TMD Fragmentation Functions

CPHI 2022
March 9, 2022

Ralf Seidl (RIKEN)

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

BELLE

Dihadron FF (IFF)

Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \to (hh)X$ $D^{h_1h_2}_{1,q}(z,m,Q^2)$ 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 FF

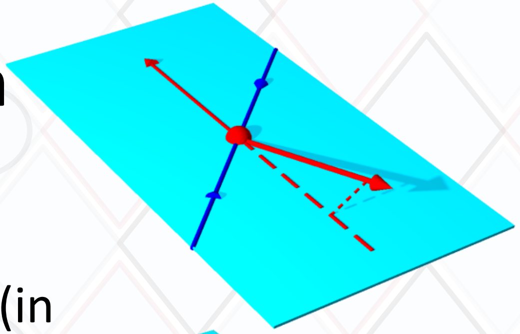
Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D_{1,q}^{h}(z, Q^2)$ PRD 88 (2013) 032011 (Babar)	Azimuthal asymmetries: $e^+e^- \to (h)(h)X,$ $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ PRD 92 (2015) 111101 (Babar K) PRL 116 (2016) 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 FF (IFF)

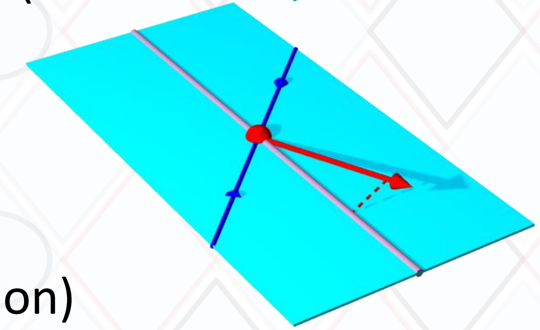
Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Dihadron cross sections $e^+e^- \to (hh)X$ $D_{1,q}^{h_1 h_2}(z, m, Q^2)$	Azimuthal asymmetries: $e^+e^- \to (hh)(hh)X,$ $\cos(\phi_1 + \phi_2),$ $H_{1,q}^{h_1,h_2,\sphericalangle}(z, Q^2, M_h)$	Unpol SIDIS, pp: $\frac{d^2\sigma}{dz dm}$

K_T Dependence of FFs in e^+e^-

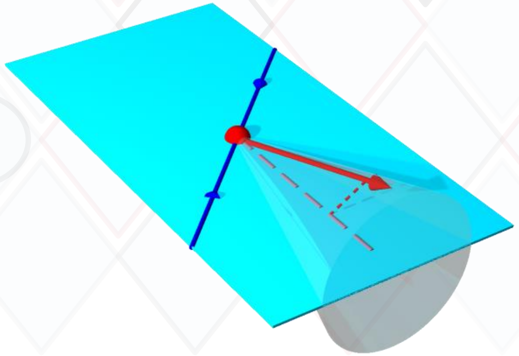
- Gain also sensitivity into transverse momentum generated in fragmentation
- Two ways to obtain transverse momentum dependence
  - Traditional 2-hadron FF
    - →use transverse momentum between two hadrons (in opposite hemispheres)
    - →Usual convolution of two transverse momenta
  - Single-hadron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



Ongoing (nearly finished)

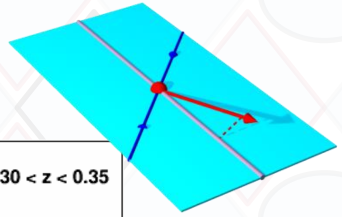


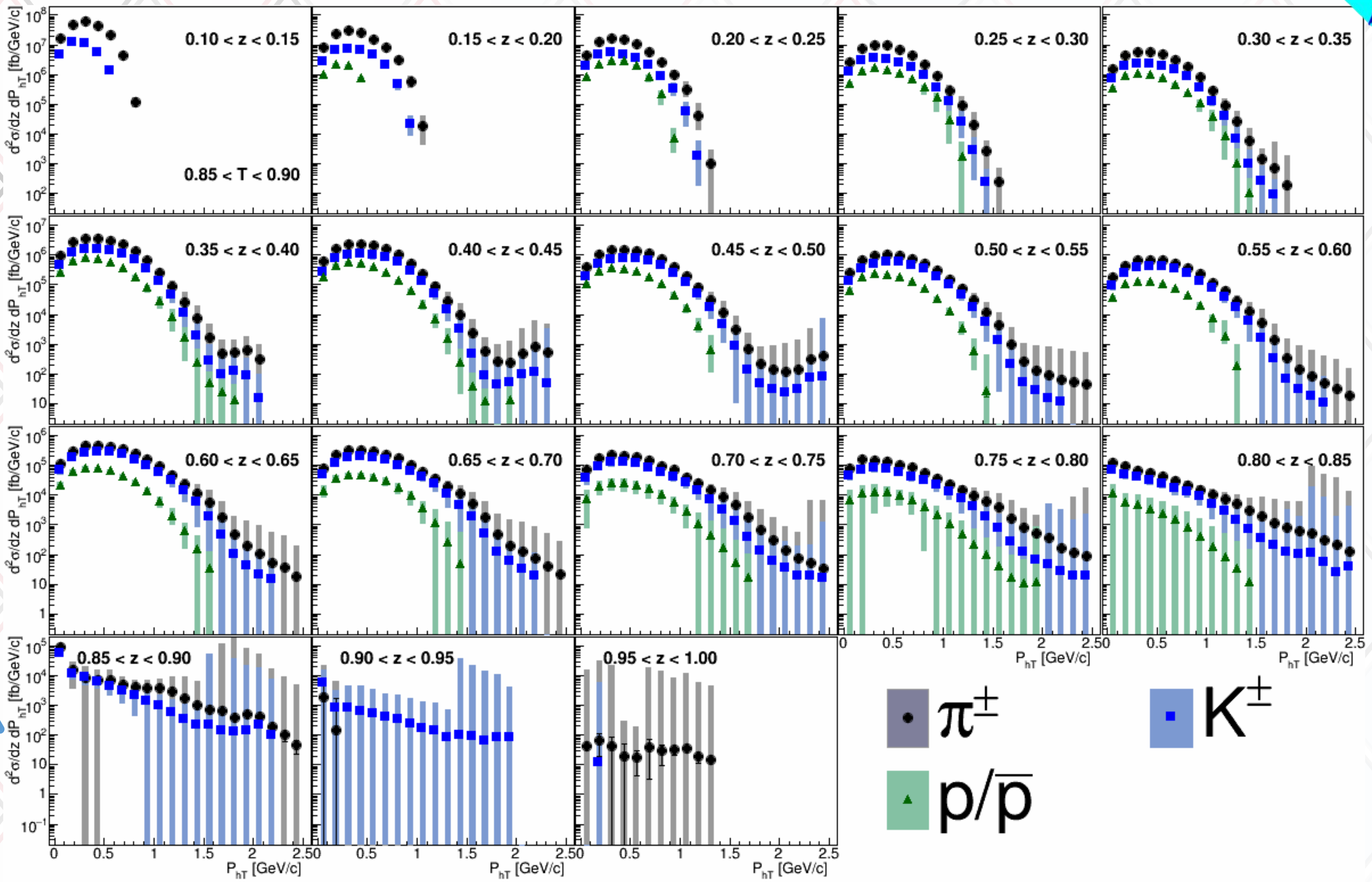
Published



Ongoing (started)

