Fragmentation Functions and SIDIS

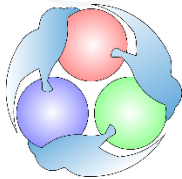
JLAB High Luminosity workshop

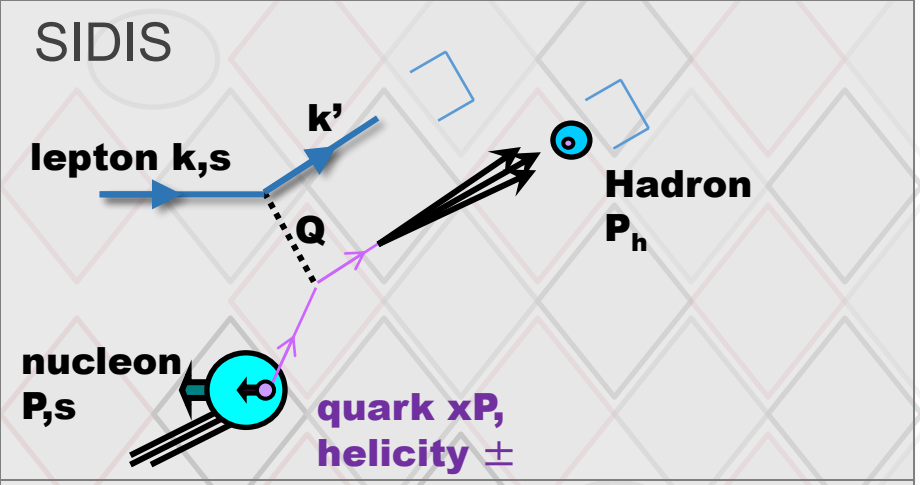
10/7/2026

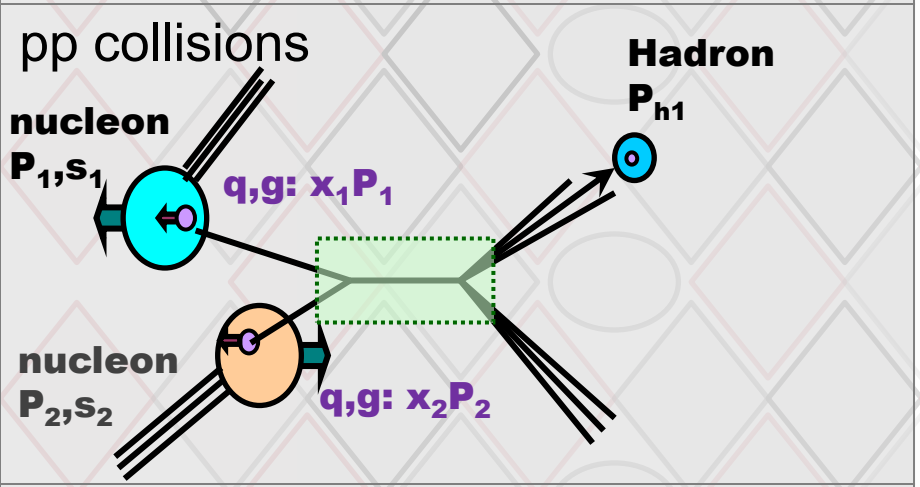
Ralf Seidl (University of Tokyo QNSI)

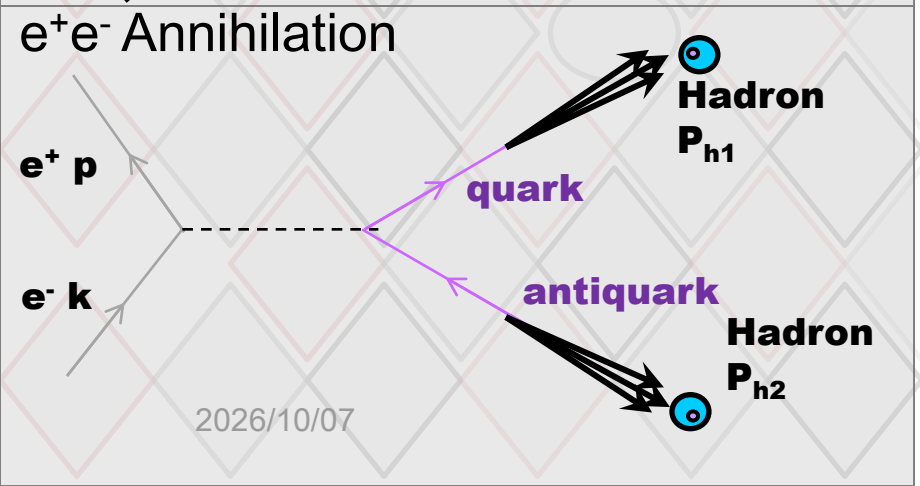












Access to Fragmentation functions

- Semi-inclusive DIS (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:

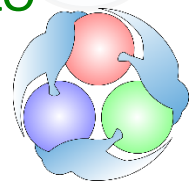
$$\sigma^h(P_T) \propto \int_{x_1,x_2,z} \sum_{a,a' \in q,g} f_a(x_1) \otimes f_{a'}(x_2) \otimes \sigma_{aa'} \otimes D_{1,q}^h(z)$$

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

- e^+e^-:

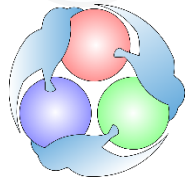
$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, k_t, Q^2) + D_{1,\bar{q}}^h(z, k_t, Q^2) \right)$$

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



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



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) hep-ex:2502.16084, (BESIII) *PRD* 111 (2025)034030 (BESIII)	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: $\frac{d^2\sigma}{dzdm}$

Single hadron FF

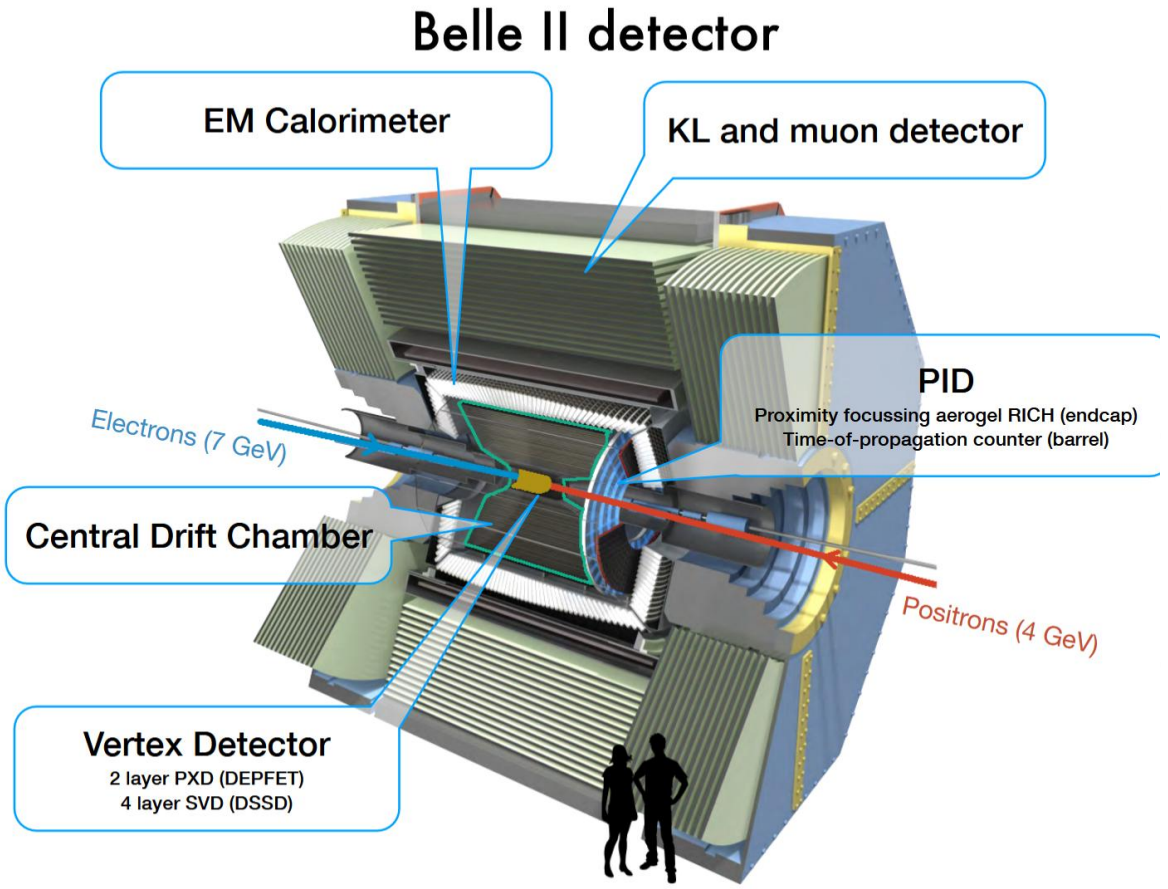
Unpolarized ingredients	Polarized ingredients	Flavor sensitivity
Single hadron cross sections: $e^+e^- \to hX$ $D_{1,q}^h(z, Q^2)$ PRL111 (2013) 062002 PRD101(2020) 092004	Azimuthal asymmetries: $e^+e^- \to (h)(h)X$, $\cos(\phi_1 + \phi_2)$ $H_{1,q}^{\perp(1)h}(z, Q^2)$ PRL 96 (2006) 232002 PRD 78 (2008) 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 $D_{1,q}^{\perp h}(z, k_T, Q^2)$ PRL 122 (2019), 042001

