DI-HADRON AND POLARIZED LAMBDAS AS NOVEL PROBES OF THE NUCLEON STRUCTURE

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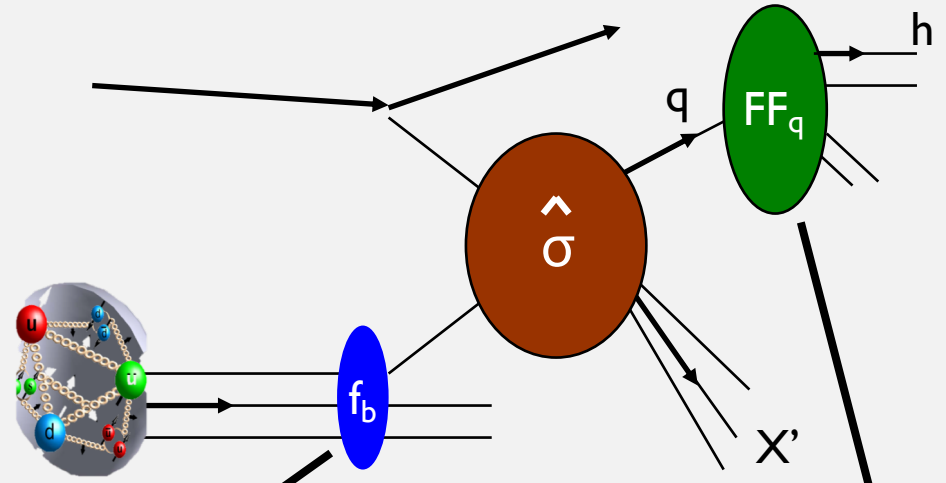
INT 10/11/2018

ACCESS NUCLEON STRUCTURE THROUGH **FRAGMENTATION FUNCTIONS**

- Particular important for transverse spin structure
  →need detailed understanding of FFs to use as 'quark polarimeter'



Proton Structure

pQCD

fragmentation function

$$\frac{d^2\sigma(ep \to \pi X)}{dx\,dz} \propto q(x,k_T) \times \frac{d\sigma^2(e\,q \to e'q')}{dx} \times FF(z,p_T)$$

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	$D_1^{h/q}(z, p_T)$ = 		$H_1^{\perp h/q}(z, p_T)$ = 
longitudinal			
Transverse (here Λ)			

"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
- **Obvious relevance for the EIC**
  - Here: Results from RHIC, Belle and plans at Jlab/Belle

ENTER POLARIZATION IN THE FINAL STATES

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

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

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

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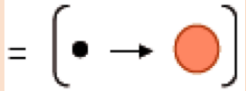
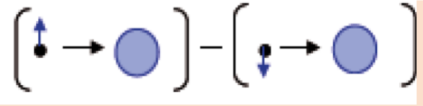
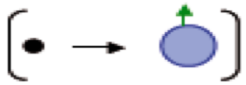
spin averaged	$D_1^{h/q}(z, p_T)$ = 		$H_1^{\perp h/q}(z, p_T)$ = 
longitudinal			
Transverse (here Λ)	$\boldsymbol{D_{1T}^{\perp \Lambda/q}(z, p_T)}$ = 		

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DI-HADRON FRAGMENTATION FUNCTIONS

Additional Observable:

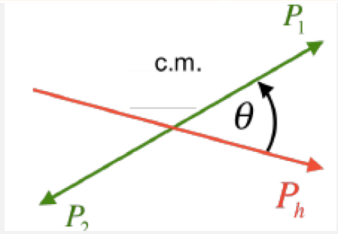
$\vec{R} = \overrightarrow{P_1} - \overrightarrow{P_2}$:

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

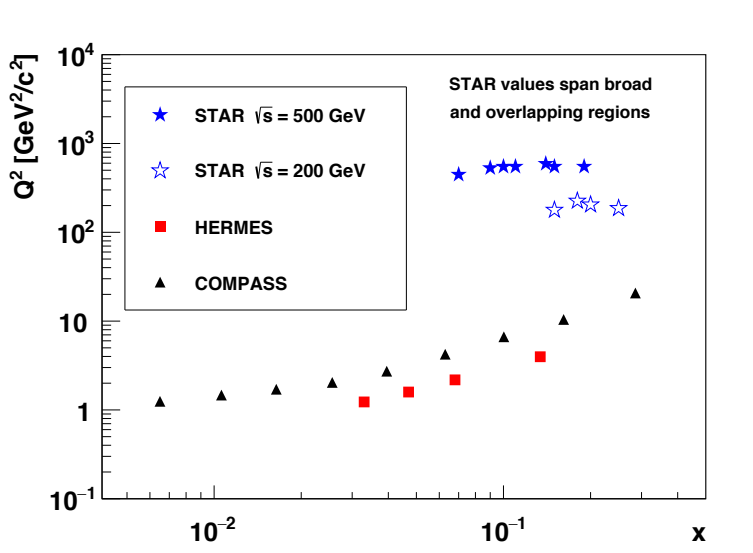
Parton polarization → / Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z,M)$ 		
longitudinal			**$G_1^{\perp}(z,M,P_h,\theta)$=**  T-odd, chiral-even →jet handedness QCD vaccum strucuture
Transverse (here Λ)	)		**$H_1^{\sphericalangle}(z,M)$=**  T-odd, chiral-odd Colinear

- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs

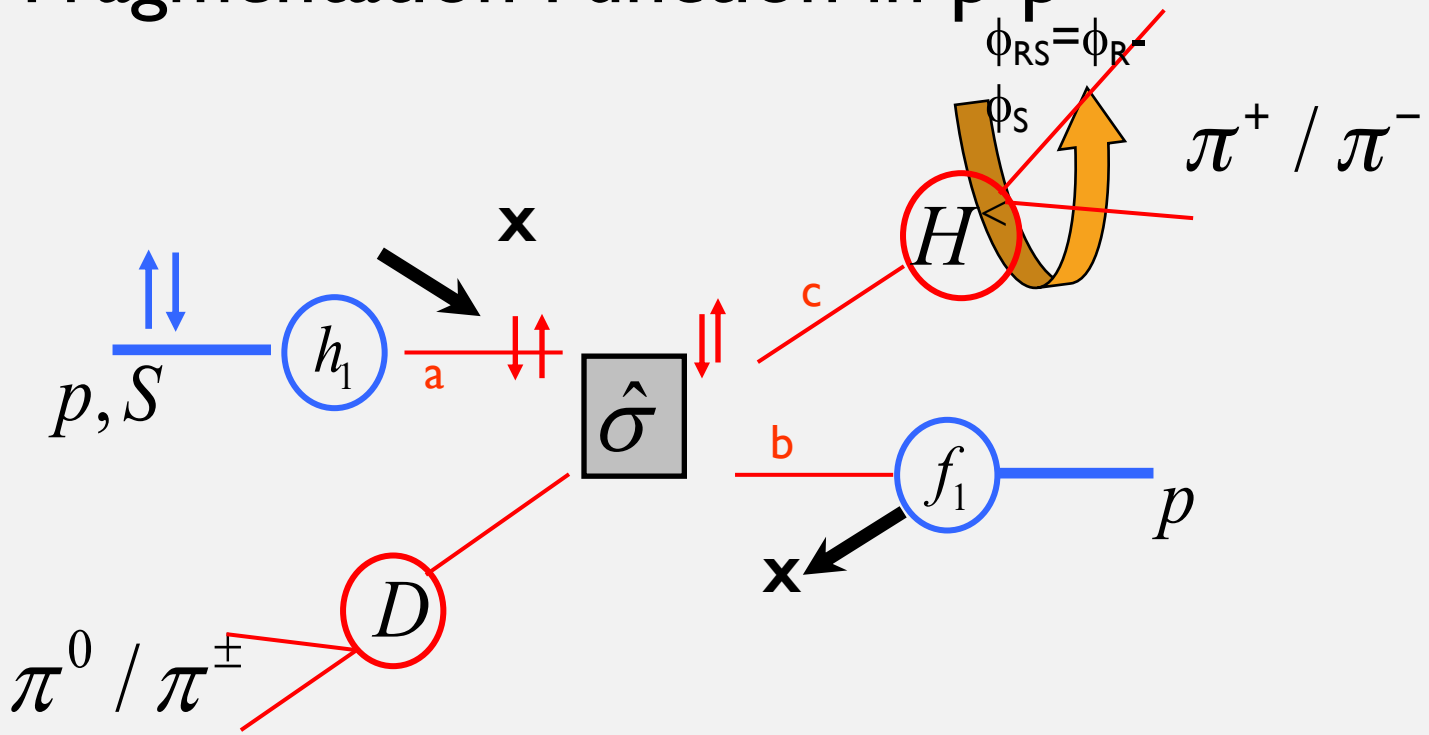


Interference Fragmentation Function in p-p

- Access to gluons
- High scale
- No jet related systematics



- Up to two orders of magnitude higher Q^2
- Valence region
- No u quark dominance
- Less x-Q^2 correlation

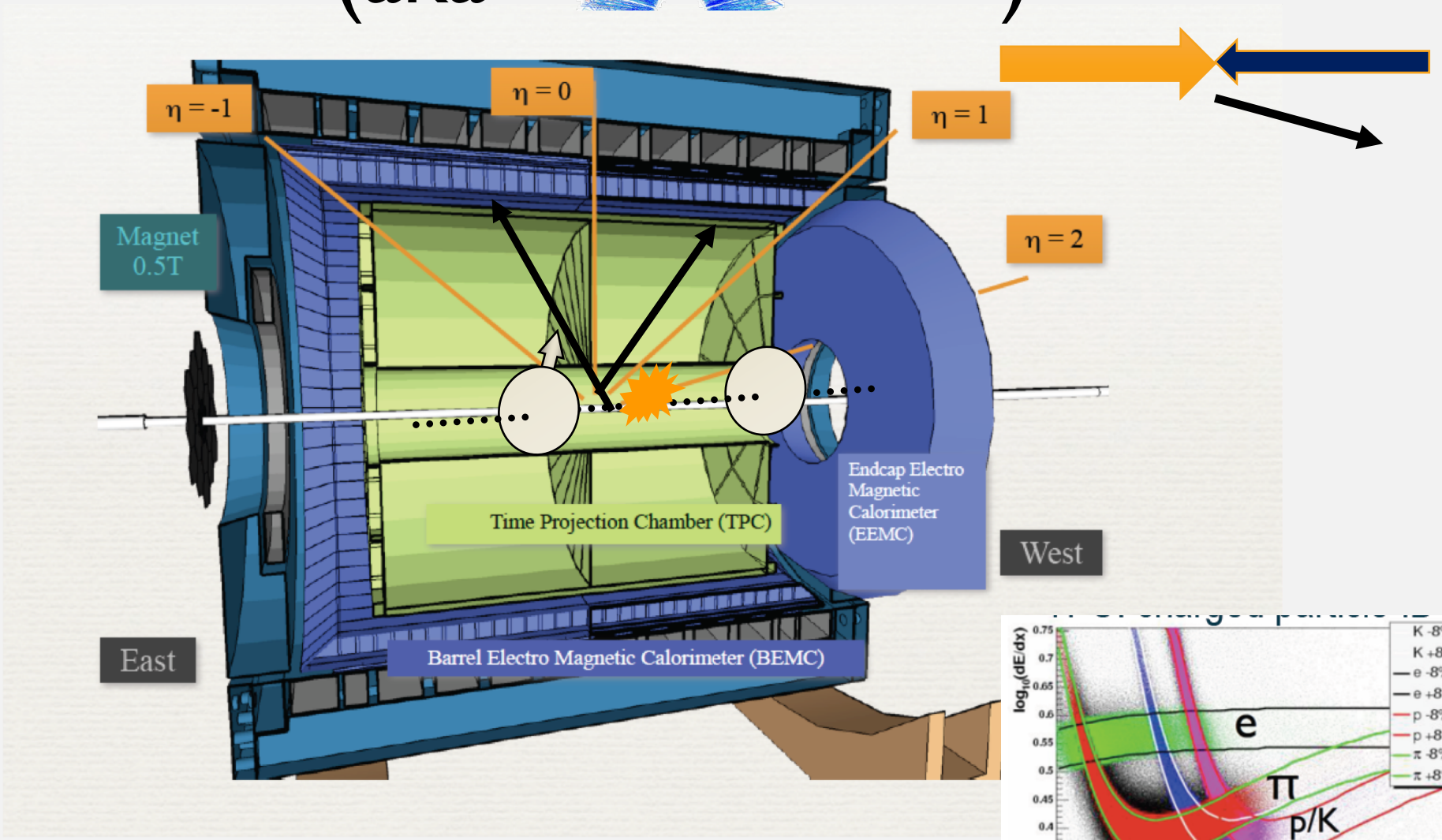


$$\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}(\Phi_{RS}) = A_{\mathrm{UT}} \sin(\Phi_{\mathrm{RS}}) \qquad A_{\mathrm{UT}} \propto h_1 \otimes H_1^\sphericalangle$$

ϕ_S: Angle between polarization vector and event plane

ϕ_R : Angle between two-hadron plane and event plane

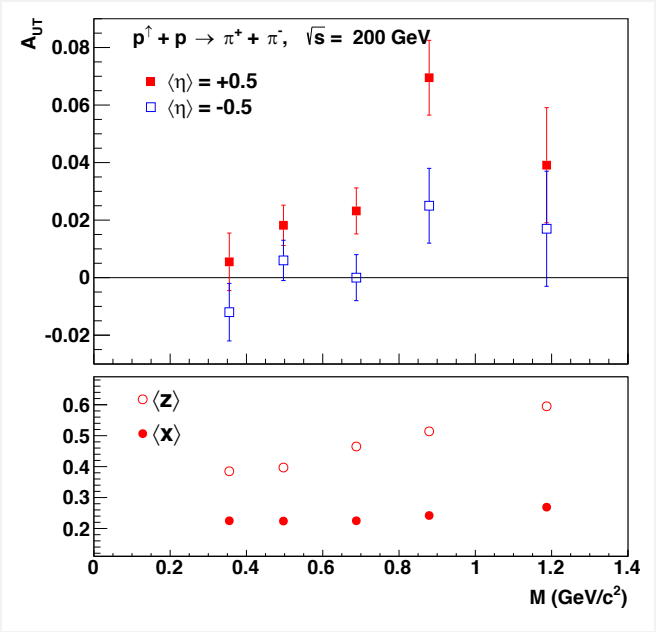
Detector for Di-Hadron Measurement (aka STAR)

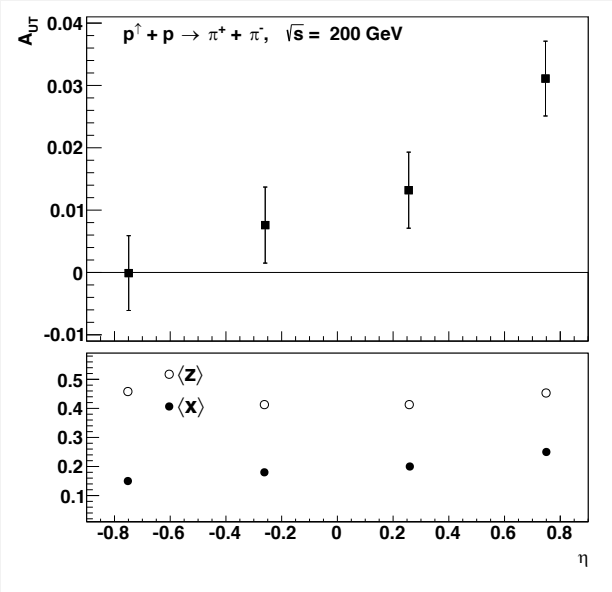


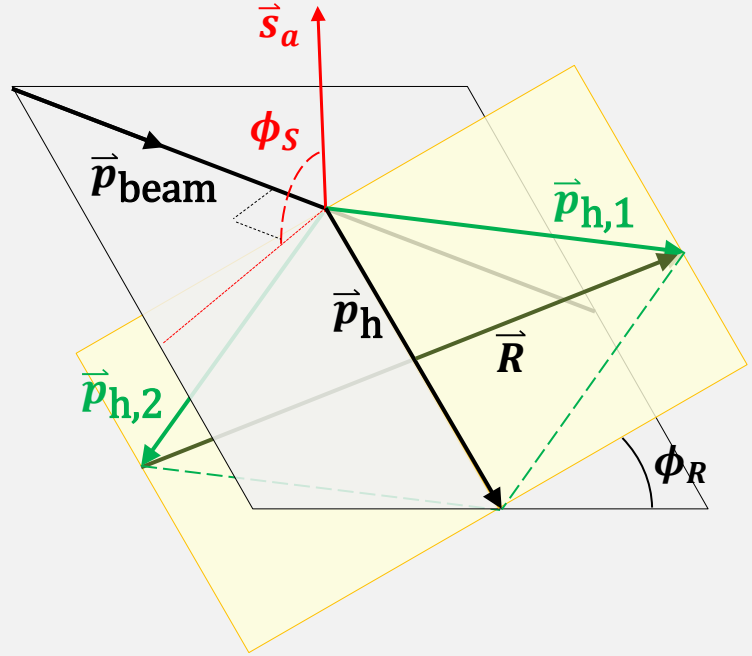
$$\eta = -log(tan\frac{\theta}{2})$$

ϕ : azimuthal angle

FIRST OBSERVATION OF DI-HADRON TSSA IN PP

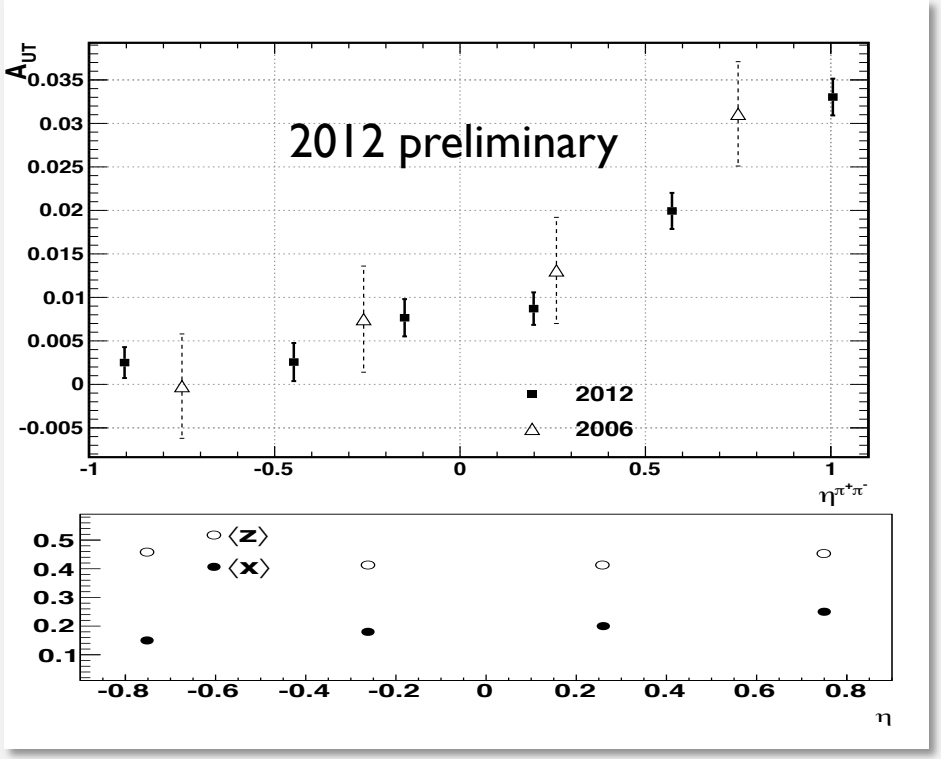






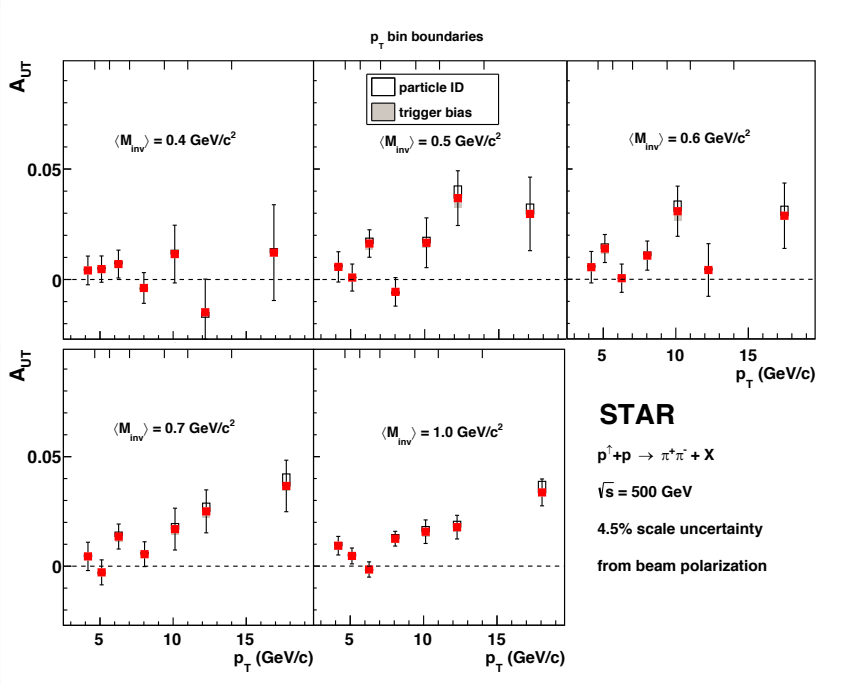
Phys.Rev.Lett. 115 (2015) 242501

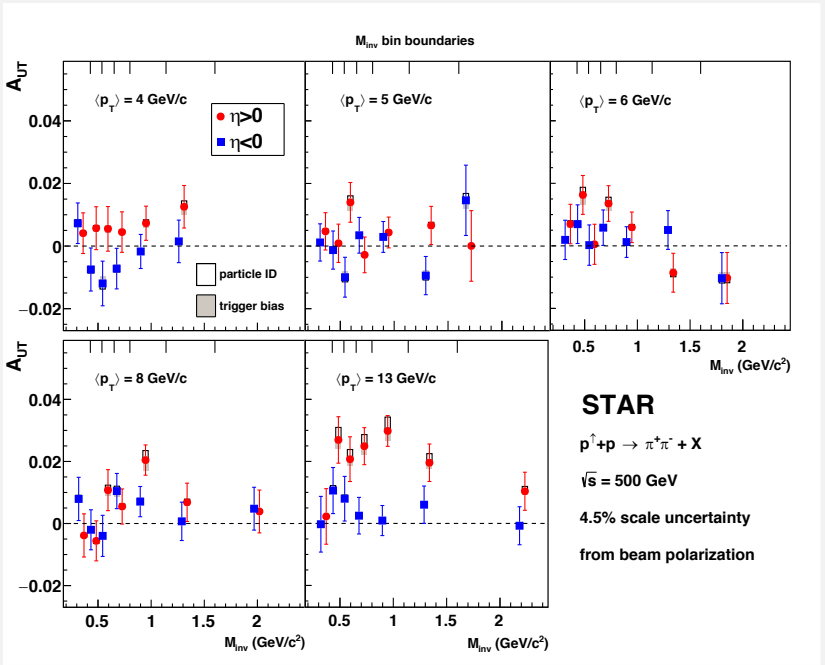
NEW DATA FROM 2012 (~10X 2006)



