Measuring Quark Polarization Dependent Di-Hadron Fragmentation Functions at Belle II

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FRAGMENTATION FUNCTIONS

INTRODUCTION

We want to know how quark properties lead to larger scale effects like hadron distribution and polarization.

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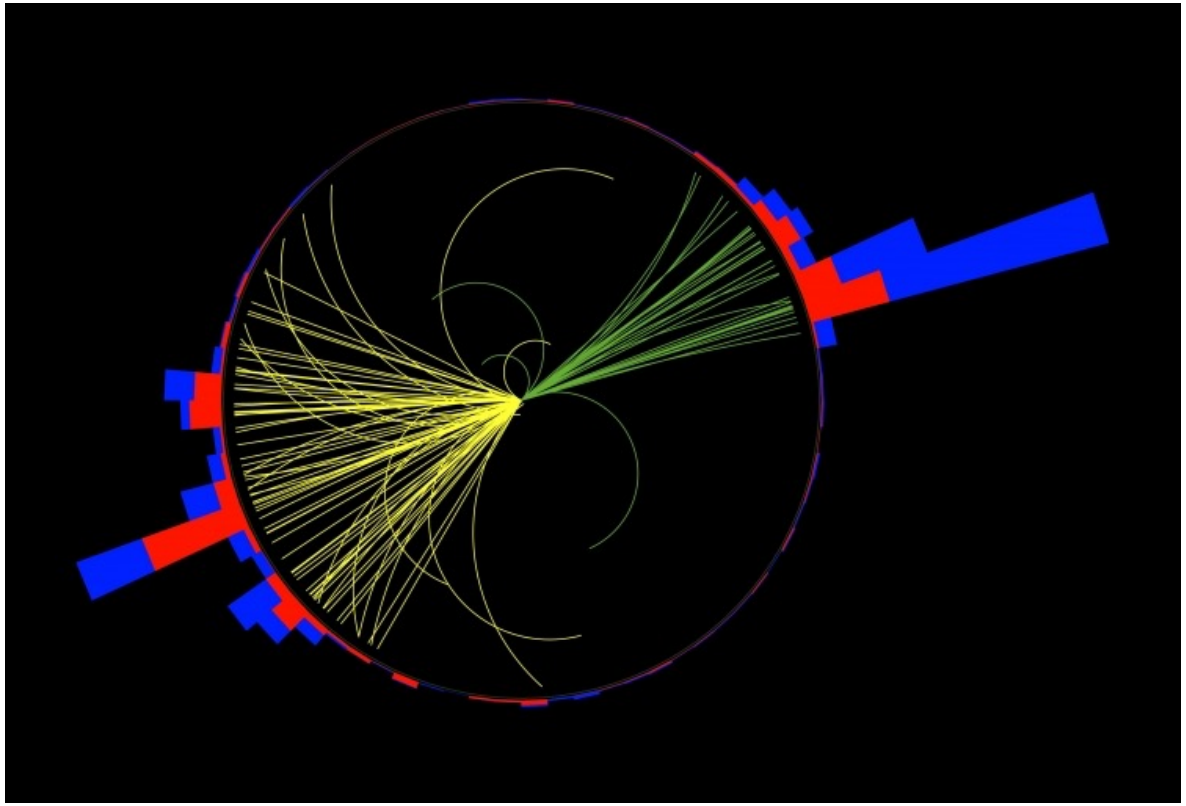
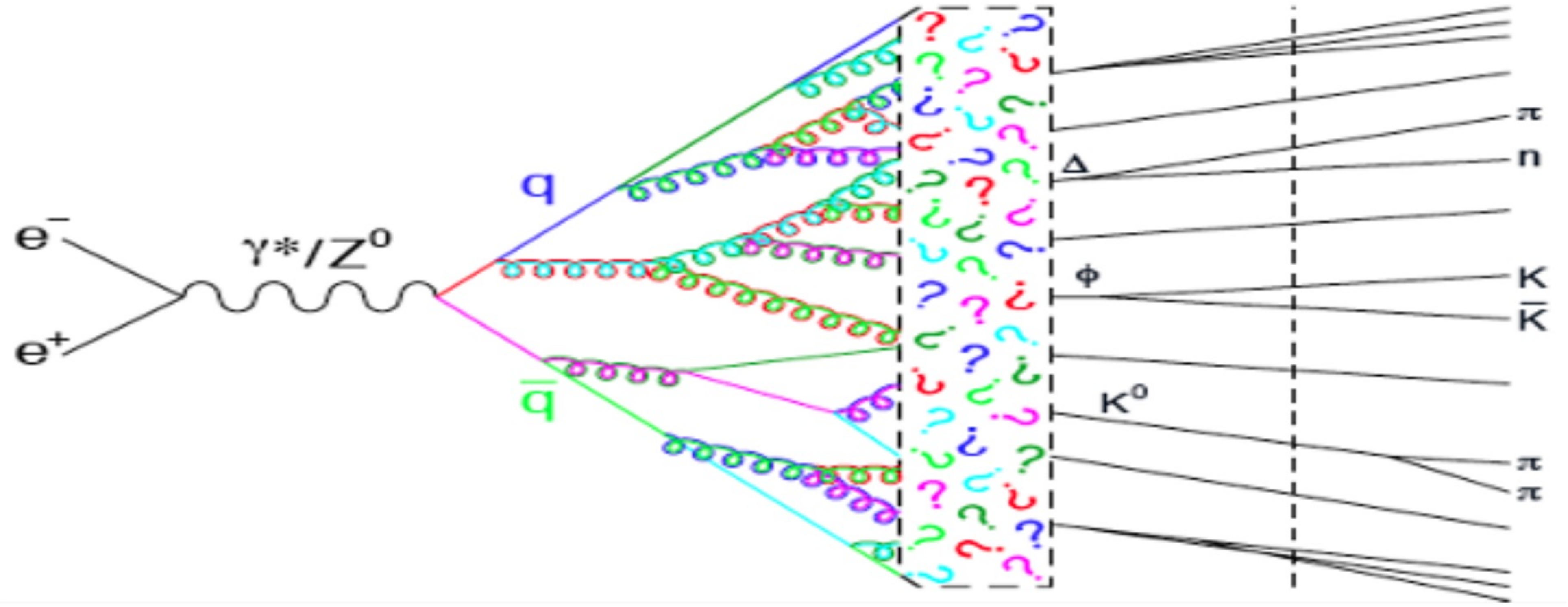
Jet: a collimated bunch of colorless, bound hadronic states