Dihadron FF (IFF)

Unpolarized ingredients	Polarized ingredients	HF/resonances/hyperons
Dihadron cross sections $e^+e^- \to (hh)X$ $D_{1,q}^{h_1h_2}(z, m, Q^2)$ 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	$e^+e^- \to (\rho^+, \rho^0, \omega, \phi, K^{*+}, K^{*0}, K_S, \eta, D^0, D^+, D^{*0}, D^{*+}, D_s^+, D^{*+})\ X$ PRD 111 (2025) 052003 $e^+e^- \to (\Lambda, \Lambda_c, \Omega, \Sigma, ...)\ X$ PRD 97 (2018) 072005

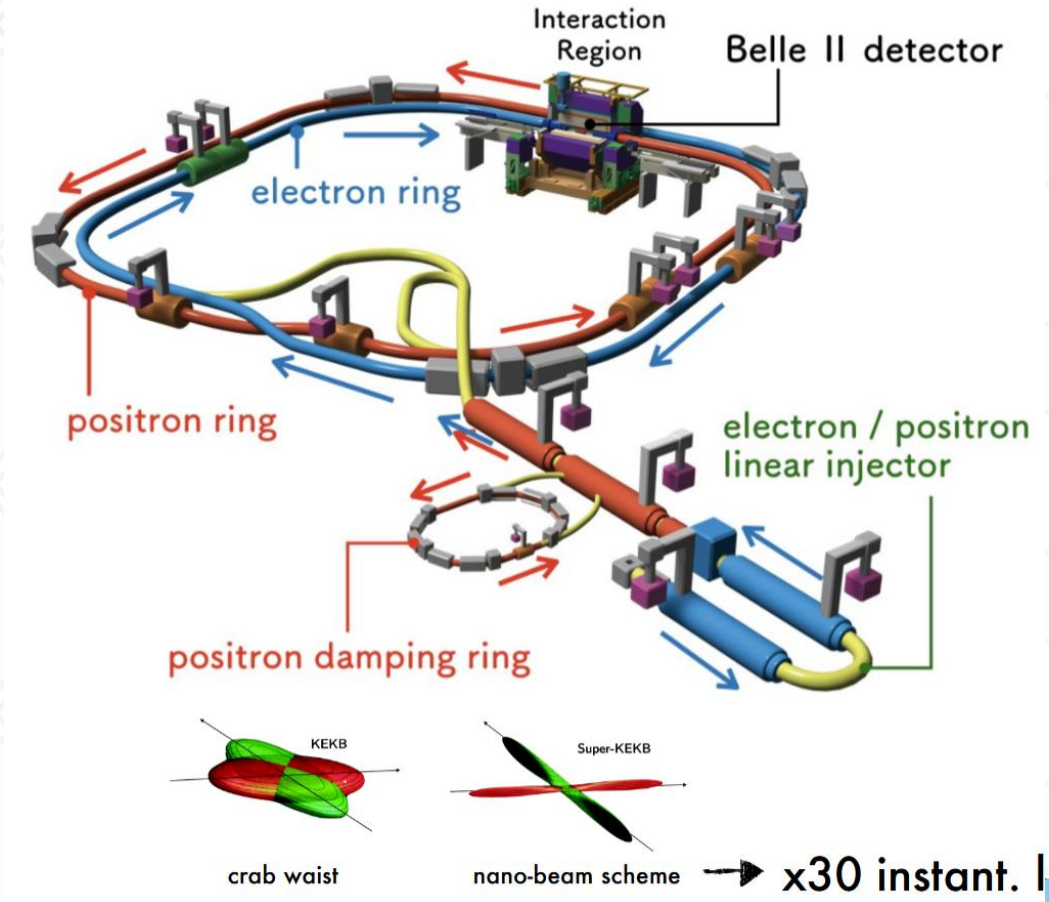
Belle/Belle II physics goals

- Main goal of Belle/BelleII:
  - CP violation in the quark sector via $B^0 - \bar{B}^0$ mixing
  - CKM matrix
  - Rare B decays
  - Spectroscopy
- Center of mass energy typically at Y(4S) resonance (10.58 GeV) → creates $B\bar{B}$ pairs to study mixing
- Asymmetric beam energies →boosted cms for longer-lived B mesons in the lab frame
- Additional runs below Y(4S) resonance ($e^+e^- \to q\bar{q}$) and scans above for Y(5S), Y(10753), etc



SuperKEKB accelerator

- Asymmetric 4 GeV e^+ on 7 GeV e^- (was 3.5 GeV on 8 GeV in KEKB)
- Nano-beams + higher beam currents to reach 30 x KEKB instantaneous luminosity
- World highest instantaneous luminosity 5.1 * 10^{34} cm^{-2} s^{-1} reached (12/2024)
- aiming to collect 50 x Belle luminosity
- Eventually add polarization



Belle and BelleII detector comparison

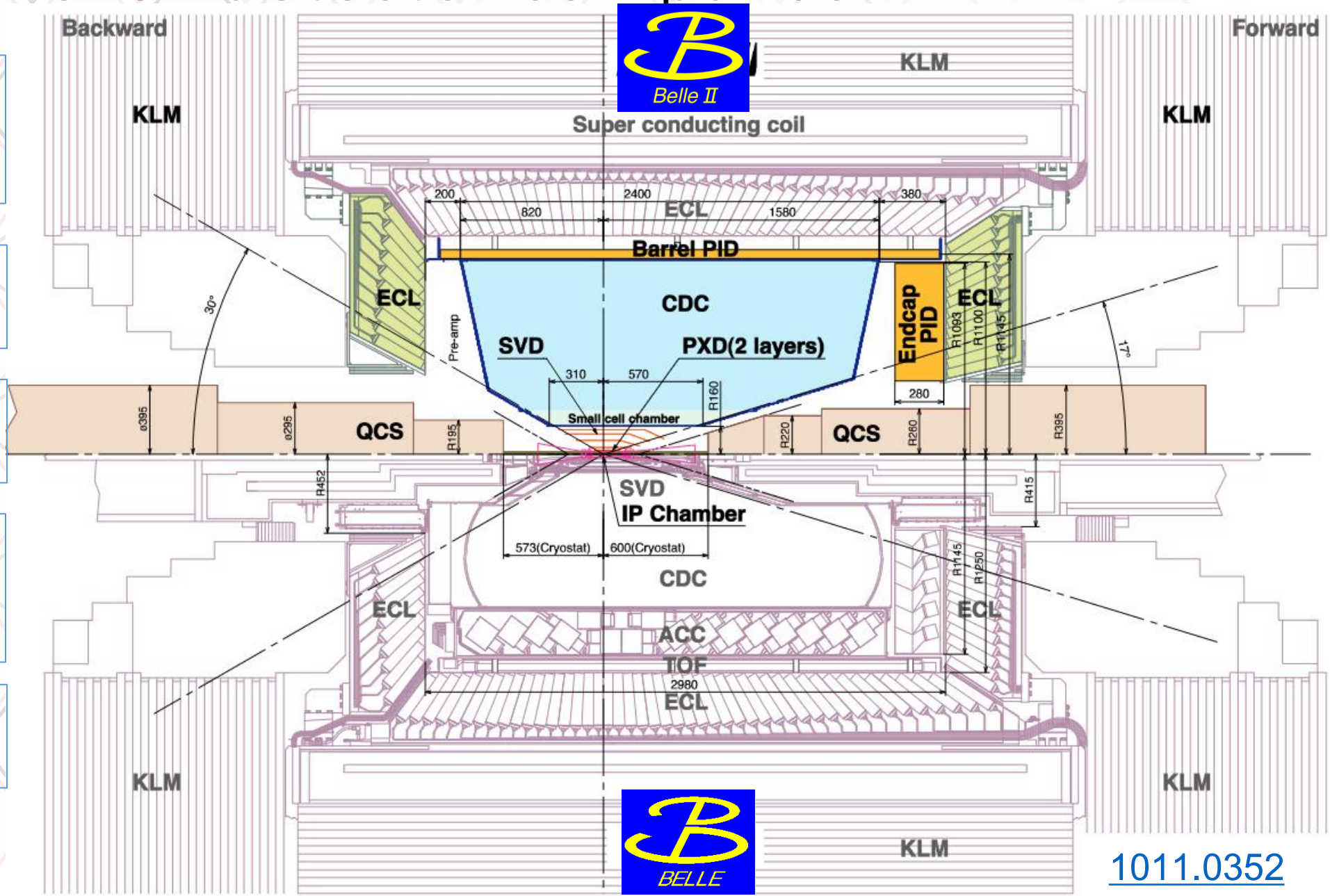
From 4 SVD layers → 2 Pixel + 4 Double-sided Strip layers

