Fragmentation measurements in Belle

PHENIX spinfest workshop

07/22/2015

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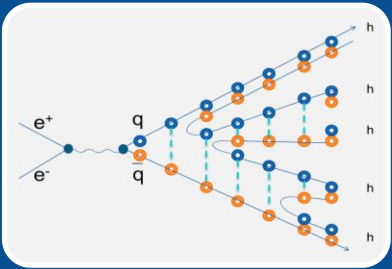
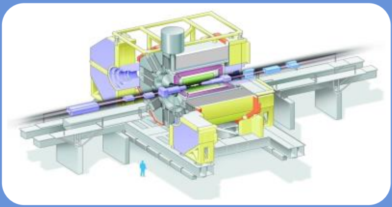
What are fragmentation functions?



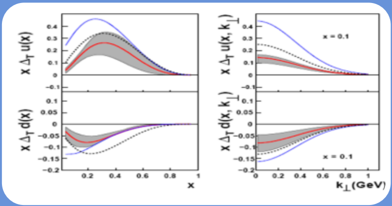
How do quasi-free partons fragment into confined hadrons？

- Does spin play a role？Flavor dependence?
- What about transverse momentum (and its Evolution)？



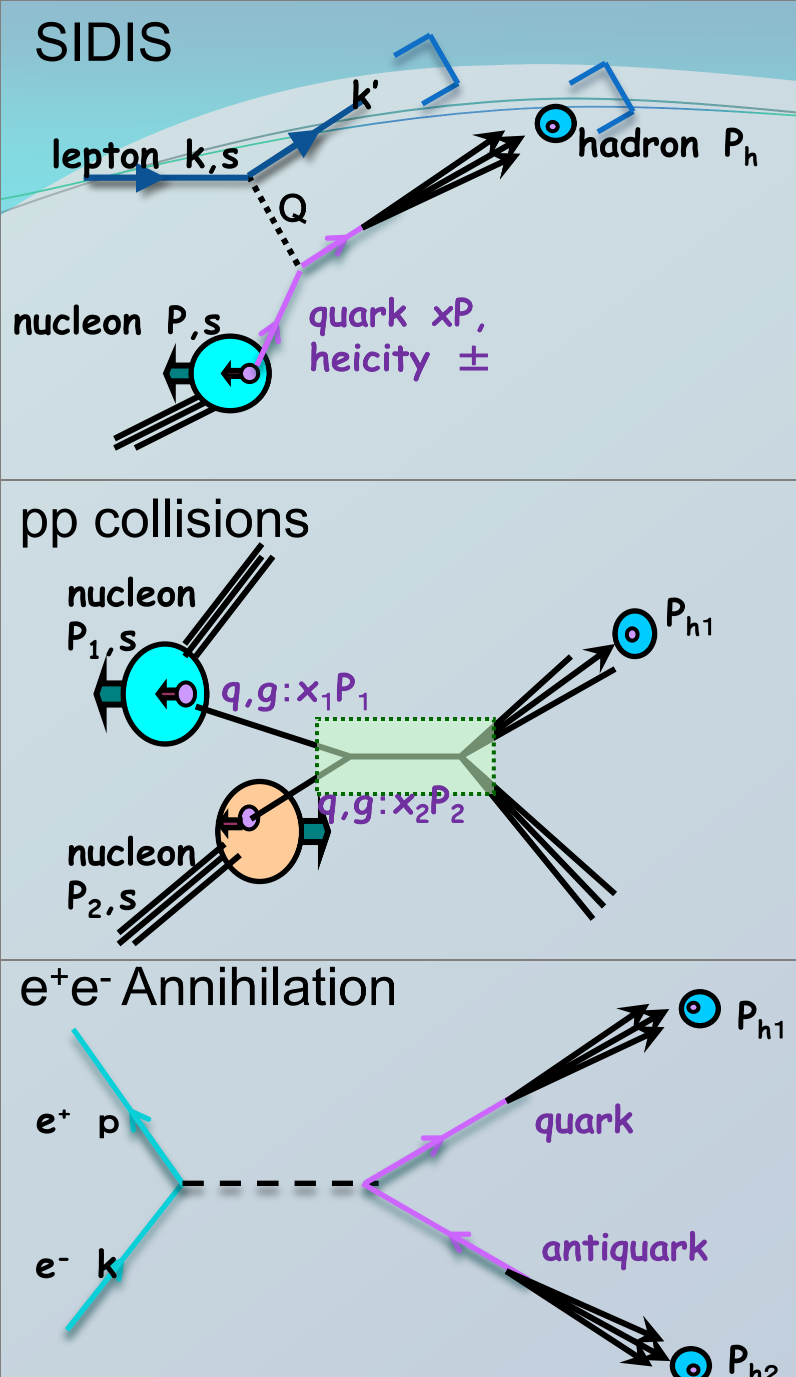
What experiments measure：

- Normalized hadron momentum in CMS： $e^+e^- \rightarrow h(z)\ X$; $z = 2E_h/\sqrt{s}$
- Hadron pairs' azimuthal distributions： $e^+e^- \rightarrow h_1\ h_2\ X$; $<\cos(\phi_1+\phi_2)>$; Collins FF、Interference（IFF）
- Cross sections or multiplicities differential in z: ep->hX, pp->hX



Additional benefits of the FF measurements：

- Pol FFs necessary input to transverse spin SIDIS und pp measurements to extract Transversity distributions function
- Flavor separation of all Parton distribution functions (PDFs) via FFs (including unpolarized PDFs)
- Baseline for any Heavy Ion measurement
- Access to exotics?



Access to FFs

- SIDIS:

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

  - Relies on unpol PDFs
  - Parton momentum known at LO
  - Flavor structure directly accessible
  - Transverse momenta convoluted between FF and PDF
- pp:

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

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

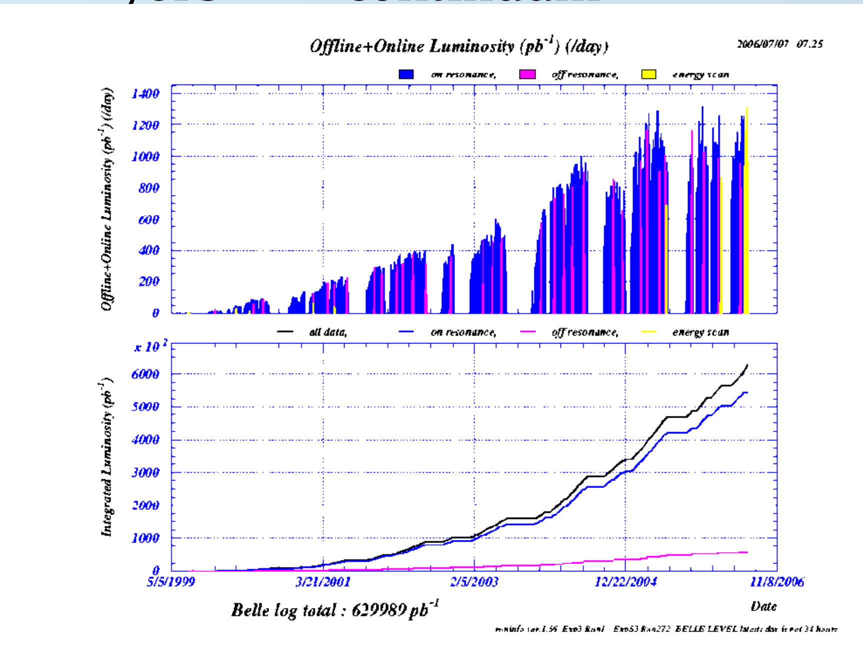
$$\sigma^h(z, Q^2, p_t) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, p_t, Q^2) + D_{1,\bar{q}}^h(z, p_t, Q^2) \right)$$

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

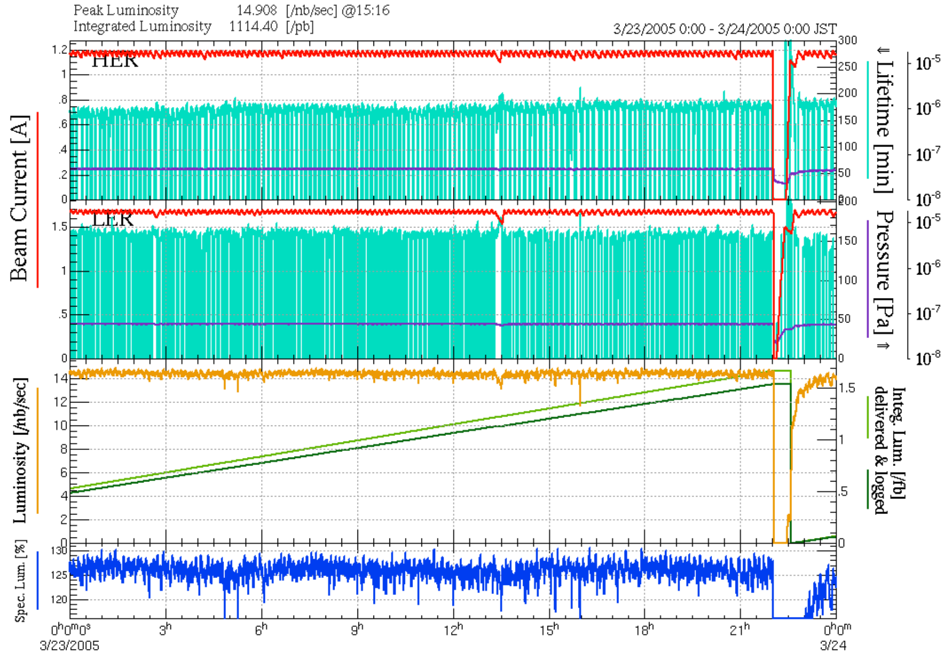
KEKB: L>2.1x10^{34}cm^{-2}s^{-1} !!

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

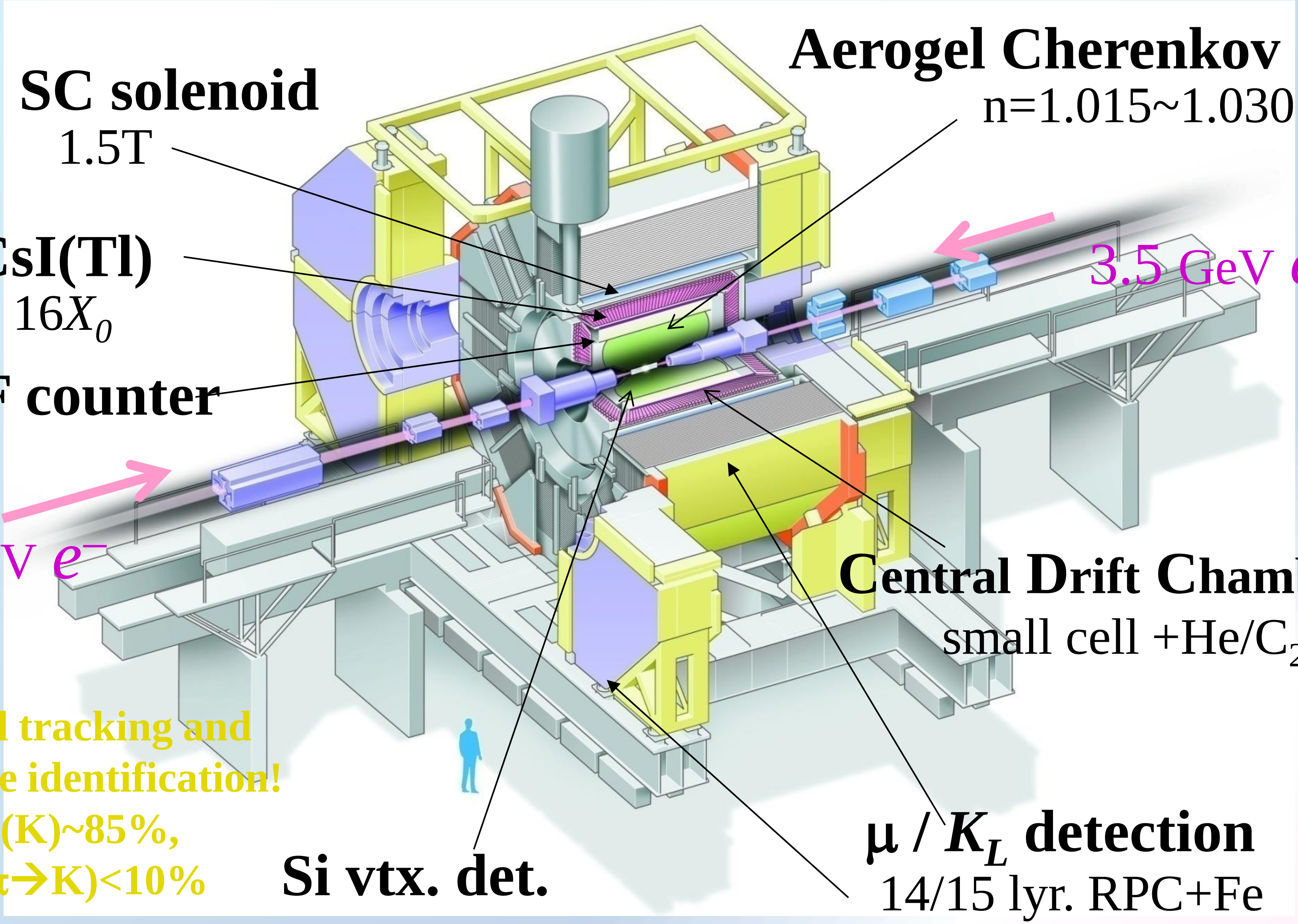
Main research at Belle:
CP violation and determination of Cabibbo Kobayashi Maskawa (CKM) matrix



