# $\nu_\tau$ kinematic search at DUNE far detector for the $\tau$—>$1\pi$ decay mode

$\nu_\tau$ meeting group

-

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DEEP UNDERGROUND NEUTRINO EXPERIMENT



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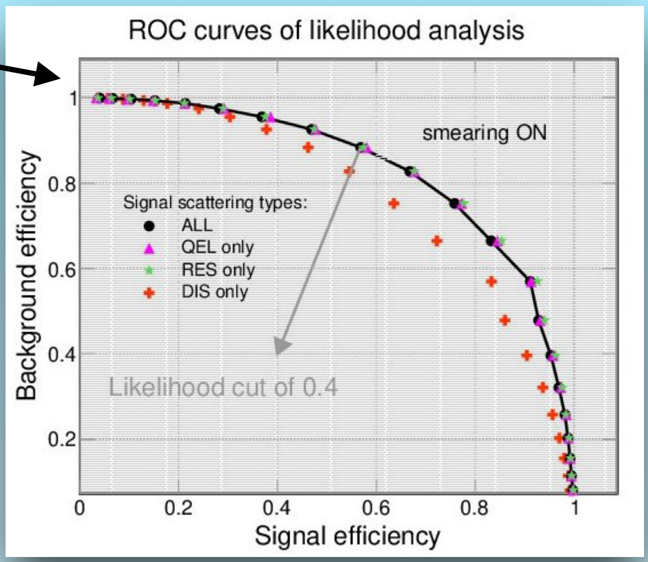
# Abstract

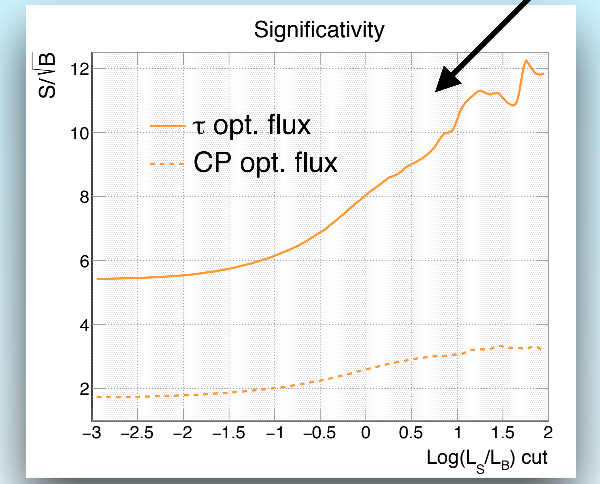
- I developed a likelihood method to identify $\nu_\tau$ CC interactions at DUNE FD (https://indico.fnal.gov/event/48406/), focusing on the τ—>ρ (and before τ—>e) decay channel, "à la NOMAD". **Large BR** (~25%), **kinematic signature** of the ρ resonance with invariant masses. Main background: NC with pairs of (π0 π±) in the final state.

- Signal/Background efficiencies curve: 95% background reached for 40% signal efficiency. Also the likelihood disfavours DIS events.




- Analysis repeated with machine learning techniques (NN and BDT) instead of more traditional likelihood tools: no improvement observed.

- Significance largely favoured with the alternative τ optimized beam flux instead of the CP optimized beam flux (signal statistics gets a factor of 6 !).




**Weakness:** ~20% contamination among the ντ events, due to misreconstruction of the ρ coming from the τ decay (because of pions in the hadronic system). Hardly improvable.

**In this talk:** τ—>1π decay mode (BR 10.83%). The single visible τ daughter particle is less prone to confusion ! + QEL can provide rather clean final states ! —> **extension of the τ—>ρ analysis** to this more exclusive topology.



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# Identify the correct charged pion of τ—>1π

The 1π decay mode can be thought as a simplified case of the ρ decay mode, so pretty quickly to set it up.
Main background = Neutral Currents with charged pions in the final state.

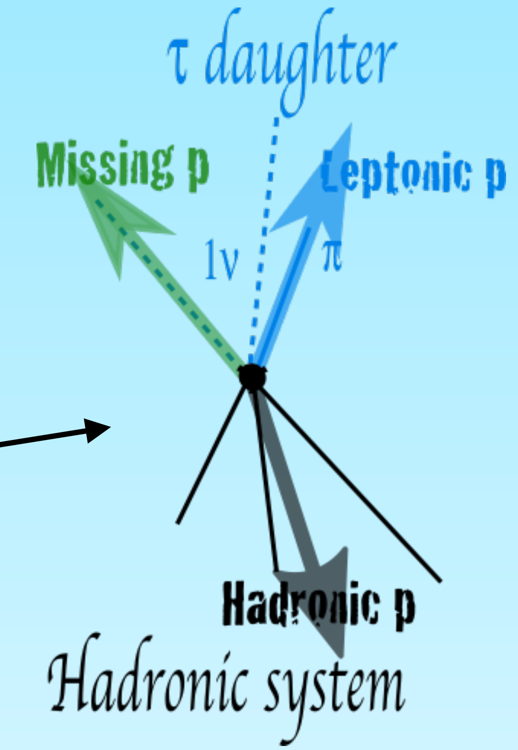
Detector effects taken into account via smearing process (energy+direction of the particles).

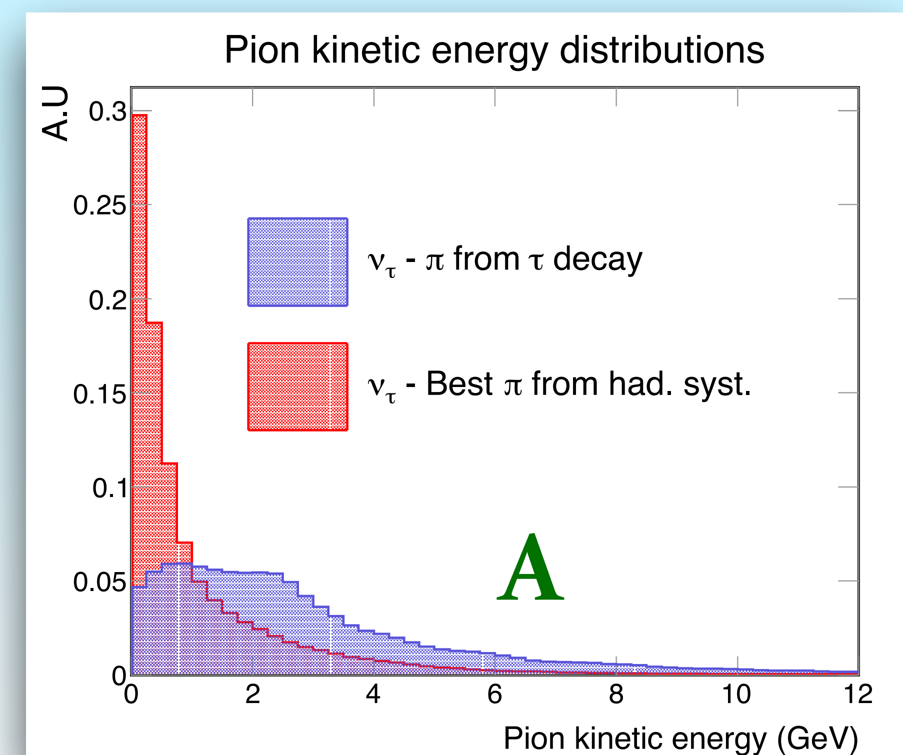
- **First step**: correctly reconstruct the τ decay system (negatively charged pion) in the ντ CC events. Define a **Medal Game** based on these 3 kinematic variables:

