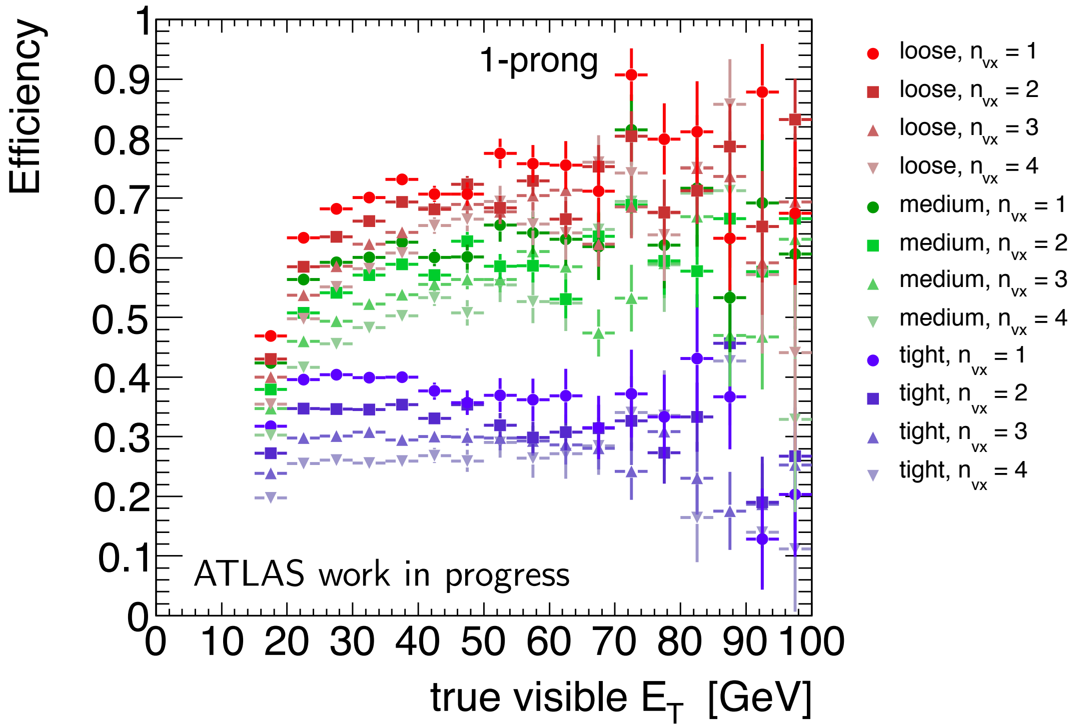
2011

- Important offline variable in 2010-2011: ***EM radius*** - “width of jet in calorimeter”

$$R_{\mathrm{EM}} = \frac{\sum_{\{\Delta R<0.4\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})\, \Delta R(\mathrm{cell,\ jet})}{\sum_{\{\Delta R<0.4\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})}$$

- ***Strong pile-up dependence*** due to using calorimeter deposits in the wide cone: $\Delta R < 0.4$.

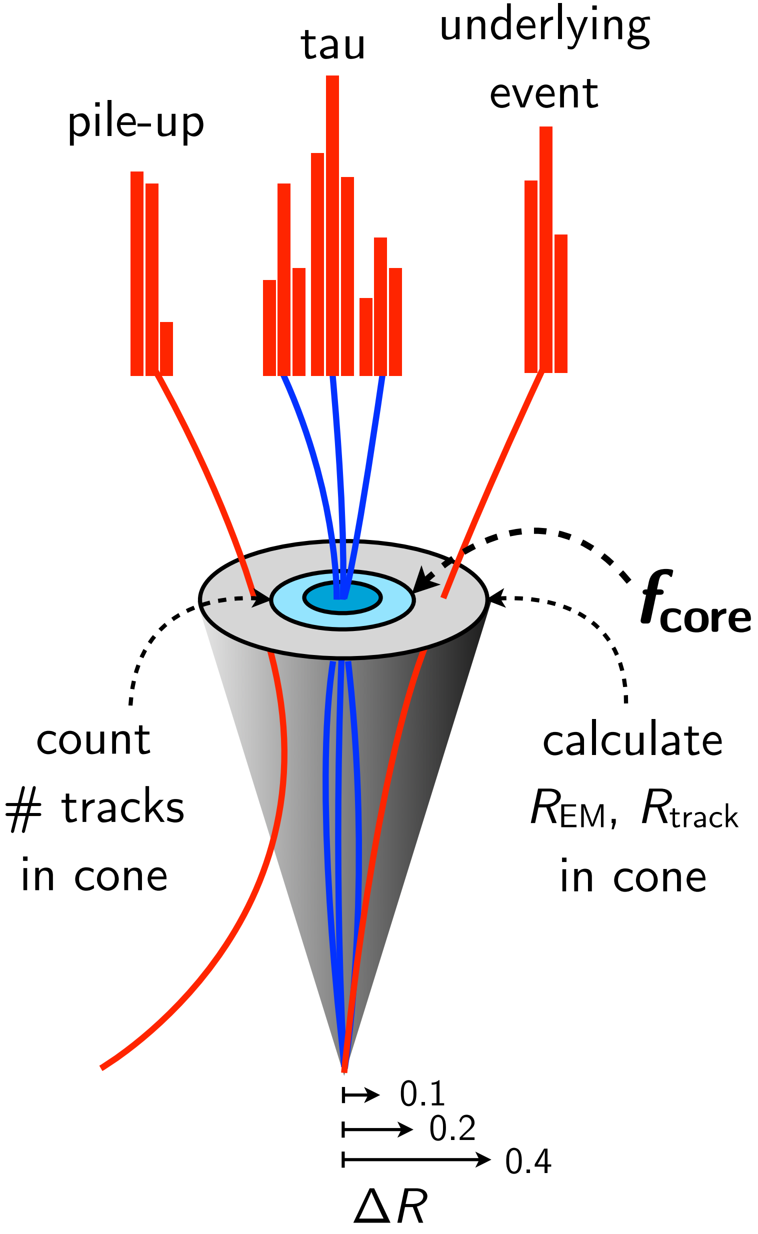




[ATLAS-CONF-2011-152]

Pile-up robust variables

2011

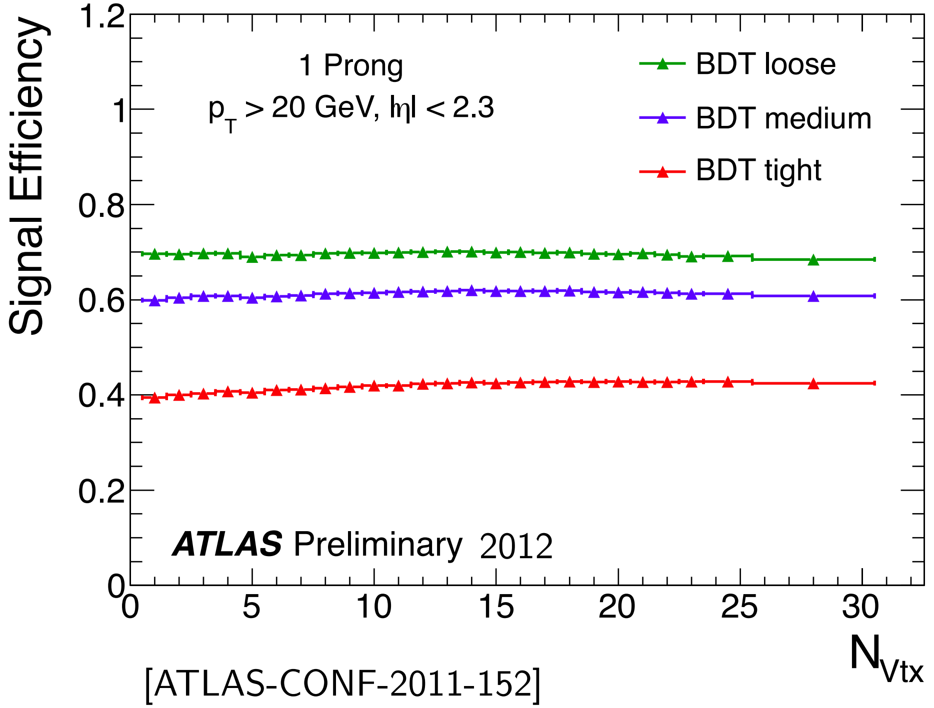


- Beginning in 2012, the core energy fraction is used instead of R_{EM}, which has less pile-up dependence by using the ratio of energies in smaller ΔR cones of 0.1 and 0.2.

$$f_{\mathrm{core}} = \frac{\sum_{\{\Delta R<0.1\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})}{\sum_{\{\Delta R<0.2\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})}$$

$$+ (0.3\%/\mathrm{vertex}) \times N(\mathrm{vertex})$$

linear pile-up correction



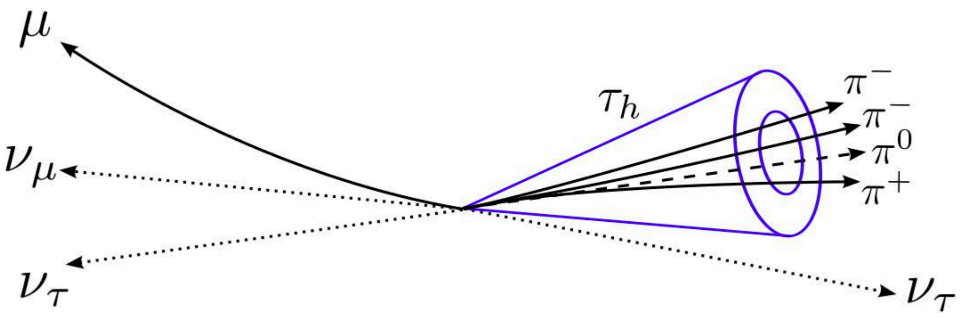
[ATLAS-CONF-2011-152]

SM $Z\rightarrow\tau\tau$

$Z \rightarrow \tau\tau$ studies

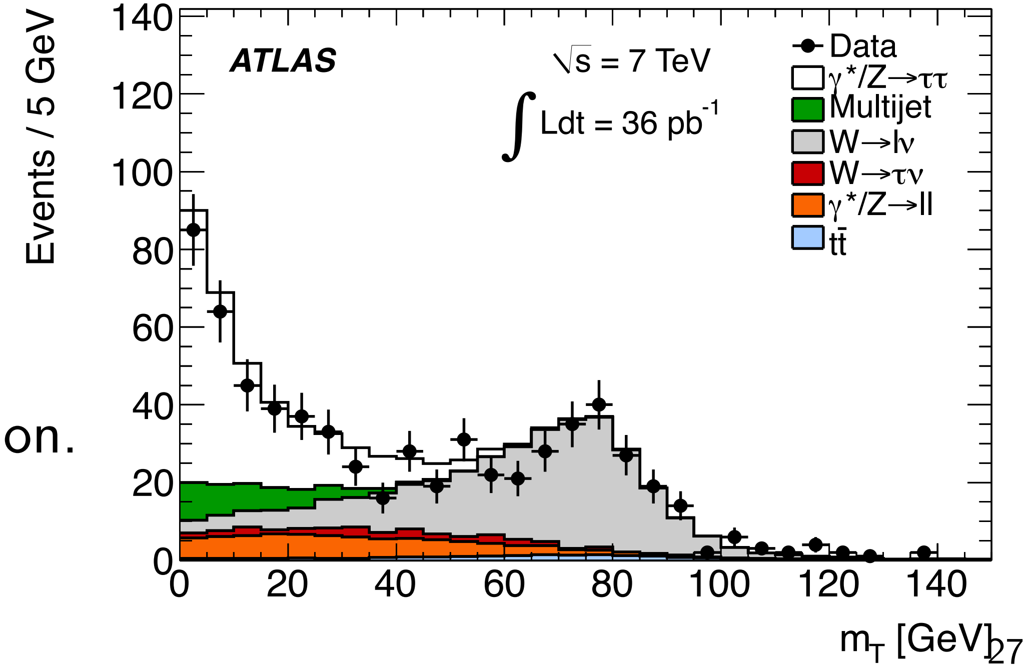
'09-'11

- Focus on lep-had final state. Trigger on e or μ.
- Able to select $Z \rightarrow \tau\tau$ control sample for ***studying tau ID***.
- Important to establish understanding of this ***irreducible background to new physics*** with taus: $H \rightarrow \tau\tau$ and $Z' \rightarrow \tau\tau$ searches.
- ***Complicated background composition***. Multijet, W/Z+jet backgrounds all compete at the same order.



Data-driven background estimates:

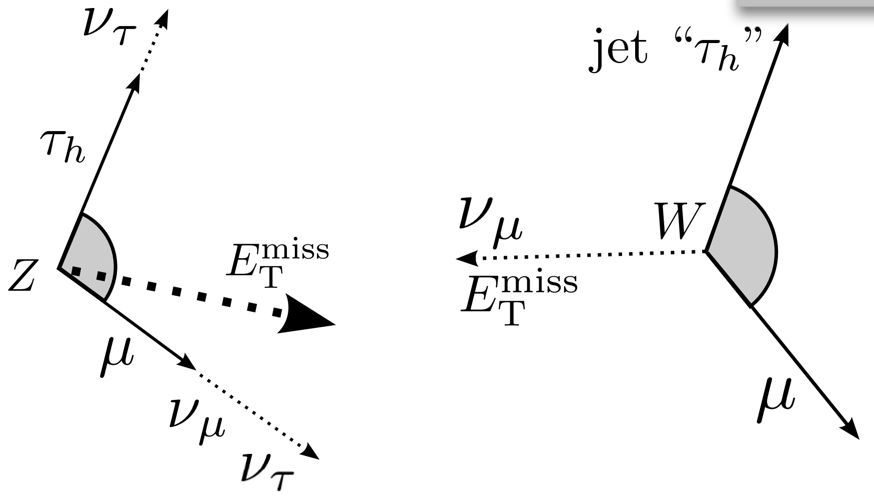
- Jet fake rate mis-modeled in ATLAS Monte Carlo. W+jet background normalized with high-m_T control region.
- Multijet background modeled from same-sign data.

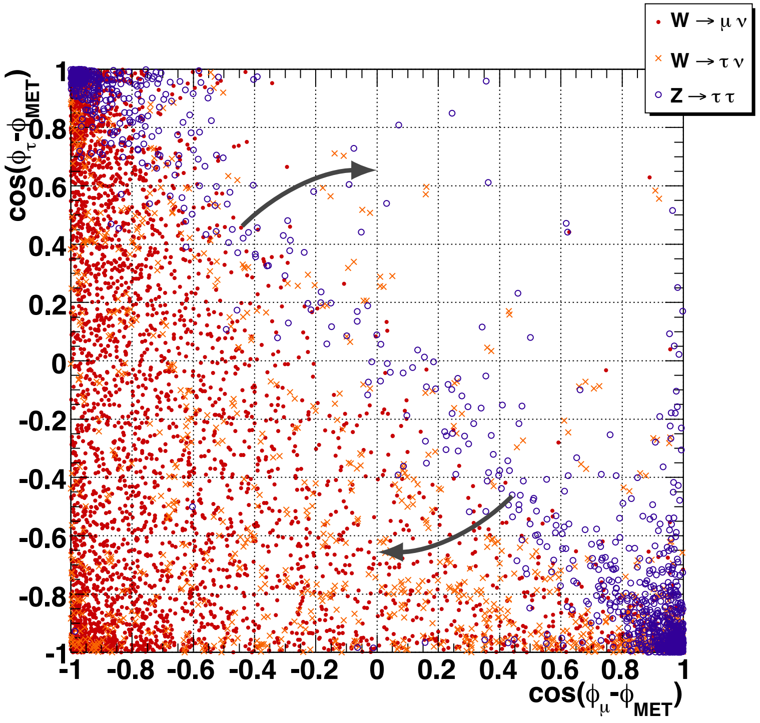


$\sum\cos\Delta\phi$ for suppressing W+jet

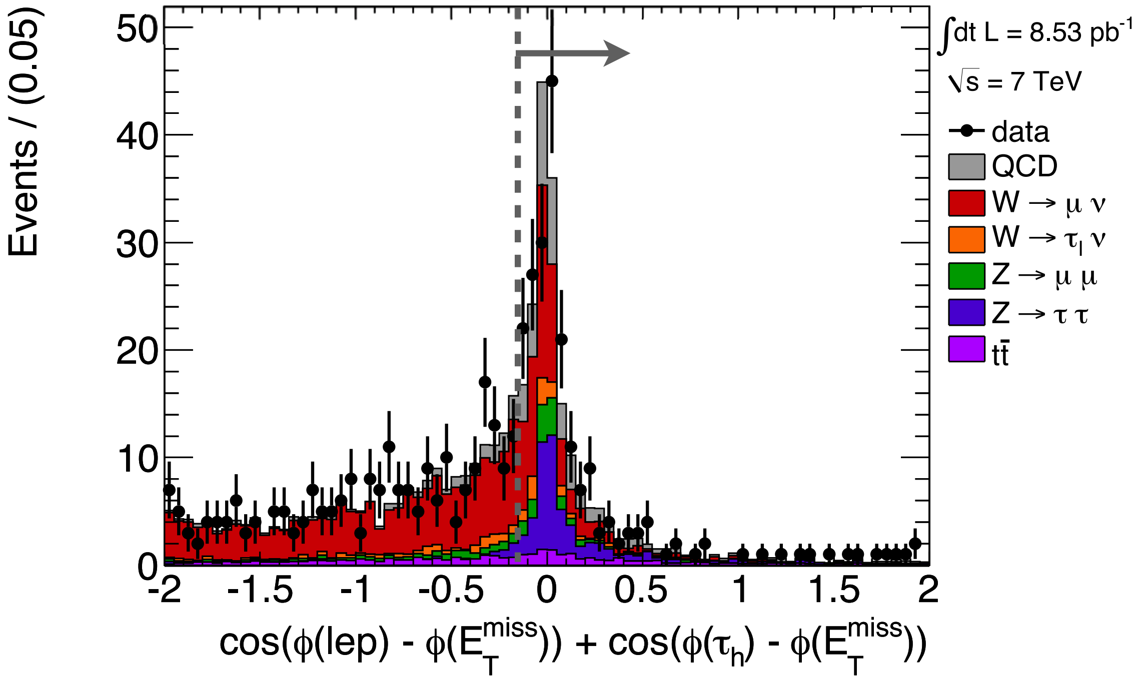
'09-'10

- ***I introduced a new variable*** for rejecting the *W*+jet background.
- Exploits the correlation of the direction of the E_T^{miss} and the decay products.
- Essentially require the E_T^{miss} to be between instead of away.
- Only dependent on E_T^{miss} direction and not the magnitude ⇒ less systematics.





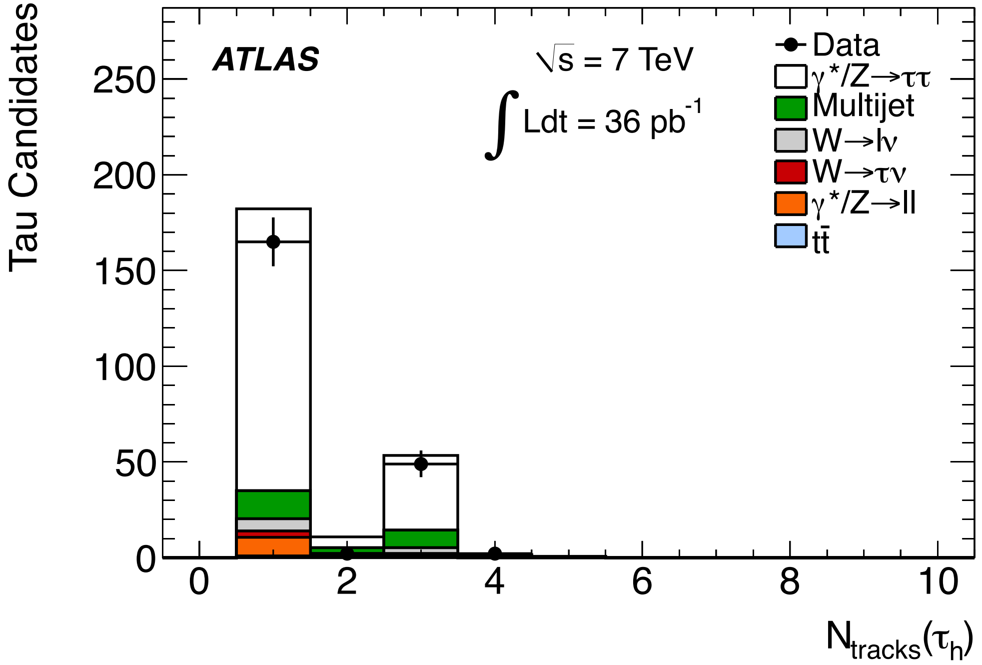
$\sum\cos\Delta\phi$ > -0.15

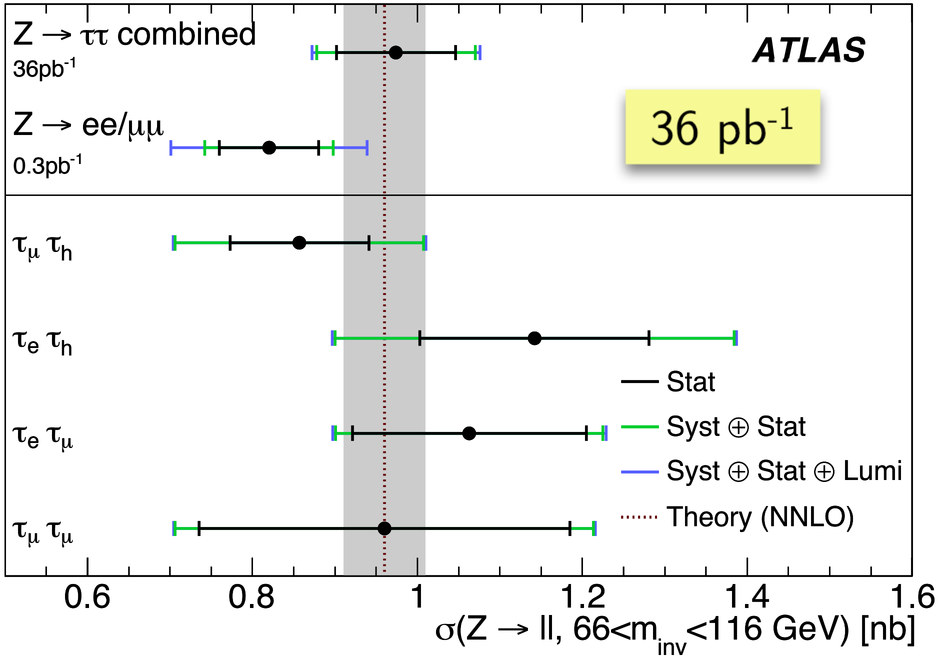


[ATL-PHYS-INT-2009-044, ATLAS-CONF-2010-097]

$Z \to \tau\tau$ cross section

'10-'11





- Claimed observation of $Z \to \tau\tau$ with 8.5 pb^{-1}.
- Measured cross section to 10% with 36 pb^{-1}, consistent with SM.
- ***Published in PRD***.

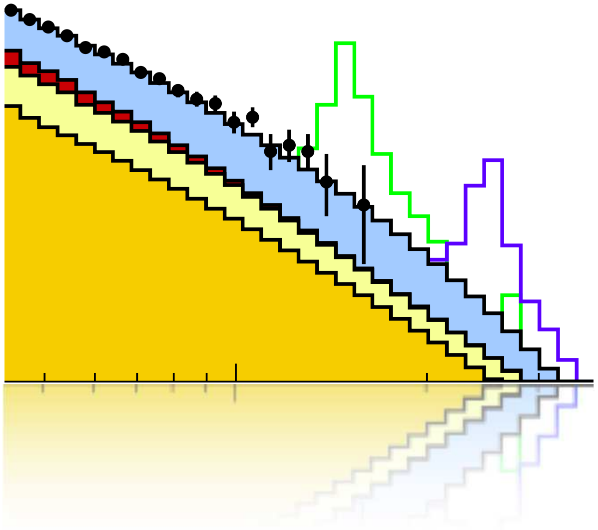
$$\sigma_{\text{combined}} = 0.97 \pm 0.07(\text{stat.}) \pm 0.07(\text{sys.}) \pm 0.03(\text{lumi.})\ \text{nb}$$

$$\sigma_{\text{theory}} = 0.96 \pm 0.05\ \text{nb at NNLO}$$

[Phys. Rev. D 84, 112006 (2011) arxiv:1108.2016v2]

New physics:

$Z' \rightarrow \tau\tau$



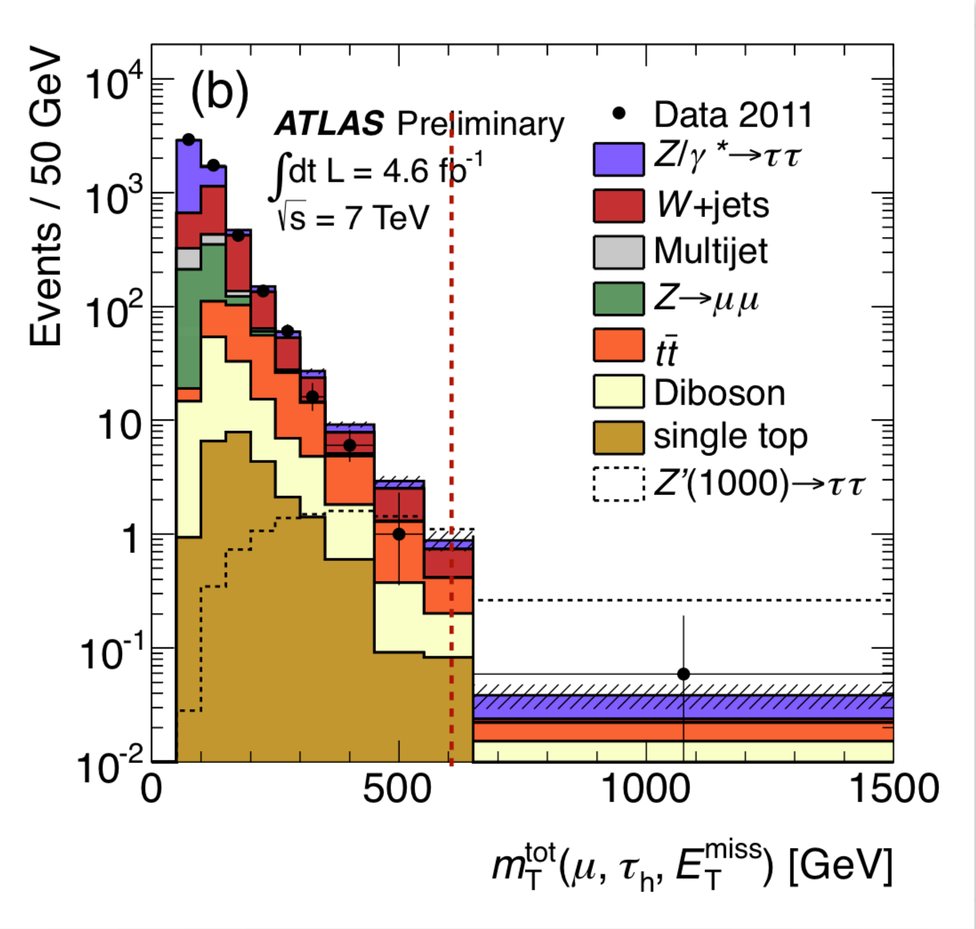
$Z' \rightarrow \tau\tau \rightarrow \mu\tau_h$

'11-'12

- Select OS back-to-back tau decays.
- Count high-mass events.

Event selection

- $p_T(\mu) > 25$, $p_T(\tau_h) > 35$ GeV
- 1-prong τ_h
- $|\Delta\phi(e, \tau_h)| > 2.7$
- opposite sign μ and τ_h
- $m_T(e, \tau_h, E_T^{miss}) > 600$ GeV



- Fake factor methods used to model multijet and W+jet backgrounds
- Need to be modeled in data-driven ways for two reasons:
  1. jet→ τ_h fake rate is mis-modeled in Monte Carlo.
  2. populate the model in the high-mass tail.

total SM = 1.4 ± 0.4 events
Z'(1000) = 5.5 ± 0.7

W+jet background estimation

'11-'12

W+jet control region

- $m_T(\mu, E_T^{\text{miss}}) = 70\text{-}200$ GeV
- isolated lepton

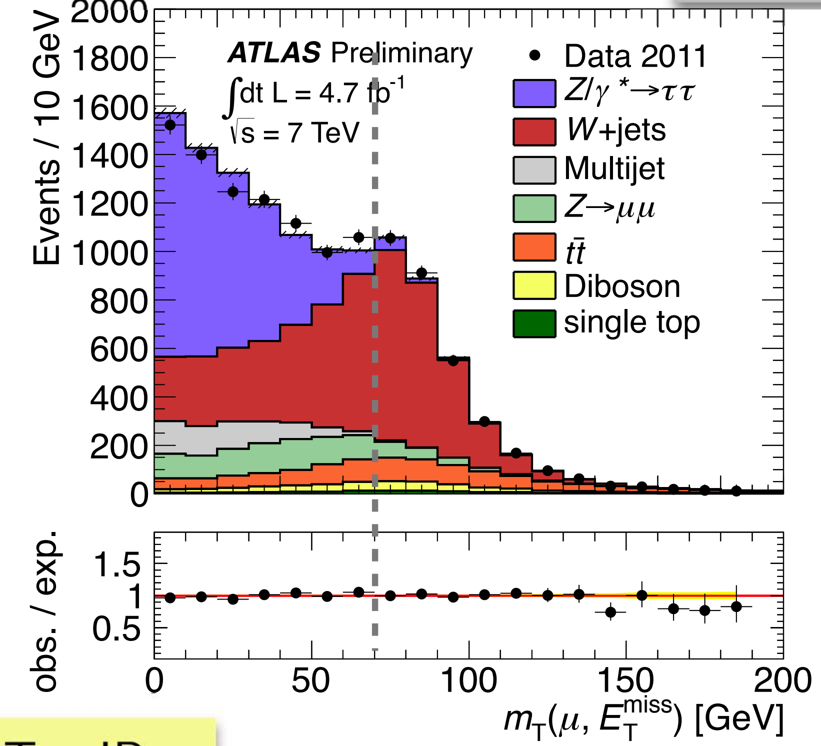
- In a W+jet control region, divide tau candidates into pass and fail identification.
- Define fake factor:

$$f_\tau(p_T,\eta) \equiv \left.\frac{N^{\text{pass }\tau\text{–ID}}(p_T,\eta)}{N^{\text{fail }\tau\text{–ID}}(p_T,\eta)}\right|_{\text{W–CR}}$$

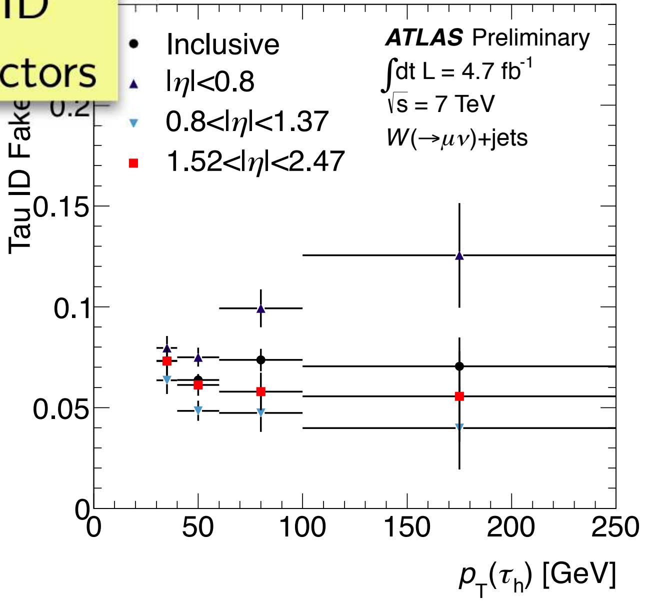
- Predict the number of W/Z+jet events:

$$N_{W/Z\text{+jet}}(p_T,\eta,x) = f_\tau(p_T,\eta)\cdot N^{\text{fail }\tau\text{–ID}}_{W/Z\text{+jet}}(p_T,\eta,x)$$

$$= f_\tau(p_T,\eta)\cdot\left(N^{\text{fail }\tau\text{–ID}}_{\text{data}}(p_T,\eta,x) - N^{\text{fail }\tau\text{–ID}}_{\text{multijet}}(p_T,\eta,x) - N^{\text{fail }\tau\text{–ID}}_{\text{MC}}(p_T,\eta,x)\right)$$

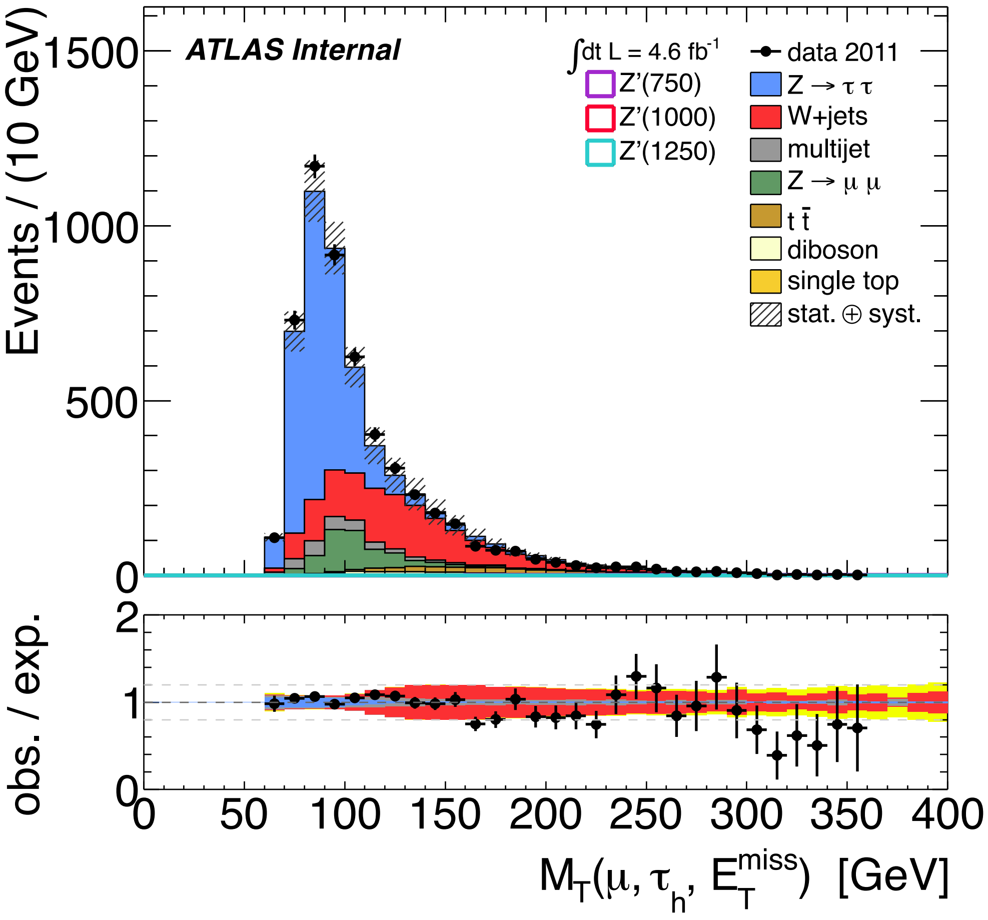


Tau ID fake-factors

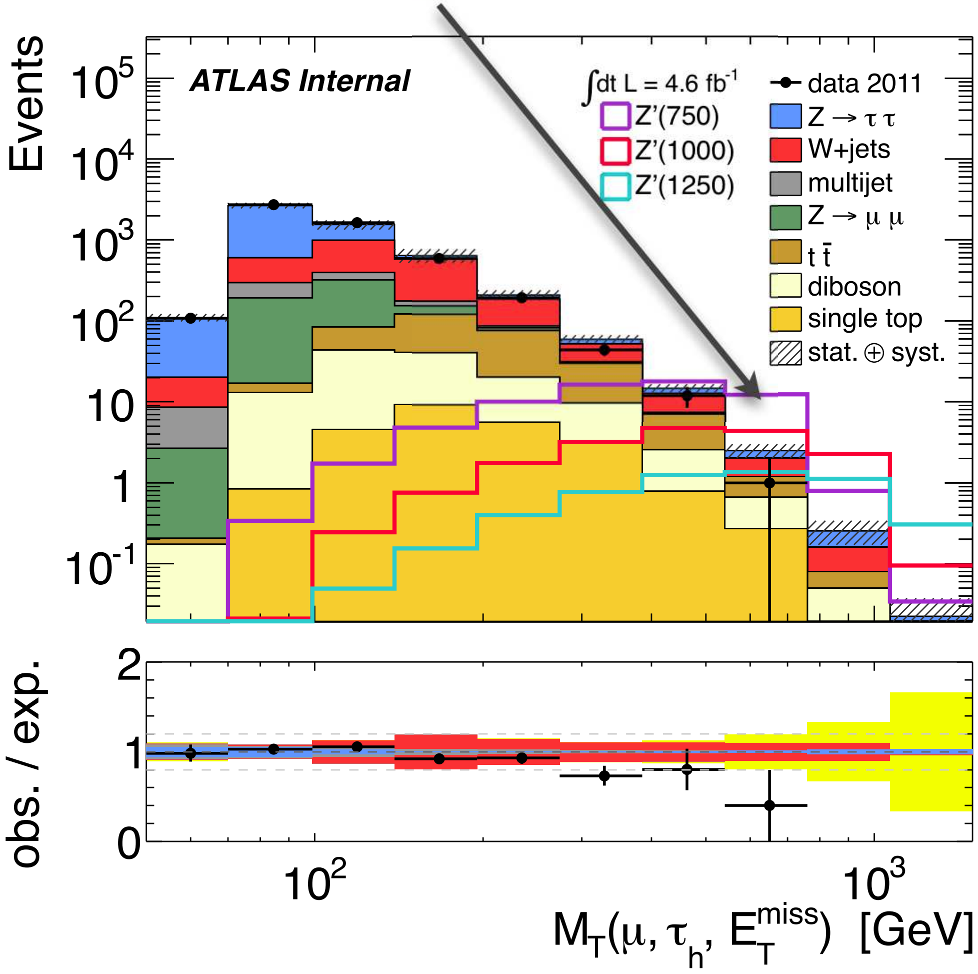


Final mass distribution

$\mu\tau_h$ final state

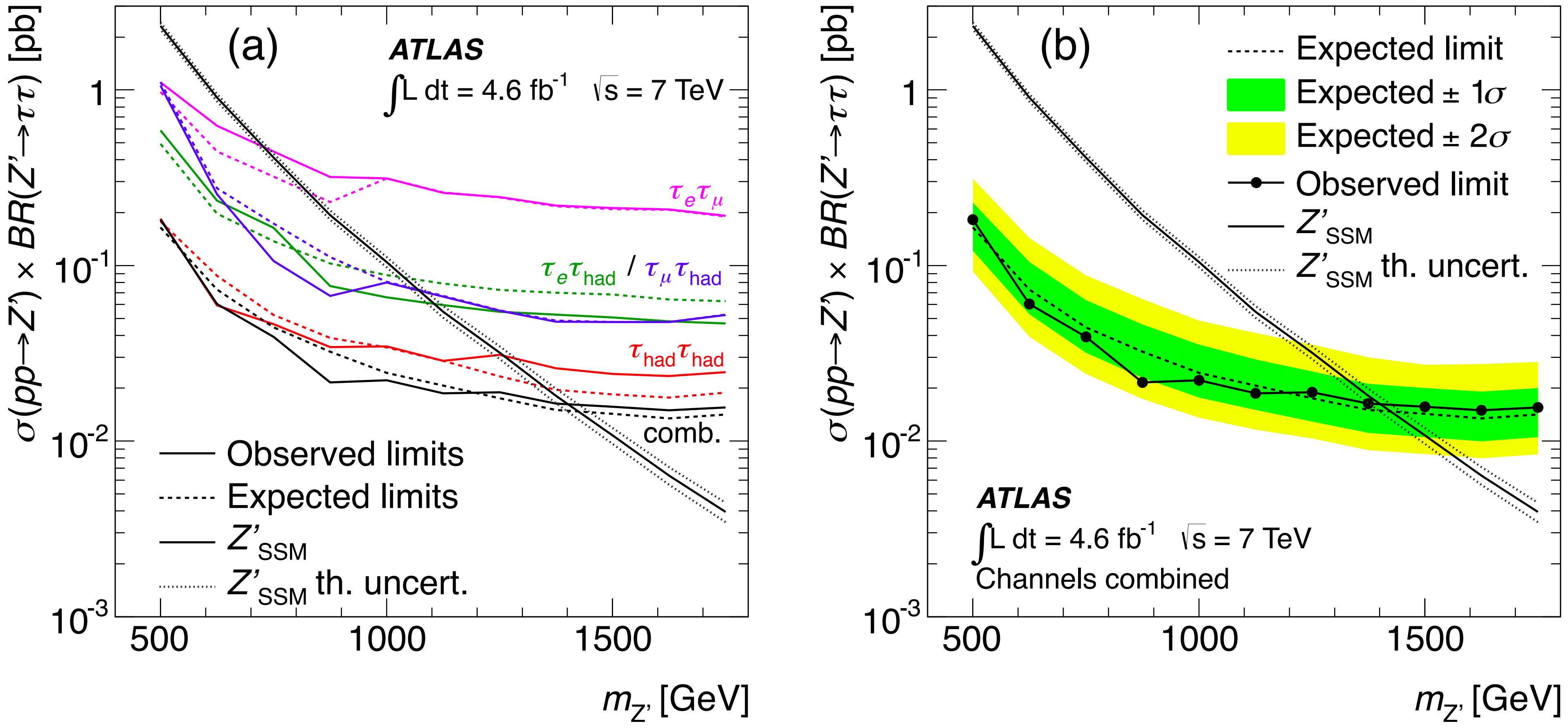


Z'$_{SSM}$ signal models



Combined limit

'11-'12



ATLAS Z' SSM Exclusions: observed (expected) @ 95% CL

- $\tau_h\tau_h$: 1.26 (1.35) TeV
- $\mu\tau_h$: 1.07 (1.06) TeV
- $e\tau_h$: 1.10 (1.03) TeV
- $e\mu$: 0.72 (0.82) TeV