- High Precision data up to x~0.25
- <z>~0.45 (access via p_T dependence)
- 2x more data on tape

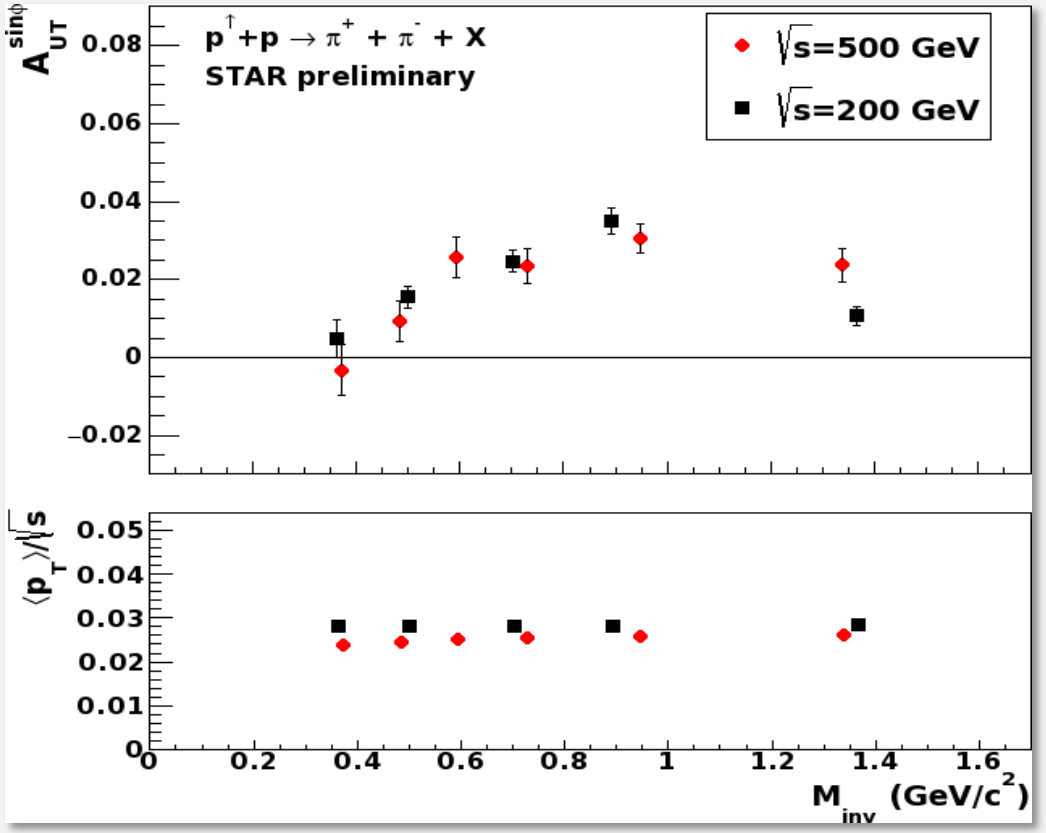
NEW: 500 GEV RESULTS





Phys.Lett. B780 (2018) 332-339

COMPARISON BETWEEN 0.2 AND 0.5 TEV FROM 2011: CONSISTENT AND NO SIGN OF EVOLUTION

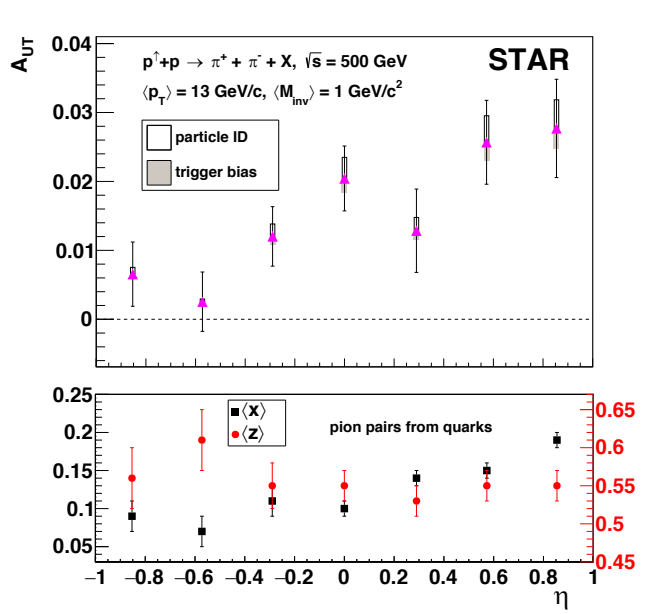


$\sim x_{Bj}$

$A_{UT} \propto h_1 \cdot H_1^{<}$

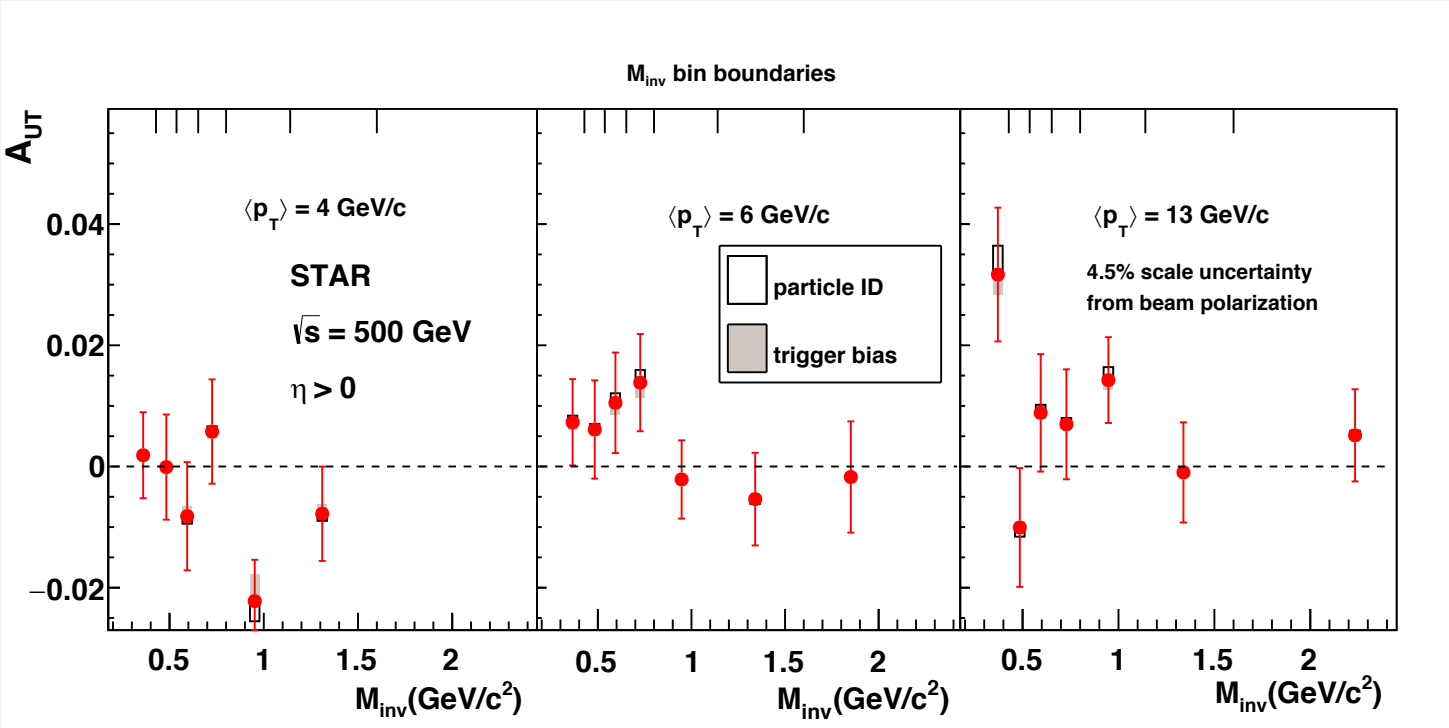
Indeed: No Evolution, Gluons do not couple to transversity!
Current run will give 15x statistics @ 500 GeV!

ETA DEPENDENCE

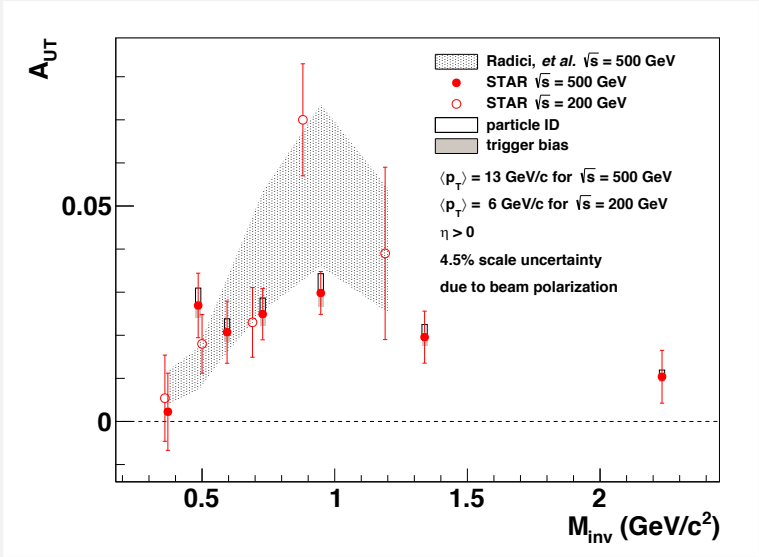


- Most sensitive to x

SAME SIDE PAIRS



IMPACT ON TRANSVERSITY EXTRACTION

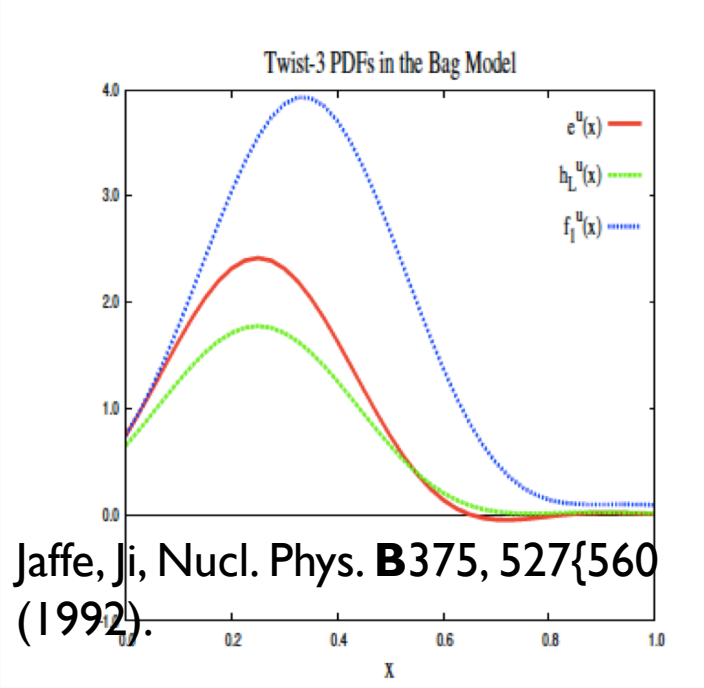


- See Marco's talk (only 200 GeV results so far)
- Impact of 500 GeV results expected to be significant

EXAMPLE, ACCESS OF e(x) in SIDIS X-SECTION

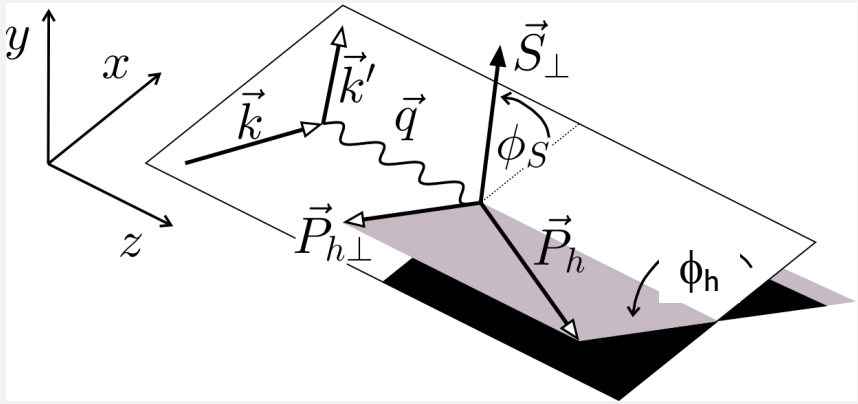
- Single hadron cross-section: mixes other contributions:

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q}\mathcal{I}\Big[-\frac{\boldsymbol{k}_T\hat{\boldsymbol{P}}_{h\perp}}{M_h}\left(xeH_1^\perp + \frac{M_h}{Mz}f_1\tilde{G}^\perp\right) + \frac{\boldsymbol{p}_T\hat{\boldsymbol{P}}_{h\perp}}{M}\left(xg^\perp D_1 + \frac{M_h}{Mz}h_1^\perp\tilde{E}\right)\Big]$$



Jaffe, Ji, Nucl. Phys. **B**375, 527{560 (1992).

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

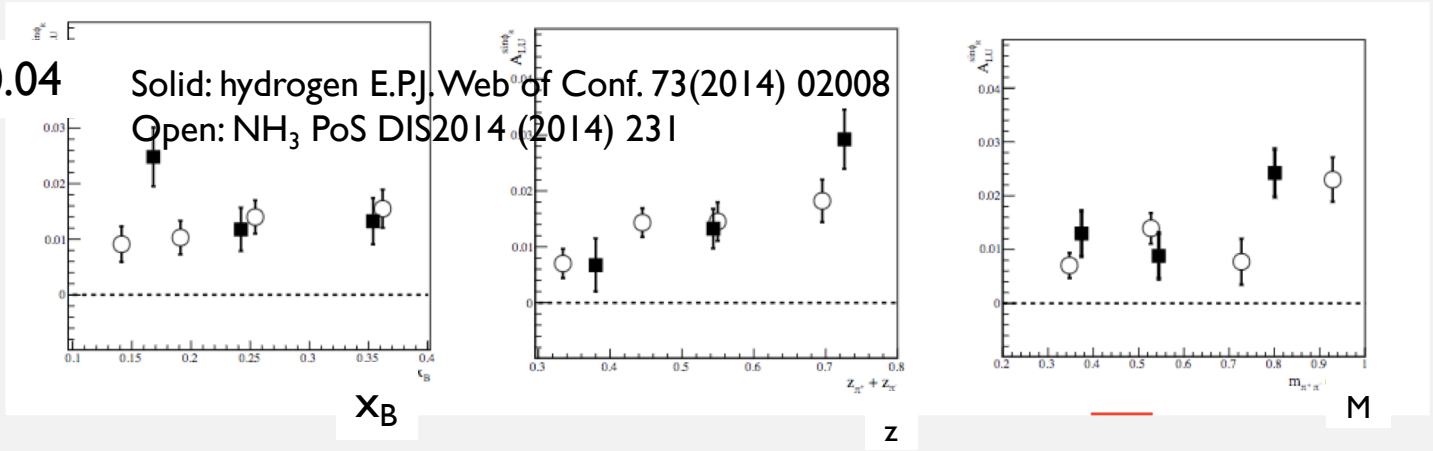


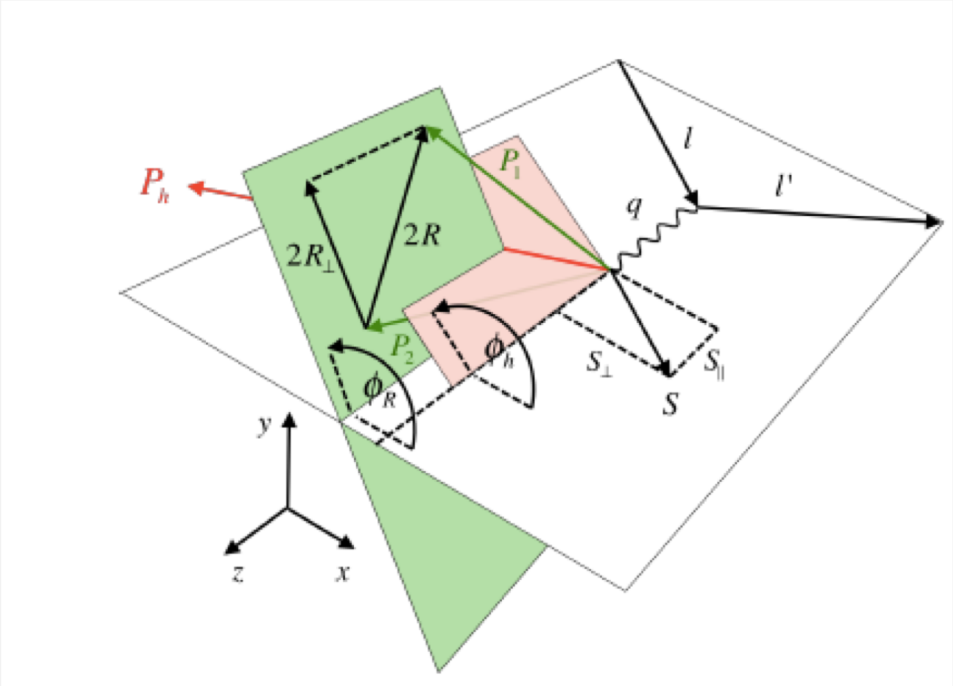
EXAMPLE, ACCESS OF e(x) in SIDIS X-SECTION

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

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

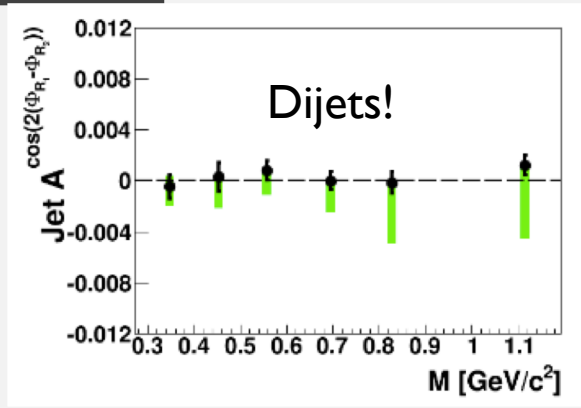
- See e.g. Aurore Courtoy, arXiv:1405.7659
- Evidence from CLAS6:



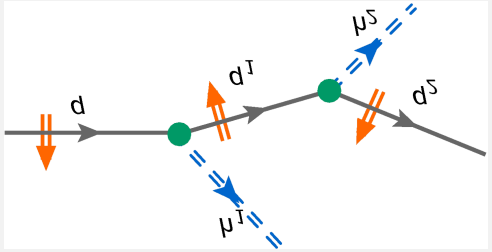


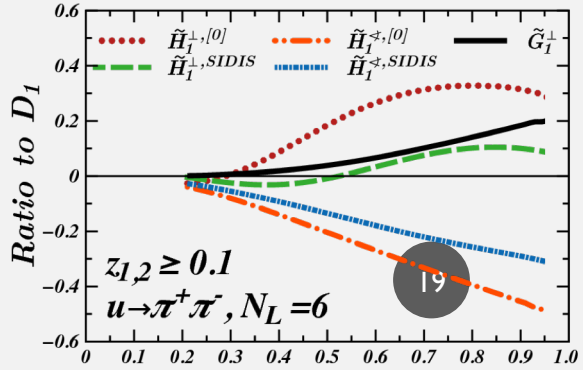
HISTORY OF WORMGEAR FF $G_1^\perp$

- 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. **B**366 (1996) 311-315 (connection to chromomagnetic effects)
- Measurement by Belle→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)→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 → Need weighted asymmetry including dependence on P_{hT}
- Accessible in SIDIS via weighted asymmetries



arXiv:1505.08020 [

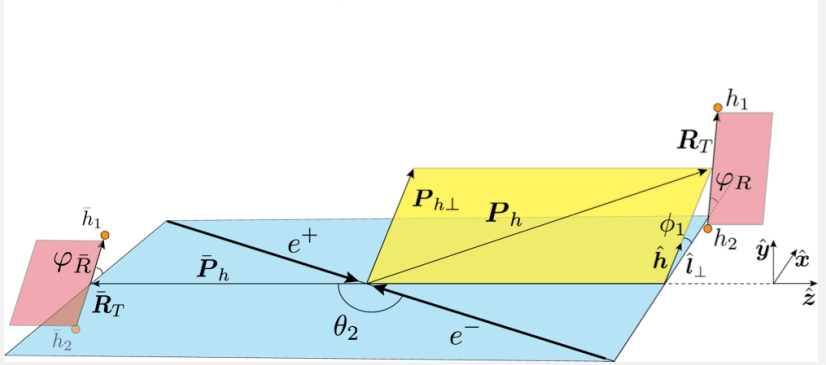




$G_1^{\perp}$ MEASUREMENT IN SIDIS AND e^+e^-

- New Observable in e^+e^-:

$$\left\langle \frac{q_T^2\left(3\sin(\varphi_q-\varphi_R)\sin(\varphi_q-\varphi_{\bar{R}})+\cos(\varphi_q-\varphi_R)\cos(\varphi_q-\varphi_{\bar{R}})\right)}{M_h\bar{M}_h}\right\rangle$$
$$=\frac{12\alpha^2A(y)}{\pi Q^2}\sum_{a,\bar{a}}e_a^2\left(G_1^{\perp a,[0]}-G_1^{\perp a,[2]}\right)\left(\bar{G}_1^{\perp\bar{a},[0]}-G_1^{\perp\bar{a},[2]}\right),$$



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

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

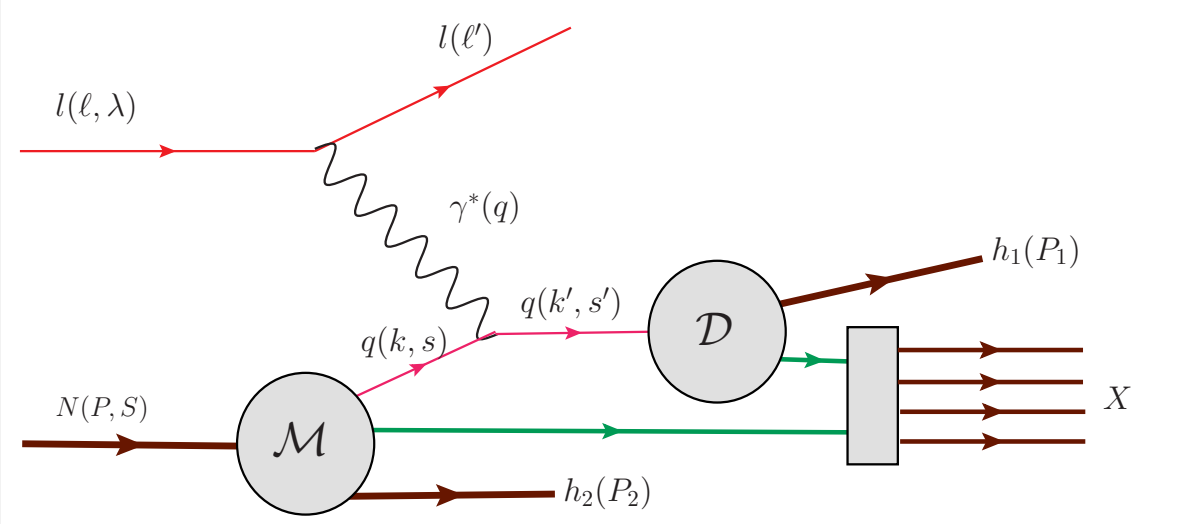
$$\left\langle \frac{P_{h\perp}\sin(\varphi_h-\varphi_R)}{M_h}\right\rangle_{UL}\sim S_L\sum_a e_a^2\; g_{1L}^a(x)\; z\; G_1^{\perp a}(z,M_h^2)$$

Matevosyan, Kotzinian ADP-17-42-T1048

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

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

DI-HADRON CORRELATIONS BETWEEN TARGET AND CURRENT FRAGMENTATION REGION



See e.g. Anselmino, Barone, Kotzinian
Phys.Lett. B706 (2011) 46-52

- Access chiral-odd Fracture functions

CLAS12

Forward Detector (FD)

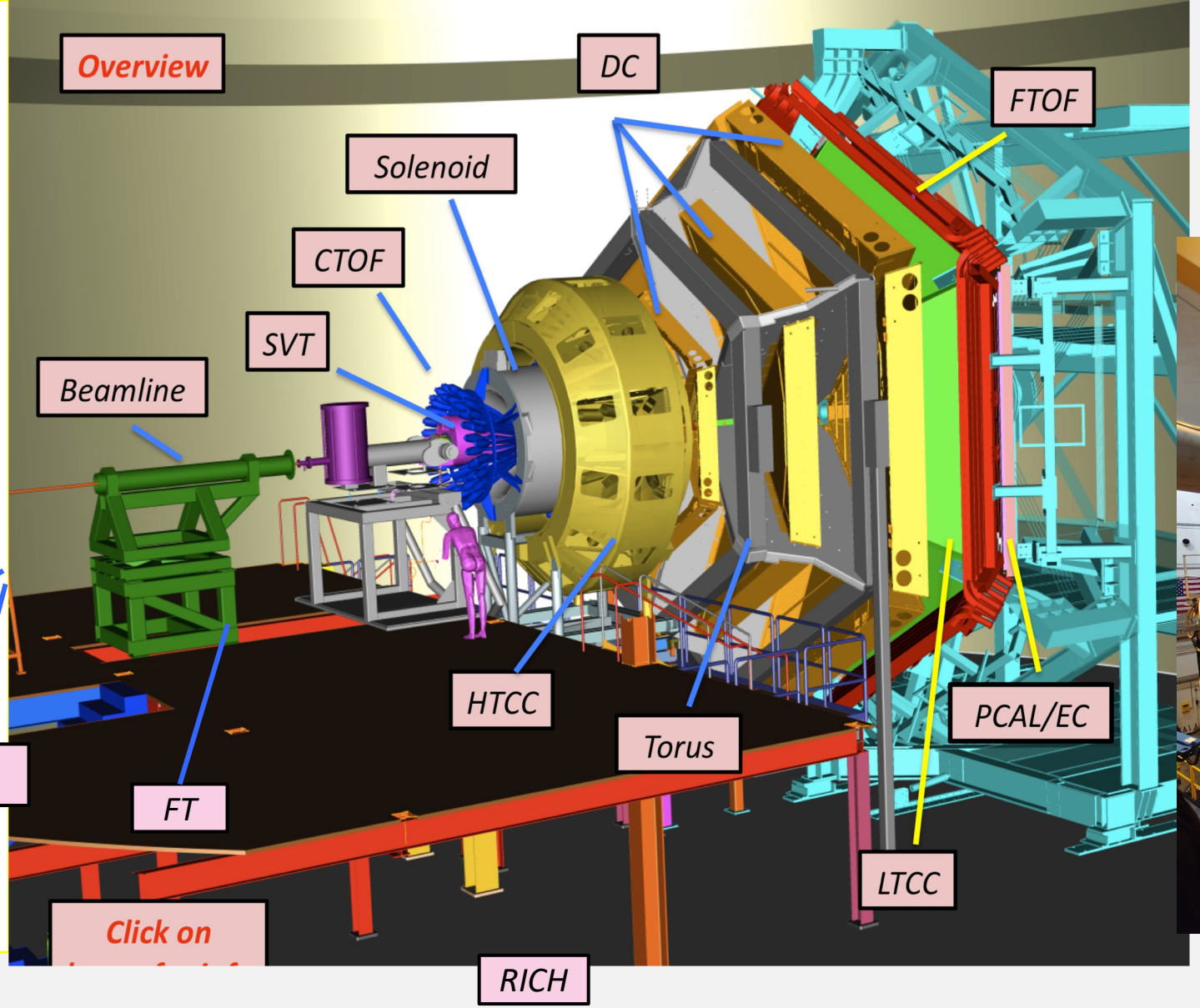
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter
- Forward Tagger
- RICH detector

Central Detector (CD)

- Solenoid magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Detector
- MicroMegas

Beamline

- Photon Tagger Dump
- Shielding
- Targets
- Moller Polarimeter
- Faraday Cup

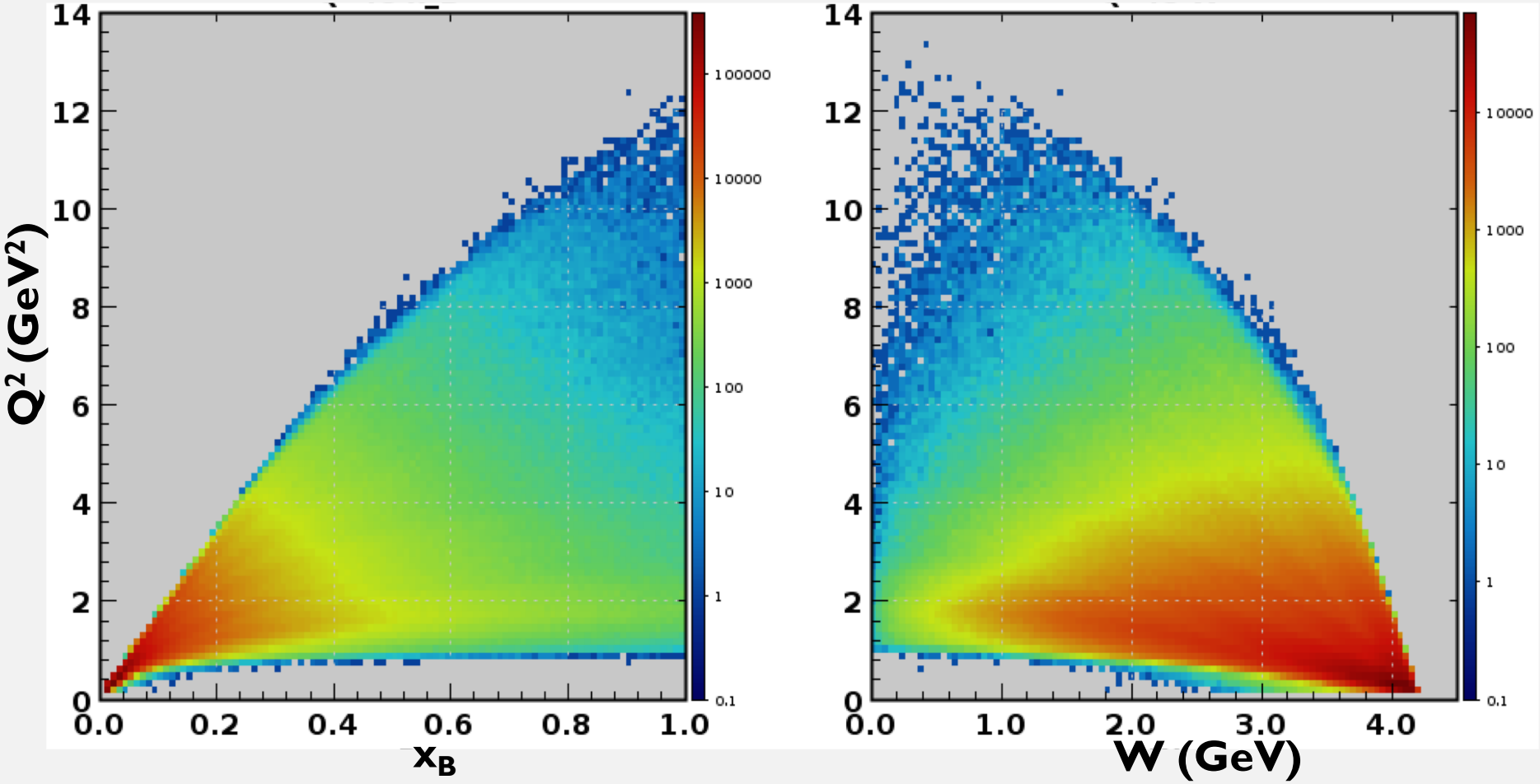


KINEMATIC COVERAGE

SIDIS cuts

Q2 > 1 GeV2 **W > 2 GeV** **Outbending torus field**

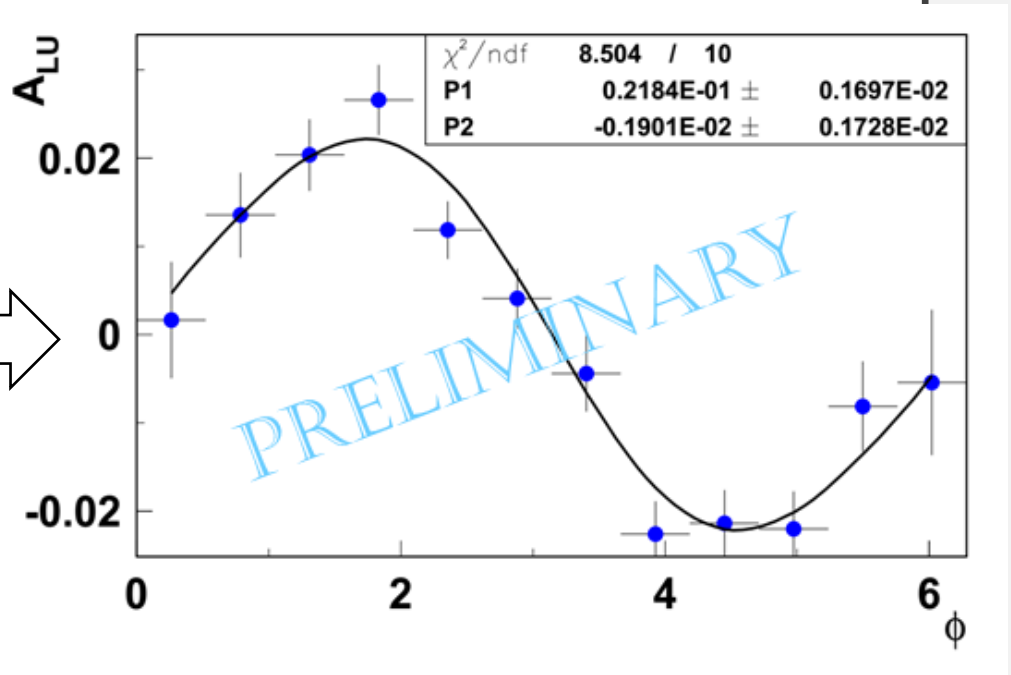
See M. Mirazita
At SPIN2018

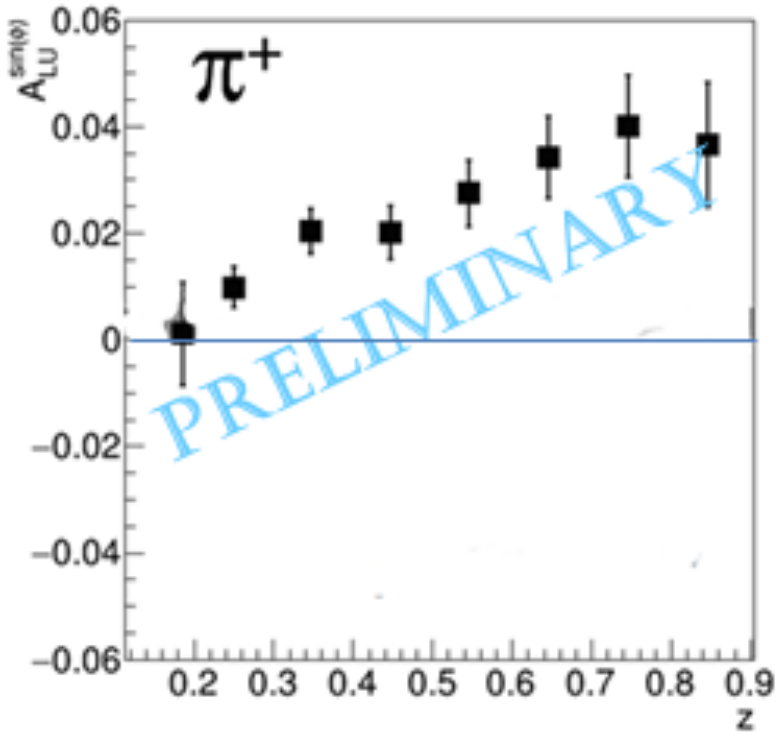


PI+ BEAM SPIN ASYMMETRY

One day of data taking
Q^2>1 GeV^2 W>2 GeV

Fully integrated kinematics



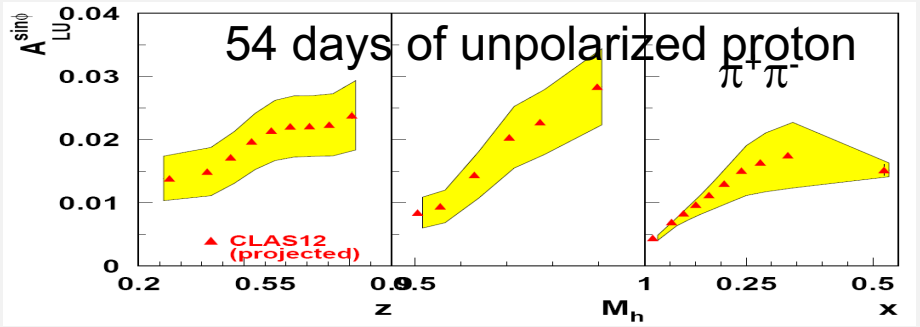


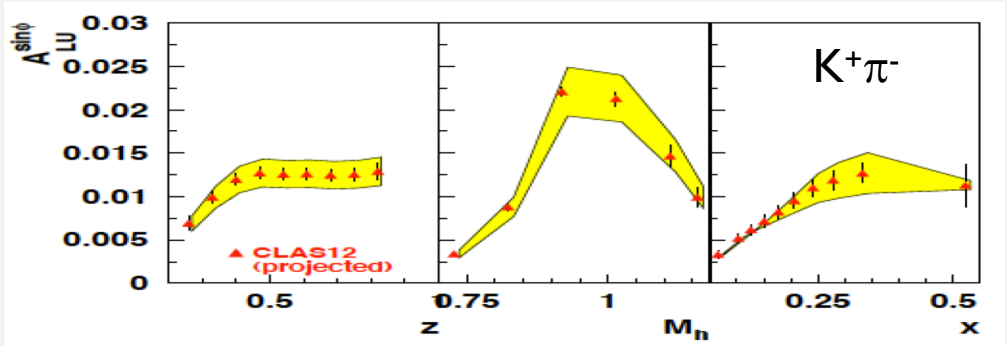
z-dependence
- **positive asymmetry**
- **rising with z**

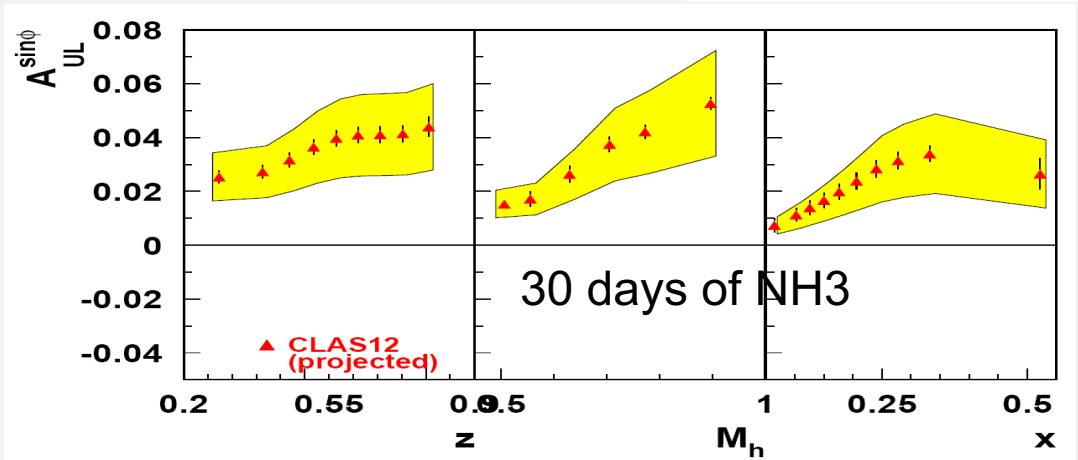
See M. Mirazita
At SPIN2018

PROJECTIONS FOR ASYMMETRIES SENSITIVE TO e(x)

