Fragmentation functions for EIC

EICで展開する新たな原子核・素粒子物理

Tokyo University, May 28-30, 2024

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Spin of the nucleon:

- Gluon spin
- Role of Sea quarks

QCD at high gluon densities

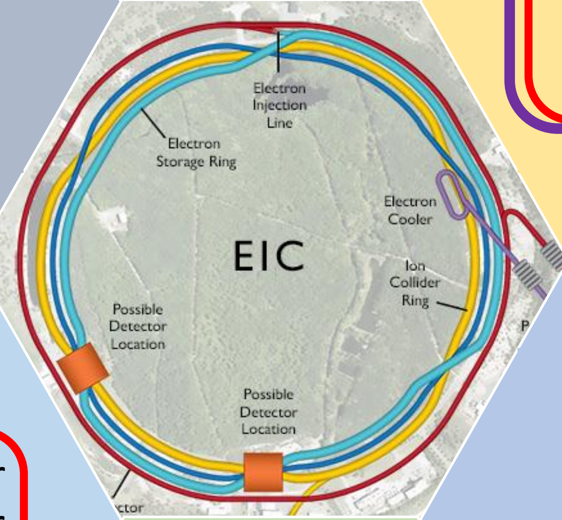
- Saturation effects

Tomography :

- 3D momentum structure (q, g Sivers, Tensor charge, TMD Evolution)
- 3D spatial structure

SIDIS Measurements: Fragmentation functions

Transverse Momentum Dependent PDFs/FFs



Nucelar effects

- Nuclear PDFs
- Passage of color through nuclear matter (nFFs, pT broadening)

Origin of the Mass

- Axial anomaly contributions
- Hadron structure

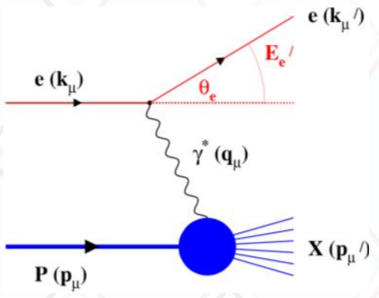
Other

- Spectroscopy (XYZ)
- EW physics
- Fragmentation
- Unpol PDFs

Tools at an EIC and basic requirements

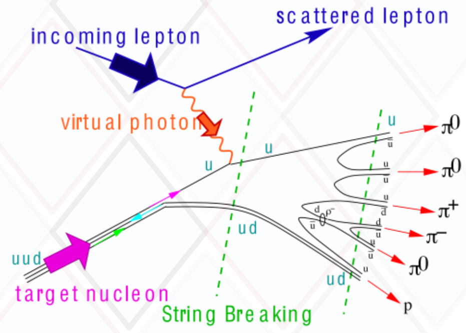
Inclusive Reactions in ep/eA:

- Physics: Structure Fcts.: g_1, F_2, F_L
- Very good electron id → identify scattered lepton
- Momentum/energy and angular resolution of e' critical
- scattered lepton → kinematics of event (x,Q^2)



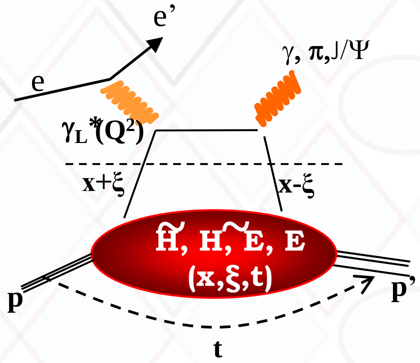
Semi-inclusive Reactions in ep/eA:

- Physics: TMDs, Helicity PDFs, FF → flavor separation, dihadron-corr.,…
  → Pion, Kaon asymmetries, cross sections
- Excellent particle ID: $\pi^\pm$,$K^\pm$,$p^\pm$ separation over a wide range in $-3<\eta<3$
  → excellent p resolution at forward rapidities
- TMDs: full Φ-coverage around γ^*, wide p_t coverage
- Excellent vertex resolution → Charm, Bottom separation



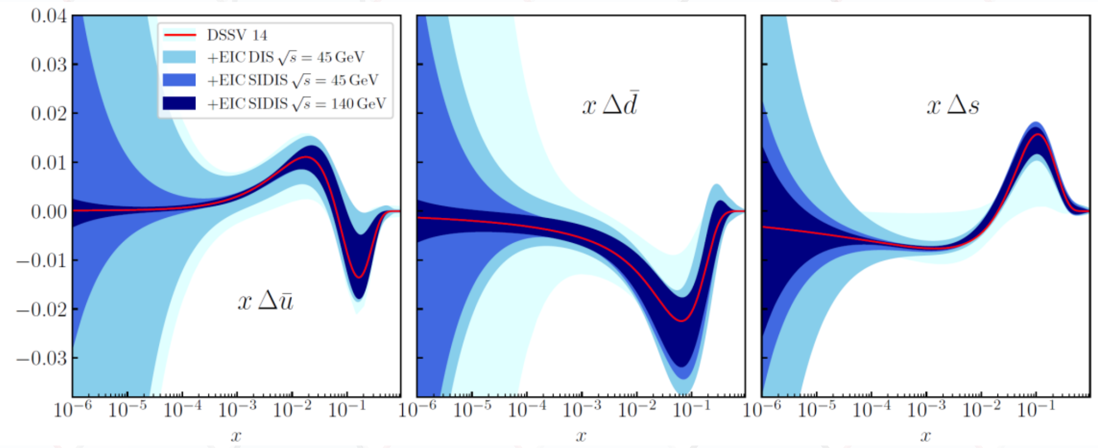
Exclusive Reactions in ep/eA:

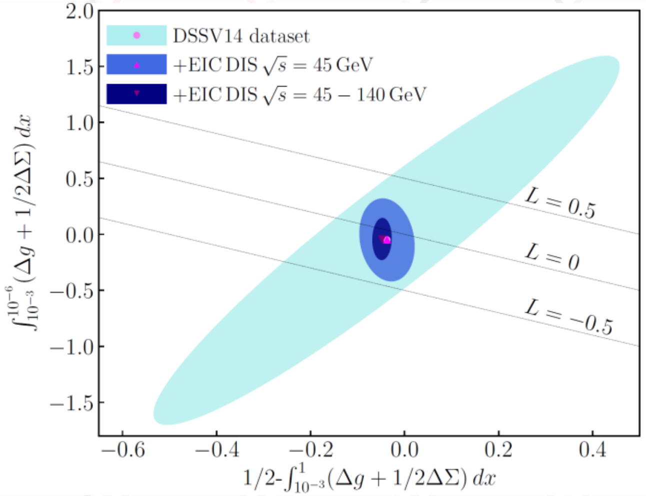
- Physics: DVCS, excl. VM/PS prod. → GPDs, parton imaging in b_T; $g(x,Q^2,b_T)$
- Exclusivity → large rapidity coverage → rapidity gap events
  ↘ reconstruction of all particles in event
- high resolution, wide coverage in t → b_t → Roman pots
- eA: veto nucleus breakup, determine impact parameter of collision
  → acceptance for neutrons in ZDCs



Gluon and sea polarization

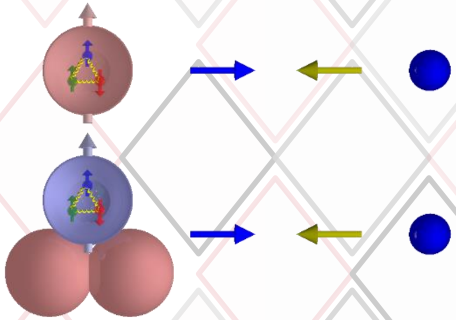
- 1 year of EIC running will pin down gluon polarization
- Using SIDIS: precise determination of sea quark helicities, especially strange contribution of interest
- Indirect determination of orbital angular momentum via sum rule
- Also interesting access to flavor via charged current reactions





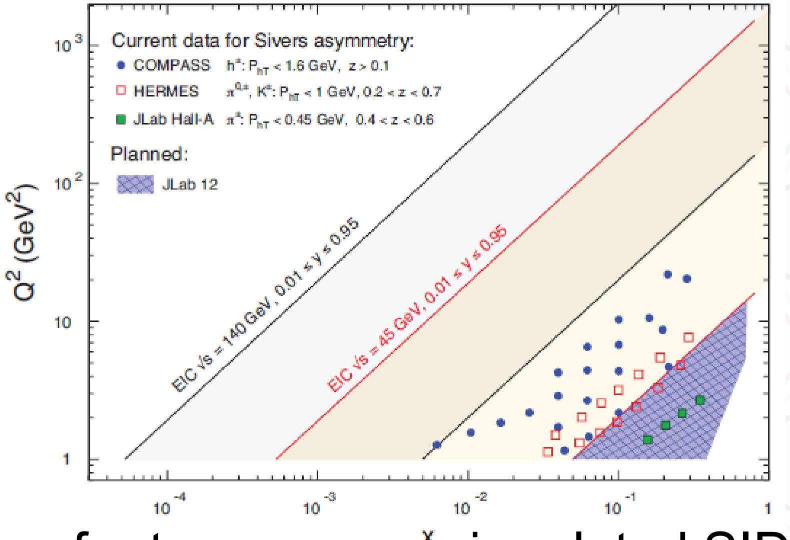
PRD 102 (2020), 094018

EIC TMD Goals: 3D Transverse spin and momentum structure

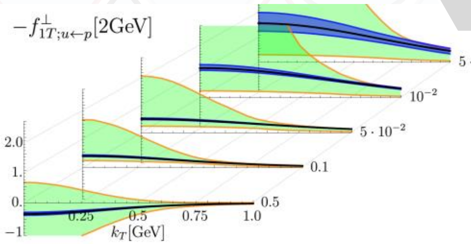


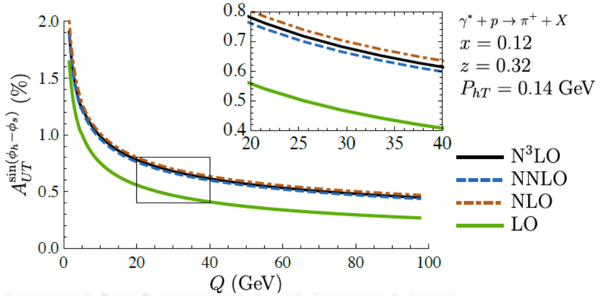
Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	3[rd] basic quark PDF; novel hadronization effects	valence+sea quarks	Q^2 (P_{hT}) range for detailed QCD dynamics

