BELLE PART 2: KAON COLLINS MEASUREMENTS

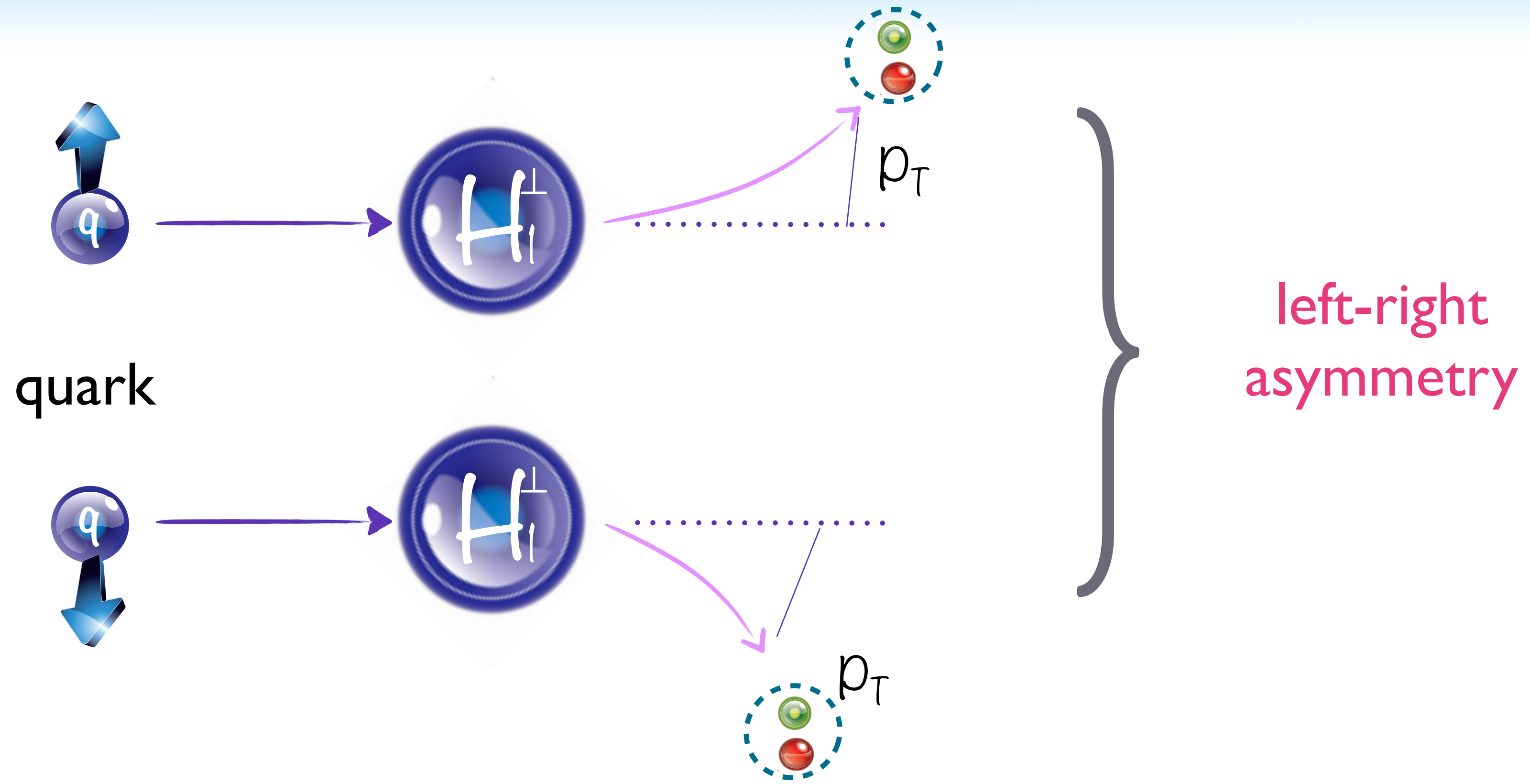
4th International Workshop on Transverse Polarisation Phenomena in Hard Processes
(Transversity 2014)
Chia, June 9th-13th 2014

Francesca Giordano, for the BELLE collaboration

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

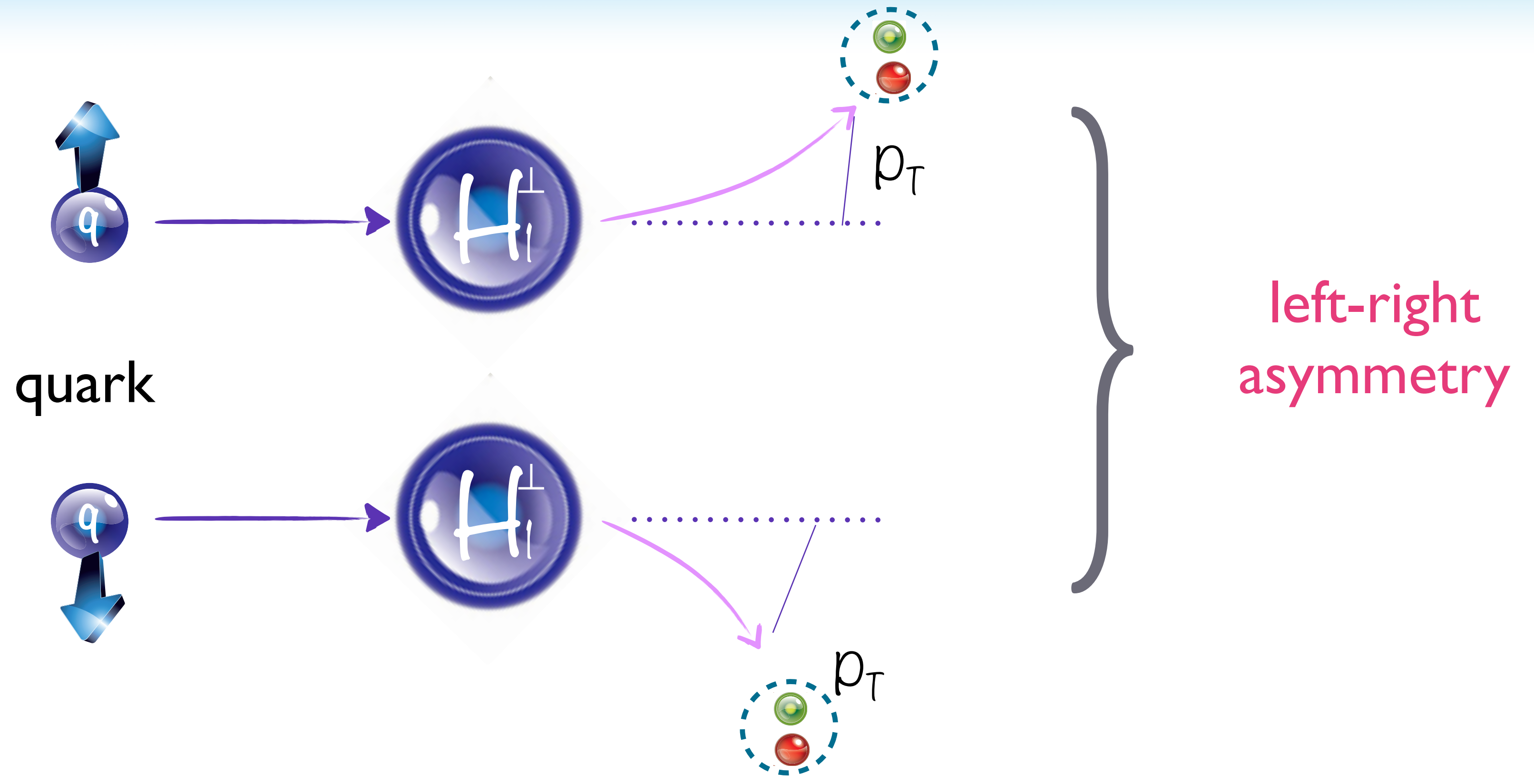
BELLE

Collins Fragmentation



Collins mechanism: correlation between the parton transverse spin and the direction of final hadron

Collins Fragmentation

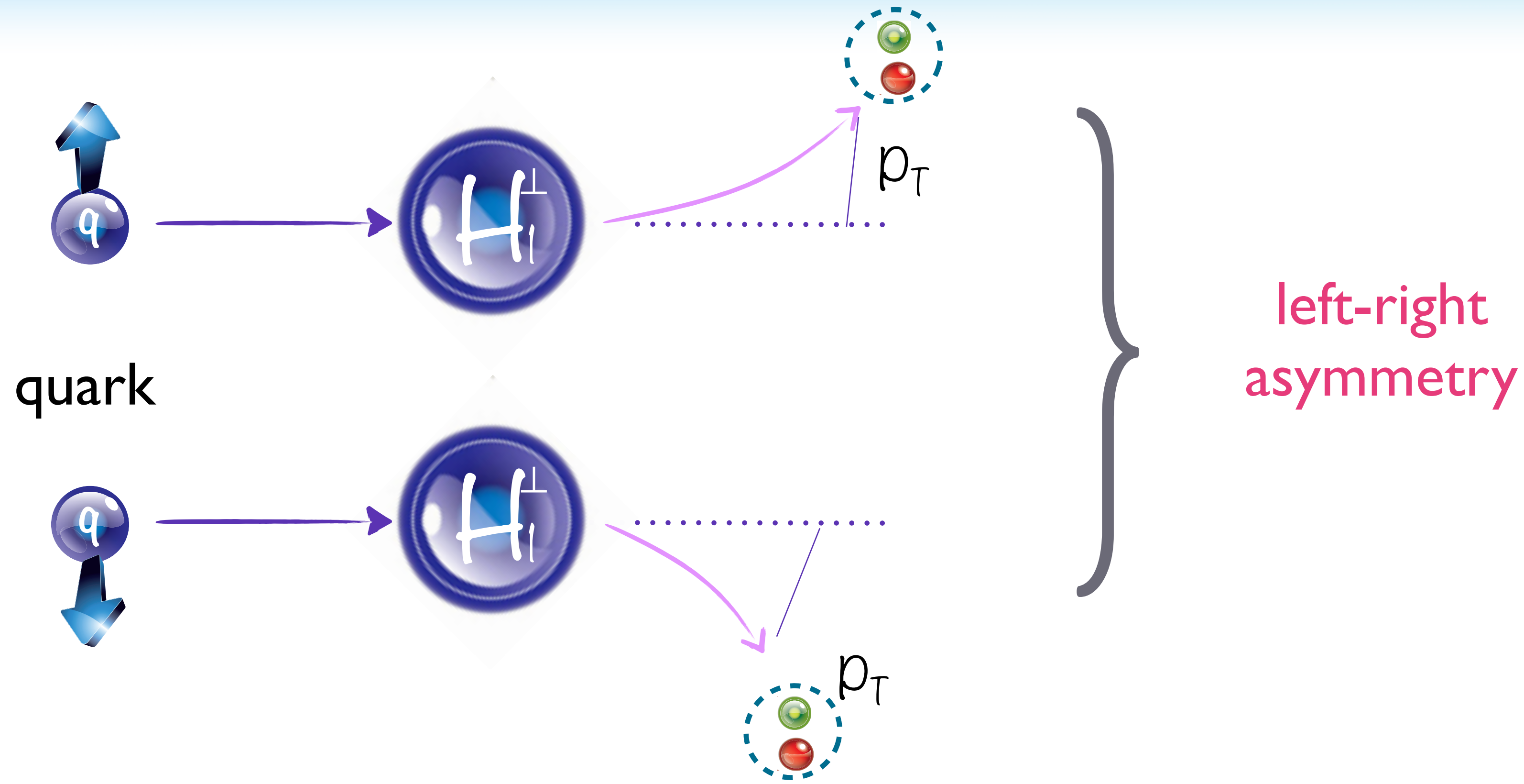


Collins mechanism: correlation between the parton transverse spin and the direction of final hadron

strictly related to the outgoing hadron tranverse momentum

TMD!

Collins Fragmentation



Collins mechanism: correlation between the parton transverse spin and the direction of final hadron

<u>strictly related to the outgoing hadron tranverse momentum</u>

TMD!

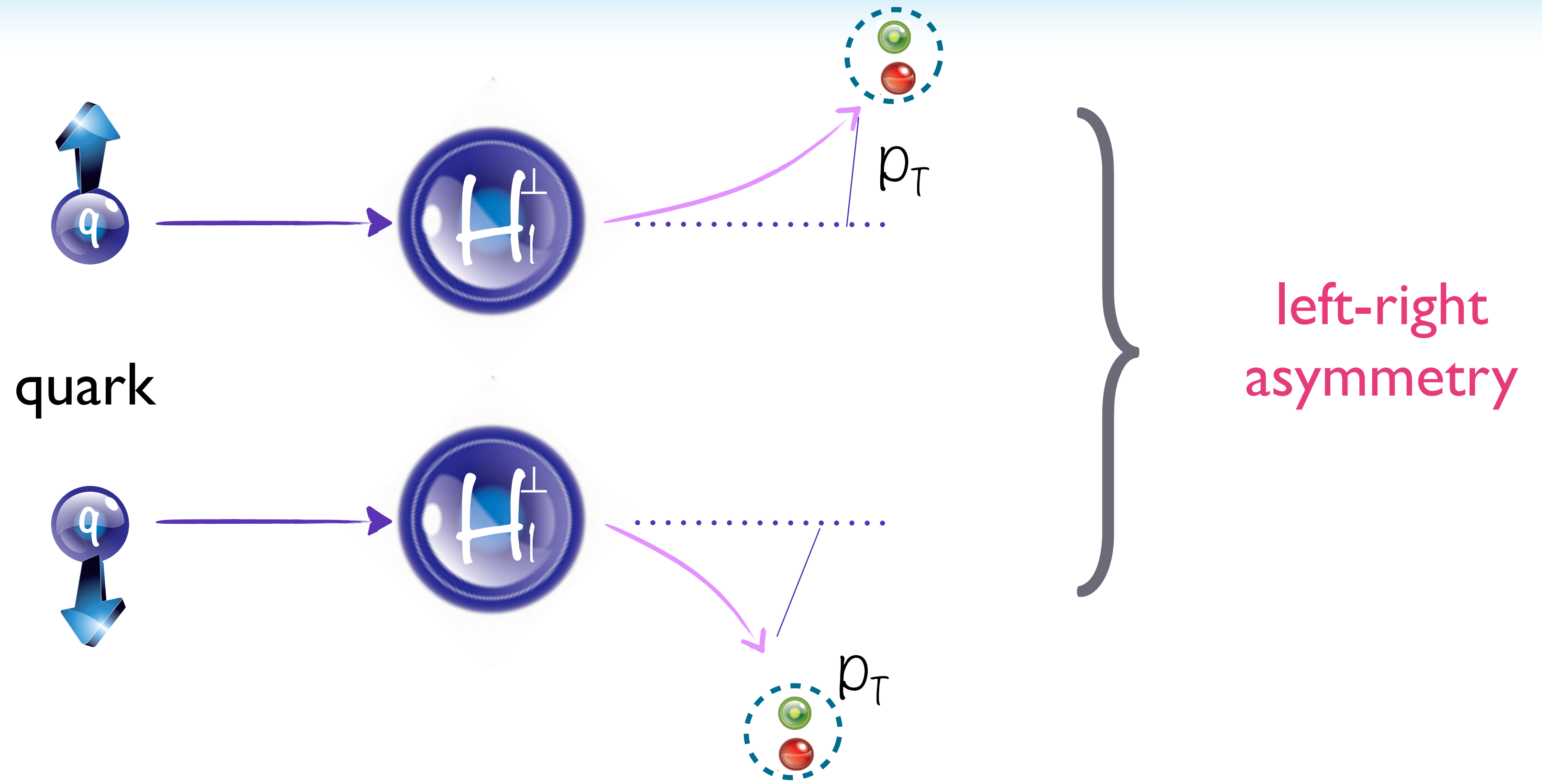
Chiral odd!

$$X \otimes H_1^{\perp}$$

chiral odd   chiral odd

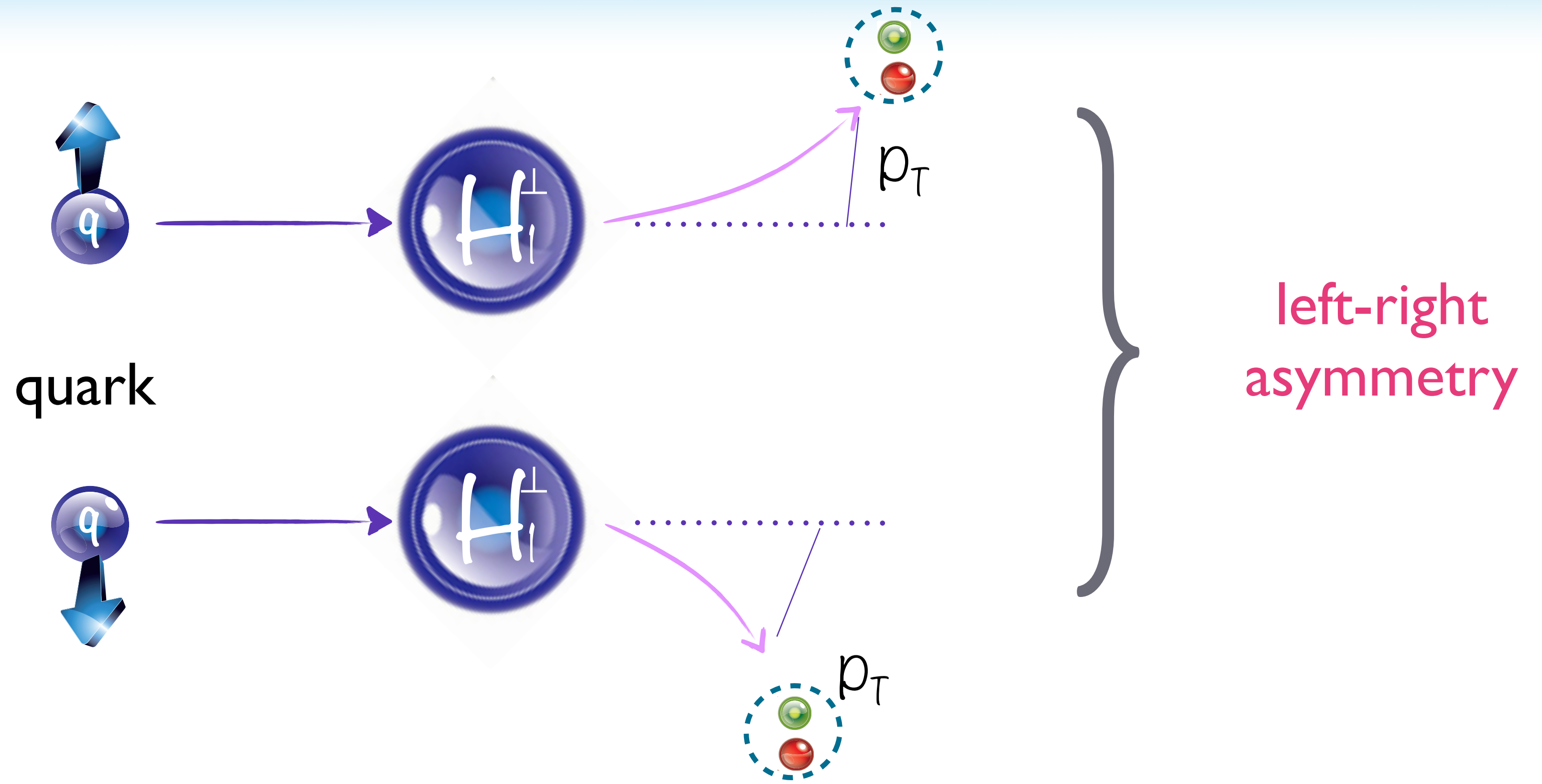
chiral even

Collins Fragmentation



In e+e- reaction, there is no fixed transverse axis to define azimuthal angles to, and even if there were one the net quark polarization would be 0

Collins Fragmentation



In e+e- reaction, there is no fixed transverse axis to define azimuthal angles to, and even if there were one the net quark polarization would be 0

But if we look at the whole event, even though the q and q̄ spin directions are unknown, they must be parallel

$$e^+e^- \to q\,\bar{q} \to h_1\,h_2\,X$$

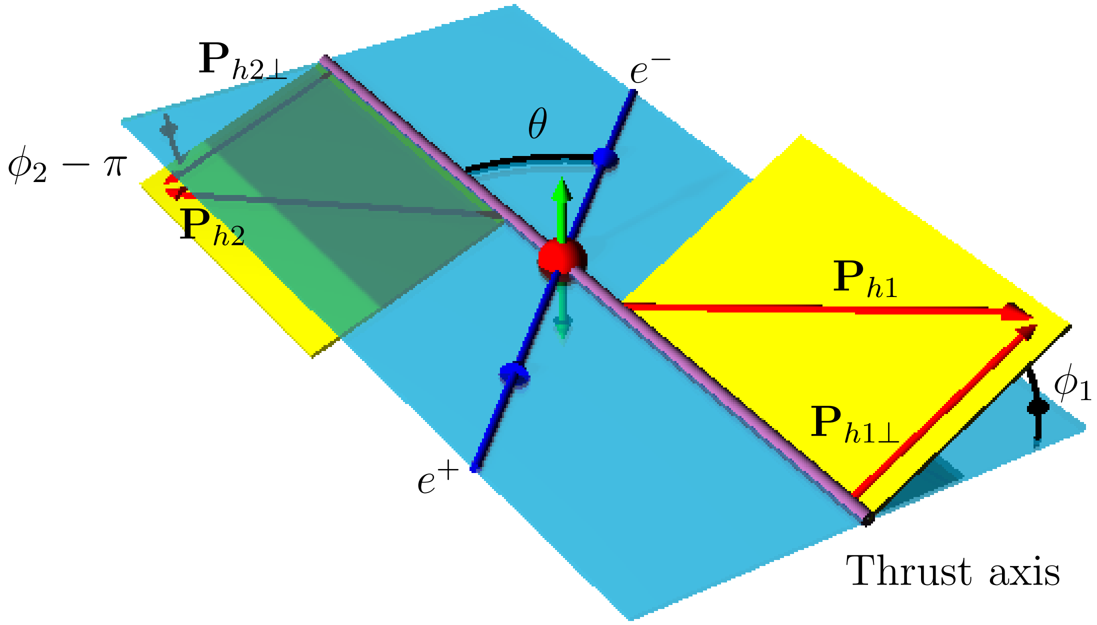
$$h = \pi,\ K$$

Reference frames

$$e^+e^- \rightarrow q\,\bar{q} \rightarrow h_1\,h_2\,X \qquad h = \pi,\; K$$

$\phi_1+\phi_2$ method:

hadron azimuthal angles with respect to the $q\bar{q}$ axis proxy

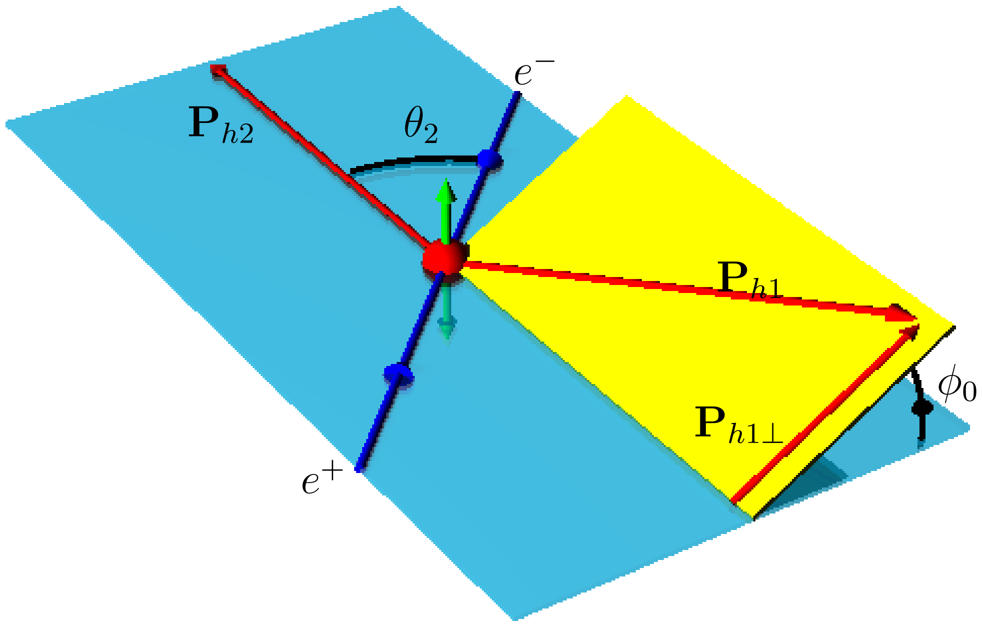


reference plane (in blue) given by the e+e- direction and the $q\bar{q}$ axis

Thrust axis= proxy for the $q\bar{q}$ axis

ϕ_0 method:

hadron 1 azimuthal angle with respect to hadron 2

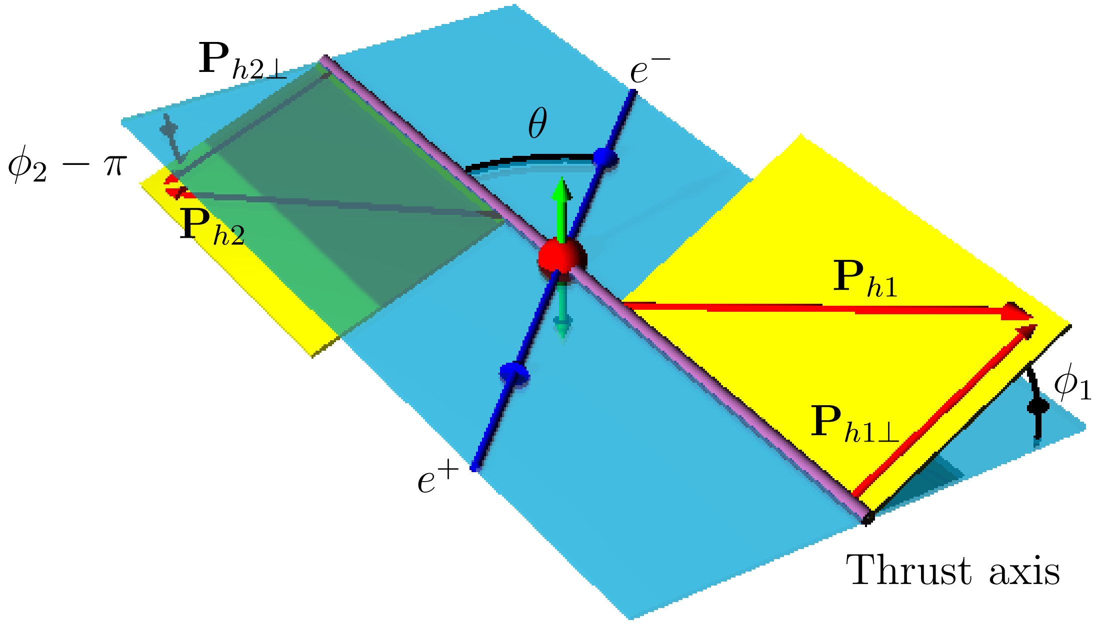


reference plane (in blue) given by the e+e- direction and one of the hadron

Reference frames

$\phi_1+\phi_2$ method:

hadron azimuthal angles with respect to the $q\bar{q}$ axis proxy

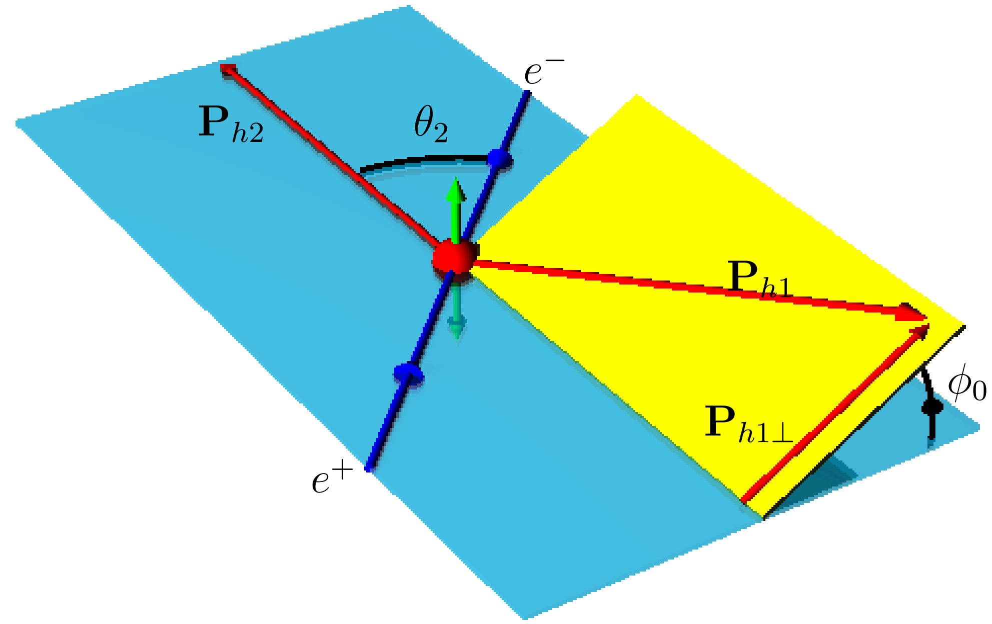


$$\sigma \sim \mathcal{M}_{12}\Big(1 + \frac{\sin^2\theta_T}{1+\cos^2\theta_T}\, cos(\phi_1+\phi_2)\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\Big)$$

$$F^{[n]}(z_i) \equiv \int d|k_T|^2 \left[\frac{|k_T|}{M_i}\right]^{[n]} F(z_i,|k_T|^2)$$