- 120/30 days of running are approved with unpolarized liquid H2/liquid D2 targets **(underway!)**
- 120 + 50 days of running are approved with longitudinally polarized NH3/ND3 targets (targets ready ~2020)







Sensitive to h_L

KEKB →SUPERKEKB: DELIVER INSTANTANEOUS LUMINOSITY X 40

Belle II

e^+ 4GeV 3.6 A

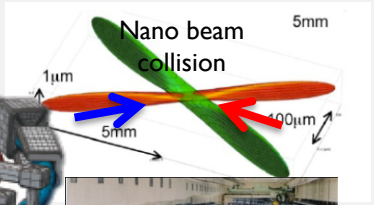
e^- 7GeV 2.6 A

(~2x KEKB)

SuperKEKB
Target: $L = 8 \times 10^{35}/cm^2/s$

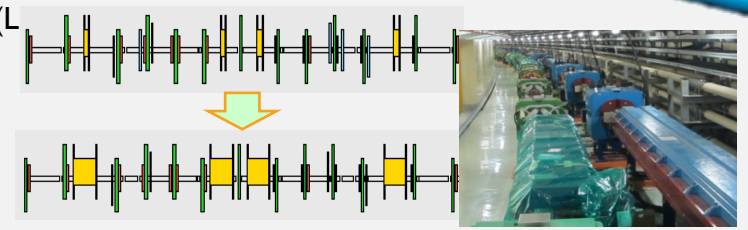
New superconducting final focusing quads (QCS) near the IP

New IR



Reinforce RF systems for higher beam current

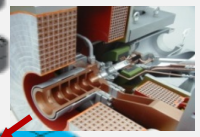
Replace short dipoles with longer ones
(L



Redesign the lattices of HER & LER to squeeze the emittance

Damping ring (new)

@1.1 GeV
To inject low emittance positrons



Positron source
New positron target / capture section

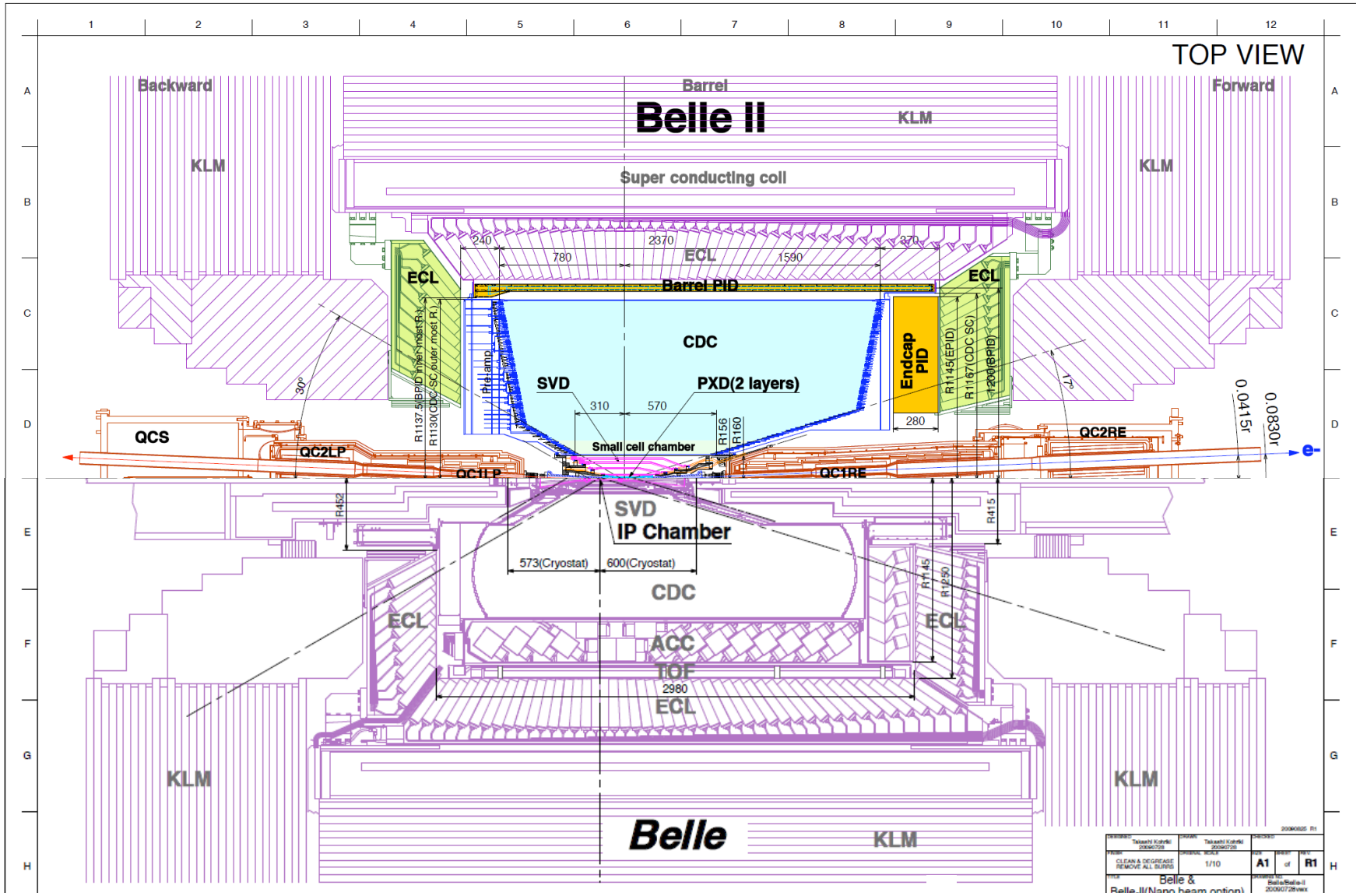
TiN-coated beam pipe with antechambers
Cu for wigglers and Al alloy for the rest

Low emittance gun

To inject low emittance electrons

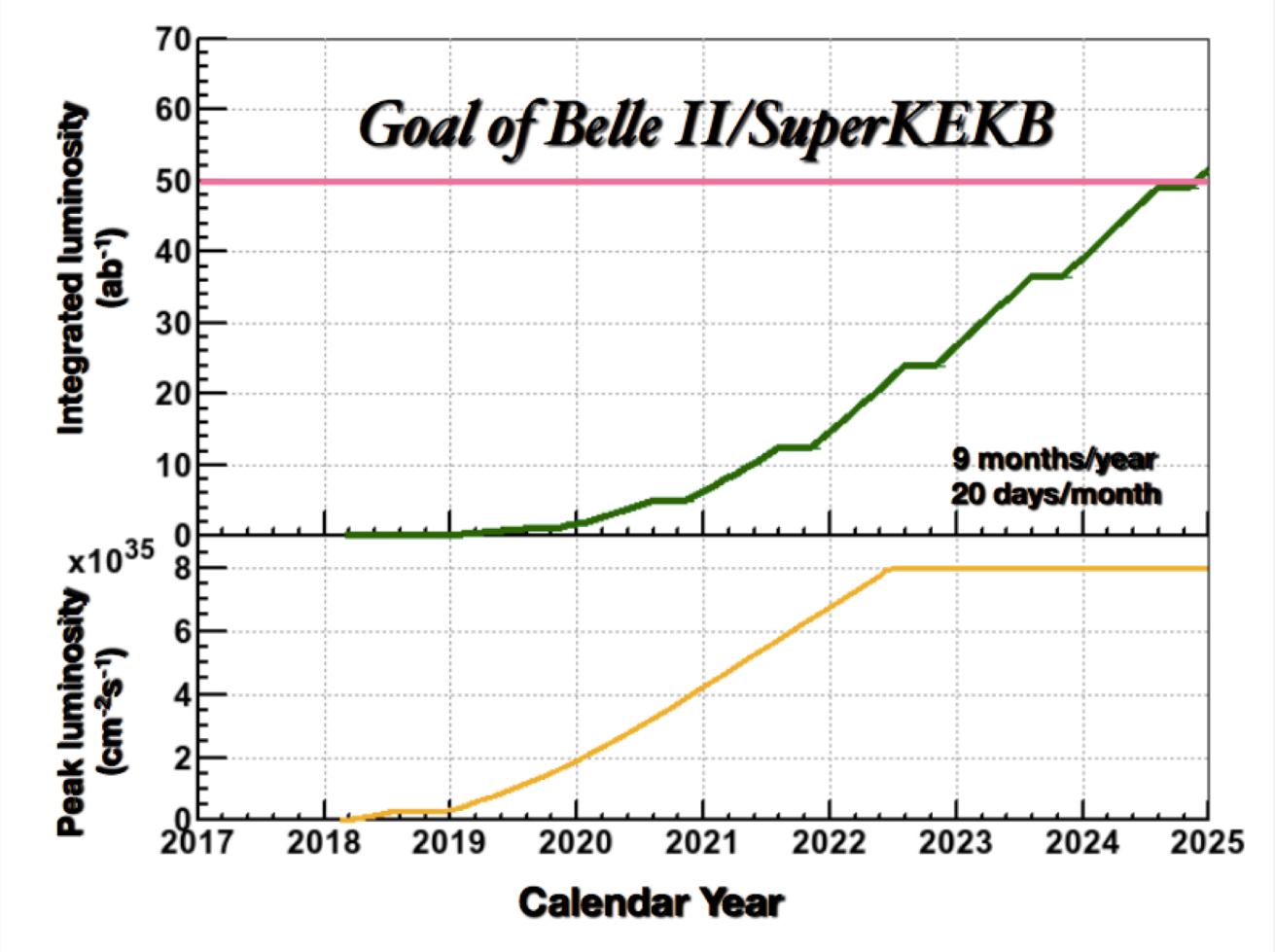
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$

BELLE II DETECTOR (COMP. TO BELLE)

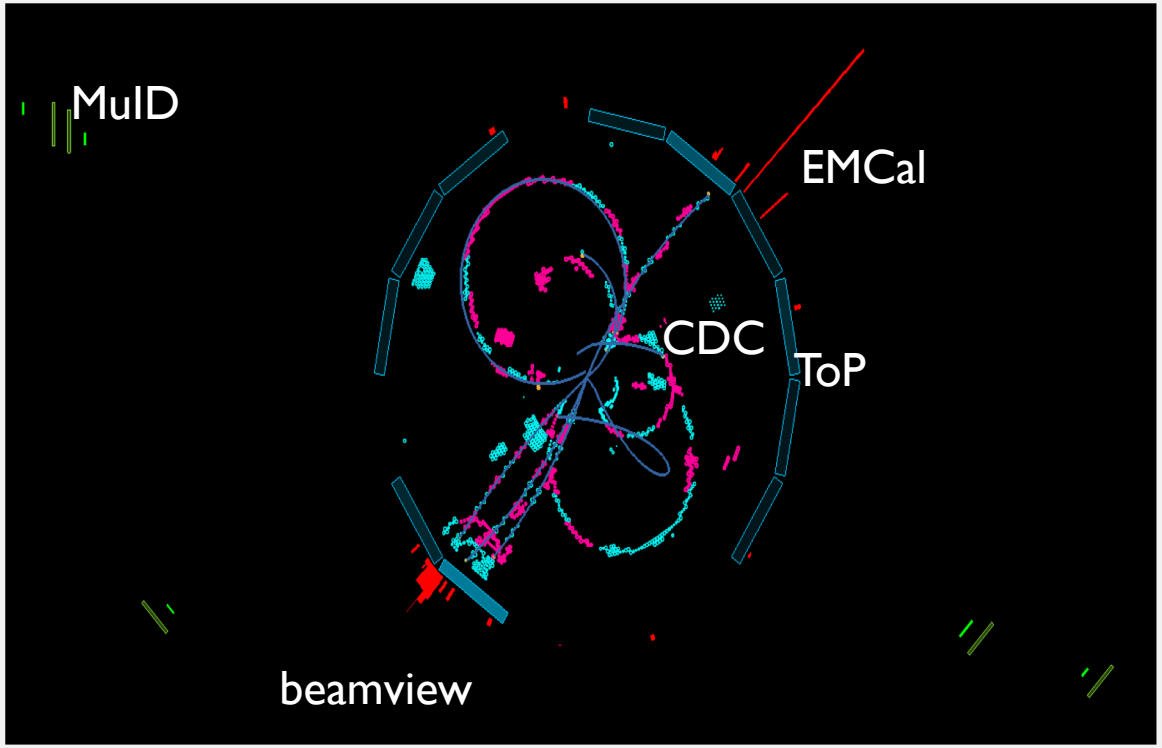


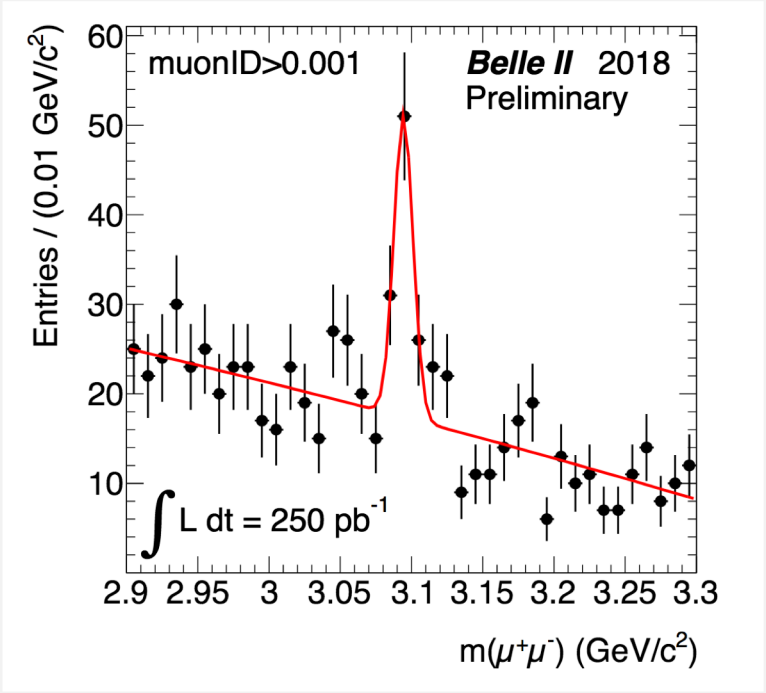
CURRENT STATUS AND SCHEDULE

- Phase 1 (complete)
  - Accelerator commissioning
- Phase 2
  - First collisions (20±20 fb^{-1})
    - (achieved 10^{33} $cm^{-2}s^{-1}$ May 23rd)
  - Partial detector
  - Background study
  - Physics possible
- Phase 3 ("Run 1", early 2019)
  - Nominal Belle II start
- **Ultimate goal: 50 ab^{-1}**



26 APRIL 2018 00:38 GMT+09:00: FIRST COLLISIONS



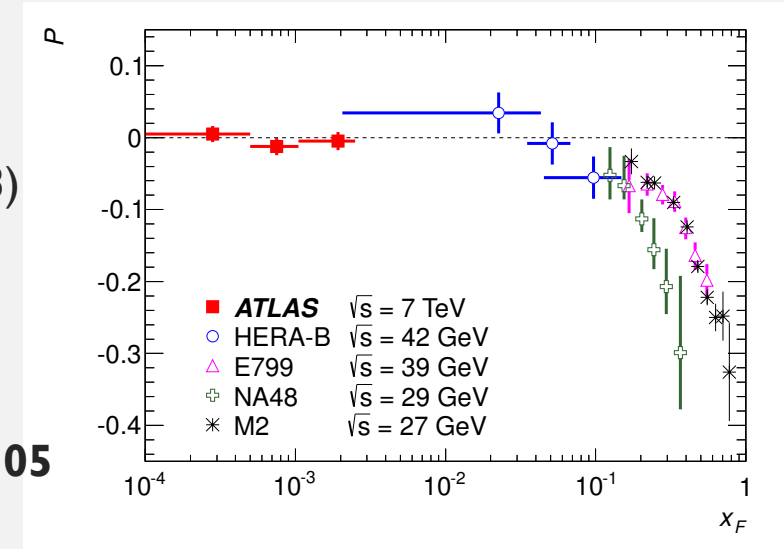


OUTLOOK DI-HADRON CHANNELS AT **RHIC**, **BELLE II** AND THE **EIC**

- 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
- …

LAMBDA PRODUCTION

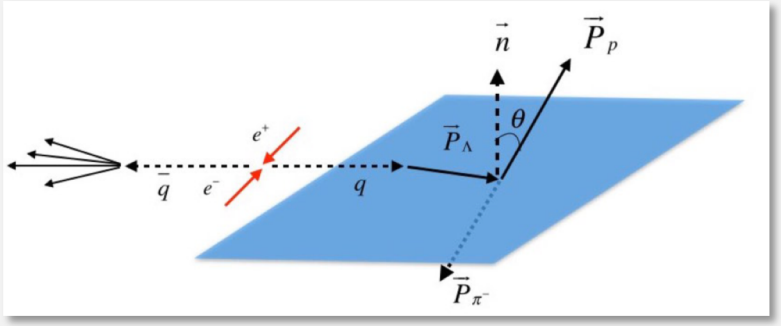
- Inclusion of polarization leads to rich hadronization structure (see e.g. Kanazawa, Metz Pitonyak, Schlegel Phys.Lett. **B**744 (2015) 385-390 , Metz, Pitonyak Phys.Lett. **B**723 (2013) 365-370
- Longstanding question: Large Λ transverse polarization in unpolarized pp collision
- →Polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- T-odd TMD but chiral-even, **Universality?** Boer, Kang, Vogelsang, Yuan **Phys.Rev.Lett. 105 (2010) 202001**
  - Needs e+e- + SIDIS measurments
- NB: previous SIDIS lambda photoproduction or very large statistical uncertainties
-