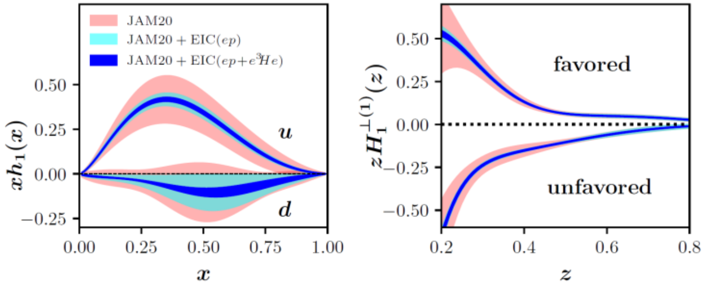
Tables from original EIC white paper



Current coverage for transverse spin related SIDIS measurements

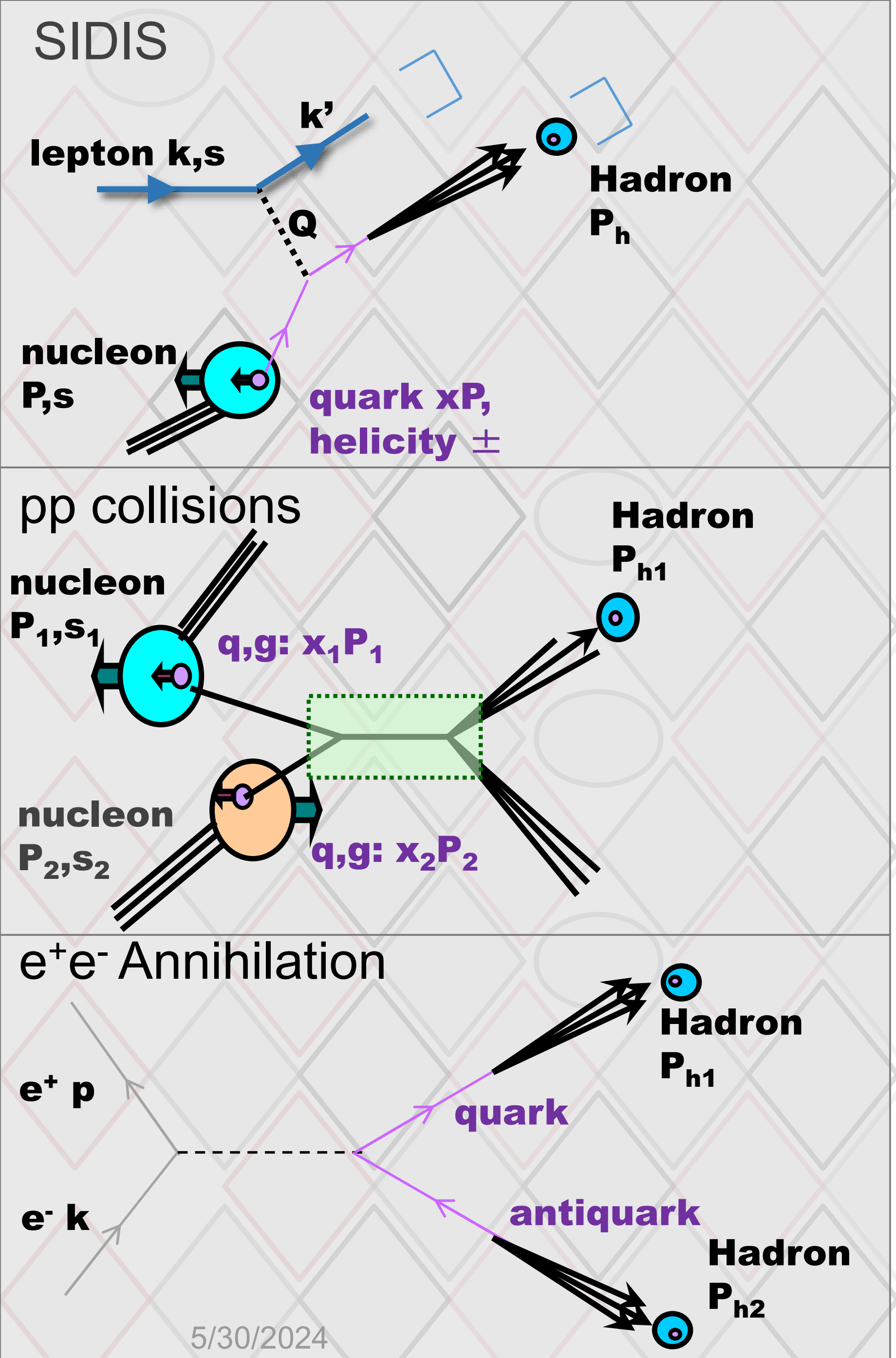






Help of Fragmentation Functions (FF) for nucleon (spin, transverse) structure

- Correlate a hadron in the final state with the struck parton:
  - Parton flavor (HF, favored vs disfavored, strange fragmentation, etc; ie: u quark into a π^+ is favored, d quark disfavored, s, ubar quarks favored in K^+ fragmentation)
  - Spin of the struck quark (Collins and Interference Fragmentation, other polarized FFs)
  - Transverse momentum of struck parton (though convolution with fragmentation transverse momentum)
- Closely related to confinement mechanism



Access to Fragmentation functions

- SIDIS:

$$\sigma^h(x, z, Q^2, P_{h\perp}) \propto \sum_q e_q^2 q(x, p_t, Q^2) D^h_{1,q}(z, k_t, Q^2)$$

  - Relies on unpol PDFs
  - Parton momentum known at LO
  - Flavor structure directly accessible
  - Transverse momenta convoluted between FF and PDF

- pp:

$$\sigma^h(P_T) \propto \int_{x_1,x_2,z} \sum_{a,a' \in q,g} f_a(x_1) \otimes f_{a'}(x_2) \otimes \sigma_{aa'} \otimes D^h_{1,q}(z)$$

  - Relies on unpol PDFs
  - leading access to gluon FF
  - Parton momenta not directly known

- e^+e^-:

$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(D^h_{1,q}(z, k_t, Q^2) + D^h_{1,\bar{q}}(z, k_t, Q^2) \right)$$

  - No PDFs necessary
  - Clean initial state, parton momentum known at LO
  - Flavor structure not directly accessible*

Single hadron FF

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D_{1,q}^{h}(z, Q^2)$ PRL111 (2013) 062002 PRD101(2020) 092004	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ PRL 96 (2006) 232002 PRD 78 (2008) 032011	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \to (h)(h)X$ PRD92 (2015) 092007 PRD101(2020) 092004 and scale dependence
Transverse momentum dependent FFs: $e^+e^- \to (h)X$ $D_{1,q}^{h}(z, k_T, Q^2)$ PRD 99 (2019) 112006	Transverse momentum dependent asymmetries $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2), Q_t$ $H_{1,q}^{\perp h}(z, k_T, Q^2)$ PRD100 (2019) 92008	Polarizing Λ fragmentation PRL 122 (2019), 042001 $D_{1,q}^{\perp h}(z, k_T, Q^2)$

BELLE

Dihadron FF (IFF)

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \to (hh)X$ $D_{1,q}^{h_1 h_2}(z, m, Q^2)$ PRD96 (2017) 032005	Azimuthal asymmetries: $e^+e^- \to (hh)(hh)X$, $\cos(\phi_1 + \phi_2)$, $H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$ PRL107 (2011) 072004	Unpol SIDIS, pp: $\frac{d^2\sigma}{dzdm}$

Single hadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D_{1,q}^{h}(z, Q^2)$ PRD 88 (2013) 032011 (Babar)	Azimuthal asymmetries: $e^+e^- \to (h)(h)X,$ $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ PRD 92 (2015) 111101 (Babar K) PRL 116 (2016) 042001 (BESIII)	Unpol SIDIS, pp: $\frac{d\sigma}{dz}$ $e^+e^- \to (h)(h)X$ and scale dependence
Transverse momentum dependent FFs: $e^+e^- \to (h)X$ $D_{1,q}^{h}(z, k_T, Q^2)$	Transverse momentum dependent asymmetries $e^+e^- \to (h)(h)X,$ $\cos(\phi_1 + \phi_2), Q_t$ $H_{1,q}^{\perp h}(z, k_T, Q^2)$ PRD 90 (2014) 052003 (Babar)	

