DEEP UNDERGROUND NEUTRINO EXPERIMENT

Kinematic τ neutrino search at DUNE far detectors

Workshop on Tau Neutrinos from GeV to EeV 2021 (NuTau2021)

-

29th September 2021

Thomas Kosc - kosc.thomas@gmail.com,
PhD student supervised by D. Autiero

Motivations

- Growing interest concerning the DUNE sensitivity to ν_μ—>ν_τ appearance at the DUNE far detectors. Expected ~30 CC beam ν_τ / 10kTon / year with the standard LBNF neutrino beam (*https://home.fnal.gov/~ljf26/DUNEFluxes/)*

- Current data: 9 from DONUT (2008), 10 from OPERA (2018), +T2K and IceCUBE —> 18 directly observed candidates.

Physics motivations (see for instance 10.1103/PhysRevD.100.016004)**:**

- Cross section measurement (leptonic universality)
- Test of the 3 massive neutrino paradigm
- Unitarity test of the PMNS matrix
- Sterile neutrino research

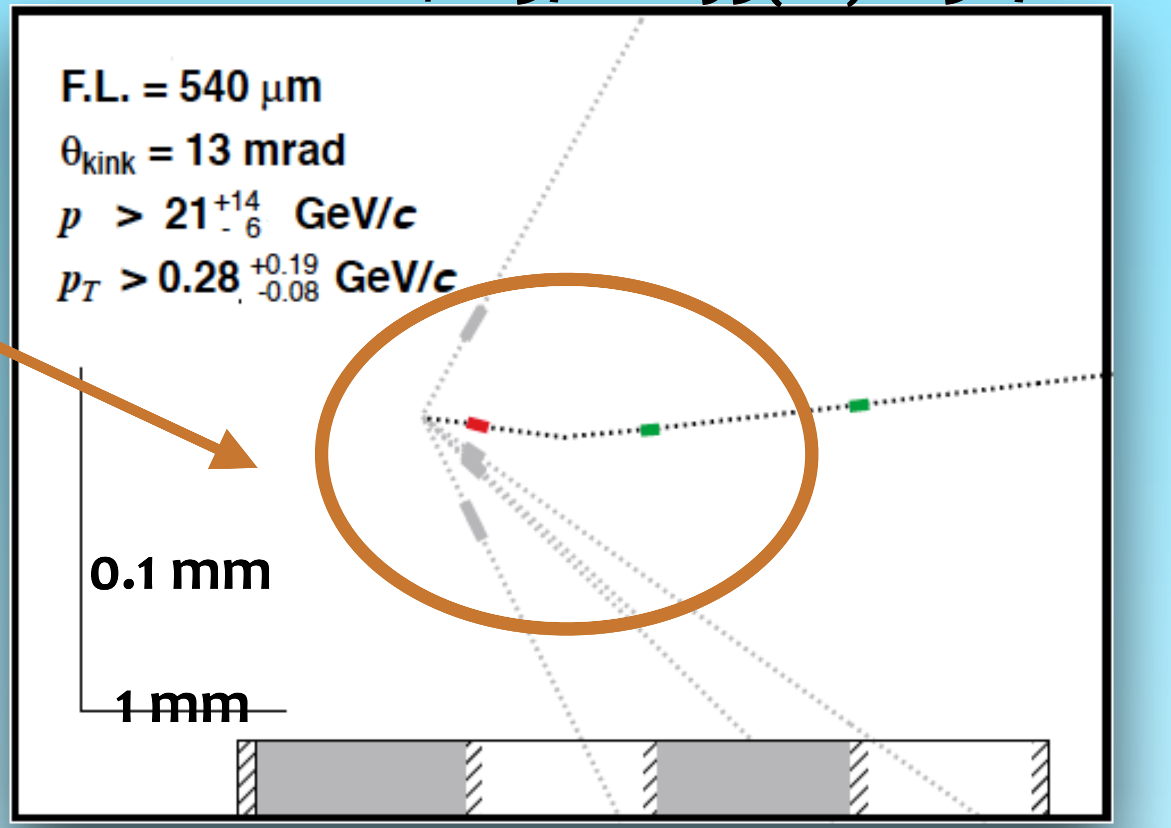
- However lack of assessement of the ν_τ identification performance. Purpose of this talk. See also **PhysRevD.102.053010**

- NuTau 2021 workshop exist for this purpose !!

"À la NOMAD"

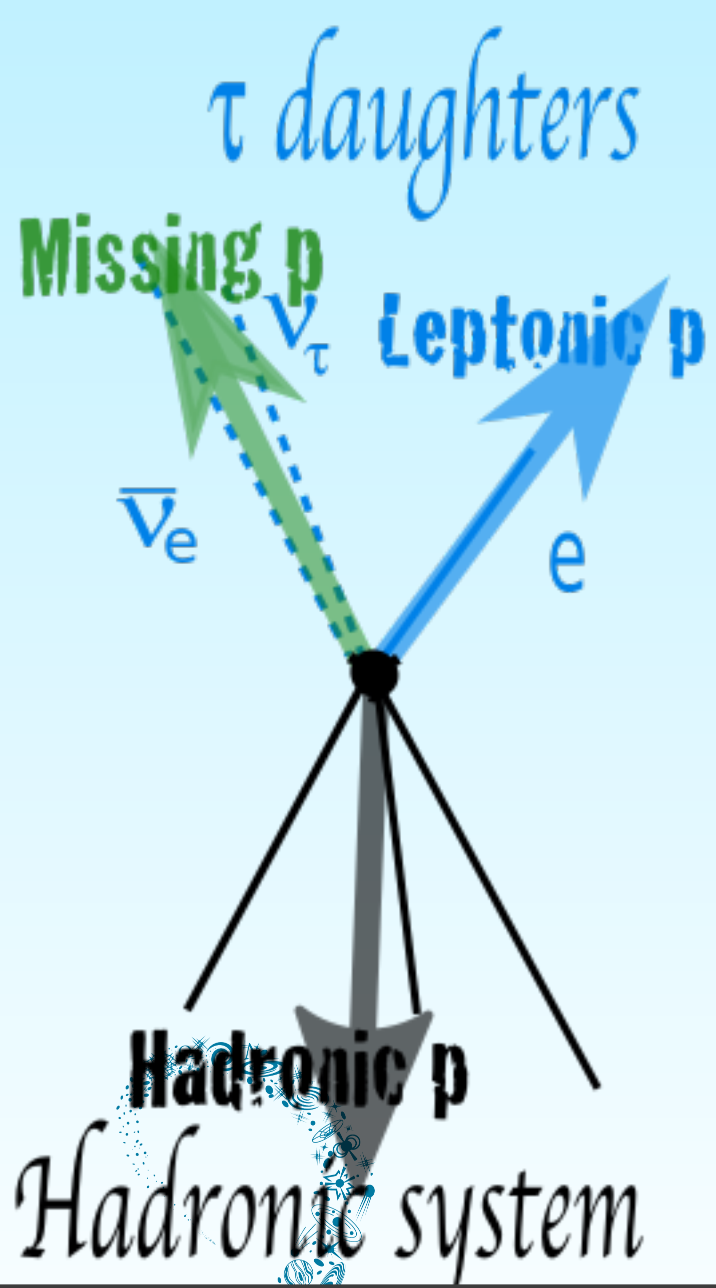
- The τ decays too promptly to allow for a direct search of the kink in DUNE (τ decay signature)

DONuT - 10.1016/S0370-2693(01)00307-0



- **Shrock and Albright** proposed in 1979 (***10.1016/0370-2693(79)90665-8***) to use kinematic methods to detect τ neutrino in beam experiments.
—> Exploit **large missing momentum** in the transverse plane due to the two undetected neutrinos for the leptonic decay modes, and angular correlations **(see Dario's talk)**.

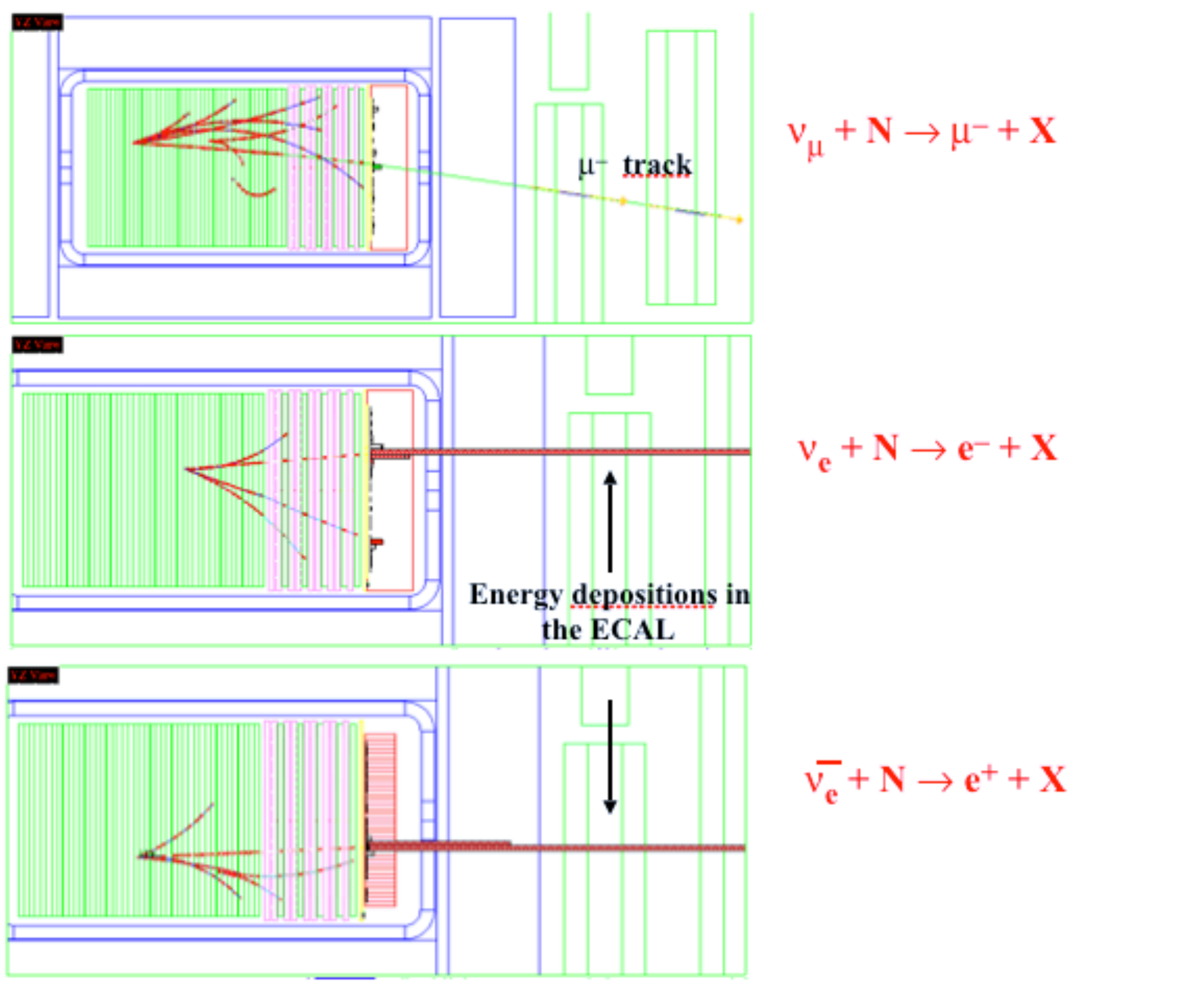
ν_τ + Ar —> e- + 2ν + X



- Idea largely exploited by NOMAD, short baseline neutrino experiment (820 m) which search for short νμ —>ν_τ apperance in the 90's with the SPS wide neutrino beam.

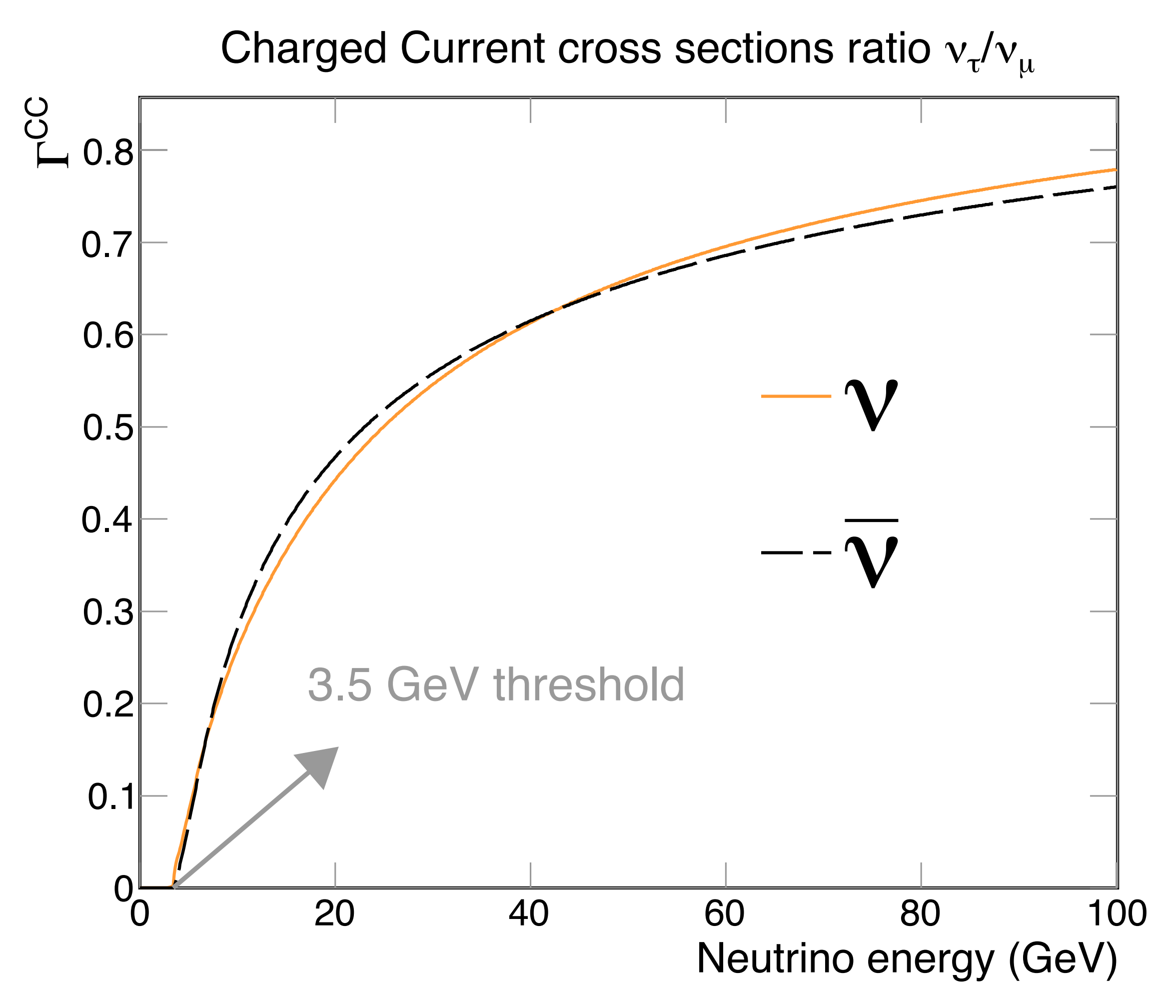
- No appearance found, greatest constraint on ν_μ—>ν_τ short baseline oscillations, with p<10^(-4)

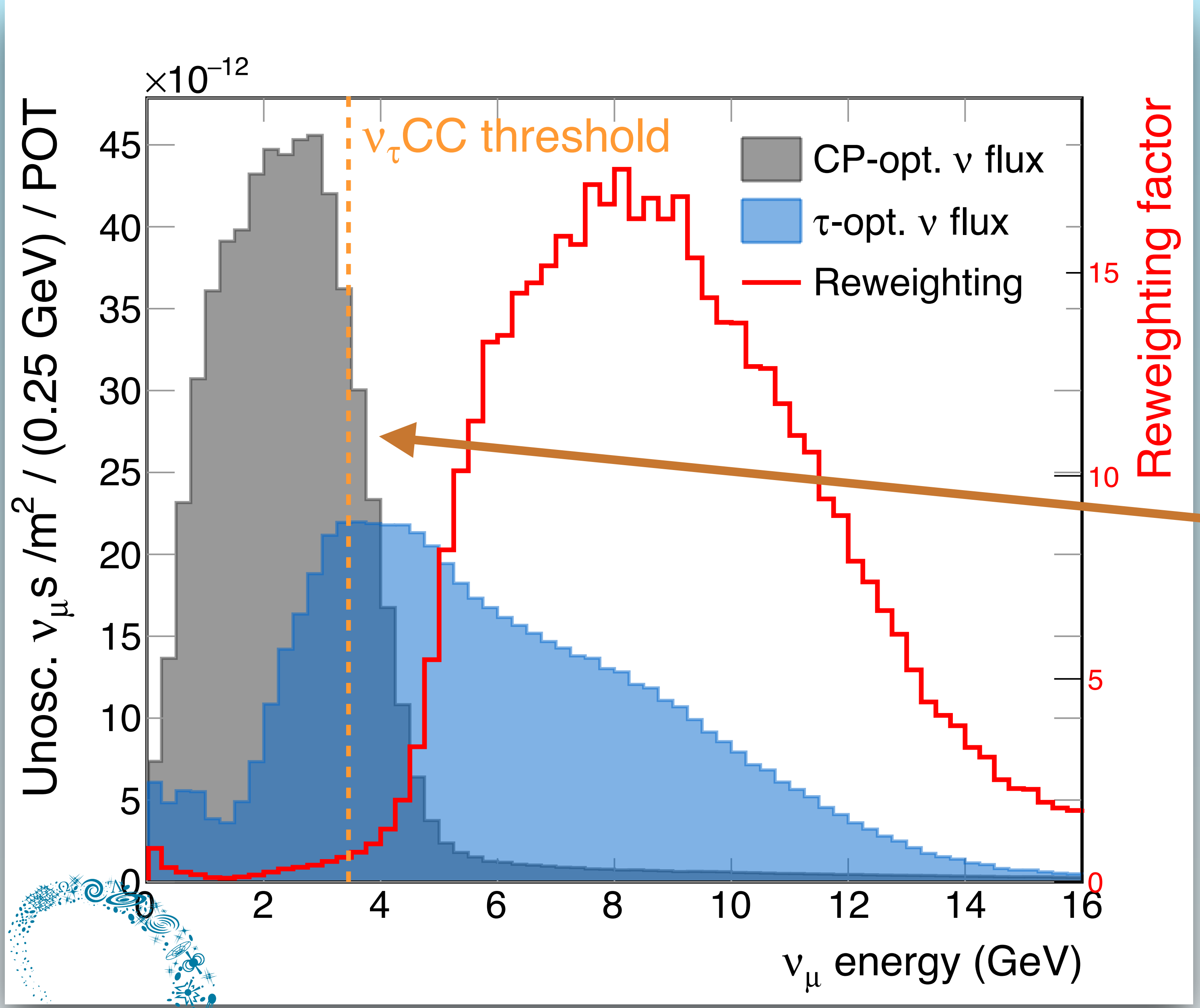
- NOMAD SBL experiment (1994-1998)
« Electronic bubble chamber »
- Magnetic spectrometer / calorimeter with excellent energy resolution at single particles level and electron identification
- fully reconstructed 1.7 M neutrino interactions



τ optimized flux

- Charged τ lepton has a high mass (1.8 GeV). Consequence:
  - QEL ν_τ interactions have a high threshold (3.45 GeV). ν_μ threshold is 0.11 GeV. High fraction of oscillated ν_τ will not produce charged current interactions.
  - Cross section suppressed at DUNE neutrino beam energies.





- Main scientific program of DUNE (oscillations) requires the use of the CP-optimized flux. Alternative beam configuration envisageable after several years of running.
  - 79% of neutrino have energy below the ν_τCC threshold in the CP-optimized configuration
  - Only 23% with the τ-optimized configuration
  - High energy events are disfavoured by $P(\nu_\mu \rightarrow \nu_\tau)$ but largely favoured by cross section. **Factor of 6 in ν_τ statistics** !

Method

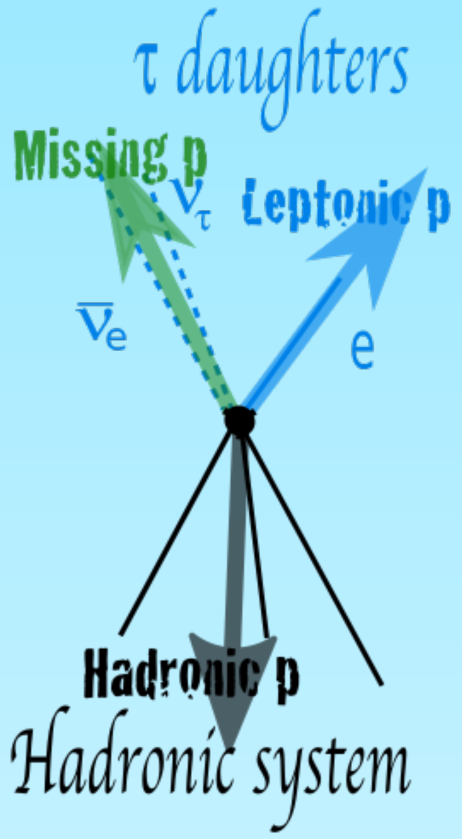
1 τ decay mode = 1 dedicated analysis

- Oscillation parameters fixed to the TDR values (arXiv:2103.04797). Re-use the simulation files produced for the TDR and assess the capability to isolate a sample ν_τ candidates.
- 1.2 MW & beam operating in neutrino mode
- Detector effects taken into account via a **smearing method** (see back-up). Assume 100% particle identification.
- Use the truth at the generator level (genie_record) to produce kinematic distributions of signal (ν_τ) and background (ν_μ, ν_e, NC).
- Produce log-likelihood ratio distributions for signal and background. Normalize to DUNE expected number of events, refer to the 3.5 years staged development plan (equivalent to 10 years with one module).