Larger drift chamber, faster readout

Improved PID with TOP and ARICH

KLM system with RPCs and scintillating fibers

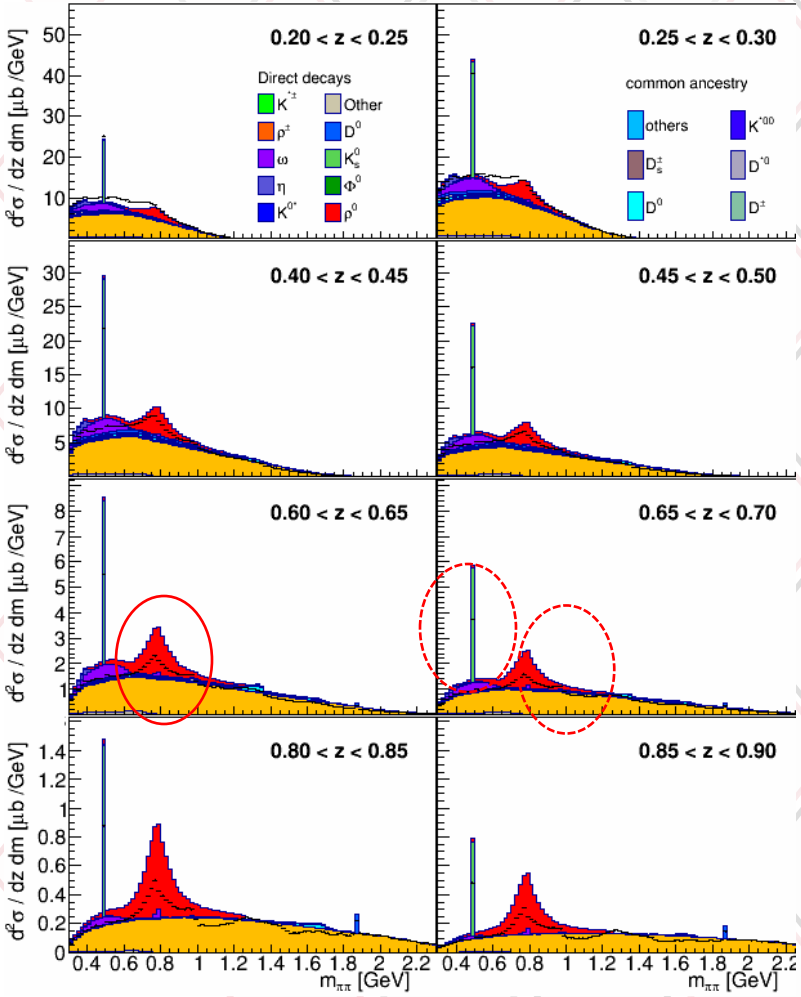
Waveform sampling readout for calorimeter



