Study on the transverse polarization of $\Lambda(\bar{\Lambda})$ and di-hadron cross sections at Belle

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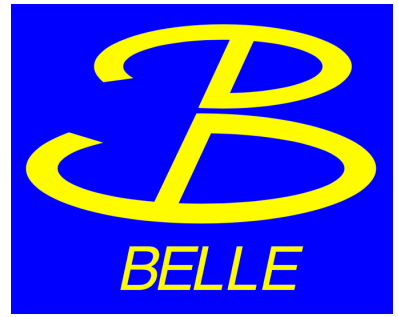
Indiana University & KEK

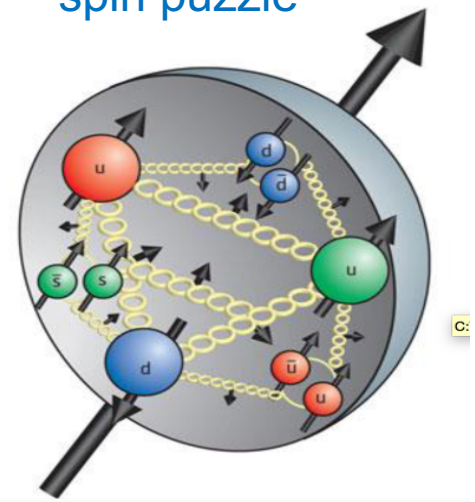
On behalf of the Belle Collaboration



Sept.1 - 5, PANIC2017, Beijing

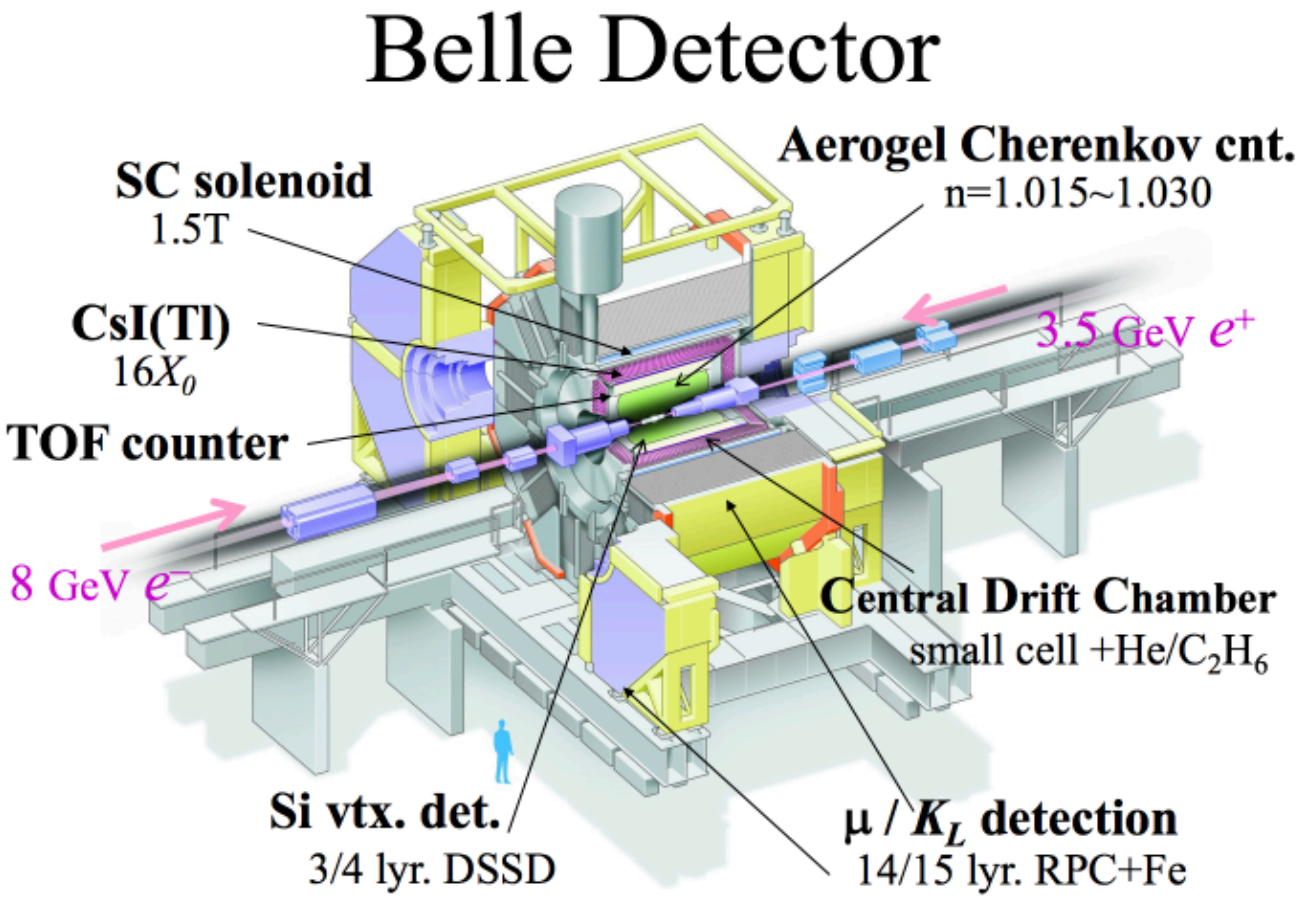
Fragmentation Functions

spin puzzle



- Fragmentation functions(FF) allow us to understand the transition of asymptotically free partons into several confined hadrons.
  - Cannot be calculated form first principles and need to be extracted experimentally.
- The polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$,
  - describes an unpolarized quark fragmenting into a transversely polarized hadron.
  - plays an important role in the "spontaneous" Λ transverse polarization, which was observed in unpolarized pp collision. **PRL36, 1113 (1976); PRL41, 607 (1978)**
  - counterpart of the Sivers parton distribution function. chiral-even.
  - can shed light on the spin structure of the Λ, especially about the quark orbital angular momentum, a missing part of the spin puzzle of the nucleon. **PRL105,202001（2010）**
- Unpolarized Di-hadron FF
  - Describes a unpolarized parton fragmenting into two hadrons inclusively
  - Unpolarized baseline for the measurements related to the spin-dependent di-hadron fragmentation functions (Interference FF).
- Large data set at Belle would allow a precise measurement of FFs.

KEKB and Belle Detector



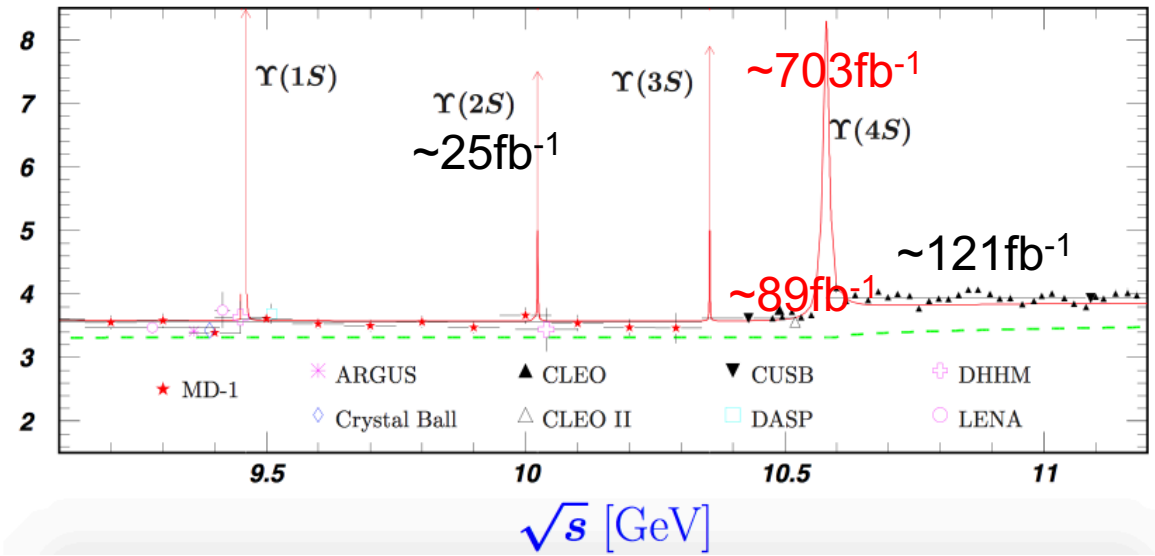
Nucl. Instrum. Meth. A479,117(2002)

