OBSERVATION OF TRANSVERSE Λ POLARIZATION AT BELLE AND NEW RESULTS ON THE INVARIANT MASS SPECTRUM OF DI-HADRON PAIRS IN E^+E^- ANNIHILATION

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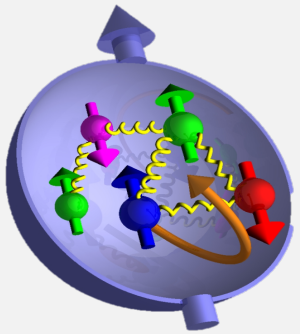
Λ Result based on analysis by Yinghui Guan
arXiv:1611.06648, BELLE-CONF-1611

DIS Birmingham 4/5/2017

STUDYING HADRON STRUCTURE E^+E^-

- Question:
  - What is the correlation between transverse momentum und spin?



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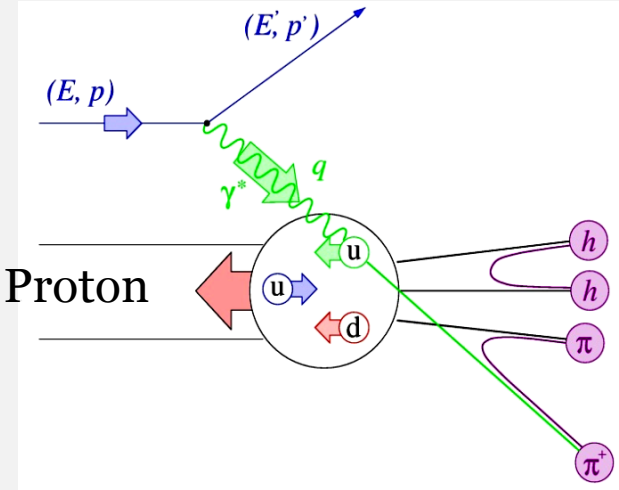


  - **Sivers effect:** Knock out quark, measure transverse momentum correlation with proton spin

STUDYING HADRON STRUCTURE IN E^+E^-

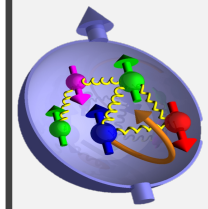
- Question:
  - What is the correlation between transverse momentum und spin?
- Reformulation:

Spacelike SIDIS

Timelike SIA

  - Create quark and measure transverse polarization dependence on transverse momentum

STUDYING HADRON STRUTURE IN E^+E^-



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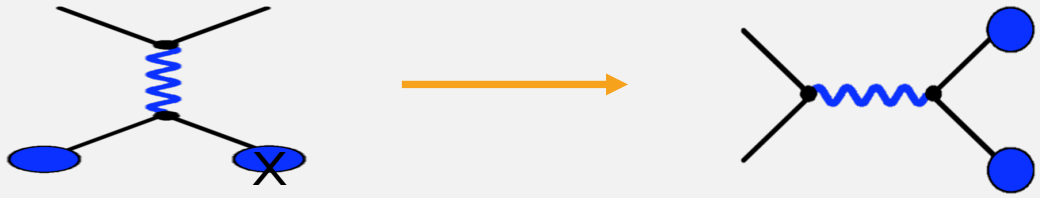

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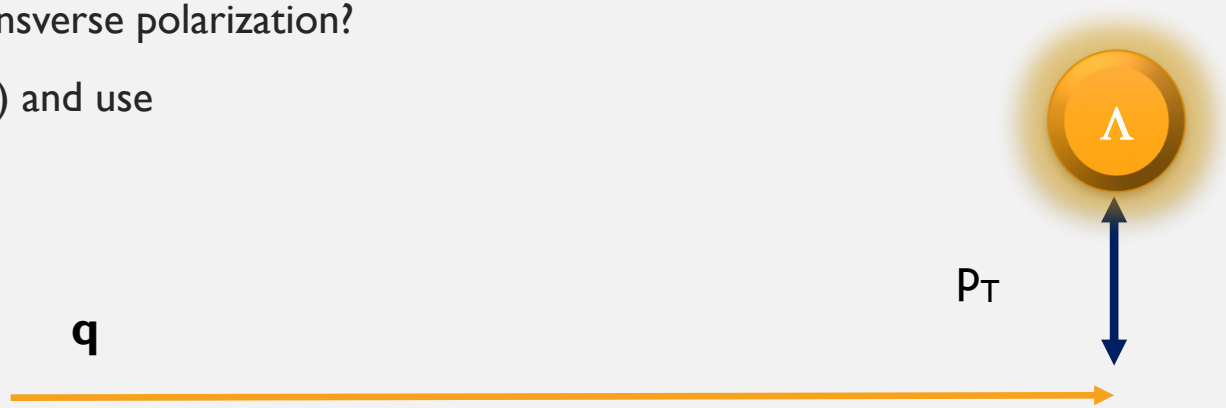
- Slight complication:
  - How to measure proton transverse polarization?
  - →replace u ←→ s quark (Λ) and use self-analyzing decay



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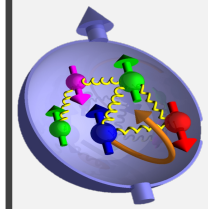

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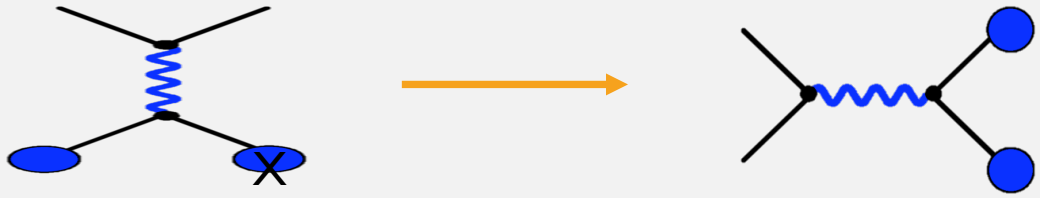

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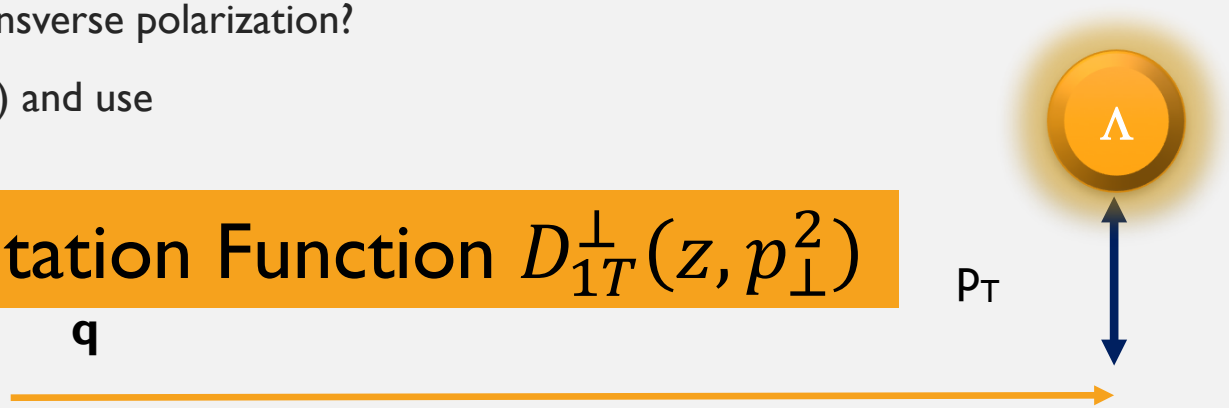
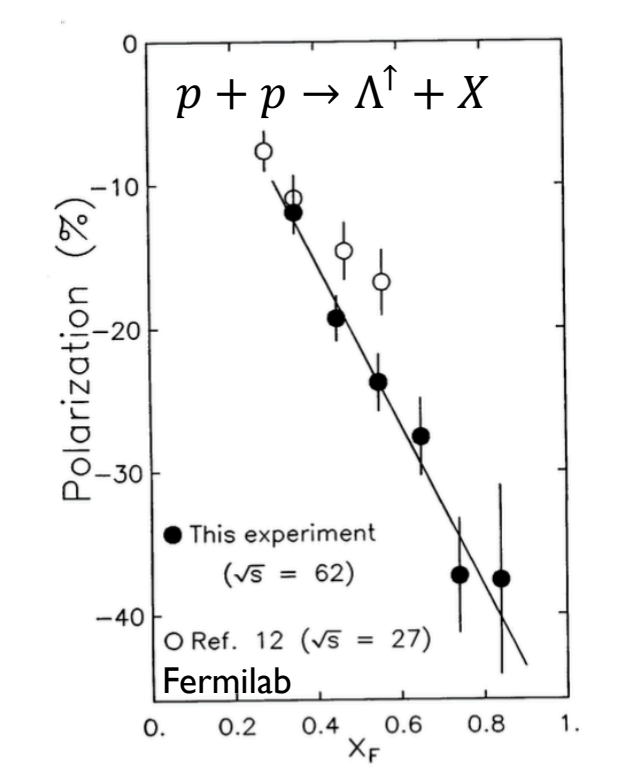
Polarizing Fragmentation Function $D_{1T}^{\perp}(z, p_{\perp}^2)$



POLARIZED HYPERON PRODUCTION

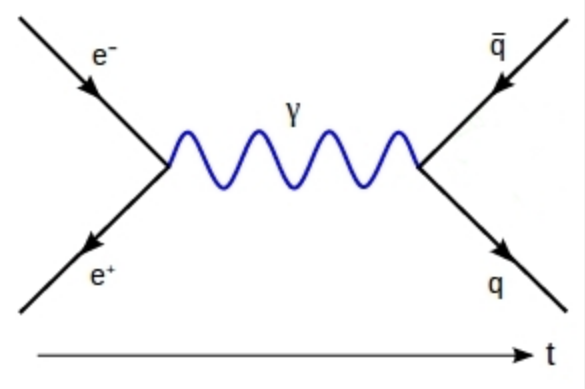
- Large Λ transverse polarization in unpolarized pp collision **PRL36, 1113 (1976); PRL41, 607 (1978)**
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- Polarizing FF is chiral-even, has been proposed as a test of universality. **PRL105,202001 (2010)**
- OPAL experiment at LEP has been looking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



