TAU RECONSTRUCTION IN FULL SIM & TAU POLARIZATION

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on behalf of the tau team (CERN/KIT/MIT/CIEMAT)

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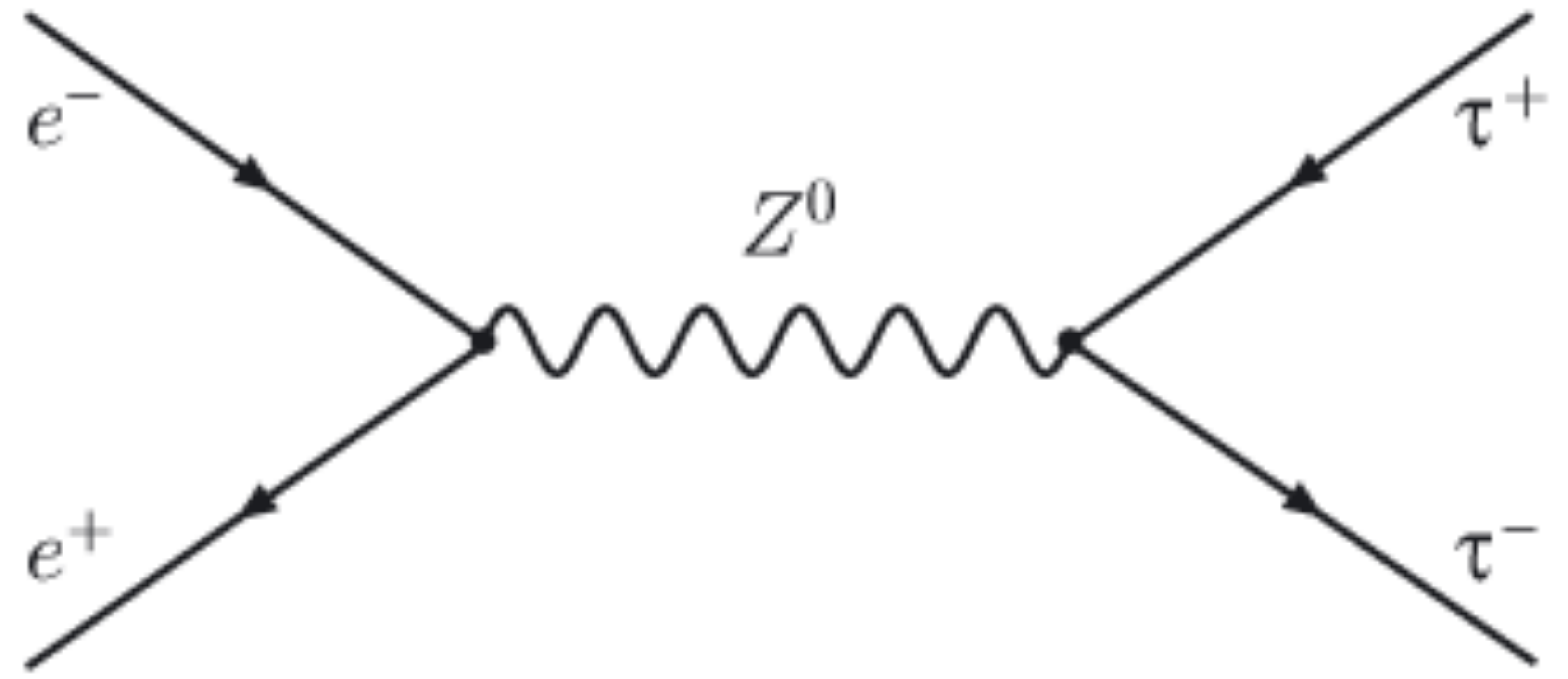
STUDYING THE TAU LEPTON AT FCC-ee

- **FCC-ee : a tau factory ?**
  - Huge $e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-$ sample (~10^{11})
    - $\sigma(e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-) = 1476.58\ pb^{-1}$ ($\sqrt{s} = 91.188\ GeV$, PYTHIA8)
  - Low-background environment with precise momentum reconstruction: high-precision measurements of tau properties

  ➡ Access to precision SM measurements and probes of BSM physics
- **Excellent benchmark for showcasing FCC potential. How?**
  - First step: algorithms for tau reconstruction in fullsim
  - Second step: physics! Showcasing tau polarization as a key SM measurement at FCCee



Working point	Z, years 1-2	Z, later
$\sqrt{s}$ (GeV)	88, 91, 94	
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140
Lumi/year (ab^{-1})	34	68
Run time (year)	2	2
Number of events	6×10^{12} Z	

TAU IDENTIFICATION

~65% of decays are hadronic

Main hadronic signatures: one or three charged hadrons + photons

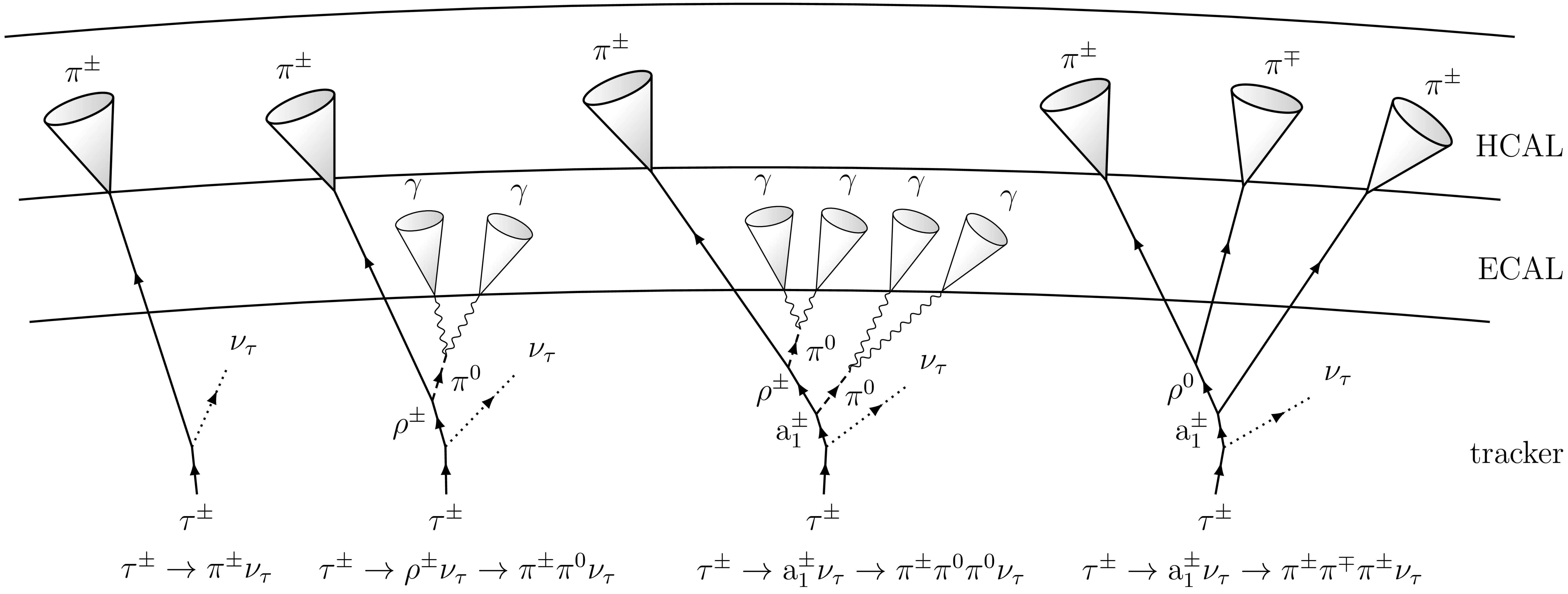


Image credit to Izaak Neutelings

Decay mode	Resonance	$\mathcal{B}$ (%)	
Leptonic decays		35.2	
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$			17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$			17.4
Hadronic decays		64.8	
$\tau^- \to h^- \nu_\tau$			11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$		25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$		9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$		9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8
Other			3.3

Low charge multiplicity. Jet invariant mass smaller than tau mass.

Identification relies on charged hadron and photon reconstruction, momentum resolution and efficiency/misid

Importance of π^0 reconstruction: photon identification and merging

Pion vs Kaon discrimination for rare decays

Missing mass, acollinearity, lepton momentum, lepton vetos as handles for dilepton/diphoton reduction. Missing p_T against diphoton

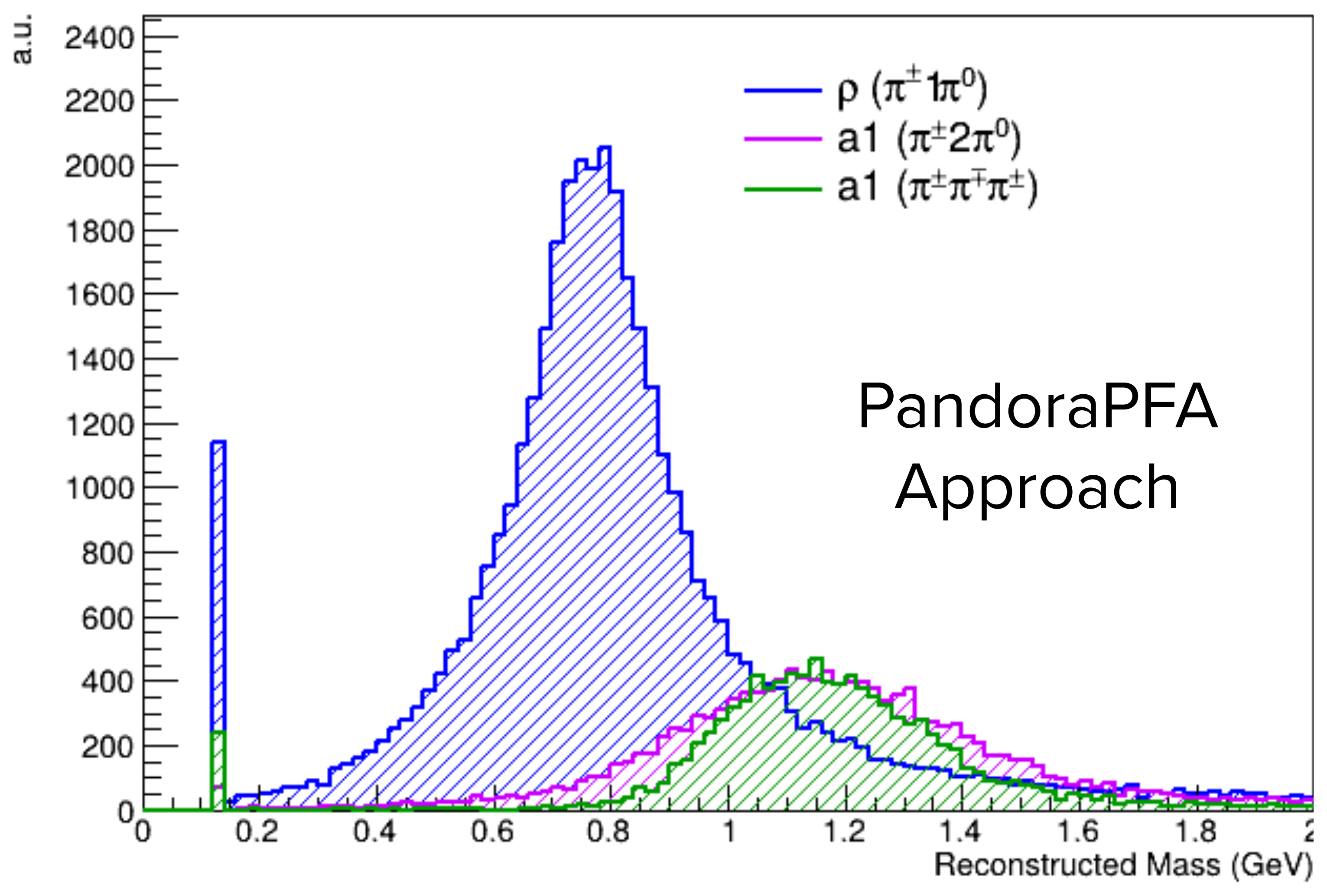
TAU RECONSTRUCTION STATUS

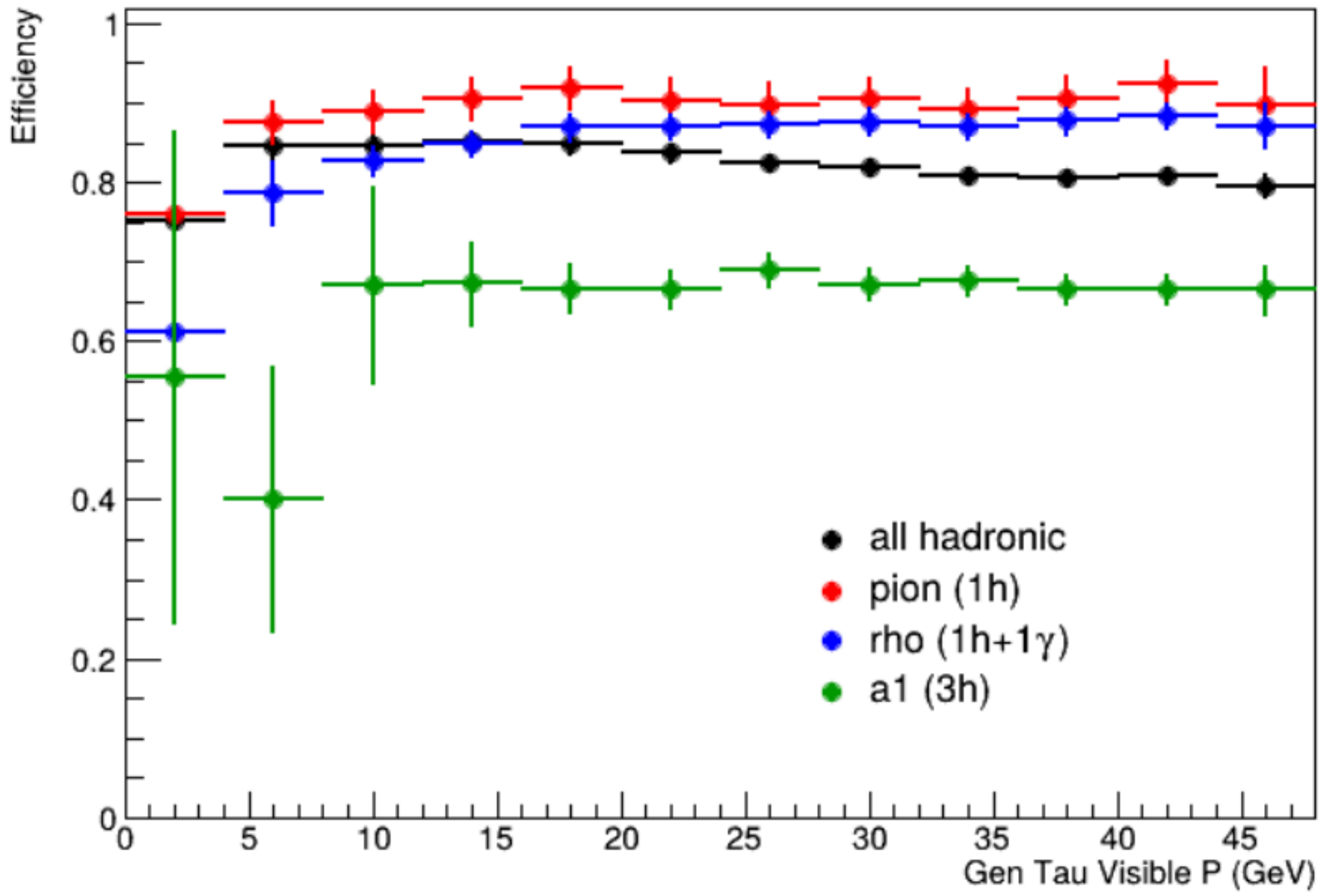
- **Delphes:**
  - Exclusive Decay Mode ID and ParticleNet: Both tested in ZH Htautau (see talk by S. Giappichini et al)
  - Note there is a dedicated ML tau reconstruction talk on Thursday by L. Tani

- **Full Simulation:**
  - Particle Transformer (Pandora-Based). Not fully studied yet, but checked in the context of Jet Flavor Tagging (S. Aumiller)
  - Exclusive DM, Pandora-Based: beta version used for tau pol studies
  - Full ML approach, GNN based: under development

TAU RECONSTRUCTION IN FULL SIMULATION: DM APPROACH

- First implementation of tau reconstruction with full simulation at FCC-ee!
- **Tested on full simulation of Ztautau (Pythia, 1M events) with CLD Detector Simulation**
- Double approach:
  - **Simple tau cone reconstruction based on PandoraPFA: first prototype**
    - Tau Identification from charged pion and photon multiplicity
    - Main Decay modes implemented (pion, ρ, a_1)
    - Good energy resolution and reasonable decay mode identification as a starting point
    - Efficiency and Purity limited by PandoraPF (pion efficiency, misidentification as neutral hadrons)
      - Possible to correct for this with a second layer on top of PandoraPF
  - **GNN approach (not reliant on Pandora)**





PandoraPFA Approach (*)	Reconstructed Tau ID						
	h	h+γ	h+2γ	h+3γ	h+4γ	3h	n
$\pi^{\pm}$	0.81	0.03	0.00	0.01	0.01	0.00	0.13
$\rho\ (\pi^{\pm}\pi^{0})$	0.03	0.21	0.59	0.07	0.01	0.00	0.09
$a_1\ (\pi^{\pm}2\pi^{0})$	0.00	0.02	0.09	0.31	0.39	0.00	0.10
$a_1\ (\pi^{\pm}\pi^{\mp}\pi^{\pm})$	0.02	0.00	0.00	0.00	0.00	0.74	0.16

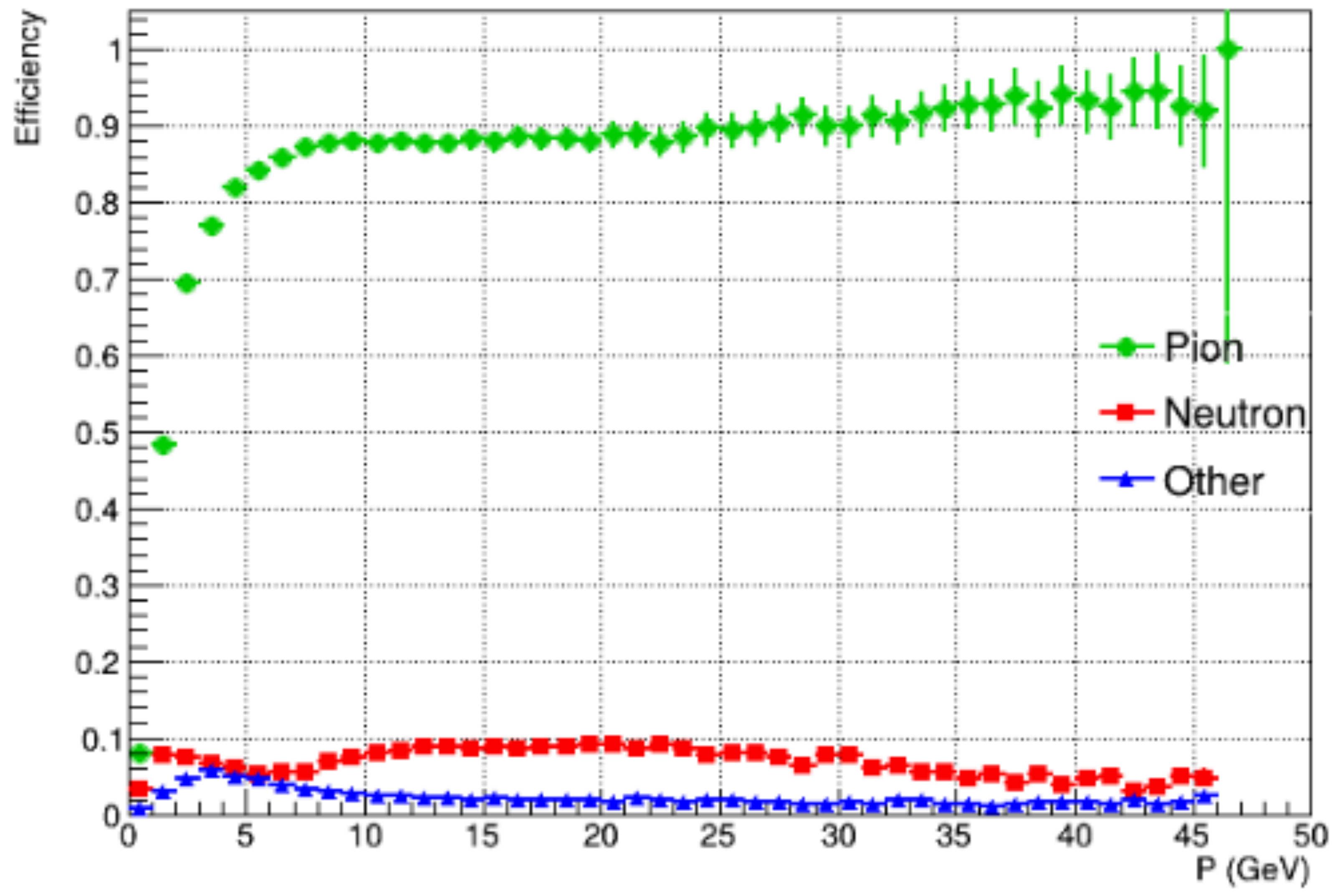
(* These are the preliminary efficiencies shown for ECFA, further tuning can be done, eg on the momentum of photons (here 0.5 GeV). The last Reco category, 'n', includes cases in which there is misidentification of pions as extra neutrons with p>1 GeV)

