ILD Analysis/Software Meeting

e^+e^- to Light Quarks

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Oct 5th, 2023

Introduction

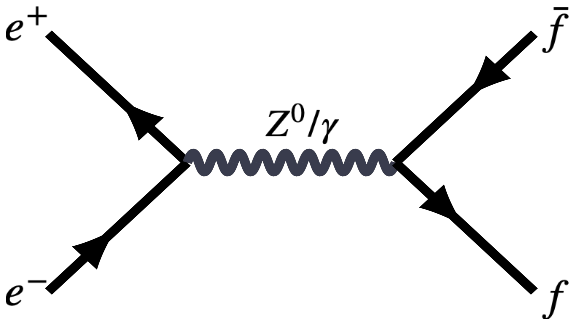
Di-fermion Production

- **Di-fermion production**
  - e^+e^- -> uu, dd, ss
  - CME 250 GeV.
  - eL pR
  - Int. Lumi. 4.2 ab^{-1}
- **Differential Cross Section**
  - Couplings can be extracted from helicity amplitudes included within the Differential Cross section

$$\frac{d\sigma}{d\cos\theta} = S(1+\cos^2\theta) + A\cos\theta$$

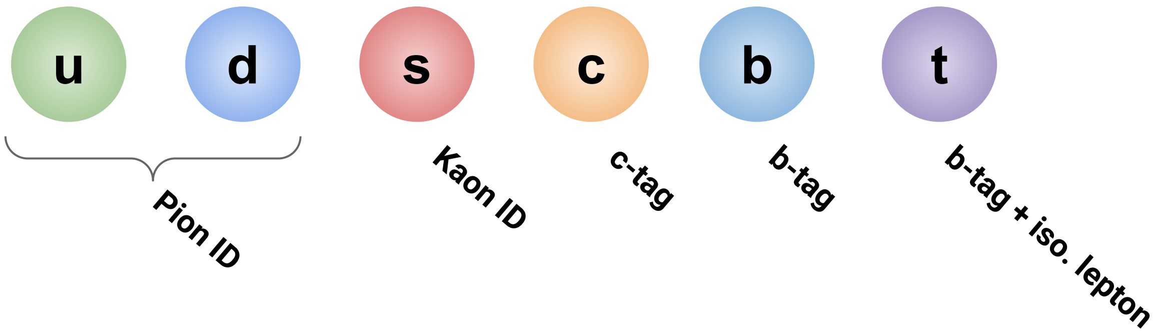
  - Extracted via forward-backward asymmetry. (AFB)

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



Energy	Process	Goal of measurements
91 GeV	$e^+e^- \to Z^0$	Z^0 physics and calibration
250 GeV	$e^+e^- \to Z^0H$	Higgs couplings
	$e^+e^- \to f\bar{f}$	Z^0/γ couplings
350 GeV	$e^+e^- \to t\bar{t}$	top mass precision
	$e^+e^- \to \nu\bar{\nu}H$	Higgs couplings
500 GeV	$e^+e^- \to t\bar{t}$	top couplings
	$e^+e^- \to t\bar{t}H$	Higgs-top coupling
	$e^+e^- \to Z^0HH$	Higgs self coupling
1000 GeV	$e^+e^- \to \nu\bar{\nu}HH$	Higgs self coupling

Towards Light Quarks



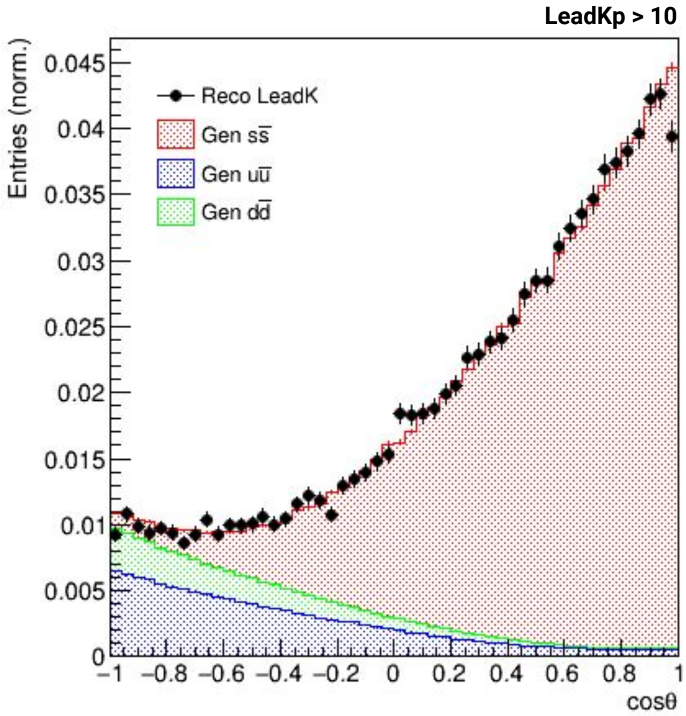
Light Quark Pair Reconstruction

- u, d are inseparable
- Both need to be separated from s-quark pair production process from the mixed sample.
- Pion ID can be used to extract combined parameters of AFB.
- One can check its consistency with the SM by seeking their combined EW coupling.
- Based on this uu/dd precise measurements, the distribution can be subtracted from uds mixture.

$$\frac{d\sigma}{d\cos\theta} = (S_u + S_d)(1 + \cos^2\theta) + (A_u + A_d)\cos\theta$$

Towards Light Quarks

- Polar angle distribution of generated ss, uu, dd production is shown.
- dd distribution is 'flipped'. This is because we discovered that majority of dd events contain hadronization via $d \to K^* \to K^+\pi^-$
- The kaon ID method used here still relies on MC generated information to consolidate the analysis by searching maximal efficiency and precision achieved.



Towards Light Quarks

- Polar angle distribution of generated ss, uu, dd production is shown.
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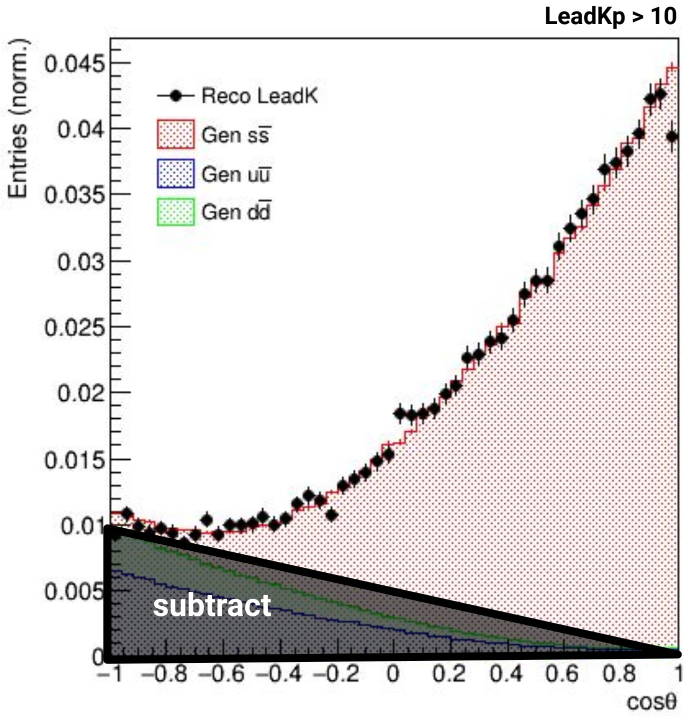
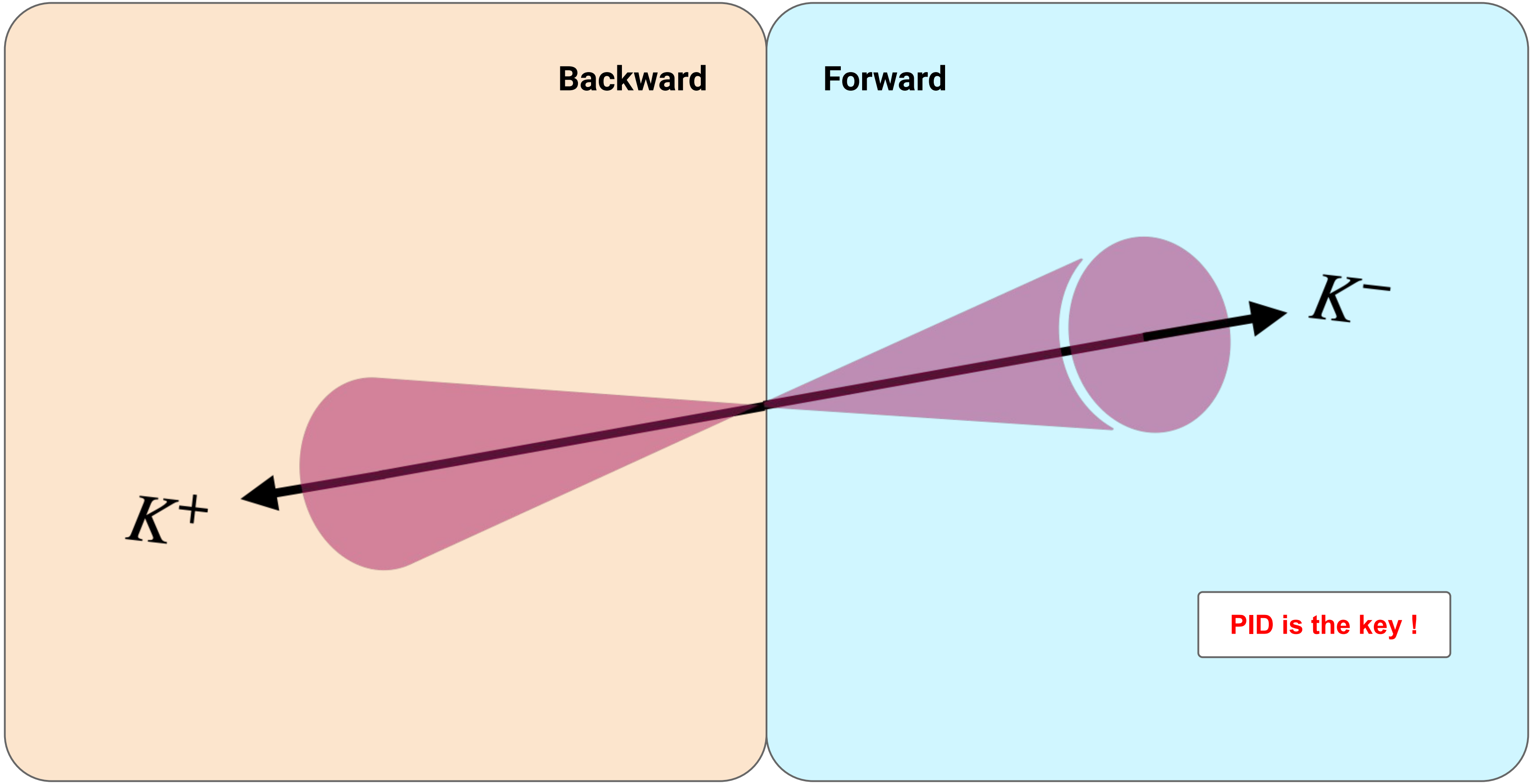


