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Measurements of the A_{FB} and $\sin^2\theta_W^{\mathrm{eff}}$ at Future Circular Electron Positron Colliders with Deep Learning

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Outline

- Introduction
- Detector, software, and MC samples
- Event selection, background suppression
- Joint flavor and charge identification of a jet
- Statistical analysis
- Conclusion

Introduction

- The Standard Model is remarkably successful, but NOT a final theory.
  - Dark matter
  - Neutrino masses
  - Matter-antimatter asymmetry

- Two Complementary Search Directions → Strong motivation for Physics Beyond the Standard Model (BSM) :
  - Direct searches: High energy frontier (e.g. LHC)
  - Indirect searches: Precision tests of SM predictions

- Future Electron-Positron Collider:
  - CEPC, FCC-ee, ILC…

- CEPC's Advantage:
  - 4×10^{12} Z bosons (orders of magnitude beyond LEP)
  - Opens new frontier for electroweak precision tests, especially flavor-specific couplings.

Mode	$\sqrt{s}$ (GeV)	L (10^{34} cm^{-2} s^{-1})	Event yields
H	240	8.3	4.3×10^6
Z	91.5	$192^{(*)}$	4.1×10^{12}
W^+W^-	155-170	26.7	5.5×10^7
$t\bar{t}$	360	0.80	0.6×10^6

Introduction

- Key EW Observable: Forward-Backward Asymmetry $\mathrm{A_{FB}}$

$$A_{\mathrm{FB}}^{f} = \frac{\sigma_F^f - \sigma_B^f}{\sigma_F^f + \sigma_B^f}$$

$$\frac{1}{\sigma_f}\frac{d\sigma_f}{d\cos\theta} = \frac{3}{8}(1+\cos^2\theta) + A_{\mathrm{FB}}^{f}\cos\theta$$

- Forward and backward are defined with respect to the incoming electron.
- For quark final states, we must reconstruct the jet direction and identify f versus anti-f.
- Flavor mistags and charge misidentification dilute the asymmetry.
- Highly sensitive to the effective weak mixing angle $\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}$.

- The even term describes the overall angular distribution.
- The coefficient of the odd term is $\mathrm{A_{FB}}$.
- The measurement is therefore a fit to the odd component of the angular distribution.

Introduction

- From A_{FB} to the effective weak mixing angle

$$A_{FB}^{f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f, \quad \mathcal{A}_f = \frac{2v_f a_f}{v_f^2 + a_f^2}$$

$$v_f = I_3^f - 2Q_f \sin^2\theta_W^{\text{eff}}, \quad a_f = I_3^f$$

  - The weak mixing angle controls the relative vector and axial-vector couplings and therefore the asymmetry.
  - The angle is extracted separately from the b, c, and s channels.
  - This is a tree-level sensitivity estimation; higher-order electroweak and flavor-dependent corrections are not included.

Introduction

- Method: ParticleTransformer
  - Treats a jet as a set of particles.
  - Uses attention to model pairwise particle-level information.
  - Learns optimal representations for joint flavor and charge identification

- Modern jet charge algorithm + Advanced AGORA detector (CEPC ref. detector):
  - Flavor-decomposed precision measurements: A_{FB}^{b}, A_{FB}^{c}, … with unprecedented statistical power.
  - Improved $\sin^2\theta_W^{eff}$ extraction:
  - Unique BSM probe: Non-universal flavor modifications (e.g., flavor-changing Z', fourth-generation quarks).

- The power of beam polarization for electroweak precision measurements was convincingly demonstrated by the SLC experiment
  - Polarization upgrades @ CEPC are under investigation

Detector, software, and MC samples

generation → full AGORA simulation and reconstruction → two-jet reconstruction
→ event selection → ParT flavor/charge tagging → angular fit

- Detector model: based on the AGORA Reference Detector

- The Monte Carlo (MC) samples:
  - Generated with Whizard 1.9.5 @ Z pole
  - Showered/hadronized with PYTHIA 6
  - Jets are reconstructed using ee-kt algorithm in FastJet
  - All particles are clustered into exactly two jets.

Event selection, background suppression

Table 1. Relevant branching fractions, cross sections, and expected event yields of the Z boson at the Z-pole energy [12] based on tree-level without initial state radiation.

