DNP, Halloween 2020

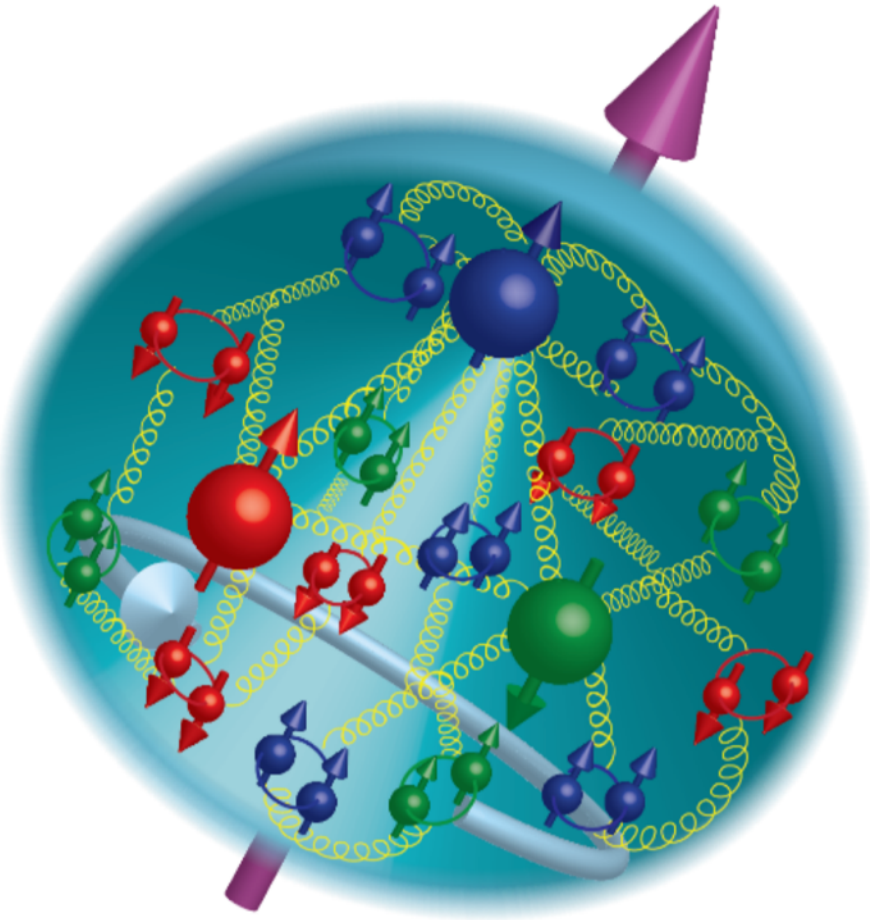
Insights from and Prospects for Belle (II) and JLab

Anselm Vossen

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

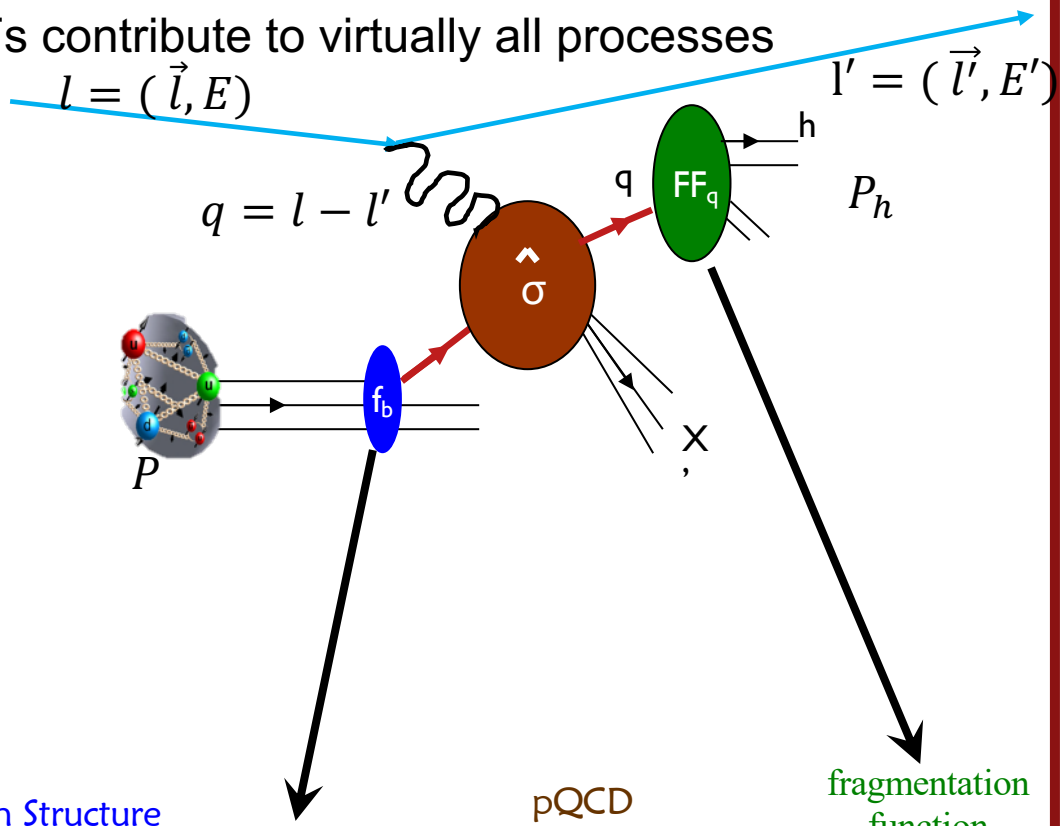
Duke UNIVERSITY

Jefferson Lab



Hard Scattering is a premier tool to probe the quark and gluon degrees of freedom

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes



- At fixed beam energy need two variables to characterize DIS event, e.g. $Q^2, \nu \rightarrow x$ in scaling regime

$$-Q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

"hard scale" of the probe

$$-x = \frac{Q^2}{2M_n \nu}:$$

bjorken **scaling variable**, in partonic picture momentum fraction of the struck parton

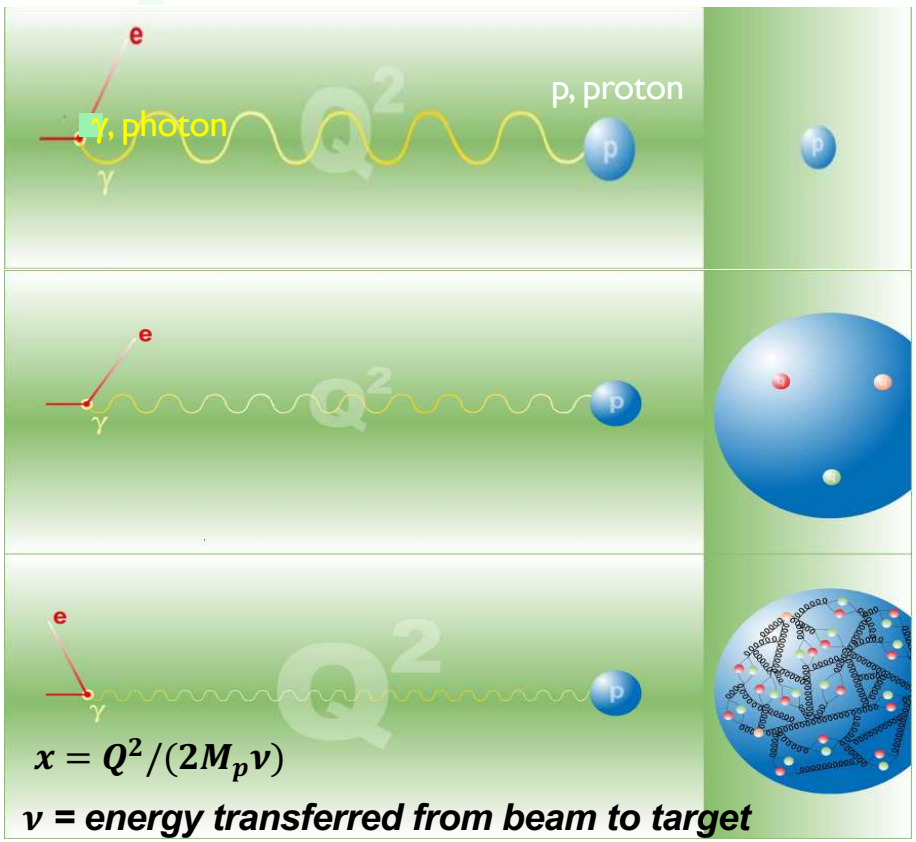
$$-z = \frac{P_\mu P_h^\mu}{P^\mu q_\mu}:$$

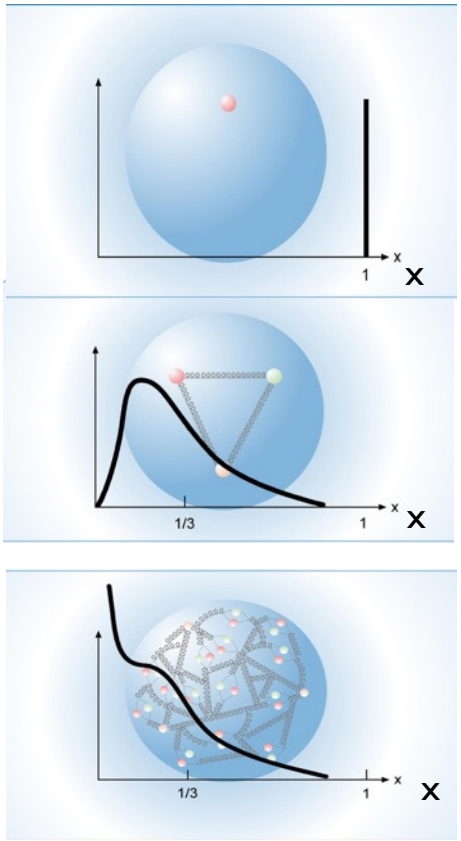
Fraction of quark momentum carried by outgoing hadron

Proton Structure — pQCD — fragmentation function

$$\frac{d^2\sigma(ep \rightarrow \pi X)}{dx\, dz\, p_{hT}} \propto q(x, k_T) \times \frac{d\sigma^2(e\, q \rightarrow e' q')}{dx} \times FF(z, p_T)\, \delta(p_{hT} - (k_T + p_T))$$

Fraction of the proton momentum carried by the parton: x

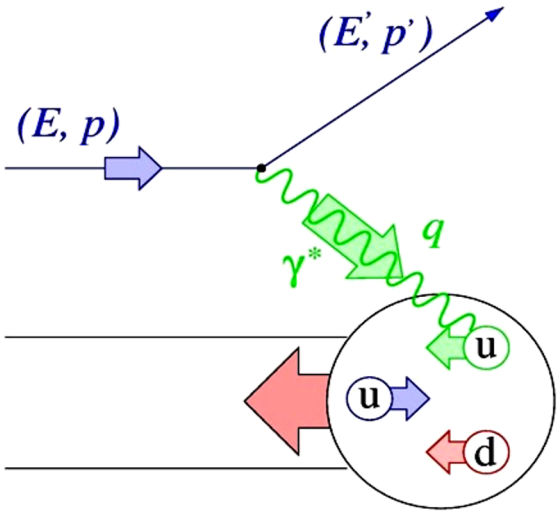


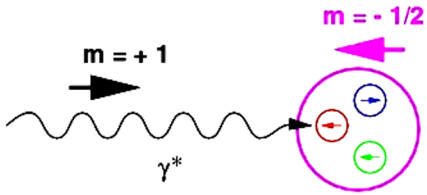


Q^2 = "Resolution"

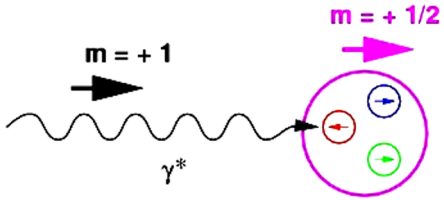
x = "Exposure"

