Fragmentation Functions

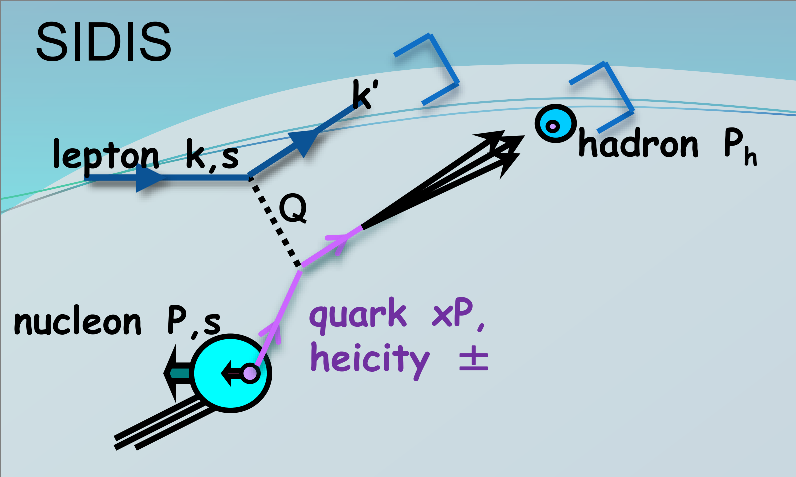
experimental overview

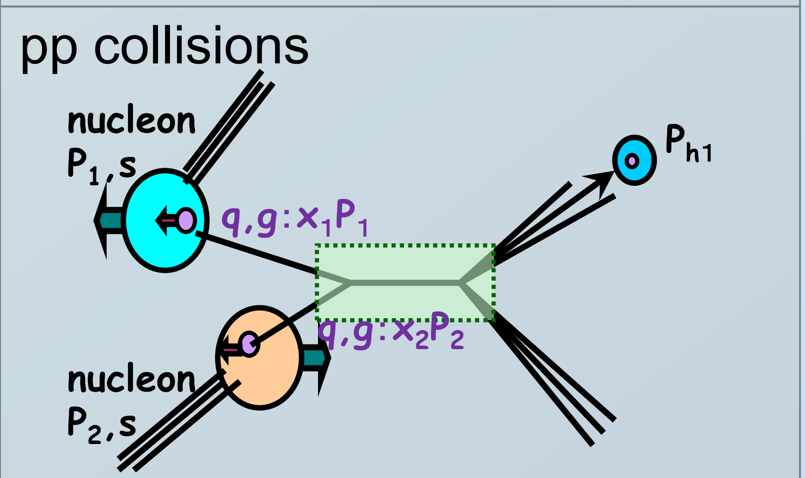
Fragmentation workshop,
Lago Maggiore, Feb 19-22, 2018

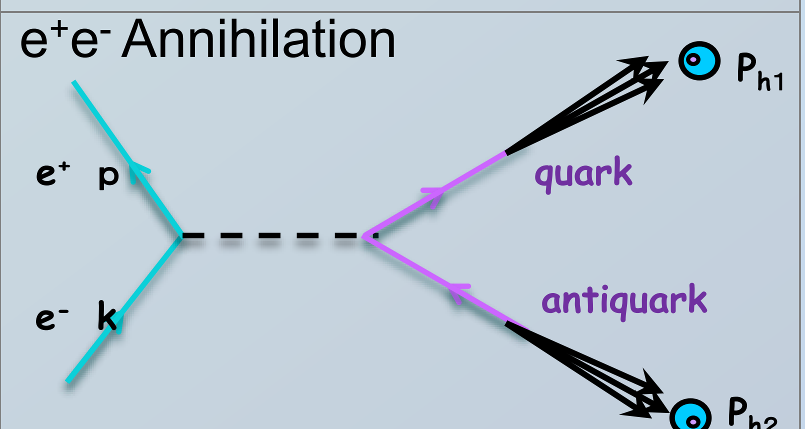
Ralf Seidl (RIKEN)

Outline

- Single hadron fragmentation
  - Unpolarized in e+e-, SIDIS and hadron collisions
  - Transverse momentum dependent Fragmentation
  - Transverse quark spin and momentum dependent Fragmentation → Collins FF
  - Transverse hadron spin → Λ pol
- Di-hadron fragmentation
  - Unpolarized for mass, z dependence (or for single hadron FFs in e+e-)
  - Transversely polarized →IFF
- Nuclear Fragmentation







Access to FFs

- SIDIS:

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

  - 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-:

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

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

Single hadron fragmentation

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

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

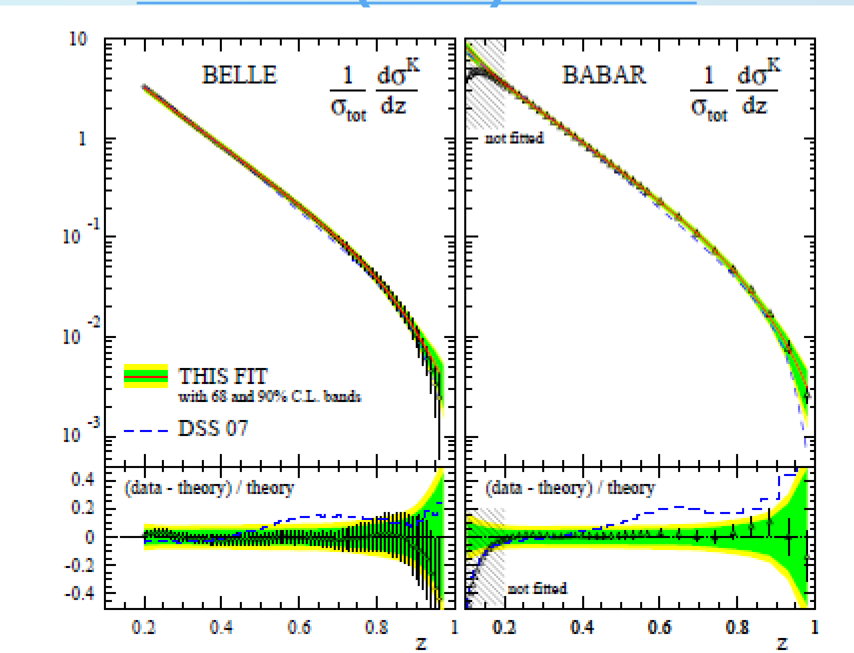
$$H_{1,q}^{\perp h}(z, k_T, Q^2) \qquad D_{1,q}^{\perp h}(z, k_T, Q^2)$$

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

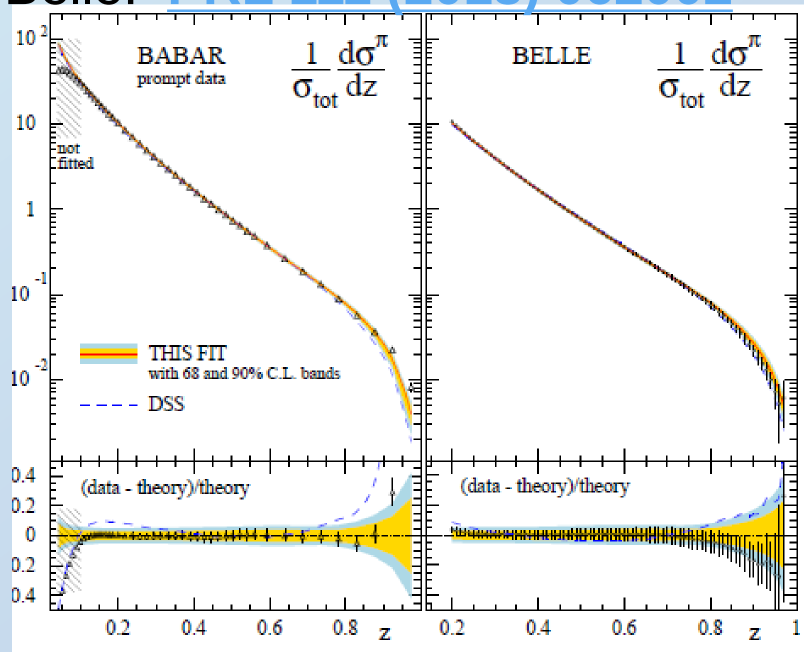
$$\mathcal{G}_{q}^{h}(z, z_h, \omega_J R, j_\perp, Q^2)$$

B factory data (Q~10GeV)

Babar: PRD 88 (2013) 032011



Belle: PRL 111 (2013) 062002

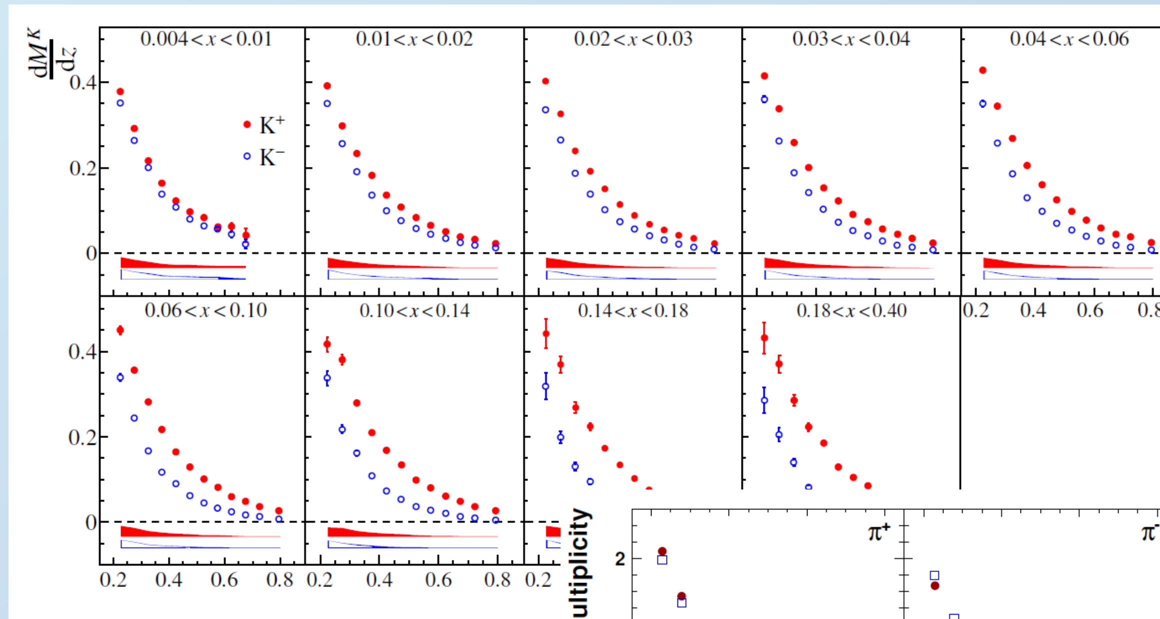


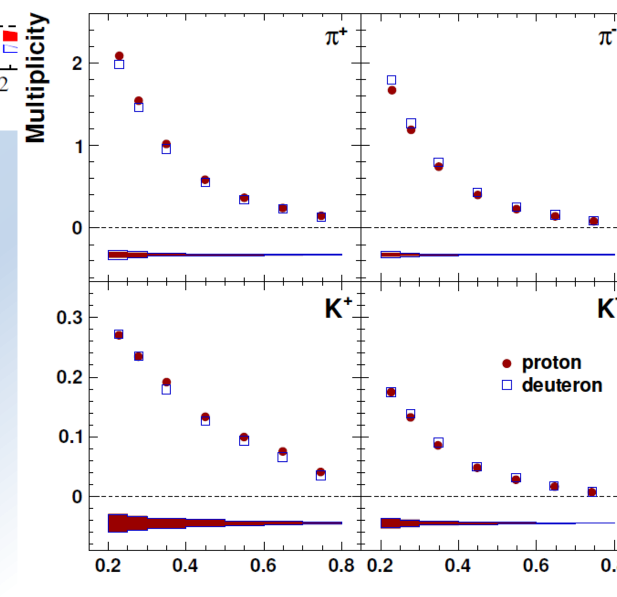
- High precision pion and kaon data from both B factory experiments
- Precision up to very high z
- Lever arm to much higher energy (Q~20 – 200GeV) data allows for determination of gluon fragmentation over evolution

SIDIS data

COMPASS Kaons: PLB767 (2017) 133-141
COMPASS pions: PLB764 (2017) 1-10
HERMES pi/K: PRD87 (2013) 074029

- SIDIS requires unpol PDFs, but generally well known
- Recently published COMPASS data now available
- HERMES data for pions and kaons available already for a while
- Some tension for kaon data between experiments

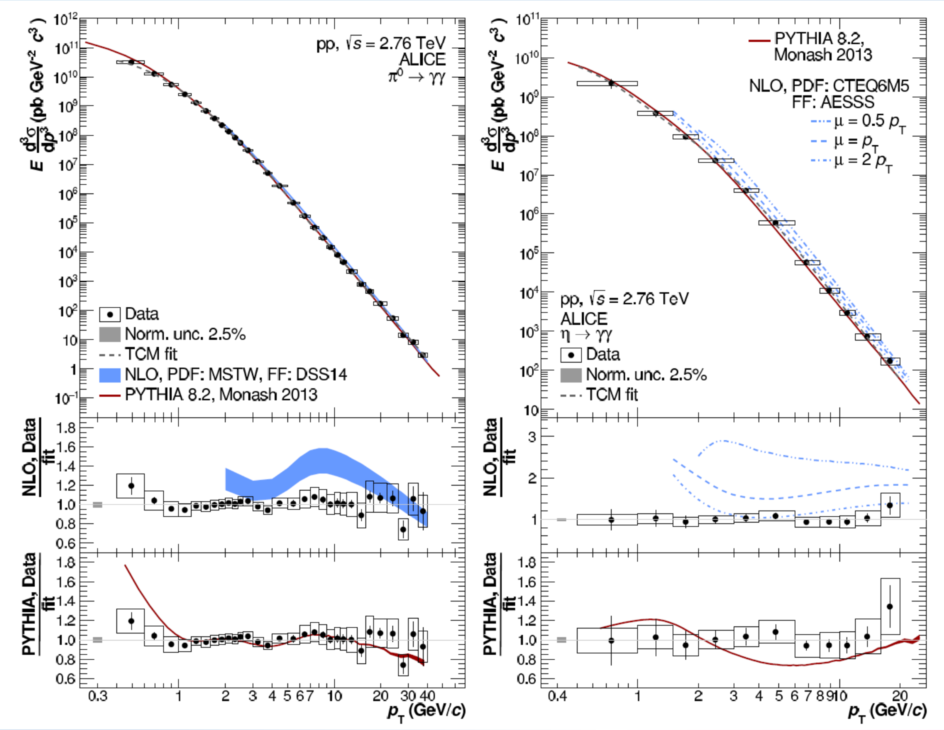




LHC single hadron cross sections

- Hadron collider data sensitive to gluon fragmentation as quark-gluon and gluon-gluon hard scattering processes dominating
- At LHC mostly π^0 and η data only available (too high energies for charged hadron PID