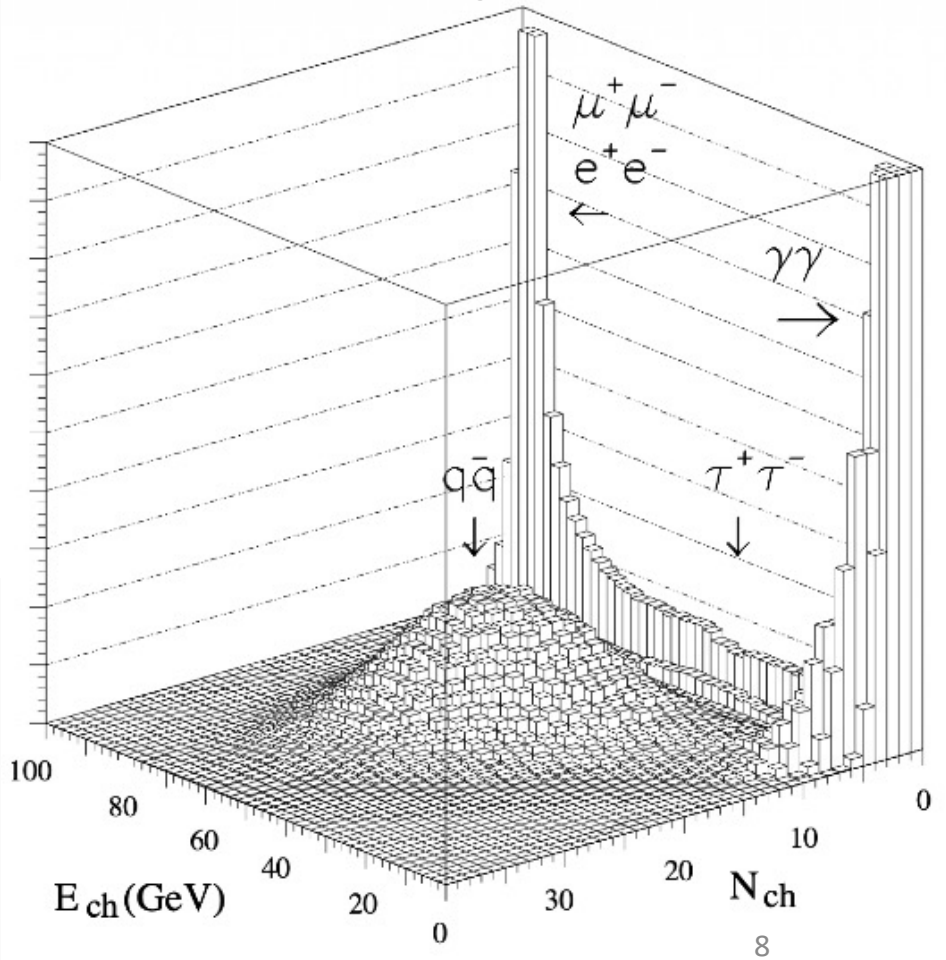
Decay Mode	Branching Fraction (%)	Cross Section (nb)	Expected Event Yields
$Z \to$ hadrons	69.911 ± 0.056	39.6	3.96×10^{12}
$Z \to e^+e^-$	3.363 ± 0.004	1.98	1.98×10^{11}
$Z \to \mu^+\mu^-$	3.366 ± 0.007	1.98	1.98×10^{11}
$Z \to \tau^+\tau^-$	3.370 ± 0.008	1.98	1.98×10^{11}

Table 2. Summary of event selection. The columns represent the different quark flavors ($b\bar{b}$, $c\bar{c}$, $s\bar{s}$, $u\bar{u}$, $d\bar{d}$) and $\tau^+\tau^-$ background, and efficiency changes (%).

	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	$\tau^+\tau^-$
Total	100	100	100	100	100	100
$E_{ch} > 20$ GeV	99.50	98.95	96.97	98.75	97.94	78.31
$N_{ch} > 8$	98.87	97.15	91.96	94.95	93.99	0.0004

- Effective suppression of leptonic and two-photon backgrounds
- Obtained a high-purity sample of qq events
- It motivates the adoption of a deep learning approach for joint flavor and charge identification.

