中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

$\alpha_s(m_\tau^2)$ measurement from hadronic tau decays on the CEPC

CHE Yuzhi

The 2024 International Workshop on the High Energy Circular Electron Positron Collider

Oct. 26, 2024, Hangzhou

Outline

1 Motivation & Introduction

- α_s is a fundamental parameter of SM.
- α_s can be precisely determined from τ
- Branching ratio & M^2_{had} distribution are the basic observables.

2 History

3 CEPC potential

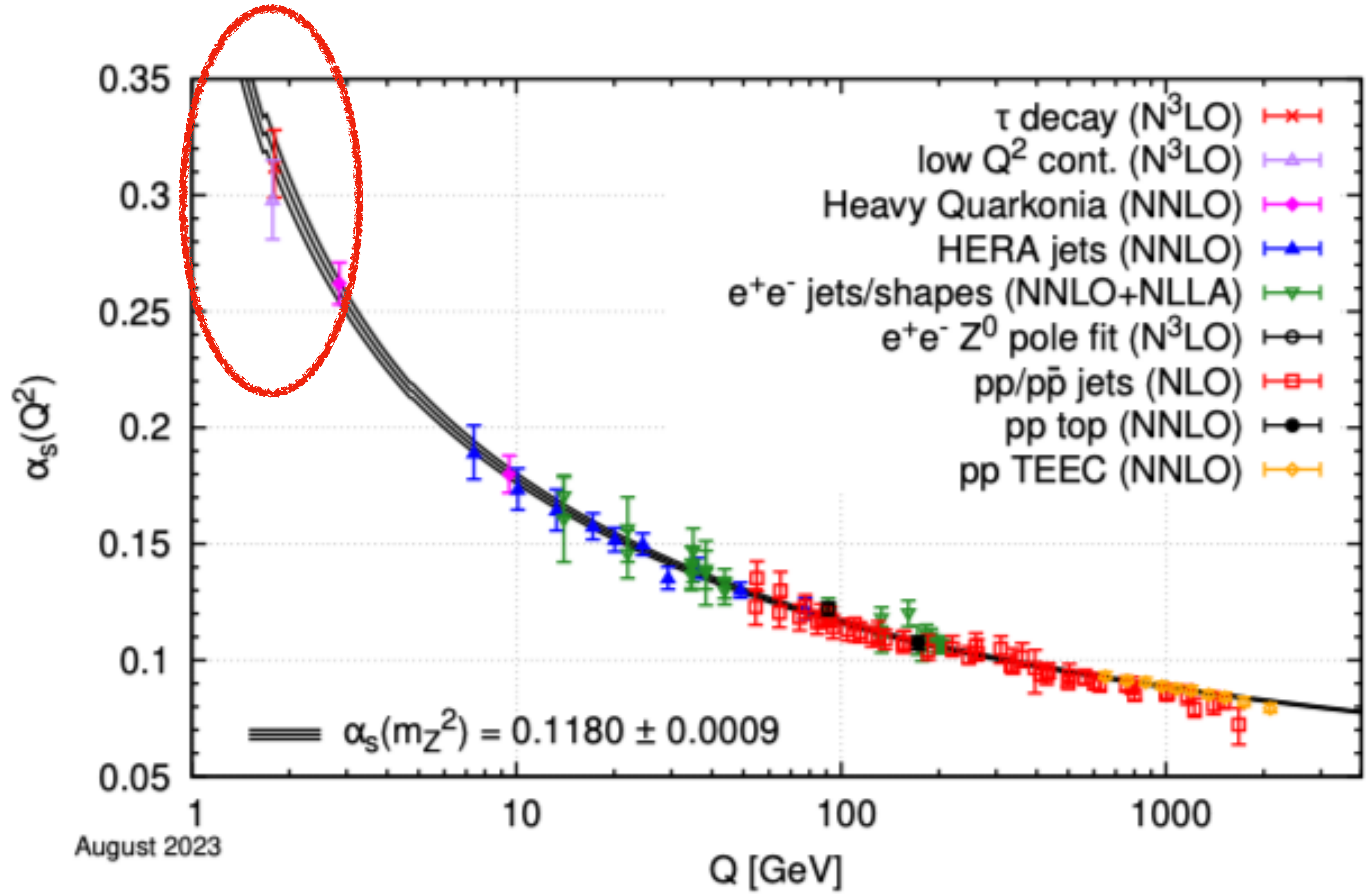
4 Summary

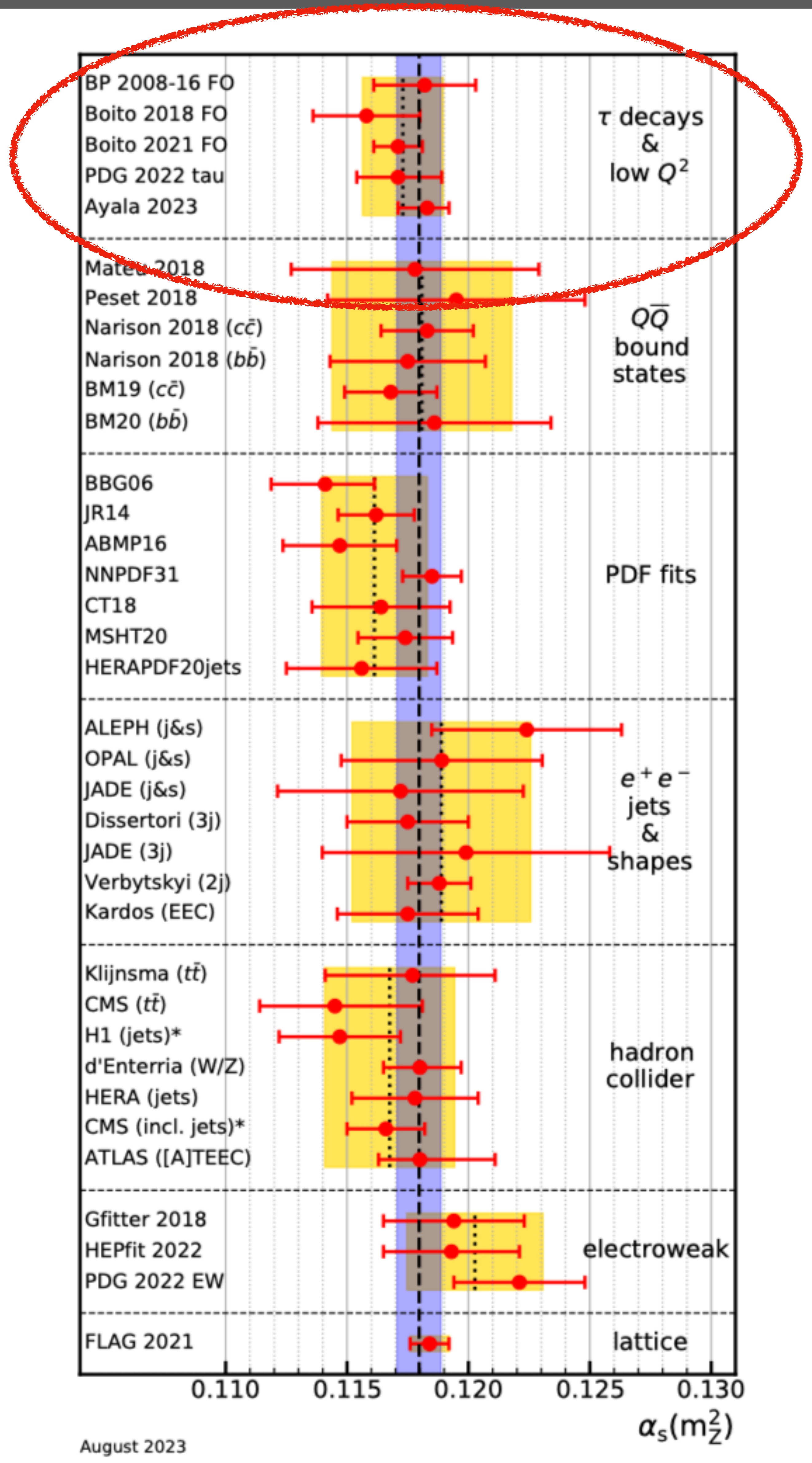
The Strong Coupling Constant α_s

- α_s sets the scale of the strength of the strong interaction, and is one of the fundamental parameters of the Standard Model (SM).

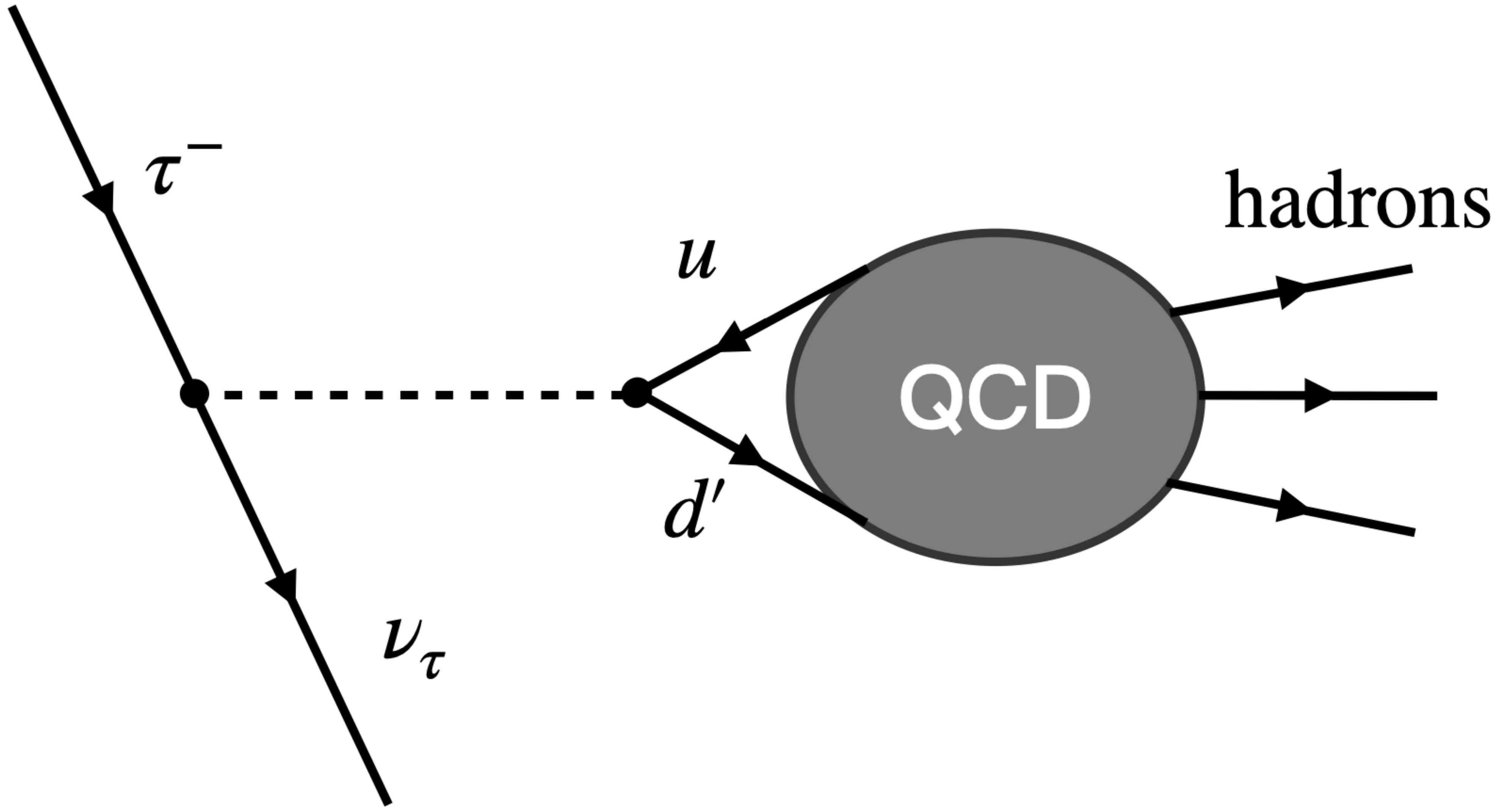
- α_s uncertainty contributes the uncertainties of:
  - Decay width of Higgs, Z bosons, …
  - Top mass, width, and its Yukawa coupling, …

- Until 2023, analyses of τ decays provided the ***most precise*** experimental determinations.





How to extract $\alpha_s(m_\tau^2)$ from hadronic τ decay?



- **Observables**: $R_\tau \equiv \dfrac{\Gamma\left(\tau \to \nu_\tau \text{ hadrons }\right)}{\Gamma\left(\tau \to l\nu_\tau\nu_l\right)} = R_{\tau,V} + R_{\tau,A} + R_{\tau,S}$
  - $R_{\tau,V+A} \equiv \dfrac{\Gamma\left(\tau \to \nu_\tau \text{ pions }\right)}{\Gamma\left(\tau \to l\nu_\tau\nu_l\right)}$
  - $R^{kl}_{\tau,V/A}(s_0) = \displaystyle\int_0^{s_0} ds \left(1 - \frac{s}{s_0}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{dR_{\tau,V/A}}{ds}$
  - $D^{kl}_\tau = \dfrac{R^{kl}_\tau}{R^{00}_\tau}$
- **Theoretical prediction**:
  - $R^{kl}_{\tau,V/A}\left(s_0\right) = N_c S_{EW} \left|V_{\text{ud}}\right|^2 \left(r^{kl}\left(1+\delta^{(0),kl}\left(s_0; \alpha_S(s_0)\right)\right) + \displaystyle\sum_{D=2,4\ldots} \delta^{kl}_{\text{ud,V/A}}\left(s_0, D\right)\right)$

$$\delta_{\text{P}} = \underbrace{\sum_{n=1} K_n\, A^{(n)}(\alpha_s)}_{\text{CIPT}} = \underbrace{\sum_{n=1} r_n\, a_\tau^n}_{\text{FOPT}} \qquad a_\tau \equiv \frac{\alpha_s(m_\tau^2)}{\pi}$$

$$\delta_{\text{NP}} \sim F\left(\left\langle \frac{\alpha_s}{\pi} \text{GG} \right\rangle, \mathcal{O}(6), \mathcal{O}(8)\right)$$

- $\alpha_S\left(M_\tau^2\right)$ can be fit from R_τ, D^{10}, D^{12}, D^{13}

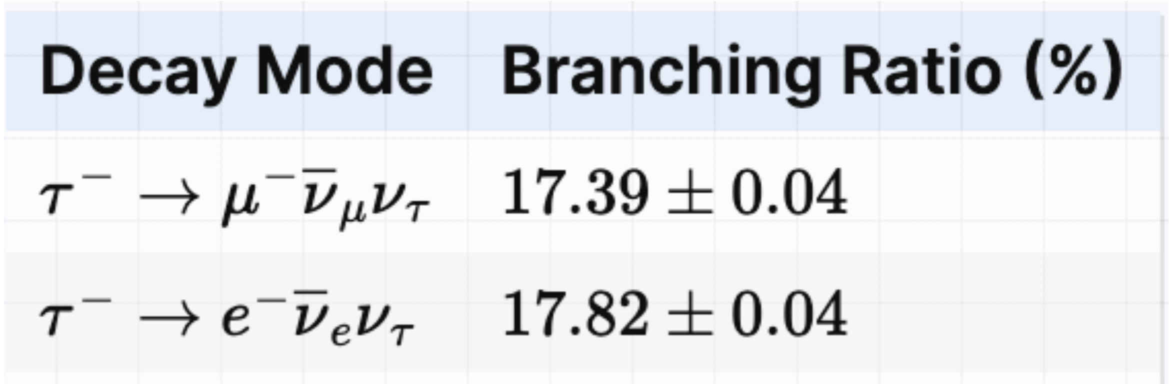
V/A denote vector/axial-vector components of non-strange hadronic τ decays.

