Tau Reconstruction

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Characteristics of tau in LC

- Tau in LC
  - Usually highly boosted
    - Weakly boosted in low-energy τs for BSM study
  - Very confined bunch of particles
    - Separation of decay modes is challenge
    - e/μ/π separation is also critical
    - Extracting kinematics on 'tau-rest frame' – precise direction measurement is needed
  - Various decay
    - Intensive efforts needed for analysis

Final state	Branching fraction
$e^-\bar{\nu}_e\nu_\tau$	$17.85 \pm 0.05\%$
$\mu^-\bar{\nu}_\mu\nu_\tau$	$17.36 \pm 0.05\%$
$\pi^-\nu_\tau$	$10.91 \pm 0.07\%$
$\rho^-\nu_\tau$ $(\rho^- \to \pi^-\pi^0)$	$25.52 \pm 0.10\%$
$a_1^-\nu_\tau$ $(a_1^- \to \pi^-\pi^0\pi^0)$	$9.27 \pm 0.12\%$
$a_1^-\nu_\tau$ $(a_1^- \to \pi^-\pi^+\pi^-)$	$8.99 \pm 0.06\%$
24 other modes	10.10%

Tau: physics target for ILD

- Higgs → $\tau\tau$
  - Branching ratio
  - CP violation (by impact param and angular info)
    - Many decay modes should be studied: lot of effort
- Precise measurement of ff production
  - Including tau polarization measurement
- BSM – stau? (low energy)
- Treatment of tau as background
  - ‘Tau tagger’ is essential
- etc.

Tau: works

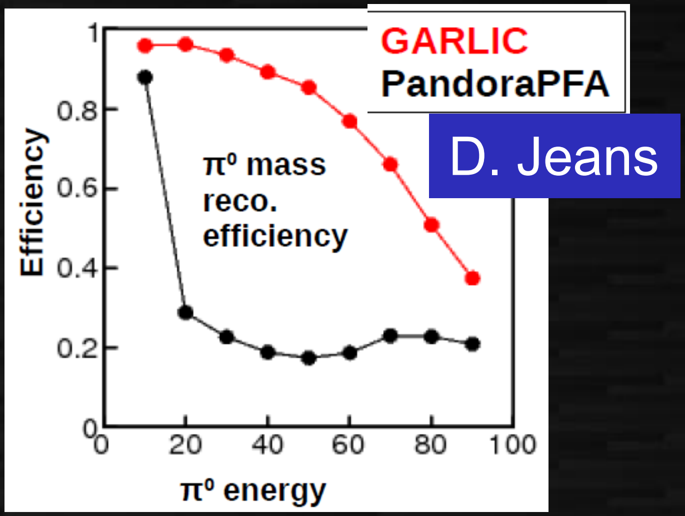
- High energy photon/π^0 reconstruction
  - Photon counting is sometimes essential
- Isolated taus: tau finder (like leptons)
  - Tau consists of multiple particles
    - Clustering and isolation criteria essential
- Taus in jets: much more difficult
  - For jet clustering, flavor tagging etc.
- Decay analysis for polarization etc.
  - Vertex/impact parameter ($c\tau = 77\ \mu m$)
  - Kinematic fitting

Taus: final reconstruction flow

1. PFA
   - High energy photon reconstruction
2. Lepton ID
   - Electron & muon separation
3. pi0 reconstruction (?)
4. Tau finder
5. Vertexing (3-prong tau)
6. Decay reconstruction
7. (Jet tau ID)

PFA: Garlic

- PFA of tau is different from that of jets
  - High-energy low-multiplicity (but concentrated) particles
  - Photon counting (→ π^0) is as important as energy resolution
  - Garlic is better than Pandora
    → how to combine if we also need to reconstruct jets? (eg. qqH → qq$\tau\tau$)



Garlic in Pandora?
Or separate run?
(Garlic → Pandora?)

Lepton ID

- Masakazu working on lepton ID including shower profile and dE/dx
- Dedicated tuning for leptons in tau may be needed
  - Off-primary vertex
  - charged pi + photons (from pi0) should not be identified as leptons
- Interface to lepton ID in tau finder needed

pi0 reconstruction

- Graham is working on??
  - but maybe for jets
- May improve tau finder performance
- More important in decay reconstruction

Tau finder

1. Tau finder without jets – easier

2. Tau finder with jets – more important
   - Tau finder in qqH → qq tautau study (by TS)
     - Not included in MarlinReco → can be published
   - Others?

