Fragmentation function measurements at Belle

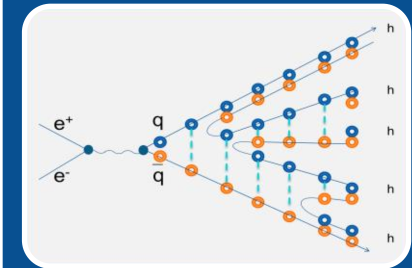
High-energy QCD and nucleon structure workshop
March 7 , 2014

Ralf Seidl
(RIKEN)

Outline

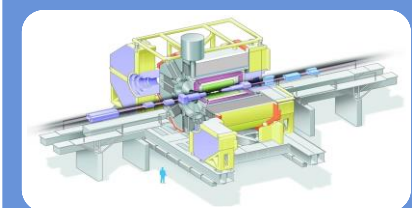
- Introduction on Fragmenation
- Unpolarized fragmentation functions and global FF fits
  - Light hadrons
  - Transverse momentum dependence
  - Heavyier hadrons and flavors
- Polarized FFs
  - Collins fragmentation
  - Interference fragmentation and global analysis
- MC tuning → impact on general B physics backgrounds
- Old things in new light – event shapes and α_S
- Outlook

What are fragmentation functions?



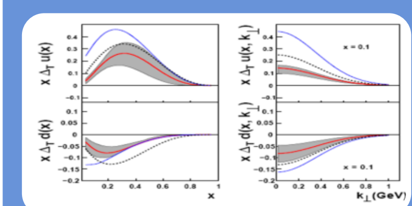
How do quasi-free partons fragment into confined hadrons？

- 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： $e^+e^- \rightarrow h_1\ h_2\ X$; $\langle\cos(\phi_1+\phi_2)\rangle$; Collins FF、Interference（IFF）
- Cross sections or multiplicities differential in z: ep->hX, pp->hX



Additional benefits of the FF measurements：

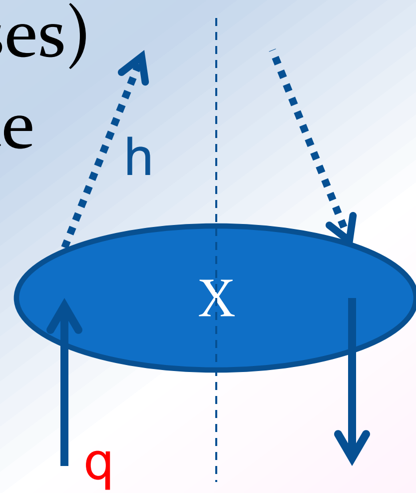
- Pol FFs necessary input to transverse spin SIDIS und pp measurements to extract Transversity distributions function
- Flavor separation of all Parton distribution functions (PDFs) via FFs (including unpolarized PDFs)
- Baseline for any Heavy Ion measurement
- Access to exotics?

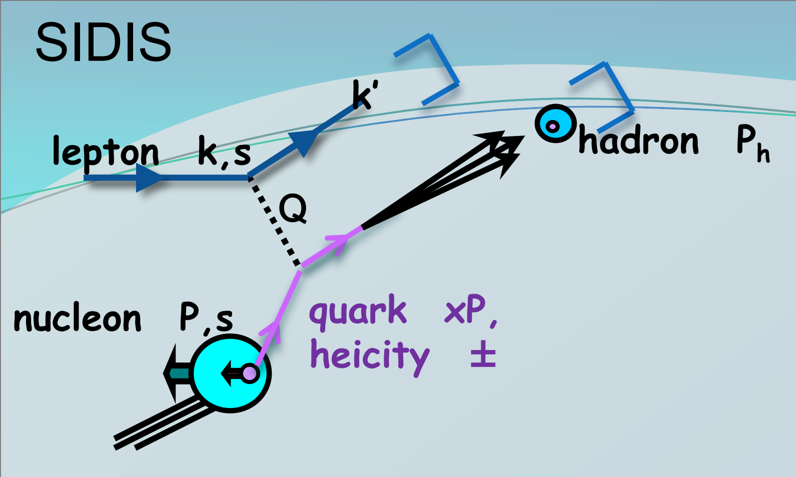
Theory definition

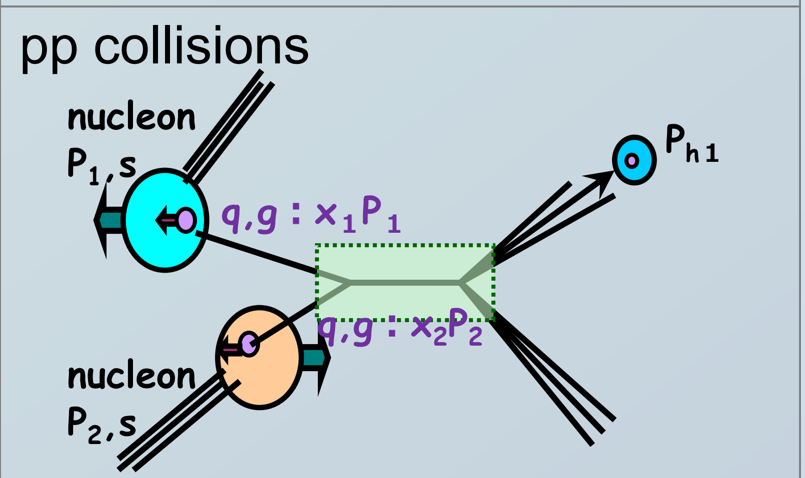
- Fragmentation functions are defined similar to parton distribution functions as bi-local operators:

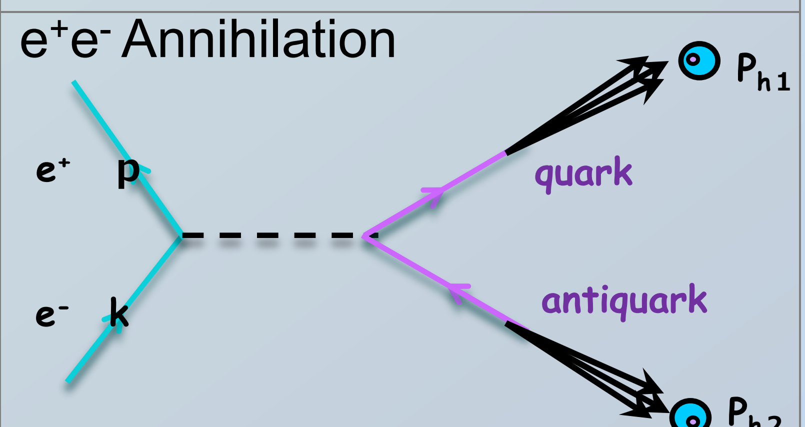
$$D_q{}^h(z) \propto \int dy^- e^{iP^+/zy^-} \mathbf{T}r\gamma^+ \langle 0|\psi(y^-)|hX\rangle\langle hX|\overline{\psi}(0)|0\rangle$$

- Density of finding a hadron h with fractional energy z = P^h/P^q off a parton q
- Non-perturbative object → measurements
- Universal (same function in different processes)
- Not accessible on the lattice (due to final state hadrons)
- Spin dependent FFs similar after applying corresponding Dirac matrices and non LC displacements y









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-:

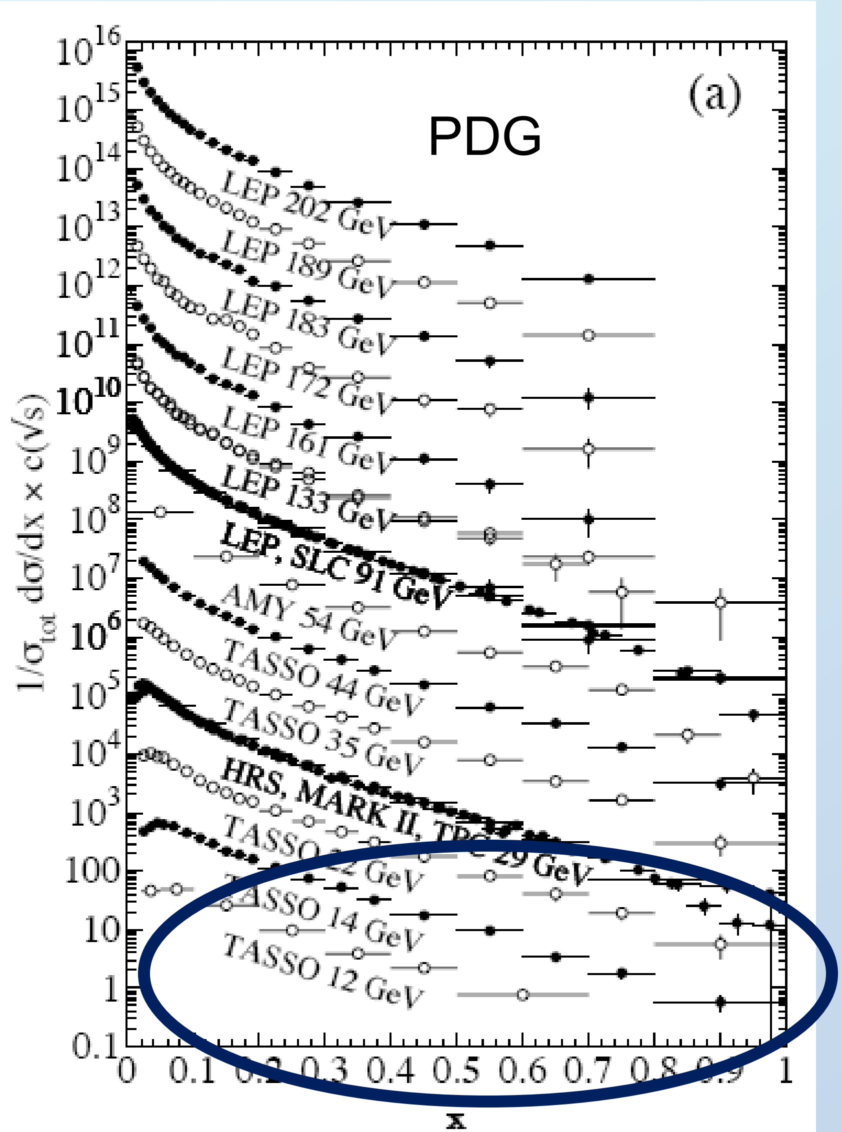
$$\sigma^h(z, Q^2, p_t) \propto \sum_q e_q^2 \left(D_{1,q}^h(z, p_t, Q^2) + D_{1,\bar{q}}^h(z, p_t, Q^2) \right)$$

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

Unpolarized fragmentation functions

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

Old e+e- data used in all fits



- Most data obtained at LEP and SLC energies,
- At lower CMS energies very little data available
- 3-jet fragmentation to access gluon FF theoretically difficult

