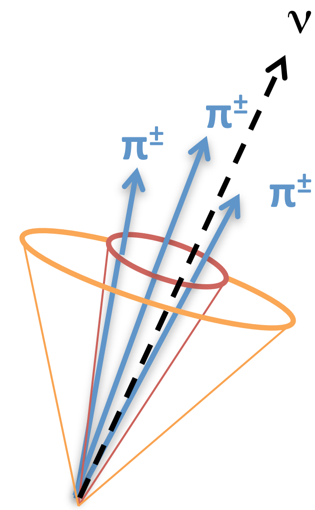
Physics with Taus at the LHC

SMU
Monday, February 27, 2012

Sarah Demers
Yale University

Outline

- ***WHY* taus?**
  - **and why not taus . . .**
- ATLAS and CMS
  - some of these things are not like the other
- The building blocks
  - Triggering, Reconstructing, Identifying
- Measurements
  - Standard Model, Higgs (SM and MSSM), H^+
- Precision
  - Polarization



What are taus?

T-shirt design by Neil Davies

What are taus?

Taus are leptons

T-shirt design by Neil Davies

What are taus?

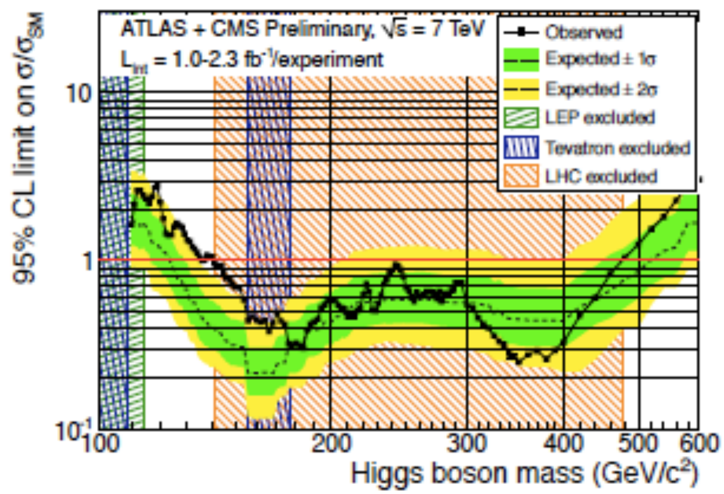
Taus are leptons

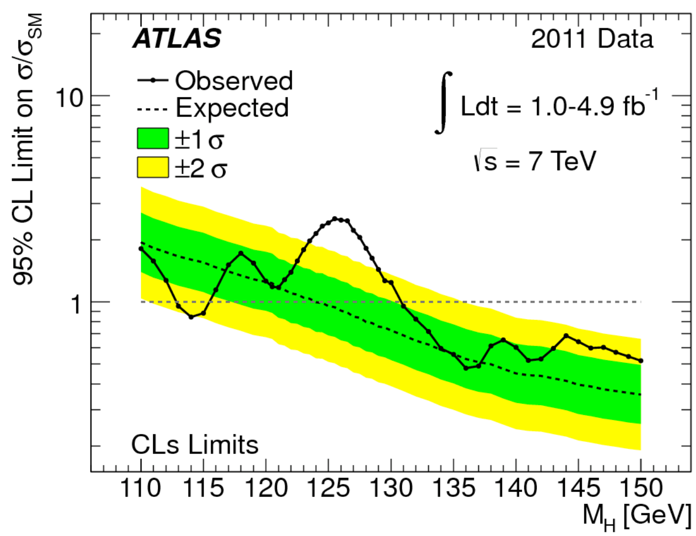
with |charge| = 1

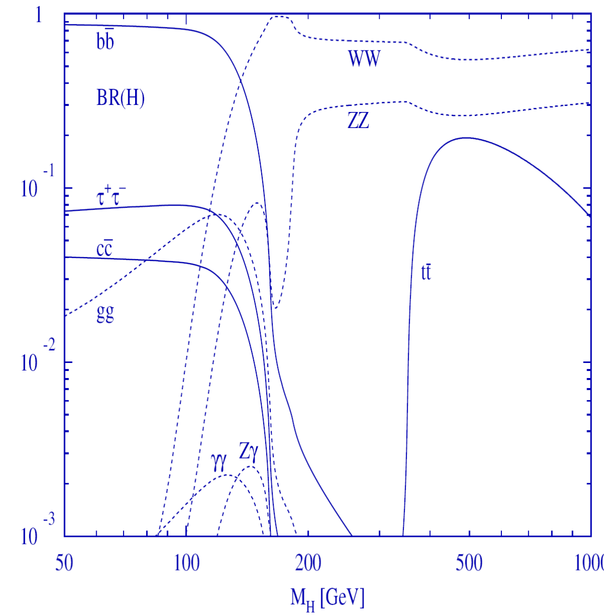
in the 3rd generation

T-shirt design by Neil Davies

Taus as Probes for "New" Physics





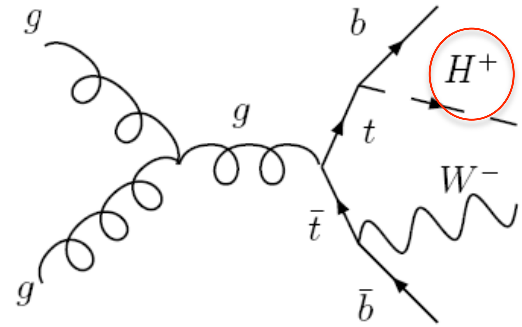


The tau, the heaviest lepton, couples strongly to the Higgs, and is relevant for a 5σ discovery in the important, but challenging, range of 115 – 130 GeV.

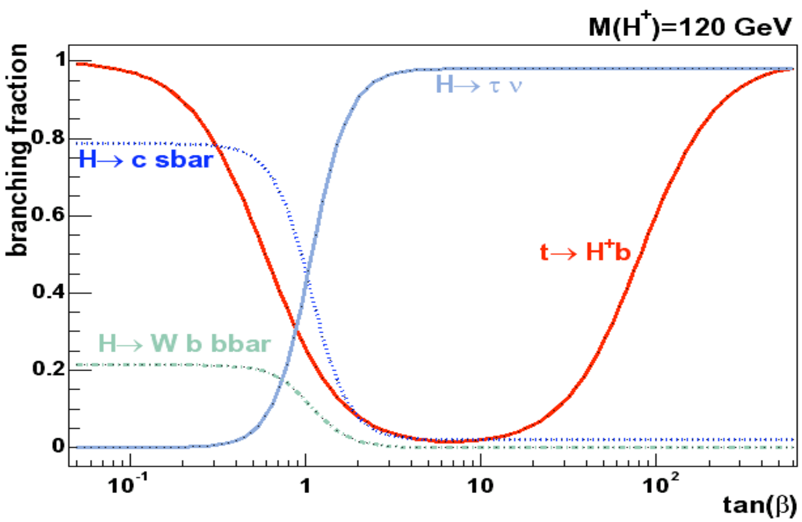
This analysis could rely (at least partially) on tau triggers.

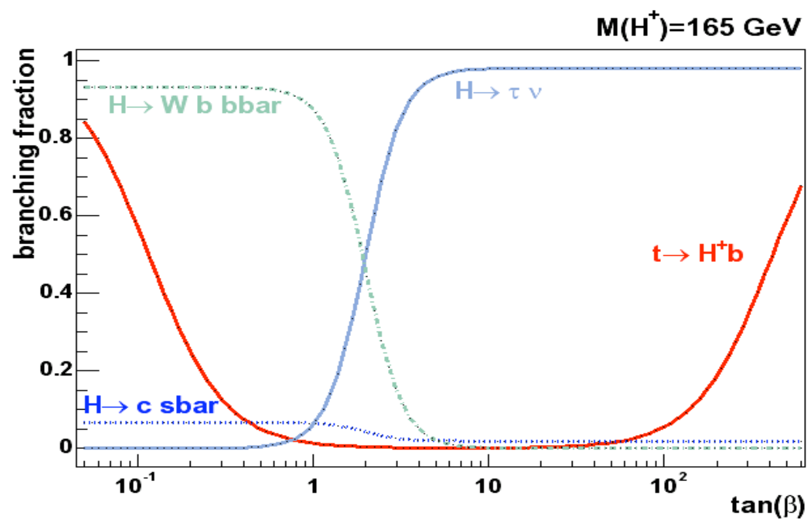
Channel analyzed by Stephen and Aidan

Charged Higgs (SUSY)

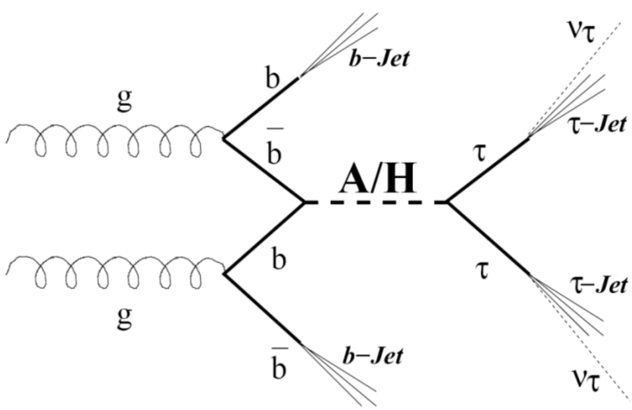


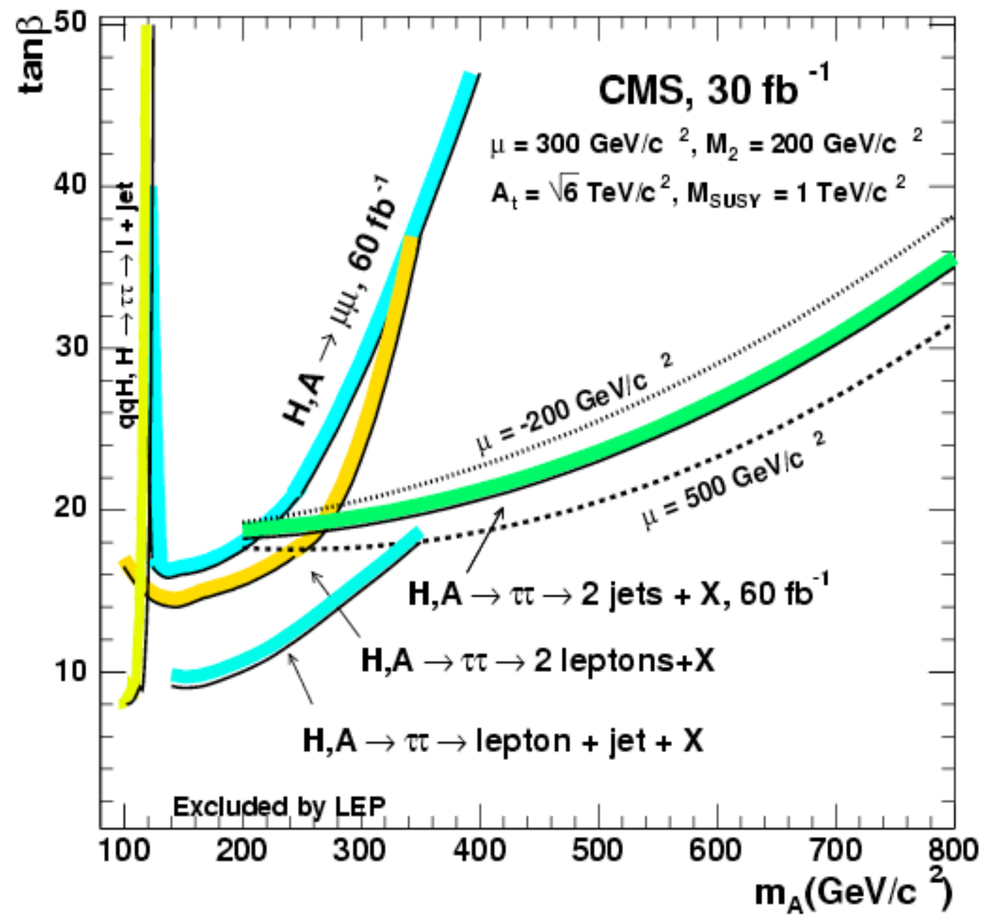
With tanβ over ~3, H^+ decays almost exclusively to taus





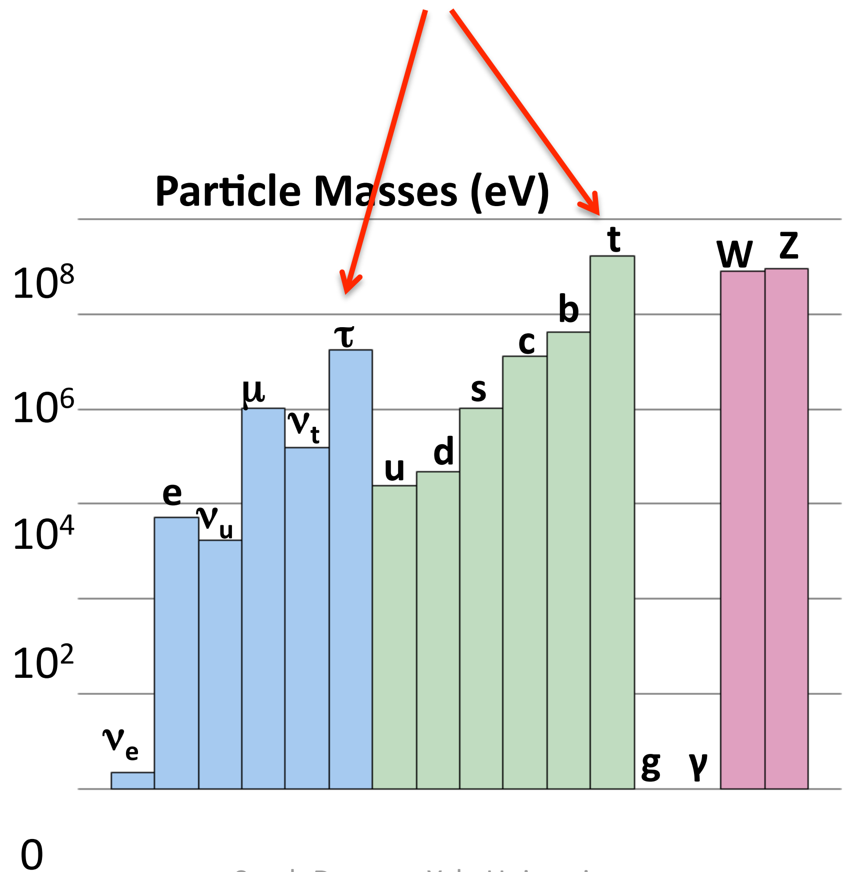
Neutral Higgs (SUSY)





Life without the Higgs?

Many Higgsless theories include new particles with preferential couplings to the third generation, often motivated by trying to explain the very heavy top quark



Understanding New Phenomena

Taus!

All decay modes should be explored to understand what we find at the LHC

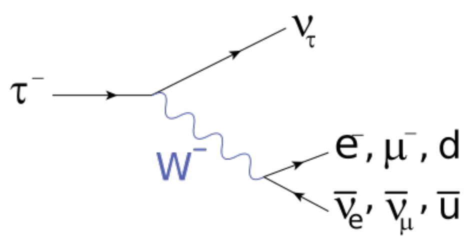
Not just electrons and muons!

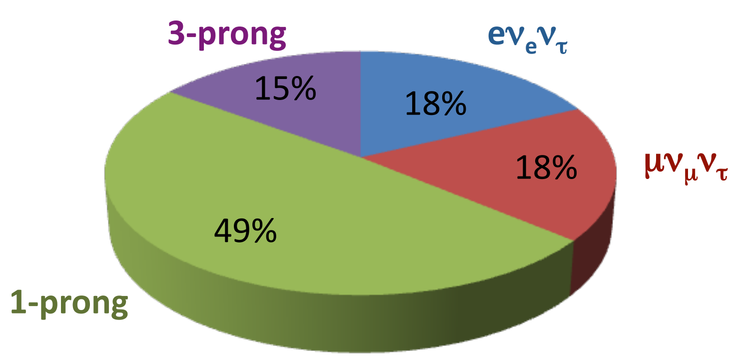
Tau decays can carry information about the polarization of the object that
decays into them

Why NOT taus?

The tau lifetime is 2.9 x 10^{-13} s.

We detect the decay products of the tau, not the tau itself.

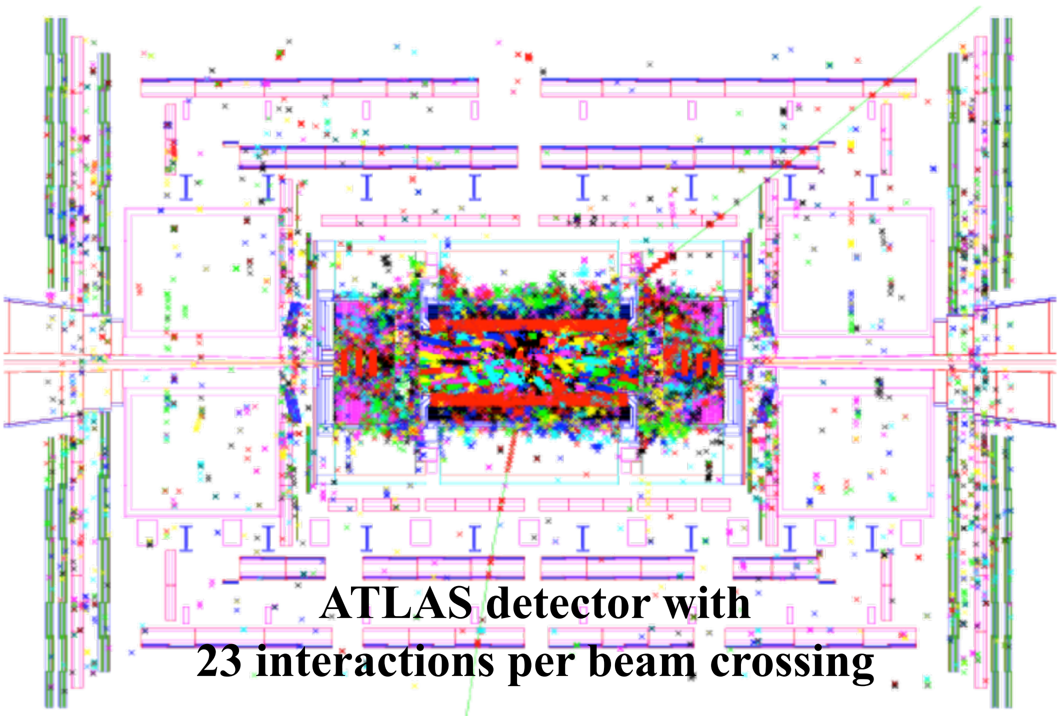


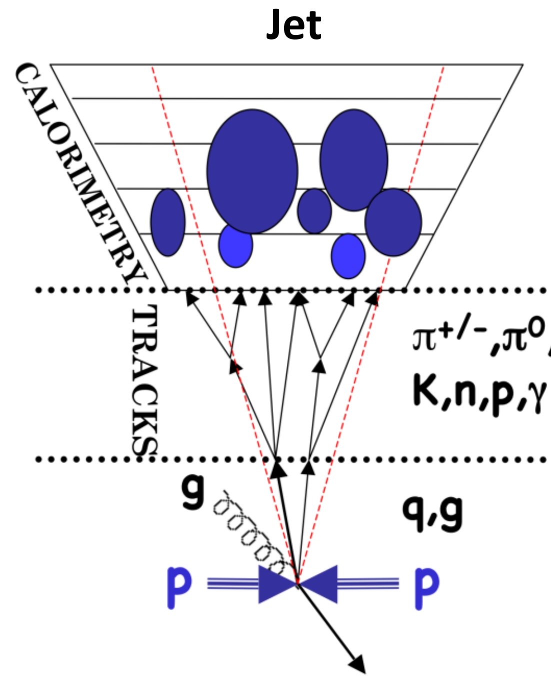


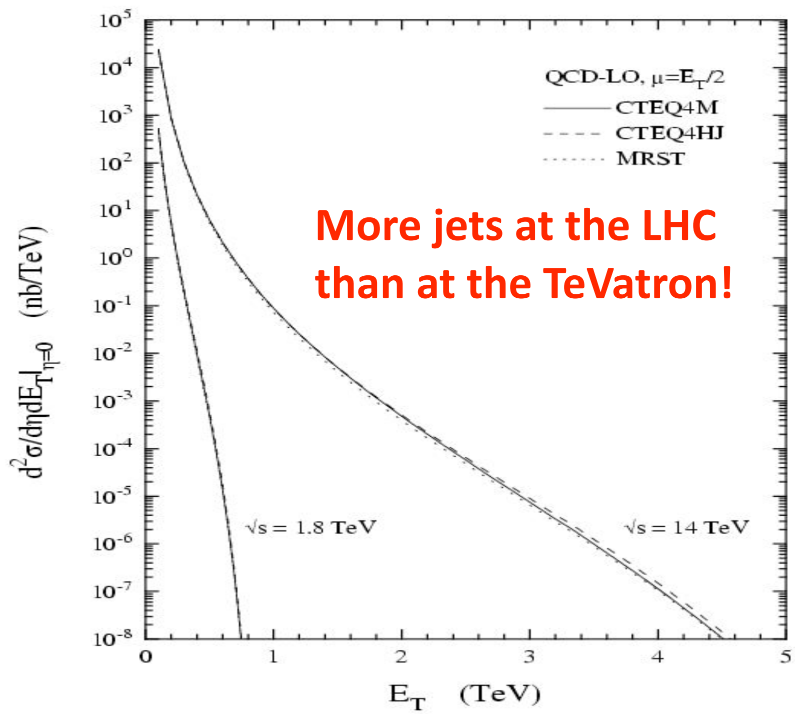
Tau branching ratios from 10^8 simulated Z->ττ events

Decay modes	TAUOLA-CLEO
$\tau \to e\nu_e\ \nu_\tau,$	17.8 %
$\tau \to \mu\nu_\mu\ \nu_\tau$	17.4 %
$\tau \to h^\pm neutr.\nu_\tau$	49.5 %
$\tau \to \pi^\pm\nu_\tau$	11.1 %
$\tau \to \pi^0\pi^\pm\nu_\tau$	25.4 %
$\tau \to \pi^0\pi^0\pi^\pm\nu_\tau$	9.19 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$	1.08 %
$\tau \to K^\pm neutr.\nu_\tau$	1.56 %
$\tau \to h^\pm h^\pm h^\pm neutr.\nu_\tau$	14.57 %
$\tau \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$	8.98 %
$\tau \to \pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	4.30 %
$\tau \to \pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.50 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.11 %
$\tau \to K_S^0 X^\pm\nu_\tau$	0.90 %
$\tau \to (\pi^0)\pi^\pm\pi^\pm\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.10 %
other modes with K	1.30 %
others	0.03 %

Why NOT taus?