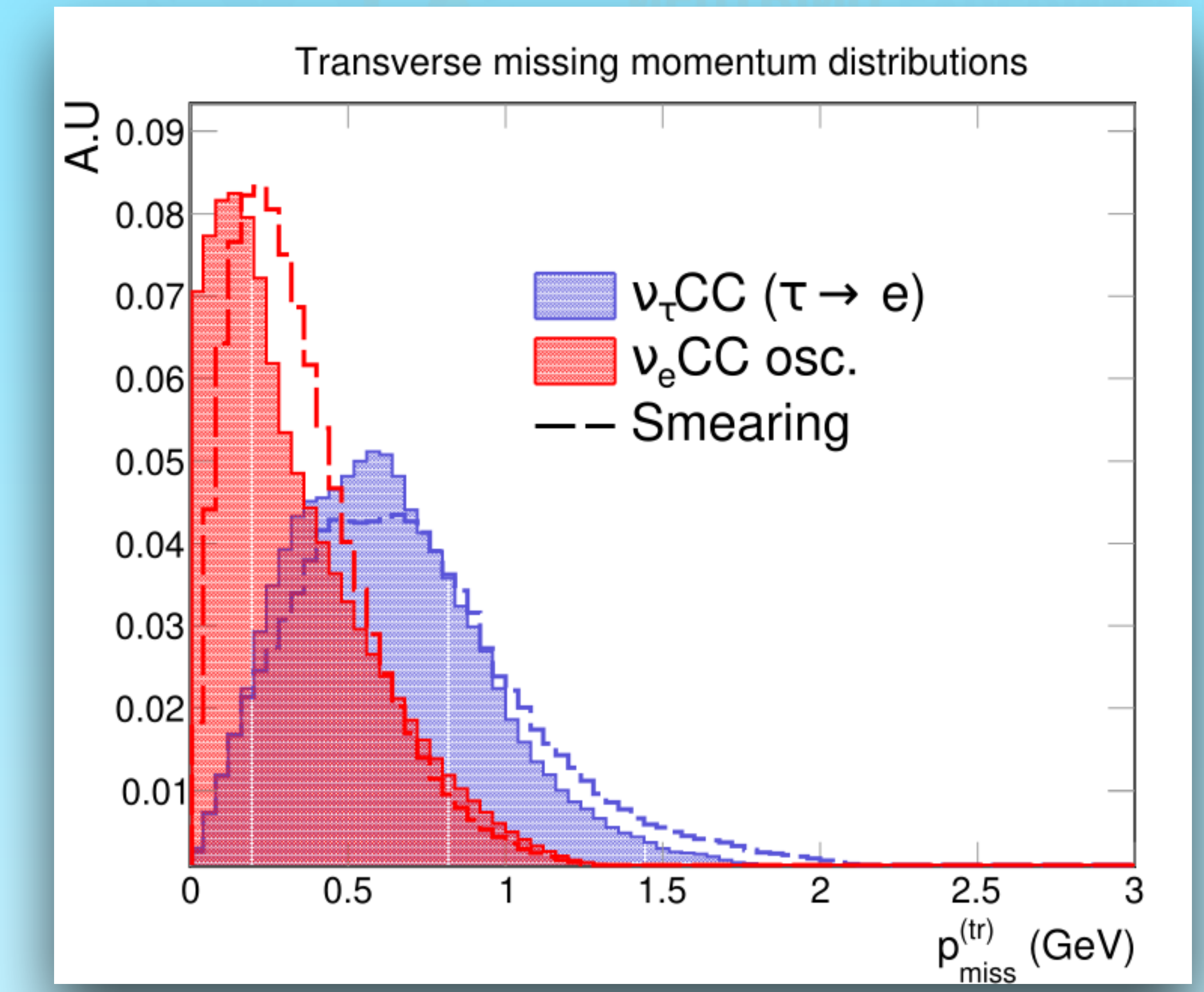
τ—>e analysis (I)

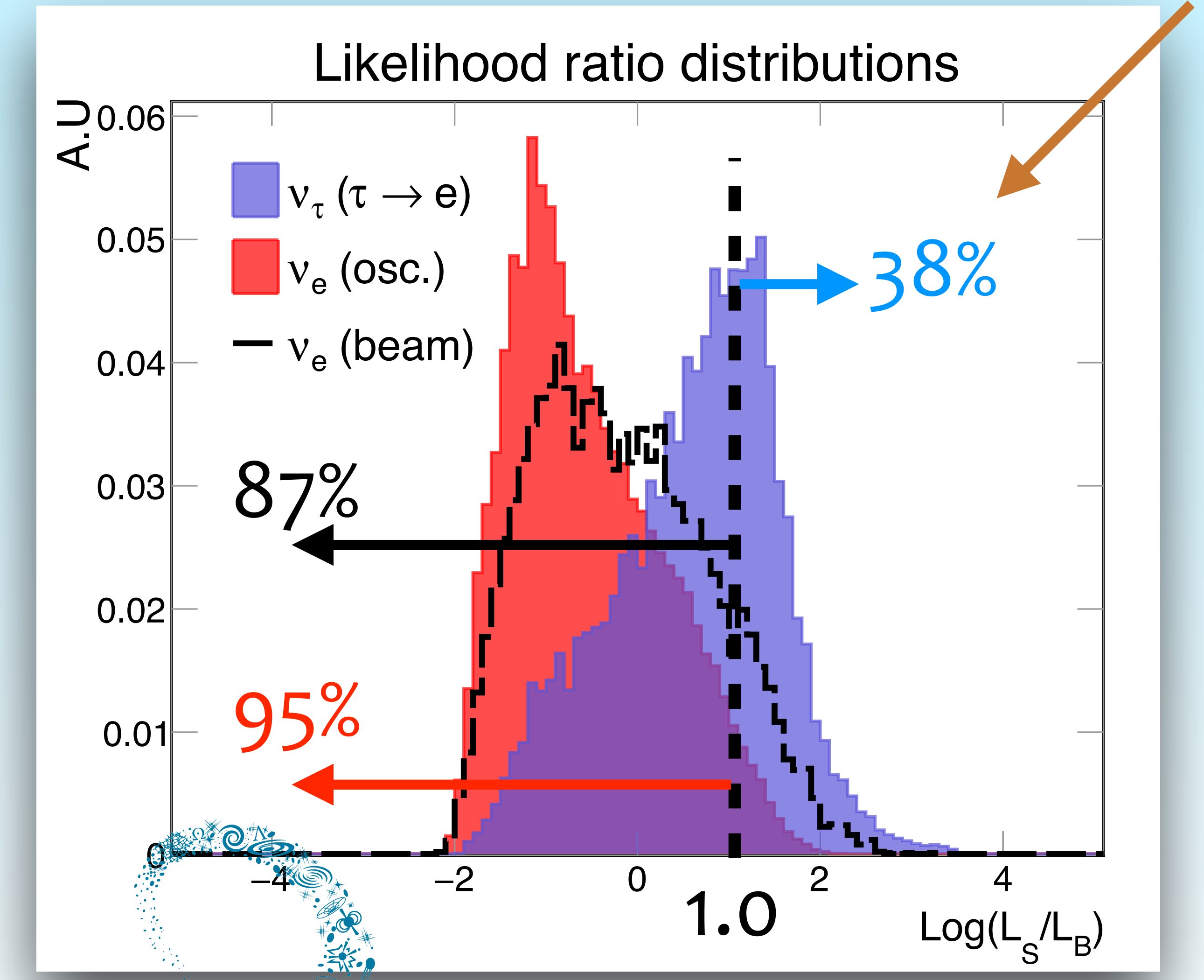
Signal = ν_τ (τ—>e) || Backgrounds = ν_e (osc. + beam)

ν_μ—>ν_e ν_e—>ν_e



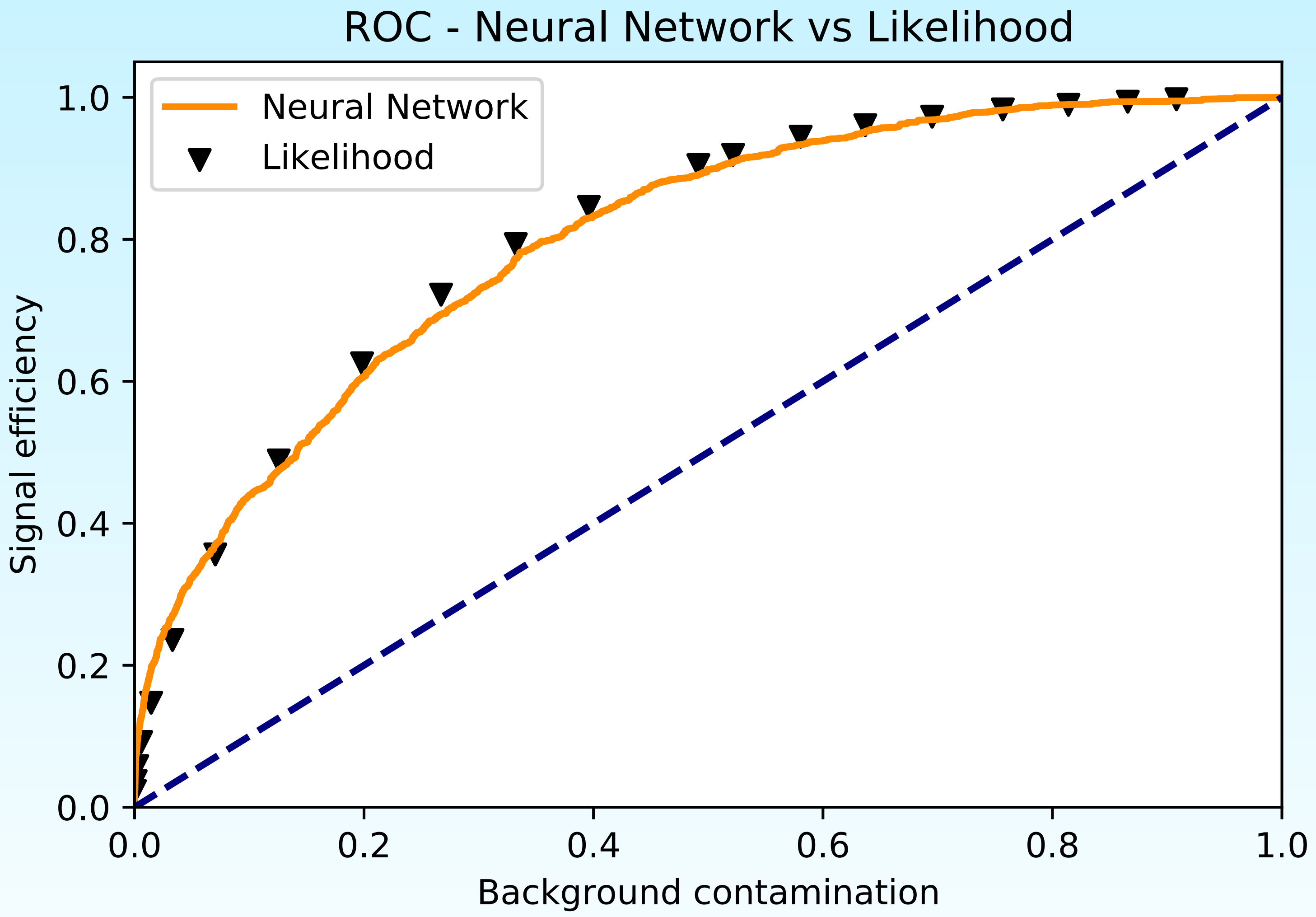
- Transverse missing momentum has **powerful separation power**. Use also hadronic and leptonic momenta and the 3 angles of the plane. 6 variables in total (see back-up).
- Irreducible missing momentum for νe due to final state interaction, Fermi momentum, neutrons …
- Corresponding log-likelihood distributions. 38% signal efficiency for 95% oscillated νe rejection and 87% beam ν_e rejection (harder separation because they have higher energy).





- Analysis repeated also with **machine learning techniques.**
- Artificial Neural Network (Tensorflow keras) and BDT (TMVA toolkit) didn't improve the likelihood S/B separation results, even in the most favorable case without smearing applied.

Samples S&B size: 30000 events

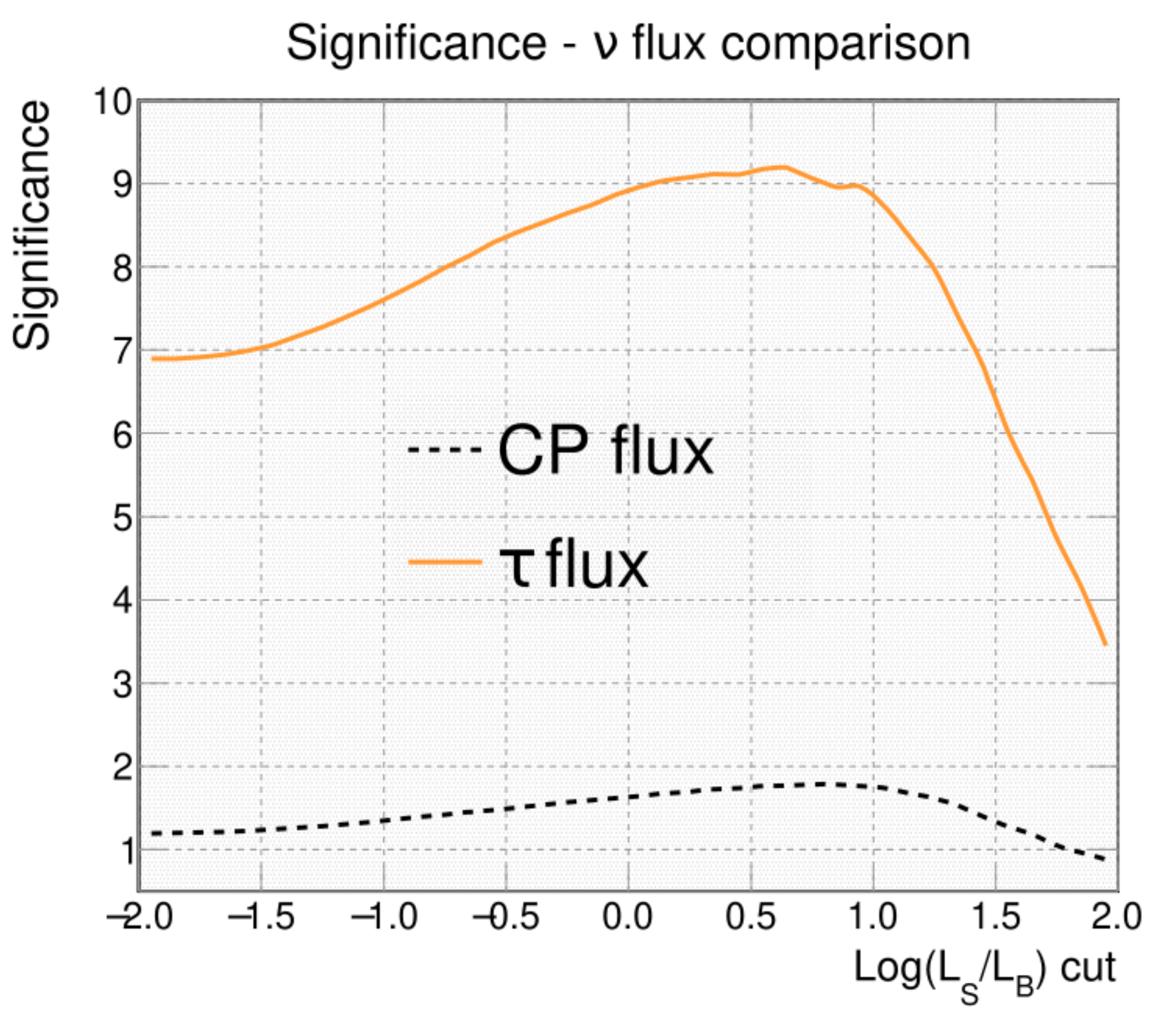


τ—>e analysis (II)

Signal = ν_τ (τ—>e) || Backgrounds = ν_e (osc. + beam)

	CP optimized flux	τ optimized flux
ν mode		
ν_e from osc.	1197	1199
$\bar{\nu}_e$ from osc.	18	11
ν_e from beam cont.	365	543
$\bar{\nu}_e$ from beam cont.	57	56
ν_μ	9660	37673
$\bar{\nu}_\mu$	741	683
ν_τ from oscillation (QEL/RES/DIS)	270 (124/62/70)	1658 (531/597/448)
$\bar{\nu}_\tau$ from oscillation	25	22
NC	8228	17564

- Significant improvement using the τ **optimized flux:**
  - ν_e from oscillations ~ constant
  - ν_e from beam contamination x1.5
  - ν_τ **statistics x6 !**
- Initial S/B gets a factor of 4 !



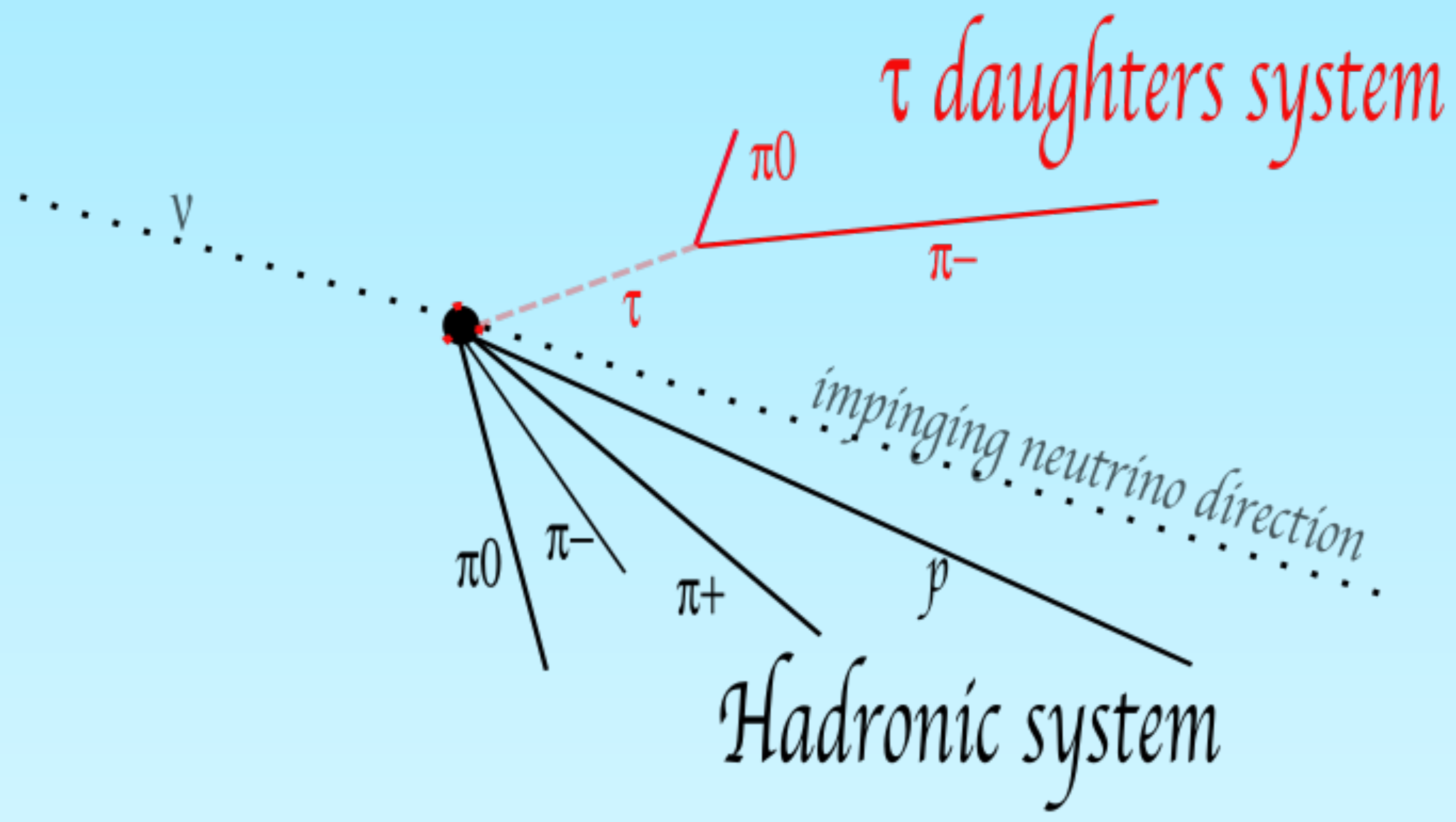
- The likelihood was found to perform slighly less well with the alternative configuration beam. However the Asimov significance (plotted as a function of the log-likelihood cut value used), 3.5 years staged normalized is **boosted (from 2 to 9 at corresponding maxima).**
- Corresponding number of events for the τ optimized beam:

log-LH cut	0.6	1.0	1.6
ντ signal	151.6 ± 1.2	98.2 ± 1.0	23.8 ± 0.7
νe (osc.)	143.6 ± 0.5	60.0 ±0 .3	6.1 ± 0.1
νe (beam)	82.3 ± 2.0	38.1 ±1 .4	6.6 ± 0.6
νe (total)	225.9 ± 2.1	98.1 ± 1.4	12.7 ± 0.6

$\tau^- \longrightarrow \rho^- \longrightarrow \pi^-\pi_0$ (I)

Signal = ν_τ ($\tau \longrightarrow \rho$) || **Background**= NC ($\geq 1\pi^\pm \geq 1\pi_0$).

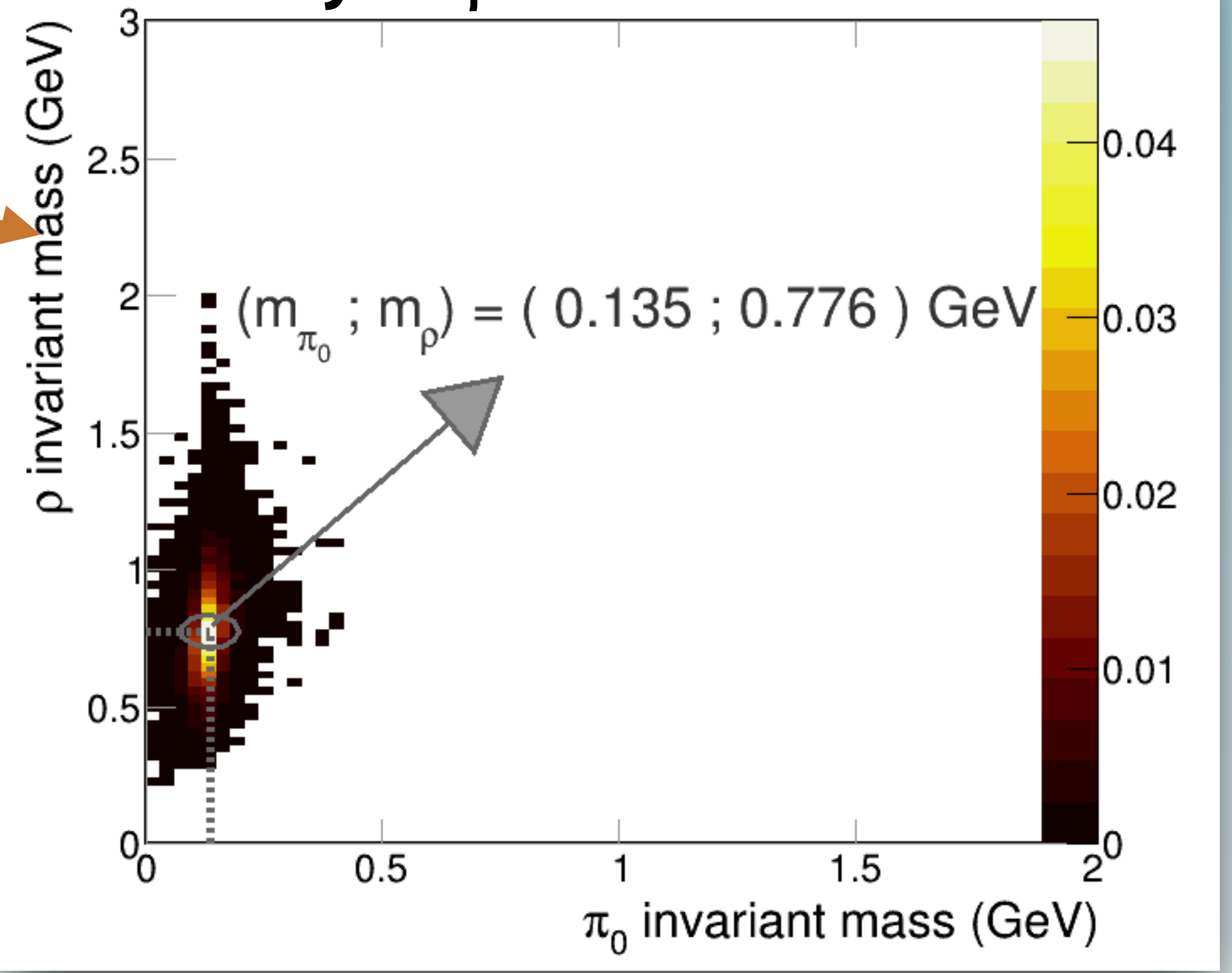
- **Large branching ratio** (25.49%), kinematic signature of the ρ resonance with **invariant masses** (ρ and π0).
- **N.B:** in this analysis neutral pions are decayed isotropically in their rest frame into two photons. 2 photons = 1 neutral pion candidate. I keep the notation π_0 instead of ($\gamma_1\gamma_2$) in the following.



- The ρ of ν_τ($\tau \longrightarrow \rho$) must be **reconstructed.** Hadronic system can provide neutral/charged pions, thus there exist combinatorics of ($\pi^\pm\pi_0$) which blurs the ρ of the τ decay.

- Make use of following variables to define a **Medal Game:**
  - Combined π0 ($\gamma_1\gamma_2$ system) and ρ **invariant masses** ($\gamma_1\gamma_2\pi^\pm$).
  - "ρ energy" = reconstructed energy of ($\gamma_1\gamma_2\pi^\pm$) (reward higher energy candidates)
  - Reward collimated candidates around the reconstructed ρ direction.

τ decayed ρ invariant masses



The Medal Game will be applied blindly to both signal and background, to select only 1 ρ candidate per event.

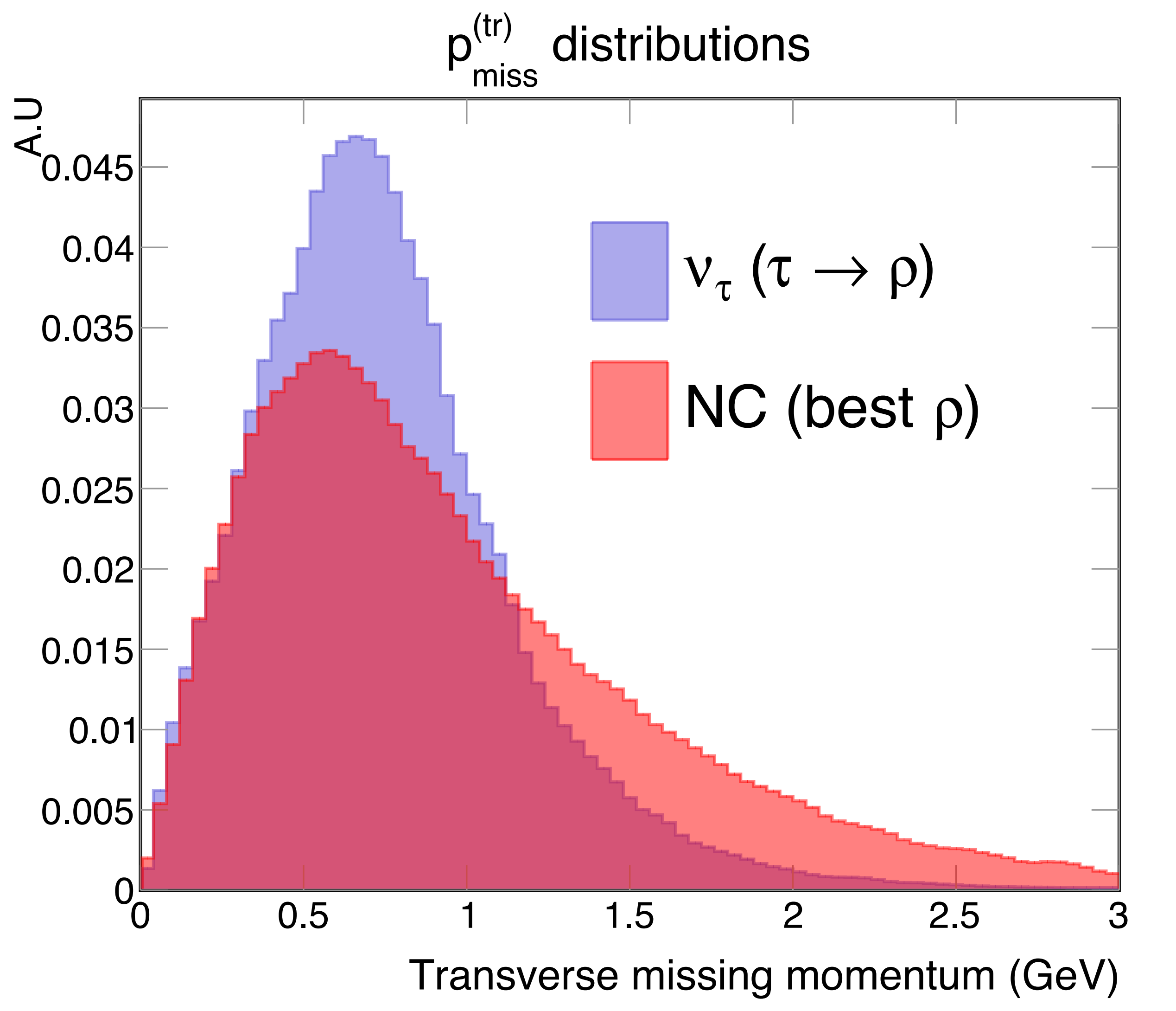
- **Results (comparing with MC truth):** 82% of correct ρ reconstruction in ν_τ($\tau \longrightarrow \rho$) events. ~52% of ν_τ events have no blurring candidate. Machine learning techniques didn't help at improving this efficiency.

