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

CEPC

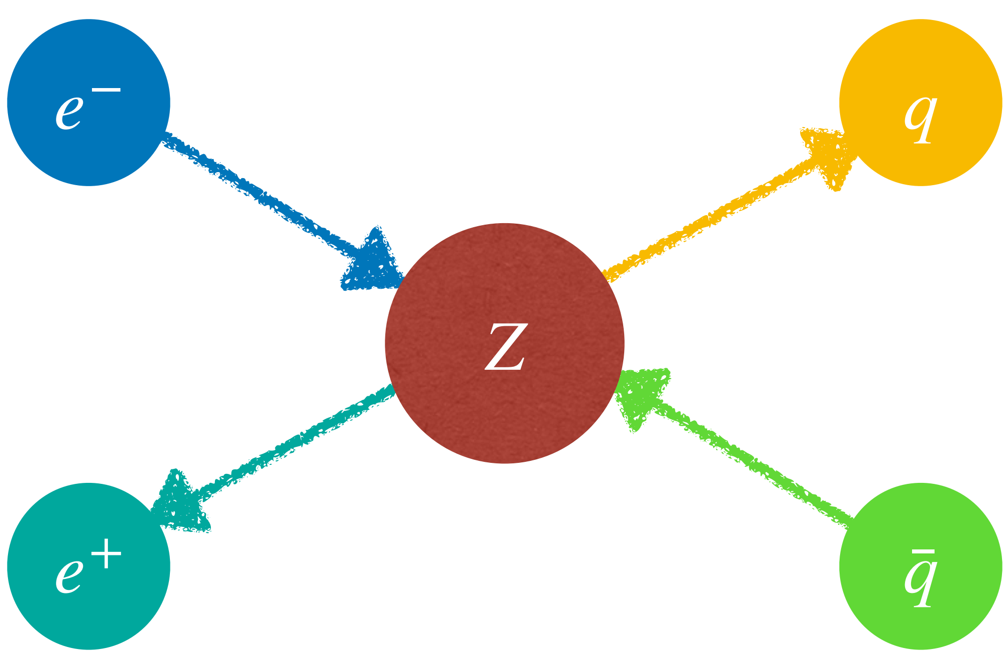
Jet Charge at CEPC

Hanhua Cui
Manqi Ruan
cuihanhua@ihep.ac.cn

CEPC Flavor Physics White Paper, September 15, 2021

Outline

- **Introduction**
- **Samples**
- **Method**
- **Results**
  - *Study of* $e^+e^- \to Z \to b\bar{b}$ *event*
  - *Study of* $e^+e^- \to Z \to c\bar{c}$ *event*
- **Conclusion**

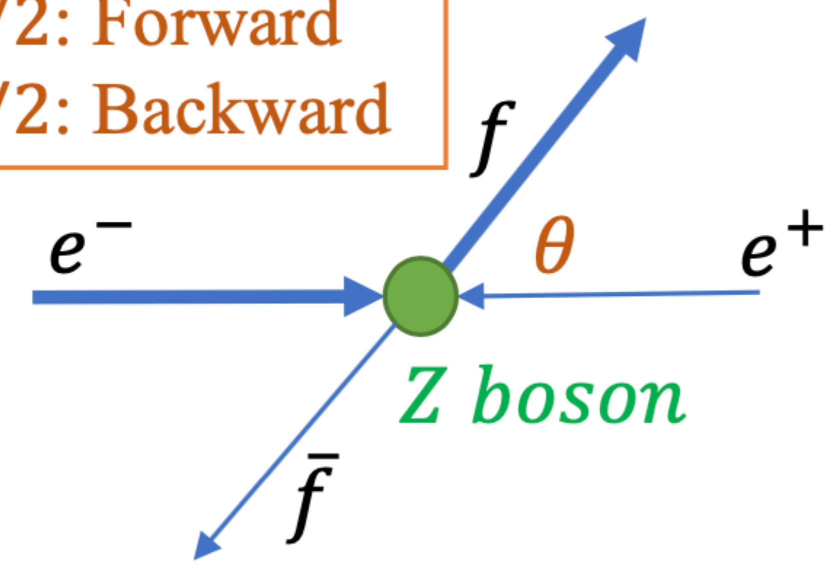


Introduction

Introduction of Jet Charge

We already have flavor tagging algorithm, Jet Charge can help find more physics

$\theta < \pi/2$: Forward
$\theta > \pi/2$: Backward



$$A_{FB}(\sin^2\theta_W) = \frac{N_F - N_B}{N_F + N_B}$$

What is Jet Charge?

- *To determine initial jet charge, namely b quark v.s. $\bar{b}$ quark / c quark v.s. $\bar{c}$ quark*

Application of Jet Charge:

- *The precision of A_{FB}(Forward and Backward Asymmetry) and $\sin^2\theta_W$ (electroweak mixing angle) measurement*
- *The precision of CP Violation measurement*
- *…*

Jet Charge at CEPC

Why CEPC?

High productivity

- *3 x 10^{11} - 10^{12} Z bosons in 2 years*
- $b\bar{b}$ *branching fraction: 15.2%*
- *0.152 × 10^{11} - 10^{12}* $b\bar{b}$

Good detector system

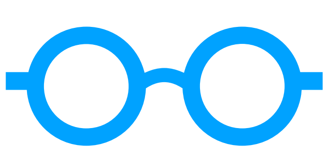
- *Good VTX reconstruction*
- *Good PID system*

Clean environment

Different particle flavors

- $\sin^2\theta_W^b$
- $\sin^2\theta_W^c$

VTX



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 $\Upsilon(4S)$)	

From CEPC CDR 2018

Jet Charge Algorithm

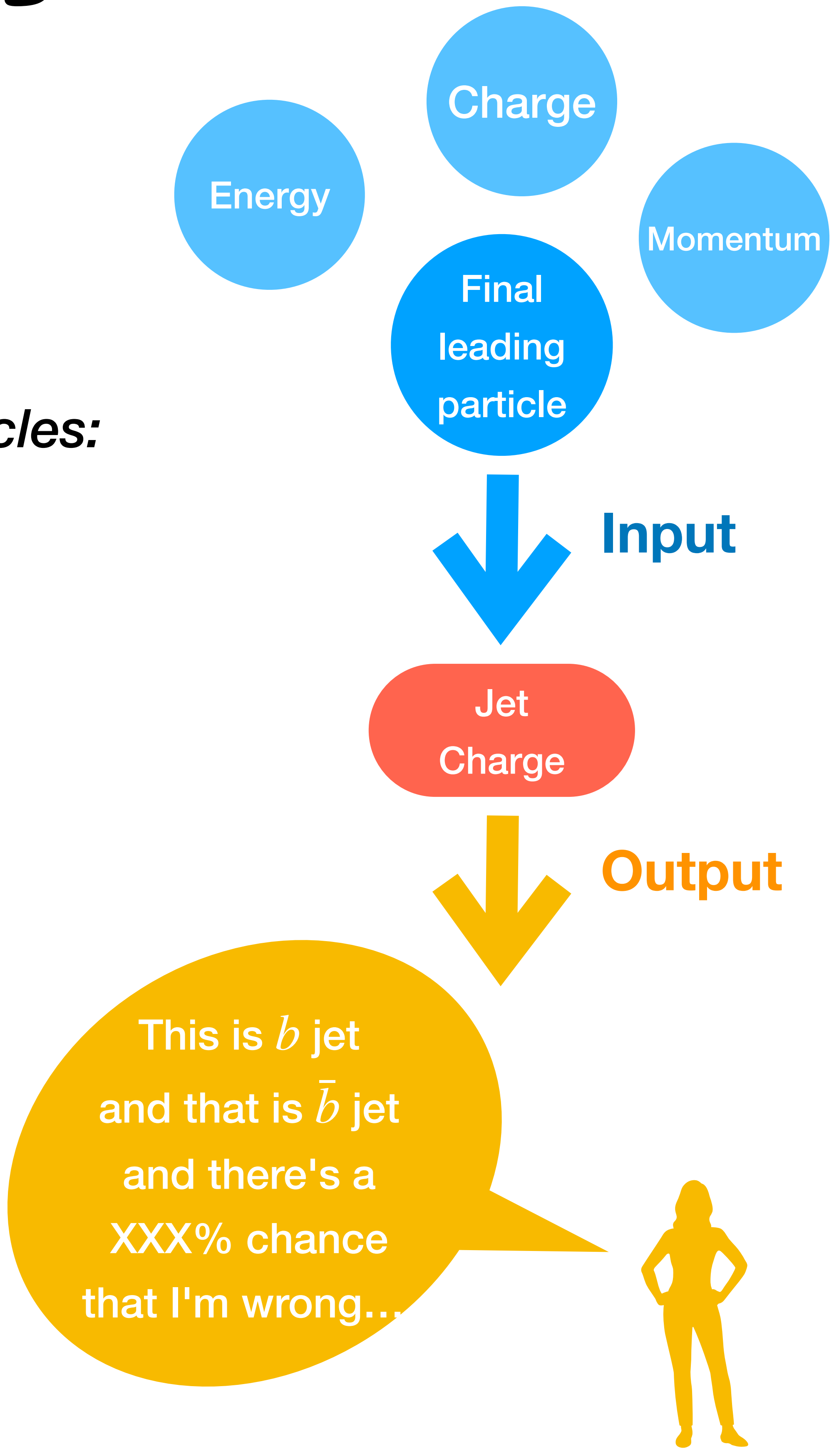
Jet Charge Algorithm at Truth Level:

