FRAGMENTATION FUNCTIONS

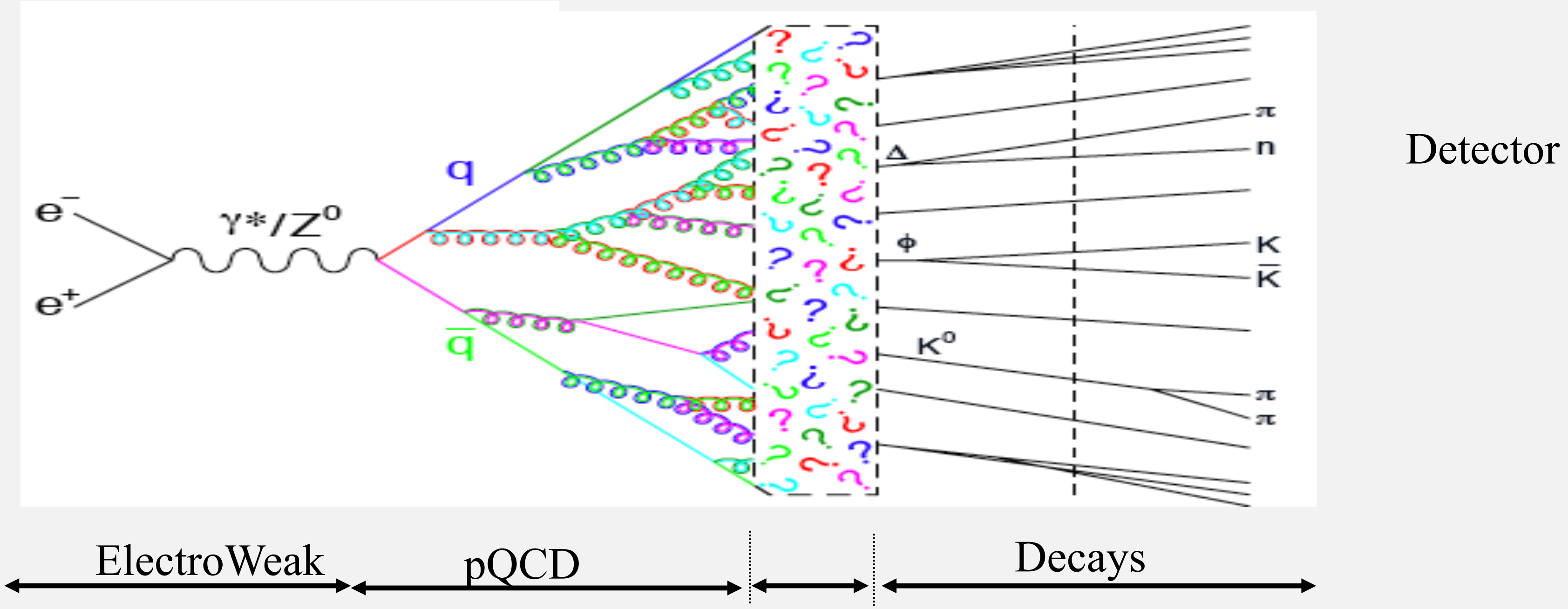
Anselm Vossen

FRAGMENTATION FUNCTIONS (FOCUS ON RECENT e^+e^- RESULTS FROM BELLE RESULTS)

Anselm Vossen

FACTORIZED QCD: HADRONIZATION DESCRIBED BY FRAGMENTATION FUNCTIONS

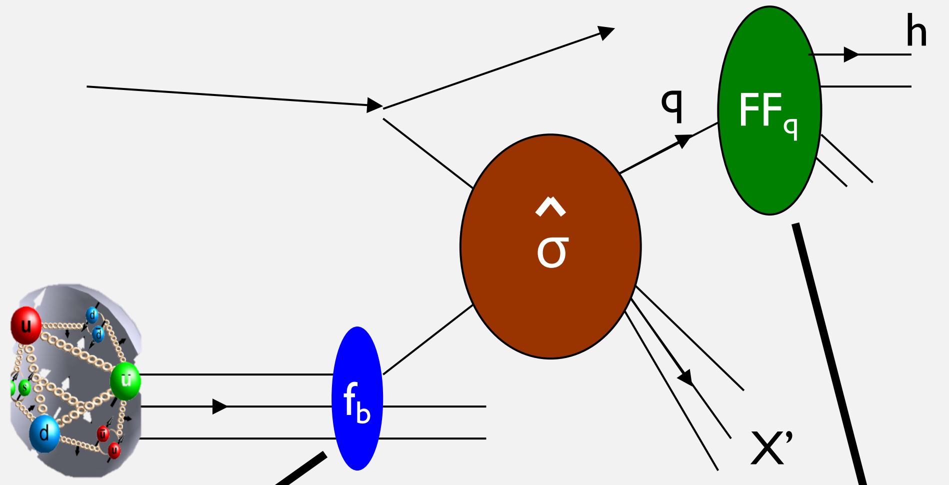
Field, Feynman (1977): Fragmentation functions encode the information on how partons produced in hard-scattering processes are turned into an observed colorless hadronic bound final-state [PRD 15 (1977) 2590]



- Complementary to the study of nucleon structure (PDFs)
- Cannot be computed on the lattice
- Questions to be asked
  - **Macroscopic effect (distribution, polarization)of microscopic properties (quantum numbers)?**
  - Effect of QCD vacuum the quark is traversing
  - Study of the formation of hadrons →e.g. Phys.Rev. D97 (2018) no.7, 072005

ACCESS NUCLEON STRUCTURE THROUGH **FRAGMENTATION FUNCTIONS**

- **Proton Structure extracted using QCD factorization theorem**
- **FFs contribute to virtually all processes**
- **Essential for model idep. Etraction of e.g.**
  - **Transverse spin structure**
  - **TMDs**
  - **…**



Proton Structure

pQCD

fragmentation function

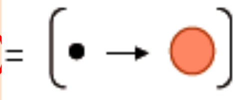
$$\frac{d^2\sigma(ep\to\pi X)}{dx\,dz}\propto q(x,k_T)\times\frac{d\sigma^2(e\,q\to e'q')}{dx}\times FF(z,p_T)$$

SINGLE HADRON PRODUCTION IN SIDIS IS A WELL TRAVELLED PATH

Observables:

z: fractional energy of the quark carried by the hadron

$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → **Hadron Polarization ↓**	**Spin averaged**	**longitudinal**	**transverse**
spin averaged	$D_1^{h/q}(z, p_T)$= 		$H_1^{\perp h/q}(z, p_T)$ = 
longitudinal			
Transverse (here Λ)			

"YOU THINK YOU UNDERSTAND SOMETHING?---NOW ADD SPIN…**IN HADRONIZATION**!"

- **→polarized final states**
- **→di-hadron correlations**

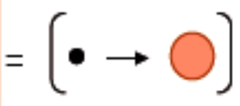
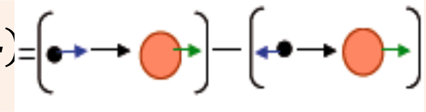
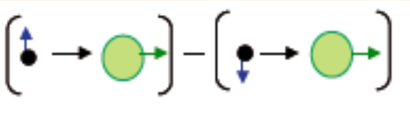
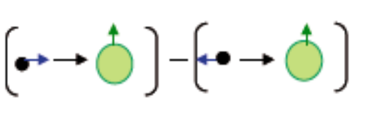
- Explore spin-orbit correlation in hadronization
- Additional degrees of freedom in final state make targeted extraction of nucleon structure possible →see $h_1(x)$, $e(x)$

ENTER POLARIZATION IN THE FINAL STATES

<u>Observables:</u>

z: fractional energy of the quark carried by the hadron

$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → Hadron Polarization ⇣	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z, p_T)$ = 		$H_1^{\perp h/q}(z, p$ = 
longitudinal		$G_1^{\Lambda/q}(z, p_T)$ = 	$H_{1L}^{h/q}(z, p_T)$ 
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z, p_T)$ = 	$G_{1T}^{h/q}(z, p_T)$ = 	$H_1^{\Lambda/q}(z, p_T)$ =  $H_{1T}^{\perp\Lambda/q}(z, p_T)$ = 

- Analogue →similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay (Λ)
- Gluon FFs similar but with circular/linear polarization (not as relevant for e+e-)

DI-HADRON FRAGMENTATION FUNCTIONS

<u>Additional Observable:</u>

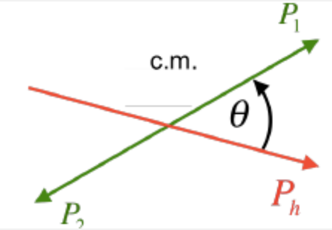
$\vec{R} = \overrightarrow{P_1} - \overrightarrow{P_2}$:

The relative momentum of the hadron pair is an additional degree of freedom:

the orientation of the two hadrons w.r.t. each other and the jet direction can be an indicator of the quark transverse spin

Parton polarization → **Hadron Polarization ⇣**	**Spin averaged**	**longitudinal**	**transverse**
spin averaged	$D_1^{h/q}(z, M)$		
longitudinal			
Transverse		**$G_1^{\perp}(z,M,P_h,\theta)$=** T-odd, chiral-even →jet handedness QCD vaccum strucuture	**$H_1^{\sphericalangle}(z,M)$=** T-odd, chiral-odd Colinear

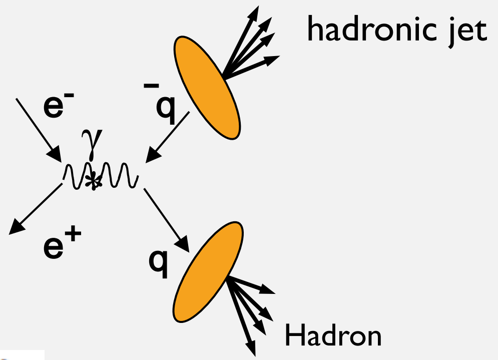
- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs



ACCESS OF FFS FOR LIGHT MESONS IN E+E- (SPIN AVERAGED CASE)

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^{e^+e^-\to hX}}{dz} := \frac{1}{\sum_q e_q^2}\left(2F_1^h(z,Q^2)+F_L^h(z,Q^2)\right),$$

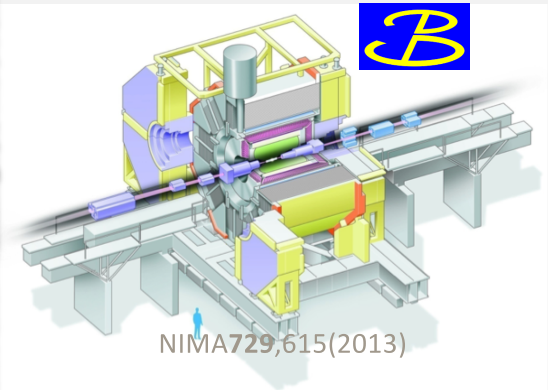
$$2F_1^h(z,Q^2) \;=\; \sum_q e_q^2\left(D_1^{h/q}(z,Q^2)+\frac{\alpha_s(Q^2)}{2\pi}\left(C_1^q\otimes D_1^{h/q}+C_1^g\otimes D_1^{h/g}\right)(z,Q^2)\right)$$



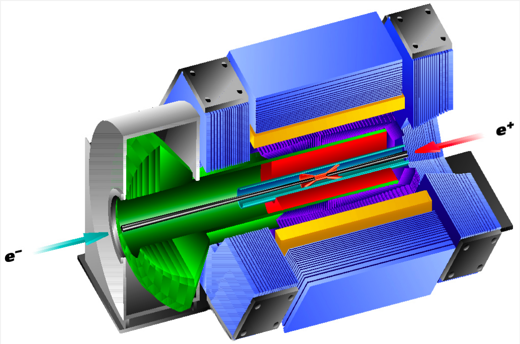
- Cleanest process→testbed for QCD calculations
- Limited access to flavor
  - (Use different couplings to γ^* and Z^0)
  - (Use polarization (SLD) and parity violating coupling)
  - **Use back-to-back correlations for different flavor combinations**
- Limited access to gluon FF
  - From evolution
  - From three jet events (but theory treatment not clear)

ROLE OF B-FACTORIES

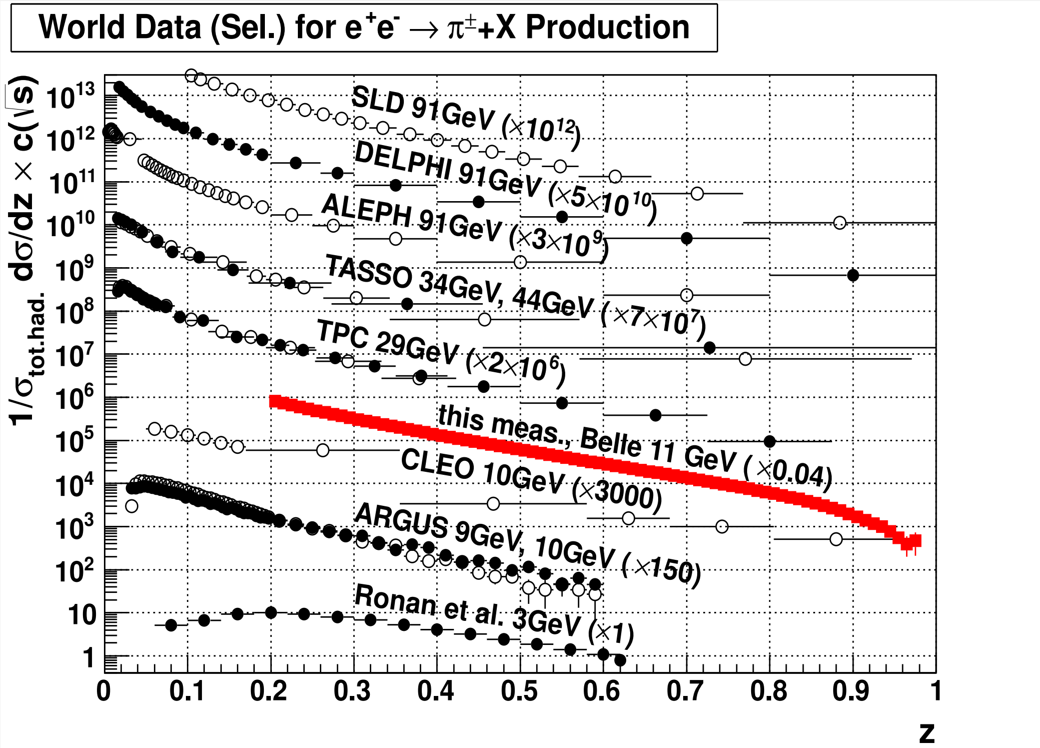
- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma=0.425$
- $L \sim 1\ ab^{-1}$



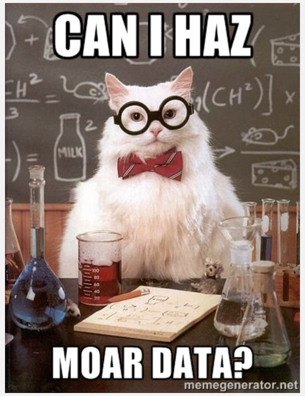
NIMA479,117(20 BABAR



- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma=0.65$
- $L \sim 500\ fb^{-1}$



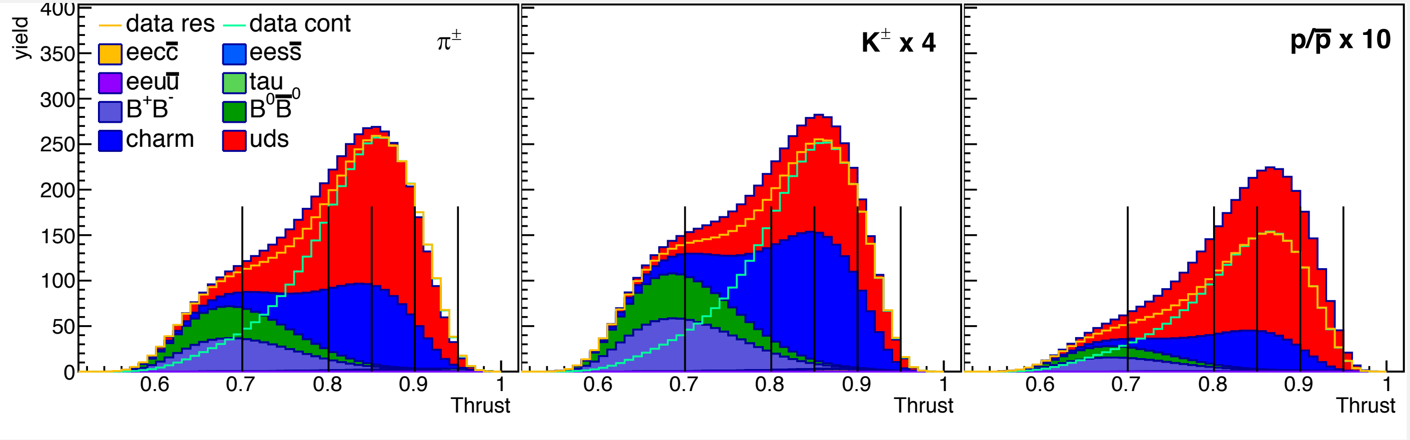
Phys.Rev.Lett. 111 (2013) 062002 (Belle)
Phys.Rev. D88 (2013) 032011 (BaBar)

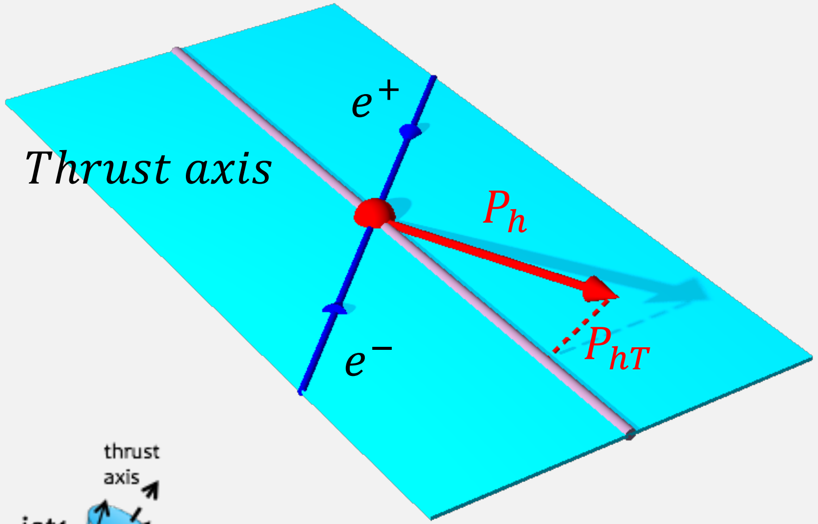


- Dominated by B factories
- Limited lever arm in $\sqrt{s}$ in particular at high z
- Precision data includes charged single hadrons π, K, p, D, Λ, charmed baryons…
- Well described at NNLO (e.g. DSS, NNFF)

NEW: P_T DEPENDENCE
PHYS.REV. D99 (2019) NO.11, 112006

- Quasi inclusive hadron production gives access to transverse momentum in fragmentation
- **Transverse momentum measured with respect to thrust axis**
- Analysis performed differentially in bins of $z, P_{hT}, Thrust$ $(18\times20\times6)$

