High precision FF measurements at BELLE

or experience on systematic limitations

HL EIC workshop
June 23, 2022

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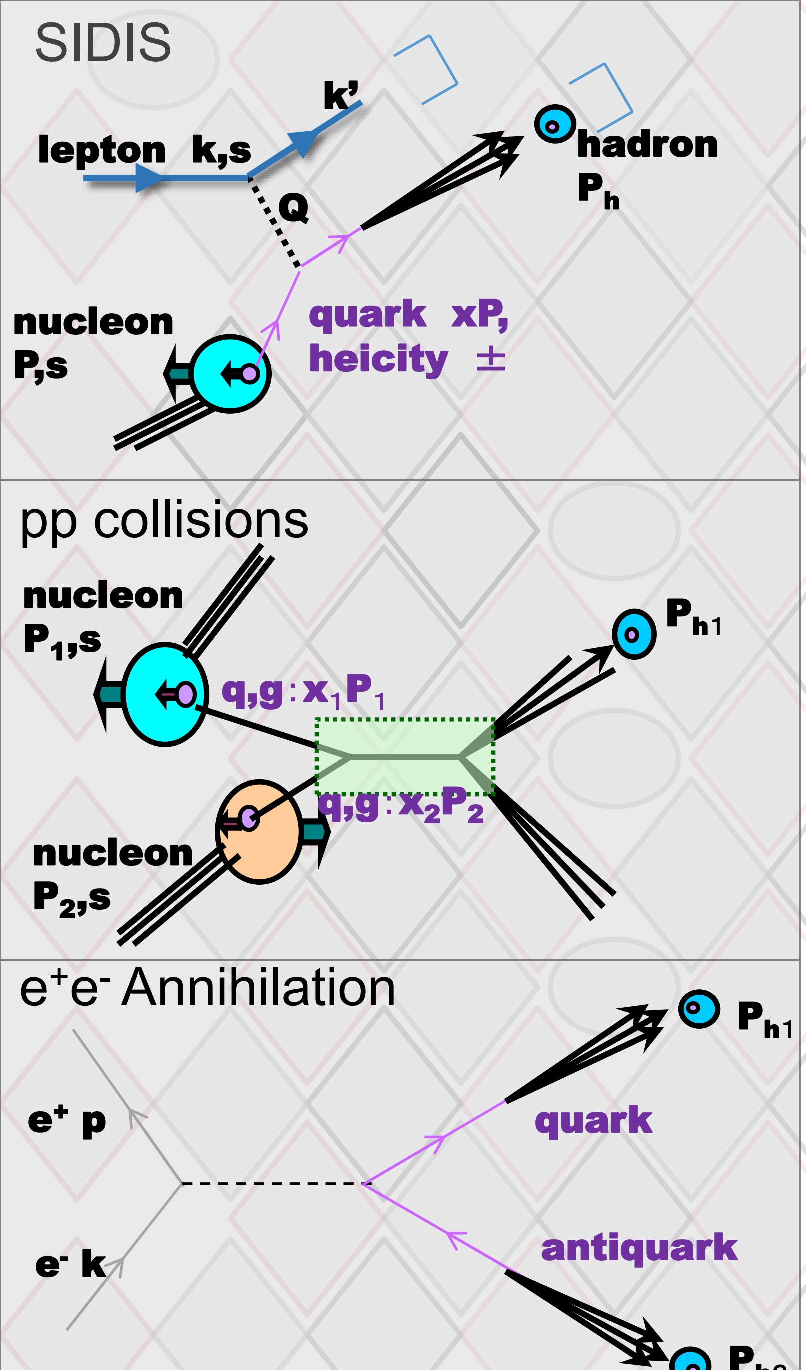
Fragmentation functions and (spin) structure of the nucleon

- Unpolarized fragmentation functions:
  - Provide flavor information in nucleon/nuclei
  - Most apparent in SIDIS measurements related to $\Delta q(x)$
  - But also required for all RHIC hadron asymmetries (especially pion A_{LL} charge ordering)
  - Transverse momentum dependence needed for Sivers and other TMDs

- Polarized fragmentation functions:
  - For transverse spin almost unique access (require two chiral-odd functions):
    - DY: δq x δq or
    - SIDIS/RHIC: δq x Collins or δq x IFF
  - FFs from Belle/Babar



Access to FFs

- 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

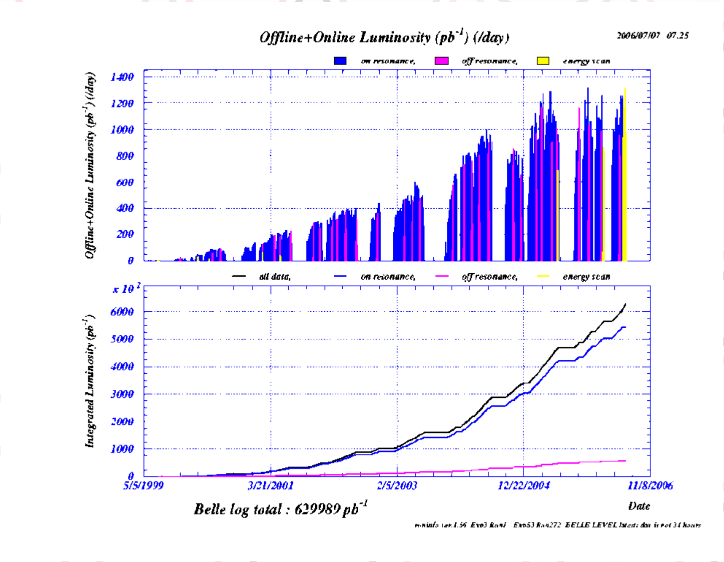
- e^+e^-:

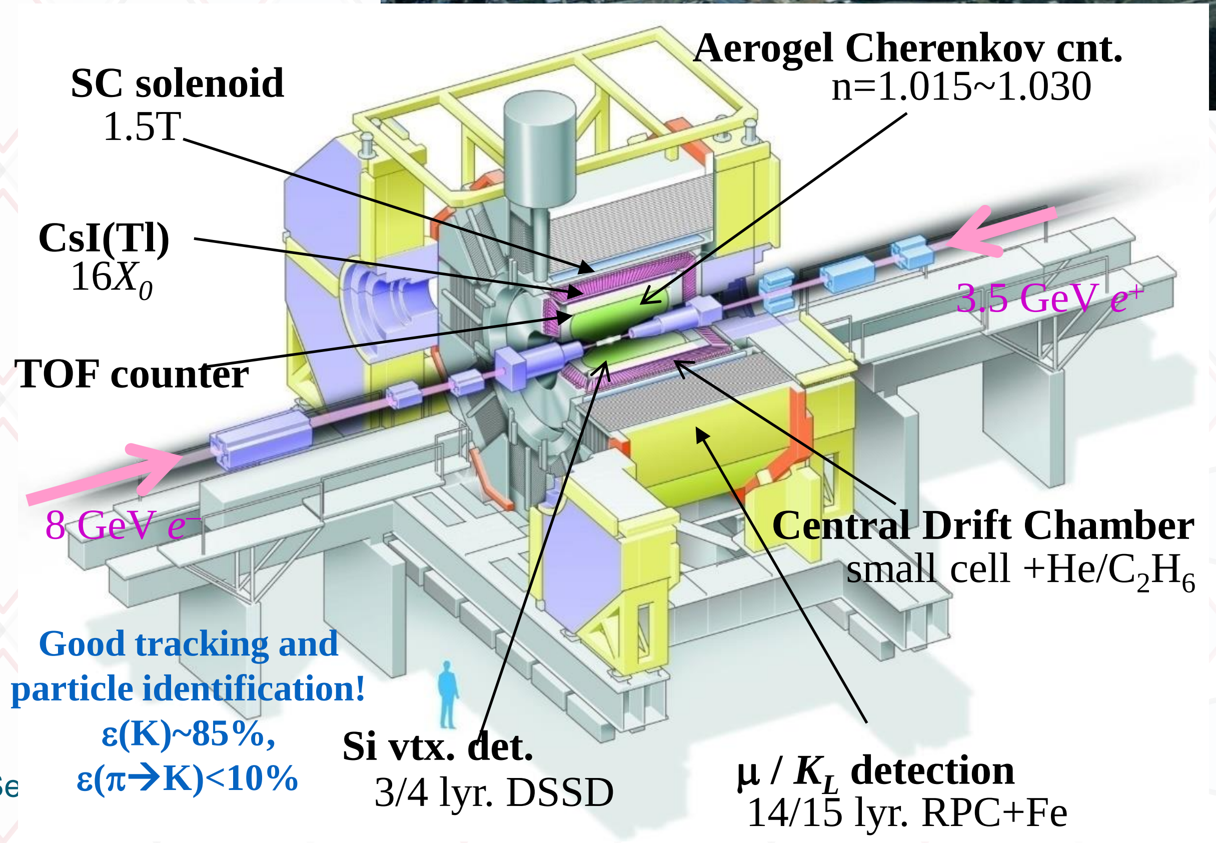
$$\sigma^h(z, Q^2, k_t) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, k_t, Q^2) + D_{1,\bar{q}}^h(z, k_t, Q^2)\right)$$

