Identification of hadronically decaying Tau Leptons at the LHC

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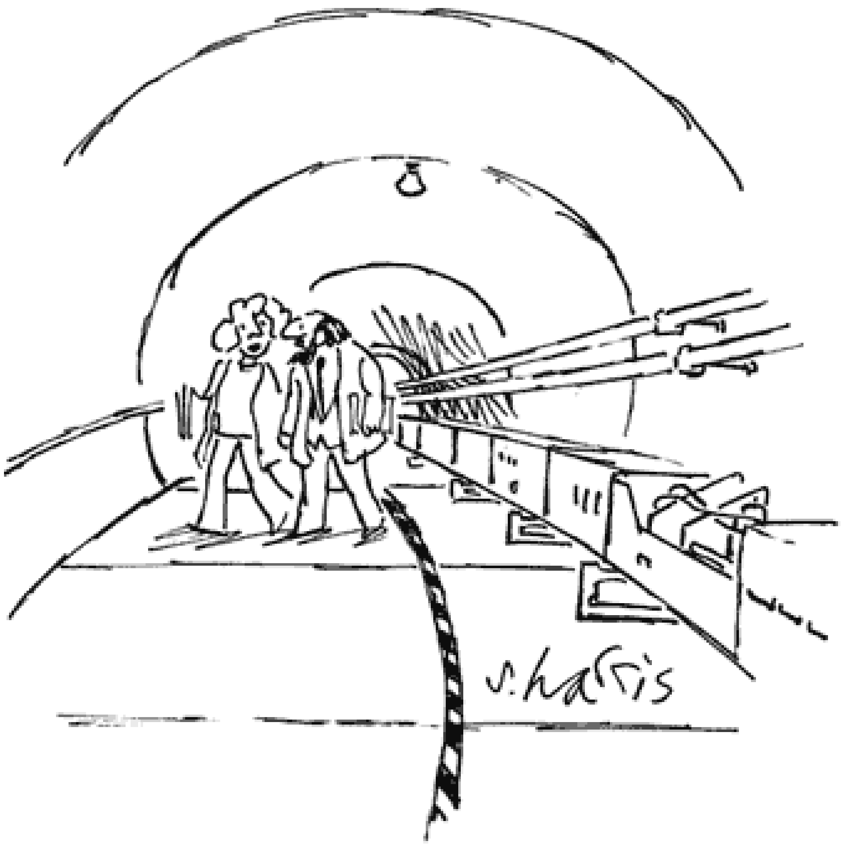
Detector Understanding with first LHC Data
01. Juli 2009 - Happy Canada Day!

Outline

- Physics potential with tau leptons
- General tau lepton properties
- ATLAS/CMS Tau Reconstruction and Identification Algorithms
- ATLAS/CMS Tau Trigger
- Remarks on Tau ID performance in early data
- Physics with tau leptons at the LHC with early data
- Concluding Remarks

Physics with Tau Leptons

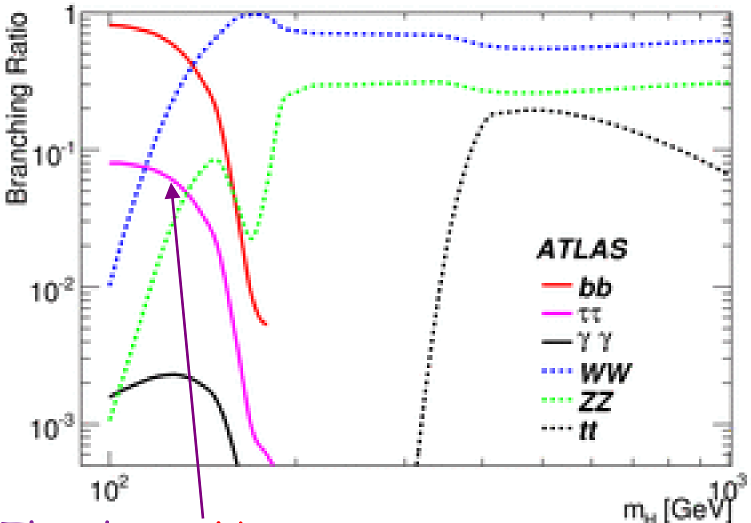


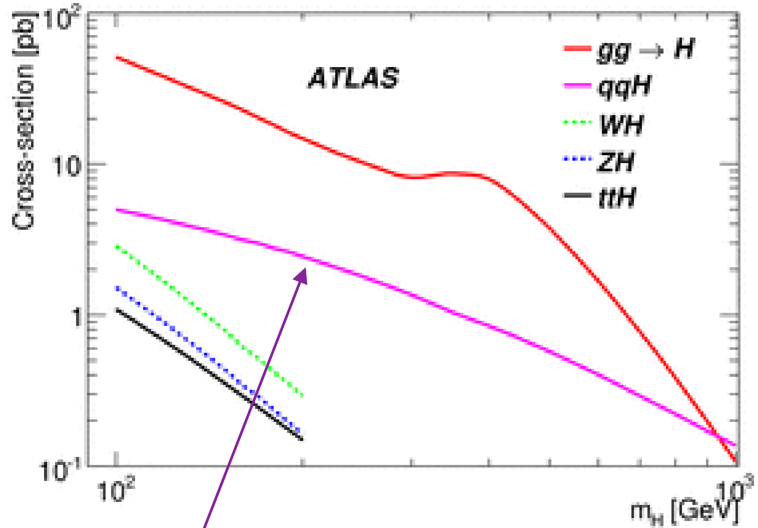
"WHAT IF WE SPEND ALL THESE BILLIONS, AND THERE JUST AREN'T ANY MORE PARTICLES TO FIND?"

Finding new particles at the LHC often involve τ-leptons in the final state

- Standard Model Higgs boson
- Supersymmetry searches
- MSSM Neutral Higgs boson
- MSSM Charged Higgs boson
- W '/ Z ' bosons with enhanced 3rd generation coupling
- other scenarios possible

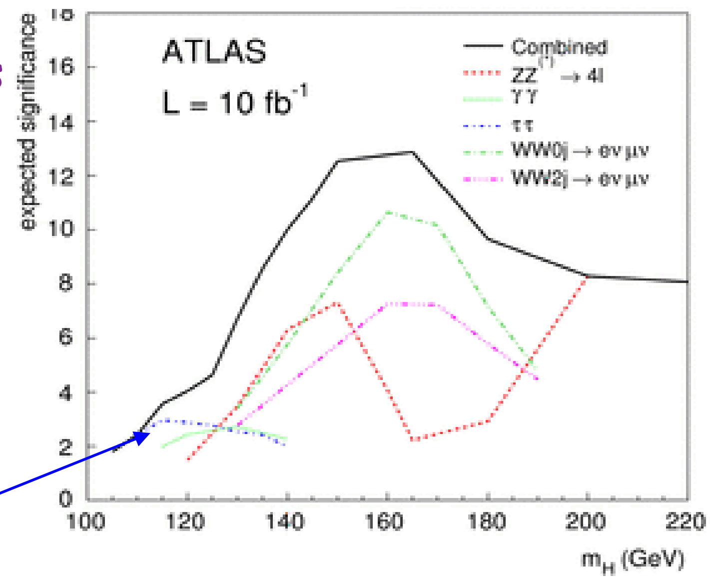
Standard Model Higgs Boson





The decay H->ττ occurs at about 10% BR at low Higgs masses

The qqH (Vector Boson Fusion) channel gives forward tagging jets in addition to the H->ττ signature

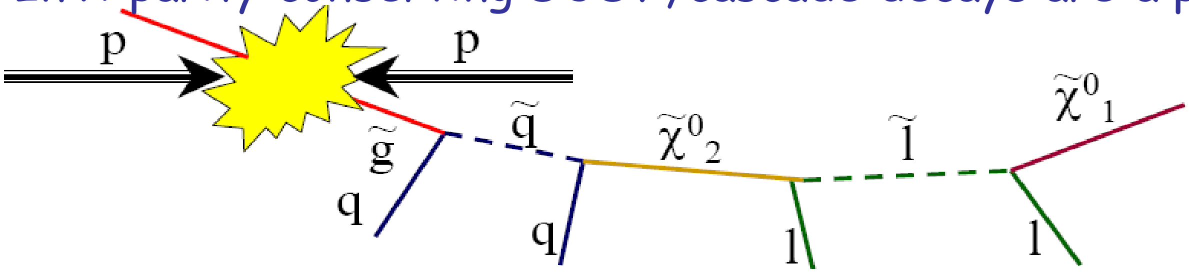


Electroweak measurements of the top mass and the W mass seem to hint at a low mass Higgs:
$m_H = 90_{-27}^{+36}$ GeV or m_H<163 GeV (95% CL)

In this region the qqH->qqττ has the most sensitivity to the SM Higgs Boson

Supersymmetry

In R-parity conserving SUSY, cascade decays are a prominent feature



NLSP decay: $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}\tau$

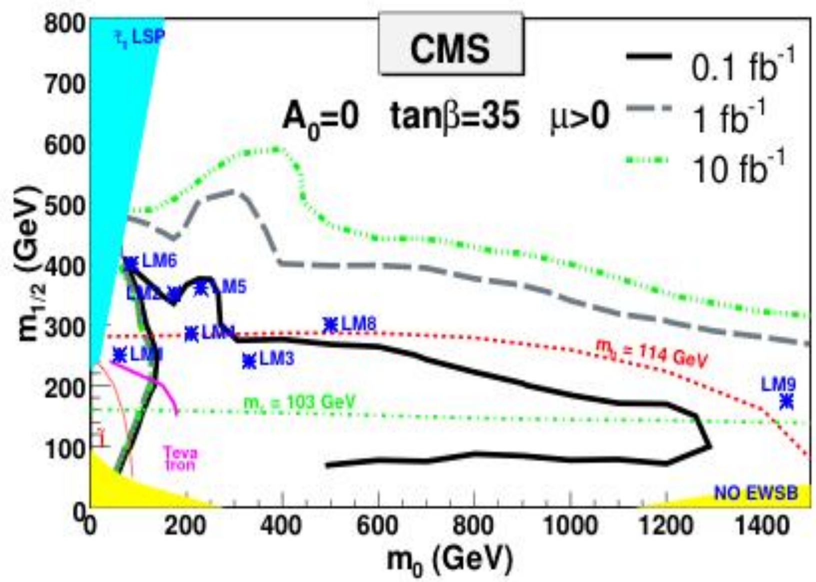
For large tanβ, we have $m_{\tilde{e}} >> m_{\tilde{\tau}}$ and so $\tilde{\chi}_2^0 \rightarrow \tilde{e}e$ is not allowed

In some regions of SUSY parameter space, signatures with taus are the most promising

di-tau (had-had) discovery reach in the m_0-$m_{1/2}$ plane

m_0 : universal scalar mass (GUT scale)

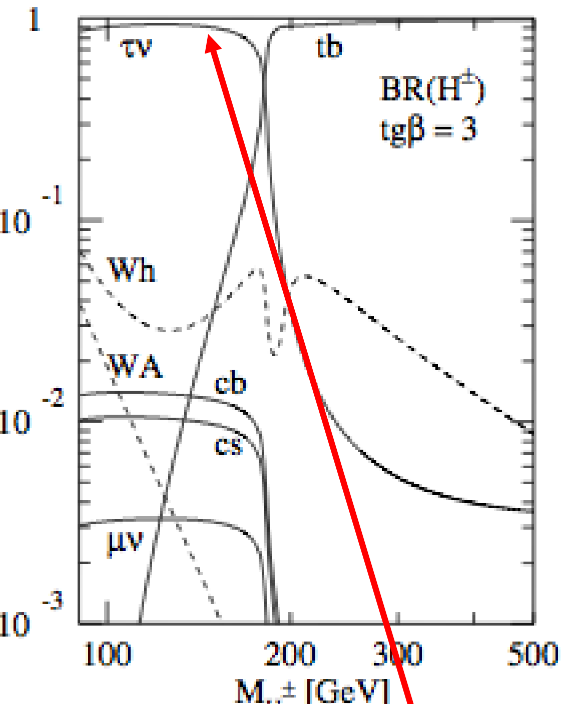
$m_{1/2}$: universal gaugino mass (GUT scale)

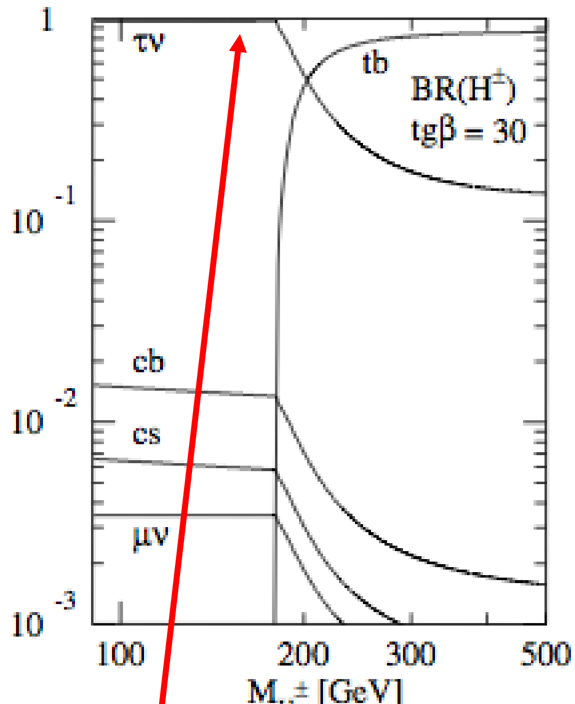


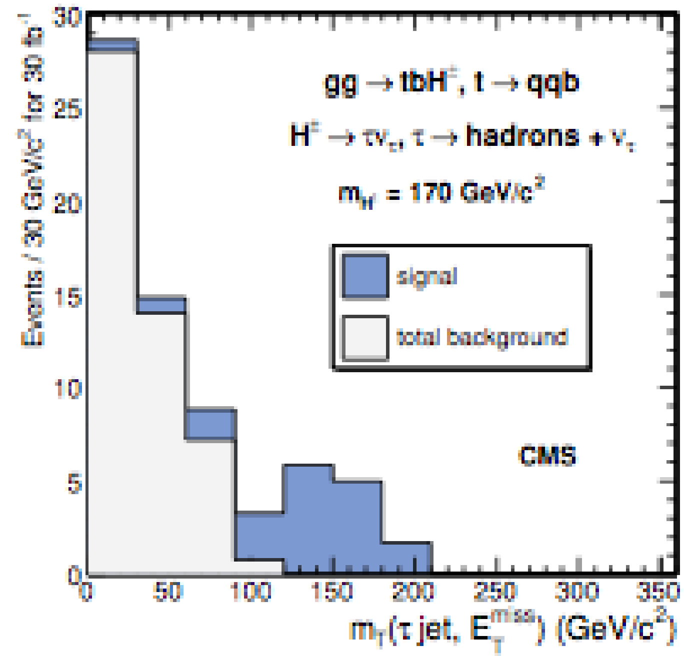
Best of both worlds - SUSY Higgs

The Higgs Sector gets much more complex with SUSY: 5 Higgs bosons!