How to extract $\alpha_s(m_\tau^2)$ from hadronic τ decay?

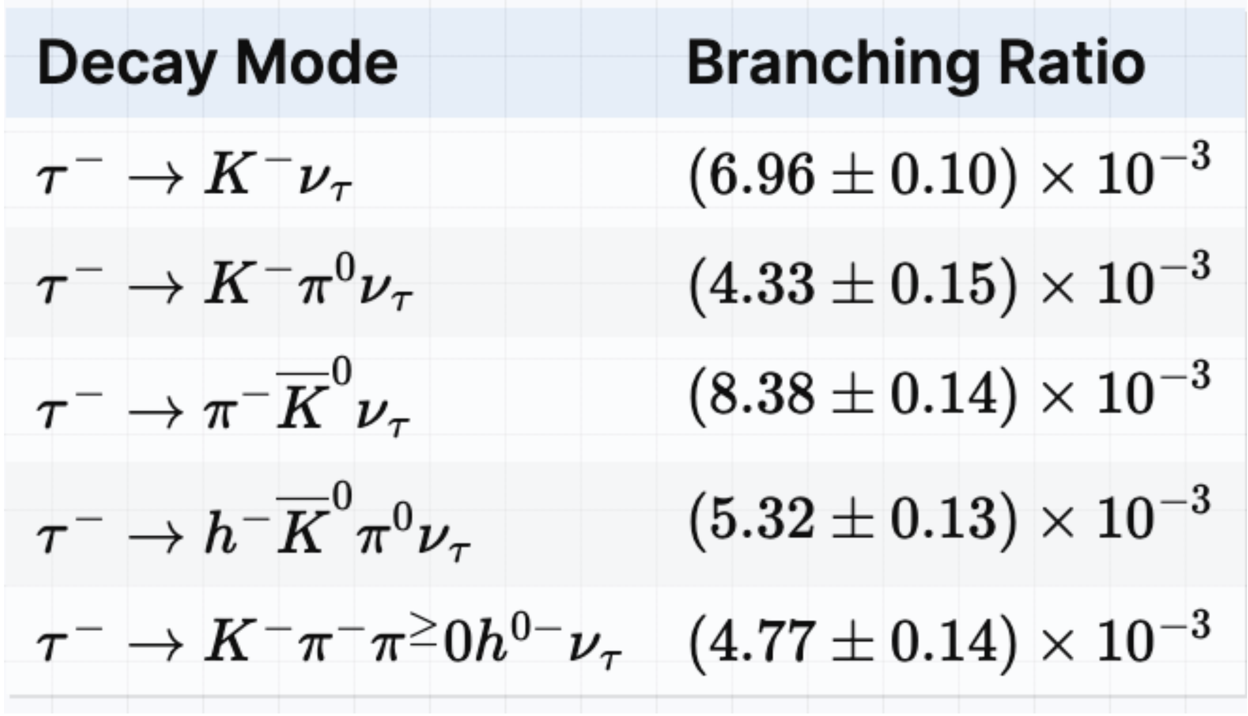
- $$R_{\tau,V+A} \equiv \frac{\Gamma\left(\tau \to \nu_\tau \text{ pions }\right)}{\Gamma\left(\tau \to l\nu_\tau\nu_l\right)} = \frac{\Gamma_h}{\Gamma_l}$$

  from the ***branching ratios***:

  $$R_{\tau,V+A} = \frac{1 - \mathcal{B}_e - \mathcal{B}_\mu - \mathcal{B}_S}{\mathcal{B}_e}$$



Decay Mode	**Branching Ratio (%)**
$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	17.39 ± 0.04
$\tau^- \to e^-\bar{\nu}_e\nu_\tau$	17.82 ± 0.04

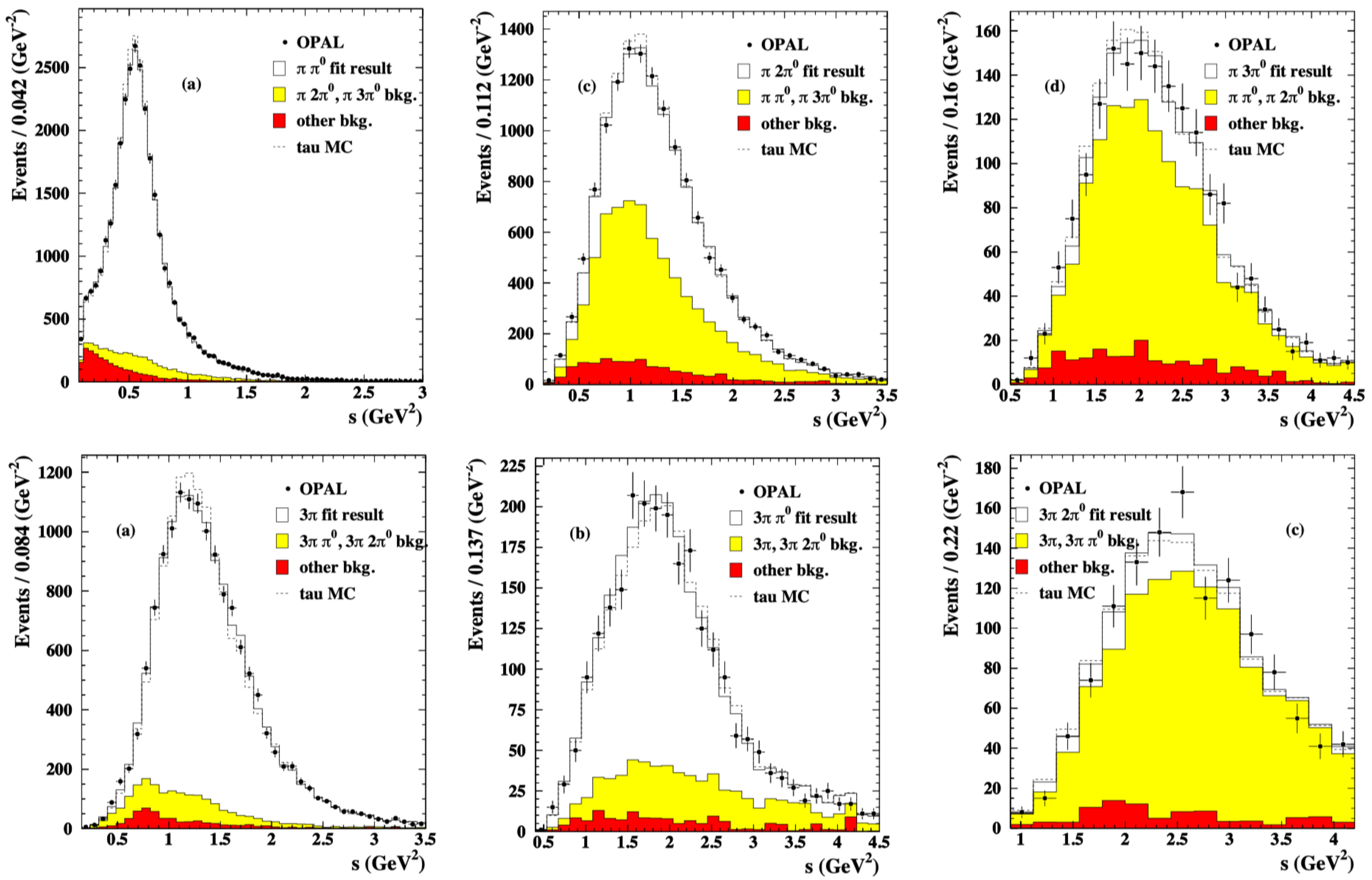


Decay Mode	**Branching Ratio**
$\tau^- \to K^-\nu_\tau$	$(6.96 \pm 0.10) \times 10^{-3}$
$\tau^- \to K^-\pi^0\nu_\tau$	$(4.33 \pm 0.15) \times 10^{-3}$
$\tau^- \to \pi^-\overline{K}^0\nu_\tau$	$(8.38 \pm 0.14) \times 10^{-3}$
$\tau^- \to h^-\overline{K}^0\pi^0\nu_\tau$	$(5.32 \pm 0.13) \times 10^{-3}$
$\tau^- \to K^-\pi^-\pi^{\geq 0}h^0\nu_\tau$	$(4.77 \pm 0.14) \times 10^{-3}$

- $$R^{kl}_{\tau,V/A}(s_0) = \int_0^{s_0} ds \left(1 - \frac{s}{s_0}\right)^k \left(\frac{s}{m_\tau^2}\right)^l \frac{dR_{\tau,V/A}}{ds}$$

  from the inclusive M^2_{had} ***distribution***: $\frac{dR_{\tau,V/A}}{ds}$

arXiv: hep-ex/9808019



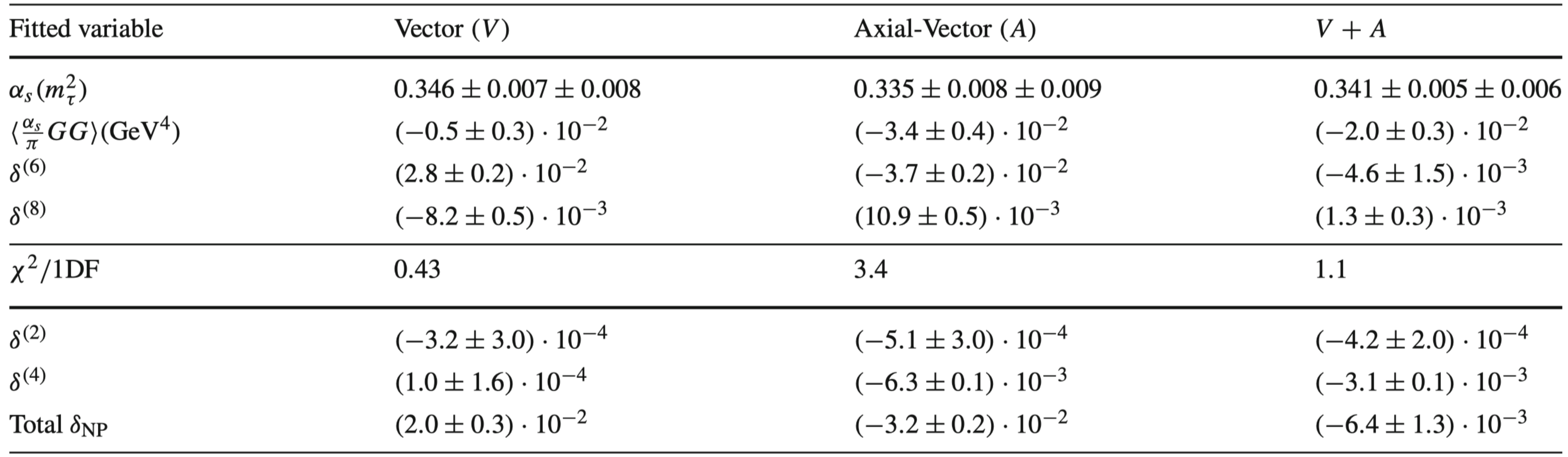
How to extract $\alpha_s(m_\tau^2)$ from hadronic τ decay?

- $R^{kl}_{\tau,V/A}\left(s_0\right) = N_c S_{EW}\left|V_{\rm ud}\right|^2\left(r^{kl}\left(1+\delta^{(0),kl}\left(s_0;\alpha_S(s_0)\right)\right) + \sum_{D=2,4\ldots}\delta^{kl}_{{\rm ud,V/A}}\left(s_0,D\right)\right)$

- $R^{kl}_{\tau,V-A}\left(s_0\right) = N_c S_{EW}\left|V_{\rm ud}\right|^2\left(\sum_{D=2,4\ldots}\delta^{kl}_{{\rm ud,V}}\left(s_0,D\right) - \sum_{D=2,4\ldots}\delta^{kl}_{{\rm ud,A}}\left(s_0,D\right)\right)$

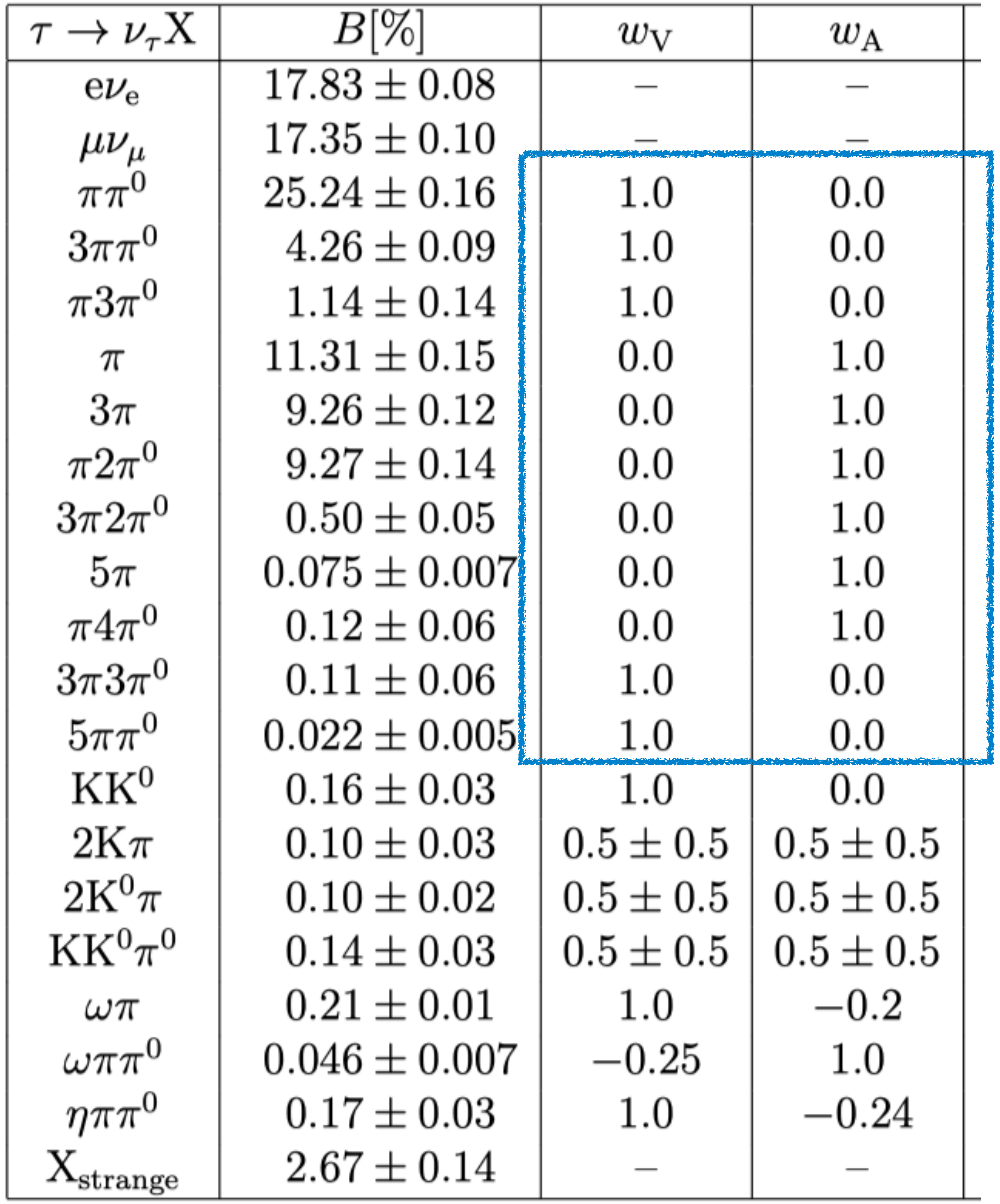
- Non-perturbative parameters can also be separately analyzed from V-A spectral moments.

