# New tools for the Higgs search in ττ channel at CDF experiment

**Andrey Elagin**
*Texas A&M University*

**OUTLINE:**

**Motivation**
**Tools:**
- **Tau lepton identification (Likelihood-based Particle Flow Algorithm)**
- **Full di-tau mass reconstruction (Missing Mass Calculator)**

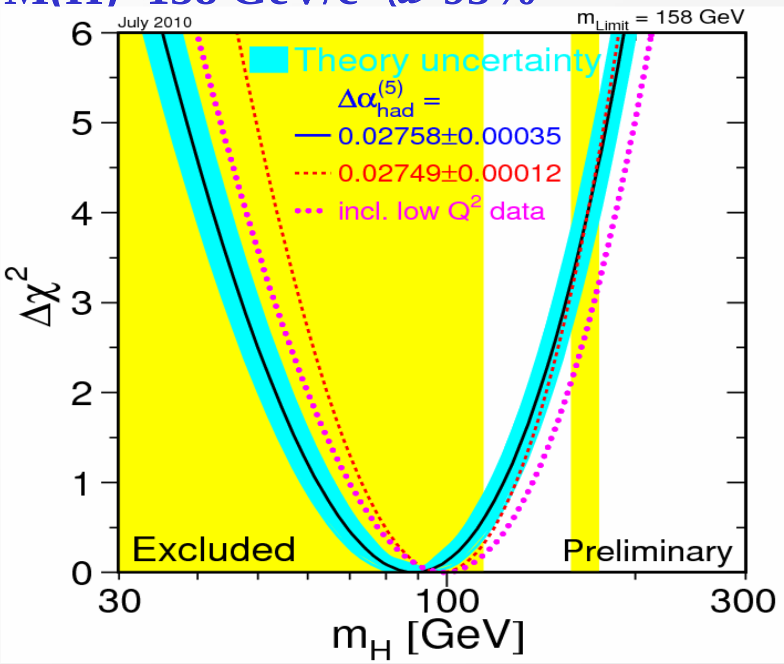
**Summary**

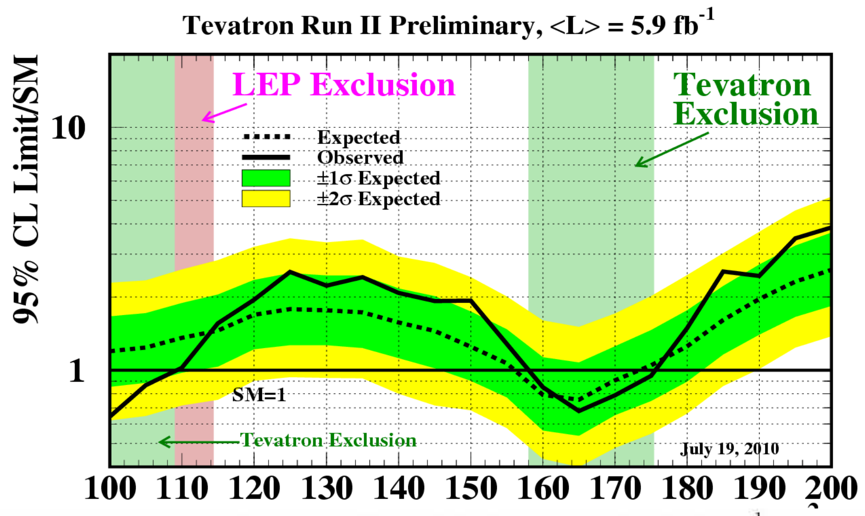
# Motivation

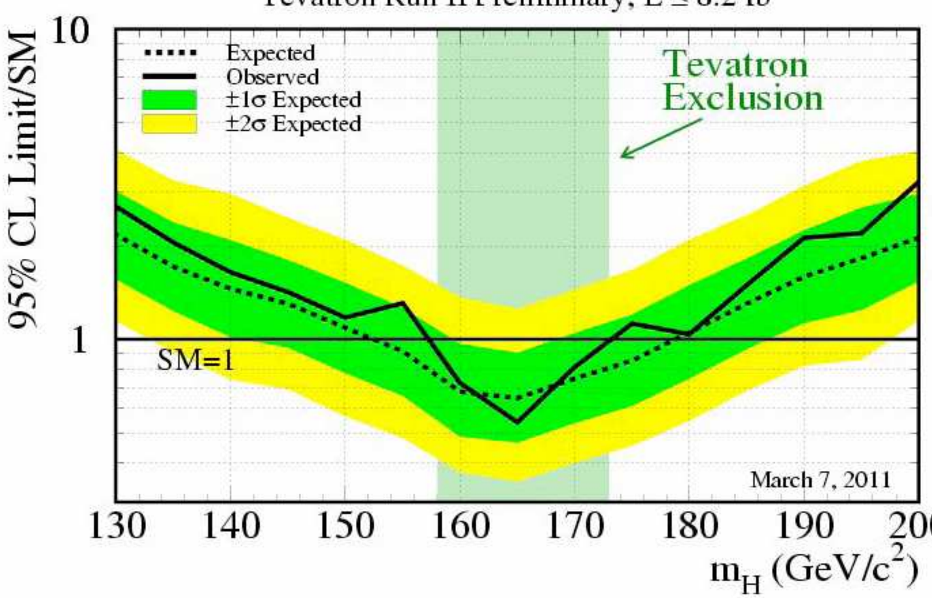
The Higgs mechanism:
- provides mass to W and Z
- breaks electroweak symmetry
- requires the existence of a single neutral scalar

The Higgs boson is the only undiscovered elementary particle in the Standard Model.

Constraints on the Higgs mass from precision electroweak measurements:
$M(H) = 89.0^{+35}_{-26}$ GeV/c$^2$
$M(H) < 158$ GeV/c$^2$ @ 95%

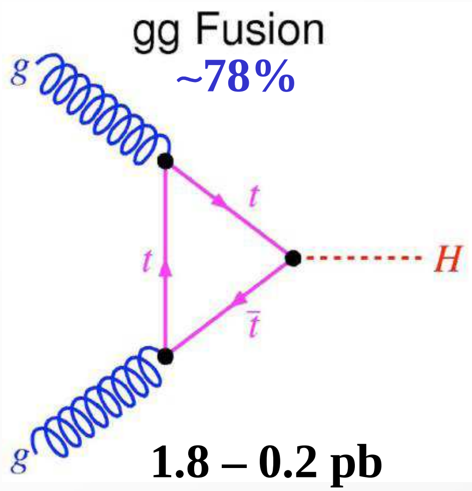


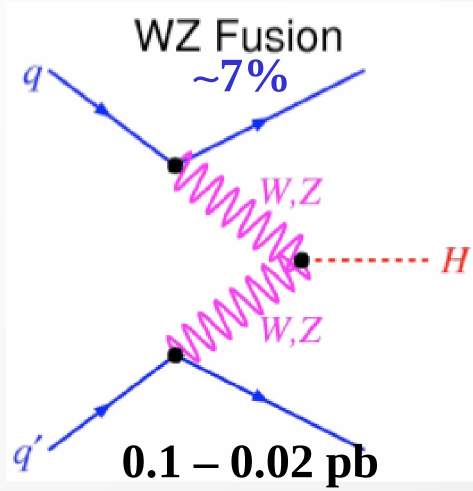



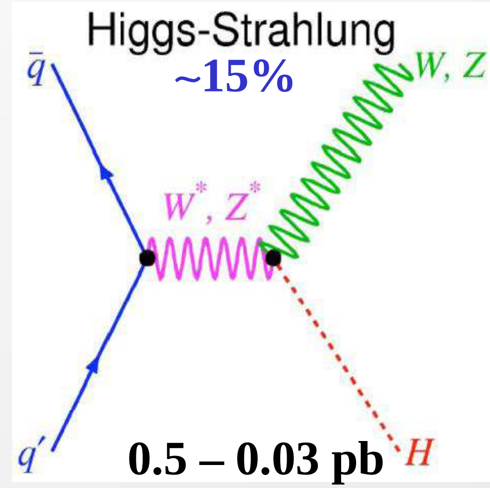



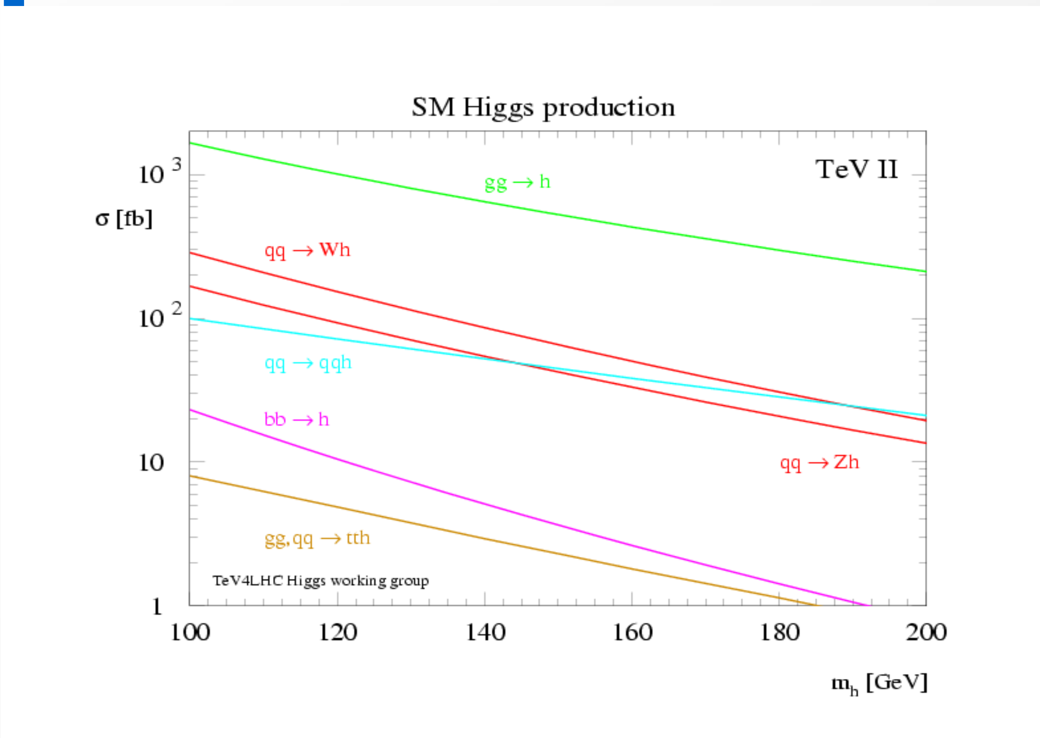

Range Excluded: $158 < m_H < 173$ GeV/c$^2$
Expected Exclusion: $153 < m_H < 179$ GeV/c$^2$