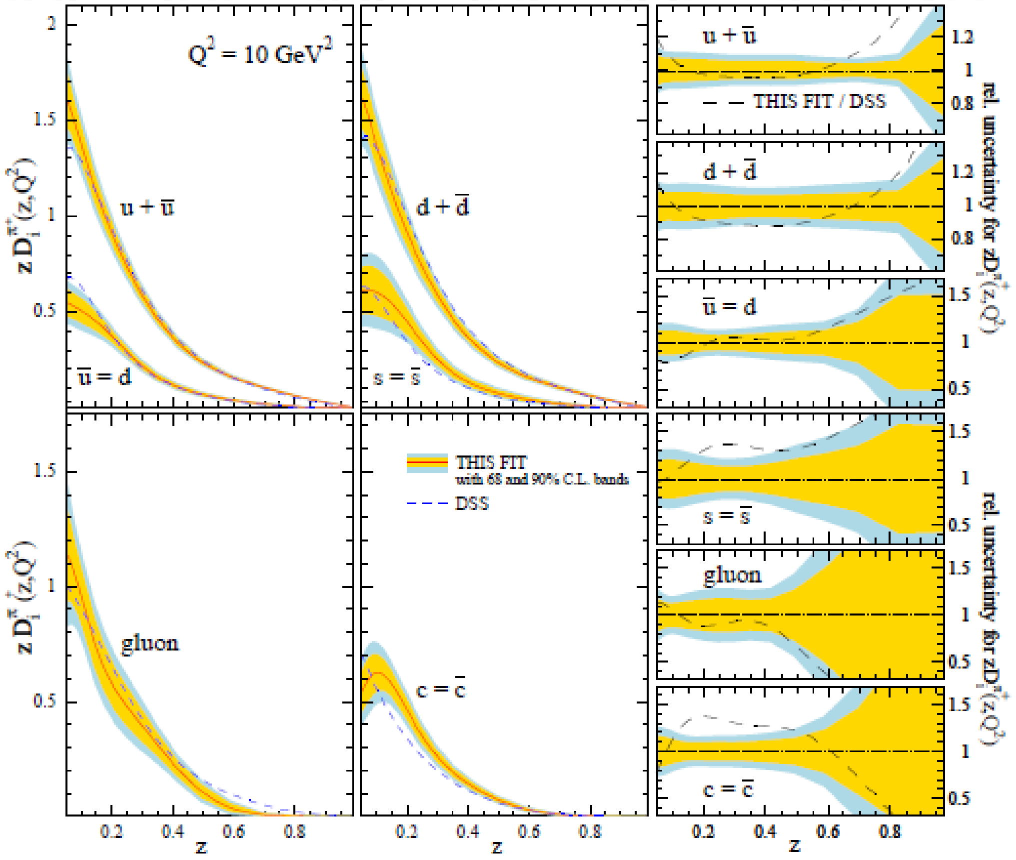
Dihadron measurements

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \to (hh)X$ $D_{1,q}^{h_1 h_2}(z, m, Q^2)$	Azimuthal asymmetries: $e^+e^- \to (hh)(hh)X,$ $\cos(\phi_1 + \phi_2),$ $H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$	Unpol SIDIS, pp: $\frac{d^2\sigma}{dz\,dm}$

Pion fragmentation

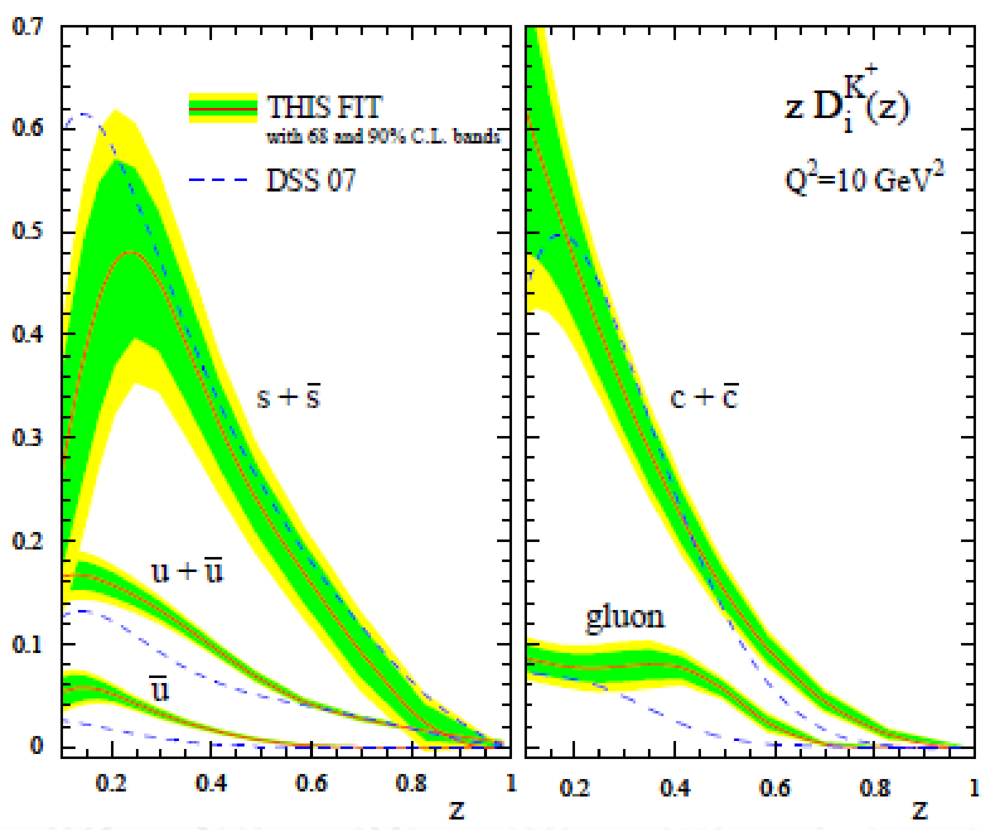
DSS15: deFlorian et.al., Phys.Rev. D91 (2015) 014035

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



Kaon fragmentation

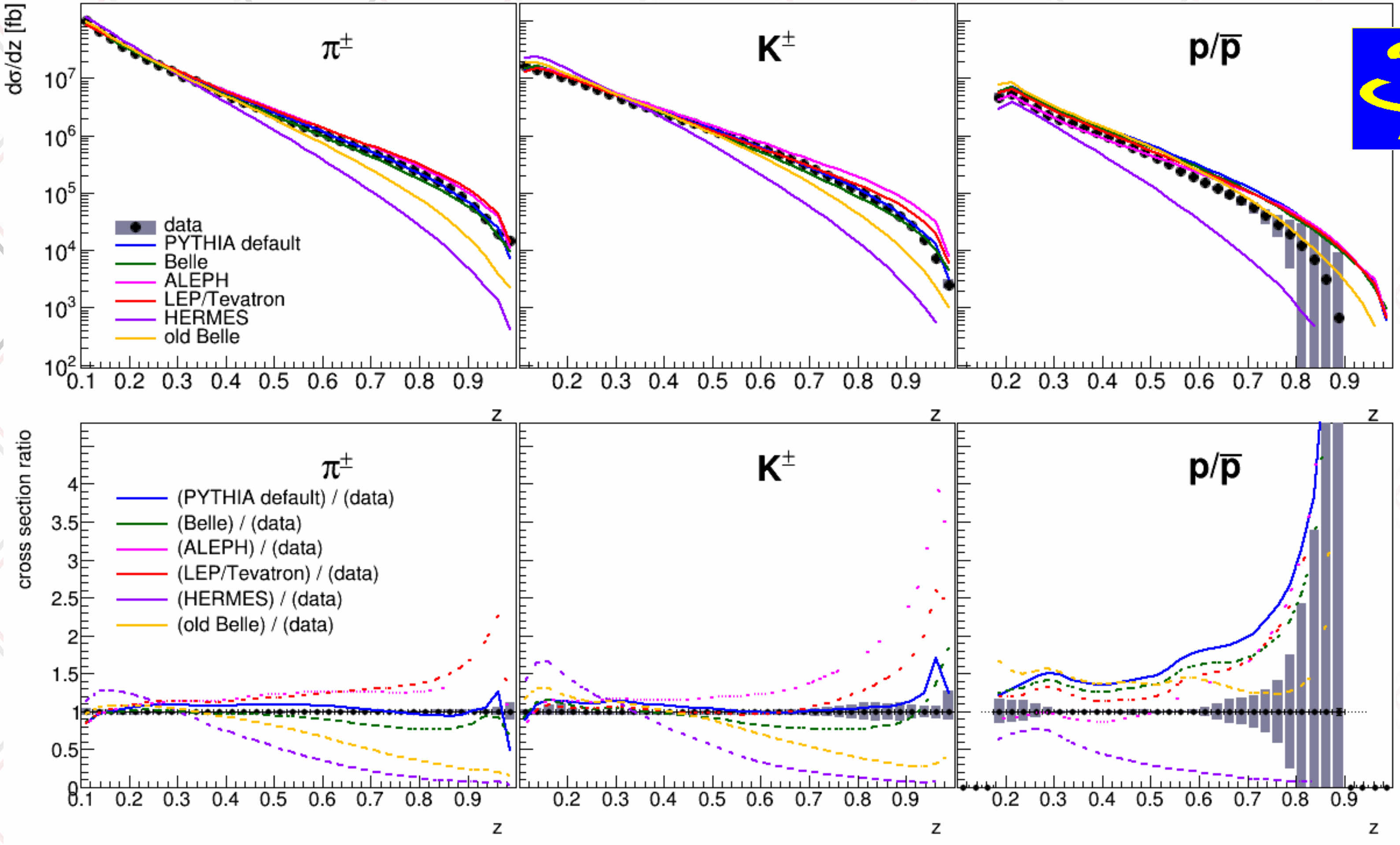
- Strange quarks are dominating kaon fragmentation
- Also dominated by favored u quark fragmentation at high-z
- At lower z penalty for producing $s\bar{s}$ pair in fragmentation ($u+\bar{u} < s+\bar{s}$)
- Charm fragmentation comparable (what about weak decays?)