easurem



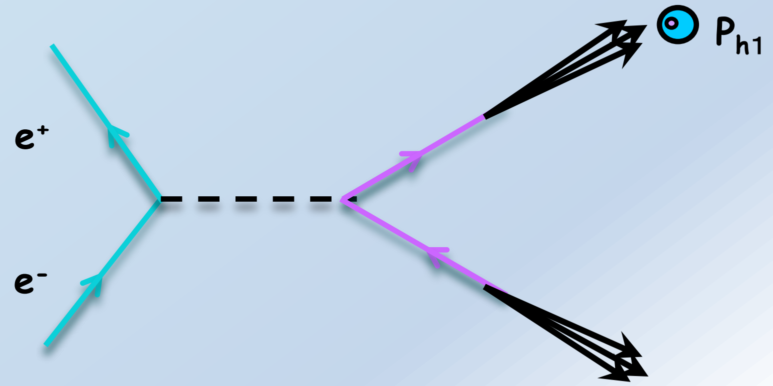
Belle Detector



Good tracking and particle identification!
ε(K)~85%,
ε(π→K)<10%

Unpolarized fragmentation functions

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



Belle PID efficiency evaluation

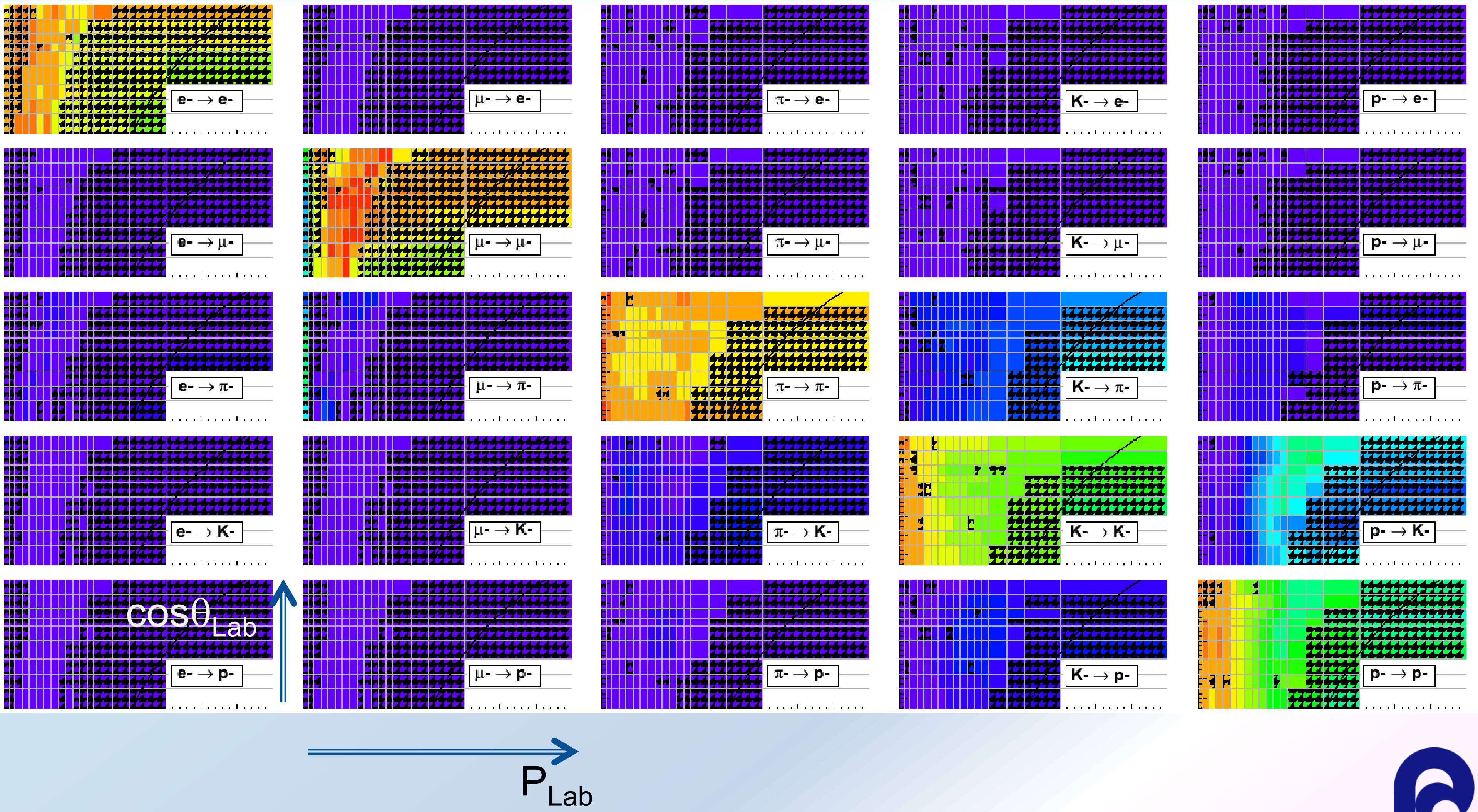
- Particle identification: create PID efficiency matrix for K,π,p,e,μ
- PID responses from MC not reliable, use well identified decays from data:
  - Use $D^* \rightarrow \pi_{slow} D^0 \rightarrow \pi_{slow}\pi_{fast}K$ for K,π identification
  - Use $\Lambda \rightarrow \pi p$ for p,π identification
  - $J/\psi \rightarrow \mu^+ \mu^-$, $e^+ e^-$ for leptons

→ Unfolding

$$\begin{pmatrix} N_e^{likelihood-cut} \\ N_\mu^{likelihood-cut} \\ N_\pi^{likelihood-cut} \\ N_K^{likelihood-cut} \\ N_P^{likelihood-cut} \end{pmatrix} = \begin{pmatrix} \epsilon_{e\rightarrow e} & \epsilon_{e\rightarrow \mu} & \epsilon_{e\rightarrow \pi} & \epsilon_{e\rightarrow K} & \epsilon_{e\rightarrow P} \\ \epsilon_{\mu\rightarrow e} & \epsilon_{\mu\rightarrow \mu} & \epsilon_{\mu\rightarrow \pi} & \epsilon_{\mu\rightarrow K} & \epsilon_{\mu\rightarrow P} \\ \epsilon_{\pi\rightarrow e} & \epsilon_{\pi\rightarrow \mu} & \epsilon_{\pi\rightarrow \pi} & \epsilon_{\pi\rightarrow K} & \epsilon_{\pi\rightarrow P} \\ \epsilon_{K\rightarrow e} & \epsilon_{K\rightarrow \mu} & \epsilon_{K\rightarrow \pi} & \epsilon_{K\rightarrow K} & \epsilon_{K\rightarrow P} \\ \epsilon_{P\rightarrow e} & \epsilon_{P\rightarrow \mu} & \epsilon_{P\rightarrow \pi} & \epsilon_{P\rightarrow K} & \epsilon_{P\rightarrow P} \end{pmatrix} \begin{pmatrix} N_e^{real} \\ N_\mu^{real} \\ N_\pi^{real} \\ N_K^{real} \\ N_P^{real} \end{pmatrix}$$

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

PID efficiencies

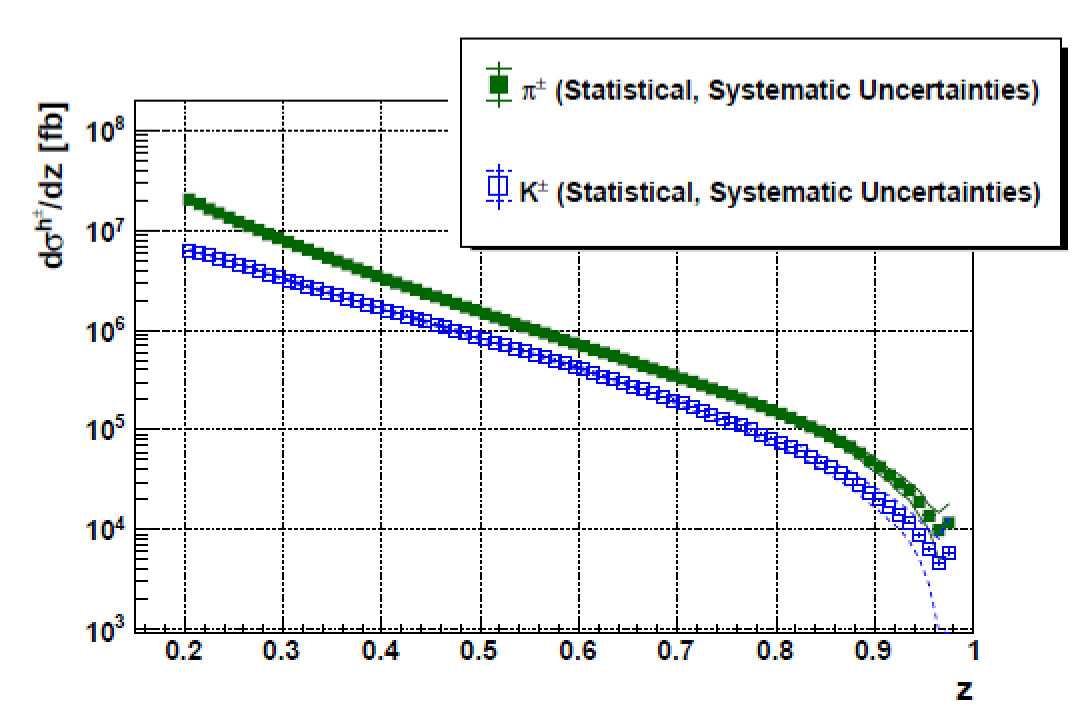


Unpolarized fragmentation

In e^+e^- annihilation:

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

Phys.Rev.Lett. 111 (2013) 062002,
Leitgab, RS, et al (Belle)



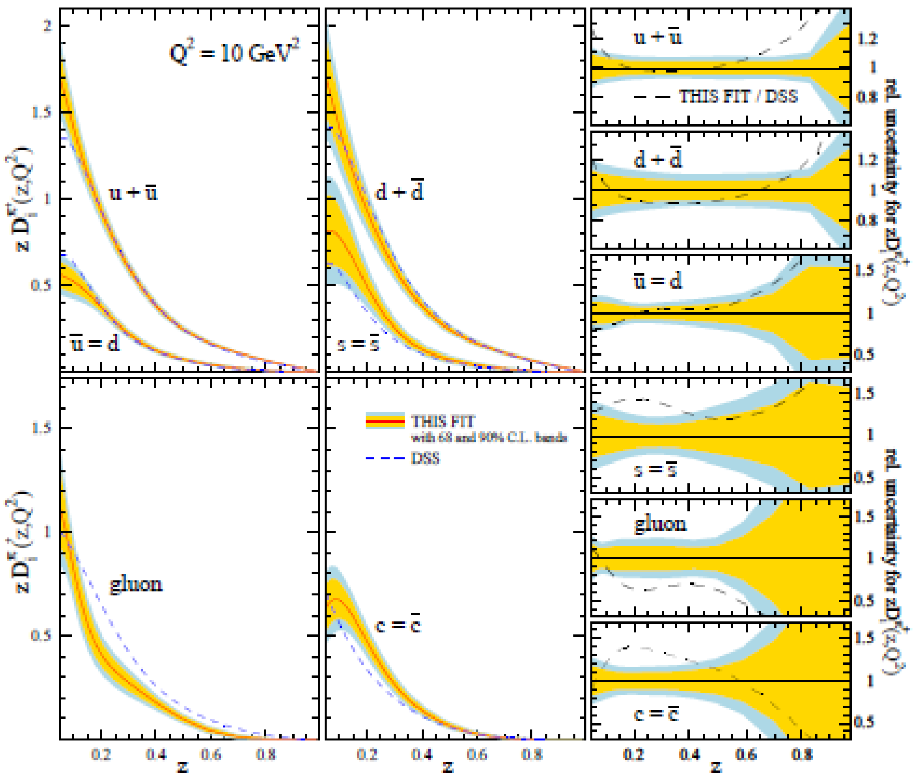
- Single-hadron cross sections at leading order in α_s related to fragmentation functions