➔ Gluon fragmentation from evolution not yet well constrained

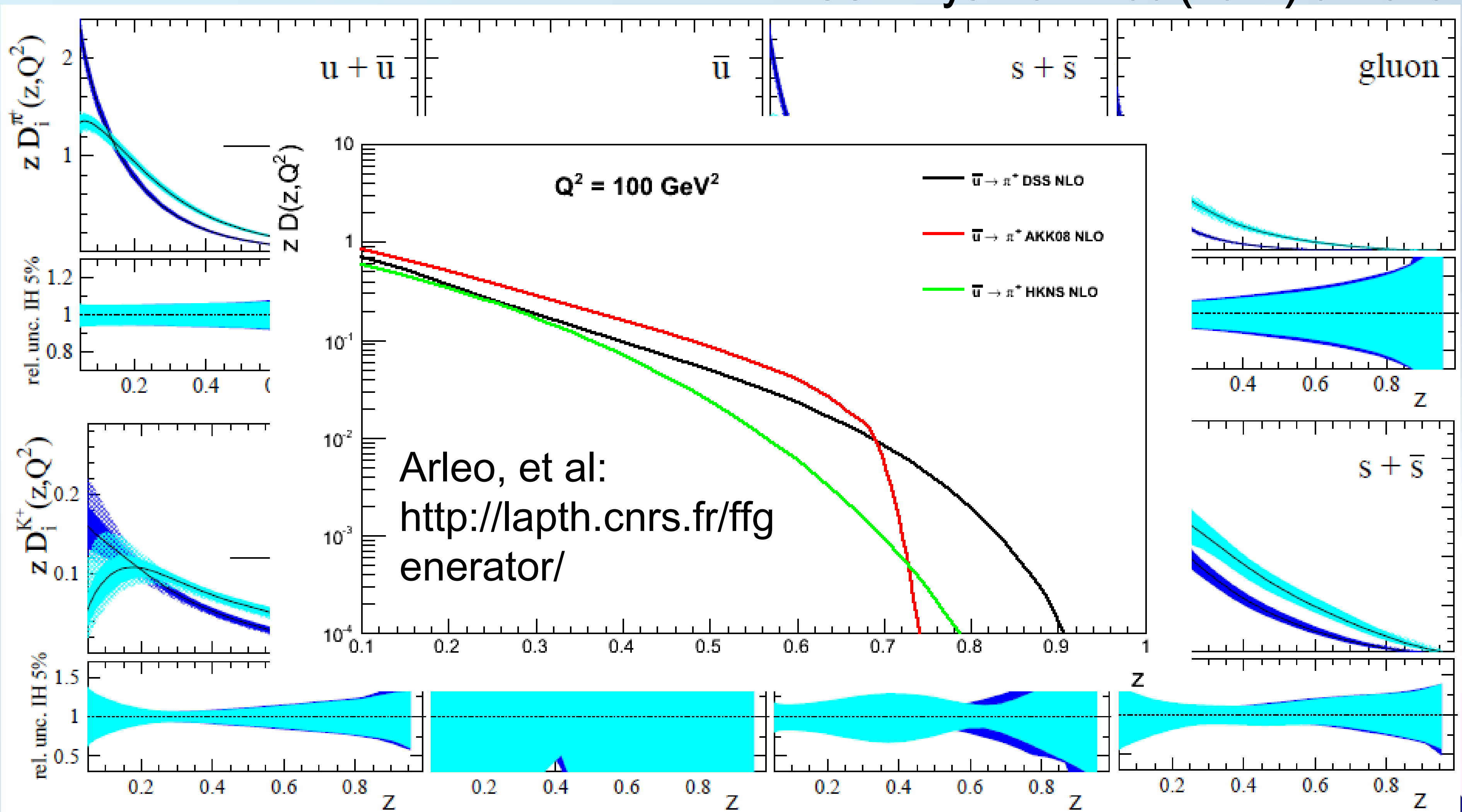
➔ Higher z FFs (>0.7) hardly available

Recent global fits

- 3 recent global fragmentation function paramterizations:
  - Hirai, Kumano, Nagai, Sudoh (HKNS): **Phys.Rev. D75 (2007) 094009**
    - e+e- world data, uncertainties
  - Albino, Kniehl, Kramer (AKK): **Nucl.Phys. B803 (2008) 42-104**
    - e+e- and pp data, large –z resummations, uncertainties
  - De Florian, Sassot, Stratmann (DSS): **Phys.Rev. D75 (2007) 114010**
    - e+e-, SIDIS and pp data, uncertainties

Current uncertainties

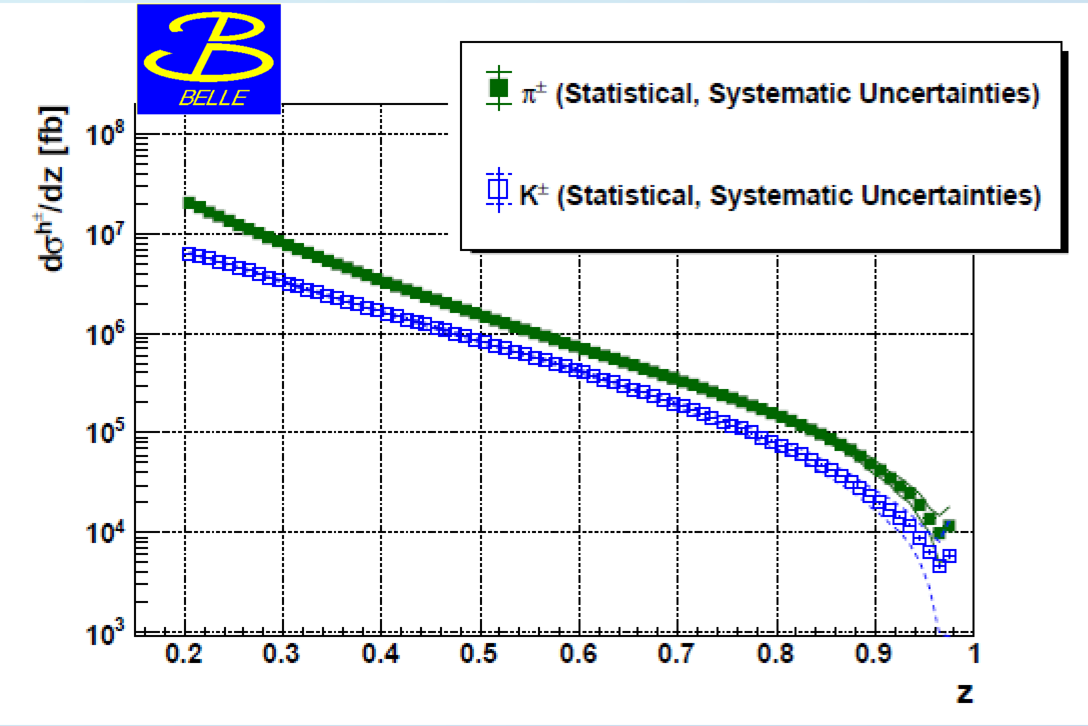
DSS: Phys.Rev. D86 (2012) 074028

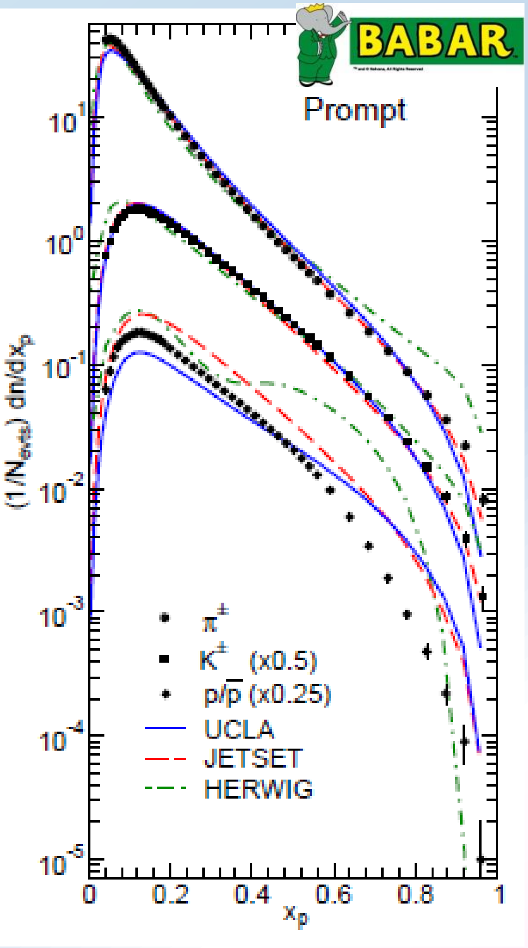


B factory data

Phys.Rev. D88 (2013) 032011 (Babar)

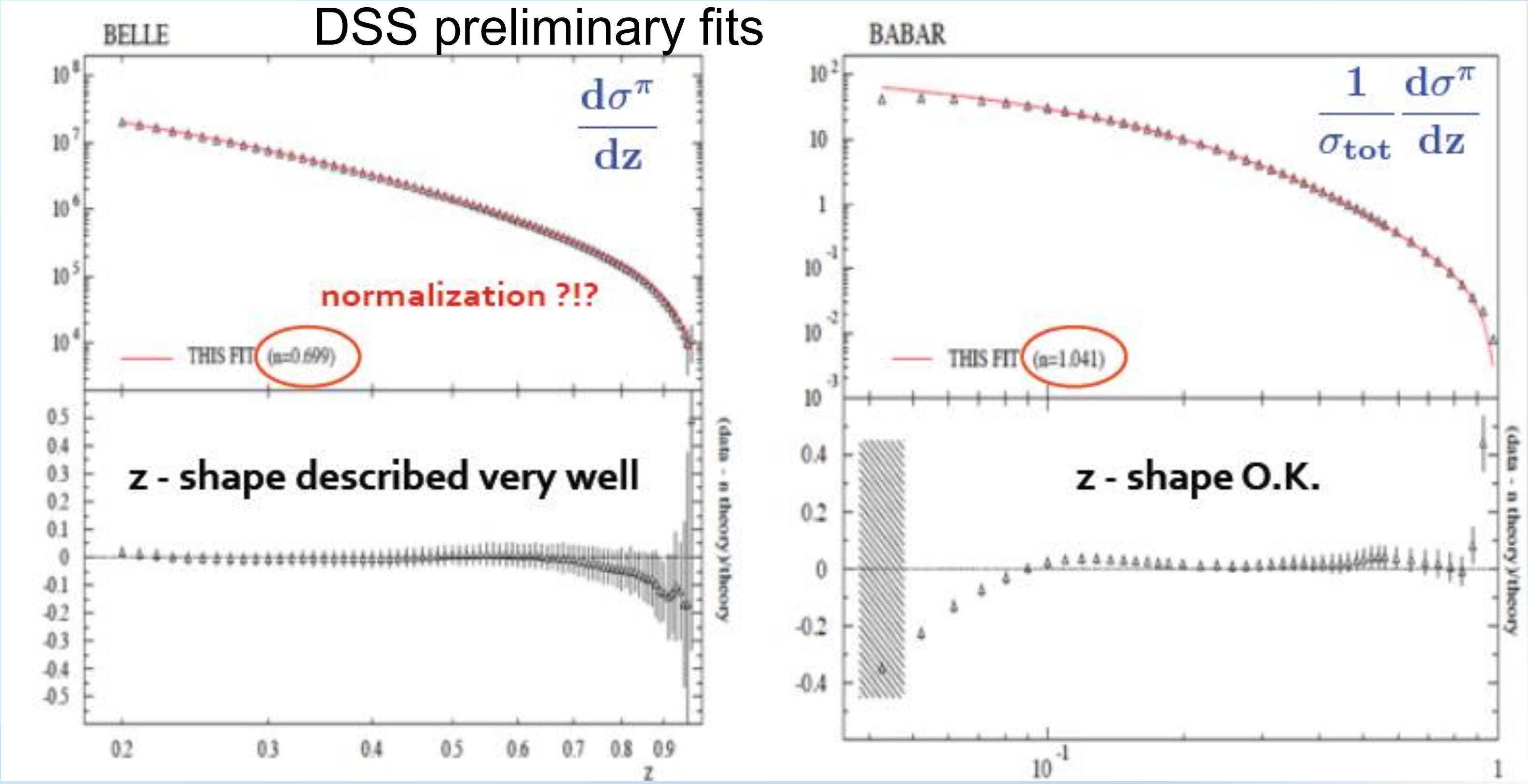
Phys.Rev.Lett. 111 (2013) 062002, Leitgab, RS, et al (Belle)





- High precisions of B factory data allows extraction of precise FFs and gives lever arm for gluon FF extraction