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

Unpolarized single hadrons

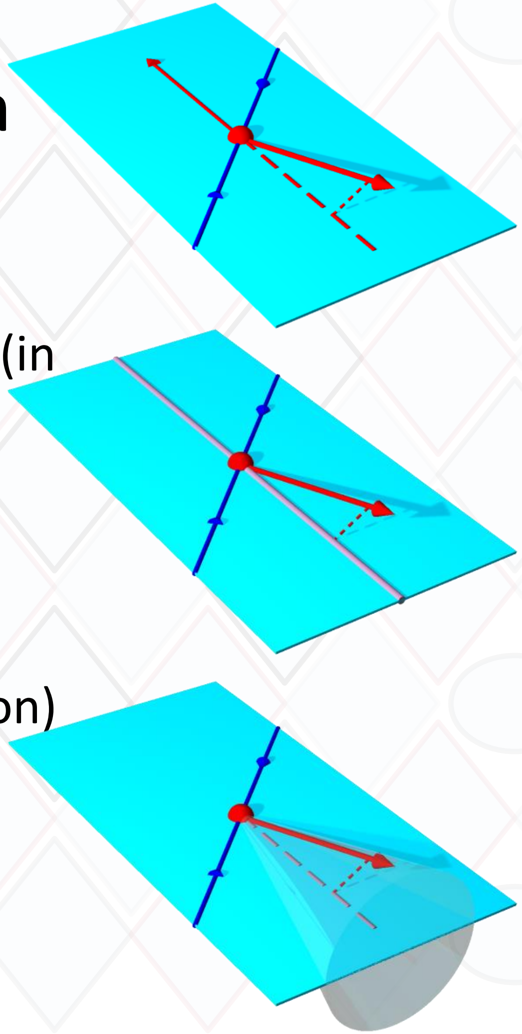
PRD 101 (2020) 092004



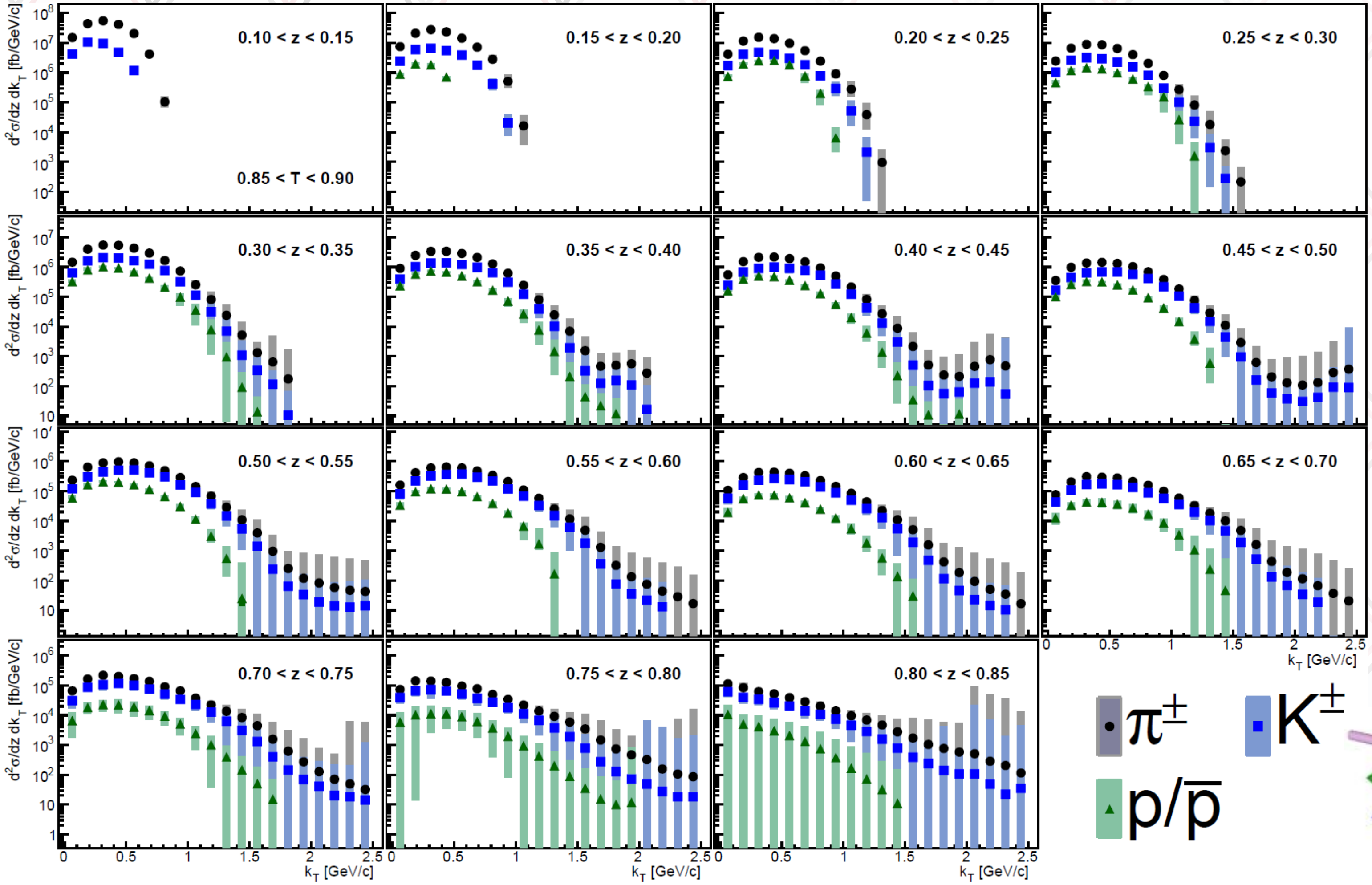
- Update with better ISR correction
- Correlated and uncorrelated uncertainties separated → improve global unpolarized FF fits

K_T Dependence of FFs in e+e-

- Gain also sensitivity into transverse momentum generated in fragmentation
- Two ways to obtain transverse momentum dependence
  - Traditional 2-hadron FF
    - →use transverse momentum between two hadrons (in opposite hemispheres)
    - →Usual convolution of two transverse momenta
  - Single-hadron FF wrt to Thrust or jet axis
    - →No convolution
    - →Need correction for $q\bar{q}$ axis (similar to a Jet function)

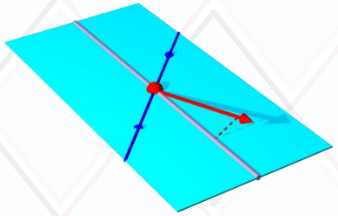


Transverse momentum dependent cross sections for pions, kaons and protons



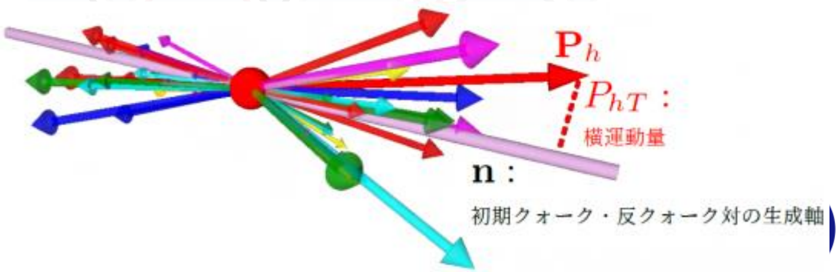
$$\frac{d^2\sigma}{dzdP_{hT}}$$

P_{hT}



Important baseline for most transverse momentum/spin dependent measurements at RHIC and EIC

RIKEN Press release: https://www.riken.jp/press/2019/20190615_1/

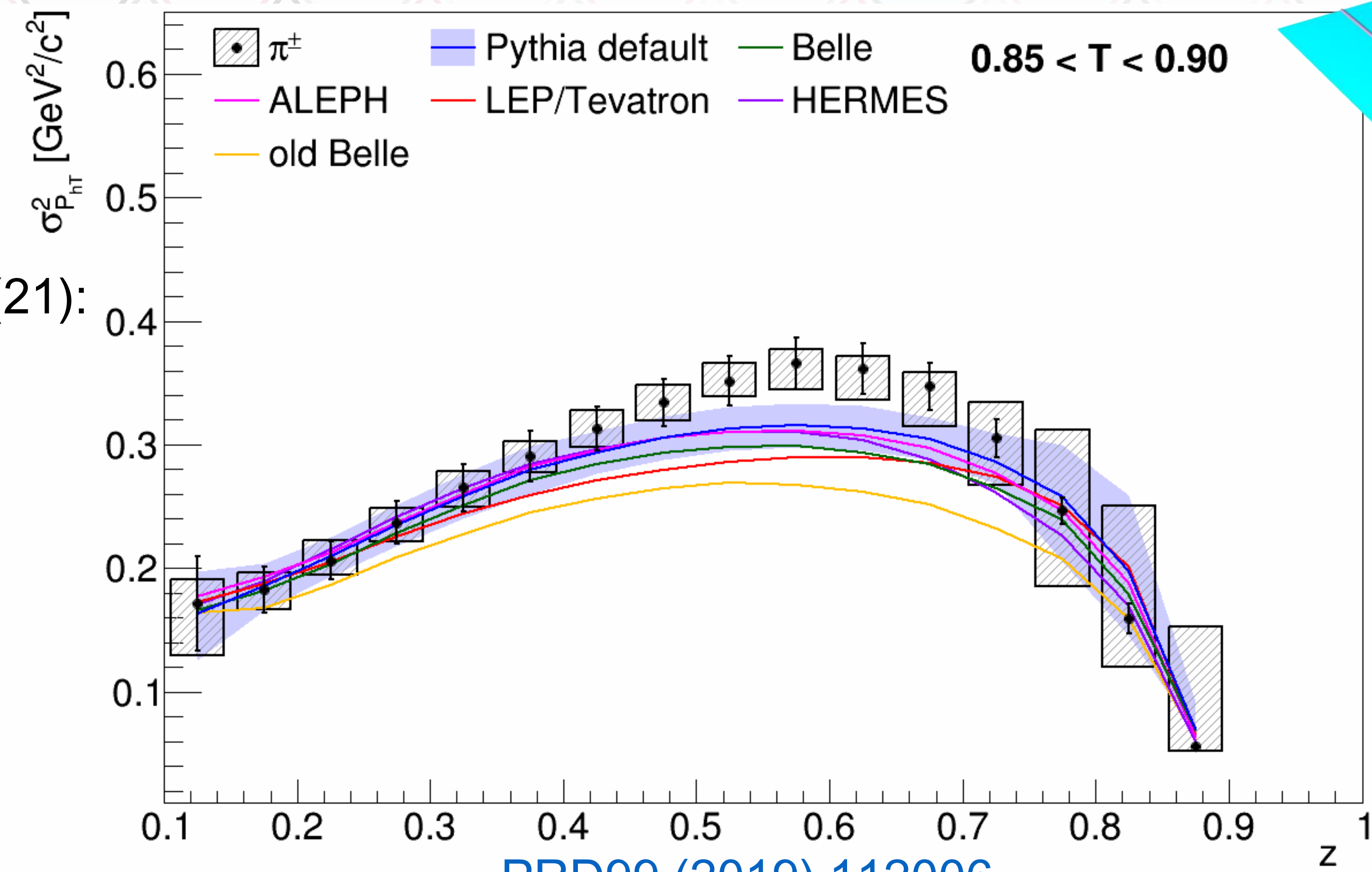


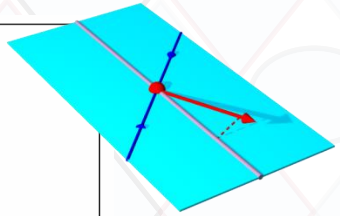
RS. et. al. [PRD99 (2019) 112006](https://doi.org/10.1103/PhysRevD.99.112006)