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

Belle Detector and KEKB

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





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 FF

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

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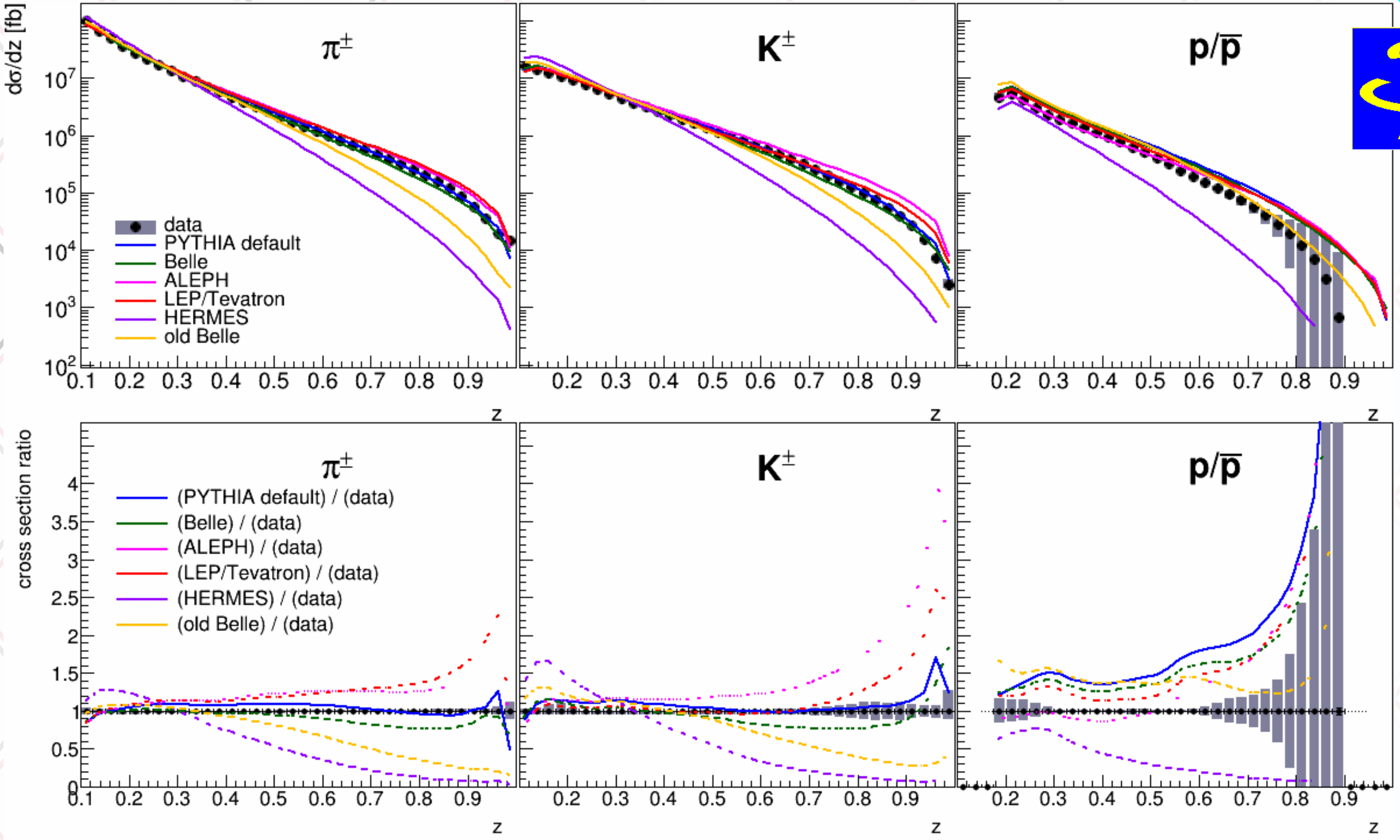
Unpolarized single hadrons

PRD 101 (2020) 092004

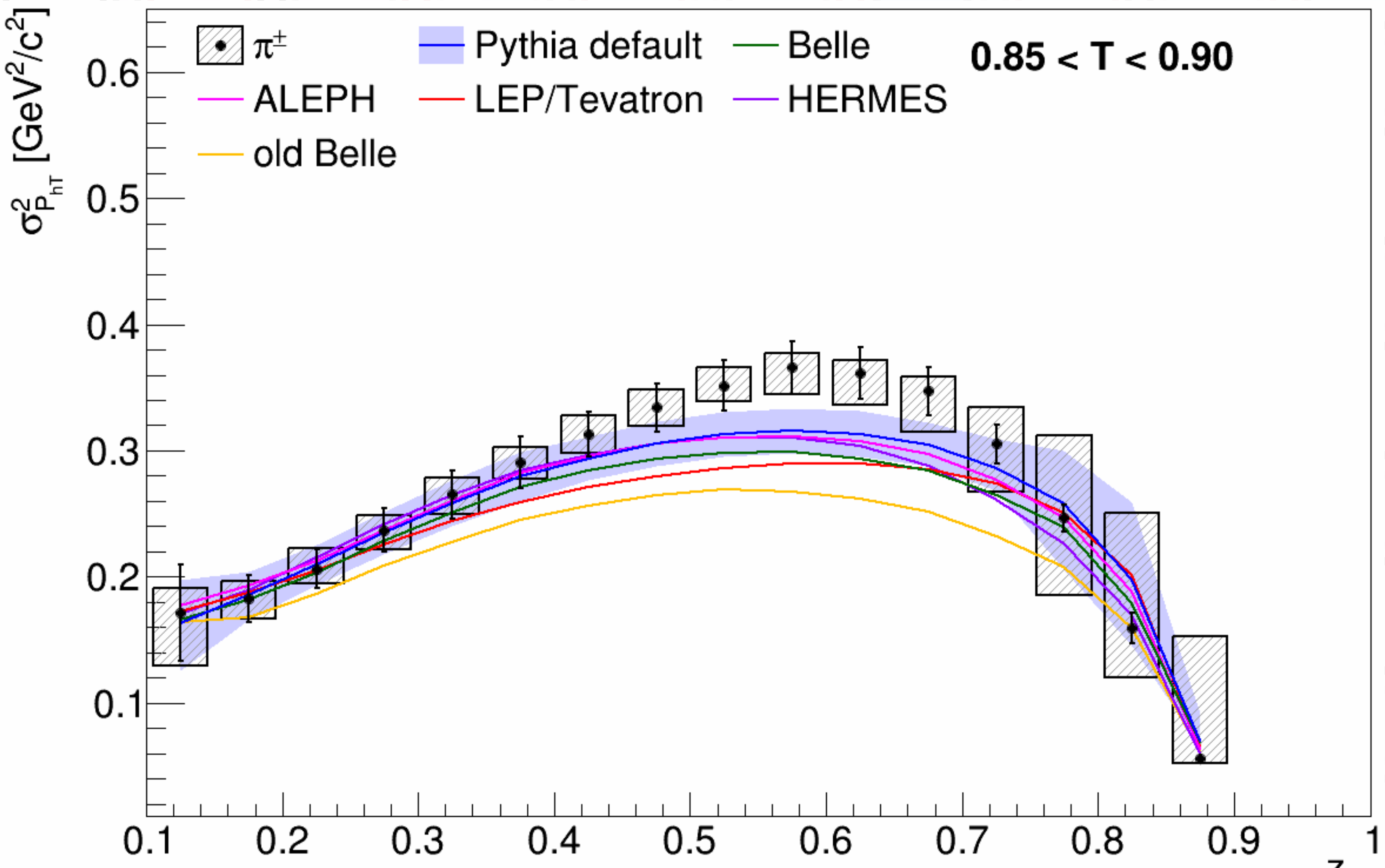


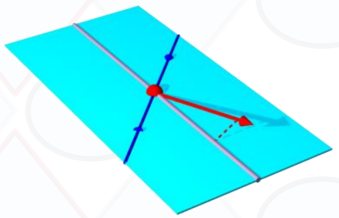
- Update with better ISR correction
- Correlated and uncorrelated uncertainties separated → improve global unpolarized FF fits