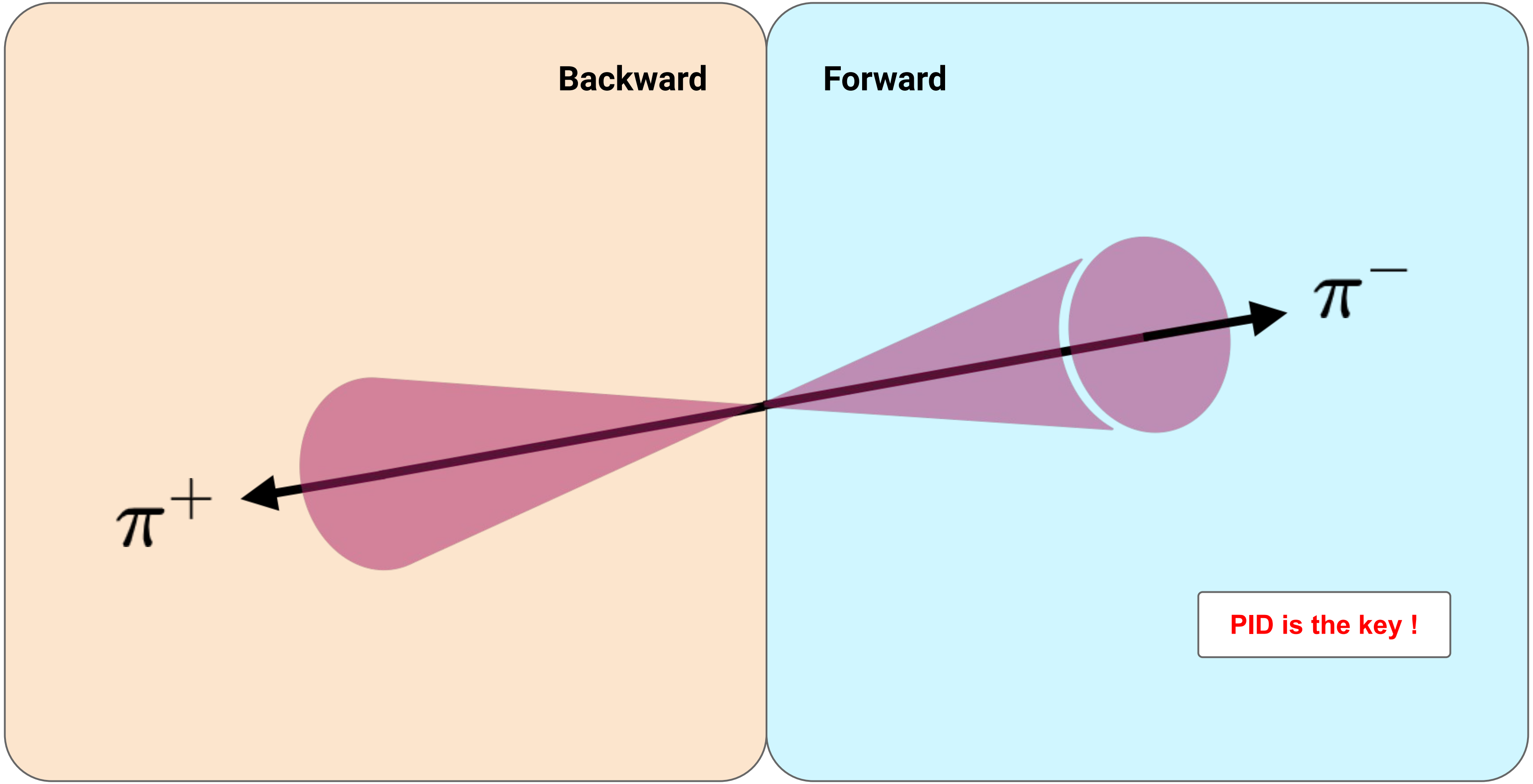
Event Structure

Event Structure



PID is the key !

Event Structure



Progress since the ILD meeting on June

What has been done and what needs to be done?

Efficiency

- Quantitative analysis on the efficiency studies.
- Consistency throughout the entire polar angle, in order to avoid bias on final AFB measurements.
- The efficiency correction to retrieve the original number of entries. (explained in coming slides)

Background studies

- Dedicated background analysis was conducted for the following processes.
  - Radiative return
  - Full hadronic WW
  - Full hadronic ZZ
  - qqH
- All processes are the major concern of backgrounds towards e+e- -> qqbar analysis.
- Preselections were applied to reject such backgrounds.

Backgrounds

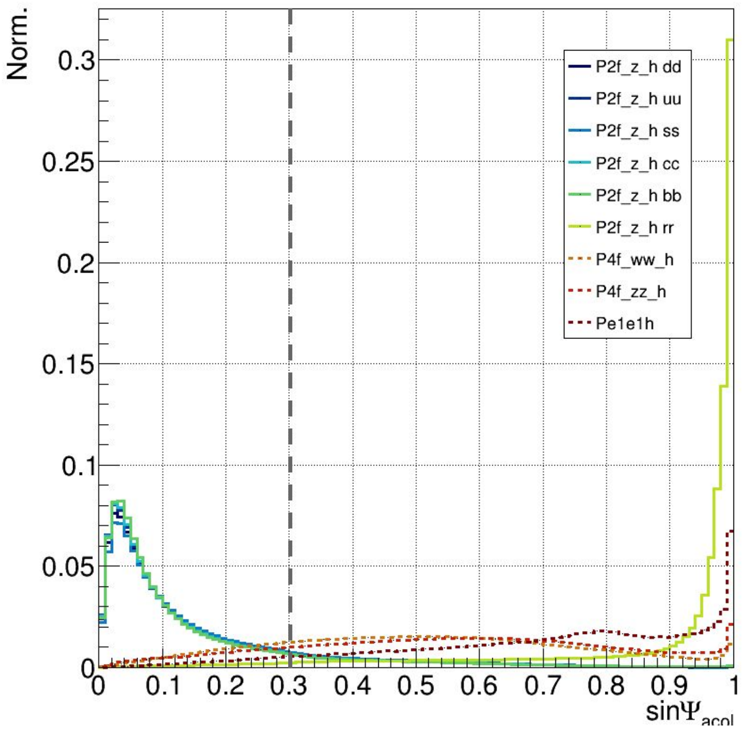
Background Analysis

- **Background processes**
  - Radiative Return (2f)
  - WW hadronic (4f)
  - ZZ hadronic (4f)
  - Higgs (e1e2H)
- **Preselections**
  - Cut 1: Photon veto (photon jet)
    - $E < 115$ GeV
    - $|\cos\theta| < 0.97$
  - Cut 2: Acolinearity
    - $\sin\Psi_{acol} < 0.3$
  - Cut 3: Invariant mass
    - $M_{jj} > 140$ GeV
  - Cut 4: Jet y23
    - $y_{23} < 0.02$
  - (Cut5: LPFO acol)
    - $\cos\theta_{L1,L2} > 0.97$

- **Signal definition**
  - QQbar Acolinearity
    - $\sin\Psi_{acol} < 0.3$
  - Invariant mass
    - $M_{qq} > 140$ GeV

Background

sinΨ

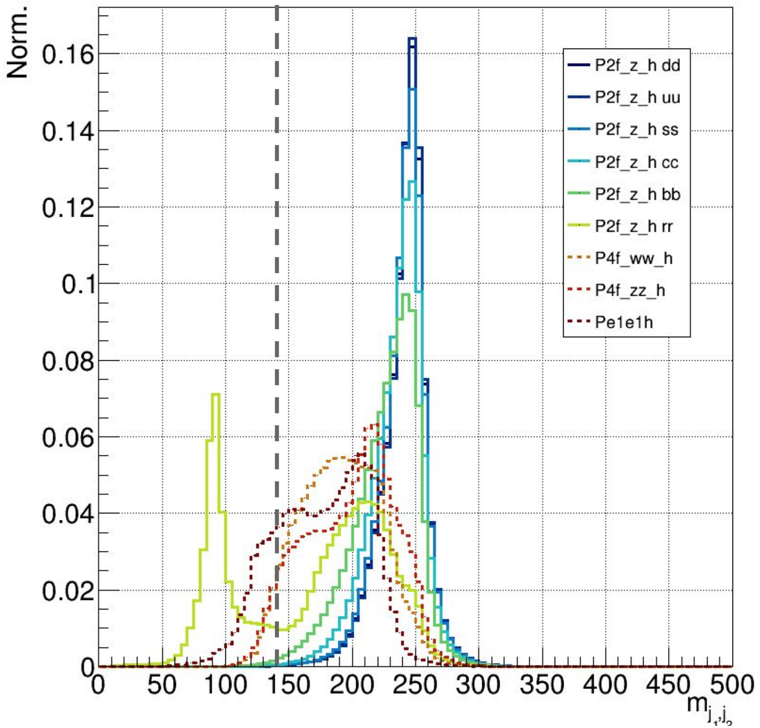


After cut 1

- Cut 1: Photon veto (photon jet)
  - E < 115 GeV
  - |cosθ| < 0.97

Background

Invariant Mass

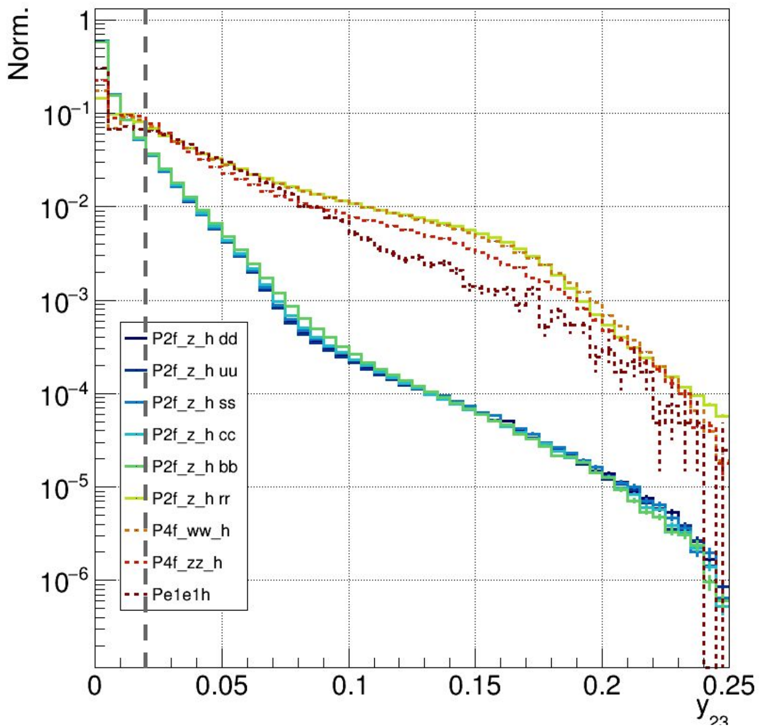


After cut 1 & cut 2

- Cut 1: Photon veto (photon jet)
  - E < 115 GeV
  - |cosθ| < 0.97
- Cut 2: Acolinearity
  - sinΨacol < 0.3

Background

Invariant Mass



After cut 1 & cut 2 & cut 3

- Cut 1: Photon veto (photon jet)
  - E < 115 GeV
  - |cosθ| < 0.97
- Cut 2: Acolinearity
  - sinΨacol < 0.3
- Cut 3: Invariant mass
  - Mjj > 140 GeV

Preselection Efficiency?

eLpR									
process	P2f_z_h	P2f_z_h	P2f_z_h	P2f_z_h	P2f_z_h	P2f_z_h	P4f_ww_h	P4f_zz_h	Pe1e1h
qqbar	dd	uu	ss	cc	bb	rr	bg	bg	bg
cut1	92.74%	93.13%	92.32%	93.34%	93.30%	54.90%	89.62%	91.13%	74.95%
cut2	78.06%	78.92%	77.22%	79.41%	79.94%	1.97%	18.63%	15.97%	5.72%
cut3	78.00%	78.86%	77.16%	79.30%	79.55%	1.29%	17.65%	14.98%	4.56%
cut4	68.98%	69.75%	68.19%	69.74%	69.48%	0.51%	7.43%	7.47%	2.31%
cut5	59.00%	59.96%	58.08%	60.22%	59.89%	0.23%	3.98%	2.88%	1.00%

eRpL									
process	P2f_z_h	P2f_z_h	P2f_z_h	P2f_z_h	P2f_z_h	P2f_z_h	P4f_ww_h	P4f_zz_h	Pe1e1h
qqbar	dd	uu	ss	cc	bb	rr	bg	bg	bg
cut1	92.66%	93.19%	92.26%	93.40%	93.22%	52.58%	94.03%	89.46%	74.97%
cut2	77.97%	79.01%	77.11%	79.49%	79.84%	1.85%	14.90%	16.64%	5.74%
cut3	77.91%	78.95%	77.05%	79.39%	79.44%	1.19%	13.22%	15.68%	4.58%
cut4	68.89%	69.84%	68.06%	69.82%	69.38%	0.46%	3.33%	8.11%	2.33%
cut5	58.88%	60.07%	57.96%	60.35%	59.76%	0.22%	1.65%	3.26%	1.02%

Particle Identification

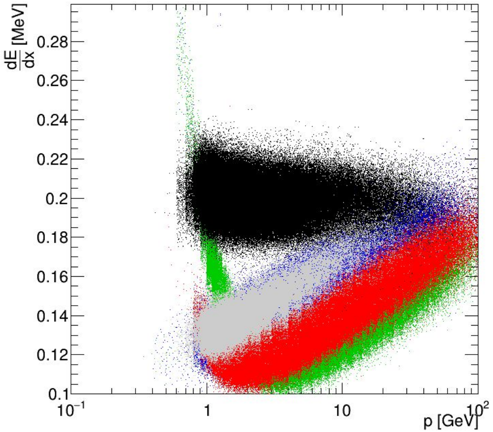
PID with dE/dx

dE/dx Particle Identification

- TPC provides information on average dE/dx values for each track.
- Bethe-Bloch formula tells each particle type has unique dE/dx vs p function.