Input:

- *Information of final leading particles:*
  - *Charge*
  - *Energy*
  - *Momentum*
  - *...*

Output:

- *Jet charge*
- *Description of Jet Charge*
  - *Misjudgment rate ω*
  - *Effective tagging power*

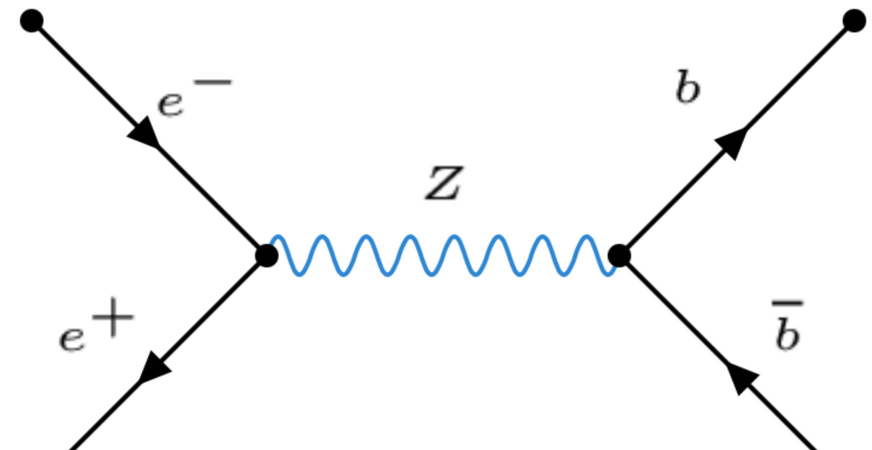


Samples

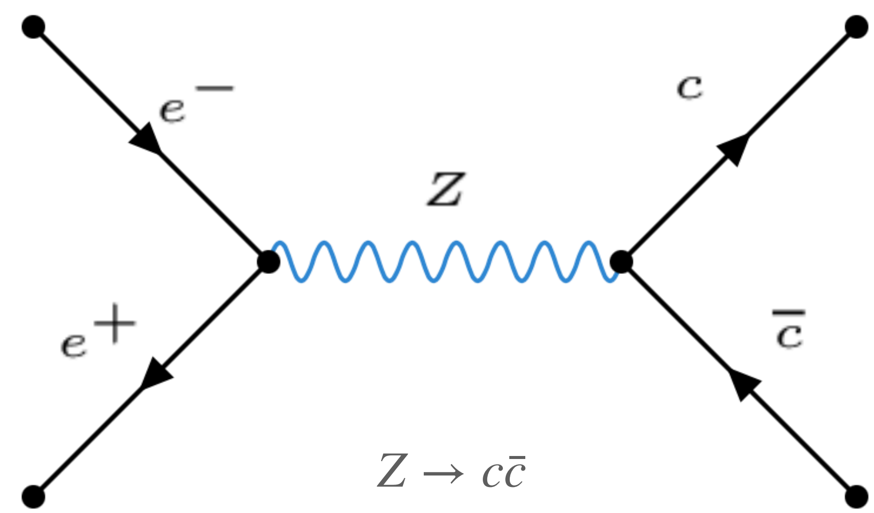
Samples

Samples:

- ***WHIZARD195***
- *CEPC* ***Z pole*** *(91.2 GeV) at Truth level*
- *16 million $Z \to b\bar{b}$ events:*
  - *easy to select*
  - *high sensitivity for $A_{FB}(\sin^2\theta_W)$ v.s. energy*
- *16 million $Z \to c\bar{c}$ events:*
  - *simpler decay behavior*



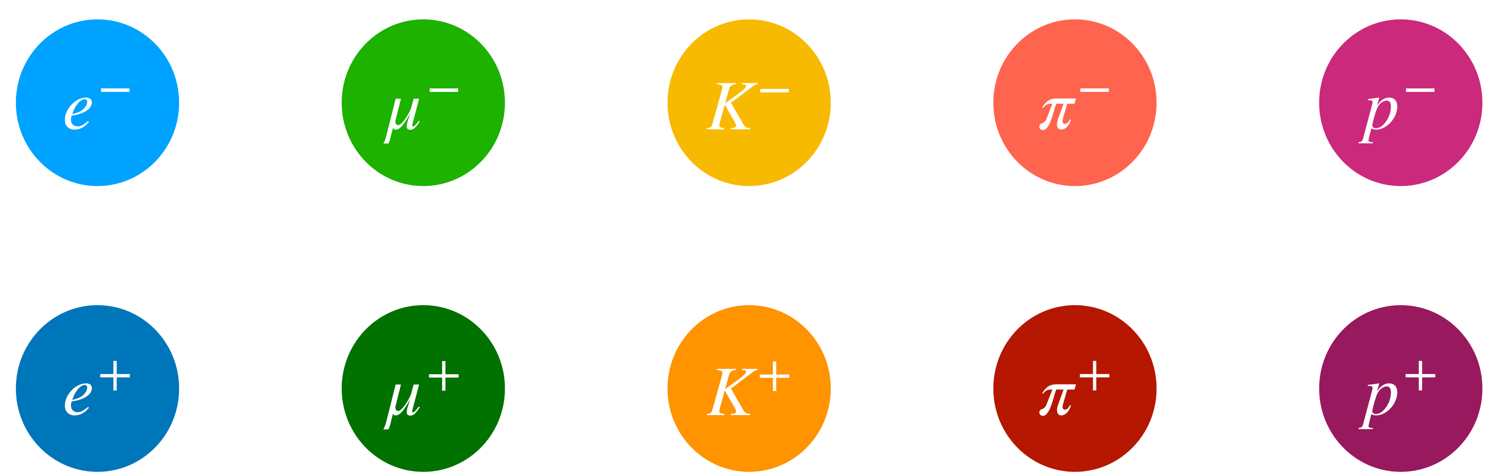
$Z \to b\bar{b}$



$Z \to c\bar{c}$

Final particles we consider:

- *leptons: e^+e^-, $\mu^+\mu^-$*
- *Kaons: K^+K^-*
- *pions: $\pi^+\pi^-$*
- *protons: p^+p^-*



Method

How to develop Jet Charge?

Jet Charge Algorithm:

- *Use Jet Clustering to divide final leading particles into two jets*
- *Find the relationship between observables(charge, energy) of final leading particles and jet charge:*
  - *For $Z \to b\bar{b}$ samples:*
    - $e^-, \mu^-, K^-, \pi^-, p^+$ *are closer to* b *jet*
    - $e^+, \mu^+, K^+, \pi^+, p^-$ *are closer to* $\bar{b}$ *jet*
  - *For $Z \to c\bar{c}$ samples:*
    - $e^+, \mu^+, K^-, \pi^+, p^+$ *are closer to* c *jet*
    - $e^-, \mu^-, K^+, \pi^-, p^+$ *are closer to* $\bar{c}$ *jet*
- *Combine the information of final leading particles of two jets*
- *Use those observables(charge, energy) of final leading particles to measure jet charge*
- *Use Misjudgment rate ω and effective tagging power to describe Jet Charge*

How to describe Jet Charge?