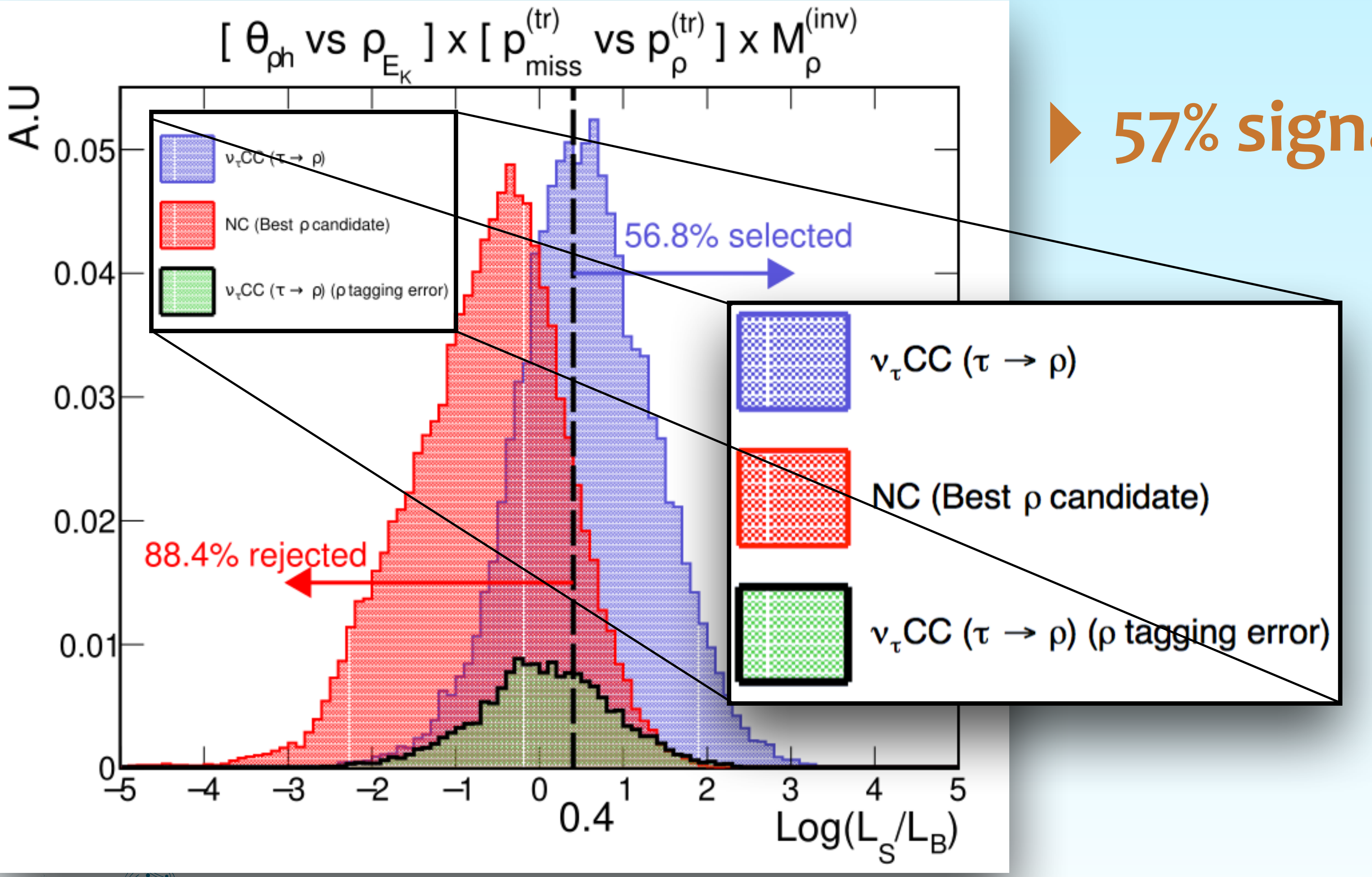
DEEP UNDERGROUND NEUTRINO EXPERIMENT

$\tau^- \longrightarrow \rho^- \longrightarrow \pi^-\pi_0$ (II)

Signal = ν_τ **(τ—>ρ) || Background=** NC $(\geq 1\pi^\pm \geq 1\pi_0)$.

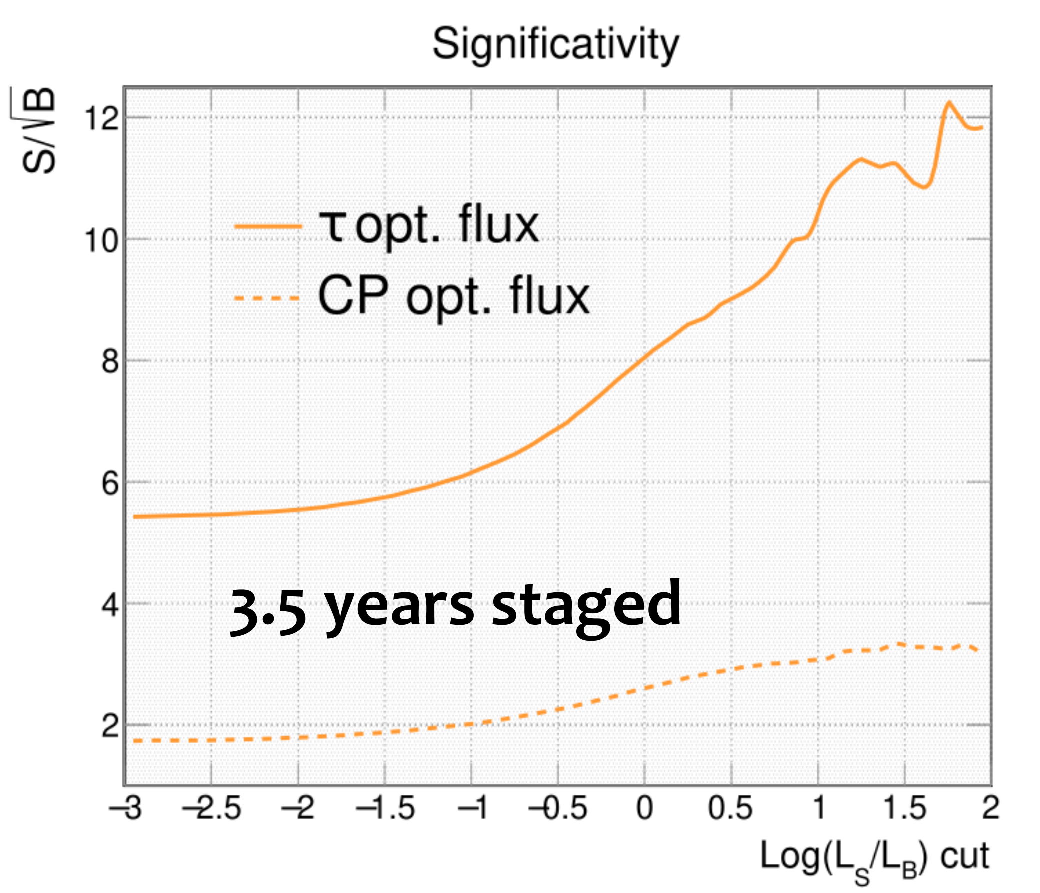
- As for τ—>e, we build the kinematic distributions to be used for the likelihood analysis.
  - **Signal:** use the MCtruth to build kinematics associated with $\rho=(\gamma_1\gamma_2\pi^-)$ of the τ decay, to avoid biasing by Medal Game.
  - **Background:** use the Medal Game to select the best ρ candidate. 1 event = 1 candidate.
- 17 kinematic variables (see back-up) are studied. Make use of the transverse plane once again. Transverse missing momentum less powerful here (S/B both have one escaping neutrino !). Below: S&B log-likelihood for an optimized set of variables.





- **57% signal efficiency & 12% background contamination**

- Use of ML techniques did not bring improvement
- **τ optimized flux brings much more sensitivity to the ν_τ appearance.**



Discussion

- This works presents the results obtained on $\nu_\mu \rightarrow \nu_\tau$ selection efficiencies based on kinematic criteria for two τ decay modes (electron and ρ). It appears in both cases the possibility to have at least 40% of selection efficiency with ~90% of background rejection.
- 3.5 years staged development plan normalization, Asimov significance ~ 2 (3) for $\tau \rightarrow e$ ($\tau \rightarrow \rho$). Boosted with the use of the alternative τ otimized neutrino beam: ~9σ significance for the two decay modes separately.
- Try QEL topologies to improve signal purity: mitigated results.
- Machine learning techniques (NN from Tensorflow keras and BDT of TMVA) did not prove more efficient. Sample size ? Robustness of likelihood.
- Not presented:
  - $\tau \rightarrow 1\pi$ decay mode (extension of the $\tau \rightarrow \rho$ to a more exclusive final state). However larger level of background makes it less sensitive.
  - $\tau \rightarrow \mu$ decay mode ~ $\tau \rightarrow e$ decay mode with a much higher level of background: negligible contribution
- Combined sensitivity of $\tau \rightarrow e$, $\tau \rightarrow \rho$ and $\tau \rightarrow 1\pi$ (QEL):

	Standard LBNF ν beam	τ optimized beam
3 channels combined		
ν_τ	44.0 ± 0.3	284.2 ± 1.6
Backgrounds	202.9 ± 2.1	375.4 ± 4.1
Significance	3.0 ± 0.0	13.2 ± 0.1

Thank you !

Back-up

Back-up Smearing

Particle	Detection Threshold (MeV)	σ	Angular Resolution (°)
$\mu^\pm$	30	/	1
$e^\pm$, π^0, γ (electromagnetic showers)	10	$\sqrt{(0.02)^2 + \frac{(0.15)^2}{E[\text{GeV}]}}$	1
Protons	50	if survives: 10% if interacts: $\sqrt{(0.05)^2 + \frac{(0.30)^2}{E[\text{GeV}]}}$	5
$\pi^\pm$	20	if survives: 5% 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

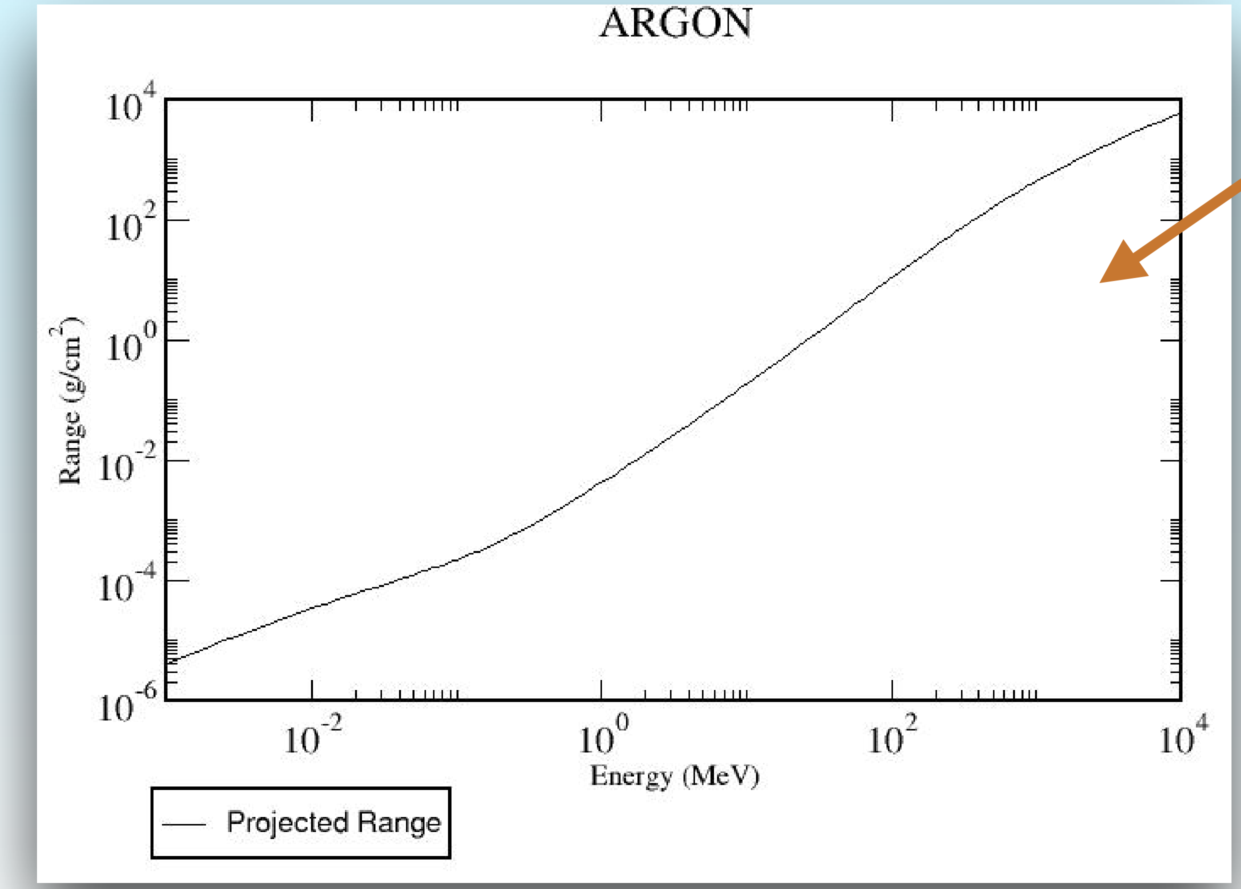
For electrons (and EM showers):

- 1704.02927
- 0812.2373

Muons: now use 5%. Shoud distinguish contained and escaping tracks

Neutrons: see CDR (1512.06148, table 3.3).

Charged hadrons (pions & protons). Proceed in several steps:



- Use NIST (https://physics.nist.gov/physrefdata/star/text/pstar.html) data of protons in liquid argon: range as a function of proton energy. Range/(particle's mass) function of βγ only: extrapolate for pions !
- Interaction length of proton in liquid argon: 85.7 cm. Convert into Rint = Range/(Mass proton), to be usable with pions as well.
- Given a charged hadron (mass m), compute its R = range/m with MCtruth. Compute psurv = exp(-R/Rint) ~ survival probability. Generate number in [0;1]. If smaller than psurv, the particle survives and only ionizes the medium. If not: secondary interaction, bad reconstruction.

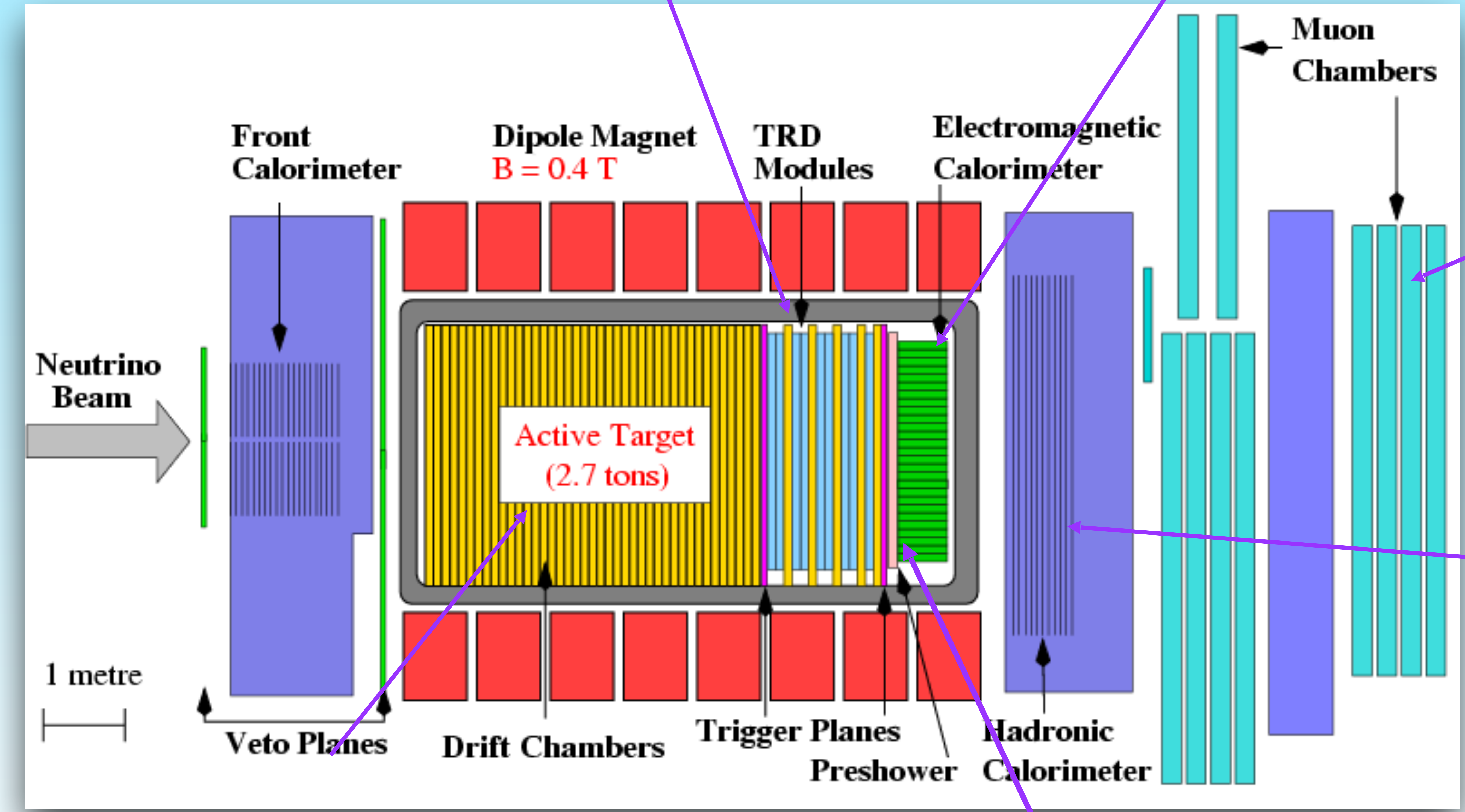
Back-up

The NOMAD detector

Transition Radiation Detector (TRD) (e identification) 9 modules (315 radiator foils followed by straw tubes plane) π rejection ~ 10^3 for electron efficiency > 90%

Electromagnetic Calorimeter (measurement of energy and position of

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus 1\%$$



Muon Chambers (μ identification) ε~ 97% for p_μ > 5 GeV/c

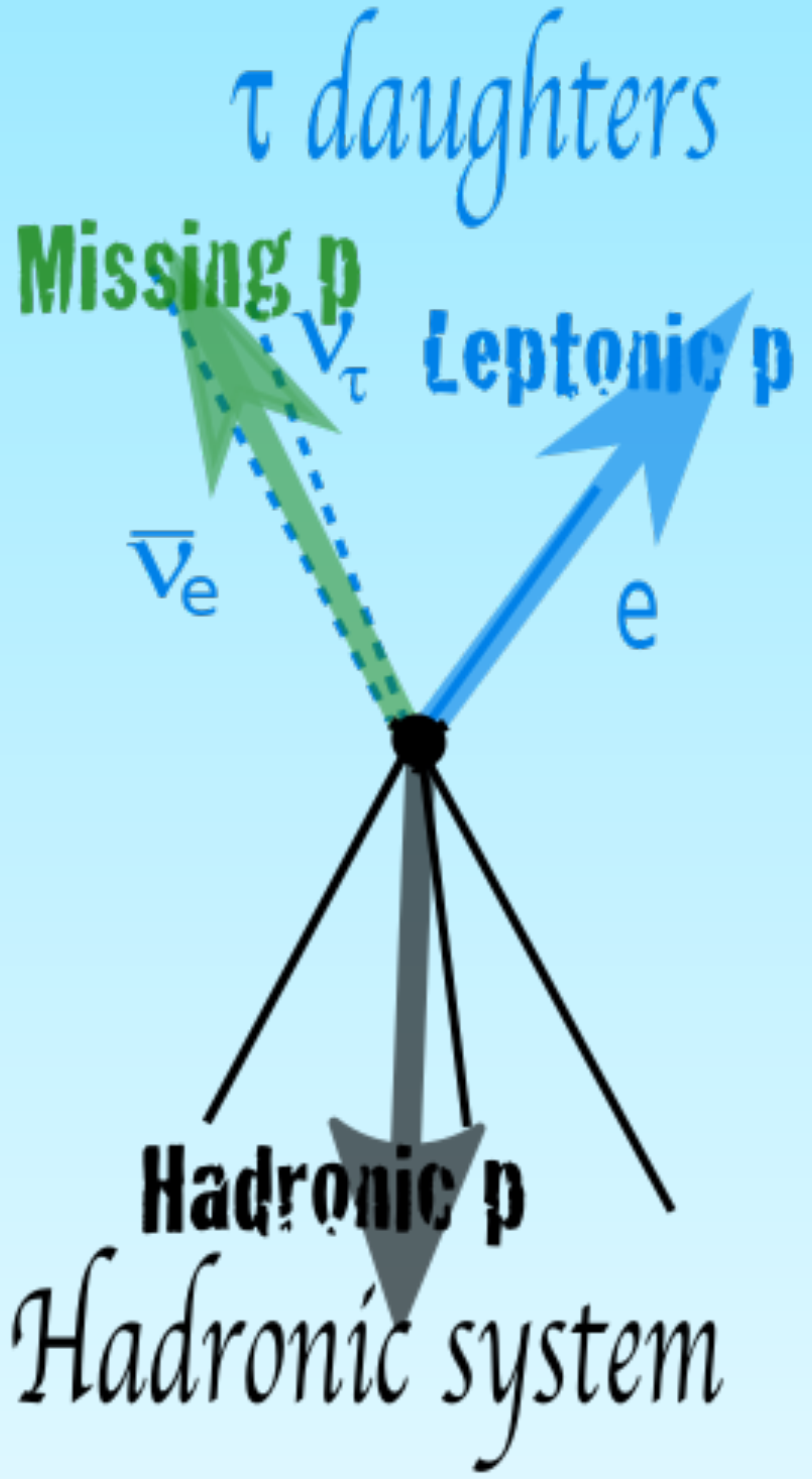
Hadronic calorimeter (n and k^0_L veto)

Drift chambers (target and momentum measurement) Fiducial mass 2.7 tons with average density 0.1 g/cm³ 44 chamber + 5 chambers in TRD region, momentum resolution 3.5% ~ (p < 10 GeV/C)

Preshower (e and γ detection) additional π rejection ~ 10^2 for electron efficiency > 90% precise γ position measurement σ(x), σ(y) ~ 1cm