ϕ_0 method:

hadron 1 azimuthal angle with respect to hadron 2



$$\sigma \sim \mathcal{M}_0\Big(1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\, cos(2\phi_0)\mathcal{F}\Big[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\Big]\Big)$$

$$\mathcal{F}[X] = \sum_{q\bar{q}}\int [2\hat{\mathbf{h}}\cdot\mathbf{k_{T1}}\hat{\mathbf{h}}\cdot\mathbf{k_{T2}} - \mathbf{k_{T1}}\cdot\mathbf{k_{T2}}]$$
$$d^2\mathbf{k_{T1}}d^2\mathbf{k_{T2}}\,\delta^2(\mathbf{k_{T1}}+\mathbf{k_{T2}}-\mathbf{q_T})X$$

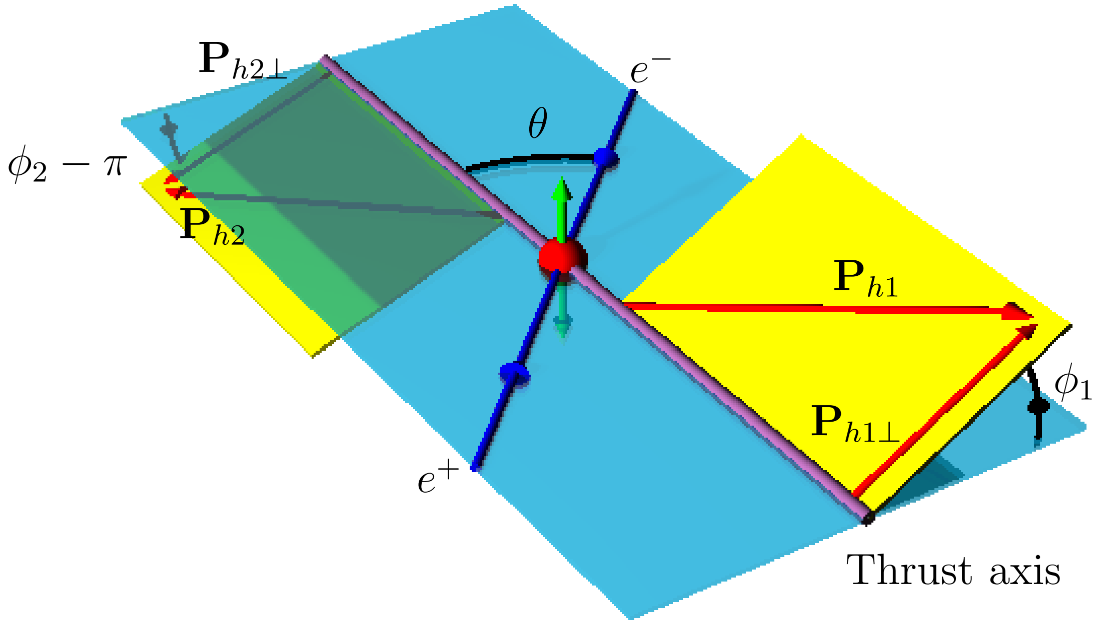
$$k_{Ti} = z_i\, p_{Ti}$$

D. Boer
Nucl.Phys.B806:23,2009

Reference frames

$\phi_1+\phi_2$ method:

hadron azimuthal angles with respect to the $q\bar{q}$ axis proxy



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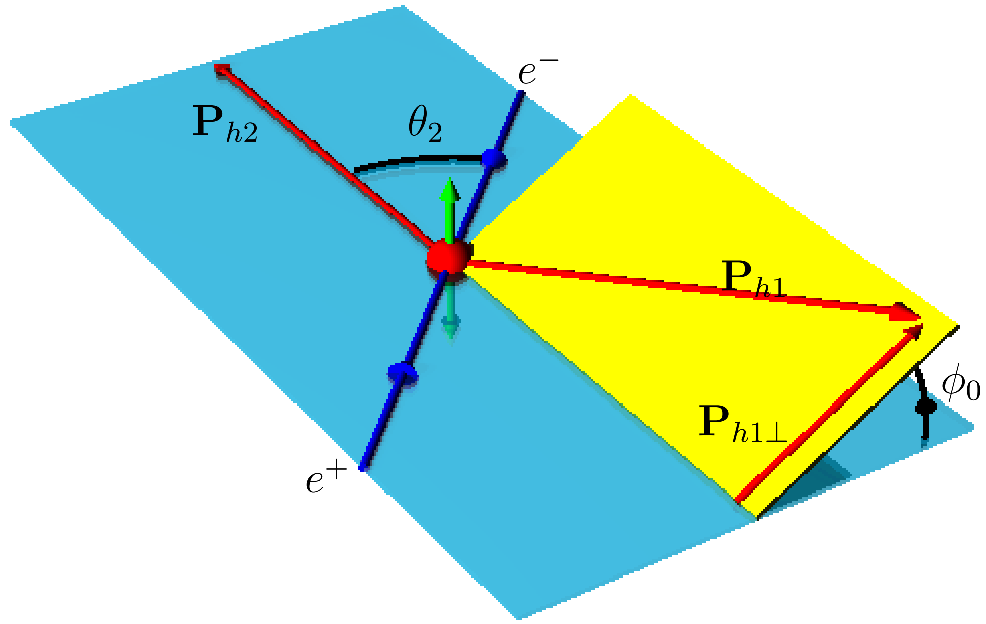

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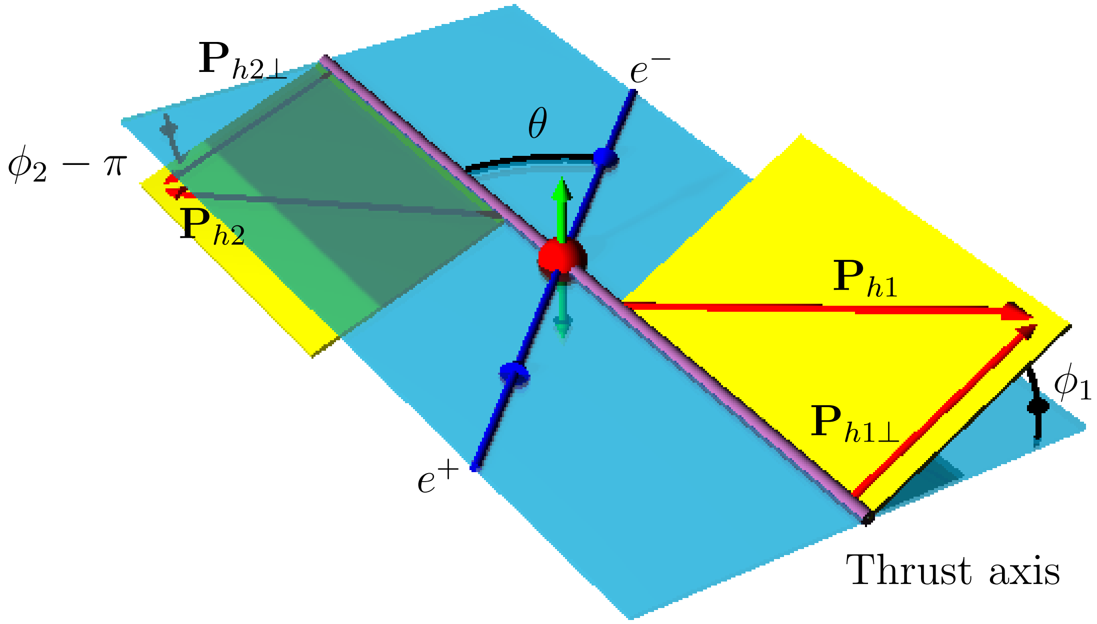

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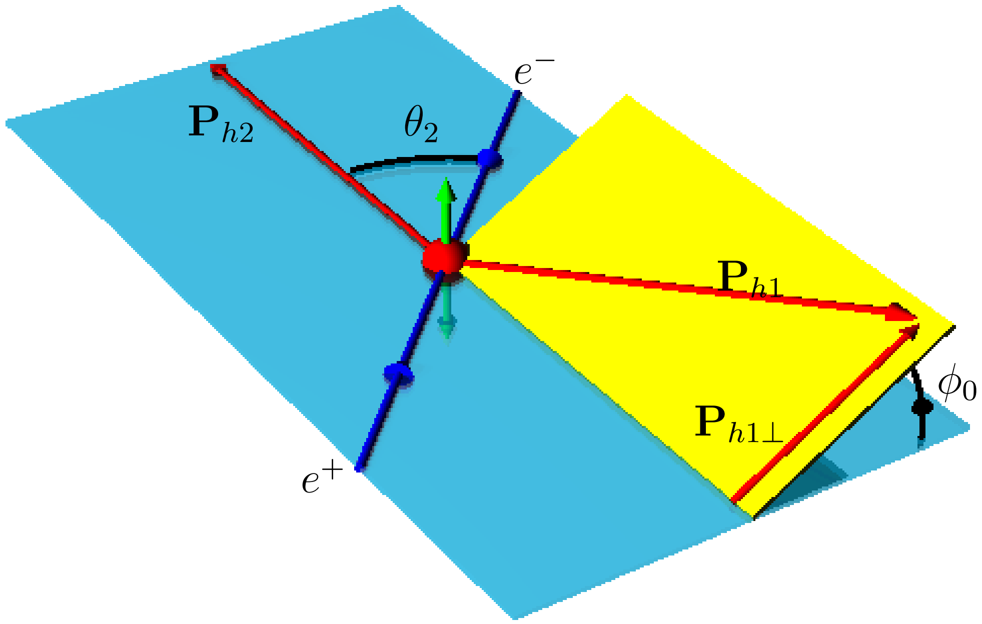

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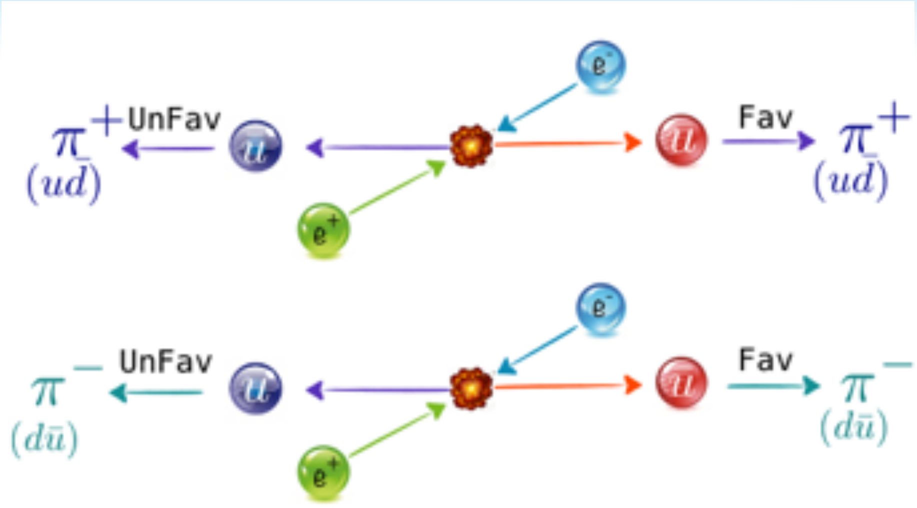
Product of 2 Collins FFs

Like-sign couples



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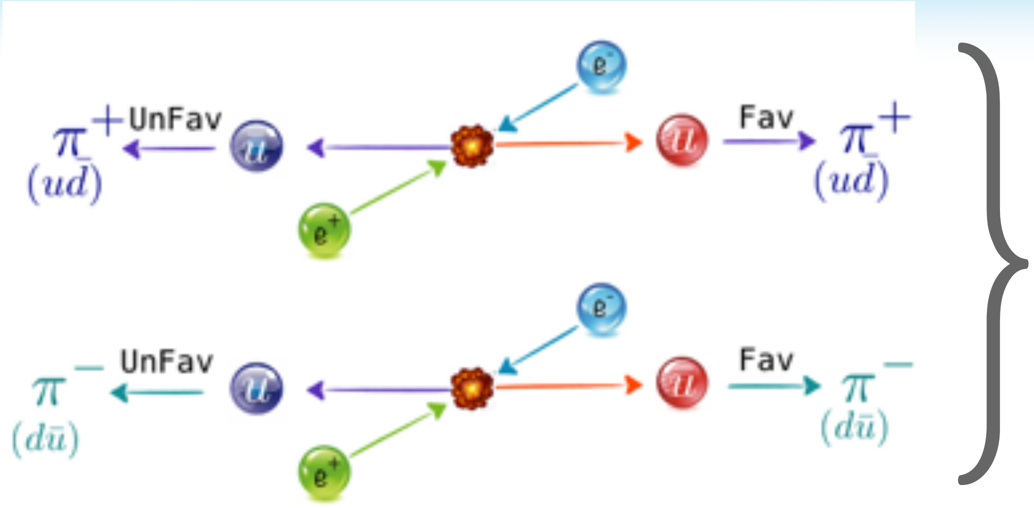
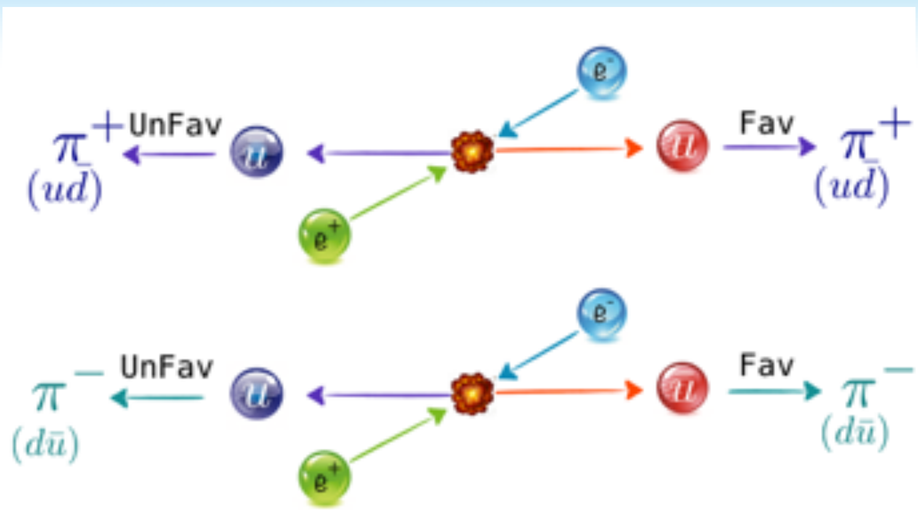
Like-sign couples



$$[\mathrm{Fav} \cdot \mathrm{UnFav}] + [\mathrm{Fav} \cdot \mathrm{UnFav}]$$

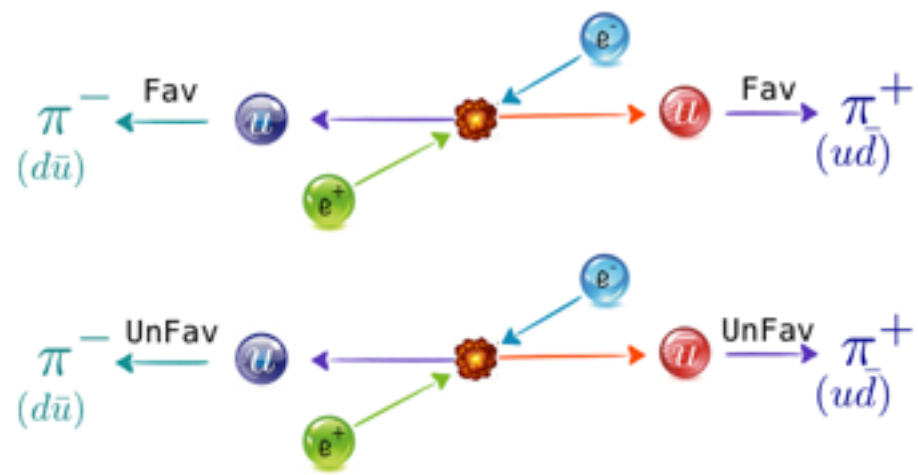
Product of 2 Collins FFs

Like-sign couples



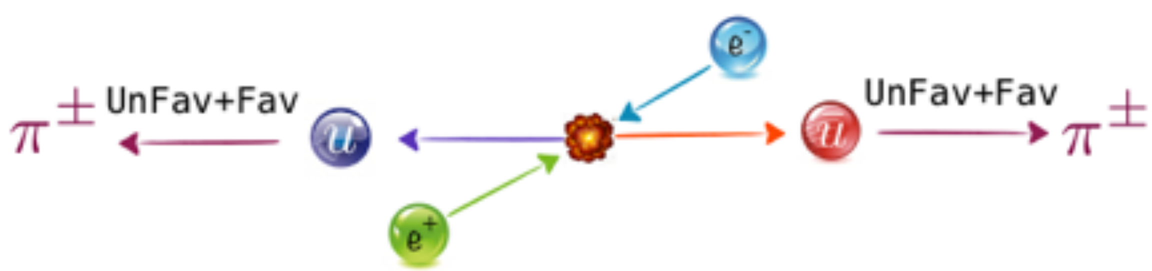
$[\text{Fav} \cdot \text{UnFav}] + [\text{Fav} \cdot \text{UnFav}]$

Unlike-sign couples



$[\text{Fav} \cdot \text{Fav}] + [\text{UnFav} \cdot \text{UnFav}]$

All charges couples



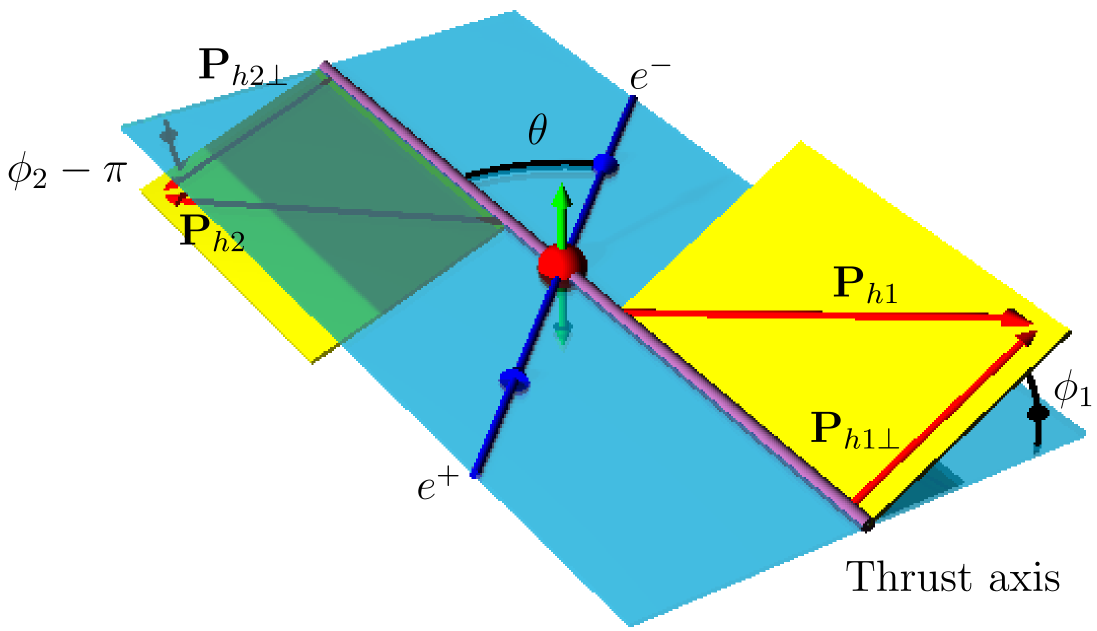
$[\text{Fav} + \text{unFav}] \cdot [\text{UnFav} + \text{Fav}]$

Reference frames

$$e^+e^- \to q\,\bar{q} \to h_1\,h_2\,X \qquad h = \pi,\ K$$

$\phi_1+\phi_2$ method:

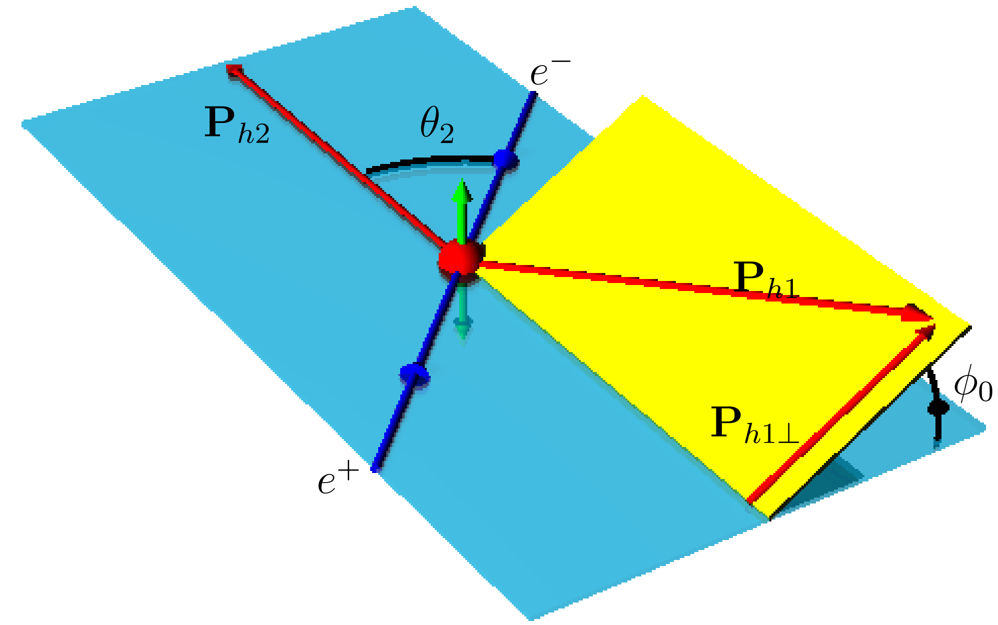
hadron azimuthal angles with respect to the $q\bar{q}$ axis proxy



$$\mathcal{R}_{12} = \frac{N_{12}(\phi_1 + \phi_2)}{\langle N_{12} \rangle}$$

ϕ_0 method:

hadron 1 azimuthal angle with respect to hadron 2



$$\mathcal{R}_0 = \frac{N_0(\phi_0)}{\langle N_0 \rangle}$$

Double-ratios

But! Acceptance and radiation effects also contribute to azimuthal asymmetries!

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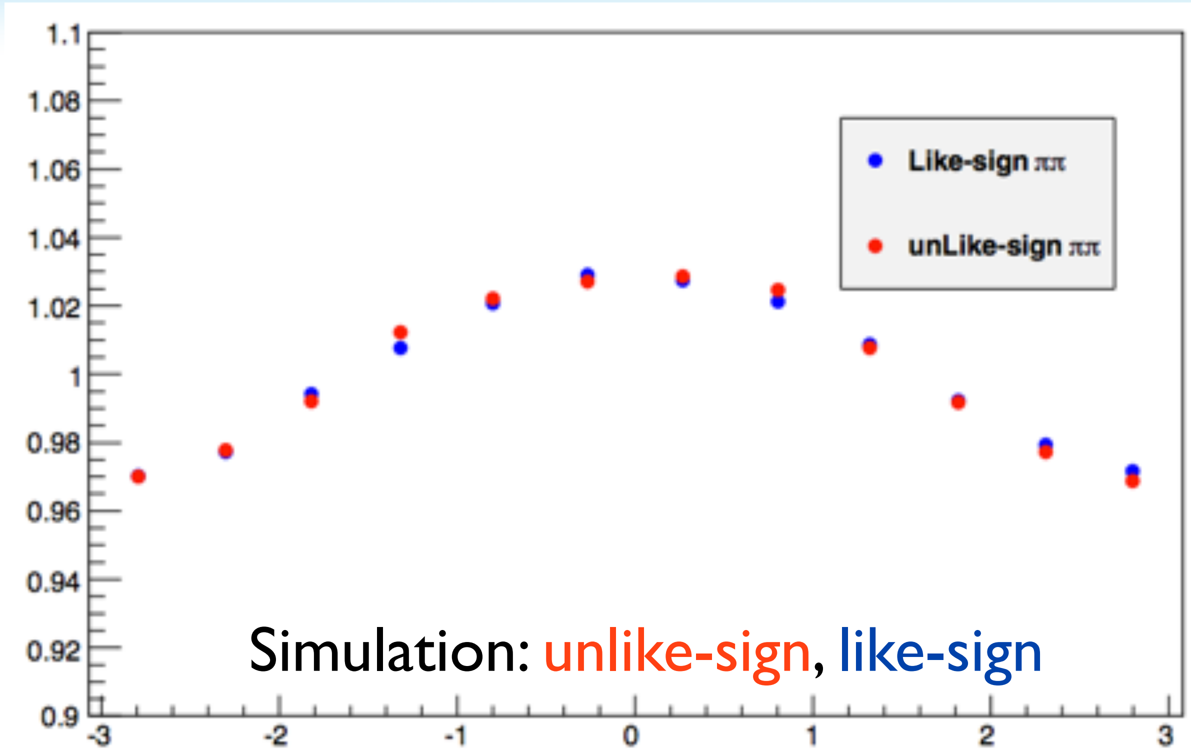
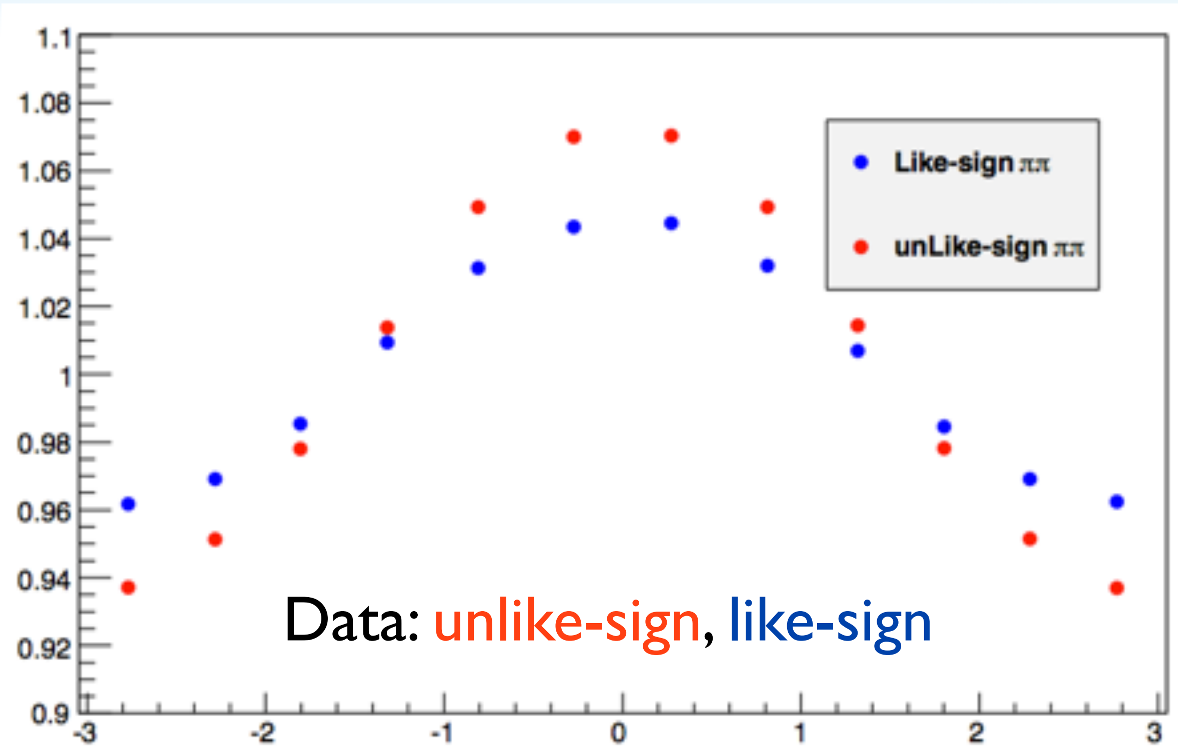
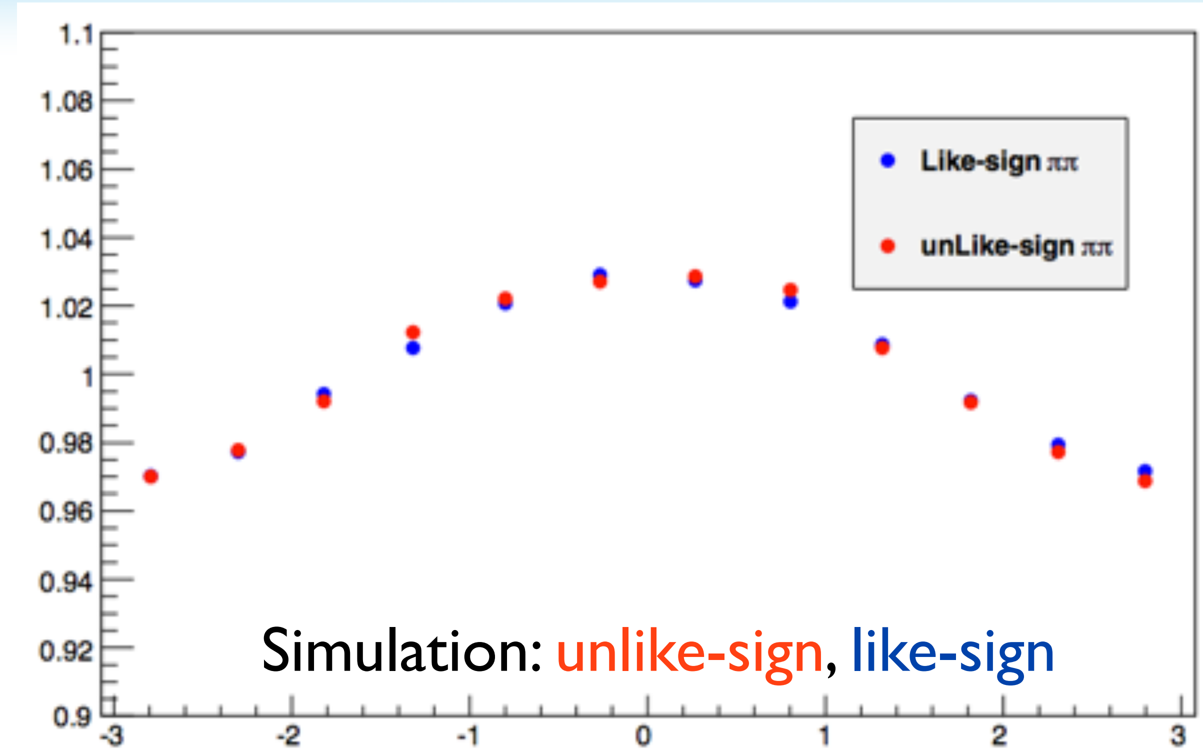
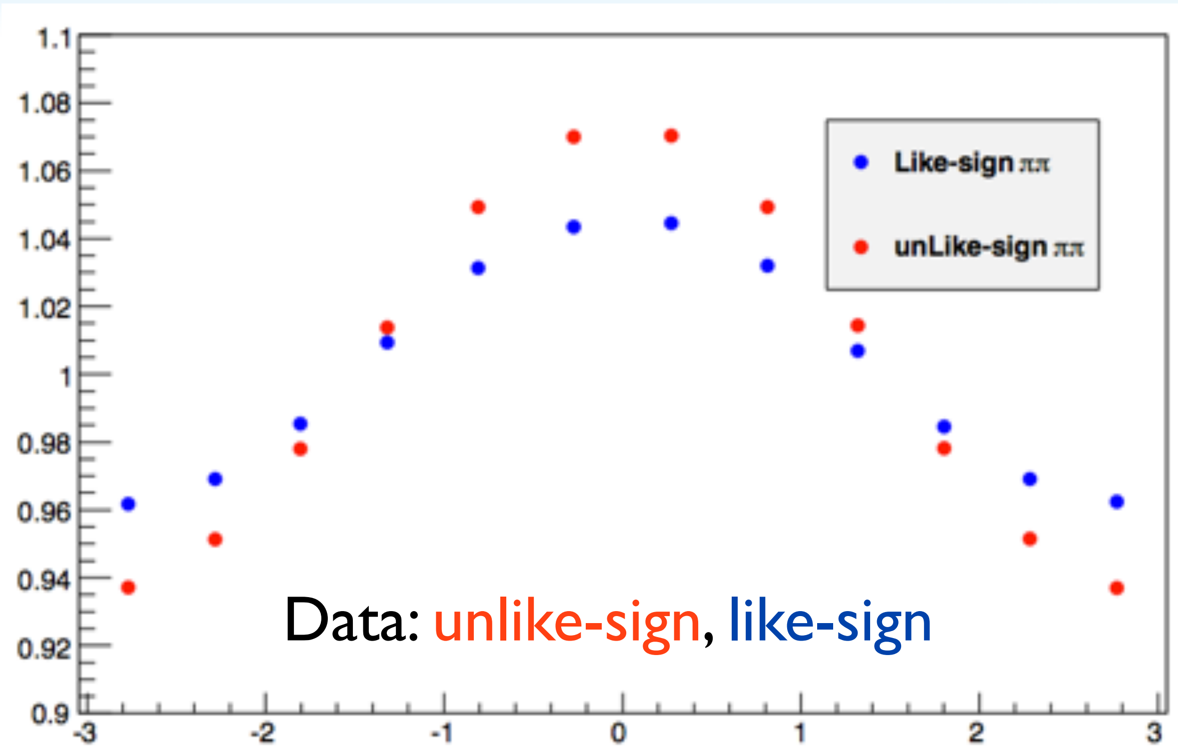