Misjudgment rate ω:

- *To describe the probability of misjudging the jet charge*

$$\omega = \frac{Number\ of\ selected\ particles\ that\ incorrectly\ reflect\ the\ charge\ flow\ of\ b\ jet\ to\ \bar{b}\ jet}{Number\ of\ selected\ final\ leading\ particles}$$

Efficiency:

- *To describe the selection efficiency of $Z \to b\bar{b}$ or $Z \to c\bar{c}$ samples:*

$$Efficiency = \frac{Number\ of\ selected\ final\ leading\ particles}{Number\ of\ all\ final\ leading\ particles}$$

- *The selected final leading particles are particles with typical flavor and energy cut and the charges of two leading particles of each jet are verse*

Effective tagging power ETP:

- *To consider both misjudgment rate ω and efficiency to describe the total performance of Jet Charge*

$$Effective\ tagging\ power = Efficiency\ *\ (1 - 2 * \omega)^2$$

Steps of studying Jet Charge

1. Because the lepton and Kaon can deliver better misjudgment rate ω than pion and proton. → Categorize the final leading particles:

$$(e, \mu, K) \ \& \ (\pi, proton)$$

2. Calculate the misjudgment rate ω and effective tagging power of each category

3. Change the energy threshold of the final leading particles

4. Study the effective tagging power in details of each B/C hadron

5. Using not only "charge verse" samples, but also "charge same" samples by energy information of the final leading particles

Steps of studying Jet Charge

Yangzhou's presentation

1. Because the lepton and Kaon can deliver better misjudgment rate ω than pion and proton. → Categorize the final leading particles:

$$(e, \mu, K) \ \& \ (\pi, proton)$$

2. Calculate the misjudgment rate ω and effective tagging power of each category

3. Change the energy threshold of the final leading particles

4. Study the effective tagging power in details of each B/C hadron

5. Using not only "charge verse" samples, but also "charge same" samples by energy information of the final leading particles

Update

Steps of studying Jet Charge

1. Because the **lepton and Kaon** can deliver better misjudgment rate ω than pion and proton. → **Categorize** the final leading particles:

   Yangzhou's presentation

   $$(e, \mu, K) \ \& \ (\pi, proton)$$

2. Calculate the misjudgment rate ω and **effective tagging power** of each category

   $Z \to b\bar{b}$ Total Effective Tagging Power = 0.127

   $Z \to c\bar{c}$ Total Effective Tagging Power = 0.282

3. Change the **energy** threshold of the final leading particles

   No energy threshold is the best case

4. Study the effective tagging power in details of **each B/C hadron**

5. Using not only "charge verse" samples, but also "**charge same**" samples by **energy** information of the final leading particles

Update

Results

Number of B/C hadrons

Num_B bbar jet → b jet ↓	0	1	2	3
0	0.02%	1.25%	0.61%	1E-05
1	1.25%	96.08%	0.03%	0.05%
2	0.61%	0.03%	0.03%	2E-07
3	8E-06	0.05%	3E-07	2E-07

each jet has one B

Num_C cbar jet → c jet ↓	0	1	2	3
0	0.016%	1.241%	0.758%	6E-05
1	1.237%	94.744%	0.030%	0.461%
2	0.754%	0.031%	0.205%	6E-05
3	6E-05	0.464%	5E-05	2E-05

each jet has one C

by WHIZARD195

Number of B/C hadrons

Num_B bbar jet → b jet ↓	0	1	2	3
0	0.02%	1.25%	0.61%	1E-05
1	1.25%	96.08%	0.03%	0.05%
2	0.61%	0.03%	0.03%	2E-07
3	8E-06	0.05%	3E-07	2E-07

82.4% decayed to leading particle

Num_C cbar jet → c jet ↓	0	1	2	3
0	0.016%	1.241%	0.758%	6E-05
1	1.237%	94.744%	0.030%	0.461%
2	0.754%	0.031%	0.205%	6E-05
3	6E-05	0.464%	5E-05	2E-05

66.2% decayed to leading particle

by WHIZARD195

Number of B/C hadrons

Num_B bbar jet → b jet ↓	0	1	2	3
0	0.02%	1.25%	0.61%	1E-05
1	1.25%	96.08%	0.03%	0.05%
2	0.61%	0.03%	0.03%	2E-07
3	8E-06	0.05%	3E-07	2E-07

Num_C cbar jet → c jet ↓	0	1	2	3
0	0.016%	1.241%	0.758%	6E-05
1	1.237%	94.744%	0.030%	0.461%
2	0.754%	0.031%	0.205%	6E-05
3	6E-05	0.464%	5E-05	2E-05

This Report is based on all cases

by WHIZARD195

$Z \to b\bar{b}$ Percent of B hadrons of b jet and $\bar{b}$ jet

percent bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar	others	all
B^0bar	17.360%	17.350%	3.369%	0.022%	2.759%	0.688%	41.548%
B^-	17.350%	17.359%	3.364%	0.022%	2.765%	0.689%	41.550%
B_s^0bar	3.355%	3.362%	0.652%	0.004%	0.545%	0.144%	8.062%
B_c^-	0.022%	0.022%	0.004%	0.00003%	0.004%	0.001%	0.052%
Λ_b	2.762%	2.762%	0.543%	0.004%	0.451%	0.121%	6.644%
others	0.653%	0.655%	0.136%	0.001%	0.119%	0.579%	2.144%
all	41.503%	41.511%	8.068%	0.053%	6.641%	2.225%	100%

by WHIZARD195

$Z \to b\bar{b}$ Percent of B hadrons of b jet and $\bar{b}$ jet

percent bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar	others	all
B^0bar	17.360%	17.350%	3.369%	0.022%	2.759%	0.688%	41.548%
B^-	17.350%	17.359%	3.364%	0.022%	2.765%	0.689%	41.550%
B_s^0bar	3.355%	3.362%	0.652%	0.004%	0.545%	0.144%	8.062%
B_c^-	0.022%	0.022%	0.004%	0.00003%	0.004%	0.001%	0.052%
Λ_b	2.762%	2.762%	0.543%	0.004%	0.451%	0.121%	6.644%
others	0.653%	0.655%	0.136%	0.001%	0.119%	0.579%	2.144%
all	41.503%	41.511%	8.068%	0.053%	6.641%	2.225%	100%

by WHIZARD195

$Z \to c\bar{c}$ Percent of C hadrons of c jet and $\bar{c}$ jet

percent cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c	others	all
D^0	4.654%	13.302%	1.717%	0.005%	1.853%	21.532%
D^+	13.290%	37.933%	4.887%	0.012%	5.220%	61.342%
D_s^0	1.712%	4.894%	0.631%	0.002%	0.690%	7.929%
$\Lambda_c$bar	0.005%	0.013%	0.002%	0.005%	0.041%	0.006%
others	1.836%	5.163%	0.679%	0.045%	1.414%	9.137%
all	21.500%	61.306%	7.916%	0.006%	9.218%	100%