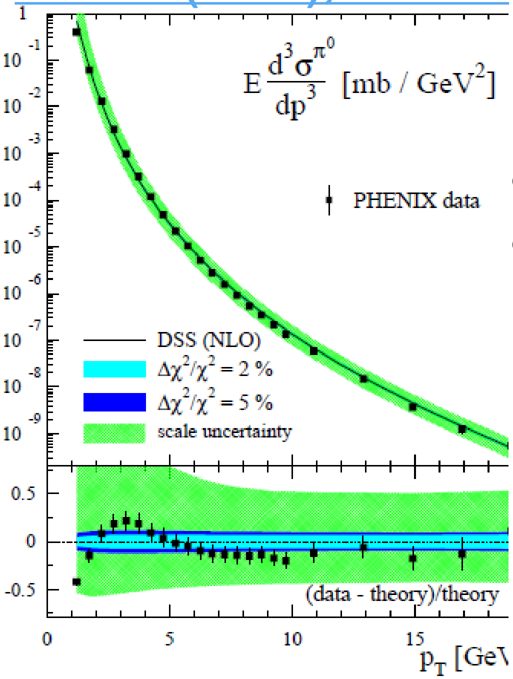
ALICE: EPJ C77 (2017) 339, EPJ. C77 (2017) 586

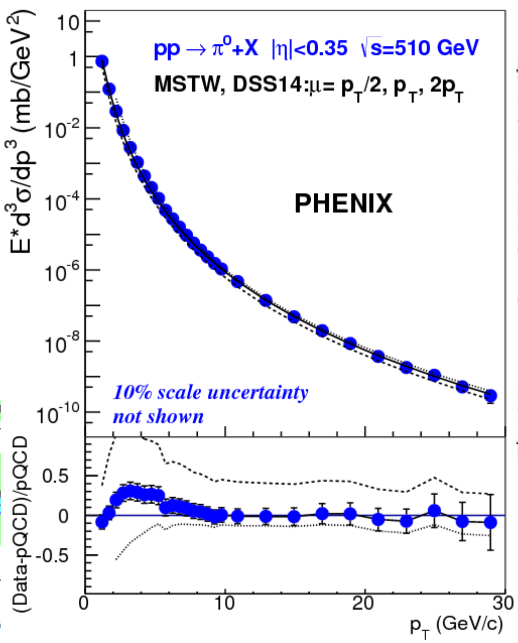


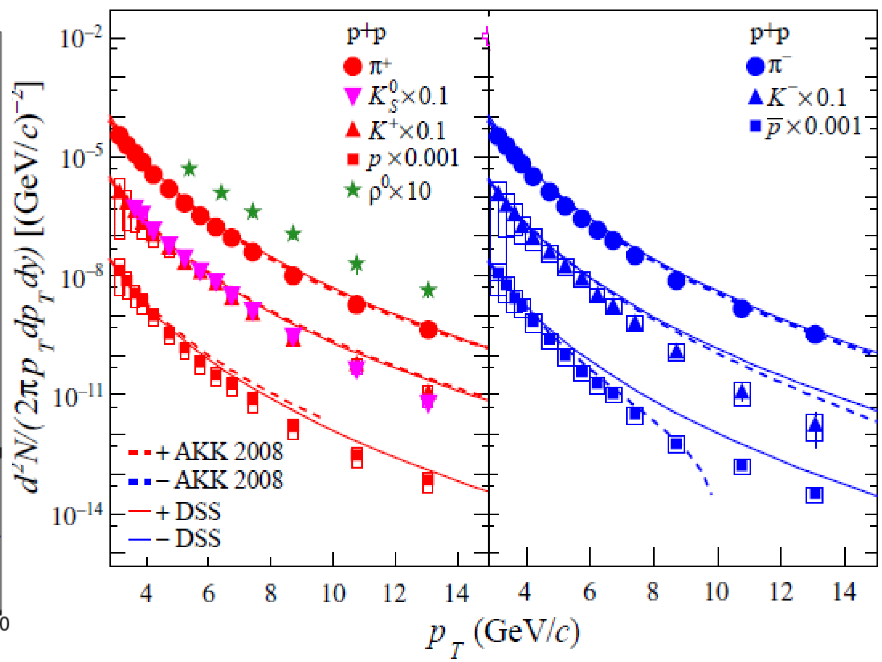
RHIC cross sections

PRD76 (2007) 051106
PRD93 (2016), 011501

PRL 108 (2012) 072302

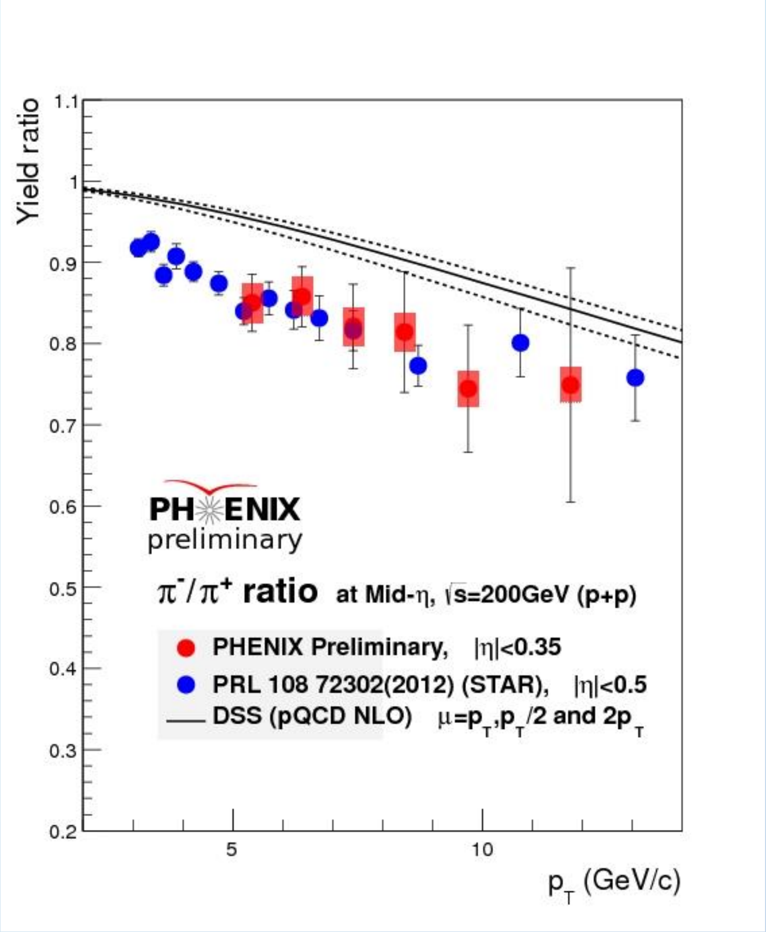






- Generally very good agreement of cross sections with NLO calculations
- Most sensitivity to gluon Fragmentation
- Also data at forward rapidities

Pion cross section charge ratio

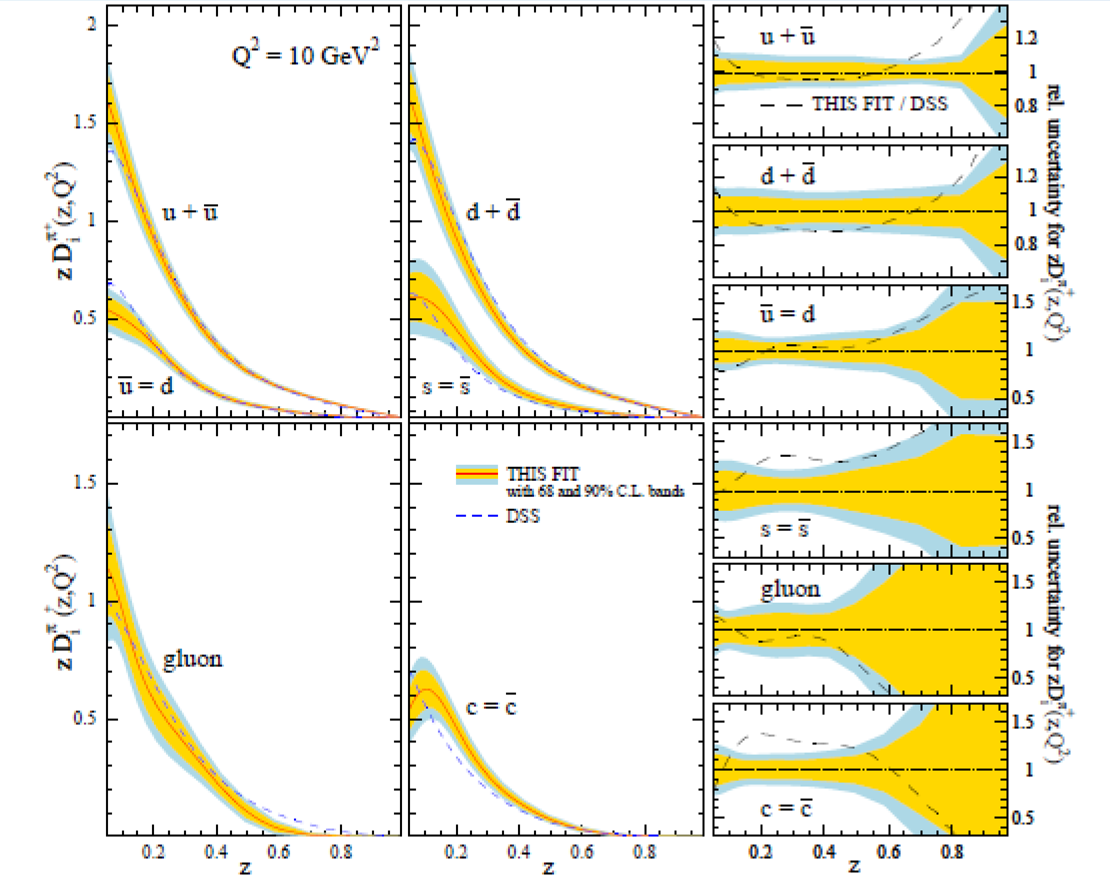


- At low P_T gluon fragmentation dominates → ratio close to 1
- Data significantly under DSS curves
- Possible explanation by smaller disfavored fragmentation u → π^-
-

Pion fragmentation

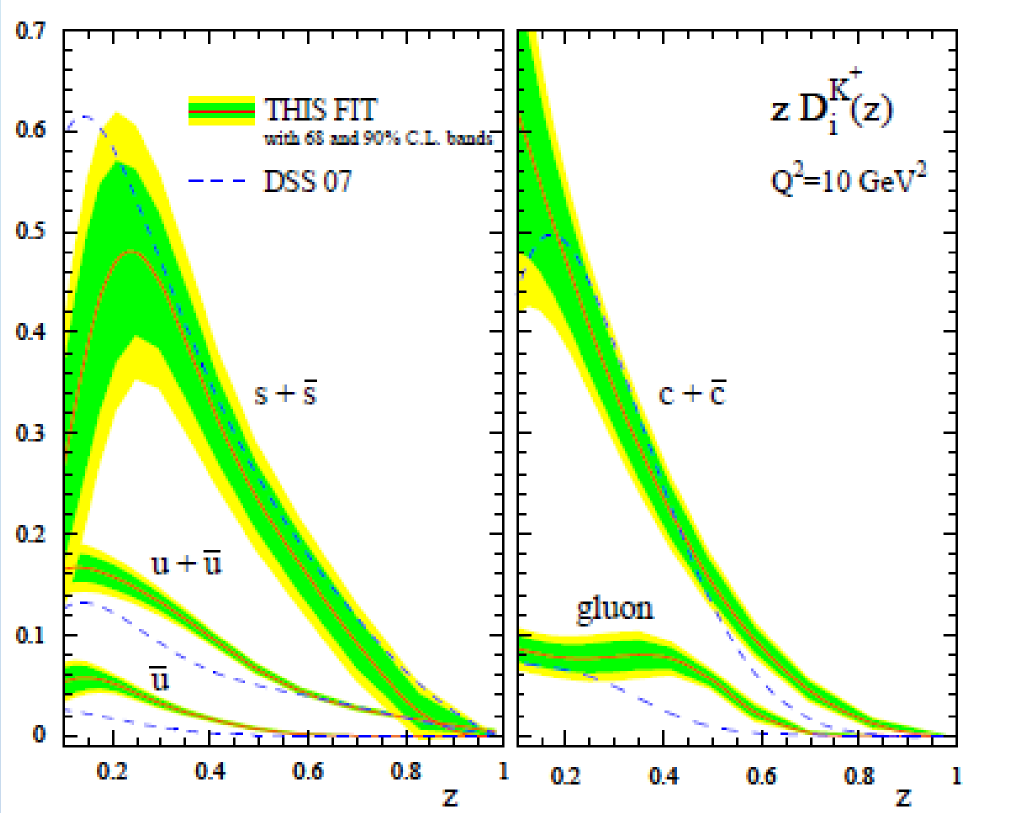
DSS15: [deFlorian et.al., Phys.Rev. D91 (2015) 014035]