ATLAS detector with
23 interactions per beam crossing


Jet
CALORIMETRY
TRACKS
π+/-,π0,
K,n,p,γ
g
q,g
p
p



Jets, jets and more JETS!

Taus were challenging at the TeVatron

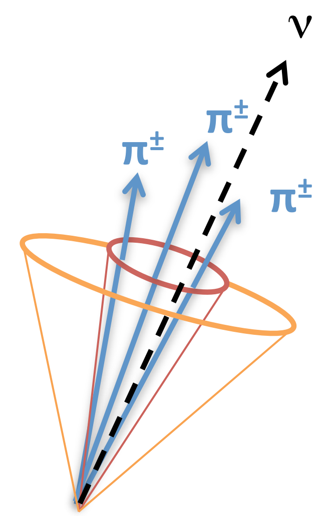
We find ourselves even more overwhelmed by jets at the LHC

Sample	cross section X branching ratio	#events/8 hours (10^{31})
dijets (p_T 8 – 17 GeV)	1.7 X 10^{10} pb	5 X 10^9
dijets (p_T 17 – 35 GeV)	1.4 X 10^9 pb	4 X 10^8
dijets (p_T 35 – 70 GeV)	9.3 X 10^7 pb	3 X 10^7
W →τυ, τ→ *had*	1.1 X 10^4 pb	3200
Z →ττ, 1τ→ *had*	1.55 X 10^3 pb	450

Definitions

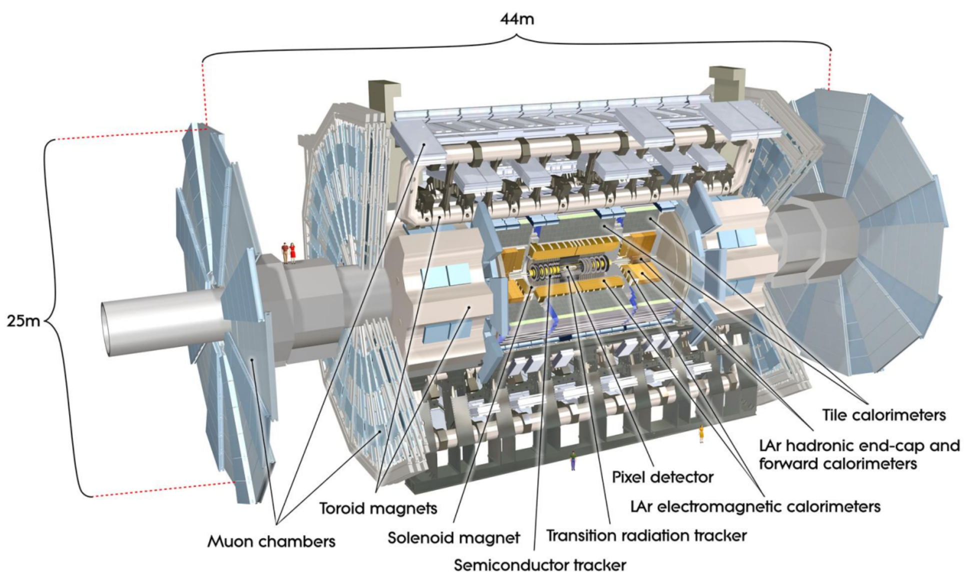
E_T = transverse energy
p_T = transverse momemtum
√s = center of mass energy

Introduction

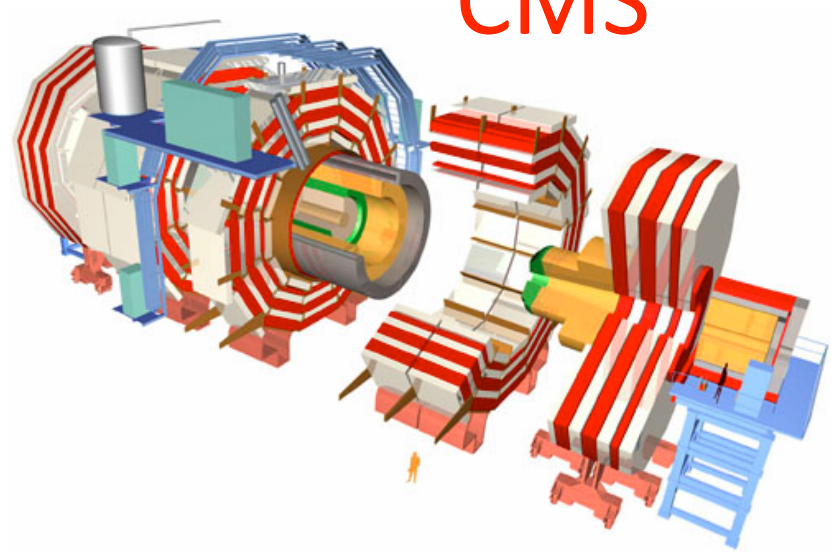


- *WHY* taus?
  - and why not taus . . .
- **ATLAS and CMS**
  - **some of these things are not like the other**

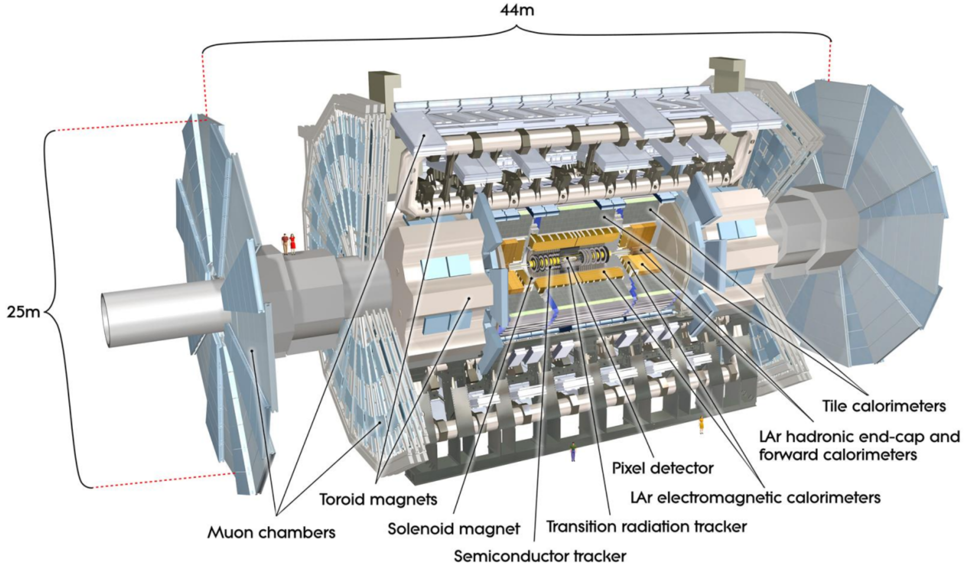
ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

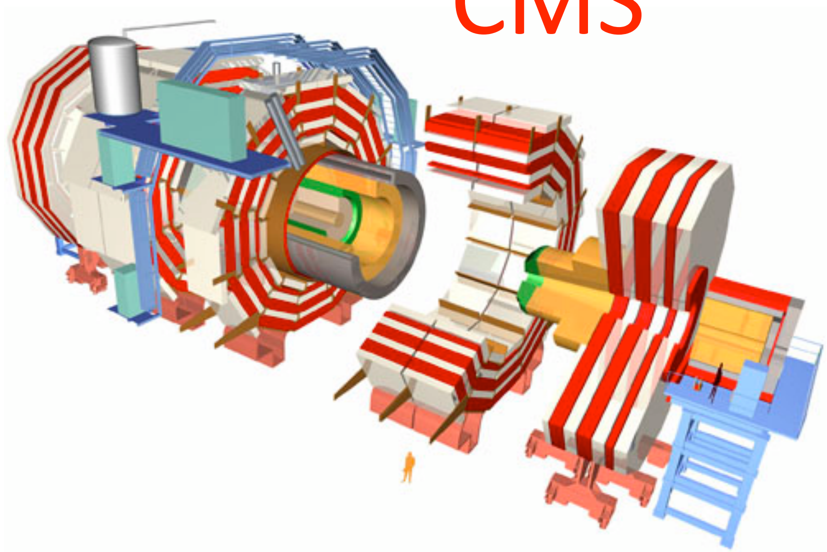
CMS



ATLAS



CMS

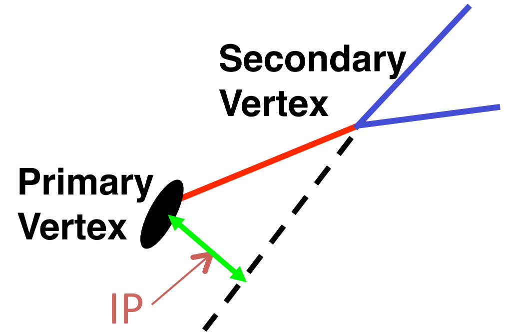


Magnetic Field

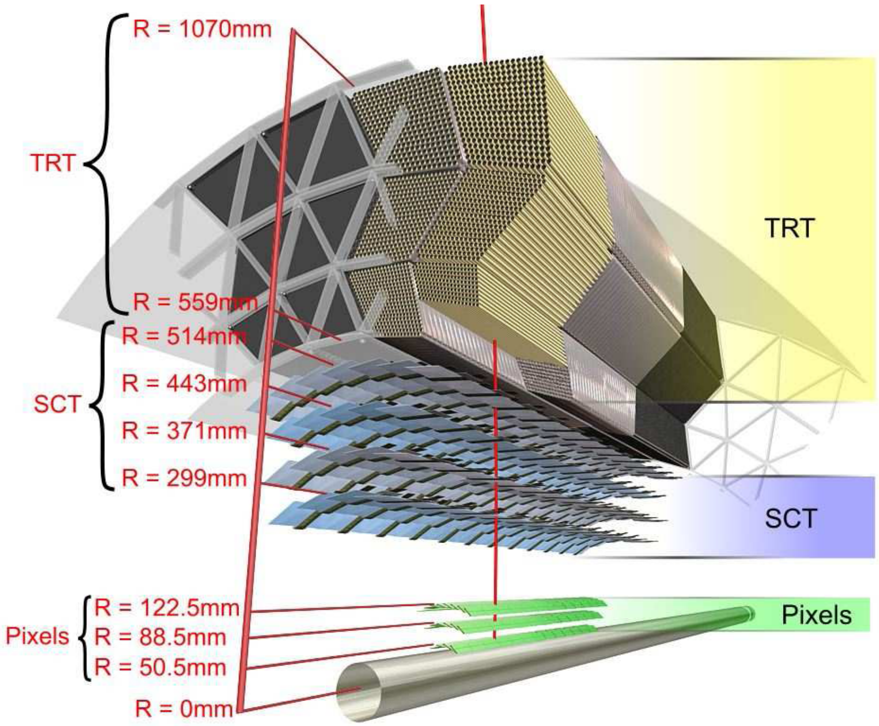
2 T

4 T

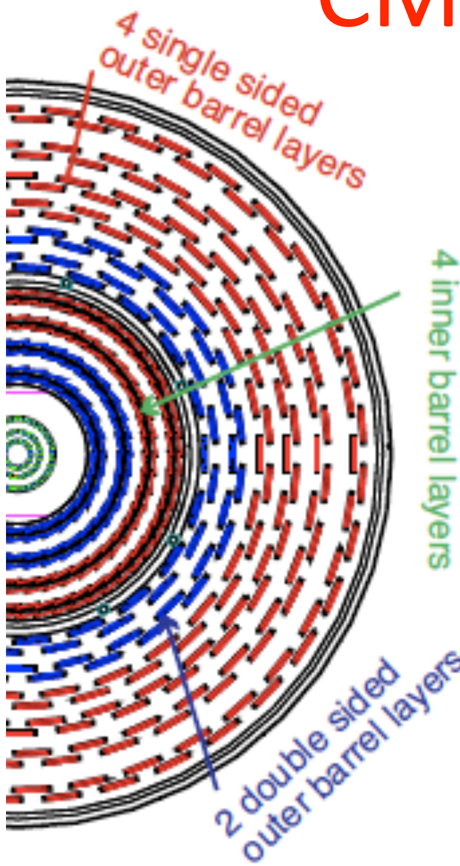
Tracking Chambers



ATLAS

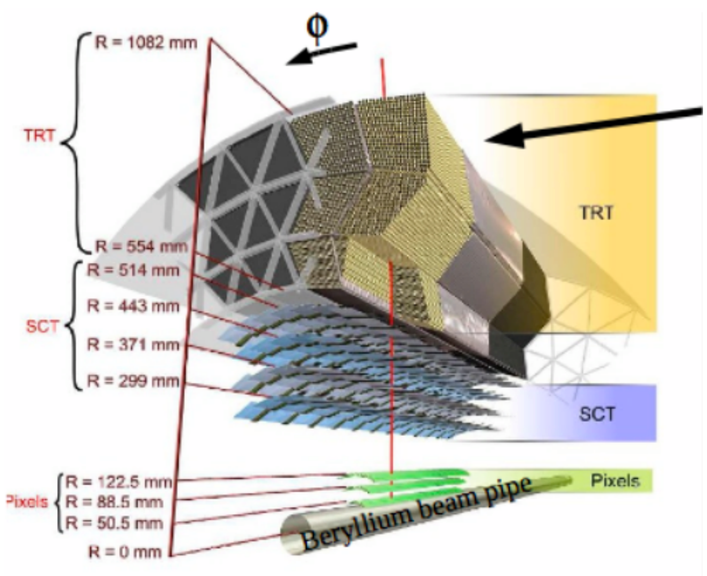


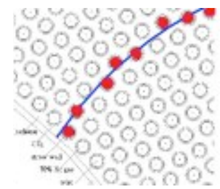
CMS



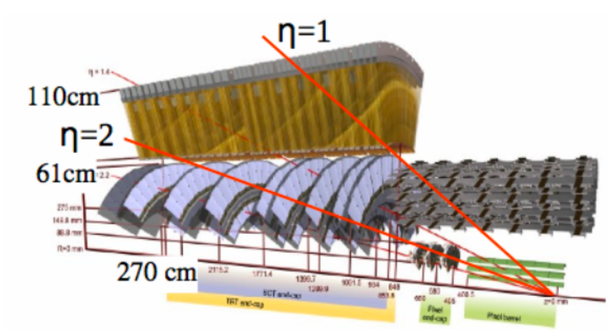
ATLAS TRT: e/π separation

[Particle Identification Performance of the ATLAS TRT Tracker: ATLAS-CONF-2011-128](#)

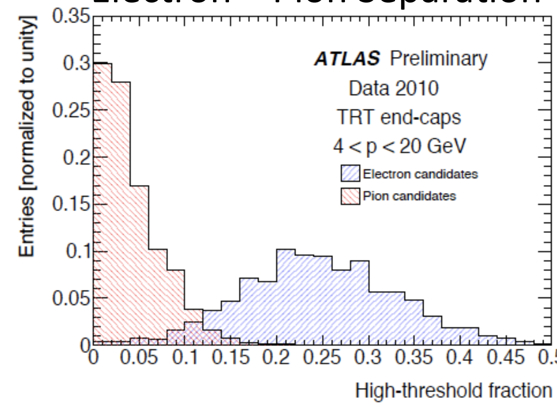




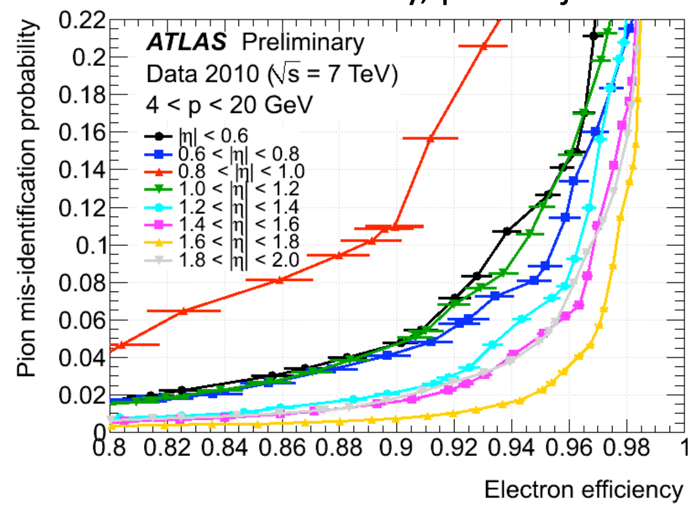
300,000 straw tubes
4 mm diameter
Radiator material between straws