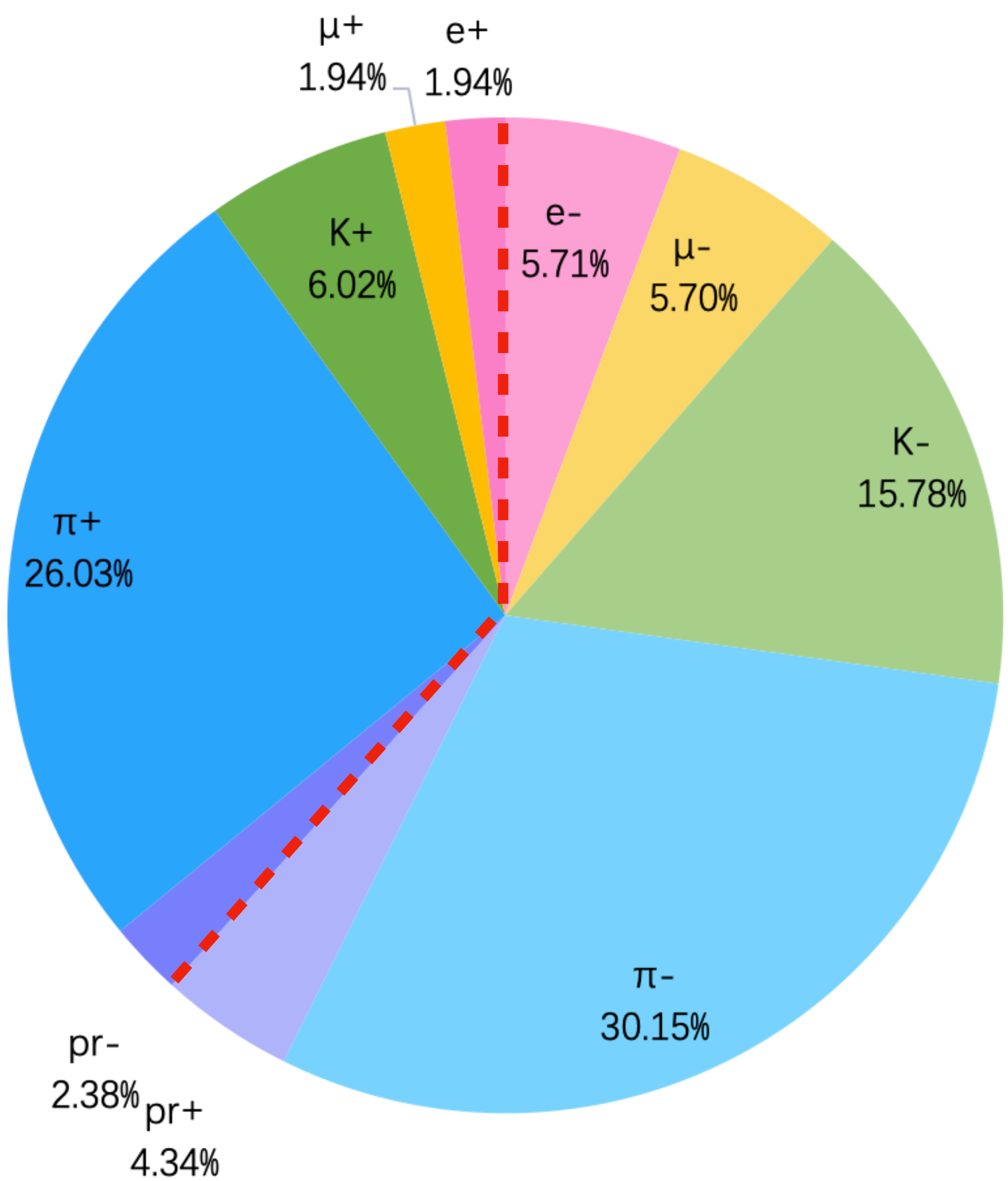
by WHIZARD195

$Z \to c\bar{c}$ Percent of C hadrons of c jet and $\bar{c}$ jet

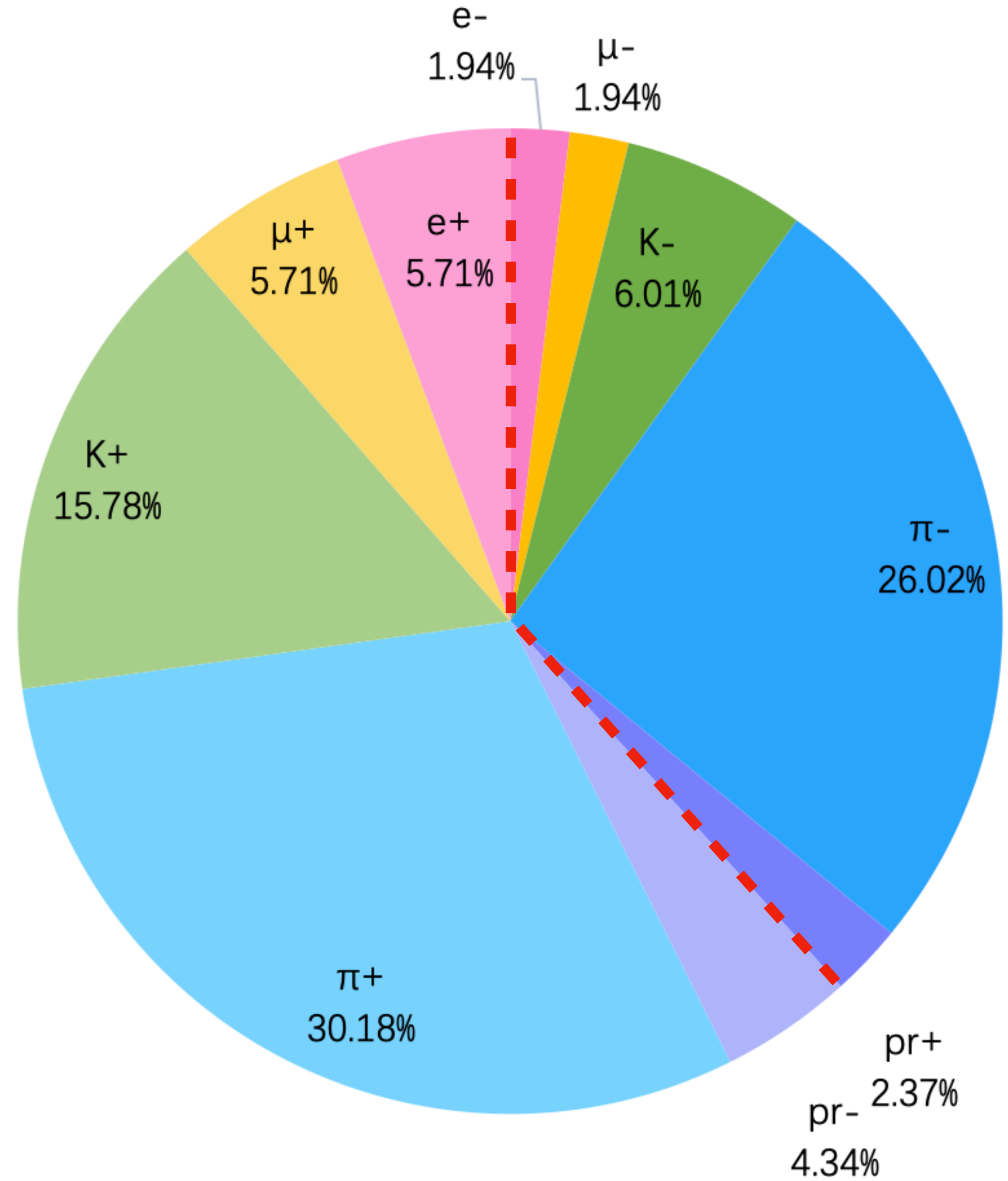
percent cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c	others	all
D^0	4.654%	13.302%	1.717%	0.005%	1.853%	21.532%
D^+	13.290%	37.933%	4.887%	0.012%	5.220%	61.342%
D_s^0	1.712%	4.894%	0.631%	0.002%	0.690%	7.929%
$\Lambda_c$bar	0.005%	0.013%	0.002%	0.005%	0.041%	0.006%
others	1.836%	5.163%	0.679%	0.045%	1.414%	9.137%
all	21.500%	61.306%	7.916%	0.006%	9.218%	100%

by WHIZARD195

$Z \to b\bar{b}$ Percent of final charged leading particles of b jet and $\bar{b}$ jet



