Parton Fragmentation Functions

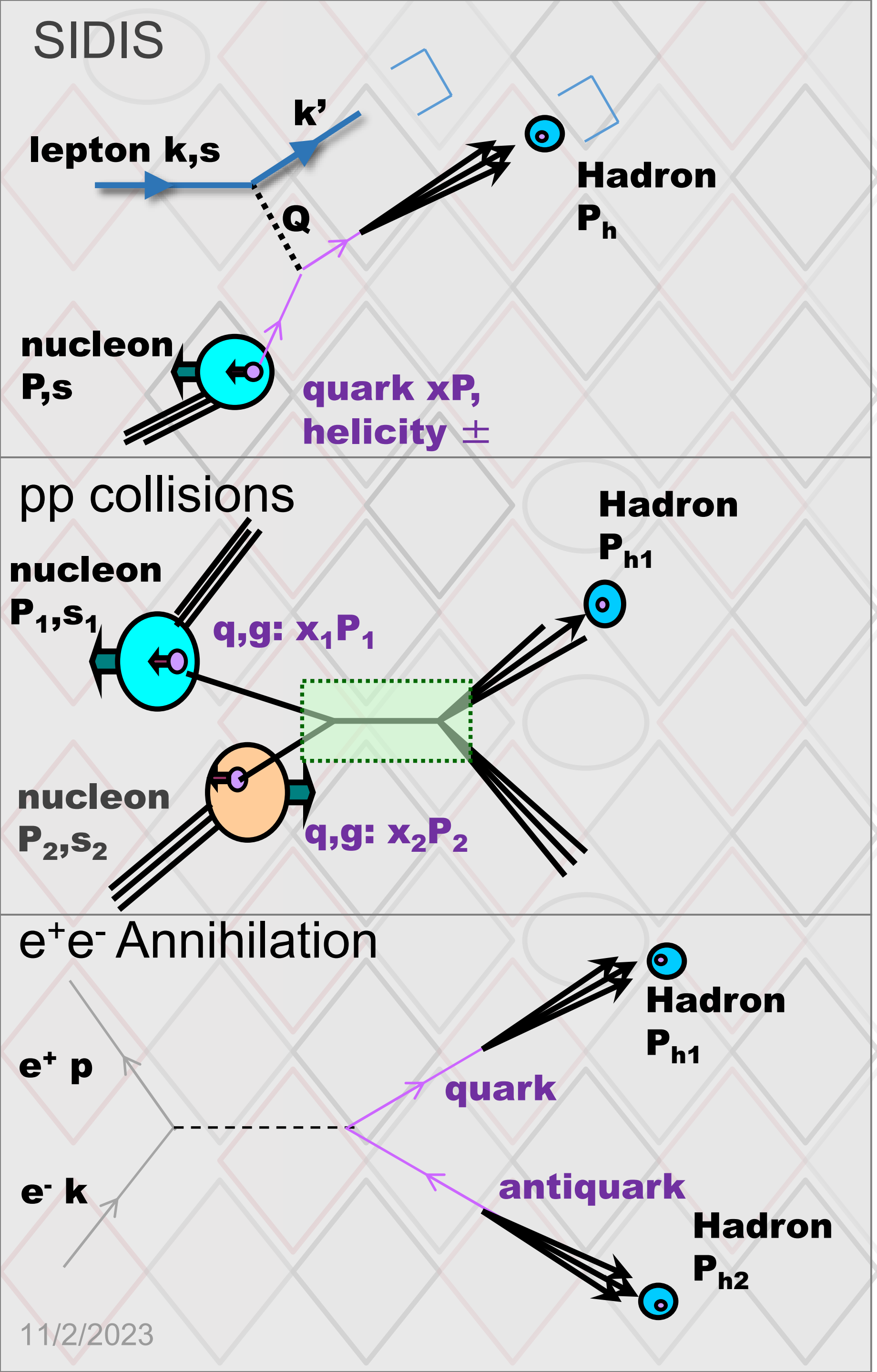
EINN2023, Paphos, Cyprus

November 2nd

Ralf Seidl (RIKEN)

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:

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

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

- pp:

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

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

- e^+e^-:

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

  - 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: $e^+e^- \to hX$ $D^{h}_{1,q}(z, Q^2)$ PRL111 (2013) 062002 PRD101(2020) 092004	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1+\phi_2)$ $H^{\perp(1)h}_{1,q}(z, Q^2)$ 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: $e^+e^- \to (h)X$ $D^{h}_{1,q}(z, k_T, Q^2)$ PRD 99 (2019) 112006	Transverse momentum dependent asymmetries $e^+e^- \to (h)(h)X$, $\cos(\phi_1+\phi_2)$,Q_t $H^{\perp h}_{1,q}(z, k_T, Q^2)$ PRD100 (2019) 92008	Polarizing Λ fragmentation PRL 122 (2019), 042001 $D^{\perp h}_{1,q}(z, k_T, Q^2)$

Dihadron FF (IFF)

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

Single hadron measurements

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

Dihadron measurements

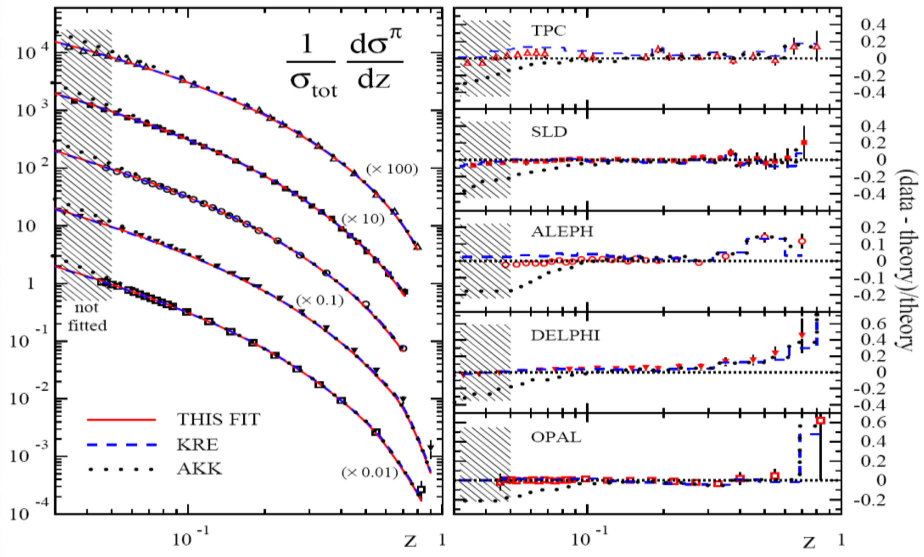
Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \rightarrow (hh)X$ $D_{1,q}^{h_1h_2}(z,m,Q^2)$	Azimuthal asymmetries: $e^+e^- \rightarrow (hh)(hh)X$, $\cos(\phi_1+\phi_2)$, $H_{1,q}^{h_1,h_2,\sphericalangle}(z,Q^2,M_h)$	Unpol SIDIS, pp: $\frac{d^2\sigma}{dzdm}$

Light hadron Fragmentation functions

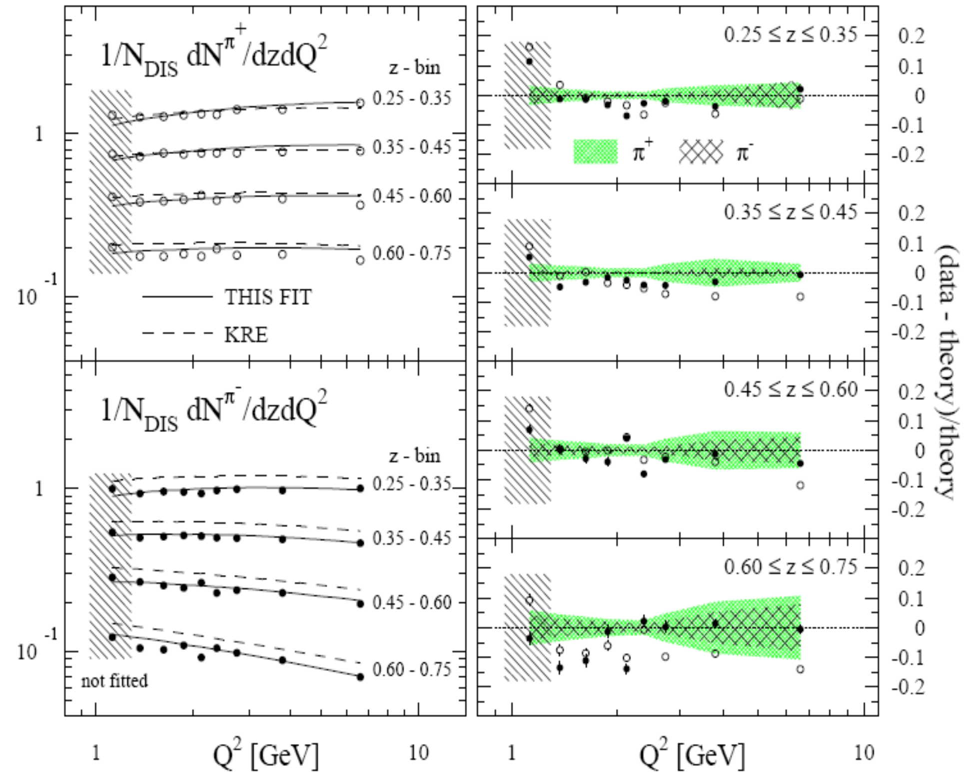
de Florian, Sassot, Stratmann

- results for $\pi^{\pm}$, $K^{\pm}$, chg. hadrons
- full flavor separation for $D_i^H(z)$ and D_g^H
- fits to all LEP, HERMES, SMC, RHIC, … data
- supersede old fits based only on e^+e^- data

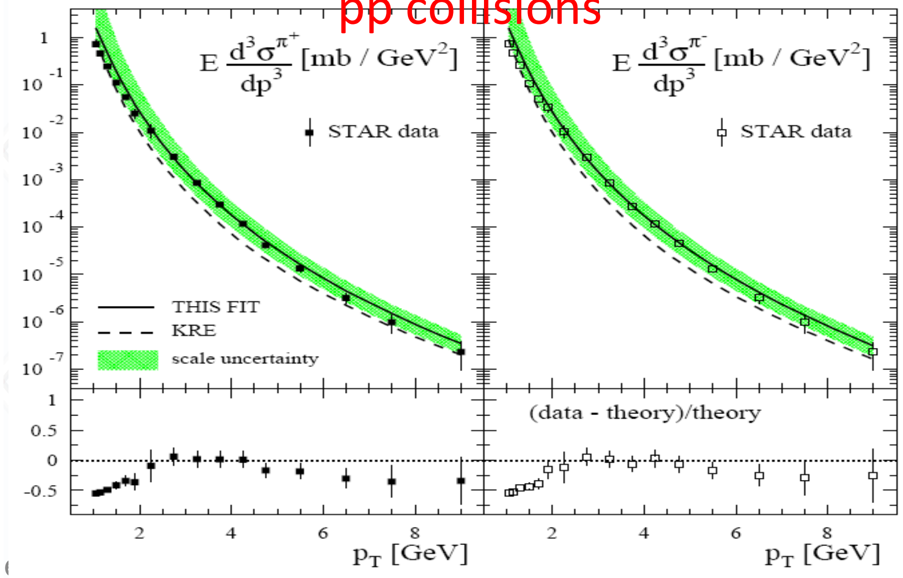
e^+e^-



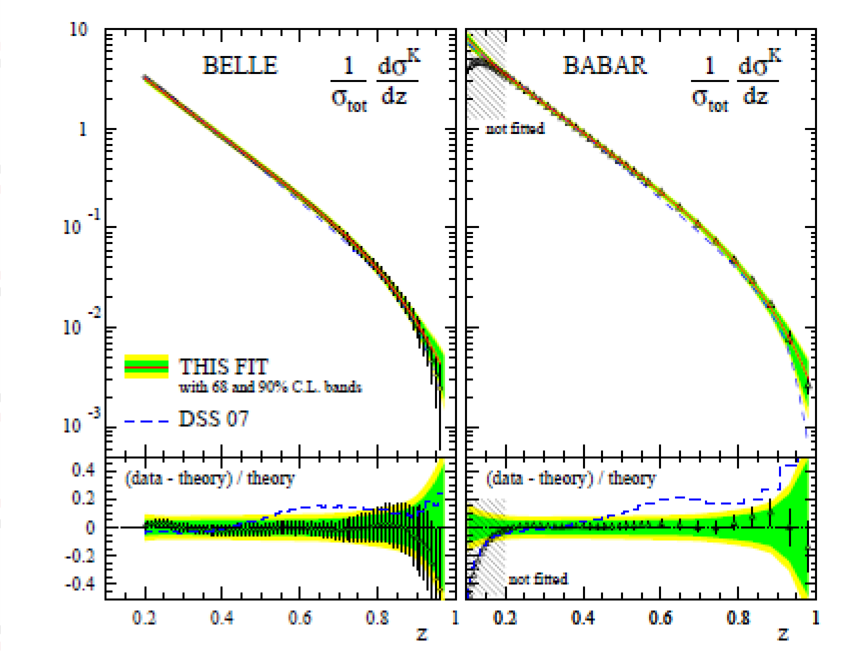
SIDIS

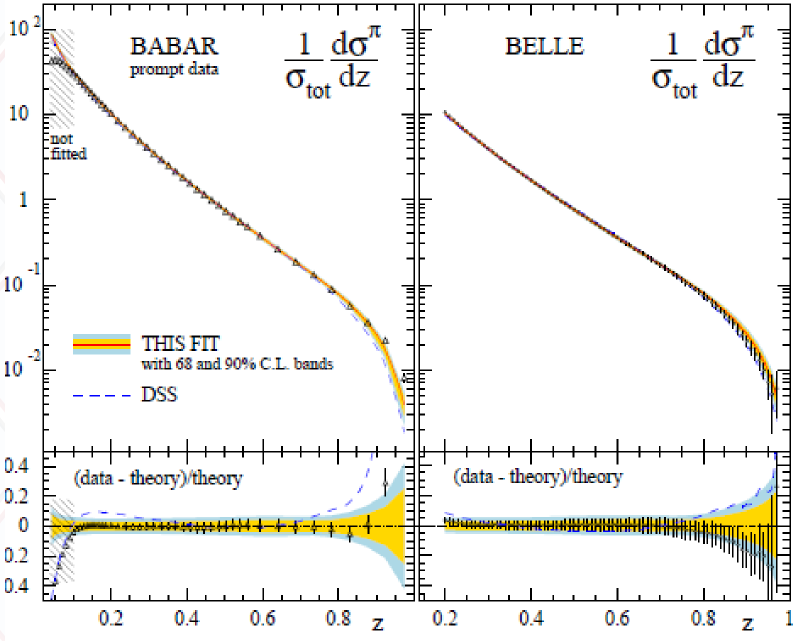


pp collisions



B factory data (Q~10GeV)