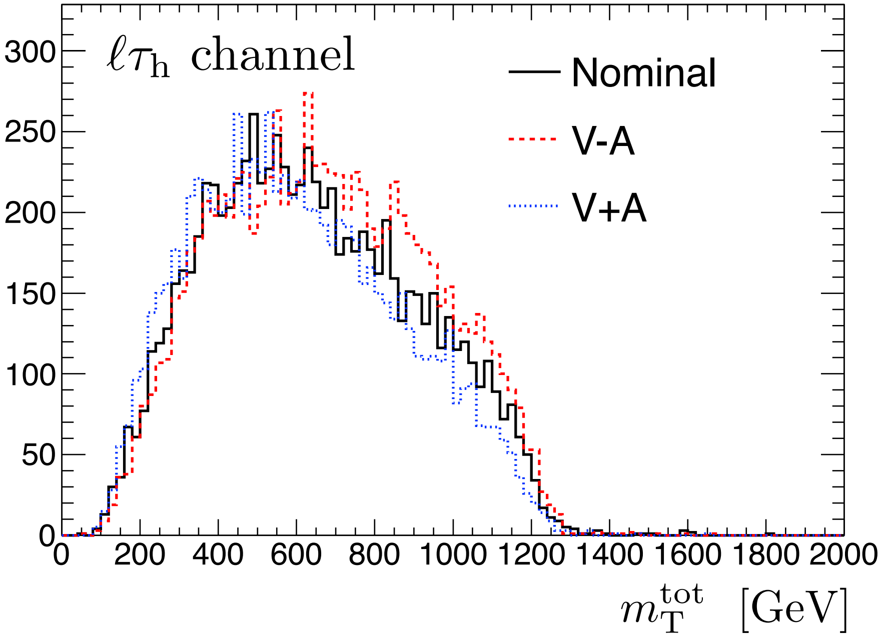
combined: 1.40 (1.42) TeV

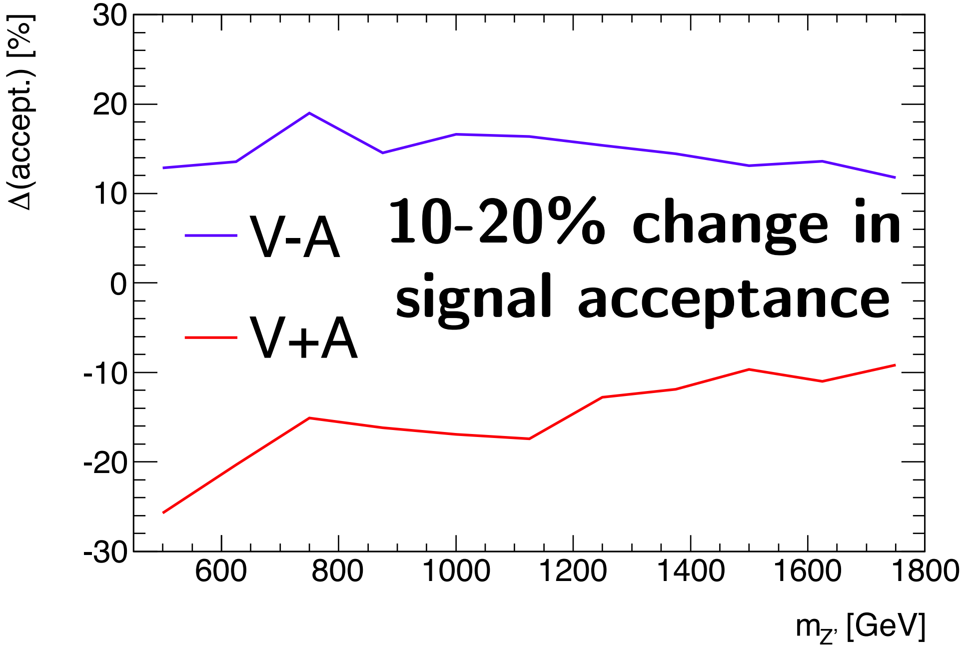
Published in PLB

[arxiv:1210.6604]

Model dependence

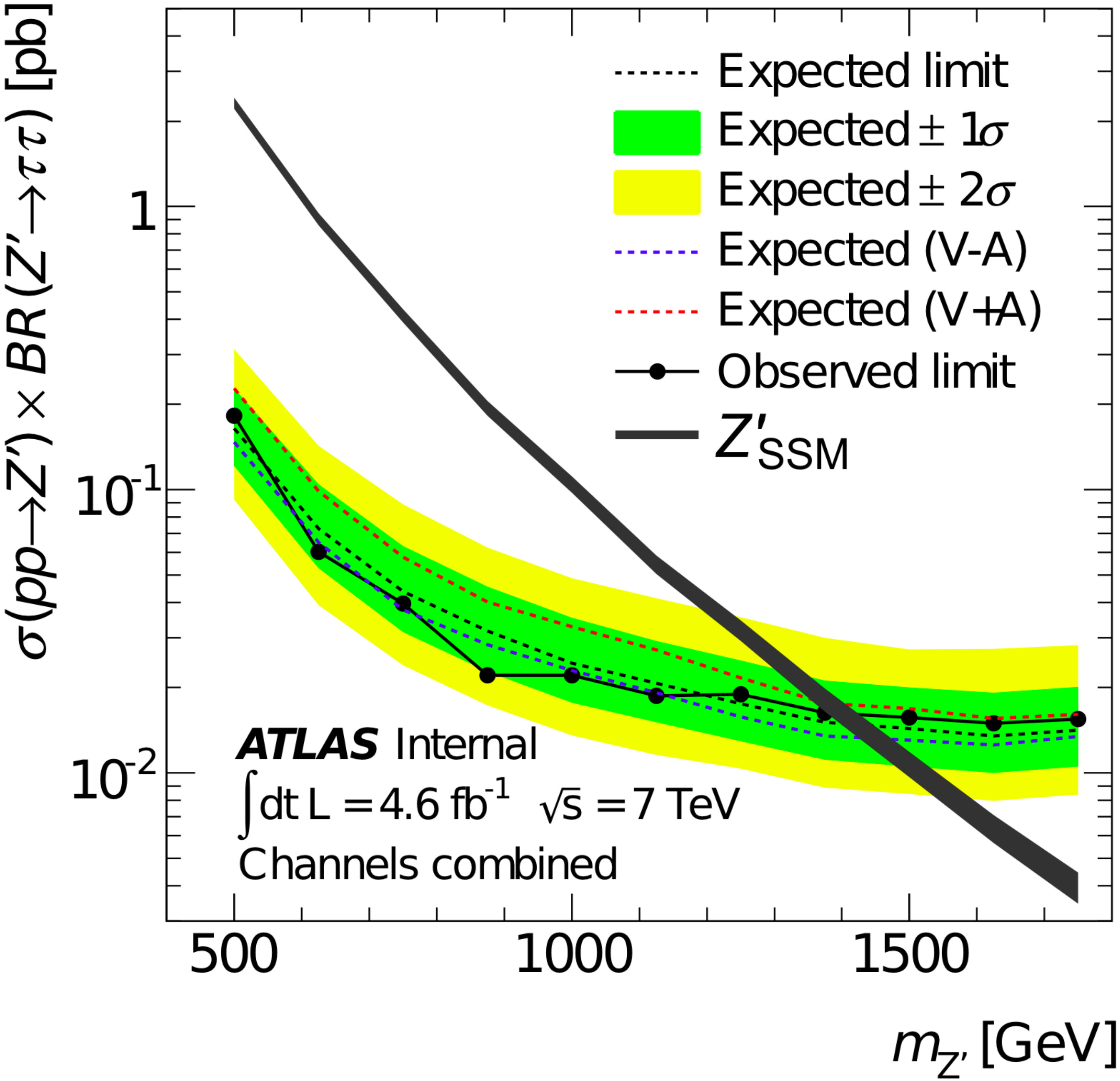
- Z'_{SSM} has the same chiral couplings as the Z of the SM, but with a higher mass.
- The visible momentum fraction in hadronic tau decays can depend on the handedness of the couplings because it decays left-handed through a W.
- To probe the dependence on the limit, we tested two extreme cases:
  1. V-A pure left
  2. V+A pure right

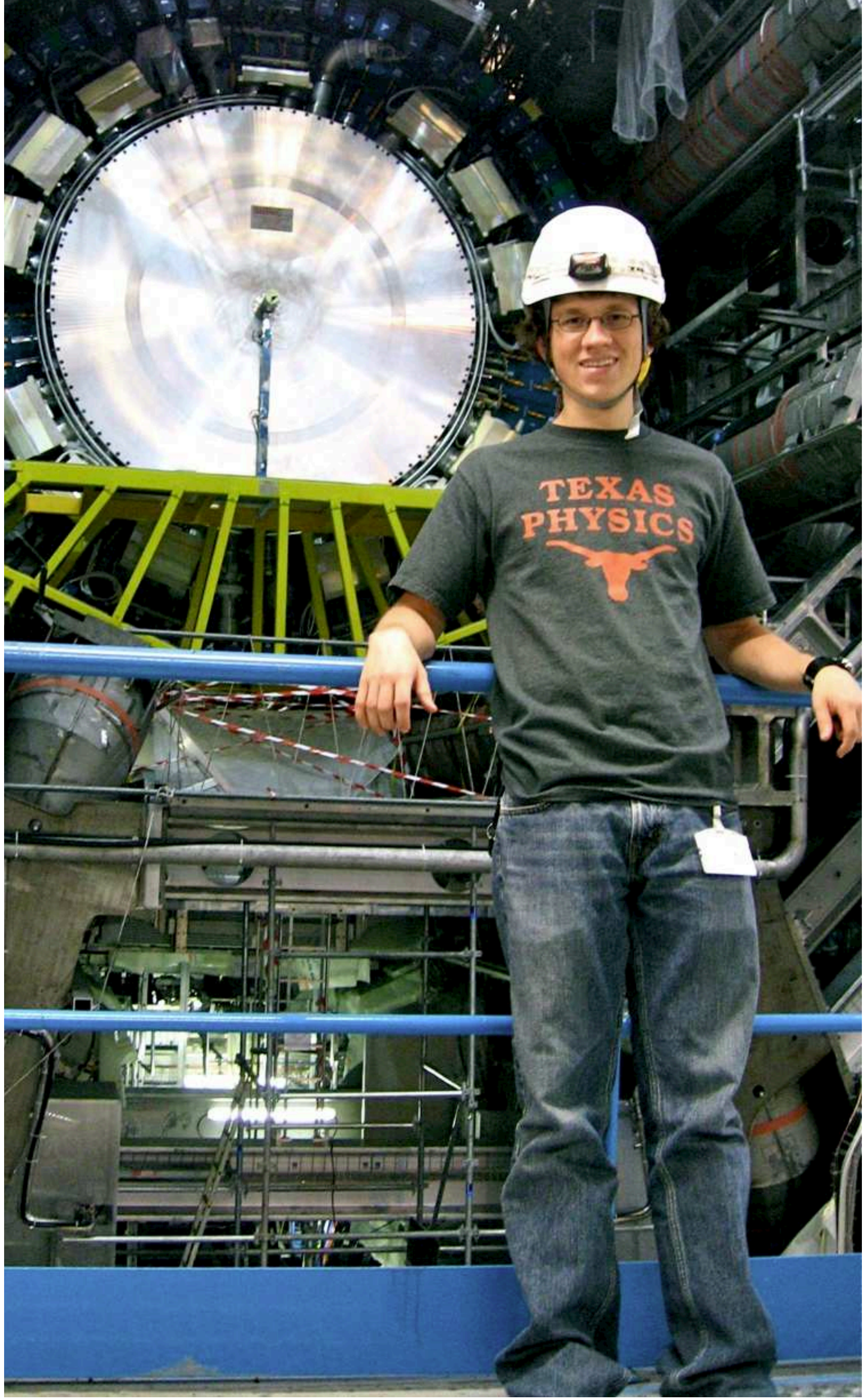




10-20% change in signal acceptance

Model dependence





Summary

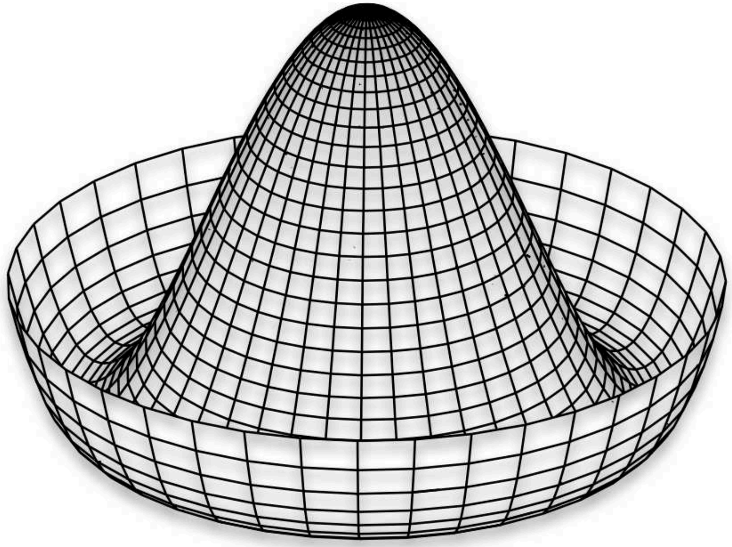
- It's been an exciting time to be a student.
- Had a lot of fun learning experimental skills during the turn-on of the LHC.
- Helped commission thresholds and hit efficiency for the TRT.
- Developed cut-based tau identification.
- Studied pile-up robustness for taus.
- Measured SM $Z \rightarrow \tau\tau$ cross section.
- Searched for new physics in high-mass ditau events.
- *Excited that discoveries at the LHC could just be beginning.*

I will always be indebted to Penn for enabling me and teaching me so much.

Penn

Back up

Review of Higgs search results



July 4, 2012
CERN announces the discovery of a new particle by ATLAS and CMS, consistent with the Higgs boson

The New York Times

Late Edition

NEW YORK, THURSDAY, JULY 5, 2012

$2.50

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

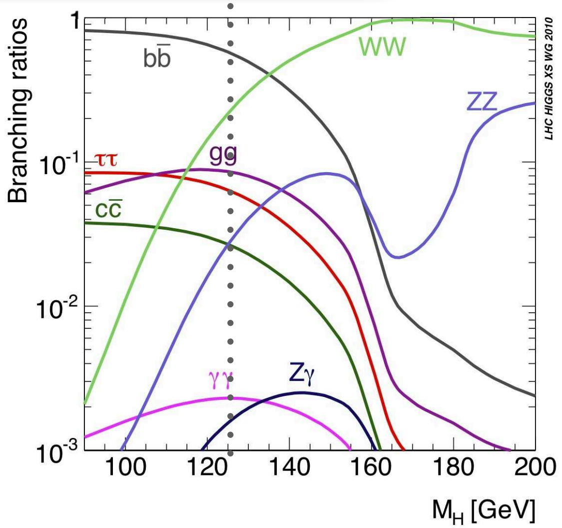
Physicists Find Elusive Particle Seen as Key to Universe

July 5 cover of the New York Times:
Physicists Find Elusive Particle Seen as Key to the Universe

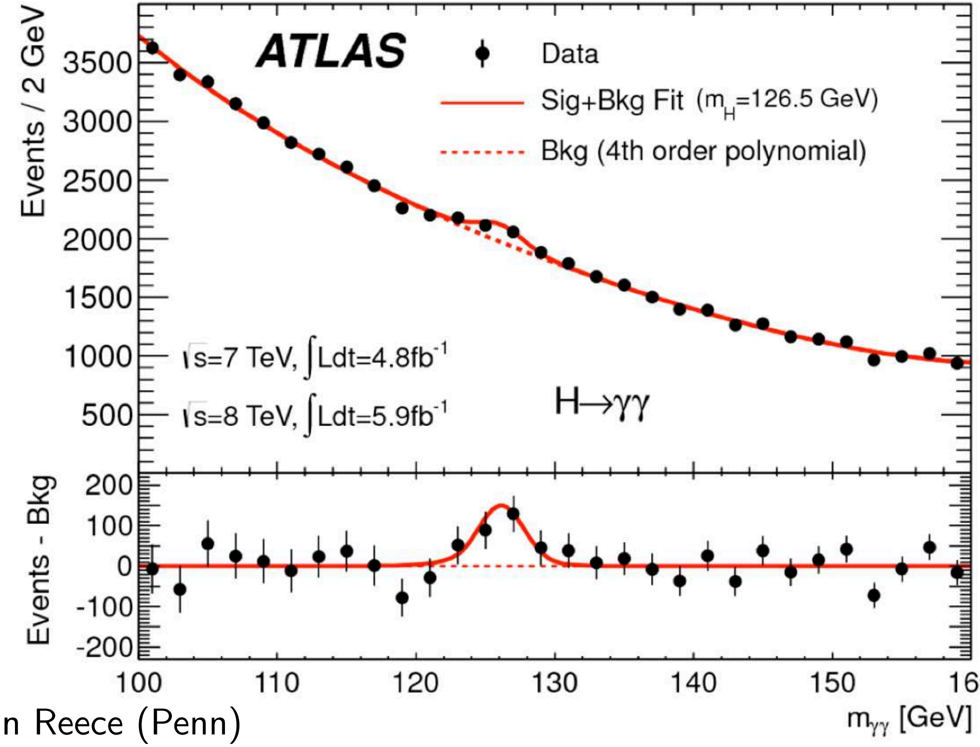
Current Higgs results

- Two channels with precise mass measurements: $\boldsymbol{H\rightarrow\gamma\gamma}$ and $\boldsymbol{H\rightarrow ZZ\rightarrow 4l}$.
- $\boldsymbol{H\rightarrow WW}$ observes a broad but clear excess.

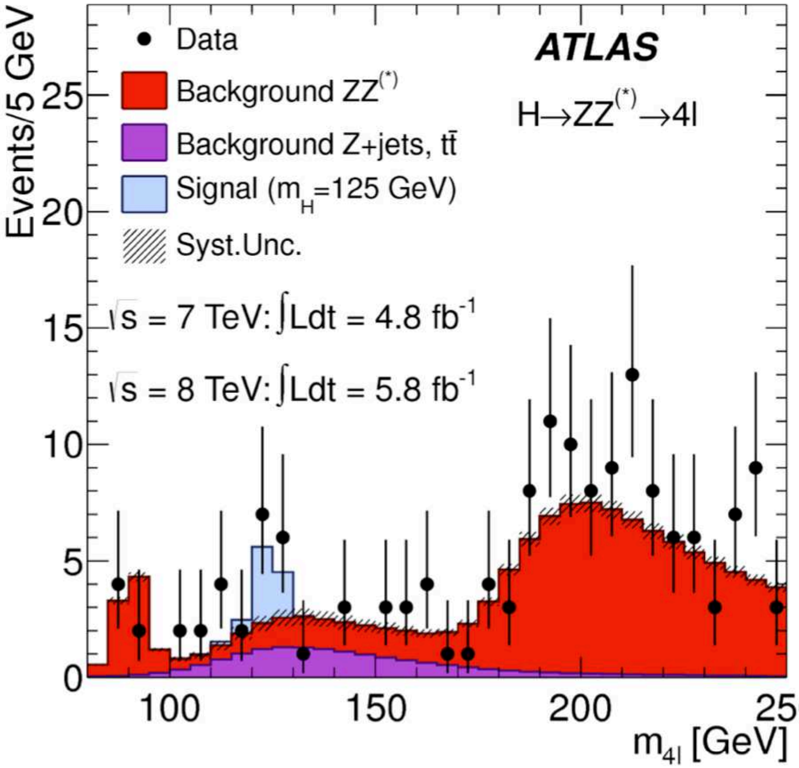
channel	bb	ττ	WW	ZZ	γγ
BR	58%	6%	22%	3%	0.2%



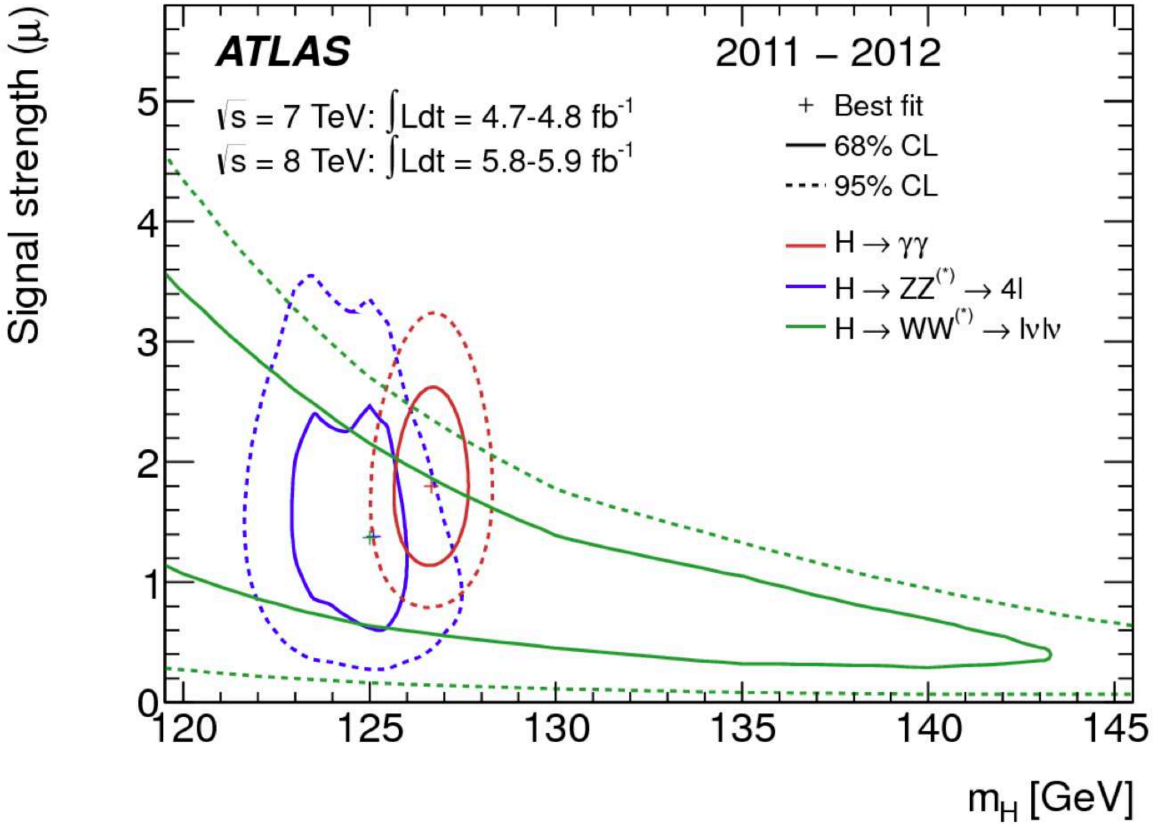
$\boldsymbol{H\rightarrow\gamma\gamma}$

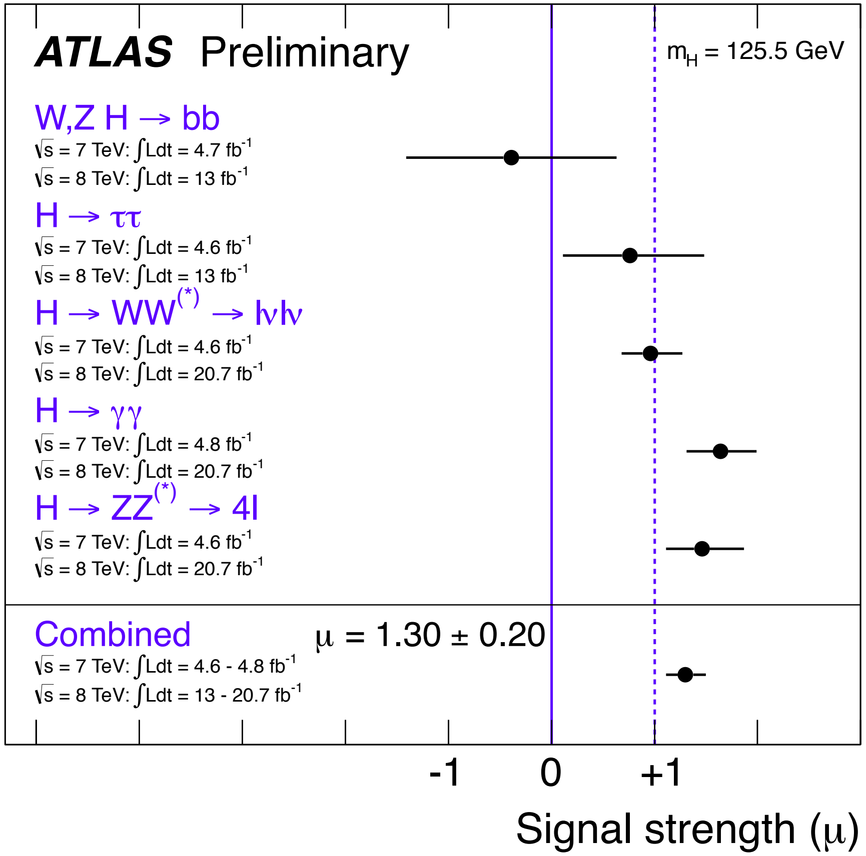


$\boldsymbol{H\rightarrow ZZ\rightarrow 4l}$



Current Higgs results

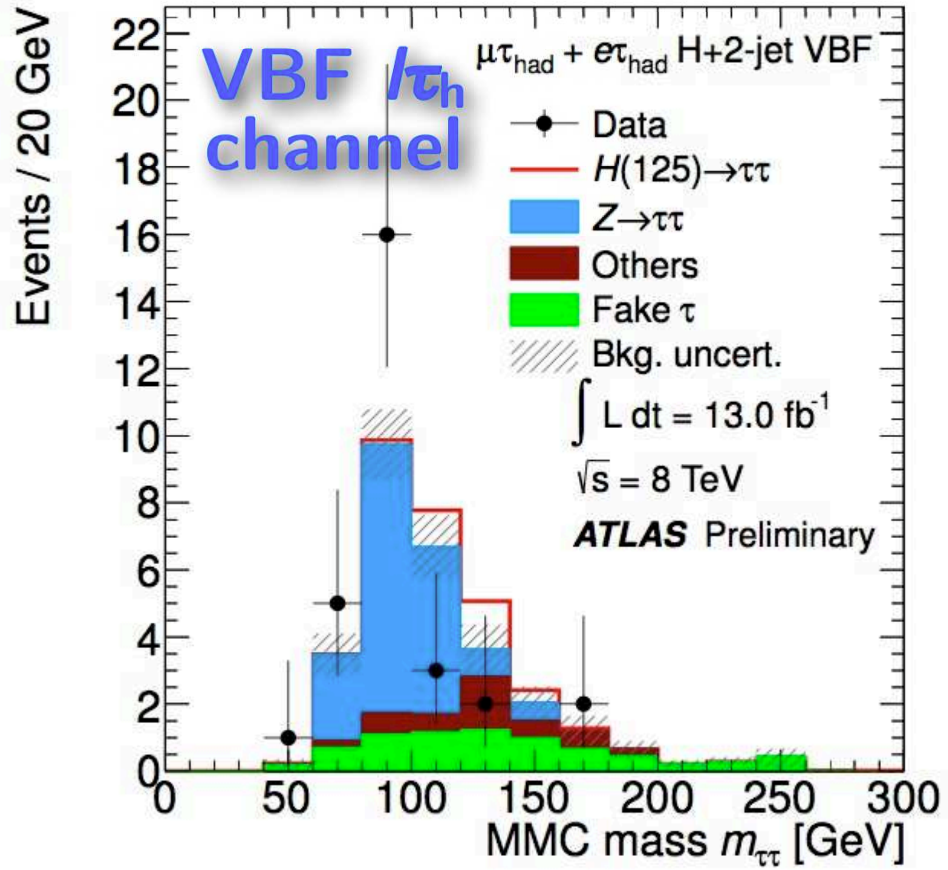


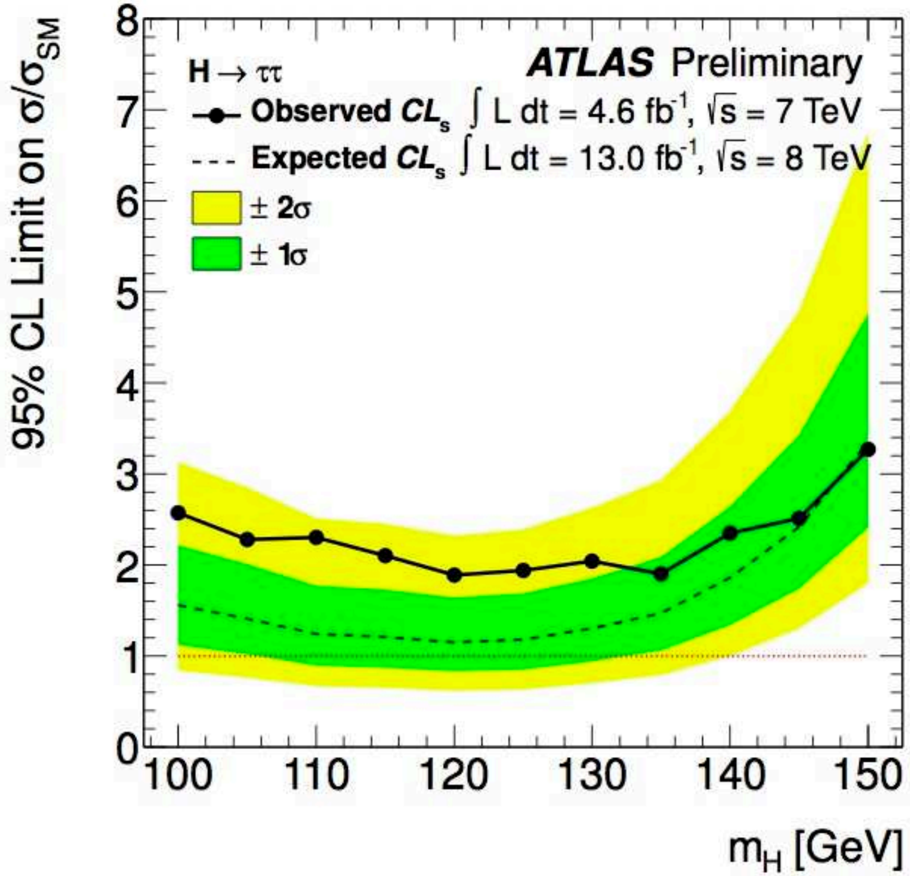


- The measurements in the $\gamma\gamma/ZZ/WW$ channels are consistent with a new neutral boson with m≈126 GeV.
- Interestingly, both ATLAS and CMS observe the signal strength in the $\gamma\gamma$ channel to be higher than the SM over 1σ, but still consistent with the SM.
- $H\rightarrow\tau\tau$ and $H\rightarrow bb$ are approaching sensitivity.

[1207.7214, ATLAS-CONF-2013-034]

Current $H\rightarrow\tau\tau$ result

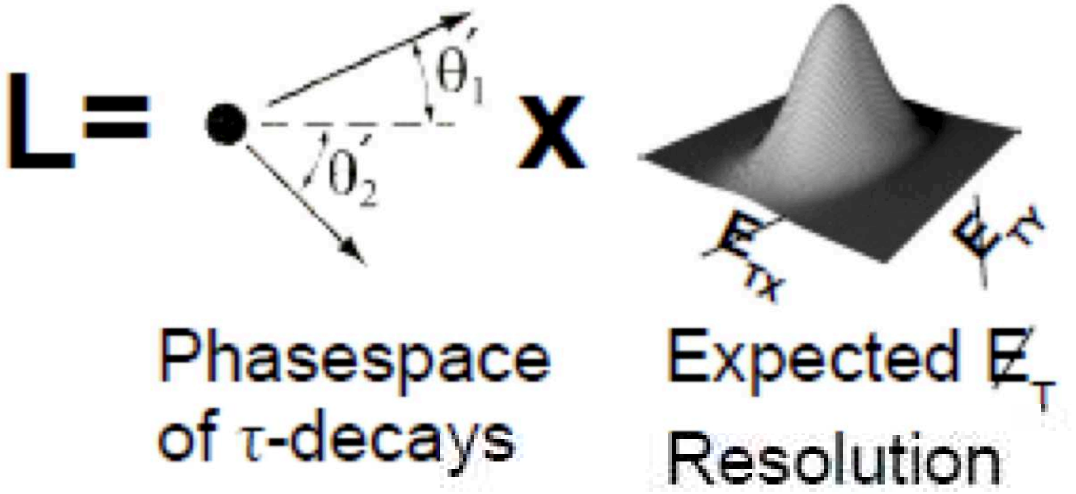




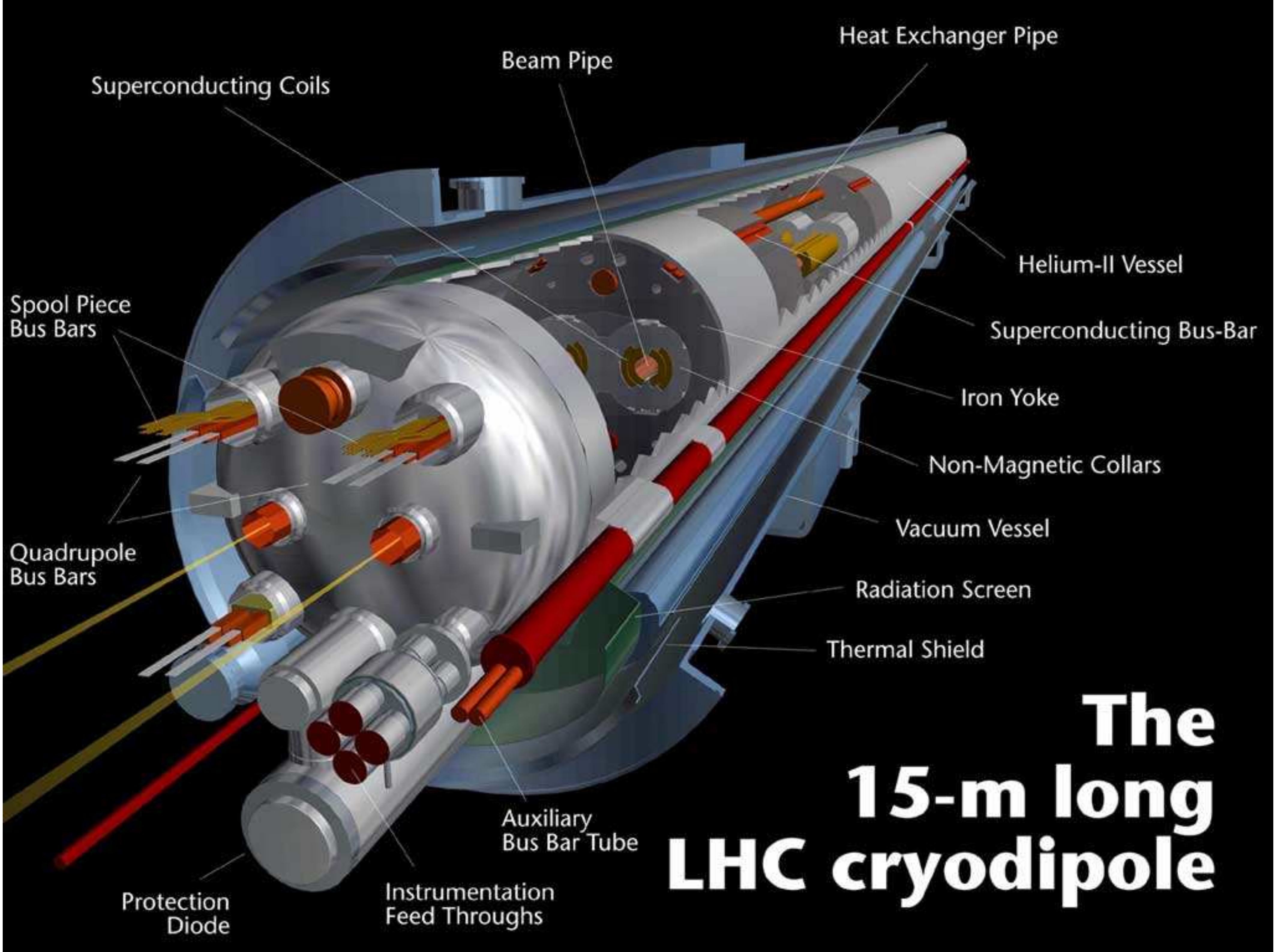
- A lot of shared experience between $Z/Z'/H\rightarrow\tau\tau$ analyses.
- Uses similar $\sum\Delta\phi$ cut for suppressing W+jet.
- Uses fake factor method for predicting fake backgrounds.
- Eagerly approaching sensitivity to 1×SM $H\rightarrow\tau\tau$.
- 21.7 fb^{-1} collected this year.