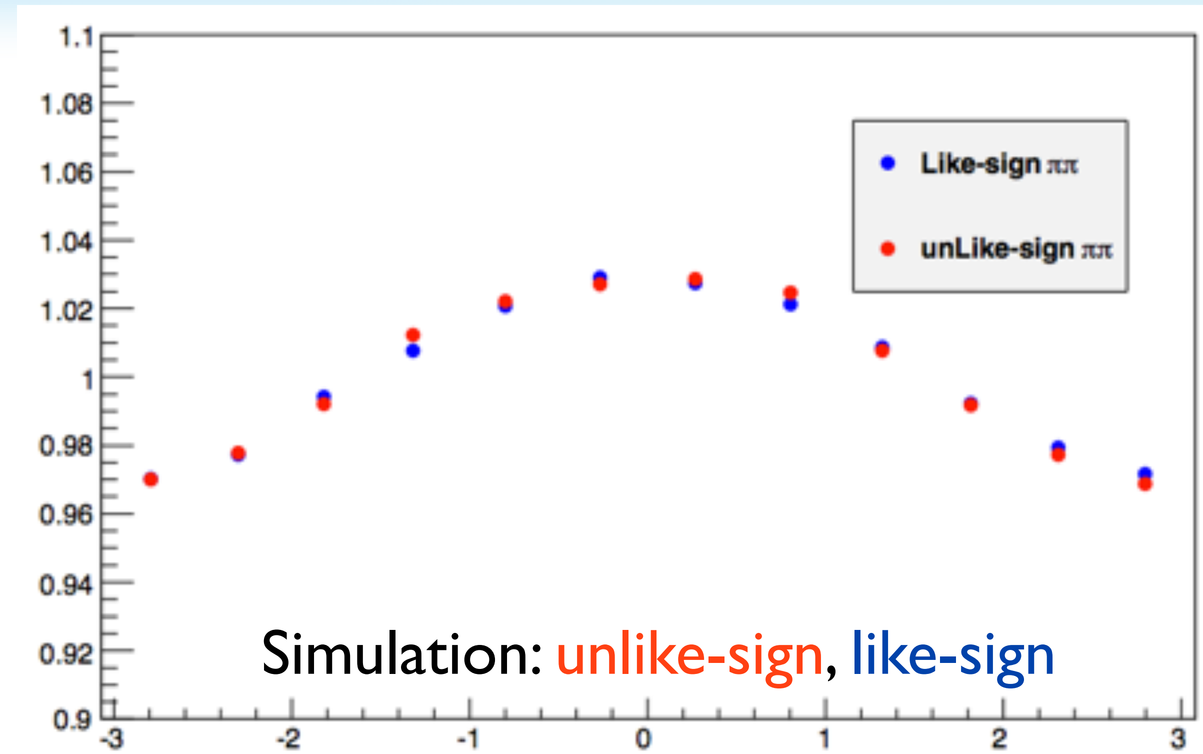
Double-ratios





Double-ratios





To reduce such non-Collins effects:
divide the sample of hadron couples in unlike-sign and like-sign (or All-charges),
and extract the asymmetries of the super ratios between these 2 samples:

Unlike-sign couples / Like-sign couples

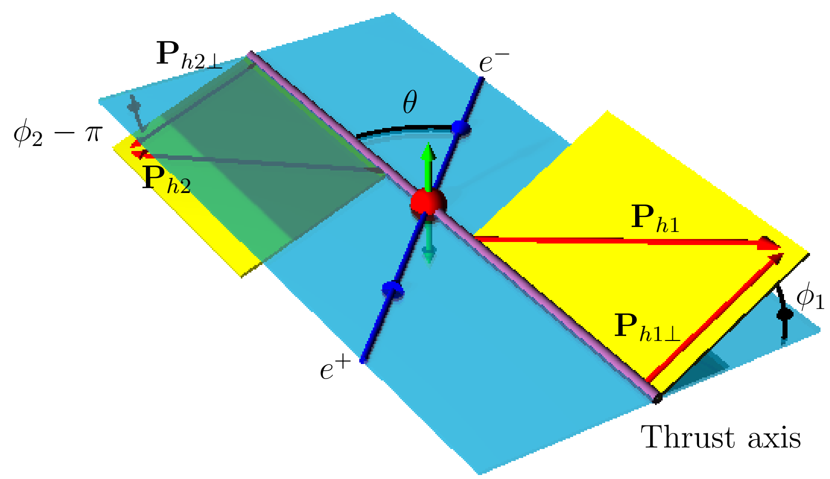
$$\mathcal{D}_{ul}^{h_1 h_2} = \mathcal{R}^U / \mathcal{R}^L$$

Unlike-sign couples / All charges

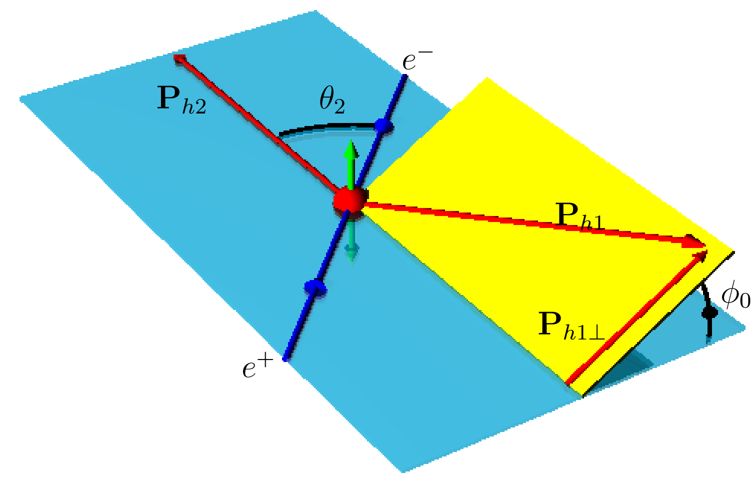
$$\mathcal{D}_{uc}^{h_1 h_2} = \mathcal{R}^U / \mathcal{R}^C$$

Double-ratios

$\phi_1+\phi_2$ method



ϕ_0 method



$$\sigma \sim \mathcal{M}_{12}\Big(1+\frac{\sin^2\theta_T}{1+\cos^2\theta_T}\cos(\phi_1+\phi_2)\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\Big)$$

$$\sigma \sim \mathcal{M}_0\Big(1+\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_0)\mathcal{F}\Big[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\Big]\Big)$$

$$\mathcal{D}_{ul}^{h_1h_2} = \mathcal{R}^U/\mathcal{R}^L$$

$$\mathcal{D}_{uc}^{h_1h_2} = \mathcal{R}^U/\mathcal{R}^C$$

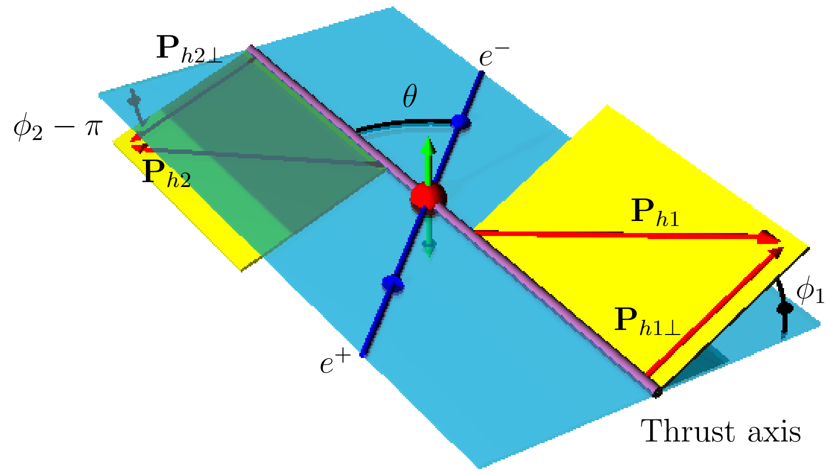
Fitted by

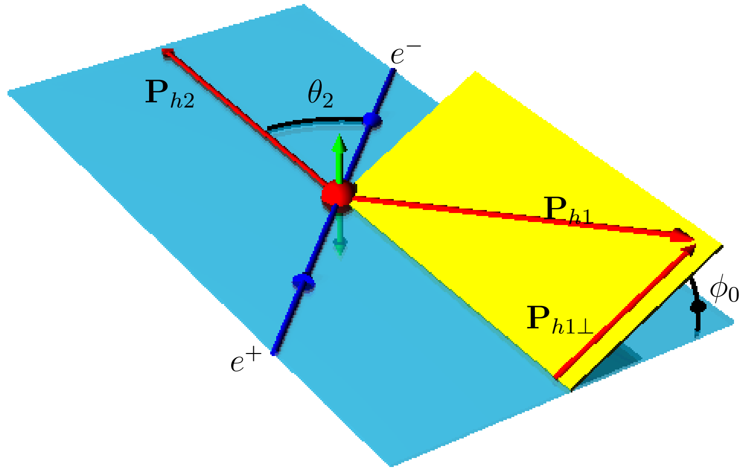
$$\mathcal{B}_{12}(1+\mathcal{A}_{12}\cos(\phi_1+\phi_2))$$

$$\mathcal{B}_0(1+\mathcal{A}_0\cos(2\phi_0))$$

Double-ratios

$\phi_1+\phi_2$ method | **ϕ_0 method**





$$\sigma \sim \mathcal{M}_{12}\Big(1+\frac{\sin^2\theta_T}{1+\cos^2\theta_T}\, cos(\phi_1+\phi_2)\,\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\Big)$$

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$$A_{12} = \frac{\sin^2\theta}{1+\cos^2\theta}\,\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}$$

$$A_0 = \frac{\sin^2\theta}{1+\cos^2\theta}\,\mathcal{F}\Big[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\Big]$$

Fitted by

$$\mathcal{B}_{12}(1+\mathcal{A}_{12}\cos(\phi_1+\phi_2))$$

$$\mathcal{B}_0(1+\mathcal{A}_0\cos(2\phi_0))$$

Kinematic variables

$z \equiv \frac{E_h}{E_p}$ hadron energy fraction with respect to parton

z_1, z_2

p_T component of hadron momentum transverse to reference direction

1. $\phi_1+\phi_2$ method: the thrust axis p_{T1}, p_{T2}
2. ϕ_0 method: hadron 2 p_{T0}

q_T component of virtual photon momentum transverse to the h_1h_2 axis in the frame where h_1 and h_2 are back-to-back

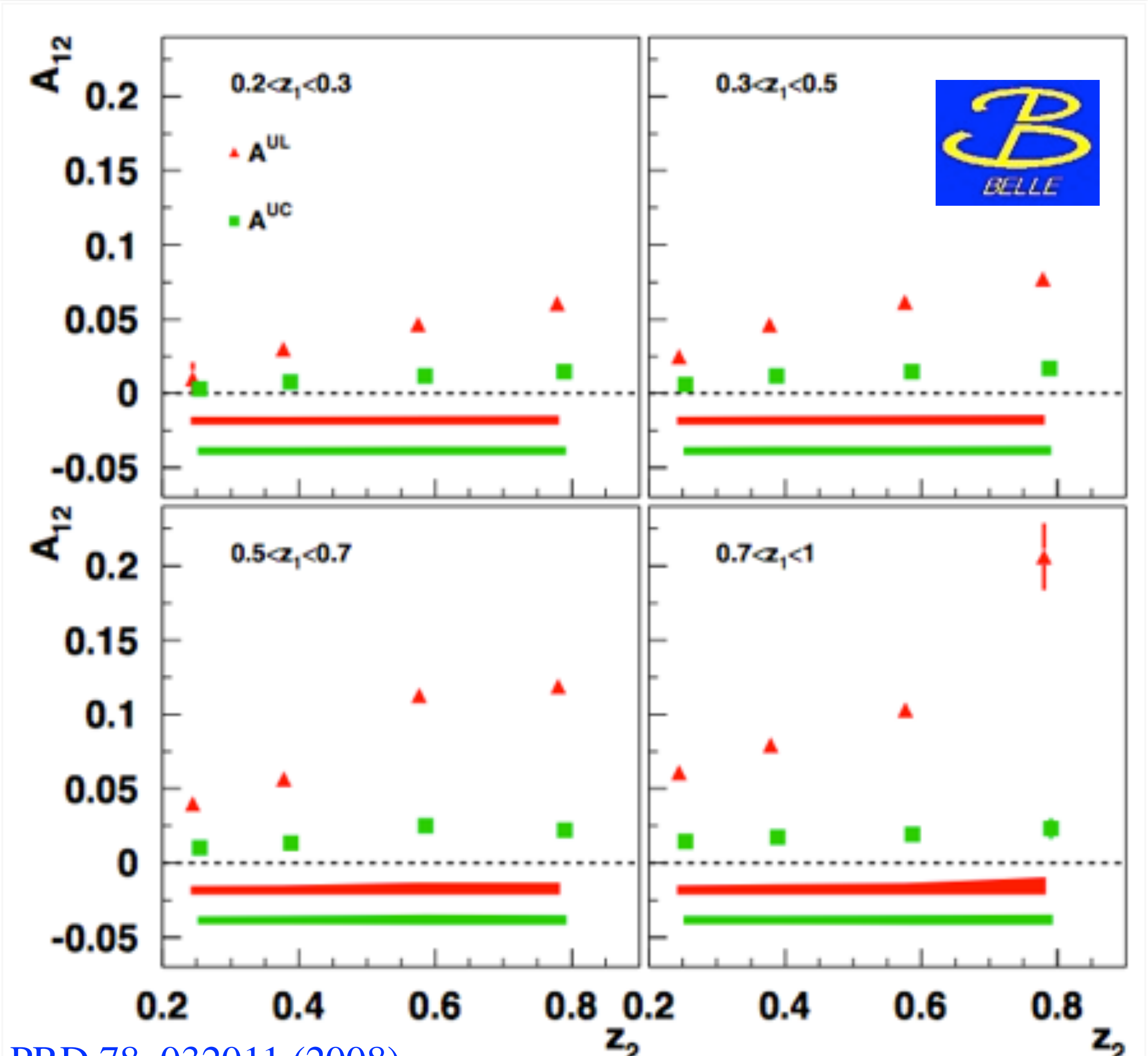
z	0.2	0.25	0.3	0.42	1				
p_{T12}	0	0.13	0.3	0.5	3				
p_{T0}	0	0.13	0.25	0.4	0.5	0.6	0.75	1	3
q_T	0	0.5	1	1.25	1.5	1.75	2	2.25	2.5
$\sin^2\theta/(1+\cos^2\theta)$	0.4	0.45	0.5	0.6	0.7	0.8	0.9	0.97	1

Belle publications
PRL 96,232002, (2006)
PRD 78, 032011 (2008)

Published results: $\pi\pi$

$\phi_1+\phi_2$ method

ϕ_0 method



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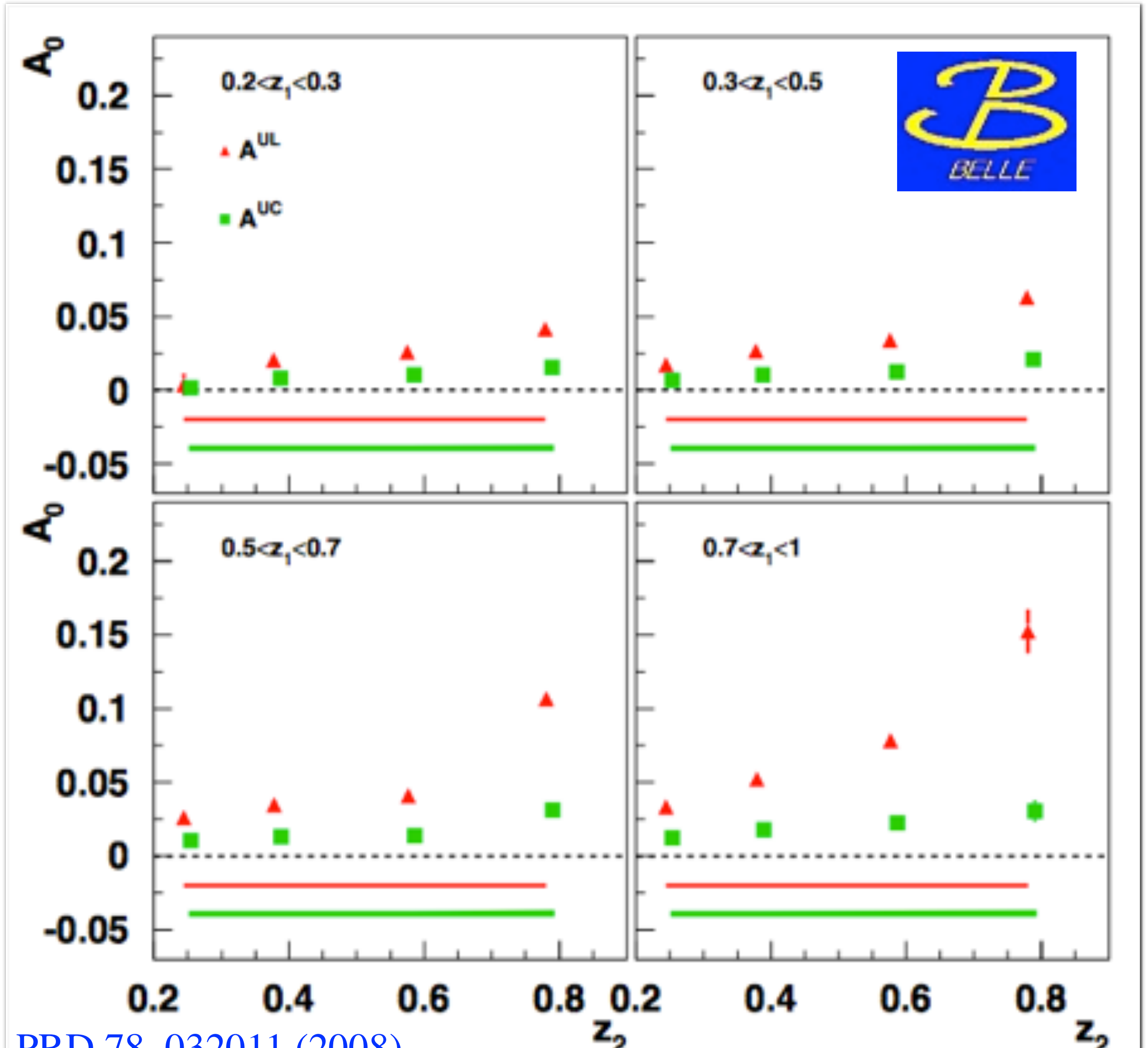

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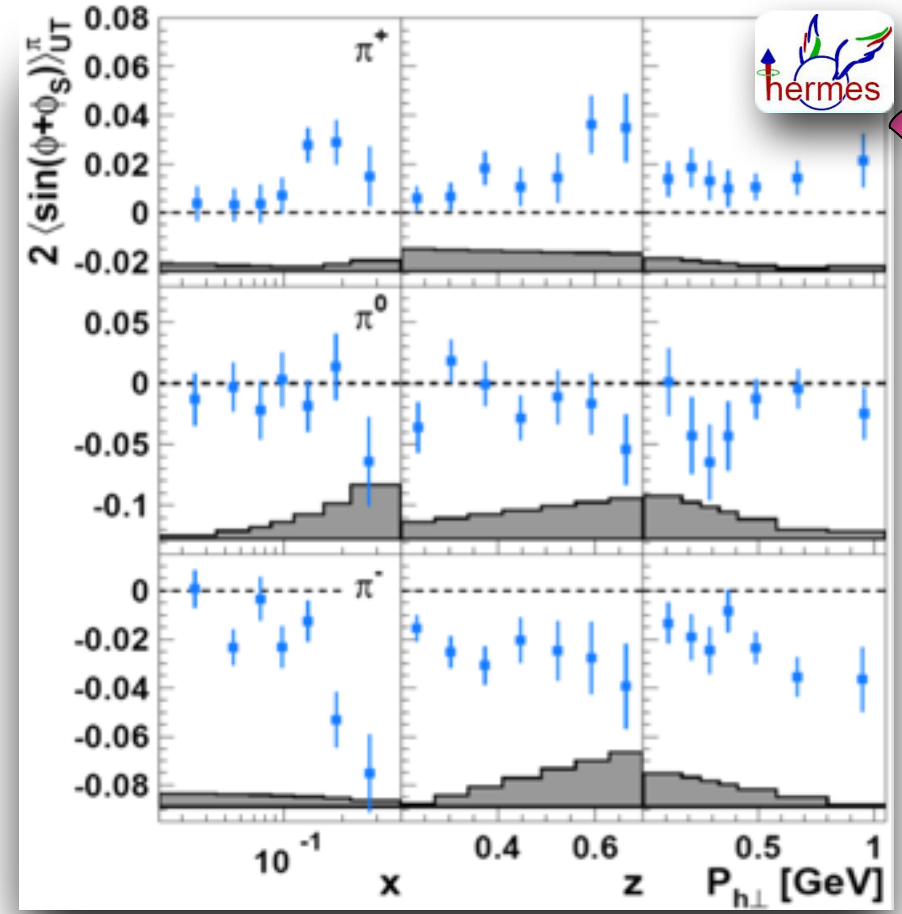
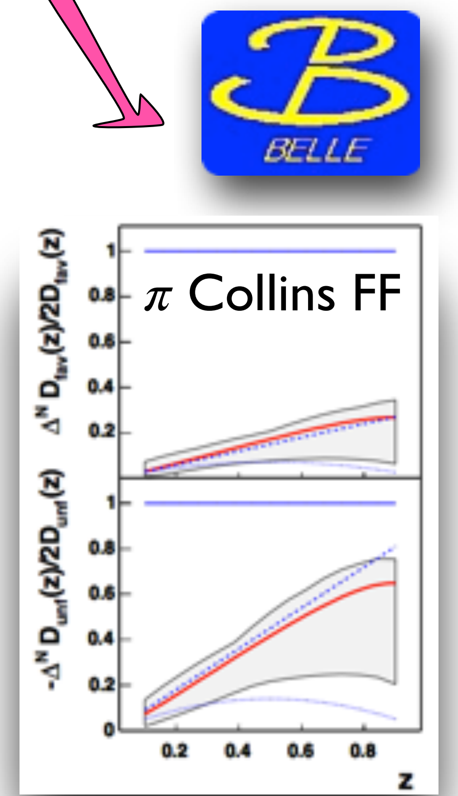
Collins amplitudes in SIDIS

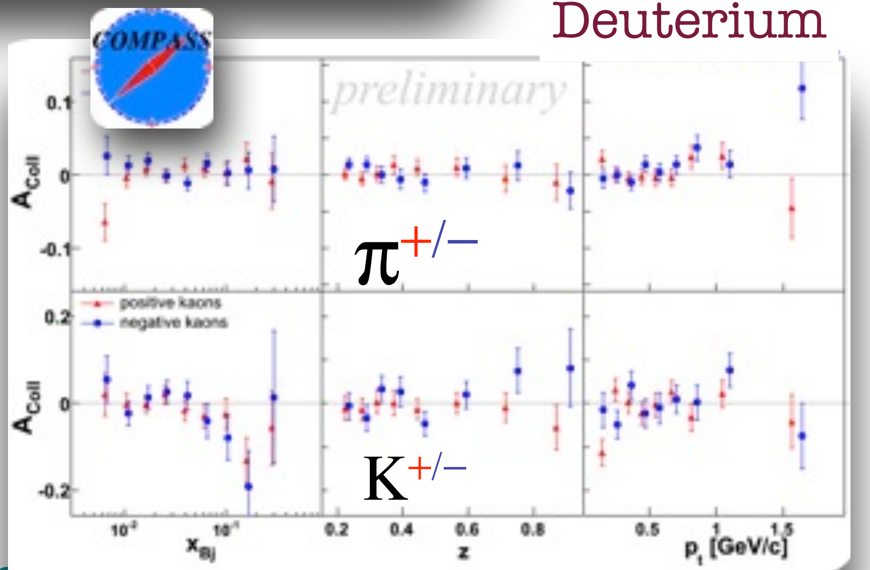
$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$

[Airapetian *et al.*, Phys. Lett. B 693 (2010) 11-16]