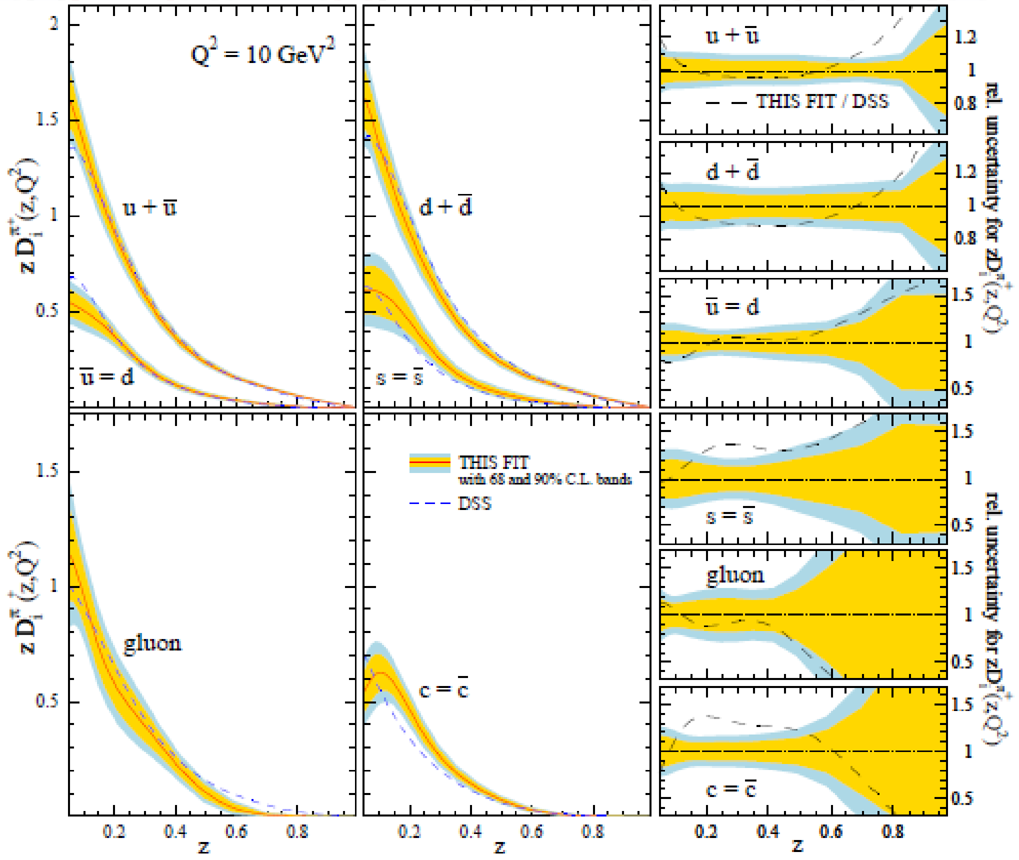


- High precision pion and kaon data from both B factory experiments
- Precision up to very high z
- Lever arm to much higher energy (Q~20 – 200GeV) data allows for determination of gluon fragmentation over evolution

Pion fragmentation

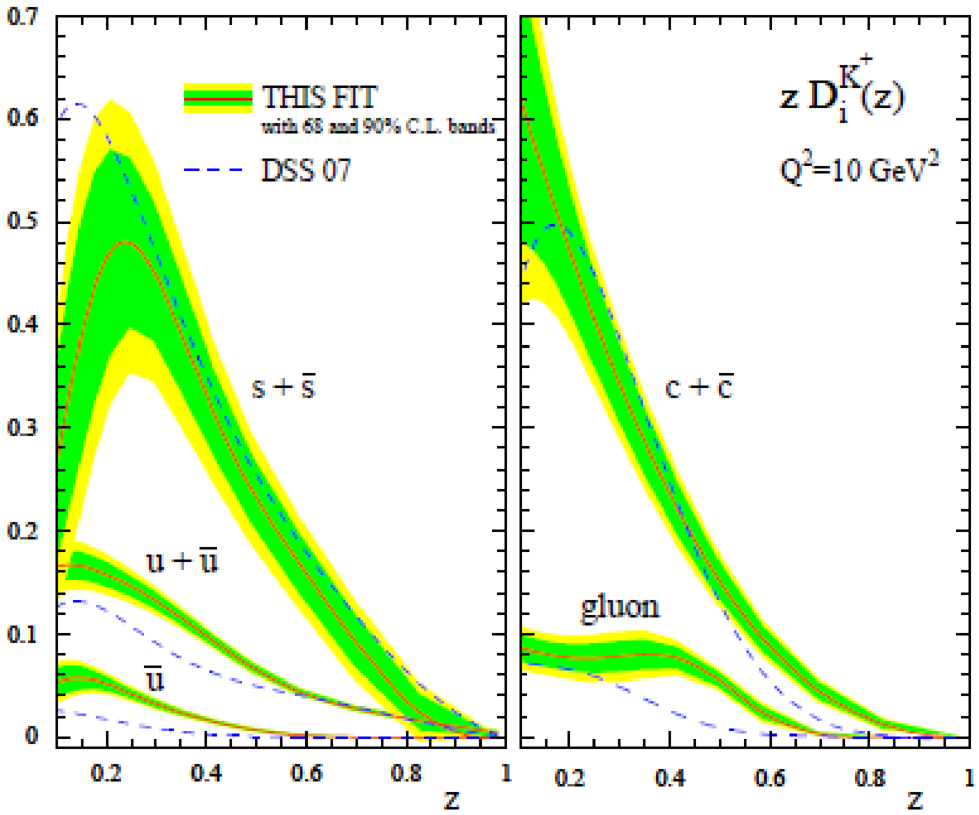
DSS15: deFlorian et.al., Phys.Rev. D91 (2015) 014035

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



Kaon fragmentation

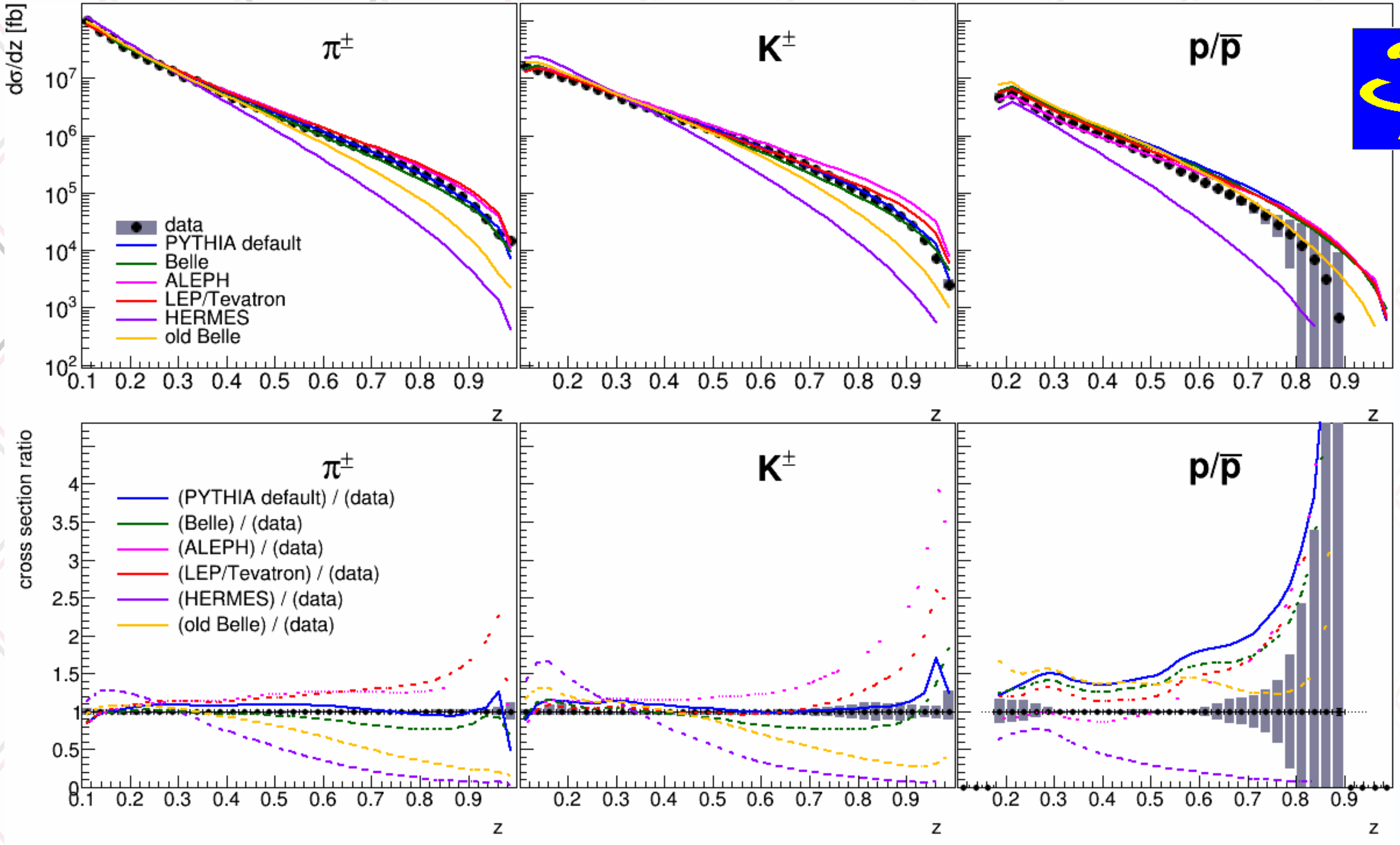
- Strange quarks are dominating kaon fragmentation
- Also dominated by favored u quark fragmentation at high-z
- At lower z penalty for producing $s\bar{s}$ pair in fragmentation ($u+\bar{u} < s+\bar{s}$)
- Charm fragmentation comparable (what about weak decays?)



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

Unpolarized single hadrons

PRD 101 (2020) 092004

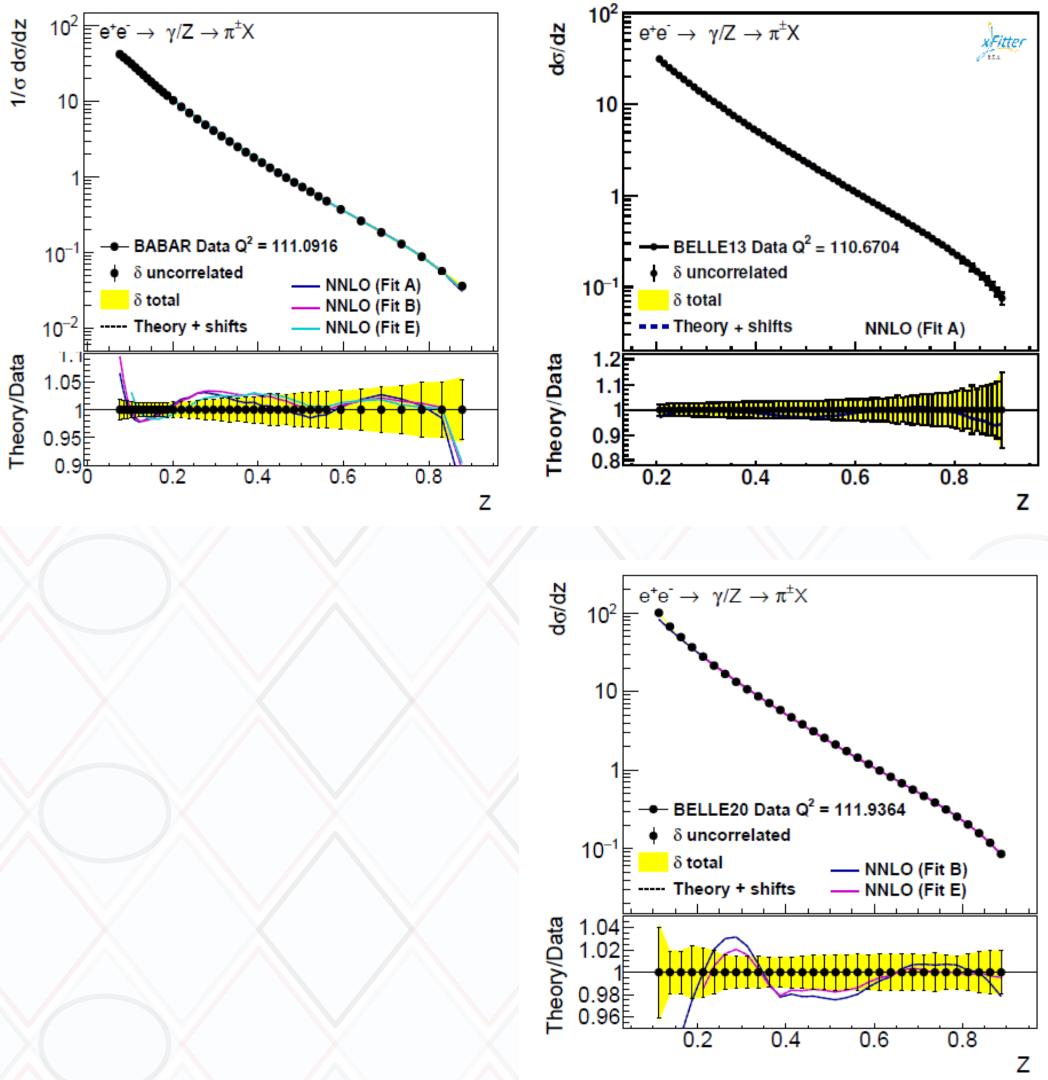


- Update with better ISR correction
- Correlated and uncorrelated uncertainties separated → improve global unpolarized FF fits

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”

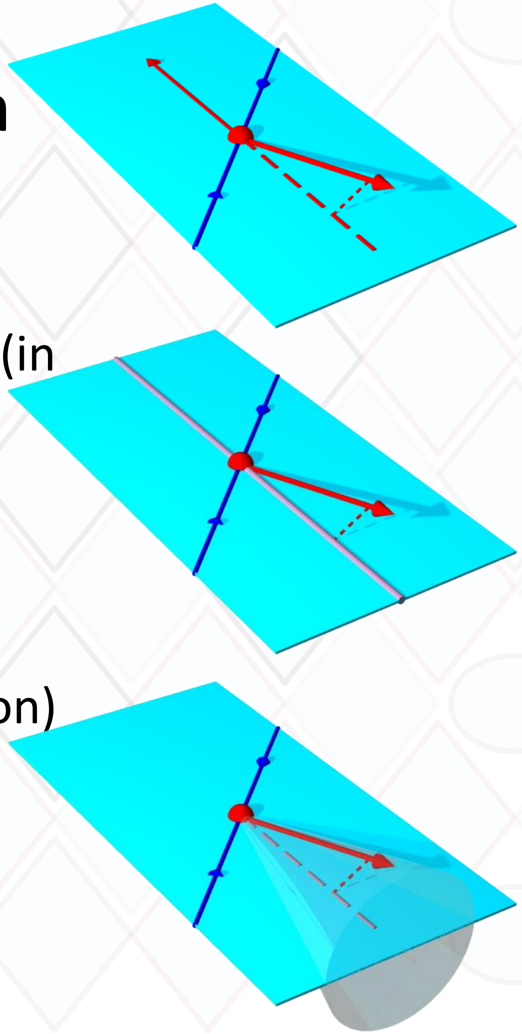
- Initial single hadron cross section measurement in very fine z binning, thus large bin-to-bin migration. Unfolding performed but assigned very conservative uncertainties → global fit’s χ^2 generally too low for our data set
- Recent update (’20) with more realistic binning, much better understanding 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 systematic symmetric (INCORRECT!)