ALEPH 2014 10.1140/epjc/s10052-014-2803-9



Fitted variable	Vector (V)	Axial-Vector (A)	$V+A$
$\alpha_s(m_\tau^2)$	$0.346 \pm 0.007 \pm 0.008$	$0.335 \pm 0.008 \pm 0.009$	$0.341 \pm 0.005 \pm 0.006$
$\langle\frac{\alpha_s}{\pi}GG\rangle(\mathrm{GeV}^4)$	$(-0.5 \pm 0.3) \cdot 10^{-2}$	$(-3.4 \pm 0.4) \cdot 10^{-2}$	$(-2.0 \pm 0.3) \cdot 10^{-2}$
$\delta^{(6)}$	$(2.8 \pm 0.2) \cdot 10^{-2}$	$(-3.7 \pm 0.2) \cdot 10^{-2}$	$(-4.6 \pm 1.5) \cdot 10^{-3}$
$\delta^{(8)}$	$(-8.2 \pm 0.5) \cdot 10^{-3}$	$(10.9 \pm 0.5) \cdot 10^{-3}$	$(1.3 \pm 0.3) \cdot 10^{-3}$
$\chi^2/1\mathrm{DF}$	0.43	3.4	1.1
$\delta^{(2)}$	$(-3.2 \pm 3.0) \cdot 10^{-4}$	$(-5.1 \pm 3.0) \cdot 10^{-4}$	$(-4.2 \pm 2.0) \cdot 10^{-4}$
$\delta^{(4)}$	$(1.0 \pm 1.6) \cdot 10^{-4}$	$(-6.3 \pm 0.1) \cdot 10^{-3}$	$(-3.1 \pm 0.1) \cdot 10^{-3}$
Total δ_{NP}	$(2.0 \pm 0.3) \cdot 10^{-2}$	$(-3.2 \pm 0.2) \cdot 10^{-2}$	$(-6.4 \pm 1.3) \cdot 10^{-3}$

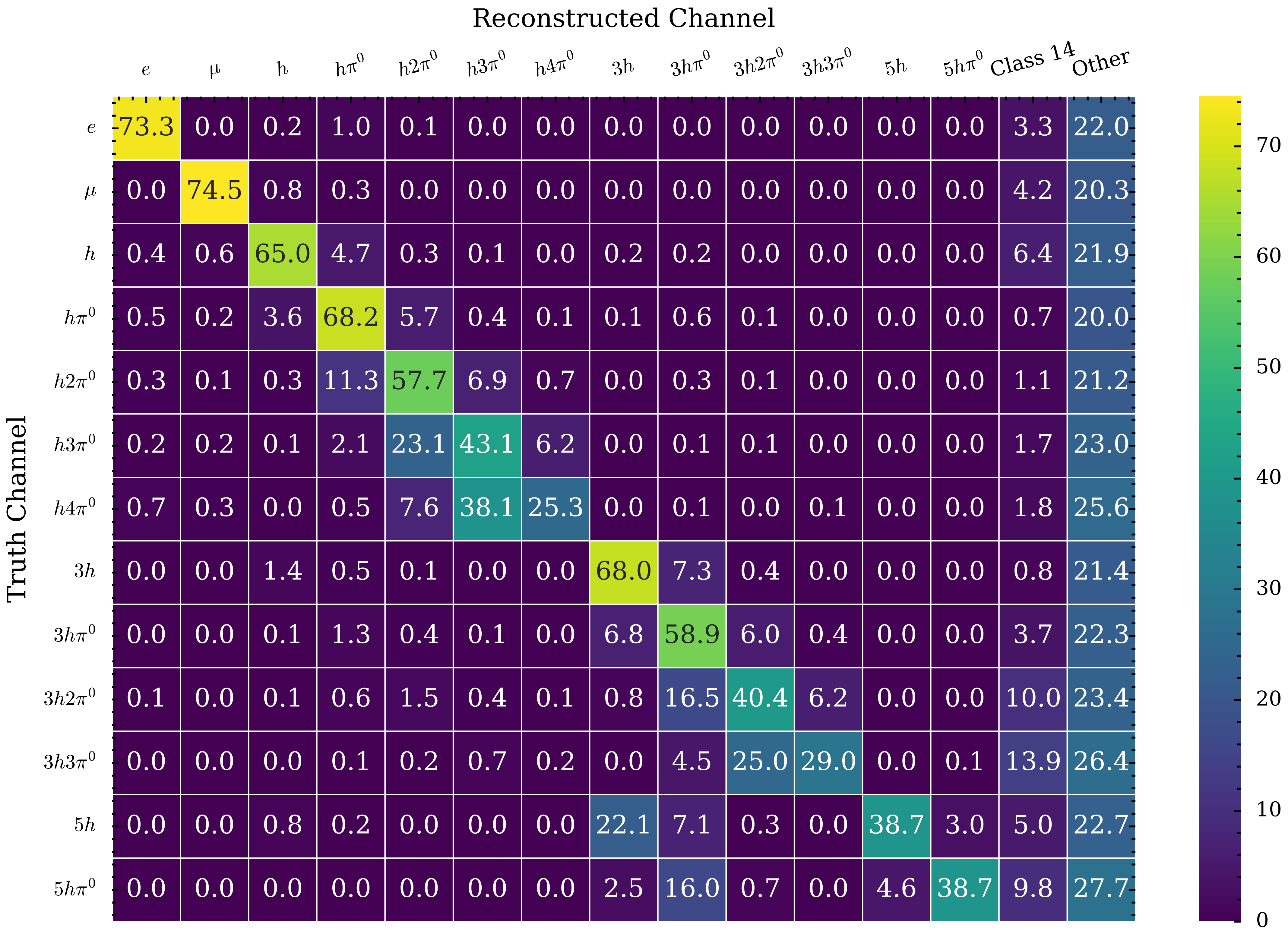
OPAL 1999 10.1007/s100529901061



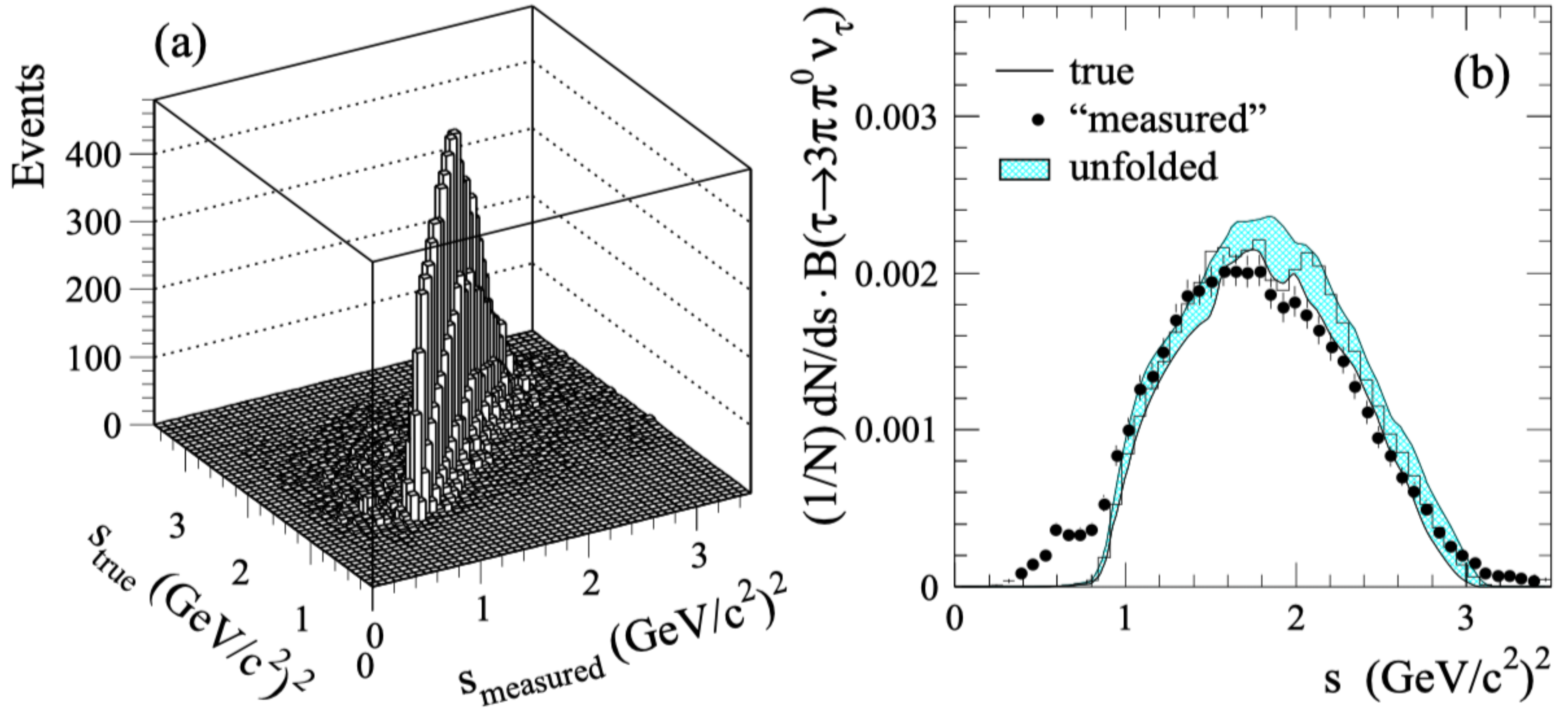
$\tau \to \nu_\tau X$	$B[\%]$	$w_{\rm V}$	$w_{\rm A}$
$e\nu_e$	17.83 ± 0.08	–	–
$\mu\nu_\mu$	17.35 ± 0.10	–	–
$\pi\pi^0$	25.24 ± 0.16	1.0	0.0
$3\pi\pi^0$	4.26 ± 0.09	1.0	0.0
$\pi 3\pi^0$	1.14 ± 0.14	1.0	0.0
π	11.31 ± 0.15	0.0	1.0
3π	9.26 ± 0.12	0.0	1.0
$\pi 2\pi^0$	9.27 ± 0.14	0.0	1.0
$3\pi 2\pi^0$	0.50 ± 0.05	0.0	1.0
5π	0.075 ± 0.007	0.0	1.0
$\pi 4\pi^0$	0.12 ± 0.06	0.0	1.0
$3\pi 3\pi^0$	0.11 ± 0.06	1.0	0.0
$5\pi\pi^0$	0.022 ± 0.005	1.0	0.0
KK^0	0.16 ± 0.03	1.0	0.0
$2\mathrm{K}\pi$	0.10 ± 0.03	0.5 ± 0.5	0.5 ± 0.5
$2\mathrm{K}^0\pi$	0.10 ± 0.02	0.5 ± 0.5	0.5 ± 0.5
$\mathrm{KK}^0\pi^0$	0.14 ± 0.03	0.5 ± 0.5	0.5 ± 0.5
$\omega\pi$	0.21 ± 0.01	1.0	−0.2
$\omega\pi\pi^0$	0.046 ± 0.007	−0.25	1.0
$\eta\pi\pi^0$	0.17 ± 0.03	1.0	−0.24
$\mathrm{X}_{\rm strange}$	2.67 ± 0.14	–	–

How to extract $\alpha_s(m_\tau^2)$ from hadronic τ decay?

$\tau^+\tau^-$ event selection → decay classification & Br measurement → $m_{\rm had}^2$ reconstruction & correction → R_τ^{kl} calculation & $\alpha_s(m_\tau^2)$ extraction



Truth Channel \ Reconstructed Channel	e	μ	h	$h\pi^0$	$h2\pi^0$	$h3\pi^0$	$h4\pi^0$	$3h$	$3h\pi^0$	$3h2\pi^0$	$3h3\pi^0$	$5h$	$5h\pi^0$	Class 14	Other
e	73.3	0.0	0.2	1.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	22.0
μ	0.0	74.5	0.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	20.3
h	0.4	0.6	65.0	4.7	0.3	0.1	0.0	0.2	0.2	0.0	0.0	0.0	0.0	6.4	21.9
$h\pi^0$	0.5	0.2	3.6	68.2	5.7	0.4	0.1	0.1	0.6	0.1	0.0	0.0	0.0	0.7	20.0
$h2\pi^0$	0.3	0.1	0.3	11.3	57.7	6.9	0.7	0.0	0.3	0.1	0.0	0.0	0.0	1.1	21.2
$h3\pi^0$	0.2	0.2	0.1	2.1	23.1	43.1	6.2	0.0	0.1	0.1	0.0	0.0	0.0	1.7	23.0
$h4\pi^0$	0.7	0.3	0.0	0.5	7.6	38.1	25.3	0.0	0.1	0.0	0.1	0.0	0.0	1.8	25.6
$3h$	0.0	0.0	1.4	0.5	0.1	0.0	0.0	68.0	7.3	0.4	0.0	0.0	0.0	0.8	21.4
$3h\pi^0$	0.0	0.0	0.1	1.3	0.4	0.1	0.0	6.8	58.9	6.0	0.4	0.0	0.0	3.7	22.3
$3h2\pi^0$	0.1	0.0	0.1	0.6	1.5	0.4	0.1	0.8	16.5	40.4	6.2	0.0	0.0	10.0	23.4
$3h3\pi^0$	0.0	0.0	0.0	0.1	0.2	0.7	0.2	0.0	4.5	25.0	29.0	0.0	0.1	13.9	26.4
$5h$	0.0	0.0	0.8	0.2	0.0	0.0	0.0	22.1	7.1	0.3	0.0	38.7	3.0	5.0	22.7
$5h\pi^0$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	16.0	0.7	0.0	4.6	38.7	9.8	27.7



10.1016/j.physrep.2005.06.007 & 10.1007/s002880050523

Outline

1 Motivation & Introduction

2 History

- Where was the data from?
- Which was the dominant uncertainty?
- Which effect contributes the larger systematical uncertainty?