3. Low energy taus

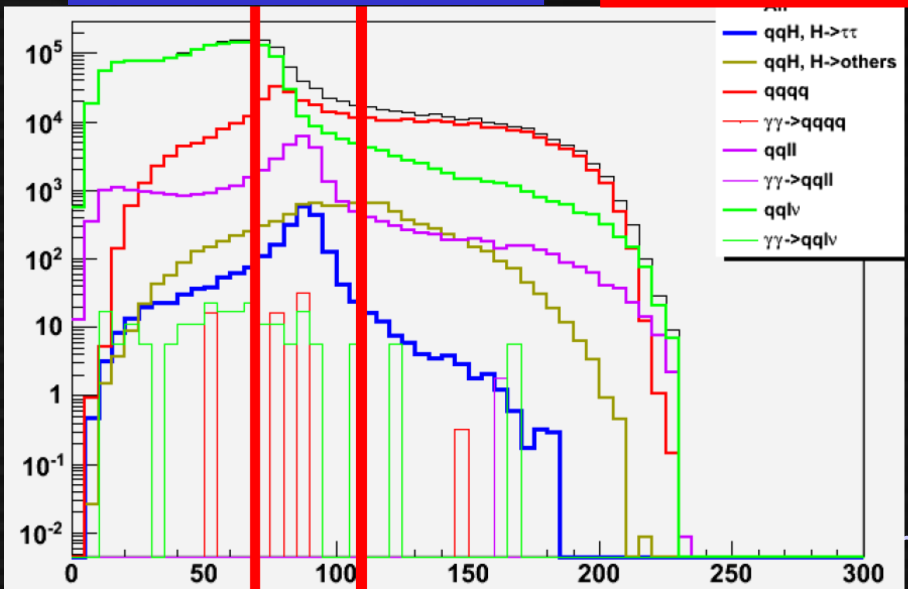
Tau finder

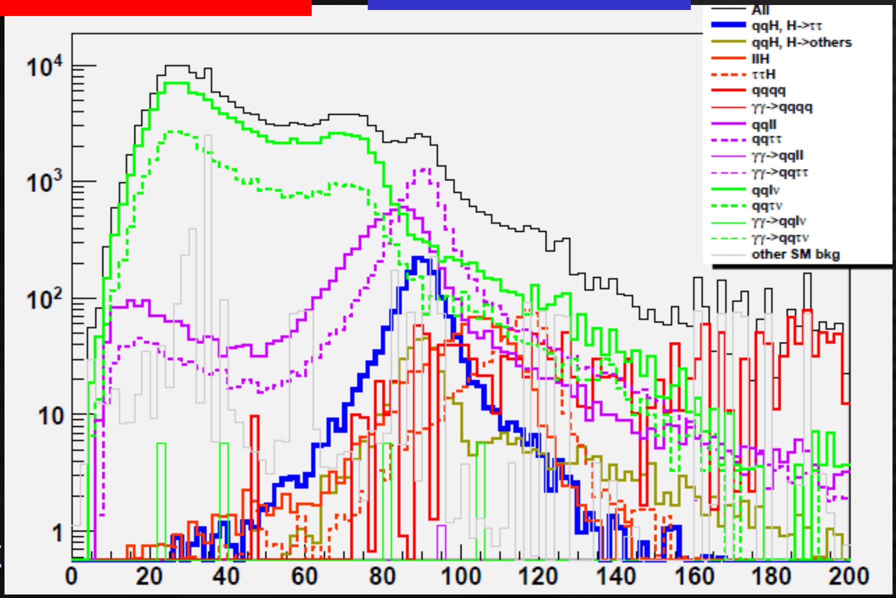
- Tau finder – key algorithm to separate tau
  - Normal jet clustering is usually not good
- Dedicated Tau finders
  - TaJet finder (tuned for qqH → qqττ)
  - DELPHI tau finder (for low energy tau)
  - Others?

Durham clustering

qqH → qqττ, 250 GeV

TaJet finder





TaJet finder (1)

High-purity tau tagging in presence of jet background

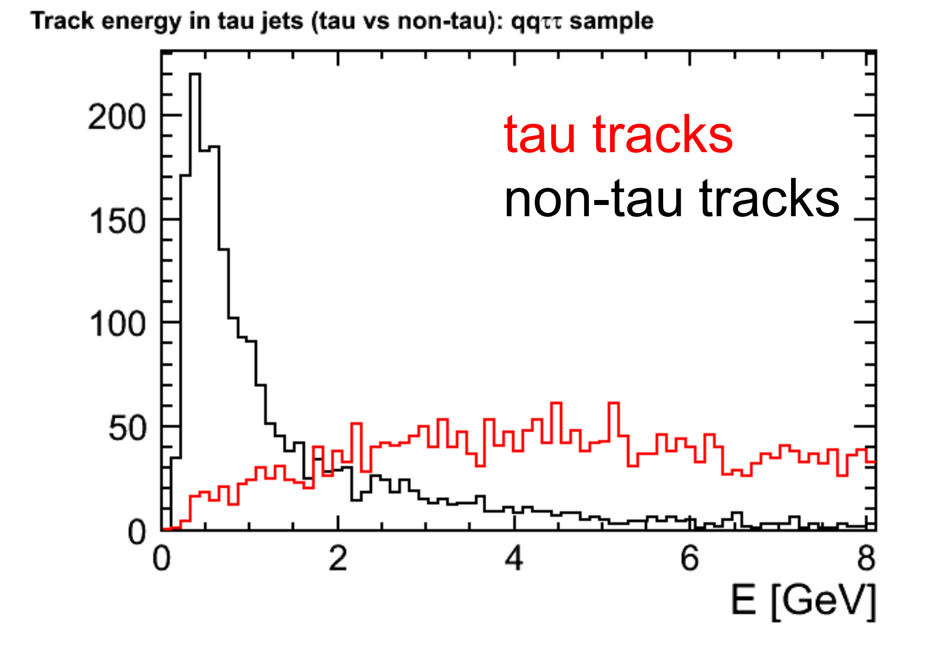
Slide from Dec. 2012
Now a bug fixed
→ slightly better

1. Order charged tracks by largest energy
2. Select the first track
3. Combine neighboring particles -> "Tau Jet"
   - Combined mass < 2 GeV && cosθ w.r.t. jet axis > 0.98
4. Tau selection (tuned for rejecting qq background)
   1. Tau Jet energy > 3 GeV
   2. Veto >=3 prong + neutrals (> 1 GeV)
   3. Cone energy ($E_{cone} < 0.1E_{taujet}$) with $\cos\theta_{cone} = 0.9$

ZZ -> qq$\tau\tau$ 250 GeV, 13600 taus	1-prong		3-prong wo/ neutral		3-prong w/ neutral	
	tau	non-tau	tau	non-tau	tau	non-tau
No cut	10326	43286	716	1616	777	4280
$E_{taujet} > 3$	8679	7145	708	1304	742	4244
$E_{cone} < 0.5E_{taujet}$	7170	1009	621	181	681	1813
$E_{cone} < 0.2E_{taujet}$	6455	446	567	64	616	1020
$E_{cone} < 0.1E_{taujet}$	6001	254	527	30	570	620

TaJet finder (2)

5. Jet charge recovery (for better efficiency)
    - Tracks with energy < 2 GeV are detached one by one until tau jet has 1 or 3 tracks and sum charge is +1 or -1
    - Jet is rejected if above condition cannot be satisfied after detaching all < 2 GeV tracks
6. Return to 2. (previous page) with the remaining tracks
    - Stop after all E > 2 GeV tracks have been processed



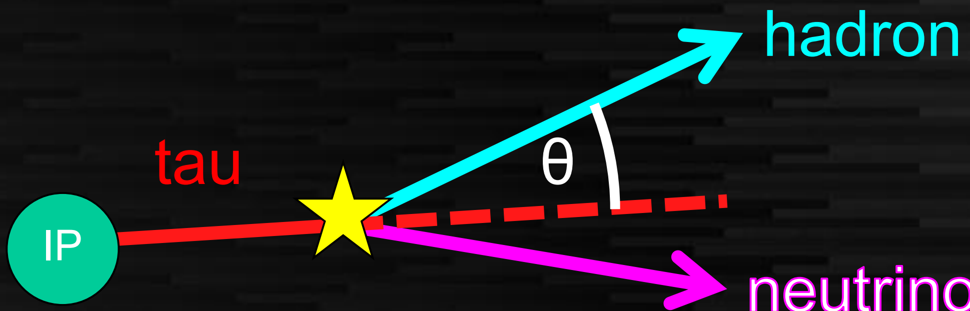
# tau jets	qqττ	qqln
0	27.1%	47.6%
1	36.3%	46.6%
2	34.0%	5.4%
>3	2.4%	0.3%