Single hadron transverse momentum 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

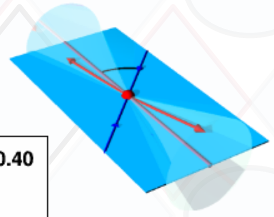


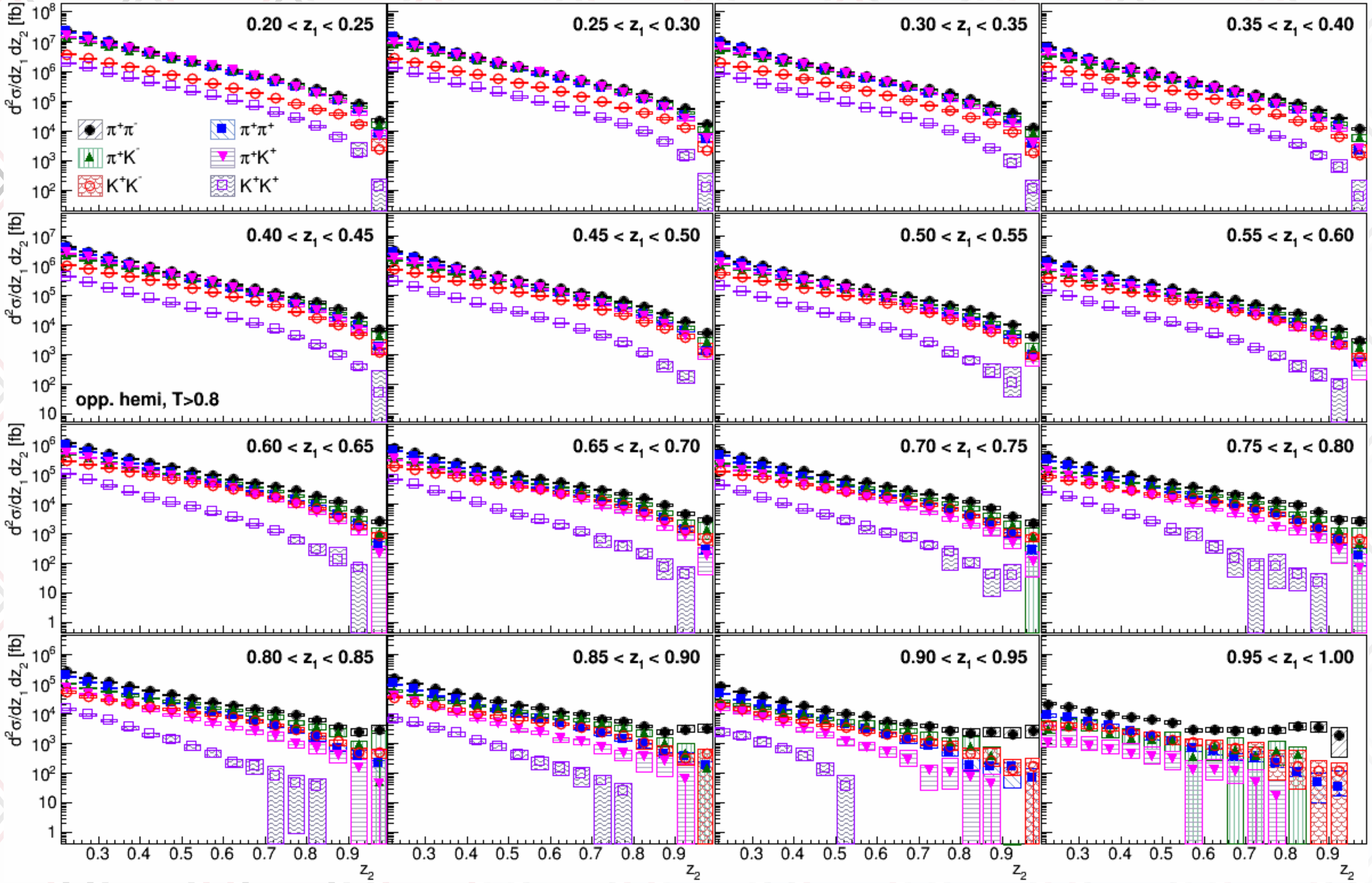


PRD99 (2019) 112006

Dihadrons in opposite hemisphere

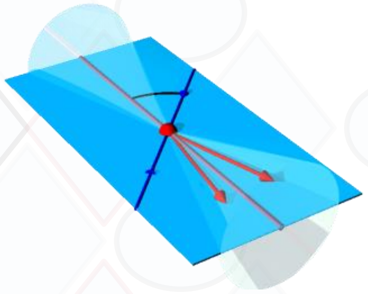
[PRD 101 (2020) 092004]