KEKB@Tsukuba, Japan

- Easiest process to access FFs (e+e- collider, clean environment).
- Large integrated luminosity!
- Close energy to SIDIS (100 GeV^2 vs 2-3 GeV^2)

Data set

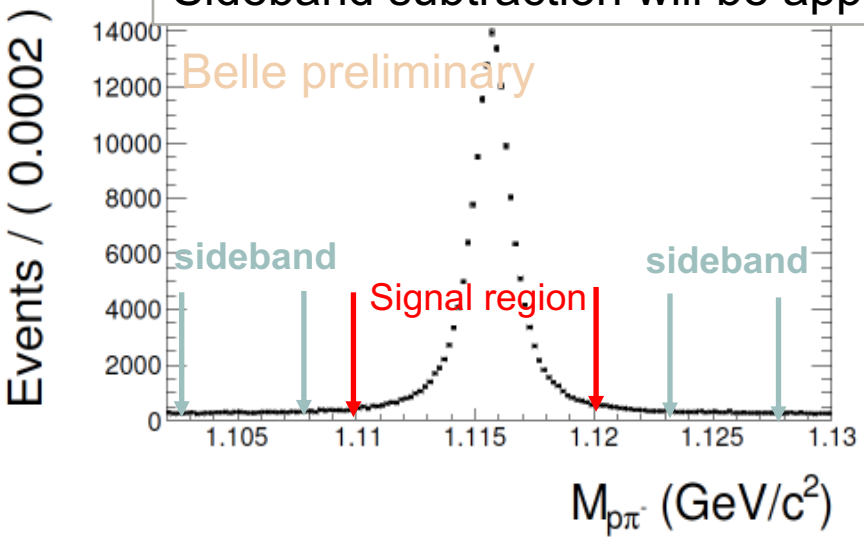
- Data sets: ~792 fb^{-1} at or near $\sqrt{s}$ ~10.58 GeV

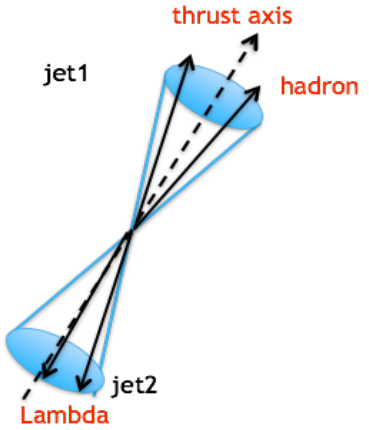


- Thrust>0.8 to select back-to-back event topology and suppress *B* decays to less than 1%.
- Signal process $\Lambda \to p\pi^-(\bar{\Lambda} \to \bar{p}\,\pi^+)$. Clear Λ peak.
- By considering light hadron ($K^{\pm}, \pi^{\pm}$) in the opposite hemisphere, we can emphasize or suppress one kind of flavor which contributes to $\Lambda(\bar{\Lambda})$.

PRL105,202001（2010）

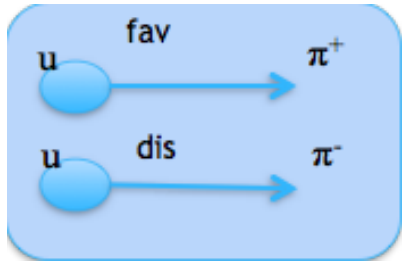
Sideband subtraction will be applied





flavor tag

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

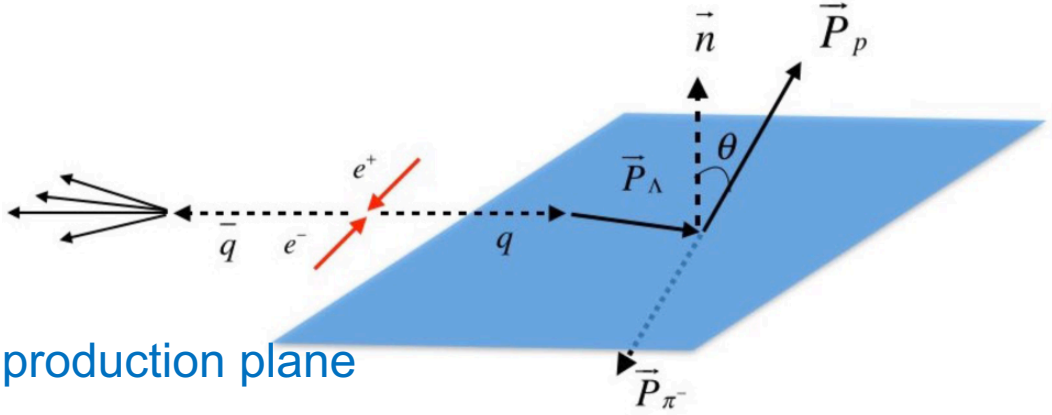


$$T = \mathrm{Max}[\frac{\sum_h |\mathbf{P_h}^{\mathrm{CMS}} \cdot \hat{\mathbf{T}}|}{\sum_h |\mathrm{P_h^{CMS}}|}]$$

Reference frames

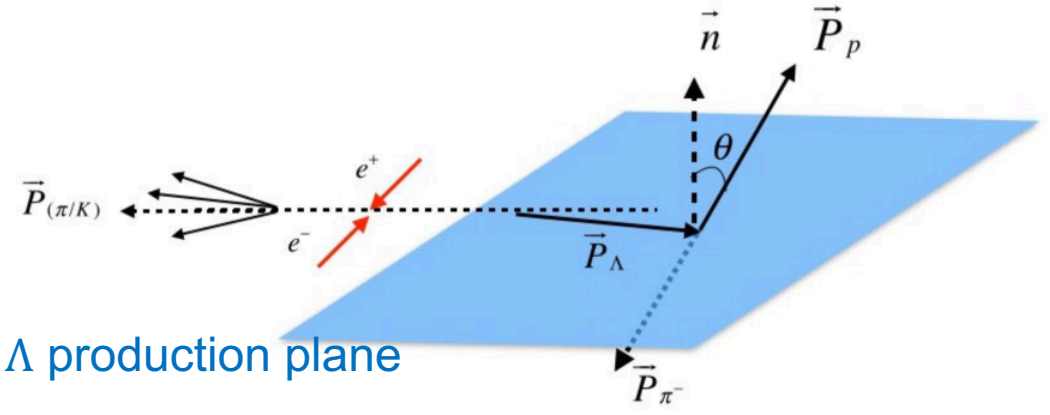
arXiv:1611.06648 BELLE-CONF-1611

Thrust Frame



Λ production plane

Hadron Frame



Λ production plane

- The reference vector $\hat{n}$ is normal to the Λ production plane.
- Give a polarization of *P*, the yield of the events follow:

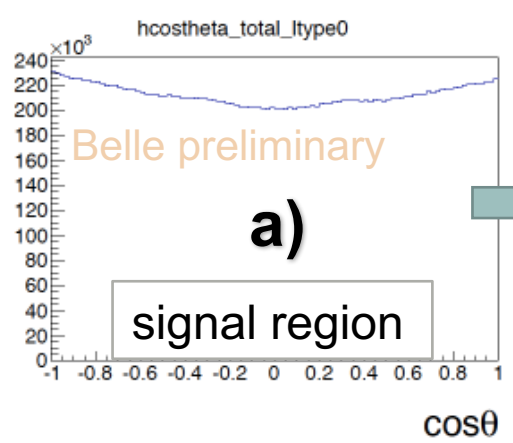
$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta$$

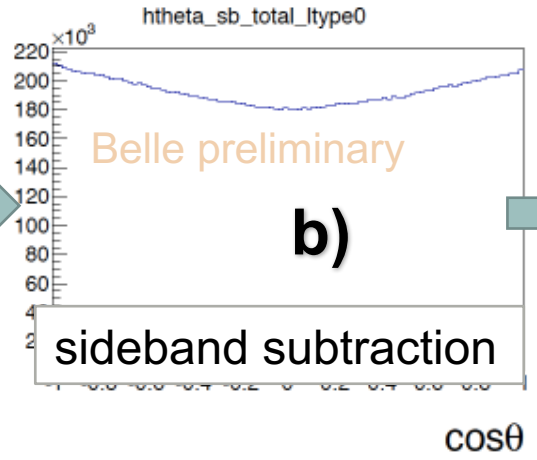
- the α is the decay parameter: α_+=0.642 ± 0.013 for Λ and α_-=-0.71 ± 0.08 for $\bar{\Lambda}$ (PDG).
- Fractional energy $z_\Lambda = 2E_\Lambda/\sqrt{s}$. The p_t is the transverse momentum of Λ relative to thrust axis in thrust frame and to hadron axis in hadron frame.

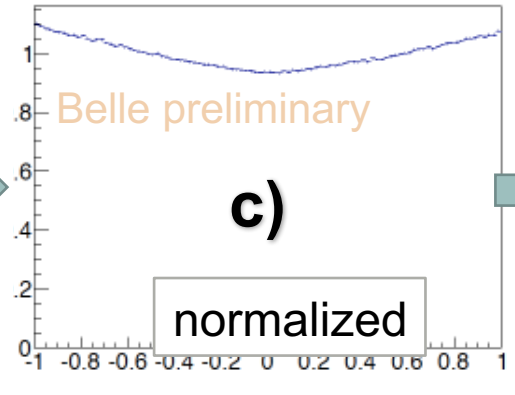
kinematic variables

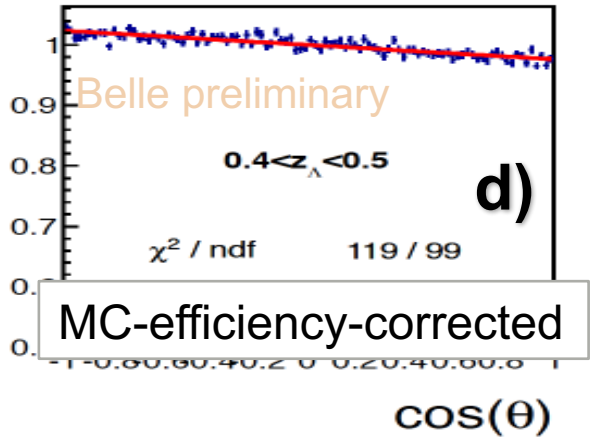
$\Lambda + X$	thrust frame	
variables	z_Λ , p_t	
$\Lambda + h + X$	thrust frame	hadron frame
variables	z_Λ, z_h, p_t	z_Λ, z_h, p_t

Analysis flow

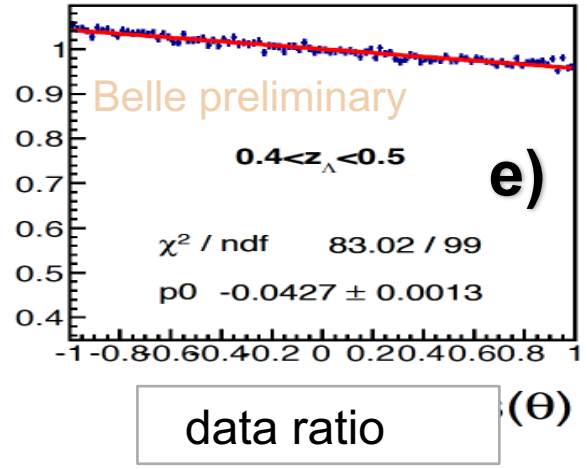






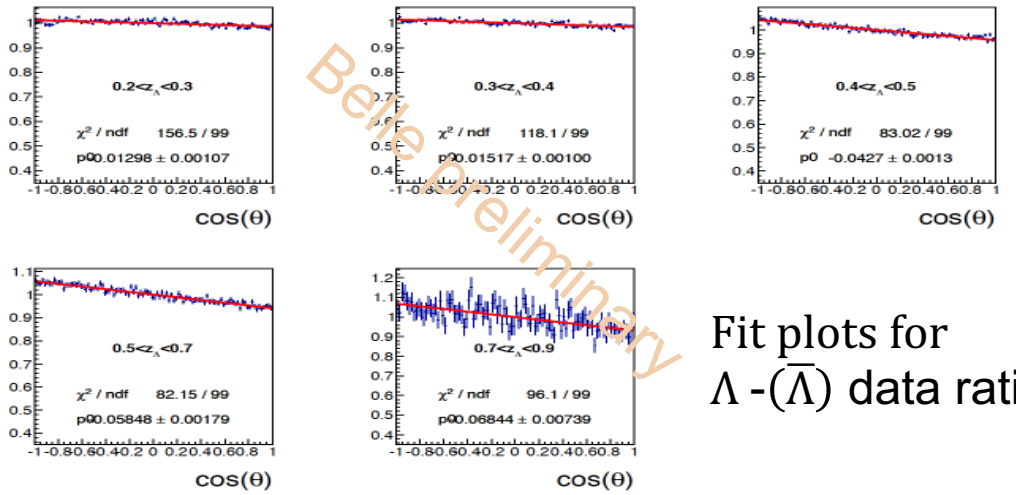


- Cosθ distribution in Λ signal region **a)** is corrected by sideband subtraction→ **b)**
- Normalized by itself, as shown in **c).**
- The shape **c)** is divided by the corresponding shape from MC, so that we obtain the efficiency-corrected curve **d)**.
- Or **c)** shape of Λ events is divided by that from anti-Λ events if we assume efficiency is independent on charge, that is **e),** this is called data ratios.
- We fit **d)** and **e)** to get the polarization of interest.