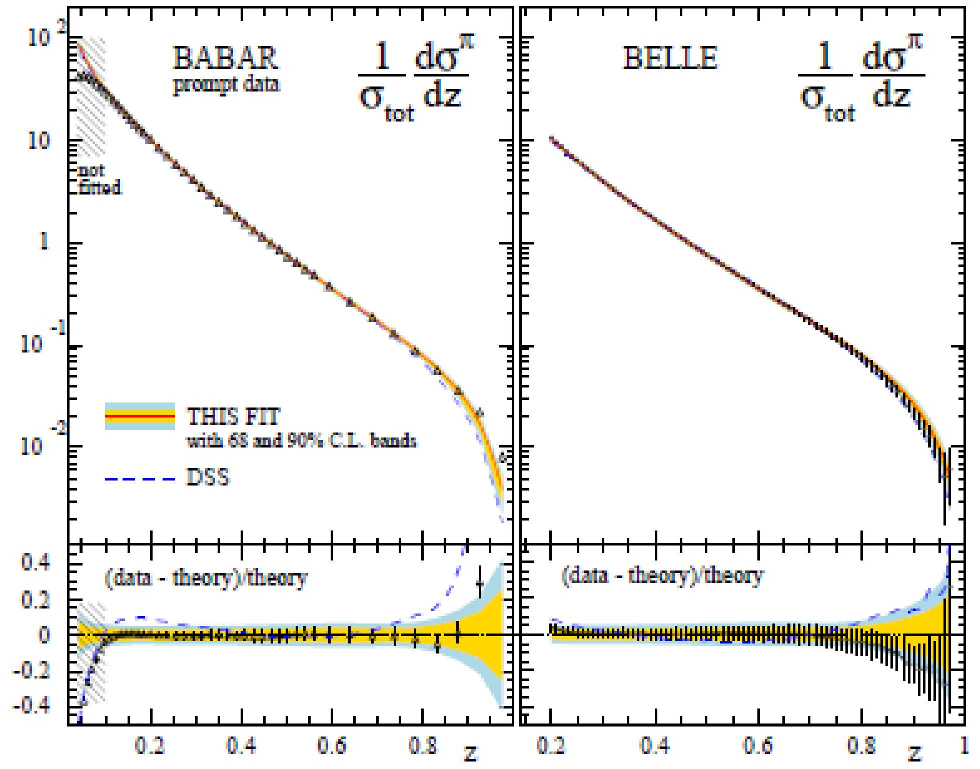
$$\sigma(e^+e^- \to hX) \propto \sum_q e_q^2 \left(D_{1,q}^h(z) + D_{1,\bar{q}}^h(z)\right)$$

- Only at higher orders access to gluon FFs

Belle data using in global FF fits

Phys.Rev. D91 (2015) 1, 014035

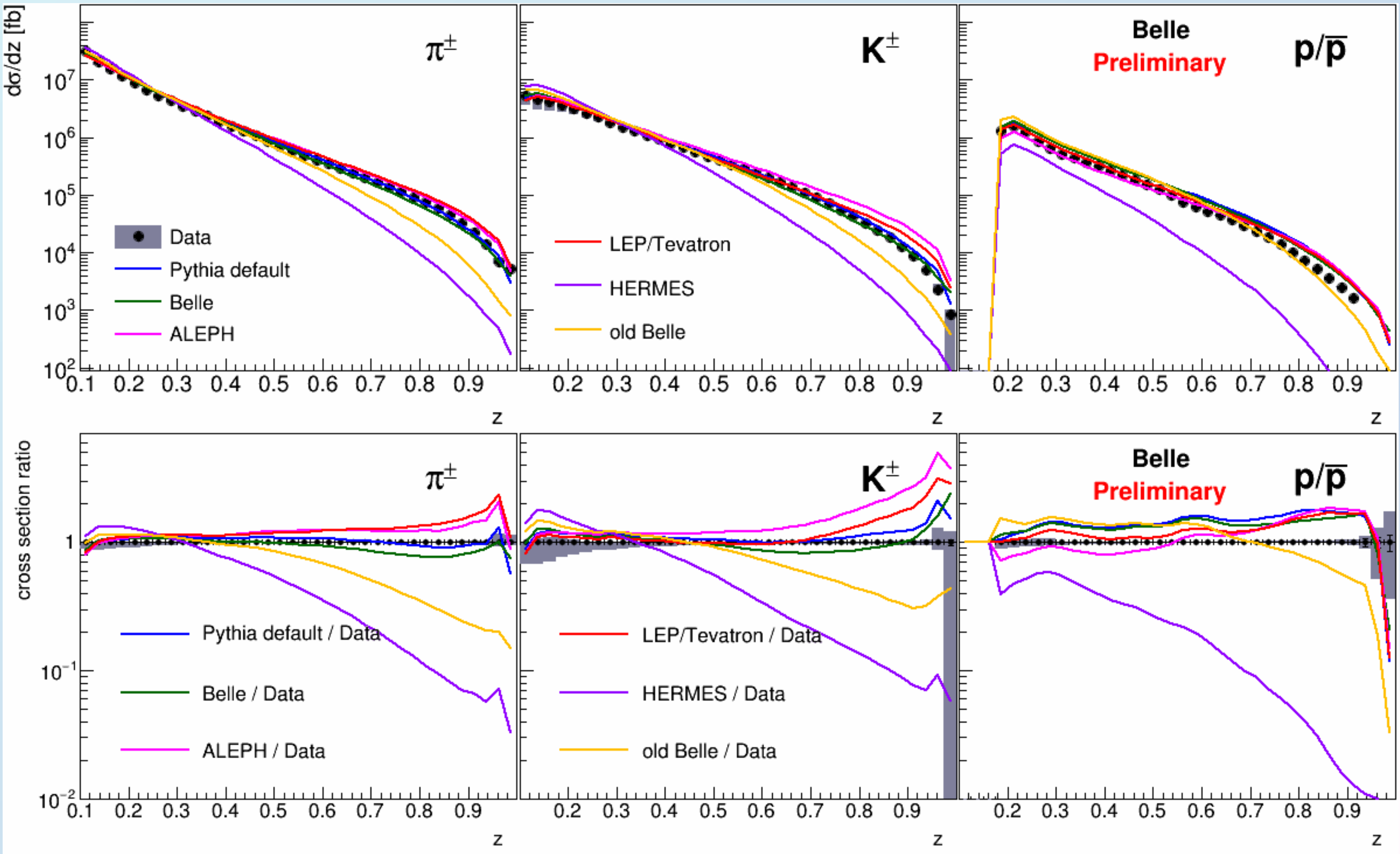




- Together with other new data substantial improvement in uncertainties
- Shift in central values

Good description of B-factory data

New addition: single protons



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

Di-hadrons

In e^+e^- annihilation:

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

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

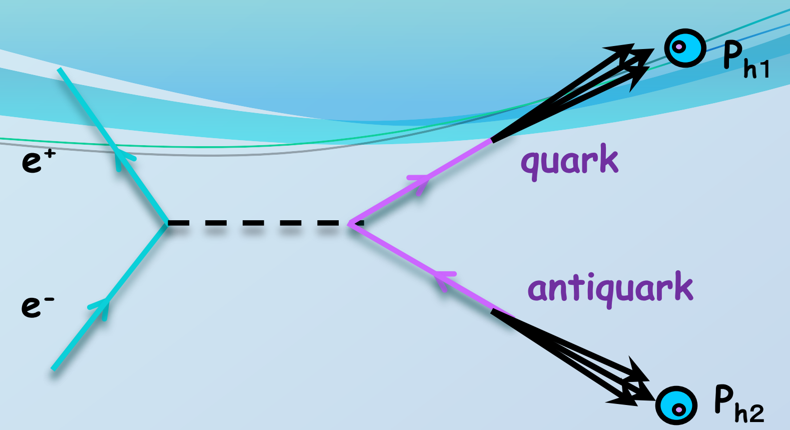
$$d\sigma(e^+e^- \to hX)/dz \propto \sum_q e_q^2 (D^h_{1,q}(z,Q^2) + D^h_{1,\bar{q}}(z,Q^2))$$

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

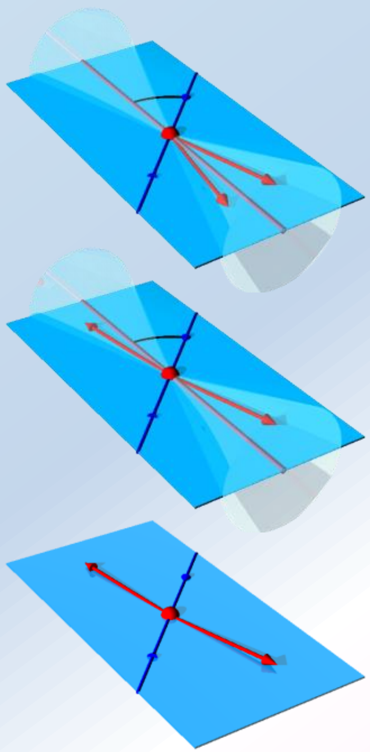
$$u\bar{u} \to \pi^+\pi^-X \propto D^{\pi^+}_{u,fav}(z_1,Q^2) \cdot D^{\pi^-}_{\bar{u},fav}(z_2,Q^2) + D^{\pi^+}_{\bar{u},dis}(z_1,Q^2) \cdot D^{\pi^-}_{u,dis}(z_2,Q^2)$$
$$u\bar{u} \to \pi^+\pi^+X \propto D^{\pi^+}_{u,fav}(z_1,Q^2) \cdot D^{\pi^+}_{\bar{u},dis}(z_2,Q^2) + D^{\pi^+}_{\bar{u},dis}(z_1,Q^2)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

- Also: unpol baseline for interference fragmentation

Setup



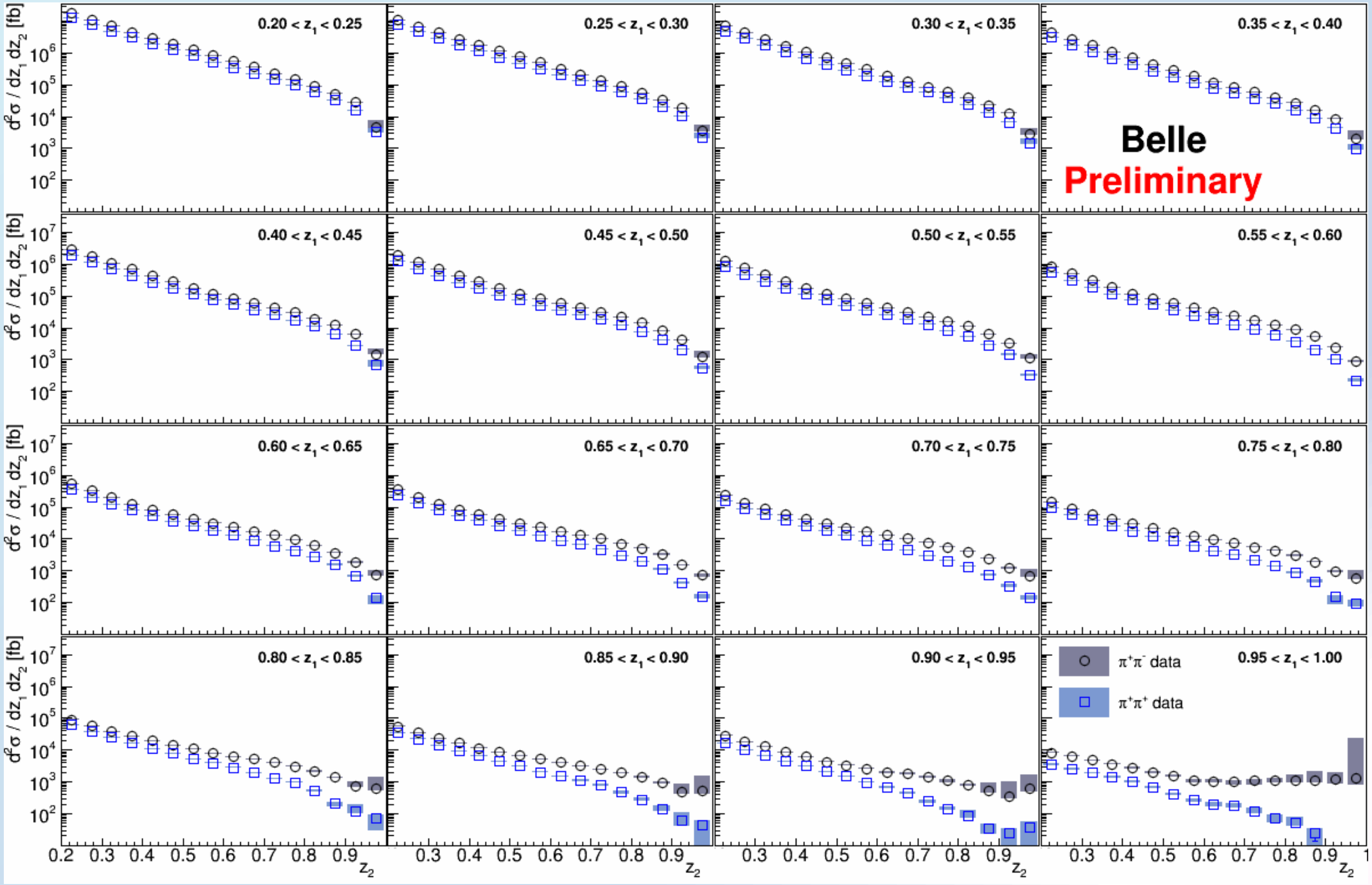
- Generally look at 4 x 4 hadron combinations (π, K, +,-)
  - Keep separate until end: only 6 independent yields
- 3 hemisphere combinations:
  - same hemisphere (thrust >0.8)
  - opposite hemisphere (thrust >0.8)
  - any combination (no thrust selection)
- 16 x 16 z_1 z_2 binning between 0.2 - 1