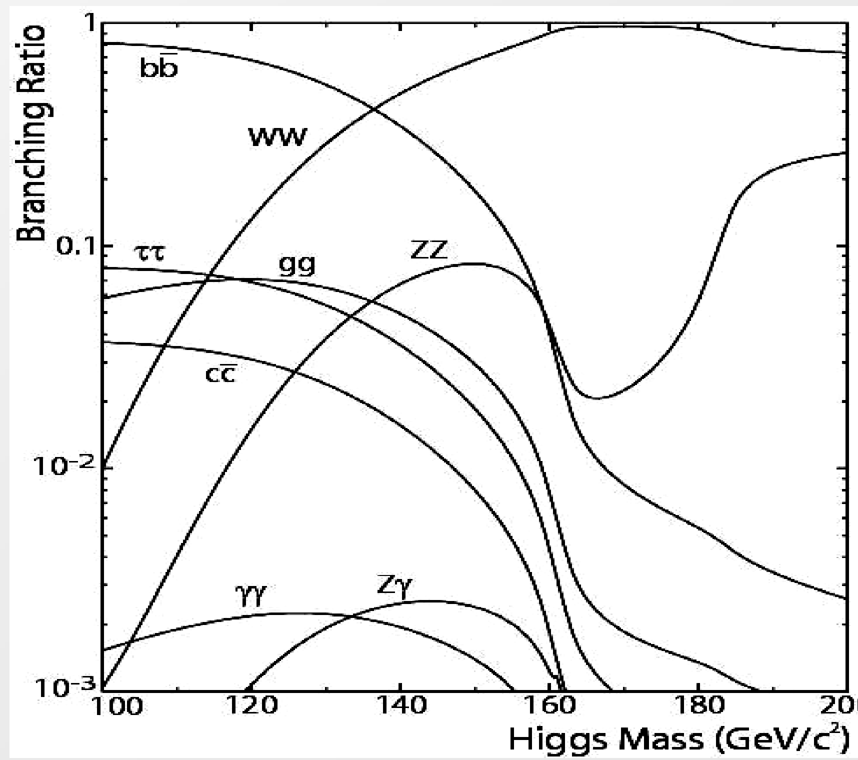
# Higgs Production and Decay Modes



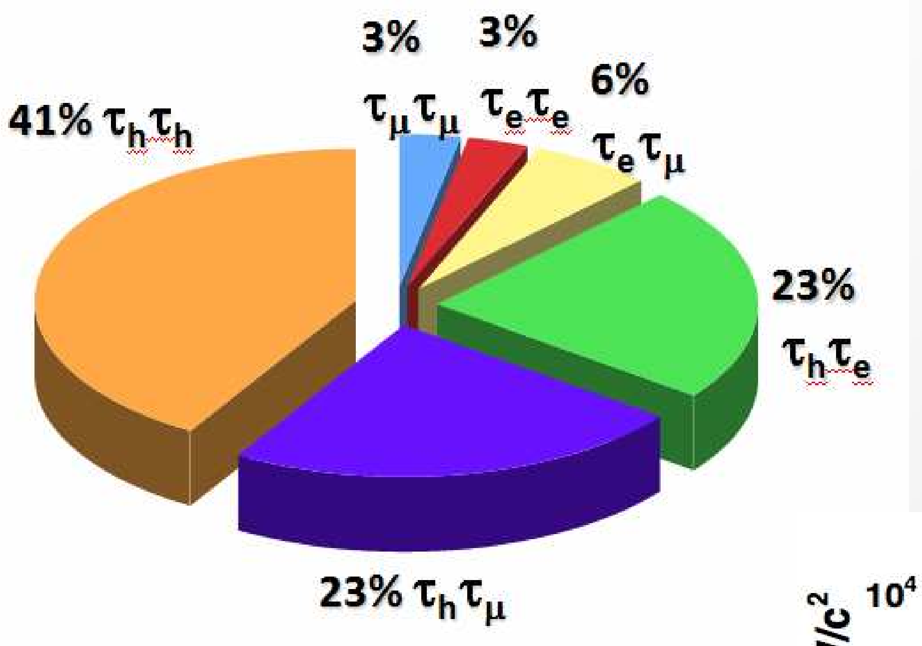



# $H \to \tau\tau$ Mode




$\tau_e \to e\, \nu_e\, \nu_\tau$ (~17%)

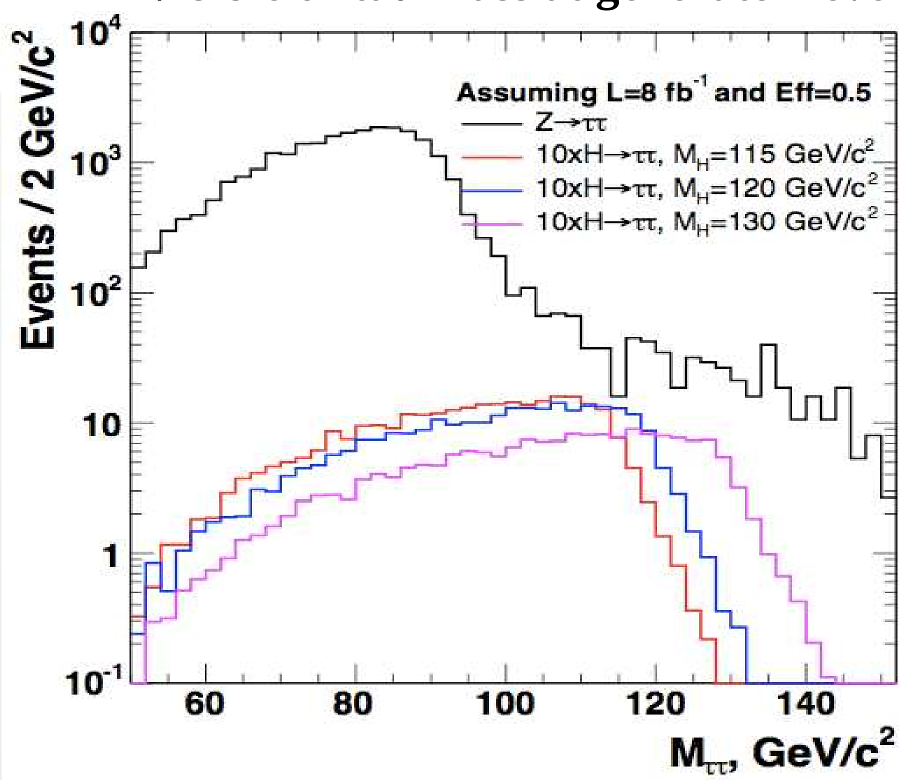
$\tau_\mu \to \mu\, \nu_\mu\, \nu_\tau$ (~17%)

$\tau_h$ (1-prong) $\to \pi^\pm N\pi^0\, \nu_\tau$ (~47%)

$\tau_h$ (3-prong) $\to 3\pi^\pm N\pi^0\, \nu_\tau$ (~15%)

**Irreducible background $Z \to \tau\tau$**

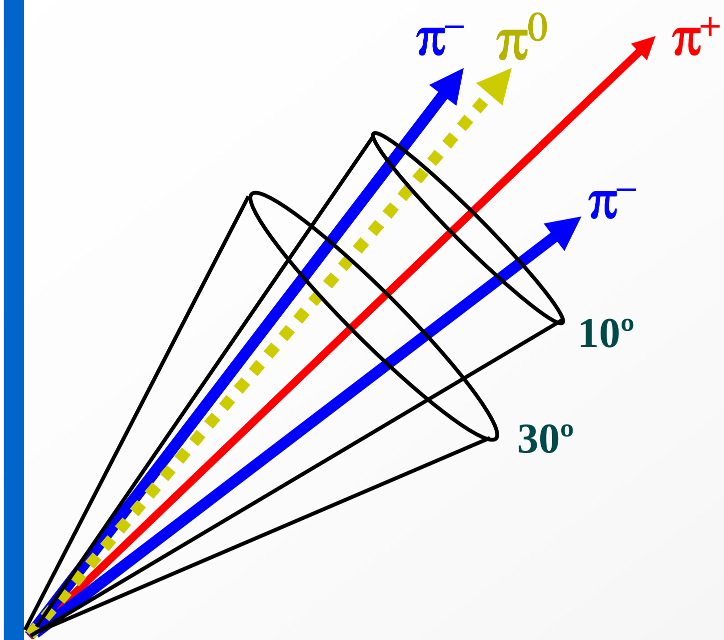
**Visible di-tau mass at generator level**