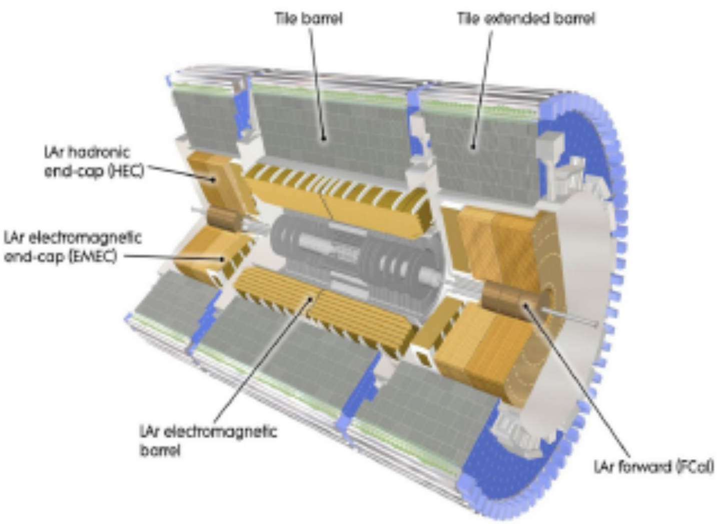
Electron – Pion Separation

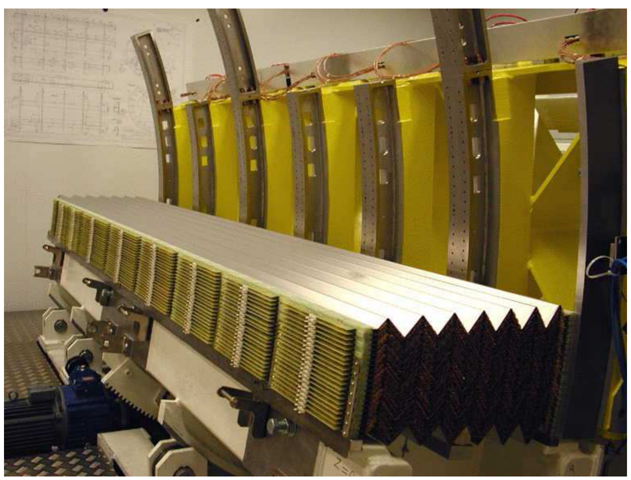


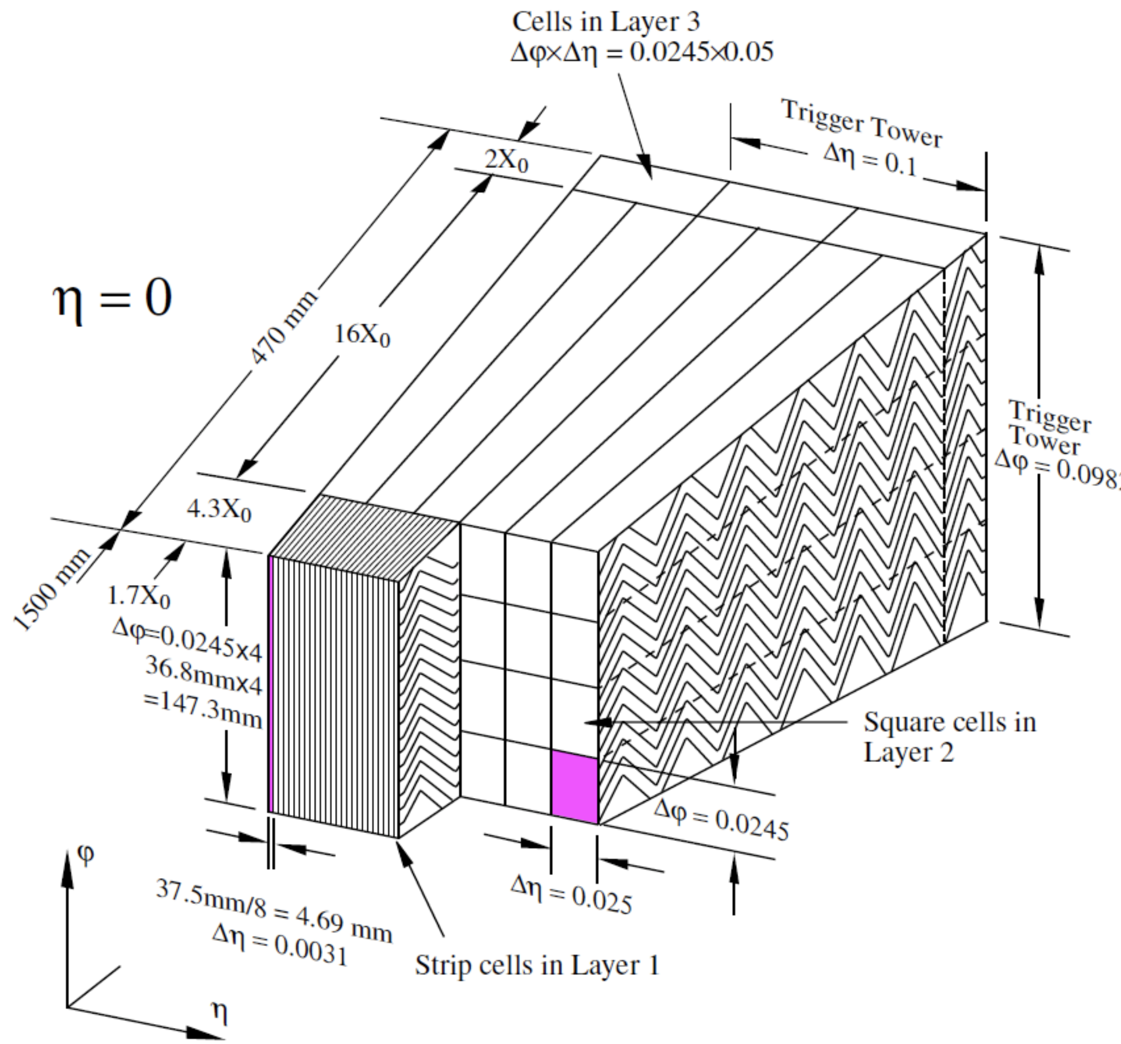
Electron efficiency, pion rejection



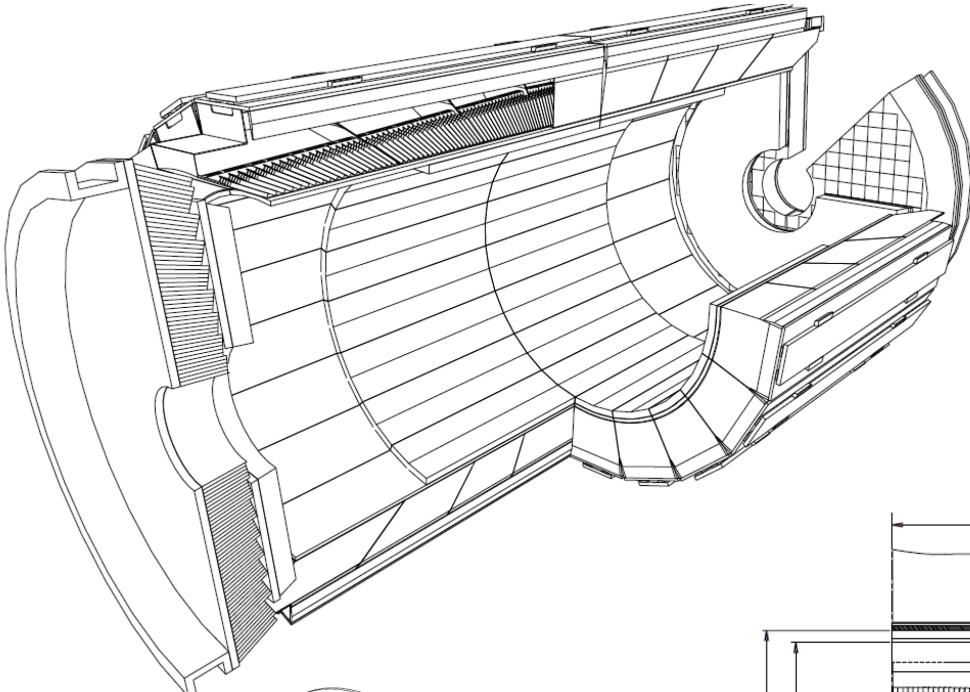
ATLAS EM Calorimeter

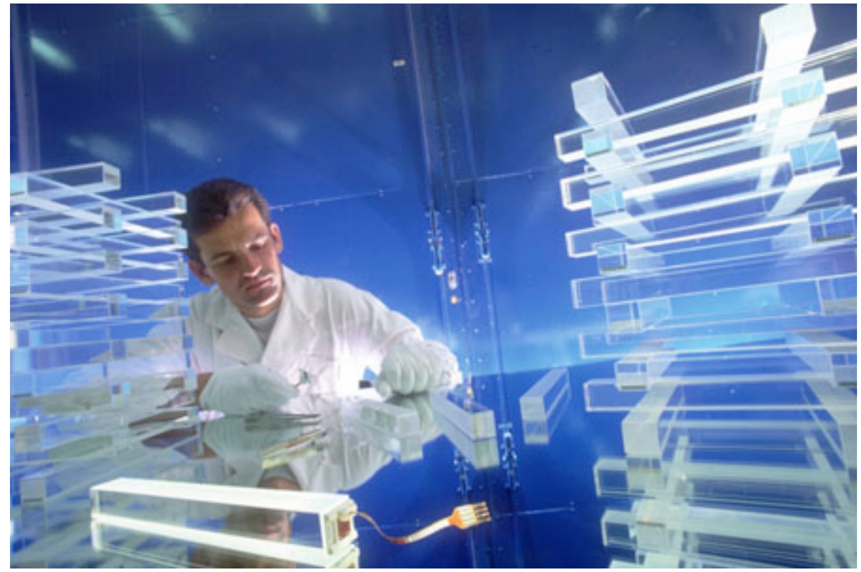


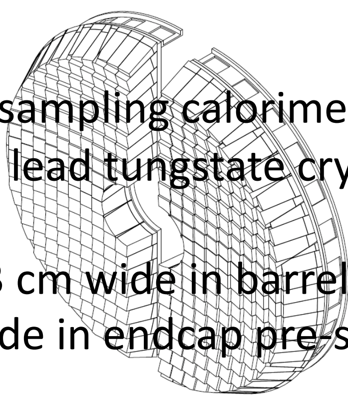




CMS EM Calorimeter

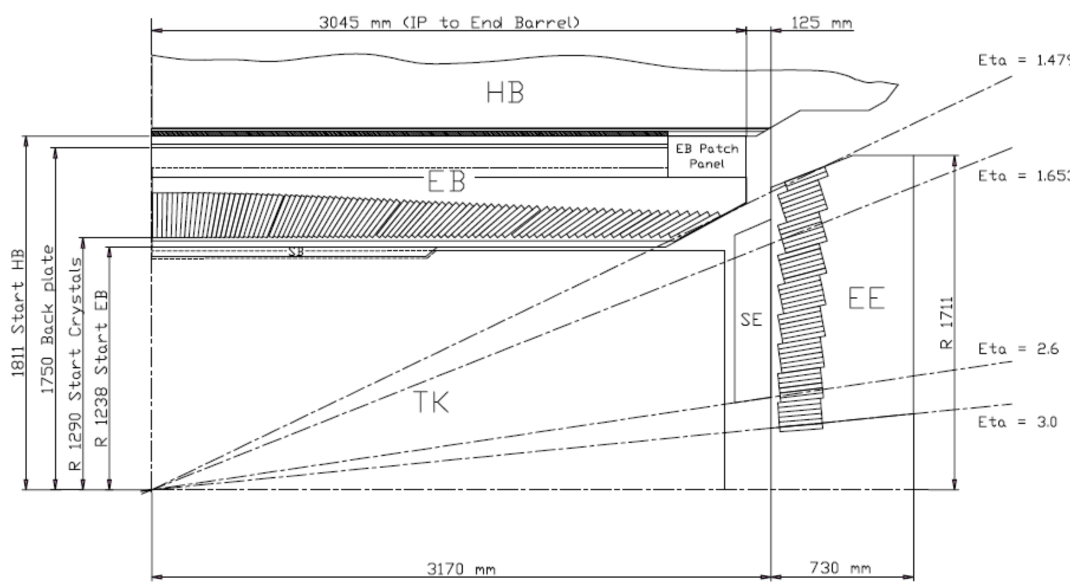






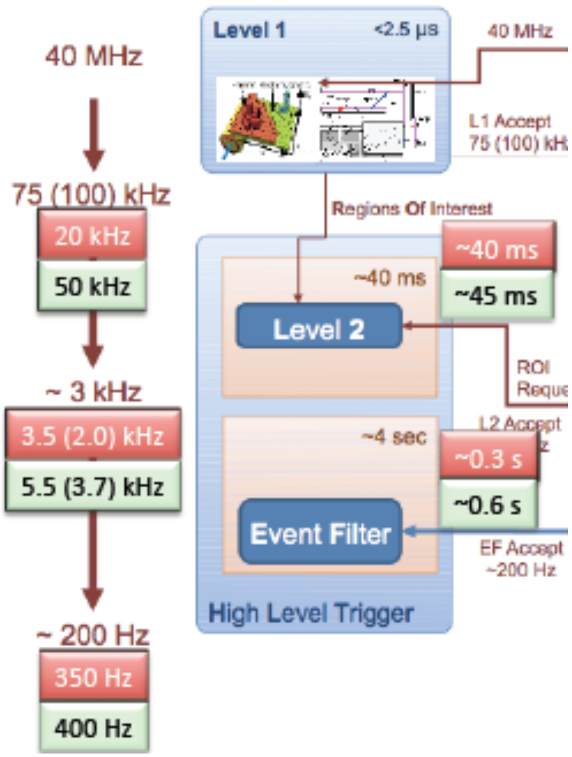
Non-sampling calorimeter
78,000 lead tungstate crystals