3 CEPC potential

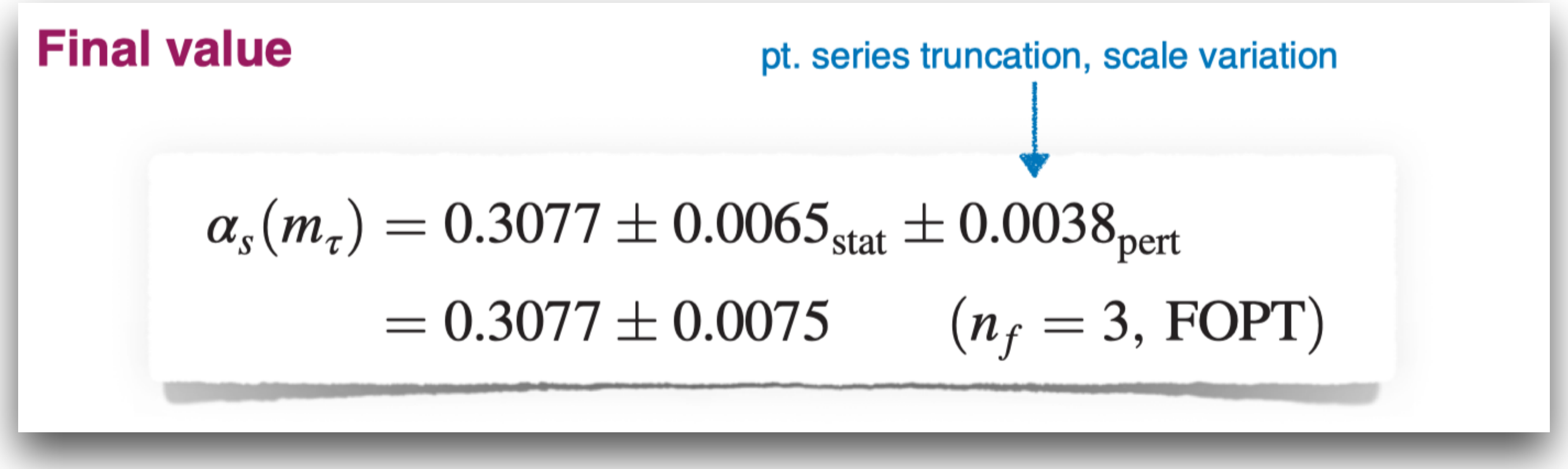
4 Summary

History of $\alpha_s(m_\tau^2)$ measurements from τ

- The previous measurements provided by:
    - **ALEPH** & **OPAL** on LEP ($\sqrt{s} \sim 91.2\,\mathrm{GeV}$)
    - **CLEO–II** on CESR ($\sqrt{s} = 10\,\mathrm{GeV}$)
- Theoretical uncertainty is decreasing.
- The $\alpha_s(m_\tau^2)$ experimental uncertainty has been dominated by systematic since 1995.

The key is the systematic uncertainty.

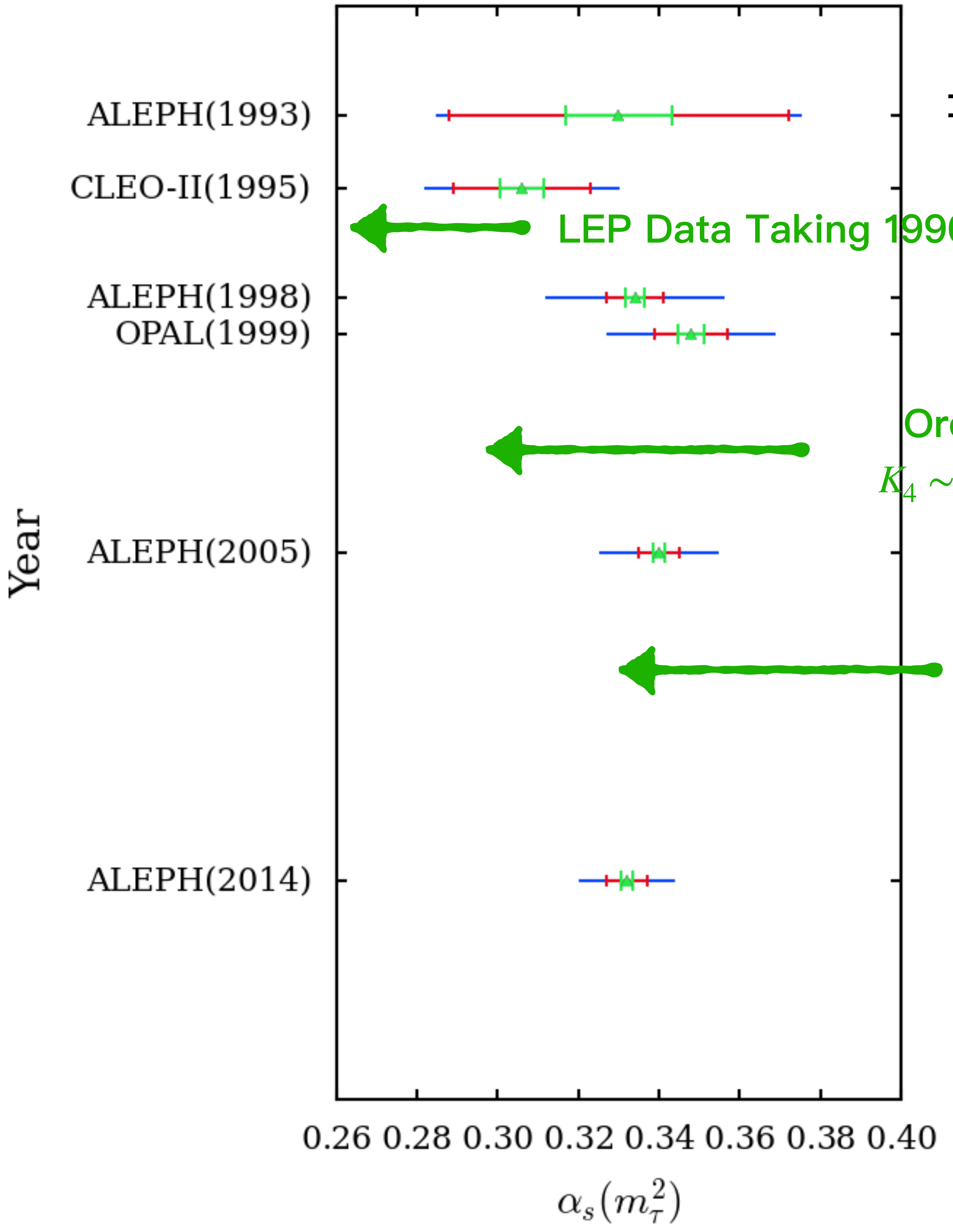
Diogo Boito, Workshop TAU2021



Final value

pt. series truncation, scale variation

$$\alpha_s(m_\tau) = 0.3077 \pm 0.0065_{\text{stat}} \pm 0.0038_{\text{pert}}$$
$$= 0.3077 \pm 0.0075 \qquad (n_f = 3,\ \text{FOPT})$$



$\pm 4.0\%_{stat} \pm 12.1\%_{sys} \pm 5.2\,\%_{theo}$

$\pm 1.8\%_{stat} \pm 5.3\%_{sys} \pm 5.6\,\%_{theo}$

LEP Data Taking 1990~1995

$\pm 0.7\%_{stat} \pm 2.0\%_{sys} \pm 6.3\,\%_{theo}$

$\pm 0.9\%_{stat} \pm 2.4\%_{sys} \pm 5.5\,\%_{theo}$

Order α_s^4 coefficient

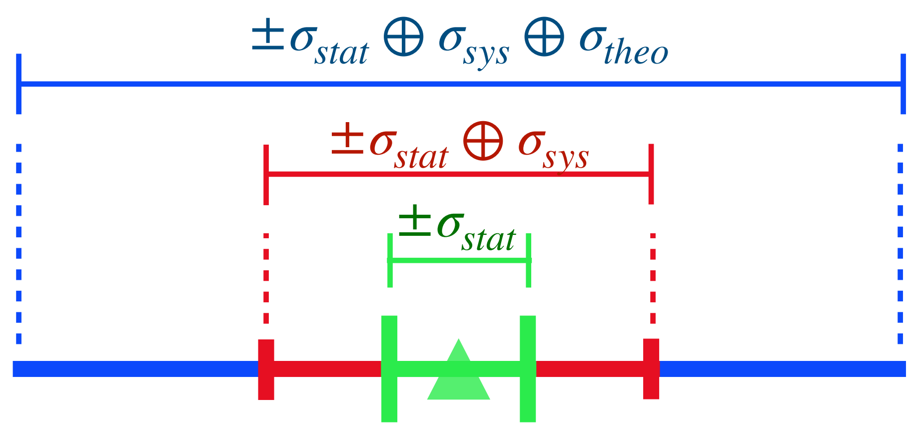
$K_4 \sim 50 \pm 50 \to 25 \pm 25$

$\pm 0.4\%_{stat} \pm 1.4\%_{sys} \pm 4.1\,\%_{theo}$

Order α_s^4 QCD Correction

PRL 101, 012002 (2008)

$\pm 0.4\%_{stat} \pm 1.4\%_{sys} \pm 3.3\,\%_{theo}$



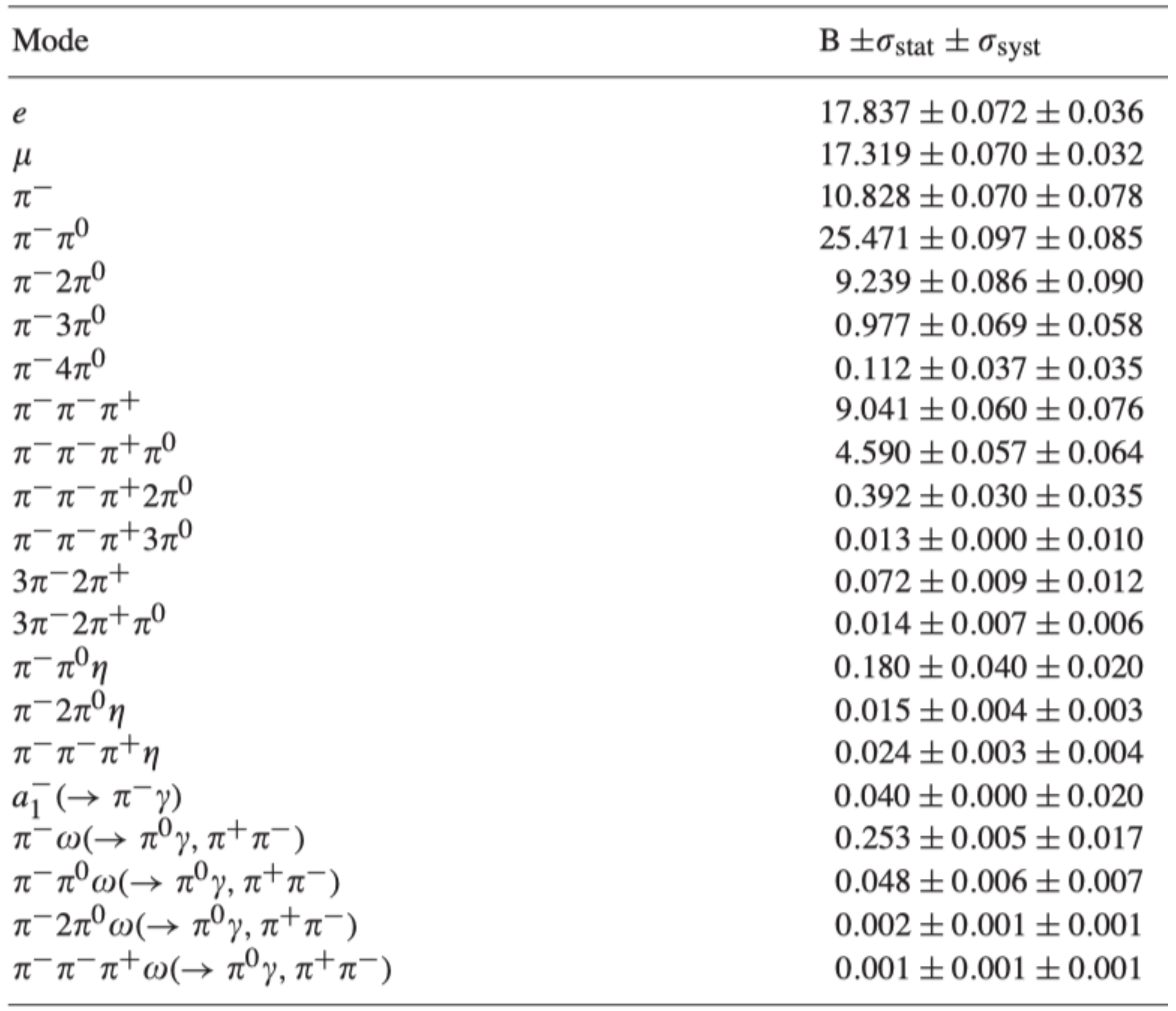
The statistical and systematical uncertainties are roughly estimated from D^{kl} roughly

Systematic uncertainty of ALEPH $Br(\tau)$ measurements

Branching ratios for exclusive $\tau^- \to X\nu_\tau$: the systematic and statistic uncertainty are comparable.

for $X = e^-, \mu^-, h^-, 3h^-$: leading contribution is particle identification & event selection

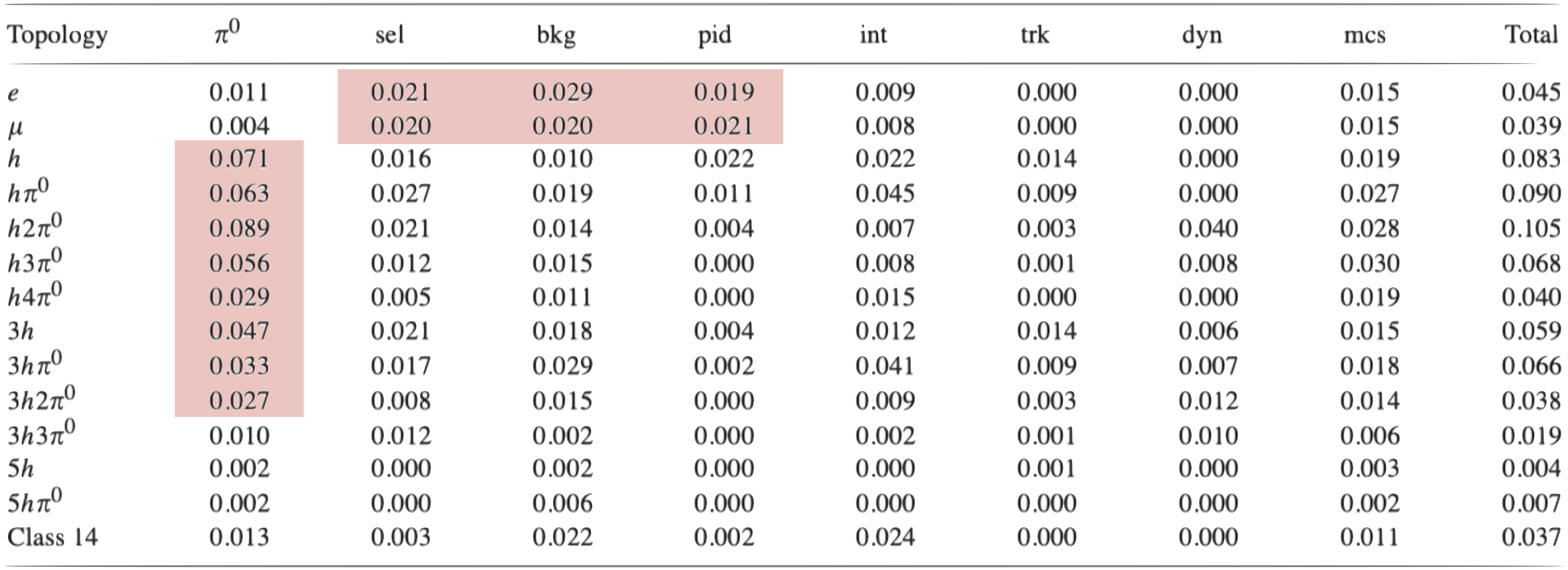
for $X = (1,3)h^- \geq 0\pi^0$: leading contribution is π^0 reconstruction