Correction chain

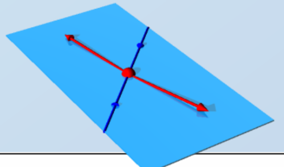
Correction	Method	Systematics
PID mis-id	PID matrices (5x5 for cos θ_{lab} and p_{lab})	MC sampling of inverted matric element uncertainties
Momentum smearing	MC based smearing matrices (256x256), SVD unfold	SVD unfolding vs analytically inverted matrix, reorganized binning, MC statistics
Non-qqbar BG removal	eeuu, eess, eecc, tau MC subtraction	Variation of size, MC statistics
Acceptance I (cut efficiency)	In barrel reconstucted vs udsc generated in barrel	MC statistics
Acceptance II	udsc Gen MC barrel to 4pi	MC statistics
Weak decay removal (optional)	udcs check evt record for weak decays	Compare to other Pythia settings
Acceptance III	Extrapolation to $\|\cos\theta\| \rightarrow 1$ in (Fit to MC)	Fit uncertainties
ISR	Keep event fraction with E> 0.995 E_{cms}	

Full results for pion pairs



Ratios to opposite charge pion pairs

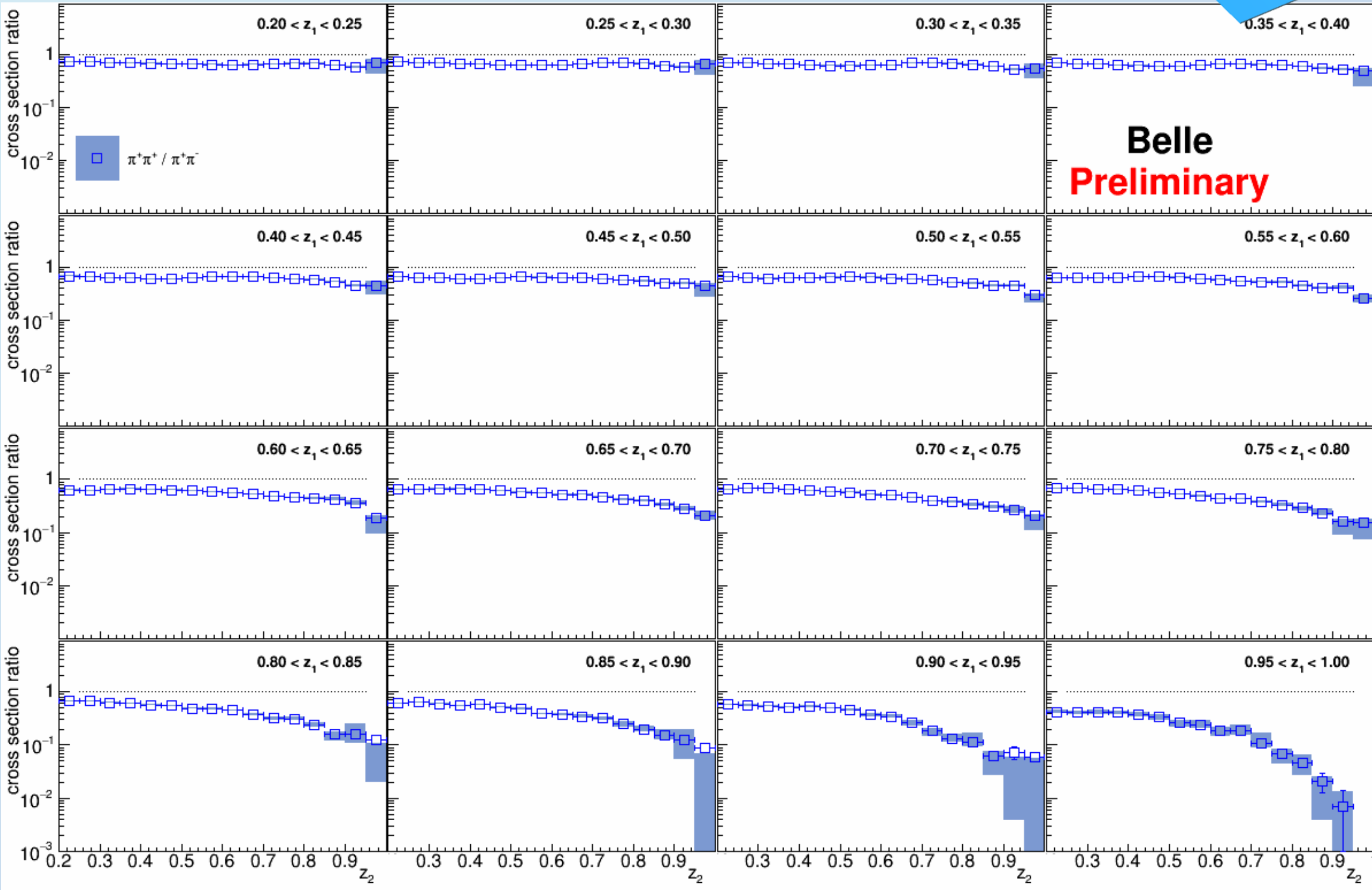
$$R \approx \frac{D_{fav}(z_1)D_{fav}(z_2) + D_{dis}(z_1)D_{dis}(z_2)}{D_{dis}(z_1)D_{fav}(z_2) + D_{fav}(z_1)D_{dis}(z_2)}$$



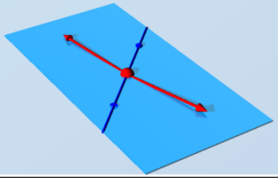
$\pi^+\pi^+$ comparable to $\pi^+\pi^-$ at low z, decreasing towards high z:

→ Favored and disfavored fragmentation similar at low z

→ Disfavored much smaller at high z



Results for diagonal z_1 z_2 bins

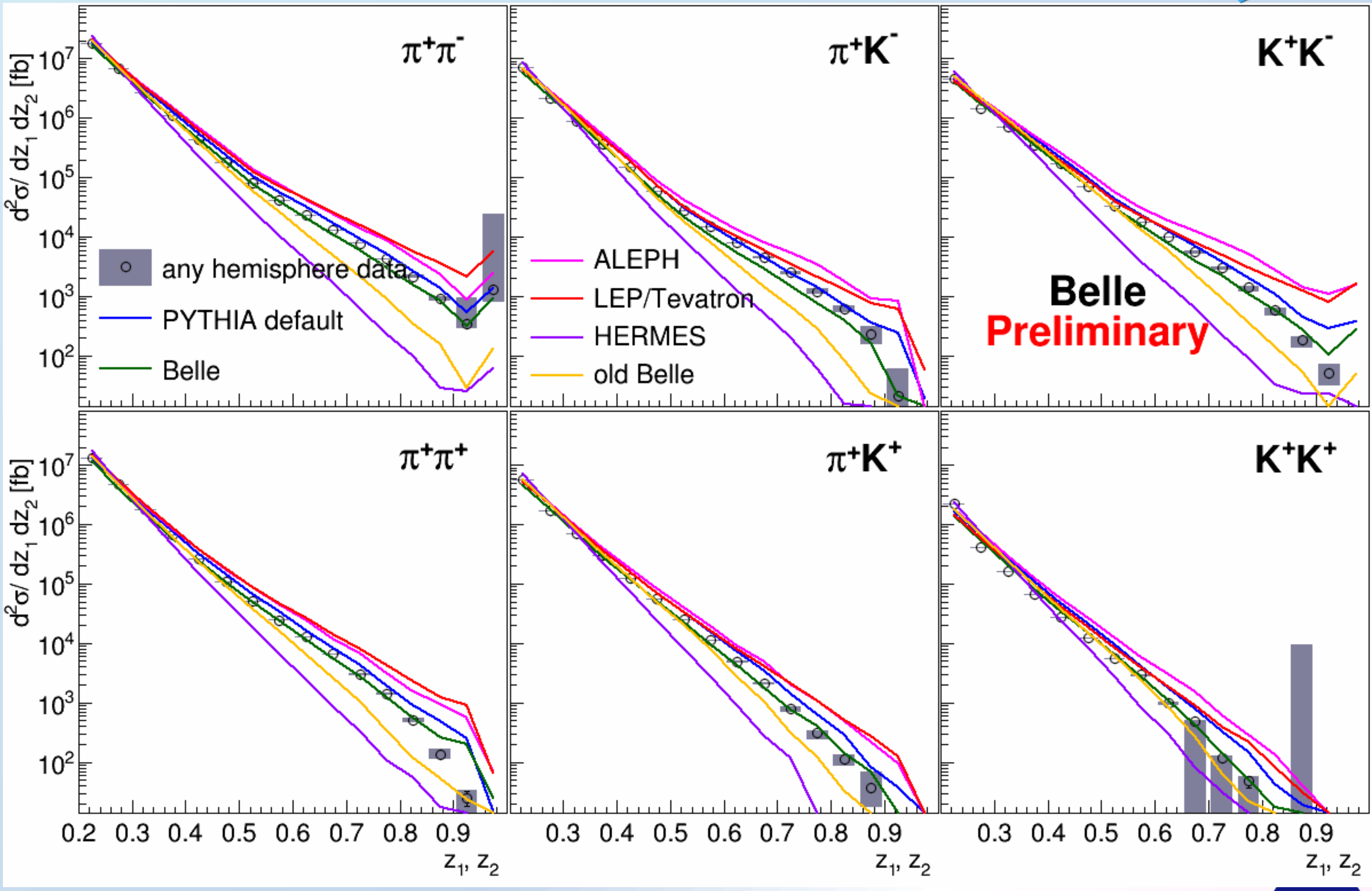


Low z dominates integral:
→Well defined, all tunes agree

High z not well measured, especially at Belle energies:
→large spread in tunes

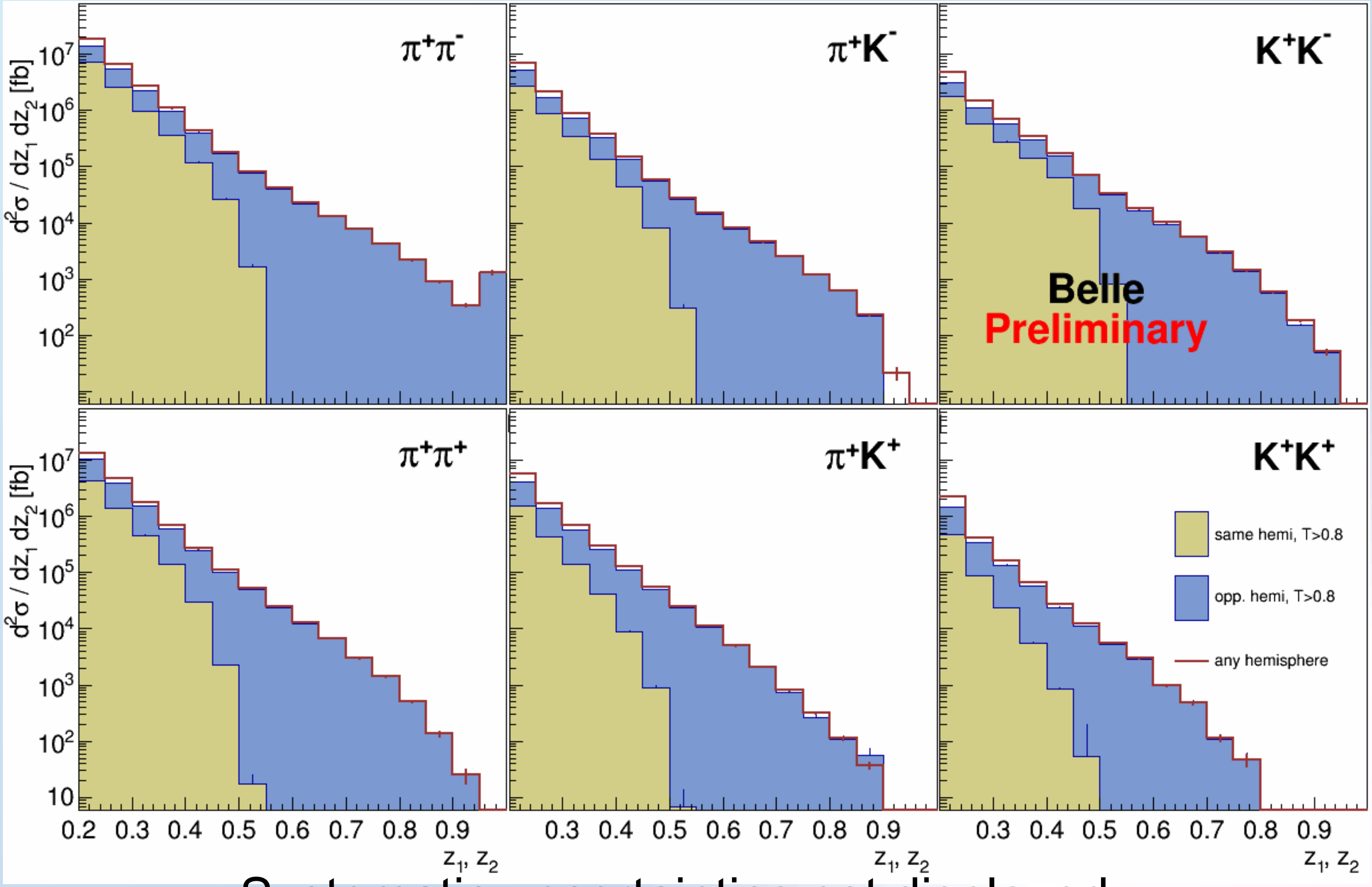
Default Pythia settings and current Belle setting with good agreement