~3 cm wide in barrel
2 mm wide in endcap pre-shower

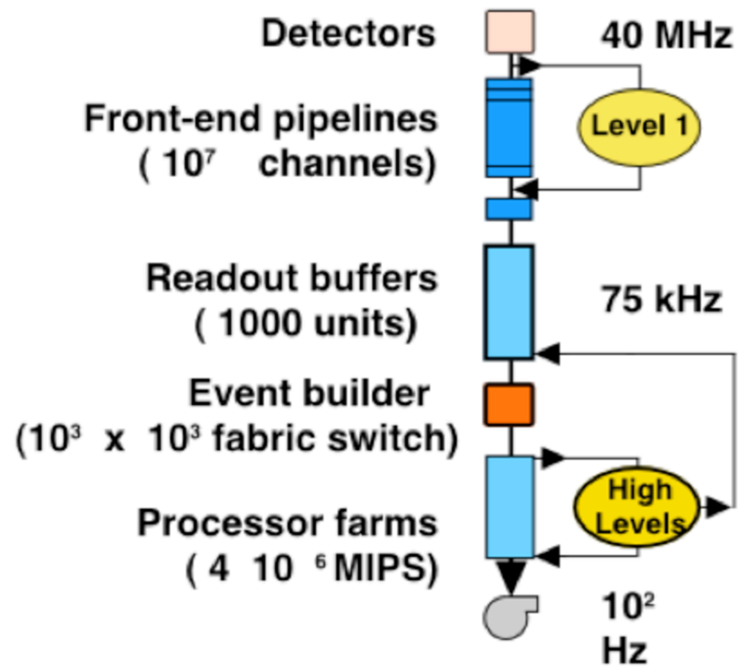


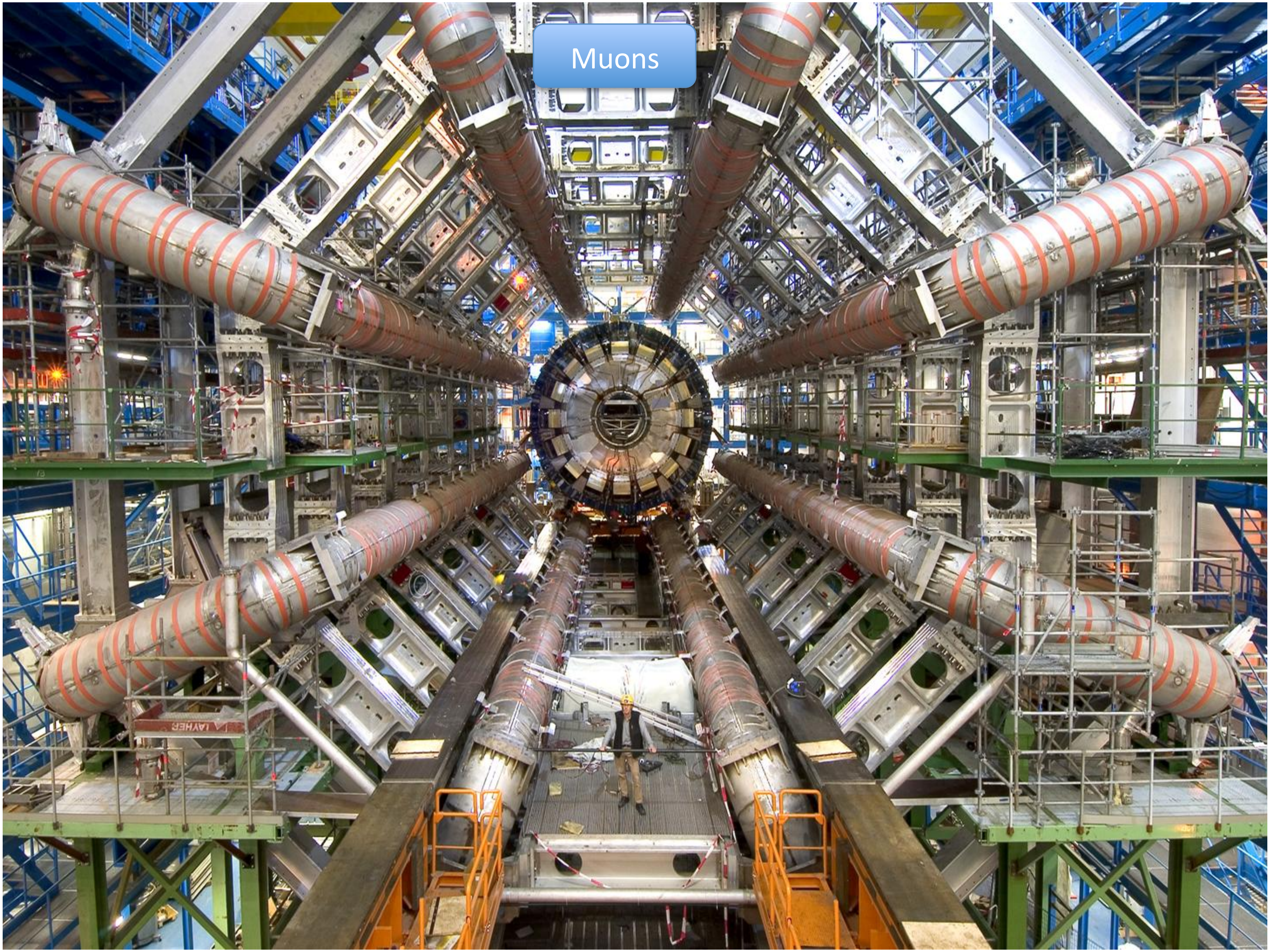
Triggers

ATLAS: 3 Levels

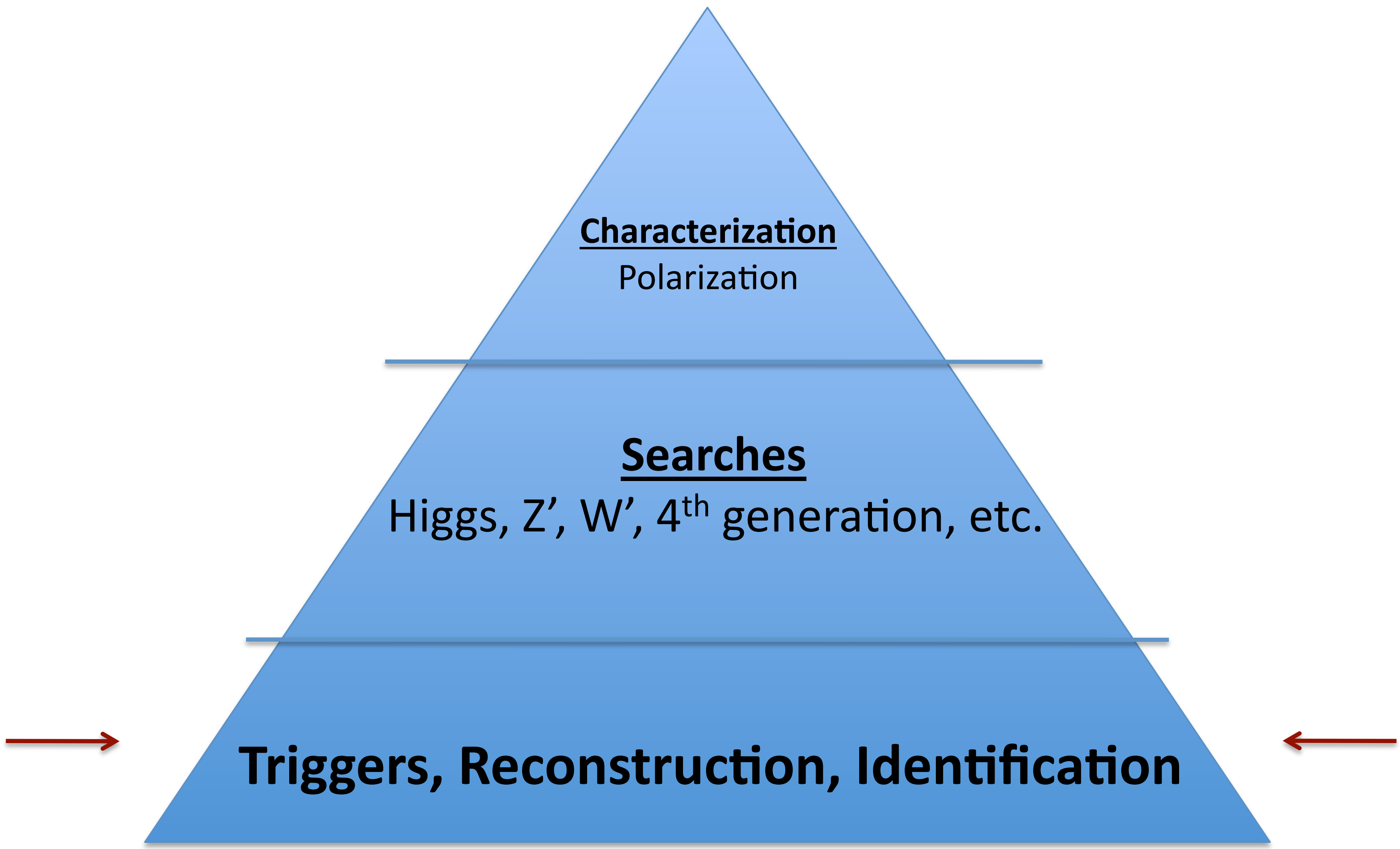


CMS: 2 Levels



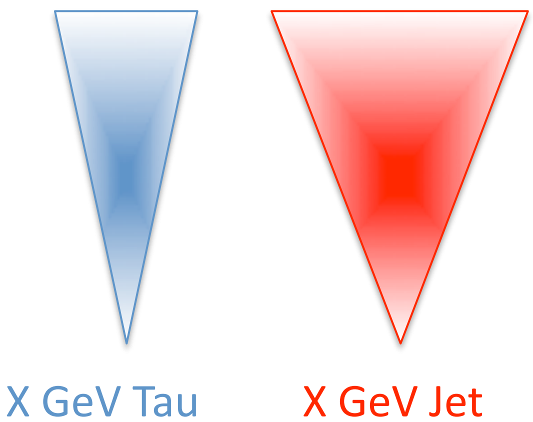

Muons

Taus at the LHC

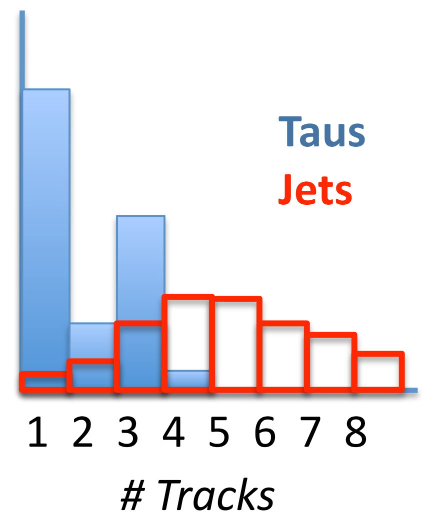


Triggering, Reconstructing, Identifying

Shape of Energy Deposit
in Calorimeter

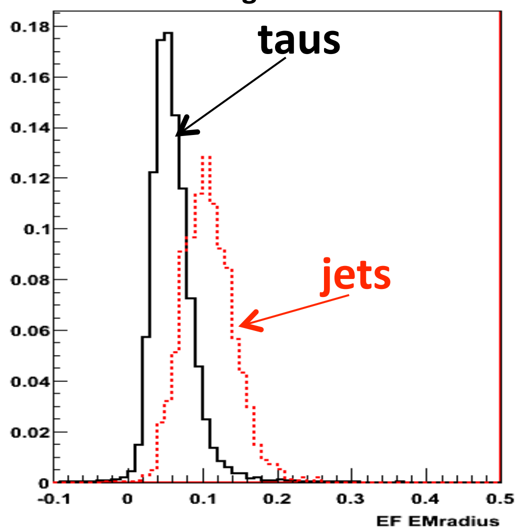


Track Multiplicity



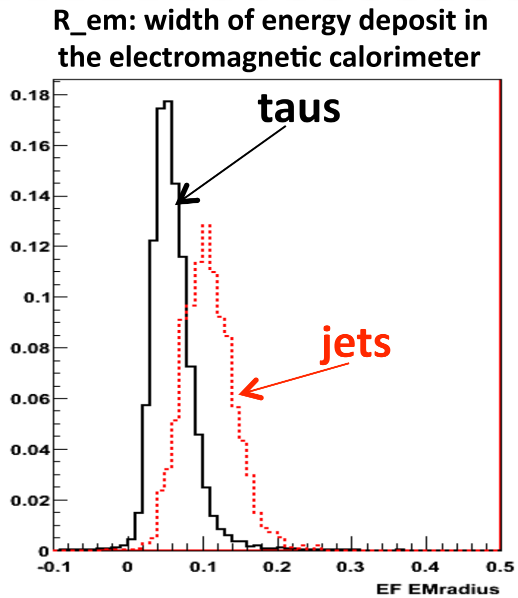
Triggering, Reconstructing, Identifying

R_em: width of energy deposit in the electromagnetic calorimeter

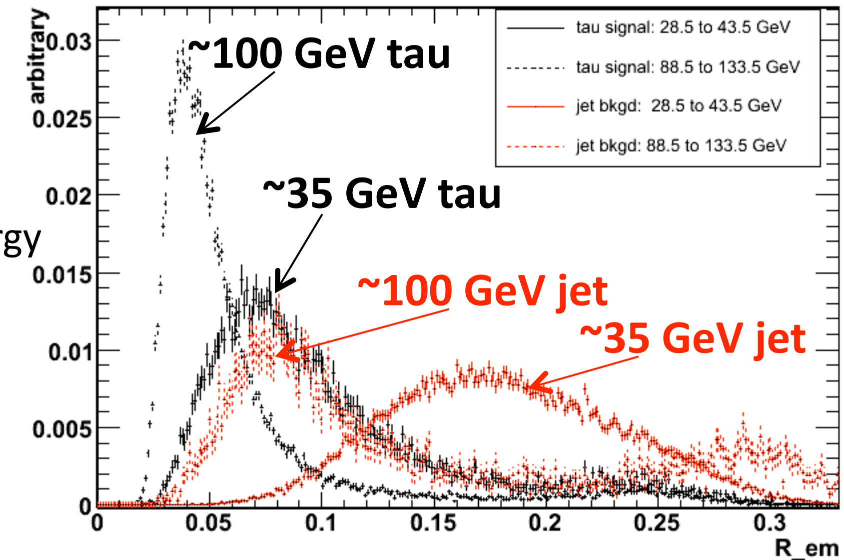


$$R_{em} = \frac{\sum_{i=1}^{n} E_{Ti}\sqrt{(\eta_i - \eta_{cluster})^2 + (\phi_i - \phi_{cluster})^2}}{\sum_{i=1}^{n} E_{Ti}}$$

Triggering, Reconstructing, Identifying



Separate in bins of energy



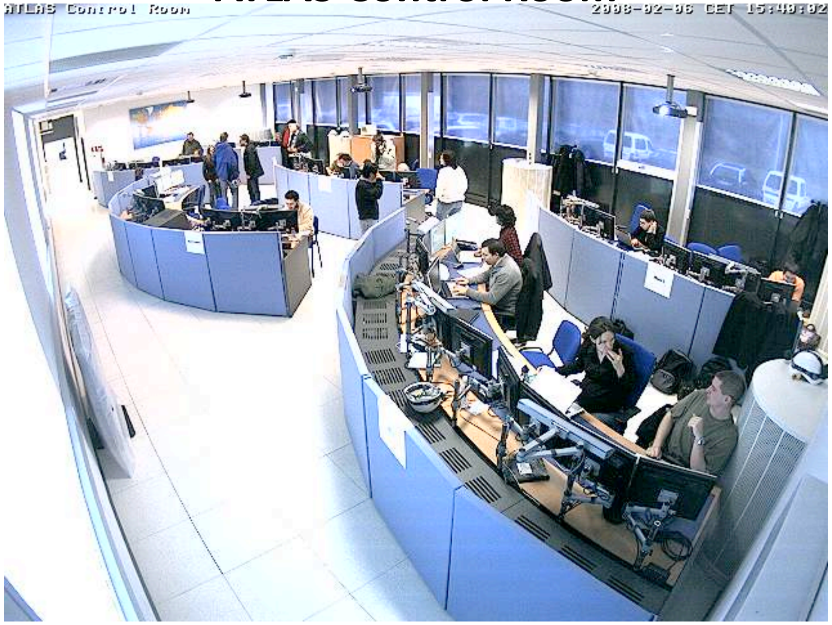
$$R_{em} = \frac{\sum_{i=1}^{n} E_{Ti}\sqrt{(\eta_i - \eta_{cluster})^2 + (\phi_i - \phi_{cluster})^2}}{\sum_{i=1}^{n} E_{Ti}}$$

also

isolation in tracking chamber

Tau Triggers

ATLAS Control Room



Level 1

Hardware

No Inner tracker information

Rely on calorimeters with low granularity

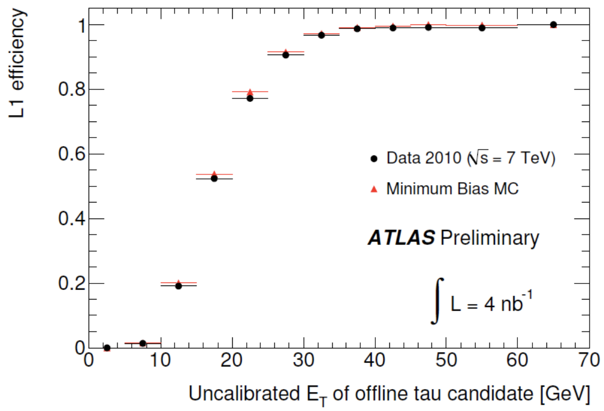
High Level Trigger

Software

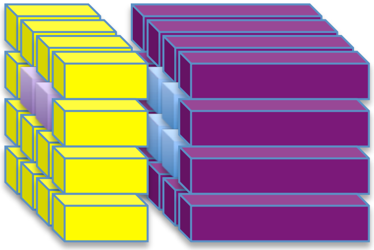
Use “offline” algorithms wherever possible

ATLAS Level 1 Tau Trigger

5 GeV L1 Tau Trigger

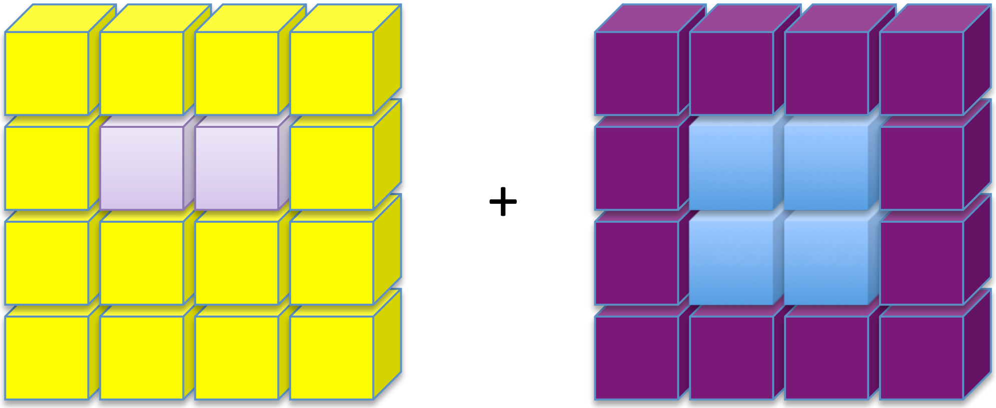


EM
Trigger Towers



HAD
Trigger Towers

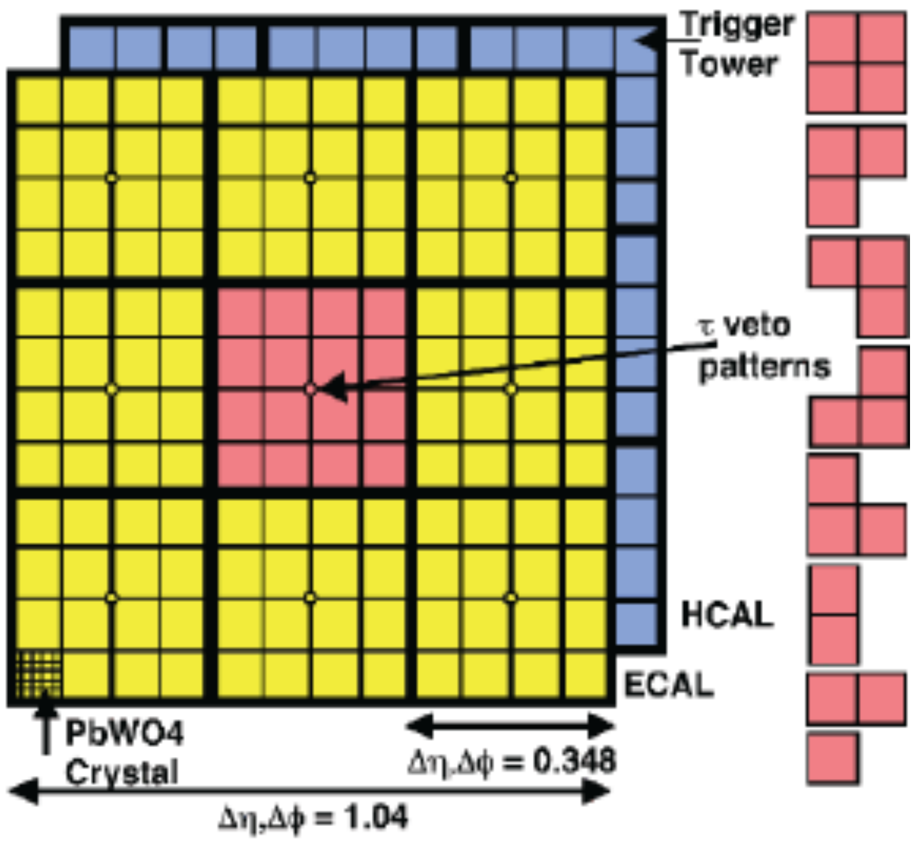
Threshold Calculation =



2 Adjacent EM Trigger Towers + *2x2 HAD Towers behind them*

$\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

CMS Level 1 Tau Trigger



Reconstruction and Identification

Major Difference: CMS uses particle flow

Reconstruction and Identification

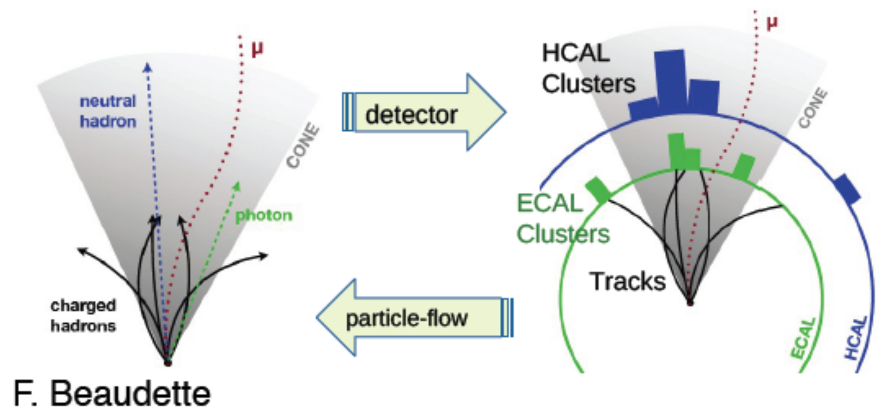
Major Difference: CMS uses particle flow