Mode	B $\pm\sigma_{\text{stat}} \pm \sigma_{\text{syst}}$
e	$17.837 \pm 0.072 \pm 0.036$
μ	$17.319 \pm 0.070 \pm 0.032$
π^-	$10.828 \pm 0.070 \pm 0.078$
$\pi^-\pi^0$	$25.471 \pm 0.097 \pm 0.085$
$\pi^-2\pi^0$	$9.239 \pm 0.086 \pm 0.090$
$\pi^-3\pi^0$	$0.977 \pm 0.069 \pm 0.058$
$\pi^-4\pi^0$	$0.112 \pm 0.037 \pm 0.035$
$\pi^-\pi^-\pi^+$	$9.041 \pm 0.060 \pm 0.076$
$\pi^-\pi^-\pi^+\pi^0$	$4.590 \pm 0.057 \pm 0.064$
$\pi^-\pi^-\pi^+2\pi^0$	$0.392 \pm 0.030 \pm 0.035$
$\pi^-\pi^-\pi^+3\pi^0$	$0.013 \pm 0.000 \pm 0.010$
$3\pi^-2\pi^+$	$0.072 \pm 0.009 \pm 0.012$
$3\pi^-2\pi^+\pi^0$	$0.014 \pm 0.007 \pm 0.006$
$\pi^-\pi^0\eta$	$0.180 \pm 0.040 \pm 0.020$
$\pi^-2\pi^0\eta$	$0.015 \pm 0.004 \pm 0.003$
$\pi^-\pi^-\pi^+\eta$	$0.024 \pm 0.003 \pm 0.004$
$a_1^-(\to \pi^-\gamma)$	$0.040 \pm 0.000 \pm 0.020$
$\pi^-\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.253 \pm 0.005 \pm 0.017$
$\pi^-\pi^0\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.048 \pm 0.006 \pm 0.007$
$\pi^-2\pi^0\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.002 \pm 0.001 \pm 0.001$
$\pi^-\pi^-\pi^+\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.001 \pm 0.001 \pm 0.001$

Table 11

Total systematic errors for branching ratios measured from the 1994–1995 data sample



Topology	π^0	sel	bkg	pid	int	trk	dyn	mcs	Total
e	0.011	0.021	0.029	0.019	0.009	0.000	0.000	0.015	0.045
μ	0.004	0.020	0.020	0.021	0.008	0.000	0.000	0.015	0.039
h	0.071	0.016	0.010	0.022	0.022	0.014	0.000	0.019	0.083
$h\pi^0$	0.063	0.027	0.019	0.011	0.045	0.009	0.000	0.027	0.090
$h2\pi^0$	0.089	0.021	0.014	0.004	0.007	0.003	0.040	0.028	0.105
$h3\pi^0$	0.056	0.012	0.015	0.000	0.008	0.001	0.008	0.030	0.068
$h4\pi^0$	0.029	0.005	0.011	0.000	0.015	0.000	0.000	0.019	0.040
$3h$	0.047	0.021	0.018	0.004	0.012	0.014	0.006	0.015	0.059
$3h\pi^0$	0.033	0.017	0.029	0.002	0.041	0.009	0.007	0.018	0.066
$3h2\pi^0$	0.027	0.008	0.015	0.000	0.009	0.003	0.012	0.014	0.038
$3h3\pi^0$	0.010	0.012	0.002	0.000	0.002	0.001	0.010	0.006	0.019
$5h$	0.002	0.000	0.002	0.000	0.000	0.001	0.000	0.003	0.004
$5h\pi^0$	0.002	0.000	0.006	0.000	0.000	0.000	0.000	0.002	0.007
Class 14	0.013	0.003	0.022	0.002	0.024	0.000	0.000	0.011	0.037

All numbers are absolute in per cent. The labels are defined as follows: photon and π^0 reconstruction (π^0), event selection efficiency (sel), non-τ background (bkg), charged particle identification (pid), secondary interactions (int), tracking (trk), Monte Carlo dynamics (dyn), Monte Carlo statistics (mcs), total systematic uncertainty (total).

10.1016/j.physrep.2005.06.007

Systematic uncertainty of ALEPH D^{kl} measurements

- **ALEPH reported experimental uncertainty components in 1998**
- The leading systematic uncertainty:
  - Branching ratios (PID + π^0 reco.)
  - (Fake−)photon and π^0 reconstructions

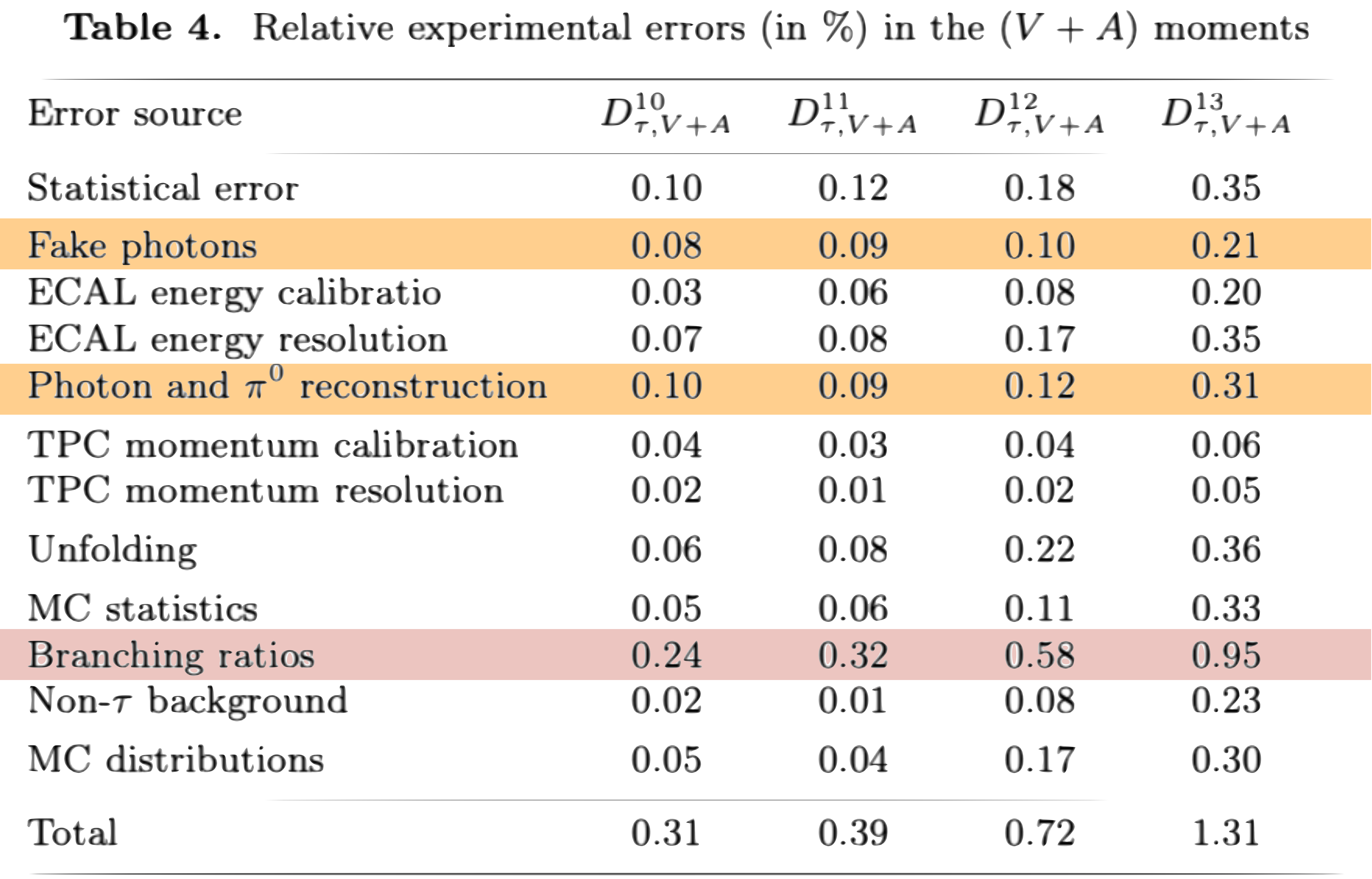


Table 4. Relative experimental errors (in %) in the $(V + A)$ moments

Error source	$D^{10}_{\tau,V+A}$	$D^{11}_{\tau,V+A}$	$D^{12}_{\tau,V+A}$	$D^{13}_{\tau,V+A}$
Statistical error	0.10	0.12	0.18	0.35
Fake photons	0.08	0.09	0.10	0.21
ECAL energy calibratio	0.03	0.06	0.08	0.20
ECAL energy resolution	0.07	0.08	0.17	0.35
Photon and π^0 reconstruction	0.10	0.09	0.12	0.31
TPC momentum calibration	0.04	0.03	0.04	0.06
TPC momentum resolution	0.02	0.01	0.02	0.05
Unfolding	0.06	0.08	0.22	0.36
MC statistics	0.05	0.06	0.11	0.33
Branching ratios	0.24	0.32	0.58	0.95
Non-τ background	0.02	0.01	0.08	0.23
MC distributions	0.05	0.04	0.17	0.30
Total	0.31	0.39	0.72	1.31

10.1007/s100529800895

Outline

1 Motivation & Introduction

2 History

3 CEPC potential

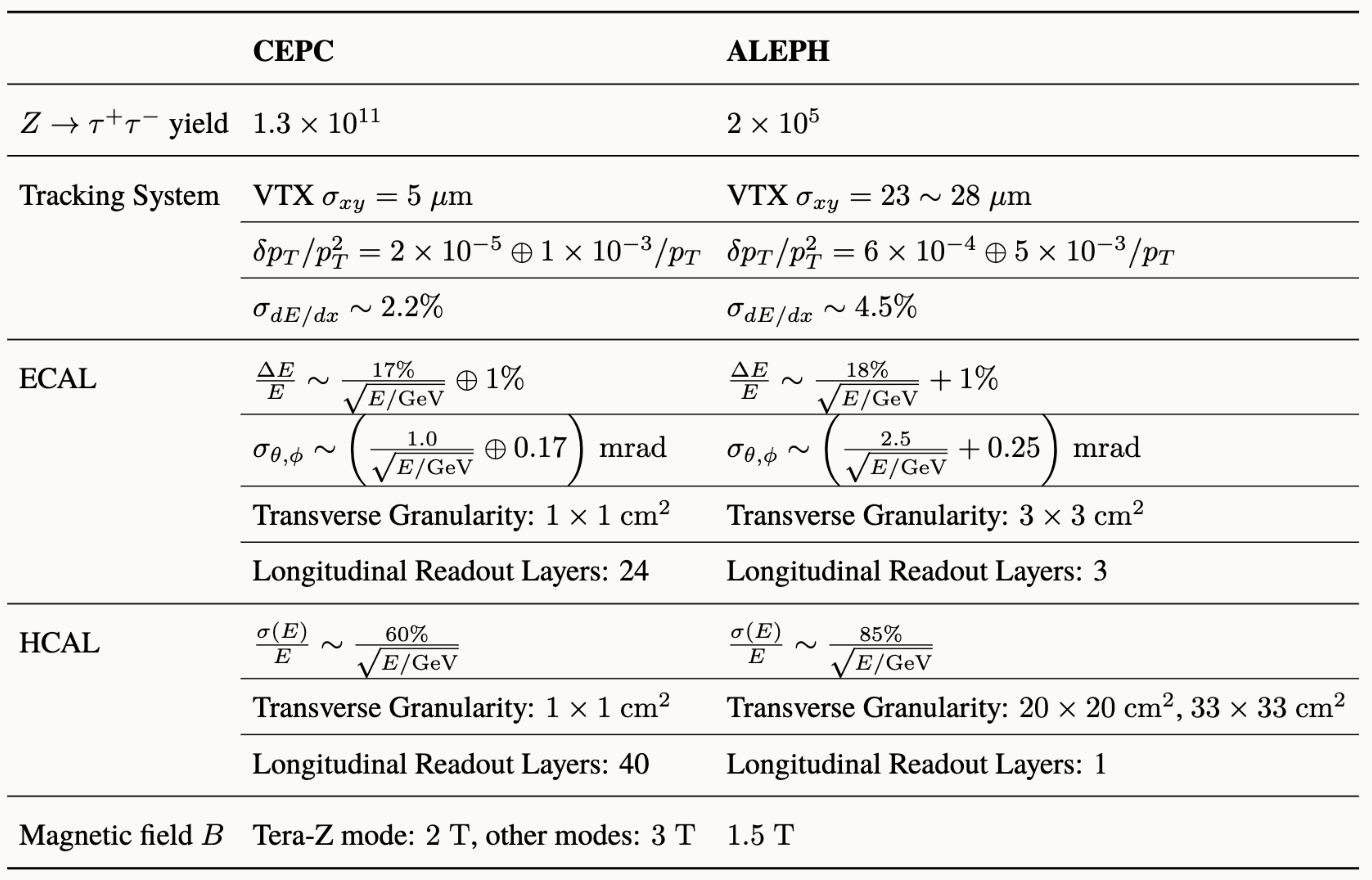
- Detector: CEPC vs. ALEPH
- τ decay identification on CEPC
- Improvement from AI for PFA

4 Summary

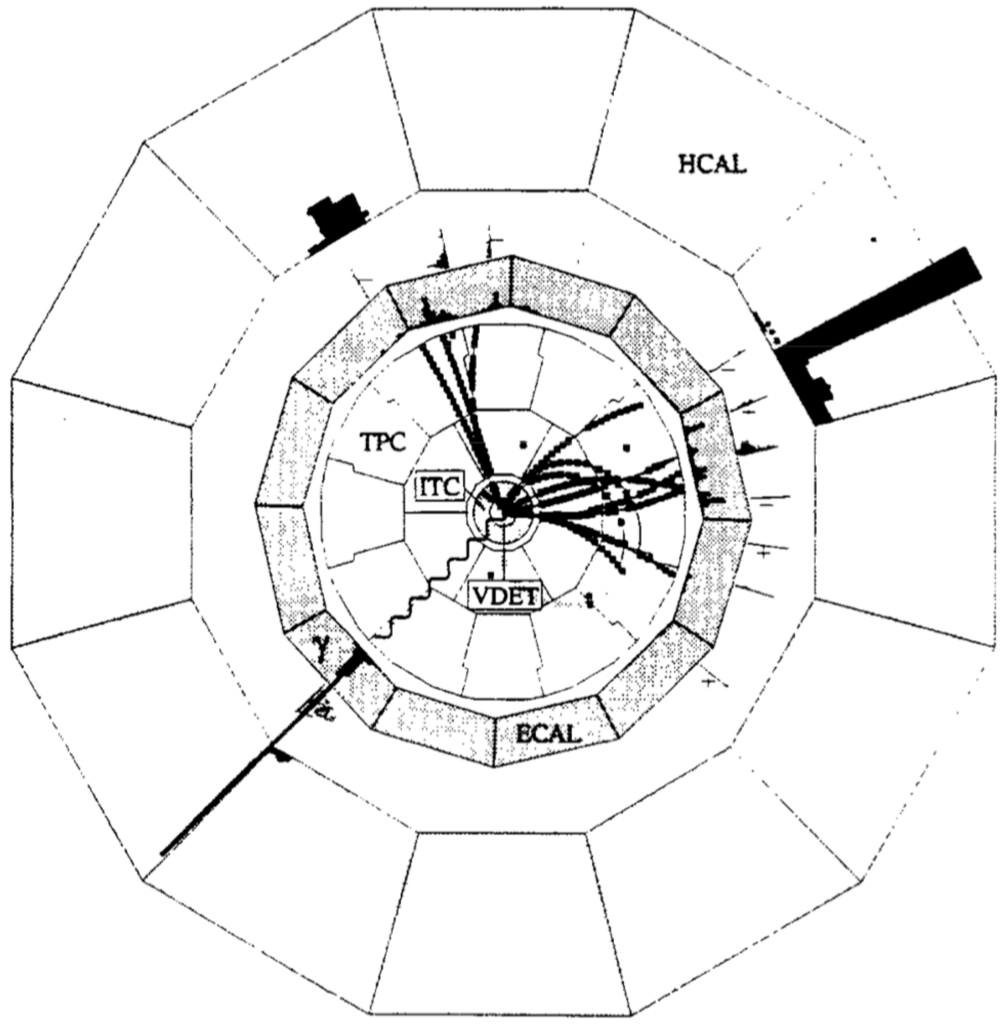
Detector Overview: CEPC vs. ALEPH

CEPC will generate 1.3×10^{11} $\tau^+\tau^-$ events, statistic uncertainty will be suppressed by ~800 times.