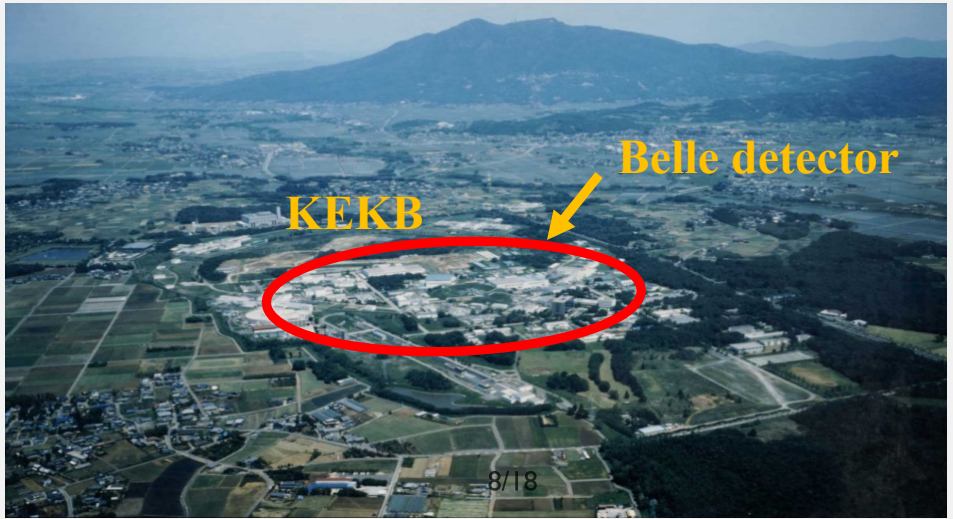
Also ISR data
(Phys.Lett. B185 (1987) 209)

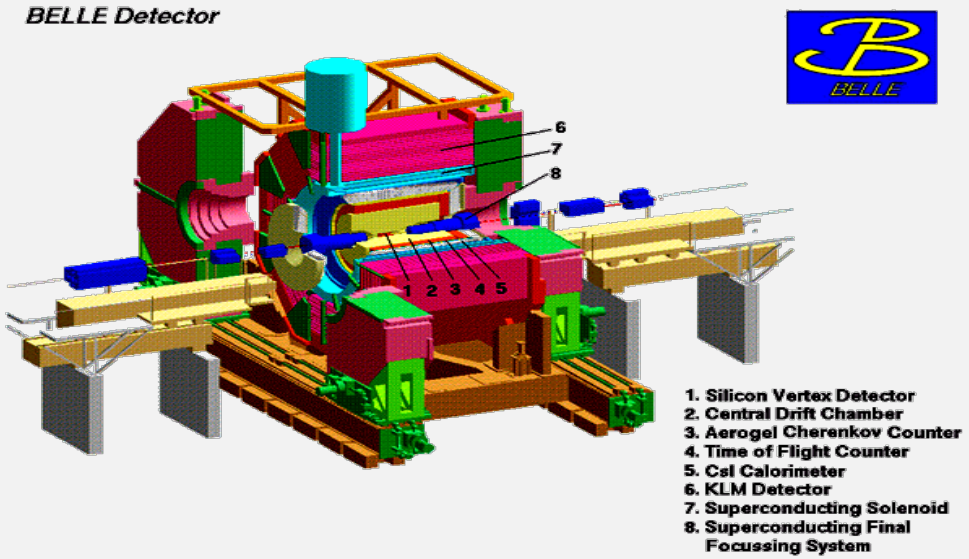
$$x_F = p_L / \max p_L \sim_{LO} x_1 - x_2 \sim_{forward} x_1$$

Measurements of Fragmentation Functions in e+e- at Belle

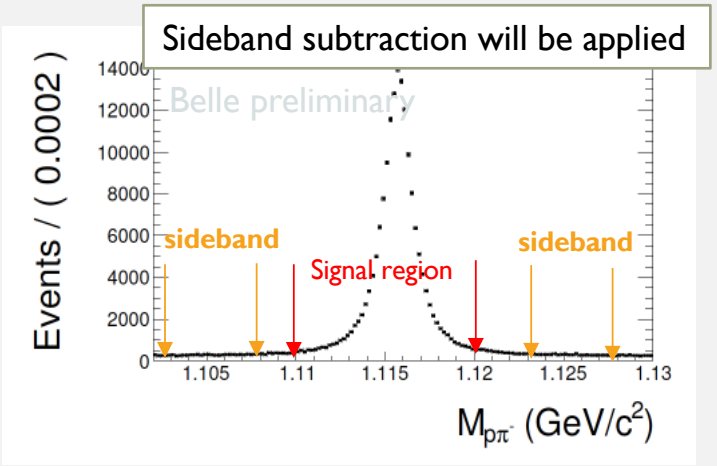


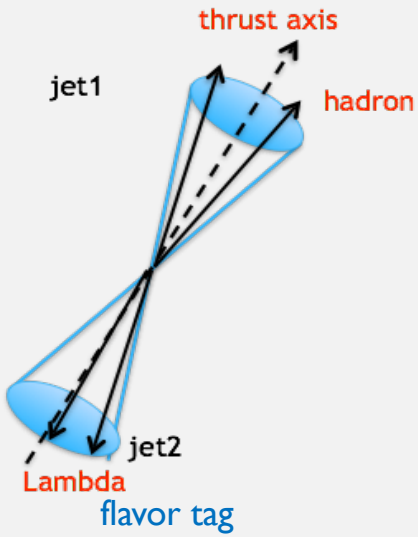
- KEKB: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - $\sqrt{s}$ **= 10.58 GeV,** $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B/B$ + continuum
  - $\sqrt{s}$ = 10.52 GeV, e+e- → qqbar (u,d,s,c) 'continuum'
- ideal detector for high precision measurements:
  - tracking acceptance θ [17 °;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - ~1.8 $*10^9$ events at 10.58 GeV,
  - ~220 $*10^6$ events at 10.52 GeV





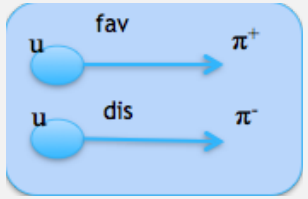
LAMBDA RECONSTRUCTION



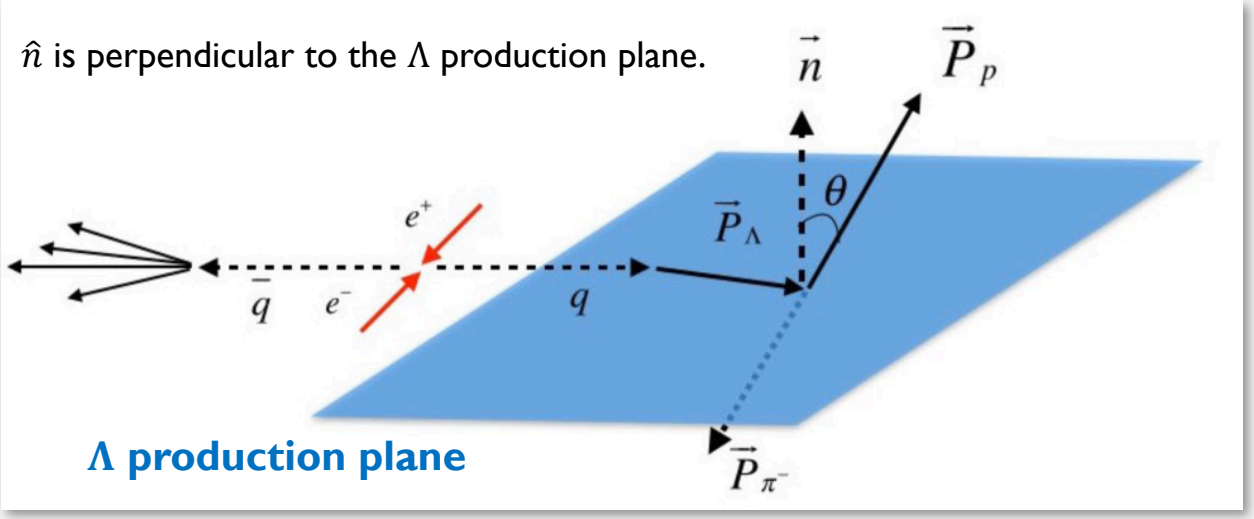


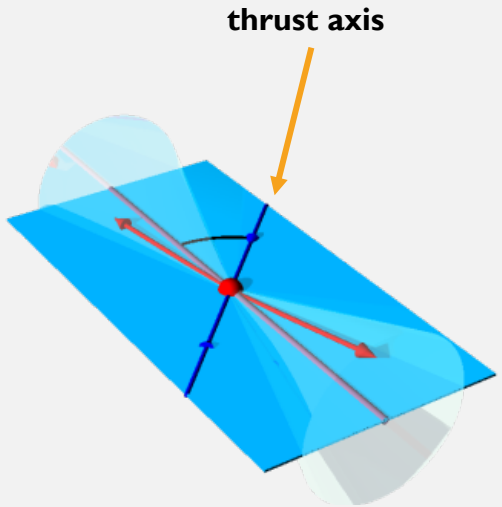
- Signal process $\Lambda \rightarrow p\pi^-(\bar{\Lambda} \rightarrow \bar{p}\,\pi^+)$. Clear Λ peak.
- Detect light hadron $(K^{\pm}, \pi^{\pm})$ in the opposite hemisphere→ enhance or suppress different flavors fragmenting in $\Lambda(\bar{\Lambda})$.

Λ(uds); π^+(u$\bar{d}$); K^+ (u$\bar{s}$)



OBSERVABLES IN Λ RESTFRAME





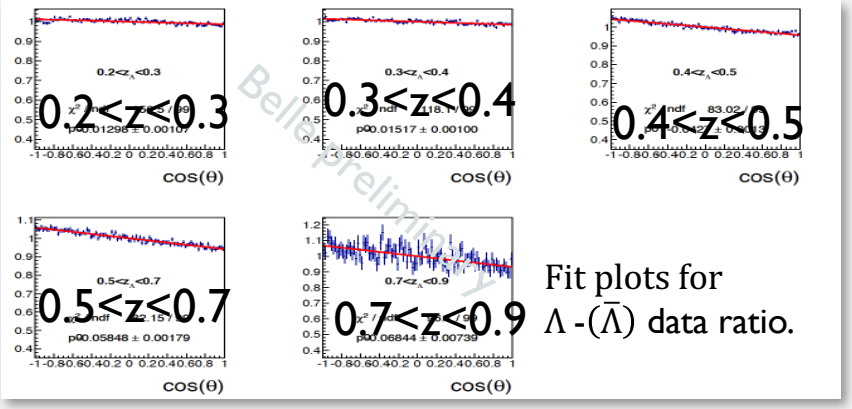
- Self-analyzing decay leads to polarization dependent distribution

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

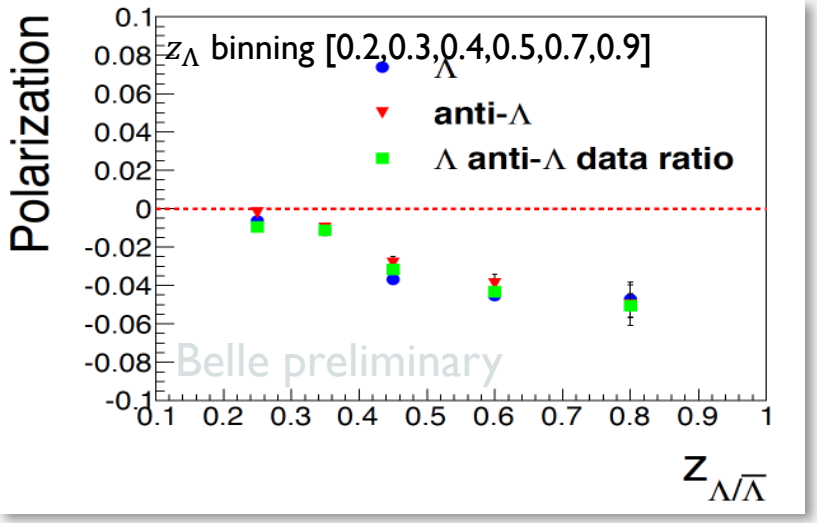
- where α is the decay parameter: α_+=0.642 $\pm$ 0.013 for Λ and α_-=-0.71 $\pm$ 0.08 for $\bar{\Lambda}$ (PDG).
- The p_t is measured as the transverse momentum of Λ relative to the **thrust axis**

FITS AND EXTRACT POLARIZATION

- Fit the acceptance corrected $\cos\theta$ distributions with $1 + p_0 cos\theta$.
- The polarization of interest: p_0/α (decay constant)
- In the data ratio, polarization is obtained via $p_0/(\alpha_+ - \alpha_-)$.
- In data ratios, the slope on the $\cos\theta$ distributions are about two times larger than that in MC-corrected ratios, the $(\alpha_+ - \alpha_-)$ is also about two times larger than $\alpha_+(\alpha_-)$.
- Results from MC-corrected ratio and data ratio are consistent with each other.
- Nonzero polarization, magnitude rises to about ~5% with $z_\Lambda = 2E_\Lambda/\sqrt{s}$.