FRAGMENTATION FUNCTIONS

INTRODUCTION

Hadronization: the process by which a parton produces a jet

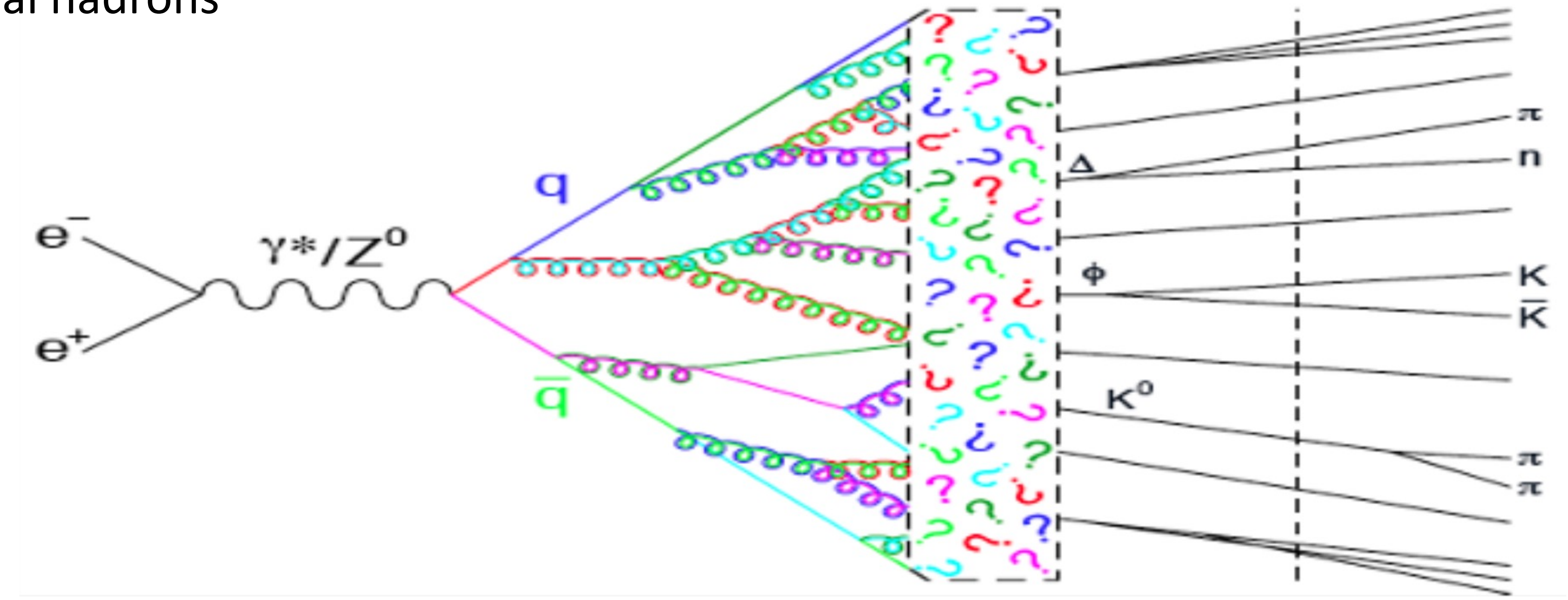


FRAGMENTATION FUNCTIONS

INTRODUCTION

Hadronization: the process by which a parton produces a jet

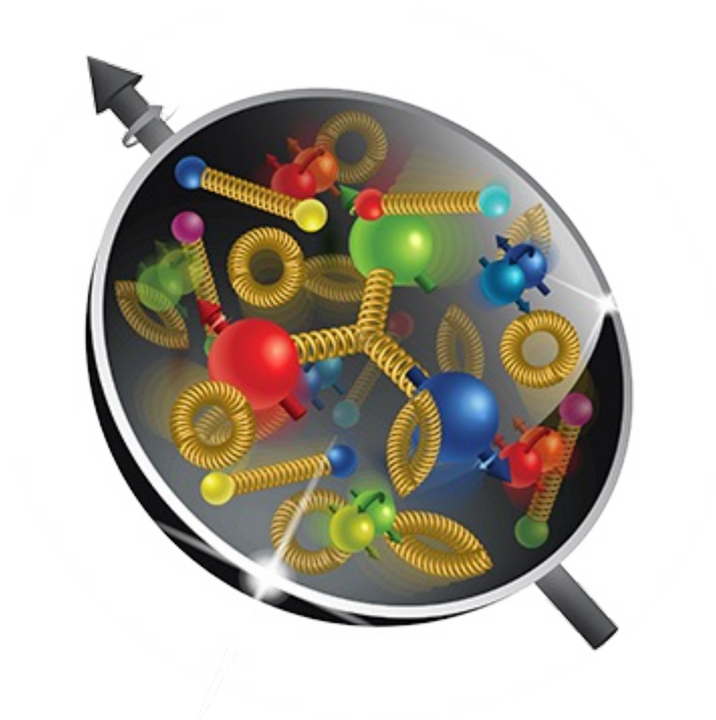
Fragmentation functions (FF): describe how color carrying quarks fragment into color neutral hadrons



FRAGMENTATION FUNCTIONS

INTRODUCTION

Parton Distribution Functions (PDF): probability densities for finding a quark or gluon with a particular momentum in a color neutral hadron



FRAGMENTATION FUNCTIONS

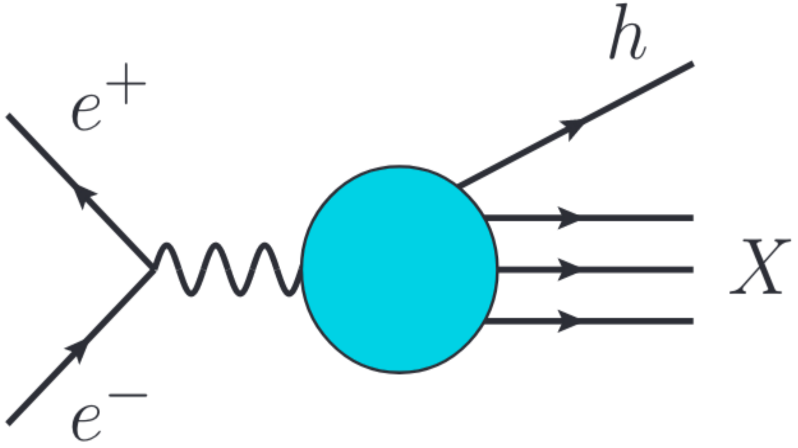
INTRODUCTION

- Fragmentation functions and parton distribution functions are universal functions and fundamental QCD objects.
- They are non-perturbative, so they cannot be calculated in QCD and (in most cases) must be determined experimentally.
- Electron-positron experiments offer the cleanest environments in which to measure fragmentation functions.

FRAGMENTATION FUNCTIONS

FACTORIZATION

Scattering amplitudes can be factorized into a perturbatively calculable part, $\hat{\sigma}$, and a non-perturbatively calculable part:



Single-inclusive annihilation:

$$\sigma^{e^+e^-\to hX} = \hat{\sigma} \otimes FF$$

Semi-inclusive deep inelastic scattering:

$$\sigma^{\ell N\to \ell hX} = \hat{\sigma} \otimes PDF \otimes FF$$

Single-inclusive proton-proton scattering:

$$\sigma^{pp\to hX} = \hat{\sigma} \otimes PDF \otimes PDF \otimes FF$$

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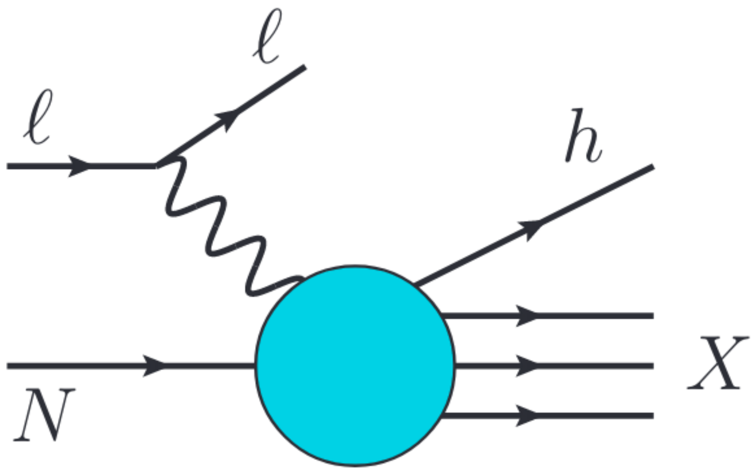