Inclusion of B-factory data in fits

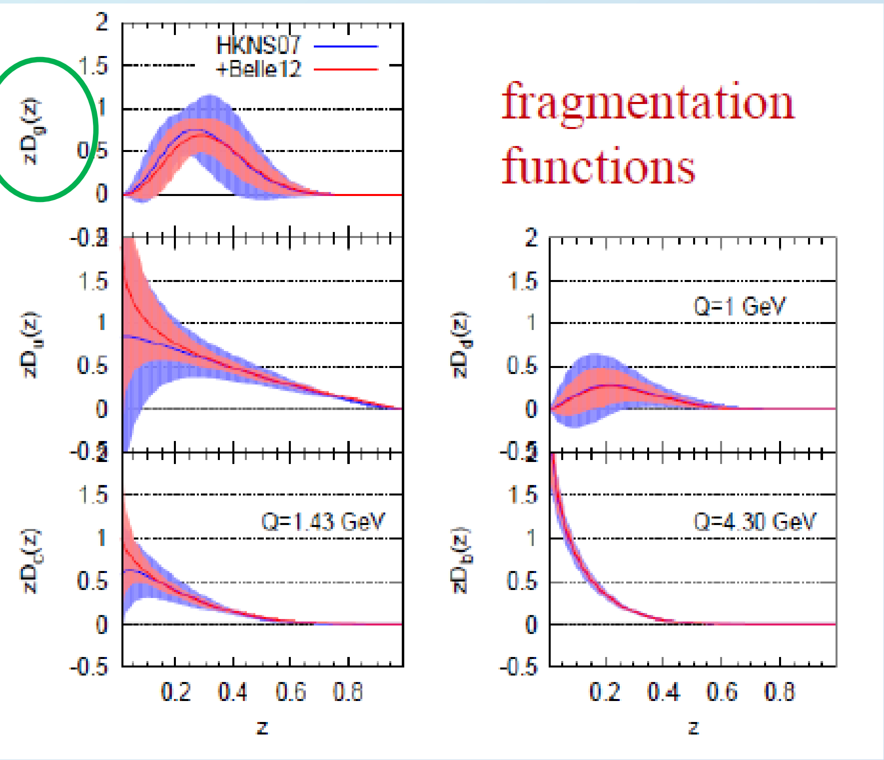


- Differences in normalization between Belle and Babar likely due to different treatment of
  - Initial state radiation (Belle shows only fraction within 0.5% around nominal sqrt(s)= 10.52GeV which excludes ~35% of events)
  - Weak decays (either none/full vs K^0,Λ removal)

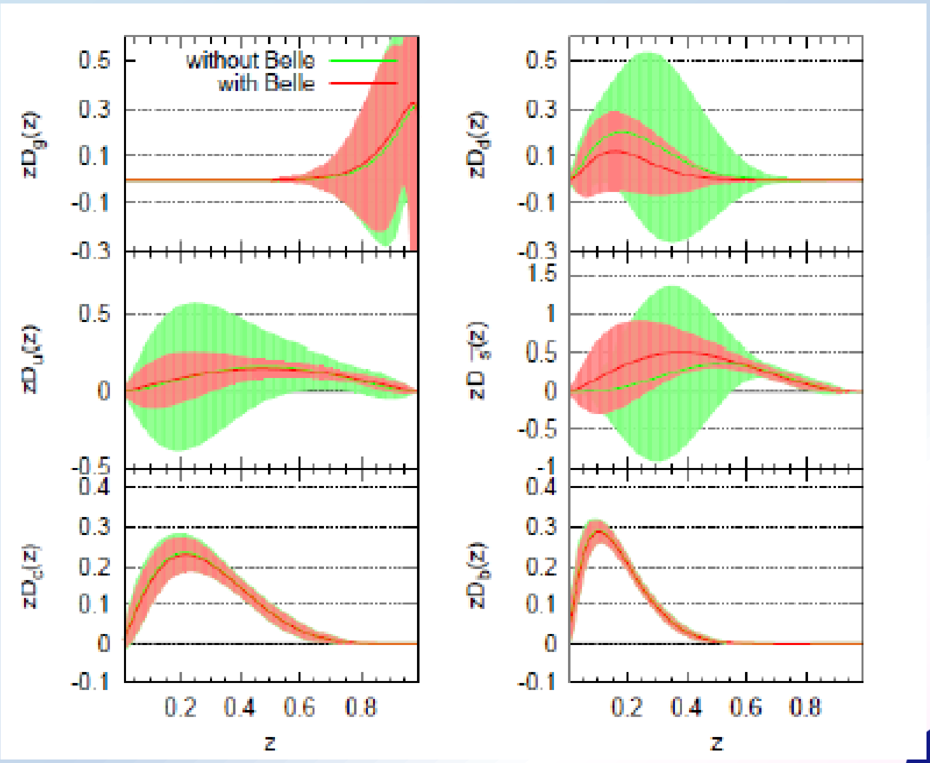
Expected Improvements for Pion and Kaon FFs

Kawamura (KEK, HKNS fit) at FF2012, based on Belle preliminary data

π^+ fragmentation



K^+ fragmentation



Unpolarized 2-hadron fragmentation

Favored	= u→π^+,d→π^-,cc.
Unfavored	= d→π^+,u→π^-,cc.

- Detect two hadrons simultaneously:

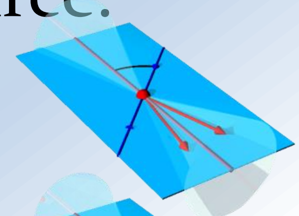
  $e^+e^- \rightarrow hhX$
- If two hadrons in opposite hemispheres one obtains sensitivity to favored/ disfavored fragmentation:

- Unlike-sign pion pairs (U):
  (favored x favored + unfavored x unfavored)
- Like-sign pion pairs (L):
  (favored x unfavored + unfavored x favored)
- any charge hadron pairs (C):
  (favored + unfavored) x (favored + unfavored)

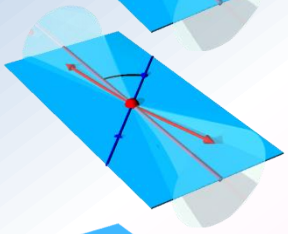
- Difficulty: contribution from one quark fragmentation q→hhX

→measure all three:

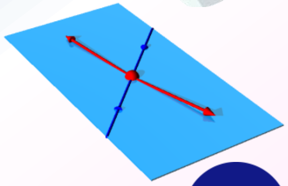
- $(hh)_{jet1}$ X



- $(h)_{jet1}(h)_{jet2}$X



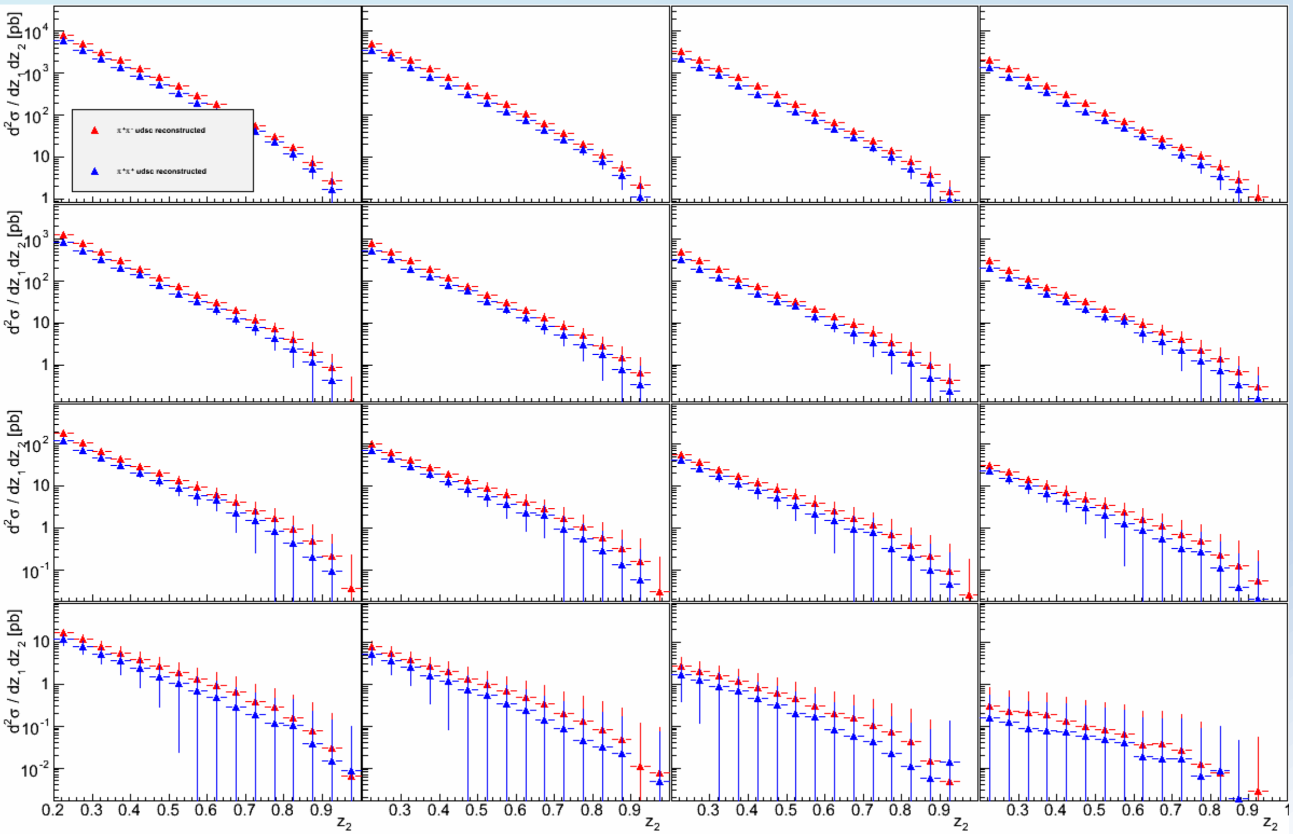
- hhX,

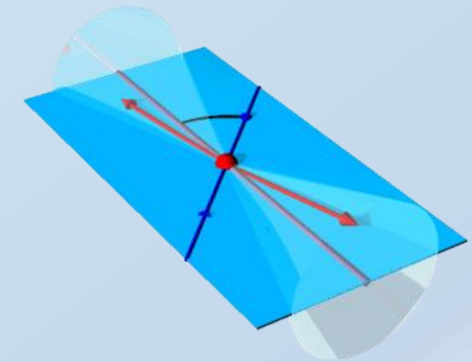


( ) requires thrust cut

Unpolarized outlook: overcoming the flavor blindness of e+e-

- Unlike-sign pion pairs (U):
  (favored x favored + unfavored x unfavored)
- Like-sign pion pairs (L):
  (favored x unfavored + unfavored x favored)





- Reconstructed udsc Monte Carlo (Pythia/Evtgen in Belle acceptance)
- opposite hemisphere pion pairs