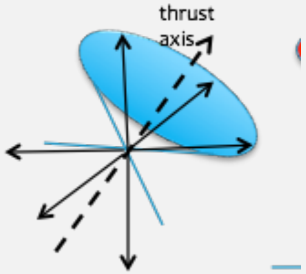




$$T = \sum_i \frac{|\mathbf{P}\cdot\hat{\mathbf{n}}|}{|P|}$$

$$\text{thrust axis} \equiv \hat{\mathbf{n}}$$

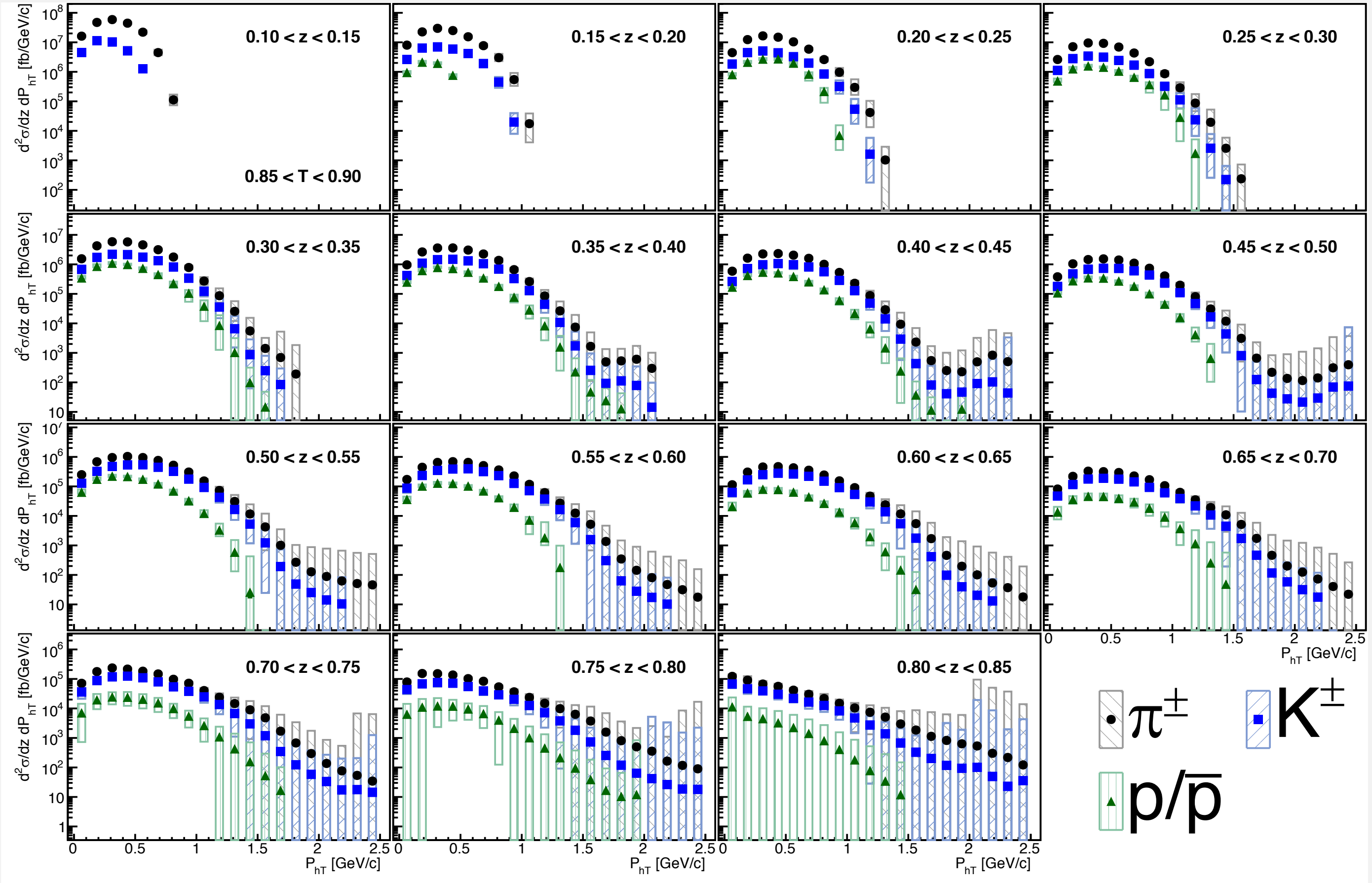
$$0.5 \leq T \leq 1$$



T~0.5

T~1

TRANSVERSE MOMENTUM DISTRIBUTIONS



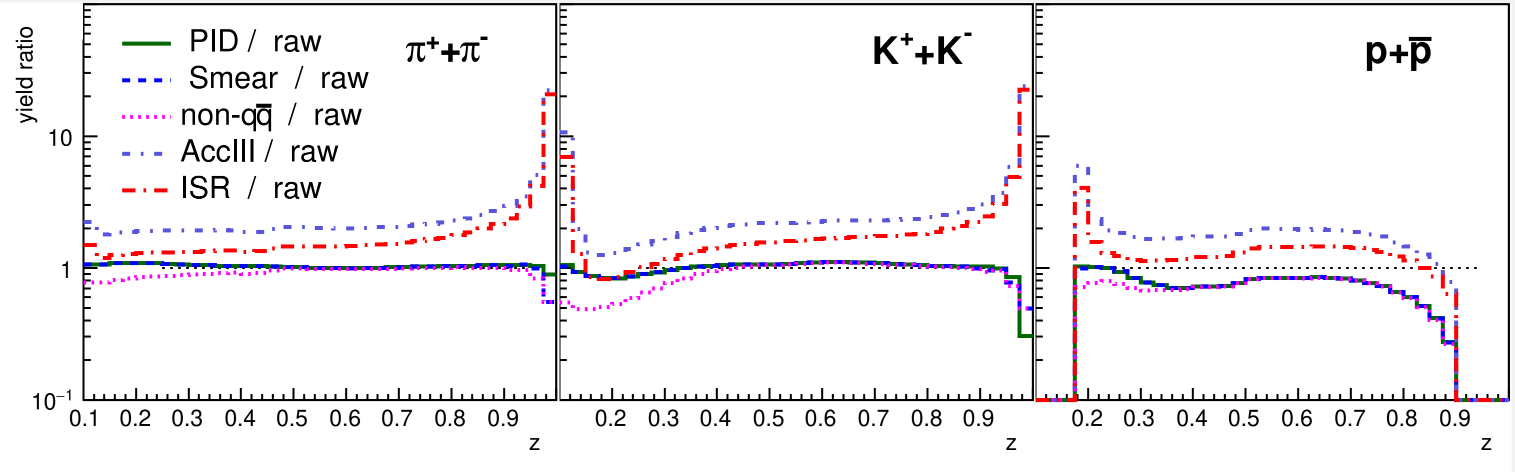
- 0.85< Thrust T < 0.9
  - Transverse momenta mostly Gaussian
  - Possible deviations for large P_{hT} tails, but also large uncertainties

FROM HADRON YIELDS TO CROSS-SECTIONS

- **Hadron yields undergo a series of corrections**
  - Particle (mis) identification [e.g. not every identified pion was a pion]
  - Smearing unfolding [e.g. measured and true momentum might differ]
  - Non $\bar{q}q$-processes [e.g. two photon processes, $\Upsilon \rightarrow B\bar{B}\ldots$)
  - "4π"-correction [selection criteria and limited acceptance]
  - QED radiation [initial-state radiation (ISR)]
- **Collins asymmetries also corrected for false asymmetries and axis (mis)recontruction**

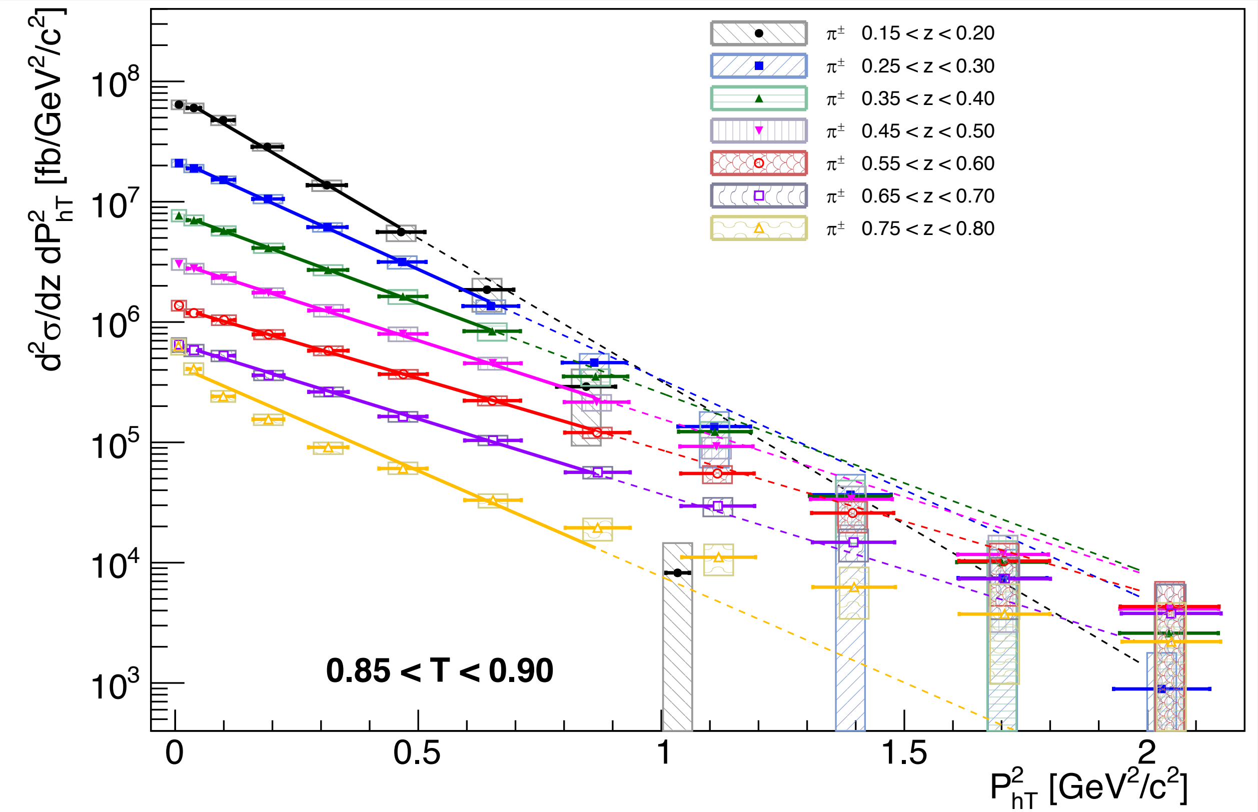
FROM HADRON YIELDS TO CROSS-SECTIONS

- **Example: single hadron inclusive cross-sections**
  - Largest effect for mesons **from acceptance** and **ISR corrections**
  - Larger PID correction for protons than for mesons



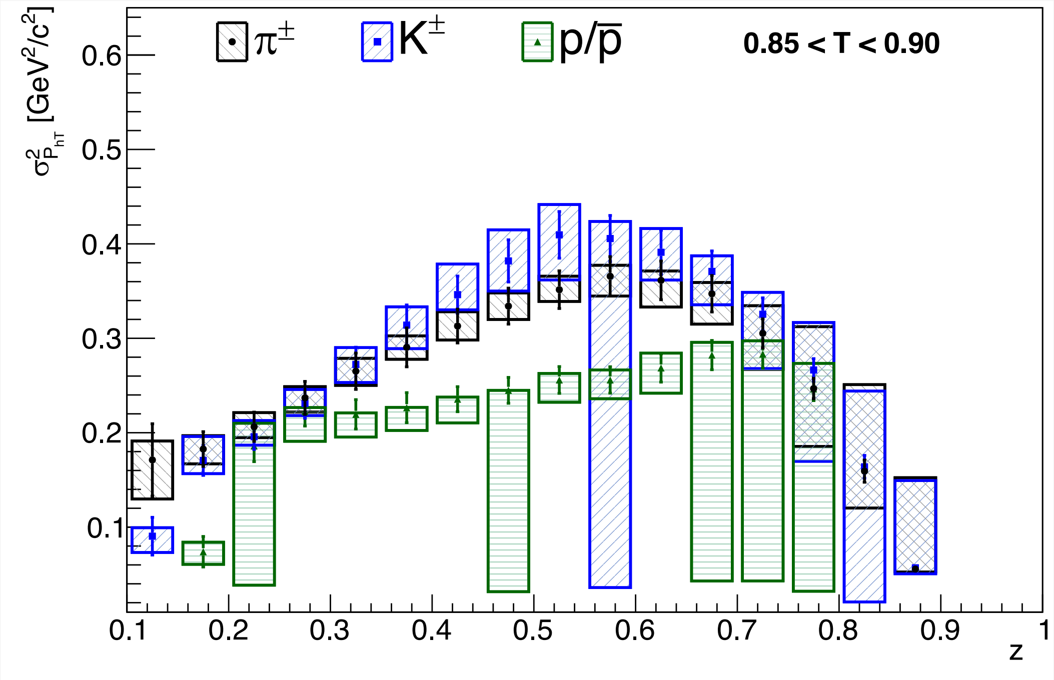
Phys.Rev. D92 (2015) no.9, 092007

TRANSVERSE MOMENTUM: GAUSSIAN WIDTHS

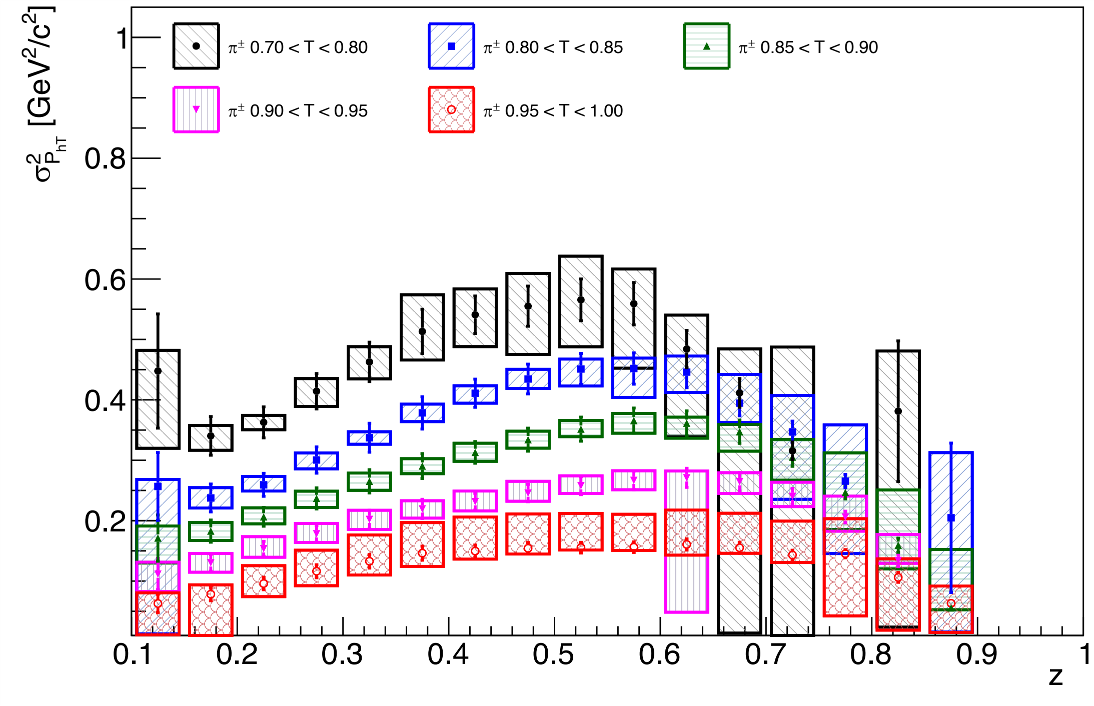


- 0.85 < T < 0.9
  - Fit Gauss to low P_{hT} data
  - Mostly well described with possible exception at high z
  - Deviation from Gauss at large P_{hT}
  - Clear increase in width with z for low values of z

GAUSSIAN WIDTH AS A FUNCTION OF Z AND T

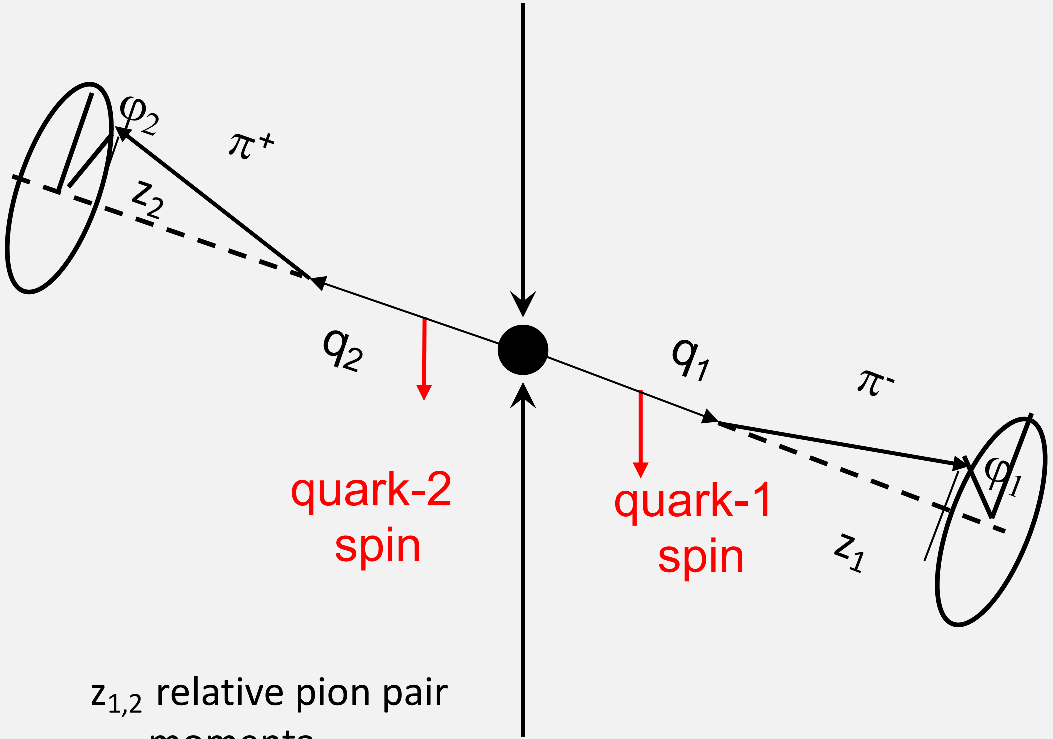


- General increase with z with turnover at larger values of z for mesons
- Protons with smaller width and more linear rise with z



- General increase with z with turnover at larger values of z for mesons
- Clear decrease of widths with increase of T
  - Particles more and more collimated

COLLINS FFs IN e^+e^-



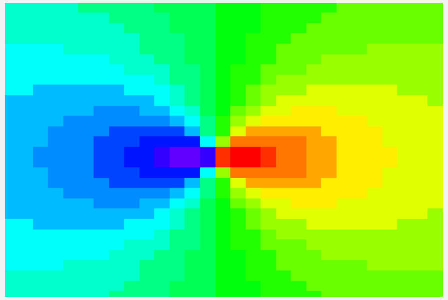
$z_{1,2}$ relative pion pair momenta

•First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ $\sqrt{s} \sim 10.6$ GeV (PRL 111,062002(2008), PRD 88,032011(2013)) leads to first extraction of transversity (Phys.Rev. D75 (2007) 054032) from SIDIS and e+e-

- Confirmed by BaBar @ $\sqrt{s} \sim 10.6$ GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
- Measured at BESIII @ $\sqrt{s} = 3.65$ GeV (PRL 116,42001(2016))

Cross-section $e^+e^- \to (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

$$\propto D_1^\perp \overline{D_1^\perp} + H_1^\perp \overline{H_1^\perp} \cos(\phi_1 + \phi_2)$$



- Access spin dependence and p_T dependence (convolution or in jet) without PDF complication
- Made possible by B-factory luminosities