Fit plots for Λ -($\bar{\Lambda}$) data ratio.

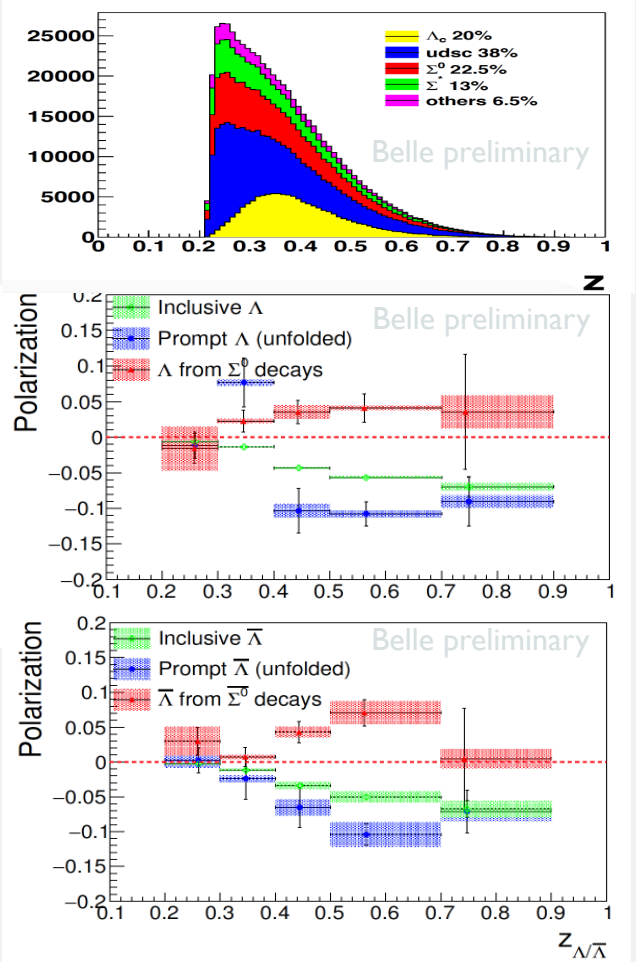


BACKGROUND UNFOLDING

- Non-Λ backgrounds are excluded out in the sideband subtraction.
- Σ^* decays to Λ strongly, is included in the signal.
- Feed-down from Σ^0(22.5%), Λ_c(20%) decays need to be understood.
- The Σ^0-enhanced ($\Sigma^0 \to \Lambda + \gamma$) (Br~100%). and Λ_c-enhanced($\Lambda_c \to \Lambda + \pi^+$)(Br~1.07%) data sets are selected and studied.
- The measured polarization can be expressed as:

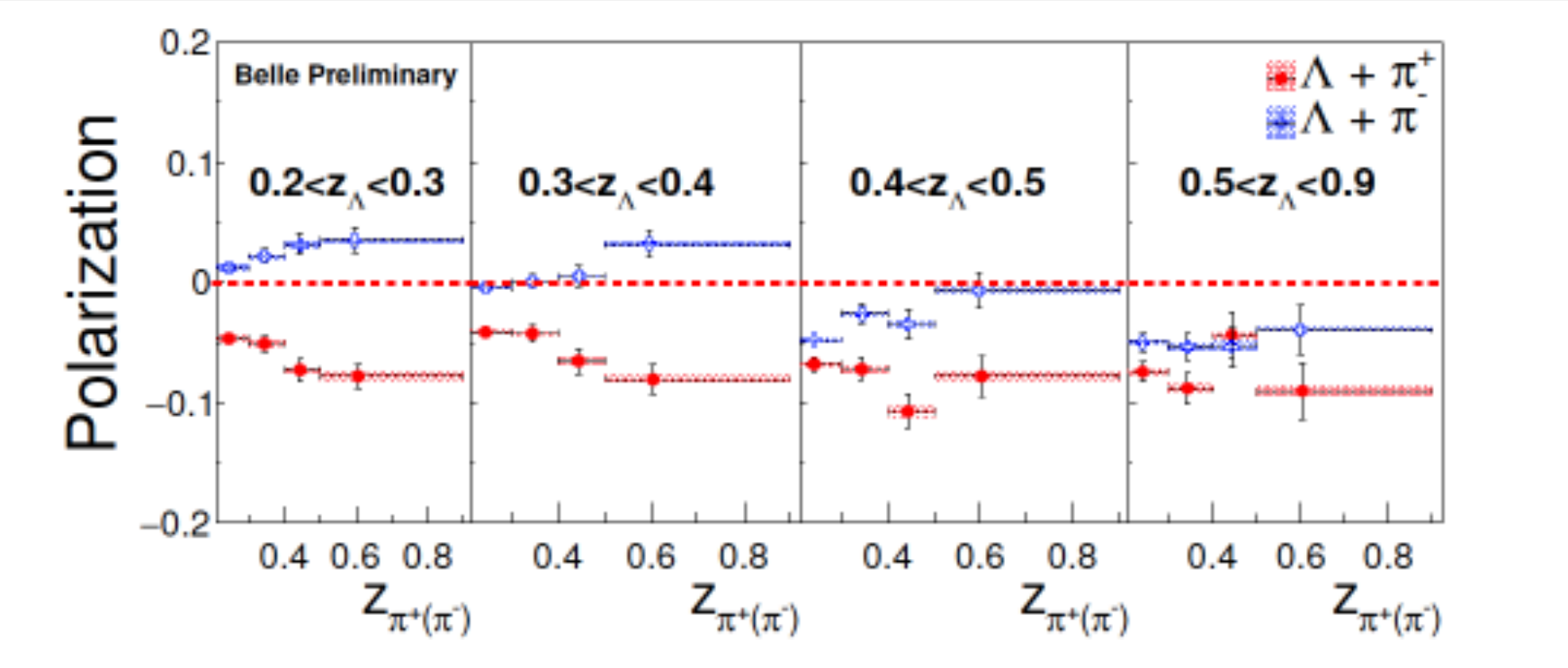
$$P^{mea.} = (1 - \sum_i F_i) P^{true} + \sum_i F_i P_i,$$

- F_i is the fraction of feed-down component i, estimated from MC. P_i is polarization of component i.
- Polarization of Λ from Σ^0 decays is found has opposite sign with that of inclusive Λ.



R. Gatto, Phys. Rev. 109, 610 (1958); Phys.Lett.B303,350(1993)

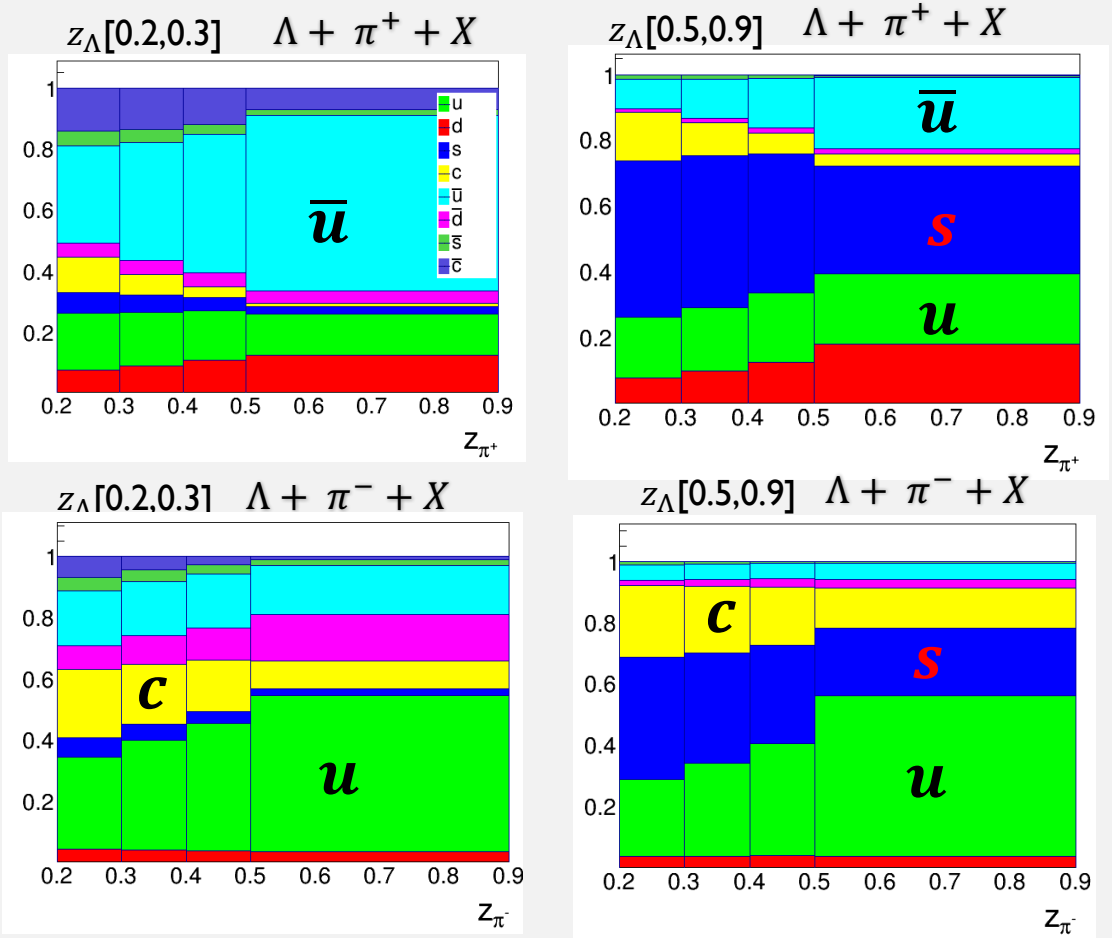
π/K TAG IN OPPOSITE HEMISPHERE



(see backup for K and Λ-bar)

- At low z_Λ, polarization in $\Lambda + h^+$ and $\Lambda + h^-$ have opposite sign. The magnitude increases with higher z_h.
- At large z_Λ, the differences between $\Lambda + h^+$ and $\Lambda + h^-$ reduce. Small deviations can still be seen and depend on z_h.