Deuterium



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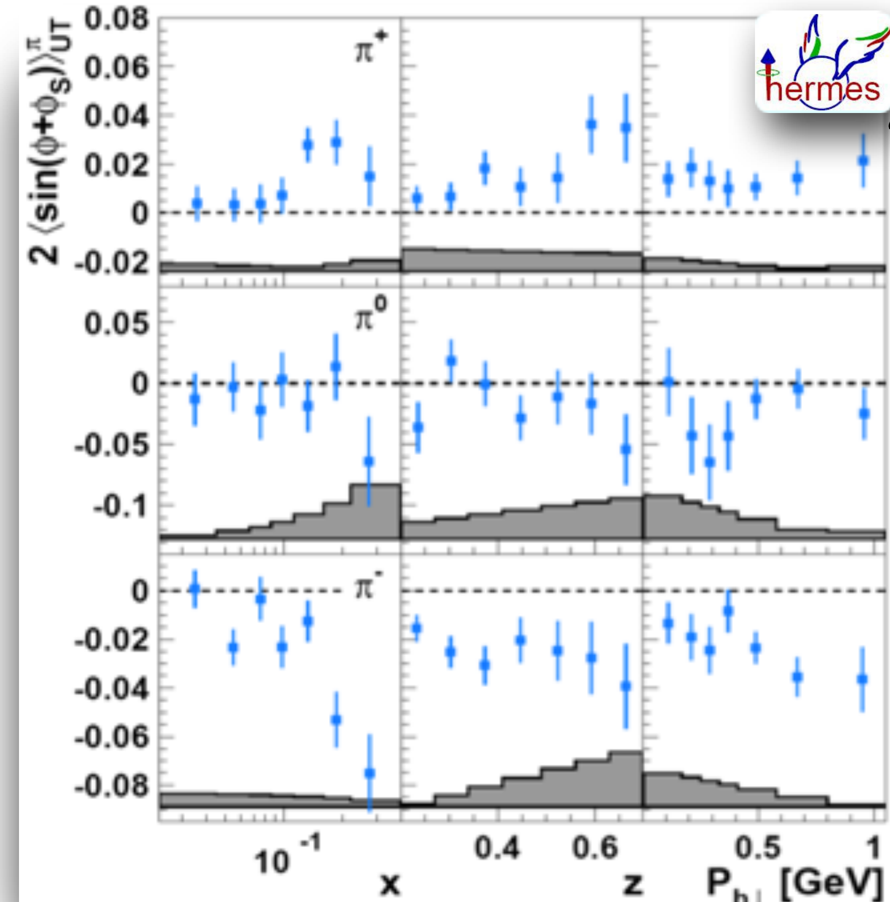
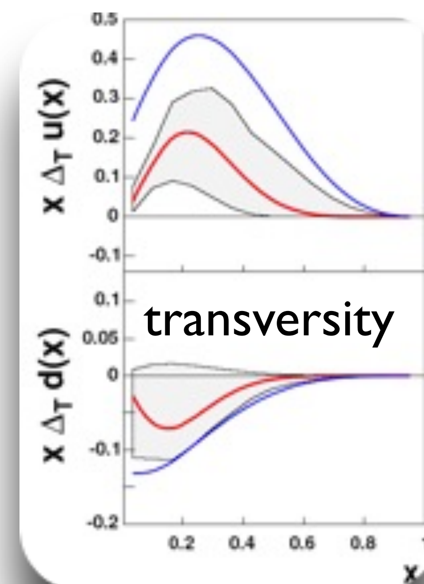
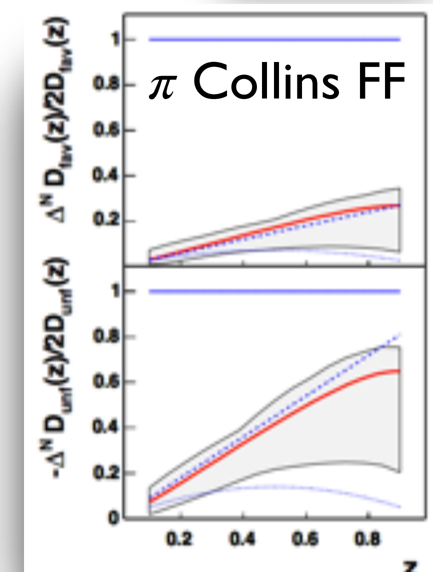


Anselmino et al.
Phys.Rev. D75 (2007)





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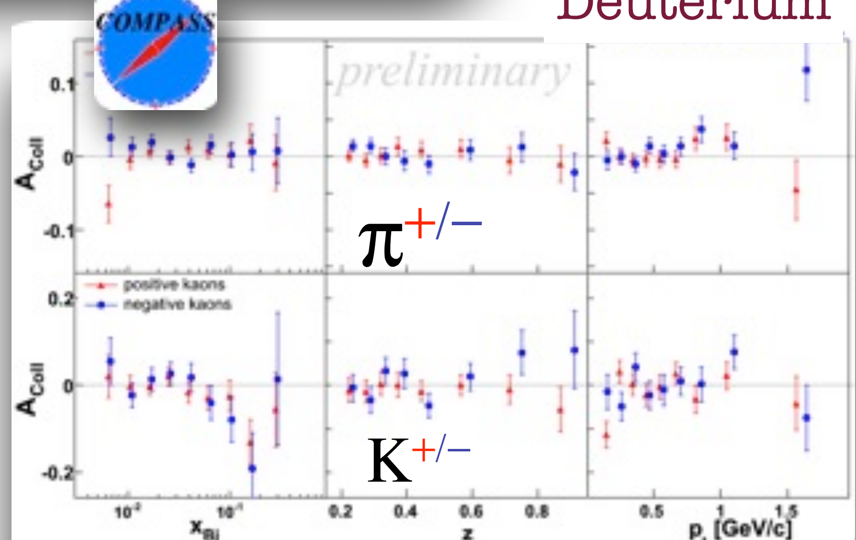

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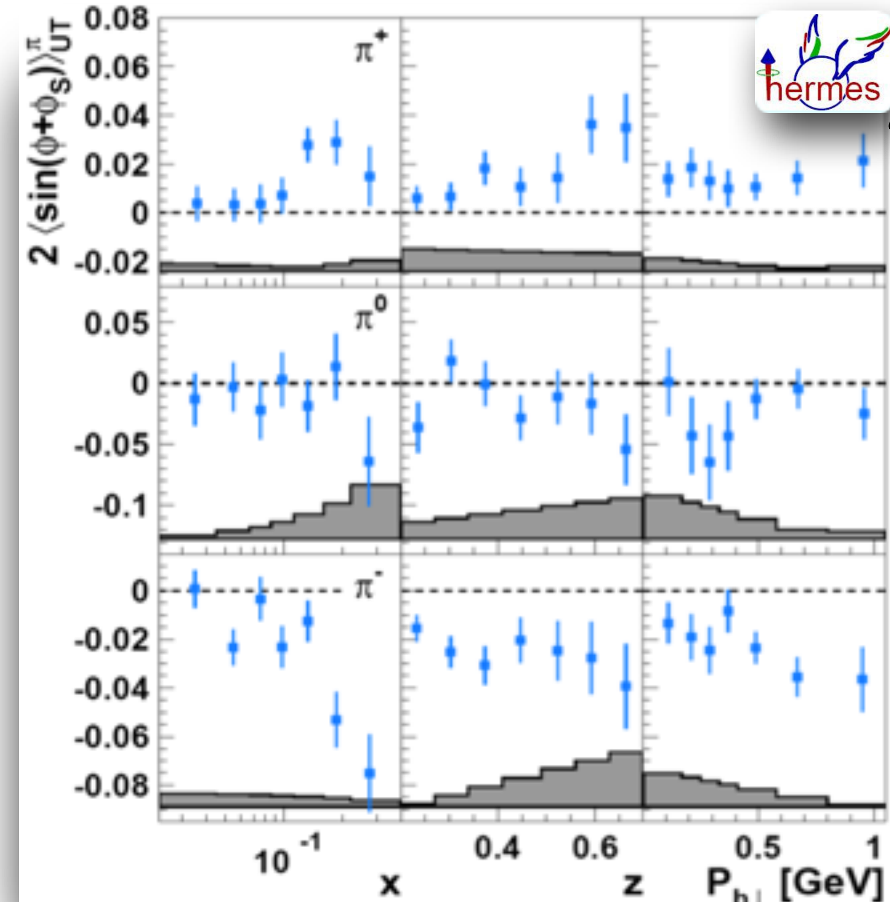

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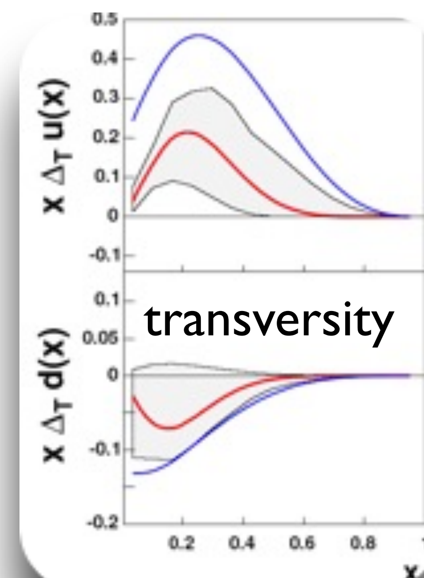
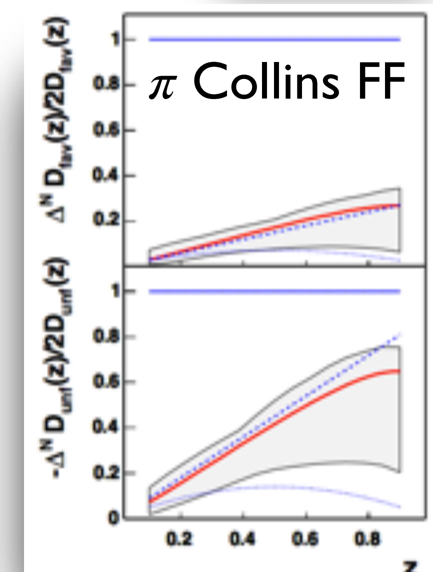
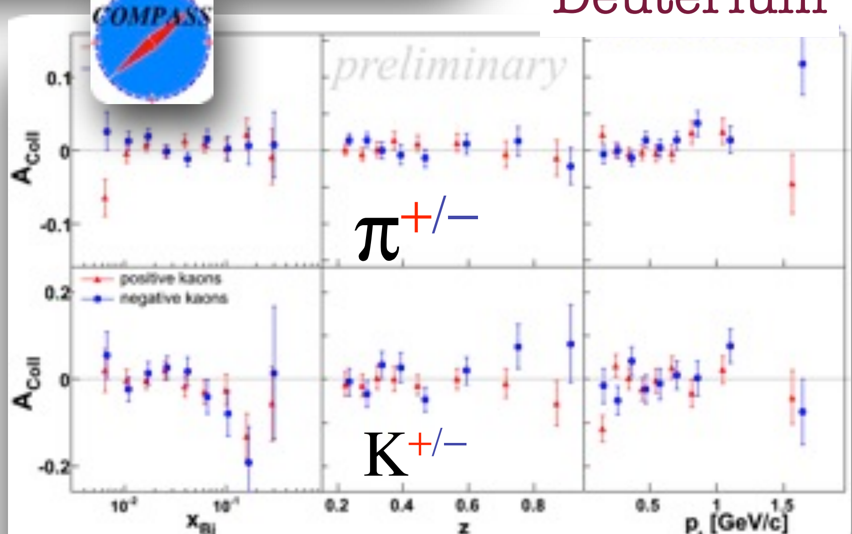
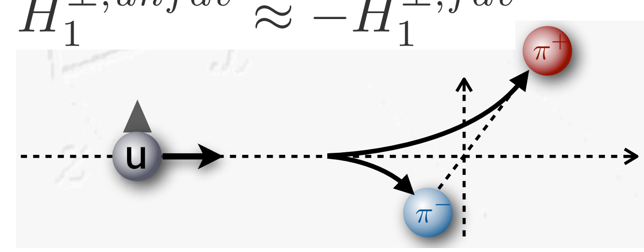




Deuterium

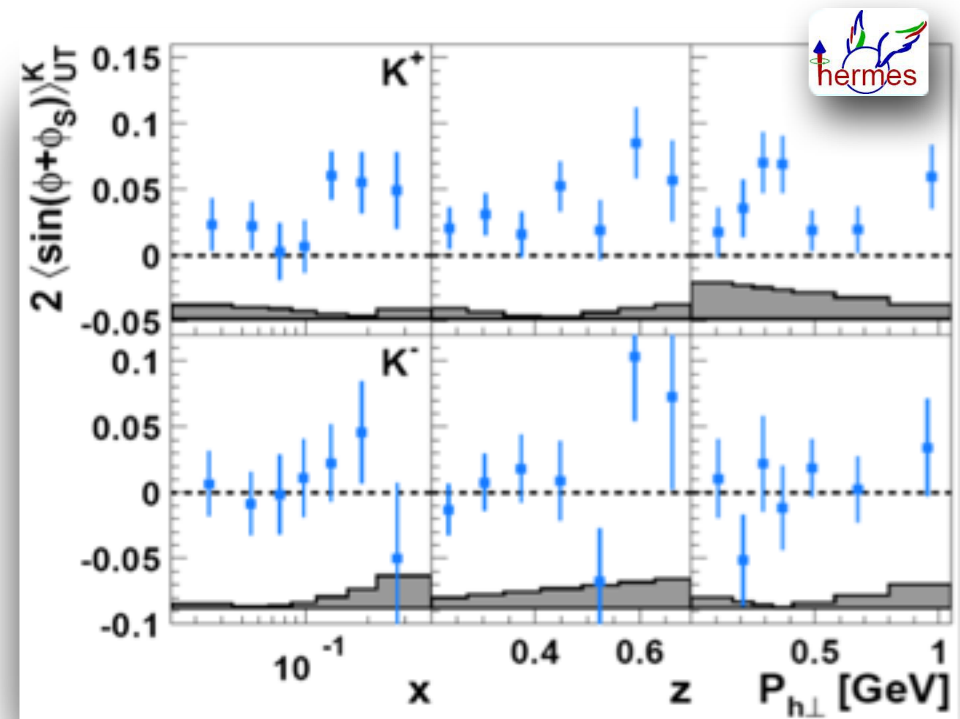


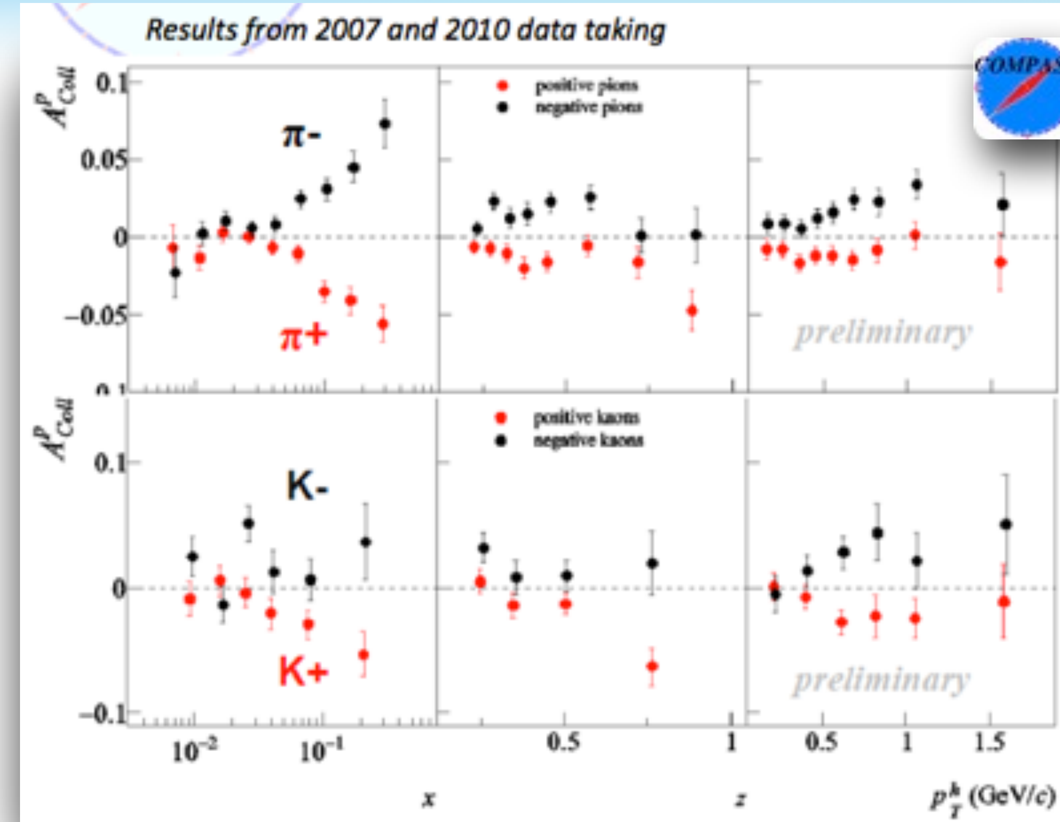
$$H_1^{\perp,unfav} \approx -H_1^{\perp,fav}$$



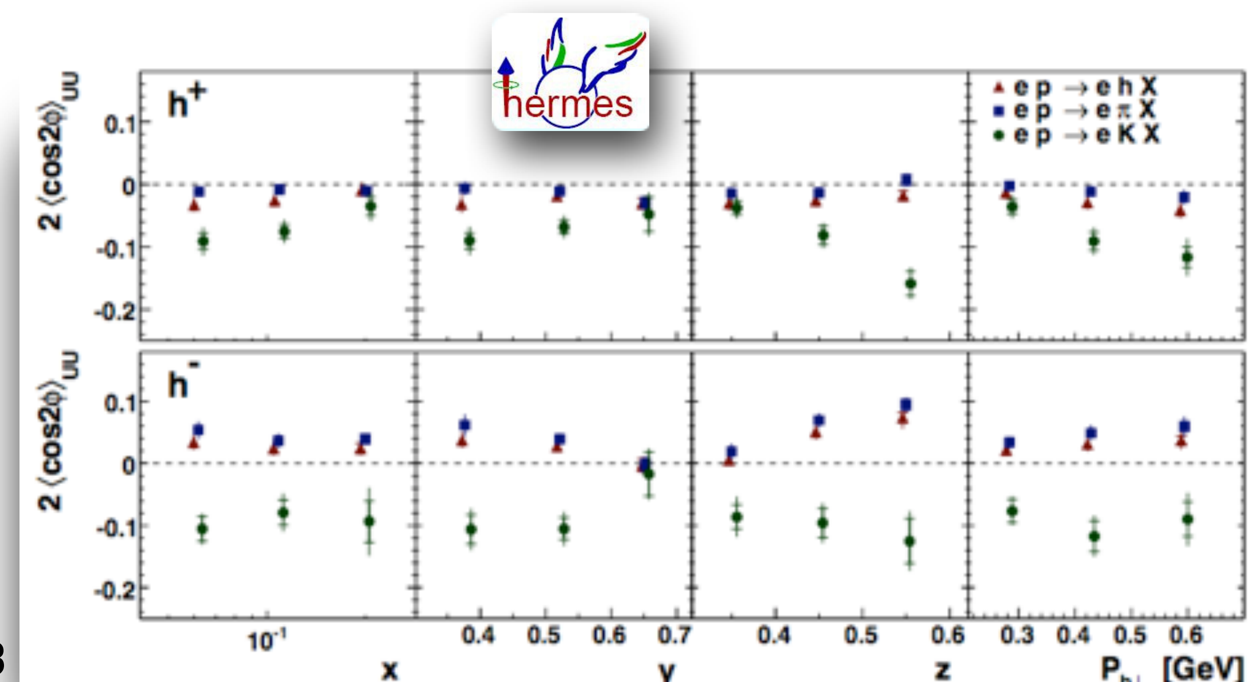
Collins amplitudes in SIDIS

$$A_{UT} \propto h_1 \otimes H_1^{\perp}$$





$$A_{UU} \propto h_1^{\perp} \otimes H_1^{\perp}$$



Collins amplitudes in SIDIS

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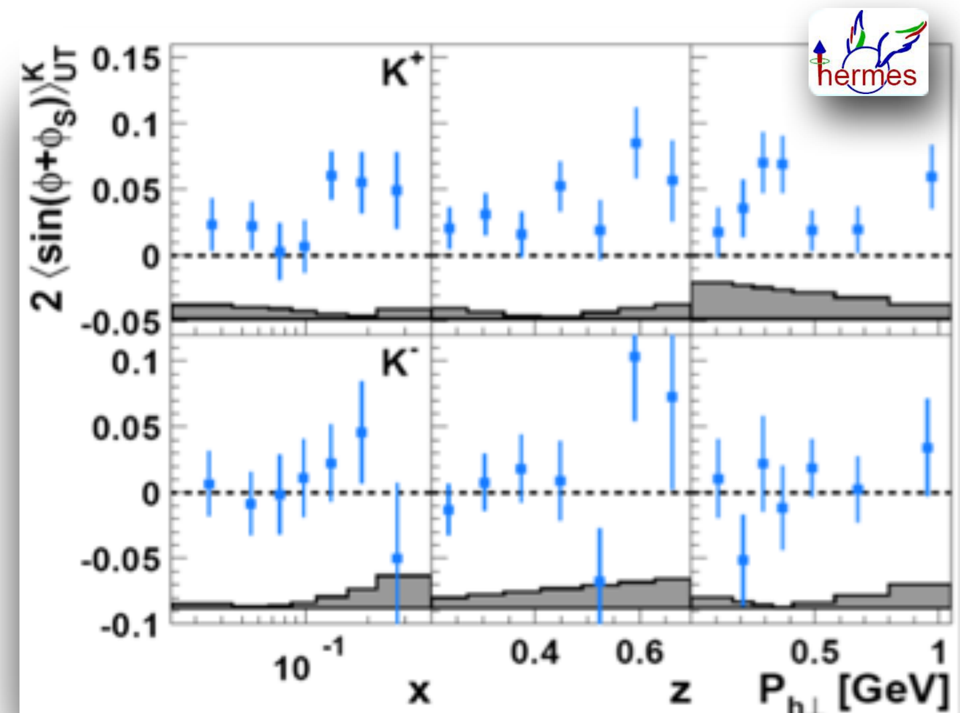
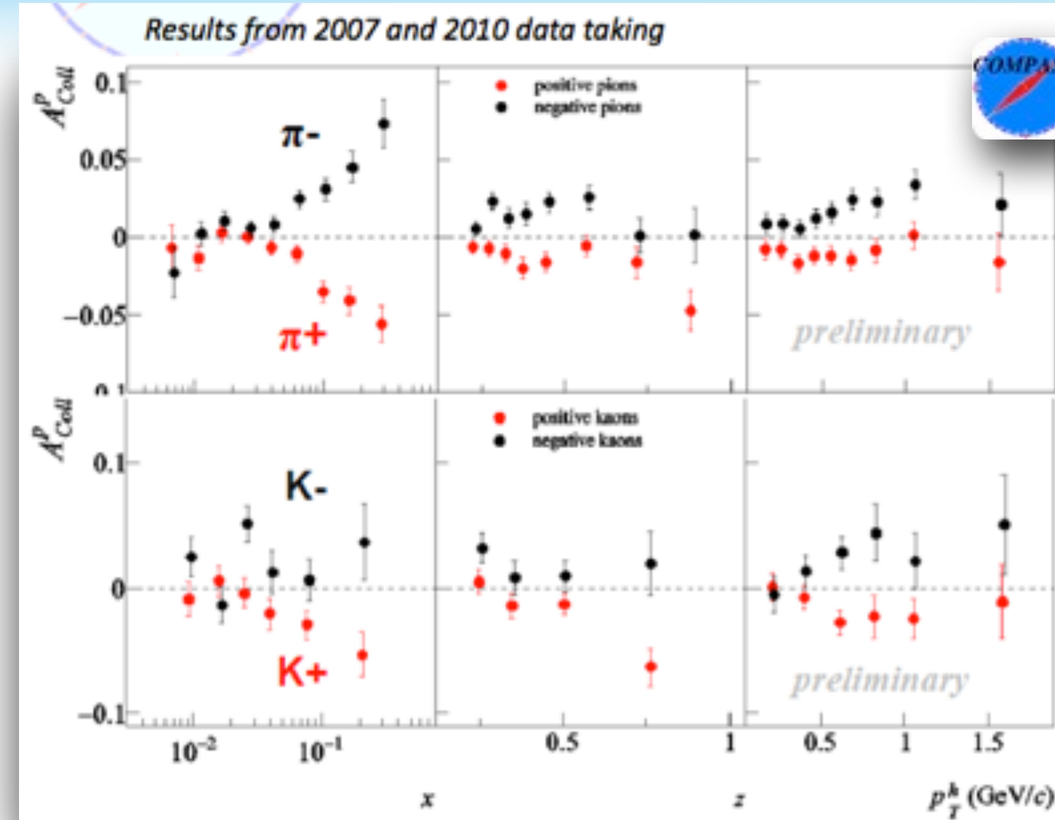
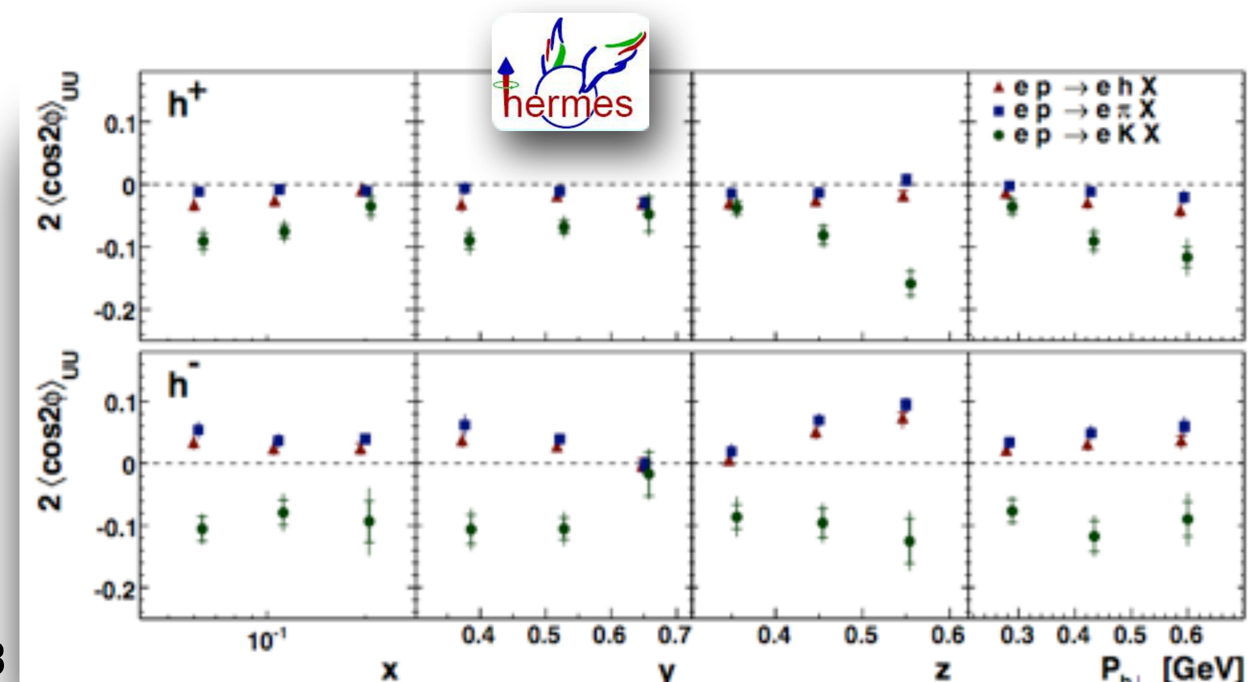


K⁺ amplitudes larger than π^+?



$$A_{UU} \propto h_1^{\perp} \otimes H_1^{\perp}$$



What's new?

	z	q_T	$\sin^2\theta/(1+\cos^2\theta)$	p_T
$\mathcal{D}_{ul}^{\pi\pi} = \mathcal{R}^{U\pi\pi}/\mathcal{R}^{L\pi\pi}$	√	√	√	New!
$\mathcal{D}_{ul}^{\pi k} = \mathcal{R}^{U\pi k}/\mathcal{R}^{L\pi k}$	New!	New!	New!	New!
$\mathcal{D}_{ul}^{kk} = \mathcal{R}^{Ukk}/\mathcal{R}^{Lkk}$	New!	New!	New!	New!

	z	q_T	$\sin^2\theta/(1+\cos^2\theta)$	p_T
$\mathcal{D}_{uc}^{\pi\pi} = \mathcal{R}^{U\pi\pi}/\mathcal{R}^{C\pi\pi}$	√	√	√	New!
$\mathcal{D}_{uc}^{\pi k} = \mathcal{R}^{U\pi k}/\mathcal{R}^{C\pi k}$	New!	New!	New!	New!
$\mathcal{D}_{uc}^{kk} = \mathcal{R}^{Ukk}/\mathcal{R}^{Ckk}$	New!	New!	New!	New!

What's new?

	z	q_T	$\sin^2\theta/(1+\cos^2\theta)$	p_T
$\mathcal{D}^{\pi\pi}_{ul} = \mathcal{R}^{U\pi\pi}/\mathcal{R}^{L\pi\pi}$	√	√	√	New!
$\mathcal{D}^{\pi k}_{ul} = \mathcal{R}^{U\pi k}/\mathcal{R}^{L\pi k}$	New!	New!	New!	New!
$\mathcal{D}^{kk}_{ul} = \mathcal{R}^{Ukk}/\mathcal{R}^{Lkk}$	New!	New!	New!	New!