Adding polarization

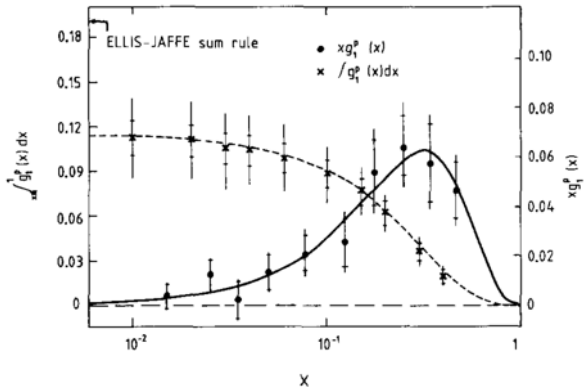




$$\sigma_{1/2} \sim \sum_i e_i^2 q_i^+$$



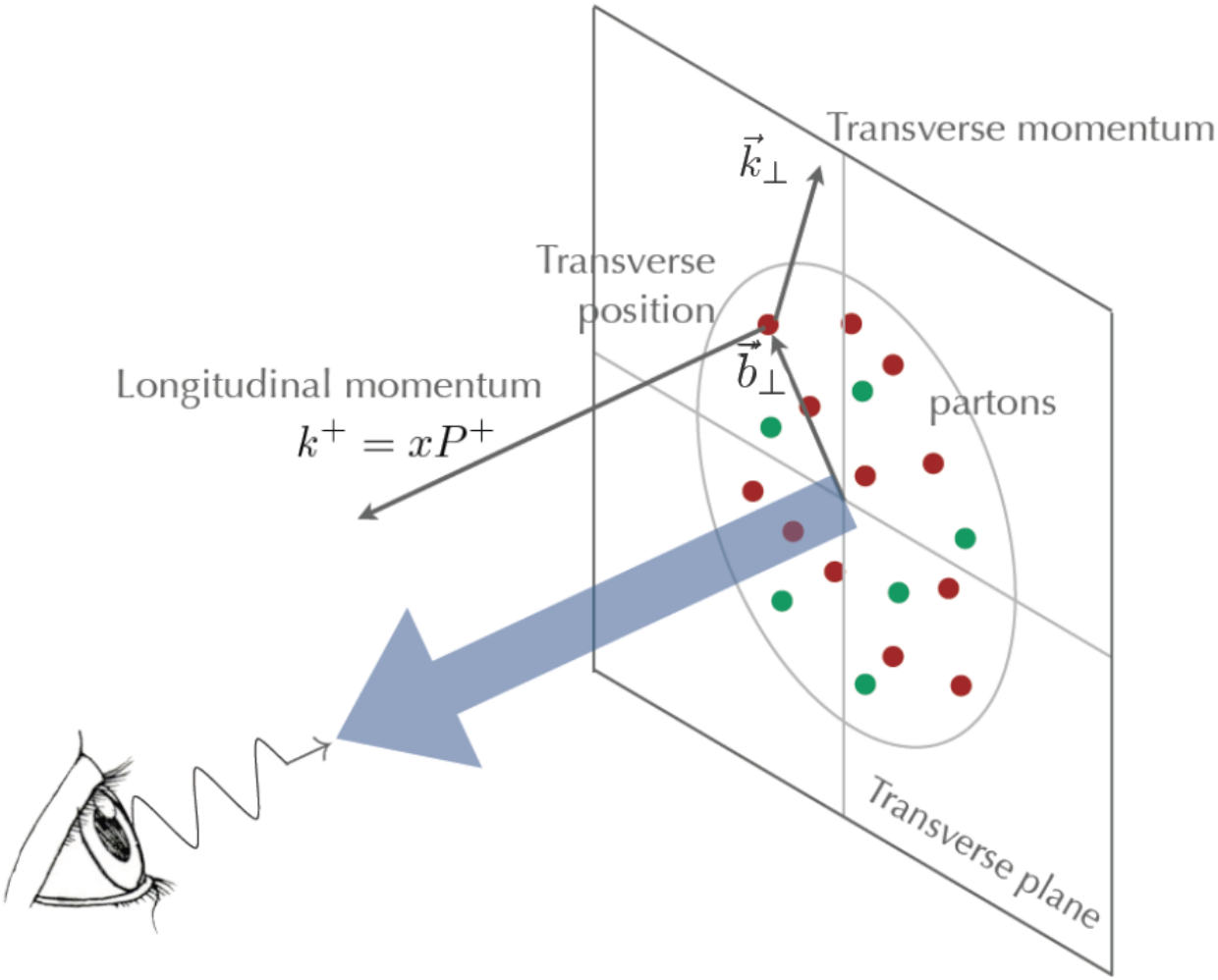
$$\sigma_{3/2} \sim \sum_i e_i^2 q_i^-$$



EMC, Phys. Lett. B206,2,364 1988

Spin kills more theories that any other observable!

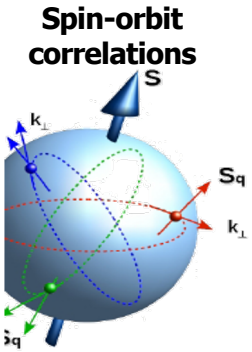
From 1D to 3D…(x, k_T)



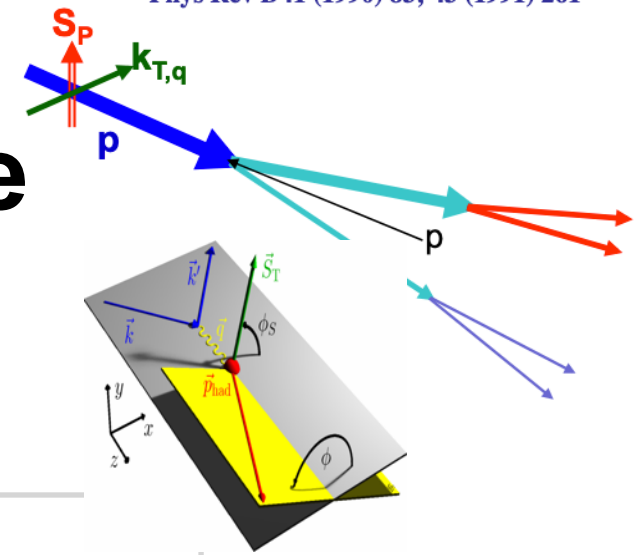
With Polarization

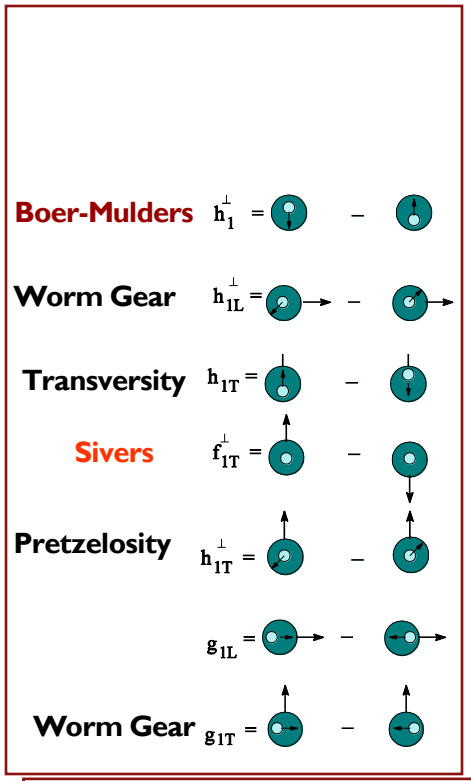
- In addition to the spin-spin correlations can have spin momentum correlations!
- TMD PDFs $f(x, k_T)$

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



SIDIS X-section in the Parton Model





$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Unpolarized

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

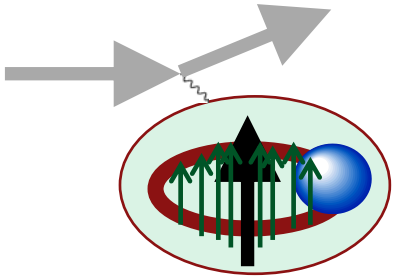
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

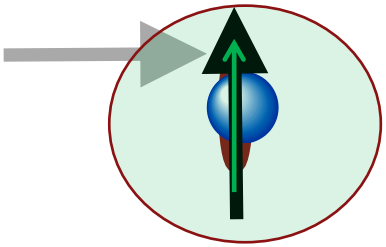
$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

Polarzied beam and target

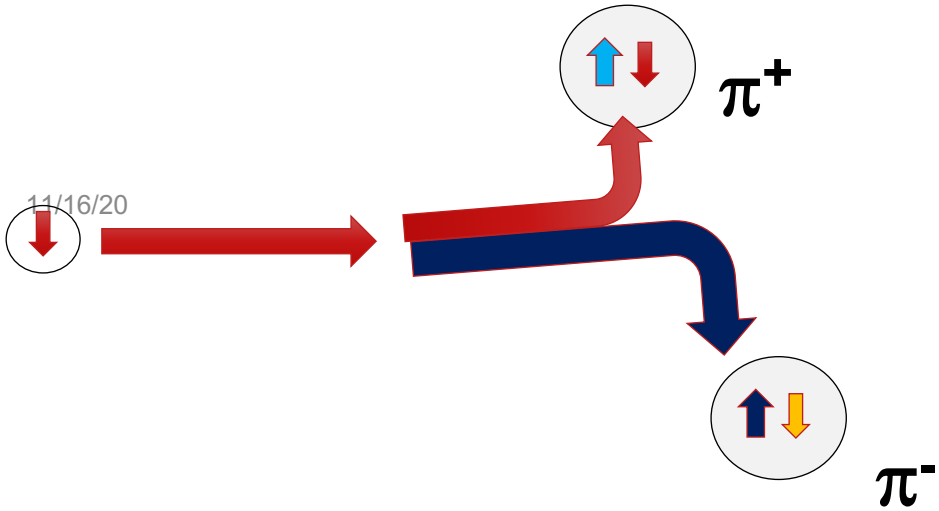
S_L and S_T: Target Polarizations; λe: Beam Polarization

x: momentum fraction carried by struck quark, z: fractional energy of hadron

- TMDs related to the transverse polarization are difficult to access
- 

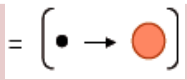


Need polarization dependent FFs as quark polarimeters

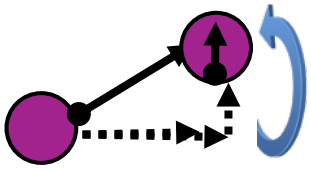


Fragmentation Functions

<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**

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)			

Adding polarization in the final state….



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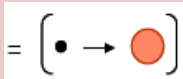
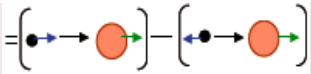
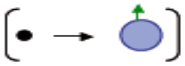
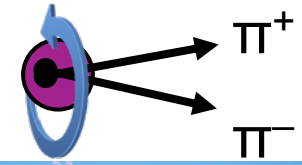
spin averaged	$D_1^{h/q}(z,p_T)$ = 		$H_1^{\perp h/q}(z,p_T)$ = 
longitudinal		$G_1^{h/q}(z,p_T)$ = 	
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$ = 		$H_1^{q/\Lambda}(z,p_T)$ = 

- Theoretically many more, in particular with polarized hadrons in the final state and transverse momentum dependence →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^-)



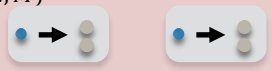
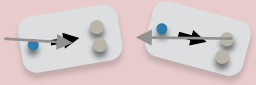
DI-HADRON FRAGMENTATION FUNCTIONS

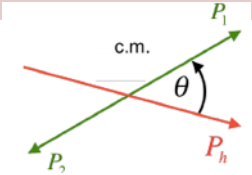
Additional Observable:

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

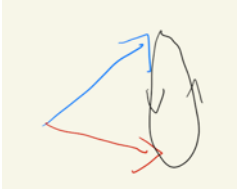
The relative momentum of the hadron pair is an additional degree of freedom:

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	$D_1^{h/q}(z,M)$ 		$H_1^{\perp h/q}(z, p_T$**M, (Ph),**$\theta)$ 'Di-hadron Collins'
Needs Interference with j Longitudinal OAM			
Needs Interference with Transverse OAM component	Type equation here.	**$G_1^{\perp}(z,M,P_h,\theta)$=**  T-odd, chiral-even →jet handedness QCD vaccum strucuture	**$H_1^{\sphericalangle}(z,M,(P_h),\theta)$=.**  T-odd, chiral-odd Colinear



