Results from e^+e^- – related to TMDs and the extraction of transversity

A more complete description of the Belle II QCD program can be found in
"Opportunities for precision QCD physics in hadronization at Belle II -- a snowmass whitepaper"
e-Print: 2204.02280 [hep-ex]

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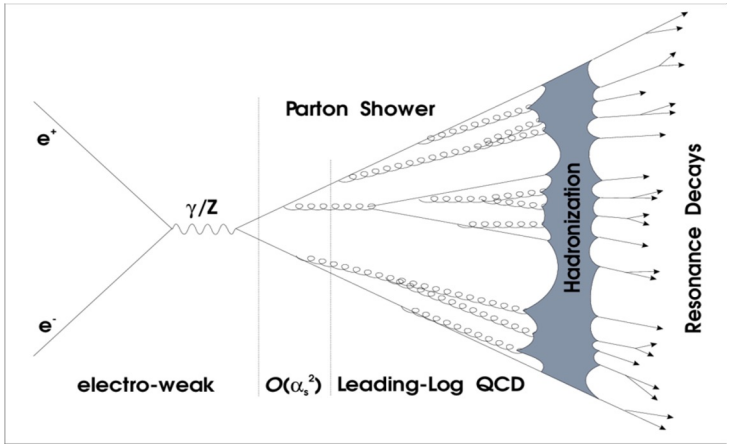
U.S. DEPARTMENT OF ENERGY | Office of Science

e^+e^- is the cleanest process to access Fragmentation Functions

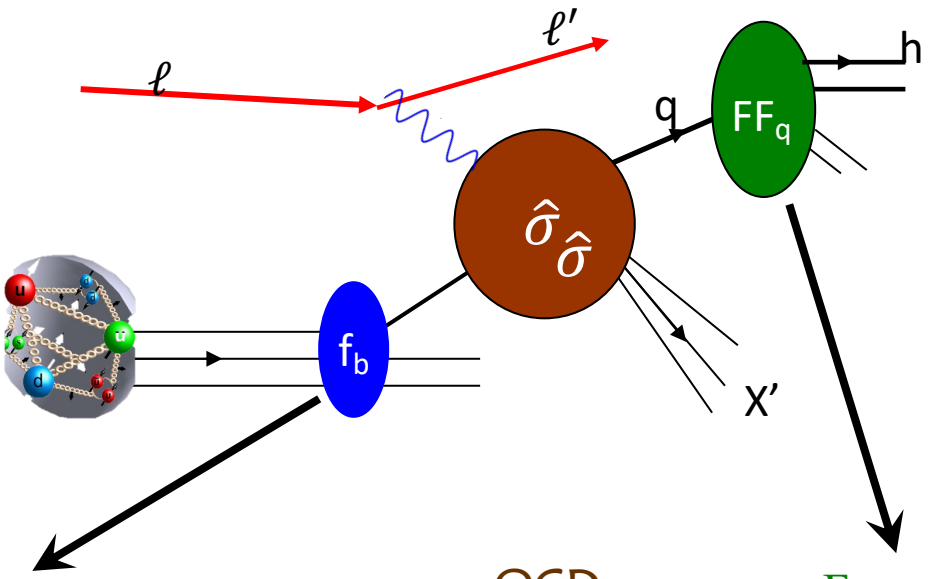


- FFs encode the non-perturbative link between perturbative QCD processes and the observed final state particles
- Determining final state polarization needs self analyzing decay (Λ)

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)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$ =	$G_{1T}^{h/q}(z,p_T)$=	$H_1^{\Lambda/q}(z,p_T)$ = $H_{1T}^{\perp\Lambda/q}(z,p_T)$ =

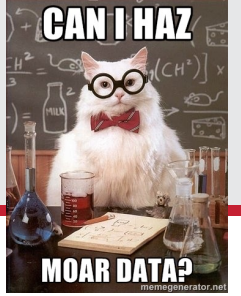
Fragmentation Functions appear almost always when accessing partonic structure of the nucleon

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes
- **Particular important for transverse spin structure**



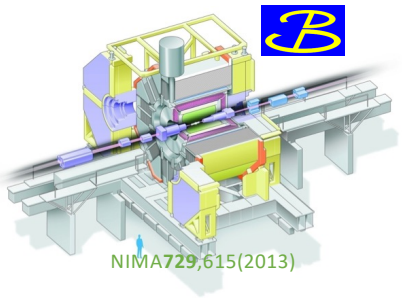
$$\frac{d^2\sigma(ep \to \pi X)}{dx\,dz} \propto \underbrace{q(x,k_T)}_{\text{Proton Structure}} \times \underbrace{\frac{d\sigma^2(e\,q \to e'q')}{dx}}_{\text{pQCD}} \times \underbrace{FF(z,p_T)}_{\text{Fragmentation Function}}$$

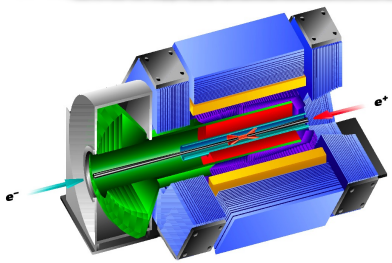
Role of b-factories



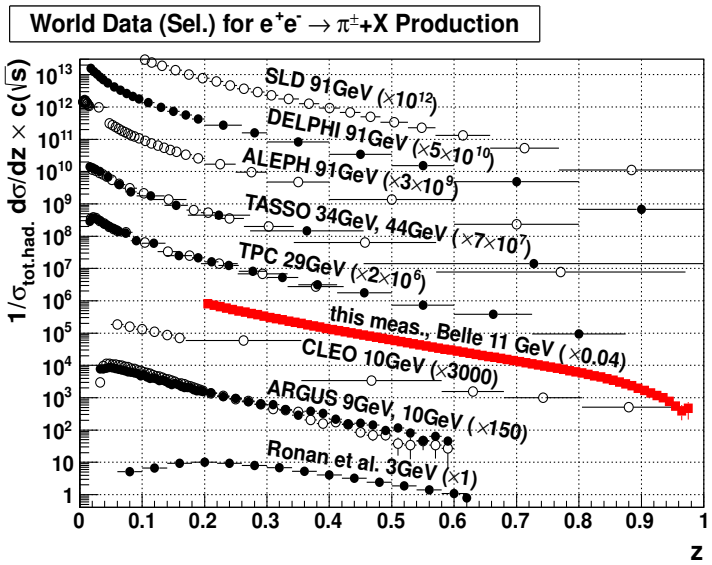
- Dominated by B factories
- Limited lever arm in $\sqrt{s}$ in particular at high z
- Precision data includes charged single hadrons π, K, p, D, baryons…
- Well described at NNLO (SIA) or NLO (SIDIS) (e.g. DEHSS /MAPFF)
- BES III with $\sqrt{s} < 4\ GeV$ tests framework at low energies (albeit low statistics)

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



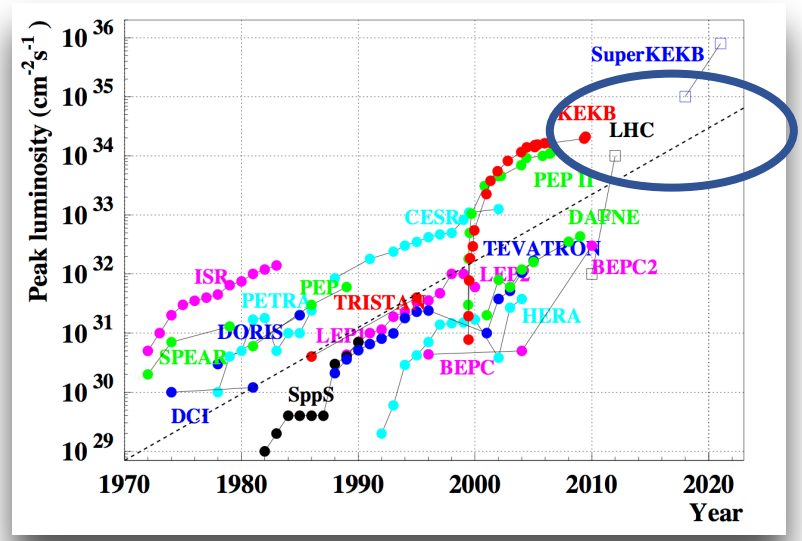


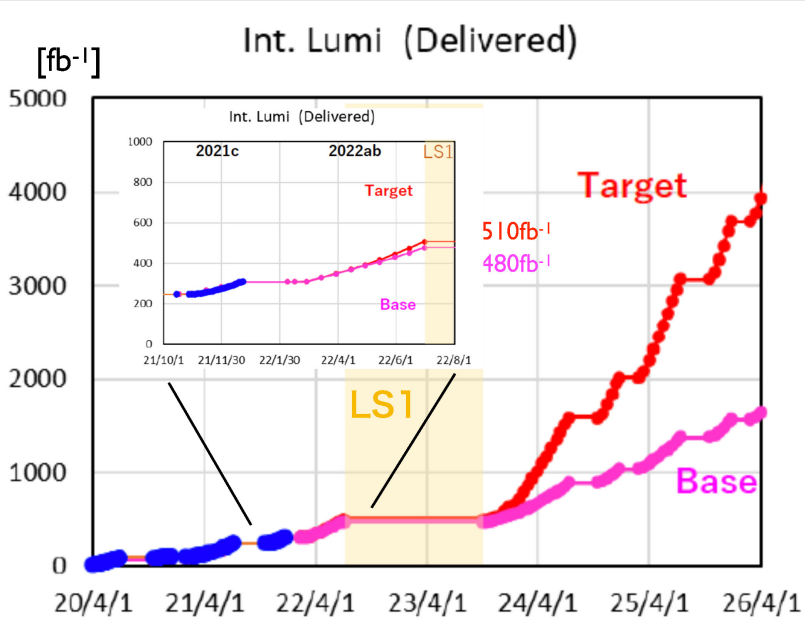
•Asymmetric-energy e^+e^- collider
• $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
• $\beta\gamma=0.65$
• L ~ 500 fb^{-1}



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

The future is now: Next Generation B factory SuperKEKB



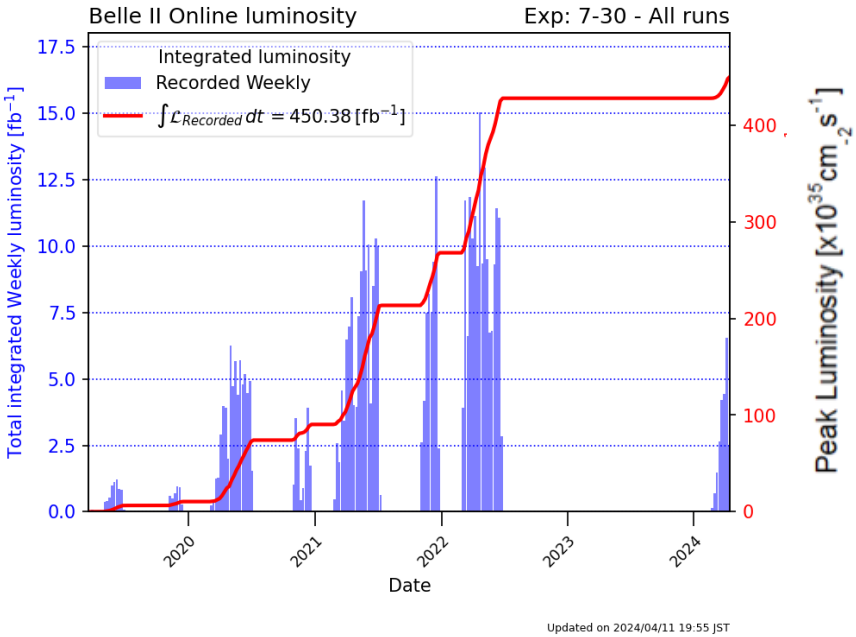


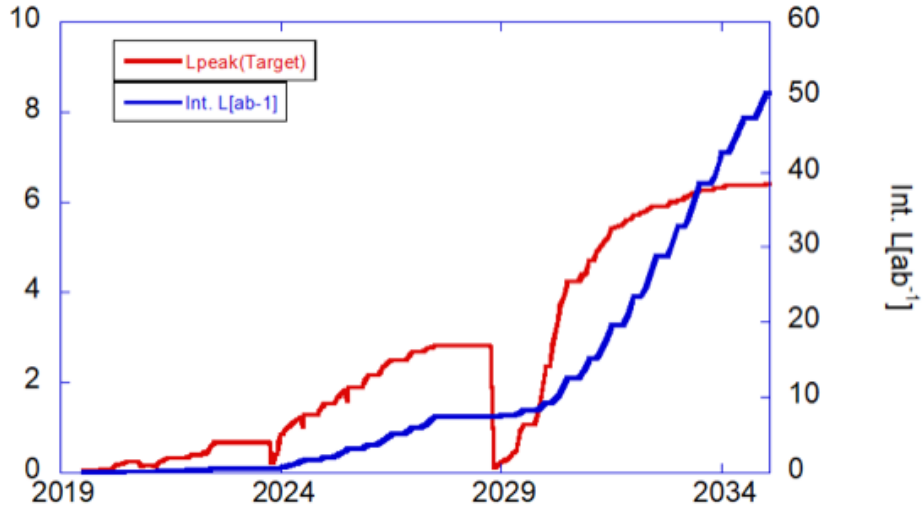
Beam currents *only* a factor of two higher than KEKB (~PEPII)

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

- Belle II already delivered world record luminosity
- Belle II aims to have significantly higher luminosity, current record: $4.7\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$.
- Future P5 recommendation: FCC-ee or muon collider up to 10 TeV
  - $\frac{1}{s}\sigma$- dependence, dataset of 10s of ab^{-1}
    $\Rightarrow$ no precision measurement outside the Z resonance

Short and long term goals



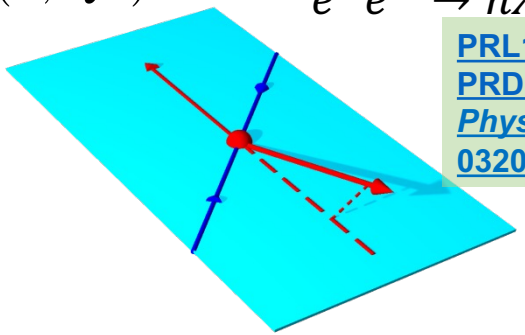


- What Belle II brings to the table for existing channels
  - High statistics
    - →complex final states
    - →complementary to EIC
  - Trigger → low multiplicities

Single Hadron FFs from Belle & BaBar

$D_{1,q}^{h}(z, Q^2)$ Single hadron cross sections:

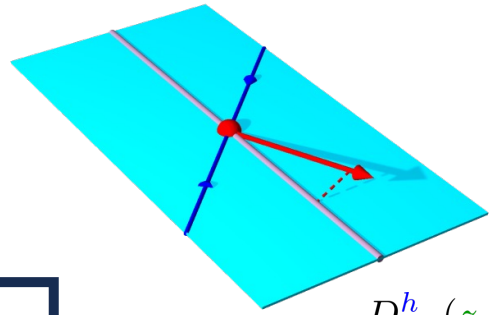
$e^+e^- \to hX$



PRL111 (2013) 062002
PRD101(2020) 092004
Phys.Rev.D 88 (2013) 032011 (BaBar)

Transverse momentum dependent asymmetries

$e^+e^- \to (h)(h)X,$

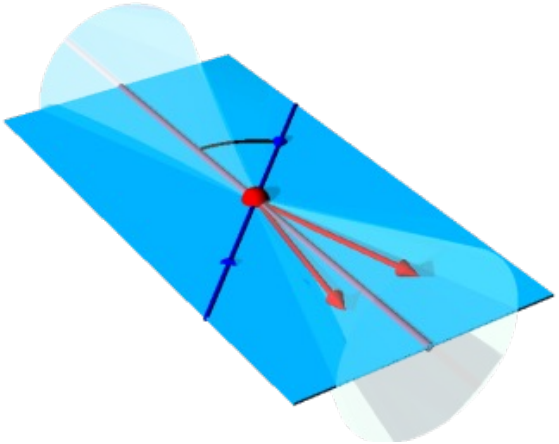


$D_{1,q}^{h}(z, k_T, Q^2)$

Unpol SIDIS, pp: $\frac{d\sigma}{dz}$

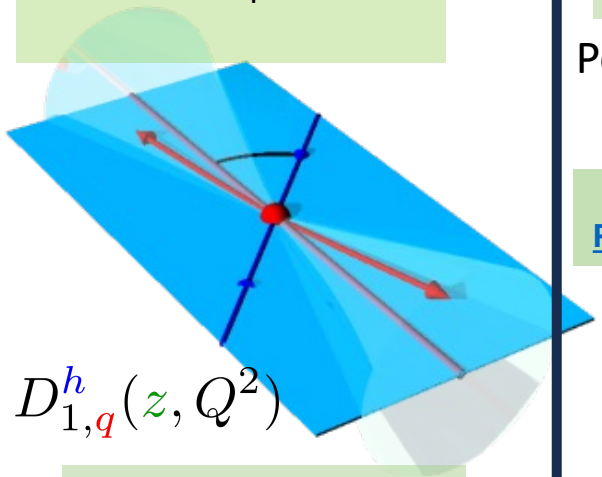
$e^+e^- \to (h)(h)X$

and scale dependence



$D_{1,q}^{h_1 h_2}(z, m, Q^2)$

PRD96 (2017) 032005



$D_{1,q}^{h}(z, Q^2)$

PRD92 (2015) 092007
PRD101(2020) 092004

Transverse momentum dependence underway

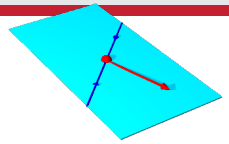
PRD 99 (2019) 112006

Polarizing Λ fragmentation

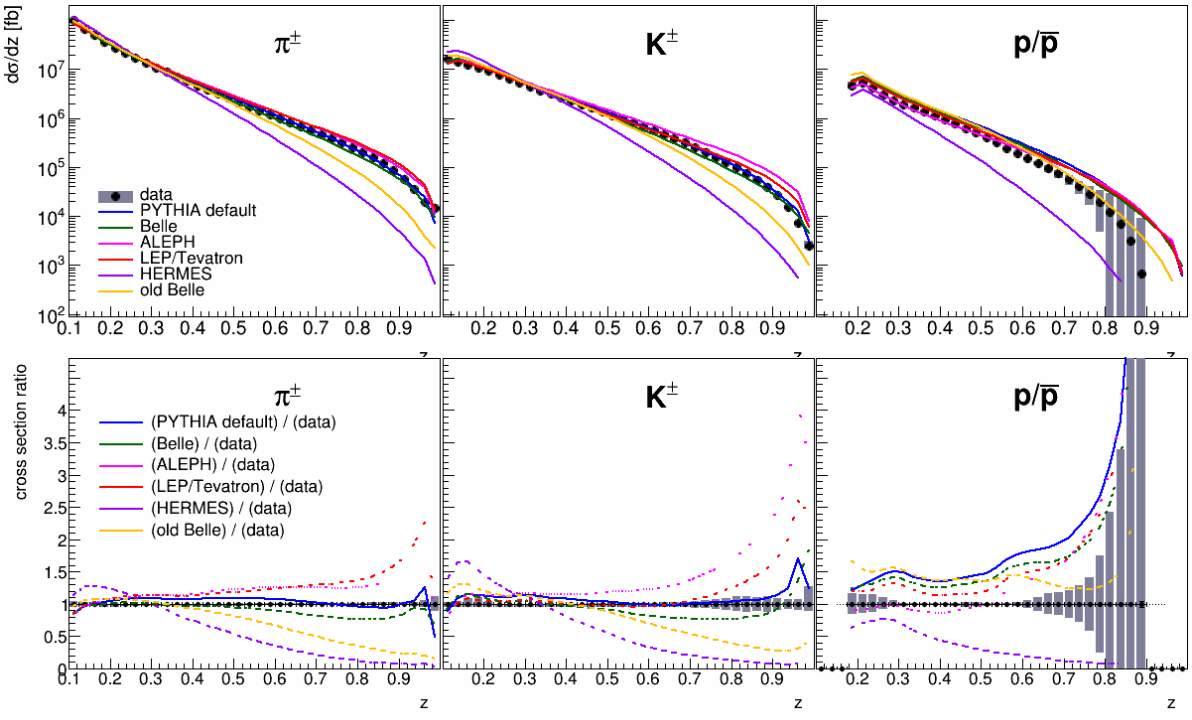
$D_{1T}^{\perp}(z, k_t, Q^2)$

PRL 122 (2019), 042001

Unpolarized single hadrons

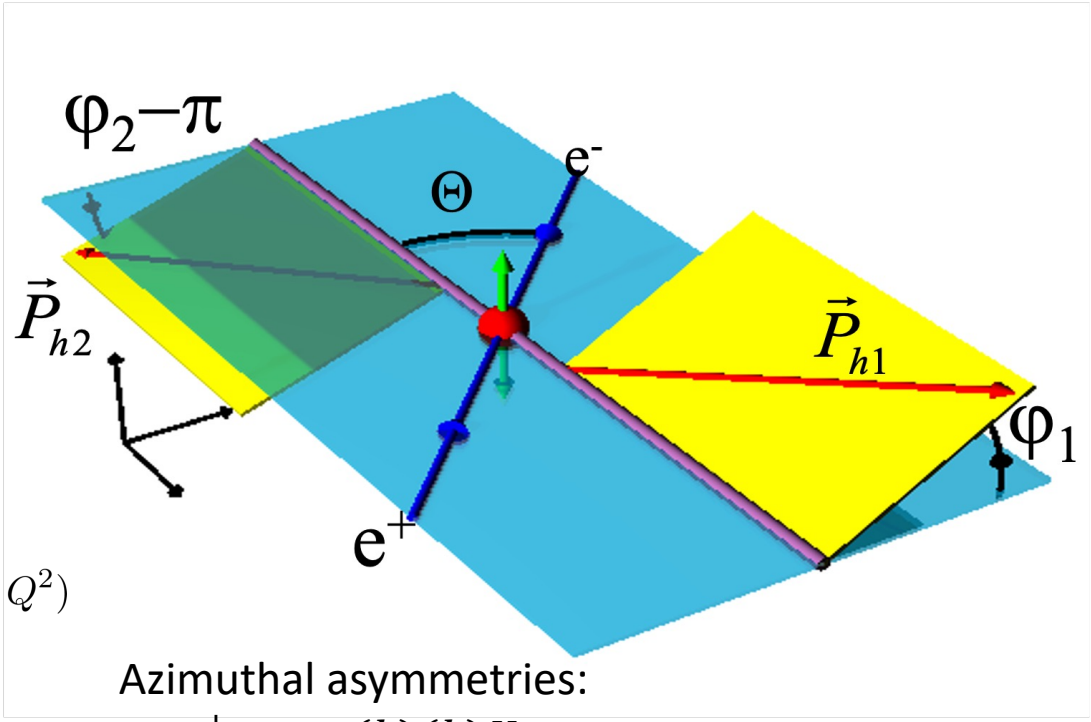


- Update with better ISR correction
- Correlated and uncorrelated uncertainties separated → improve global unpolarized FF fits