Cross sections various hadrons





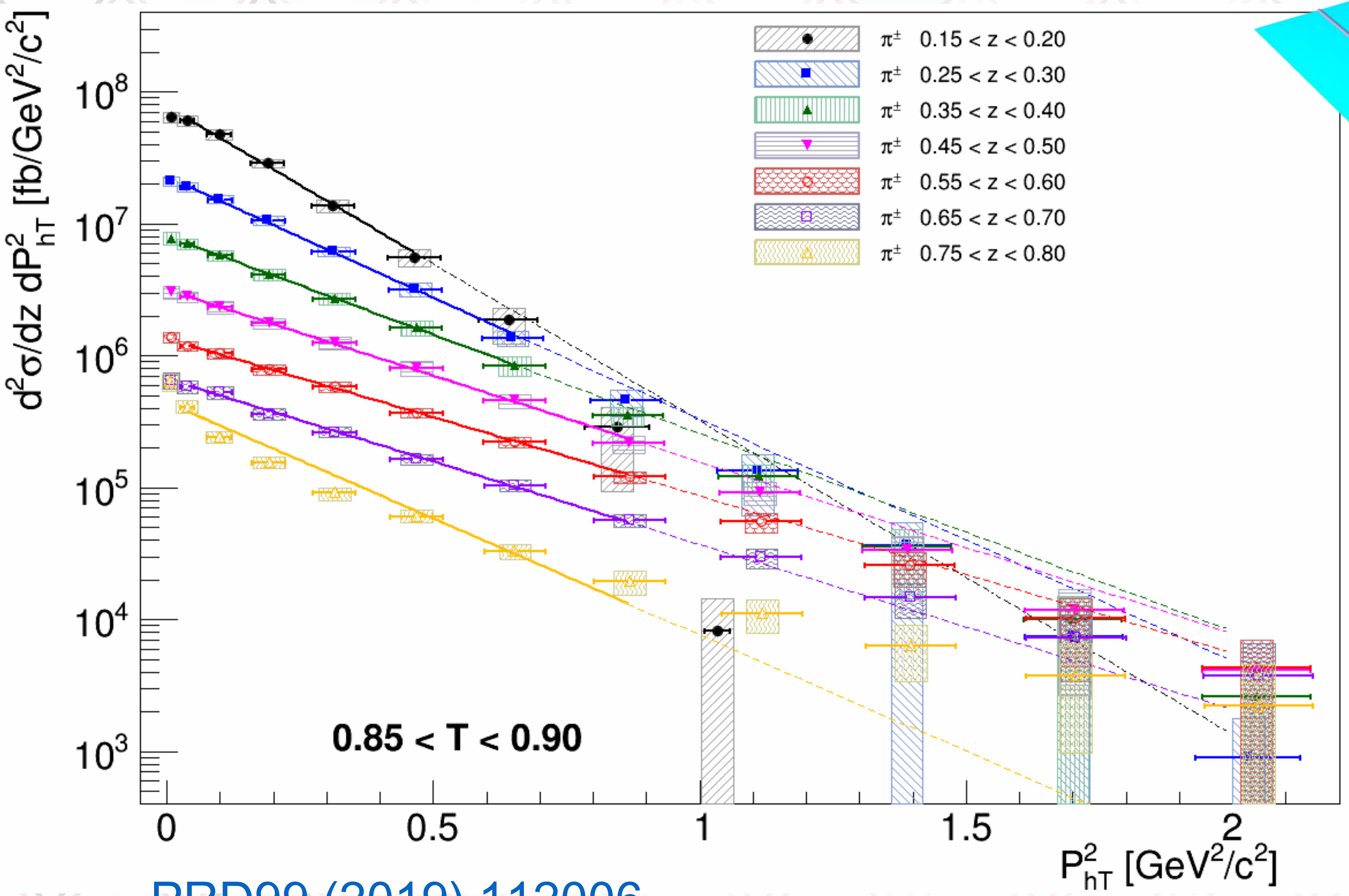
$$\frac{d^2\sigma}{dz dP_{hT}}$$

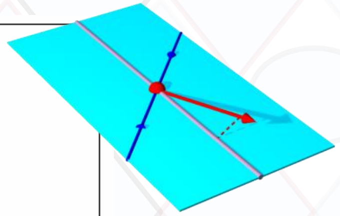
P_{hT}

RS. et. al. 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}

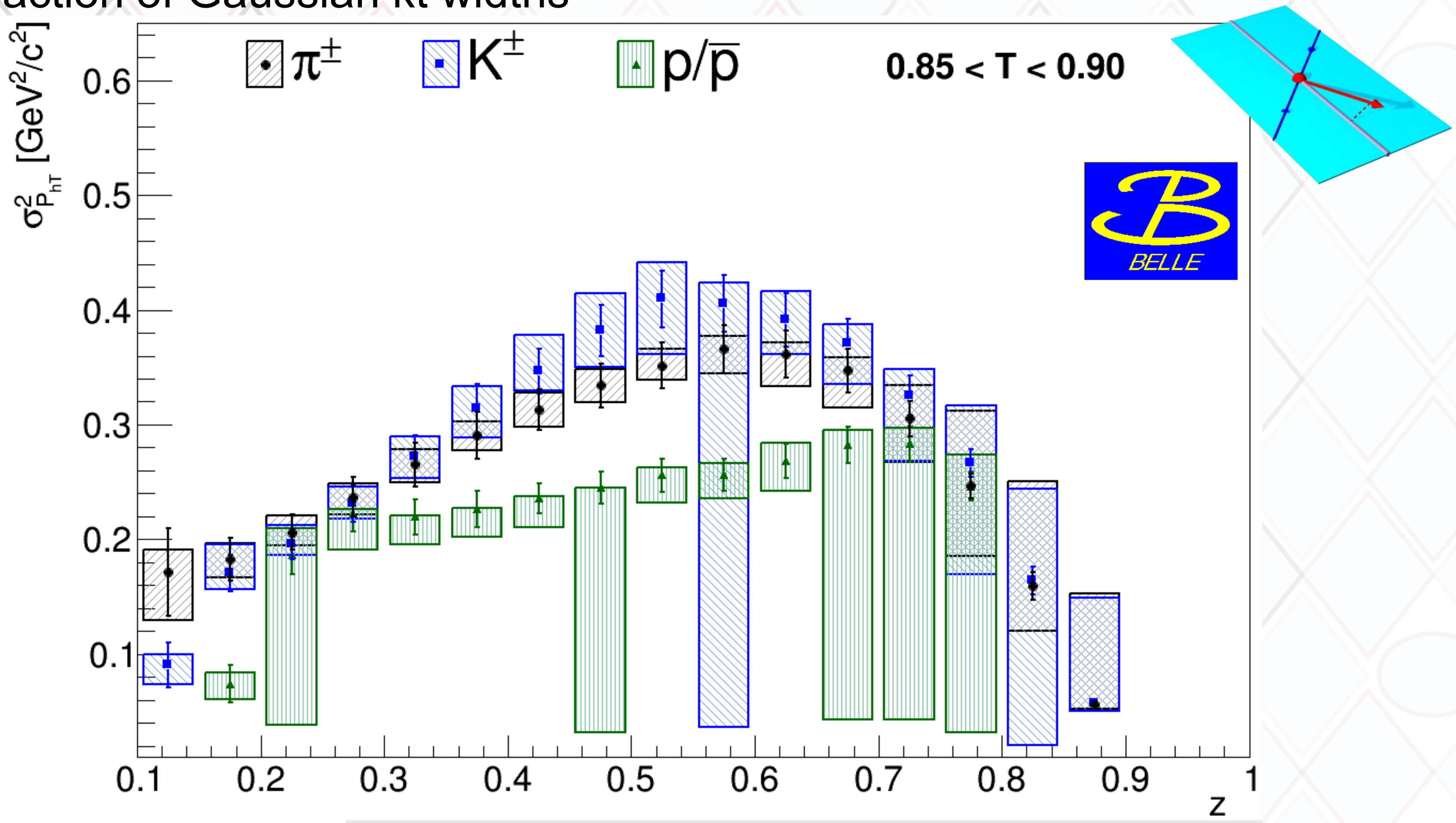




PRD99 (2019) 112006

Transverse momentum dependent unpol FFs:

- First direct (no convolutions) measurement of z and kt dependence
- Extraction of Gaussian kt widths



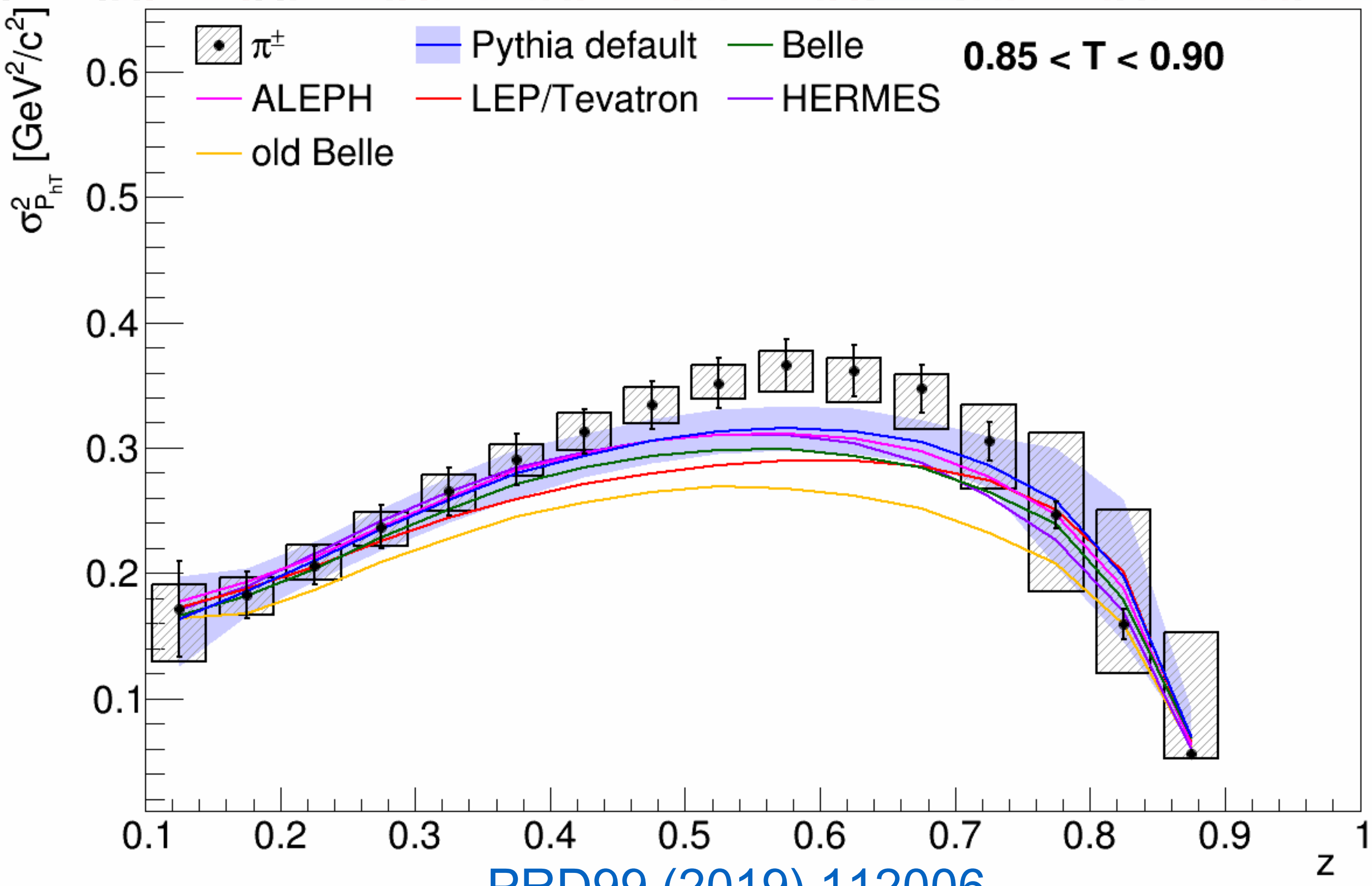
PRD99 (2019) 112006

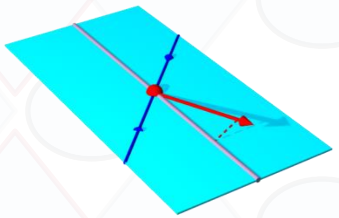
Current phenomenological models: no or linear z dependence only