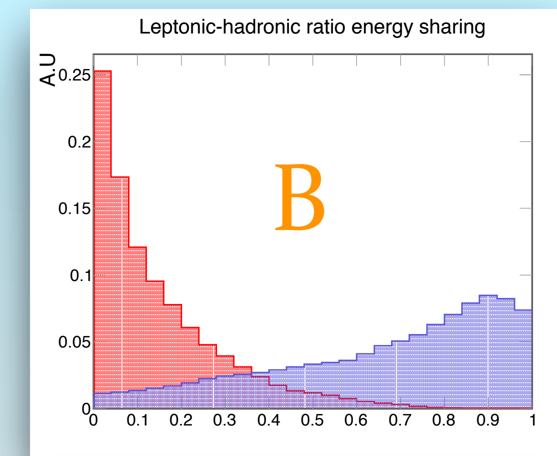
  A. **Kinetic energy of the charged pion candidate**

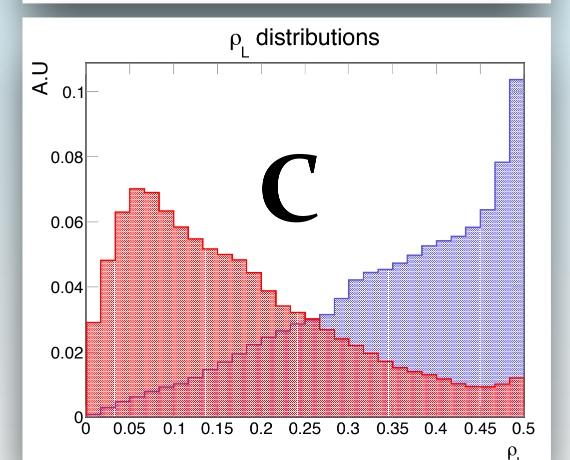
  B. **Pion kinetic energy sharing normalized to the total event visible energy.**

  C. **Transverse plane fraction of momentum:** $\rho_L = \frac{p_\pi^{(tr)}}{p_\pi^{(tr)} + p_{miss}^{(tr)} + p_{had}^{(tr)}}$




**Results** on ντ CC

**63%** have only the charged pion of the τ in the final state: no confusion possible.

**37%** of the events have pions from the hadronic system in addition to the τ decay pion.
**31%** of the events have the τ decay pion correctly reconstructed.

63+31 = **94% correct π identification**

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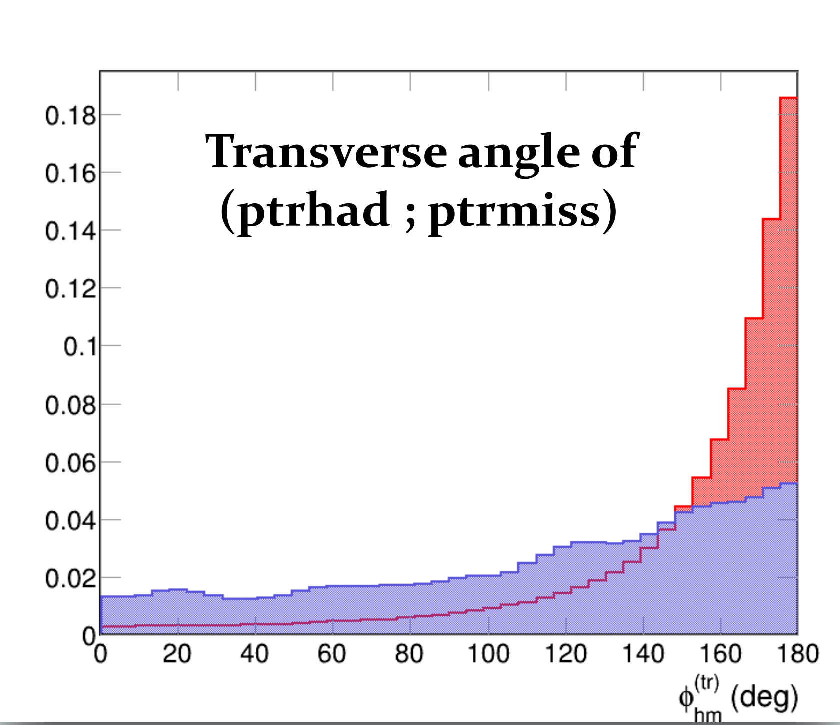
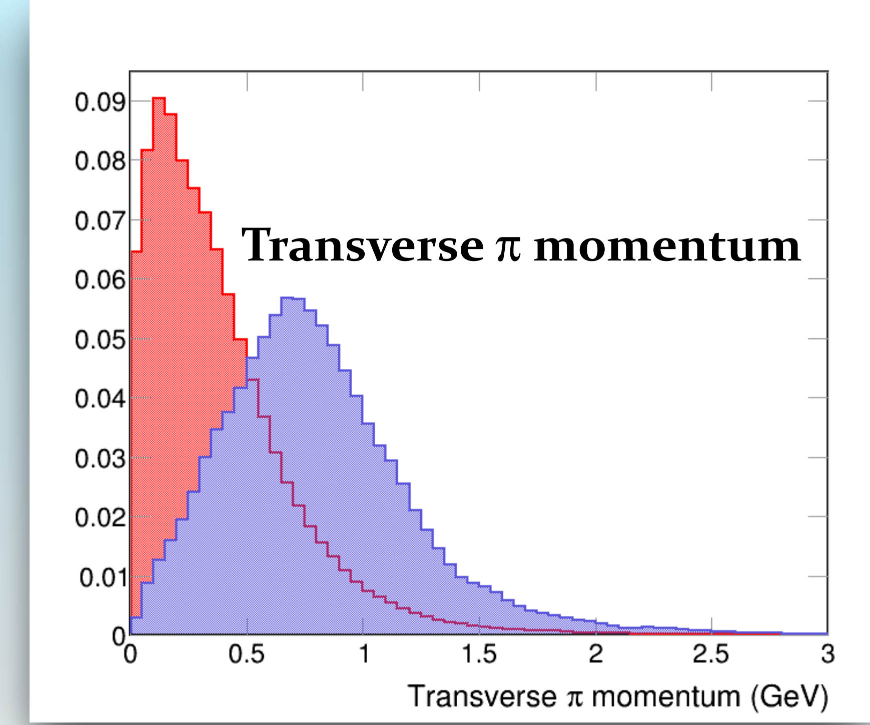
# Kinematic distribution ντ VS NC(>1pi)