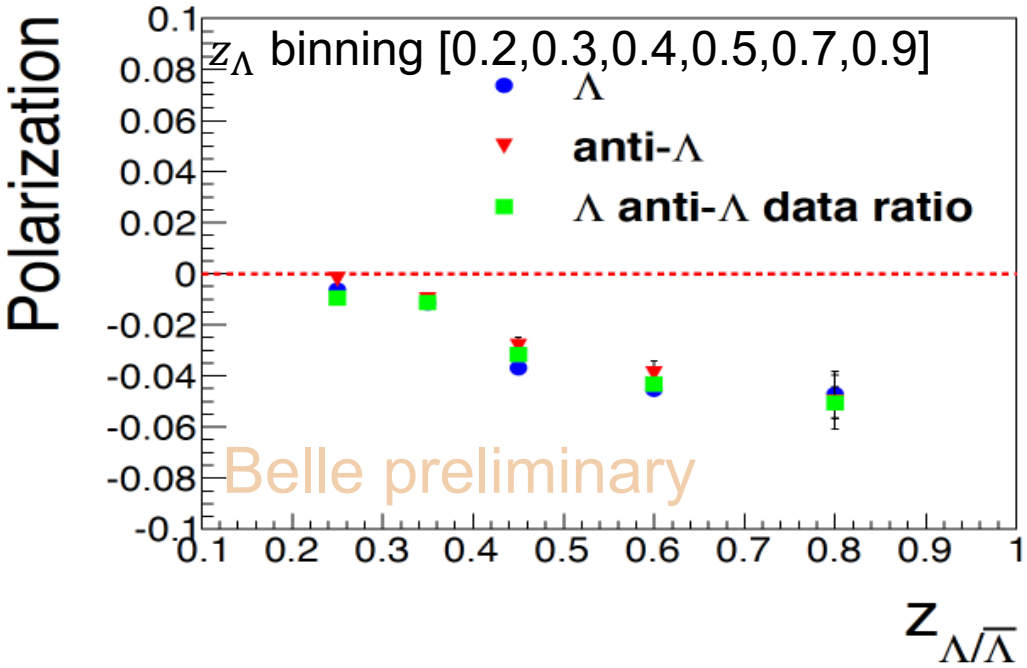


Extract polarization

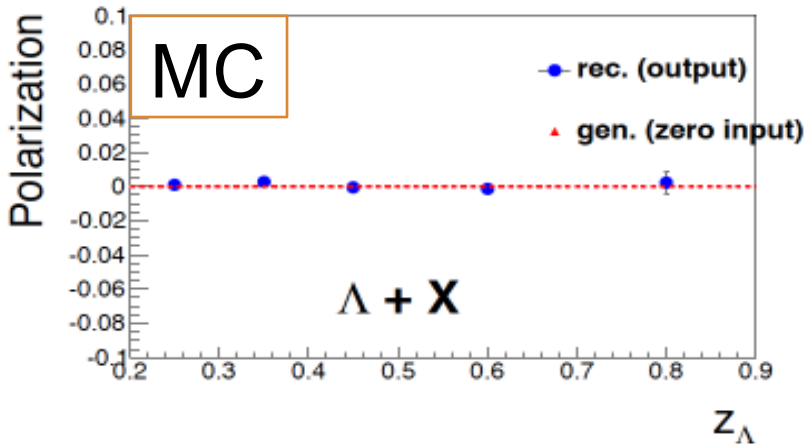
- Fit to the cosθ distributions with the simple function $1 + p_0 cos\theta$.
- The polarization of interest: p_0/α.
- In the data ratio, polarization is obtained via $p_0/(\alpha_+ - \alpha_-)$.
- In data ratios, the slope on the cosθ distributions are about two times larger than that in MC-corrected 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 was seen, the magnitude rises from zero to about ~5% with growing fraction energy $z_\Lambda = 2E_\Lambda/\sqrt{s}$.



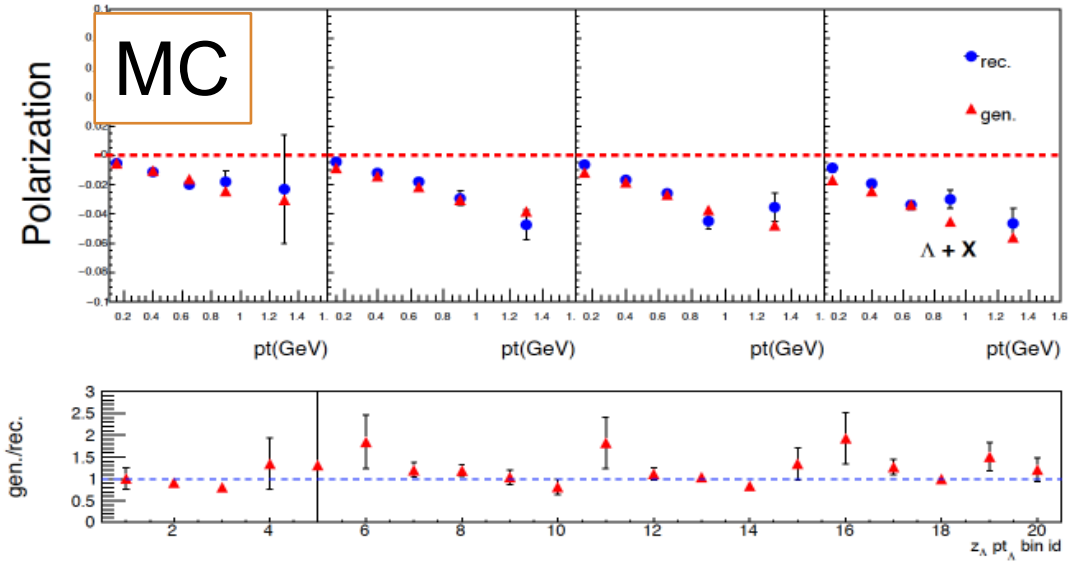
Fit plots for Λ -($\overline{\Lambda}$) data ratio.