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



Kaon fragmentation

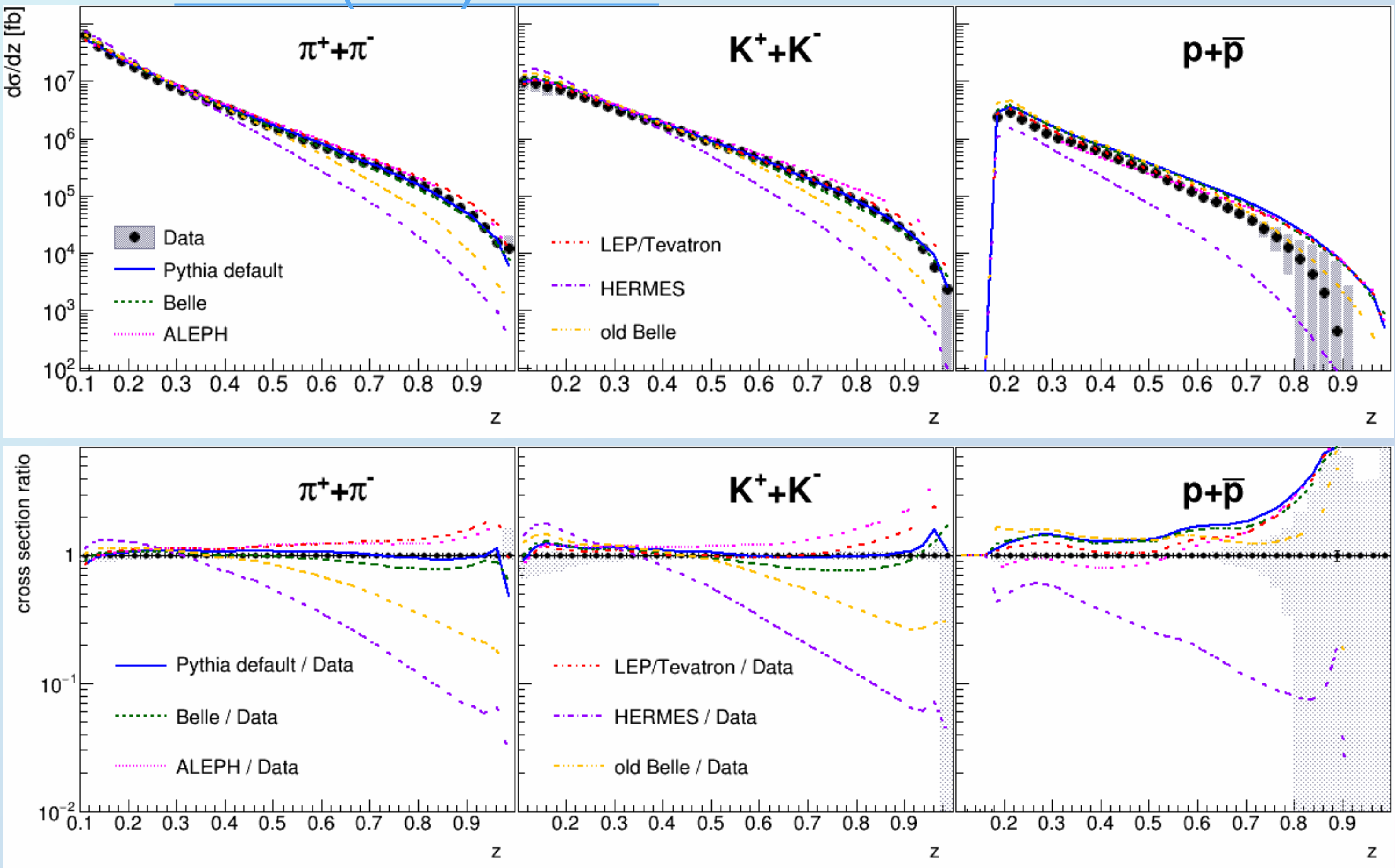
DHESS PRD 95 (2017) 094019



- Strange quarks are dominating kaon fragmentation
- Again likely dominated by favored fragmentation
- 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?)

New addition: single protons

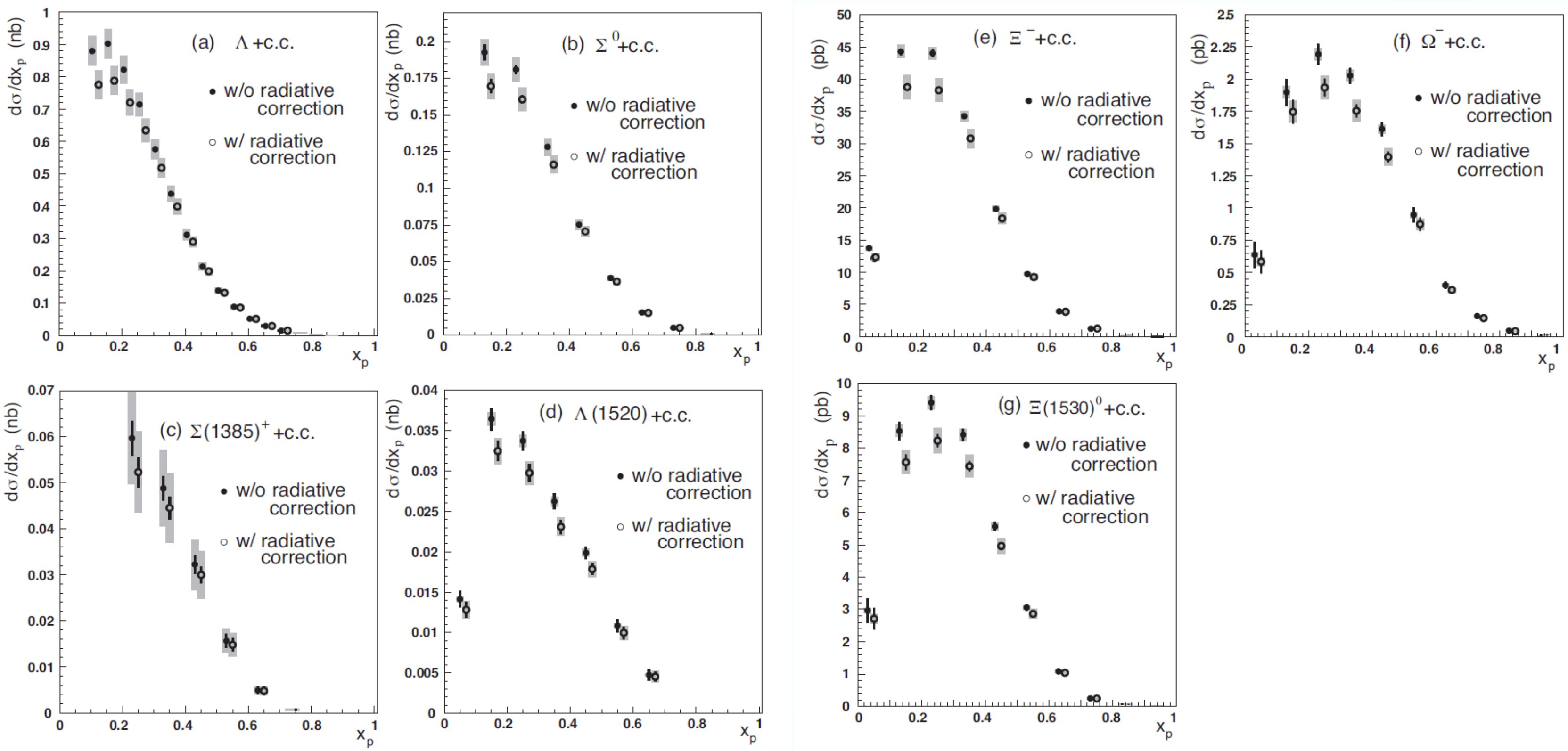
PRD92 (2015) 092007



- Default Pythia and current Belle in good agreement with pions and kaons
- Protons not well described by any tune

Hyperon Fragmentation

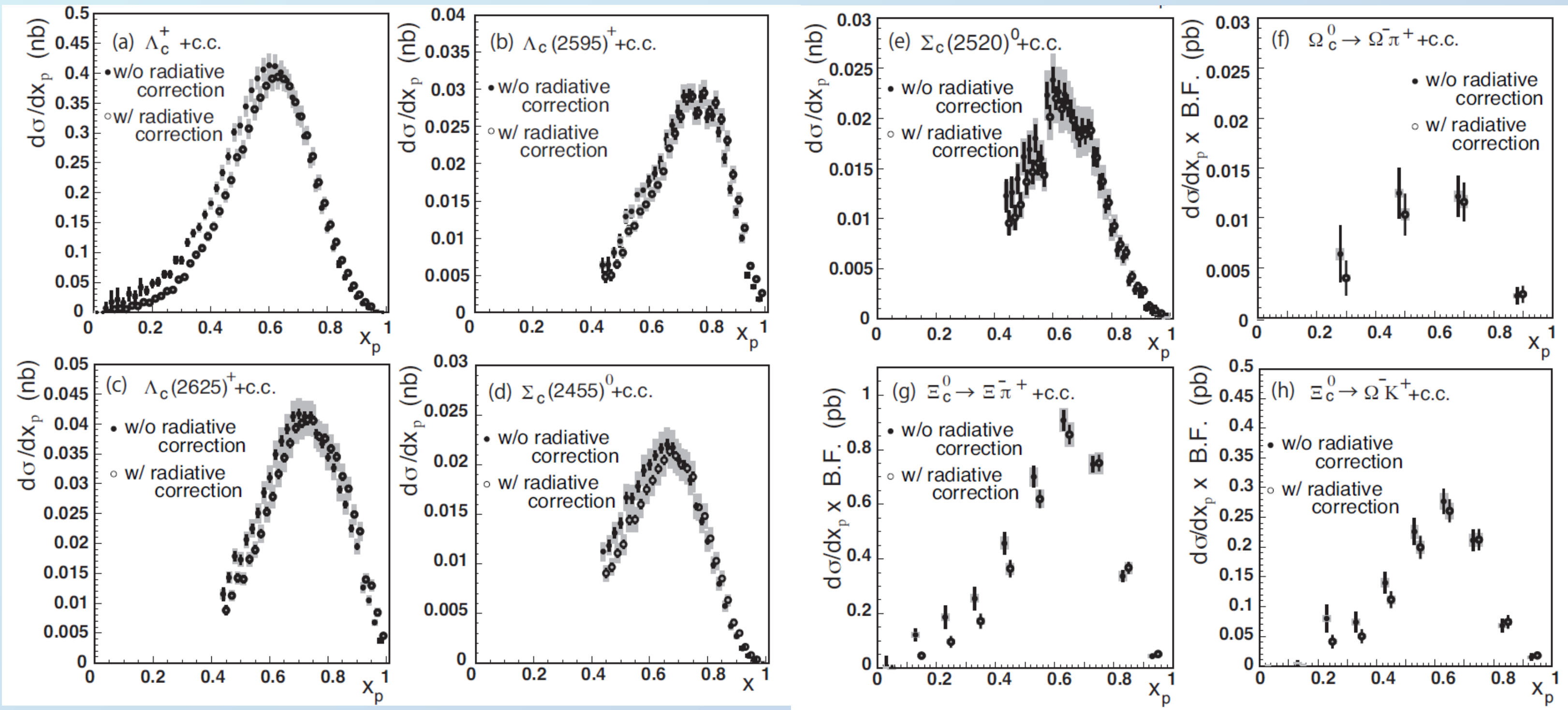
Belle: Niiyama et. al. arXiv:1706.06791



Hyperons similar to light hadron fragmentation → peaking at low z (x_p)

Charmed baryon Fragmentation

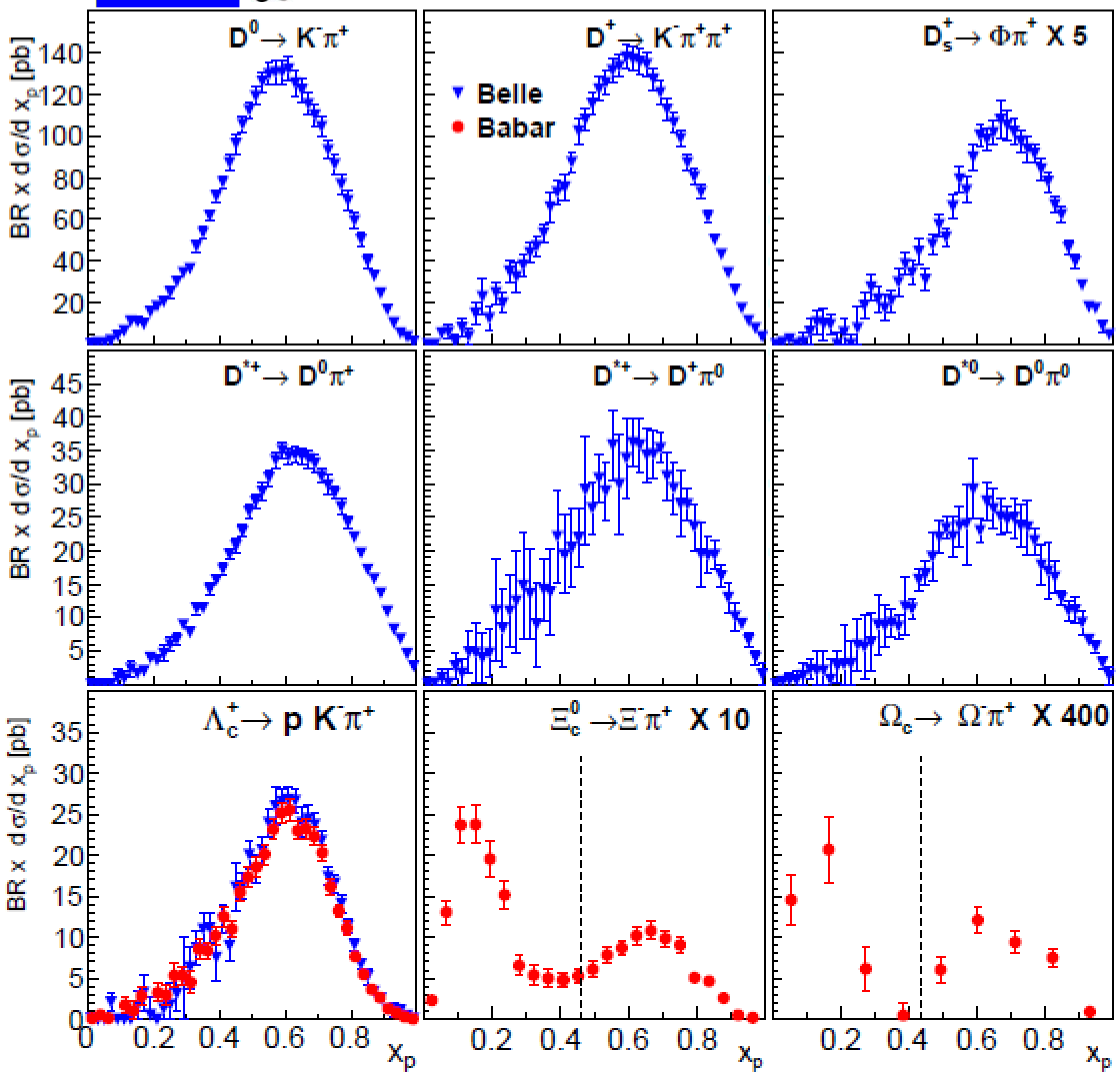
Belle: Niiyama et. Al. [arXiv:1706.06791]