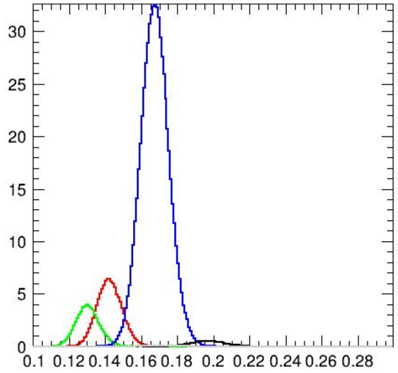
Leading PFO

- uu & dd hadronize into pions or kaons.
- Those hadrons will possess high momentum among jet constituents
- The PFO with the highest momentum in a jet is called the Leading PFO (LPFO)



dE/dx vs. p
Each color represent different types of particles.

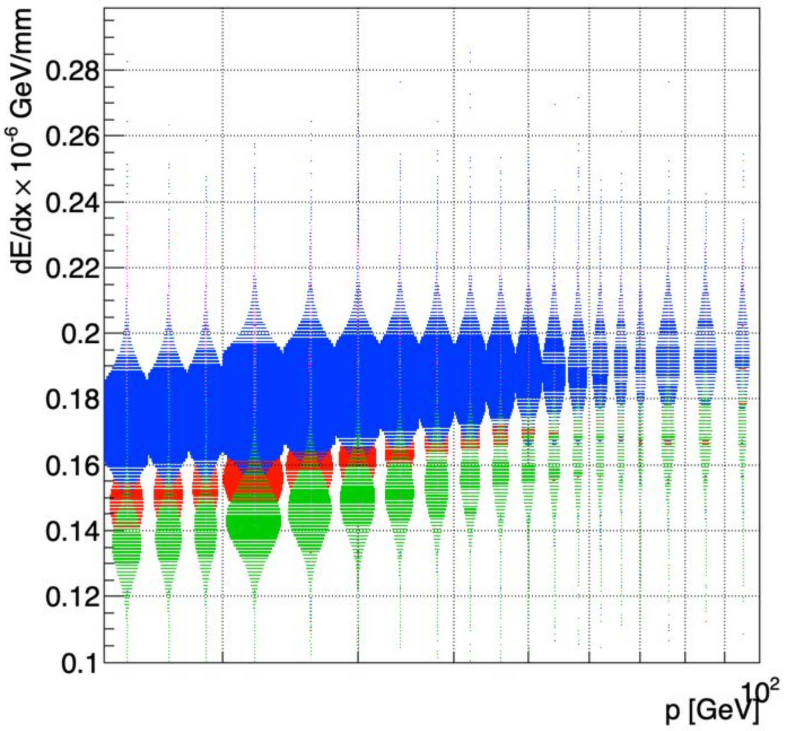
Red:	Kaon
Blue:	Pion
Green:	Proton
Gray:	Muon
Black:	Electron



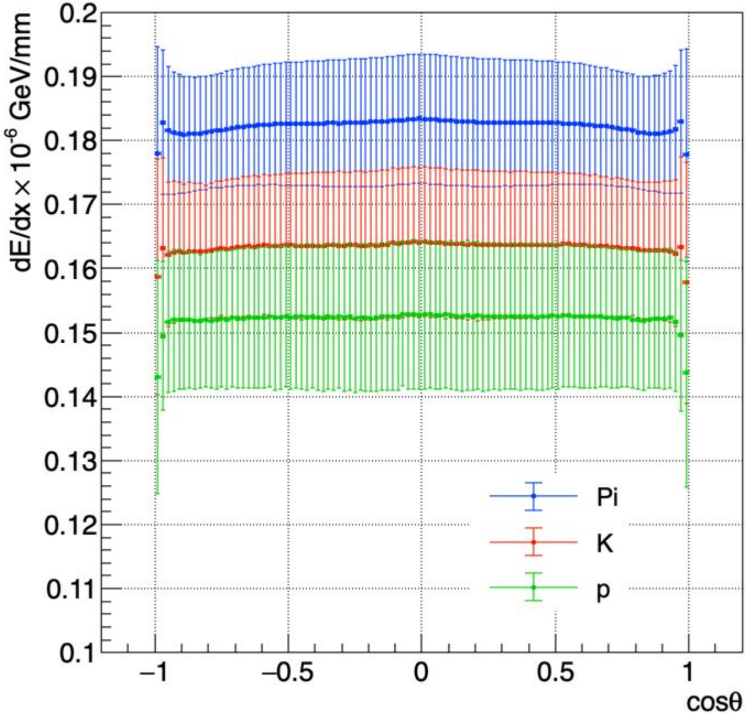
p = 10.0 - 11.5 GeV

dE/dx projection of above plot for momentum between 10 - 11.5 GeV.

dE/dx vs p



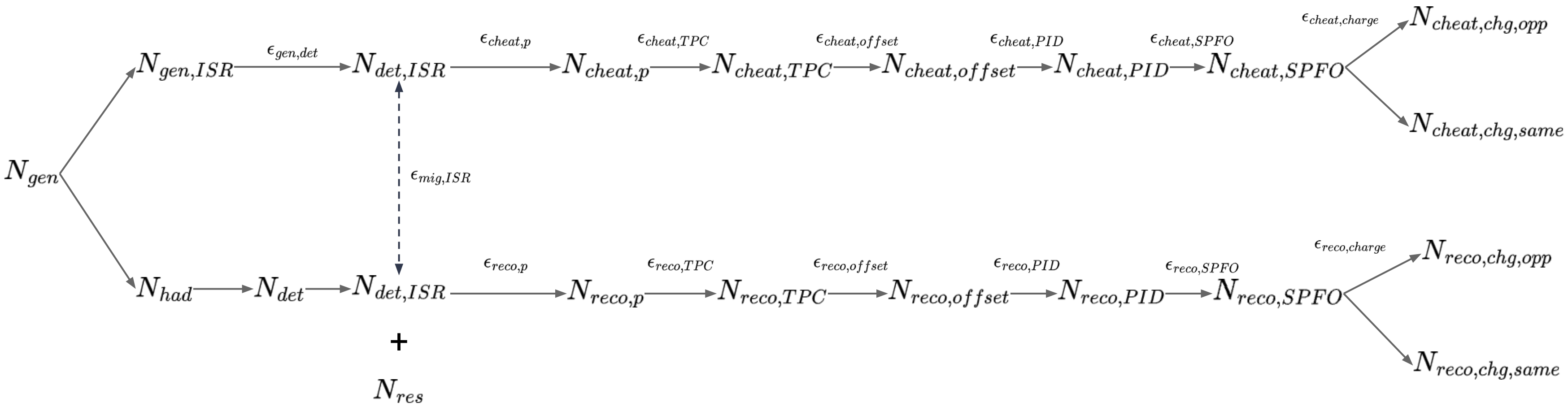
dE/dx × 10^-6 GeV/mm
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
p [GeV]
10^2



dE/dx × 10^-6 GeV/mm
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
−1
−0.5
0
0.5
1
cosθ
Pi
K
p

Efficiency

Efficiency



cuts [i] = {p, TPC, offset, PID, SPFO, charge}

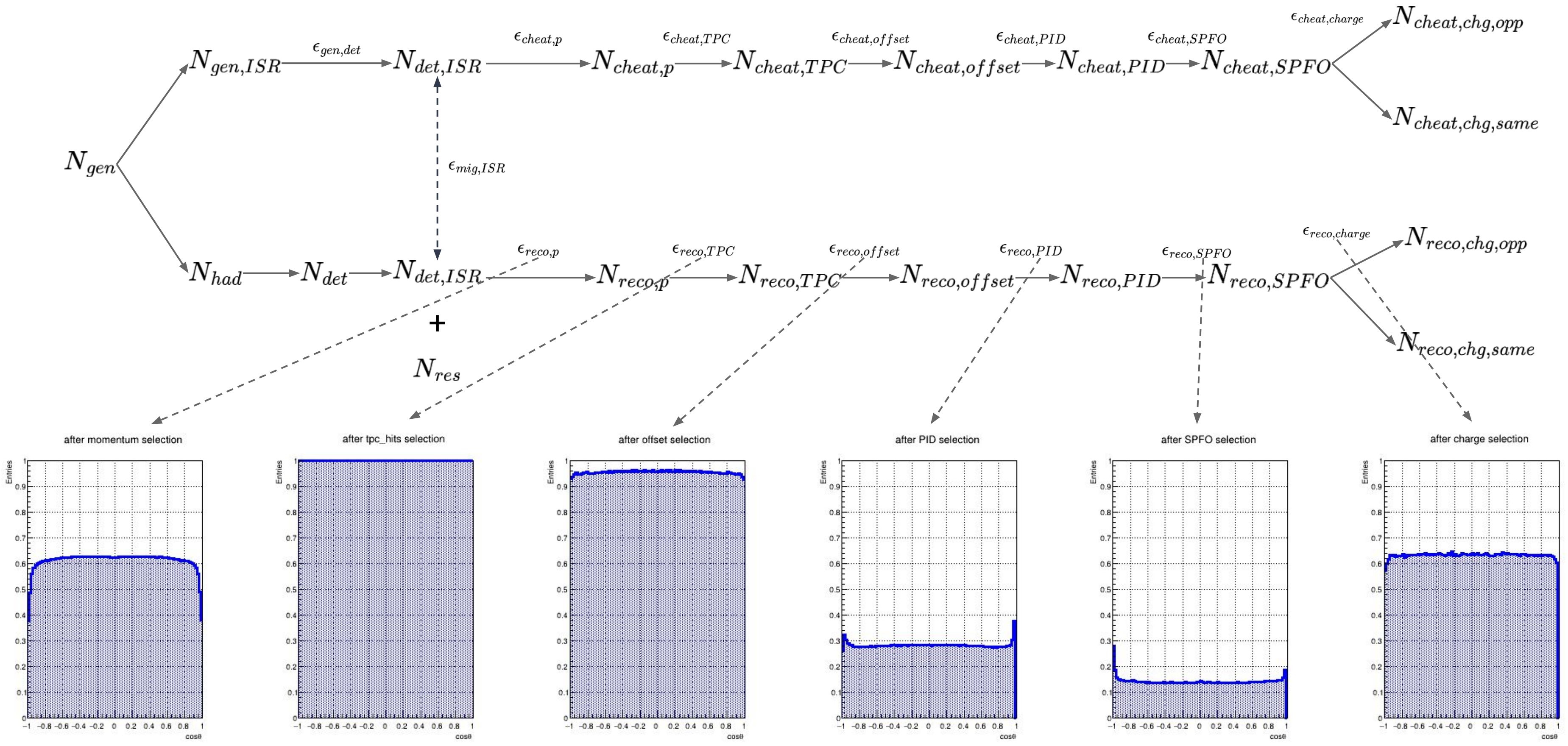
$$\epsilon_i = \frac{N_{i+1}}{N_i}$$

$$N_i = N_{det,ISR} \cdot \prod_0^i \epsilon_i$$

Double Tagging Criteria

- Momentum
  - p > 15 GeV
- TPC hits
  - no cut at the moment
- Offset
  - 1.0 mm
- PID
  - dEdx value cut
- SPFO
  - Veto event when there is a close competitor of LPFO with opposite charge

