# Hadronization at CLAS12 and Belle (II)

Anselm Vossen

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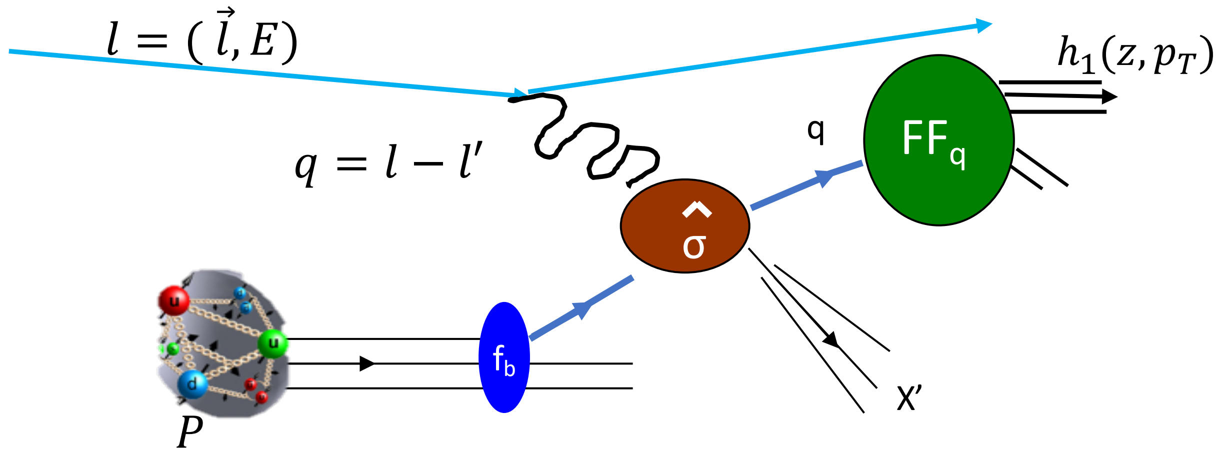
U.S. DEPARTMENT OF ENERGY | Office of Science

Duke UNIVERSITY

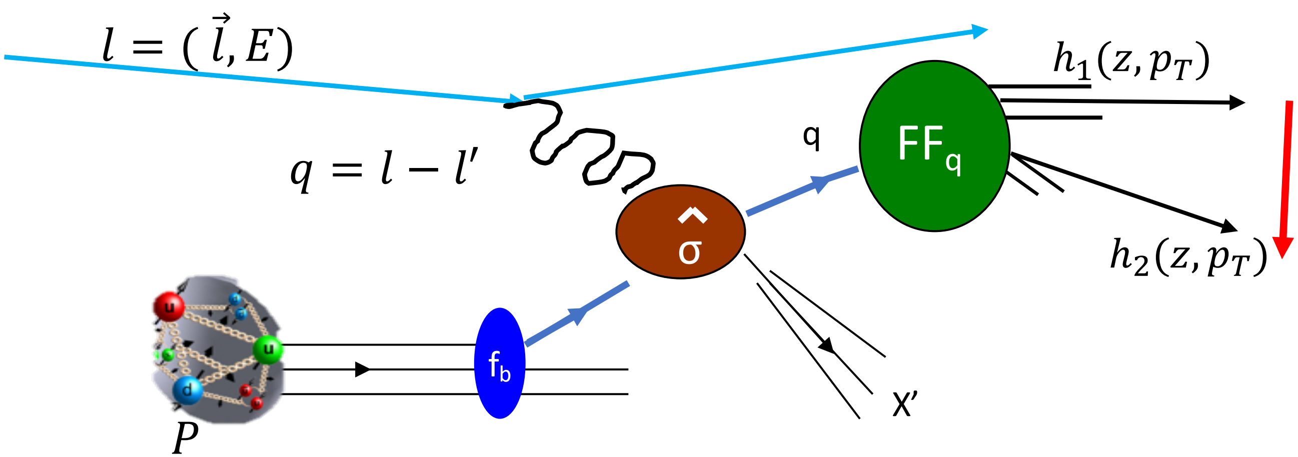
Jefferson Lab

# In a factorized picture, hadronization can be described by Fragmentation functions




- LO/LT: probability of finding hadron with momentum fraction $z$
- <u>Observables:</u>
  - z: fractional energy of the quark carried by the hadron
  - $p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

# In a factorized picture, hadronization can be described by Fragmentation functions

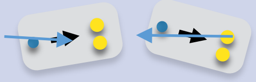
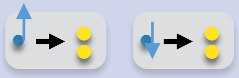


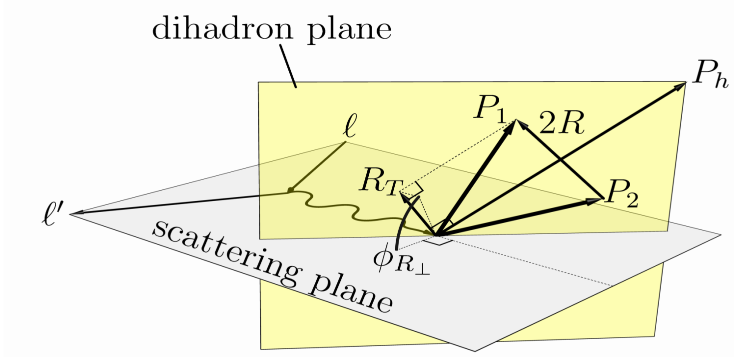

$\vec{P_h} = \vec{P_1} - \vec{P_2}$

$\vec{R} = \vec{P_1} - \vec{P_2}$

# Di-hadron fragmentation Functions

More degrees of freedom→More information about correlations in final state

| Parton polarization → | Spin averaged | longitudinal | transverse |
|---|---|---|---|
| | | **$G_1^{\perp}(z,M,P_h,\theta)$=**<br>T-odd, chiral-even<br>→jet handedness<br>QCD vaccum strucuture  | **$H_1^{\sphericalangle}(z,M,(P_h),\theta)$=.**<br>T-odd, chiral-odd<br>Colinear  |



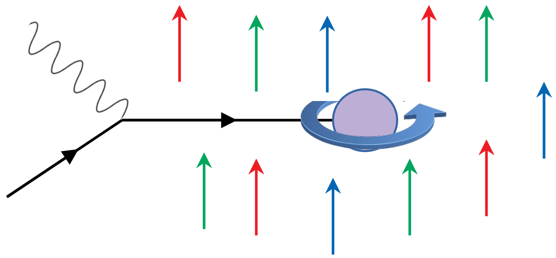
# Twist3: Accessing e(x) in di- and single hadron $F_{LU}$

- Di-hadrons: extra degree of freedom of di-hadron FFs allow more targeted access

$$F_{LU}^{\sin\phi_R} = -x\frac{|\vec{R}|\sin\theta}{Q}\left[\frac{M}{M_{\pi\pi}}x e^q(x) H_1^{\sphericalangle q}(z, cos\theta, M_{\pi\pi}) + \frac{1}{z} f_1^q(x)\tilde{G}(z, \cos\theta, M_{\pi\pi})\right]$$

Phys.Rev.D 88 (2013) 114502

Boer-Mulders Force”:
Transverse force exerted by color field on q↑ after scattering, in an unpolarized nucleon



# Twist3: Accessing e(x) in di- and single hadron $F_{LU}$

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- In single hadrons: Complicated combination of four terms in the structure function.
- TMD factorization at twist-3 not yet proven!

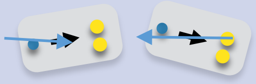
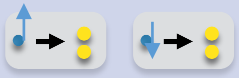
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x e H_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot p_T}{M}\left(x g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

twist-3 pdf | Collins FF | unpolarized PDF | twist-3 FF | twist-3 t-odd PDF | unpolarized FF | Boer-Mulders | twist-3 FF

convolution

# Di-hadron fragmentation Functions

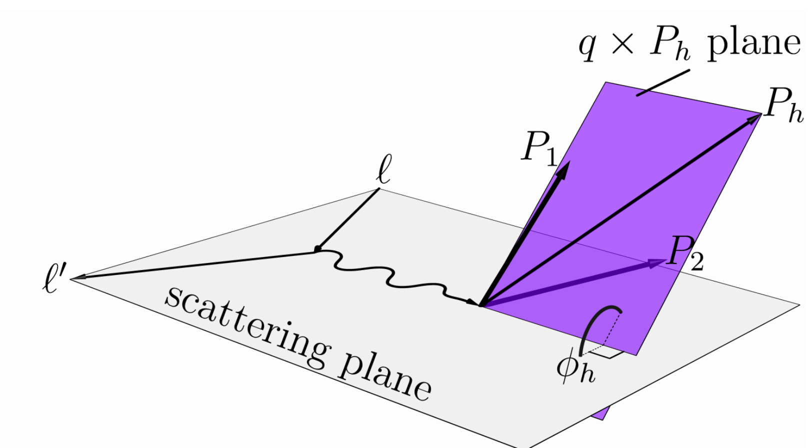
More degrees of freedom→More information about correlations in final state

| Parton polarization → | Spin averaged | longitudinal | transverse |
|---|---|---|---|
| | Type equation here. | $G_1^{\perp}(z,M,P_h,\theta)=$<br>T-odd, chiral-even<br>→jet handedness<br>QCD vaccum strucuture<br> | **$H_1^{\sphericalangle}(z,M,(P_h),\theta)=.$**<br>T-odd, chiral-odd<br>Colinear<br> |

# Access to $G_1^\perp$ at leading twist

$$d^9\sigma_{LU} = -\sum_a \frac{\alpha^2 e_a^2}{2\pi Q^2 y} |\lambda_e| \, C(y) \, \frac{|\vec{R}_T|}{M_h} \left\{ \sin(\phi_h - \phi_R) \, \mathcal{I}\left[ \frac{\vec{k}_T \cdot \hat{P}_{h\perp}}{M_h} \, f_1 \, G_1^\perp \right] + \cos(\phi_h - \phi_R) \, \mathcal{I}\left[ \frac{\hat{P}_{h\perp} \wedge \vec{k}_T}{M_h} \, f_1 \, G_1^\perp \right] \right\}$$

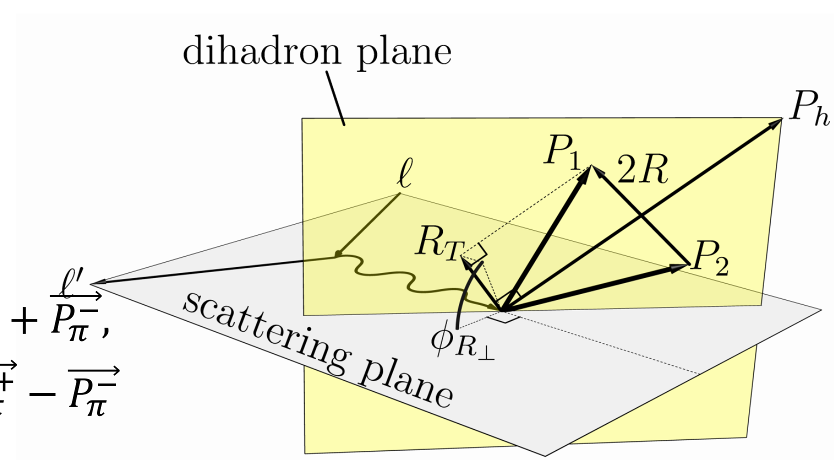
$$\Rightarrow A_{LU}^{\sin(\phi_h - \phi_R)} \propto f_1 \cdot G_1^\perp$$