Diagonal z_1,z_2 bins



Hemisphere composition

Same hemisphere contribution drops rapidly
Consistent with LO assumption of
Same hemisphere: single quark → di-hadron FF: ($z_1+z_2<1$)
Opposite hemisphere: single quark→single hadron FF



Systematic uncertainties not displayed

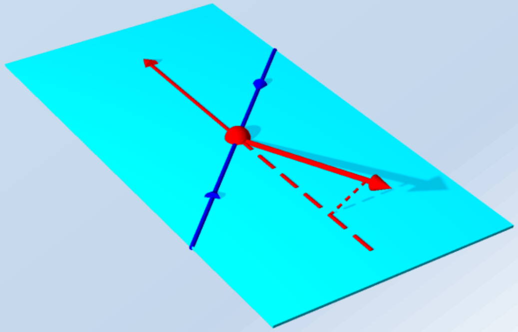
Transverse momentum dependence

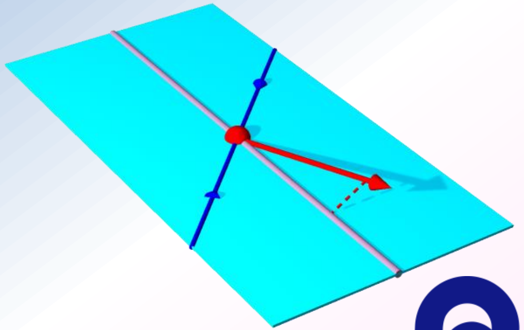
Aka un-integrated PDFs and FFs

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

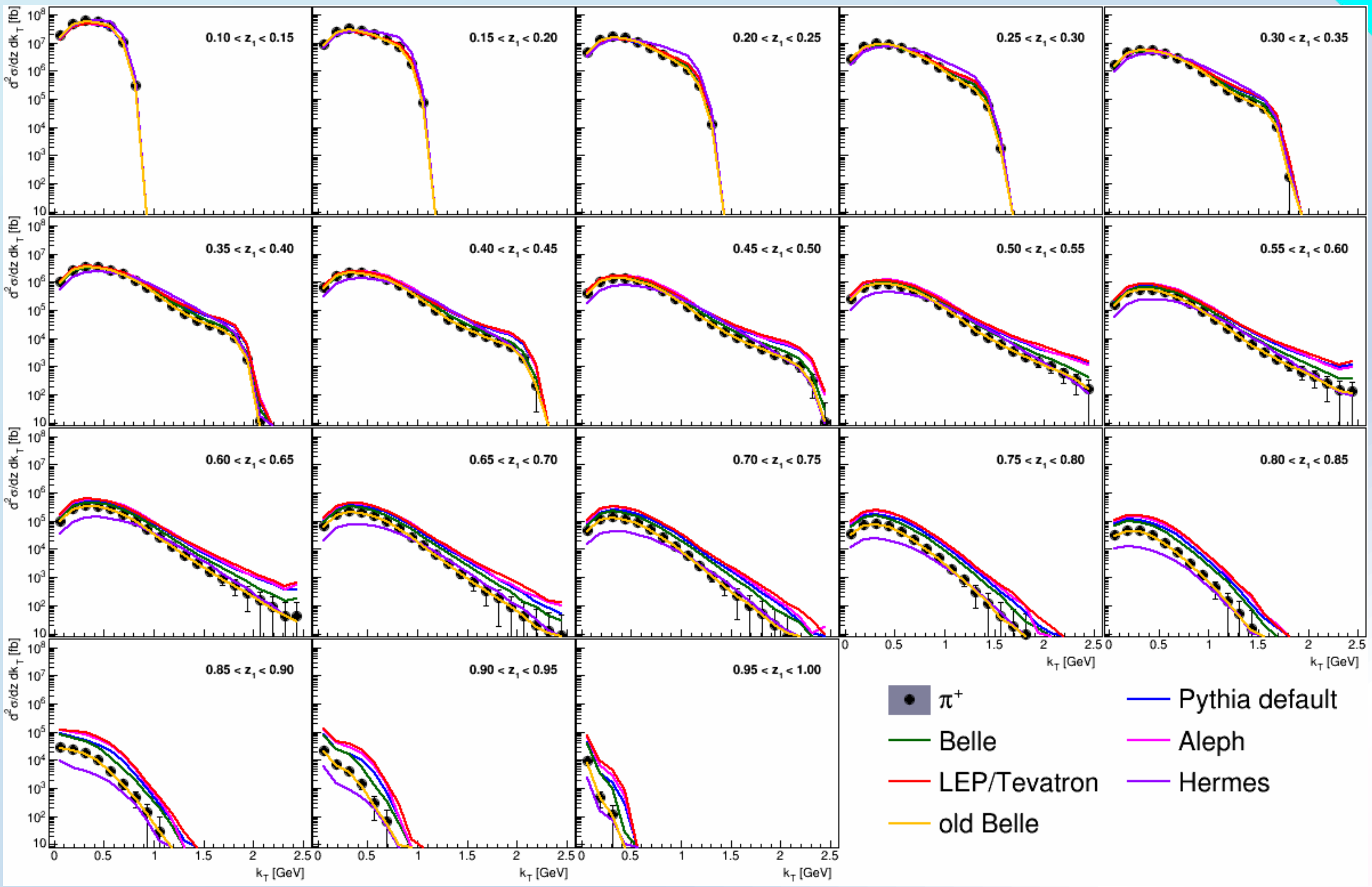
K_T Dependence of FFs

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





MC example of k_T sensitivities



Spin dependent fragmentation

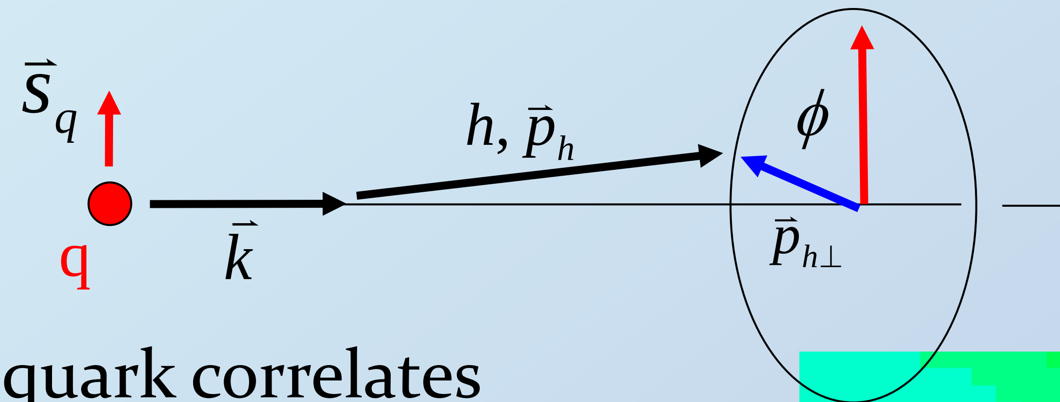
$$H_{1,q}^{h,\perp}(z, Q^2, k_t)$$

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

Collins fragmentation function

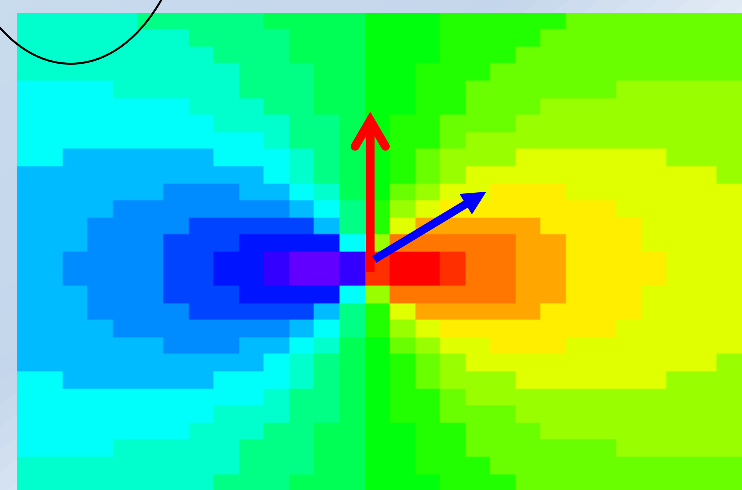
J. Collins, Nucl. Phys. B396, (1993) 161

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



- Spin of quark correlates with hadron transverse momentum

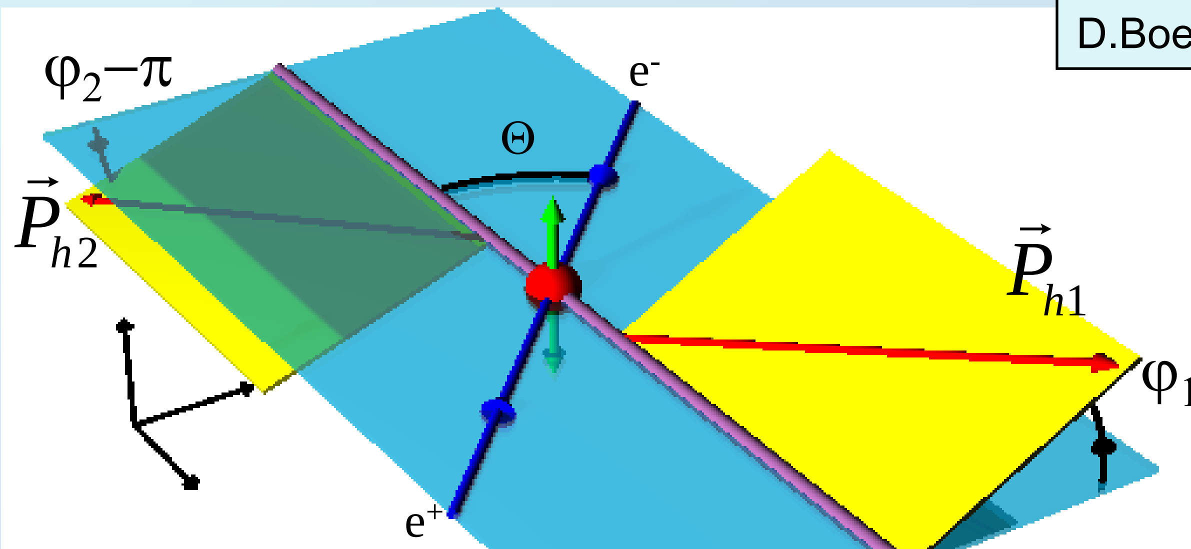
➔translates into azimuthal anisotropy of final state hadrons

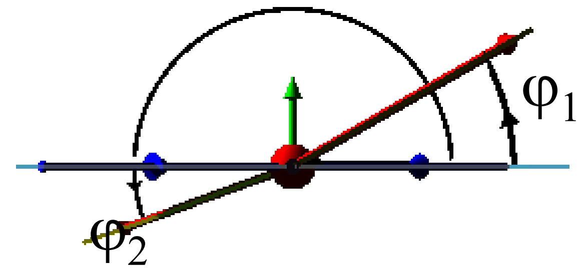


Collins fragmentation in e^+e^- :
Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e^+e^- CMS frame:

D.Boer: **Nucl.Phys. B806 (2009) 23-6**





2-hadron inclusive transverse momentum dependent cross section:

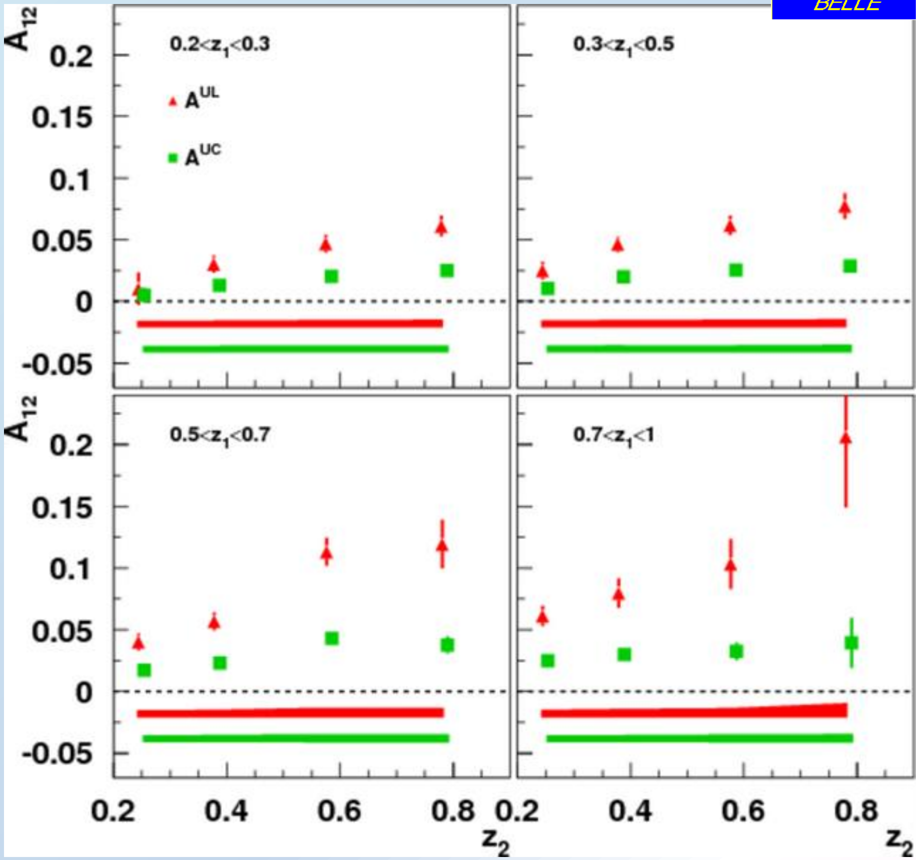
$$\frac{d\sigma\left(e^+e^- \to h_1h_2X\right)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\cos(\varphi_1+\varphi_2)H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4}\sin^2\Theta$$