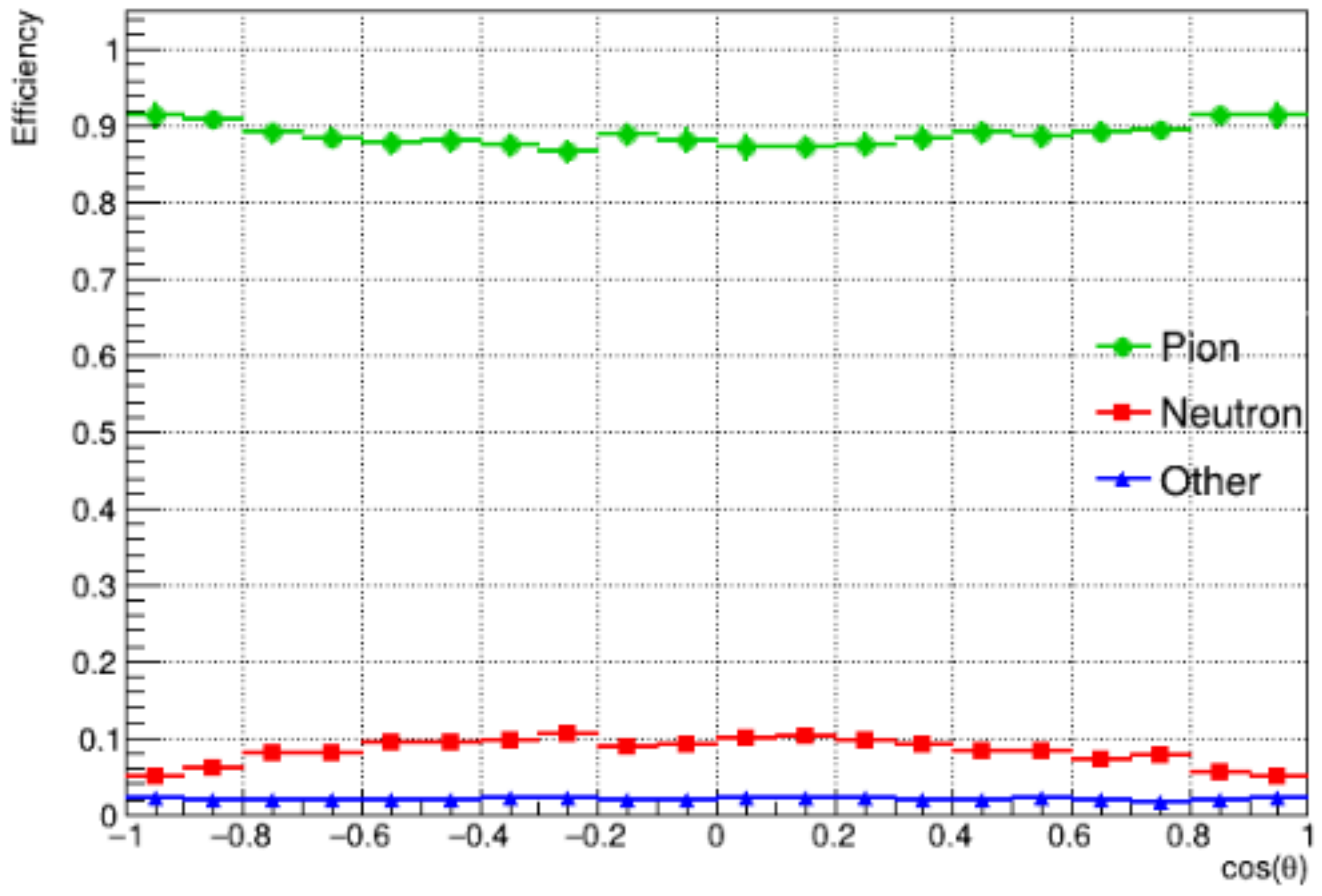
EFFICIENCIES IN PANDORAPFA

Pion efficiency

Notice pions being misidentified as neutrons

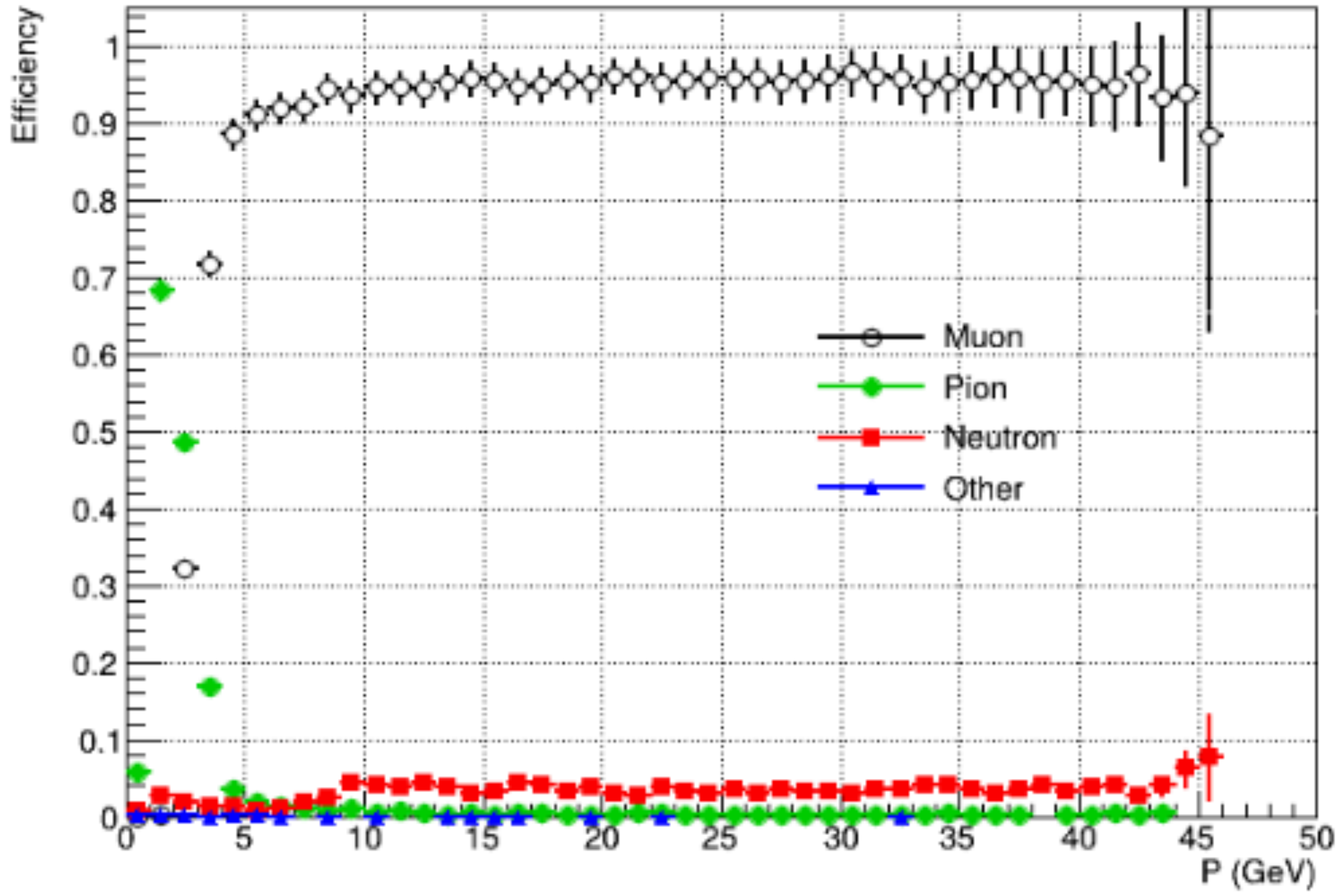
Plans to implement a fix with a second ID layer on top

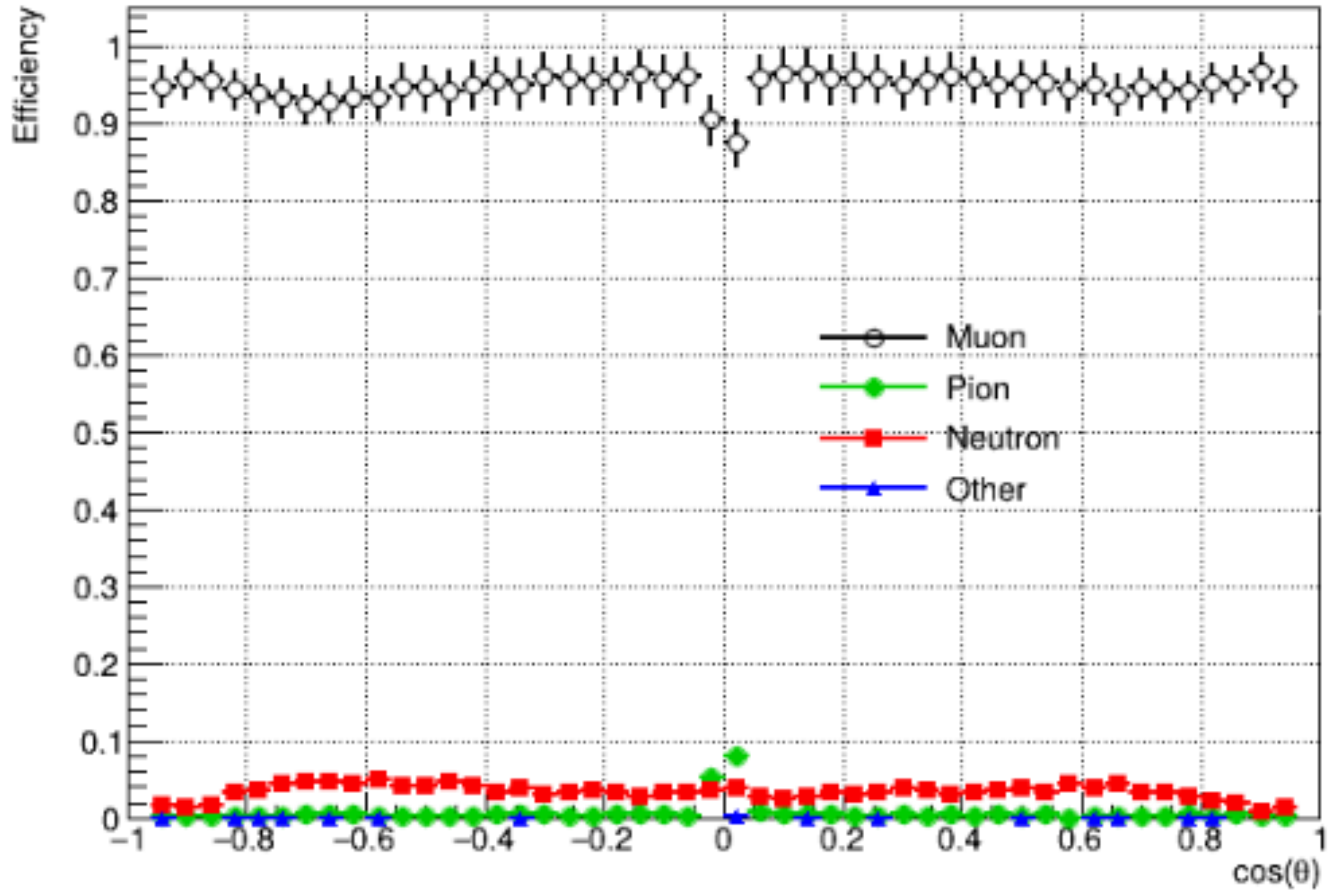




Muon efficiency

Reconstruction for muons changed to include MinTrackCandidateEnergy=4 (needed to improve efficiency in the 4-7 GeV range)

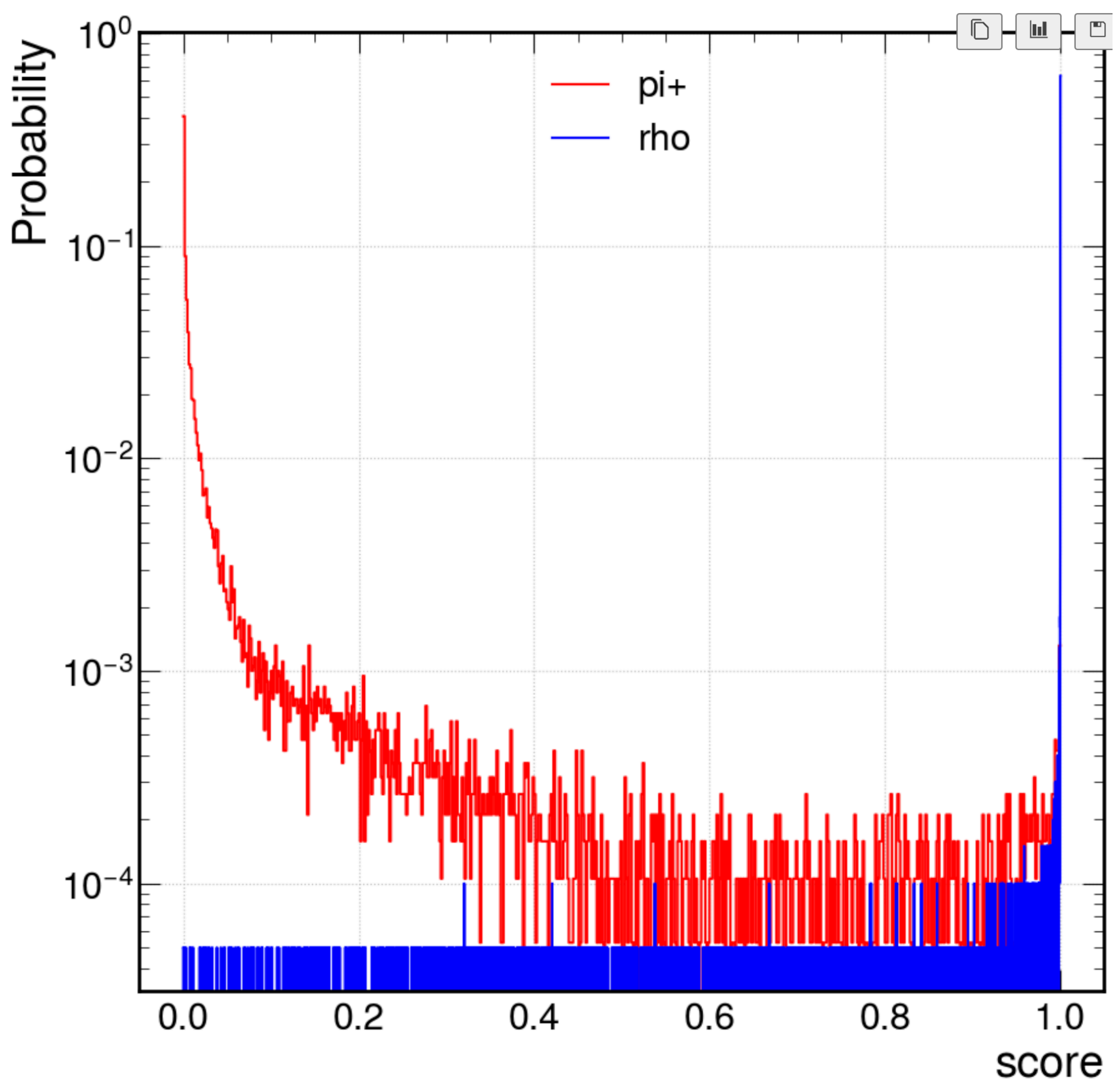


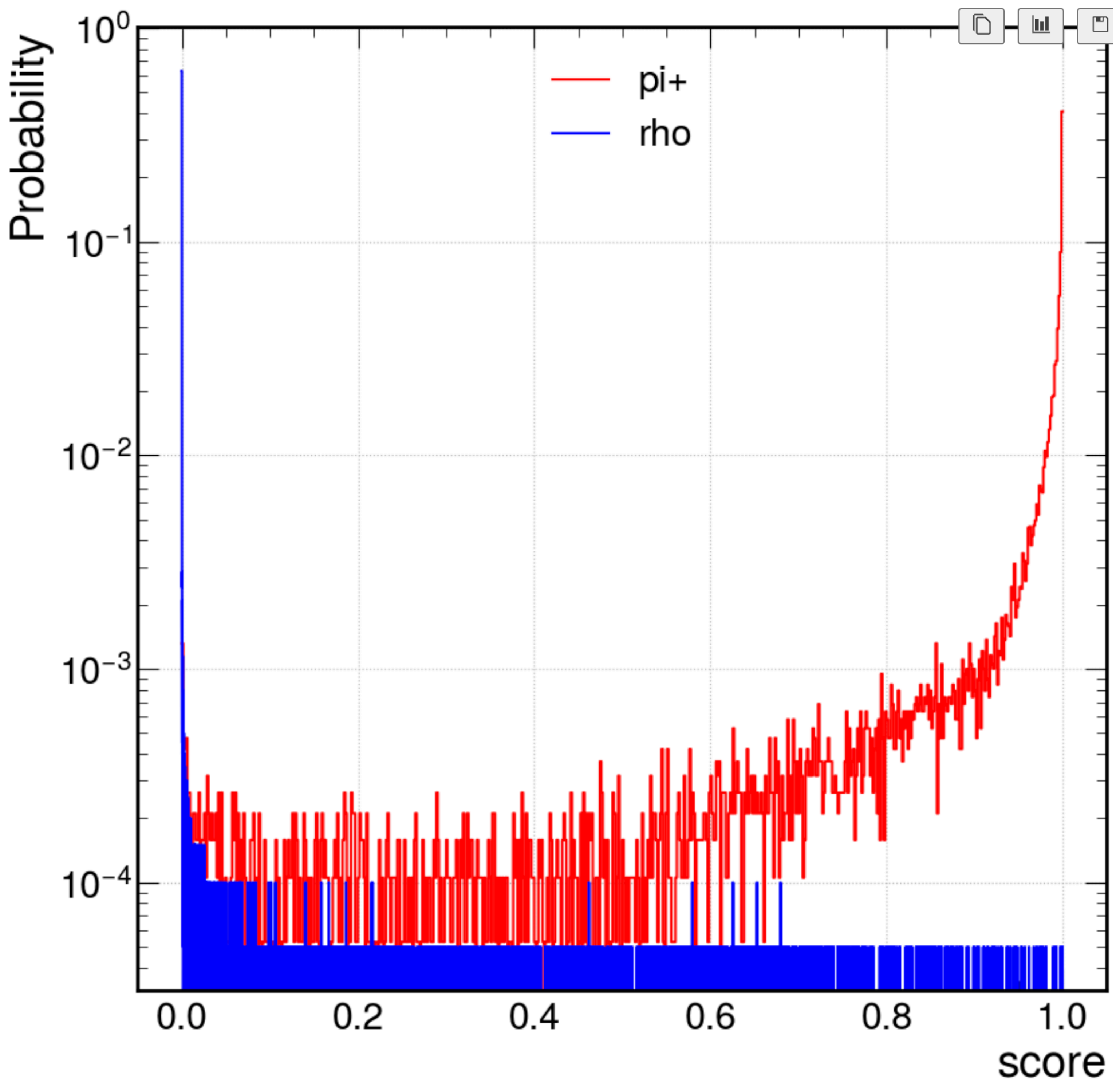


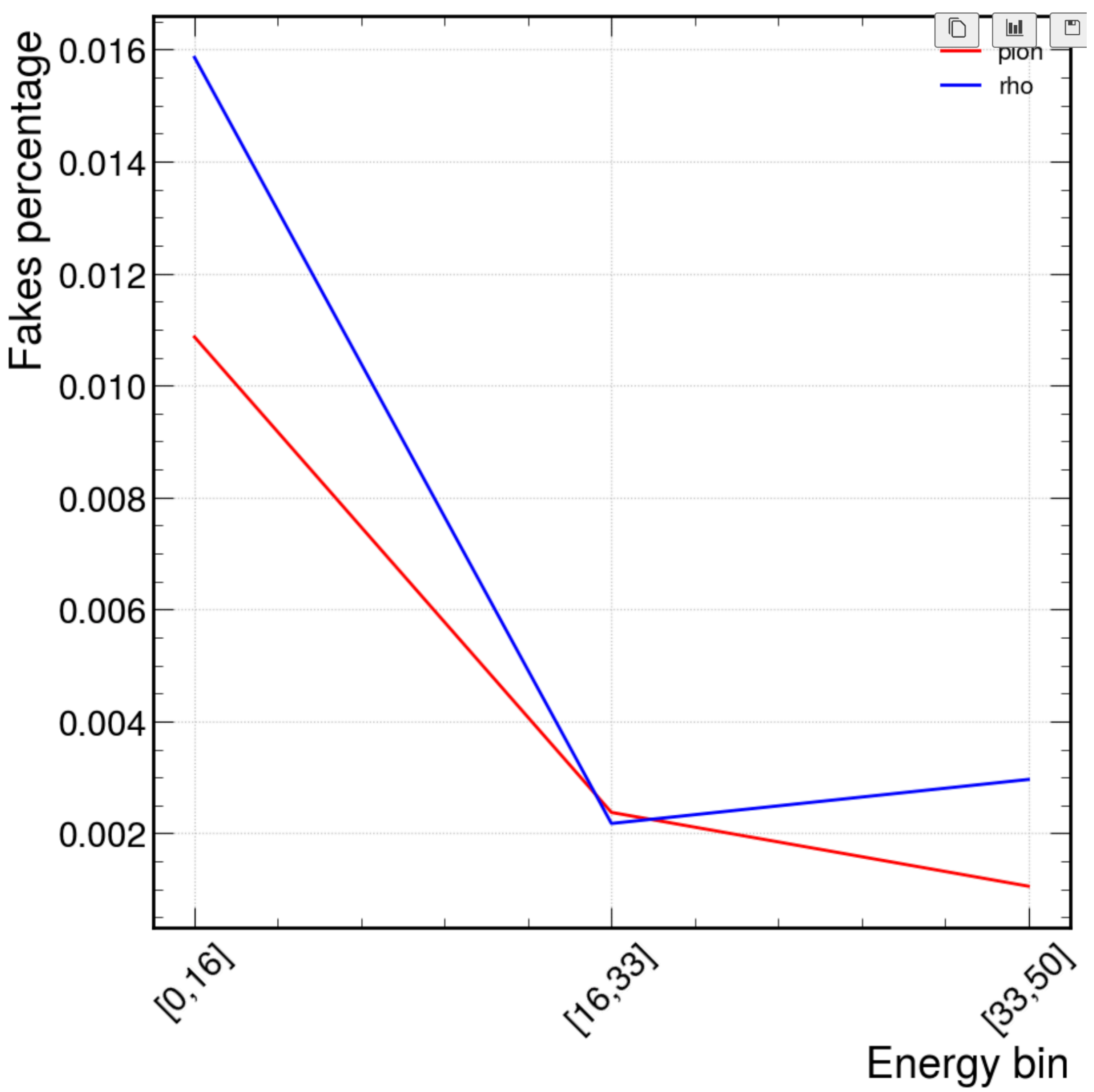
ML TAU RECONSTRUCTION IN CLD FULL SIMULATION