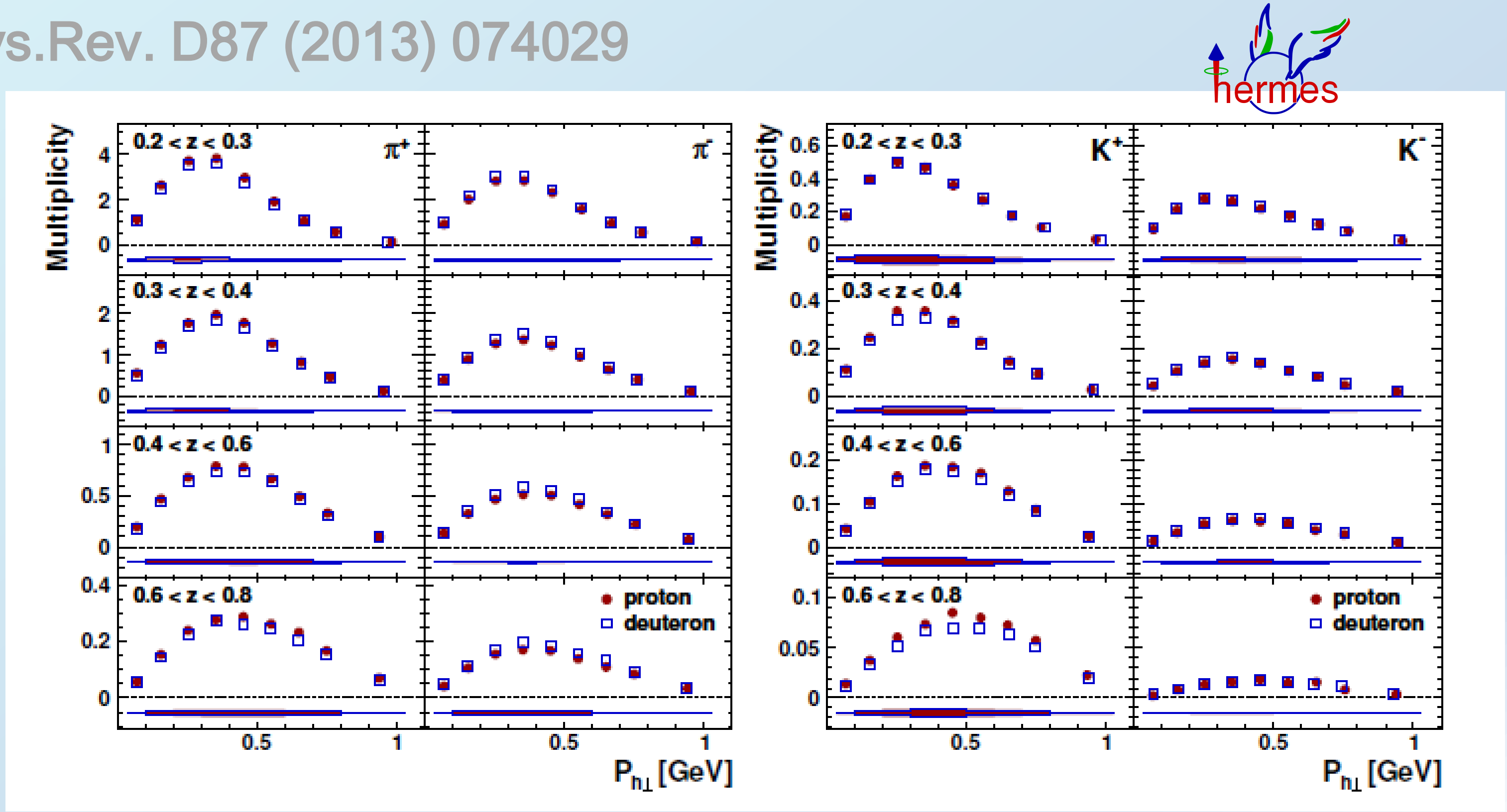
Transverse momentum dependence

Aka un-integrated PDFs and FFs

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

Hermes P_T dependence

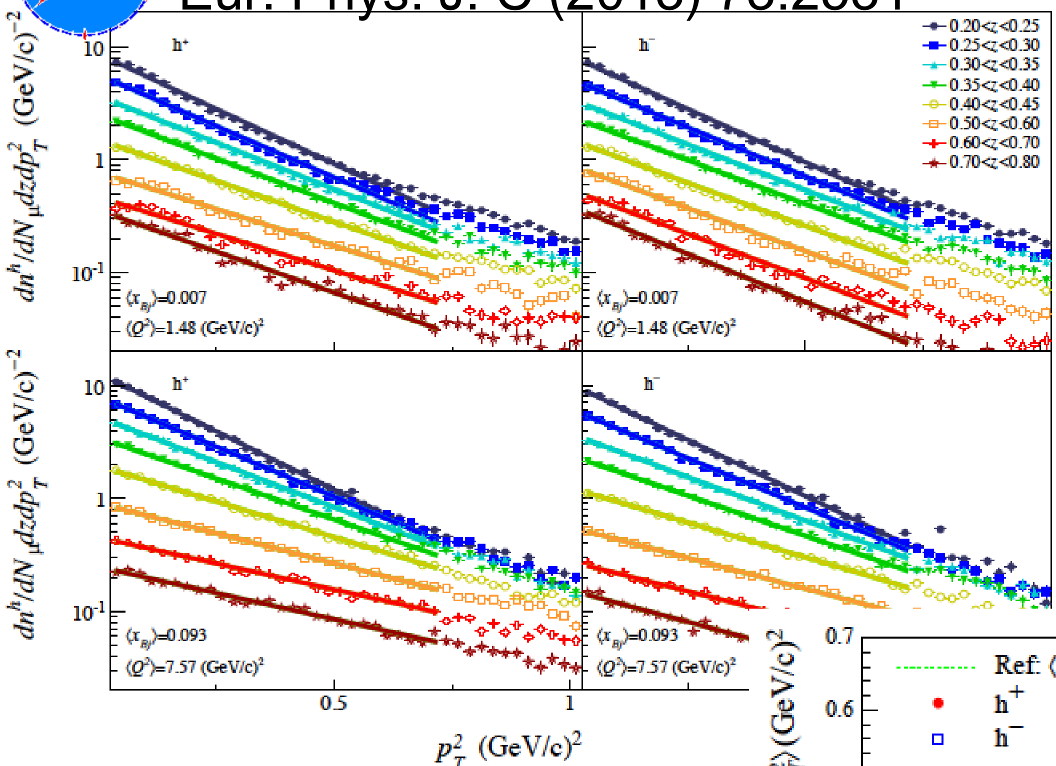
Phys.Rev. D87 (2013) 074029



- Width increases with z
- K- (all sea) wider
- p and d distributions similar → little favored disfavored difference
- Full 5 dim data available at: http://hermesmults.appspot.com/

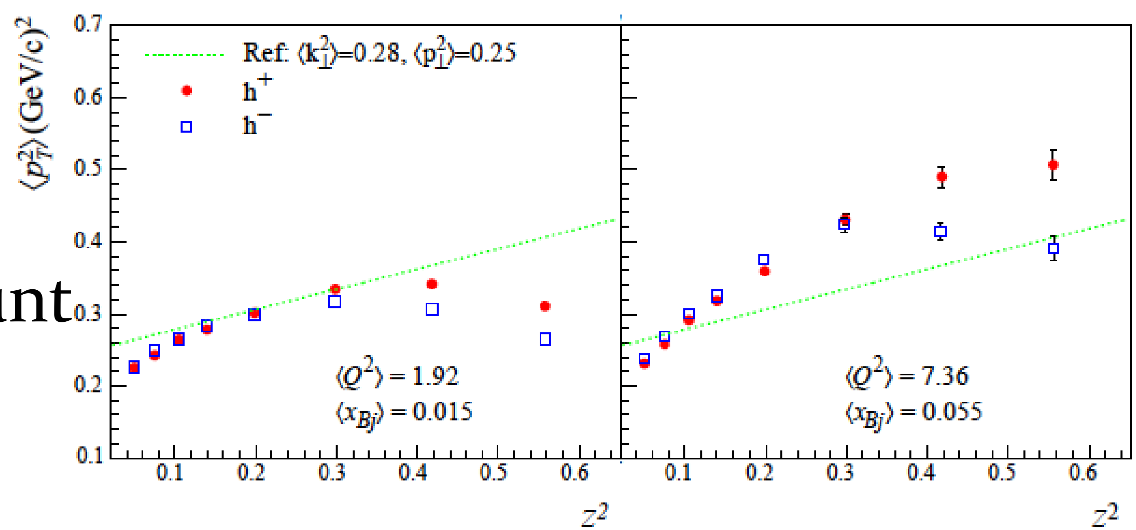
Compass P_T dependence

Eur. Phys. J. C (2013) 73:2531



- At high pt also contribution by higher order pQCD effects

- Need to take z and x dependence into account as convoluted



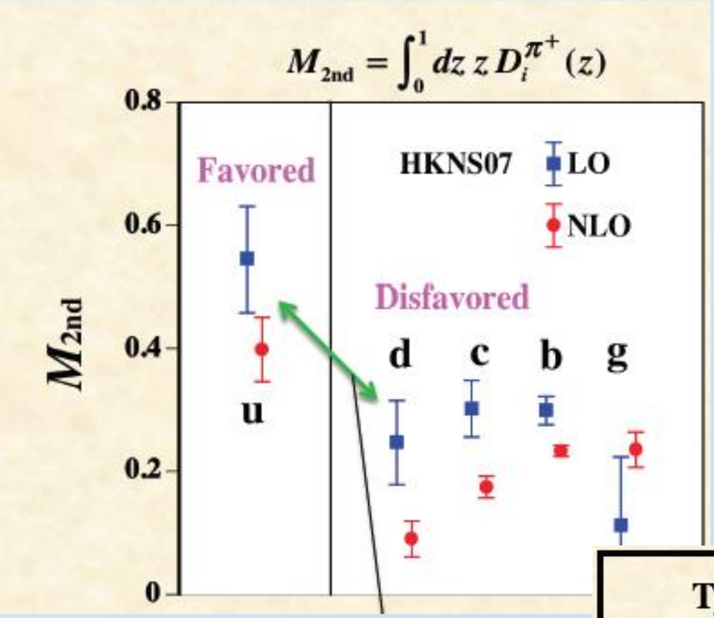
Kt dependence at B factories

- Again very clean initial state in e^+e^-
- q-qbar axis can be approximated by thrust axis or detect individual jet axes

- Analysis started and ongoing

Exotic Fragmentation functions

Kumano (KEK) FF12 and PRD77(2008)017504



- General Idea: Use large difference between favored (valence) and disfavored (sea) of hadrons to find valence structure of potentially exotic hadrons, eg fo(980):

Type	Configuration	2nd Moment	Peak z
Nonstrange $q\bar{q}$	$(u\bar{u}+d\bar{d})/\sqrt{2}$	$M(s)<M(u)<M(g)$	$z_{max}(s)<z_{max}(u)\simeq z_{max}(g)$
Strange $q\bar{q}$	$s\bar{s}$	$M(u)<M(s)\lesssim M(g)$	$z_{max}(u)<z_{max}(s)\simeq z_{max}(g)$
Tetraquark	$(u\bar{u}s\bar{s}+d\bar{d}s\bar{s})/\sqrt{2}$	$M(u)=M(s)\lesssim M(g)$	$z_{max}(u)=z_{max}(s)\simeq z_{max}(g)$
$K\bar{K}$ Molecule	$(K^+K^-+K^0\bar{K}^0)/\sqrt{2}$	$M(u)=M(s)\lesssim M(g)$	$z_{max}(u)=z_{max}(s)\simeq z_{max}(g)$
Glueball	gg	$M(u)=M(s)<M(g)$	$z_{max}(u)=z_{max}(s)<z_{max}(g)$

Strange baryon & Charmed baryon production rates

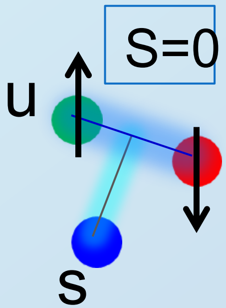
Taken from Hadron13 talk by Sumihama-san

Strange baryons

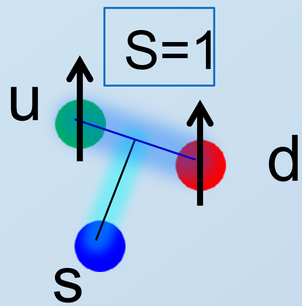
Λ, Σ(uds)

[qq](S=0 or 1)+[s]