Gaussian widths comparison to MC

first direct (no convolutions) measurement of z dependence of Gaussian widths

MSTP(21):
0.28
0.325
0.36
0.36
0.37
0.40



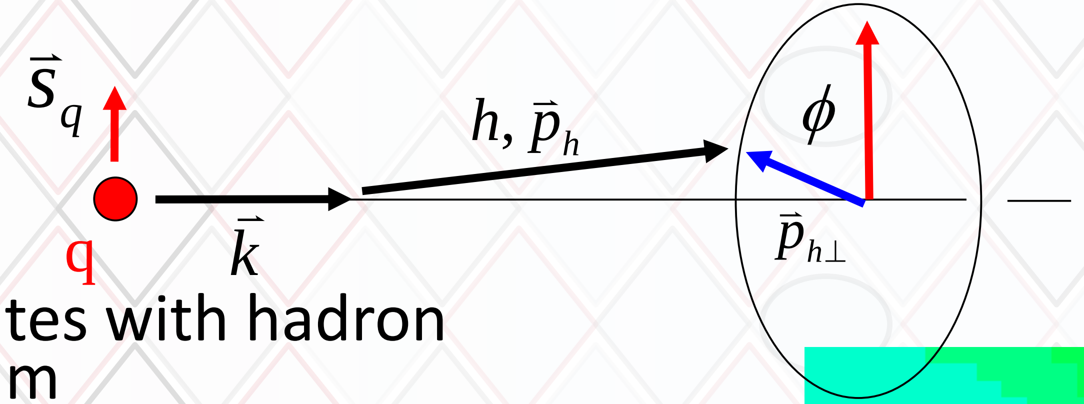


PRD99 (2019) 112006

Collins fragmentation function

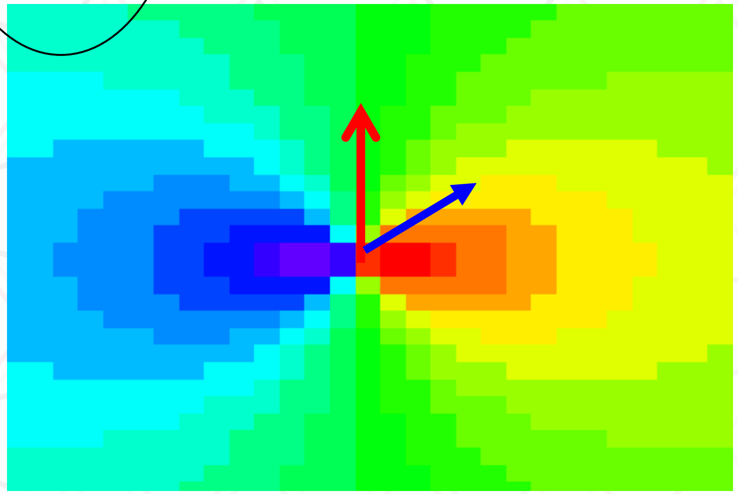
J. Collins, Nucl. Phys. B396, (1993) 161

$$D^h_{q\uparrow}(z, P_{h\perp}) = D^h_{1,q}(z, P^2_{h\perp}) + H^{\perp h}_{1,q}(z, P^2_{h\perp}) \frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{z M_h}$$



- Spin of quark correlates with hadron transverse momentum

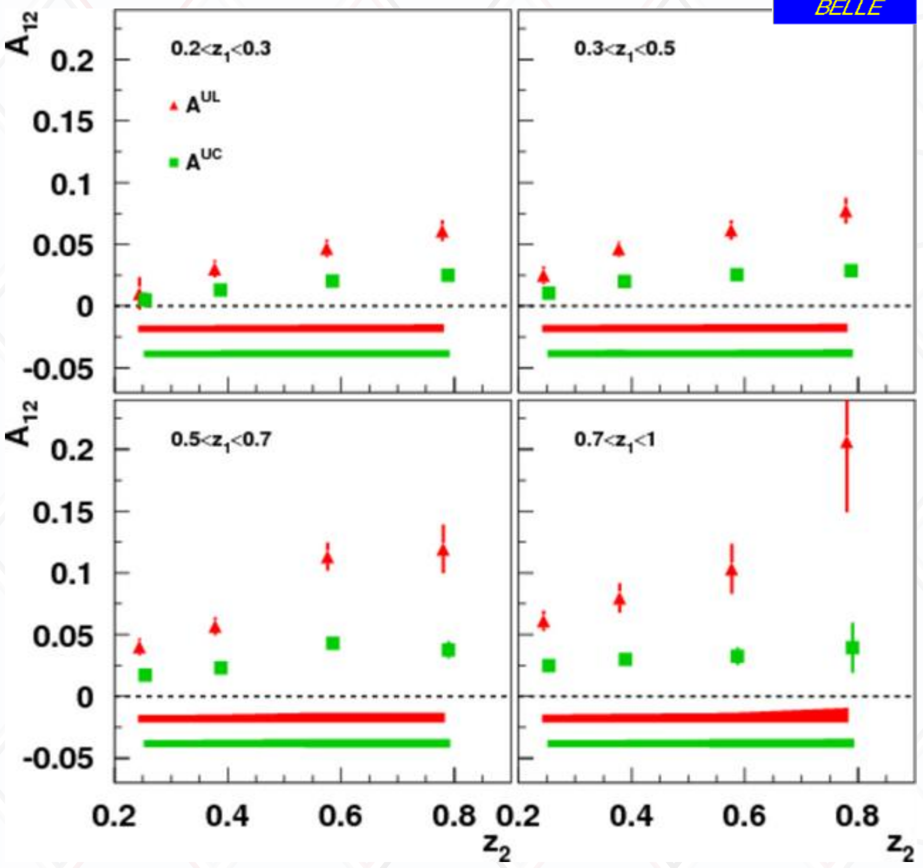
➔translates into azimuthal anisotropy of final state hadrons



Needed at the EIC to access Transversity and Boer-Mulders (quark spin-orbit) function

Belle Collins asymmetries

- Red points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over like sign pion pair ratio : A^{UL}
- Green points : $\cos(\phi_1 + \phi_2)$ moment of Unlike sign pion pairs over any charged pion pair ratio : A^{UC}
- Collins fragmentation is large effect
- Consistent with SIDIS indication of sign change between favored and disfavored Collins FF

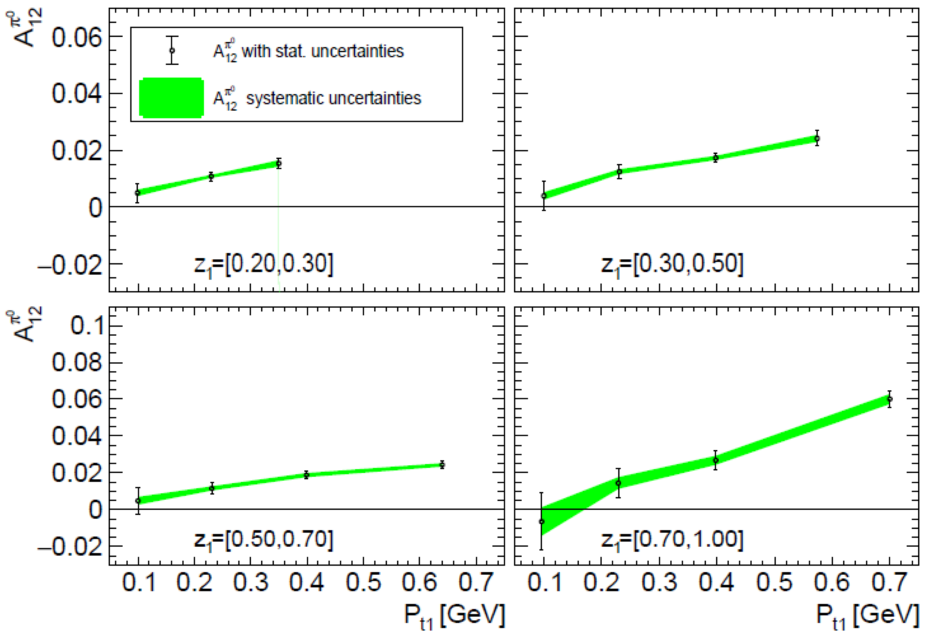


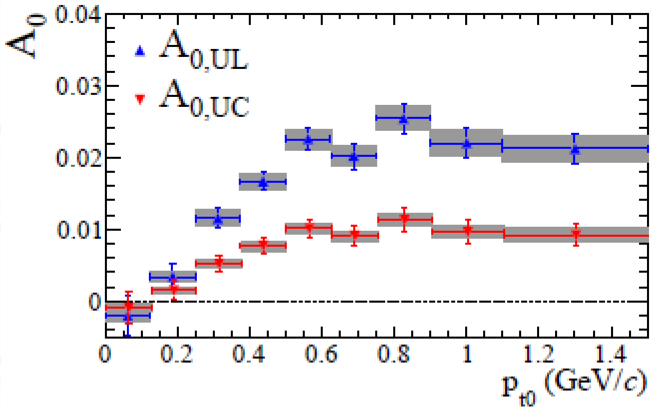
RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Transverse momentum