b jet

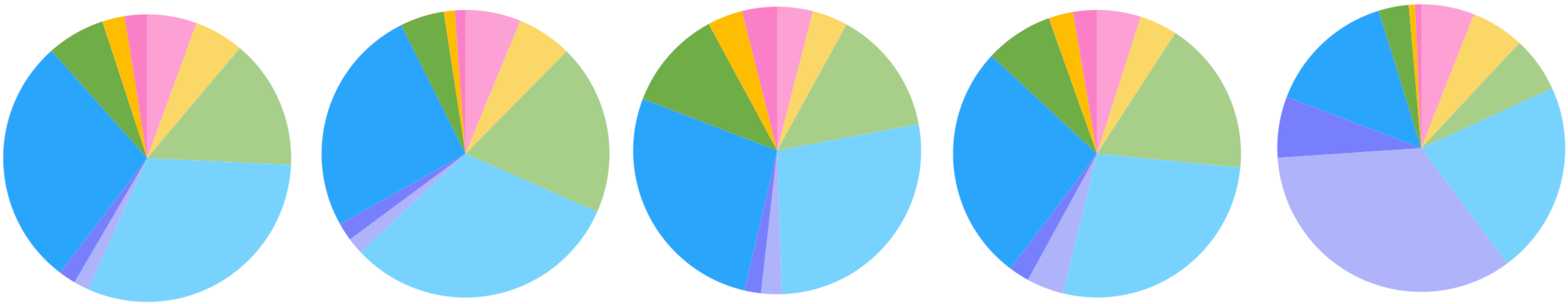


$\bar{b}$ jet

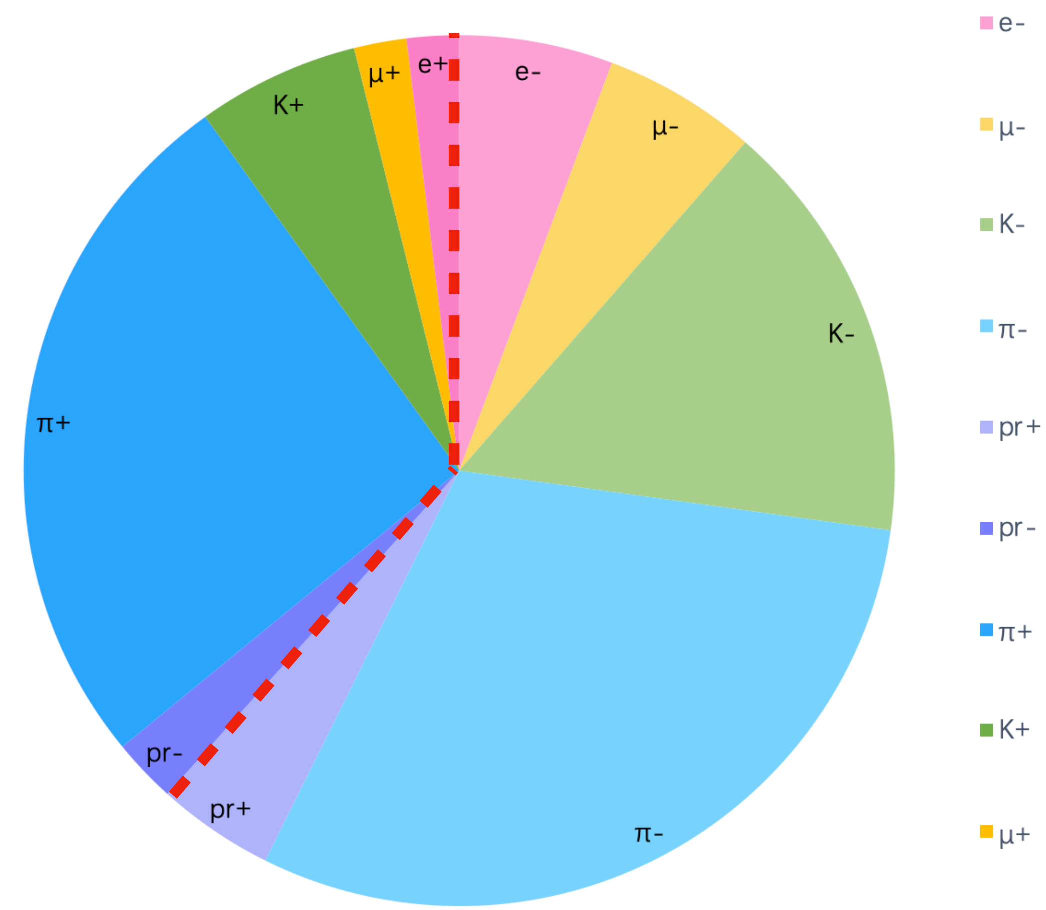
☞ *The distribution of each charged particle of two jets is asymmetry*

$Z \to b\bar{b}$

Percent of final charged leading particles of b jet



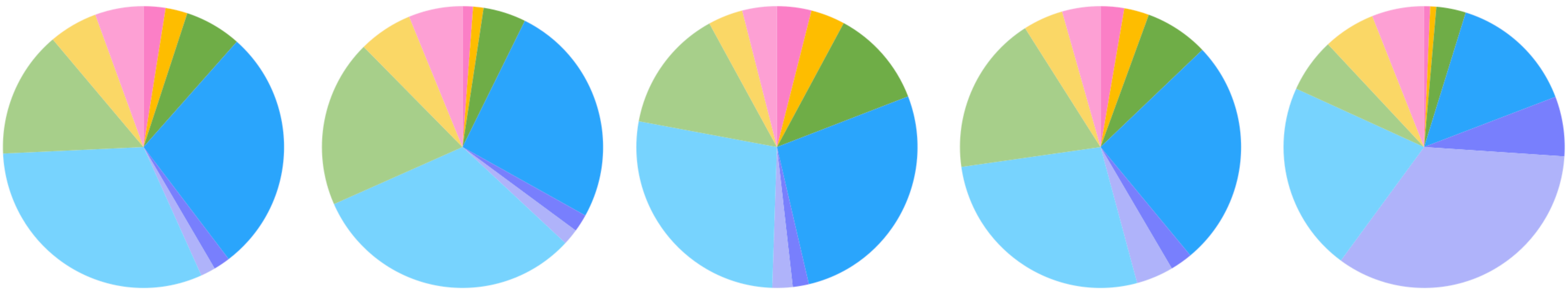
$\bar{B}^0$ * 0.415 B^- * 0.416 $\bar{B}^0_s$ * 0.081 B^-_c * 0.0005 Λ_b * 0.066



