Jet Charge Reconstruction at CEPC

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CONTENTS

01 Introduction

Jet Charge Introduction

What is "Jet Charge of b-jet system"?

Initial particle charge (b or anti-b).

What is the application of "Jet Charge of b-jet system"?

1. The precision of A_{FB}(Forward-Backward Asymmetry) measurement.
2. The precision of CP Violation parameter measurement in B hadron system.
3. …

We already have flavor tagging algorithm, jet charge information can help searching for more physics.

A_{FB} Physics Introduction

Theory of A_{FB}:

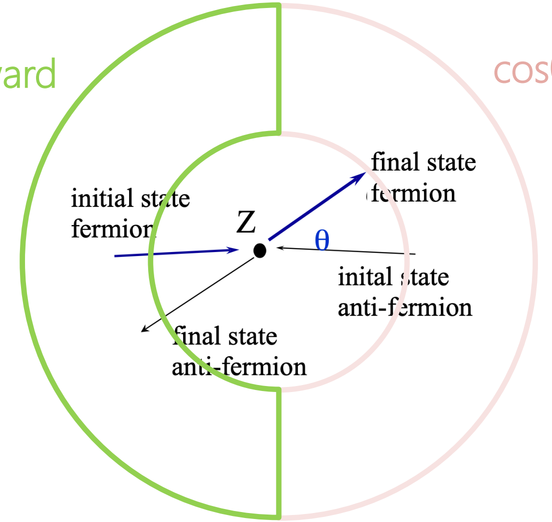
1. Z propagator has different coupling strength with left and right fermions.
2. Therefore, the final angular momentum distribution in ee→Z→ ff is asymmetrical.

Why A_{FB} need Jet Charge?——A_{FB} uncertainty:

1. A_{FB} Statistical uncertainty:
   - $N_{Forward}$ and $N_{Backward}$
     - Branching ratio, acceptance and efficiency affect $N_{Forward}$ and $N_{Backward}$.
2. A_{FB} Systematic uncertainties:
   - ① Dominant effect: Charge mis-identification
   - ② Negligible effect: direction, energy, momentum, efficiency determination

cosθ<0 : backward

cosθ>0 : forward



$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = A_{FB}(\sin^2\theta^f_{\text{eff}})$$

Using Jet Charge to measure A_{FB} at CEPC

1. High Productivity
   3×10^{12} Z bosons in 2 years → Low statistical uncertainty → High precision.

2. Accurate detector system.
   1. Good VTX system
   2. Good PID system

3. $A_{FB}(\sin^2\theta_W)$ depends on center-of-mass energy & particle flavors
   1. higher energy scale
      Measure $\sin^2\theta_W$ in different energy scale to test the running effect to higher energy scale.
   2. Flavor comparison
      Compare $\sin^2\theta_W$ between different flavor channels.

4. Clean Environment
   CEPC has cleaner environment than hadron collider and lower background.

02 Methods

Samples : ee → Z → bb

Why use ee → Z → bb?

- Easy to select
- High sensitivity of $A_{FB}(\sin^2\theta_W)$ vs energy cut

Dominant decay:

- b→c+W
  - W→l+v (semileptonic decay) or qq→hadron.
  - c→X+s→X+K

Final particles we consider:

- e+, e-, μ+, μ-, K+, K-, π+, π-, proton, antiproton

How to develop Jet Charge Algorithm

- Input: final leading particle information of the jet (eg: charge, energy, momentum, ……)
- Output: the charge of the jet (coming from b quark or bbar quark) and misjudgment rate ω

How to develop Jet Charge Algorithm

- Use jet clustering to divide final leading particles into two jets.
- Find the relationship between observables of final leading particles and jet charge.
- Use observables of final leading particles to measure jet charge.

How to develop Jet Charge Algorithm

- Use Jet Charge misjudgment rate ω to measure the accuracy of Jet Charge Algorithm in each event in Truth Level.
  - Leading particle: {e, μ, K} / {π, proton}
  - Kaon from different decay chains
  - Leptons from different decay chains

- Use Jet Charge misjudgment rate ω to measure the accuracy of Jet Charge Algorithm in each jet in Truth Level.(Combine two jets to improve Jet Charge Algorithm.)
  - Leading particle: {e, μ, K} / {π, proton}
  - Kaon from different decay chains
  - Leptons from different decay chains

- Use Jet Charge misjudgment rate ω to measure the accuracy of Jet Charge Algorithm in Full Simulation.

- Understand the difference between ω in Truth Level and ω in Full Simulation, and study the influence of CEPC detector performance on Jet Charge misjudgment rate ω.

How to develop Jet Charge Algorithm

- Use VTX information to improve Jet Charge Algorithm.
- Use Jet Charge Algorithm to the precision measurement of relative benchmark.(eg: The precision of A_{FB}(Forward-Backward Asymmetry) measurement.)

ε, p^+, p^-, Misjudgment Rate ω

$$\epsilon_{\text{tag}} = \frac{N_R + N_W}{N_U + N_R + N_W}$$

$$\omega = \frac{N_W}{N_R + N_W}$$

p^+: if angle(x,bbar) < angle(x,b), $p^+ = \int_0^{\pi/2}$ angle(x,b)

p^-: if angle(x,bbar) > angle(x,b), $p^- = \int_{\pi/2}^{\pi}$ angle(x,b)

$p^+ + p^- = 1$

$\omega = \min(p^+, p^-)$

Accuracy

$$\mathcal{A}_{\text{true}}(t) = \frac{N_{\overline{B}}^{\text{true}}(t) - N_{B}^{\text{true}}(t)}{N_{\overline{B}}^{\text{true}}(t) + N_{B}^{\text{true}}(t)}$$

$$\mathcal{A}_{\text{obs}}(t) = \frac{N_{\overline{B}}(t) - N_{B}(t)}{N_{\overline{B}}(t) + N_{B}(t)}$$

$$\begin{aligned} N_{\overline{B}}(t) &= (1-\omega_{\overline{B}})N_{\overline{B}}^{\text{true}}(t) + \omega_B N_B^{\text{true}}(t) \\ N_B(t) &= (1-\omega_B)N_B^{\text{true}}(t) + \omega_{\overline{B}} N_{\overline{B}}^{\text{true}}(t) \end{aligned}$$

$$A_{FB}^{\text{obs}} = \frac{1-2\omega}{(1-\omega)^2+\omega^2} A_{FB}^{\text{true}}$$

$$\text{Accuracy} = \sqrt{\frac{1}{\varepsilon}\frac{(1-\omega)^2+\omega^2}{(1-2\omega)^2}}$$

03 Results

03-1

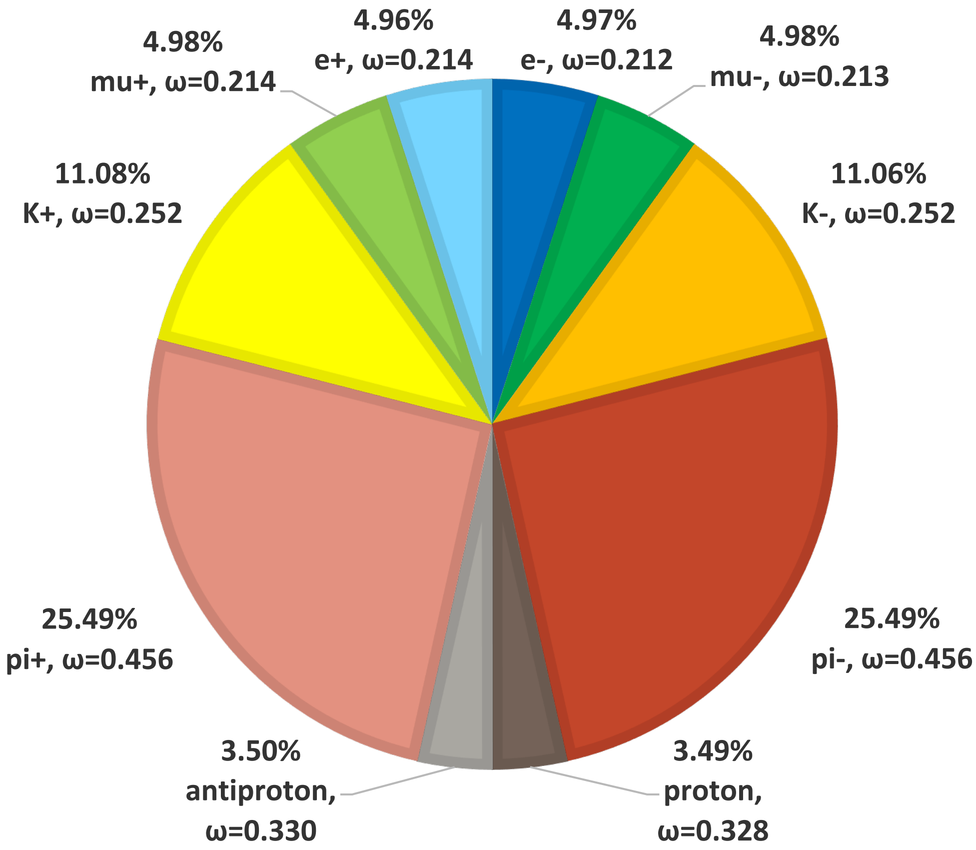
For each event,
Final Leading Particles: e μ K π p

b-hadron VS b-bar-hadron Probability

Truth level:

→b-bar ↓b	B^+(u b-bar)	B^0(d b-bar)	Bs(s b-bar)	Bc+(c b-bar)	Λ_b-bar	other-b-bar-baryons	
B^-(u-bar b)	10.01%	10.04%	3.19%	0.01%	6.55%	1.70%	31.51%
B^0-bar(d-bar b)	10.03%	9.92%	3.27%	0.01%	6.67%	1.70%	31.60%
Bs-bar(s-bar b)	3.20%	3.21%	1.04%	0.004%	2.15%	0.57%	10.17%
Bc^-(c-bar b)	0.01%	0.01%	0.004%	0%	0.008%	0.001%	0.04%
Λ_b(udb)	6.69%	6.70%	2.16%	0.008%	4.54%	1.16%	21.26%
other-b-baryons	1.70%	1.70%	0.56%	0.001%	1.17%	0.31%	5.43%
	31.63%	31.57%	10.22%	0.03%	21.08%	5.45%	100%