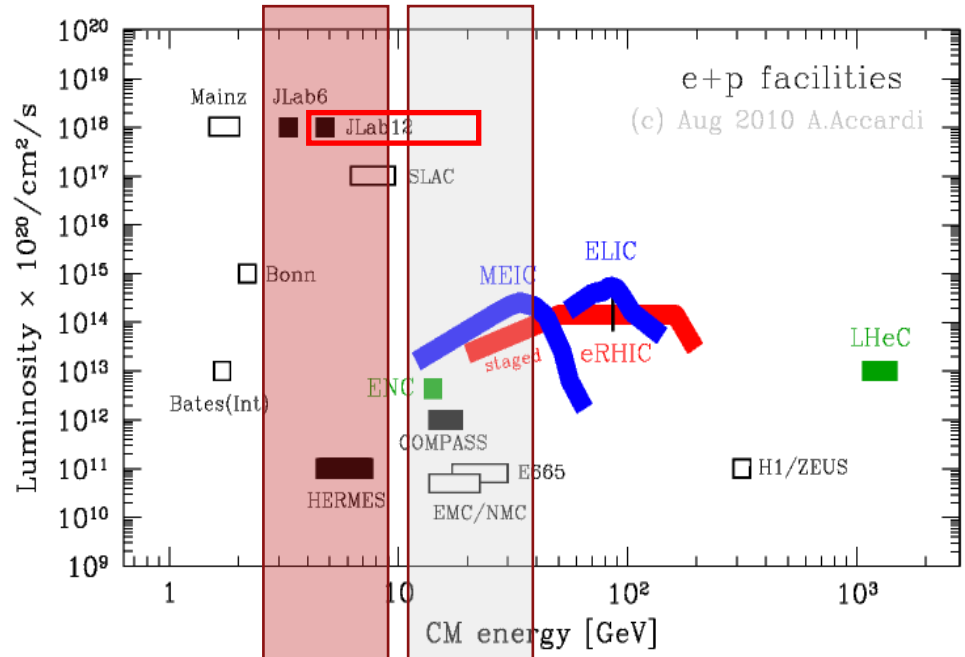
- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ→
    Needs to be mapped completely!! (no information yet)
    - Energy dependence? (→VM fractions….)
  - Relative and total angular momentum →In principle endless tower of FFs



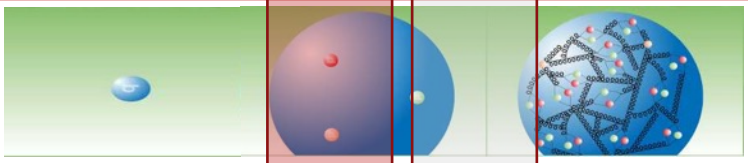
Comparison to Previous and Planned Facilities

Exposure

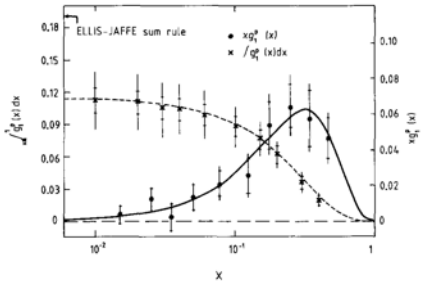
Valence Quarks



Glue and sea-quarks



wavelength



- naïve constituent model and experimental results: Valence region important for nucleon spin properties
- To extract 3D structure: Need luminosity

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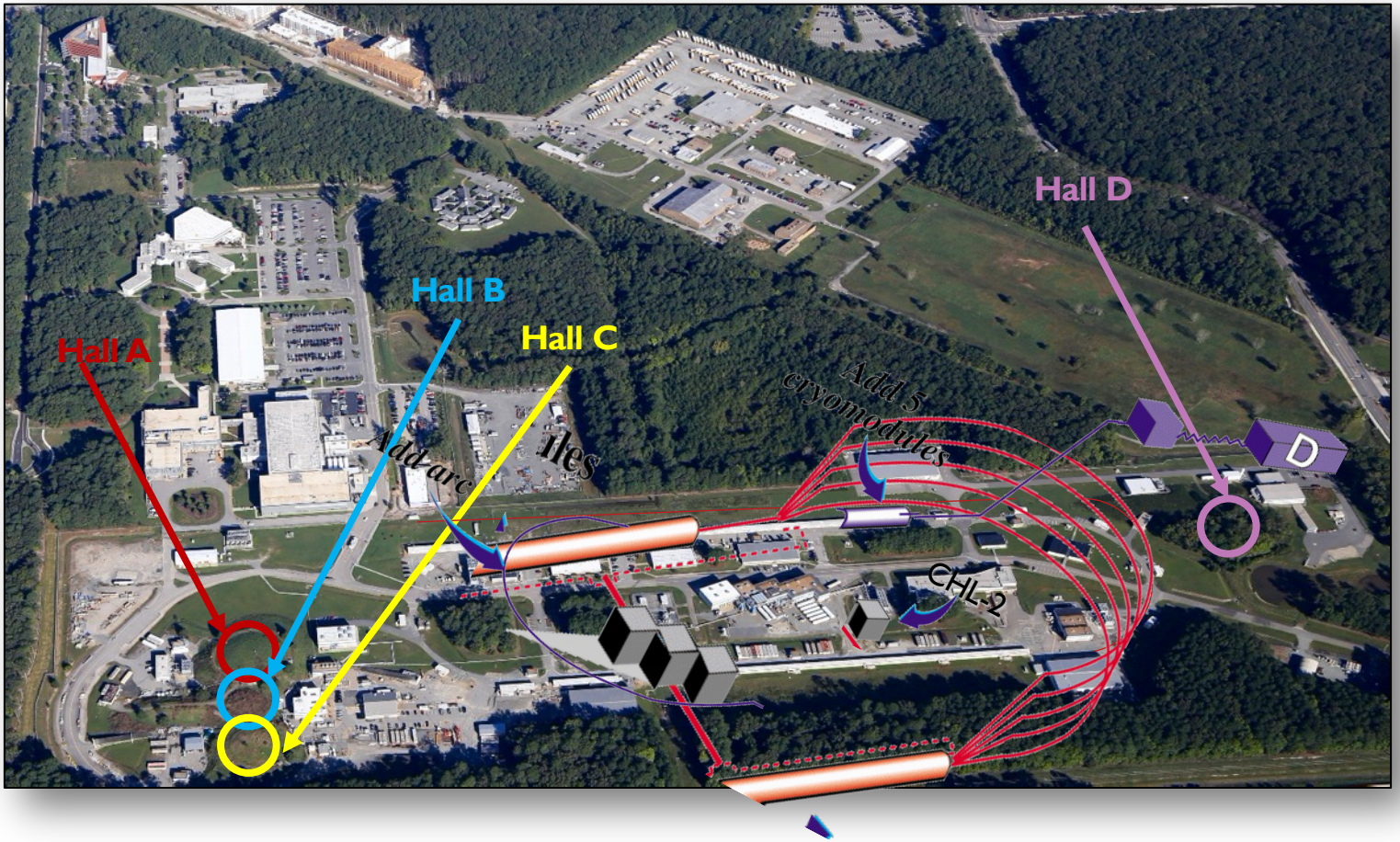
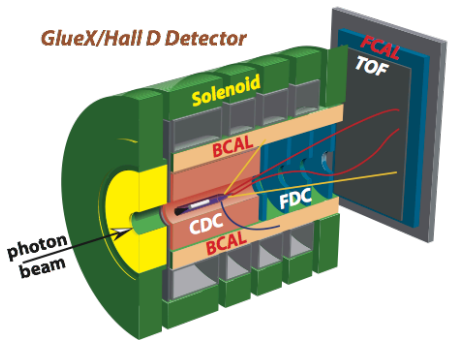
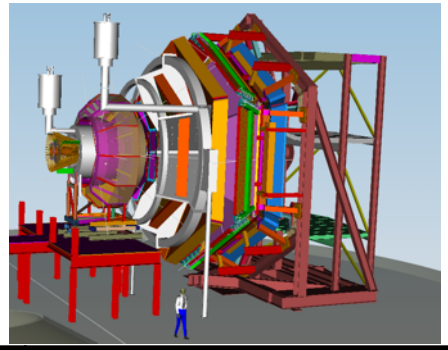
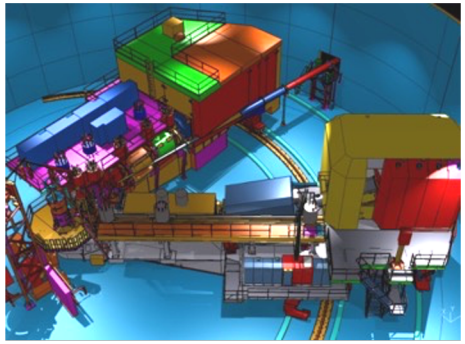
Jefferson Lab with CEBAF at 12 GeV

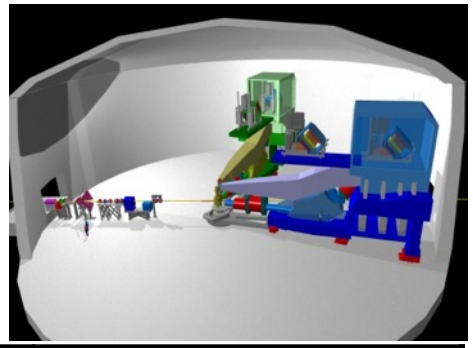


Detector Requirements: Complementarity









Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	custom installations
polarized photons	hermeticity	precision	
E_γ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	
particle ID			

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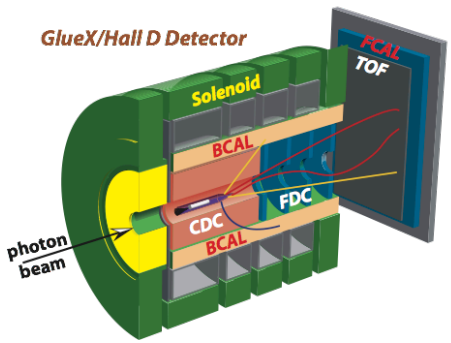
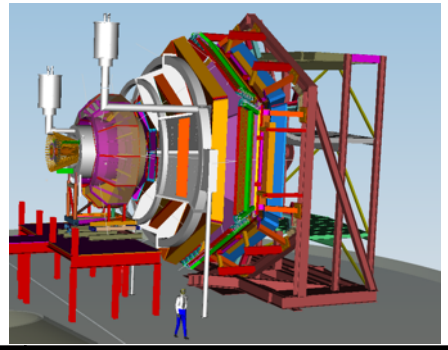
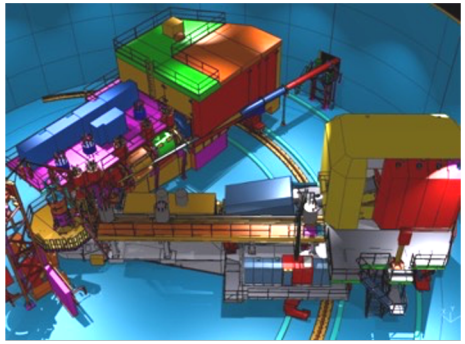
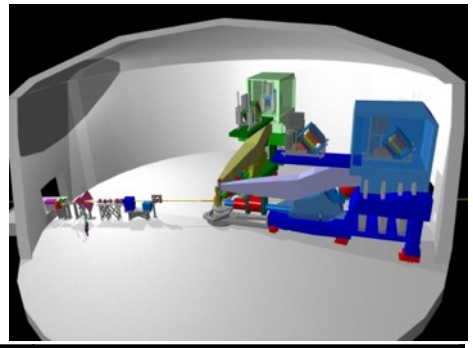
Detector Requirements: Complementarity









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10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent moment	
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Tentative Timelines relevant for TMD program shown here

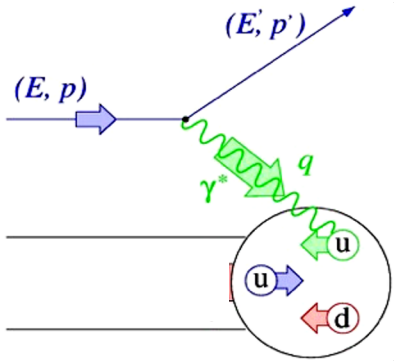
CLAS12 in Hall B

- 2018-2020: unpolarized proton/deuterium target – long. polarized beam
  - →Results shown here correspond to 15% of approved p-Data (120/90 beam days)
- FY22 polarized long target?
- Polarized He3 (long/trans)
- Polarized transverse HD