H^0, h^0: CP Even neutral A^0: CP Odd neutral H^+, H^-: charged Higgs (shown)







Note high branching ratio to $\tau\nu$ especially for high $\tan\beta$ and low mass

Tau final states also important for MSSM neutral Higgs boson searches

Exotic Gauge Boson Production

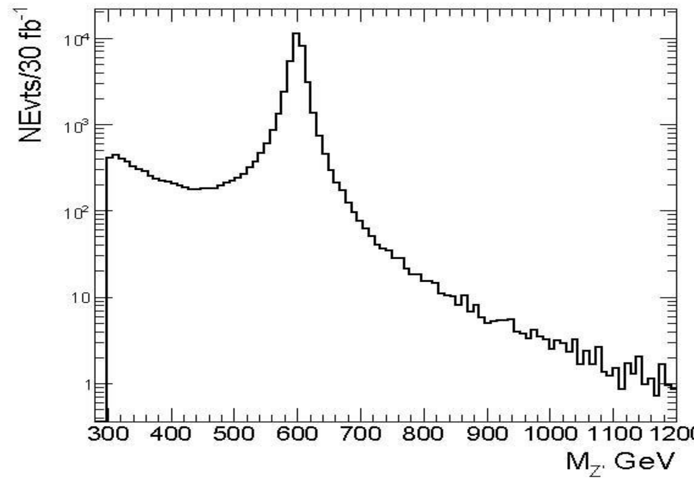
New Heavy Gauge Bosons such as W ' and Z ' bosons are predicted for some models

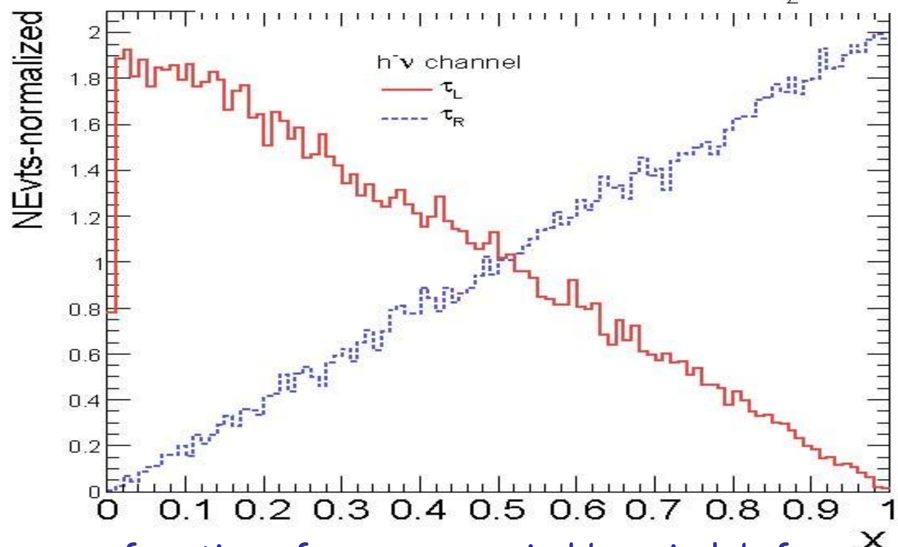
Perhaps such bosons have preferential couplings (or maybe even exclusive couplings) to third generation leptons/quarks

Could look for a $Z' \rightarrow \tau\tau$ or $W' \rightarrow \tau\nu$ excess above background

Even if no preferential couplings to third generation can infer other properties using τ-channels: Z ' polarization

We would want to separate out left-handed and right-handed τ-leptons (hadronically decaying)





fraction of energy carried by τ in lab frame

Basic Tau Properties

Tau Branching Ratios

- Leptonic Decay Modes
  $e/\mu\nu_{e\mu}\nu_\tau$ 35%
- 1Prong Hadronic Decay Modes

$\pi^-\nu_\tau$	11%	47%
$\pi^-\pi^0\nu_\tau$	25%	
$\pi^-\pi^0\pi^0\nu_\tau$	9%	
$\pi^-\pi^0\pi^0\pi^0\nu_\tau$	1%	
$K^- +$ Neutrals	1.5%	

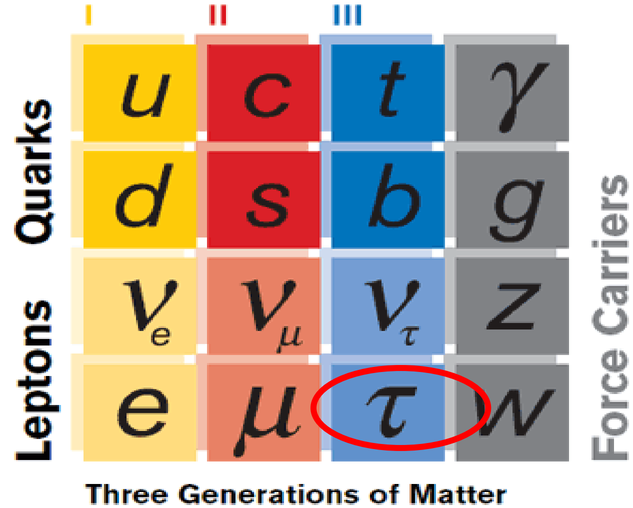
- 3Prong Hadronic Decay Modes

$\pi^-\pi^+\pi^-\nu_\tau$	9%	15%
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$	4.5%	
$K^-\pi^+\pi^-\nu_\tau$	0.4%	

- Other Modes ($\sim 3\%$)

Tau Characteristics

- $m_\tau \sim 1.7\mathrm{GeV}$
- $c\tau = 87\mu\mathrm{m}$
- Hadronic Decays are well Collimated Collection of Charged and Neutral Pions/Kaons
- Most have 1 or 3 Charged Tracks
- Leading Pion Direction Reproduces τ Direction Well.



observed first in 1977 by Martin Perl et al. (SLAC-LBL)

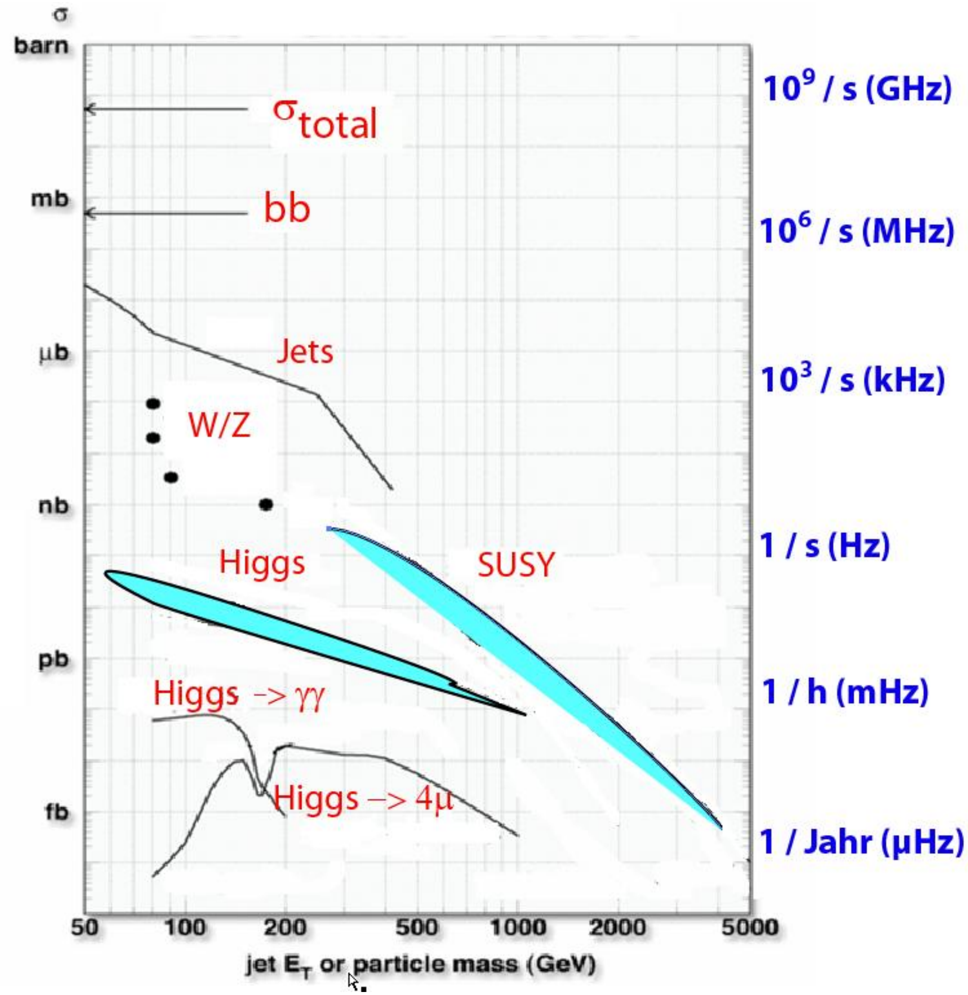
Because leptonic tau decays cannot really be separated from electrons and muons, we say „tau reconstruction and ID“ to refer to hadronically decaying tau leptons

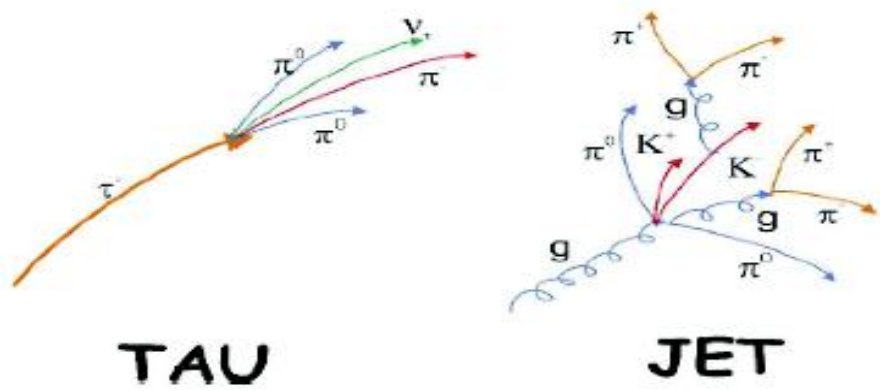
We try to distinguish between 1-prong and 3-prong tau decays (neglect 5-prong)
We may in some cases try to reconstruct the number of π^0 in the tau decay

Taus and Jets

Both hadronically decaying taus and jets deposit energy in the EM and Had calorimeters

Challenge: separate out a clean sample of taus from the overwhelming QCD jet rate!





TAU

- narrow, collimated
- 1 or 3 tracks
- higher fractional EM deposit
- can define isolation regions with low activity
- leading track carries much of tau momentum

JET

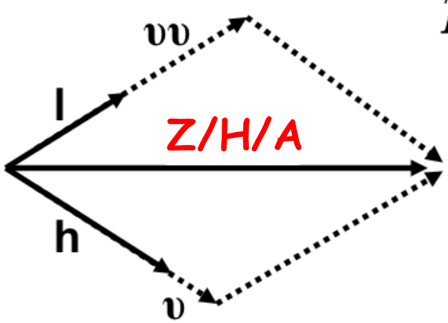
- wide
- can have many tracks
- higher fractional HAD deposit
- isolation regions busy
- jet momenta spread over tracks

Reconstructing the ττ invariant mass

Use the collinear approximation to reconstruct the ττ mass

- A good approximation when the parent particle is heavily boosted
- Assume that the tau decay products are collinear to the tau direction
- Note: approximation breaks down when the decay daughters are back-to-back

$$p_{T,\tau_l} + p_{T,\tau_h} = p_{T,l} + p_{T,h} + p_{T,\mathrm{miss}}$$



$$\vec{p}_\tau = \frac{\vec{p_l}}{x_\tau}$$

Fraction of the tau momentum carried by the visible daughter

$$x_{\tau_h} = \frac{p_{x,h}p_{y,l} - p_{y,h}p_{x,l}}{p_{x,h}p_{y,l} + p_{x,miss}p_{y,l} - p_{y,h}p_{x,l} - p_{y,miss}p_{x,l}}$$

$$x_{\tau_l} = \frac{p_{x,h}p_{y,l} - p_{y,h}p_{x,l}}{p_{x,h}p_{y,l} - p_{x,miss}p_{y,h} - p_{y,h}p_{x,l} + p_{y,miss}p_{x,h}}$$

$$M_{\tau\tau} \approx \frac{M_{lh}}{\sqrt{x_{\tau_l}x_{\tau_h}}}$$

The ATLAS Tau Reconstruction Algorithm

The ATLAS Tau Reconstruction Algorithm can be organized in four steps

1) Seed Building
- track seed finding
- calorimeter seed finding

2) Base Reconstruction
- track association
- calculation of ID variables
- energy/energy flow calculation

3) Tau Substructure Reconstruction
- pi0 cluster reconstruction
- conversion track removal

4) Identification Algorithms
- electron and muon vetoes
- cut-based ID
- multi-variate ID: projective likelihood, NN, boosted decision trees, probability density range searches

ATLAS properties:

ATLAS has pixel/SCT/TRT with B = 2 T

tracker provides coverage to $|\eta| < 2.5$

ECAL (LAr calorimeter) covers to $|\eta| < 3.2$ with high granularity

HCAL is 25 times coarser than the ECAL:
proper coverage to $|\eta| < 3.2$
forward coverage $3.2 < |\eta| < 4.9$

tracker $X/X_0 = 0.5 - 1.8$ lengths

Tau Seeds at ATLAS

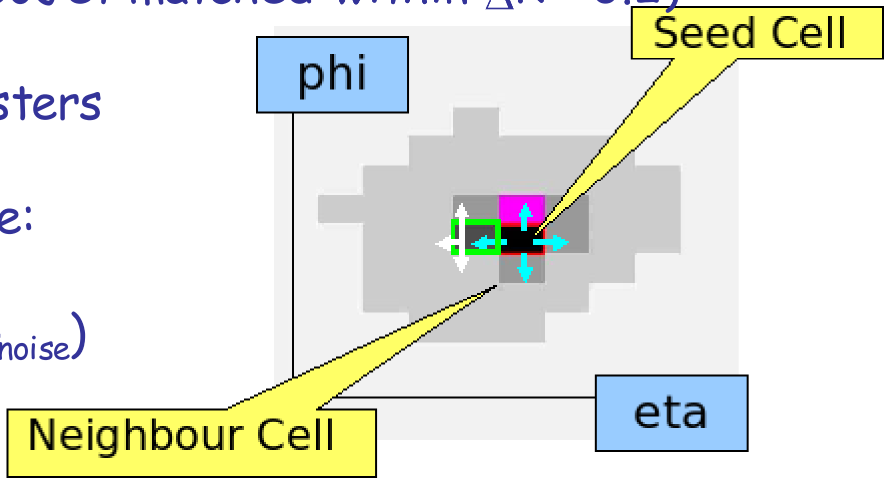
Three categories of tau candidates based on the seed composition:

- track-only seeded candidates (quality track with $p_T > 6$ GeV)
- calo-only seeded candidates (TopoJet with $E_T > 10$ GeV)
- candidates seeded by both (track and TopoJet matched within $\Delta R < 0.2$)

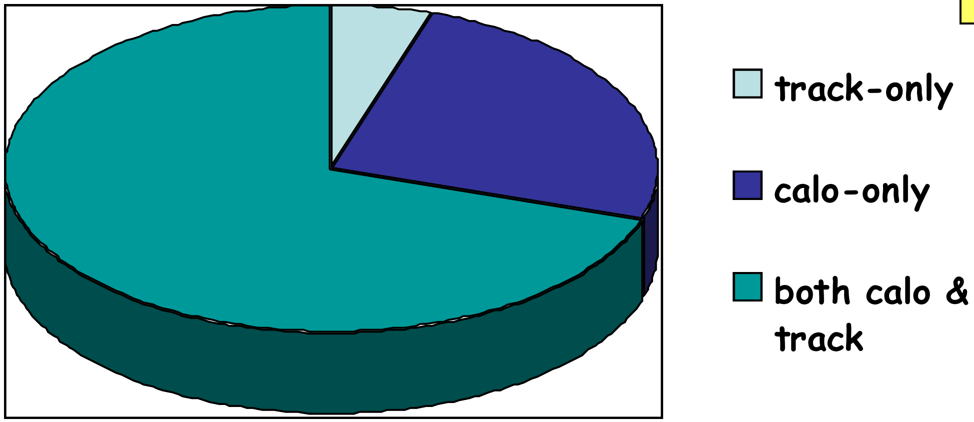
TopoJet - cone algorithm run over TopoClusters

TopoCluster - iterative clustering procedure:

- start with seed cells (exceed $4\sigma_{noise}$)
- add neighbour cells (exceed $2\sigma_{noise}$ and $0\sigma_{noise}$)
- split cluster if multi local maxima



topocluster schematic

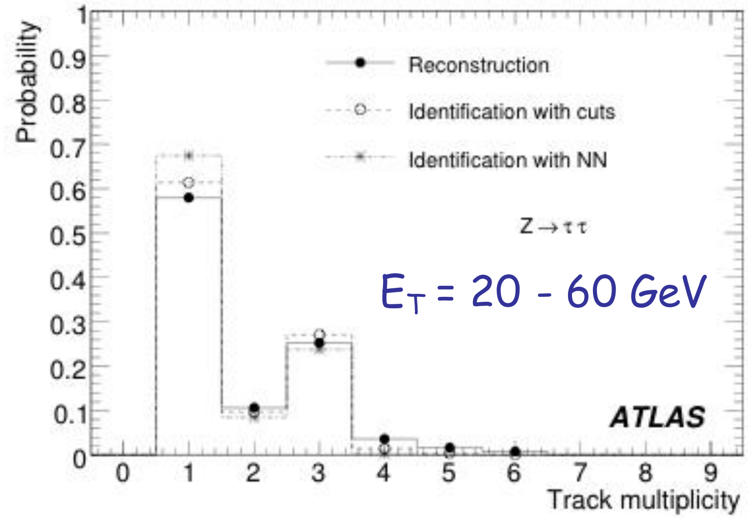


seed composition for truth-matched tau candidates in $Z \rightarrow \tau\tau$

both-seeded candidates the most „truth worthy“

Base Reconstruction at ATLAS

Direction (η,φ) of tau determined by leading track (unless no track seed - then determined by jet barycentre)

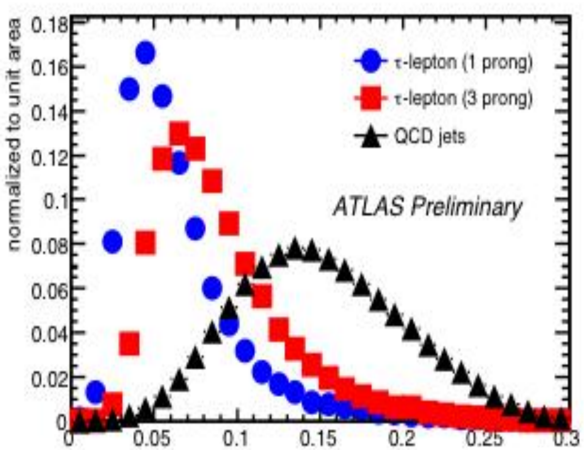


Quality tracks associated in $\Delta R < 0.2$ of seed direction

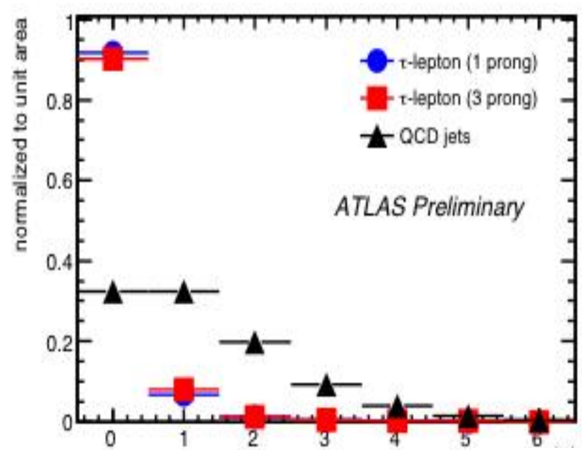
Energy calculated by:

- cell weighting (default): $E_{calib} = w(\eta,\varphi,i) \times E_{raw}$
- energy flow: neutral energy + charged track momenta terms (corrected for energy leakage)

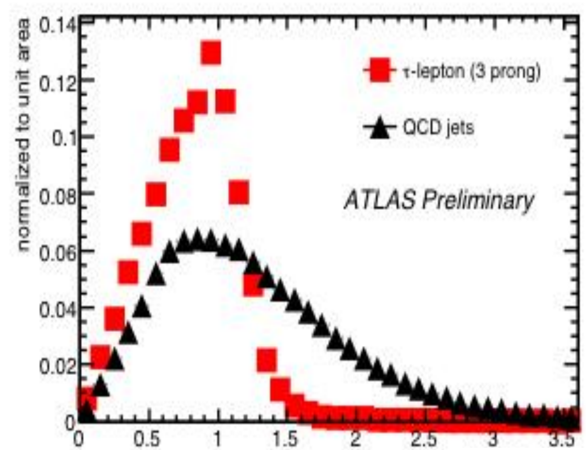
ID variables calculated: isolation, width, ratios of calo energy and track momenta



EM Radius



isolation tracks



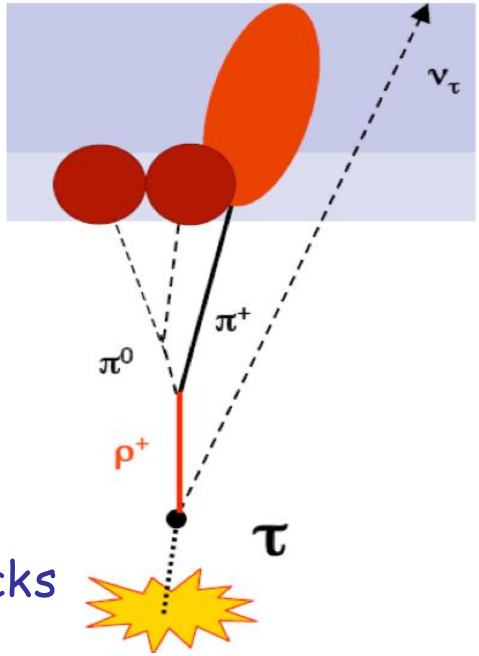
M_{tracks}

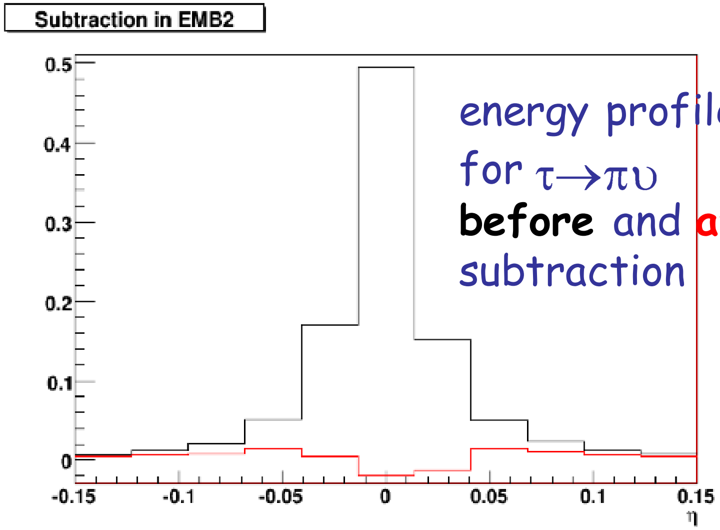
Reconstruction of π^0 showers in tau decays

Just as 1-prong and 3-prong taus have different calo properties, so do $\tau^- \to \pi^- \upsilon$ and $\tau^- \to \rho^- \upsilon \to \pi^- \pi^0 \upsilon$

If possible, it makes sense to require different cuts/pdfs to identify $\tau^- \to \pi^- \upsilon$ and $\tau^- \to \rho^- \upsilon$ decay if we can separate them

ATLAS reconstructs π^0 subshowers by reconstructing EM topoclusters - but need to eliminate clusters from charged particles:
parametrized shower subtraction for clusters matched to tracks





energy profiles for $\tau \to \pi \upsilon$ **before** and **after** subtraction

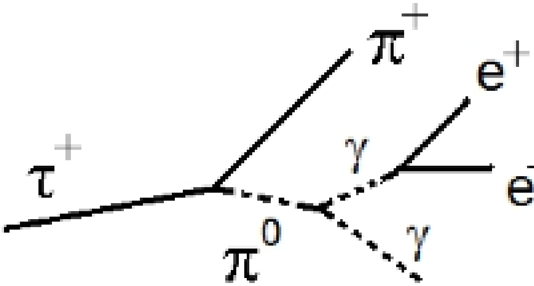
Barrel region

decay	0 π^0	1 π^0	$\geq$ 2 π^0
$\tau \to \pi \upsilon$	61%	23%	16%
$\tau \to \rho \upsilon$	18%	50%	32%
$\tau \to a_1 \upsilon$	9%	36%	55%

Conversion Track Tagging in tau decays

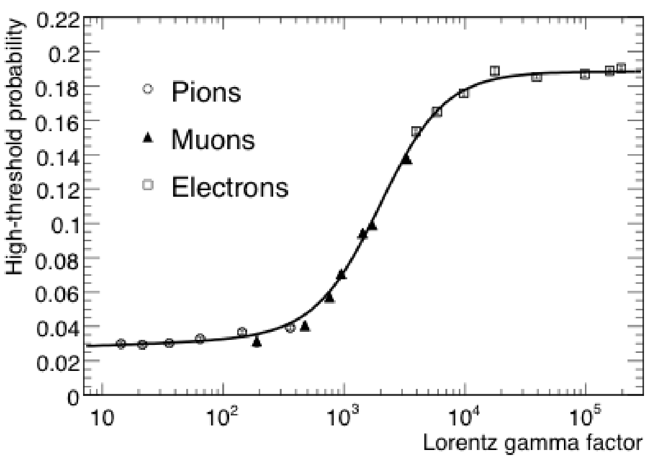
In approximately 40.5% of τ-decays a π^0 is present

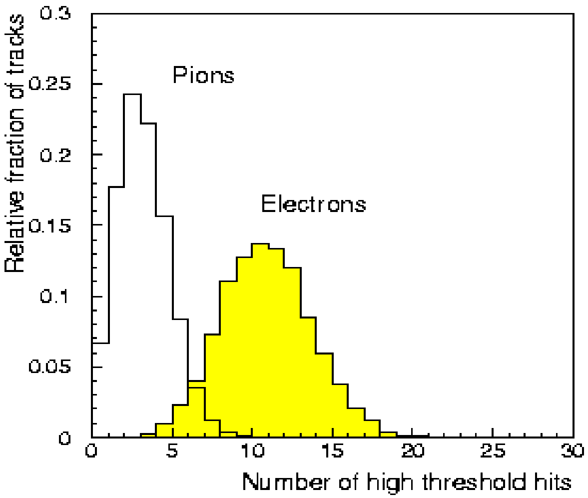
The process $\pi^0 \to \gamma\gamma$ and $\gamma \to e^+e^-$ distorts the track spectrum of τ-leptons - can we tag such tracks as conversion tracks?



There are studies at ATLAS to identify two-track vertex candidates and then calculate electron probability that track originated from an electron

Main property: high threshold TRT (Transition Radiation Tracker) hits
- electrons radiate photons which also can produce hits in the TRT gas hence providing more hits at „high" threshold



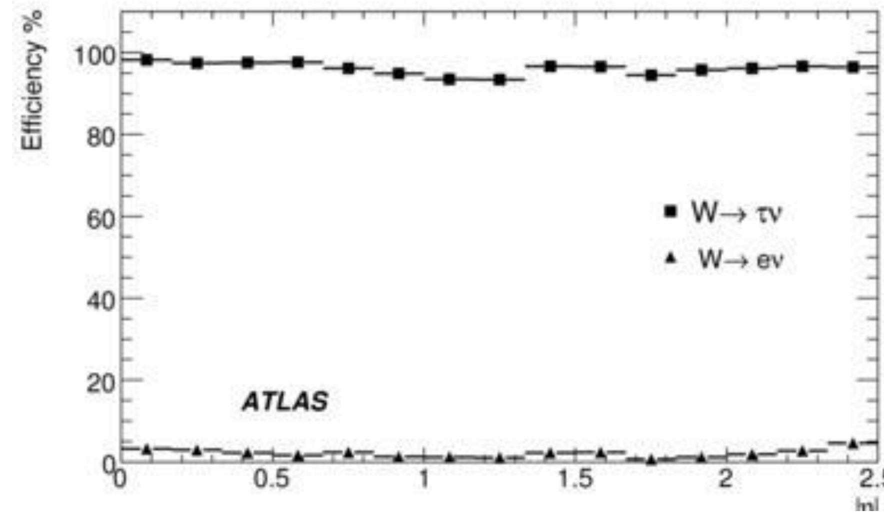


if we tag tracks from conversions, we can reduce the bias introduced on the τ track multiplicity spectrum

Electron Veto at ATLAS

Tau candidates are divided into categories based on:

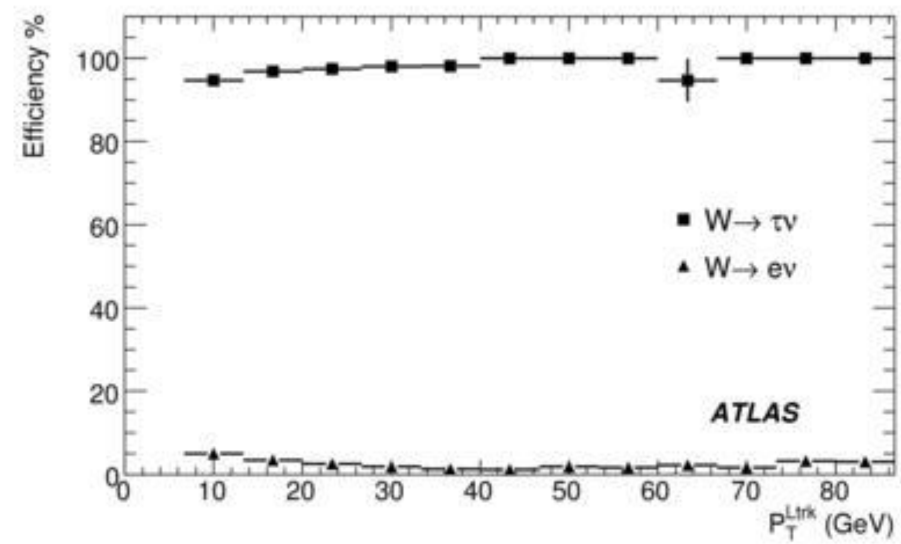
- E^{HCAL} (energy deposited in HCAL)
- E^{strip}_{max} (energy in strip layer that is not associated to leading track)



Then (category-dependent) cuts to veto electrons are placed on:

- $E^{ECAL}_{T}/p_{T}^{lead\ trk}$
(ratio of transverse energy in ECAL to transverse momentum of leading track)

- $N^{TRT}_{HT}/N^{TRT}_{LT}$
(ratio of high threshold to low threshold hits in the TRT)



Tau ID algorithms at ATLAS

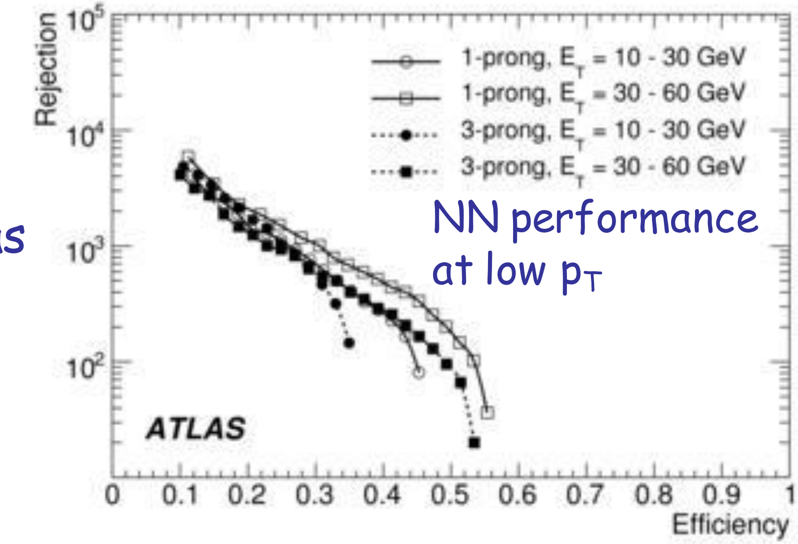
The ID at ATLAS is needed to separate τ-leptons from jets

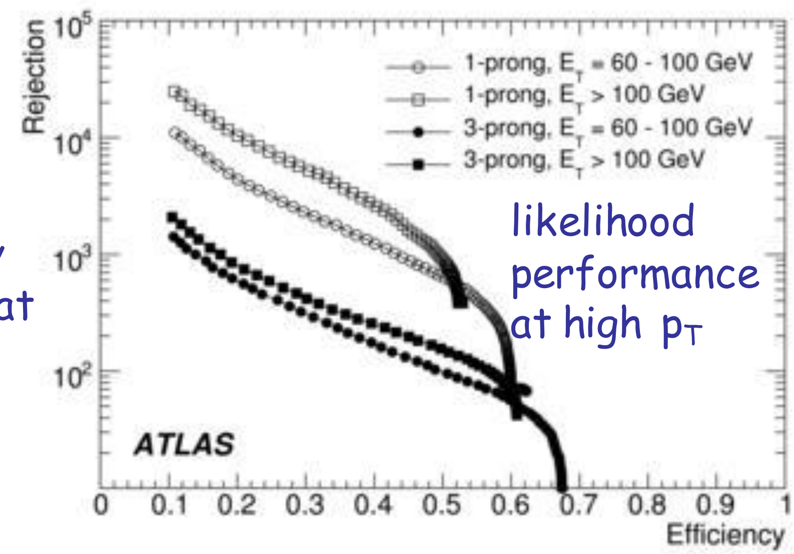
ID algorithms are based on the variables such as isolation fraction, EM radius calculated in the base reconstruction

ATLAS has studied the following:
- cut-based
- Bayesian Projective Likelihood
- Probability Density Range Searches
- Neural Networks
- Boosted Decision Trees

Note that while multi-variate techniques can give very high performance on MC - for first data, it may be that „simpler is better“

cut-based approaches have preference in the early data taking period (more on this a bit later)





The CMS Tau Reconstruction Algorithm

The CMS Tau Reconstruction Algorithm is organized in three steps

1) General Particle Flow Reconstruction
- iterative tracking algorithm
- calorimeter clustering using topological clusters
- links from tracks to clusters
- particle ID and energy calibration

2) Base Tau Reconstruction and Identification
- Cone algorithm to make jets of particles
- match to charged track
- isolation from charged hadrons and photons

3) Higher Level Identification
- other variables to suppress QCD jets
- special criteria to reject electrons and muons

CMS properties:

CMS has silicon tracker with
B = 3.8 T

tracker provides coverage to $|\eta| < 2.6$

ECAL (crystal calorimeter) covers to
$|\eta| < 3.0$ with high granularity

HCAL is 25 times coarser
than the ECAL:
proper coverage to $|\eta| < 3.0$
forward coverage $3.0 < |\eta| < 5.0$

tracker X/X_0 = 0.4 - 1.6 lengths

Particle Flow Algorithm at CMS

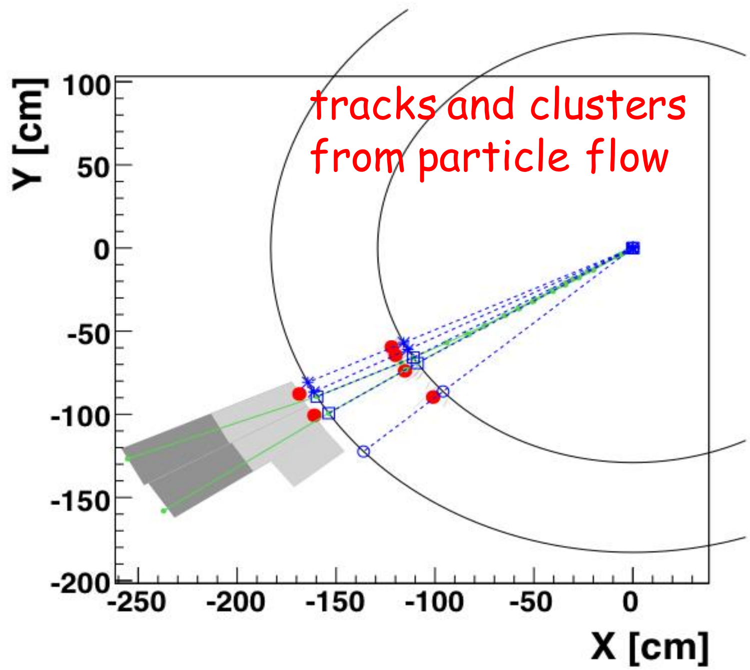
Particle Flow: Reconstruction of all particles in the event using all detector subsystems

Iterative tracking:

- start with very tight criteria on reconstructed tracks (seed tracks)
- remove hits associated to selected tracks from consideration
- loosen tracking criteria to reconstruct additonal tracks without removed hits
- iterative procedure gives high efficiency, while reducing fakes due to hit removal of already selected tracks
- finally loosen constraints on primary vertex to pick up tracks from K^0_S and Λ tracks

Calo clustering (topoclusters):

- cluster seed - local maxima exceeding threshold
- add iteratively neighbouring cells exceeding threshold
- separate clustering in different calorimeter components



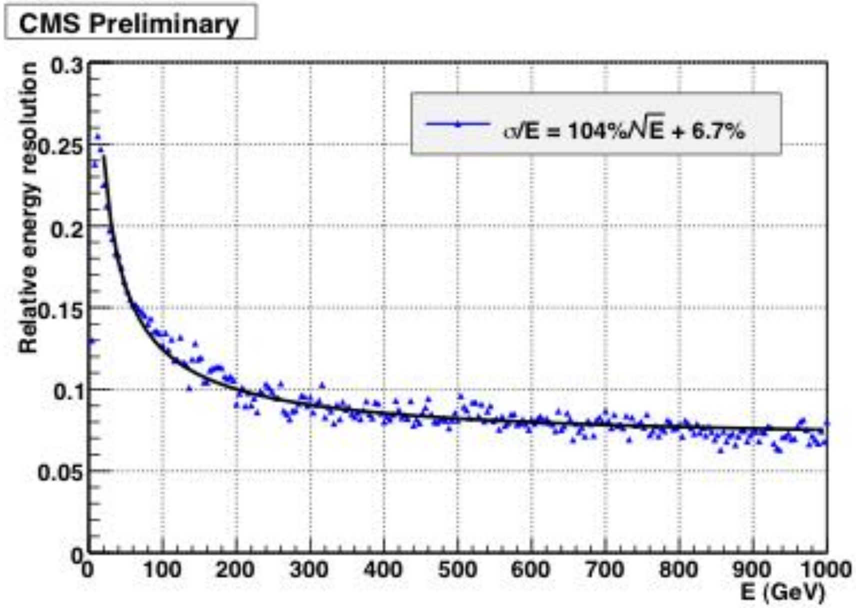
Particle Flow Algorithm at CMS

Track extrapolation to calorimeter systems at the expected depth and linked to clusters if the extrapolation is within cluster boundaries

Clusters are linked to other clusters similarly (using cluster boundaries)

Particle ID performed to assign particle flow objects in the following order:
- muons
- electrons
- charged hadrons
- photons
- neutral hadrons

comparison of tracks to calorimeter information determines which hypothesis is best



Energy Calibration:
$E_{calib} = a + b(E,\eta)E_{ECAL} + c(E,\eta)E_{HCAL}$
where coefficients are tuned to MC for now

Cone algorithm of 0.5 to make „particle-flow jets“ - start of tau reco

Base Tau Reconstruction and ID at CMS

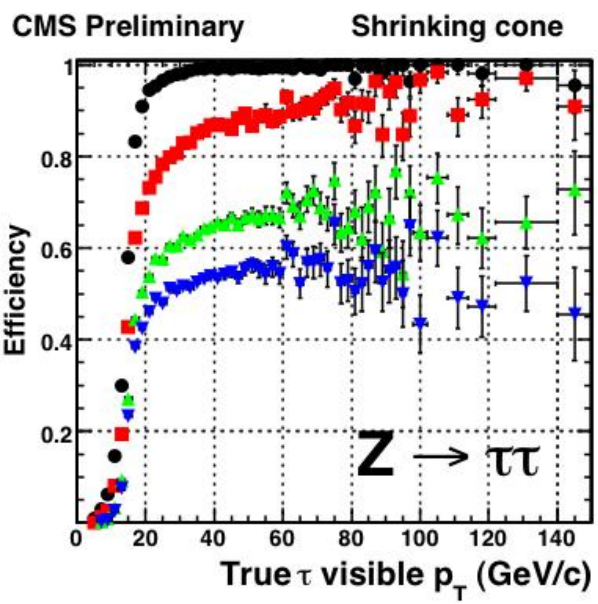
Take „particle flow jets“ with p_T > 15 GeV and require charged hadron candidate with p_T > 5 GeV within ΔR<0.1 of jet direction (forms the leading track)

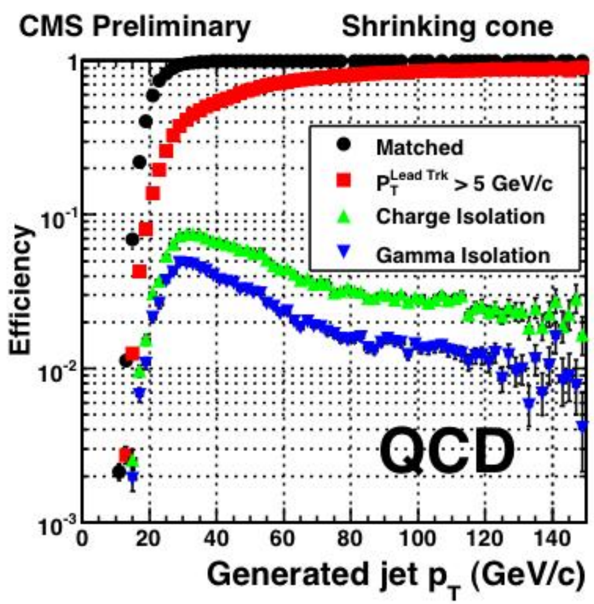
Note:
p_T cut should be tuned to analysis

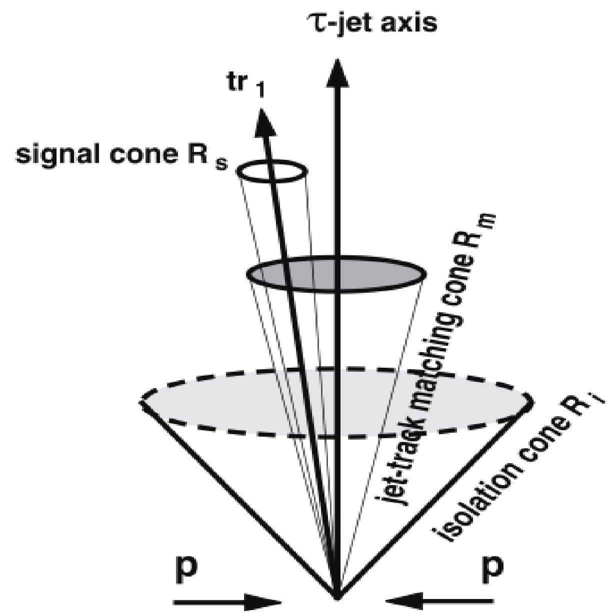
Define a „signal cone“ and „isolation annulus“ around the leading track
- **fixed cones**: 0-0.07 for signal, and 0.07-0.45 for isolation in (η, φ) space
- **shrinking cones**: signal cone limit at $5/E_T$ within 0.07-0.15

No charged hadron candidates or photon candidates allowed in isolation annulus

In development: use particle-flow algorithm to reconstruct secondary tracks from photon conversions (to further reject photons)