*cf.* single-hadron $\phi_h$

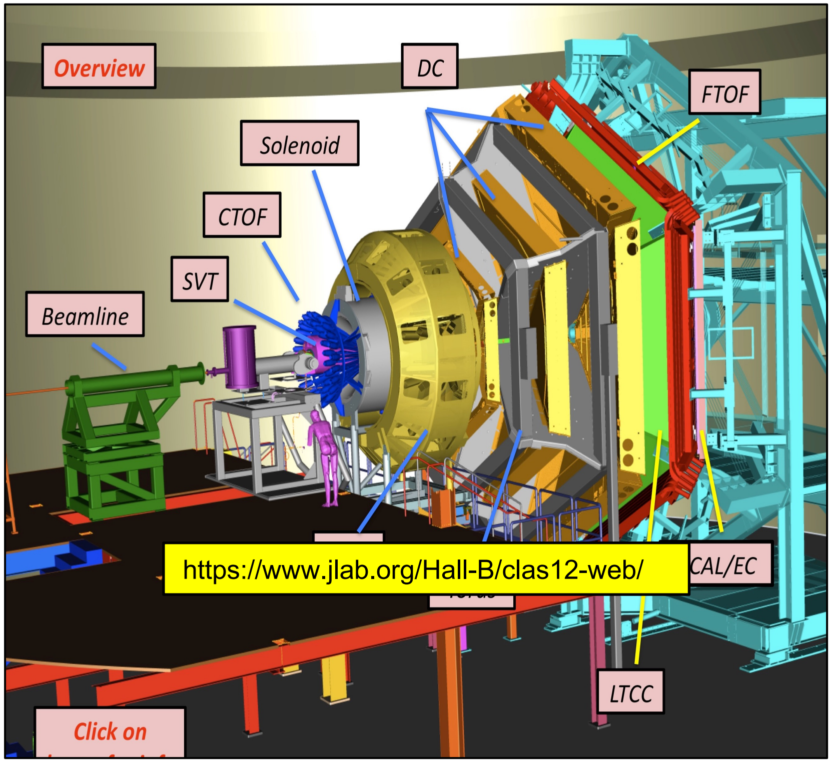
$$\overrightarrow{P_h} = \overrightarrow{P_\pi^+} + \overrightarrow{P_\pi^-},$$

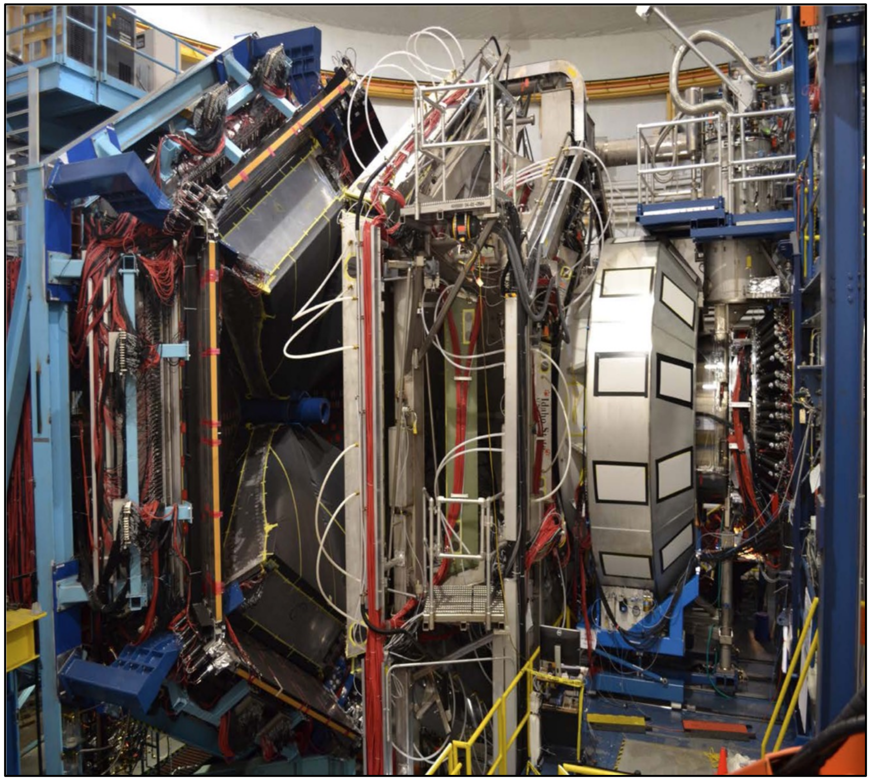
$$2\vec{R} = \overrightarrow{P_\pi^+} - \overrightarrow{P_\pi^-}$$



# CLAS12 Experimental Setup

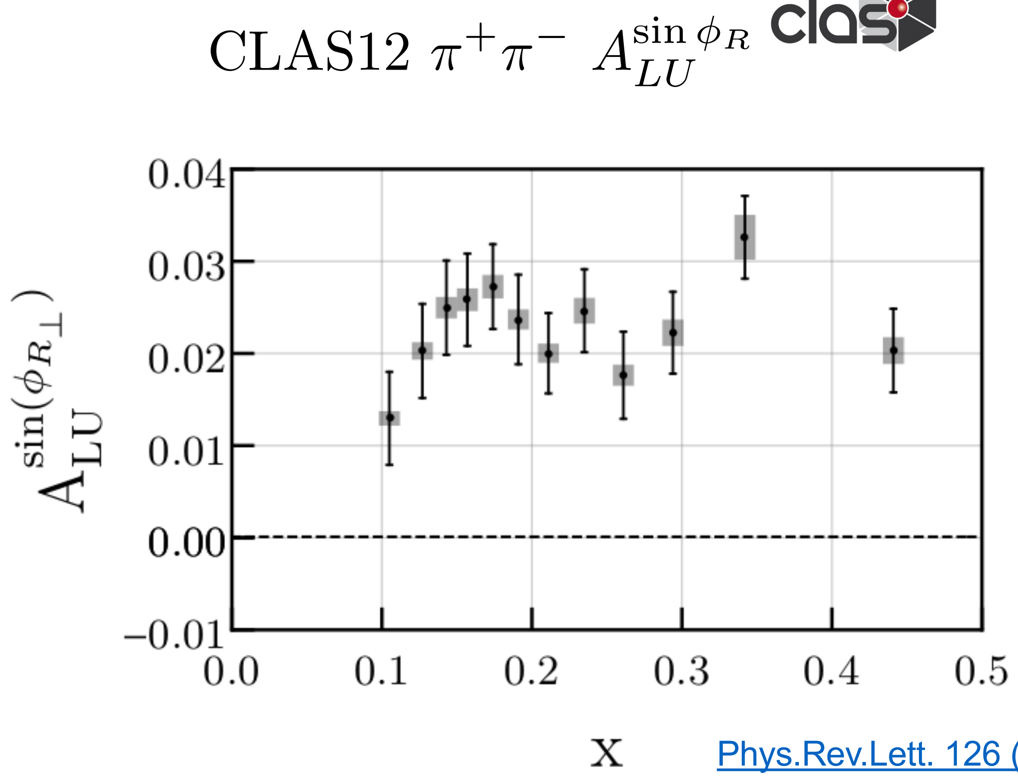
- CLAS12: very high luminosity, wide acceptance, low $Q^2$ (higher twist measurements)
- Began data taking in Spring 2018 – many “run periods” now available.
- 10.6 (2018) and 10.2 (2019) GeV electron beam, longitudinally polarized beam, liquid $H_2$ target.



V. Burkert et al., Nucl. Instrum. Meth. A 959 (2020) 163419

# Dihadron $A_{LU}$ Measurements – Proton Target



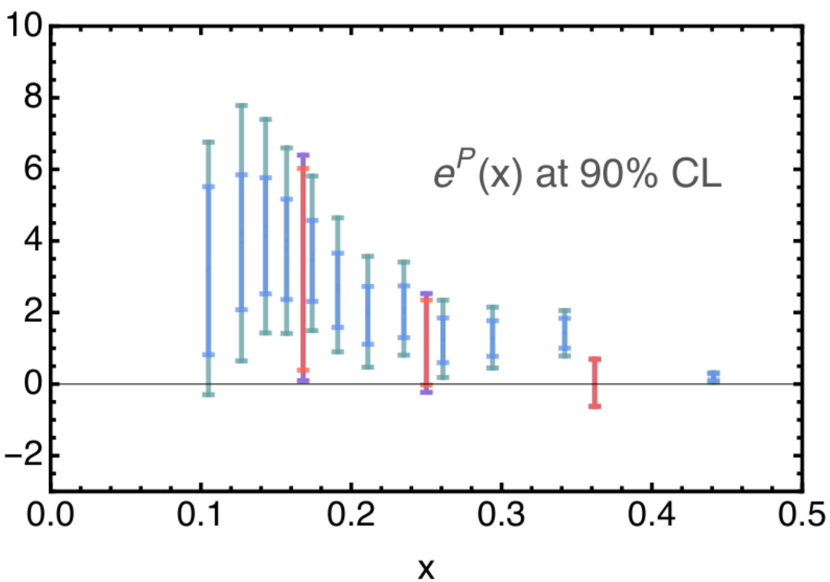

Phys.Rev.Lett. 126 (2021) 152501

- $\propto e(x) H_1^{\angle}$ point-by-point

# New e(x) Extraction – Proton Flavor Combination

$$A_{LU}^{\sin\phi_R} \propto \frac{M}{Q}\frac{\sum_q e_q^2\left[xe^q(x)\,H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi}) + \frac{m_{\pi\pi}}{zM}\,f_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi})\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,m_{\pi\pi})}$$

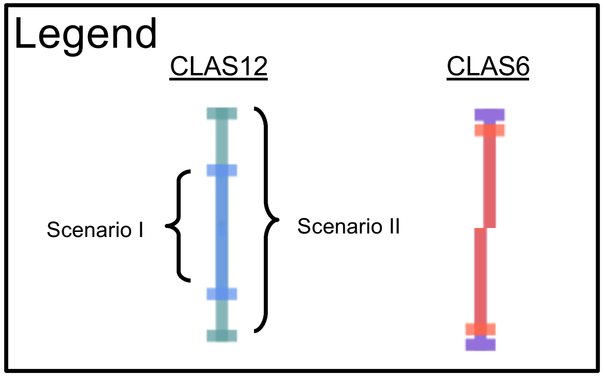
twist-3 DiFF




Courtoy, Aurore, et al. *Phys.Rev.D* 106 (2022)

Courtoy, Aurore – [CPHI 2022]

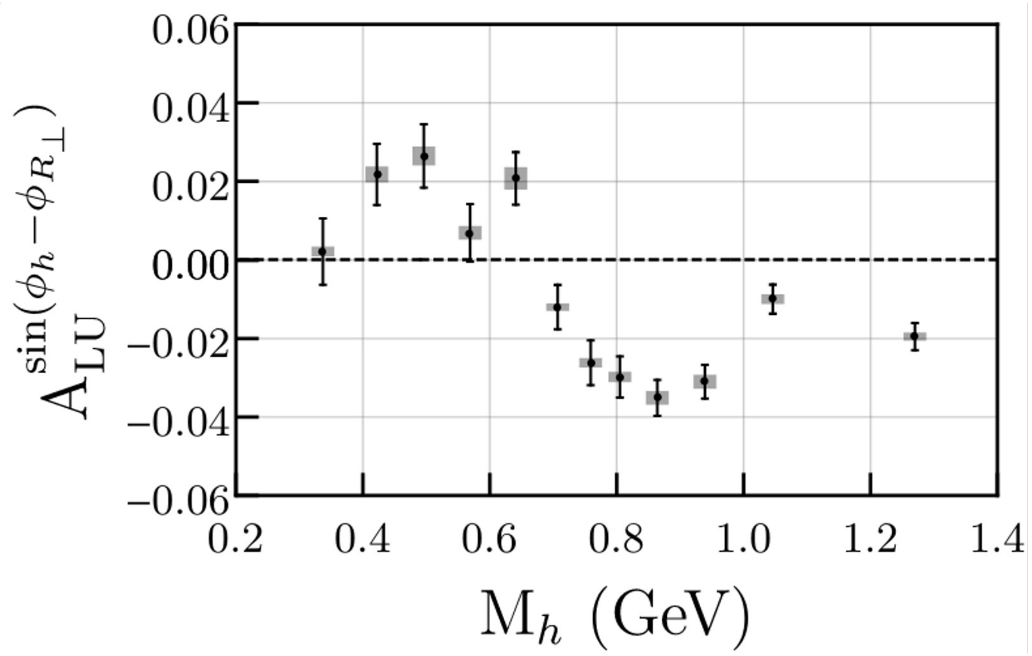
- **Scenario I: Wandzura-Wilczek (WW) Approximation**
  - Drop twist-3 DiFF
- **Scenario II: Beyond WW approximation**
  - Estimate max integrated twist-3 DiFF from COMPASS $A_{UL}$ and $A_{LL}$