Gaussian widths comparison to MC

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

Pythia6
MSTP(21):
0.28
0.325
0.36
0.36
0.37
0.40



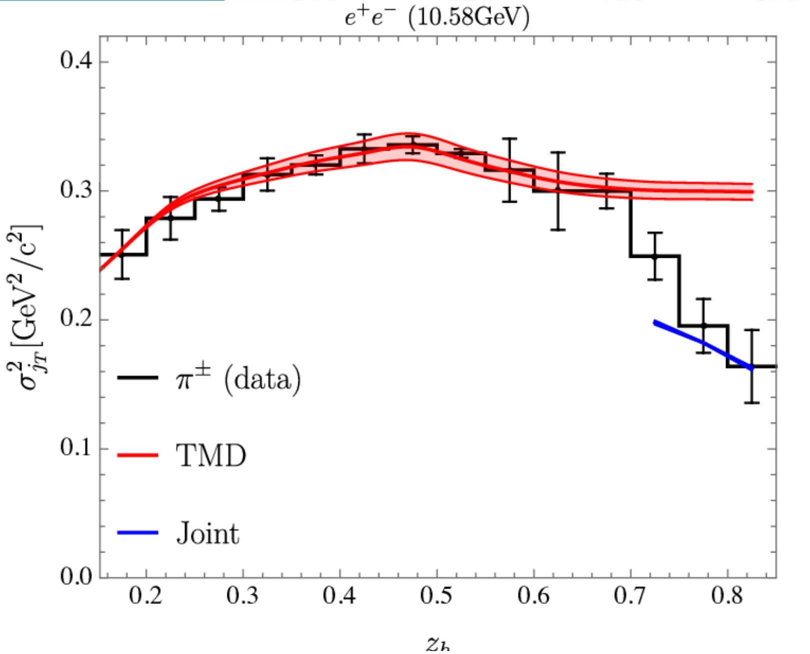


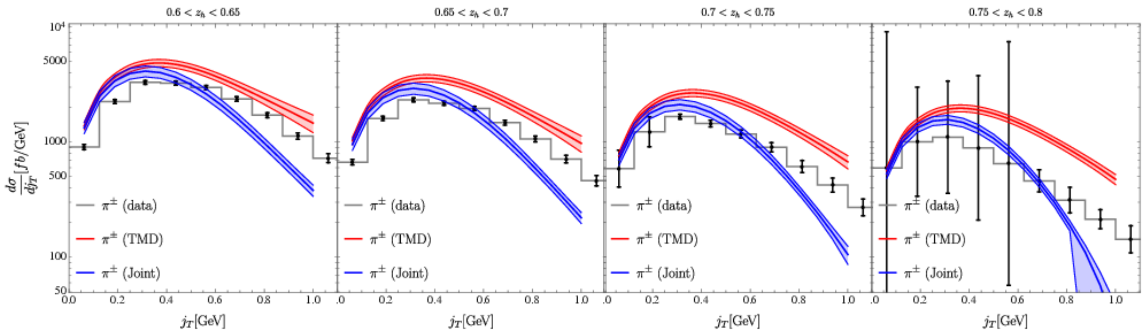
PRD99 (2019) 112006

Phenomenological Fits of cross sections I

[*Kang, et. al. JHEP* 12 (2020) 127](#)

- SCET formalism
- Inclusion of Thrust axis possible in similar way to Jet functions TMD and threshold resummation needed
- TMD region of j_T<<Q
- Additional description for high-z region

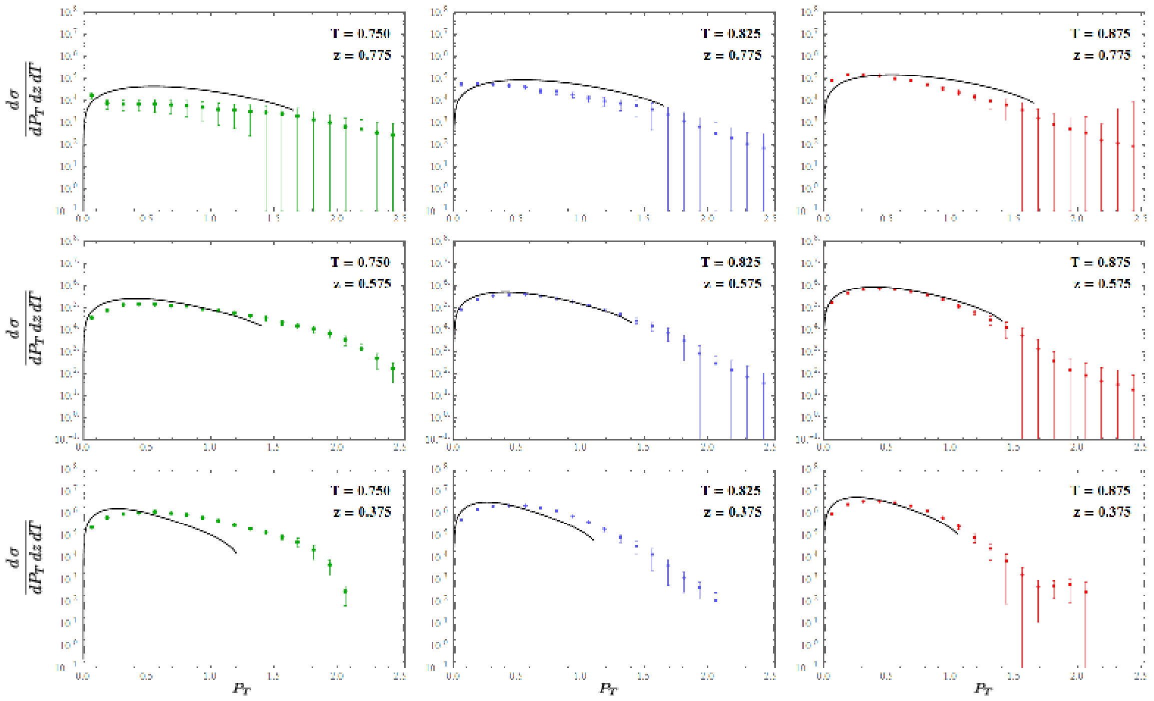




Phenomenological Fits of cross sections II

[Boglione, Simonelli *JHEP* 02 (2021) 076](#)

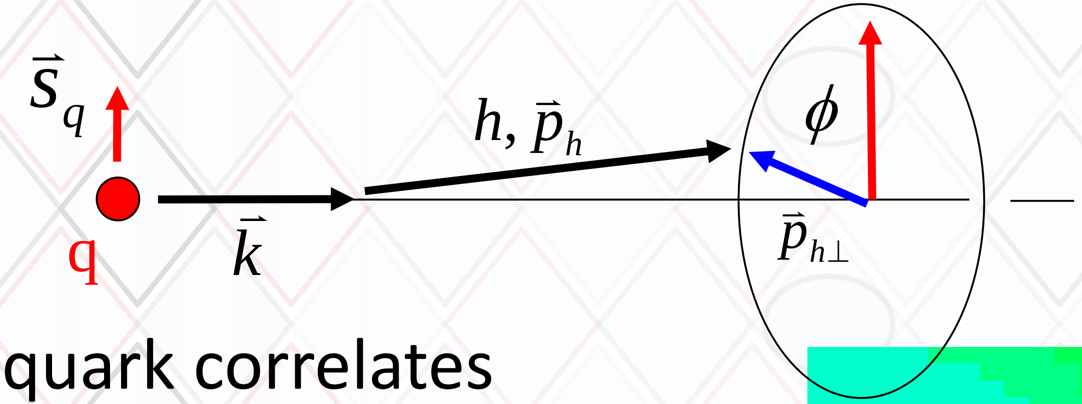
- NLO and NLL description of cross sections, based on NNFF1.0_NLO
- Collinear parts of phase space need to be cut out (esp. high P_T)
- Intermediate Thrust range can be described well
- High thrust and high z range would need different pheno treatment