Back-up

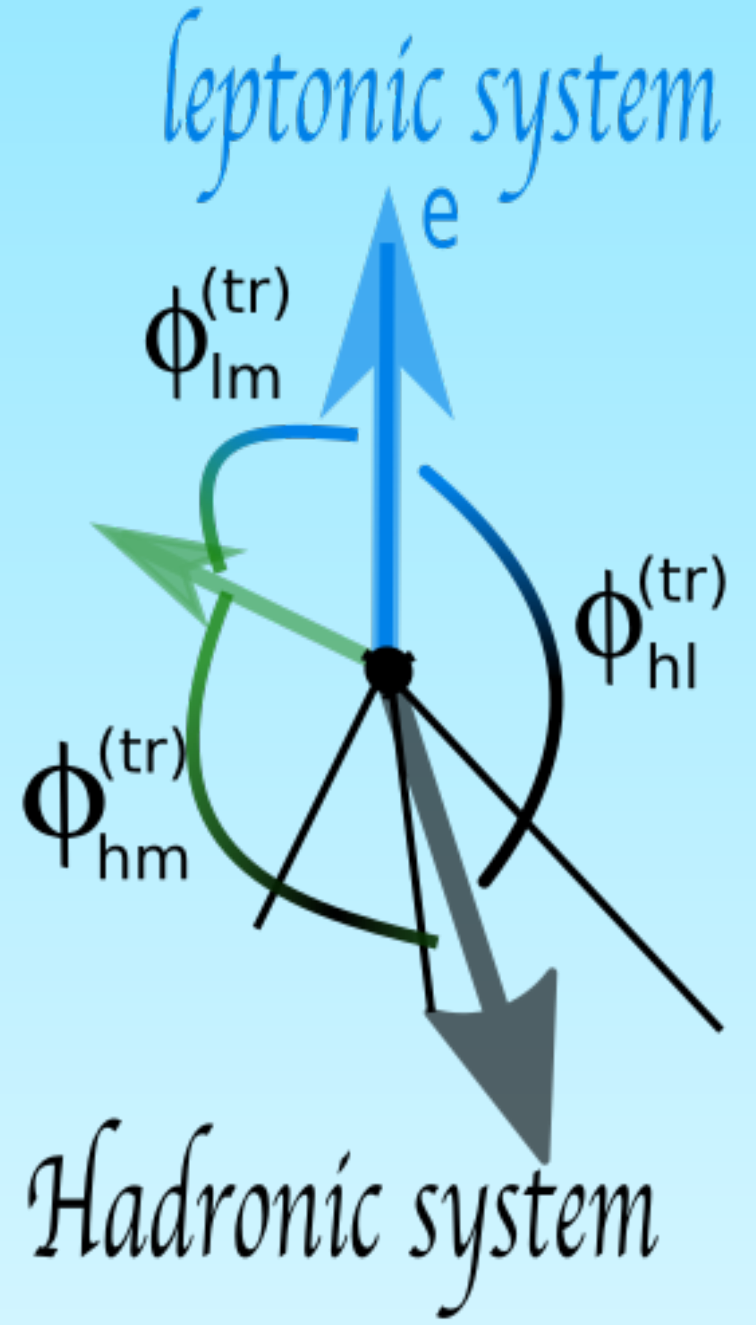
τ—>e kinematics



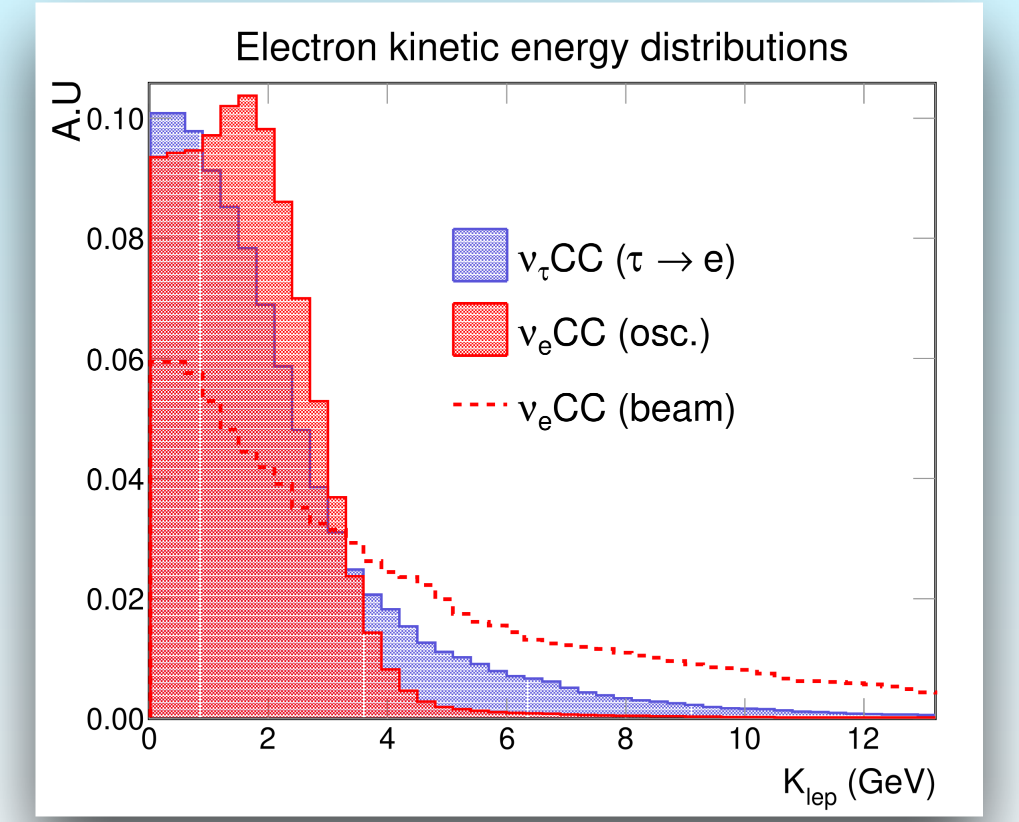
ντCC schematic view - transverse plane

Studied 8 kinematic variables:

- Transverse plane momenta of electron, hadronic system and missing = - (electron+hadronic system). The impinging neutrino brings no energy in the transverse plane. Use the angles as well.
- The kinetic energy of the electron (higher energy expected for ντ than oscillated νe).
- Asymmetry ratio in the transverse plane: $$p_{asym} = \frac{p_{lep} - p_{had}}{p_{lep} + p_{had}}$$ Was not found helpful.



Argue that the kinetic energy of the electron is a **tricky** variable.

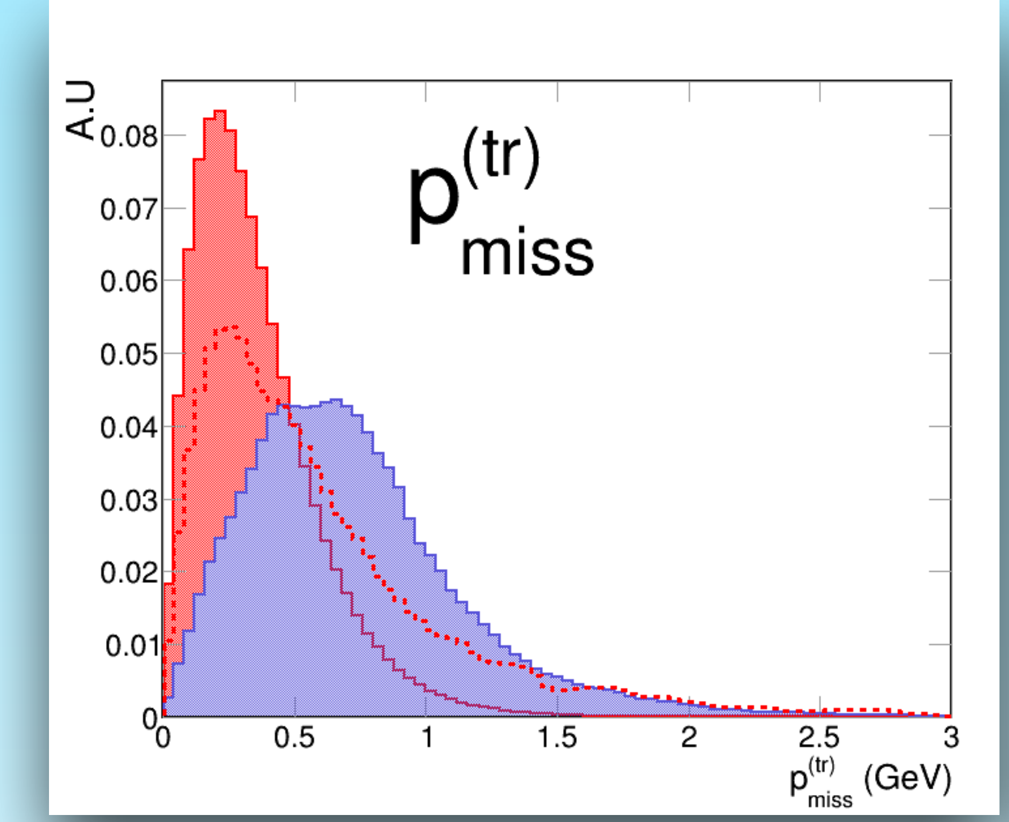


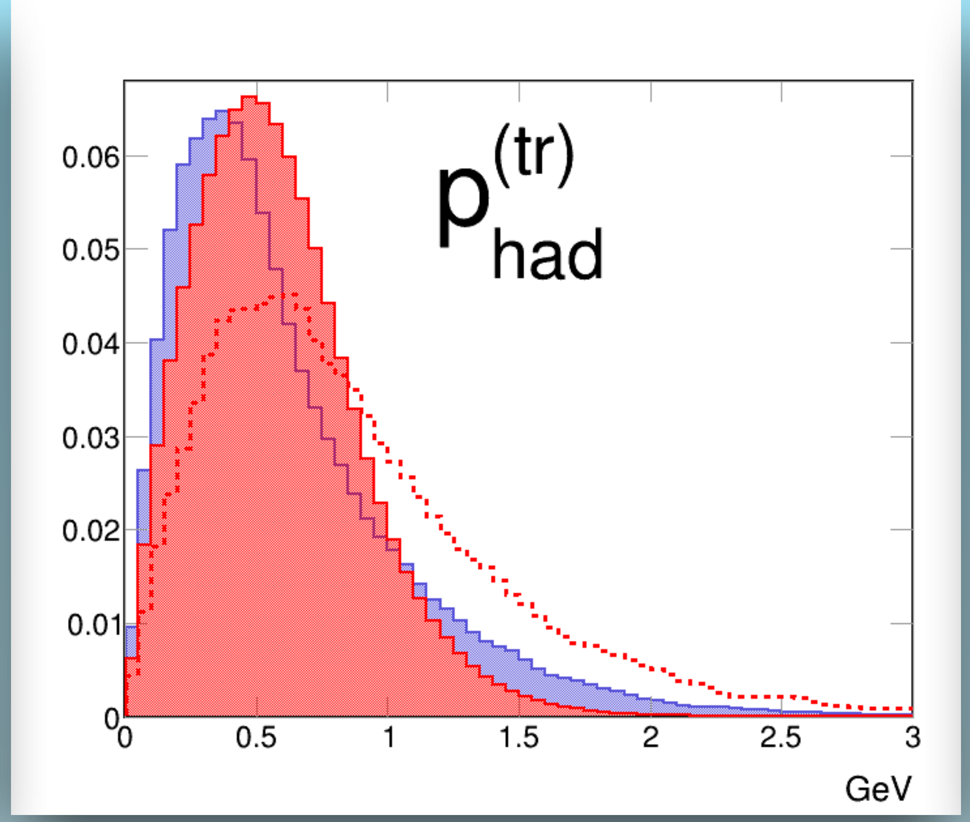
In this plot (electron kin. energy, no smearing effect), split the contribution of ne from oscillations (νμ—>νe, red filled) and νe from beam contamination (νe—>νe survival, red dashed line).
The blue histogram is the signal ντ(τ—>e). See that beam νe stands at much higher energy than oscillated νe, with signal in between. No energy region of preferred signal at all, thus useless for likelihood purposes.

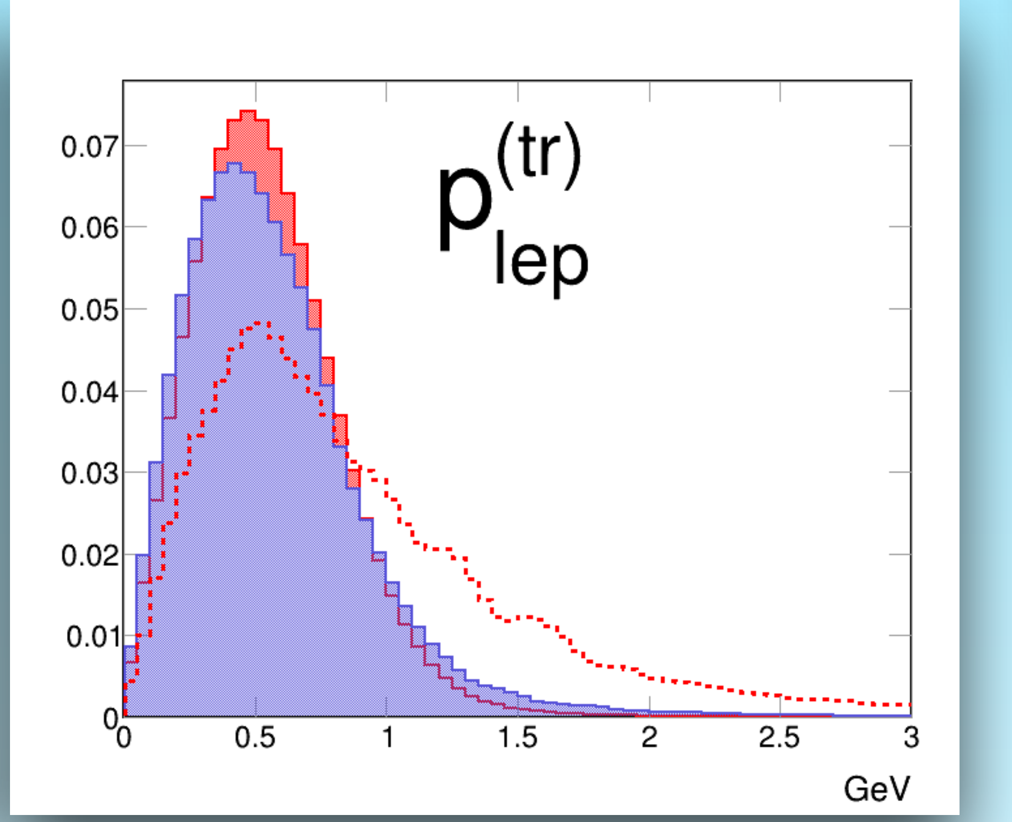
Back-up

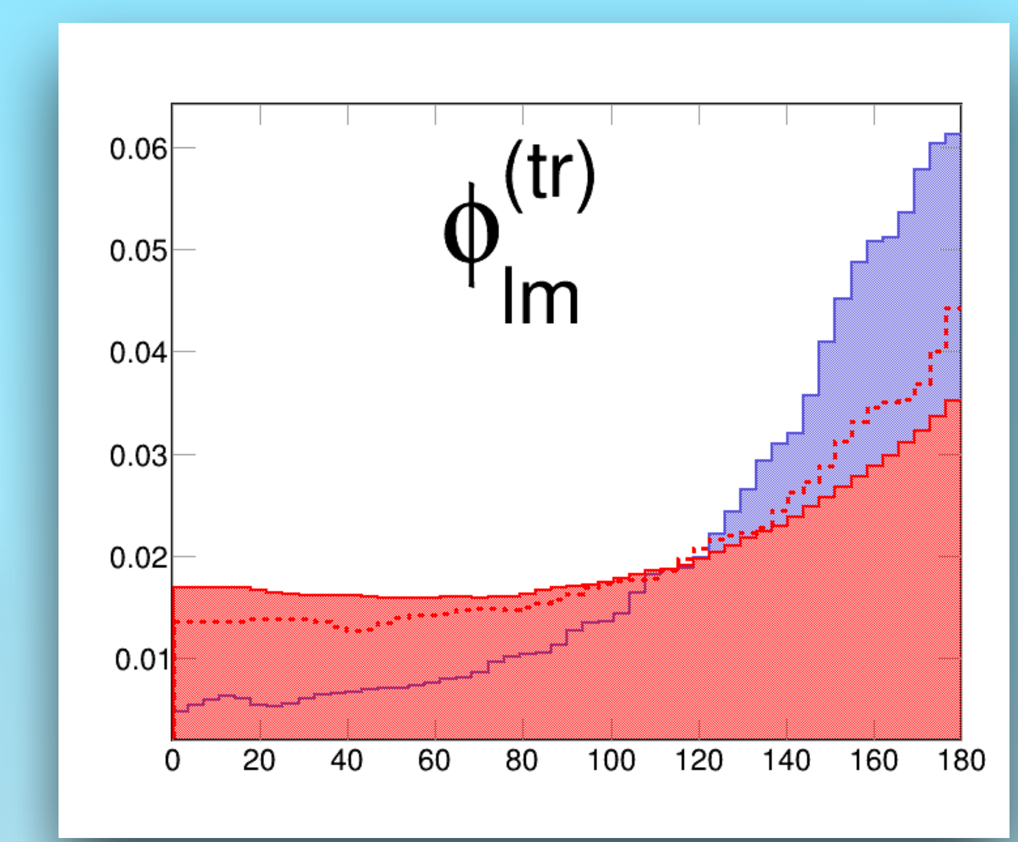
τ—>e kinematics

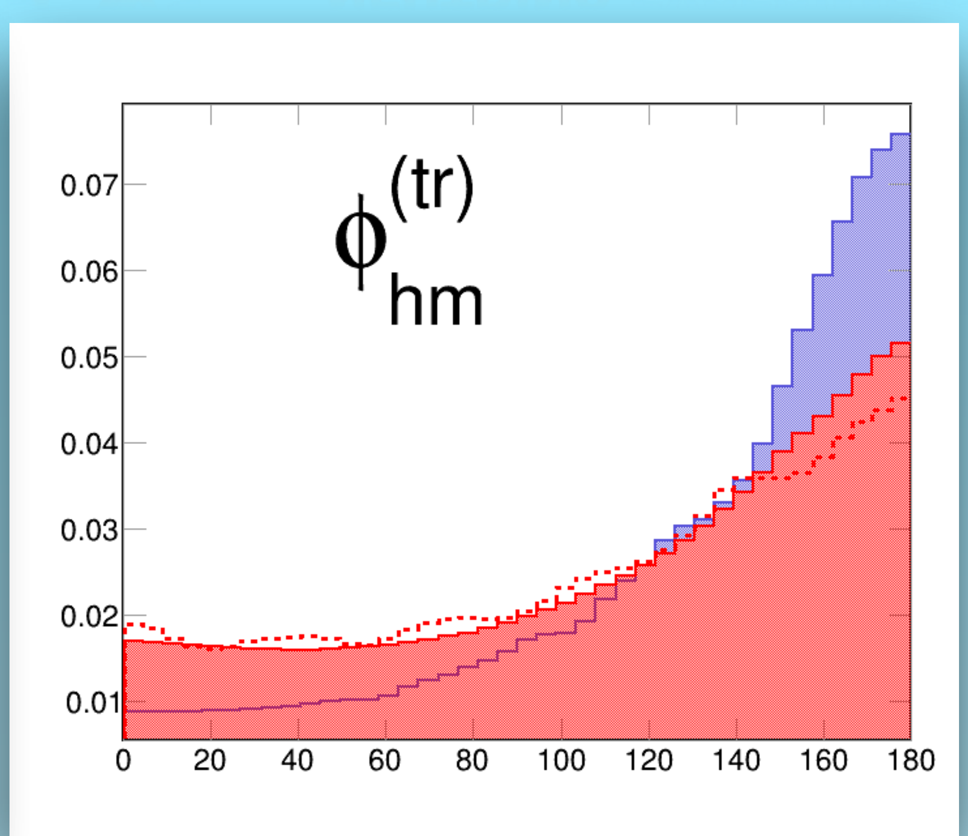
Thus we're left with transverse plane kinematics only.

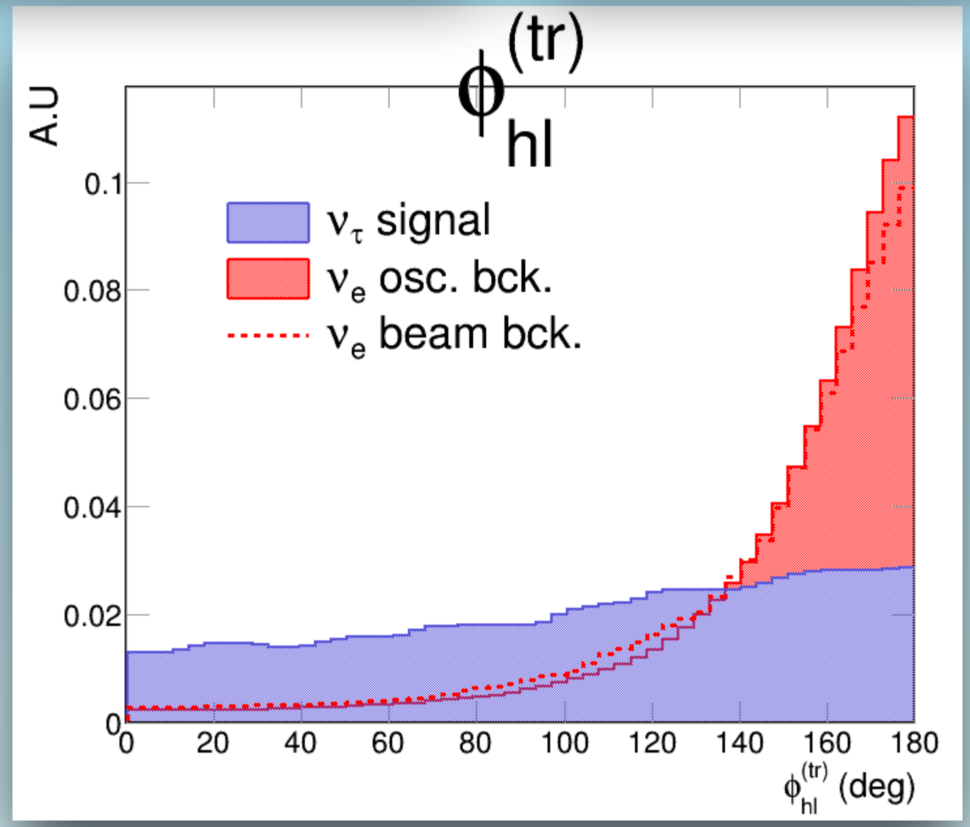












- Electron and hadronic system bring the same transverse momentum for ντ and oscillated νe. However beam νe bring more of the two. Consequence: more transverse missing momentum for beam ne than oscillated νe. For ντ remind that the two final state neutrinos still dominate the process.

- Hadronic (h) and electron (l for "lepton") tend to go back to back for νe. Angles distributions same for oscillated and beam νe.

Back-up

τ—>e kinematics

Optimize the likelihood analysis for the ντ and oscillated ne samples (dominant background expected). Then test the beam νe samples under the ''ντ VS oscillated νe hypothesis''.

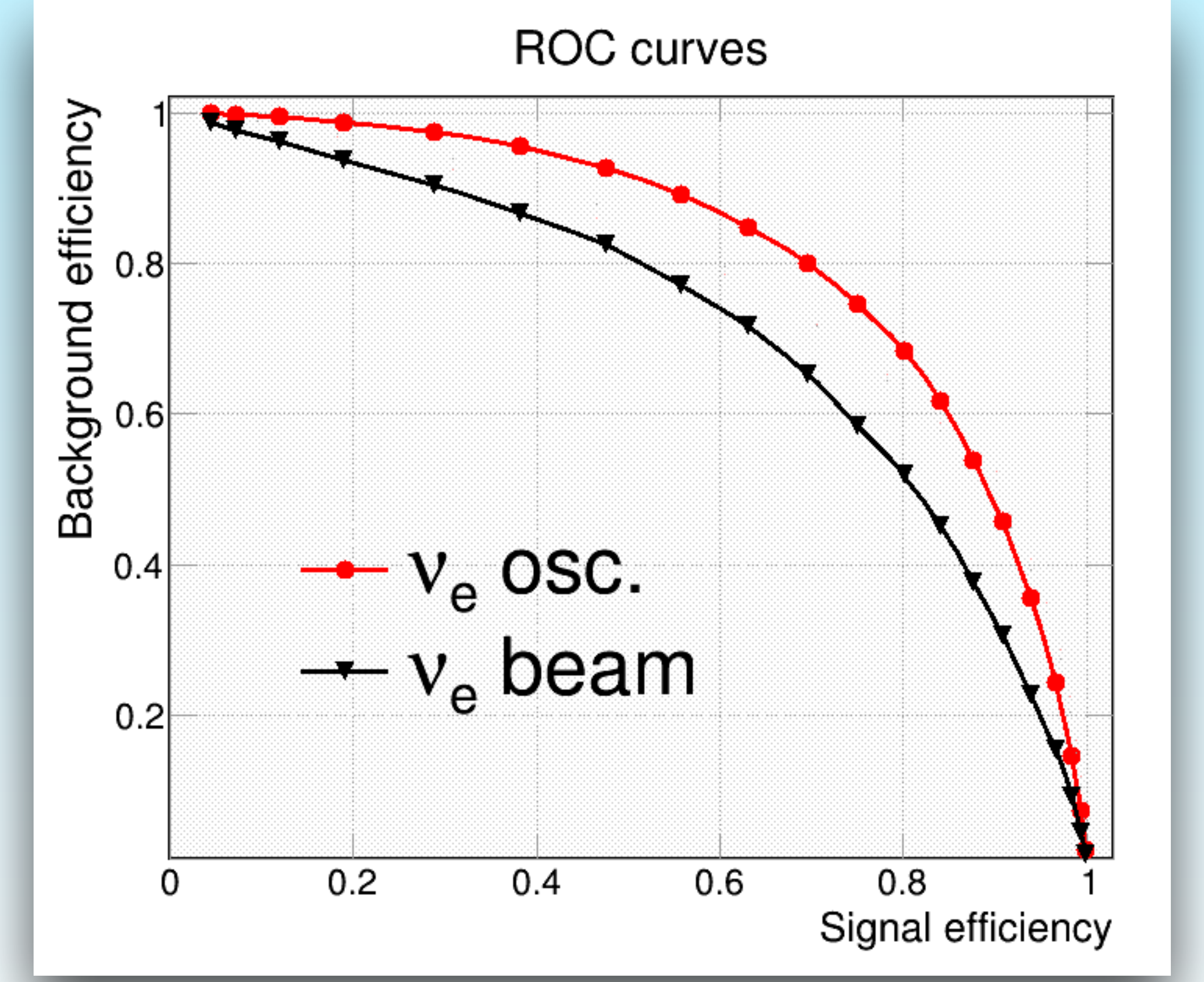
Combine two different distributions (1) and (2) as Avoid repeating the same information in (1) and (2).

$$L = \log\left(\frac{L_S^{(1)} \times L_S^{(2)}}{L_B^{(1)} \times L_B^{(2)}}\right) = L^{(1)} + L^{(2)}$$

[x1 ; x2] is the 2-dimensional distribution in the plane (x1, x2). Powerful for correlated variables.