NEW PT DEPENDENCE FROM BELLE

Unlike/**L**ikesign

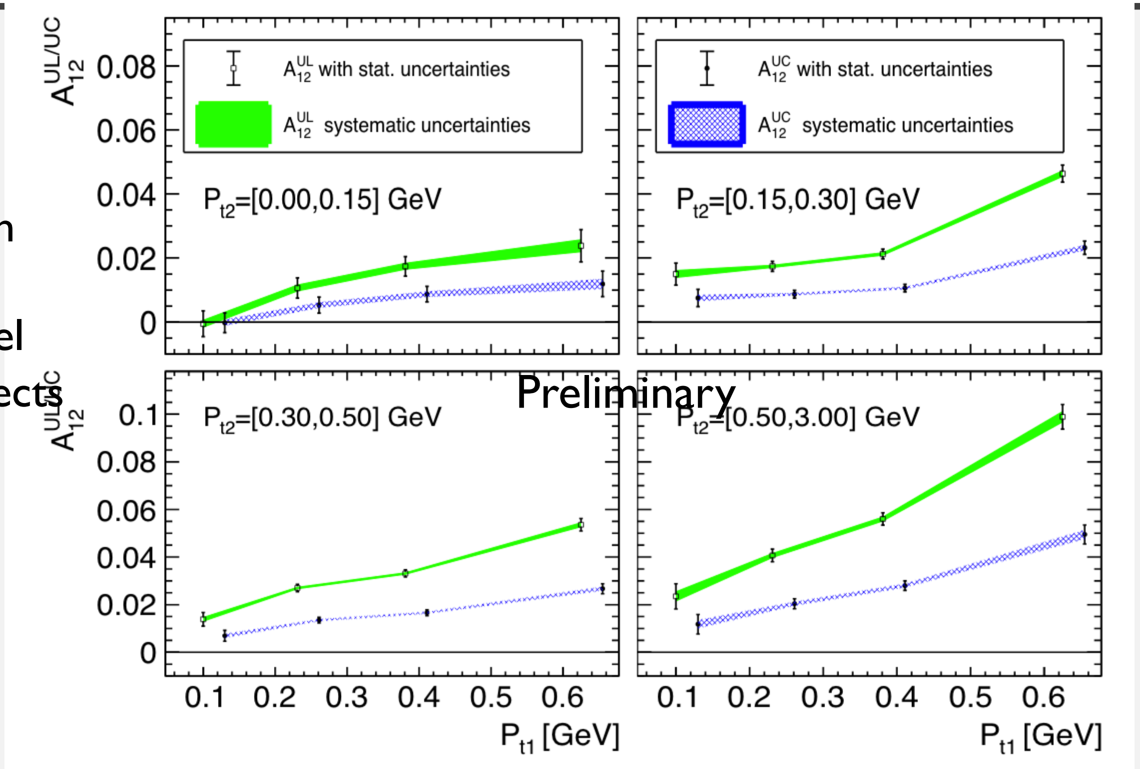
Ratios to cancel acceptance effects

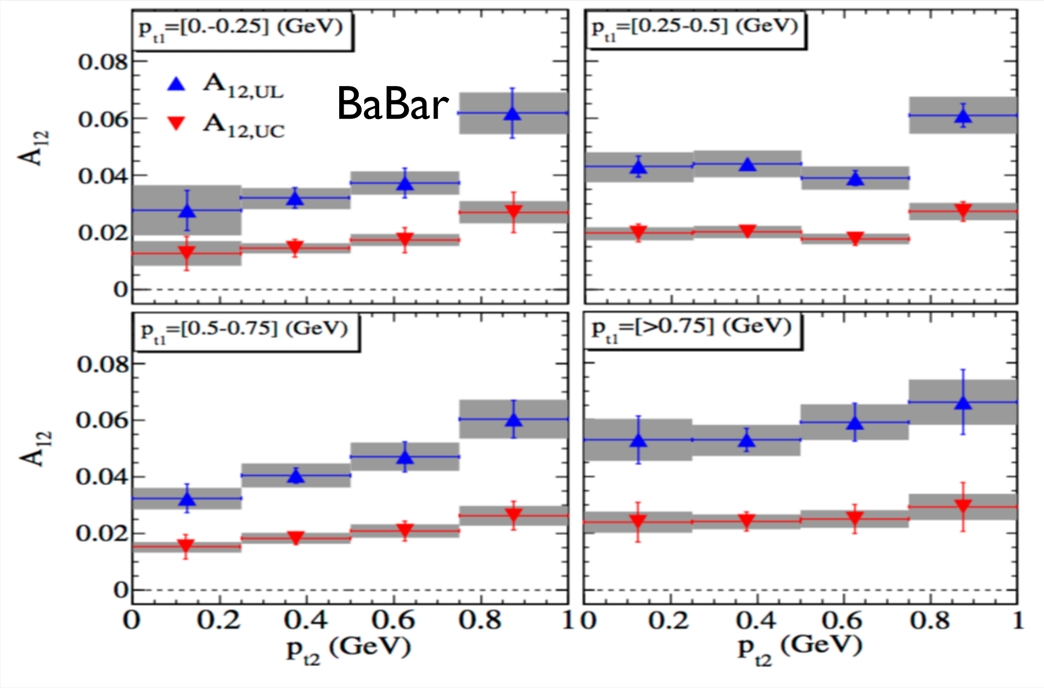
Unlike:

fav*fav+dis*dis

Like:

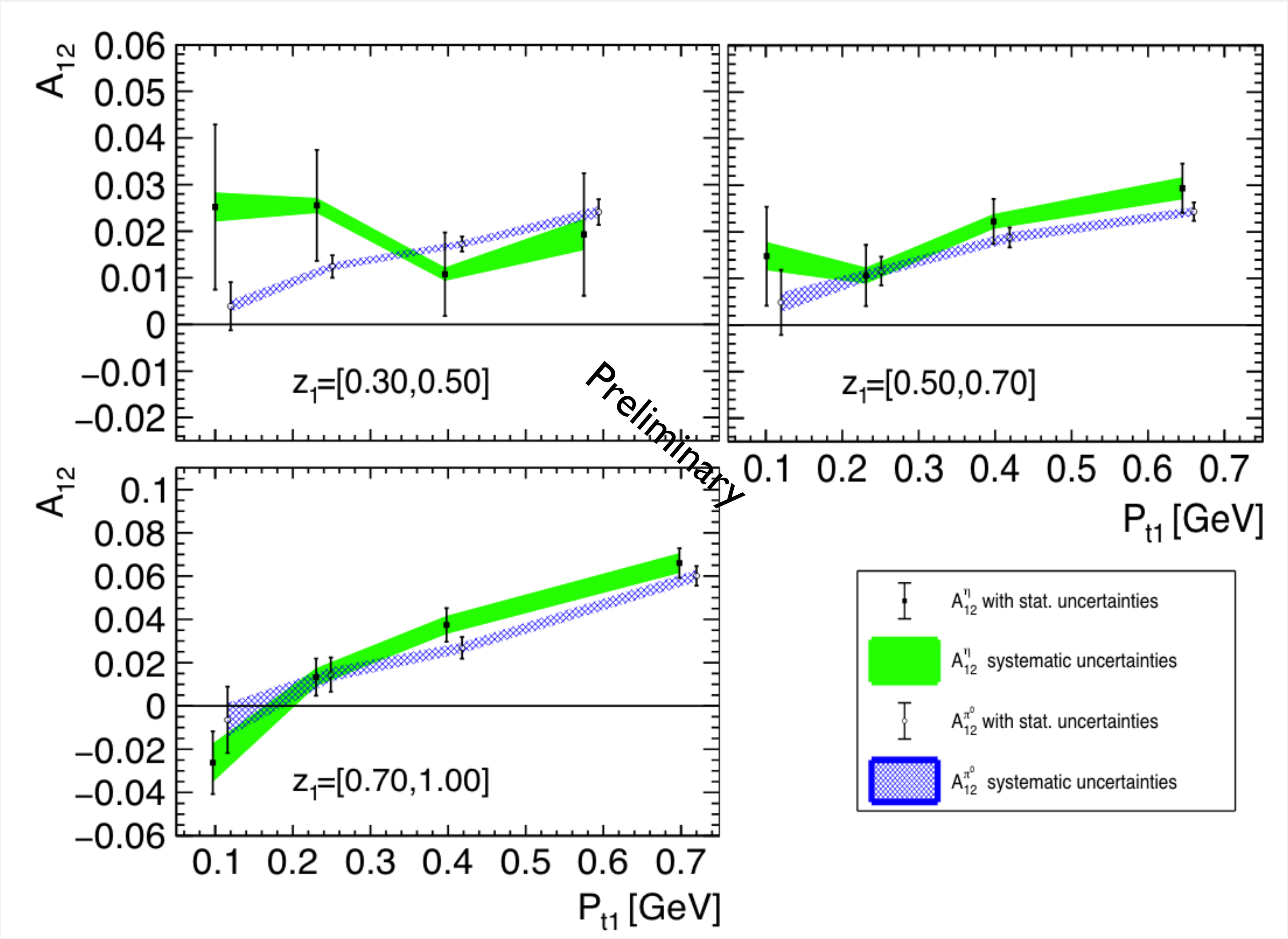
fav*dis





- Trend consistent with BaBar
- Direct comparison difficult due to different correction schemes (thrust vs $q\bar{q}$ −axis)

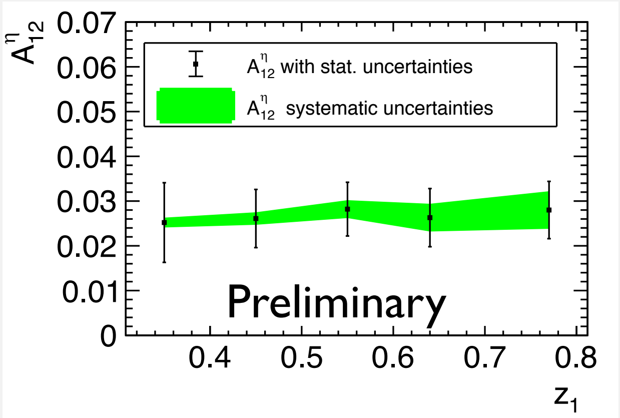
NEW π^0/η FROM BELLE



$$\mathcal{R}^{\pi^0}_{12} = \frac{R^{0\pm}_{12}}{R^{L}_{12}} = \frac{\pi^0\pi^+ + \pi^0\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

$$\mathcal{R}^{\eta}_{12} = \frac{R^{\eta\pm}_{12}}{R^{L}_{12}} = \frac{\eta\pi^+ + \eta\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

- **Rise with $z_{1,2}$, similar to charged pions**

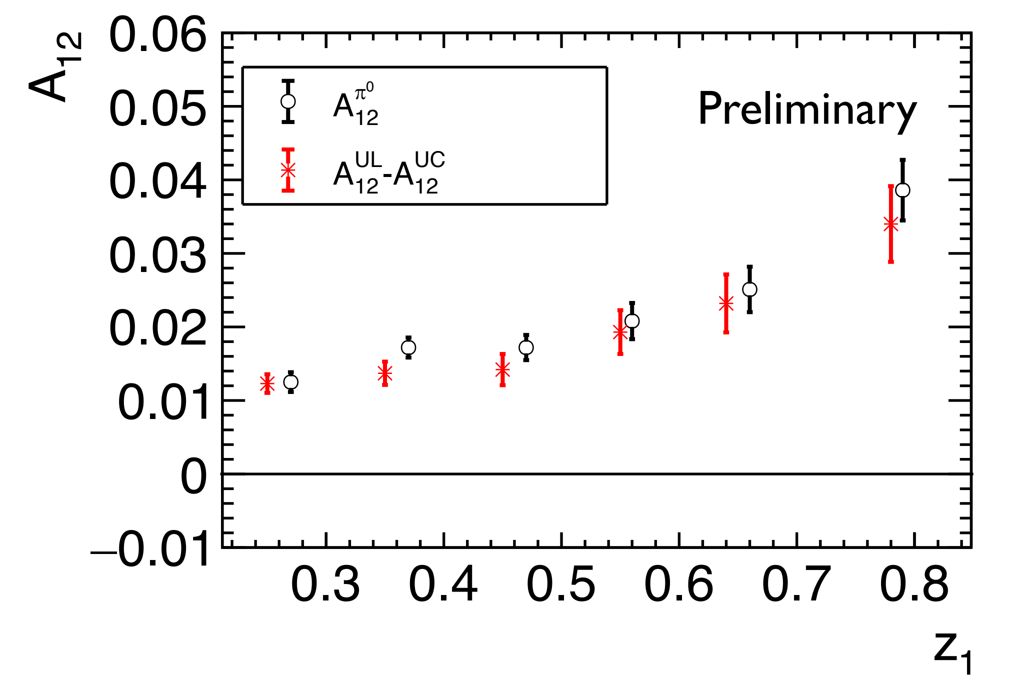


- η almost flat except large z

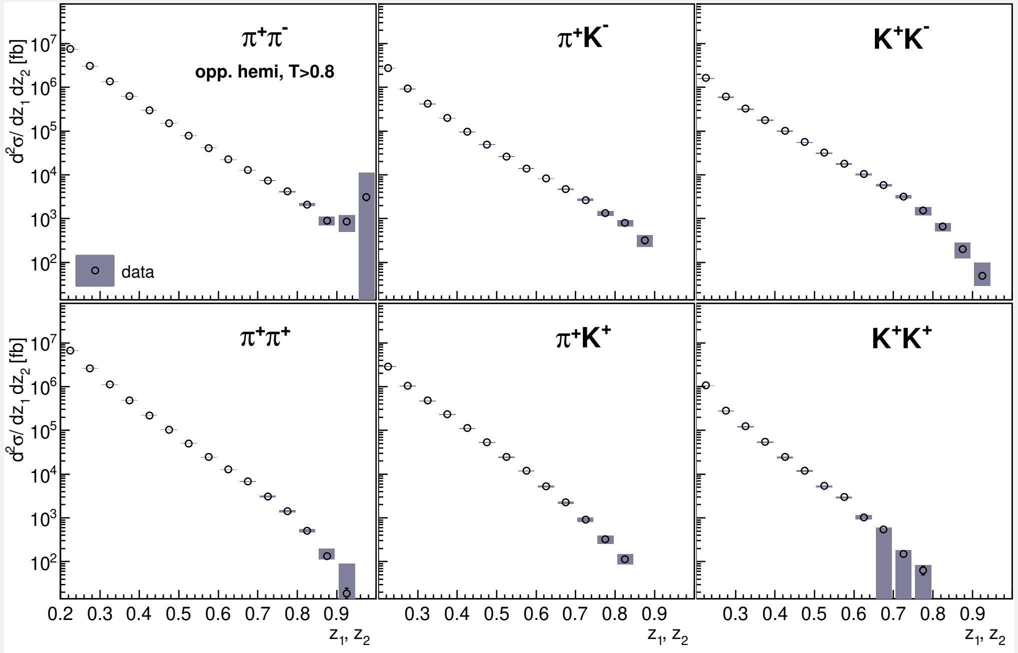
CONSISTENCY BETWEEN NEUTRAL AND CHARGED PIONS

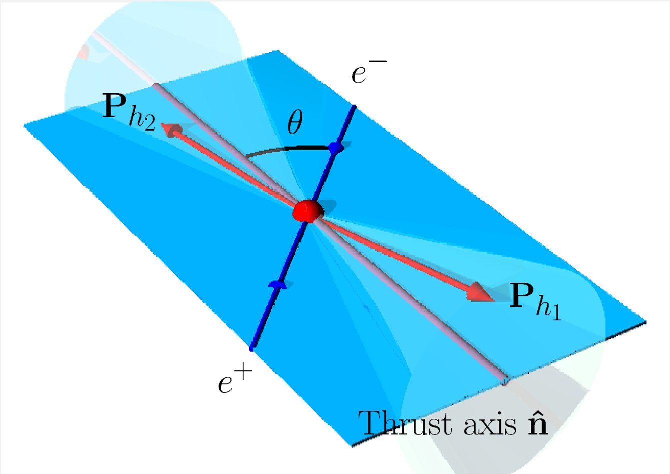
$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} \approx 1 + \cos(\phi_{12})\frac{\sin^2(\theta)}{1+\cos^2(\theta)}$$
$$\times \left\{ \frac{5(H_1^{\perp,fav} + H_1^{\perp,dis}) \otimes (H_1^{\perp,fav} + H_1^{\perp,dis}) + 4H_{1,s\to\pi}^{\perp,dis} \otimes H_{1,s\to\pi}^{\perp,dis}}{5(D_1^{fav} + D_1^{dis}) \otimes (D_1^{fav} + D_1^{dis}) + 4D_{1,s\to\pi}^{dis} \otimes D_{1,s\to\pi}^{dis})} - \frac{10H_1^{\perp,fav} \otimes H_1^{\perp,dis} + 2H_{1,s\to\pi}^{\perp,dis} H_{1,s\to\pi}^{\perp,dis}}{10D_1^{fav} \otimes D_1^{dis} + 2D_{1,s\to\pi}^{dis} \otimes D_{1,s\to\pi}^{dis}} \right\}.$$

$$= \mathbf{A}_{12}^{\mathbf{UL}} - A_{12}^{UC} \ (Isospin)$$



PRD92 (2015) 092007 BACK-TO-BACK



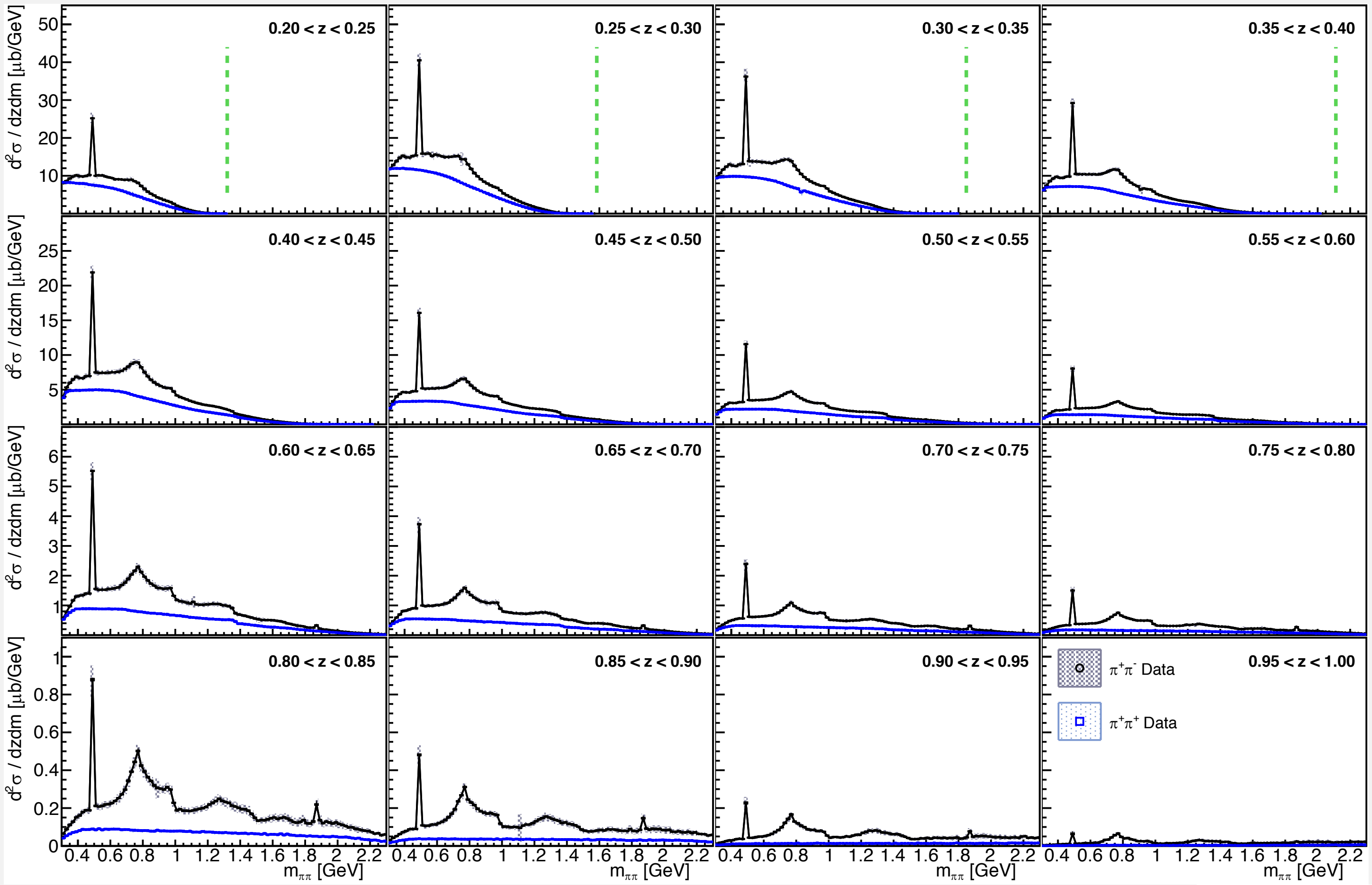


$$T = \max \frac{\sum_h |P_h^{CMS} \cdot \hat{n}|}{\sum_h |P_h^{CMS}|}$$

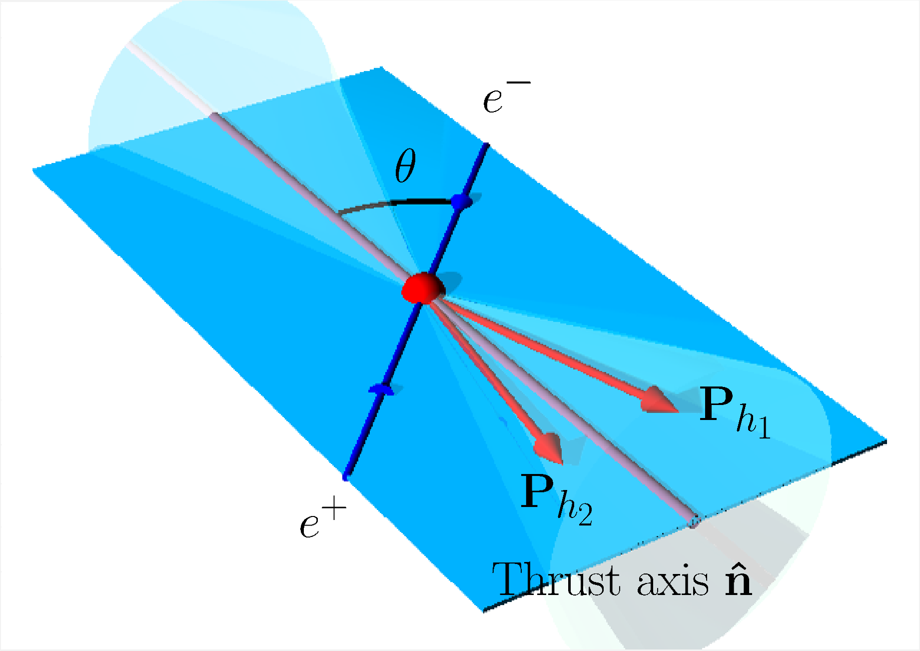
- Also
  - 'any-hemisphere' (a la de Florian & Vanni (Phys Lett B 578 (2004) 139)
  - Same-hemisphere→di-hadrons