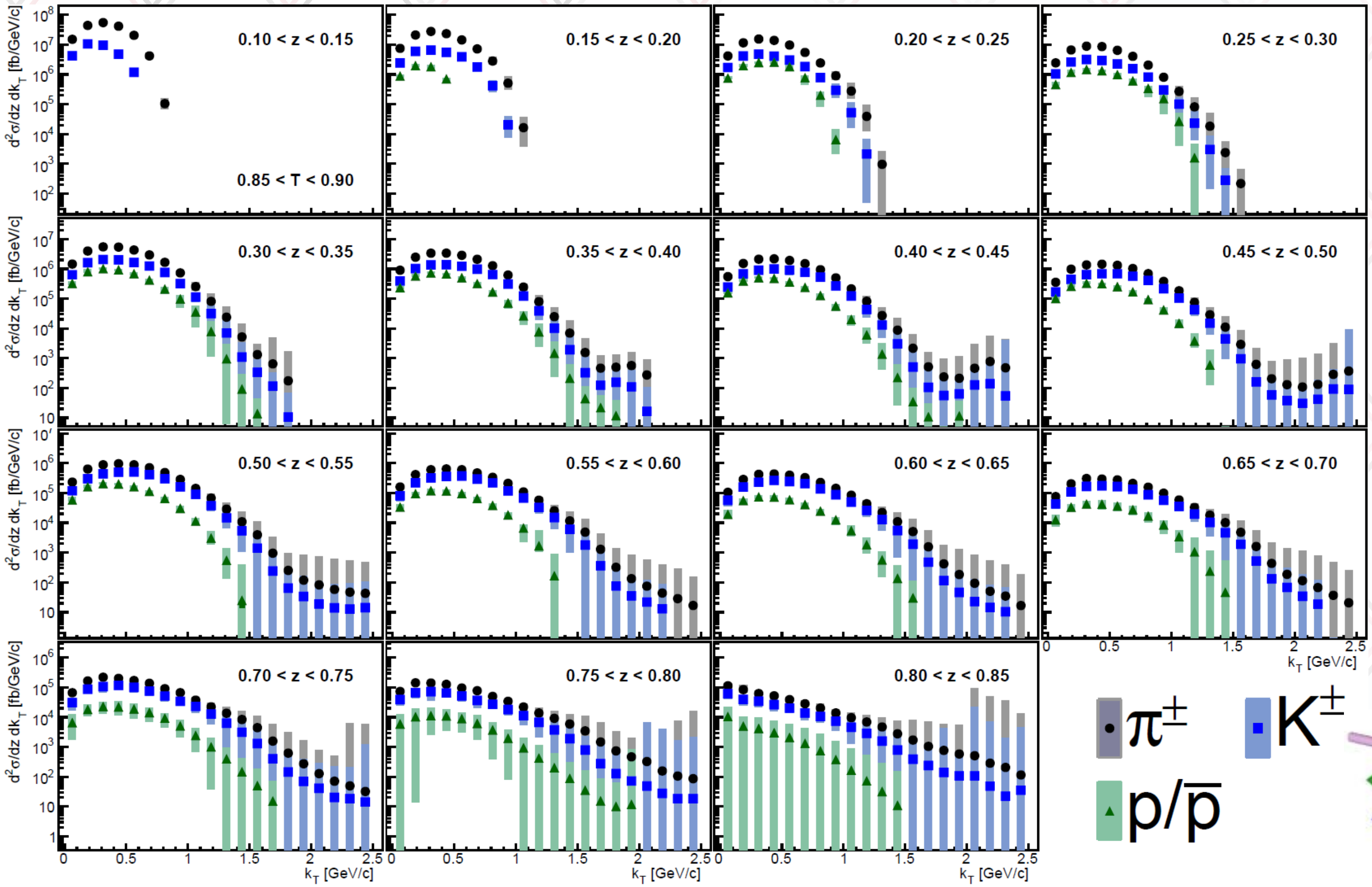
xFitter: Phys.Rev.D 104 (2021) 056019

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)

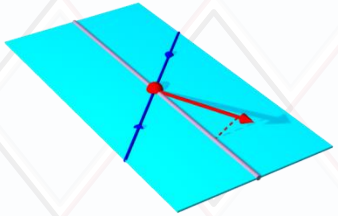


Transverse momentum dependent cross sections for pions, kaons and protons



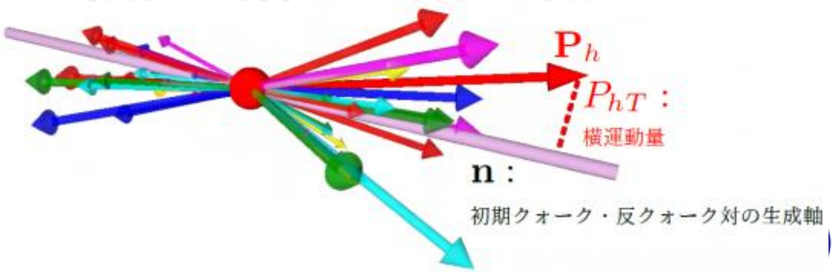
$$\frac{d^2\sigma}{dz\,dP_{hT}}$$

P_{hT}



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

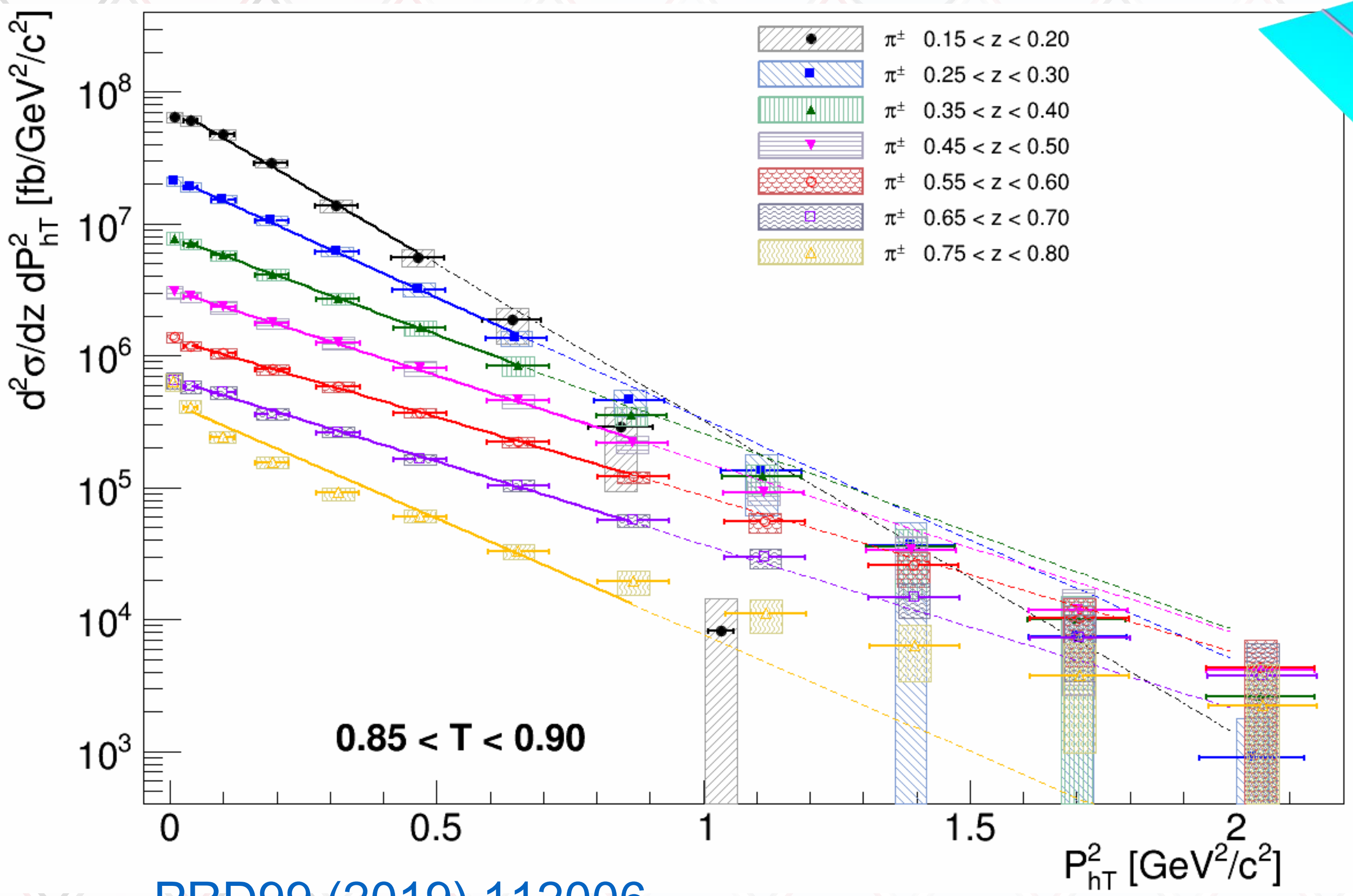
RIKEN Press release: https://www.riken.jp/press/2019/20190615_1/

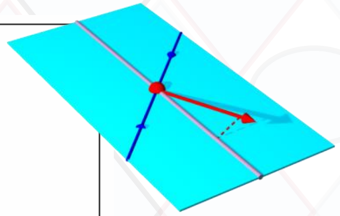


RS. et. al. [PRD99 (2019) 112006](PRD99 (2019) 112006)

Fits vs P_{hT}^2

Fit exponential to smaller transverse momenta for Gaussian P_{hT} dependence and power low at higher P_{hT}



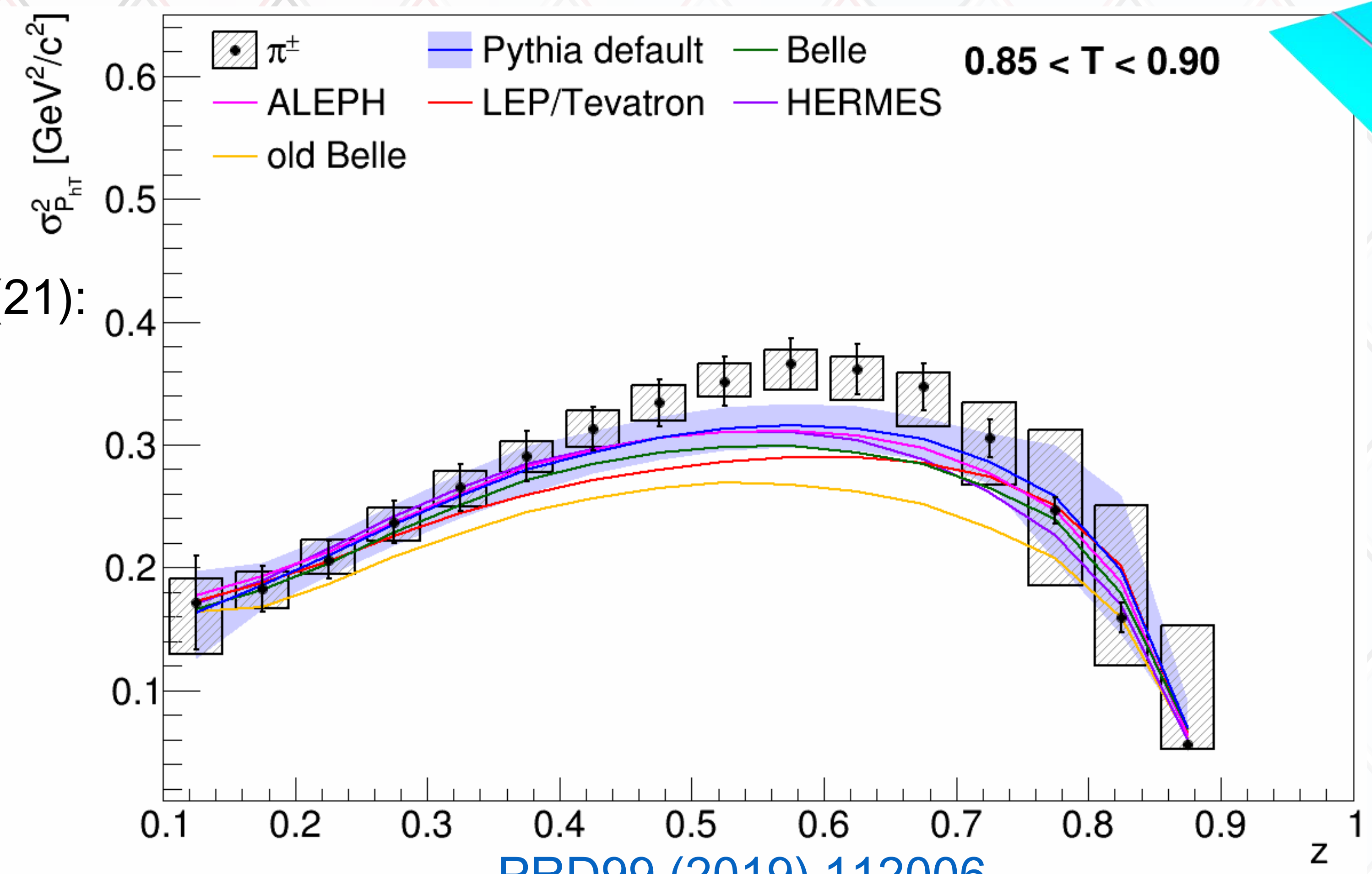


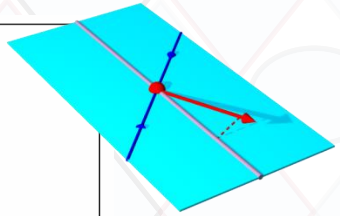
PRD99 (2019) 112006

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



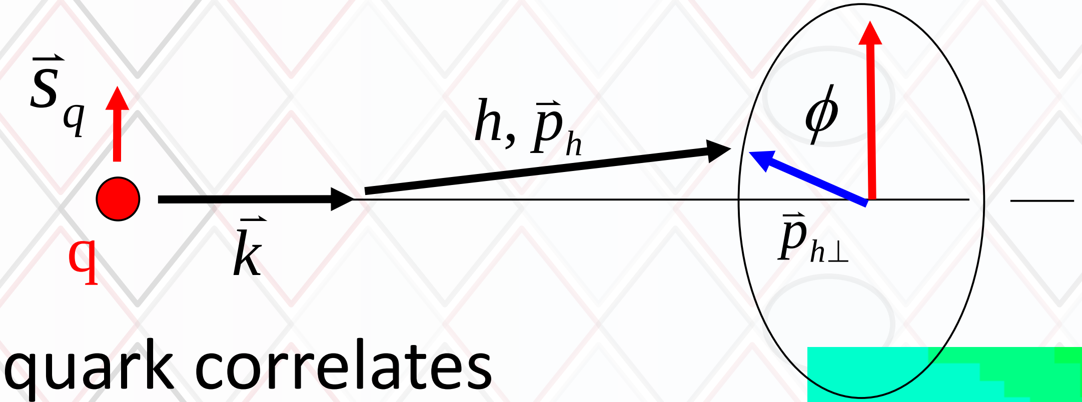


PRD99 (2019) 112006

Collins fragmentation function

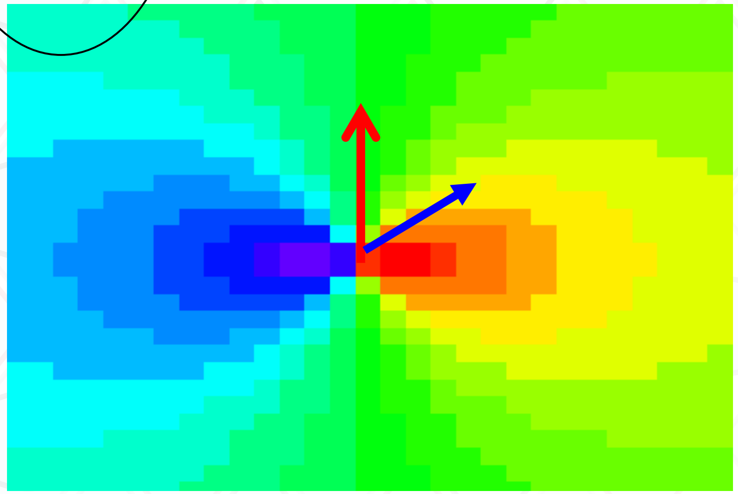
J. Collins, Nucl. Phys. B396, (1993) 161