purity of tau in qqττ:
94.2% overall
96.5% for # tau jets == 2

Tau flight direction

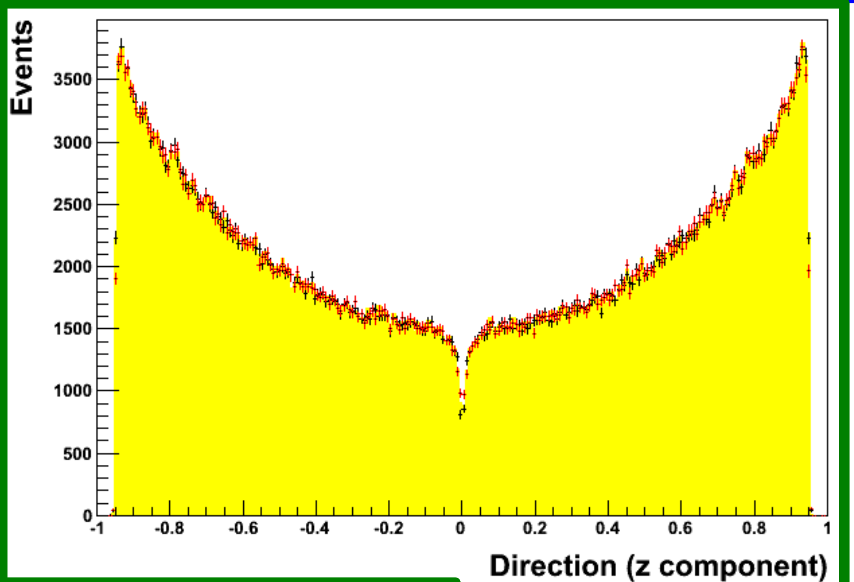
- should help with polarization measurement
  - 3 degrees of freedom of tau four-vector
  - 3 constraints:
    1. $E_\tau = \sqrt{s}/2$
    2. tau/hadron angle from two-body decay kinematics
    3. tau track must meet the hadron track at a point (1-prong) or the vertex (3-prong)
  - can be solved for tau direction analytically

a sneak preview of this concept will be shown for 1-prong events
using first-order approximation for tracks (using line segment instead of helix)



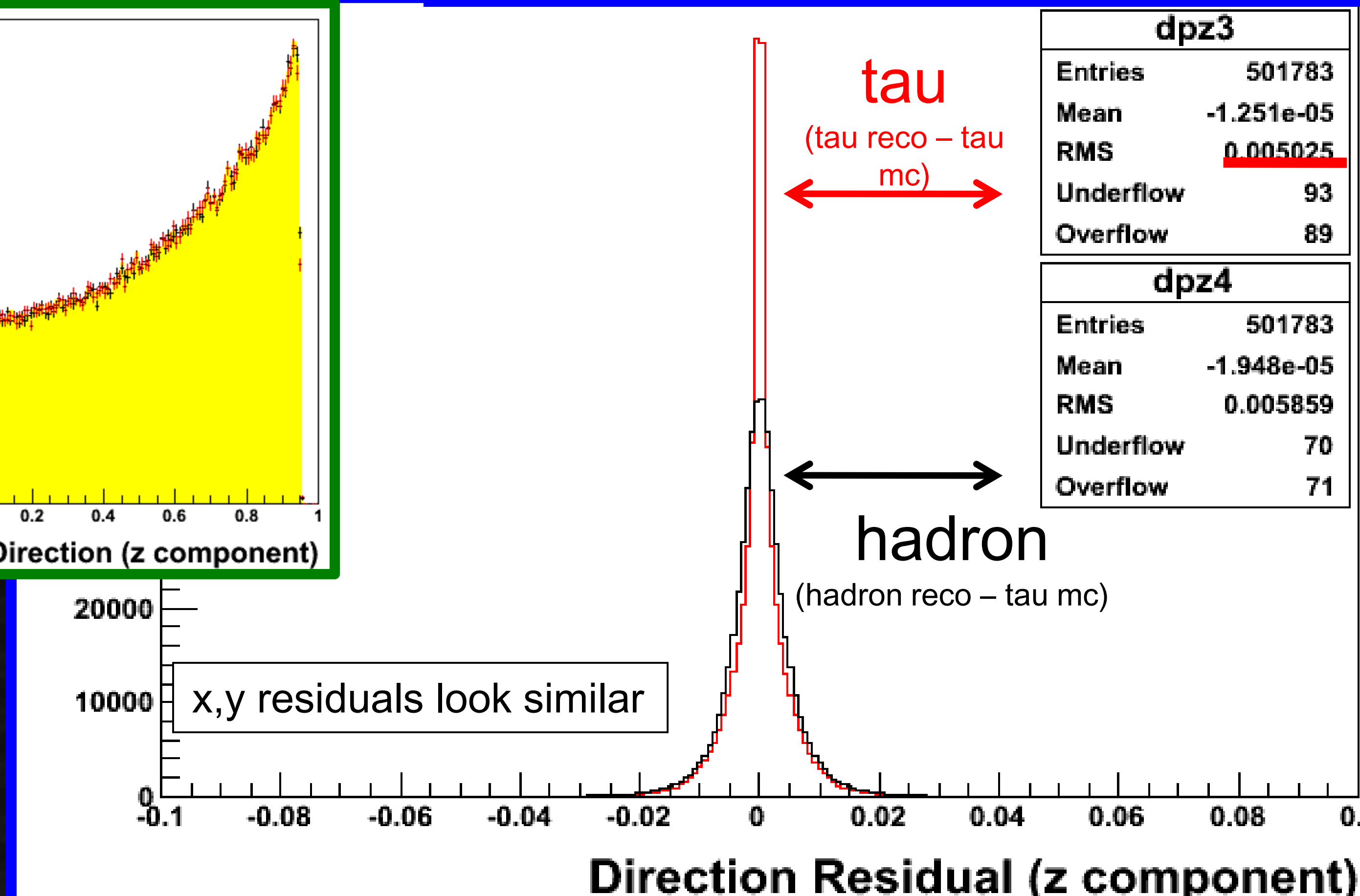
Tau flight direction (1-prong events)