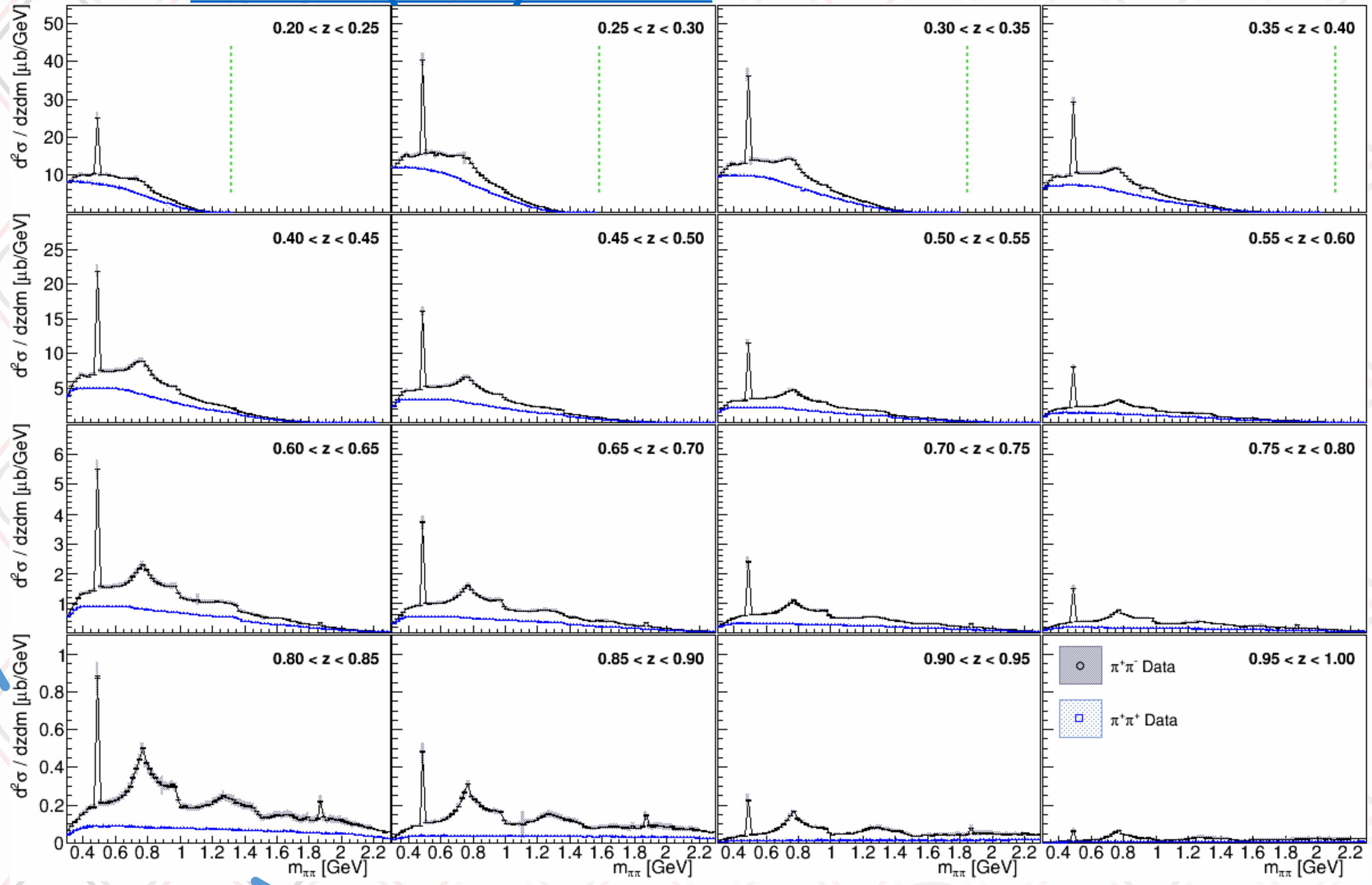


Di-hadron mass dependence (same hemisphere)

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



$\frac{d^2\sigma}{dzdm_{\pi\pi}}$



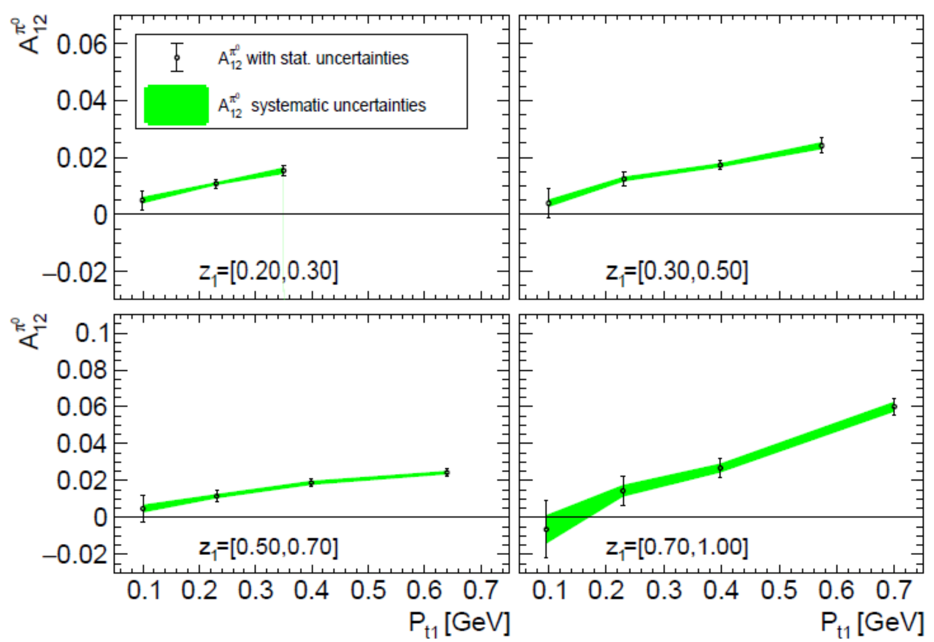
$m_{\pi\pi}$

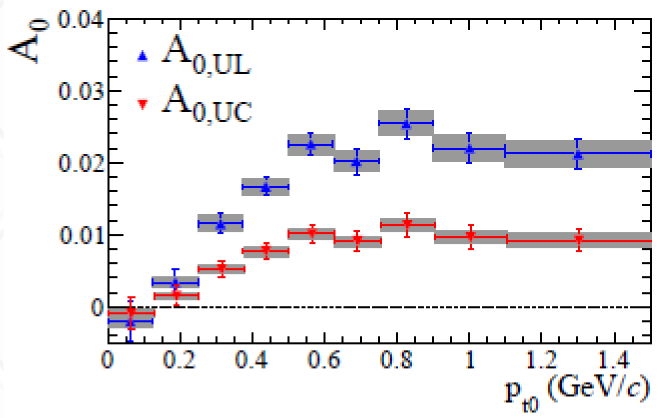
- Important input for IFF based transversity global analysis
- Individual resonances, etc quite visible; interesting for FF in itself

Collins transverse momentum dependence

- 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





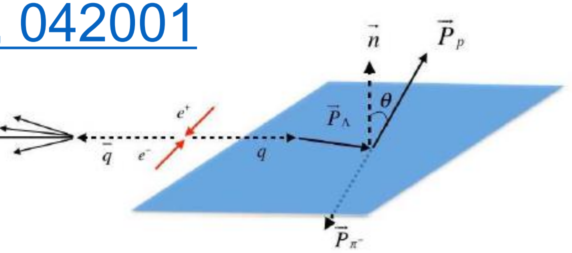
PRD 90 (2014) 052003 (Babar)

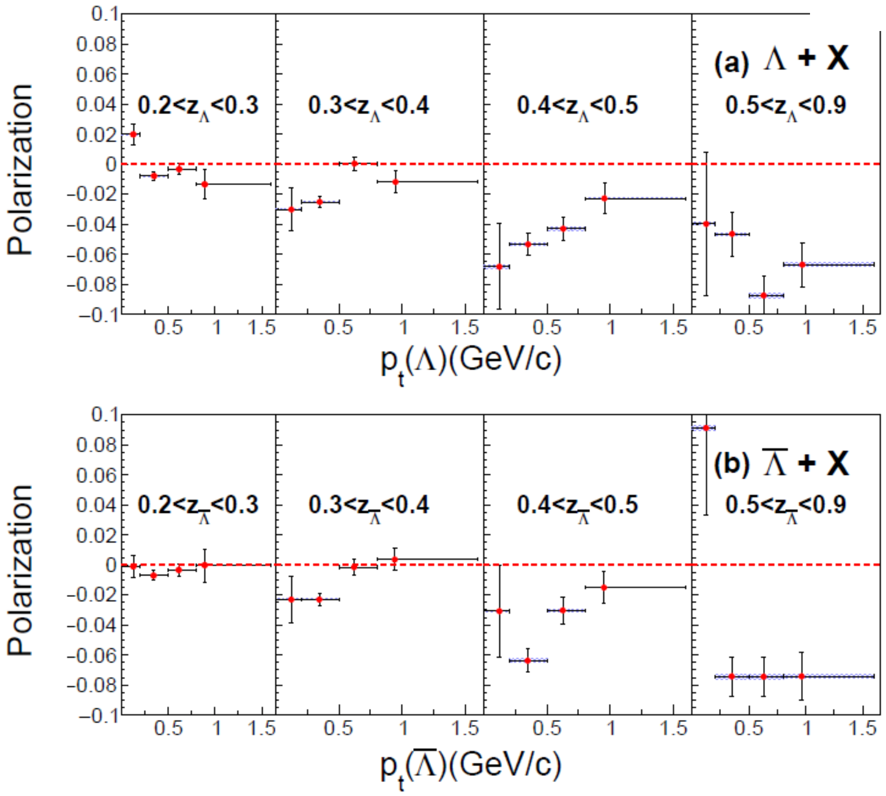
Λ polarization, transverse momentum dependence

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

- 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

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





Systematics that limit the Belle Fragmentation measurements*

- PID systematics
- Acceptance corrections
- ISR/FSR corrections
- Tune/MCEG dependence

- Multidimensional detector smearing unfolding
- Interplay of uncertainties; correlated and uncorrelated errors and combination of those, asymmetric uncertainties