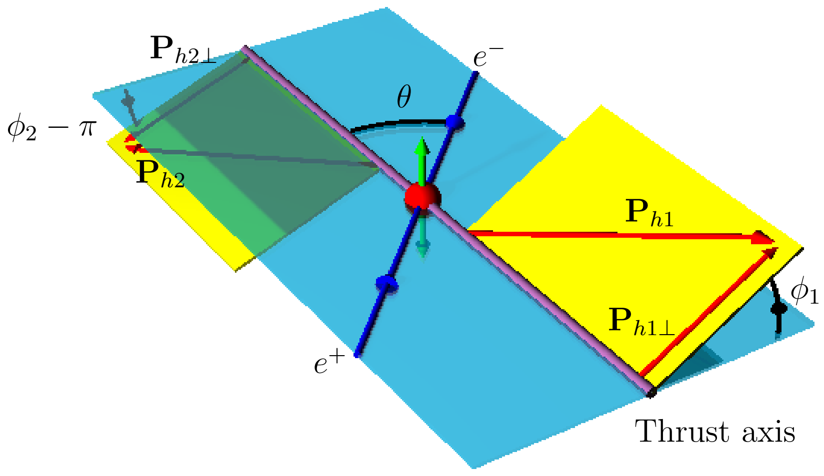
	z	q_T	$\sin^2\theta/(1+\cos^2\theta)$	p_T
$\mathcal{D}^{\pi\pi}_{uc} = \mathcal{R}^{U\pi\pi}/\mathcal{R}^{C\pi\pi}$	√	√	√	New!
$\mathcal{D}^{\pi k}_{uc} = \mathcal{R}^{U\pi k}/\mathcal{R}^{C\pi k}$	New!	New!	New!	New!
$\mathcal{D}^{kk}_{uc} = \mathcal{R}^{Ukk}/\mathcal{R}^{Ckk}$	New!	New!	New!	New!

Word of caution: this analysis is mainly aimed at kaons, so kinematic cuts and binning are optimized for kaons, and the same values used for pion too.

→ $\pi\pi$ results cannot be compared directly to published results

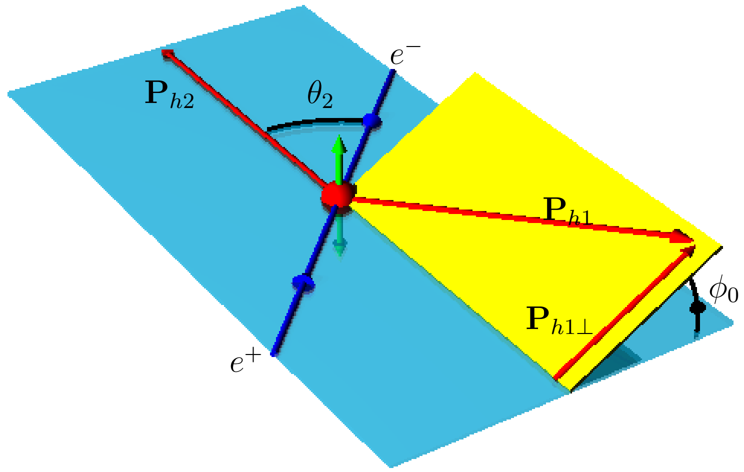
What's new?

$\phi_1+\phi_2$ method



$$\sigma \sim \mathcal{M}_{12}\Big(1 + \frac{\sin^2\theta_T}{1+\cos^2\theta_T}\, cos(\phi_1+\phi_2)\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\Big)$$

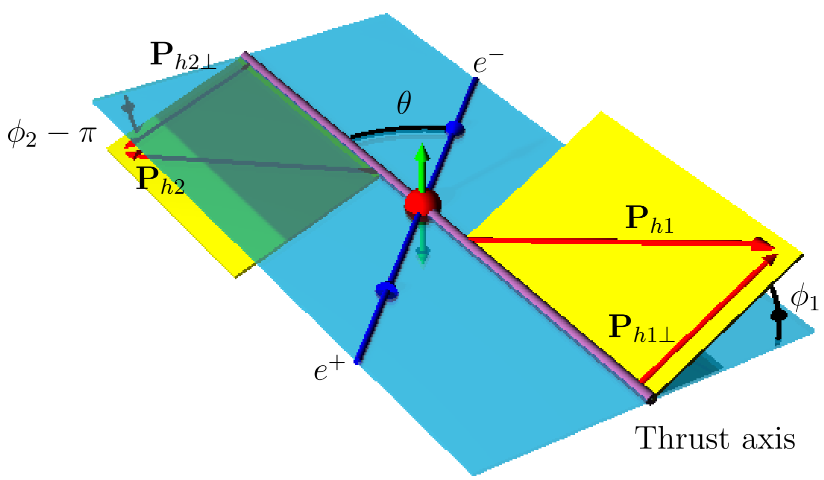
ϕ_0 method



$$\sigma \sim \mathcal{M}_0\Big(1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\, cos(2\phi_0)\mathcal{F}\Big[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\Big]\Big)$$

What's new?

$\phi_1+\phi_2$ method



$$\sigma \sim \mathcal{M}_{12}\Big(1 + \frac{\sin^2\theta_T}{1+\cos^2\theta_T} cos(\phi_1+\phi_2)\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\Big)$$

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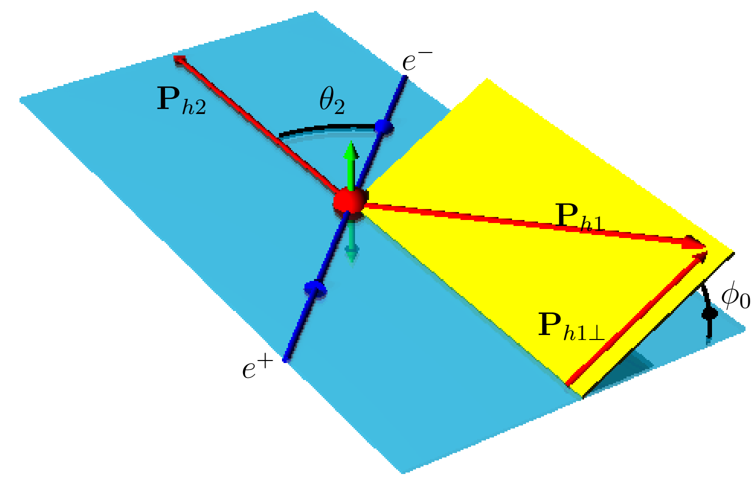

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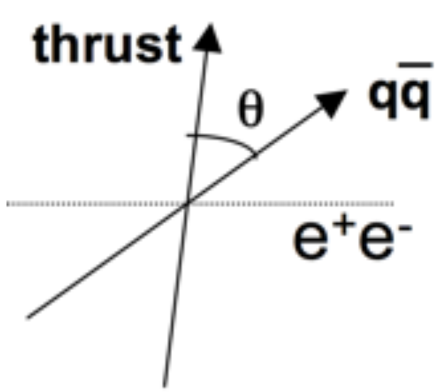
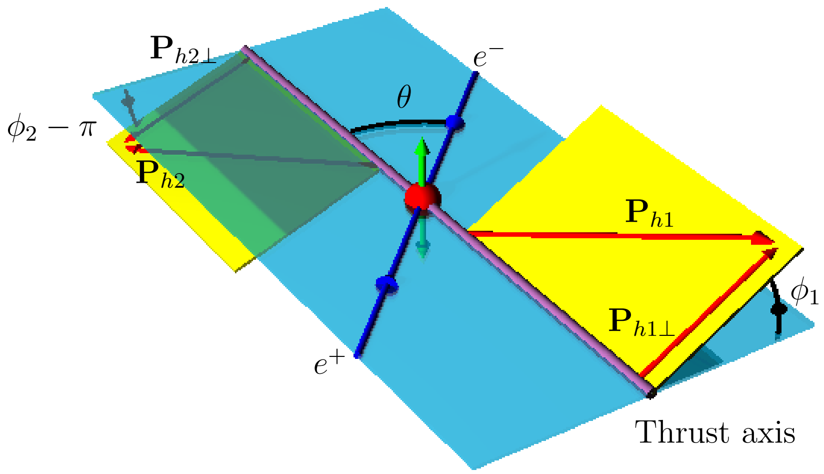


Both interesting: different integration of FFs in p_{Ti}, might provide information on the Collins p_T dependence

Technically more complicated: require the determination of a $q\bar{q}$ proxy (Thrust axis)

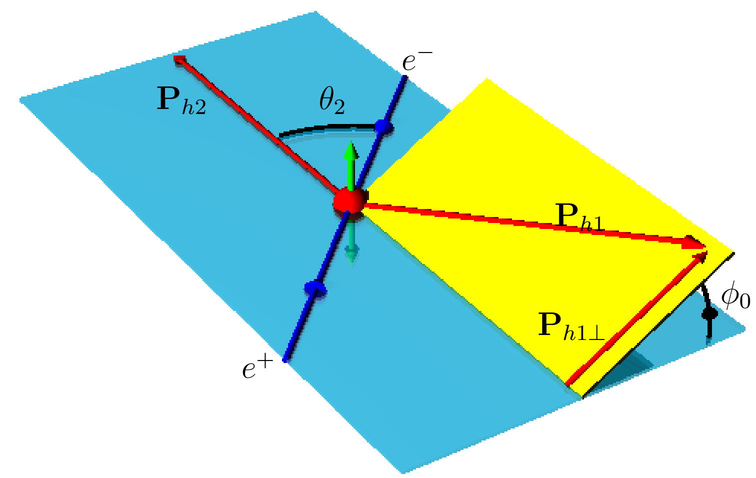
What's new?

$\phi_1+\phi_2$ method

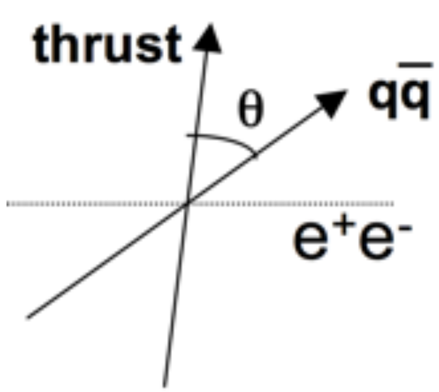


$$\sigma \sim \mathcal{M}_{12}\Big(1+\frac{\sin^2\theta_T}{1+\cos^2\theta_T}\,cos(\phi_1+\phi_2)\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\Big)$$

ϕ_0 method



$$\sigma \sim \mathcal{M}_0\Big(1+\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,cos(2\phi_0)\mathcal{F}\Big[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\Big]\Big)$$



Both interesting: different integration of FFs in p_{Ti}, might provide information on the Collins p_T dependence

Technically more complicated: require the determination of a $q\bar{q}$ proxy (Thrust axis)

Particle ID correction

$$N^{j,raw} = P_{ij} N^i$$

$i = \pi, K$

$j = e, \mu, \pi, K, p$

Perfect PID ⇨ $j = i$

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$$N^{j,raw} = P_{ij} N^i$$

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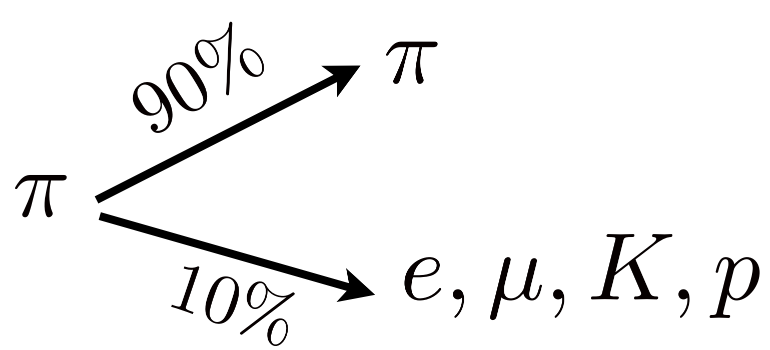
$j = e, \mu, \pi, K, p$

Perfect PID ⇨ $j = i$

ε(π) ≳ 90% ε(K) ≳ 85%



$$P_{ij} = \begin{pmatrix} P_{e\to e} & P_{e\to\mu} & P_{e\to\pi} & P_{e\to K} & P_{e\to p} \\ P_{\mu\to e} & P_{\mu\to\mu} & P_{\mu\to\pi} & P_{\mu\to K} & P_{\mu\to p} \\ P_{\pi\to e} & P_{\pi\to\mu} & P_{\pi\to\pi} & P_{\pi\to K} & P_{\pi\to p} \\ P_{K\to e} & P_{K\to\mu} & P_{K\to\pi} & P_{K\to K} & P_{K\to p} \\ P_{p\to e} & P_{p\to mu} & P_{p\to\pi} & P_{p\to K} & P_{p\to p} \end{pmatrix}$$

Particle ID correction

$i = \pi, K$

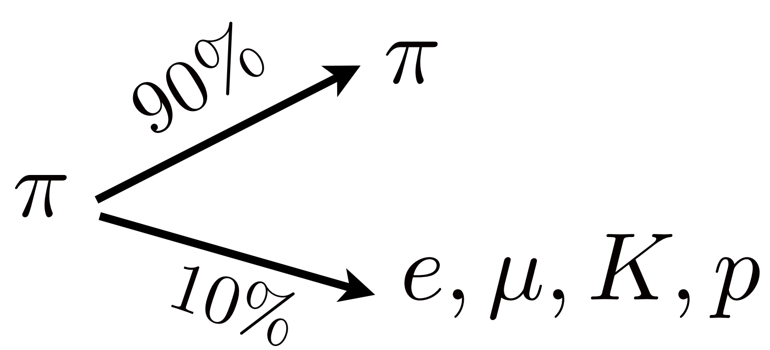
$j = e, \mu, \pi, K, p$

$$N^{j,raw} = P_{ij} N^i$$

$$N^i = P^{-1}_{ij} N^{j,raw}$$

Perfect PID ⇨ $j = i$

ε(π) ≳ 90% ε(K) ≳ 85%



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How to determine the P_{ij}?

$$D^* \rightarrow D^0 \pi^+_{slow}, \quad D^0 \rightarrow K^- \pi^+_{fast}$$

From data!

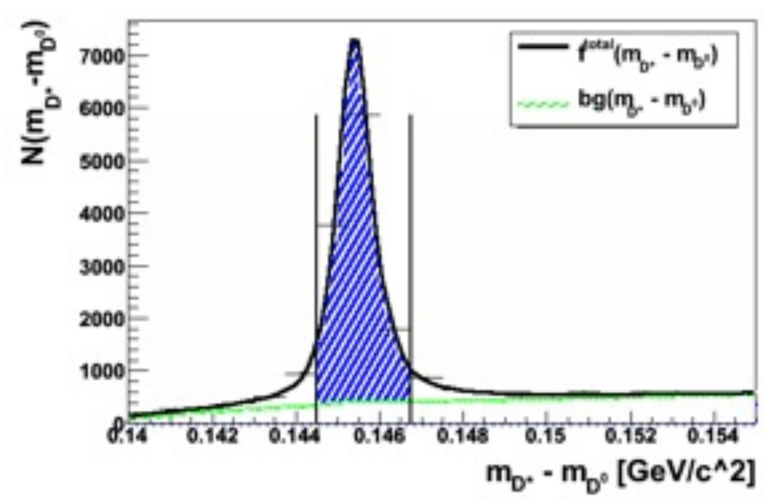
How to determine the P_{ij}?

From data!

$$D^* \to D^0 \; \pi^+_{slow}$$

$$D^0 \to K^- \; \pi^+_{fast}$$

$$m_D^* - m_D^0$$



Negative hadron = K^-
(no PID likelihood used)

How to determine the P_{ij}?

From data!

$$D^* \longrightarrow D^0 \longrightarrow K^-$$
$$D^* \longrightarrow \pi^+_{slow}, \quad D^0 \longrightarrow \pi^+_{fast}$$

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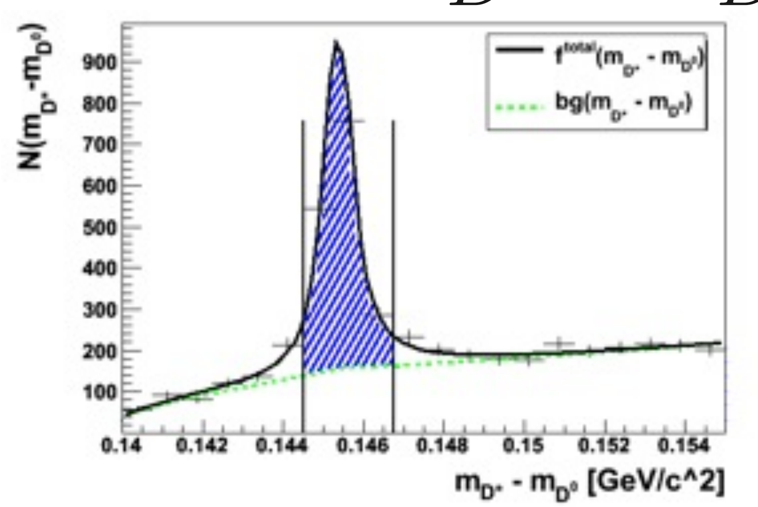
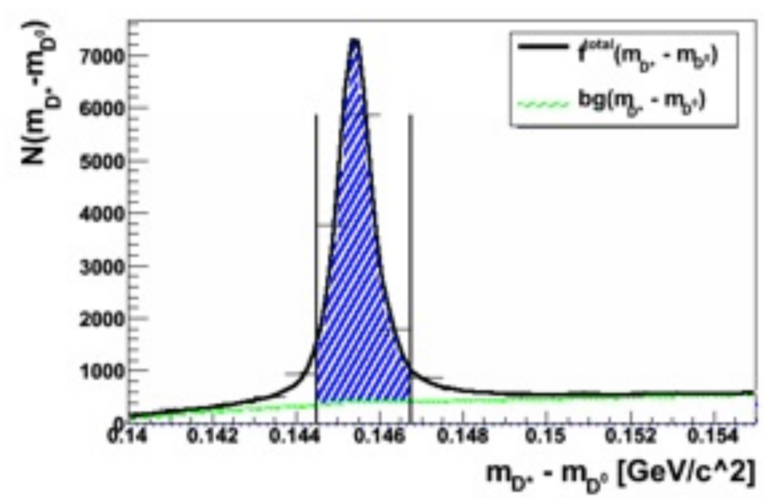


Negative hadron identified as π^-

$$m_D^* - m_D^0$$



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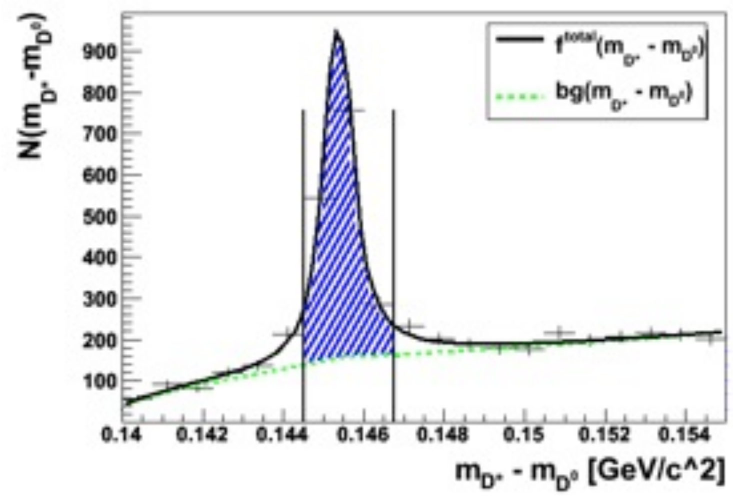
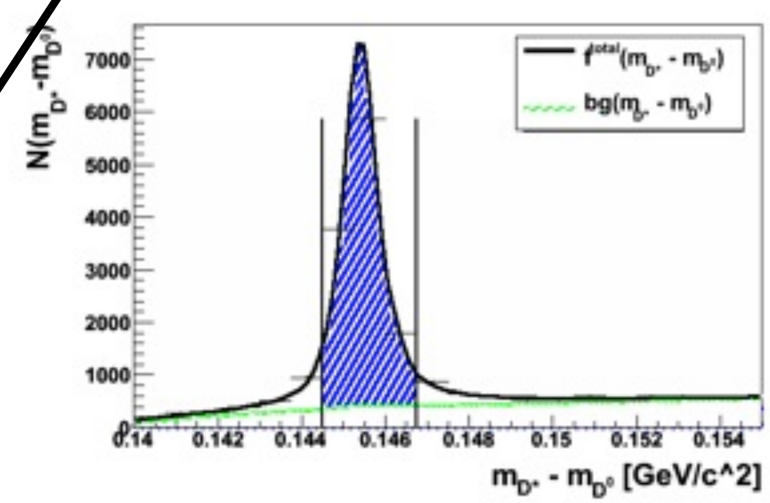


Negative hadron identified as π^-

$$P_{K^- \to \pi^-}$$

$$m_D^* - m_D^0$$



Negative hadron = K^-
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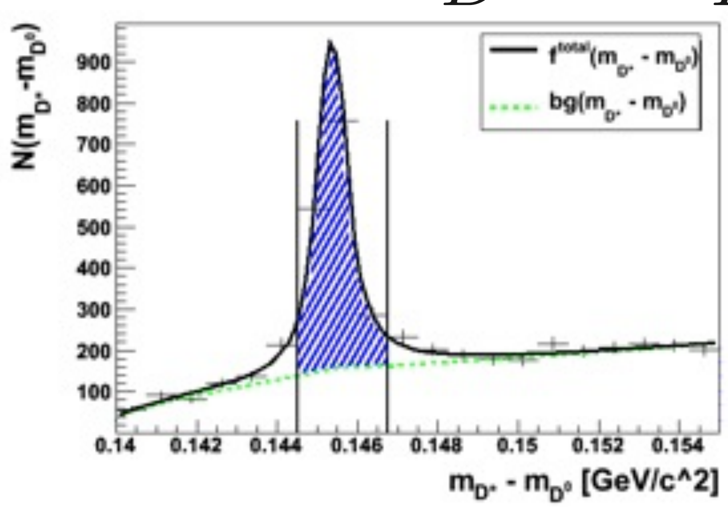
How to determine the P_{ij}?

From data!

$$D^* \longrightarrow D^0 \longrightarrow K^-$$
$$D^* \longrightarrow \pi^+_{slow} \qquad D^0 \longrightarrow \pi^+_{fast}$$

$$m_D^* - m_D^0$$

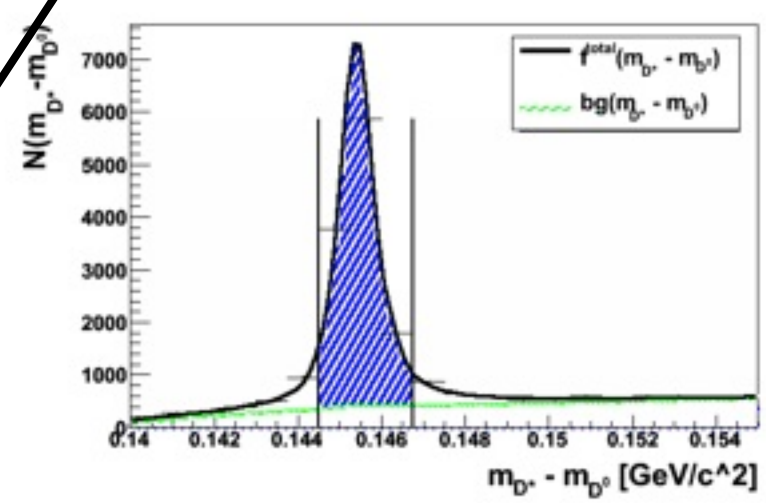


Negative hadron identified as π^-

$$P_{K^- \to \pi^-}$$

K^-

$$m_D^* - m_D^0$$



$$P_{K^- \to K^-}$$

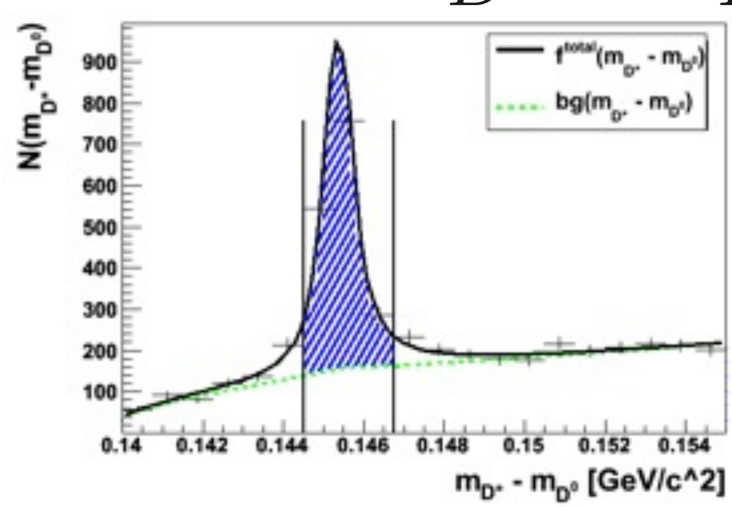
Negative hadron = K^-
(no PID likelihood used)

How to determine the P_{ij}?

From data!

$$D^* \rightarrow D^0 \, \pi^+_{slow}, \quad D^0 \rightarrow K^- \, \pi^+_{fast}$$

$m_D^* - m_D^0$



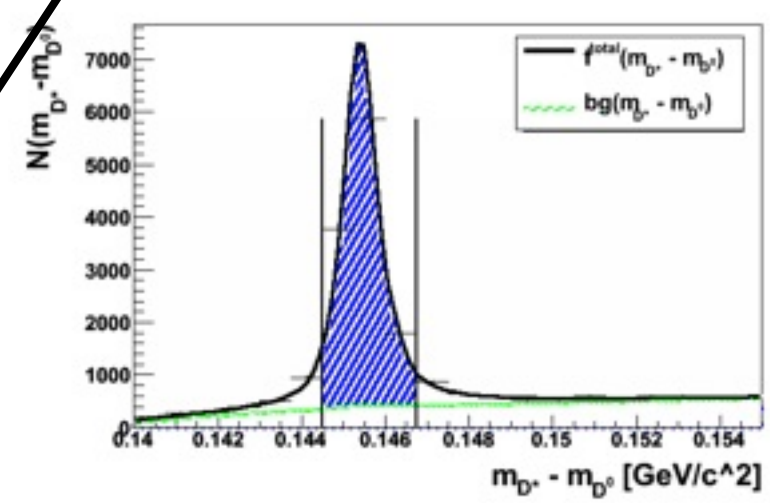
Negative hadron identified as π^-

K^-

$\bar{p}$

$P_{K^- \rightarrow \pi^-}$

$m_D^* - m_D^0$



Negative hadron = K^-
(no PID likelihood used)

$P_{K^- \rightarrow K^-}$

$P_{K^- \rightarrow \bar{p}}$

How to determine the P_{ij}?

From data!

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$$D^0 \rightarrow K^- \, \pi^+_{fast}$$

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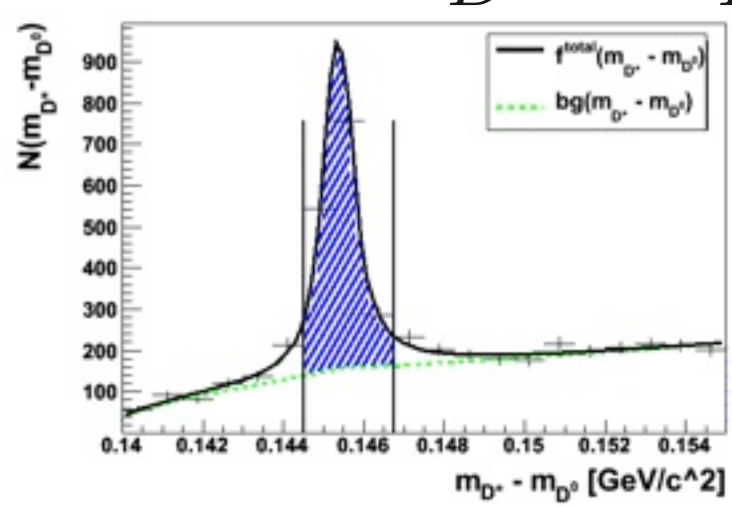
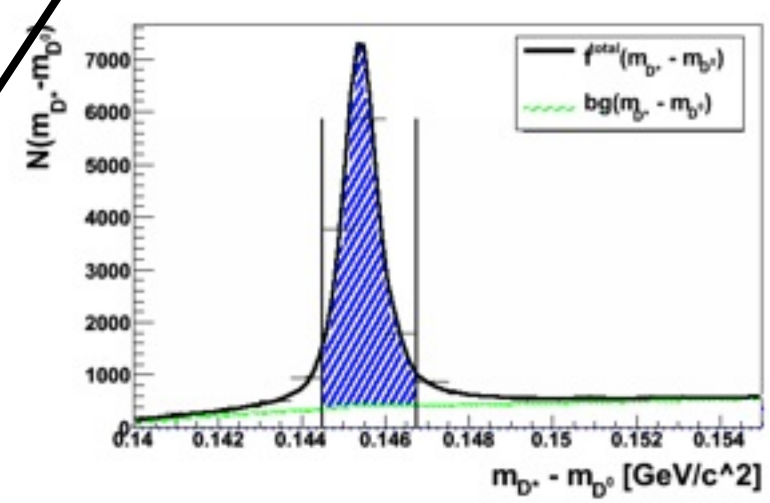


Negative hadron identified as π^-

K^- $\bar{p}$ μ^-

$$P_{K^- \rightarrow \pi^-}$$

$$m_D^* - m_D^0$$



Negative hadron = K^- (no PID likelihood used)

$$P_{K^- \rightarrow K^-}$$
$$P_{K^- \rightarrow \bar{p}}$$
$$P_{K^- \rightarrow \mu^-}$$

How to determine the P_{ij}?