tau direction in lab frame

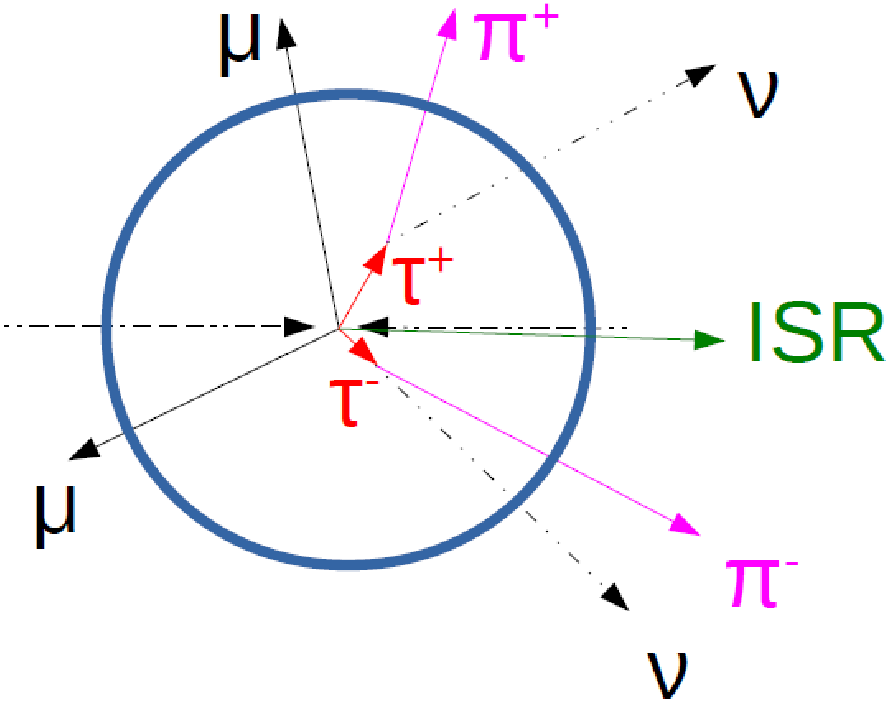


-hadron dir (reco)
-tau dir (reco)
-tau dir (mc)

tau direction residual (reco – mc)



tau direction successfully reconstructed (3-prong work next)
better than assuming tau dir = hadron dir (rms: 0.0059 > 0.0050)



Unmeasured quantities

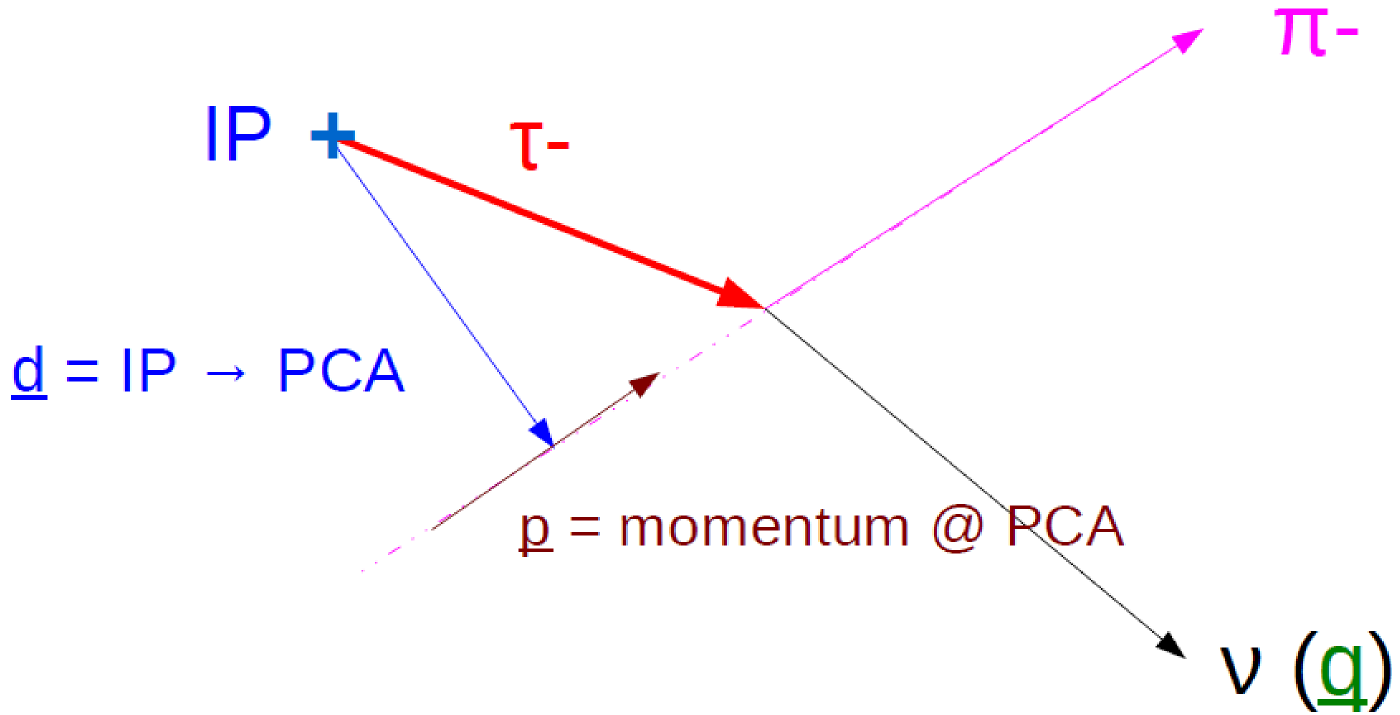
2 x neutrino 3-momenta
lost ISR photons

ZH → $\mu\mu\tau\tau$
Full kinematic reconstruction
by D. Jeans

Kinematic constraints

overall 4-momentum conservation
2 x tau decay kinematics ← more details next

tau-tau mass (if we assume H->tau tau)
mu-mu mass not useful: resolution much better than Z width



d and p are perpendicular in x-y, but not in 3d

define d' = p x (d x p) ← inside p-d plane, perpendicular to p

neutrino momentum q lies in plane of d and p

so we can write: q = |q| (cosψ p* + sinψ d'*)