Also Λ_c measurements by:
BaBar: PRD 75,012003 (2007)
and Cleo

Charmed hadrons carry large fraction of parton momentum

Charmed Fragmentation



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

- Heavier particles generally plotted vs normalized momentum $x_p = \frac{P^h}{P^h_{max}}$
- Unlike light hadrons charmed hadrons contain large fraction of charm quark momentum

Transverse momentum dependence

Aka un-integrated PDFs and FFs

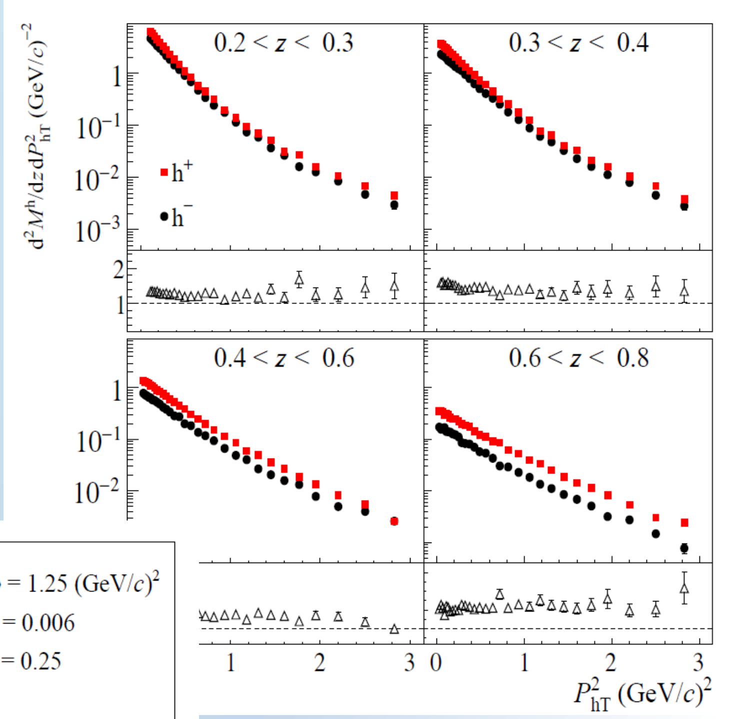
$$D^{h}_{1,q}(z, Q^2, k_t)$$

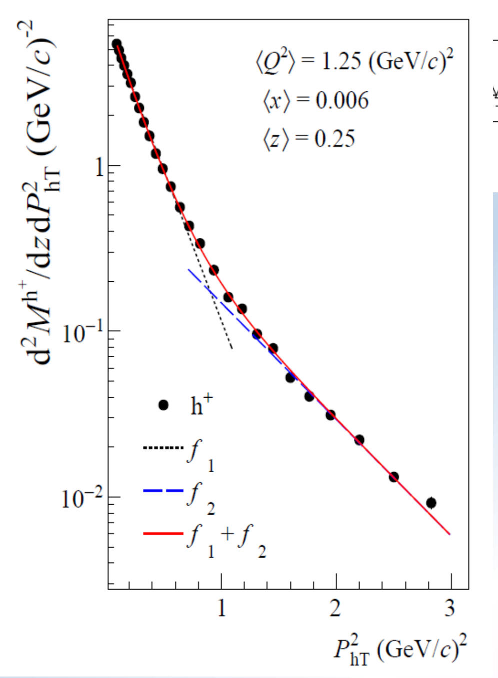
Transverse momentum dependent fragmentation in SIDIS

COMPASS
[PRD97 (2018) 032006]

- Convolution of TMD PDFs and FFs; only $P_{h\perp}$
- known
- Various recent results from HERMES and COMPASS
- Non-perturbative $P_{h\perp}$

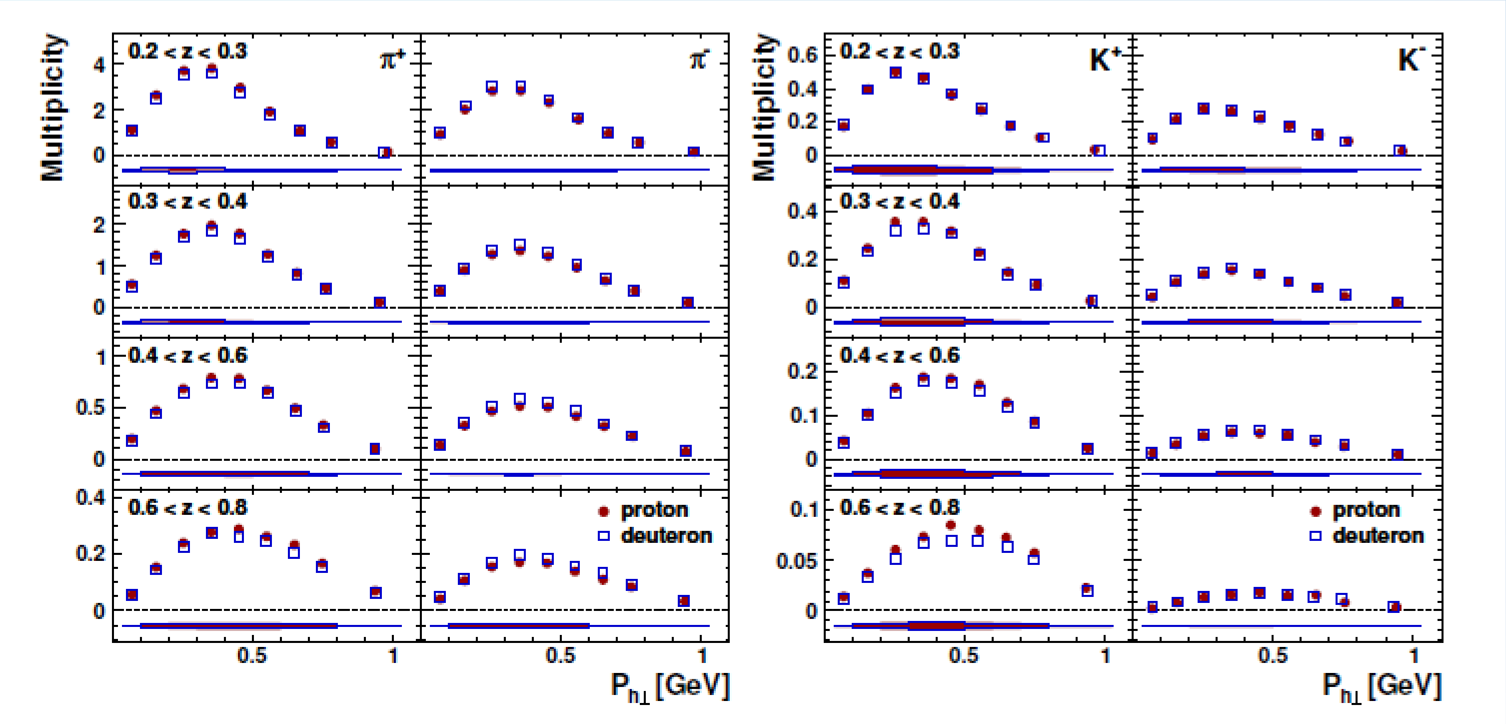
region can be described by Gaussian, perturbative region needs additional function





Hermes P_T dependence

Phys.Rev. D87 (2013) 074029



- Width increases with z
- K- (all sea) wider
- p and d distributions similar → little favored disfavored difference
- Full 5 dim data available at: http://hermesmults.appspot.com/

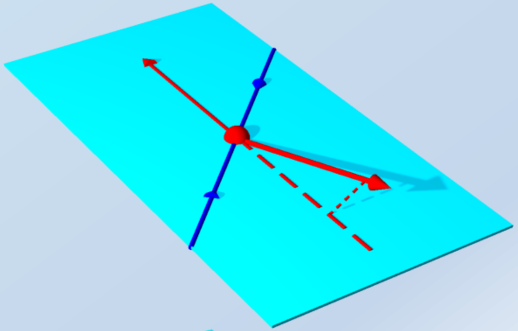
Unpol TMD FFs from hadron colliders

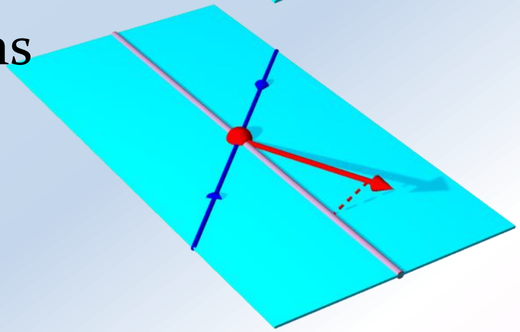
- So far "only" Collins results from STAR at 200 and 500 GeV

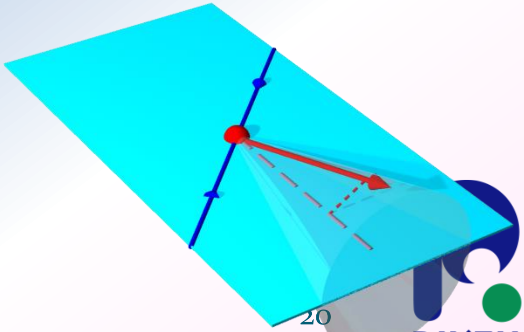
- Some unpol results from LHC?

K_T Dependence of FFs in e+e-

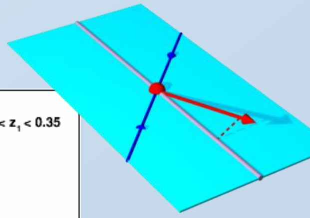
- Gain also sensitivity into transverse momentum generated in fragmentation
- Two ways to obtain transverse momentum dependence
  - Traditional 2-hadron FF
    - → use transverse momentum between two hadrons (in opposite hemispheres)
    - → Usual convolution of two transverse momenta
  - Single-hadron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