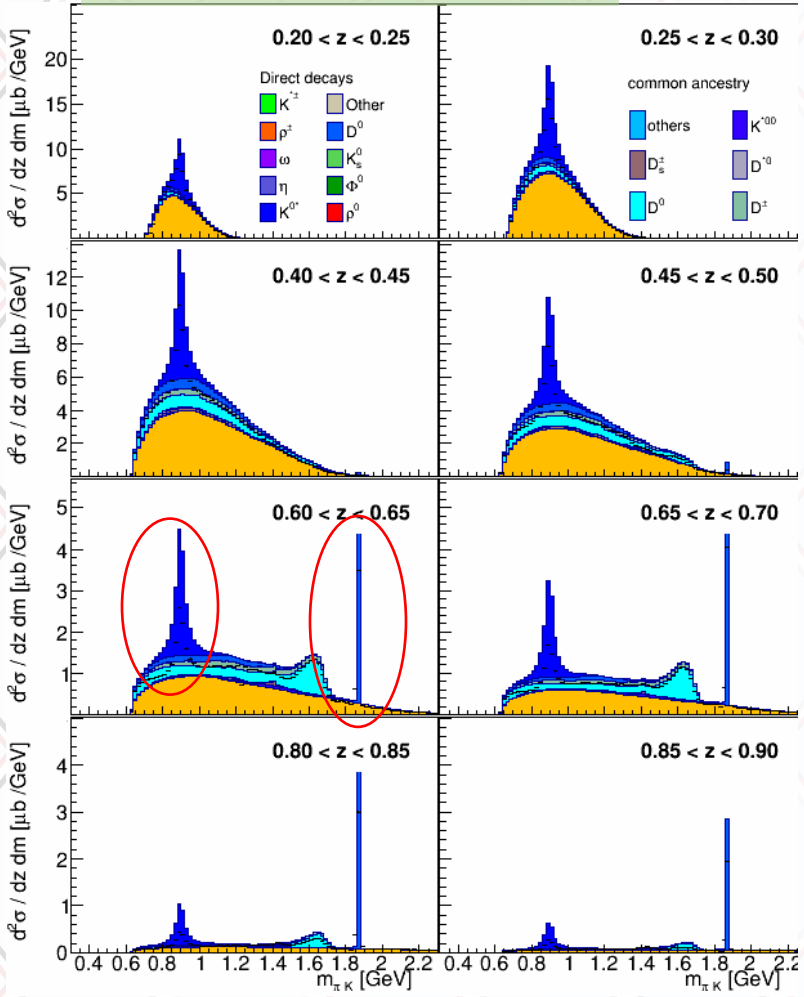
1011.0352

From mass cross sections to resonances

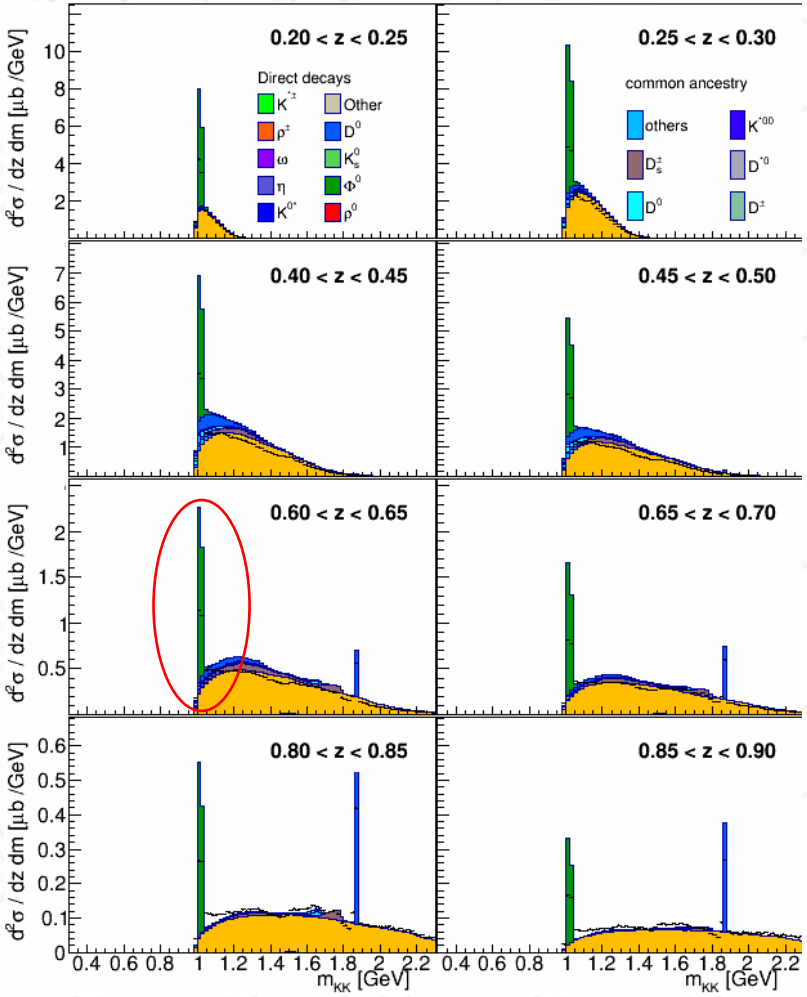
PRD96 (2017) 032005



$\pi^+\pi^-$



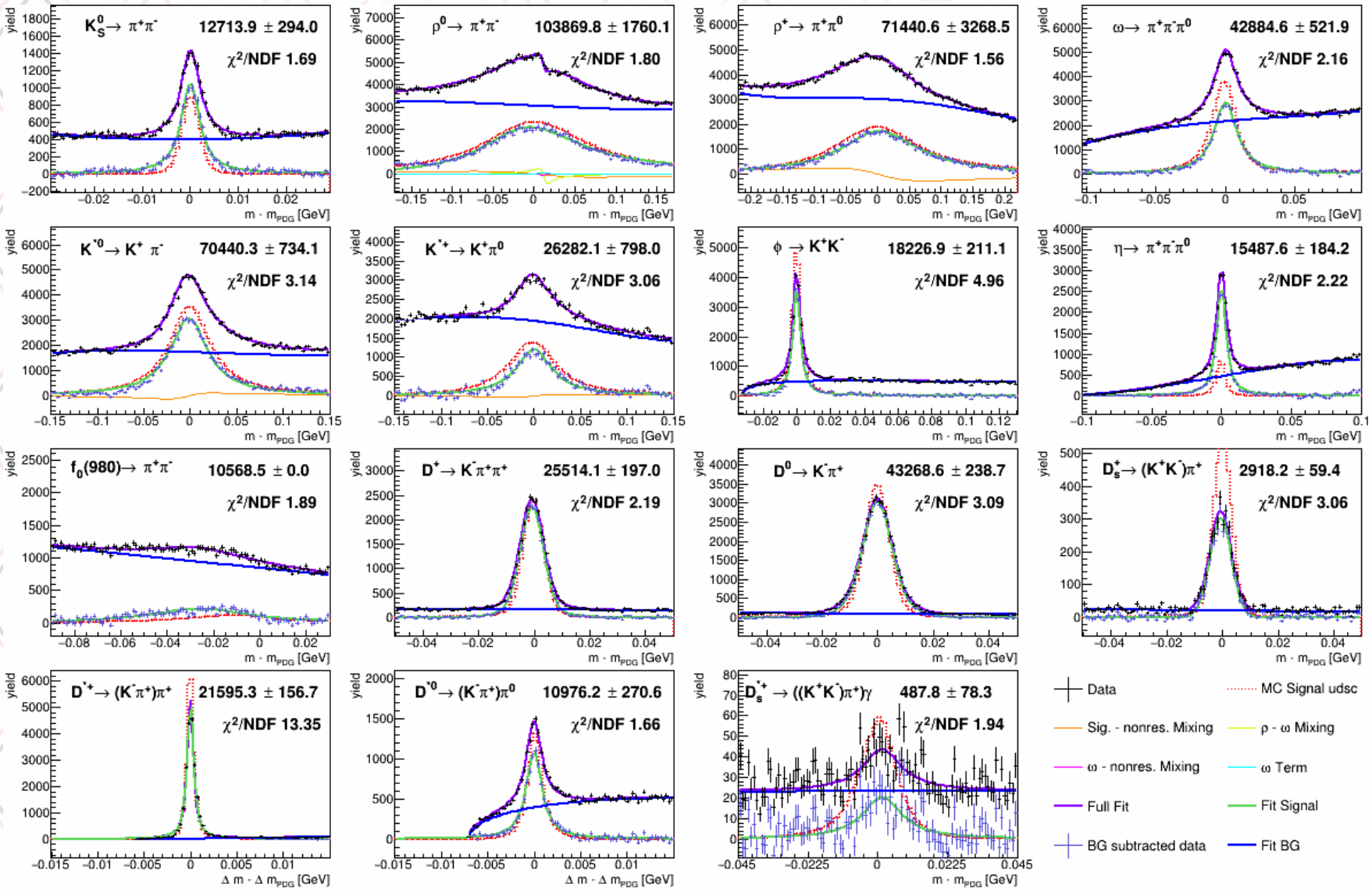
π^+K^-



K^+K^-

Mass fits

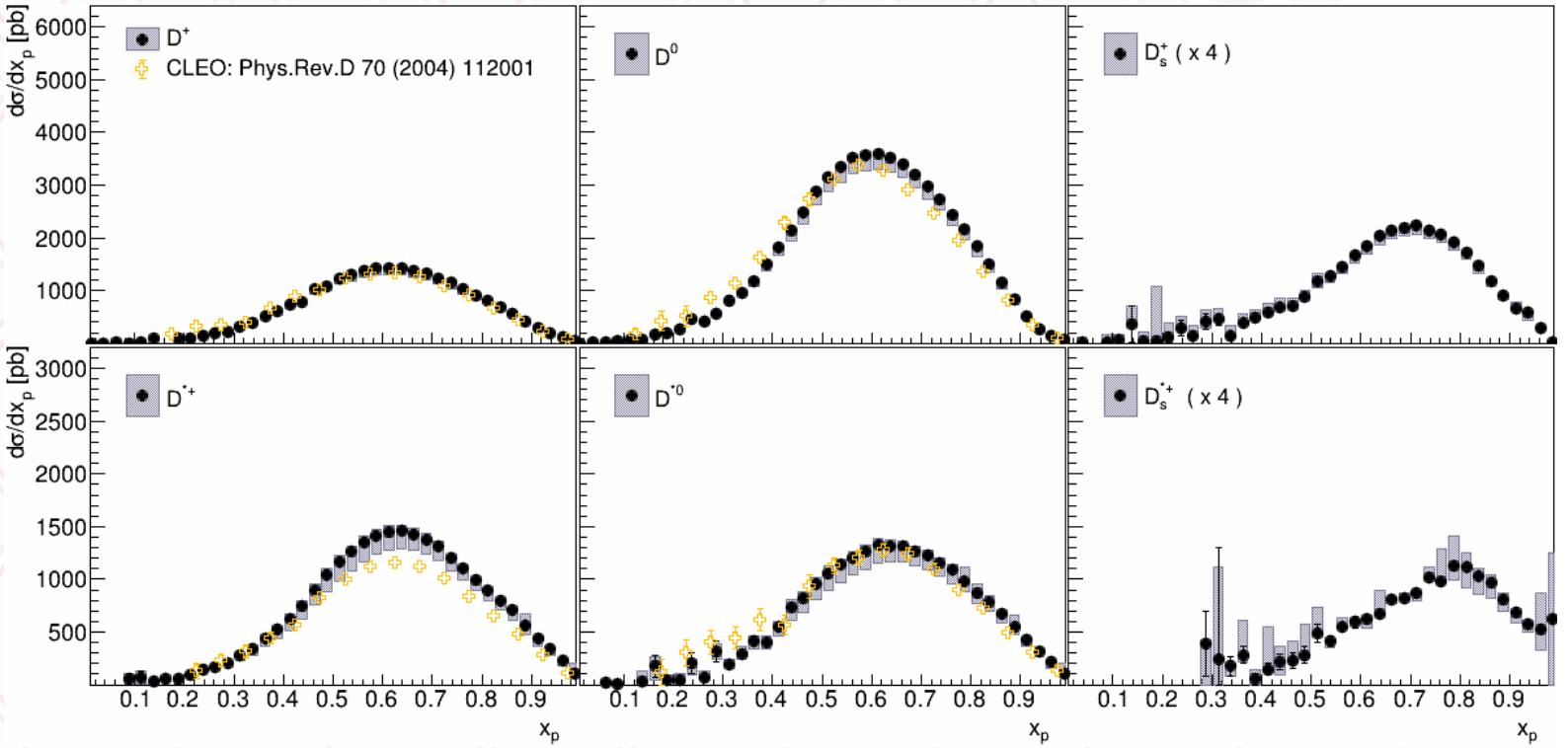
- Fit invariant masses by Breit-Wigners or Gaussians
- Backgrounds described by polynomials, except ϕ and D* where threshold functions were used
- Interference with non-resonant background included for wide resonances, also with ω for ρ^0



Charm meson results

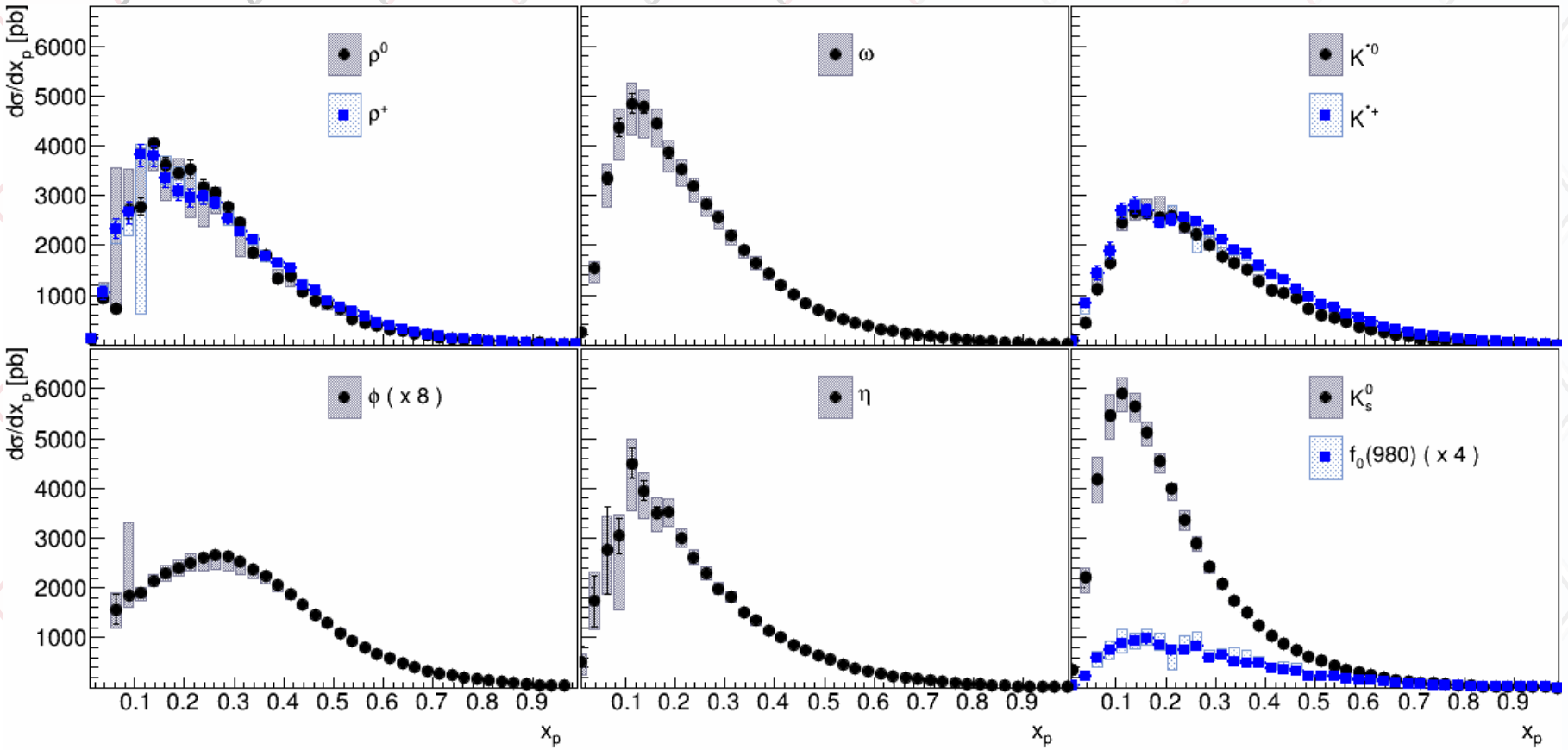
- Consistent with older results before ISR correction which was assumed to be flat in older publications
- Magnitude similar but shapes slightly shifted dues to ISR correction