- **GNN approach (not reliant on Pandora):** excellent separation of rho and pion channels
- Model trained on pi, rho, e, mu generated with pythia exclusive decays (same number of taus per class)
- Inputs:
  - All ECAL and HCAL hits and the track state at calorimeter
  - Hits inputs are (x,y,z) coordinates in the detector, energy
  - Track inputs (x,y,z), momentum p

D. García

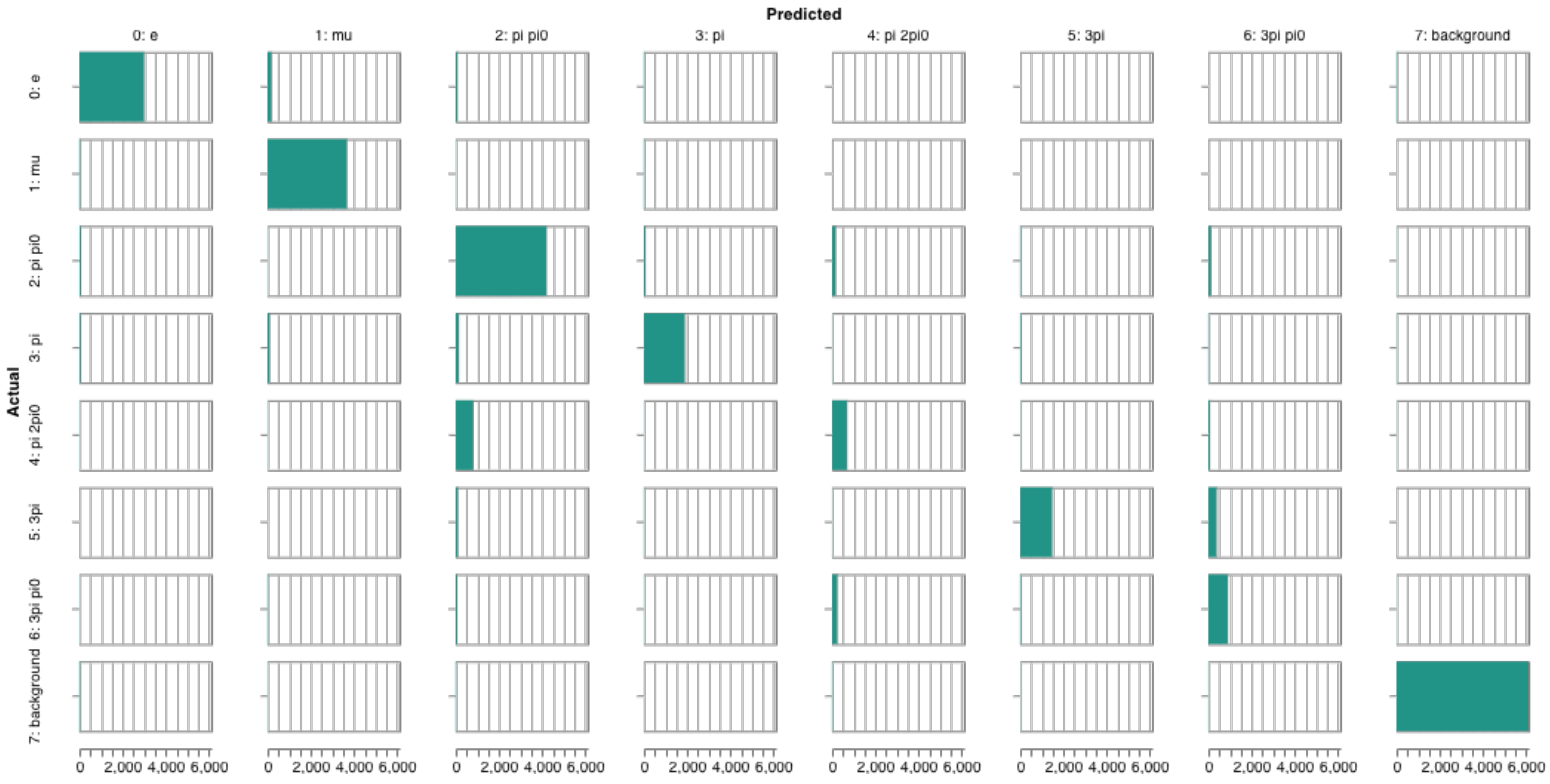


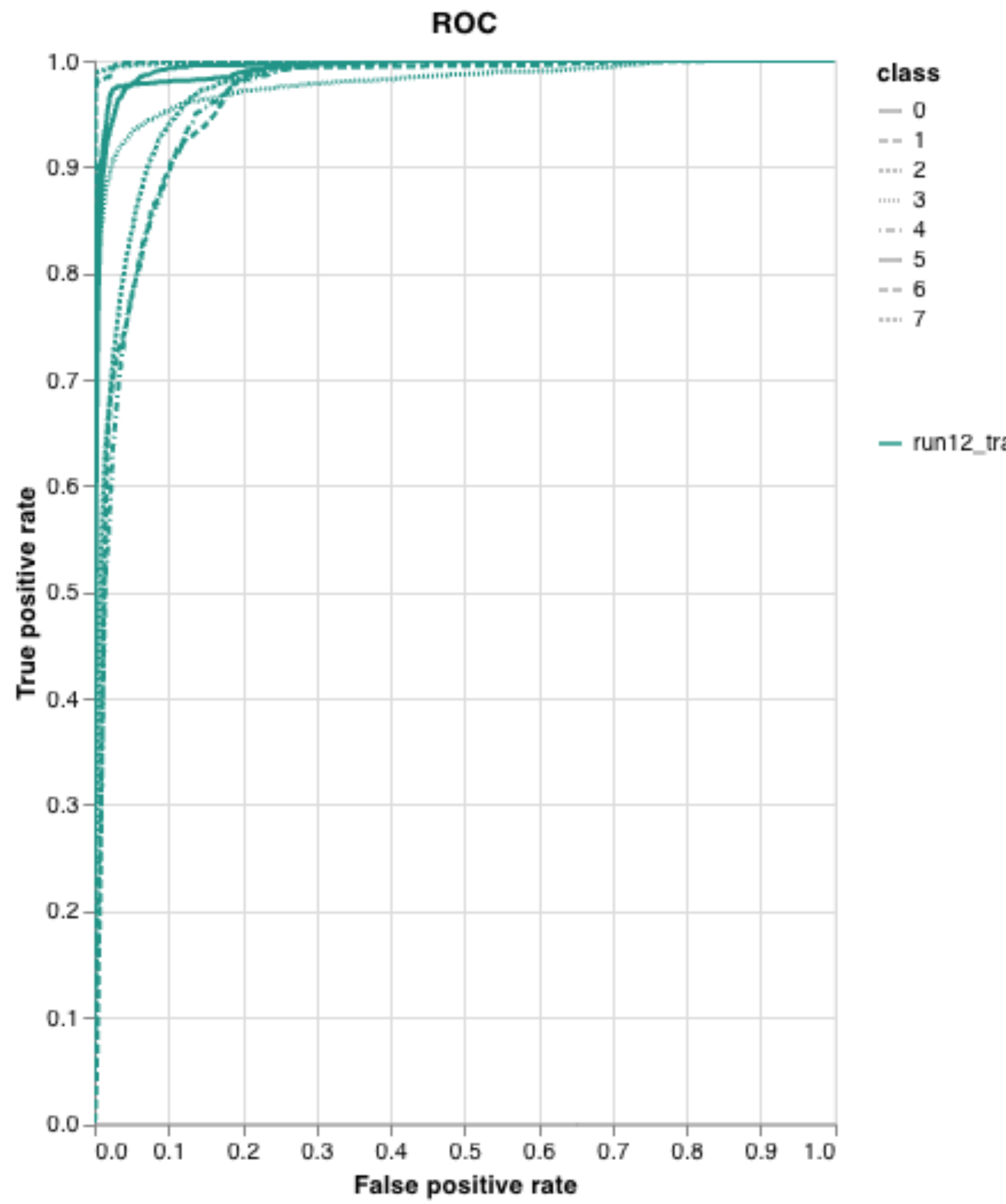




ML APPROACH RECONSTRUCTION

G. Brodbek
X. Zuo, D. García

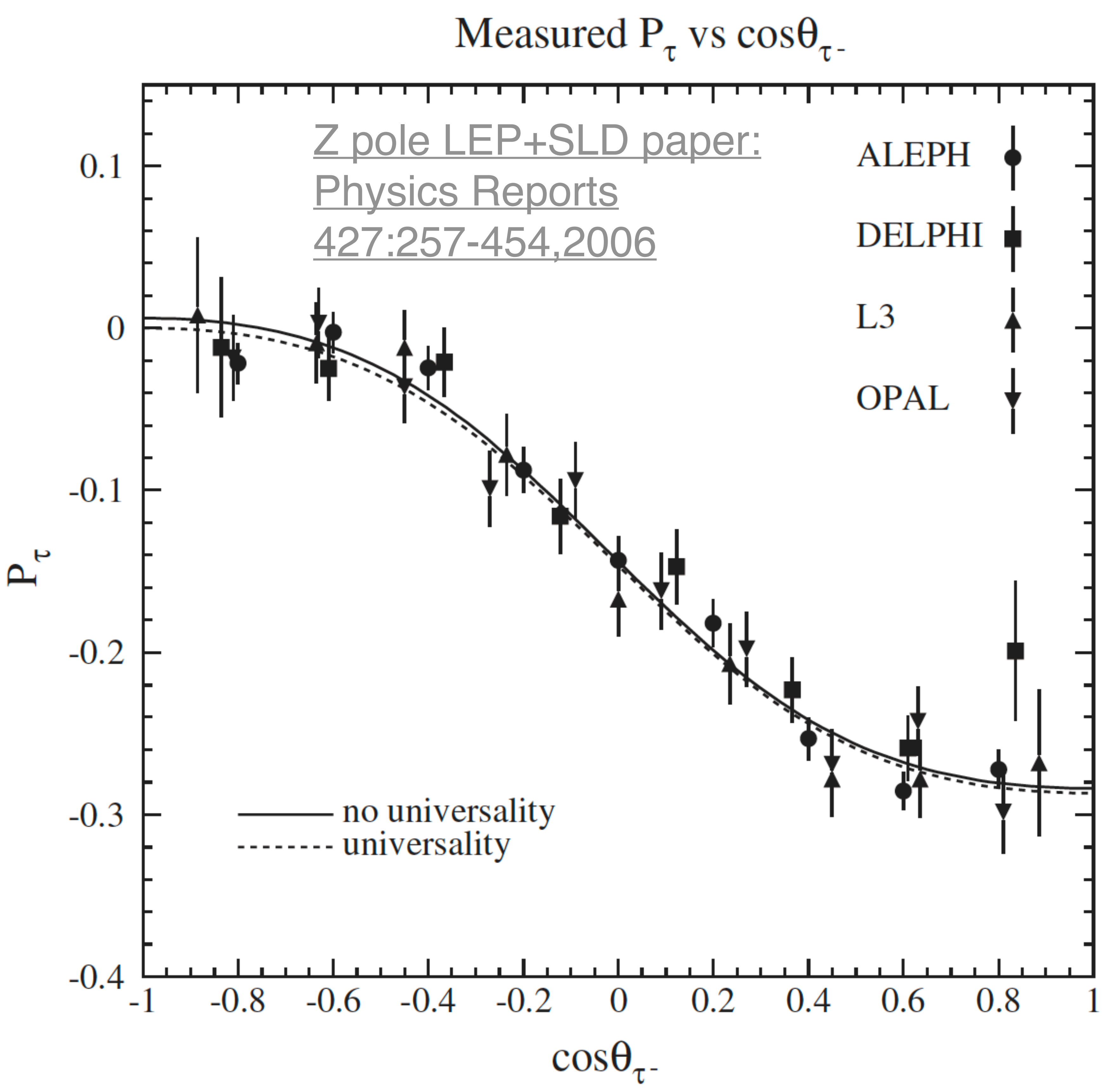




- Independent of Pandora: recovery of efficiency
- pi0 identification (resolved vs merged)
- “background" includes both Zqq events and Bhabha scattering events
- Identification vs Muons and Electrons also on a ML basis
- Slightly larger migration between rho/a1 categories than expected (under study)

- Next steps: combine the training with a reconstruction of the kinematics of the taus (by D. Garcia) and in depth comparison with DM-based.

TAU POLARIZATION MEASUREMENT BASICS



$$\mathscr{A}_e(LEP) = 14.98 \pm 0.48(stat) \pm 0.09(syst)$$
$$\mathscr{A}_\tau(LEP) = 14.39 \pm 0.35(stat) \pm 0.26(syst)$$

Probe of the vector and axial couplings of the Z. One of the most sensitive tests of electroweak parameters, including $\sin^2\theta_W$.

Rely on the dependence of kinematic distributions of the observed τ decay products on the helicity of the parent τ lepton.

$$\mathcal{P}_\tau \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

$P_\tau (\cos\theta)$: nearly independent determination of A_τ and A_e

At LEP: dominated by statistical uncertainty. At FCC-ee: dominated by systematic uncertainty

Start by looking at A_τ: larger impact of systematic uncertainties. Medium term plan: full analysis, both A_e and A_τ.

LEP UNCERTAINTIES

ALEPH: Eur.Phys.J.C20:401-430,2001

	A_τ						
Systematic effect	h	ρ	$3h$	$h2\pi^0$	e	μ	$acol$
eff. $h \to h$ id.	0.17	0.06	-	0.06	0.20	0.35	0.01
misid. $(e,\mu) \to h$	0.24	0.05	-	0.09	0.13	0.25	0.57
$\tau\tau$ selection	0.13	0.03	0.01	0.01	0.03	0.04	-
τ BR and background	0.04	0.05	0.03	0.09	0.01	0.02	0.02
tracking	0.08	0.07	0.22	-	-	0.21	0.30
γ-reconstruction	-	0.22	0.29	0.66	-	-	-
π^0-reconstruction	0.11	0.29	0.68	0.62	-	-	-
fake photons	0.31	0.17	0.28	0.75	-	-	-
ECAL scale	-	0.20	0.33	0.63	0.15	-	-
ECAL + HCAL cut	0.22	-	-	-	-	-	-
modelling	-	-	0.68	0.68	-	-	-
non-τ background	0.24	0.16	0.07	0.05	0.73	0.50	0.60
τ MC statistics	0.34	0.30	0.61	0.77	0.73	0.80	1.44
TOTAL	0.66	0.57	1.30	1.70	1.07	1.06	1.69

	A_e						
Systematic effect	h	ρ	$3h$	$h2\pi^0$	e	μ	acol
tracking	0.04	-	-	-	-	0.05	-
non-τ background	0.13	0.08	0.02	0.07	1.23	0.24	0.24
modelling	-	-	0.40	0.40	-	-	-
TOTAL	0.13	0.08	0.40	0.41	1.23	0.24	0.24

