

CPHI-2020, CERN, February 2020

# Polarized Fragmentation Functions

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Research supported by the  
 U.S. DEPARTMENT OF  
**ENERGY** | Office of  
Science

**Duke**  
UNIVERSITY

 **Jefferson Lab**

# Single Hadron production In SIDIS is a well travelled path

## Observables:








$z$ : fractional energy of the quark carried by the hadron

$p_{h,T}$ : transverse momentum of the hadron wrt the quark direction: **TMD FFs**

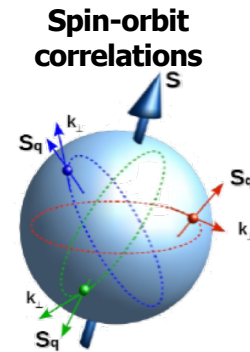


Parton polarization → Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z, p_T) = \left[ \bullet \rightarrow \circ \right]$		$H_1^{\perp h/q}(z, p_T) = \left[ \uparrow \rightarrow \circ \right] - \left[ \downarrow \rightarrow \circ \right]$
longitudinal			
Transverse (here $\Lambda$ )			

# Transverse momentum dependent distributions (TMDs)

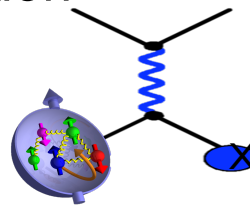
N \ q	U	L	T
U			
L			
T			

- In addition to the spin-spin correlations can have spin momentum correlations!

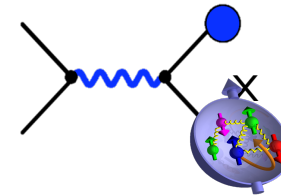


# PDF in SIDIS $\Leftrightarrow FF$ in $e^+e^-$

- E.g. Sivers  $\Leftrightarrow \Lambda^\uparrow$  production

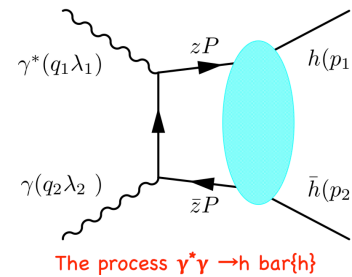
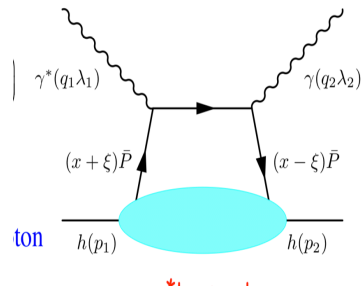


Spacelike SIDIS



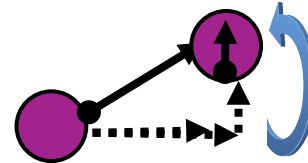
Timelike SIA

- GPDs  $\Leftrightarrow$  GDAs (not discussed here)

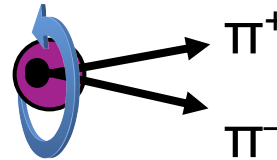


# “You think you understand something?---Now add spin...in Hadronization!”

- → polarized final states



- → di-hadron correlations



- Explore spin-orbit correlation in hadronization
- Additional degrees of freedom in final state make targeted extraction of nucleon structure possible → see  $h_1(x)$ ,  $e(x)$
- New Fragmentation Functions

# Enter polarization in the final States



## Observables:

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longitudinal		$G_1^{\Lambda/q}(z, p_T) = \left[ \bullet \rightarrow \circ \rightarrow \bullet \right] - \left[ \bullet \rightarrow \circ \rightarrow \downarrow \bullet \right]$	$H_{1L}^{h/q}(z, p_T) = \left[ \uparrow \bullet \rightarrow \circ \rightarrow \bullet \right] - \left[ \downarrow \bullet \rightarrow \circ \rightarrow \bullet \right]$
Transverse (here $\Lambda$ )	$D_{1T}^{\perp \Lambda/q}(z, p_T) = \left[ \bullet \rightarrow \circ \uparrow \right]$	$G_{1T}^{h/q}(z, p_T) = \left[ \bullet \rightarrow \circ \uparrow \right] - \left[ \bullet \rightarrow \circ \downarrow \right]$	$H_1^{\Lambda/q}(z, p_T) = \left[ \uparrow \bullet \rightarrow \circ \uparrow \right] - \left[ \downarrow \bullet \rightarrow \circ \uparrow \right]$ $H_{1T}^{\perp \Lambda/q}(z, p_T) = \left[ \uparrow \bullet \rightarrow \circ \uparrow \right] - \left[ \downarrow \bullet \rightarrow \circ \downarrow \right]$

- Analogue → similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay ( $\Lambda$ )
- Gluon FFs similar but with circular/linear polarization (not as relevant for e+e-)

# DI-HADRON FRAGMENTATION FUNCTIONS

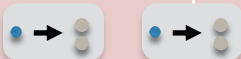




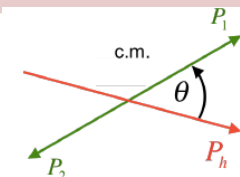
Additional Observable:

$$\vec{R} = \vec{P}_1 - \vec{P}_2 :$$

The relative momentum of the hadron pair is an additional degree of freedom:

*the orientation of the two hadrons w.r.t. each other and the jet direction can be an indicator of the quark transverse spin*

Parton polarization → Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z, M)$ 		$H_1^{\perp h/q}(z, p_T \mathbf{M}, (\mathbf{P}_h), \theta)$ 'Di-hadron Collins'
longitudinal			
Transverse	Type equation here.	$\mathbf{G}_1^{\perp}(z, \mathbf{M}, \mathbf{P}_h, \theta) =$ T-odd, chiral-even → jet handedness QCD vacuum structure 	$H_1^{\ast}(z, \mathbf{M}, (\mathbf{P}_h), \theta) =$ T-odd, chiral-odd Collinear 



- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in  $\theta \rightarrow$   
Needs to be mapped completely!! (no information yet)
    - Energy dependence? ( $\rightarrow$  VM fractions....)
  - Relative and total angular momentum  $\rightarrow$  In principle endless tower of FFs

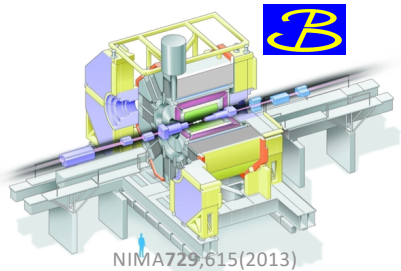
# Some specific points of interest

- Spin orbit correlations in hadronization (e.g.  $G_1^\perp$ )
  - Interference patterns of different relative partial waves
- Access to aspects of the nucleon structure difficult in single hadrons
  - Examples:
    - Boer-Mulders w/o Cahn, twist3
    - $e(x) \rightarrow$  See T. Hayward's talk
- $\Lambda$  production
  - sensitive to s quarks
  - FF counterpart to Sivers  $\rightarrow$  universality etc
  - Test twist3 calculations
- **Additional degrees of freedom  $\rightarrow$  Need large statistics**



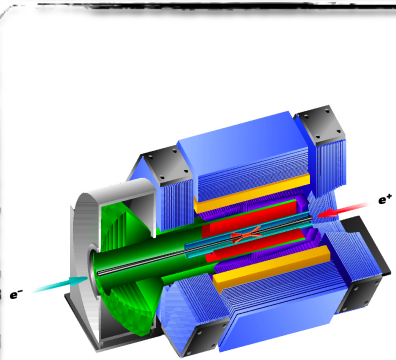
# Role of B-factories

- Asymmetric-energy  $e^+e^-$  collider
- $\sqrt{s} \sim 10.6$  GeV ( $\Upsilon(4S)$ )
- $\beta\gamma=0.425$
- $L \sim 1$   $\text{ab}^{-1}$

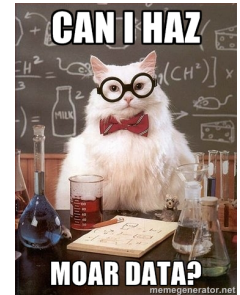


NIMA729,615(2013)

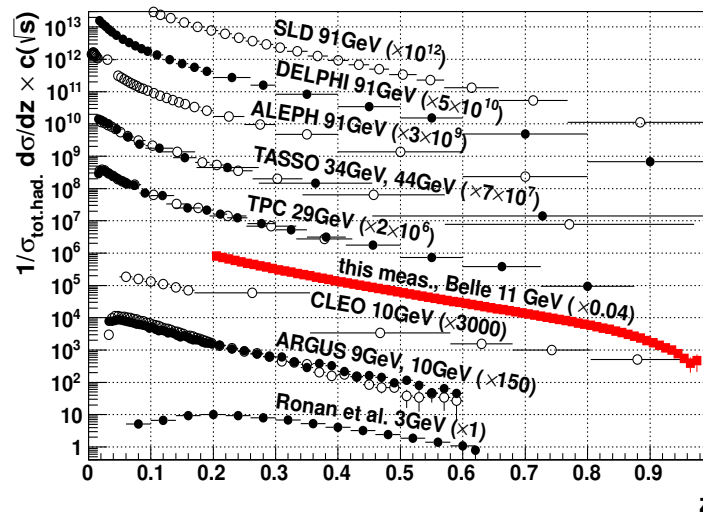
NIMA479,117(2007) **BaBar**



- Asymmetric-energy  $e^+e^-$  collider
- $\sqrt{s} \sim 10.6$  GeV ( $\Upsilon(4S)$ )
- $\beta\gamma=0.65$
- $L \sim 500$   $\text{fb}^{-1}$



World Data (Sel.) for  $e^+e^- \rightarrow \pi^\pm + X$  Production



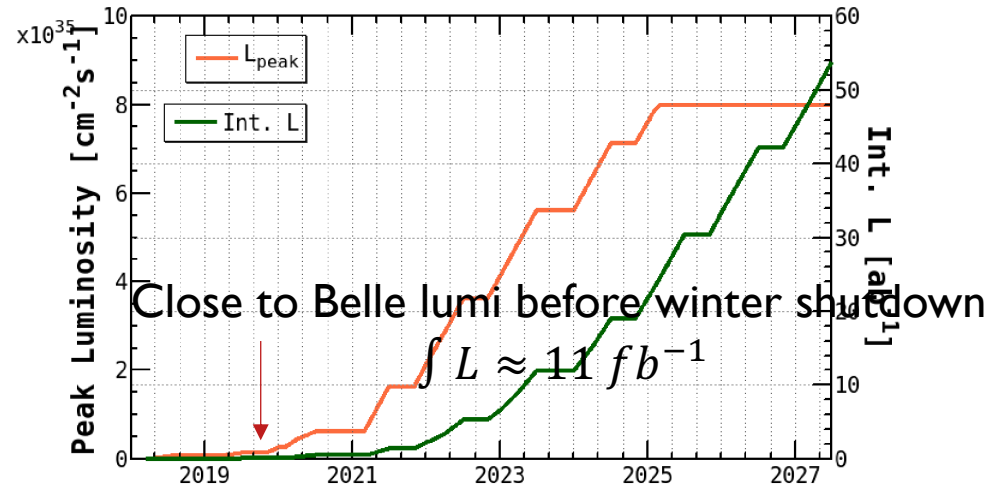
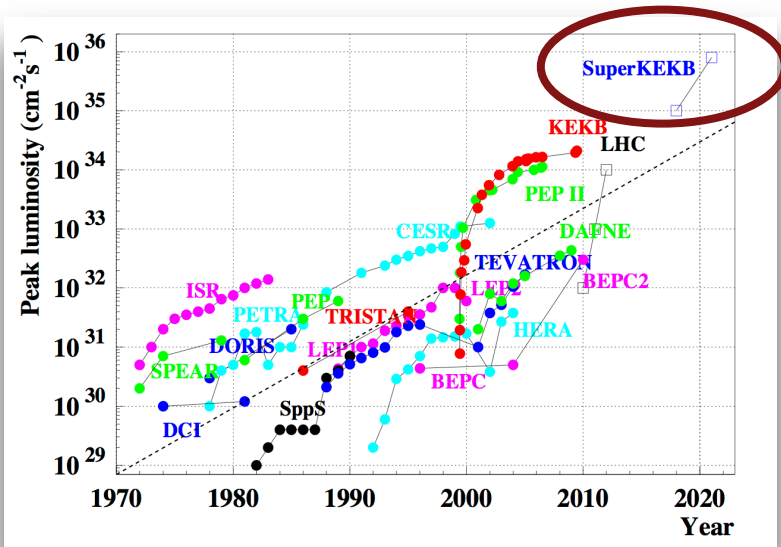
Phys.Rev.Lett. 111 (2013) 062002 (Belle)

Phys.Rev. D88 (2013) 032011 (BaBar)

- Dominated by B factories
- Limited lever arm in  $\sqrt{s}$  in particular at high  $z$
- Precision data includes charged single hadrons  $\pi$ ,  $K$ ,  $\rho$ ,  $D$ ,  $\Lambda$ , charmed baryons...
- Well described at NNLO (e.g. DSS, NNFF)

# The future is now: Next Generation B factory SuperKEKB

Belle/KEKB recorded  $\sim 1000 \text{ fb}^{-1}$ . Now have to change units on the y-axis to  $\text{ab}^{-1}$

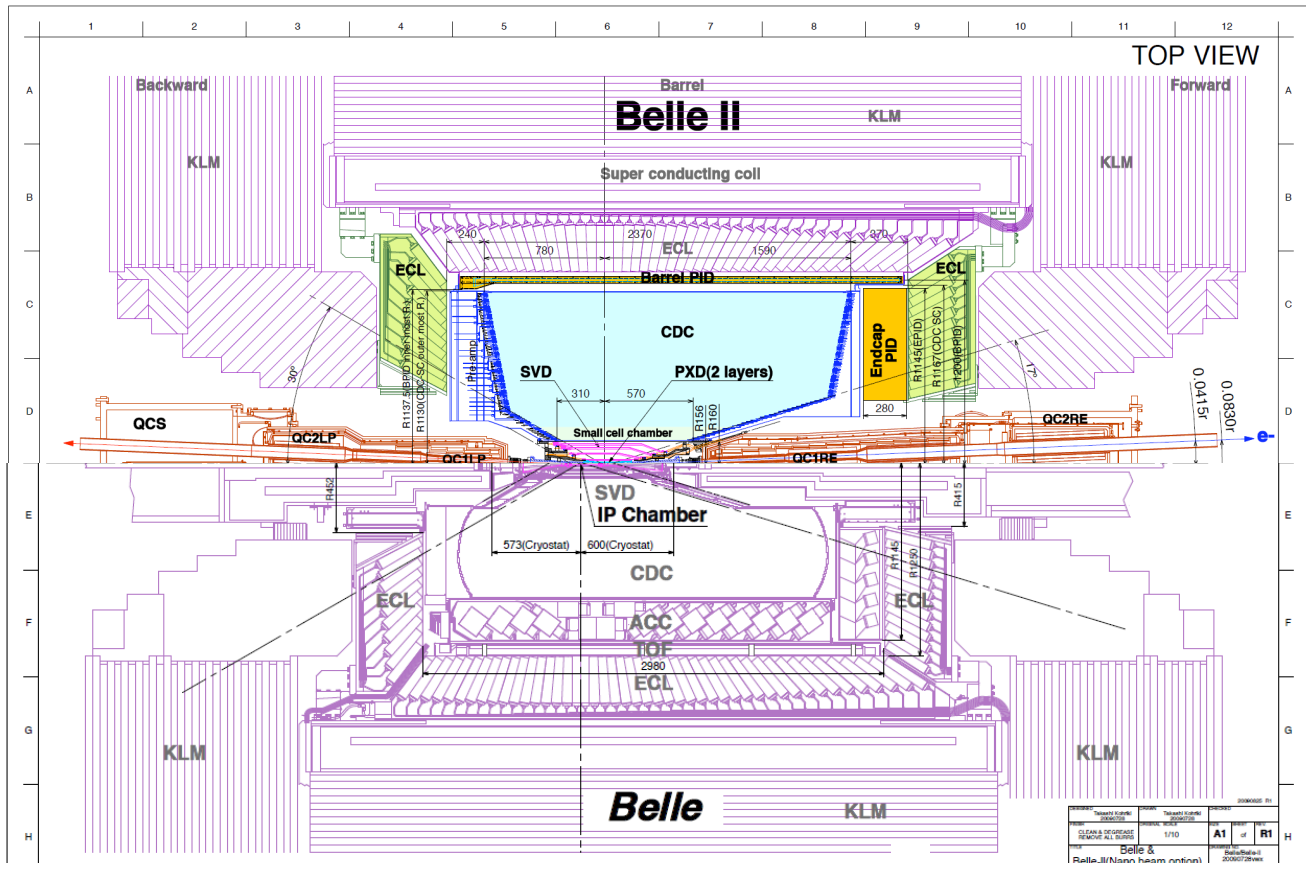


Beam currents *only* a factor of two higher than KEKB ( $\sim \text{PEP II}$ )