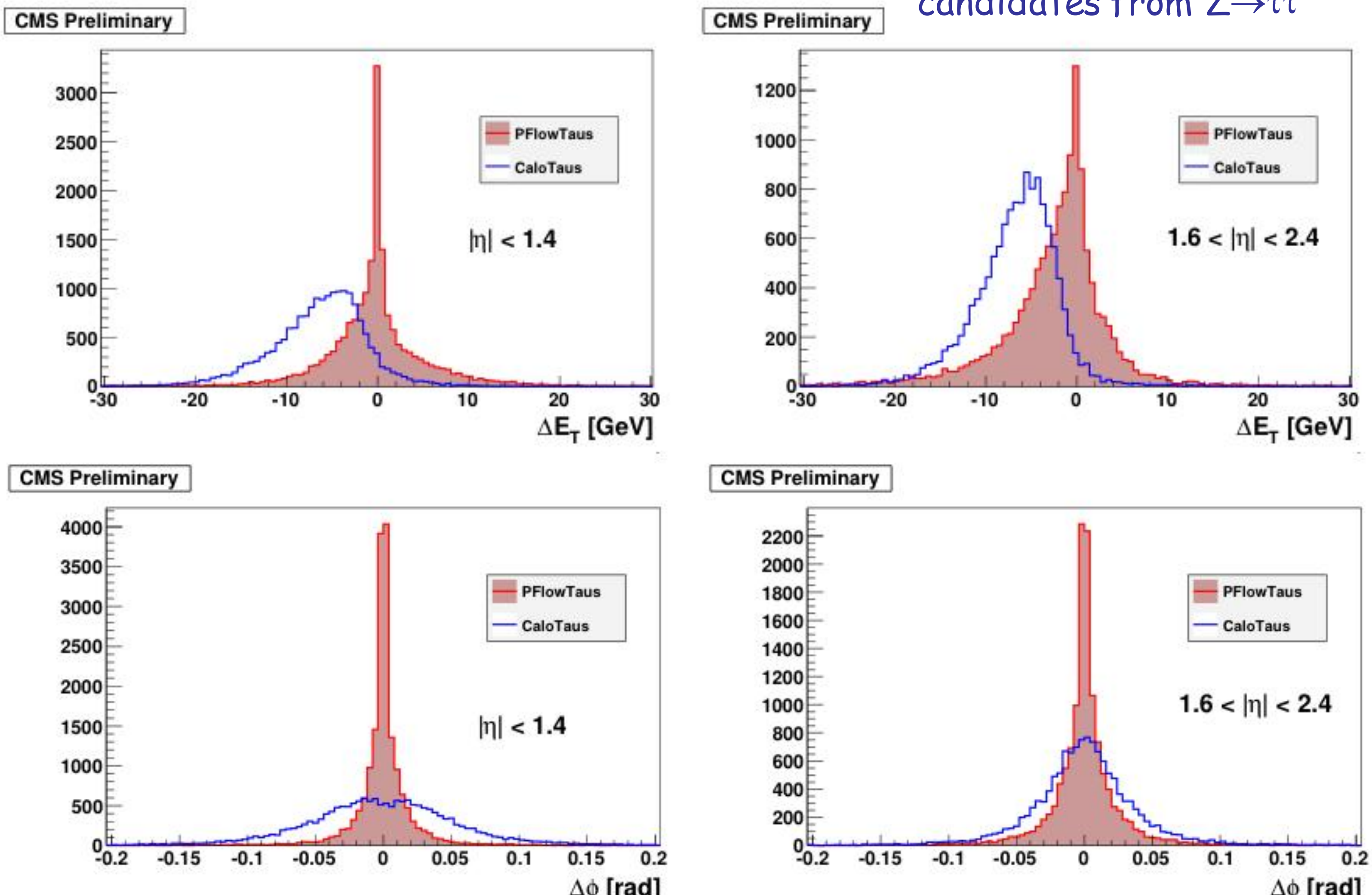






Energy and Direction Resolutions at CMS

candidates from $Z \to \tau\tau$



track information helps improve the resolutions on E_T, η, and φ

Higher Level Tau ID at CMS

Higher level tools to further suppress QCD jets constantly being developed/refined
But many fake taus can come from electrons - electron vetoes are necessary!
Use multi-variate techniques of tracking+calorimeter information to pre-ID electrons

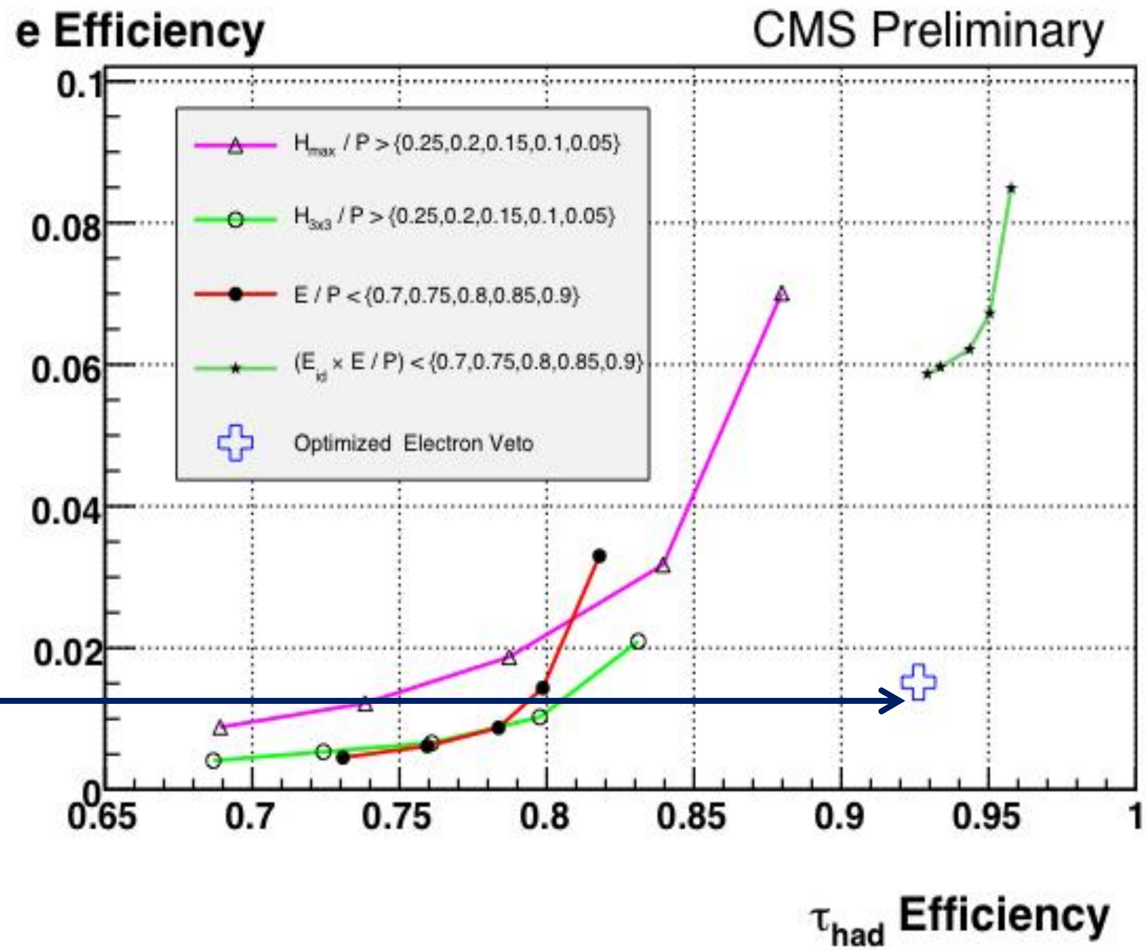
Key variables for electron veto:

E/P: ECAL energy divided by momentum of track
(~1 for electrons, smaller for tau pions)

H_{3x3}/P: HCAL energy divided by momentum of track
(~0 for electrons, flatter for tau pions)

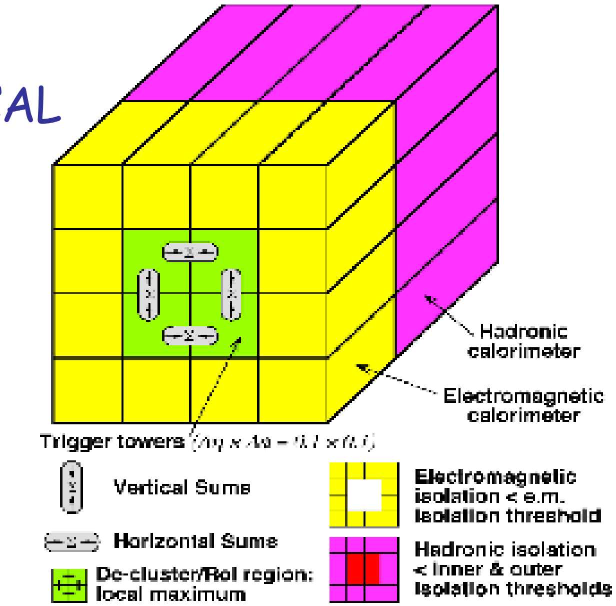
Optimized tuning of cuts performed

Muon veto has also been studied



The ATLAS Tau Trigger

At Level 1, hardware trigger uses calorimeter towers of $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ in 2x1 group in ECAL and 2x2 group in HCAL

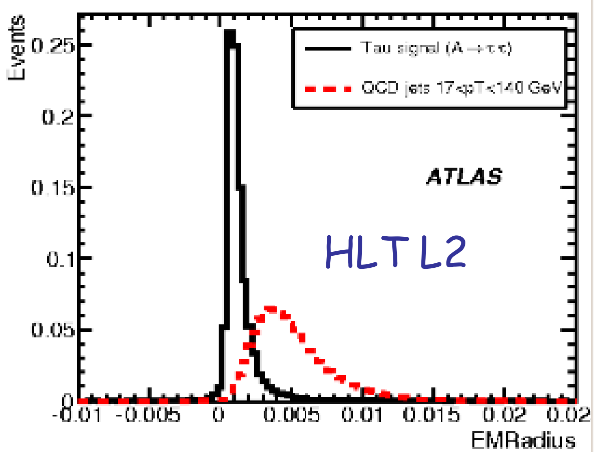


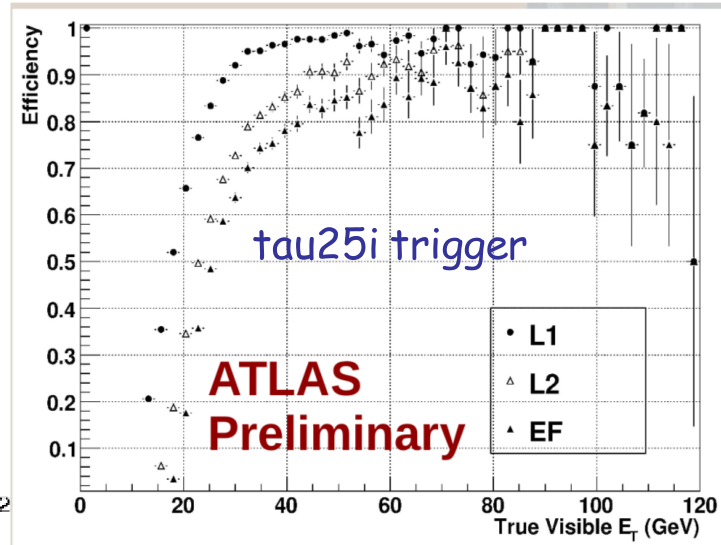
EM/Hadronic isolation also used in 0.1 wide ring around the seed tower

HLT L2 uses ID variables such as:
track multiplicity, isolation, narrowness of candidate

HLT EventFilter uses „pseudo-offline“ algorithms to reconstruct candidate and filter out fakes

rejection of jets from the HLT is approxmately 20





Single Tau triggers,
multi-tau triggers,
tau + E_T^{miss} triggers
all available

The CMS Tau Trigger - Level 1

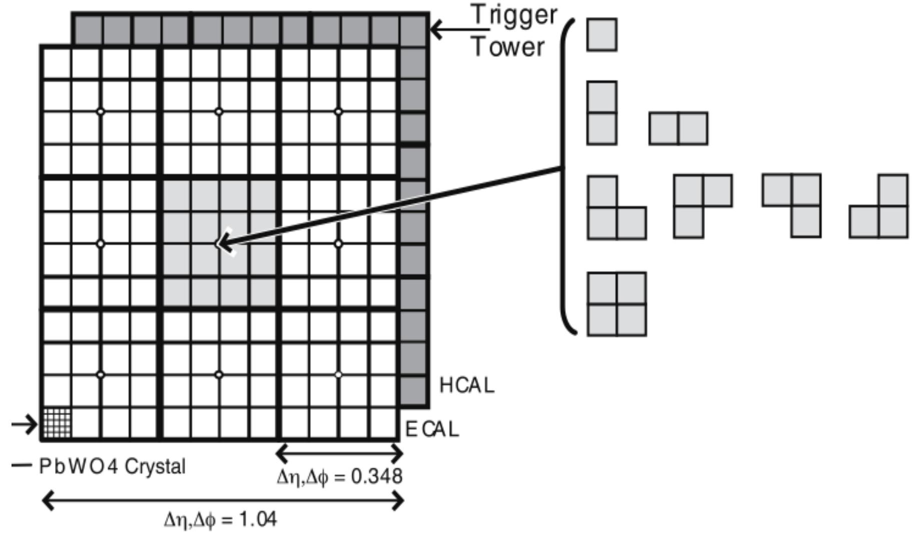
At L1, the CMS calorimeter trigger towers are about 0.087x0.087 in (η,φ)

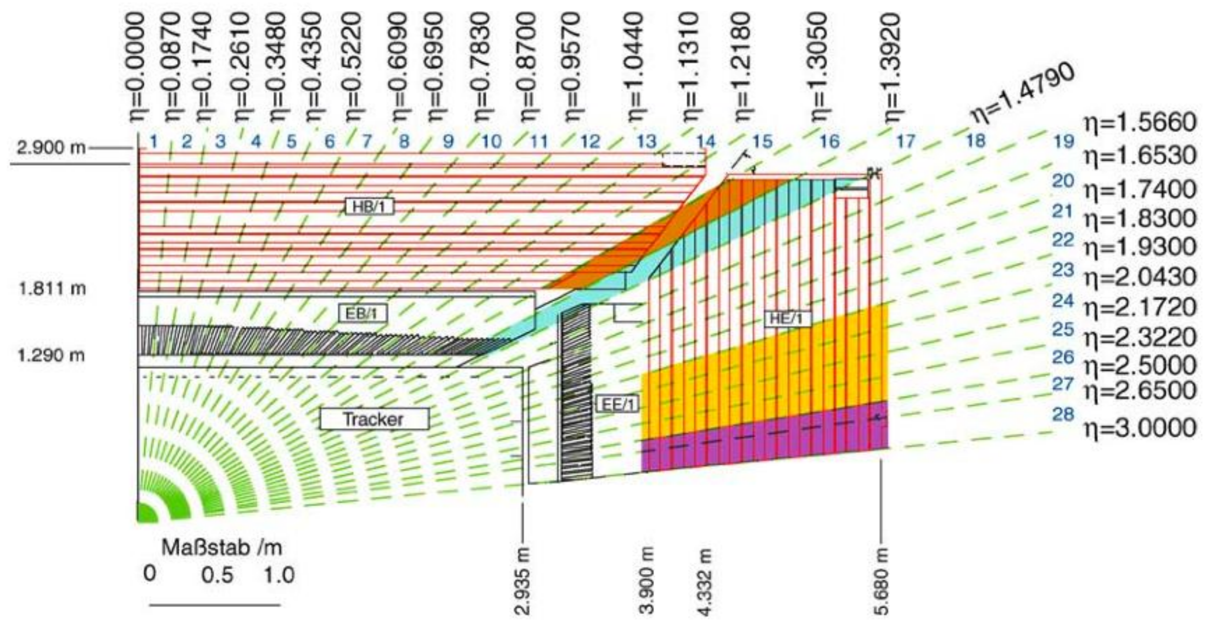
4x4 regions are examined and matched to predetermined patterns