[ATLAS-CONF-2012-160]

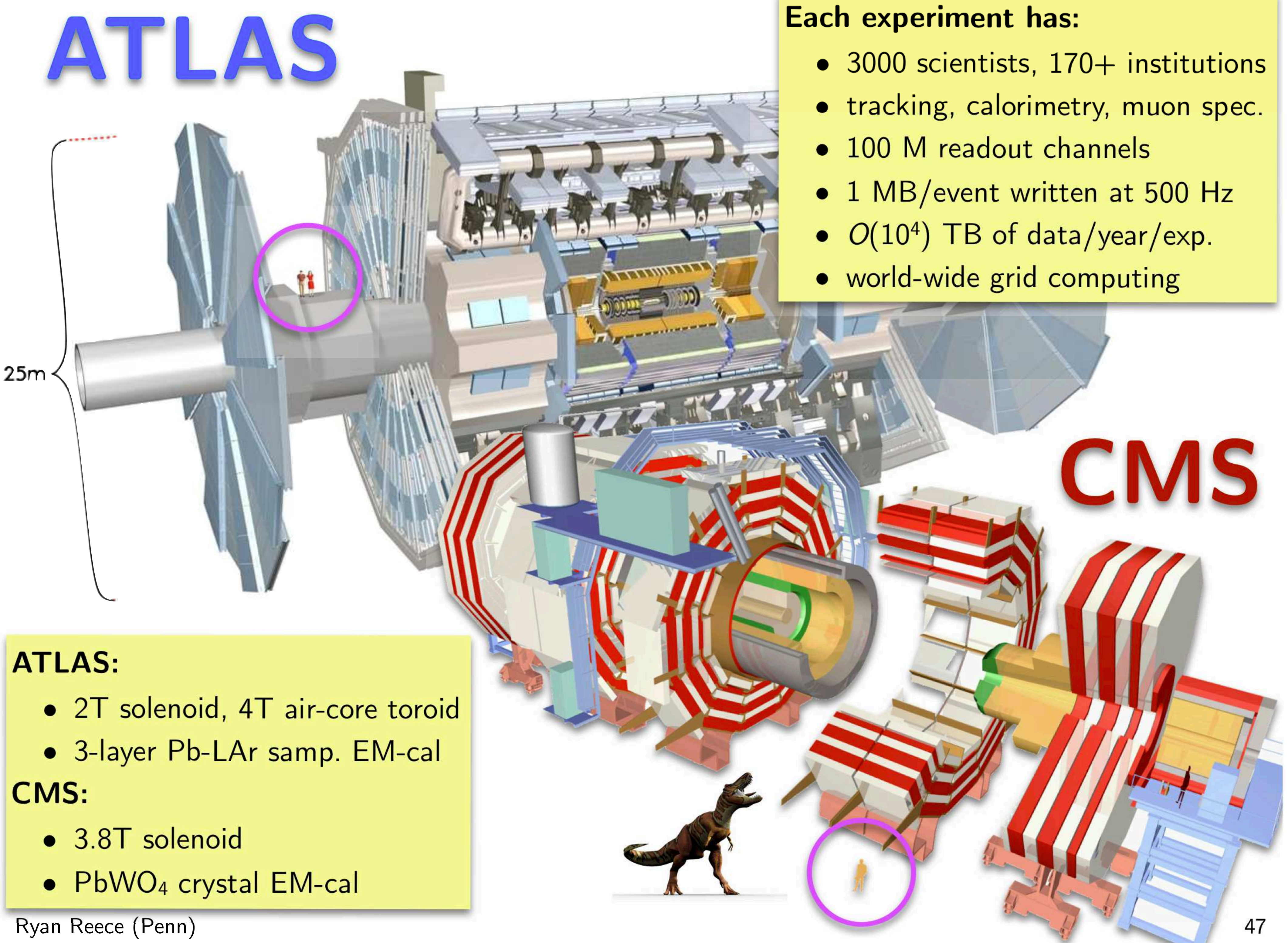
MMC mass


L=
θ_1'
θ_2'
x
$\not{E}_{Tx}$
$\not{E}_{Ty}$
Phasespace of τ-decays
Expected $\not{E}_T$ Resolution

The LHC, ATLAS, and CMS



The 15-m long LHC cryodipole



Each experiment has:

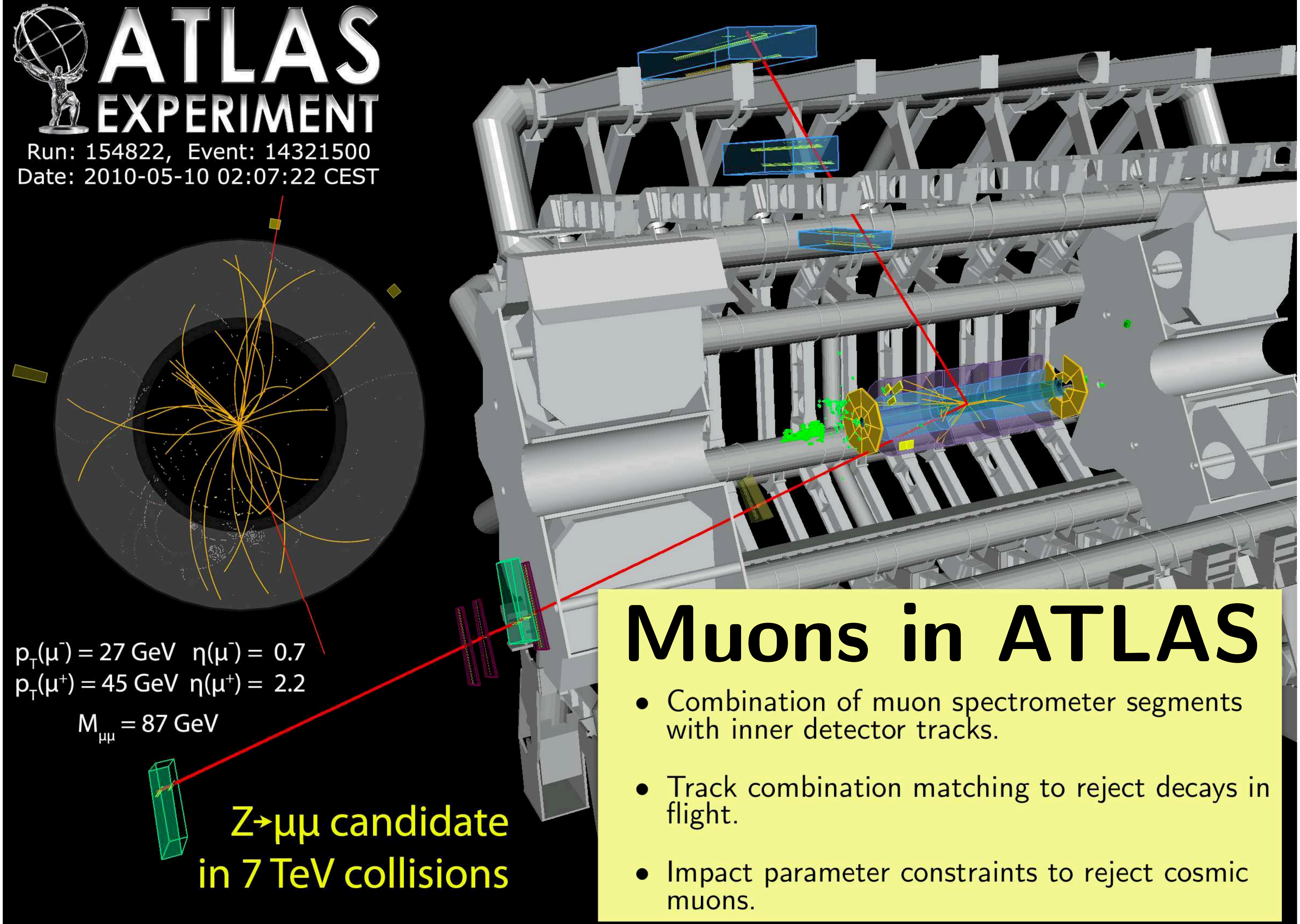
- 3000 scientists, 170+ institutions
- tracking, calorimetry, muon spec.
- 100 M readout channels
- 1 MB/event written at 500 Hz
- $\mathcal{O}(10^4)$ TB of data/year/exp.
- world-wide grid computing

ATLAS:

- 2T solenoid, 4T air-core toroid
- 3-layer Pb-LAr samp. EM-cal

CMS:

- 3.8T solenoid
- $PbWO_4$ crystal EM-cal



ATLAS EXPERIMENT

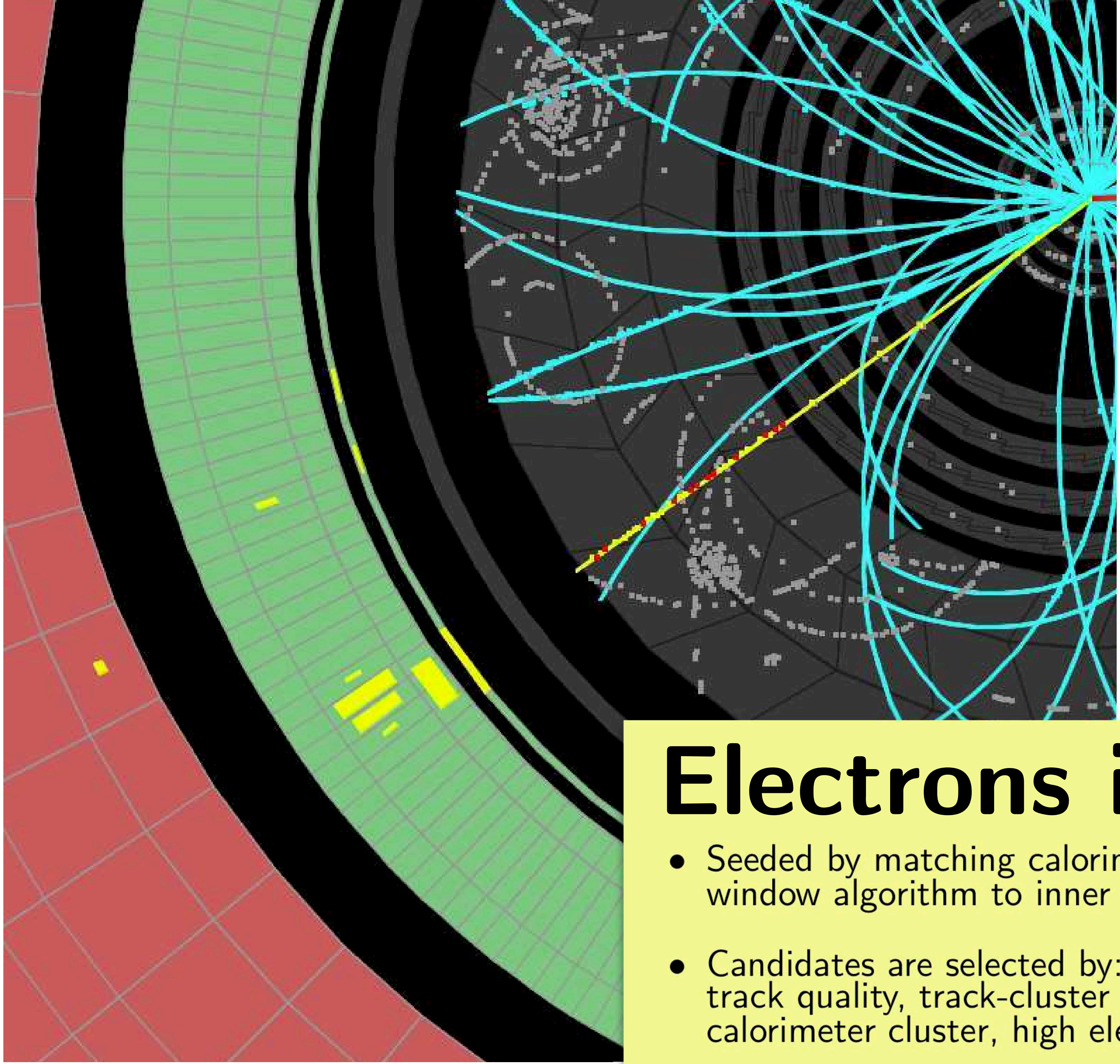
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST

$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV

$Z \to \mu\mu$ candidate
in 7 TeV collisions

Muons in ATLAS

- Combination of muon spectrometer segments with inner detector tracks.
- Track combination matching to reject decays in flight.
- Impact parameter constraints to reject cosmic muons.

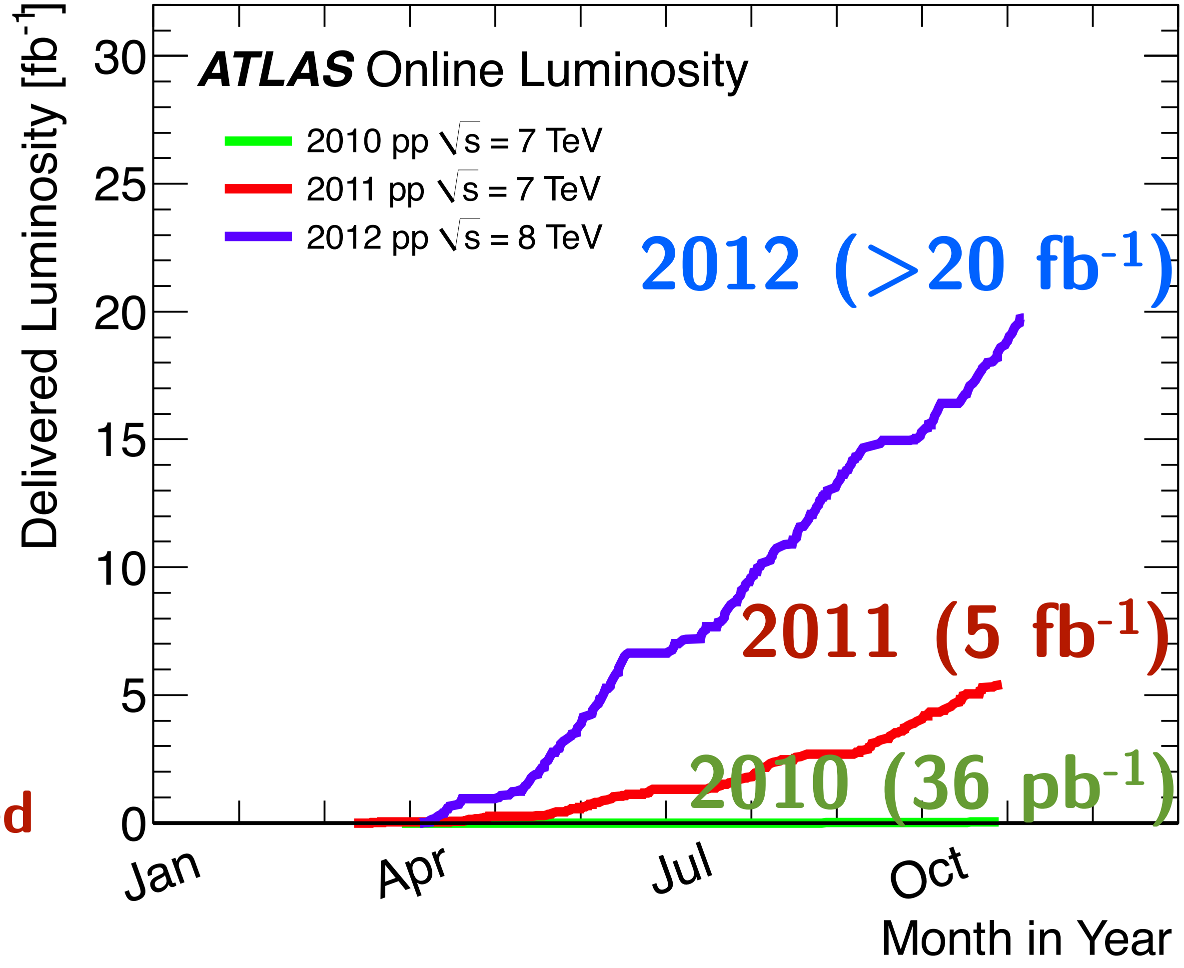


Electrons in ATLAS

- Seeded by matching calorimeter clusters from a sliding-window algorithm to inner detector tracks.
- Candidates are selected by:
  track quality, track-cluster matching, narrow calorimeter cluster, high electromagnetic fraction
- Tight candidates have cuts on E/p and high thresholds hits from the transition radiation in the TRT.

Timeline of taus at ATLAS

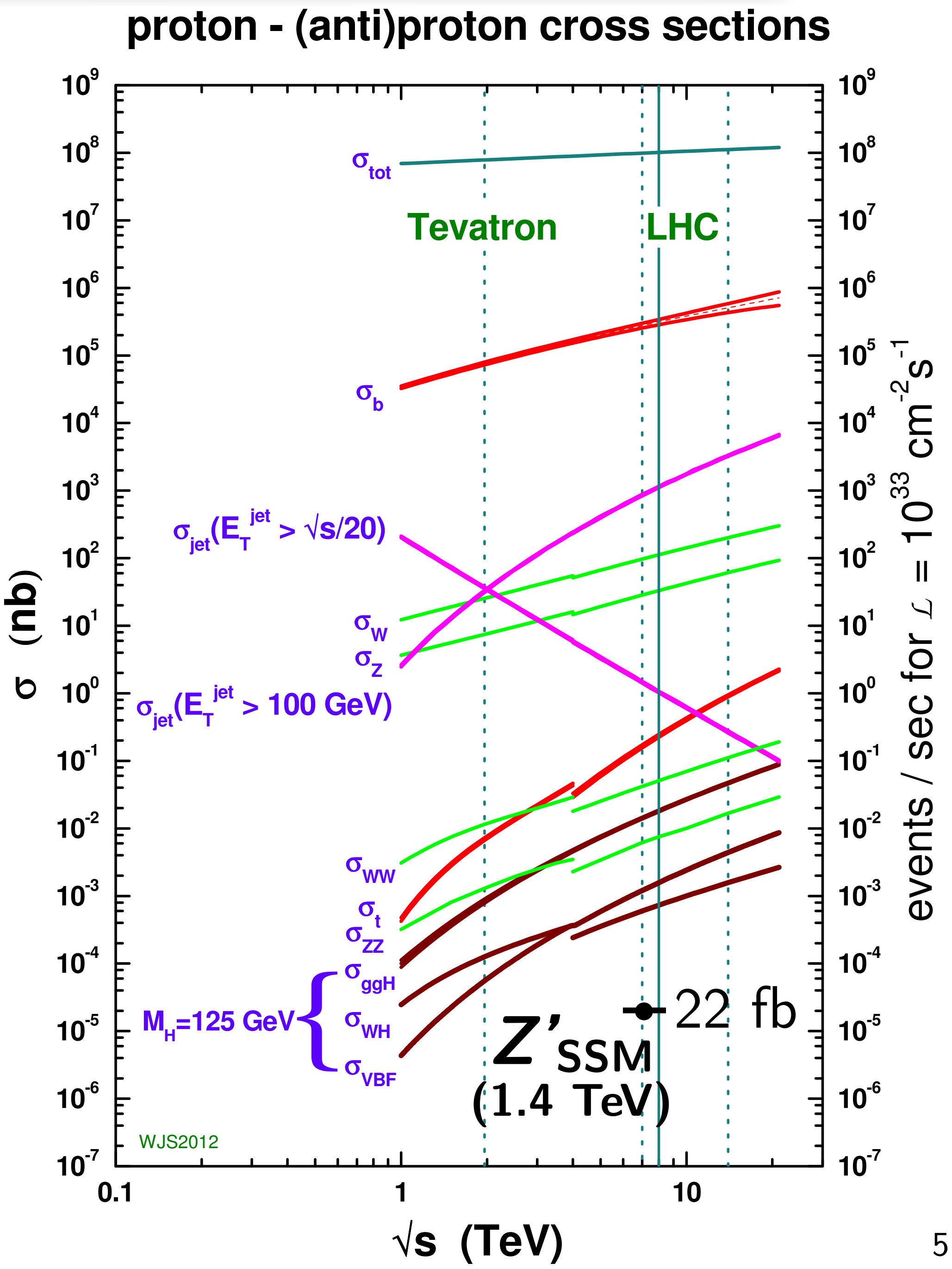
- Nov 2010: Obs. of $W\to\tau\nu$ (546 nb^{-1})
- Feb 2011: Obs. of $Z\to\tau\tau$ (8.5 pb^{-1})
- July 2011: $W\to\tau\nu$ and $Z\to\tau\tau$ cross section measurements (36 pb^{-1})
- Feb 2012: $Z\to\tau\tau$ cross section (1.5 fb^{-1})
- June 2012: SM $H\to\tau\tau$ excluded 3-4×SM at $m_H\approx125$ GeV [arXiv:1206.5971]
- Several other analyses: MSSM $H\to\tau\tau$, $t\bar{t}$ with τ, $H^+\to\tau\nu$, $Z'\to\tau\tau$, SUSY τ+MET, ...



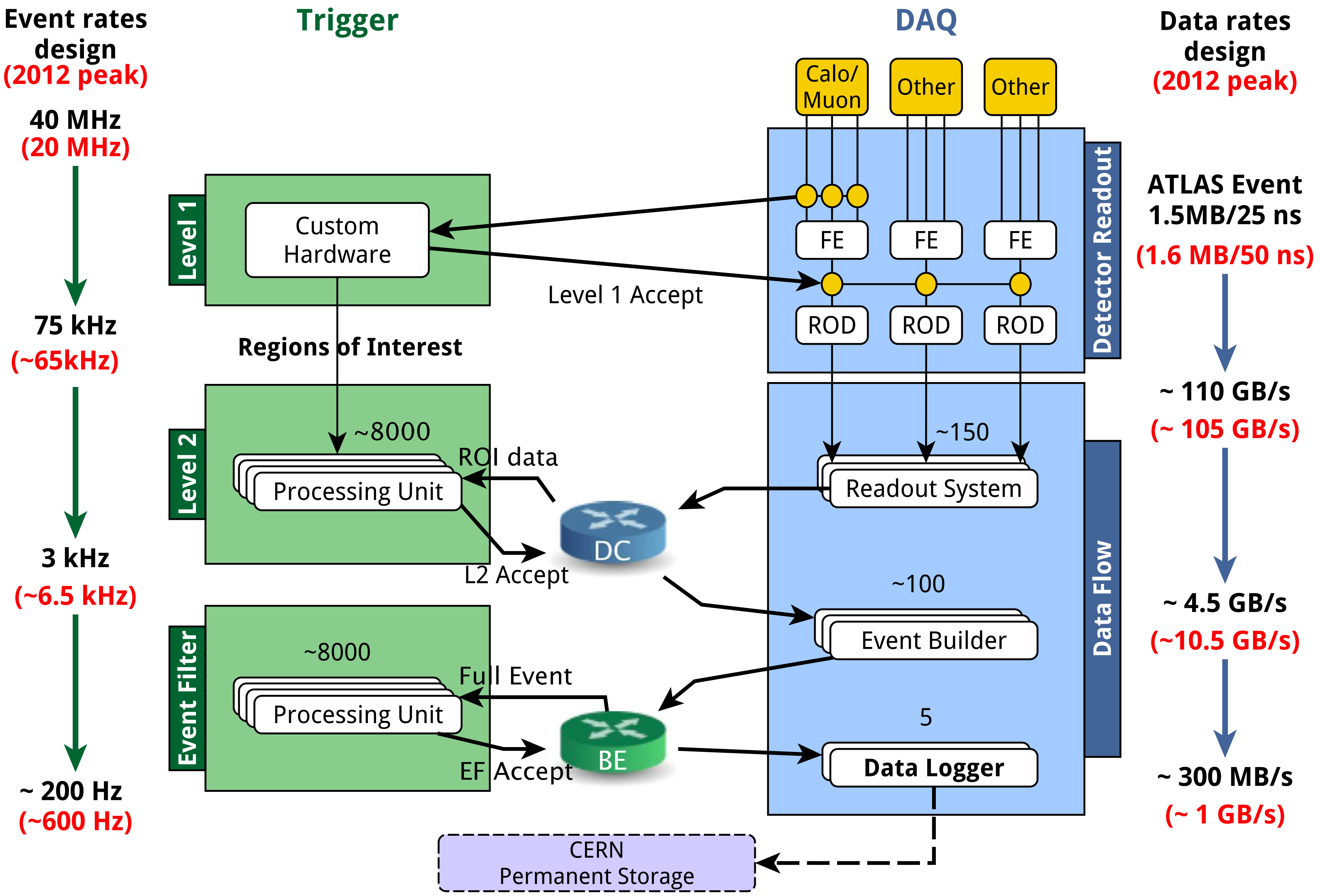
- Now eagerly waiting to see if $H\to\tau\tau$ will be excluded at 1×SM this year?

We need high energies

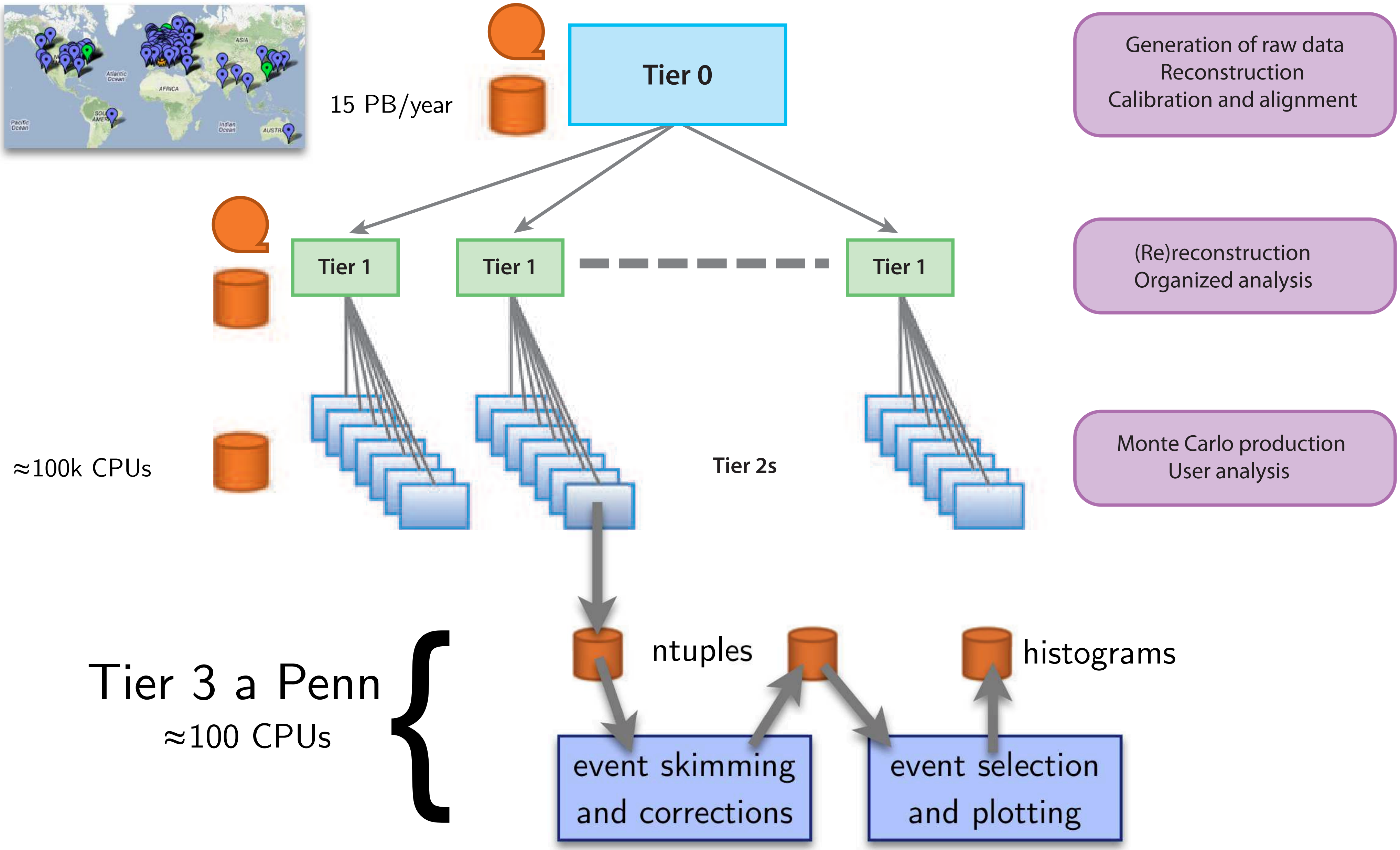
- To probe physics at the TeV scale and beyond we need a high-energy collider.
- The cross section ⇒ production rate grows significantly with the collision energy, $\sqrt{s}$.
- *W*, *Z*, top, Higgs, *Z'*, ...



Trigger and DAQ



Computing infrastructure



15 PB/year

Tier 0

Generation of raw data
Reconstruction
Calibration and alignment

Tier 1 **Tier 1** **Tier 1**

(Re)reconstruction
Organized analysis

≈100k CPUs

Tier 2s

Monte Carlo production
User analysis

Tier 3 a Penn
≈100 CPUs

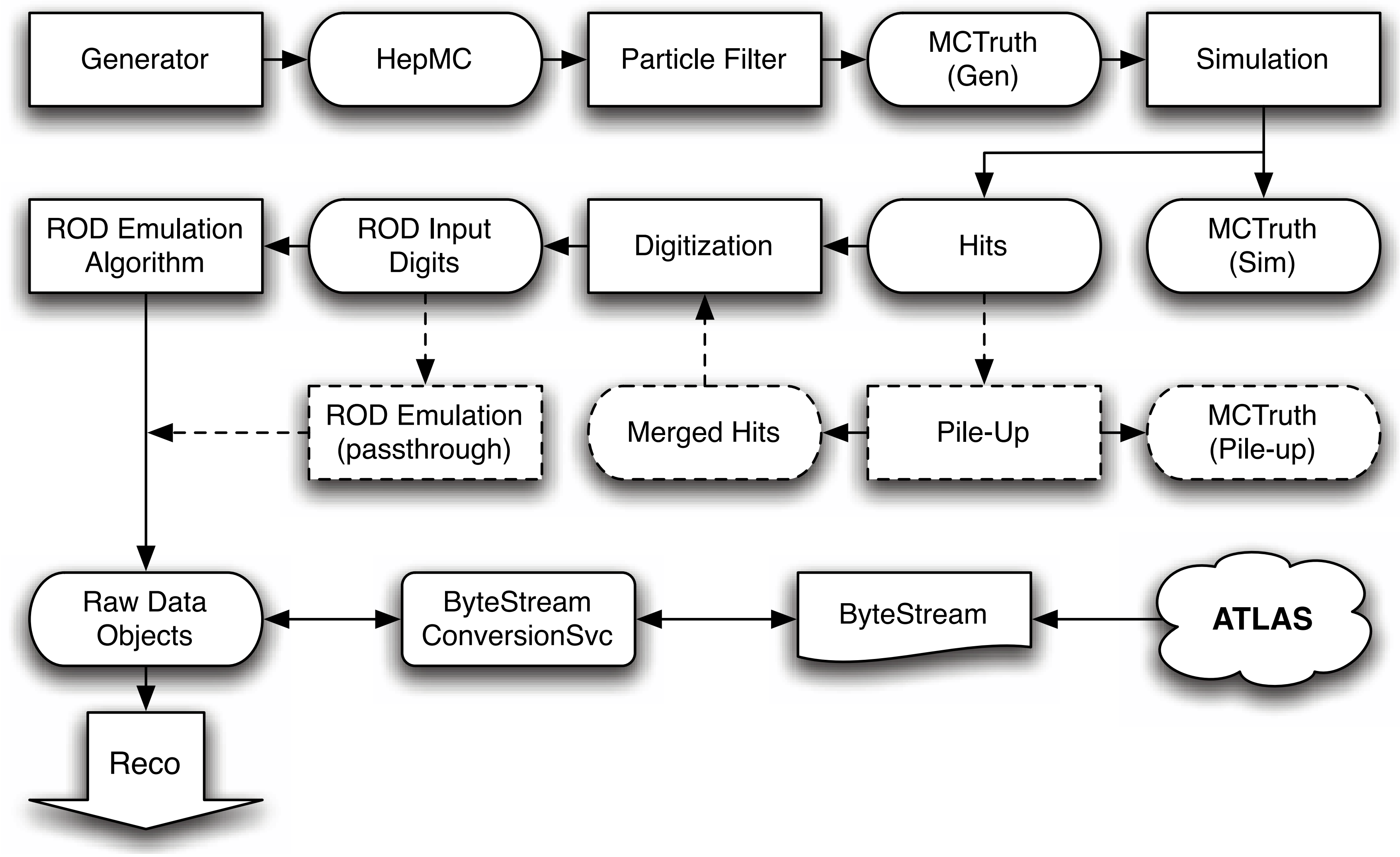
ntuples

histograms

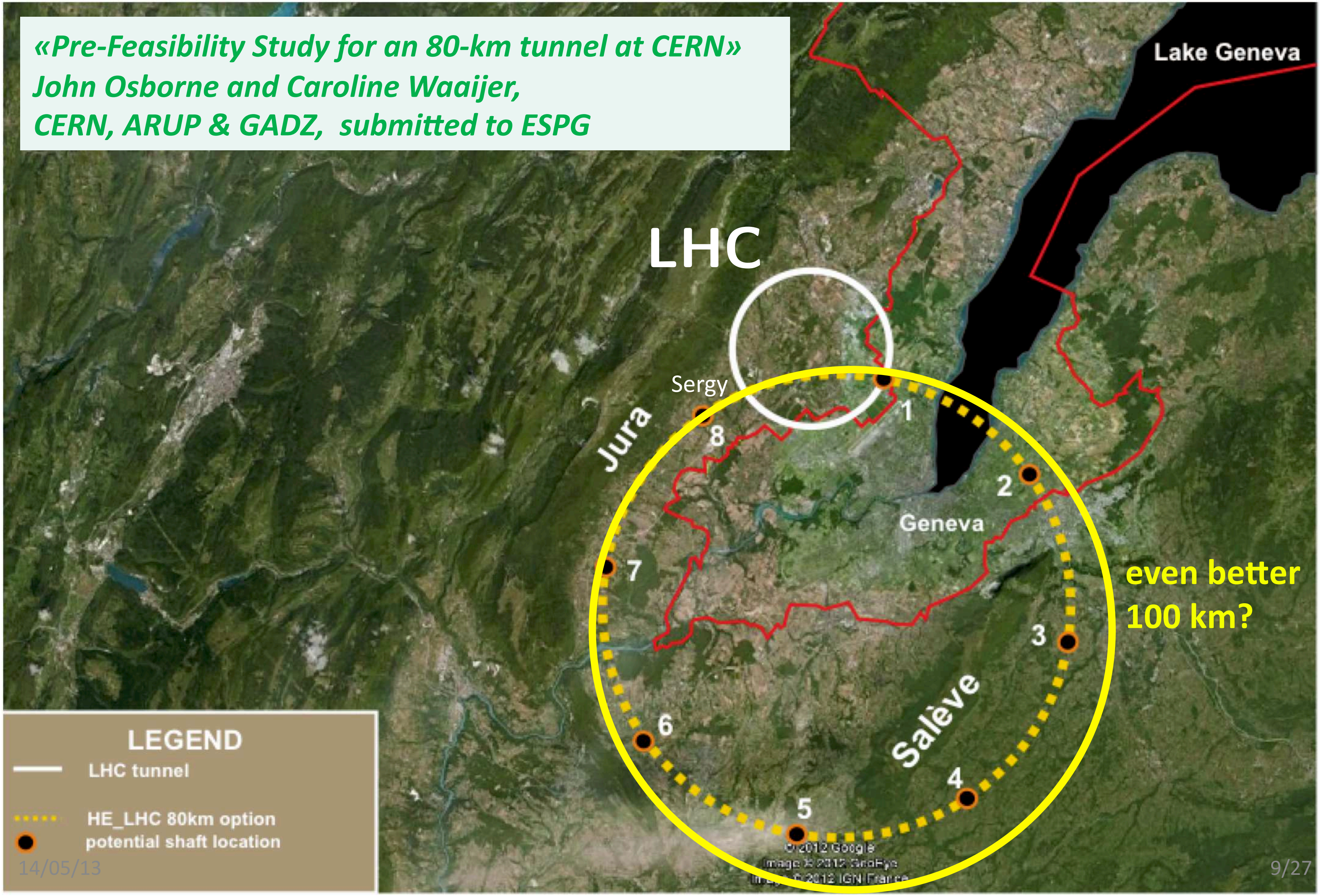
event skimming and corrections

event selection and plotting

MC simulation chain


Generator
HepMC
Particle Filter
MCTruth (Gen)
Simulation
Hits
MCTruth (Sim)
Digitization
ROD Input Digits
ROD Emulation Algorithm
ROD Emulation (passthrough)
Merged Hits
Pile-Up
MCTruth (Pile-up)
Raw Data Objects
ByteStream ConversionSvc
ByteStream
ATLAS
Reco

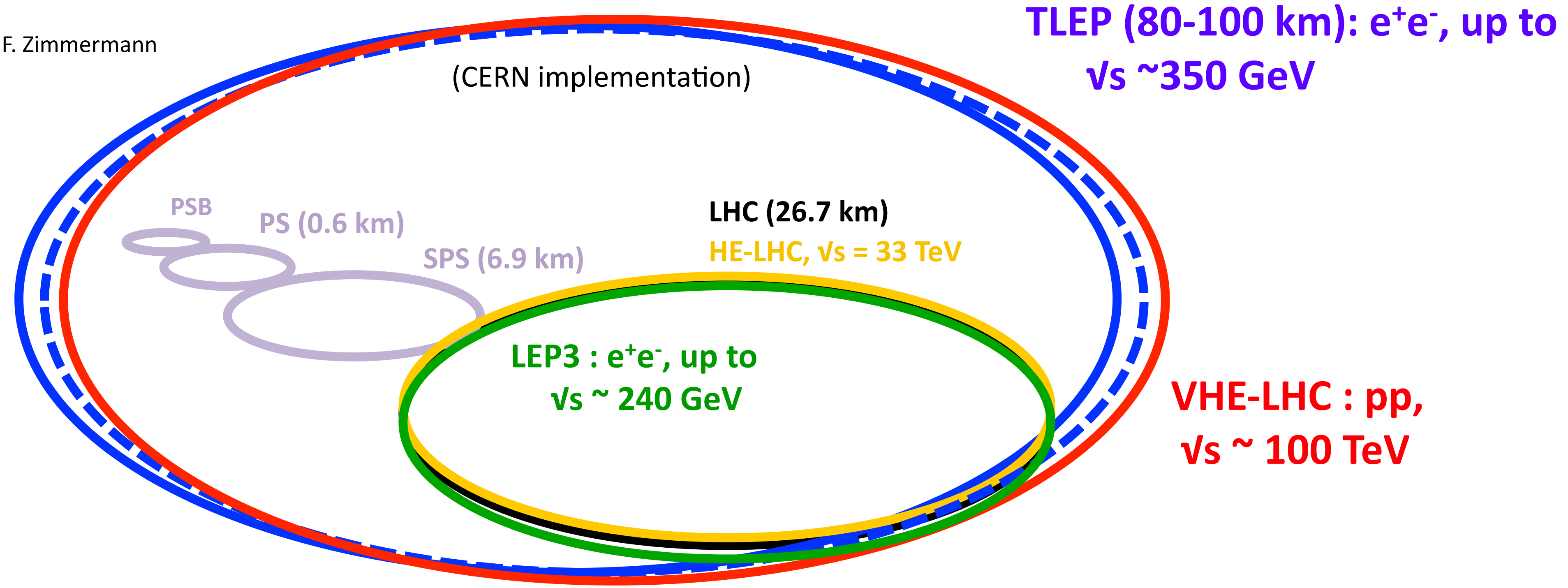
Future: 80-100 km tunnel?



«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG

[Colin Bernet (CERN)]

Future: LEP3, HE-LHC, TLEP, VHE-LHC

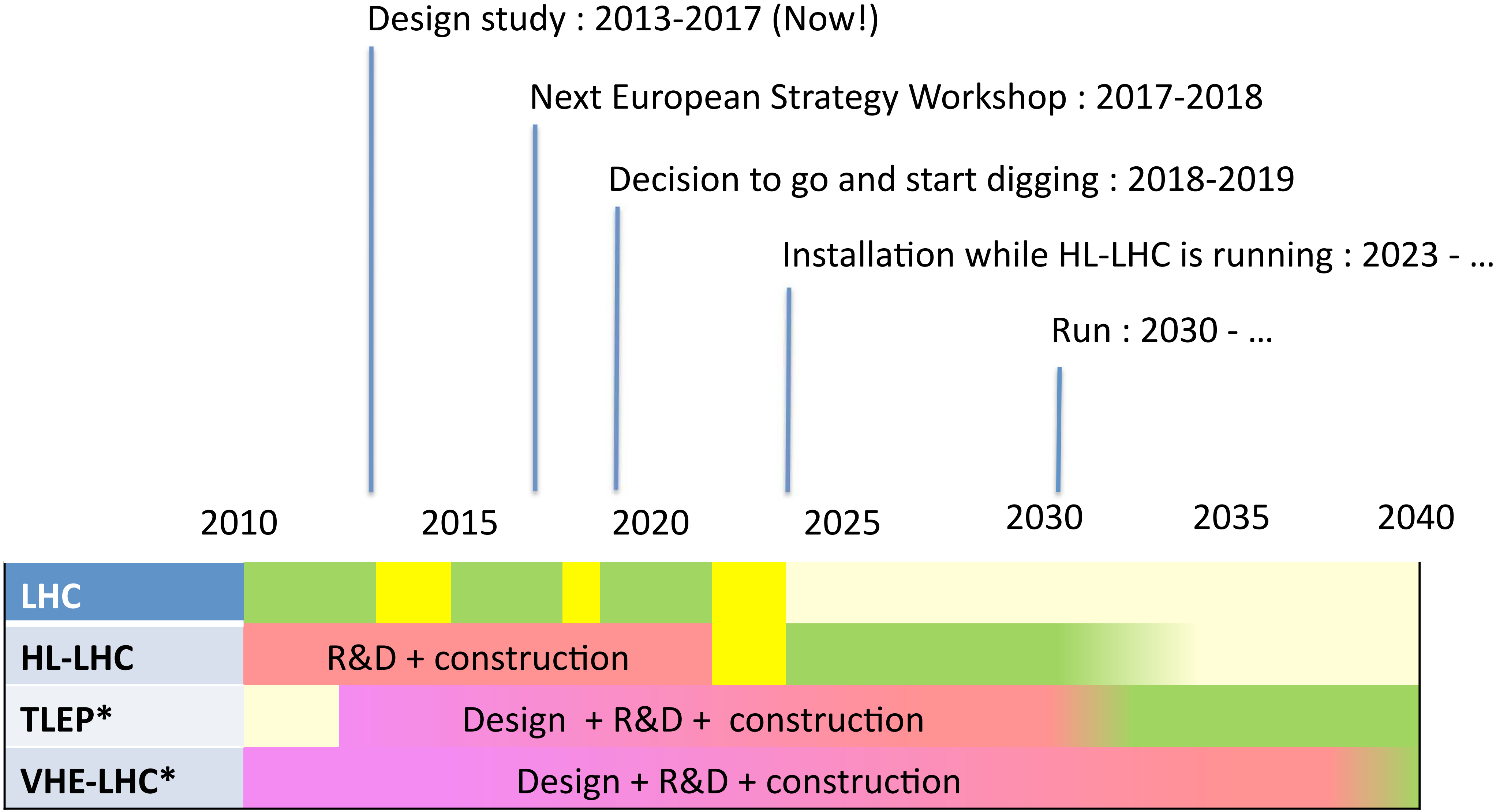


- **TLEP Physics case : Precision measurements sensitive to multi-TeV New Physics**
  - TeraZ ($\sqrt{s}$~m_Z), MegaW ($\sqrt{s}$~$2m_W$), Higgs Factory ($\sqrt{s}$~240 GeV), top ($\sqrt{s}$~350 GeV)

- **Followed by VHE-LHC : Direct search for New Physics in the 10-100 TeV range**
  - $\sqrt{s}$ ~ 100 TeV with 20T magnets
  - Also allows the HHH coupling to be measured to a few %

[Colin Bernet (CERN)]

Possible timescale



Design study : 2013-2017 (Now!)