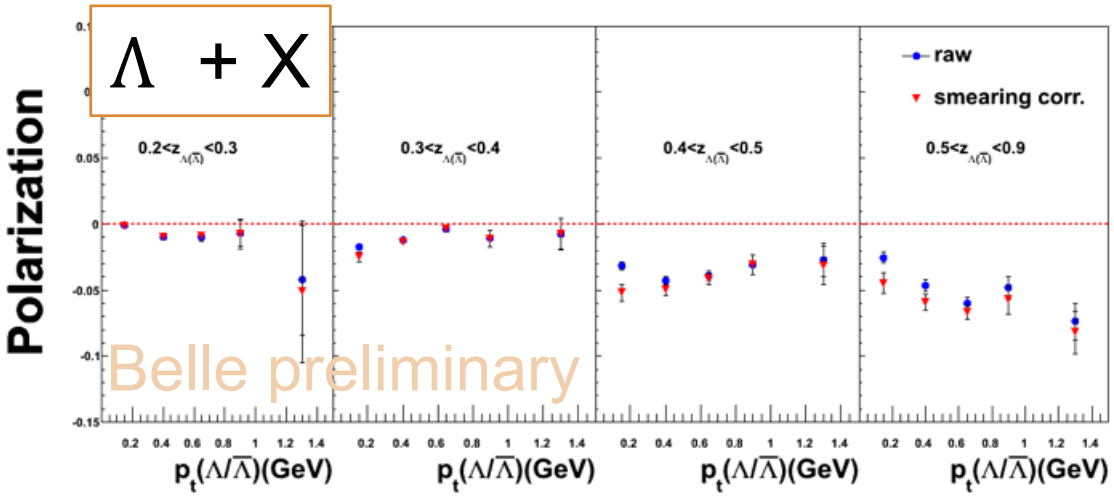


MC validation & Smearing correction



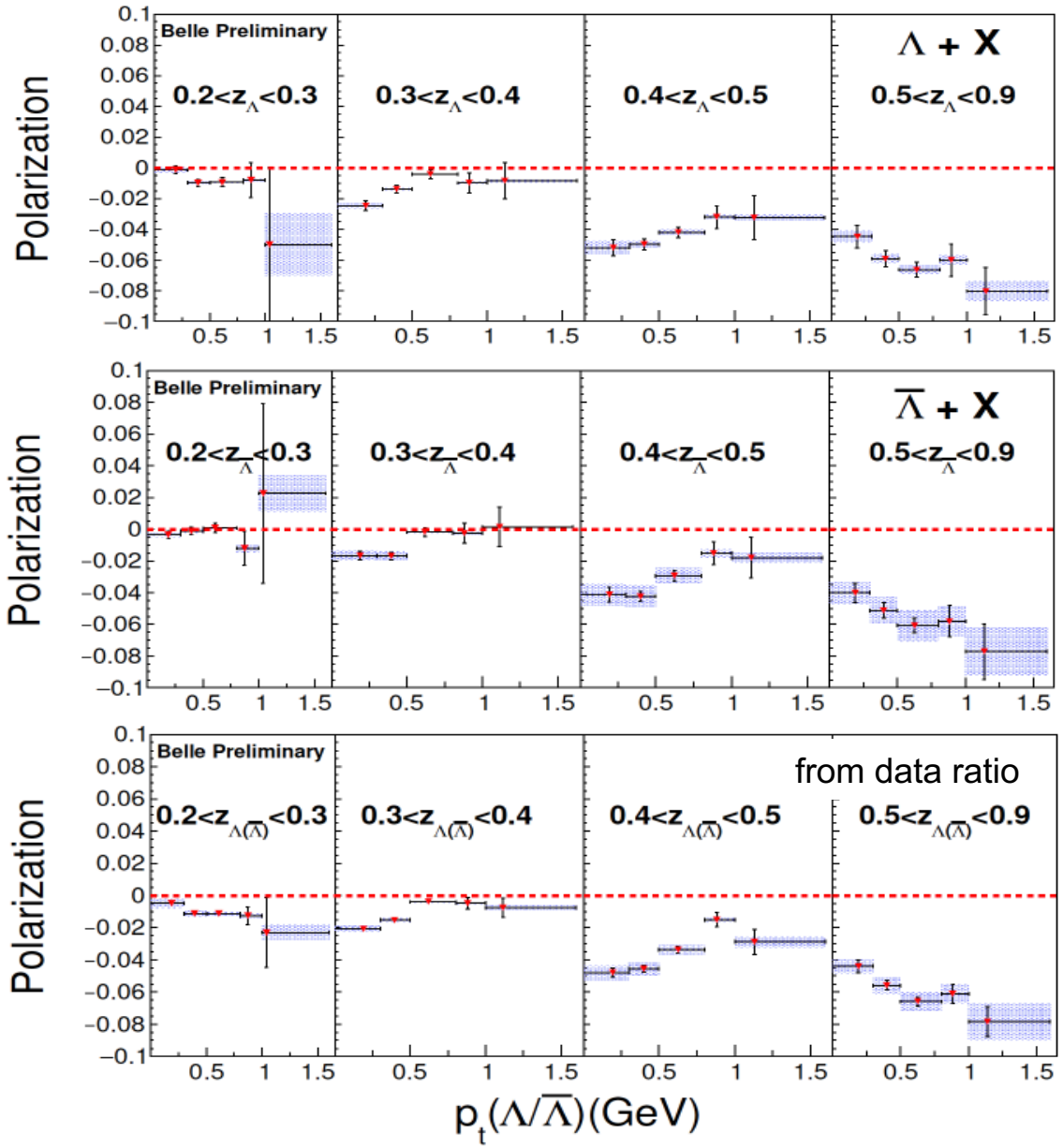
- Zero polarization is observed in MC, as expected.
- Smearing effects caused by the detector acceptance and resolution are estimated using the weighted-MC with nonzero polarization input.
- In thrust frame, the polarization is found underestimated in reconstruction, correction factors ranges 1.0-1.3 depends on the [z,p_t].
- In hadron frame, the polarization observed in reconstruction is consistent with input. No need for correction.





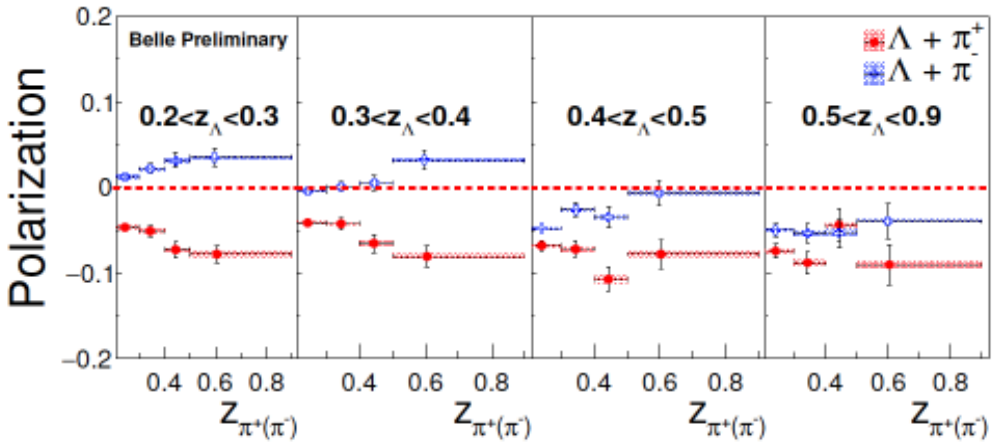
arXiv:1611.06648

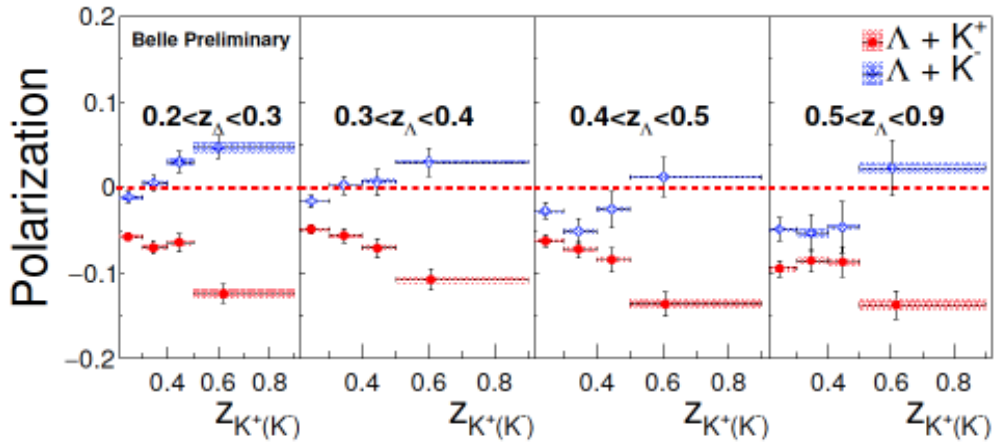
Results in thrust frame vs. (z,p_t)