Then the area is expanded to 3x3 regions of 4x4 towers (12x12 in total)
If central region has more energy than its eight neighbours

Level 1 τ-leptons with lower transverse energy need to be prescaled to control the trigger rates

Multi τ-lepton triggers are also possible





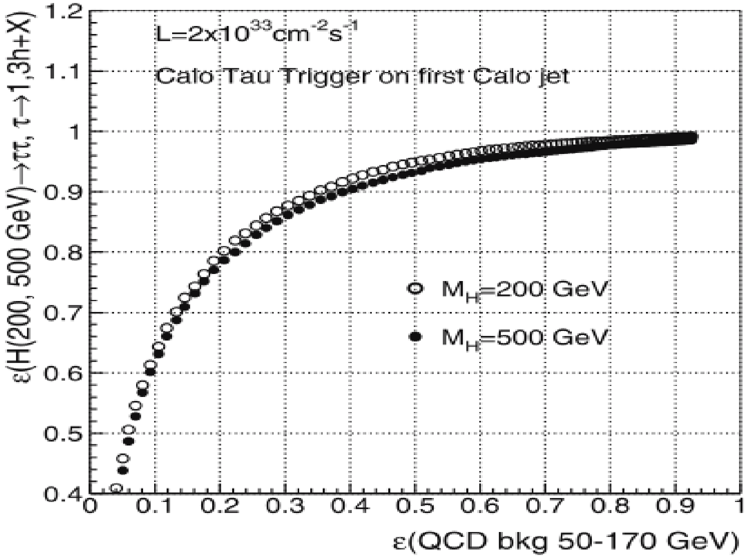
The CMS Tau Trigger - HLT

The High Level Trigger reconstructs tau candidates from the **calorimeter** or from the **pixel** detector

Level-1 τ-jets provide a seed to HLT

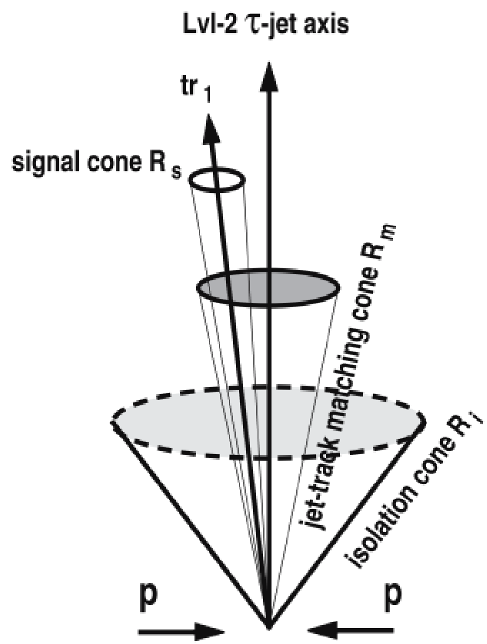
Calo HLT τ-candidates must pass isolation criteria:
$P_{isol} = \Sigma E_T^{0.4} - \Sigma E_T^{0.13} < P_{threshold}$

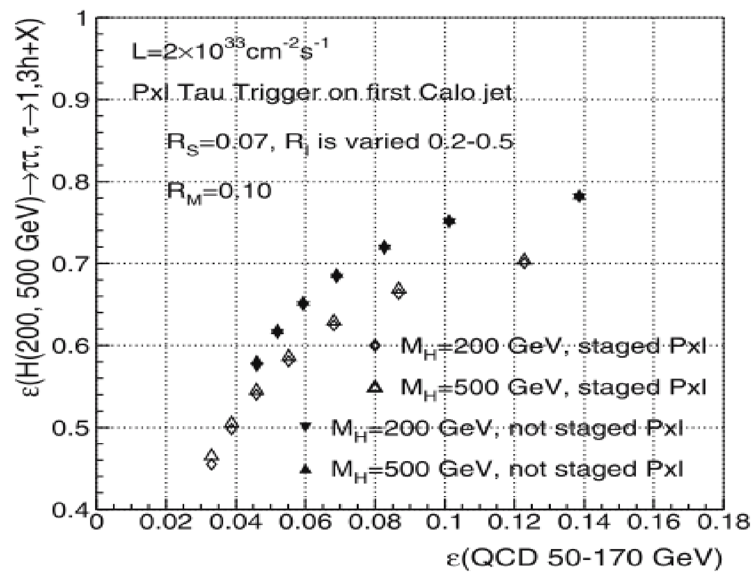
regional jet finding (in region of L1 τ-jets) speeds up processing



Pixel HLT τ-candidates are reconstructed around L1 τ-jets with the fast track finding algorithm

Requires no tracks found in isolation cone





How do we measure the reco/ID performance?

Needs	**Measures for tau ID performance**	**Analyses affected**
jet/electron suppression	efficiency/rejection	all
same sign background determination	good charge ID	$Z \to \tau\tau$, $H/A \to \tau\tau$, $Z' \to \tau\tau$, some SUSY searches
additional evidence of tau excess (in early data)	unbiased track multiplicity	$W \to \tau\nu$, $Z \to \tau\tau$, inclusive SUSY searches
trigger on taus	trigger efficiency/rejection and prescale	$W \to \tau\nu$, $H^{\pm} \to \tau\nu$
invariant/visible mass reconstruction	resolutions on tau energy and direction (E, η, φ)	$Z \to \tau\tau$, $H/A \to \tau\tau$, $Z' \to \tau\tau$, SUSY stau mass measurement
label tau decay modes	π^0 reconstruction	exclusive SUSY searches, $Z' \to \tau\tau$ polarization studies

Rejection vs Efficiency

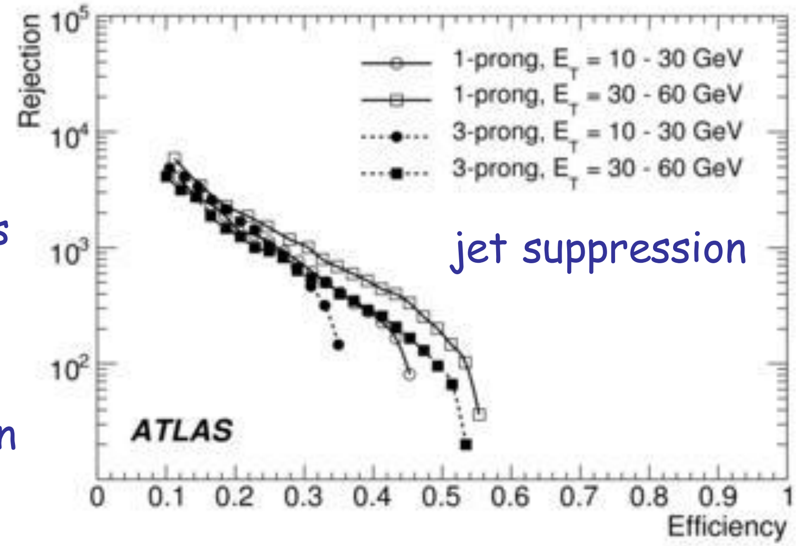
With QCD processes having a rate of 10^6 higher than Electroweak processes - suppression of multi-jet backgrounds is crucial

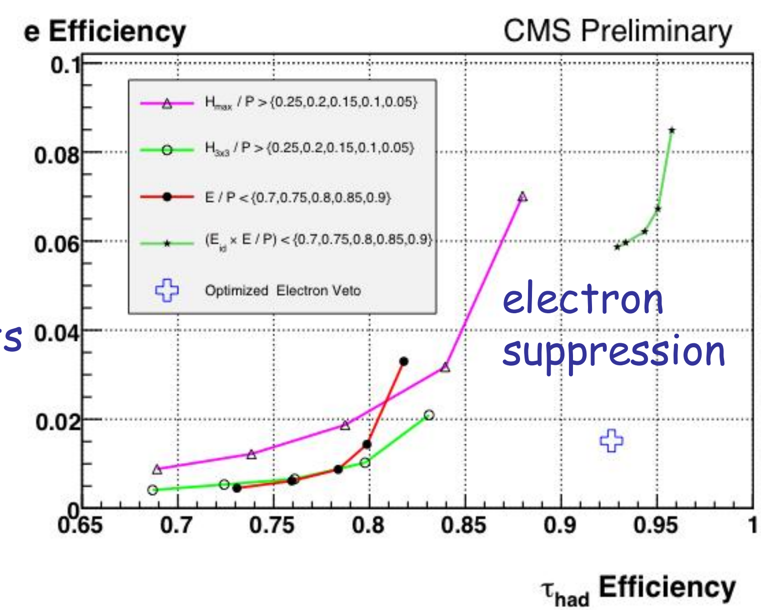
Algorithms also need to suppress electron/muon fakes as well - but not at such a high level of rejection

•Tight cuts: high purity, low signal yield
•Loose cuts: high efficiency, background contamination

Optimal working point depends on analysis and the luminosity available:
• W/Z analyses - tighter cuts?
• Higgs/SUSY searches - loose cuts?
• low luminosity - looser cuts?
• high luminosity - tighter cuts?

Note that the efficiency of tau ID and rejection on jets need to be measured in data!
(more on this later)





Charge Determination & Track Multiplicity

Charge determination & track multiplicity heavily depend on the track selection
- rejecting fake tracks and efficient ID of pion/kaon tracks is crucial
- tagging tracks from conversion can help correct the track multiplicity

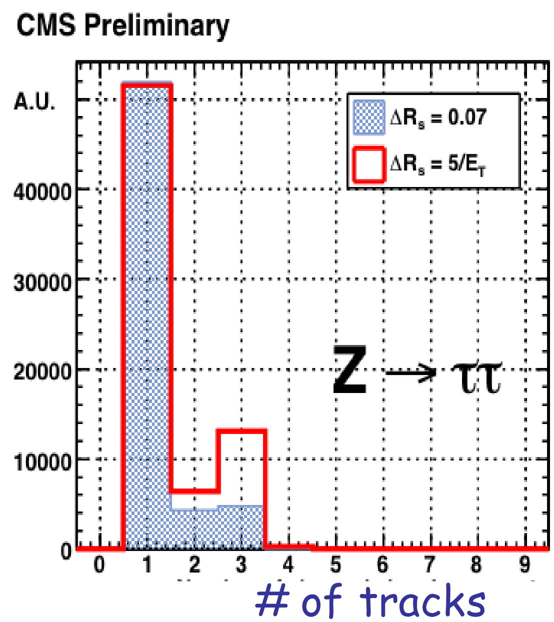
Analyses with first data will face skepticism that the signal is „from τ-leptons“
- one good cross check of this is the track multiplicity spectrum for signal region τ-candidates - dominated by 1-prong and 3-prong candidates

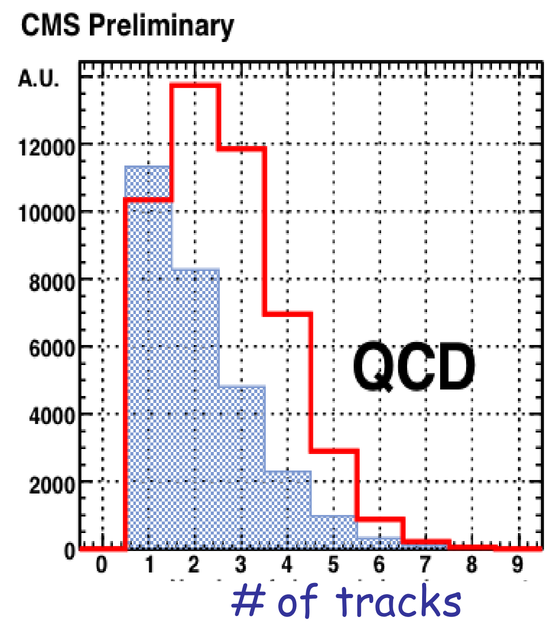
Note that QCD fakes tend to have large track multiplicity:

- higher fraction of fakes in 3-prong bin

Advanced analyses (i.e. VBF $H\to\tau\tau$) may want to bias the track spectrum towards lower track multiplicity to kill multijet background.

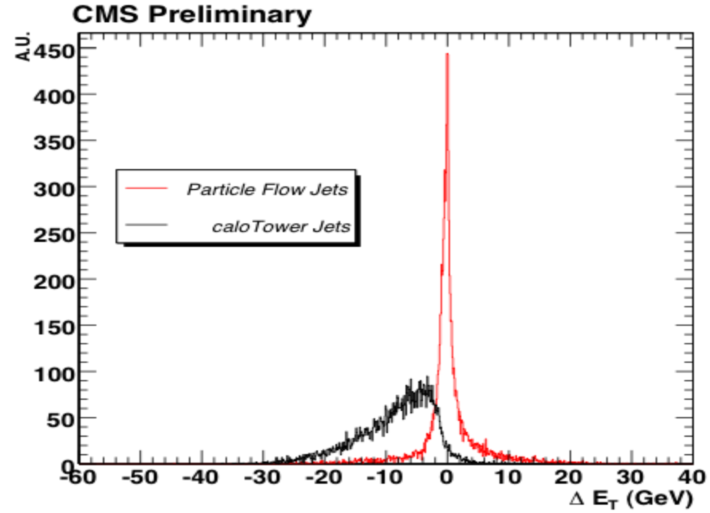
(other ways to confirm signal excess - i.e. invariant mass peak above background distributions)





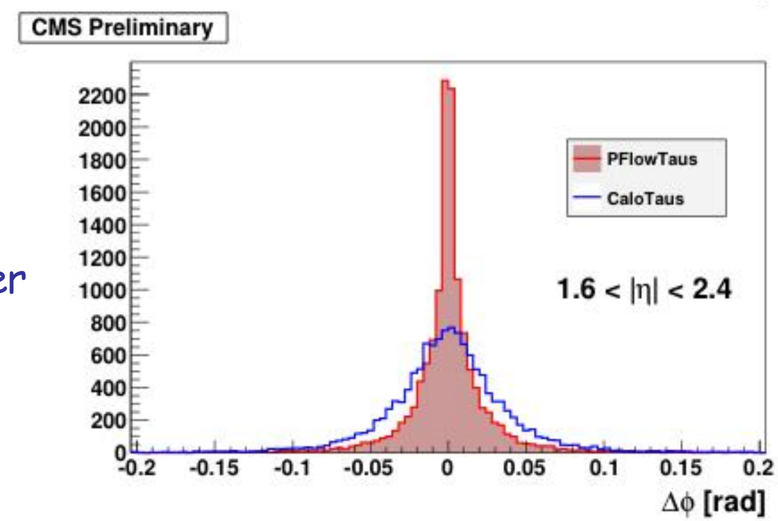
Energy & Direction Resolutions

Analyses looking to reconstruct the $\tau\tau$ invariant or visible mass will want good resolution of the τ-lepton kinematics (E_T, η, φ)



Energy/particle flow determinations of such kinematics take into account track info which has better resolution at low p_T

At high p_T, there may be difficulties because the narrowing of τ-candidates makes individual components harder to distinguish
(calo-determination may be more stable)



Energy/particle flow usually underestimate QCD jet energy, while being accurate for τ-leptons because of prominence of EM calorimeter info to HAD calorimeter (this reduces the effective QCD cross-section)

Tau ID in early data

Optimizing the rejection/efficiency of τ-ID in Monte Carlo is interesting but data will be a much different story!