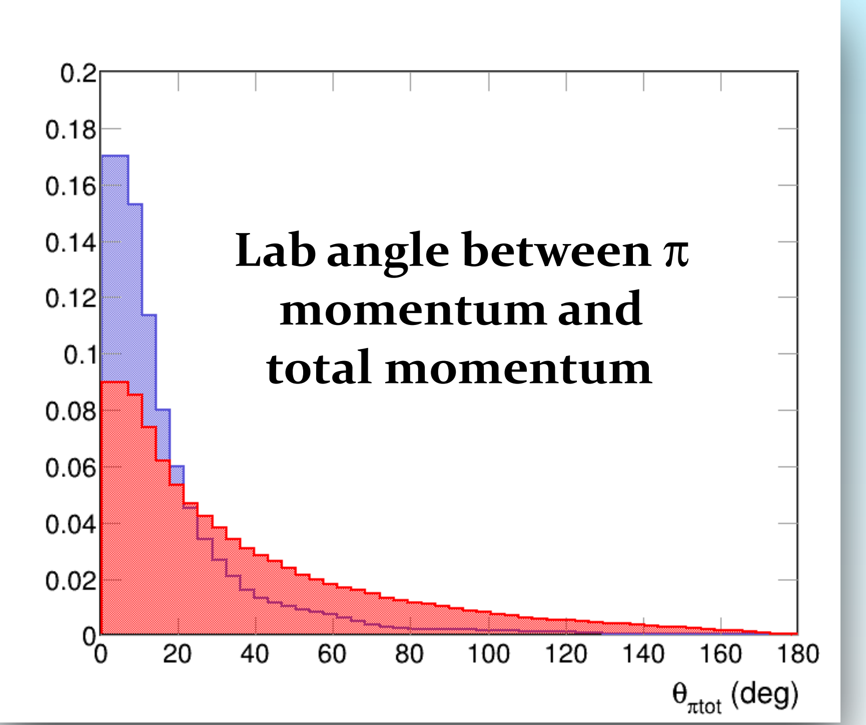
The main background is composed of Neutral Current interactions with at least 1π in the final state. For this background we apply the previous Medal Game ranking method, and build Probability Density Functions for the background.
For the signal we directly use the MC truth to identify the π of the τ decay (corresponds to 94% of cases).

- 14 kinematic variables are used to build the p.d.f:
  - The 3 used for the π Medal Game.
  - 4 lab angles between the π momentum, hadronic momentum, beam direction and total final state momentum.
  - 3 transverse plane angles (missing, π and had. momenta)
  - 3 transverse momenta moduli
  - Transverse mass defined as $M^{(tr)} = 2\sqrt{p_{\pi}^{(tr)} p_{miss}^{(tr)}} \left| \sin\left(\frac{\phi_{m\pi}^{(tr)}}{2}\right) \right|$

**Blue: ντ (signal), true t—>p || Red: NC1π (background), best π candidate**



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# Log-likelihood ratio distributions

Searched for optimized combination of previous variables, which allowed for a good S/B discrimination.

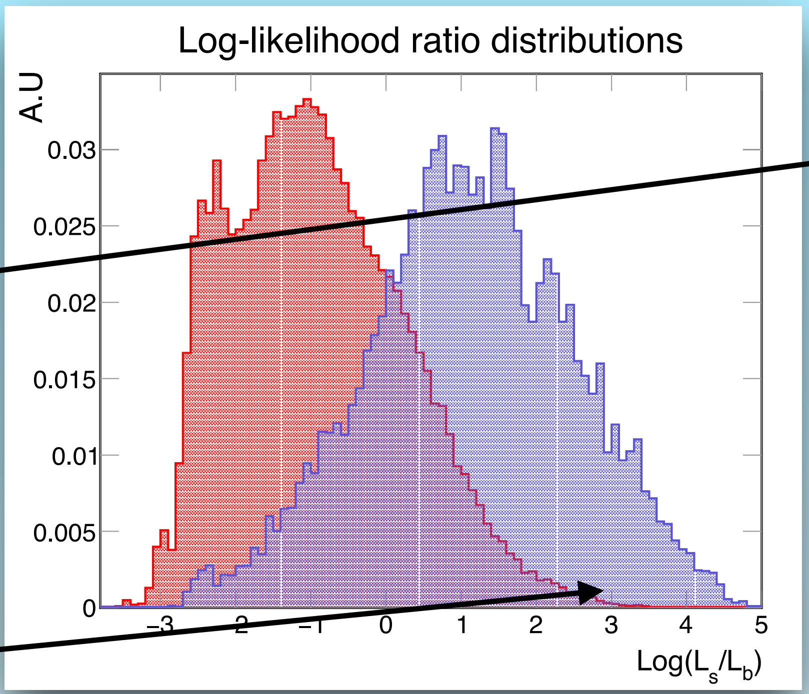
Used the 2-dimensional distribution of **pion kinetic energy and pion-had energy sharing** combined with a 2-dimensional correlation of **lab angles**, combined with **transverse π momentum**.

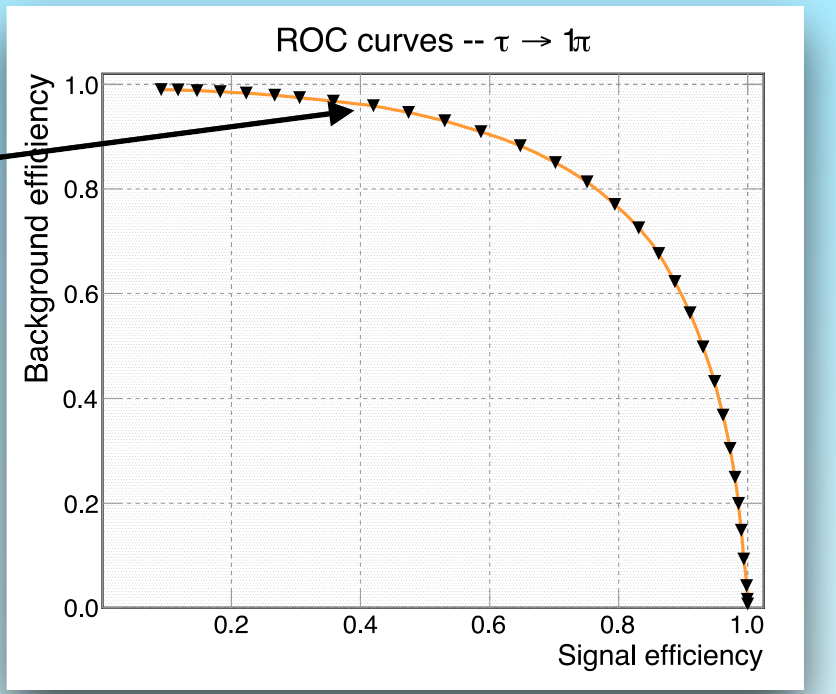
$$\left[\theta_{\pi tot};\theta_{h\pi}\right]$$

## Results:

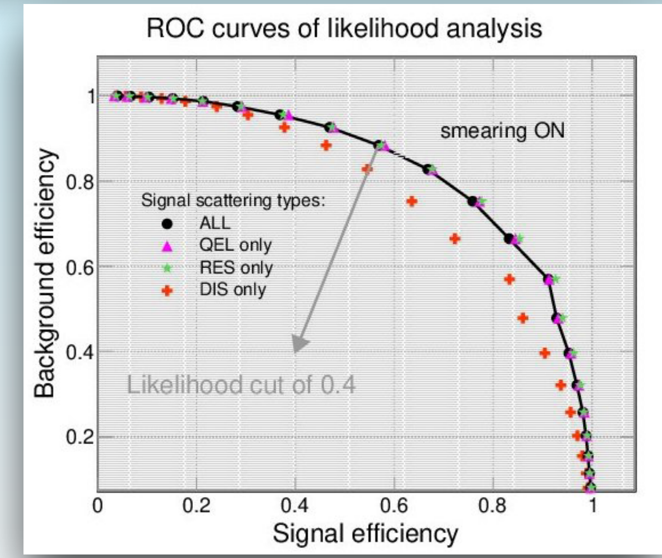
Rather impressive separation power ! More than 95% of background rejection for 40% sigal efficiency

Possibility of finding very low background regions.




As for comparison, remember the ROC curve for the τ—>ρ search:




**Promising decay mode !**



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# But… normalisation to 3.5 years staged (TDR-like)

We should weight the excellent discriminating power previously showed with the high NC background rate.