Net (anti-)alignment of transverse quark spins

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

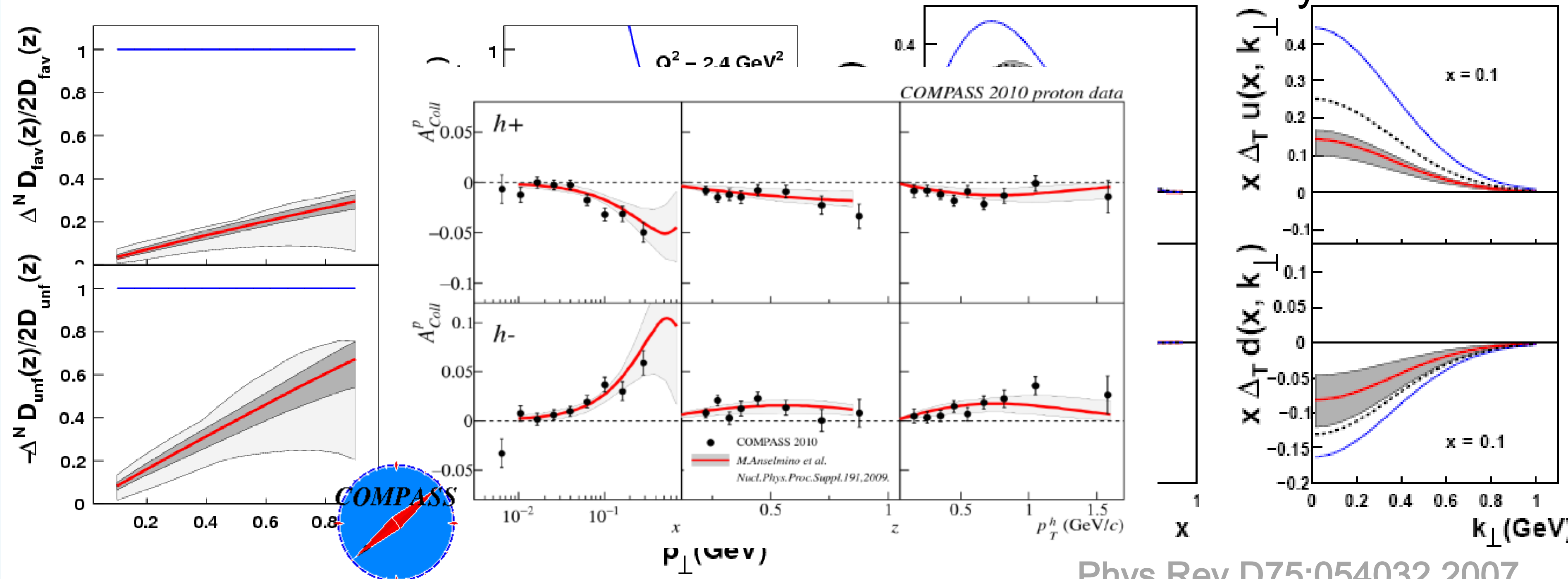


RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

Global Fit of Collins FF and Transversity (HERMES, COMPASS d, Belle)

Collins function

Transversity

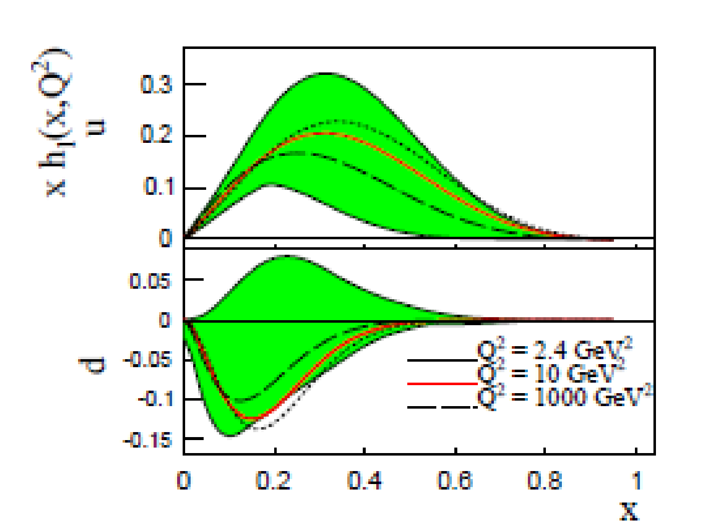


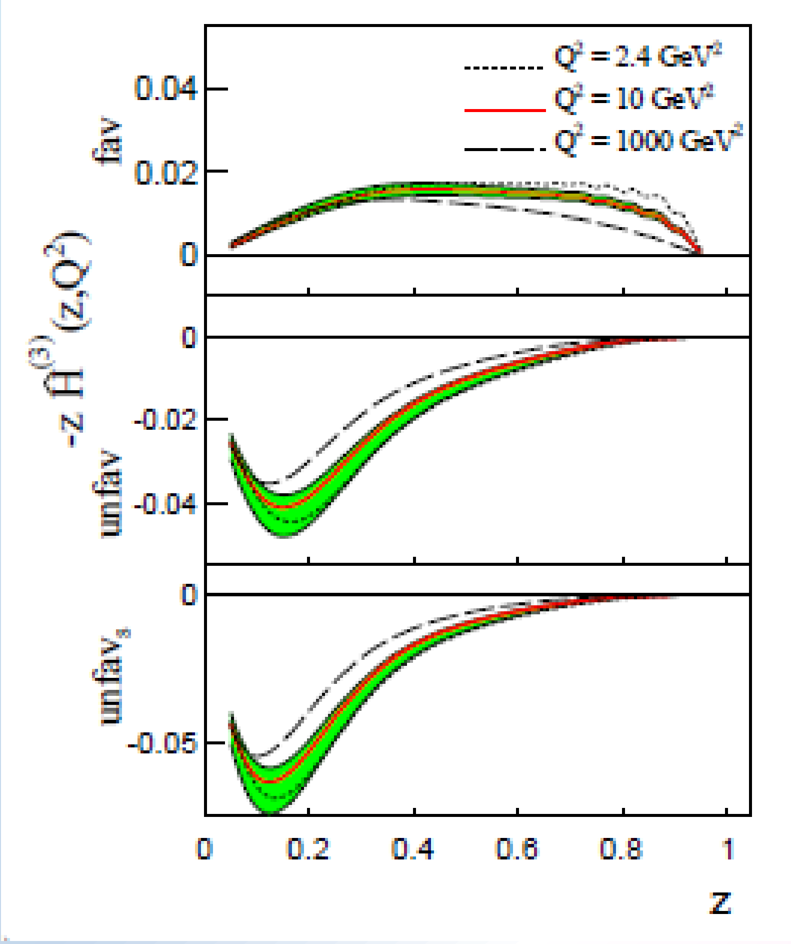
Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.191:98-107,2009

- Latest SIDIS data not included inFIT
- Open questions:
  - TMD evolution unknown (however from Belle to HERMES no large differences seen)
  - Kt dependence from Assumption (Belle measurements planned)
- Interference FF (IFF) as independent Cross check

Collins evolution

Kang, Prokudin, Sun and Yuan,
arXiv:1505.05589



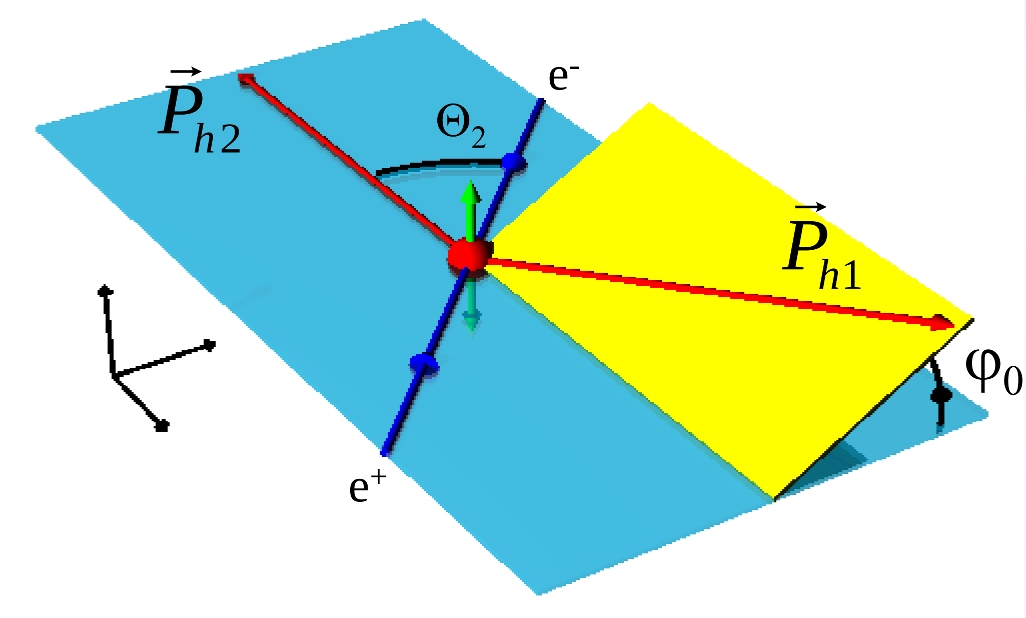


- First Transversity extraction taking TMD evolution into account
- Still many assumptions on transvserse momentum dependence necessary
- Only moderate scale dependence in final results but large effect on e+e- asymmetries

Kaons, etas and other hadrons

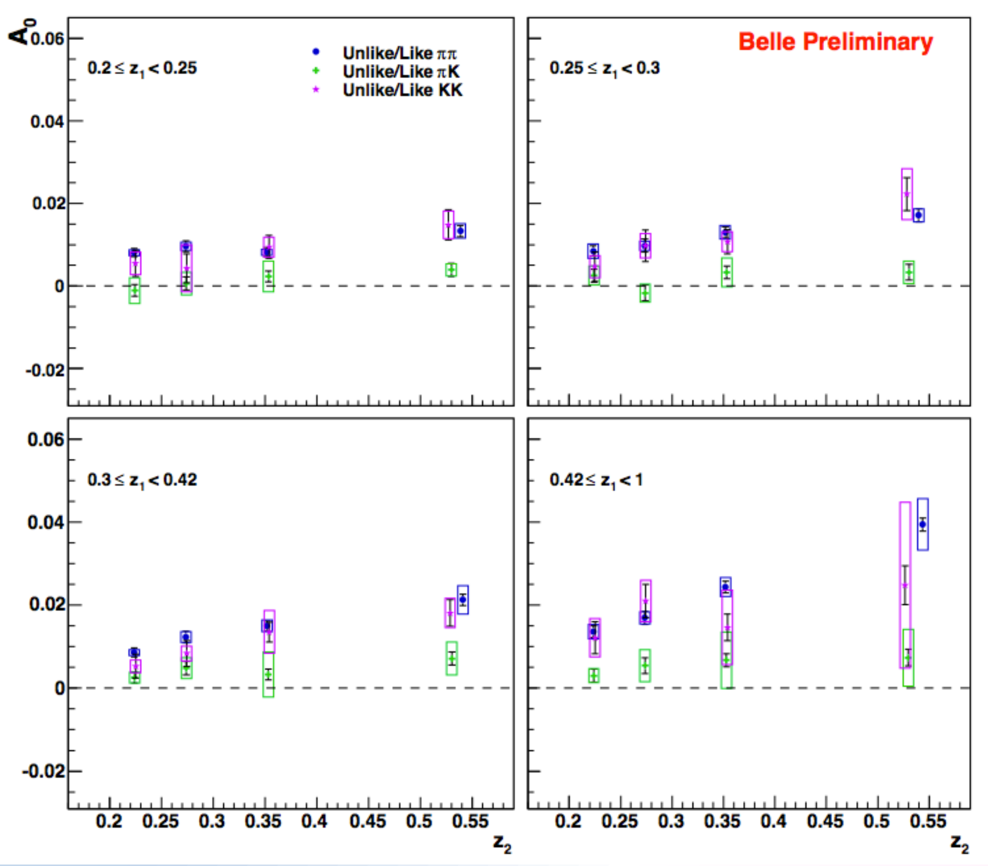
- Need Kaon Collins fragmentation:
  - to understand HERMES/COMPASS kaon data
  - Flavor separation of transversity
- Inflation of FF functions:
  - u,d →π: 2
  - u,d,s →π,K: 6+