Particle Flow

Clusters and links signals from sub-detectors

Produces list of particle candidates

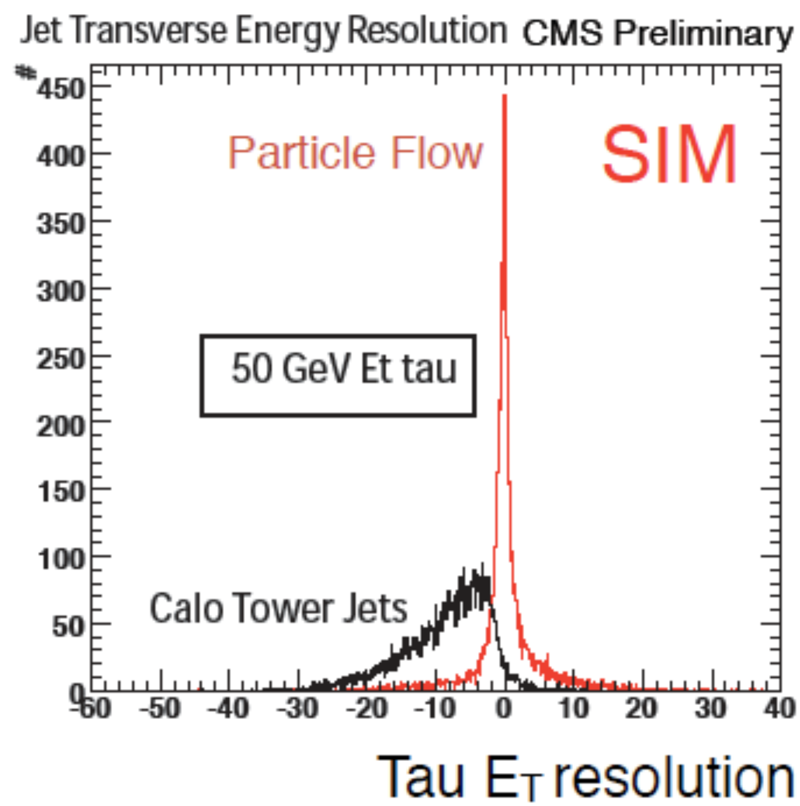
To user: looks like Monte Carlo



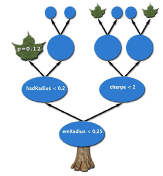
Reconstruction and Identification

Major Difference: CMS uses particle flow

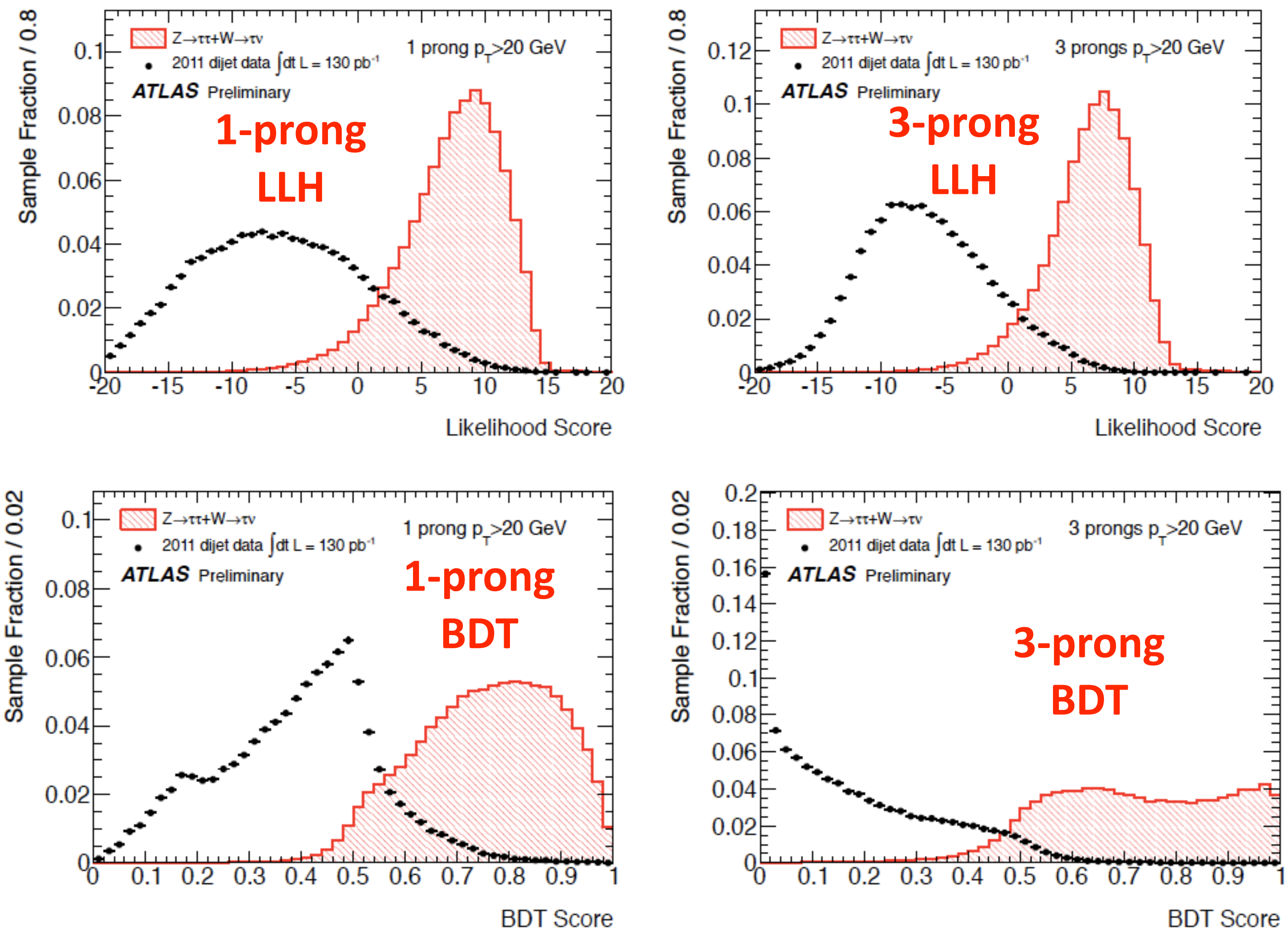
Particle Flow
Clusters and links signals from sub-detectors
Produces list of particle candidates
To user: looks like Monte Carlo



ATLAS Tau Identification



Cuts, log-likelihood,
& boosted decision trees



Variable	Eqn.	Jet discriminants					
		Cut		LLH		BDT	
		1	m	1	m	1	m
R_{track}	11	•	•	•	•	•	•
f_{track}	12	•	•			•	•
f_{core}	13			•	•	•	•
$N^{\mathrm{iso}}_{\mathrm{track}}$		•	•	•		•	•
R_{Cal}	14			•		•	•
f_{iso}	15						
$m_{\mathrm{eff.\ clusters}}$	16					•	•
m_{tracks}	18				•		•
$S_{\mathrm{T}}^{\mathrm{flight}}$	19		•		•		•
$S_{\mathrm{lead\ track}}$	20					•	•
$f_{\mathrm{2\ lead\ clusters}}$				•			
$f_{\mathrm{3\ lead\ clusters}}$						•	•
ΔR_{max}					•		•
f_{EM}	21						
f_{HT}	22						
$f^{\mathrm{track}}_{\mathrm{Had}}$	23						
$E^{\mathrm{strip}}_{\mathrm{T,max}}$							
$f^{\mathrm{track}}_{\mathrm{EM}}$	24						
R_{Had}	25						
$E^{\mathrm{iso}}_{\mathrm{T,corr}}$	26	•	•				

CMS Tau Identification

Two Identification Methods

Hadrons Plus Strips (HPS)

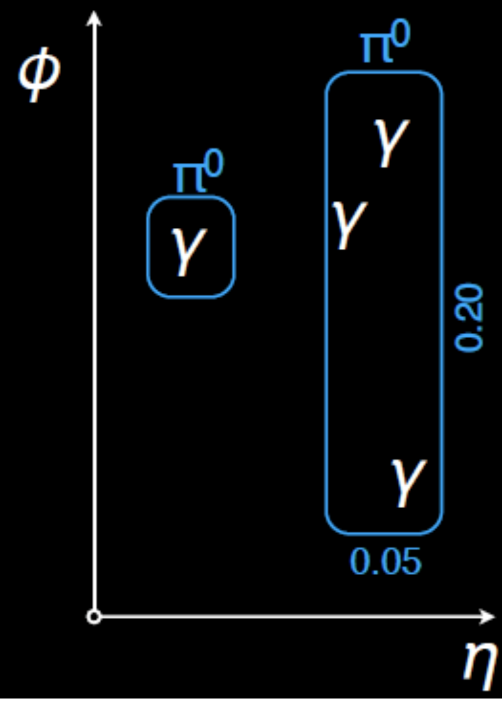
Tau Neural Classifier (TaNC)

Slide from Evan Friis

Hadrons Plus Strips Algorithm

build signal components combinatorially

cluster gammas into π^0 candidates using η-ϕ strips



build all possible taus that have a 'tau-like' multiplicity from the seed jet

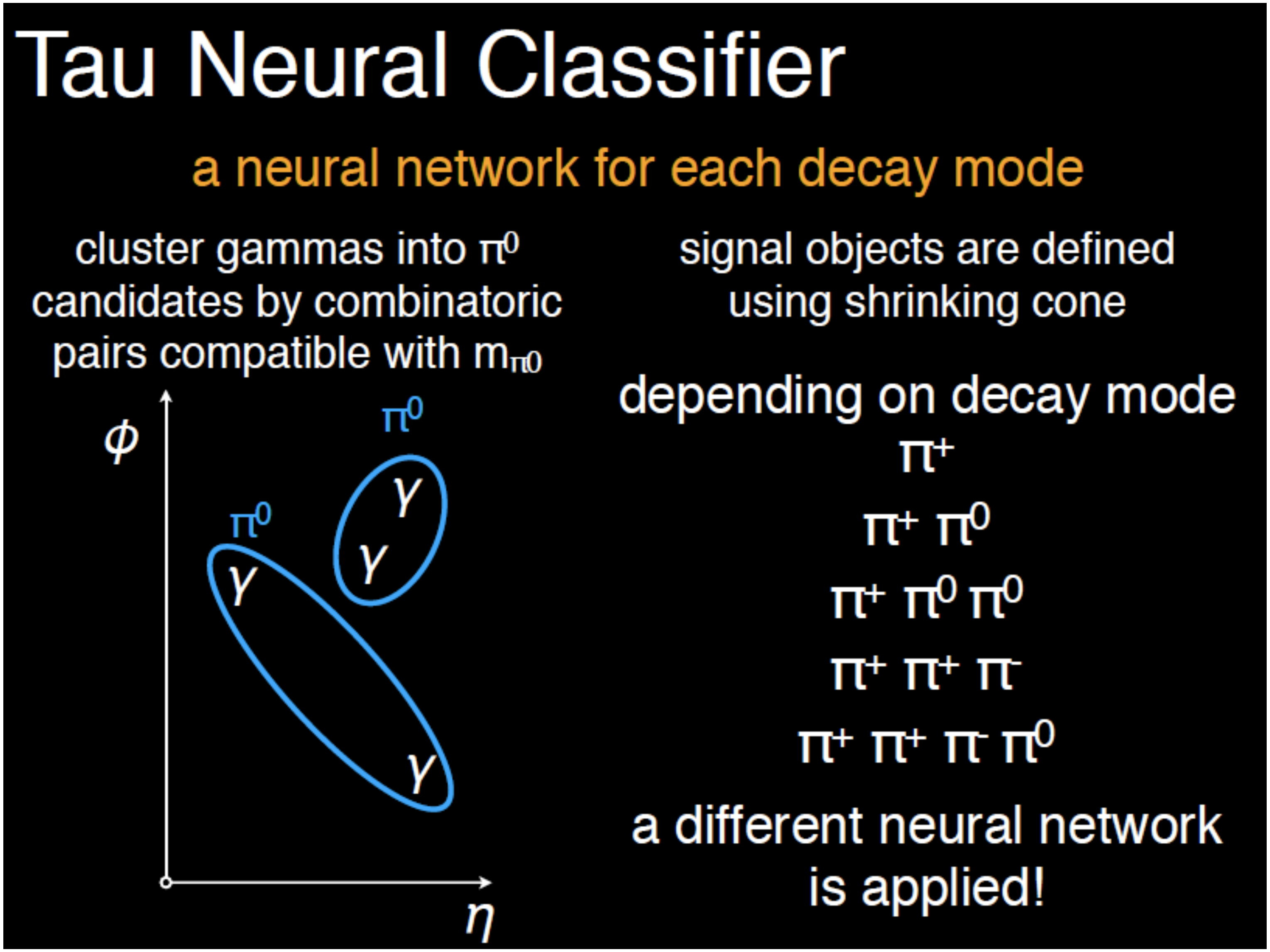
π^+

$\pi^+ \pi^0$

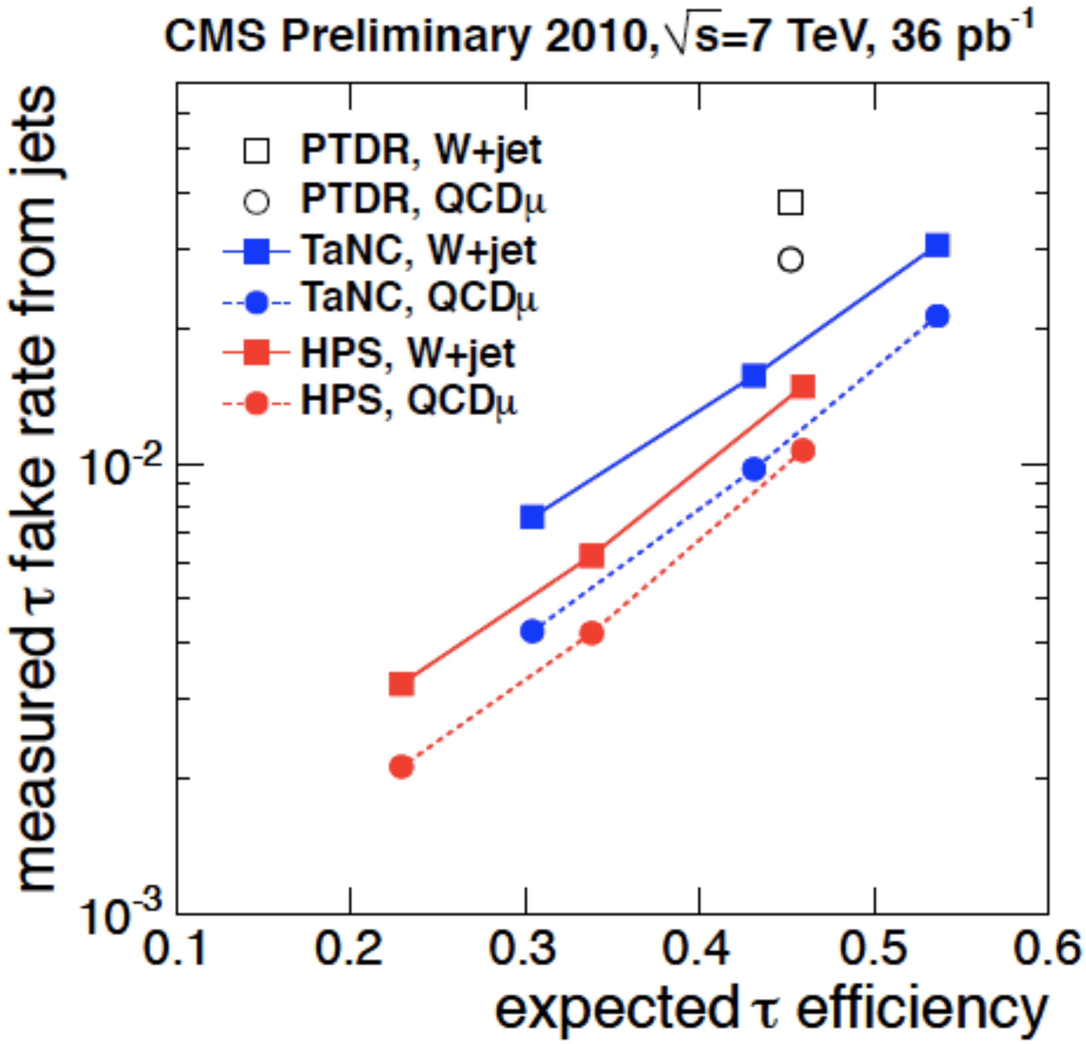
$\pi^+ \pi^+ \pi^-$

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

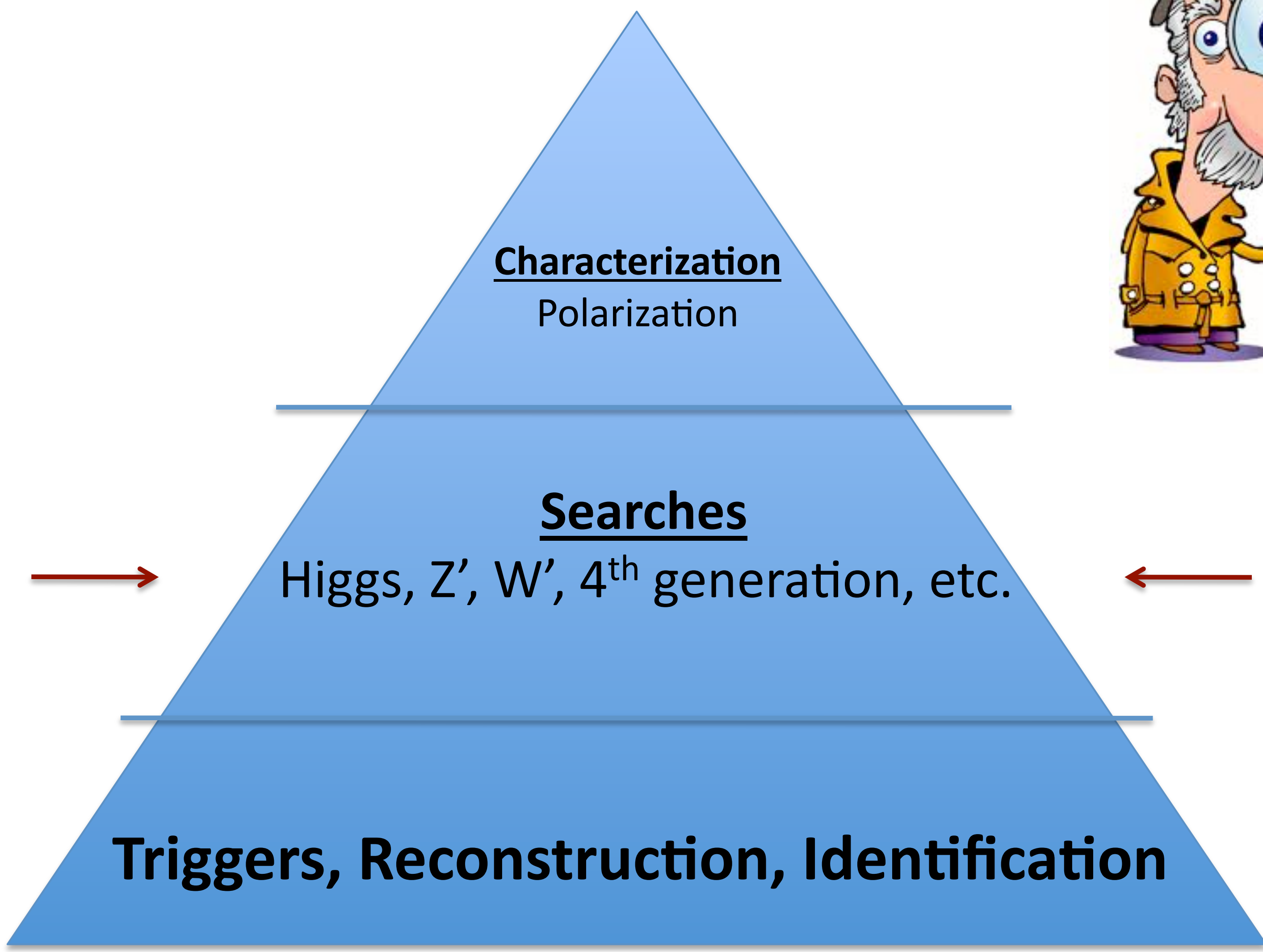
Slide from Evan Friis



Performance (2010)