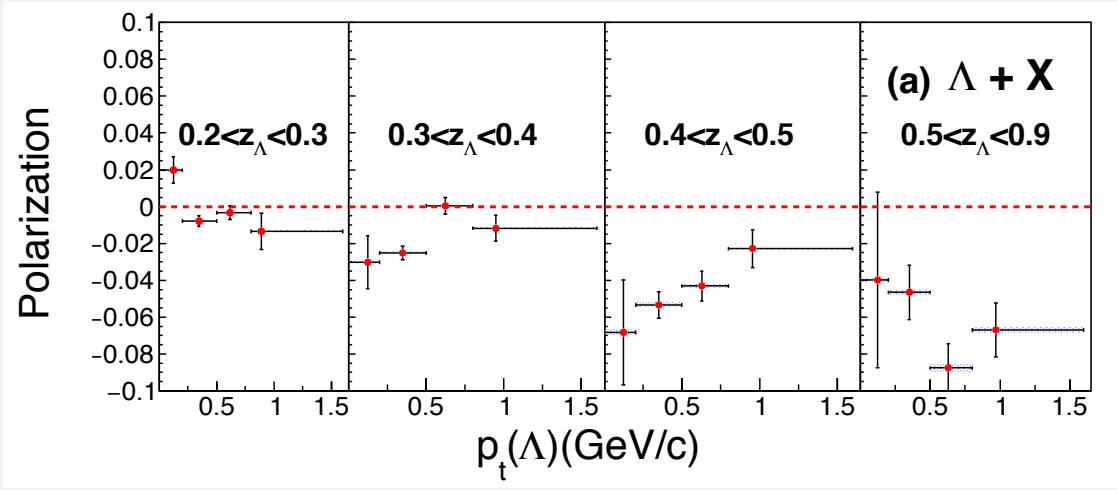


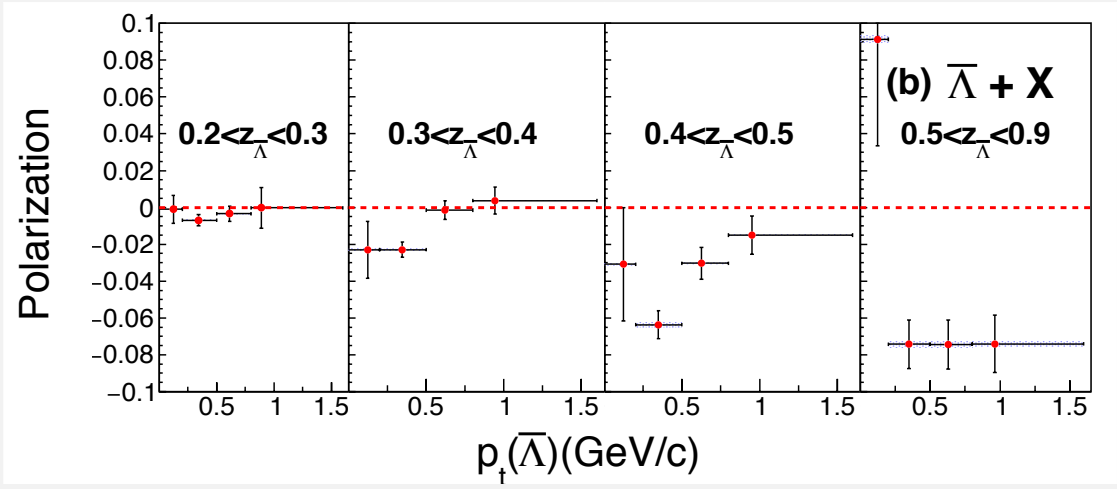
Phys.Rev. D91 (2015) no.3, 032004

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

FIRST OBSERVATION BY BELLE

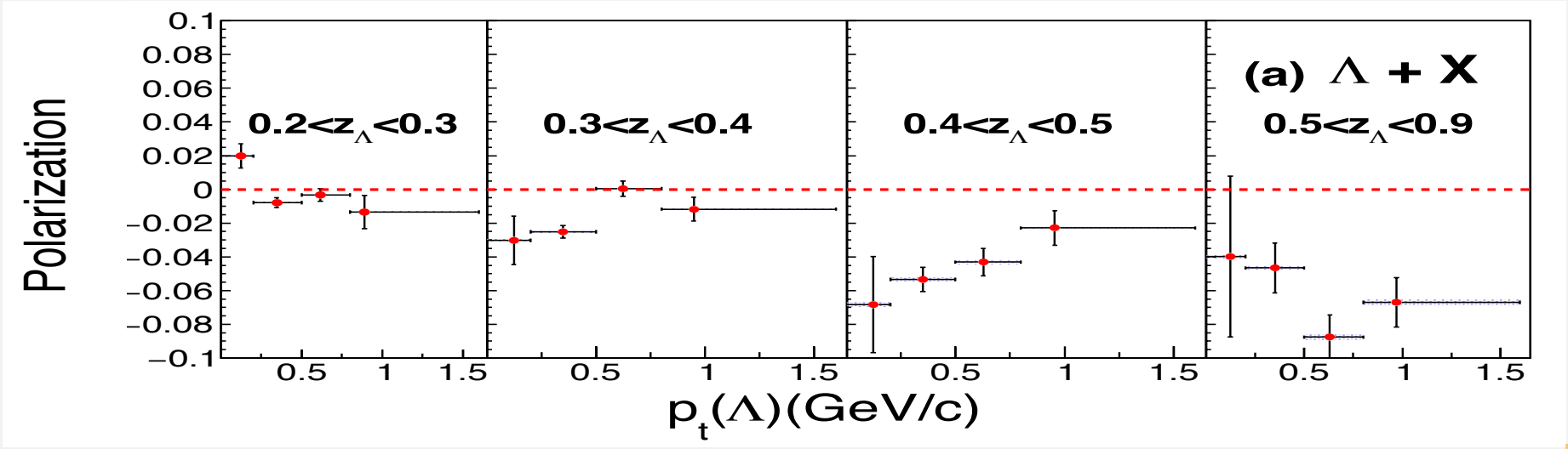


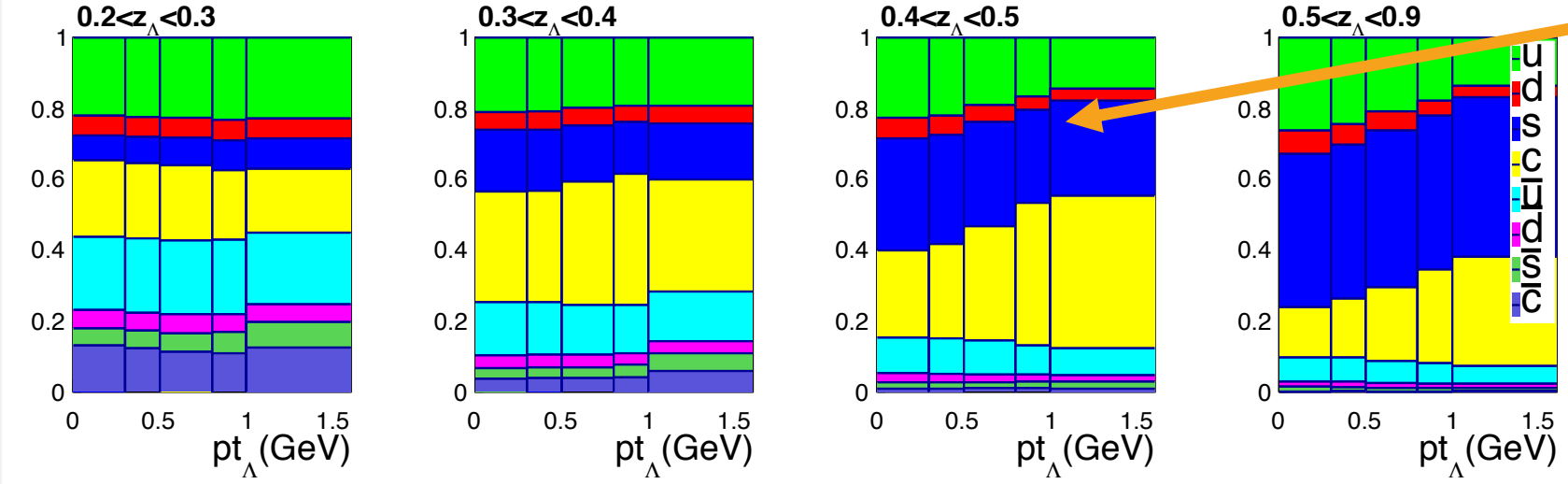




arXiv:1808.05000, **submitted to PRL**

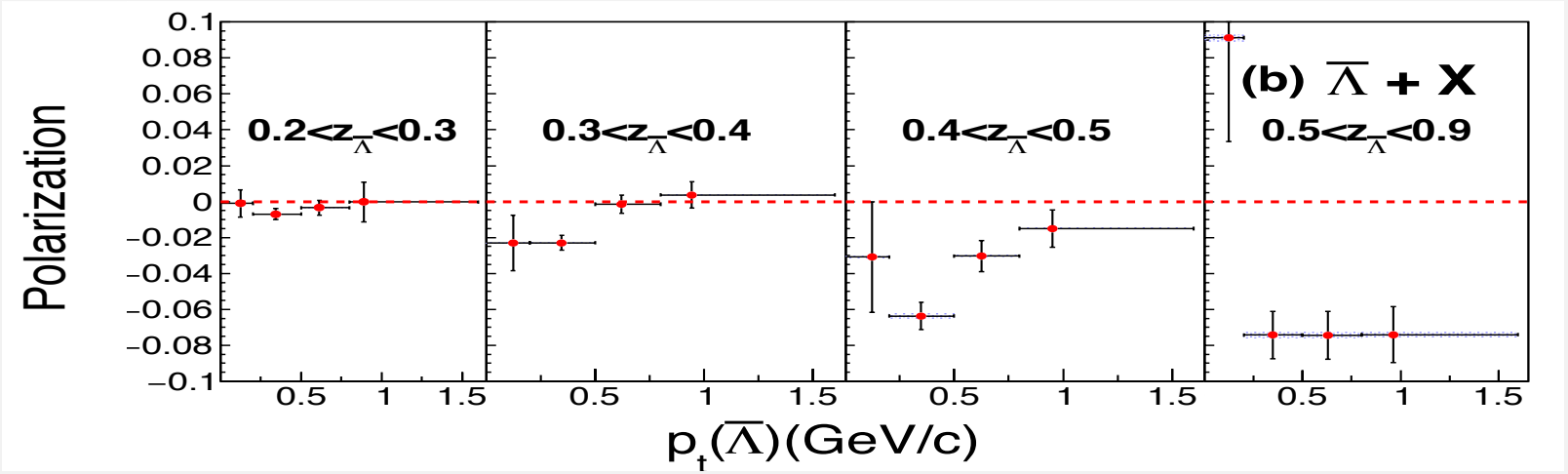
ASYMMETRIES EXPLAINED BY FLAVOR DECOMPOSITION?

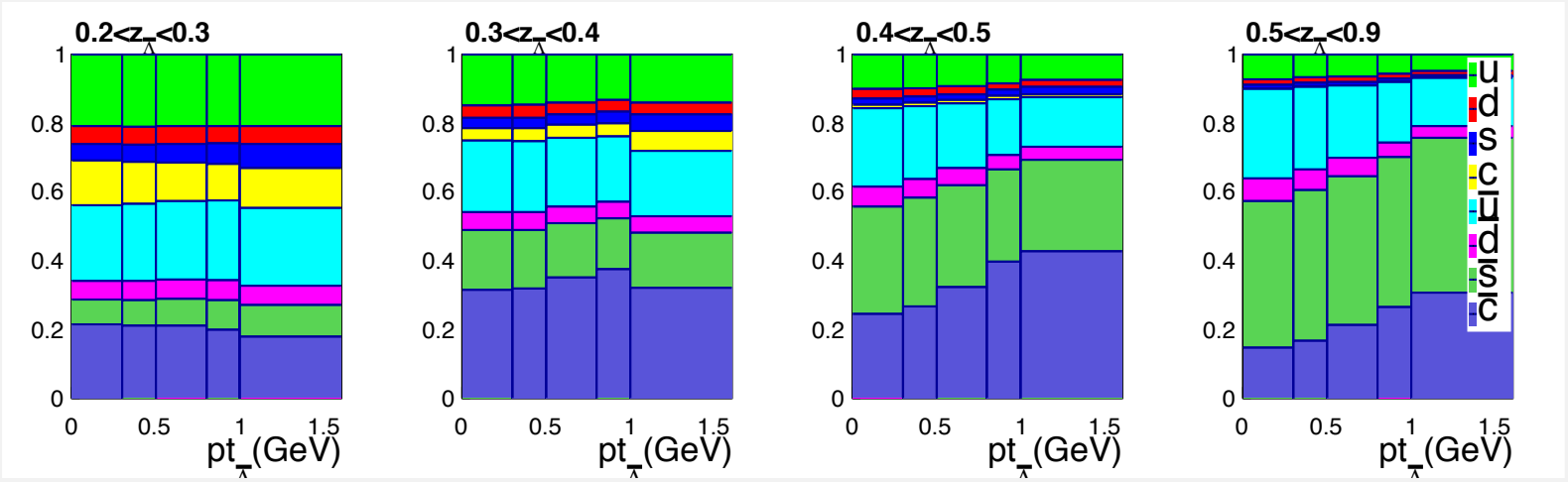




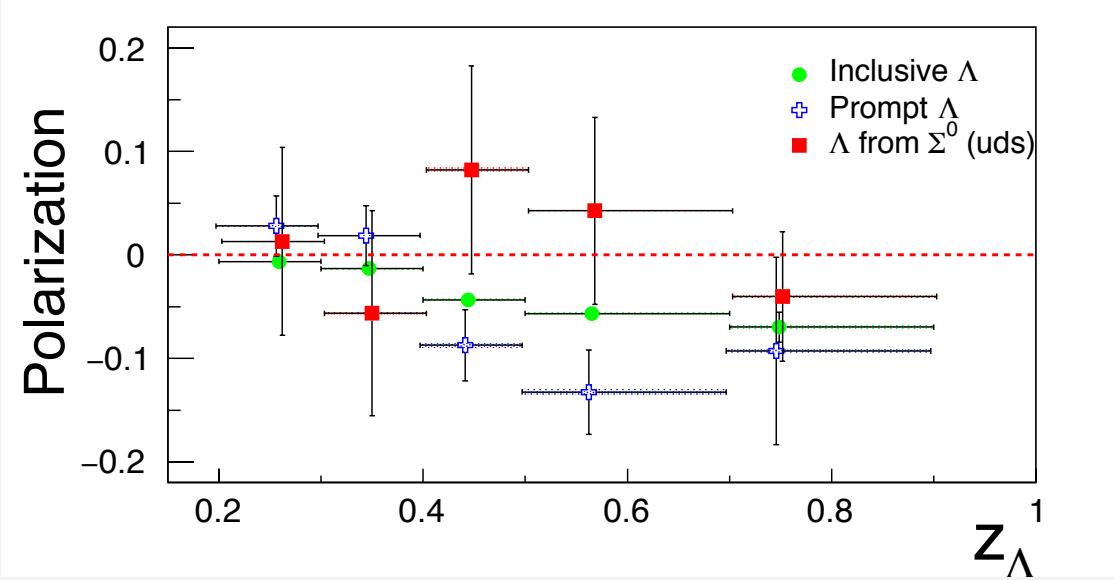
u-quark carry polarization? Or shape explainable with drop in strange? (but rise in p_T should Compenate?)

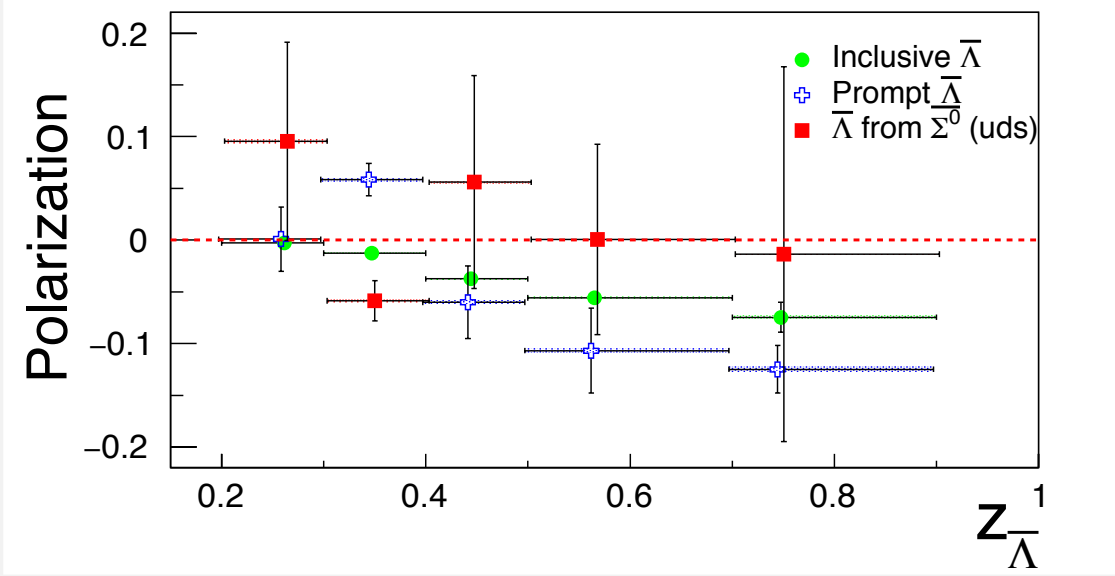
ANTI-Λ ANALOGUE



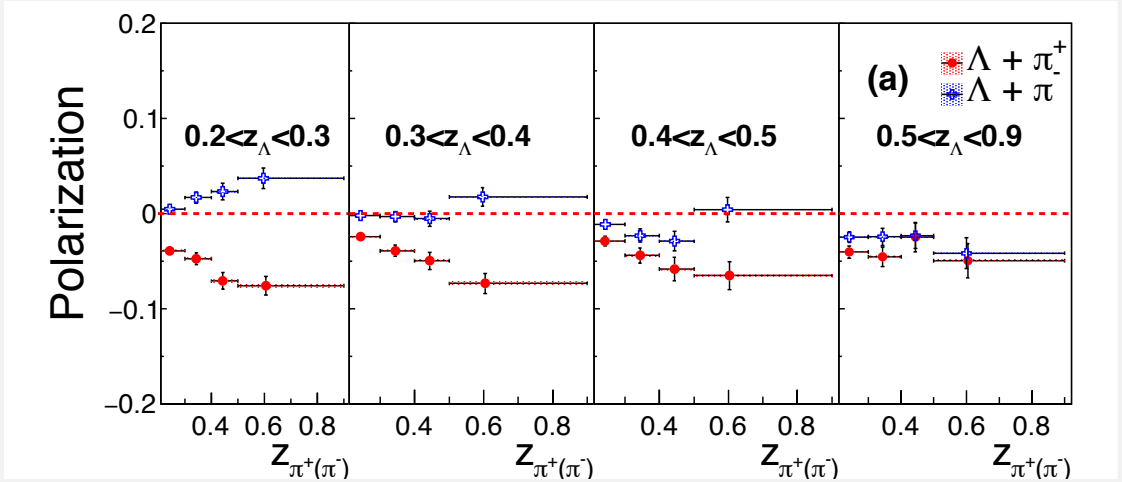


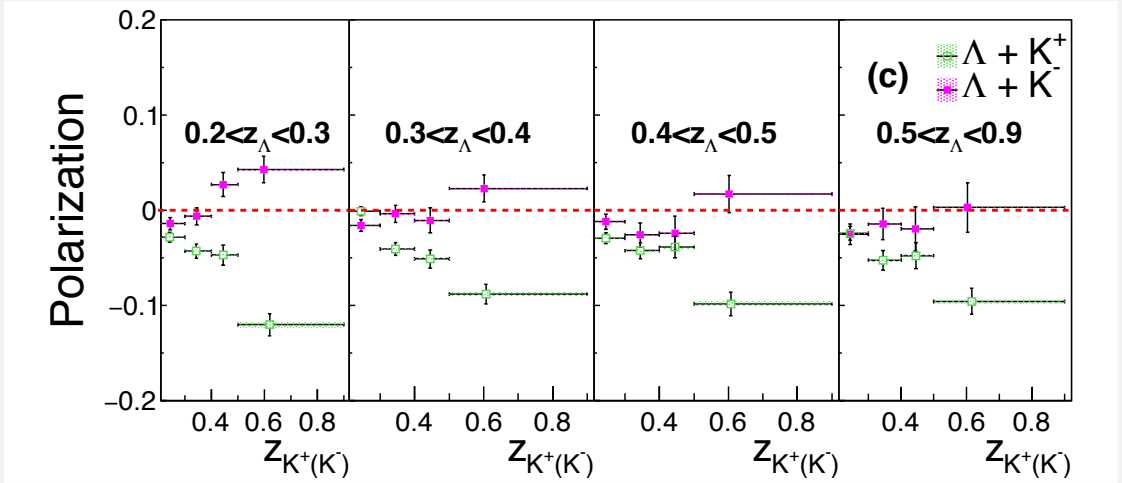
A FIRST: CORRECTION FOR FEED-DOWN AND CHARM CONTRIBUTION

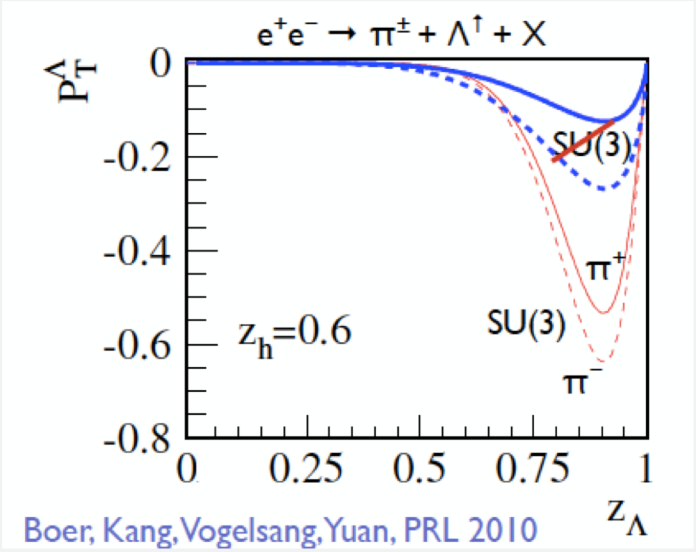




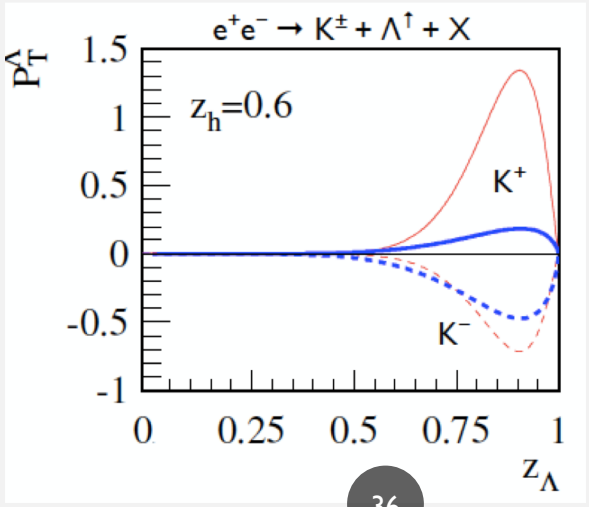
TENSION WITH THEORY: ASSOCIATED PRODUCTION