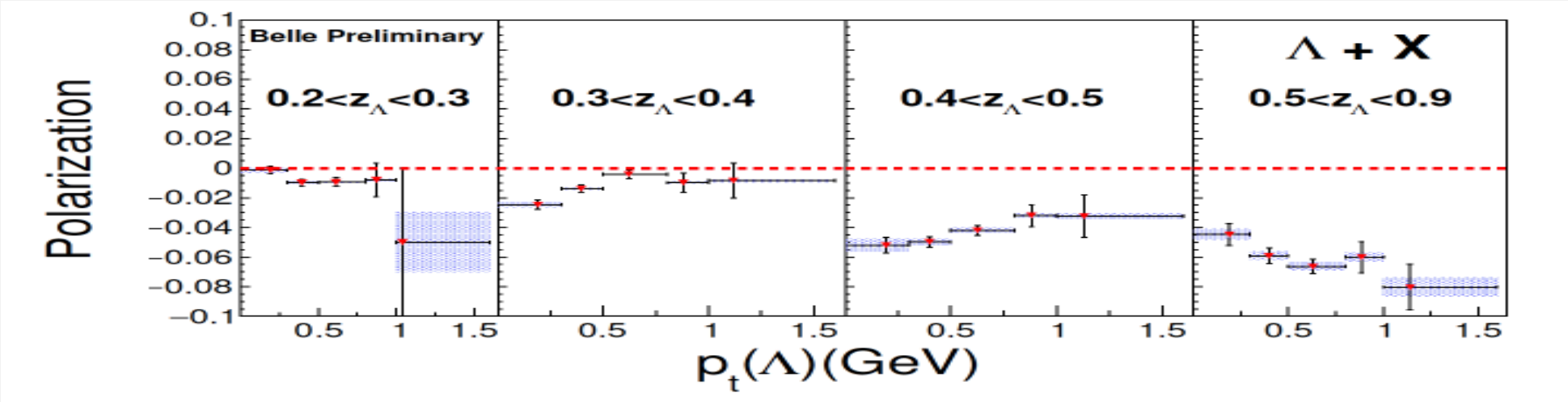
QUARK FLAVOR TAG BY THE LIGHT HADRON



- An attempt to look at the flavor tag effect of the light hadron, based on MC. (Pythia6.2)
- The fractions of various quark flavors going to the Λ's hemisphere are shown in different $[z_\Lambda\ z_h]$ region.
- MC indicates that the tag of the quark flavors is more effective at low z_Λ and high z_h. It explains why at low z_Λ and high z_h, polarization in $\Lambda + h^+$ and $\Lambda + h^-$ have opposite sign.

…and analogous for the kaon…

Z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION



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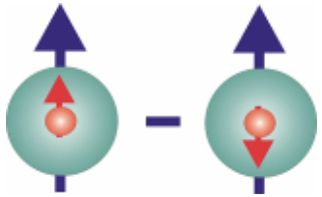
- Results are consistent between Λ and $(\bar{\Lambda})$ and Λ -$(\bar{\Lambda})$ data ratio.
- Correlation with opposite hemisphere light meson →quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge cf Sivers
    Asymmetries corrected for feed-down contributions from Σ and Λ_c

ACCESSING THE NUCLEONS SPIN TRANSVERSE SPIN STRUCTURE

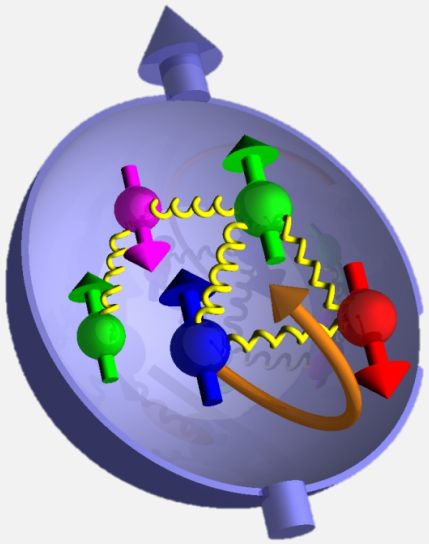
$h_1^q(x)$



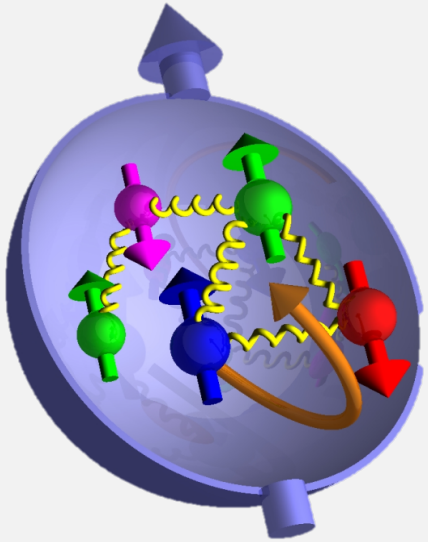
transversity PDF

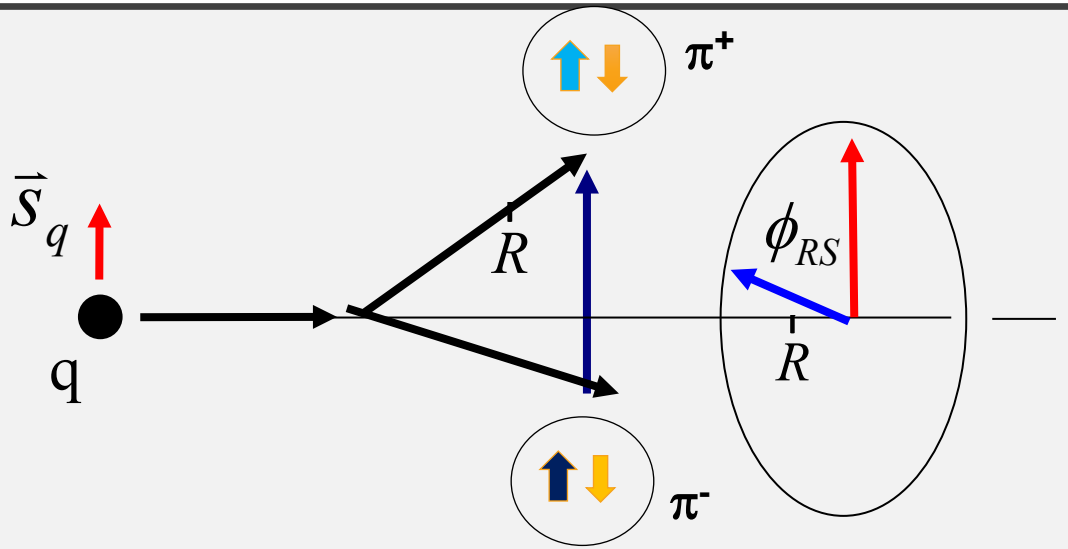
quark with spin parallel to the nucleon spin in a transversely polarized nucleon

Chiral odd, poorly known
Cannot be measured inclusively
➔Need for Quark Polarimeter!



NEED TRANSVERSE POLARIZATION DEPENDENT FRAGMENTATION FUNCTIONS



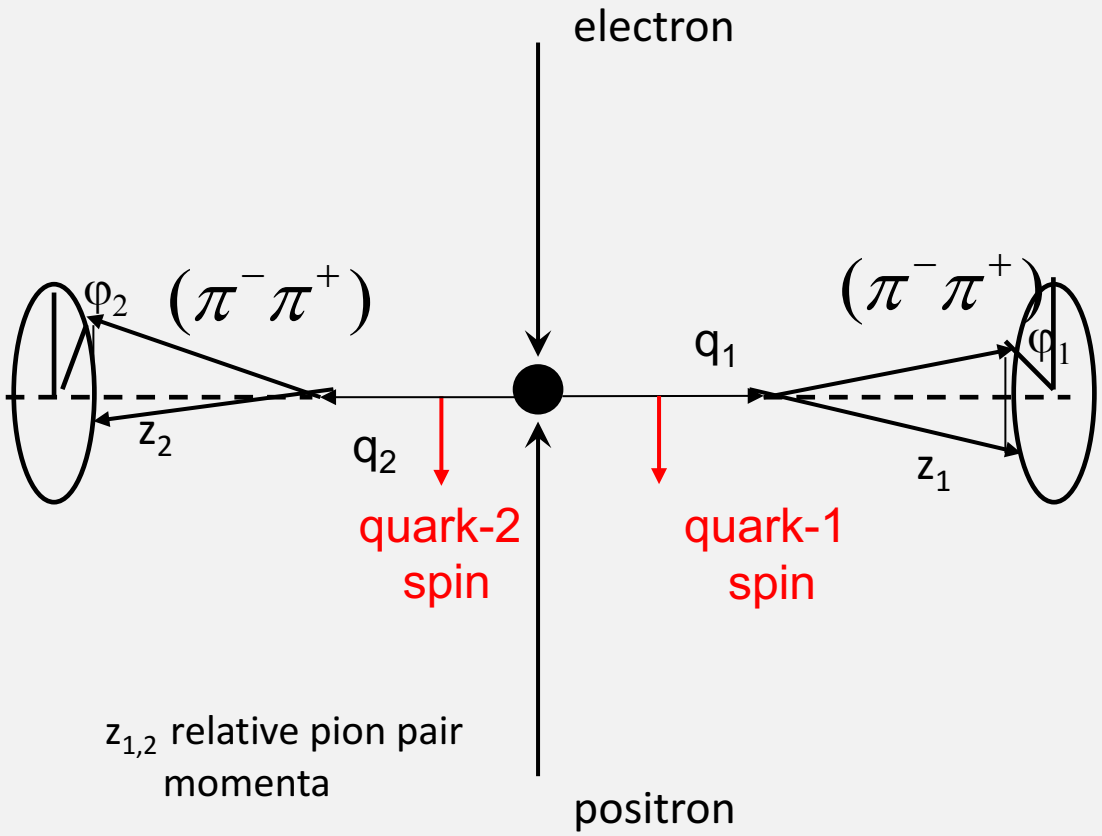


Interference Fragmentation Function: $H_1^{\sphericalangle}(z, M)$

Strength of Correlation between quark polarization and azimuthal modulation of hadron pair distribution