Taus at the LHC



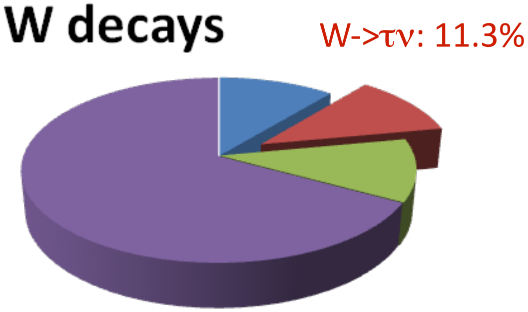
Standard Model Measurements

Z decays

Interest
Background in Higgs Search

Challenges
Missing Energy (missing info for reconstructing mass)
Trigger

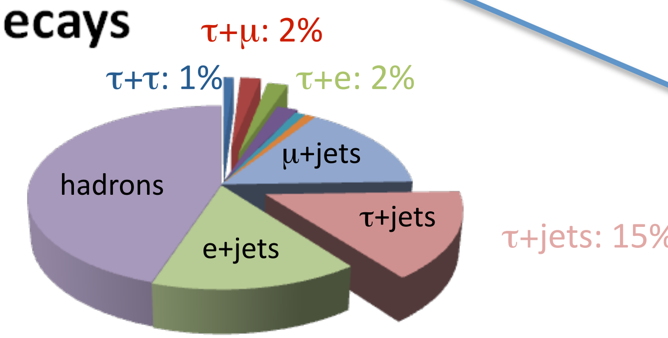
W decays



Interest
Early Tau Observation

Challenges
Trigger

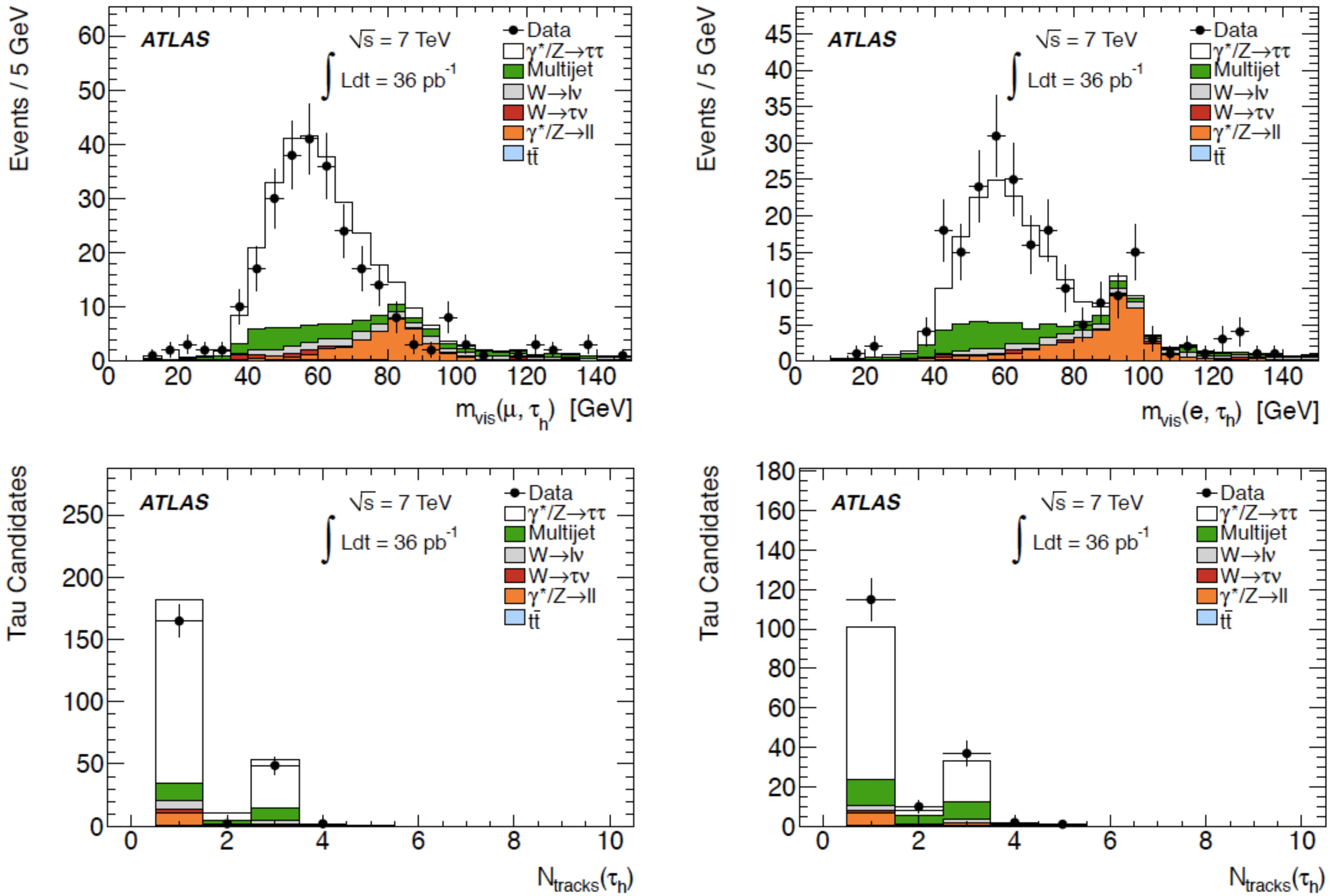
$t\bar{t}$ decays



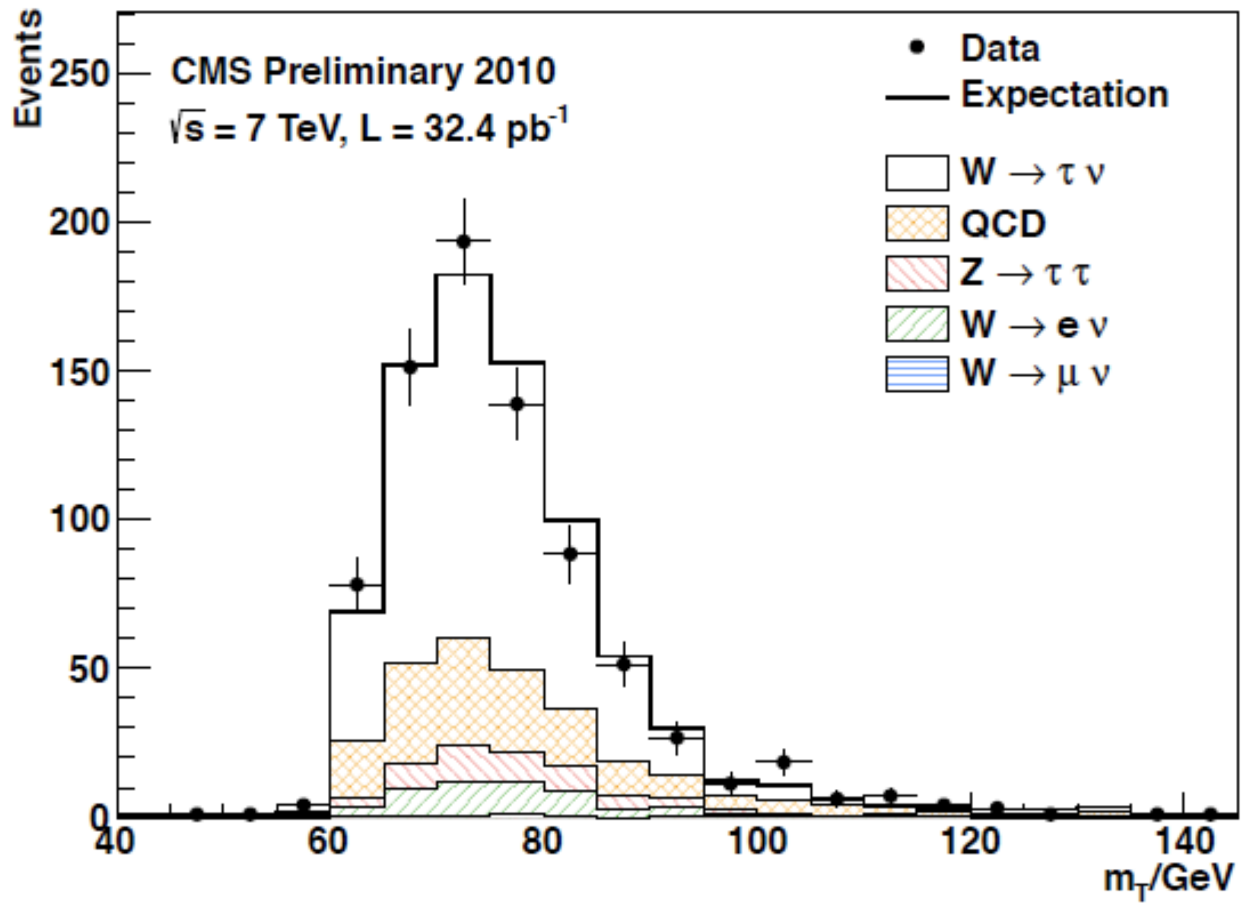
Interest
Charged Higgs Search
Calibration Sample

Challenges
Signal/Background

SM Measurements: Z->$\tau_l\tau_h$

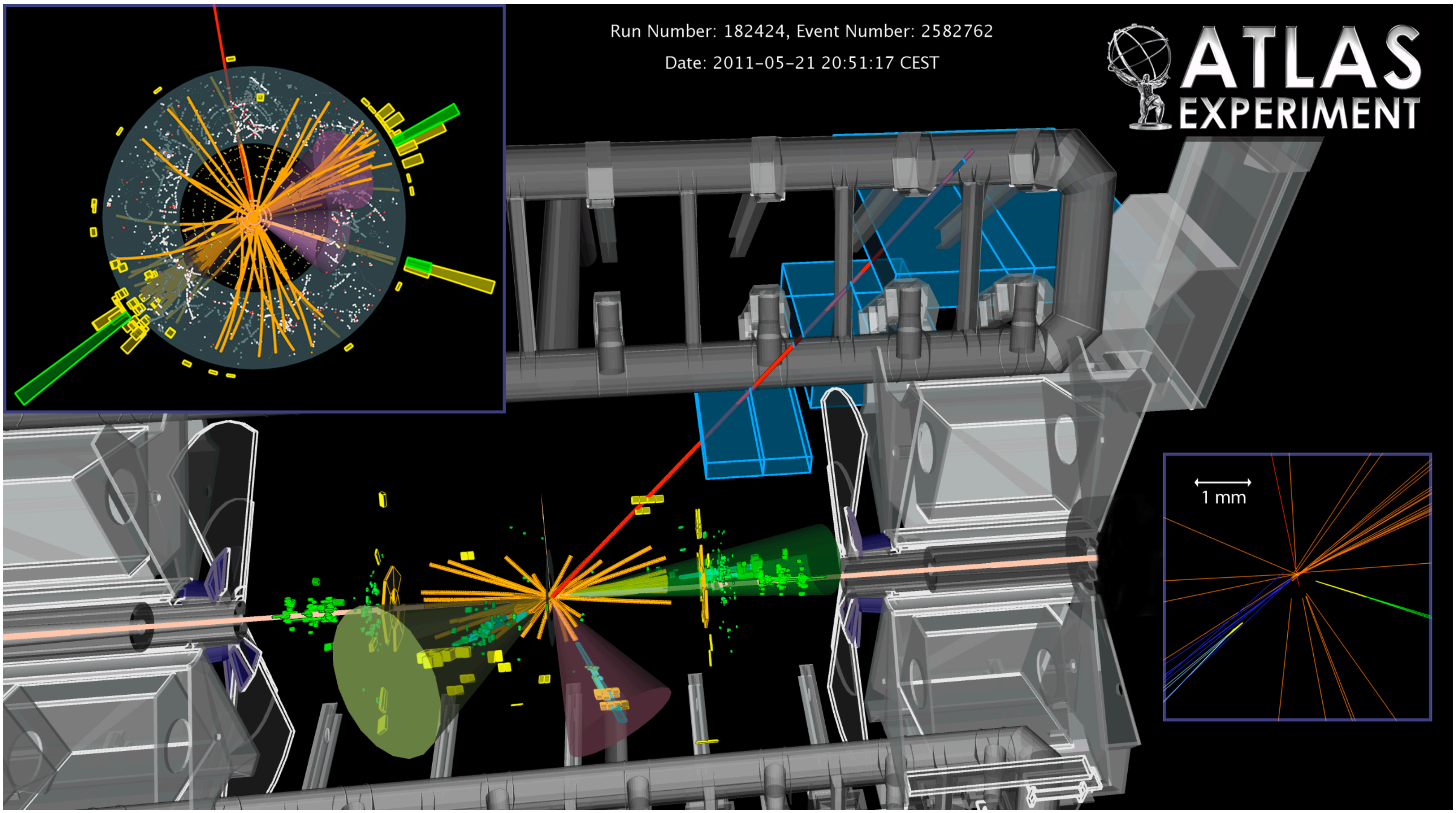


SM Measurements: W->$\tau_h\nu$



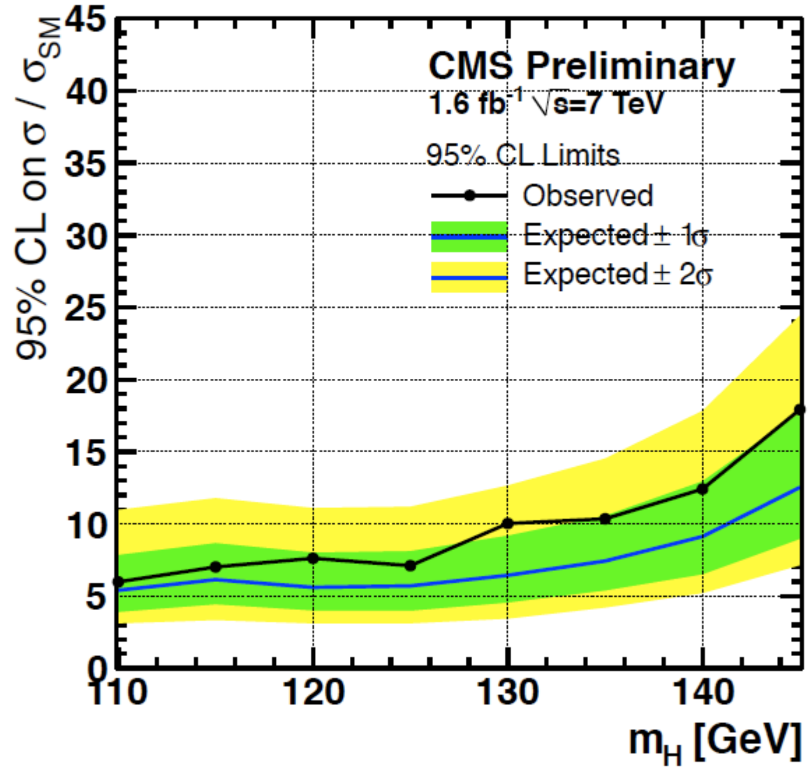
Top events with taus

tau-muon dilepton candidate

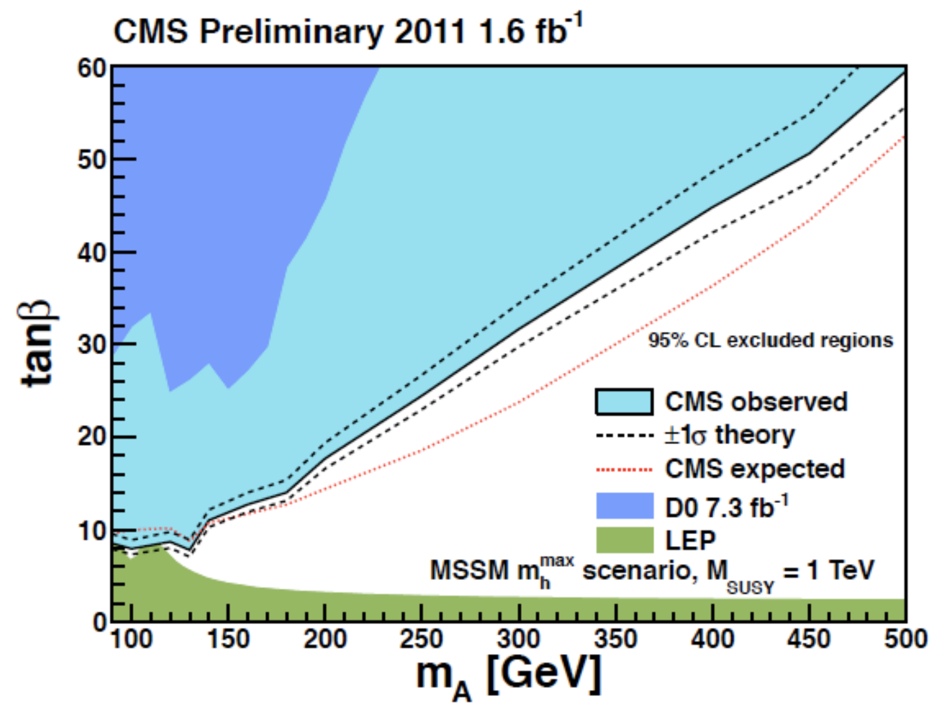


CMS: Higgs -> ττ

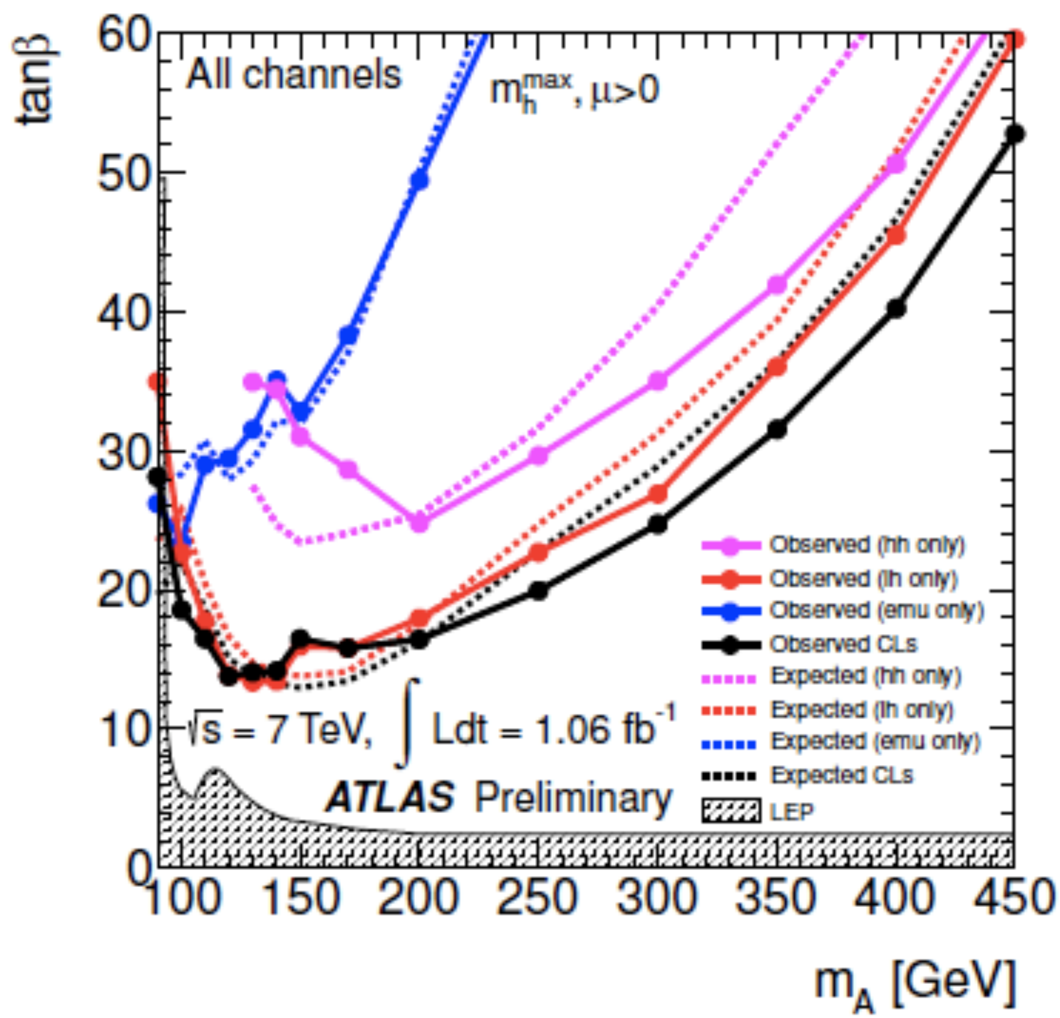
SM Exclusion Plot



SUSY Exclusion Plot



ATLAS MSSM H->ττ



Search for the Charged Higgs

If

- *the charged Higgs exists and has a mass less than the mass of the top quark*

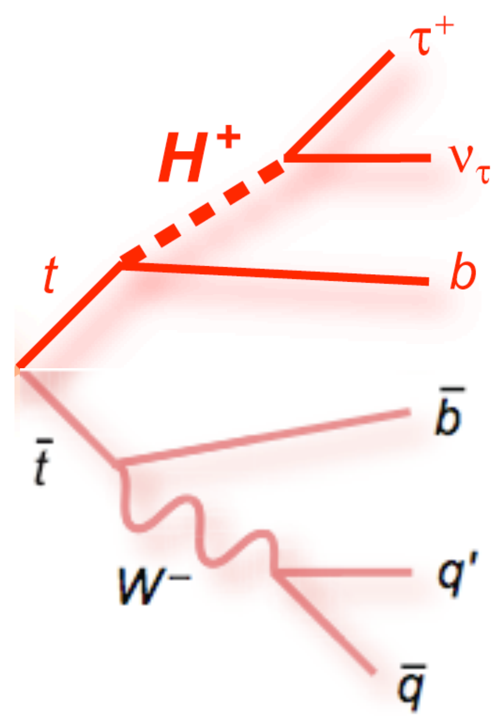
Then

- *the primary production mechanism for the charged Higgs will be via top quarks*

Since

- *the primary source of top quarks is within ttbar production*

Top quark pairs provide a nice playground for searching for and constraining the allowed masses of the charged Higgs