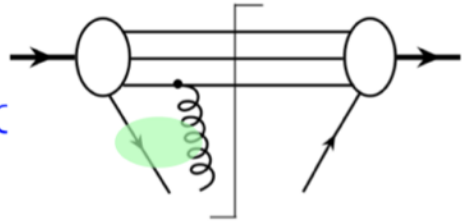
Hall A

- 2023 Transverse single spin asymmetries on He3 (64 beam days)
- 2028 SoLID with He3/proton target (long/transverse)

F_{LU} is sensitive to $e(x)$



$T^{(3)}(x,x) \propto$



Qiu, Sterman, 1991, …

- Twist-3 encode quark-gluon correlations
- Collinear twist-3 $e(x), h_L(x), g_T(x)$
- $e(x)$ can be interpreted as transverse force on transversely polarized quarks by the gluon field after being struck

Accessing e(x) in di- and single hadron F_{LU}

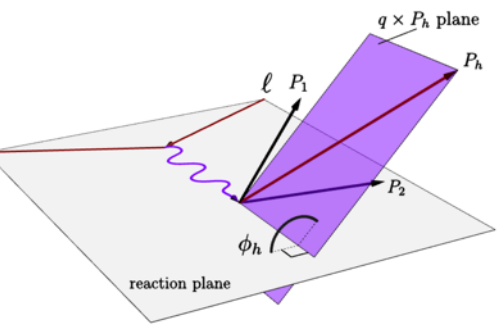
- Di-hadrons: extra degree of freedom of di-hadron FFs allow more targeted access

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

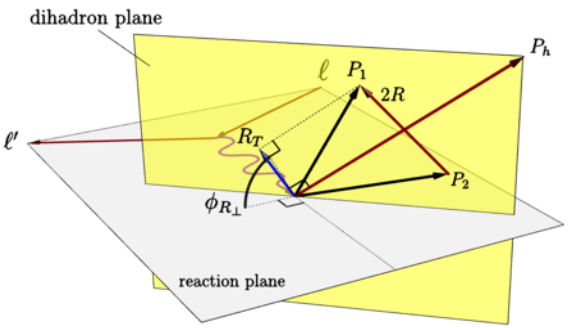
- In single hadrons: Complicated combination of four terms in the structure function.
- TMD factorization at twist-3 not yet proven!

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

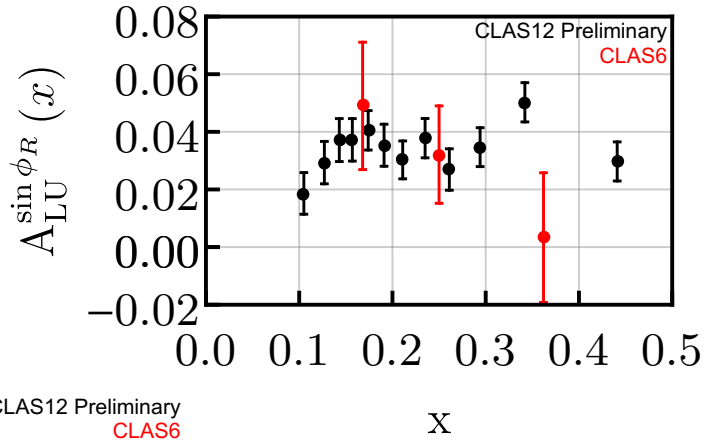
twist-3 pdf | Collins FF | unpolarized PDF | twist-3 FF | twist-3 t-odd PDF | unpolarized FF | Boer-Mulders | twist-3 FF

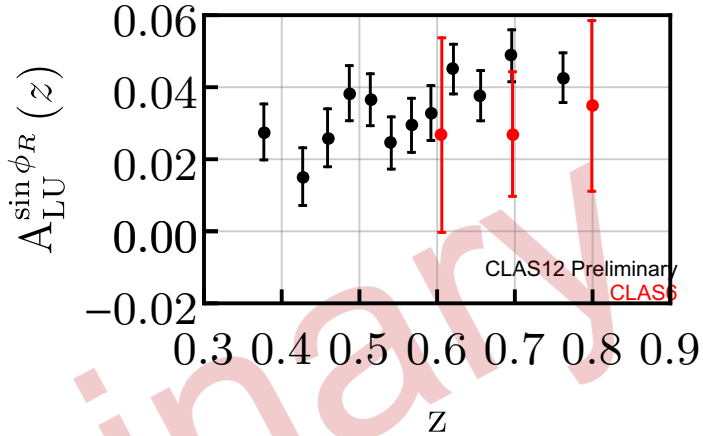


$$\overrightarrow{P_h} = \overrightarrow{P_\pi^+} + \overrightarrow{P_\pi^-},$$
$$2\vec{R} = \overrightarrow{P_\pi^+} - \overrightarrow{P_\pi^-}$$



$\sin(\phi_R)$ modulations

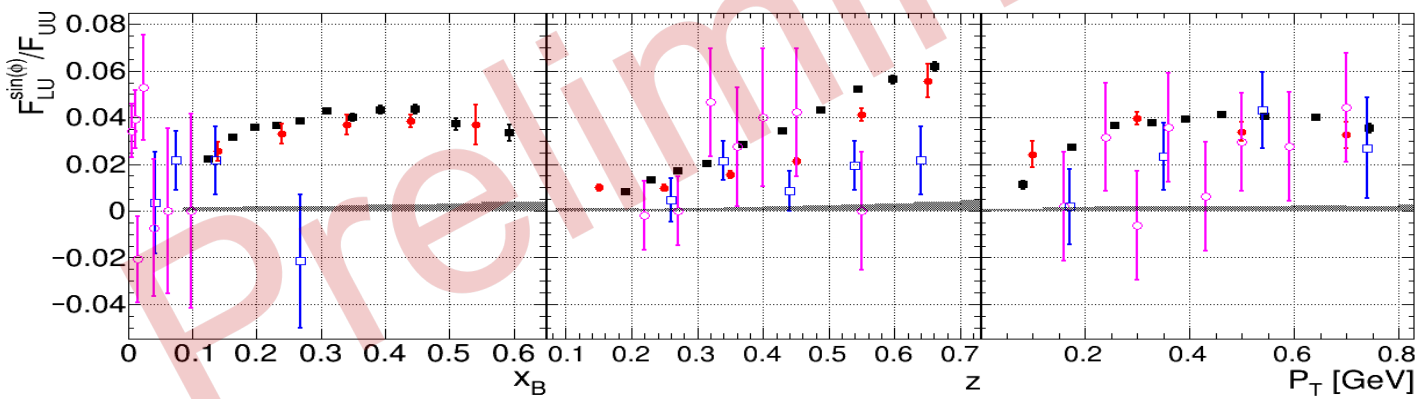




$\propto e(x)$

CLAS12 PreliminaryCLAS6

CLAS12 Preliminary
CLAS6

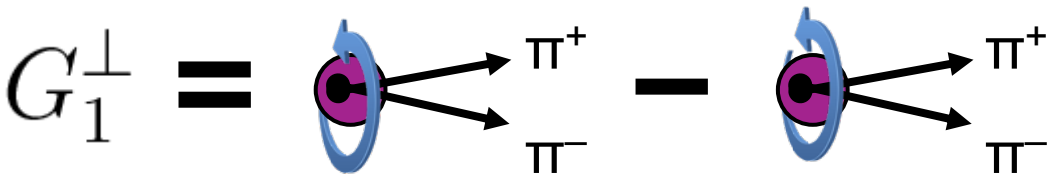


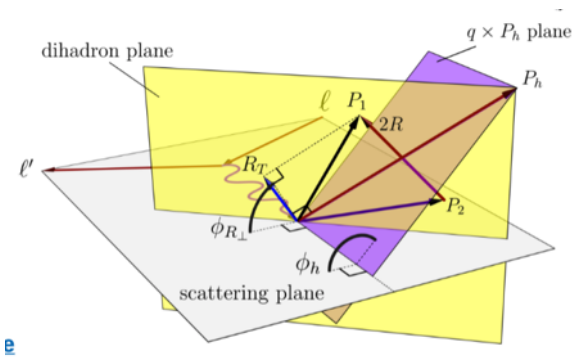
■ CLAS12 [this work]	■ CLAS [PRD 98 (2014)]
▫ HERMES [Phys. Let. B 648 (2007)]	▫ COMPASS [Nucl. Phys. B 886] (2014)]

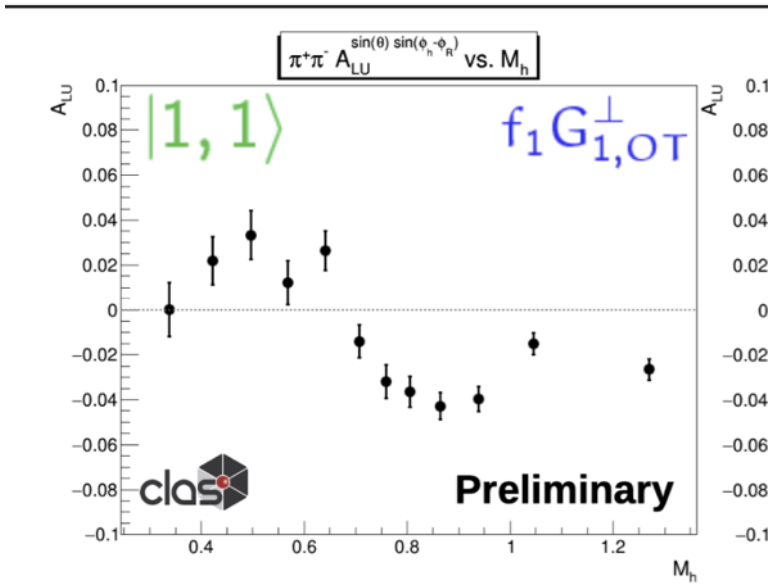
Focus of this CLAS12 study: A multidimensional study in Q^2, x_B, z and P_T