*that are likely also relevant to EIC (SI)DIS measurements

Correction chain for most Belle FF related xsec results

Correction	Method	Systematics
PID mis-id	PID matrices (5 x 5 types in 9 cos θ_{lab} x 17 p_{lab} bins)	MC sampling of inverted matric element uncertainties, variation of PID correction method
Momentum smearing	MC based smearing matrices, SVD unfolding	SVD unfolding vs analytically inverted matrix, reorganized binning, MC statistics
Non-qqbar BG removal	eeuu, eess, eecc, tau MC subtraction, (Υ(5S) decays)	Variation of size, MC statistics
Acceptance I (cut efficiency)	In barrel: reconstructed vs generated MC	MC statistics
Acceptance II	Various generated MCs: barrel to 4π	MC statistics, variation in tunes
Weak decay removal (optional)	udcs check evt record for weak decays	Compare to other Pythia settings
ISR	ISR on vs ISR off in Pythia	Variations in tunes

PID correction

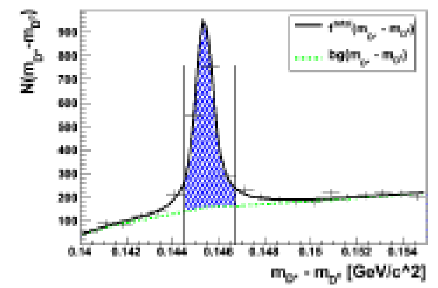
- Both at Belle and EIC an interplay between many PID detectors (Aerogel, TOF, CDC, KLM, EMCAL) + tracking

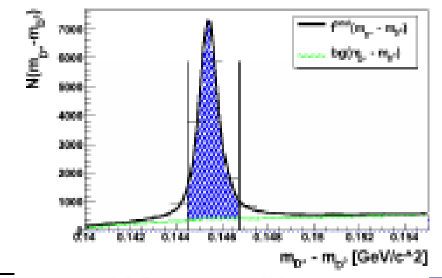
→description of PID efficiencies via MC limited

- Try to obtain efficiencies based on data, but will strongly depend on lab momentum and polar angle

→17 x 9 p_{Lab} x θ_{Lab} bins

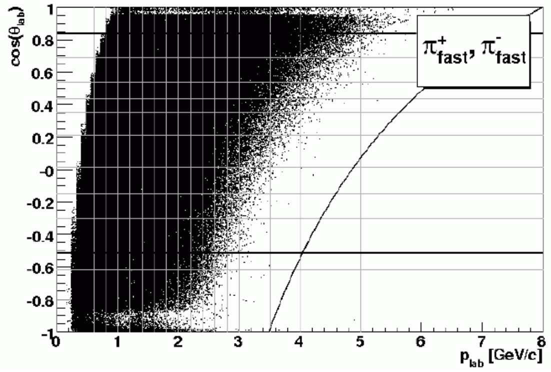
- Electrons, muons via J/Psi decays
- Kaon/pion identification via $D^{*\pm} \rightarrow D^0(K\pi)\pi^{\pm}$ (mass distribution + charge of slow pion)
- Protons via Λ decays
- (possible other decays that could be used $K_s \rightarrow \pi\pi$, $\phi \rightarrow KK$,etc)
- General difficulty of combinatoric BG below mass peaks

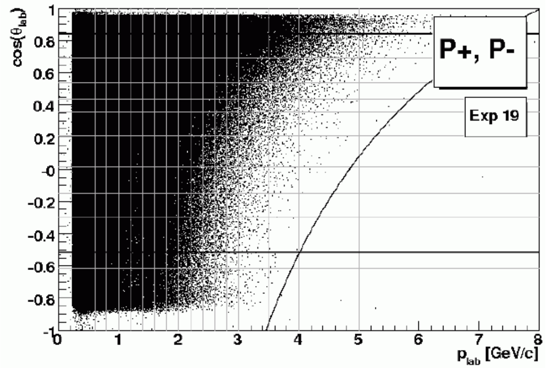


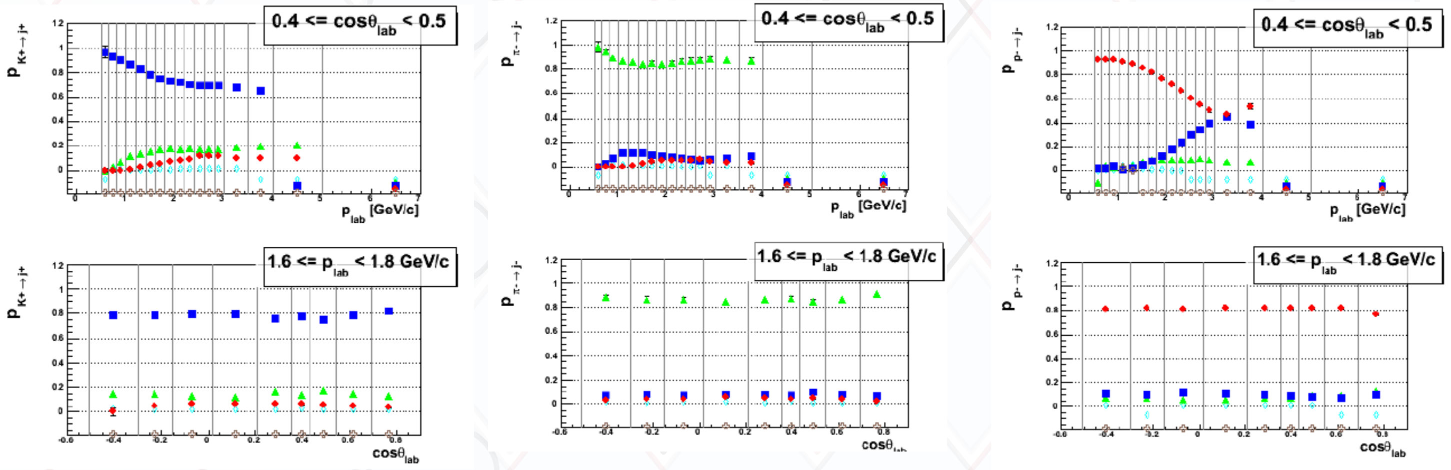


Belle PID efficiency evaluation

- Sources of uncertainties:
  - Nonzero backgrounds below mass peaks
  - Kinematically inaccessible regions (try other particles, or fall back to MC extrapolating from accessible region)
  - Statistical uncertainties through matrix inversion (Sampling technique)