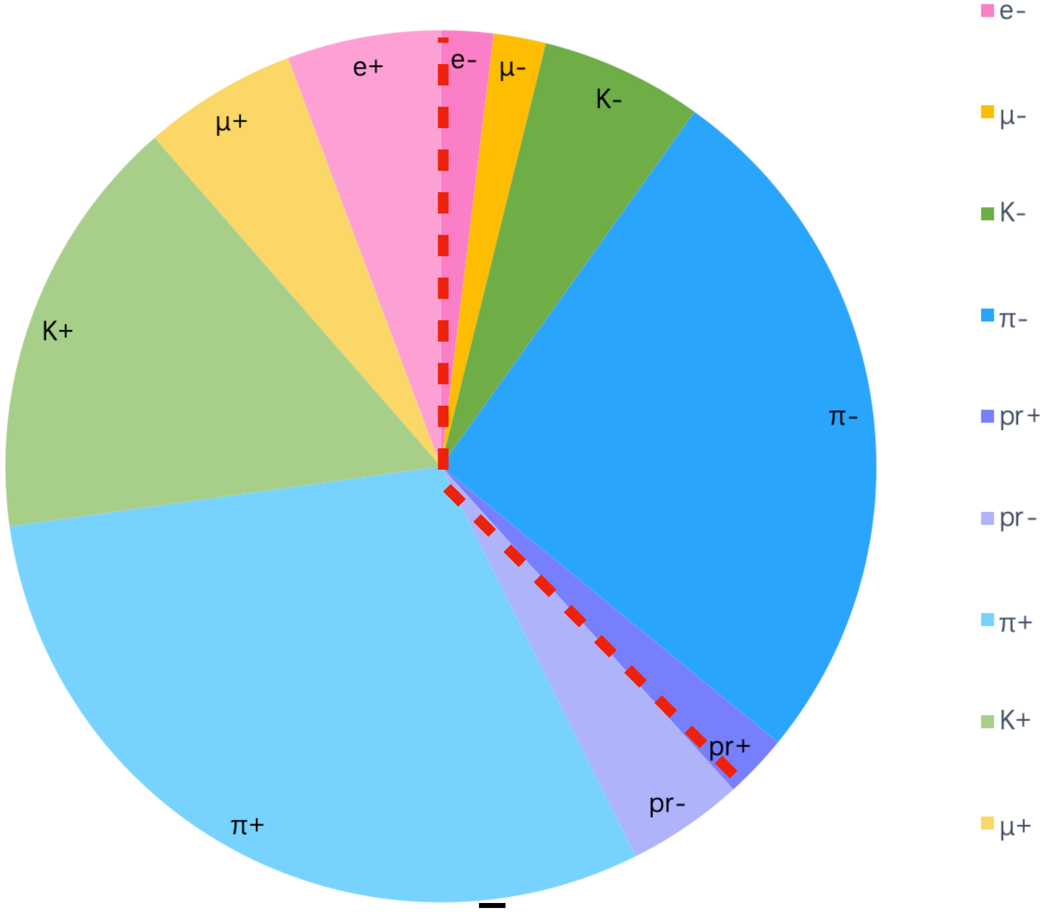
All B, b jet

$Z \rightarrow b\bar{b}$

Percent of final charged leading particles of $\bar{b}$ jet

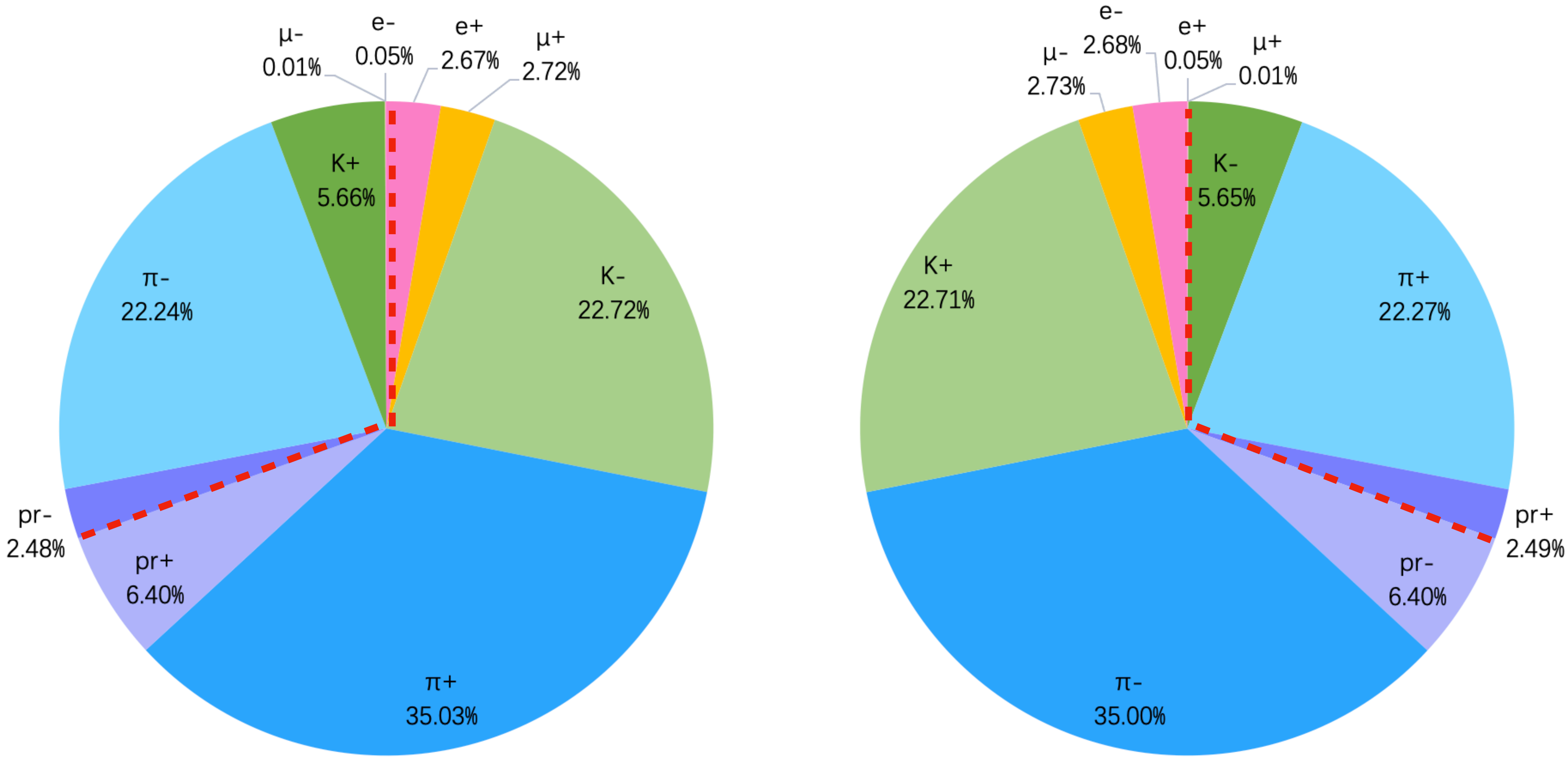


B^0 * **0.415** B^+ * **0.415** B_s^0 * **0.081** B_c^+ * **0.0005** $\bar{\Lambda}_b$ * **0.066**



All B, $\bar{b}$ jet

$Z \to c\bar{c}$ Percent of final charged leading particles of c jet and $\bar{c}$ jet

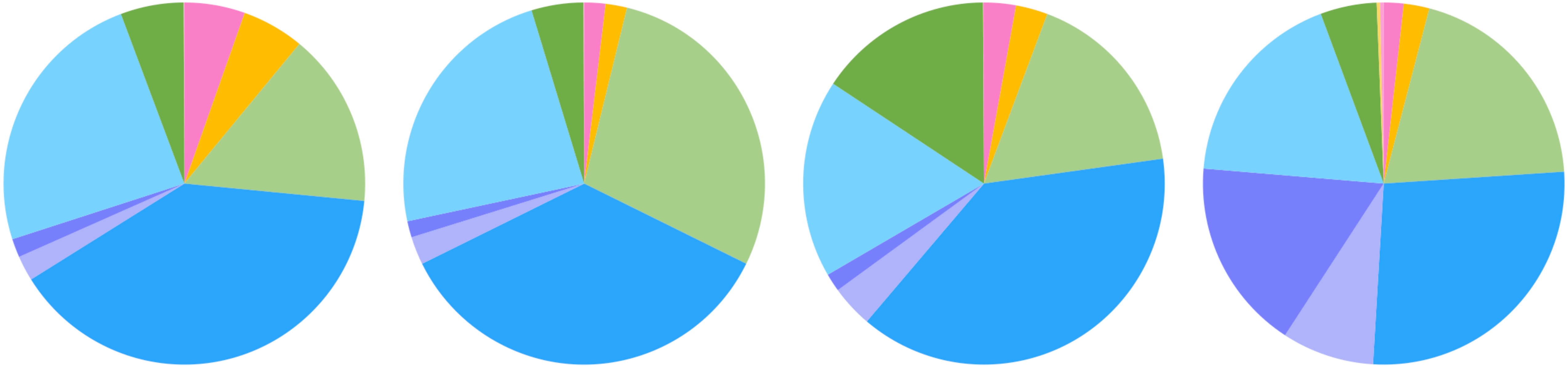


c jet $\bar{c}$ jet

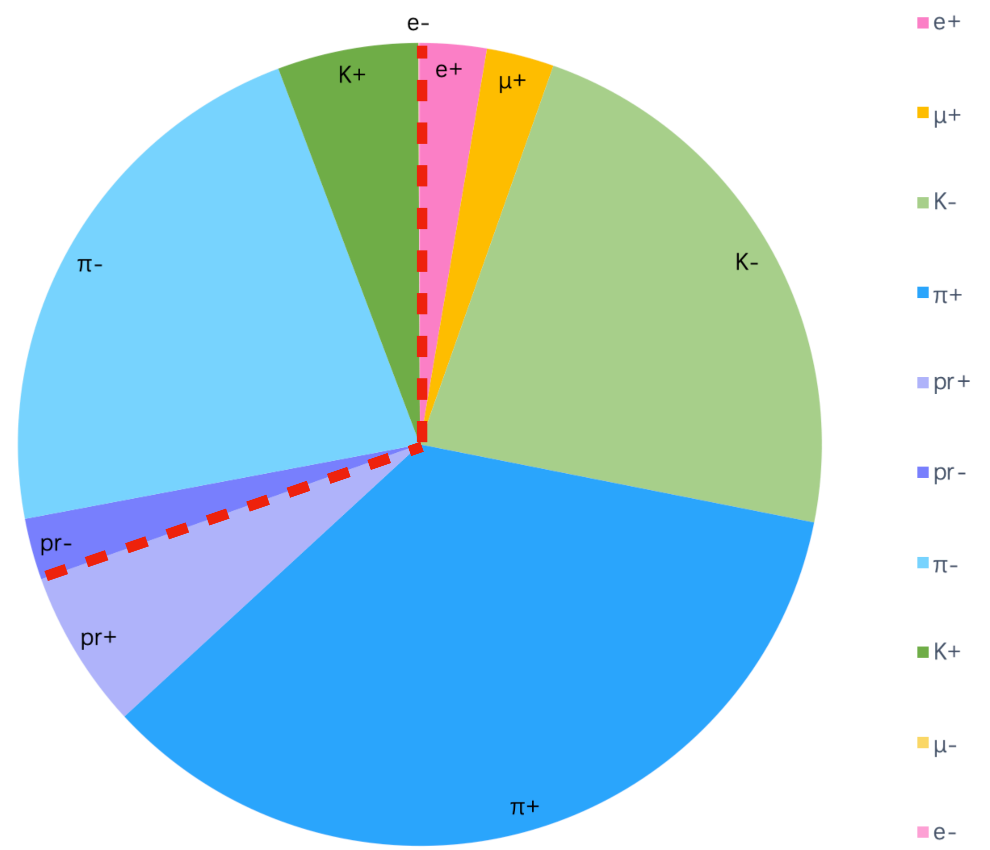
☞ *The distribution of each charged particle of two jets is asymmetry*