PRD 111 (2025) 052003 (Belle)



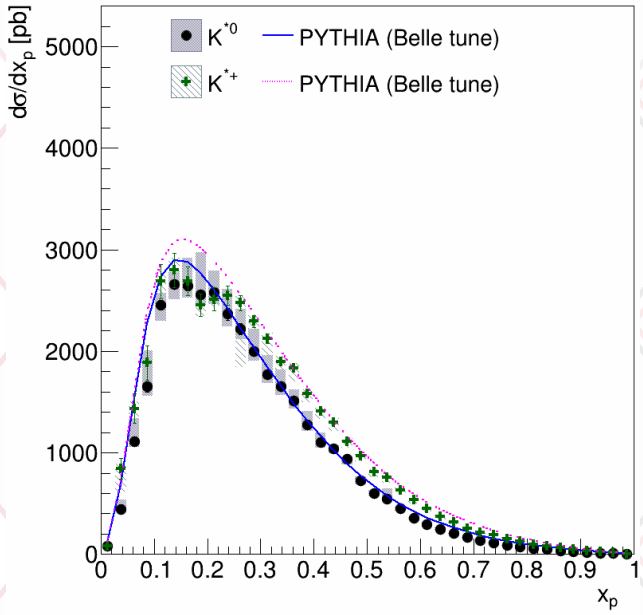
Light hadron results

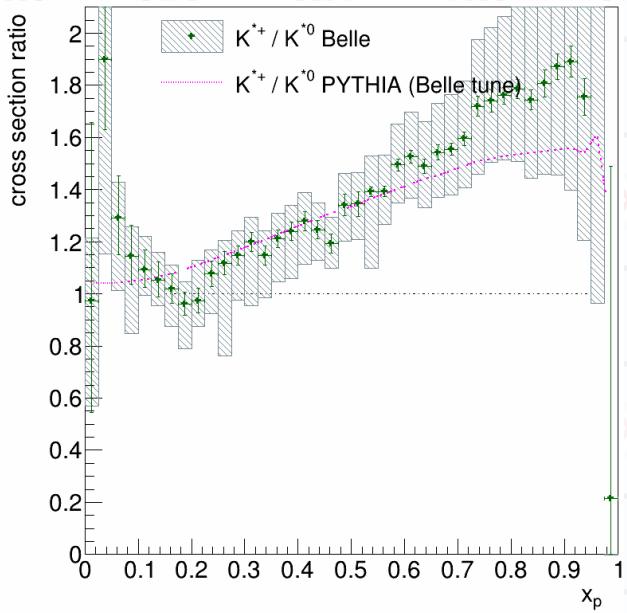
PRD 111 (2025) 052003 (Belle)

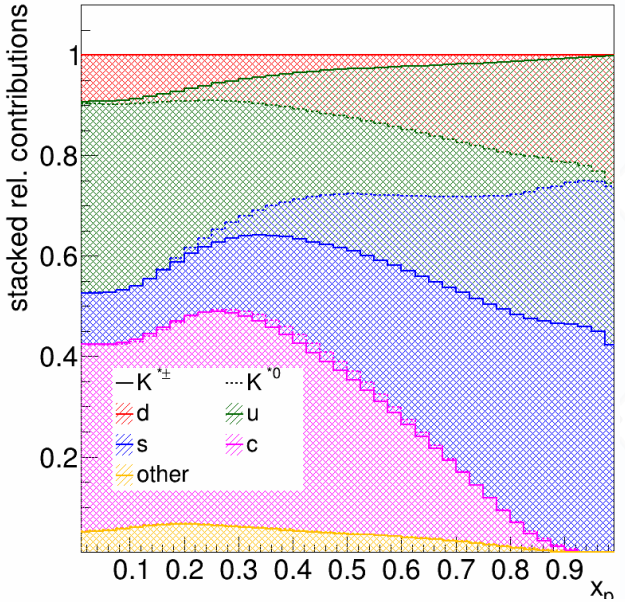


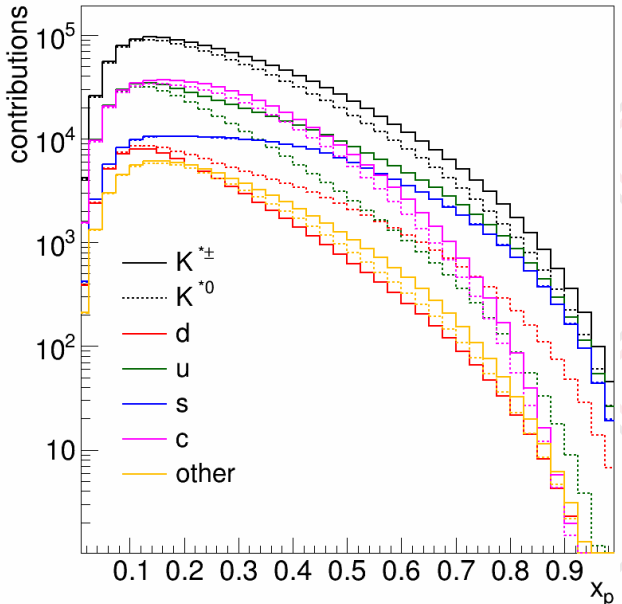
- Vector mesons extracted for the first time at B factory energies
- Generally, very high precision, except low xp where low-momentum efficiency uncertainties and large backgrounds are significant
- Peaking structure seen, increasing with mass as expected

K* charged to neutral ratios

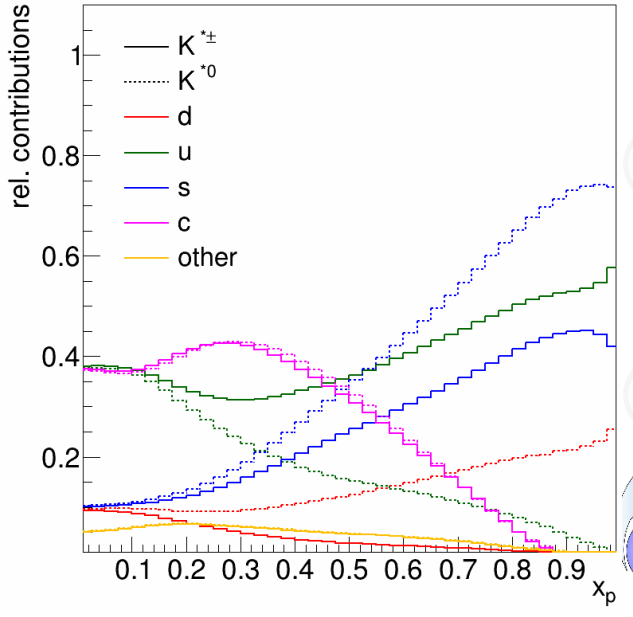




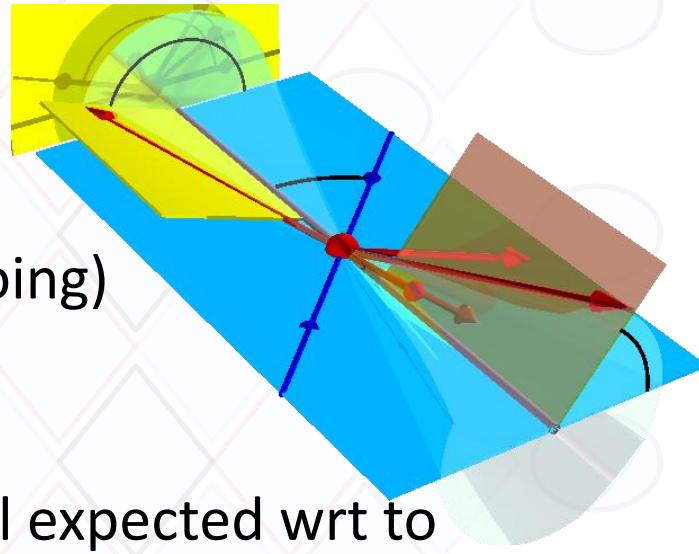




- Favored fragmentation u→K vs d→K different because of number of initial u/ubar pairs in e^+e^- over d/dbar pairs (due to e_q^2 weight)
- Strange fragmentation same
- Charm feed-down similar