where x* is a unit vector: x / |x|

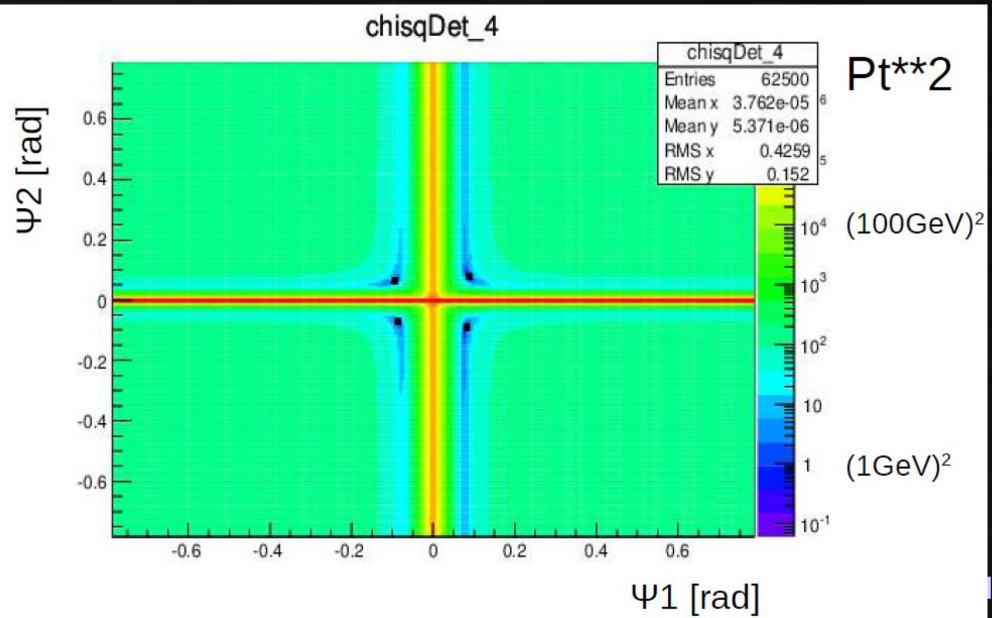
We know that the invariant mass of (p + q) is m_{tau}

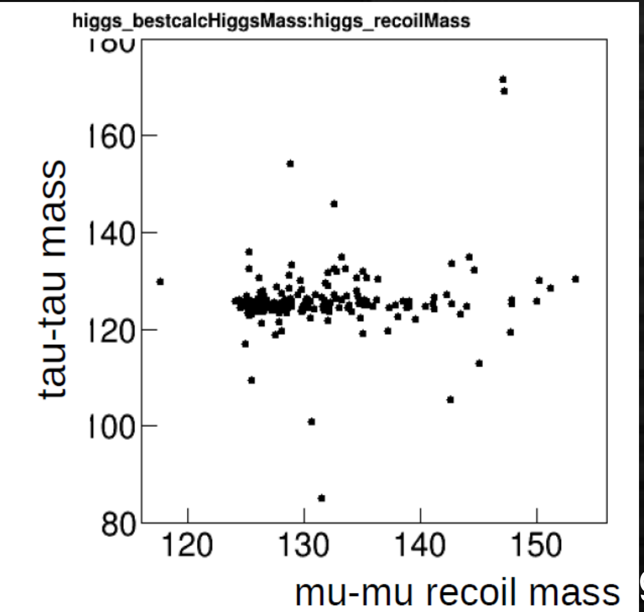
so we can calculate the neutrino energy |q| for each value of ψ

by requiring pt-balance in the event [sum px = sum py = 0]
it is possible (but somewhat messy) to calculate the angles Ψ
due to finite resolution of measured quantities,
a real solution is not always possible
More robust approach is to do a
standard minimisation [i.e. not a constrained fit]
to minimise the event pT

Minuit minimisation separately in each quadrant (no constraints needed)
→ Four solutions

For now, define "best" solution as one with smallest value of
pT + missing mass
If we have zero or one ISR photon, missing mass = 0





Summary

It's interesting to try to fully reconstruct taus:
- they can act as "polarimeters"
  - → can reconstruct their spin state by looking at their decay products

The ILC machine and detectors have great potential for tau reco:
- tiny beam spot
- high precision vertex detector

In hadronic tau decays of (tau tau + "X") processes
- we can calculate the tau neutrino momenta with good precision
  - if we can measure pT of "X"
    - If this is not possible, other approaches may be possible
      - → make different assumptions about event

Kinematic fitting should give some improvements in precision
- take account of uncertainties in measured quantities
  - tools are ~in hand

Tau in Jets

- No real work now
- High-energy secondary pions (+ associated pi0s) can be identified as tau candidate
  - Need to check

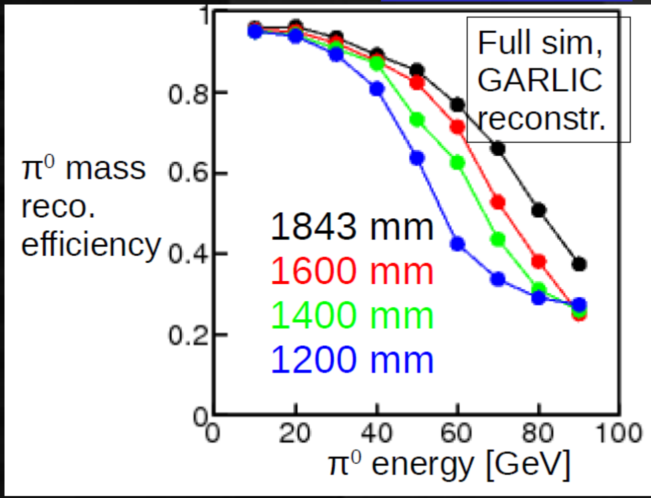
Tau: possible works this week

- Establish standard tau finder
  - Parameters should be tuned on analysis
  - Integration with lepton finder
- Garlic + Pandora? (PFA task?)
- 'Tau decay reconstruction?'
  - Seems rather analysis task than tools
  - Maybe some helping tool is possible
  - Examination of tau 3-prong vertex
- Jet in tau? (not in this timescale?)

Tau and Detector Optimization

- Radius
  - Particle separation
  - Isolation of tau from jets (also B field affects)
- Pixel size
  - Particle separation
    - Ultra-high granular pixels at first layers of ECAL may help (eg. MAPS)
- Photon energy resolution
  - meson ($\pi^0/\rho/a_1$) reconstruction
- Impact parameter resolution
  - For angular analysis of CP violation