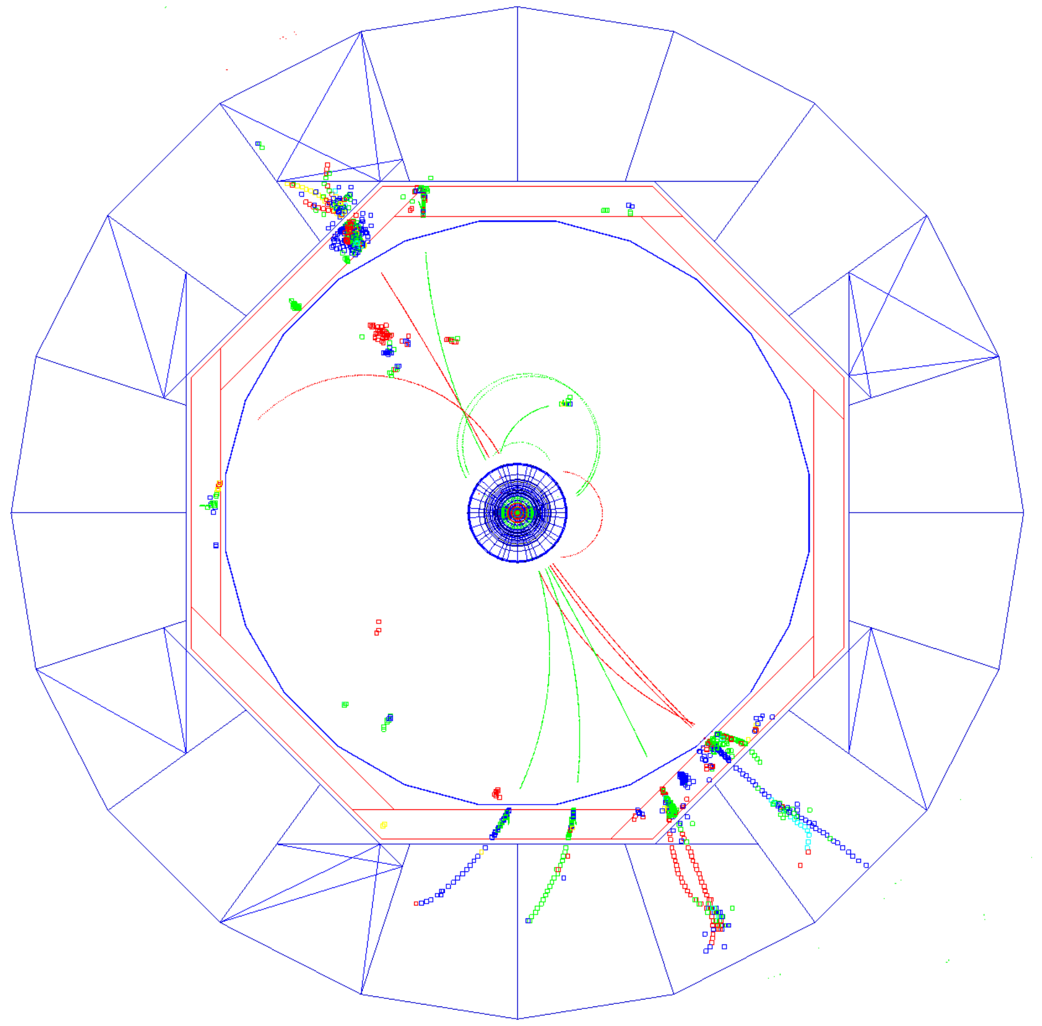
CEPC detector has: better dE/dx for PID; higher granularity for γ/π^0 reconstruction (also beneficial to PID).



	CEPC	**ALEPH**
$Z \to \tau^+\tau^-$ yield	1.3×10^{11}	2×10^5
Tracking System	VTX $\sigma_{xy} = 5\ \mu\mathrm{m}$	VTX $\sigma_{xy} = 23 \sim 28\ \mu\mathrm{m}$
	$\delta p_T/p_T^2 = 2 \times 10^{-5} \oplus 1 \times 10^{-3}/p_T$	$\delta p_T/p_T^2 = 6 \times 10^{-4} \oplus 5 \times 10^{-3}/p_T$
	$\sigma_{dE/dx} \sim 2.2\%$	$\sigma_{dE/dx} \sim 4.5\%$
ECAL	$\frac{\Delta E}{E} \sim \frac{17\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1\%$	$\frac{\Delta E}{E} \sim \frac{18\%}{\sqrt{E/\mathrm{GeV}}} + 1\%$
	$\sigma_{\theta,\phi} \sim \left(\frac{1.0}{\sqrt{E/\mathrm{GeV}}} \oplus 0.17\right)$ mrad	$\sigma_{\theta,\phi} \sim \left(\frac{2.5}{\sqrt{E/\mathrm{GeV}}} + 0.25\right)$ mrad
	Transverse Granularity: $1 \times 1\ \mathrm{cm}^2$	Transverse Granularity: $3 \times 3\ \mathrm{cm}^2$
	Longitudinal Readout Layers: 24	Longitudinal Readout Layers: 3
HCAL	$\frac{\sigma(E)}{E} \sim \frac{60\%}{\sqrt{E/\mathrm{GeV}}}$	$\frac{\sigma(E)}{E} \sim \frac{85\%}{\sqrt{E/\mathrm{GeV}}}$
	Transverse Granularity: $1 \times 1\ \mathrm{cm}^2$	Transverse Granularity: $20 \times 20\ \mathrm{cm}^2$, $33 \times 33\ \mathrm{cm}^2$
	Longitudinal Readout Layers: 40	Longitudinal Readout Layers: 1
Magnetic field B	Tera-Z mode: 2 T, other modes: 3 T	1.5 T



ALEPH Event display



CEPC Event display

CEPC performance is based on the CEPC concept design.
New detector design includes higher VTX, TOF and calorimeter energy resolution.

Artificial event selection & classification

- Reproduce cut−based event selection & classification on CEPC full simulation
  - Reject non−τ background: multiplicity & missing energy through ν
  - $\pi^0 \to \gamma\gamma$ pairing by invariant mass

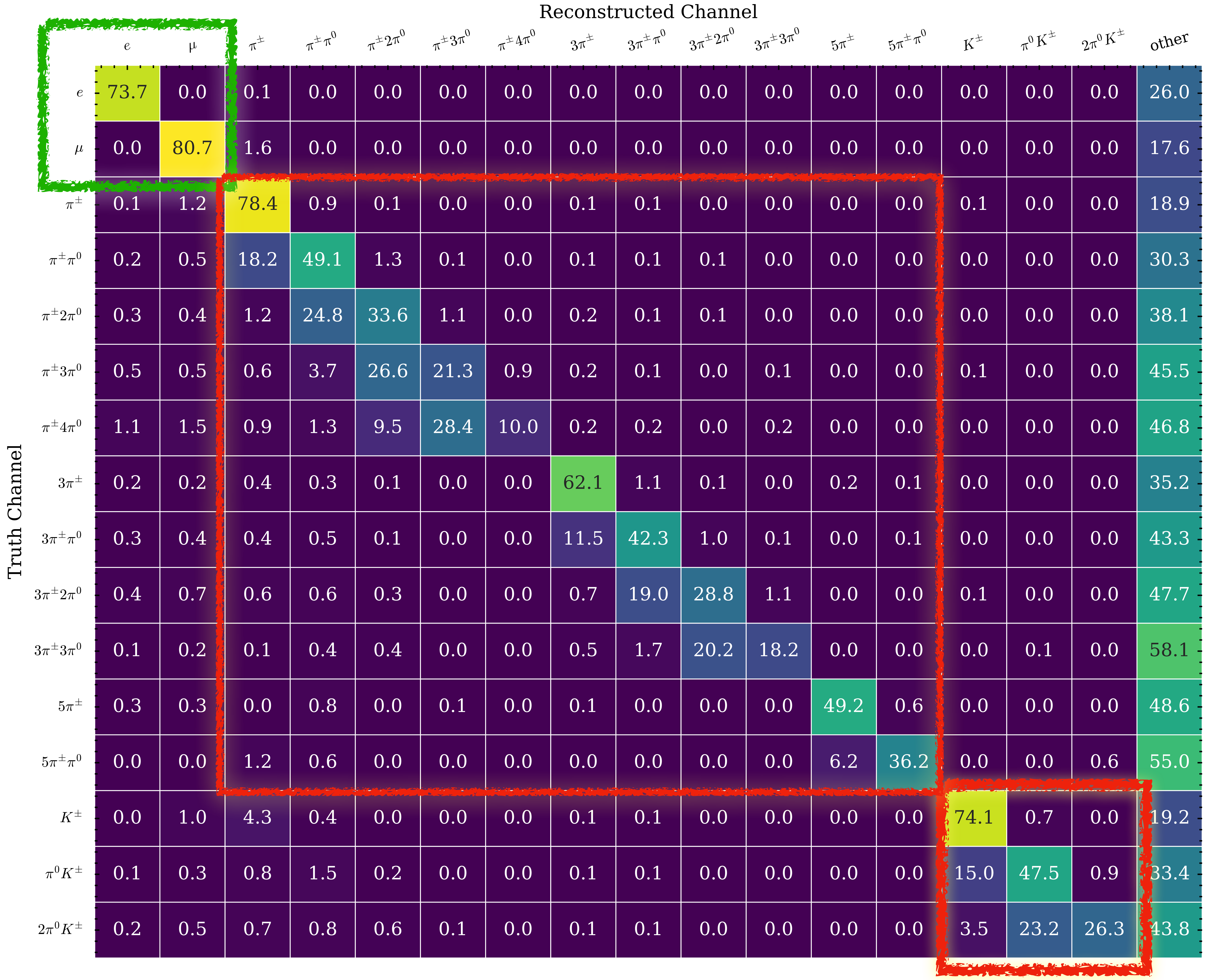
🙂 non−τ background fraction at percent level.

🙂 Good selection for leptonic channel & hadronic channel w/o π^0

😕 **Significant channel migration due to π^0**

Unsolved π^0 should be corrected in enough details

	ee	$\mu\mu$	$u\bar{u}/d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\tau\tau$
Initial	1.3×10^{11}	1.3×10^{11}	1.1×10^{12}	6.3×10^{11}	4.8×10^{11}	6.0×10^{11}	1.3×10^{11}
N_{track}	1.2×10^{11}	1.3×10^{11}	2.3×10^{10}	1.5×10^{10}	4.9×10^{9}	3.7×10^{9}	1.3×10^{11}
Scattering angle	1.1×10^{11}	1.2×10^{11}	1.4×10^{10}	9.8×10^{9}	1.5×10^{9}	6.7×10^{8}	1.2×10^{11}
Total energy	3.2×10^{8}	2.9×10^{9}	6.9×10^{8}	7.8×10^{8}	3.8×10^{8}	4.0×10^{8}	1.2×10^{11}
Jet anlge	3.2×10^{8}	4.0×10^{8}	6.5×10^{8}	7.4×10^{8}	3.6×10^{8}	3.9×10^{8}	1.1×10^{11}