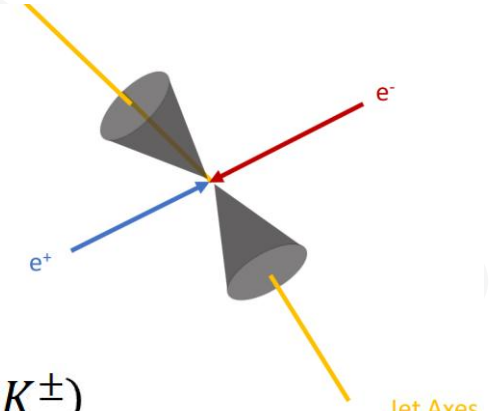
Further analysis plans at BelleII



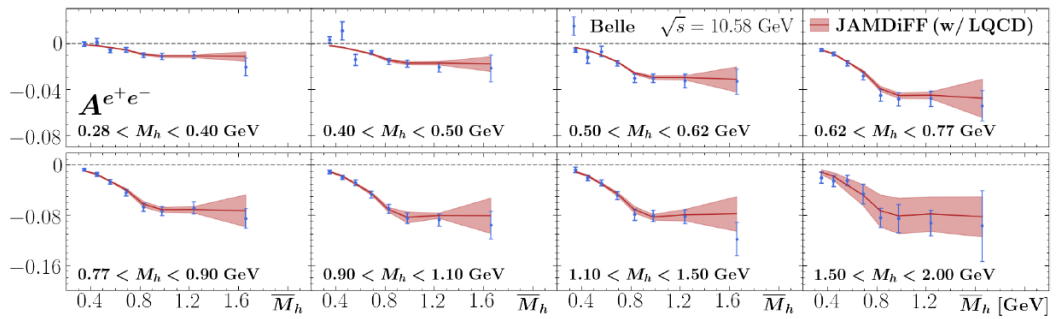
- πK, KK IFF measurements (close to be finished)
- Jet transverse momenta (ongoing)
- Spin-spin correlations in polarized hadron fragmentation (ongoing)
- Multidimensional Collins fragmentation functions
- Kaon Collins fragmentation functions
- VM TMDs and Collins asymmetries (sign change in Artru model expected wrt to mesons)
- Hidden charm in Fragmentation (e+e-→J/PsiX)?
- Energy-Energy correlators (https://arxiv.org/abs/2507.17478)
- scale-dependence of FFs through ISR
- MC tuning efforts (explicit request by HERWIG to look at di-baryons/baryon-antibaryon pairs)

IFF for pion-kaon combinations

Katherine Parham (Duke)

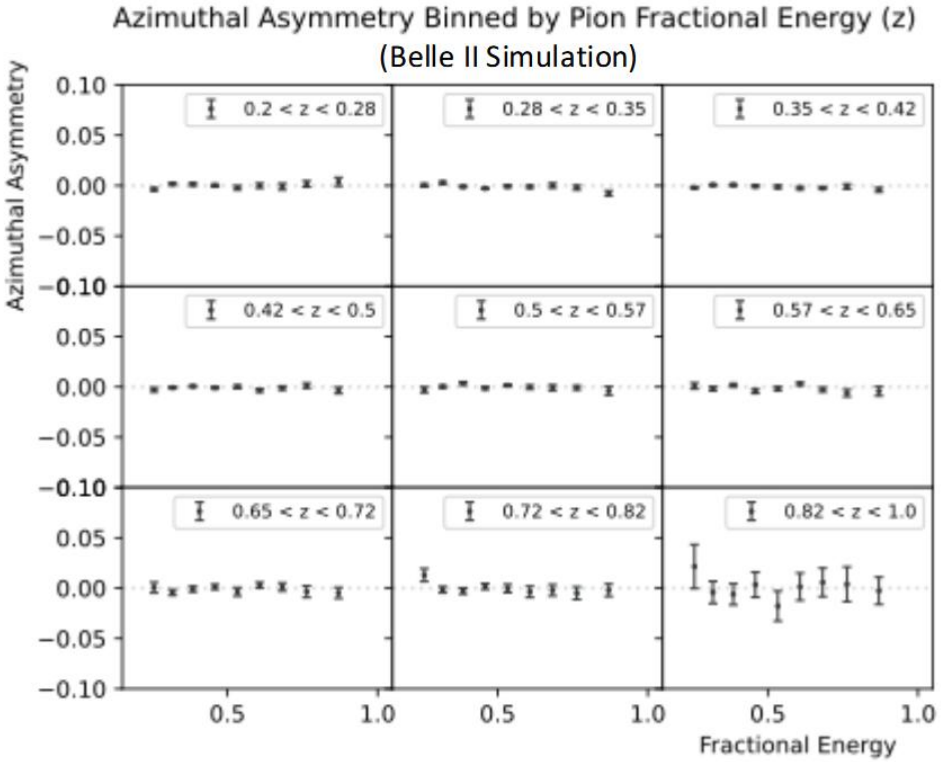


- Extend the previously published $\pi^+\pi^-$ IFFs to πK and KK
- Increase sensitivity to strange quark IFF
- Unlike previous publication, concentrate on jet axae instead of thrust
- MC studies show no false asymmetries



JAMDiFF: PRL 132 (2024) 091901

$e^+e^- \to (\pi^+\pi^-)(\pi^\pm K^\pm)$



TMD Jets in e^+e^-

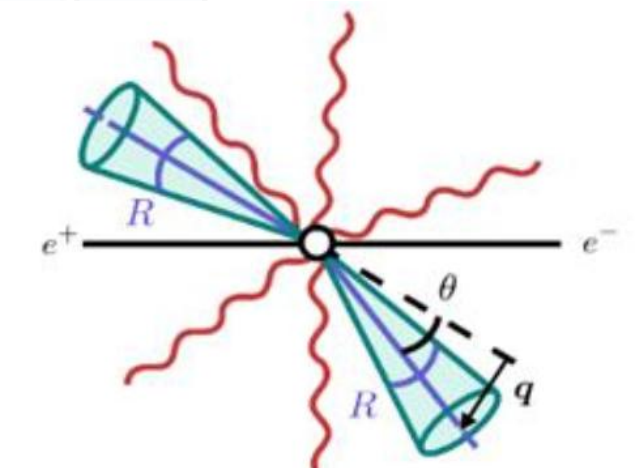
Simon Schneider(Duke)

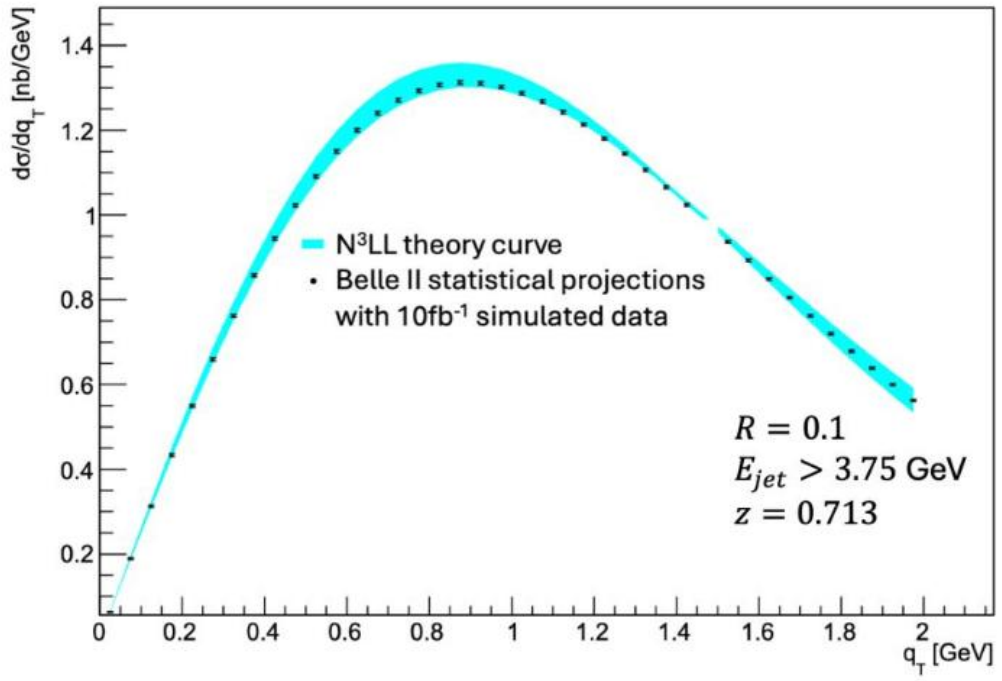
- Similar to unpolarized di-hadron transverse momentum imbalance, study di-jet imbalance

$$\mathbf{Q} = \frac{\mathbf{P_1}}{z_1} + \frac{\mathbf{P_2}}{z_2}$$

$$\mathbf{z_i} = \frac{2E_i}{\sqrt{s}}$$

- Similar extension to SIDIS at EIC





Gutierrez-Reyes et al. JHEP 2019, 31 (2019)

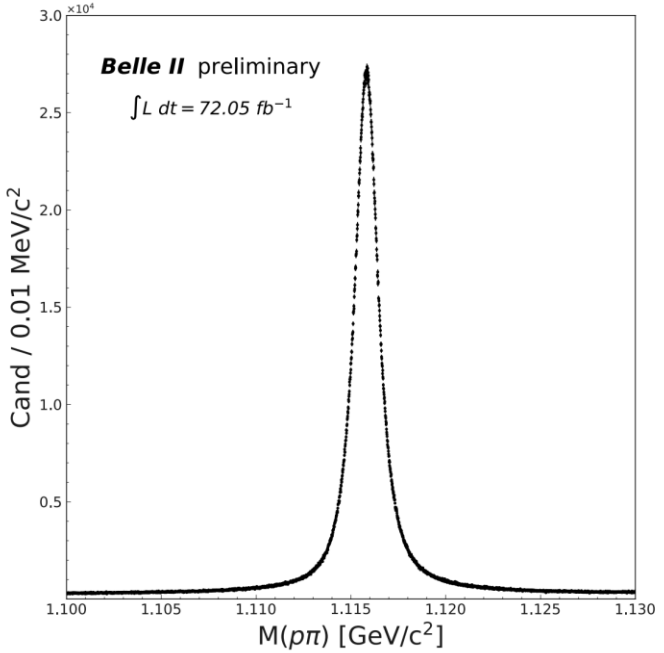
Spin correlations through hadronization

Cynthia Nunez (Duke)

$$e^+e^- \to q\bar{q} \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)X$$

- How much of the initial $q\bar{q}$ spin correlation survives hadronization?
- Proton and antiproton decay angles to analyze the two-hyperon spin correlation
- Measure opening-angle $P_{\Lambda\bar{\Lambda}}$, longitudinal C_{LL}, and transverse C_{TT} correlations as a function of $(z_\Lambda, z_{\bar{\Lambda}})$
  - Theory connects C_{TT} to a Bell-type observable
- Probe polarized fragmentation functions without polarized beams or target, related to combination of

$$H_{1T,q}^{h}(z, Q^2) \quad \text{and} \quad H_{1T,q}^{\perp h}(z, k_T, Q^2)$$

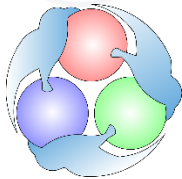


BELLE2-NOTE-PL-2020-031

Found. Phys. 11, 171 (1981)
PRD 106, L031501 (2022)
PRD 109, 116003 (2024)
arXiv:2510.13951 (2025)
JHEP 11, 082 (2025)
JHEP 11, 082 (2025)
PRD 111, 054035 (2025)