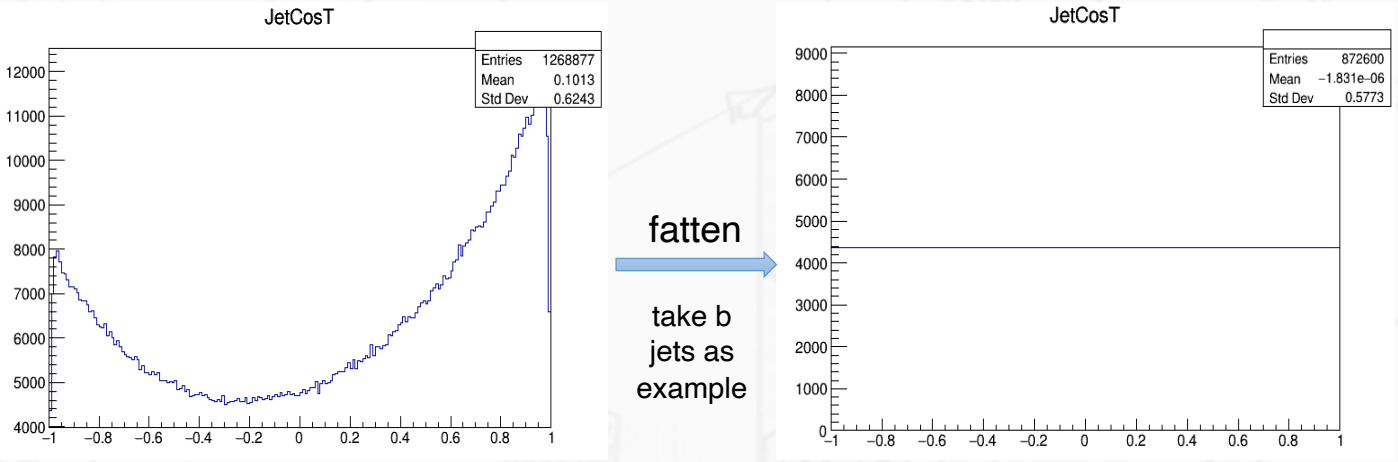
- Other four-fermion backgrounds are negligible
  - small cross sections and distinct event topologies.



Joint flavor and charge identification

- Data sets
  - 10 categories (flavors × charges)
  - 7,000,000 jets in total
  - train:validation:test = 5:1:1

- Jet $\cos\theta$ flatten in training
  - angular prior removed, avoiding an efficiency bias from ParT learning angular features.



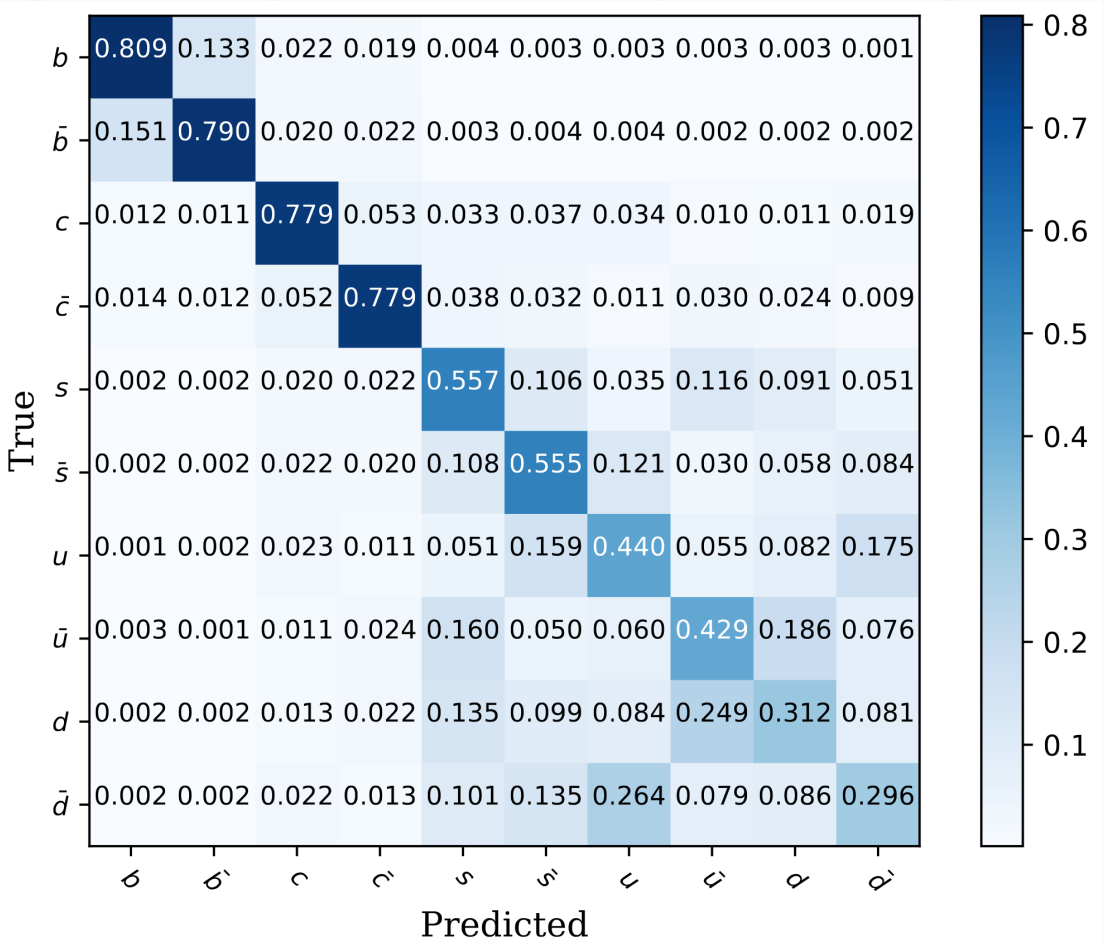
- Input variables
  - Kinematics
  - Particle type/charge
  - Track impact parameters
  - ECAL/HCAL information