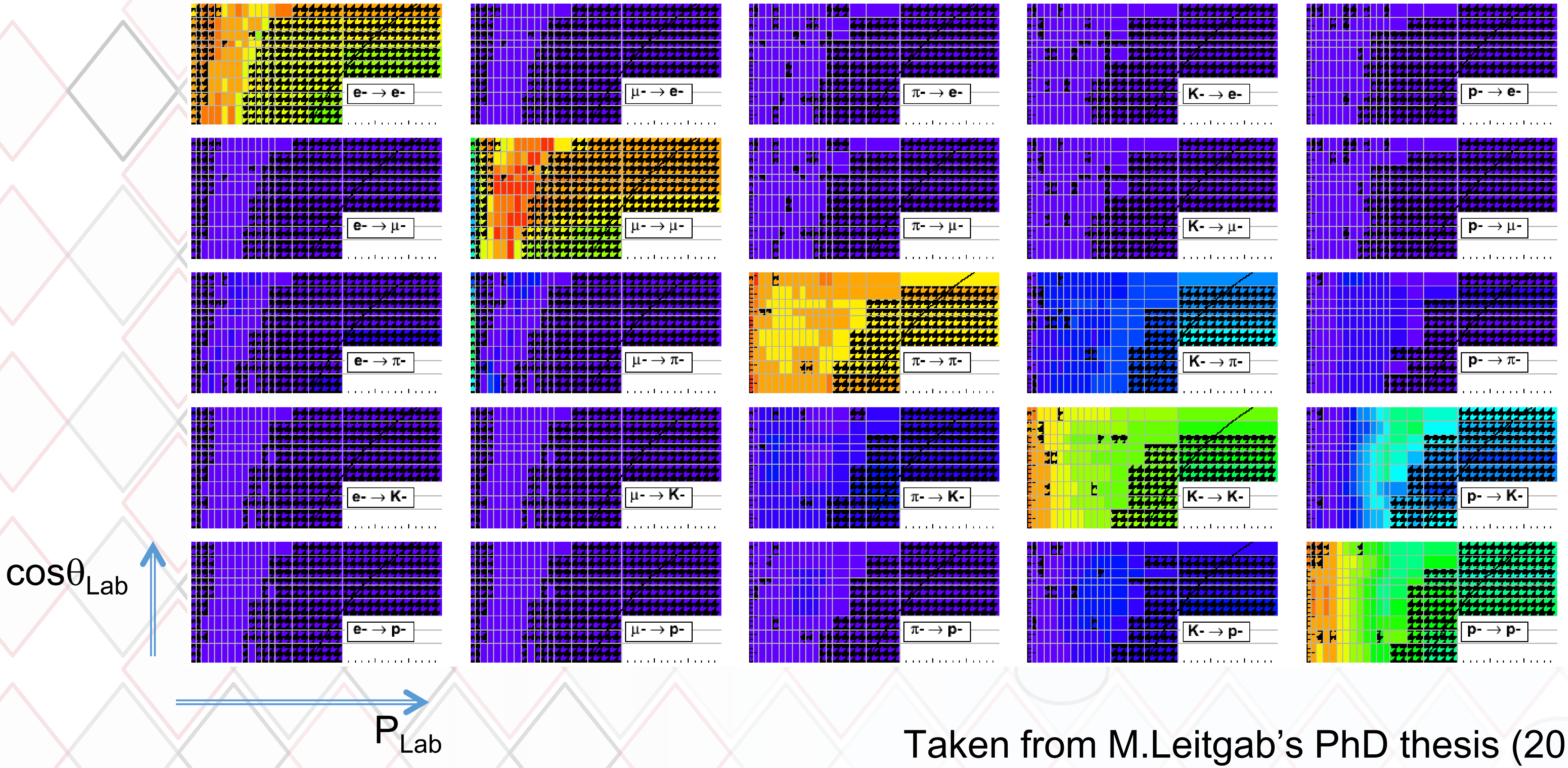




		REAL Particles				
		π	K	p	μ	e
Reconstructed particles	π					
	K					
	p					
	μ					
	e					

Taken from M.Leitgab's PhD thesis (2013)

PID efficiencies

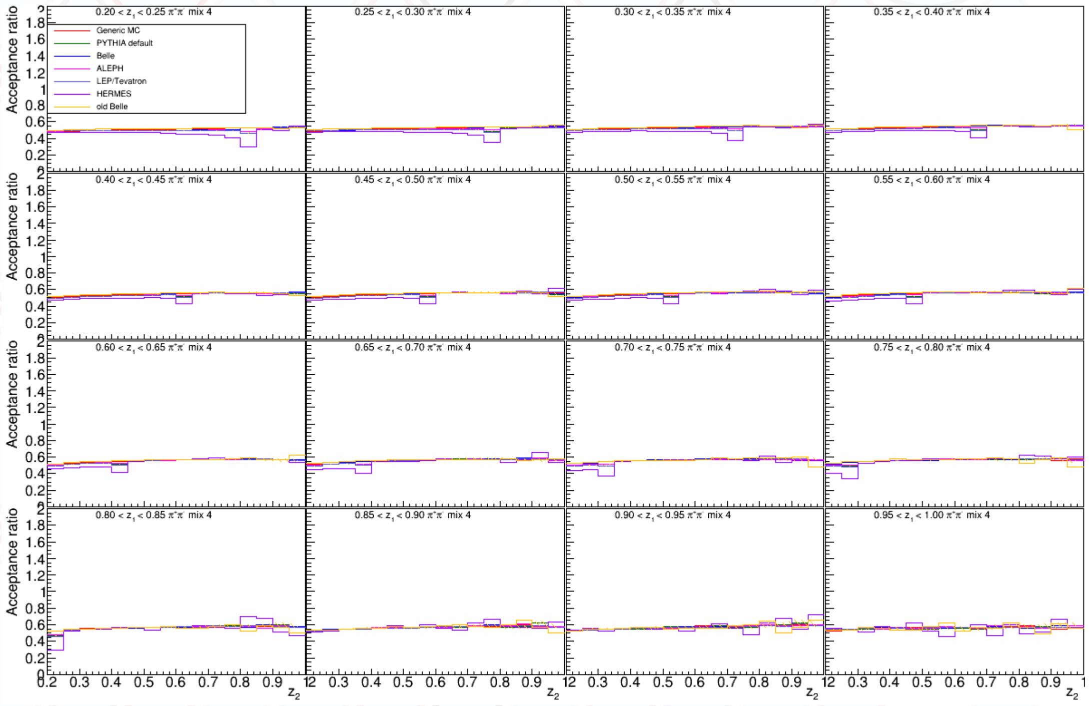


Taken from M.Leitgab's PhD thesis (2013)

Acceptance

- Correcting from your detector acceptance to 4π in principle straightforward, but:
- Will to some extend again depend on your actual measurement, e.g. partonic $1+\cos^2\theta$ dependence needs to be fulfilled for z→1, but below will depend on FFs (z dependence, strong decays, etc)

→Tune dependence



ISR/FSR

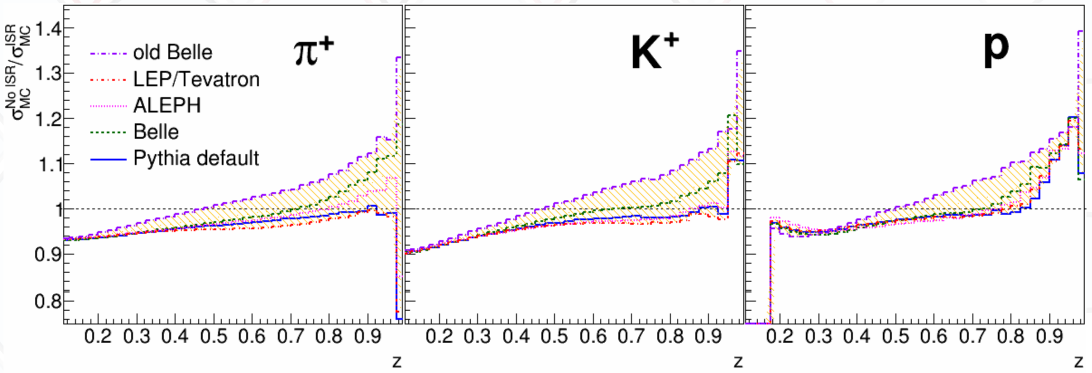
- We correct for ISR by calculating cross section ratios in the MC with ISR switched off (MSTP(13) =0) over on (=1)
- Mostly straightforward correction in e+e-; ISR reducing qqbar system energy → moving hadron momenta (and z) to lower values
- However, also changes the boost of the qqbar system