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FRAGMENTATION FUNCTIONS

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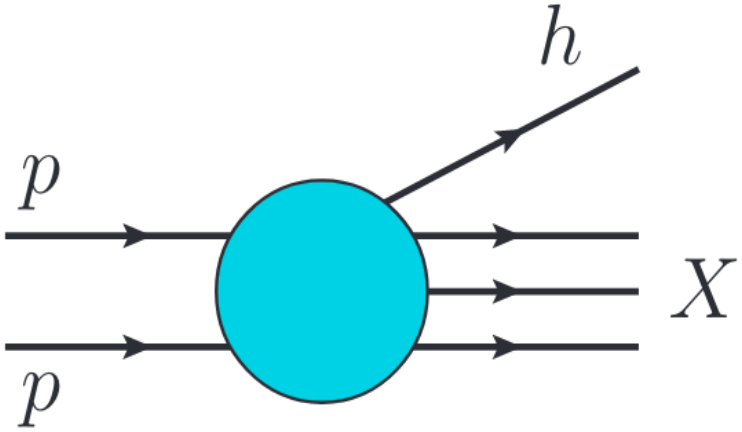
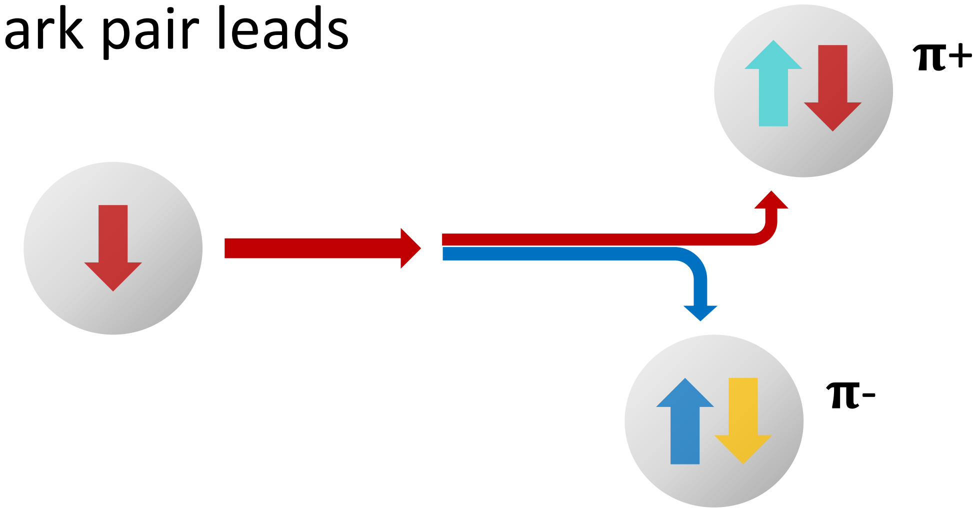


FRAGMENTATION FUNCTIONS

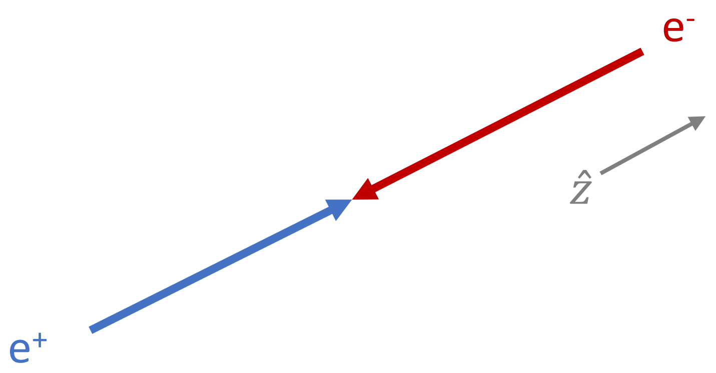
QUARK POLARIZATION DEPENDENT DI-HADRON FF

- The $H_1^{\sphericalangle}$ FF is dependent on the polarization of the parent quark and produces a pair of spin-0 hadrons.
- $H_1^{\sphericalangle}$ observable:
  - Conservation of angular momentum leads to left and right asymmetry
  - The spin correlation between a quark-antiquark pair leads to a correlation between the azimuthal angle of the di-hadron pairs it produces
  - The amplitude of the resulting asymmetry in the azimuthal angle is directly proportional to $H_1^{\sphericalangle}\overline{H_1^{\sphericalangle}}$



$H_1^{\measuredangle}$ EXTRACTION

AZIMUTHAL ANGLE MEASUREMENT

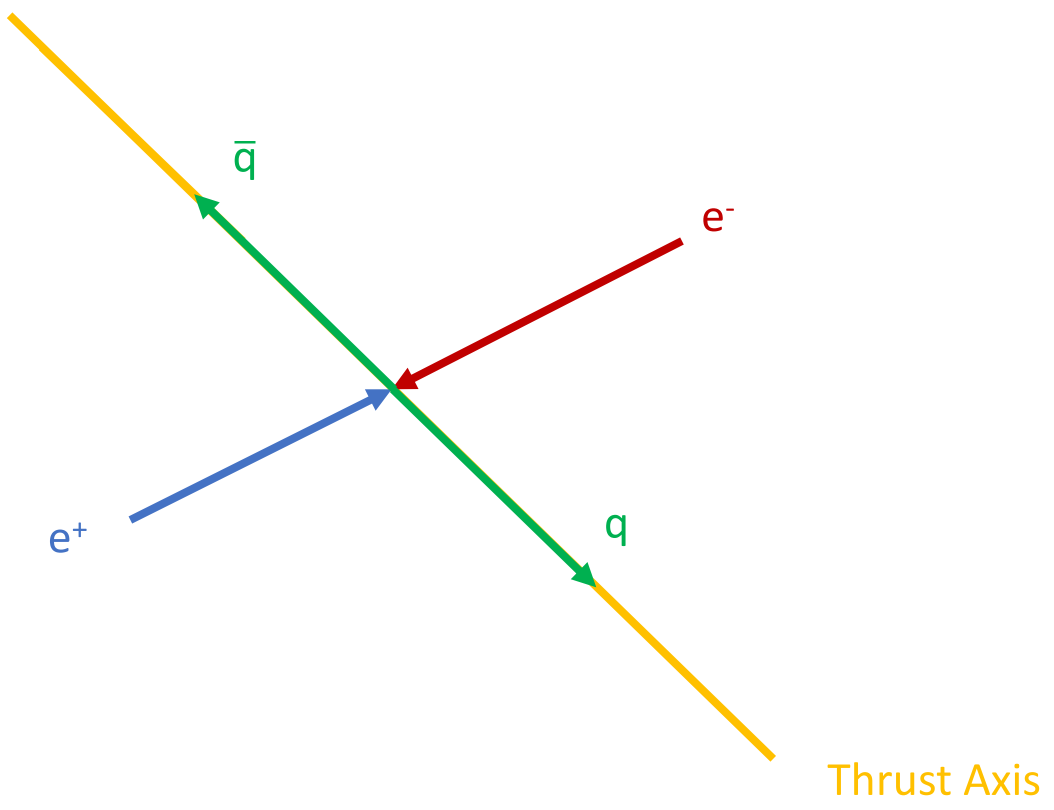


EVENT CUTS

- Number of hits in the CDC > 20
- Particles originate from the $e^+ e^-$ collision point
  - dr < 2cm
  - |dz| < 4 cm
- Visible energy is between 7 GeV and 12 GeV