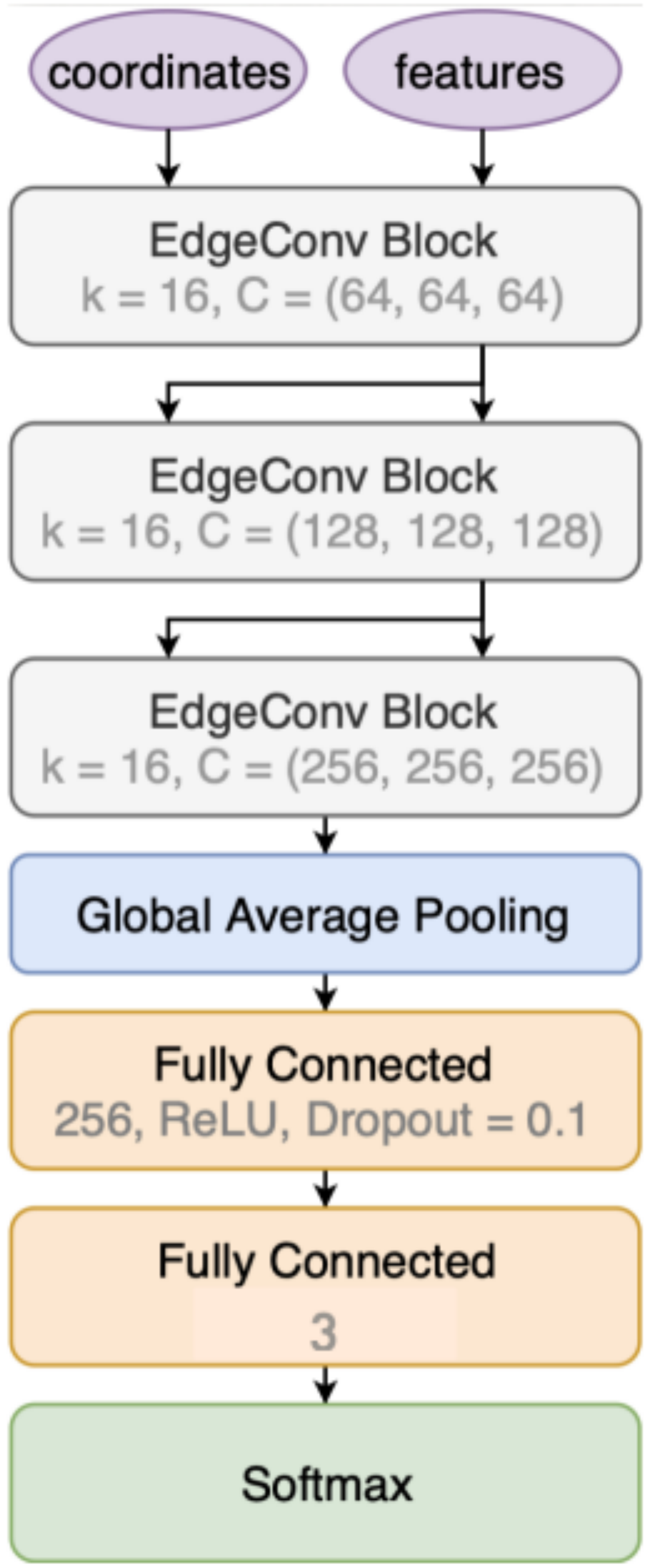


	e	μ	$\pi^\pm$	$\pi^\pm\pi^0$	$\pi^\pm2\pi^0$	$\pi^\pm3\pi^0$	$\pi^\pm4\pi^0$	$3\pi^\pm$	$3\pi^\pm\pi^0$	$3\pi^\pm2\pi^0$	$3\pi^\pm3\pi^0$	$5\pi^\pm$	$5\pi^\pm\pi^0$	$K^\pm$	$\pi^0K^\pm$	$2\pi^0K^\pm$	other
e	73.7	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	26.0
μ	0.0	80.7	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.6
$\pi^\pm$	0.1	1.2	78.4	0.9	0.1	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0	18.9
$\pi^\pm\pi^0$	0.2	0.5	18.2	49.1	1.3	0.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	30.3
$\pi^\pm2\pi^0$	0.3	0.4	1.2	24.8	33.6	1.1	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	38.1
$\pi^\pm3\pi^0$	0.5	0.5	0.6	3.7	26.6	21.3	0.9	0.2	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.0	45.5
$\pi^\pm4\pi^0$	1.1	1.5	0.9	1.3	9.5	28.4	10.0	0.2	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	46.8
$3\pi^\pm$	0.2	0.2	0.4	0.3	0.1	0.0	0.0	62.1	1.1	0.1	0.0	0.2	0.1	0.0	0.0	0.0	35.2
$3\pi^\pm\pi^0$	0.3	0.4	0.4	0.5	0.1	0.0	0.0	11.5	42.3	1.0	0.1	0.0	0.1	0.0	0.0	0.0	43.3
$3\pi^\pm2\pi^0$	0.4	0.7	0.6	0.6	0.3	0.0	0.0	0.7	19.0	28.8	1.1	0.0	0.0	0.1	0.0	0.0	47.7
$3\pi^\pm3\pi^0$	0.1	0.2	0.1	0.4	0.4	0.0	0.0	0.5	1.7	20.2	18.2	0.0	0.0	0.0	0.1	0.0	58.1
$5\pi^\pm$	0.3	0.3	0.0	0.8	0.0	0.1	0.0	0.1	0.0	0.0	0.0	49.2	0.6	0.0	0.0	0.0	48.6
$5\pi^\pm\pi^0$	0.0	0.0	1.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	36.2	0.0	0.0	0.6	55.0
$K^\pm$	0.0	1.0	4.3	0.4	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	74.1	0.7	0.0	19.2
$\pi^0K^\pm$	0.1	0.3	0.8	1.5	0.2	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	15.0	47.5	0.9	33.4
$2\pi^0K^\pm$	0.2	0.5	0.7	0.8	0.6	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	3.5	23.2	26.3	43.8

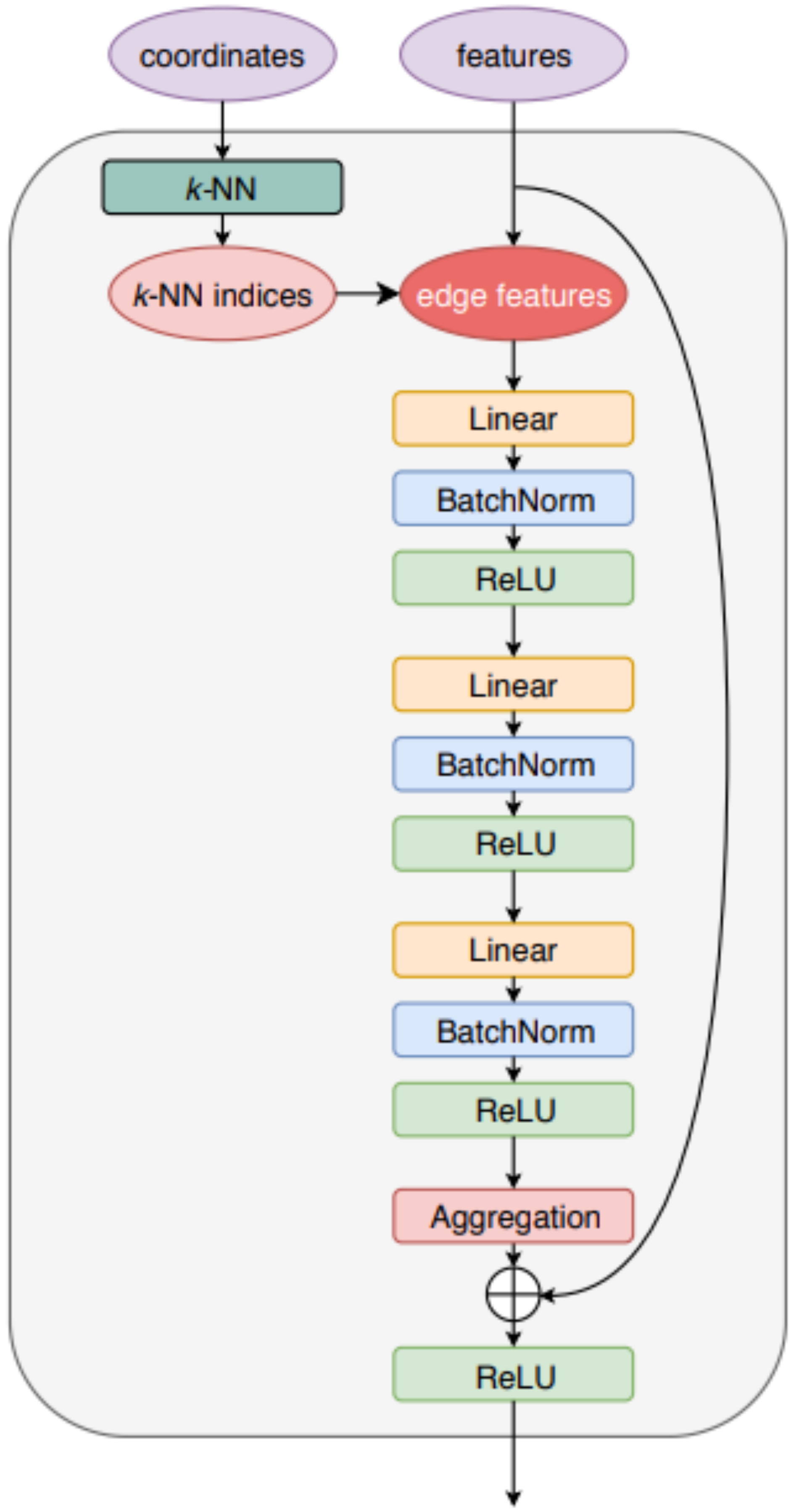
Non–strange hadronic τ decay channel identification on CEPC

- A Graph Neutral Network model are preliminary trained for τ decay identification.
- **MC Sample**:
  - CEPC CDR baseline
  - $Z \to \tau^+\tau^-$; $\tau^- \to$ inclusive;
  - $\tau^+ \to \pi^+\overline{\nu}_\tau$, $\pi^+\pi^0\overline{\nu}_\tau$,$\pi^+2\pi^0\overline{\nu}_\tau$, $3\pi^+\overline{\nu}_\tau$, $3\pi^+\pi^0\overline{\nu}_\tau$
  - 2×10^5 event/channel.
- **Truth mode tagging**: Generator decay chain of τ^+.
- **Divided into** train, validation, test samples (7:2:1)
- Reconstructed particles are divided into 2 hemisphere: Jet^- & Jet^+, and only use information from the Jet^+.
- **Characteristics:** 4–momenta, Cluster timing (MC truth), PID

Phys. Rev. D 101, 056019 (2020)



coordinates
features
EdgeConv Block
k = 16, C = (64, 64, 64)
EdgeConv Block
k = 16, C = (128, 128, 128)
EdgeConv Block
k = 16, C = (256, 256, 256)
Global Average Pooling
Fully Connected
256, ReLU, Dropout = 0.1
Fully Connected
3
Softmax

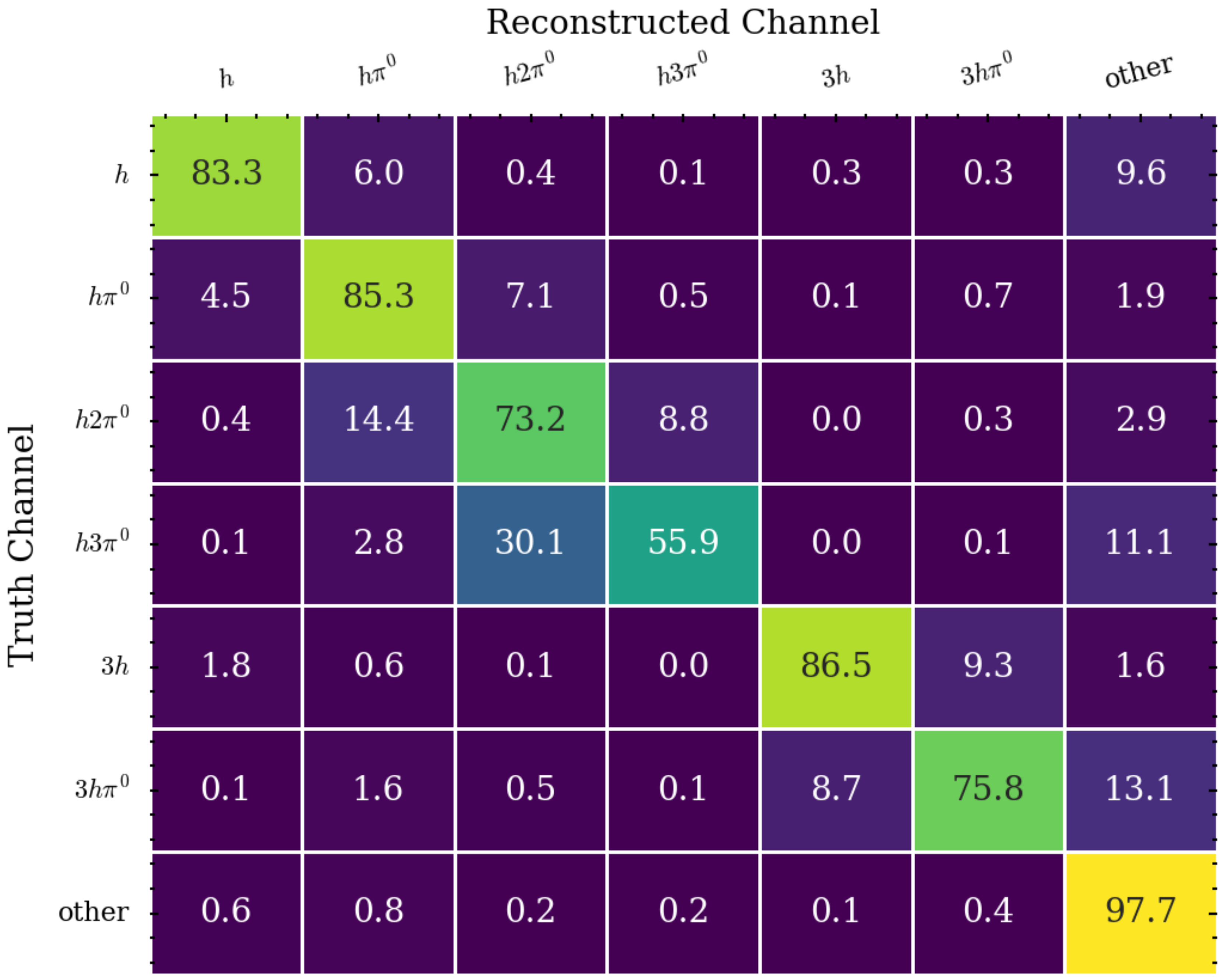


coordinates
features
k-NN
k-NN indices
edge features
Linear
BatchNorm
ReLU
Linear
BatchNorm
ReLU
Linear
BatchNorm
ReLU
Aggregation
ReLU

Non-strange hadronic τ decay channel identification on CEPC

The impurity are reduced by a factor of 1.5 ~ 5.