# CLAS12 Beam Spin Asymmetry Measurements

## Twist 2

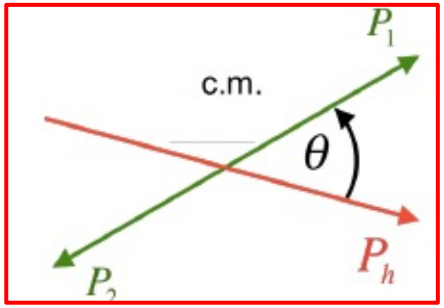
$$A_{LU} \sim f_1 G_1^{\perp|\ell,m\rangle}$$

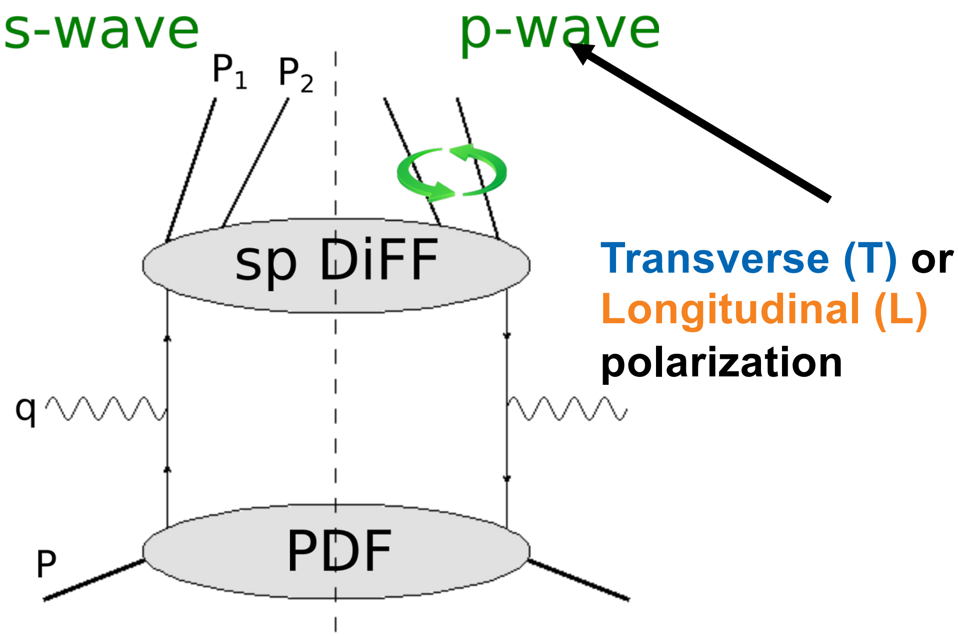


# Next Step: Partial Wave analysis

- Transverse polarization dependent effect comes from interference effect
  - Here interference between different partial waves
  - Dihadron FF expands on a basis of spherical harmonics
  - Angular momentum eigenvalues | ℓ, m >

➔**Explore dihadron fragmentation depending on relative angular momentum**



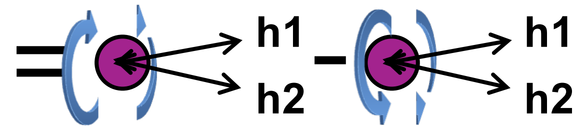



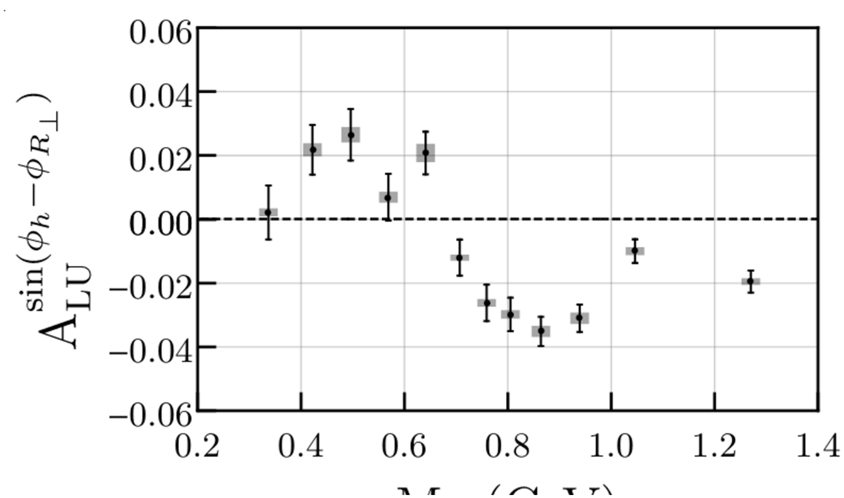
# CLAS12 Beam Spin Asymmetry Measurements

## Twist 2

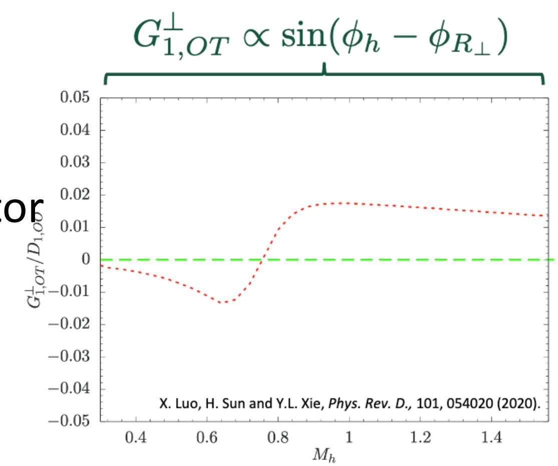
$$A_{LU} \sim f_1 G_1^{\perp|\ell,m\rangle}$$

$$G_1^{\perp|\ell,m\rangle} =$$



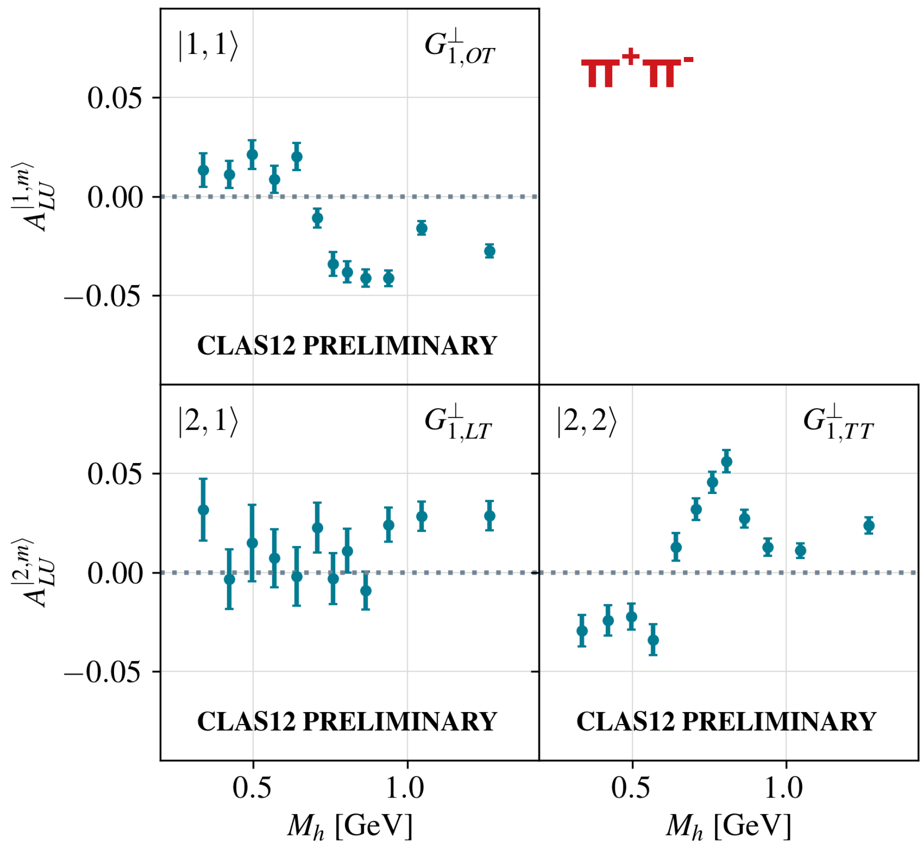

In good agreement with spectator Model predictions



# Twist-2 $A_{LU}$ at $M_h$ Bins

Sensitive to $f_1 \cdot G_1^{\perp}$

Twist-2 $A_{LU}$ Amplitudes



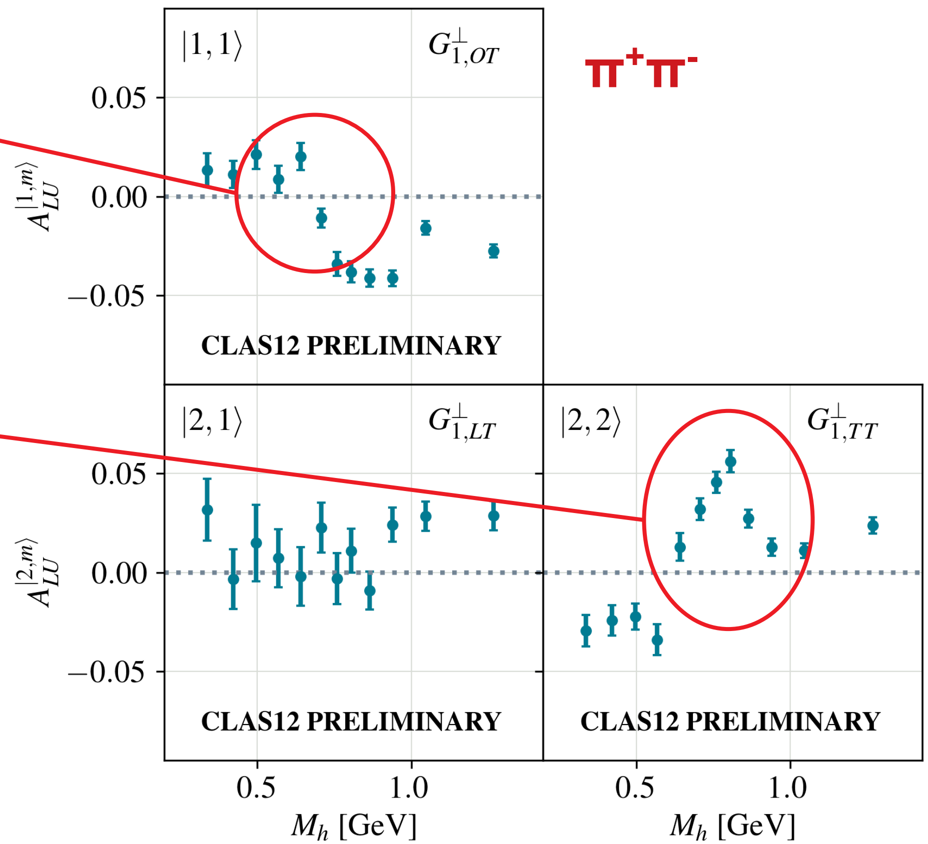

e-Print: 2107.12965 [hep-ex]