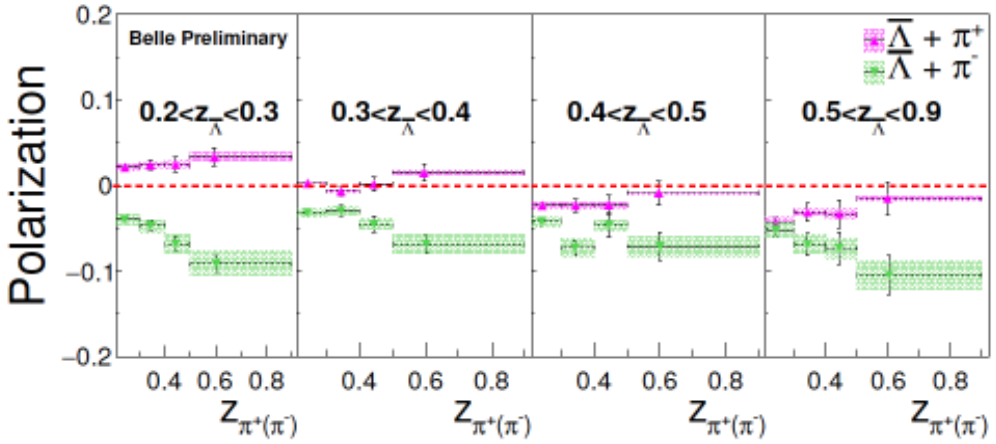


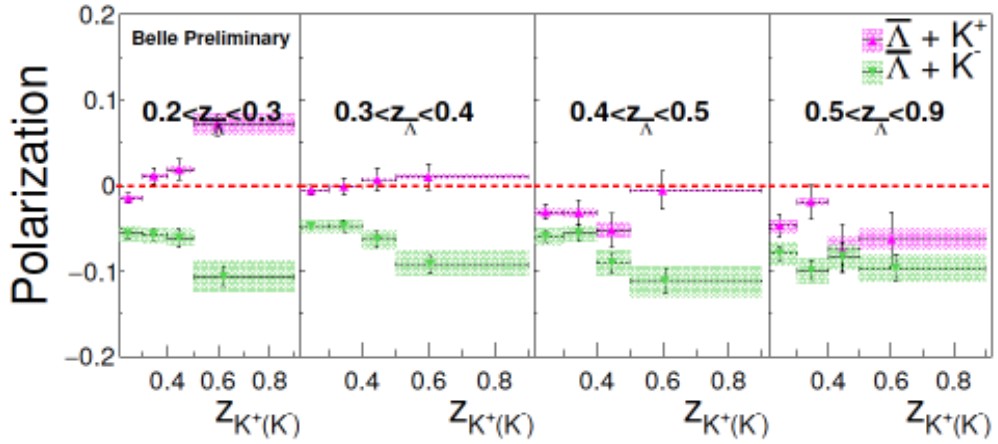
- Four z bins and five p_t bins are applied: z_Λ=[0.2,0.3,0.4,0.5,0.9]; p_t=[0.0,0.3,0.5,0.8,1.0,1.6] GeV
- Nonzero polarization was observed. Interesting shape as a function of (z_Λ, p_t).
- The polarization rise with higher p_t in the lowest z_Λ and highest z_Λ bin. But decreases and reverses around 1 GeV in the intermediate z_Λ bins.
- Results are consistent between Λ and ($\bar{\Lambda}$) and Λ -($\bar{\Lambda}$) data ratio.
- Error bars are statistical uncertainties and shaded areas show the systematic uncertainties.

Results in thrust frame vs. (z_Λ, z_h)