→accumulation of (supposedly) high kt particles wrt thrust axis

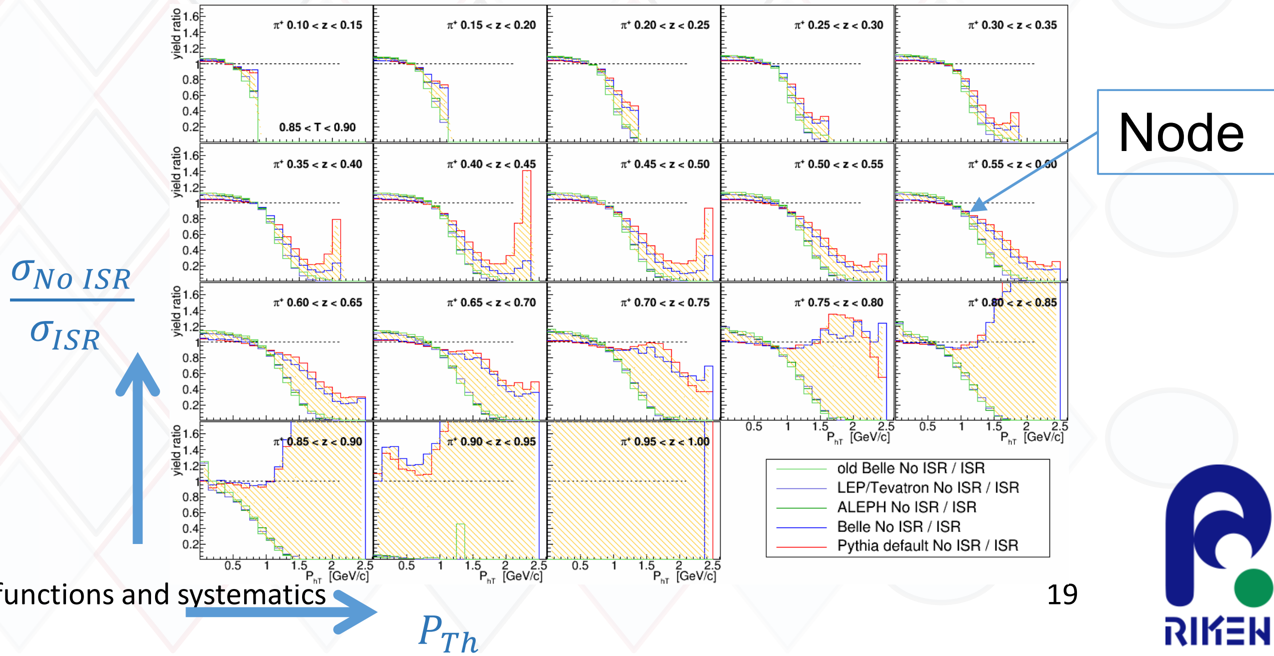
→accumulation of higher-mass di-hadrons from opposite (true) hemispheres

- Similar (+spin) effects need to be considered in SIDIS measurements!
- Also: see Tune dependence

recent single/dihadron update: [PRD 101 (2020) 092004]



Single hadron transverse momentum dependentresults: [PRD99 (2019) 112006]



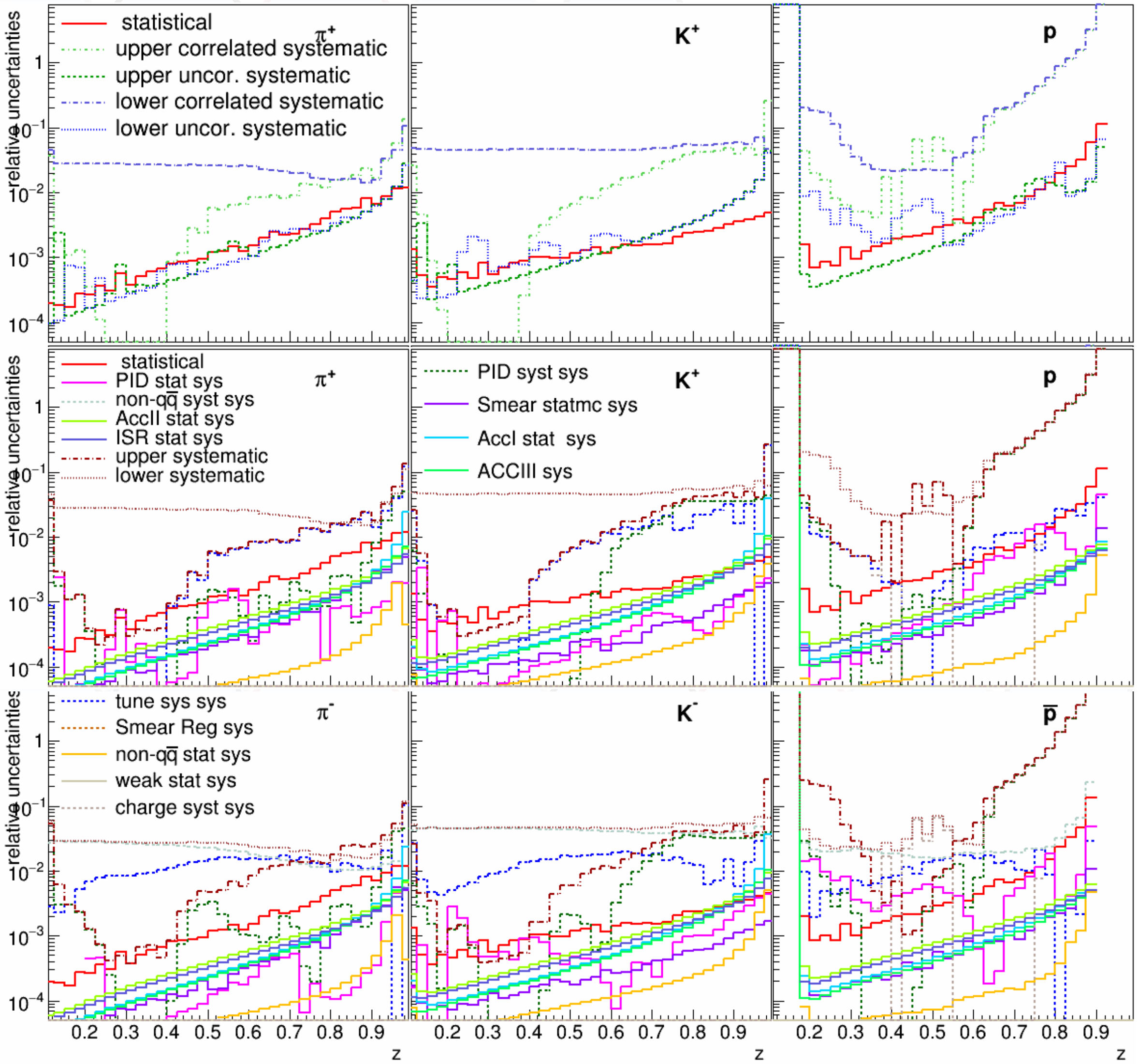
Unfolding

- Unfolding (smearing correction) in principle straightforward, but:
- Regularization with SVD unfolding can be tricky, need to good initial description of data yields, only artificial multi-dimensional unfolding possible→source of uncertainties
- Iterative unfolding (eg RooUnfold's Bayes unfolding) generally more reliable, up to three dimensions directly available

- However:
  - MC needs a good description of the detector response
  - (significantly) larger amount of MC data wrt to actual data, especially important for multi-dimensional unfolding

Tune dependence

- Some efforts to systematically improve the MC tunes for a certain cms energy (Professor → apprentice)
- Relies heavily on the measurements itself and choice of input measurements
- Ideally will give you reasonable uncertainty ranges on all relevant MC tune parameters, so far mostly variation of some tunes that “kind of work” (somewhere)
- Requires many simulations of each reasonable parameter set, preferably including full detector description



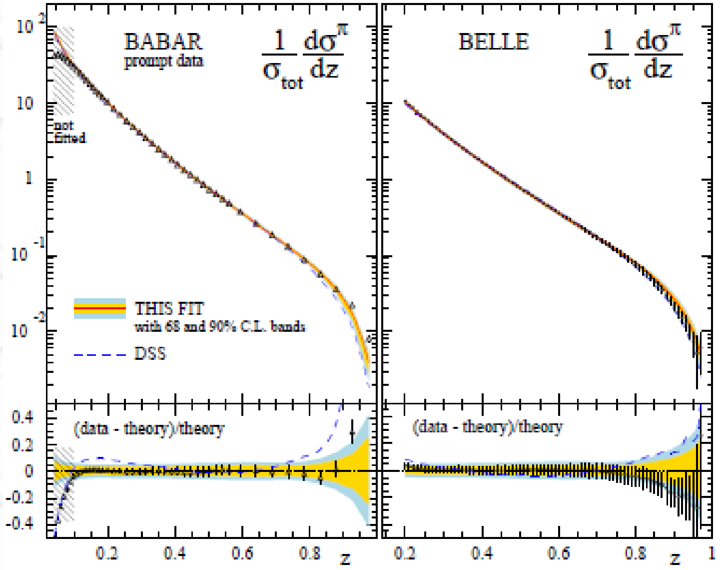
Total, individual upper and individual lower uncertainty budgets for single hadron cross sections: PRD101(2020) 092004