# Twist-2 $A_{LU}$ at $M_h$ Bins

Sign change near ρ mass

Enhancement at ρ mass (and a sign change)

**ρ meson → p-wave $\pi^+\pi^-$**




e-Print: 2107.12965 [hep-ex]

# Relation to Monte Carlo Event Generators (MCEGs)

## Fragmentation Functions

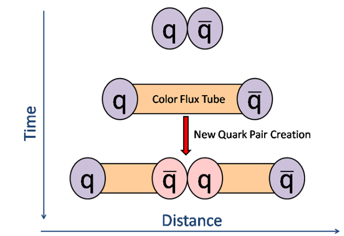
- Focus on more '**inclusive**' measurements → factorization holds
- Recent activity in more exclusive measurements (in particular jets)
- Needs MCEGs for experimental extraction
- Very precise extractions→Benchmark for MCEGs

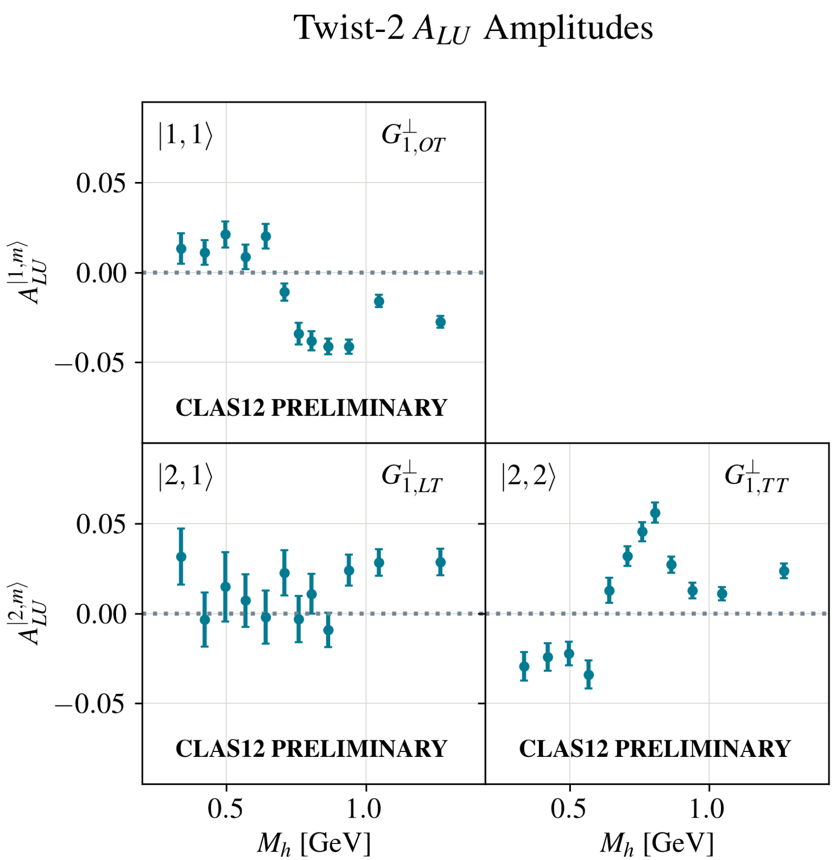
## Hadronization Model in MCEG

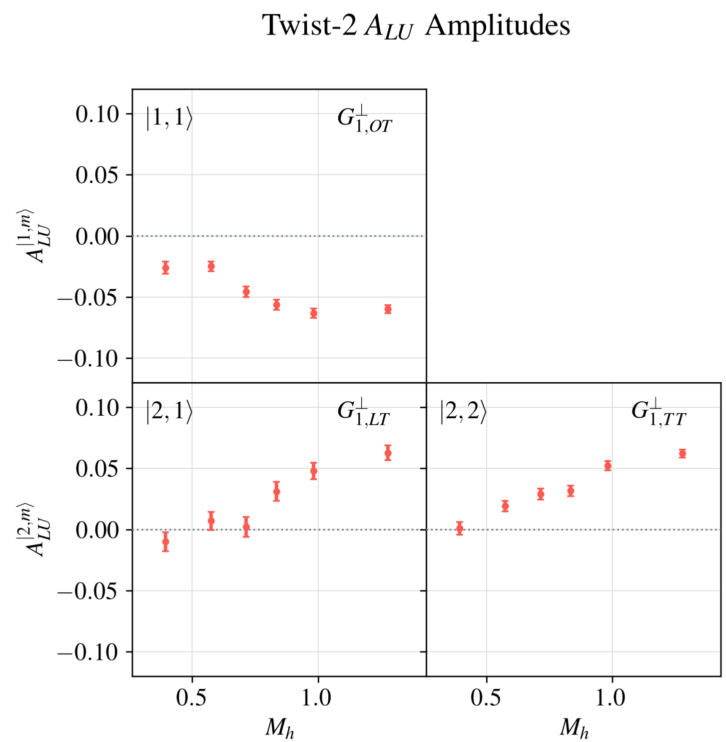
- Exclusive final states
- "Hard" subprocesses well constrained by theory
- Measurements focusing on MCEG improvement different from measurements extracting hard physics (grooming) or FFs (more exclusive)

# Compare Partial Wave Decomposition in MC and Data

- Comparing to Polarized Lund model here (StringSpinner, A. al, *Comput.Phys.Commun.* 272 (2022))



# Future plans

## Twist 2

Target Polarization

| Beam Polarization | U | L | T |
|---|---|---|---|
| U | $f_1 D_1$ $h_1^\perp H_1$ | $h_{1L}^\perp H_1$ $g_{1L} G_1$ | $f_{1T}^\perp D_1$ $g_{1T} G_1$ $h_1 H_1$ $h_{1T}^\perp H_1$ |
| L | $f_1 G_1$ | $g_{1L} D_1$ | $g_{1T} D_1$ $f_{1T}^\perp G_1$ |

## Twist 3

Target Polarization

| Beam Polarization | U | L | T |
|---|---|---|---|
| U | $h H_1$ $f_1 \tilde{D}$ $f^\perp D_1$ $h_1^\perp \tilde{H}$ | $h_L H_1$ $g_{1L} \tilde{G}$ $f_L^\perp D_1$ $h_{1L}^\perp \tilde{H}$ | $f_T D_1$ $h_1 \tilde{H}$ $h_T H_1$ $g_{1T} \tilde{G}$ $h_T^\perp H_1$ $f_{1T}^\perp \tilde{D}$ $f_T^\perp D_1$ $h_{1T}^\perp \tilde{H}$ |
| L | $e H_1$ $f_1 \tilde{G}$ $g^\perp D_1$ $h_1^\perp \tilde{E}$ | $e_L H_1$ $g_{1L} \tilde{D}$ $g_L^\perp D_1$ $h_{1L}^\perp \tilde{E}$ | $g_T D_1$ $h_1 \tilde{E}$ $e_T H_1$ $g_{1T} \tilde{D}$ $e_T^\perp H_1$ $f_{1T}^\perp \tilde{G}$ $g_T^\perp D_1$ $h_{1T}^\perp \tilde{E}$ |

- 2018-2020 $A_{LU}$
- 2022-2023 $A_{UL}$, $A_{LL}$
- Future (?) $A_{UT}$, $A_{LT}$
- (any time) $F_{UU}$

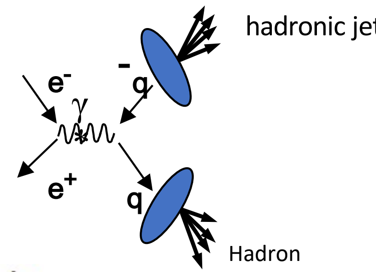
- Boer-Mulders, $F_{UU,L}$ (?), …

# More results and ongoing hadronization at CLAS12

See also T. Hayward's talk

- Di-hadrons
  - Prelim results on deuterium target, pairs including $\pi^0$ (see backup)
  - Analysis underway:
    - $\pi/K$, $K/K$ pairs
    - Multiplicities
    - Target spin asymmetries
- Single hadrons
  - Beam spin asymmetries: Phys.Rev.Lett. 128 (2022) 6, 062005
  - Multiplicities
- $\Lambda$ hyperon production
  - Longitudinal spin transfer prelim results: In the proceedings of Spin 21: e-Print: 2201.06480 [nucl-ex]
  - Underway:
    - polarizing ↑ FF
- Back-to-back correlations to access fracture functions in BSAs: e-Print: 2208.05086

# Access of FFs for light mesons in $e^+e^-$ (spin averaged case)

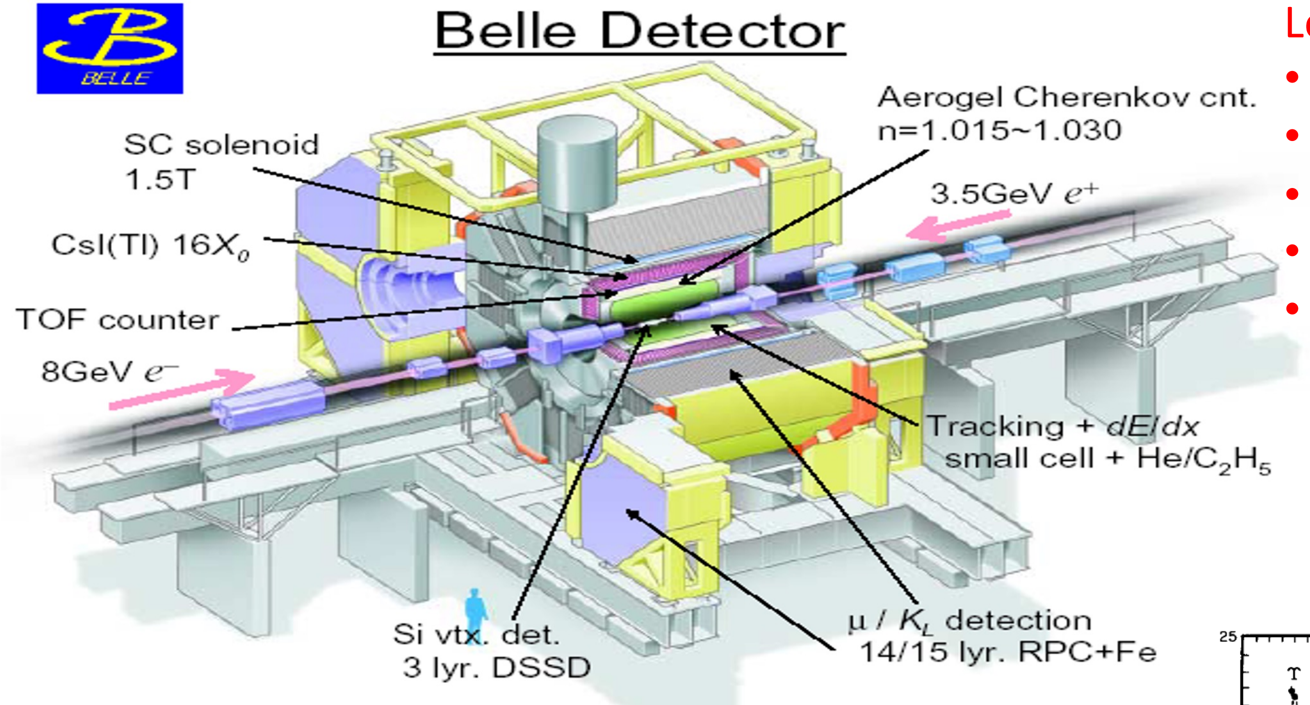



$$\frac{1}{\sigma_{\text{tot}}}\frac{d\sigma^{e^+e^-\to hX}}{dz} := \frac{1}{\sum_q e_q^2}\left(2F_1^h(z,Q^2) + F_L^h(z,Q^2)\right),$$