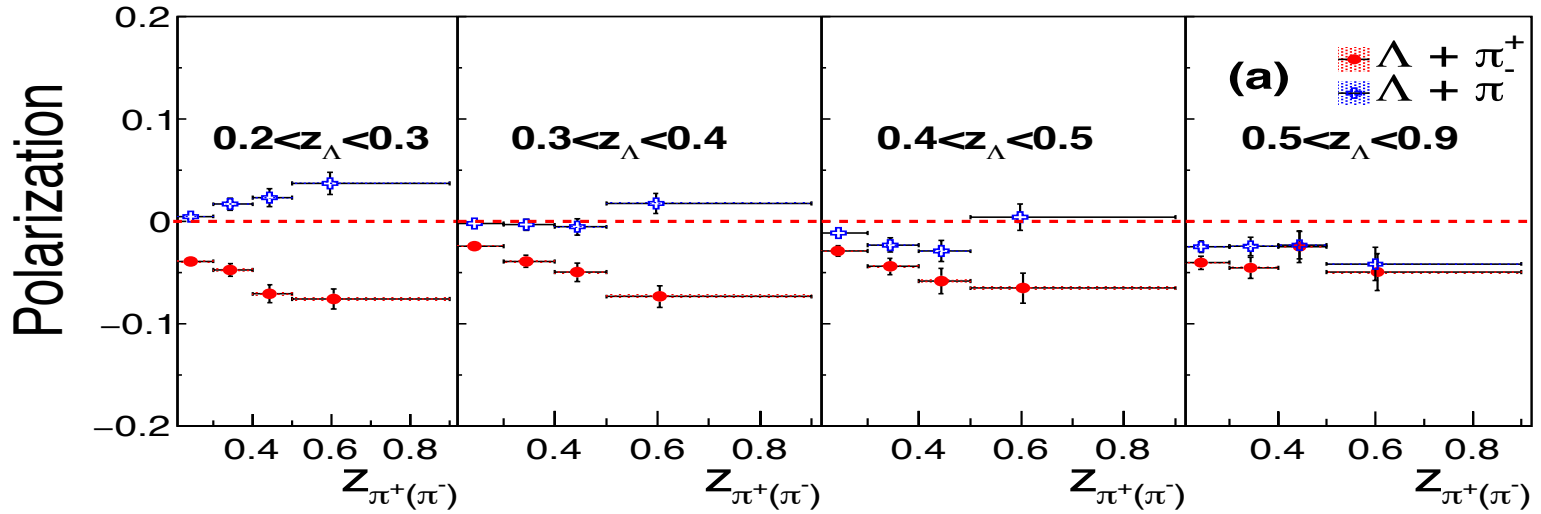


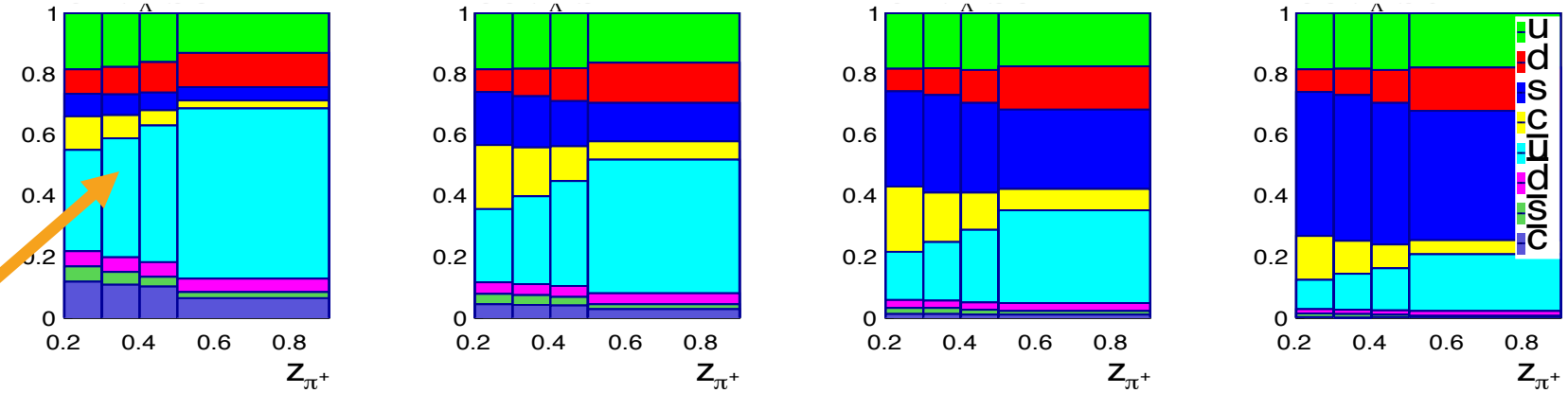


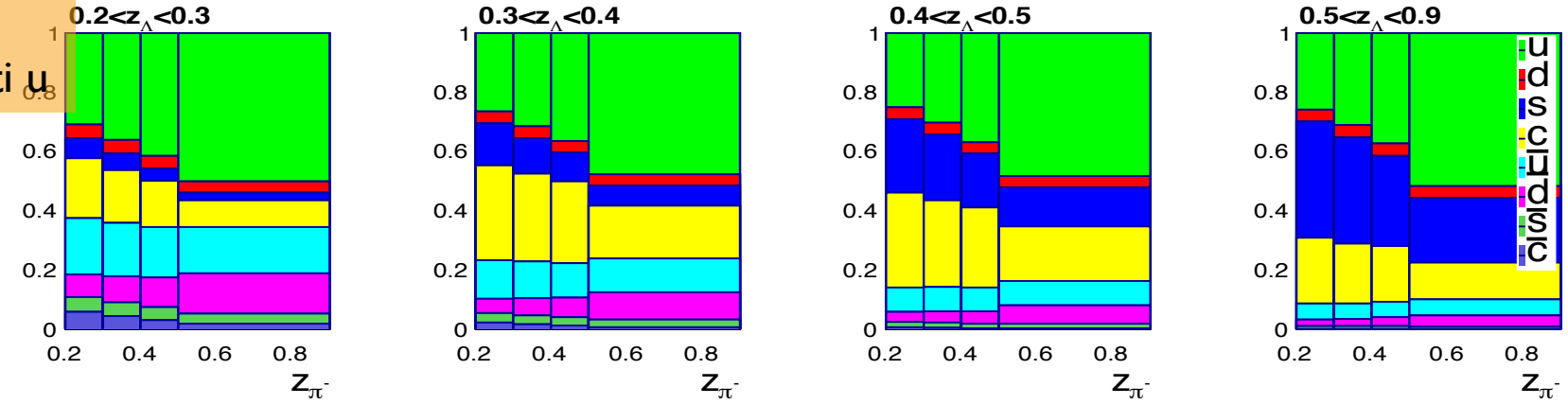


Boer, Kang, Vogelsang, Yuan, PRL 2010



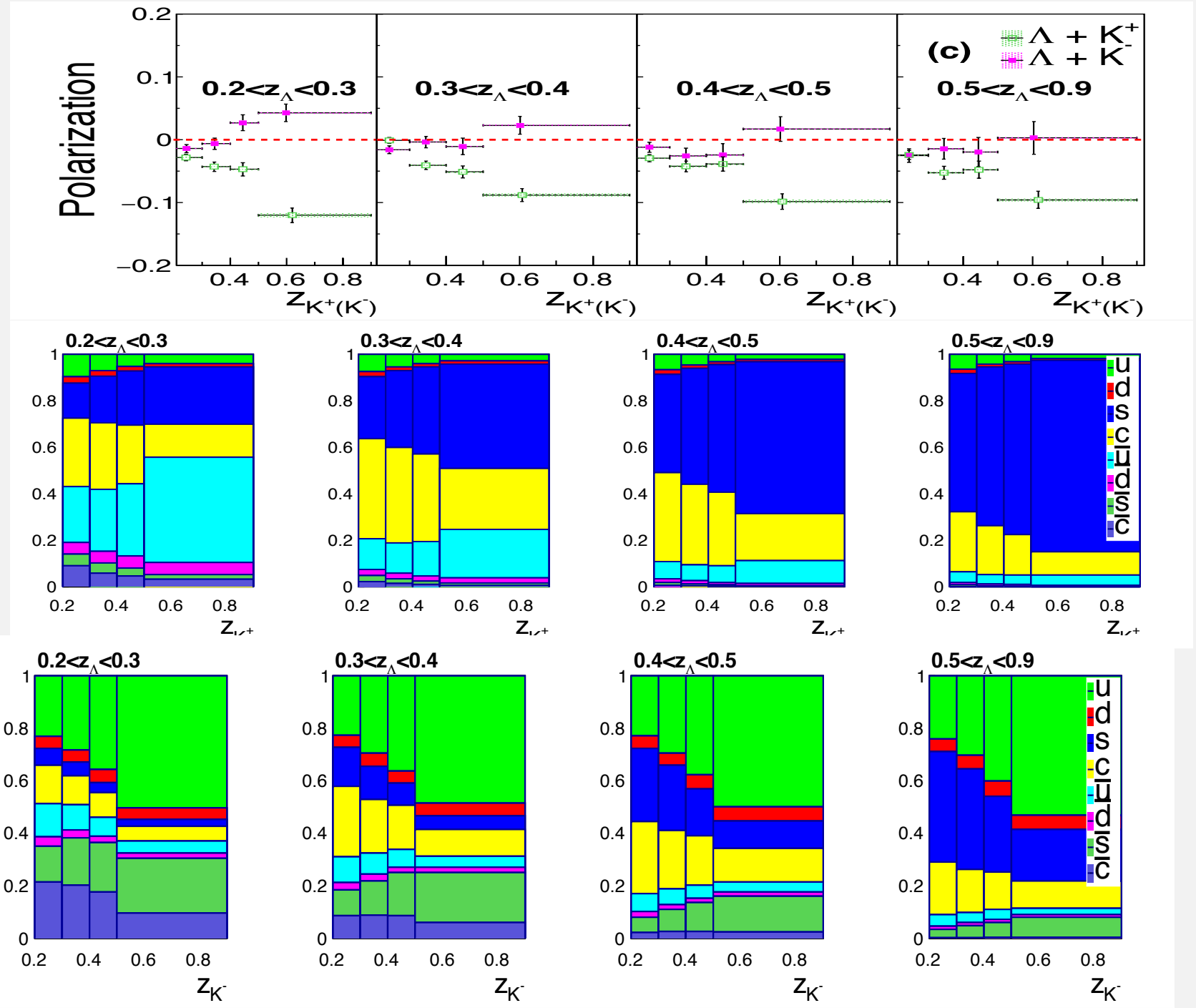






Low Λ z, high π z
Dominated by anti u

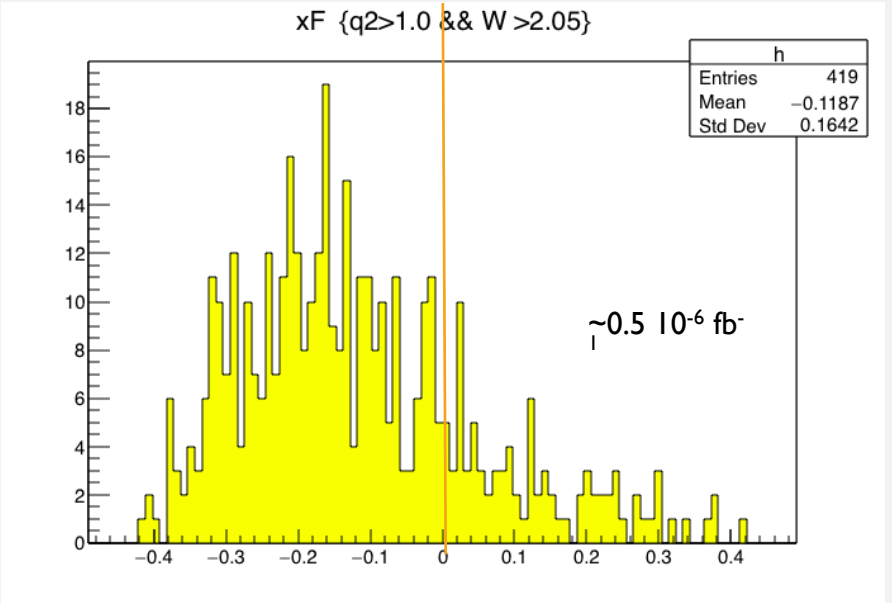
High Λ z, low π z
Dominated by strange for π^+ and u for π^- but asymmetries Simliar?



High Λ z, low K z Dominated by strange for π^+ and u for K reflected in asymmetries

Λ AT CLAS

- Plenty of Λ physics at CLAS6 -- but mostly target or exclusive production
- CLAS12 could do semi-inclusive 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 ~100M Λs is initial running with unpolarized target in acceptance

OUTLOOK TO Λ PHYSICS AT RHIC, EIC AND BELLE II

- **Λ physics offers exciting opportunities at the EIC and Belle II**
- Currently virtually no precision data from SIDIS (current fragmentation)
- Belle proof of principle that large polarizations can be observed
- At the **EIC** we can
  - Probe flavor decomposition of $\boldsymbol{D_{1T}^{\perp \Lambda/q}}$
  - Test Universality of $\boldsymbol{D_{1T}^{\perp \Lambda/q}}$
  - Access transversity in a colinear way using $\boldsymbol{H_{1T}^{\Lambda/q}}$
  - ....
- **BELLE II** will allow measure correlations between $\Lambda^{\uparrow}$ single, di-hadron and $\Lambda^{\uparrow}$ production
- …
- At **RHIC** look at polarizing Λ in jets?

SUMMARY & CONCLUSION

- Lambda and di-hadron production open up exciting possibilities to access the nucleon structure and learn about spin orbit correlations in hadronization
- Existing STAR data provides ample opportunity to explore at high scales and measure gluon FFs
- CLAS12 and Belle II will provide large datasets to study di-hadron correlations
- At EIC clean measurements at high scales can be performed
  - Access to nucleon structure in a complimentary (and more targeted way)
  - Test universality and flavor structure of FFs

Workshop on Novel Probes of the Nucleon Structure in SIDIS, e^+e^- and pp (FF2019)

Duke University

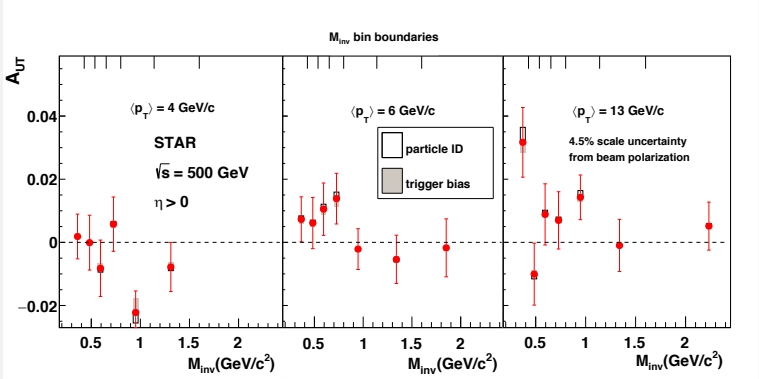
March 14-16 2019

Organizing Committee

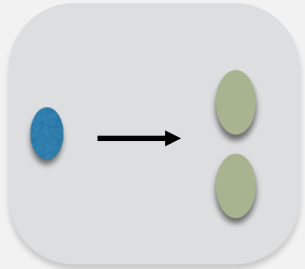
Harut Avakian (Jlab) (co-chair)
Keith Griffioen (W&M)
Kyungseon Joo (Uconn)
Marco Radici (INFN)
Ralf Seidl (RIKEN)
Anselm Vossen (Duke/Jlab, chair)
Jixie Zhang (UVA)

Contact:
anselm.vossen@duke.edu

BACKUP


M_inv bin boundaries
A_UT
⟨p_T⟩ = 4 GeV/c
STAR
√s = 500 GeV
η > 0
⟨p_T⟩ = 6 GeV/c
particle ID
trigger bias
⟨p_T⟩ = 13 GeV/c
4.5% scale uncertainty
from beam polarization
0.04
0.02
0
−0.02
0.5
1
1.5
2
M_inv(GeV/c²)

DI-HADRON FRAGMENTATION FUNCTIONS



Additional Observable:

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

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

Do not need

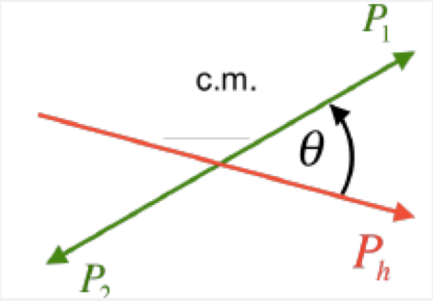
Small $\vec{R}$: non-perturbative object.

$G_1^{\perp}$: T-odd FF

- chiral-even function
- log. polarized q → two unp. Hadrons
- →connection to jet-handedness and (possibly) QCD vacuum structure

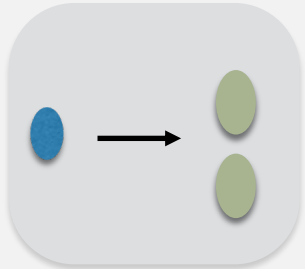
$H_1^{\sphericalangle}$: T-odd FF

- Chiral-odd function
- Transv. polarized q → two unp. Hadrons
- →Collinear! (unlike Collins)



- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs
  - Analogue of 1h production with spin in final state

DI-HADRON FRAGMENTATION FUNCTIONS



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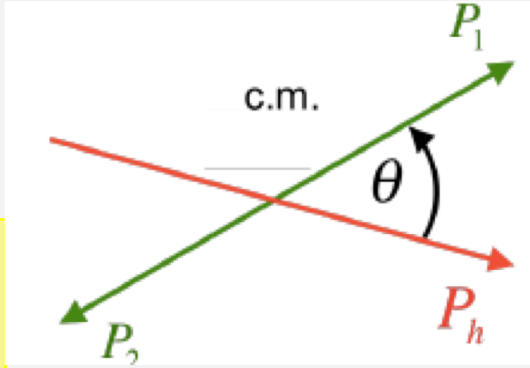

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  - Partial wave decomposition in θ
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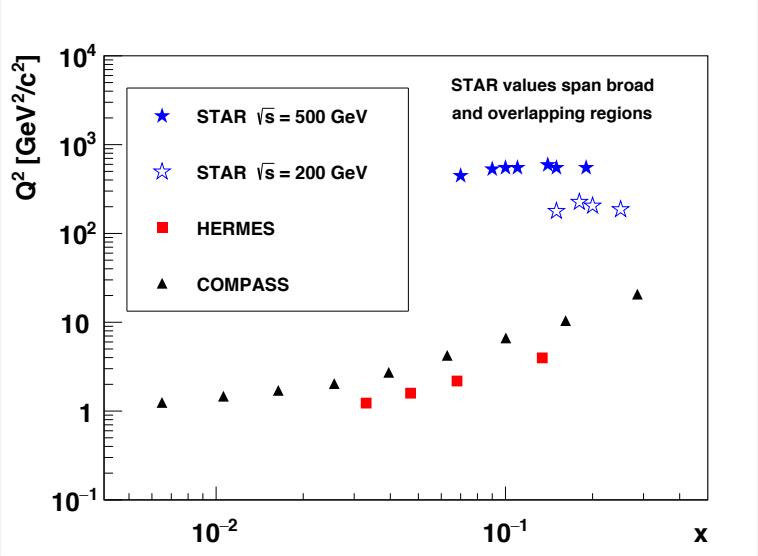
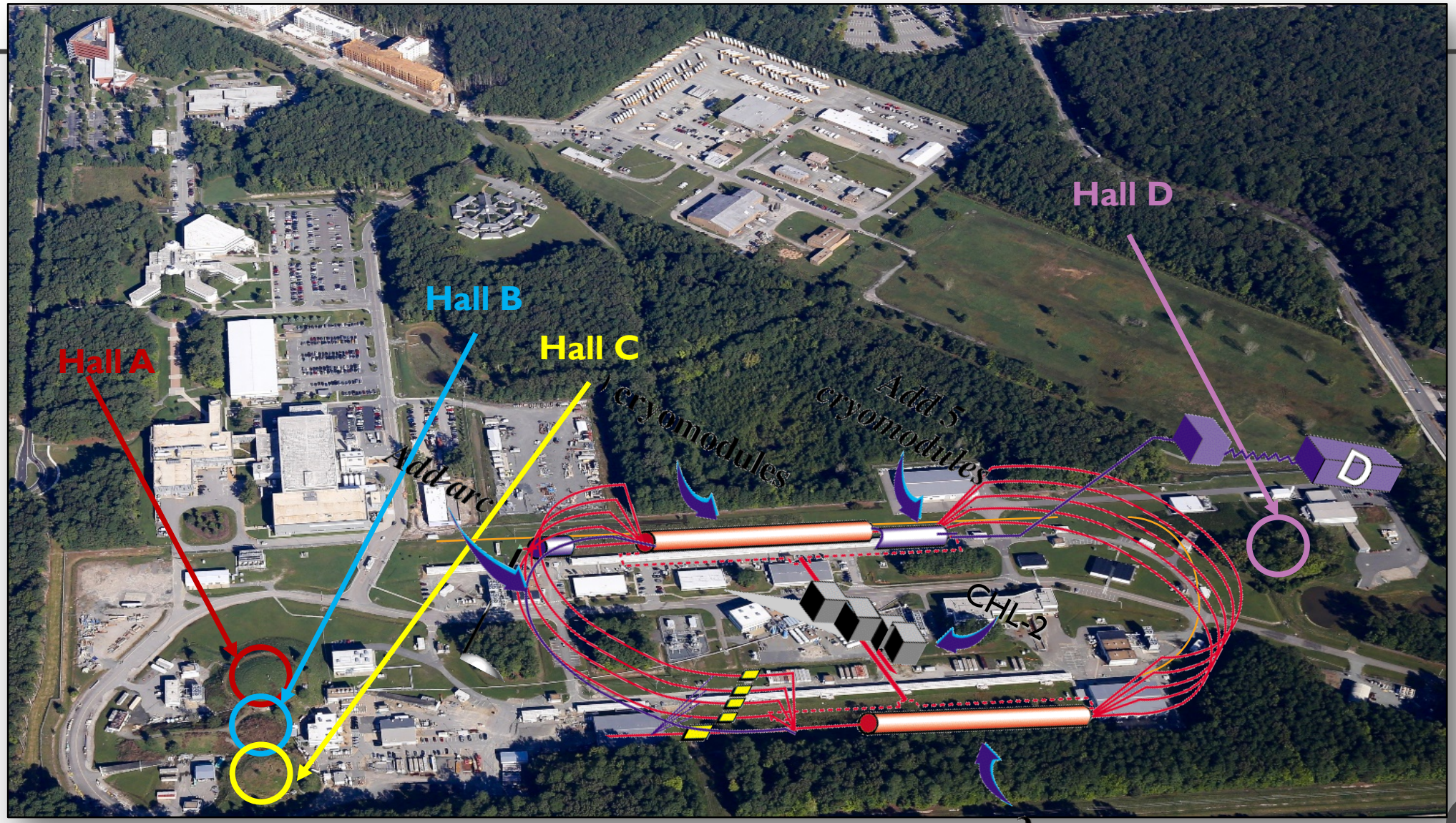
JEFFERSON LAB