From data!

$$D^* \rightarrow D^0 \, \pi^+_{slow}, \quad D^0 \rightarrow K^- \, \pi^+_{fast}$$

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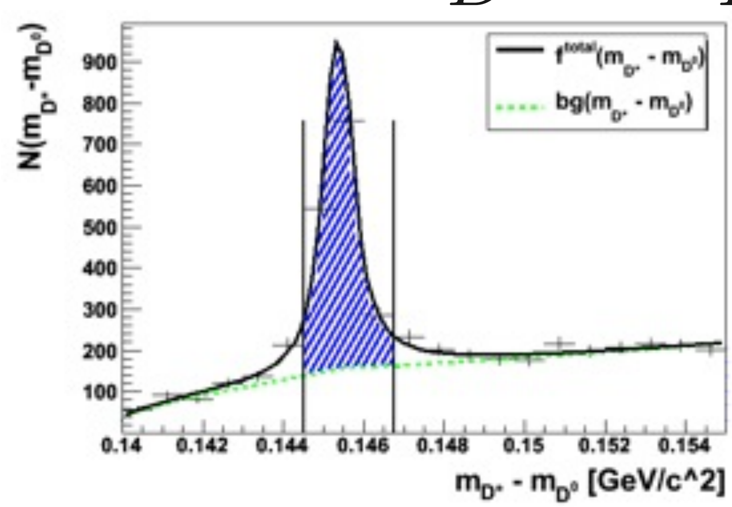
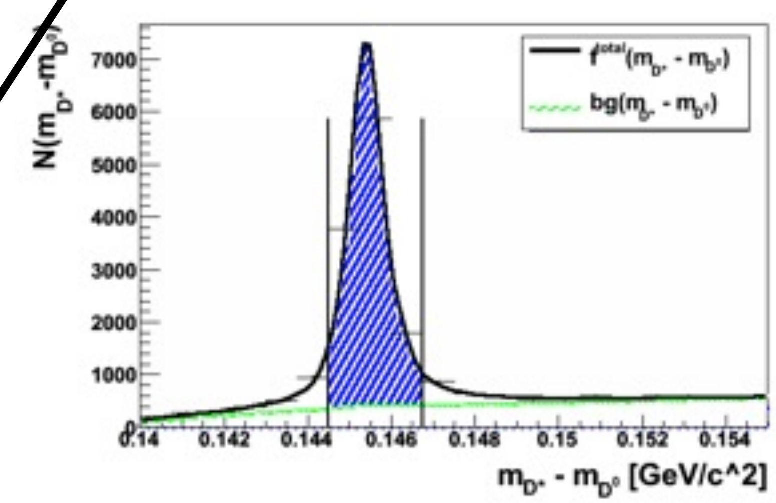


Negative hadron identified as π^-

$\rightarrow K^-, \bar{p}, \mu^-, e^-$

$$P_{K^- \rightarrow \pi^-}$$

$m_D^* - m_D^0$



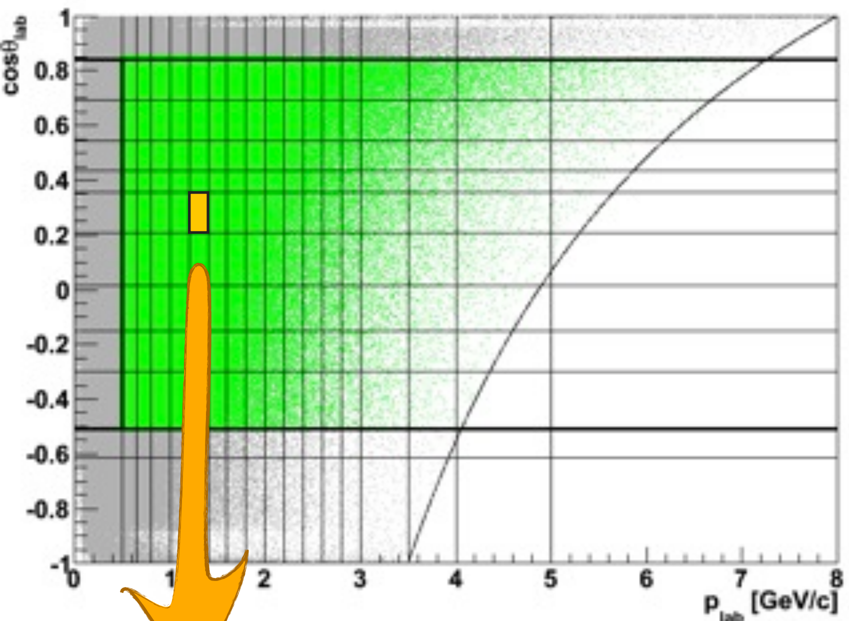
Negative hadron = K^-
(no PID likelihood used)

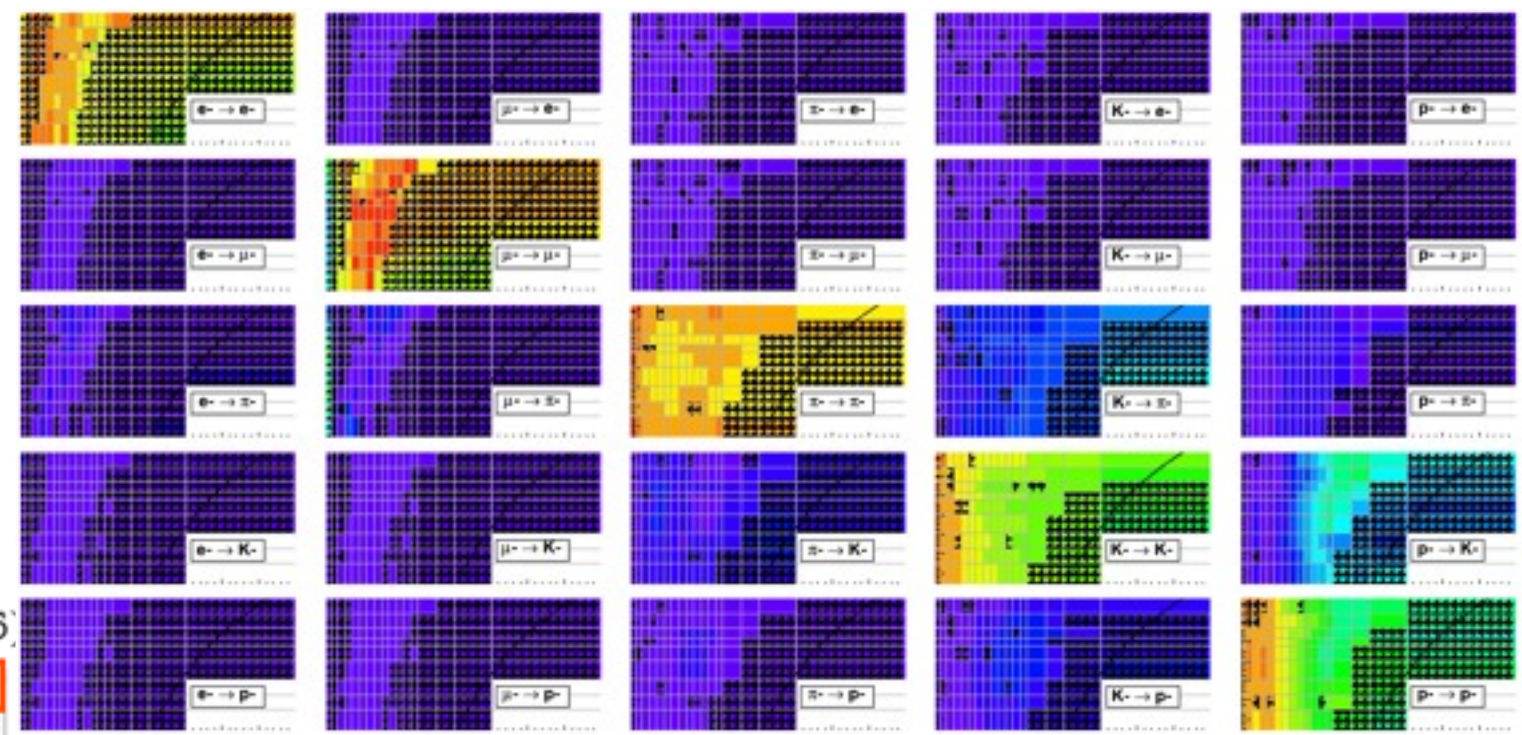
$$P_{K^- \rightarrow K^-}$$
$$P_{K^- \rightarrow \bar{p}}$$
$$P_{K^- \rightarrow \mu^-}$$
$$P_{K^- \rightarrow e^-}$$

2D correction

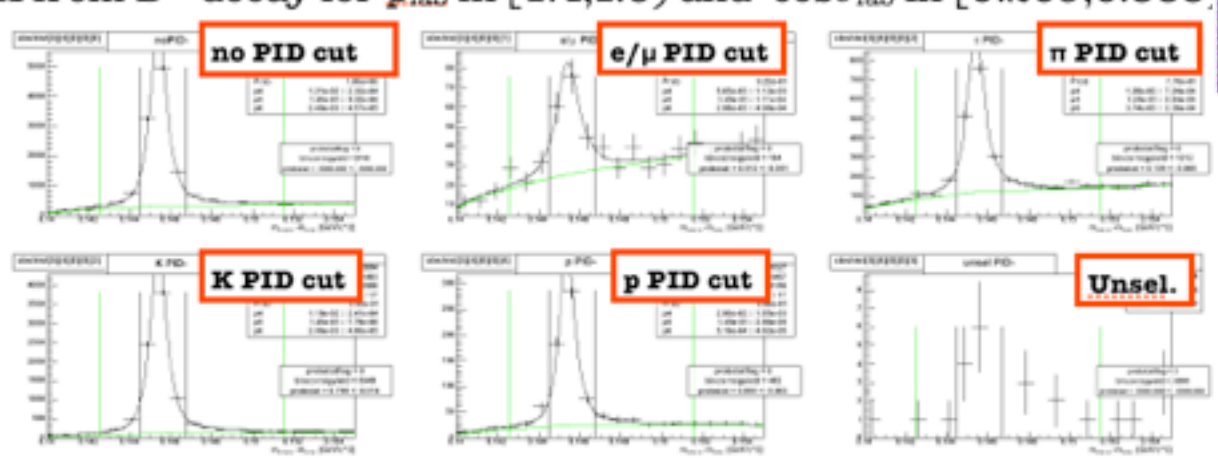
Detector performance depends on momentum and scattering angle!

$$P_{ij} \Rightarrow P_{ij}(p,\theta)$$

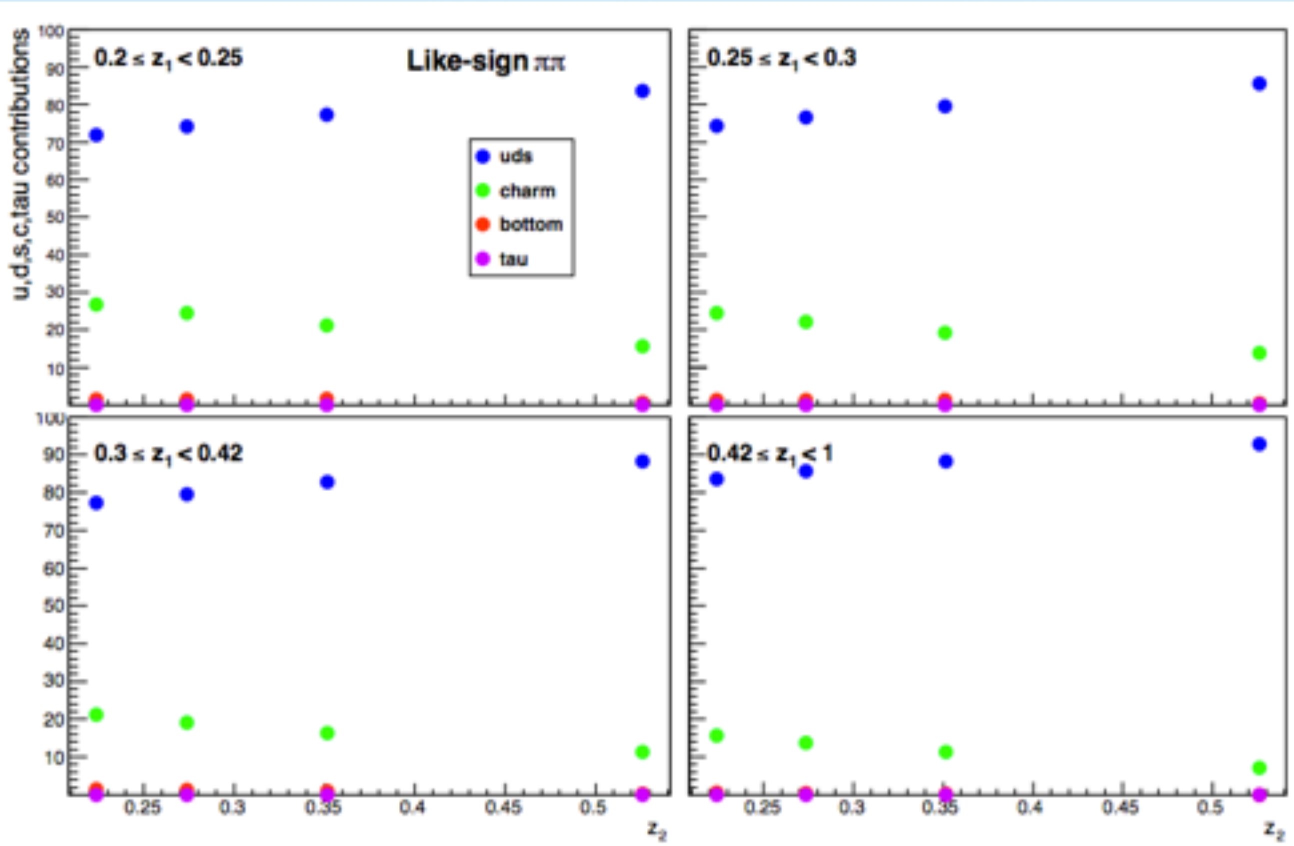




K from D* decay for p_{lab} in [1.4,1.6) and $\cos\theta_{lab}$ in [0.209,0.355)

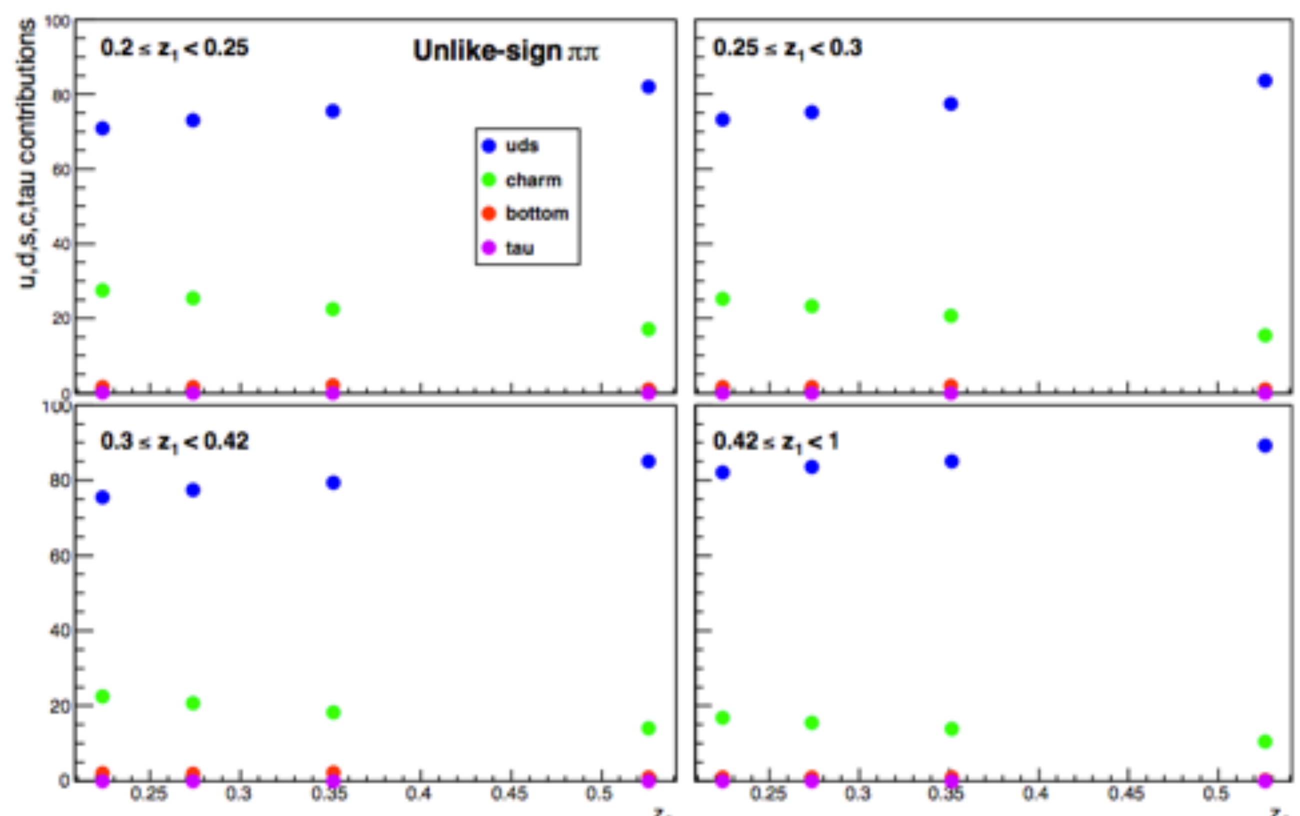


uds-charm-bottom-tau contributions

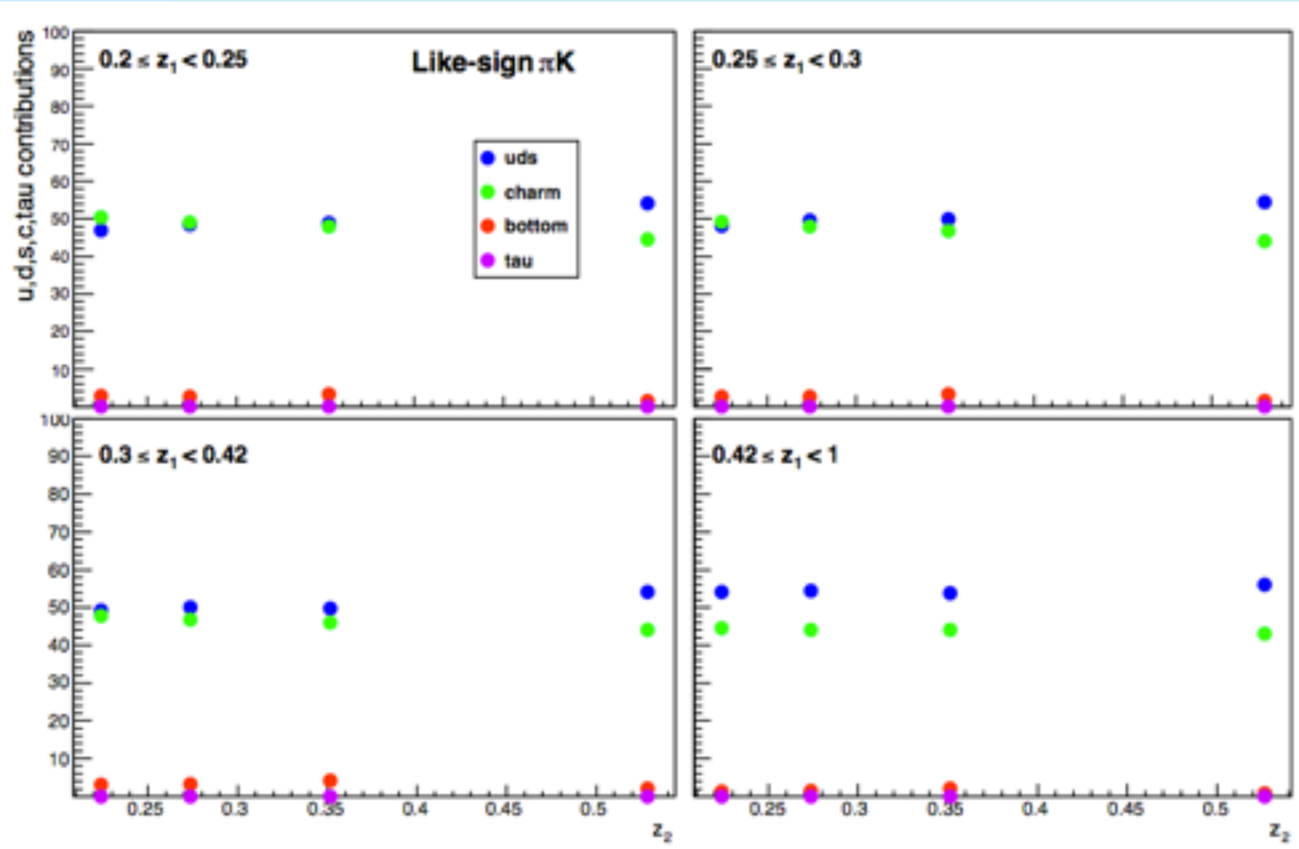


$\pi\pi$ couples

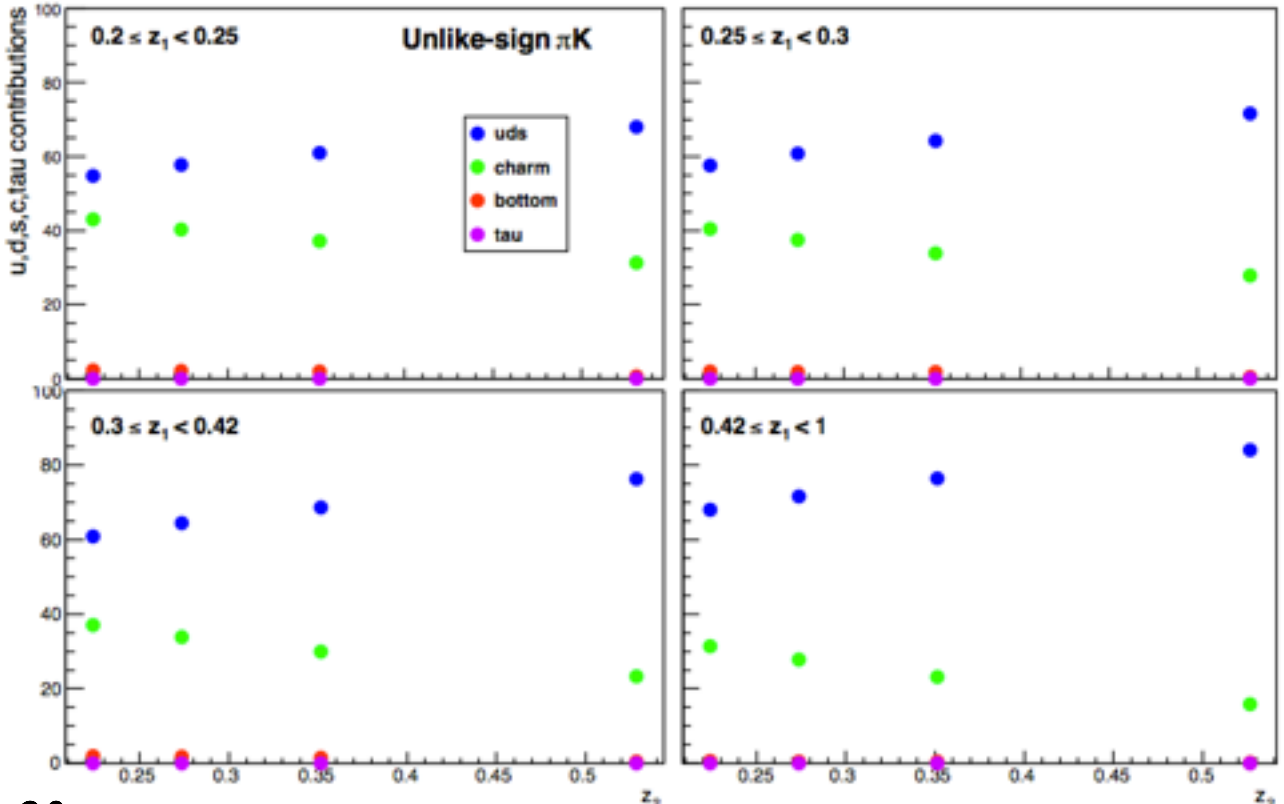
Published $\pi\pi$ studied a charm enhanced data and found charm contribute only as dilution
=> charm contribution corrected out