D. Jeans

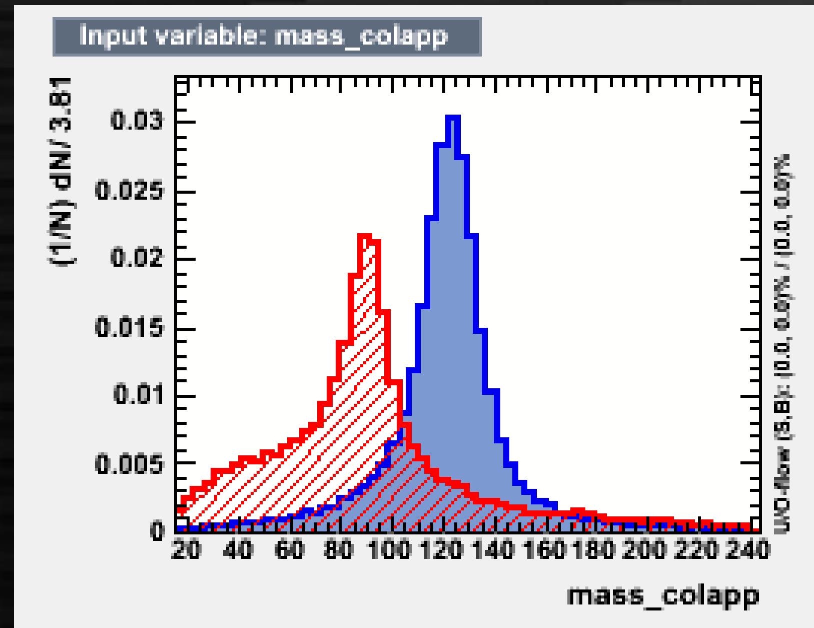


Analysis: H → ττ

S. Kawada

Analysis condition

- PandoraPFA (no Garlic)
- DBD geometry
- TaJet finder
- Collinear approx. (only on qqH, llH)
- No reconstruction of tau decay products



Mττ @ qqH 250 GeV

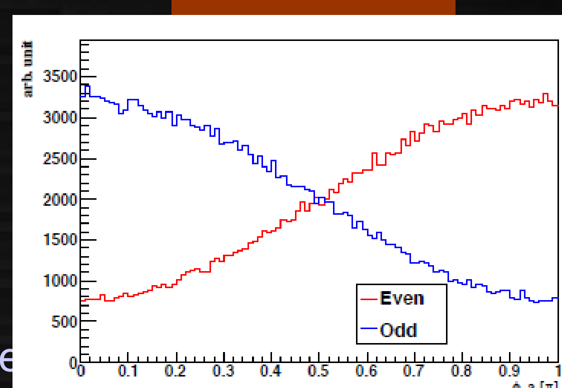
$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$	$q\bar{q}h$	e^+e^-h	$\mu^+\mu^-h$	$\nu\bar{\nu}h$	Combined
250 GeV, 250 fb^{-1}	3.4%	14.4%	11.3%	32.4%	3.2%
500 GeV, 500 fb^{-1}	4.6%	25.2%	17.8%	6.9%	3.7%

CMS 3 ab^{-1}: 2-5%

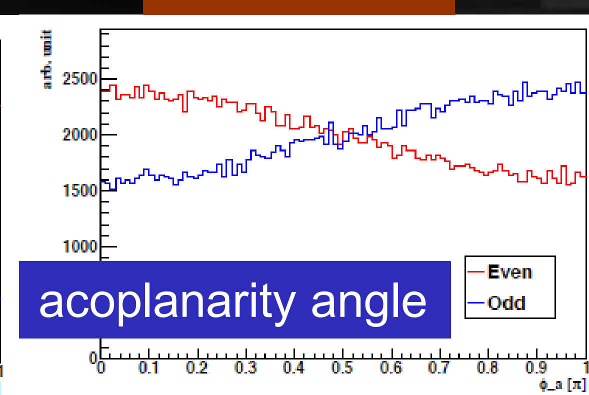
Analysis: Higgs CP

- Identifying CP-even and CP-odd mixing of Higgs
  - CP odd (H →) ZZ couples only with loop
    - More difficult to see the non-SM Higgs mixing
  - (H →) $\tau\tau$ is directly coupled to CP-odd Higgs
- Complicated analysis to identify CP mixing
  - Clear separation of Higgs decay mode
    - Angular parameters differ by decay modes
  - Kinematics of tau-rest frame critical
    - cannot perfectly reconstruct kinematics of taus using impact parameters with momentum of decay products

$\tau\tau \rightarrow \pi\nu\pi\nu$



$\tau\tau \rightarrow e\nu\nu\pi\nu$



acoplanarity angle

Analysis: $e^+e^- \rightarrow \tau\tau$

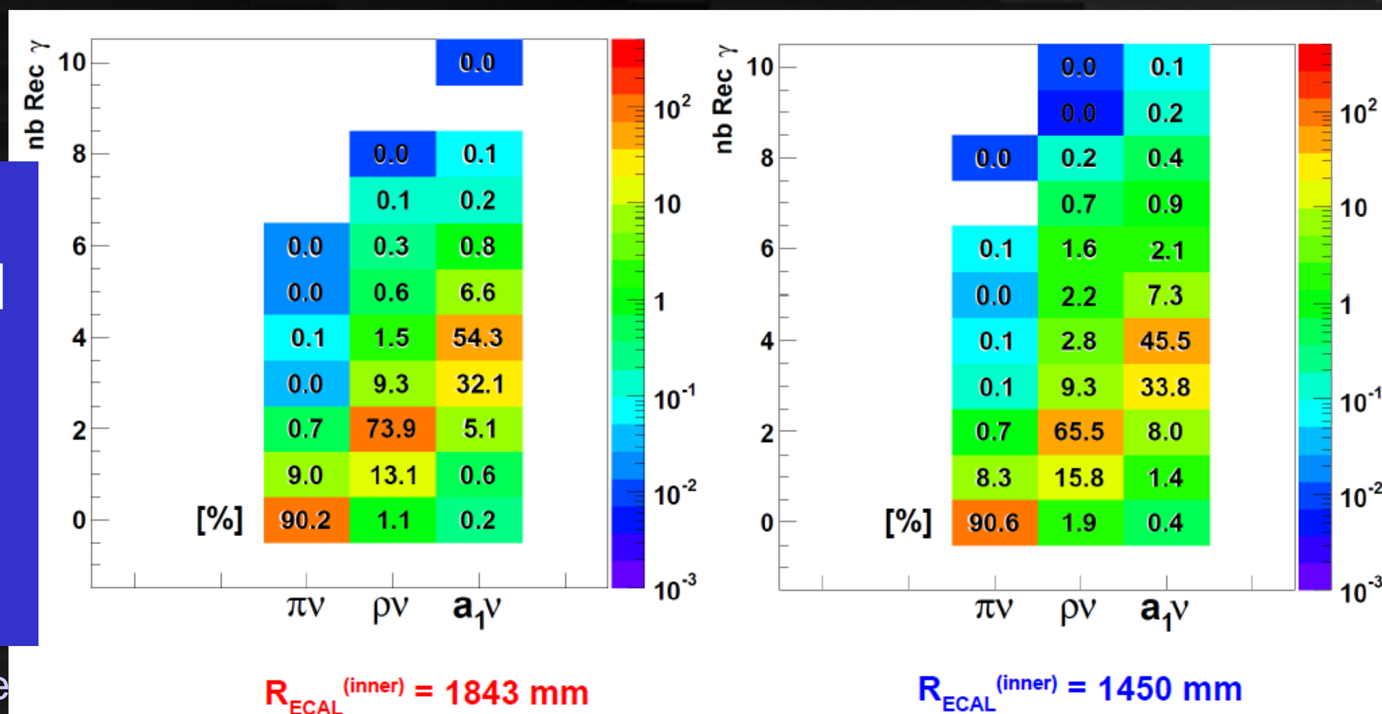
H. Tran

Analysis condition
- 250 GeV CM energy
- Garlic v3.0.2 (no jets)
- Compare performance of various radius with constant aspect ratio
- SiECAL