Variable	Definition
$\cos\theta$	cosine of polar angle of particle
$\phi\sin\theta$	azimuth angle times sine of polar theta of particle
ΔR	$\sqrt{\delta\theta^2+\delta\phi^2}$, angular separation between the particle and the jet axis
PID	particle ID
E	energy of a particle
Q	electric charge of a particle
$\log E$	logarithm of the particle's energy
$\log P$	logarithm of the particle's momentum
p_T	transverse momentum of a particle
D_0	impact parameter of a track in the r-ϕ plane
Z_0	impact parameter of a track along the z axis
D_0/σ_{D_0}	significance of the impact parameter in the r-ϕ plane
Z_0/σ_{Z_0}	significance of the impact parameter along the z axis
prob	$\int_{\chi^2}^{\infty} p(x, N=2)\,dx$, where $\chi^2=(D_0/\sigma_{D_0})^2+(Z_0/\sigma_{Z_0})^2$
N_{ECal}	Number of clusters of a PFO that fall into the ECAL region
N_{HCal}	Number of clusters of a PFO that fall into the HCAL region
E_{ECal}	Total energy sum of clusters of a PFO in the ECAL region
E_{HCal}	Total energy sum of clusters of a PFO in the HCAL region

Joint flavor and charge identification

- The model achieves high classification performance
  - The flavor identification accuracy exhibits a clear and expected hierarchy
  - The significant confusion between b-quarks and anti-b-quarks, a possible source: neutral-B mixing and cascade decays
  - The confusion between c-quark and anti-c-quark is considerably smaller by displaced vertices and charged kaons.
  - The discrimination between s-quark and anti-s-quark is also challenging and more sensitive to fragmentation and light-flavor contamination.

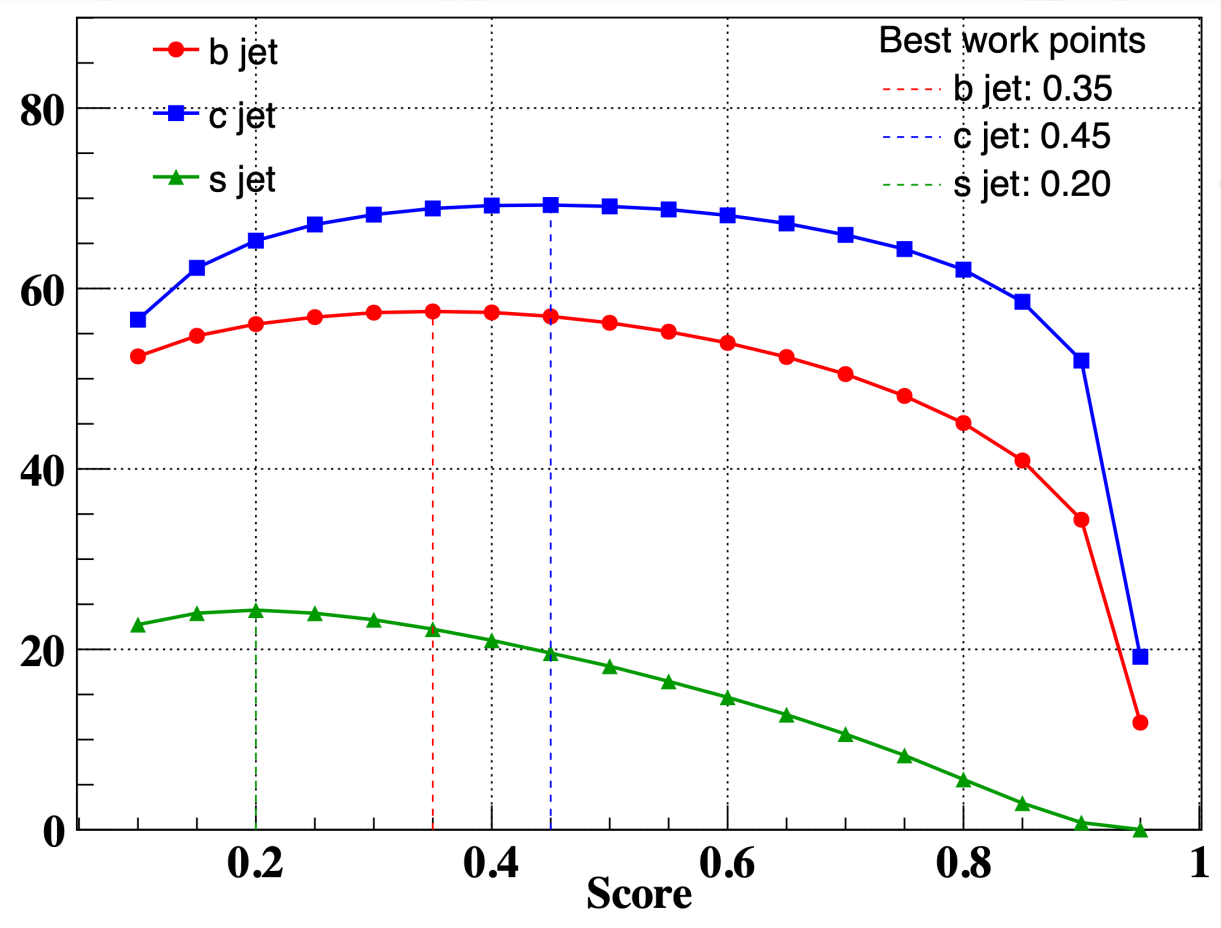
- The performance is comparable with JOI, which is reported in TDR