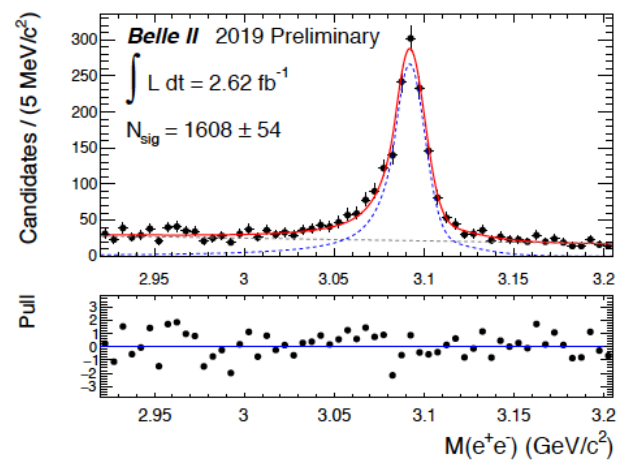
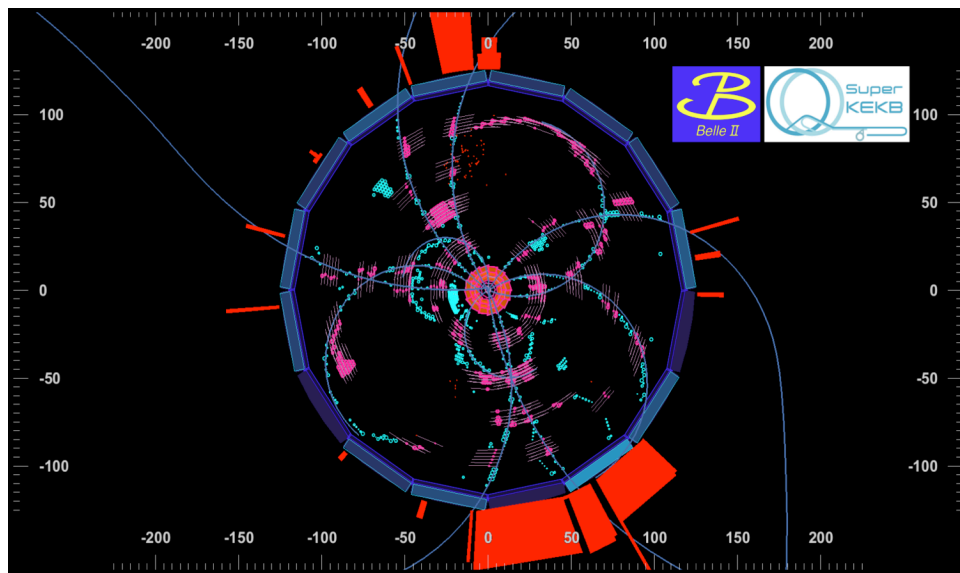
“nano-beams” are the key; vertical beam size is **50nm** at the IP

- $\int L$  needed to map out fully differential  $d\sigma$  of polarized FF
  - $\theta$ , flavor dependence for di-hadrons
  - $p_T, Z, Z_{\pi, K}$  for  $\Lambda$  (also correction for feed-down needs statistics)

# Belle II Detector (comp. to Belle)

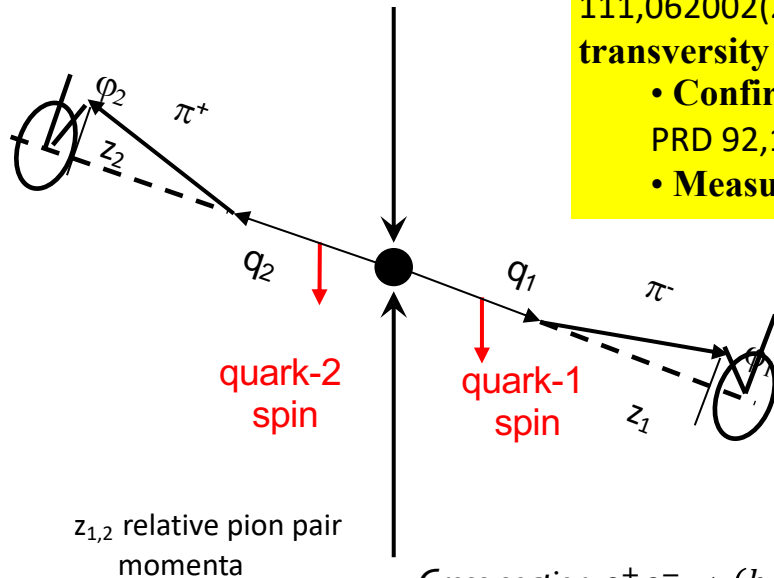


## 2019: First Collisions in Phase 3, the Physics Run



Clear signals for  $B \rightarrow J/\psi X$  in  $\sim 1/2$  of Phase 3 data.

# Collins FFs IN $e^+e^-$

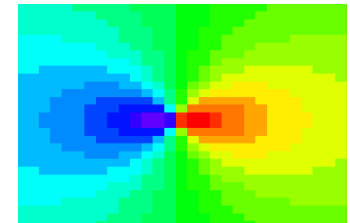


• **First non-zero independent measurement** of the Collins effect for pion pairs in  $e^+e^-$  annihilation by **Belle** Collaboration @  $\sqrt{s} \sim 10.6$  GeV (PRL 111,062002(2008), PRD 88,032011(2013)) leads to **first extraction of transversity** (Phys.Rev. D75 (2007) 054032 ) from SIDIS and  $e^+e^-$

- **Confirmed by BaBar** @  $\sqrt{s} \sim 10.6$  GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for  $KK$  and  $K\pi$ )
- **Measured at BESIII** @  $\sqrt{s} = 3.65$  GeV (PRL 116,42001(2016))

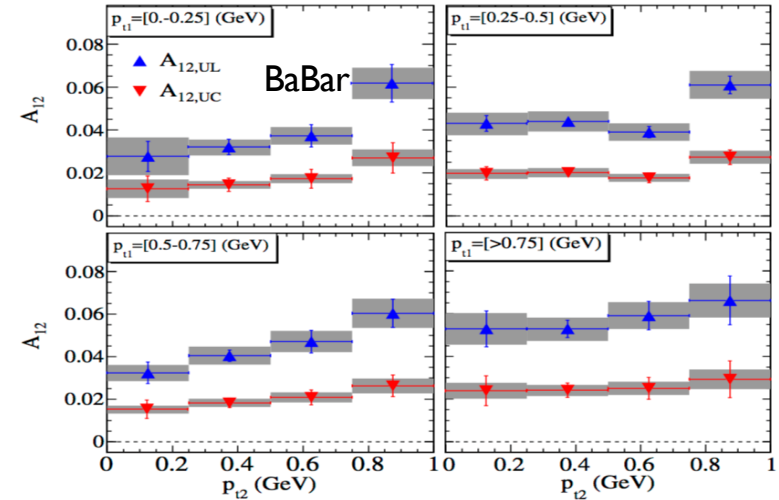
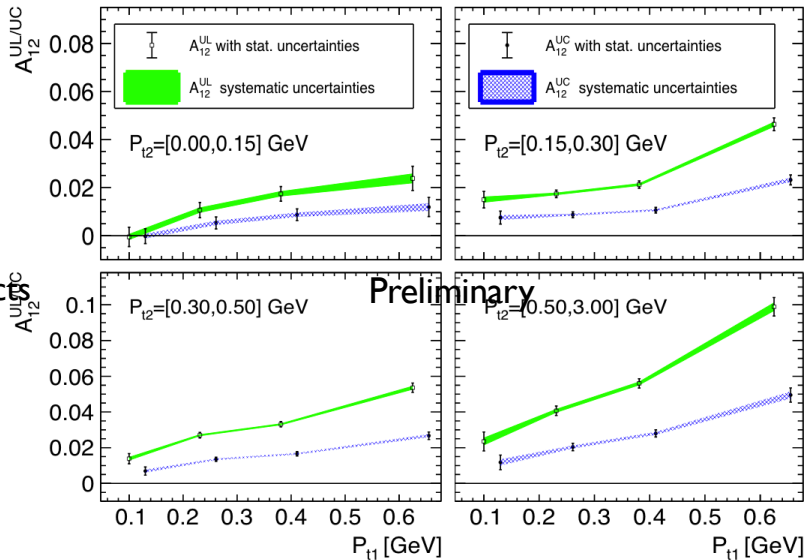
$$\text{Cross-section } e^+e^- \rightarrow (h_1 h_2)(\bar{h}_1 \bar{h}_2) + X$$

$$\propto D_1^\perp D_1^\perp + H_1^\perp H_1^\perp \cos(\phi_1 + \phi_2)$$



- Access spin dependence and  $p_T$  dependence (convolution or in jet) without PDF complication
- Made possible by B-factory luminosities

# New: $P_t$ dependence of charged pions from Belle



Unlike/Likesign

Ratios to cancel acceptance effects

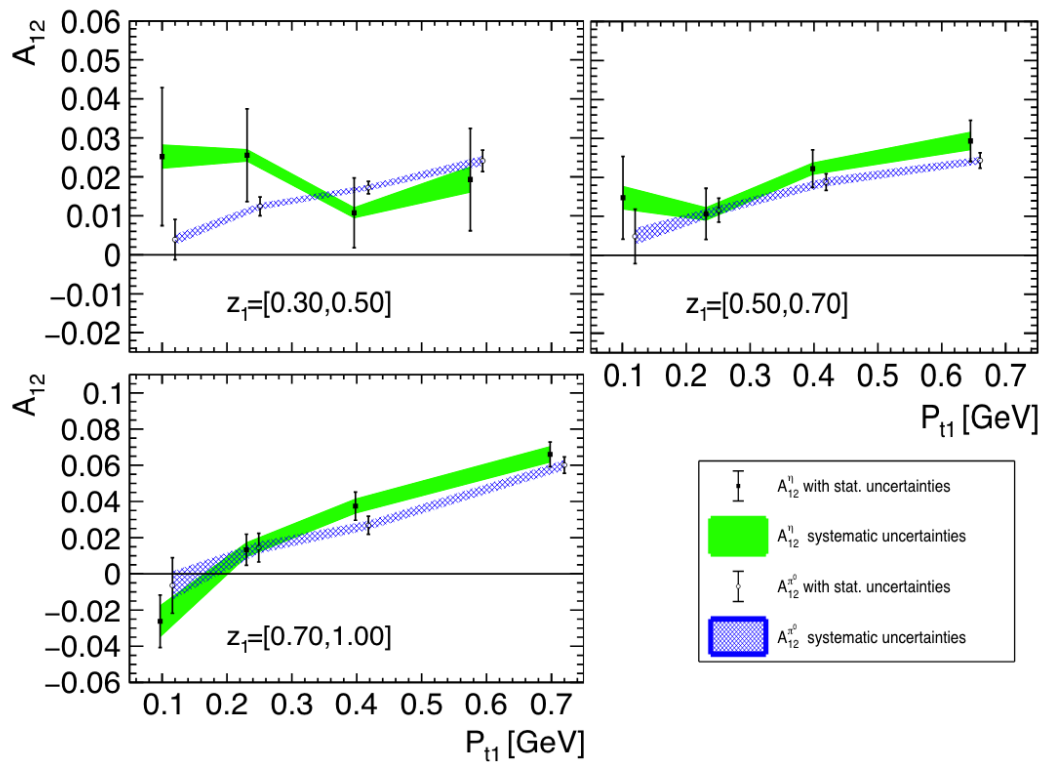
Unlike:  
fav\*fav+dis\*dis

Like:  
fav\*dis

Preliminary

- Trend consistent with BaBar
- Direct comparison difficult due to different correction schemes (thrust vs  $q\bar{q}$  –axis)

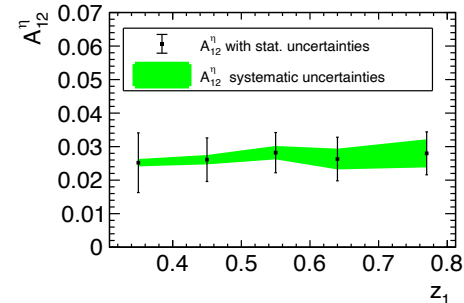
# New: $\pi^0/\eta$ from Belle



$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^L} = \frac{\pi^0\pi^+ + \pi^0\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

$$\mathcal{R}_{12}^{\eta} = \frac{R_{12}^{\eta\pm}}{R_{12}^L} = \frac{\eta\pi^+ + \eta\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

- Rise with  $z_{1,2}$ , similar to charged pions



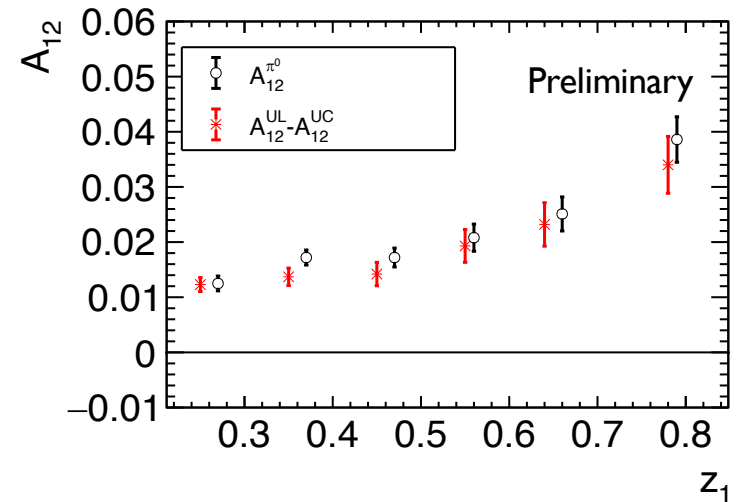
- $\eta$  almost flat except large  $z$

# Consistency between Neutral and charged pions

$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^L} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1 + \cos^2(\theta)}$$