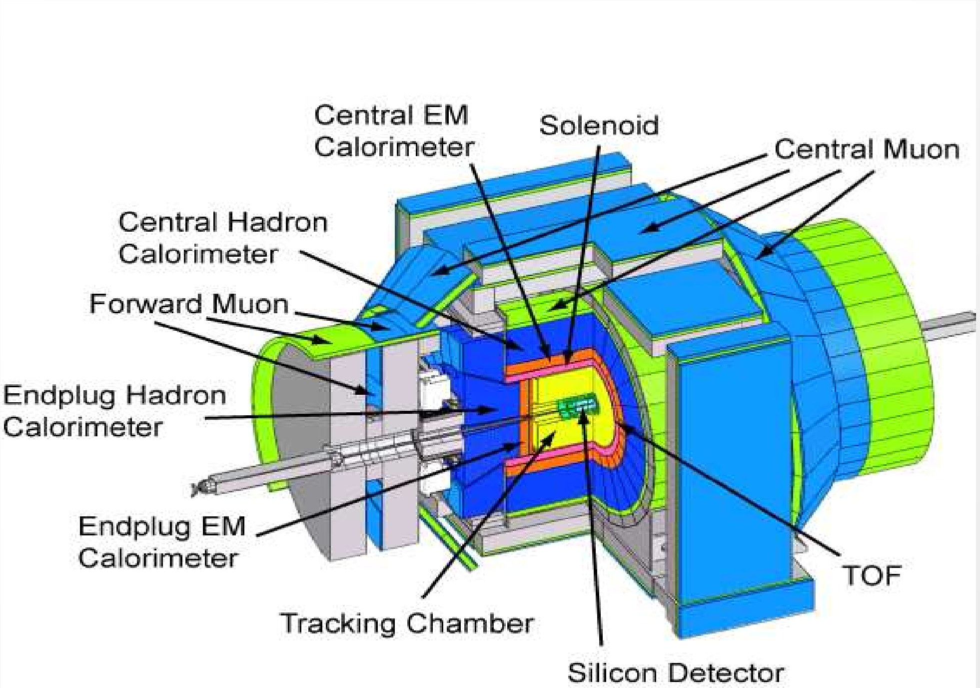



**Key elements to extract tiny Higgs signal:**

- **Efficiently identify $\tau_h$**
- **Precisely reconstruct $M_{\tau\tau}$**

# $\tau_h$ Reconsruction




*Common axis: "seed" (highest $p_T$) track.*

*signal cone: $\alpha$ = min[0.17, max(5 GeV/$E^{calo}$,0.05)] ~10°*

*→ tau decay products (energy measurements, classification)*

*isolation annulus: $\alpha$ - 30°*

*→ quark or gluon jets veto*

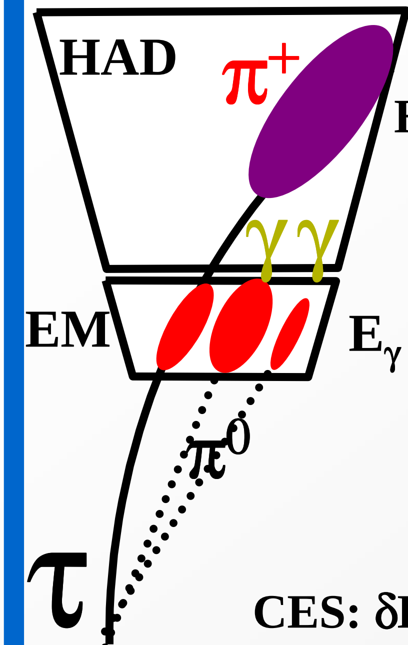
*Typical CDF analysis requires:*

- *$E_T$ (seed calorimeter tower) > 6 GeV*
- *$N_{trks}$ = 1 or 3*
- *$\sum_{iso} p_T^{trk} < 1\text{-}2$ GeV/c*
- *$\sum_{iso} p_T^{\pi^0} < 1$ GeV/c*
- *$M_{trks} < 1.8$ GeV/$c^2$, $M(\tau) < 2.5$ GeV/$c^2$*

# Particle Flow Algorithm (PFA)

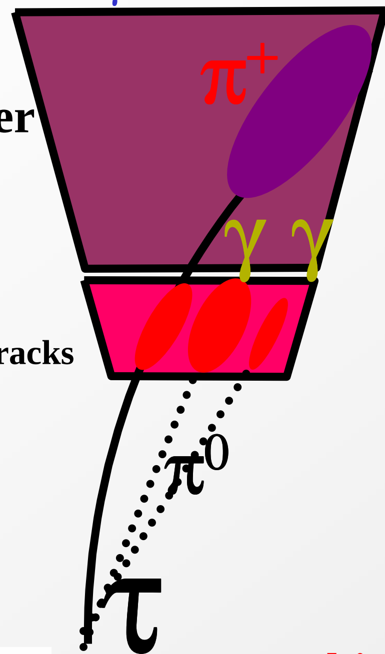
**Calorimeter approach:** $E_\tau = E^{EM} + E^{HAD}$

**PFA in case of tau:** $E_\tau = E_{tracks} + E_\gamma$

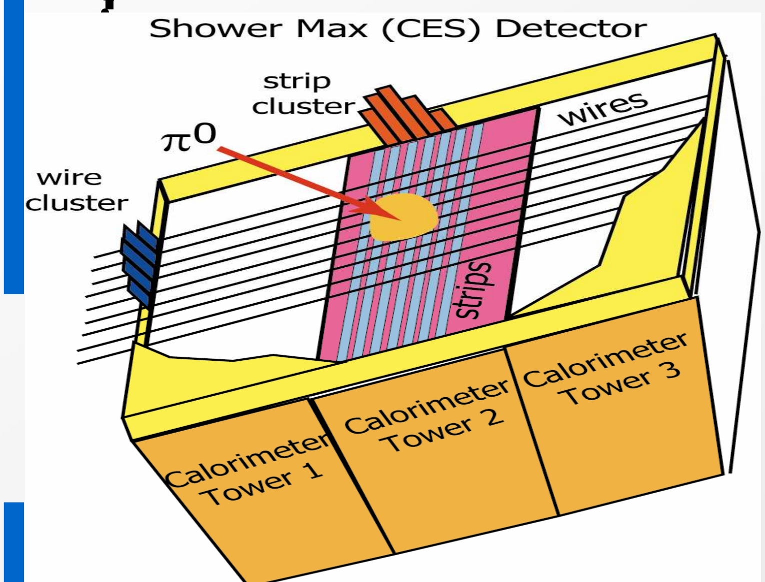



**High calorimeter segmentation is required**

$E_\gamma = E^{EM} - E^{EM}_{tracks}$




**CES: $\delta E/E \geq 23\%$**




**CDF detector parameters:**

**COT (Tracker):** $\delta p_T/p_T^2 \approx 0.0015\ (GeV/c)^{-1}$

**EM :** $\delta E_T/E_T \approx 0.135/\sqrt{E_T} + 0.02$

**HAD:** $\delta E_T/E_T \approx 0.5/\sqrt{E_T} + 0.03$

**Simple PFA:**

$E_\tau = E_{track} + E_\gamma^{CES}$

***doesn't yield the best result due to poor CES resolution***

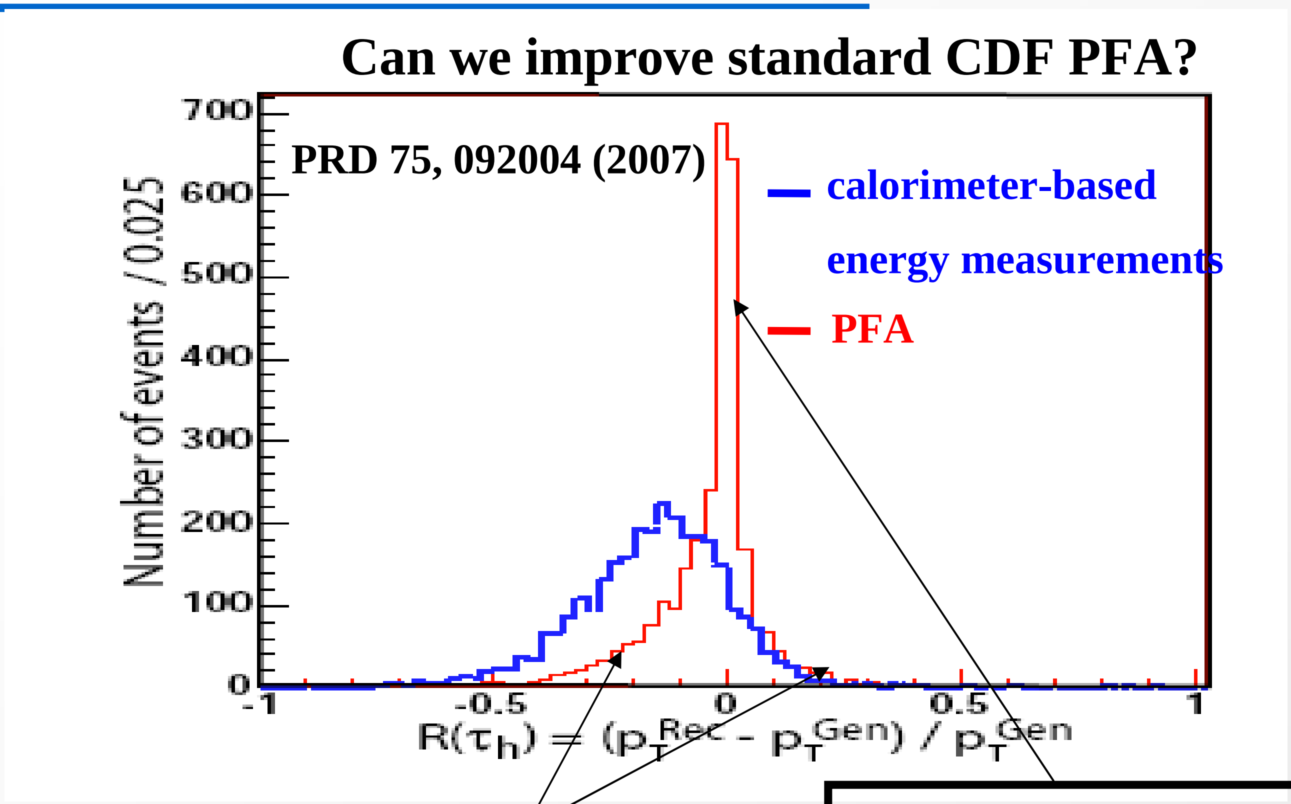
**Standard CDF PFA:**

**Combine EM and CES information to guess $E_\gamma$**

$E_\tau = E_{tracks} + E_\gamma$

**$E_\gamma$ is determined by global detector response based on many ad-hoc parameters.**

# PFA vs Traditional Calorimetry




**Poor guess on photon energy**

**About 33% hadronic decays consist of only charged tracks. When identified correctly those are measured perfectly in the tracker.**

**PFA+Likelihood:**

**Substitute ad-hoc parameters by the likelihood function:**

$$\mathbf{L = f_{\pi\gamma}^{COT,EM,HAD,CES}(p_T^{COT}, E^{EM}, E^{HAD}\ E^{CES} \mid E_\gamma, E_\pi)}$$

maximize L and measure tau energy as $\mathbf{E^{\tau}_{rec} = E_\pi + E_\gamma}$

# Construction of the Likelihood Function

$$L = f_{\pi\gamma}^{COT,EM,HAD,CES}(p_T^{COT}, E^{EM}, E^{HAD}\ E^{CES} \mid E_\gamma, E_\pi) =$$

$$= f_{\pi\gamma}^{EM,HAD}(E^{EM}, E^{HAD} \mid E_\gamma, E_\pi) \times f_\gamma^{CES}(E^{CES} \mid E_\gamma)$$

**Excellent resolution of the tracker makes it fixed parameter.**

$$f_{\pi\gamma}^{EM,HAD} = \iint f_\pi^{EM,HAD}(x, y; E_\pi) \times f_\gamma^{EM,HAD}(E^{EM} - x, E^{HAD} - y; E_\gamma)\,dxdy$$

- **Scan over $E_\gamma$ to find maximum of L**
- **visible tau energy $E^\tau_{rec} = E_\pi + E_\gamma$**