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



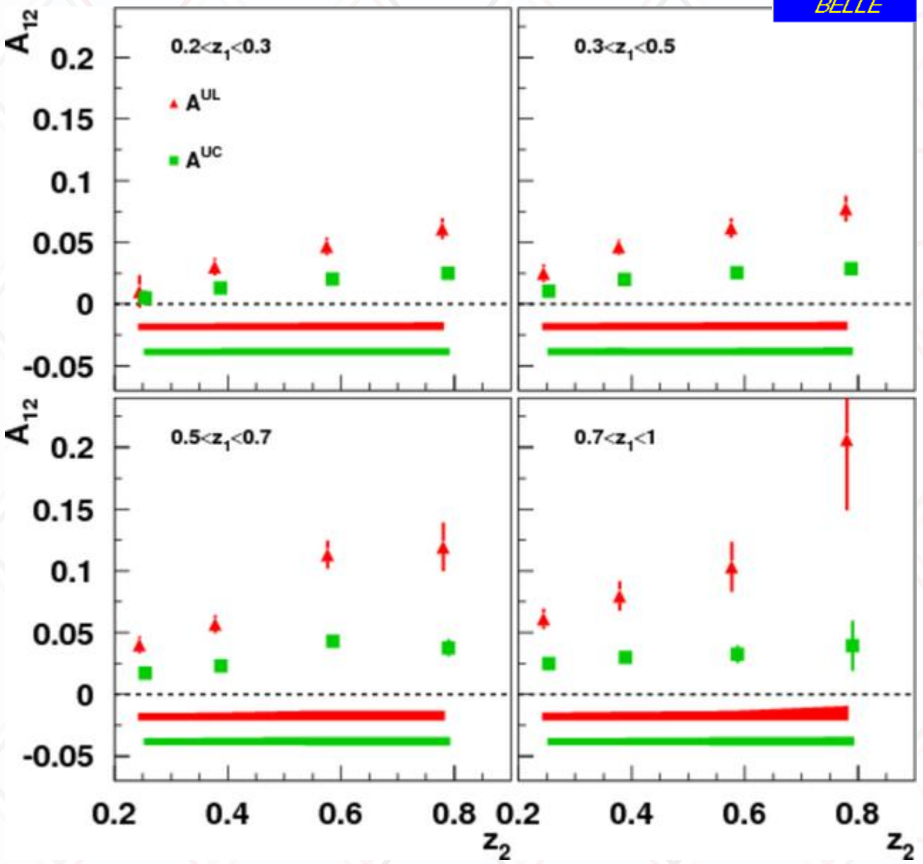
- Spin of quark correlates with hadron transverse momentum

➔translates into azimuthal anisotropy of final state hadrons



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

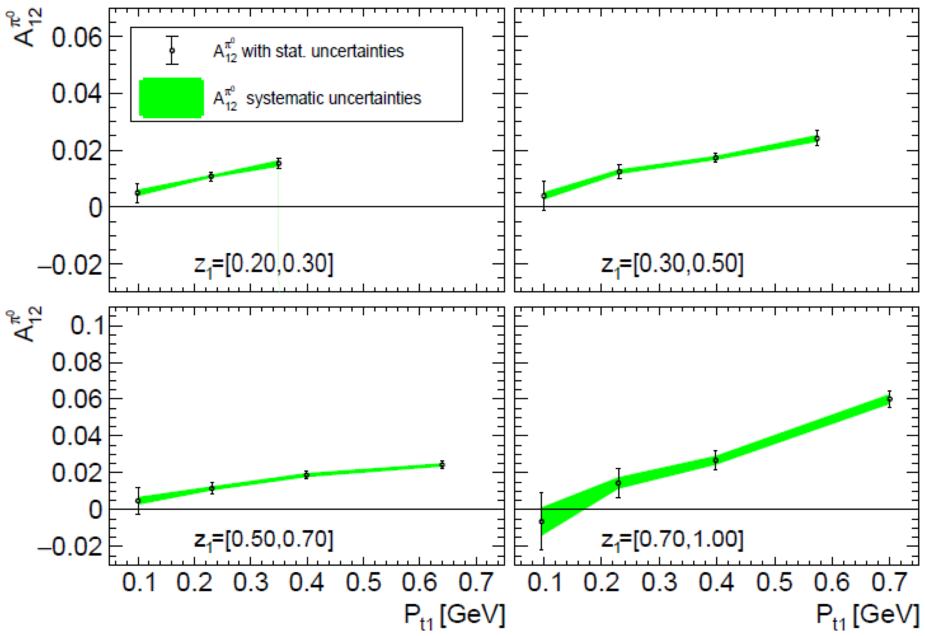


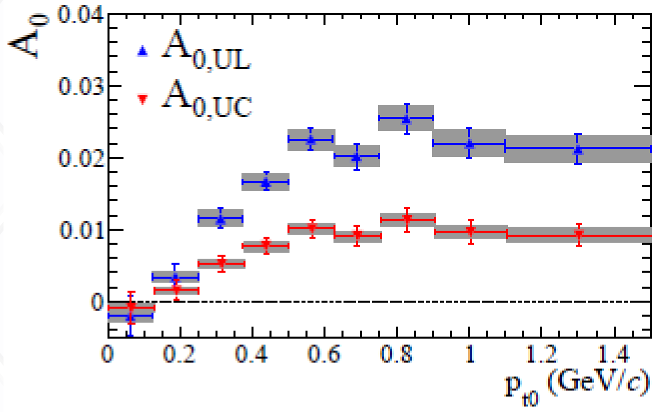
RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

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



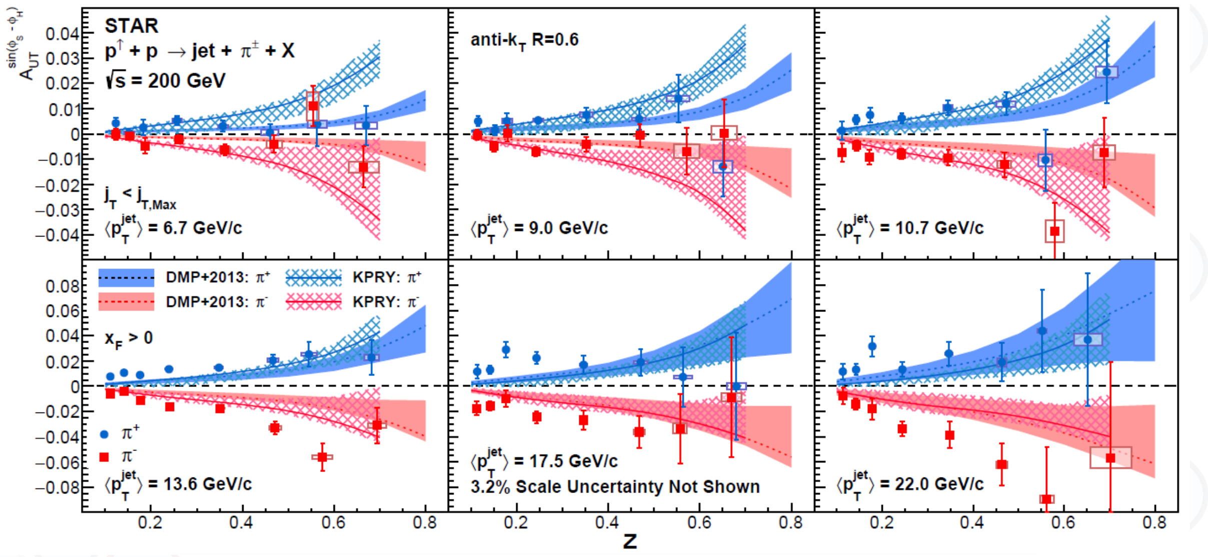


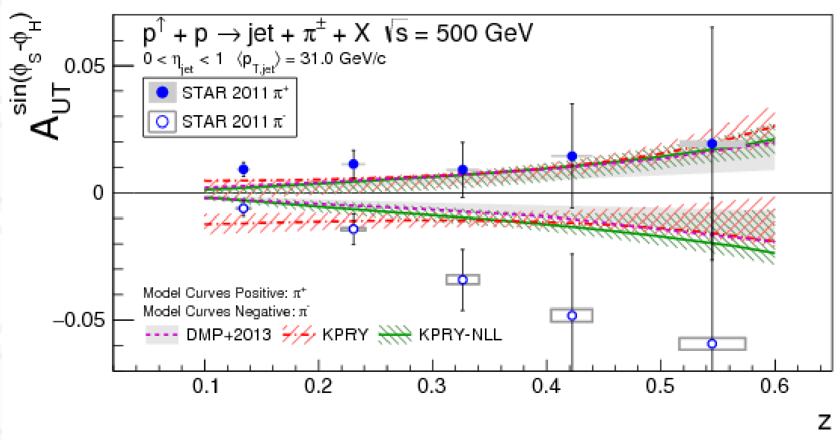
PRD 90 (2014) 052003 (Babar)

Transversity in proton collisions

- Nonzero Collins asymmetries (hadron in jets) at central rapidities at 200 and 500 GeV
- Substantial theoretical progress for hadron in jet measurements
  - unpolarized: Kaufmann et al.
  - polarized Kang et al.
- For roughly same x and kt similar size → evolution effects moderate?
- But generally slightly larger than global fits from SIDIS/e+e-
- More to come from sPHENIX in near future

STAR: Phys.Rev.D 106 (2022) 072010, 2022



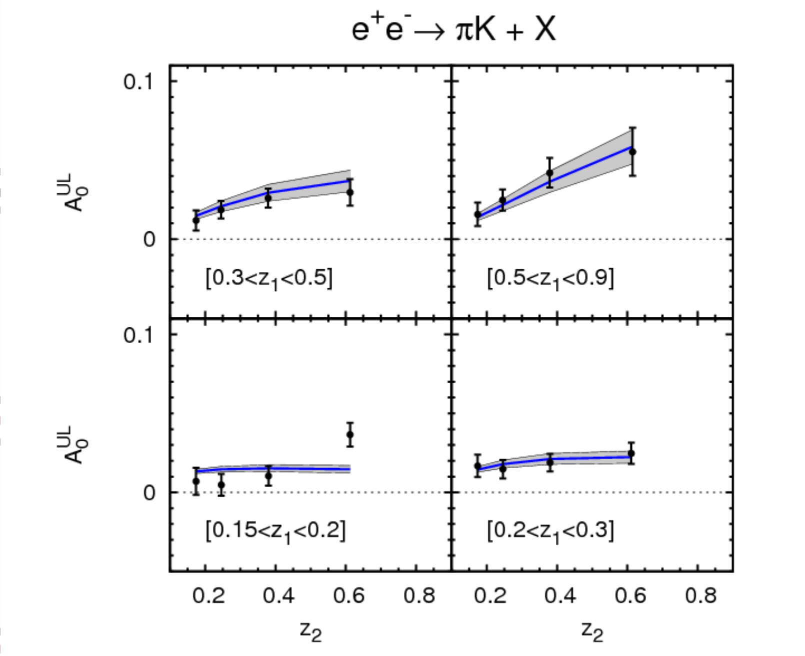


STAR: *Phys.Rev.D* 97 (2018) 032004

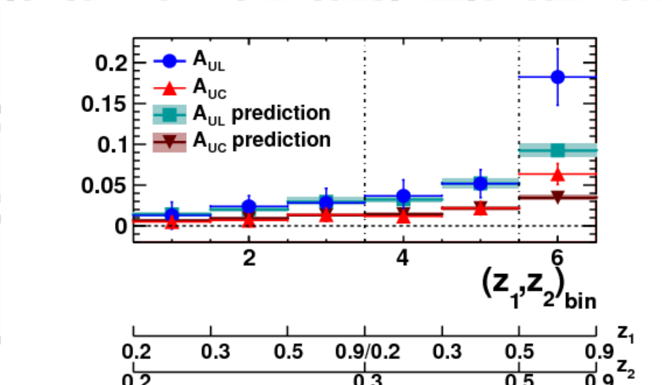
Quark transversity via Collins: Kaons

BABAR: [PRD 92 (2015) 111101]

Anselmino et al: [PRD 93 (2016) 034025]



BESIII: [PRL 116 (2016) 042001]

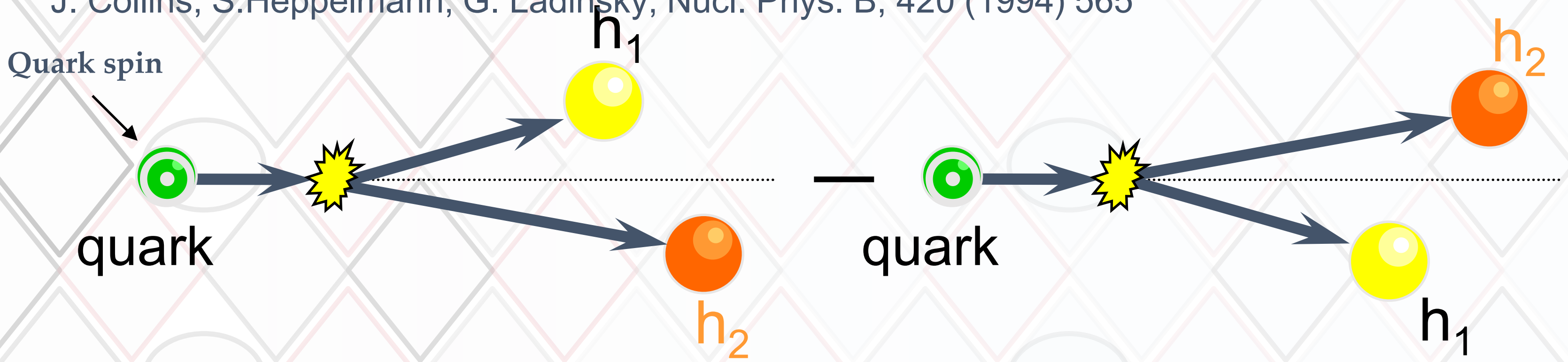


- Addition of kaon Collins fragmentation strongly needed for flavor decomposition of quark transversity
- Large amount of potentially participating FFs well described by light and "heavy" favored and disfavored FFs
- Allows inclusion of HERMES and COMPASS kaon asymmetries (+eventually EIC) in fits
-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

Interference fragmentation as alternative Transversity channel

Interference fragmentation function $H_1^{\sphericalangle}$

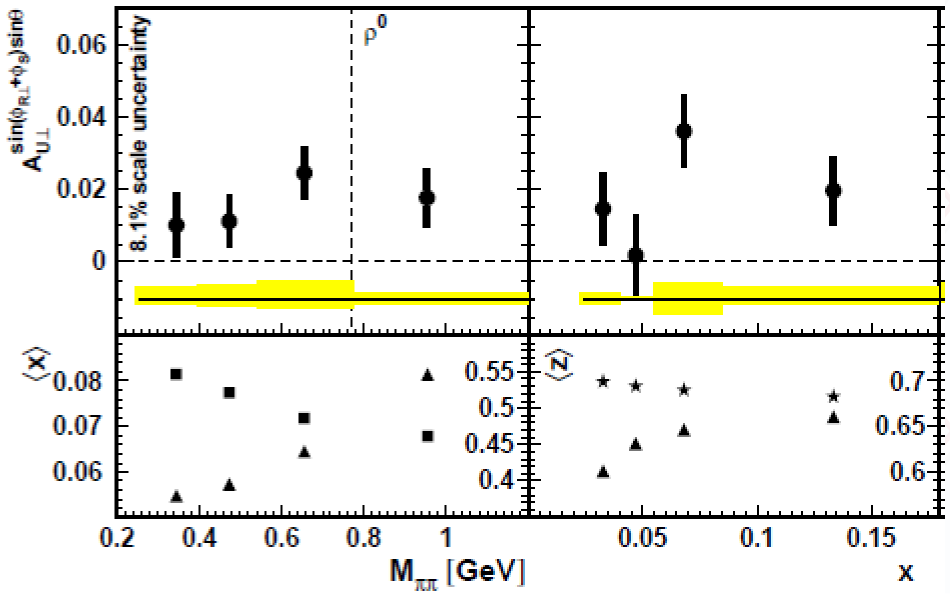
J. Collins, S.Heppelmann, G. Ladinsky, Nucl. Phys. B, 420 (1994) 565