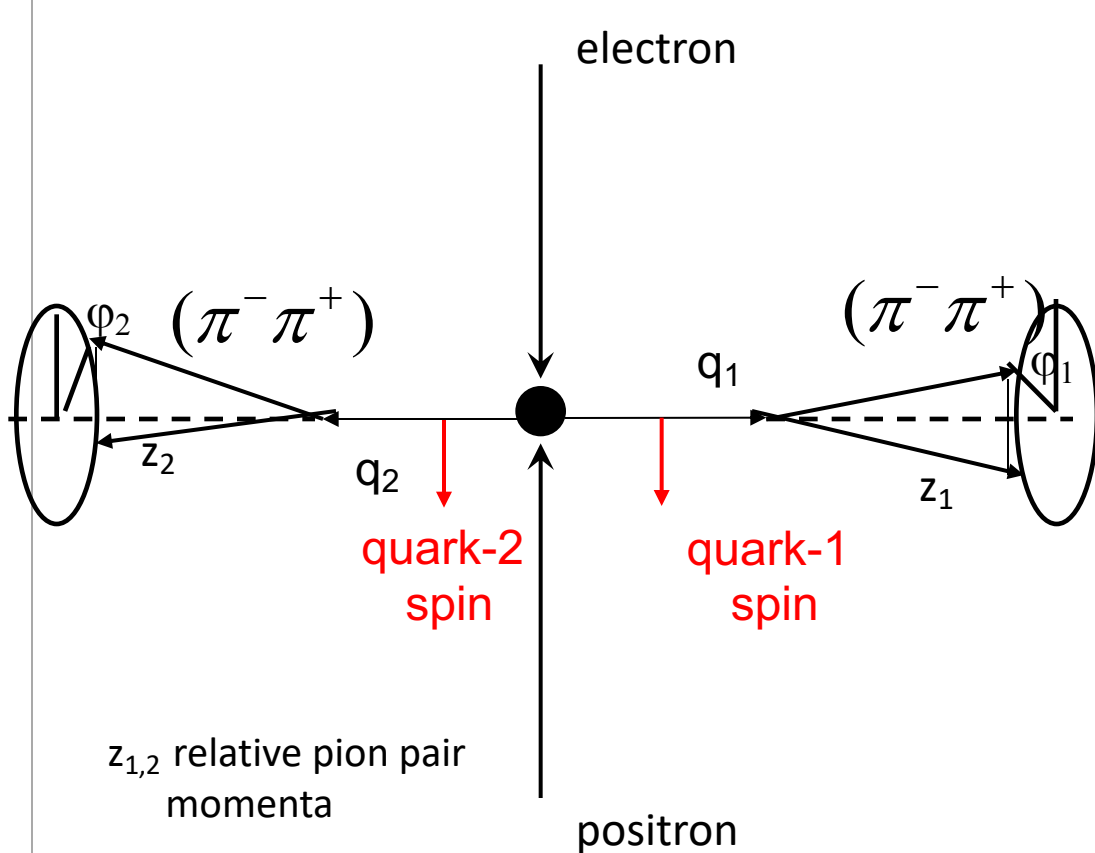
$$\times \left\{ \frac{5(H_1^{\perp,fav} + H_1^{\perp,dis}) \otimes (H_1^{\perp,fav} + H_1^{\perp,dis}) + 4H_{1,s \rightarrow \pi}^{\perp,dis} \otimes H_{1,s \rightarrow \pi}^{\perp,dis}}{5(D_1^{fav} + D_1^{dis}) \otimes (D_1^{fav} + D_1^{dis}) + 4D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} - \frac{10H_1^{\perp,fav} \otimes H_1^{\perp,dis} + 2H_{1,s \rightarrow \pi}^{\perp,dis} H_{1,s \rightarrow \pi}^{\perp,dis}}{10D_1^{fav} \otimes D_1^{dis} + 2D_{1,s \rightarrow \pi}^{dis} \otimes D_{1,s \rightarrow \pi}^{dis}} \right\}$$

**=  $A_{12}^{UL} - A_{12}^{UC}$  (Isospin)**





# Measuring transverse spin dependent di-Hadron Correlations In unpolarized $e^+e^-$ Annihilation into Quarks



Interference effect in  $e^+e^-$  quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

## Experimental requirements:

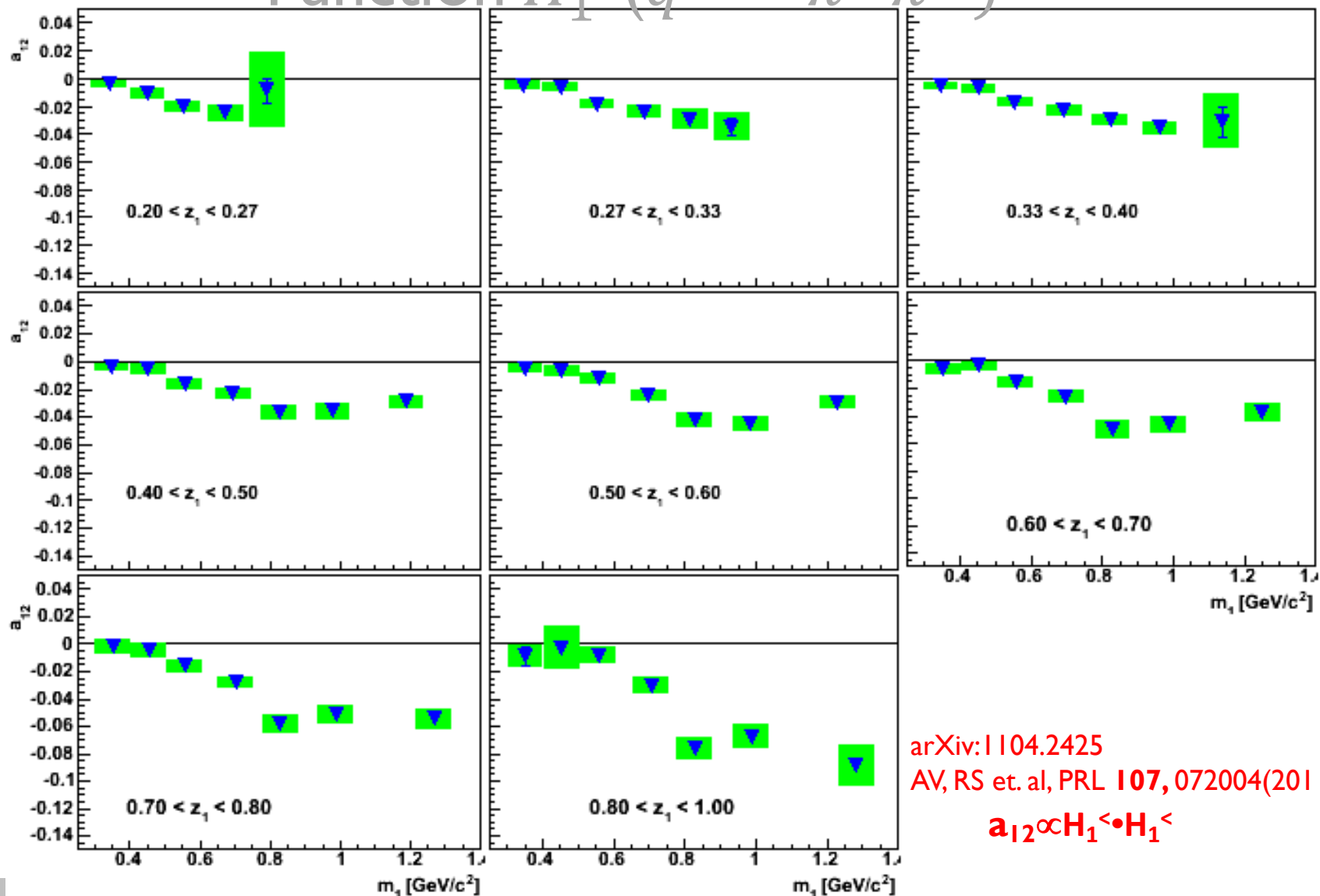
- Small asymmetries  $\rightarrow$  very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

$$A \propto H_1^\zeta(z_1, m_1) \bar{H}_1^\zeta(z_2, m_2) \cos(\phi_1 + \phi_2)$$



# First measurement of Interference Fragmentation

Function  $H_1^< (q^\uparrow \rightarrow \pi^+ \pi^-)$



arXiv:1104.2425  
 AV, RS et. al, PRL **107**, 072004(2011)

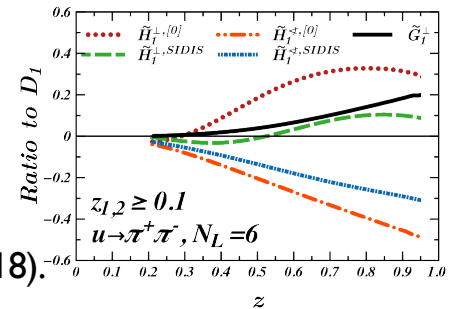
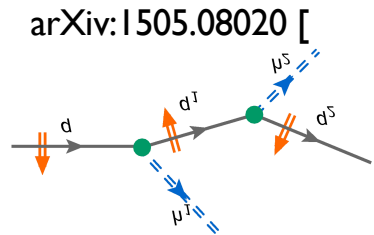
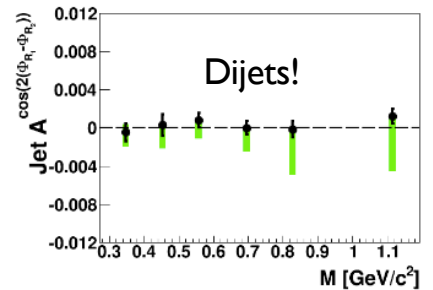
$$a_{12} \propto H_1^< \cdot H_1^<$$

$$G_1^\perp = \text{Diagram 1} - \text{Diagram 2}$$

The diagram shows the definition of the wormgear FF  $G_1^\perp$  as the difference between two diagrams. Each diagram depicts a proton (represented by a purple circle with a blue ring) interacting with a photon (represented by a blue circle with a blue ring). The first diagram shows the photon interacting with the proton and producing a  $\pi^+$  and a  $\pi^-$ . The second diagram shows the photon interacting with the proton and producing a  $\pi^+$  and a  $\pi^-$  in a different configuration.

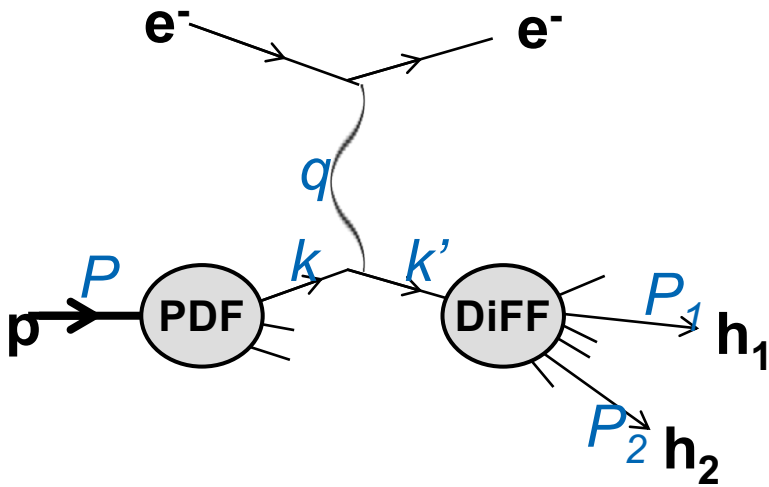
# History of wormgear FF $G_1^\perp$

- First suggestion to observe in  $e^+e^-$  by Boer, Jakob, Radici, PRD67 (2003) 094003
  - Postulate connection to jet handedness proposed by Efremov and Kharzeev Phys.Lett. B366 (1996) 311-315 (connection to chromomagnetic effects)
- Measurement by Belle  $\rightarrow$  No signal
- New model calculations by Matevosyan et al connecting  $G_1^\perp$  with single hadron Collins effect in string fragmentation (a bit like worm gear functions)  $\rightarrow$  Interesting to learn about spin momentum correlations in hadronization: sizable asymmetries contradicted by Belle result??
- Mistake found in Boer et. al: Phys.Rev. D97 (2018) no.7, 074019  $\rightarrow$  Need weighted asymmetry including dependence on  $P_{hT}$
- Accessible in SIDIS via weighted asymmetries



Matevosyan., Bacchetta, Boer, Courtoy, Kotzinian, Radici, Thomas: Phys. Rev. D 97, 074019 (2018).

# SIDIS Dihadron Production at CLAS12: $e^- p \rightarrow e^- h_1 h_2 X$



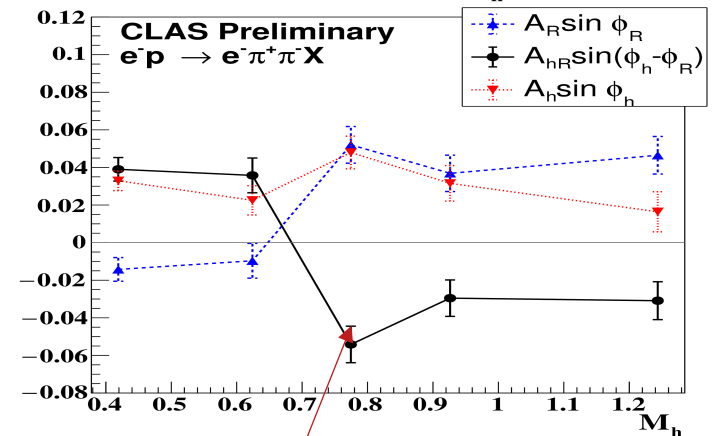
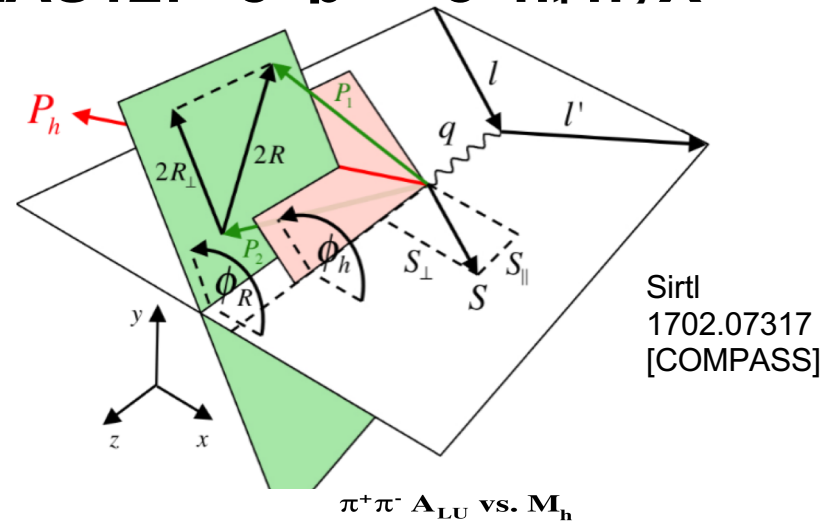
## Momenta and Angles

$$P_h = P_1 + P_2 \quad \leftarrow \quad \phi_h$$

$$R = \frac{1}{2} (P_1 - P_2) \quad \leftarrow \quad \phi_R$$

$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{UL} \sim S_L \sum_a e_a^2 g_{1L}^a(x) \approx G_1^{\perp a}(z, M_h^2)$$

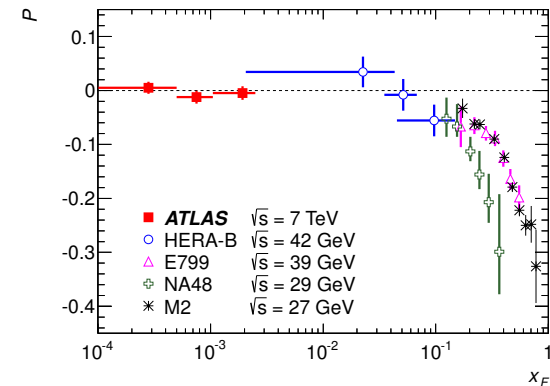
$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{LU} \sim \lambda_e \sum_a e_a^2 f_1^a(x) \approx G_1^{\perp a}(z, M_h^2)$$



Note the sign change in  $M_{\pi\pi}$ !  
 What does this mean in terms of the underlying processes?  
 Looks more 'Jaffe et al' like?