Percent and ω of final charged leading particles



$\omega_{all} = \Sigma(\omega_i * \text{Probability}^{N(statistics)}{}_i)$

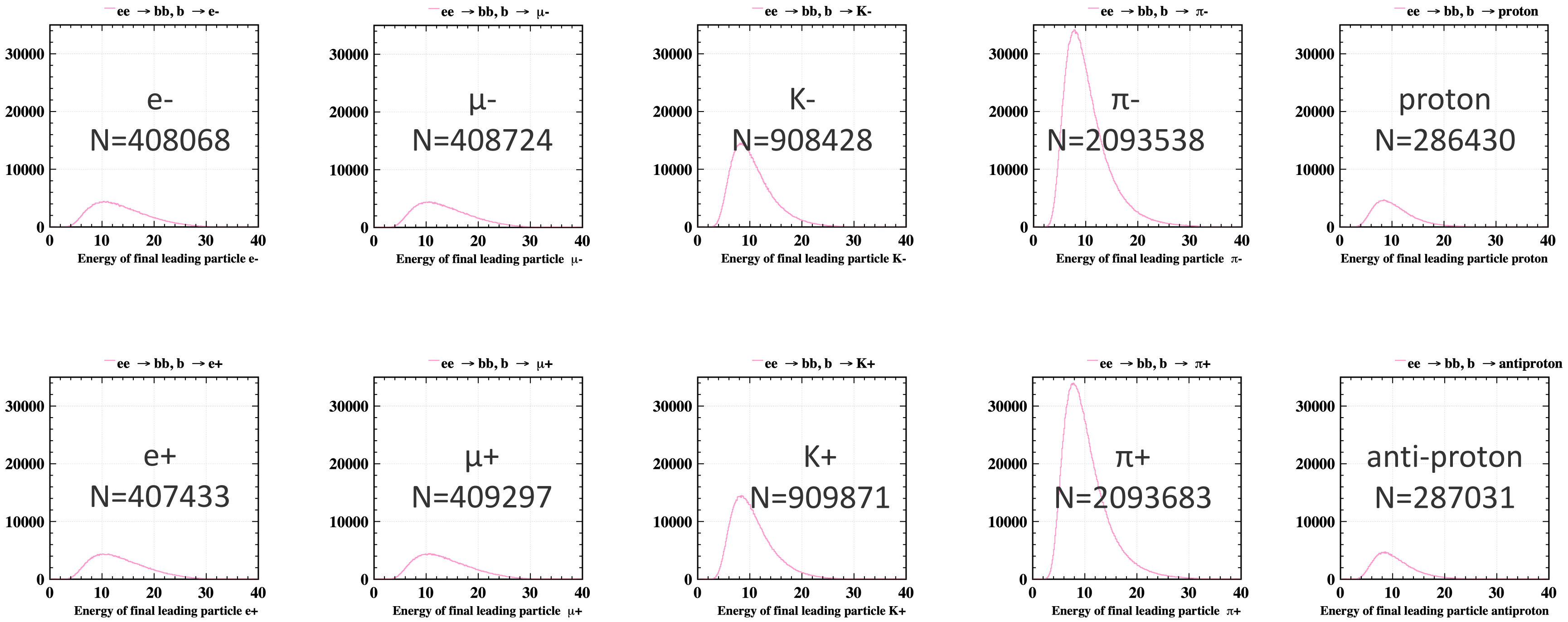
$\omega_{all\ leading\ particles} = 0.354$

$\omega_{without\ \pi} = 0.247$

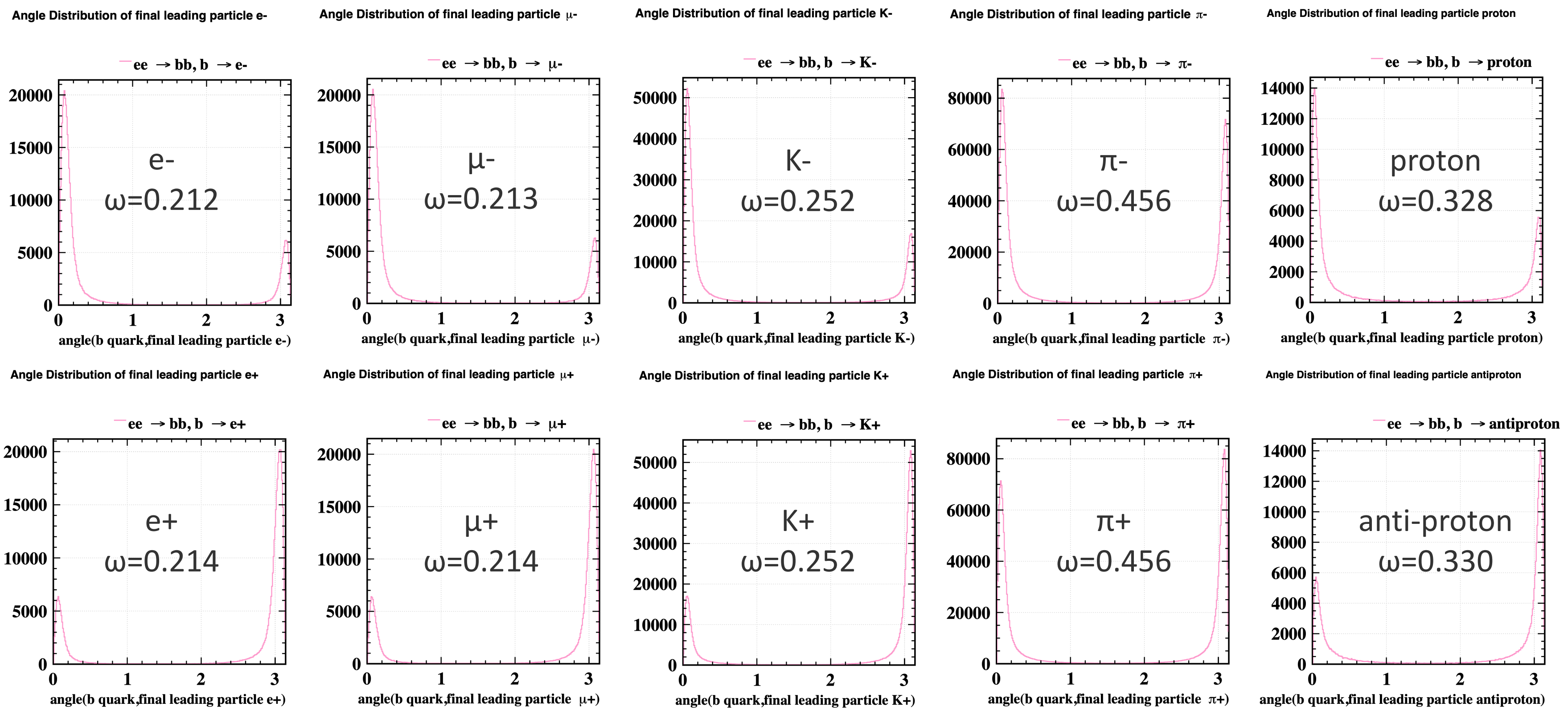
$\omega_{without\ \pi\&proton} = 0.234$

$\omega_{leptons} = 0.213$

Energy spectrum of final leading particle



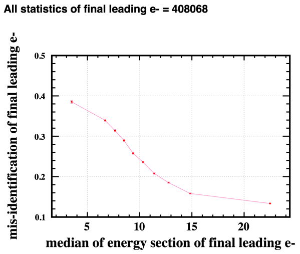
Angle distribution of final leading particle



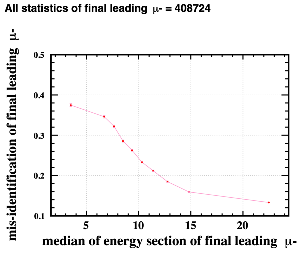
Misjudgment rate ω vs energy section

$$\omega_{\text{leading particle}} = \Sigma(\omega_i * \text{Probability}^{N(\text{statistics})}{}_i * \text{Probability}^{E(\text{energy})}{}_i)$$

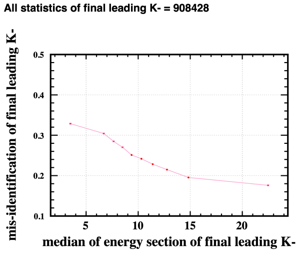
$\omega_{e-} = \Sigma(\omega_i * PN_i * PE_i) = 0.212$



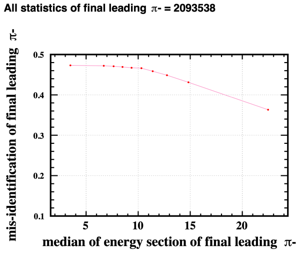
$\omega_{\mu-} = \Sigma(\omega_i * PN_i * PE_i) = 0.213$



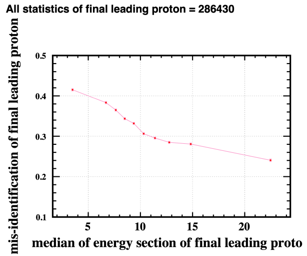
$\omega_{K-} = \Sigma(\omega_i * PN_i * PE_i) = 0.252$



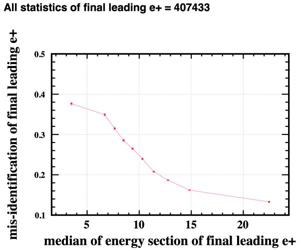
$\omega_{\pi-} = \Sigma(\omega_i * PN_i * PE_i) = 0.456$