Collins fragmentation function

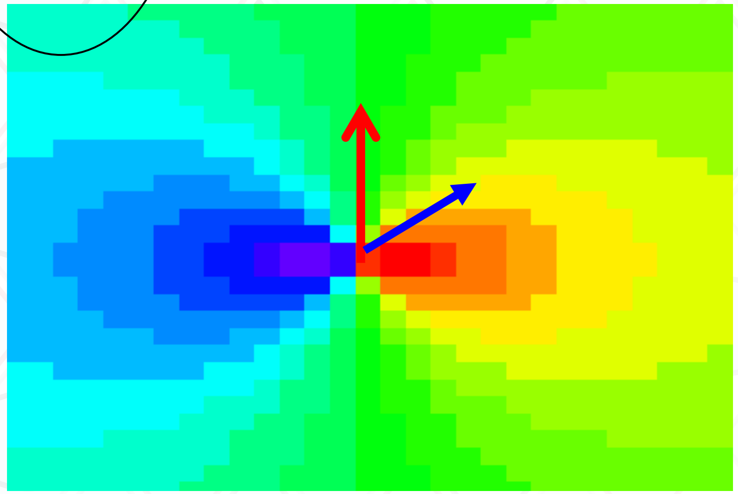
J. Collins, Nucl. Phys. B396, (1993) 161

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



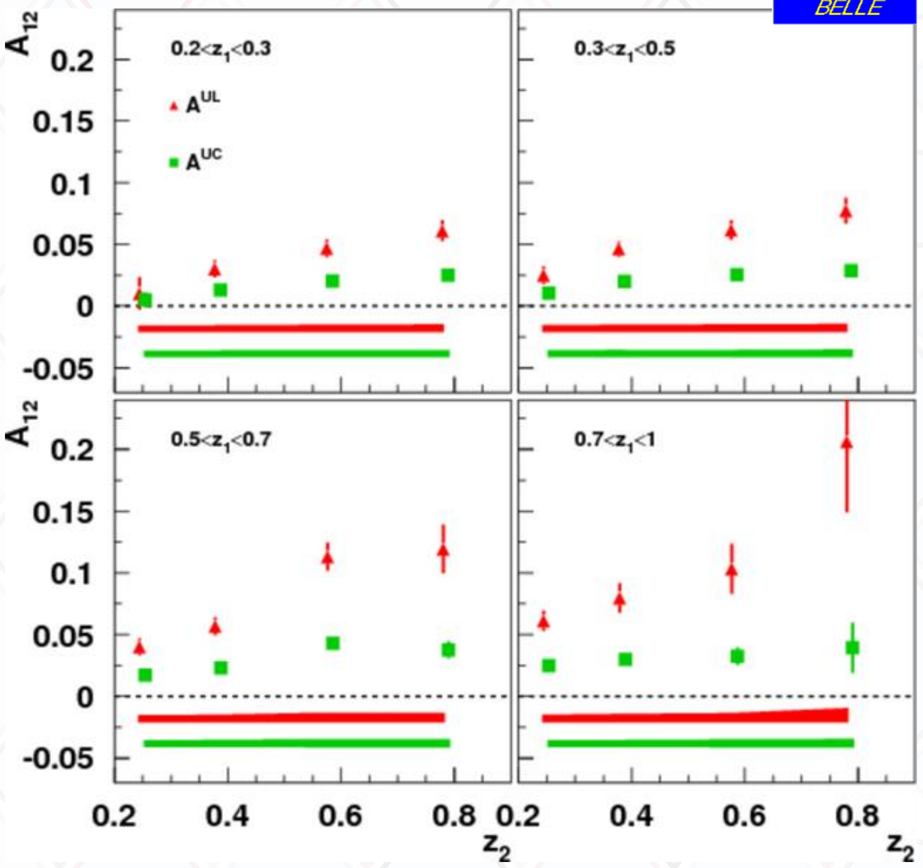
- Spin of quark correlates with hadron transverse momentum

➔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

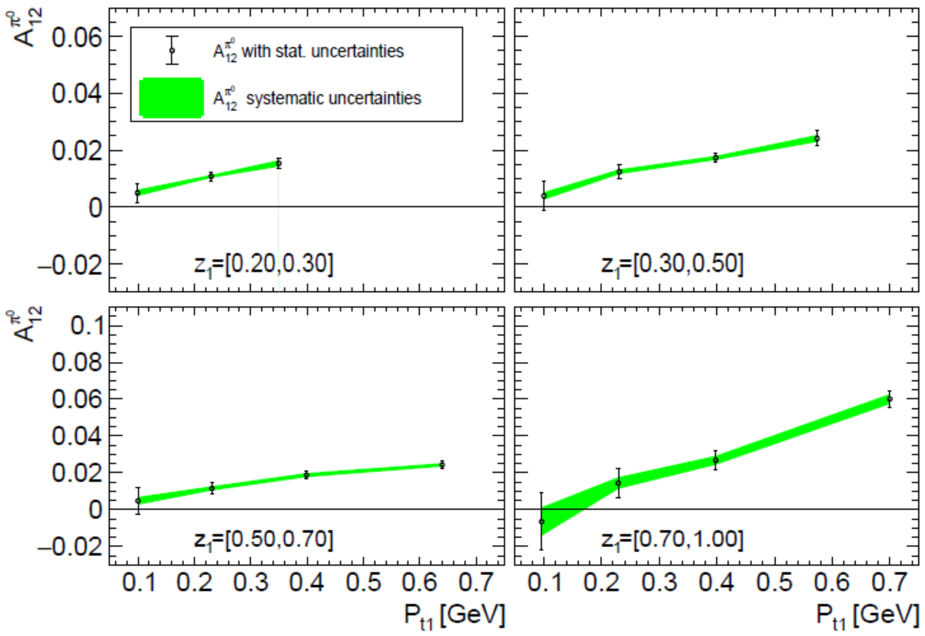


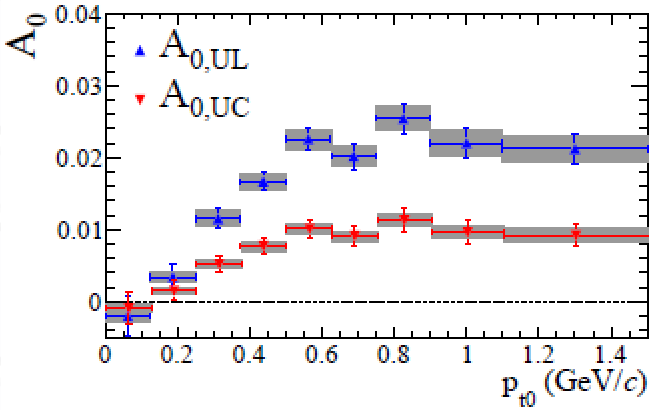
RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Transverse momentum

- Add transverse momentum to Collins asymmetries' z dependence
- Currently only 1 or 2-dimensional extractions available (qt, z1xz$_2$, $p_{t1}xp_{t2}$,z_1xp_{t1})
- Increasing asymmetries with both z and pt, but pt reach limited
- Multidimensional extractions needed

PRD100 (2019) 92008



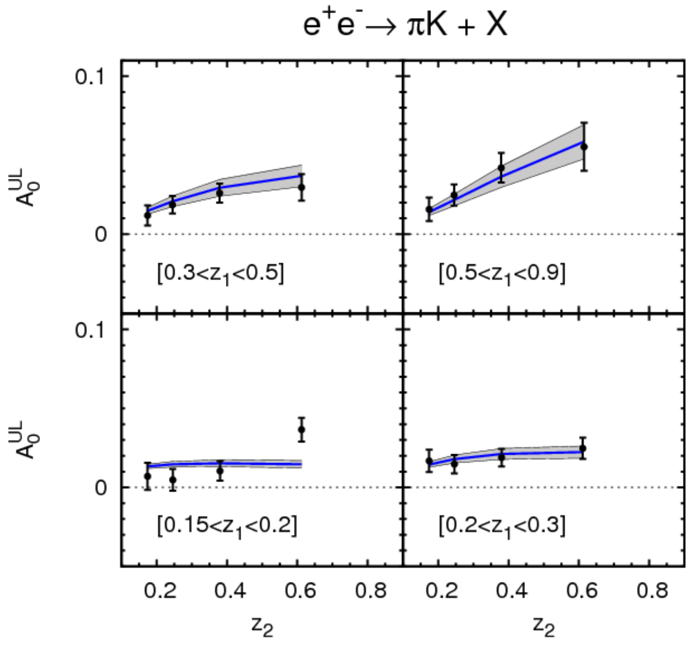


PRD 90 (2014) 052003 (Babar)

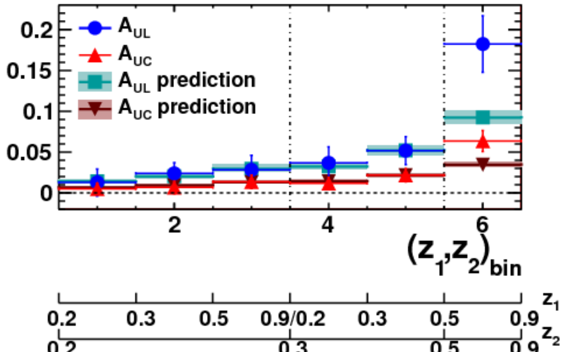
Quark transversity via Collins: Kaons

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

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) x 6 (z_2) x 5(k_{t1}) x 5(k_{t2}) x 1 (costheta) x 8 (phi) for A_{12} method
  - 6 (z_1) x 6 (z_2) x 10(q_t) x 1 (costheta) x 8 (phi) for A_0 method