# Lambda Production

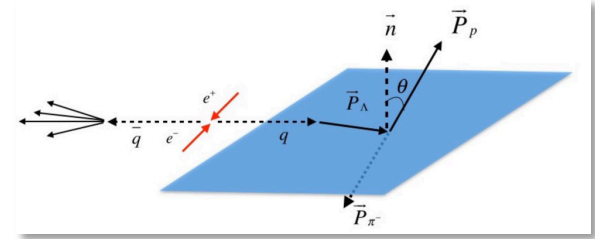
- Longstanding question: Large  $\Lambda$  transverse polarization in unpolarized pp collision
- $\rightarrow$  Polarizing FF  $D_{1T}^\perp(z, p_\perp^2)$ ?
- T-odd TMD but chiral-even, **Universality?** Boer, Kang, Vogelsang, Yuan **Phys.Rev.Lett. 105 (2010) 202001**
  - Needs  $e^+ e^-$  and SIDIS measurements
- NB: previous SIDIS lambda photoproduction or very large statistical uncertainties



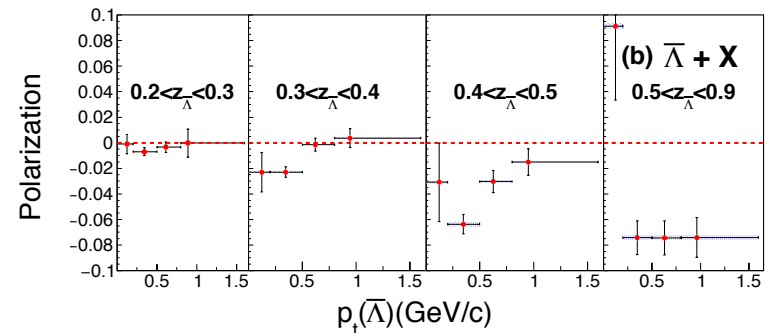
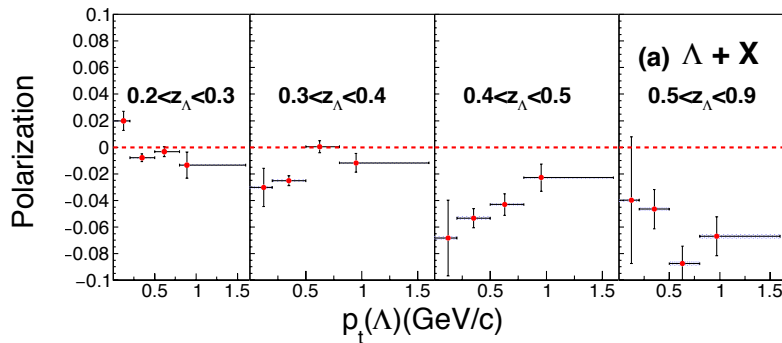
**Phys.Rev. D91  
(2015) no.3, 032004**

NB: e799  
beryllium target  
Na48 beryllium  
About 50%  
decay  
contributions

# $z_\Lambda$ , $p_T$ Dependence of observed $\Lambda$ polarization

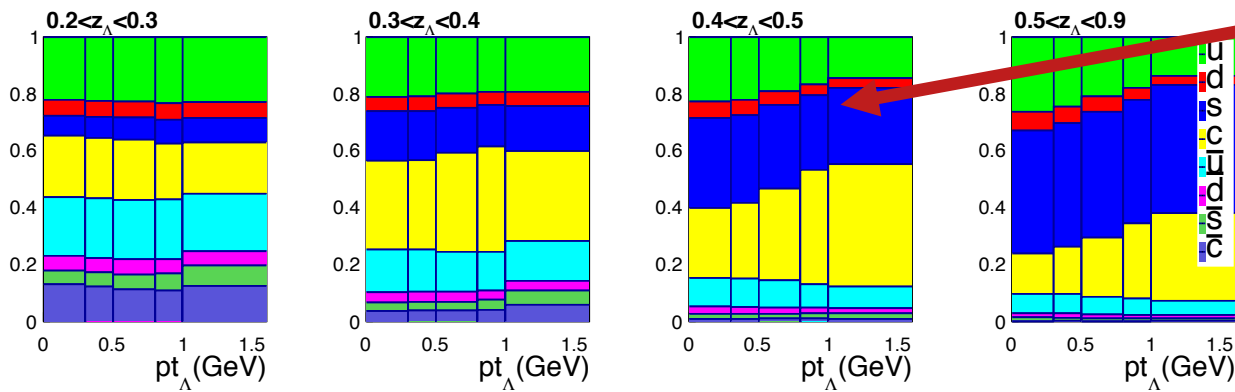
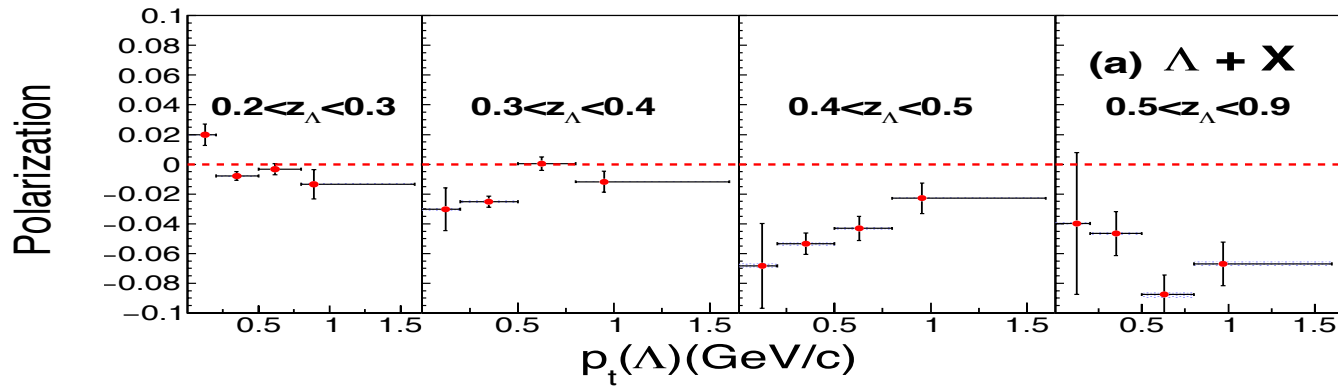


- Polarization rises with  $p_T$  in the lowest  $z_\Lambda$  and highest  $z_\Lambda$  bin. But the dependence reverses around 1 GeV in the intermediate  $z_\Lambda$  bins  $\rightarrow$  **Unexpected!**
  - Expect  $\mathbf{P} \cdot \mathbf{p}_q \times \mathbf{p}_\perp$  behavior (see e.g. Anselmino, Kishore, Mukherjee, Phys.Rev. D100 (2019) no.1, 014029)
- Results are consistent between  $\Lambda$  and ( $\bar{\Lambda}$ )



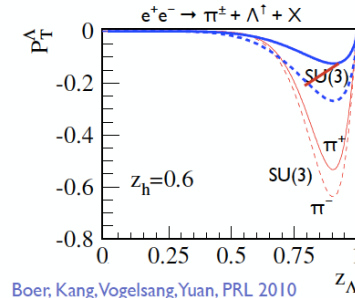
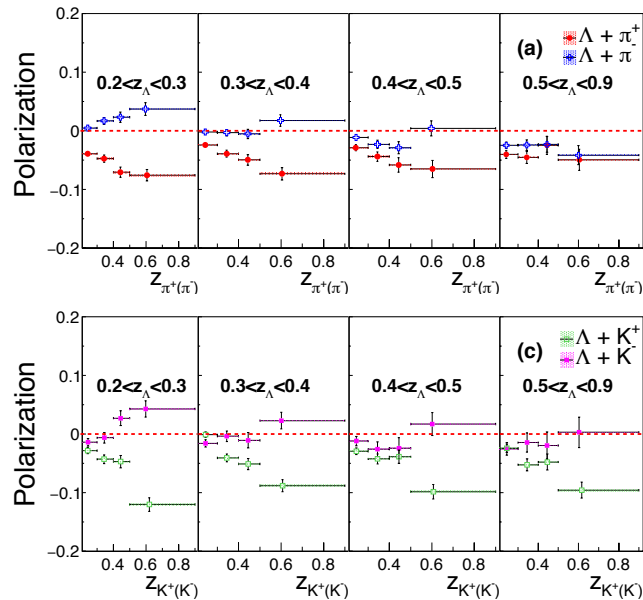
Phys. Rev. Lett. 122, 042001 (2019)

# Asymmetries explained by flavor decomposition?

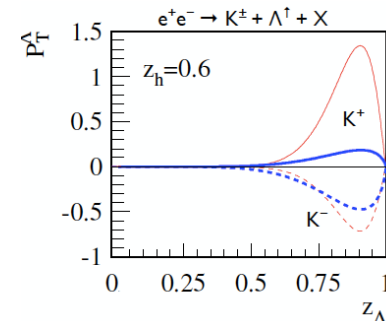


u-quark carry polarization?  
Or shape explainable with drop in strange?  
(but rise in  $p_T$  should Compensate?)

# Tension with theory: ASSOCIATED PRODUCTION



Boer, Kang, Vogelsang, Yuan, PRL 2010

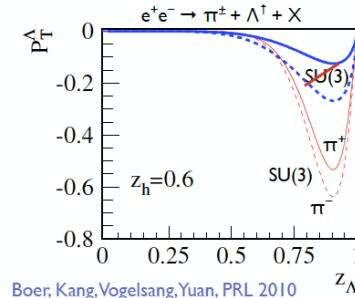
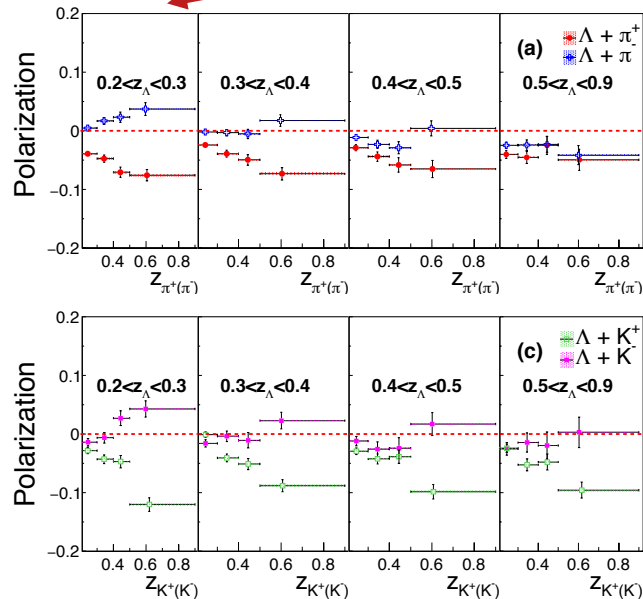


- Correlation with opposite hemisphere light meson  $\rightarrow$  quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge cf Sivers
- Only experimental results on T-odd, chiral even FF  $\rightarrow$  **Important to understand!**

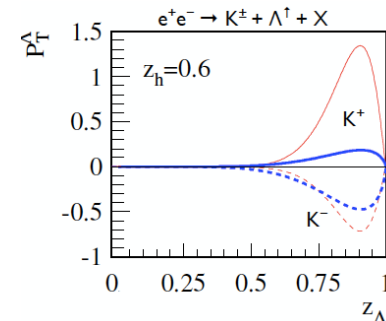


# Tension with theory: ASSOCIATED PRODUCTION

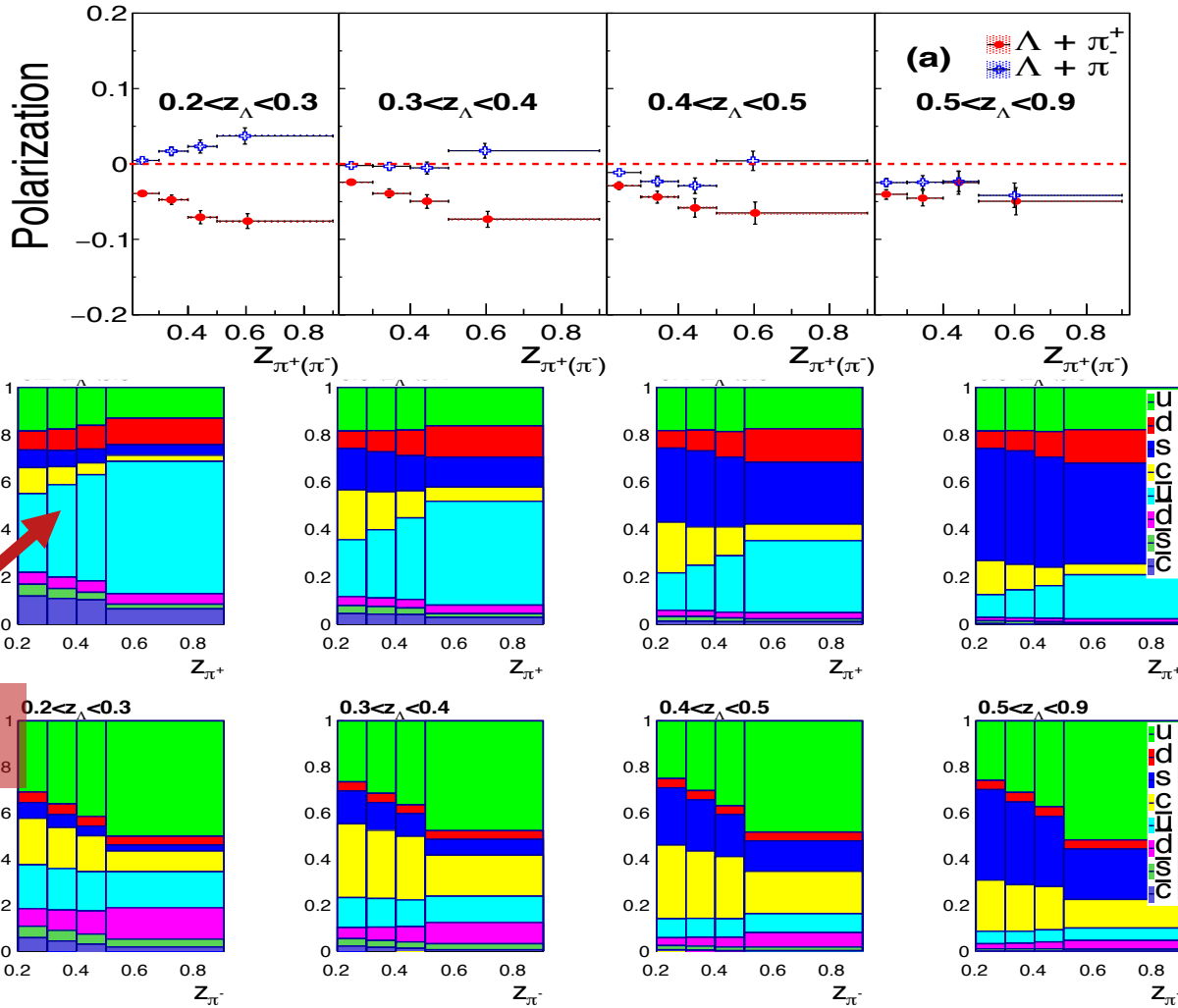
Enhanced  $|P|$  already at low  $z$



Boer, Kang, Vogelsang, Yuan, PRL 2010



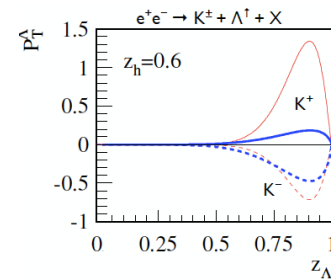
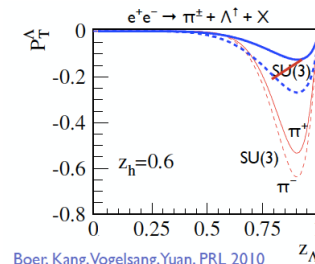
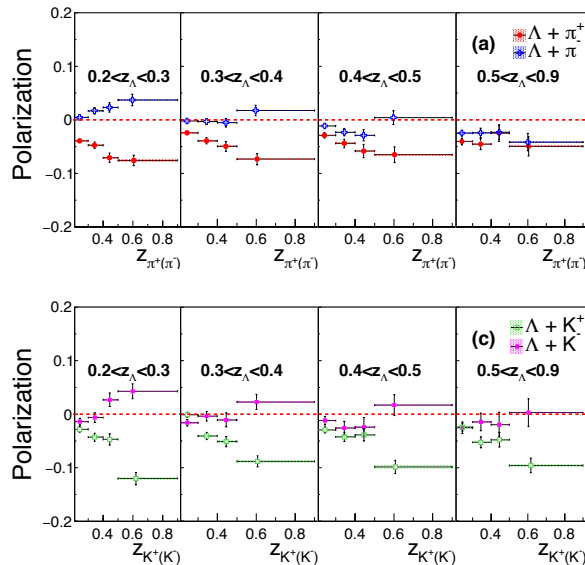
- Correlation with opposite hemisphere light meson  $\rightarrow$  quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge cf Sivers
- Only experimental results on T-odd, chiral even FF  $\rightarrow$  **Important to understand!**



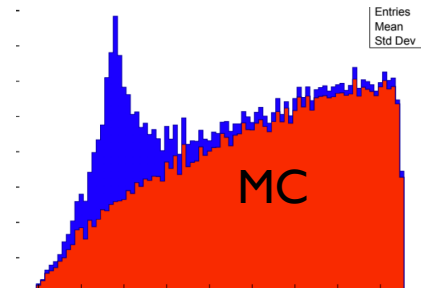
High  $\Lambda z$ , low  $\pi z$   
 Dominated by strange for  $\pi^+$  and u for  $\pi^-$  but asymmetries similar?