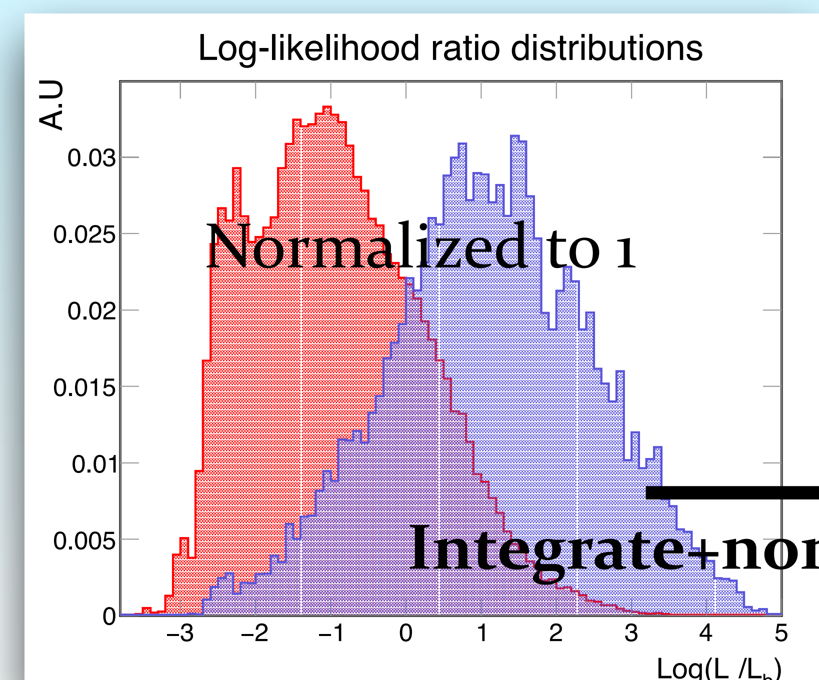
| | density = 2.8 g.cm$^{-3}$ | Shen-Ritzwoller | Crustal |
|---|---|---|---|
| $\nu$ mode | | | |
| $\nu_e$ from osc. | 1197 (564) | 1207 (555) | 1202 (559) |
| $\bar{\nu}_e$ from osc. | 18 (29) | 18 (30) | 18 (30) |
| $\nu_e$ from beam cont. | 365 (371) | 365 (372) | 365 (371) |
| $\bar{\nu}_e$ from beam cont. | 57 (56) | 57 (56) | 57 (56) |
| $\nu_\mu$ | 9660 (9674) | 9659 (9675) | 9660 (9675) |
| $\bar{\nu}_\mu$ | 741 (732) | 741 (732) | 741 (732) |
| $\nu_\tau$ from oscillation | 270 (290) | 270 (290) | 270 (290) |
| $\bar{\nu}_\tau$ from oscillation | 25 (26) | 25 (26) | 25 (261) |
| NC | 8228 (8228) | 8228 (8228) | 8228 (8228) |

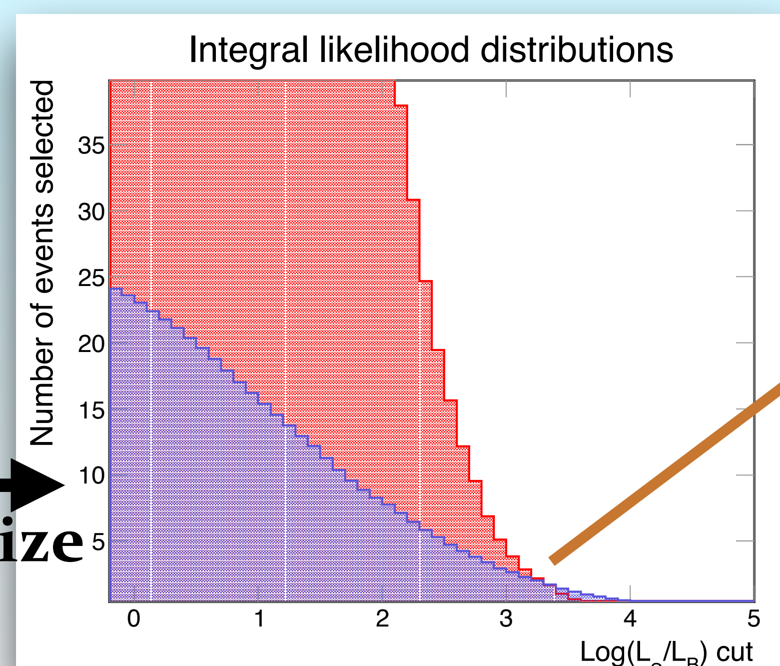
Expected number of events:

- 10.83% * 270 = **29 signal events**
- 47.2% of NC have at least 1$\pi$ in the final state, and participate to the effective background. 8228 * 0.472 ~ **3880** !!

Initial S/B of 0.8%

**Consequence**: the nice discriminating power is eaten by the large amount of background compared to signal.




**S/B reaches 1 after it remains about 2 signal events (efficiency selection of about 5%)**

**Cut at 3 rejects 99% of background**



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# Improve S/B - QEL like events ?

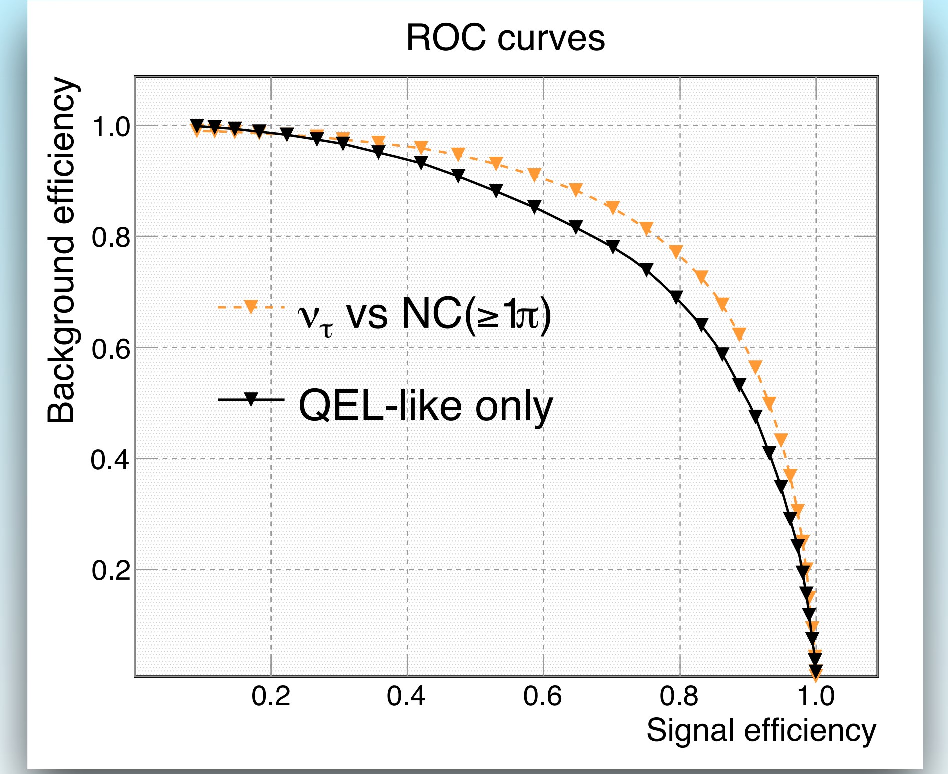
- For the $\tau \rightarrow \rho$ analysis I had observed the likelihood performed less well on DIS events. We may improve the S/B by requiring exclusive final states, as $1\pi^{\pm}1p$, like in $\nu\tau$ QEL events.