Target: separation of 1-prong hardonic decay

$\pi^- \nu_\tau$	$10.91 \pm 0.07\%$
$\rho^- \nu_\tau \ (\rho^- \rightarrow \pi^- \pi^0)$	$25.52 \pm 0.10\%$
$a_1^- \nu_\tau \ (a_1^- \rightarrow \pi^- \pi^0 \pi^0)$	$9.27 \pm 0.12\%$

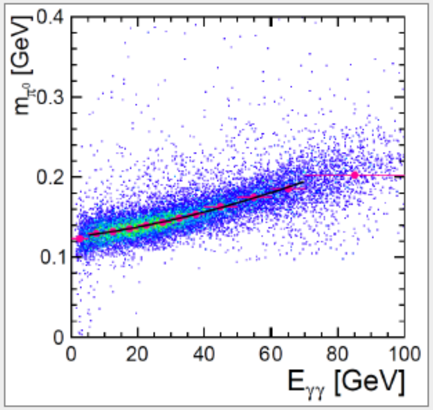
number of reconstructed photons with MVA photon selection

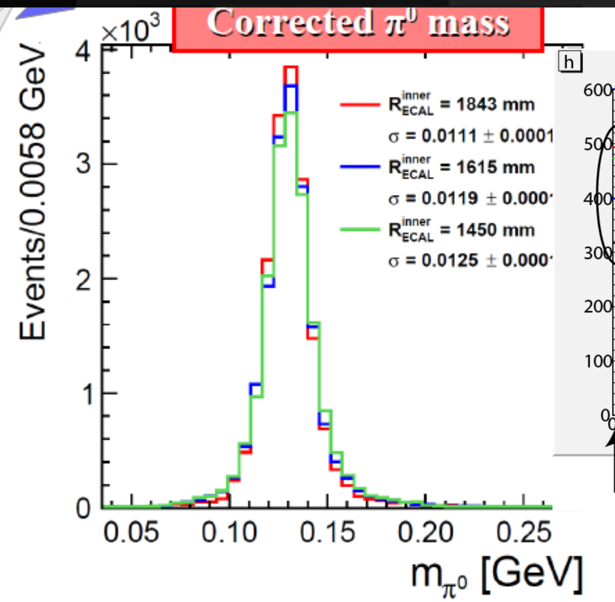


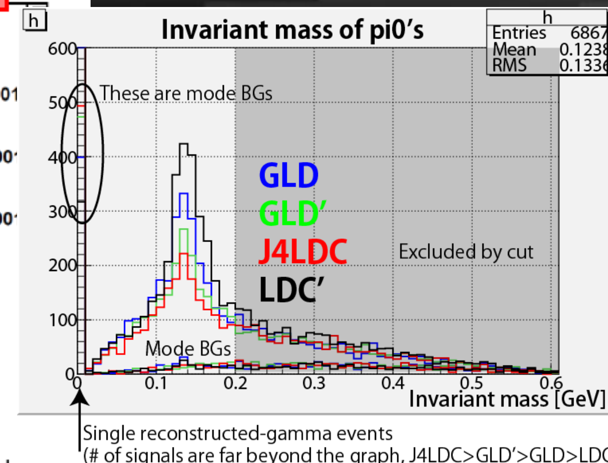
Analysis: $e^+e^- \rightarrow \tau\tau$

H. Tran

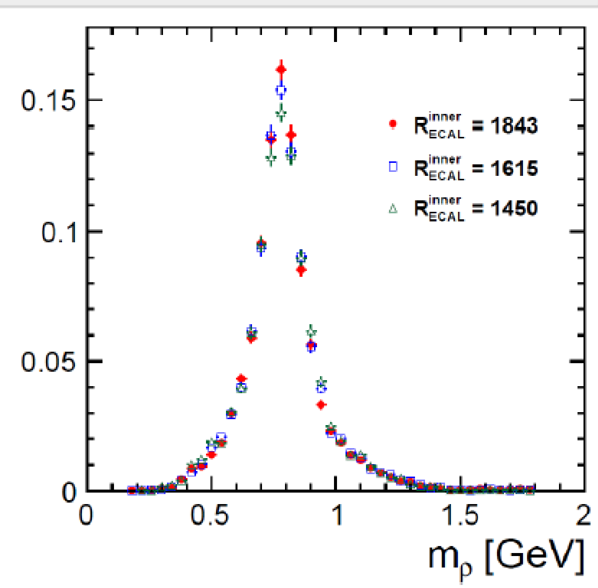
- Fit mass dependence on $\gamma\gamma$ energy with a parabola
- correct to mean value

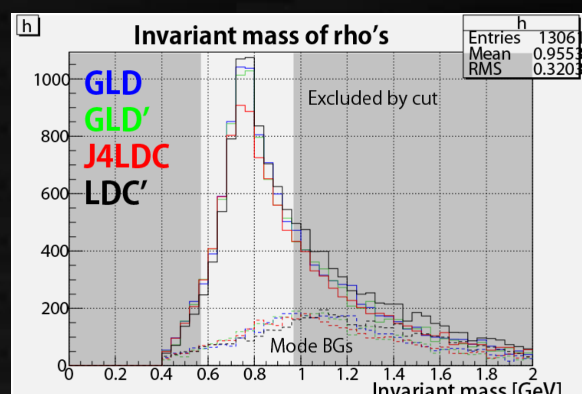






cf. 500 GeV, Pandora
1cm pixel except LDC'