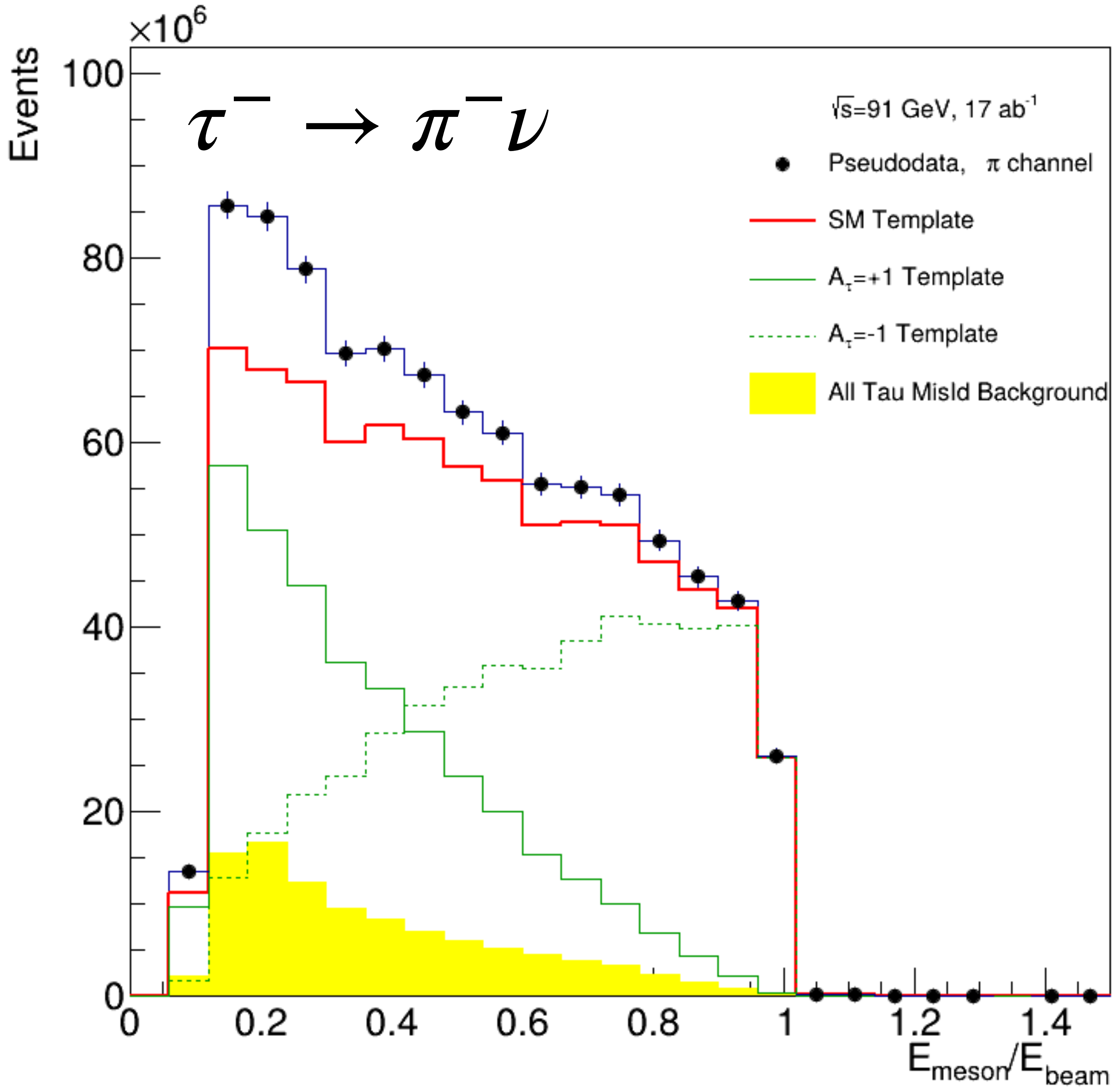
Physics Reports 427:257-454,2006

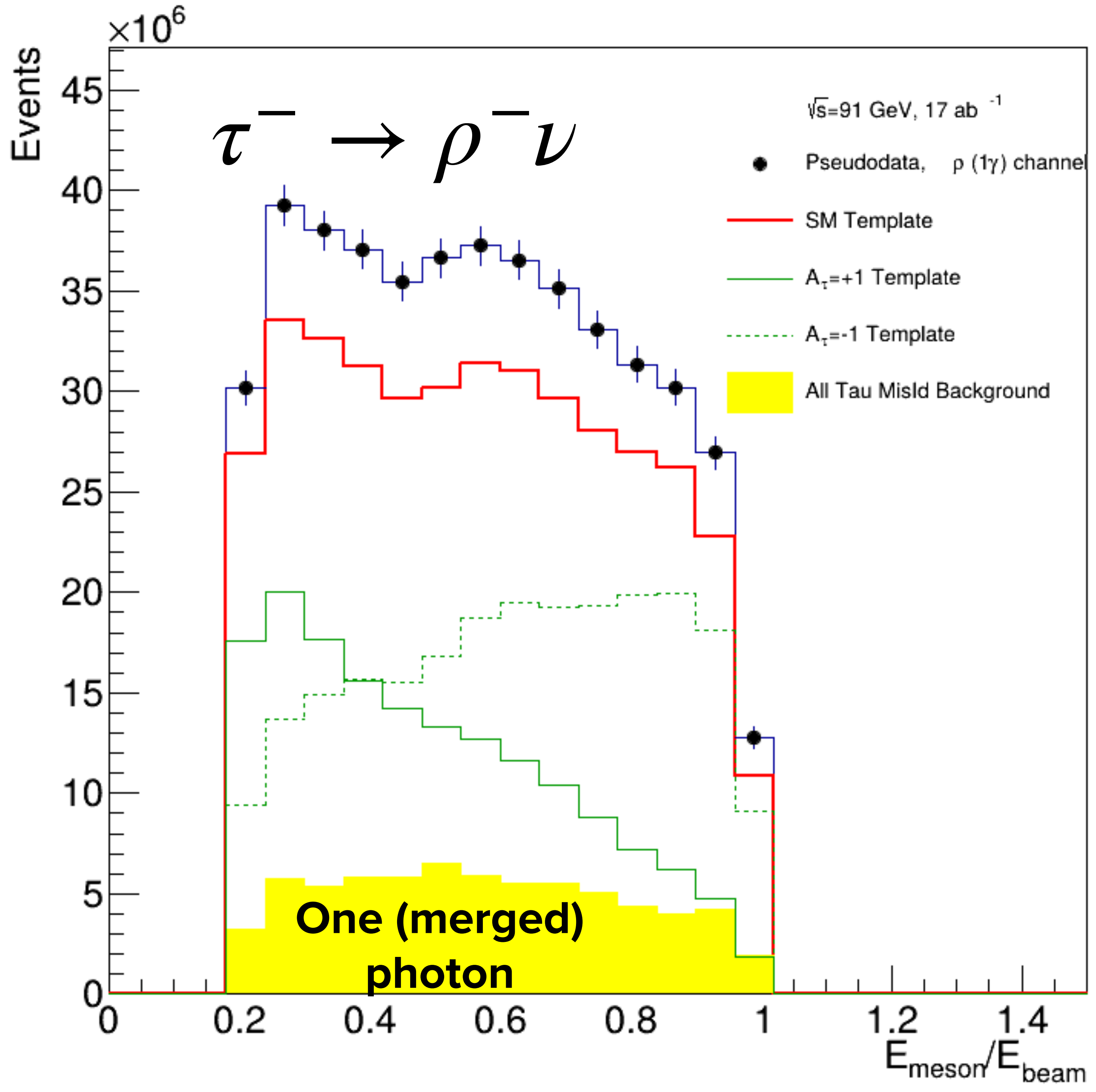
Experiment	$\mathscr{A}_\tau$	$\mathscr{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$

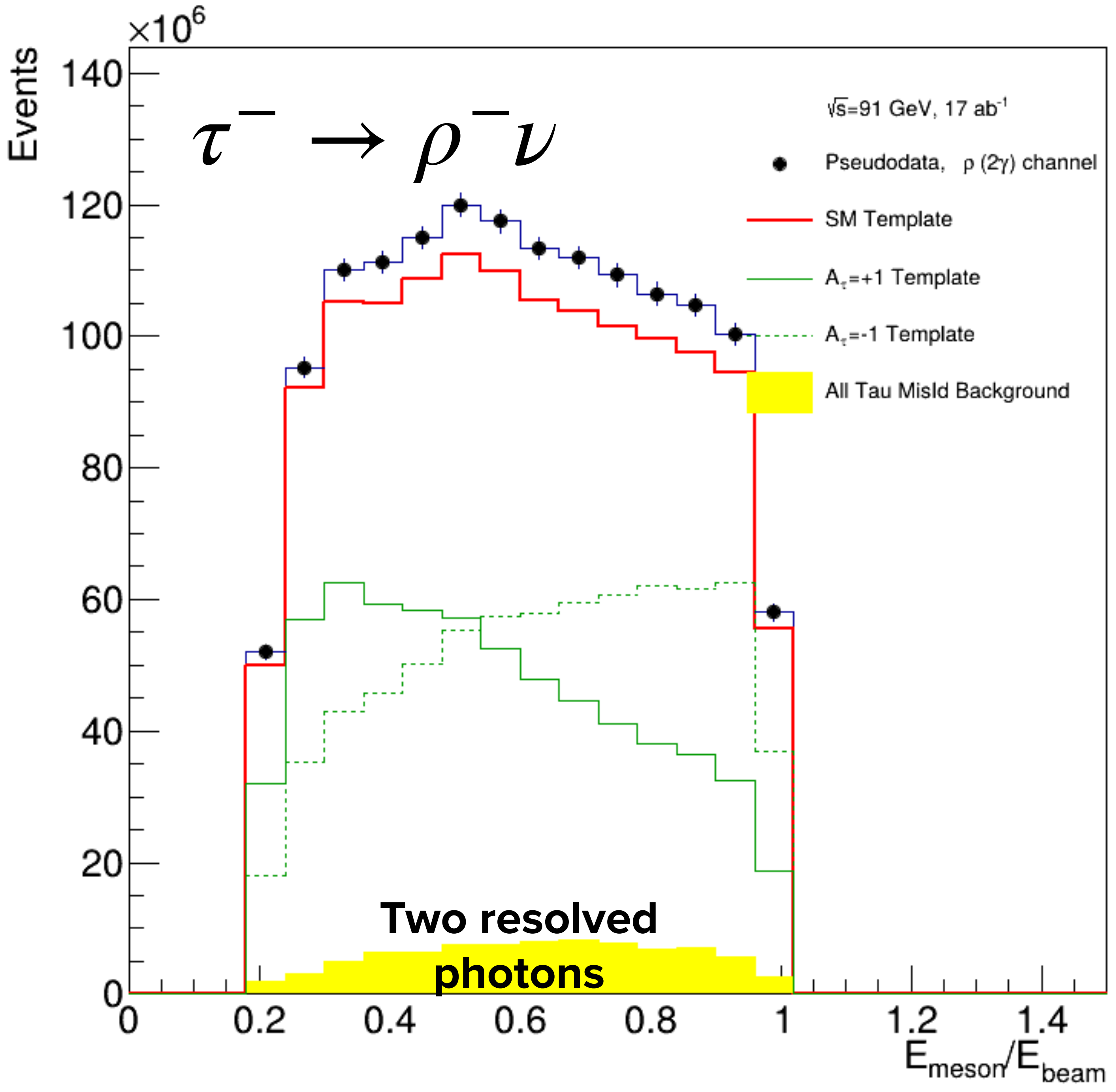
- Main modes: pion and rho decays
- Low momentum track and photon identification is key
- Uncertainties vary largely between LEP experiments, by almost a factor of 2: importance of detector concept. Full simulation needed to do a proper assessment of FCC-ee sensitivity.
- At FCC-ee: large samples for determination of track and photon efficiencies, scales: expect much smaller uncertainties overall
- **Assuming a factor of 10 improvement in systematics wrt to the LEP detectors (from the combined result), A_τ systematic uncertainty < 0.02%**

STUDY OF TAU POLARIZATION AT FCC-EE RECONSTRUCTION

- **Setup of the polarization study using FullSim Pythia simulated samples (CLD detector): exercise in a 'real' analysis the tau reconstruction algorithms developed for FCC-ee**
  - Note that the MC statistics that we have right now are much smaller than the real data sample: only 1M Ztautau events: to be fixed
  - For now we are using the Pandora-based exclusive DM finding algo, will be compared to ML in the future .
- **As a first approach: $Z \rightarrow \tau_l \tau_h$ selection (only one hadronic tau + one muon or electron)**
  - For now, target the two main decay modes: **PION $\tau^- \rightarrow \pi^- \nu$ and RHO $\tau^- \rightarrow \rho^- \nu$**
  - In the ρ channel: important to study π^0 reconstruction. Splitting categories with merged photon vs 2 resolved photons
  - Backgrounds driven by photon & pion identification (ρ contamination in pion channel, $\pi^- \pi^0 \pi^0$ in rho channel with two resolved leptons). Further reduction of background possible.

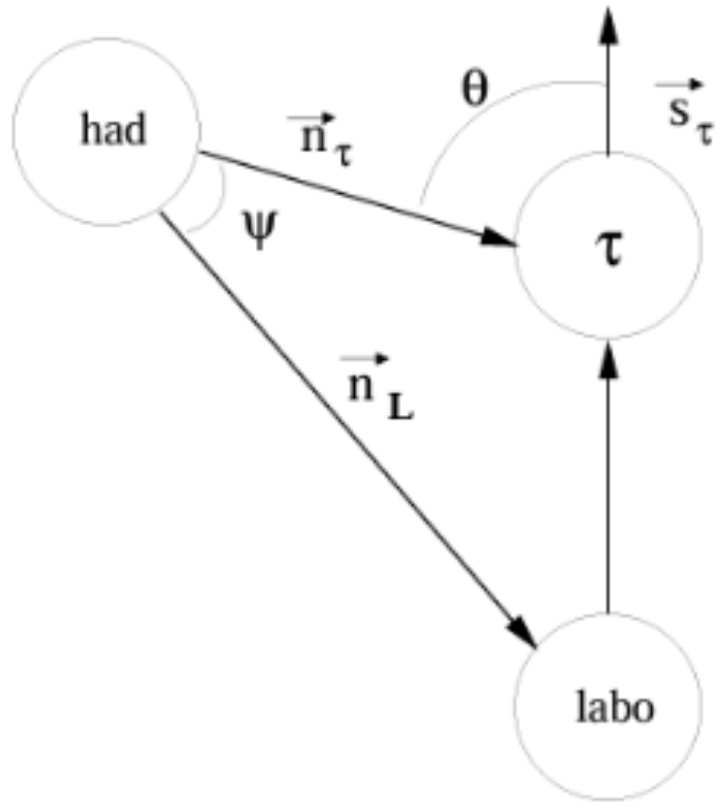






OPTIMAL VARIABLES WITH FCC-ee FULLSIM?

- Study of In depth study of optimal variables in progress
  - $x = E_{meson}/E_{beam}$ **can be enough as polarimeter for pion channel (as in LEP)**
  - **Not sufficient for Rho: LEP-like ω_ρ for rho channel**
    - Following the description of the variables in two LEP thesis: L. Duflot ('93) and I. Nikolic ('96)
    - This version of the variables does not require to reconstruct the tau direction (left to future iterations)

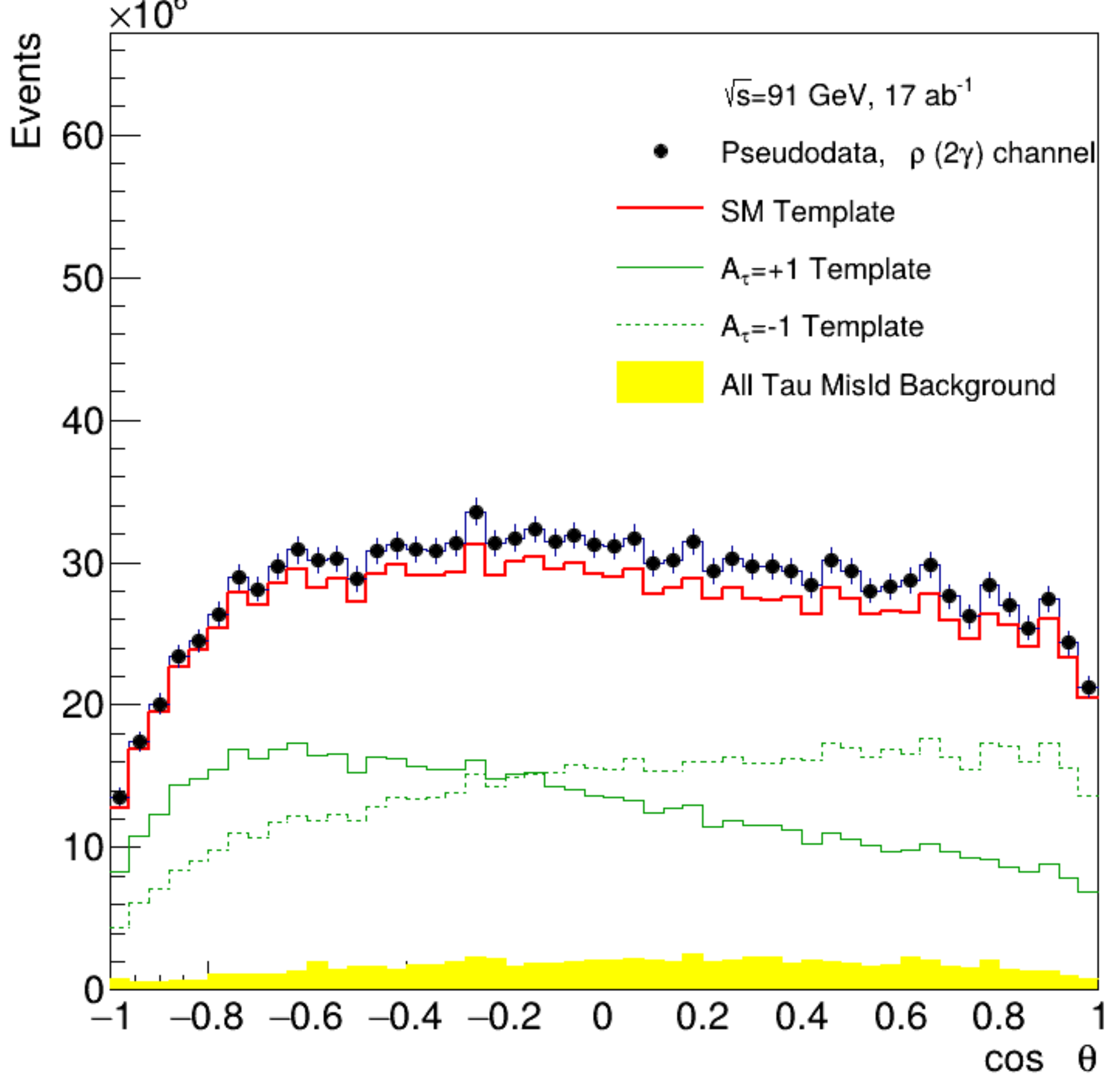


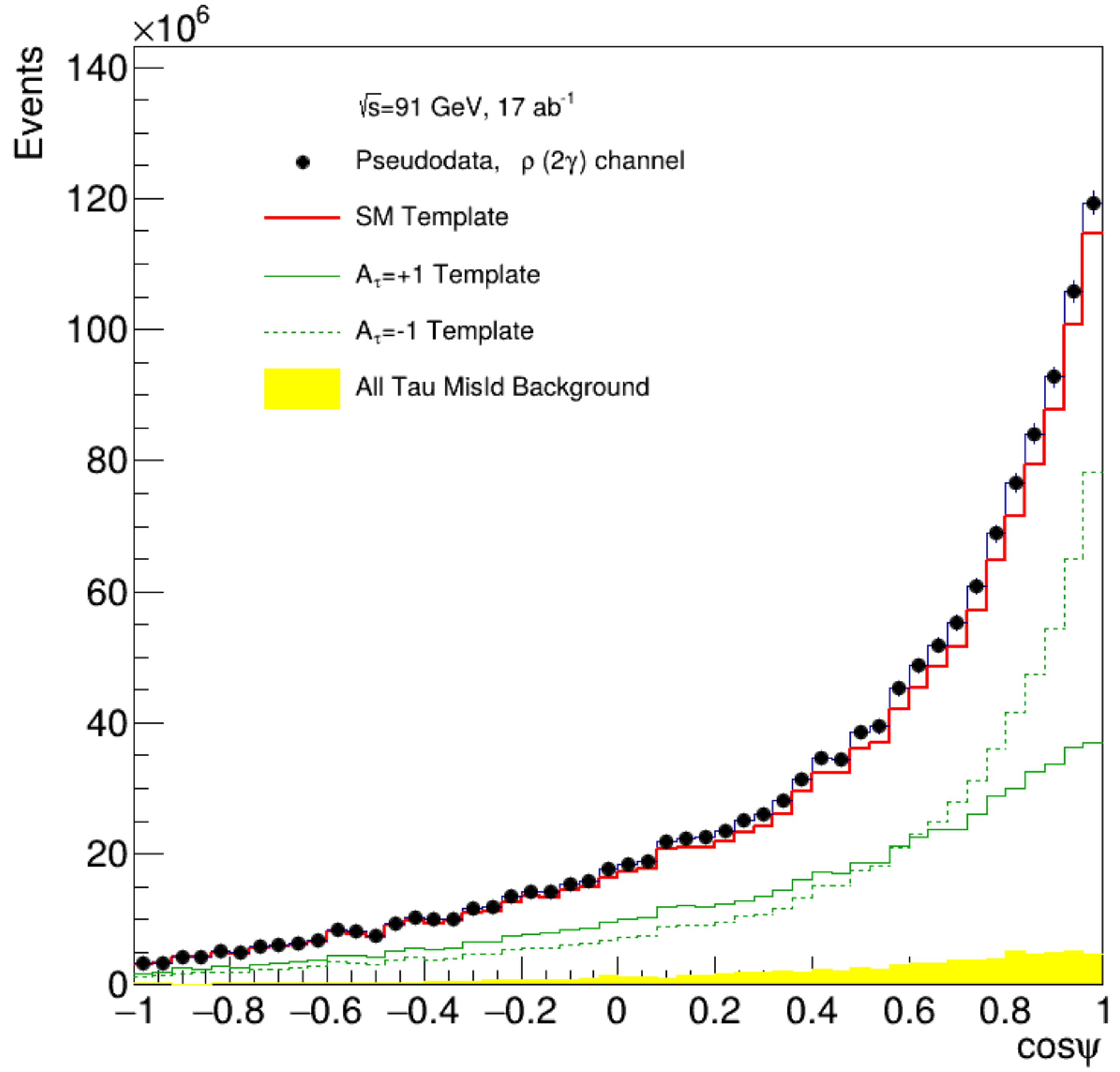
$$\cos\theta = \frac{2xm_\tau^2 - m_\tau^2 - m_h^2}{(m_\tau^2 - m_h^2)(\sqrt{1 - 4m_\tau^2/s})}$$