- proper MC modeling of variables is going to be inaccurate
- many variables require precision alignment/calibration before they are effective (secondary vertexing, track impact parameters, hadronic calibration)
- many variables will have different behaviour due to underlying event and pile-up (track and calorimeter isolation with wide cones)

For early data - can try to use only variables suspected to be under control with tens/hundreds of pb^{-1}

Try to avoid using multi-variate techniques, and use rectangular cuts instead

ATLAS looked at optimization of rectangular cuts on a set of „safe variables“

i.e. EM radius, calorimeter isolation with narrow cone, width of track system, ratio of E_T^{EM} to E_T^{HAD} at the EM scale, ratio of EM/HAD energy to Σp_T^{tracks}

Optimization for different p_T bins, different efficiencies is being studied

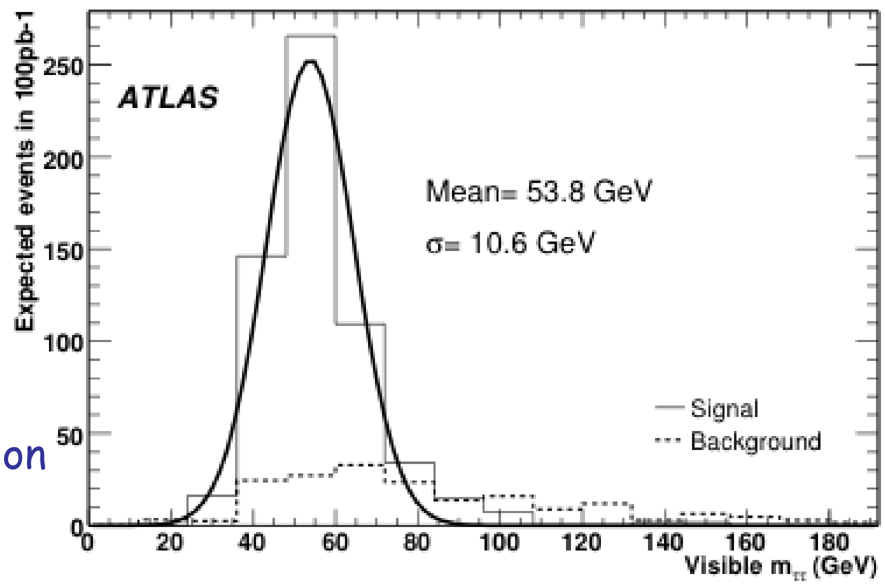
The $Z \to \tau\tau$ Channel

The $Z \to \tau\tau$ channel (one τ_{lep} decays leptonically, one τ_{had} decays hadronically) will be the most important channel to make data-based studies of τ_{had}-lepton properties

- main backgrounds: top pairs, W+jets, $Z \to \mu\mu$, $Z \to ee$, multi-jets
- typical cuts may include: electron/muon ID and isolation, $M_T(lep, E_T^{MISS})$, τ_{had}-ID
  ΣE_T^{jets}, dilepton veto, b-tag veto, E_T^{MISS}
- identifying one leg as electron/muon (tag-side) gives an unbiased sample of τ_{had}-leptons on the other leg (probe-side) that can be used for study

The background determination from multi-jet and W+jets contributions will be challenging to estimate (MC not reliable)

- Split to „same sign“ and „opposite sign“ samples (multijets equal in both while signal dominates opposite sign)
- Define control regions to confirm bkgd estimation
  - high $M_T(lep, E_T^{MISS})$ for W+jets bkgd
  - non-isolated leptons for multijet bkgd



Understanding τ-ID with $Z \rightarrow \tau\tau$

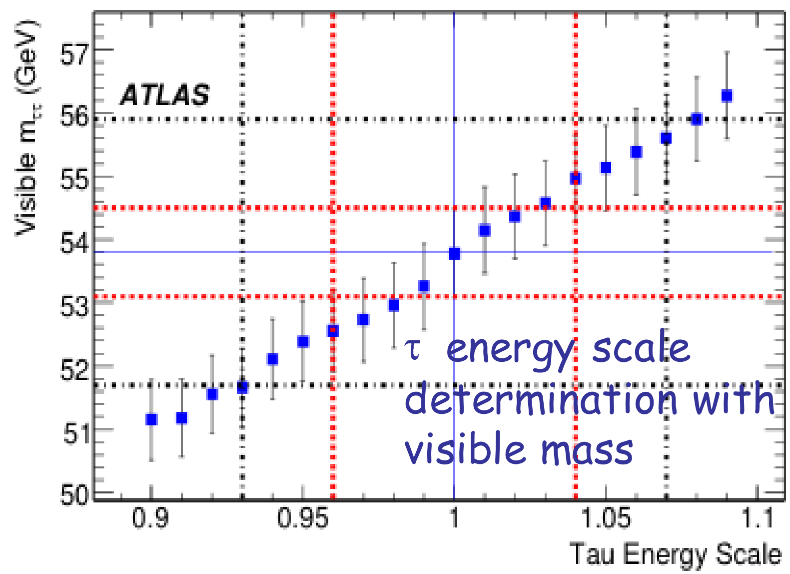
The $Z \rightarrow \tau\tau$ sample will be a key control sample for understanding τ-ID with data

Tag (electron/muon) and probe (τ-lepton) methods can be used to understand:
- the τ-ID efficiency (inclusive / 1-prong / 3-prong)
- the τ-trigger efficiency (for different thresholds/trigger streams)

Using the known $\sigma(pp \rightarrow Z) \times BR(Z \rightarrow \tau\tau)$, efficiencies can be measured in data
- global scale factor to correct for such differences in MC and data
- eventually PDFs for ID variables can also be corrected with data input

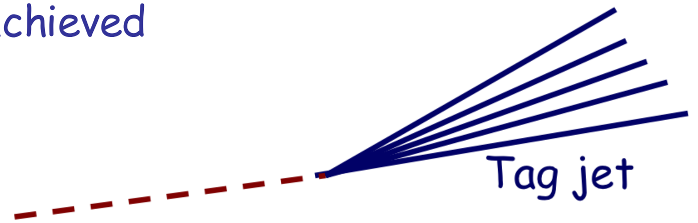
The visible mass distribution of the $Z \rightarrow \tau\tau$ products can be used to evaluate the energy scale for the τ-leptons
(cell weighting/energy flow)

The invariant mass of $Z \rightarrow \tau\tau$ products can be reconstructed using collinear approximation
- should peak at well measured Z mass (91.2 GeV)
- uncertainty dominated by E_T^{MISS}
- peak of distribution gives us a handle on the E_T^{MISS} scale



Measuring τ fake rates in jet samples

This can be done with very early data - and studies can be achieved before the $Z \rightarrow \tau\tau$ sample is well-established



Fake Rate = (# probe jets passing τ-ID) / (# probe jets)

Real τ-production is ~negligible in comparison with jet production

- can be corrected by MC subtraction of real τ-lepton contribution)
  (MC more reliable for W/Z and top events than for QCD jet events)

Can further ensure a „jet pure" sample by:

- requiring back-to-back jets
- p_T balance between jets: $\Delta p_T(\text{jets}) < p_T^{\text{lead jet}} / 2$
- very „jet-like" tag jet: $N_{\text{track}}^{\text{tag-jet}} > 4$ (or increase track cut for higher p_T)

No other requirements on probe jet - need to keep unbiased sample of jets

Fake rate should be computed for different E_T, η bins (maybe even as function of φ)
Statistics will not be a problem (so will do better than MC studies!)
Can generate background PDFs from data

The $W \to \tau\nu$ Channel

Despite ~10 greater signal yield for $W \to \tau\nu$ compared to $Z \to \tau\tau$, this is more challenging due to lack of additional τ-lepton leg

- heavily dependent on τ-lepton triggers and E_T^{MISS}
- in fact $\tau + E_T^{MISS}$ triggers used - rates will have to be controlled (prescales for higher luminosity)

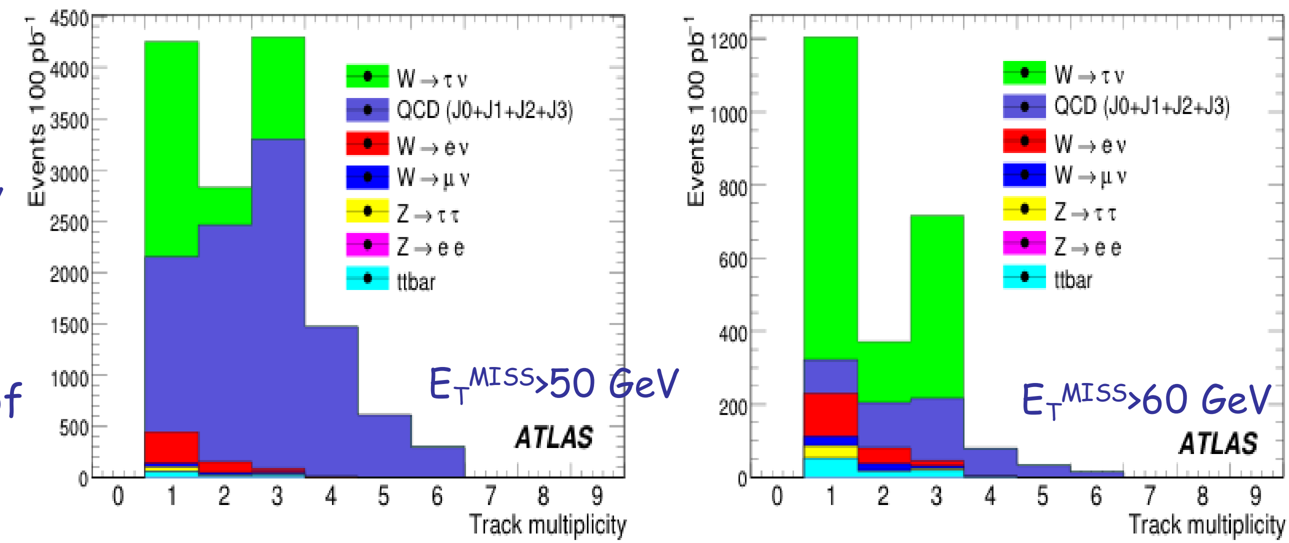
Backgrounds: $W \to e\nu$, $W \to \mu\nu$, $Z \to \tau\tau$, $Z \to ee$, top pairs, multi-jets

$W \to \tau\nu$ channel will depend on the τ-ID fake rate measurement for background estimation (no same sign control sample)
QCD control samples can be defined with τ-candidates failing isolation criteria

The E_T^{MISS} cut will be crucial

Because of tau trigger, the sample of τ-leptons is already biased

Nevertheless can hope to provide useful cross checks of $Z \to \tau\tau$ measurements



Taus with Tops

τ-leptons coming from top pair production give a τ-sample with higher p_T than $Z\to\tau\tau$
Typical topology is $t\bar{t} \to WbW\bar{b} \to qq'b\tau\upsilon\bar{b}$ or $t\bar{t} \to WbW\bar{b} \to l\nu b\tau\upsilon\bar{b}$

Trigger paths: τ trigger, τ + E_T^{MISS} trigger, multi-jet trigger, lepton trigger

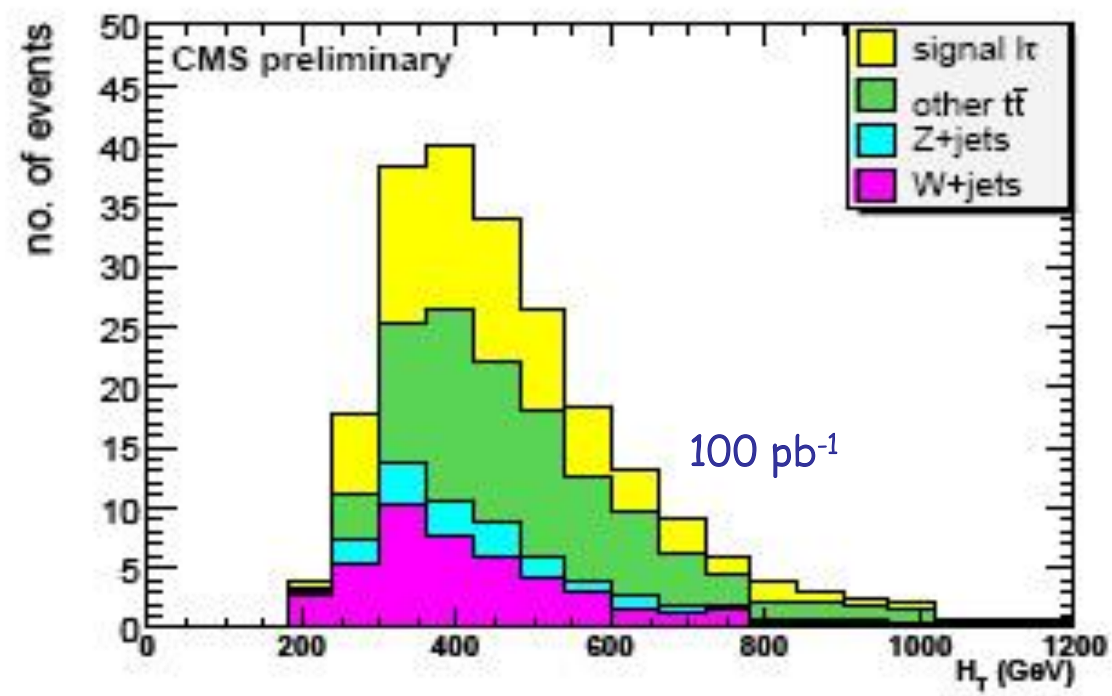
Can use b-tagging to help select top events since W+jets background is large

For lepton-τ channel, same sign events can be used as background control sample

Nice cross check to $Z\to\tau\tau$ for τ-ID efficiency and τ-trigger efficiency when using events selected with unbiased trigger

Could be the best study sample of τ-leptons with higher p_T

Perhaps even τ-energy scale determination is possible by comparing p_T^{top} in tau decay channels vs lepton decay channels



Summary

Physics with τ-lepton final states offers many exciting possibilities

CMS/ATLAS have well developed algorithms and detailed MC studies for hadronically decaying τ-lepton reconstruction and identification

CMS/ATLAS have infrastructure/plans for studying τ-ID with first data

A variety of trigger paths at both experiments involve τ-signatures, whether alone, multi-τ triggers or in combination with leptons objects/E_T^{MISS}

W/Z boson and top production are key channels in the early data era at LHC to understand τ-ID and measure:
offline/trigger efficiency, energy scale, fake rates, other characteristics

Lots of work/opportunities for young researchers to make their impact on this important signature and exciting physics over the next few years!