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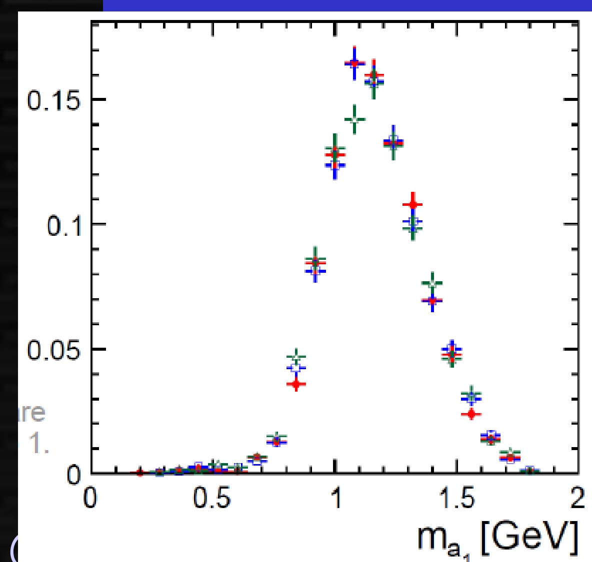
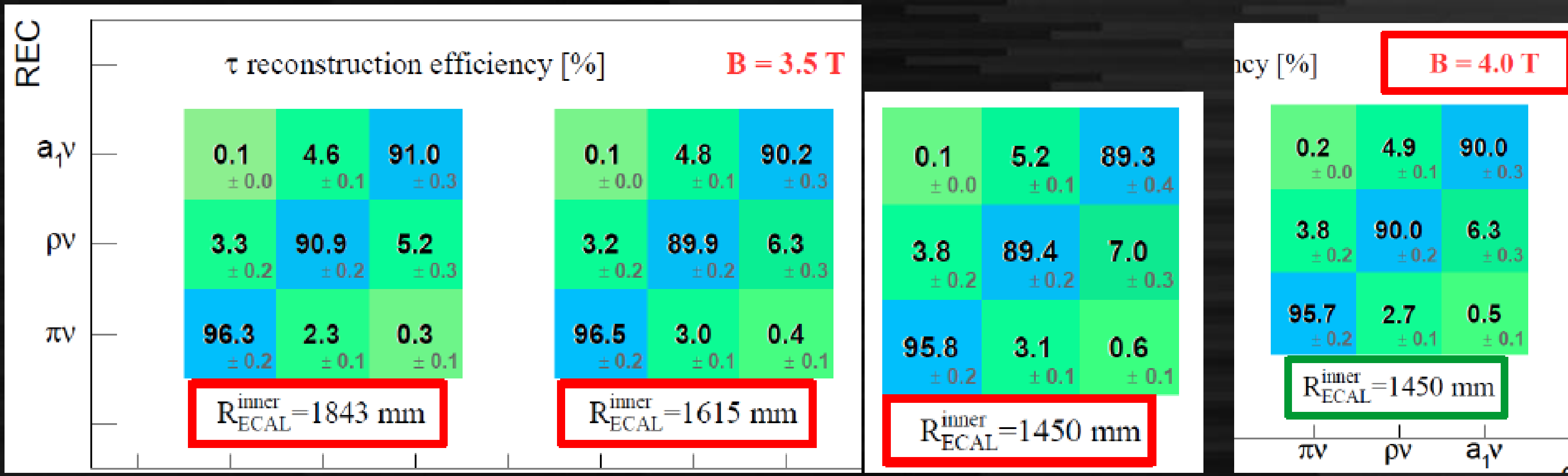
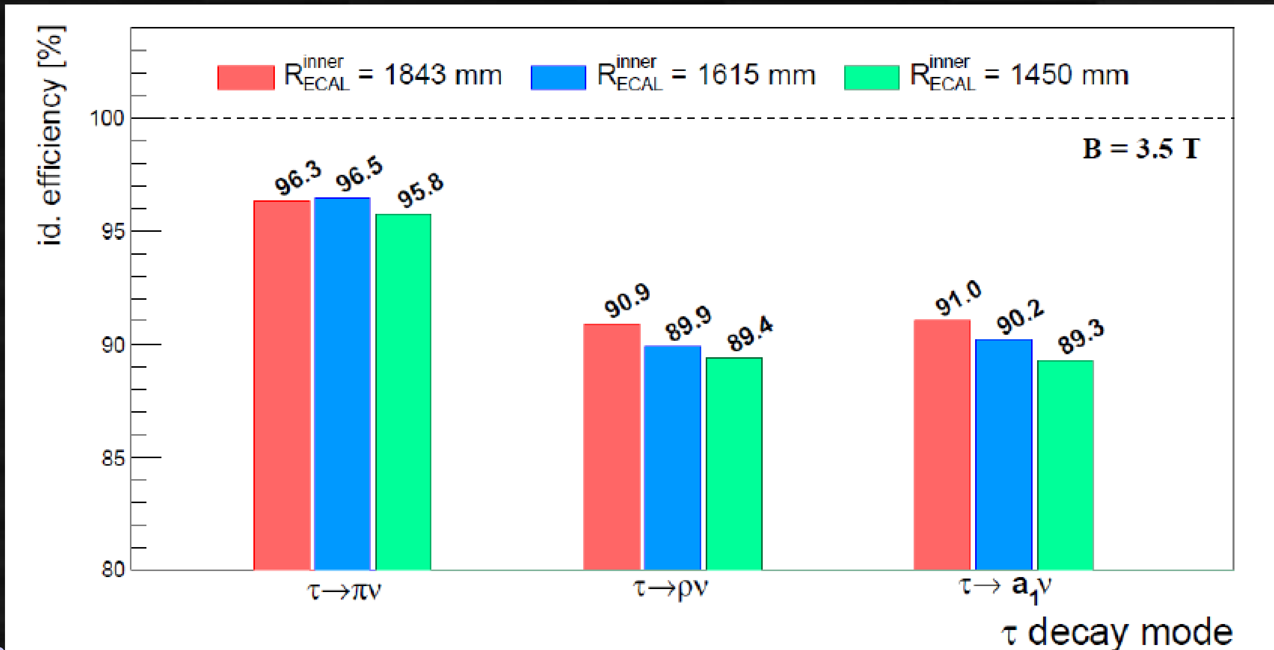


Analysis: $e^+e^- \rightarrow \tau\tau$

H. Tran





Final comments

- Detector challenge
  - Decay reconstruction for
    - Higgs CP (seems most important)
    - ff polarization – niche market physics??
    - others?
  - Low energy stau
    - Low energy track/photon reconstruction
- Other perspectives for calorimeter optimization than quark jets
- Analysis and software is critical
  - Optimization is not easy – same as quark jets