***Example of one MC event:***

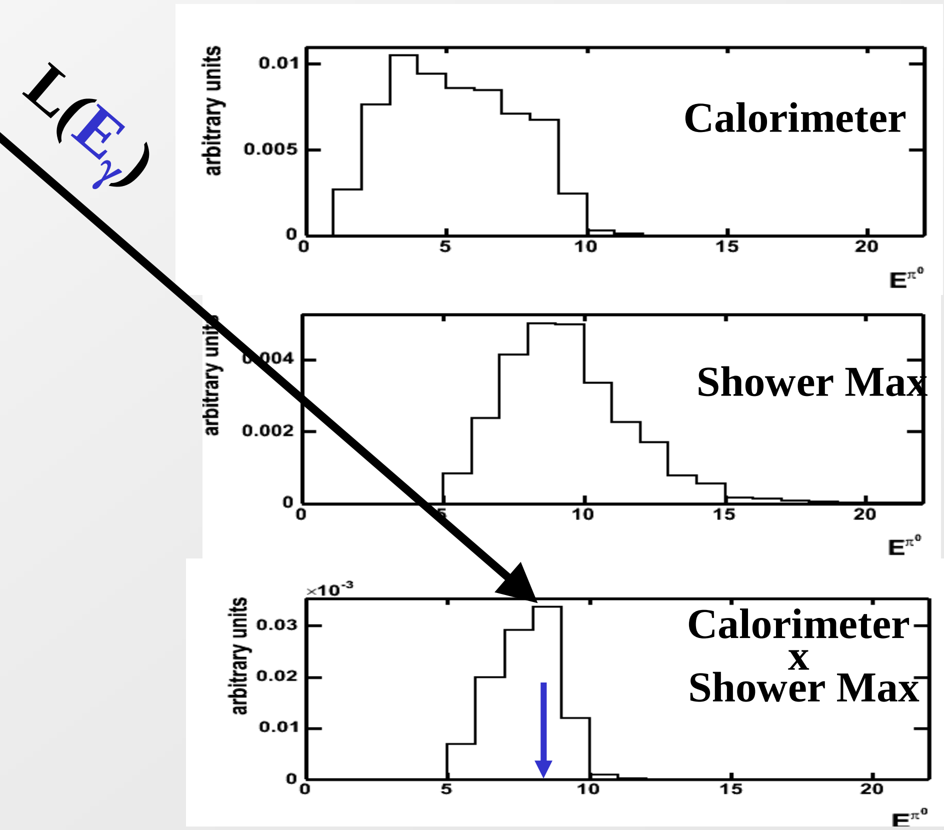
Tracker: $p_T$ = 13.8 GeV/c

EM: $E_{dep}$ = 8.4 GeV;

HAD: $E_{dep}$ = 6.1 GeV

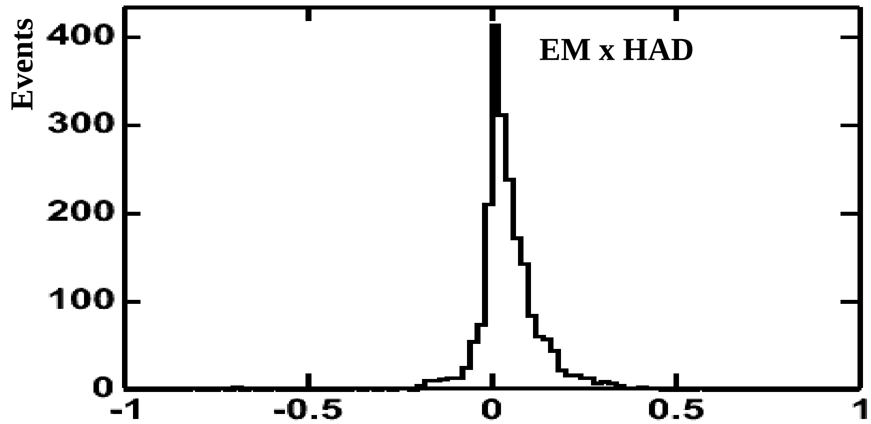
CES: cluster = 8.0 GeV

True photon energy = 5.1 GeV

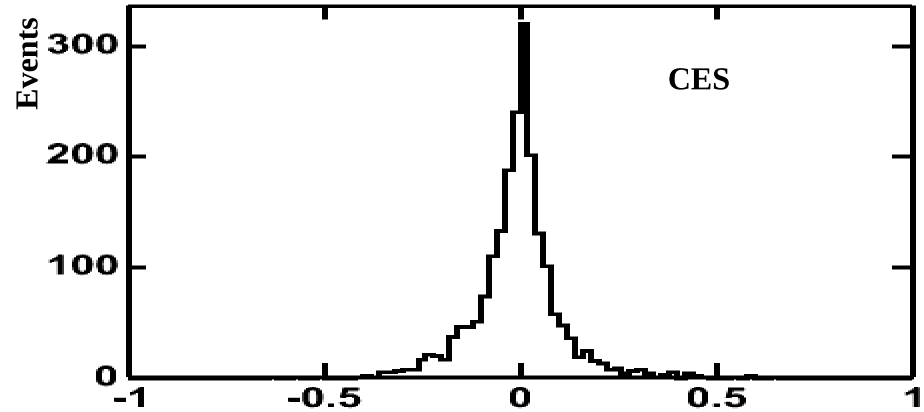


# Reconstruction of visible tau energy

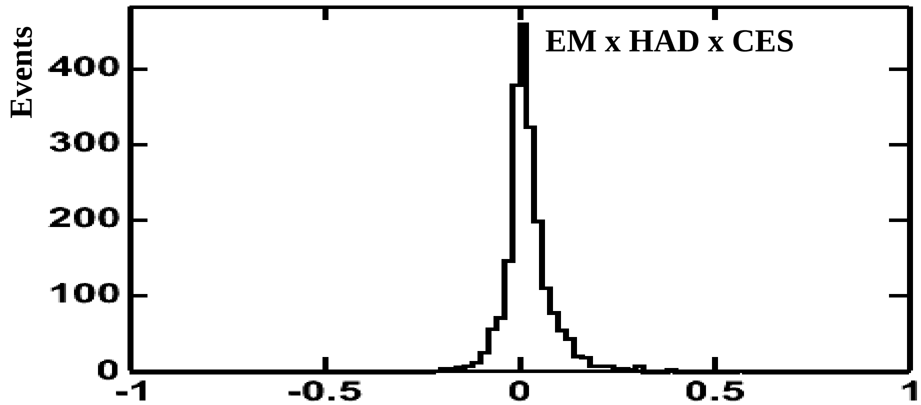
## 1 prong taus with 1 $\pi^0$




$(E_{tau}^{rec} – E_{tau}^{true} )/ E_{tau}^{true}$




$(E_{tau}^{rec} – E_{tau}^{true} )/ E_{tau}^{true}$



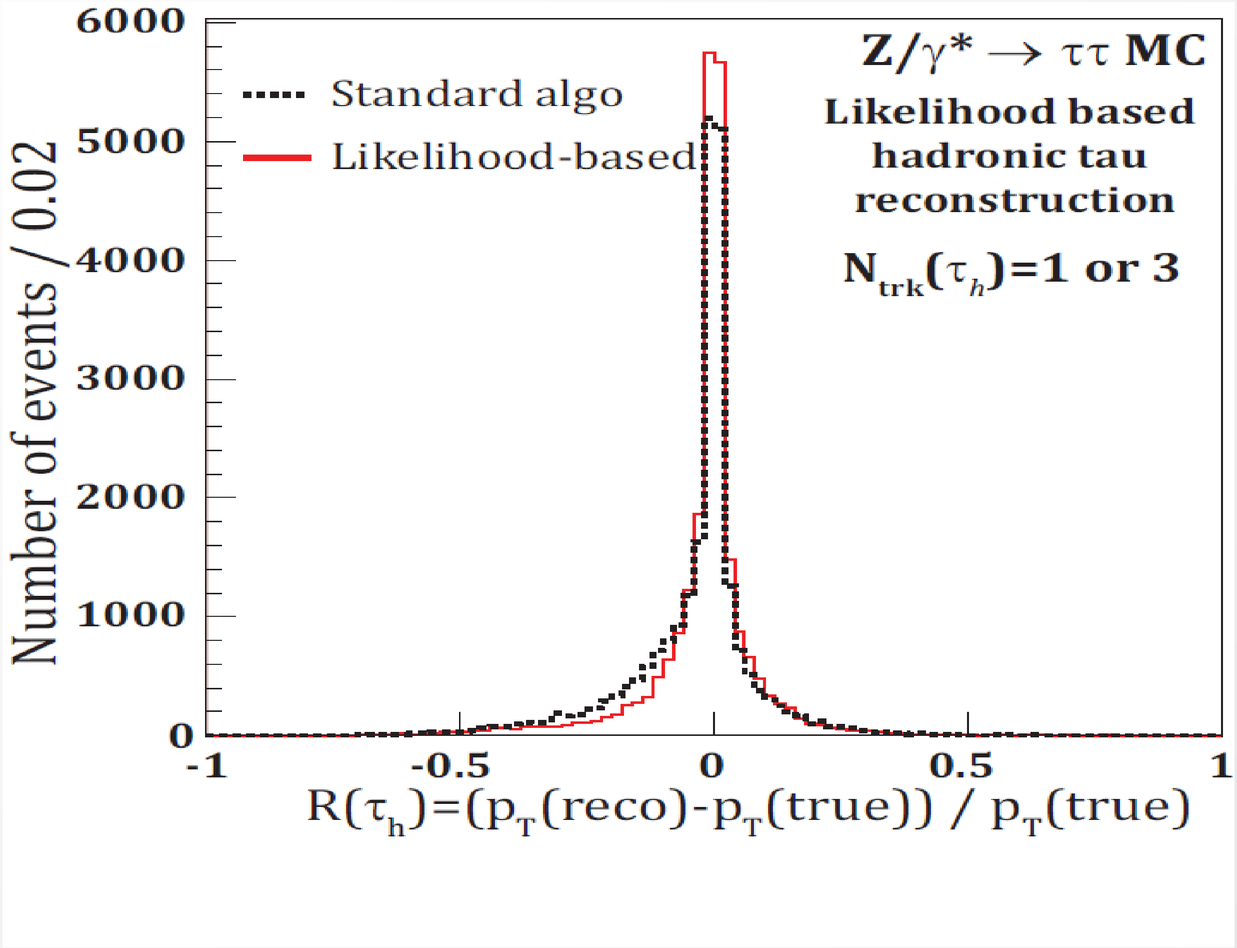

$(E_{tau}^{rec} – E_{tau}^{true} )/ E_{tau}^{true}$

**Tau selection for these plots:**

- MC Dataset $Z \rightarrow \tau\tau$
- 1 track + $\pi^0$ in the final state
- seed track $p_T$ > 6 GeV
- $|\eta|<1$

# Algorithm Performance in MC

**MC Dataset Z→ ττ, one tau decays in hadronic mode another decays to electron or muon**



# "Clean Taus" Event Selection ($Z\rightarrow\tau_h\tau_e$ and $Z\rightarrow\tau_h\tau_\mu$)

**For the testing of the algorithms event selection result in clean sample of taus with 6 times reduced acceptance to the $H \rightarrow \tau\tau$ events. Selections are relaxed for the Higgs search.**