Determination of working points

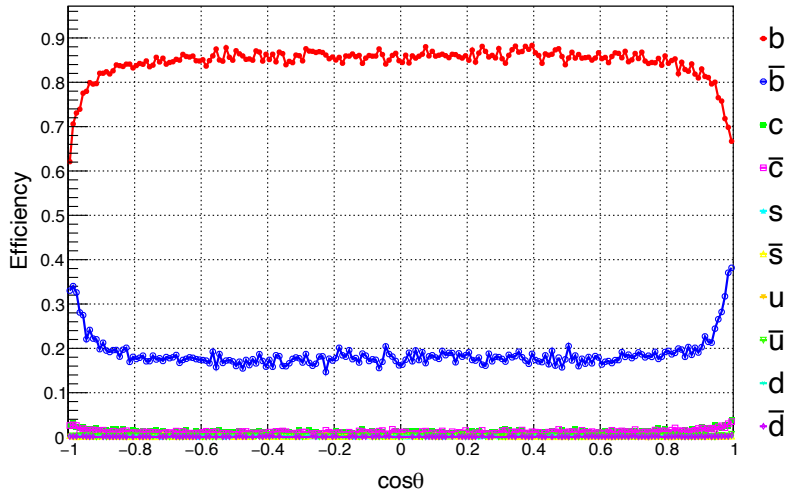
- The working point is chosen to maximize the overall jet charge identification performance, weighted by the production cross sections

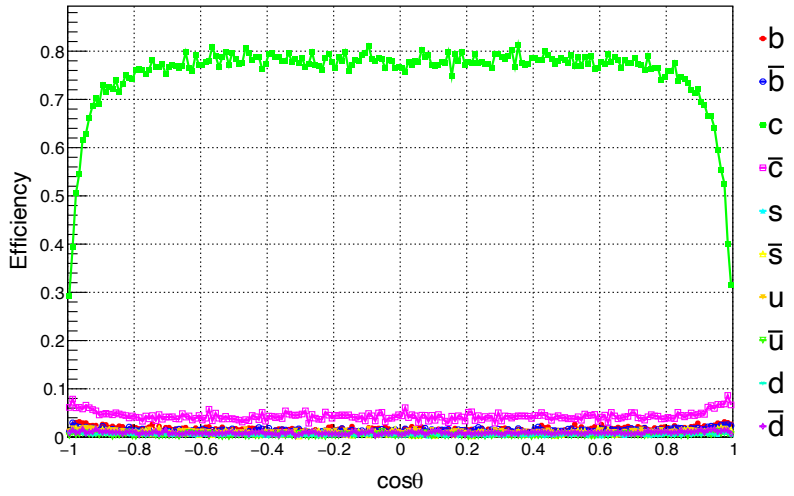
$$\mathrm{FoM} = \sum_i \sigma_i \times \epsilon_i \times \rho_i \times \left(\frac{1}{\sigma_i}\frac{\partial \sigma_i}{\partial A_{\mathrm{FB}}}\right)^2$$
$$= \sum_i \epsilon_i \times \rho_i \times \frac{1}{\sigma_i}\left(\frac{8}{3}\cos\theta_i\right)^2,$$