PRD 101 (2020) 092004

Polarized FFs from Belle



$H_{1,q}^{\perp(1)h}(z, Q^2)$

Azimuthal asymmetries:

$$e^+e^- \to (h)(h)X,$$

$$\sigma \propto D_1\overline{D_1} + H_1\overline{H_1}\cos(\phi_1 + \phi_2)$$

PRL 96 (2006) 232002
PRD 78 (2008) 032011
*PRD*100 (2019) 9, 092008 (p_T, π^0, η)
Phys.Rev.D 90 (2014) 5, 052003 (BaBar)
Phys.Rev.D 92 (2015) 11, 111101
(BaBar, kaon)

- Statistics Hungry, only possible at B-factories

P_T dependence of $H_1^\perp$ from Belle/BaBar/BESIII

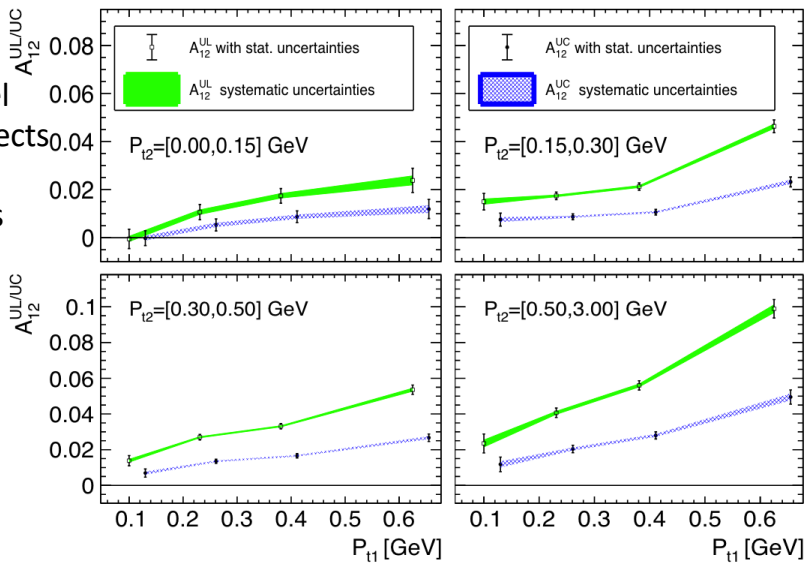
- Trend consistent with BaBar
- Direct comparison difficult due to different correction schemes (thrust vs $q\bar{q}$ –axis)

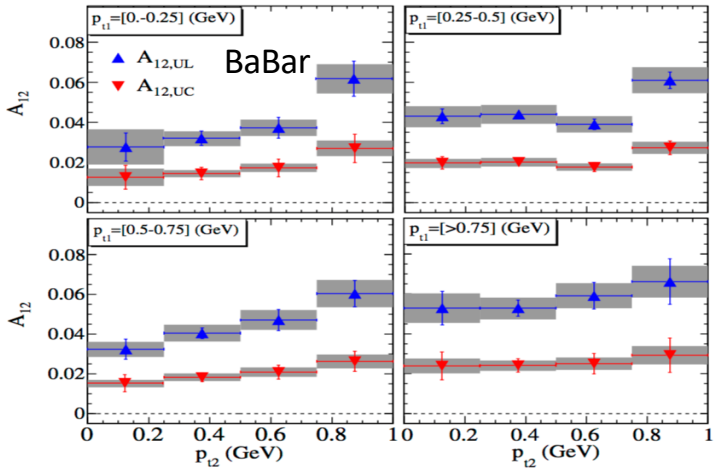
Unlike/**L**ikesign

Ratios to cancel acceptance effects

Unlike:
fav*fav+dis*dis

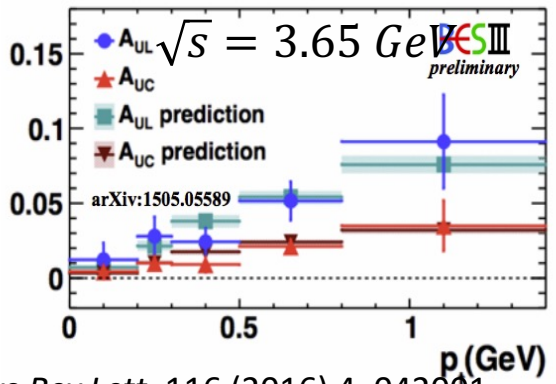
Like:
fav*dis





Phys.Rev.D 90 (2014) 5, 052003

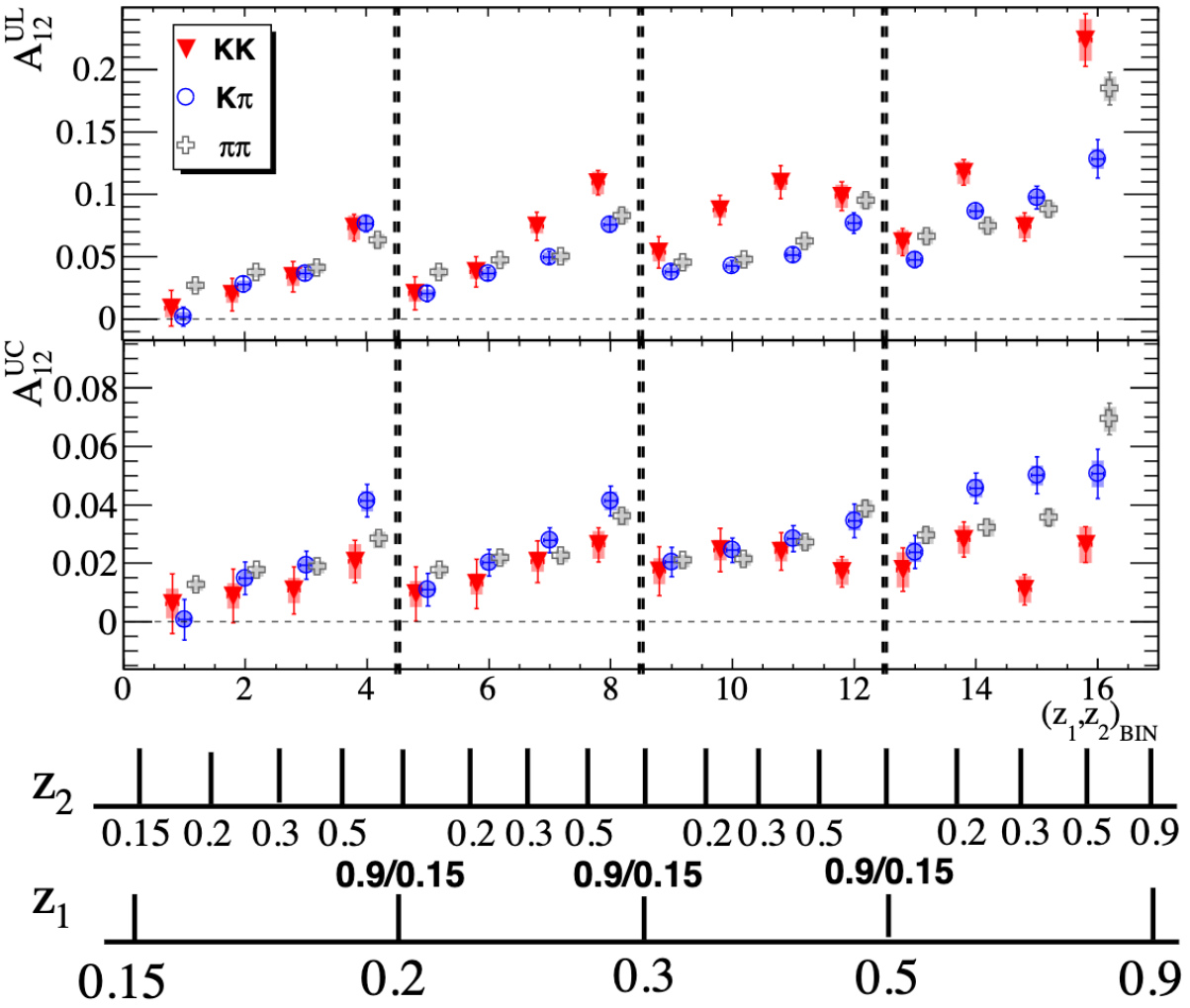
- Results from BESIII are largely consistent with TMD evolution
- Ditto: $\Lambda^\uparrow$ from LEP to Belle energies



Phys.Rev.D 100 (2019) 9, 092008

Phys.Rev.Lett. 116 (2016) 4, 042001

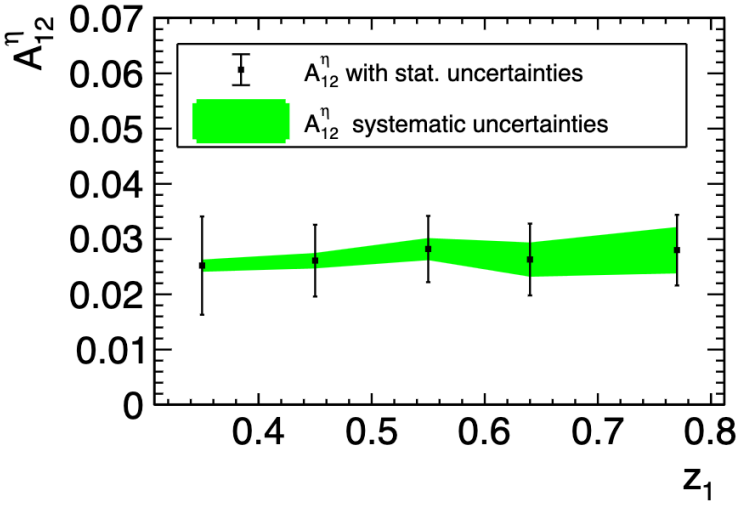
BaBar: K^+K^- asymmetries > $\pi^+\pi^-$



- *Phys.Rev.D* 92 (2015) 11, 111101

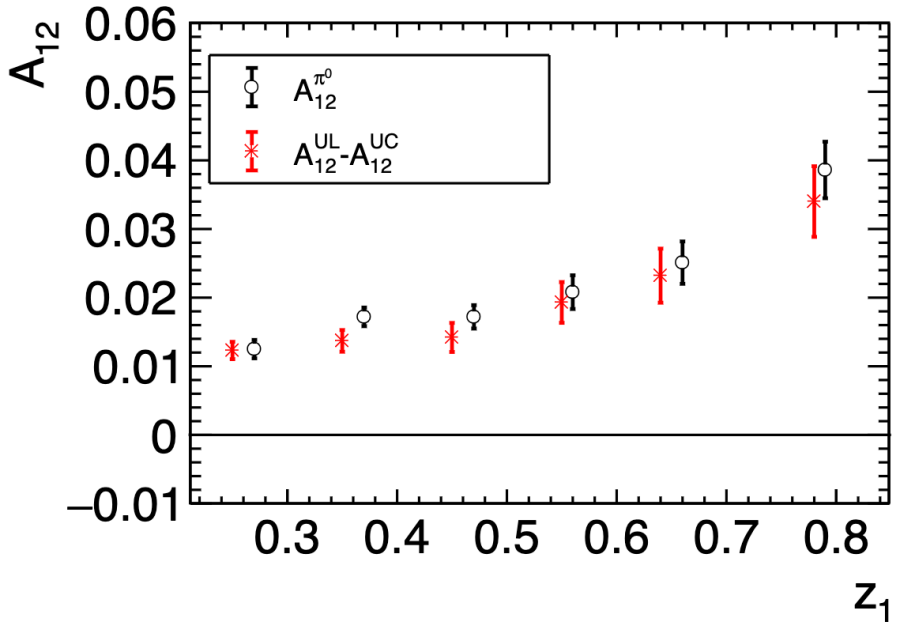
Consistency between Neutral and charged pions

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



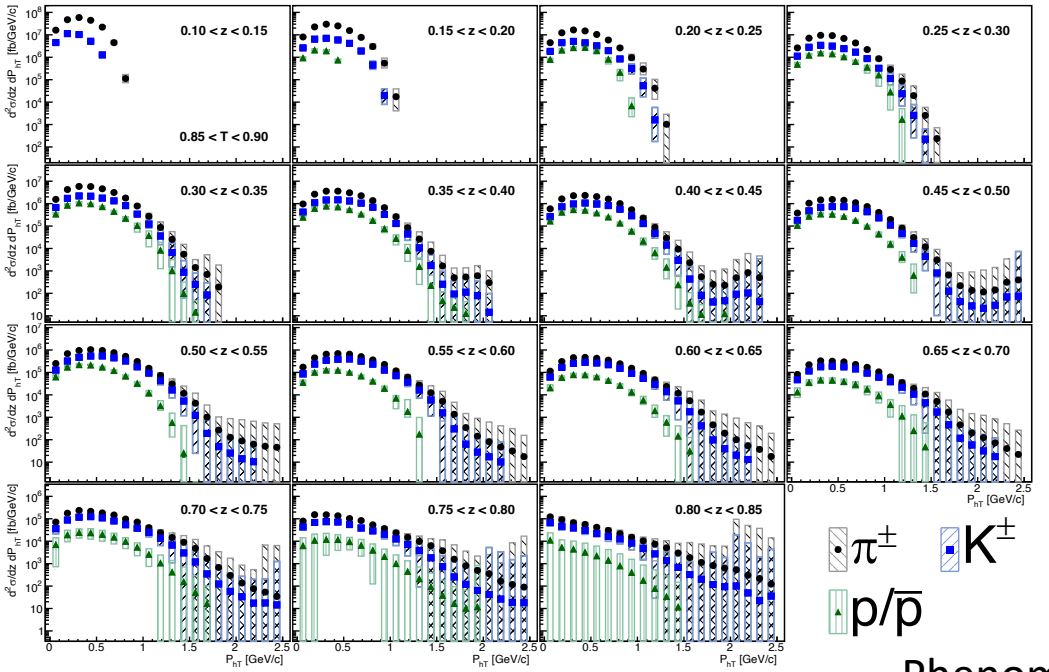
$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} = \frac{\pi^{0}\pi^{+} + \pi^{0}\pi^{-}}{\pi^{+}\pi^{+} + \pi^{-}\pi^{-}}$$

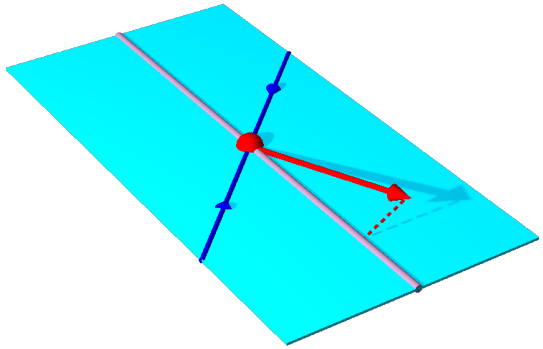
$= A_{12}^{UL} - A_{12}^{UC}$ ***(Isospin)***



Transverse momentum distributions

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





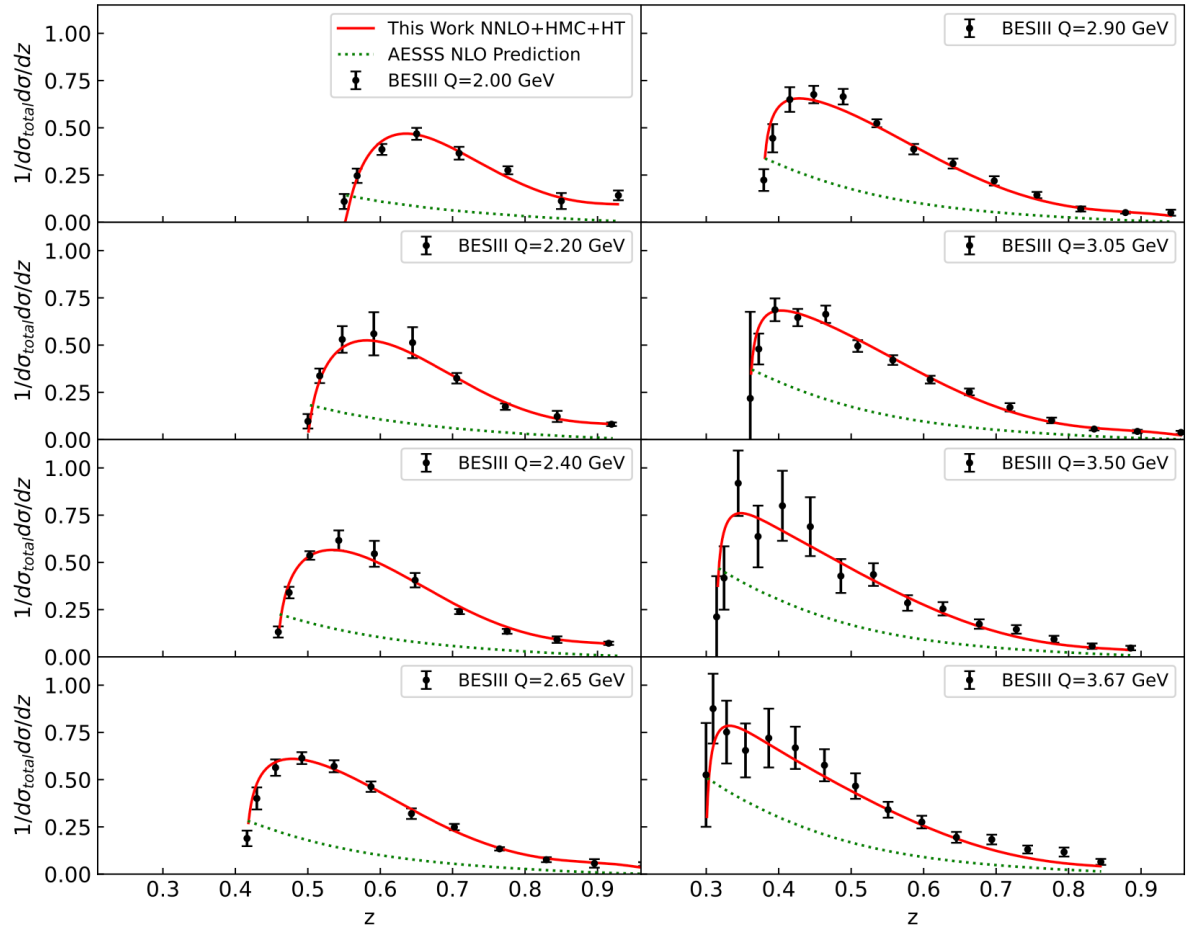
Phys.Rev.D 99 (2019) 11, 112006

Phenomenology:

- Boglione, Simonelli *JHEP* 09 (2023) 006
- Kang, Shao, Zhao *JHEP* 12 (2020) 127)

New measurements and fits to π^0, K_S, η from BES III

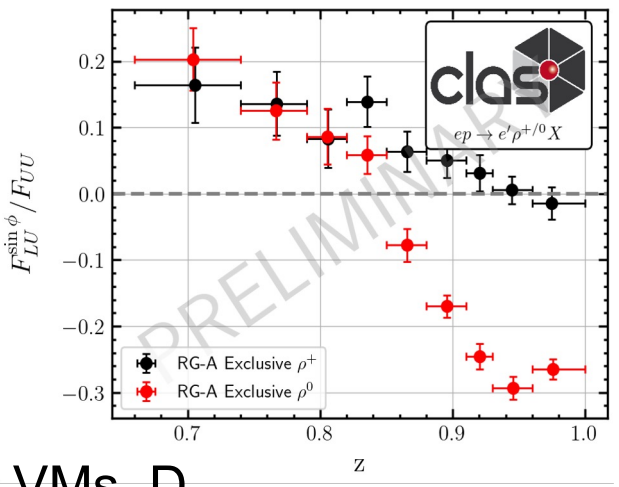
- New fit to SIA data incorporating higher twist shows good agreement with BES III data down to 2 GeV