KINEMATIC COVERAGE AND COMPARISON WITH SIDIS

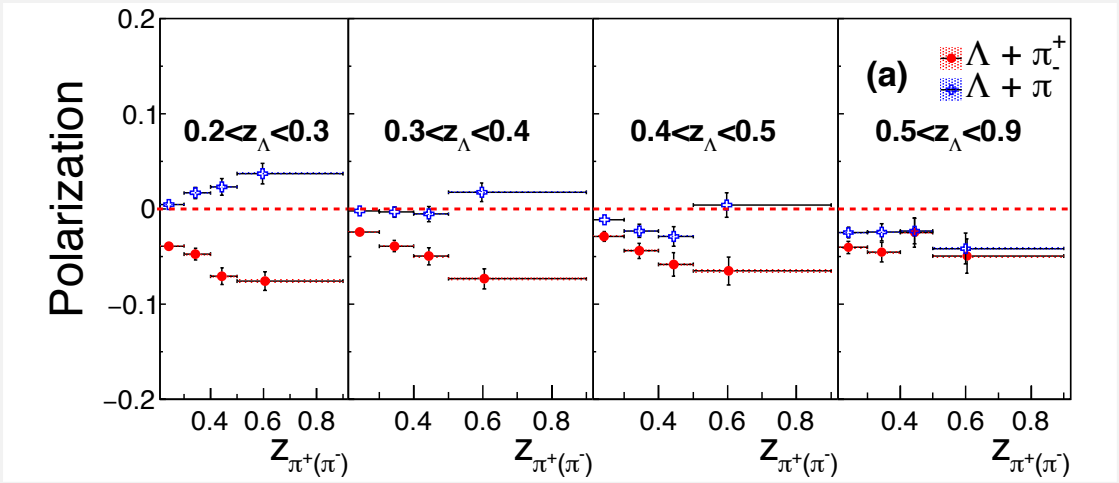


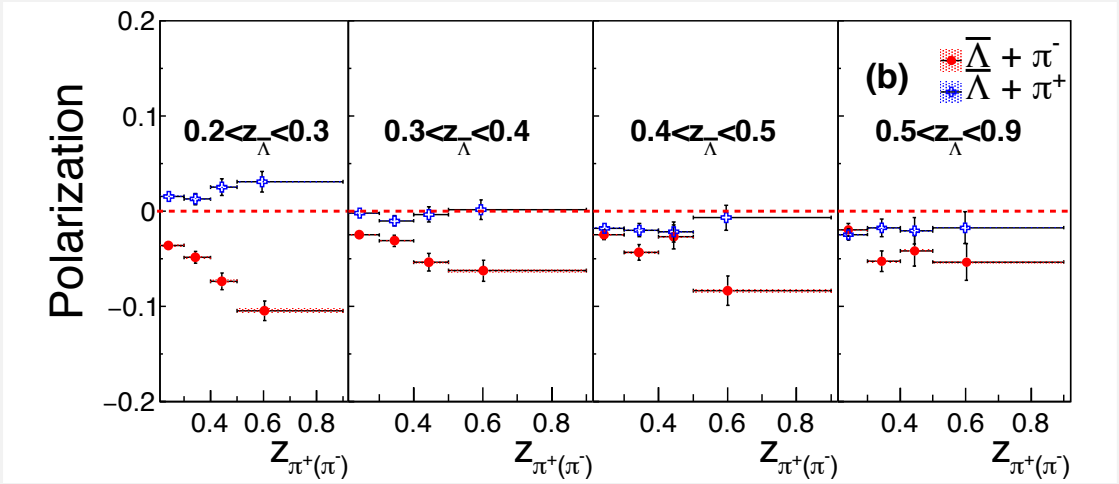
- Up to two orders of magnitude higher Q^2
- Valence region
- No u quark dominance
- Less x-Q^2 correlation

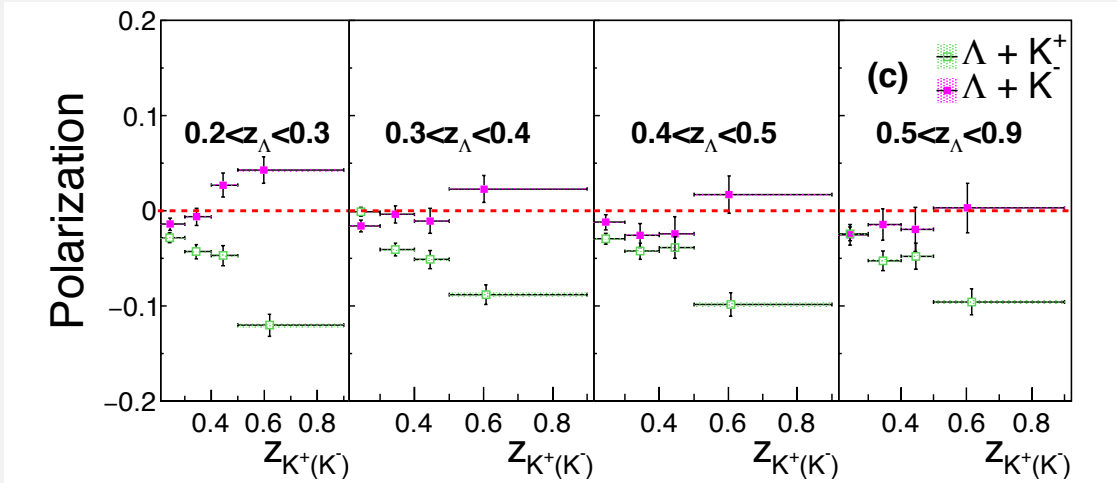
JEFFERSON LAB WITH CEBAF AT 12 GEV

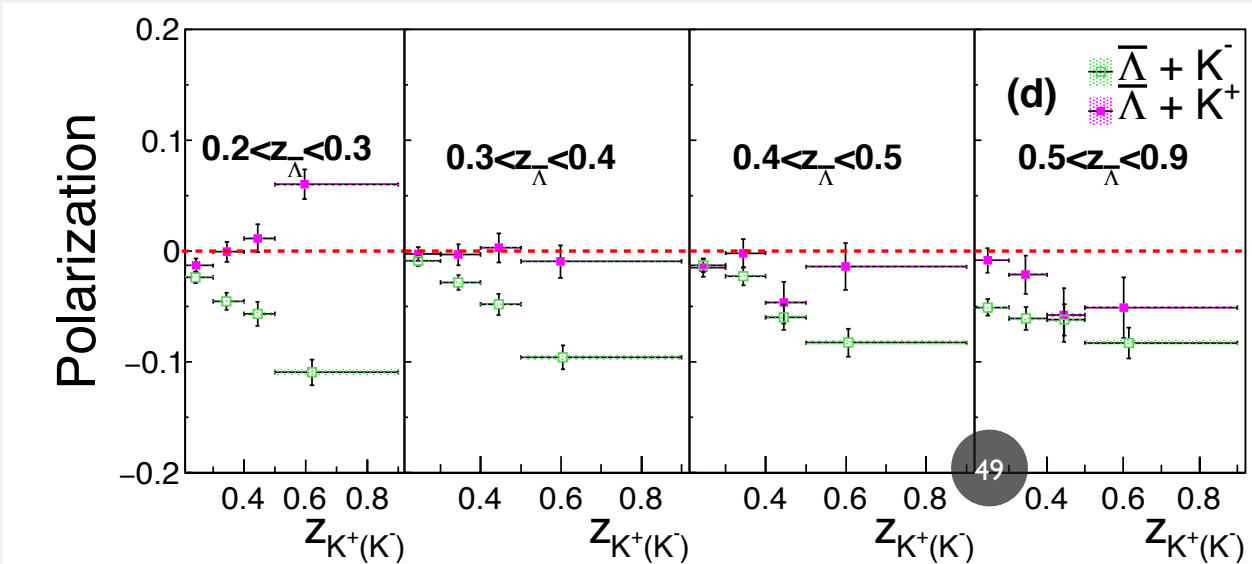


ASSOCIATED PRODUCTION

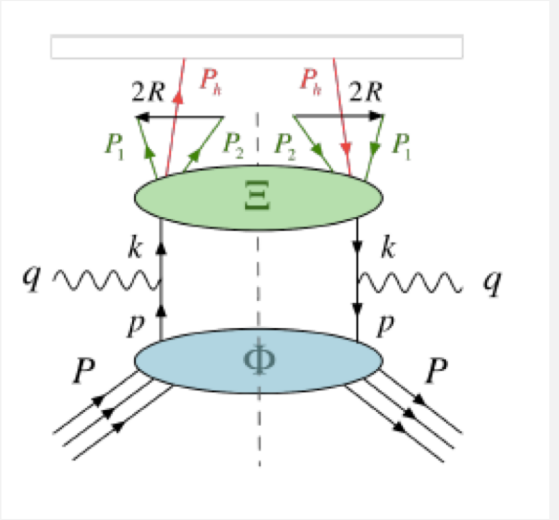




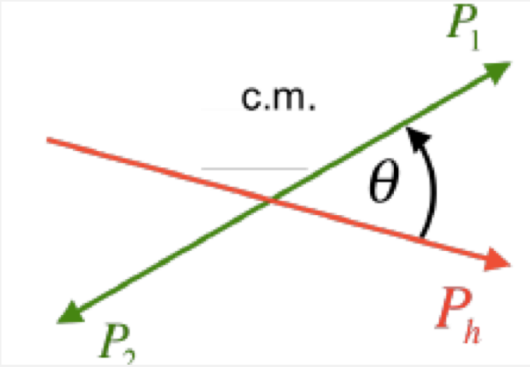




DI-HADRON FRAGMENTATION FUNCTIONS



- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs
  - Analogue of 1h production with spin in final state
- Transverse polarization dependence in collinear framework $H^{\angle}$→ **Most precise extraction of transversity** → See M. Radici talk
- **Minimize systematics in pp**: No thrust axis, theoretically and experimentally cleaner
- **Makes 'new' FFs possible,** such as $G_1^{\perp}$:T-odd chiral even. In 1h case, this needs polarized hadron in the final state
- **→See Monday talk by Ralf**

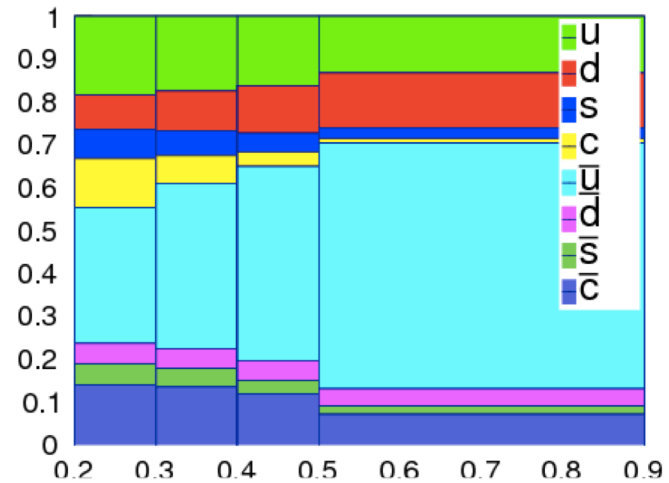


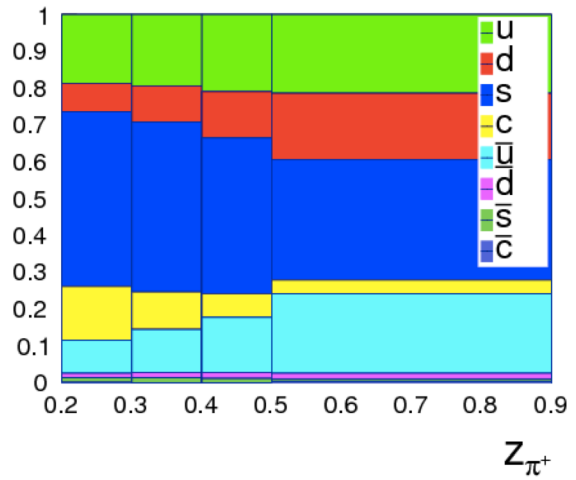
FLAVOR COMPOSITION

$0.2<z_\Lambda<0.3$

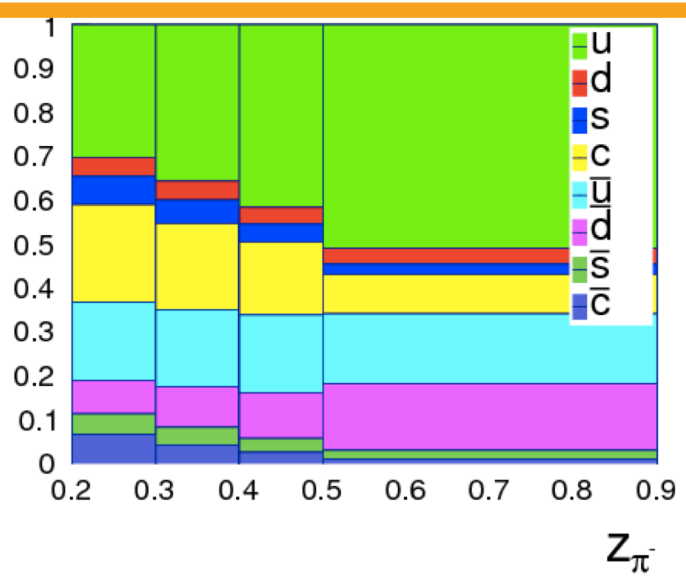
$0.5< z_\Lambda <0.9$

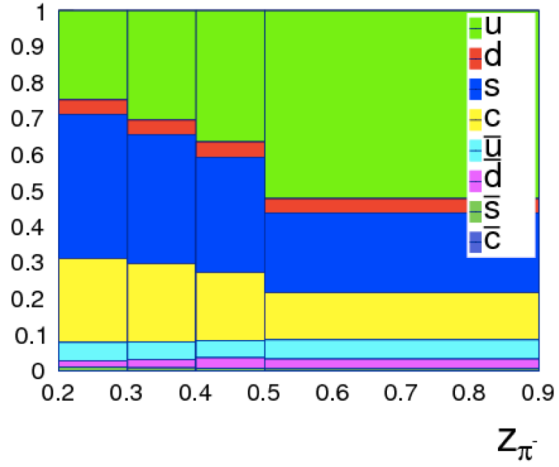
π^+





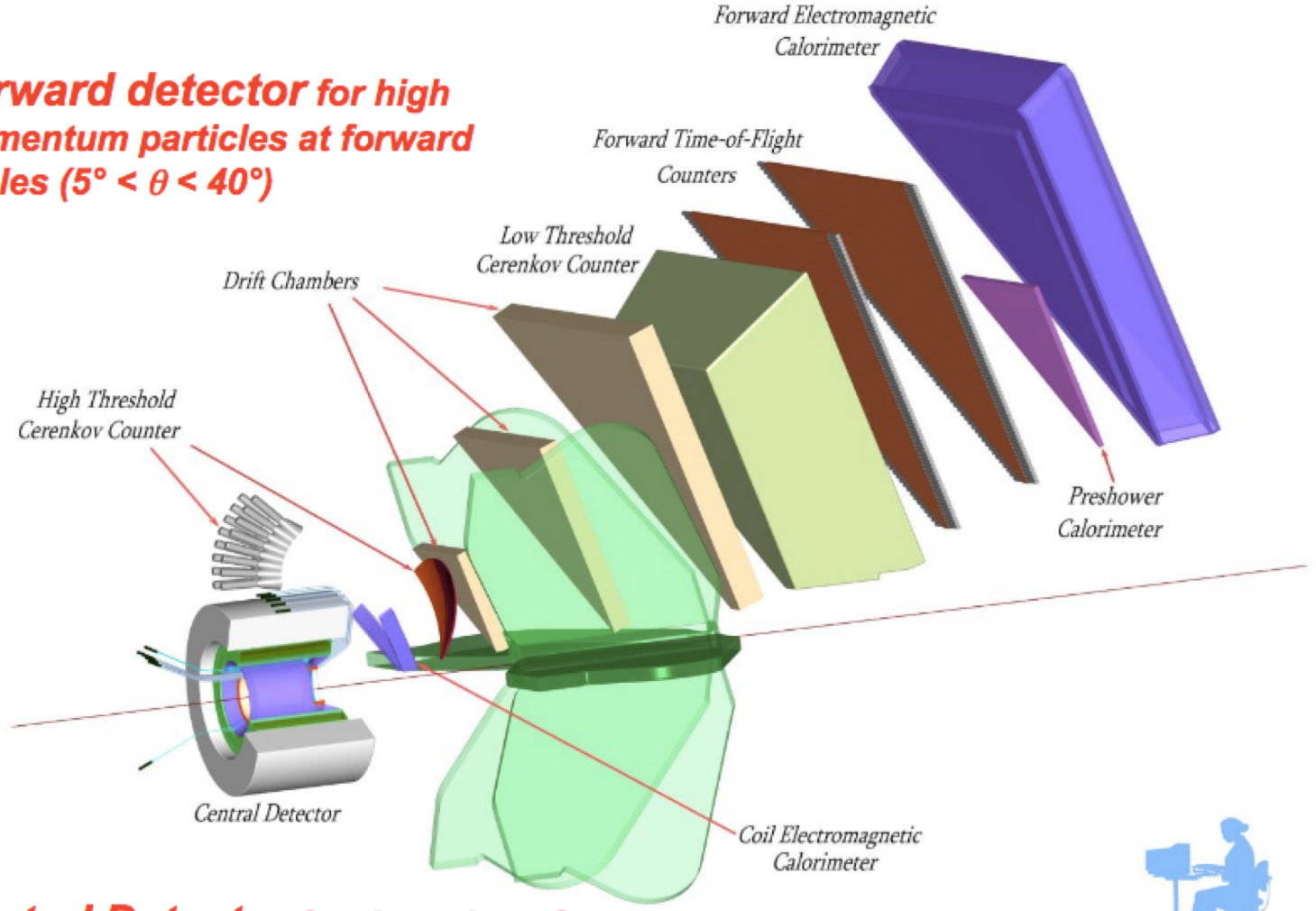
π^-





CLAS12

Forward detector for high momentum particles at forward angles ($5° < \theta < 40°$)

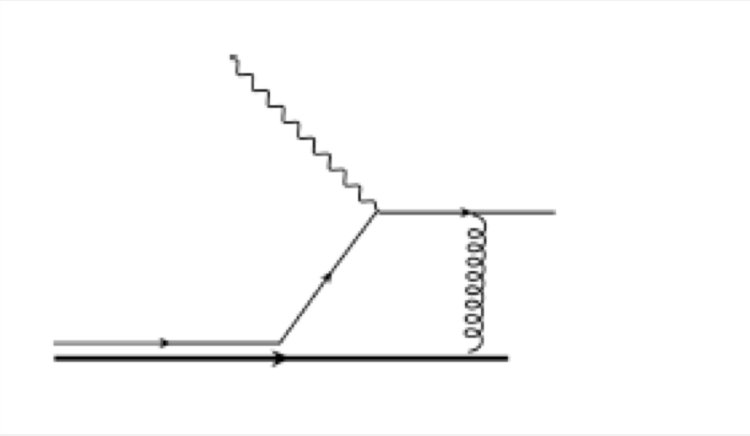


Central Detector for detection of particles at large angles ($\theta > 35°$)

QUARK-GLUON INTERACTIONS

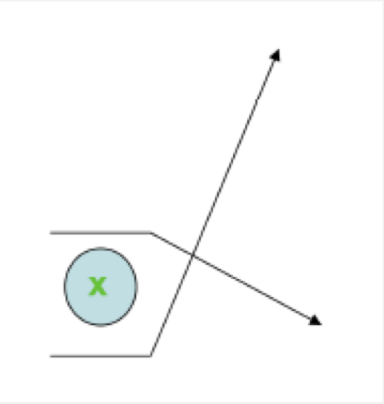
- Quarks probed in deep-inelastic scattering move in gluon background field
  - Gauge link Integrated effect of quark gluon interactions
- Some of the most interesting effects can be attributed to the dependence of these interactions on spatial deformations and polarization of PDFs
  - **Example: Sivers effect**

$$\langle \mathbf{k}_\perp \rangle \sim \left\langle P,S \left| \bar{q}(0)\gamma^+ \int_0^\infty d\eta^- G^{+\perp}(\eta) q(0) \right| P,S \right\rangle$$