MASS DEPENDENCE OF DI-HADRONS IN SAME HEMISPHERE→DI-HADRON FF

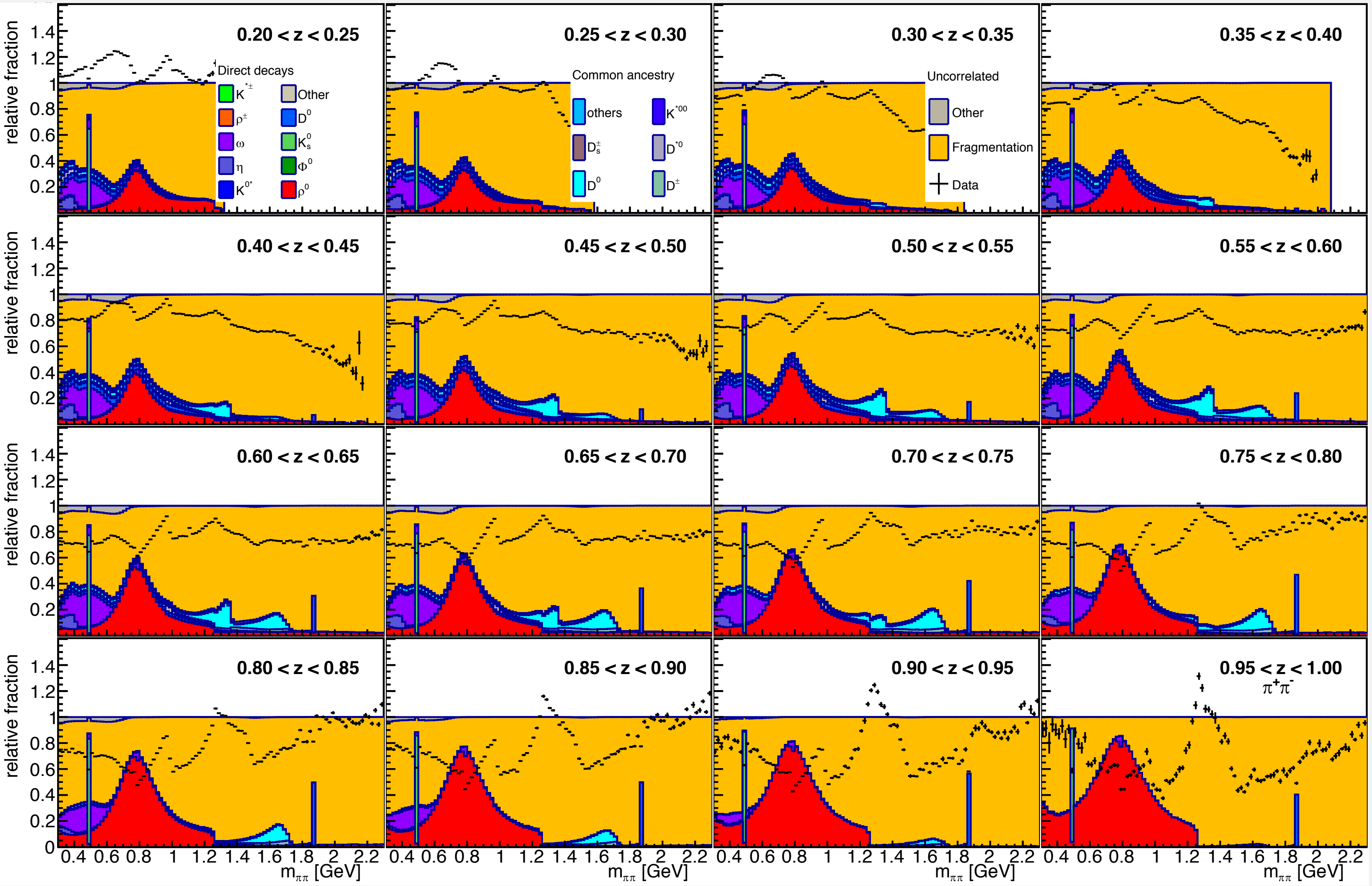
(Phys.Rev. D96 (2017) no.3, 032005)



m [GeV]



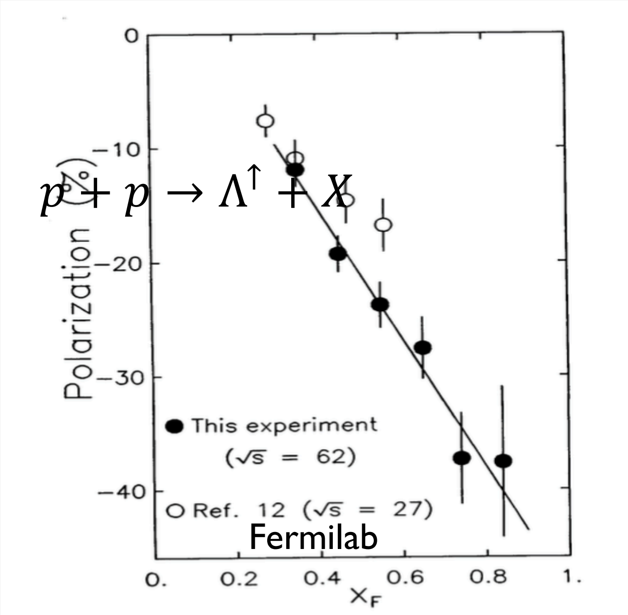
IMPORTANCE OF CORRELATED PRODUCTION



POLARIZED HYPERON PRODUCTION

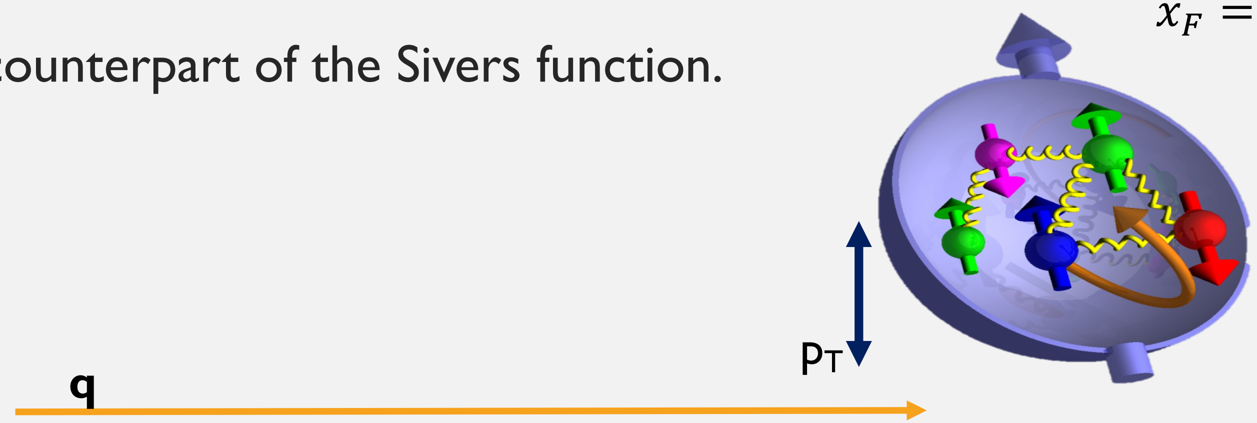
- Large Λ transverse polarization in unpolarized pp collision PRL36, 1113 (1976); PRL41, 607 (1978)
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^{2})$?
- Polarizing FF is chiral-even, has been proposed as a test of universality. PRL105,202001 (2010)
- OPAL experiment at LEP has studied transverse Λ polarization, no significant signal was observed. Eur. Phys. J. C2, 49 (1998)
- FF counterpart of the Sivers function.

$p + p \to \Lambda^{\uparrow} + X$



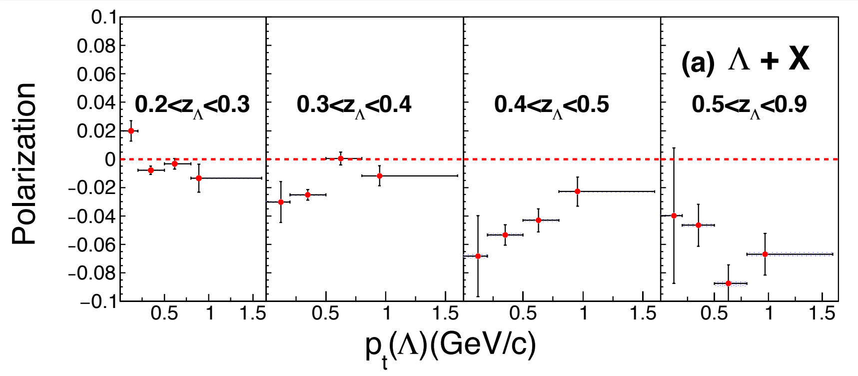
ISR data
(**Phys.Lett. B185 (1987) 209)**

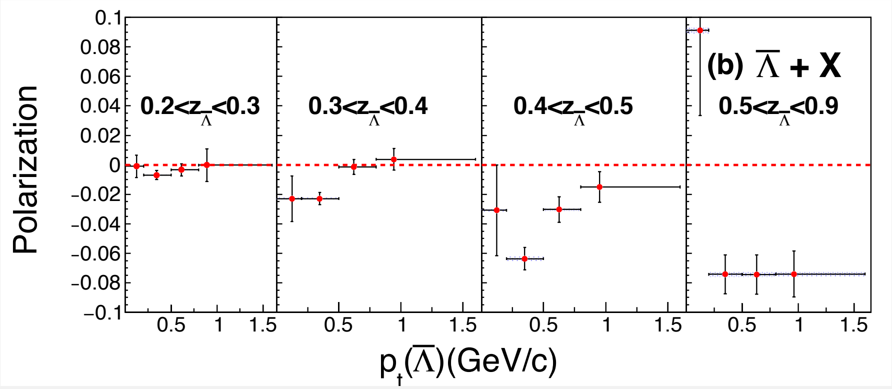
$x_F = p_L / \max p_L \sim_{LO} x_1 - x_2 \sim_{forward} x_1$



z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION

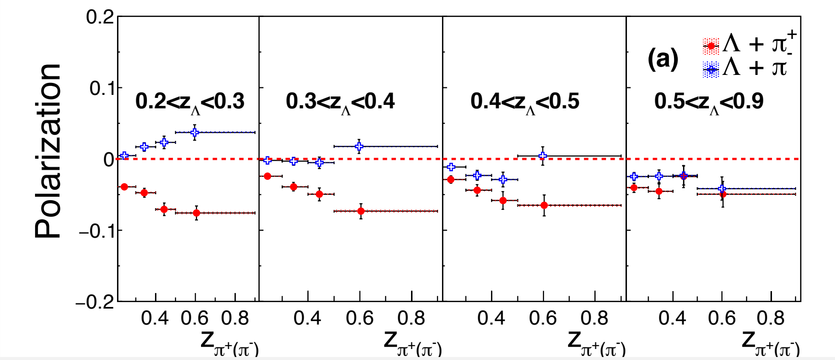
- Polarization rises with p_t in the lowest z_Λ and highest z_Λ bin. But the dependence reverses around 1 GeV in the intermediate z_Λ bins→**Unexpected!**
- Results are consistent between Λ and $(\bar{\Lambda})$

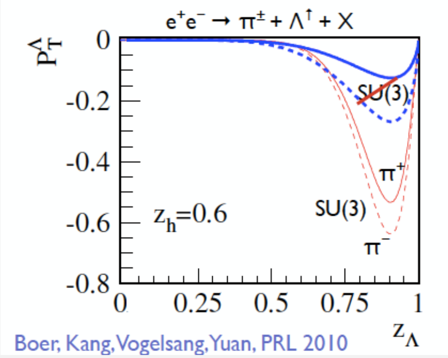


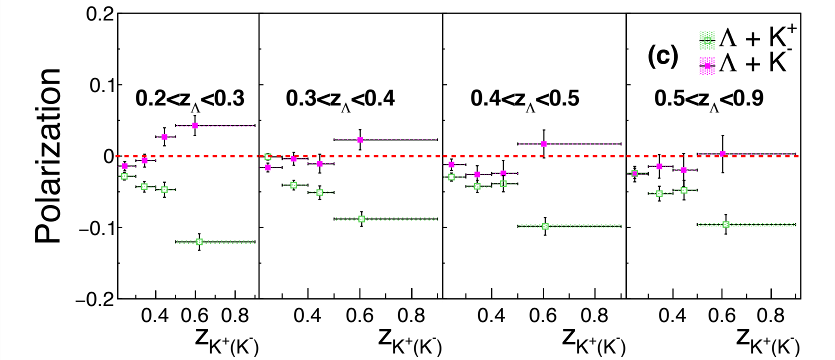


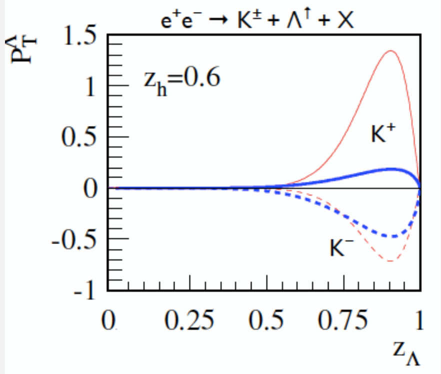
Phys. Rev. Lett. 122, 042001 (2019)

TENSION WITH THEORY: ASSOCIATED PRODUCTION



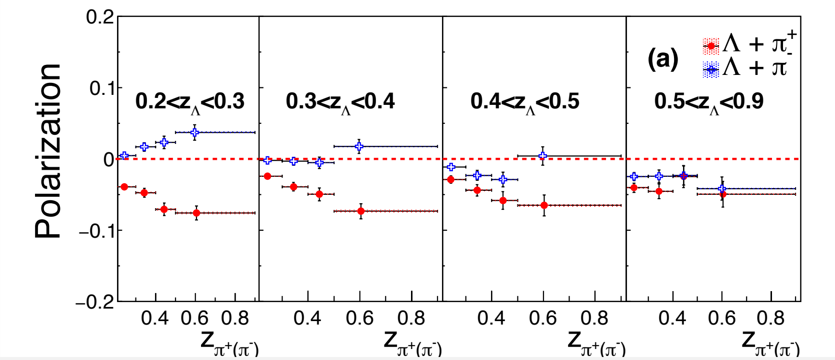


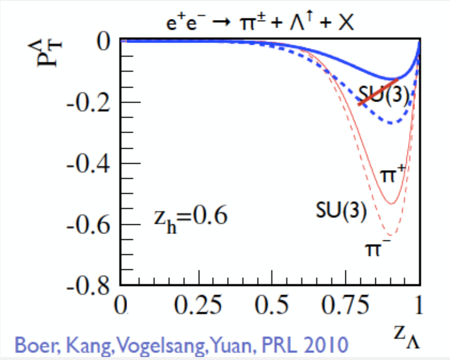


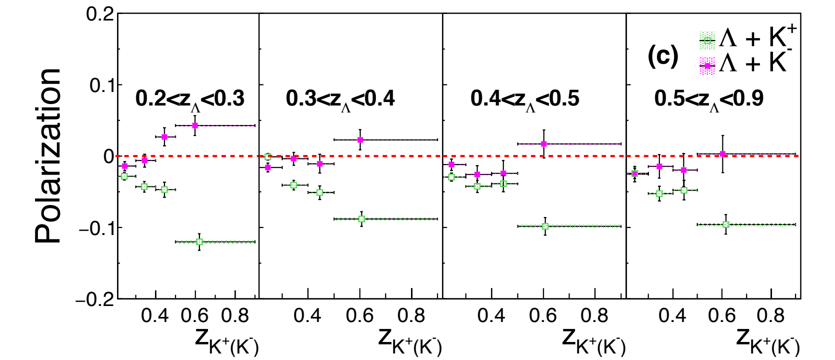


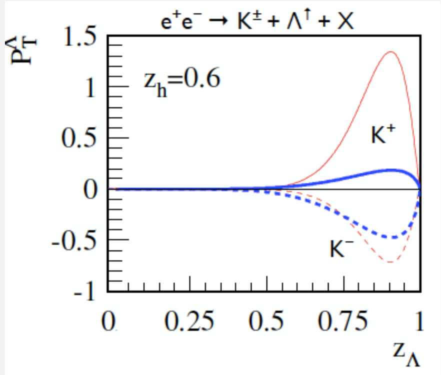
- Correlation with opposite hemisphere light meson →quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge cf Sivers
- Only experimental results on T-odd, chiral even FF →**Important to understand!**