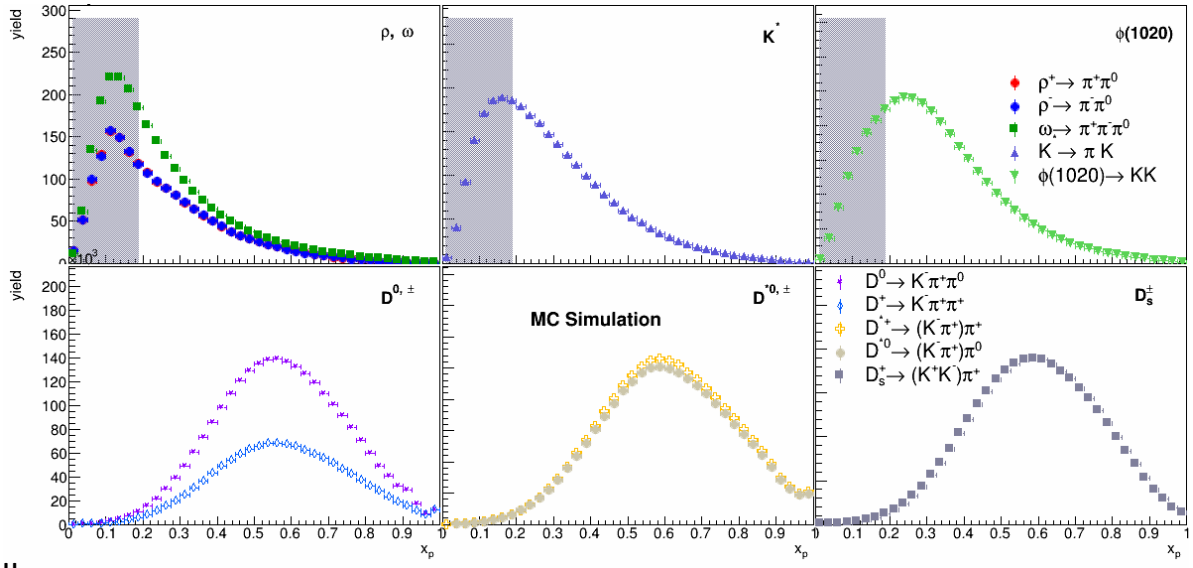
e-Print: [2404.11527]

Vector meson plans

- Asymmetries of vector mesons can be large
- Contributions to single hadron fragmentation
➔Study vector meson decay



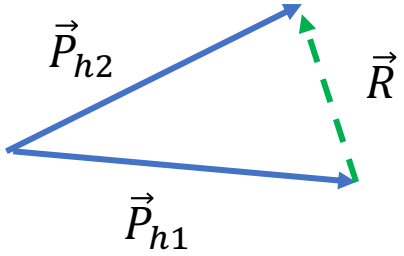
- **Ongoing: Decaying particle FFs**
  - Study the explicit differential cross sections for VMs, D mesons as a function of x_p



- Example from MC at Belle energies (for 4π acceptance):

Step beyond single hadrons:
Dihadron 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:

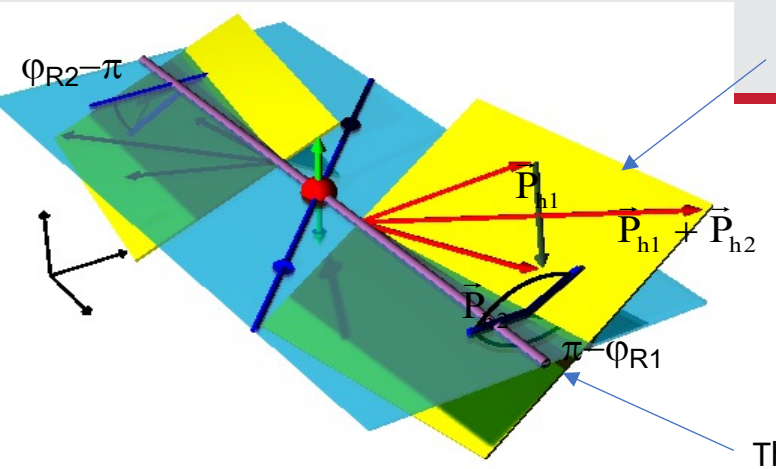


More degrees of freedom→More information about correlations in final state
→See e.g. recent extraction of Twist3 $e(x)$ (e-Print: 2203.14975 [hep-ph])

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

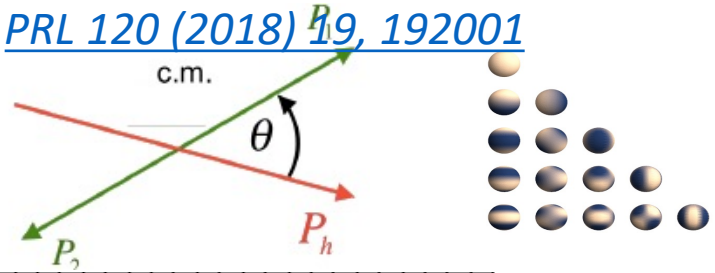
Parton polarization → / Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z, M)$ 		$H_1^{\perp h/q}(z, p_T\text{M, (Ph)},\theta)$ 'Di-hadron Collins'
longitudinal			
Transverse		**$G_1^{\perp}(z,M,P_h,\theta)$=** T-odd, chiral-even →jet handedness QCD vaccum strucuture 	**$H_1^{*}(z,M, (P_h),\theta)$=.** T-odd, chiral-odd Colinear 

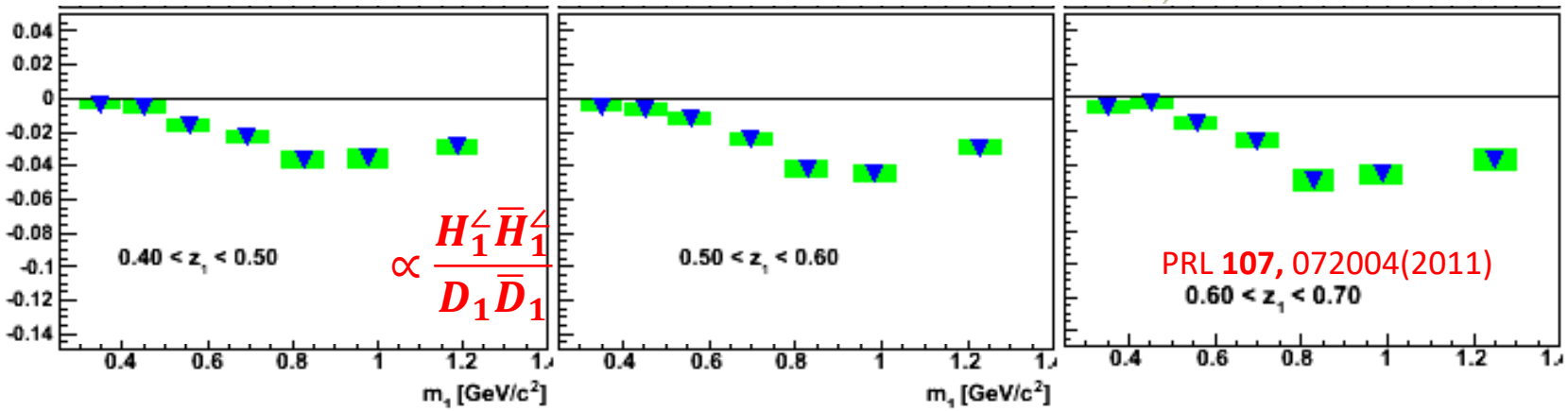
Di-Hadron measurements at Belle



Transversity Extractions:

- Cocuzza et al Phys.Rev.D 109 (2024) 3, 034024
- Radici et al. *PRL 120 (2018) 19, 192001*

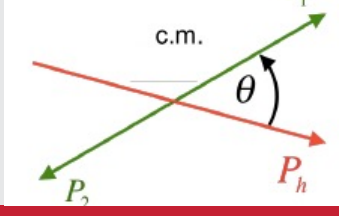




- Relative momentum of hadrons can carry away angular momentum
  - Relative and total angular momentum → In principle endless tower of FFs
  - Polarization dependent FFs: Interference of QCD amplitudes with different angular momentum → Dependence on $P_l^m(\theta)$

→ Partial wave decomposition can extract different interference terms (difficult for Single H FFs)

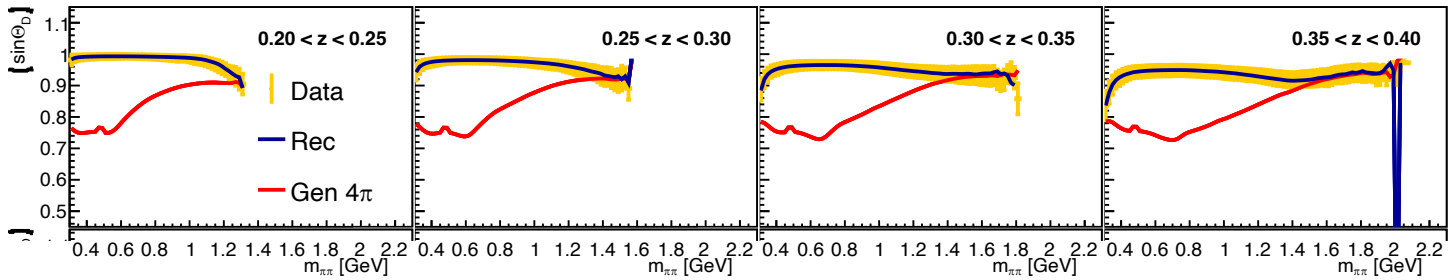
Acceptance Impact on Partial Wave composition



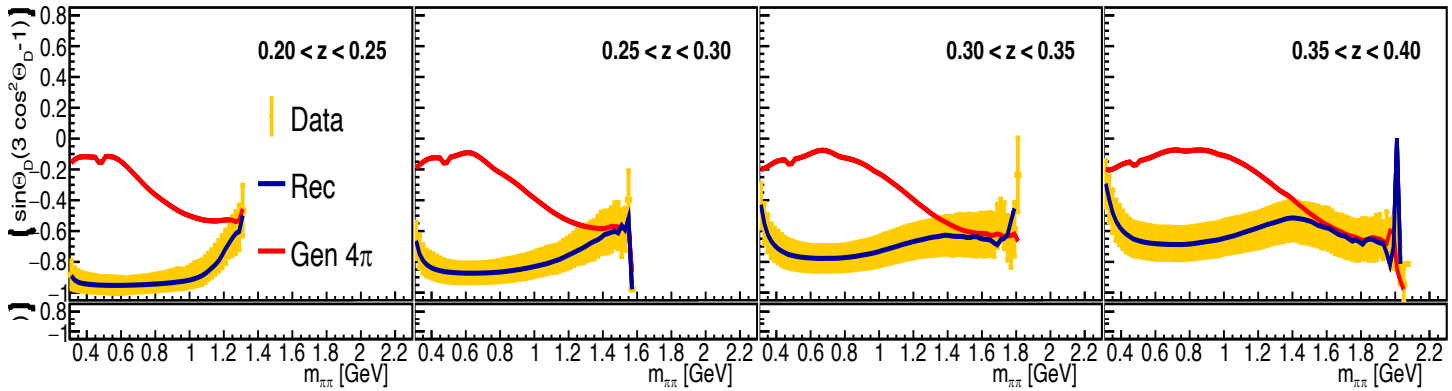
- Consider dependence of FFs on decay angle θ
- Higher order PWs lead to different moments in θ and ϕ
  → These are different FFs that are mixed by the acceptance
  ➔dependent on experiment, different evolution

➔up to 10% effect on transversity extraction

$\sin\theta$



$\sin\theta\,(\cos^2\theta - 1)$



PRD96 (2017) 032005

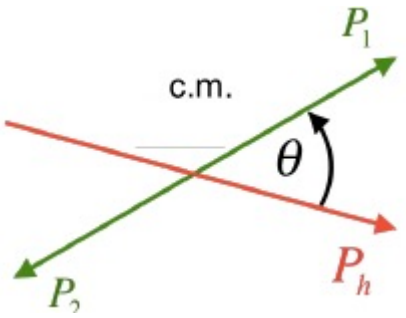
Belle II prospects

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

➔unbinned unfolding

➔Describe hadronization dynamics

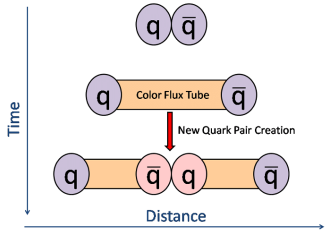
➔Bridge between FFs and MCEGs

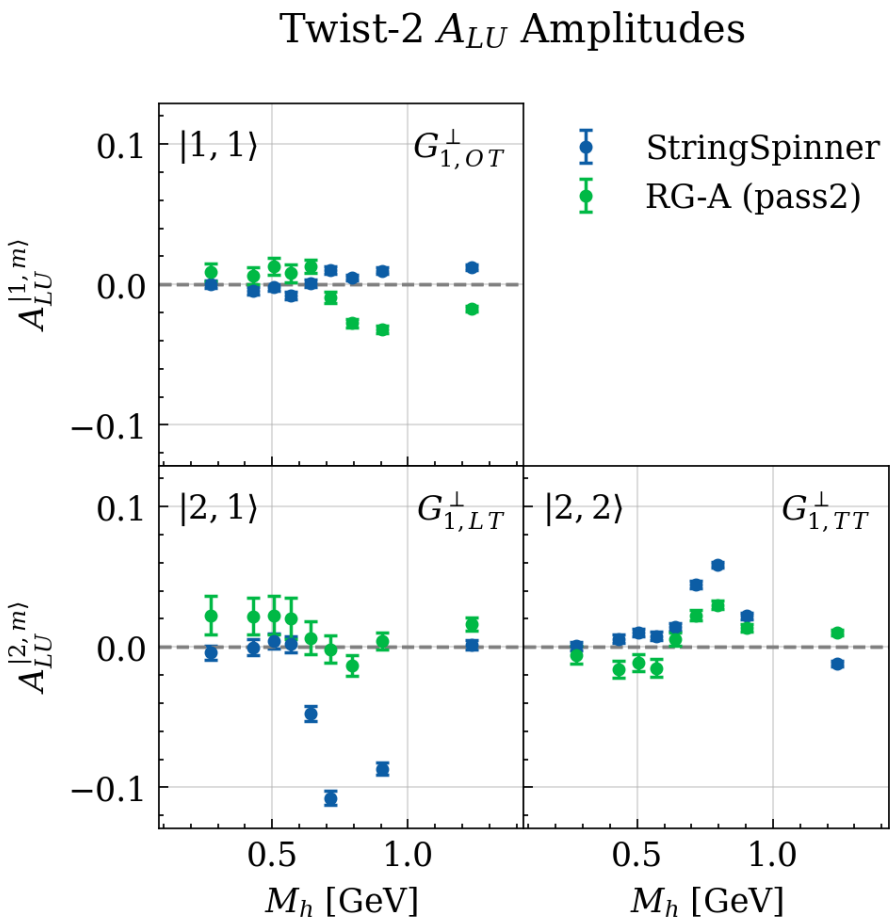


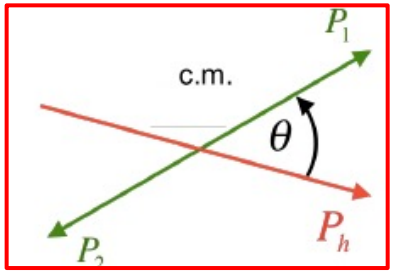
- Currently Underway using Belle II data:
  - Back-to-back di-hadron (**in-jet** and using Thrust axis)
  - Near term plans:
    - $G_1^{\perp}$ sensitive measurement
    - Kaons

Compare Partial Wave Decomposition in MC and Data

- Comparing to Polarized Lund model here (StringSpinner $3P_0$ *model*, A. Kerbizi et al, *Comput.Phys.Commun.* 272 (2022))





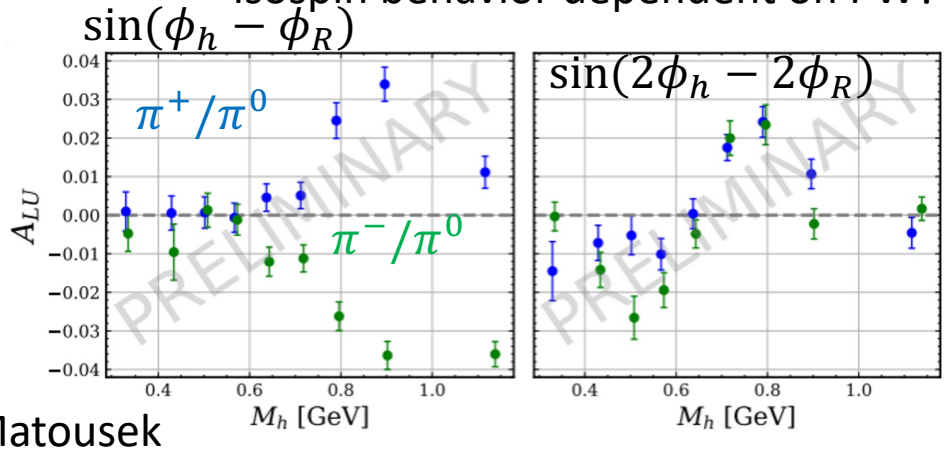


- See more MC tuning studies in QCD whitepaper
- E.g. charge, flavor correlations (Phys.Rev.D 105 (2022) 5, L051502)

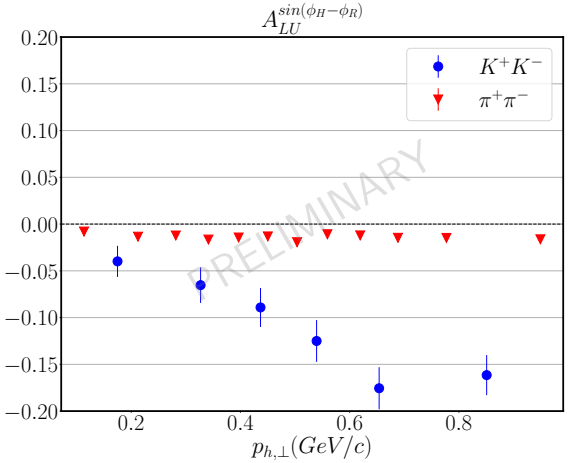
G Matousek

π^0 and Kaon combinations (SIDIS@CLAS12)

Isospin behavior dependent on PW?



G Matousek



C Pecar

- $A_{LU} \propto \frac{f(x,k_t)G_1^{\perp}(z,p_t)}{f(x,k_t)D(z,p_t)} \approx \frac{G_1^{\perp}}{D_1}$
- Kaon ≫ Pions for sp interference (not all PW terms)
  - FF effect?
  - $\pi^{\pm}/\pi^0$ ordering dependent on PW

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

- Jet physics (will) play an important role at the EIC and LHC
- Precision measurements in e^+e^- annihilation will test current theoretical understanding (N^3LL)
- Lower energies like Belle in particular sensitive to hadronization effects
- Example: Transverse Momentum Imbalance ← → TMD framework

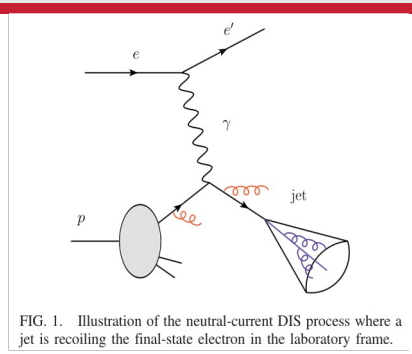
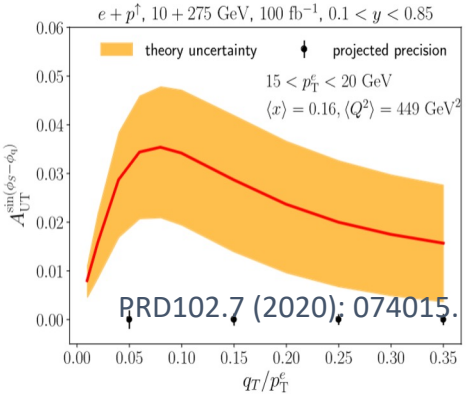
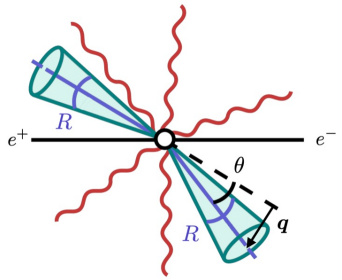
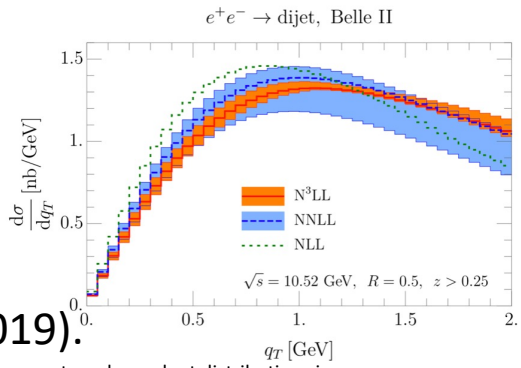


FIG. 1. Illustration of the neutral-current DIS process where a jet is recoiling the final-state electron in the laboratory frame.



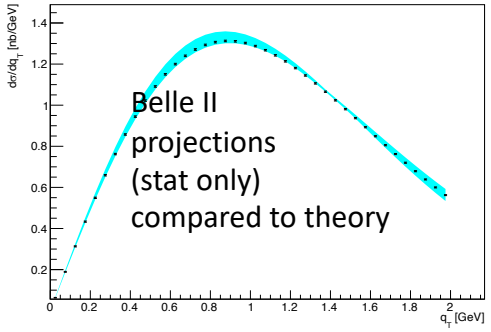
PRD102.7 (2020): 074015.