We observe that:

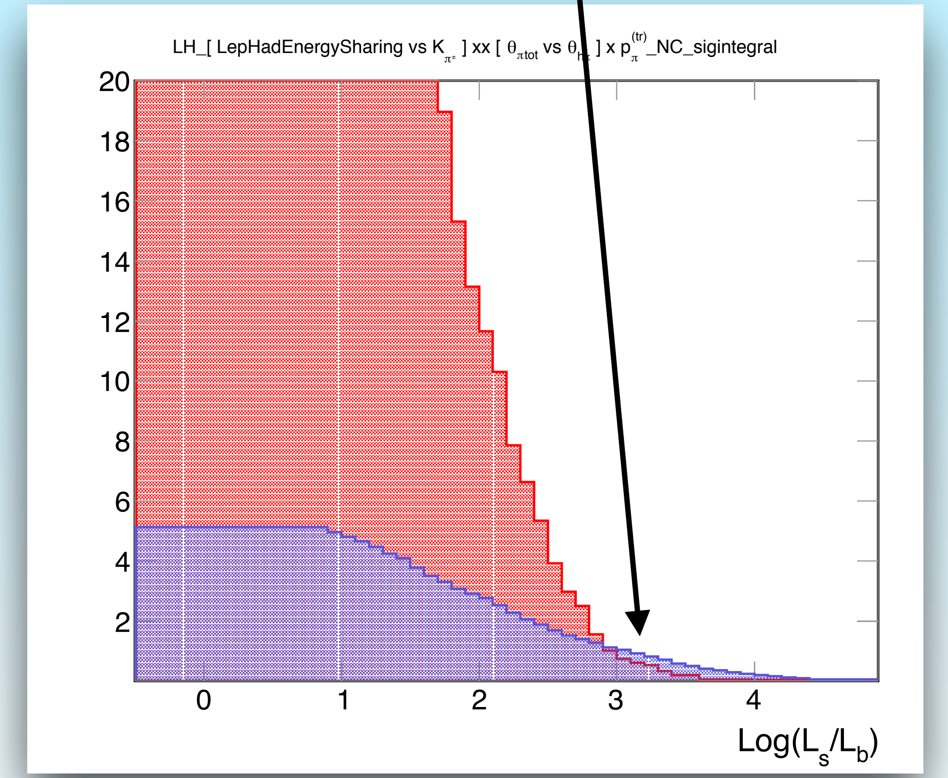
- About 27% of the $\nu\tau$CC have QEL-like topology (while 46% of $\tau$ events are actual QEL at the generator level). There is a contamination of non-QEL events at the height of 2%.
- About 12% of NC(>1$\pi$) have a QEL-like topology.

The new initial S/B is **8/459 .**

**The likelihood performs less well on the QEL-like subsets.**




**Not clear improvement of the S/B in the low background region. S/B~1 for about 1 signal event.**



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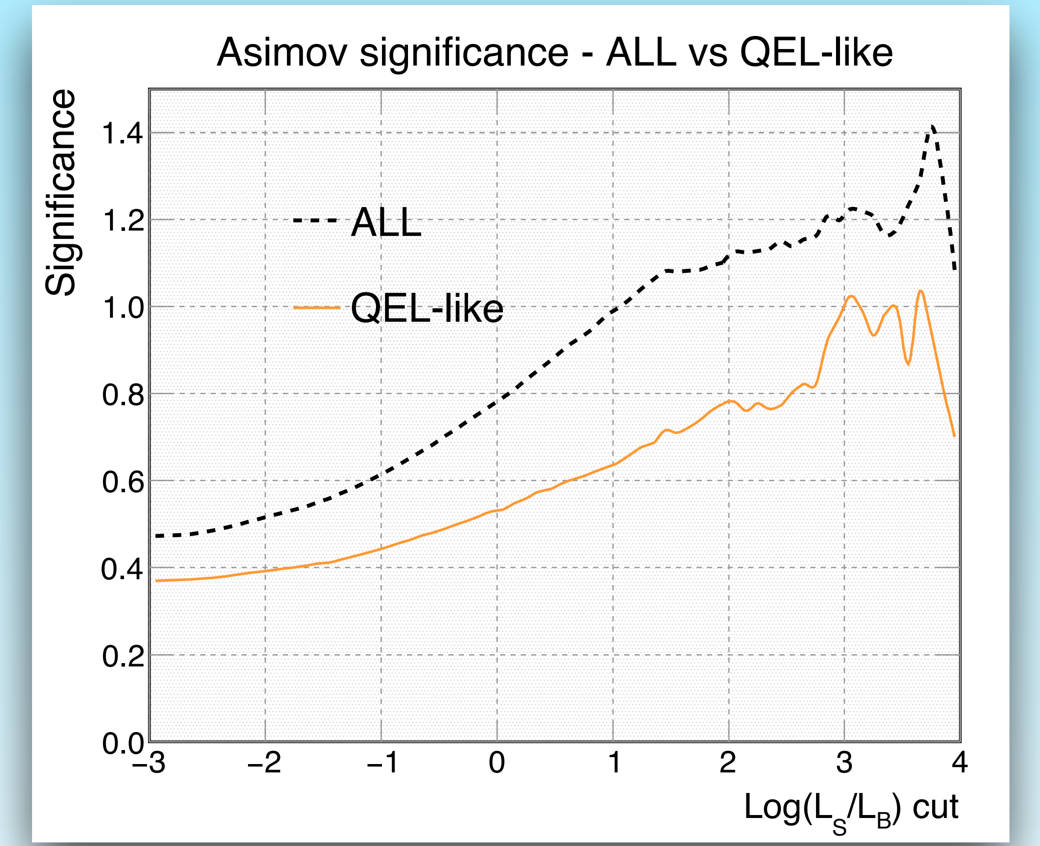
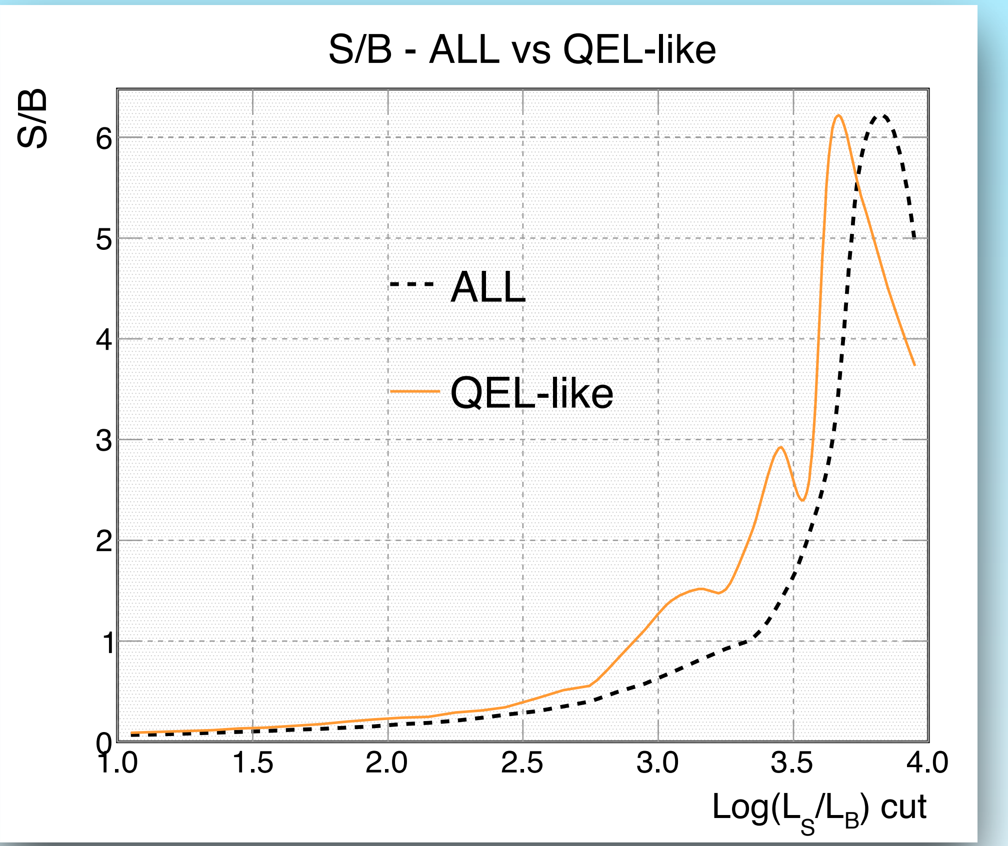
# S/B and significance - QEL-like