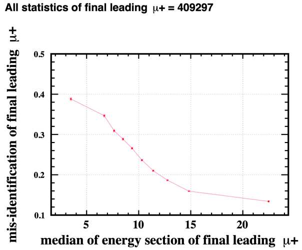
$\omega_{proton} = \Sigma(\omega_i * PN_i * PE_i) = 0.328$



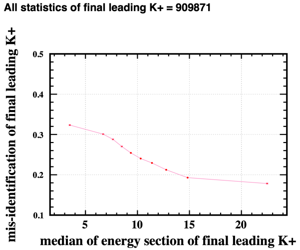
$\omega_{e+} = \Sigma(\omega_i * PN_i * PE_i) = 0.214$



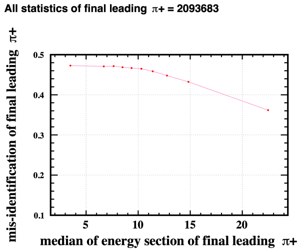
$\omega_{\mu+} = \Sigma(\omega_i * PN_i * PE_i) = 0.214$



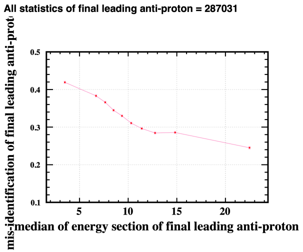
$\omega_{K+} = \Sigma(\omega_i * PN_i * PE_i) = 0.252$



$\omega_{\pi+} = \Sigma(\omega_i * PN_i * PE_i) = 0.456$



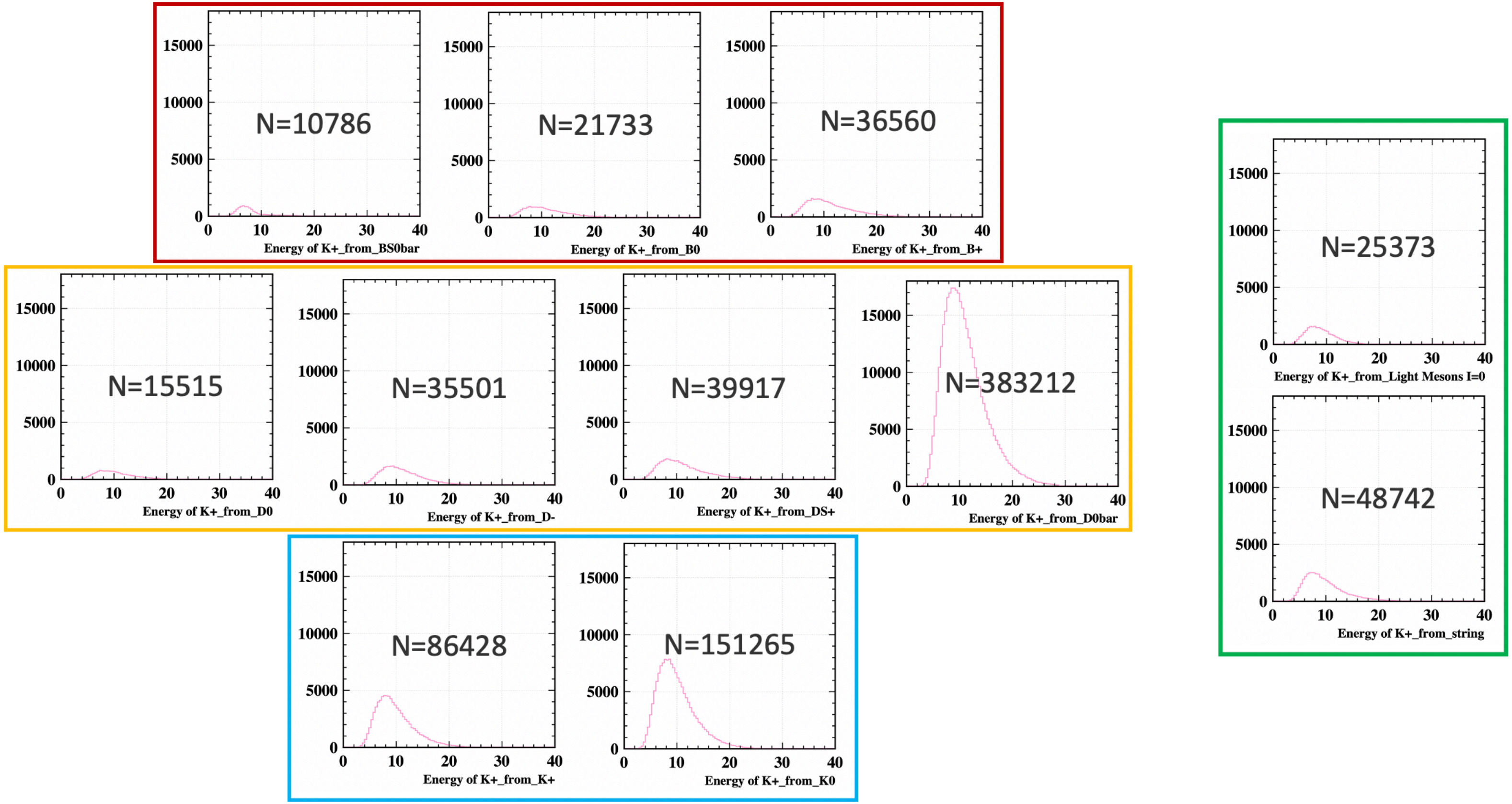
$\omega_{antiproton} = \Sigma(\omega_i * PN_i * PE_i) = 0.330$



03-2

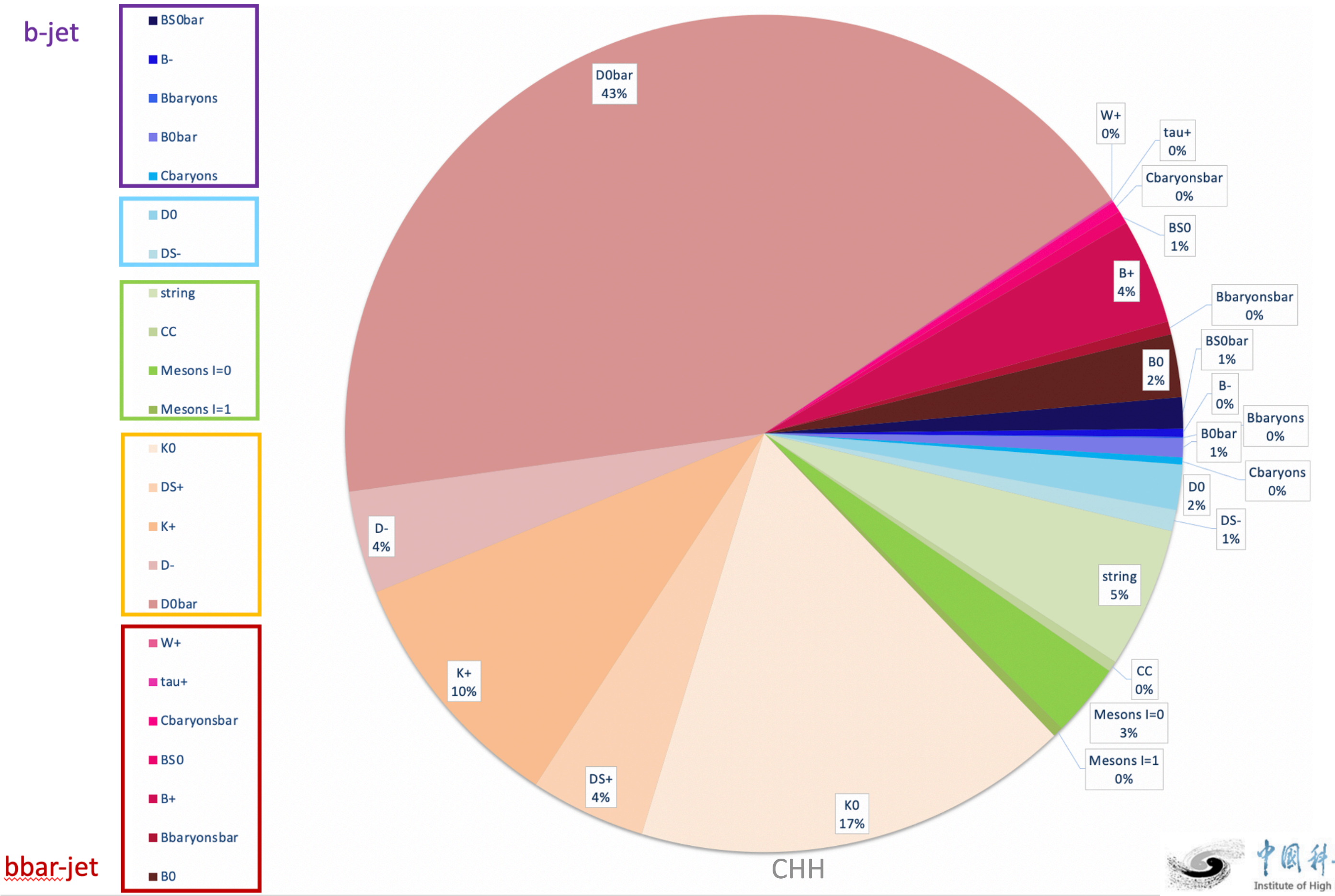
For each event, Final Leading Particles: K+

Energy spectrum of final leading K+ from different decay chains



Misjudgment rate ω of final leading K+ from different decay chains
All statistics = 909166

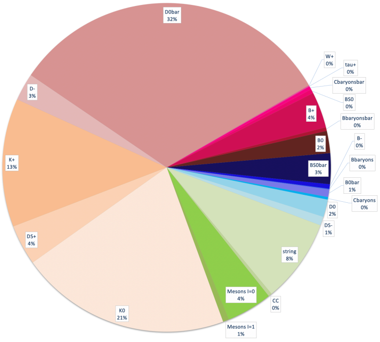
Percent of final leading K+ from different decay chains