- Add transverse momentum to Collins asymmetries' z dependence
- 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

PRD100 (2019) 92008



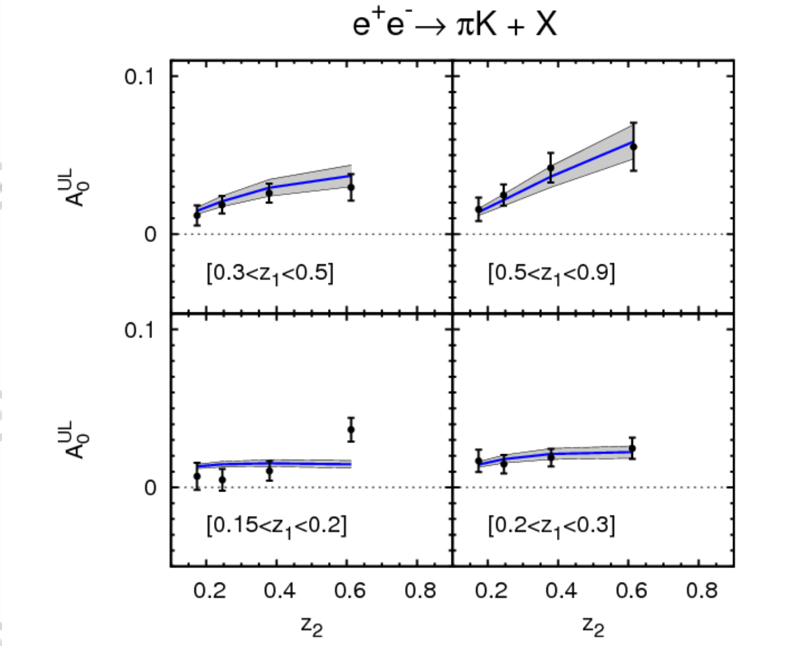


PRD 90 (2014) 052003 (Babar)

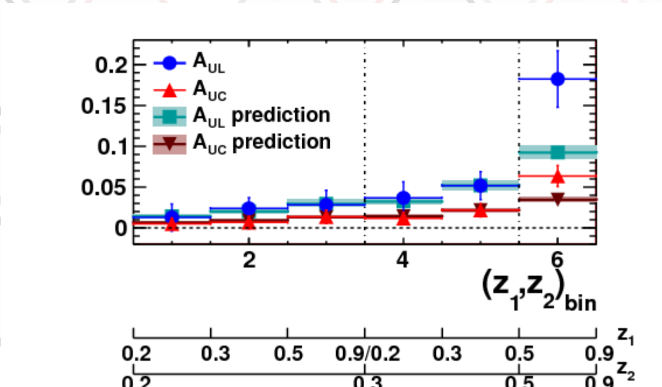
Quark transversity via Collins: Kaons

BABAR: PRD 92 (2015) 111101

Anselmino et al: PRD 93 (2016) 034025



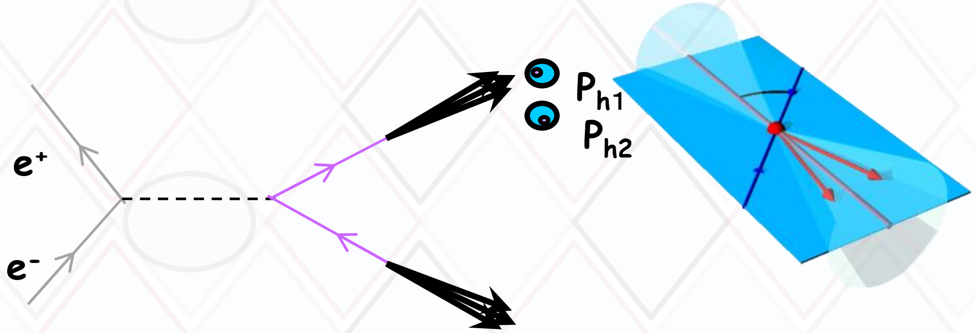
BESIII: PRL 116 (2016) 042001



- 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

Di-hadron fragmentation functions

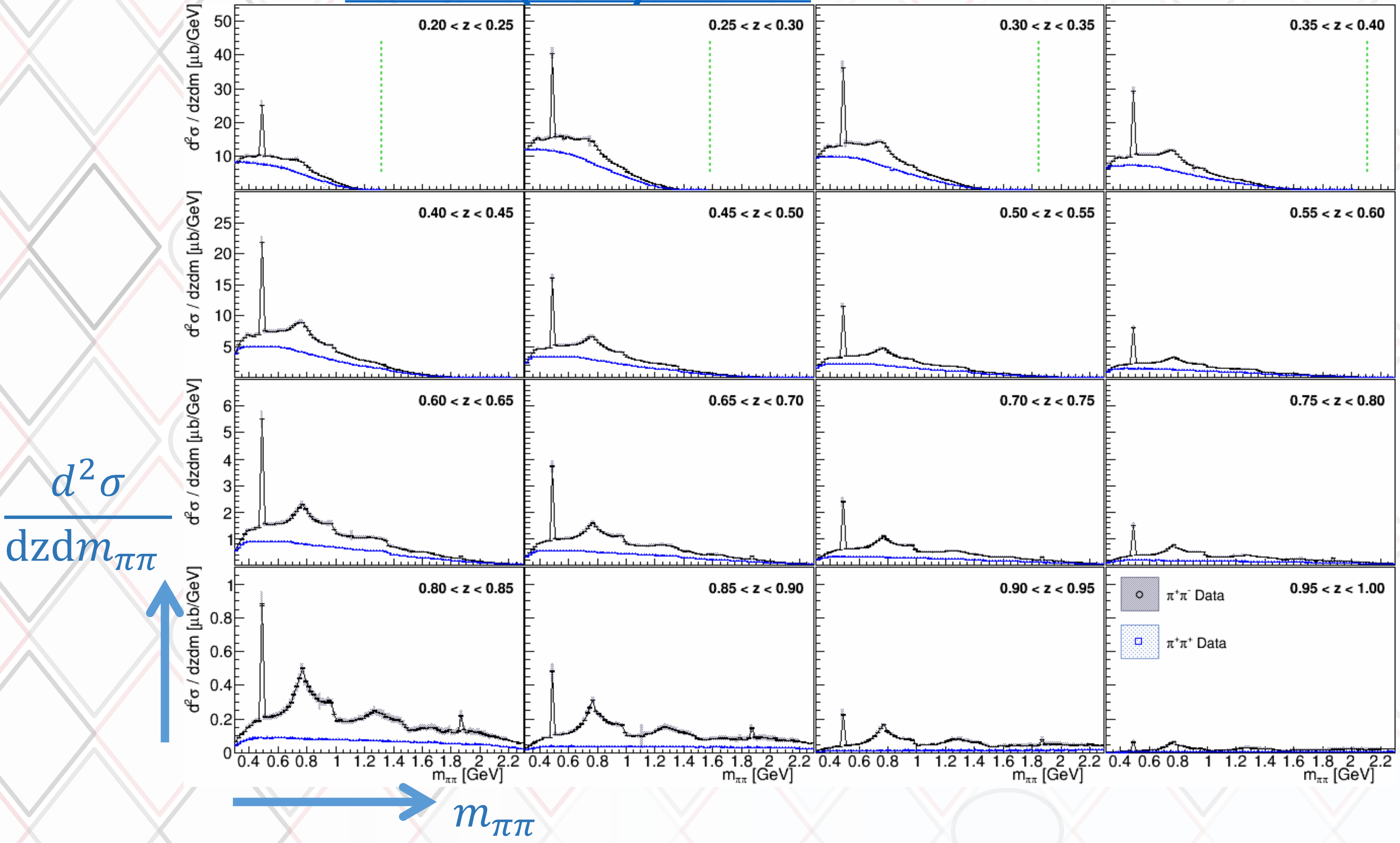
$$D_{1,q}^{h_1 h_2}(z, m, Q^2)$$

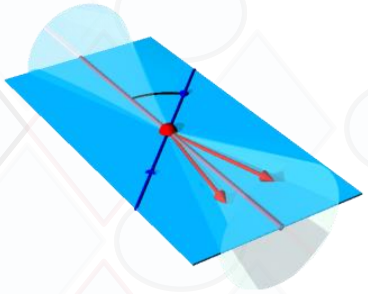


and transverse spin dependent interference fragmentation function

Di-hadron FF mass dependence (same hemisphere)