- Di-hadron vs single hadron
  - Collinear factorization is shown to be valid → TMD factorization is less certain in p+p *(Rogers, Mulders, arXiv:1010.2977)*
  - No model uncertainties from transverse momentum dependence of FF and PDF
  - No need to separate Sivers/Collins effects as in single hadron measurement
  - Completely independent measurement
  - Doesn't need jet reconstruction
  - Evolution is known
  - But unpolarized and polarized di-hadron fragmentation functions needed

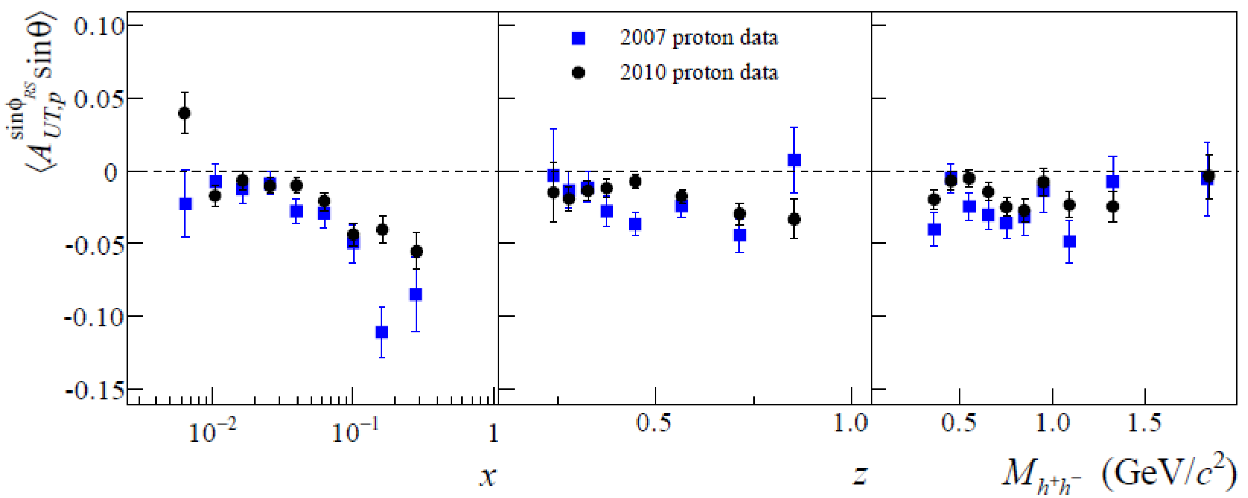
SIDIS IFF measurments

HERMES: JHEP 0806, 017 (2008)

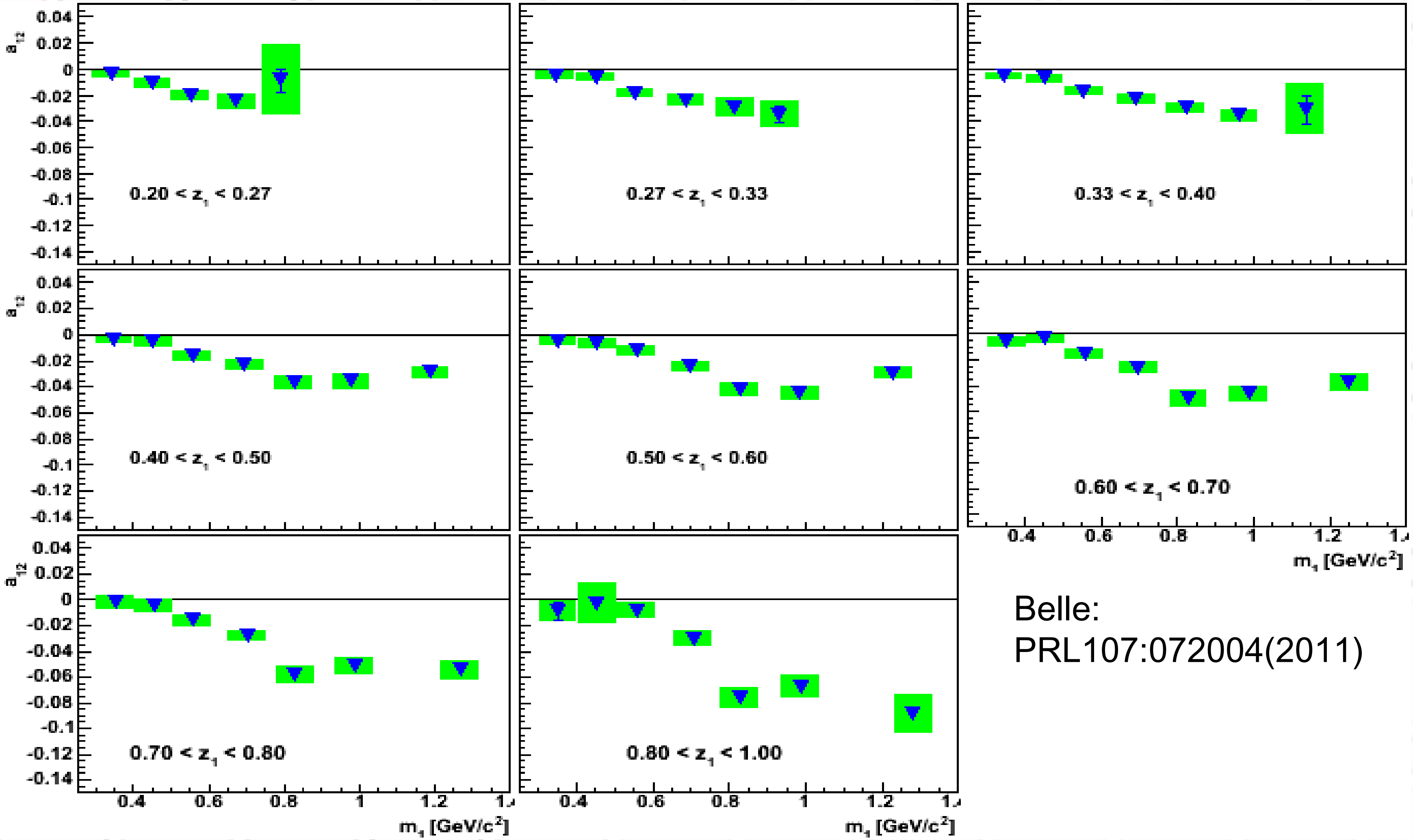


- Again sizeable asymmetries in SIDIS seen from HERMES and COMPASS
- Consistent with each other

COMPASS: Phys.Lett. B736 (2014)



Also Belle fragmentation measurements available



Belle:
PRL107:072004(2011)

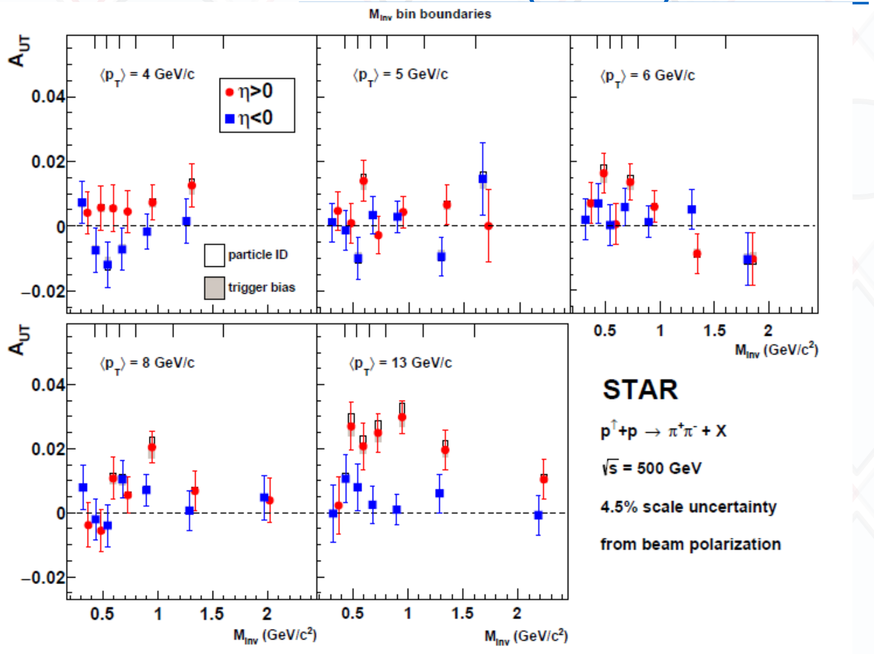
STAR IFF results

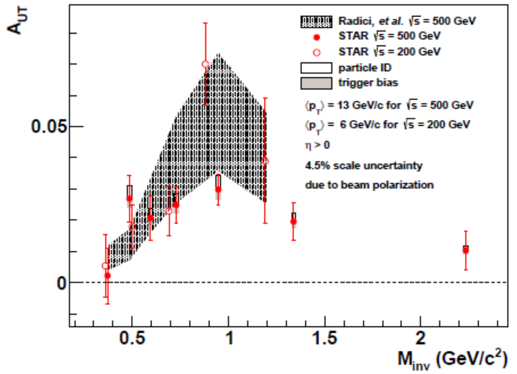
STAR 510 GeV: PLB780 (2018) 332
200GeV: PRL 115 (2015) 242501

- Now both 200 and 510 GeV results finalized
- Both with substantial nonzero effects at:
  - Forward rapdities
  - Higher Pt
  - Masses around 1 GeV
- First theory predictions from SIDIS+Belle consistent with magnitude

  → will help improve transversity uncertainties

  →but gluon DIFFs not well known

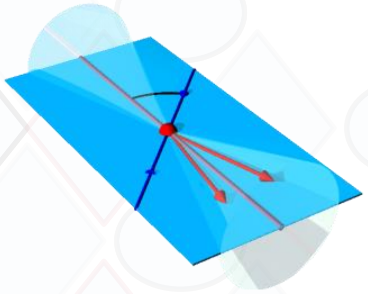


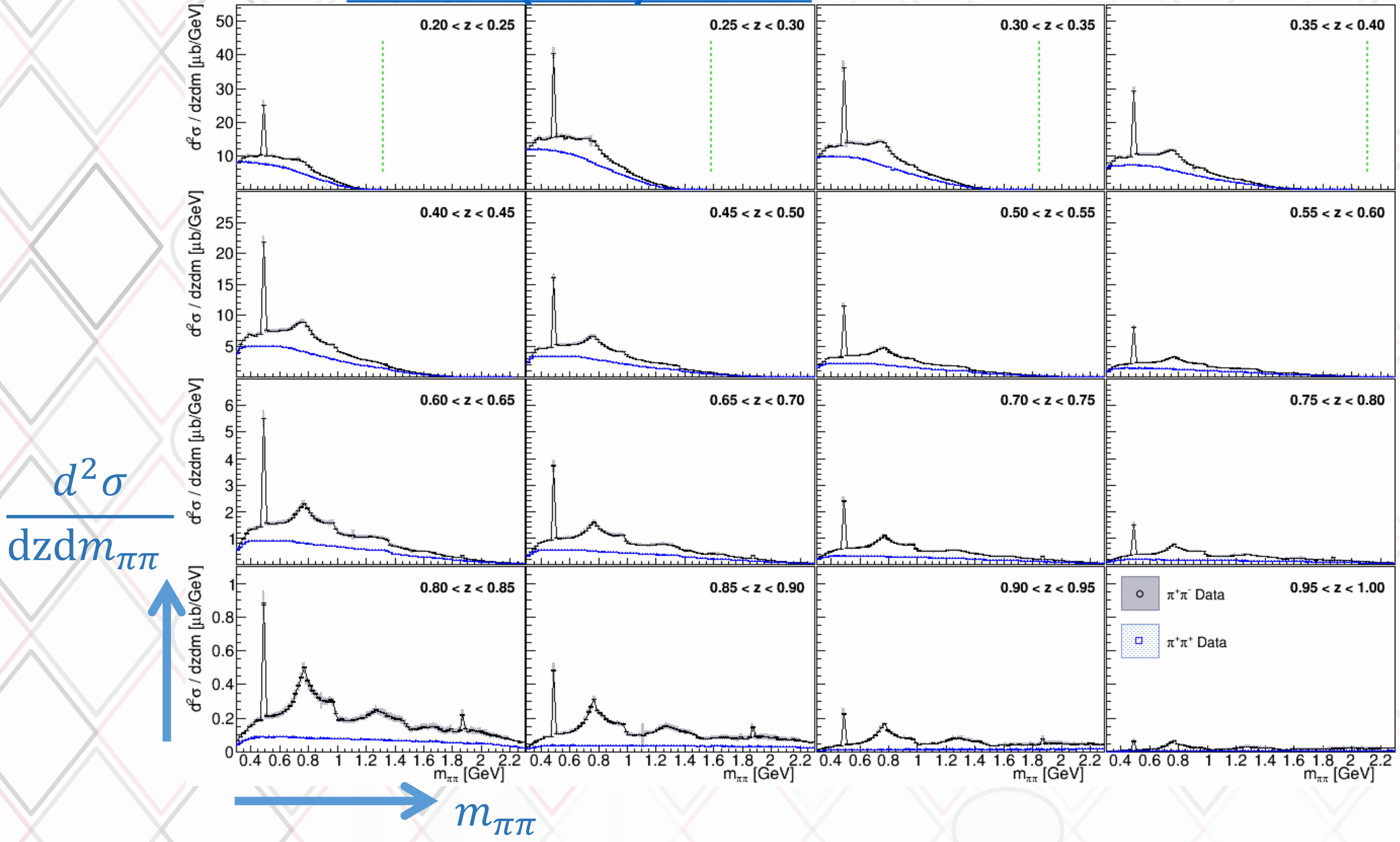


Radici et al: PRD97 (2018) 074019

Di-hadron FF mass dependence (same hemisphere)

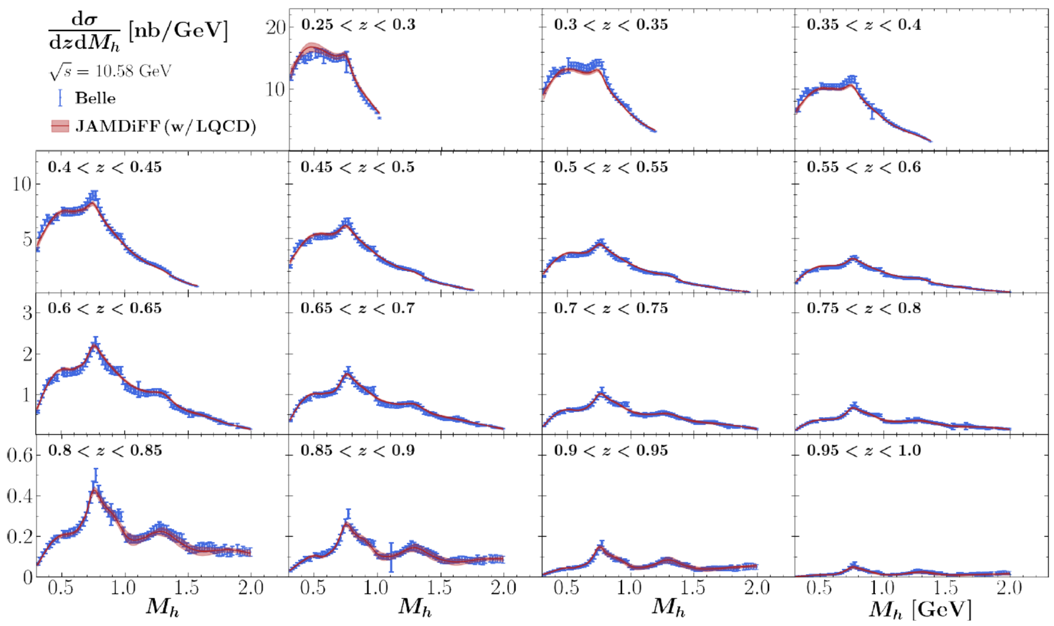
Belle: RS et.al. [PRD96 (2017) 032005]