$$\text{où} \quad x = 2\frac{E_h}{\sqrt{s}} \quad \text{et} \quad s = 4E_b^2$$

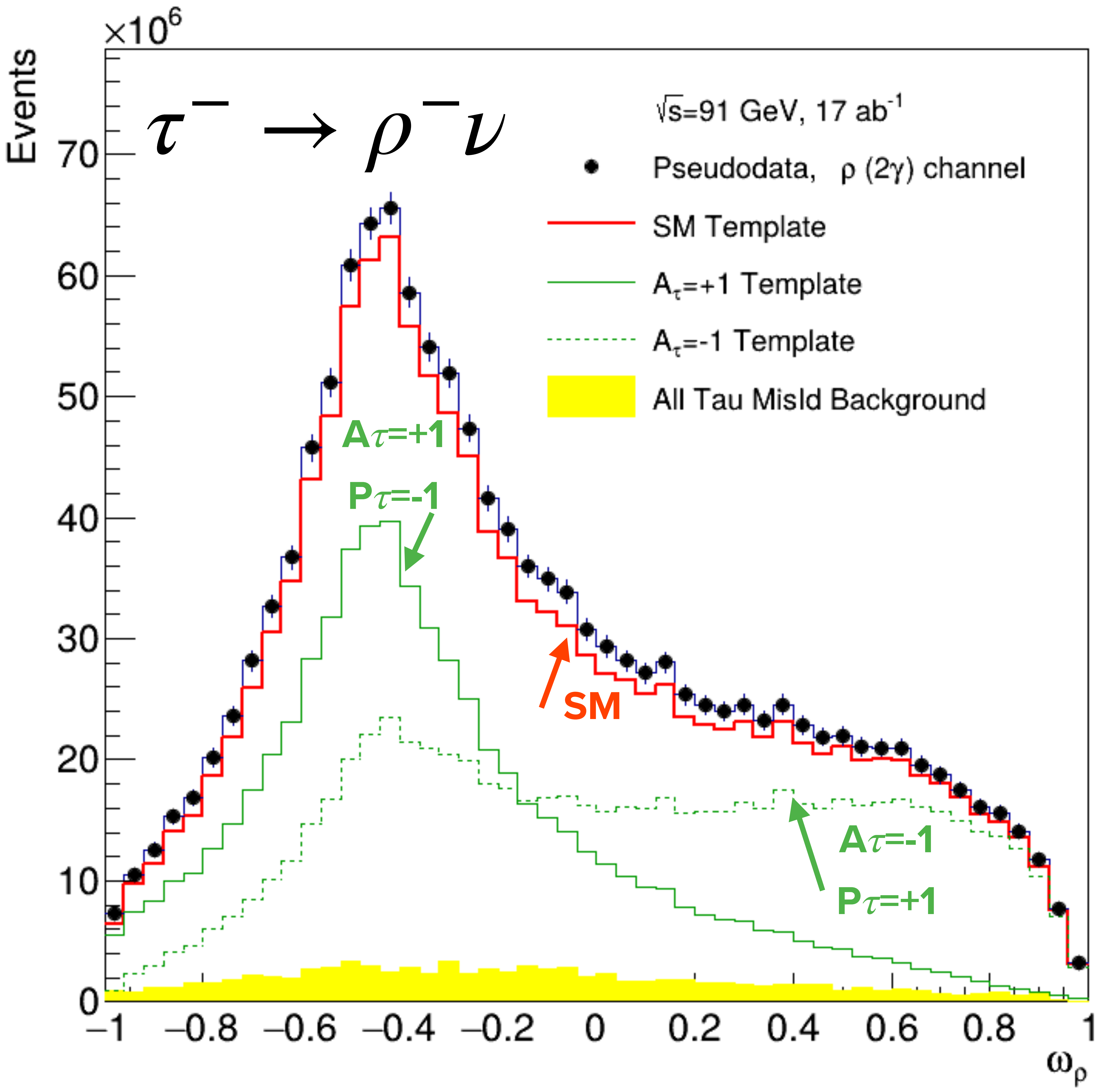
$$\cos\psi = \frac{x(m_\tau^2 + Q^2) - 2Q^2}{(m_\tau^2 - Q^2)\sqrt{x^2 - 4Q^2/s}}$$

$$\omega_\rho = \frac{(-2 + \frac{m_\tau^2}{Q^2} + 2(1 + \frac{m_\tau^2}{Q^2})\frac{3\cos\psi - 1}{2}\frac{3\cos^2\beta - 1}{2})\cos\theta + 3\sqrt{\frac{m_\tau^2}{Q^2}}\frac{3\cos^2\beta - 1}{2}\sin 2\psi\sin\theta}{2 + \frac{m_\tau^2}{Q^2} - 2(1 - \frac{m_\tau^2}{Q^2})\frac{3\cos\psi - 1}{2}\frac{3\cos^2\beta - 1}{2}}$$





POLARIZATION MEASUREMENT: FIRST STEP



- Polarization templates derived via reweighing from a single Pythia8 sample
  - Validation with Monte Carlo with set +1/-1 polarization (also in Pythia8)
- As a first approach: extraction of Polarization via LogLikelihood fit of the ‘optimal variable

$$N_i = B_i + S \times \left(\frac{1+\mathcal{P}_\tau}{2} T_i^P + \frac{1-\mathcal{P}_\tau}{2} T_i^M \right)$$

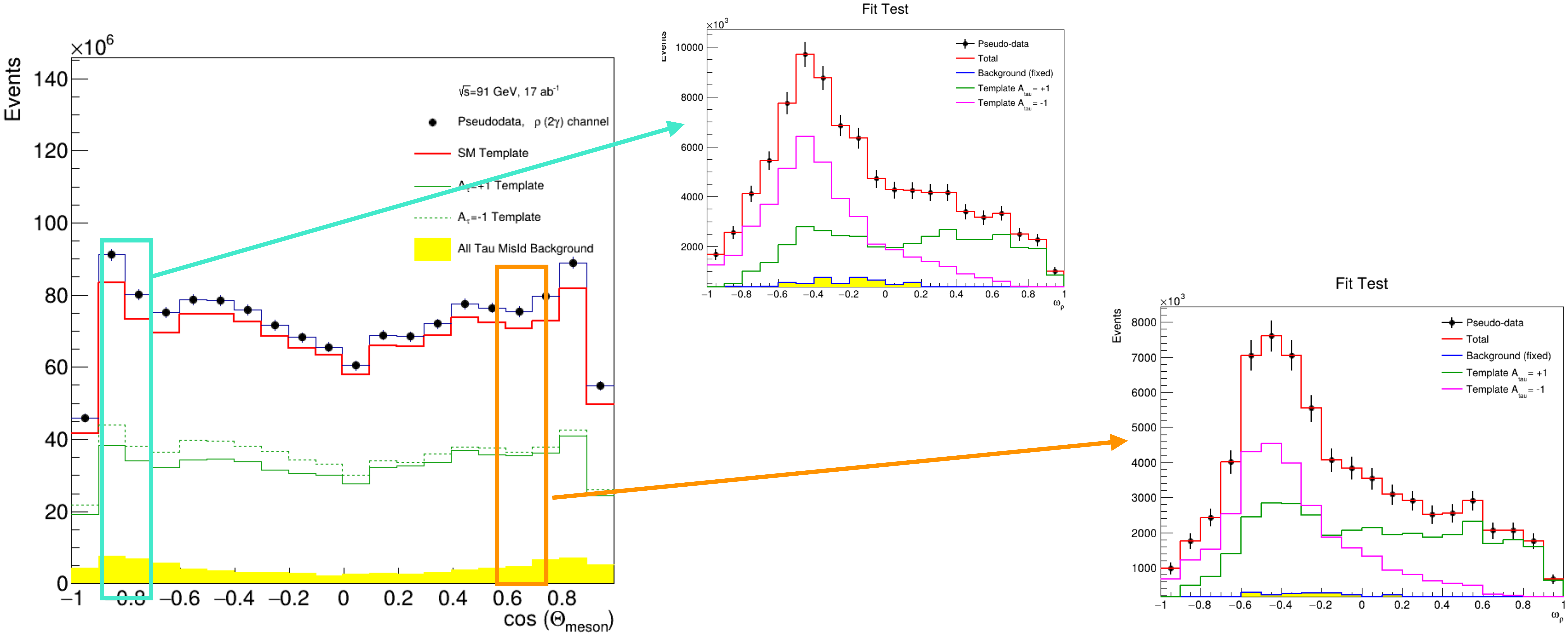
Statistical uncertainty from fit for 17 ab^{-1} (just 1 exp, 1 year, only one decay mode): (15.000 +- 0.007)%

Extrapolating to full statistics, full set of final states and decay modes: <<0.01%

POLARIZATION MEASUREMENT: BINNED APPROACH

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

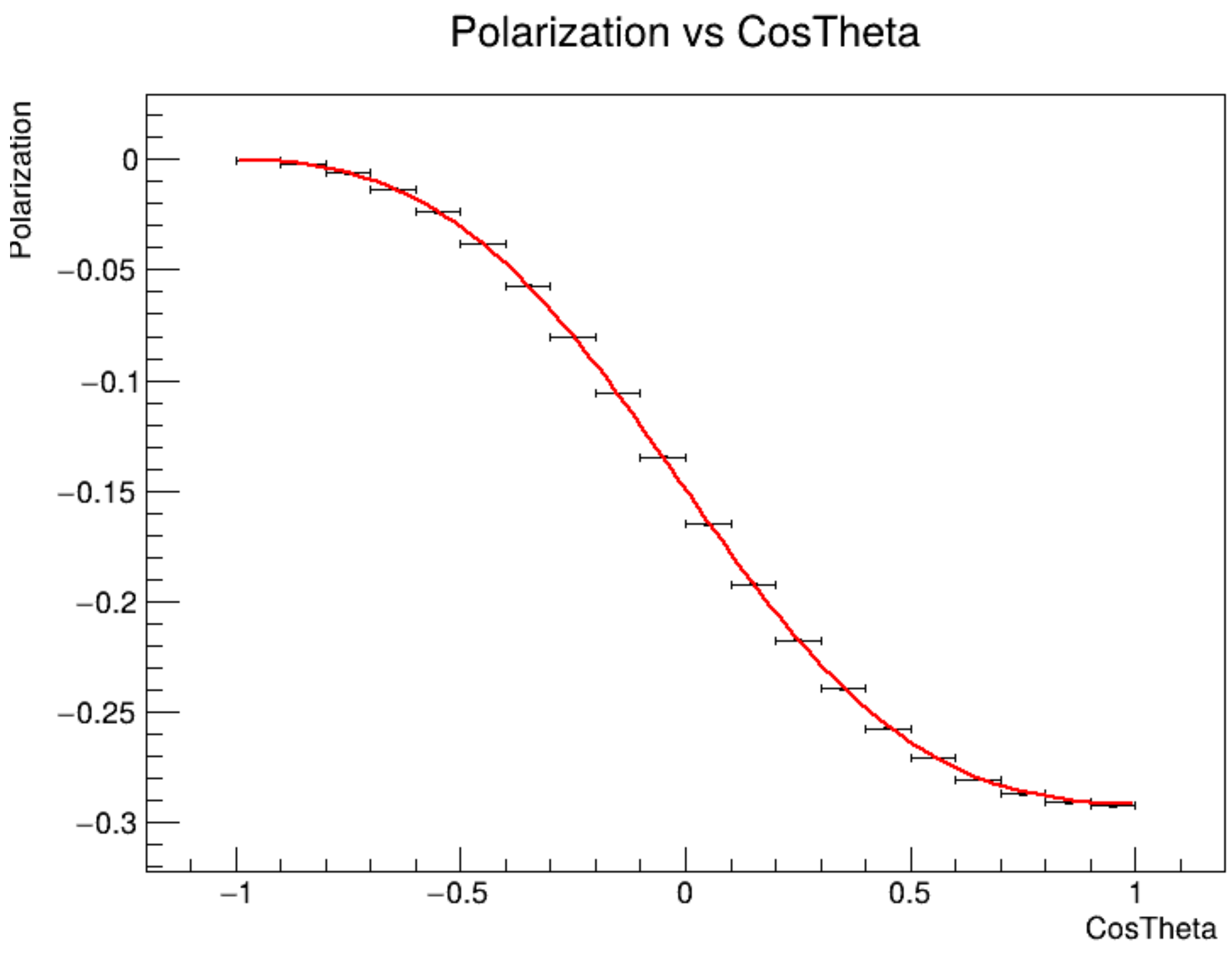
- To extract both asymmetries: exploit dependence on cosTheta



POLARIZATION MEASUREMENT: BINNED APPROACH

1. Extract P_τ in bins of $\cos\theta_\tau$
2. Simultaneous fit for Ae and A_τ

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta)+2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta)+2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$



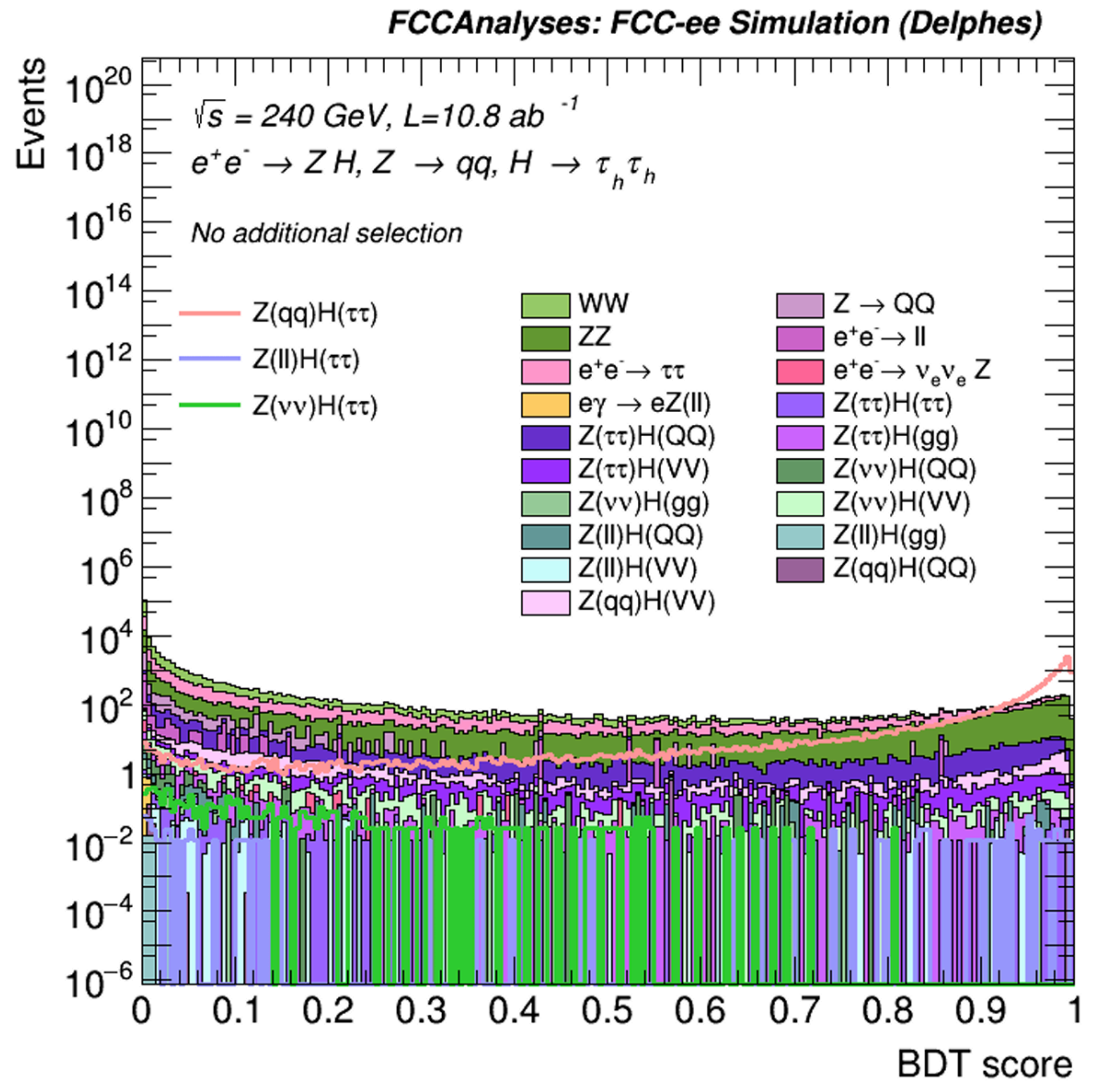
- **First look at the fit with only one channel & limited stats:**

```
Result for 17 ab-1 only one channel (semileptonic,
Rho with 2 resolved photons):

Aτ: 14.9527 +- 0.0070 %
Ae: 14.9407 +- 0.0094 %
->sin2theta_effective (from Ae): 0.23122+-0.00001

Input used for the template weights:
sin2theta_effective= 0.2312  -> Atau=Ae=14.955%
```

- Note this is not the final statistical uncertainty, this is a very small fraction of the data sample
- Closure under study (binning, templates, effect of very limited MC statistics, etc)
- **Next: backgrounds & systematics!**

BONUS: HIGGS & TAUS

Slide added in response to one of the questions in the morning session

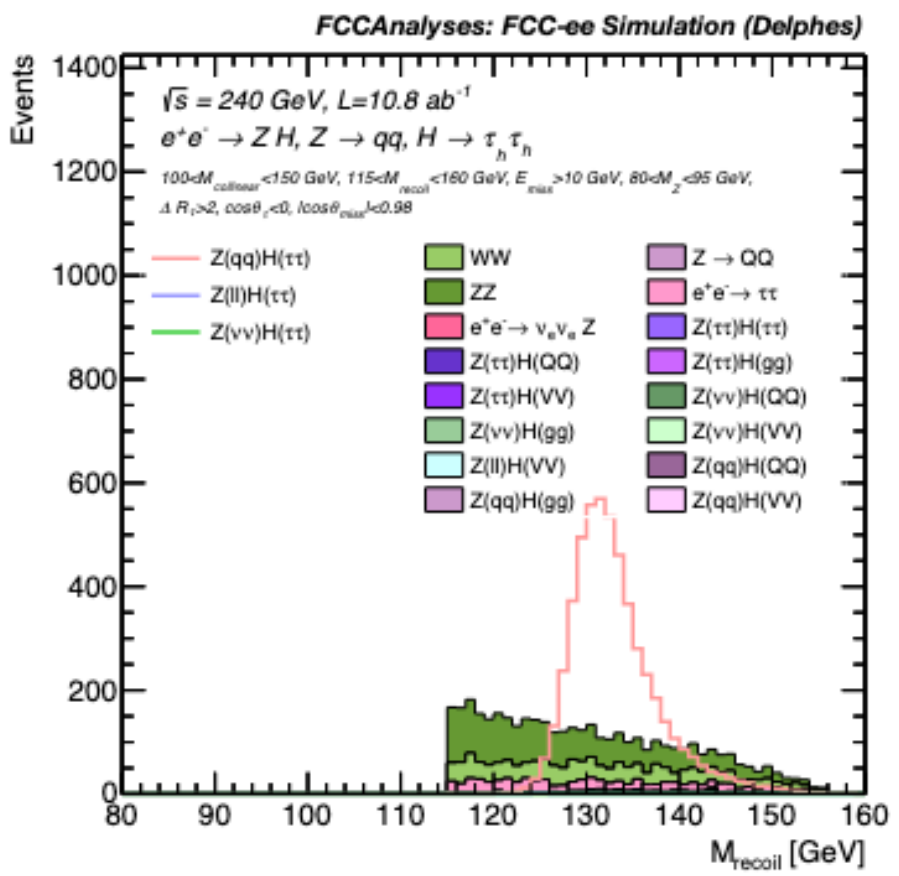


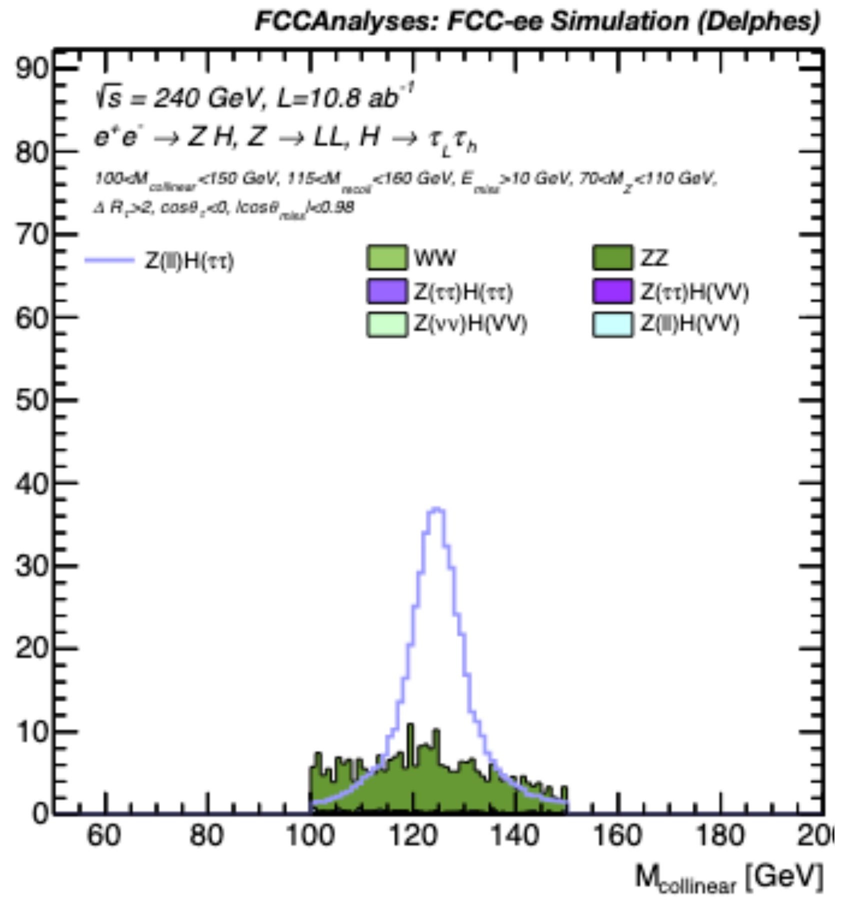
- Beyond the precision measurement tau properties: taus are a essential part of the Higgs and BSM physics program
- **Delphes $e^+e^- \to ZH,\, H \to \tau\tau$ analysis at √s = 240 GeV with IDEA**
  - Cross-section
  - Yukawa coupling
  - CP interpretation