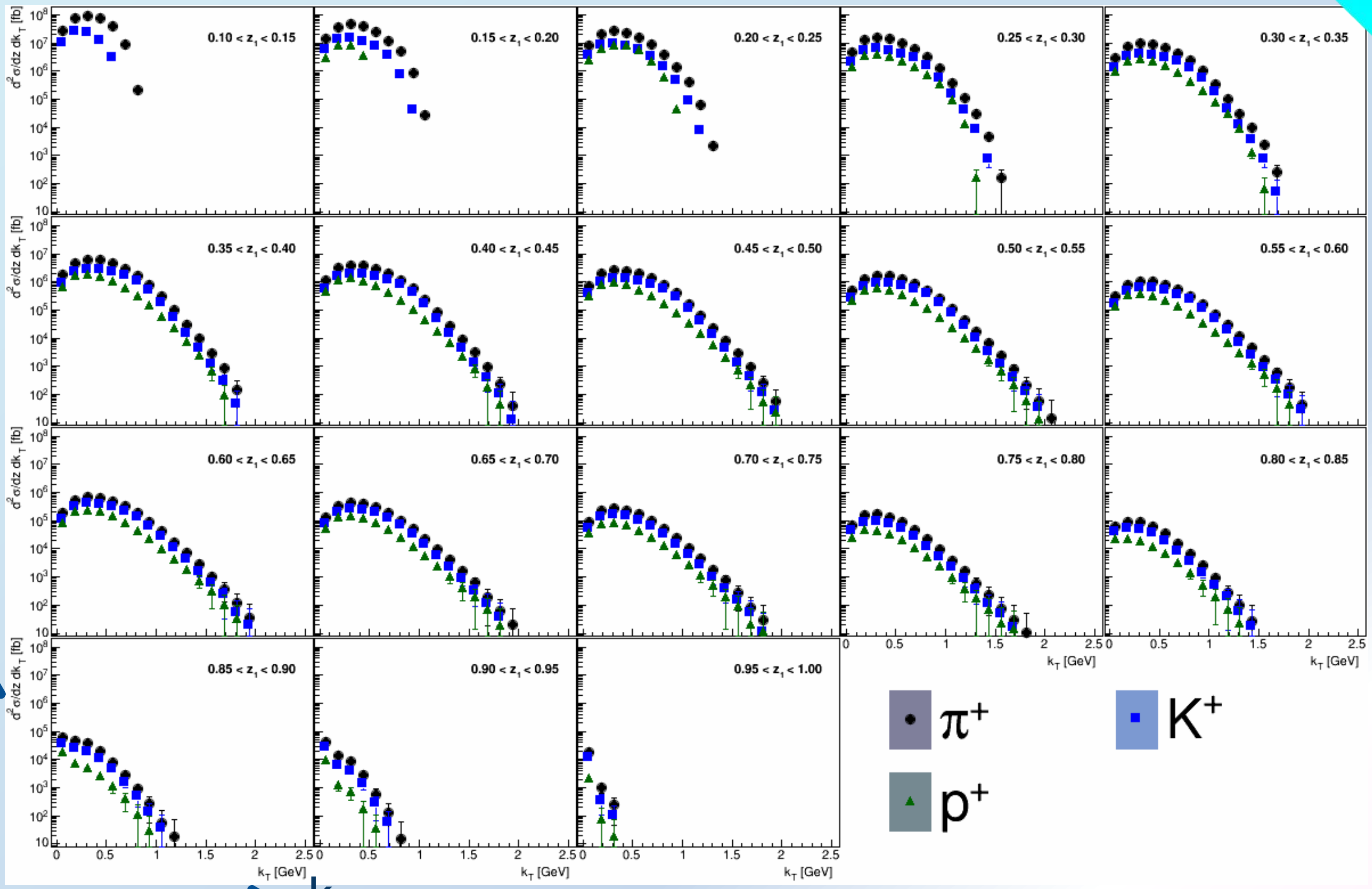


MC sample for various hadrons



MC simulation

$$\frac{d^2\sigma}{dz\,dk_T}$$



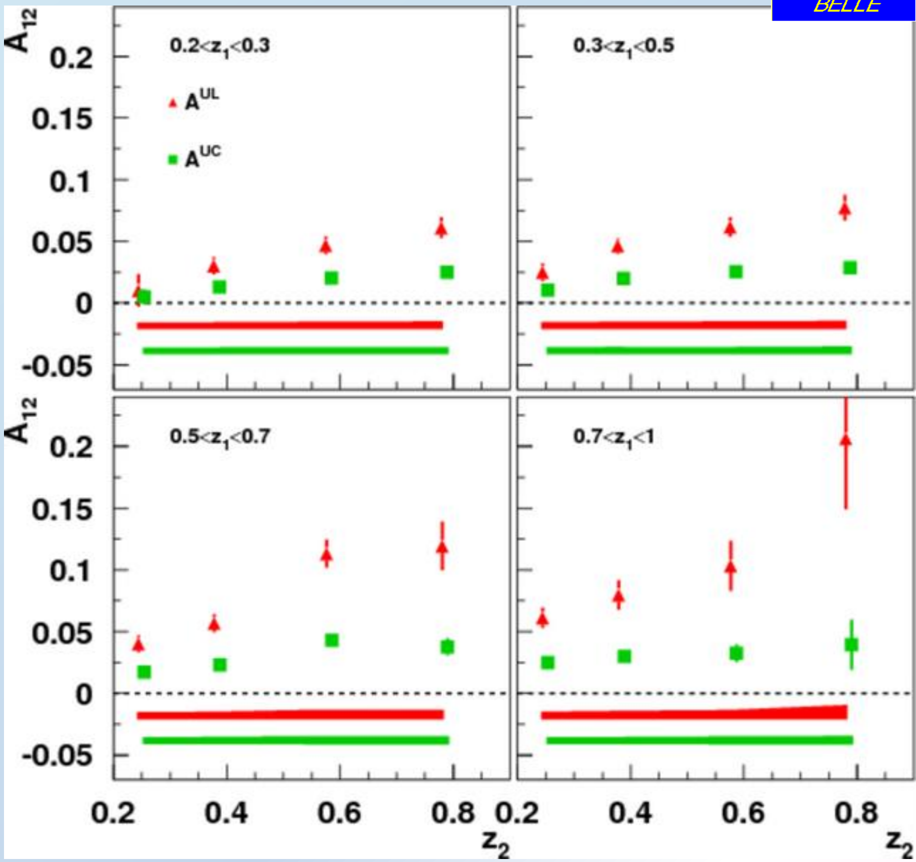
kT

Spin dependent single hadron fragmentation

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

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

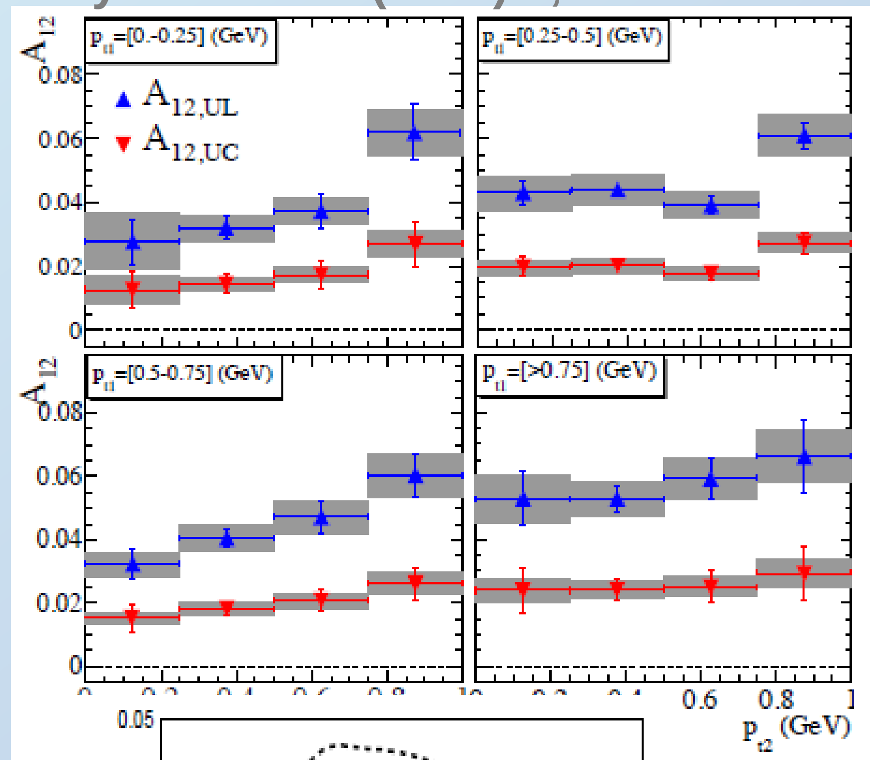


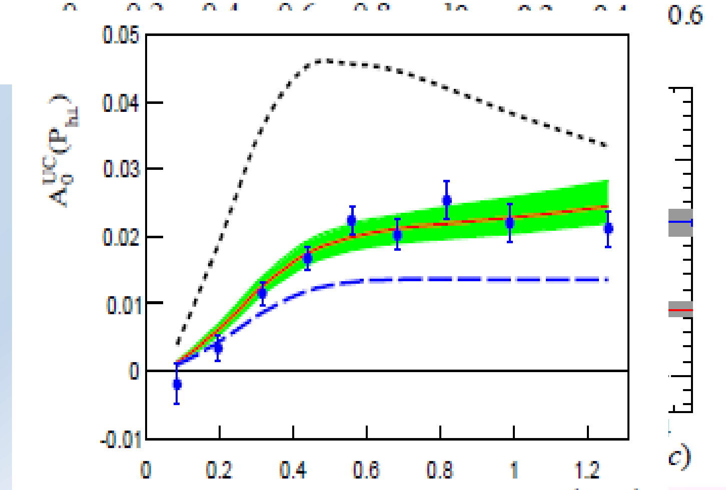
RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Explicit transverse momentum dependence

Phys.Rev. D90 (2014) 5, 052003

- First explicit transverse momentum dependent extraction for Collins asymmetries (relative to thrust axis* or second hadron)
- Global Transversity and Collins fit ([PRD93 (2016) 014009](PRD93 (2016) 014009))able to reproduce the dependence

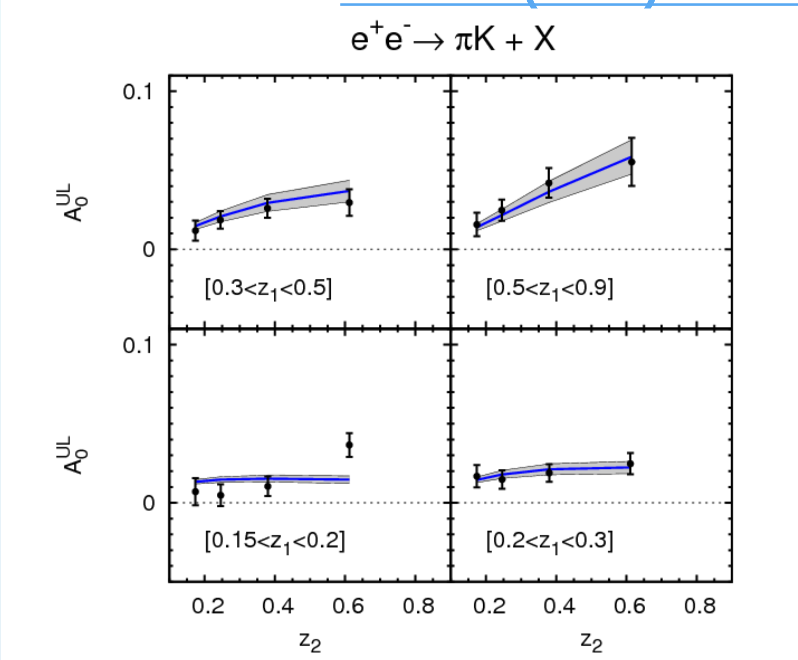




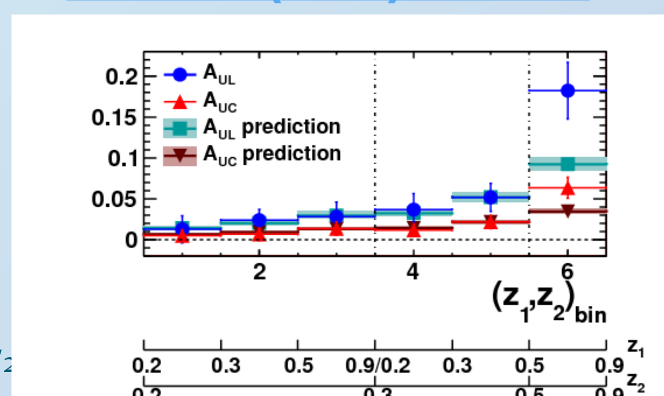
Quark transversity via Collins: Kaons

BABAR: PRD 92 (2015) 111101

Anselmino et al: PRD 93 (2016) 034025



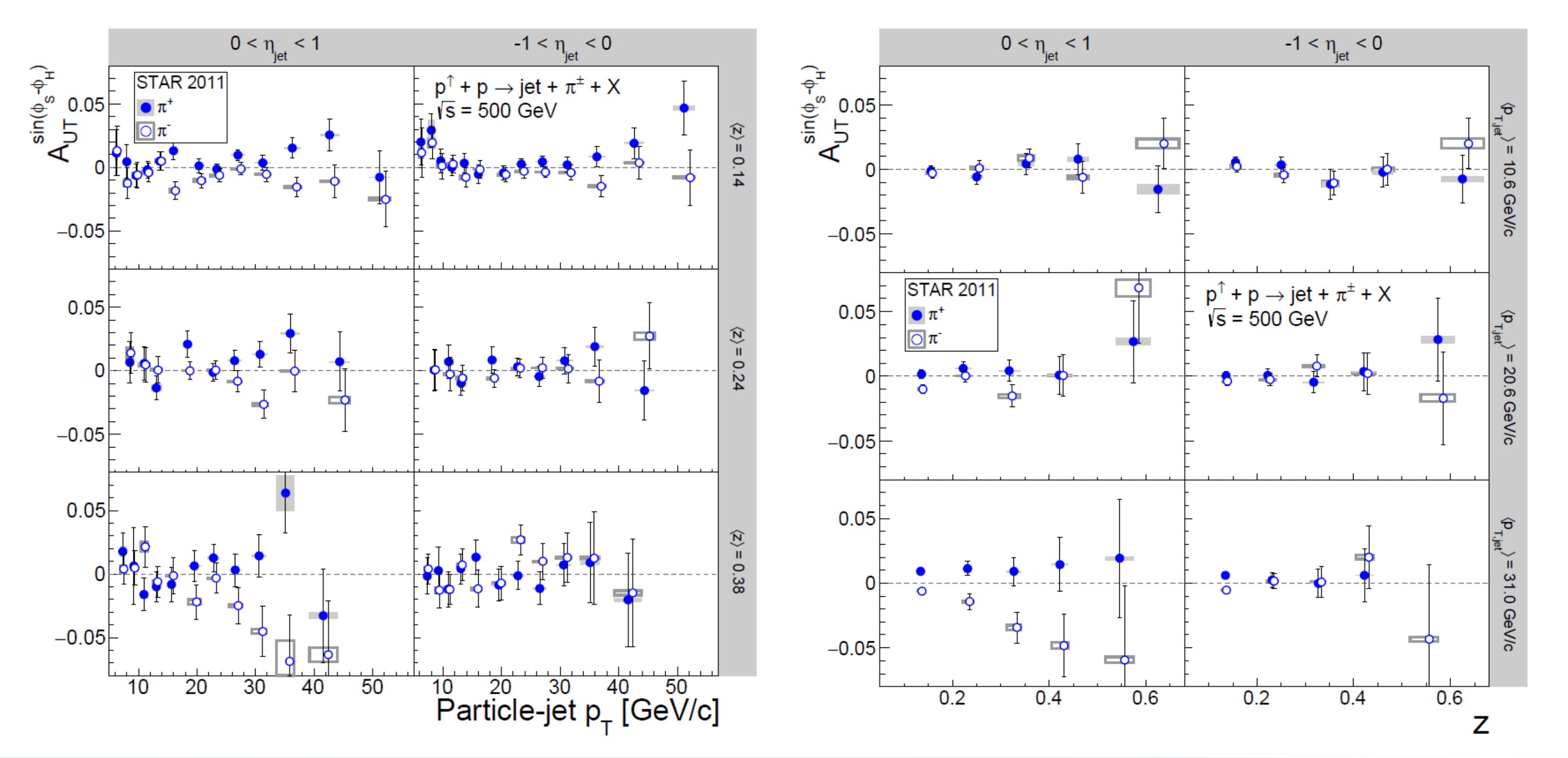
BESIII: PRL 116 (2016) 042001



- 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
- Also: unpolarized kaon multiplicities from COMPASS