Efficiency

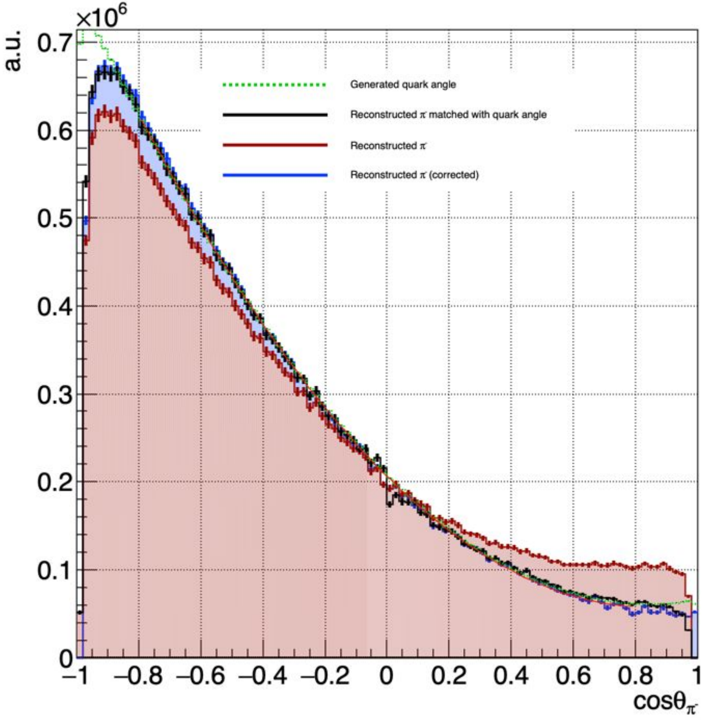


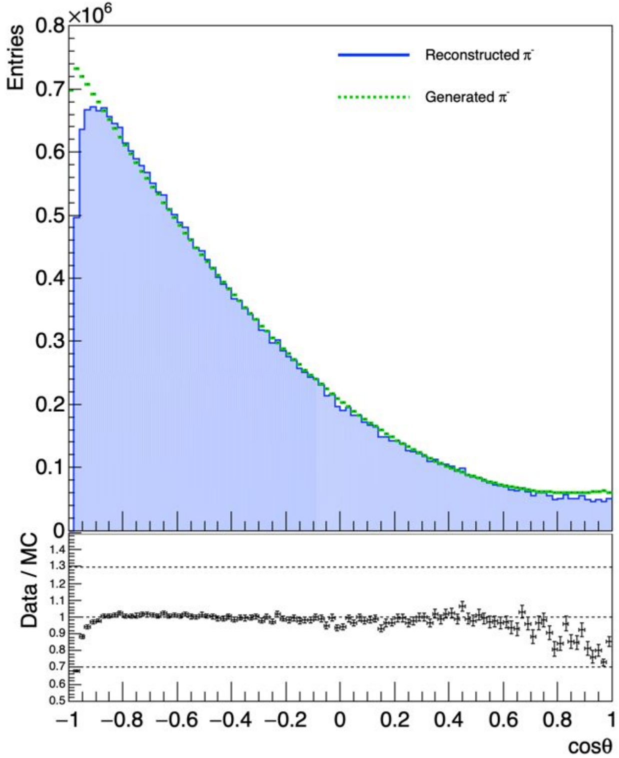
N_{gen}
$N_{gen,ISR}$
$\epsilon_{gen,det}$
$N_{det,ISR}$
$\epsilon_{cheat,p}$
$N_{cheat,p}$
$\epsilon_{cheat,TPC}$
$N_{cheat,TPC}$
$\epsilon_{cheat,offset}$
$N_{cheat,offset}$
$\epsilon_{cheat,PID}$
$N_{cheat,PID}$
$\epsilon_{cheat,SPFO}$
$N_{cheat,SPFO}$
$\epsilon_{cheat,charge}$
$N_{cheat,chg,opp}$
$N_{cheat,chg,same}$
$\epsilon_{mig,ISR}$
N_{had}
N_{det}
$N_{det,ISR}$
$\epsilon_{reco,p}$
$N_{reco,p}$
$\epsilon_{reco,TPC}$
$N_{reco,TPC}$
$\epsilon_{reco,offset}$
$N_{reco,offset}$
$\epsilon_{reco,PID}$
$N_{reco,PID}$
$\epsilon_{reco,SPFO}$
$N_{reco,SPFO}$
$\epsilon_{reco,charge}$
$N_{reco,chg,opp}$
$N_{reco,chg,same}$
+
N_{res}
after momentum selection
after tpc_hits selection
after offset selection
after PID selection
after SPFO selection
after charge selection
Entries
cosθ

Polar Angle Results

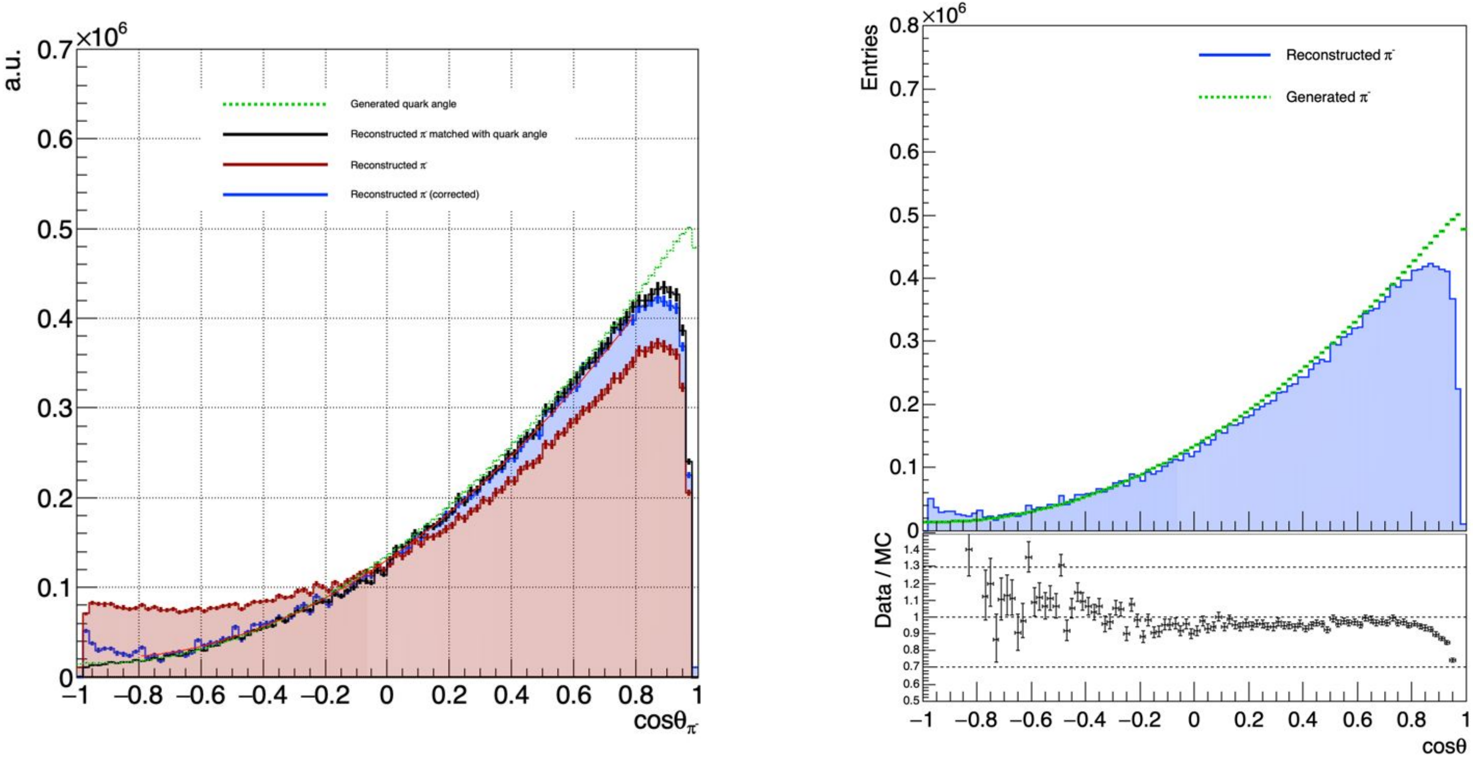
eLpR

Polar Angle (uu)



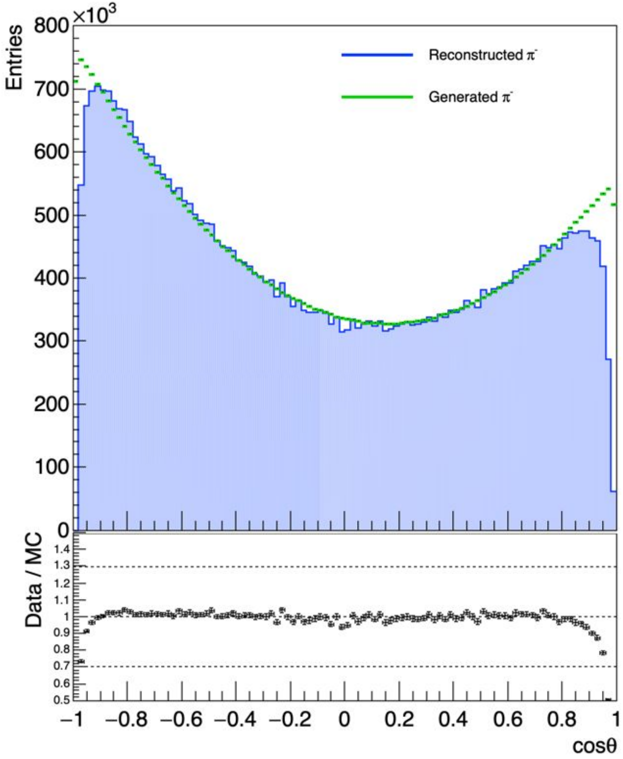


Polar Angle (dd)



Polar Angle (uu)

- **ud mixing**
  - Both Gen and Reco polar angle from uu and dd were added.
  - Generated dd is scaled to 0.9 upon addition
    - this to due to difference in selection efficiency between uu and dd?
  - Fit between |cosθ| < 0.9 is performed



Fit Results

uu process

	S	σS	A	σA
Gen	2.924e5	5.05e1	-4.910e5	1.19e2
Reco	2.061e5	3.80e2	-3.513e5	9.28e2

	AFB	Chi2 / ndf
Gen	-0.62957	112.622 / 88
Reco	-0.63553	132.781 / 88

dd process

	S	σS	A	σA
Gen	2.015e5	4.19e1	3.794e5	9.45e1
Reco	1.304e5	3.64e2	2.364e5	8.96e2

	AFB	Chi2 / ndf
Gen	0.705765	146.276 / 88
Reco	0.681675	191.634 / 88

ud process

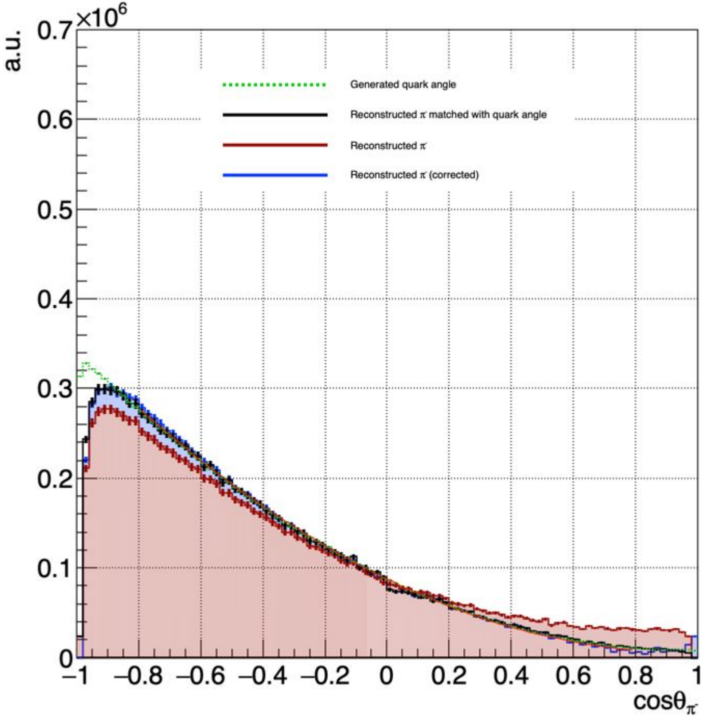
	S	σS	A	σA
Gen	3.359e5	4.47e1	-1.060e5	1.16e2
Reco	3.364e5	5.27e2	-1.143e5	1.40e3