- Apply PID unfolding to obtain pion-pion, pion-kaon and kaon-kaon combinations
- Currently use only ϕ_o method:



Preliminary results

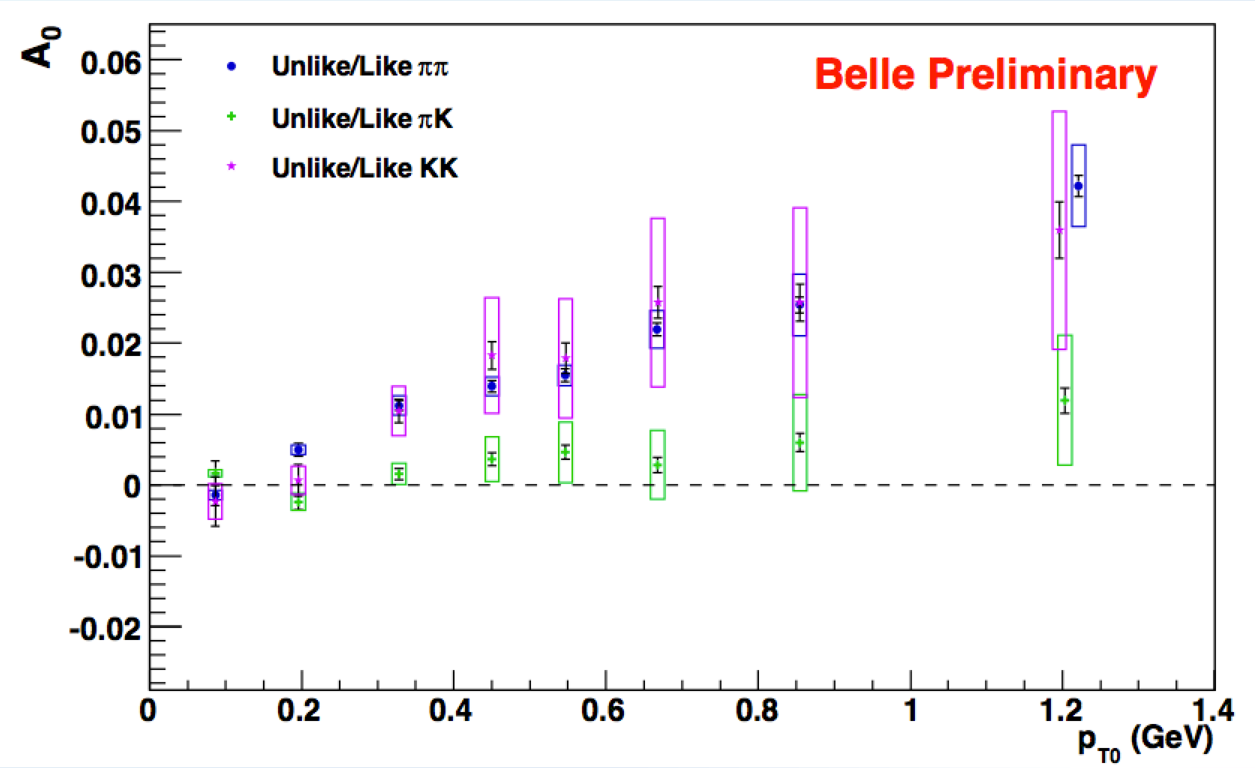
- First pion-kaon and kaon-kaon Collins results.
- Pion-pions consistent with previous results
- Pion-pion and kaon-kaon of similar shape and magnitude
- Pion-kaon substantially smaller



Charm contribution not corrected

Kaon Collins vs P_T

- Asymmetries (integrated over z) increasing with transverse momentum
- Asymmetries on light neutral hadron - pion combinations forthcoming

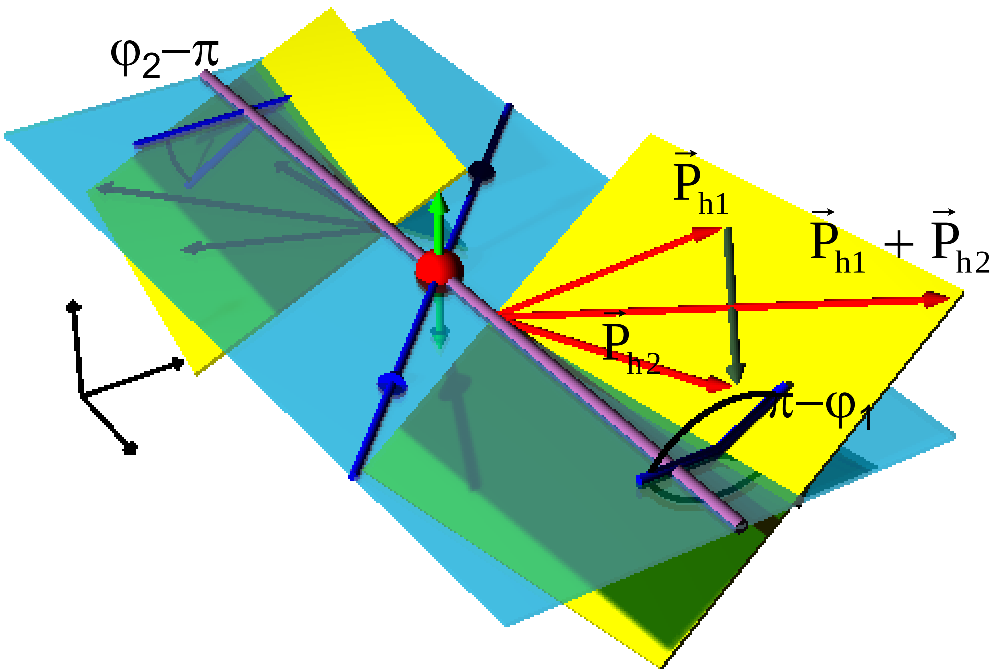


Interference fragmentation

- Again azimuthal anisotropy of distribution of hadron pairs wrt transverse quark spin
- Collinear treatment of interference fragmentation → evolution known (Cecciopieri et al: **Phys.Lett. B650 (2007) 81-89**)

Interference Fragmentation (IFF) in e^+e^-

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]

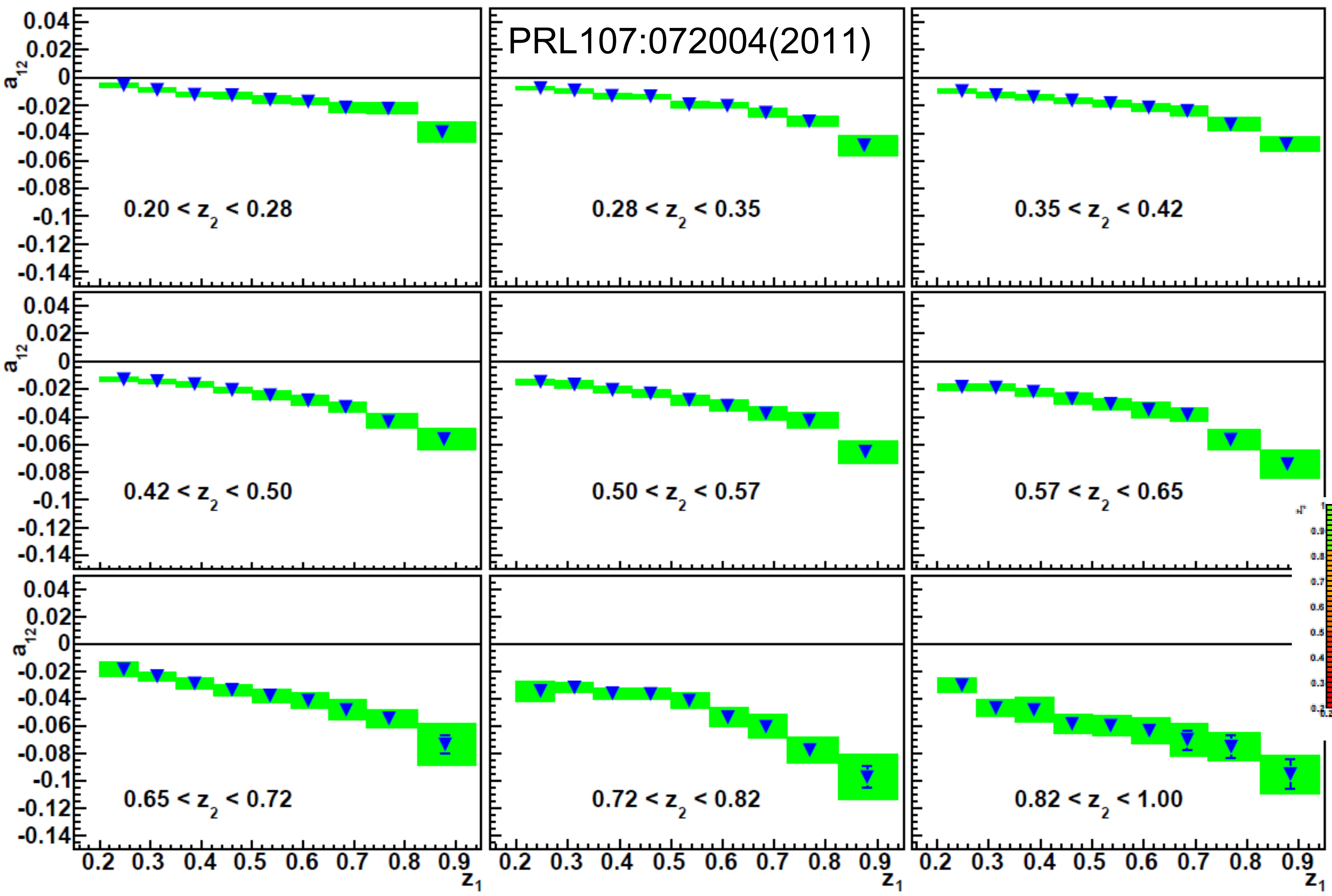


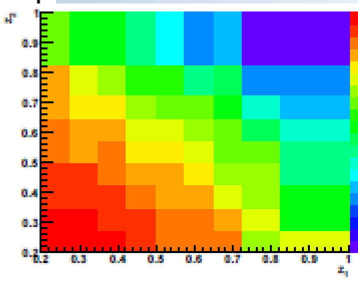
Model predictions by:

- Jaffe et al. [PRL **80,**(1998)]
- Radici et al. [PRD **65,**(2002)]

$$A \propto H_1^{\angle}(z_1, m_1)\overline{H}_1^{\angle}(z_2, m_2)\cos(\varphi_1+\varphi_2)$$

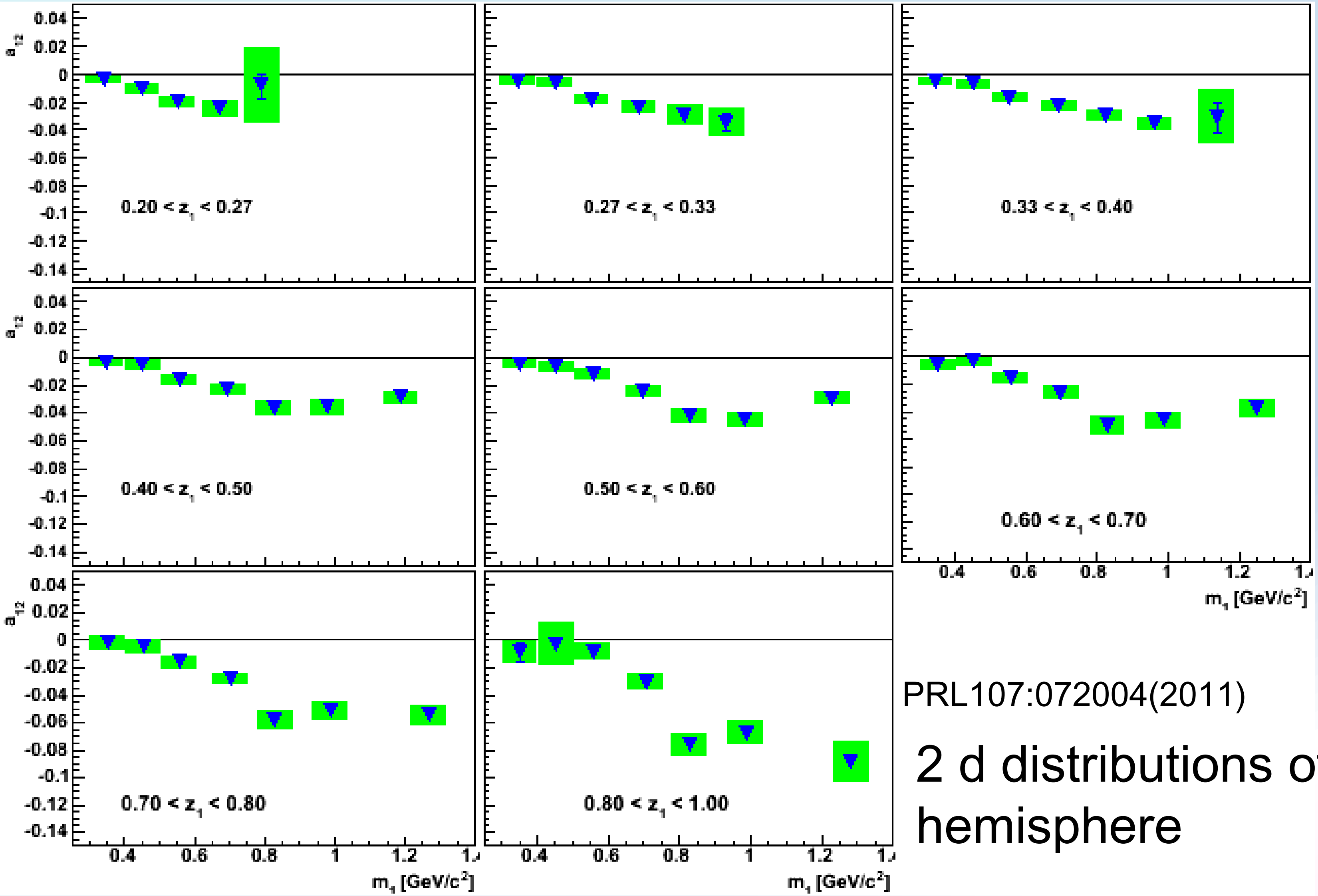
Belle IFF asymmetries: (z_1x z_2) Binning