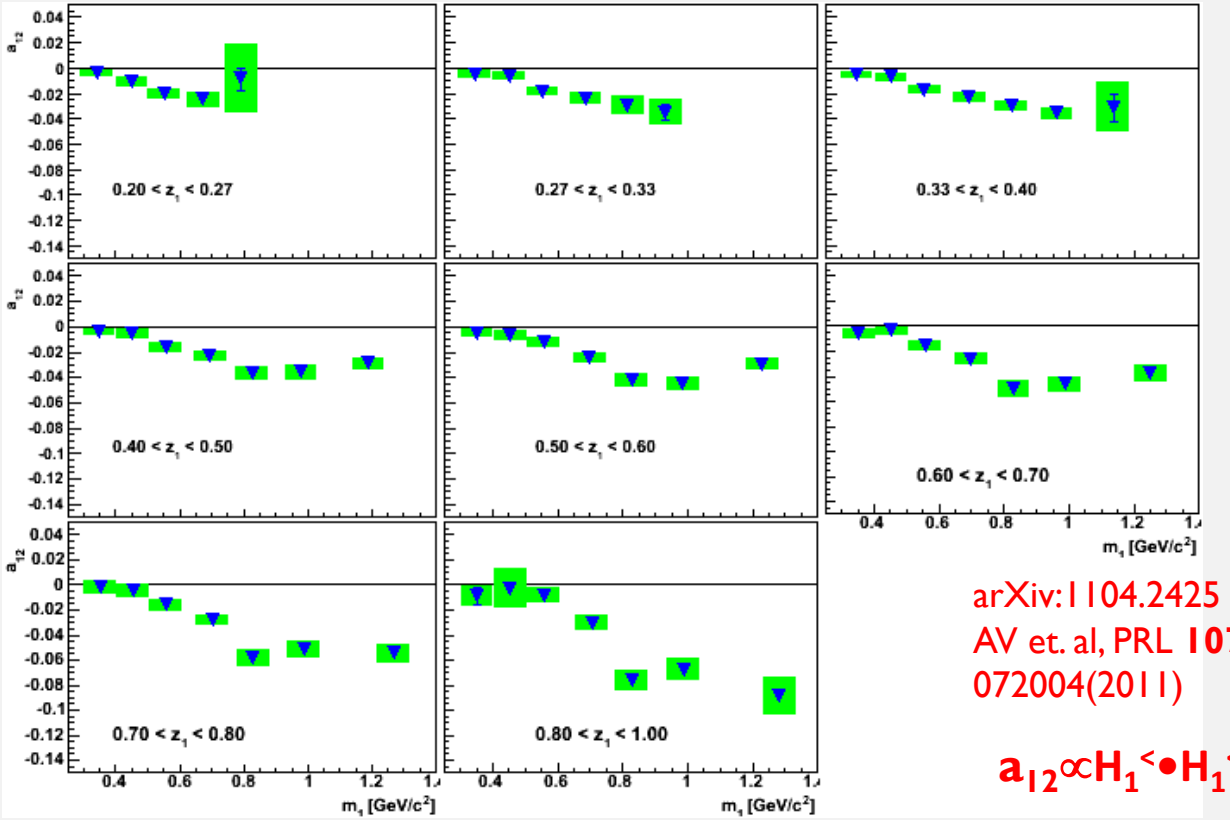
- Depends on z: Fractional energy of the parent quark carried by the hadrons
- M: invariant mass of the di-hadron pair

ACCESS IN BACK-TO-BACK CORRELATIONS



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

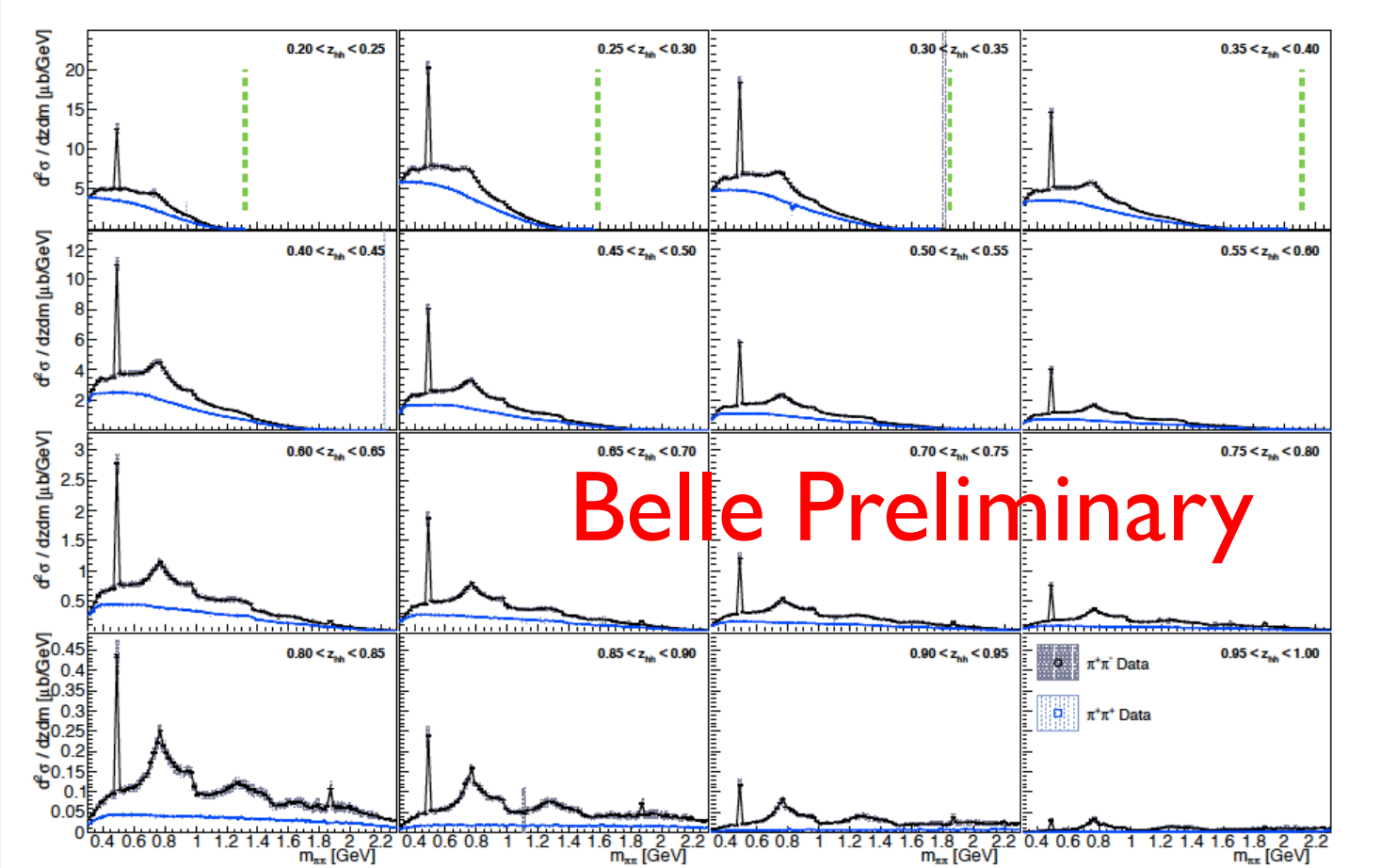
OBSERVATION OF SPIN DEPENDENT DI-HADRON CORRELATIONS AT BELLE



arXiv:1104.2425
AV et. al, PRL **107,** 072004(2011)

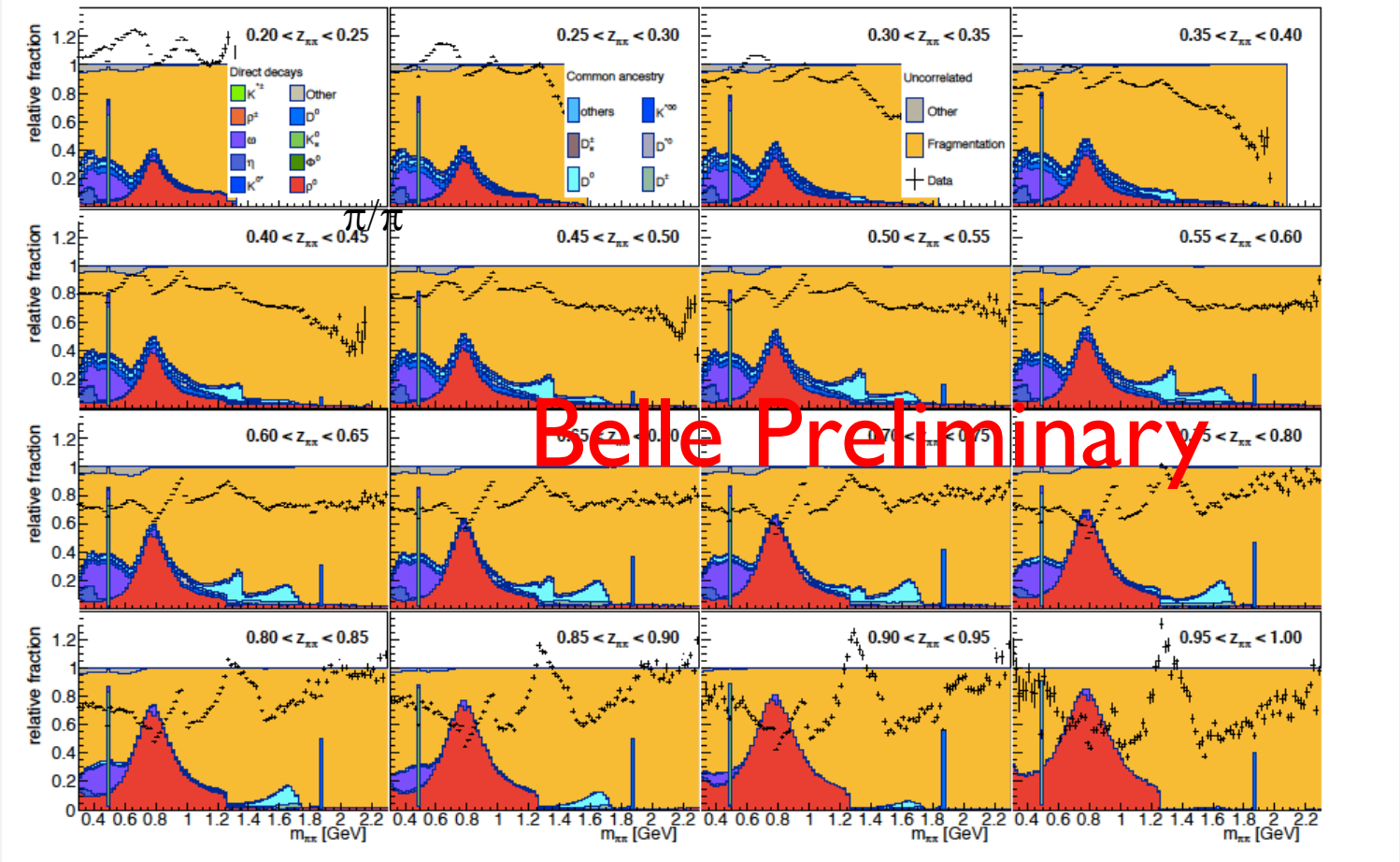
$$a_{12} \propto H_1^{<} \bullet H_1^{<} / (D_1^{<} \bullet D_1^{<})$$