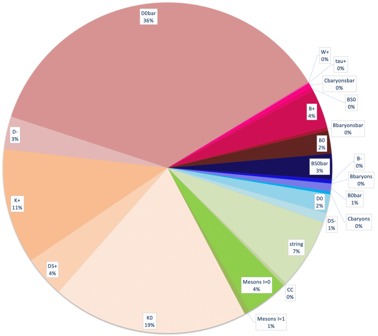
CHH

Percent of final leading K+ from different decay chains vs energy section

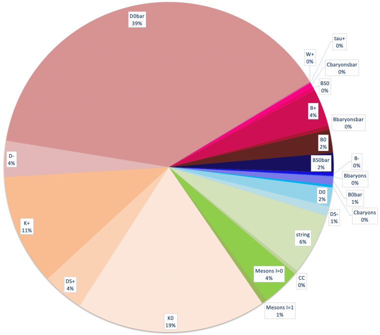
Energy (0.8,6.18)



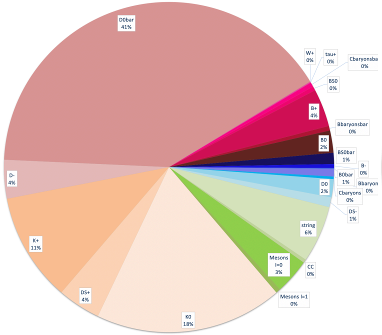
Energy (6.18,7.21)



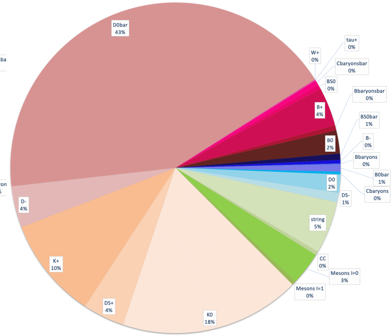
Energy (7.21,8.07)

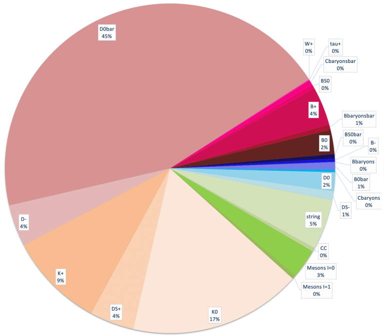


Energy (8.07,8.92)

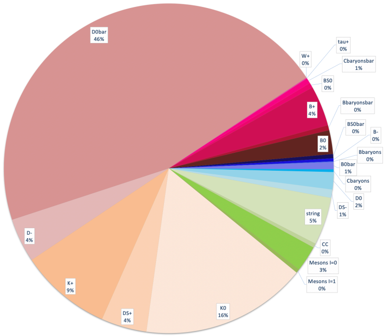


Energy (8.92,9.81)

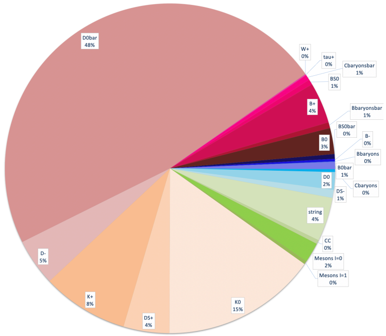




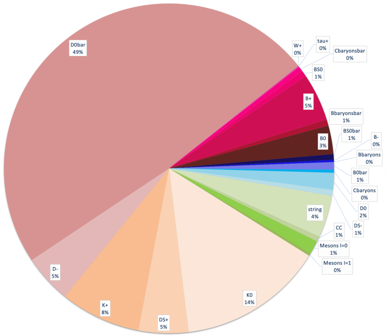
Energy (9.81,10.81)



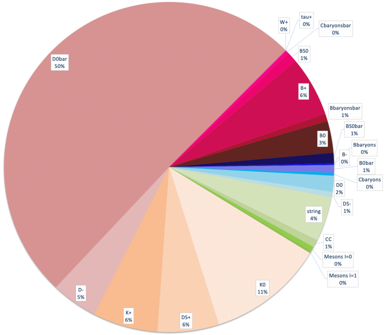
Energy (10.81,11.98)



Energy (11.98,13.55)



Energy (13.55,16.10)

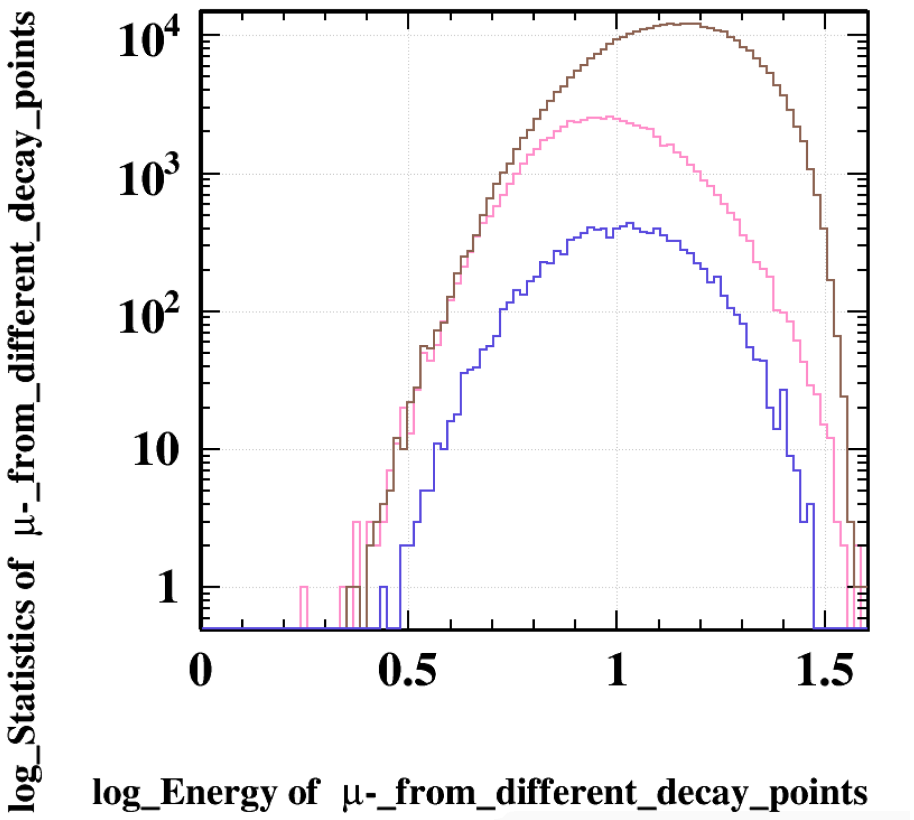


Energy (16.10,28.85)

03-3

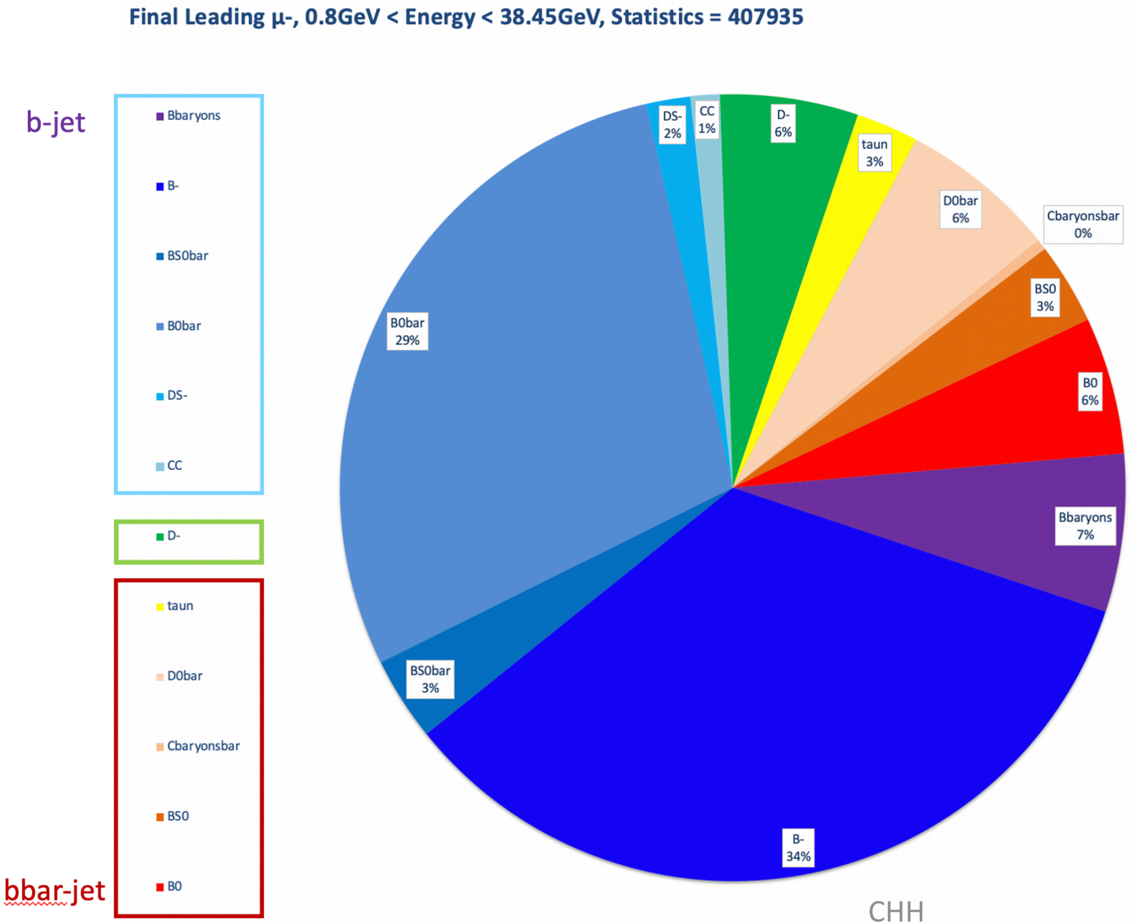
For each event,
Final Leading Particles: μ-