TENSION WITH THEORY: ASSOCIATED PRODUCTION

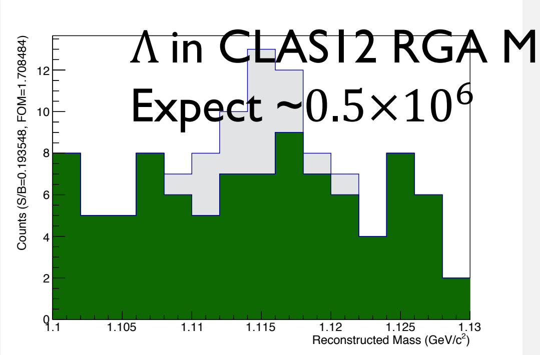




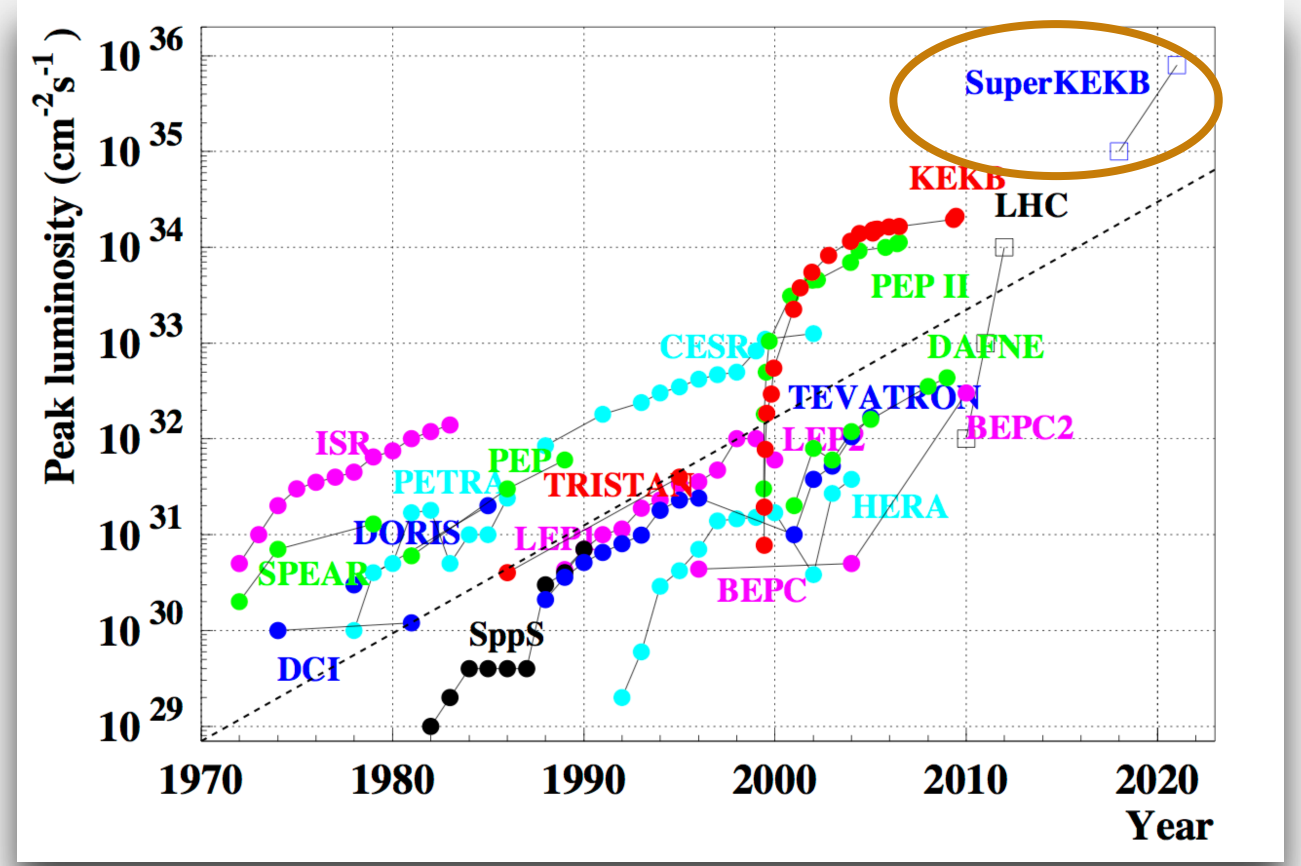




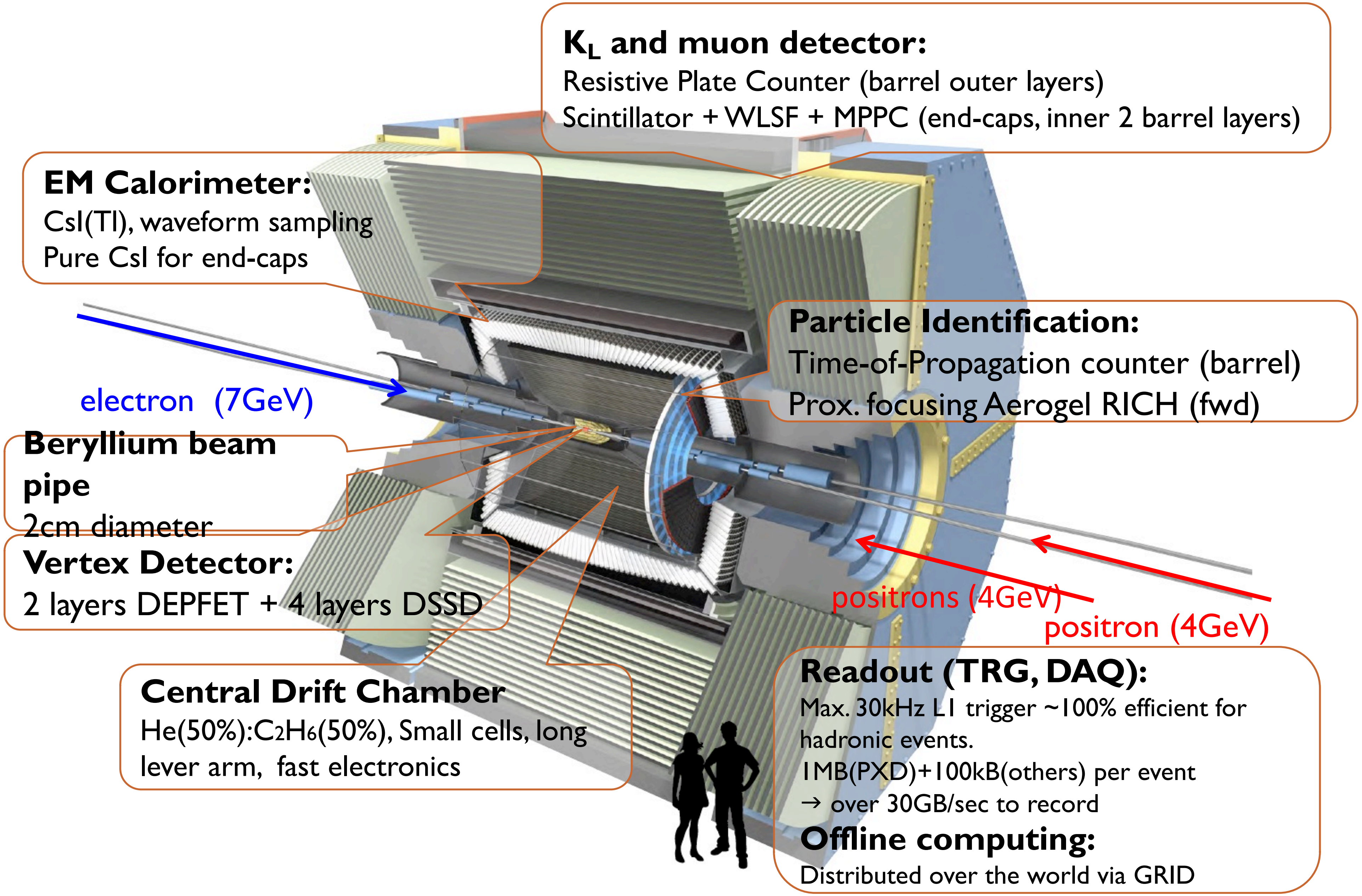
- Correlation with opposite hemisphere light meson →quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge cf Sivers
- Only experimental results on T-odd, chiral even FF →**Important to understand!**
- **E.g. Lambda polarization at CLAS12 or EIC**



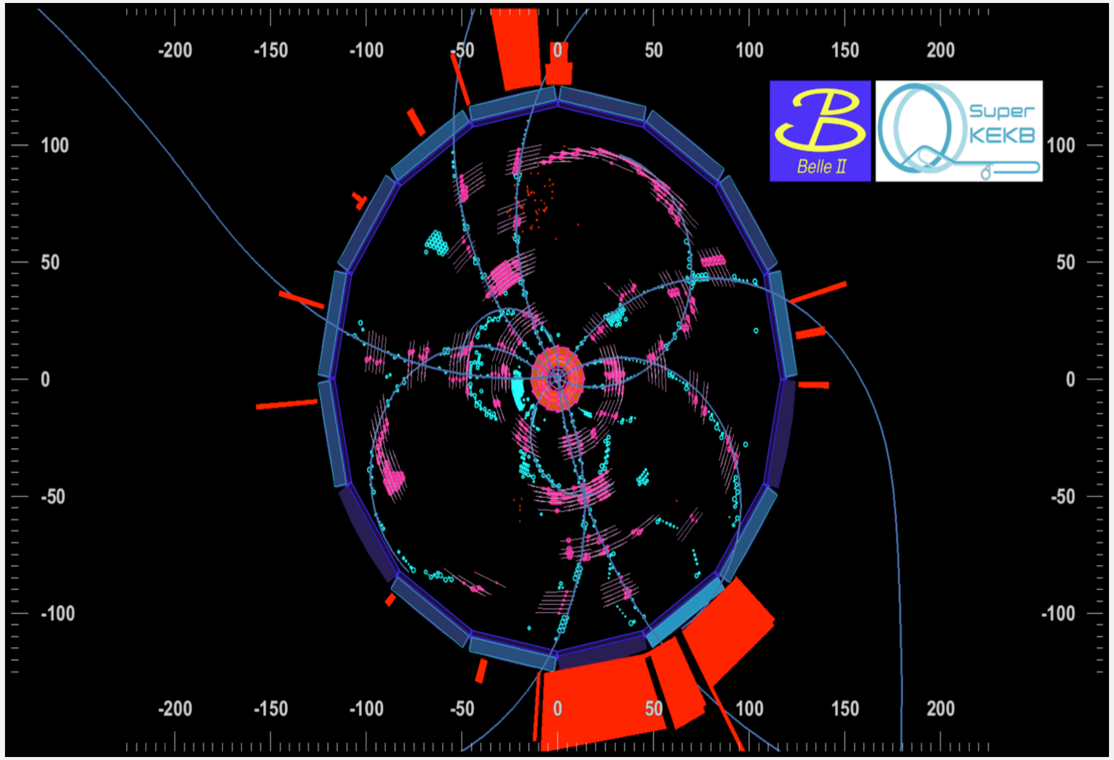
THE FUTURE IS NOW: NEXT GENERATION B FACTORY SUPERKEB

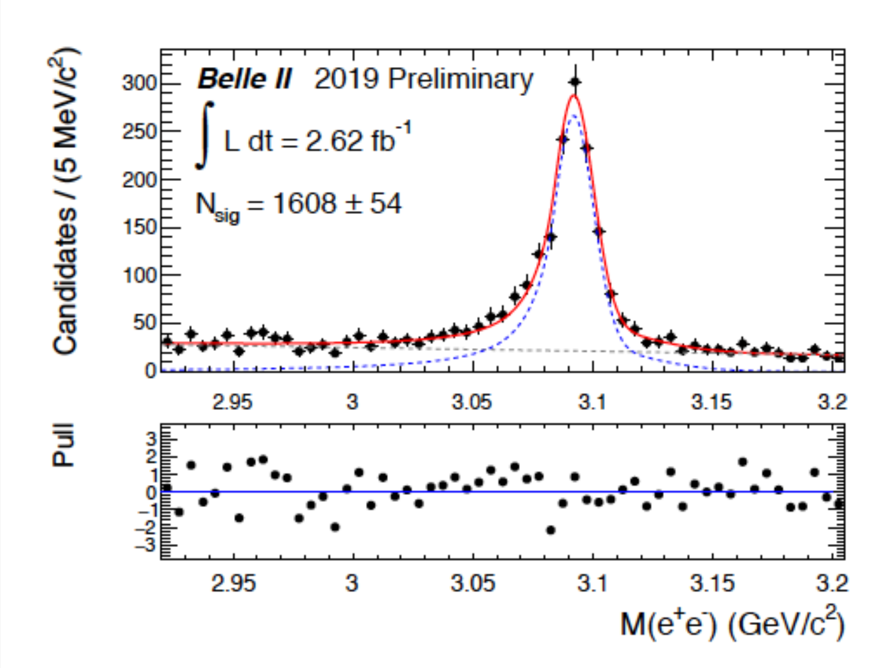


CUT VIEW OF BELLE II DETECTOR



2019: First Collisions in Phase 3, the Physics Run





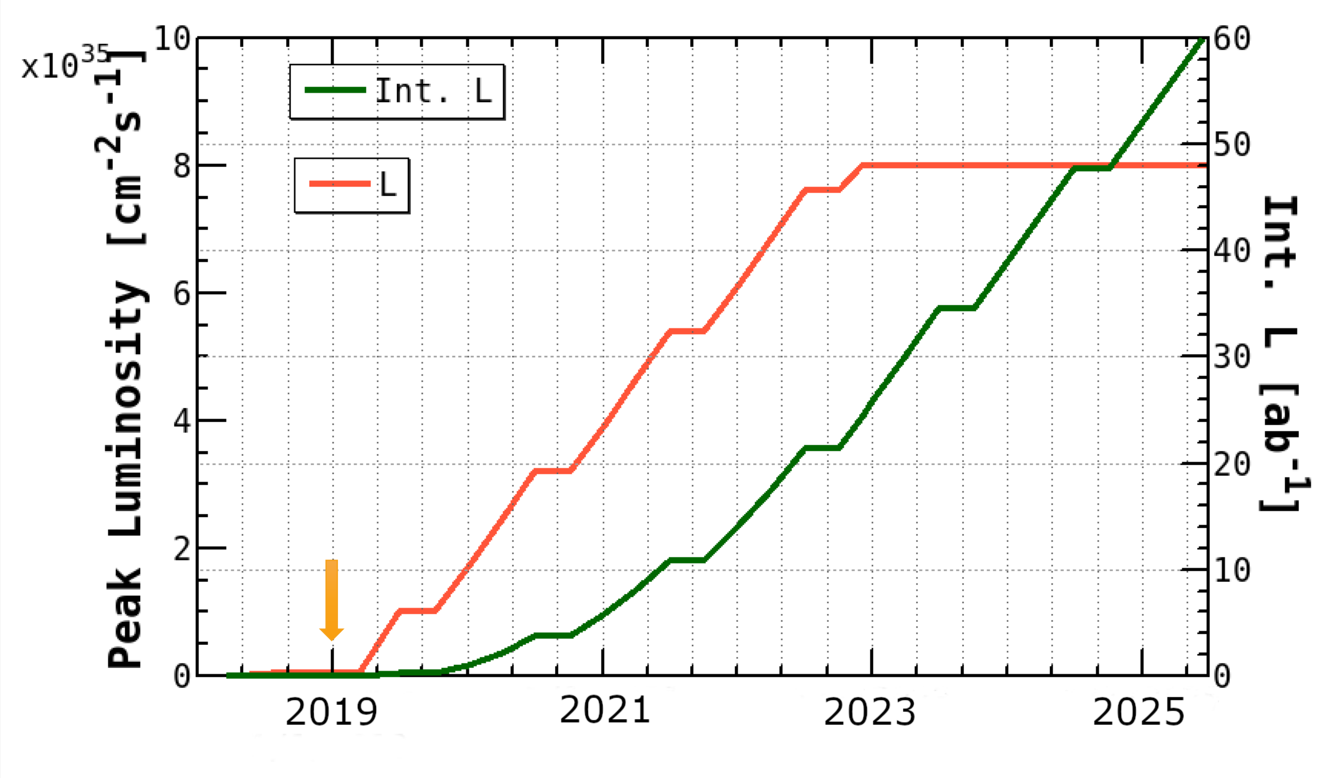
Clear signals for B→J/ψ X in ~1/2 of Phase 3 data.

SUPERKEKB/BELLE II LUMINOSITY PROFILE

Belle/KEKB recorded ~1000 fb^{-1} . Now have to change units on the y-axis to ab^{-1}

Beam currents *only* a factor of two higher than KEKB (~PEPII)

“nano-beams” are the key; vertical beam size is 50nm at the IP



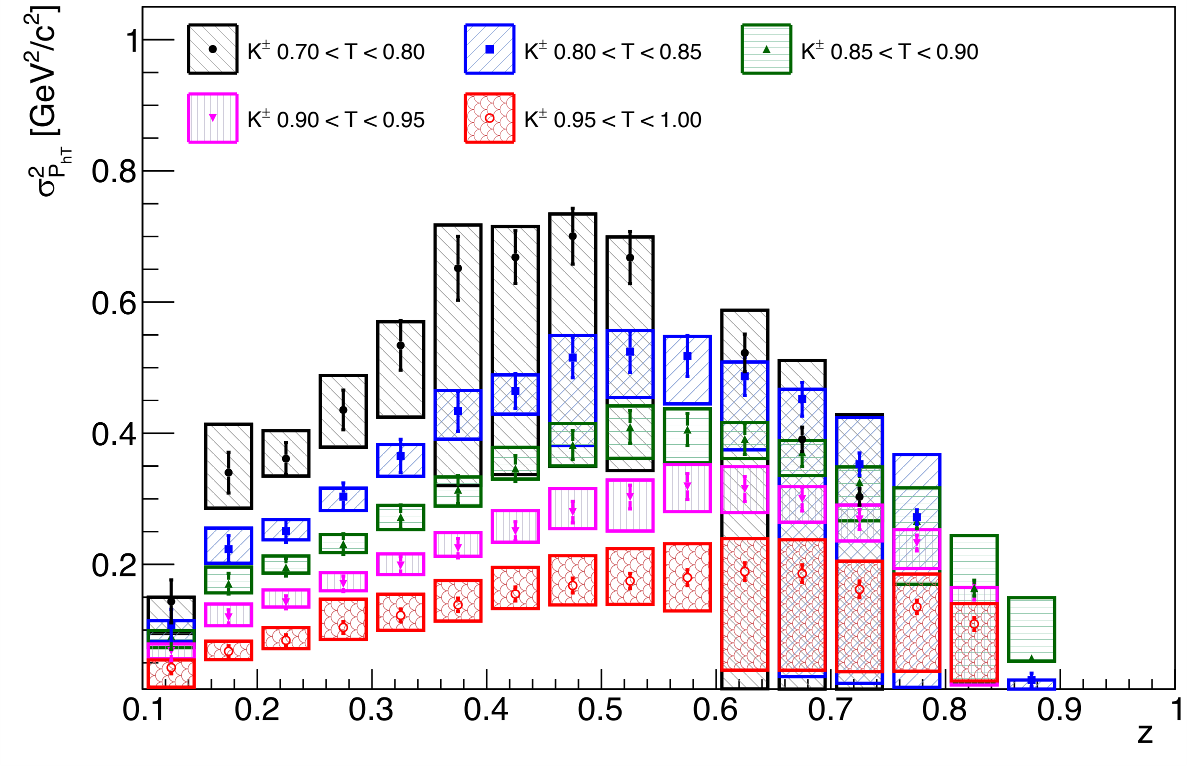
SUMMARY AND OUTLOOK

- **Precision measurements of FFs was essential in recent progress in the field of TMDs**
- **A continued program is needed**
  - for the model independent extraction of TMDs and transverse spin structure (and more) from JLab12 and EIC
  - Studying hadronization
  - Exploring complex QCD mechanisms in a clean configuration
- **Pioneering measurements at Belle and precision measurements at Belle II in the future**

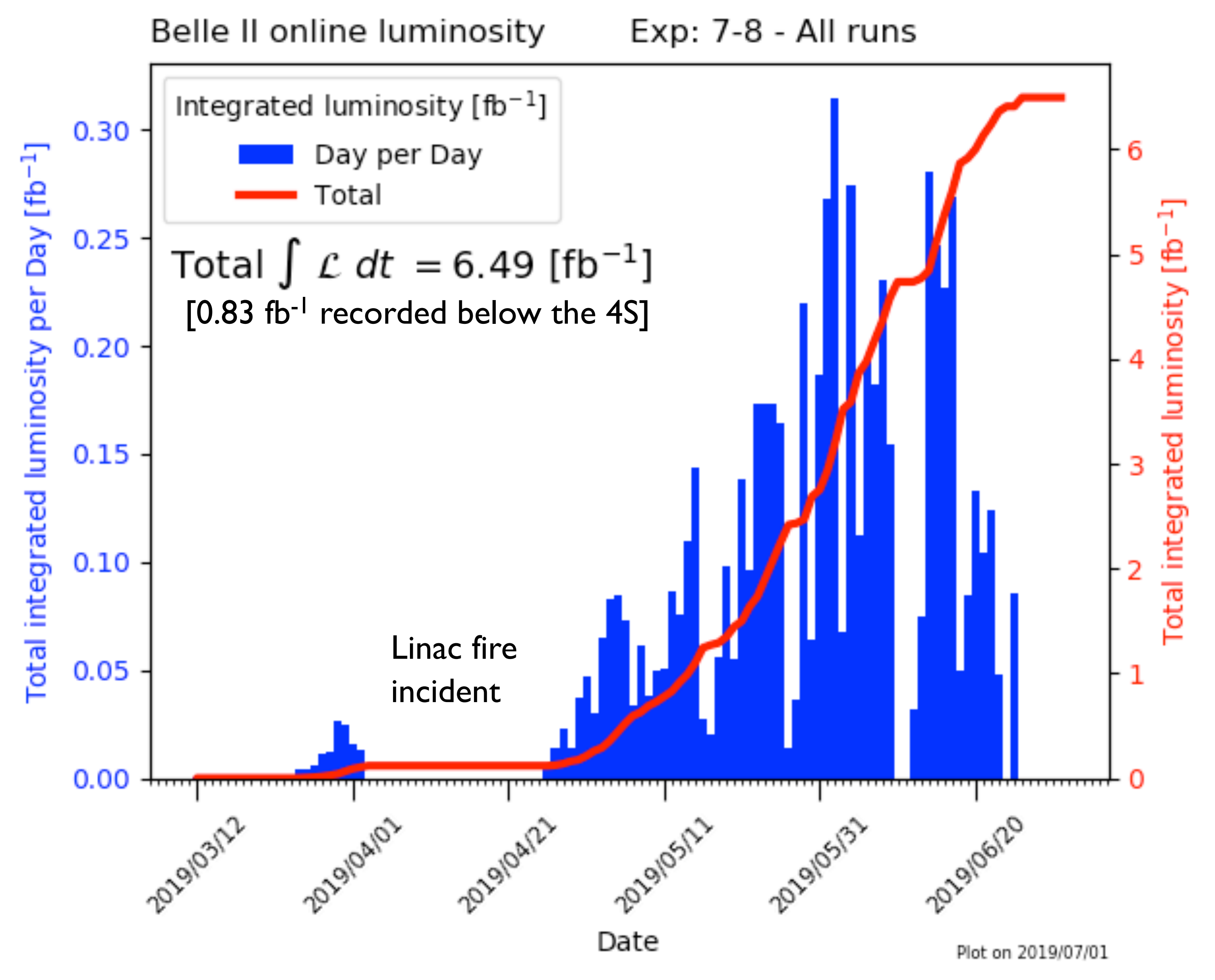
NEED FOR **PRECISION FF PROGRAM** IN THE 12GEV/EIC ERA

- **Fundamental questions in QCD**
  - Study spin-orbit correlations in Hadronization
  - Universality of TMD FFs →Analogue to questions in the PDF sector (Sivers)
  - e^+e^- : Testbed for QCD calculations
  - Generally: Test our models/theory for hadron formation
- **Essential to JLAB12GeV+EIC**
  - Model independent extraction of transverse spin structure
  - Model independent extraction of TMDs
  - Access to twist3 PDFs

THRUST DEPENDENCE



Spring 2019, First Phase 3 Physics Run: "*It was a wild ride*"



Only 2 months of collisions.