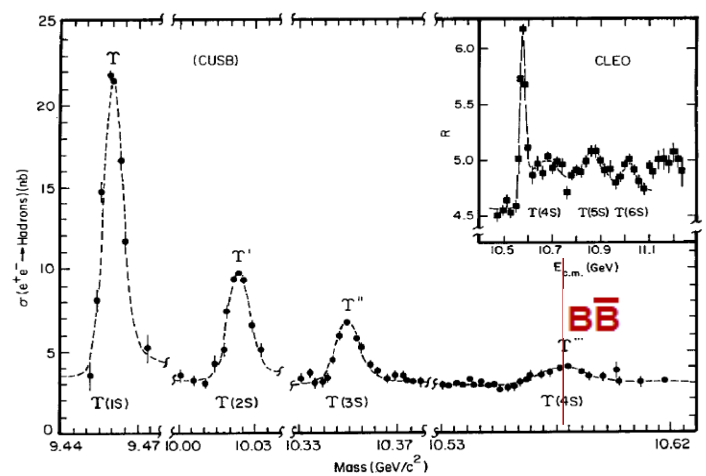
$$2F_1^h(z,Q^2) = \sum_q e_q^2\left(D_1^{h/q}(z,Q^2) + \frac{\alpha_s(Q^2)}{2\pi}\left(C_1^q \otimes D_1^{h/q} + C_1^g \otimes D_1^{h/g}\right)(z,Q^2)\right)$$

- Cleanest process→testbed for QCD calculations

# Belle Experiment at KEK (1999 - 2010)




Long and successful FF program
- Unpolarized
- Collins
- Di-hadron
- $\Lambda$
- Polarized Di-jet



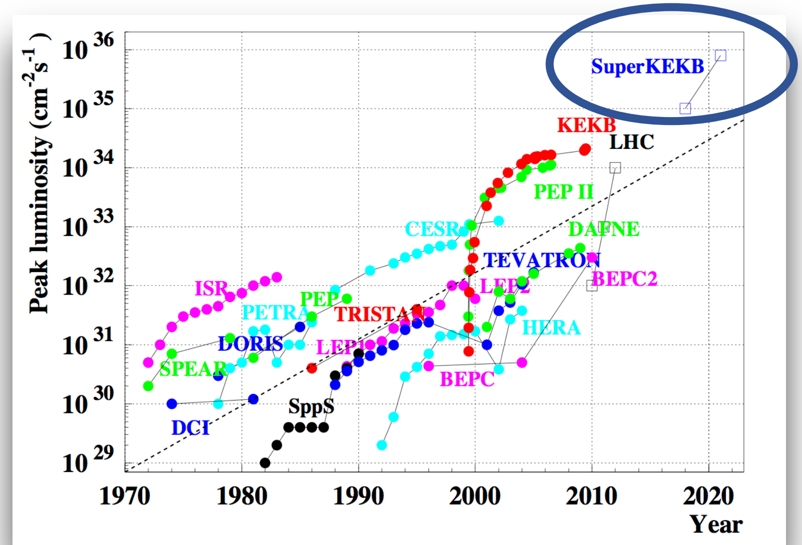

| Exp. | Scans / Off-res. fb$^{-1}$ | $\Upsilon(5S)$ 10876 MeV fb$^{-1}$ | $10^6$ | $\Upsilon(4S)$ 10580 MeV fb$^{-1}$ | $10^6$ | $\Upsilon(3S)$ 10355 MeV fb$^{-1}$ | $10^6$ | $\Upsilon(2S)$ 10023 MeV fb$^{-1}$ | $10^6$ | $\Upsilon(1S)$ 9460 MeV fb$^{-1}$ | $10^6$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CLEO | 17.1 | 0.4 | 0.1 | 16 | 17.1 | 1.2 | 5 | 1.2 | 10 | 1.2 | 21 |
| BaBar | 54 | $R_b$ scan | | 433 | 471 | 30 | 122 | 14 | 99 | — | |
| Belle | 100 | 121 | 36 | 711 | 772 | 3 | 12 | 25 | 158 | 6 | 102 |

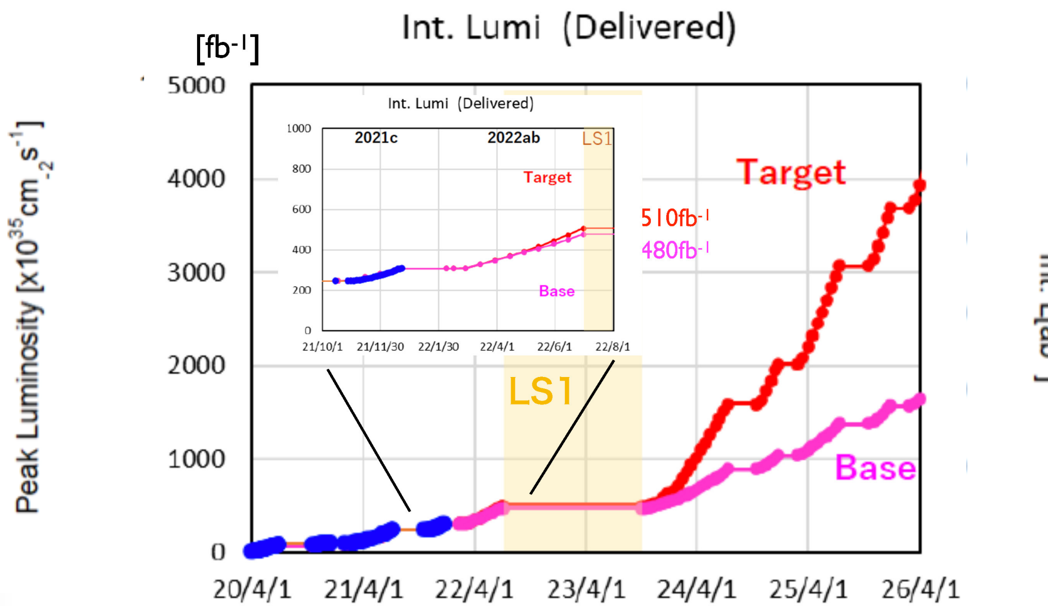
+About 4x10$^6$ events per $fb^{-1}$ off-resonance

From: *PTEP* 2019 (2019) 12, 123C01, *PTEP* 2020 (2020) 2, 029201

# The future is now: Next Generation B factory SuperKEKB

•




Beam currents *only* a factor of two higher than KEKB (~PEPII)

"nano-beams" are the key; vertical beam size is 50nm at the IP

- Belle II already delivered world record luminosity

- Belle II will have 50× Belle luminosity (100 × BaBar)

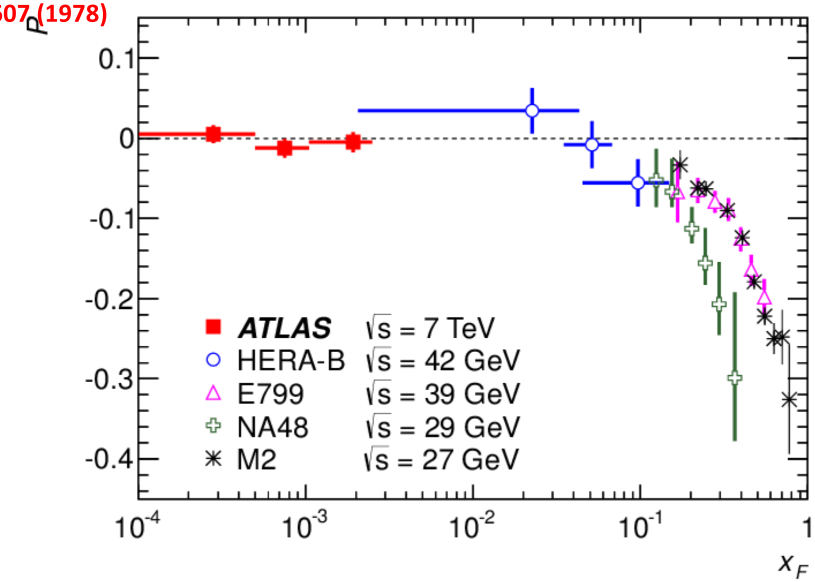
  QCD program spelled out:

  "[Opportunities for precision QCD physics in hadronization at Belle II -- a snowmass whitepaper]"

  e-Print: 2204.02280 [hep-ex]

# Polarized Hyperon Production

- Large $\Lambda$ transverse polarization in unpolarized pp collision PRL36, 1113 (1976); PRL41, 607 (1978)
- Caused by polarizing FF
  $D_{1T}^{\perp}(z, p_{\perp}^{2})$ =  ?
- Polarizing FF is chiral-even, has been proposed PRL105,202001 (2010)
  as a test of universality.
- FF counterpart of the Sivers function.
- OPAL experiment at LEP has studied transverse $\Lambda$ polarization, no significant signal was observed. Eur. Phys. J. C2, 49 (1998)

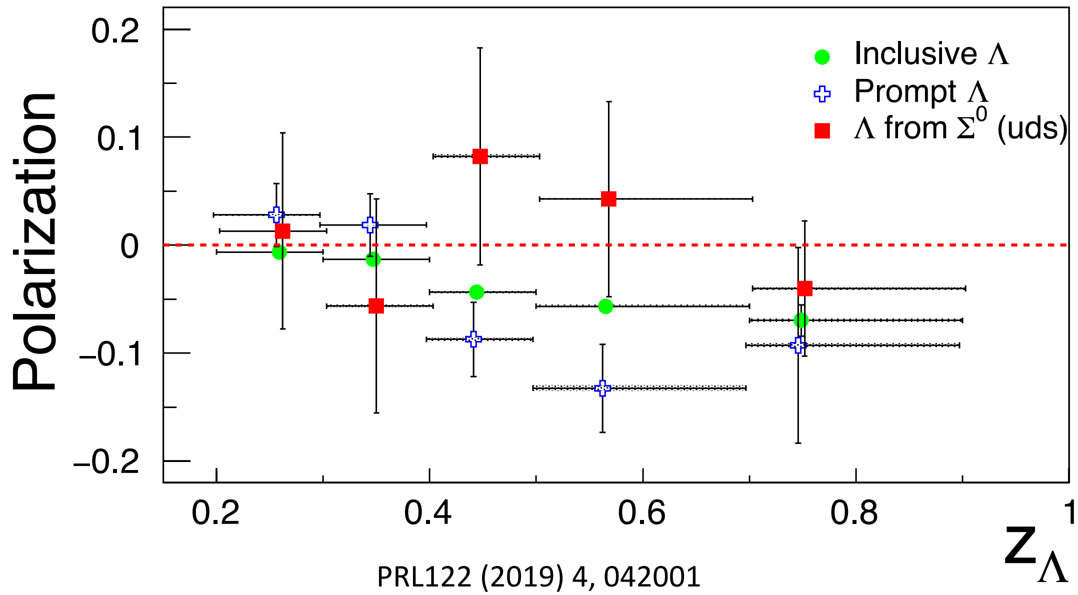



PRD 91, 032004 (2015)