JHEP. **2019,** 31 (2019).

Gutierrez-Reyes, D., Scimemi, I., Waalewijn, W.J. *et al.* Transverse momentum dependent distributions in e^+e^- and semi-inclusive deep-inelastic scattering using jets. *J. High Energ. Phys.* **2019,** 31 (2019).

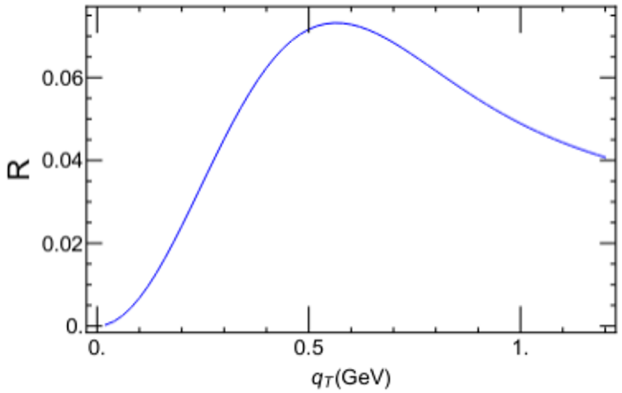


Using $R = 1.0, E_{jet} > 3.75\ GeV$,

Azimuthal Asymmetries in back-to-back jets

- New suggestion: Measure Colllins-like back-to-back azimuthal correlations for jets

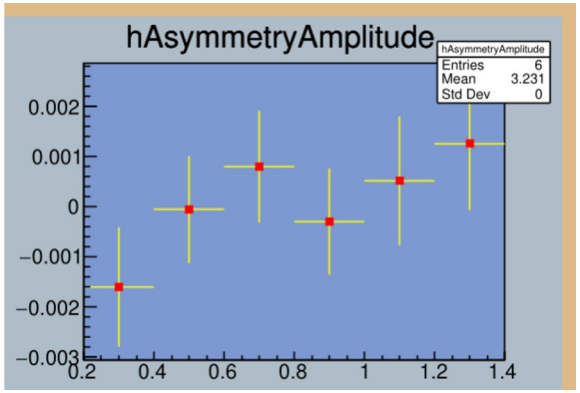
➔**Sensitive to transversity**



The time-reversal odd side of a jet

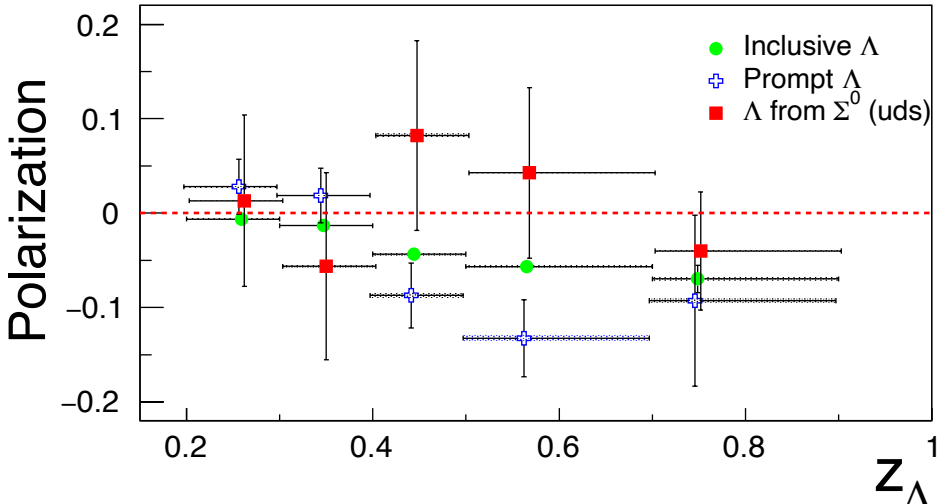
•*Fund.Res.* 3 (2023) 346-350, e-Print: 2104.03328 [hep-ph]

- Current Belle II projections for acceptance effects encouraging
- Charm contributions will be important
- Analysis about to enter Collaboration Review

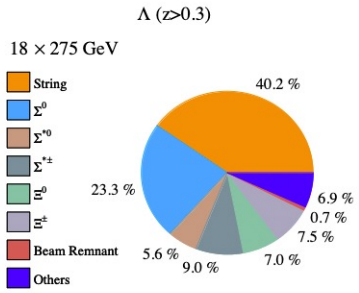


S. Schneider

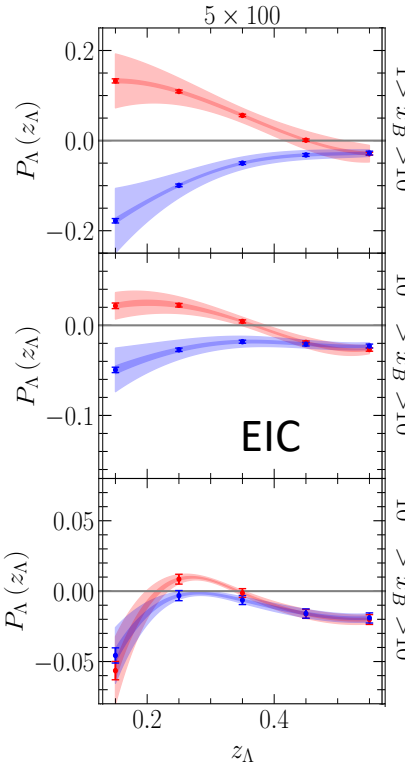
Belle II Makes Precision Λ program possible!



PRL122 (2019) 4, 042001



Example,
Λ feeddown at the EIC



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

- Complementary Statistics to Λ program at the EIC
  - Universality test
  - Λ FFs to extract polarized PDFs
  - Flavor separation
  - …

Summary

- FFs from e^+e^- are crucial for the extraction of transversity and TMDs from SIDIS, pp data
- Data from B-factories is crucial for high precision measurements
- Continued effort is needed in precision era to provide input and complimentarity for JLab12/EIC
- A recent White Paper lays out the QCD program for Belle II

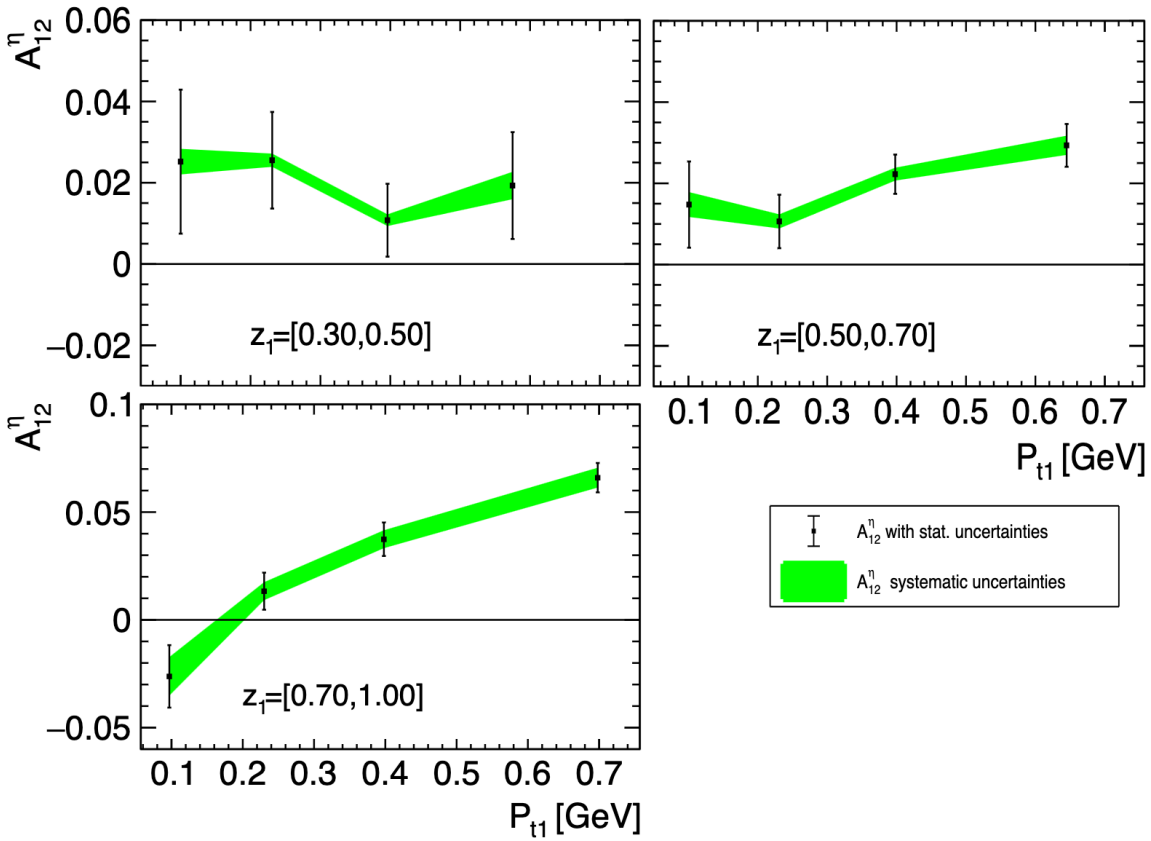
- **Some recent efforts shown**
  - Updated single/di-hadron cross-sections
  - p_T dependence of Collins effect and D_1
  - Polarization dependent kaon FFs
  - Polarizing Λ

- **Future directions**
  - Partial wave decomposition of di-hadron asymmetries/cross-sections
  - Di-hadron asymmetries/cross-sections including π^0, Kaons
  - Jets

- **Other interesting topics not discussed**
  - Collins effect for charm quarks and heavy quark fragmentation
  - Studies of nonperturbative beyond QCD factorization theorems
  - Entanglement studies
  - Polarized Belle II

π^0/η from Belle

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

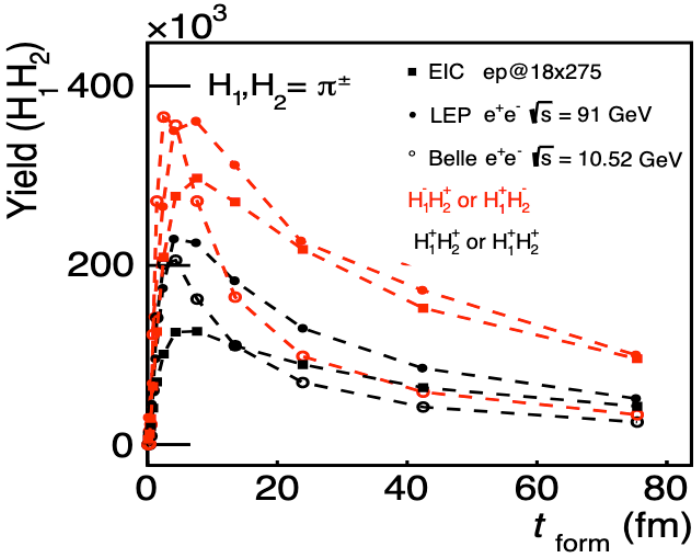


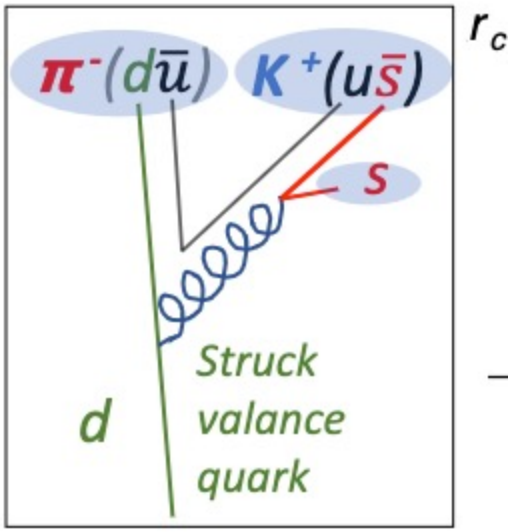
$$\mathcal{R}_{12}^{\eta} = \frac{R_{12}^{\eta\pm}}{R_{12}^{L}} = \frac{\eta\pi^+ + \eta\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

almost flat except large z

BaBar $K^+K^-, \pi K$ pairs: Phys.Rev.D 92 (2015) 11, 111101

Probe String Fragmentation in charge, flavor correlations





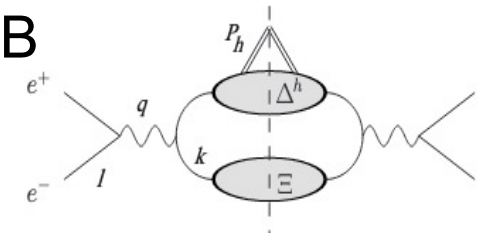
- Belle II mainly in non-perturbative regime
- M. Mouli Mondal @ CPHI2022
- See more MC tuning studies in QCD whitepaper

Phys.Rev.D 105 (2022) 5, L051502

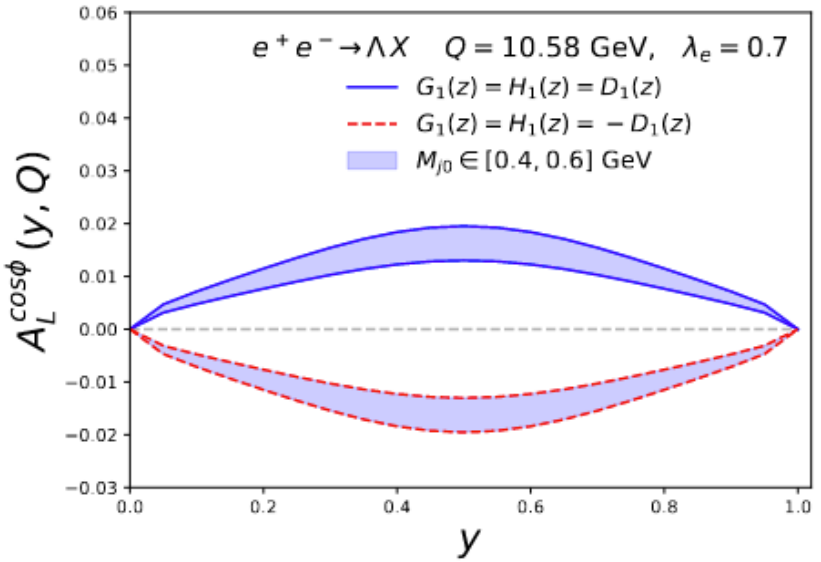
Jet mass

- Proposal to polarize electron beam at SuperKEKB

→ Whitepaper: e-Print: 2205.12847



- Can access jet mass
- ”QCD Higgs mechanism”



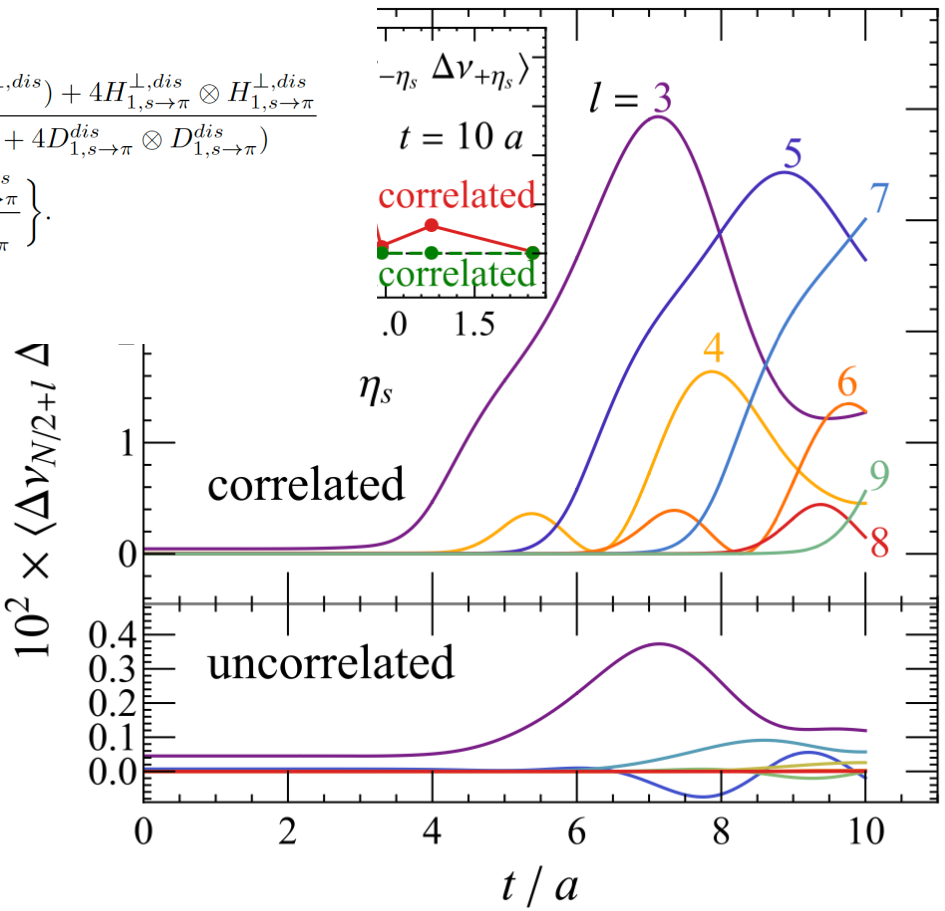
$$\frac{d\sigma^L}{d\Omega dz} \propto \lambda_e \sum_a \left\{ \frac{1}{2} C(y) G_1^{a\to\Lambda}(z,Q) + 2D(y)|S_T|\cos(\phi)\frac{M_\Lambda}{Q}\left(\frac{1}{z} G_T^{a\to\Lambda}(z,Q) + \frac{m_a^{dyn}}{M_\Lambda} H_1^{a\to\Lambda}(z,Q) \right) \right\}$$

See also A. Accardi, A. Signori, *Phys.Lett.B* 798 (2019) 134993

Entanglement

- Handedness

$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1+\cos^2(\theta)} \times \left\{ \frac{5(H_1^{\perp,fav} + H_1^{\perp,dis}) \otimes (H_1^{\perp,fav} + H_1^{\perp,dis}) + 4H_{1,s\to\pi}^{\perp,dis} \otimes H_{1,s\to\pi}^{\perp,dis}}{5(D_1^{fav} + D_1^{dis}) \otimes (D_1^{fav} + D_1^{dis}) + 4D_{1,s\to\pi}^{dis} \otimes D_{1,s\to\pi}^{dis}} - \frac{10H_1^{\perp,fav} \otimes H_1^{\perp,dis} + 2H_{1,s\to\pi}^{\perp,dis} H_{1,s\to\pi}^{\perp,dis}}{10D_1^{fav} \otimes D_1^{dis} + 2D_{1,s\to\pi}^{dis} \otimes D_{1,s\to\pi}^{dis}} \right\}.$$

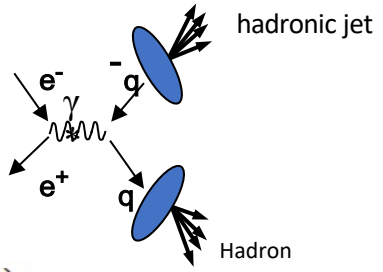


Florio et al, PRL 131, 021902 (2023)

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

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

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

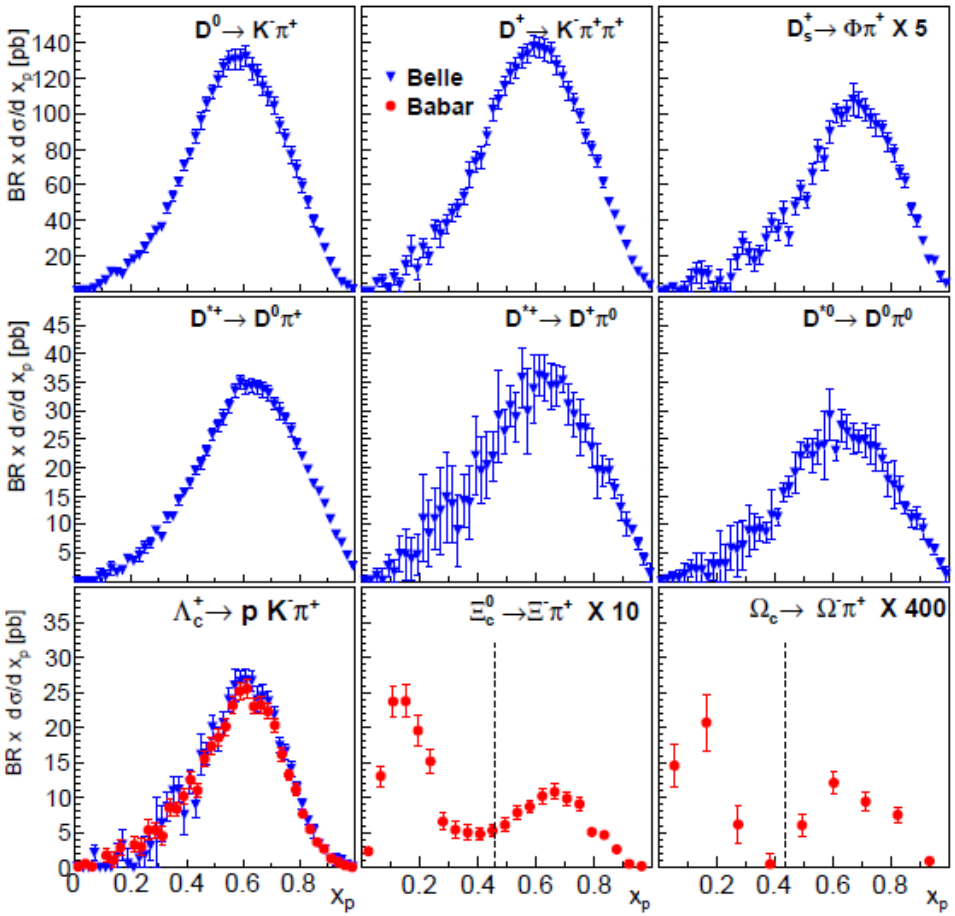


- Cleanest process→testbed for QCD calculations
- Limited access to flavor
  - (Use different couplings to γ^* and Z^0)
  - (Use polarization (SLD) and parity violating coupling)
  - **Use back-to-back correlations for different flavor combinations**
- Limited access to gluon FF
  - From evolution
  - From three jet events (but theory treatment not clear)