Energy spectrum of final leading μ- from different decay chains



Misjudgment rate ω of final leading μ- from different decay chains
All statistics = 407935

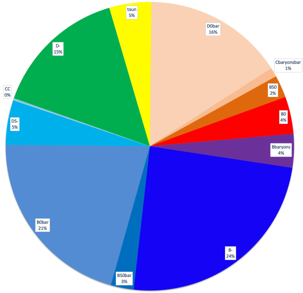
Percent of final leading μ- from different decay chains



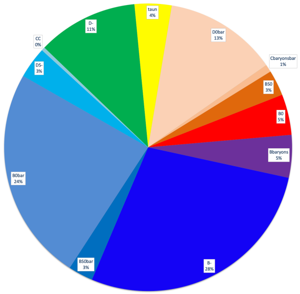
CHH

Percent of final leading μ- from different decay chains vs energy section

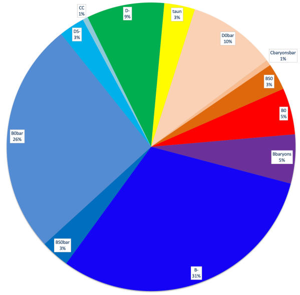
Energy (0.8,7.33)



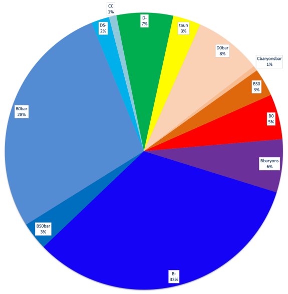
Energy (7.33,8.80)



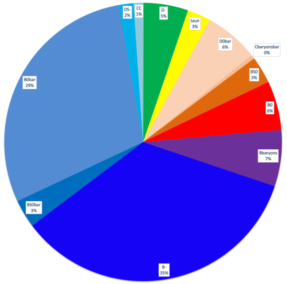
Energy (8.80,10.09)

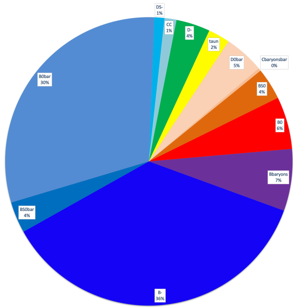


Energy (10.09,11.34)

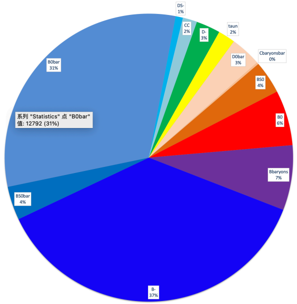


Energy (11.34,12.65)

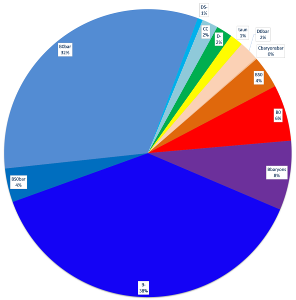




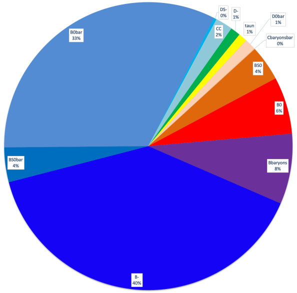
Energy (12.65,14.10)



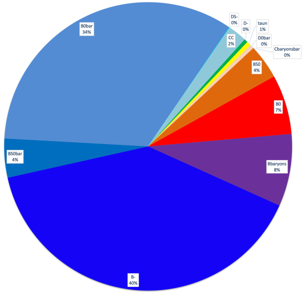
Energy (14.10,15.77)



Energy (15.77,17.85)



Energy (17.85,20.85)



Energy (17.85,38.45)

03-3

For each jet,
Final Leading Particles: e, μ, K

Efficiency of final leading e, μ, K from different decay chains

$$\text{Efficiency1} = \frac{N_{\{e,\ \mu,\ K\}}}{N_{\{e,\ \mu,\ K,\ \pi,\ \text{proton}\}}}$$

$$\text{Efficiency2} = \frac{N_{\{e,\ \mu,\ K\},\{\text{charge of b-jet}+\text{charge of bbar-jet}=0\}}}{N_{\{e,\ \mu,\ K\}}}$$

$$\text{Efficiency3} = \frac{N_{\{e,\ \mu,\ K\},\{\text{charge of b-jet}<0\ \&\&\ \text{charge of bbar-jet}>0\}}}{N_{\{e,\ \mu,\ K\},\{\text{charge of b-jet}+\text{charge of bbar-jet}=0\}}}$$

Purpose: Efficiency3 -> 1

04 Conclusion

Conclusion

"Jet Charge of b-jet system" is to judge initial particle charge (b or anti-b)
"Jet Charge of b-jet system" is important to the precision measurement of such as A_{FB}
CEPC has obvious advantages at using Jet Charge to measure A_{FB}

To develop Jet Charge Algorithm,

- ✓ Use Jet Charge misjudgment rate ω to measure the accuracy of Jet Charge Algorithm in each event in Truth Level.
- ➢ Use Jet Charge misjudgment rate ω to measure the accuracy of Jet Charge Algorithm in each jet in Truth Level.
  - Leading particle: {e, μ, K} / {π, proton}
  - Kaon from different decay chains
  - Leptons from different decay chains
- ☐ Use Jet Charge misjudgment rate ω to measure the accuracy of Jet Charge Algorithm in Full Simulation.
- ☐ Understand the difference between ω in Truth Level and ω in Full Simulation, and study the influence of CEPC detector performance on Jet Charge misjudgment rate ω.
- ☐ Combine two jets to improve Jet Charge Algorithm.
- ☐ Use VTX information to improve Jet Charge Algorithm.
- ☐ Use Jet Charge Algorithm to the precision measurement of relative benchmark.(eg: The precision of A_{FB}(Forward-Backward Asymmetry) measurement.)

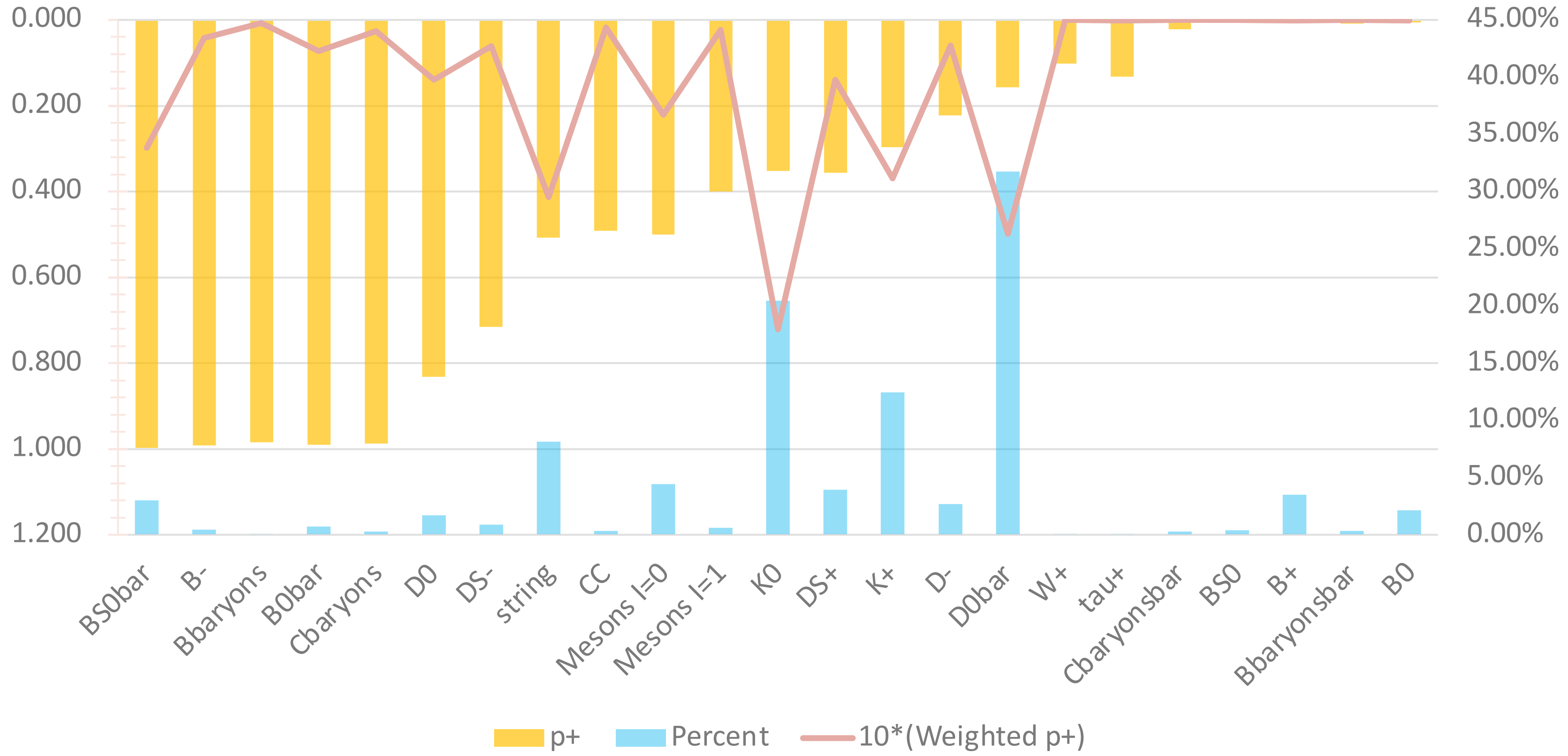
T H A N K   Y O U !   ^ . ^

BACK UP 1:

Misjudgment rate ω of final leading K+ from different decay chains vs energy section

Misjudgment rate ω of final leading K+ from different decay chains vs energy section

0.8GeV < Energy < 6.18GeV, Statistics = 90868



Misjudgment rate ω of final leading K+ from different decay chains vs energy section

6.18GeV < Energy < 7.21GeV, Statistics = 91679

Misjudgment rate ω of final leading K+ from different decay chains vs energy section

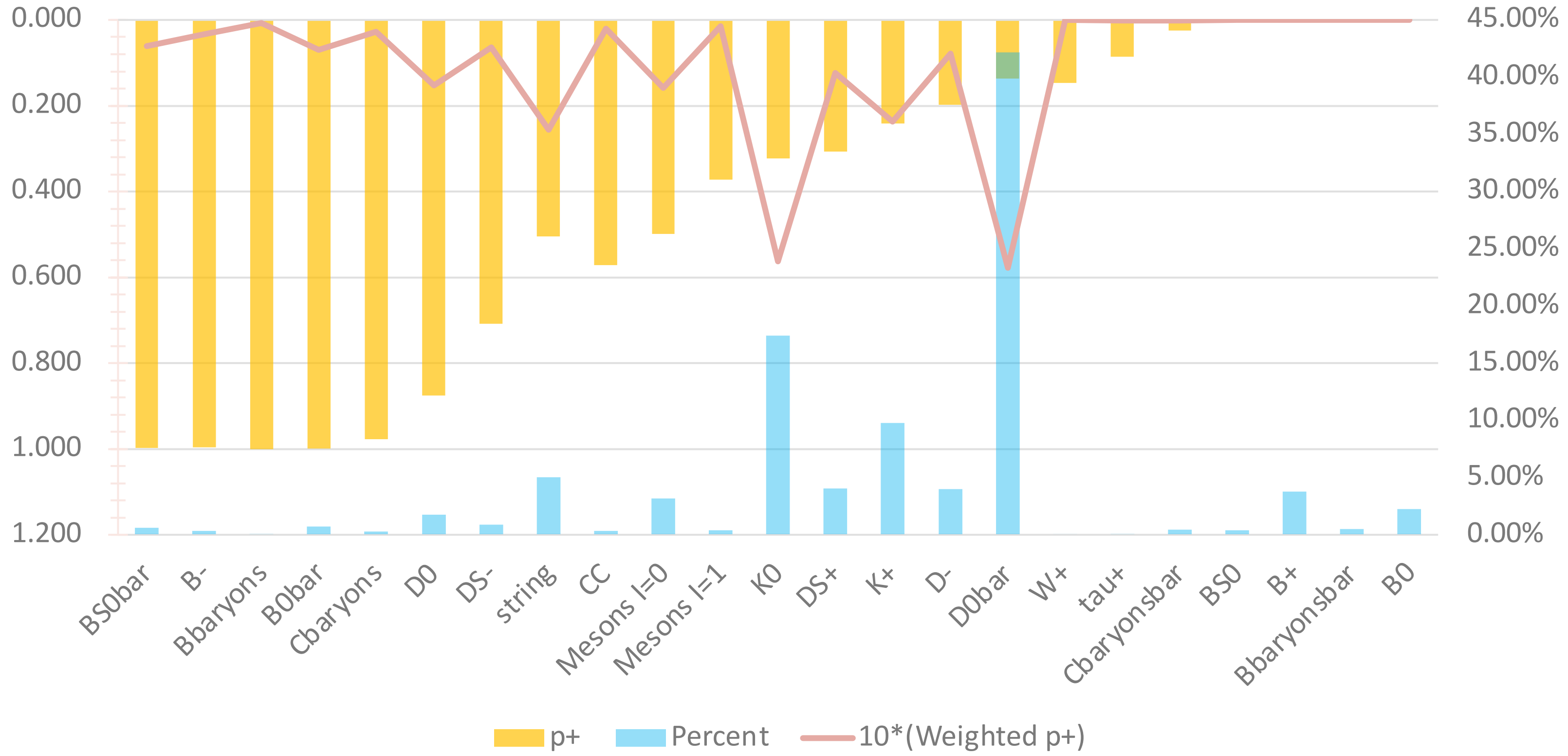
7.21GeV < Energy < 8.07GeV, Statistics = 90241

Misjudgment rate ω of final leading K+ from different decay chains vs energy section

8.07GeV < Energy < 8.92GeV, Statistics = 91196

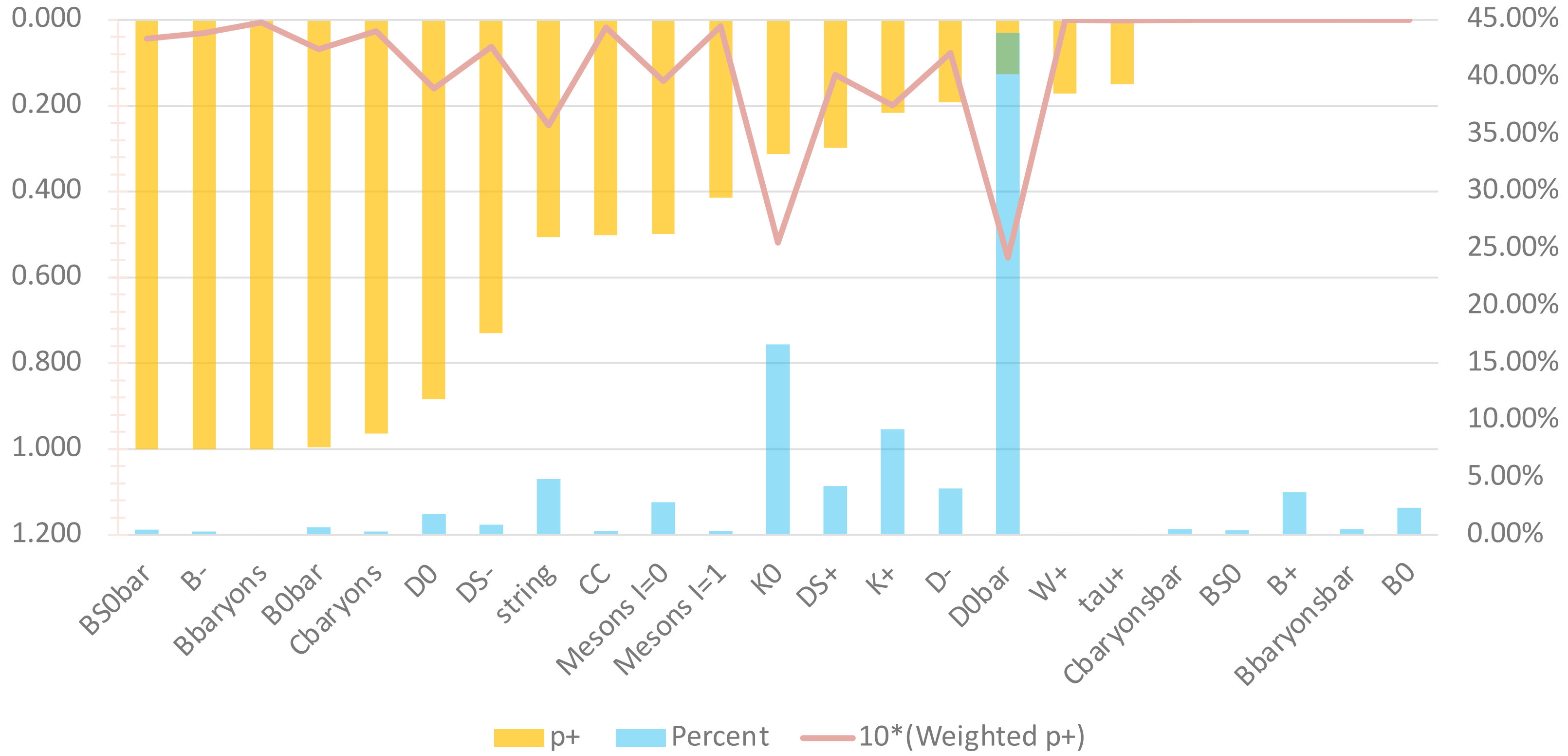
Misjudgment rate ω of final leading K+ from different decay chains vs energy section

8.92GeV < Energy < 9.81GeV, Statistics = 90966



Misjudgment rate ω of final leading K+ from different decay chains vs energy section