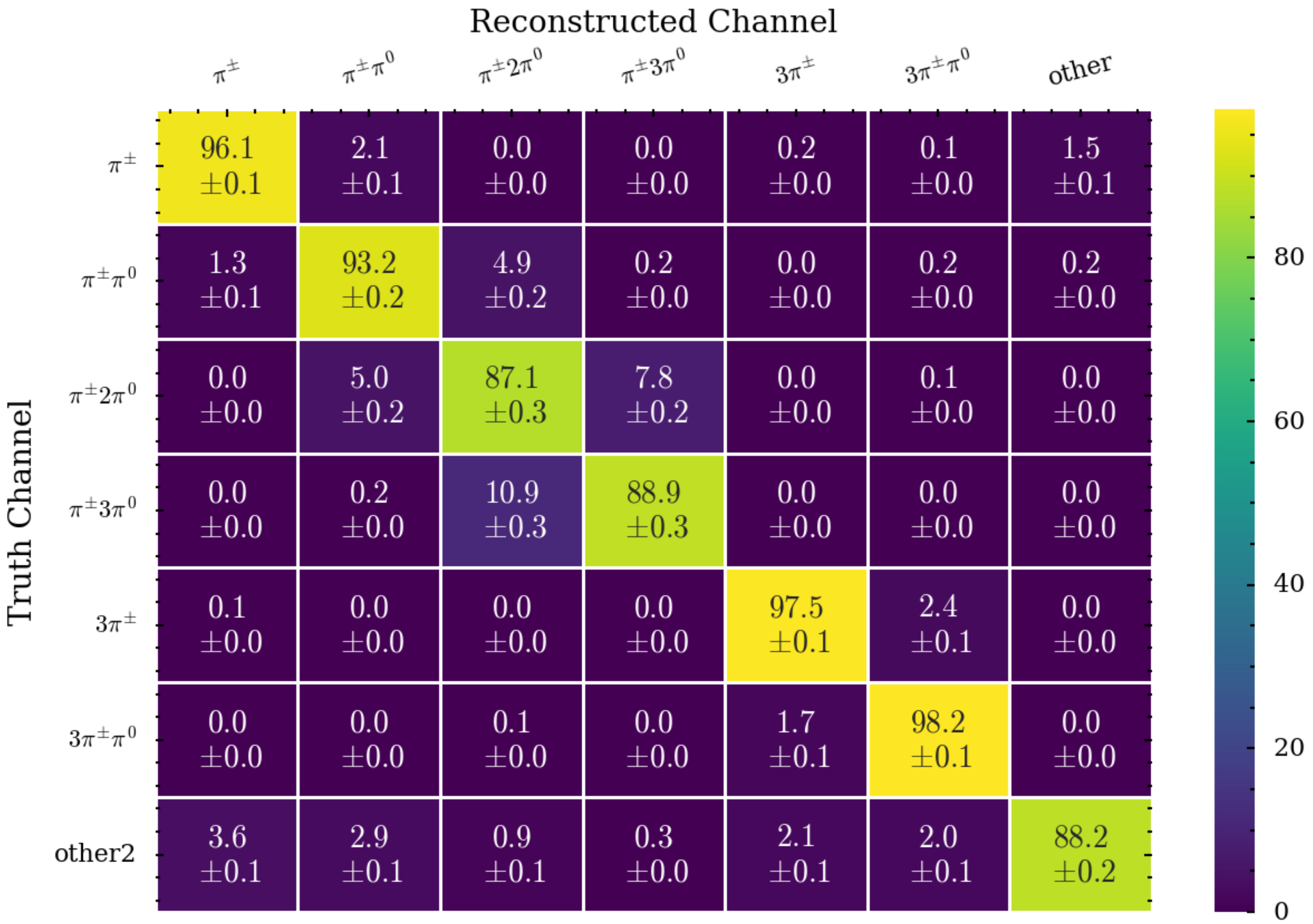
ALEPH
10.1016/j.physrep.2005.06.007



Reconstructed Channel

Truth Channel	h	$h\pi^0$	$h2\pi^0$	$h3\pi^0$	$3h$	$3h\pi^0$	other
h	83.3	6.0	0.4	0.1	0.3	0.3	9.6
$h\pi^0$	4.5	85.3	7.1	0.5	0.1	0.7	1.9
$h2\pi^0$	0.4	14.4	73.2	8.8	0.0	0.3	2.9
$h3\pi^0$	0.1	2.8	30.1	55.9	0.0	0.1	11.1
$3h$	1.8	0.6	0.1	0.0	86.5	9.3	1.6
$3h\pi^0$	0.1	1.6	0.5	0.1	8.7	75.8	13.1
other	0.6	0.8	0.2	0.2	0.1	0.4	97.7

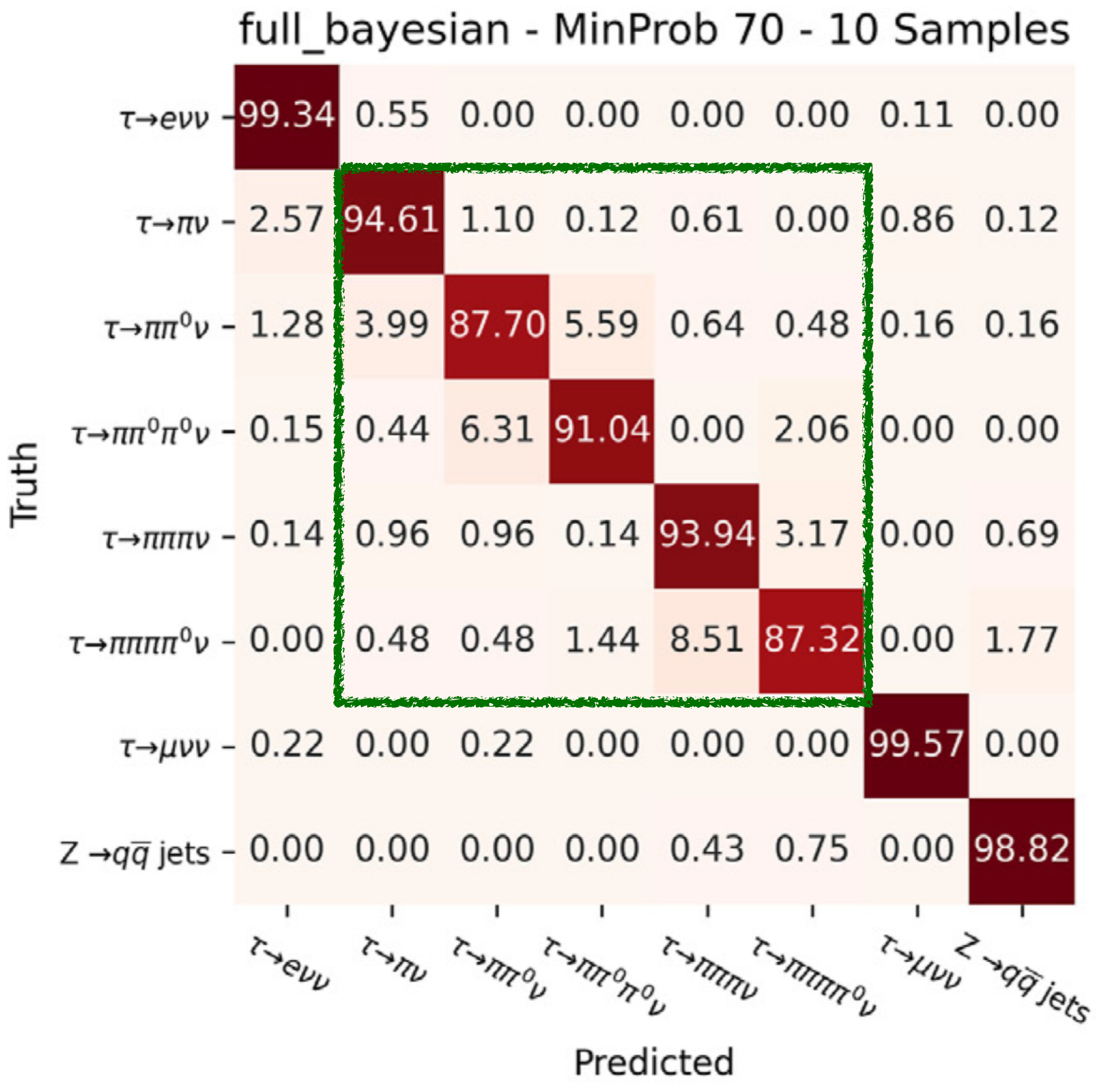
CEPC GNN



Reconstructed Channel

Truth Channel	$\pi^\pm$	$\pi^\pm\pi^0$	$\pi^\pm 2\pi^0$	$\pi^\pm 3\pi^0$	$3\pi^\pm$	$3\pi^\pm\pi^0$	other
$\pi^\pm$	96.1 $\pm$0.1	2.1 $\pm$0.1	0.0 $\pm$0.0	0.0 $\pm$0.0	0.2 $\pm$0.0	0.1 $\pm$0.0	1.5 $\pm$0.1
$\pi^\pm\pi^0$	1.3 $\pm$0.1	93.2 $\pm$0.2	4.9 $\pm$0.2	0.2 $\pm$0.0	0.0 $\pm$0.0	0.2 $\pm$0.0	0.2 $\pm$0.0
$\pi^\pm 2\pi^0$	0.0 $\pm$0.0	5.0 $\pm$0.2	87.1 $\pm$0.3	7.8 $\pm$0.2	0.0 $\pm$0.0	0.1 $\pm$0.0	0.0 $\pm$0.0
$\pi^\pm 3\pi^0$	0.0 $\pm$0.0	0.2 $\pm$0.0	10.9 $\pm$0.3	88.9 $\pm$0.3	0.0 $\pm$0.0	0.0 $\pm$0.0	0.0 $\pm$0.0
$3\pi^\pm$	0.1 $\pm$0.0	0.0 $\pm$0.0	0.0 $\pm$0.0	0.0 $\pm$0.0	97.5 $\pm$0.1	2.4 $\pm$0.1	0.0 $\pm$0.0
$3\pi^\pm\pi^0$	0.0 $\pm$0.0	0.0 $\pm$0.0	0.1 $\pm$0.0	0.0 $\pm$0.0	1.7 $\pm$0.1	98.2 $\pm$0.1	0.0 $\pm$0.0
other2	3.6 $\pm$0.1	2.9 $\pm$0.1	0.9 $\pm$0.1	0.3 $\pm$0.0	2.1 $\pm$0.1	2.0 $\pm$0.1	88.2 $\pm$0.2

GNN on FCC-ee IDEA detector
10.3389/fphy.2022.909205



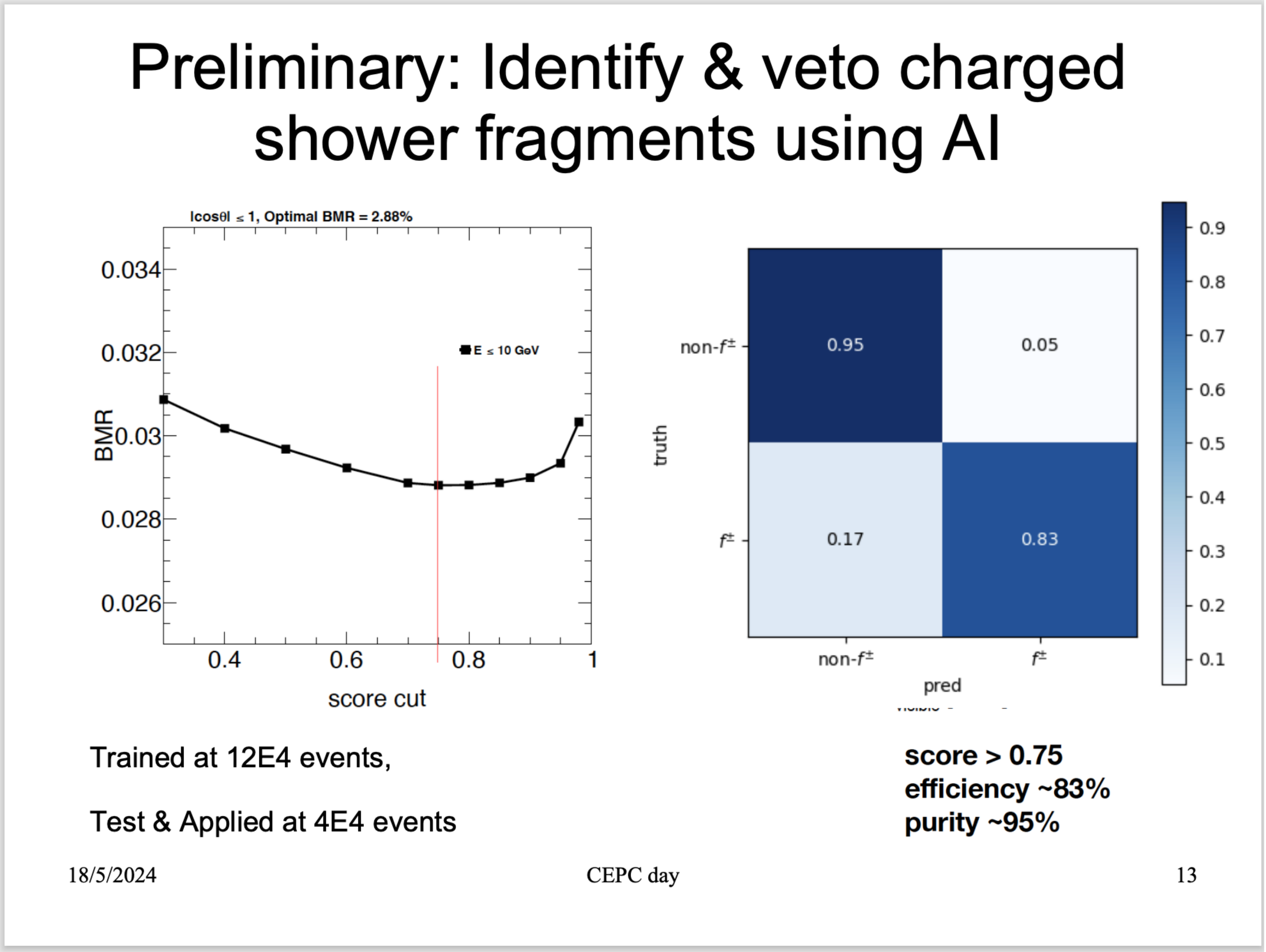
full_bayesian - MinProb 70 - 10 Samples

Truth \ Predicted	$\tau\to e\nu\nu$	$\tau\to\pi\nu$	$\tau\to\pi\pi^0\nu$	$\tau\to\pi\pi^0\pi^0\nu$	$\tau\to\pi\pi\pi\nu$	$\tau\to\pi\pi\pi\pi^0\nu$	$\tau\to\mu\nu\nu$	$Z\to q\bar{q}$ jets
$\tau\to e\nu\nu$	99.34	0.55	0.00	0.00	0.00	0.00	0.11	0.00
$\tau\to\pi\nu$	2.57	94.61	1.10	0.12	0.61	0.00	0.86	0.12
$\tau\to\pi\pi^0\nu$	1.28	3.99	87.70	5.59	0.64	0.48	0.16	0.16
$\tau\to\pi\pi^0\pi^0\nu$	0.15	0.44	6.31	91.04	0.00	2.06	0.00	0.00
$\tau\to\pi\pi\pi\nu$	0.14	0.96	0.96	0.14	93.94	3.17	0.00	0.69
$\tau\to\pi\pi\pi\pi^0\nu$	0.00	0.48	0.48	1.44	8.51	87.32	0.00	1.77
$\tau\to\mu\nu\nu$	0.22	0.00	0.22	0.00	0.00	0.00	99.57	0.00
$Z\to q\bar{q}$ jets	0.00	0.00	0.00	0.00	0.43	0.75	0.00	98.82

ANN benefits on PFA & improve the decay classification

- Fake neutral PFOs can be well identified based on:
    - Space–time structure of clusters in calorimeters.
    - Information from tracker
    - Environmental clusters.
- Fake photon is hopefully to be well suppressed on 5D high granular calorimeter.

AI Assistant Arbor Algorithm @ SiW ECAL + GSHCAL



Preliminary: Identify & veto charged shower fragments using AI

Trained at 12E4 events,

Test & Applied at 4E4 events

score > 0.75
efficiency ~83%
purity ~95%

18/5/2024 CEPC day 13

https://indico.ihep.ac.cn/event/22442/contributions/157327/attachments/78297/97397/BMR%20of%202.9-TOTORO.pdf

Summary

- CEPC will deliver 1.3×10^{11} $\tau^+\tau^-$ events during the Tera-Z operation, providing good opportunity for τ decay analysis and $\alpha_s(m_\tau^2)$ extraction.

- From the ALEPH's history and theoretical developments:

  - The analysis is dominated by **systematical uncertainty**.

  - γ/π^0 **reconstruction** dominates the systematic of hadronic τ decays (through channel classification & mass resolution).

  - **Charged PID** contributes the systematic of channels with only charged hadrons/leptons + neutrinos.

- CEPC has Better dE/dx resolution, vertex resolution and high-granularity calorimeter.

- Utilizing the ANN technology, τ decay modes can be classified with up to 5 times lower impurity, which performance is possible to be further improved.

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Thanks

CHE Yuzhi

The 2024 International Workshop on the High Energy Circular Electron Positron Collider

Oct. 26, 2024, Hangzhou