$m_u, m_d \approx m_s$ ➡ [qqs], uniform



Λ



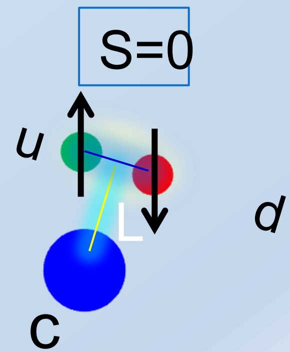
Σ

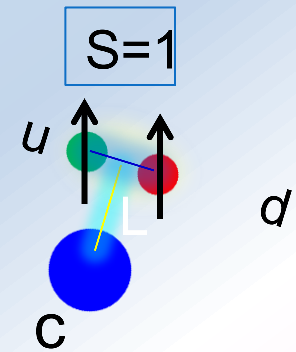
Charmed baryons

Λ_c, Σ_c(udc)

[qq](S=0 or 1)+[c]

$m_u, m_d << m_c$ ➡ diquark + Quark [qq] [c]





Λ_c > Σ_c

Good diquark[ud] + c > Bad diquark[ud] + c

good di-quark > bad di-quark

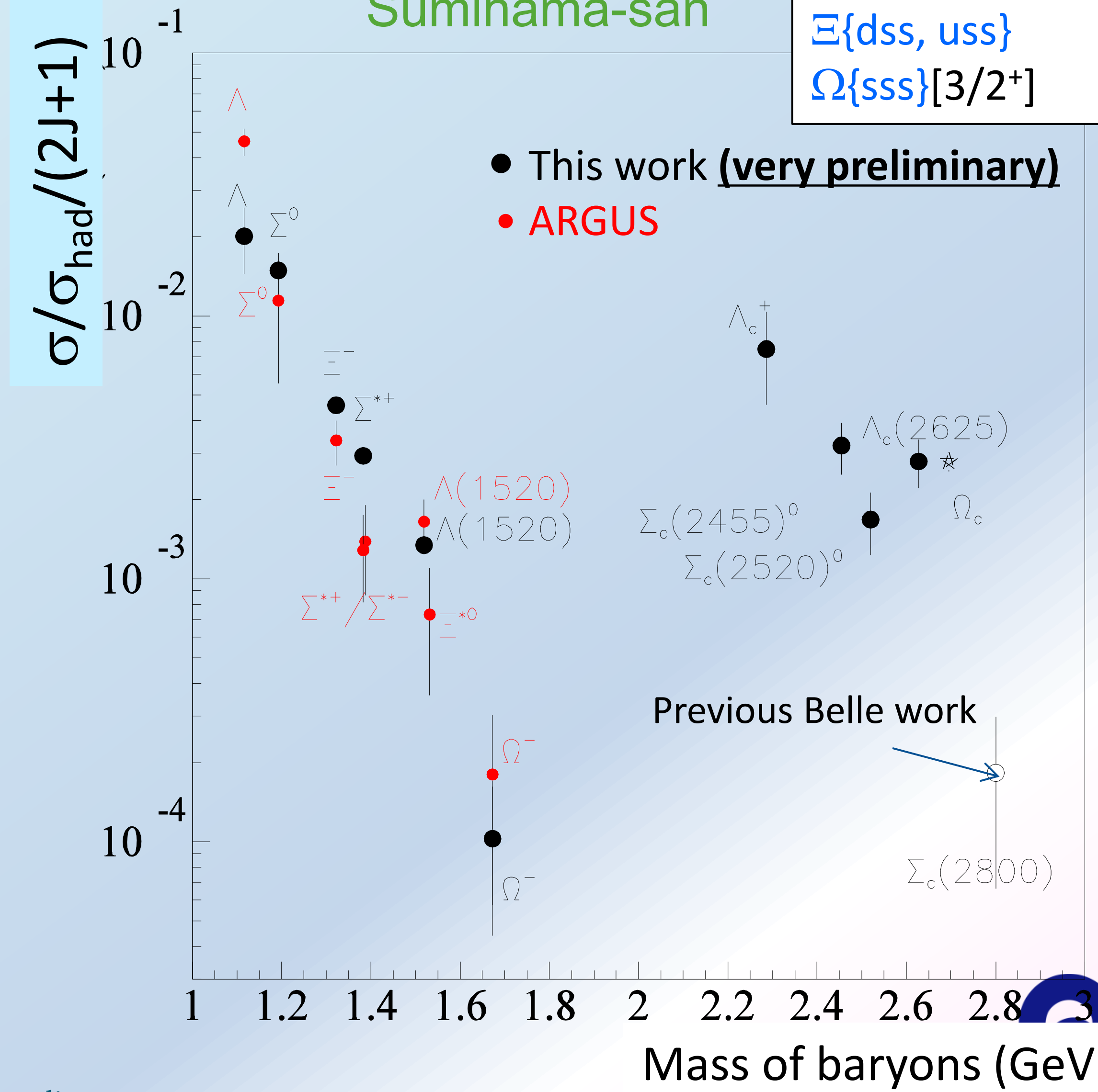
due to strong attractive force of good diquark

Baryon results

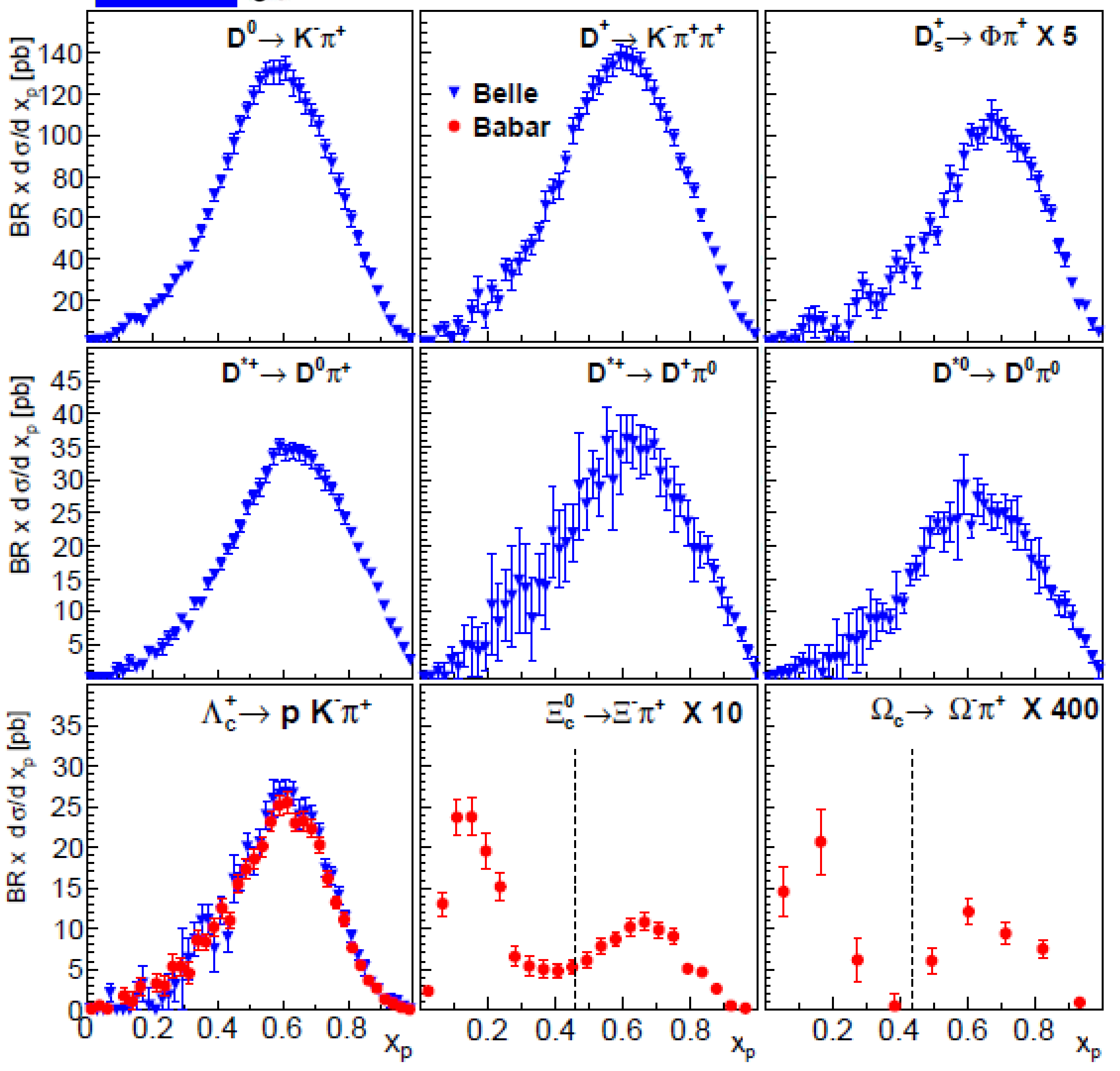
Taken from Hadron13 talk by Sumihama-san

Λ\{uds\}
$\Lambda(1520)[3/2^-]$
Σ\{dds,uds,uud\}
$\Sigma(1385)[3/2^+]$
Ξ\{dss, uss\}
Ω\{sss\}$[3/2^+]$

- Mass dependence
  strange ≠ charm
  not lie on the same line
- Large discrepancy to ARGUS on Λ, and Σ*
  treatment of feed down?
- Deviation of $\Lambda(1520)[3/2^-]$ is not clear.
- $\Omega < \Lambda, \Sigma, \Xi$
  → Ω[sss] with "↑↑↑"
  no good diquark



Charmed Fragmentation



PRL.95, 142003 (2005)(Babar)
PRD73, 032002 (2006) (Belle)
PRD75, 012003 (2007)(Babar)
PRL 99, 062001 (2007)(Babar)

- Heavier particles generally plotted vs normalized momentum $x_p = \frac{P^h}{P^h_{max}}$
- Unlike light hadrons charmed hadrons contain large fraction of charm quark momentum

Spin dependent fragmentation

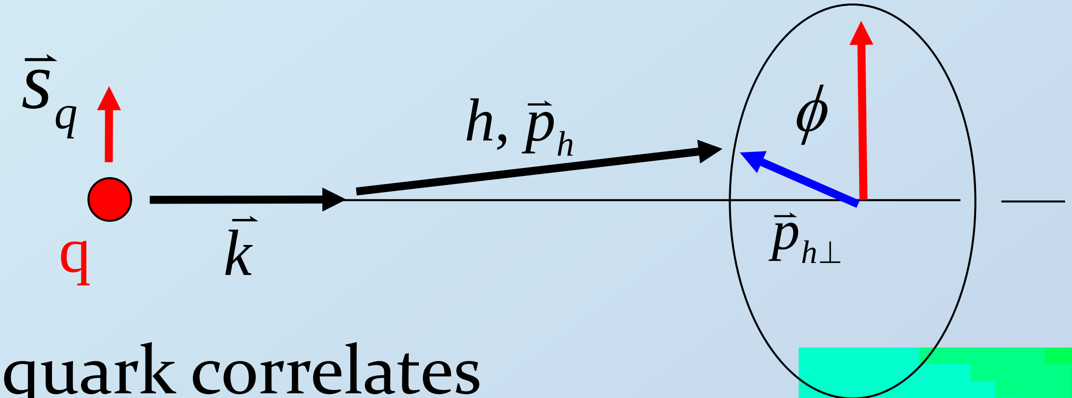
$$H_{1,q}^{h,\perp}(z, Q^2, k_t)$$

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

Collins fragmentation function

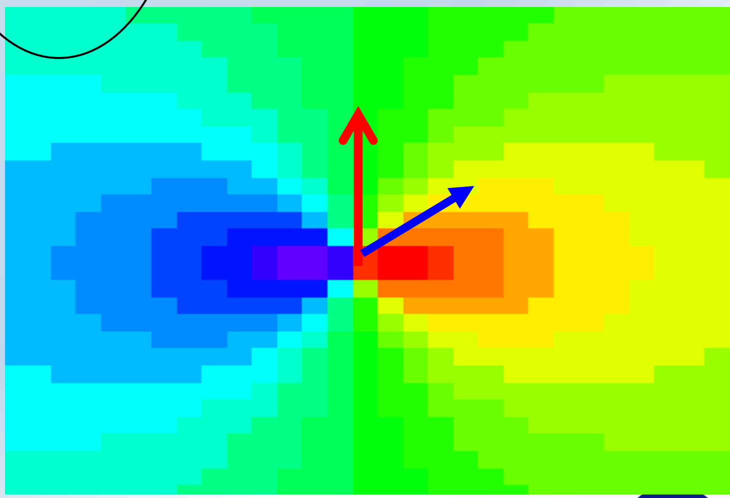
J. Collins, Nucl. Phys. B396, (1993) 161