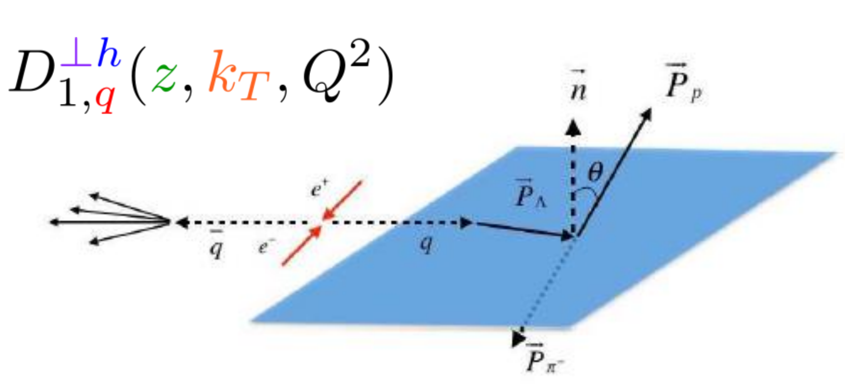
- Perform most correction steps similar to recent analyses (PID, smearing)
  - Possibly simplified smearing unfolding as each z_1-z_2 bin separately (z smearing almost nonexistent in such a binning)
  - non-qqbar removal, charm removal, ISR correction and acceptance might require introduction of nonzero MC asymmetries

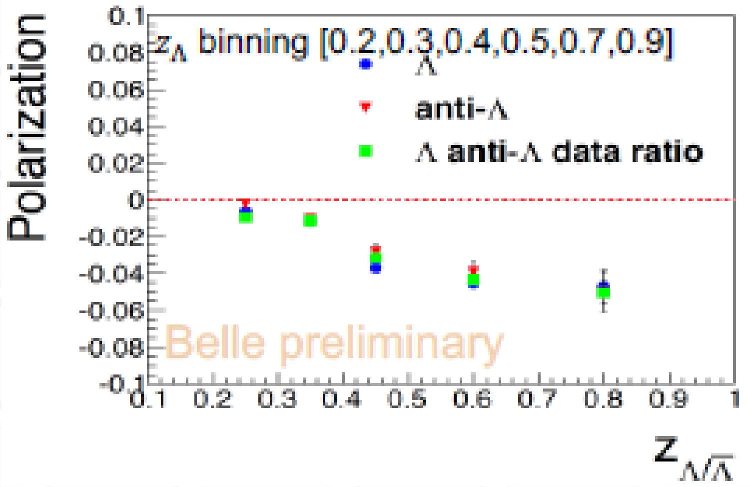
Single Λ polarization measurements

- 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

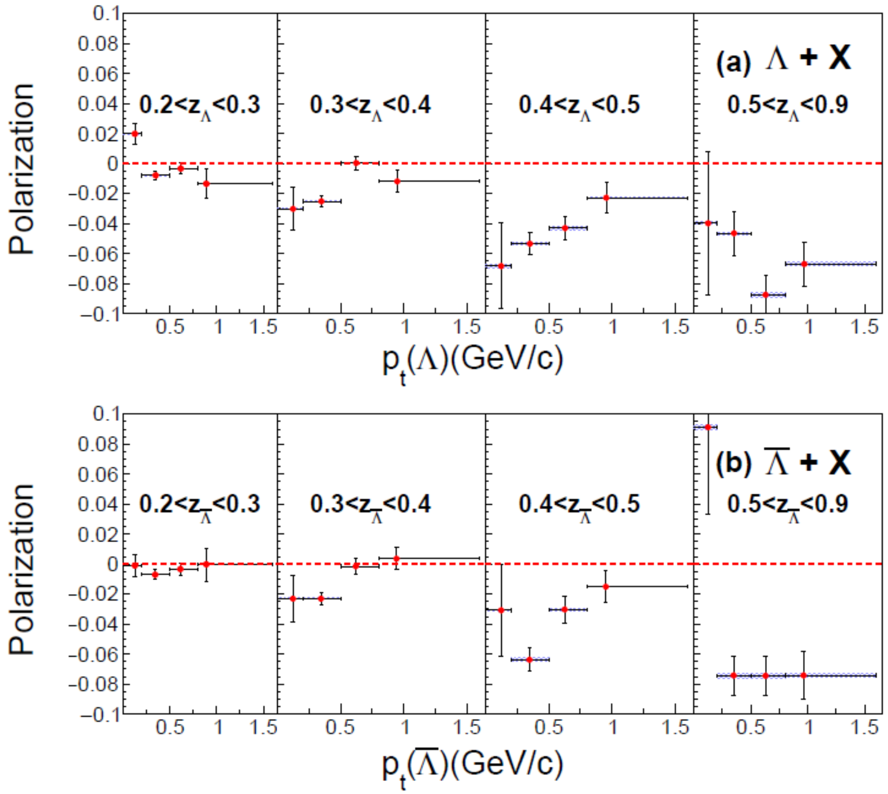
YingHui Guan (Indiana/KEK):
PRL 122 (2019), 042001