- Asimov significance better than S/sqrt(B) for low S and B

$$Z_A = \sqrt{2\left((S+B)\ln(1+\frac{S}{B}) - S\right)} \xrightarrow{S \ll B} \frac{S}{\sqrt{B}}$$




- Can also display the signal/background ratio




- Lower significance with QEL-like condition (left plot), and S/B ratio not improved (right plot).



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# Conclusion

- I extended the $\tau \longrightarrow \rho \longrightarrow \pi^- \pi_0$ analysis to the exclusive $\tau \longrightarrow 1\pi$ decay mode.

- A likelihood approach can achieve a nice separation power (40% signal efficiency for 4% background contamination, so S/B = 10).

- However this large separation power is absorbed by the low signal (10.83% BR) and the large background (about half of NC have at least one charged pion in the final state) expected at the DUNE FD.

- **Not discussed here**: we can expect a slight improvement if we add the charged pion identification, not done yet.


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# Back up



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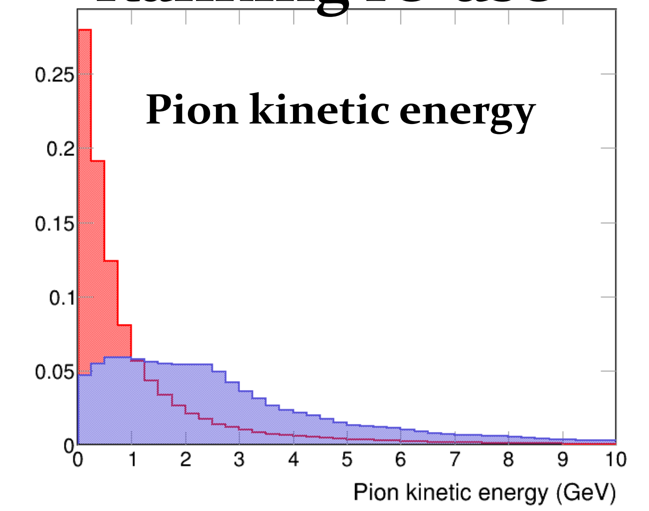
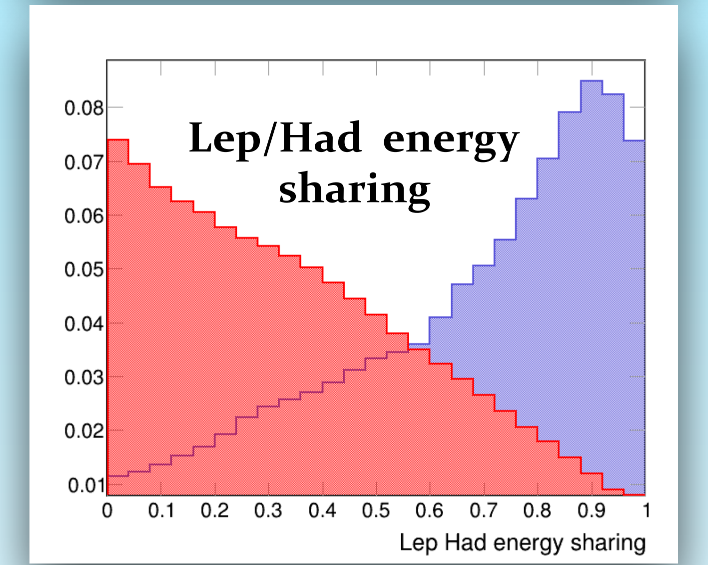
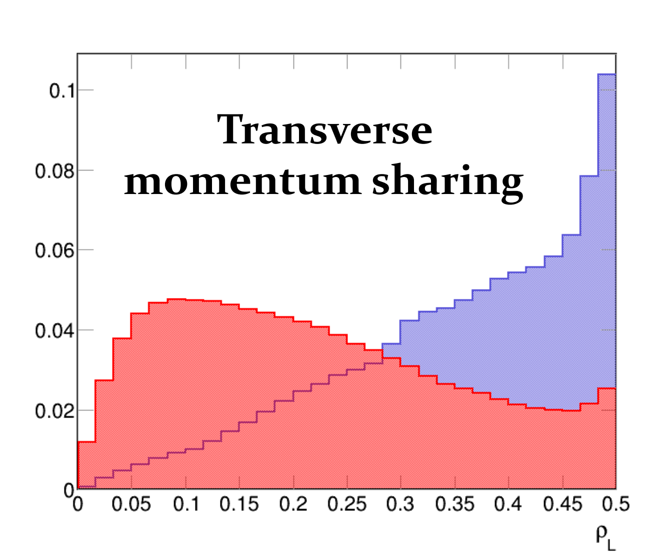
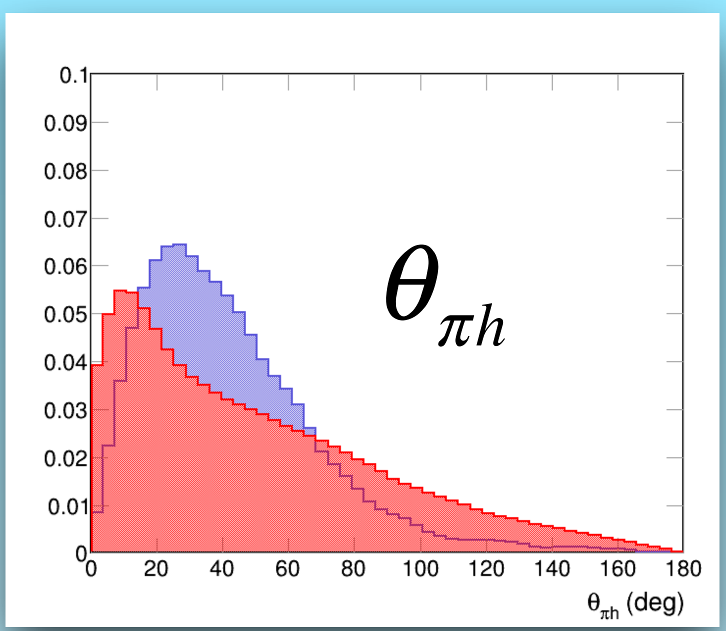
# Kinematic distributions - (I) !