$H_1^{\measuredangle}$ EXTRACTION

AZIMUTHAL ANGLE MEASUREMENT



THRUST

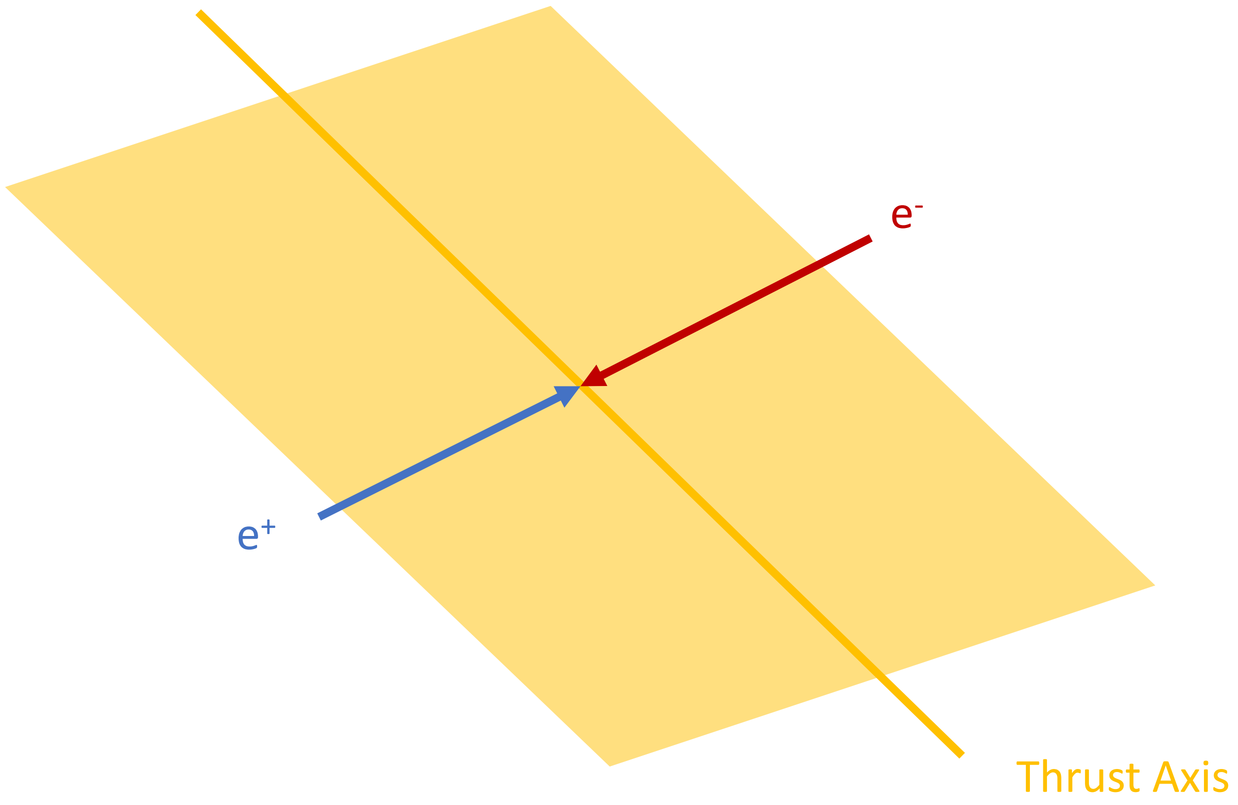
$$T = \max_{|\hat{n}|=1}\left[\frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}\right]$$

In a perfectly di-jet event, T = 1.0
In a perfectly spherical event T = 0.5

The thrust axis, $\hat{n}$, is a good approximation of the $q\bar{q}$ axis when thrust is close to 1.0