Next European Strategy Workshop : 2017-2018

Decision to go and start digging : 2018-2019

Installation while HL-LHC is running : 2023 - …

Run : 2030 - …

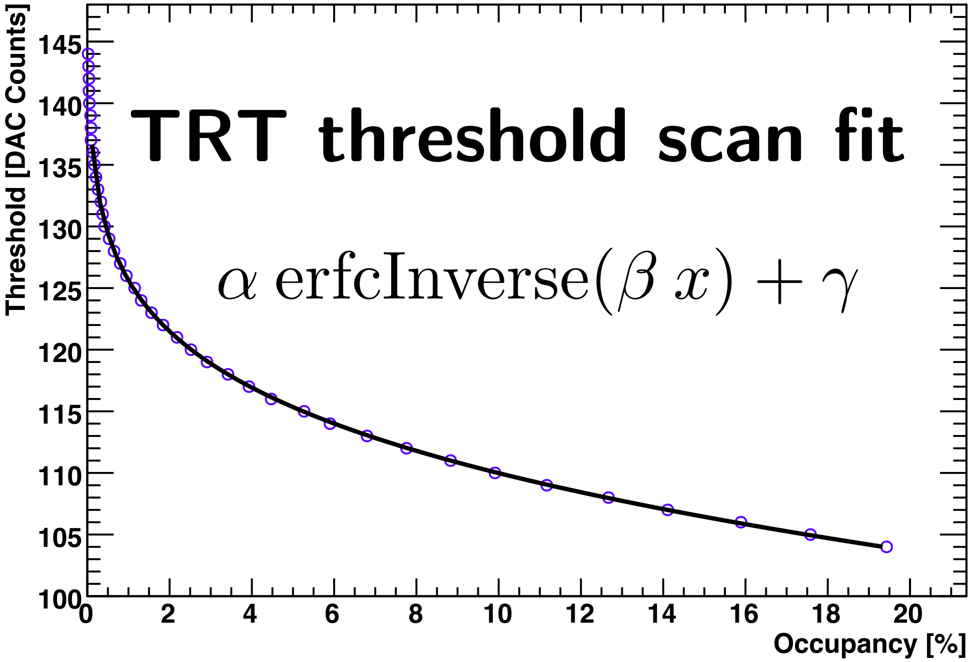
[Colin Bernet (CERN)]

Transition Radiation Tracker

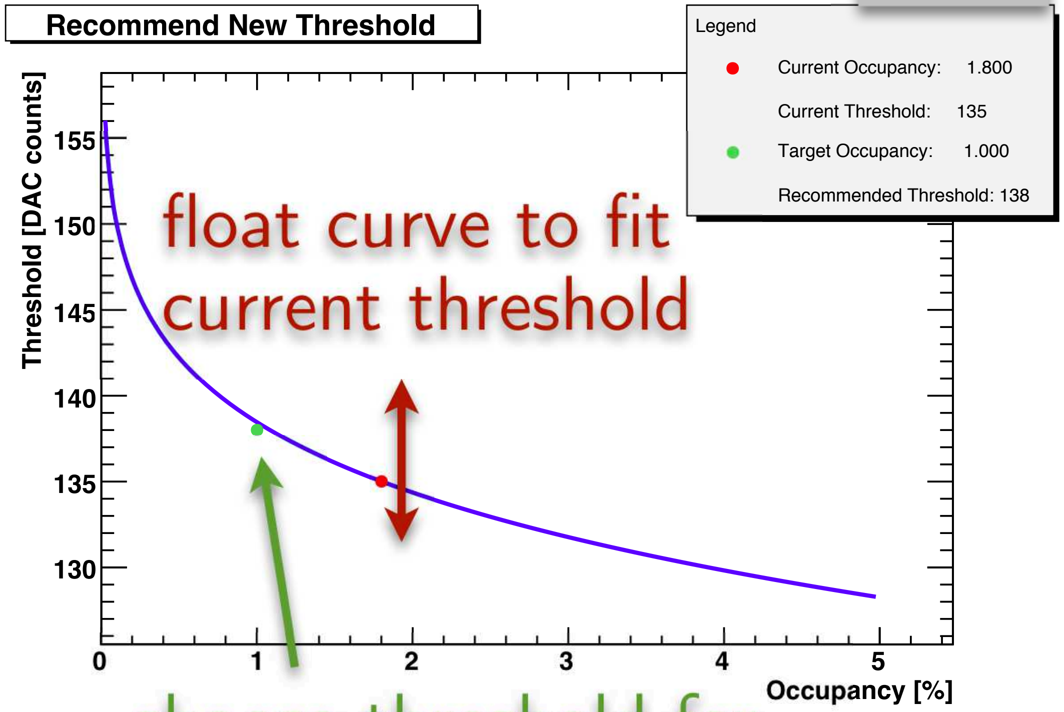
ATLAS

TRT threshold calibration

2008


TRT threshold scan fit

$$\alpha\,\mathrm{erfcInverse}(\beta\,x)+\gamma$$



float curve to fit current threshold

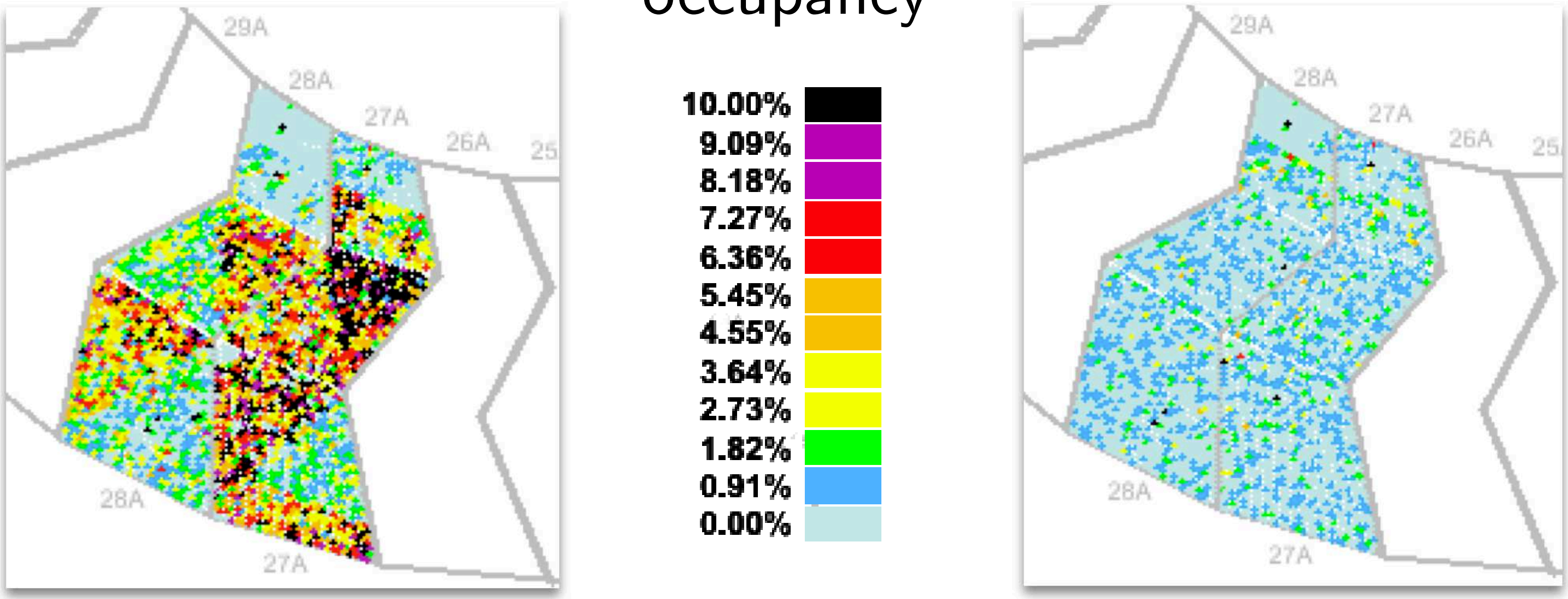
choose threshold for desired occupancy

- Fit a parametrization to the data from a scan varying the analog-to-digital thresholds in the discriminator chips on the TRT front-end.
- Wrote an algorithm for calibrating the thresholds *channel-by-channel* to reach a uniform noise occupancy by floating the functional form.

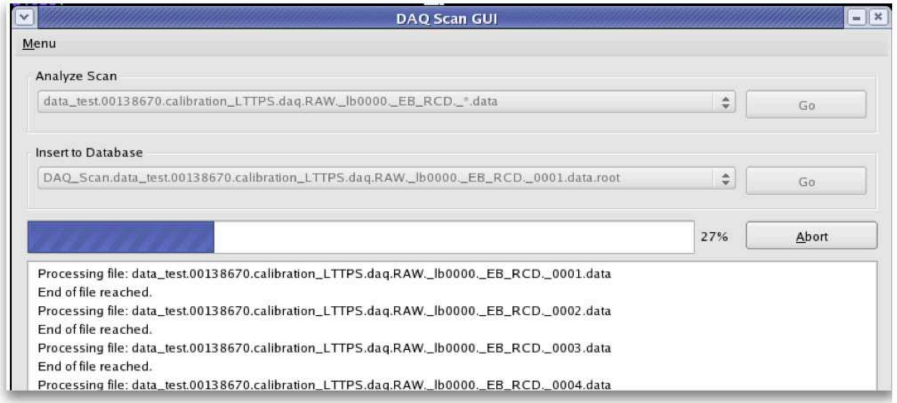
TRT threshold calibration

2008

Before noise occupancy **After**



- Developed a GUI making it easy for shifters to archive scans to a database for monitoring long-term detector health.
- Still used in the regularly scheduled calibration periods between beam fills.
- Supported TRT as part of DAQ on-call team.



Analyze Scan: data_test.00138670.calibration_LTTPS.daq.RAW._lb0000._EB_RCD._*.data

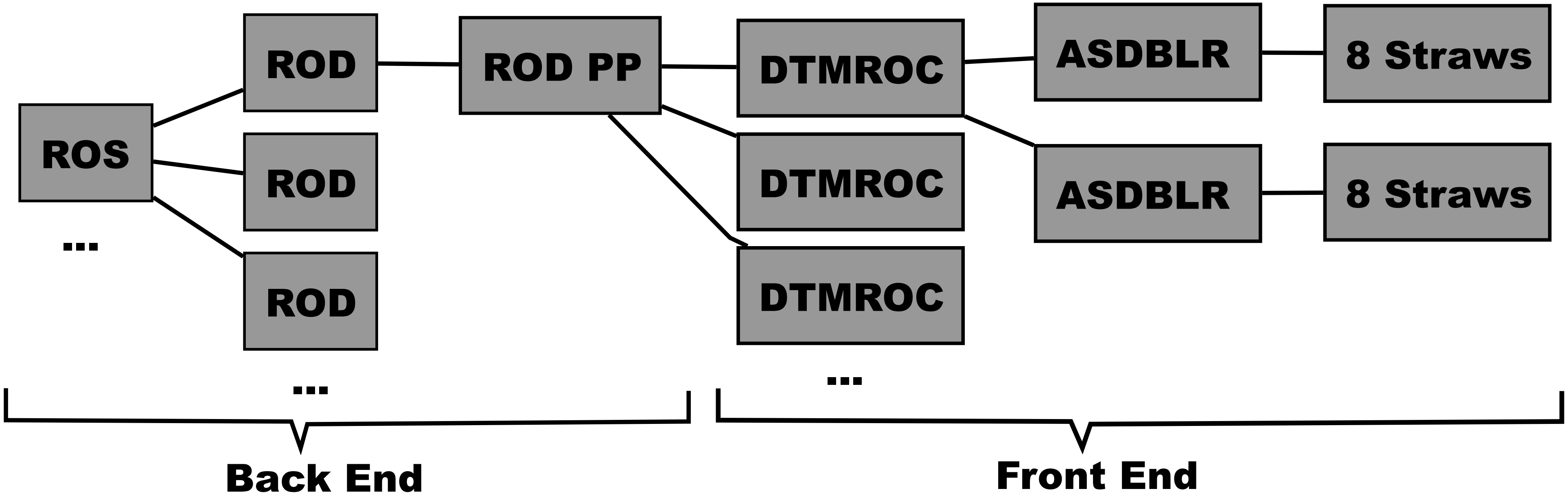
Insert to Database: DAQ_Scan.data_test.00138670.calibration_LTTPS.daq.RAW._lb0000._EB_RCD._0001.data.root

27%

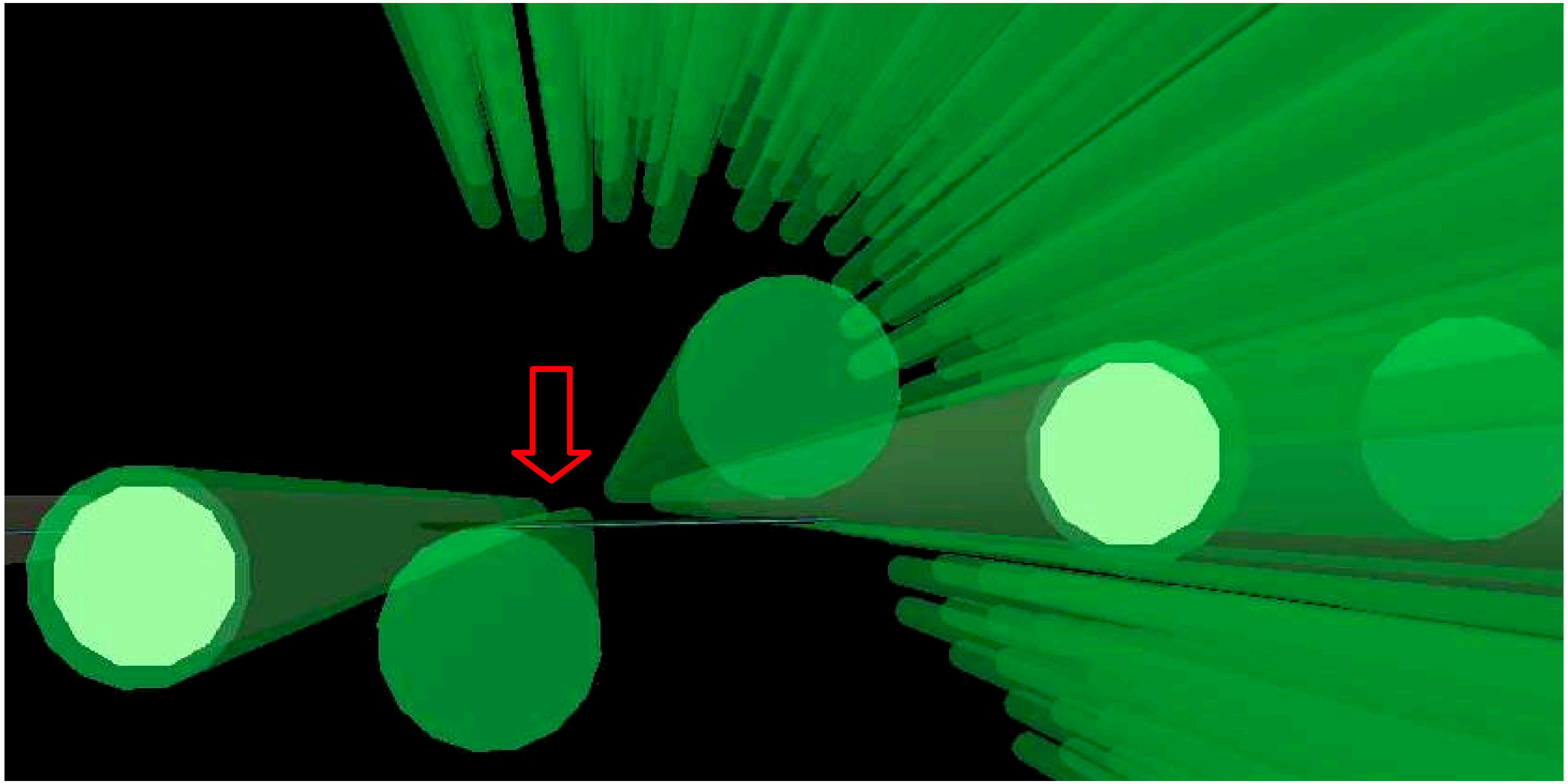
```
Processing file: data_test.00138670.calibration_LTTPS.daq.RAW._lb0000._EB_RCD._0001.data
End of file reached.
Processing file: data_test.00138670.calibration_LTTPS.daq.RAW._lb0000._EB_RCD._0002.data
End of file reached.
Processing file: data_test.00138670.calibration_LTTPS.daq.RAW._lb0000._EB_RCD._0003.data
End of file reached.
Processing file: data_test.00138670.calibration_LTTPS.daq.RAW._lb0000._EB_RCD._0004.data
```

[ATL-INDET-INT-2008-002]

TRT Read-out


ROS
...
ROD
ROD
ROD
...
ROD PP
DTMROC
DTMROC
DTMROC
...
ASDBLR
ASDBLR
8 Straws
8 Straws
Back End
Front End

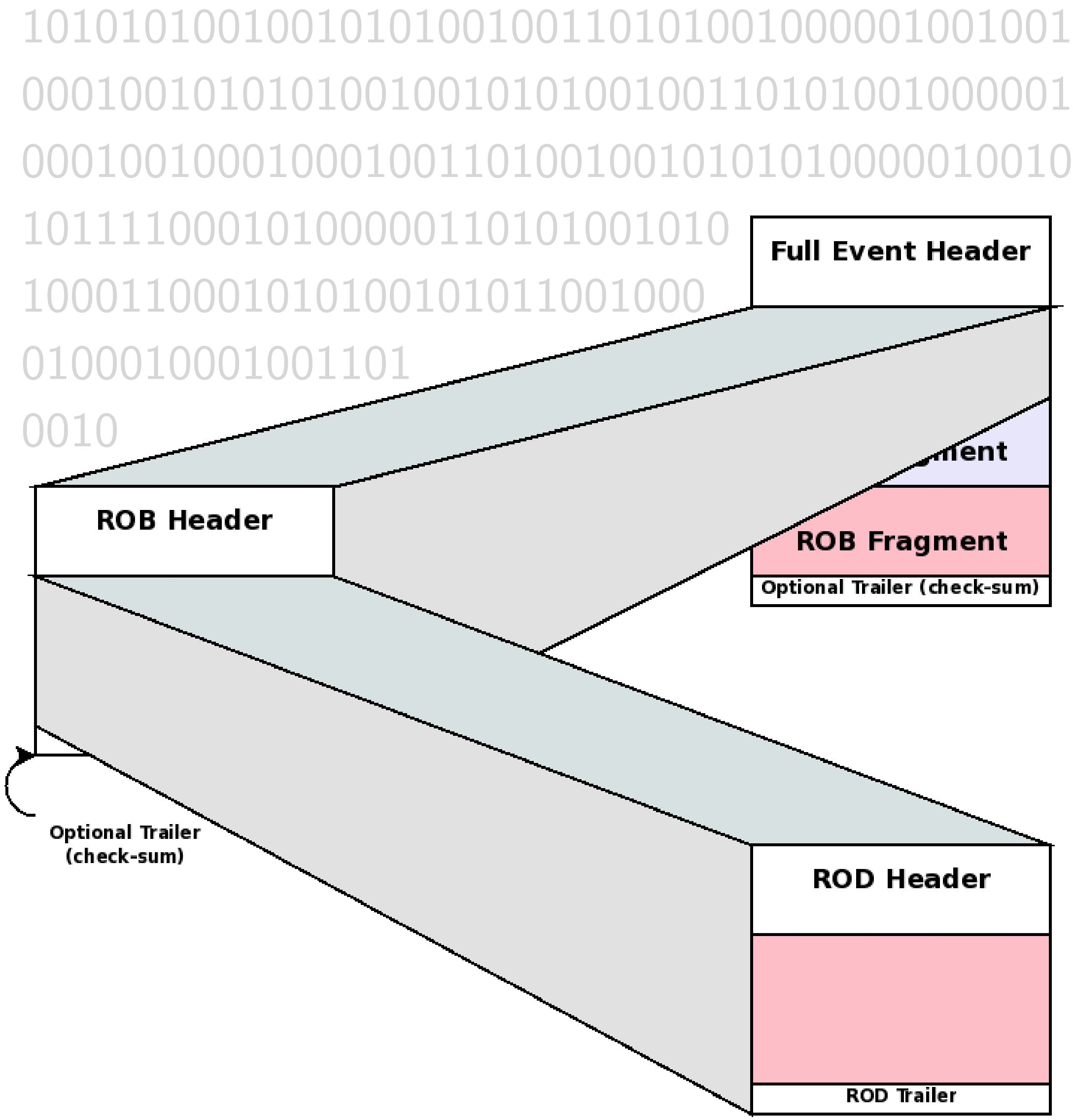
TRT hit efficiency



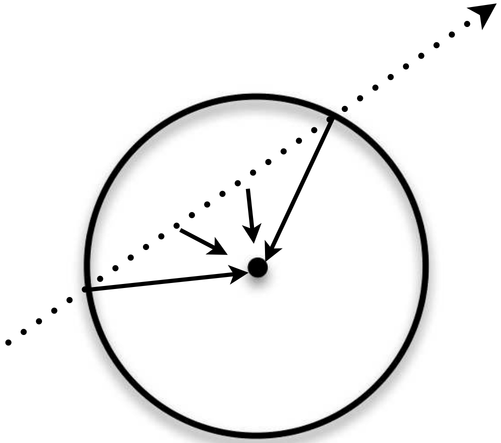
Parsing ATLAS raw data

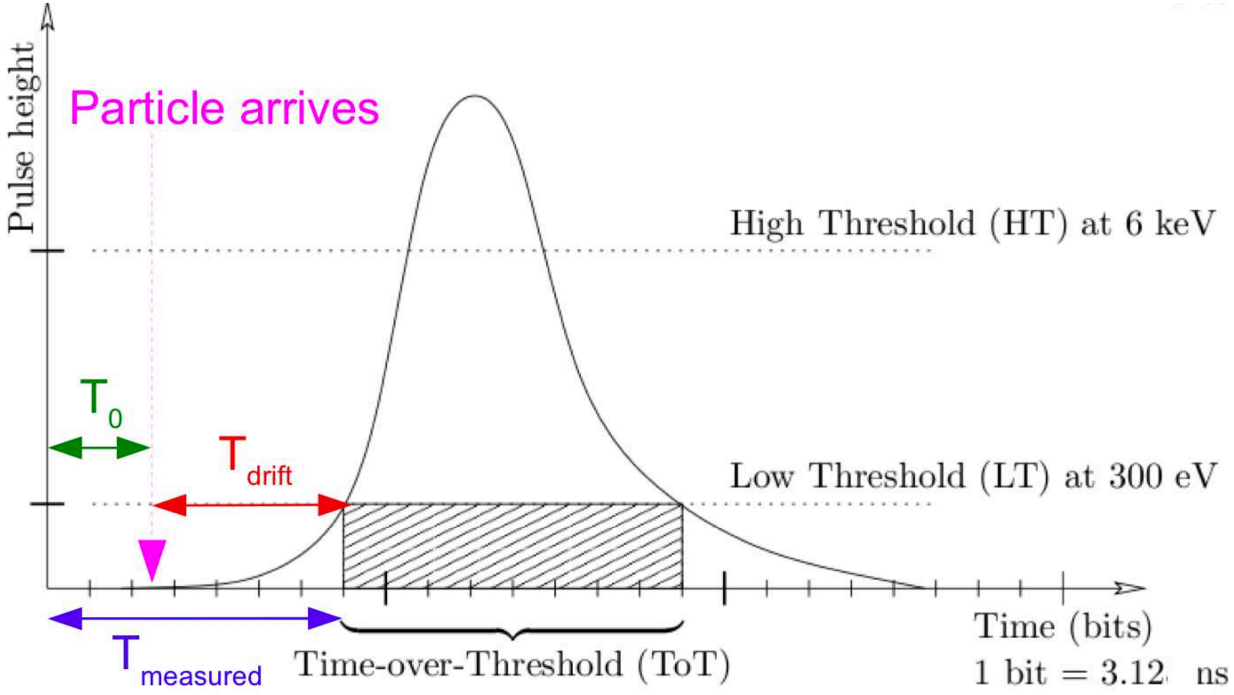
2007

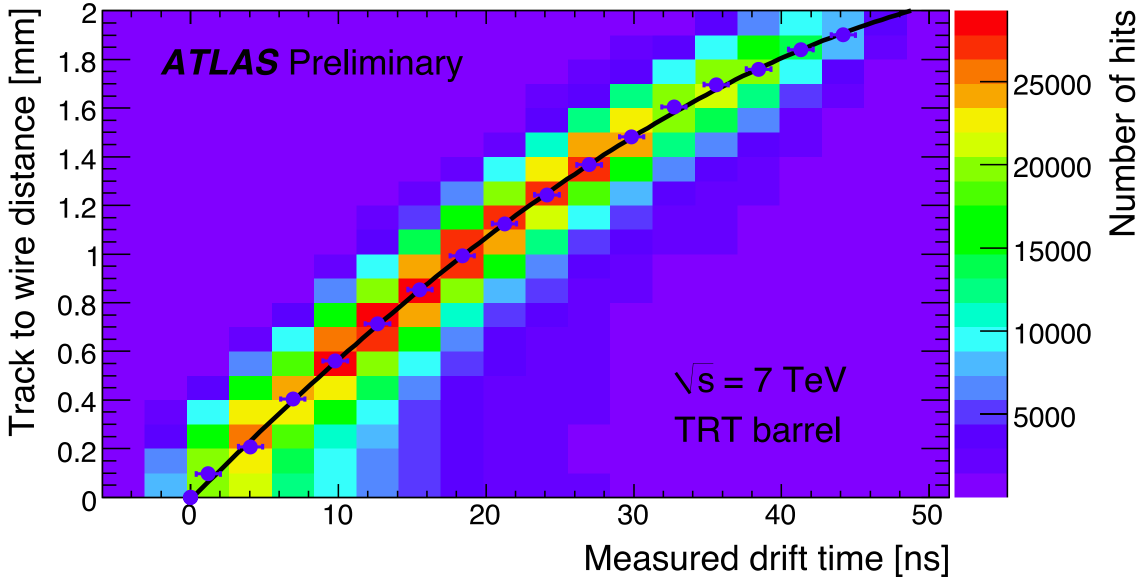
- Official libraries for parsing the ATLAS raw data were not finalized.
- Groups doing commissioning were still writing their own tools.
- My first software project was to write a library for parsing the ATLAS raw data for TRT commissioning purposes.
- Later, I used it to parse TRT threshold scans.



TRT Straw Hits



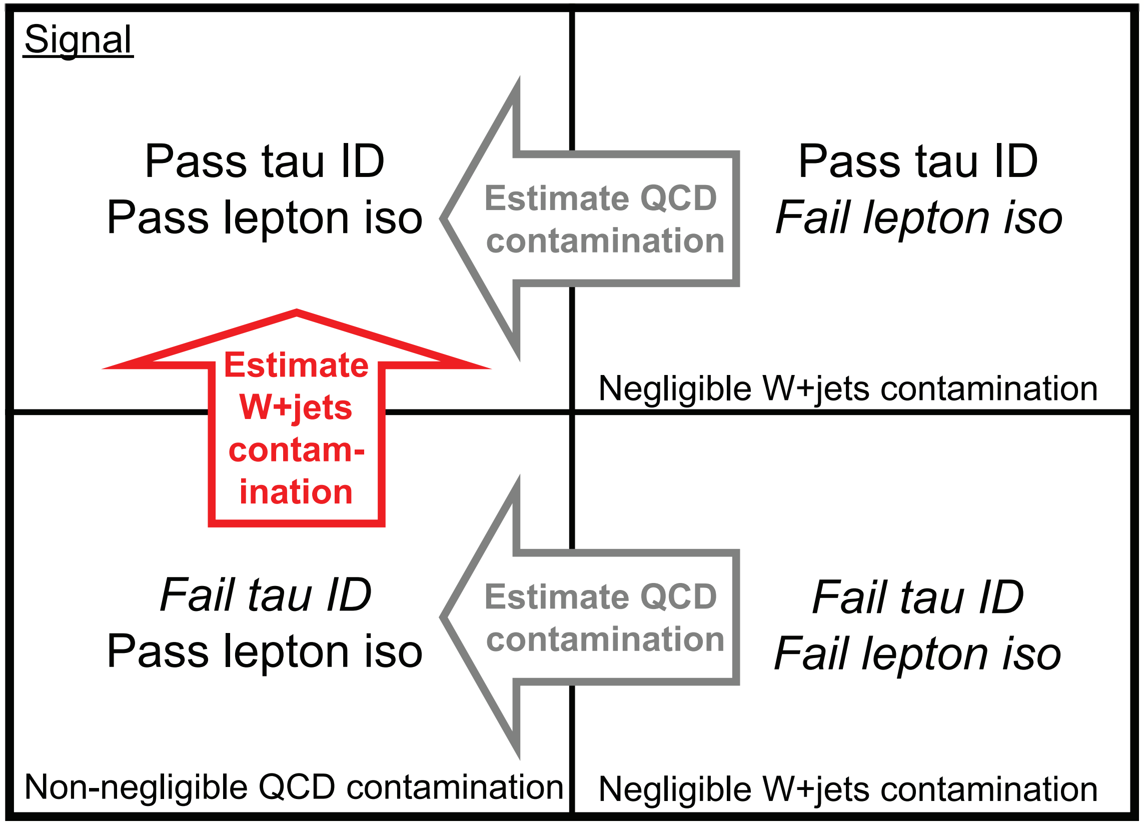




$Z' \rightarrow \tau\tau$

Double fake factor procedure

'11-'12



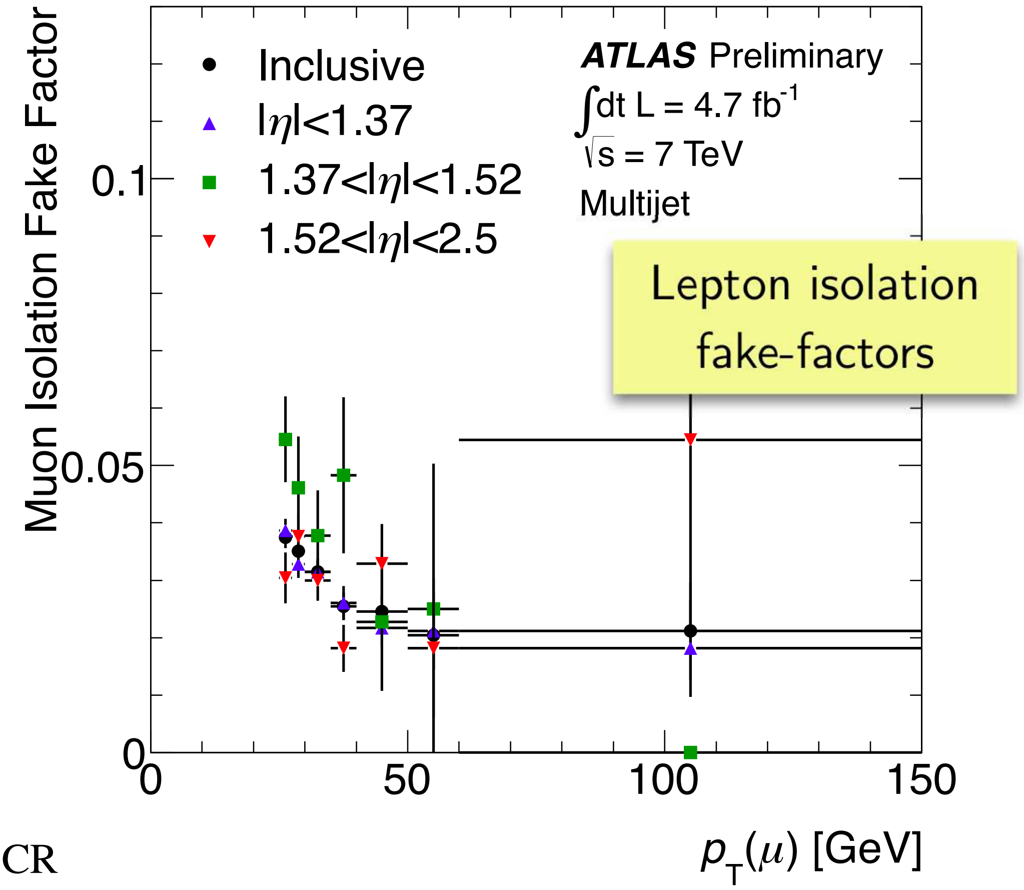
- The multijet contamination is estimated from the rate of non-isolated leptons, in both the signal region that passes tau ID, and the sample that fails.
- Then, the corrected number of tau candidates failing ID are weighted to predicted the W+jet background.
- This way, *the corrections are small at each step*.

Multijet background estimation

'11-'12

Multijet control region

- no isolation
- $E_{\mathrm{T}}^{\mathrm{miss}} < 30$ GeV
- $m_{\mathrm{T}}(\mu,\, E_{\mathrm{T}}^{\mathrm{miss}}) < 30$ GeV



Lepton isolation fake-factors

- In the control region, divide leptons into pass and fail isolation.
- Define fake factor:

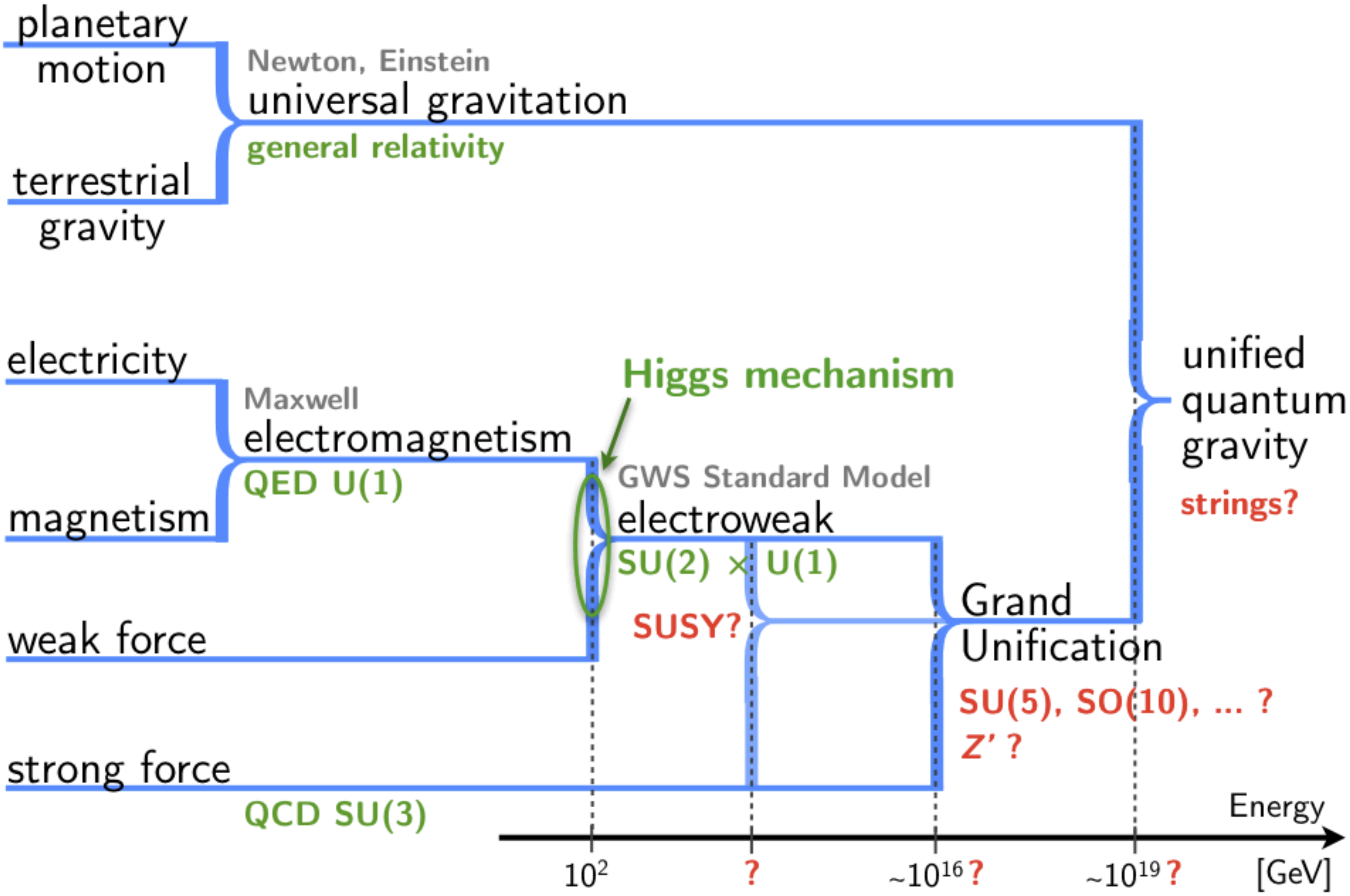
$$f_{\mu\text{–iso}}(p_{\mathrm{T}}, \eta) \equiv \left.\frac{N^{\text{pass } \mu\text{–iso}}(p_{\mathrm{T}}, \eta)}{N^{\text{fail } \mu\text{–iso}}(p_{\mathrm{T}}, \eta)}\right|_{\text{multijet–CR}}$$

- Predict the number of multijet events:

$$N_{\text{multijet}}(p_{\mathrm{T}}, \eta, x) = f_{\mu\text{–iso}}(p_{\mathrm{T}}, \eta) \cdot N^{\text{fail } \mu\text{–iso}}_{\text{multijet}}(p_{\mathrm{T}}, \eta, x)$$

$$= f_{\mu\text{–iso}}(p_{\mathrm{T}}, \eta) \cdot \left(N^{\text{fail } \mu\text{–iso}}_{\text{data}}(p_{\mathrm{T}}, \eta, x) - N^{\text{fail } \mu\text{–iso}}_{\text{MC}}(p_{\mathrm{T}}, \eta, x)\right)$$

Unification



Event summary

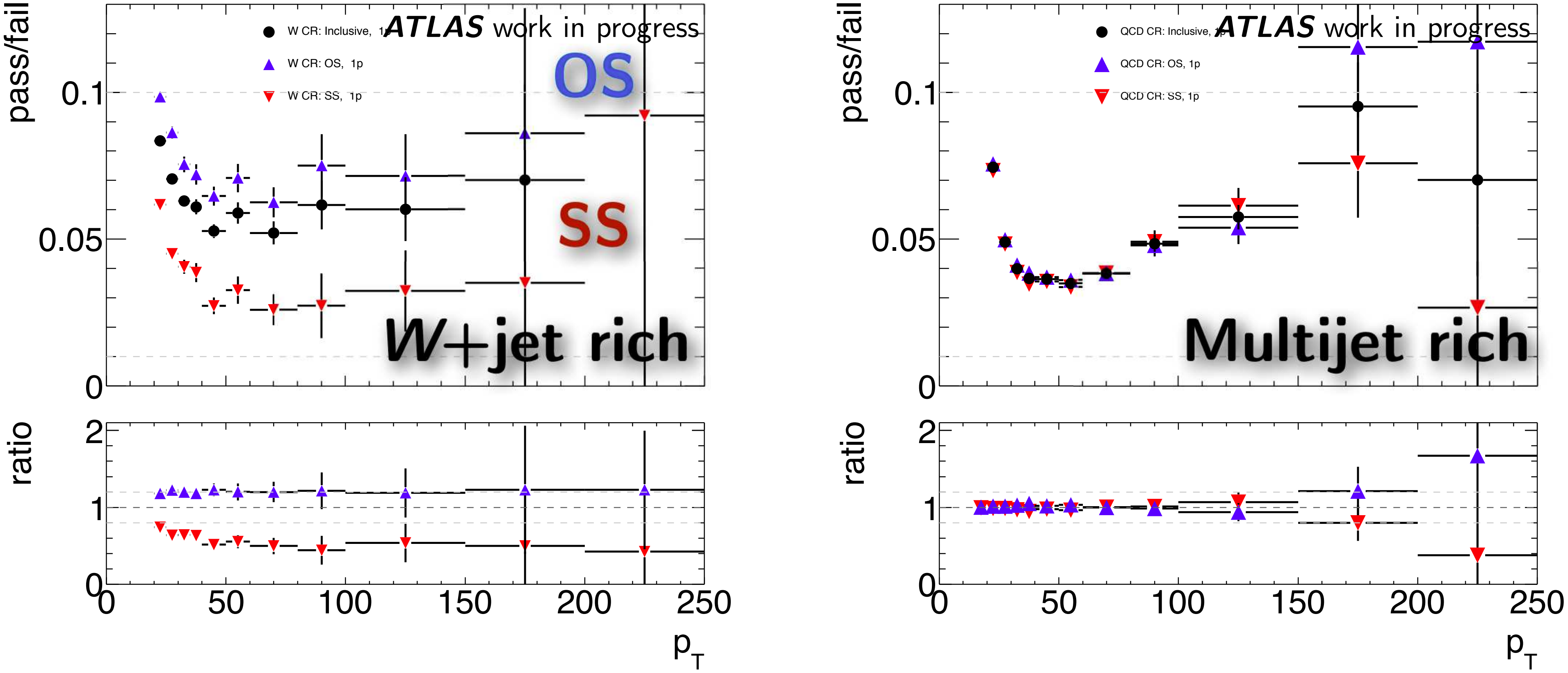
	$\tau_{\rm had}\tau_{\rm had}$	$\tau_\mu\tau_{\rm had}$	$\tau_e\tau_{\rm had}$	$\tau_e\tau_\mu$
$m_{Z'}$ [GeV]	1250	1000	1000	750
$m_{\rm T}^{\rm tot}$ threshold [GeV]	700	600	500	350
$Z/\gamma^* \to \tau\tau$	0.73±0.23	0.36±0.06	0.57±0.11	0.55±0.07
W+jets	< 0.03	0.28±0.22	0.8 ±0.4	0.33±0.10
$Z(\to \ell\ell)$+jets	< 0.01	< 0.1	< 0.01	0.06±0.02
$t\bar{t}$	< 0.02	0.33±0.15	0.13±0.09	0.97±0.22
Diboson	< 0.01	0.23±0.07	0.06±0.03	1.69±0.24
Single top	< 0.01	0.19±0.18	< 0.1	< 0.1
Multijet	0.24±0.15	< 0.01	< 0.1	< 0.01
Total expected background	0.97±0.27	1.4 ±0.4	1.6 ±0.5	3.6 ±0.4
Events observed	2	1	0	5
Expected signal events	6.3 ±1.1	5.5 ±0.7	5.0 ±0.5	6.72±0.26
Signal efficiency (%)	4.3	1.1	1.0	0.4

Systematics

Uncertainty [%]	Signal				Background			
	hh	μh	eh	$e\mu$	hh	μh	eh	$e\mu$
Stat. uncertainty	1	2	2	3	5	20	23	7
Eff. and fake rate	16	10	8	1	12	16	4	3
Energy scale and res.	5	7	6	2	$^{+22}_{-11}$	3	8	5
Theory cross section	8	6	6	5	9	4	4	5
Luminosity	4	4	4	4	2	2	2	4
Data-driven methods	–	–	–	–	$^{+21}_{-11}$	6	16	–

Table 2: Uncertainties on the estimated signal and total background contributions in percent for each channel. The following signal masses, chosen to be close to the region where the limits are set, are used: 1250 GeV for $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ (hh); 1000 GeV for $\tau_{\mu}\tau_{\mathrm{had}}$ (μh) and $\tau_{e}\tau_{\mathrm{had}}$ (eh); and 750 GeV for $\tau_{e}\tau_{\mu}$ ($e\mu$). A dash denotes that the uncertainty is not applicable. The statistical uncertainty corresponds to the uncertainty due to limited sample size in the MC and control regions.

Observed variance in fake-rates



(BDTMedium)

- Hypothesis: quarks vs gluons
- Divide the issue into two questions:

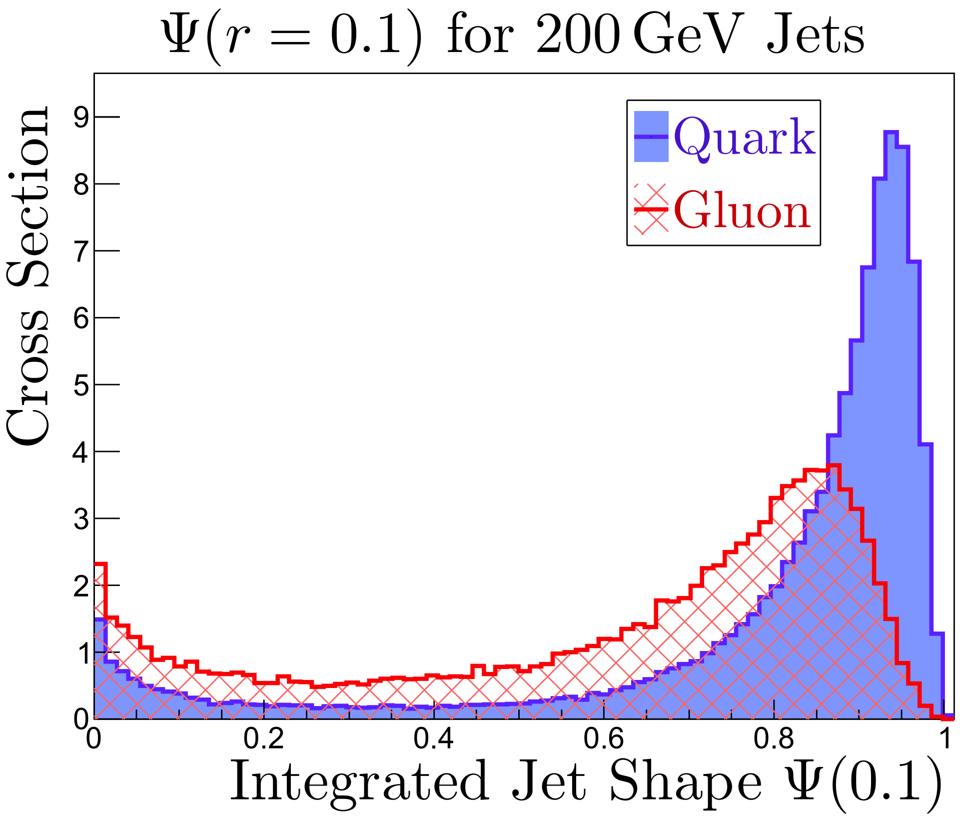
  1. *Why do quarks and gluons have different tau fake-rates?*

  2. *How does the quark/gluon fraction vary among samples?*

Jet width for quark/gluons

Why do quarks and gluons have different tau fake-rates?