STAR Collins asymmetris

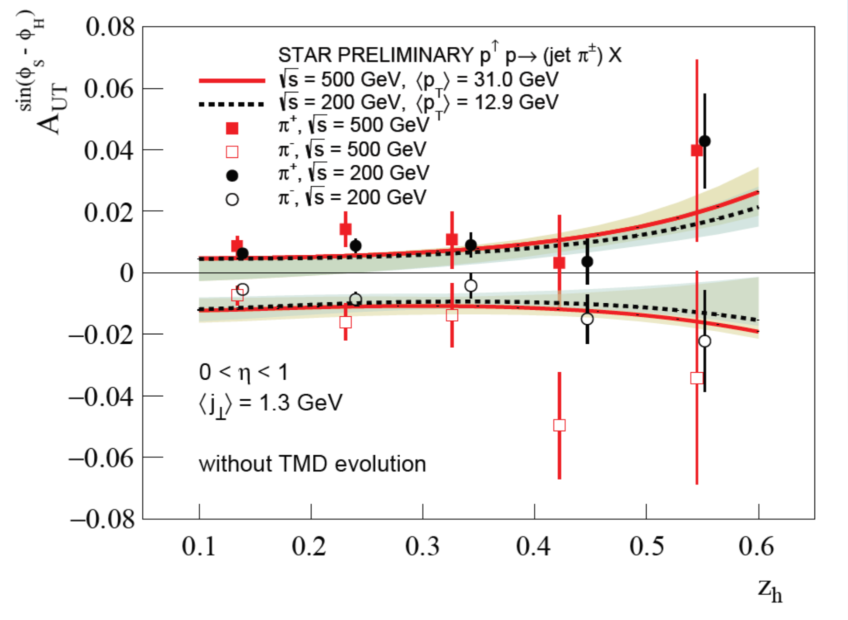
500 GeV: [PRD97 (2018) 032004]



- Little indication of evolution efects

Kang, Prokudin, Ringer, Yuan: [PLB774 (2017) 635-642]

STAR 200: **Int.J.Mod.Phys.Conf.Ser. 40 (2016) 1660040**



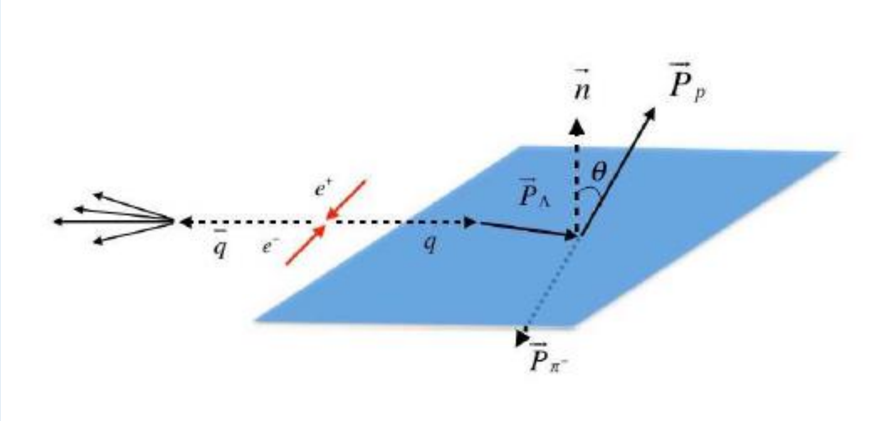
Single Λ polarization measurements

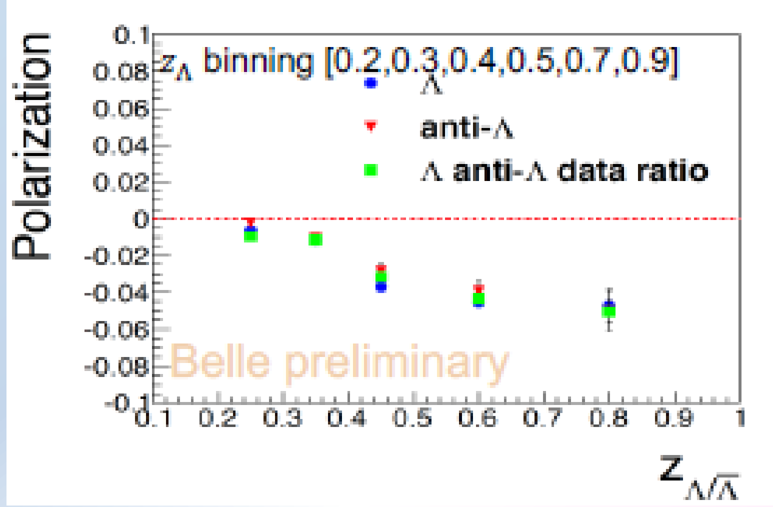
YingHui Guan (Indiana/KEK):
arXiv:1611.06648

- 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





Spin transfer D_{TT}

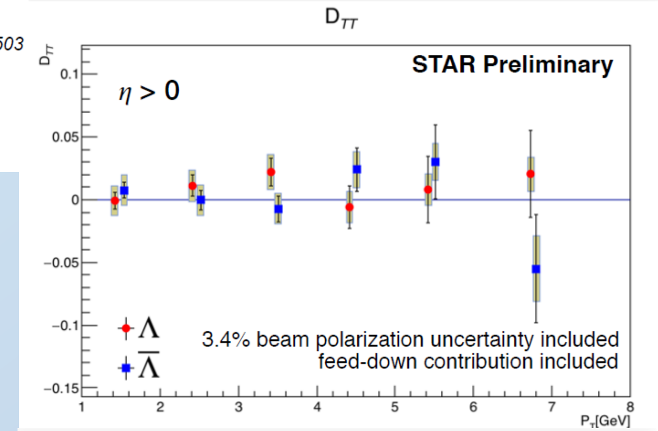
Jincheng Mei (STAR) at DIS 2017

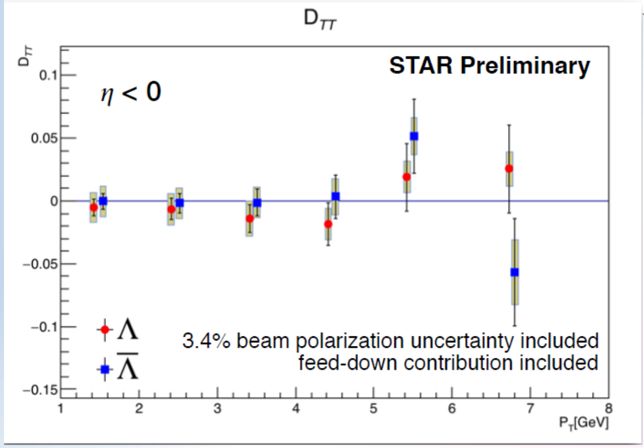
$$d\Delta_T\sigma^{(p_\perp p\to H_\perp X)} \propto \sum_{abcd}\int dx_a\, dx_b\, dz\, \delta f_a(x_a) f_b(x_b)\, d\Delta_T\sigma^{(a_\perp b\to c_\perp d)}\Delta_T D_c^H(z)$$

Xu, Liang, Sichtermann. Phys.Rev. D73 (2006) 077503

- transversity distribution ($\delta f_a(x_a)$)
- pQCD calculation ($d\Delta_T\sigma^{(a_\perp b\to c_\perp d)}$)
- transversely polarized fragmentation function ($\Delta_T D_c^H(z)$)

- Potentially access to transversity via polarized fragmentation function H_1
- Spin transfer is the single spin asymmetry
- At present consistent with zero

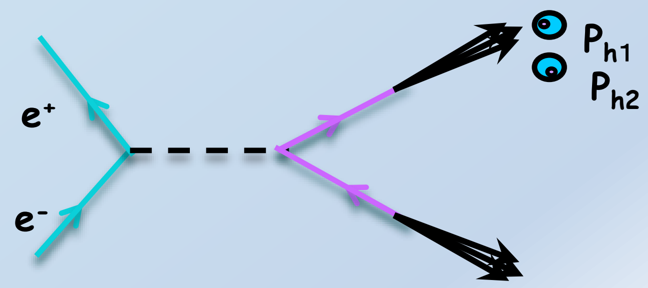




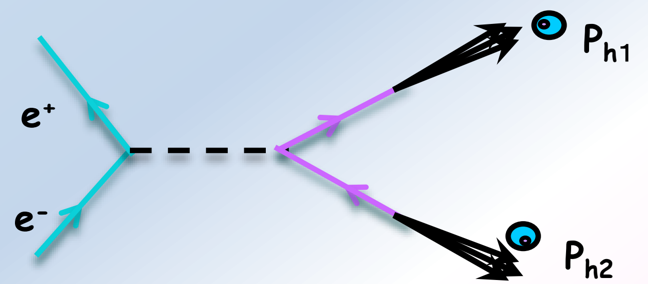
Di-hadron fragmentation functions

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

$$H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$$



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



Di-hadrons

In e^+e^- annihilation:

$$Q = \sqrt{s}$$
$$z = \frac{2E_h}{Q} \approx \frac{E_h}{E_q}$$

- Single inclusive hadron multiplicities (e+e-→hX) sum over all available flavors and quarks and antiquarks:

$$d\sigma(e^+e^- \to hX)/dz \propto \sum_q e_q^2 (D_{1,q}^h(z,Q^2) + D_{1,\bar{q}}^h(z,Q^2))$$

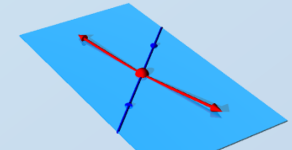
- Especially distinction between favored (ie u→π^+) and disfavored ($\bar{u}$ →π^+) fragmentation would be important
- Idea: Use di-hadron fragmentation, preferably from opposite hemispheres and access favored and disfavored combinations:

$$u\bar{u} \to \pi^+\pi^- X \quad \propto \quad D_{u,fav}^{\pi^+}(z_1,Q^2) \cdot D_{\bar{u},fav}^{\pi^-}(z_2,Q^2) + D_{\bar{u},dis}^{\pi^+}(z_1,Q^2) \cdot D_{u,dis}^{\pi^-}(z_2,Q^2)$$
$$u\bar{u} \to \pi^+\pi^+ X \quad \propto \quad D_{u,fav}^{\pi^+}(z_1,Q^2) \cdot D_{\bar{u},dis}^{\pi^+}(z_2,Q^2) + D_{\bar{u},dis}^{\pi^+}(z_1,Q^2) \cdot D_{u,fav}^{\pi^+}(z_2,Q^2)$$

- Also: unpol baseline for interference fragmentation

Ratios to opposite charge pion pairs

$$R \approx \frac{D_{dis}(z_1)D_{fav}(z_2) + D_{fav}(z_1)D_{dis}(z_2)}{D_{fav}(z_1)D_{fav}(z_2) + D_{dis}(z_1)D_{dis}(z_2)}$$

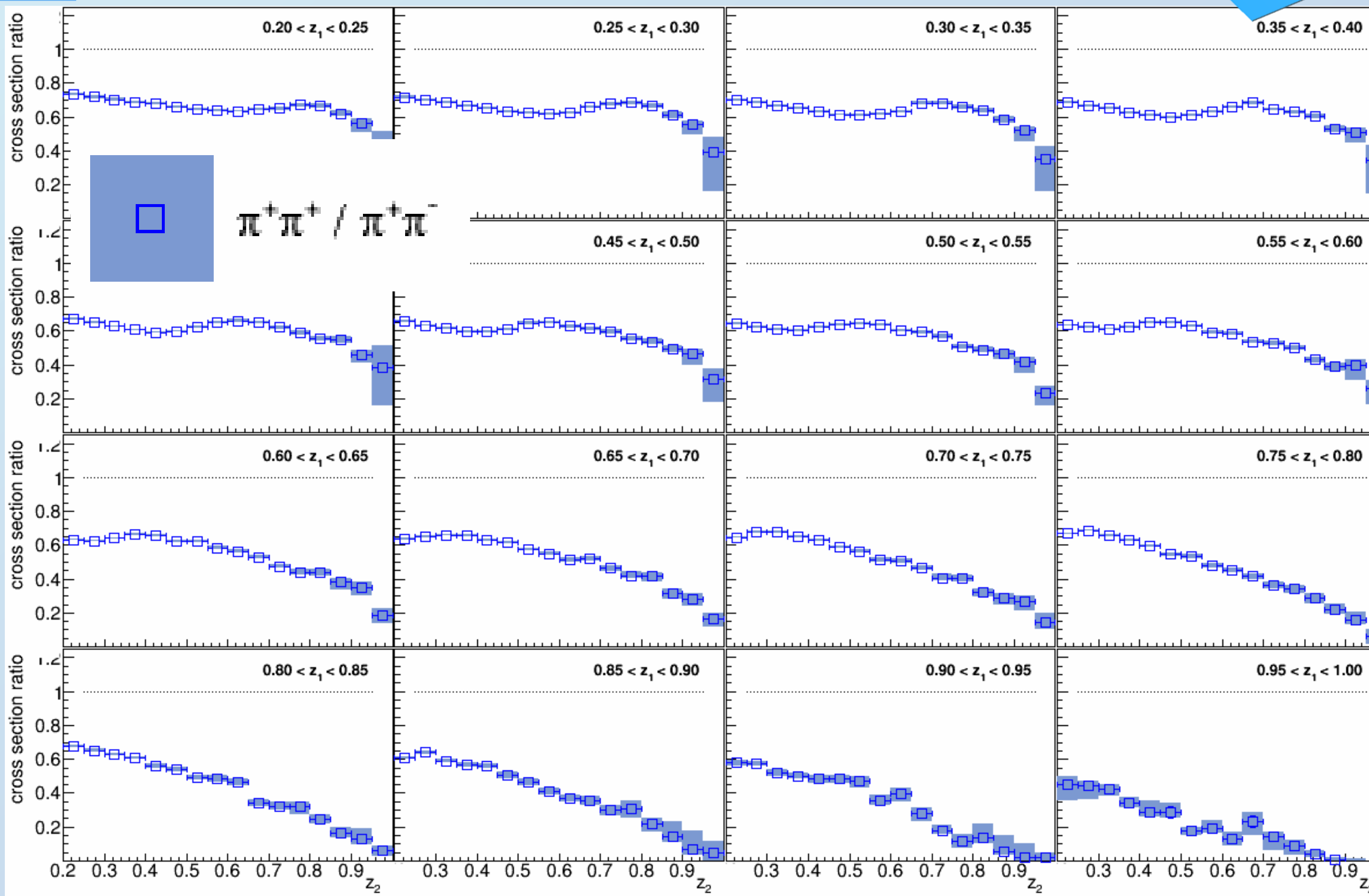


PRD92 (2015) 092007

$\pi^+\pi^+$ comparable to $\pi^+\pi^-$ at low z, decreasing towards high z:

→ Favored and disfavored fragmentation similar at low z

→ Disfavored much smaller at high z



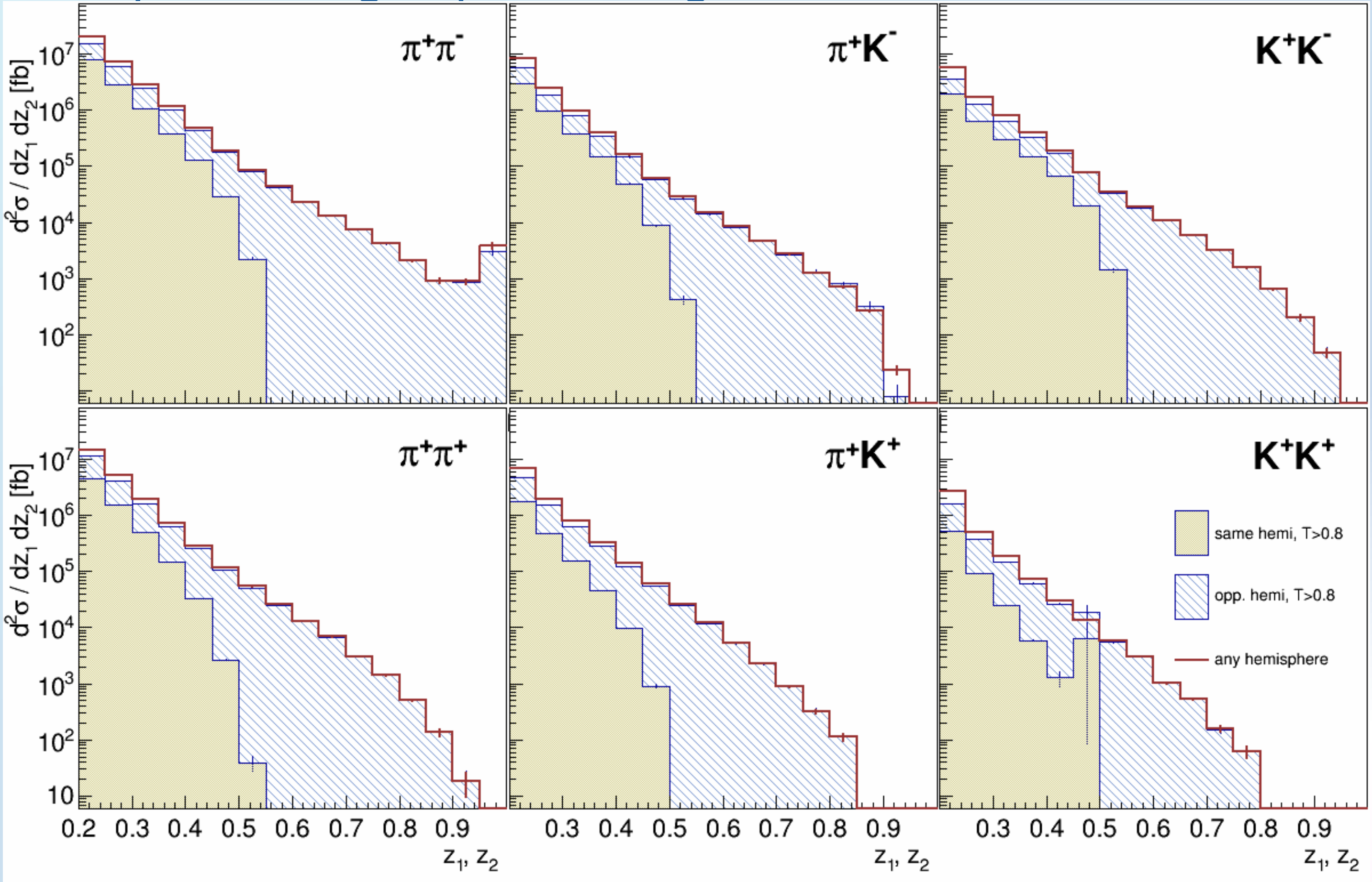
Hemisphere composition

Same hemisphere contribution drops rapidly: Consistent with LO assumption of

Same hemisphere: single quark → di-hadron FF: (z_1+z_2 <1)

Opposite hemisphere: single quark→single hadron FF

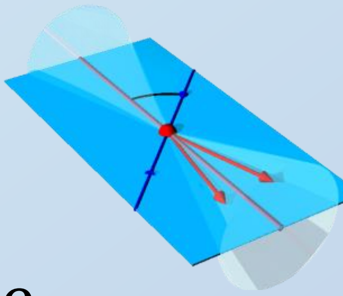
Diagonal z_1,z_2 bins



Belle: RS et.al., PRD92 (2015) 092007

Systematic uncertainties not displayed

Explicit di-hadron mass dependence



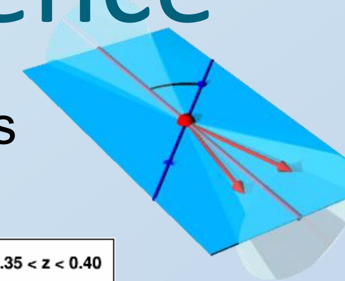
- IFF related asymmetries extracted by Belle in 2011 (PRL107:072004(2011))
- SIDIS (JHEP 0806 (2008),PLB713 (2012)) and RHIC ([PRL 115 (2015) 242501]) IFF asymmetries published
- Global fits currently missing unpolarized di-hadron FF baseline

➔Belle to the rescue

- Use same hemisphere di-hadrons for this analysis
- 16 z bins between 0.2 – 1
- 100 mass bins between 0.3 – 2.3 GeV

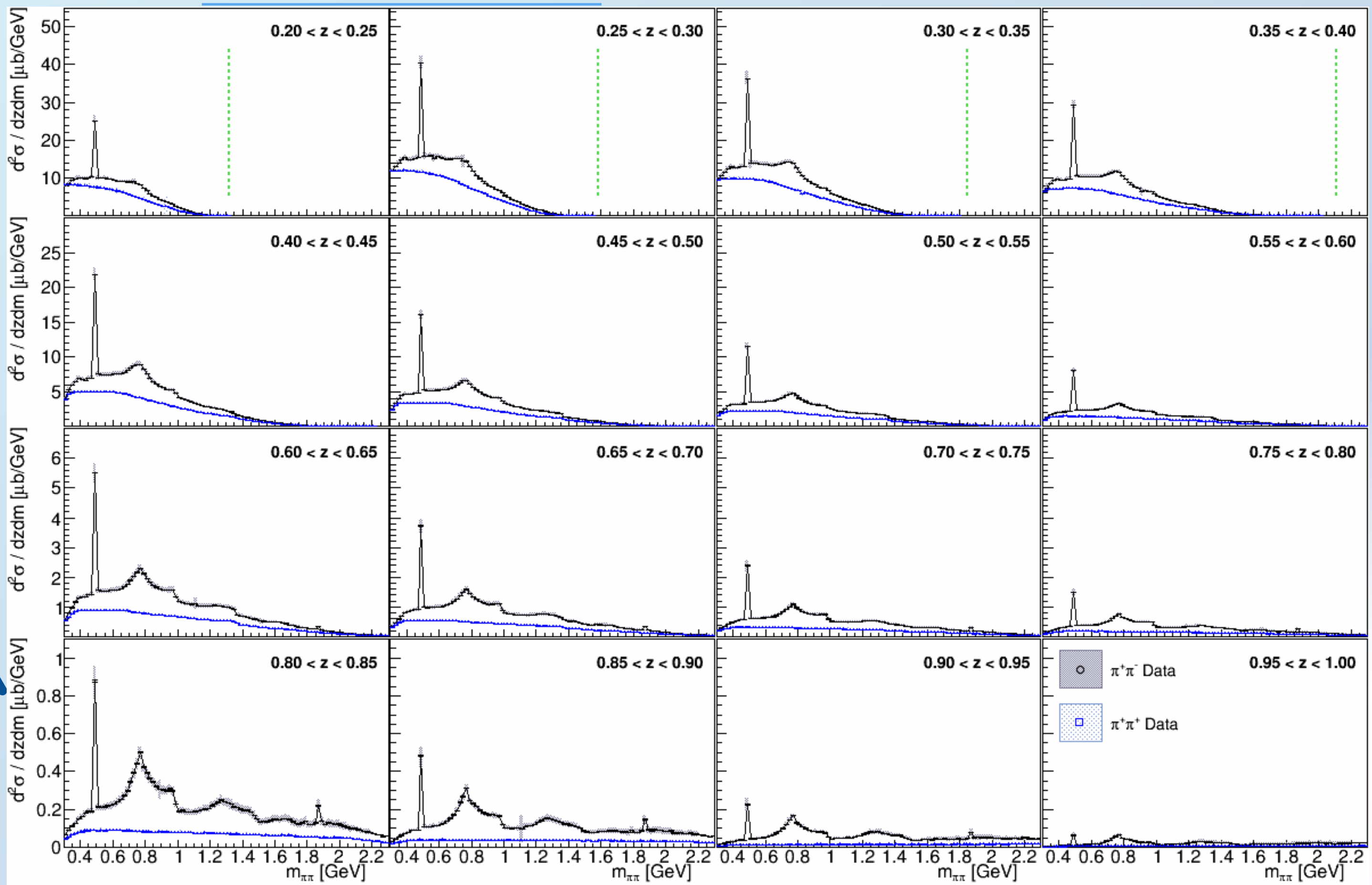
Di-hadron mass dependence

Similar analysis in same hemisphere and mass – combined z binning. Important input for IFF based transversity global analysis



Belle: RS et.al. arXiv:1706.08348

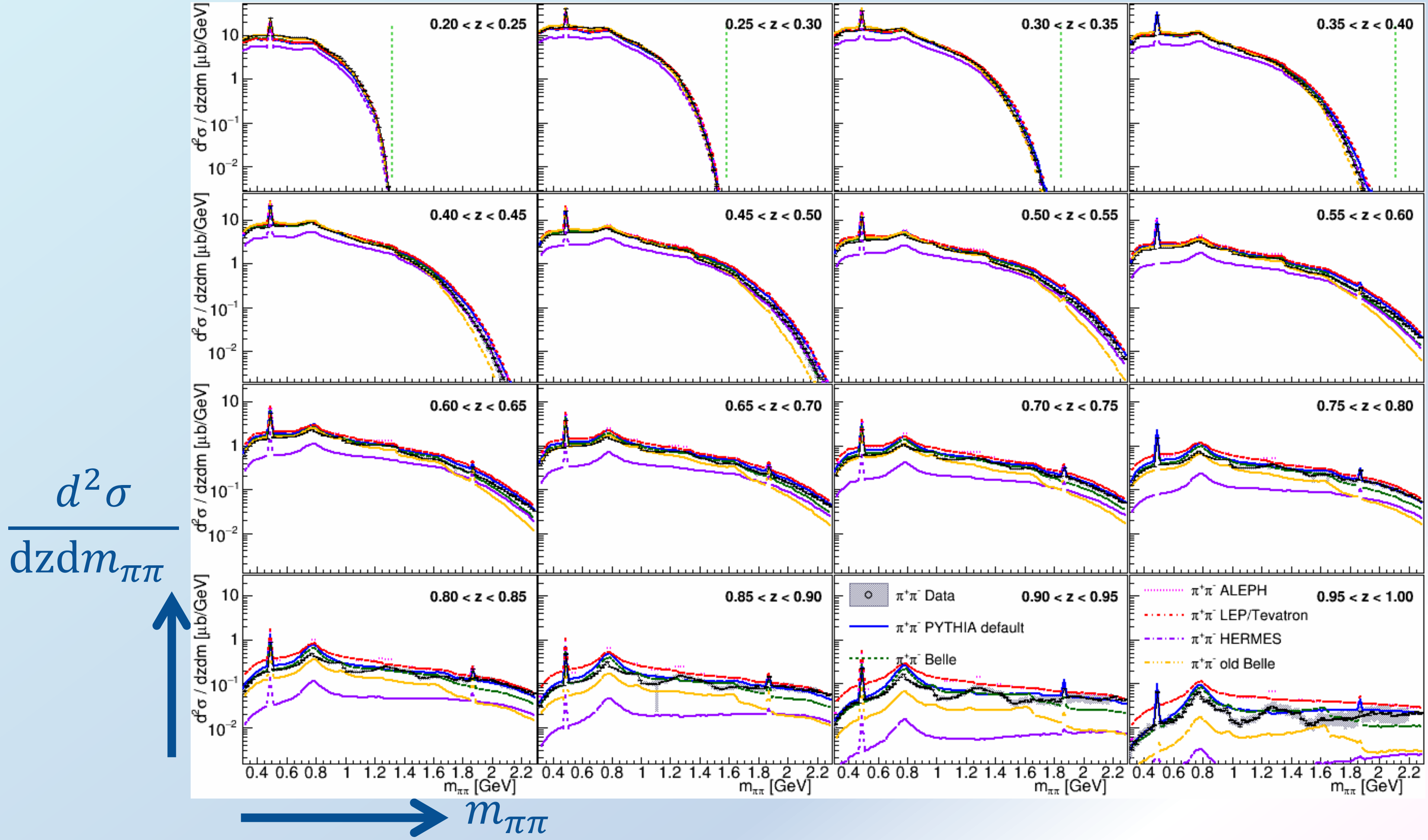
$$\frac{d^2\sigma}{\mathrm{dzd}m_{\pi\pi}}$$