$H_1^{\sphericalangle}$ EXTRACTION

AZIMUTHAL ANGLE MEASUREMENT

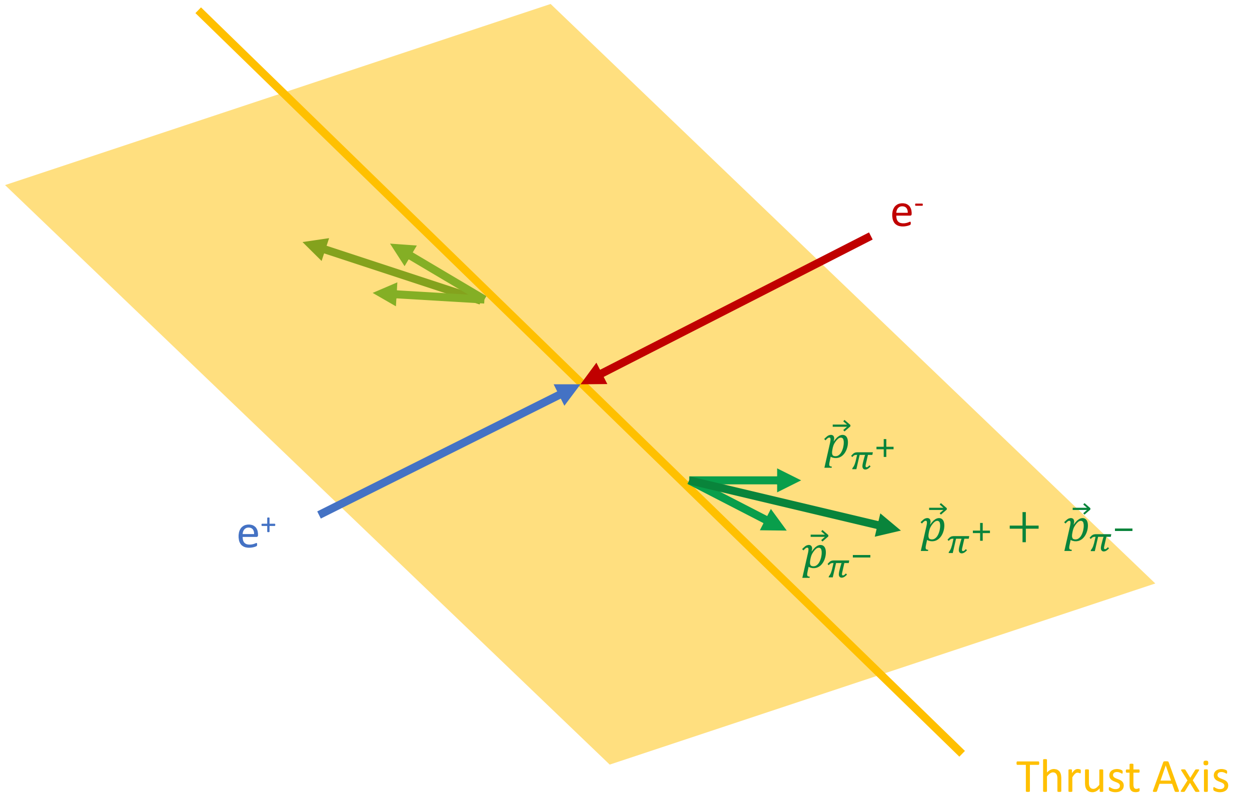


THRUST CUTS

- Thrust > 0.8
- $|\hat{z}$ of the thrust axis$|$ > 0.75

$H_1^{\sphericalangle}$ EXTRACTION

AZIMUTHAL ANGLE MEASUREMENT

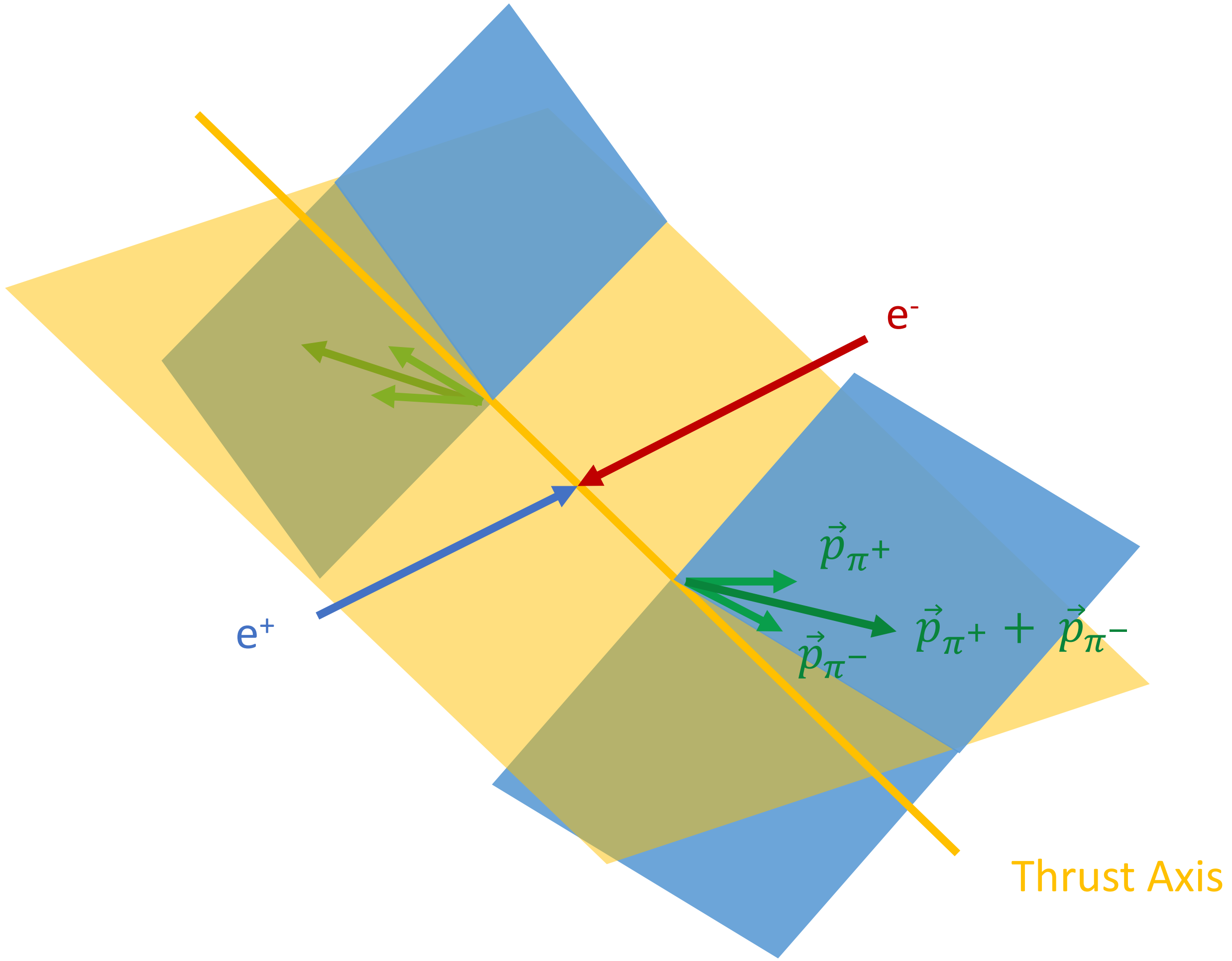


PION CUTS

- Transverse momentum > 0.1 GeV/c
- Full Belle II barrel acceptance
  - cosine between pion momenta and the beam axis > -0.79
  - cosine between pion momenta and the beam axis < 0.74
- |cosine between pion momenta and thrust axis| > 0.8
- Carries at least 10% of the total event energy
- pionID > 0.7

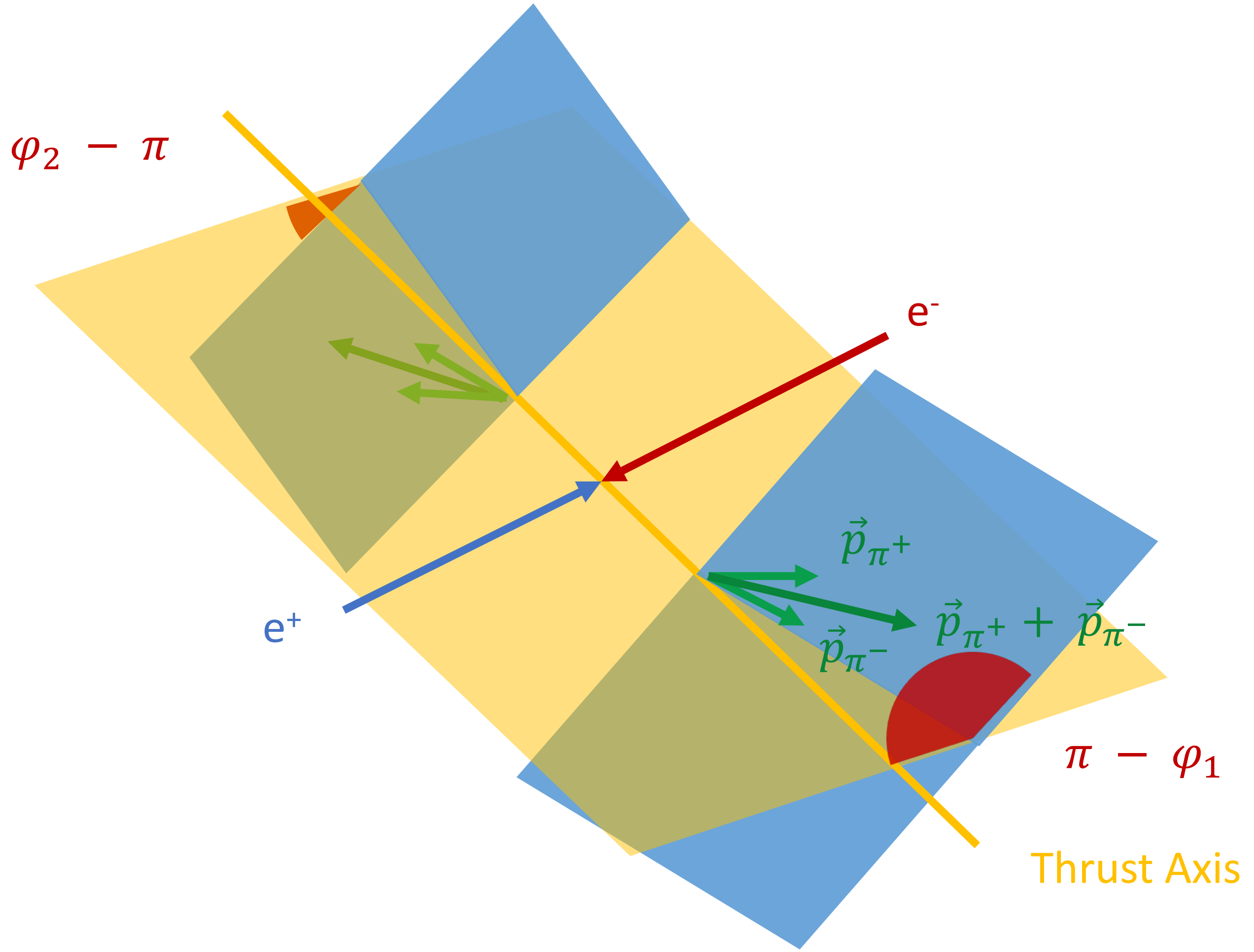
$H_1^{\sphericalangle}$ EXTRACTION

AZIMUTHAL ANGLE MEASUREMENT



$H_1^{\measuredangle}$ EXTRACTION

AZIMUTHAL ANGLE MEASUREMENT



ANGLE CALCULATION

$$\varphi_{1,2} = sgn\left[\hat{n} \cdot \left\{(\hat{z} \times \hat{n}) \times \left(\hat{n} \times P_{h1,2}\right)\right\}\right] \times arccos\left(\frac{\hat{z} \times \hat{n}}{|\hat{z} \times \hat{n}|} \cdot \frac{\hat{n} \times P_{h1,2}}{|\hat{n} \times P_{h1,2}|}\right)$$