# Belle II Makes Precision Λ program possible!

First observation of $\Lambda^{\uparrow}$ at Belle!
(Here feed-down corrected)

Not shown: Associate production in tension with theory prediction→needs to be understood

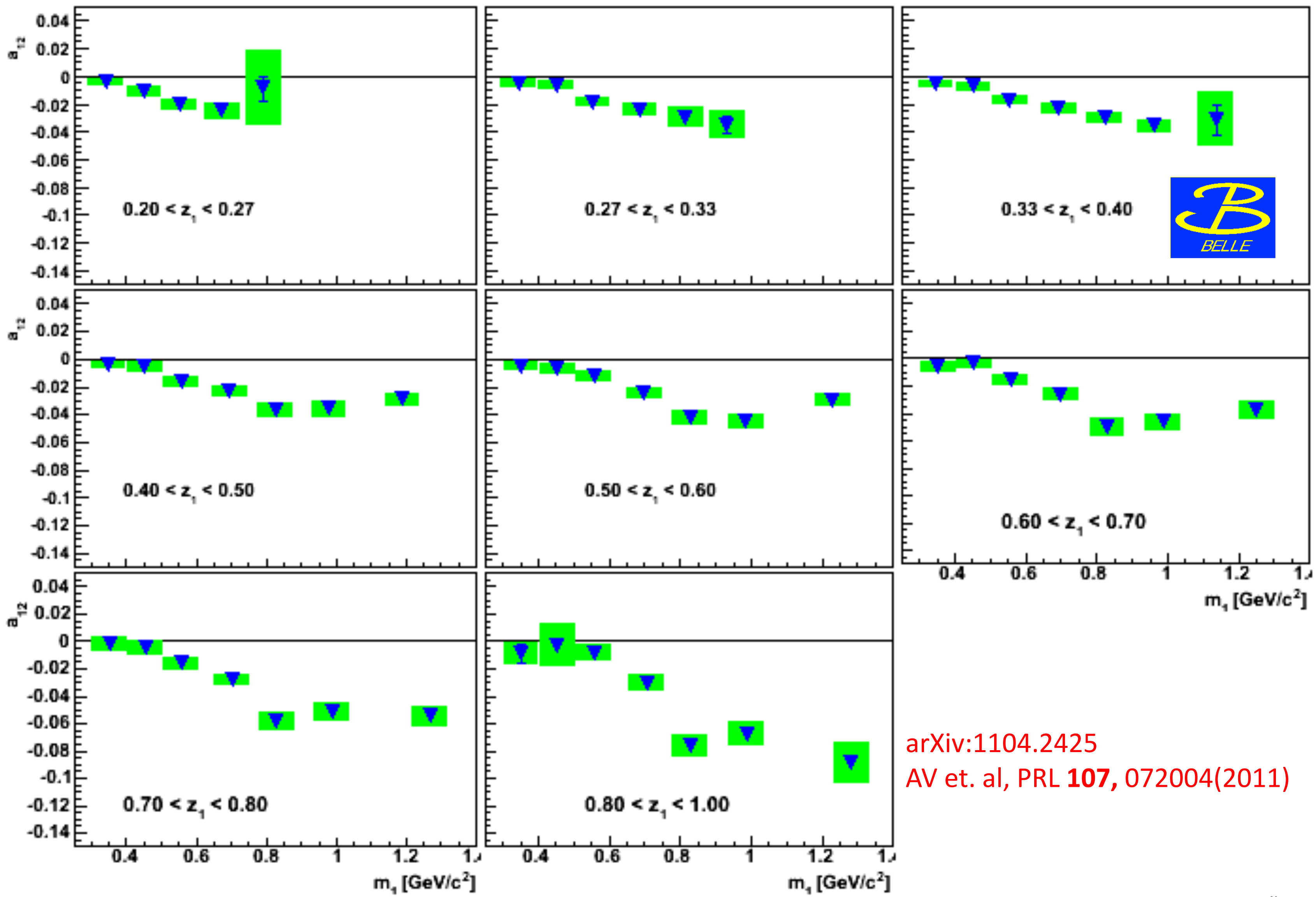



PRL122 (2019) 4, 042001

- Opportunities at Belle II:
  - Feed down correction for $p_T$ dependence and associated production
    - (currently only for z dependence, introduces large uncertainties)
    - $\Lambda^{\uparrow} - \Lambda^{\uparrow}$ correlations
    - Extension to tensor polarized FFs: e-Print: 2206.11742 [hep-ph]
    - ….
  - Explore low $p_T$ region (not shown here) with higher statistics and better tracking resolution

# First measurement of Interference Fragmentation Function

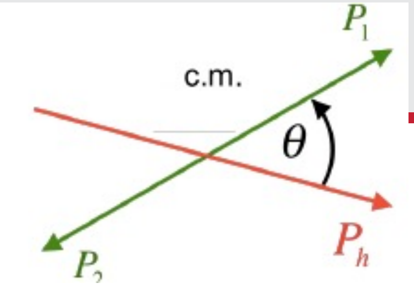
## $a_{12} \propto H_1^{<} * H_1^{<}$



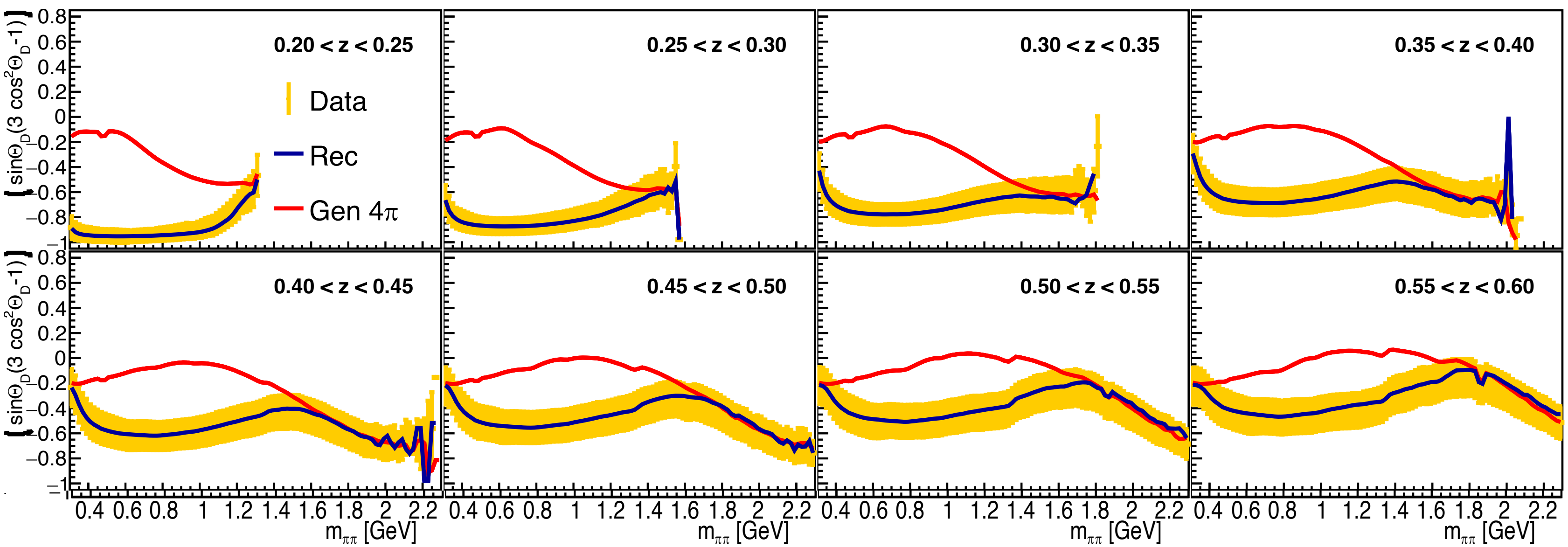

arXiv:1104.2425

AV et. al, PRL **107,** 072004(2011)

# Acceptance Impact on Partial Wave composition




- Consider dependence of FFs on decay angle $\theta$
- Higher order PWs lead to different moments in $\theta$ and $\phi$
  → These are different FFs that are mixed by the acceptance
  →up to 10% effect on the extraction of transversity
  →Describe hadronization dynamics
  →Bridge between FFs and MCEGs

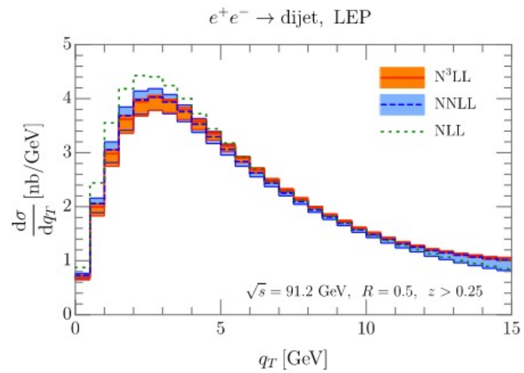


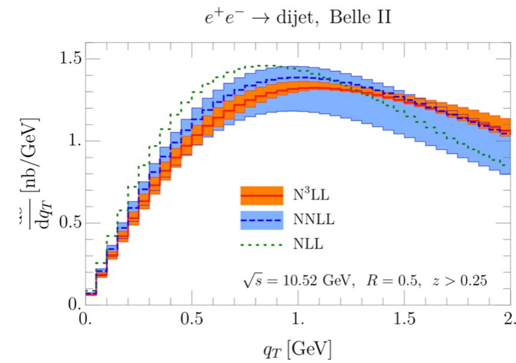

Belle Collaboration Phys.Rev. D96 (2017) no.3, 032005

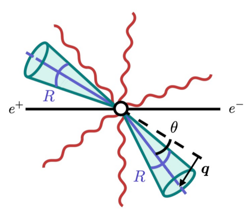
- Belle II prospects: Sufficient statistics for full partial wave decomposition

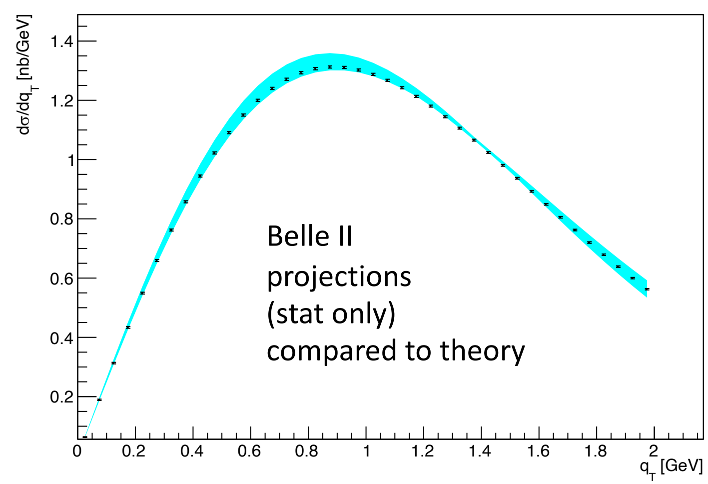
# Brand New Opportunities at Belle II: Precision Jet Physics in $e^+e^-$

- Jet physics (will) play an important role at the EIC and LHC
- Precision measurements in $e^+e^-$ annihilation will test current theoretical understanding
- Lower energies like Belle in particular sensitive to hadronization effects
- Example: Transverse Momentum Imbalance ← → TMD framework




Using $R = 1.0, E_{jet} > 3.75\ GeV$,

# Summary $e^+e^-$

- $e^+e^-$ annihilation allow for precision studies of QCD
- Belle II will provide world record statistics for
  - Precision measurements of fragmentation functions with complex final states
  - Tune MC generators
  - Probe Jet calculations at low scales where hadronization effects play a significant role
  - Constrain HVP, Hlbl contributions to g-2
  - Constrain $\alpha_S$
  - Test QCD calculations of event shapes
  - More information in "Opportunities for precision QCD physics in hadronization at Belle II -- a snowmass whitepaper"
    e-Print: 2204.02280 [hep-ex]