9.81GeV < Energy < 10.81GeV, Statistics = 91757

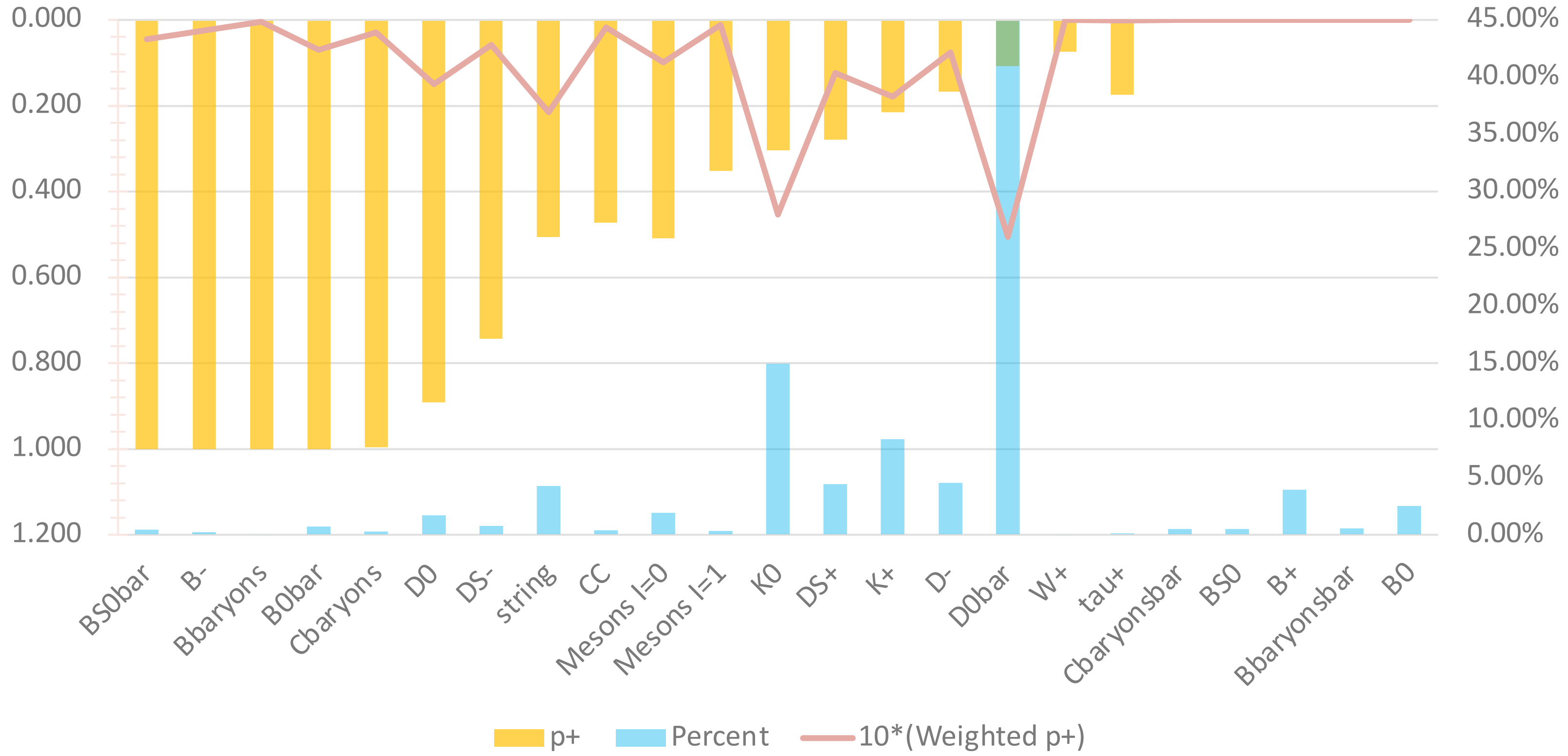


Misjudgment rate ω of final leading K+ from different decay chains vs energy section

10.81GeV < Energy < 11.98GeV, Statistics = 89854

Misjudgment rate ω of final leading K+ from different decay chains vs energy section

11.98GeV < Energy < 13.55GeV, Statistics = 91219



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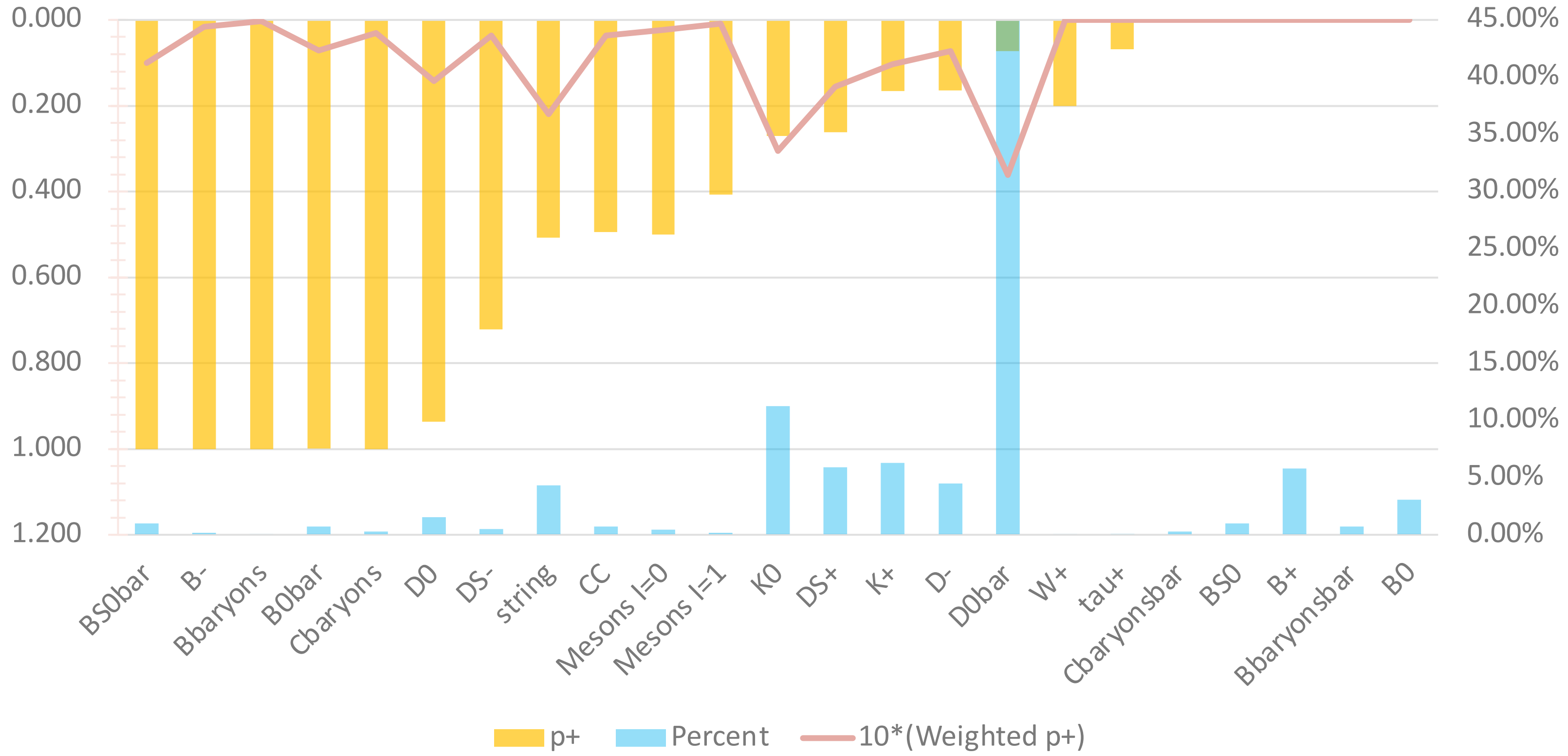
Misjudgment rate ω of final leading K+ from different decay chains vs energy section

13.55GeV < Energy < 16.10GeV, Statistics = 92145

Misjudgment rate ω of final leading K+ from different decay chains vs energy section

16.10GeV < Energy < 28.85GeV, Statistics = 89241



BACK UP 2:
Additional Theory Introductions

What is $\sin^2\theta_W$

- Weak Mixing Angle (θ_W) is the angle by which spontaneous symmetry breaking rotates the original W_0 and B_0 vector boson plane, producing as a result the Z_0 boson, and the photon.

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} \begin{pmatrix} \cos\theta_w & \sin\theta_w \\ -\sin\theta_w & \cos\theta_w \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

- It also gives the relationship between the masses of the W and Z bosons: $\cos\theta_W = \frac{m_W}{m_Z}$

Why $\sin^2\theta_W$ is important?

Observables:

	experimental precision
Fine structure constant： α	10^{-9}
Fermi constant： G_μ	10^{-7}
Mass of Z boson： M_Z	10^{-5}
Mass of W boson： M_W	10^{-4}
Effective weak mixing angle： $\sin^2\theta_{eff}$	10^{-3}

Weak mixing angle is important.

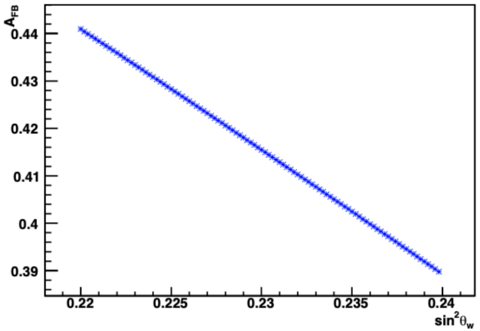
But it has the worst precision among fundamental parameters.

Function: $A_{FB}(\sin^2\theta_W)$

$$\frac{d\sigma}{d\cos\theta} \propto 1+\cos^2\theta + \frac{8}{3}A_{FB}^{b}\cos\theta$$

$$A_{FB}^{b,0} = \frac{3}{4}\left(\frac{2g_V^e g_A^e}{(g_V^e)^2+(g_A^e)^2}\right)\left(\frac{2g_V^b g_A^b}{(g_V^b)^2+(g_A^b)^2}\right)$$

$$\sin^2\theta_W^{\text{eff,f}} = \frac{1}{4|q_f|}\left(1-\frac{g_V^f}{g_A^f}\right)$$



The average A_{FB} VS $\sin^2\theta_W$ for ee → Z → uu events at Z pole.

A_{FB} has roughly a linear relationship to $\sin^2\theta_W$.

定义 $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$; 测量 $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$ (实际上通过角分布)

其中 $\sigma_F = 2\pi\int_0^1 \frac{d\sigma}{d\Omega}d(\cos\theta)$, $\sigma_B = 2\pi\int_{-1}^0 \frac{d\sigma}{d\Omega}d(\cos\theta)$.