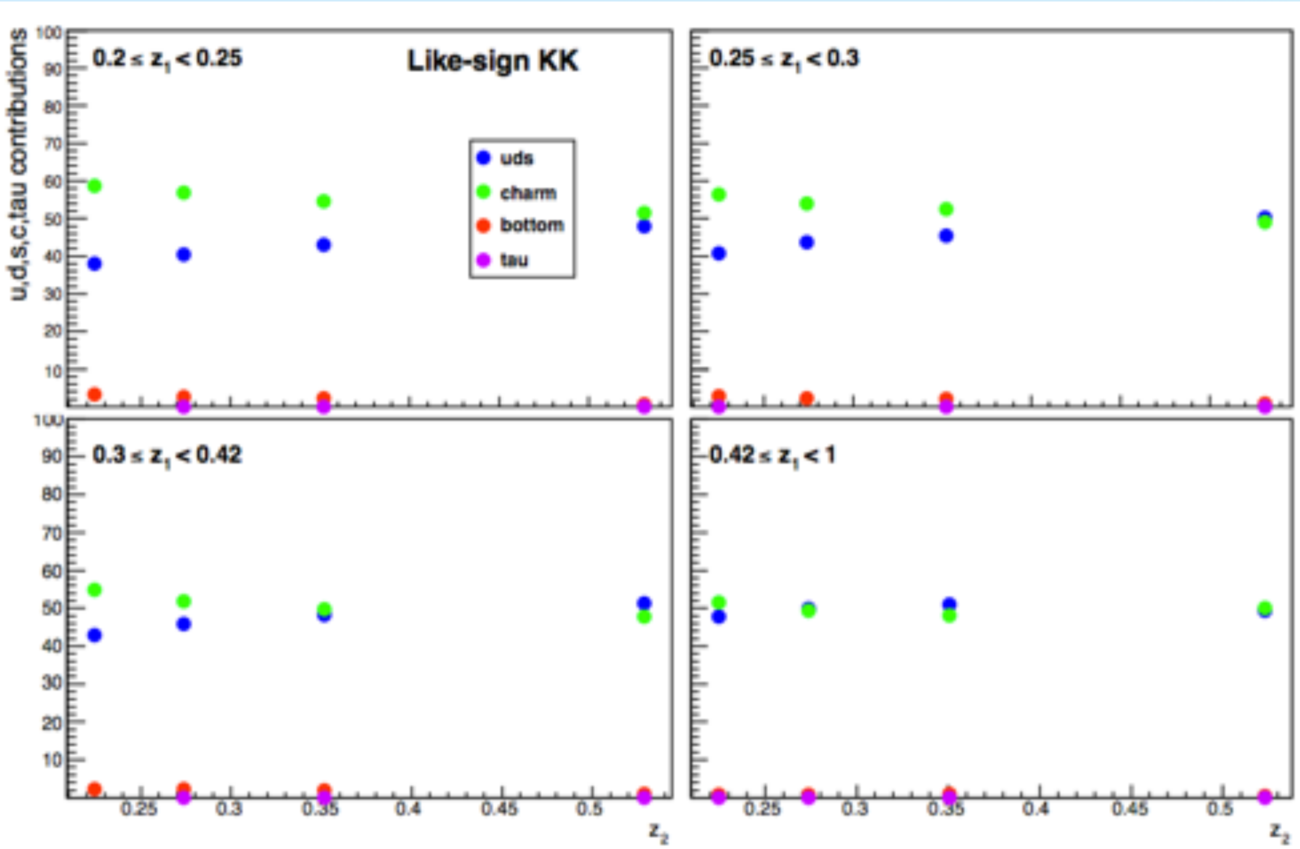
uds-charm-bottom-tau contributions



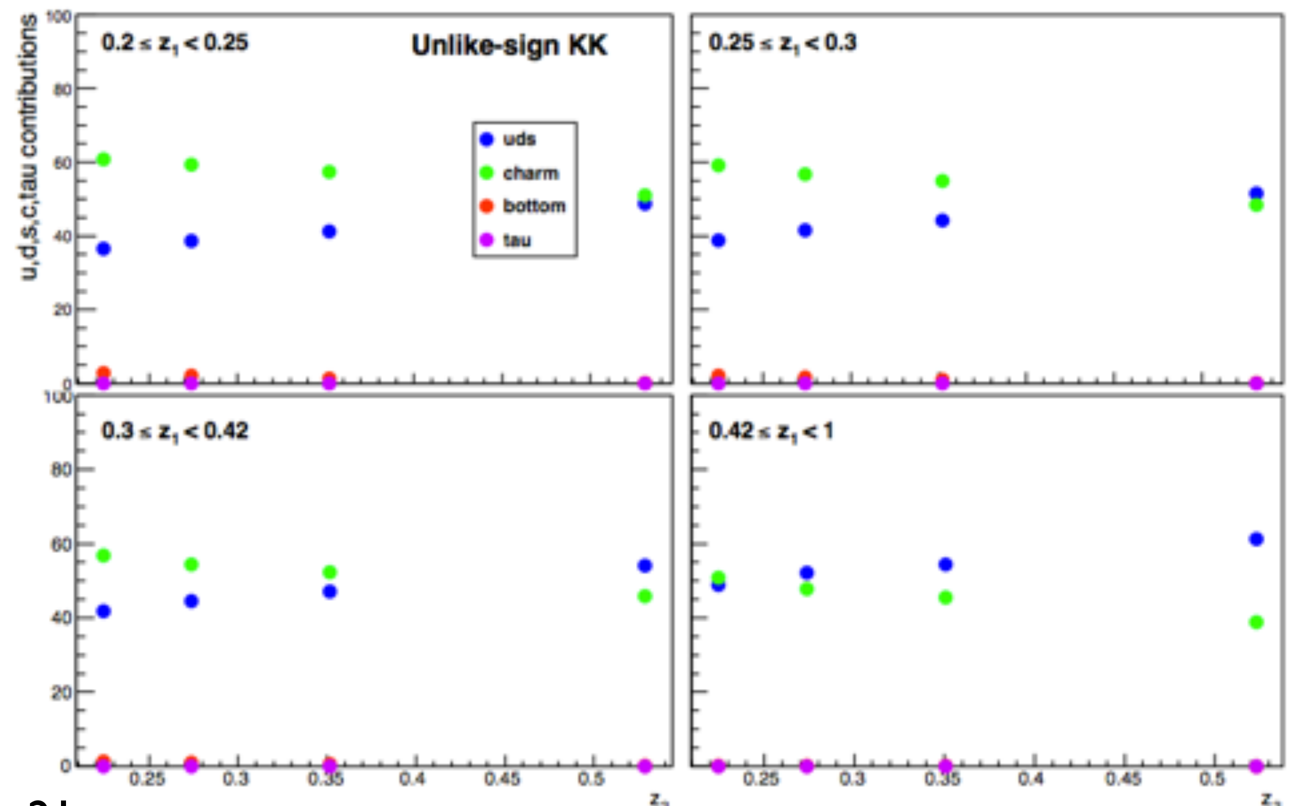
πK couples



uds-charm-bottom-tau contributions



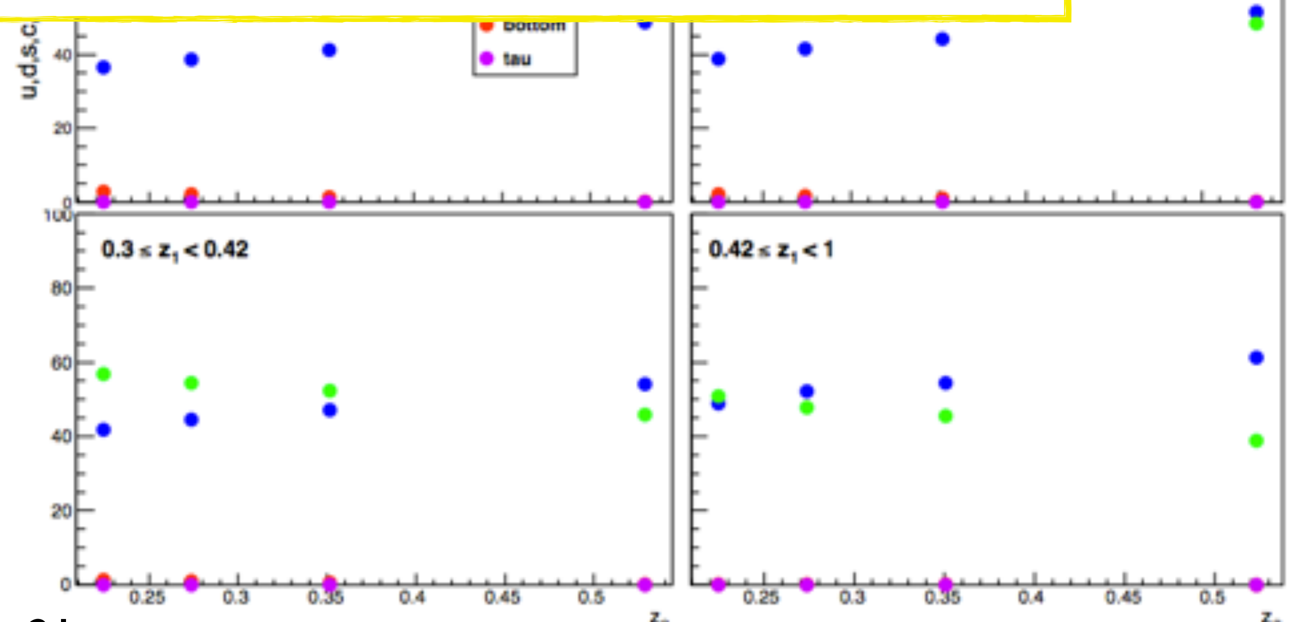
KK couples



uds-charm-bottom-tau contributions

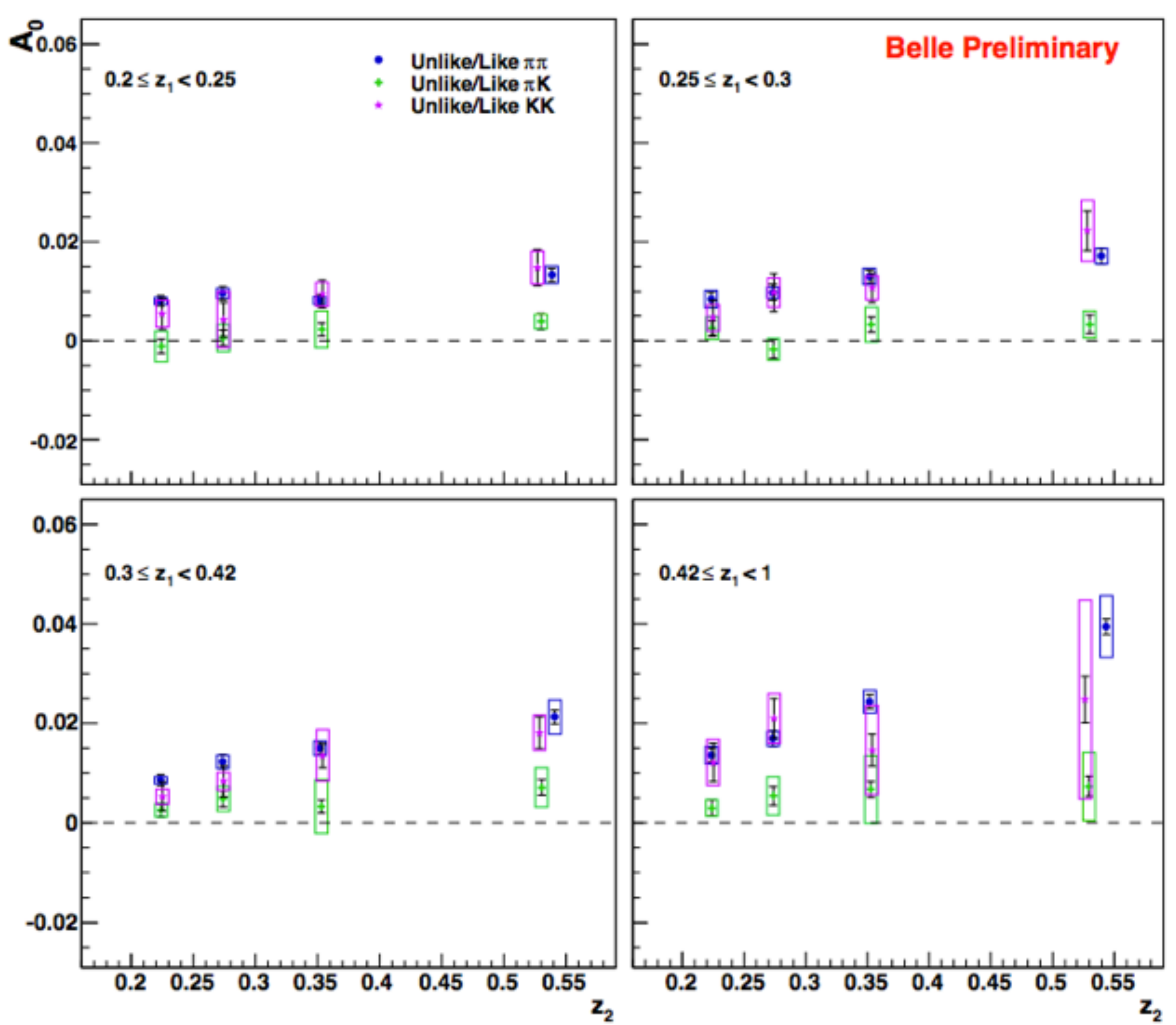
KK couples

For the moment charm contribution
is not being corrected out
in any of the samples ($\pi\pi$, πK, KK)



Collins asymmetries

ϕ_0 asymmetries

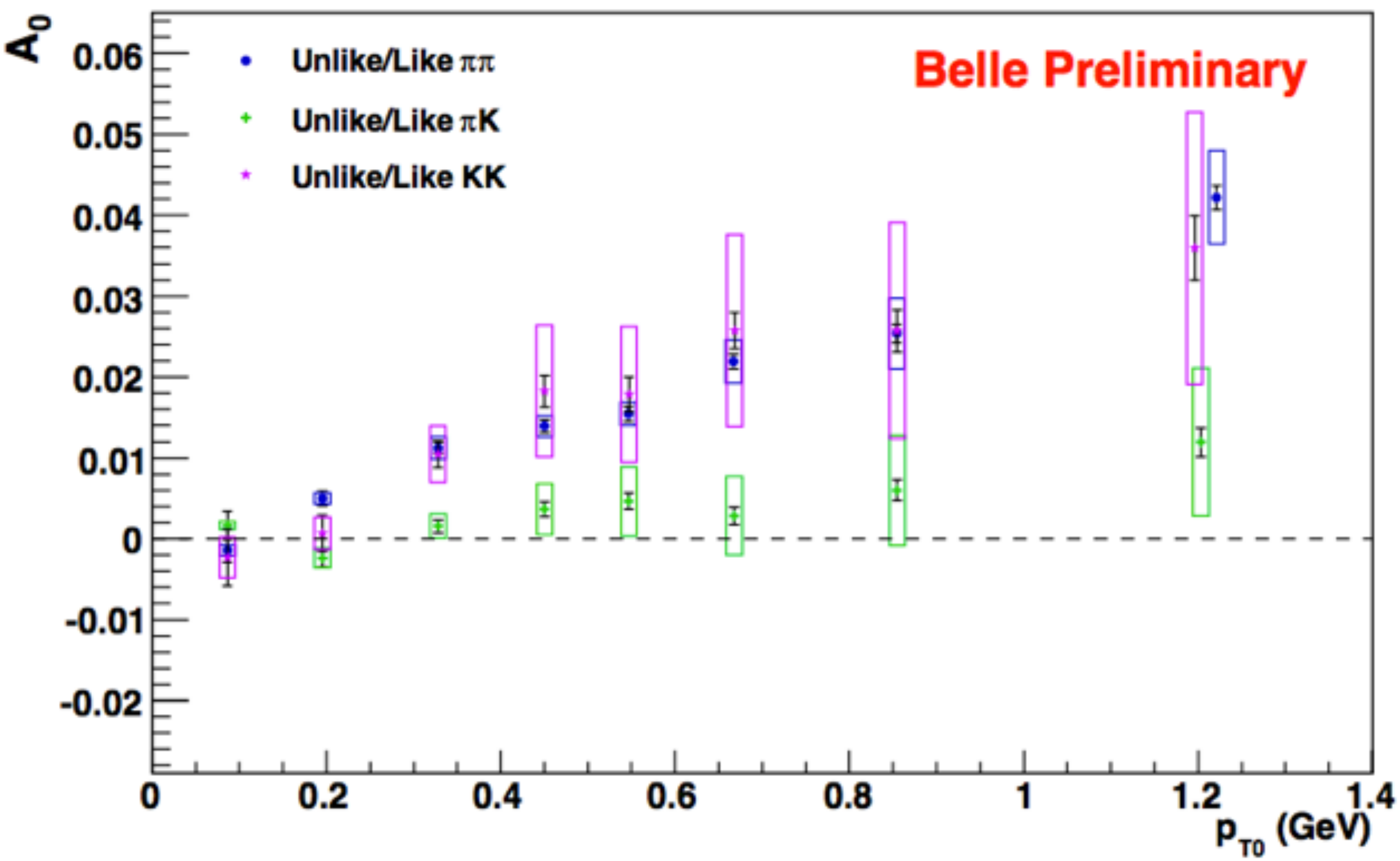


$\pi\pi$ => non-zero asymmetries, increase with z_1, z_2

πK => asymmetries compatible with zero

KK => non-zero asymmetries, increase with z_1,z_2 similar size of pion-pion

ϕ_0 asymmetries

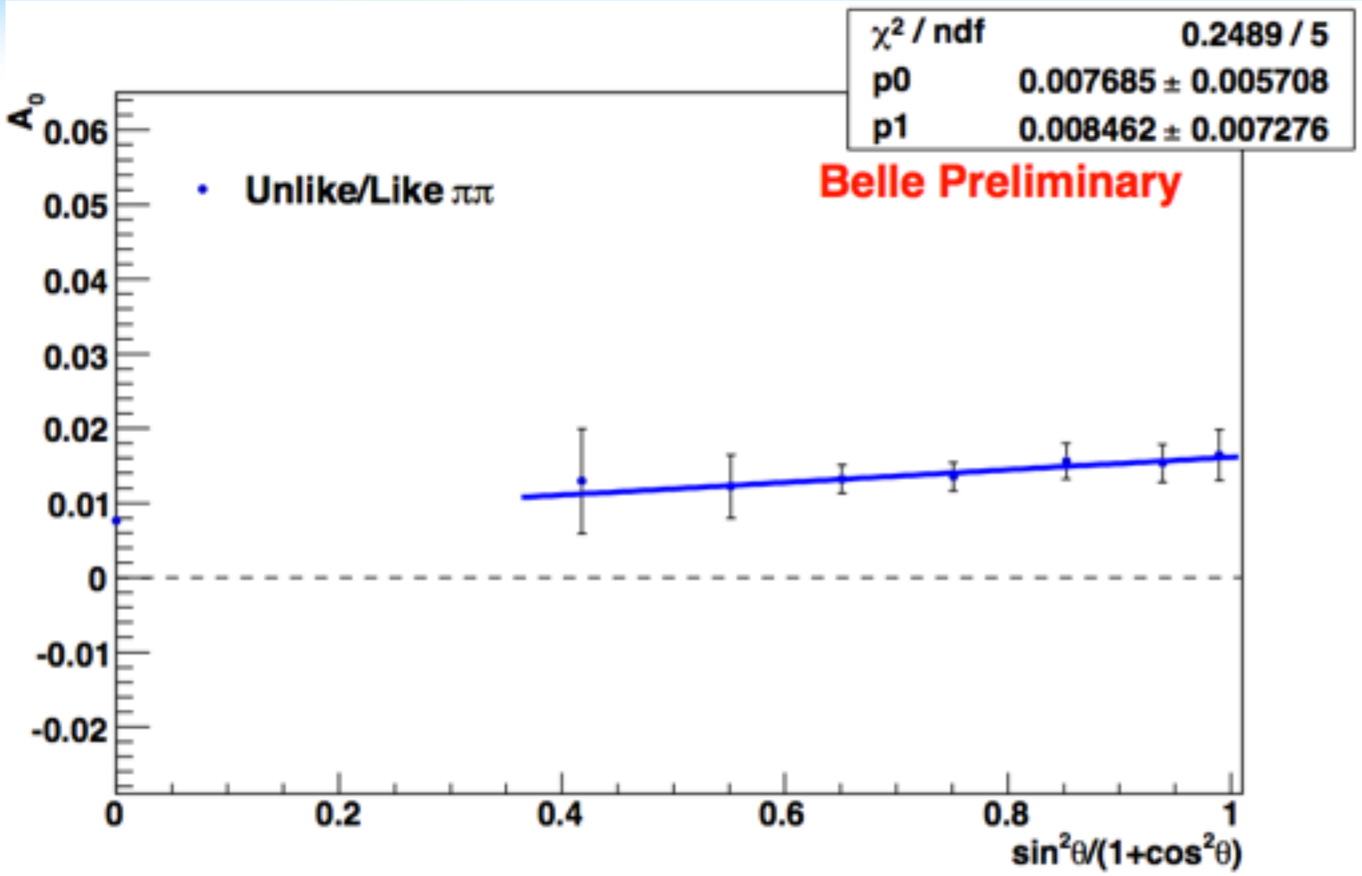


$\pi\pi$ => non-zero asymmetries, increase with z_1, z_2

πK => asymmetries compatible with zero

KK => non-zero asymmetries, increase with z_1,z_2 similar size of pion-pion

$\pi\pi$ versus $\sin^2\theta/(1+\cos^2\theta)$



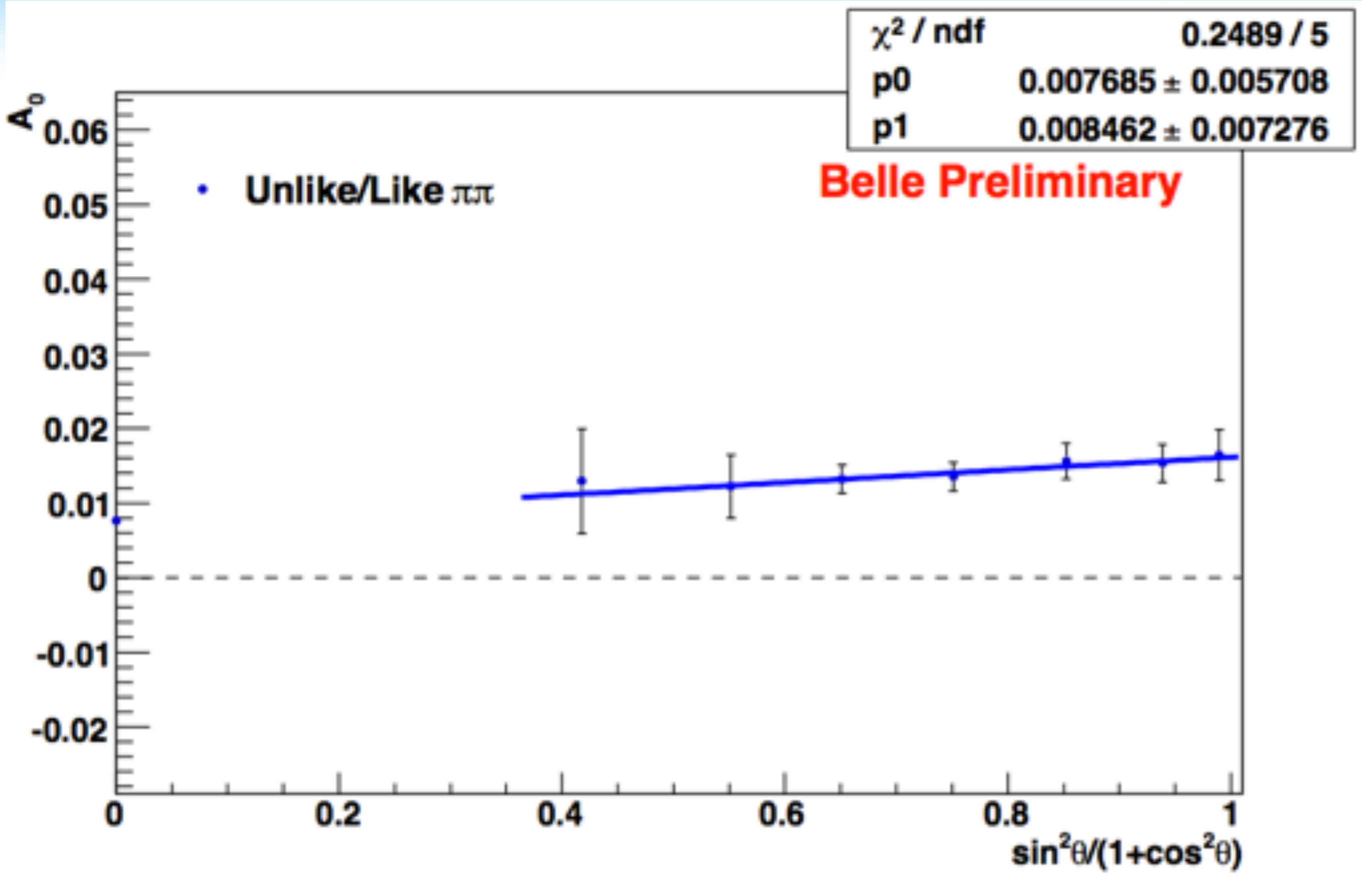
$$A_0 = \frac{\sin^2\theta}{1+\cos^2\theta}\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1^\perp(z_1)\bar{D}_1^\perp(z_2)}\right]$$

linear in $\sin^2\theta/(1+\cos^2\theta)$,

go to 0 for $\sin^2\theta/(1+\cos^2\theta) \rightarrow 0$

fit form: $p_0 + p_1 \sin^2\theta/(1+\cos^2\theta)$

$\pi\pi$ versus $\sin^2\theta/(1+\cos^2\theta)$



$$A_0 = \frac{\sin^2\theta}{1+\cos^2\theta}\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1^\perp(z_1)\bar{D}_1^\perp(z_2)}\right]$$

linear in $\sin^2\theta/(1+\cos^2\theta)$,

go to 0 for $\sin^2\theta/(1+\cos^2\theta) \to 0$

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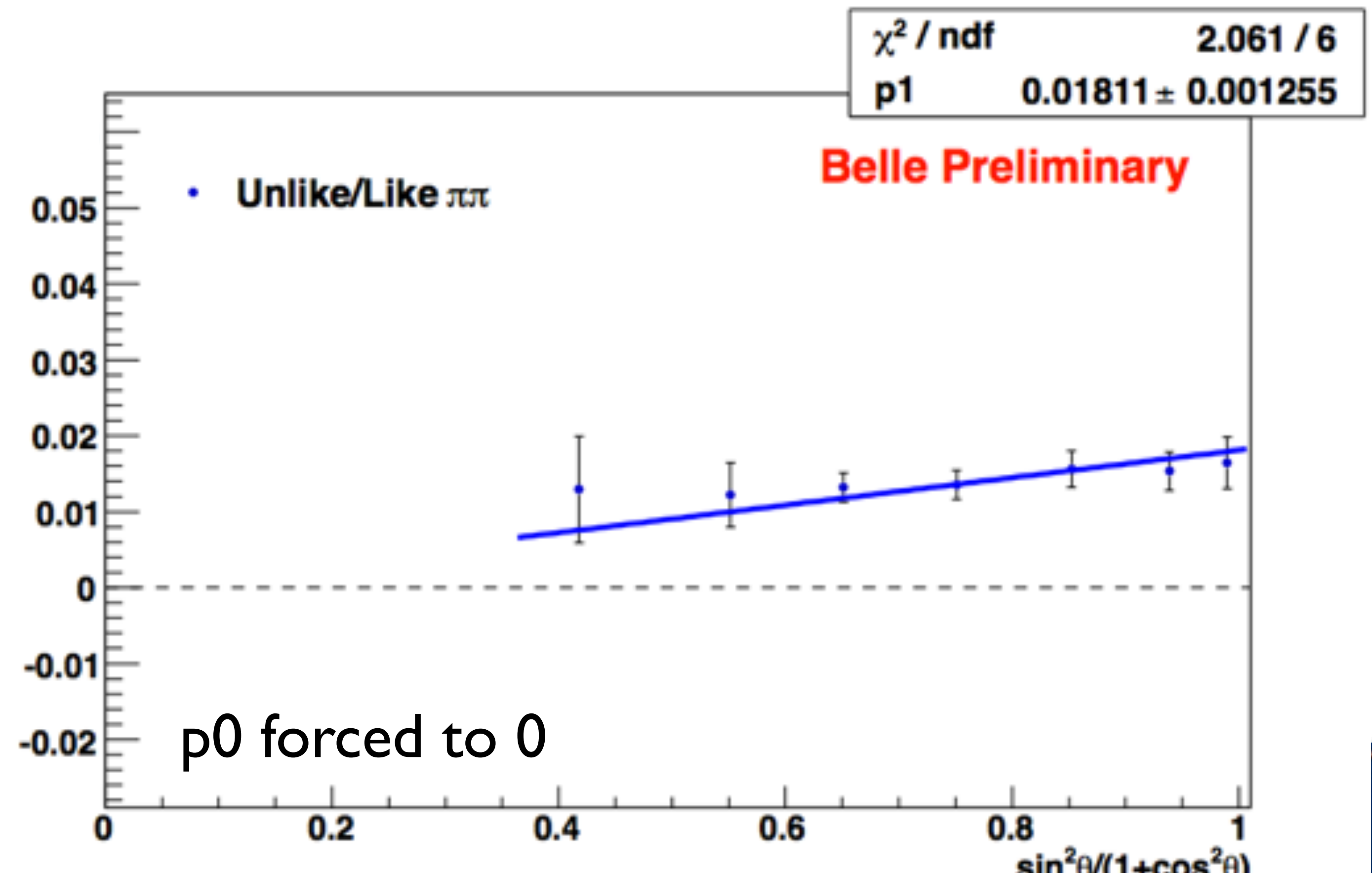
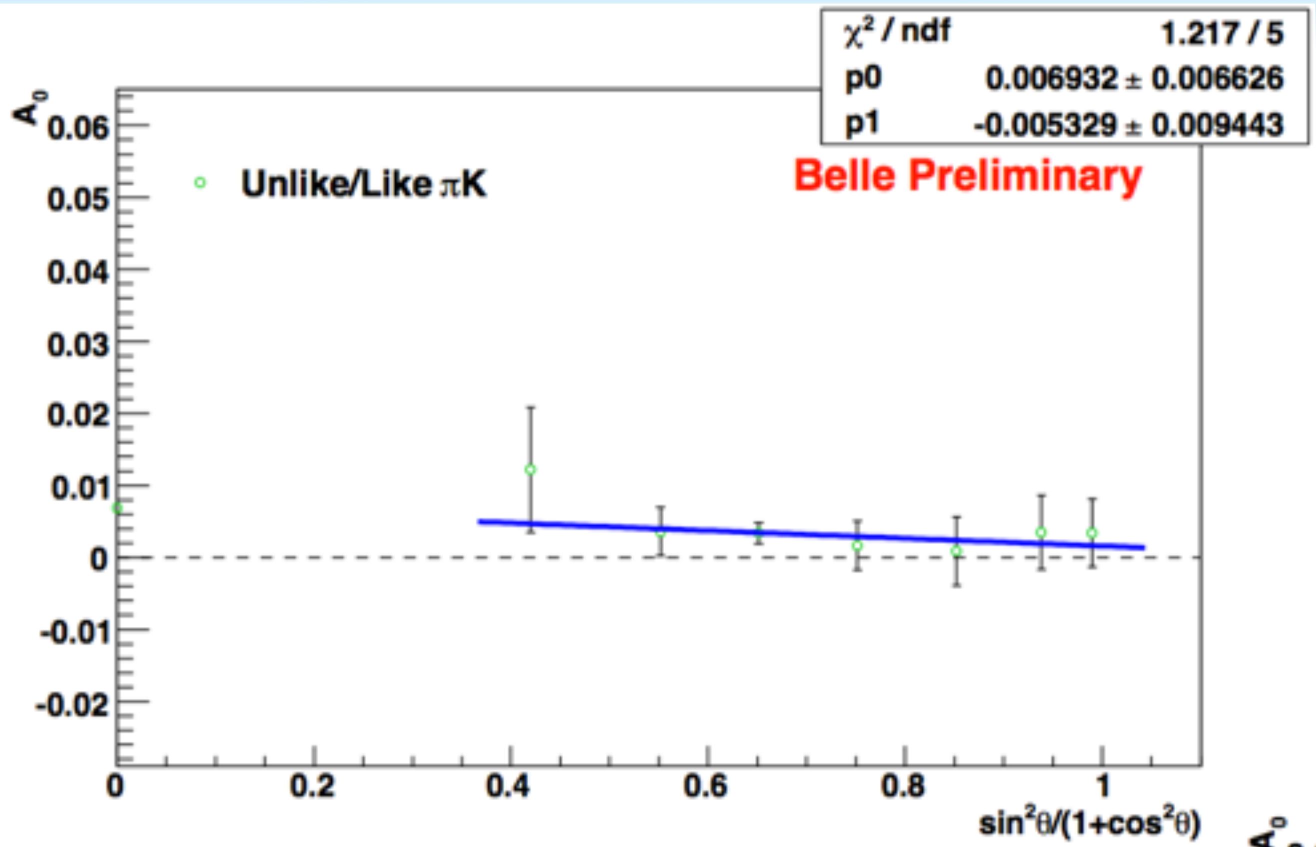


πK versus $\sin^2\theta/(1+\cos^2\theta)$



$$A_0 = \frac{\sin^2\theta}{1+\cos^2\theta}\mathcal{F}\left[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\right]$$