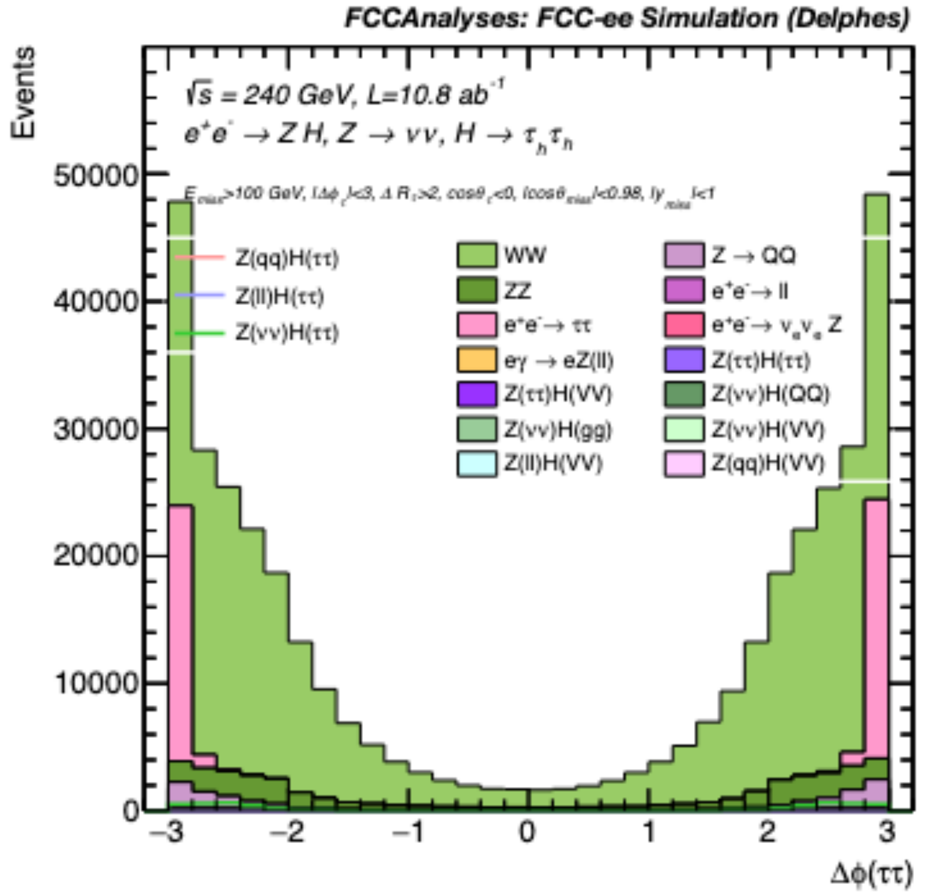
S. Giappichini

- Comparison of two tau reconstruction algorithms: exclusive DM vs ParticleNet.
- Full final state coverage (Z decays, combinatorics of Higgs decay)
- Relative uncertainty on $\sigma_{ZH} \times \mathscr{B}(H \to \tau\tau)$ for 10.8 ab^{-1} :

	Explicit tau reconstruction	PNet tau reconstruction
Cut-based analysis	±1.17 %	±0.94 %
BDT analysis 200 trees	±1.06 %	±0.85 %







SUMMARY

- **The FCC-ee will (also) be a tau factory**
- Very rich program! Exploit the **huge sample (10[11]) of $e^+e^- \to Z \to \tau^+\tau^-$ decays** to measure the properties of the tau lepton, and derive **stringent tests of the SM**
- Tau measurements pose **demanding detector requirements** on momentum resolution, on the knowledge of the vertex detector dimensions, on e/μ/π separation over the whole momentum range, and require fine granularity and high efficiency in the tracker and electromagnetic calorimeter
- Implementations of **tau reconstruction using full simulation** (traditional and ML-based) coming together for detailed systematic studies for detector optimization
- Studies of **tau polarization** in progress to showcase tau reconstruction: preliminary analysis setup exercised on full simulated samples and dedicated tau reconstruction algorithms. Currently moving on to assess systematic uncertainties.

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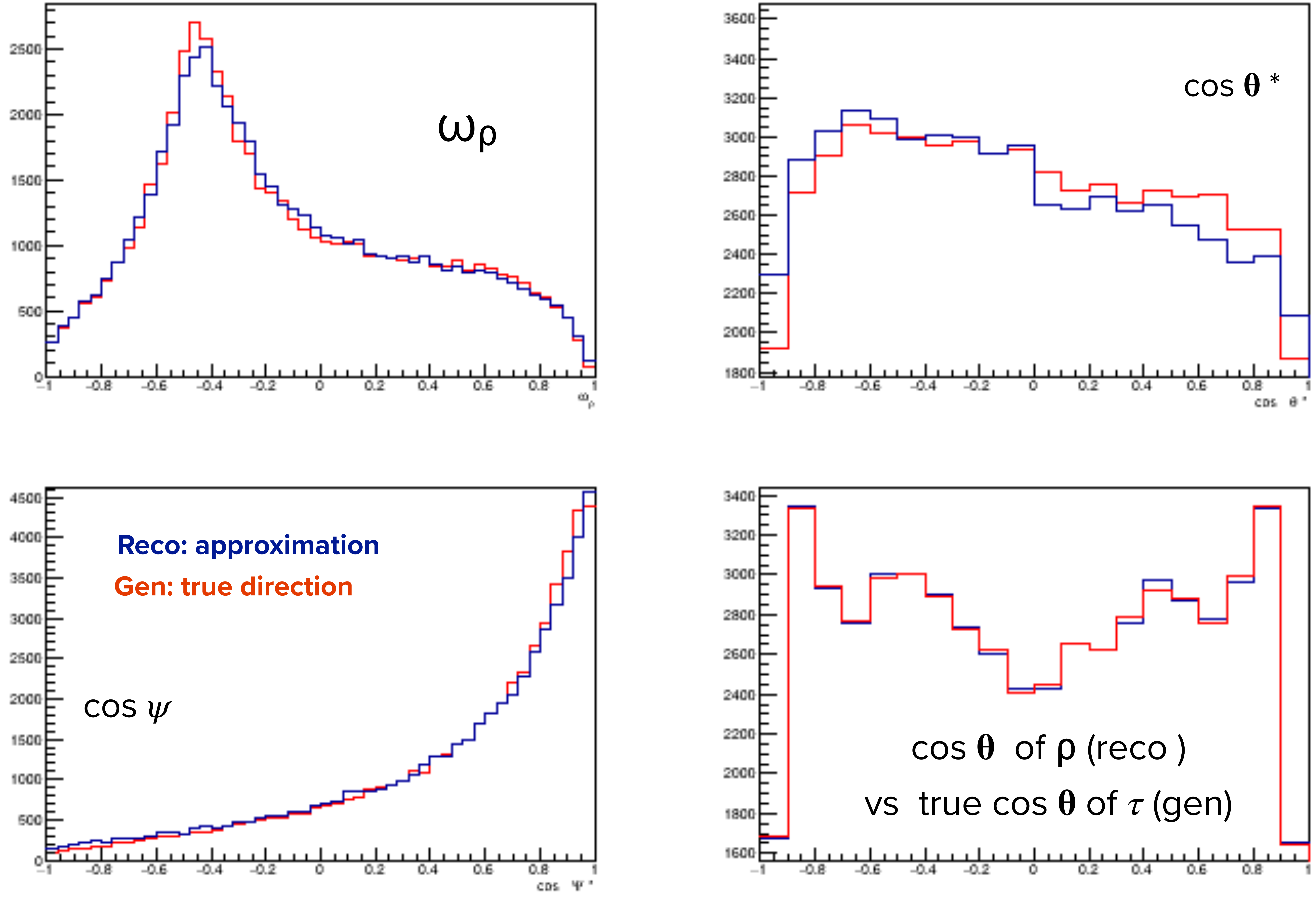
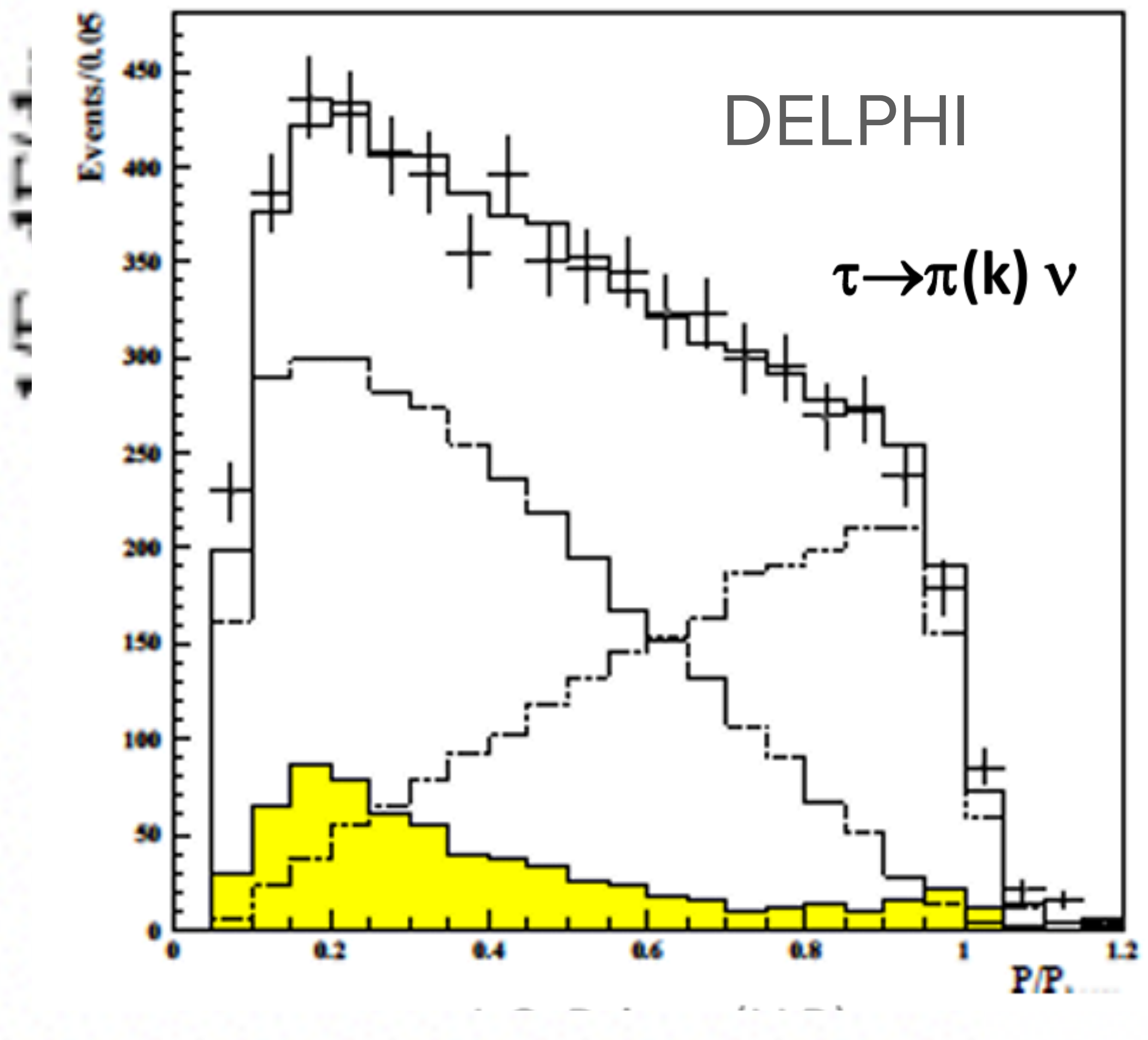
Consolidación Investigadora 2023: CNS2023-144781

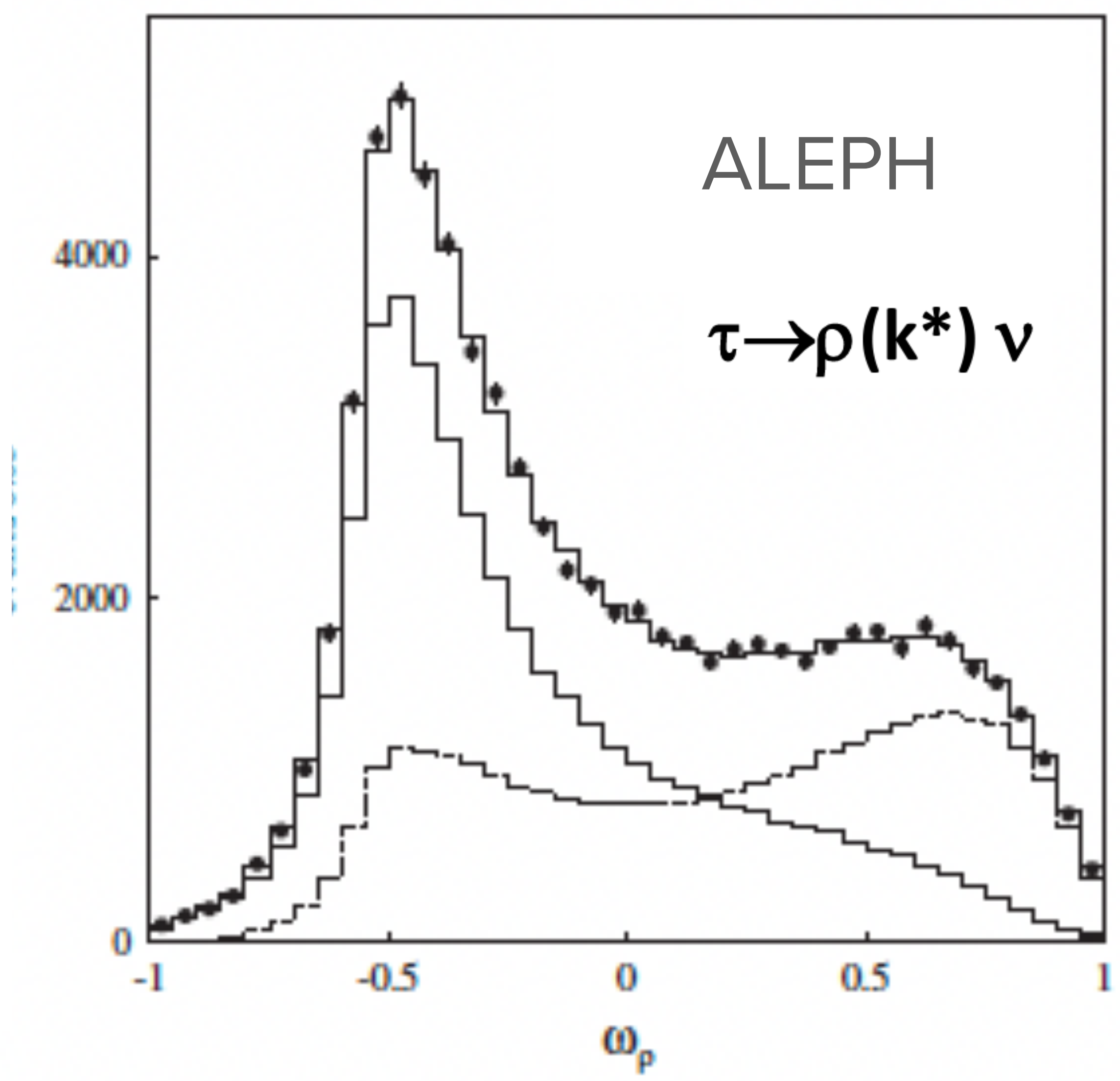
GEN VS RECO ?

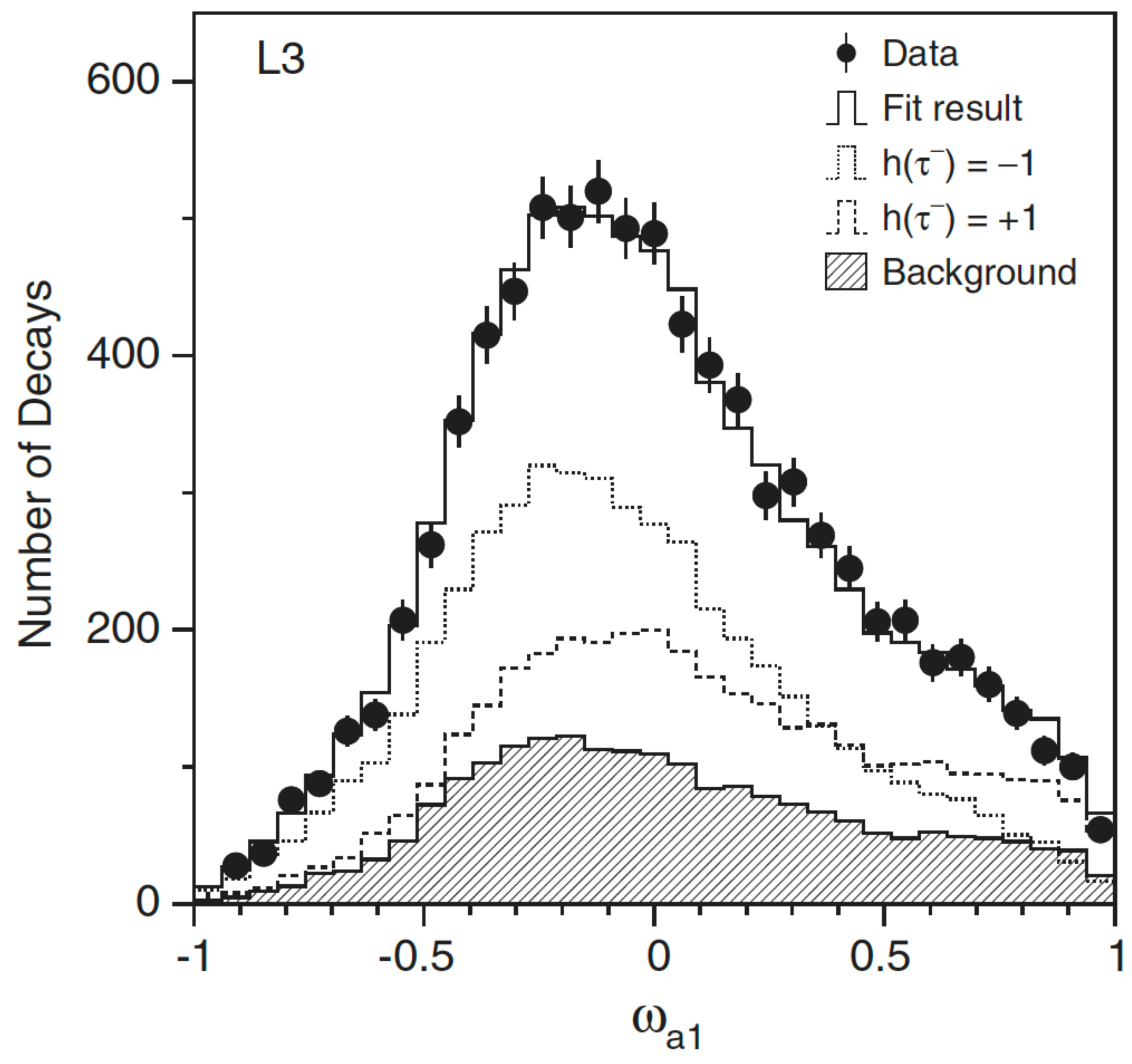
- Not yet reconstructing the true tau direction, but nevertheless reasonable approximation of ‘true’ tau angles. Worse agreement for cos θ *