$Z \to c\bar{c}$

Percent of final charged leading particles of c jet



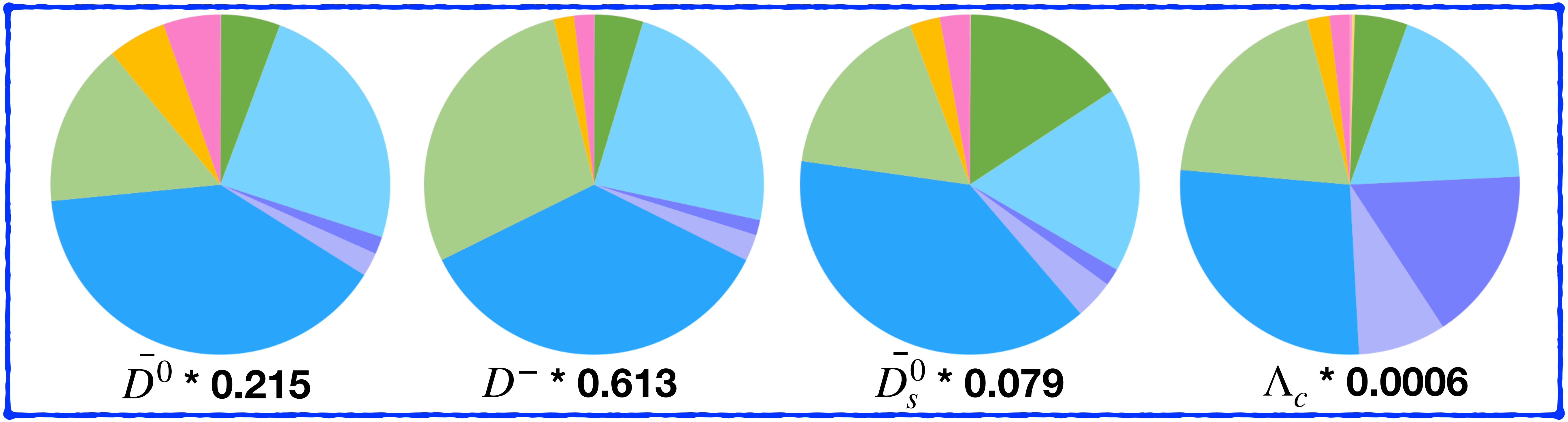
D^0 * 0.215 D^+ * 0.613 D_s^0 * 0.079 $\bar{\Lambda}_c$ * 0.0006

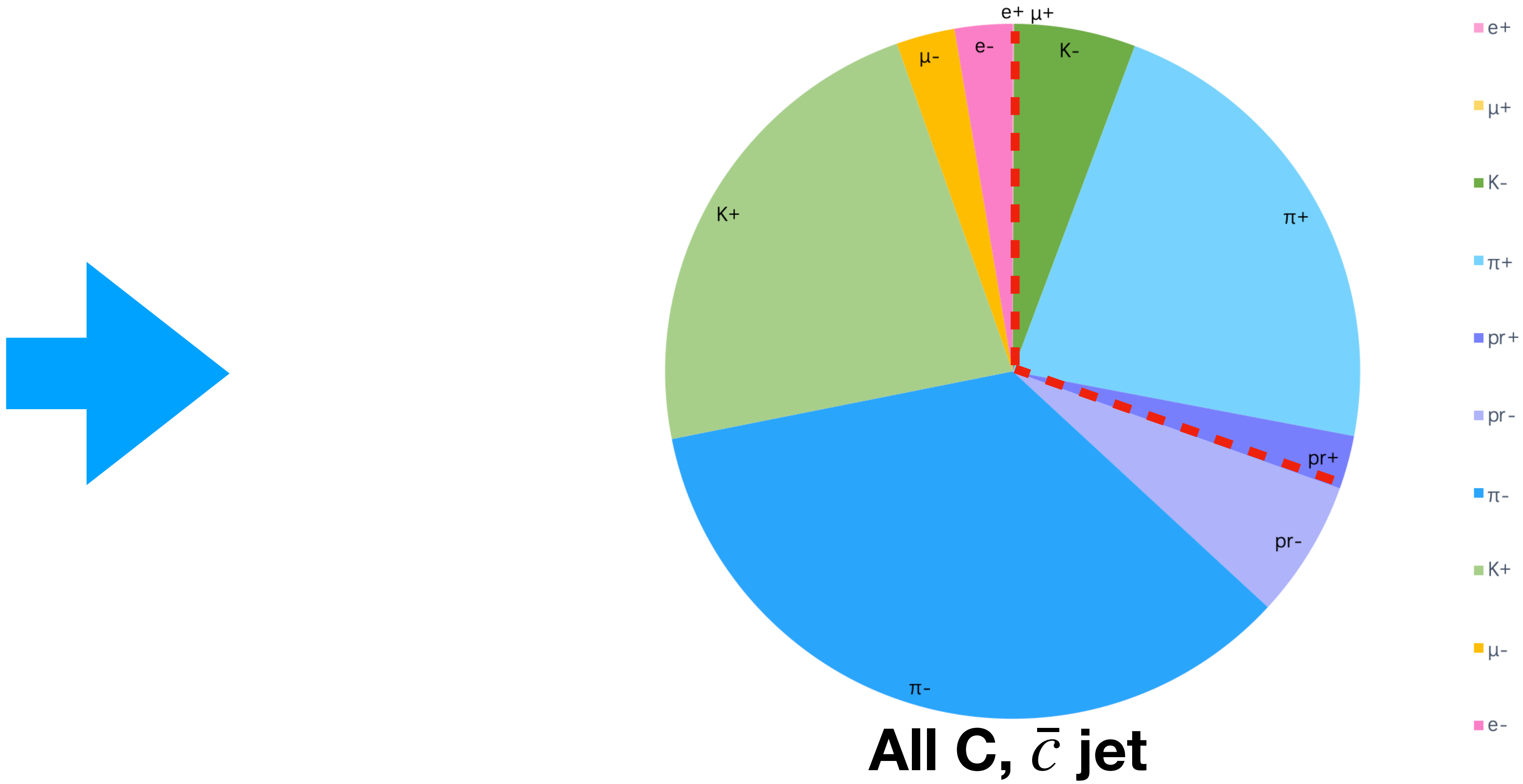


All C, c jet

$Z \rightarrow c\bar{c}$

Percent of final charged leading particles of $\bar{c}$ jet





Charge verse, Charge same, Charge correct

For leading e, μ, K of b jet and $\bar{b}$ jet

charge bbar jet → b jet ↓	+	-
+	19.54%	7.15%
-	53.81%	19.50%

For leading e, μ, K of c jet and $\bar{c}$ jet

charge cbar jet → c jet ↓	+	-
+	13.96%	69.12%
-	2.90%	14.01%

Charge verse

Charge correct

Charge verse, Charge same, Charge correct

For leading e, μ, K of b jet and $\bar{b}$ jet

charge bbar jet → b jet ↓	+	-
+	19.54%	7.15%
-	53.81%	19.50%

Charge verse

Charge correct

Charge same

For leading e, μ, K of c jet and $\bar{c}$ jet

charge cbar jet → c jet ↓	+	-
+	13.96%	69.12%
-	2.90%	14.01%

Two methods of using energy information for same charge samples

About 7.9% and 6.7% improvement for $Z \to b\bar{b}$ & $Z \to c\bar{c}$ samples

1. **For the two leading particles of two jets, measure jet charge by the charge of the leading particle with higher energy.**