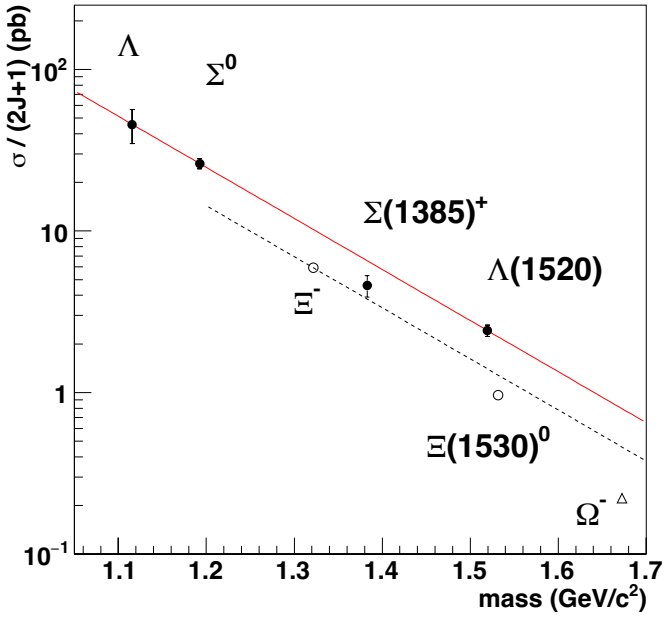
Belle II can signficcantly improve our knowledge of heavy flavor fragmentation

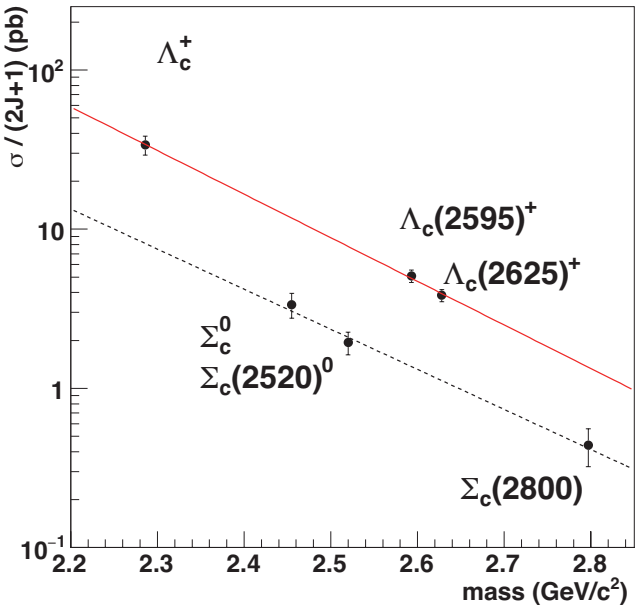
- Single hadron differential cross sections for Λ, Σ, Ξ, Ω, Λ_c, Σ_c, Ξ_c, Ω_c (etc) vs x_p available
- Heavier particles generally plotted vs normalized momentum
- Unlike light hadrons charmed hadrons contain large fraction of charm quark momentum ➔peaked at larger x_p
- Belle analysis of vector mesons ρ, ω, K^* and D mesons underway
- Belle II prospects: Multidimensional extraction, p_T dependence

PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)



Mass Dependence of σ →test hadronization model



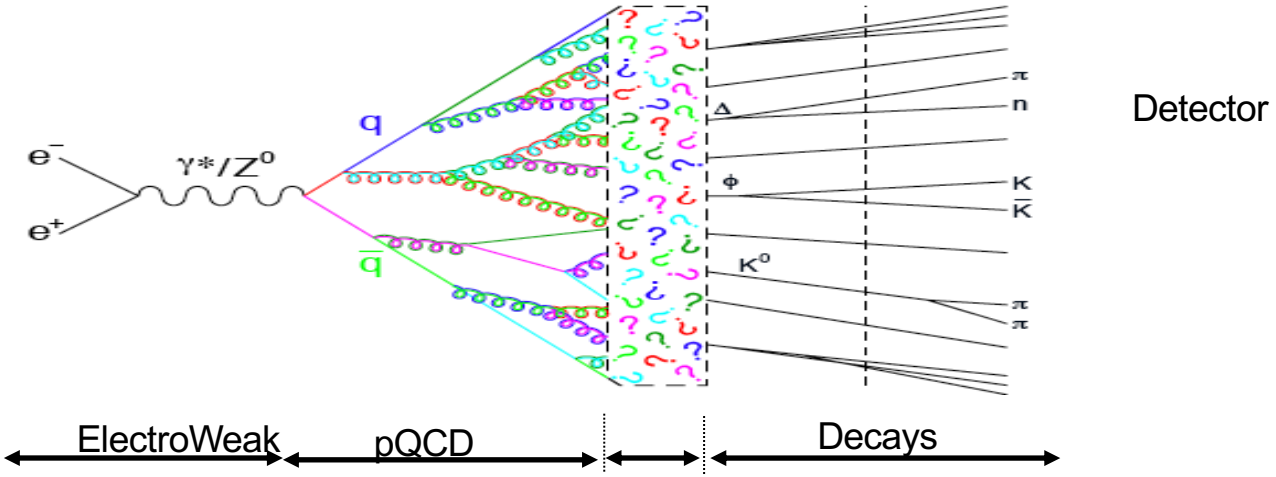


- Found consistent with di-quark model

PRD 97, 072005 (2018)

Factorized QCD: Hadronization described by Fragmentation Functions

Field, Feynman (1977): Fragmentation functions encode the information on how partons produced in hard-scattering processes are turned into an observed colorless hadronic bound final-state [PRD 15 (1977) 2590]



- Complementary to the study of nucleon structure (PDFs)
- Cannot be computed on the lattice
- Questions to be asked
  - **Macroscopic effect (distribution, polarization)of microscopic properties (quantum numbers)?**
  - Effect of QCD vacuum the quark is traversing
  - Study of the formation of hadrons →e.g. Phys.Rev. D97 (2018) no.7, 072005

MC tuning studies

- Event Shapes
- Jet rates vs resolution, hemisphere,
- Event rates relative to event plane (and z, p_T), including baryons
- Multiplicities of resonance production ($\rho, \omega, K^*, \phi, \Lambda, \Sigma, \Xi, \Omega$)
  - Ratios between pseudo-scalar and vector mesons (also important for cosmic events)
- Charge/strangeness/baryon number compensation along event axis

Polarized Hyperon Production

- Large Λ transverse polarization in unpolarized pp collision PRL36, 1113 (1976); PRL41, 607 (1978)
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- Polarizing FF is chiral-even, has been proposed PRL105,202001 (2010) as a test of universality.
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- First Observation at Belle !

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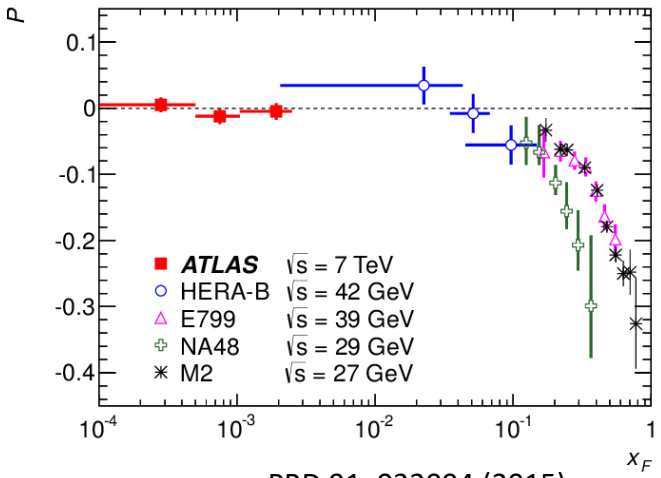
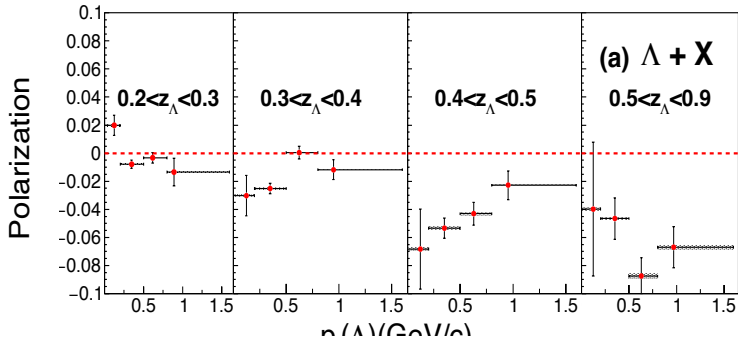
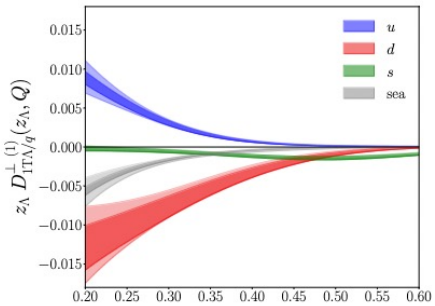


PRD 91, 032004 (2015)



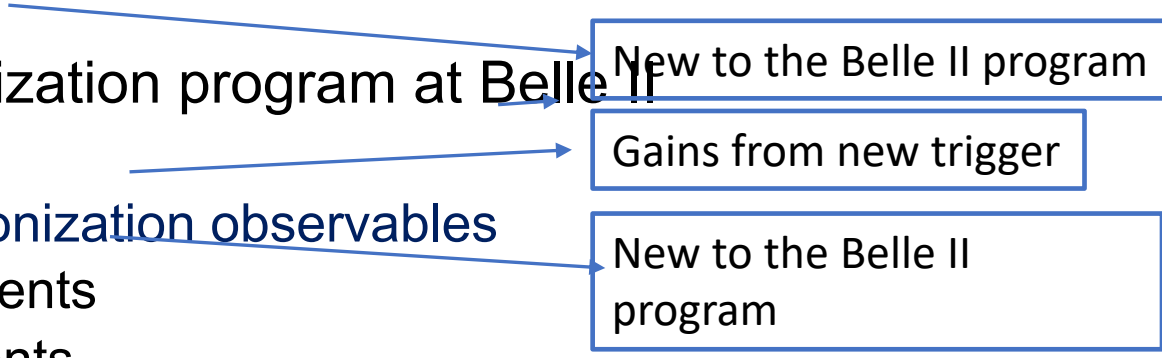


PRD 105 (2022) 9, 094033

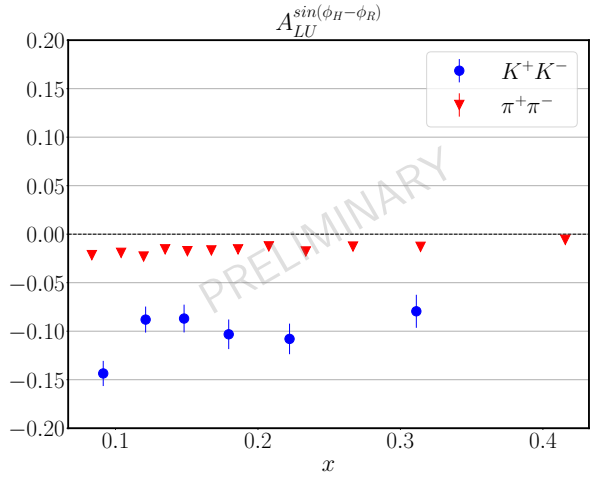
What is the Belle II program?

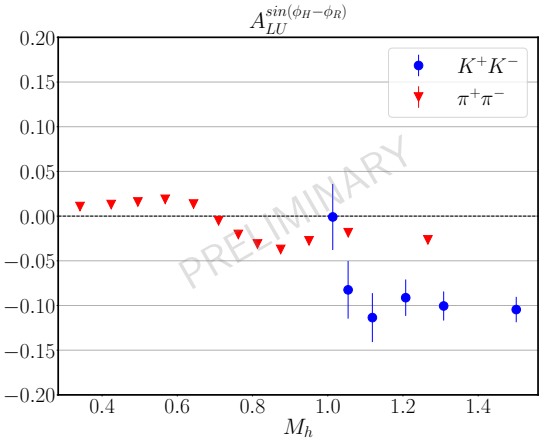
- What Belle II brings to the table for existing channels
  - High statistics
    - →complex final states
    - →complementary to EIC
  - Trigger → low multiplicities

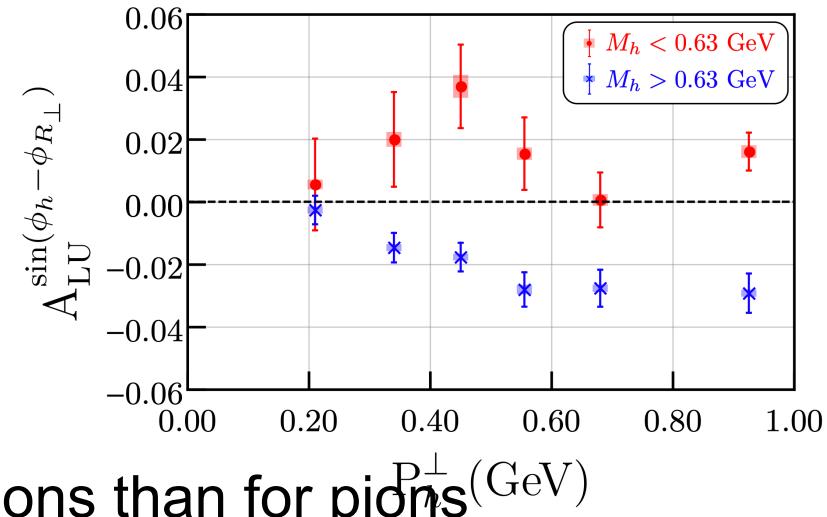
- Highlights of the Hadronization program at Belle II
  - Jets
  - Non factorizable hadronization observables
  - g-2 related measurements
  - α_s related measurements



Asymmetries sensitive to $G_1^\perp$



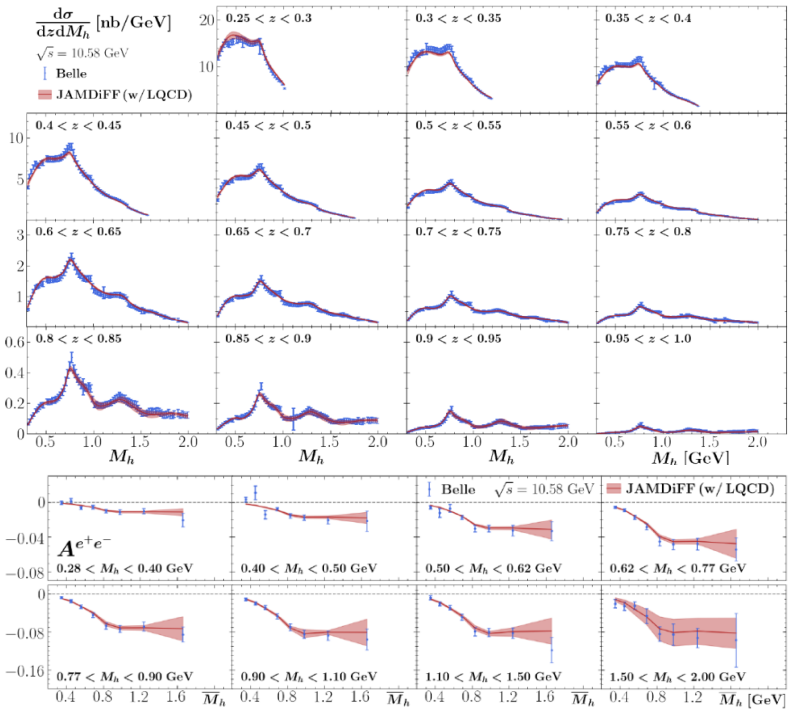


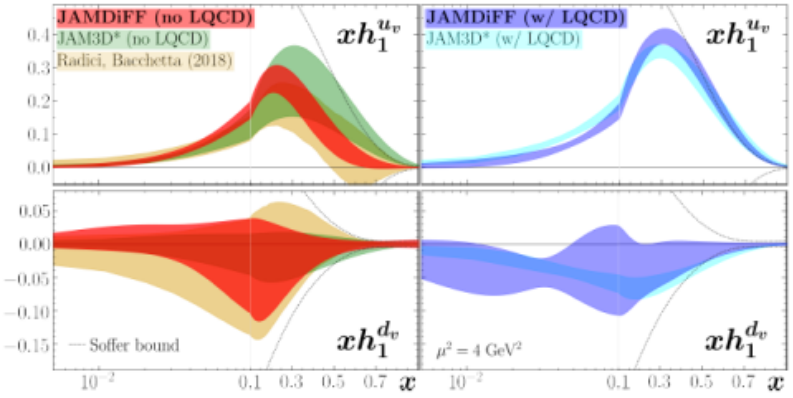


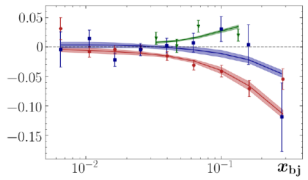
- sp –interference term larger for kaons than for pions
- Not true for all interference terms (not shown)
- $M_{KK} > m_\phi$ can account for $p_\perp$ dependence

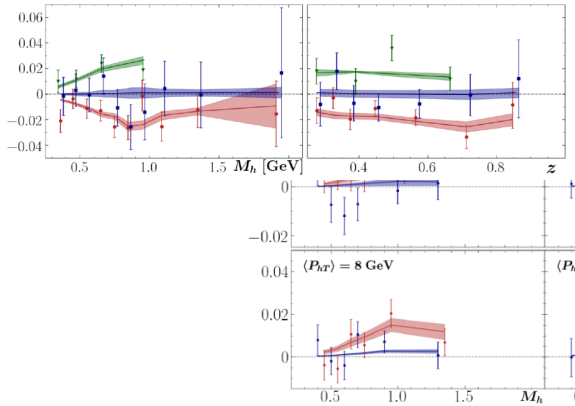
Global fits of Dihadron FFs

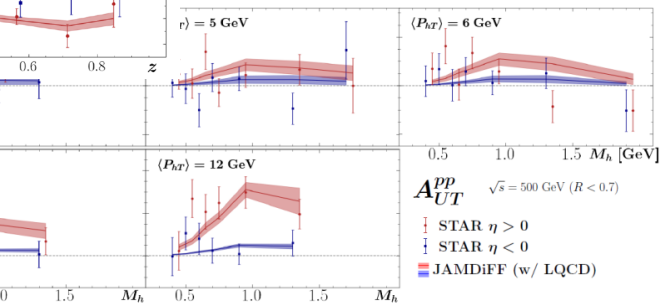
- Global fits taking SIDIS data, RHIC data, ... unt











Cocuzza et al. https://arxiv.org/abs/2306.12998
Also Radici et al. *PRL 120 (2018) 19, 192001*

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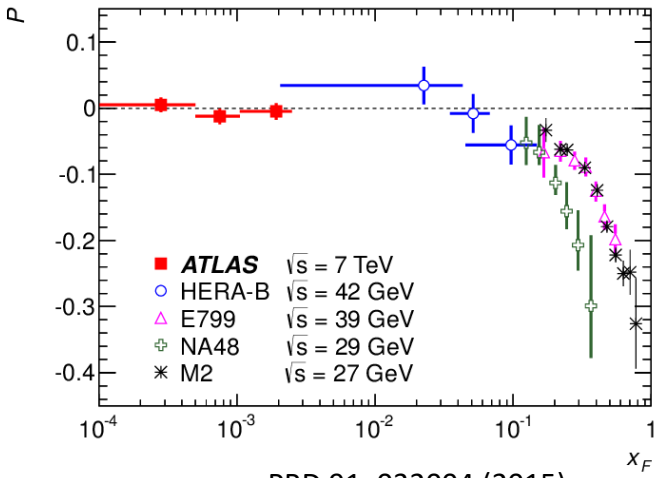
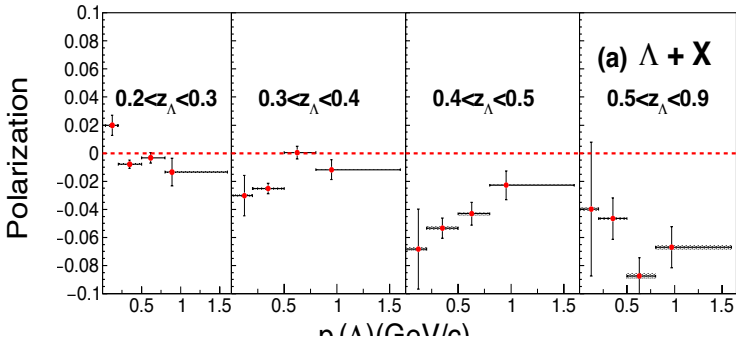
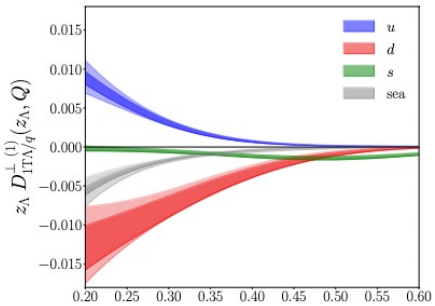