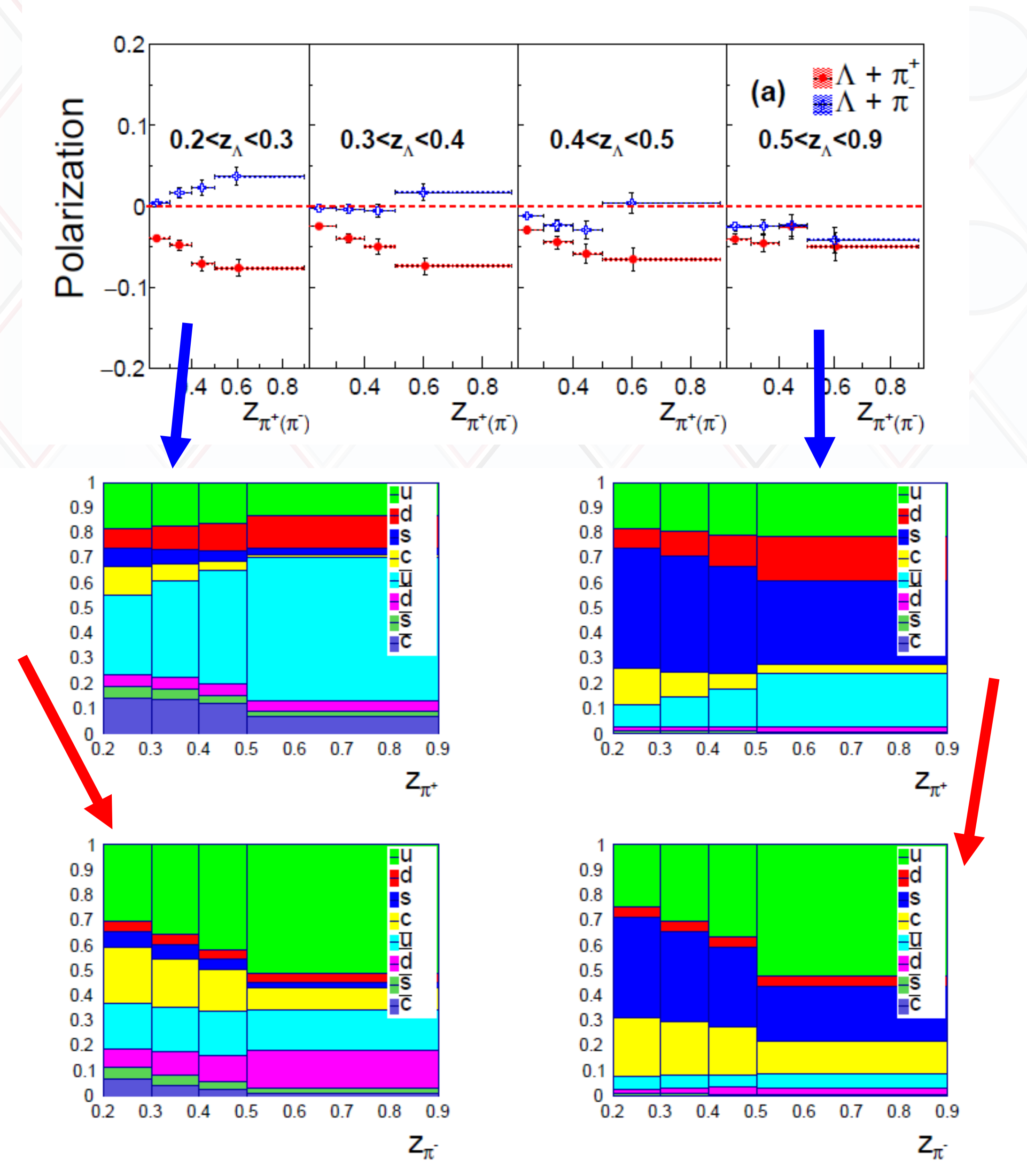
Transverse momentum dependence

- 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

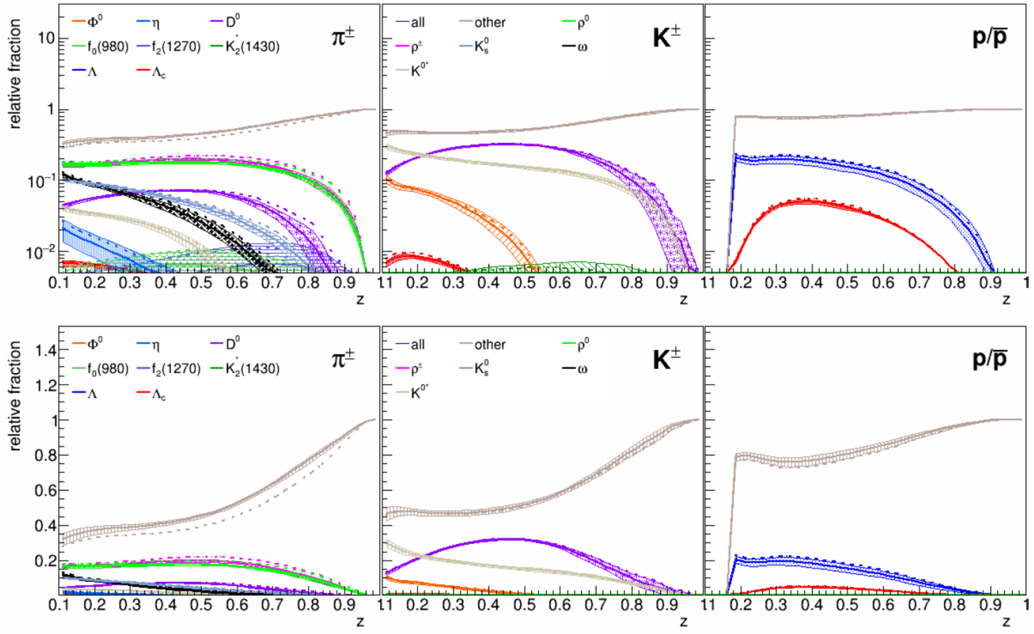
- Interesting z_π and z_Λ dependence :
- At low z_Λ light quark fragmentation dominant, some charm in π^- → different signs
- At high z_Λ strange + charm fragmentation more relevant → same signs
- Several fits to data with slightly different results



Not TMD(yet) but indirectly related: Weak and strong decay feed-down

- Hadrons from Weak decays technically not part of FF definition, but often included
- Strong decays part of total sum over hadronic final state
- Both can affect the z (and transverse momentum) dependence of the detected hadrons:
  - naturally included in unpolarized MC,
  - in part added to polarized generators (→Albi)
  - How does PHENO handle this (additional parameters?)

Decaying hadron fractions in light hadrons at √s = 10.58 GeV (PYTHIA6):

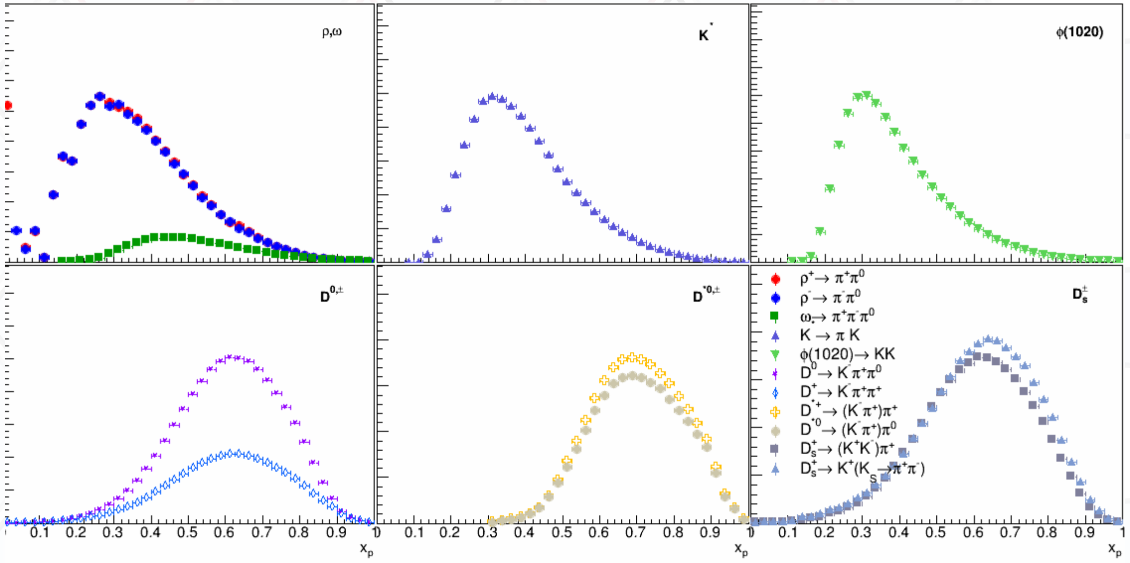


Bands: various Pythia tunes, including PARJ(11) range from 0.3-0.55
Dashed lines: default, but PARJ(11) =0.6

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 (within Barrel acceptance):

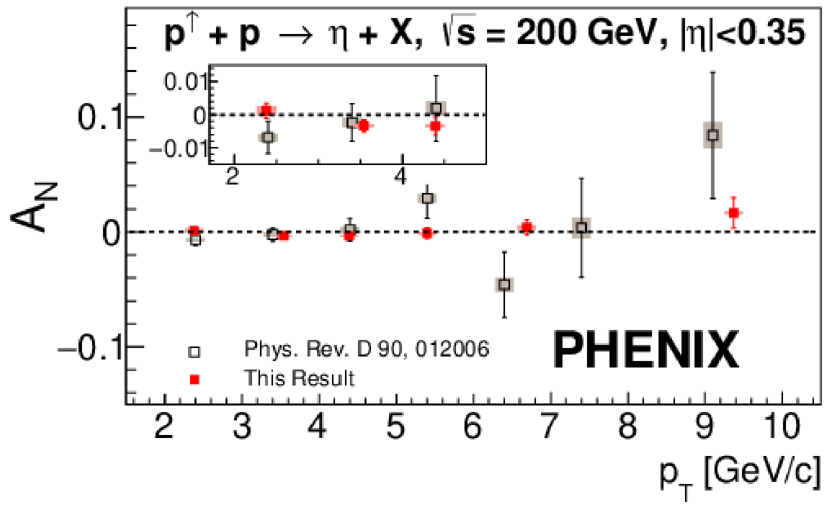


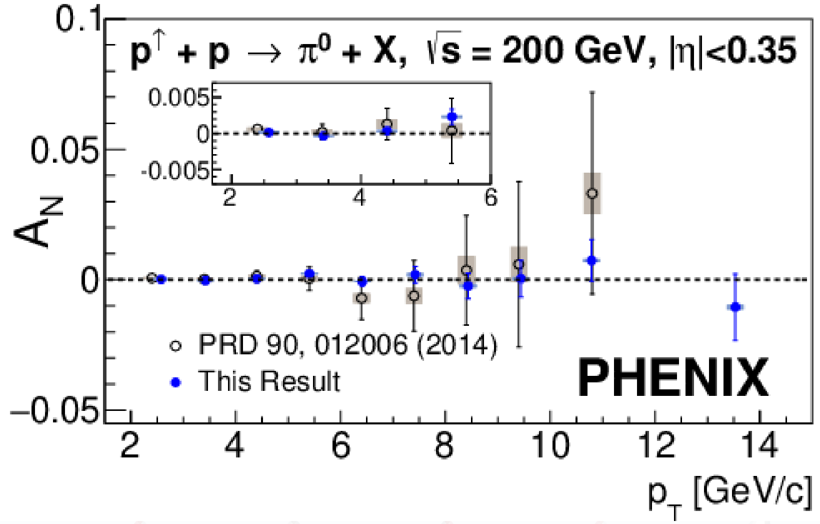
Next/other steps: PHENIX/sPHENIX and EIC

Central rapidity pion and eta A_Ns

PRD 103 (2021) 052009

- Central asymmetries consistent with zero
- sensitive to quark-gluon and tri-gluon correlation functions in initial and final state effects
- Possible reasons for small asymmetries: Cancelations between flavors or initial/final state effects, lower x than forward (valence effects)
- Possible effects pushed below the 1% level
- Substantial updates for π^0 and η single spin asymmetries at central rapidity

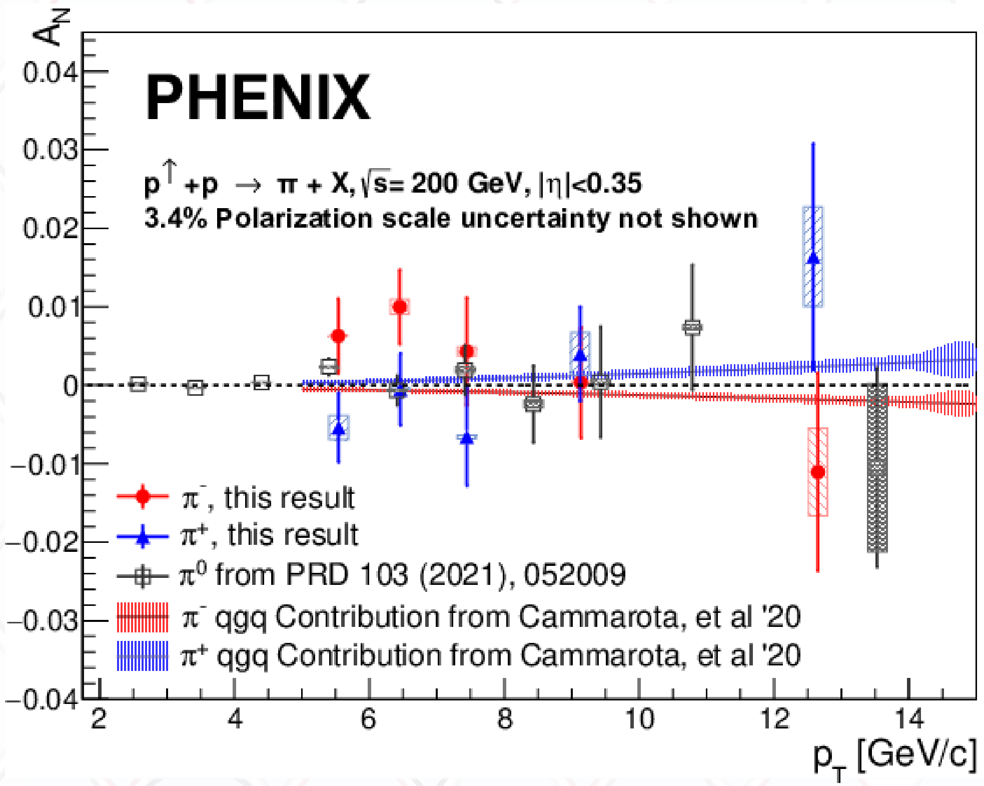




Charged pion A_Ns at mid-rapidity

- Charged pion A_N consistent with zero and π^0 results for each charge
- But indication of differences between charges seen → could be an indication of flavor dependent effect in initial (up vs down quarks) or final state ($u \rightarrow \pi^+$ vs $u \rightarrow \pi^-$)