# Save the Date

**25th International Symposium on Spin Physics will be hosted by Duke University in Durham, NC**

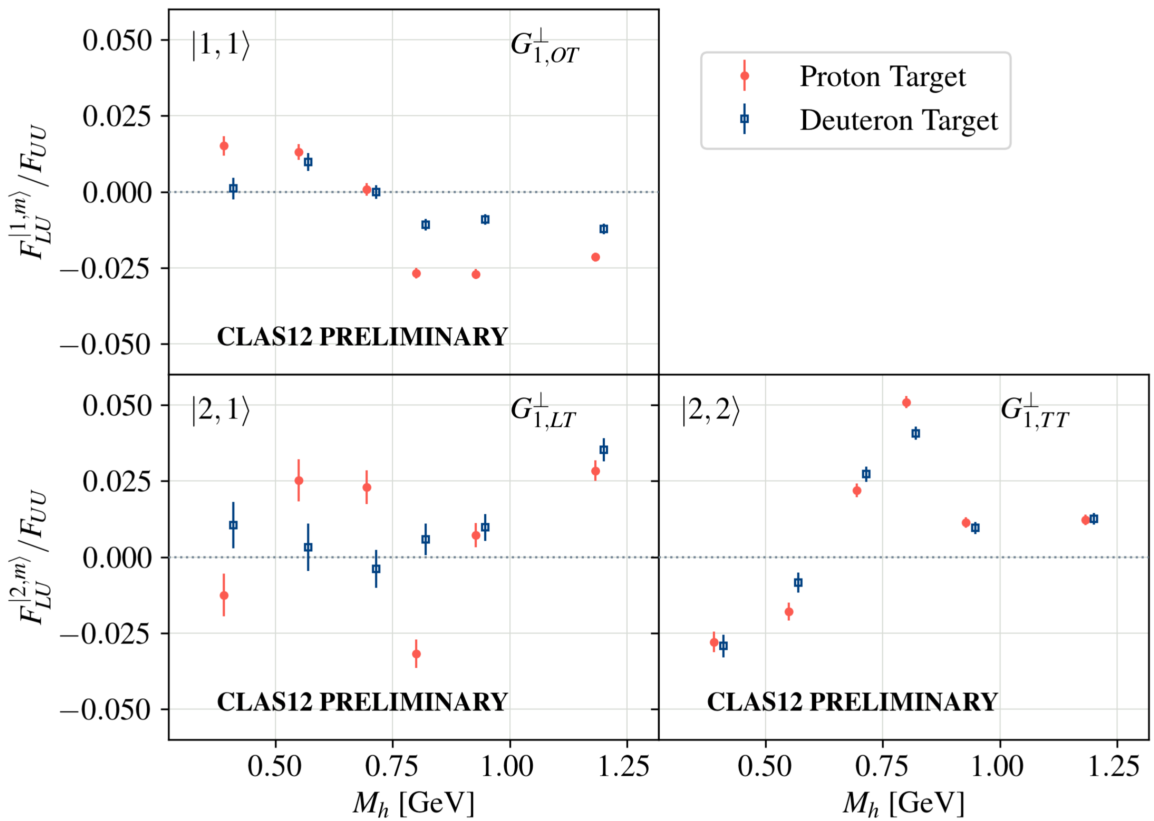
**September 24-29 2023**

# $M_h$ Bins

Twist-2 $F_{LU}/F_{UU}$ Amplitudes

Different targets → $f_1$ flavors

$$A_{LU,\mathbf{p}}^{|\ell,m\rangle} \propto \left(4xf^{u_V} - xf^{d_V}\right) G_1^{|\ell,m\rangle}$$
$$A_{LU,\mathbf{d}}^{|\ell,m\rangle} \propto \left(xf^{u_V} + xf^{d_V}\right) G_1^{|\ell,m\rangle}$$



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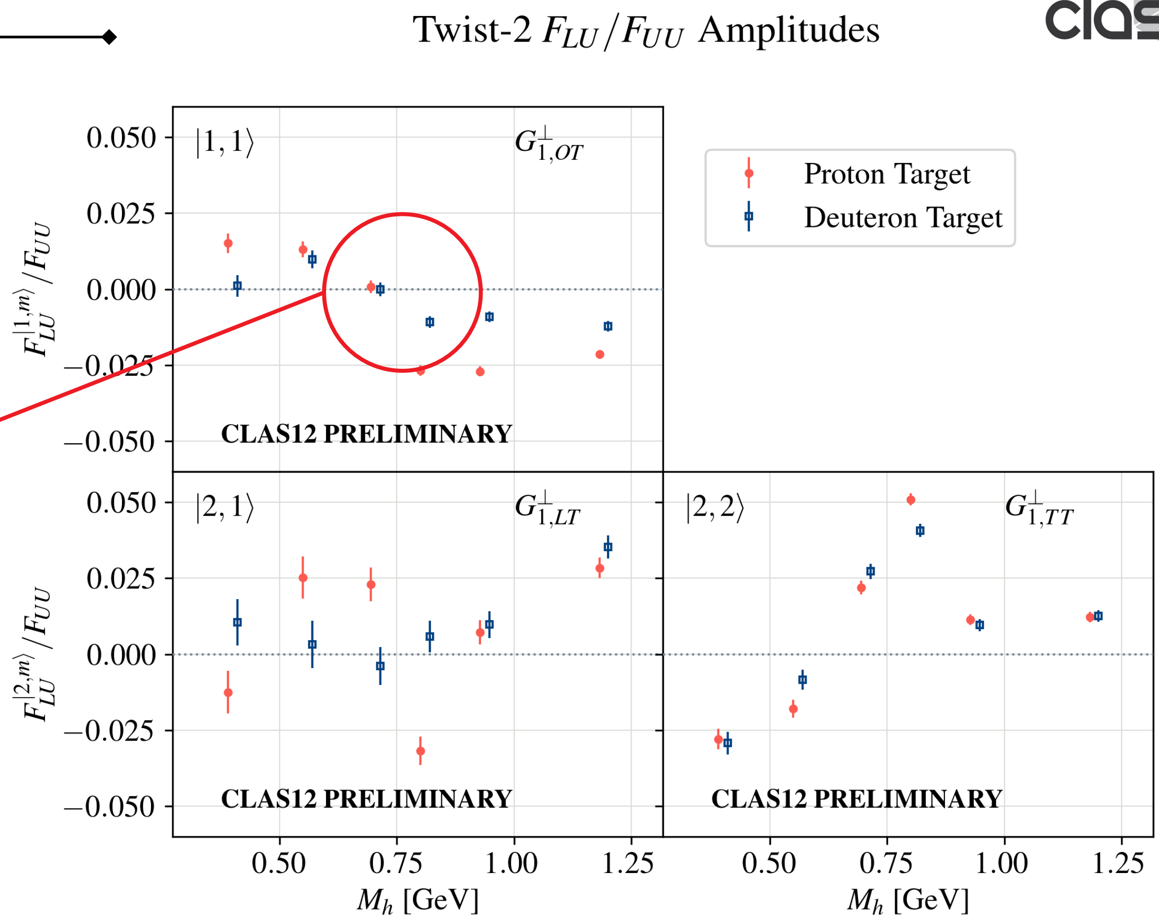
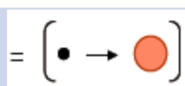
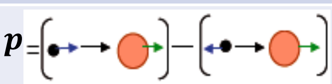
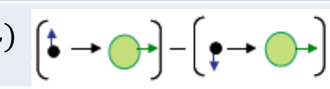
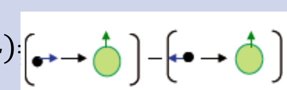
**Sign change near ρ mass**



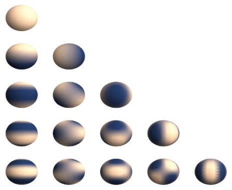
# FFs with single hadrons in the final state

- Analogue →similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay ($\Lambda$)

| Parton polarization → <br> Hadron Polarization ⇣ | Spin averaged | longitudinal | transverse |
|---|---|---|---|
| spin averaged | $D_1^{h/q}(z, p_T)$ =  | | $H_1^{\perp h/q}(z, p_T)$ =  |
| longitudinal | | $G_1^{\Lambda/q}(z, p$ =  | $H_{1L}^{h/q}(z, p_T)$  |
| Transverse (here $\Lambda$) | $D_{1T}^{\perp\Lambda/q}(z, p_T)$ =  | $G_{1T}^{h/q}(z, p_T)$ =  | $H_1^{\Lambda/q}(z, p_T)$ =  <br> $H_{1T}^{\perp\Lambda/q}(z, p_T)$ =  |

- Encode Spin-Orbit correlations in hadronization
- Needed to access (spin dependent) parton structure of the nucleon
- Can probe fundamental QCD questions (e.g. $D_{1T}^{\perp} \leftrightarrow f_{1T}^{\perp}$)

# Belle II prospects

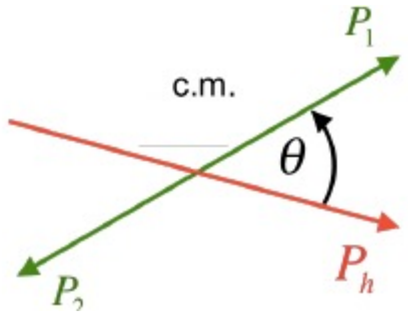


- Higher order PWs lead to different moments in $\theta$ and $\phi$
- In models, evolution of the different PWs different
- Important to have a full picture to understand mixing effects in ratios/partial integrals/acceptance
- Missing info from partial wave estimated to have effects up to 10% e.g. on extraction of transversity

- Full partial wave decomposition ➔full description of two-particle correlations in hadronization