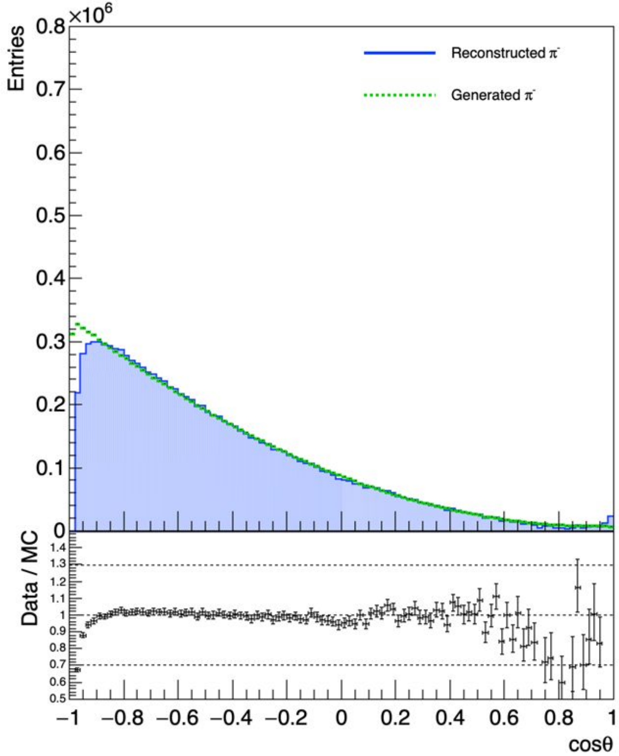
	AFB	Chi2 / ndf
Gen	-0.118425	114.438 / 88
Reco	-0.127492	160.860 / 88

chi2 / ndf = 1.83

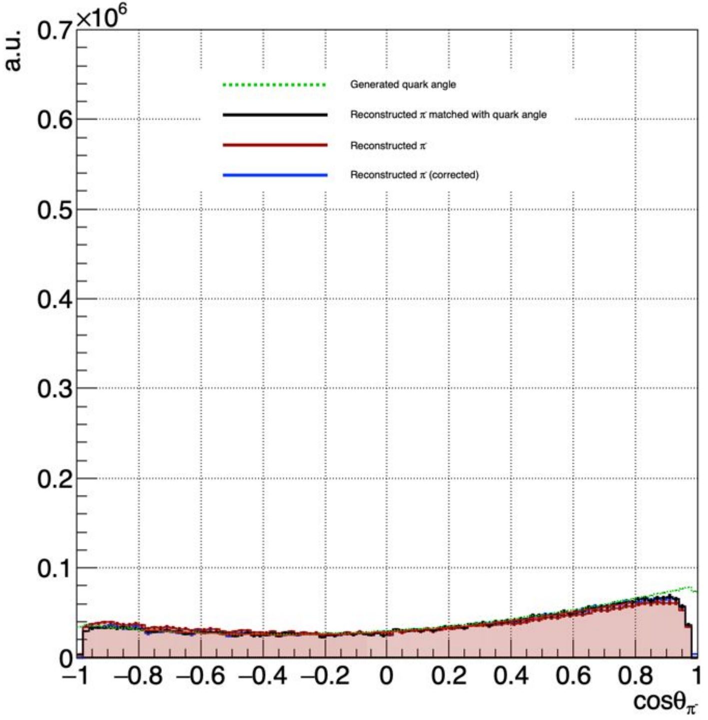
eRpL

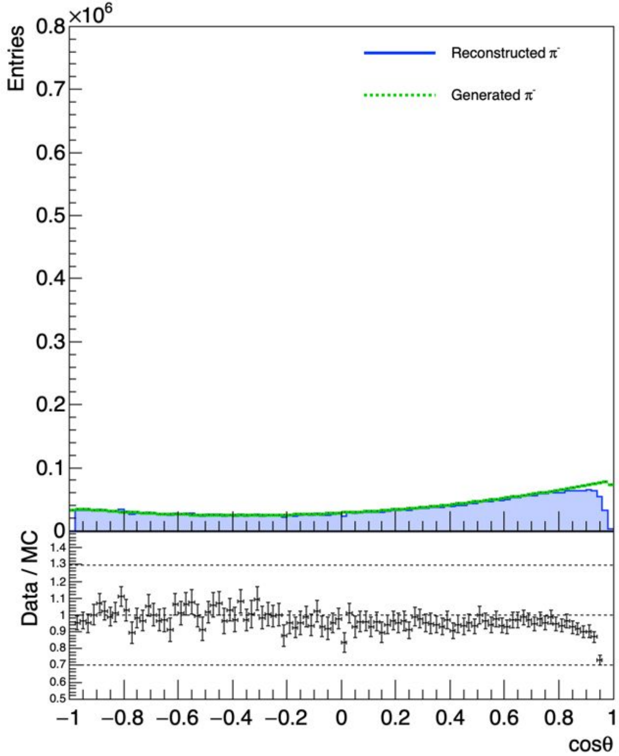
Polar Angle (uu)



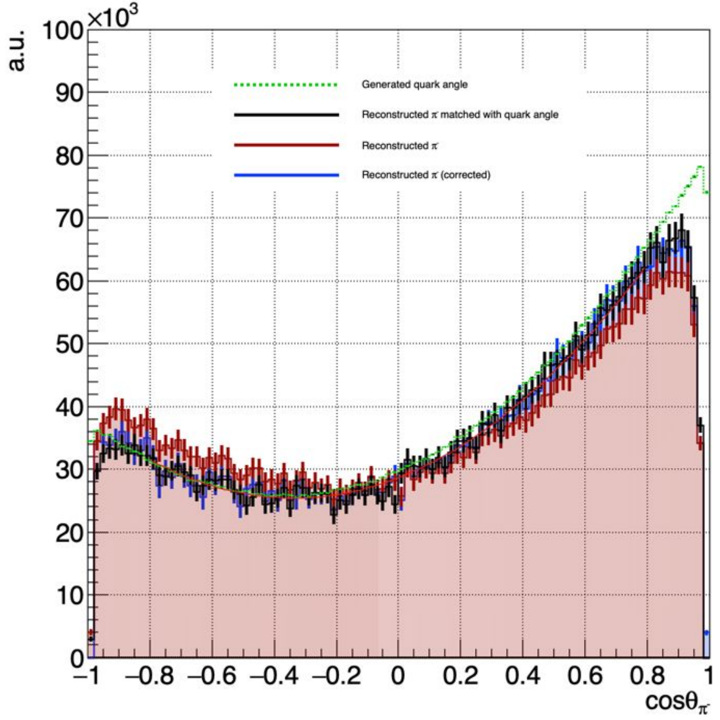


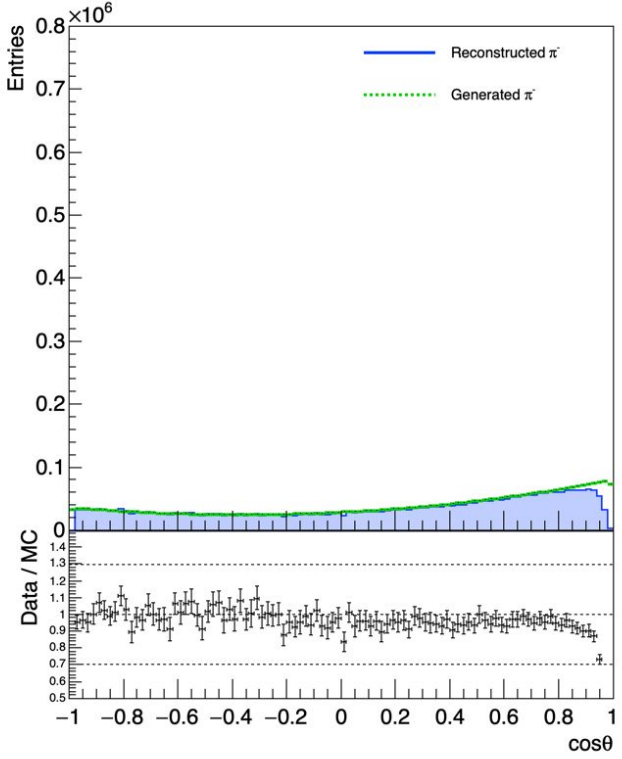
Polar Angle (dd)





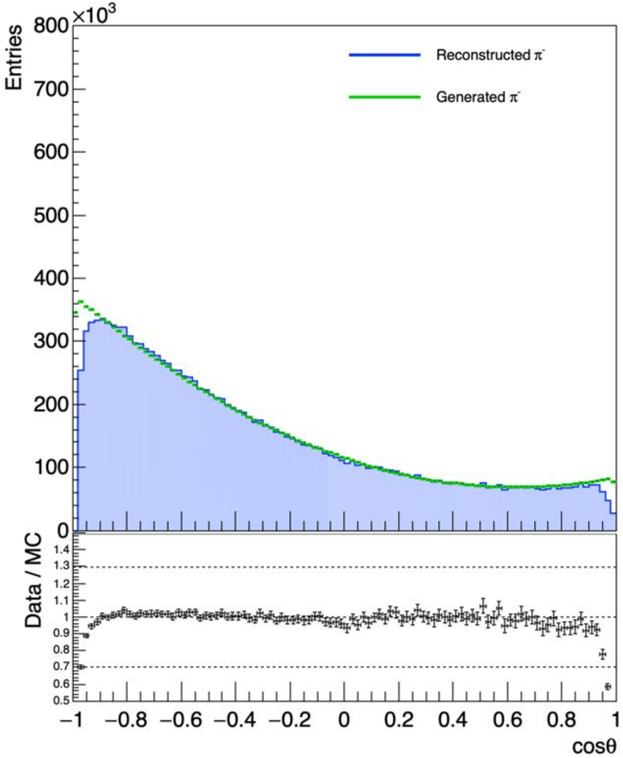
Polar Angle (dd)





Polar Angle (ud)