**Trigger: inclusive lepton trigger paths (requires high $p_T$ lepton candidate)**

### Tau ID cuts:

highest track $p_T$ > 6 GeV/c; $\sum p_T$ (trk) > 10 GeV/c

$|\eta|<1$ ; $d_0 < 0.2$ cm

$M^{trk} \leq 1.8$ GeV/c$^2$

$I_{trk}(0.17<\Delta R<0.52) \leq 1$ GeV/c

$N_{trk}^{\tau,cone} = 1$ or 3

EM/(EM+HAD) < 0.9 (anti electron cut)

(EM+HAD)/$E_{trks}$ > 0.5 (anti muon cut)

### Electron ID cuts:

Standard CDF selection with these additional cuts:

20 GeV/c < pT < 40 GeV/c

$I_{trk}(\Delta R<0.52) < 1$ GeV/c (for $N_{pr}(\tau_h)=1$)

E/P <1.1 (if $N_{pr}(\tau_h)=1$)

$I_{trk}(\Delta R<0.7) = 0$ (for $N_{pr}(\tau_h)=3$)

$N_{svx} > 0$ (for $N_{pr}(\tau_h)=3$)

### Muon ID cuts:

Standard CDF selections with these additional cuts:

20 GeV/c < pT < 40 GeV/c

$I_{trk}(\Delta R<0.52) < 1$ GeV/c

### Topology cuts:

$\Delta\phi\ (\tau_h,\tau_l) > 2.9$

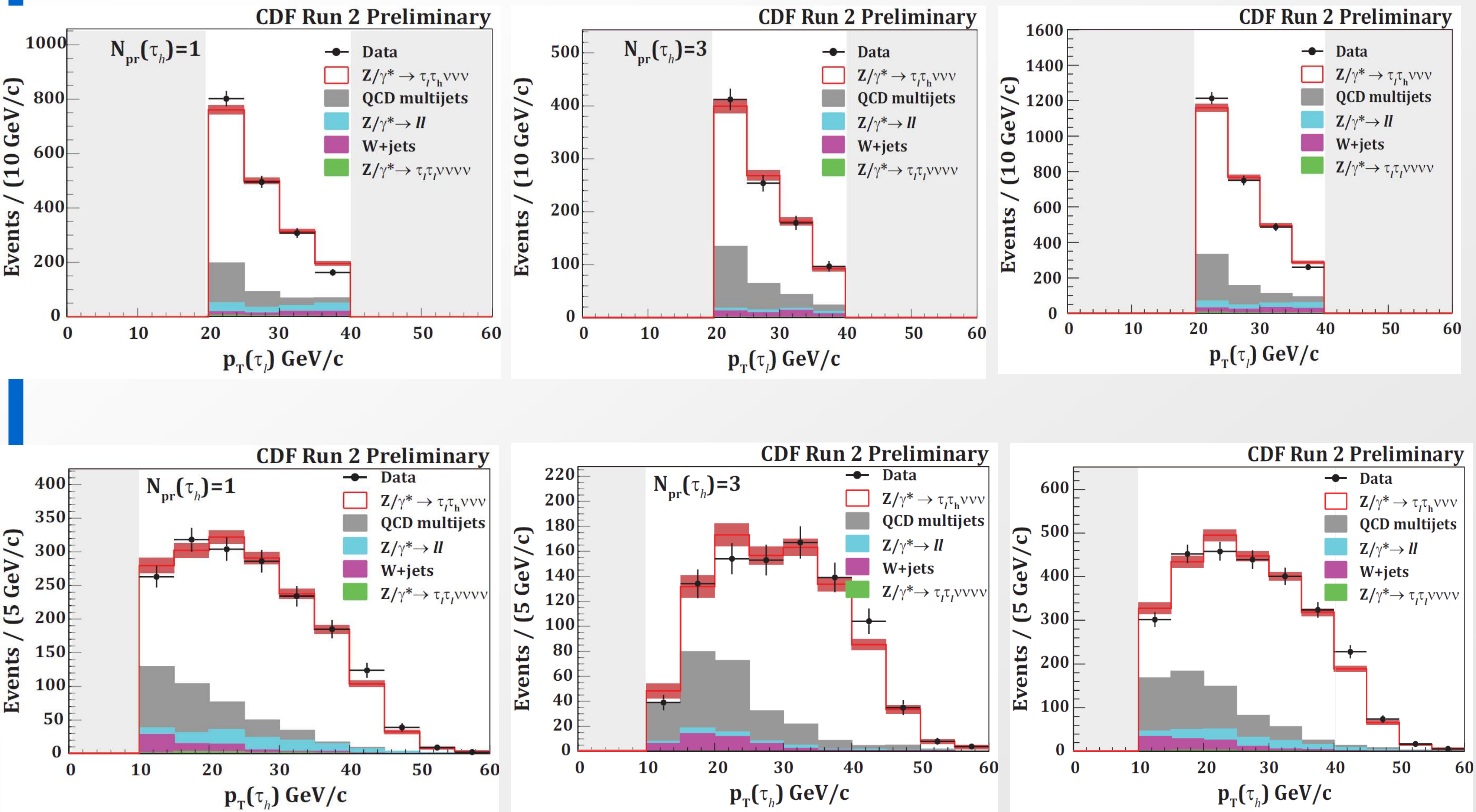
N(jets) = 0

66 GeV/c$^2$ < M(trk-trk) < 111 GeV/c$^2$

76 GeV/c$^2$ < M(EM-EM) < 106 GeV/c$^2$

# “Clean Taus” Data Sample

**Backgrounds: QCD – Same Sign events; other – MC**

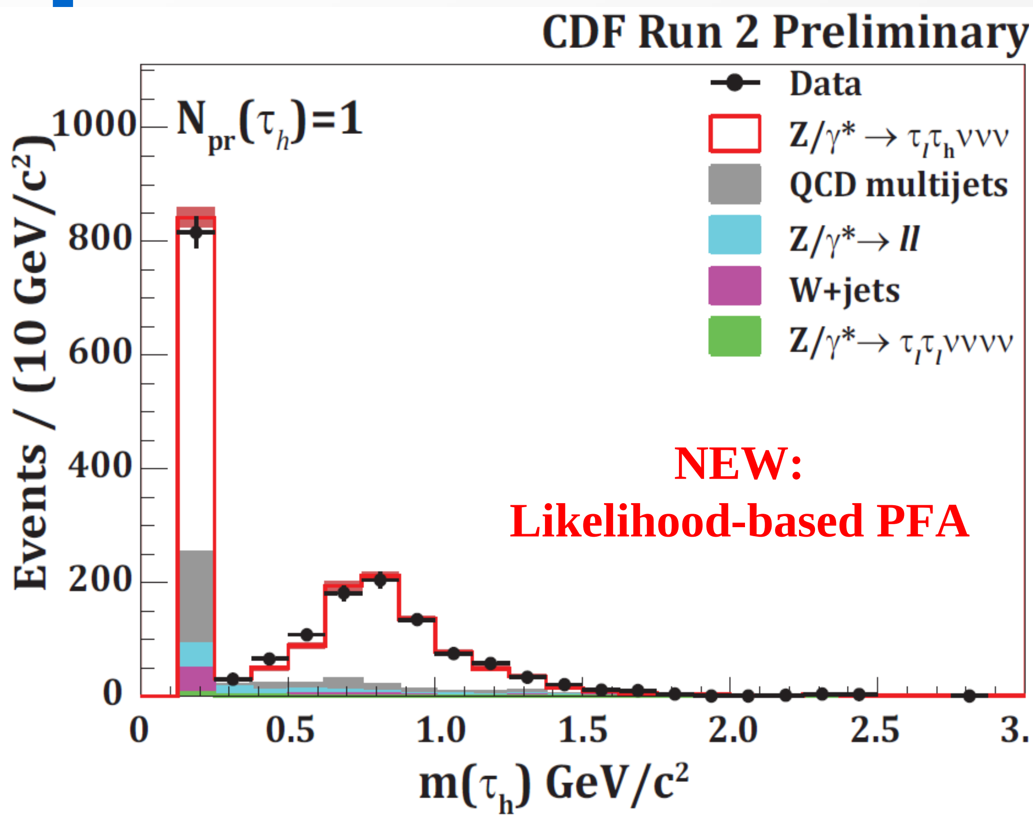


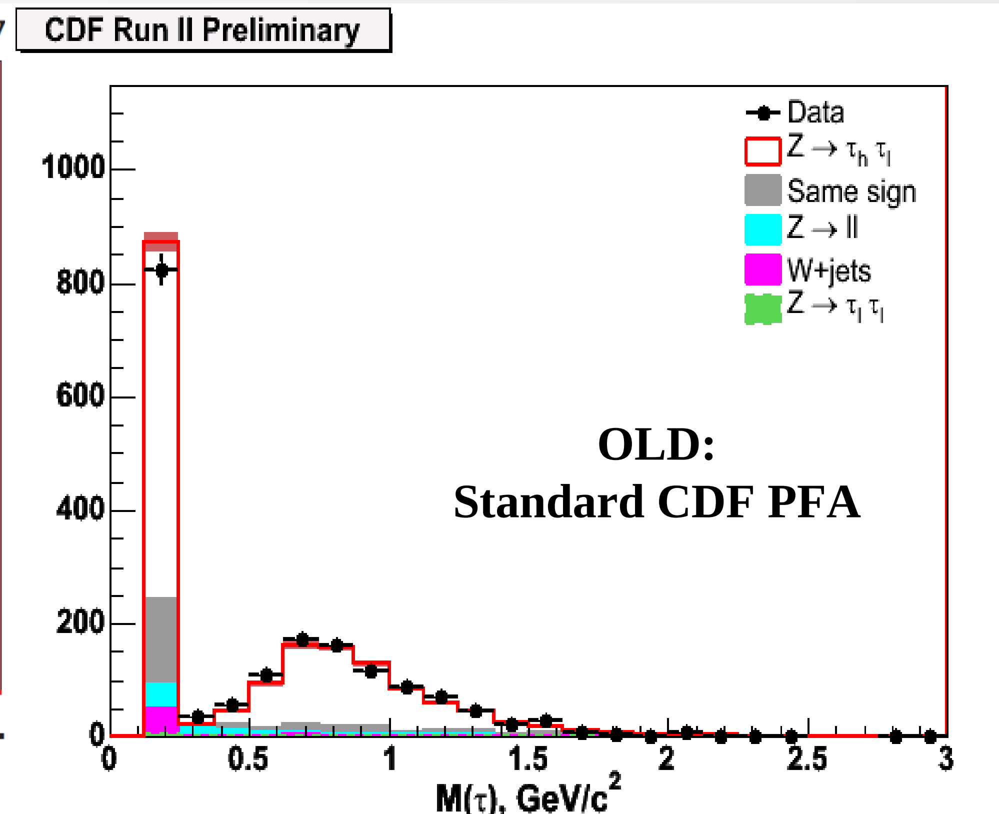
# Performance of the Likelihood-based PFA