NEW: SPIN INTEGRATED DI-HADRON FF $D_1^<$



- Ralf Seidl et. al., to be submitted to Phys.Rev.D.
- PiK and KK in backup

DATA MC COMPARISON



- Default Pythia, other tunes in backup

SUMMARY & OUTLOOK

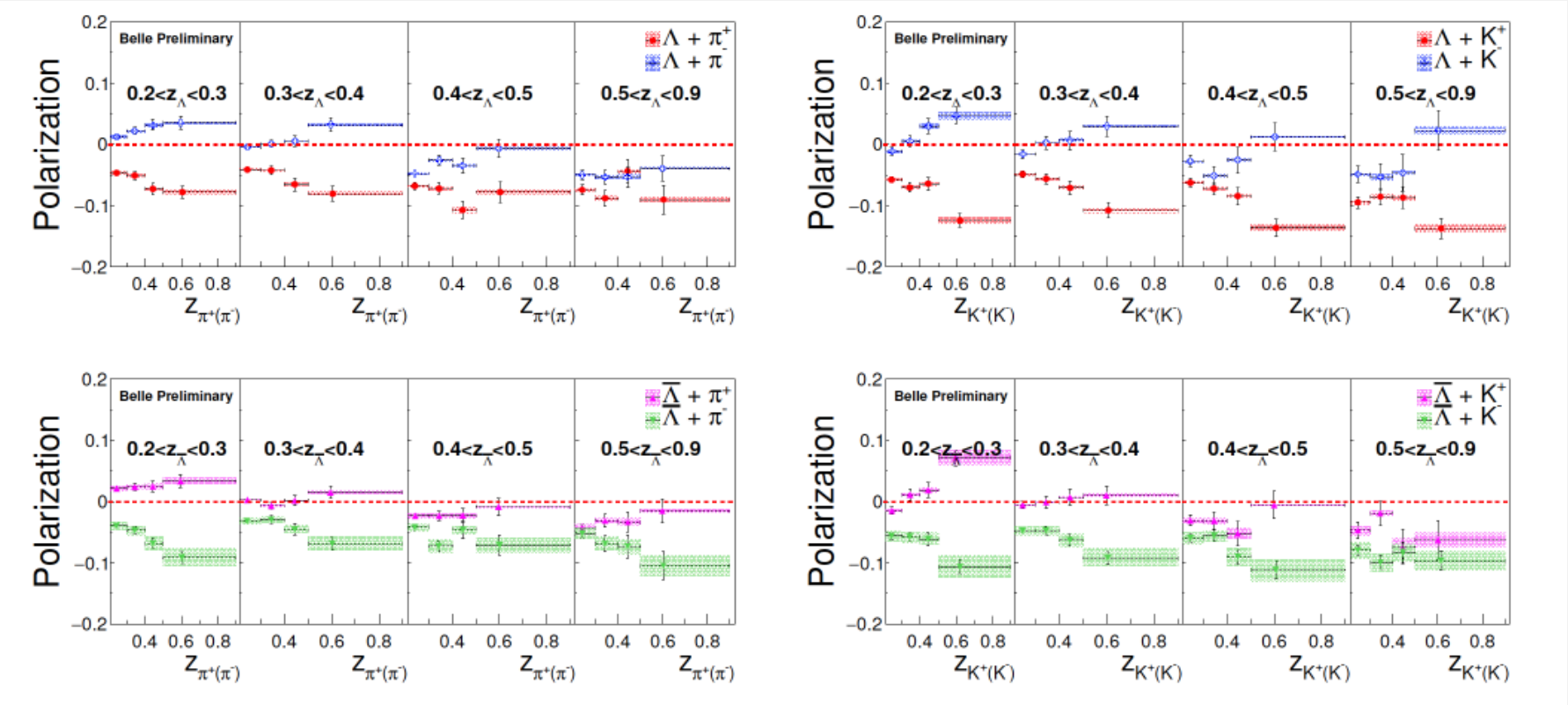
- New results on transverse polarization of Λ baryons
  - Future results on quark transverse polarization dependent Λ fragmentation
- New results on the unpolarized di-hadron FF

SUMMARY

- First observation of transverse Λ polarization in e+e-
- Many interesting features in pT dependence
- Future plans: spin dependent Λ polarization and more

BACKUP

π/K TAG IN OPPOSITE HEMISPHERE



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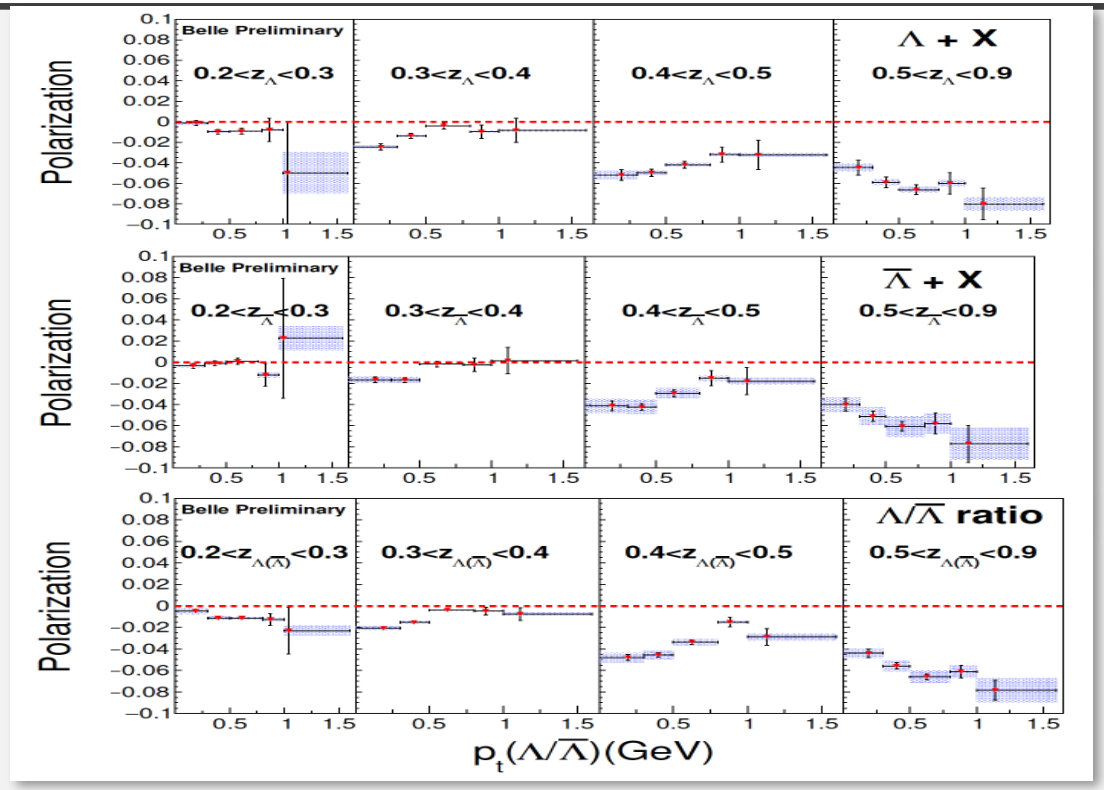
Z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION



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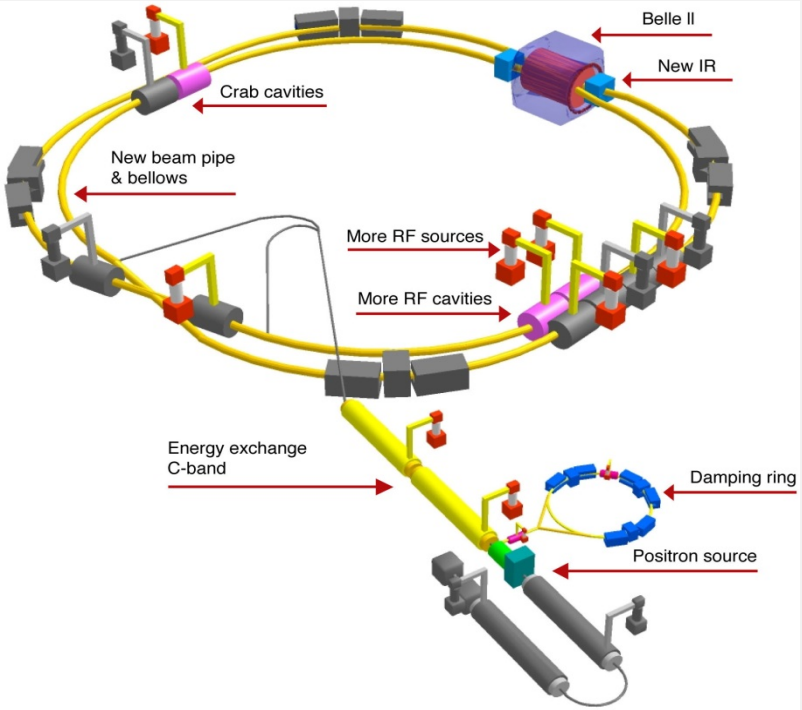
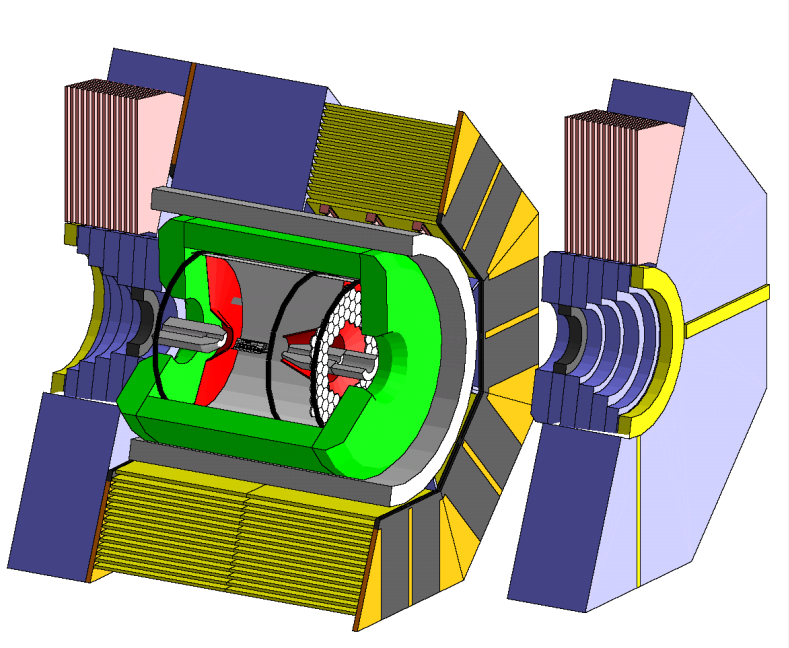
  - Sign of asymmetry dependent on quark charge cf Sivers
    Asymmetries corrected for feed-down contributions from Σ and Λ_c

KEKB/BELLE→SUPERKEKB, UPGRADE

- Aim: super-high luminosity ~10^{36} $cm^{-2}s^{-1}$ (~40x KEK/Belle)
- Upgrades of Accelerator (Nano-beams + Higher Currents) and Detector (Vtx,PID, higher rates, modern DAQ)
- **SuperKEKB achieved First Turns Milestone**
- Significant US contribution