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



- Spin of quark correlates with hadron transverse momentum

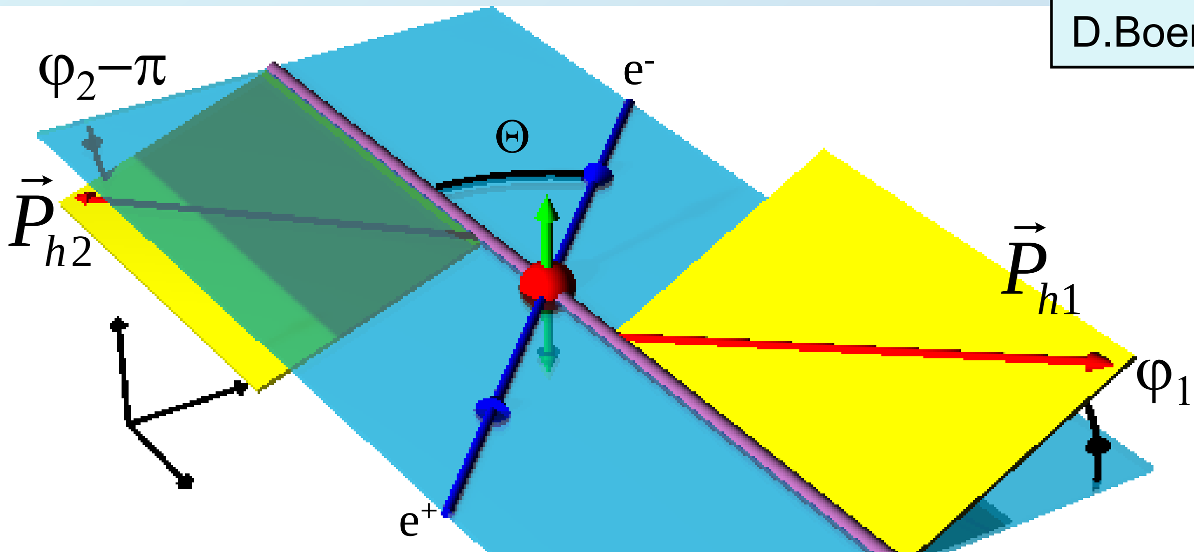
➔translates into azimuthal anisotropy of final state hadrons

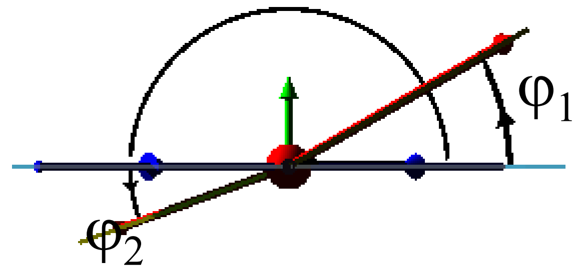


Collins fragmentation in e^+e^- : Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e^+e^- CMS frame:

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





2-hadron inclusive transverse momentum dependent cross section:

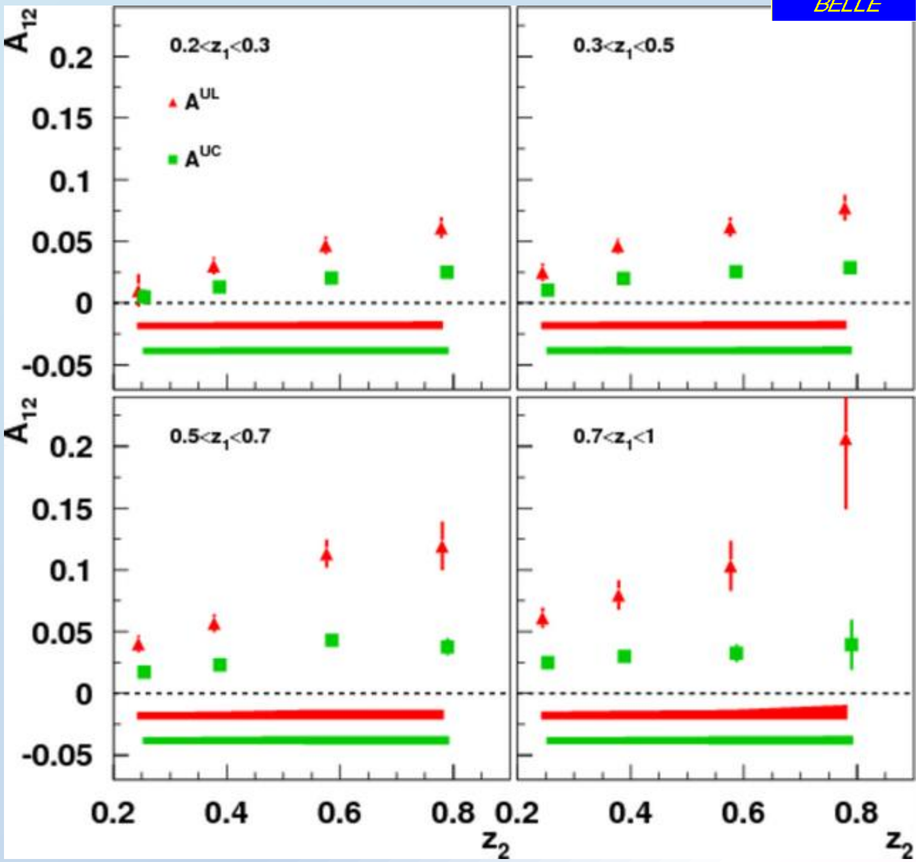
$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega\, dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\, cos(\varphi_1+\varphi_2) H_1^{\perp[1]}(z_1)\overline{H}_1^{\perp[1]}(z_2)$$

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

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

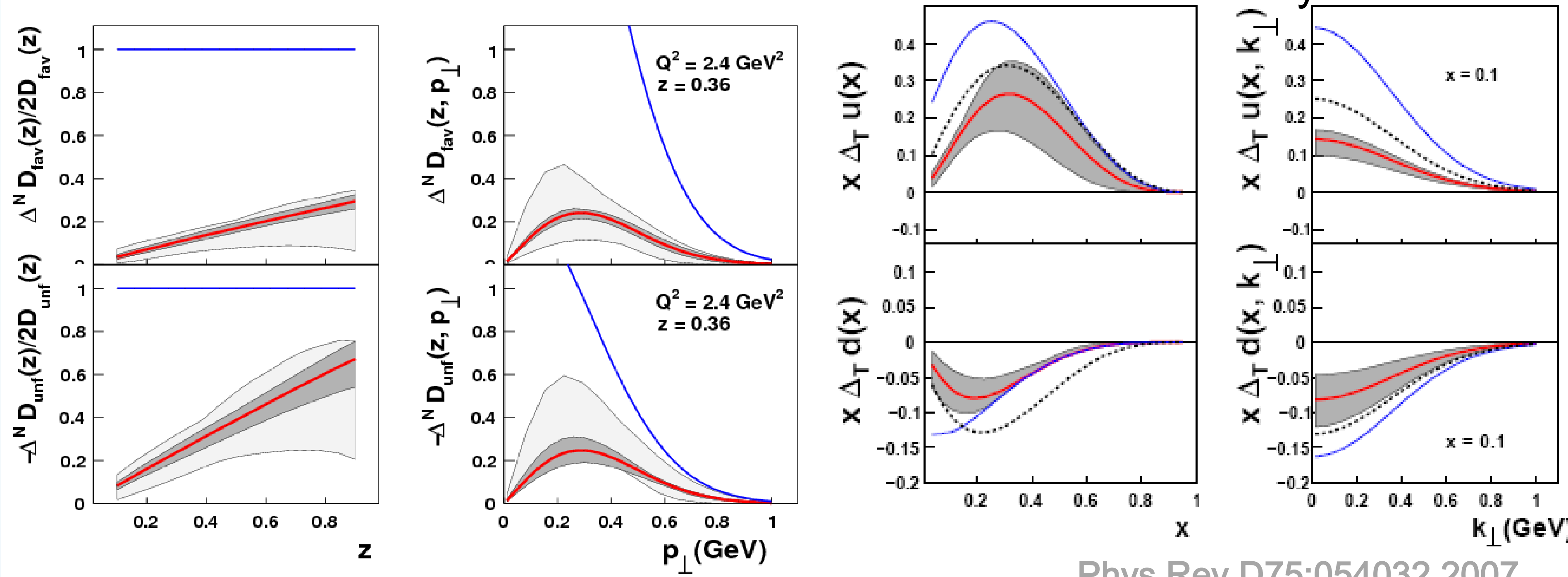


RS et al (Belle), PRL96: 232002
PRD 78:032011, Erratum D86:039905

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

Collins function

Transversity



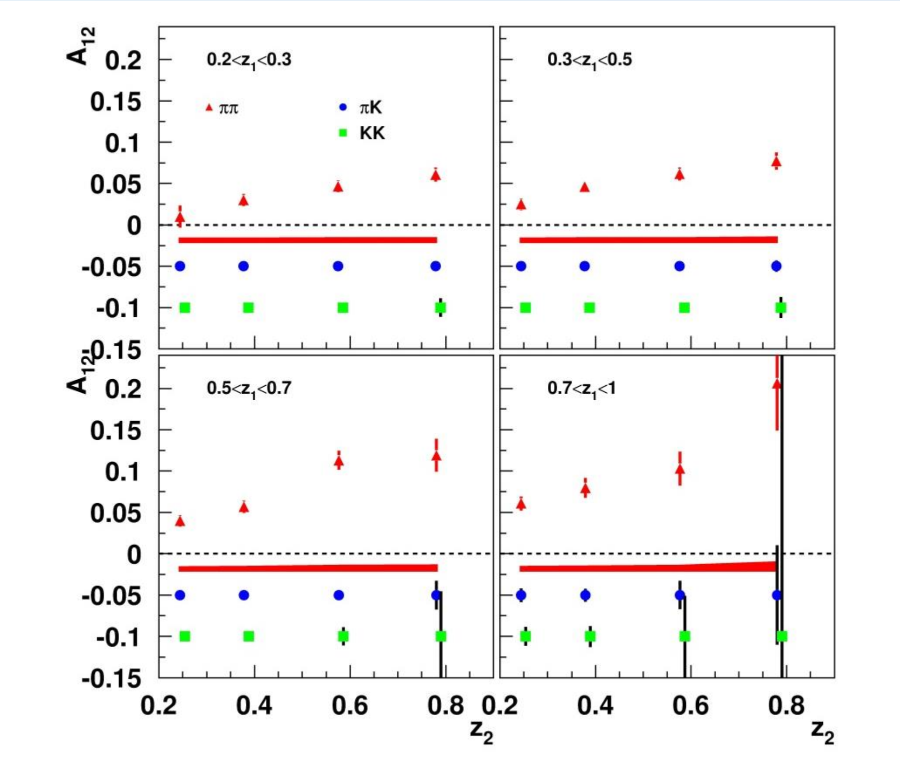
Phys.Rev.D75:054032,2007, update in Nucl.Phys.Proc.Suppl.191:98-107,2009