**40% of all hadronic taus decay via ρ(770):** $\tau^{\pm}_{h} \rightarrow \nu_{\tau} + \rho^{\pm} \rightarrow \nu_{\tau} + \pi^{0} + \pi^{\pm}$

**Invariant mass of the ρ(770) is very sensitive to relatively small perturbations in 4-momentum assigned to $\pi^0$ and $\pi^{\pm}$. Good test for likelihood-based method.**

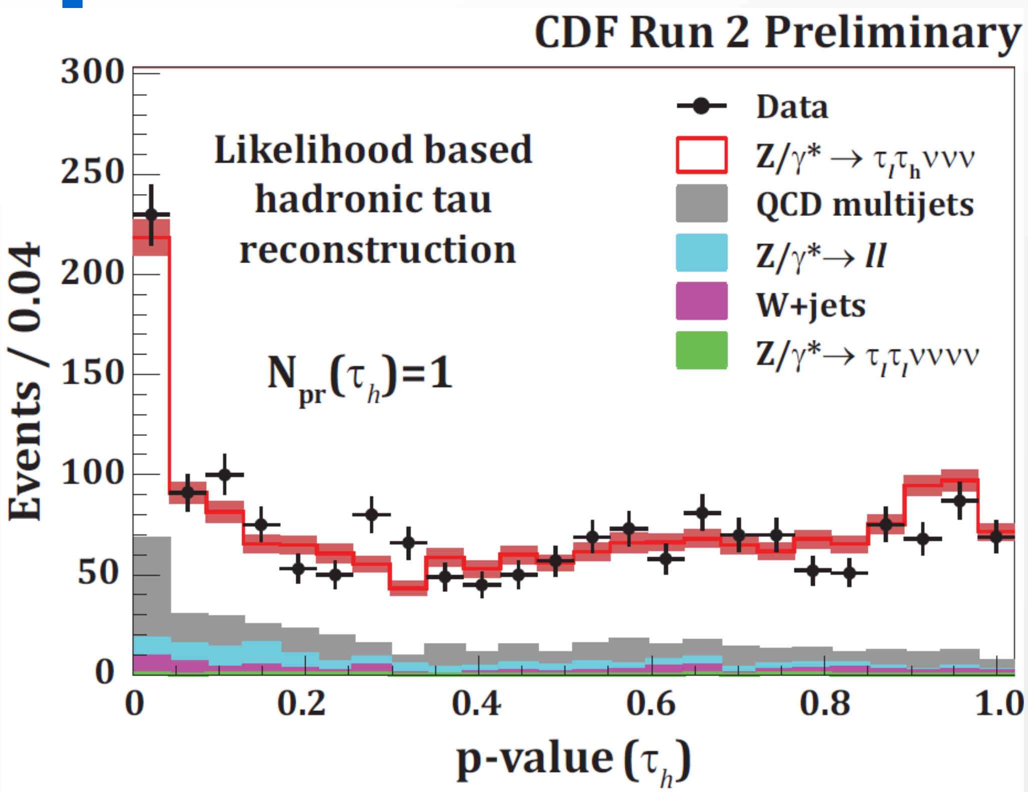
## Tau Invariant Mass Test
## 1-prong taus

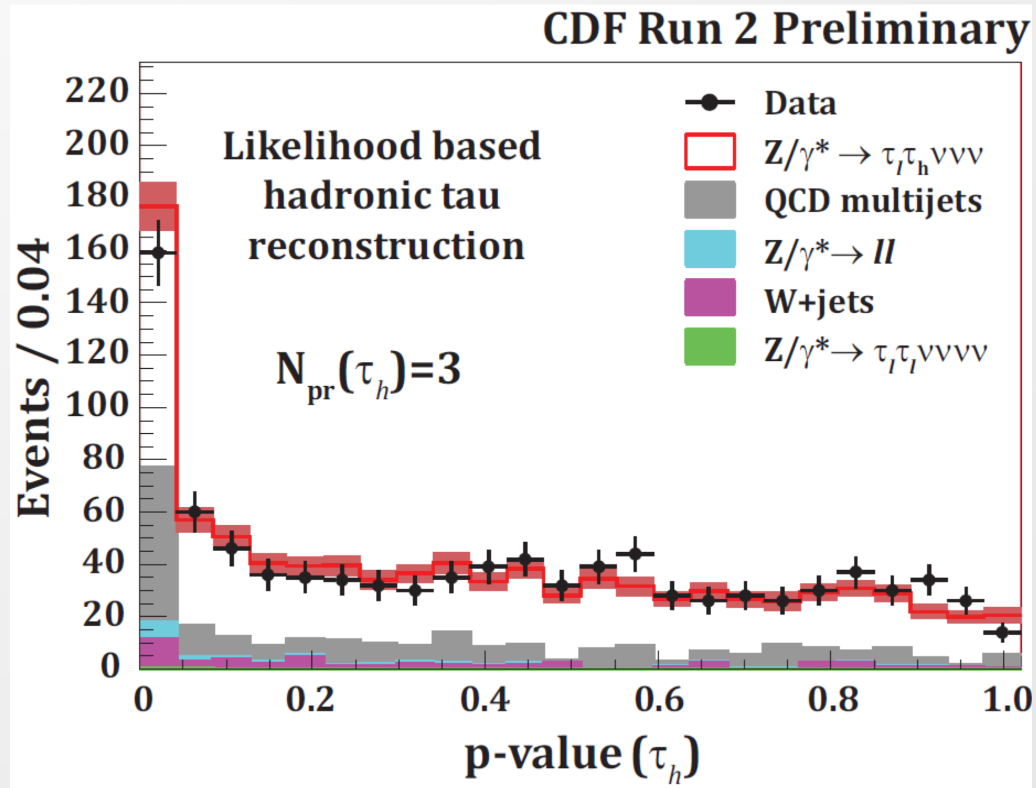


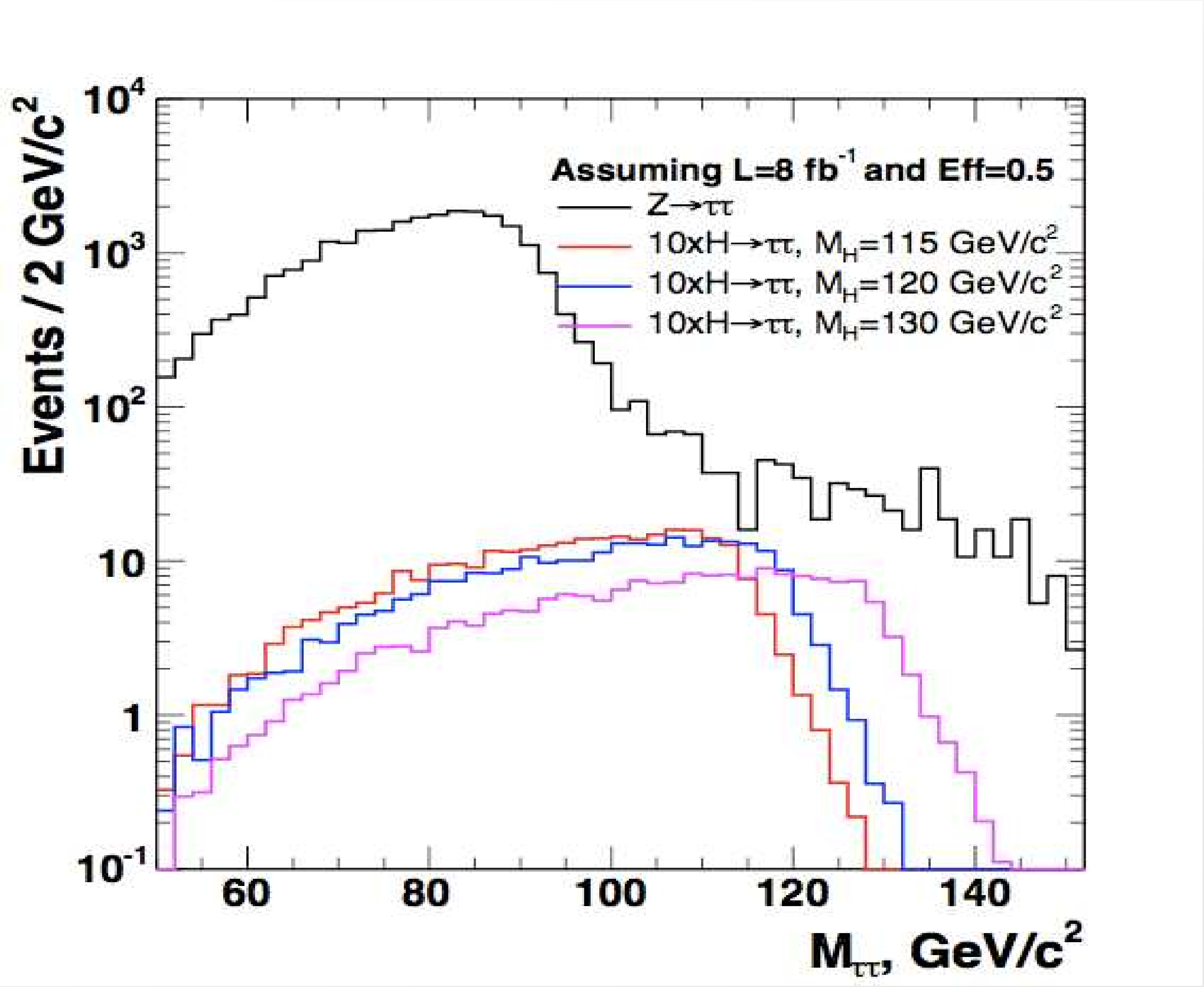
# Performance of the Likelihood-based PFA