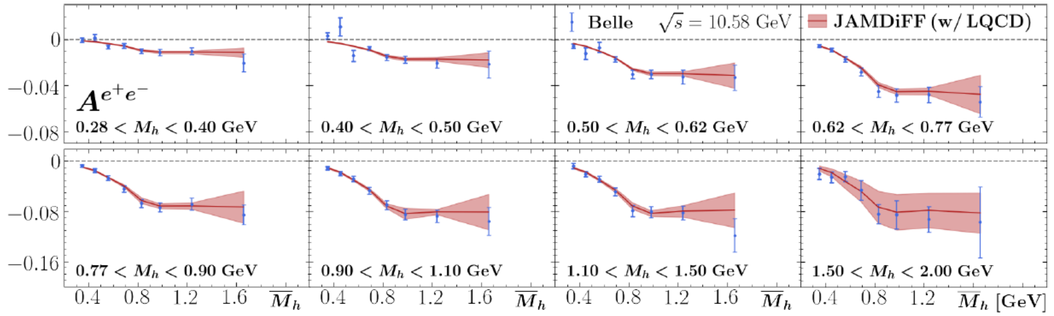


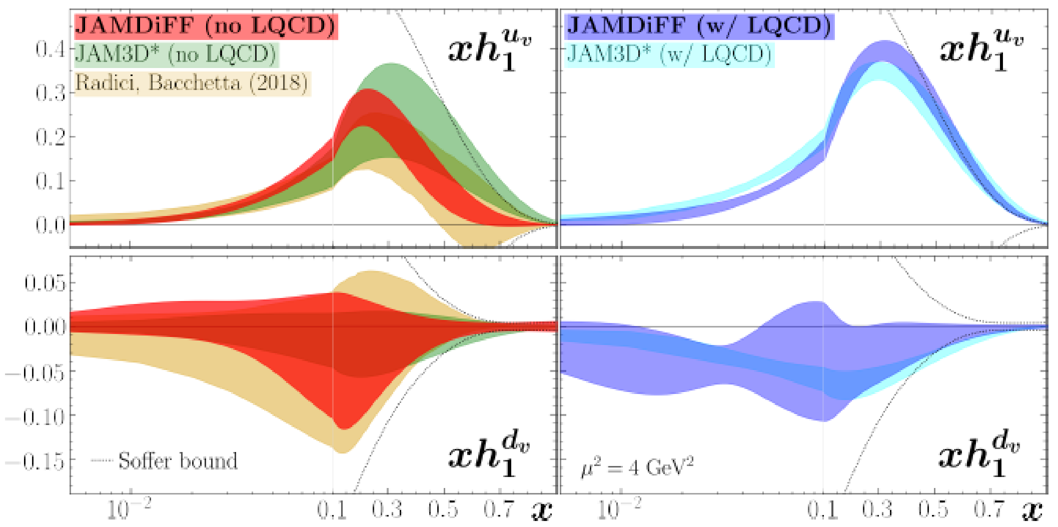


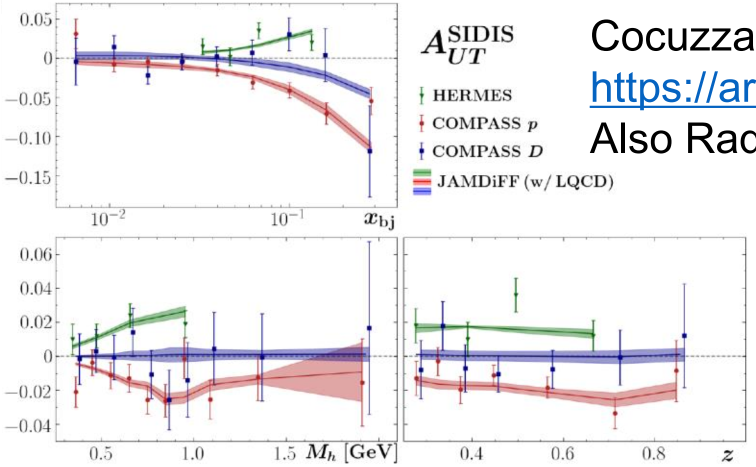
- Important input for IFF based transversity global analysis
- Individual resonances, etc quite visible; interesting for FF in itself (→soon)

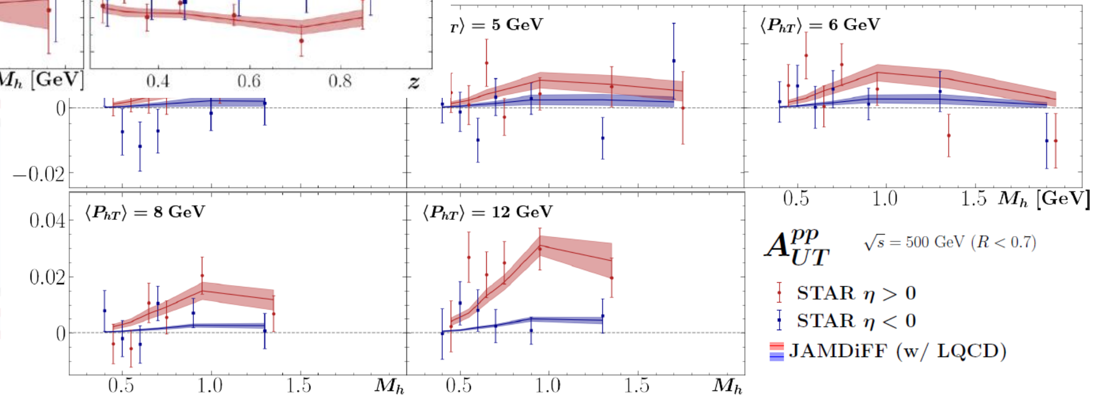
Global fits of Dihadron FFs











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

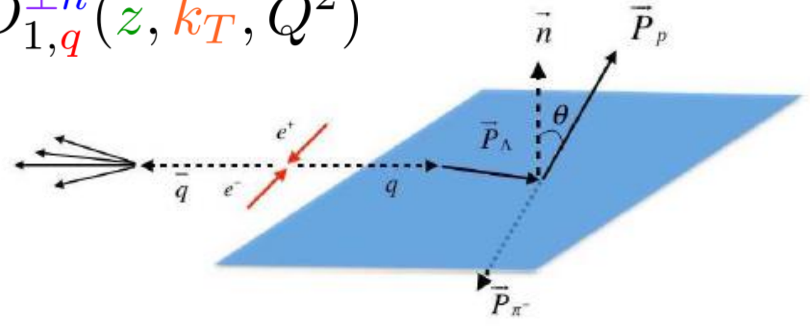
- Related to open question about Λ polarization in hadron collisions from 40 years ago!
- Fragmentation counterpart to the Sivers Function:

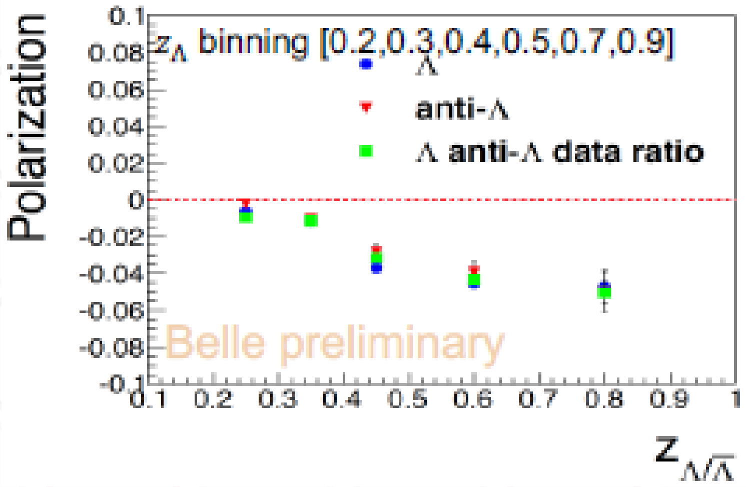
  unpolarized parton fragments into transversely polarized baryon with transverse momentum wrt to parton direction

- Reconstruct Λ, its transverse momentum and polarization

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

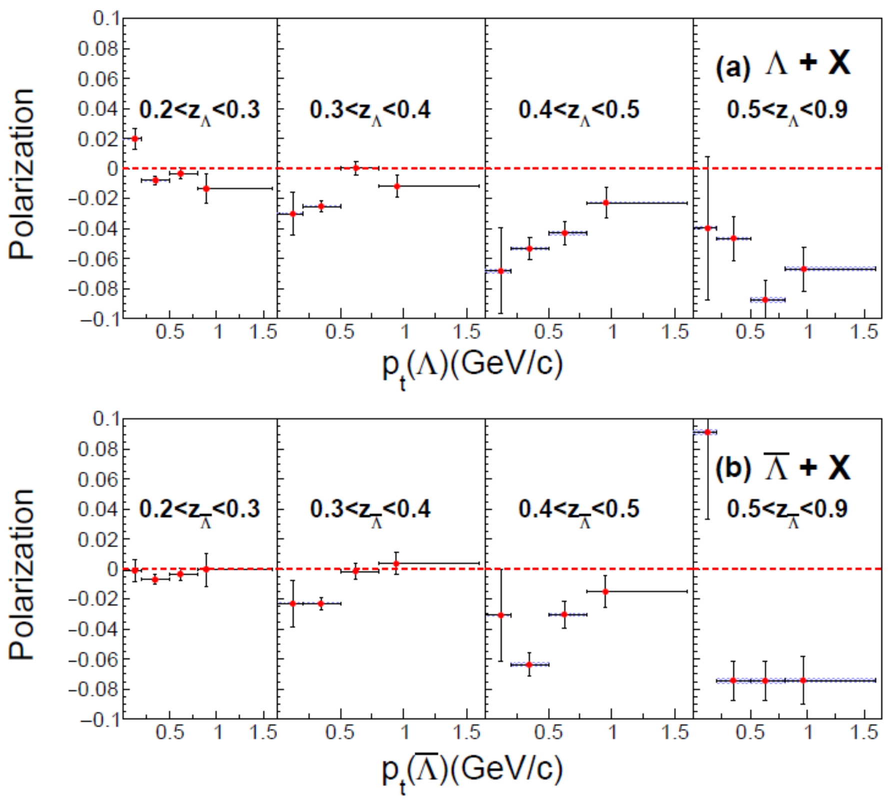
$$D_{1,q}^{\perp h}(z, k_T, Q^2)$$





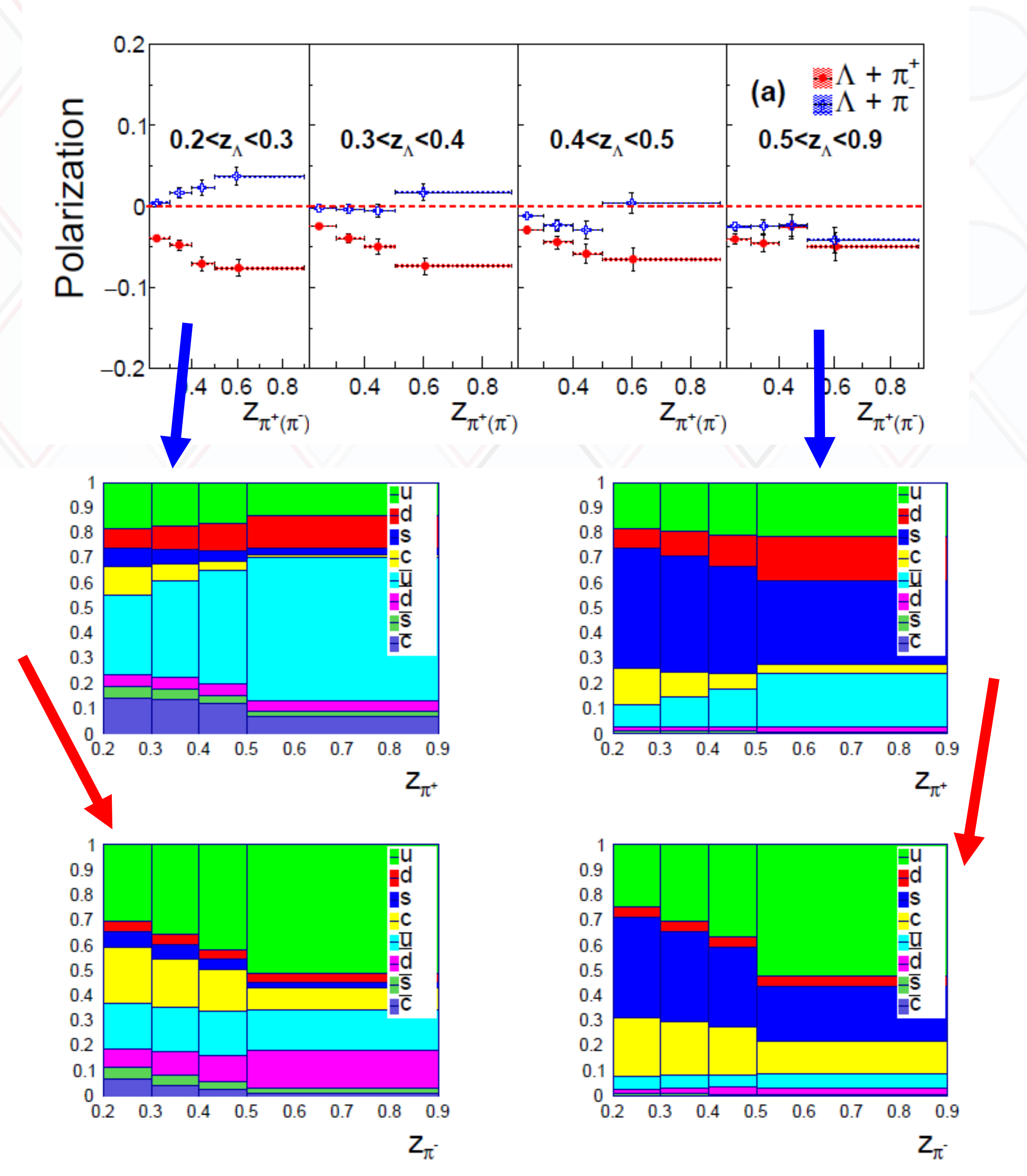
Transverse momentum dependence

- 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

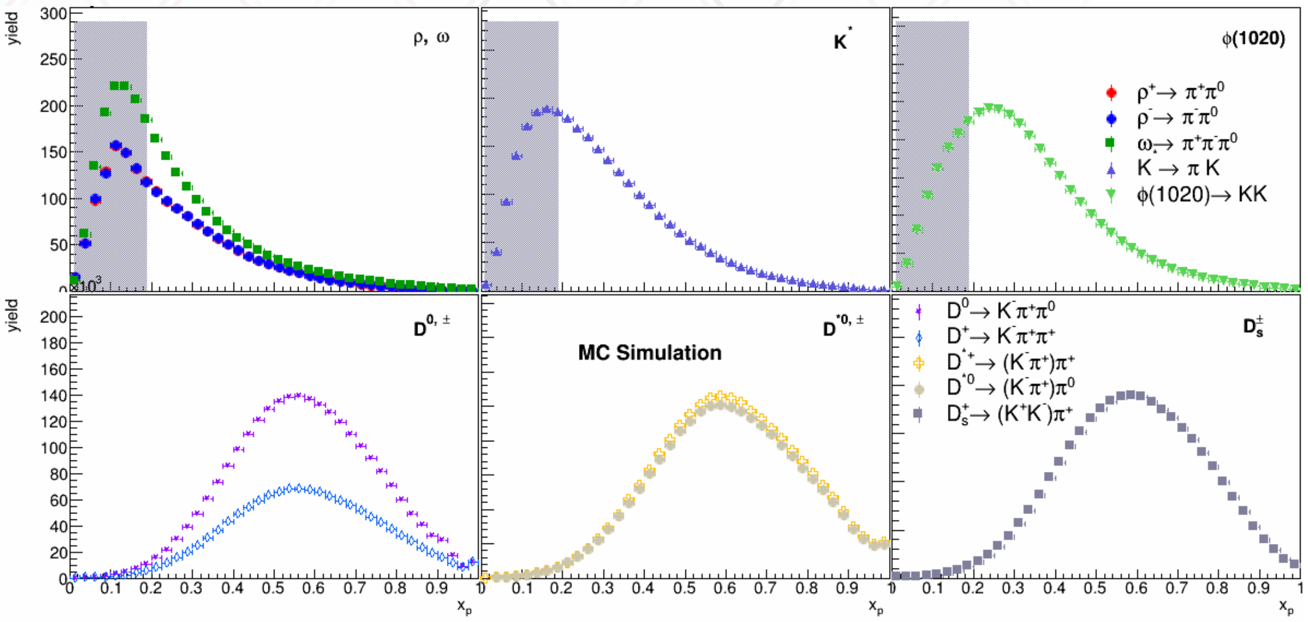
- Interesting z_π and z_Λ dependence :
- At low z_Λ light quark fragmentation dominant, some charm in π^- → different signs
- At high z_Λ strange + charm fragmentation more relevant → same signs
- Several fits to data with slightly different results