$m_{\pi\pi}$

Mass dependence comparisons to Pythia tunes

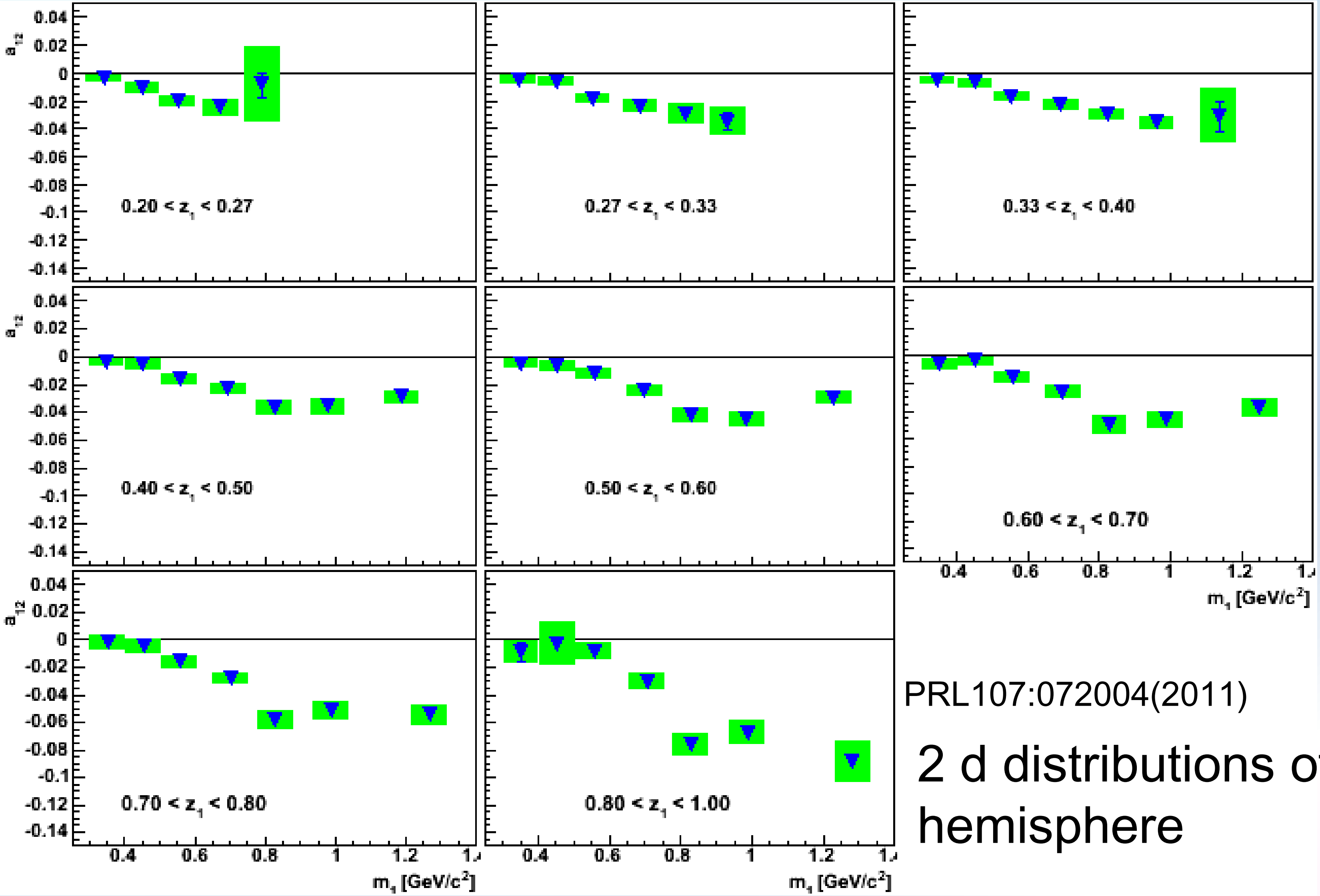
Magnitude and z dependence reasonable in Pythia 6.4 default,
Intermediate mass structure better described by LEP tunes (higher spin mesons)



Spin dependent di-hadron fragmentation

$$H_{1,q}^{h_1,h_2,\sphericalangle}(z,Q^2,M_h)$$

Belle IFF asymmetries: (z_1x m_1) Binning

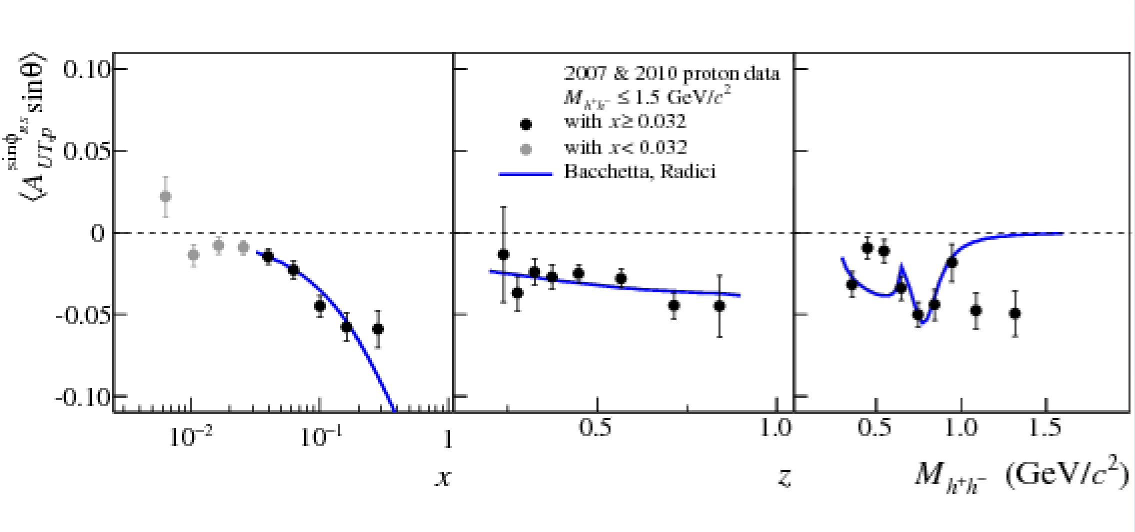


PRL107:072004(2011)

2 d distributions of one hemisphere

First transversity extraction from HERMES, COMPASS and Belle IFF data

Using Belle IFF and HERMES or COMPASS to extract transversity compared to Collins FF based global analysis:



Courtoy, Bacchetta, Radici:
Phys.Rev.Lett. 107 (2011) 012001 and arXiv:1206.1836,
latest update JHEP 1505 (2015) 123
HERMES: JHEP 0806 (2008)
COMPASS: PLB713 (2012), PLB736 (2014) 124

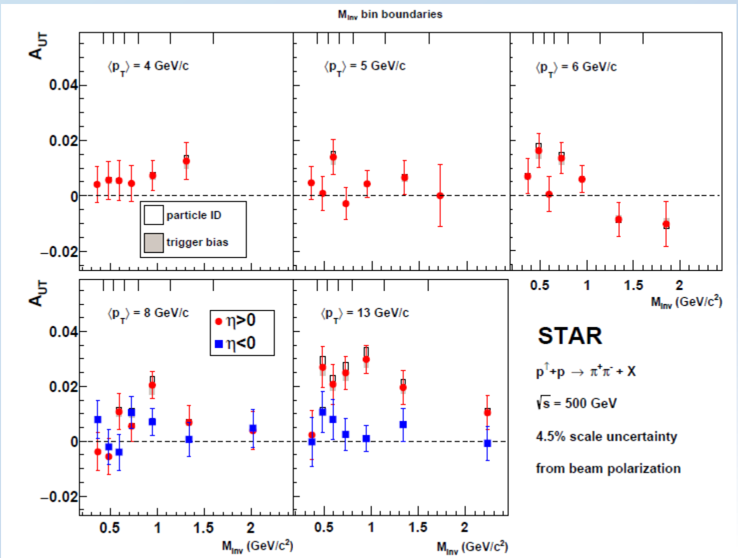
- recent IFF analysis and Collins Transversity comparable

→CollinsFF evolution weak?

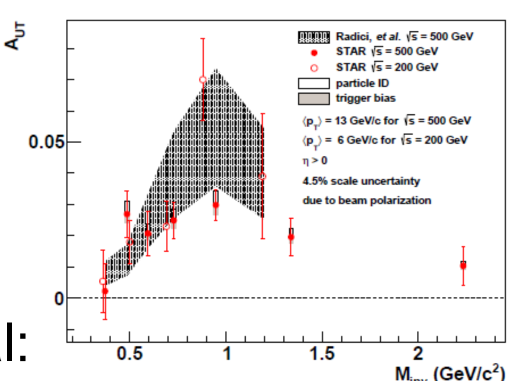
- But many assumptions at this point on unpol DiFFs

STAR IFF results

STAR 510 GeV:
http://arxiv.org/abs/arXiv:1710.10215
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



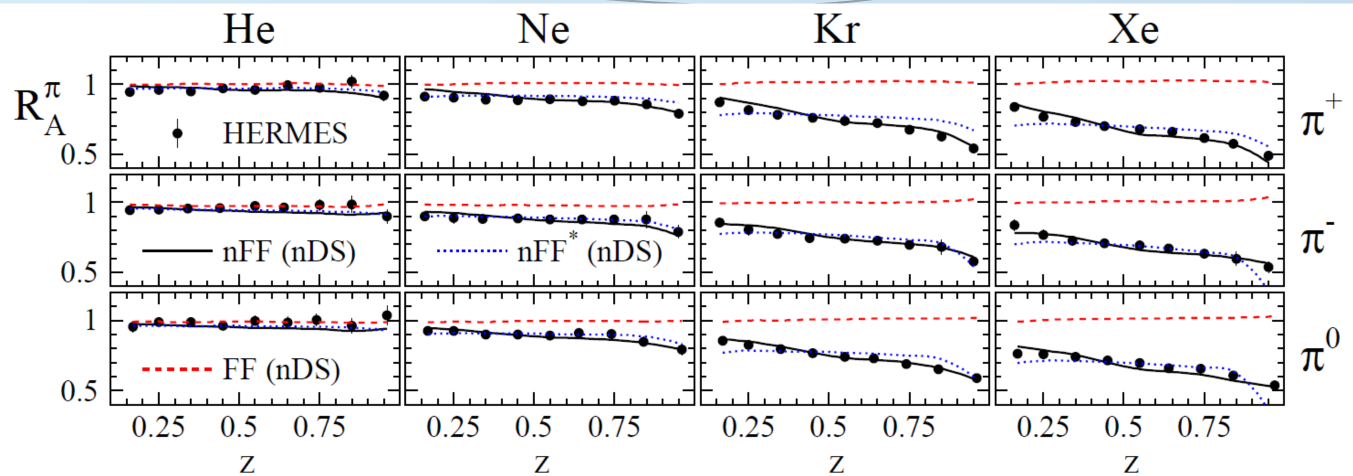
Radici et al:
http://arxiv.org/abs/arXiv:1802.05212

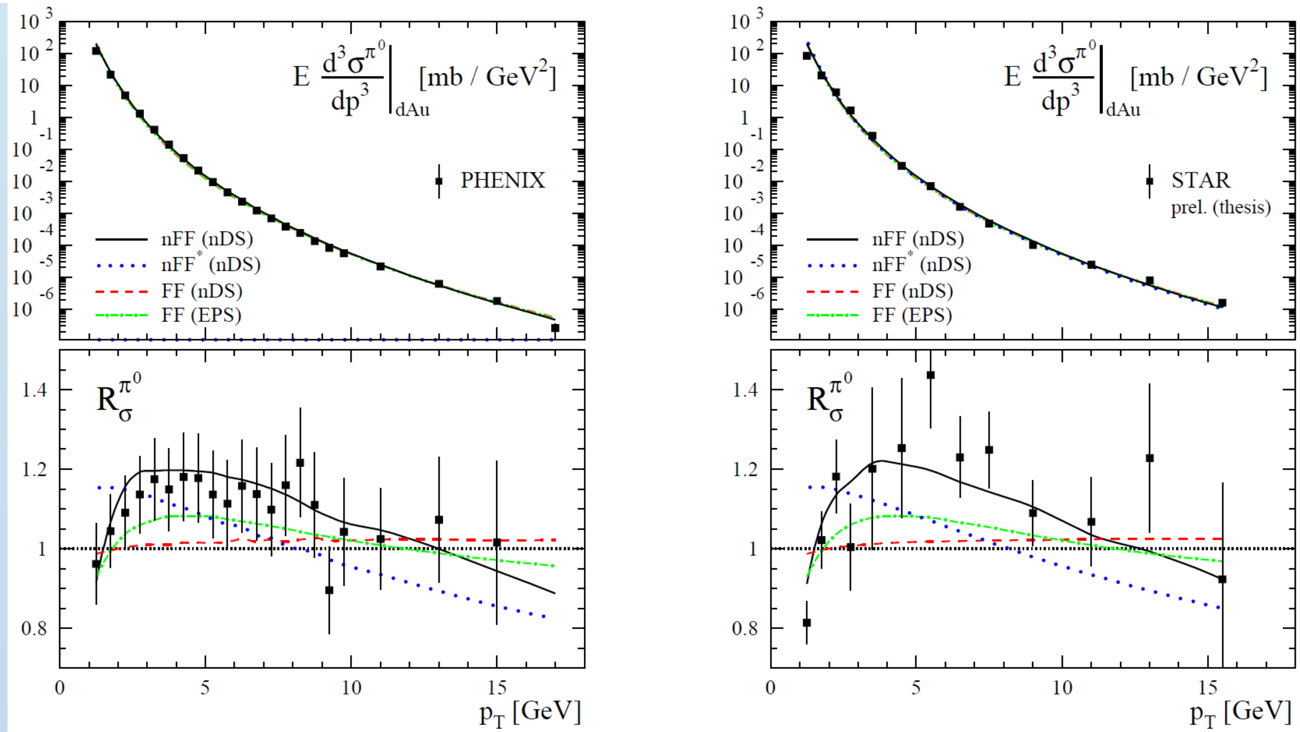
Nuclear FFs

$$D^{h}_{1,q/A}(z,Q^2)$$

nFFs

- Some difficulty disentangling nPDFs and nFFs
- Limited amount of data so far
- More to come form RHIC pA and LHC pPb





Summary and outlook

- Several finalized single hadron FF related measurements became available in the past several years form SIDIS,e+e-, RHIC and LHC
- Kt dpendent FFs (pol/unpol) so far only available from SIDIS, soon to get e+e- data as well
- Nonzero Lambda polarization!
- Also several other baryon/hyperon/charmed baryon cross sections available now
- STAR Collins and IFF results mostly finalized for older data, more to come