Optimized combination used in the presentation: $\left[p_{lep}^{(tr)}; p_{miss}^{(tr)}\right] \times \left[\phi_{hm}^{(tr)}; \phi_{hl}^{(tr)}\right]$

Combine transverse momentum correlations and transverse angles.



Display the likelihood efficiencies as a ROC curve = background efficiency (or background rejection) VS signal efficiency, for the two types of background.

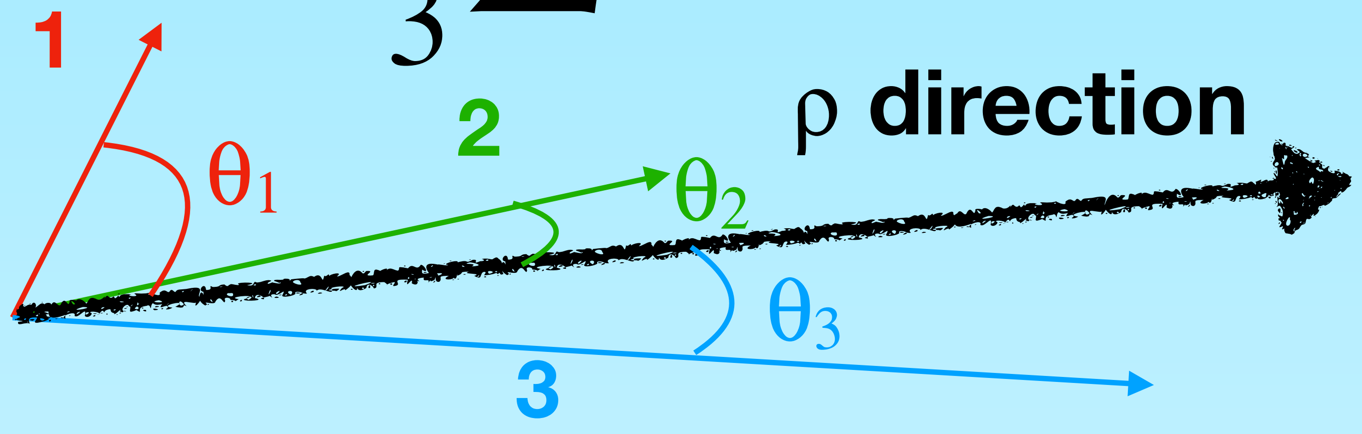
Likelihood less efficient at rejecting beam νe (attributed to transverse missing momentum less discriminating, see previous slide).

Efficiencies found to clearly improve when limiting to QEL only (require 1 electron and 1 proton detected in the final state). However, found that the significance is not improved.

Back-up

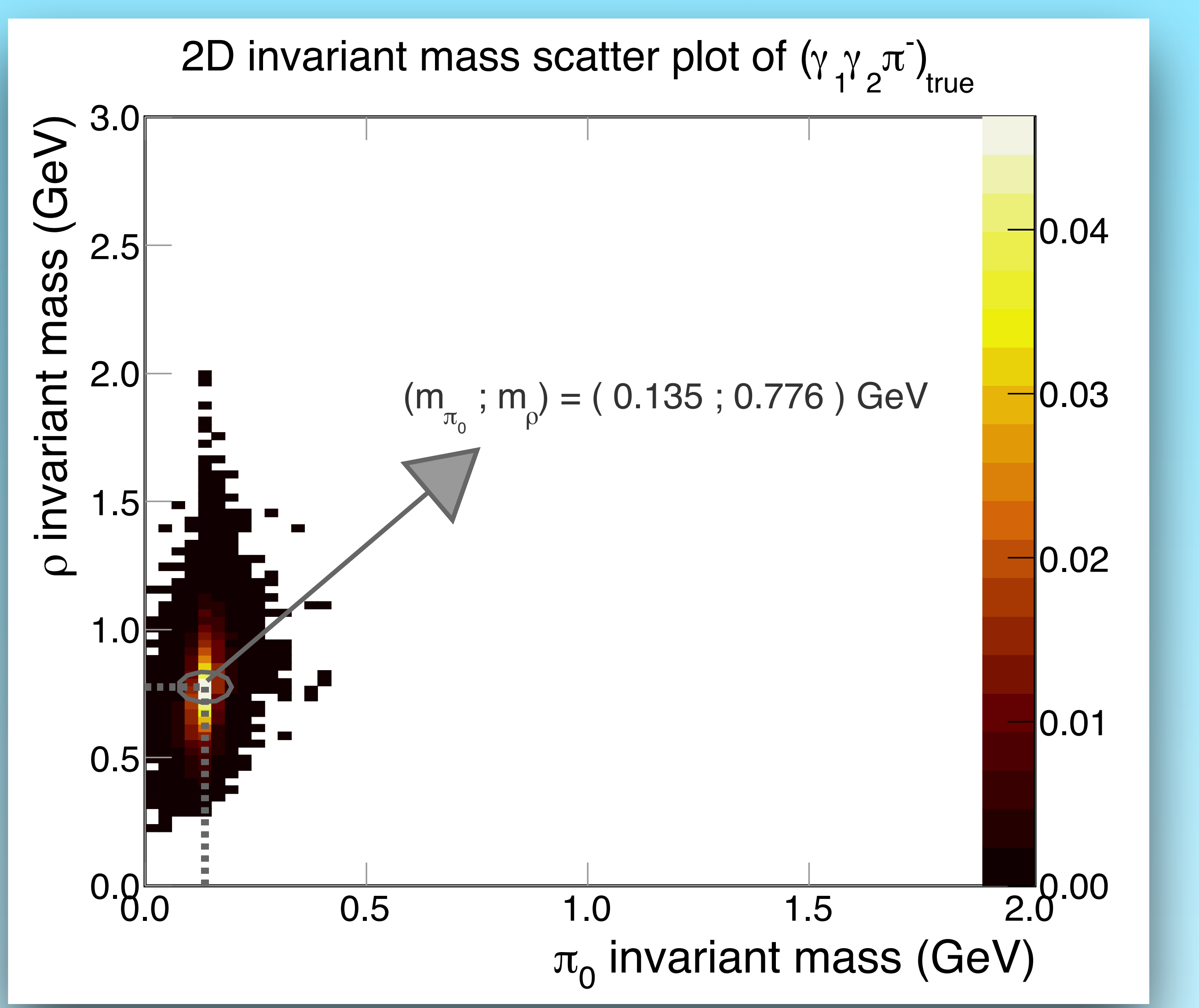
$\tau \to \rho \to \pi^- \pi_0 \to \pi^- \gamma_1 \gamma_2$ Medal Game

$$\bar{\theta} = \frac{1}{3} \sum \theta_i$$



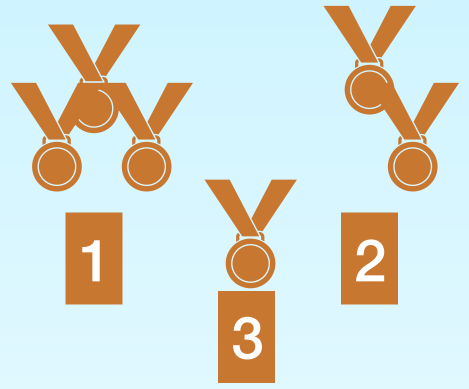
Given a $\nu\tau(\tau \to \rho)$ event, expect that:

- Invariant masses ($\pi0$ and ρ) fall not too far from ($m_{\pi0}$; m_ρ) = (0.135 ; 0.776) GeV. Reward candidates with smaller d.
- Hadronic pions have less energy than pions of the τ decay. Reward candidates for which sum of three particle's energy is the greatest.



$$d = \sqrt{\left(M_{\pi_0}^{(inv)} - m_{\pi_0}\right)^2 + \left(M_\rho^{(inv)} - m_\rho\right)^2}$$

- Leptonic and hadronic system have different direction. Reward not too scattred candidates.



Each candidates competes for each variable. The 3 best are rewarded with medals. Compare the total number of medals: winning ρ candidate !

Level of ambiguity (ρ candidate multiplicity):

Assume $\nu\tau(\tau \to \rho)$ with hadronic system providing $1\pi^\pm$ and $1\pi_0$ (=2γ). How many ρ candidates = ($\pi^\pm\gamma_1\gamma_2$) available triplets ?
ρ from τ decay **(1)**, misreconstruct π^- **(1)**, misreconstruct one γ **(2x2=4)**, misreconstruct the two γ **(1)**, misreconstruct one γ and π^- **(2x2=4)**, misreconstructs all three **(1)**. **Thus 12 ρ candidates !**

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Back-up

$\tau \longrightarrow \rho \longrightarrow \pi^-\pi_0 \longrightarrow \pi^-\gamma_1\gamma_2$ kinematic variables

17 variables:

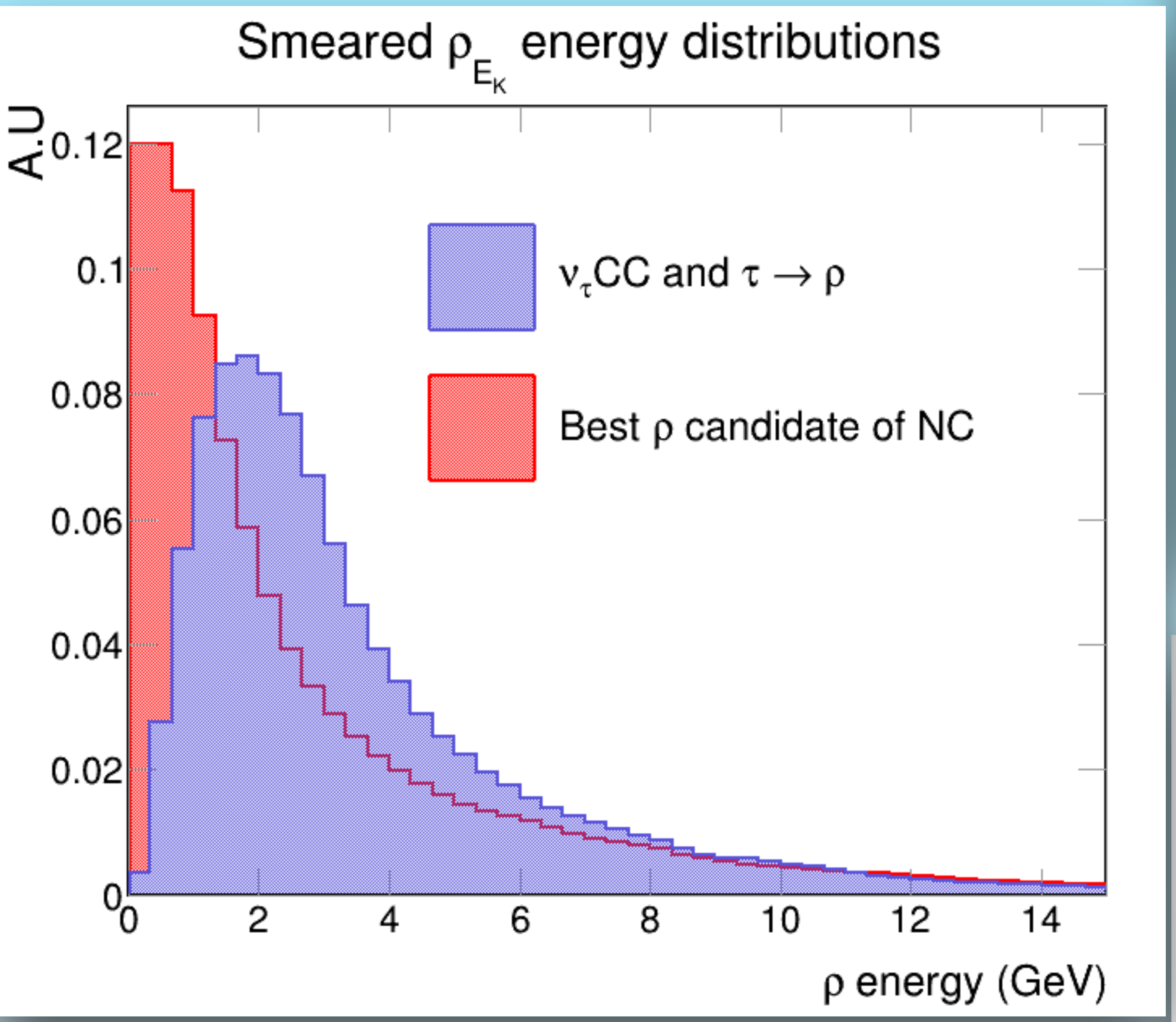
- Pions kinetic energiy, their sum (~ ρ energy), pion energy sharing. $r_\pi^K = \dfrac{E_{\pi\pm}^K}{E_{\pi\pm}^K + E_{\pi 0}^K}$ ⟶ $E_{\pi_0}^K; E_{\pi^\pm}^K; \rho_K; r_\pi^K$
- Invariant masses for π_0 and $(\pi_0\pi^\pm)$ systems. ⟶ $M_{\pi_0}^{(inv)}; M_\rho^{(inv)}$
- Various space angles (θ) between system momenta : ρ, h(hadronic), total, ν (beam direction). Some of these angles are representative of the isolation of the ρ candidate with respect to the hadronic system. ⟶ $\theta_{\rho h}; \theta_{\rho tot}; \theta_{h\nu}; \theta_{\rho\nu}$
- Transverse plane information of had. syst., ρ syst. and missing component (modulus of the momentum, plus relative direction with angle ϕ, as for τ—>e analysis). ⟶ $p_\rho^{(tr)}; p_{had}^{(tr)}; p_{miss}^{(tr)}; \phi_{h\rho}^{(tr)}; \phi_{hm}^{(tr)}; \phi_{m\rho}^{(tr)}$
- Tranvserse mass ⟶ $M^{(tr)} = 2\sqrt{p_\pi^{(tr)} p_{miss}^{(tr)}} \left| \sin\left(\dfrac{\phi_{m\pi}^{(tr)}}{2}\right) \right|$

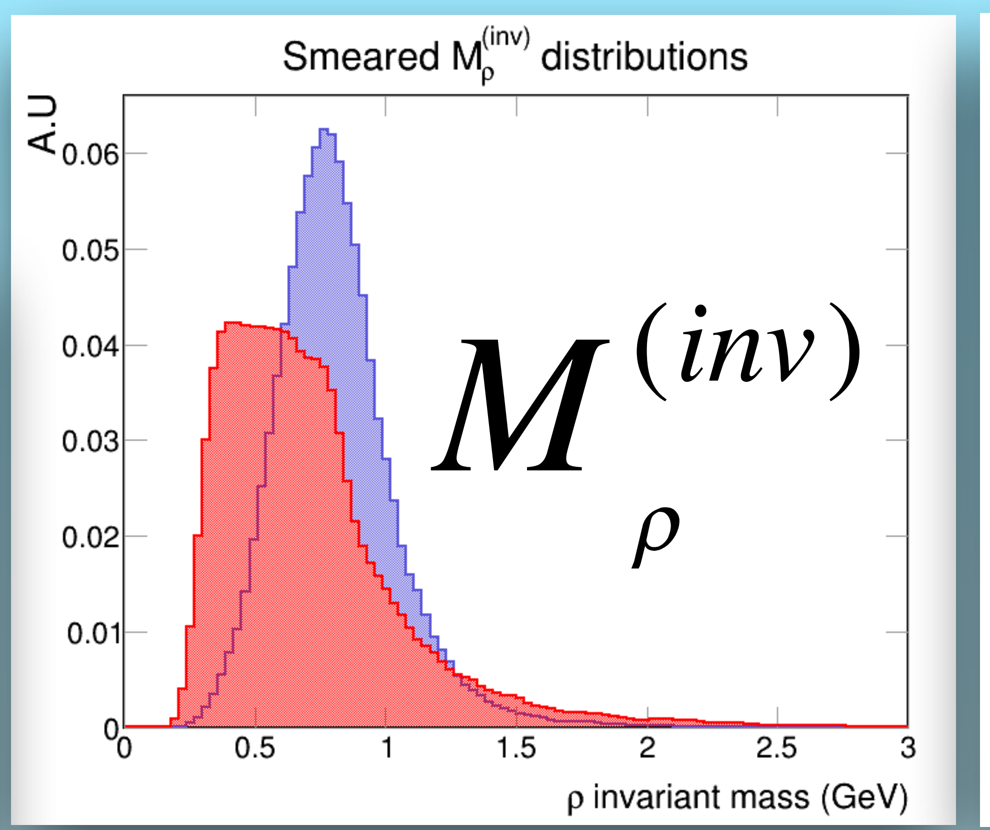
Optimal combination used in this presentation: $\left[\theta_{\rho h}; \rho_K\right] \times \left[p_{miss}^{(tr)}; p_\rho^{(tr)}\right] \times M_\rho^{(inv)}$

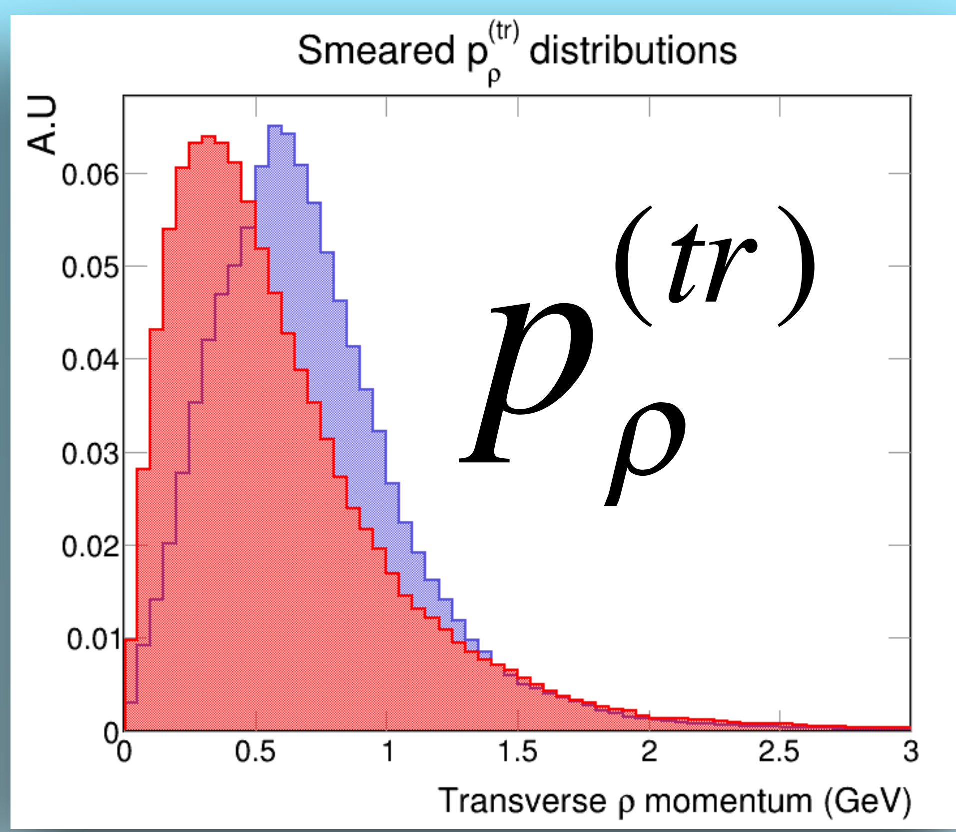
DEEP UNDERGROUND NEUTRINO EXPERIMENT

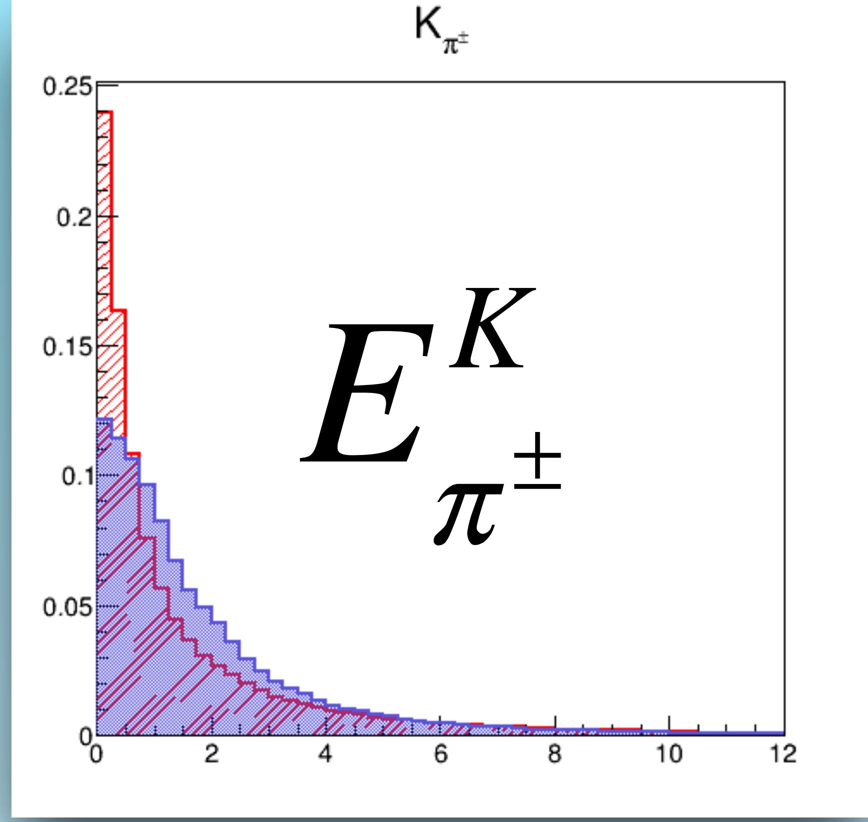
Back-up

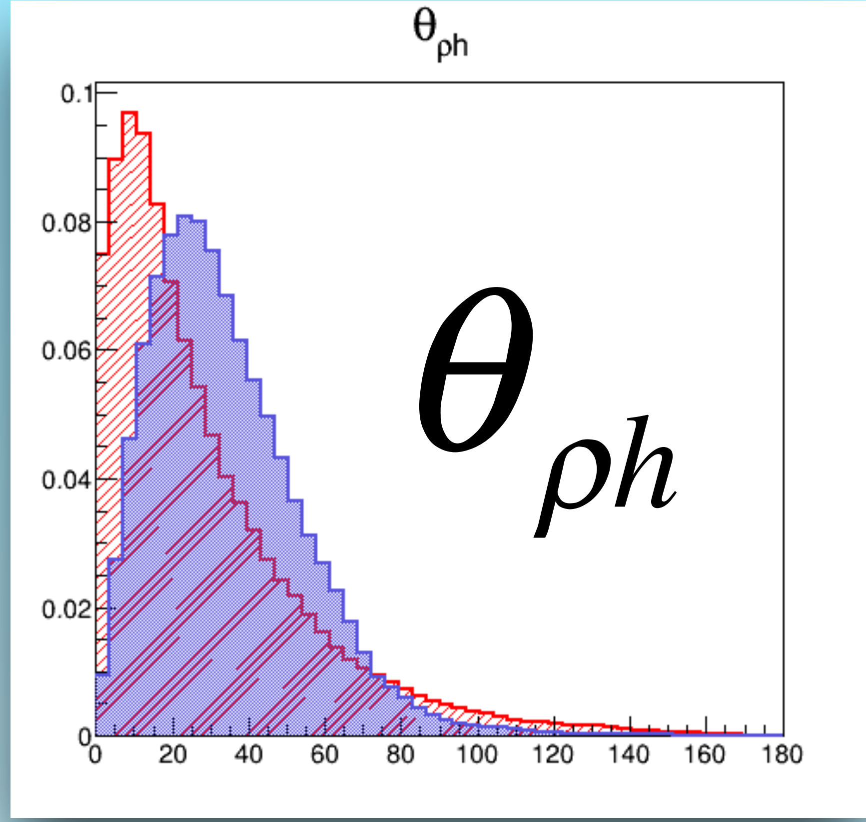
$\tau \rightarrow \rho \rightarrow \pi^- \pi_0 \rightarrow \pi^- \gamma_1 \gamma_2$ distributions