Many thanks to the Workshop Organizers for
the invitation and the privelige to participate!

Further Reading

Further reading CMS:

"CMS TDR: Physics Performance" J. Phys. G34: 995 (2007)

"Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and E_T^{MISS}"
CMS PAS PFT-09/001

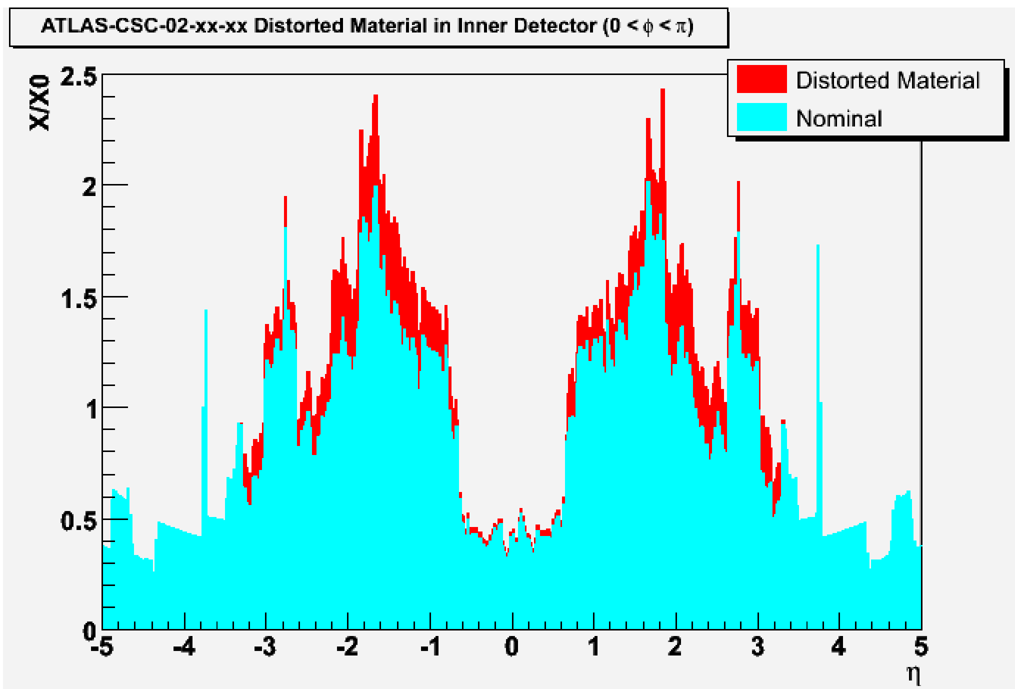
"CMS Strategies for Tau Reconstruction and Identification using Particle-Flow Techniques"
CMS PAS PFT-08/001

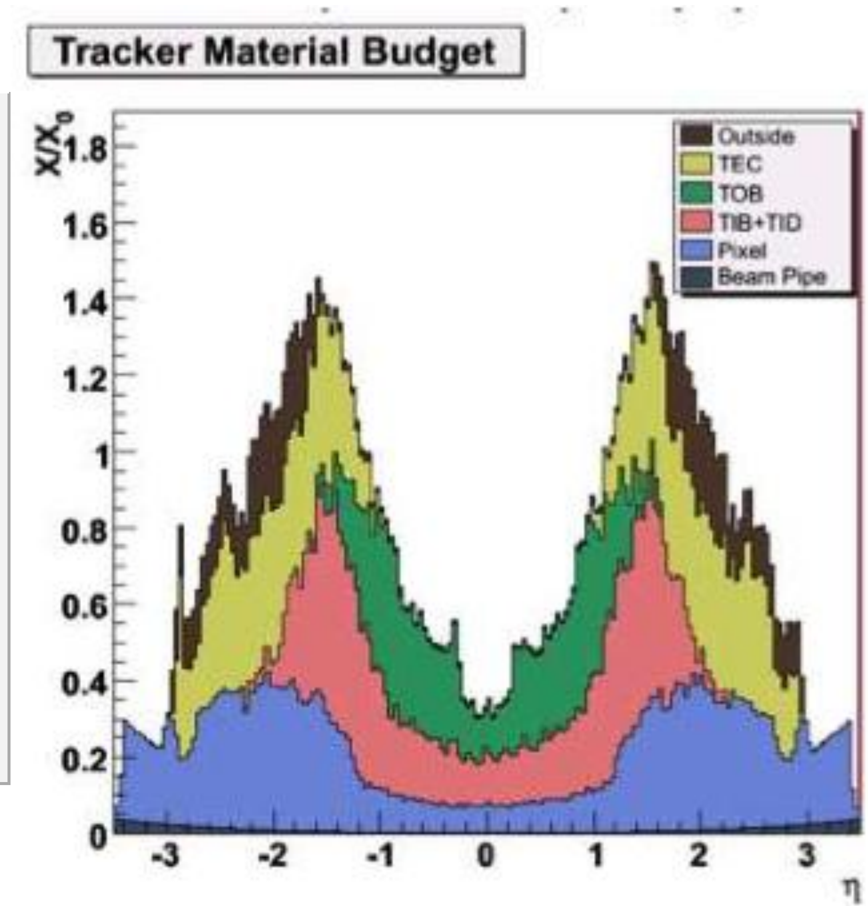
Further reading ATLAS:

"Expected Performance of the ATLAS Experiment: Detector, Trigger, Physics"
CERN-OPEN-2008-020

"The ATLAS Experiment at the CERN Large Hadron Collider"
JINST 3 (2008) S08003

Detector Depth: Radiation Lengths

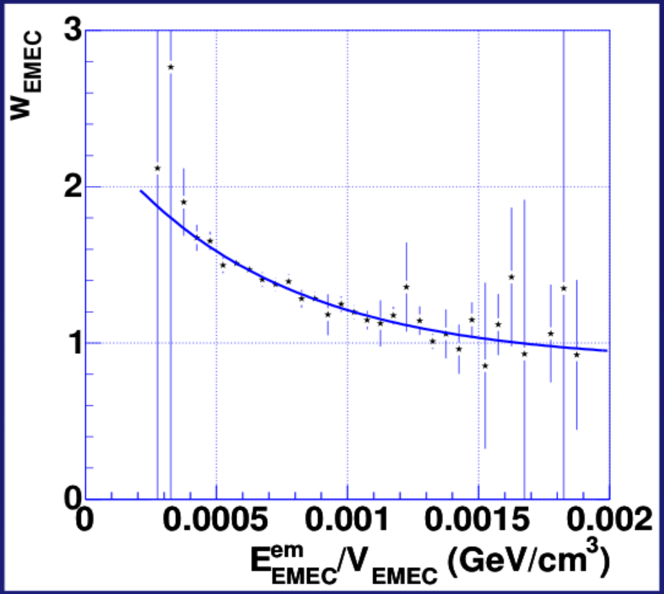


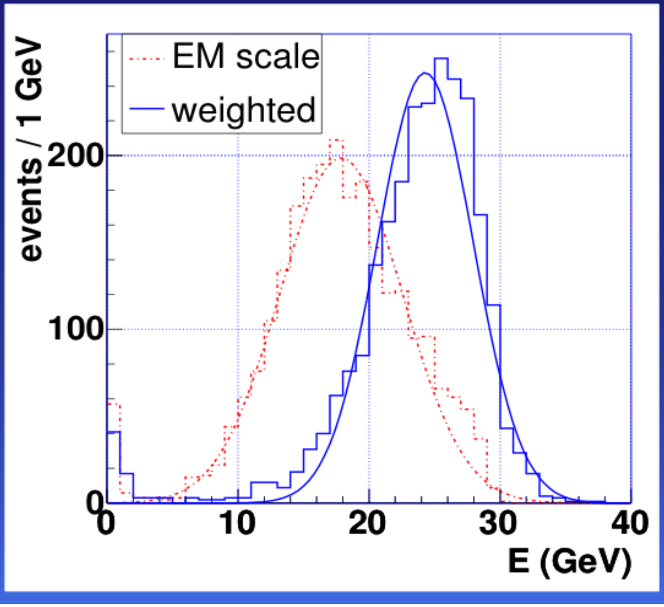


Track Quality Criteria at ATLAS

	Leading Track	Default Track	Loose Track
$p_T >$	6 GeV	1 GeV	1 GeV
$\|d_0\| <$	2 mm	1 mm	2 mm
$\|\Delta z\|*\sin(\theta) <$	10 mm	1.5 mm	10 mm
$N_{Si}^{Hit} \geq$	7	7	7
$N_{Pix}^{Hit} \geq$	0	2	0
$N_{Blay}^{Hit} \geq$	0	1	0

H1 Weighting Method (pedagogical example)





$$E' = w\,E$$
$$w = \left[c_1 \exp\left(-c_2\,E/V\right) + c_3\right]$$

- $w \to 1$ for large E/V:
  - $c_3 \approx 1$
  - weighting does not change electromagnetic clusters
- small energy density dominated by hadronic activity: $w > 1$:
  - $c_{1,2} > 0$
  - exact values depend on total cluster energy, choice of weighted unit (cell or cluster), . . .
- plot shows 30 GeV pions from 2002 EMEC–HEC test beam as a simple cluster weight example
  - restrict sample to pions fully contained in the EMEC
  - plot E_{beam}/E vs. E/V with E, V: cluster energy and volume, respectively
  - extract weight function
  - compare resolution for weighted and unweighted sample

Energy: energy flow details at ATLAS

$$E_T^{eflow} = E_T^{emcl} + E_T^{neuEM} + \sum p_T^{track} + \sum resE_T^{chrgEMTrk} + resE_T^{neuEM}$$

E_T^{emcl}: EM clustered energy not matched to track

Σp_T^{track}: sum of track transverse momenta replaces E_T^{chrgEM} and $E_T^{chrgHAD}$

E_T^{neuEM}: EM energy left over collected by cells in 0.2 of leading track

$\Sigma resE_T^{chrgEMTrk}$: $\max(0, E_T^{chrgEM} - 0.7 \times p_T^{track})$
corrects for leakage of photon showers to cells which matched to charged hadrons

$resE_T^{neuEM}$: $-0.1 \times p_T^{track}$
corrects for double counting of of EM leakage from charged hadrons

π^0 reconstruction - shower subtraction

The reconstruction of π^0 clusters requires the removal of energy deposited by $\pi^\pm$ mesons:
cell energy subtraction using parametrized shower development

$$w_i = c_L \int_{cellvolume} f_L(\eta - \eta_{trk}, \varphi - \varphi_{trk}) \cosh(\eta) d\eta d\varphi$$

c_L: longitudnal weights (based on which layer in ECAL)

f_L: lateral parametrization in (η,φ) space

Can test/tune on sample of $\tau^\pm \rightarrow \pi^\pm \upsilon$ true decays - should get zero energy in calorimeter after the subtraction

Stau Mass Measurement

Most important tau related SUSY parameter: $\tilde{\tau}_1$ mass measurement

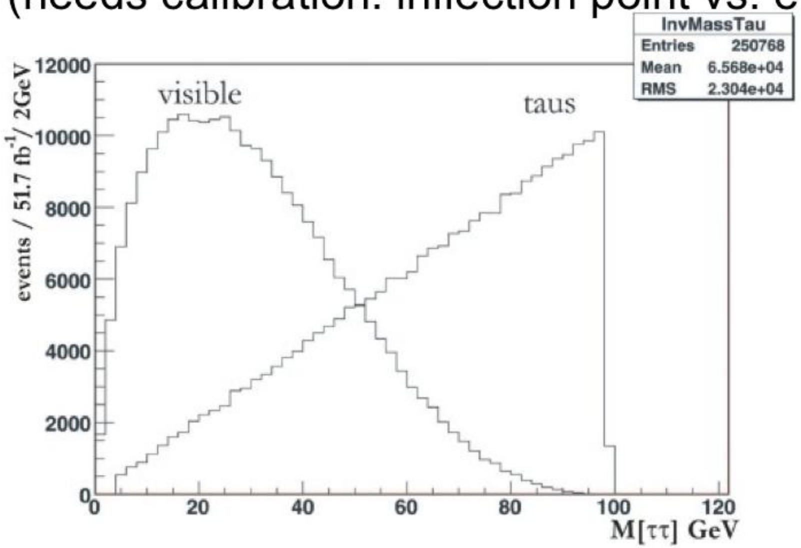
Obtained from di-tau invariant mass spectrum in decay chain

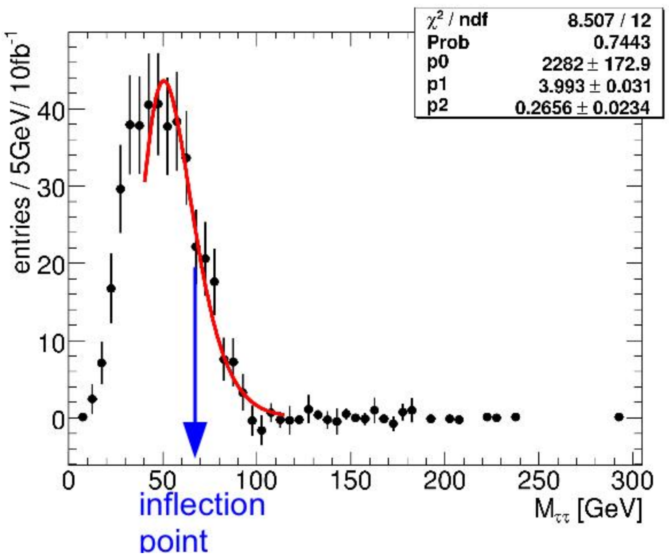
$$\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \rightarrow \tilde{\chi}_1^0 \tau^{\pm} \tau^{\mp}$$

Endpoint of undecayed tau mass spectrum depends on $\tilde{\tau}_1$ mass.

Escaping neutrino energy in tau decays makes this endpoint hardly directly measurable

Choose e. g. inflection point of trailing edge as endpoint sensitive observable (needs calibration: inflection point vs. endpoint)





Tau Polarization in SUSY

Polarisation of taus from stau decay $\tilde{\tau}_1^{\pm} \rightarrow \tau^{\pm}\tilde{\chi}_1^0$ is a probe of the $\tilde{\chi}_1^0$ composition and can be used to discriminate between different models of SUSY breaking:

- Universal SUGRA models: $P_\tau \simeq +1$
- For most non-universal SUGRA models: $P_\tau \simeq \cos^2\theta_\tau - \sin^2\theta_\tau$
- AMSB models: $P_\tau \simeq -1$
- For many GMSB models: $P_\tau = \sin^2\theta_\tau - \cos^2\theta_\tau$