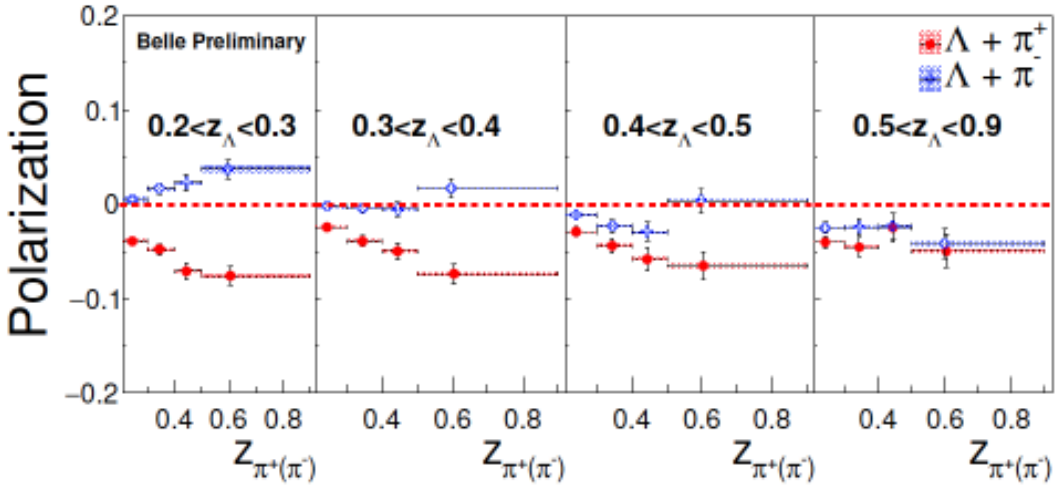


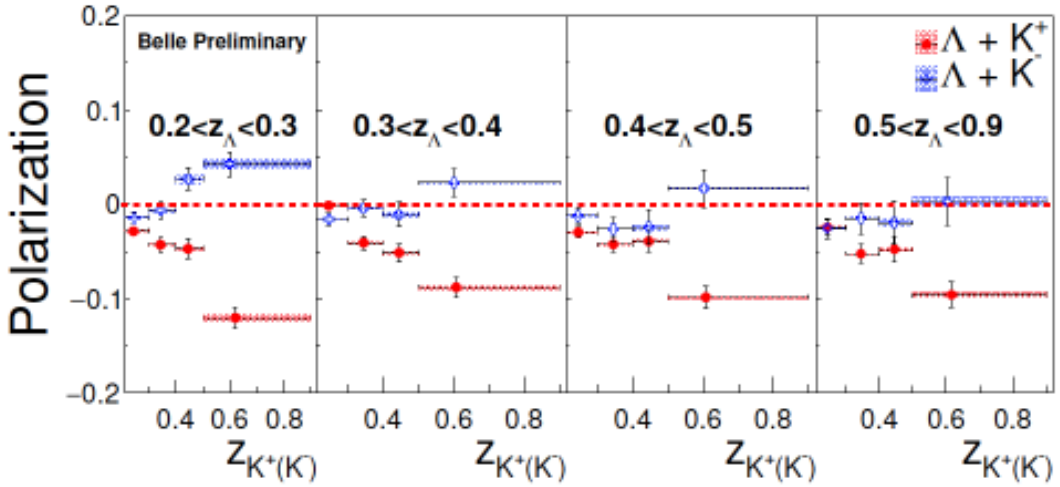


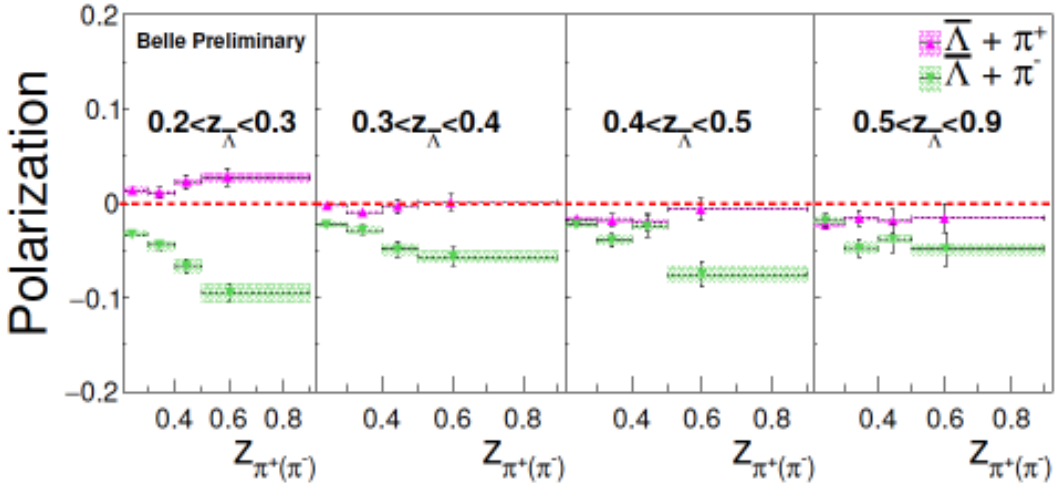


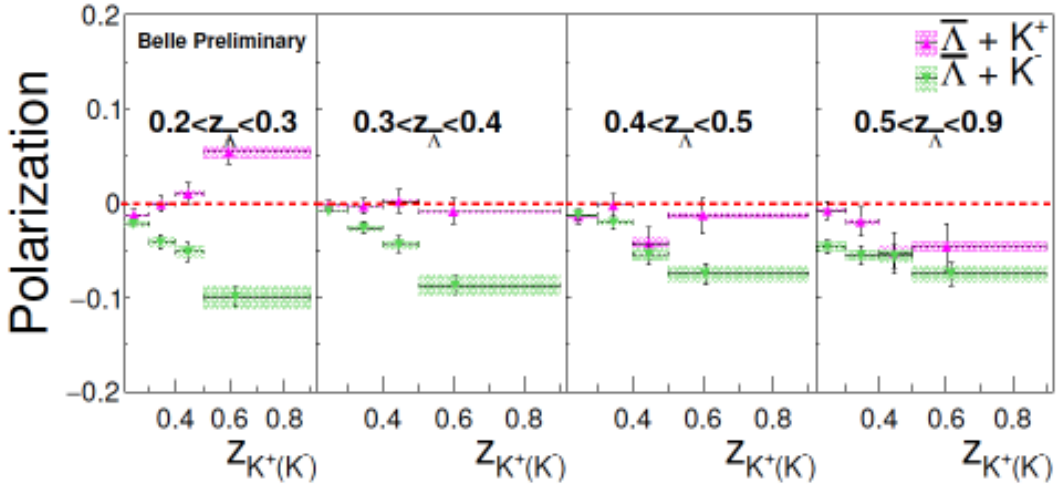
- In $\Lambda + h^+$, polarization keeps negative, the magnitude increases with higher z_h.
- In $\Lambda + h^-$, at low z_Λ, polarization is positive, at high z_Λ, polarization is negative.

Results in hadron frame vs. (z_Λ, z_h)



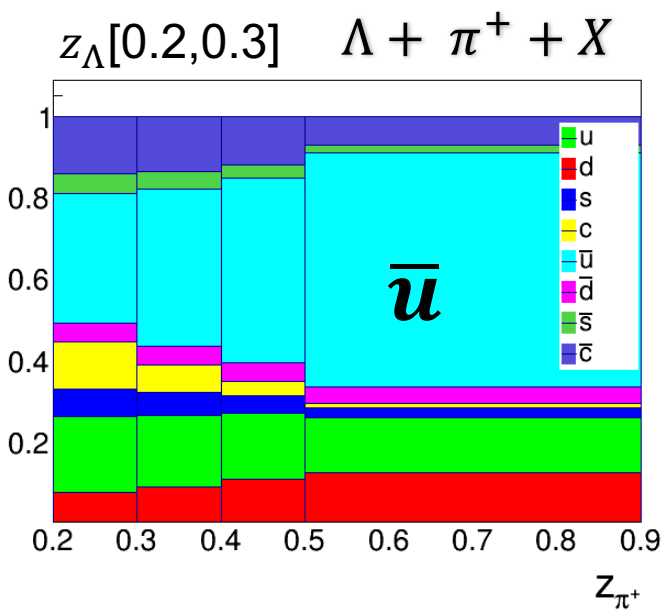


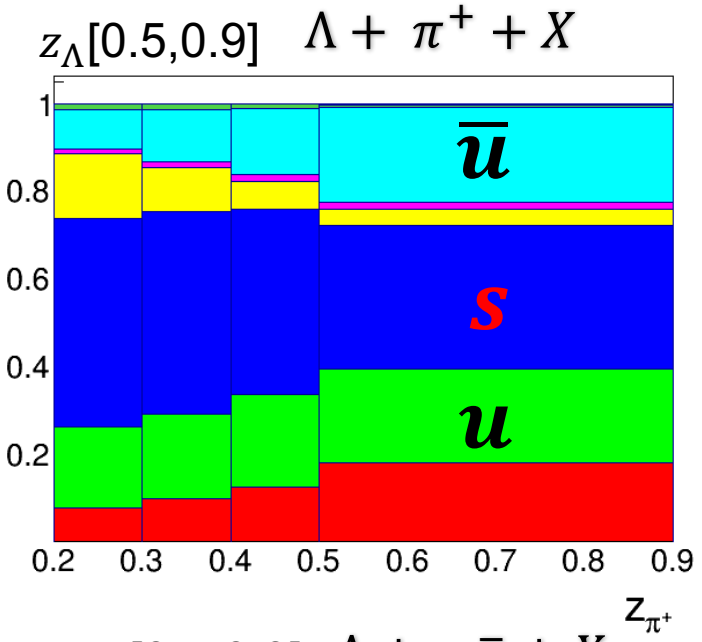


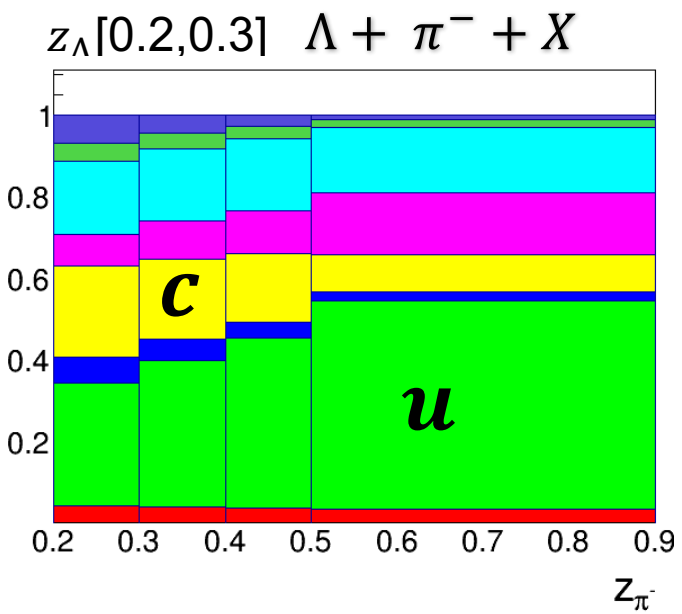


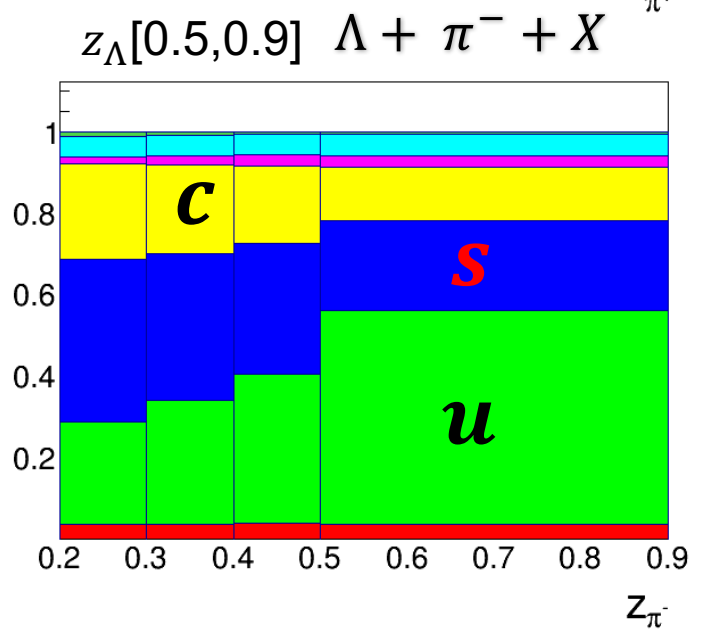
- Similar results with that in the thrust frame.
- Results from charge-conjugate modes are consistent with each other.