- Initial quark flavor matters!

# Tension with theory: ASSOCIATED PRODUCTION



- Correlation with opposite hemisphere light meson  $\rightarrow$  quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge of Sivers
- Only experimental results on T-odd, chiral even FF  $\rightarrow$  **Important to understand!**
- **E.g. Lambda polarization at CLAS12 or EIC**
- Currently investigating feasibility of  $\Lambda^\uparrow$  at CLAS12  $\rightarrow$  exploratory measurement
- EIC will be enable precision studies of  $\Lambda$  polarization



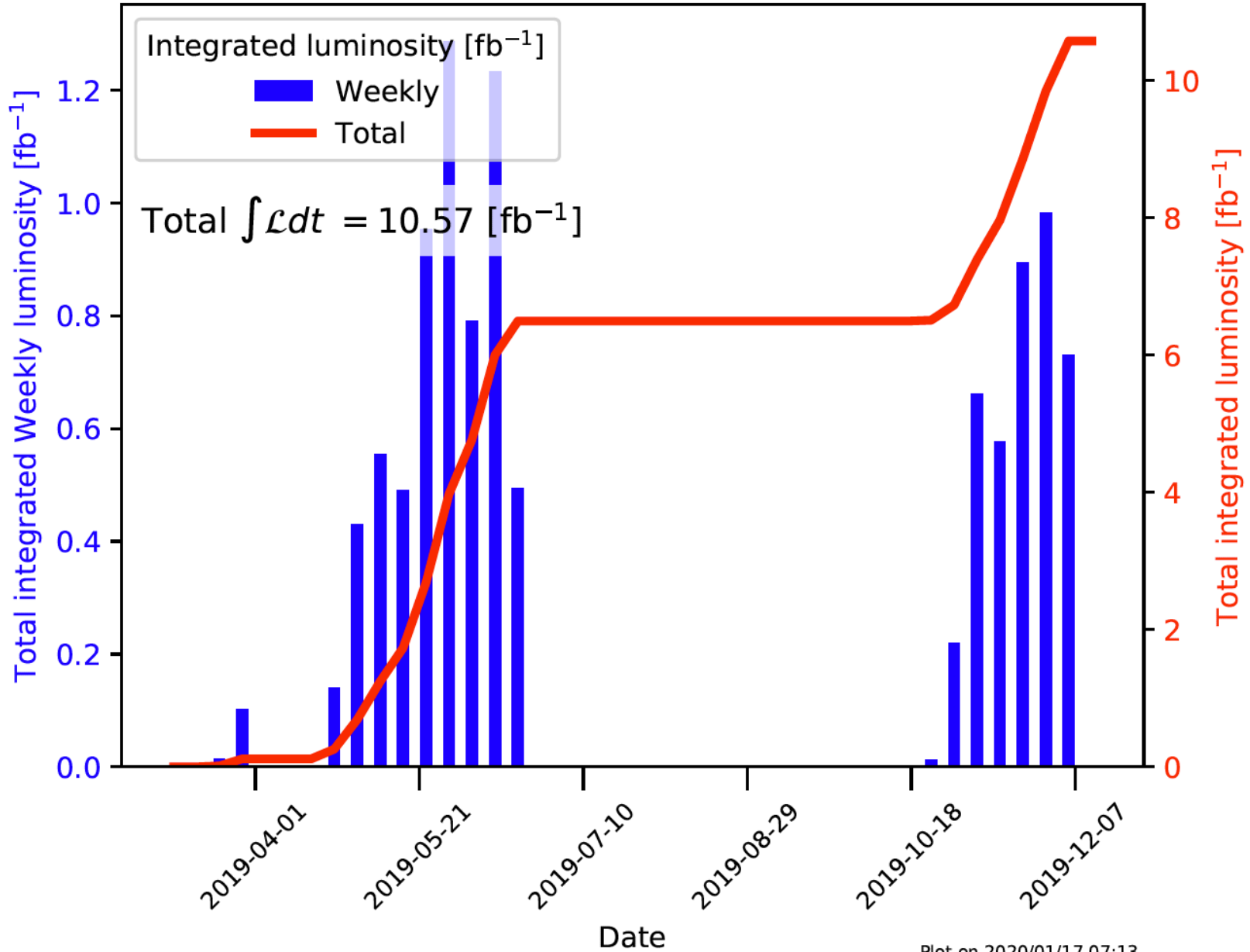
# Summary and Outlook

- Polarizing Fragmentation Functions provide exciting inputs in non-perturbative dynamics in hadronization
- Compared to PDFs, field is still in the beginning
- Interesting new results on Collins for neutral mesons, polarizing  $\Lambda$ , di-hadron FFs,
- Need multi-differential measurements on di-hadron FFs,  $\Lambda^\uparrow$  in SIDIS
- EIC will open exciting opportunities study polarized FFs, will be game changer for study of  $\Lambda$
- Polarized di-hadron production will enable targeted access to intricate aspects of the nucleon structure using data from CEBAF12, RHIC and EIC

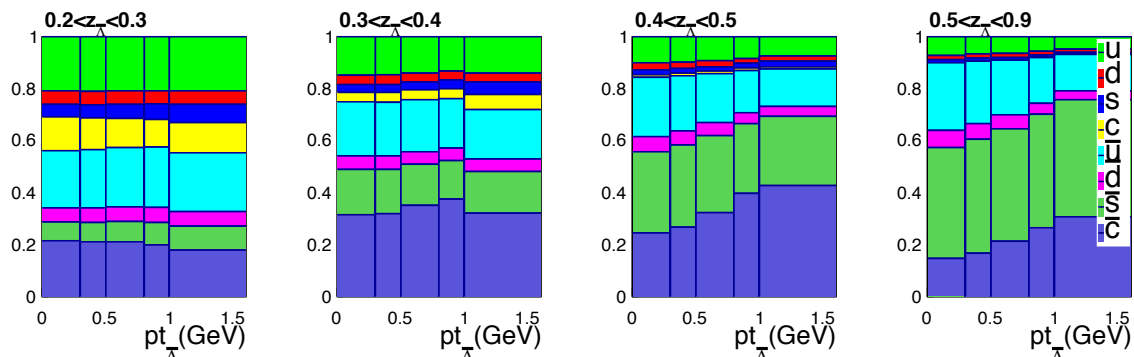
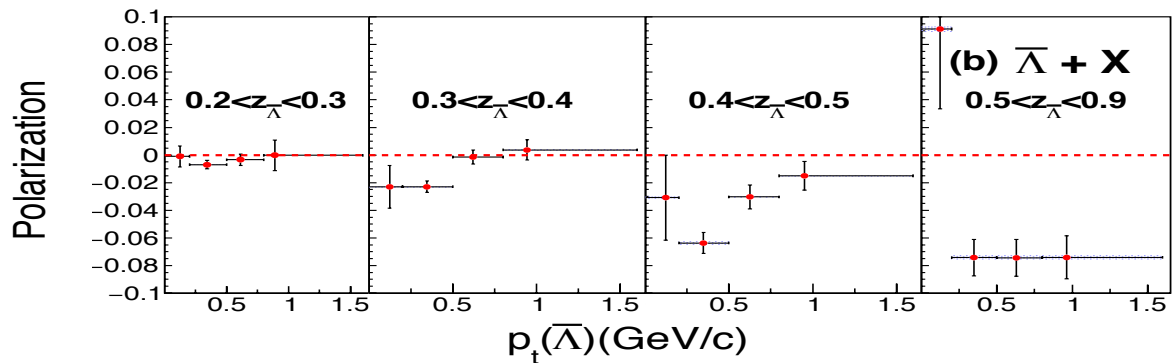


# Belle II Online luminosity

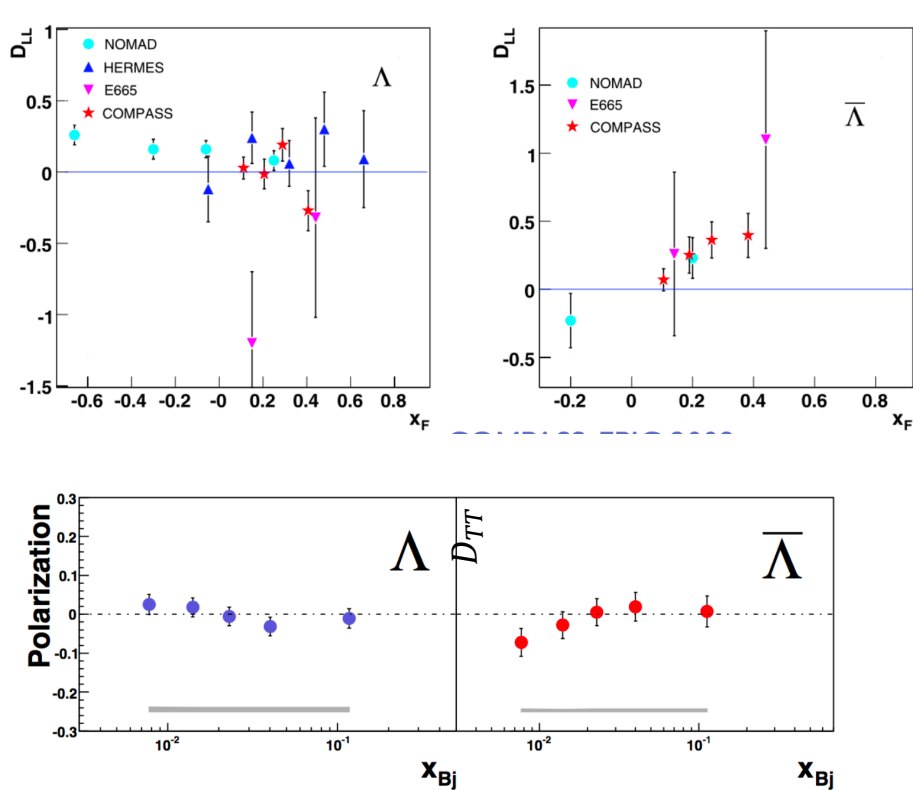
Exp: 7-8-9-10 - All runs



# Anti- $\Lambda$ analogue

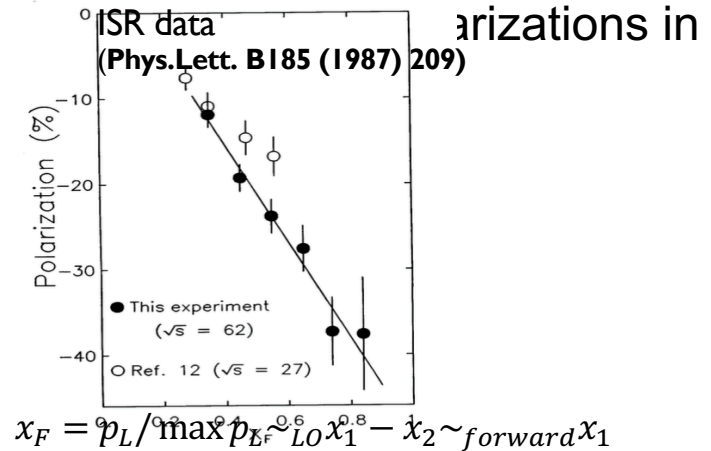


# State of the art for $\Lambda$ in SIDIS



T. Negrini, PhD thesis

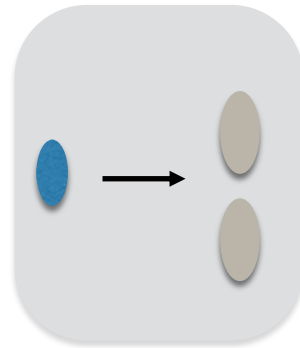
- Limited data from compass
- Hermes  $Q^2 \approx 0$   
 $p + p \rightarrow \Lambda^\uparrow + X$
- STAR measurements of longitudinal/transverse spin transfer in  $pp$ : Phys.Rev. D98 (2018) no.9, 091103, Phys.Rev. D98 (2018) no.11, 112009



$$x_F = p_L / \max p_L \approx 0.6 x_1^{0.8} - x_2 \sim_{forward} x_1$$



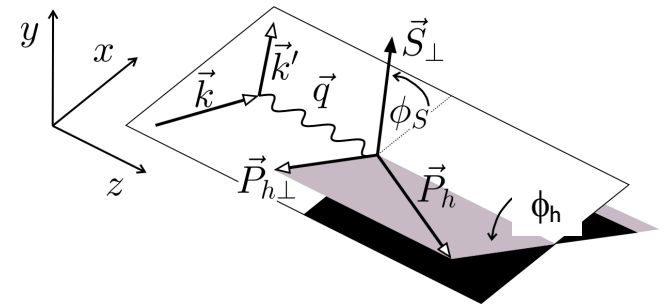
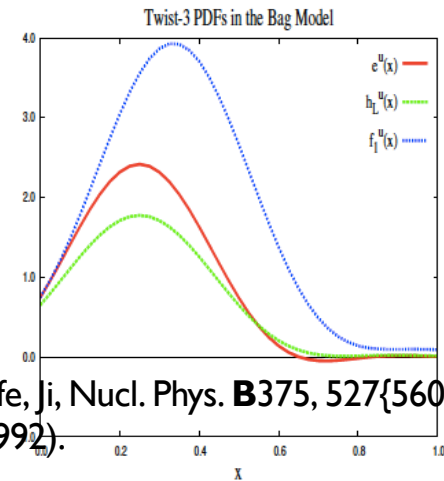
# Di-Hadron production



# Example, Access of $e(x)$ in SIDIS x-section

- Single hadron cross-section: mixes other contributions:

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



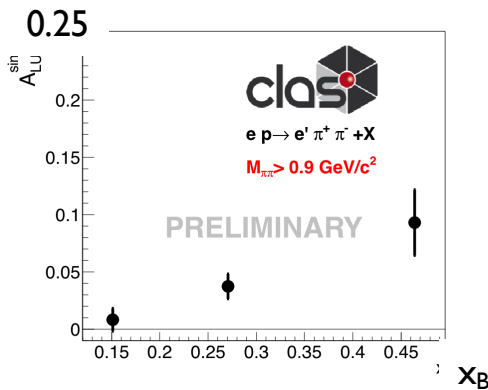
M. Burkhardt:  $e(x)$  can be interpreted as transverse force (integrated BM)

# Example, Access of $e(x)$ in SIDIS x-section

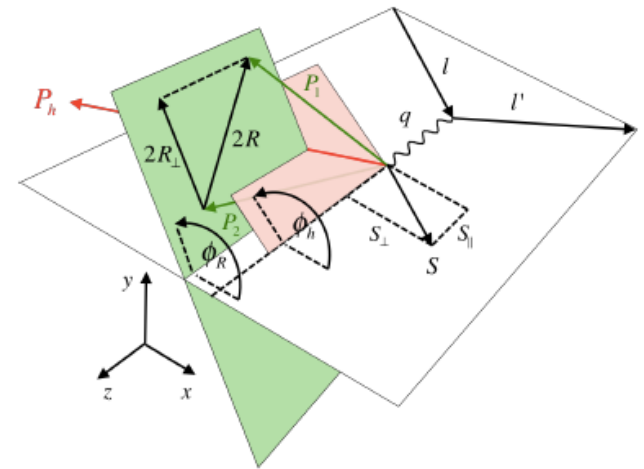
- Di-hadron cross section: Clean access to  $e(x)$

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

- See e.g. Aurore Courtoy, arXiv:1405.7659



AV, DNP 2018



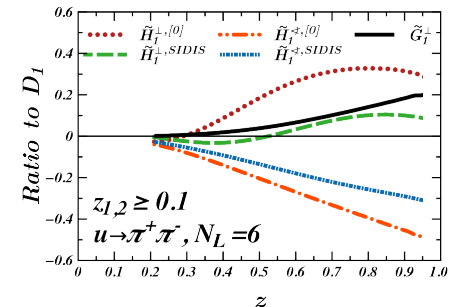
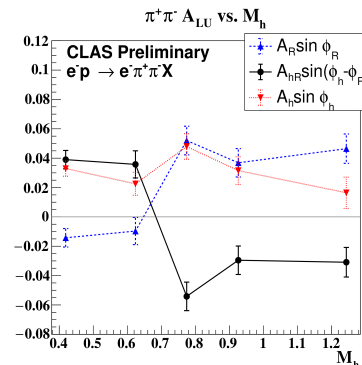
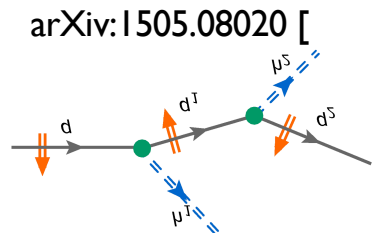
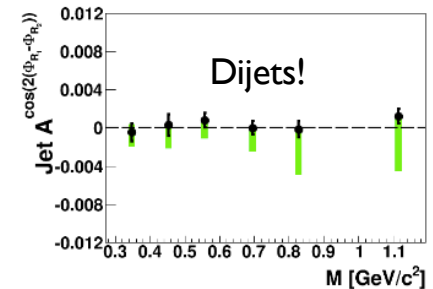
$$G_1^\perp = \text{Diagram 1} - \text{Diagram 2}$$

Diagram 1: A purple circle with a blue ring around it, emitting two particles:  $\pi^+$  and  $\pi^-$ .

Diagram 2: A purple circle with a blue ring around it, emitting two particles:  $\pi^+$  and  $\pi^-$ .

# History of wormgear FF $G_1^\perp$

- First suggestion to observe in  $e^+e^-$  by Boer, Jakob, Radici, PRD67 (2003) 094003
  - Postulate connection to jet handedness proposed by Efremov and Kharzeev Phys.Lett. B366 (1996) 311-315 (connection to chromomagnetic effects)
- Measurement by Belle  $\rightarrow$  No signal
- New model calculations by Matevosyan et al connecting  $G_1^\perp$  with single hadron Collins effect in string fragmentation (a bit like worm gear functions)  $\rightarrow$  Interesting to learn about spin momentum correlations in hadronization: sizable asymmetries contradicted by Belle result??
- Mistake found in Boer et. al: Phys.Rev. D97 (2018) no.7, 074019  $\rightarrow$  Need weighted asymmetry including dependence on  $P_{hT}$
- Accessible in SIDIS via weighted asymmetries



# $G_1^\perp$ measurement in SIDIS and $e^+e^-$

- New Observable in  $e^+e^-$

$$\left\langle \frac{q_T^2 (3 \sin(\varphi_q - \varphi_R) \sin(\varphi_q - \varphi_{\bar{R}}) + \cos(\varphi_q - \varphi_R) \cos(\varphi_q - \varphi_{\bar{R}}))}{M_h \bar{M}_h} \right\rangle$$

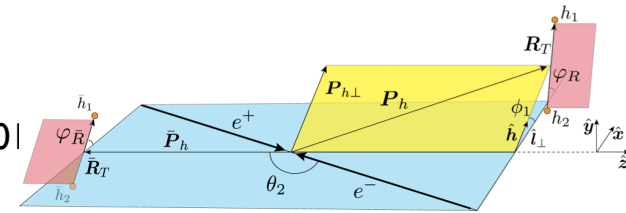
$$= \frac{12\alpha^2 A(y)}{\pi Q^2} \sum_{a, \bar{a}} e_a^2 (G_1^{\perp a, [0]} - G_1^{\perp a, [2]}) (\bar{G}_1^{\perp \bar{a}, [0]} - G_1^{\perp \bar{a}, [2]}),$$

Matevosyan., Bacchetta, Boer, Courtoy, Kotzinian, Radici, Thomas: Phys. Rev. D 97, 07401

- New Observable in SIDIS with longitudinal target and beam spin asymmetries

$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{UL} \sim S_L \sum_a e_a^2 g_{1L}^a(x) \approx G_1^{\perp a}(z, M_h^2)$$

$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{LU} \sim \lambda_e \sum_a e_a^2 f_1^a(x) \approx G_1^{\perp a}(z, M_h^2)$$



Matevosyan, Kotzinian ADP-17-42-T1048

N.B. Compass did not observe significant asymmetry for unweighted asymmetry

Update on CLAS12 Analysis at DNP 2019

# Summary

- EIC needs input from  $e^+e^-$  to fulfill physics promise → Belle II provides necessary statistics
- Polarized Final states are a way to
  - Mapping of spin-orbit correlations in hadronization
  - Complementary access to twist3 and TMD PDFs
  - Resolve questions in  $\Lambda$  production
- Also interesting
  - In medium fragmentation (polarization dependent?)
  - In jet fragmentation
- See also D. Boer "Overview of Spin Physics at EIC", PoS SPIN2018 (2019) 167

# Outlook Di-hadron channels at RHIC, Belle II and the EIC

- Measurements at **RHIC** and **EIC** are complementary!
- **Transversity through di-hadron channel**
  - STAR data on tape (2012 + 2x more), order of magnitude more 500 GeV
  - Unpolarized x-section for gluon FF
- Twist3  $e(x)$ 
  - Should be possible at **RHIC** and **EIC**
- Wormgear FF  $G_{1\perp}$ 
  - Precision measurements in  $A_{LU}$  at **RHIC** and **EIC** possible
  - Need to check universality (T-odd, chiral-even)
- Other di-hadron channels
  - Boer-Mulders → Can decouple from Cahn effect in di-hadrons by measuring azimuthal modulations around  $P_h$  (also planned at CLAS12)
- **Belle II** will contribute measurements for precision extraction of di-hadron FFs for pions and kaons
- ...

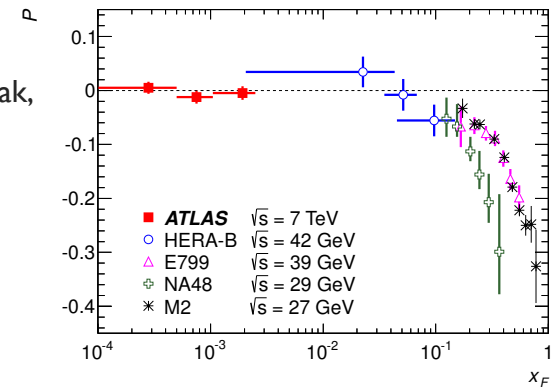
# Importance of FFs at/FOR the EIC

- Fragmentation Functions to fulfill EIC science mission
  - Need for precise mapping of TMD FFs
  - Angular momentum in final state
- QCD studies in hadronization
  - Spin orbit correlation in hadronization
    - Di-hadron correlations
    - Polarized  $\Lambda$ 's
- Data from  $e^+e^-$  and SIDIS needed. → We cannot calculate FFs
- Belle & **Belle II** to measure FFs in  $e^+e^-$



# Lambda Production

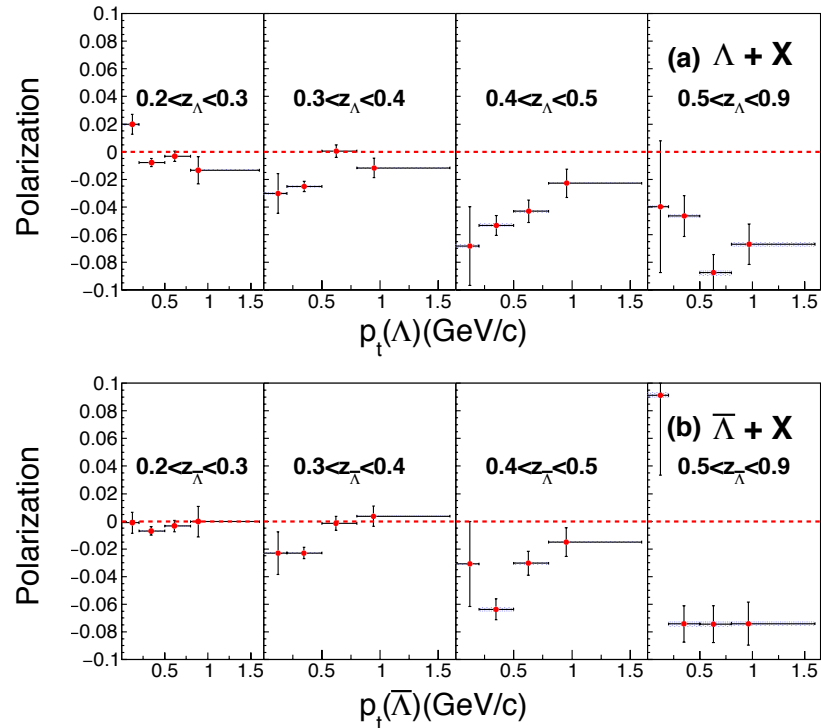
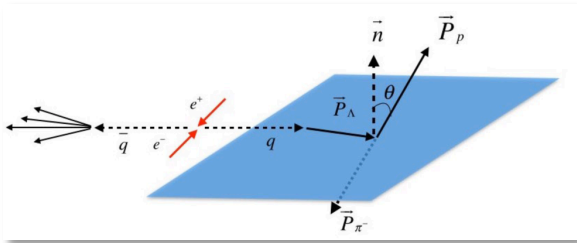
- Inclusion of polarization leads to rich hadronization structure (see e.g. Kanazawa, Metz Pitonyak, Schlegel Phys.Lett. **B744** (2015) 385-390 , Metz, Pitonyak Phys.Lett. **B723** (2013) 365-370)
- Longstanding question: Large  $\Lambda$  transverse polarization in unpolarized pp collision
- $\rightarrow$  Polarizing FF  $D_{1T}^\perp(z, p_\perp^2)$ ?
- T-odd TMD but chiral-even, **Universality?** Boer, Kang, Vogelsang, Yuan **Phys.Rev.Lett.** **105** (2010) 202001
  - Needs e+e- + SIDIS measurements
- NB: previous SIDIS lambda photoproduction or **very** large statistical uncertainties



**Phys.Rev. D91**  
**(2015) no.3, 032004**

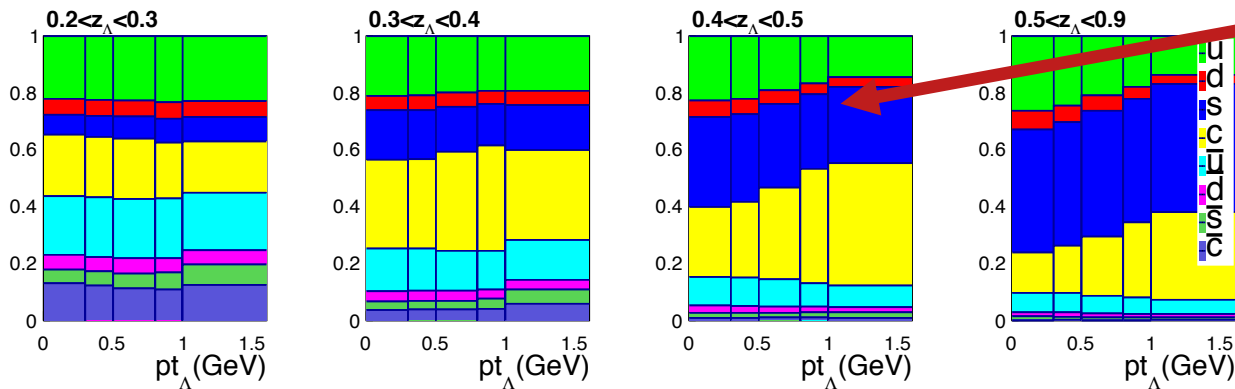
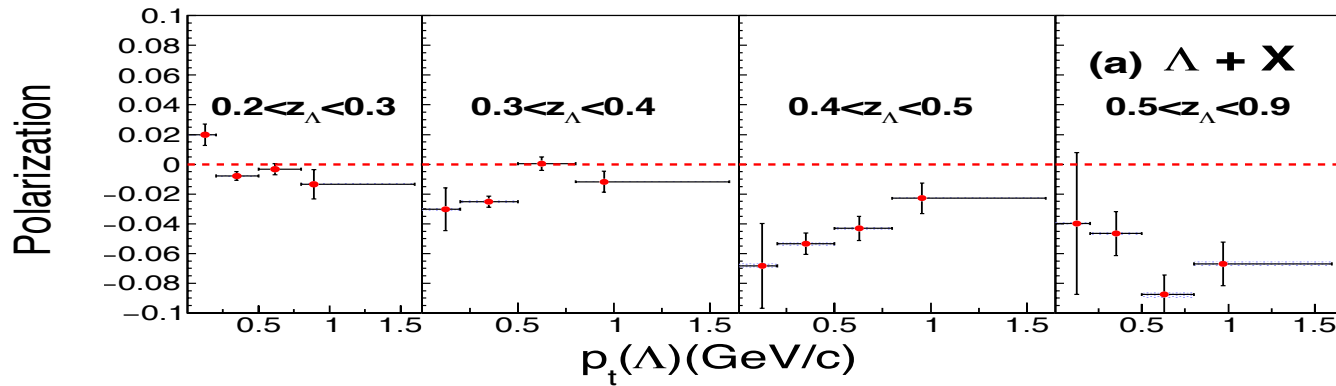
NB: e799  
 beryllium target  
 Na48 beryllium  
 About 50%  
 decay  
 contributions