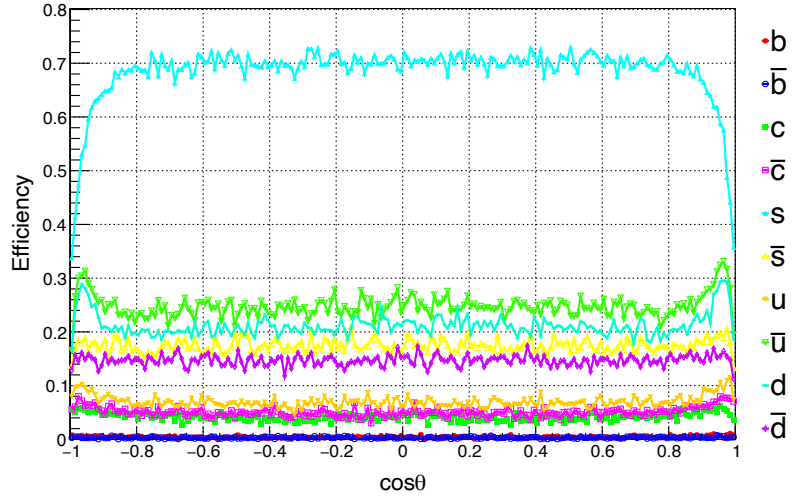


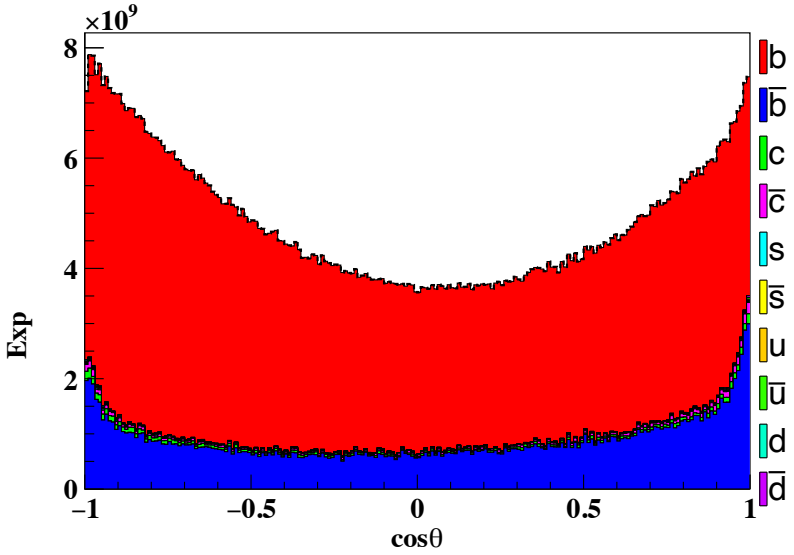
- The results are consistent with expectation.
  - The lower threshold for s-jets reflects the greater challenge in distinguishing strange quarks