Planned updates: Collins multidimensional analysis and Kaon combinations

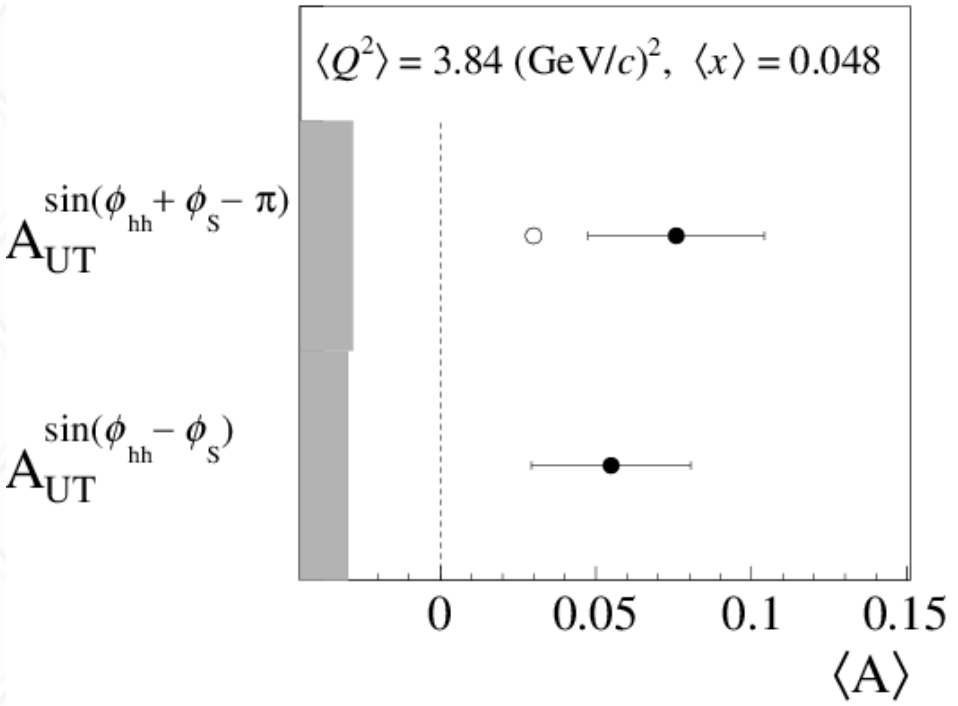
- Currently revisiting kaon combinations of the Collins asymmetries
- While doing so, try to perform a full multi-dimensional analysis:
  - Consider :
  - 6 (z_1) x 6 (z_2) x 5(k_{t1}) x 5(k_{t2}) x 1 (costheta) x 8 (phi) for A_{12} method
  - 6 (z_1) x 6 (z_2) x 10(q_t) x 1 (costheta) x 8 (phi) for 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



Artru model sign change for VMs

- Artru string fragmentation model suggests sign change from pseudoscalar to vector meson Collins FF, also implemented in StringSpinner package of Pythia8
- Some indication from COMPASS (π^+ asymmetry negative, ρ^0 positive)

COMPASS: *PLB* 843 (2023) 137950



Rho Collins FF, difference between PS and VM

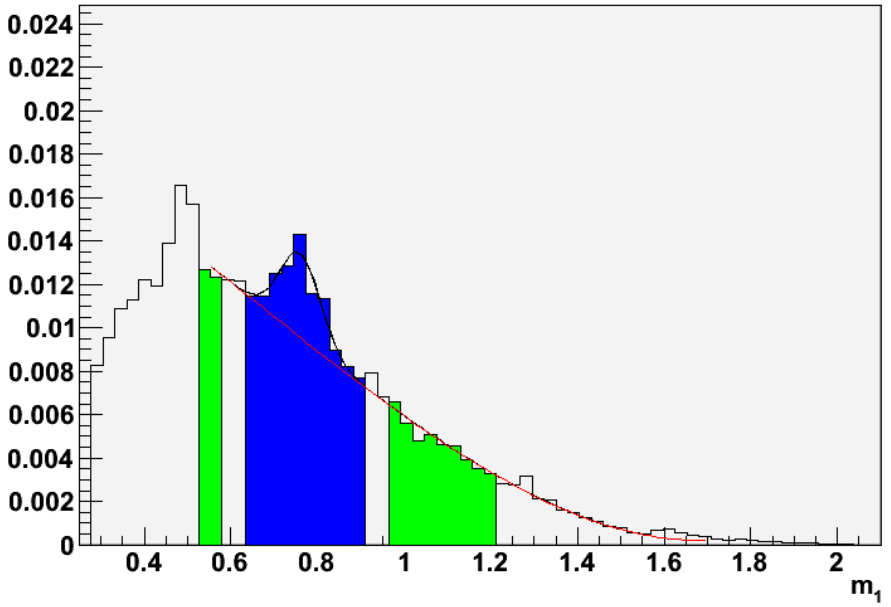
- Measure Collins effect for e^+e^- $\rightarrow \pi^{\pm}\rho^0$ X
- According to Artru model sign change expected wrt. pion Collins:

$$a_{12}(\pi^{\pm}\rho^0) = - a_{12}(\pi^{\pm}\pi^{\pm})$$

- Instead of double ratios to eliminate acceptance/radiative effects use combinatoric BG

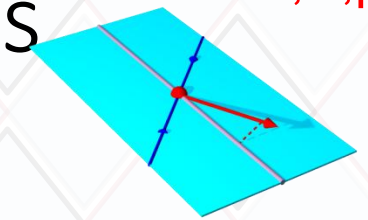
- Normally:

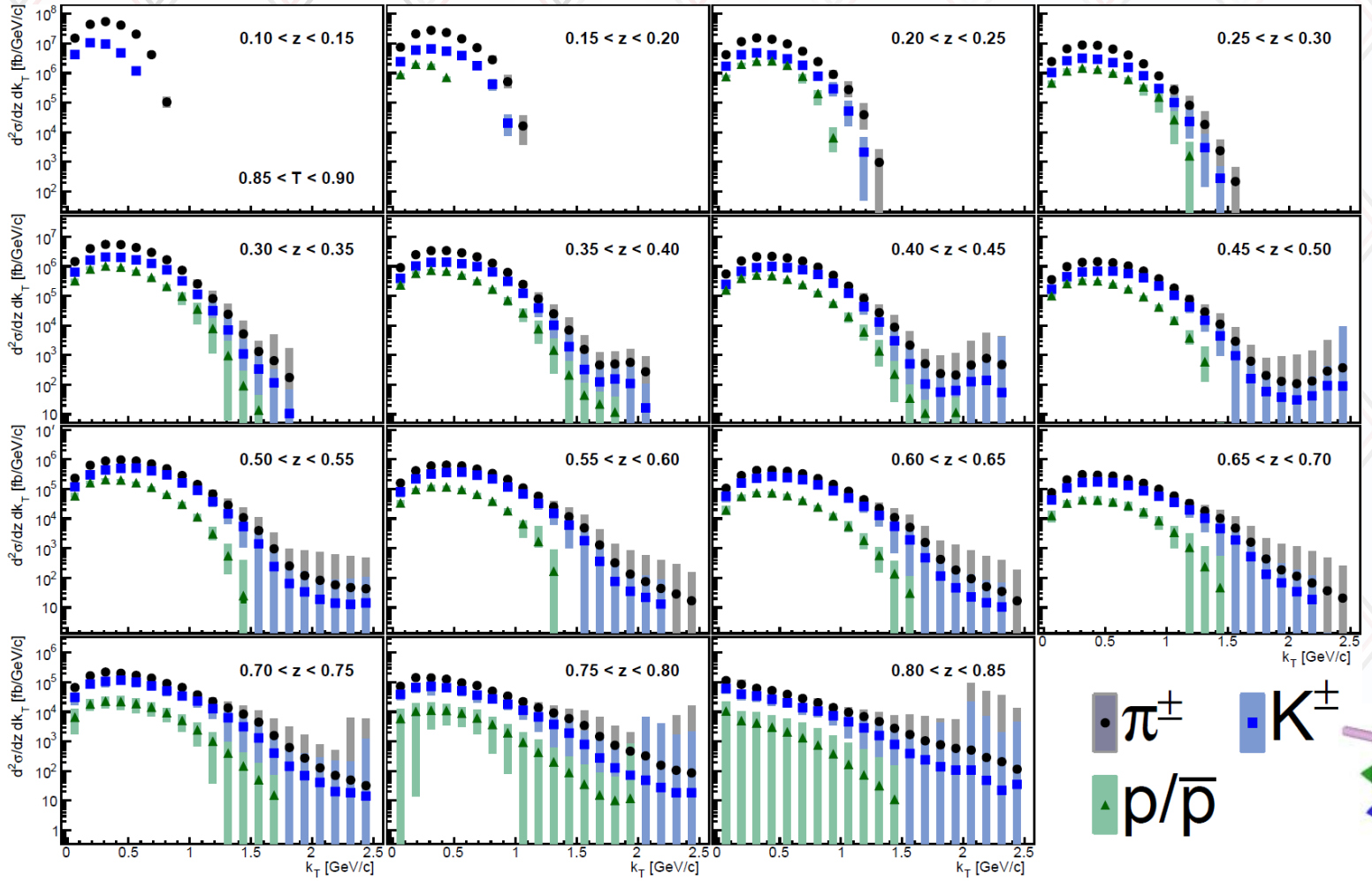
$$A_{Real} = \frac{N_{All}}{N_{Signal}} A_{Signal} - \frac{N_{BG}}{N_{Signal}} A_{BG}$$