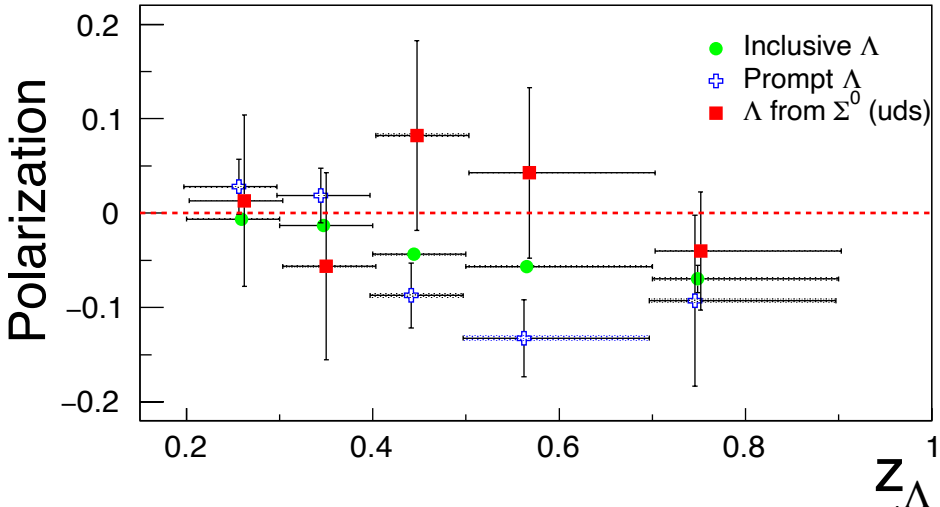
PRD 91, 032004 (2015)



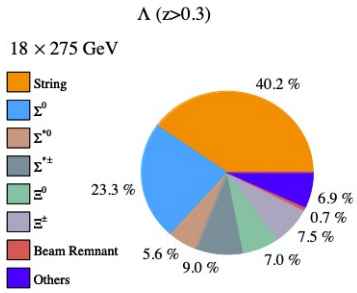


PRD 105 (2022) 9, 094033

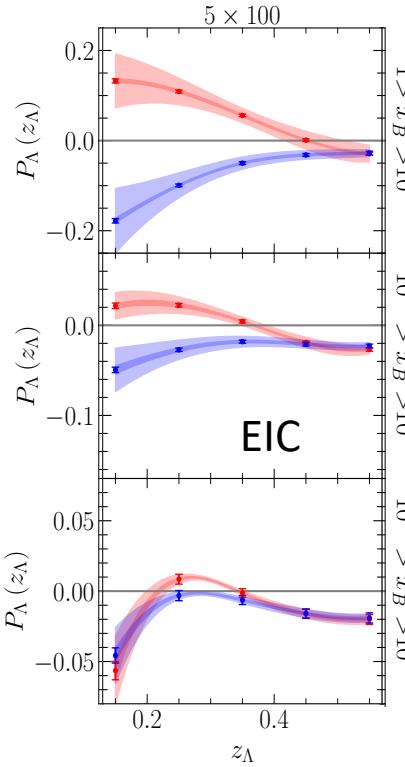
Belle II Makes Precision Λ program possible!



PRL122 (2019) 4, 042001



Example,
Λ feeddown at the EIC



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

- Complementary Statistics to Λ program at the EIC
  - Universality test
  - Λ FFs to extract polarized PDFs
  - Flavor separation
  - …

What is the Belle II QCD program?

- What Belle II brings to the table for existing channels
  - High statistics
    - →complex final states
    - →complementary to EIC
  - Trigger → low multiplicities

- Highlights of the Hadronization program at Belle II
  - Jets
  - Non factorizable hadronization observables
  - g-2 related measurements
  - α_s related measurements

New to the Belle II progra

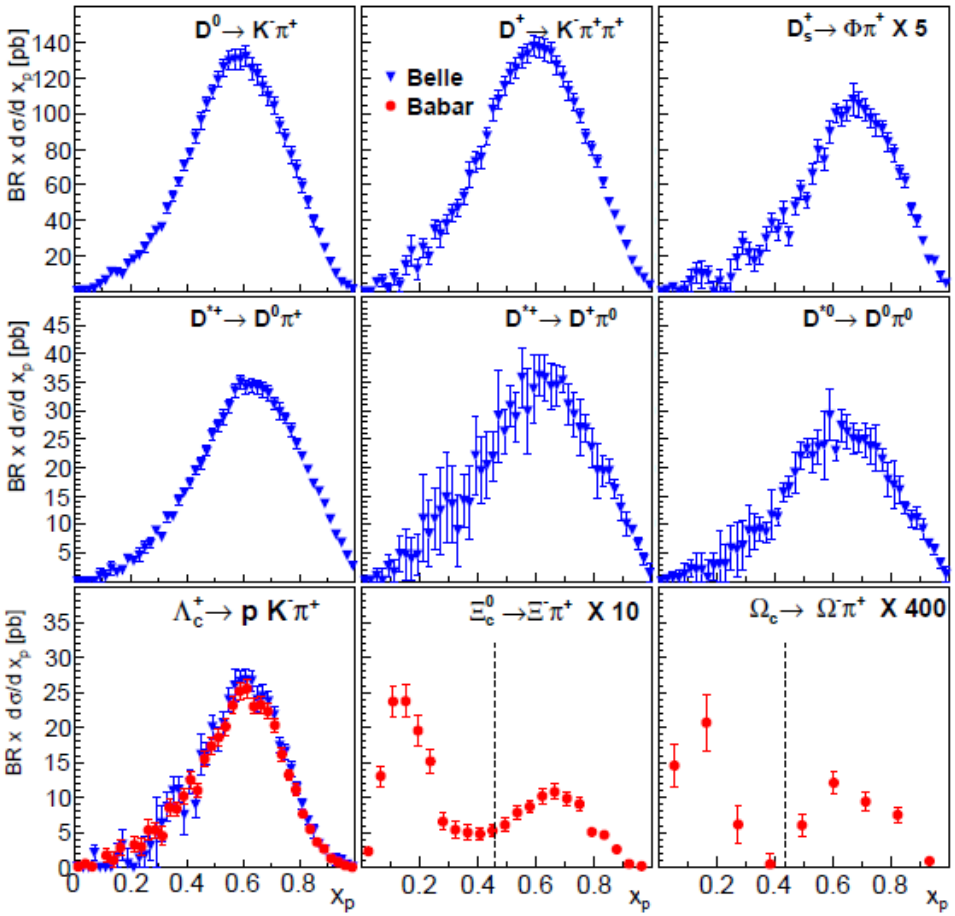
Gains from new trigger

New to the Belle II program

Belle II can signficantly improve our knowledge of heavy flavor fragmentation

- Single hadron differential cross sections for Λ, Σ, Ξ, Ω, Λ_c, Σ_c, Ξ_c, Ω_c (etc) vs x_p available
- Heavier particles generally plotted vs normalized momentum
- Unlike light hadrons charmed hadrons contain large fraction of charm quark momentum ➔peaked at larger x_p
- Belle analysis of vector mesons ρ, ω, K^* and D mesons underway
- Belle II prospects: Multidimensional extraction, p_T dependence

PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

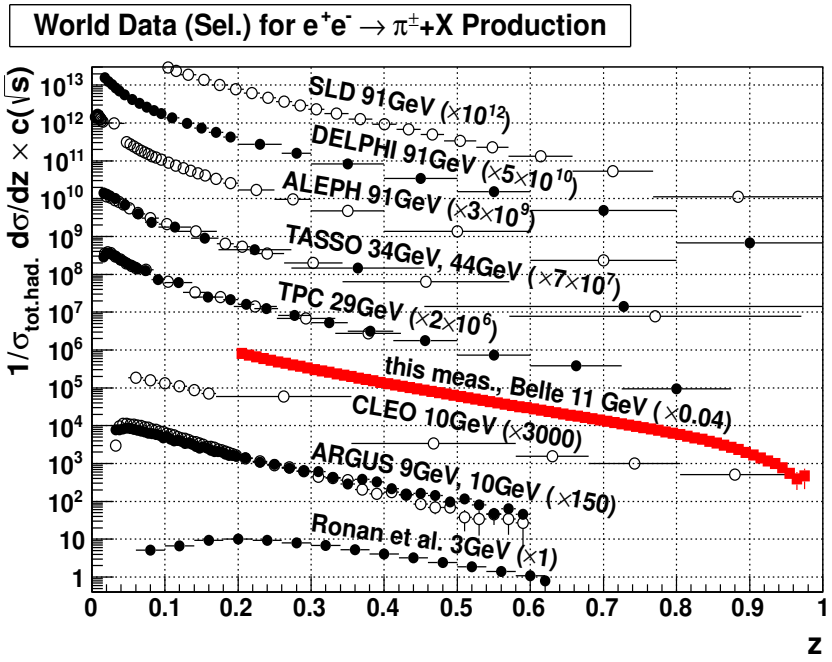


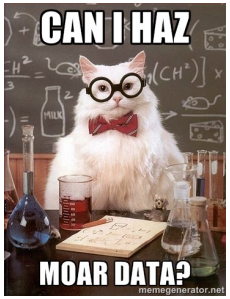
Facilities

Concentrate on B2

World Data on e^+e^-

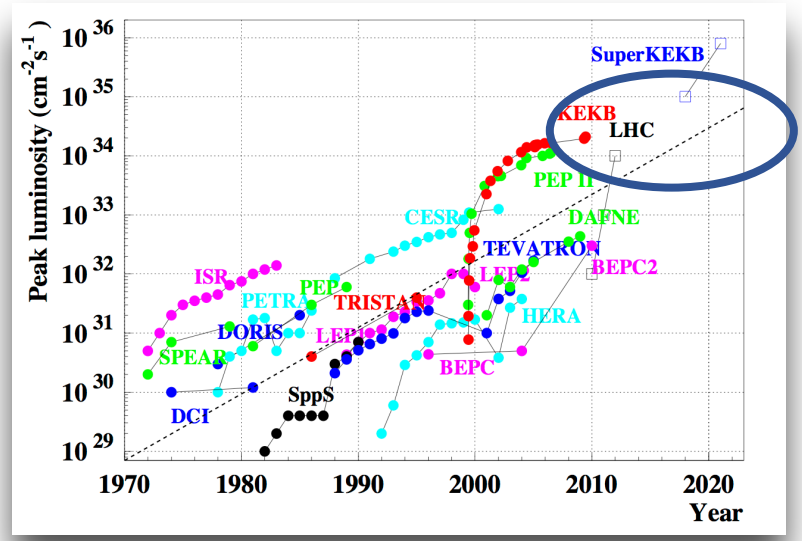
- Dominated by B factories
- Limited lever arm in $\sqrt{s}$ in particular at high z
- Precision data includes charged single hadrons π, K, p, D, Λ, charmed baryons…

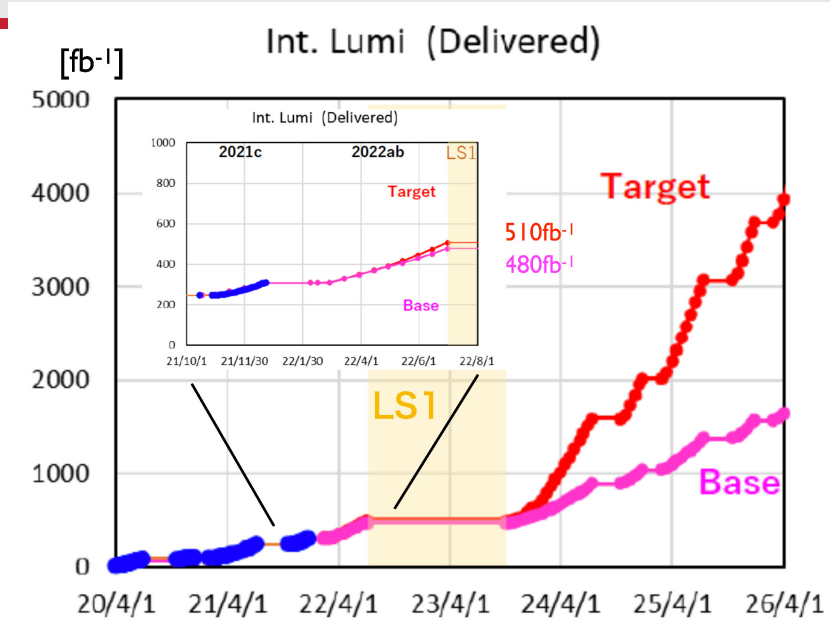




Phys.Rev.Lett. 111 (2013) 062002 (Belle)
Phys.Rev. D88 (2013) 032011 (BaBar)

The future is now: Next Generation B factory SuperKEKB





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

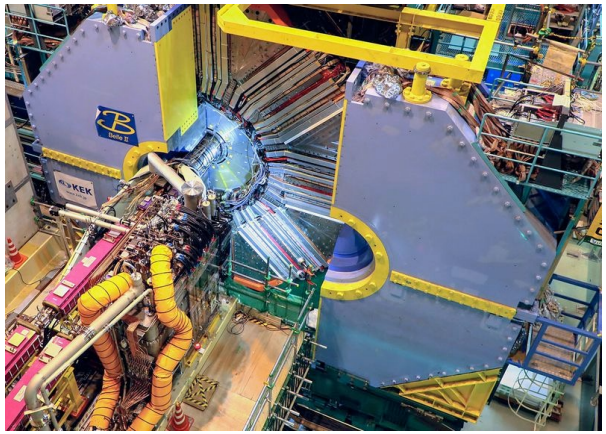
"nano-beams" are the key; vertical beam size is 50nm at the IP

Belle II already delivered world record luminosity

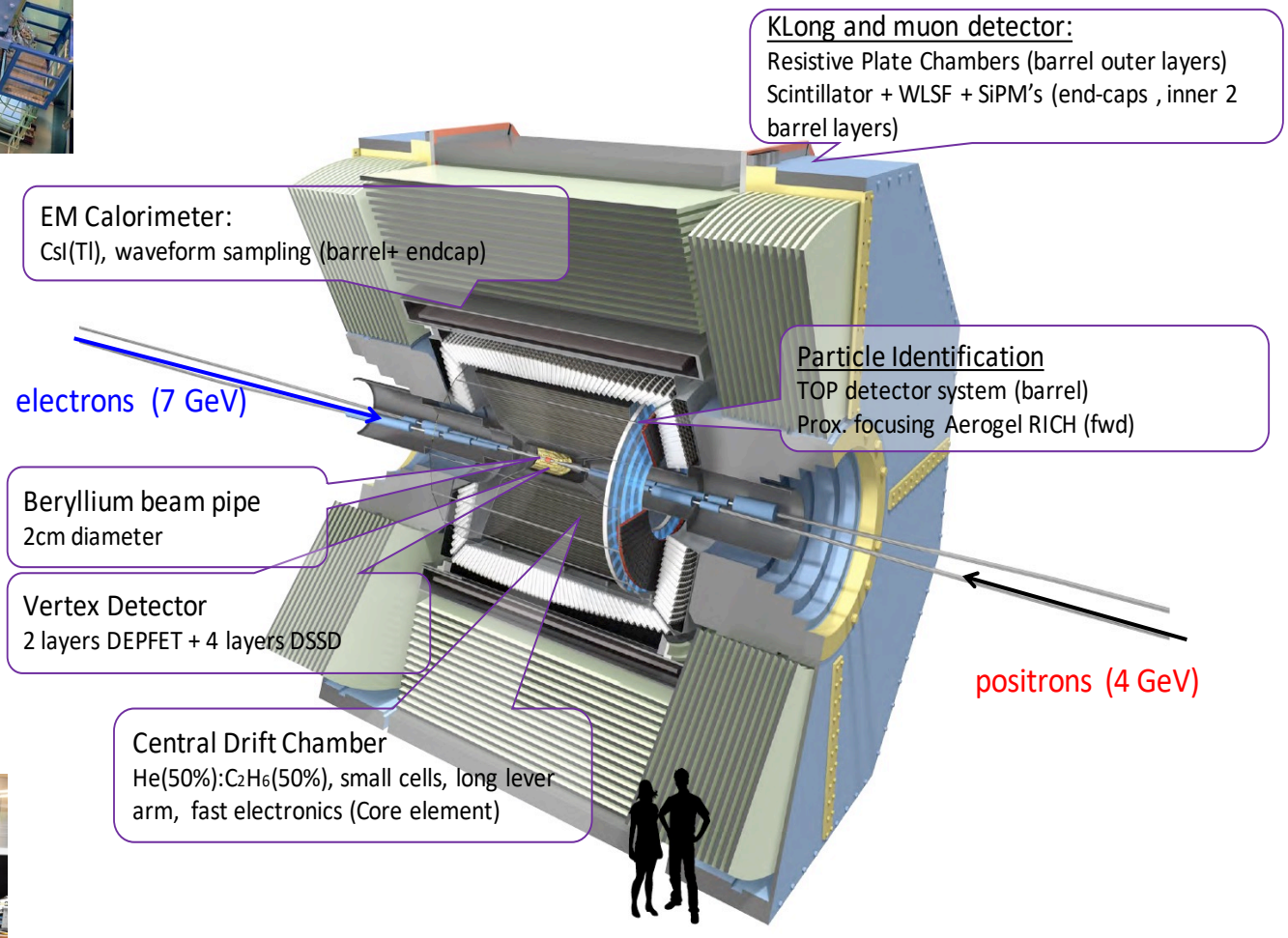
Belle II aims to have significantly higher luminosity, current record: $4.7 \times 10^{34} cm^{-2} s^{-1}$.

Future P5 recommendation: FCC-ee or muon collider up to 10 TeV

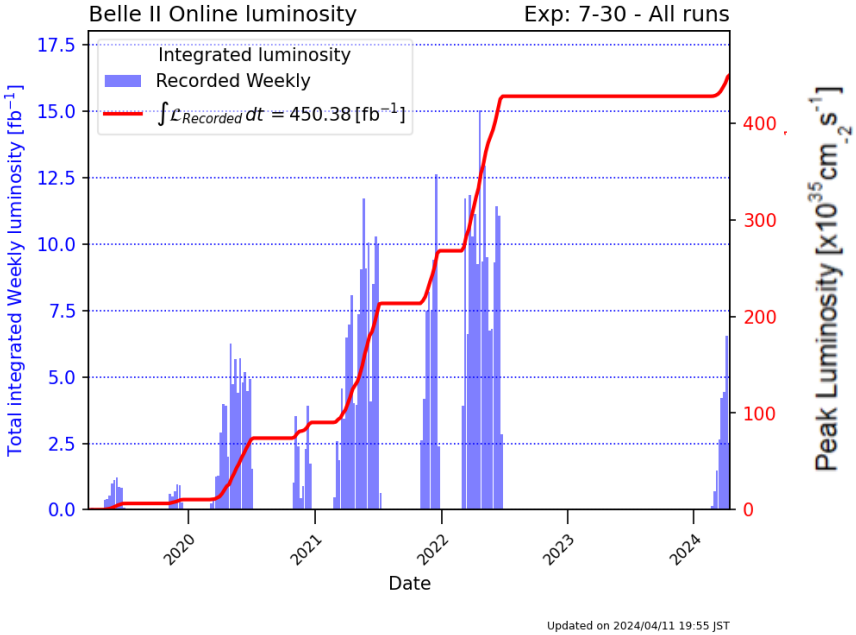
- $\frac{1}{s}\sigma$- dependence, dataset of 10s of ab^{-1}
  $\Rightarrow$ no precision measurement outside the Z resonance