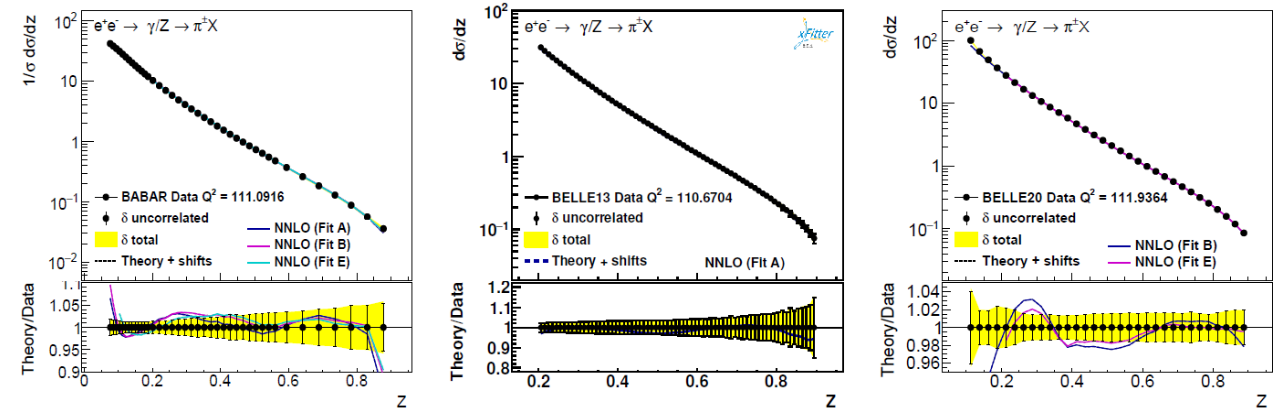
From “your errors are too conservative” to “your errors are too precise”

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,
  - all systematics symmetric (INCORRECT!)

Phys.Rev. D91 (2015) 1, 014035





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

Future work at Belle, BelleII

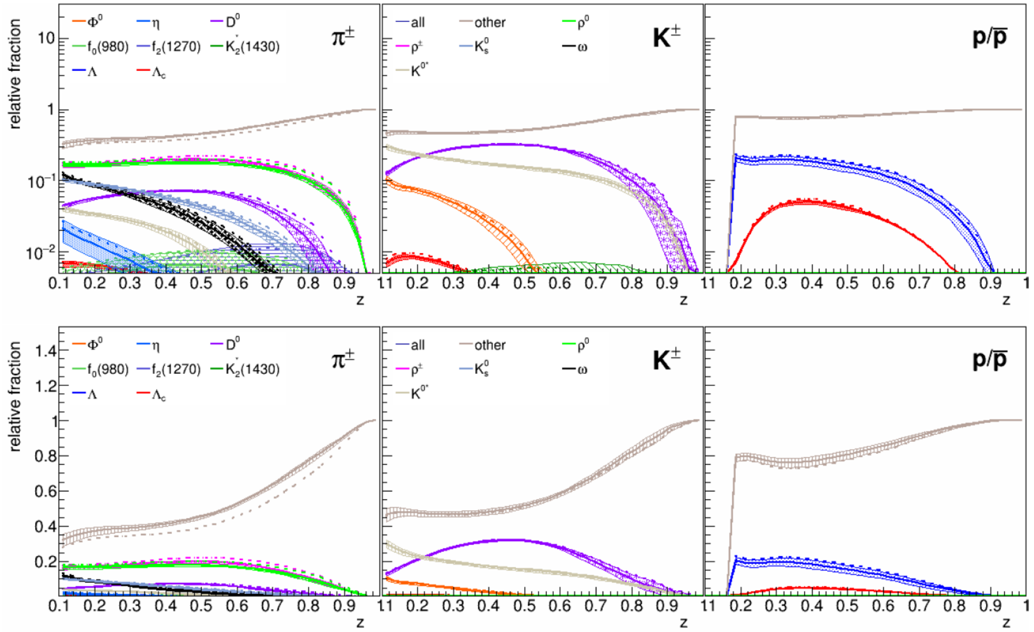
See also Snowmass white paper: https://arxiv.org/abs/2204.02280

- Improve/Tune the MC description of fragmentation
  - “Traditional" event shapes like thrust and (linear) sphericity
  - Identified particle spectra including π, K ,p, γ, $\pi 0$, η ; multi-dimensionally
  - Resonance (especially Vector-mesons) and heavier baryon cross sections
  - Tests of charge, strangeness, baryon number conservation, especially along thrust direction/hemispheres
  - Jet measurements
  - Make all information available to Theorists/MCEGs →Hepdata/RIVET
- Comparisons of MC description of polarized fragmentation
- Jet-based fragmentation measurements

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
  - How does PHENO handle this (additional parameters?)

Decaying hadron fractions in light hadrons at $\sqrt{s}$ = 10.58 GeV (PYTHIA6):

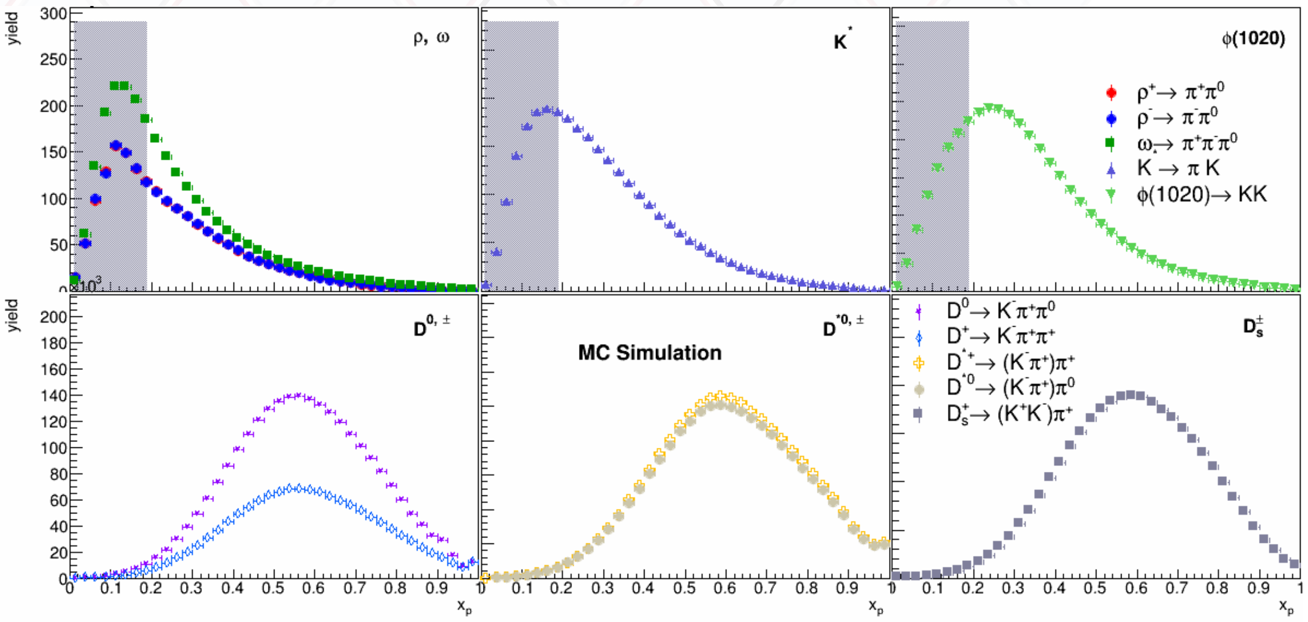


Bands: various Pythia tunes, including PARJ(11 VM to PS ratio) range from 0.3-0.55
Dashed lines: default, but PARJ(11) =0.6

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 (for 4π acceptance):



Summary

- Many Belle/Babar/BES3 fragmentation related measurements available that form the basis for semi-inclusive DIS measurements:
  - Unpolarized single hadrons, and transverse momentum dependence wrt thrust axis
  - Collins asymmetries (k_t dependent, kaons)
  - Polarizing Λ fragmentation
  - Detailed di-hadron cross section and asymmetry measurements
- Most of these measurements are systematics limited with the main uncertainties from MC tune-dependence, PID corrections, kinematic unfolding, treatment of ISR/FSR
- Need to reduce systematics and provide as much information (individual contributions, type of uncertainty) to fitters
- 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
  - More to come from Belle and BelleII