See talks by Timothy Hayward/Stefan Diehl

Wormgear FF $G_1^{\perp}$

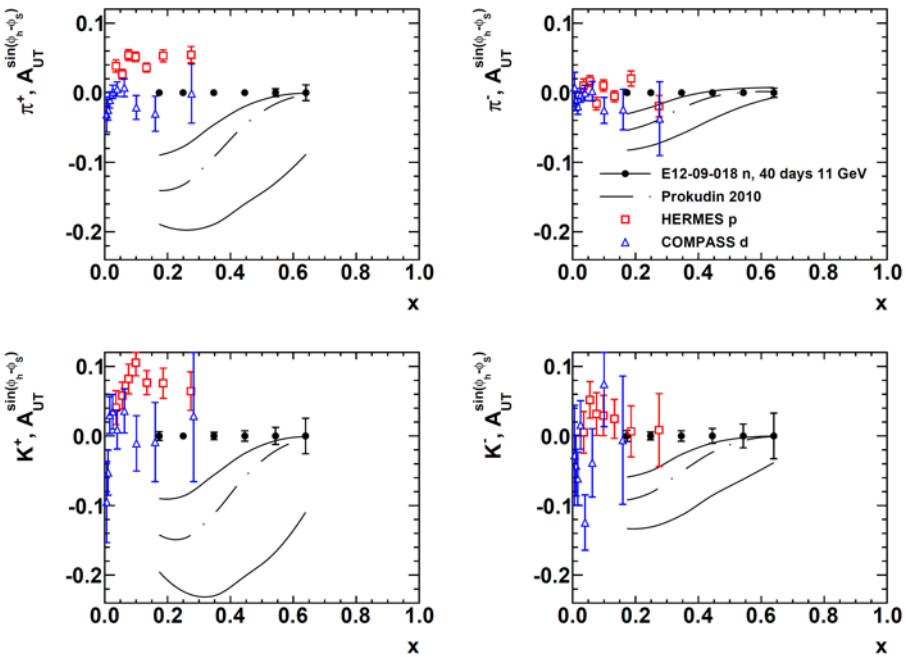




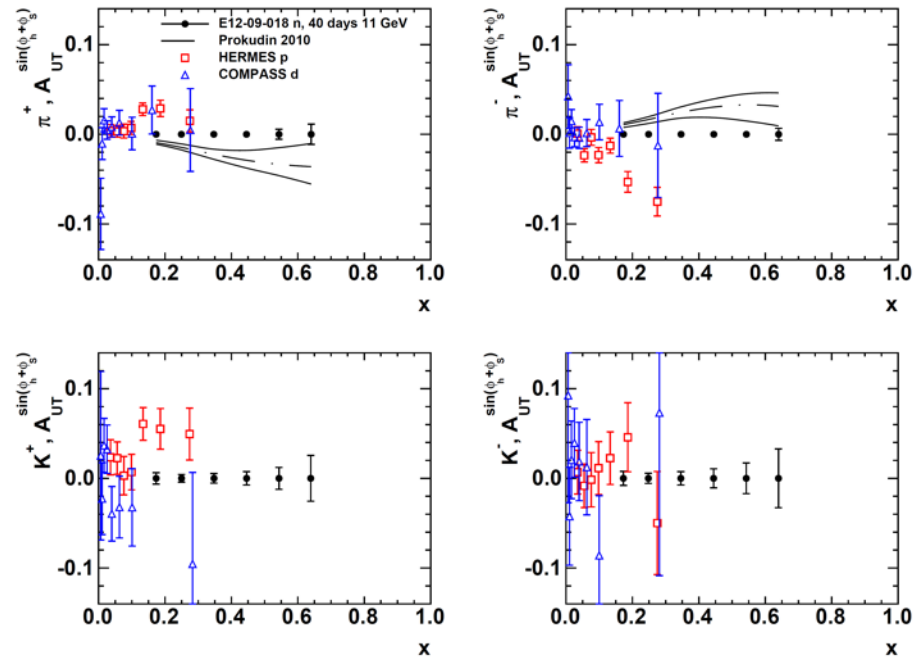


- If we allow for transverse momentum, enters cross-section at leading twist
- $\sigma_{LU} \propto \sin(\phi_h - \phi_R)\, f(x) G_1^{\perp}(z)$
- First measurement!
- See talk by Christopher Dilks

SBS+BB Projected Results: Collins and Sivers SSAs



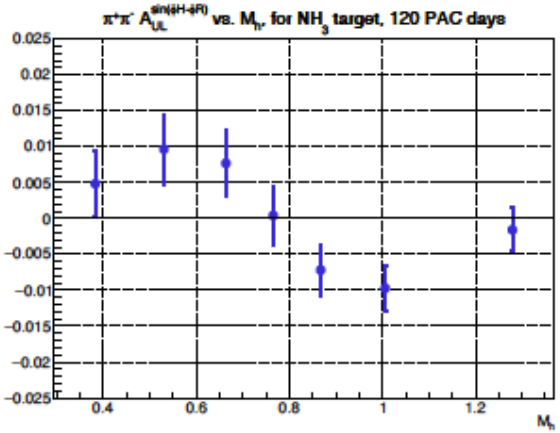
Projected A_{UT}^{Sivers} vs. x (11 GeV data only)

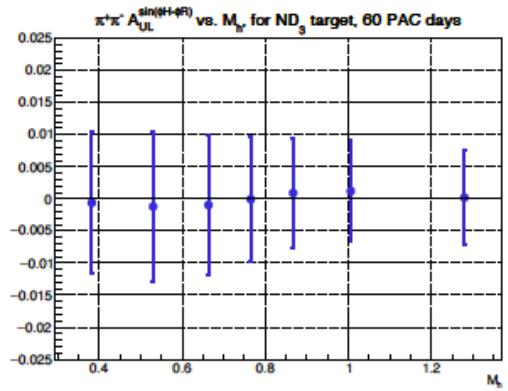


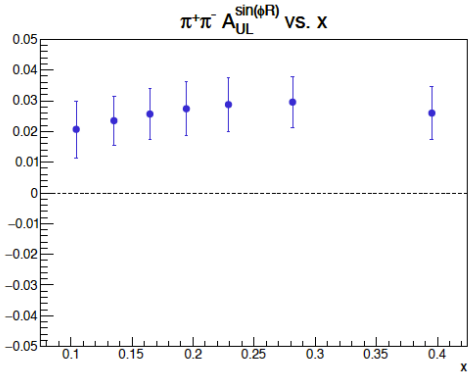
Projected $A_{UT}^{Collins}$ vs. x (11 GeV data only)

- E12-09-018 will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than Hall A E06-010 neutron data. *Near-future more precise COMPASS deuteron data will sharpen expected impacts, urgency of E12-09-018*
- SBS installation starts 2020. E12-09-018 could run as early as 2022; 2023 more likely.

Future running with polarized targets







A_{UL} projections sensitive to $G_1^{\perp}$ for 120 PAC days on NH_3

A_{UL} projections sensitive to $G_1^{\perp}$ for 60 PAC dayson ND_3

A_{UL} projections sensitive to h_L for 30 PAC dayson He_3

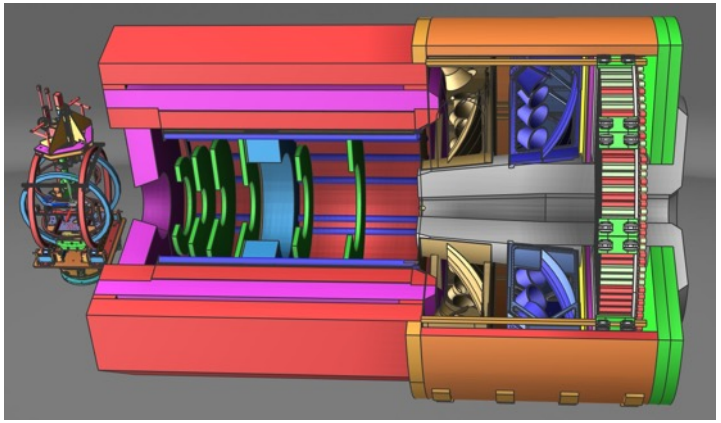
Target	Dilution f	Polarization P
NH_3	0.2	0.85
ND_3	0.285	0.35

- He_3: 50% polarization, 0.27 dilution
- Compared to Hall A: Can do di-hadrons and easier access to transverse momentum dependence
- Statistics in Hall A likely better

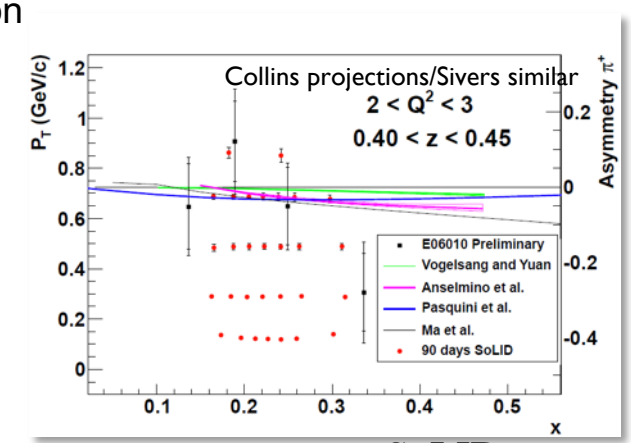
Nucleon momentum tomography and confined motion

Polarized ^{3}He (``neutron") @ SoLID

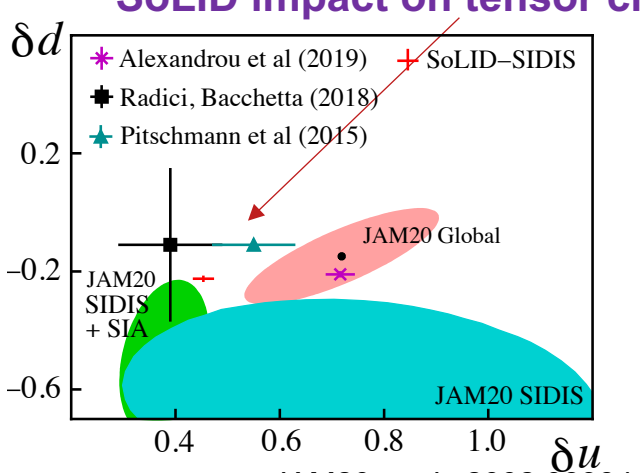
SoLID provides *unique* capability combining high luminosity ($10^{37\text{-}39}$ /cm^2/s) (>100 of CLAS12; >1000 times of EIC) and **large acceptance** with full ϕ coverage to maximize the science return of the 12-GeV CEBAF upgrade



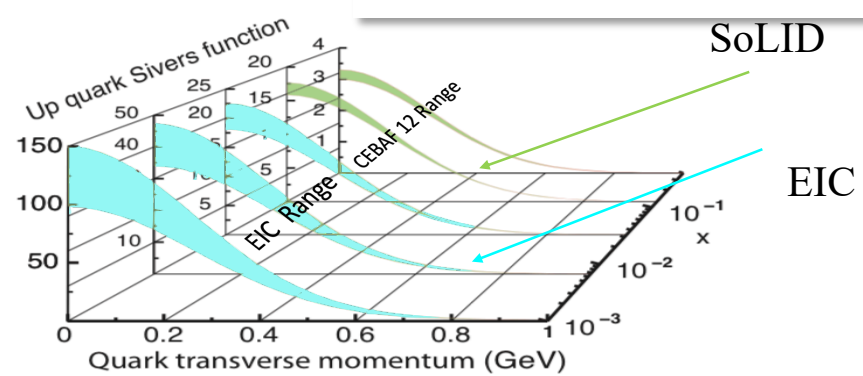
- Sivers: an example of TMDs
- Confined quark motion inside nucleon
- Quantum correlations between nucleon spin and quark motion
- QCD dynamics



SoLID impact on tensor charge

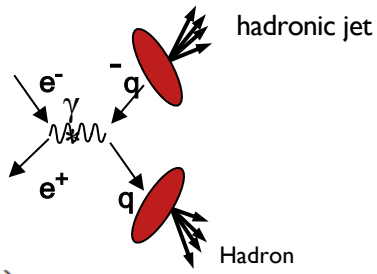


JAM20: arxiv:2002.08384



- Tensor charge: a fundamental QCD quantity to test lattice QCD
- Probe new physics combined with EDMs

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

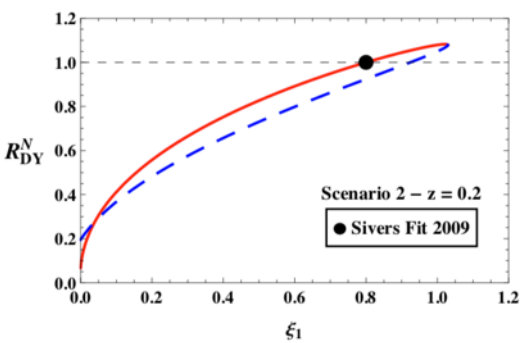


$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{e^+e^-\to hX}}{dz} := \frac{1}{\sum_q e_q^2}\left(2F_1^h(z,Q^2)+F_L^h(z,Q^2)\right),$$

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

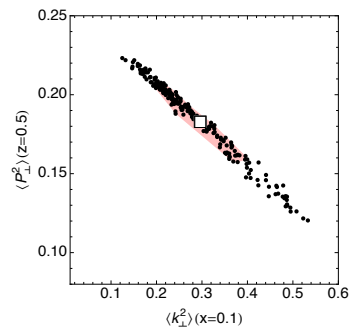
- Cleanest process→testbed for QCD calculations

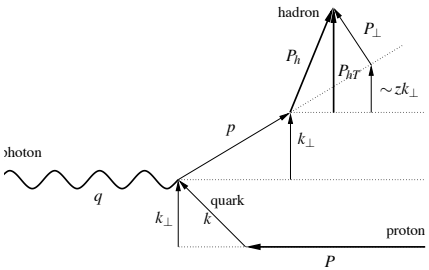
  - SIDIS necessary to extract flavor dependence of FFs but cannot disentangle source of pT



variation in Sivers effect varying $\xi = \frac{k_T}{p_T}$

Phys.Rev. D98 (2018) no.9, 094023

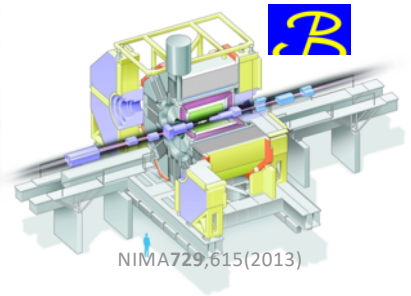




JHEP 1311 (2013) 194

Role of b-factories

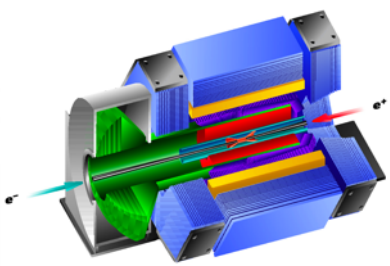
- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma=0.425$
- $L \sim 1$ ab^{-1}