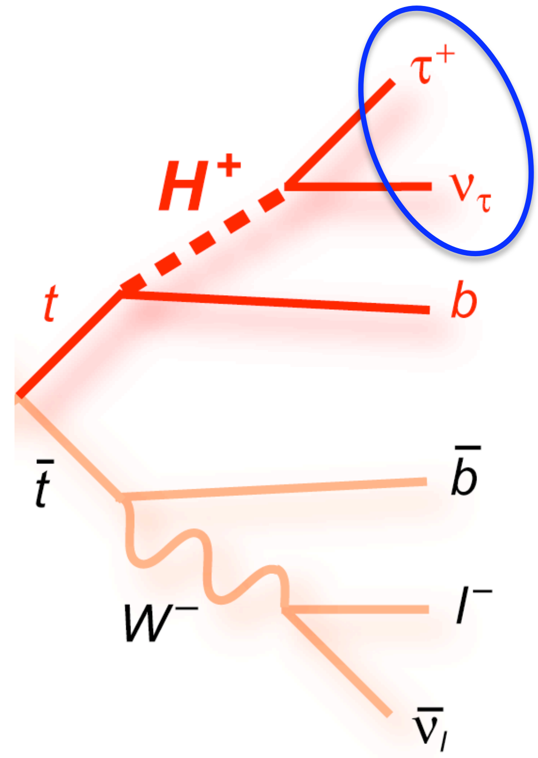
Search for the Charged Higgs

When $\tan\beta$ is greater than ~3, the H^+ decays almost exclusively to $\tau\nu$

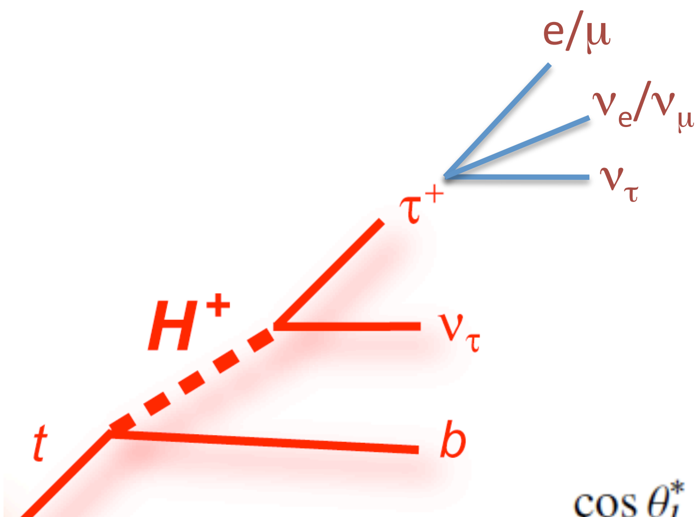
This search was performed with 1.03 fb^{-1} of 2011 ATLAS data in both the **single lepton** and **dilepton** channels

Presence of H+ ends up giving excess of leptons:
$B(H+ \rightarrow \tau\nu \rightarrow l + N\nu) \simeq 35\%$ while $B(W \rightarrow l + N\nu) \simeq 25\%$

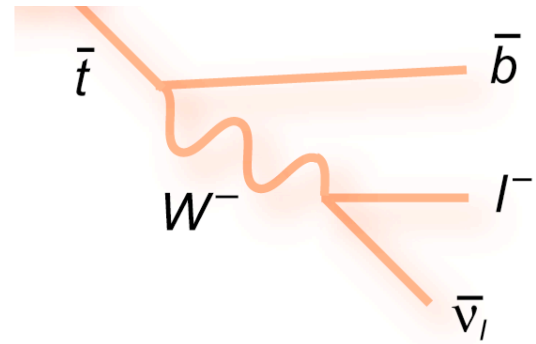
but additional handles are needed:
$\cos\theta^*_l$ and transverse mass of the H^+



Discriminating variables: $\cos\theta^*_l$

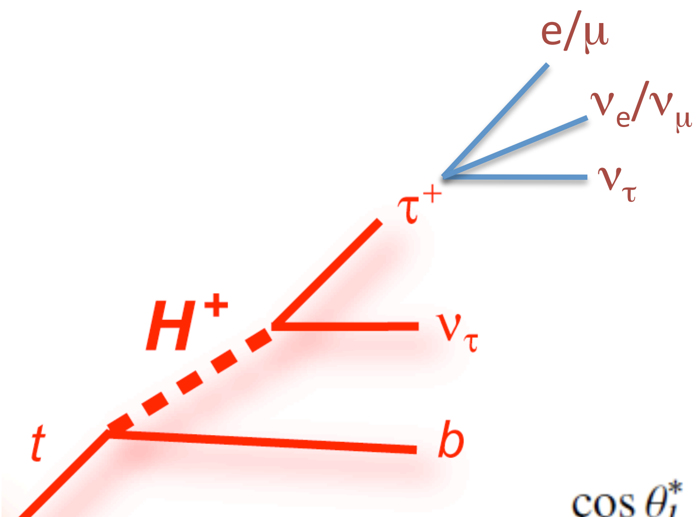


vs.

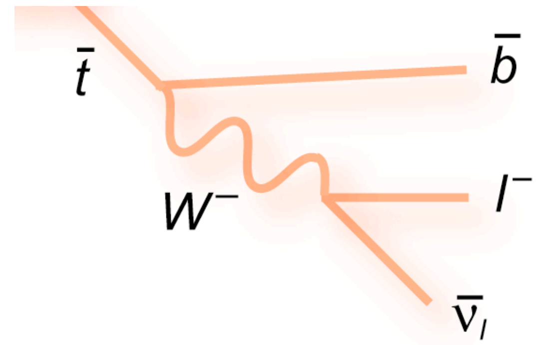


$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{\text{top}}^2 - m_W^2} - 1 \simeq \frac{4\, p^b \cdot p^l}{m_{\text{top}}^2 - m_W^2} - 1$$

Discriminating variables: $\cos\theta^*_l$



vs.



$$\cos\theta^*_l = \frac{2m^2_{bl}}{m^2_{top} - m^2_W} - 1 \simeq \frac{4\,p^b \cdot p^l}{m^2_{top} - m^2_W} - 1$$

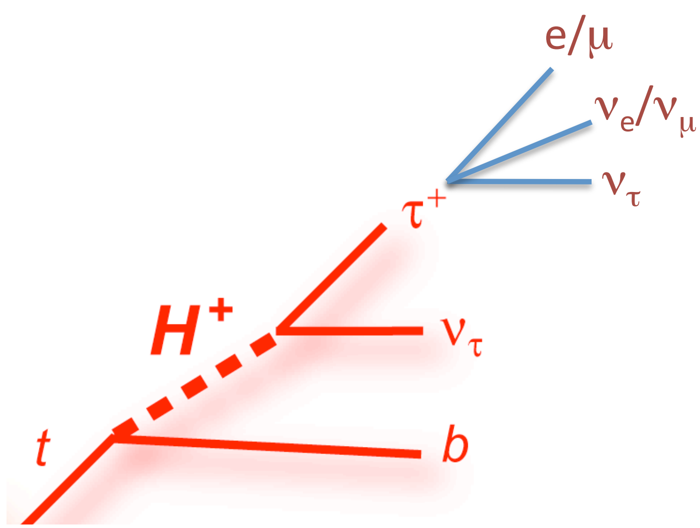
$$p^b \cdot p^l = 2E_b E_l(1 - \cos\theta_{bl}) = 4E_b E_l \sin^2(\theta_{bl}/2)$$

Variable commonly used to measure polarization of W in top quark events

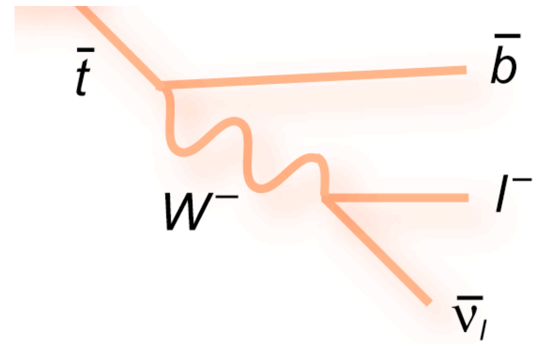
Here, with H^+ heavier than the W, the b-quark tends to have less momentum in H+ events also, leptons from the tau decays tend to have less momentum than from Ws

All of this works to push $\cos\theta^*_l$ toward the value of -1

Discriminating variables: transverse mass of Higgs



vs.



Define H$^+$ transverse mass

For single lepton channel, maximize the lepton + p_T^{miss}:

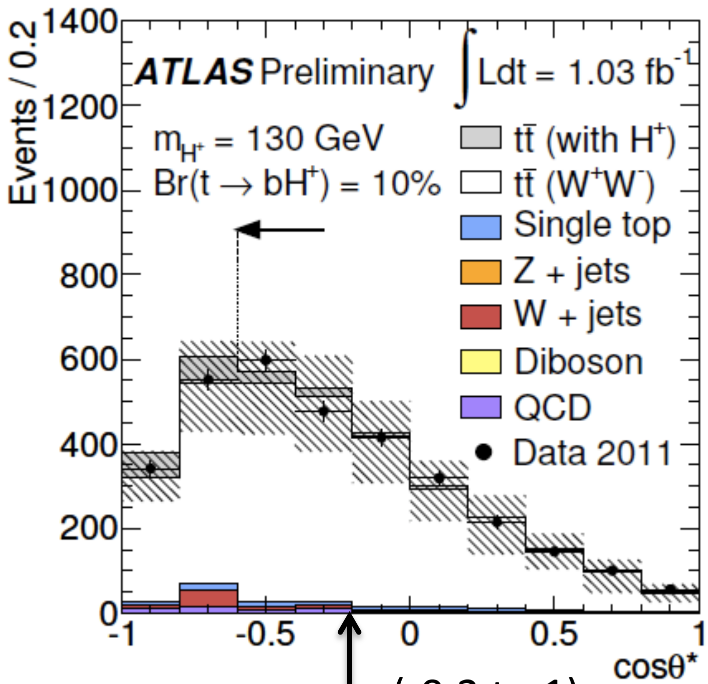
$$(m_T^H)^2 = \left(\sqrt{m_{top}^2 + (\vec{p_T}^l + \vec{p_T}^b + \vec{p_T}^{miss})^2} - p_T^b \right)^2 - \left(\vec{p_T}^l + \vec{p_T}^{miss} \right)^2$$

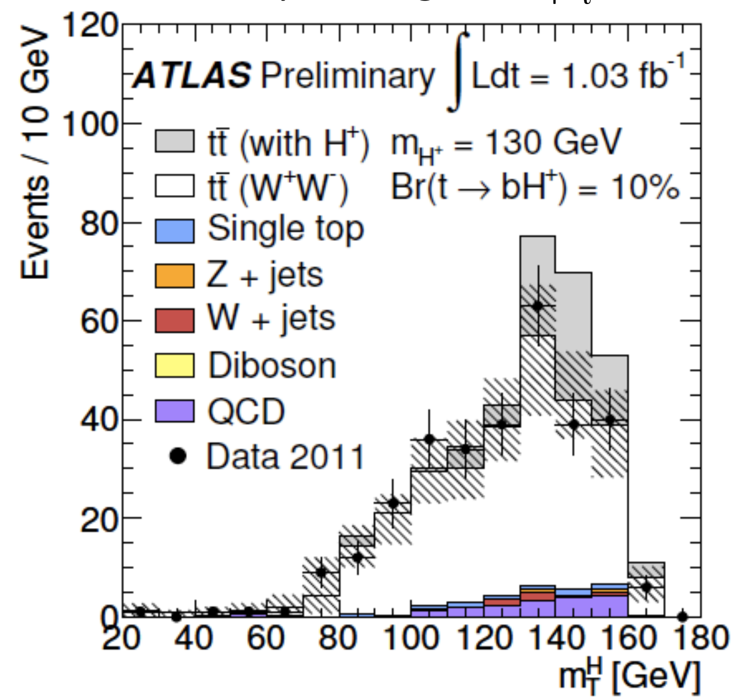
$$(p^{miss} + p^l + p^b)^2 = m_{top}^2$$

Situation is slightly more complicated in dilepton case

Charged Higgs: Single Lepton Results

Signal region, with additional requirement that "transverse mass of W" < 60 GeV to enhance charged boson decays through $\tau \to l\nu_l\nu_\tau$



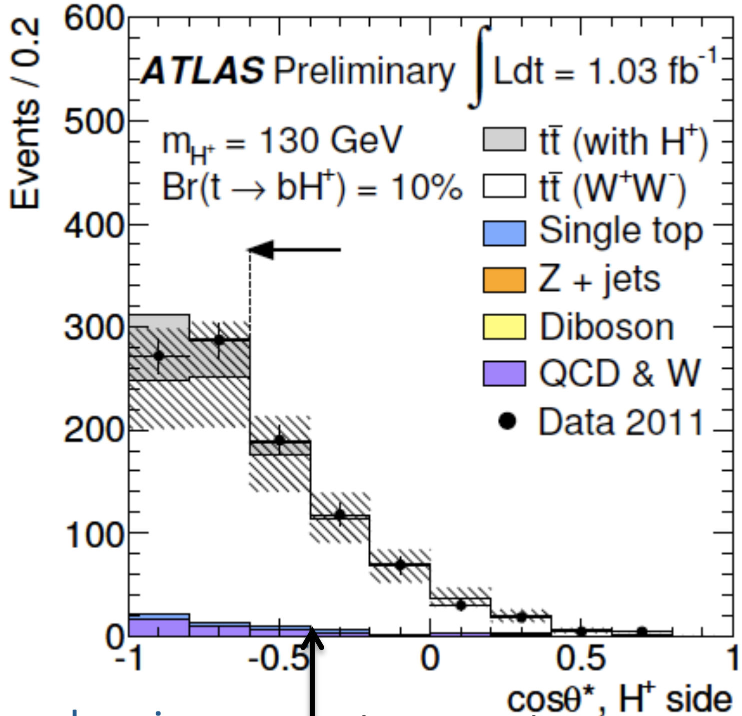


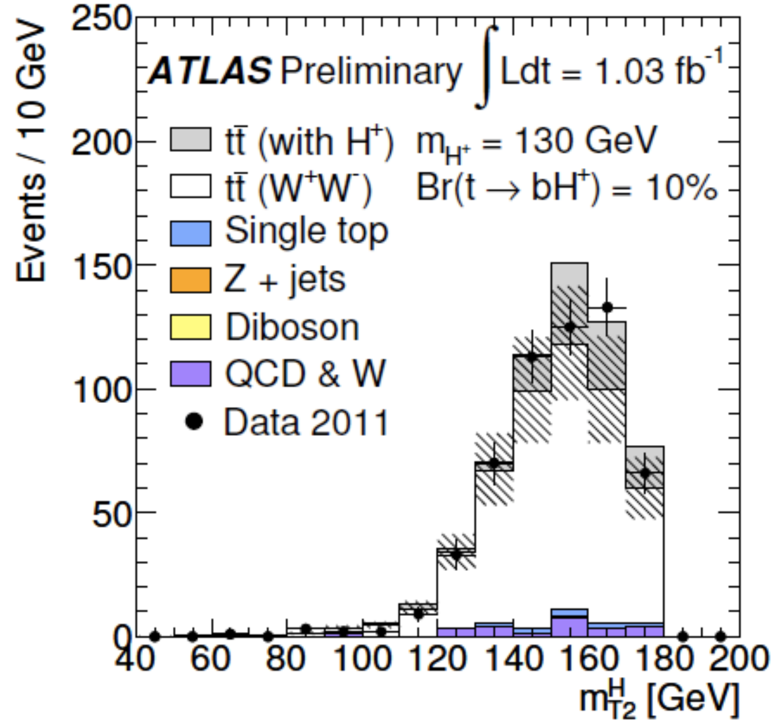
Signal region

(-0.2 to 1)

SM enriched region
for fitting to cross section: $t\bar{t} \to b\bar{b}W^+W^-$
165.1 pb

Charged Higgs: Dilepton Results





Signal region

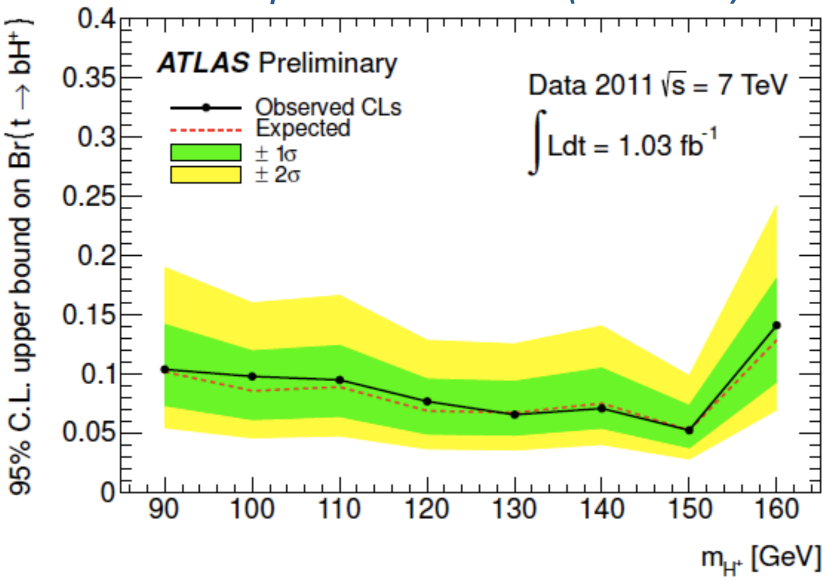
(-0.4 to 1)

SM enriched region
for fitting to cross section: $t\bar{t} \rightarrow b\bar{b}W^+W^-$
150.4 pb

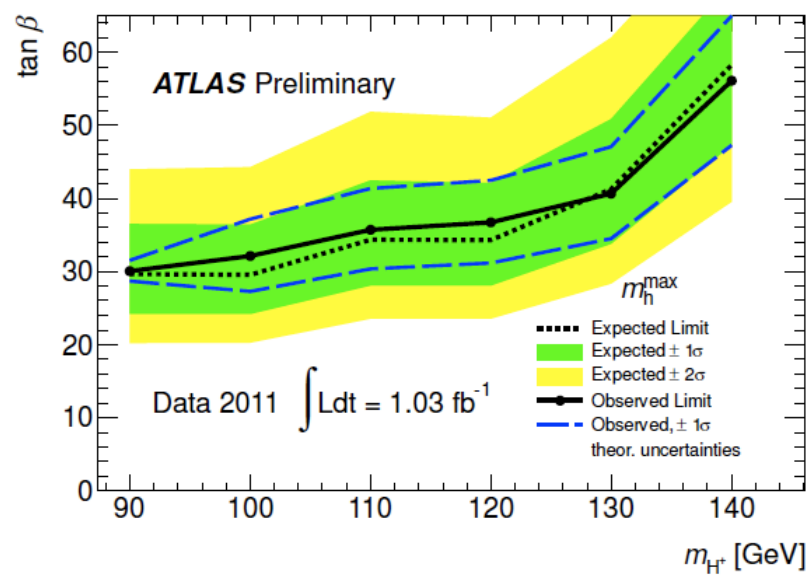
Combined Limits

Assuming B($H^+ \rightarrow \tau\nu$) = 1,
place upper limits on the branching fraction B($t \rightarrow bH^+$)

In the 90 – 160 GeV range,
upper limits between 5.2% and 14.1%
are placed on the B($t \rightarrow bH^+$)