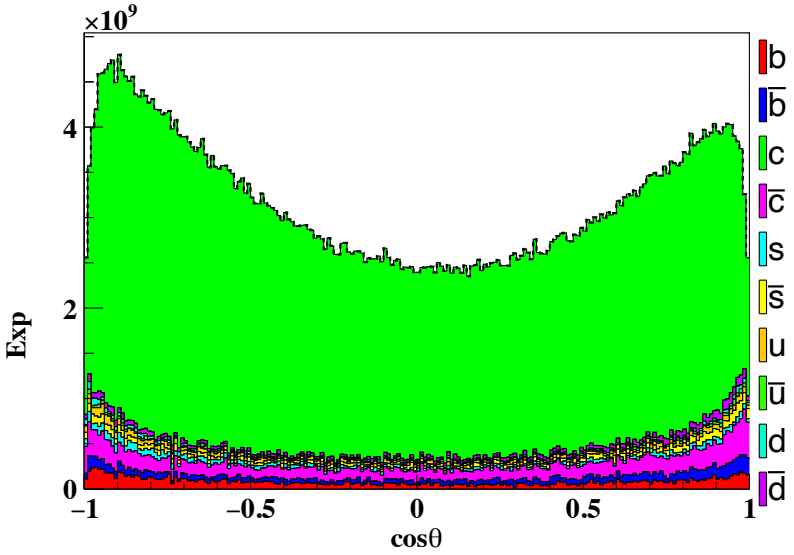
Efficiency curves and expected events

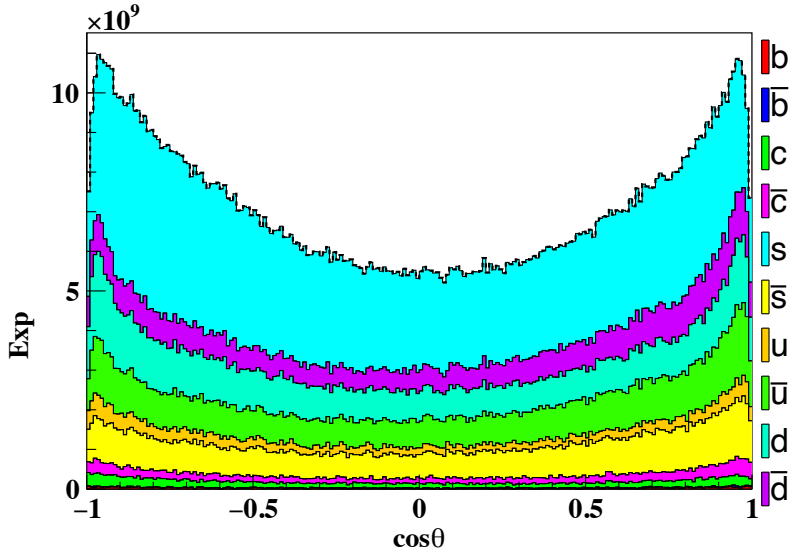












Measurement of A_{FB}

- The expected number of events for reconstructed flavor j (5 flavor) in bin i (200) is:

$$N_{i,j}^{\mathrm{exp}} = \mathcal{L} \sum_{k} \sigma_{i,j} \epsilon_{i,j,k},$$

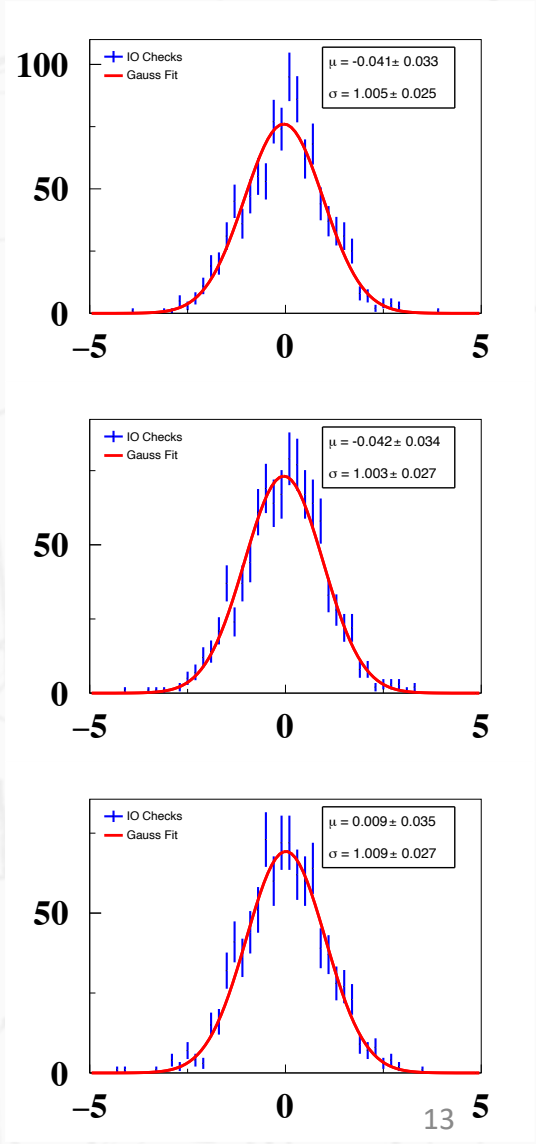
$$\sigma_{i,j} = (1 + \cos^2\theta_i + \frac{8}{3} A_{FB,j} \cos\theta_i)\Delta,$$

- A_{FB} could be extracted via a binned maximum likelihood fit

$$\mathcal{L}(A_{FB,j}, N_j^{\mathrm{prod}}) = \prod_i \frac{\mu_{i,j}^{n_{i,j}} e^{-\mu_{i,j}}}{n_{i,j}!},$$

- To estimate the statistical precision, and joint flavor and charge identification
  - Generate 1000 toy Monte Carlo samples.
- The results (10^{-3}) are listed below:

	This work	world averages	FCC-ee ref.
δA_{FB}^b	0.012	16	0.033
δA_{FB}^c	0.019	50	0.056
δA_{FB}^s	0.017	148	0.060



Pull = (O - I) / error

Measurement of $\sin^2\theta_W^{eff}$

- The published relative uncertianties of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ are at the 10^{-3} level
  - The sensitivity obtained from $A_{\mathrm{FB}}^{0,b}$ is better than that from $A_{\mathrm{FB}}^{0,l}$, because the cross section for quark final states is larger than that for leptonic decays.