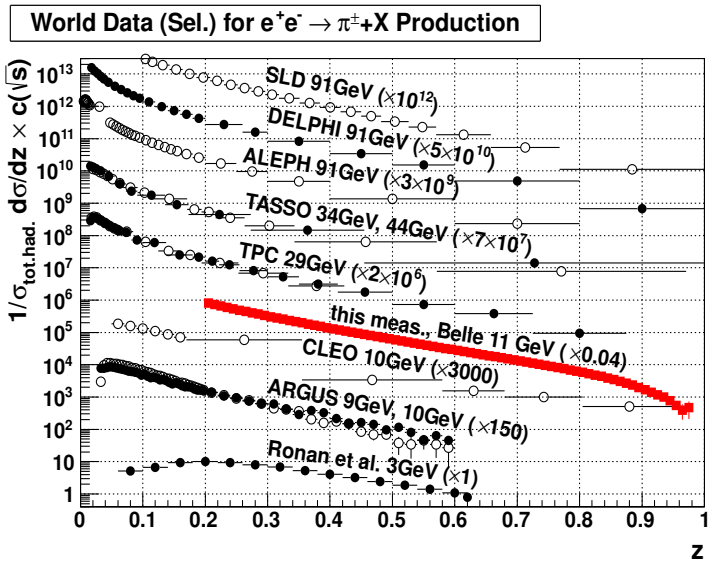


NIMA729,615(2013)

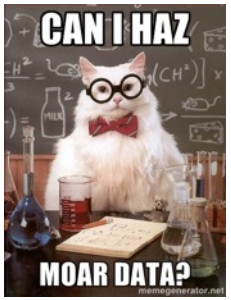
NIMA479,117(2002)

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





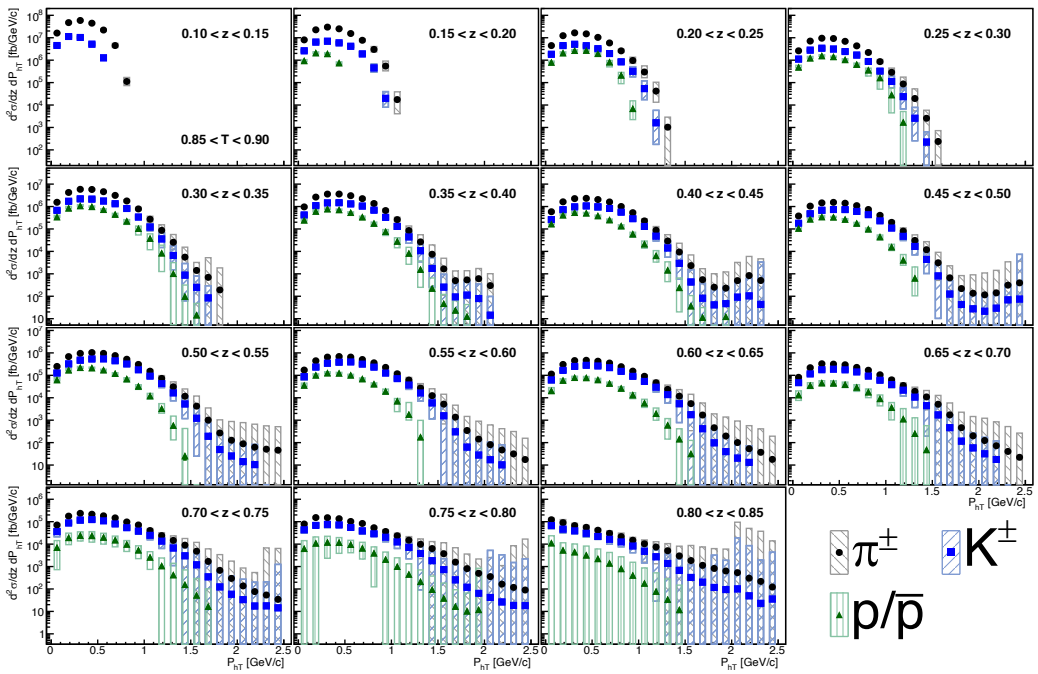
Phys.Rev.Lett. 111 (2013) 062002 (Belle)
Phys.Rev. D88 (2013) 032011 (BaBar)

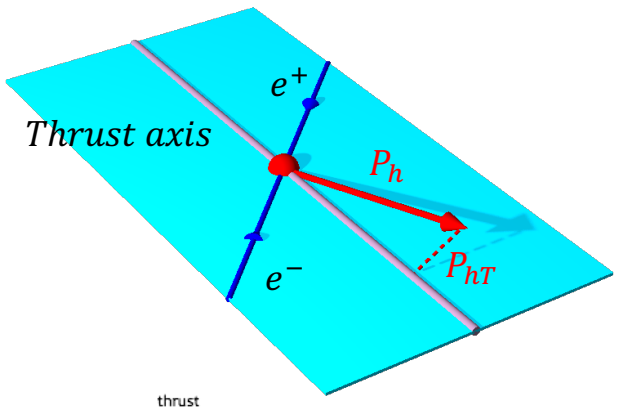


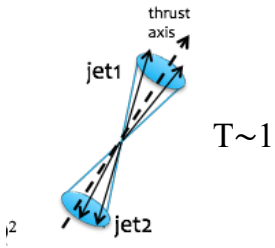
- Dominated by B factories
- Limited lever arm in $\sqrt{s}$ in particular at high z
- Precision data includes charged single hadrons π, K, p, D, Λ, charmed baryons…
- Well described at NNLO (e.g. DSS, NNFF)

New: P_T dependence
Seidl et al, Phys.Rev. D99 (2019) no.11, 112006

- Quasi inclusive hadron production gives access to transverse momentum in fragmentation
- **Transverse momentum measured with respect to thrust axis**



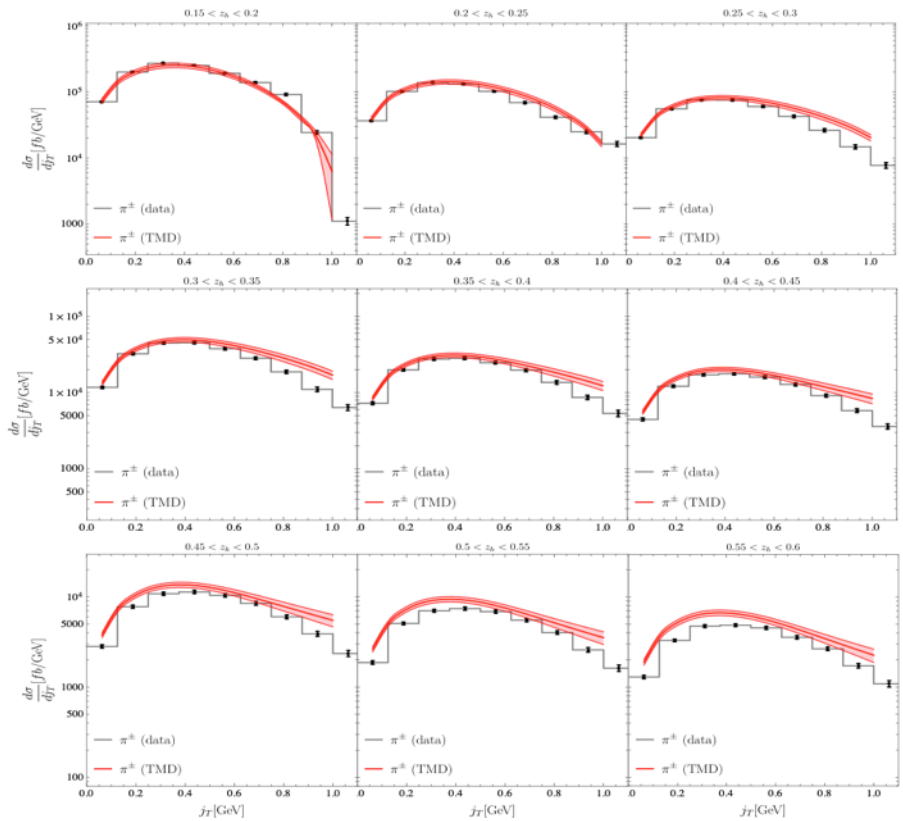




- 0.85< Thrust T < 0.9
  - Transverse momenta mostly Gaussian
  - Possible deviations for large P_{hT} tails, but also large uncertainties

Theory description of p_T vs thrust made progress

- Factorization and resummation derived



From Kang, Shao, Zhao
e-Print: 2007.14425 [hep-ph]

See also Boglione, Simonelli e-Print: 2007.13674 [hep-ph]
Makris, Ringer, Waalewijn 2009.11871 [hep-ph]

Polarized Hyperon Production

PRL36, 1113 (1976); PRL41, 607 (1978)

- Large Λ transverse polarization in unpolarized pp collision
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- Polarizing FF is chiral-even, has been proposed as a test of univers

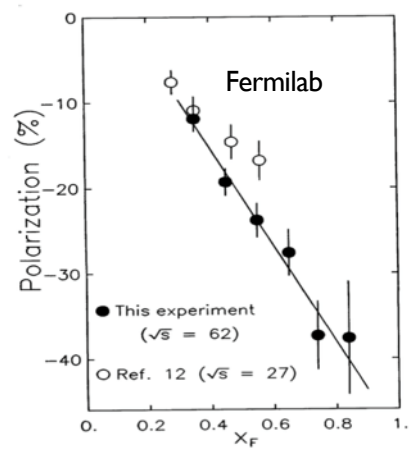
PRL105,202001 (2010)

- OPAL experiment at LEP has studied transverse Λ polarization, no s observed.

Eur. Phys. J. C2, 49 (1998)

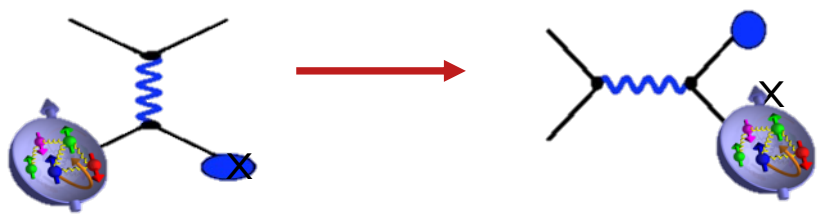
- $\Lambda^{\uparrow}$ production counterpart of the Sivers function.