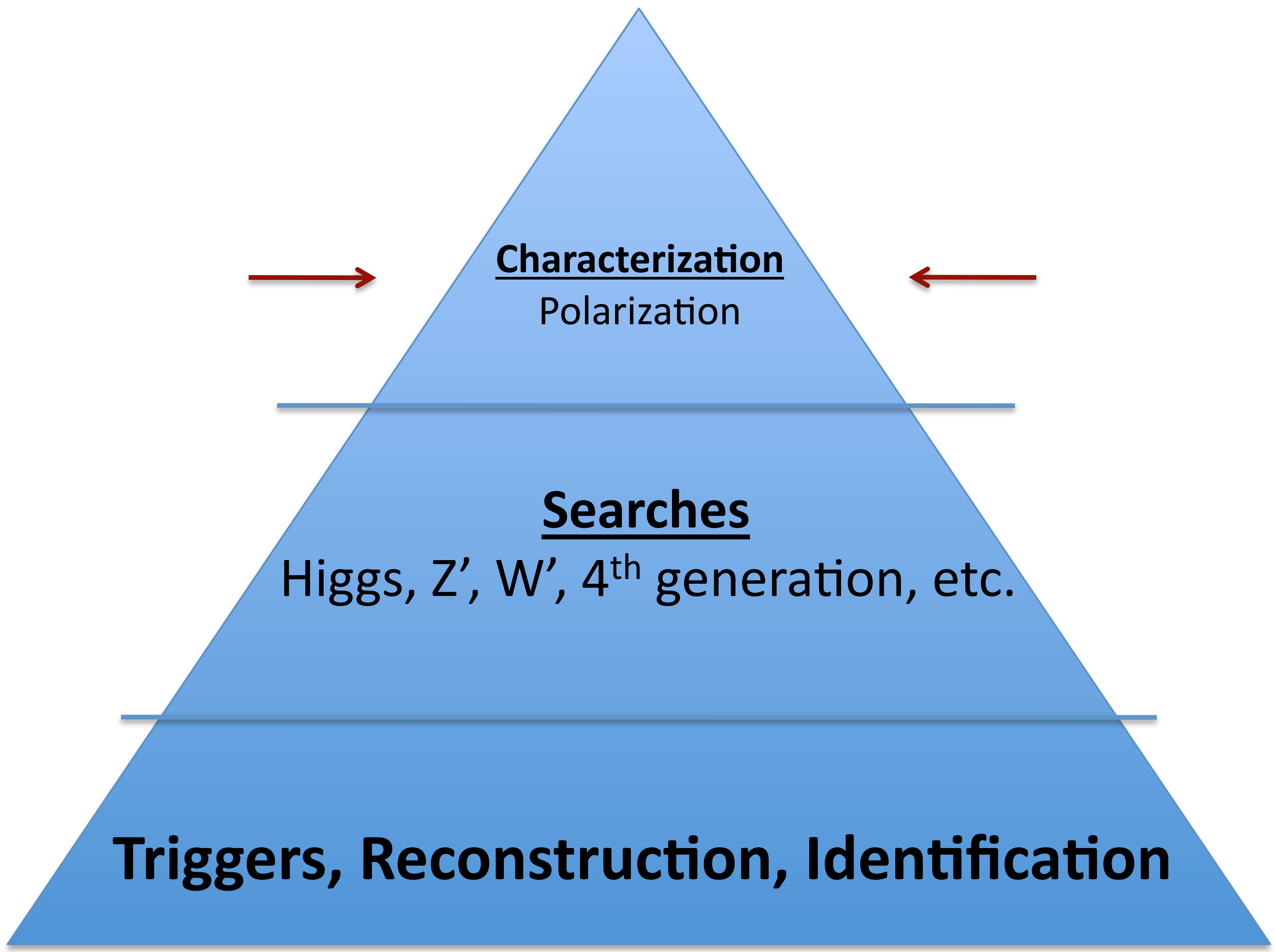


In m^{max}_h scenario of MSSM
tan β > 30–56 is excluded for H+ masses
90 GeV < mH^+ < 140 GeV



Theoretical Uncertainty Band
missing one-loop EW corrections
missing two-loop QCD corrections
uncertainties related to running b-quark mass

Taus at the LHC



Polarization

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

Relative cross section of right- and left-handed taus

Process	$W \to \tau_h \nu_\tau$	$Z \to \tau\tau$	$H \to \tau\tau$	$H^- \to \tau\nu$
P_τ	-1	≈ -0.15	0	+1

The ability to access tau polarization would give us information regarding the resonance that decays to taus

Polarization

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

Relative cross section of right- and left-handed taus

Process	$W \to \tau_h \nu_\tau$	$Z \to \tau\tau$	$H \to \tau\tau$	$H^- \to \tau\nu$
P_τ	-1	≈ -0.15	0	+1

The ability to access tau polarization would give us information regarding the resonance that decays to taus

How to access Polarization?

Neutrino has *intrinsic parity*: its angular momentum vector points opposite to its velocity vector, regardless of reference frame.

Neutrinos are left-handed, Anti-neutrinos are right-handed

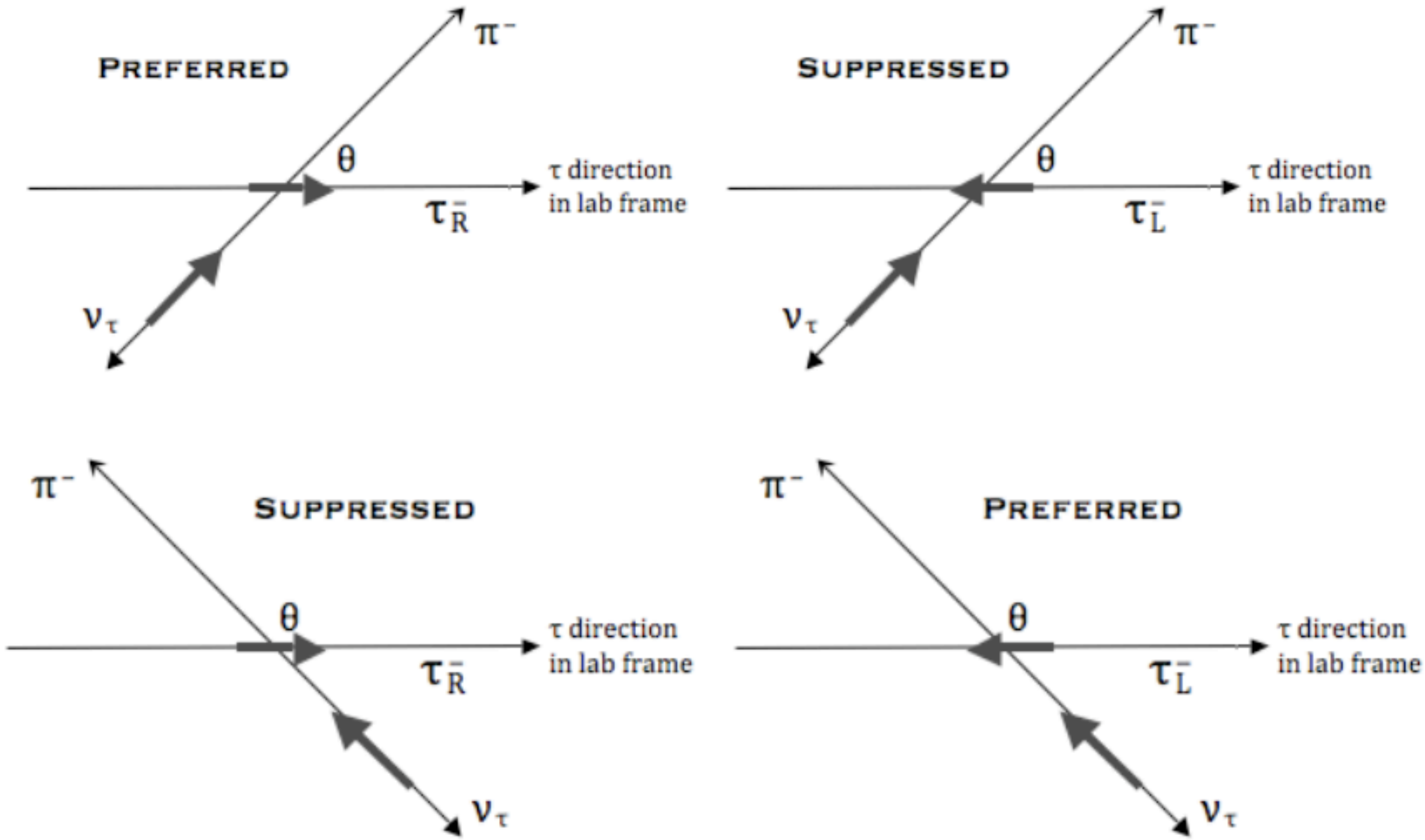
Angular momentum is conserved -> angle between tau decay products depends on the handed-ness of the tau

$$\cos\theta = \frac{2x - 1 - y^2}{1 - y^2}$$

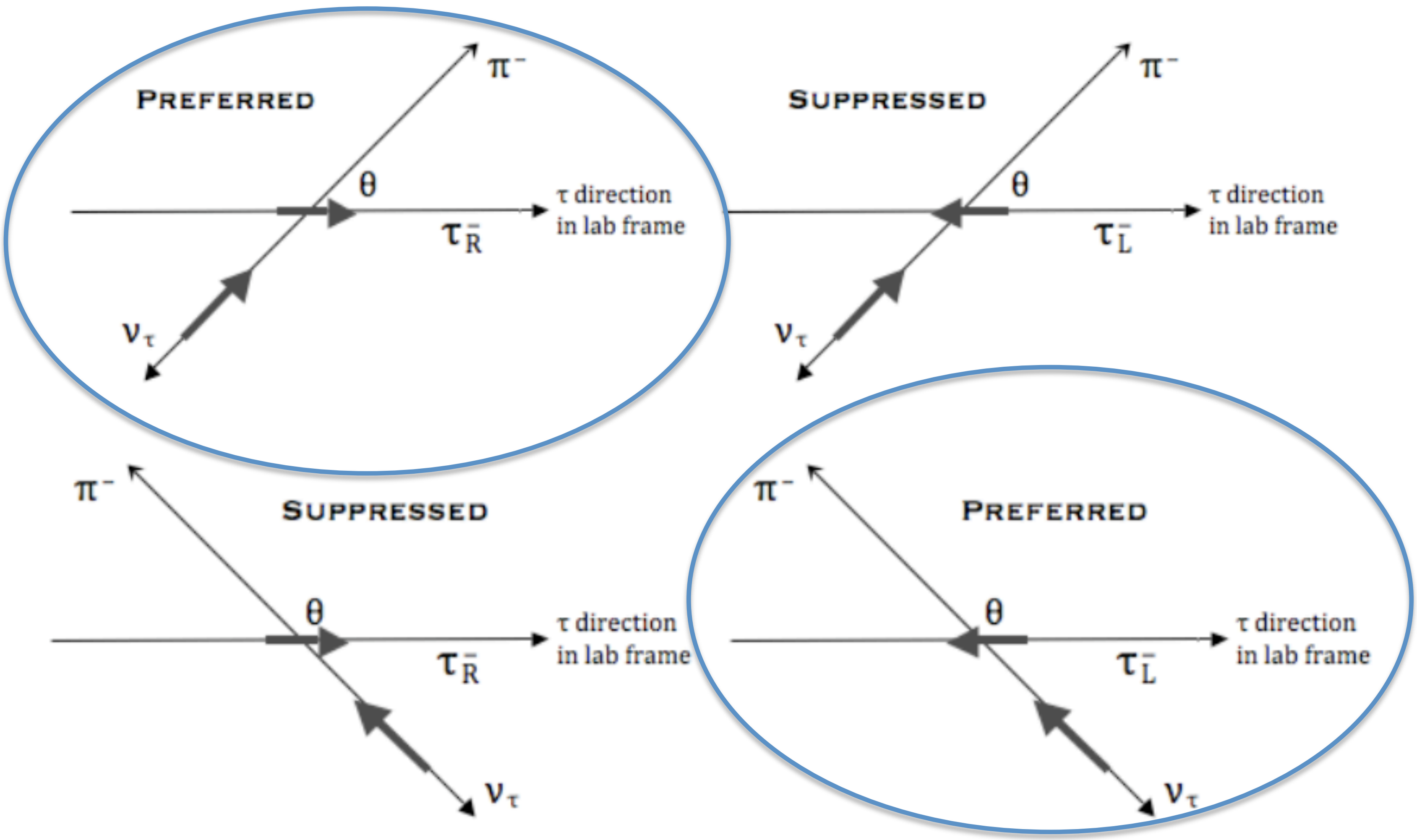
$$x = E_h / E_\tau$$

y refers to the fraction of the tau mass in the hadronic system m_h / m_τ

Polarization: taus decay in detector



Polarization: taus decay in detector



How to access Polarization?

Neutrino has *intrinsic parity*: its angular momentum vector points opposite to its velocity vector, regardless of reference frame.

Neutrinos are left-handed, Anti-neutrinos are right-handed

Angular momentum is conserved -> angle between tau decay products depends on the handed-ness of the tau

$$\cos\theta = \frac{2x - 1 - y^2}{1 - y^2}$$

$$x = E_h / E_\tau$$

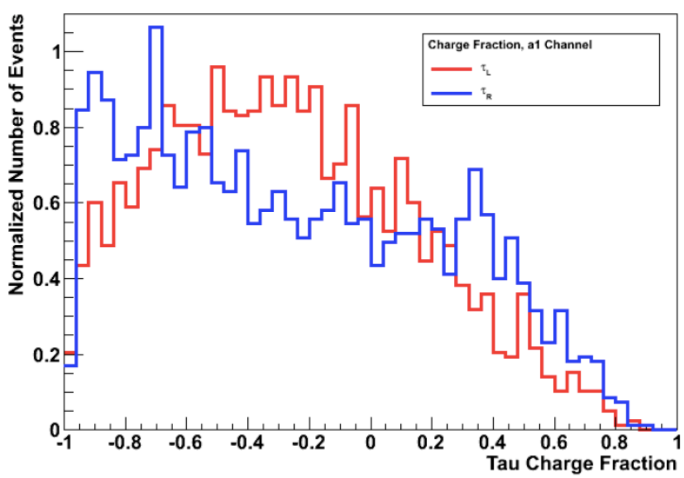
But we don't know the total energy of the tau

y refers to the fraction of the tau mass in the hadronic system m_h/m_τ

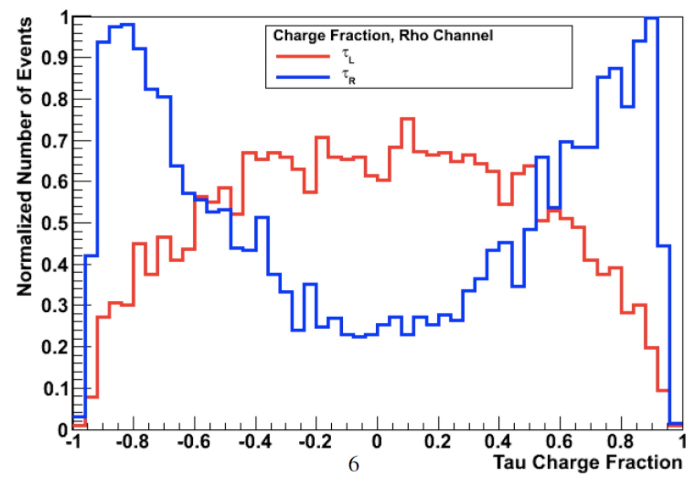
How to access Polarization

$$\frac{E_{\mathrm{T}}^{\pi^-} - E_{\mathrm{T}}^{\pi^0}}{p_{\mathrm{T}}} \approx 2\frac{p_{\mathrm{T}}^{trk}}{p_{\mathrm{T}}} - 1 = \Upsilon.$$

1. $\tau^{\pm} \to \pi^{\pm}\nu$, **the $\pi^{\pm}$ channel**[2] (11.6%)
2. $\tau^{\pm} \to \rho^{\pm}\nu \to \pi^{\pm}\pi^{0}\nu$, **the $\rho^{\pm}$ channel**[3] (26.0%)
3. $\tau^{\pm} \to a_1^{\pm}\nu \to \rho^{\pm}\pi^{0}\nu \to \pi^{\pm}2\pi^{0}\nu$, **the $a_1^{\pm}$ channel** (10.8%)



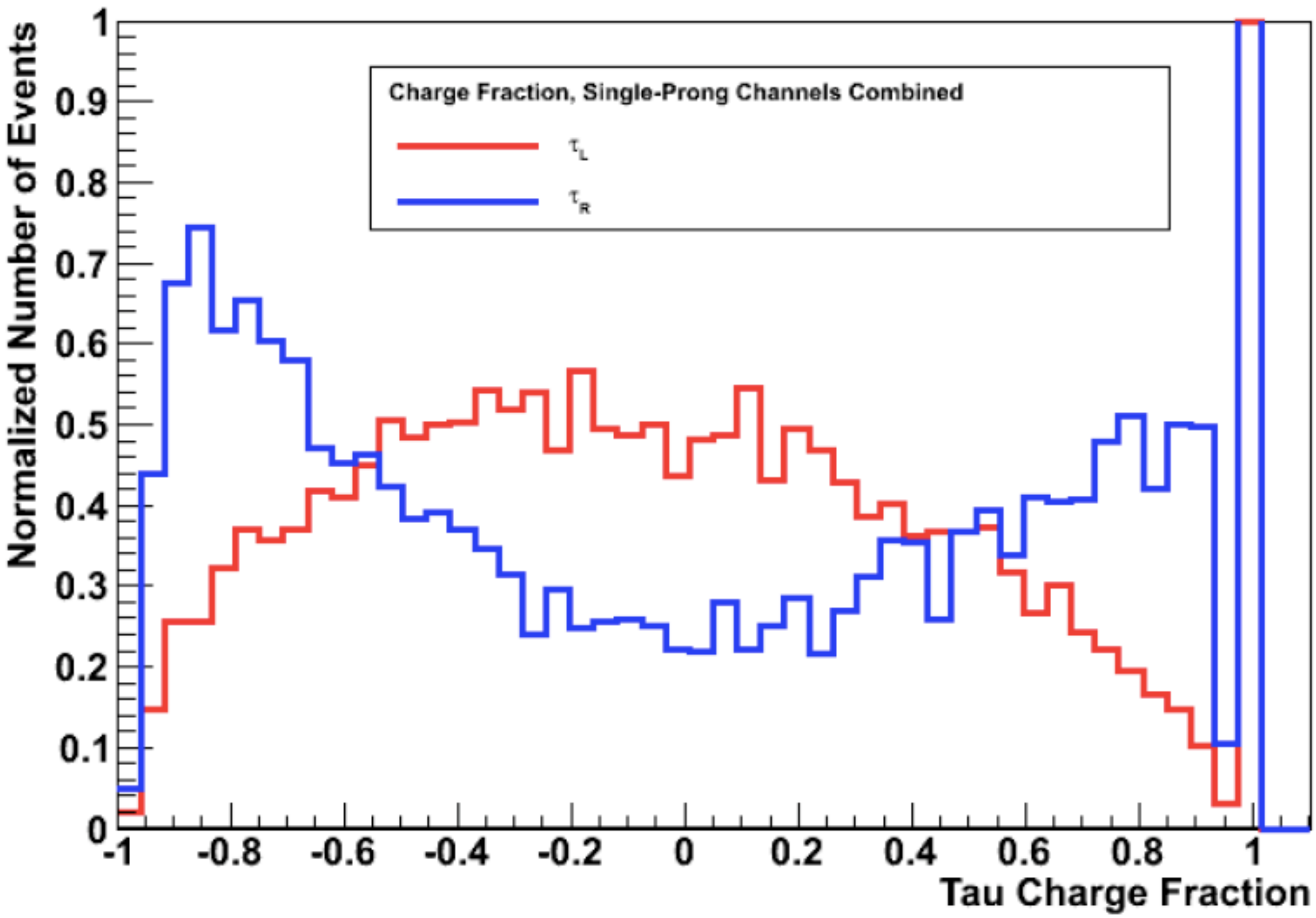
(b) Charge Fraction in the a_1 Channel



6

(c) Charge Fraction in the Rho Channel

Generator-Level Study



Polarization: Next Steps

This is where I would have shown you results…

Keep your eyes open for Moriond EW results!

Conclusions

Watch for results in Moriond!

The physics motivation for using taus as probes to discover and/or understand new phenomena at the LHC is compelling.

The tools are in place and rapidly improving to maximize the reach of the tau physics program.

In spite of the promise and the progress, we remain in many ways the few, the proud, and the crazy. We are always looking for company!

The addition of polarization to our arsenal of tools is critical for the future of characterizing new physics at the LHC.

THANKS very much for the opportunity to talk about taus!