	$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	$\delta\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ (10^{-3})
LEP, $A_{FB}^{0,b}$	0.23221±0.00029	1.3
LEP, $A_{FB}^{0,l}$	0.23099±0.00053	2.3
SLC, A_{LR}	0.23098±0.00026	1.2
LEP+SLC	0.23153±0.00016	0.70

- To extract $\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}}$ from the simulated data, a similar binned extended maximum likelihood is performed
- 1000 toy Monte Carlo samples, pull distributions follow a normal distribution
- The results (10^{-6}) are listed
  - Improvements in both statistical precision and analysis methods

	b	c	s	FCC-ee
$\delta\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	1.0	1.5	1.4	4.2

Extension to polarization scenario

- The power of beam polarization for electroweak precision measurements was convincingly demonstrated by the SLC experiment
  - With less statistics using a polarized electron beam
  - A precision comparable to — and in some respects exceeding
- The expected bin-by-bin number of left(right)-handed events

$$N^{\mathrm{exp}}_{L(R),i,j} = \mathcal{L}\Delta \sum_k \sigma_{L(R),i,j}\epsilon_{i,j,k},$$

- $\sin^2\theta^{\mathrm{eff}}_{\mathrm{W}}$ could be extracted via a binned maximum likelihood fit

$$\mathcal{L}(\sin^2\theta^{\mathrm{eff}}_W, N^{\mathrm{prod}}_{L,j}, N^{\mathrm{prod}}_{R,j}) = \prod_i \frac{\mu^{n_{L,i,j}}_{L,i,j} e^{-\mu_{L,i,j}}}{n_{L,i,j}!} \times \frac{\mu^{n_{R,i,j}}_{R,i,j} e^{-\mu_{R,i,j}}}{n_{R,i,j}!},$$

- 1000 toy Monte Carlo samples, pull distributions are consistent with a normal distribution
- The results (10^{-6}) are listed
  - Higher polarization leads to better precision
  - b-jet > c-jet > s-jet

P_e	0.5	0.6	0.7	0.8	unpol.
b	0.51	0.50	0.49	0.48	1.0
c	0.66	0.65	0.63	0.61	1.5
s	0.83	0.82	0.81	0.79	1.4

Discussion of systematic uncertainties

- The control of systematic uncertainties become the dominant challenge.

- Beam energy and polarization
  - The systematic uncertainty from beam energy (0.2MeV) is estimated to be 1.7×10^{-6} for A_{FB} and 1.0×10^{-6} for $\sin^2\theta_W^{\mathrm{eff}}$
  - Affects of luminosity (10^{-4}) are lower than the statistical uncertainty by an order of magnitude
  - Assuming a 0.1% relative uncertainty on the polarization, the corresponding systematic uncertainty is 1.7×10^{-5}

Source	A_{FB}	$\sin^2\theta_W^{\mathrm{eff}}$
Beam energy	1.7×10^{-6}	1.0×10^{-6}
Luminosity	1.8×10^{-6}	3.4×10^{-7}
Polarization	-	1.7×10^{-5}
QCD corrections	10^{-4}	10^{-4}

- QCD and hadronization modeling
  - The systematic uncertainty from QCD corrections is estimated to be at the 10^{-4} level
  - These effects must be modeled into next generation event generators, which must be validated and tuned with high statistics data

Discussion of systematic uncertainties

- Detector modeling
  - The tracks and photons: abundant Bhabha and dimuon events at the Z-pole enable a data-driven validation of the detector simulation
  - The corresponding systematic uncertainties to be controlled at the same level as the statistical.

- Flavor-tagging calibration
  - A straightforward choice is taking a half the data as control sample
  - The efficiency and mistag rates could be controlled to the same level of the statistical uncertainty
  - Cross validation with different ML models

- Background contamination
  - The uncertainty in the normalization and shape of these backgrounds must be controlled to a level well below the statistical precision

- Beamstrahlung effects
  - The associated systematic uncertainty — mainly from mis-modeling of photon emission — does not affect jet energy, direction, or identification
  - Be safely ignored as a background in precision jet analyses

Conclusion

- The potential is evaluated for measuring the forward-backward asymmetry A_{FB} and the effective weak mixing angle $\sin^2\theta_W^{eff}$ @ future Z factories, based on a sample of 4×10^{12} Z bosons.
- With unpolarized beams, the projected relative statistical precision on A_{FB} is about 10^{-5} level, and the weak mixing angle reaches the 10^{-6} level.
- Benefit of polarized collision is demonstrated, which provides complementary electron-coupling information and improve the statistical sensitivity.
- The control of systematic uncertainties will become the dominant challenge.

Thank you!