# first Observation By Belle



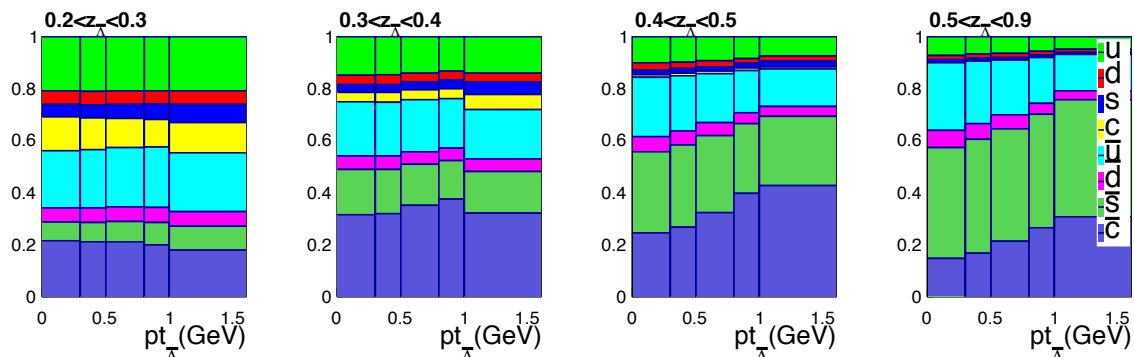
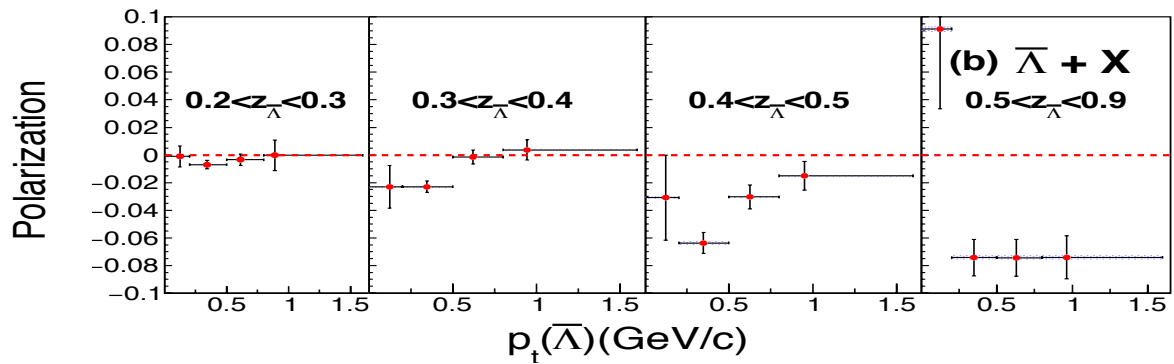
[arXiv:1808.05000](https://arxiv.org/abs/1808.05000), submitted to PRL

# Asymmetries explained by flavor decomposition?

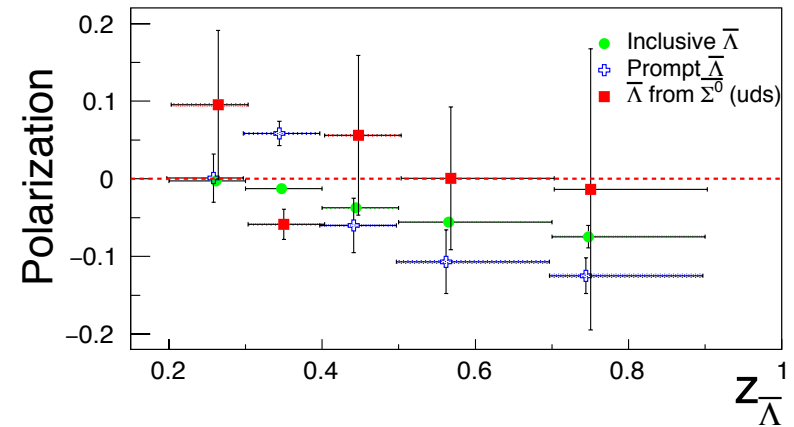
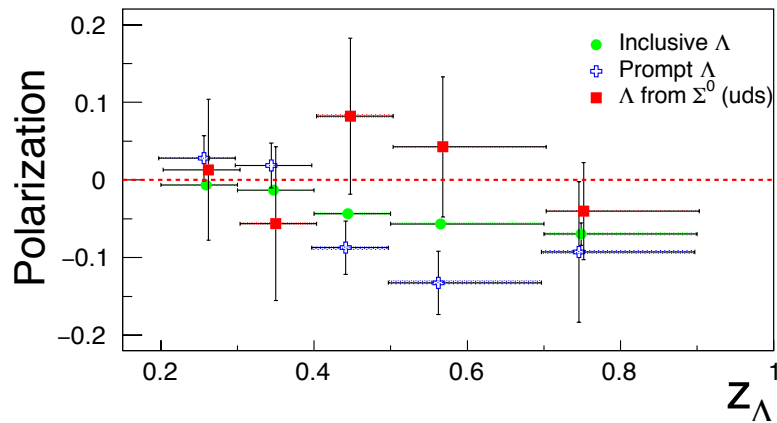


u-quark carry polarization?  
Or shape explainable with drop in strange?  
(but rise in  $p_T$  should Compensate?)

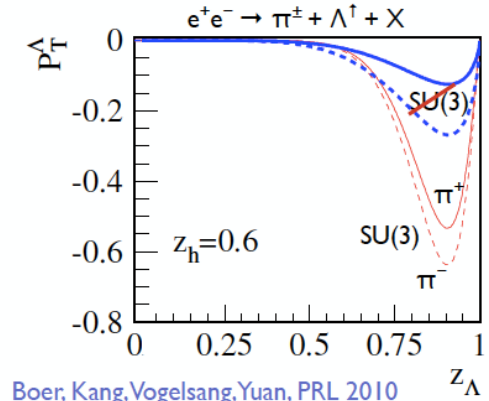
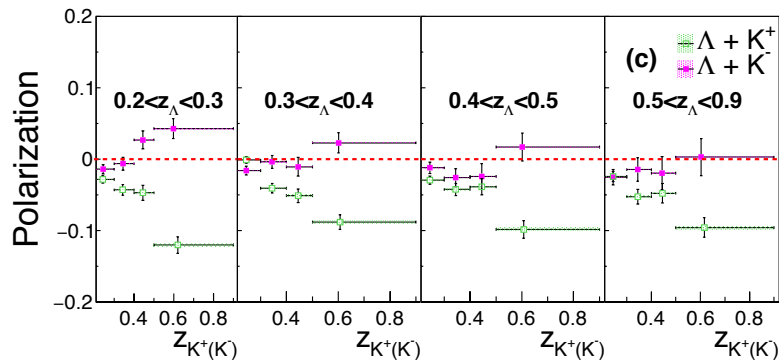
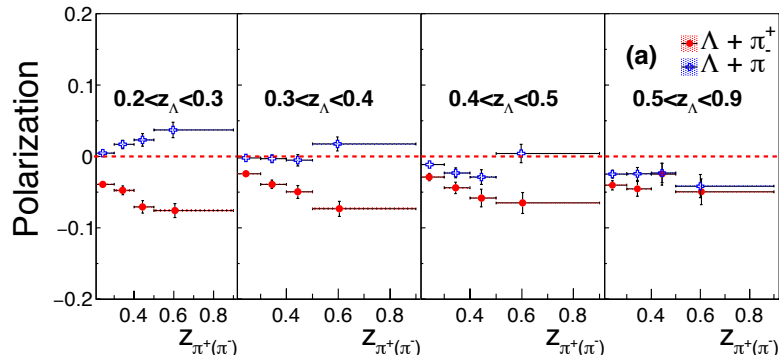
# Anti- $\Lambda$ analogue



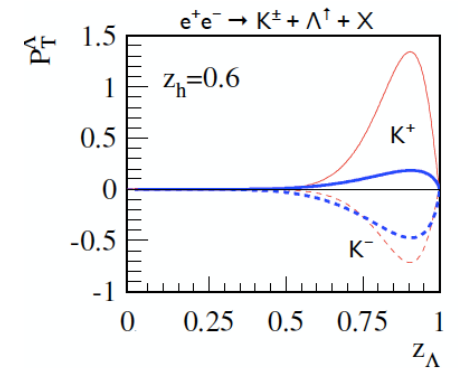
# A first: Correction for feed-down and charm contribution

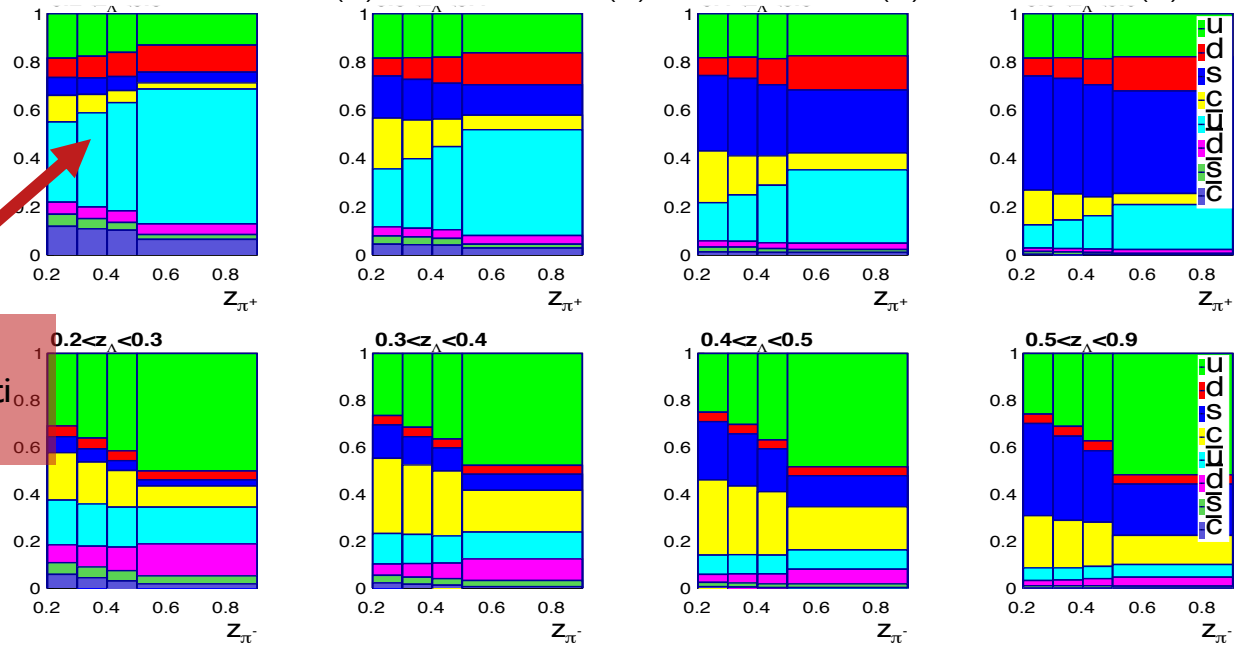
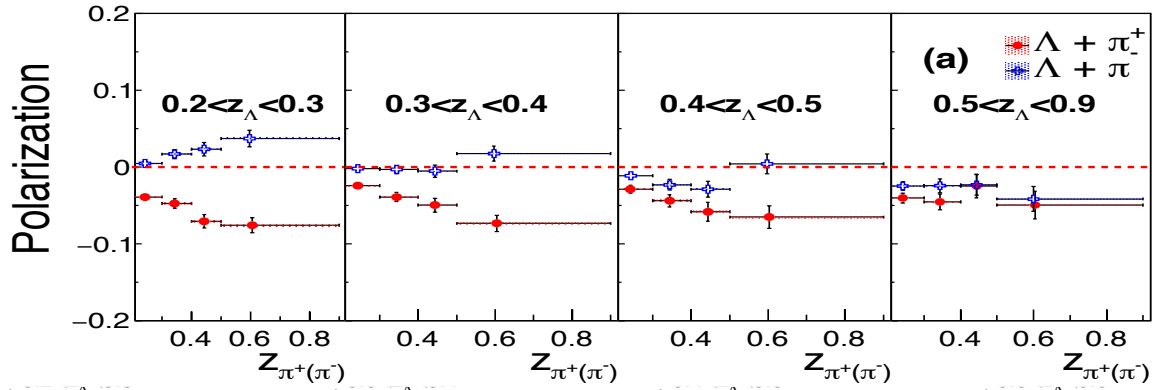


# Tension with theory: ASSOCIATED PRODUCTION



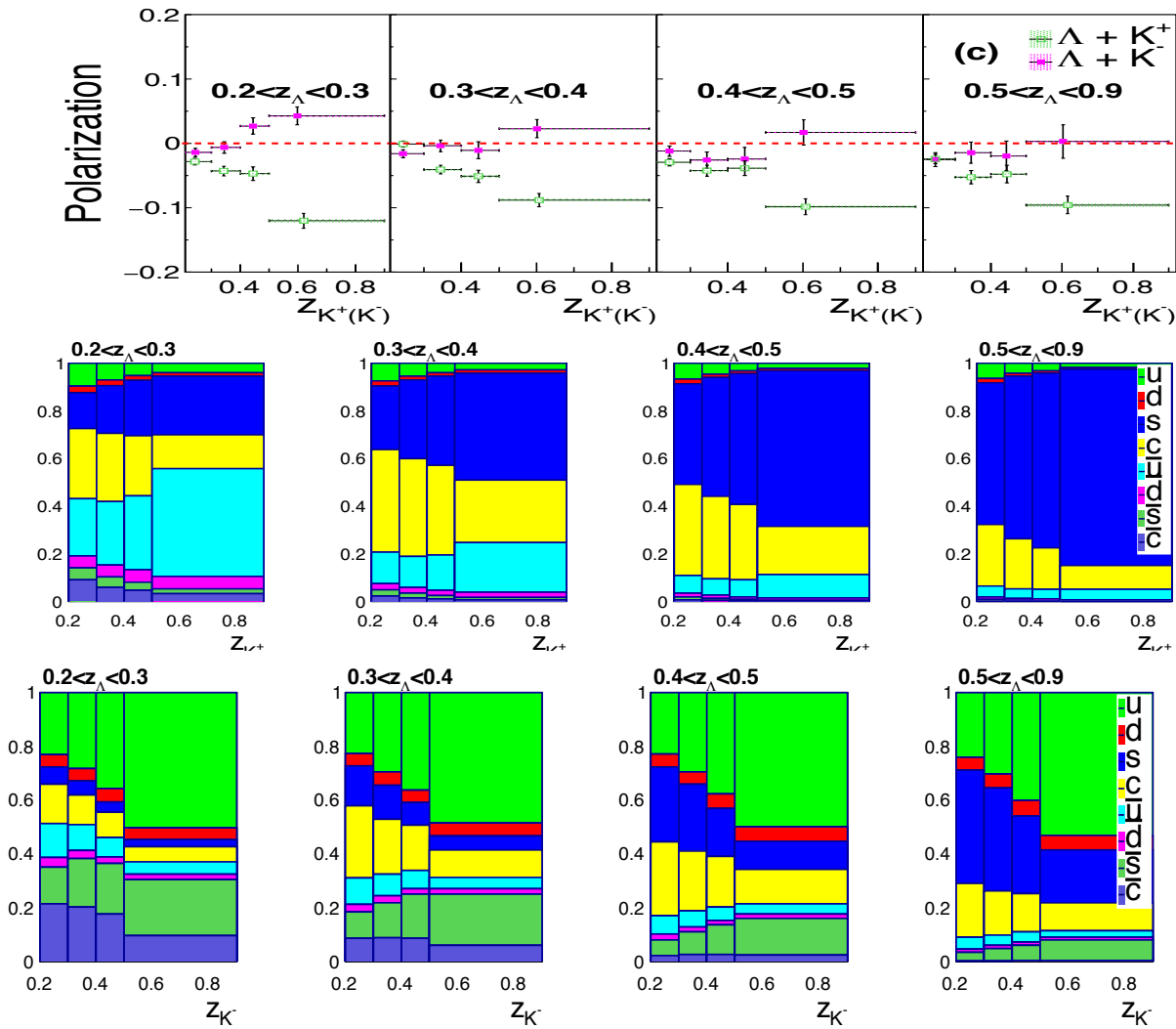
Boer, Kang, Vogelsang, Yuan, PRL 2010





Low  $\Lambda z$ , high  $\pi z$   
 Dominated by anti- $u$

High  $\Lambda z$ , low  $\pi z$   
 Dominated by strange for  $\pi^+$  and  $u$  for  $\pi^-$  but asymmetries similar?