- **ud mixing**
  - Same mixing as eLpR



Fit Results

uu process

	S	σS	A	σA
Gen	8.753e4	2.52e1	-1.663e5	6.01e1
Reco	8.738e4	2.69e2	-1.685e5	6.84e2

	AFB	**Chi2 / ndf**
Gen	-0.712651	109.124 / 78
Reco	-0.723176	96.5223 / 78

dd process

	S	σS	A	σA
Gen	2.968e4	1.43e1	2.154e4	3.92e1
Reco	2.868e4	1.81e2	1.941e4	5.01e2

	AFB	**Chi2 / ndf**
Gen	0.272170	75.6468 / 78
Reco	0.253806	41.9851 / 78

ud process

	S	σS	A	σA
Gen	1.158e5	2.64e1	-1.461e5	6.57e1
Reco	1.159e5	3.00e2	-1.493e5	7.71e2

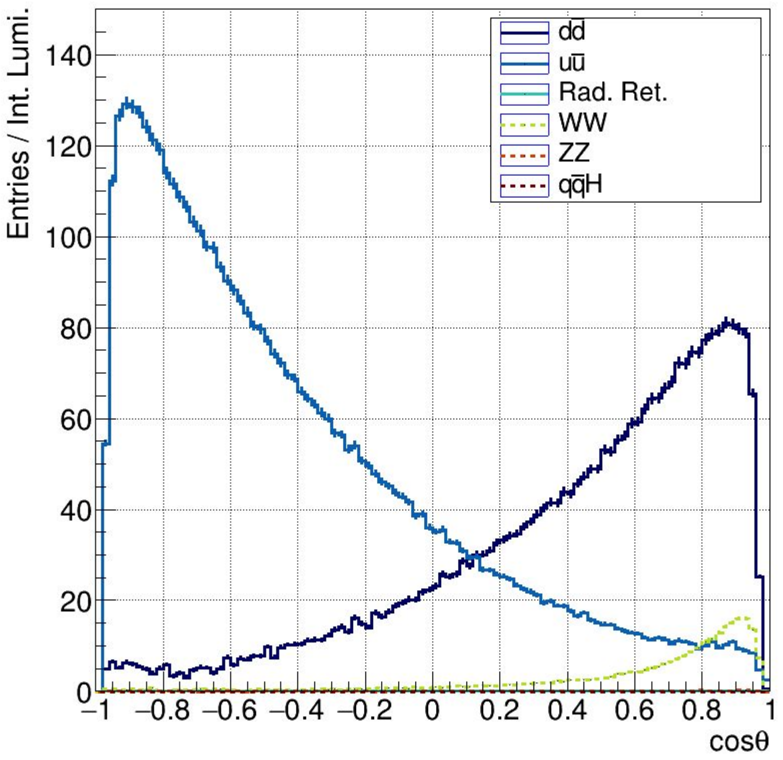
	AFB	**Chi2 / ndf**
Gen	-0.472885	127.343 / 88
Reco	-0.482792	65.6328 / 88

chi2 / ndf = 0.75

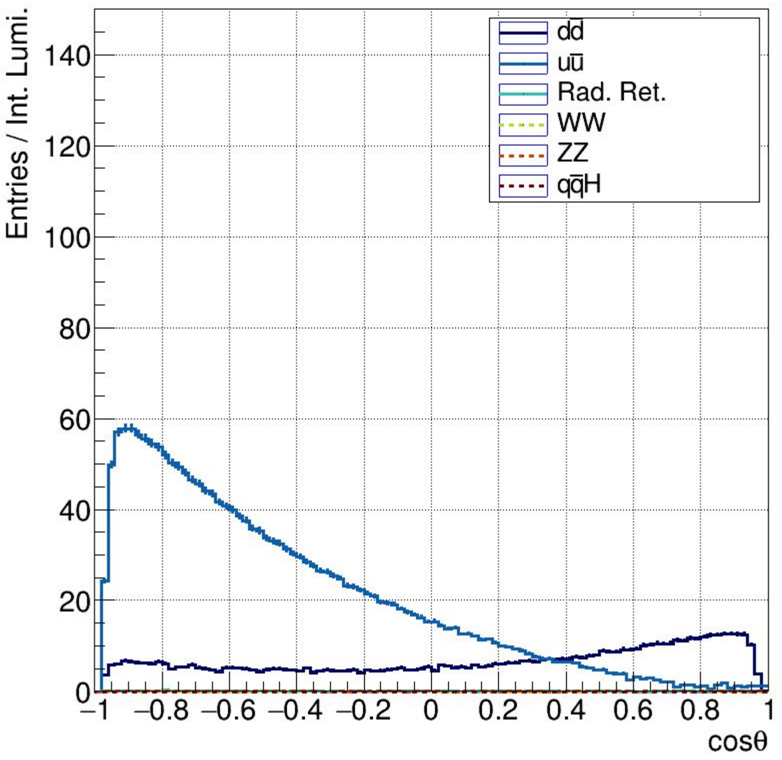
Background

Background

eLpR

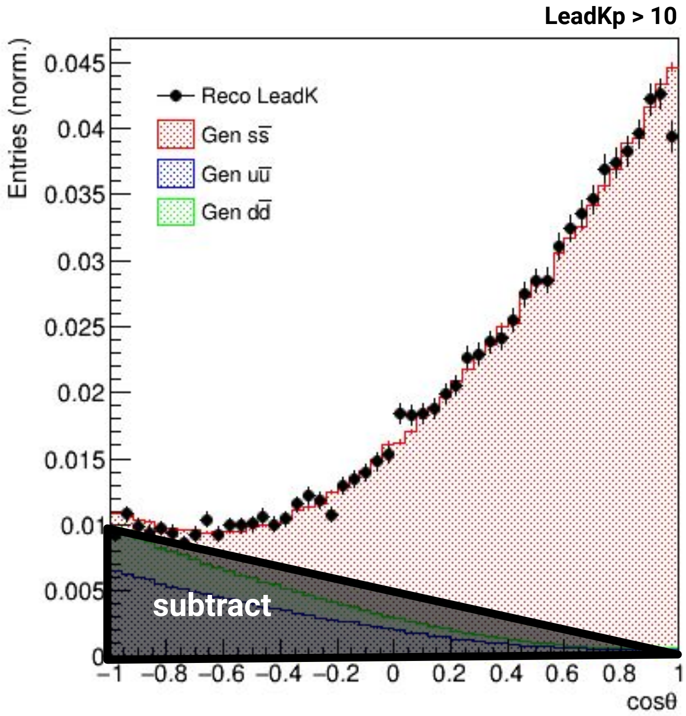


eRpL



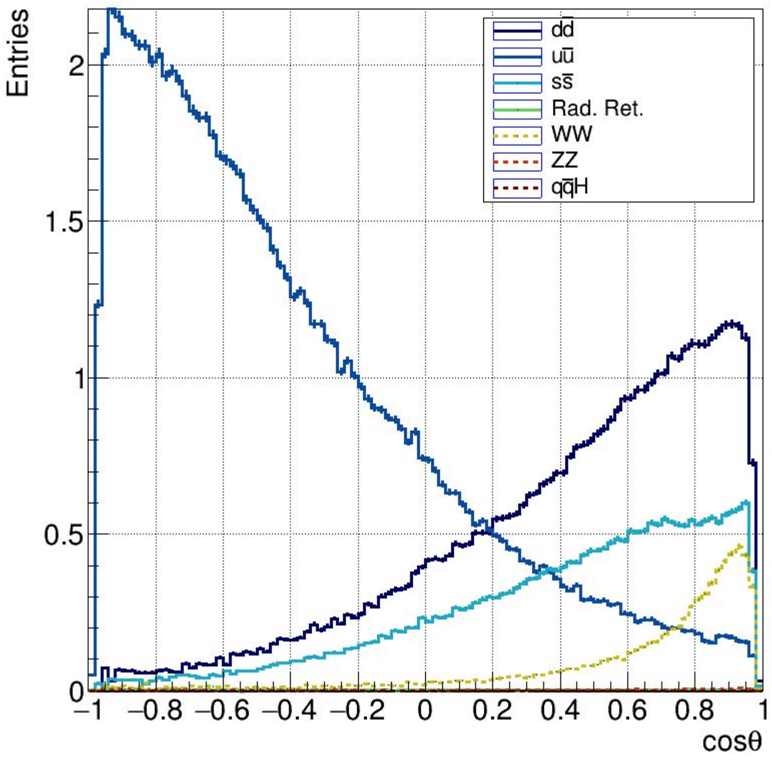
ssbar mixing

- The original motivation was to eliminate the contribution from the uu and dd effect by selecting the events with leading pions.
- After the selection, one can subtract the events upon ss analysis, by requiring the leading PFO not to be identified as pion.
- This assumes that the ss can well be isolated from uu and dd.

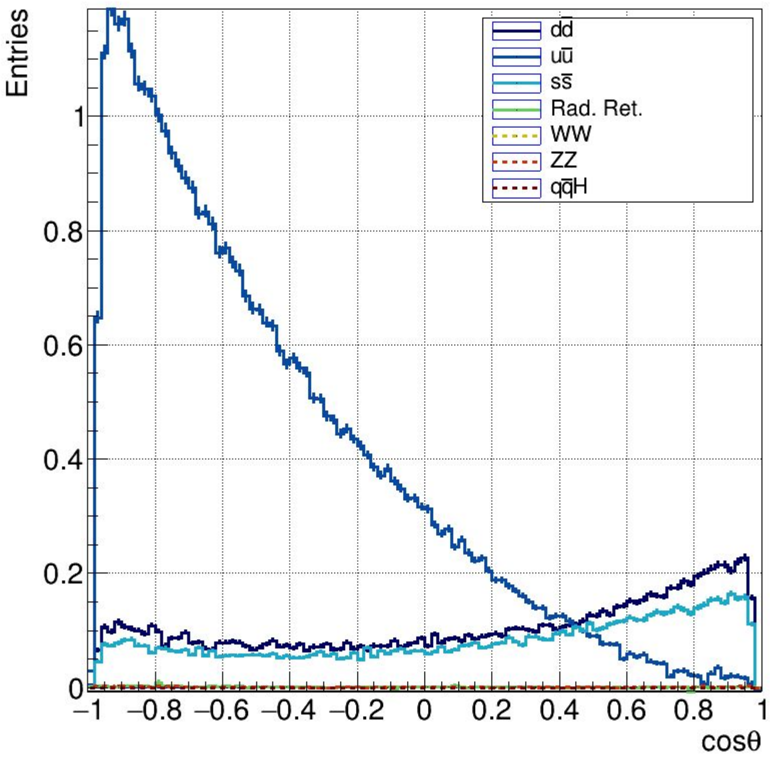


Background

eLpR



eRpL



* Efficiency correction was removed for these plots for technical reasons.

Background

Table 6.6: Summary of the selected event sample for 5 tagging modes in data and simulation.

Mode	Data Events	MC prediction
K^+K^-	1290	1312.2
$K^+\Lambda^0, K^-\bar{\Lambda}^0$	219	213.5
$\Lambda^0\bar{\Lambda}^0$	17	13.7
$K^\pm K^0_s$	1580	1617.3
$\Lambda^0 K^0_s, \bar{\Lambda}^0 K^0_s$	193	194.1
Total:	3299	3350.8

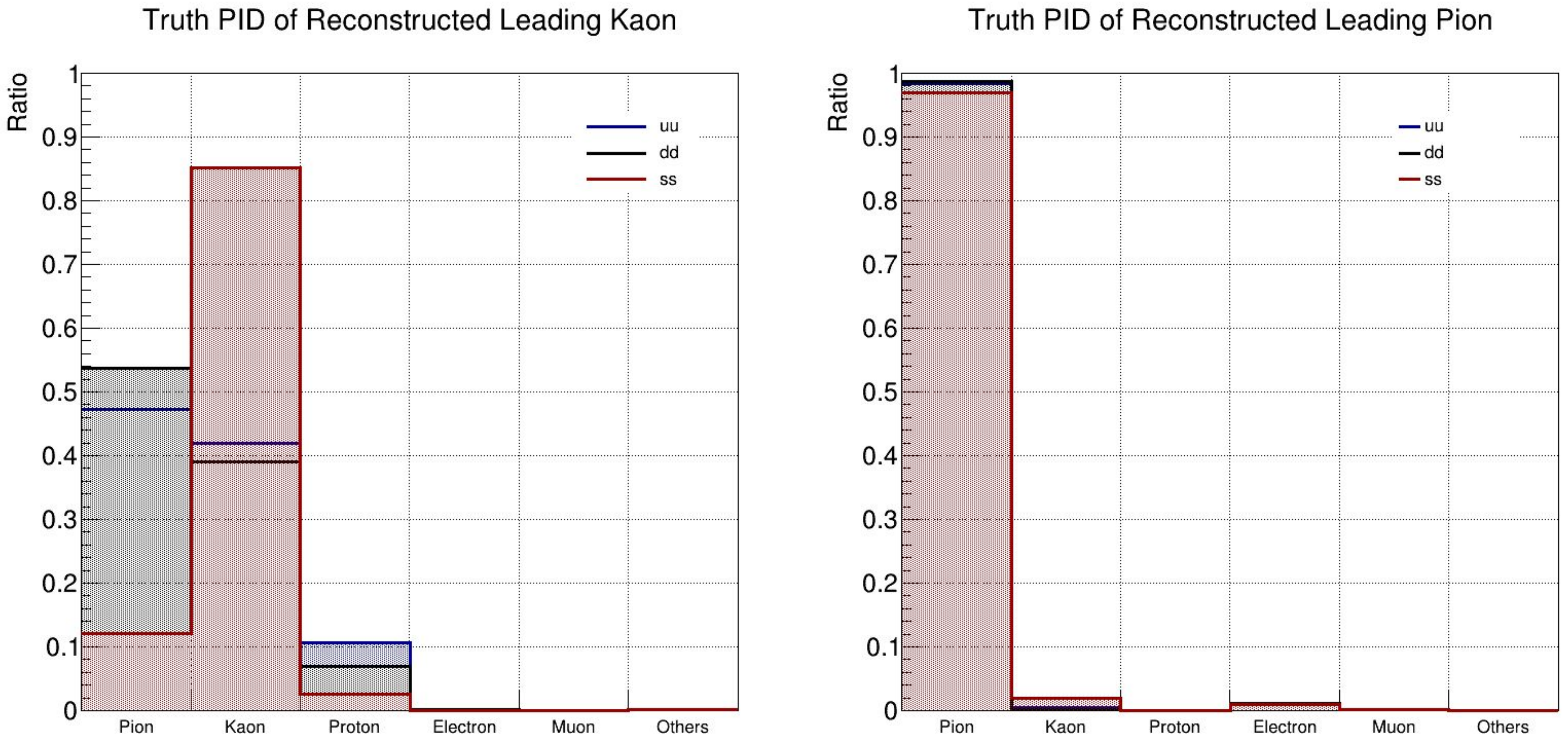
(SLAC-Report, 1999)

- There are limited number of modes where ss process can produce hard pions.
- SLAC report suggests that there are possible contributions from Λ0 or K0-short which can further disintegrate into Pion
- Although the Λ are suppressed using the offset cut, the final polar angle distribution clearly shows the substantial amount of contribution from ss.
- Possible solution could be veto the secondary LPFO not to be identified as Kaons.