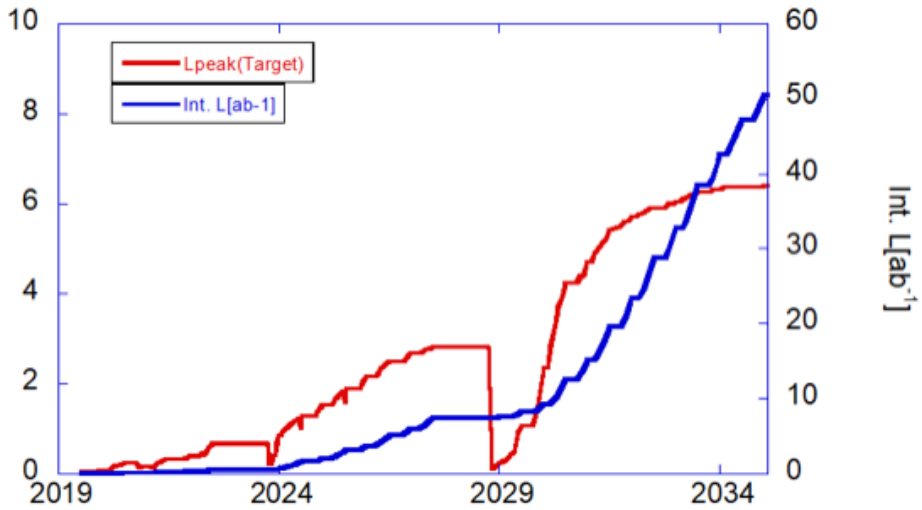


Enter Belle II



Short and long term goals

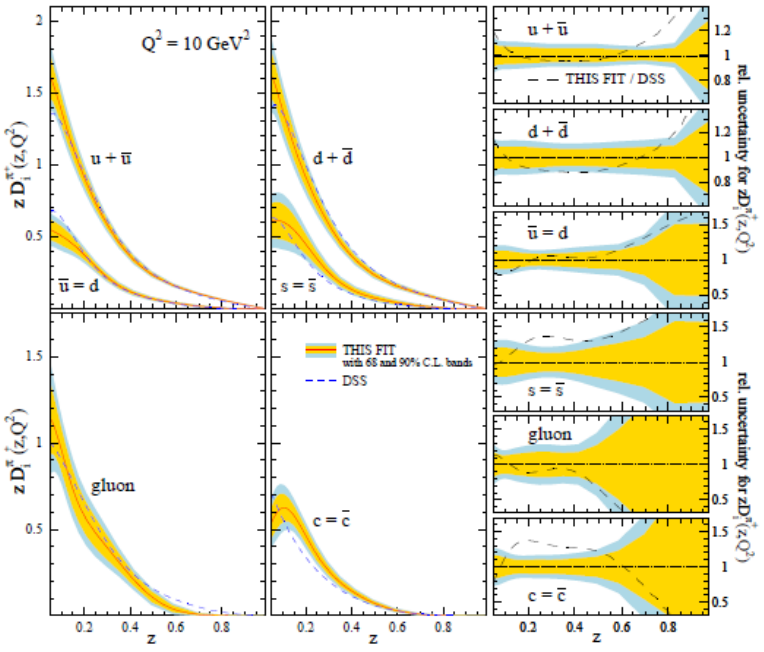




Pion fragmentation

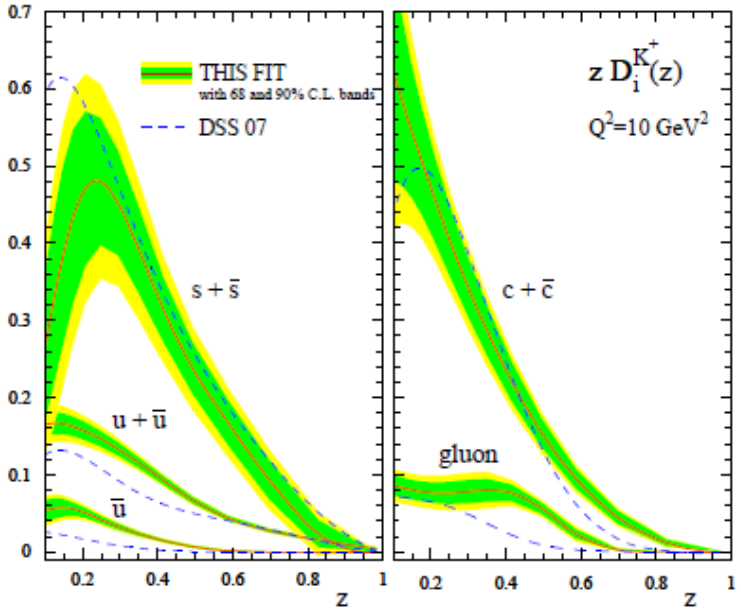
- Light quarks symmetric
- Dominated by favored fragmentation especially at high z
- Gluon substantial but falling off faster than quarks

DSS15: deFlorian et.al., Phys.Rev. D91 (2015) 014035



Kaon fragmentation

- Strange quarks are dominating kaon fragmentation
- Also dominated by favored u quark fragmentation at high-z
- At lower z penalty for producing $s\bar{s}$ pair in fragmentation ($u+\bar{u} < s+\bar{s}$)
- Charm fragmentation comparable (what about weak decays?)

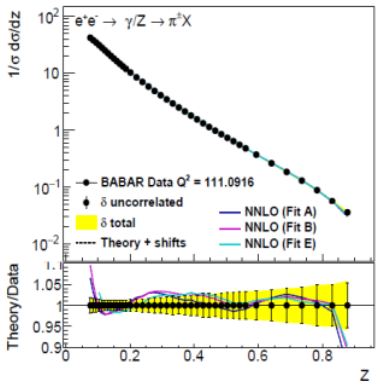


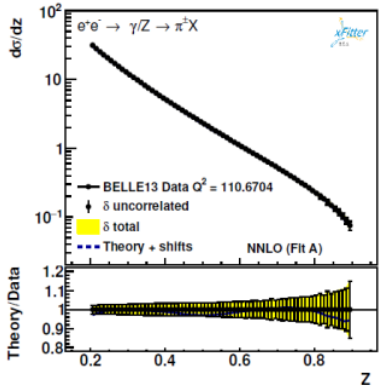
DEHSS *Phys.Rev.D* 95 (2017) 9, 094019

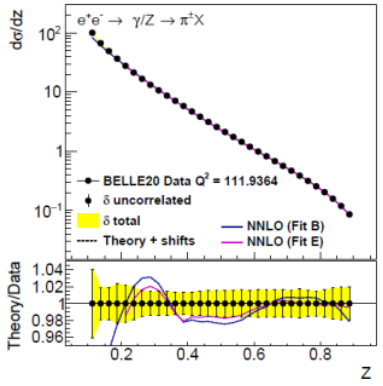
From “your errors are too conservative” to “your errors are too precise”

One group: “However we do not consider it because of a poor control of the degree of correlation of systematic uncertainties”

- Initial single hadron cross section measurement in very fine z binning, thus large bin-to-bin migration. Unfolding performed but assigned very conservative uncertainties → global fit’s χ^2 generally too low for our data set
- Recent update (’20) with more realistic binning, much better understanding of all systematic uncertainty sources, correlated and uncorrelated uncertainties provided separately
- However, fitters would prefer:
  - all systematics separately (will be done in the future),
  - all systematics symmetric (INCORRECT!)



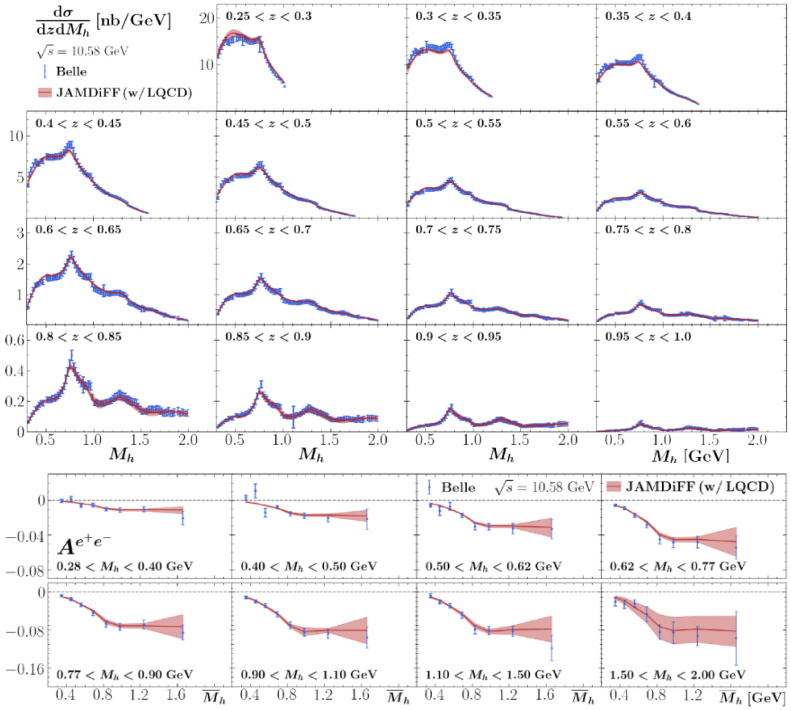


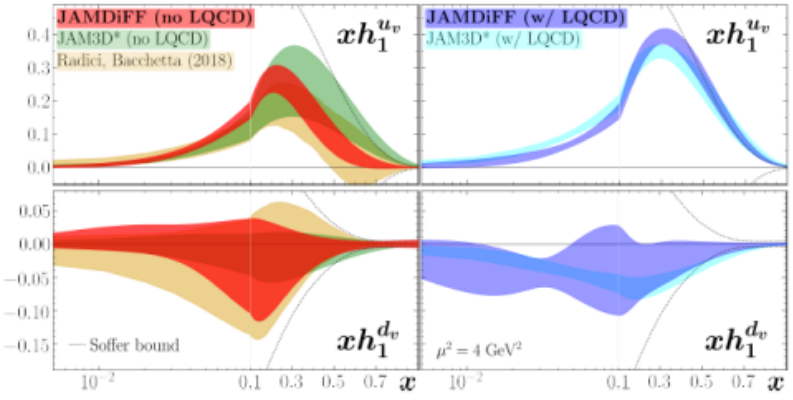


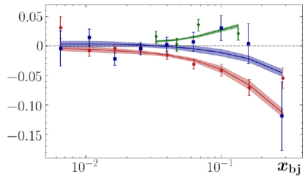
xFitter: [*Phys.Rev.D* 104 (2021) 056019]

Basics

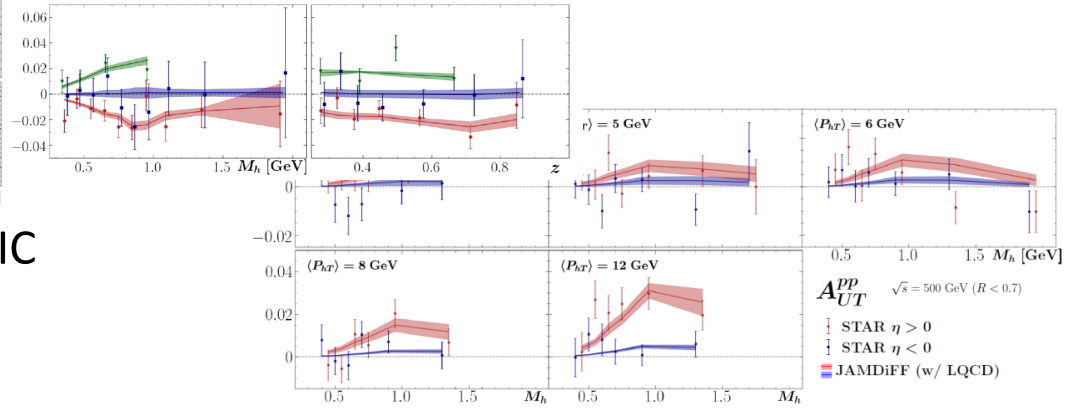
Global fits of Dihadron FFs







Cocuzza et al. https://arxiv.org/abs/2306.12998
Also Radici et al. *PRL 120 (2018) 19, 192001*



- Global fits taking SIDIS data, RHIC data, Belle data (polarized and unpolarized) into account

IFF, partial wave

Kaons

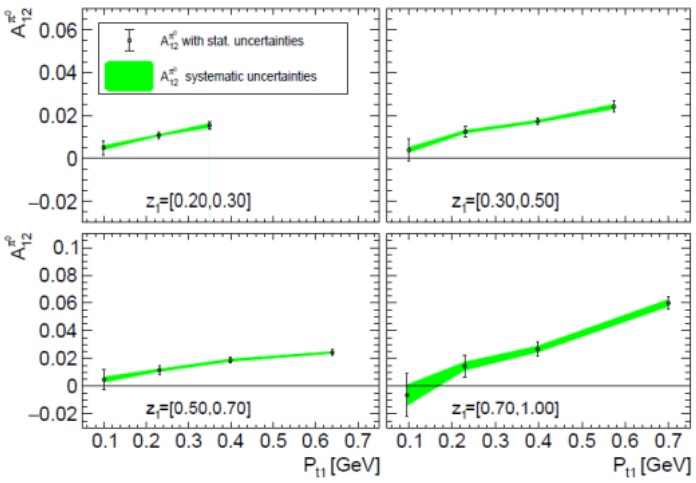
Outlook

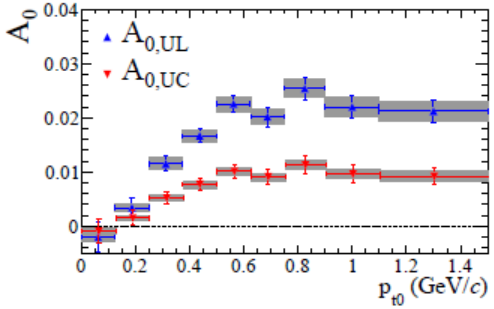
- Kharzeev paper?

- Opportunities paper

Transverse momentum

- Add transverse momentum to Collins asymmetries' z dependence PRD100 (2019) 92008
- Currently only 1 or 2-dimensional extractions available (q_t, z_1x z_2, p_{t1}x p_{t2},z_1xp_{t1})
- Increasing asymmetries with both z and pt, but pt reach limited
- Multidimensional extractions needed



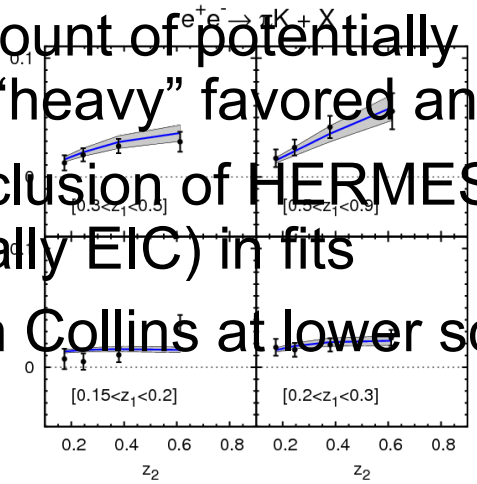


PRD 90 (2014) 052003 (Babar)

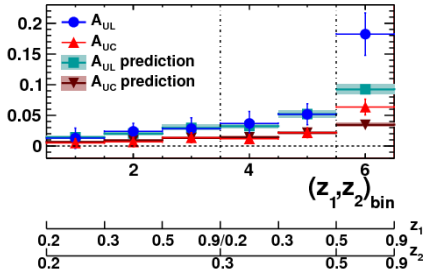
Quark transversity via Collins: Kaons

- Addition of kaon Collins fragmentation strongly needed for flavor decomposition of quark transversity
- Large amount of potentially participating FFs well described by light and “heavy” favored and disfavored FFs
- Allows inclusion of HERMES and COMPASS kaon asymmetries (+eventually EIC) in fits
- Also: pion Collins at lower scale(BESIII) consistent with TMD evolution

BABAR: PRD 92 (2015) 111101
Anselmino et al: PRD 93 (2016) 034025



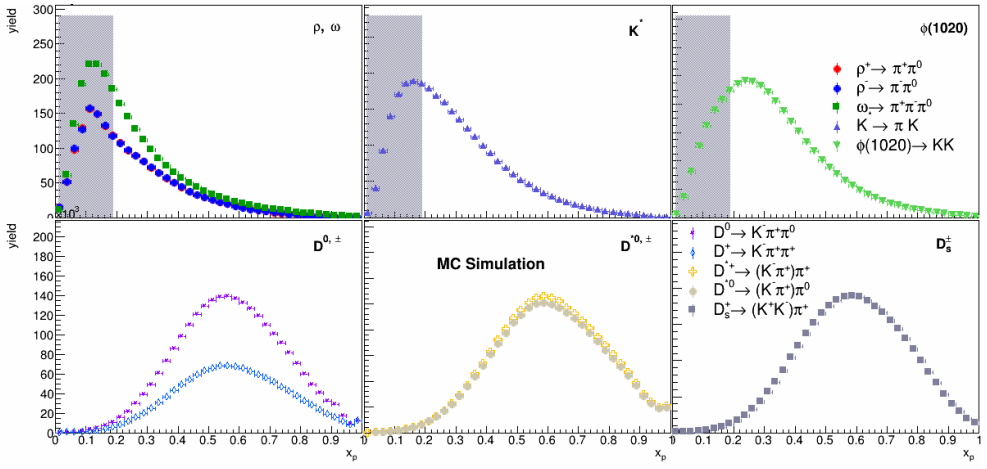
BESIII: PRL 116 (2016) 042001



Ongoing: Decaying particle FFs

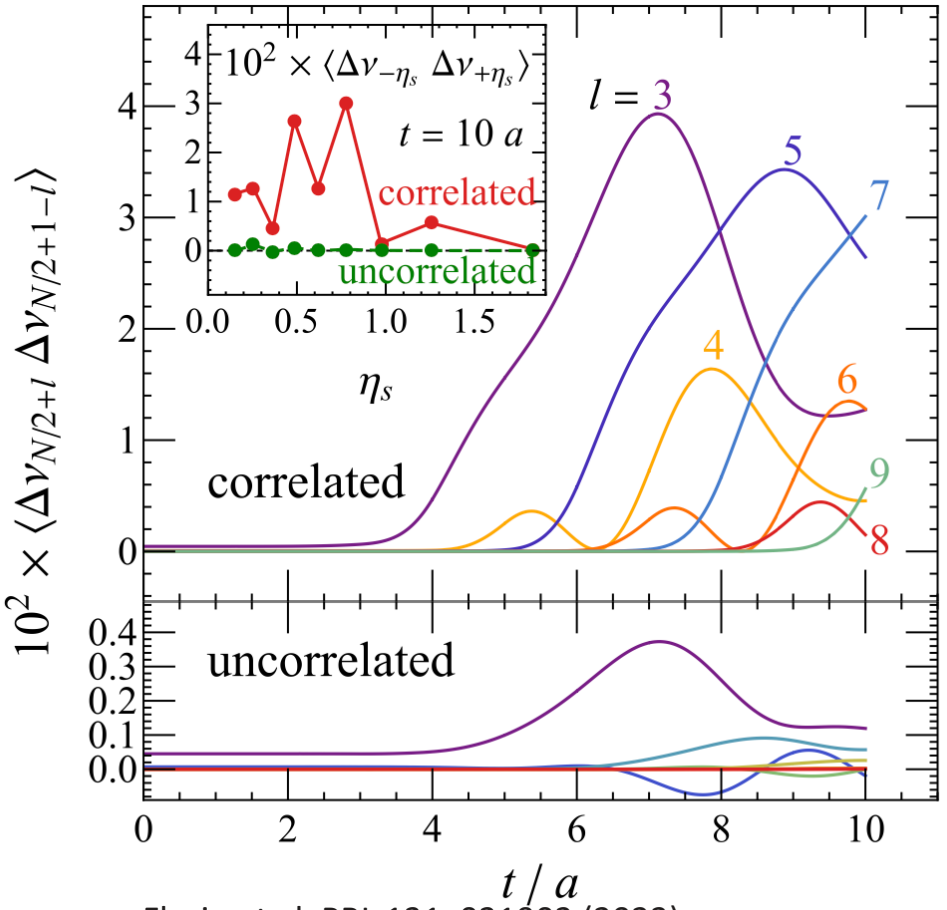
- Study the explicit differential cross sections for VMs, D mesons as a function of x_p
- Mostly mass distributions and fits well-behaved, except for ρ–ω (interference) and more exotic resonances
- Also of interest for ultra high-energetic cosmic ray air shower research (muon problem)

- Example from MC at Belle energies (for 4π acceptance):



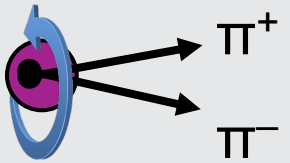
Important resource for EIC, RHIC and HI physics

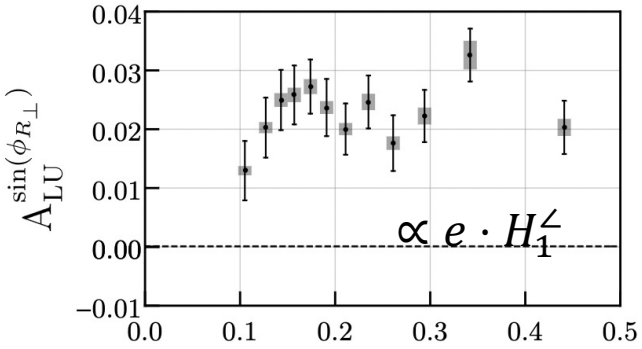
Entanglement



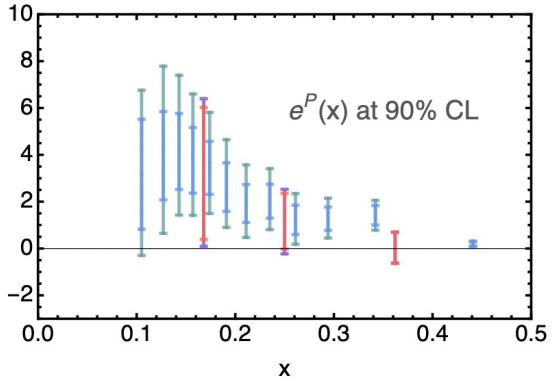
Florio et al, PRL 131, 021902 (2023)