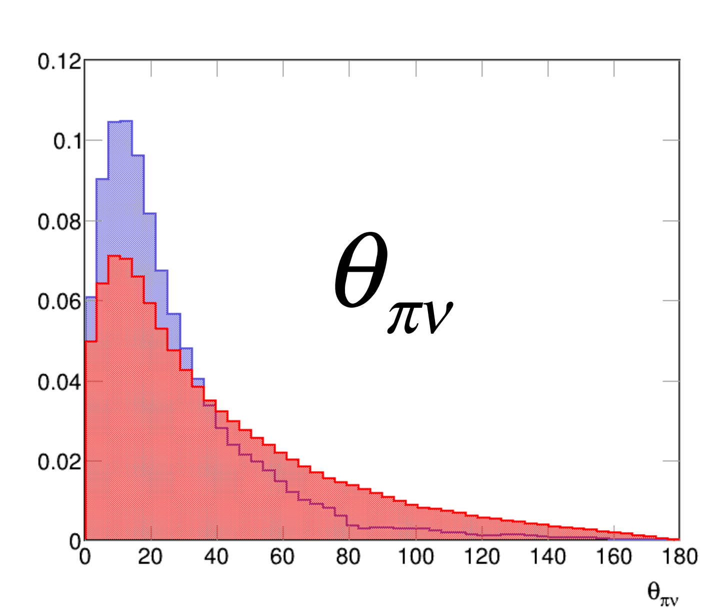
## Ranking re-use

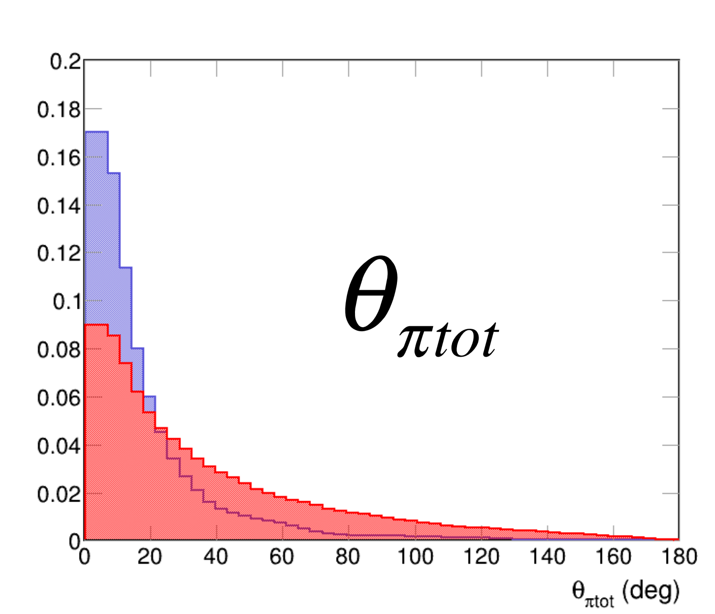


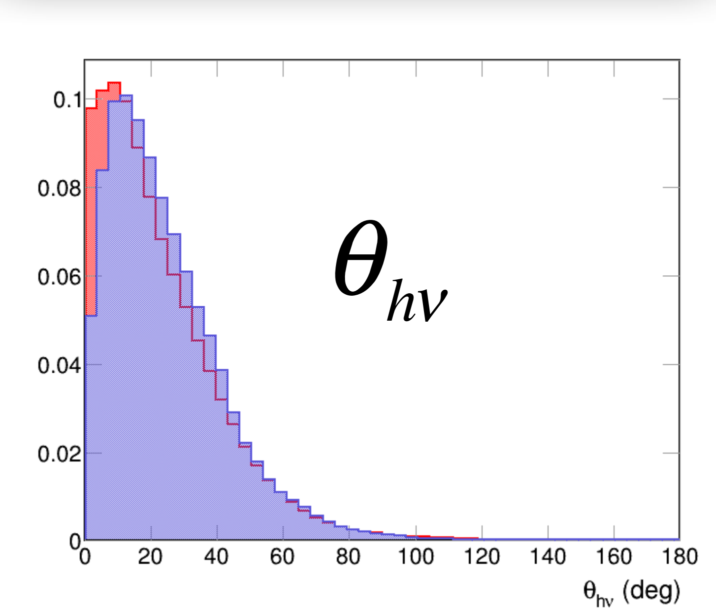




**Lab angles**



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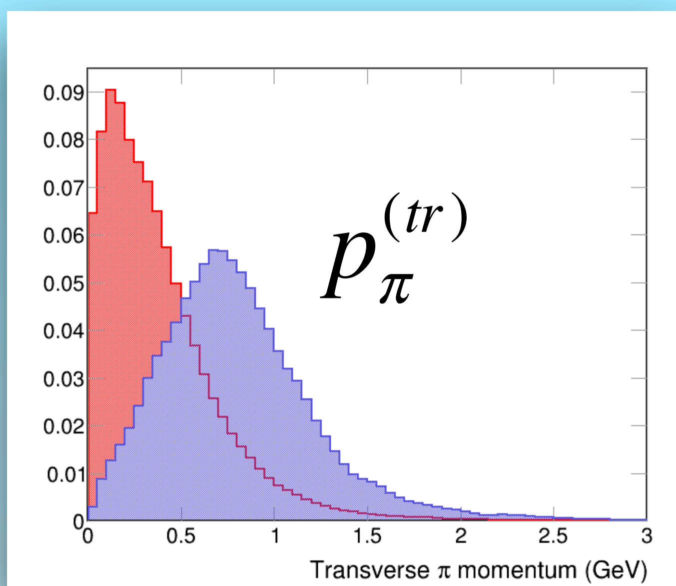
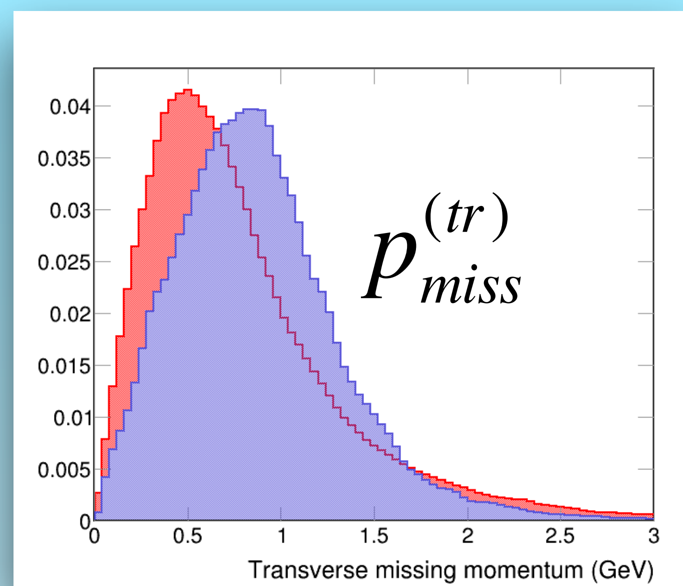
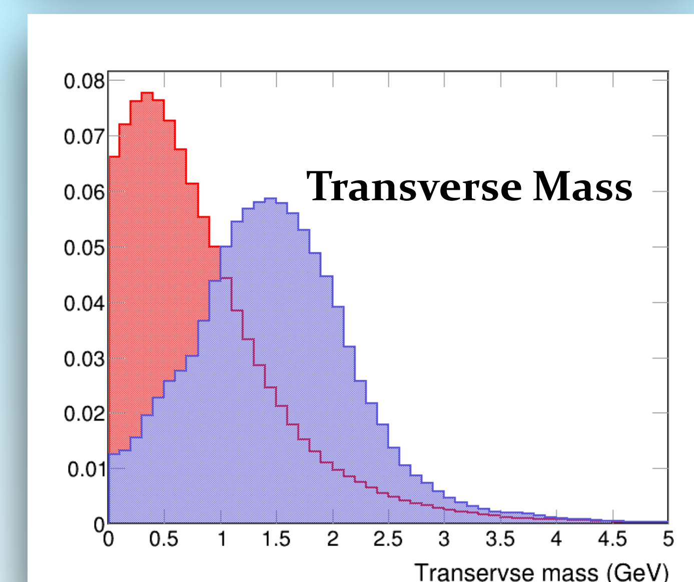
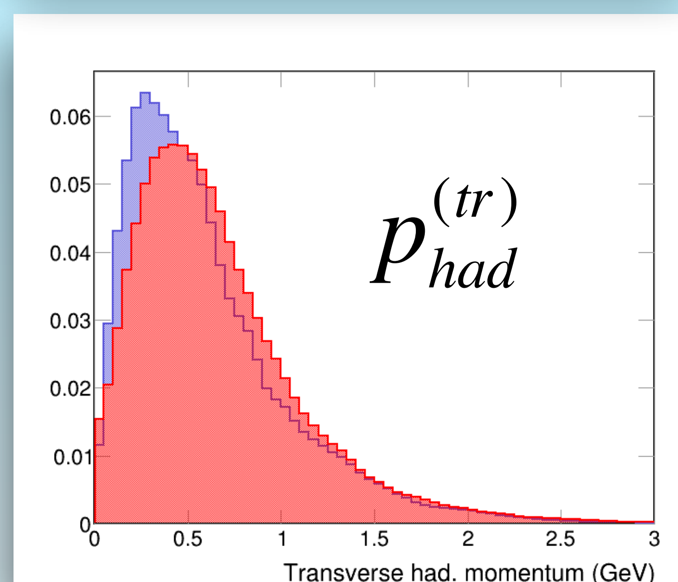
# Kinematic distributions (II) !