其中 $\frac{d\sigma}{d\Omega} \propto a(1+\cos^2\theta)+2b\cos\theta$

其中 $a=[(g_L^e)^2+(g_R^e)^2][(g_L^f)^2+(g_R^f)^2]$

$b=[(g_L^e)^2-(g_R^e)^2][(g_L^f)^2-(g_R^f)^2]$

计算得 $A_{FB} = \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} = \frac{3}{4}\frac{b}{a} = \frac{3}{4}\left[\frac{(g_L^e)^2-(g_R^e)^2}{(g_L^e)^2+(g_R^e)^2}\right]\left[\frac{(g_L^f)^2-(g_R^f)^2}{(g_L^f)^2+(g_R^f)^2}\right] = \frac{3}{4}A_e \cdot A_f$

$g_V^2+g_A^2 = 2(g_L^2+g_R^2)$, $g_V g_A = g_L^2-g_R^2$

其中 $A_f = \frac{(g_L^f)^2-(g_R^f)^2}{(g_L^f)^2+(g_R^f)^2} = \frac{2g_V^f g_A^f}{(g_V^f)^2+(g_A^f)^2} = \frac{\frac{g_V^f}{g_A^f}}{1+\left(\frac{g_V^f}{g_A^f}\right)^2}$

其中 $g_V = I_W^{(3)} - 2Q\sin^2\theta_W$. $g_A = I_W^{(3)}$

Z与费米子的矢量耦合 Z与费米子的轴矢量耦合.

$\frac{g_V}{g_A} = 1 - \frac{2Q\sin^2\theta_W}{I_W^{(3)}}$ for charged leptons $Q=-1$. $I_W^{(3)} = -\frac{1}{2}$ $1-4\sin^2\theta_W$.

$g_V \neq g_A \Rightarrow A_{FB} \neq 0$.

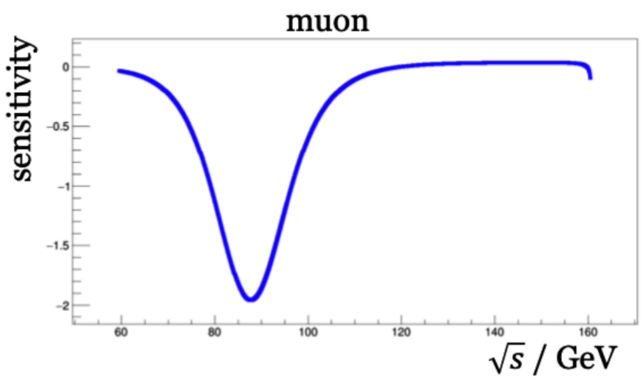
可通过测量 $A_{FB}^e, A_{FB}^\mu, A_{FB}^\tau \Rightarrow \frac{g_V}{g_A} \Rightarrow \sin^2\theta_W$

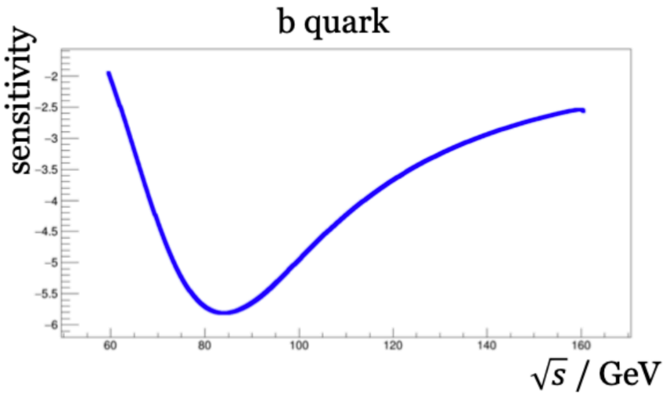
Sensitivity of A_{FB} to $\sin^2\theta_W$

The sensitivity of A_{FB} to $\sin^2\theta_W$, depends on center-of-mass energy and particle flavors.

A_{FB} is sensitive to $\sin^2\theta_W(e)$, and insensitive to $\sin^2\theta_W(b)$.

$$\text{sensitiviy} = \frac{\Delta \sin^2 \theta^{\ell}_{\text{eff}}}{\Delta A_{FB}}$$

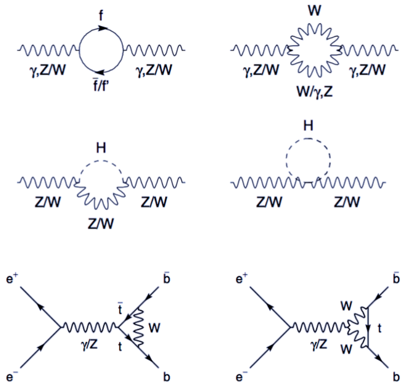




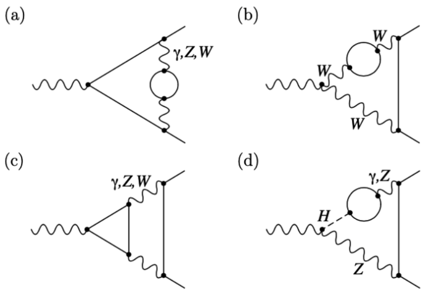
Why $\sin^2\theta_W$ measurement need precision?

0.1% uncertainty: effect from 2-loop contribution, one order magnitude larger than theoretical uncertainty.

EW global fitting is limited by the experimental results.



1-loop diagrams contribute to $\sin^2\theta_{eff}$, shifting its value by 3.7%



2-loop diagrams contribute to $\sin^2\theta_{eff}$, shifting its value by ~0.2%

$\sin^2\theta_W$ Precision at LEP and CEPC

LEP in 1990s :

A_{FB} and $\sin^2\theta_W$: precision ~0.1% (statistical uncertainty dominant)
Known loop corrections to $\sin^2\theta_W$: ~4%

CEPC CDR :

A_{FB} and $\sin^2\theta_W$: precision ~0.01% (need specific measurement)

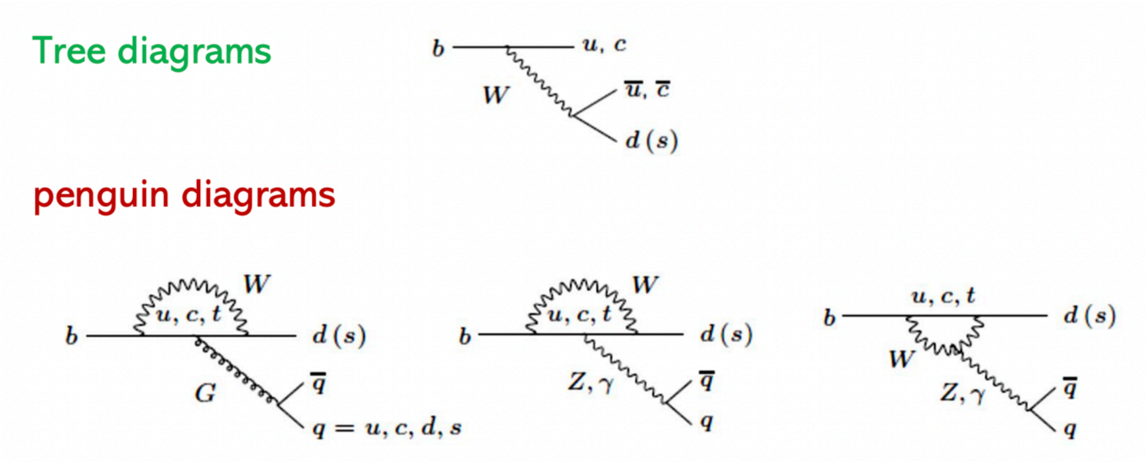
b quark decay

Dominant decay:

b→c+W→c+l+v (semileptonic decay) or b→c+W→c+qq→c+hadron.
b→X+c→X+Y+s→X+Y+K (s+uds→K)

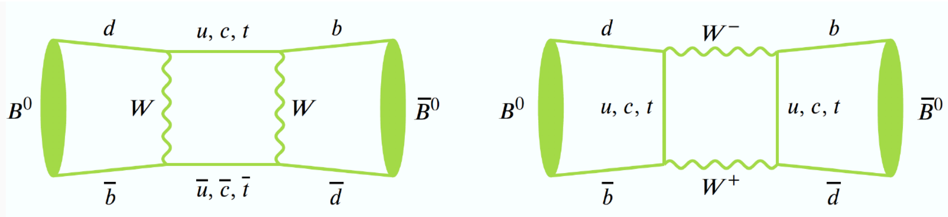
Final particles we consider:

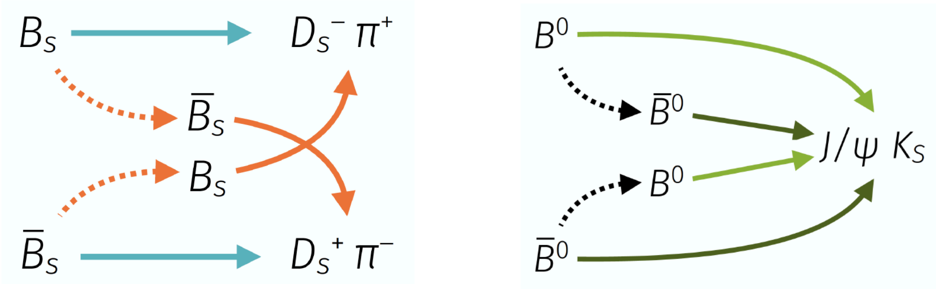
e+, e-, μ+, μ-, K+, K-, π+, π-, proton, antiproton



B^0 & anti-B^0 mixing

Oscillation between B^0 and B^0-bar:





Flavor production at different experiments

Particle	Tera-Z	Belle II	LHCb
b hadrons			
B^+	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B^0	6×10^{10}	3×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	3×10^{13}
B_s	2×10^{10}	3×10^{8} ($5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S)$)	8×10^{12}
b baryons	1×10^{10}		1×10^{13}
Λ_b	1×10^{10}		1×10^{13}
c hadrons			
D^0	2×10^{11}		
D^+	6×10^{10}		
D_s^+	3×10^{10}		
Λ_c^+	2×10^{10}		
τ^+	3×10^{10}	5×10^{10} ($50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S)$)	

[Dong et al.(2018)]