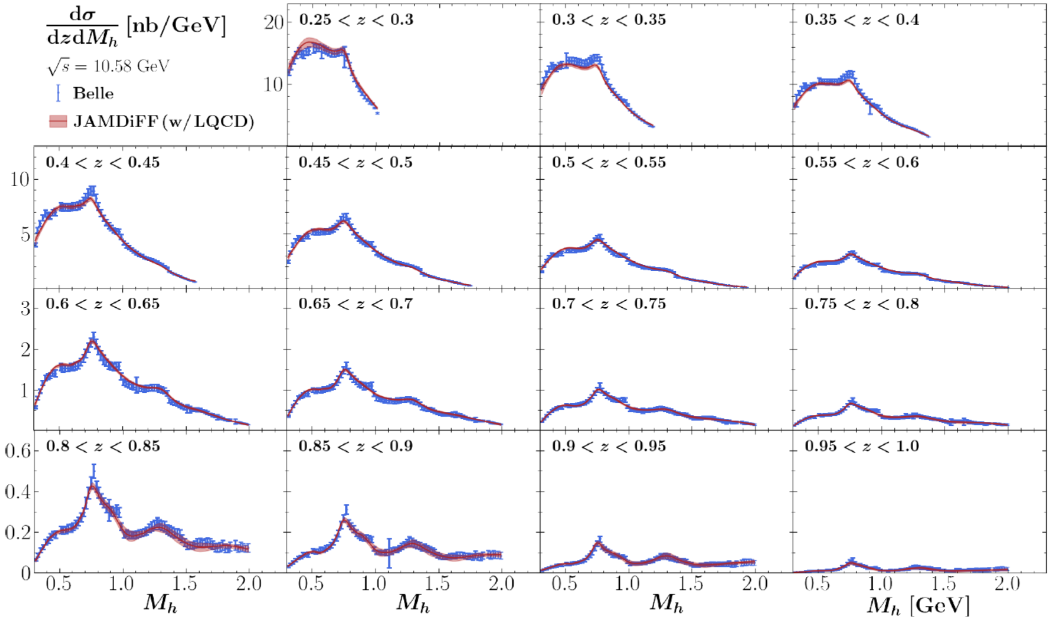
Belle: RS et.al. PRD96 (2017) 032005

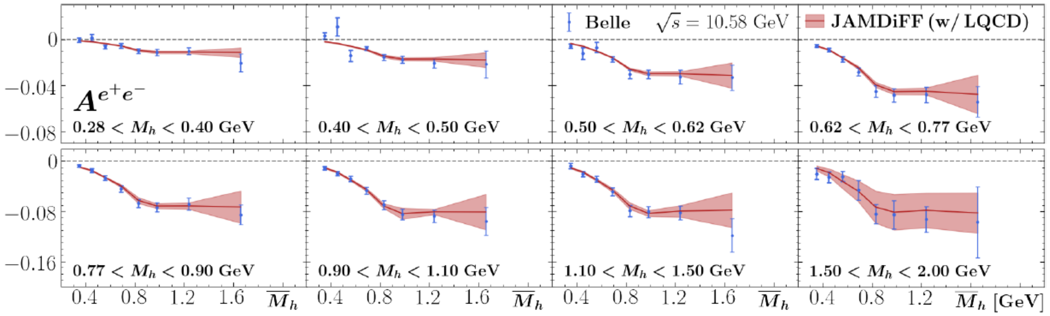


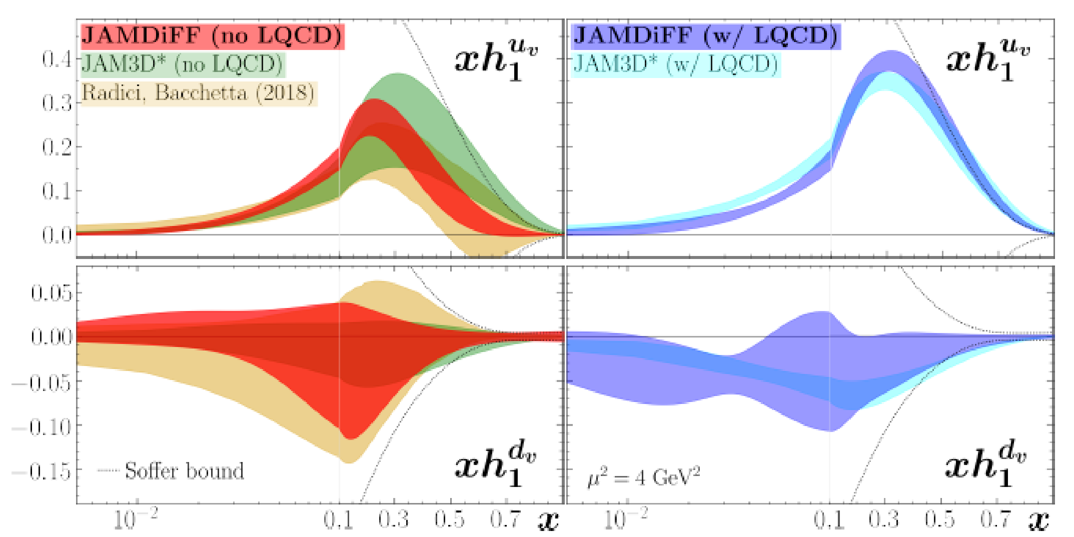


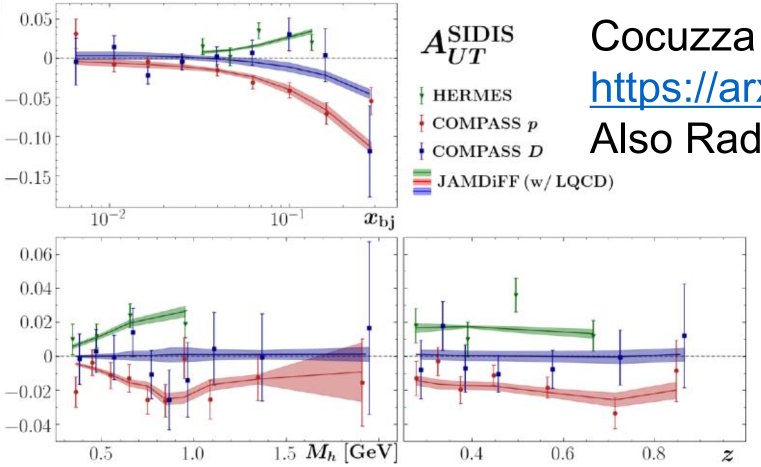
- Important input for IFF based transversity global analysis
- Individual resonances, etc quite visible; interesting for FF in itself (→soon)

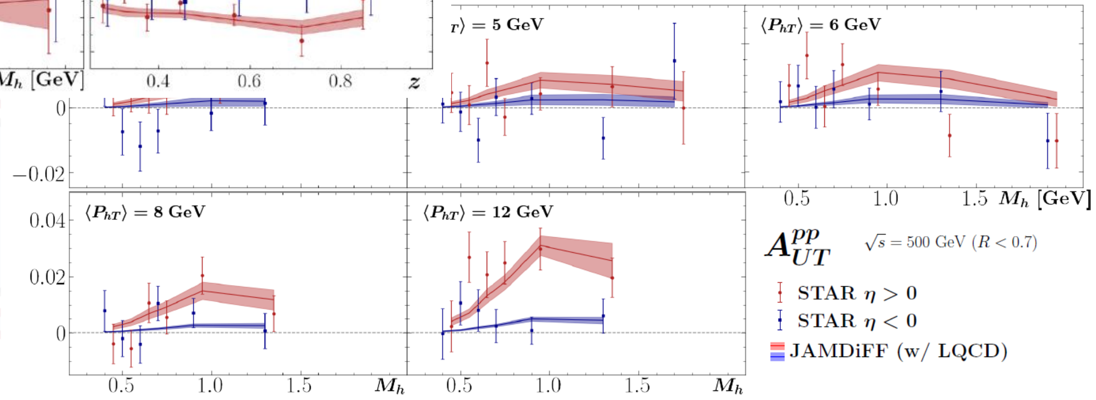
Global fits of Dihadron FFs











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

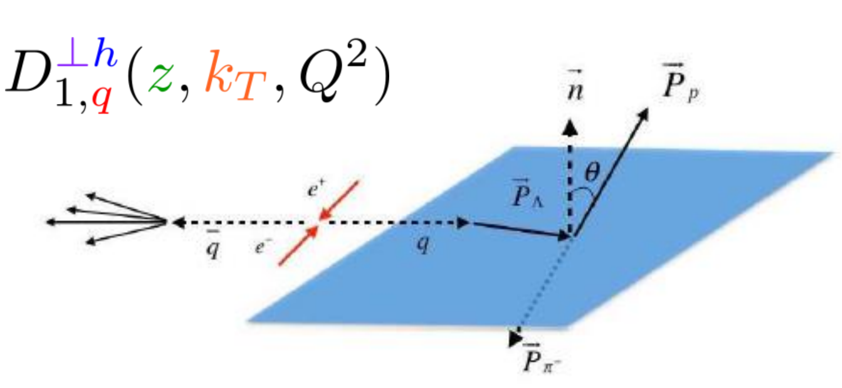
- Global fits taking SIDIS data, RHIC data, Belle data (polarized and unpolarized) into account

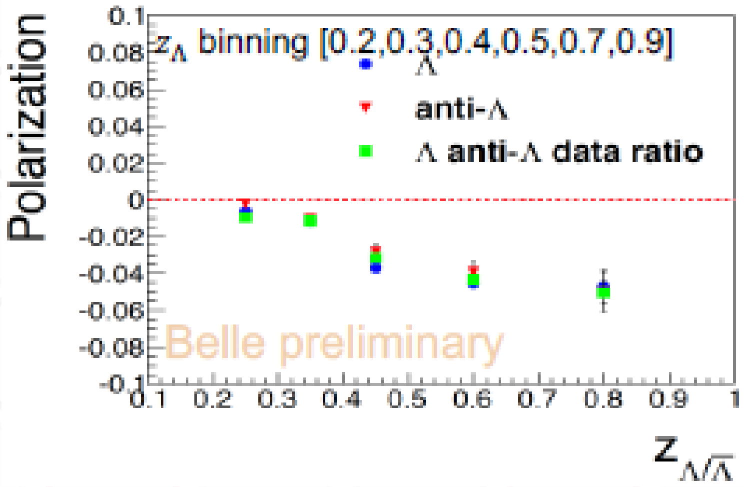
Single Λ polarization measurements

- Related to open question about Λ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:

  unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction
- Reconstruct Λ, its transverse momentum and polarization