Magnitude increasing with z

Belle IFF asymmetries: $(z_1 x\ m_1)$ Binning

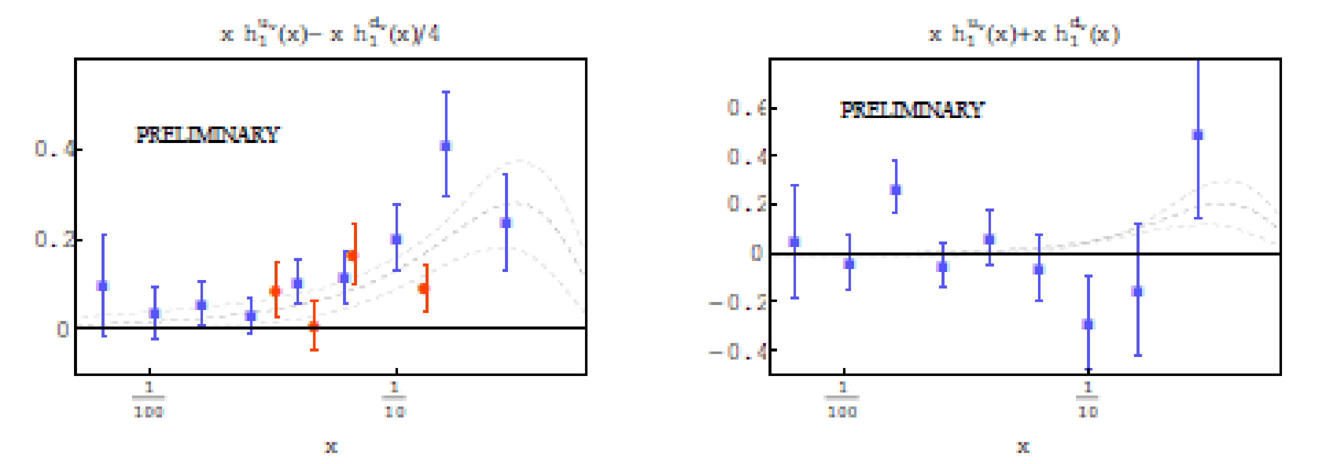


PRL107:072004(2011)

2 d distributions of one hemisphere

First transversity extraction from HERMES, COMPASS and Belle IFF data

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



Courtoy, Bacchetta, Radici:
Phys.Rev.Lett. 107 (2011) 012001 and
arXiv:1206.1836
HERMES: JHEP 0806 (2008)
COMPASS: Phys.Lett. B713 (2012)

- recent IFF analysis and Collins Transversity comparable

→CollinsFF evolution weak?

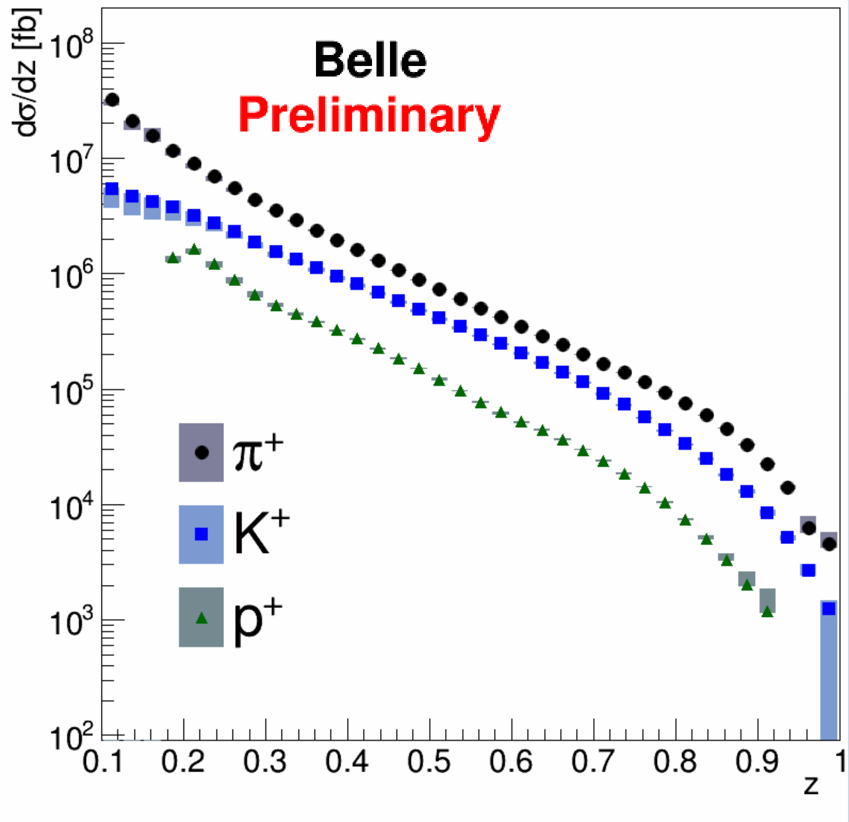
- But many assumptions at this point
- STAR and PHENIX Preliminary data not yet used

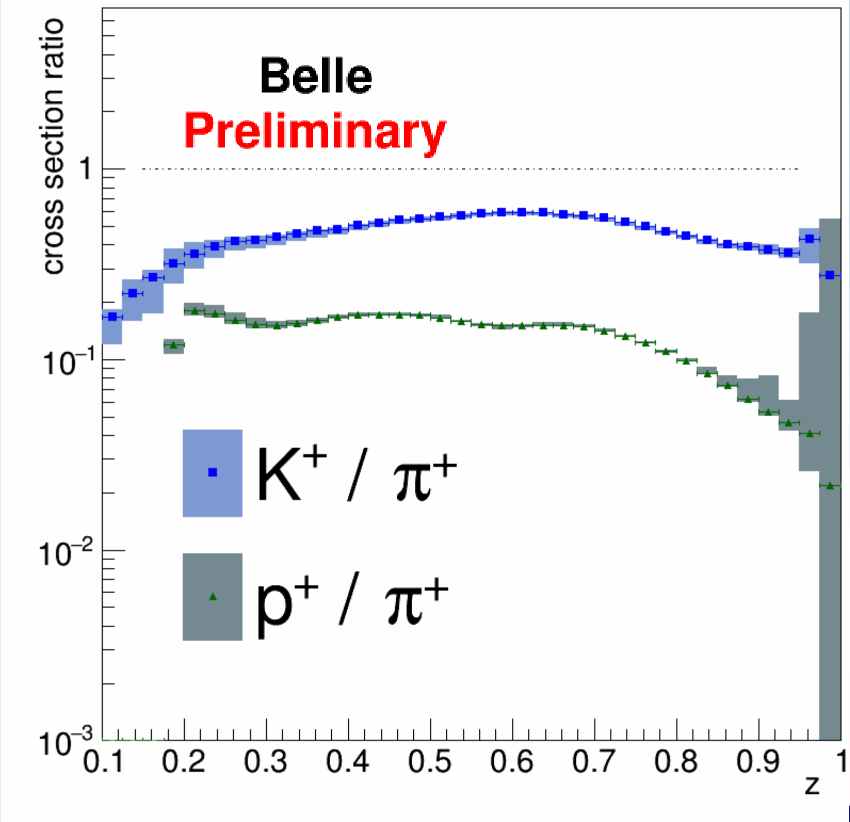
Summary and outlook

- Unpolarized single-hadron cross sections extracted and already used in global FF fits
- First di-hadron + single proton cross sections from e^+e^- extracted
  - Access to disfavored fragmentation via ordering of pion and kaon pairs
- Transverse momentum dependent FF analysis ongoing
- Collins asymmetries for pions used in global transversity analysis
- New Kaon related Collins asymmetries preliminary, eta to follow soon
- Interference FF asymmetries also used in global extractions

Single hadrons

Previously un-published Proton cross sections extracted





Differences in Pythia/JetSet settings

Par	0	1	9	10	11	12	13	udscatlas	udschermes
	Pythia def.	belle	Atlas	Aleph	LEP/tev.	Hermes	gen Belle		
PARJ(1)	0.1			0.106	0.073	0.029			0.029
PARJ(2)	0.3			0.285	0.2	0.283			0.283
PARJ(3)	0.4			0.71	0.94	1.2			1.2
PARJ(4)	0.05			0.05	0.032				
PARJ(11)	0.5			0.55	0.31				
PARJ(12)	0.6			0.47	0.4				
PARJ(13)	0.75			0.65	0.54				
PARJ(14)	0.0	0.0	0.0	0.02	0.0	0.0	0.05	0.0	0.0
PARJ(15)	0.0	0.0	0.0	0.04	0.0	0.0	0.05	0.0	0.0
PARJ(16)	0.0		0.0	0.02	0.0	0.0	0.05	0.0	0.0
PARJ(17)	0.0	0.0	0.0	0.2	0.0	0.0	0.05	0.0	0.0
PARJ(19)	1			0.57					
PARJ(21)	0.36			0.37	0.325	0.400	0.28	0.28	0.400
PARJ(25)	1				0.63		0.27	0.27	
PARJ(26)	0.4			0.27	0.12		0	0	
PARJ(33)	0.8		0.8	0.8	0.8	0.3		0.8	0.8
PARJ(41)	0.3			0.4	0.5	1.94	0.32	0.32	1.94
PARJ(42)	0.58			0.796	0.6	0.544	0.62	0.62	0.544
PARJ(45)	0.5					1.05			1.05
PARJ(46)	1.						1.0	1.0	
PARJ(47)	1.				0.67				
PARJ(54)	-0.050	-0.040	-0.050	-0.04	-0.050	-0.050		-0.050	-0.050
PARJ(55)	-0.005	-0.004	-0.005	-0.0035	-0.005	-0.005		-0.005	-0.005
PARJ(81)	0.29			0.292	0.29		0.38	0.38	
PARJ(82)	1.0			1.57	1.65		0.5	0.5	
MSTJ(11)	4			3	5		4	4	
MSTJ(12)	2			3		1			1
MSTJ(26)	2	0	2	2	2	2	0	2	2
MSTJ(45)	5					4			4
MSTJ(107)	0	1	0	0	0	0	1	0	0

VM suppression

P_x,P_y Gauss width

Lund params

Λ_{QCD} and E cutoff

Pythia/Jetset parameters

PARJ(1)	:	Diquark suppression relative to quark antiquark production
PARJ(2)	:	Strangeness suppression relative to u or d pair production
PARJ(3)	:	Extra suppression of strange diqurks relative to strange quark production
PARJ(4)	:	Axial (ud_1) vs scalar (ud_0) diquark suppression
PARJ(11)	:	Light meson with spin 1 probability
PARJ(12)	:	Strange meson with spin 1 probability
PARJ(13)	:	Charm meson with spin 1 probability
PARJ(14)	:	Spin 0 meson with L = 1 and J = 1 probability
PARJ(15)	:	Spin 1 meson with L = 1 and J = 0 probability
PARJ(16)	:	Spin 1 meson with L = 1 and J = 1 probability
PARJ(17)	:	Spin 1 meson with L = 1 and J = 2 probability
PARJ(19)	:	Extra baryon suppression relative to regular diquark suppression (if MSTJ(12) = 3)
PARJ(21)	:	Gaussian Width of p_x and p_y for primary hadrons
PARJ(25)	:	η production suppression factor
PARJ(26)	:	η' production suppression factor
PARJ(33)	:	Energy cutoff of fragmentation process
PARJ(41)	:	Lund a parameter: $(1-z)^a$
PARJ(42)	:	Lund b parameter: $exp(-bm_\perp^2/z)$
PARJ(45)	:	addition to a parameter for diquarks
PARJ(46)	:	modification of Lund fragmentation for heavy quarks with Bowler, charm, bottom
PARJ(47)	:	modification of Lund fragmentation for heavy quarks with Bowler, bottom
PARJ(54)	:	charm fragmentation functional form and value if MSTJ(11) = 2 or 3
PARJ(55)	:	bottom fragmentation functional form and value if MSTJ(11) = 2 or 3
PARJ(81)	:	Λ_{QCD} for parton showers
PARJ(82)	:	invariant mass cut-off for parton showers