$H_1^{\sphericalangle}$ EXTRACTION

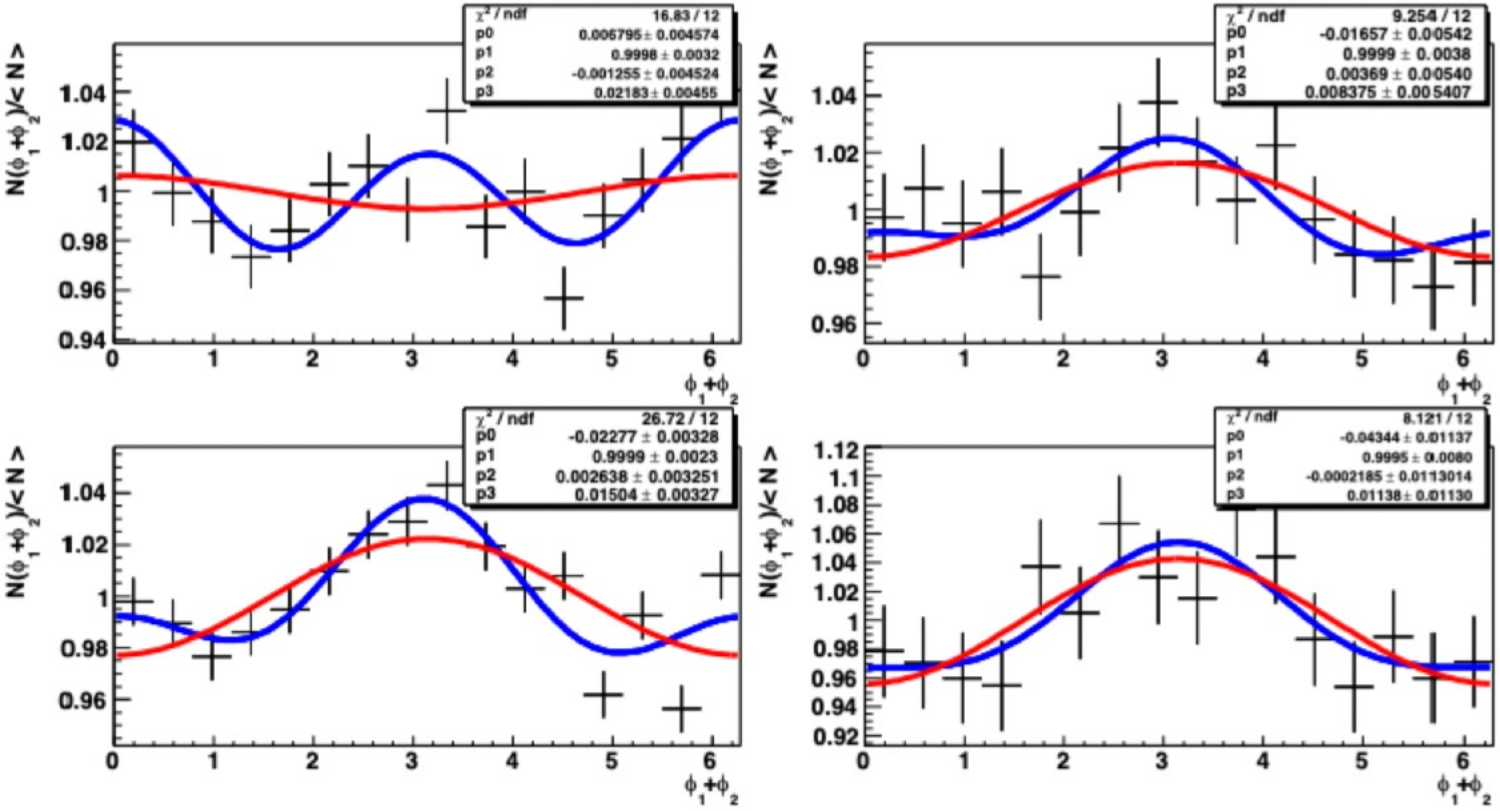
BELLE RESULTS

Extracting the asymmetry (p_0) from the azimuthal angle:

Azimuthal Angle: $\varphi_1 + \varphi_2$

Histogram Fits:

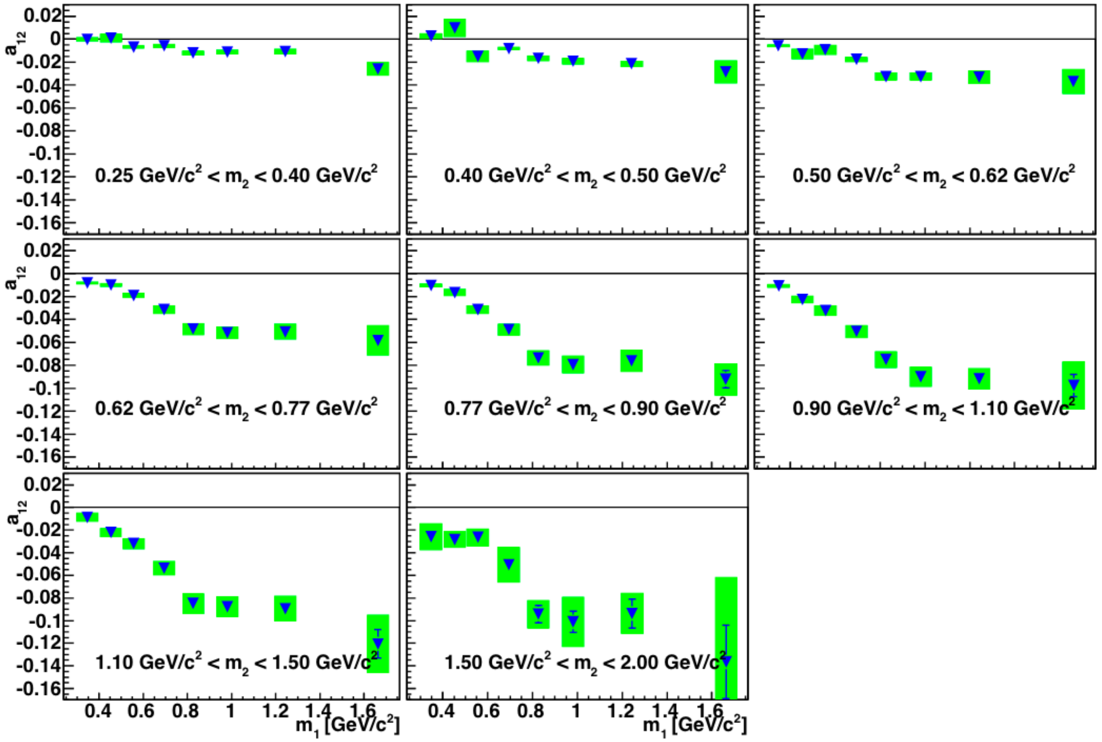
- (red) $p_0 \cos(\varphi_1 + \varphi_2) + 1$
- (blue) $p_0 \cos(\varphi_1 + \varphi_2) + p_1 + p_2 \sin(\varphi_1 + \varphi_2) + p_3 \cos(2(\varphi_1 + \varphi_2))$



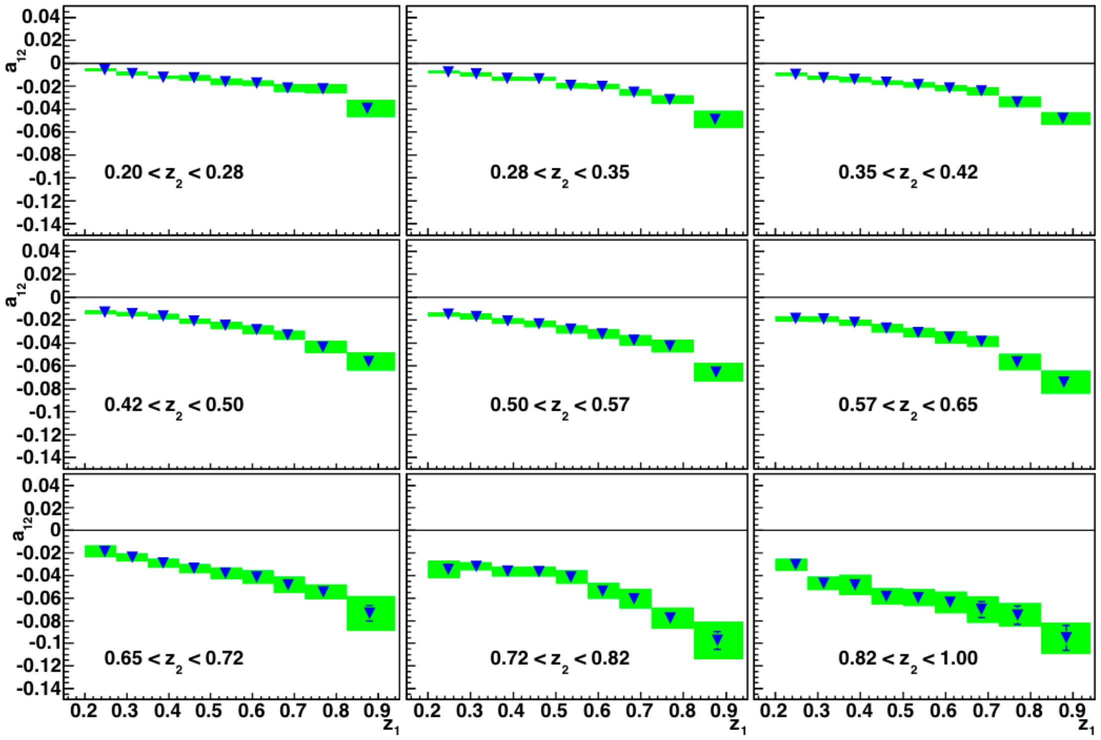
Phys. Rev. Lett. 107, 072004 (2011).