➔Describe hadronization dynamics

➔Bridge between FFs and MCEGs



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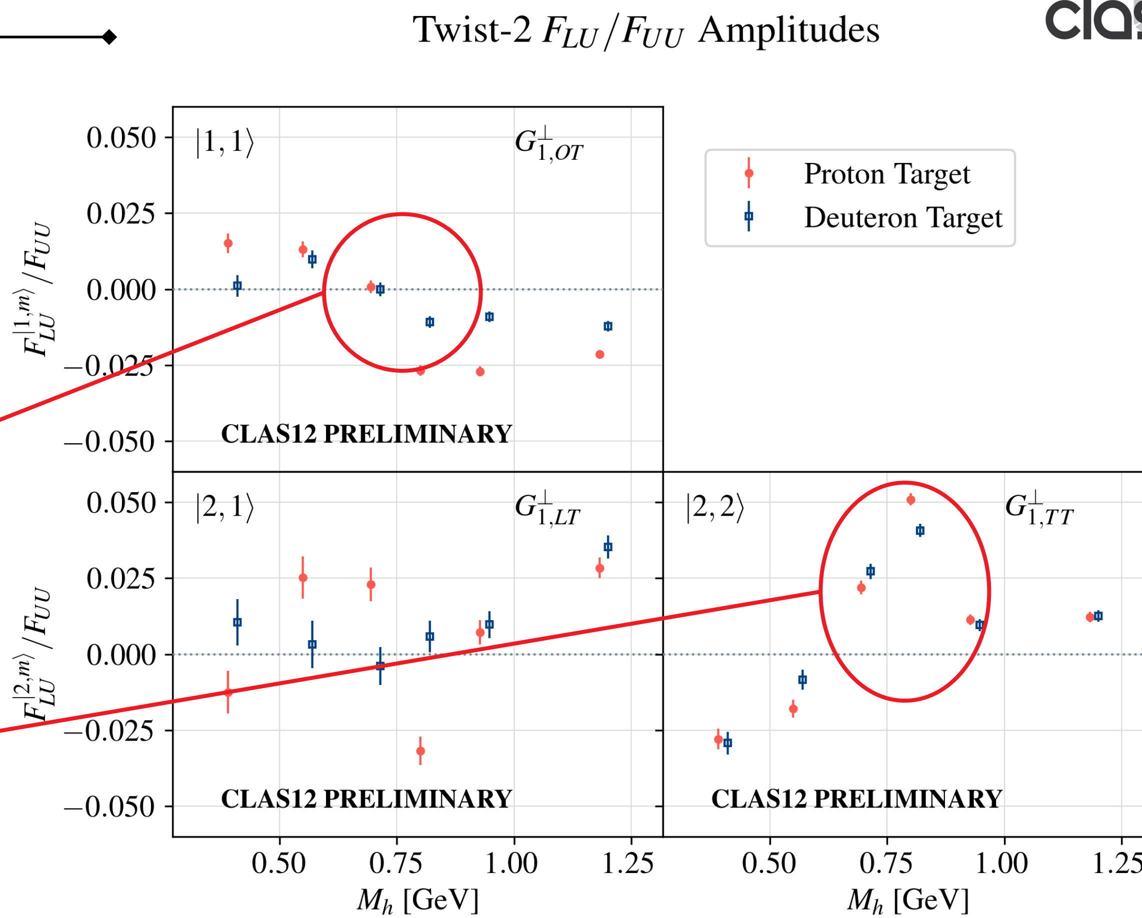
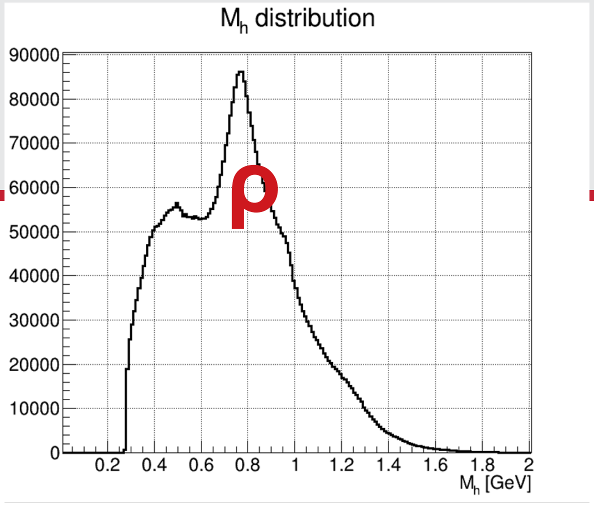



**Sign change near ρ mass**

**Enhancement at ρ mass (and a sign change)**

**ρ meson → p-wave $\pi^+\pi^-$**



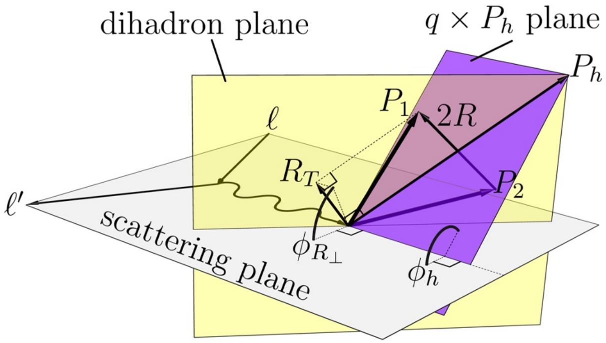

- P-wave mainly from $\rho-$resonance

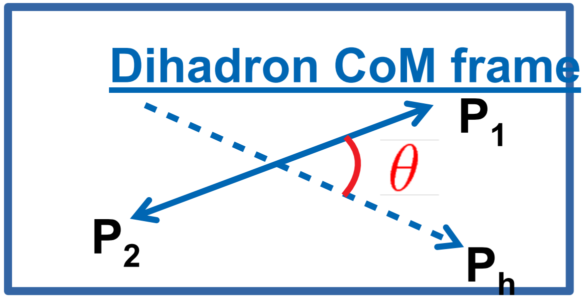
## $A_{LU}$ Modulations

**Twist 2:** $P_{\ell,m}(\cos\theta)@\sin(m\phi_h - m\phi_R)$

**Twist 3:** $P_{\ell,m}(\cos\theta)@\sin\big((1-m)\phi_h + m\phi_R\big)$

associated Legendre polynomials

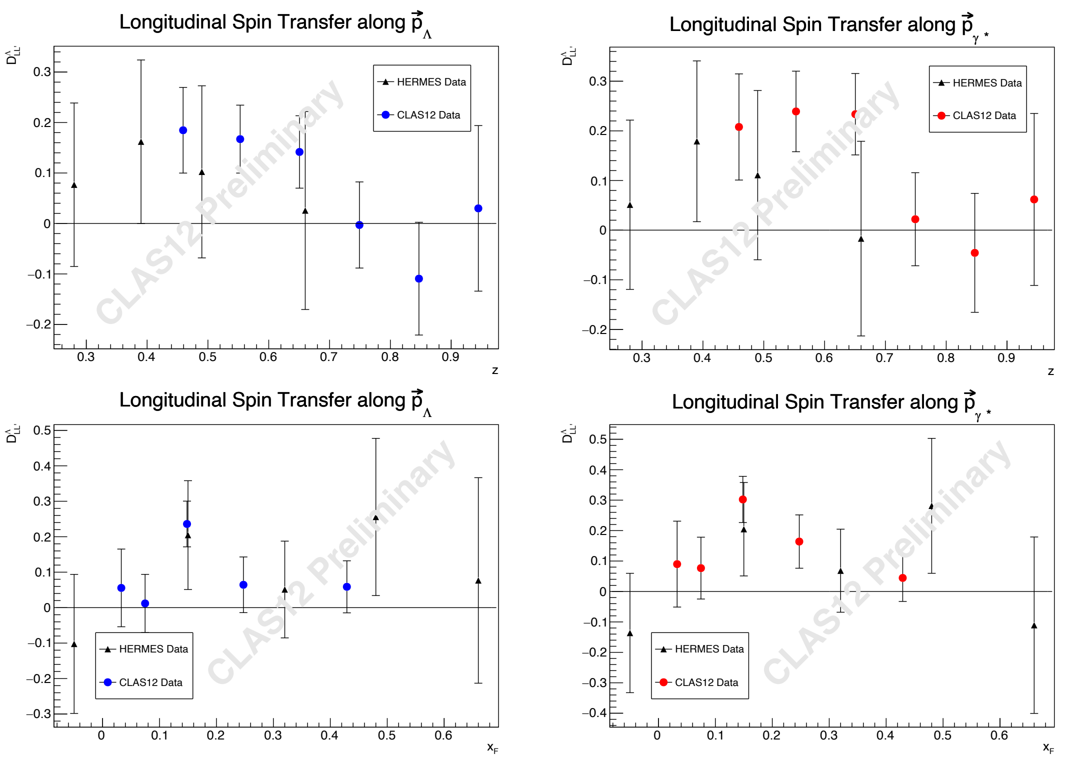


# Helicity Balance: Comparison with HERMES

vs. $z$

vs. $x_F$



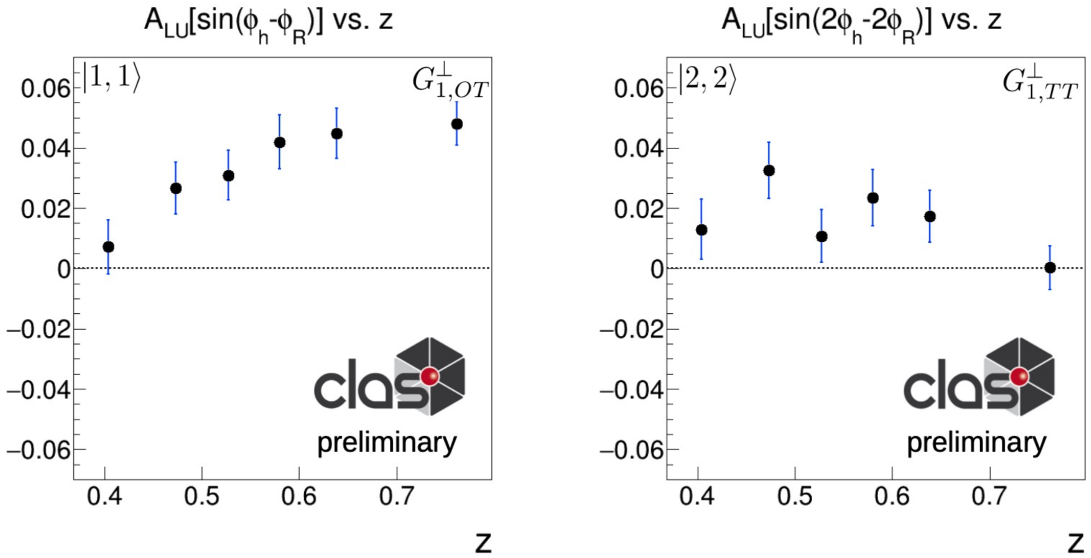

**Note**: errors are solely statistical

HERMES Results from:
A. Airapetian, et al.
Physical Review D, 74(7),
Oct 2006.

# CLAS12 $\pi^+\pi^0$ $A_{LU}$ Preliminary Measurement

clc

$\pi^+\pi^0$



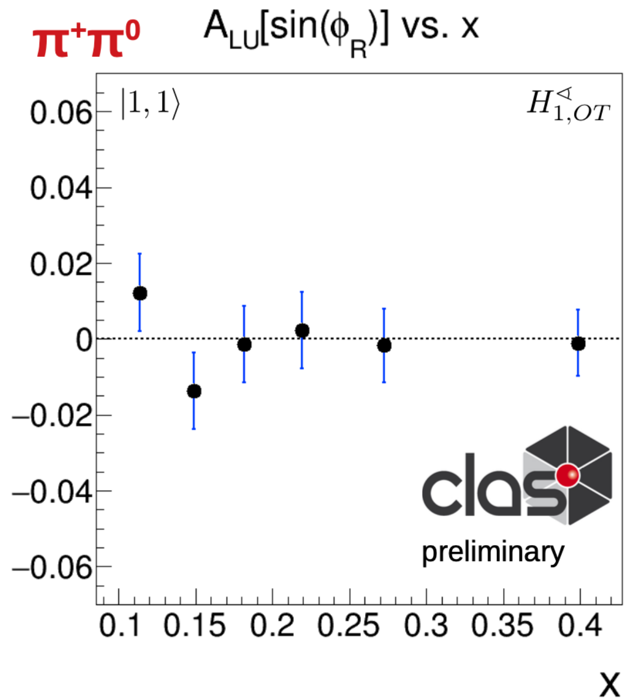

e-Print: 2201.05732 [h

- z dependence of $\sin(\phi_h - \phi_R)$ amplitude has a slow rise
- $\sin(2\phi_h - 2\phi_R)$ may be relatively constant / decreasing

C. Dilks

C Dilks at CPHI 2022

# CLAS12 $\pi^+\pi^0$ $A_{LU}$ Preliminary Measurement




e-Print: 2201.05732 [hep-ex]

- Twist-3 amplitude of $\sin(\phi_R)$ is consistent with zero for $\pi^+\pi^0$
- cf. $\pi^+\pi^-$ |1,1>, which is about +4% → Flavor (channel) dependence of $H_1$

C. Dilks

C Dilks at CPHI 2022