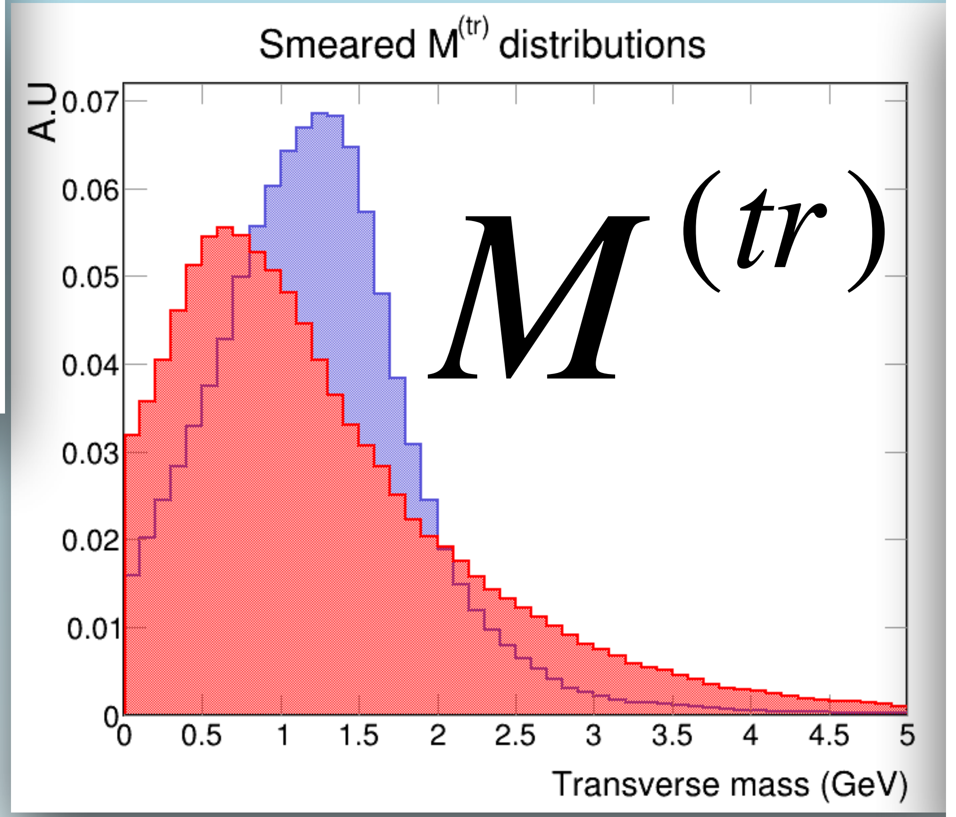


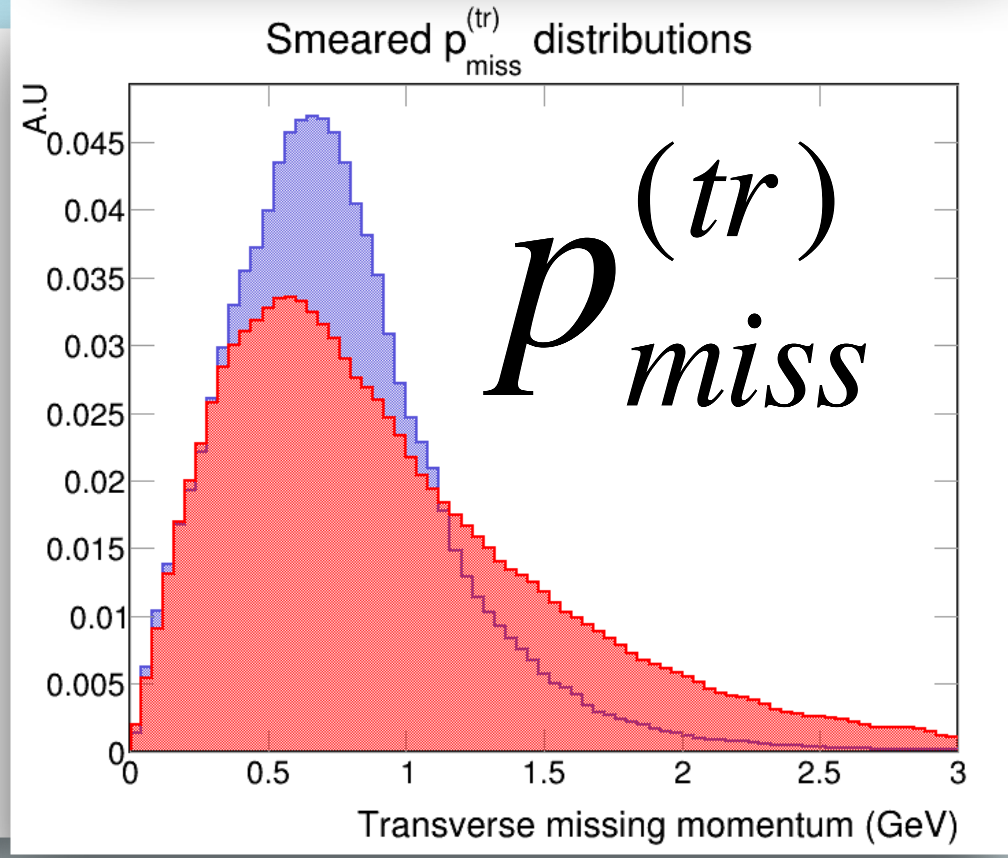


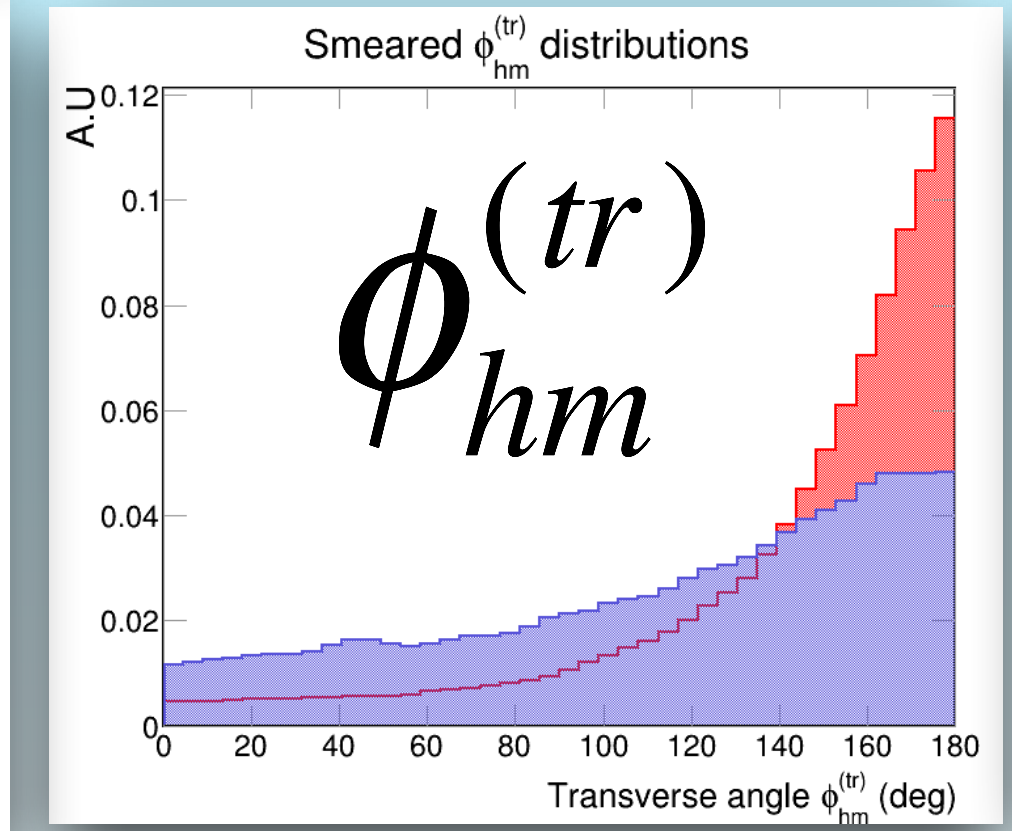


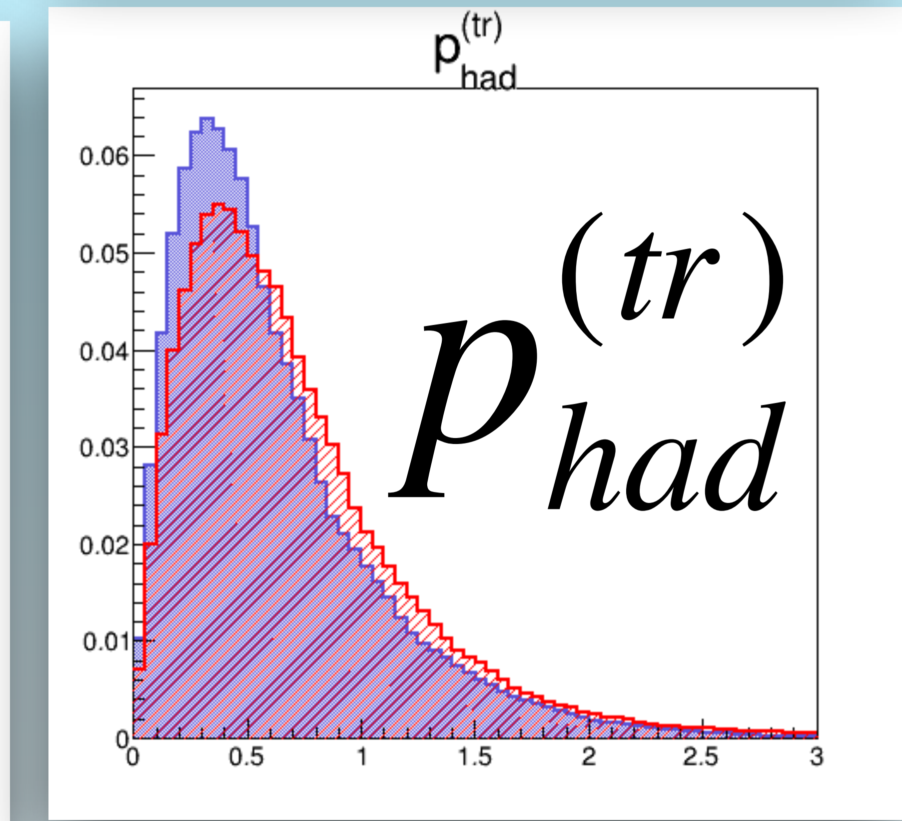












Blue: ντ(τ—>ρ), using the correct ρ candidate (MCtruth). Red: NC($\geq 1\pi^{\pm} \geq 1\pi_0$), picking best ρ candidate according to Medal Game. For the likelihood analysis, we use the Medal Game for bth signal and background. Thus the correct ρ of a ντ event might be misreconstructed.

Back-up — $\tau^- \rightarrow \pi^- \nu_\tau$ analysis

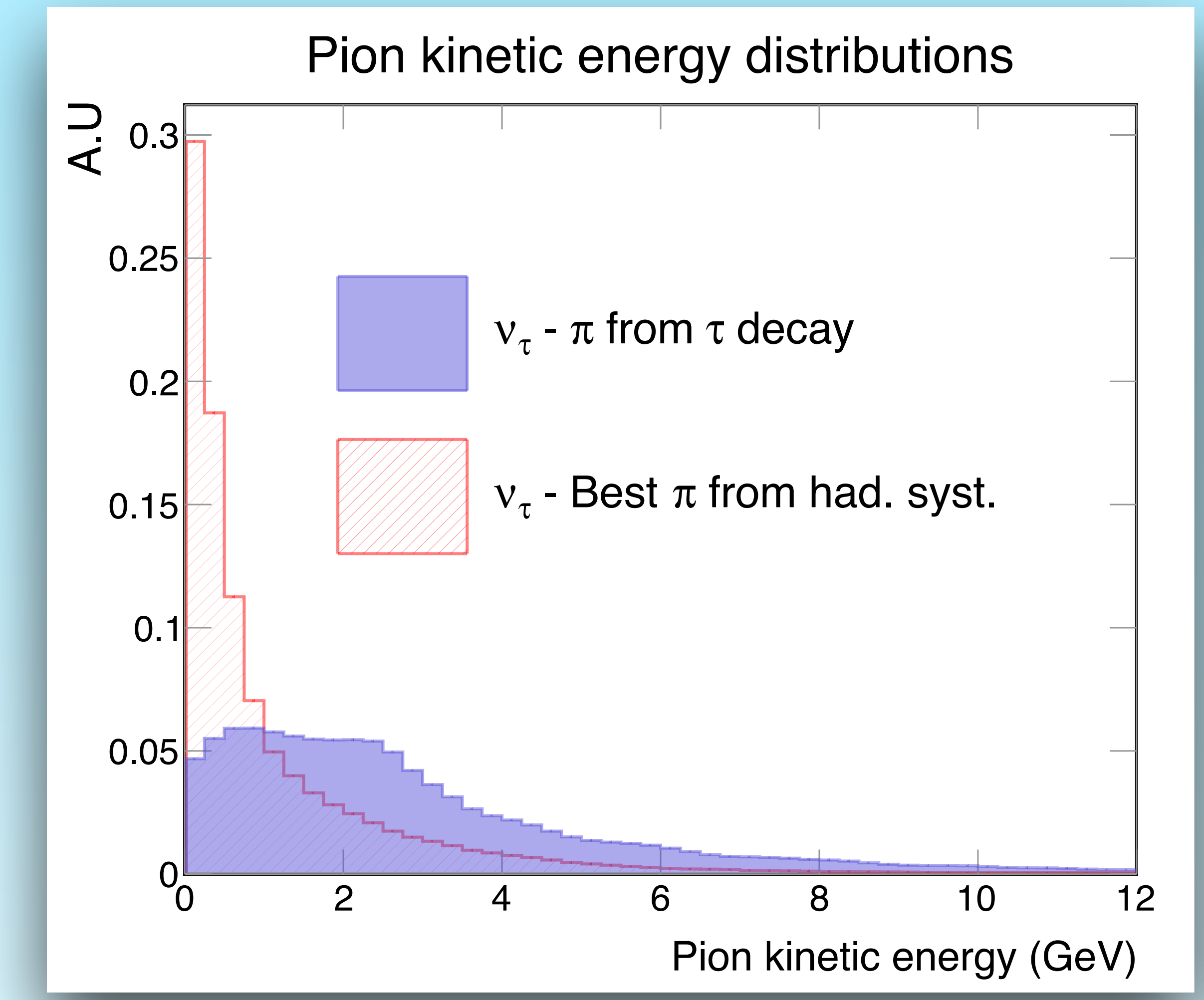
Exploit lower τ reconstruction ambiguity and quite large branching ratio (~11%).

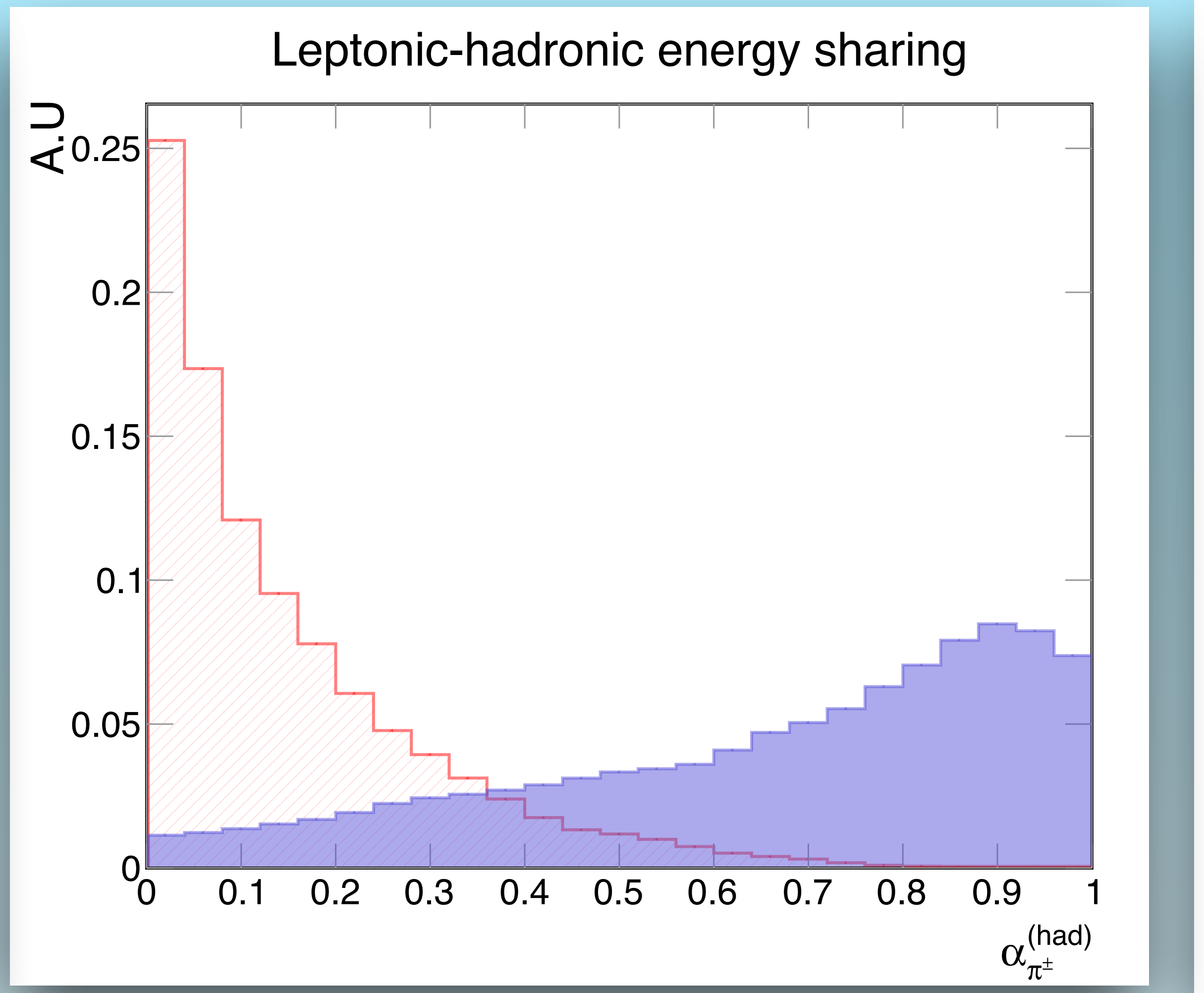
Medal Game

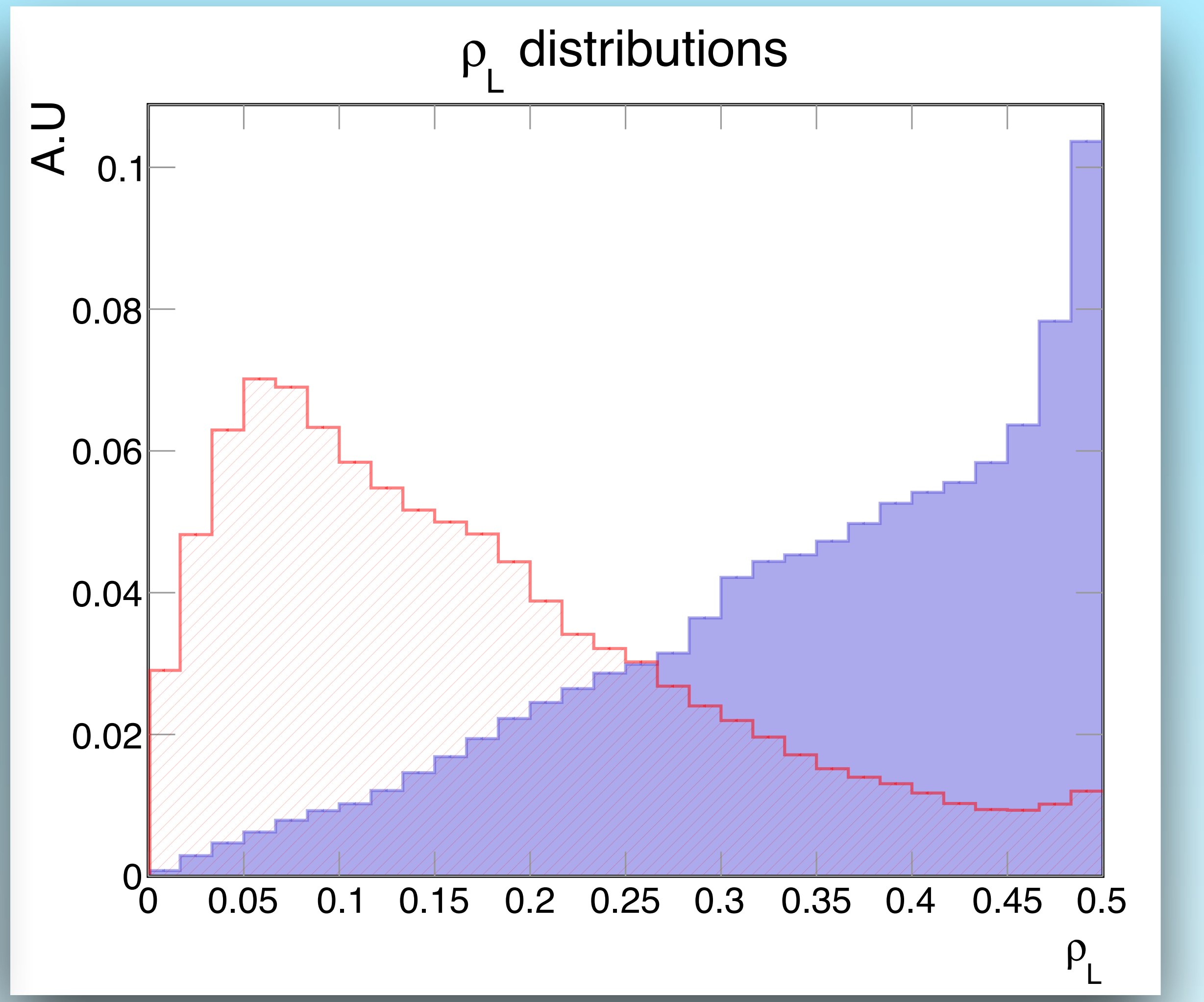
$$\alpha_\pi^K = \frac{E_\pi^K}{E_\pi^K + E_{had}^K}$$

Reward higher energy pions, pions with higher α variable, and finally the fraction of pion transvers emomentum ρ_L

$$\rho_L = \frac{p_\pi^{(tr)}}{p_\pi^{(tr)} + p_{had}^{(tr)} + p_{miss}^{(tr)}}$$







Eff = 63.5+30.5 = 94.0%

Real Eff = 30.5 / (100-63.5-0.4) = 84%

Had. syst. pions	0	1	2	3	>3
Fraction (%)	63.7	23.6	7.1	3.6	2.0

True π rank	-1	0	1	2	3	>3
Fraction (%)	0.4	63.5	30.5	4.7	0.7	0.2

Back-up — $\tau^- \rightarrow \pi^- \nu_\tau$ analysis

Kinetic variables studied

17 variables:

- The 3 variables of the Medal Game

- Various space angles (θ) between system momenta : ρ, h(hadronic), total, ν (beam direction). Some of these angles are representative of the isolation of the π candidate with respect to the hadronic system.

$$\theta_{\rho h};\theta_{\rho tot};\theta_{h\nu};\theta_{\rho\nu}$$

- Transverse plane information of had. syst., π syst. and missing component (modulus of the momentum, plus relative direction with angle Φ, as for τ—>e analysis).