- 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 outlook: Kaons, eta

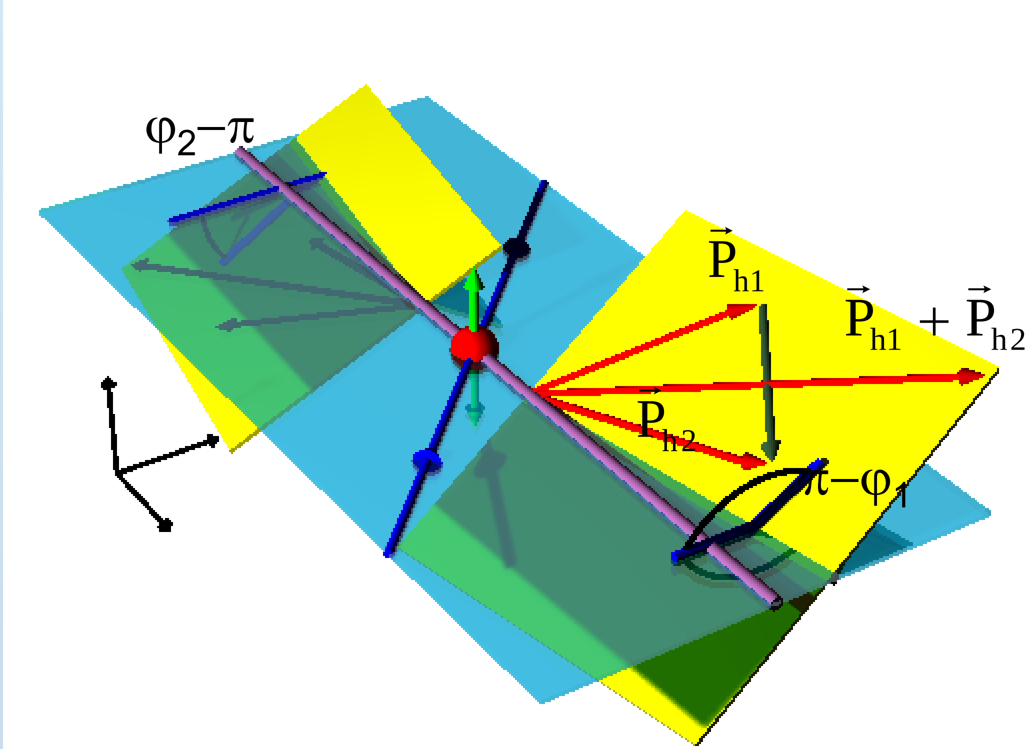
- Need Kaon Collins fragmentation:
  - to understand HERMES/COMPASS kaon data
  - Flavor separation of transversity
- Inflation of FF functions:
  - u,d →π: 2
  - u,d,s →π,K: 6+

- RHIC η A_Ns larger than π^0
- Sign change predicted for VMs



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)]



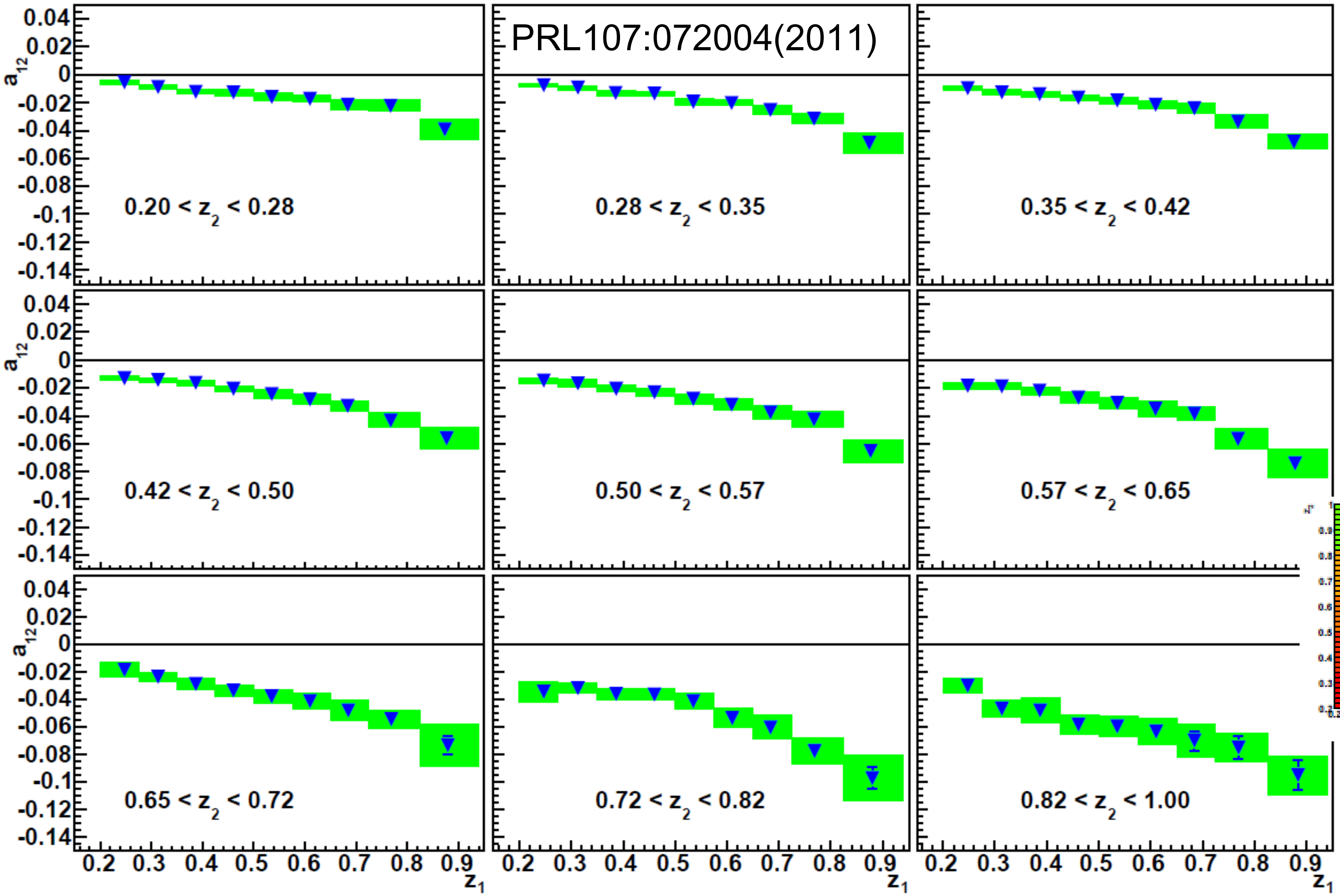
Model predictions by:

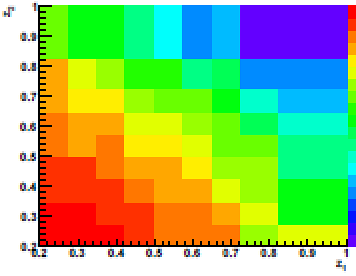
•Jaffe et al. [PRL **80,**(1998)]

•Radici et al. [PR**D 65,**(2002)]

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

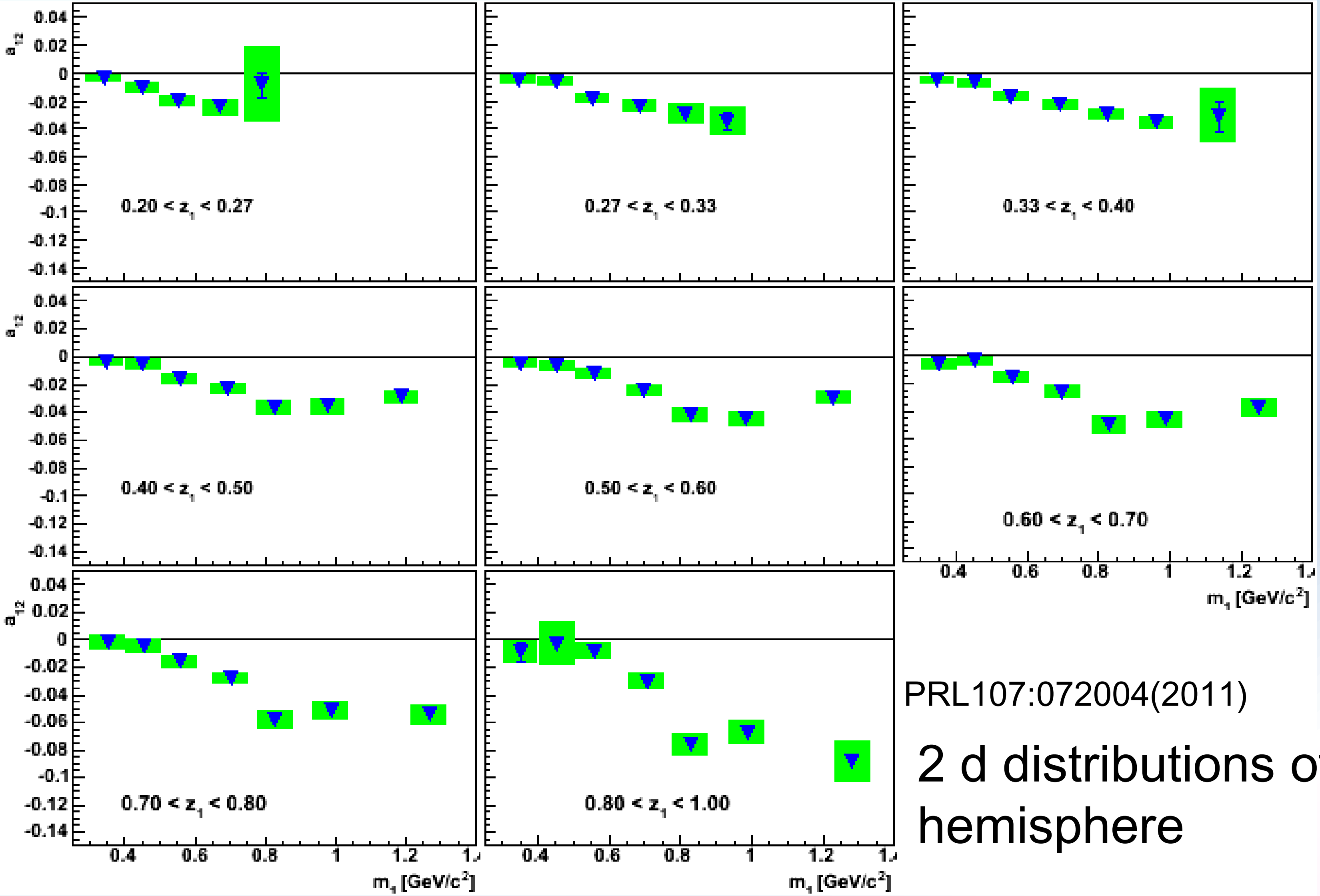
Belle IFF asymmetries: (z_1x z_2) Binning