$p + p \rightarrow \Lambda^{\uparrow} + X$



ISR data
(Phys.Lett. B185 (1987) 209)

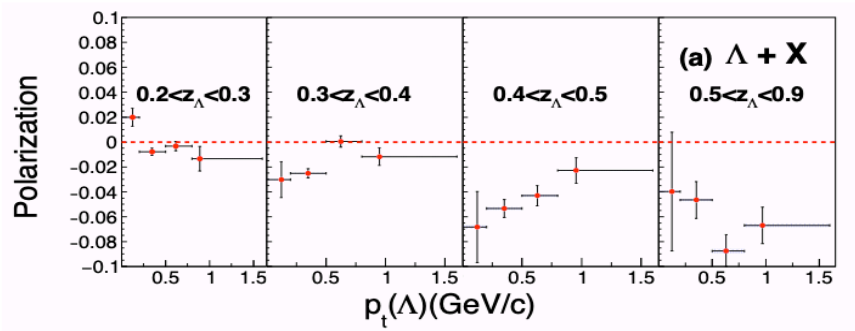
$x_F = p_L / \max p_L \sim_{LO} x_1 - x_2 \sim_{forward} x_1$



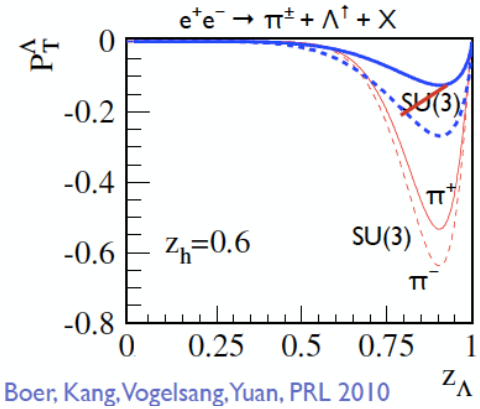
Spacelike SIDIS

Timelike SIA

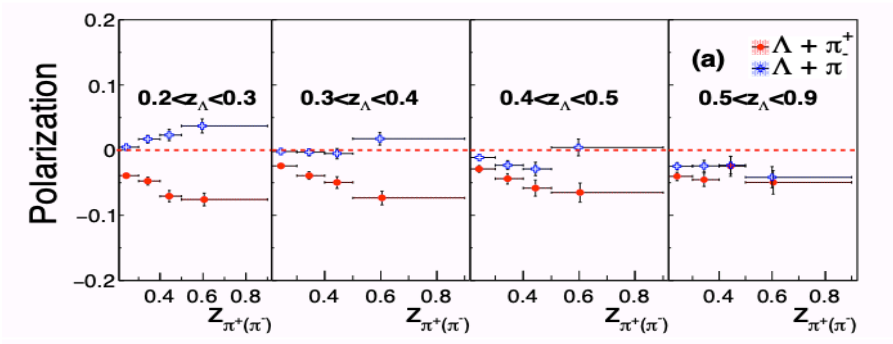
z_Λ, p_T Dependence of observed Λ polarization

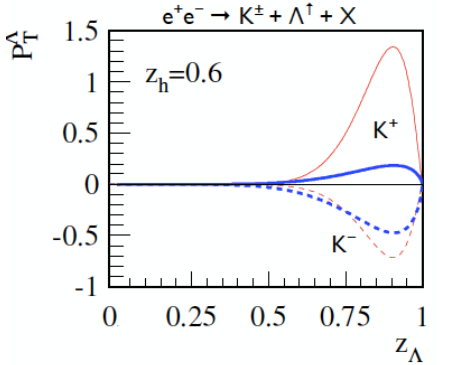


Y. Guan, *Phys.Rev.Lett.* 122 (2019) 4, 042001



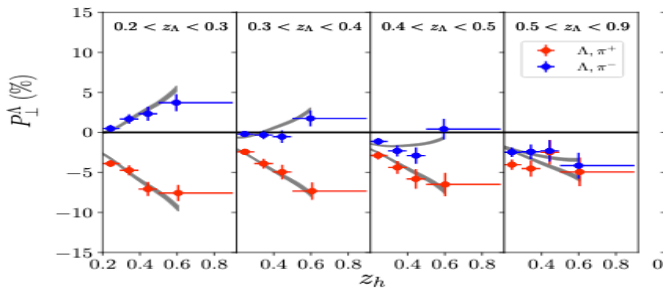
Boer, Kang, Vogelsang, Yuan, PRL 2010

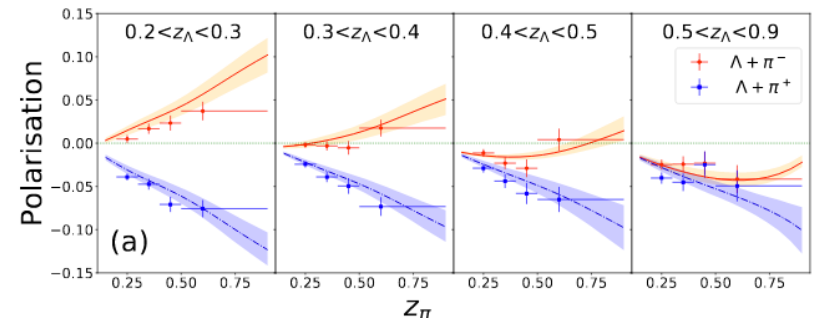


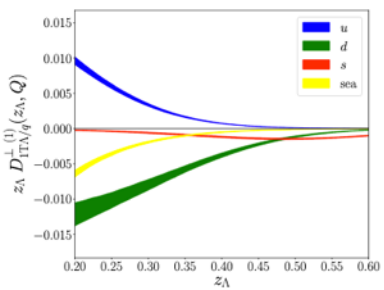


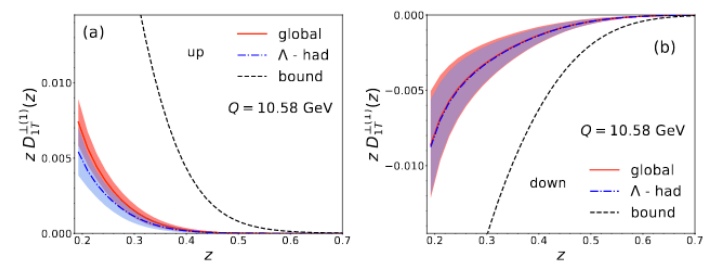
- Polarization rises with p_t in the lowest z_Λ and highest z_Λ bin. But the dependence reverses around 1 GeV in the intermediate z_Λ bins→**Unexpected!** (might be related to fragmenting quark flavor dependence on z_1,z_2)
- Correlation with opposite hemisphere light meson →quark flav/charge dependence

Extraction of Lambda FF from Belle data



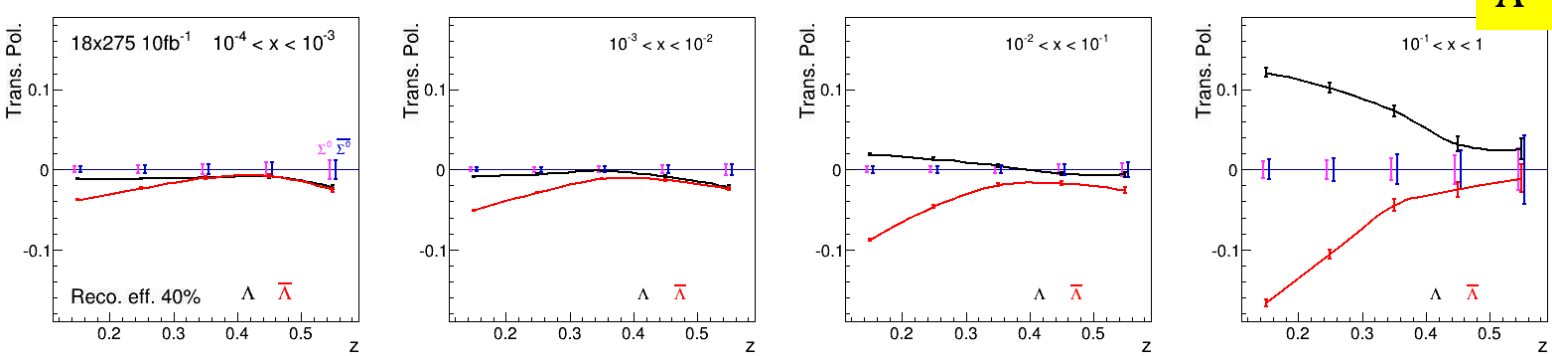






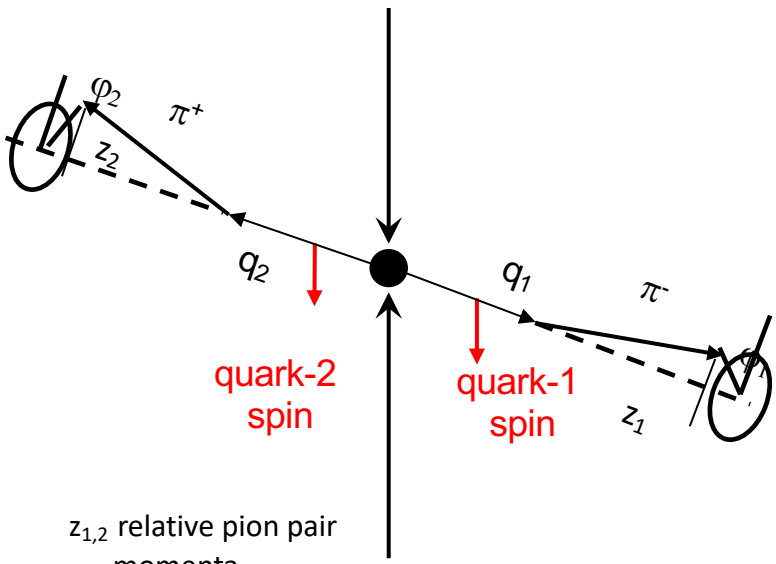
Callos, Kang, Terry, 2003.04828 [hep-ph], (left) D'Alesio, Murgia, Zaccheddu, *Phys.Rev.D* 102 (2020) 5, 054001 (right)

$\Lambda^{\uparrow}$ at the EIC



Kang, Terry, Vossen, Zhang produced for the EIC YR

Collins FFs in e^+e^-



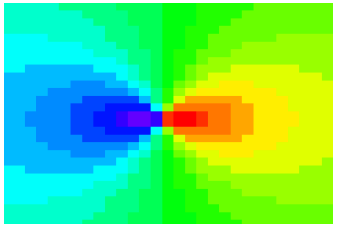
$z_{1,2}$ relative pion pair momenta

•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 Kπ)
- Measured at BESIII @ $\sqrt{s} = 3.65$ GeV (PRL 116,42001(2016))

Cross-section $e^+e^- \to (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

$$\propto D_1^{\perp}\,\overline{D_1^{\perp}} + H_1^{\perp}\,\overline{H_1^{\perp}}\cos(\phi_1 + \phi_2)$$



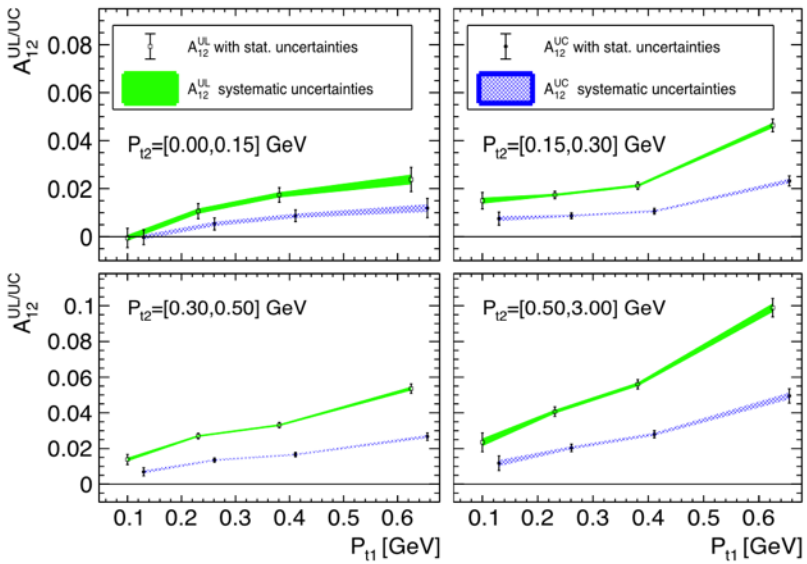
- Access spin dependence and p_T dependence (convolution or in jet) without PDF complication
- Made possible by B-factory luminosities