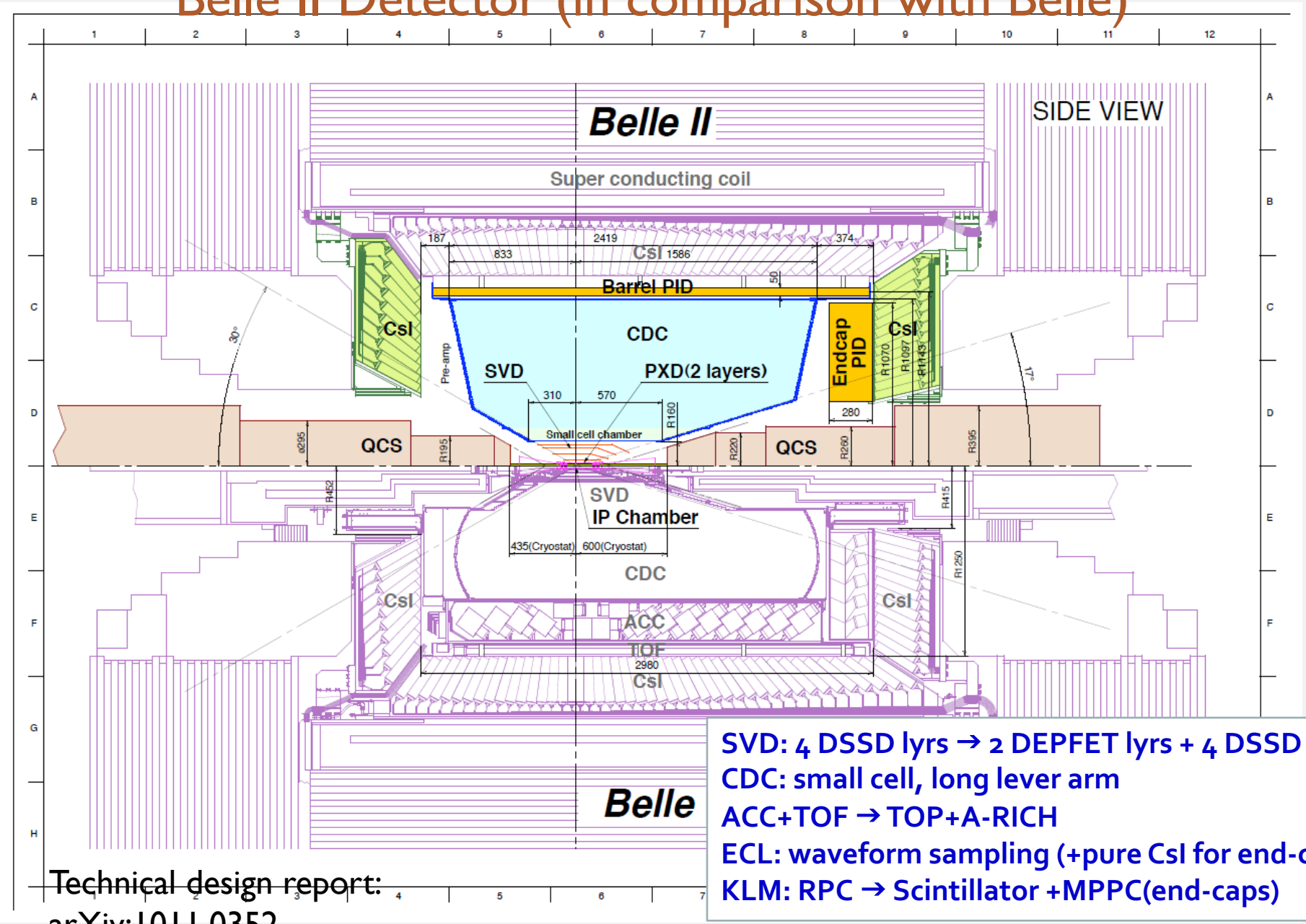


Start of comissioning in 2016



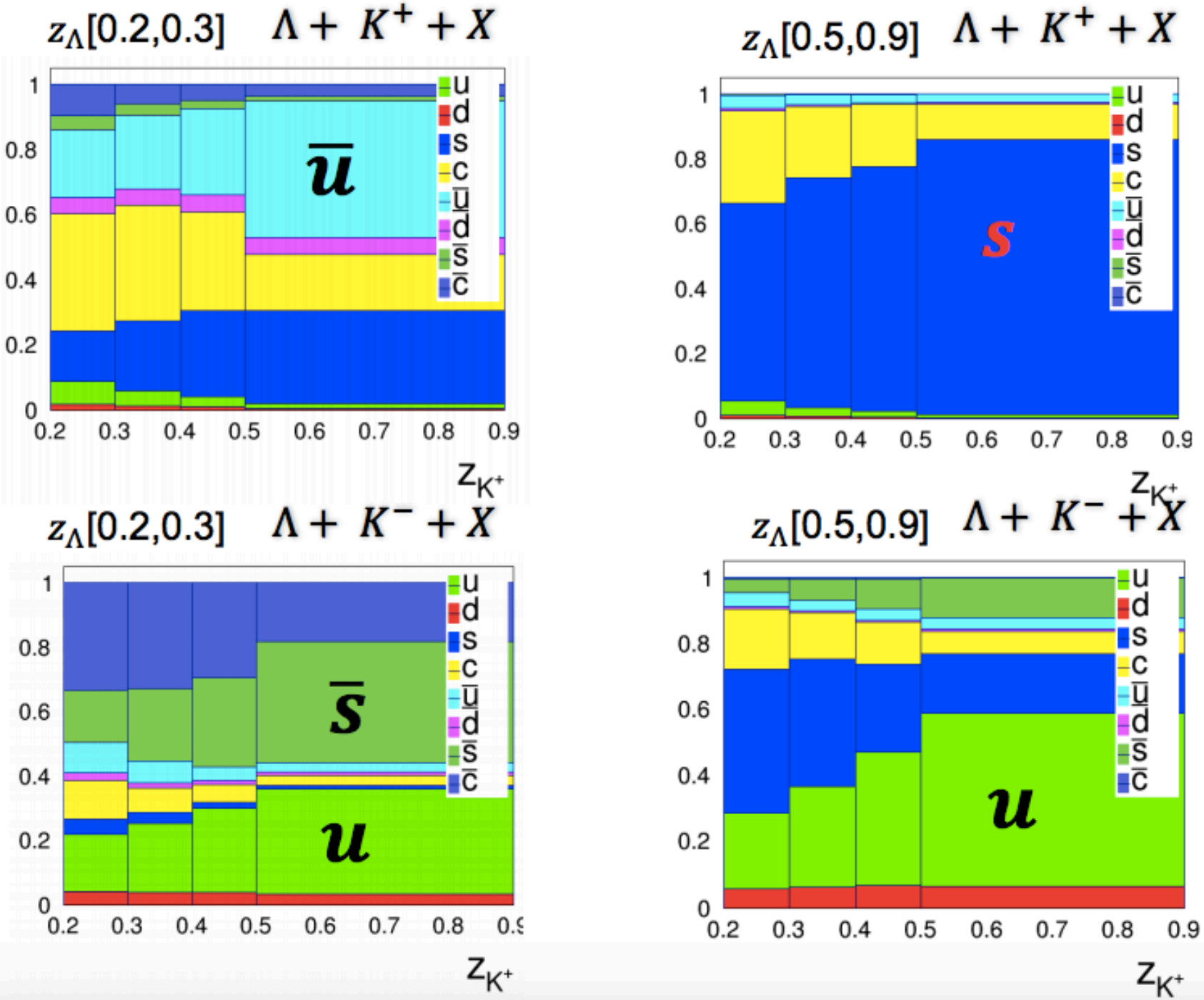
http://belle2.kek.jp

Belle II Detector (in comparison with Belle)



SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for end-caps)
KLM: RPC → Scintillator +MPPC(end-caps)