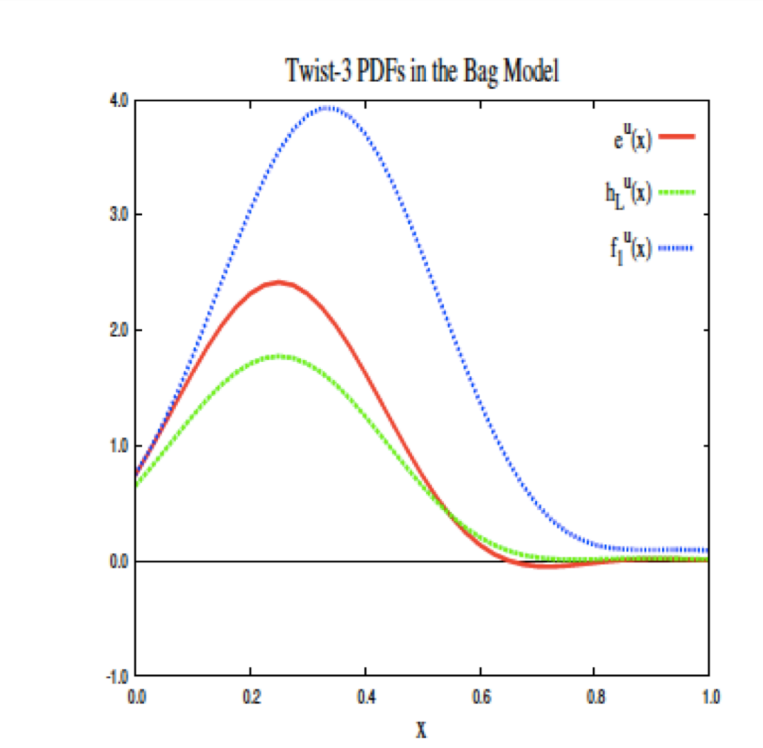
- The instant quark gluon interactions are described by Twist3 PDFs
- Projections of
-

$$\Phi^\mu_{Aij}(x) = \int \frac{\mathrm{d}\tau}{2\pi}\, \mathrm{e}^{\mathrm{i}\tau x} \langle PS|\bar{\phi}_j(0)\, gA^\mu(\tau n)\, \phi_i(\tau n)|PS\rangle\,.$$

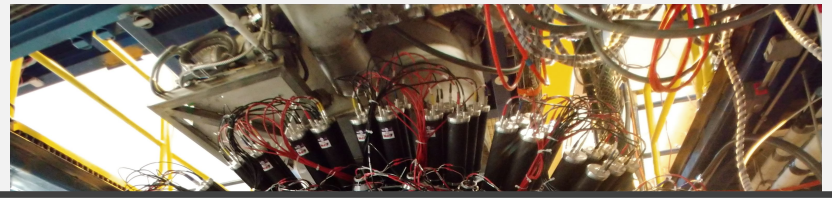


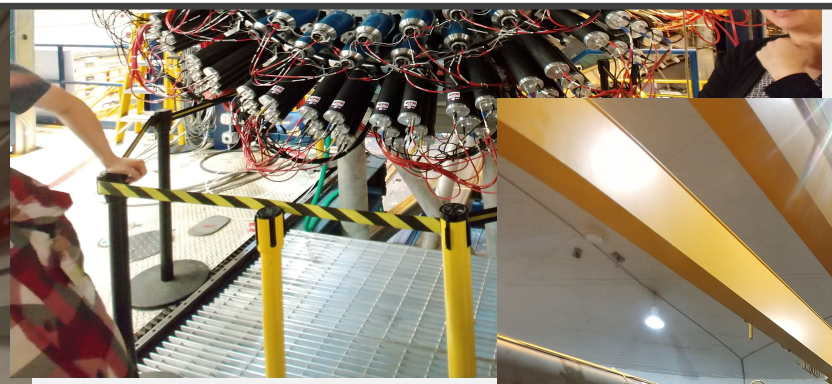
EXAMPLE E(X)

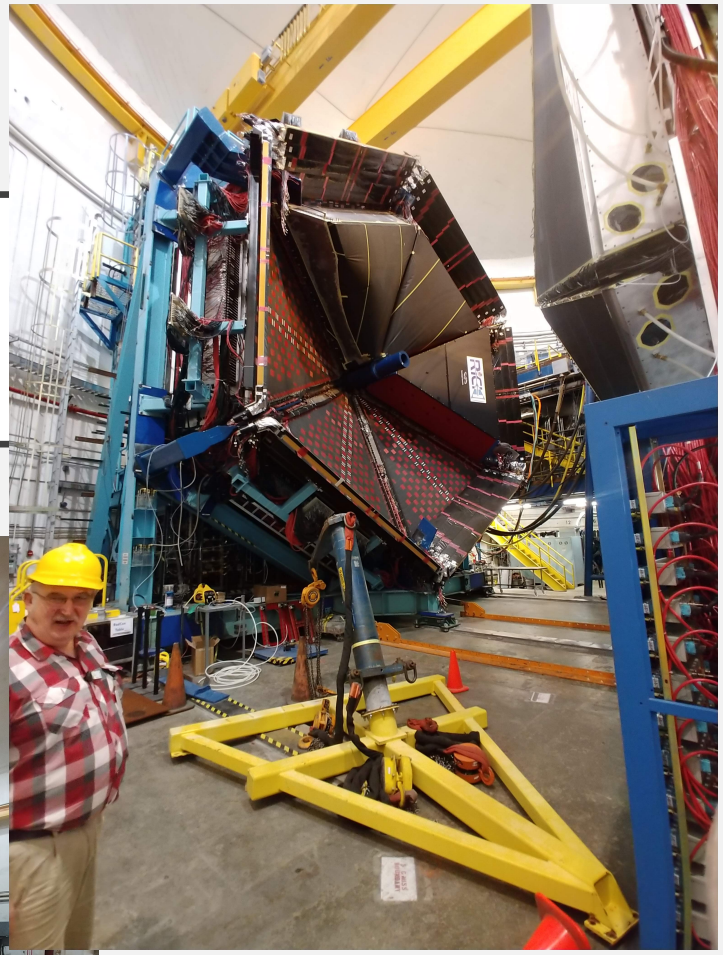
- Transverse force on transversely polarized quarks (Burkhardt)
- Model calculations show significant magnitude:



Jaffe, Ji, Nucl. Phys. **B**375, 527{560 (1992).





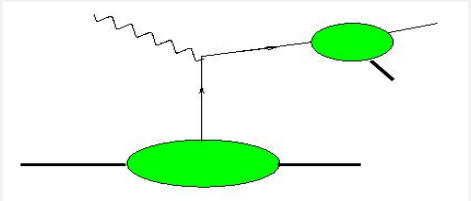


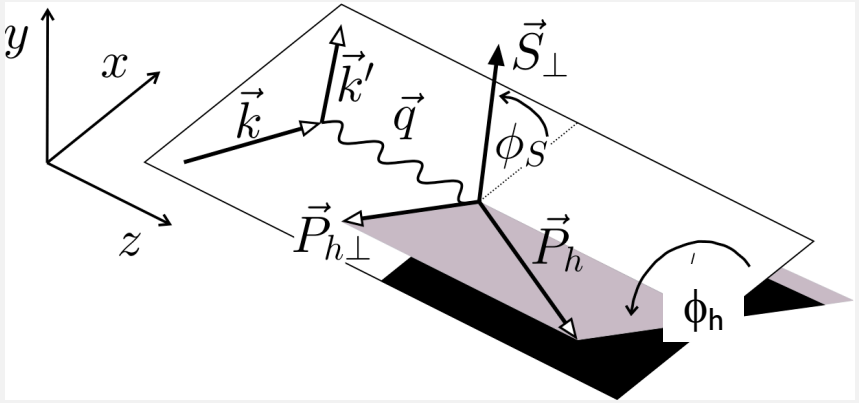
EXAMPLE, ACCESS OF e(x) in SIDIS X-SECTION

- Single hadron cross-section: mixes other contributions:

WW Approximation

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q}\mathcal{I}\Big[-\frac{\boldsymbol{k}_T\hat{\boldsymbol{P}}_{h\perp}}{M_h}\left(xeH_1^\perp + \frac{M_h}{Mz}f_1\tilde{G}^\perp\right) + \frac{\boldsymbol{p}_T\hat{\boldsymbol{P}}_{h\perp}}{M}\left(xg^\perp D_1 + \frac{M_h}{Mz}h_1^\perp\tilde{E}\right)\Big]$$





NEED NEW PROBES BEYOND 1H

- **Additional degrees of freedom to resolve ambiguities :**
- Di-hadron Correlations
- Polarized Λ production

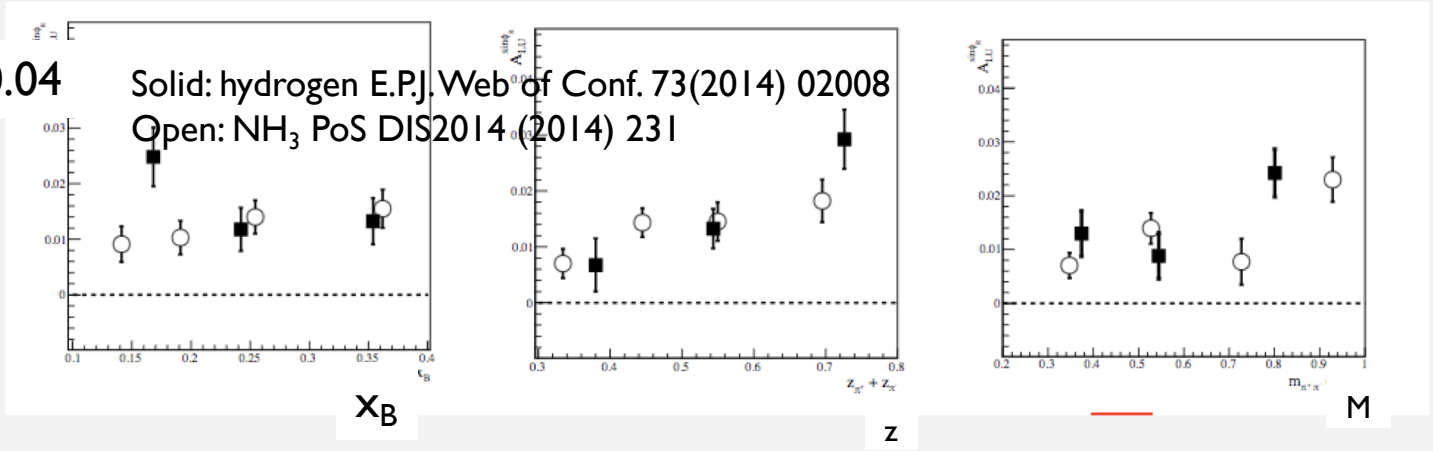
EXAMPLE, ACCESS OF e(x) in SIDIS X-SECTION

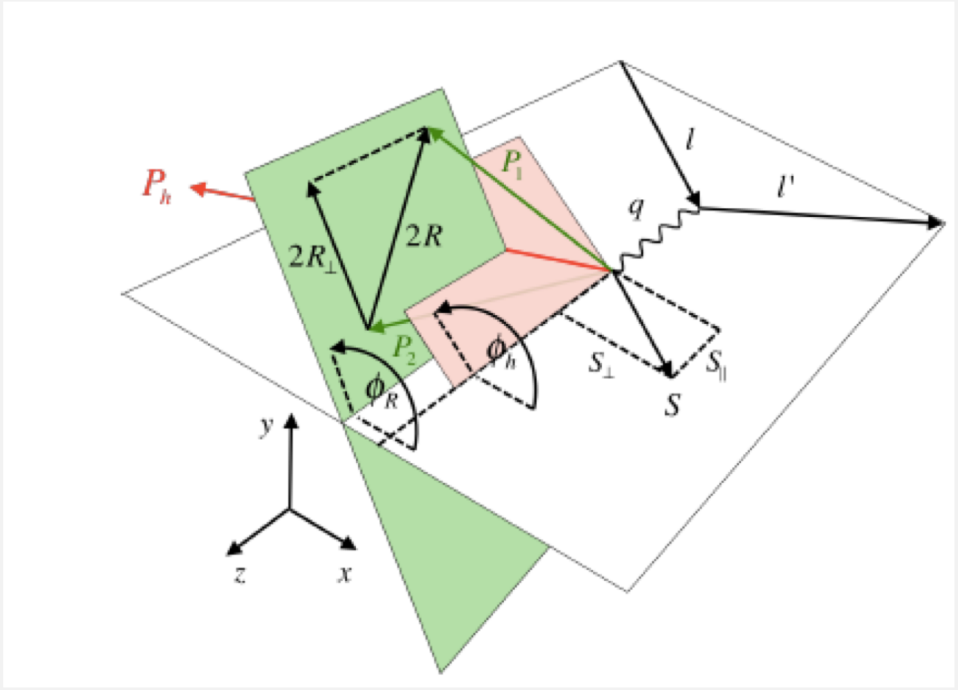
- Di-hadron cross section: Clean access to e(x)

WW Approximation

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

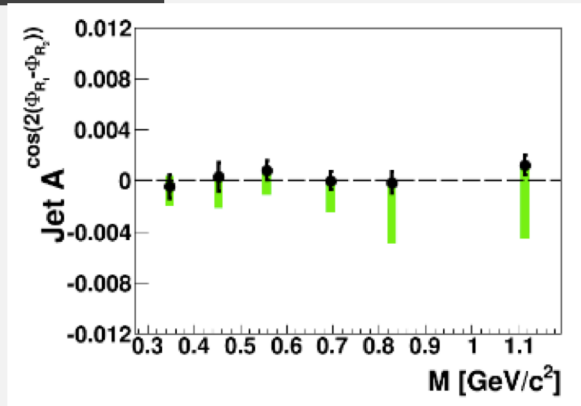
- Evidence from CLAS6:



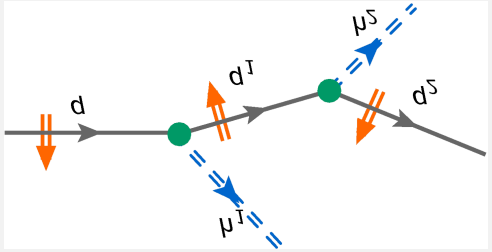


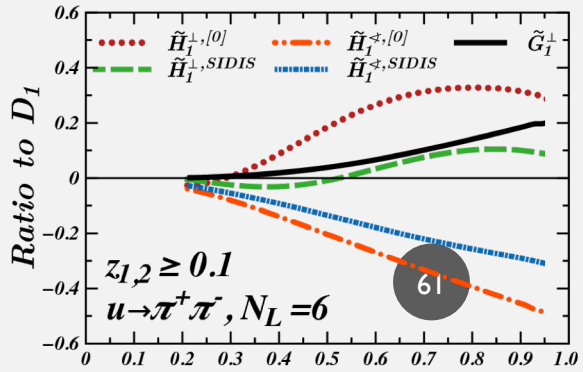
HISTORY OF $G_1^\perp$

- 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. **B**366 (1996) 311-315 (connection to chromomagnetic effects)
- Measurement by Belle→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)→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 → Need weighted asymmetry including dependence on P_{hT}
- Accessible in SIDIS via weighted asymmetries



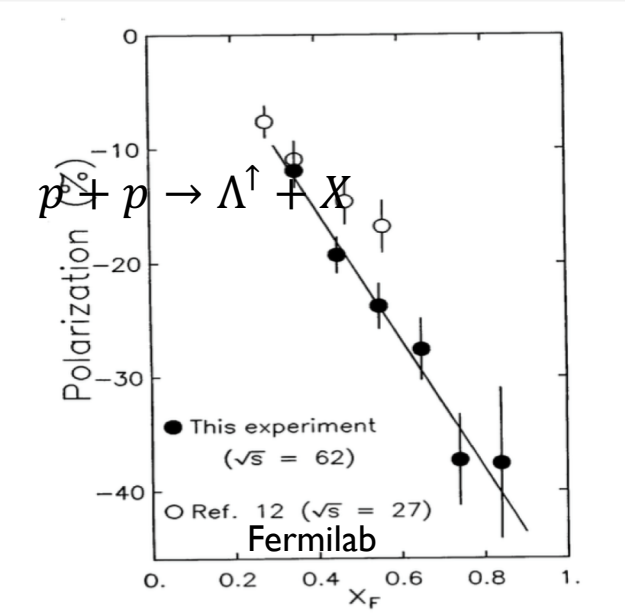
arXiv:1505.08020 [





LAMBDA PRODUCTION

- Inclusion of polarization leads to rich hadronization structure (see e.g. Kanazawa, Metz Pitonyak, Schlegel Phys.Lett. **B**744 (2015) 385-390 , Metz, Pitonyak Phys.Lett. **B**723 (2013) 365-370
- Longstanding question: Large Λ transverse polarization in unpolarized pp collision
- →Polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
-



ISR data

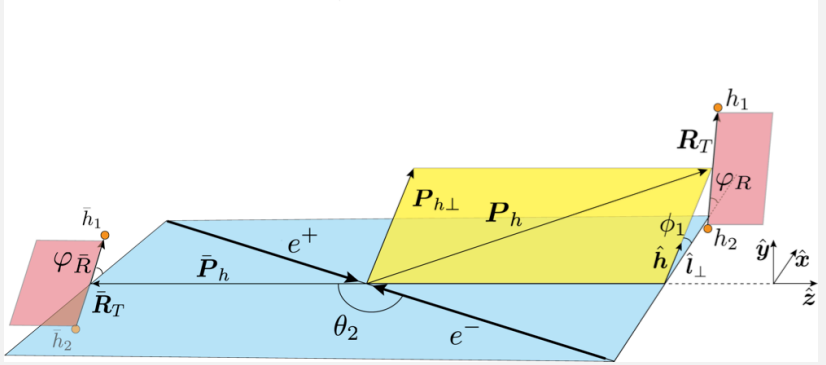
(**Phys.Lett. B185 (1987) 209)**

$$x_F = p_L / \max p_{L\sim LO}^{} x_1 - x_{2\sim forward} x_1$$

$G_1^{\perp}$ MEASUREMENT IN SIDIS AND e^+e^-

- New Observable in e^+e^-:

$$\left\langle \frac{q_T^2\left(3\sin(\varphi_q-\varphi_R)\sin(\varphi_q-\varphi_{\bar{R}})+\cos(\varphi_q-\varphi_R)\cos(\varphi_q-\varphi_{\bar{R}})\right)}{M_h\bar{M}_h}\right\rangle$$
$$=\frac{12\alpha^2A(y)}{\pi Q^2}\sum_{a,\bar{a}}e_a^2\left(G_1^{\perp a,[0]}-G_1^{\perp a,[2]}\right)\left(\bar{G}_1^{\perp\bar{a},[0]}-G_1^{\perp\bar{a},[2]}\right),$$



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

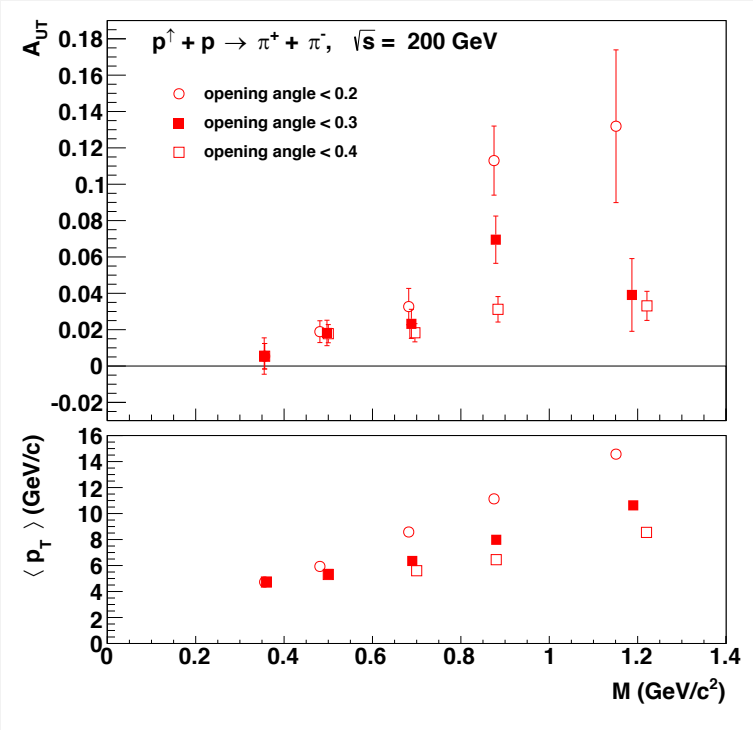
- New Observable in SIDIS with longitudinal target and beam spin asymmetries :

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

Matevosyan, Kotzinian ADP-17-42-T1048

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

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


A_{UT}
$p^{\uparrow} + p \rightarrow \pi^{+} + \pi^{-}$, $\sqrt{s}$ = 200 GeV
opening angle < 0.2
opening angle < 0.3
opening angle < 0.4
$\langle p_T \rangle$ (GeV/c)
M (GeV/c^2)