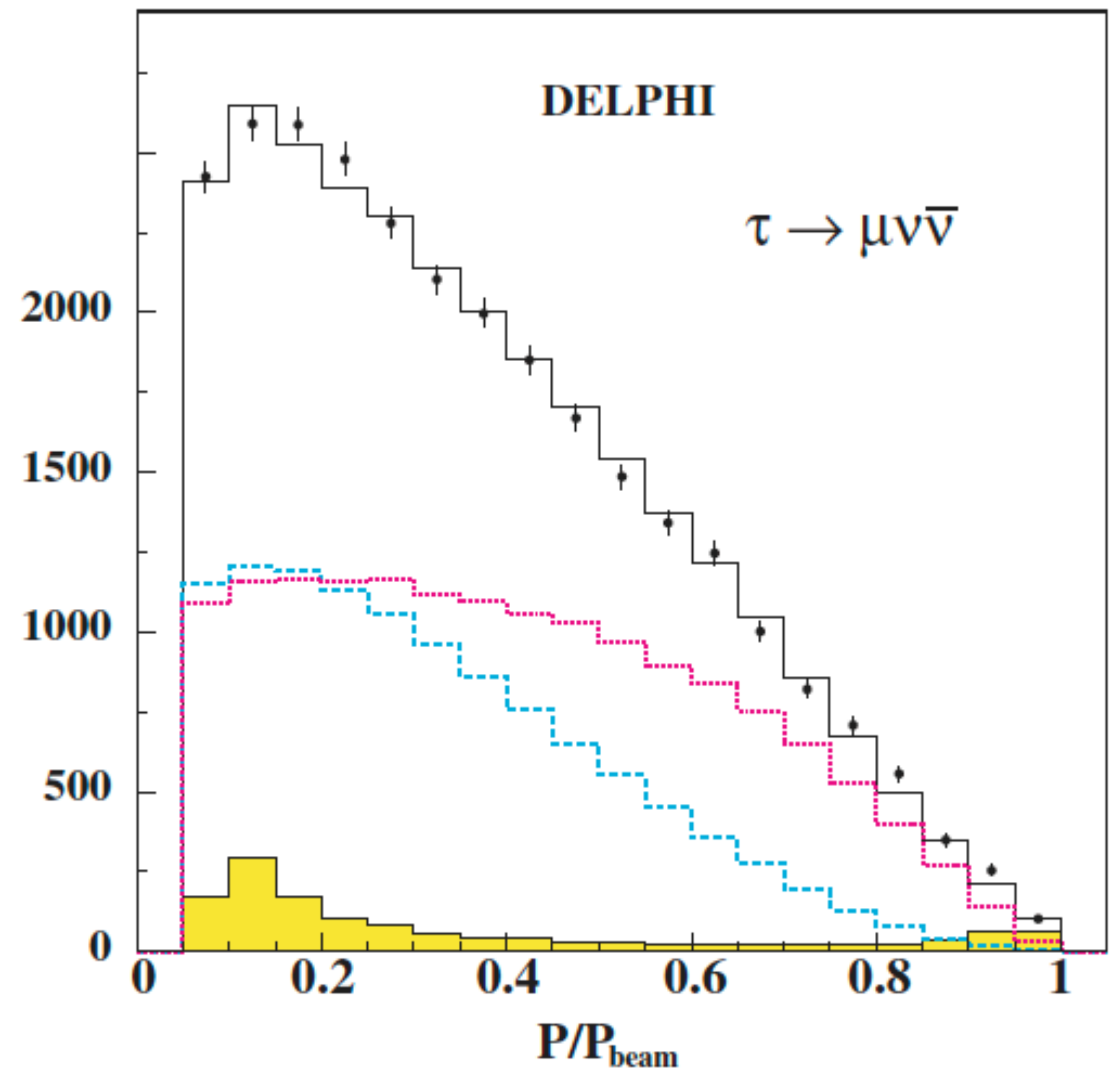


POLARIMETERS OR OPTIMAL VARIABLES AT LEP









- Pion channel: Energy Meson / Energy Beam

$$x_\pi = \frac{E_\pi}{E_{beam}}, \qquad \frac{1}{\Gamma}\frac{d\Gamma}{dx_\pi} = 1 + \mathscr{P}_\tau(2x_\pi - 1)$$

- Rho channel: θ, ψ, ω_ρ

$$\frac{1}{\Gamma}\frac{d\Gamma^{\lambda_\rho=0}}{d\cos\theta^*} = \frac{m_\tau^2/2}{m_\tau^2 + 2m_\rho^2}(1 + \mathscr{P}_\tau \cos\theta^*),$$

$$\frac{1}{\Gamma}\frac{d\Gamma^{\lambda_\rho=\pm1}}{d\cos\theta^*} = \frac{m_\rho^2}{m_\tau^2 + 2m_\rho^2}(1 - \mathscr{P}_\tau \cos\theta^*),$$

$$\omega_\rho = \frac{W_+(\theta^*, \psi) - W_-(\theta^*, \psi)}{W_+(\theta^*, \psi) + W_-(\theta^*, \psi)},$$

- For a_1: ω for three body decay
- For leptons: x_l

TAU PHYSICS PROGRAM

FCC feasibility Mid-term report -
Deliverable #8, physics and Experiments

FUTURE CIRCULAR COLLIDER

- Precision Measurements: lifetime, mass, and decay branching ratios
- Test of Lepton universality
- Rare decays
- Lepton Flavour Violation
- Tau polarization
- CP Violation Studies
- Higgs Couplings
- BSM searches

Observable	present value	±	error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times10^6)$	216290	±	660	**0.3**	<60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration

Overview in Mogens Dam Eur. Phys. J. Plus (2021) 136:963

TAU LIFETIME

$$PDG : \tau_\tau = (290.3 \pm 0.5) \times 10^{-15} s, c\tau = 87.03 \mu m$$

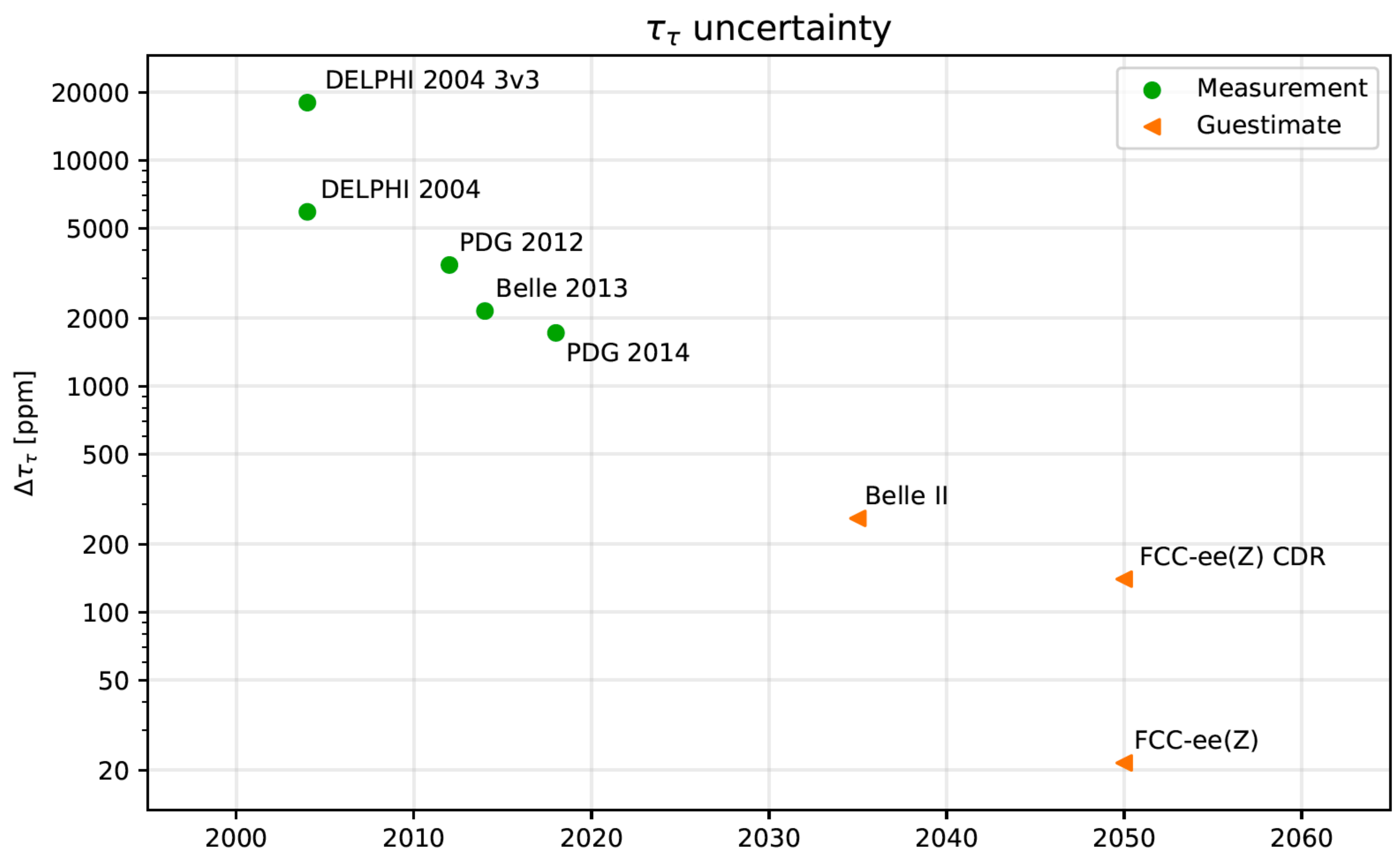
At Z-pole energies, the τ lifetime is determined via measurement of the flight distance

$$\tau_\tau = \frac{\lambda_\tau}{\beta\gamma} = \frac{\lambda_\tau m_\tau}{\sqrt{E_\tau^2 - m_\tau^2}} = \frac{\lambda_\tau m_\tau}{\sqrt{(E_{\text{beam}} - E_{\text{rad}})^2 - m_\tau^2}} .$$

FCC-ee impact parameter resolution projected to be **5 times better than LEP** → substantial improvement expected.

Extrapolation from DELPHI, based on tau pairs with double hadronic decays 3-prong vs. 3-prong (as in Belle 2013 best measurement, to profit from tau direction reconstruction using vertices)

→ **down to ~20ppm.**



	DELPHI 2004 [fs]	DELPHI 2004 [ppm]	FCC-ee(Z) 210 ab^{-1} [ppm]
statistical uncertainty	5.2	18000	15.0
luminosity-dependent systematics	1.3	4500	3.9
- background	0.2		
- reconstruction bias	0.8		
- vertex detector alignment	1.0		
luminosity-independent systematics			
- detector length scale	-	100	5.0
- average tau energy	-	-	1.0
- radiative energy loss	0.1	350	11.5
- tau mass	-	68	9.0
total systematics			15.9
total uncertainty			21.5

A. Lusiani

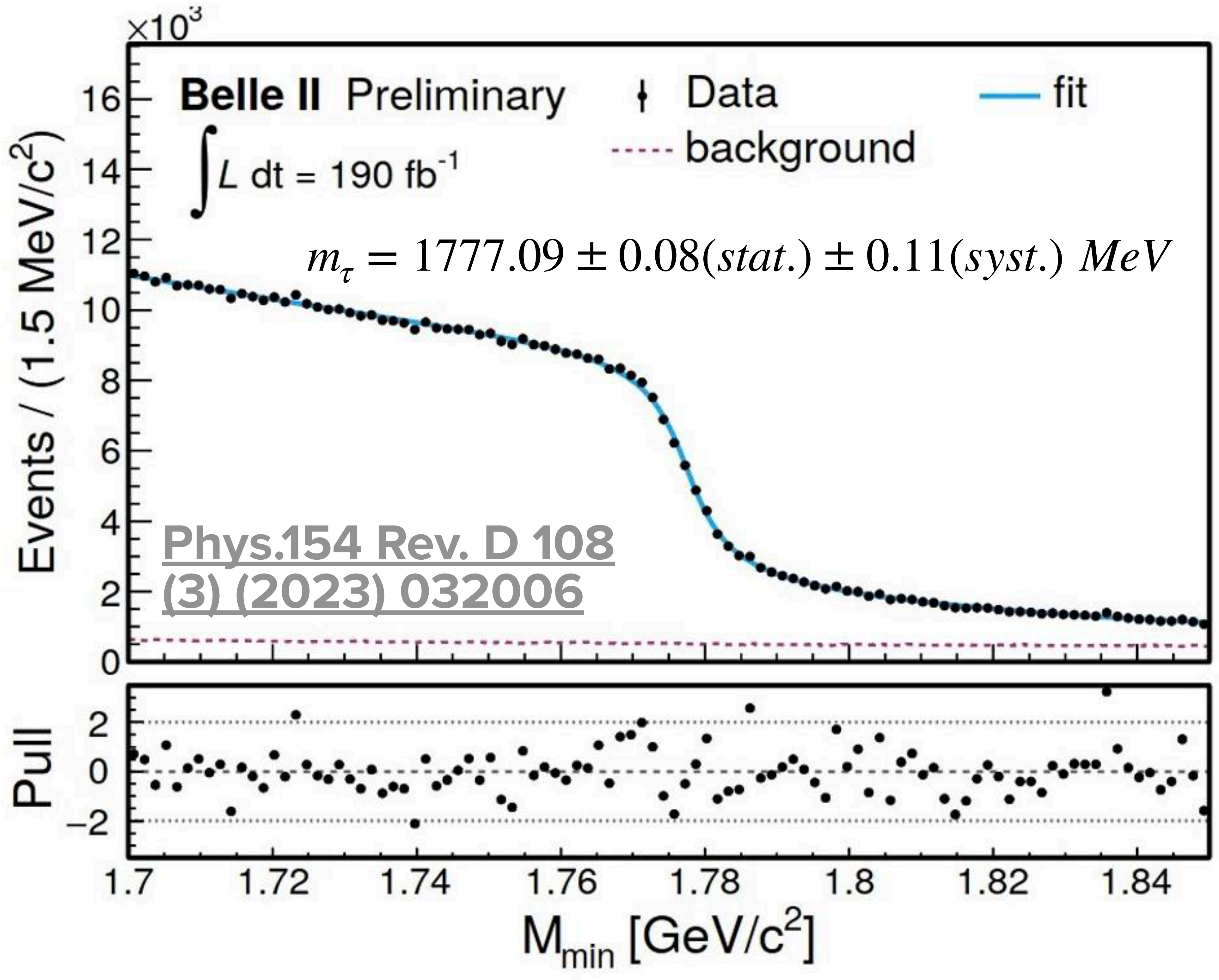
TAU MASS

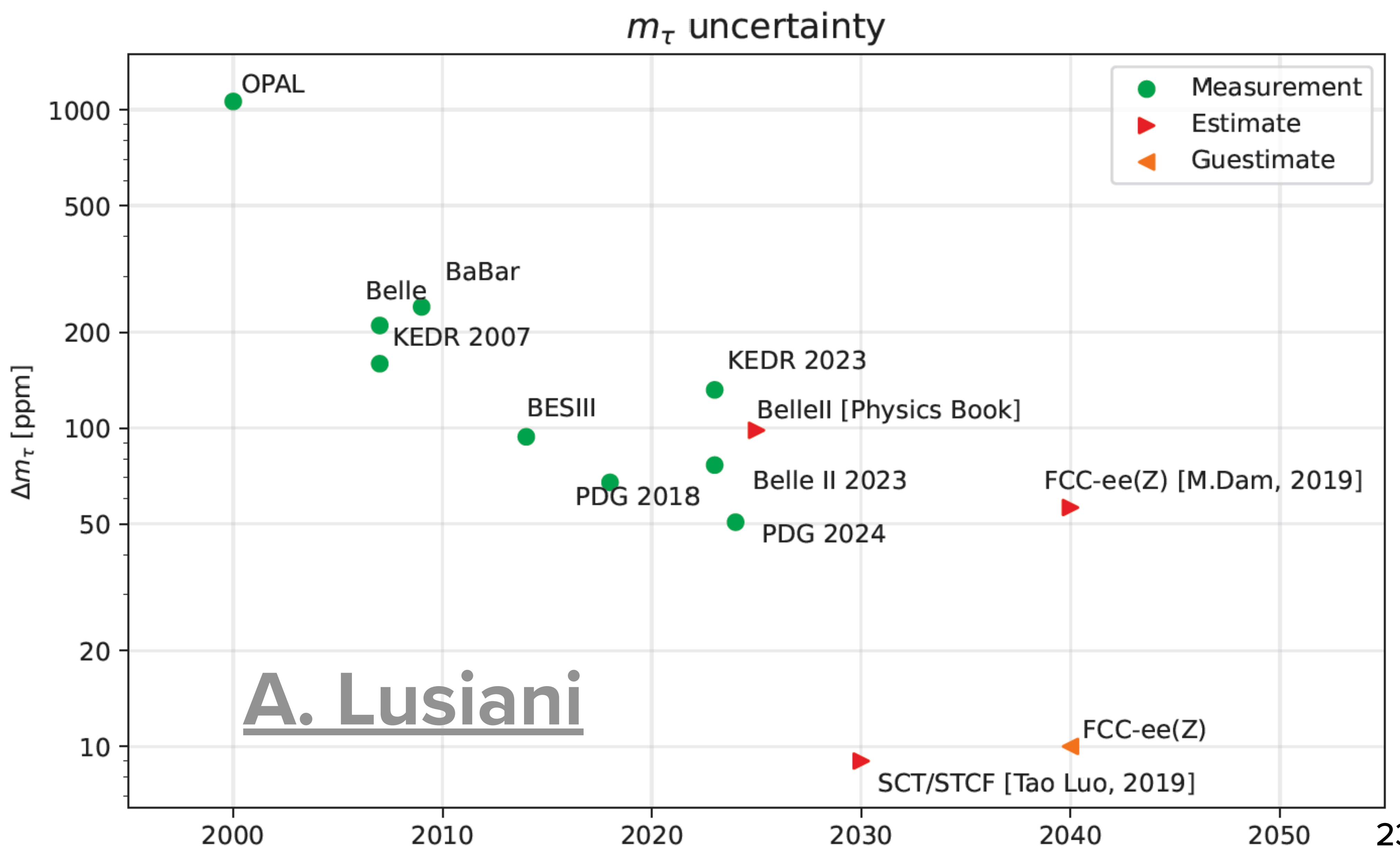
- Most precise measurement currently: Belle II fit to the reconstructed tau pseudo-mass distribution, using hadronic decays $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$. Systematically limited.