- $\Psi(r)$ = fraction of jet energy within $\Delta R < r$.
- Quark jets are more narrow than gluon jets of the same energy.
- Tau identification prefers narrow candidates.



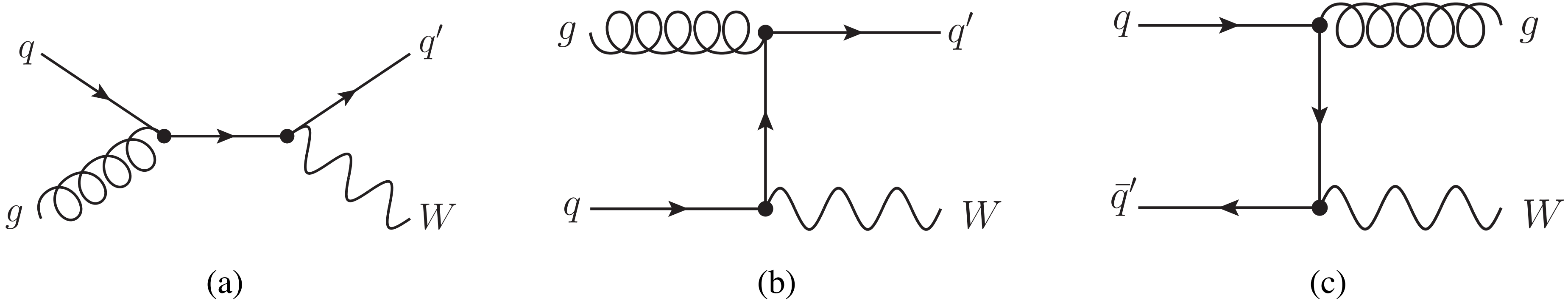
- This is consistent with samples of quark-enriched jets, like W+jet, having higher fake-rates.

J. Gallicchio, M. Schwartz. “Quark and Gluon Tagging at the LHC”. arXiv:1106.3076.

OS vs SS *W*+jet

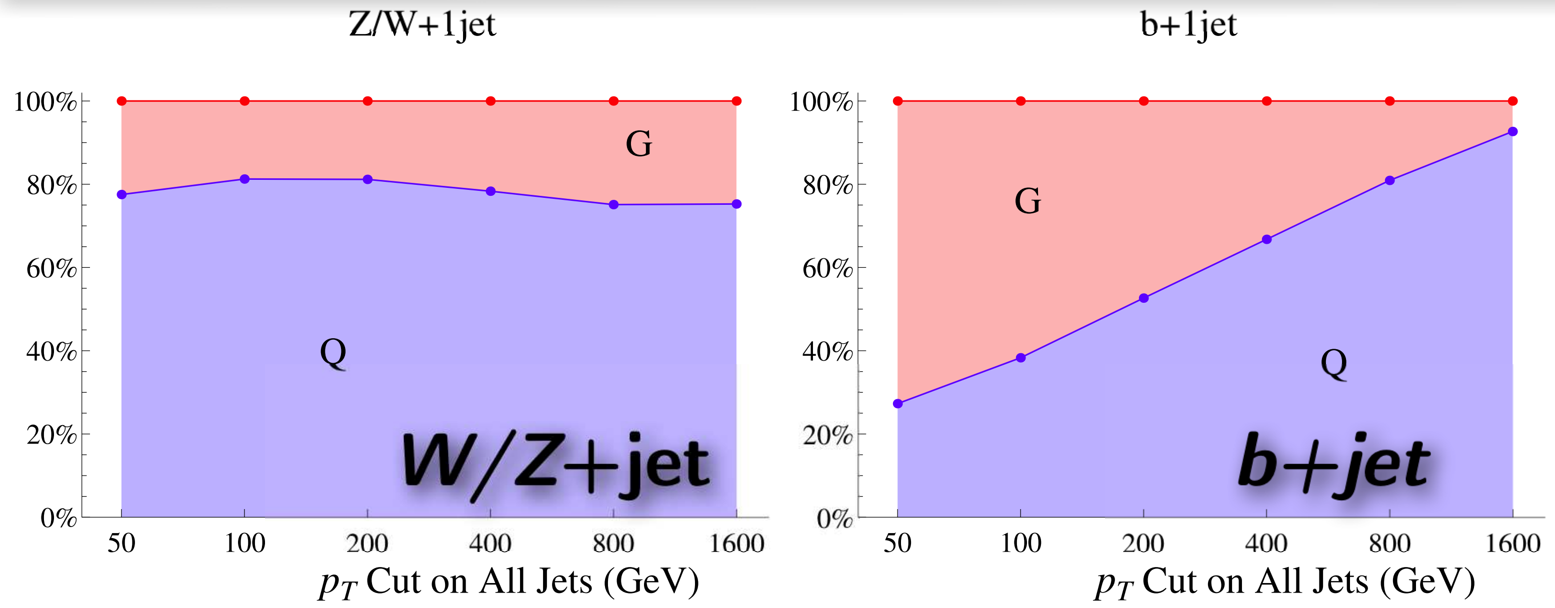
How does the quark/gluon fraction vary among samples?

Leading order *W*+jet production:

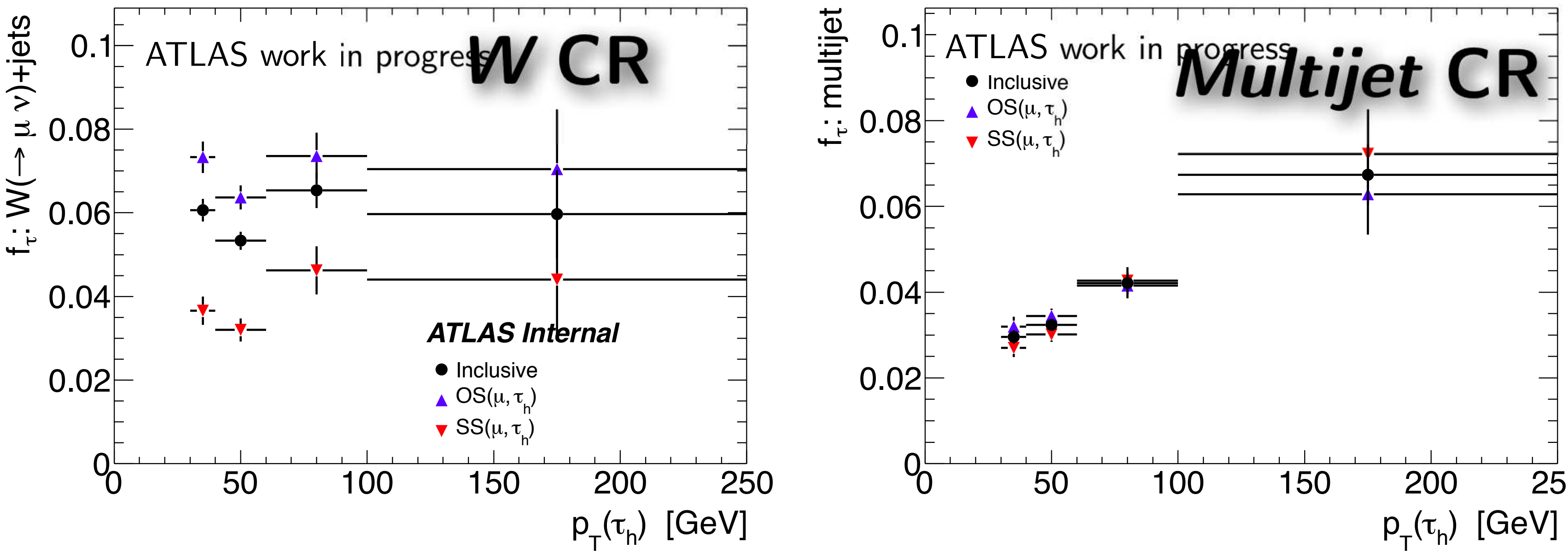


- The charge of the quark should correlate with the reconstructed charge of the tau candidate, therefore (a) and (b) preferably produce opposite sign W+jet events.
- OS and SS will have different quark/gluon fractions.

Fake factors more quark-like at high-p_T

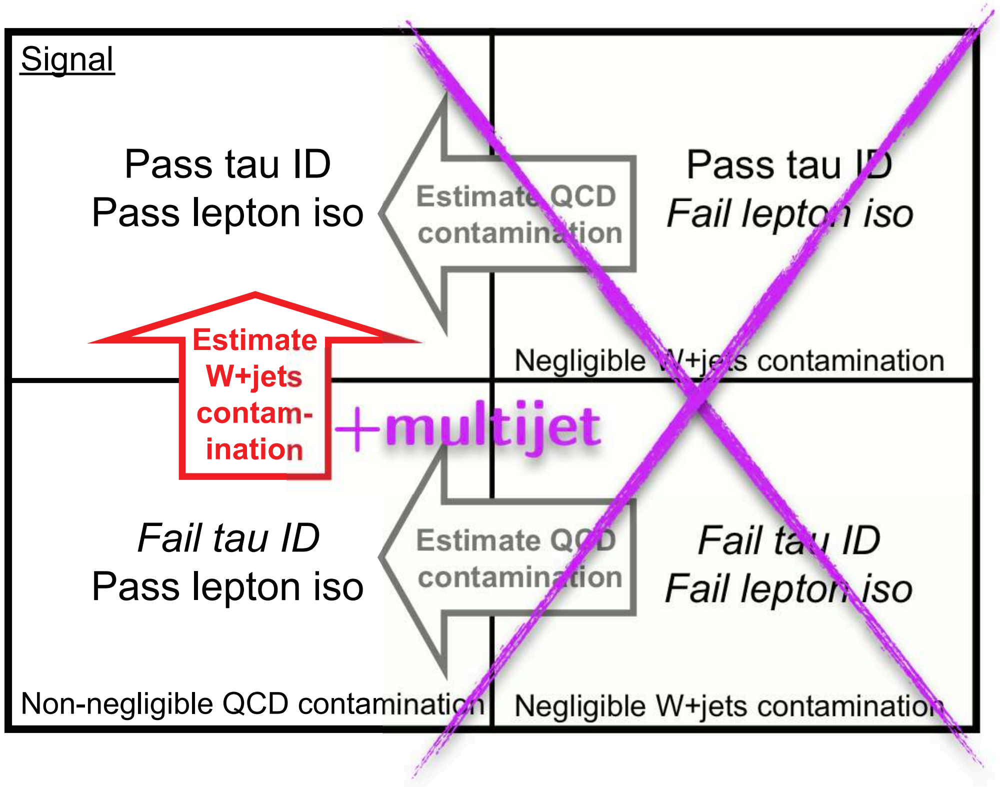


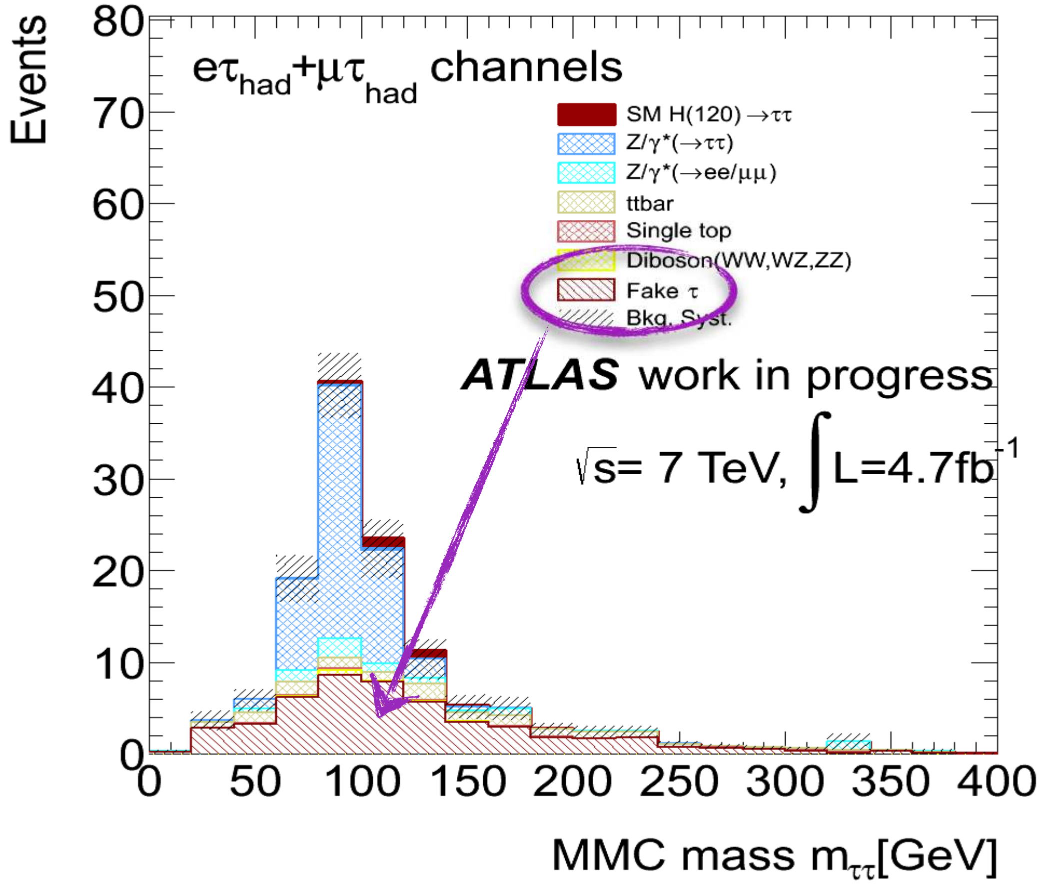
J. Gallicchio, M. Schwartz. “Pure Samples of Quark and Gluon Jets at the LHC”. arXiv:1104.1175



our support note: ATLAS-CONF-2012-067

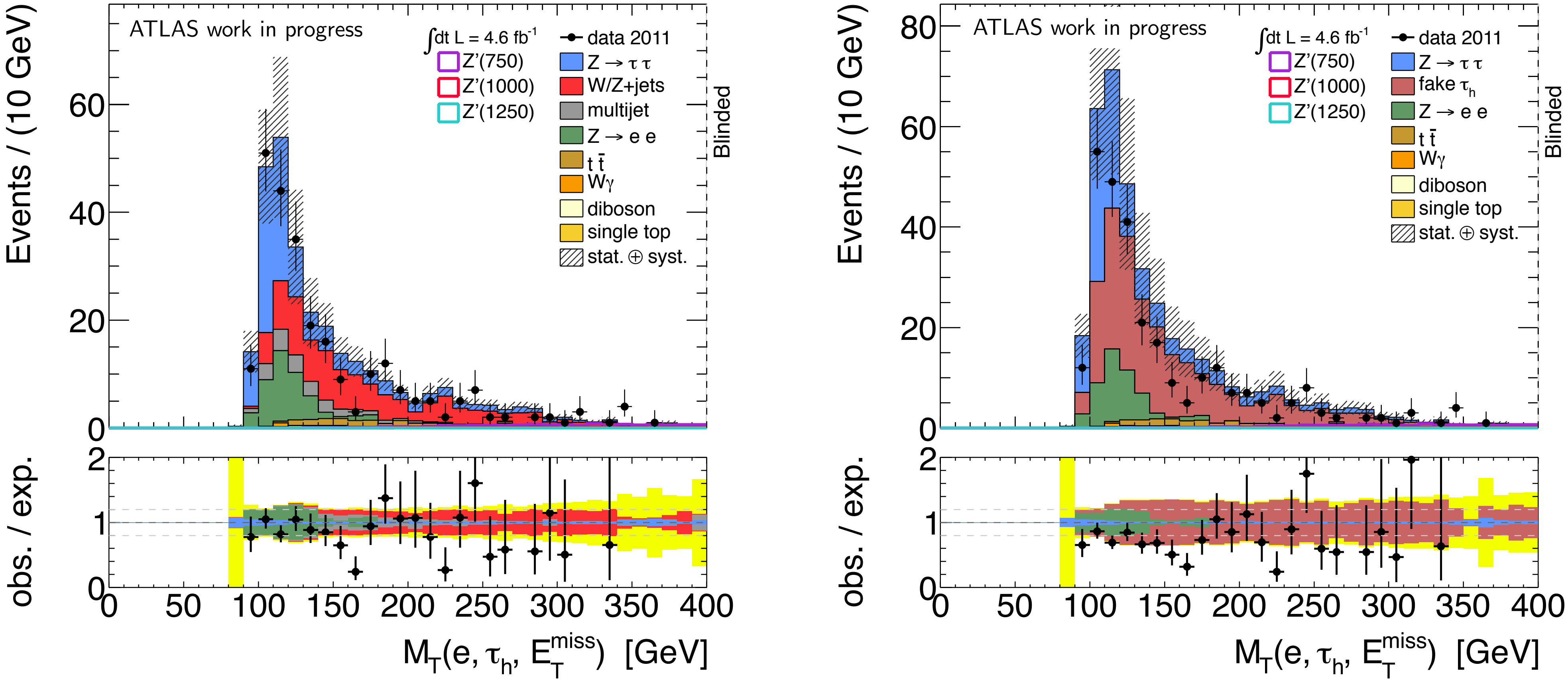
Cross-check: single fake factor method





- Avoid issues of subtracting multijet from W/Z+jets background
- $H\rightarrow\tau\tau$ uses a fake factor method covering all tau fakes from W/Z+jets *and* multijet
- instead of estimating multijet independently with isolation fake factors

Cross-check: single fake factor method



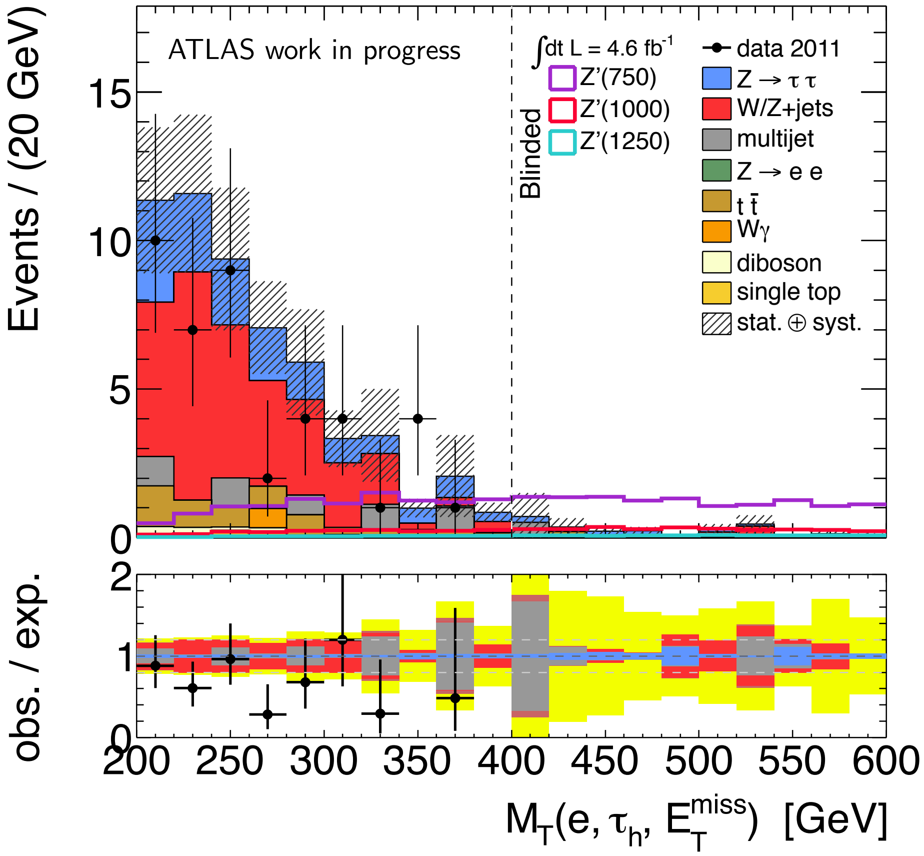
double fake factor

single fake factor

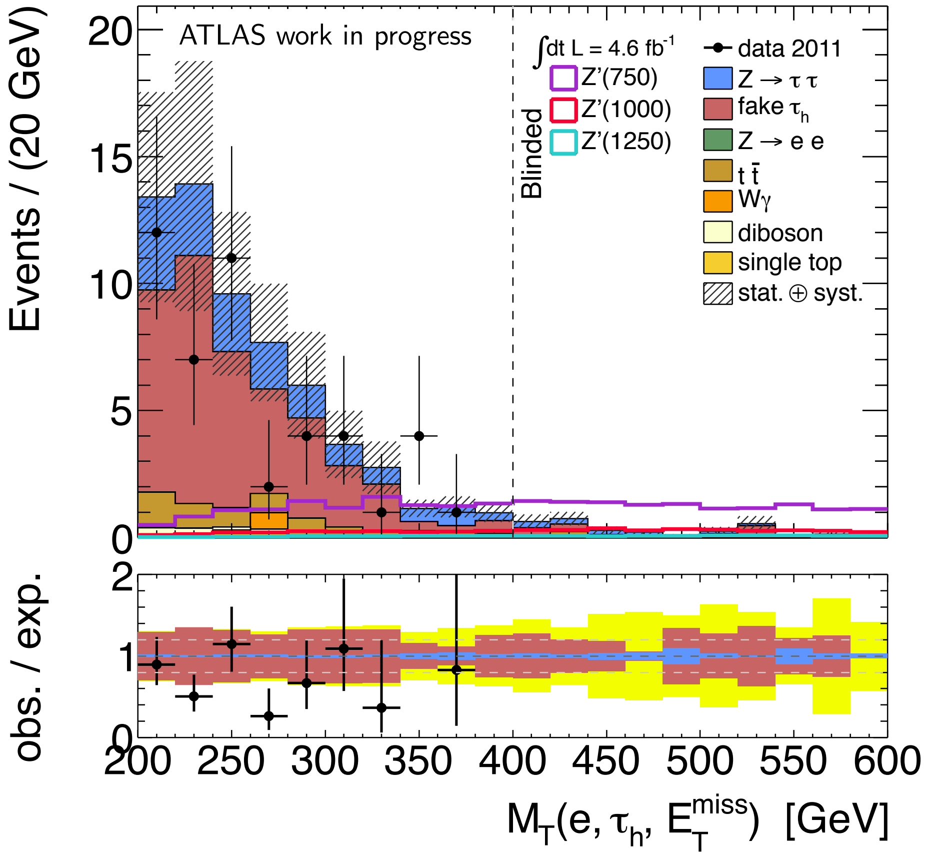
- as expected, the single fake factor method over-estimates in regions where the multijet contamination is large

Cross-check: single fake factor method

double fake factor



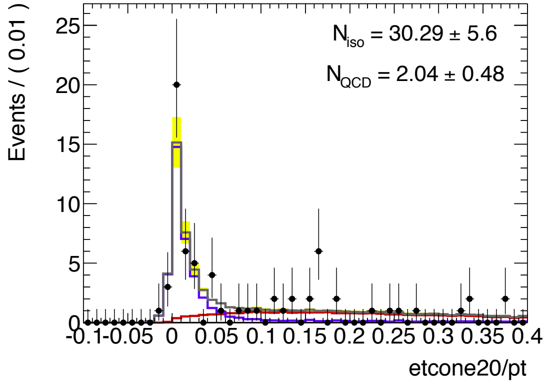
single fake factor



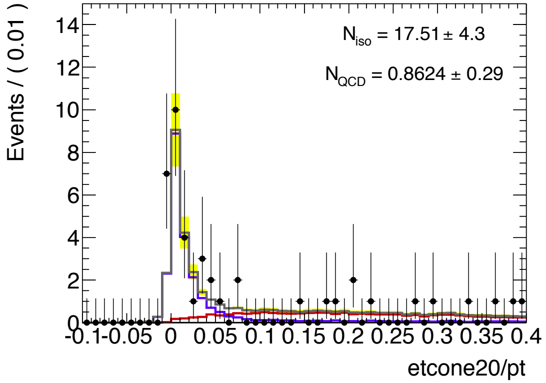
	double fake factor			single fake factor
	W/Z+jets	multijet	total	fake τ_{h}
$M_{\mathrm{T}} > 400$ GeV	0.8(6)	0.3(3)	1.1(4)	1.3(4)
$M_{\mathrm{T}} > 500$ GeV	0.8(4)	< 0.1	0.8(4)	0.9(4)

Lepton isolation fitting

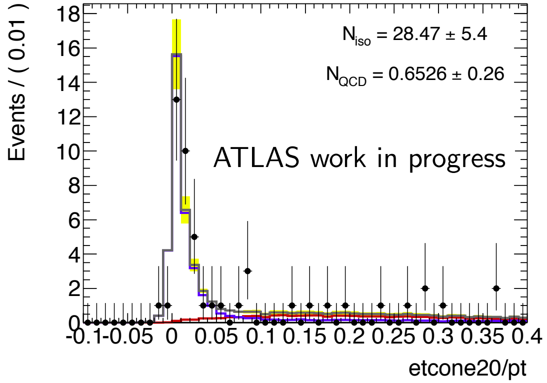
- Used to cross-check the fake-factor QCD estimate.
- Similar in concept: predict normalization from the rate of non-isolated leptons.
- Fit calorimeter isolation with data-driven templates from QCD and W+jet control regions. Do fits separately in 6 p_T bins:



p_T = 25-27.5 GeV



p_T = 27.5-30 GeV

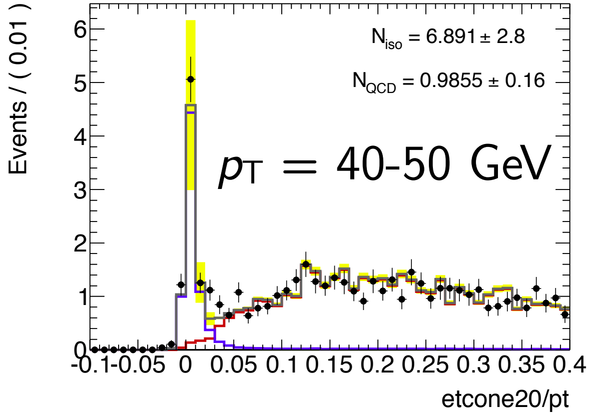


p_T = 30-35 GeV

Agrees with the lepton isolation fake-factor method:

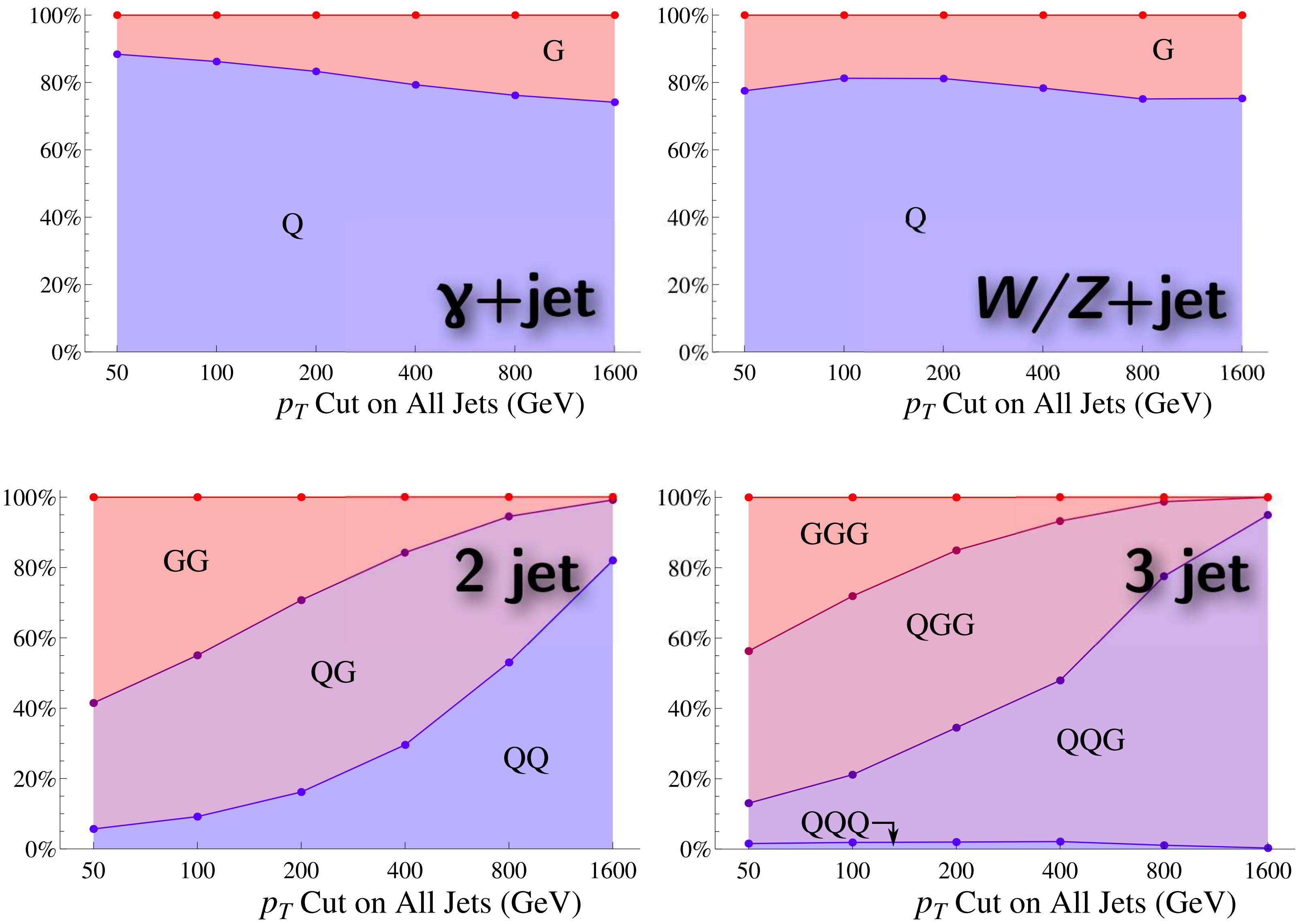
	fake-factor	fitting
baseline	6.3(6)	4.3(4)
$p_T(\tau_h) > 80$ GeV	2.7(3)	1.8(2)
$p_T(\mu) > 40$ GeV	0.29(8)	0.31(8)
$m_{eff}(\mu, \tau_h, E_T^{miss}) > 400$ GeV	0.05(3)	0.05(3)

Fits work in failing tau ID region as well:



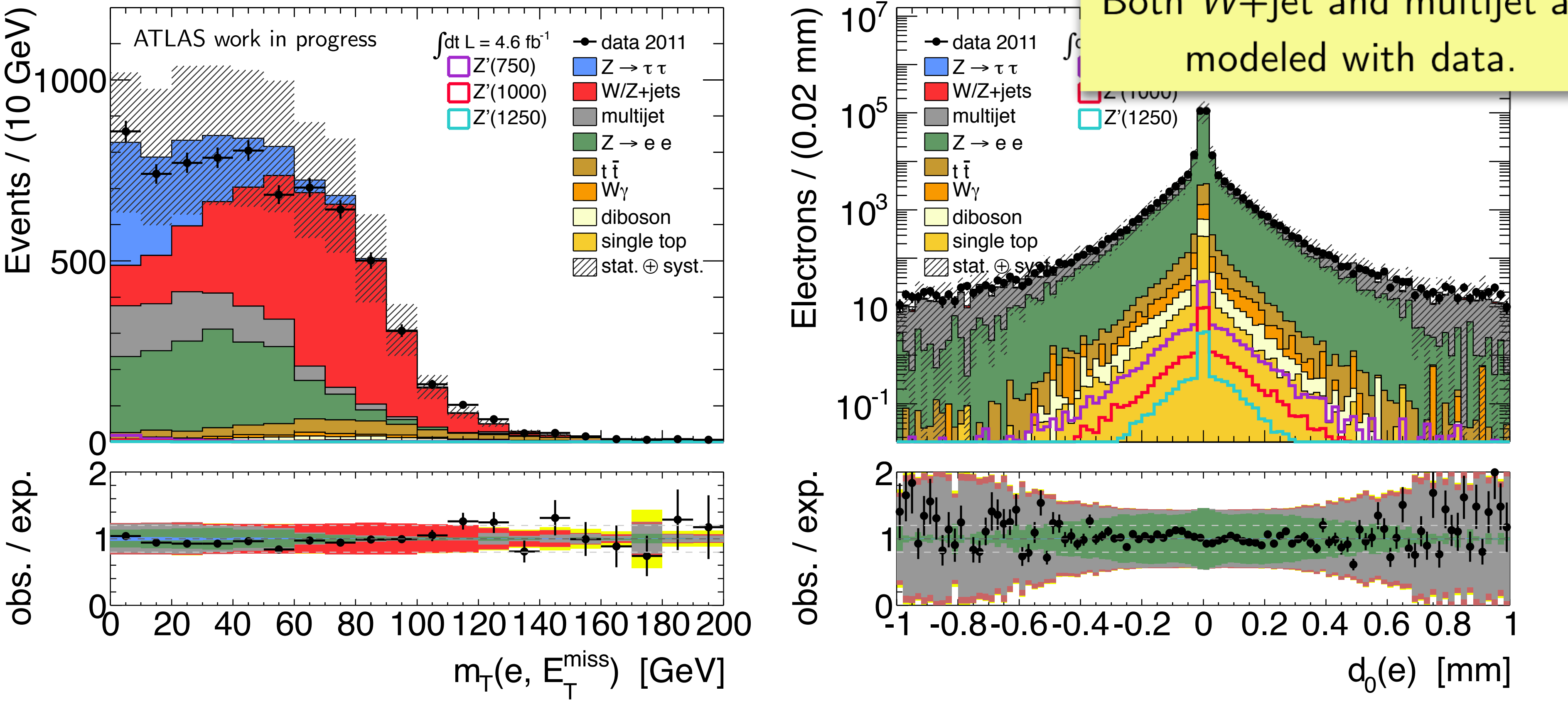
p_T = 40-50 GeV

Madgraph predicted Quark/Gluon



J. Gallicchio, M. Schwartz. “Pure Samples of Quark and Gluon Jets at the LHC”. arXiv:1104.1175

Control plots



Both *W*+jet and multijet are modeled with data.

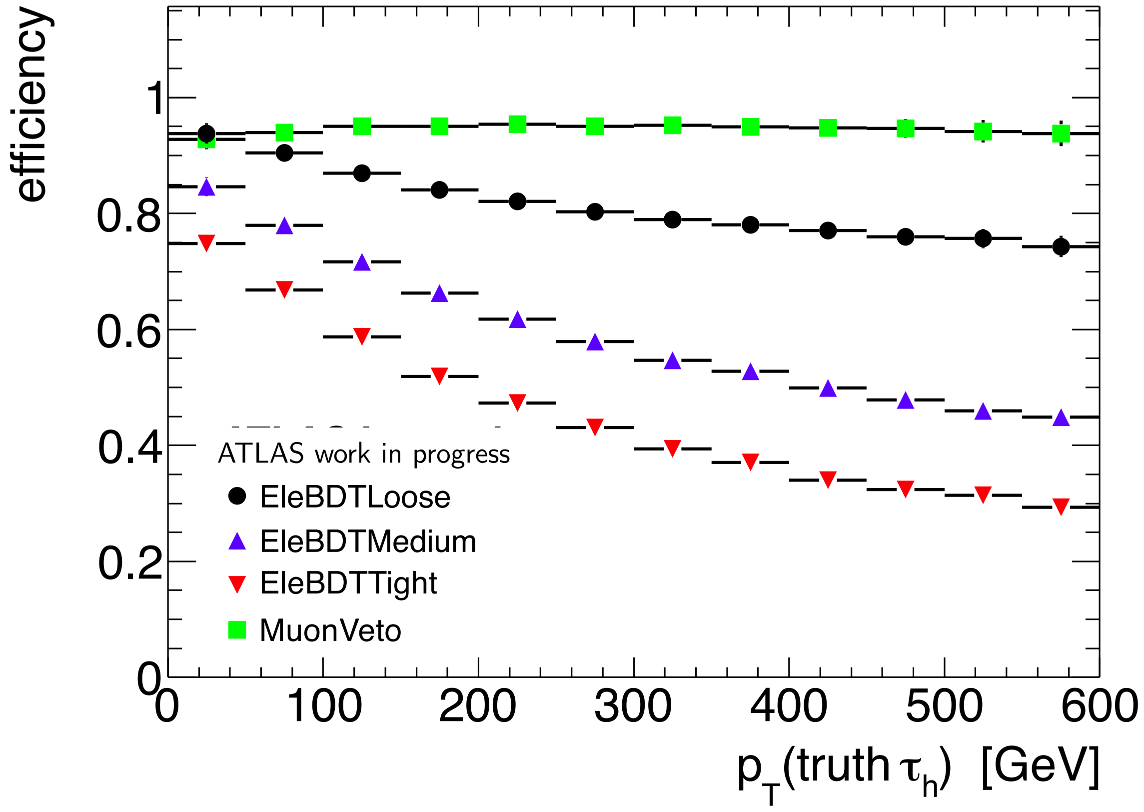
Figure 28: (left) The distribution of the transverse mass of the combination of the selected electron and the $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}}(e, E_{\mathrm{T}}^{\mathrm{miss}})$. in events with exactly one selected electron, no additional preselected electrons or muons, and exactly one selected 1-prong tau. (right) The distribution of the electron impact parameter, d_0, in events with exactly one selected electron, no additional preselected electrons or muons, and exactly one 1-prong tau candidate (without ID).

Electron veto

from tau WG $Z \to ee$ tag-and-probe with 2.6/fb from 2011

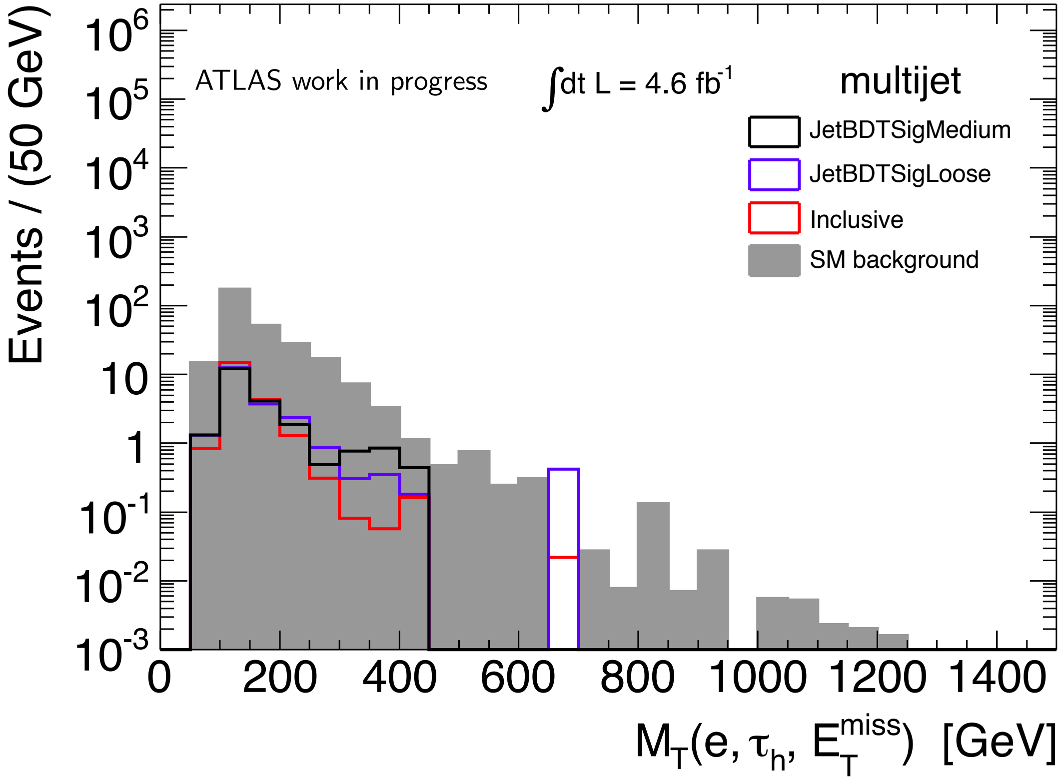
	$\vert\eta\vert < 1.37$	$1.37 < \vert\eta\vert < 1.52$	$1.52 < \vert\eta\vert < 2.0$	$2.0 < \vert\eta\vert$
BDT medium e-veto	1.64(0.81)	1.0(1.0)	0.71(0.63)	2.90(1.42)
BDT loose e-veto	1.21(0.30)	0.96(0.46)	0.59(0.21)	1.76(0.55)

- above are the scale factors and errors for the EleBDTMedium e-veto
- These SF have huge ≈100% uncertainties, and we've also previously shown that this veto is inefficient at high p_T.