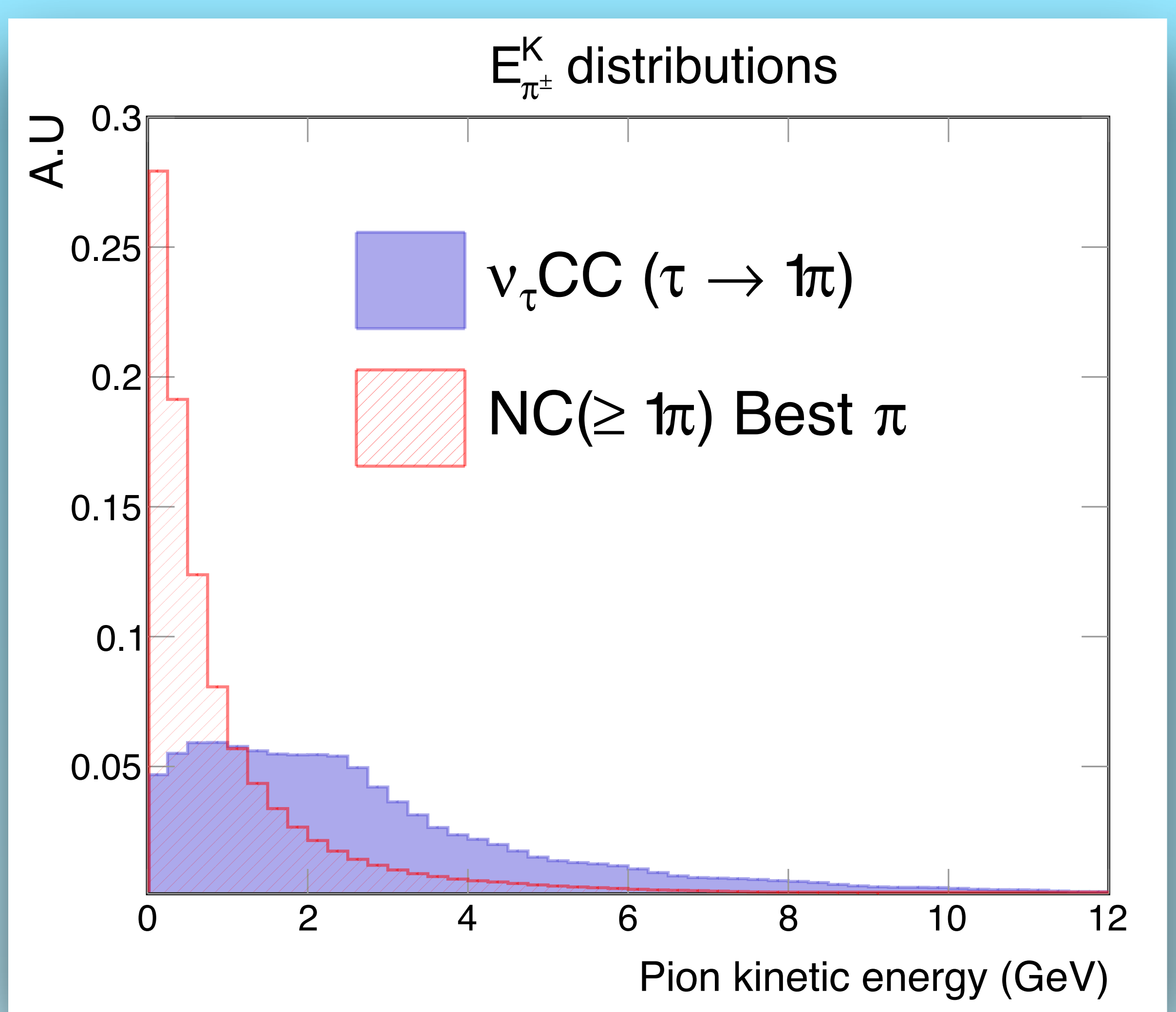
$$p_{\rho}^{(tr)};p_{had}^{(tr)};p_{miss}^{(tr)};\phi_{h\rho}^{(tr)};\phi_{hm}^{(tr)};\phi_{m\rho}^{(tr)}$$

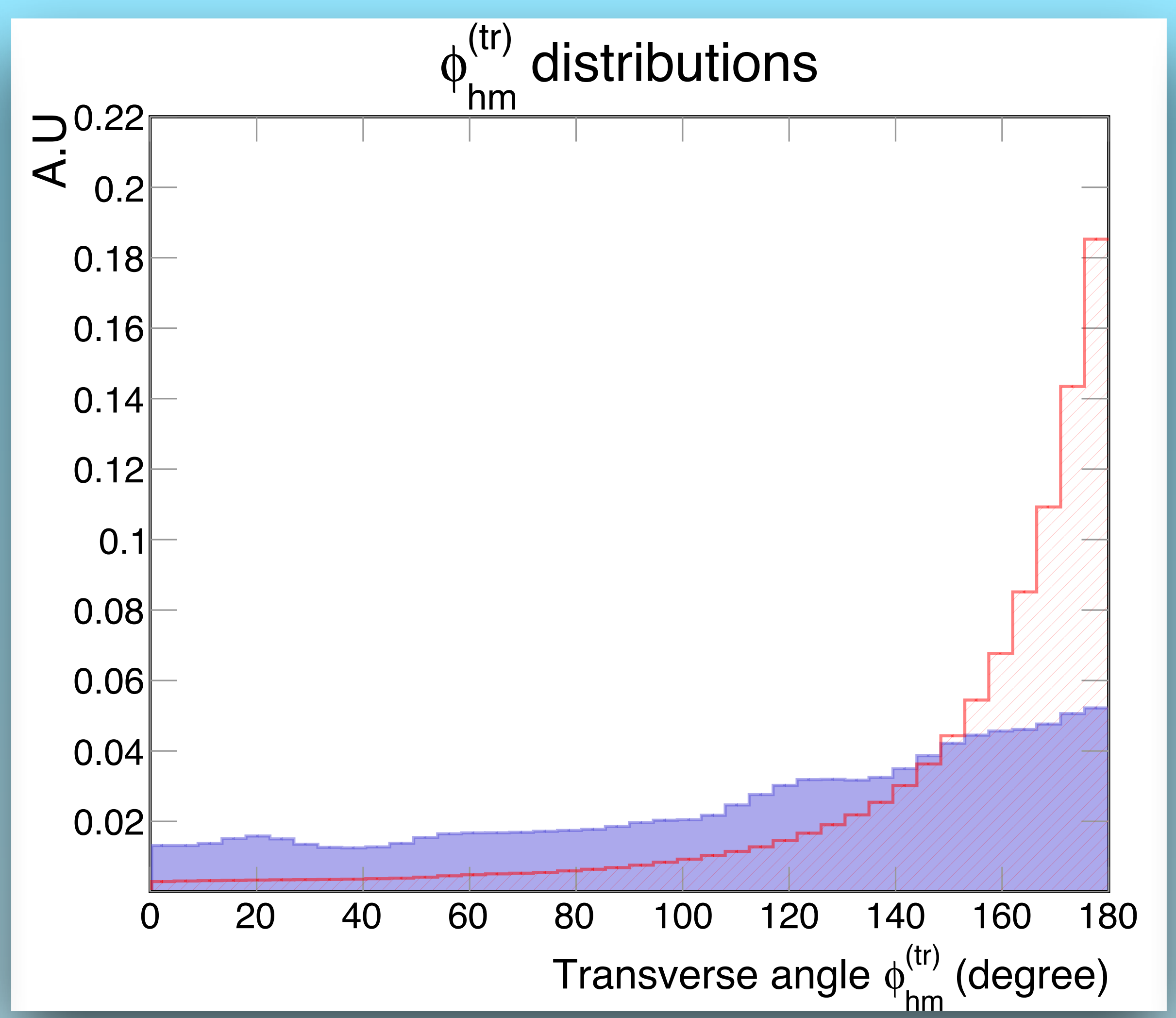
- Transverse mass

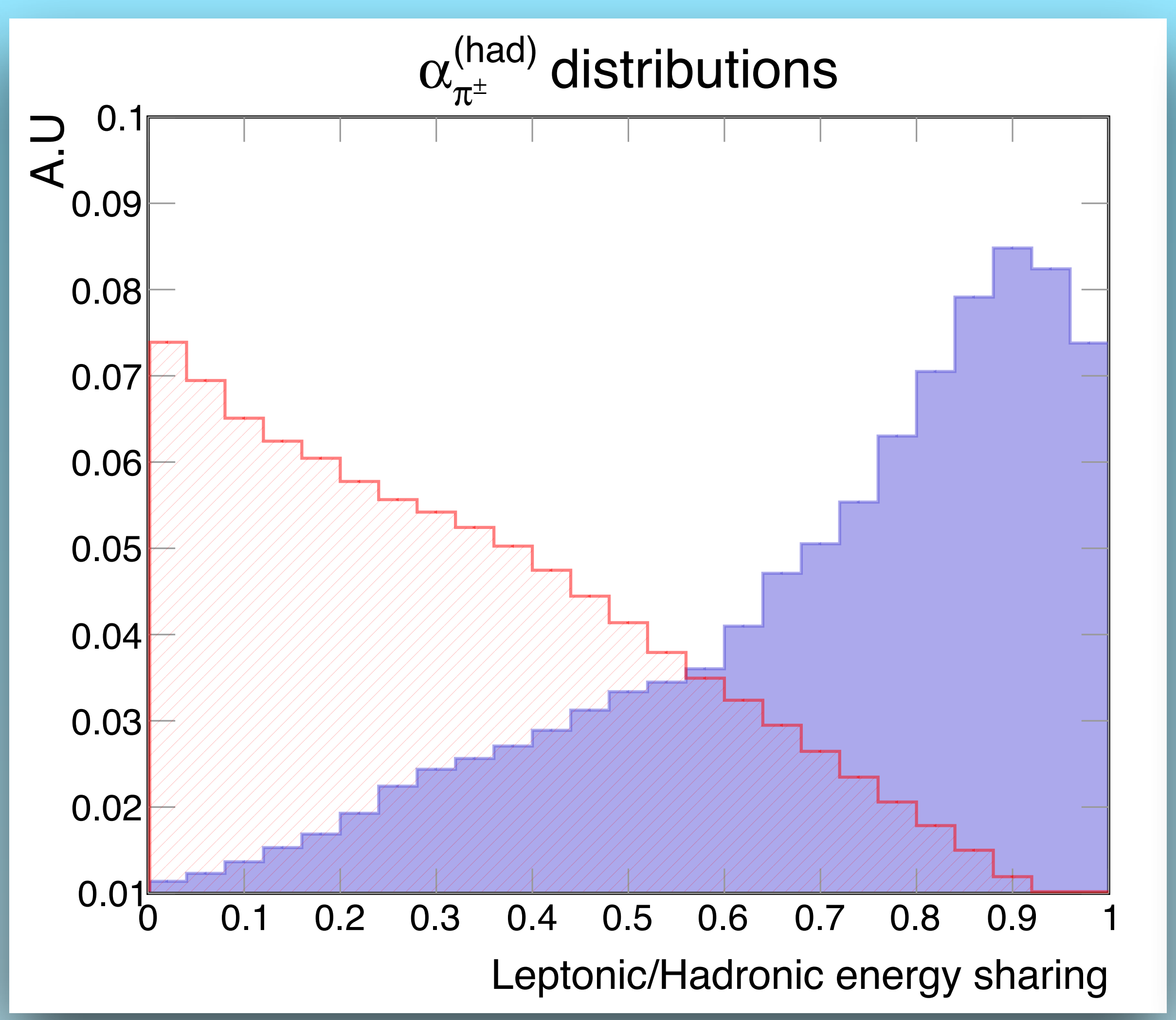
$$M^{(tr)} = 2\sqrt{p_{\pi}^{(tr)}p_{miss}^{(tr)}}\left|\sin\left(\frac{\phi_{m\pi}^{(tr)}}{2}\right)\right|$$

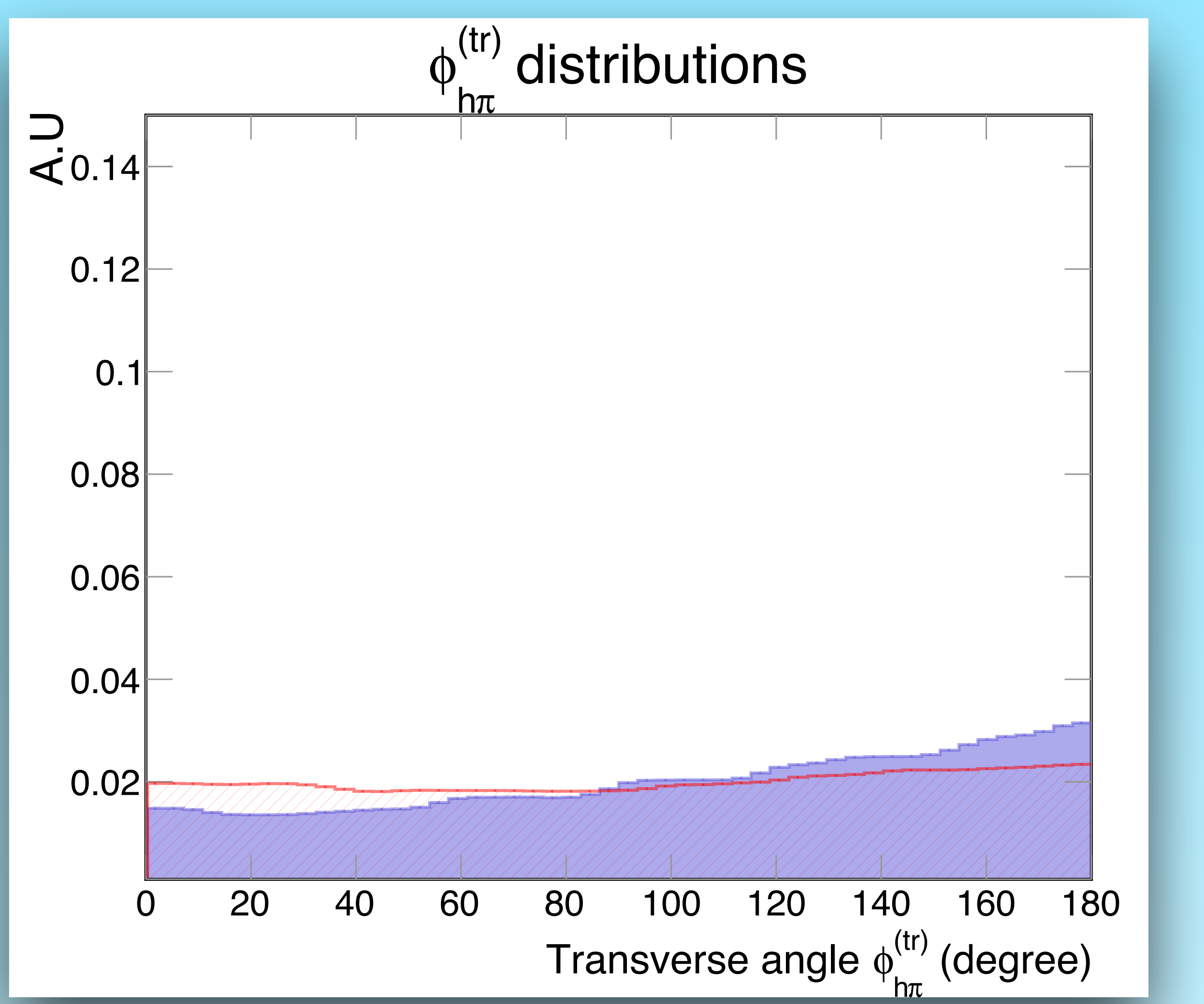
~ Subset of the variables used in the τ—>ρ analysis

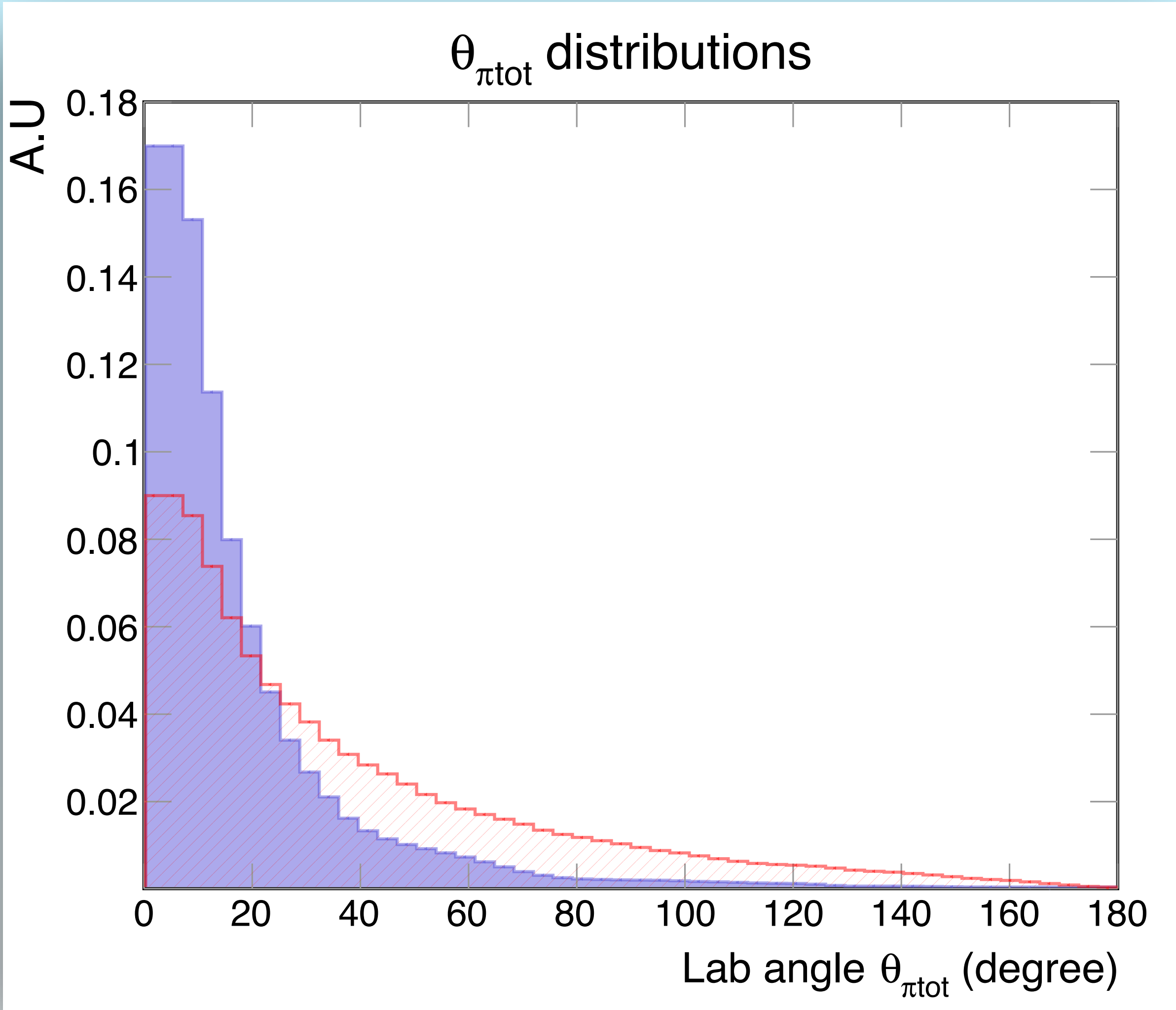
Back-up — $\tau^- \longrightarrow \pi^- \nu_\tau$ analysis Distributions