Technical design report:
arXiv:1011.0352


$z_\Lambda[0.2,0.3]$ $\Lambda + K^+ + X$
$z_\Lambda[0.5,0.9]$ $\Lambda + K^+ + X$
$z_\Lambda[0.2,0.3]$ $\Lambda + K^- + X$
$z_\Lambda[0.5,0.9]$ $\Lambda + K^- + X$
u
d
s
c
$\bar{u}$
$\bar{d}$
$\bar{s}$
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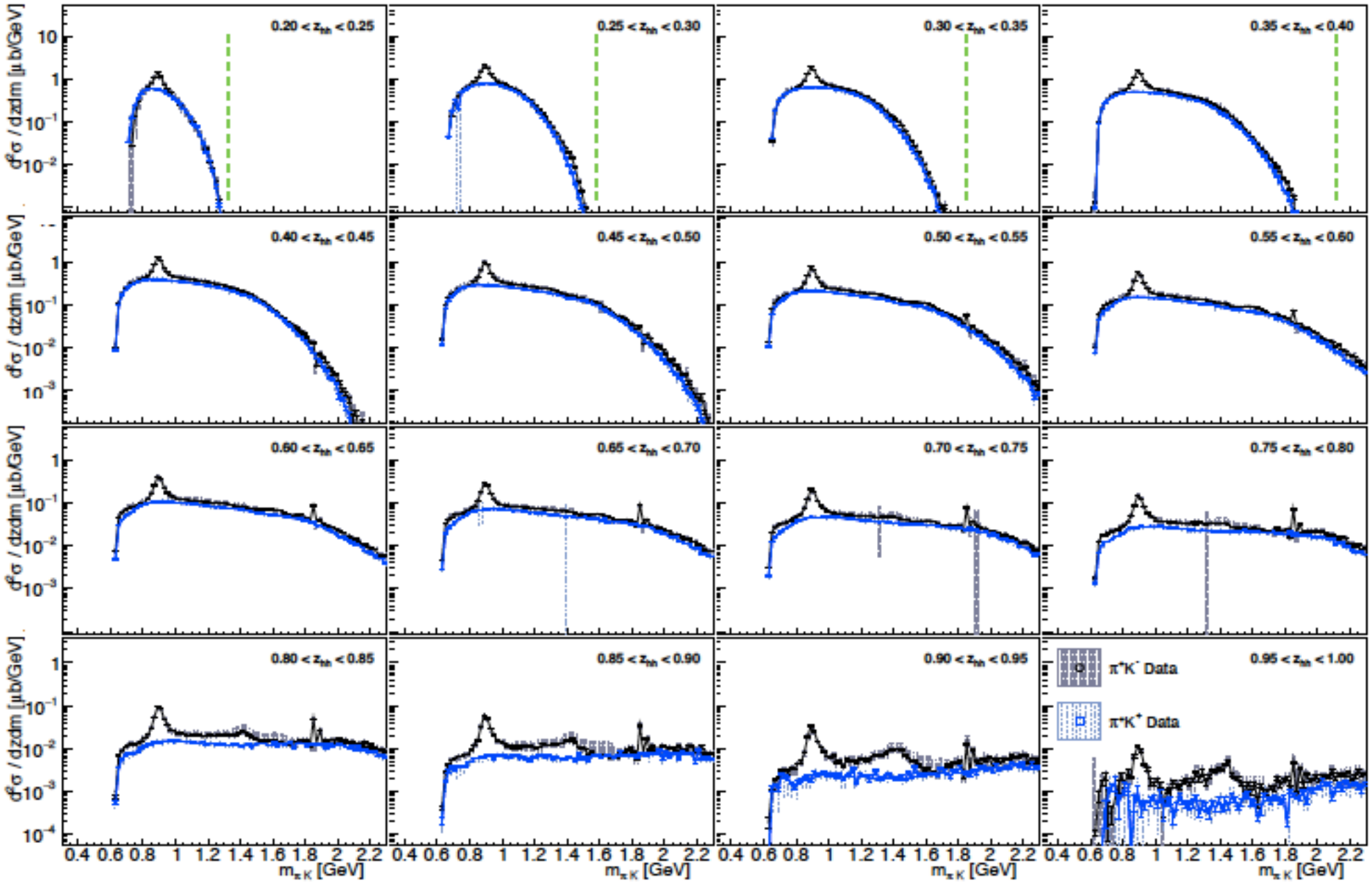
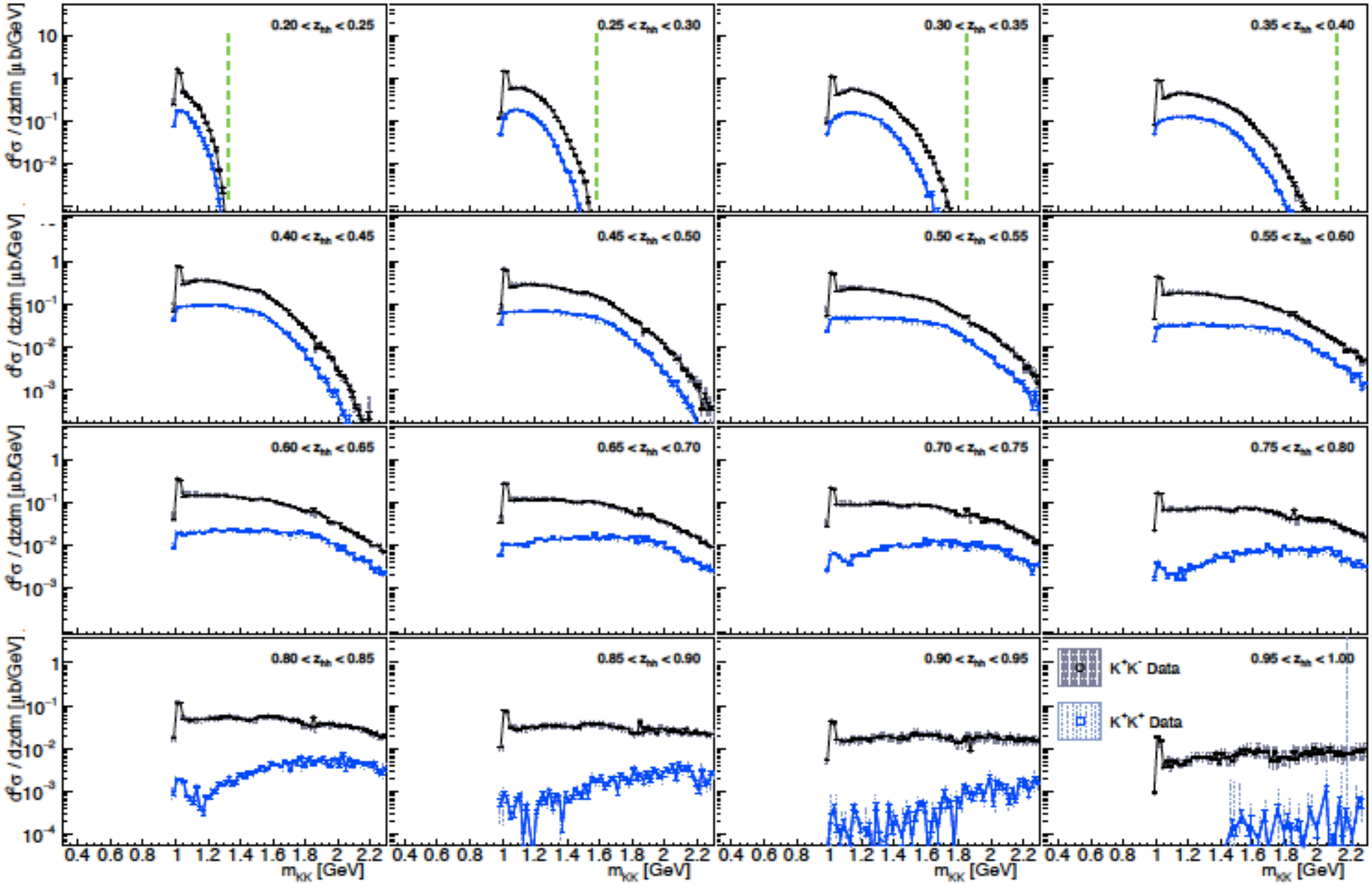
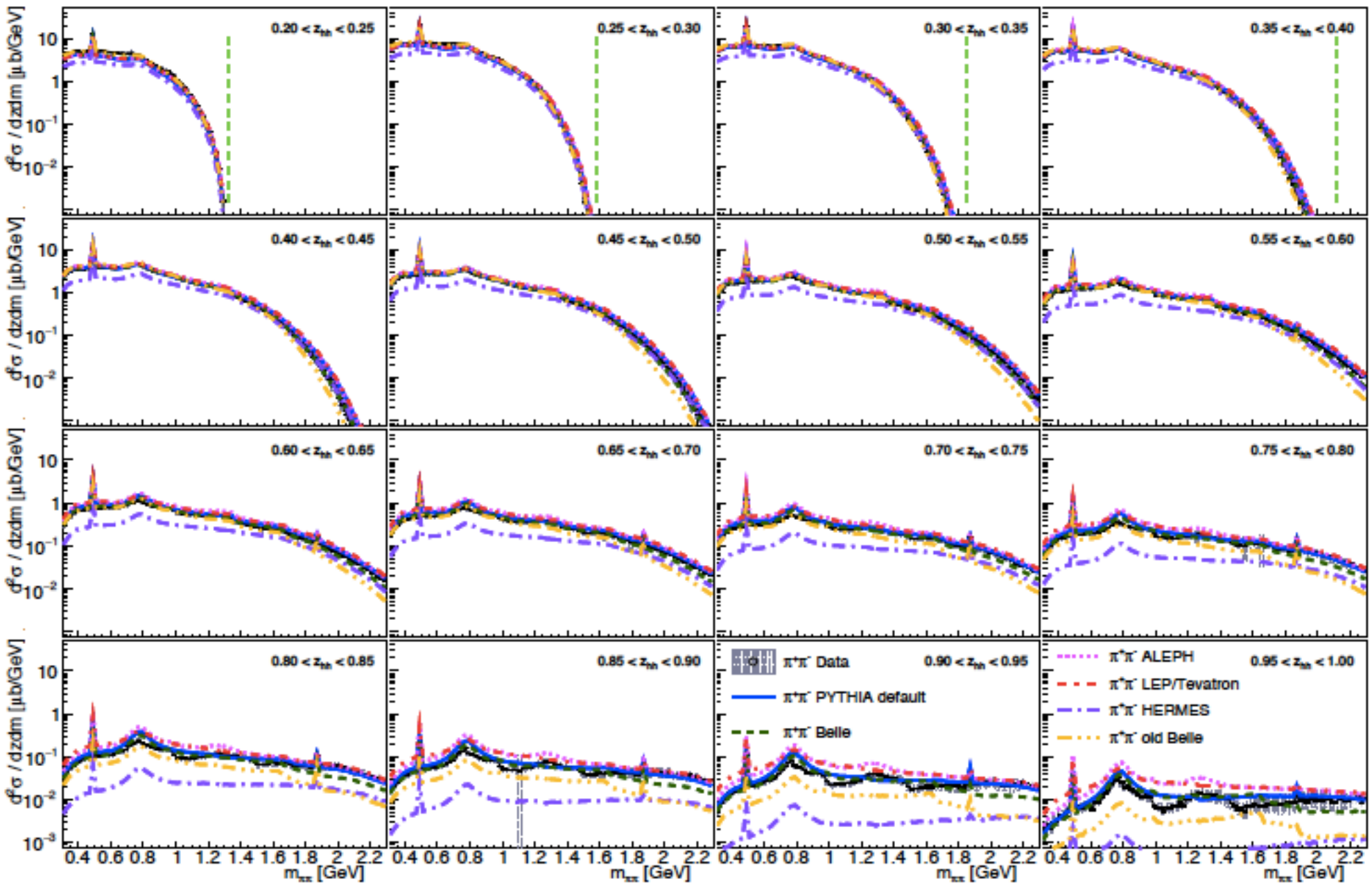
$\bar{u}$
s
$\bar{s}$
u
z_{K^+}


0.20 < z_hh < 0.25
0.25 < z_hh < 0.30
0.30 < z_hh < 0.35
0.35 < z_hh < 0.40
0.40 < z_hh < 0.45
0.45 < z_hh < 0.50
0.50 < z_hh < 0.55
0.55 < z_hh < 0.60
0.60 < z_hh < 0.65
0.65 < z_hh < 0.70
0.70 < z_hh < 0.75
0.75 < z_hh < 0.80
0.80 < z_hh < 0.85
0.85 < z_hh < 0.90
0.90 < z_hh < 0.95
0.95 < z_hh < 1.00
π⁻K⁻ Data
π⁻K⁺ Data
d²σ / dzdm [μb/GeV]
m_πK [GeV]


$d^2\sigma$ / dzdm [μb/GeV]
$0.20 < z_{hh} < 0.25$
$0.25 < z_{hh} < 0.30$
$0.30 < z_{hh} < 0.35$
$0.35 < z_{hh} < 0.40$
$0.40 < z_{hh} < 0.45$
$0.45 < z_{hh} < 0.50$
$0.50 < z_{hh} < 0.55$
$0.55 < z_{hh} < 0.60$
$0.60 < z_{hh} < 0.65$
$0.65 < z_{hh} < 0.70$
$0.70 < z_{hh} < 0.75$
$0.75 < z_{hh} < 0.80$
$0.80 < z_{hh} < 0.85$
$0.85 < z_{hh} < 0.90$
$0.90 < z_{hh} < 0.95$
$0.95 < z_{hh} < 1.00$
K^+K^- Data
K^+K^+ Data
m_{KK} [GeV]


0.20 < z_hh < 0.25
0.25 < z_hh < 0.30
0.30 < z_hh < 0.35
0.35 < z_hh < 0.40
0.40 < z_hh < 0.45
0.45 < z_hh < 0.50
0.50 < z_hh < 0.55
0.55 < z_hh < 0.60
0.60 < z_hh < 0.65
0.65 < z_hh < 0.70
0.70 < z_hh < 0.75
0.75 < z_hh < 0.80
0.80 < z_hh < 0.85
0.85 < z_hh < 0.90
0.90 < z_hh < 0.95
0.95 < z_hh < 1.00
d²σ / dzdm [μb/GeV]
m_xx [GeV]
π⁺π⁻ Data
π⁺π⁻ PYTHIA default
π⁺π⁻ Belle
π⁺π⁻ ALEPH
π⁺π⁻ LEP/Tevatron
π⁺π⁻ HERMES
π⁺π⁻ old Belle