New P_t dependence from Belle

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

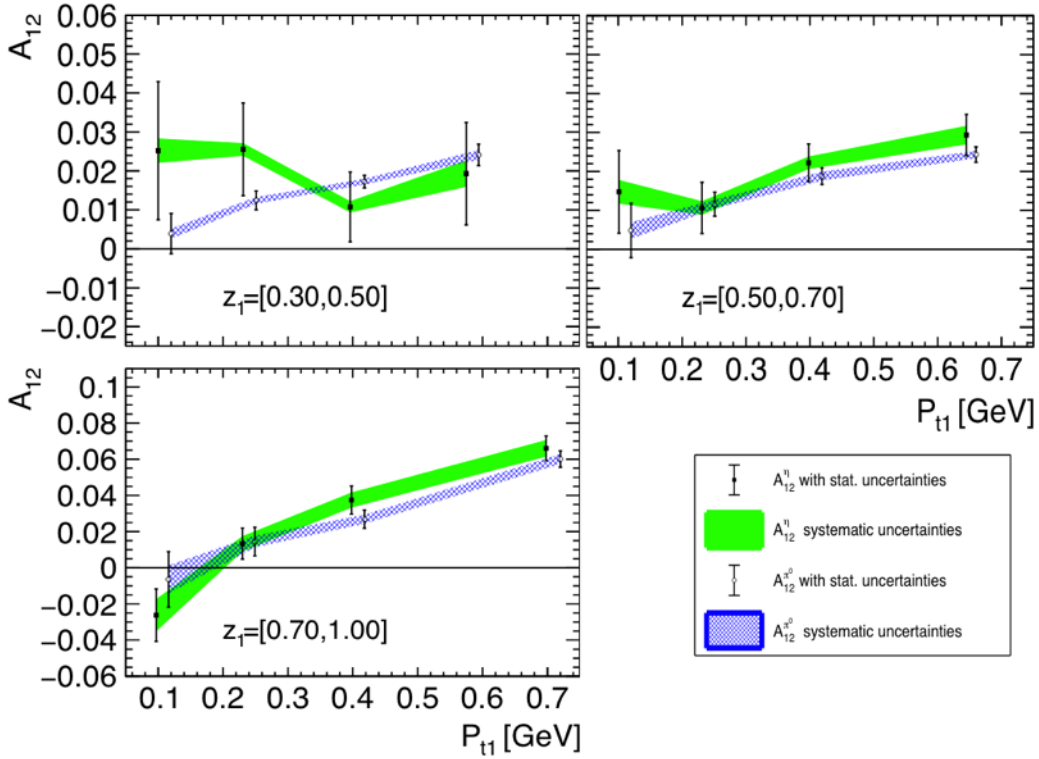
Unlike/**L**ikesign

Ratios to cancel acceptance effects
<u>Unlike:</u>
fav*fav+dis*dis
<u>Like:</u>
fav*dis



New π^0/η from Belle

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



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

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

The future is now: Next Generation B factory SuperKEKB

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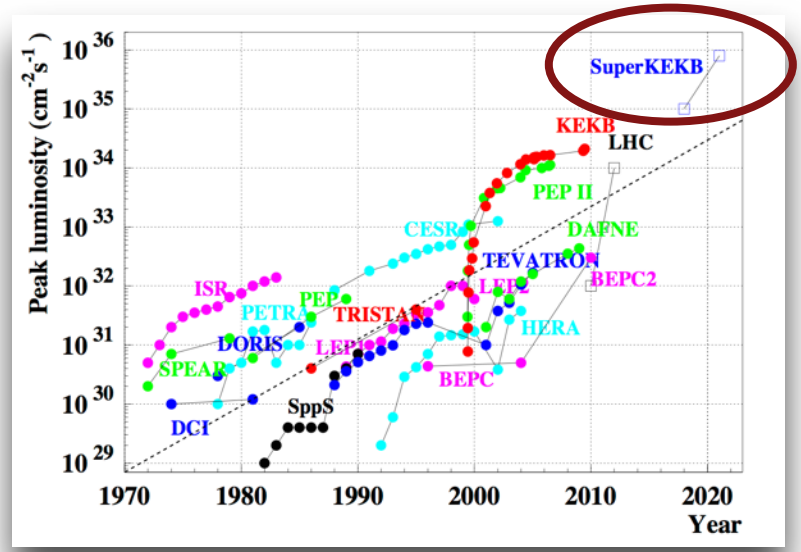
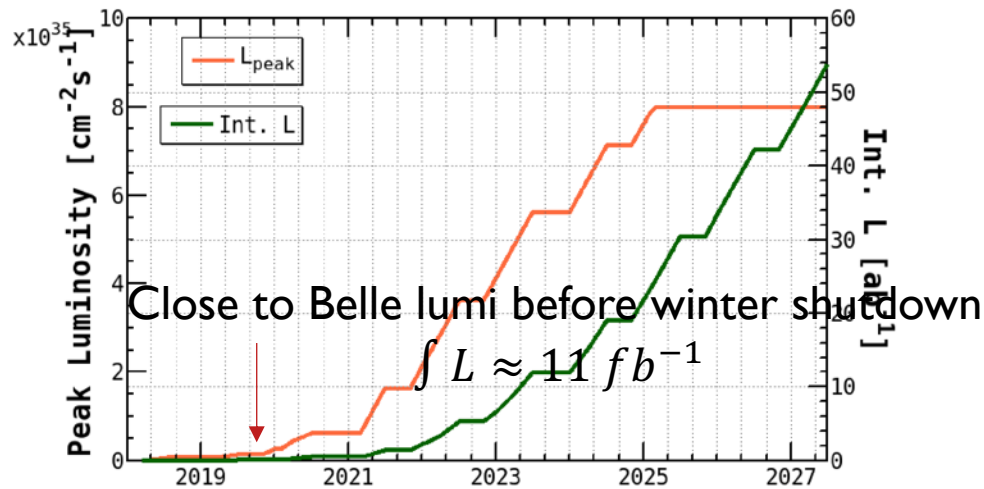


Belle/KEKB recorded ~1000 fb^{-1} . Now have to change units on the y-axis to ab^{-1}

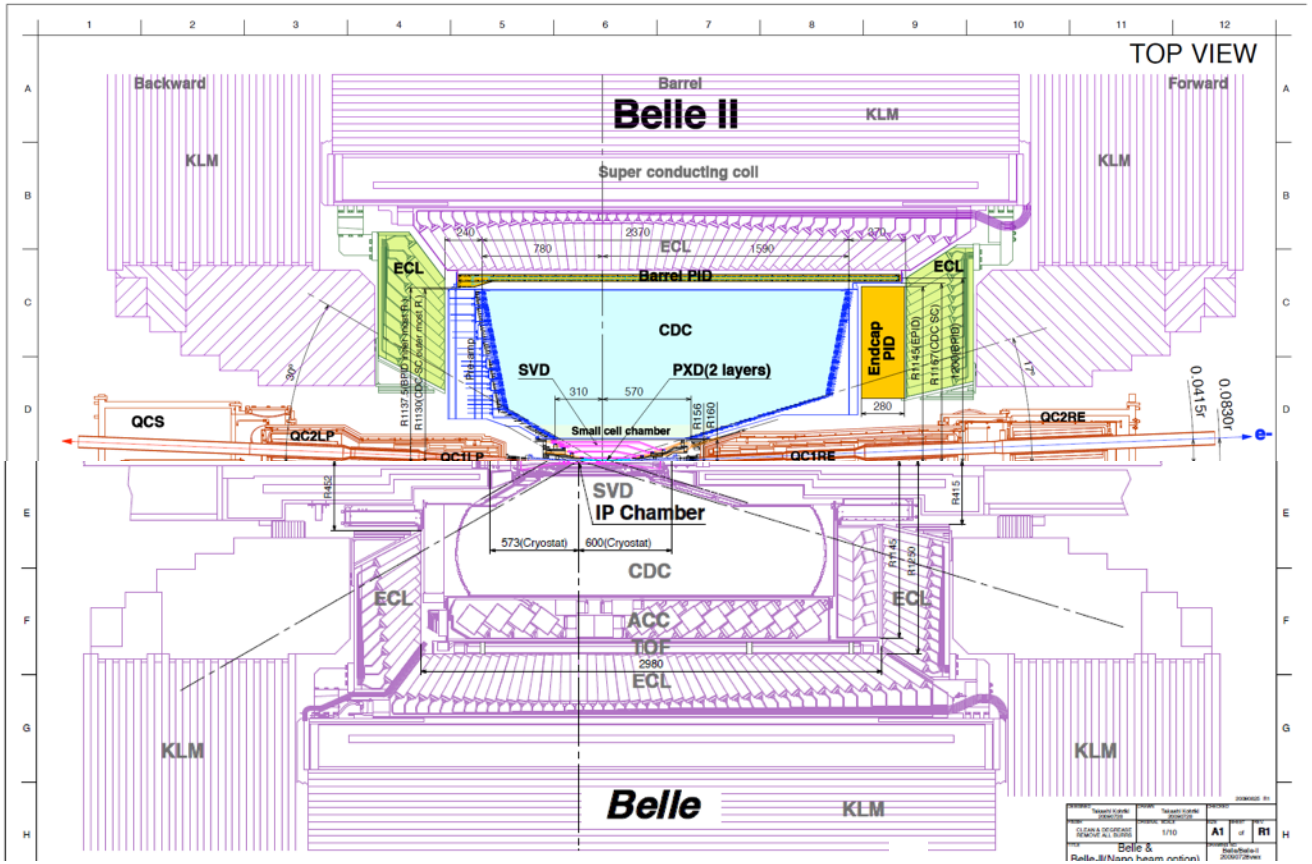


Beam currents *only* a factor of two higher than KEKB (~PEPII)

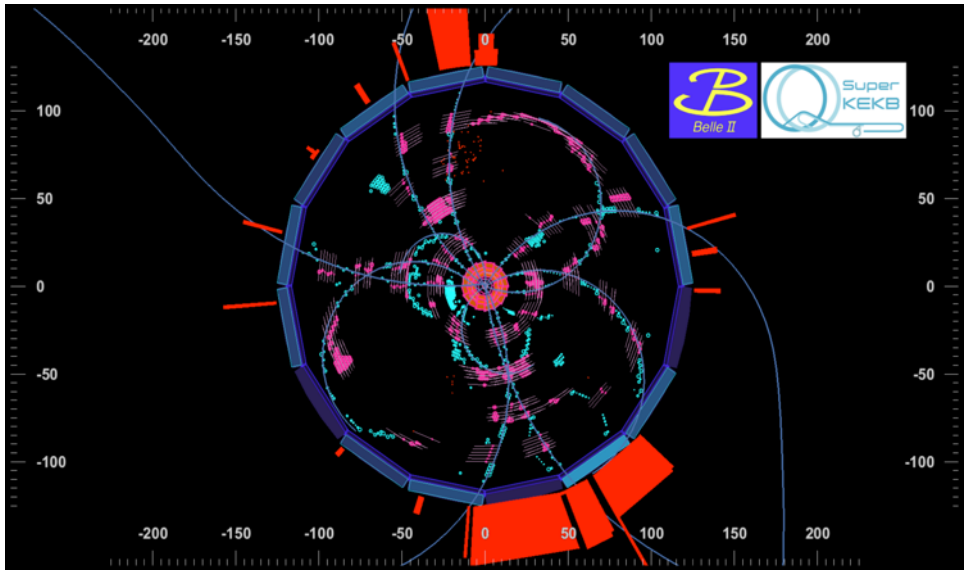
"nano-beams" are the key; vertical beam size is 50nm at the IP

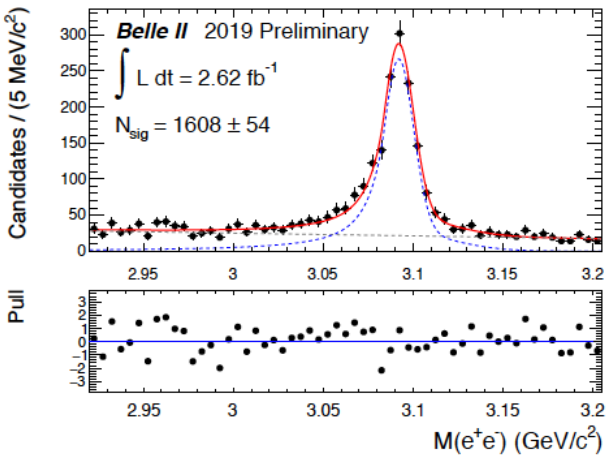
- $\int L$ needed to map out fully differential $d\sigma$ of polarized FF
  - θ , flavor dependence for di-hadrons
  - $p_T, z, z_{\pi,K}$ for Λ (also correction for feed-down needs statistics)
  - Kaon single hadrons

Belle II Detector (comp. to Belle)



2019: First Collisions in Phase 3, the Physics Run





Clear signals for B→J/ψ X in ~1/2 of Phase 3 data.

Conclusion

- Jlab has rich program in TMD physics, 3D nucleon Femtography in general
- Near term: CLAS12 has first exciting results available
- Medium term: Hall A/SoLID will provide unparalleled precision

- Belle/Belle II has rich program to study hadronization
- Results crucial ingredient to extract transverse momentum dependence/flavor dependence of TMDs from single/di-hadron channels
- Lambda production in e+e- provides complimentary tests of QCD