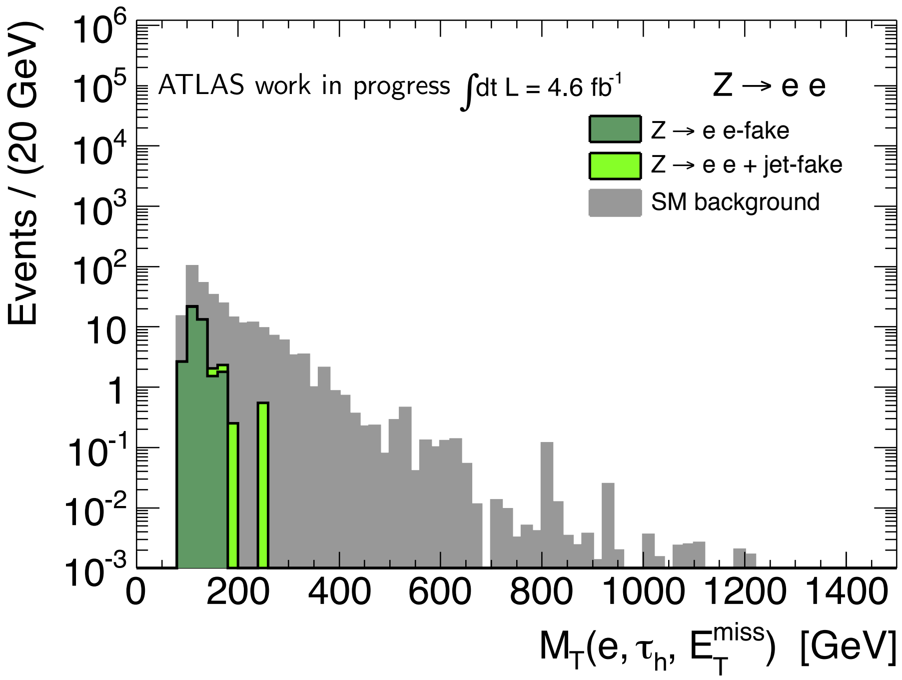


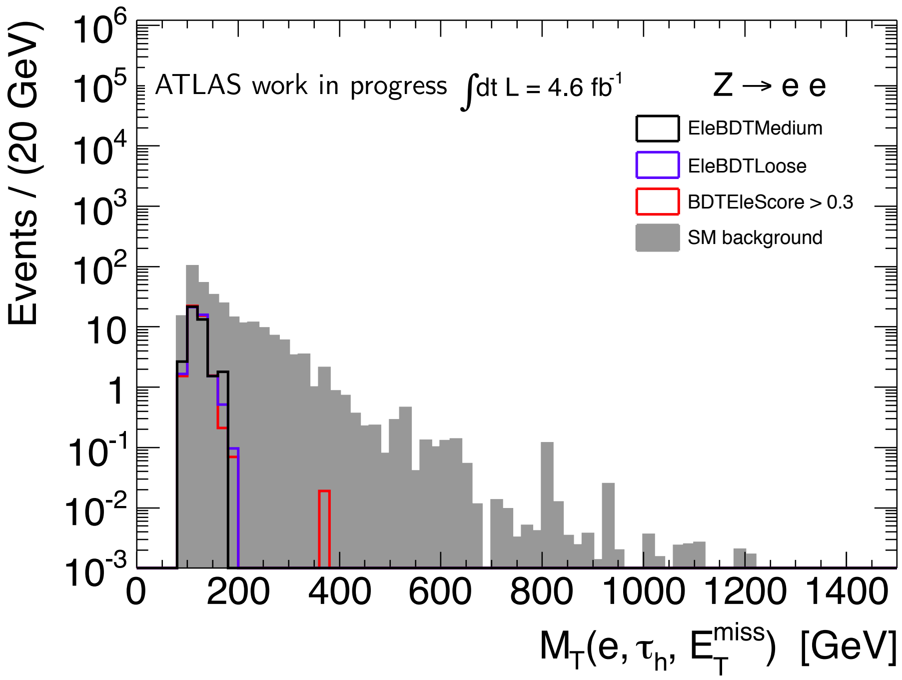
Multijets background

- Loosened tau ID requirement in the anti-isolated lepton + tau data sample used to model the multijet background.
- Sample with tau ID is already multijet dominated. Loosening tau ID improves stats.
- Shapes are statistically consistent. Inclusive shape scaled to the prediction with medium tau ID to give the estimate in the tail.



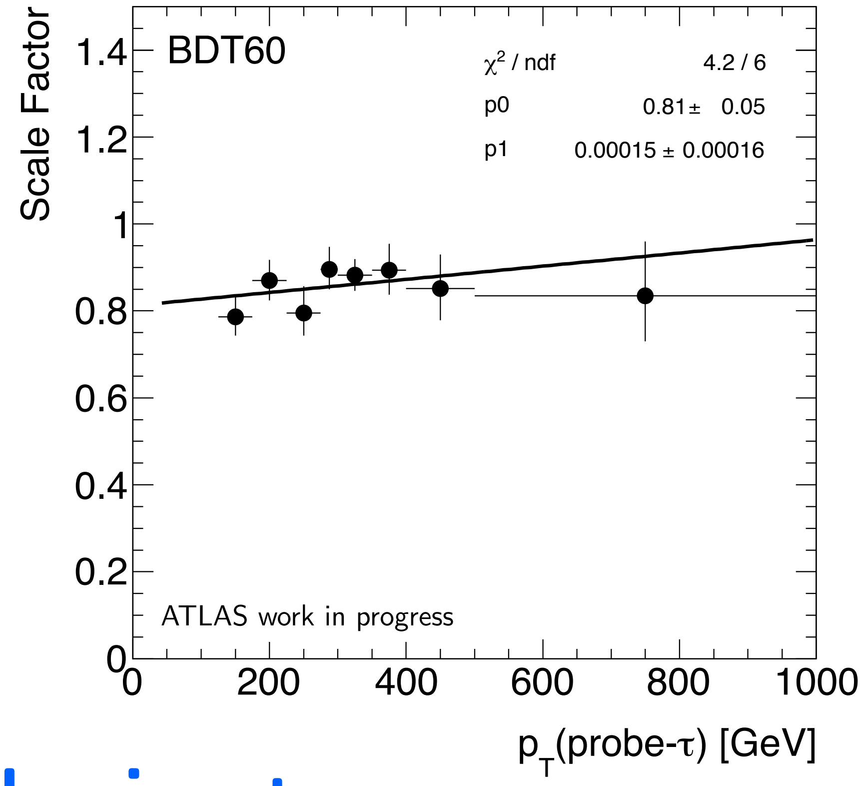
$Z \to ee$ + jets background





- Categorize Monte Carlo events by electron or jet faking tau.
- Loosen electron veto in Monte Carlo sample matched to electron fakes.
- Shapes are consistent, and only driven by the $Z \to ee$ kinematics.
- $Z \to ee$ with e-faking tau is negligible
- $Z \to ee$ + jet-fake covered with the data-driven W/Z+jet tau fake factor method.

High-p_T tau efficiency systematic



- The dominant systematic uncertainty for the Z' signal and the $Z \to \tau\tau$ background.
- Low p_T uncertainty of 4% taken from the Tau WG blessed $Z \to \tau\tau$ tag-and-probe.
- No high-p_T control sample of true taus.
- Assume mis-modeling comes from either:
  1. tau kinematics (TAUOLA)
  2. detector response to high-p_T pions **←dominant**
- Instead of using true taus, measure the trend in the scale factor for fakes from dijet events.

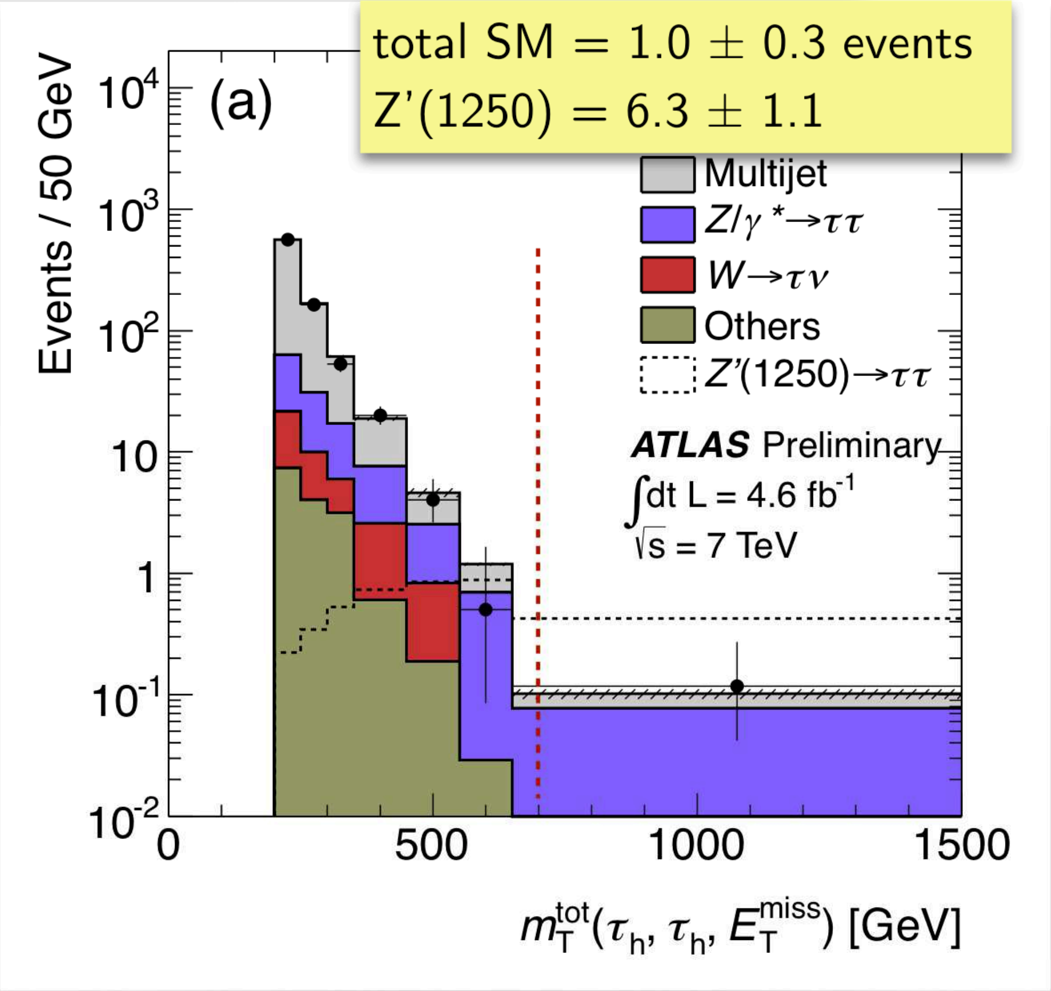
- $p_T \leq 100$ GeV: $\Delta\varepsilon = 4\%$ (taken from the $Z \to \tau\tau$ measurement)
- $p_T > 100$ GeV: $\Delta\varepsilon = 4 + 0.016(p_T - 100)\%$, with p_T in GeV (taken from the dijets measurement).

$Z' \to \tau\tau \to \tau_h\tau_h$

- New gauge bosons predicted in many GUTs with additional U(1).
- Best limit on $m(Z'\to ee/\mu\mu) > 2.3$ TeV from CMS [arxiv:1206.1849].
- Important to test the couplings to all lepton flavors.

Event selection

- 2 BDT loose 1 or 3-prong taus with $p_T(\tau_h) > 50$ GeV
- opposite sign
- $|\Delta\phi(e,\ \tau_h)| > 2.7$
- $m_T(\tau_h,\ \tau_h,\ E_T^{miss}) > 700$ GeV



total SM = 1.0 ± 0.3 events

Z'(1250) = 6.3 ± 1.1

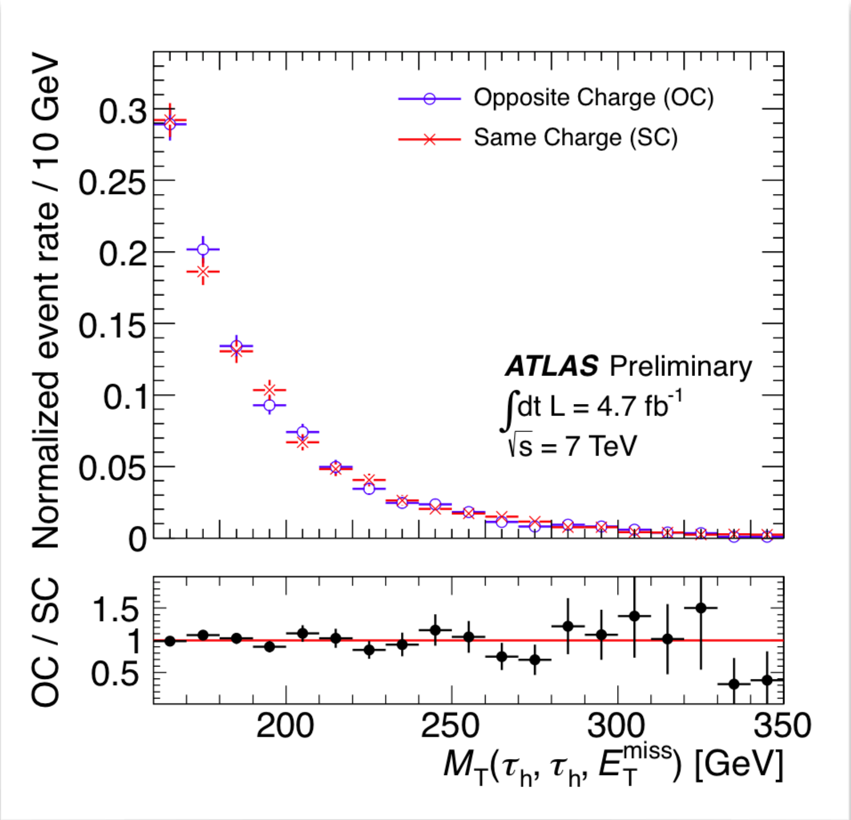
- Tau ID efficiency uncert. ≈ 11% on the signal. (4% from $Z \to \tau\tau$ tag-and-probe)
- Jet/tau energy scale uncert. ≈ +22/-11%
- Multijet modeled by fitting the shape of the SS data. uncert. ≈ +21/-11%

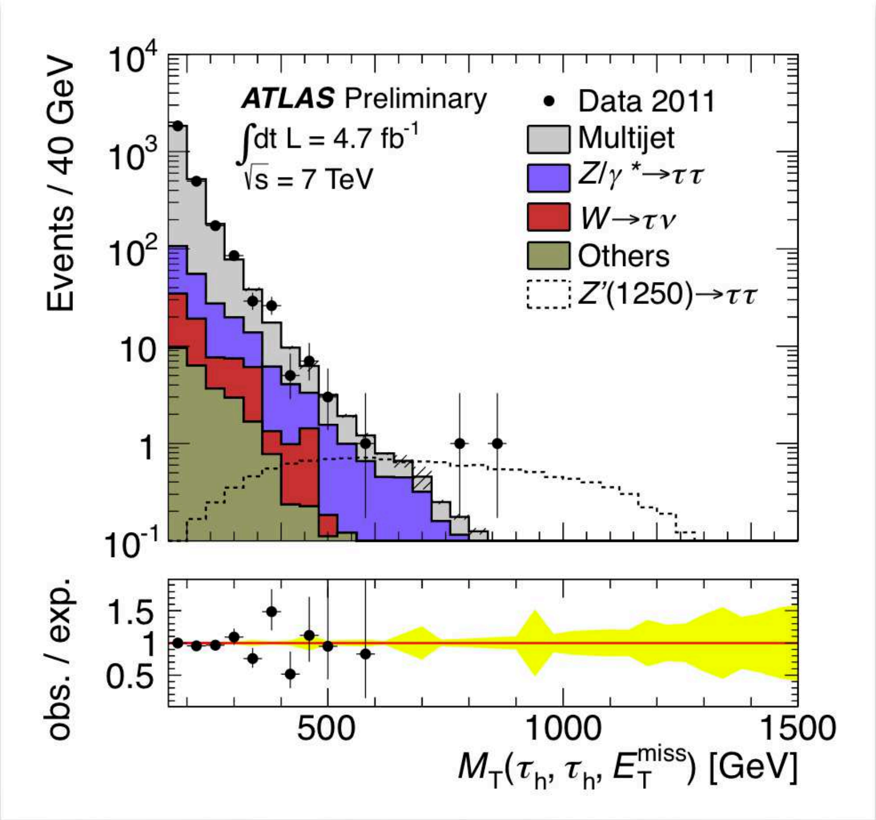
[ATLAS-CONF-2012-067]

Data-driven multijet

Fit same-sign (SS) data with dijet function:

$$f(M_\mathrm{T}|p_0,p_1,p_2) = p_0 \cdot M_\mathrm{T}{}^{p_1+p_2\log M_\mathrm{T}}.$$

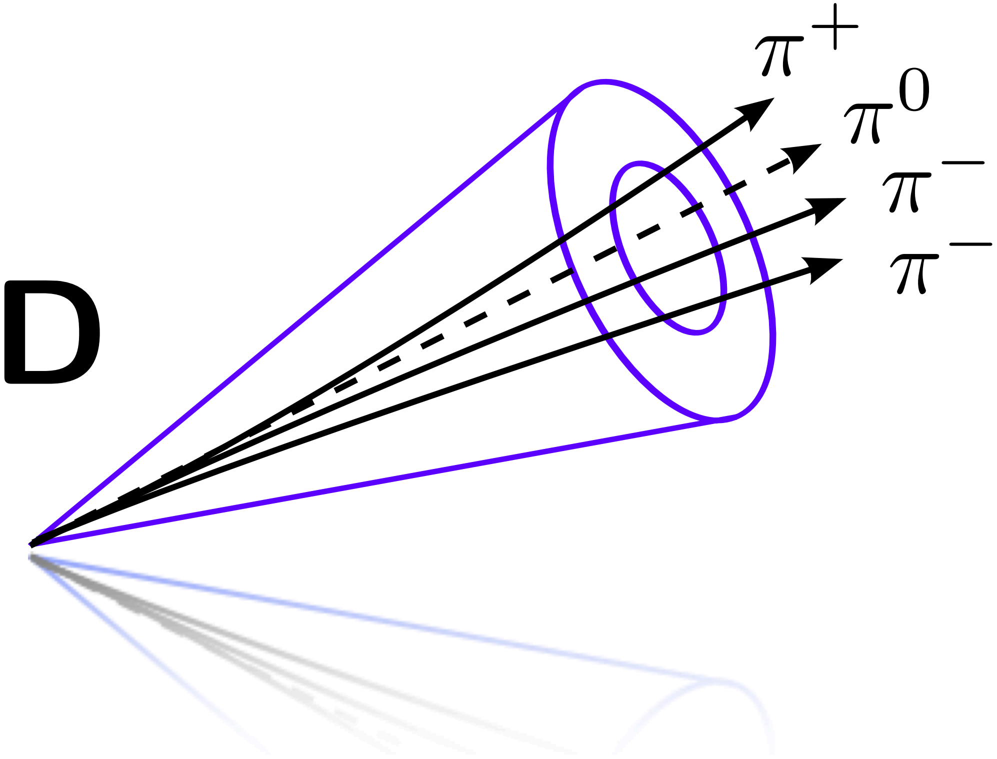


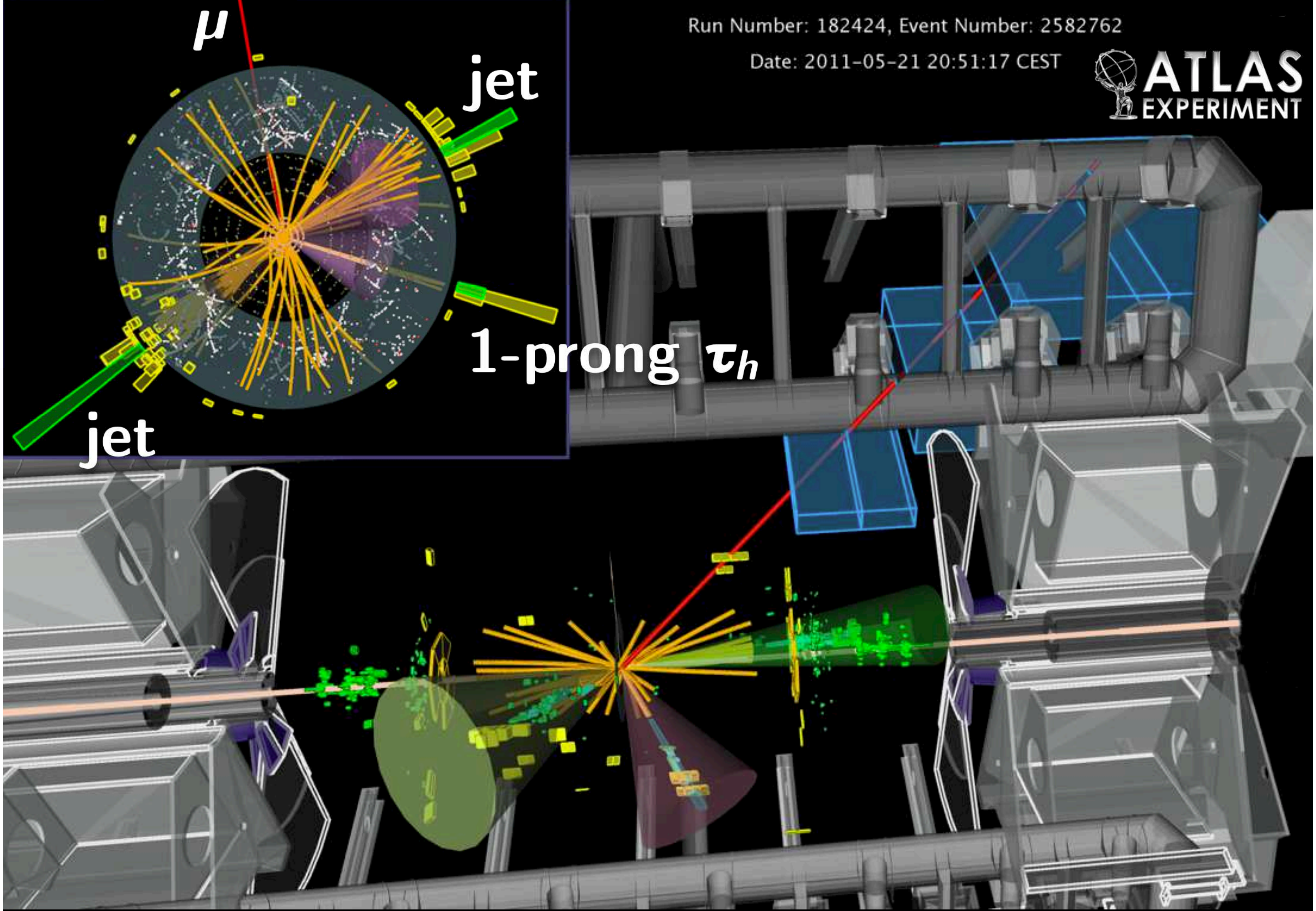


- OS/SS shapes agree well
- normalize in OS sideband with $200 < M_T < 250$ GeV

[ATLAS-CONF-2012-067]

ATLAS Tau ID

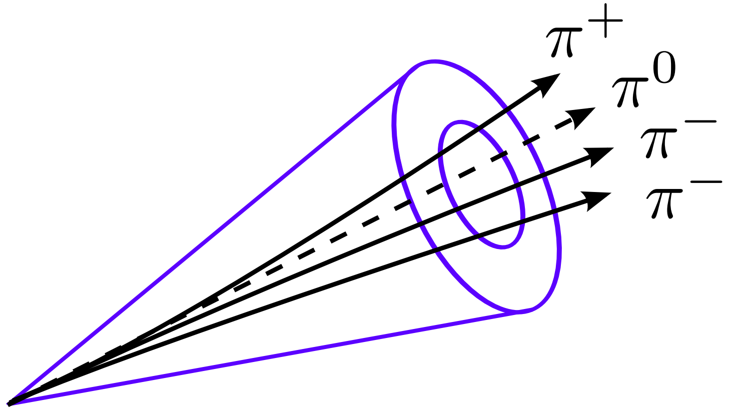




$t\bar{t} \to b\bar{b}(\mu\nu)(\tau_{\mathrm{h}}\nu)$ candidate

Phenomenology of tau decays

$\tau^- \to$	$e^- \, \bar{\nu}_e \, \nu_\tau$	17.8%	leptonic 35.2%
	$\mu^- \, \bar{\nu}_\mu \, \nu_\tau$	17.4%	
	$\pi^- \, \pi^0 \, \nu_\tau$	25.5%	1 prong 49.5%
	$\pi^- \, \nu_\tau$	10.9%	
	$\pi^- \, 2\pi^0 \, \nu_\tau$	9.3%	
	$K^- \, (N\pi^0) \, (NK^0) \, \nu_\tau$	1.5%	
	$\pi^- \, 3\pi^0 \, \nu_\tau$	1.0%	
	$\pi^- \, \pi^- \, \pi^+ \, \nu_\tau$	9.0%	3 prong 15.2%
	$\pi^- \, \pi^- \, \pi^+ \, \pi^0 \, \nu_\tau$	4.6%	



Current tau identification variables

1. Core energy fraction* $$f_{\mathrm{core}} = \frac{\sum_{\{\Delta R<0.1\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})}{\sum_{\{\Delta R<0.2\}} E_{\mathrm{T}}^{\mathrm{EM}}(\mathrm{cell})}$$
2. Leading track momentum fraction*
3. Track radius $$R_{\mathrm{track}} = \frac{\sum_{\{\Delta R<0.4\}} p_{\mathrm{T}}(\mathrm{track})\, \Delta R(\mathrm{track,\ jet})}{\sum_{\{\Delta R<0.4\}} p_{\mathrm{T}}(\mathrm{track})}$$
4. Number of isolation tracks $N_{\mathrm{trk}}^{0.2<\Delta R<0.4}$
5. Leading track impact parameter significance $$S_{\mathrm{lead\ track}} = \frac{d_0}{\sigma_{d_0}}$$
6. Transverse flight path significance $$S_{\mathrm{T}}^{\mathrm{flight}} = \frac{L_{\mathrm{T}}^{\mathrm{flight}}}{\sigma_{L_{\mathrm{T}}^{\mathrm{flight}}}}$$
7. Mass of track system
8. Maximum ΔR between jet-axis and core tracks

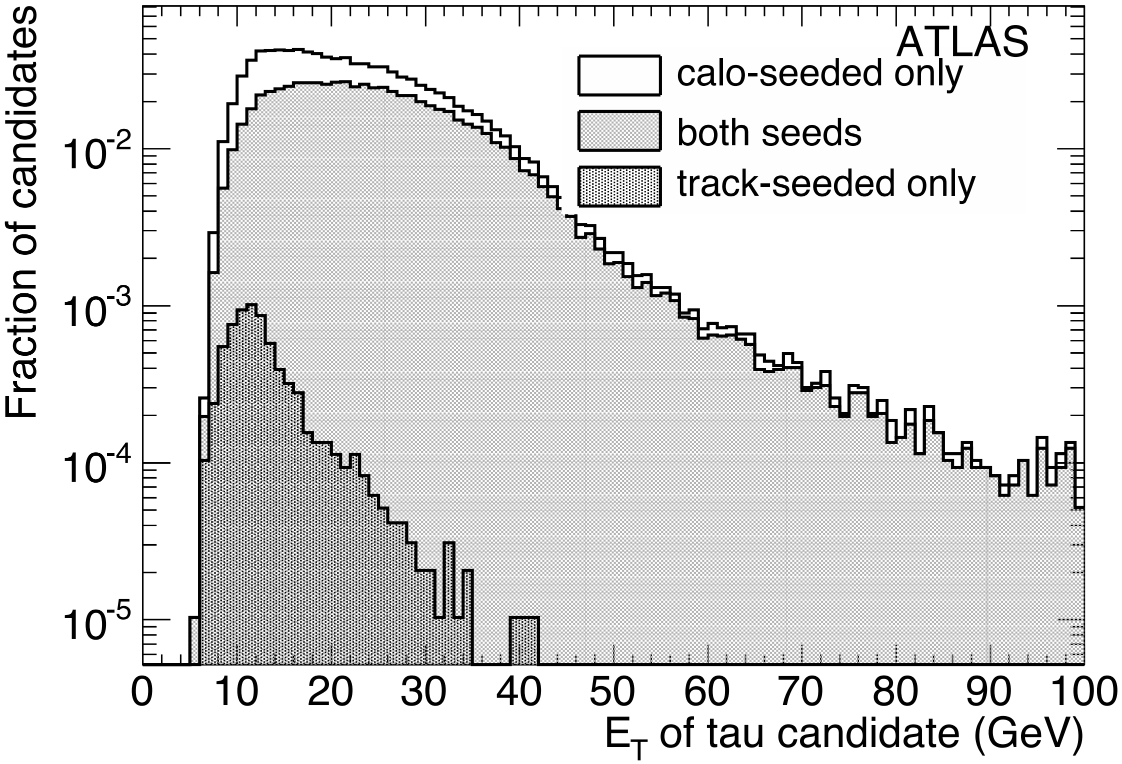
*has pile-up correction term linear in N(vertex)

Seeds of reconstruction

Once upon a time, there were two tau reconstruction algorithms. 2009

1. **tauRec** - seeded by $p_{\mathrm{T}} > 10$ GeV anti-k_{T} 0.4 topo-jets. "calo-seeded"

2. **tau1p3p** - seeded by $p_{\mathrm{T}} > 6$ GeV inner detector tracks. "track-seeded"



Since virtually all candidates have a calo-seed, we effectively merged the variable calculation of both algorithms, using only calo-seeds.

"Performance of the tau reconstruction and identification algorithm with 14.2.20 and mc08" [ATL-COM-PHYS-2009-229]

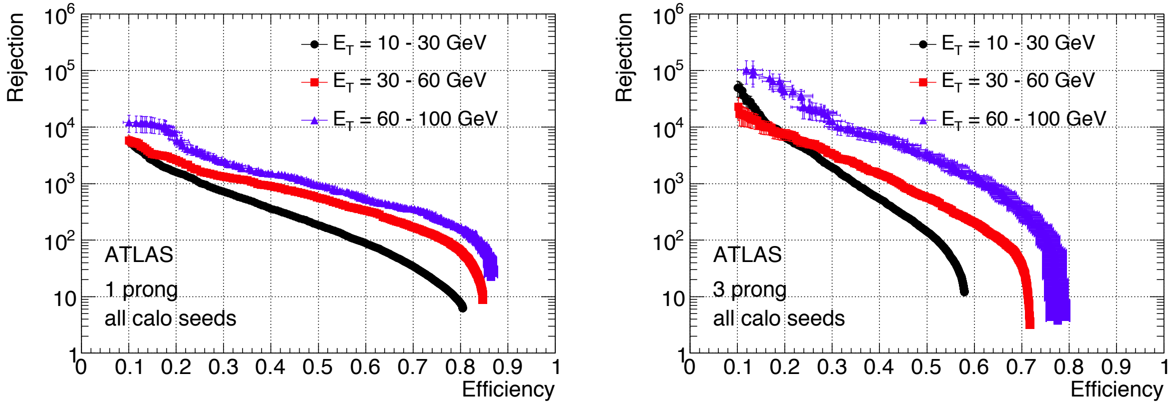
Early MV identification

2009

- **Jet-tau discrimination**

  Prefers narrow calorimeter jets, likelihood-based discriminant.

$$R_{\mathrm{EM}} = \frac{\sum_i^{\Delta R_i < 0.4} E_{\mathrm{T},i}^{\mathrm{EM}} \Delta R_i}{\sum_i^{\Delta R_i < 0.4} E_{\mathrm{T},i}^{\mathrm{EM}}},$$

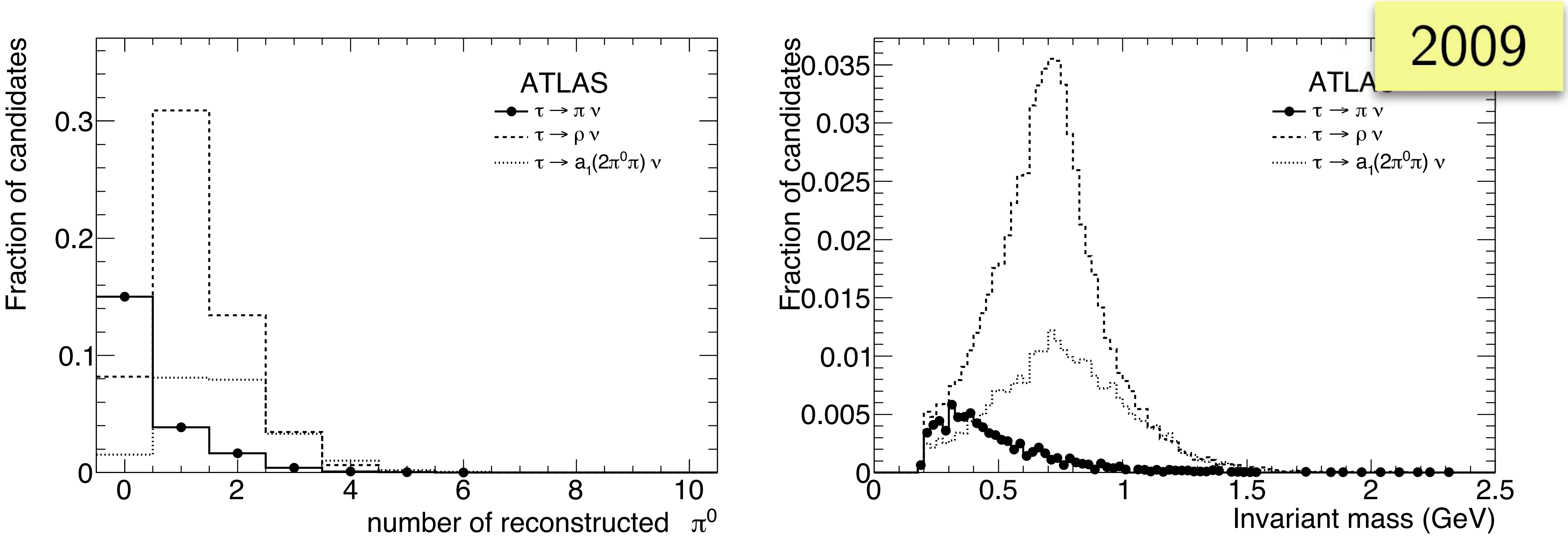


- **Electron-tau discrimination**

	IsEle(%)			IsEle_eg(%)		
Candidate	Overall	1P	3P	Overall	1P	3P
τ from W$\rightarrow \tau\nu$	93.2	92.7	95.3	99.8	99.8	99.8
τ form A$\rightarrow \tau\tau$	93.3	92.5	96.3	99.9	98.8	99.5
Electron form W$\rightarrow e\nu$	2.8	2.4	0.1	14.8	13.4	0.3
Electron form A$\rightarrow \tau\tau$	5.9	4.5	0.5	18.0	15.8	0.8

[ATL-COM-PHYS-2009-229]

Early sub-structure studies

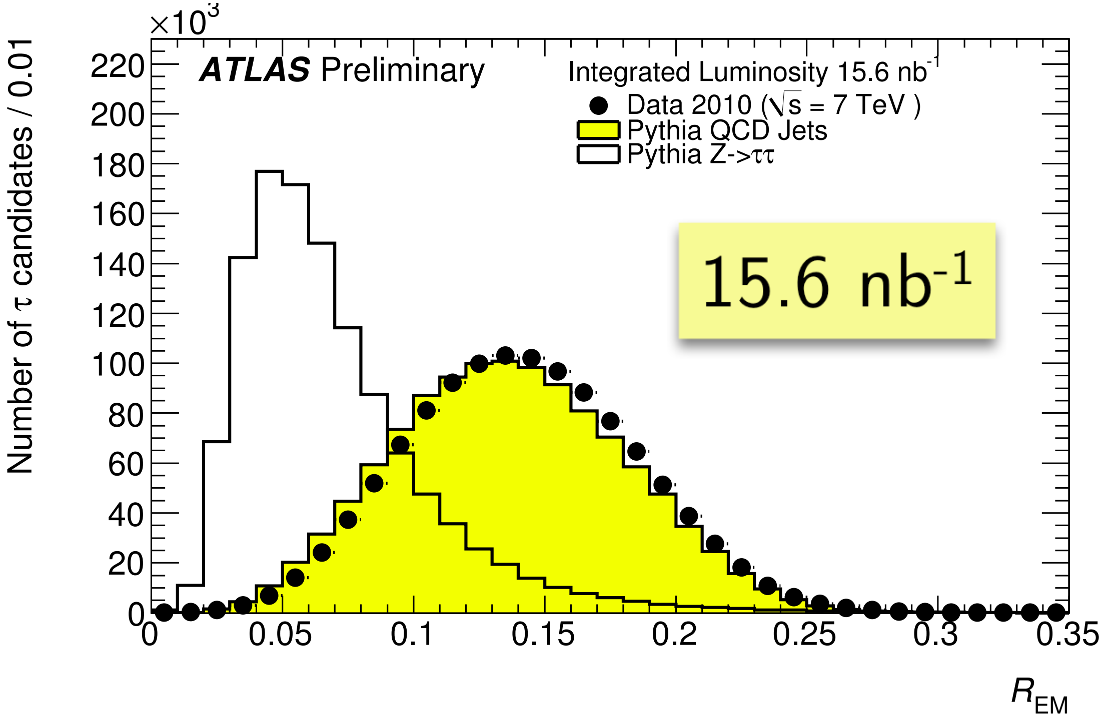


2009

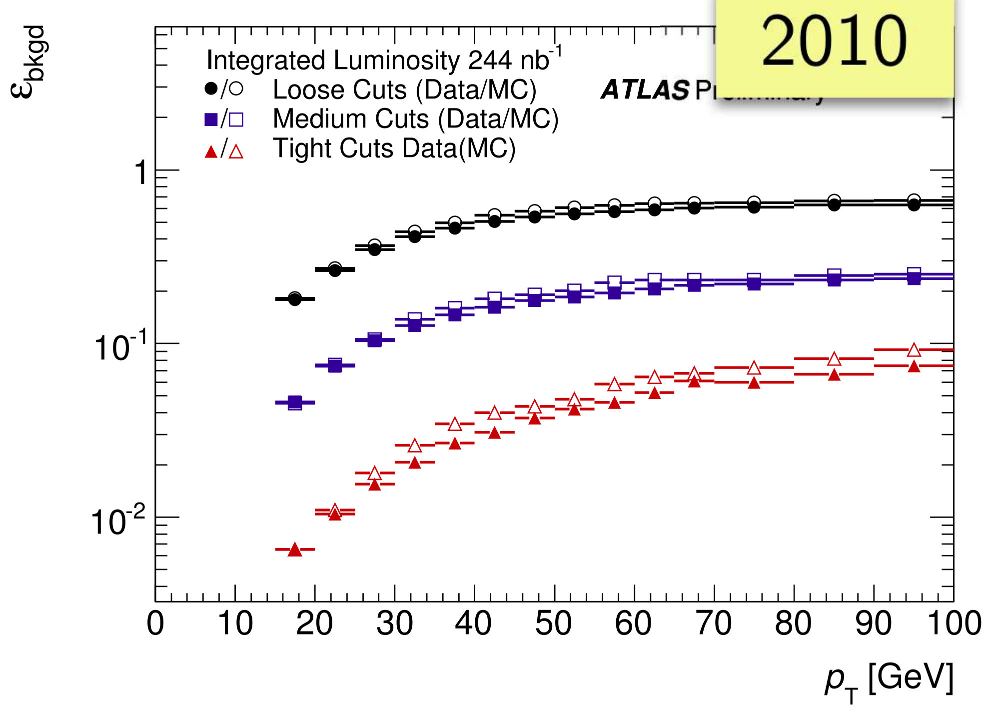
- Monte Carlo based substructure studies
- Cell-based shower-shape subtraction π^0 reconstruction.
- Still unvalidated with data.

[ATL-COM-PHYS-2009-229]

First data



15.6 nb^{-1}



2010

- First comparisons of background distributions and the QCD fake-rate between data and Monte Carlo.
- Already see that MC over-estimates the jet fake-rate. $\Rightarrow k_W \approx 0.5$

"Reconstruction of hadronic tau candidates in QCD events at ATLAS with 7 TeV pp collisions" [ATLAS-CONF-2010-059]

"Tau Reconstruction and Identification Performance in ATLAS" [ATLAS-CONF-2010-086]

Tau discriminants

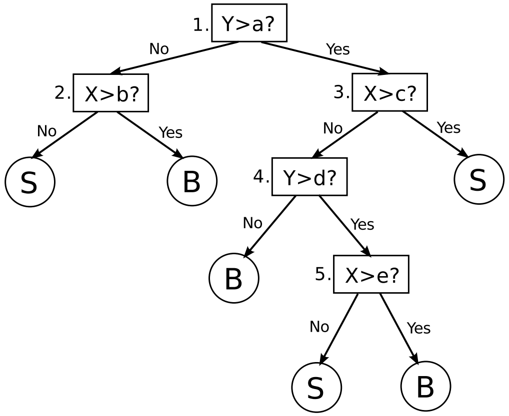
- **Cuts**

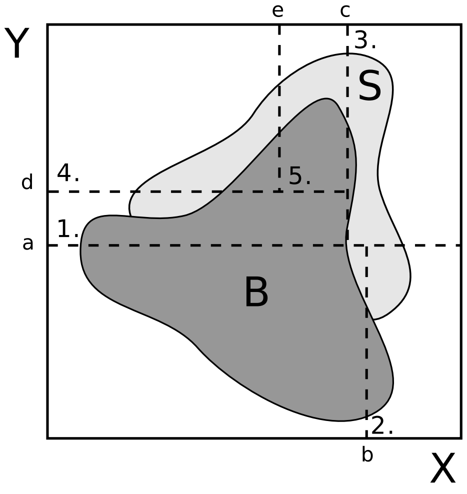
  p_{T}-parametrized cuts on R_{EM} and R_{track}, and a cut on f_{track}.