L(peak) ~5.5 x 10^{33}/cm^2/sec (β_y^*=3mm)

L(SuperKEKB peak, last week) ~1.2 x 10^{34}/cm^2/sec ($\rightarrow \beta_y^*$=2mm)

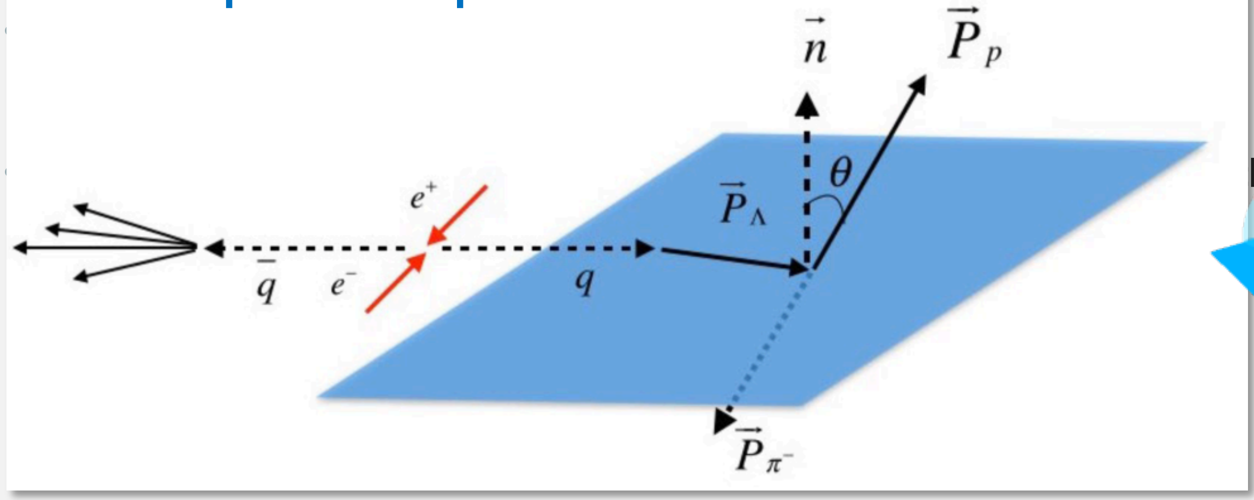
Comparable to PEP-II best but bkgs X 3 too large to turn on Belle II

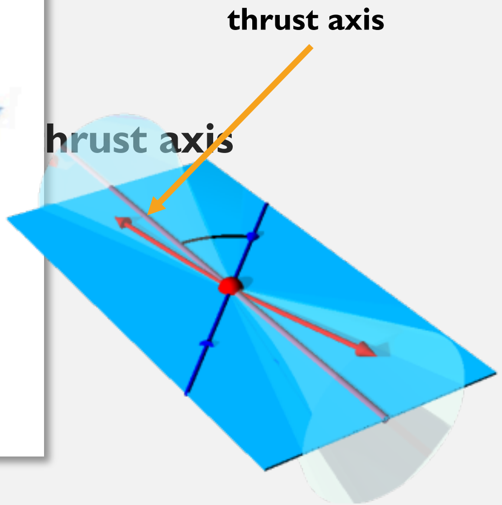
OBSERVABLES IN Λ RESTFRAME

$\hat{n}$ is perpendicular to the Λ production plane.

- Self-analyzing decay leads to polarization dependent distribution

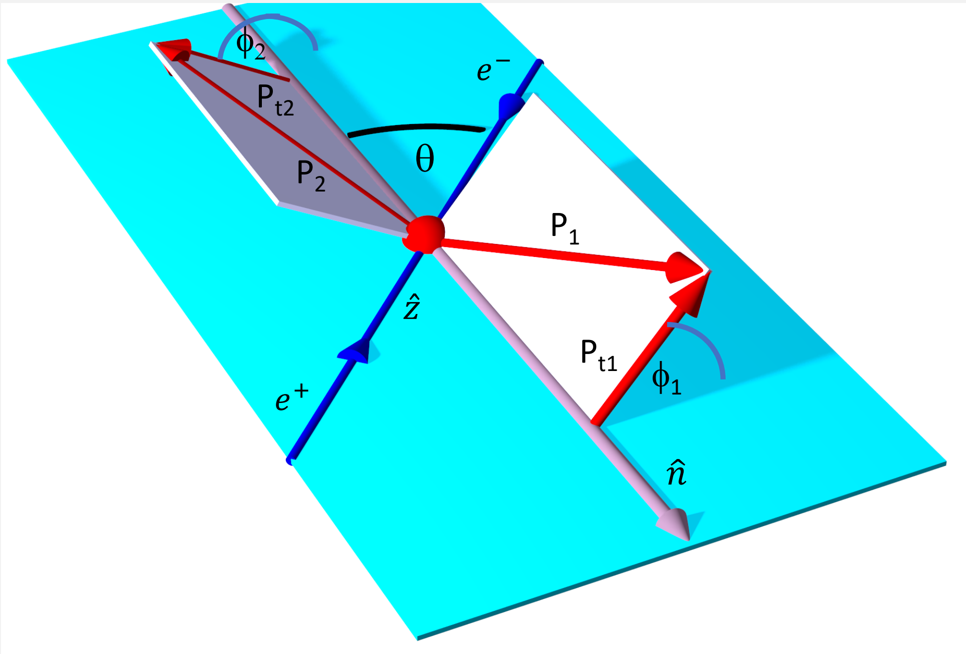
Λ production plane



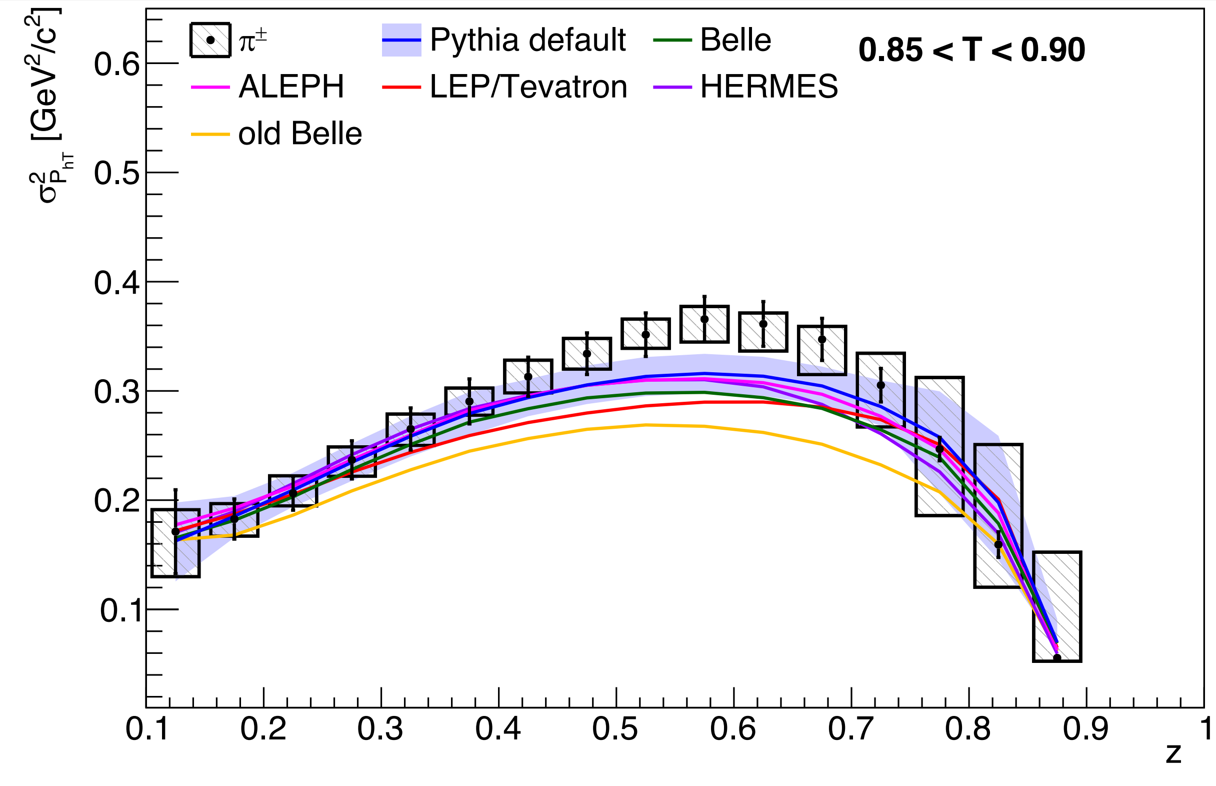


$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta$$

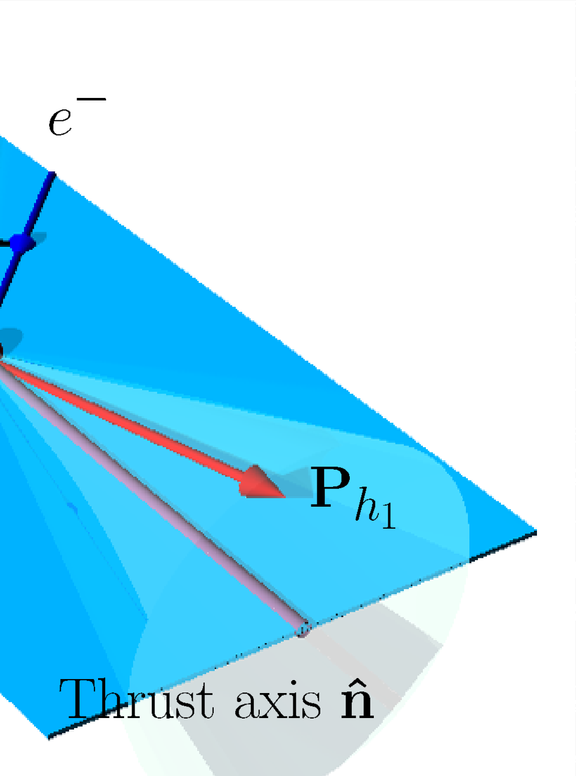
COLLINS

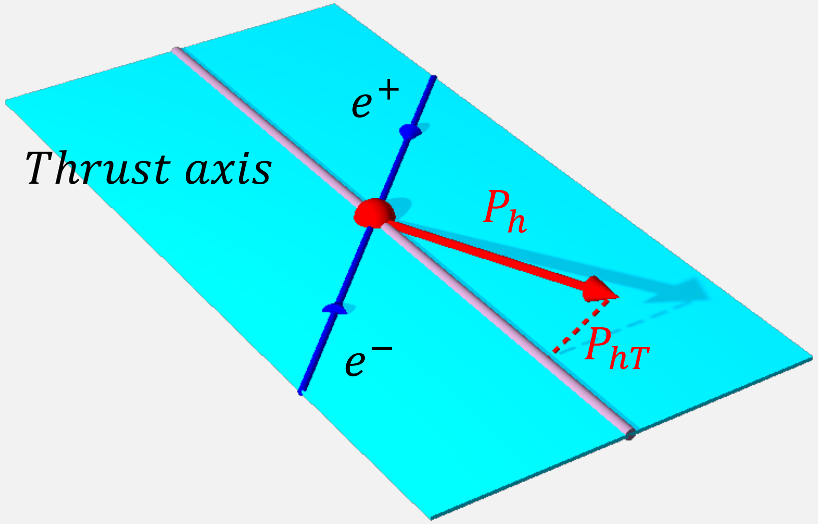


COMPARISON OF GAUSSIAN WIDTHS WITH MC MODELS

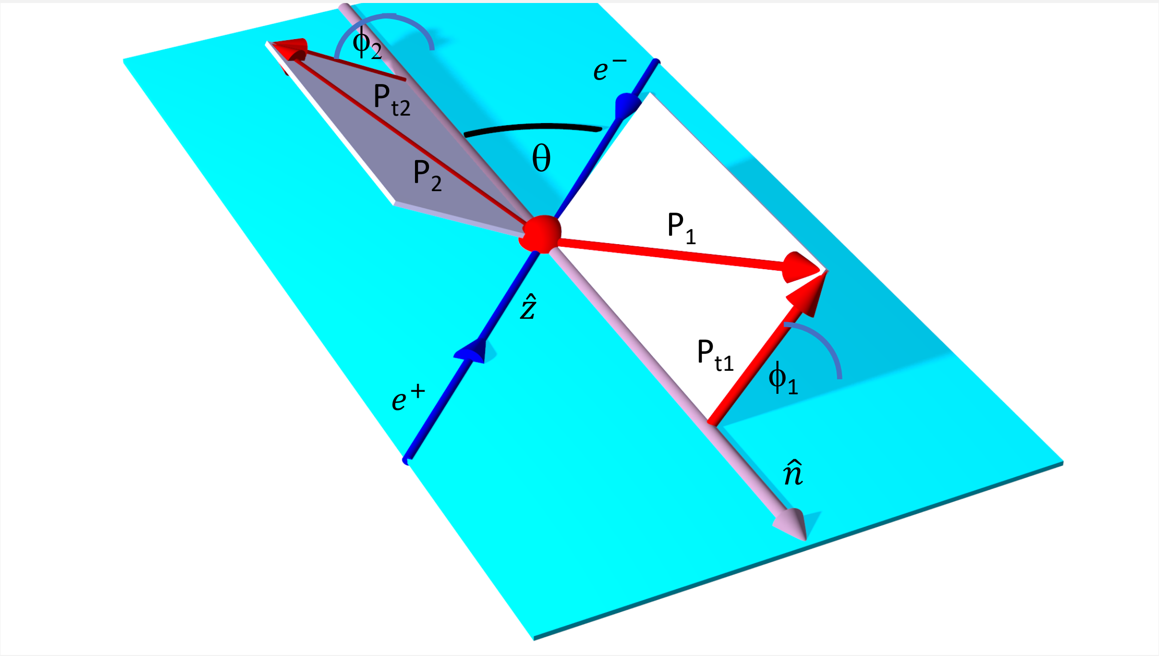


- Discrepancy at intermediate z

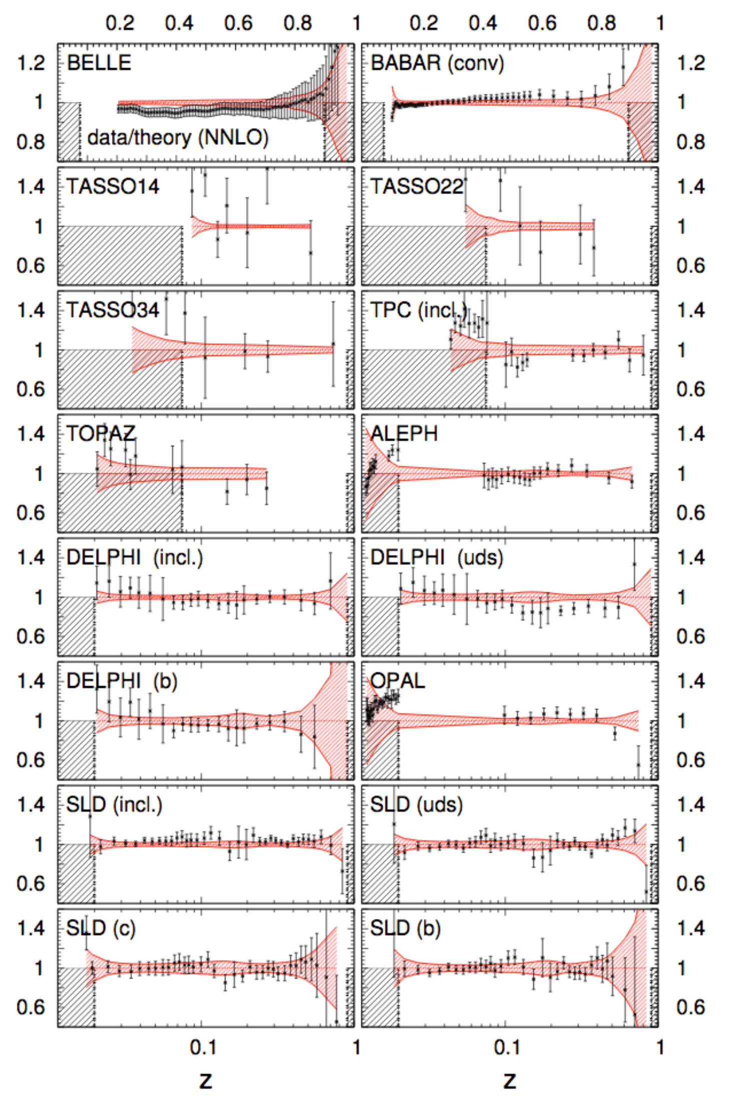

e^-
$\mathbf{P}_{h_1}$
Thrust axis $\hat{\mathbf{n}}$

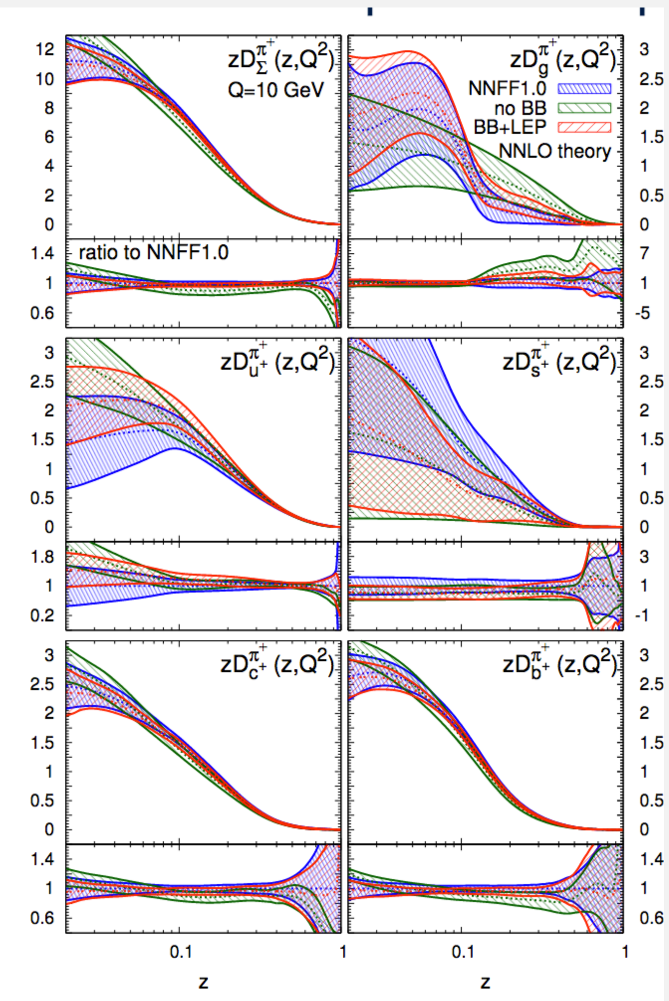

e^+
Thrust axis
P_h
e^-
P_{hT}

POLARIZED (E.G. COLLINS)



INCLUSIVE π/K WELL DESCRIBED BY THEORY AT NNLO

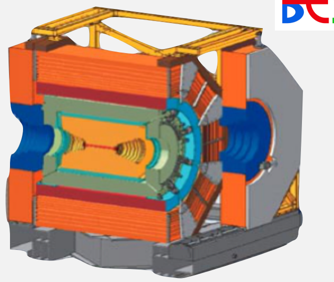




- Here
  - NNFF, [EPJ C77 (2017) 516
  - but DSS similar

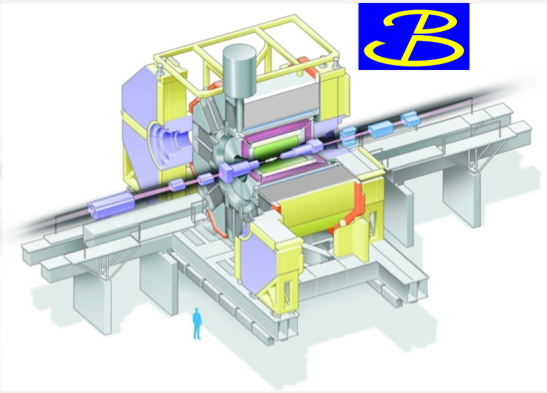
THE BESII, BELLE AND BABAR EXPERIMENTS

NIMA**614**,345(2010)