Better: di-hadrons





Phys.Rev.Lett. 126 (2021) 152501

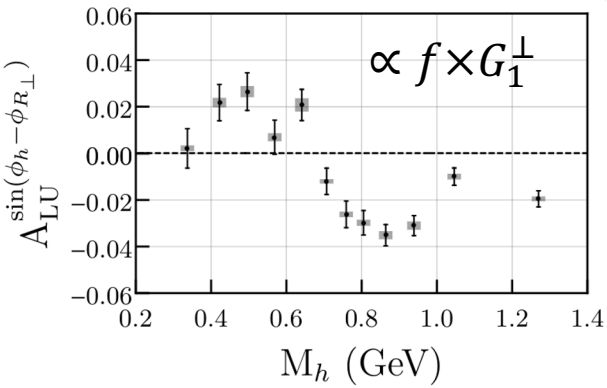


C. Dilks/T. Hayward

Phys.Rev.D 106 (2022) 1, 014027

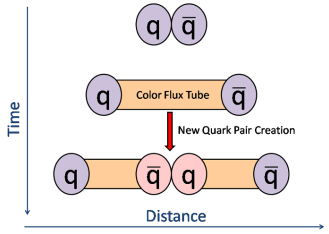
$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\,x\,e^q(x)\,H_1^{\sphericalangle q}(z,\cos\theta,m_{hh}) + \frac{1}{z}\,f_1^q(x)\,\tilde{G}^{\sphericalangle q}(z,\cos\theta,m_{hh})\right],$$

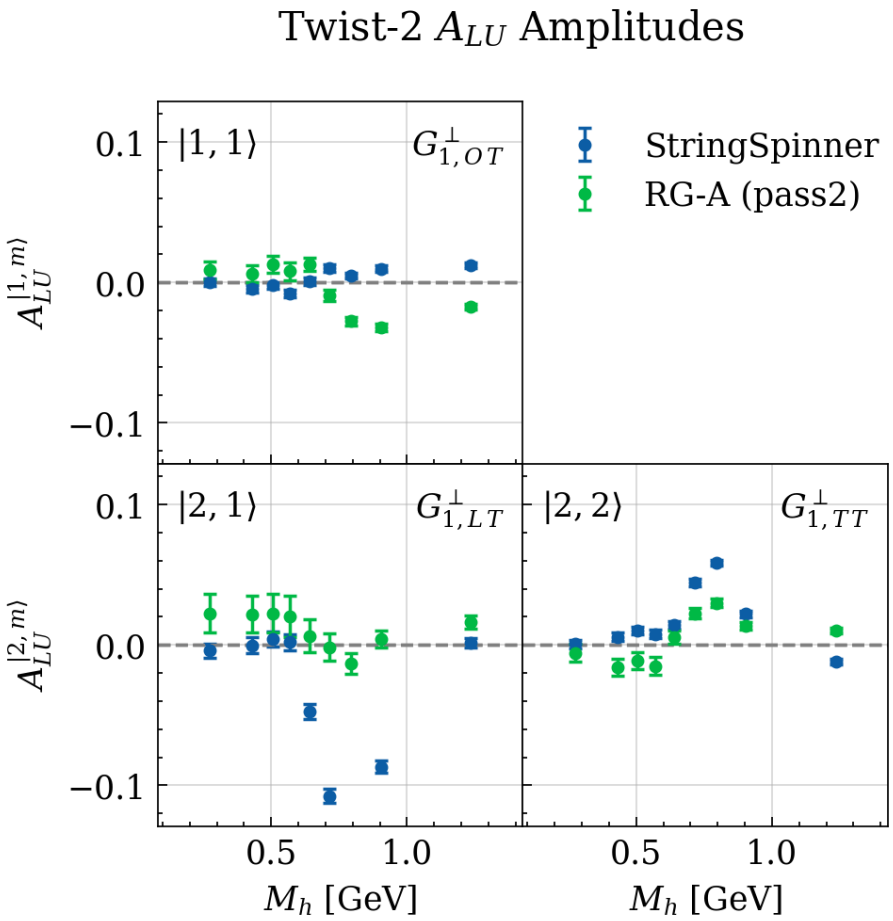
- First extraction of $e(x)$
- Further constrains from F_{UL} and F_{LL}
- First signal for $G_1^{\perp}$
  - Interesting resonance structure consistent with models
    (e.g. Luo, Sun, Xie, *Phys.Rev.D* 101 (2020) 5, 054020)

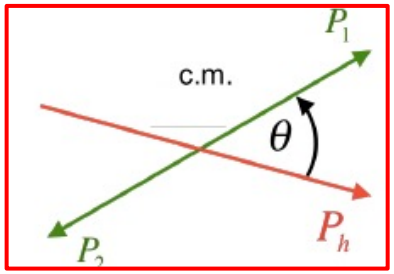


Compare Partial Wave Decomposition in MC and Data

- Comparing to Polarized Lund model here (StringSpinner $3P_0$ *model*, A. Kerbizi et al, *Comput.Phys.Commun.* 272 (2022))







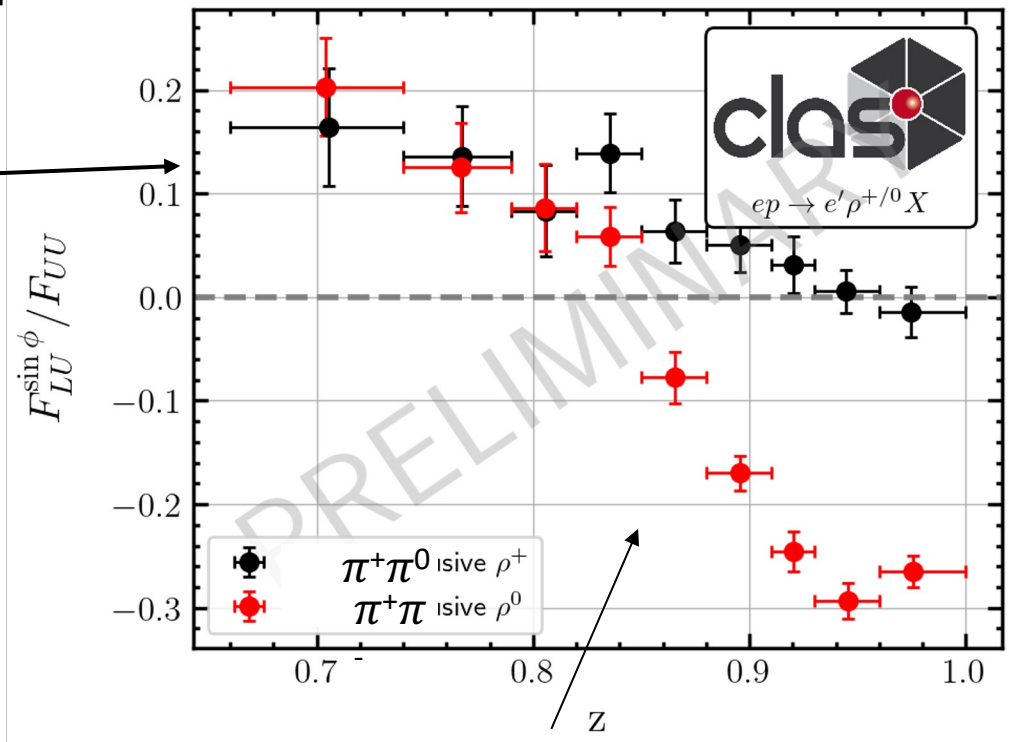
G Matousek

Near-exclusive $\pi^+\pi^-$, $\pi^+\pi^0$ production

★ We can constrain/better understand the contribution of ρ^0, ρ^+ decays on our single hadron asymmetries by looking at near exclusive (M_X < 1.1 GeV) channels

★ Strong yet similar asymmetries observed **(both productions came from struck *u* quark)**

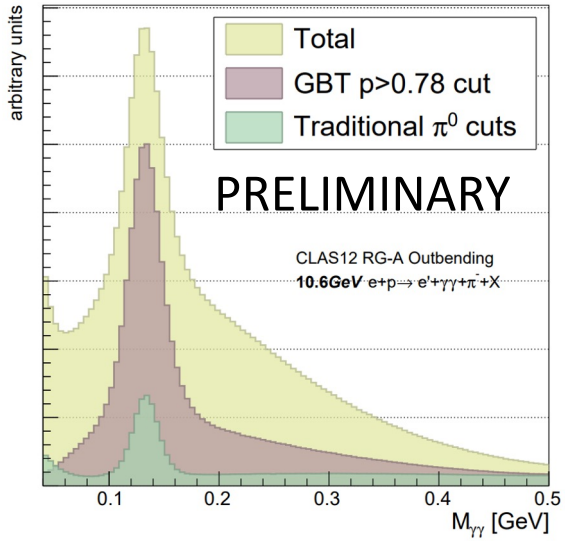
→See talk by K. Joo



★ Different mechanism for neutral ρ^0 at high z (low |t|) → GPDs, gluon contributions

G. Matousek

Dihadron Production $ep \to e\pi^{\pm}\pi^{0}(X)$



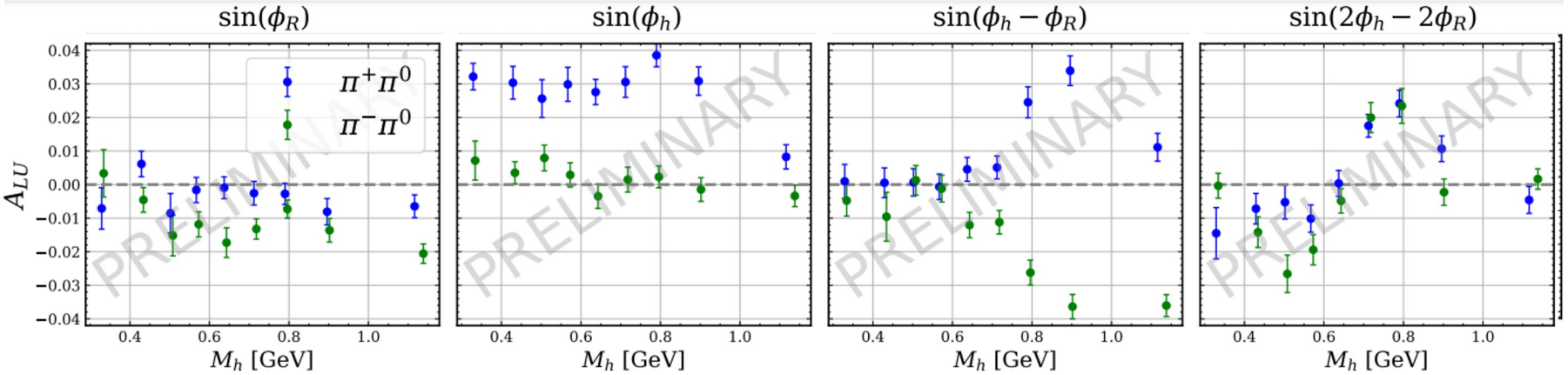
★ Nearest-neighbor GBDT model to reduce γ background

★ Negative **sin(ϕ_R)** asymmetry for **π-π0** → e(x) extraction
★ Strong positive **sin(ϕ_h)** asymmetry for **π+π0** → u quark dominated channels (seen in 1h SIDIS frequently)

★ Isospin symmetries of G_1 DiFF observed in **sin(ϕ_h - ϕ_R)**
★ Strong enhancement near resonant region

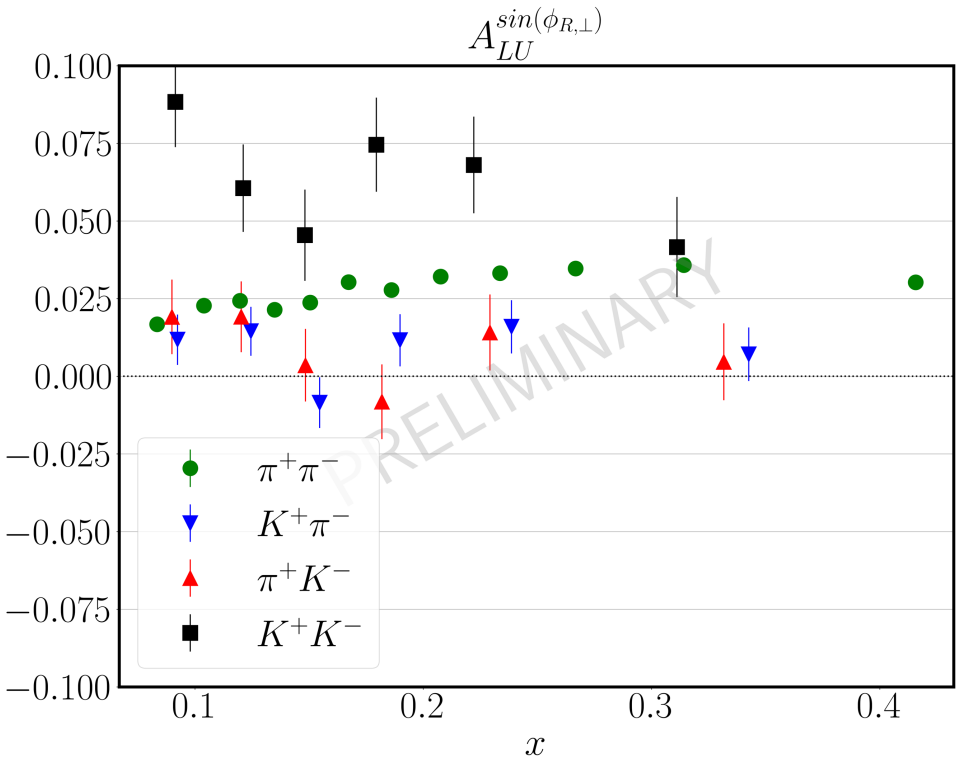
$e \otimes H_1^{\perp|\ell,m>}$

$f_1 \otimes G_1^{\perp|\ell,m>}$



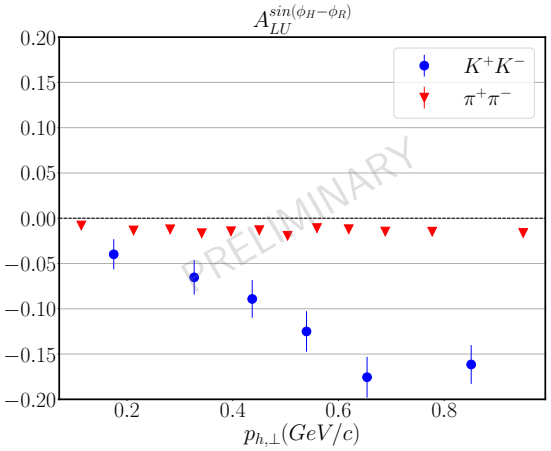
Slide by G. Matousek

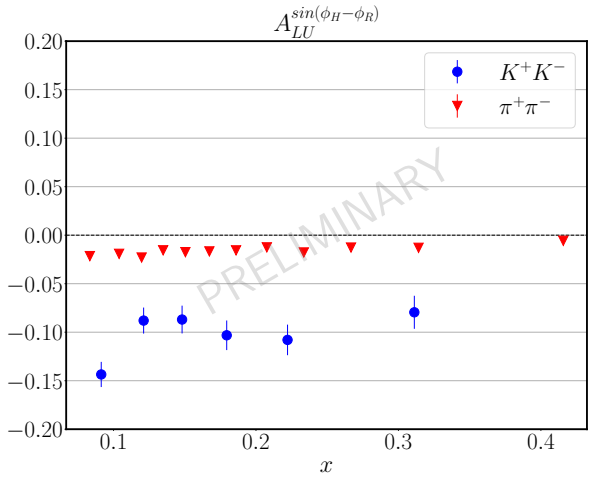
Kaons

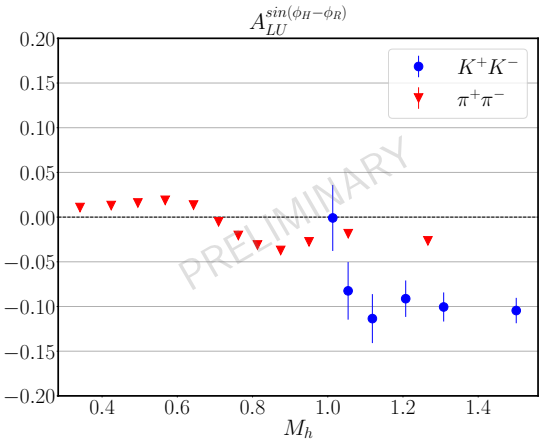


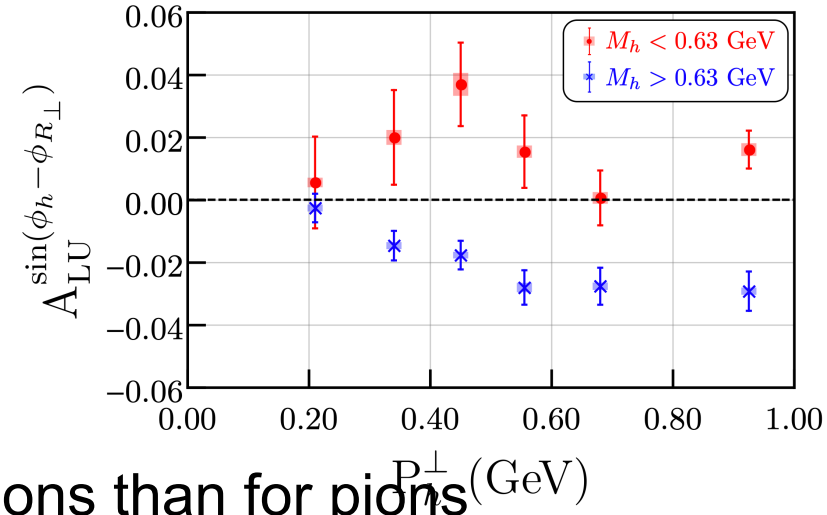
- Kaon ≫ Pions
  - Assuming u –quark dominance →FF effect?
  - Twist3 FF relevant?
  - Or $e(x)$ for strange quarks

Asymmetries sensitive to $G_1^\perp$



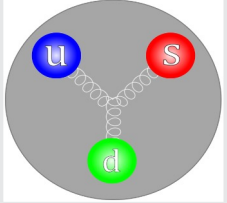






- sp –interference term larger for kaons than for pions
- Not true for all interference terms (not shown)
- $M_{KK} > m_\phi$ can account for $p_\perp$ dependence

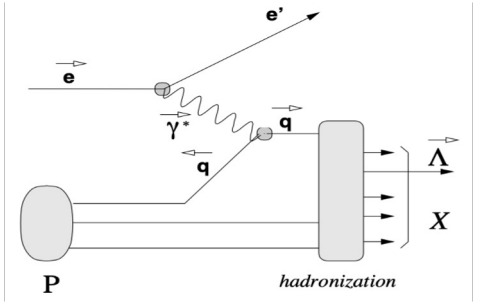
Lambda Program at CLAS12



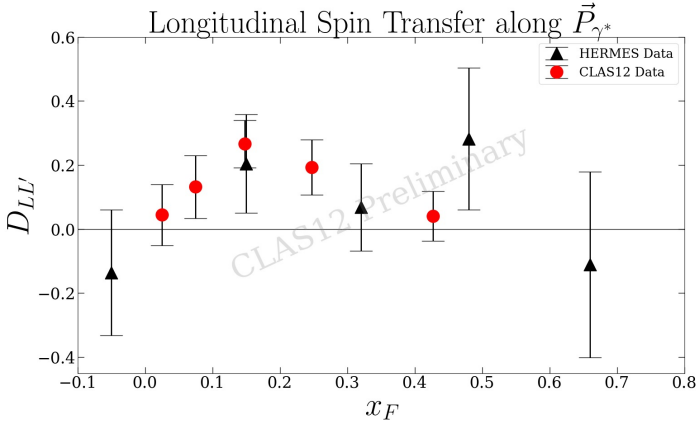
- **Constituent Quark Model (CQM)**
  - Predicts *s* quark carries 100% of the Λ hyperon spin
- "Do polarized *u*-quarks from current fragmentation transfer their longitudinal spin to the lambda?" → Test spin structure

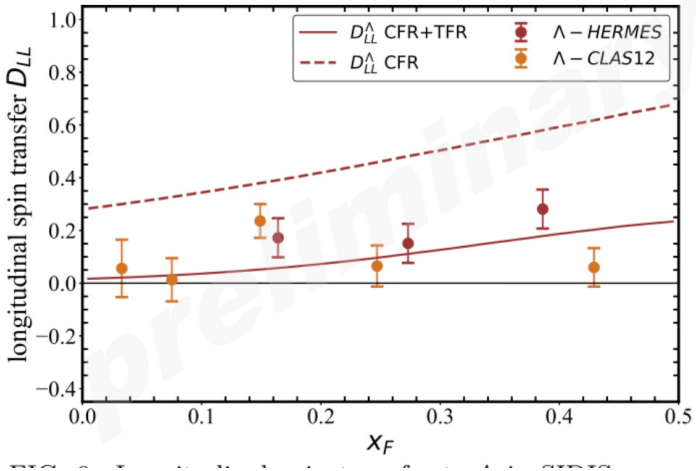
$$P_\Lambda = P_b D(y) D^\Lambda_{LL'},$$

longitudinal spin-transfer



Xiaoyan Zhao at





M. McEneaney

Part of planned extensive Lambda program with larger statistics: Transverse, polarizing…

Summary and Outlook

- **JLAB12 provides several orders of magnitude higher luminosity than any other lepton scattering facility!**
- **High precision data in the valence region**
  - Proton, deuteron, helium targets
  - Beam spin, longitudinal/transverse target polarizations
  - Multidimensional measurements
  - Analyses beyond leading twist/CFR regime
- **First results from BSAs and longitudinal spin asymmetries**
  - Precision data to extract TMDs
  - New target-current correlations
  - Intriguing flavor dependencies
  - Insights into spin-orbit correlations in hadronization using partial wave decomposition
- **Future at CLAS12 and SoLID**
  - Full program with data with longitudinal target(s)
  - Transverse target
  - Modulations of the unpolarized cross-section
  - …
- EIC Complementarity
  - Phase space
  - Depolarization factors