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \le m_\tau$$

- **FCC-ee should be able to significantly reduce the main systematic effects**
  - Statistical precision extrapolated from OPAL to FCC-ee with $6{\cdot}10^{12}$ Z decays: 0.9 ppm
  - Leading systematics in Belle:
    - Beam energy: 39 ppm at Belle ➔ 1ppm at FCC-ee
    - Track momentum scale: 34 ppm at Belle ➔ 2ppm at FCC-ee (using J/Psi mass)
  - Alignment systematics expected to scale with statistics
  - Other systematics (fit function, estimator bias, ISR/FSR, detector material, tau decay): at Belle, 0.05 MeV or 29 ppm. **Factor of 3 improvement assumed possible at FCC-ee.**

➡ **Precision at FCC: $\sigma(m_\tau)$ ~ 0.018 MeV , 10 ppm**



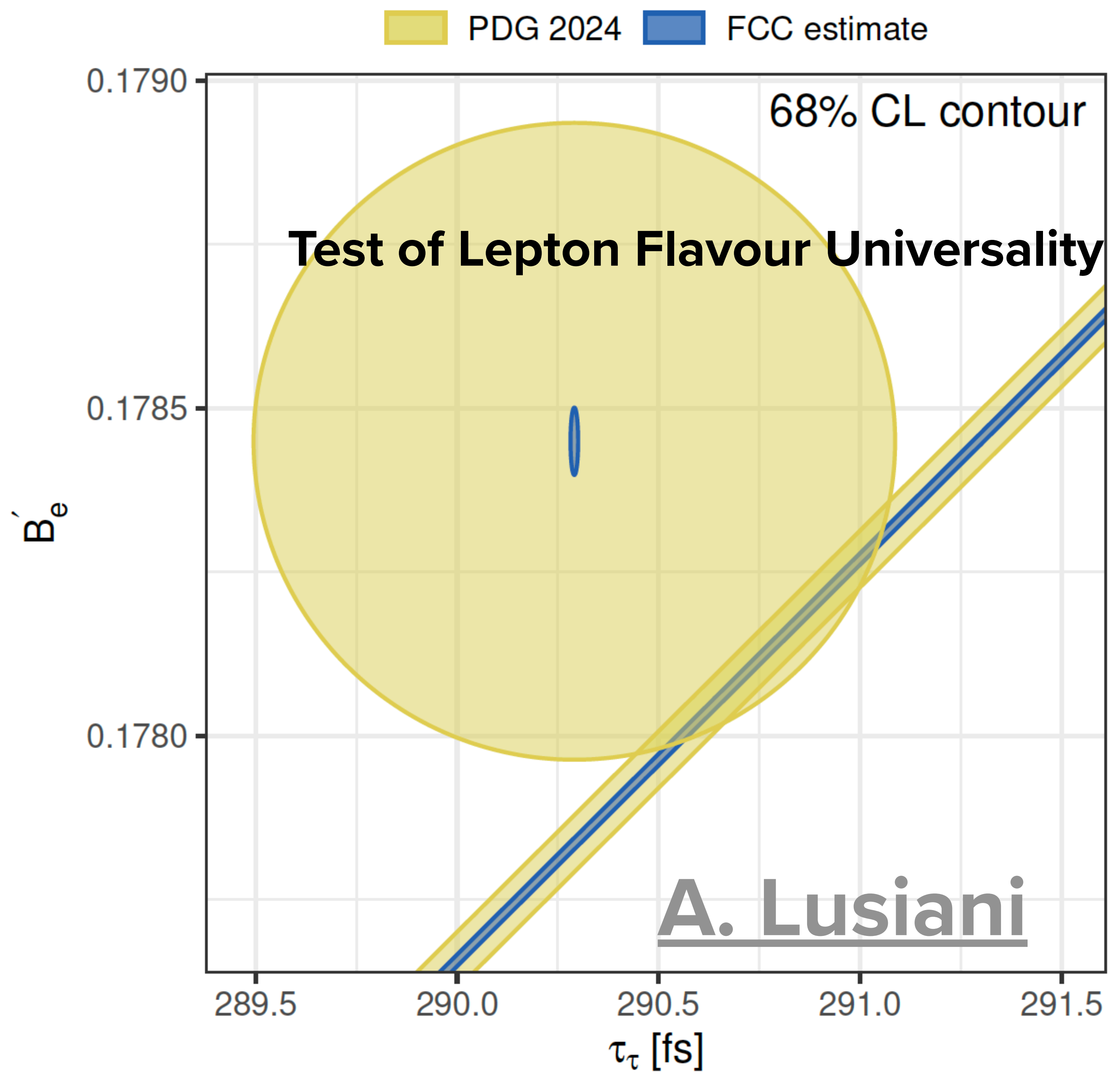


TAU DECAYS

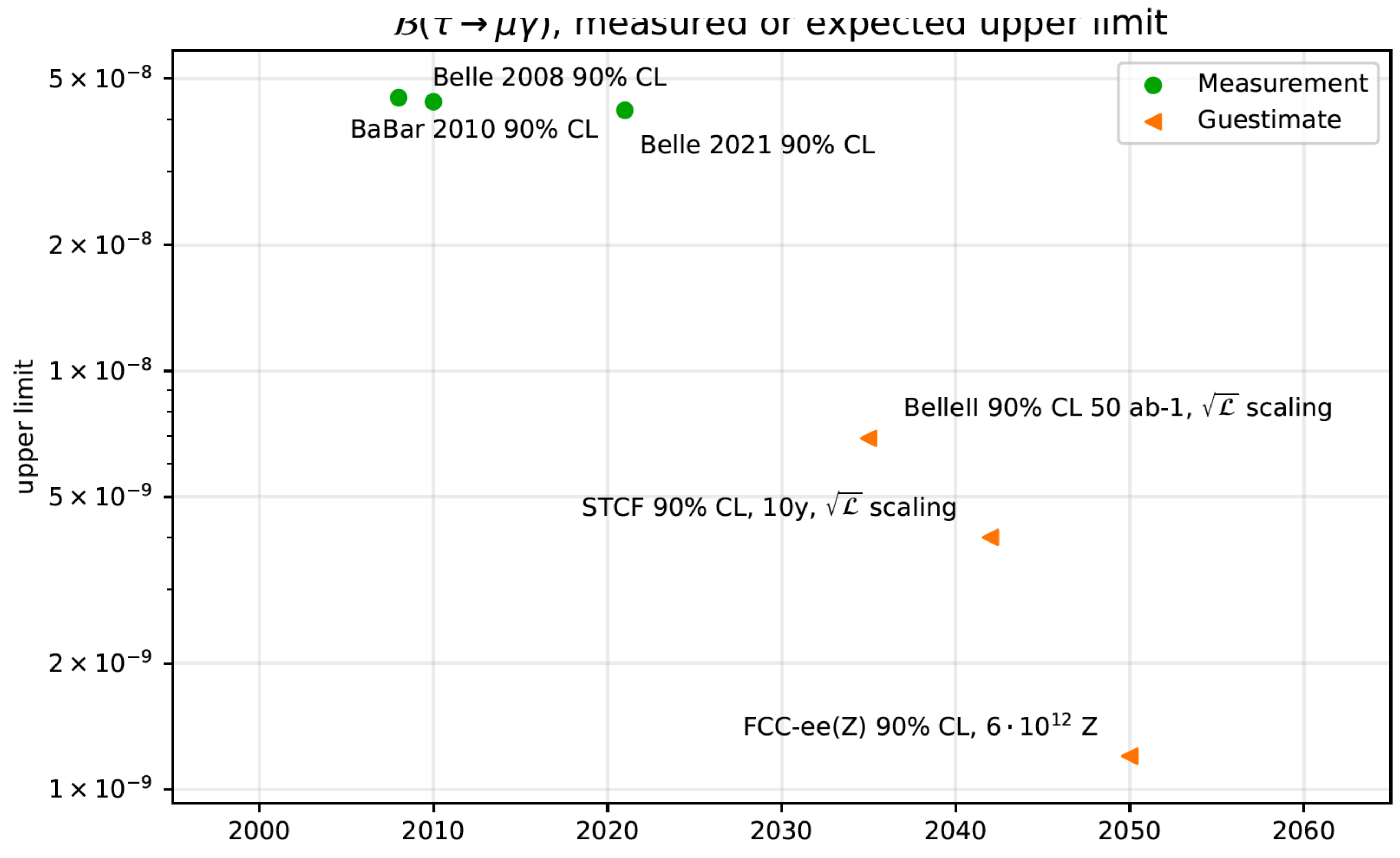
- **Leptonic branching fractions ($\tau \rightarrow l\bar{\nu}\nu$)**
  - Extrapolation difficult, systematically dominated (eg related to photon and π^0 reconstruction).
  - The extrapolated statistical precision at FCC-ee with $6{\cdot}10^{12}$ Z decays is 4.0 ppm
  - Complex systematic uncertainties. Assuming 1/10 of the ALEPH systematic: 190ppm
  - Requirements: Good EM energy resolution ($< 20\,\%/\sqrt{E}$ (LEP)), Granular EM calorimeter (< 15 x 15 mrad^2 (LEP))
  - Probe of **Lepton Flavour Universality**

$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \mathcal{B}(\tau \rightarrow \ell\bar{\nu}\nu) \cdot \frac{\tau_\mu}{\tau_\tau} \cdot \left(\frac{m_\mu}{m_\tau}\right)^5,$$

(plus radiative corrections terms)



- **Searches for LFV Decays: $\tau \rightarrow \mu\gamma$, $\tau \rightarrow \mu\mu\mu$**
  - Projection by M. Dam : 1, 2 order of magnitude improvement with respect to the current bounds.
  - $\tau \rightarrow \mu\gamma$: Importance of backgrounds, photon energy, and position resolution



FCC-EE PERFORMANCE & TAUS

assumed baseline FCC-ee detector performance	
track momentum	$\frac{\sigma_p}{p} = 0.02 \cdot 10^{-3} \cdot p_T(\text{GeV}) \oplus 1 \cdot 10^{-3}$
track impact parameter	$\sigma_{d_0} = \frac{15\,\mu\text{m}}{\sin^{3/2}\theta} \oplus 5\,\mu\text{m}$
electromagnetic energy	$\frac{\sigma_{E_\gamma}}{E_\gamma} = \frac{15\%}{E_\gamma} \oplus 1\%$
electromagnetic energy xy position	$\sigma_{\gamma,xy} = \frac{6\,\text{mm}}{E(\text{GeV})} \oplus 2\,\text{mm}$

A. Lusiani: Tau Physics Prospects at FCC-ee

Tau pairs at past, present and future e^+e^- colliders

	CLEO, CLEOIII	LEP 100	Belle, BABAR	Belle II	SCT	STCF	CEPC(Z)	FCC-ee(Z)
E_{CM} [GeV]	$\sim$10.6	92	$\sim$10.6	$\sim$10.6	$2-6$	$2-7$	92	
$\int \mathcal{L} dt$ [ab^{-1}]	0.01		1.5	50	10			240
tau pairs	$1 \cdot 10^7$	$0.8 \cdot 10^6$	$1.4 \cdot 10^9$	$46 \cdot 10^9$	$30 \cdot 10^9$		$30 \cdot 10^9$	$270 \cdot 10^9$

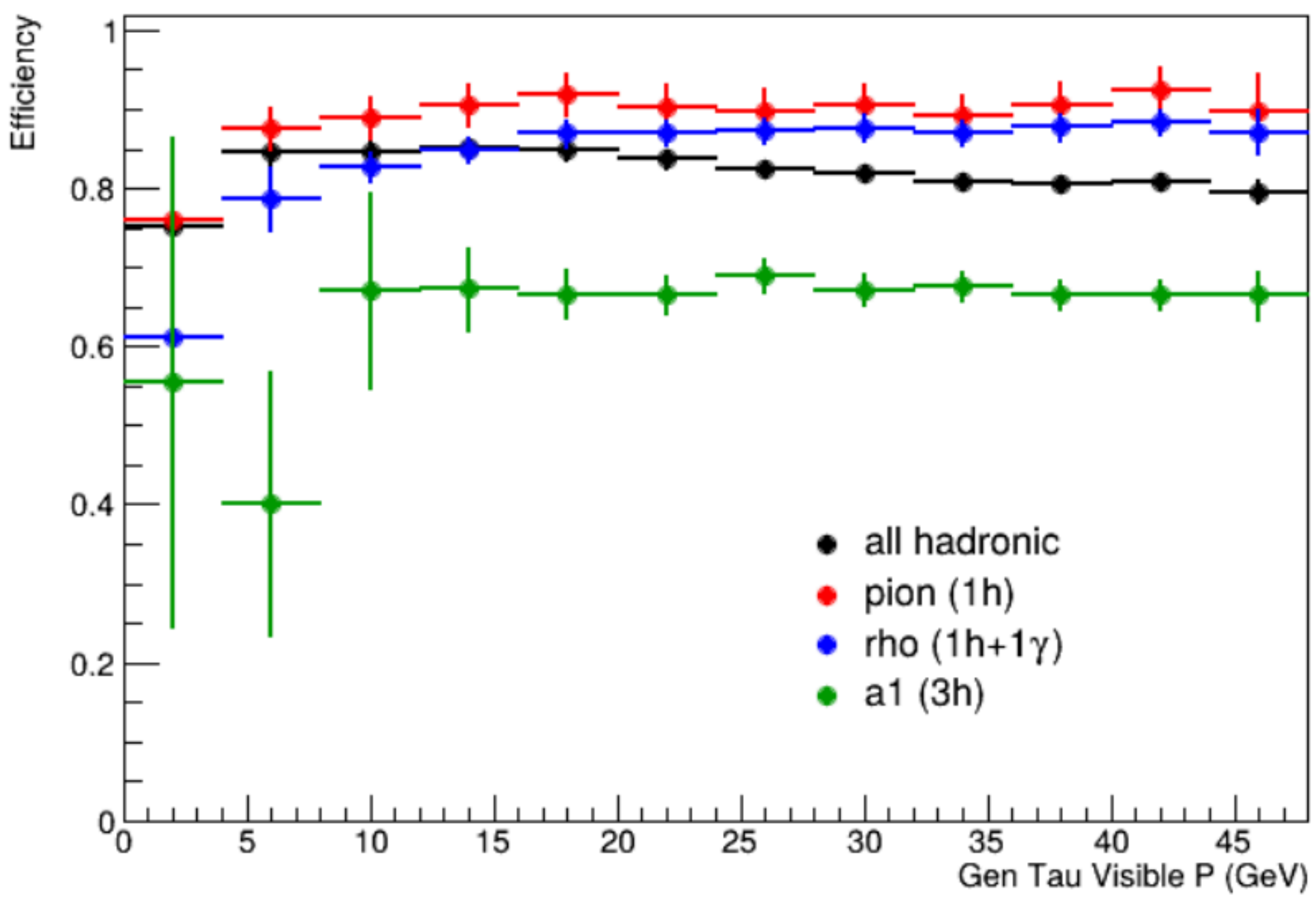
note: SCT & SCFT tau pairs estimate assuming 10 years of tau-pairs-optimized CM energies running

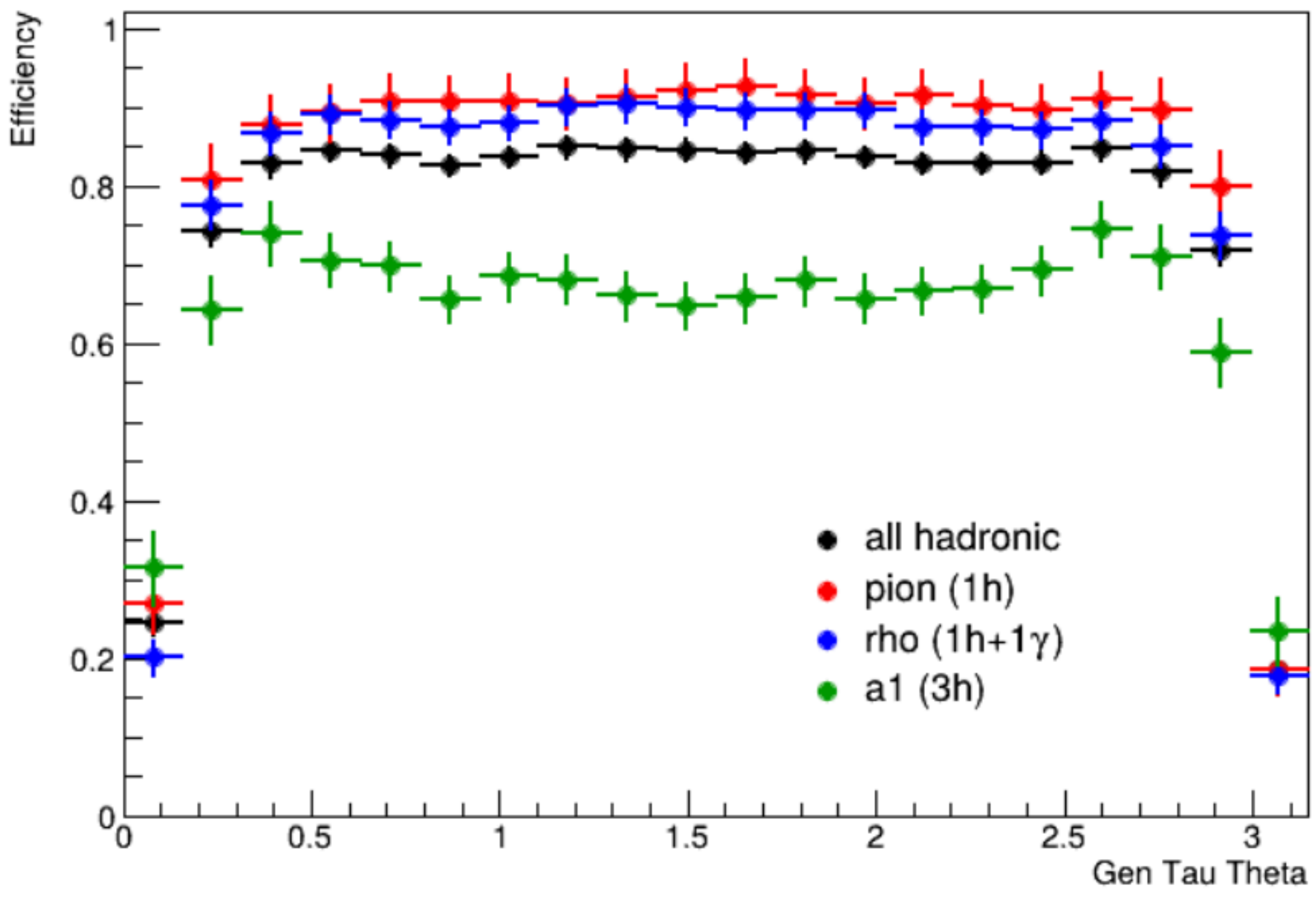
Conditions for tau physics measurements

- Z peak collisions best for most measurements
  - pure and efficient tau pair selection selecting on just one of the two taus
  - track multiplicity separates very well $\tau^+\tau^-$ from $q\bar{q}$
  - high momenta reduce multiple scattering uncertainty in impact parameter measurements
- threshold measurements at $E = 2m_\tau \sim 3.5$ GeV best for tau mass
  - threshold measurements help some LFV searches and tau BRs (super charm-tau factories)
- B-factories bested LEP with statistics on e.g. small branching fractionss, LFV searches, tau lifetime

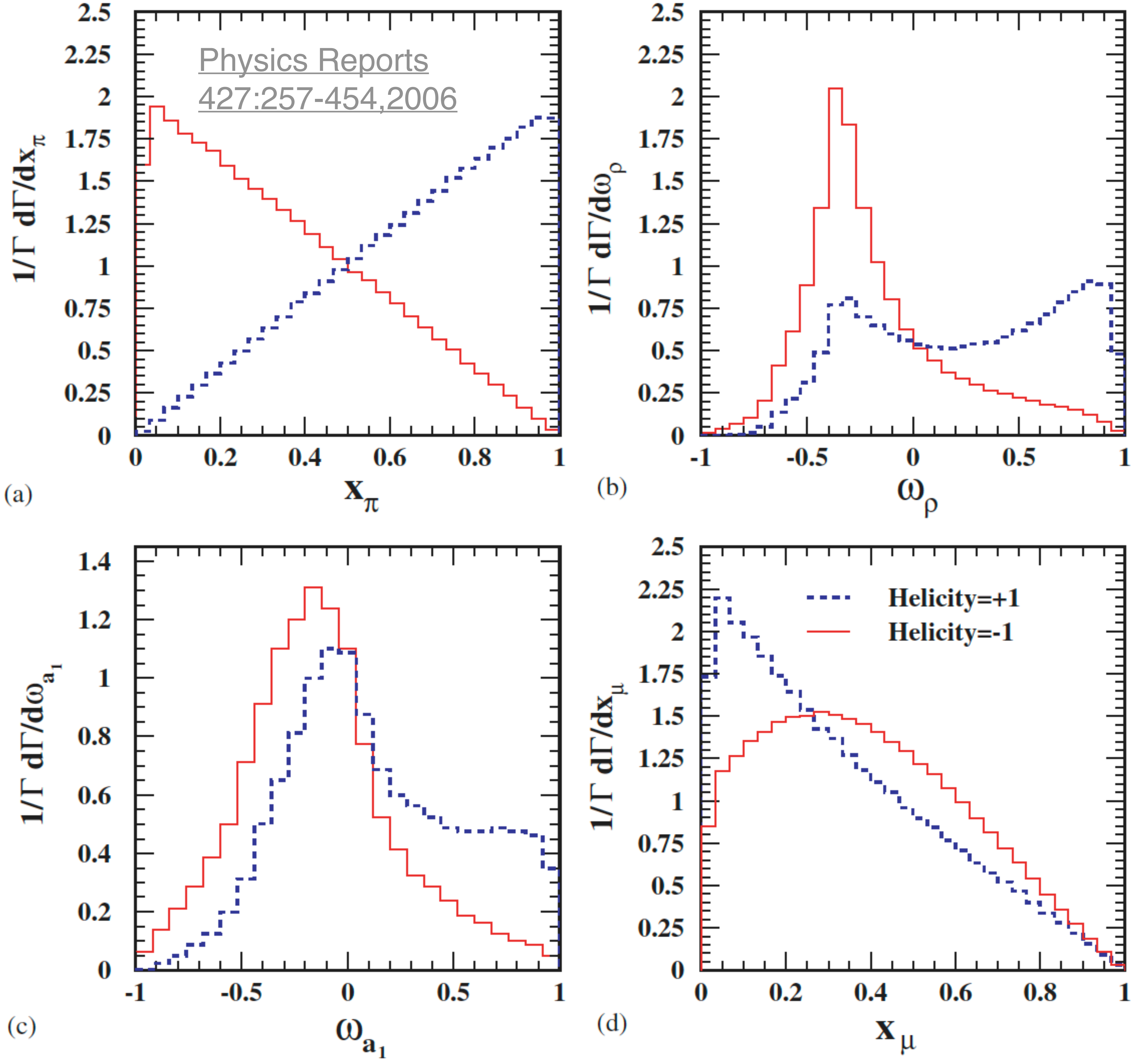
A. Lusiani's talk

EXCLUSIVE DM FINDING





TAU POLARIZATION AT LEP: EXAMPLE VARIABLES



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- For a_1 : ω for three pion decay
- For leptons: x_l

CURRENT ASYMMETRY PARAMETERS IN THE PDG

Asymmetry parameters [h]

$$A_e = 0.1515 \pm 0.0019$$
$$A_\mu = 0.142 \pm 0.015$$
$$A_\tau = 0.143 \pm 0.004$$
$$A_s = 0.90 \pm 0.09$$
$$A_c = 0.670 \pm 0.027$$
$$A_b = 0.923 \pm 0.020$$

weak-mixing angle	$\sin^2\hat{\theta}(M_Z)$ ($\overline{\mathrm{MS}}$)	$0.231\,21(4)^{\dagger\dagger}$