Transverse momentum dependent cross sections for pions, kaons and protons

Try to extend from π,K,p to ρ,K*,ϕ



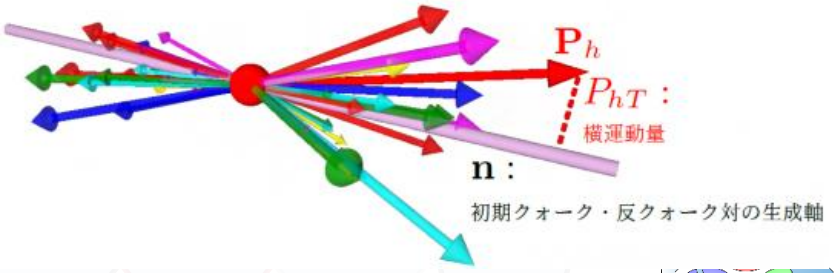


$$\frac{d^2\sigma}{dz dP_{hT}}$$

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/

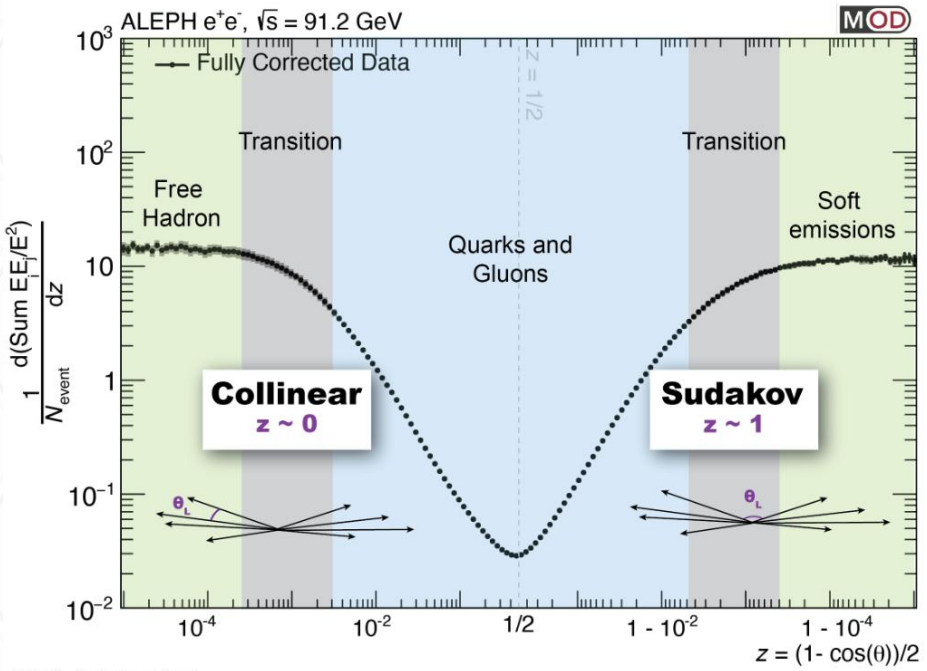


RS. et. al. PRD99 (2019) 112006

EECs in e^+e^- (and SIDIS)

- Look at correlations between particles as a function of their opening angle:
- Small angle: decays, di-hadron fragmentation (nonperturbative)
- Larger angles: parton splitting (perturbative)
- Very large angles: opposite jets (nonperturbative)
- Can this be also used at lower energies such as at Belle and the EIC?
- Some ideas to also look at Fragmentation Energy Correlators to extract a collinear transverse spin analyzer

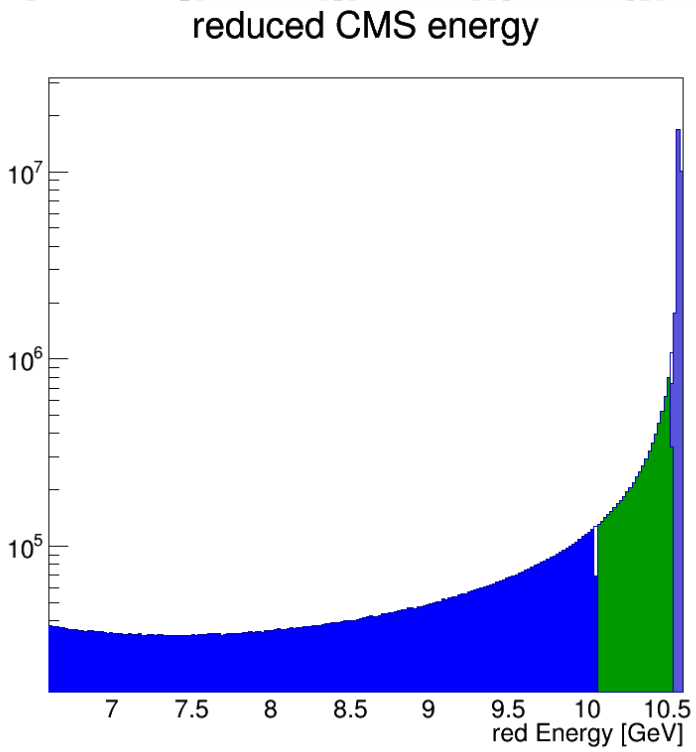
Electron-positron alliance:
https://arxiv.org/abs/2505.11828

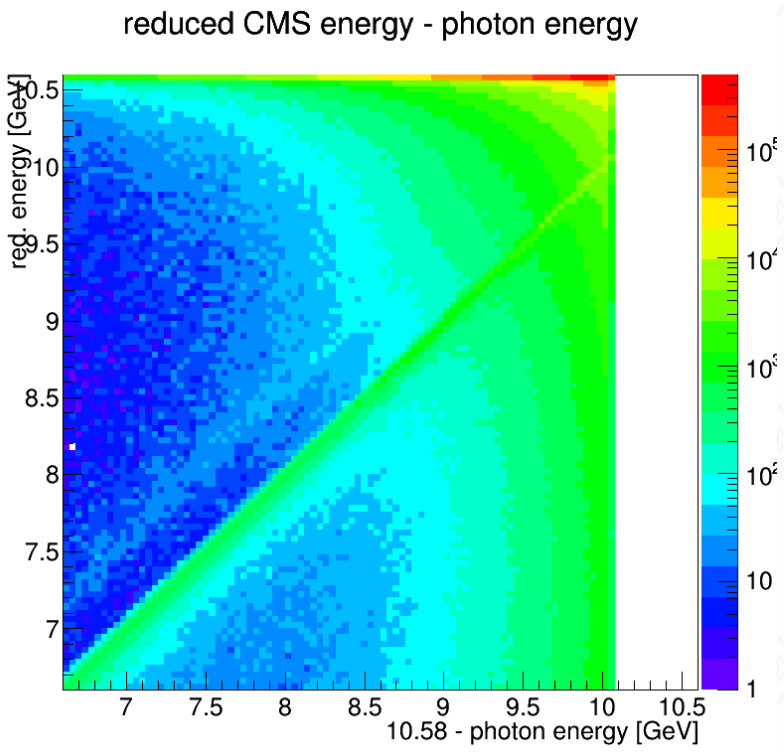


$$\mathrm{E2C}(z) = \sum_{\mathrm{i,j}}^{\mathrm{n}} \int d\sigma \frac{E_\mathrm{i} E_\mathrm{j}}{E^2} \delta(z - z_\mathrm{ij})$$

$$z = \frac{1 - \cos\theta_\mathrm{ij}}{2}$$

CMS energy of the qqbar system test





udsc MC

- Remove detected photon(E>0.5GeV) from system
- Correlation to true CMS energy seen
- Possible improvements:
  - Correlation w/ angle to the thrust axis
  - Small angles to the beam directions
  - Mostly from the higher energy beam
  - Total reconstructed energy

Summary

- Fragmentation functions are crucial to access the nucleon structure in semi-inclusive DIS and pp collisions:
  - 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 TMDs/3D momentum structure
- New results on D mesons and various lighter hadrons, important for HF studies and VM spin effects
- Many relevant FF measurements obtained from B factories, more to come from Belle II (Interference fragmentation, jet transverse momenta, etc)
- Will be very important also for the EIC