$H_1^{\sphericalangle}$ EXTRACTION
BELLE RESULTS

Asymmetry by Invariant Mass Bins:

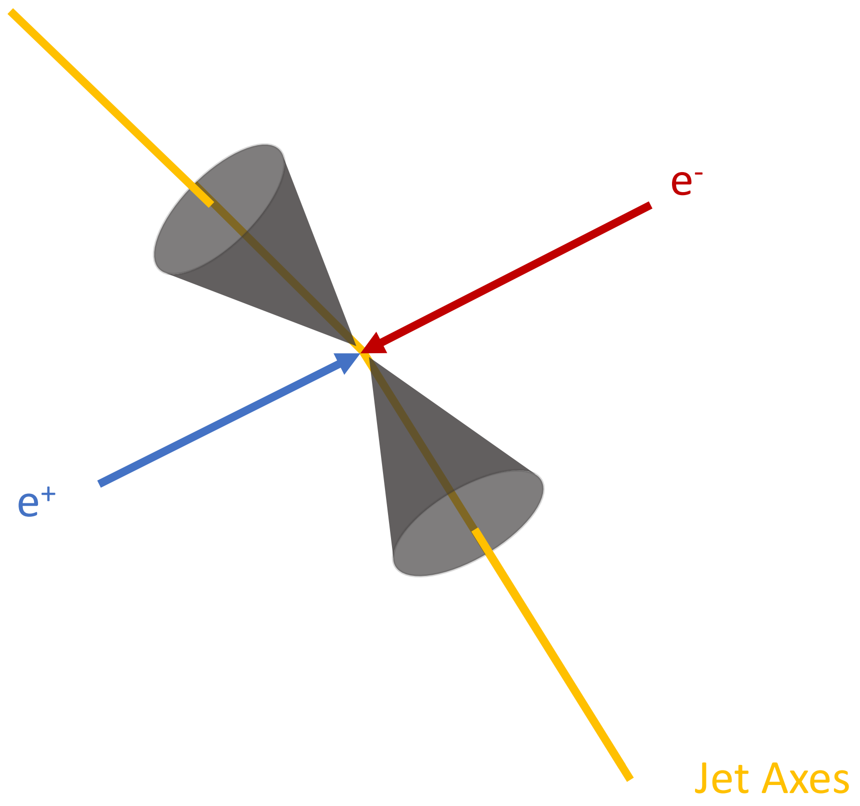


Asymmetry by Pion Fractional Energy Bins:



Phys. Rev. Lett. 107, 072004 (2011).

$H_1^{\measuredangle}$ EXTRACTION
USING JET ALGORITHMS



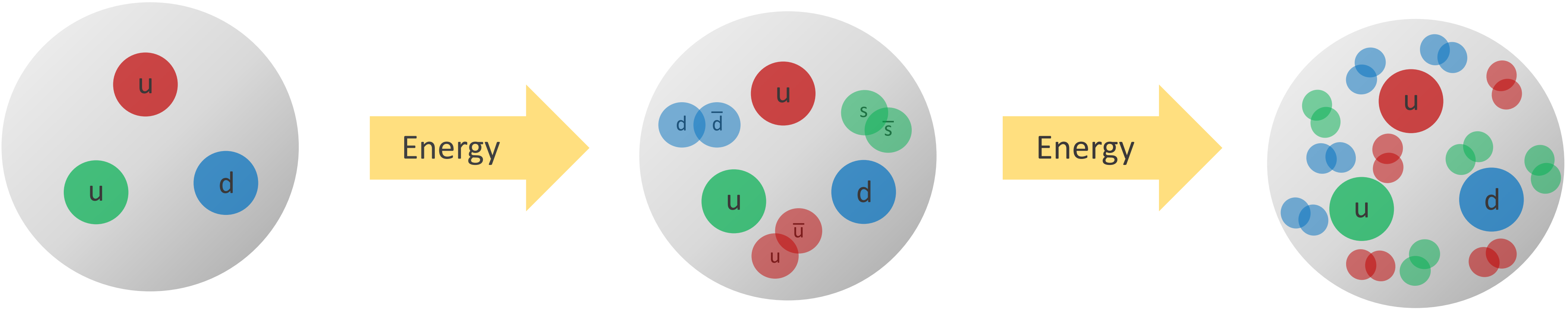
JET AXES

- Jets are well defined observables and produce better results than the naïve $q\bar{q}$ axis.
- Resulting FFs in e^+e^- are directly connected to FFs in SIDIS
- Jet analysis of FFs has been done at Belle before (arXiv: 1505.08020)

FUTURE RESEARCH

KAON INCLUSIVE MEASUREMENTS

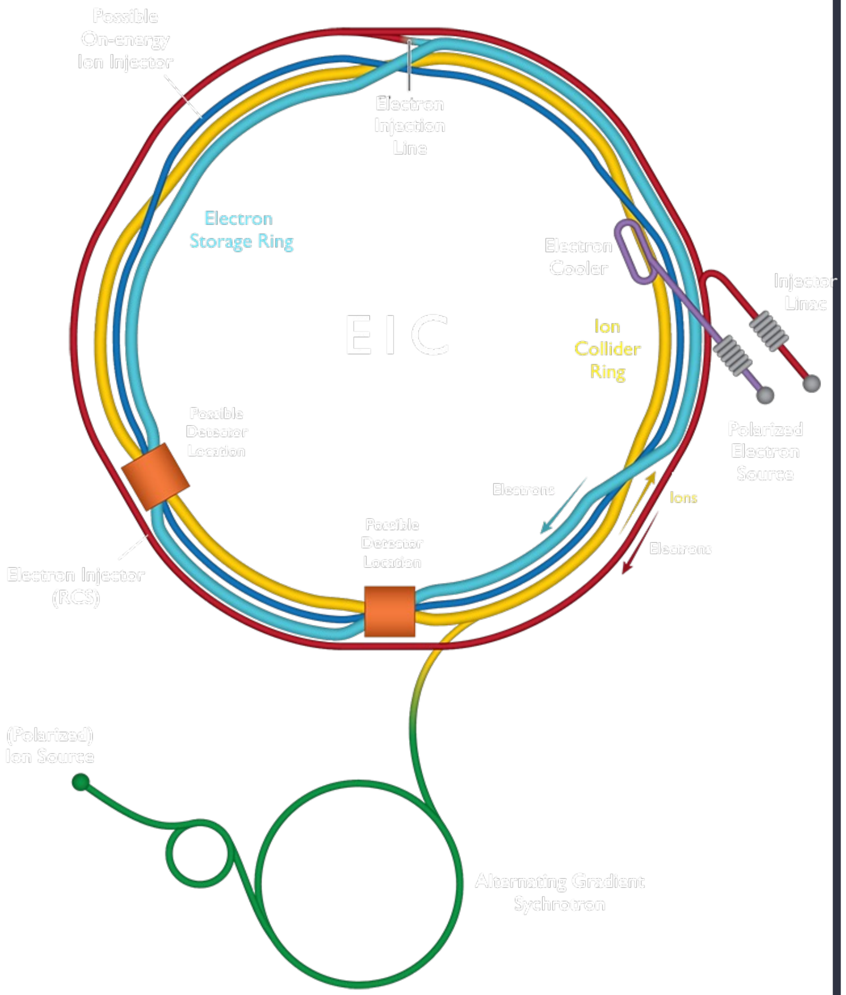
- The same measurement of $H_1^{\sphericalangle}$ can be made with $K^+ K^-$, $K^+ \pi^-$, or $\pi^+ K^-$ pairs
- Kaon inclusive measurements are sensitive to the strange quark
- Resulting $H_1^{\sphericalangle}$ measurements could be used to describe the distribution of strange quarks within the nucleon