## p-value test

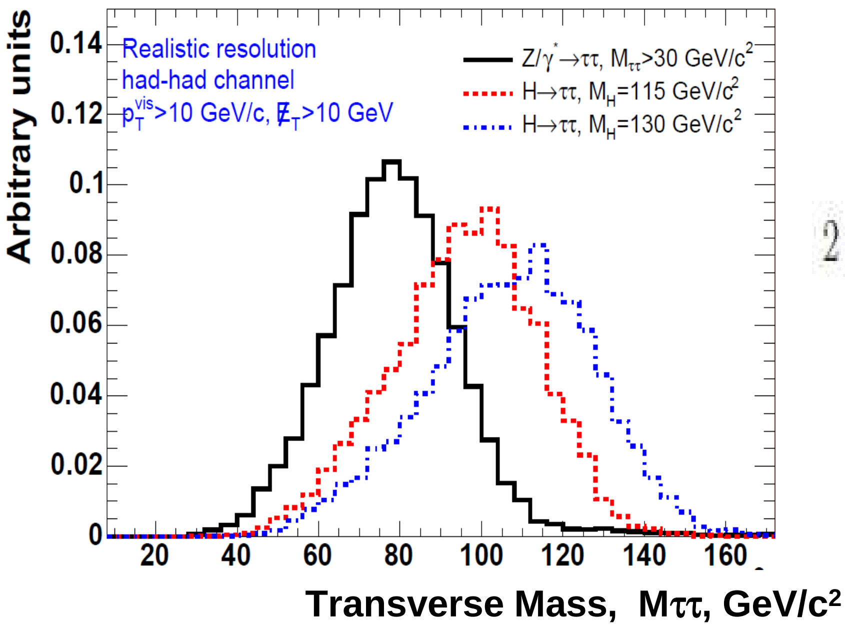


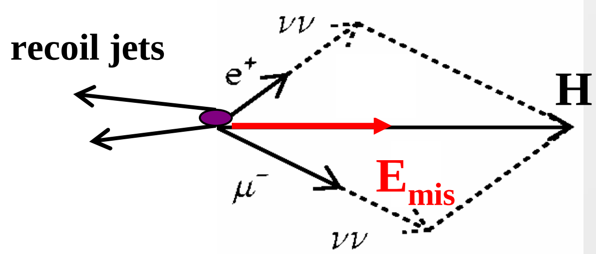
# Need for M(ττ) Reconstruction

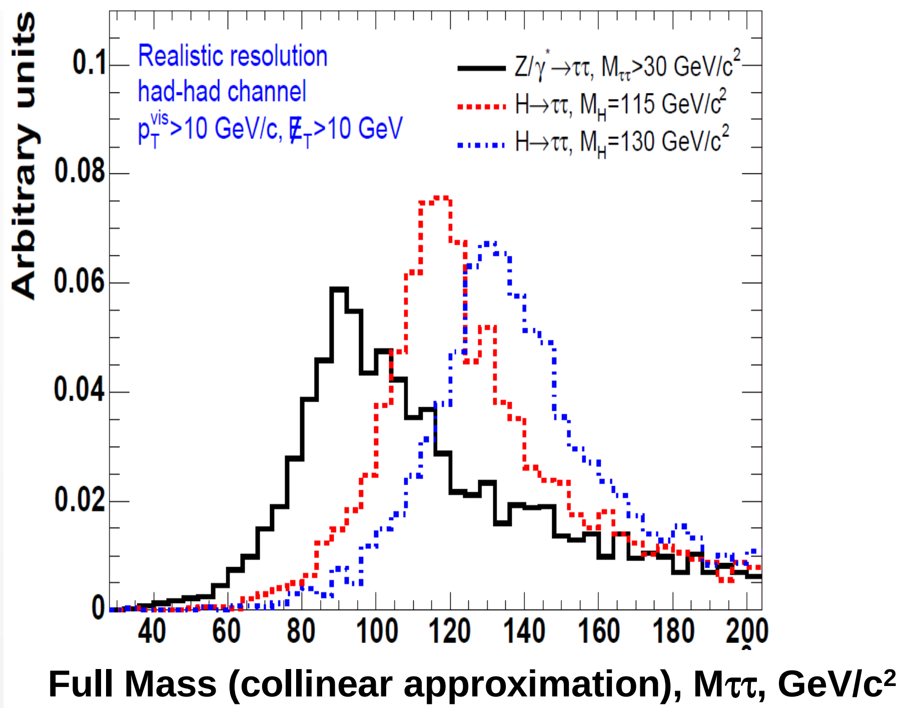


# Existing Methods for M(ττ) Reconstruction




$$M^2(\tau_{\text{vis}_1}, \tau_{\text{vis}_2}, \not{E}_T) = m^2_{\text{vis}_1} + m^2_{\text{vis}_2} + 2 \times \left( \sqrt{m^2_{\text{vis}_1} + p^2_{\text{vis}_1}} \sqrt{m^2_{\text{vis}_2} + p^2_{\text{vis}_2}} + \not{E}_T \sqrt{m^2_{\text{vis}_1} + p^2_{\text{vis}_1}} + \not{E}_T \sqrt{m^2_{\text{vis}_2} + p^2_{\text{vis}_2}} \right) - 2 \times \left( \vec{p}_{\text{vis}_1} \cdot \vec{p}_{\text{vis}_2} + \vec{p}_{\text{vis}_1} \cdot \vec{\not{E}}_T + \vec{p}_{\text{vis}_2} \cdot \vec{\not{E}}_T \right)$$




**Tau is boosted due to M(Z/H)>>M(τ)**
**Assume that neutrinos are collinear with visible tau decay products and solve 2 equations with 2 unknowns.**

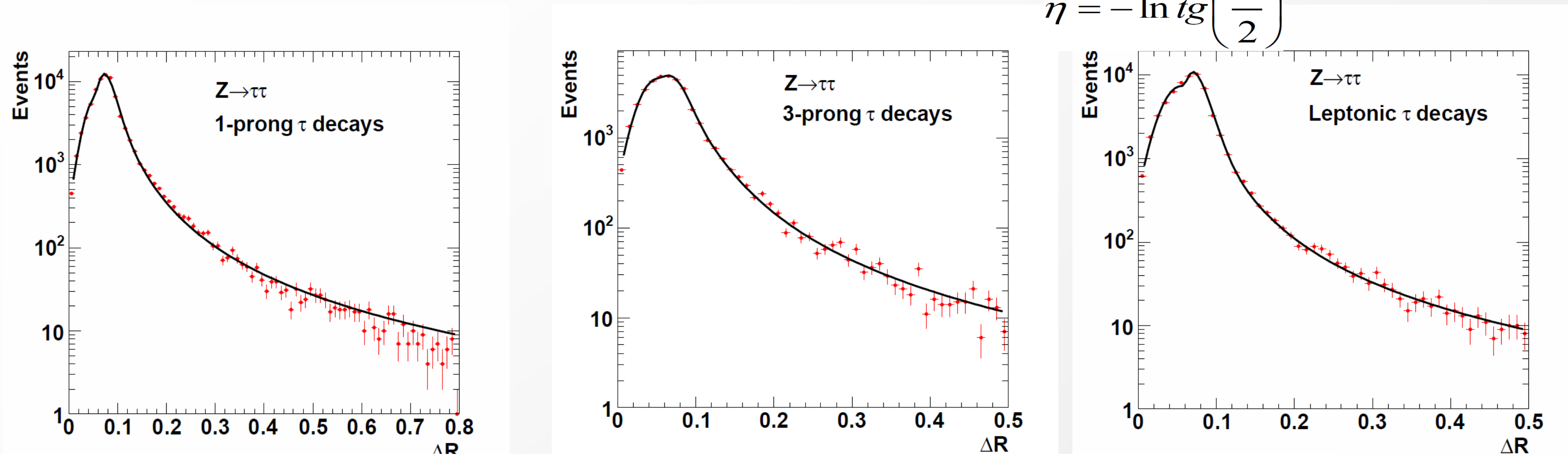
$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{vis}_1} \cos\phi_{\text{vis}_1} + p_{\text{mis}_2} \sin\theta_{\text{vis}_2} \cos\phi_{\text{vis}_2}$$
$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{vis}_1} \sin\phi_{\text{vis}_1} + p_{\text{mis}_2} \sin\theta_{\text{vis}_2} \sin\phi_{\text{vis}_2},$$

# Missing Mass Calculator (MMC)

$$\Delta R = \sqrt{(\eta_{vis} - \eta_{mis})^2 + (\phi_{vis} - \phi_{mis})^2}$$

**Neutrinos are not collinear with visible tau:**

$$\eta = -\ln tg\left(\frac{\vartheta}{2}\right)$$




$$\not{E}_{T_x} = p_{mis_1} \sin\theta_{mis_1} \cos\phi_{mis_1} + p_{mis_2} \sin\theta_{mis_2} \cos\phi_{mis_2}$$

$$\not{E}_{T_y} = p_{mis_1} \sin\theta_{mis_1} \sin\phi_{mis_1} + p_{mis_2} \sin\theta_{mis_2} \sin\phi_{mis_2}$$

$$M_{\tau_1}^2 = \underline{m_{mis_1}^2} + m_{vis_1}^2 + 2\sqrt{p_{vis_1}^2 + m_{vis_1}^2}\sqrt{p_{mis_1}^2 + \underline{m_{mis_1}^2}} - 2p_{vis_1}p_{mis_1}\cos\Delta\theta_{vm_1}$$