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)

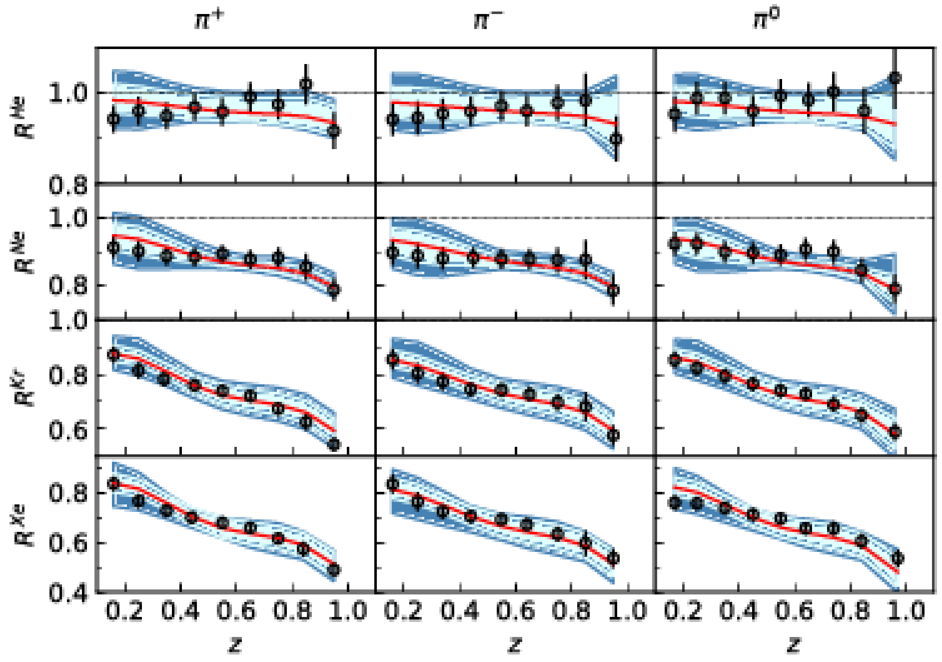
- Example from MC at Belle energies (for 4π acceptance):



Important resource for EIC, RHIC and HI physics

Nuclear Fragmentation functions

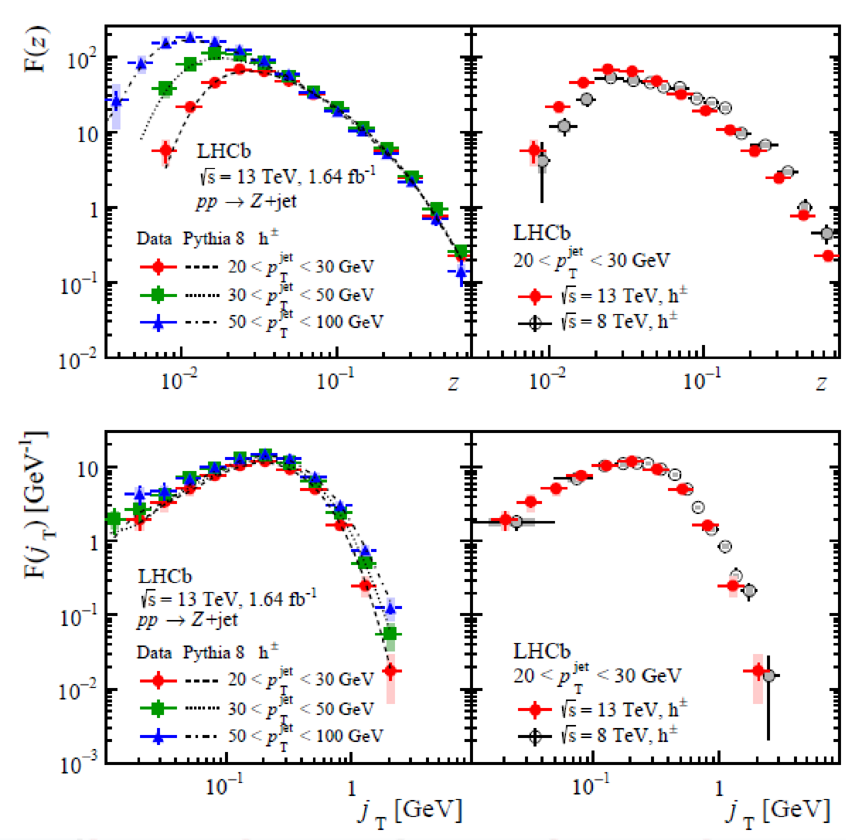
- Revisiting global nFF analysis using xFitter at NLO
- Good description of HERMES data
- predictions differ from the low-scale preliminary CLAS data



[Zurita: arxiv2101.01088]

Other venues to access fragmentation: h in jet

- Study hadron fragmentation within a jet
- Momentum fraction and transverse momentum defined relative to jet momentum and direction: $z = \frac{p_h \cdot P_{jet}}{P_{jet}^2}$
- Can be related to conventional fragmentation functions via jet Functions

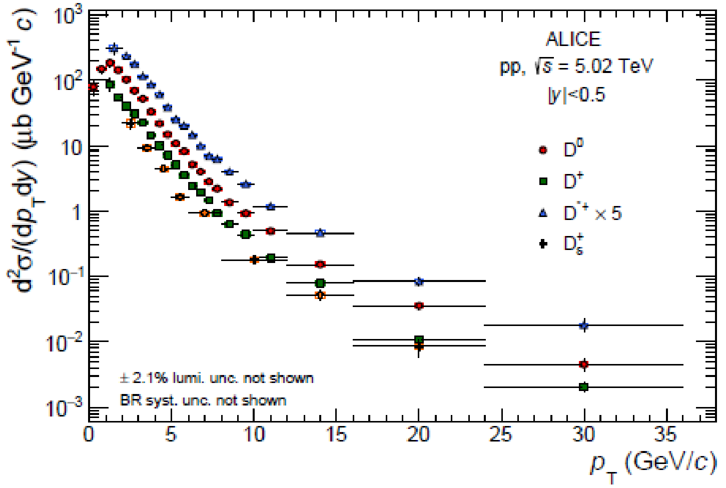


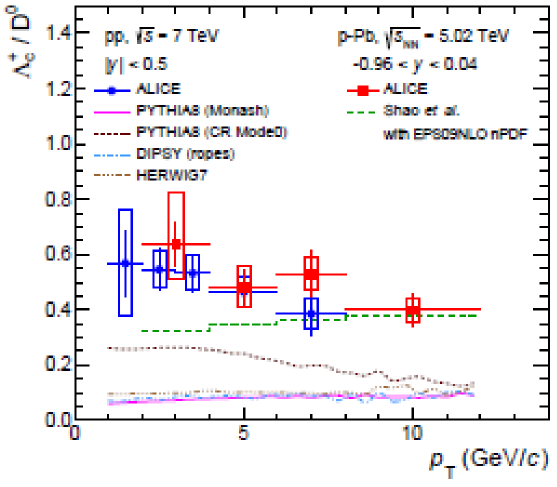
LHCb: arxiv2208.11691

Universality of Fragmentation!?

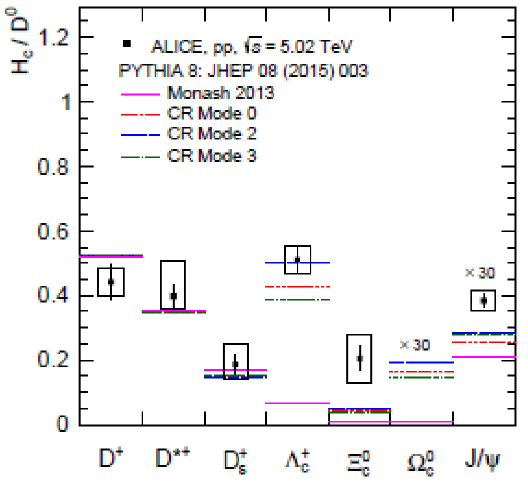
- Generally light hadron production can be well-described by universal FFs in different processes
- Charmed mesons appear to be also ok
- However, there appear to be substantially more charmed baryons produced in hadronic collisions
- Suggestions that color-recombination with remnants can cause increased rates

ALICE: *EPJC* 79 (2019) 388





ALICE: *JHEP* 04 (2018) 108



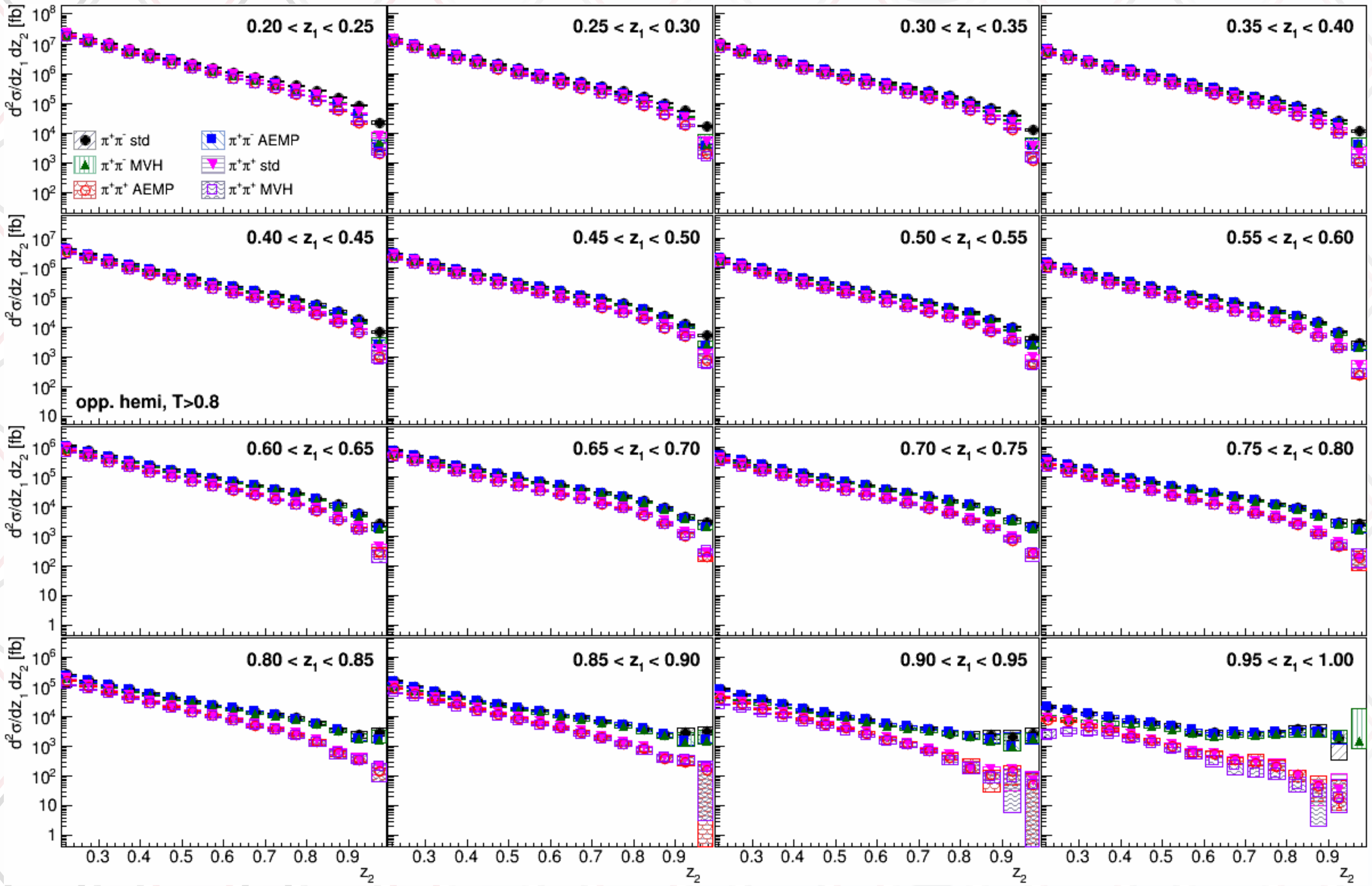
ALICE: *PRD* 105 (2022) L011103

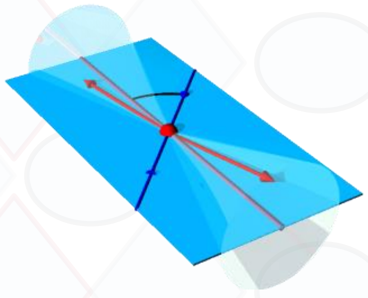
Summary

- e^+e^- is an excellent source to study fragmentation
- Crucial information for any SIDIS/pp measurements to access PDFs
- Sensitivity not only to collinear FFs but also TMD FFs:
  - Light hadron fragmentation
  - Explicitly kt dependent unpol FFs
  - Collins asymmetries
  - Polarizing Λ fragmentation
  - Dihadron fragmentation (pol and unpol)
  - Nearly back-to-back di-hadron measurements
  - Role of D and Vector Meson fragmentation and its impact on light hadrons
- New additions such as hadron in jet measurements, hint at non-universality for charmed baryons in hadronic collisions
- More to come