Backup

Particle Identification

K/Pi ID purity



Leading PFO

LPFO Selection

Charge Check

Momentum Check

TPC Hit Check

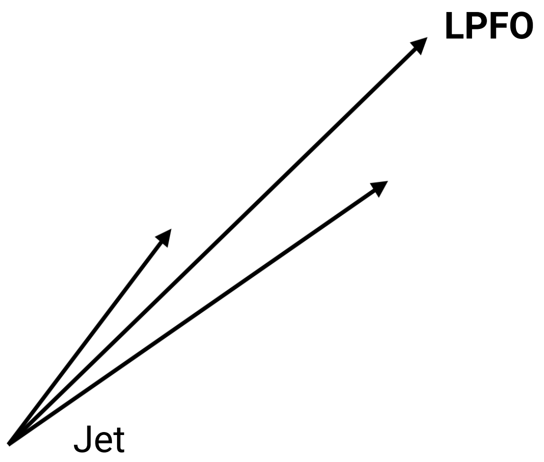
IP Check

dE/dx Minimum Check

SPFO Check

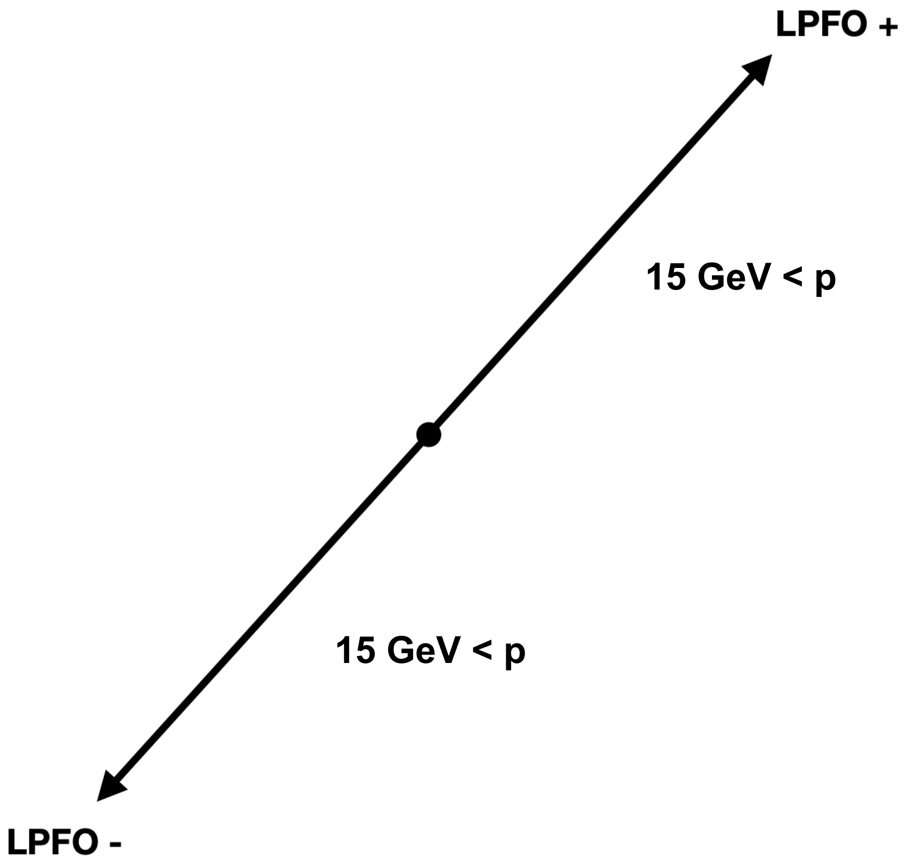
Leading PFO (LPFO)

- Particle with *highest* momentum within a Jet.
- QQbar typically disintegrate into a pair of energetic Kaons or Pions.
- We choose LPFO among **charged PFOs** inside a jet.



Charge & Momentum

- LPFO Selection
- **Charge Check**
- **Momentum Check**
- TPC Hit Check
- IP Check
- dE/dx Minimum Check
- SPFO Check



Impact Parameter

LPFO Selection

Charge Check

Momentum Check

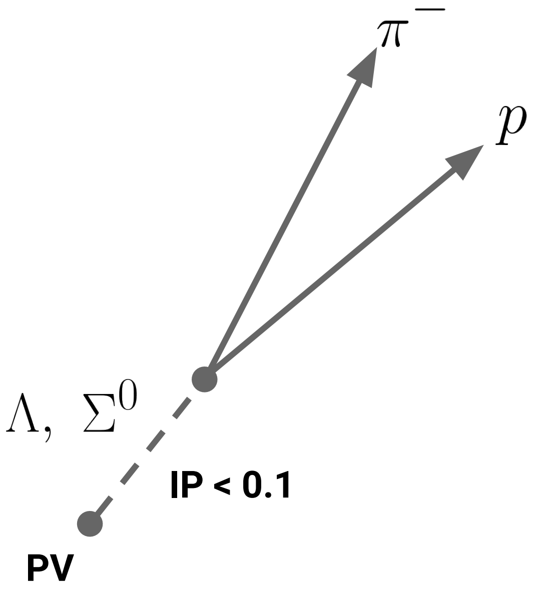
TPC Hit Check

IP Check

dE/dx Minimum Check

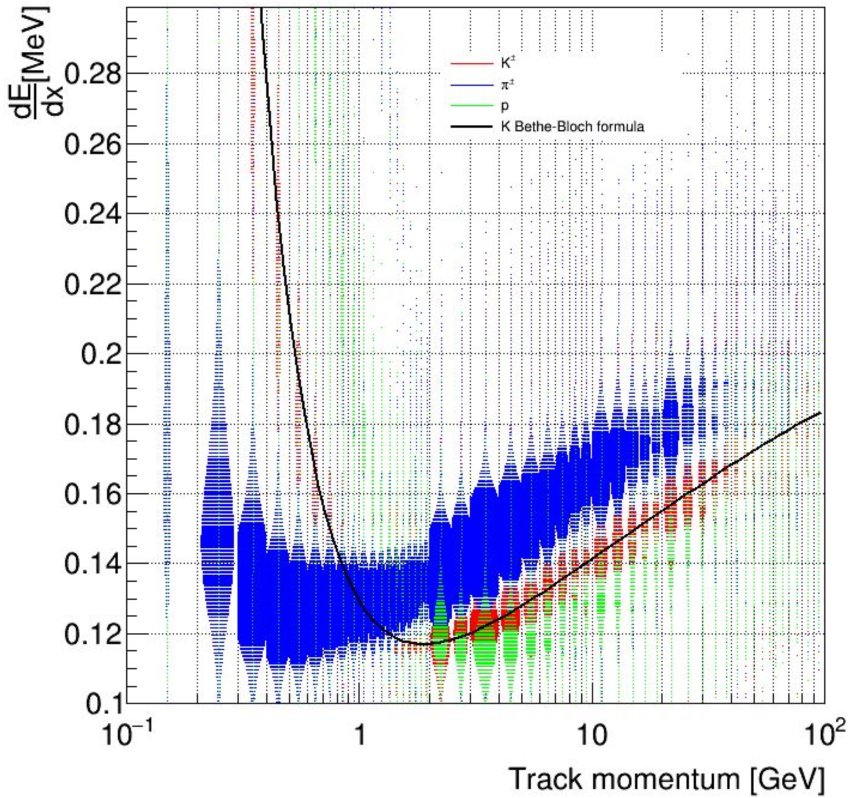
SPFO Check

Hyperon Suppression



dE/dx Minimum

- LPFO Selection
- Charge Check
- Momentum Check
- TPC Hit Check
- IP Check
- **dE/dx Minimum Check**
- SPFO Check



SPFO Check

LPFO Selection

Charge Check

Momentum Check

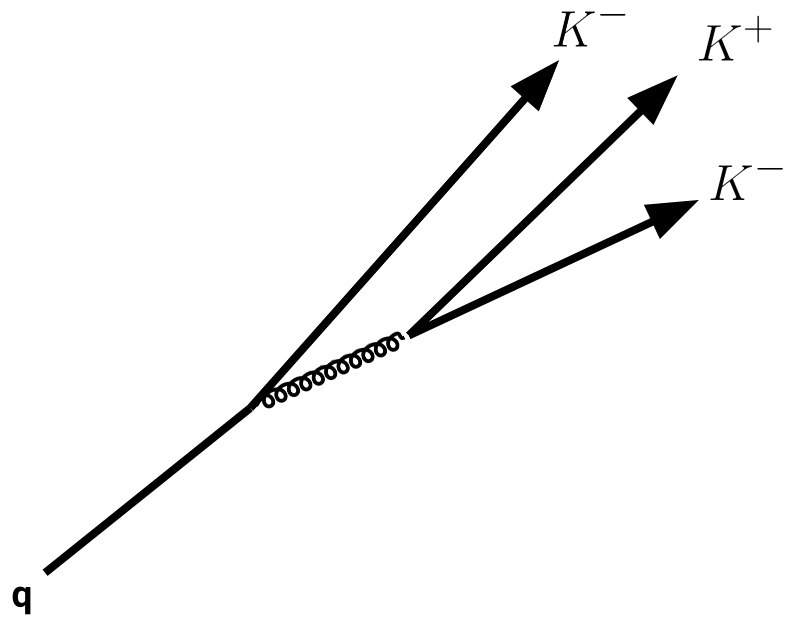
TPC Hit Check

IP Check

dE/dx Minimum Check

SPFO Check

Secondary PFO (SPFO) Check



SPFO Check

LPFO Selection

Charge Check

Momentum Check

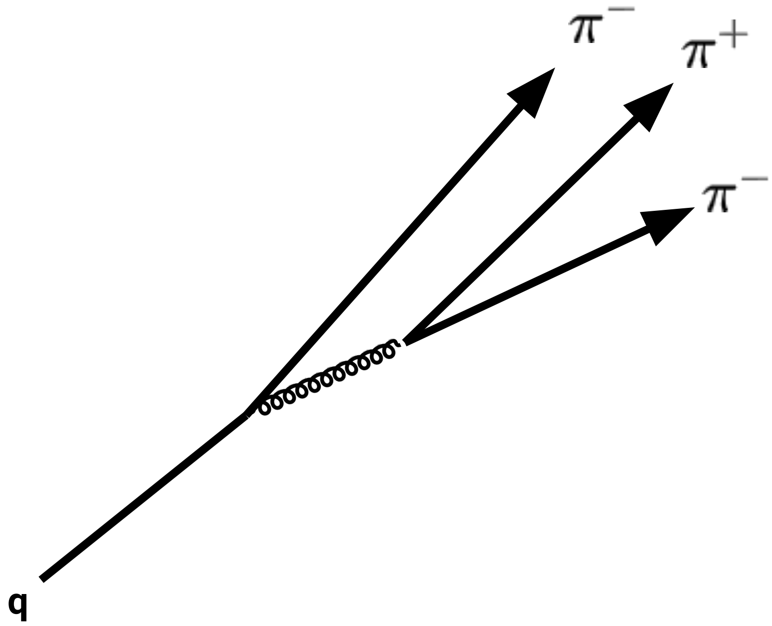
TPC Hit Check

IP Check

dE/dx Minimum Check

SPFO Check

Secondary PFO (SPFO) Check



SPFO Check

- LPFO Selection
- Charge Check
- Momentum Check
- TPC Hit Check
- IP Check
- dE/dx Minimum Check
- **SPFO Check**