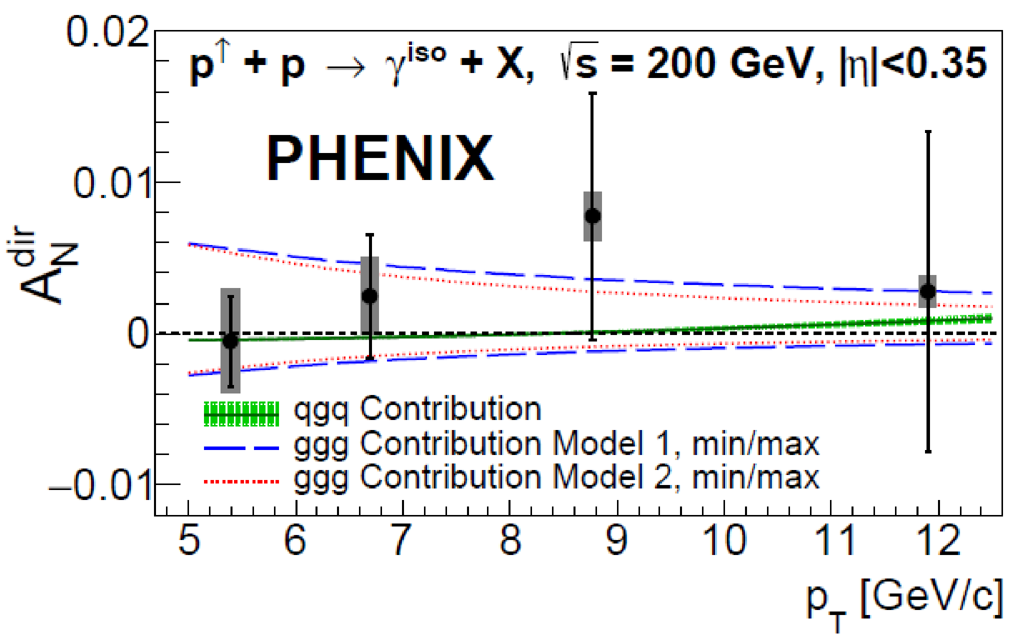
arXiv:2112.05680 (accepted for PRD)

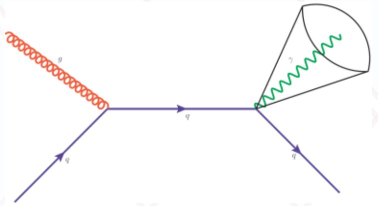


First direct photon A_Ns

- First direct photon A_N extracted at RHIC
- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function well, since quark impact expected to be small

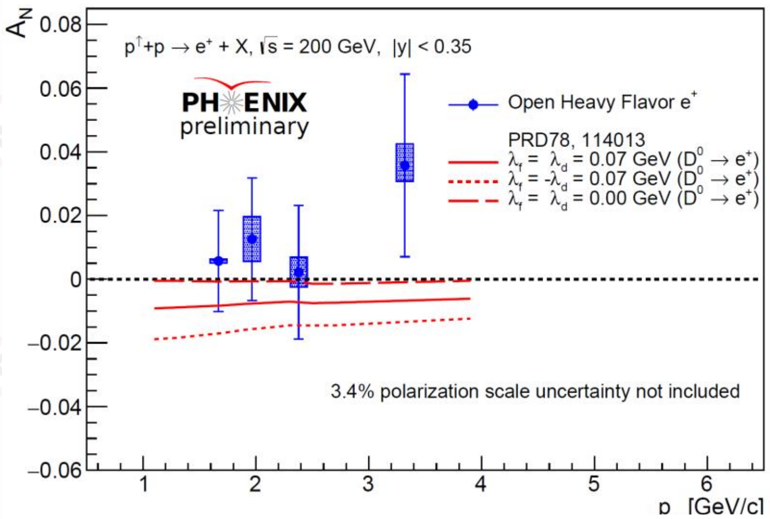
Phys.Rev.Lett. 127 (2021) 162001

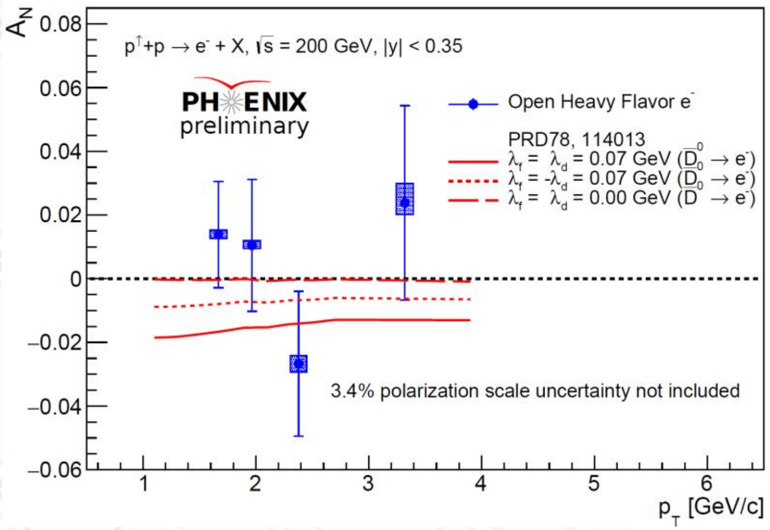


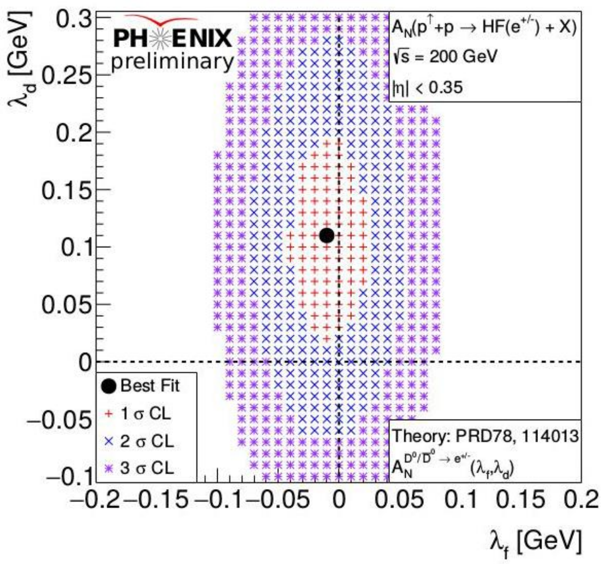


Heavy Flavor electron A_Ns

- Sensitive to tri-gluon correlators
- Potential to constrain parameter ranges in D meson A_N theory calculations: PRD78, 114013 (Z.B. Kang, J.W. Qiu, W. Vogelsang, F. Yuan)
- Final result will have added lower P_T data points

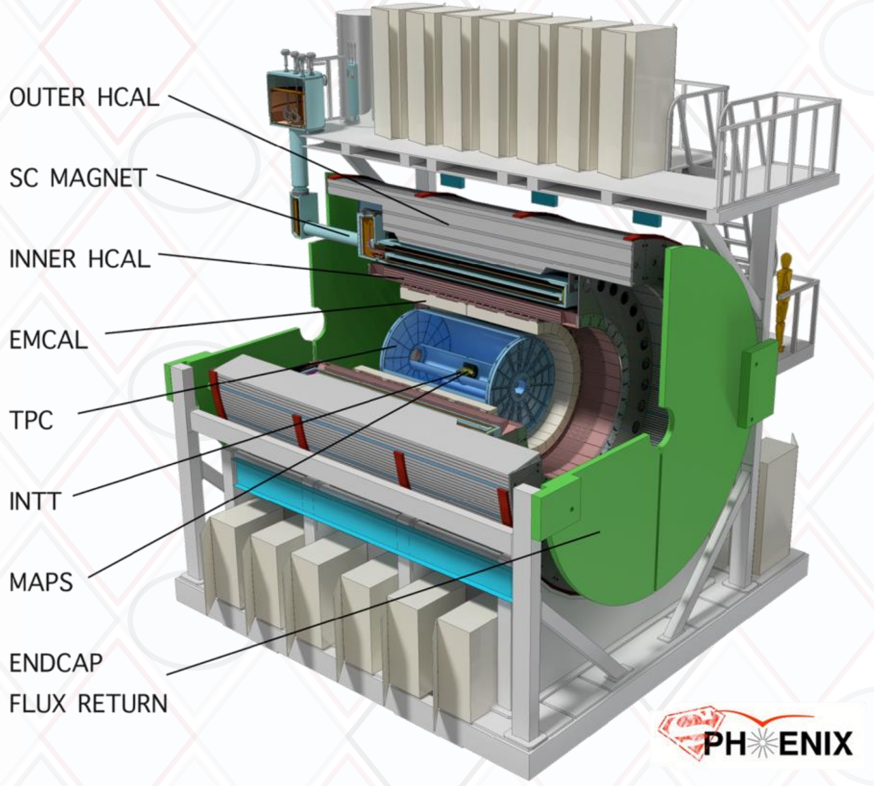






sPHENIX

- Compact detector with good Jet and tracking capabilities over large range ($|\eta|<1.4$) using BaBar 1.5 T solenoid
- Main purpose for remaining HI physics such as jet and Upsilon state R_{AA} measurements
- Many cold-QCD possibilities