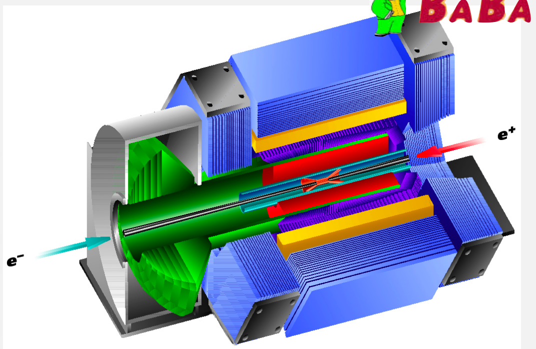
- Symmetric e^+e^- collider
- $\sqrt{s}$ = [2 - 4.6] GeV
- 62 pb^{-1} @ 3.65 GeV used for Collins studies
- Below open-charm threshold

- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma$=0.425
- L ~ 1 ab^{-1}



NIMA**479**,117(2002)

NIMA**729**,615(2013)

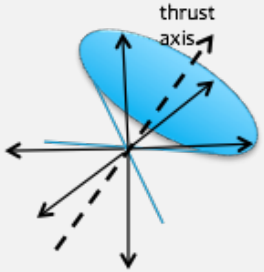


- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma$=0.65
- L ~ 500 fb^{-1}

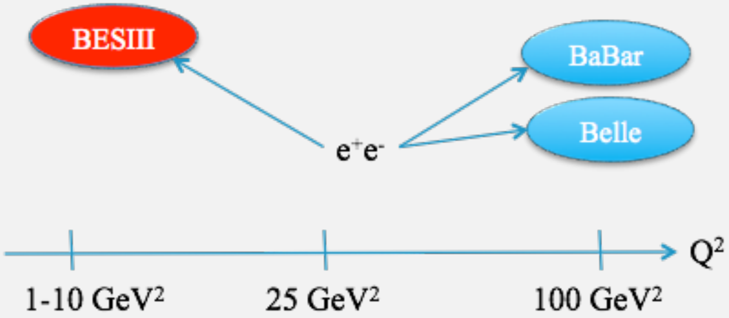
$$T = \sum_i \frac{|\mathbf{P} \cdot \hat{\mathbf{n}}|}{|P|}$$

thrust axis $\equiv \hat{\mathbf{n}}$

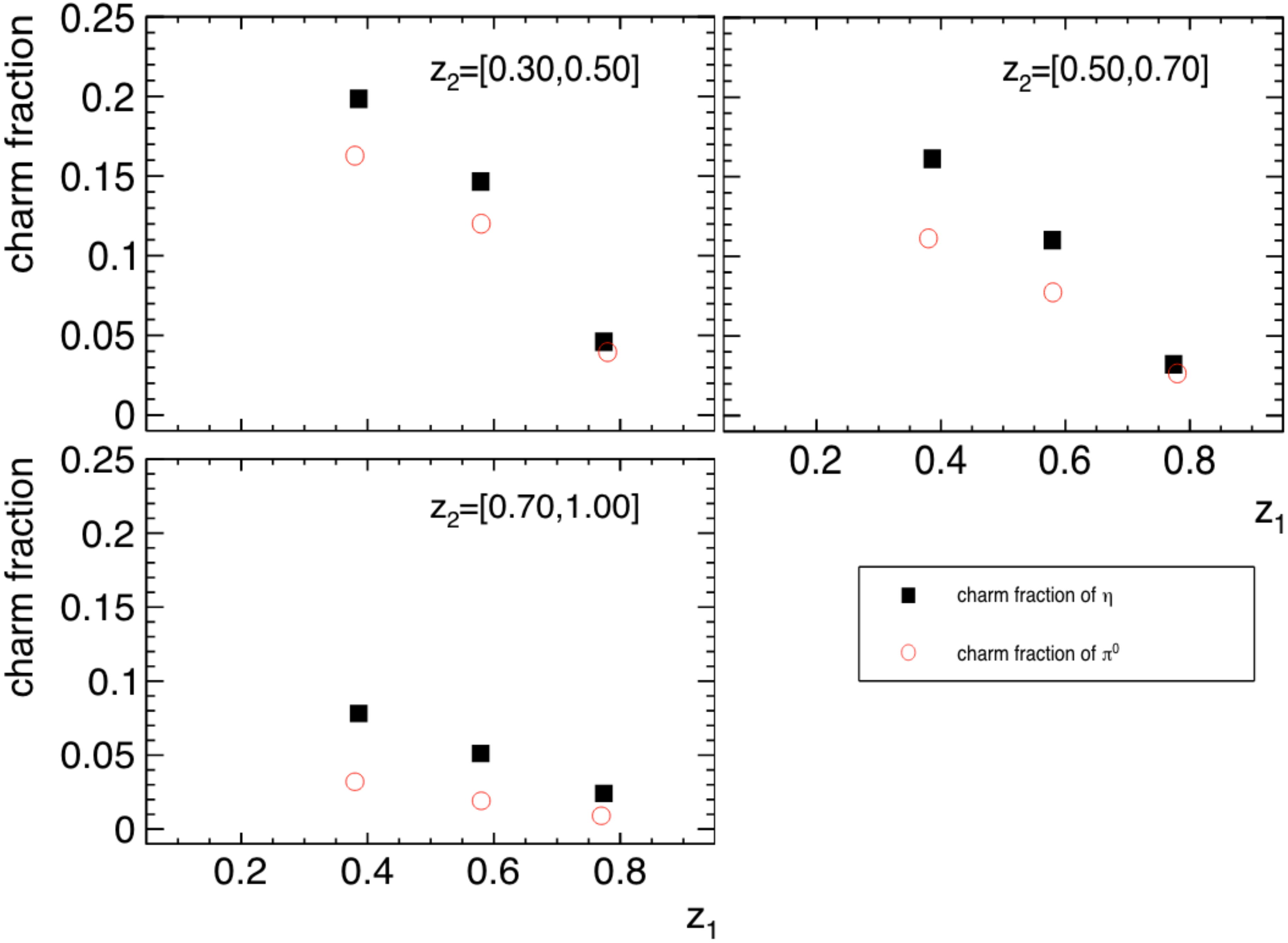
$0.5 \leq T \leq 1$



T~0.5



T~1



charm fraction
z2=[0.30,0.50]
z2=[0.50,0.70]
z2=[0.70,1.00]
0.25
0.2
0.15
0.1
0.05
0
0.2
0.4
0.6
0.8
z1
charm fraction of η
charm fraction of π0

"YOU THINK YOU UNDERSTAND SOMETHING?---NOW ADD SPIN…**IN HADRONIZATION**!"

- **→polarized final states**
- **→di-hadron correlations**

- Explore spin-orbit correlation in hadronization
- Additional degrees of freedom in final state make targeted extraction of nucleon structure possible →see $h_1(x)$, $e(x)$
- New Fragmentation Functions
- **Obvious relevance for the EIC**
  - Here: Results from RHIC, Belle and plans at Jlab/Belle

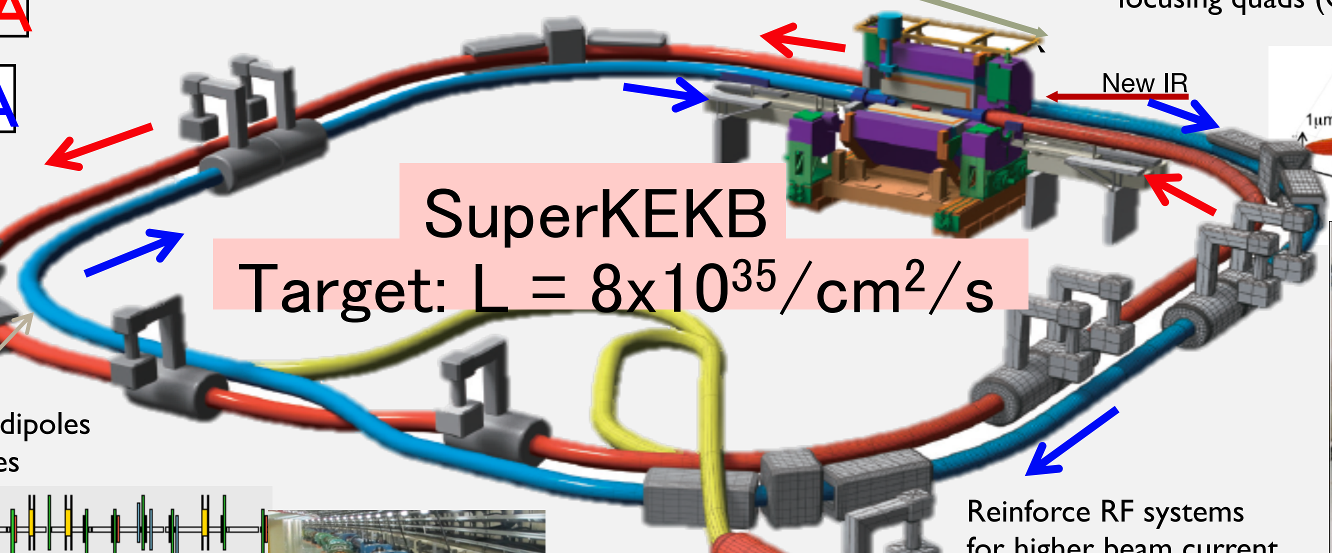
KEKB →SUPERKEKB: DELIVER INSTANTANEOUS LUMINOSITY X 40

Belle II

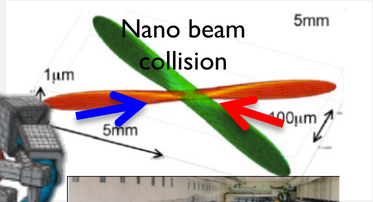
e^+ 4GeV 3.6 A

e^- 7GeV 2.6 A

(~2x KEKB)

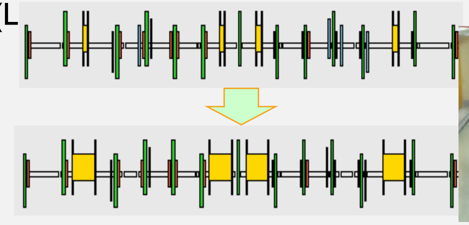


New superconducting final focusing quads (QCS) near the IP

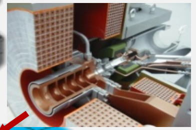


Replace short dipoles with longer ones

(L



Reinforce RF systems for higher beam current



Positron source

New positron target / capture section

Redesign the lattices of HER & LER to squeeze the emittance

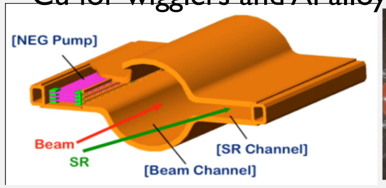
Damping ring (new)

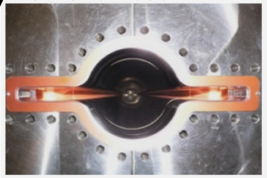
@1.1 GeV

To inject low emittance positrons

TiN-coated beam pipe with antechambers

Cu for wigglers and Al alloy for the rest





Low emittance gun

To inject low emittance electrons

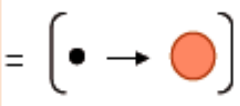
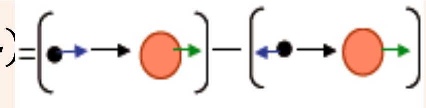
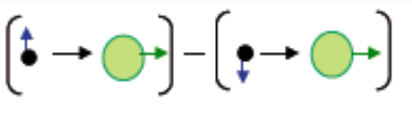
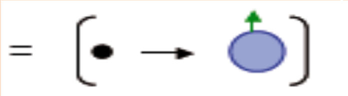
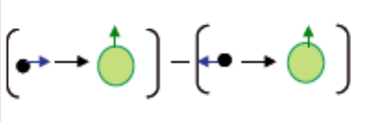
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

ENTER POLARIZATION IN THE FINAL STATES

<u>Observables:</u>

z: fractional energy of the quark carried by the hadron

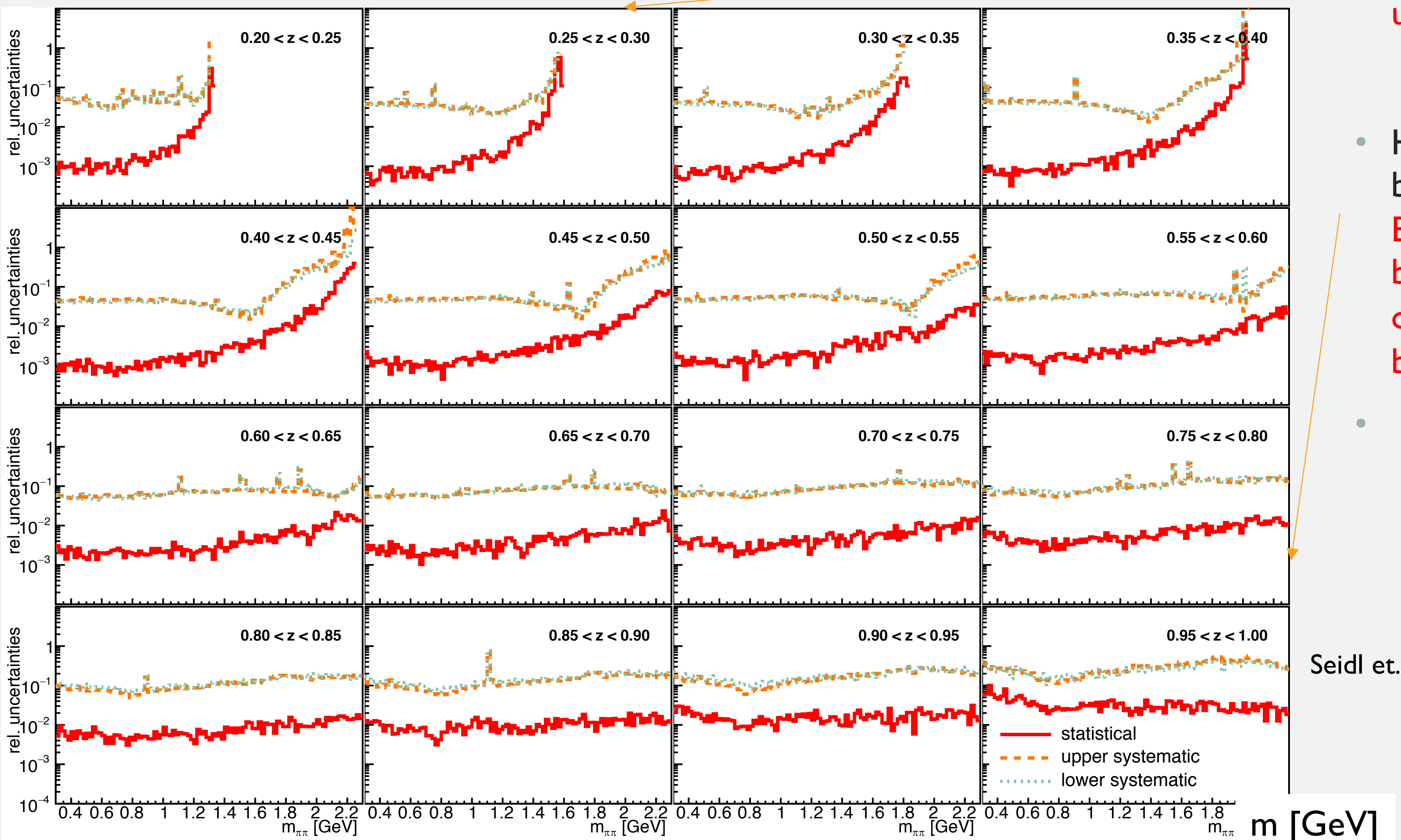
$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → Hadron Polarization ⇣	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z,p_T)$ = 		$H_1^{\perp h/q}(z,p_T)$ = 
longitudinal		$G_1^{\Lambda/q}(z,p_T)$ = 	$H_{1L}^{h/q}(z,p_T)$ 
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$ = 	$G_{1T}^{h/q}(z,p_T)$= 	$H_1^{\Lambda/q}(z,p_T)$ =  $H_{1T}^{\perp\Lambda/q}(z,p_T)$ = 

- Analogue →similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay (Λ)
- Gluon FFs similar but with circular/linear polarization (not as relevant for e+e-)

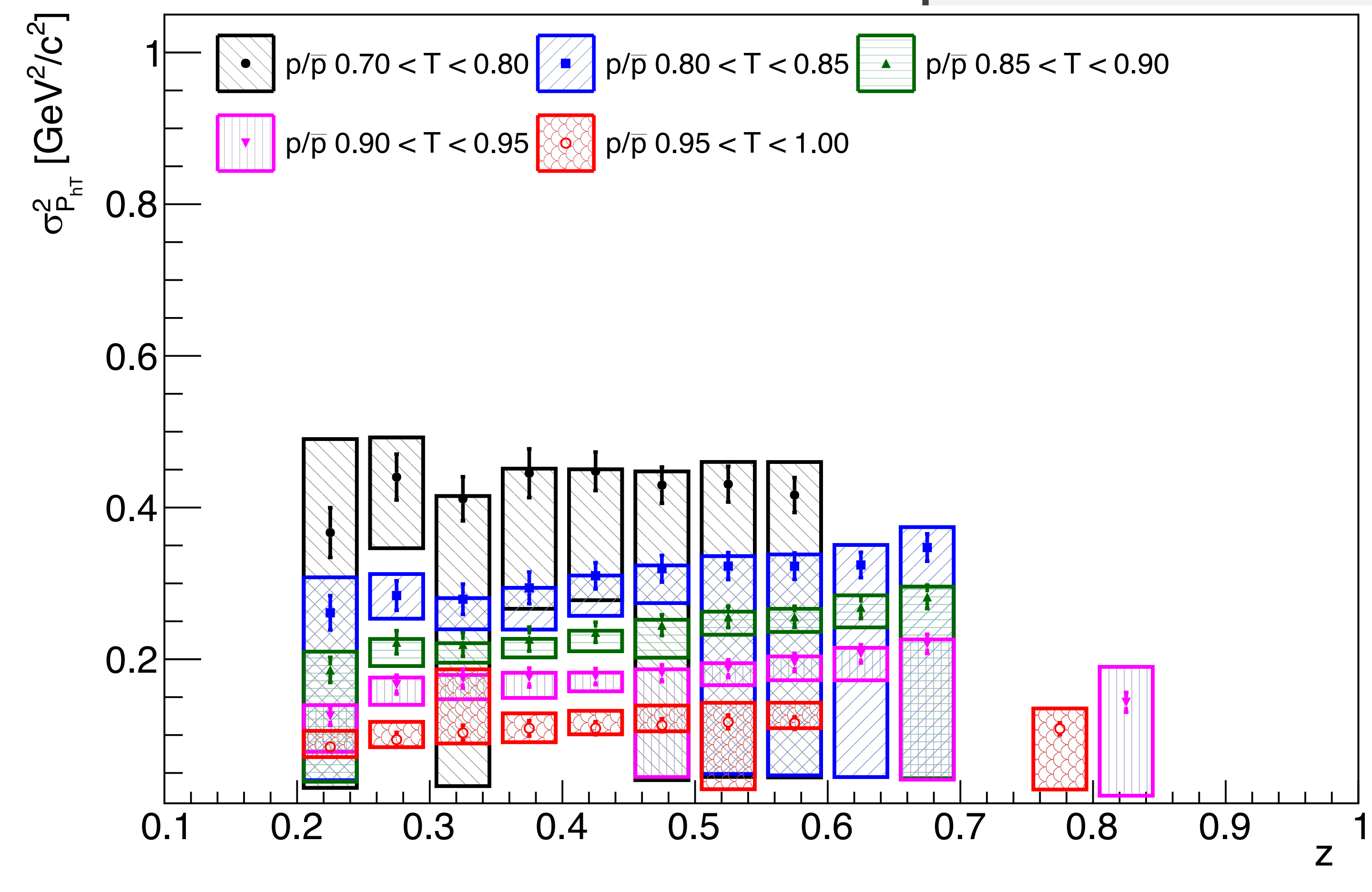
DI-HADRONS

RESULTS SYSTEMATICS DOMINATED



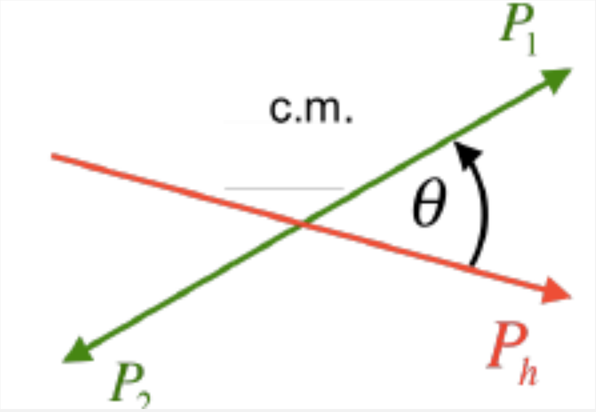
- Low z: Dominated by PID uncertainties
  Belle II prospects: Improved PID, higher statistics to improve uncertainties on PID
- High z: Dominated by ISR uncertainties
  Belle II prospects: better understanding of ISR radiation with better statistics
-

Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

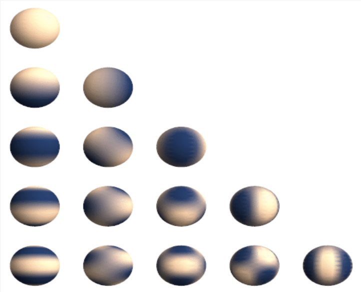


$\sigma^2_{P_{hT}}$ [GeV^2/c^2]
p/p̄ 0.70 < T < 0.80
p/p̄ 0.80 < T < 0.85
p/p̄ 0.85 < T < 0.90
p/p̄ 0.90 < T < 0.95
p/p̄ 0.95 < T < 1.00
1
0.8
0.6
0.4
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z

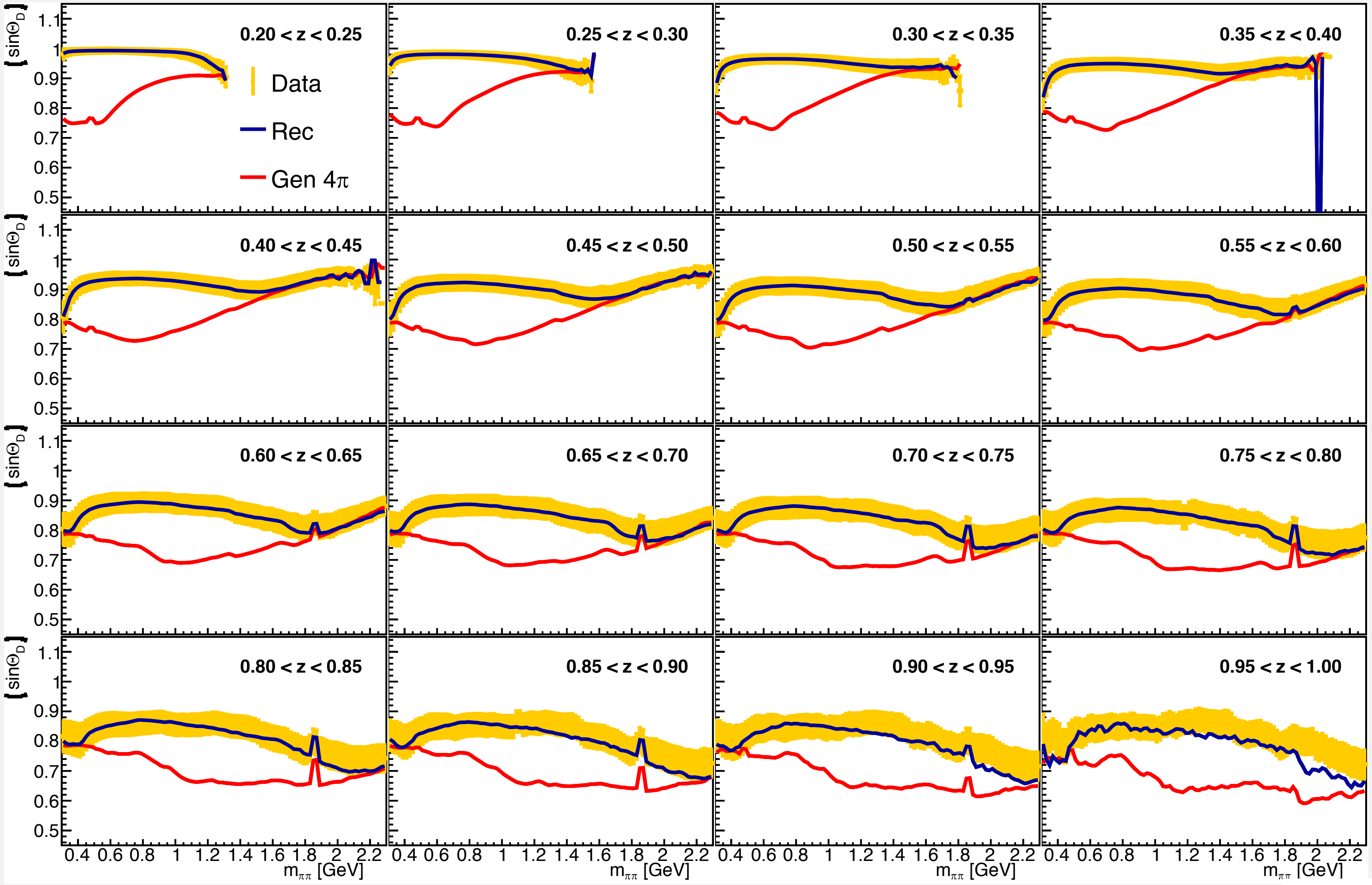
BELLE II PROSPECTS



- Partial Wave decomposition (more general: θ dependence)
- Higher order PWs lead to different moments in θ and ϕ
- In models, evolution of the different PWs different
- Important to have a full picture to understand mixing effects in ratios/partial integrals/acceptance
- Missing info from partial wave estimated to have effects up to 10% e.g. on extraction of transversity



ACCEPTANCE IMPACT ON PARTIAL WAVE COMPOSITION



m [GeV]

Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

- Belle II prospects: Sufficient statistics for full partial wave decomposition
-

ACCELERATOR DESIGN: NANO BEAM SCHEME

Invented by Pantaleo Raimondi for SuperB

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

Lorentz factor

Beam current

Beam-Beam parameter $\xi_y \propto \sqrt{(\beta_y^*/\varepsilon_y)}$

Geometrical reduction factors (crossing angle, hourglass effect)

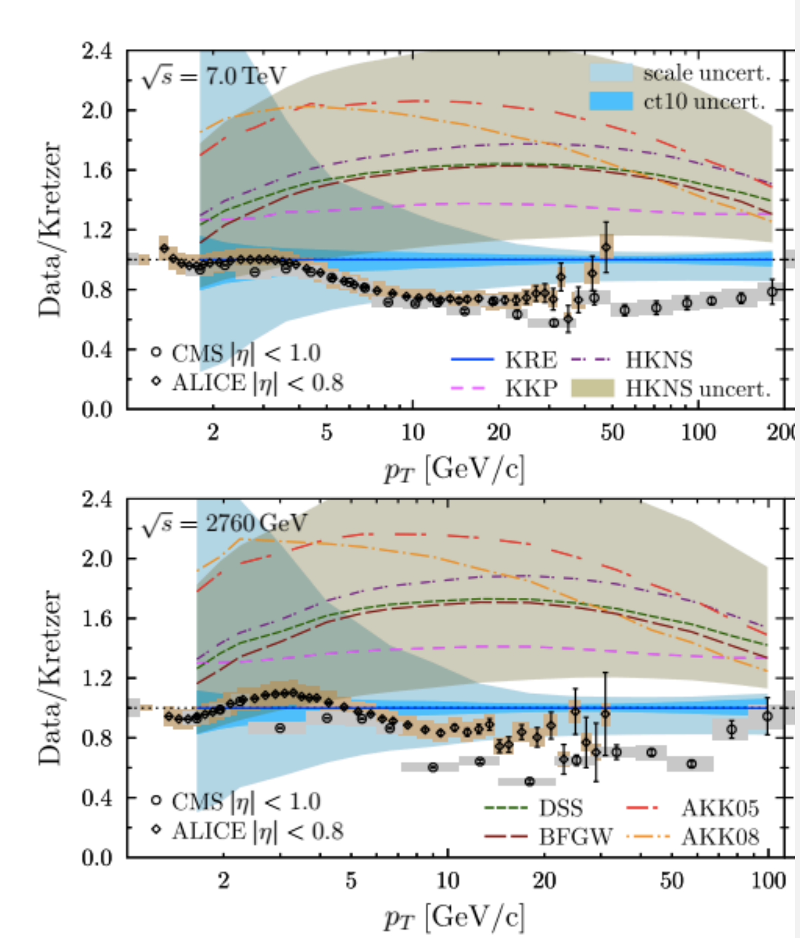
Beam aspect ratio at IP

Vertical beta function at IP

	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

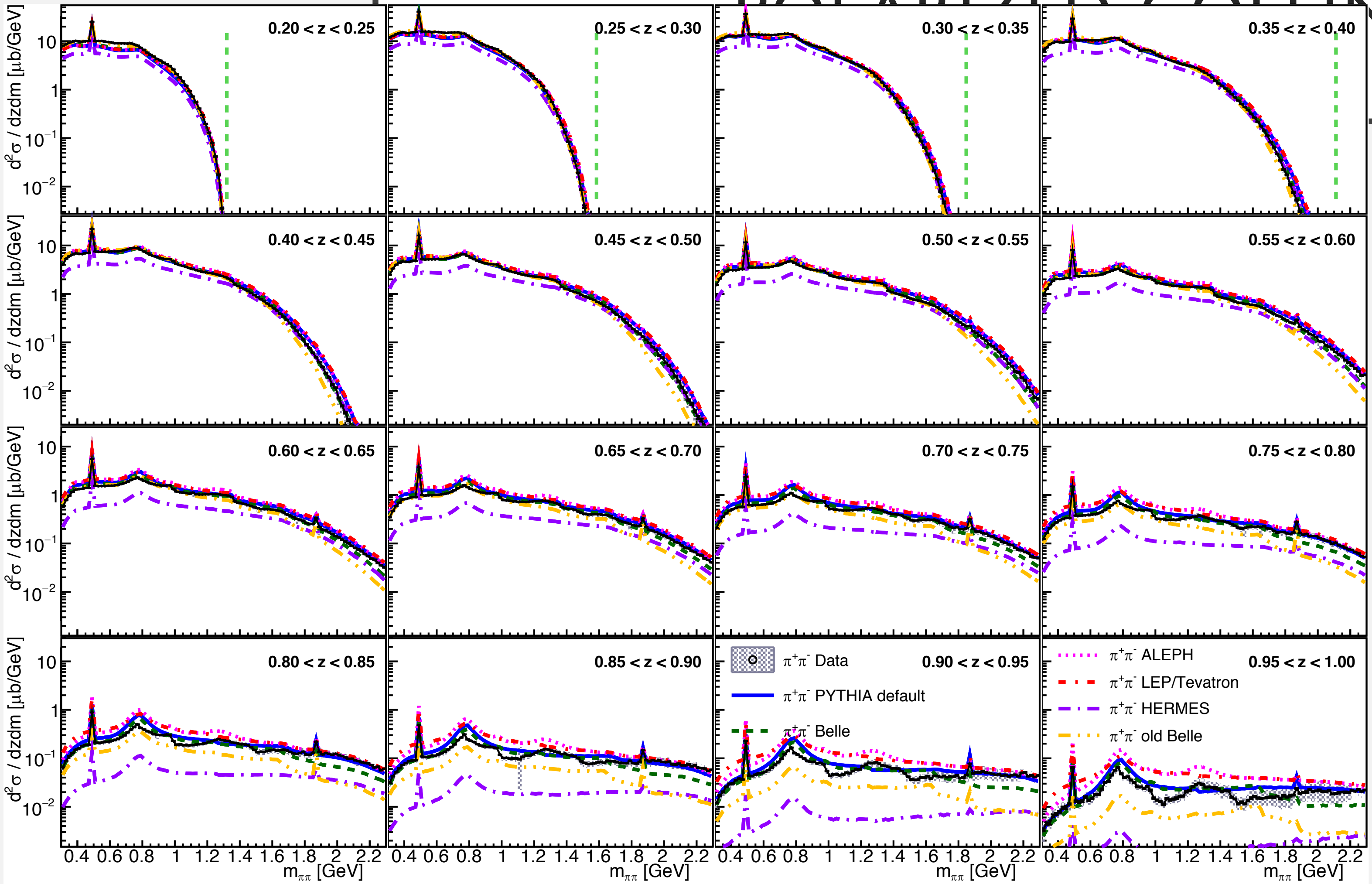
SURPRISES POSSIBLE WHEN NEW DATA BECOMES AVAILABLE

- Example:
  - Hadron Spectra at the LHC confronted with current FF sets
  - **Large disagreement!**

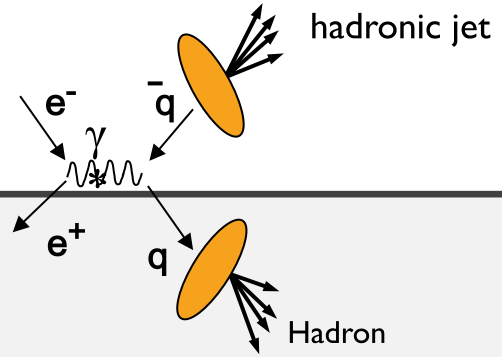


D. d'Enterria, K. J. Eskola, I. Helenius, H. Paukkunen, Nucl. Phys. B883 (2014) 615.

POLARIZED COLLINS



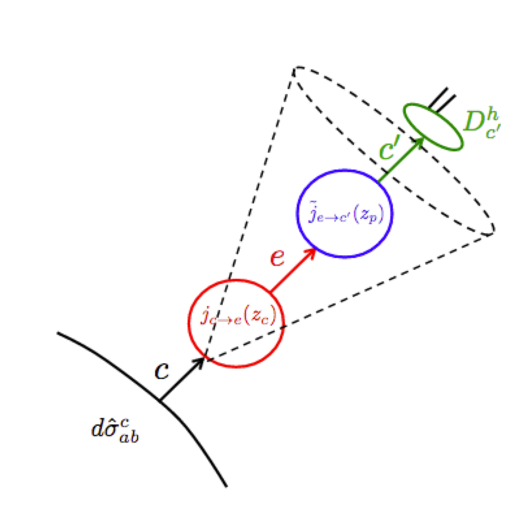
$$= \frac{1}{\sum_q e_q^2}\left(2F_1^h(z,Q^2) + F_L^h(z,Q^2)\right),$$



$$\frac{d^3\sigma^{pp\to(h,\mathrm{jet})X}}{dP_T^{\mathrm{jet}}\, d\eta^{\mathrm{jet}}\, dz} \propto \sum_{i,j,k} f_1^{i/p_a}(x_a) \otimes f_1^{j/p_b}(x_b) \otimes \hat{\sigma}^{ij\to k\mathrm{jet}} \otimes D_1^{h/p_k}\left(\frac{z}{z_k}\right)$$

- h-h, Jet-hadron (back-to-back)
- γ-hadron (back-to-back)
- Hadron in jet

$$\frac{E_h\, d^3\sigma^{pp\to hX}}{d^3P_h} = \sum_{i,j,k,l} \int \frac{dx_a}{x_a} \int \frac{dx_b}{x_b} \int \frac{dz}{z^2} f_1^{i/p_a}(x_a)\, f_1^{j/p_b}(x_b)\, D_1^{h/k}(z)\, \hat{\sigma}^{ij\to kl}\, \delta(\hat{s}+\hat{t}+\hat{u}),$$

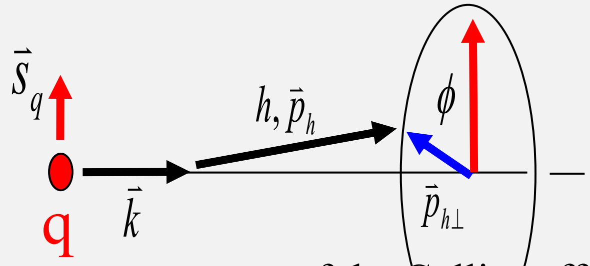


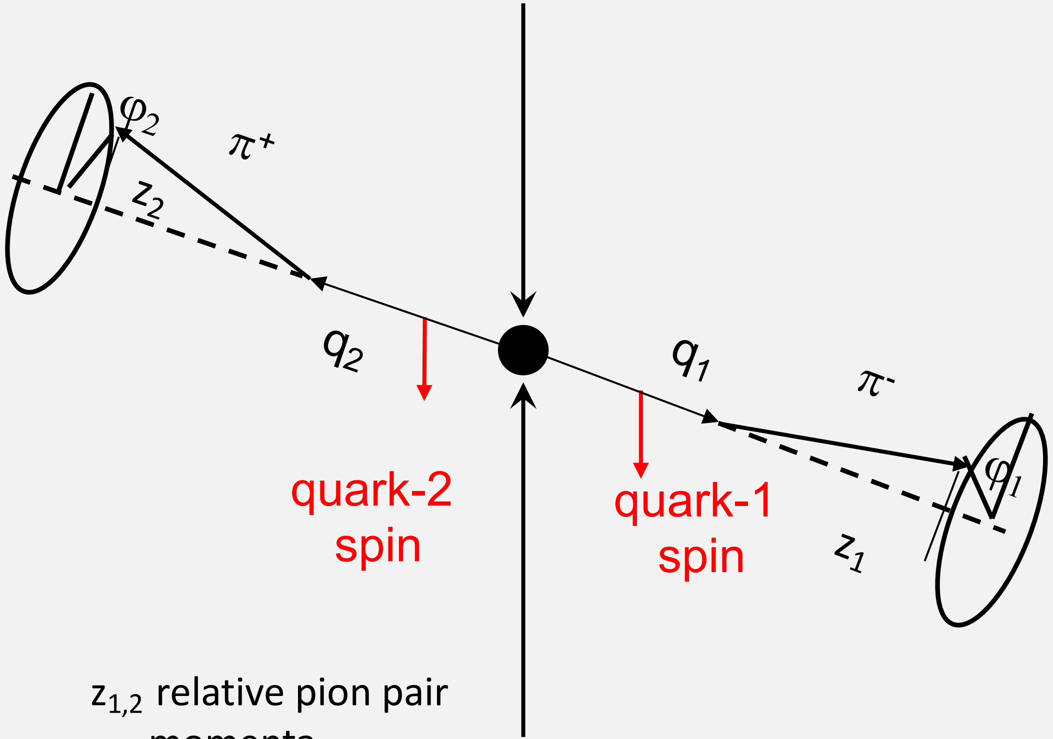
Kaufmann, Mukherjee, Vogelsang,
Phys.Rev. D92 (2015) no.5, 054015

CORRELATION MEASUREMENTS IN e^+e^-

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

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





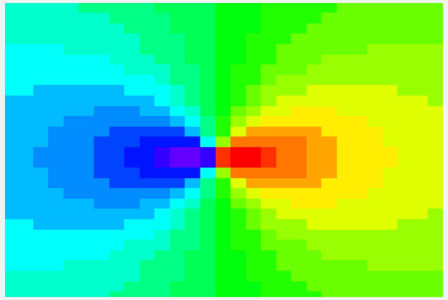
$z_{1,2}$ relative pion pair momenta

•First non-zero independent measurement of the Collins effect for pion pairs in e+e- annihilation by Belle Collaboration @ √s ~ 10.6 GeV (PRL 111,062002(2008), PRD 88,032011(2013)) leads to first extraction of transversity (Phys.Rev. D75 (2007) 054032) from SIDIS and e+e-

- Confirmed by BaBar @ √s ~ 10.6 GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
- Measured at BESIII @ √s = 3.65 GeV (PRL 116,42001(2016))

Cross-section $e^+e^- \rightarrow (h_1 h_2)(\overline{h_1}\ \overline{h_2}) + X$

$$\propto D_1^{\perp}\ \overline{D_1^{\perp}} + H_1^{\perp}\ \overline{H_1^{\perp}} \cos(\phi_1 + \phi_2)$$



- Access spin dependence and p_T dependence (convolution or in jet) without PDF complication
- Made possible by B-factory luminosities