CONTRIBUTION TO THE FIELD

NUCLEON STRUCTURE

- The EIC will be built using the components and space left by the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Lab
- It will be the first polarized electron-proton collider
- It will be uniquely suited to measure the contributions of quarks and gluons to the proton spin
- Because the EIC is a deep inelastic scattering experiment, light quark fragmentation functions are critical to unlocking its full science potential



SUMMARY

- Fragmentation functions:
  - Fundamental QCD objects
  - Describe the hadronization process
  - Necessary to study nucleon structure

- Electron positron annihilation provides the cleanest environment to study FFs

- New measurement of $H_1^{\sphericalangle}$
  - Sensitive to the strange quark
  - With respect to the jet axis

- New measurements are critical to upcoming experiments at JLab and the EIC

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BACKUP SLIDES

FULLY DIFFERENTIAL CROSS SECTION

$$
\begin{aligned}
&\frac{d\sigma(e^+e^-\to(h_1h_2)(\bar h_1\bar h_2)X)}{d\boldsymbol{q}_T\,dz\,d\xi\,dM_h^2\,d\phi_R\,d\bar z\,d\bar\xi\,d\bar M_h^2\,d\phi_{\bar R}\,dy\,d\phi^l}\\
&=\sum_{a,\bar a} e_a^2\frac{6\alpha^2}{Q^2}z^2\bar z^2\Bigg\{A(y)\mathcal{F}[D_1^a\bar D_1^a]+\cos(2\phi_1)B(y)\mathcal{F}\left[(2\hat{\boldsymbol h}\cdot\boldsymbol k_T\hat{\boldsymbol h}\cdot\bar{\boldsymbol k}_T-\boldsymbol k_T\cdot\bar{\boldsymbol k}_T)\frac{H_1^{\perp a}\bar H_1^{\perp a}}{(M_1+M_2)(\bar M_1+\bar M_2)}\right]\\
&-\sin(2\phi_1)B(y)\mathcal{F}\left[(\hat{\boldsymbol h}\cdot\boldsymbol k_T\hat{\boldsymbol g}\cdot\bar{\boldsymbol k}_T+\hat{\boldsymbol h}\cdot\bar{\boldsymbol k}_T\hat{\boldsymbol g}\cdot\boldsymbol k_T)\frac{H_1^{\perp a}\bar H_1^{\perp a}}{(M_1+M_2)(\bar M_1+\bar M_2)}\right]+\cos(\phi_R+\phi_{\bar R}-2\phi^l)\\
&\times B(y)|\boldsymbol R_T||\bar{\boldsymbol R}_T|\mathcal{F}\left[\frac{H_1^{\sphericalangle a}\bar H_1^{\sphericalangle a}}{(M_1+M_2)(\bar M_1+\bar M_2)}\right]+\cos(\phi_1+\phi_R-\phi^l)B(y)|\boldsymbol R_T|\mathcal{F}\left[\hat{\boldsymbol h}\cdot\bar{\boldsymbol k}_T\frac{H_1^{\sphericalangle a}\bar H_1^{\perp a}}{(M_1+M_2)(\bar M_1+\bar M_2)}\right]\\
&-\sin(\phi_1+\phi_R-\phi^l)B(y)|\boldsymbol R_T|\mathcal{F}\left[\hat{\boldsymbol g}\cdot\bar{\boldsymbol k}_T\frac{H_1^{\sphericalangle a}\bar H_1^{\perp a}}{(M_1+M_2)(\bar M_1+\bar M_2)}\right]+\cos(\phi_1+\phi_{\bar R}-\phi^l)B(y)|\bar{\boldsymbol R}_T|\\
&\times\mathcal{F}\left[\hat{\boldsymbol h}\cdot\boldsymbol k_T\frac{H_1^{\perp a}\bar H_1^{\sphericalangle a}}{(M_1+M_2)(\bar M_1+\bar M_2)}\right]-\sin(\phi_1+\phi_{\bar R}-\phi^l)B(y)|\bar{\boldsymbol R}_T|\mathcal{F}\left[\hat{\boldsymbol g}\cdot\boldsymbol k_T\frac{H_1^{\perp a}\bar H_1^{\sphericalangle a}}{(M_1+M_2)(\bar M_1+\bar M_2)}\right]+A(y)|\boldsymbol R_T||\bar{\boldsymbol R}_T|\\
&\times\Bigg(\sin(\phi_1-\phi_R+\phi^l)\sin(\phi_1-\phi_{\bar R}+\phi^l)\mathcal{F}\left[\hat{\boldsymbol h}\cdot\boldsymbol k_T\hat{\boldsymbol h}\cdot\bar{\boldsymbol k}_T\frac{G_1^{\perp a}\bar G_1^{\perp a}}{M_1M_2\bar M_1\bar M_2}\right]+\sin(\phi_1-\phi_R+\phi^l)\cos(\phi_1-\phi_{\bar R}+\phi^l)\\
&\times\mathcal{F}\left[\hat{\boldsymbol h}\cdot\boldsymbol k_T\hat{\boldsymbol g}\cdot\bar{\boldsymbol k}_T\frac{G_1^{\perp a}\bar G_1^{\perp a}}{M_1M_2\bar M_1\bar M_2}\right]+\cos(\phi_1-\phi_R+\phi^l)\sin(\phi_1-\phi_{\bar R}+\phi^l)\mathcal{F}\left[\hat{\boldsymbol g}\cdot\boldsymbol k_T\hat{\boldsymbol h}\cdot\bar{\boldsymbol k}_T\frac{G_1^{\perp a}\bar G_1^{\perp a}}{M_1M_2\bar M_1\bar M_2}\right]+\cos(\phi_1-\phi_R+\phi^l)\\
&\times\cos(\phi_1-\phi_{\bar R}+\phi^l)\mathcal{F}\left[\hat{\boldsymbol g}\cdot\boldsymbol k_T\hat{\boldsymbol g}\cdot\bar{\boldsymbol k}_T\frac{G_1^{\perp a}\bar G_1^{\perp a}}{M_1M_2\bar M_1\bar M_2}\right]\Bigg)\Bigg\},
\end{aligned}
$$

$\boldsymbol{R}_T$: The transverse part of the relative momentum between the hadrons

$M_{1,2}$: Mass of hadron 1,2

$\phi_R-\phi^l$: The azimuthal angle with respect to the lepton frame

A kinematic factor dependent only on θ in the center of mass frame:

$$B(y)=\frac{sin^2\theta}{4}$$

$\mathcal{F}$: The convolution

D. Boer, R. Jakob, and M. Radici, Phys. Rev. D 67, 094003 (2003).

BACKUP SLIDES

WTA UUBAR MC BINNING