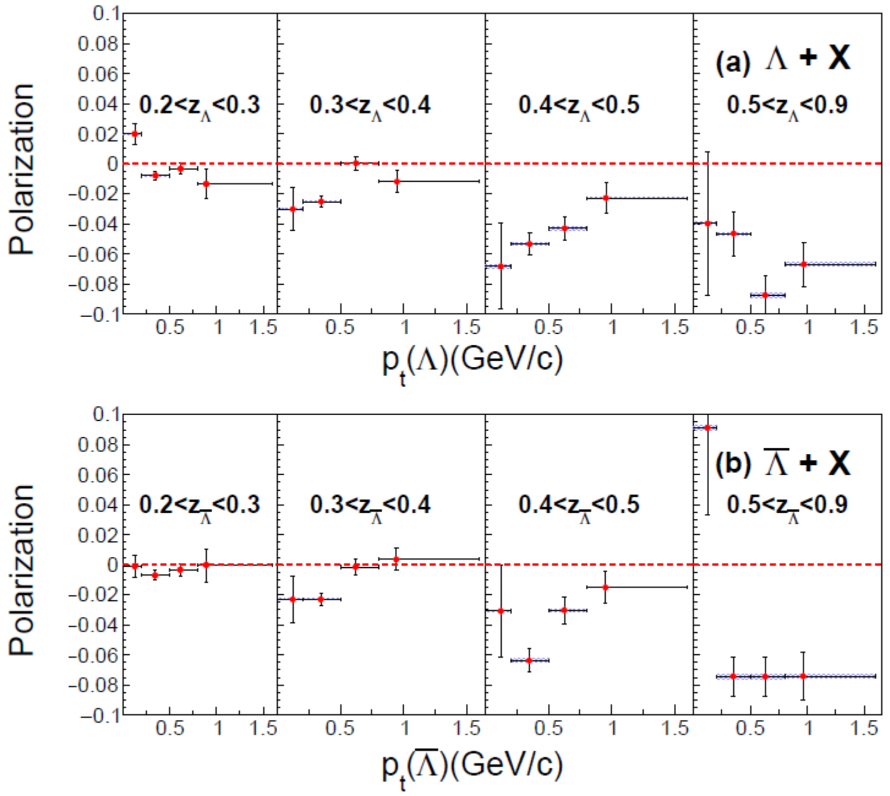
YingHui Guan (Indiana/KEK):
[PRL 122 (2019), 042001]





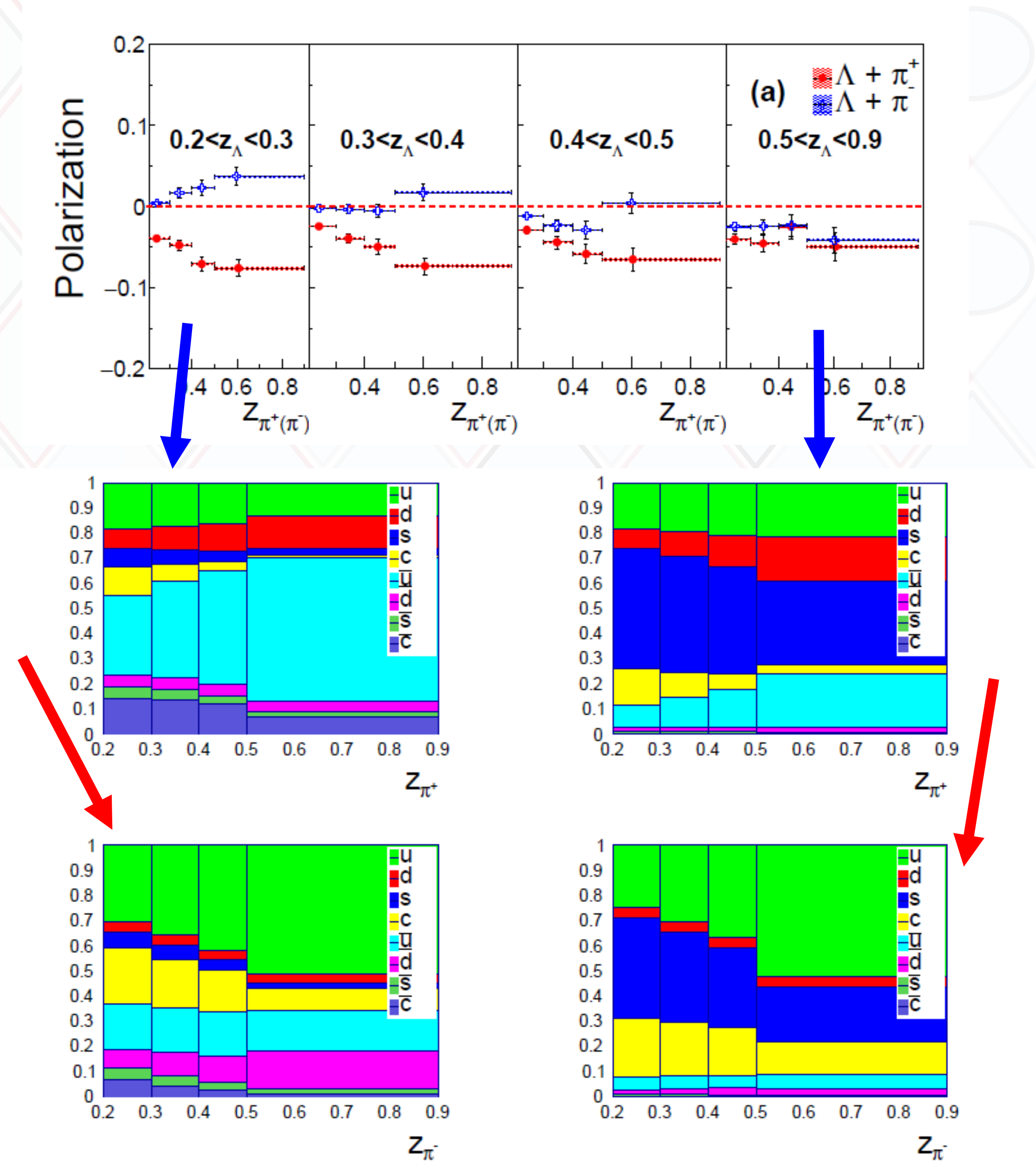
Transverse momentum dependence

- Different behavior for low and high-z :
- At low z small
- At intermediate z falling Polarization with P_t
- At high z increasing polarization with P_t



Opposite hemisphere pion correlation

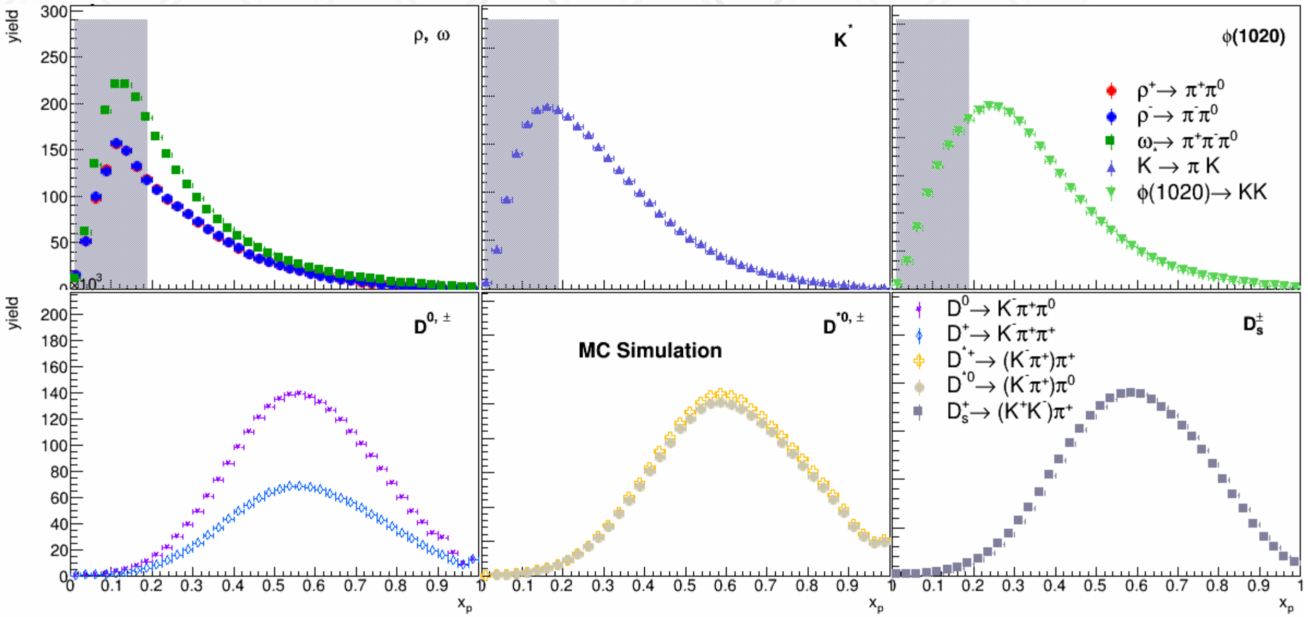
- Interesting z_π and z_Λ dependence :
- At low z_Λ light quark fragmentation dominant, some charm in π^- → different signs
- At high z_Λ strange + charm fragmentation more relevant → same signs
- Several fits to data with slightly different results



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

Summary

- Fragmentation functions are crucial to access the goals of the EIC in semi-inclusive DIS:
  - Unpolarized FFs are needed for unpolarized (n)PDFs and (anti)quark spin contributions
  - Polarized FFs are needed for Transversity and tensor charge
  - Transverse momentum dependent FFs for
- Many relevant FF measurements obtained from B factories, more to come
- At the EIC the spin structure and the 3 Dimensional momentum structure of the nucleon will be accessed and greatly improved compared to the current knowledge