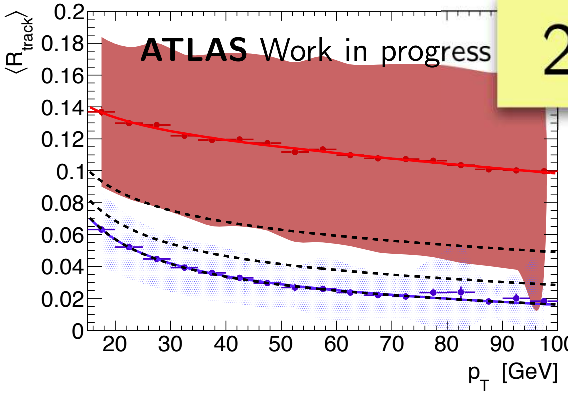
- **Projective likelihood**

  $$d = \ln\left(\frac{L_S}{L_B}\right) = \sum_{i=1}^{N} \ln\left(\frac{p_i^S(x_i)}{p_i^B(x_i)}\right)$$

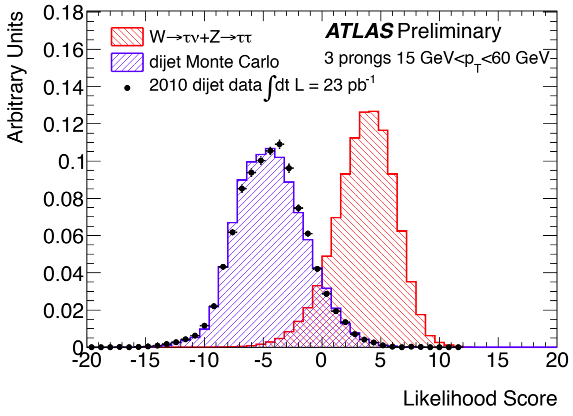
- **Boosted decision trees (BDT)**

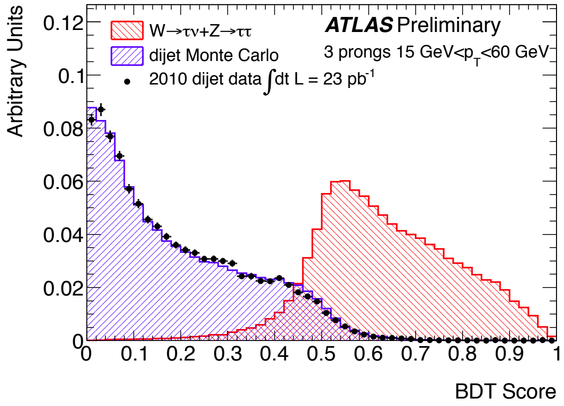




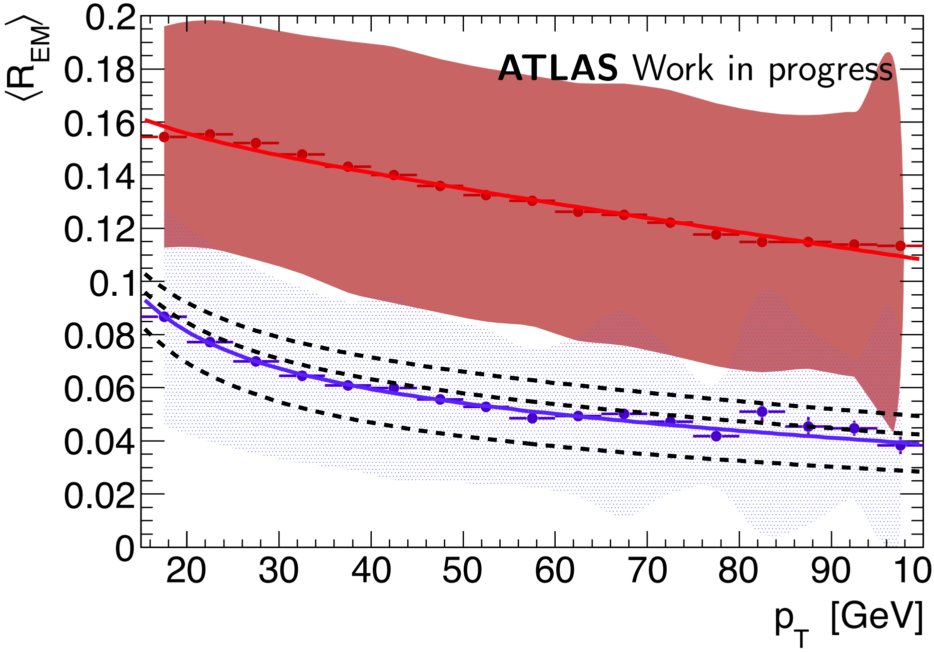


2010

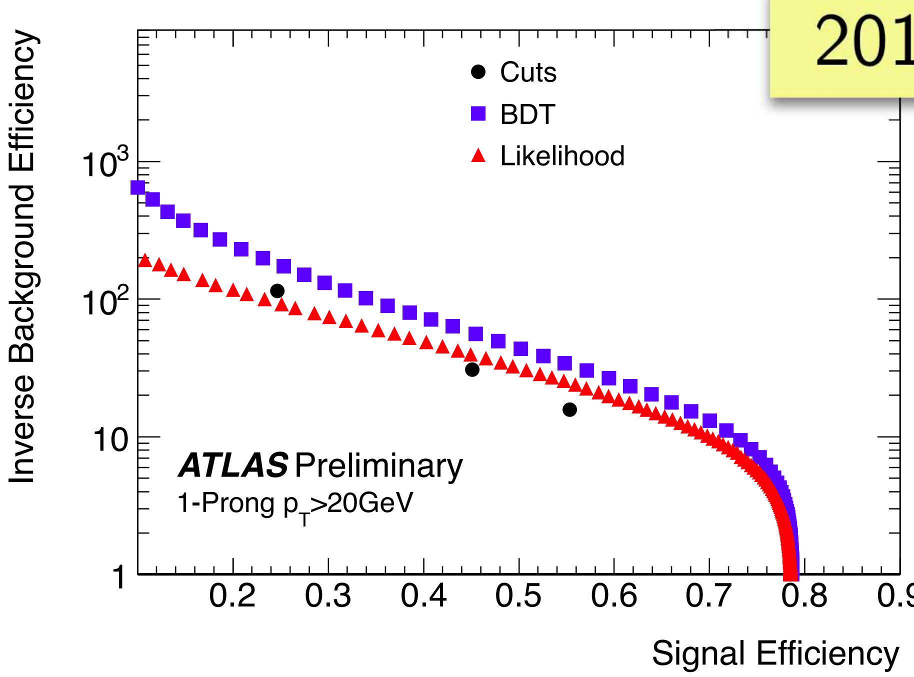




Maturing of discriminants



2010

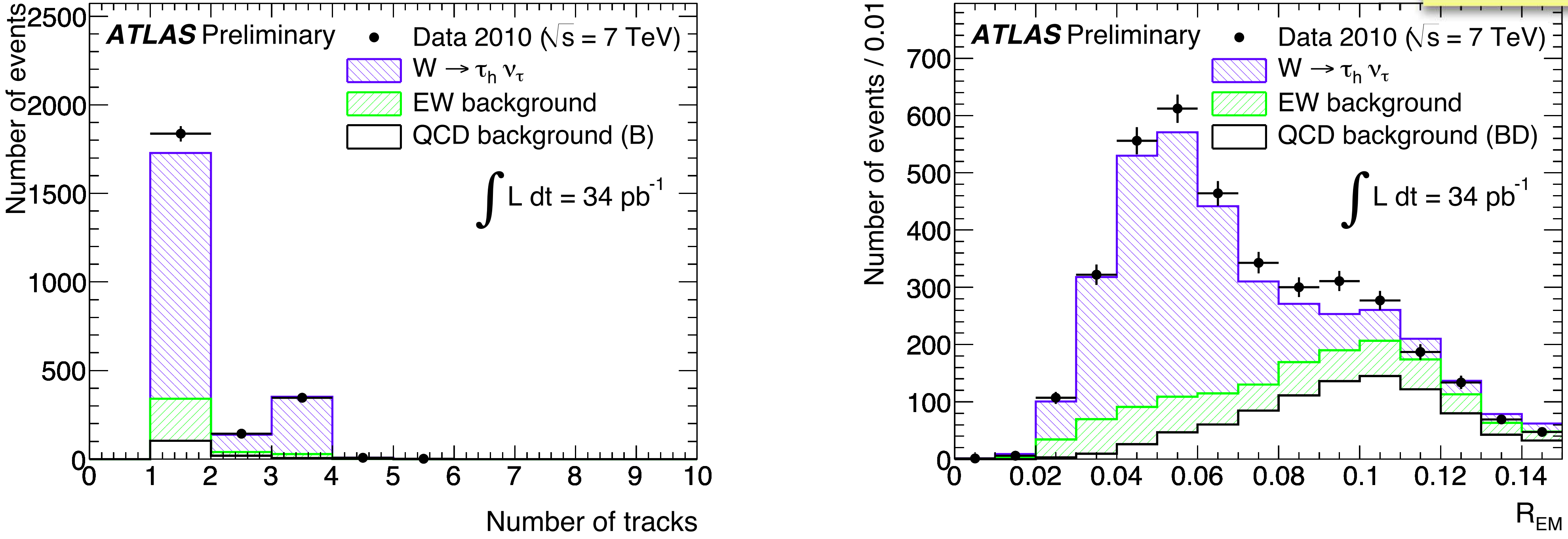


- Cuts are pt-parametrized to account for the Lorentz collimation of boosted taus.
- Experience grows with LLH and BDT discriminants, which become the preferred discriminants in 2011.

"Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons in the ATLAS Experiment" [ATLAS-CONF-2011-077, ATL-PHYS-INT-2011-068]

Seeing first hadronic taus

2010



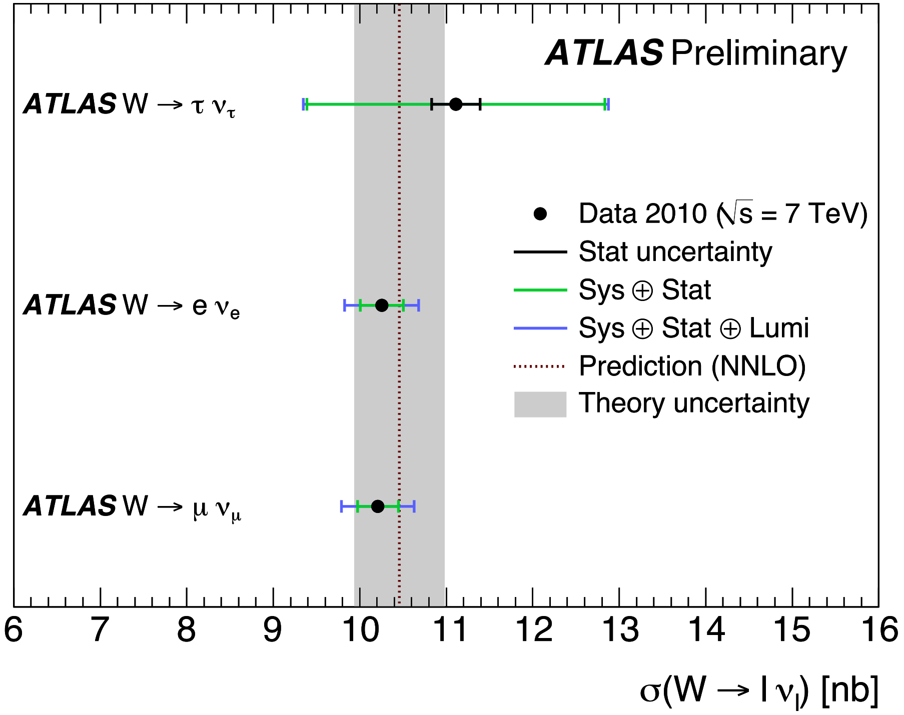
- Nov 2010: Observation of $W \to \tau_h \nu$ [ATLAS-CONF-2010-097]
- Feb 2011: Observation of $Z \to \tau_h \tau_l$ [ATLAS-CONF-2011-010]

$W\to\tau\nu$ cross section

2010

$$\sigma(W \to \tau\nu) = 11.1 \pm 0.3(\text{stat.}) \pm 1.7(\text{sys.}) \pm 0.4(\text{lumi.})\ \text{nb}$$

$$\sigma_{\text{theory}} = 10.46 \pm 0.52\ \text{nb at NNLO}$$



Dominant systematics

- $\tau_{\rm h}$ efficiency 10.3%
- $\tau_{\rm h}$ energy scale 8.0%
- $\tau_{\rm h}$ + MET trigger efficiency 7.0%
- luminosity 3.4%
- acceptance 2.3%

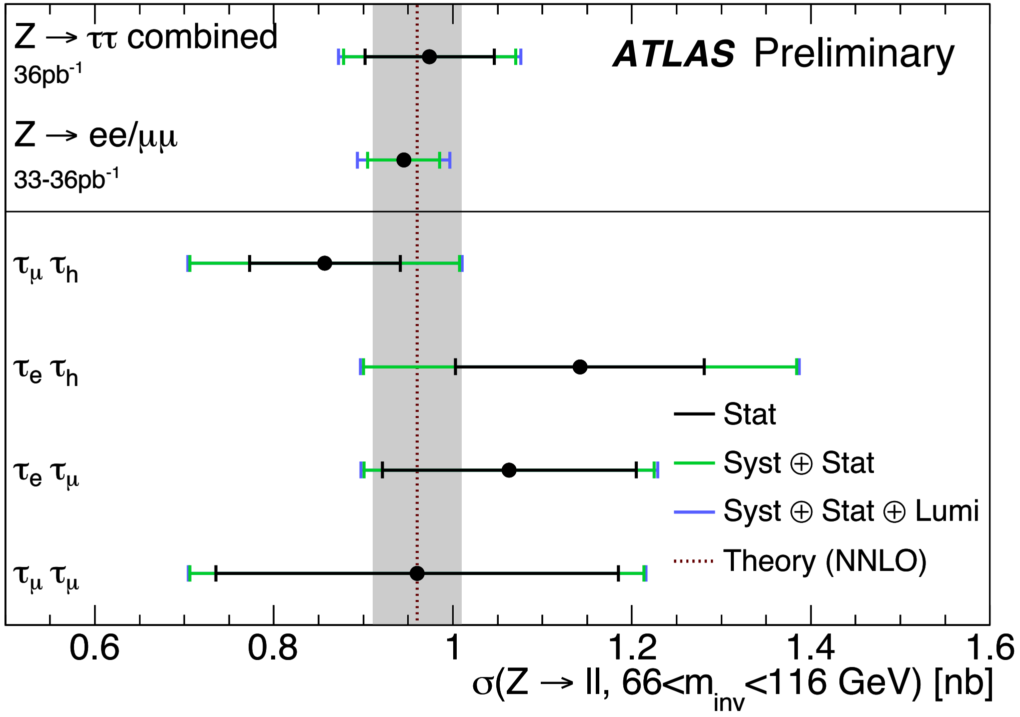
"Measurement of the $W\to\tau\nu$ cross section in pp collisions at sqrt(s)= 7 TeV with the ATLAS experiment" [arXiv:1108.4101]

$Z\to\tau\tau$ cross section

2011

$$\sigma_{\text{combined}} = 0.97 \pm 0.07(\text{stat.}) \pm 0.07(\text{sys.}) \pm 0.03(\text{lumi.})\ \text{nb}$$

$$\sigma_{\text{theory}} = 0.96 \pm 0.05\ \text{nb at NNLO}$$



Dominant systematics

- τ_{h} energy scale 11%
- τ_{h} efficiency 8.6%
- μ efficiency 8.6%
- e efficiency 3-10%
- acceptance 3%
- luminosity 3.4%

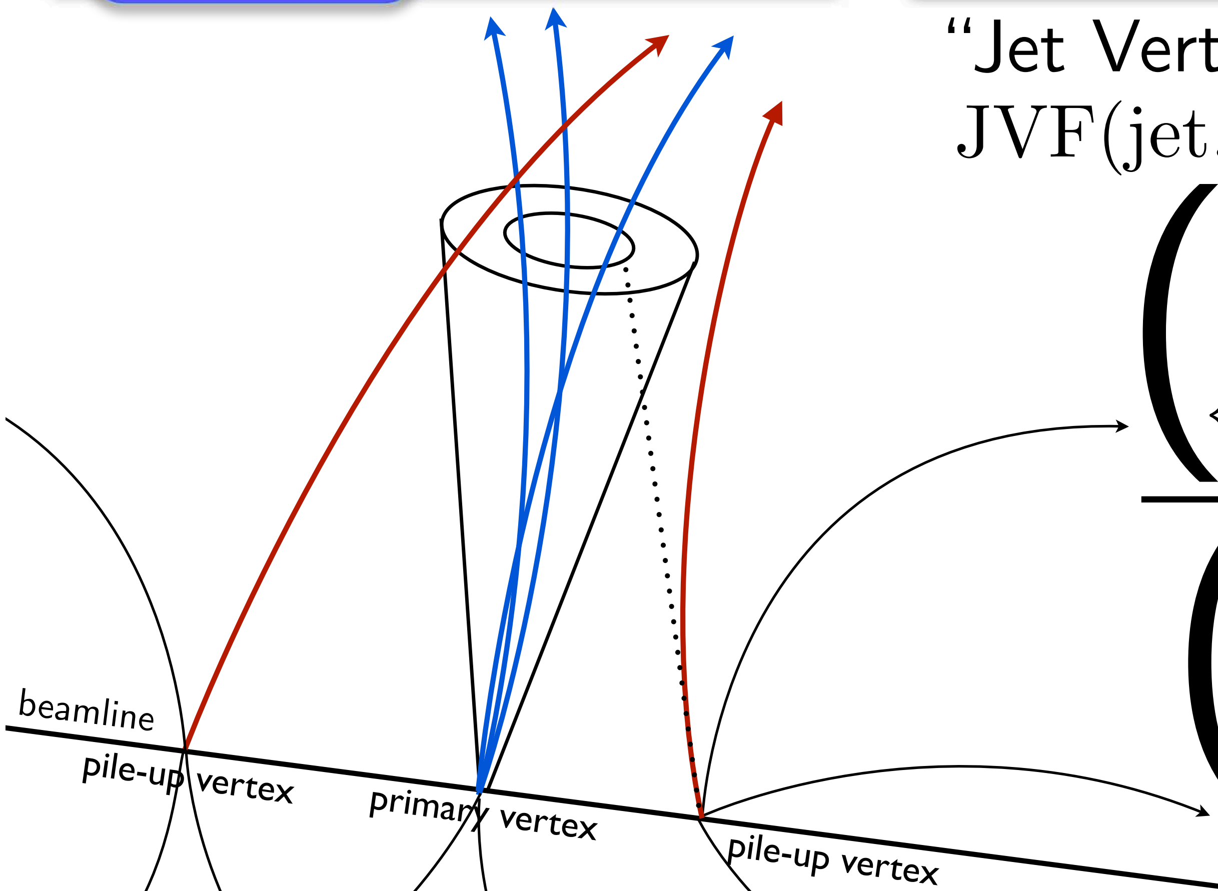
“Measurement of the $Z\to\tau\tau$ cross section in pp collisions at sqrt(s)= 7 TeV with the ATLAS detector” [arXiv:1108.2016]

Tau vertex association

Tau track selection

- $p_T > 1$ GeV,
- Number of pixel hits ≥ 2,
- Number of pixel hits + number of SCT hits ≥ 7,
- $|d_0| < 1.0$ mm,
- $|z_0 \ \sin\theta| < 1.5$ mm,

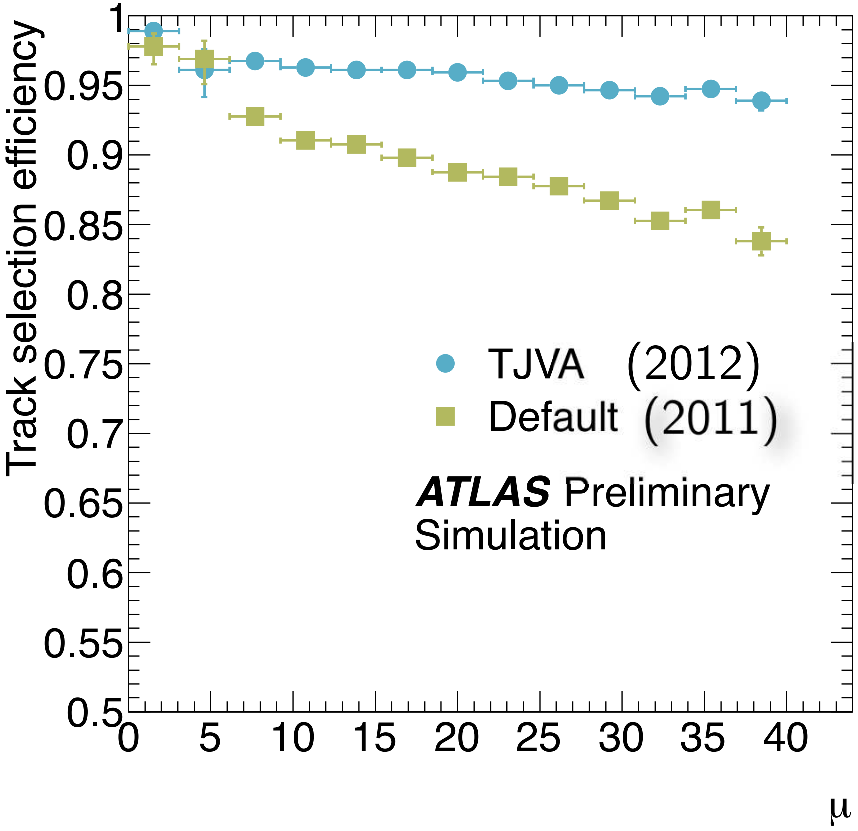
- The d_0 and z_0 requirements depend on the choice of vertex.
- Beginning in 2012, choose the vertex with the highest JVF for that tau candidate.

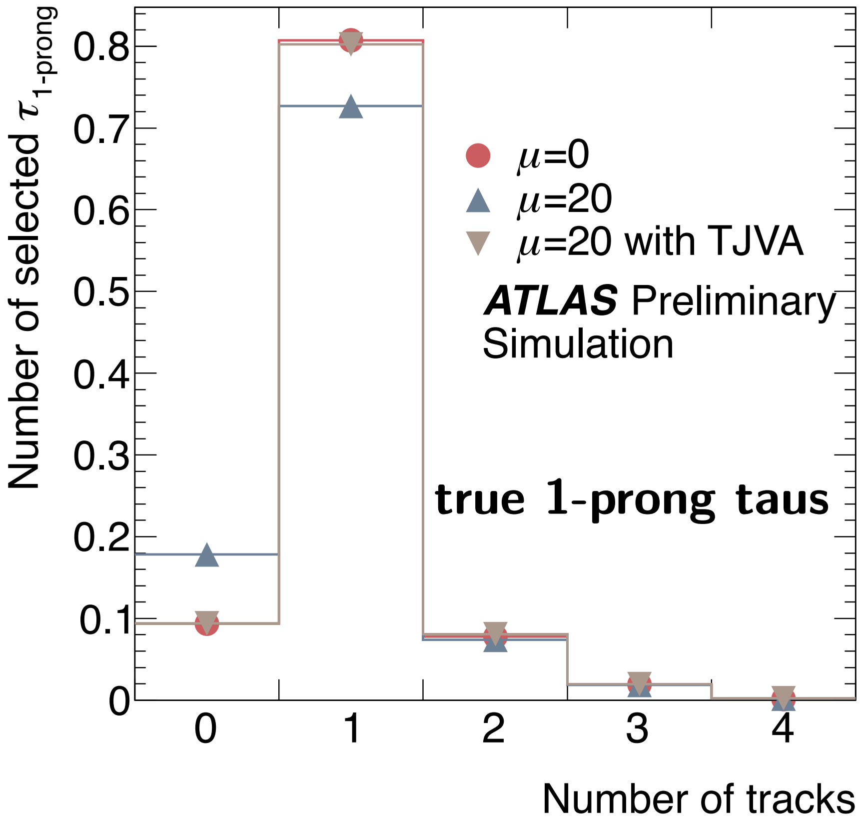


"Jet Vertex Fraction"

$$\mathrm{JVF}(\mathrm{jet},\mathrm{vertex}) = \frac{\left(\displaystyle\sum_{\left\{\substack{\text{tracks matched}\\ \text{to jet and vertex}}\right\}} p_\mathrm{T}(\mathrm{track})\right)}{\left(\displaystyle\sum_{\left\{\substack{\text{tracks matched}\\ \text{to jet}}\right\}} p_\mathrm{T}(\mathrm{track})\right)}$$

Track selection efficiency



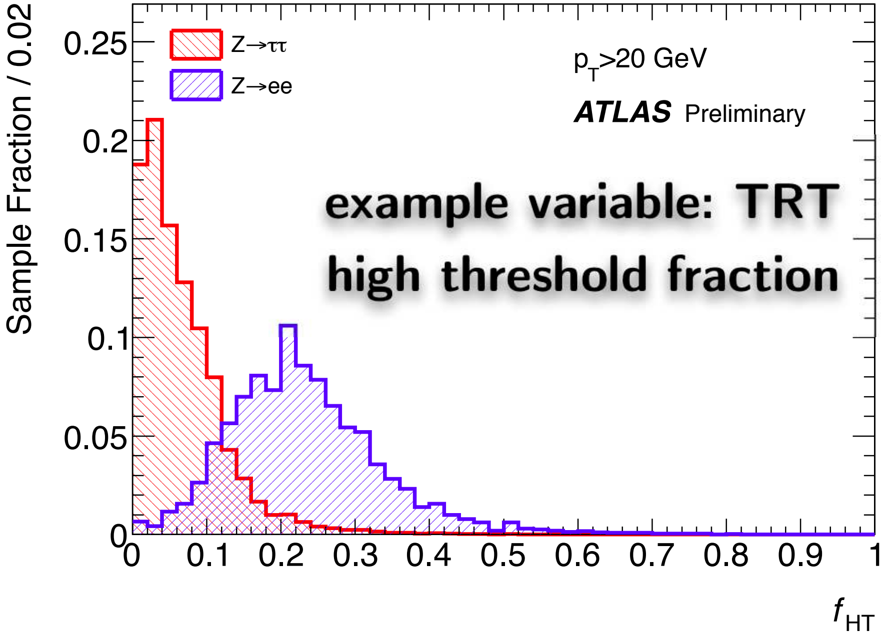


- In 2011, the track selection for tau candidates cut on the d_0 and z_0 with respect to the vertex with the highest $\sum p_T{}^2$.
- Selecting the vertex with the highest JVF recovers efficiency in high pile-up (Tau Jet Vertex Association).

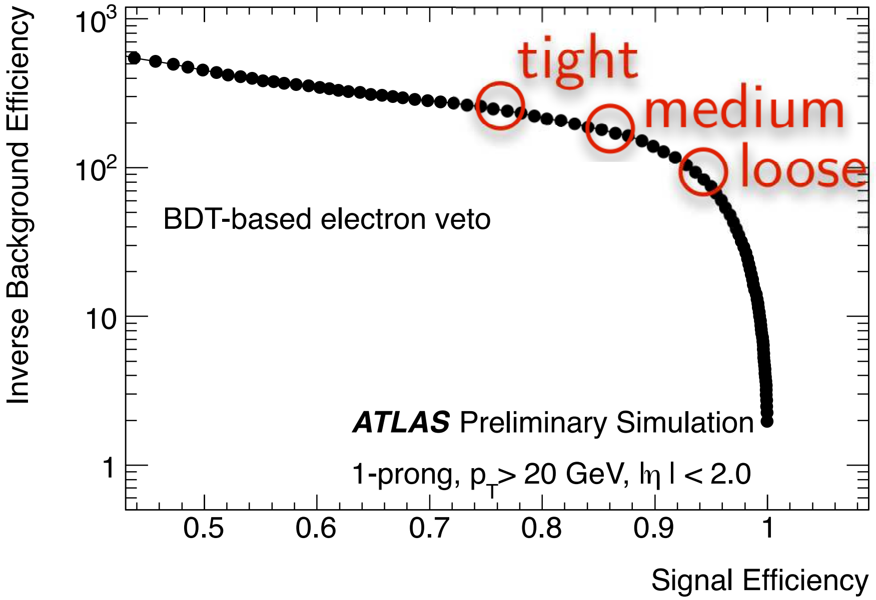
[ATLAS-CONF-2012-142]

Electron veto

- Electrons provide a track and calorimeter deposit that can fake hadronic tau decay identification.
- ATLAS provides a BDT to discriminate electrons from tau candidates, even after removing overlaps with selected electrons.
- Tight/Medium/Loose working points are defined (≈75%, 85%, 95% efficient).
- In 2012, the BDT is being re-optimized to have better efficiency at high-p_T.



example variable: TRT high threshold fraction



[ATLAS-CONF-2011-152, ATLAS-CONF-2012-142]

Tau triggering

1. **Level 1:** (latency 2.5 μs)

   Coarse EM+Had calorimeter trigger towers $\Delta\eta\times\Delta\quad = 0.1\times0.1$. Candidate passing thresholds on the sum of energies:

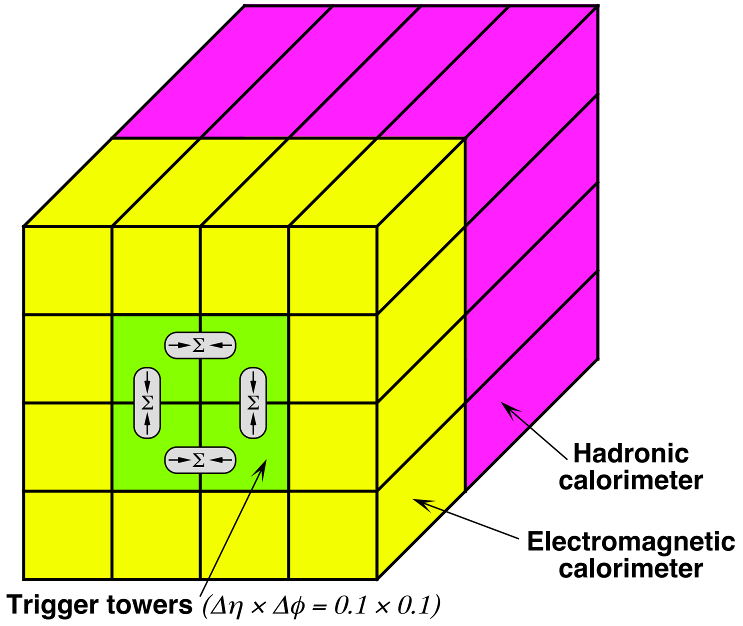
   1. highest 2×1 towers
   2. surrounding 4×4 isolation ring

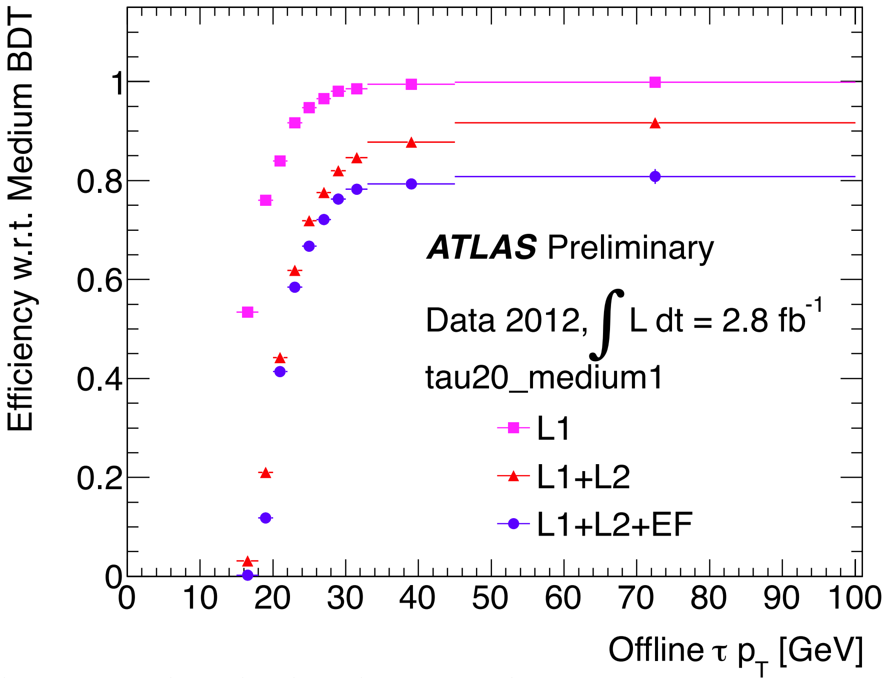
2. **Level 2:** (latency 40 ms)

   Fast tracking. Region-of-interest (RoI) calculation of track- and calorimeter-based ID variables. Similar selection to offline cut-based ID.

3. **Event Filter:** (latency 4 s)

   Beginning in 2012, started using the offline BDT algorithm at the EF trigger.





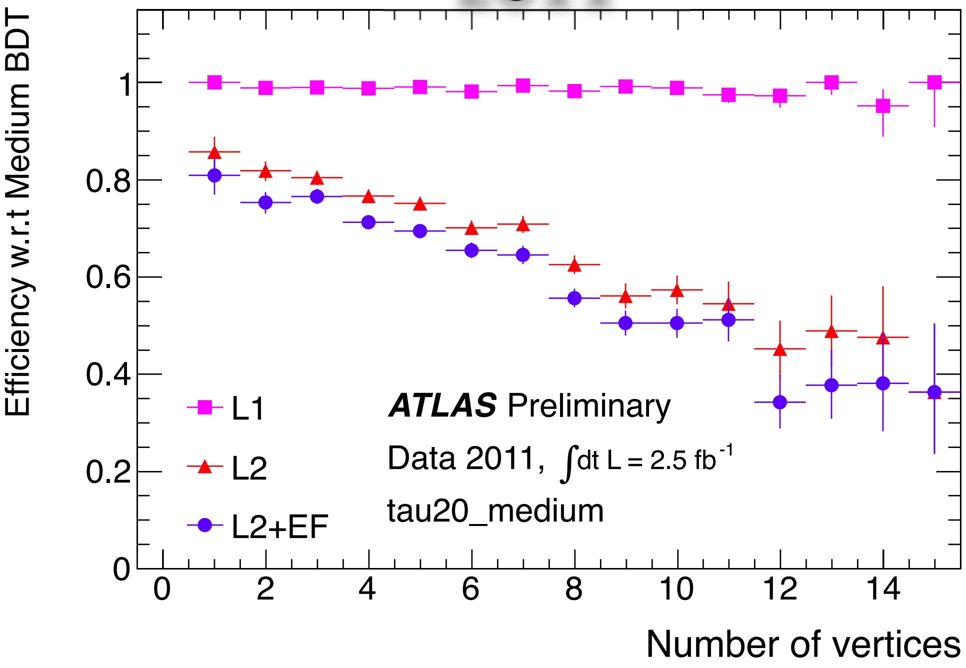
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauTriggerPublicResults

L2 pile-up robustness

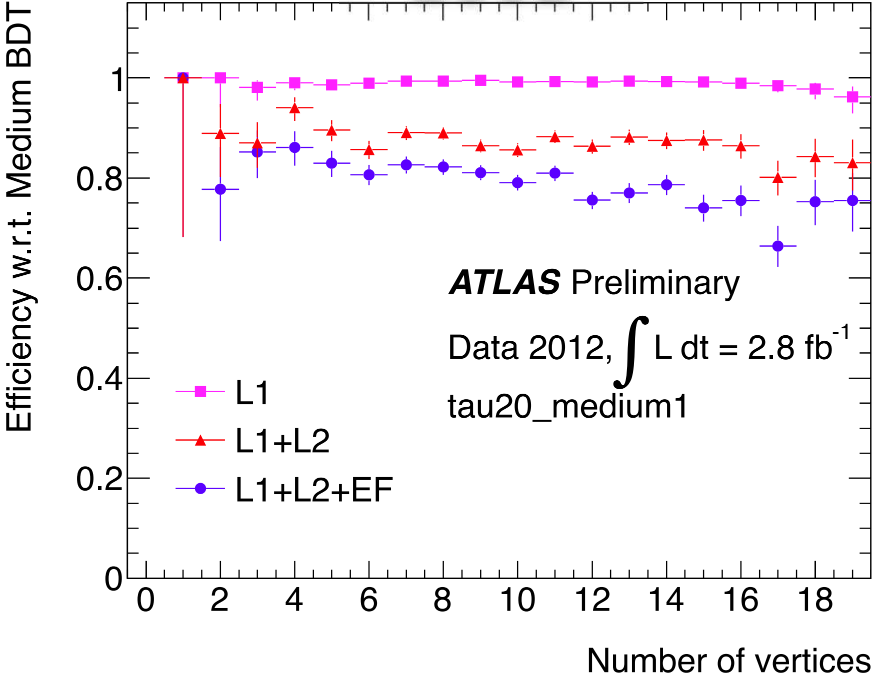
Example improvements to variable definitions to lessen sensitivity to pile-up:

- Smaller ΔR cone for calculating EM radius 0.4→0.2
- Select tracks within $\Delta z < 2$ mm of the highest-p_{T} track within the RoI (cannot vertex at L2).

2011



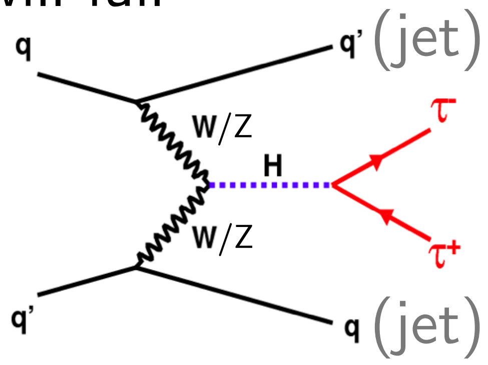
2012

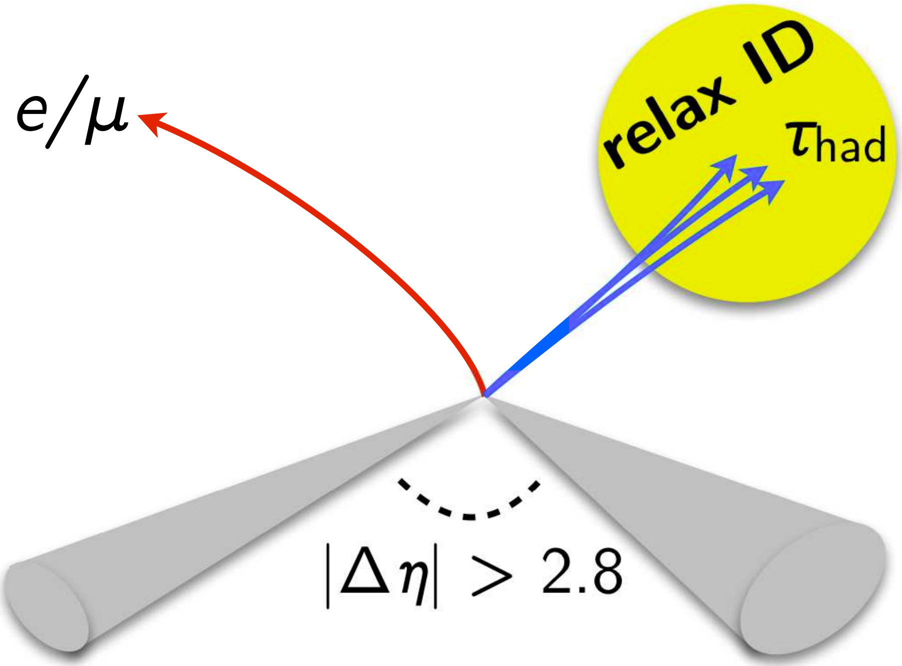


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauTriggerPublicResults

VBF triggers

- New VBF triggers *relax tau identification* required at L2 and the EF by adding requirements for forward jets.
- This increases the control sample of tau candidates that will fail identification, used to ***estimate the fake contribution***.
- Being evaluated for the H→ττ→ lep+τ_{had} search.





VBF reqs:

- 2 L2 jets $p_{\mathrm{T}} > 15$ GeV, $|\Delta\eta| > 2.5$
- 2 EF jets $p_{\mathrm{T}} > 25$ GeV, $|\Delta\eta| > 2.8$, $M_{\mathrm{jj}} > 400$ GeV

Trigger menu

$\tau_{\mathrm{had}}+\mu$	$\tau_{\mathrm{had}}+e$
tau20_medium1_mu15	tau20Ti_medium1_e18vh_medium1
mu15_vbf_L1TAU8_MU10	e18vh_medium1_vbf_2L1TAU11I_EM14VH

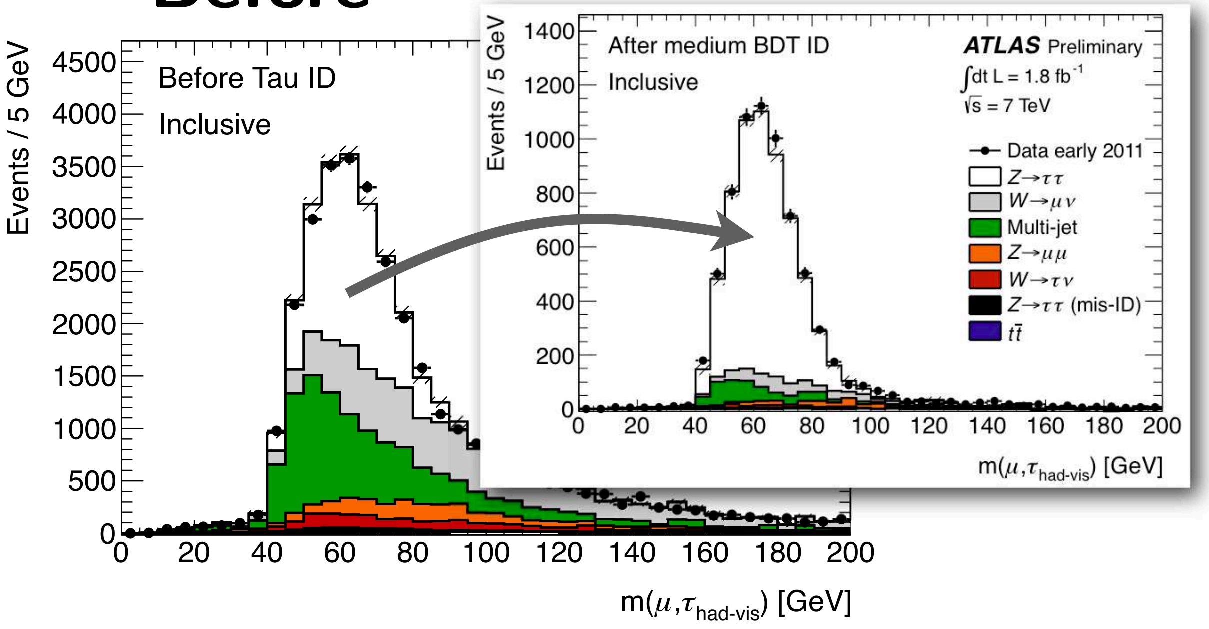
New as of periods G1, H2

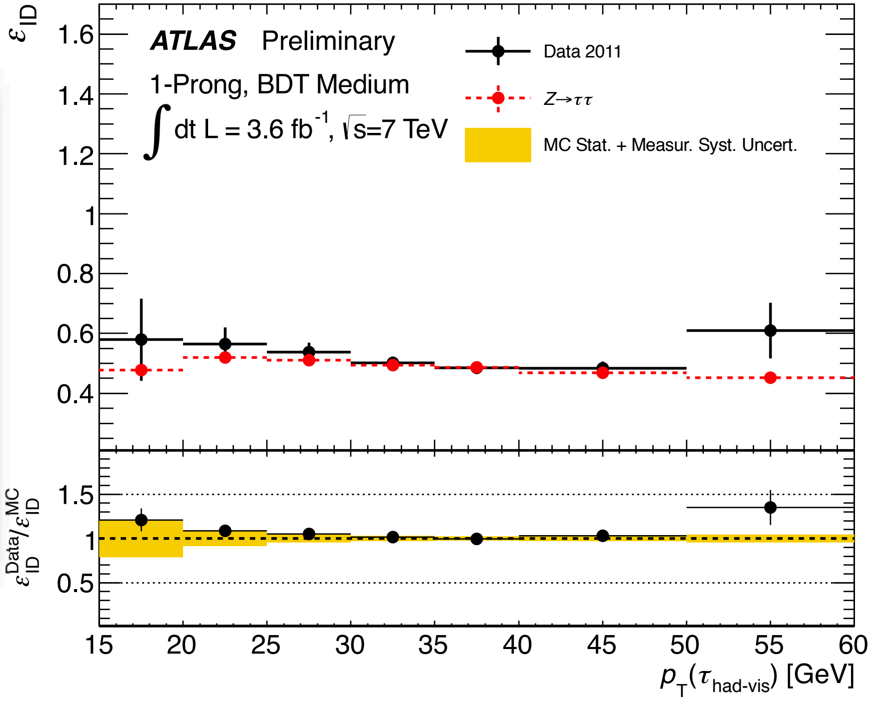
Identification efficiency

- ***Tag-and-probe*:** selecting a sample of a known composition without some ID, so one can probe its efficiency.
- For the case of tau ID, select $Z \to \tau\tau \to \mu\tau_h 3\nu$ by triggering on the muon and selecting events with muon + tau candidate.