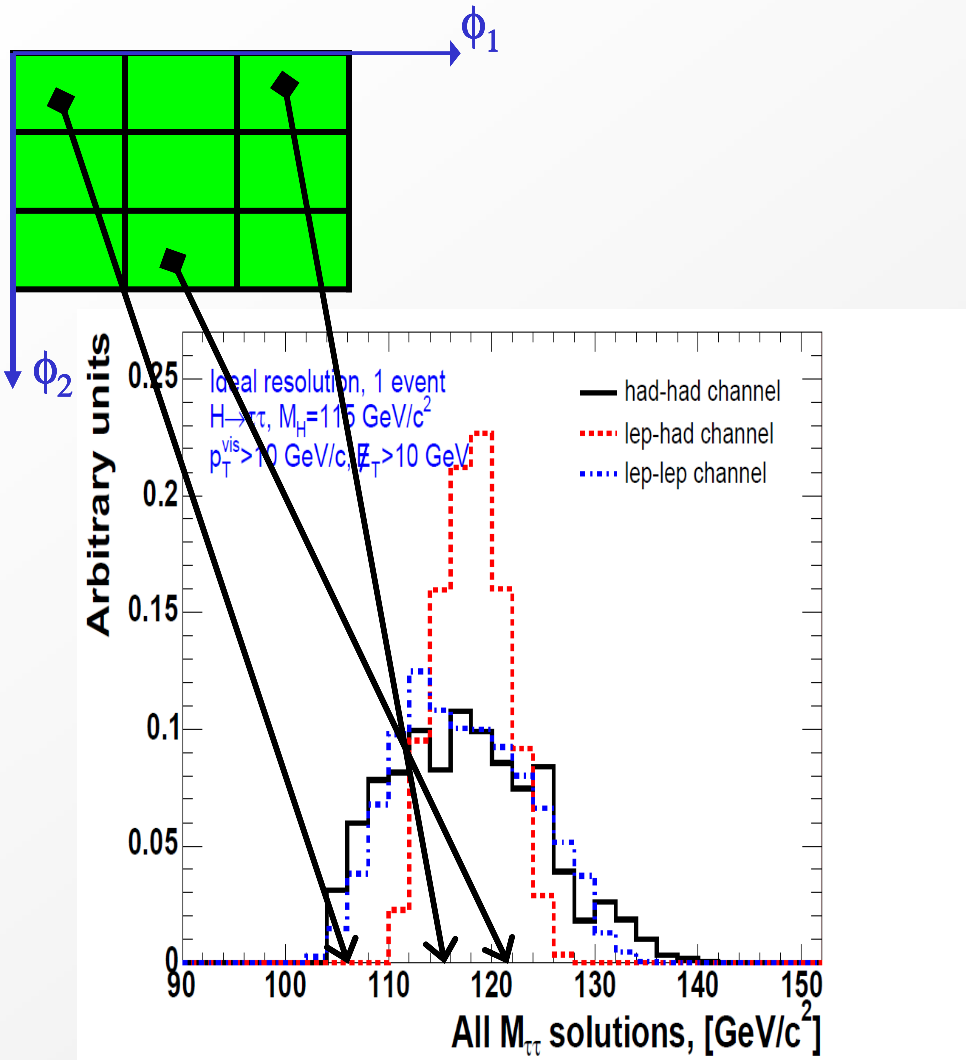
$$M_{\tau_2}^2 = \underline{m_{mis_2}^2} + m_{vis_2}^2 + 2\sqrt{p_{vis_2}^2 + m_{vis_2}^2}\sqrt{p_{mis_2}^2 + \underline{m_{mis_2}^2}} - 2p_{vis_2}p_{mis_2}\cos\Delta\theta_{vm_2}$$

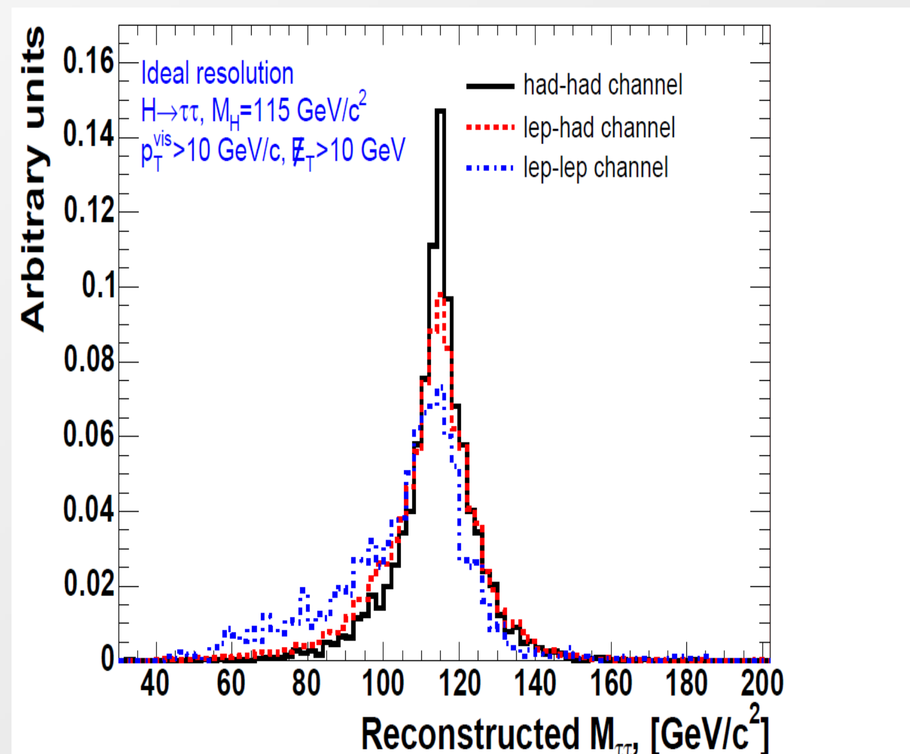
**(*)**

**$E_{Tx}$, $E_{Ty}$, $P_{vis12}$, $m_{vis12}$, $\theta_{vis12}$, $\phi_{vis12}$ – measured values**
**$M_\tau$ = 1.777 GeV/c$^2$**
**$P_{mis12}$, $\theta_{mis12}$, $\phi_{mis12}$, $m_{mis12}$ – N unknowns (N(had-had)=6, N(had-lept)=7, N(lept-lept)=8)**

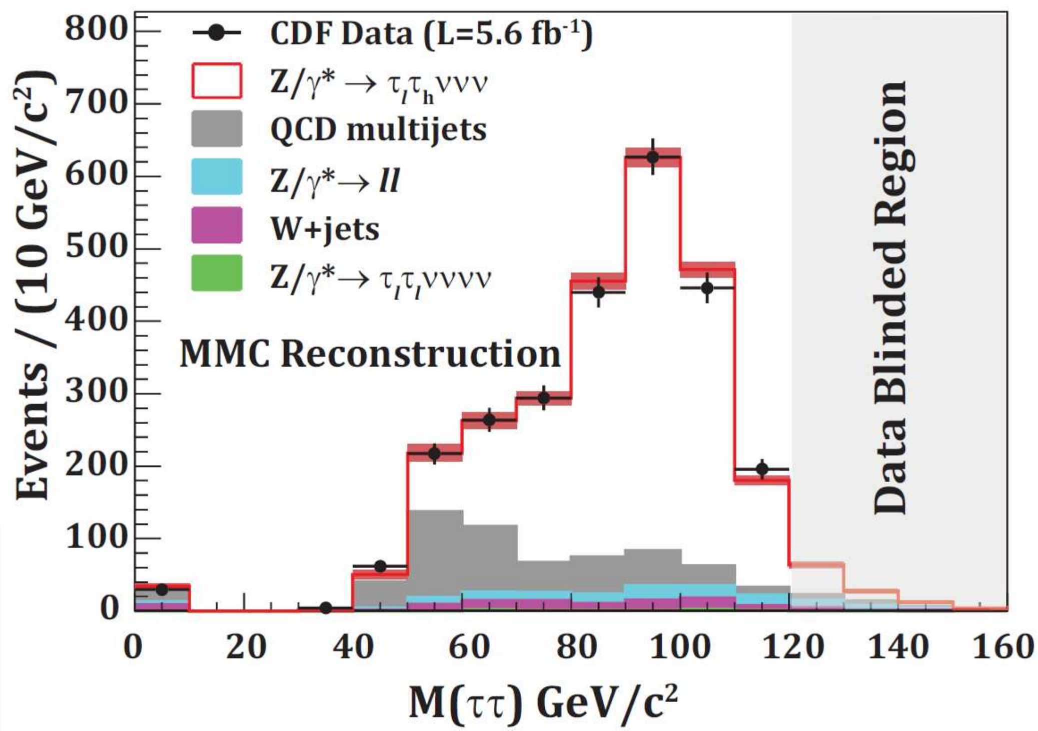
# Missing Mass Calculator (MMC)

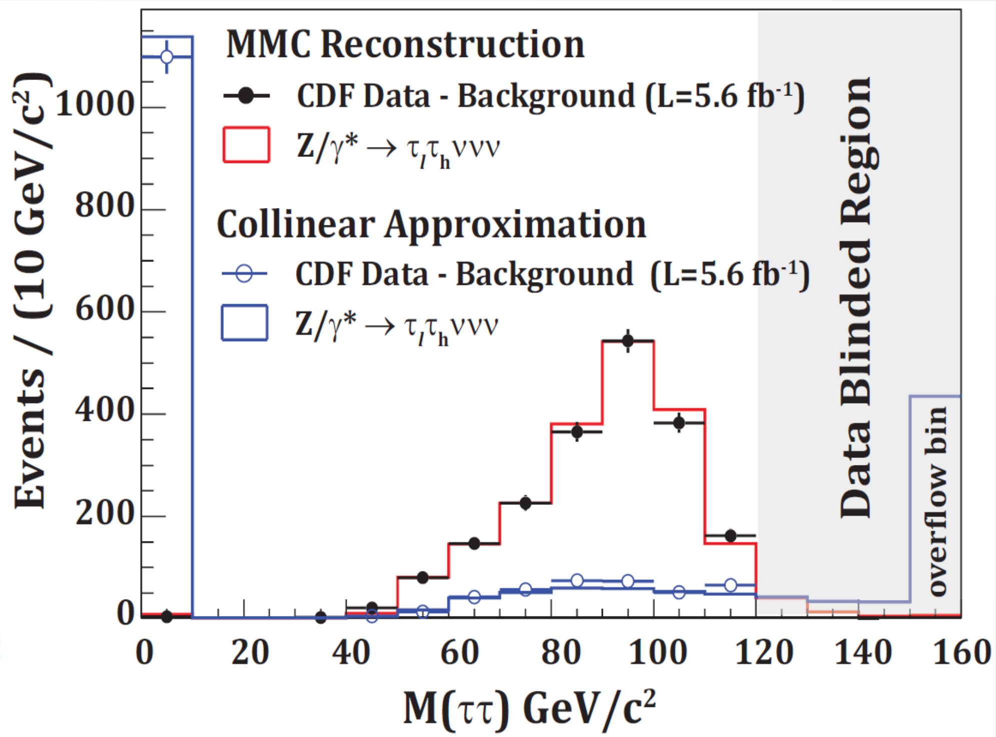
**Define parameter space of the size N-4 ($\phi 1, \phi 2$, [$m_{mis1}$], [$m_{mis2}$])**
**System (*) can be resolved for $P_{mis12}$ and $\theta_{mis12}$ for every point in the parameter space.**
**Calculate di-tau mass and assign a weight to it according to probability from $\Delta$R distribution.**
**Make M($\tau\tau$) distribution by scanning the parameter space take highest bin as a solution.**



# Performance of the MMC Algorithm




| | MMC | Collinear approximation |
|---|---|---|
| Efficiency, % | 99 | 42 |
| Resolution, % | 16 | 35 |

# Summary

- New tools (Likelihood-based PFA and MMC) have been developed.
- Their performance was tested with data $Z \rightarrow \tau\tau$ events.
- Likelihood-based PFA improves energy measurements and particle ID.
- Missing Mass Calculator allows for full reconstruction of full di-tau mass. For the first time full mass of $\tau\tau$ resonances is reconstructed without loss in reconstruction efficiency.
- Both algorithms are implemented into the $H \rightarrow \tau\tau$ analysis at CDF.
- Stay tuned for new results which take advantage of these tools.