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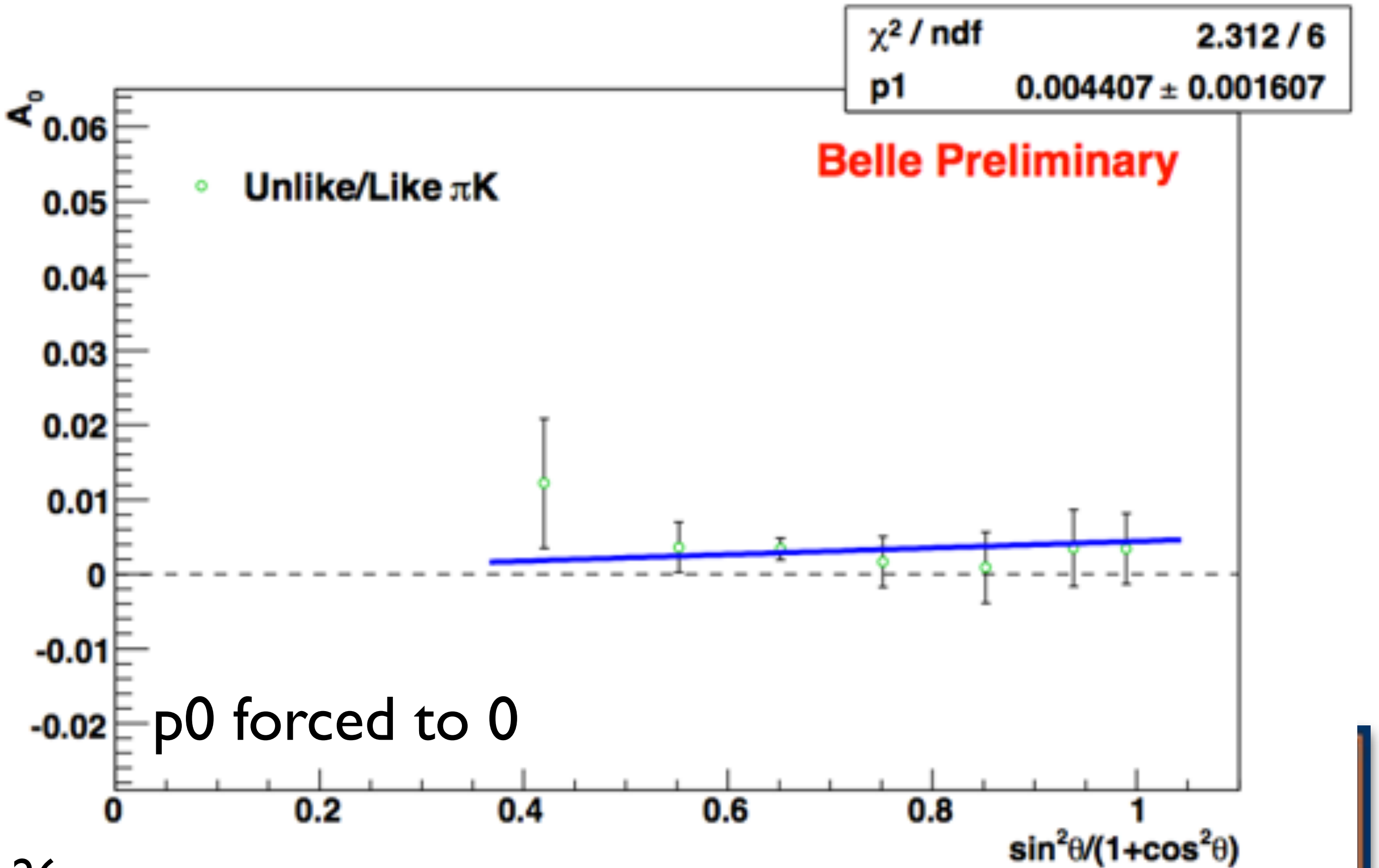
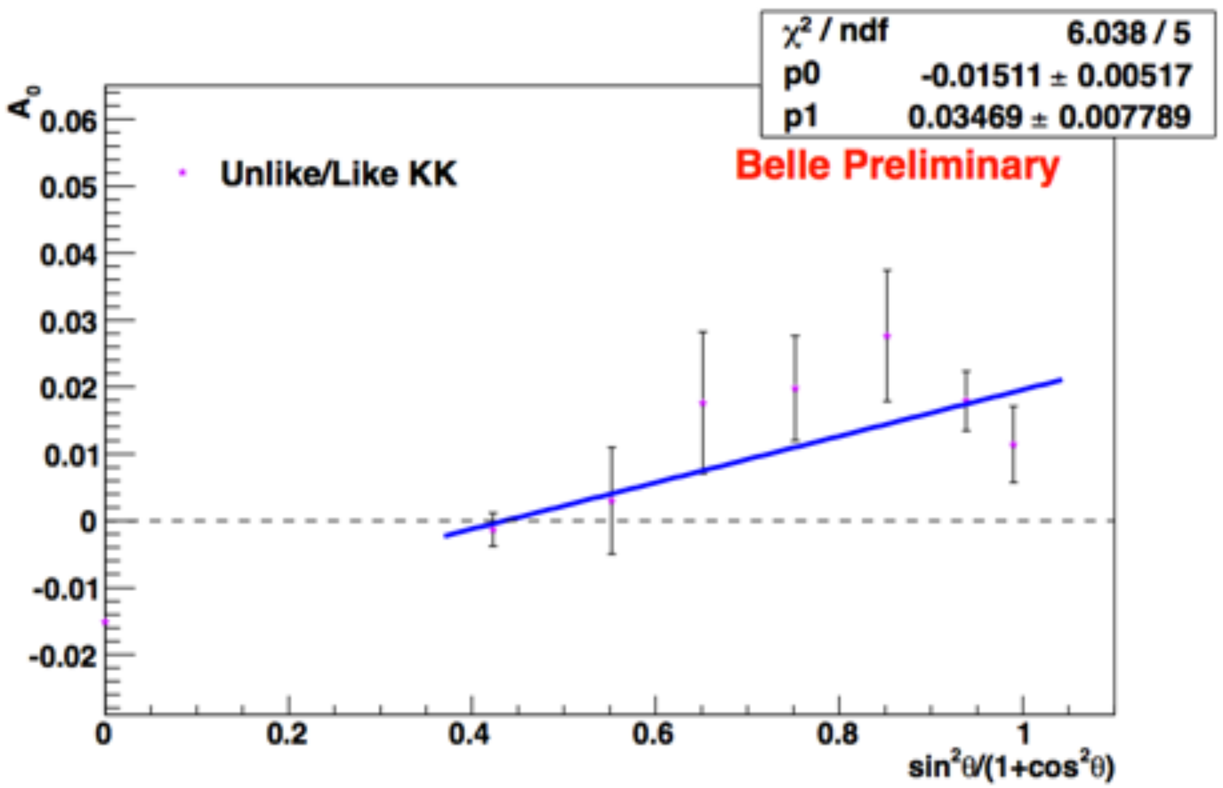


KK versus $\sin^2\theta/(1+\cos^2\theta)$



$$A_0 = \frac{\sin^2\theta}{1+\cos^2\theta}\,\mathcal{F}\left[\frac{H_1^\perp(z_1)\bar{H}_1^\perp(z_2)}{D_1^\perp(z_1)\bar{D}_1^\perp(z_2)}\right]$$

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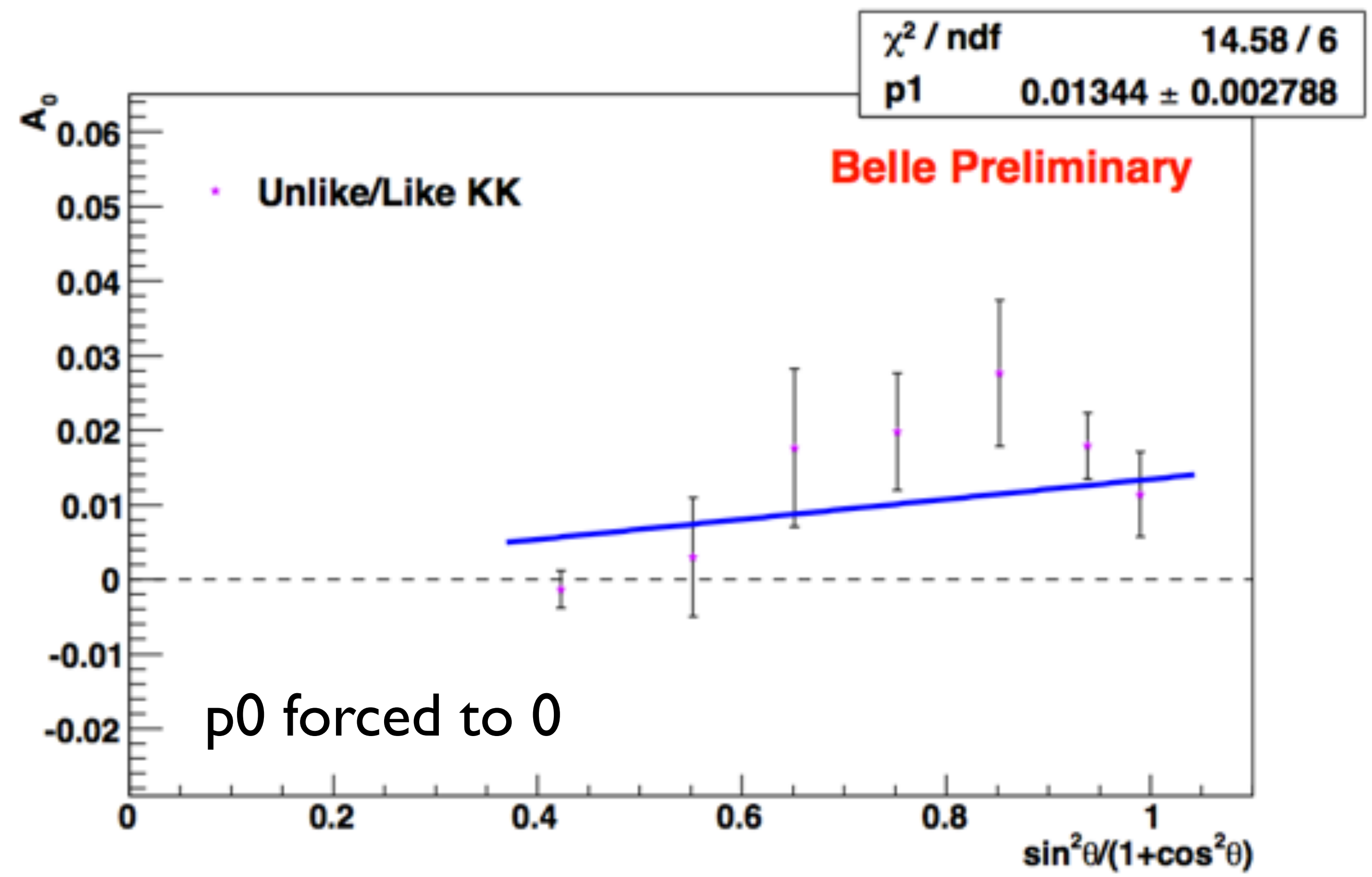

Fragmentation contributions

$u,\, d \to \pi\ (u\bar{d},\ \bar{u}d)$

$$D^{fav} = D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^+}$$
$$D^{dis} = D_u^{\pi^-} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_{\bar{d}}^{\pi^-}$$

$s \to \pi\ (u\bar{d},\ \bar{u}d)$

$$D^{dis}_{s\to\pi} = D_s^{\pi^+} = D_s^{\pi^-} = D_{\bar{s}}^{\pi^+} = D_{\bar{s}}^{\pi^-}$$

$u,\, d \to K\ (u\bar{s},\ \bar{u}s)$

$$D^{fav}_{u\to K} = D_u^{K^+} = D_{\bar{u}}^{K^-}$$
$$D^{dis}_{u,d\to K} = D_u^{K^-} = D_{\bar{u}}^{K^+} = D_d^{K^+} = D_{\bar{d}}^{K^-} = D_d^{K^-} = D_{\bar{d}}^{K^+}$$

$s \to K\ (u\bar{s},\ \bar{u}s)$

$$D^{fav}_{s\to K} = D_s^{K^-} = D_{\bar{s}}^{K^+}$$
$$D^{dis}_{s\to K} = D_s^{K^+} = D_{\bar{s}}^{K^-}$$

In the end we are left with 7 possible fragmentation functions:

$$D^{fav},\ D^{dis},\ D^{dis}_{s\to\pi},\ D^{fav}_{u\to K},\ D^{dis}_{u,d\to K},\ D^{fav}_{s\to K},\ D^{dis}_{s\to K}$$

Assuming charm contribute only as a dilution

Fragmentation contributions

For pion-pion couples:

$$D^{\frac{U_{\pi\pi}}{L_{\pi\pi}}} \propto 1 \quad + \cos 2\phi_0 \frac{\sin^2\theta}{1+cos^2\theta} \left(\frac{5H_1^{fav} H_2^{fav} + 5H_1^{dis} H_2^{dis} + 2H_{1\,s\to\pi}^{dis} H_{2\,s\to\pi}^{dis}}{5D_1^{fav} D_2^{fav} + 5D_1^{dis} D_2^{dis} + 2D_{1\,s\to\pi}^{dis} D_{2\,s\to\pi}^{dis}} - \frac{5H_1^{fav} H_2^{dis} + 5H_1^{dis} H_2^{fav} + 2H_{1\,s\to\pi}^{dis} H_{2\,s\to\pi}^{dis}}{5D_1^{fav} D_2^{dis} + 5D_1^{dis} D_2^{fav} + 2D_{1\,s\to\pi}^{dis} D_{2\,s\to\pi}^{dis}} \right)$$

For pion-Kaon couples:

$$D^{\frac{U_{\pi K}}{L_{\pi K}}} \propto 1 + \cos 2\phi_0 \frac{\sin^2\theta}{1+cos^2\theta} \times$$

$$\left(\frac{4H_1^{fav} H_{2\,K}^{fav} + H_{1K}^{dis}(5H_2^{dis} + H_2^{fav}) + H_{2K}^{dis}(5H_1^{dis} + H_1^{fav}) + 4\,H_{1K}^{fav} H_2^{fav} + H_{1s\to\pi}^{dis}(H_{2s\to K}^{dis} + H_{2s\to K}^{fav}) + H_{2s\to\pi}^{dis}(H_{1s\to K}^{fav} + H_{1s\to K}^{dis})}{4D_1^{fav} D_{2\,K}^{fav} + D_{1K}^{dis}(5D_2^{dis} + D_2^{fav}) + D_{2K}^{dis}(5D_1^{dis} + D_1^{fav}) + 4\,D_{1K}^{fav} D_2^{fav} + D_{1s\to\pi}^{dis}(D_{2s\to K}^{dis} + D_{2s\to K}^{fav}) + D_{2s\to\pi}^{dis}(D_{1s\to K}^{fav} + D_{1s\to K}^{dis})} \right.$$

$$\left. \frac{H_{2\,K}^{dis}(5H_1^{fav} + H_1^{dis}) + 4\,H_{1\,K}^{fav} H_2^{dis} + 4H_1^{dis} H_{2K}^{fav} + H_{1K}^{dis}(5H_2^{fav} + H_2^{dis}) + H_{1s\to\pi}^{dis}(H_{2s\to K}^{fav} + H_{2s\to K}^{dis}) + (H_{1s\to K}^{dis} + H_{1s\to K}^{fav})H_{2s\to\pi}^{dis}}{D_{2\,K}^{dis}(5D_1^{fav} + D_1^{dis}) + 4\,D_{1\,K}^{fav} D_2^{dis} + 4D_1^{dis} D_{2K}^{fav} + D_{1K}^{dis}(5D_2^{fav} + D_2^{dis}) + D_{1s\to\pi}^{dis}(D_{2s\to K}^{fav} + D_{2s\to K}^{dis}) + (D_{1s\to K}^{dis} + D_{1s\to K}^{fav})D_{2s\to\pi}^{dis}} \right)$$

For Kaon-Kaon couples:

$$D^{\frac{U_{KK}}{L_{KK}}} \propto 1 \quad + \cos 2\phi_0 \frac{\sin^2\theta}{1+cos^2\theta} \left(\frac{4H_{1K}^{fav} H_{2\,K}^{fav} + 6H_{1\,K}^{dis} H_{2K}^{dis} + H_{1s\to K}^{dis} H_{2s\to K}^{dis} + H_{1s\to K}^{fav} H_{2s\to K}^{fav}}{4D_{1K}^{fav} D_{2\,K}^{fav} + 6D_{1\,K}^{dis} D_{2K}^{dis} + D_{1s\to K}^{dis} D_{2s\to K}^{dis} + D_{1s\to K}^{fav} D_{2s\to K}^{fav}} - \frac{4H_{1K}^{fav} H_{2\,K}^{dis} + 4H_{1\,K}^{dis} H_{2K}^{fav} + 2H_{1K}^{dis} H_{2K}^{dis} + H_{1s\to K}^{dis} H_{2s\to K}^{fav} + H_{1s\to K}^{fav} H_{2s\to K}^{dis}}{4D_{1K}^{fav} D_{2\,K}^{dis} + 4D_{1\,K}^{dis} D_{2K}^{fav} + 2D_{1K}^{dis} D_{2K}^{dis} + D_{1s\to K}^{dis} D_{2s\to K}^{fav} + D_{1s\to K}^{fav} D_{2s\to K}^{dis}} \right)$$

Fragmentation contributions

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$$D^{\frac{U_{\pi\pi}}{L_{\pi\pi}}} \propto 1 \quad + \cos 2\phi_0 \frac{\sin^2\theta}{1+cos^2\theta} \left(\frac{5H_1^{fav} H_2^{fav} + 5H_1^{dis} H_2^{dis} + 2H^{dis}_{1\,s\to\pi} H^{dis}_{2\,s\to\pi}}{5D_1^{fav} D_2^{fav} + 5D_1^{dis} D_2^{dis} + 2D^{dis}_{1\,s\to\pi} D^{dis}_{2\,s\to\pi}} - \frac{5H_1^{fav} H_2^{dis} + 5H_1^{dis} H_2^{fav} + 2H^{dis}_{1\,s\to\pi} H^{dis}_{2\,s\to\pi}}{5D_1^{fav} D_2^{dis} + 5D_1^{dis} D_2^{fav} + 2D^{dis}_{1\,s\to\pi} D^{dis}_{2\,s\to\pi}} \right)$$

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$$\left(\frac{4H_1^{fav} H_{2\,K}^{fav} + H_{1K}^{dis}(5H_2^{dis}+H_2^{fav}) + H_{2K}^{dis}(5H_1^{dis}+H_1^{fav}) + 4\,H_{1K}^{fav} H_2^{fav} + H^{dis}_{1s\to\pi}(H^{dis}_{2s\to K}+H^{fav}_{2s\to K}) + H^{dis}_{2s\to\pi}(H^{fav}_{1s\to K}+H^{dis}_{1s\to K})}{4D_1^{fav} D_{2\,K}^{fav} + D_{1K}^{dis}(5D_2^{dis}+D_2^{fav}) + D_{2K}^{dis}(5D_1^{dis}+D_1^{fav}) + 4\,D_{1K}^{fav} D_2^{fav} + D^{dis}_{1s\to\pi}(D^{dis}_{2s\to K}+D^{fav}_{2s\to K}) + D^{dis}_{2s\to\pi}(D^{fav}_{1s\to K}+D^{dis}_{1s\to K})} \right.$$

$$\left. \frac{H_{2\,K}^{dis}(5H_1^{fav}+H_1^{dis}) + 4\,H_{1\,K}^{fav} H_2^{dis} + 4H_1^{dis} H_{2K}^{fav} + H_{1K}^{dis}(5H_2^{fav}+H_2^{dis}) + H^{dis}_{1s\to\pi}(H^{fav}_{2s\to K}+H^{dis}_{2s\to K}) + (H^{dis}_{1s\to K}+H^{fav}_{1s\to K})H^{dis}_{2s\to\pi}}{D_{2\,K}^{dis}(5D_1^{fav}+D_1^{dis}) + 4\,D_{1\,K}^{fav} D_2^{dis} + 4D_1^{dis} D_{2K}^{fav} + D_{1K}^{dis}(5D_2^{fav}+D_2^{dis}) + D^{dis}_{1s\to\pi}(D^{fav}_{2s\to K}+D^{dis}_{2s\to K}) + (D^{dis}_{1s\to K}+D^{fav}_{1s\to K})D^{dis}_{2s\to\pi}} \right)$$

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$$D^{\frac{U_{KK}}{L_{KK}}} \propto 1 \quad + \cos 2\phi_0 \frac{\sin^2\theta}{1+cos^2\theta} \left(\frac{4H_{1K}^{fav} H_{2\,K}^{fav} + 6H_{1\,K}^{dis} H_{2K}^{dis} + H^{dis}_{1s\to K} H^{dis}_{2s\to K} + H^{fav}_{1s\to K} H^{fav}_{2s\to K}}{4D_{1K}^{fav} D_{2\,K}^{fav} + 6D_{1\,K}^{dis} D_{2K}^{dis} + D^{dis}_{1s\to K} D^{dis}_{2s\to K} + D^{fav}_{1s\to K} D^{fav}_{2s\to K}} - \frac{4H_{1K}^{fav} H_{2\,K}^{dis} + 4H_{1\,K}^{dis} H_{2K}^{fav} + 2H_{1K}^{dis} H_{2K}^{dis} + H^{dis}_{1s\to K} H^{fav}_{2s\to K} + H^{fav}_{1s\to K} H^{dis}_{2s\to K}}{4D_{1K}^{fav} D_{2\,K}^{dis} + 4D_{1\,K}^{dis} D_{2K}^{fav} + 2D_{1K}^{dis} D_{2K}^{dis} + D^{dis}_{1s\to K} D^{fav}_{2s\to K} + D^{fav}_{1s\to K} D^{dis}_{2s\to K}} \right)$$

Not so easy! A full phenomenological study needed!

Summary & outlook

- ϕ_0 asymmetries
  - present similar features for $\pi\pi$ and KK couples
  - very small/compatible with zero for πK couples
  - for $\pi\pi$ and πK the $\sin^2\Theta/(1+\cos^2\Theta)$ dependence of asymmetries are not inconsistent with a linear dependence going to zero
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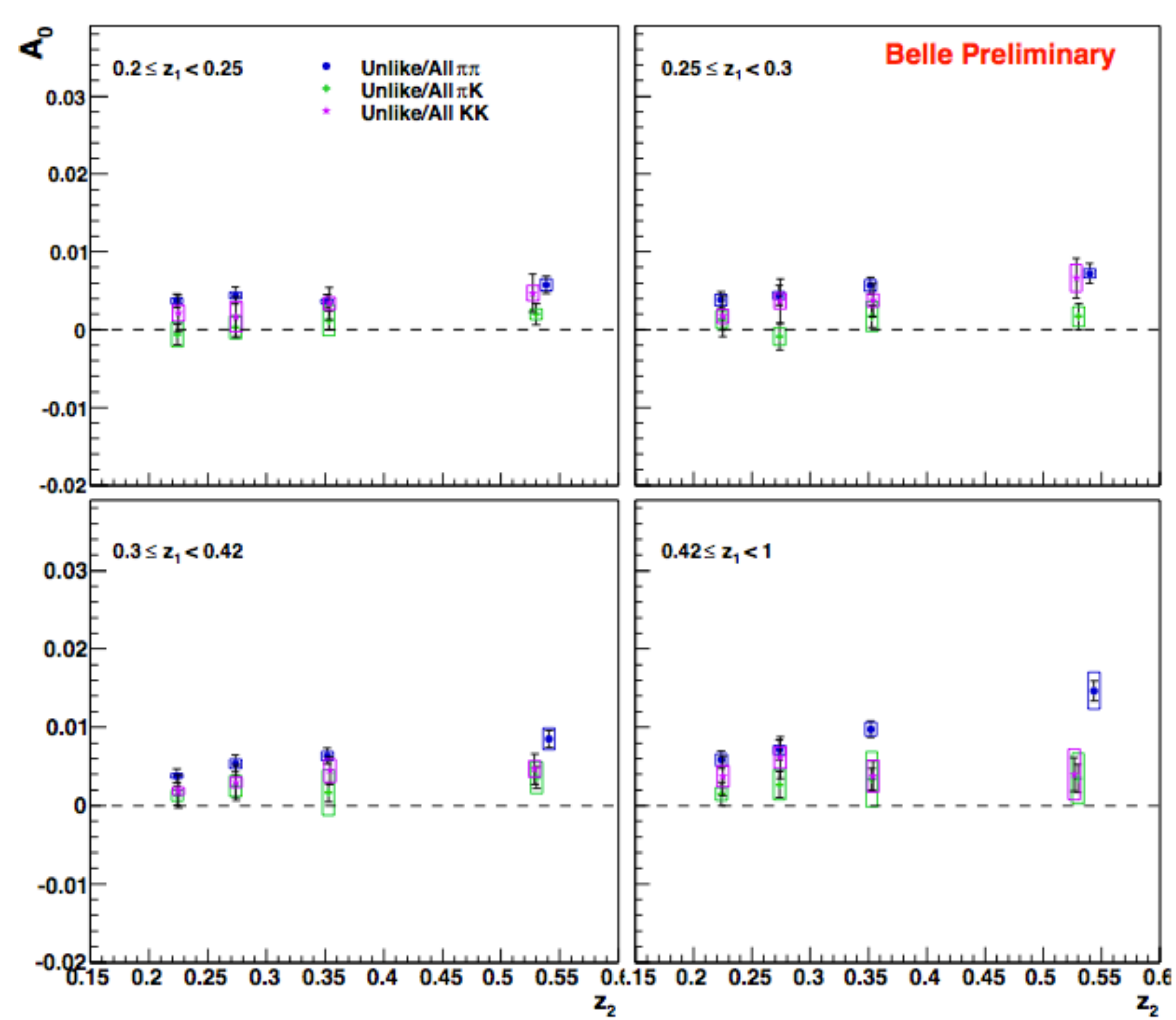
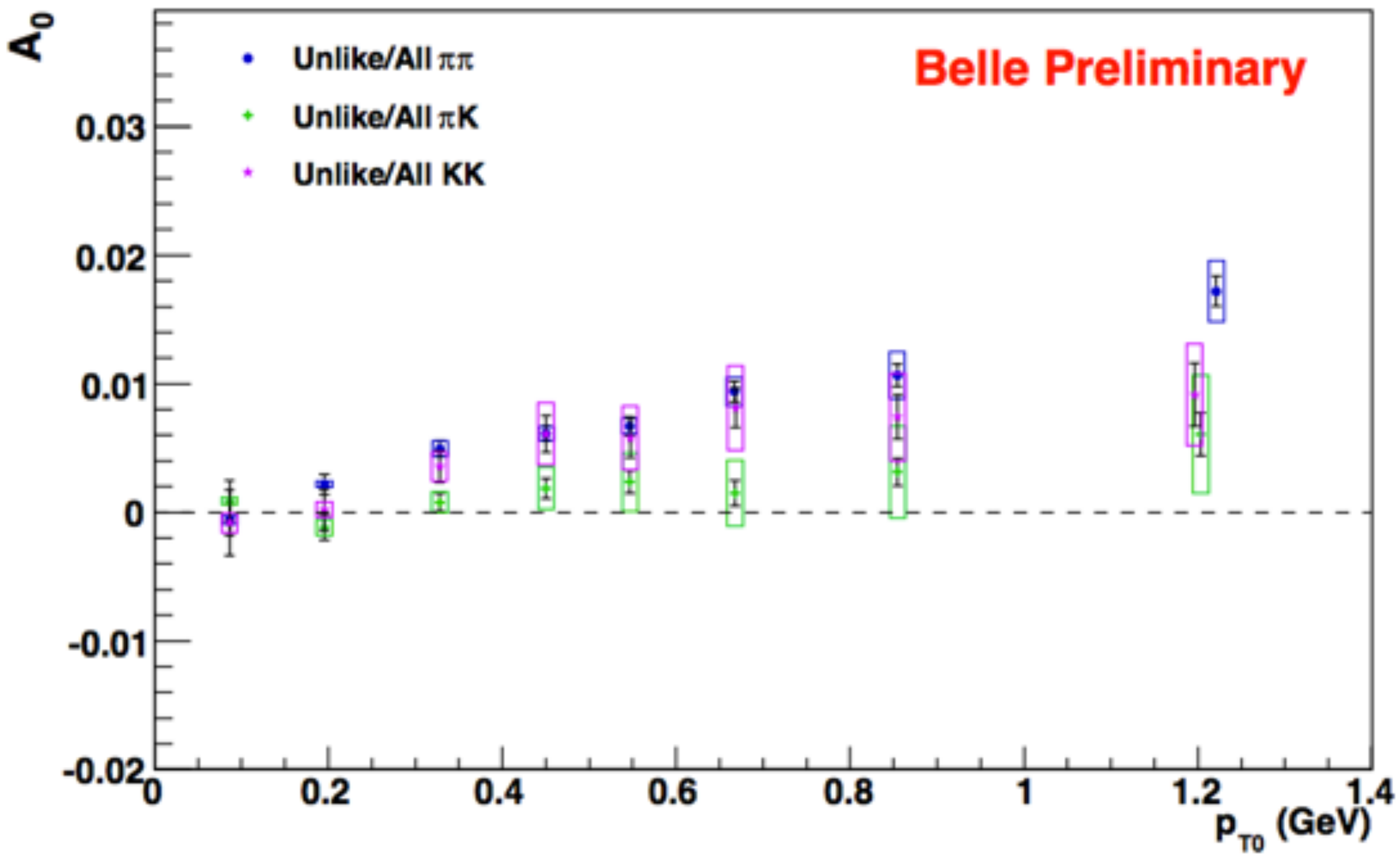
Stay tuned!

Backups

ϕ_0 asymmetries



ϕ_0 asymmetries



More ϕ_0 asymmetries