   For $Z \to b\bar{b}$: Improve Effective Tagging Power from 0.127 to 0.137

   For $Z \to c\bar{c}$: Improve Effective Tagging Power from 0.127 to 0.136

2. **For the two leading particles and two sub-leading particles of two jets, measure jet charge by the charge of the leading particle which has higher energy difference with the sub-leading particle.**

   For $Z \to b\bar{b}$: Improve Effective Tagging Power from 0.282 to 0.301

   For $Z \to c\bar{c}$: Improve Effective Tagging Power from 0.282 to 0.294

Two methods of using energy information for same charge samples

The first method is better

1. For the two leading particles of two jets, measure jet charge by the charge of the leading particle with higher energy.

   For $Z \to b\bar{b}$: Improve Effective Tagging Power from 0.127 to 0.137

   For $Z \to c\bar{c}$: Improve Effective Tagging Power from 0.127 to 0.136

2. For the two leading particles and two sub-leading particles of two jets, measure jet charge by the charge of the leading particle which has higher energy difference with the sub-leading particle.

   For $Z \to b\bar{b}$: Improve Effective Tagging Power from 0.282 to 0.301

   For $Z \to c\bar{c}$: Improve Effective Tagging Power from 0.282 to 0.294

$Z \to b\bar{b}$ Effective Tagging Power of B Hadrons

Total Effective Tagging Power = 12.736%

% bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar
B^0bar	7.792	14.044	3.491	8.346	20.179
B^-	13.965	20.604	8.734	14.568	27.854
B_s^0bar	3.486	8.882	0.363	3.046	13.346
B_c^-	7.820	14.426	0.774	-	23.294
Λ_b	20.268	27.788	13.064	22.841	37.460

charge verse

Total Effective Tagging Power = 13.716%

% bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar
B^0bar	8.403	15.213	3.775	8.961	22.144
B^-	15.137	22.434	9.500	16.784	30.450
B_s^0bar	3.730	9.673	0.382	3.406	14.756
B_c^-	8.639	15.817	1.061	-	25.021
Λ_b	22.224	30.313	14.518	26.729	40.840

charge verse & same

$Z \to b\bar{b}$ Effective Tagging Power with error of B Hadrons

Total Effective Tagging Power = (13.716 ± 0.014)%

% bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar
B^0bar	8.403 ±0.026	15.213 ±0.037	3.775 ±0.037	8.961 ±0.768	22.144 ±0.110
B^-	15.137 ±0.047	22.434 ±0.062	9.500 ±0.063	16.784 ±1.071	30.450 ±0.134
B_s^0bar	3.730 ±0.037	9.673 ±0.063	0.382 ±0.024	3.406 ±0.954	14.756 ±0.187
B_c^-	8.639 ±0.732	15.817 ±1.063	1.061 ±0.495	-	25.021 ±3.309
Λ_b	22.224 ±0.110	30.313 ±0.134	14.518 ±0.186	26.729 ±3.322	40.840 ±0.3915

charge verse & same

$Z \to b\bar{b}$ Weighted Effective Tagging Power of B Hadrons

Total Effective Tagging Power = 12.736%

% bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar
B^0bar	1.353	2.437	0.118	0.002	0.557
B^-	2.423	3.577	0.294	0.003	0.770
B_s^0bar	0.117	0.299	0.002	0.0001	0.073
B_c^-	0.002	0.003	0.00003	-	0.0008
Λ_b	0.560	0.768	0.071	0.0008	0.169

charge verse

Total Effective Tagging Power = 13.716%

% bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar
B^0bar	1.459	2.640	0.127	0.002	0.611
B^-	2.627	3.895	0.320	0.004	0.842
B_s^0bar	0.125	0.325	0.003	0.0001	0.080
B_c^-	0.002	0.003	0.00005	-	0.0009
Λ_b	0.614	0.837	0.079	0.001	0.184

charge verse & same

$Z \to c\bar{c}$ Effective Tagging Power of C Hadrons

Total Effective Tagging Power = 28.214%

% cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c
D^0	25.605	28.561	21.514	19.581
D^+	28.544	31.285	24.395	20.631
D_s^0	21.452	24.252	17.423	17.200
$\Lambda_c$bar	17.549	23.176	16.968	9.852

charge verse

Total Effective Tagging Power = 30.116%

% cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c
D^0	27.184	30.702	22.353	21.430
D^+	30.644	33.779	25.816	23.834
D_s^0	22.287	25.670	18.006	18.191
$\Lambda_c$bar	19.851	25.439	18.952	11.079

charge verse & same

$Z \to c\bar{c}$ Effective Tagging Power **with error** of C Hadrons

Total Effective Tagging Power = (30.116 ± 0.022)%

% cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c
D^0	27.184 ±0.098	30.702 ±0.062	22.353 ±0.144	21.430 ±2.681
D^+	30.644 ±0.062	33.779 ±0.039	25.816 ±0.093	23.834 ±1.801
D_s^0	22.287 ±0.144	25.670 ±0.093	18.006 ±0.204	18.191 ±3.931
$\Lambda_c$bar	19.851 ±2.628	25.439 ±1.783	18.952 ±3.898	11.079 ±5.685

charge verse & same

$Z \to c\bar{c}$ Weighted Effective Tagging Power of C Hadrons

Total Effective Tagging Power = 28.214%

% cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c
D^0	1.192	3.800	0.370	0.0009
D^+	3.794	11.870	1.1925	0.002
D_s^0	0.367	1.187	0.110	0.0003
$\Lambda_c$bar	0.0008	0.003	0.0003	0.00005

charge verse

Total Effective Tagging Power = 30.116%

% cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c
D^0	1.265	4.085	0.384	0.001
D^+	4.074	12.817	1.262	0.003
D_s^0	0.382	1.257	0.114	0.0003
$\Lambda_c$bar	0.0009	0.003	0.0004	0.00006

charge verse & same

Conclusion

Main results:

- *For $Z \to b\bar{b}$ at Truth level:*
    - *Using only charge verse, effective tagging power = 0.127*
    - *Using also charge same, effective tagging power = **0.137***
- *For $Z \to c\bar{c}$ at Truth level:*
    - *Using only charge verse, effective tagging power = 0.282*
    - *Using also charge same, effective tagging power = **0.301***
- *For different B/C hadrons of $Z \to b\bar{b}$ & $Z \to c\bar{c}$:*
    - *Effective tagging power*
    - *High dependence of different hadron channels*

Next…

☞ *Jet Charge in typical channels (e.g. B_s, B_c, Λ_b, …)*

Thanks!

Back Up

$Z \to b\bar{b}$ Correlation Measurement of B hadrons of b jet and $\bar{b}$ jet

σ bbar jet → b jet ↓	B^0	B^+	B_s^0	B_c^+	$\Lambda_b$bar
B^0bar	12.475	11.195	4.459	0.612	0.069
B^-	11.216	11.930	3.359	0.670	1.456
B_s^0bar	1.424	2.830	0.749	-0.185	4.988
B_c^-	-0.658	-0.598	-0.181	0.200	0.537
Λ_b	0.848	0.829	3.774	0.537	5.644

$$\sigma = \frac{Residual}{Uncertainty}$$

$Z \to c\bar{c}$ **Correlation Measurement of C hadrons of c jet and $\bar{c}$ jet**

percent cbar jet → c jet ↓	D^0bar	D^-	D_s^0bar	Λ_c
D^0	4.898	13.006	4.039	-52.660
D^+	11.554	27.343	5.356	-98.559
D_s^0	2.389	6.724	1.483	-29.477
$\Lambda_c$bar	-50.636	-88.425	-28.634	8.590

$$\sigma = \frac{Residual}{Uncertainty}$$