Magnitude increasing with z

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

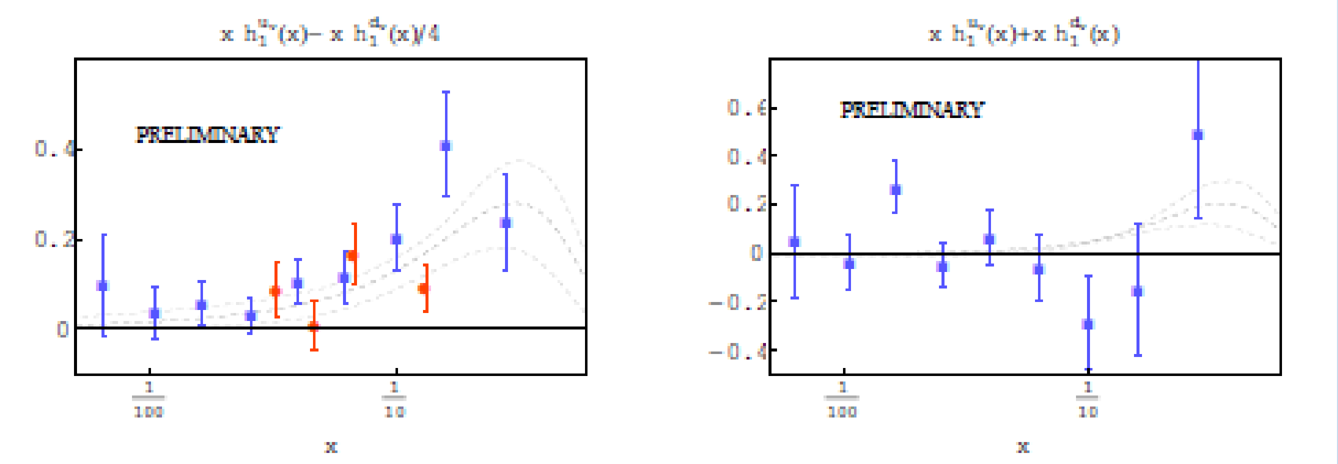


PRL107:072004(2011)

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

IFF outlook

- Kaon related IFF analysis equally necessary for flavor decomposition
- Charged combinations (eg $\pi^0\pi$) analysis also required
- Goal: flavor decomposition of transversity via IFF channel

- However: Requirements for flavor decomposition:
  - Unpolarized di-hadron FFs as baseline
  - Treatment of charm contribution

Charm separation in fragmentation analysis

- Problem: light quark and charm separation in fragmentation measurements difficult
  - Sucessfully performed for Collins case via charm enhanced D* candidate sample
  - For IFF measurements too large bias by D* selection→ not performed
- Best strategy: minimally biasing charm enhancement via displaced vertices with Belle2 vertex detector

Our signal is aFlavor Physicist's background (aka MC tuning)

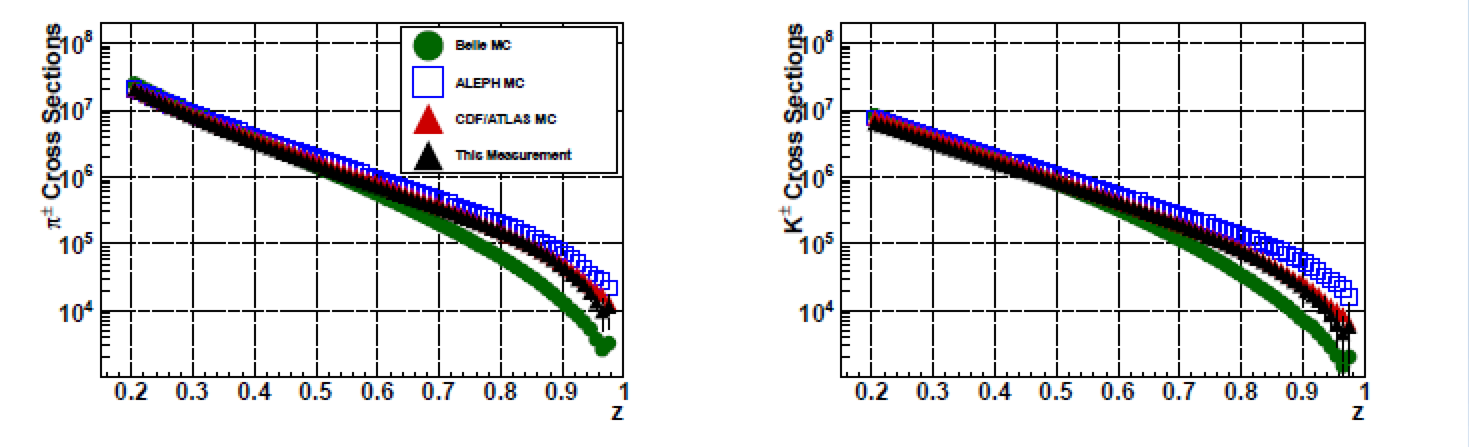
- Continuum (udsc q-qbar pair production) fragmentation creates background for B physics measurements
- Most can be just fit empirically under peaking Backgrounds (ΔE, Mbc, inv mass)

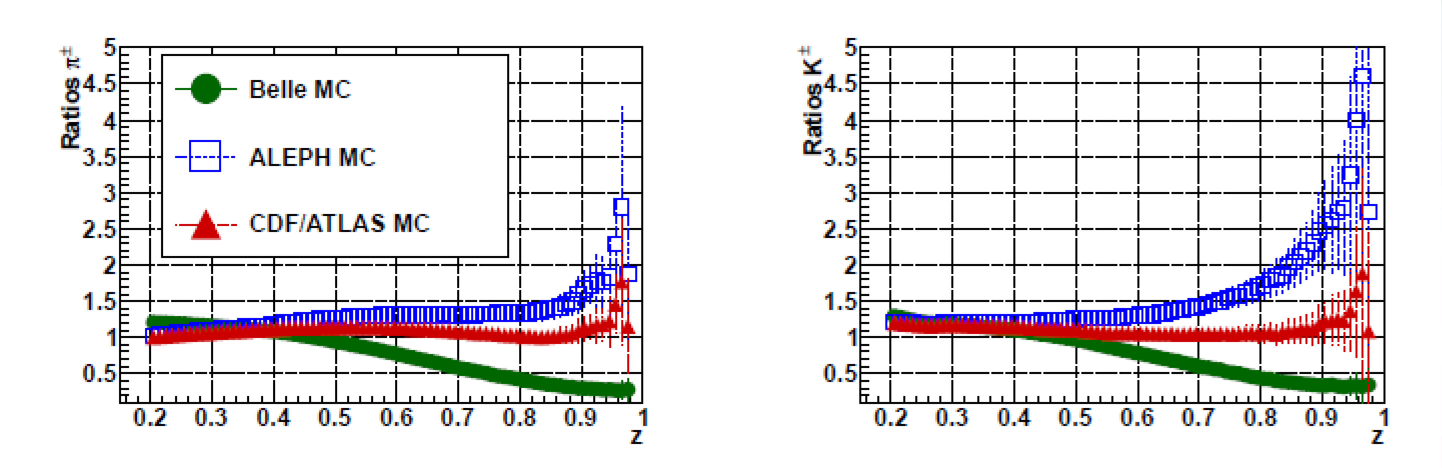
- However, if general MC description inadequate backgrounds will also not match under peaks

➔ Need to optimize the MC to best describe the continuum data

Comparison of light hadron FFs to other tunes

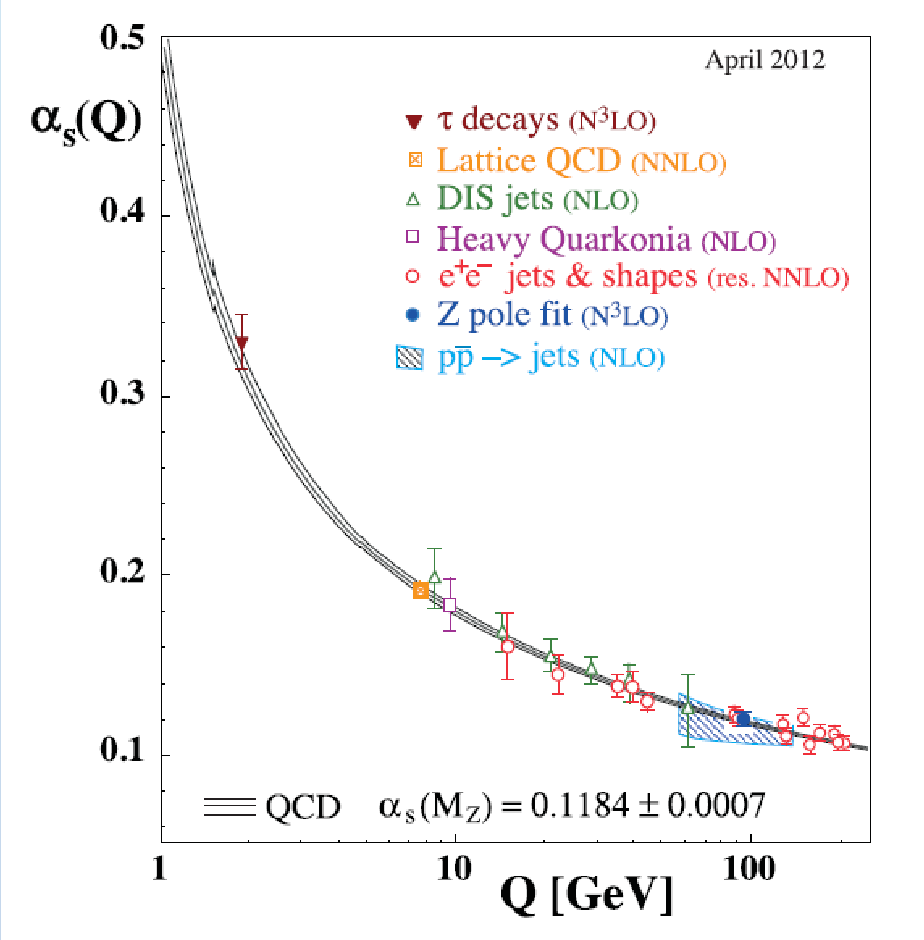
Martin Leitgab (UIUC)





Event shapes

- Using the event shapes, especially 3jet cross sections one can obtain the size of the strong coupling α_S
- see the actual running of the coupling
- Other information about running coupling from DIS jets, tau decays, etc



Summary and Outlook

- Light and charmed hadron fragmentation function measurements ongoing but only the more obvious hadrons measured so far
  - Possibility to understand the process of fragmentation (and QCD) better
  - Potentially learn about exotics
  - Transverse momentum generation
  - Use for global QCD analysis of parton distribution functions
- Spin dependent fragmentation functions measured and ongoing
  - Spin analyzers
  - Use for global QCD analysis of transversely polarized parton distribution functions
- MC tuning necessary for better agreement with Data
  - Also important as background source for B related measurements
  - Some initial studies performed also in Belle
  - Need to improve for future precision

Other fragmentation measurements

- Vector mesons and two particle resonances
- Lambda polarized fragmentation function
- Lambda spin - transverse momentum correlation
- Local parity violation studies

Belle light hadron fragmentation activity

	RIKEN/RBRC	Illinois	Indiana	Bilbao	Titech
Unpol FFs $e^+e^- \rightarrow hX$: $e^+e^- \rightarrow (hh)X$, $(h)(h)X$, hhX: Unpol k_T dependence:	 Charged di-hadrons: Ralf Seidl	Charged hadrons (π,K,P): Martin Leitgab	π^0 ,η^0: Hairong Li	P, long prd Charlotte Hulse Charlotte Hulse	
Collins FFs $e^+e^- \rightarrow (h)(h)X$: k_T dependence:	$\pi\rho^0$: Ralf Seidl $\pi\pi$: Ralf Seidl	πK,KK: Francesca Giordano Francesca Giordano	$\pi\pi^o$: Hairong Li	 Charlotte Hulse	
Interference FF: $e^+e^- \rightarrow (hh)(hh)X$	Charged $\pi\pi$: Ralf Seidl		Charged $\pi\pi$: Anselm Vossen $\pi\pi^o$: Anselm Vossen		Charged πK, KK: Nori-aki Kobayashi
Local P̶ : Λ(polFF,SSA) : Handetness: Jet-jet asy:			Anselm Vossen Anselm Vossen		

Black: about to start
Green:ongoing
Grey: finished