Before

After Tau ID



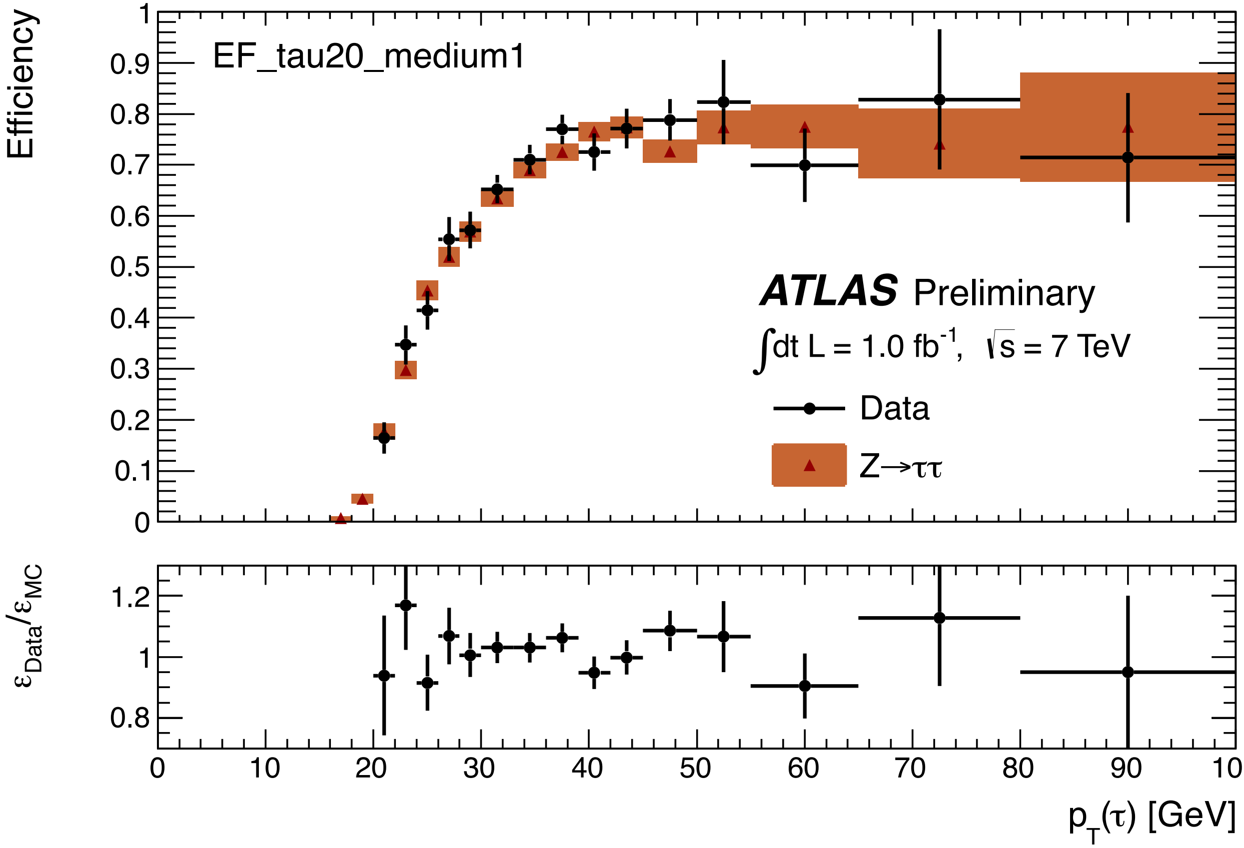


- Scale factor ≈ 1, known to a few percent, 2-3% (1-prong), 5-6% multi-prong.

[ATLAS-CONF-2012-142]

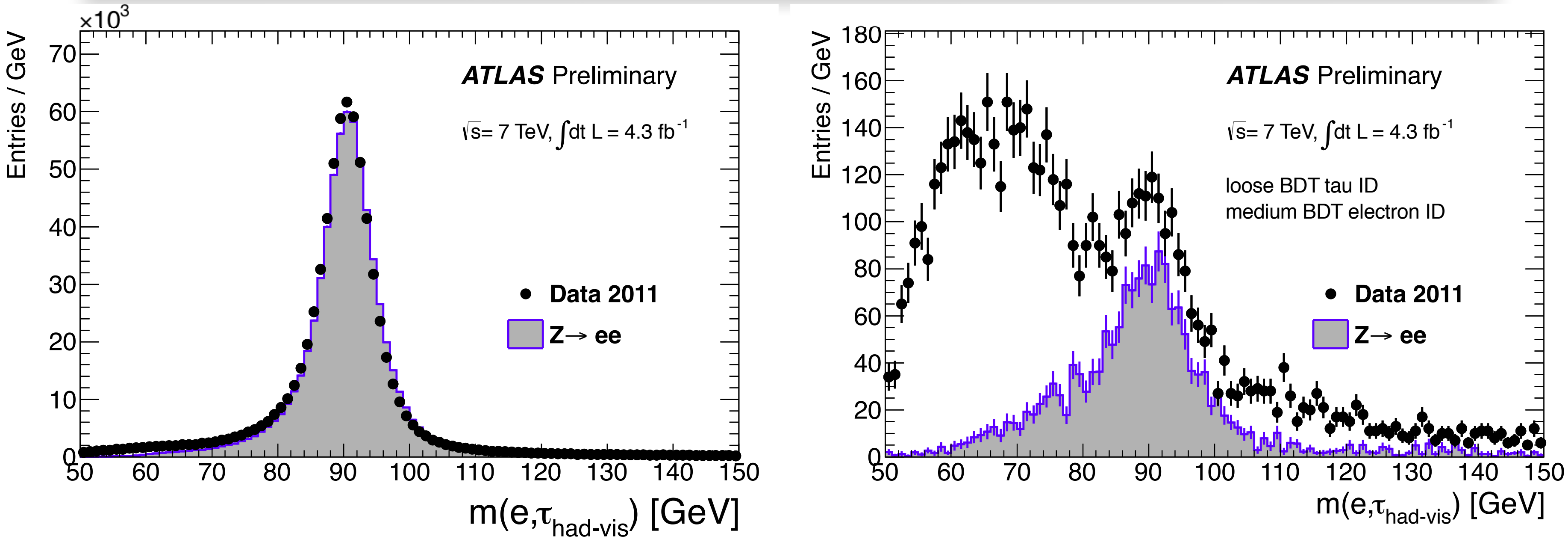
Trigger efficiency

- The same $Z \to \tau\tau \to \mu\tau_h 3\nu$ tag-and-probe sample is used to measure the efficiency of the tau triggers.
- Known to $O(5\%)$ in the turn-on.
- Improving with statistics in 2012.



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauTriggerPublicResults

Electron veto fake rate



- Tag *e* + tau candidates
- Probe the *e*-veto efficiency after removing overlap with selected electrons.

data/MC scale factor and uncertainty

from Z→ee tag-and-probe with 2.6/fb from 2011

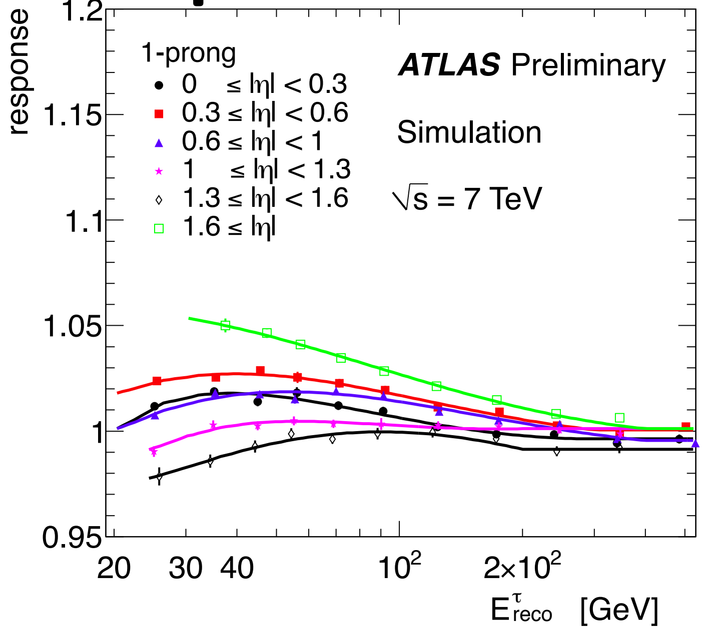
electron BDT veto	$\lvert\eta_{\mathrm{trk}}\rvert < 1.37$	$1.37 < \lvert\eta_{\mathrm{trk}}\rvert < 1.52$	$1.52 < \lvert\eta_{\mathrm{trk}}\rvert < 2.00$	$\lvert\eta_{\mathrm{trk}}\rvert > 2.00$
loose	0.96±0.22	0.8±0.3	0.47±0.14	1.7 ±0.4
medium	1.3 ±0.5	-	0.5 ±0.4	2.8 ±1.3

- Statistically limited by the sample that pass the veto, giving uncertainties ≈ 50-100%.
- Improving with the data added in 2012.

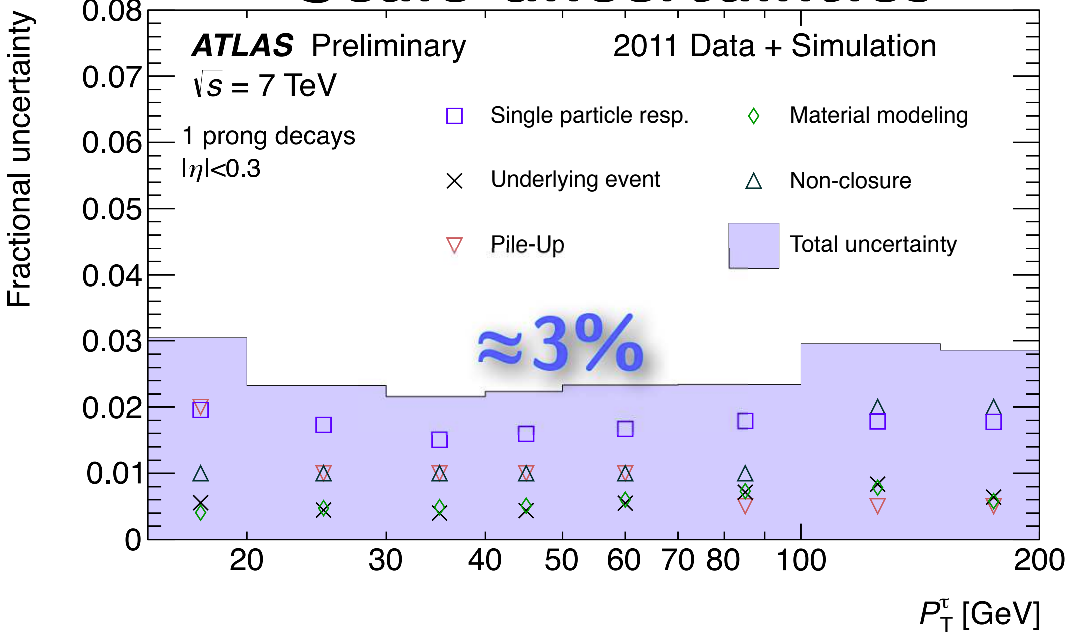
[ATLAS-CONF-2012-142]

Energy scale

Response functions



Scale uncertainties



- Tau candidates are first brought from the EM to the Jet Energy Scale with LC calibration of the clusters within $\Delta R < 0.2$ (from 0.4 to be pile-up robust).
- Then response functions are calibrated with tau Monte Carlo to make final corrections of a few percent.
- Uncertainties are determined by smearing the Monte Carlo truth according the tau decays true composition, using uncertainties constrained by single particle response measurements (CTB, E/p, $Z \rightarrow ee/\pi^0$-resp.)

[ATLAS-CONF-2012-054]

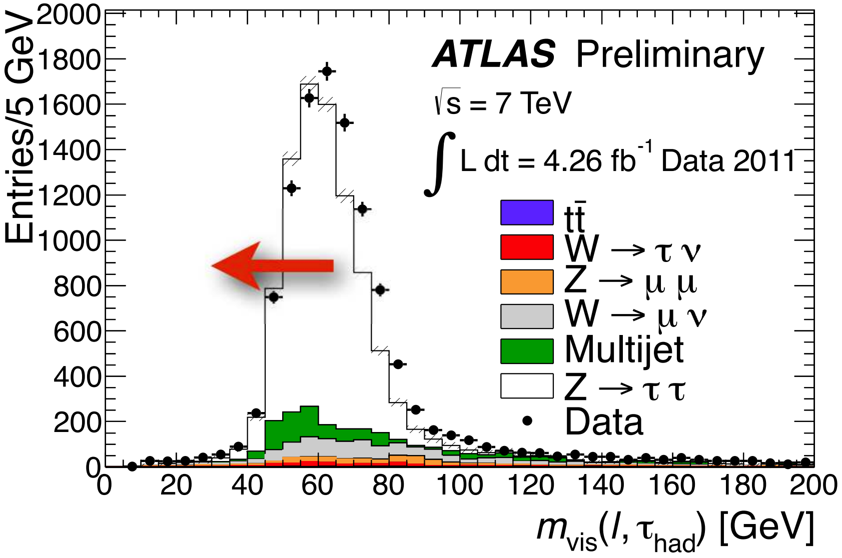
Energy scale cross check

- Tau energy scale is manually shifted in the modeling.
- Median of the visible mass peak is used to decide which scale matches the data.
- Toy experiments are used to estimate the uncertainty.

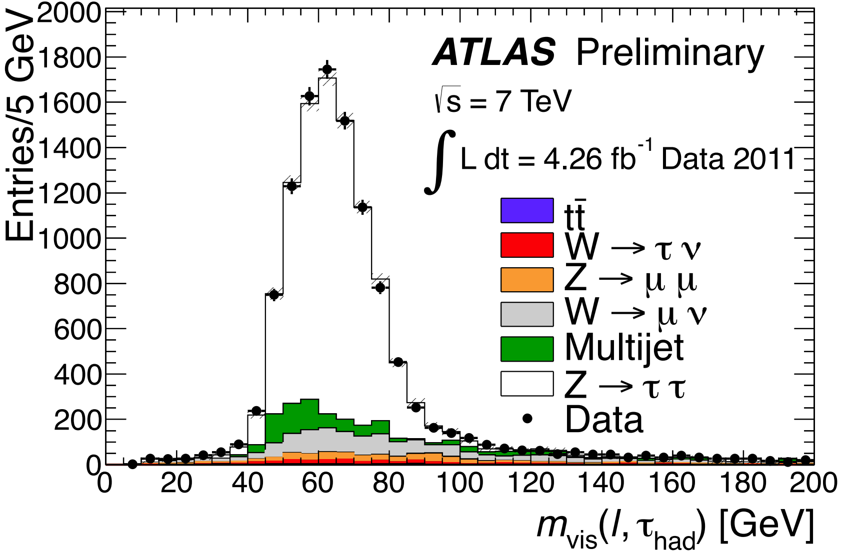
$\|\eta\|$	best scale	uncert.
0.0-0.8	-1.5%	3.3%
0.8-2.5	+1.5%	2.8%

- Scale consistent with 1 within single-particle-response uncertainties ≈ 3%.
- May become primary method with more data.

scale shifted -10%



best fit +1.5%

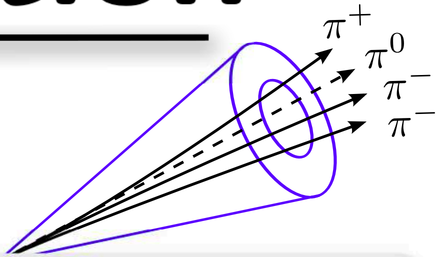


[ATLAS-CONF-2012-054]

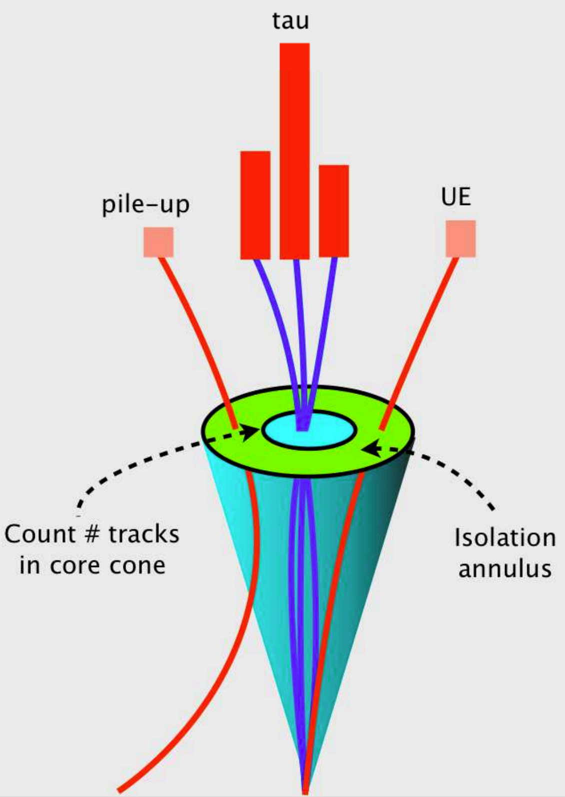
CMS Tau ID

High-p_{T} τ_h reconstruction

- Hadronic decays dominantly to 1 or 3 $\pi^{\pm}$ and possibly a few additional π^0s
- Decay in beam-pipe: $c\tau \approx 87$ µm

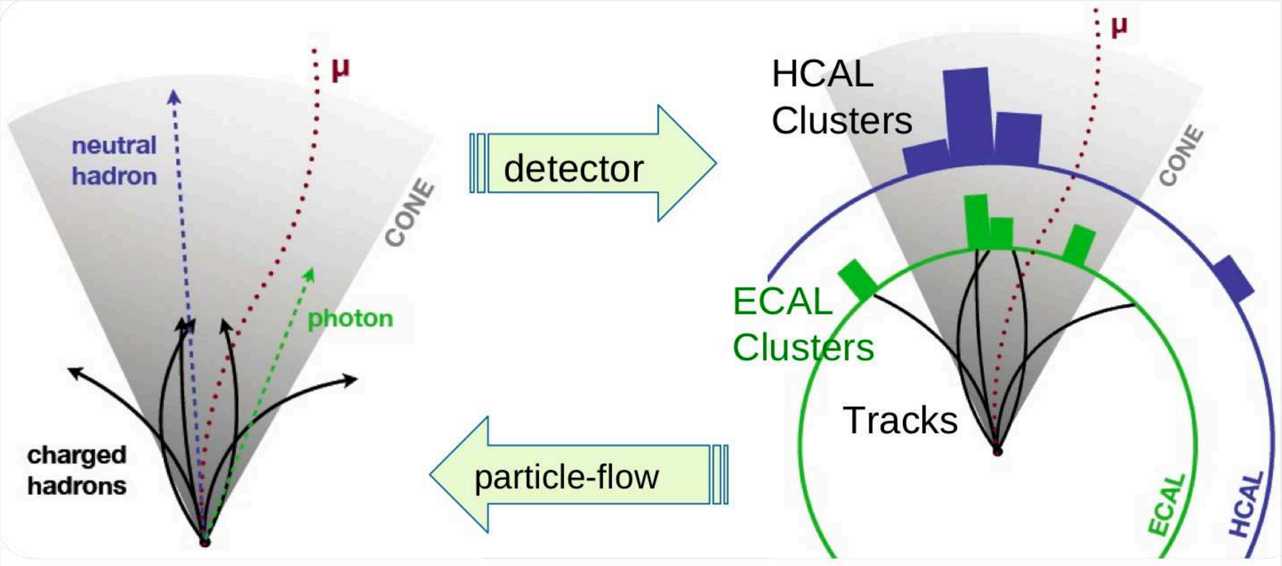


ATLAS



- τ_h reco seeded by calorimeter jets
- associate tracks in $\Delta R < 0.2$, select 1 or 3
- combine calorimeter and tracking information in a BDT or likelihood discriminant, preferring narrow clustering, hadronic activity

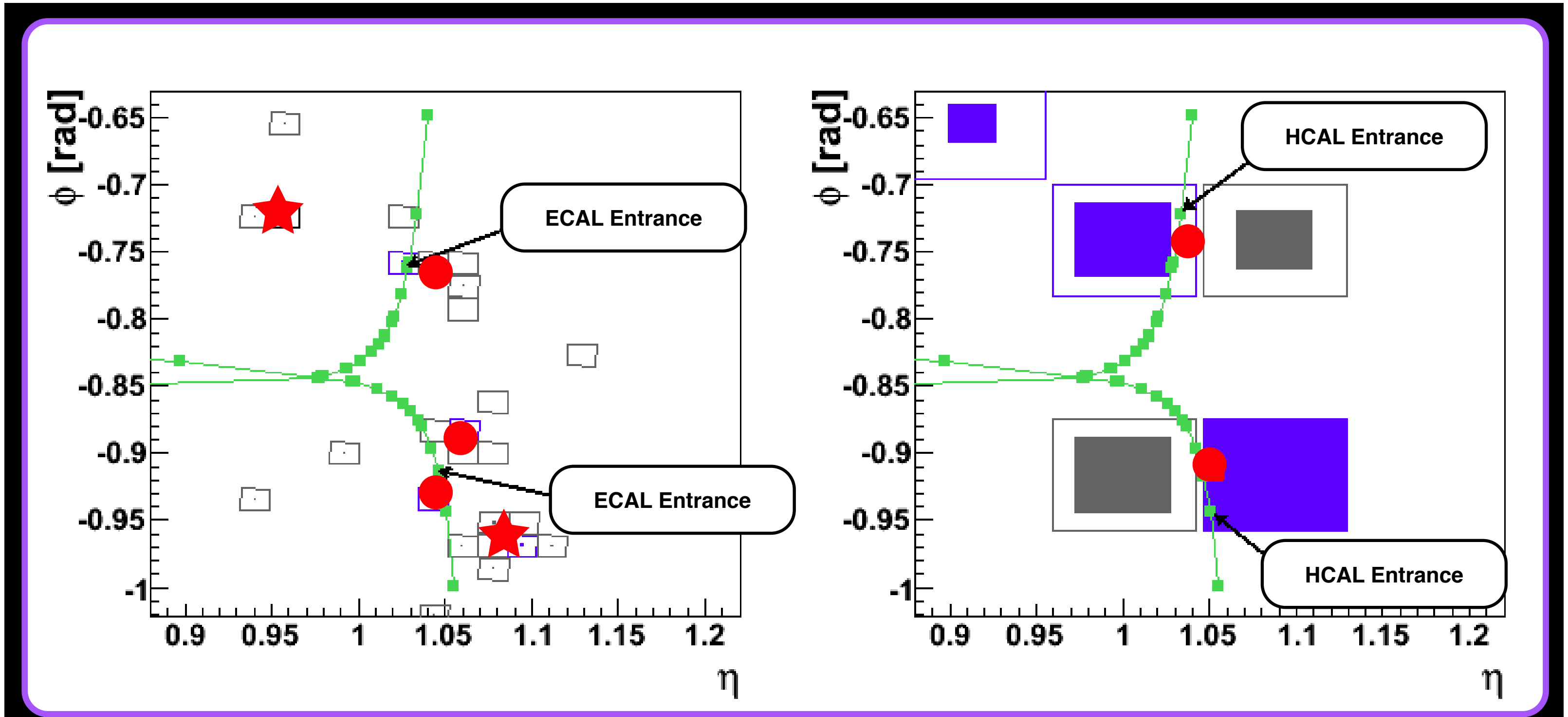
CMS



- particle-flow reconstructs constituent 4-vectors
- τ_h reco seeded by particle-flow hadrons
- Hadron Plus Strip (HPS) algorithm for counting π^0s
- isolation cone for rejecting QCD jets

[ATLAS-CONF-2011-152, CMS PAS TAU-11-001]

CMS Particle Flow

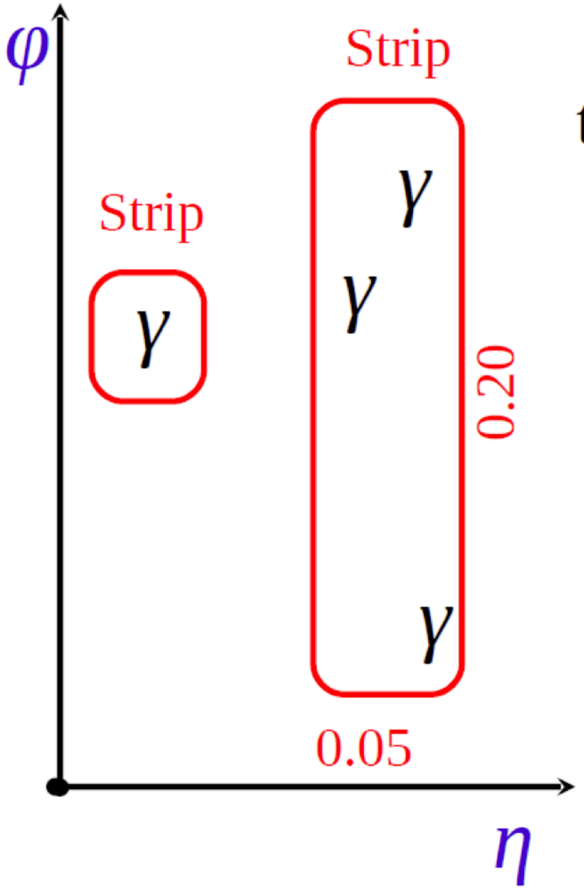


● cluster linked to track
★ unlinked cluster
🟩 tracker hit

see CMS PAS PFT-10-002

- Matches track to clusters to form charged and neutral PF objects.
- PF objects are used as input for all CMS tau reconstruction.

CMS: Hadron Plus Strip (HPS)



Build all possible taus
that have a ‘tau-like’multiplicity
from the seed jet

π^+

$\pi^+ \pi^0$

$\pi^+ \pi^+ \pi^-$

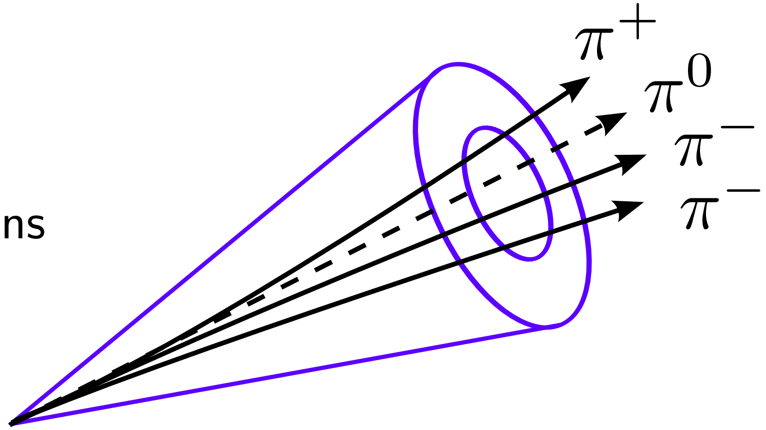
tau that is ‘most isolated’
with compatible m_{vis}
is the final tau candidate
associated to the seed jet

Discrimination with calorimeter based isolation $\Delta R < 0.5$.

[CMS PAS TAU-11-001]

CMS: Tau Neural Classifier (TaNC)

- Uses a ***shrinking core-cone***:
  - $\Delta R(\text{photons}) < 0.15$ for photons
  - $\Delta R(\text{charged}) < (5\ \text{GeV})/E_\text{T}$ for charged hadrons
  - $\Delta R(\text{charged}) < \Delta R(\text{isolation}) < 0.5$



- Immediately discarded if the candidate doesn't match an expected tau decay mode.

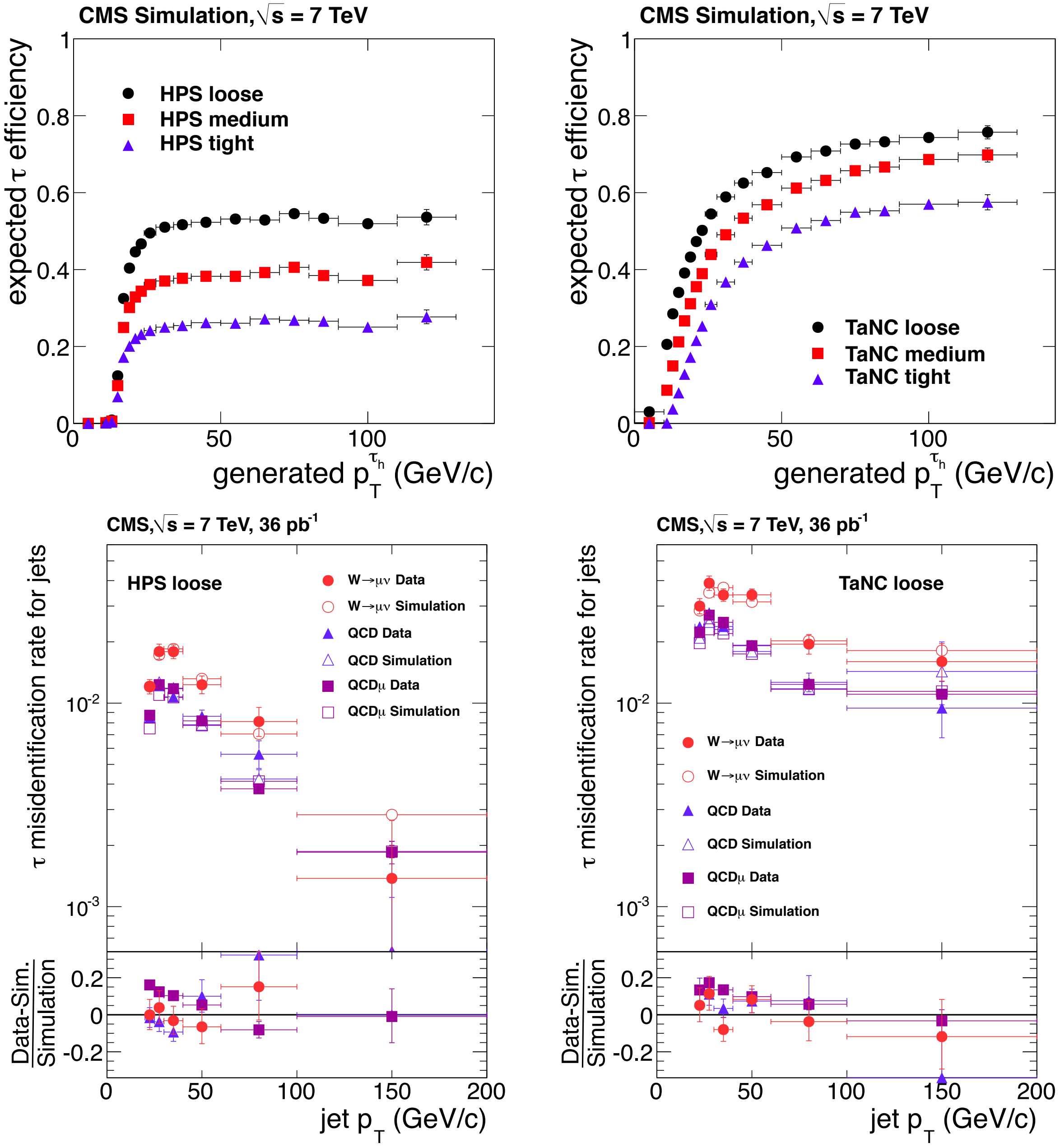
Decay mode	Resonance	Mass (MeV/c^2)	Branching fraction (%)
$\tau^- \to h^- \nu_\tau$			11.6%
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ^-	770	26.0%
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	a_1^-	1200	9.5%
$\tau^- \to h^- h^+ h^- \nu_\tau$	a_1^-	1200	9.8%
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8%

- Dedicated Neural-net classifier for each decay mode

[CMS PAS TAU-11-001]

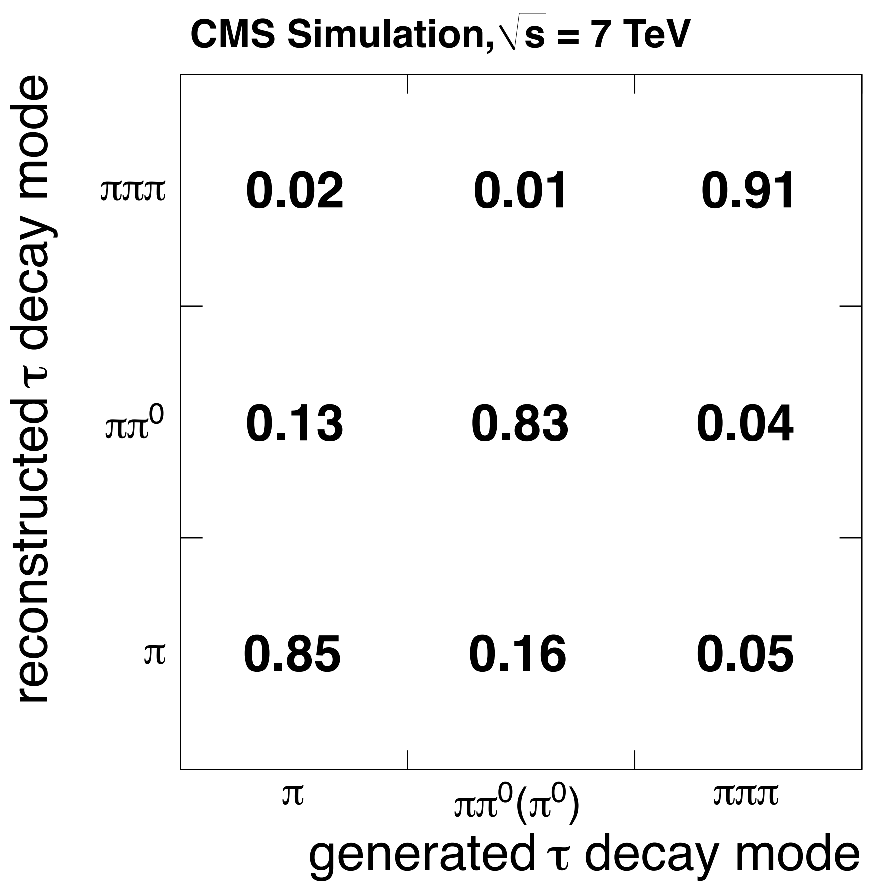
CMS Performance

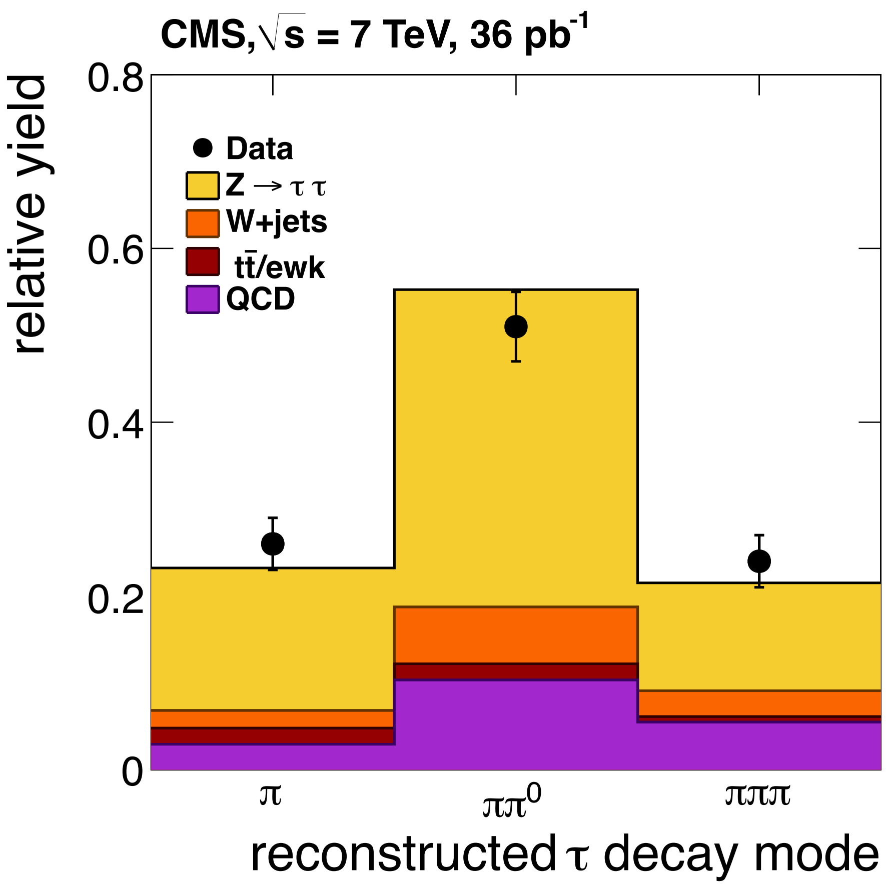
- Not trivial to compare ATLAS and CMS tau performance because we bin fake-rates in N(track) instead of categorizing the decay mode.



[CMS PAS TAU-11-001]

CMS decay mode ID





[CMS PAS TAU-11-001]

Calorimeter granularity

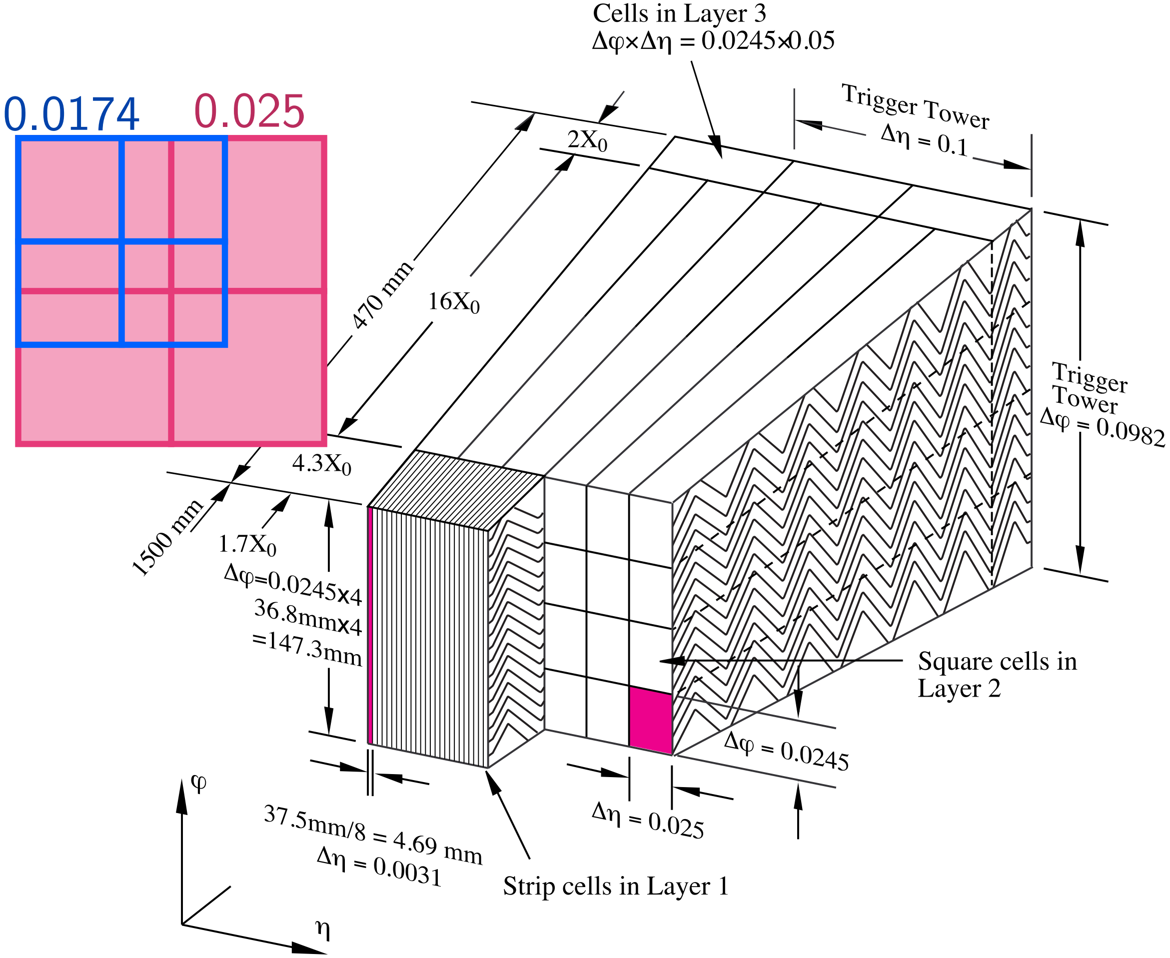
ATLAS

- $B = 2.0$ T
- $\Delta\eta \times \Delta\phi =$ 0.025×0.0245
- R = 0.4 anti-k_T topo-jets

CMS

- $B = 3.8$ T
- $\Delta\eta \times \Delta\phi =$ 0.0174×0.0174
- R = 0.5 anti-k_T PF-jets

ATLAS Barrel EM Calorimeter



Granularity could fundamentally limit our capacity to reconstruct sub-structure / π^0s.