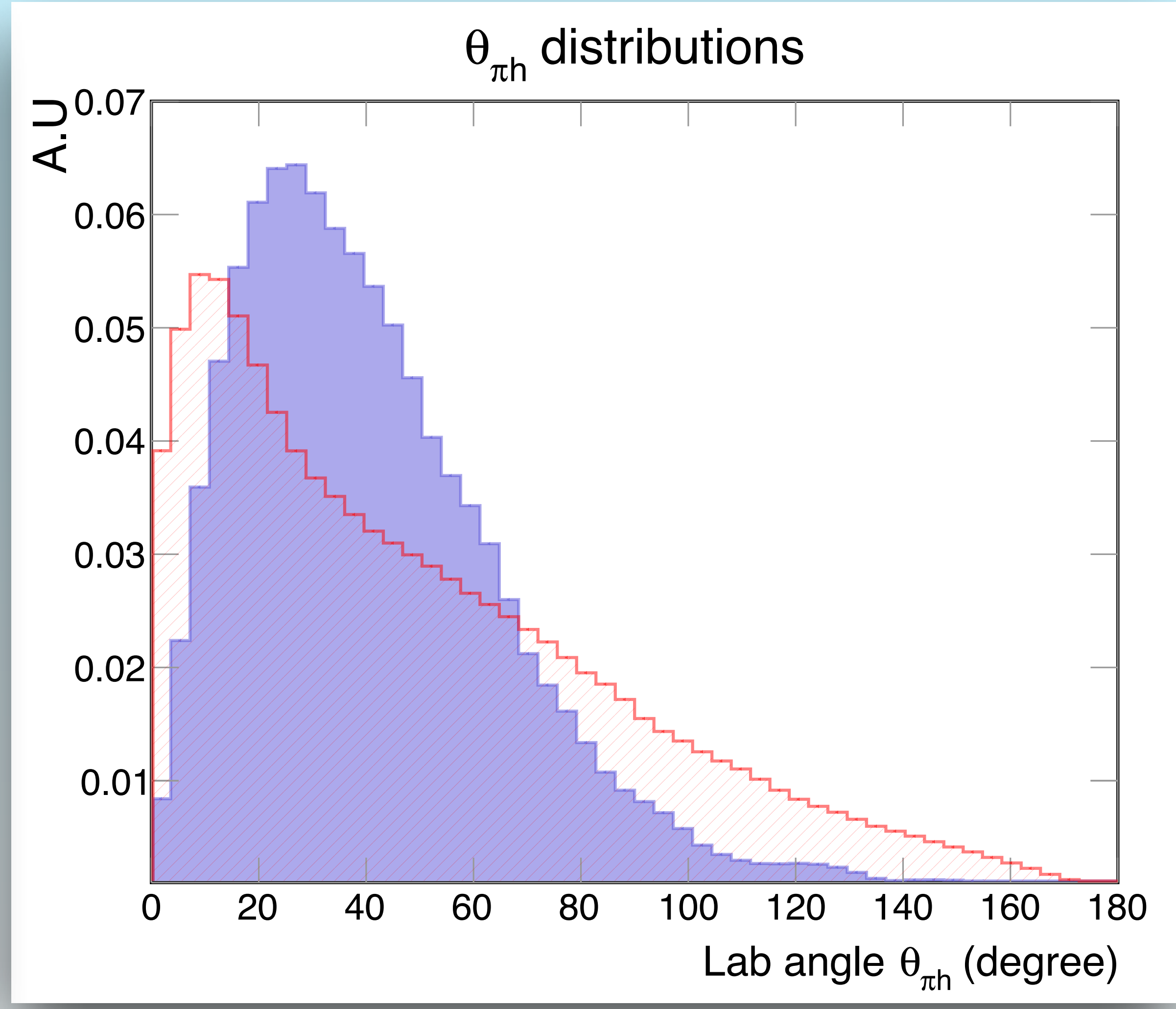


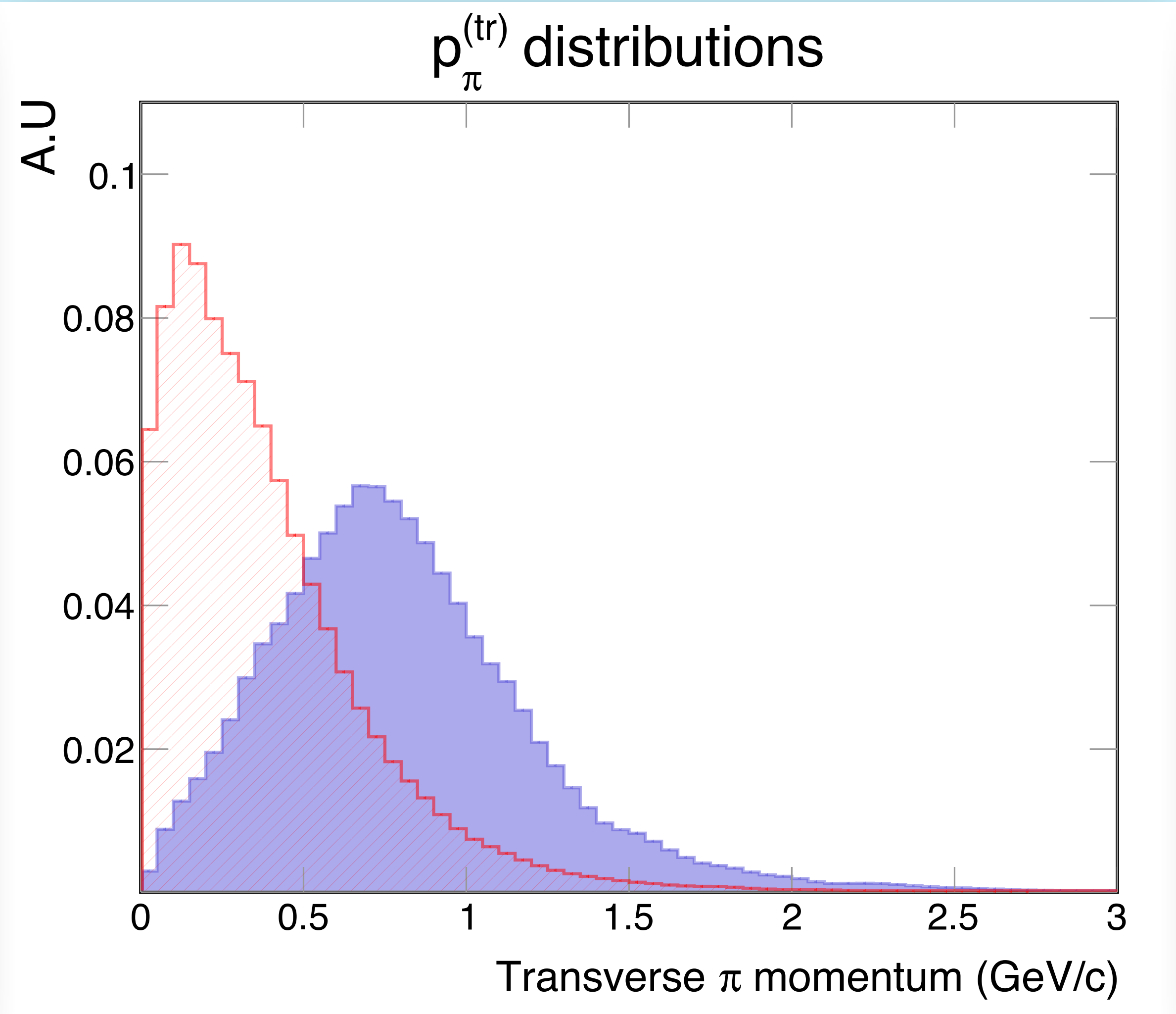


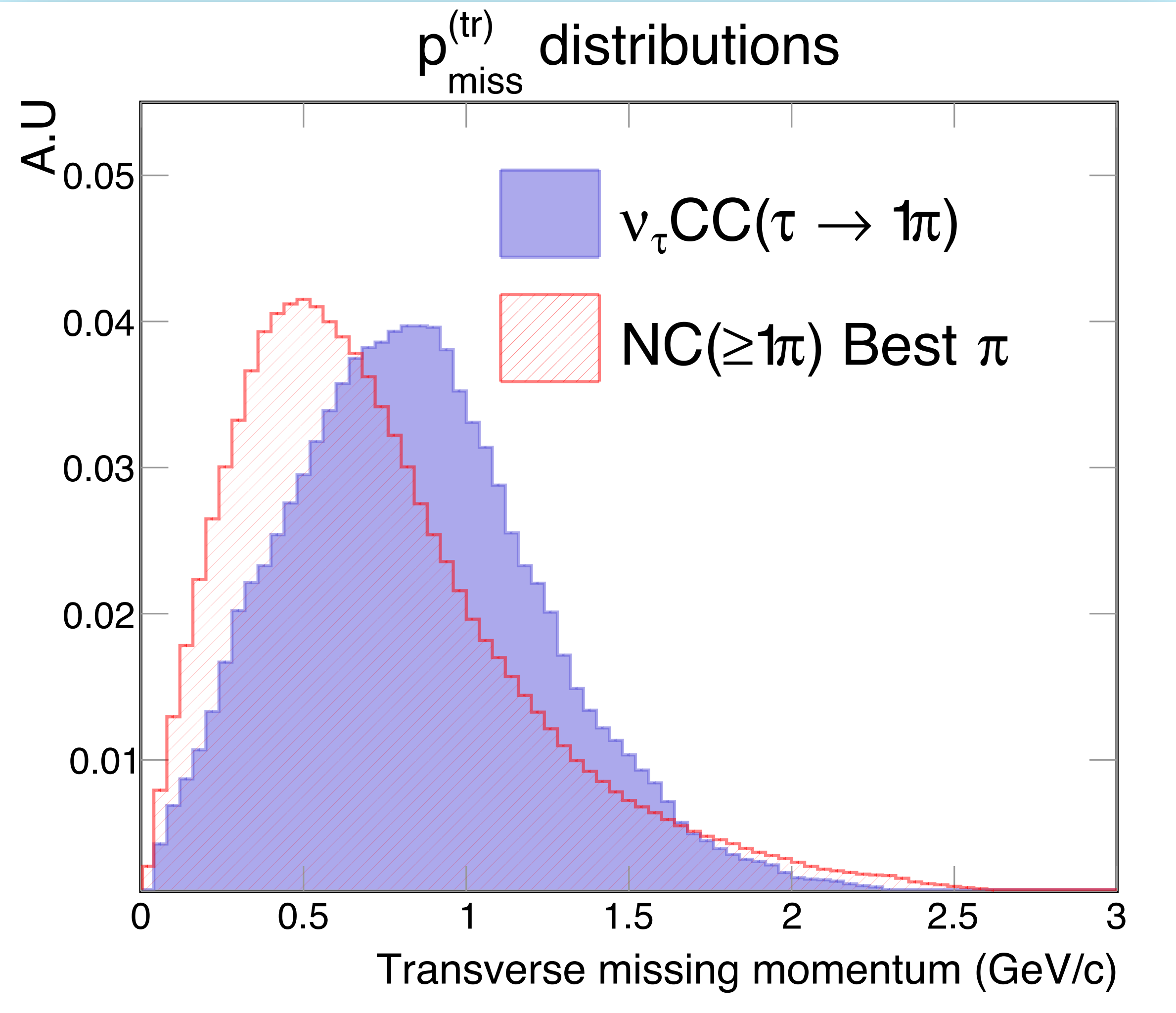




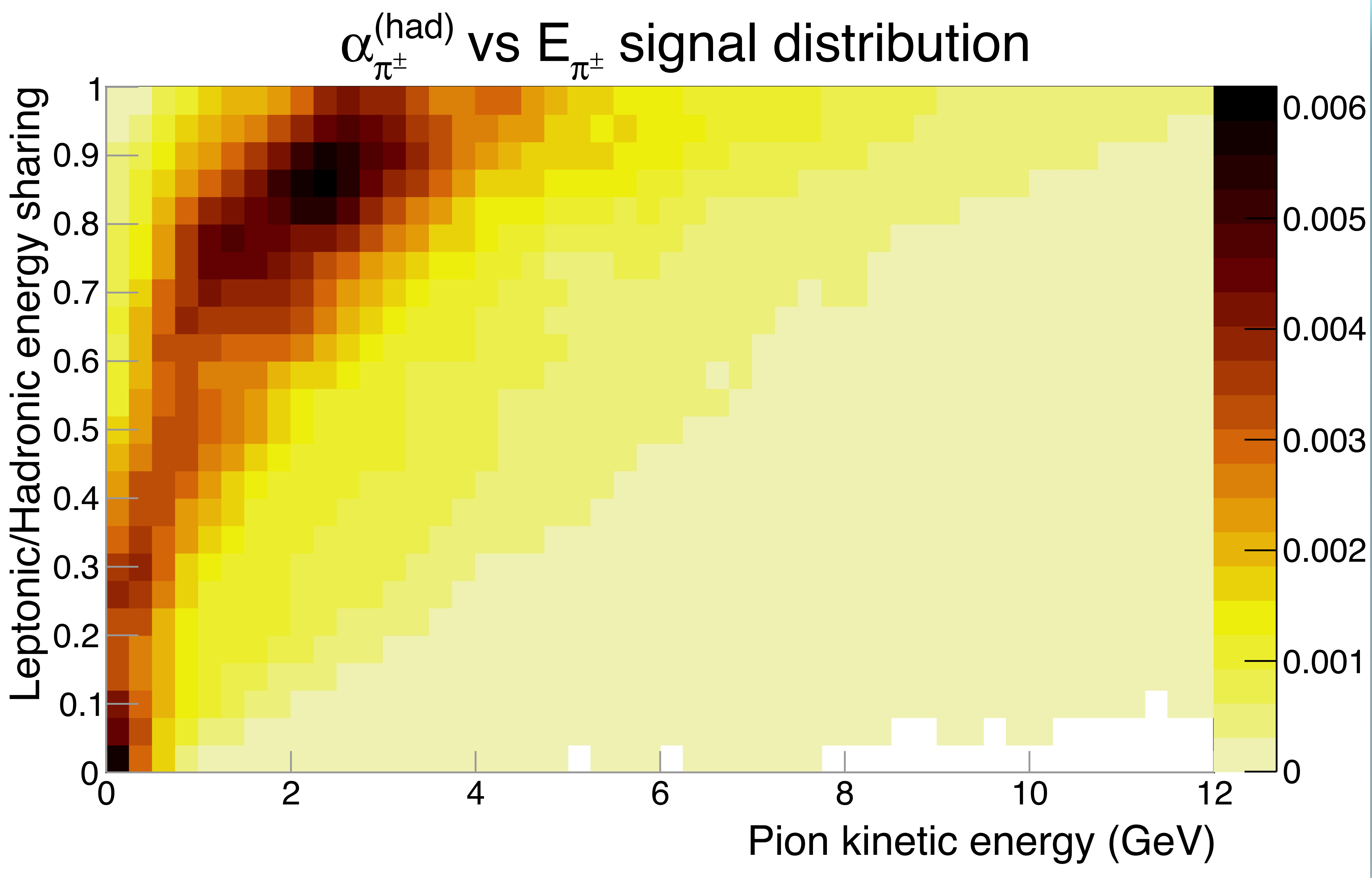


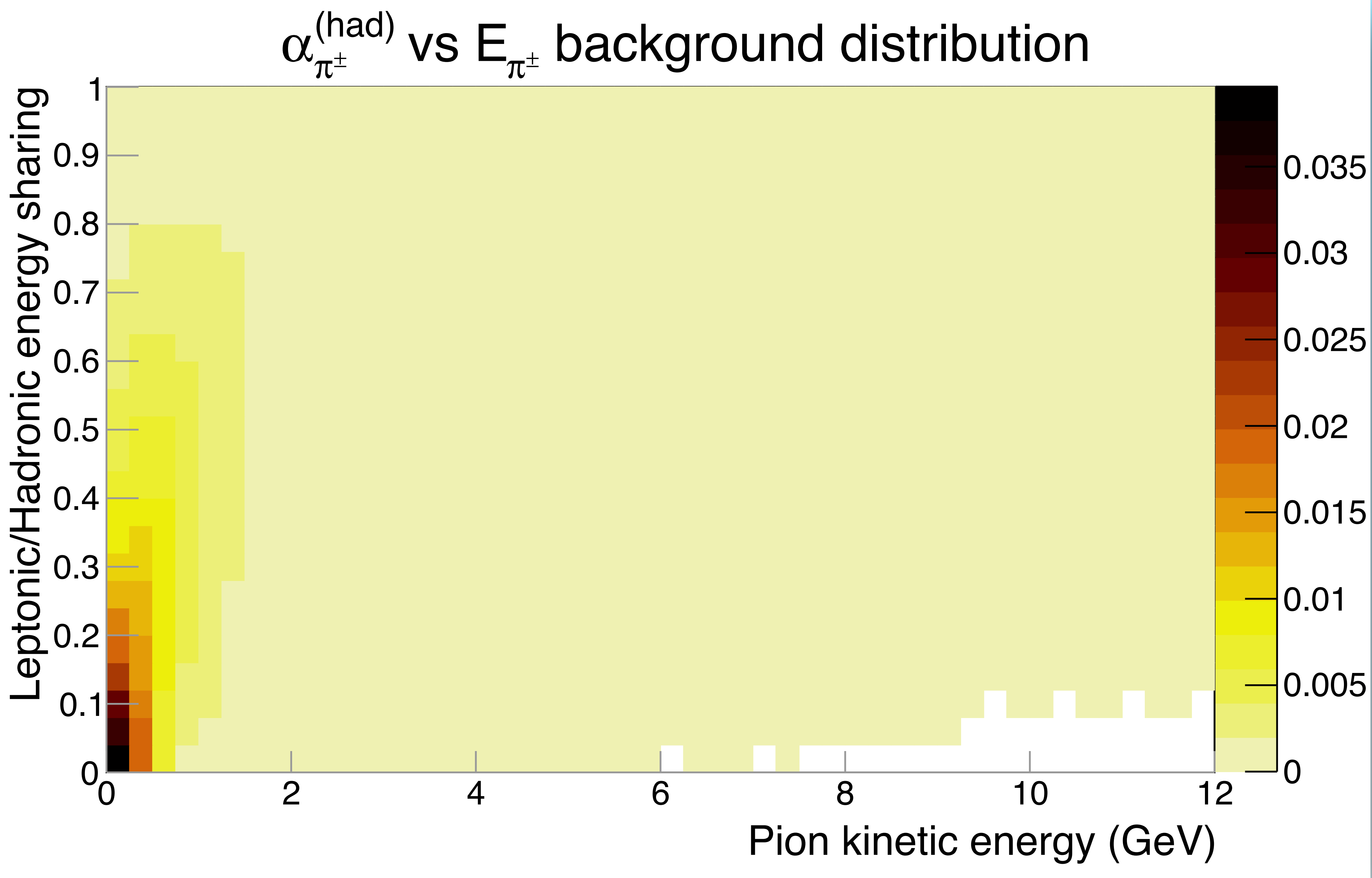






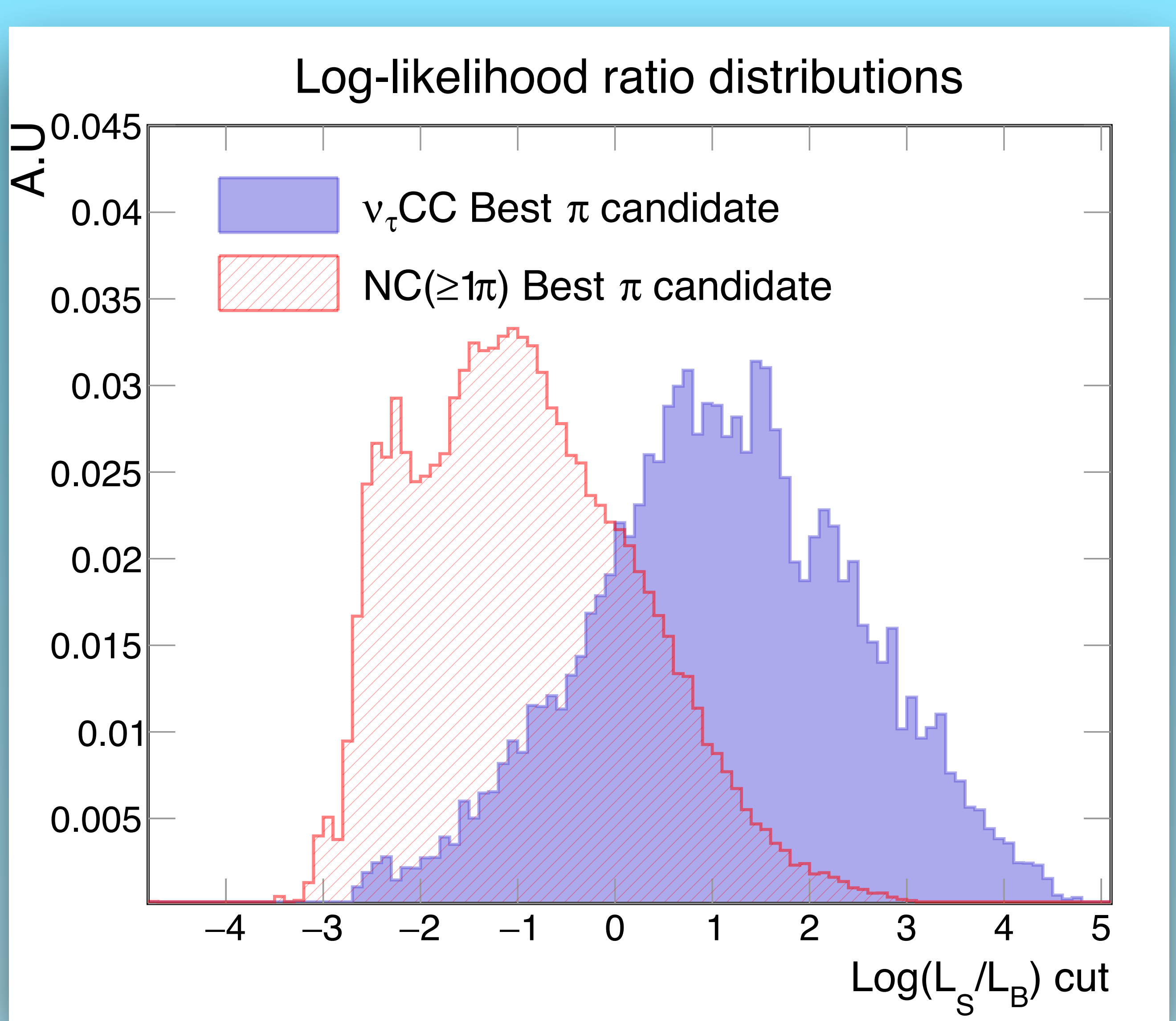
Back-up — $\tau^- \rightarrow \pi^- \nu_\tau$ analysis Distributions

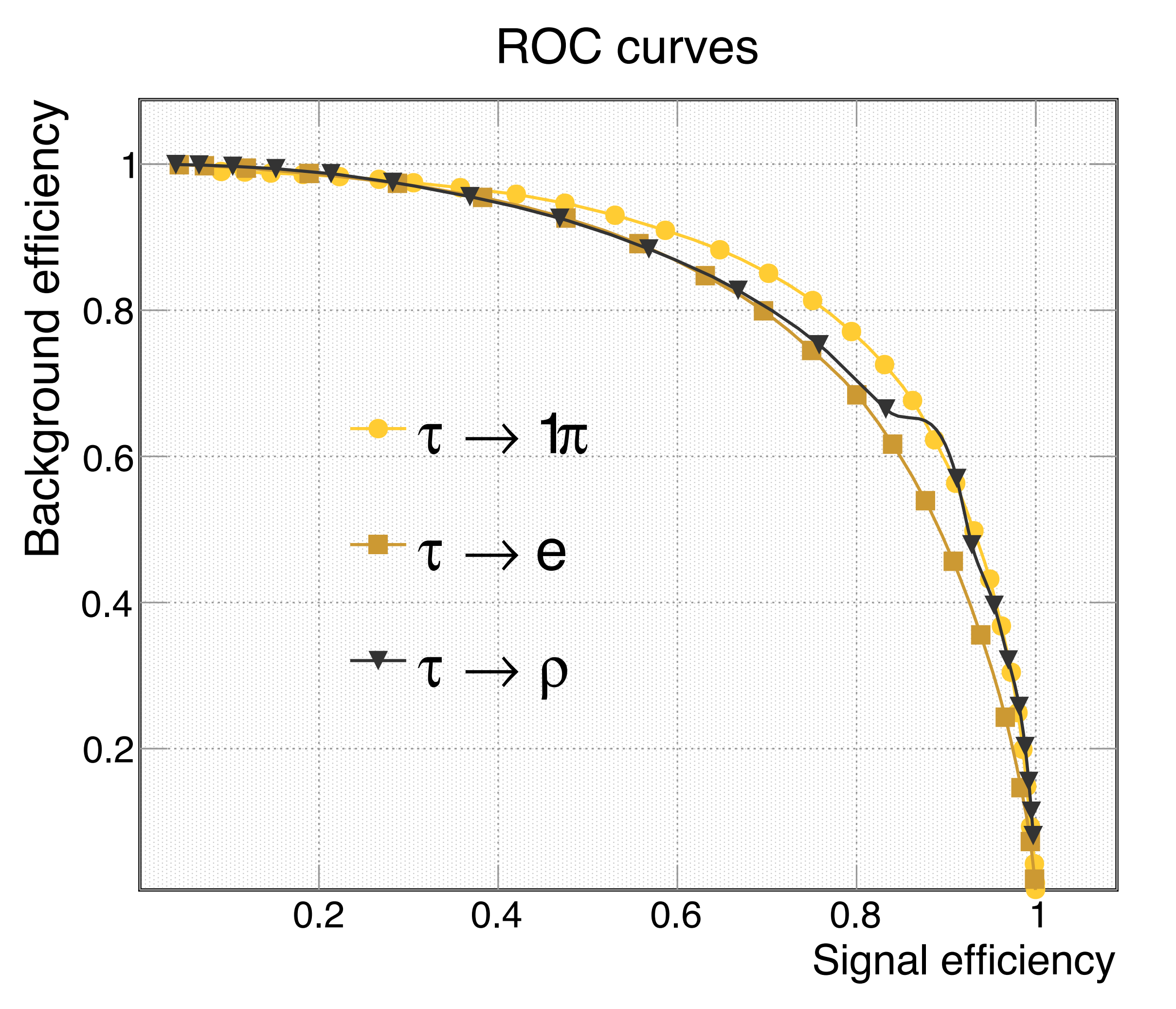


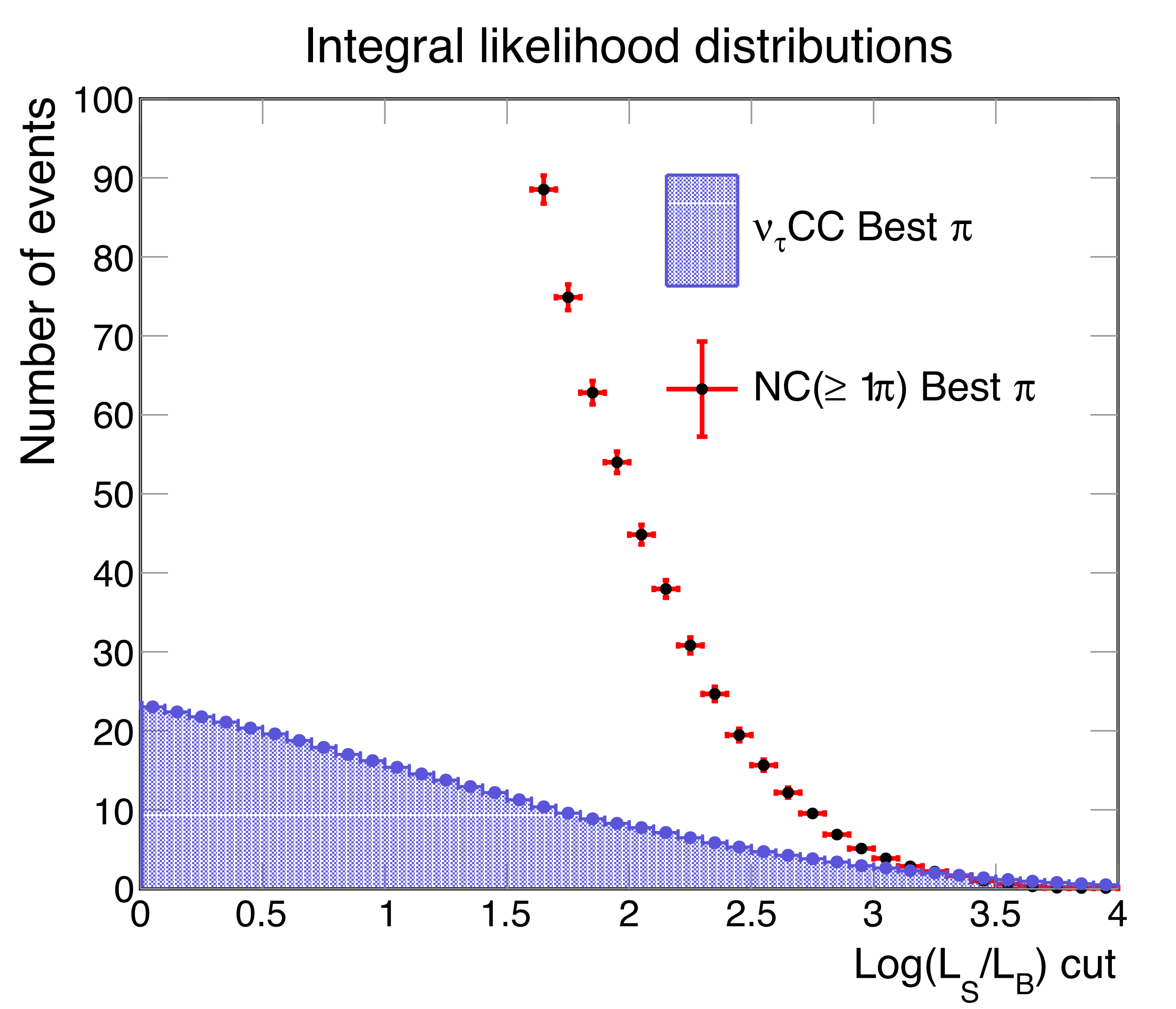


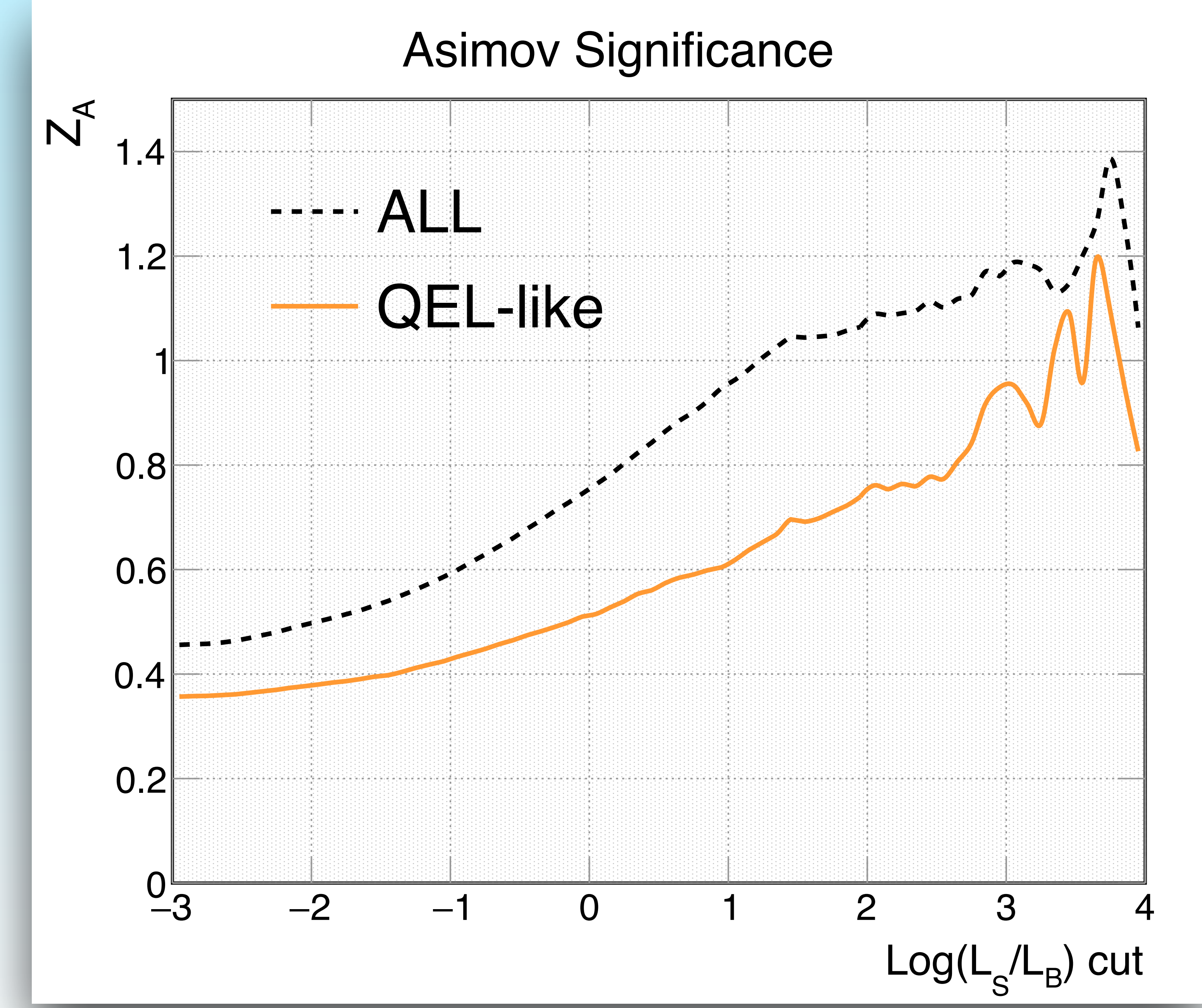
Back-up — $\tau^- \longrightarrow \pi^- \nu_\tau$ analysis   Likelihood results

Use the combination $$\left[\alpha_\pi^{(had)}; E_\pi^K\right] \times \left[\theta_{\pi tot}; \theta_{\pi h}\right] \times p_\pi^{(tr)}$$









- Decay mode analysis with the best S/B separation score
- Decay mode analysis with the least favourable inital S/B ratio (29/4169…)
- Thus least sensitive decay mode to study out of the three
- No improvement restricting to QEL-like events