Secondary PFO (SPFO) Check

- Find SPFO such that:
  - Charged Kaon
  - Charge must be opposite to LPFO Kaon (same sign does not create confusion)
  - Must have least 10 GeV momentum
- If there is such SPFO -> veto

Acceptance

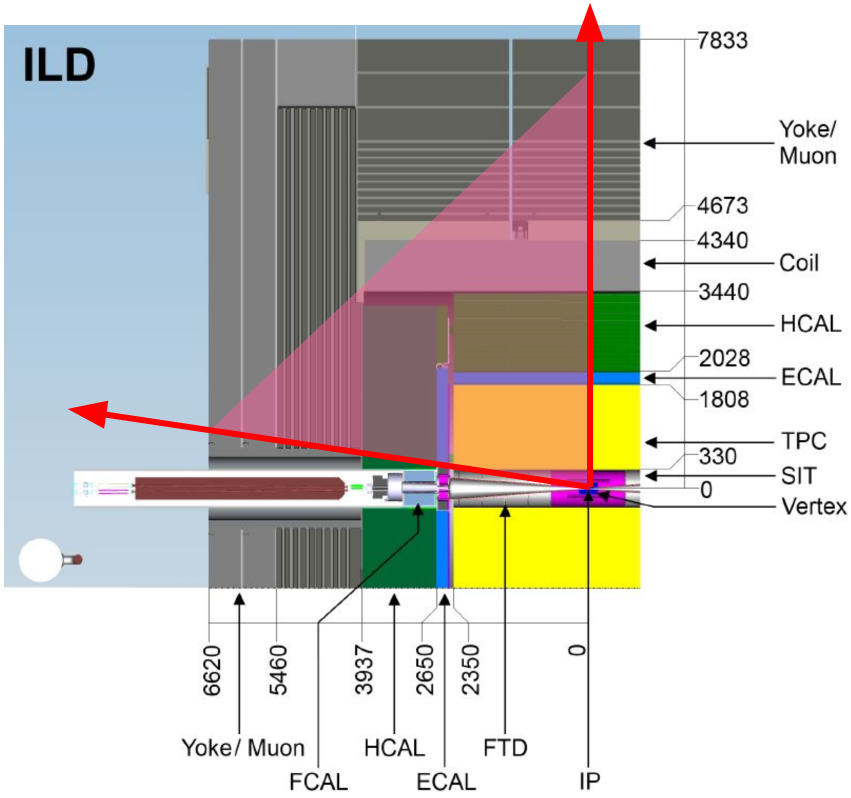
Stability & Purity

Acceptance Correction

- Detector acceptance is not uniform throughout different polar angles.
- The reconstruction efficiency depends on the detector acceptance.
- **Stability**: Measure of detector resolution.
    - Stability act as reconstruction efficiency, if the ILD has 100% tracking efficiency.
- **Purity**: Purity for reconstructing Kaon and Pion

$$\text{stability} = \frac{N_{rec} \cap N_{gen}}{N_{gen}}$$

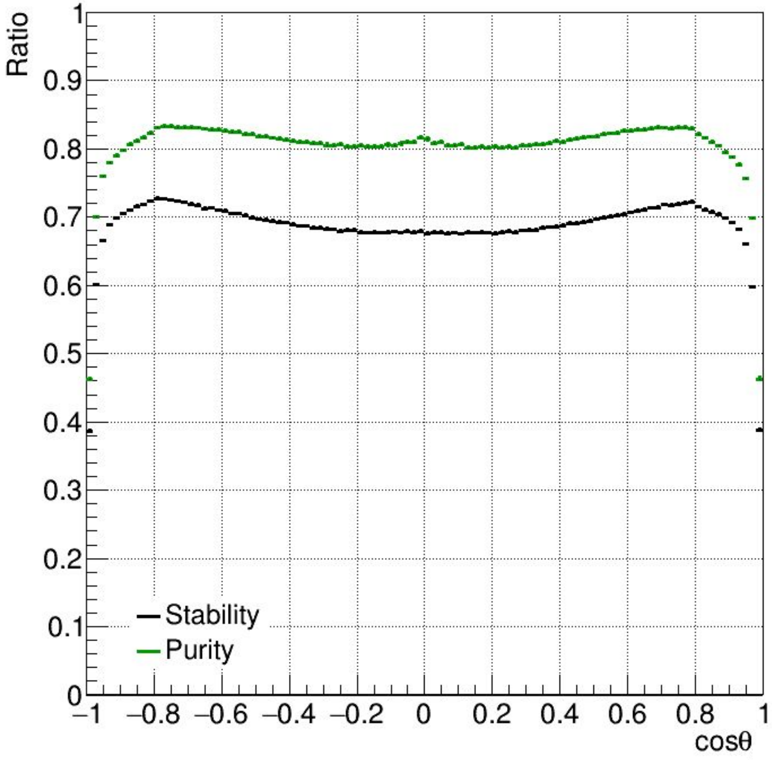
$$\text{purity} = \frac{N_{rec} \cap N_{gen}}{N_{reco}}$$



Detector Acceptance (Kaon)

Purity and Stability

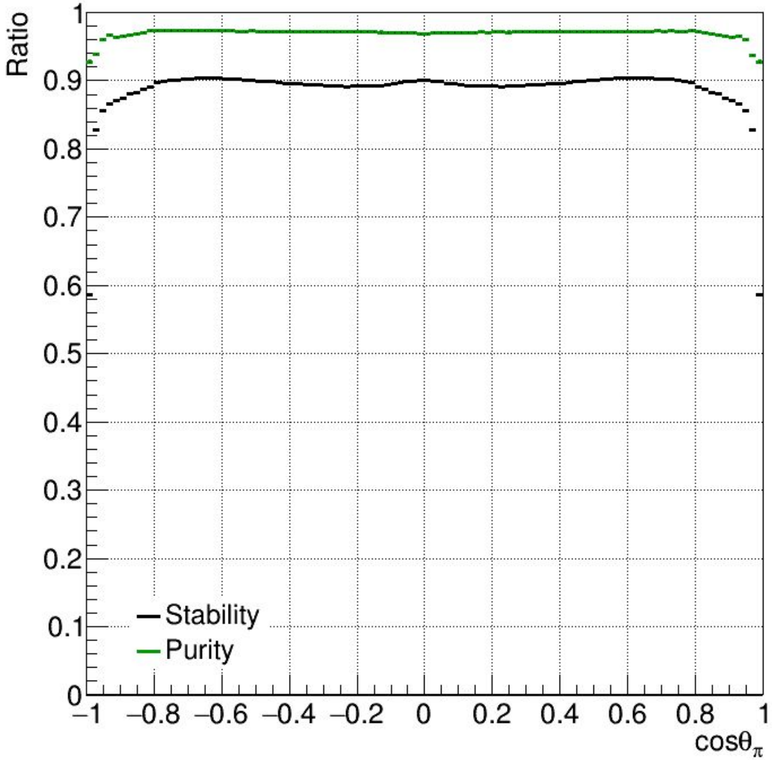
- Kaon identification purity & stability for **ss sample** is shown.
- High purity in Kaon identification can be seen
- Acceptance at the both edges of the detector drops above |cosθ| > 0.8
- Purity maintained above 0.8 on average.



Detector Acceptance (Pion)

Purity and Stability

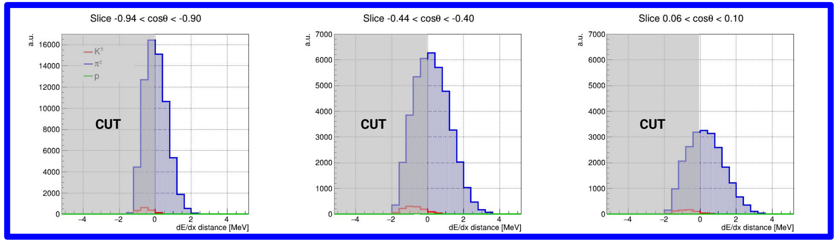
- Pion identification purity & stability for **ud sample** without pion dE/dx cut
- High purity in pion identification can be seen
- Stability is also remains high before the pion dE/dx cut.
- Detector acceptance structure can be seen on both center and forward region of the detector.

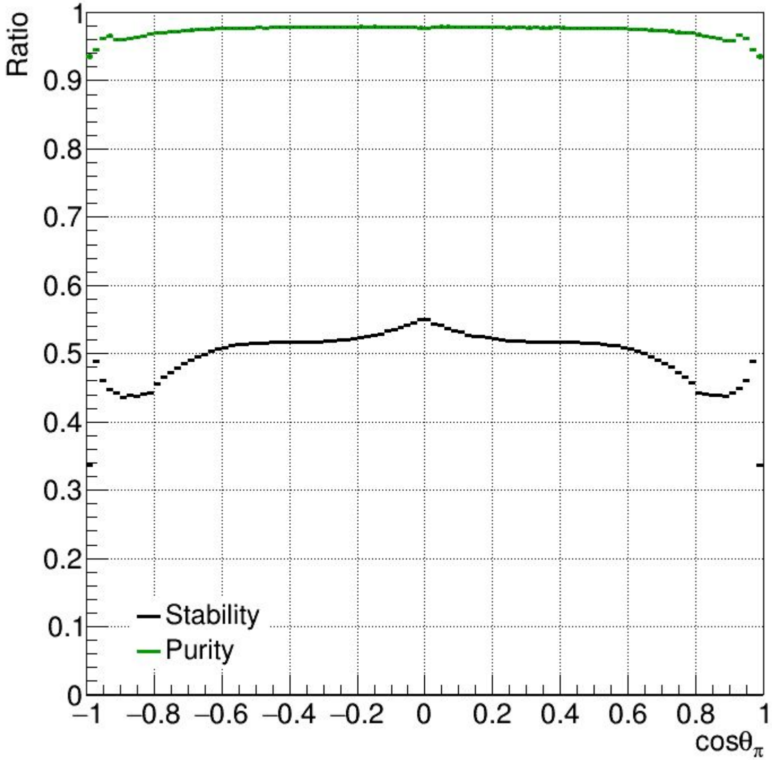


Detector Acceptance (Pion)

Purity and Stability

- Pion identification purity & stability for **ud sample** is shown.
- High purity in pion identification can be seen
- Stability is lowered to average of 0.5 due to sever cut to pion dE/dx distance.
  (pi dE/dx dist > 0)
- Detector acceptance structure can be seen on both center and forward region of the detector.





Double Charge Measurements

Double Charge Measurements

Migrations

- Migration occurs when reconstructing a particle charge opposite to its true charge in the parton level.
  - Misreconstruction from dE/dx distance PID.
  - Acceptance
- Such mistake flips the reconstructed quark angle (assuming back-to-back scenario)
- pq-method
  - Also used in bbar measurements.
  - Details can be found here. (Sviatoslav, 2017 - p.104)

$$N_{acc} = p^2 N + q^2 N$$
$$N_{rej} = 2pqN$$
$$1 = p + q$$

$$p = \frac{N \pm \sqrt{N(N - 2N_{rej})}}{2}$$
$$q = \frac{N \mp \sqrt{N(N - 2N_{rej})}}{2}$$