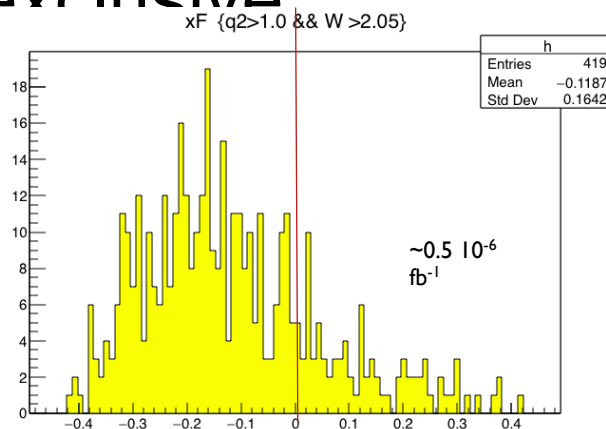


High  $\Lambda$  z, low  $K$  z  
 Dominated by strange for  $\pi^+$  and u  
 for  $K$  reflected in asymmetries



# $\Lambda$ at CLAS

- Plenty of  $\Lambda$  physics at CLAS6 -- but mostly target or ~~exclusive~~ production
- CLAS12 could do so many lambdas



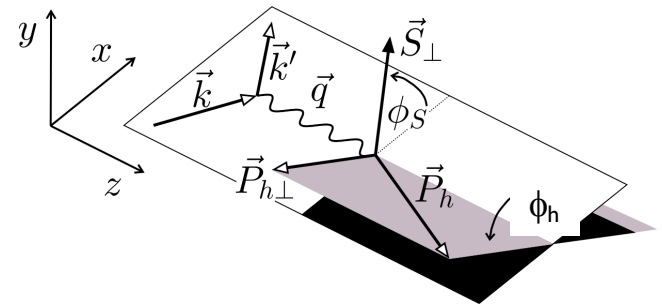
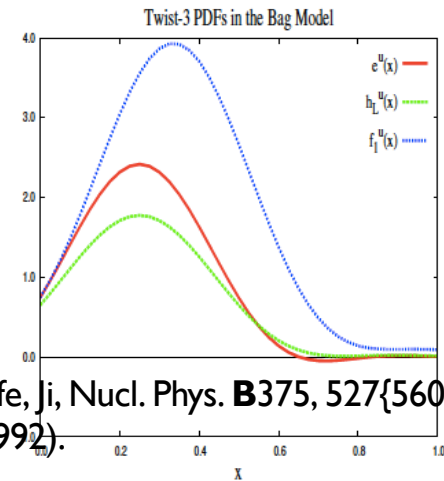
- Would open up many physics topics
- Example, compare with  $\Lambda^{\uparrow}$  production in  $e^+e^-$  (Boer, Kang, Vogelsang, Yuan, PRL. 105 (2010) 202001, learn about TMD factorization)
- **Optimistically** expect  $\sim 100\text{M}$   $\Lambda$ s is initial running with unpolarized target in acceptance

# Example, Access of $e(x)$ in SIDIS x-section

- Single hadron cross-section: mixes other contributions:

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

See M. Burkhardt talk on interpretations as transverse force on struck quark

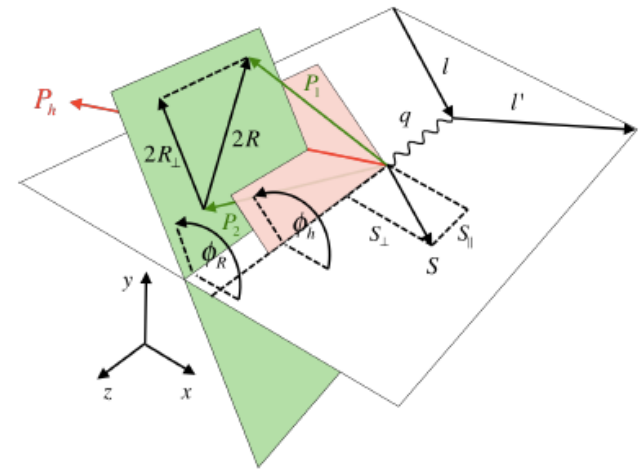
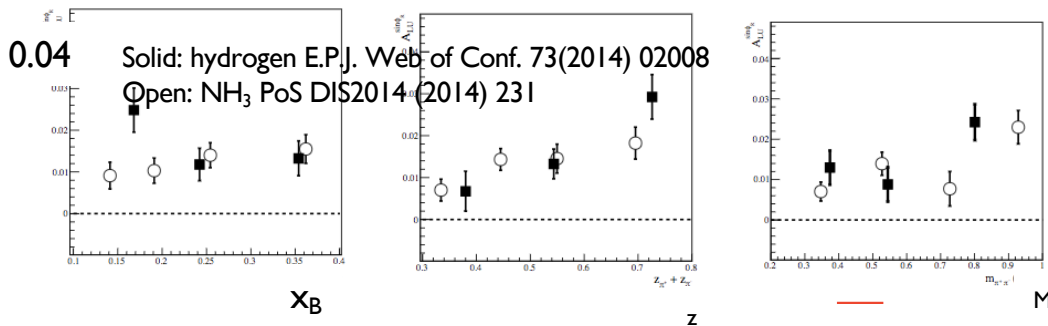


# Example, Access of $e(x)$ in SIDIS x-section

- Di-hadron cross section: Clean access to  $e(x)$

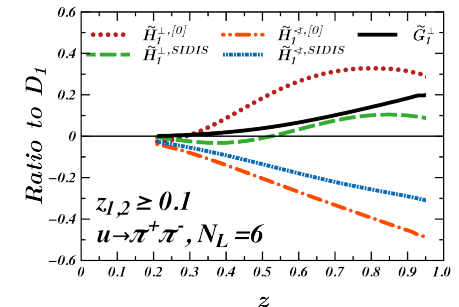
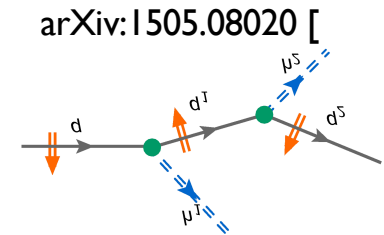
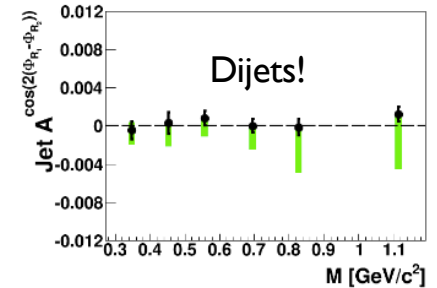
$$F_{LU}^{\sin\phi_R} = -x \frac{|R| \sin\theta}{Q} \left[ \frac{M}{m_{hh}} x e^q(x) H_1^{\triangleleft q}(z, \cos\theta, m_{hh}) + \frac{1}{z} f_1^q(x) \tilde{G}^{\triangleleft q}(z, \cos\theta, m_{hh}) \right],$$

- See e.g. Aurore Courtoy, arXiv:1405.7659
- Evidence from CLAS6:



# History of wormgear FF $G_1^\perp$

- First suggestion to observe in  $e^+e^-$  by Boer, Jakob, Radici, PRD67 (2003) 094003
  - Postulate connection to jet handedness proposed by Efremov and Kharzeev Phys.Lett. **B366** (1996) 311-315 (connection to chromomagnetic effects)
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- Accessible in SIDIS via weighted asymmetries

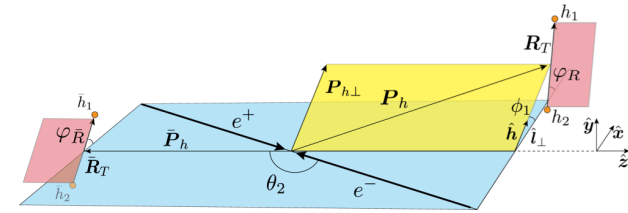


# $G_1^\perp$ measurement in SIDIS and $e^+e^-$

- New Observable in  $e^+e^-$

$$\left\langle \frac{q_T^2 (3 \sin(\varphi_q - \varphi_R) \sin(\varphi_q - \varphi_{\bar{R}}) + \cos(\varphi_q - \varphi_R) \cos(\varphi_q - \varphi_{\bar{R}}))}{M_h \bar{M}_h} \right\rangle$$

$$= \frac{12\alpha^2 A(y)}{\pi Q^2} \sum_{a,\bar{a}} e_a^2 \left( G_1^{\perp a, [0]} - G_1^{\perp a, [2]} \right) \left( \bar{G}_1^{\perp \bar{a}, [0]} - \bar{G}_1^{\perp \bar{a}, [2]} \right),$$



Matevosyan., Bacchetta, Boer, Courtoy, Kotzinian, Radici, Thomas: Phys. Rev. **D** 97, 074019 (2018).

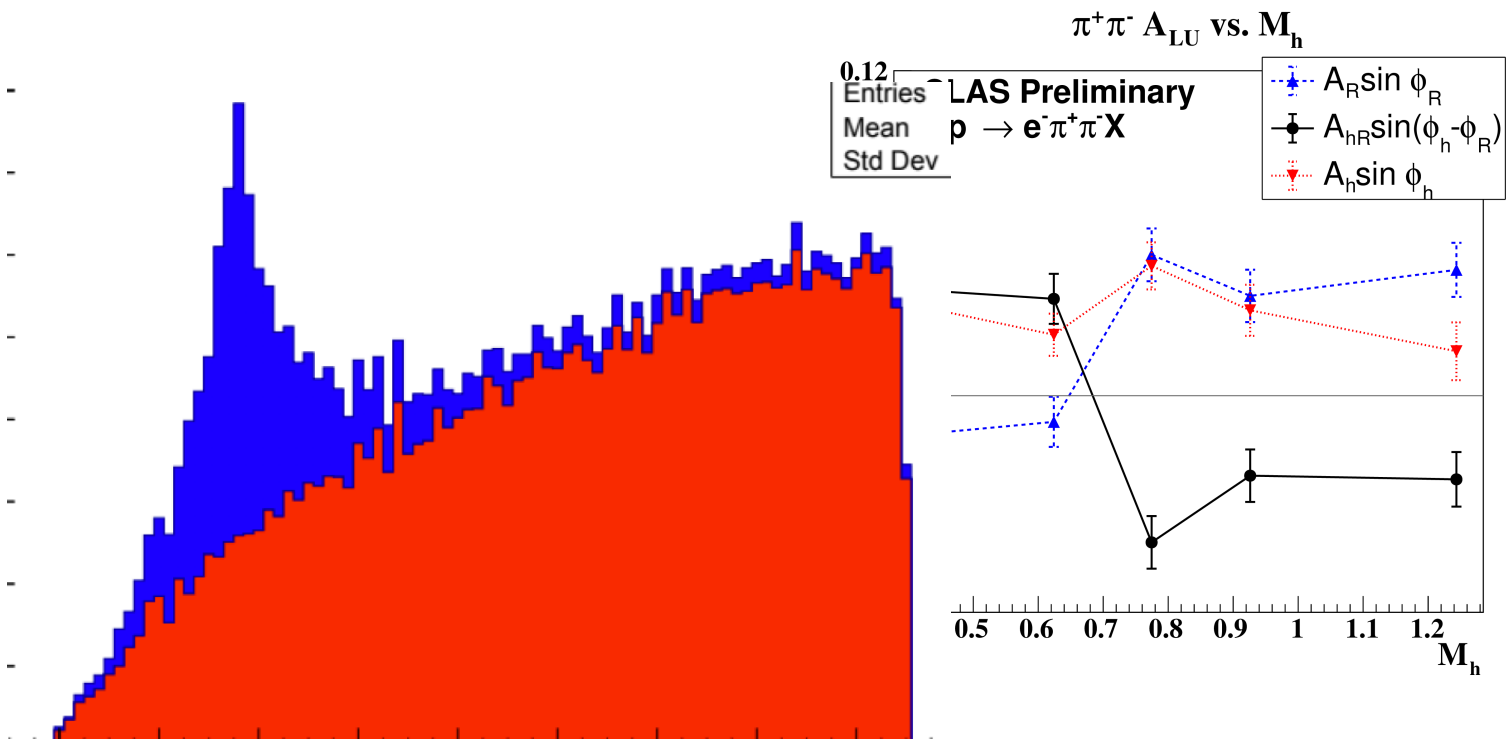
- New Observable in SIDIS with longitudinal target and beam spin asymmetries

$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{UL} \sim S_L \sum_a e_a^2 g_{1L}^a(x) \approx G_1^{\perp a}(z, M_h^2)$$

$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{LU} \sim \lambda_e \sum_a e_a^2 f_1^a(x) \approx G_1^{\perp a}(z, M_h^2)$$

Matevosyan, Kotzinian ADP-17-42-T1048

N.B. Compass did not observe significant asymmetry for unweighted asymmetry



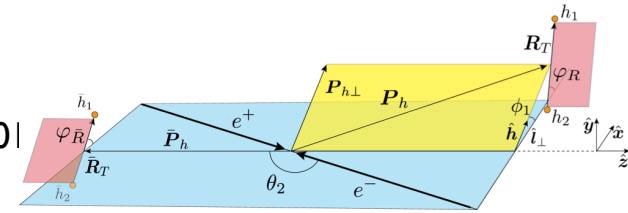
# $G_1^\perp$ measurement in SIDIS and $e^+e^-$

- New Observable in  $e^+p$

$$\left\langle \frac{q_T^2 (3 \sin(\varphi_q - \varphi_R) \sin(\varphi_q - \varphi_{\bar{R}}) + \cos(\varphi_q - \varphi_R) \cos(\varphi_q - \varphi_{\bar{R}}))}{M_h \bar{M}_h} \right\rangle$$

$$= \frac{12\alpha^2 A(y)}{\pi Q^2} \sum_{a, \bar{a}} e_a^2 (G_1^{\perp a, [0]} - G_1^{\perp a, [2]}) (\bar{G}_1^{\perp \bar{a}, [0]} - G_1^{\perp \bar{a}, [2]}),$$

Matevosyan., Bacchetta, Boer, Courtoy, Kotzinian, Radici, Thomas: Phys. Rev. D 97, 07401



- New Observable in SIDIS with longitudinal target and beam spin asymmetries

$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{UL} \sim S_L \sum_a e_a^2 g_{1L}^a(x) \approx G_1^{\perp a}(z, M_h^2)$$

$$\left\langle \frac{P_{h\perp} \sin(\varphi_h - \varphi_R)}{M_h} \right\rangle_{LU} \sim \lambda_e \sum_a e_a^2 f_1^a(x) \approx G_1^{\perp a}(z, M_h^2)$$

- N.B. Compass did not observe significant asymmetry for unweighted asymmetry

Update on CLAS12 Analysis at DNP 2019

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