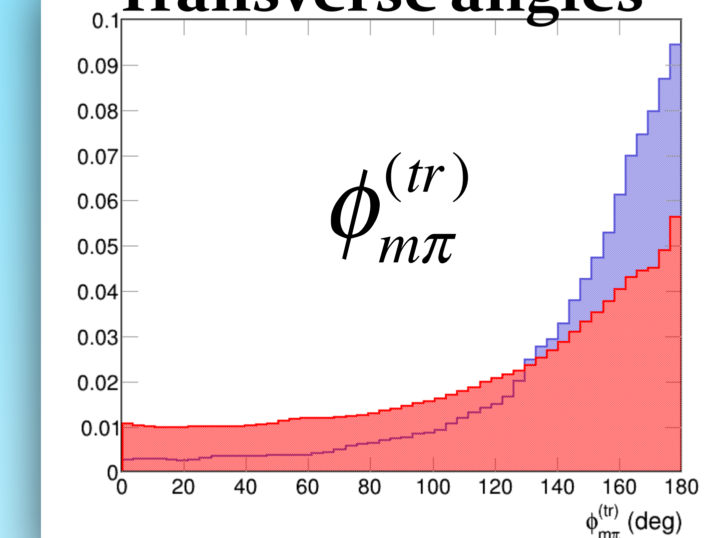



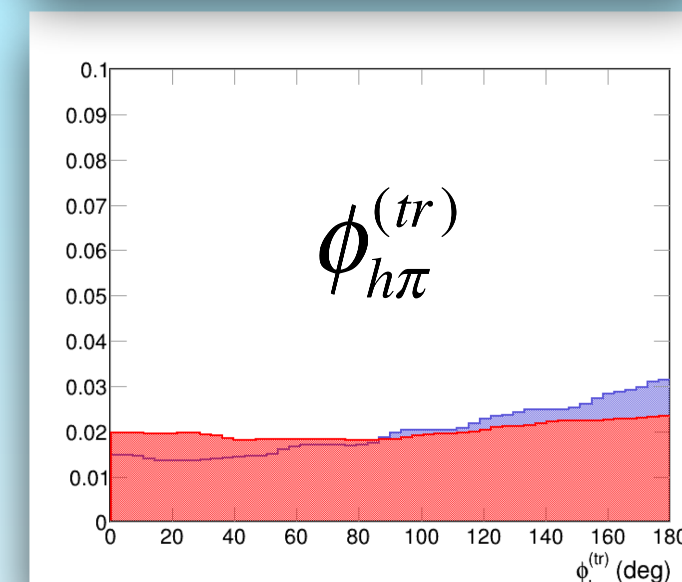



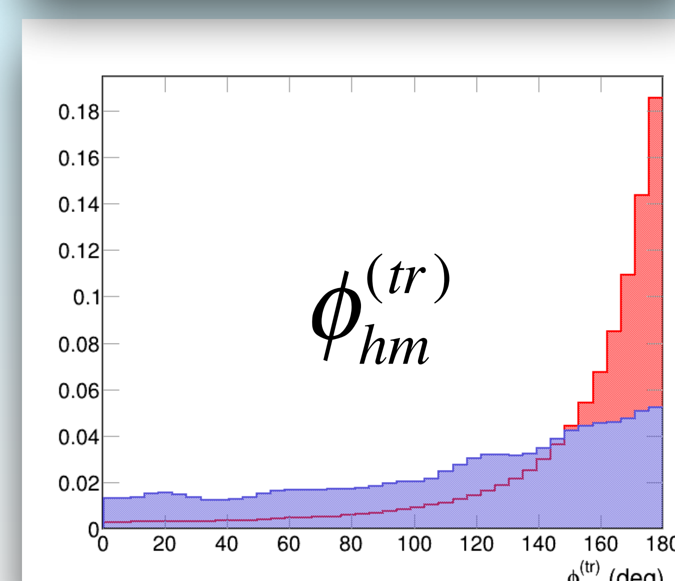




## Transverse momenta and mass

## Transverse angles



# Detector effects: Smearing

| Particle | Detection Threshold (MeV) | $\sigma$ | Angular Resolution (°) |
|---|---|---|---|
| $\mu^{\pm}$ | 30 | / | 1 |
| $e^{\pm}$, $\pi^0$, $\gamma$ (electromagnetic showers) | 10 | $\sqrt{(0.02)^2 + \frac{(0.15)^2}{E[\text{GeV}]}}$ | 1 |
| Protons | 50 | if survives: 10%<br>if interacts: $\sqrt{(0.05)^2 + \frac{(0.30)^2}{E[\text{GeV}]}}$ | 5 |
| $\pi^{\pm}$ | 20 | if survives: 5%<br>if interacts: $\sqrt{(0.05)^2 + \frac{(0.30)^2}{E[\text{GeV}]}}$ | 1 |
| Neutrons | 50 | if detected: $\frac{0.4}{\sqrt{E[\text{GeV}]}}$ | 5 |
| Others | 50 | $\sqrt{(0.05)^2 + \frac{(0.30)^2}{E[\text{GeV}]}}$ | 5 |

- For protons and charged pions, given their true energy, we compute their range and compare it the interaction range of proton in liquid argon (https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html). Interaction length of protons in argon is 85.7 cm.
  Survival probability = exp(-R/Rinteraction), then generate a random number in [0;1] to decide whether the hadron survives.

- Electrons, neutral and pions and photons: EM shower reconstruction (https://arxiv.org/abs/0812.2373)

- Neutrons: 10% chance to go undetected.



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