Proposed run schedule, year 1-3

sPHENIX BUP2021 [sPH-TRG-2021-001], 24 (& 28) cryo-week scenarios

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\|<10$ cm	Samp. Lum. $\|z\|<10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-str]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-str]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

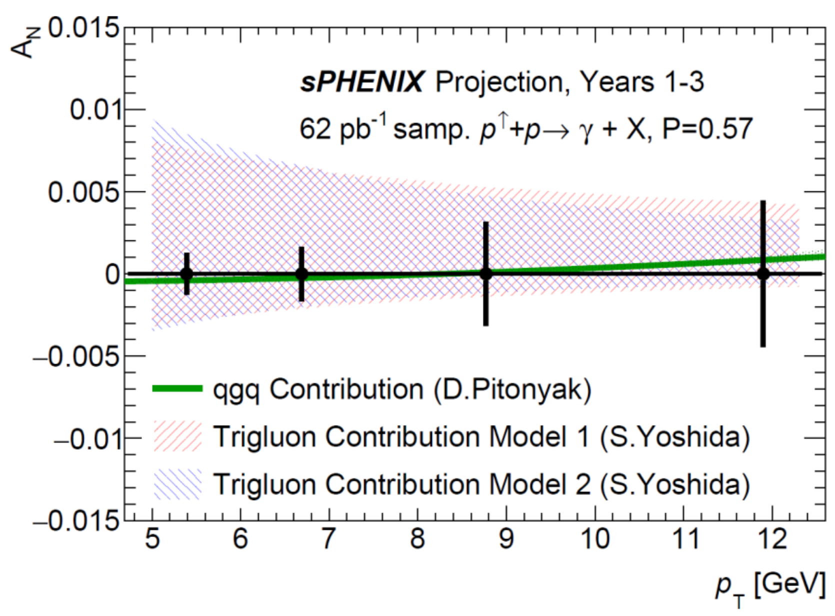
sPHENIX asked to consider
20-28 week runs in 2024

- (Trans-)polarized $p+p$, $p+A$ with streaming readout for 28 weeks in Run24
- But short Run24 would endanger the $p+A$ data!

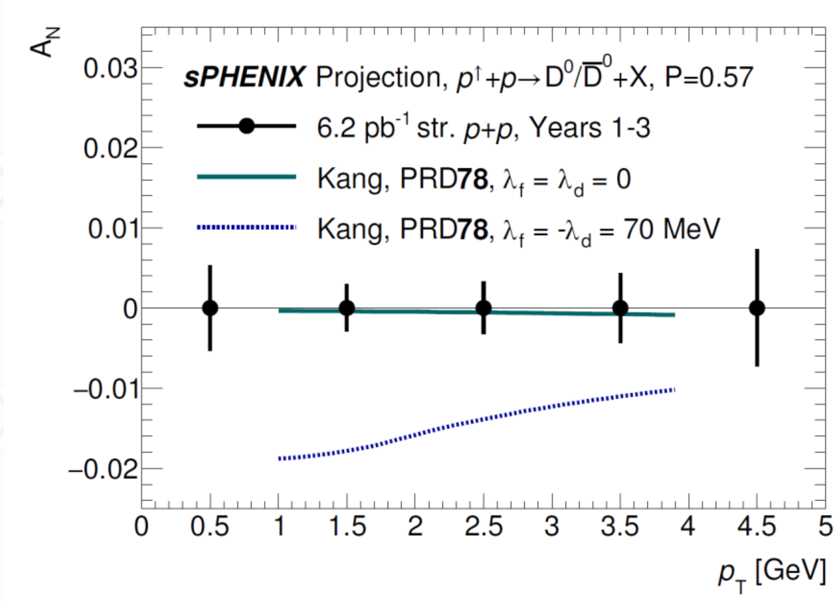
Gluon dynamics via γ, HF TSSA

sPHENIX BUP2021 [sPH-TRG-2021-001]

TSSA of prompt photon
EMCal-based trigger

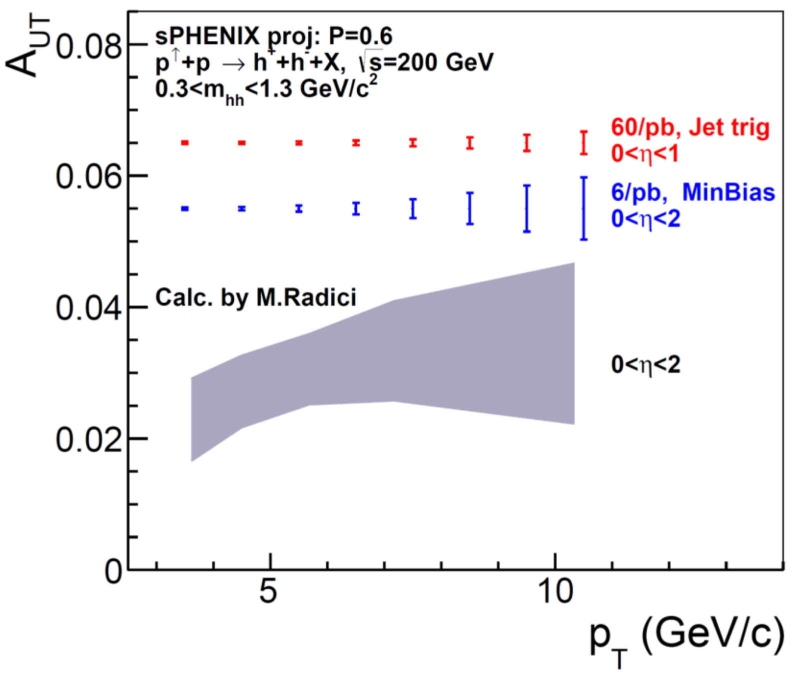


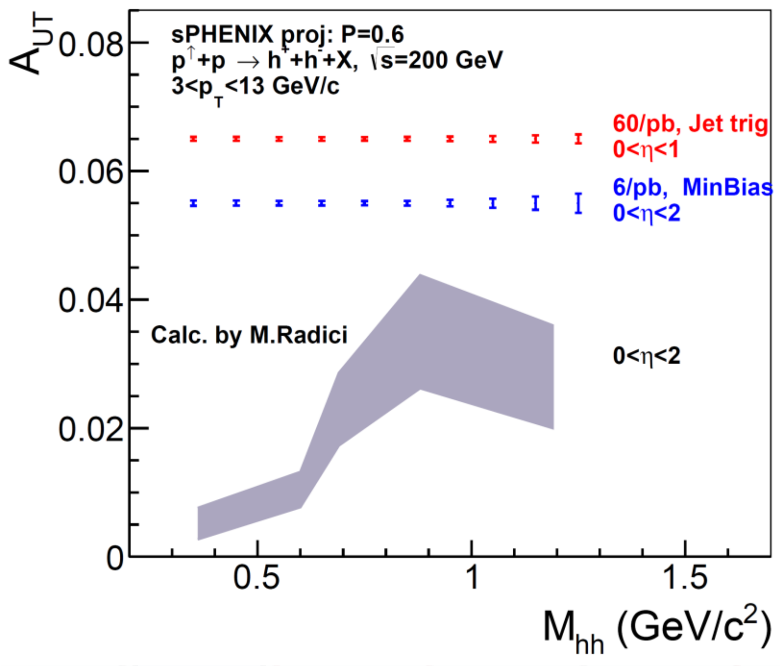
TSSA of prompt $D^0 \to \pi K$
Enabled by streaming readout



Transversity via charged particle IFF

- Tremendous stat. enabled by both calorimetric jet trigger and streaming readout
- Need theory collaboration in the treatment of no-PID charged tracks & multi-dim binning
- Similarly: Sensitivity via Collins fragmentation function (hadron in jet measurements)





Summary

- Many Belle/Babar/BES3 TMD fragmentation related measurements available:
  - Unpolarized single hadrons wrt thrust axis
  - Collins asymmetries (kt dependent, kaons)
  - Polarizing L fragmentation
- More measurements on going for:
  - Other venues for unpolarized TMDs (opposite hemisphere dihadrons, hadron in jet)
  - Multi-dimensional extractions of Collins asymmetries
  - Other studies ongoing on the fragmentation of VMs and Ds
- study of quark/gluon dynamics at PHENIX/sPHENIX also closely related to TMD FFs