Comparison of definitions: pion pairs in opposite hemispheres

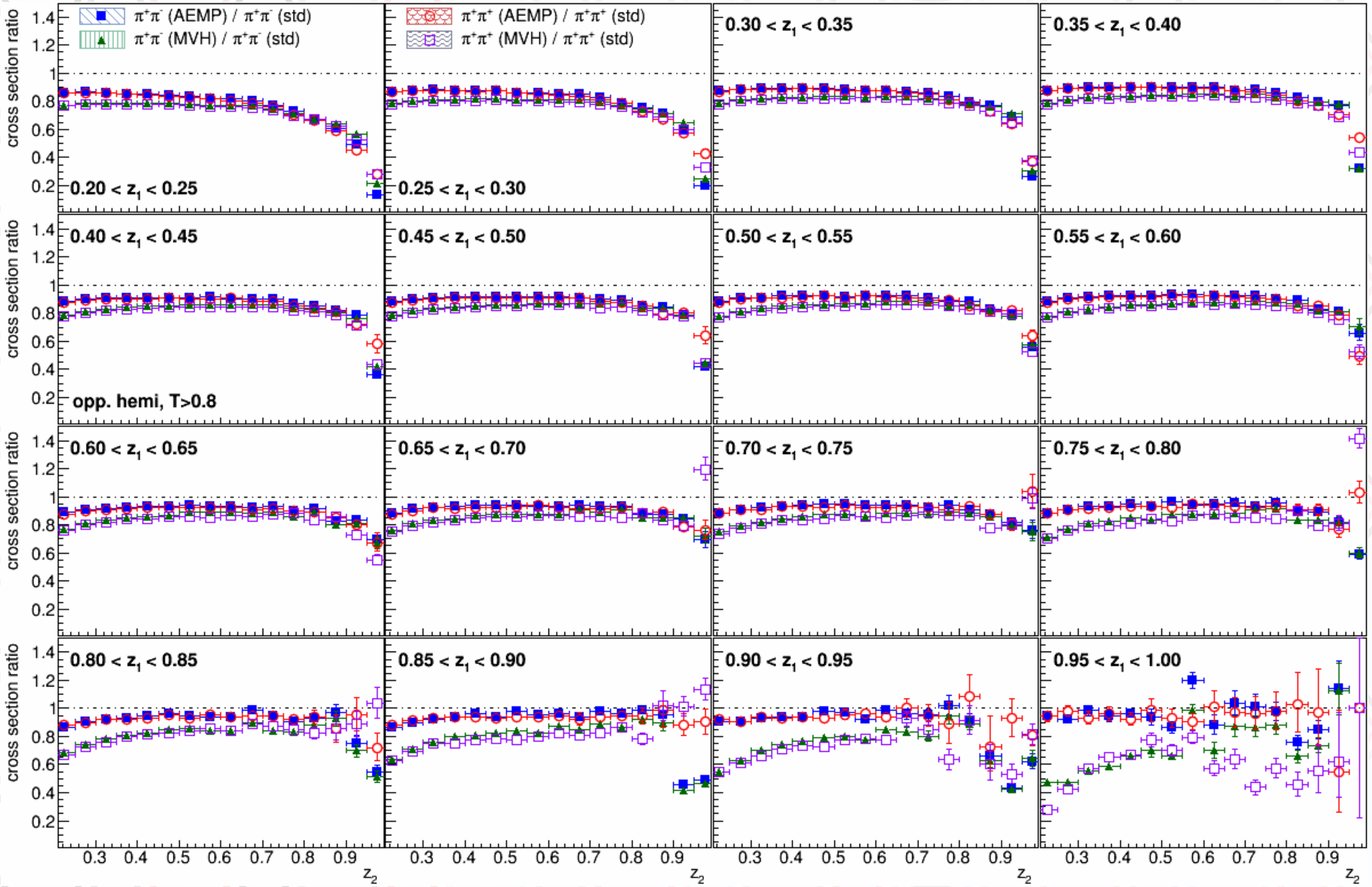
[RS et al, PRD 101 (2020) 092004](#)





Ratios to standard definitions: pion pairs in opposite hemisphere

RS et al, PRD 101 (2020) 092004



AEMP : suppressed at small factional energies, at high z close to unity

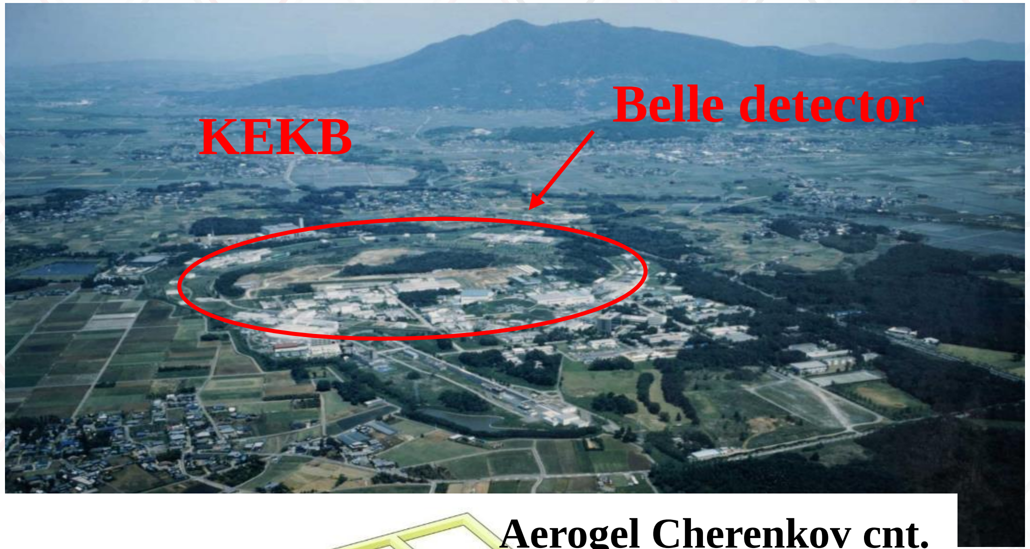
MvH : further suppressed due to transverse momentum

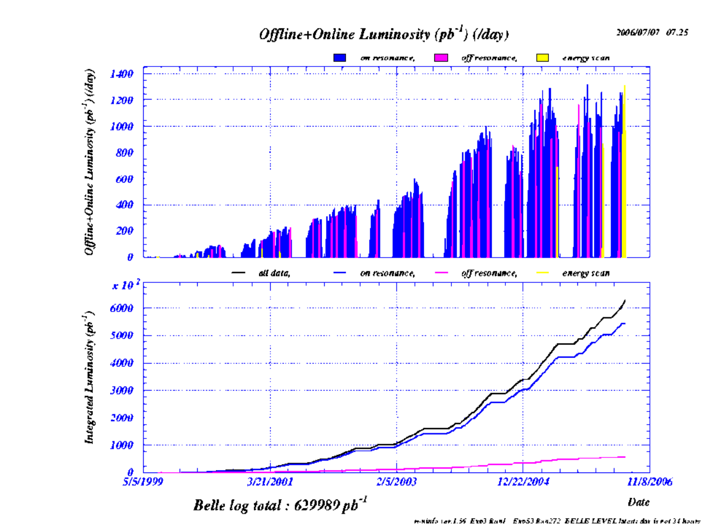
Ongoing work: Collins multidimensional analysis and Kaon combinations

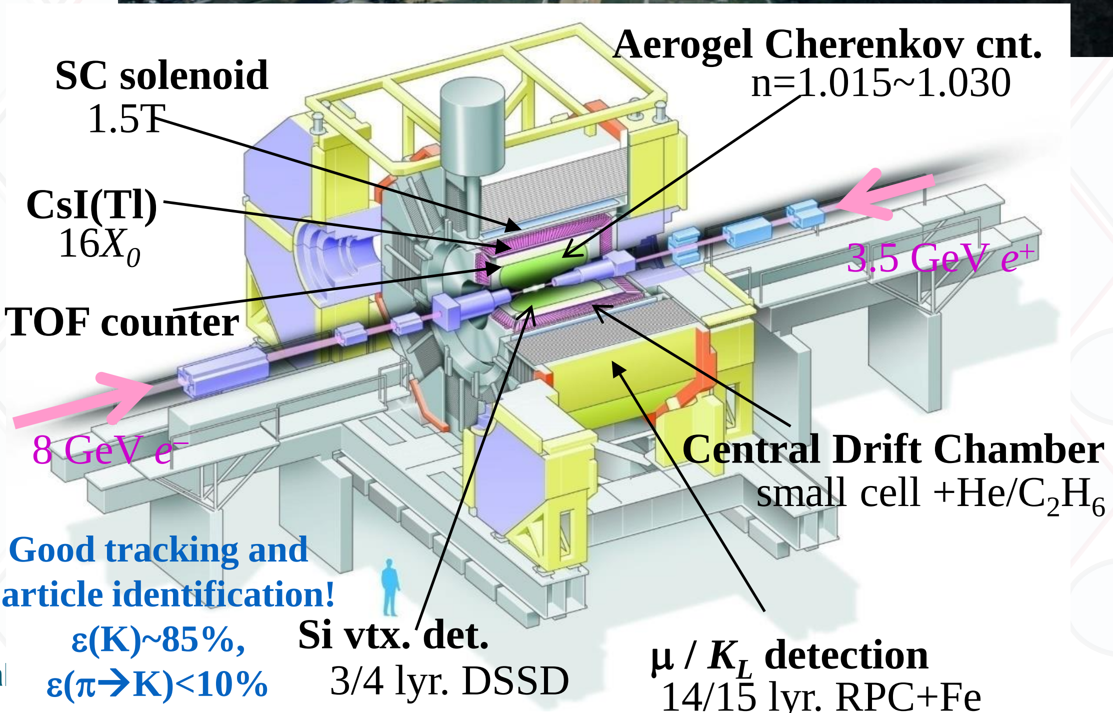
- Currently revisiting kaon combinations of the Collins asymmetries
- While doing so, try to perform a full multi-dimensional analysis:
  - Consider :
  - $6 (z_1) \times 6 (z_2) \times 5(k_{t1}) \times 5(k_{t2}) \times 1$ (costheta) x 8 (phi) for A_{12} method
  - $6 (z_1) \times 6 (z_2) \times 10(q_t) \times 1$ (costheta) x 8 (phi) for A_0 method
- Perform most correction steps similar to recent analyses (PID, smearing)
  - Possibly simplified smearing unfolding as each z_1-z_2 bin separately (z smearing almost nonexistent in such a binning)
  - non-qqbar removal, charm removal, ISR correction and acceptance might require introduction of nonzero MC asymmetries

Belle Detector and KEKB

- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV (Υ(4S))
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\ \bar{B}$
- Continuum production: 10.52 GeV
- $e^+e^- \rightarrow q\ \bar{q}$ (u,d,s,c)
- Integrated Luminosity: >1000 fb^{-1}
- >70fb^{-1} => continuum







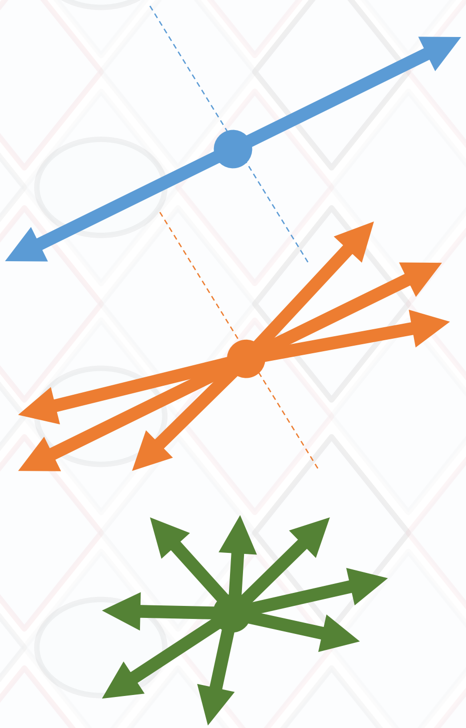
Thrust definition

- Event shape variable thrust is defined as:

$$T \overset{max}{=} \frac{\sum_h |\mathbf{P}_h \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h|}$$

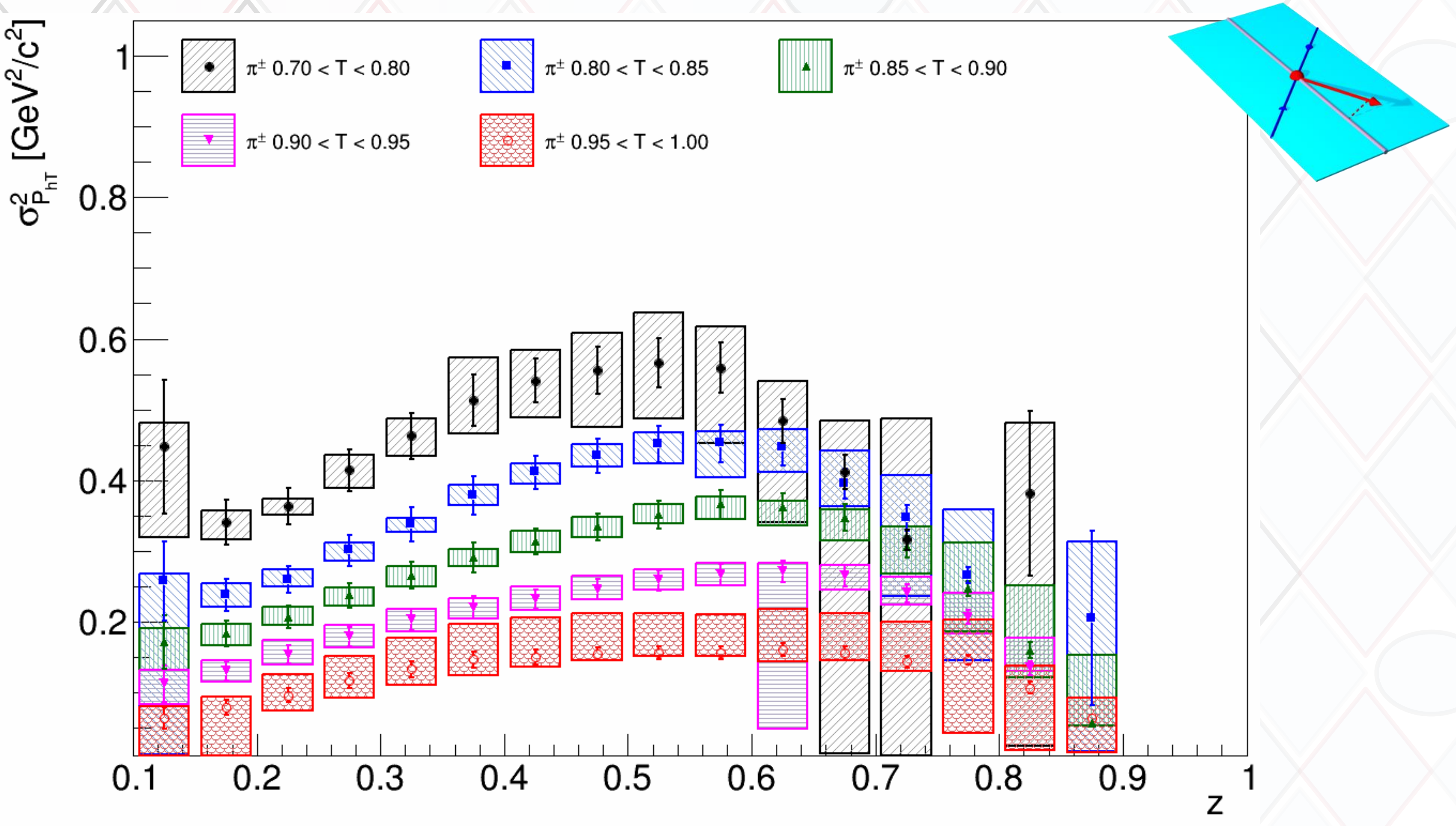
- All final-state particles are included in the sum
- A two-jet-like event has a high thrust value
- A completely spherical event has a thrust value of 0.5

- Thrust axis **n** also defines the hemispheres



Gaussian widths, thrust dependence

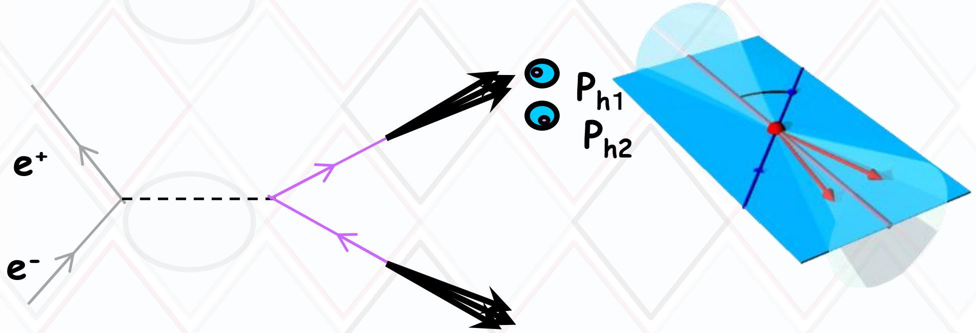
Gaussian widths get narrower with higher Thrust



PRD99 (2019) 112006

Di-hadron fragmentation functions

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



$$D_{1,q}^{h}(z_1, Q^2) D_{1,q}^{h}(z_2, Q^2)$$