Quark flavor tag by the light hadron









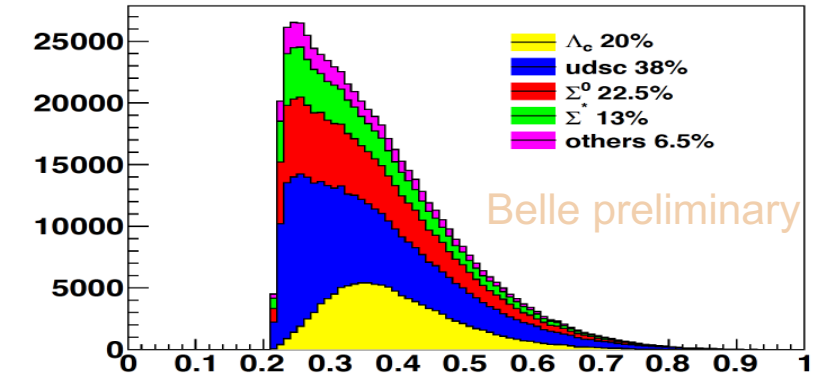
- An attempt to look at the flavor tag effect of the light hadron, based on MC. (Pythia6.2)
- The fractions of various quark flavors going to the Λ's hemisphere are shown in different $[z_\Lambda\ z_h]$ region.
- MC indicates that the tag of the quark flavors is more effective at low z_Λ and high z_h.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

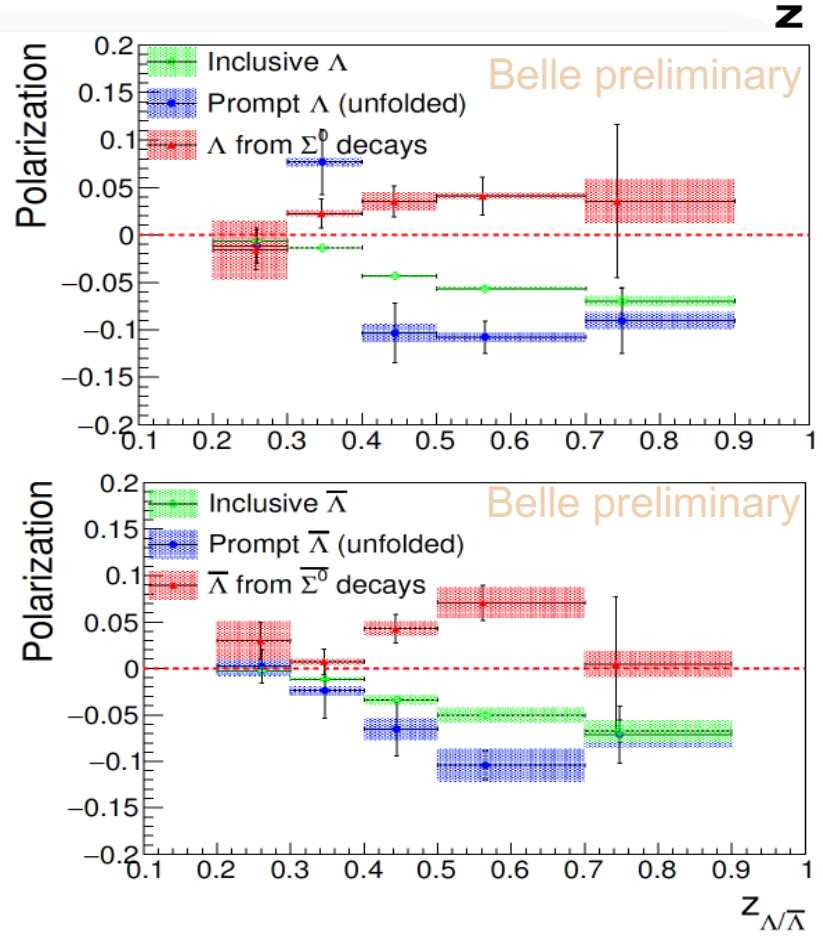
Background unfolding

- 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:

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

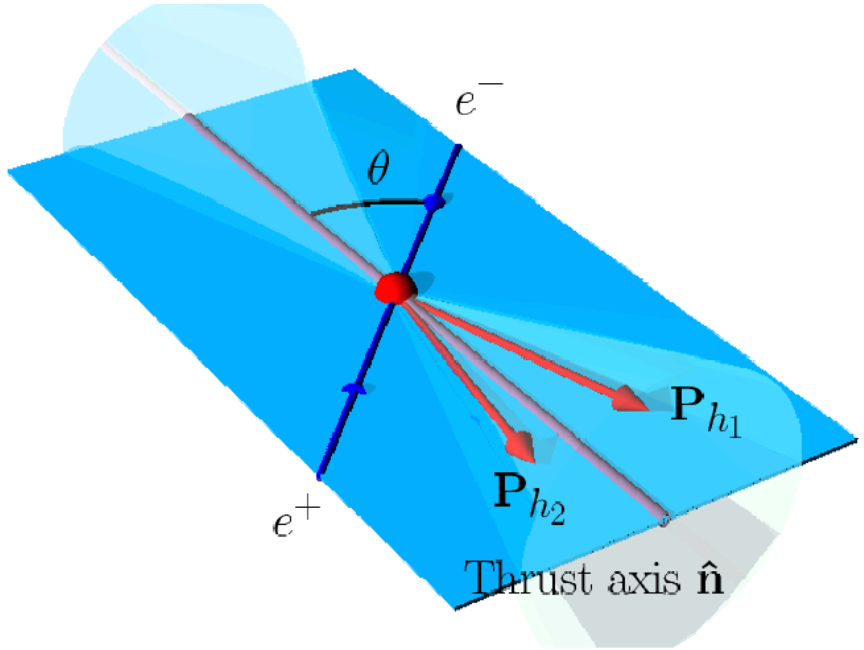
- F_i is the fraction of feed-down component i, estimated from MC. P_i is polarization of component i.
- Polarization of Λ from Σ^0 decays is found has opposite sign with that of inclusive Λ. Phys. Rev. 109, 610 (1958); Phys.Lett.B303,350(1993)





Di-hadrons FF

Phy. Rev. D 92 092007 (2015)
arXiv:1706.08348, accepted by Phy. Rev. D



$$\frac{\mathrm{d}^2\sigma(e^+e^- \to h_1h_2X)}{\mathrm{d}z\mathrm{d}m_{h_1h_2}} \propto$$

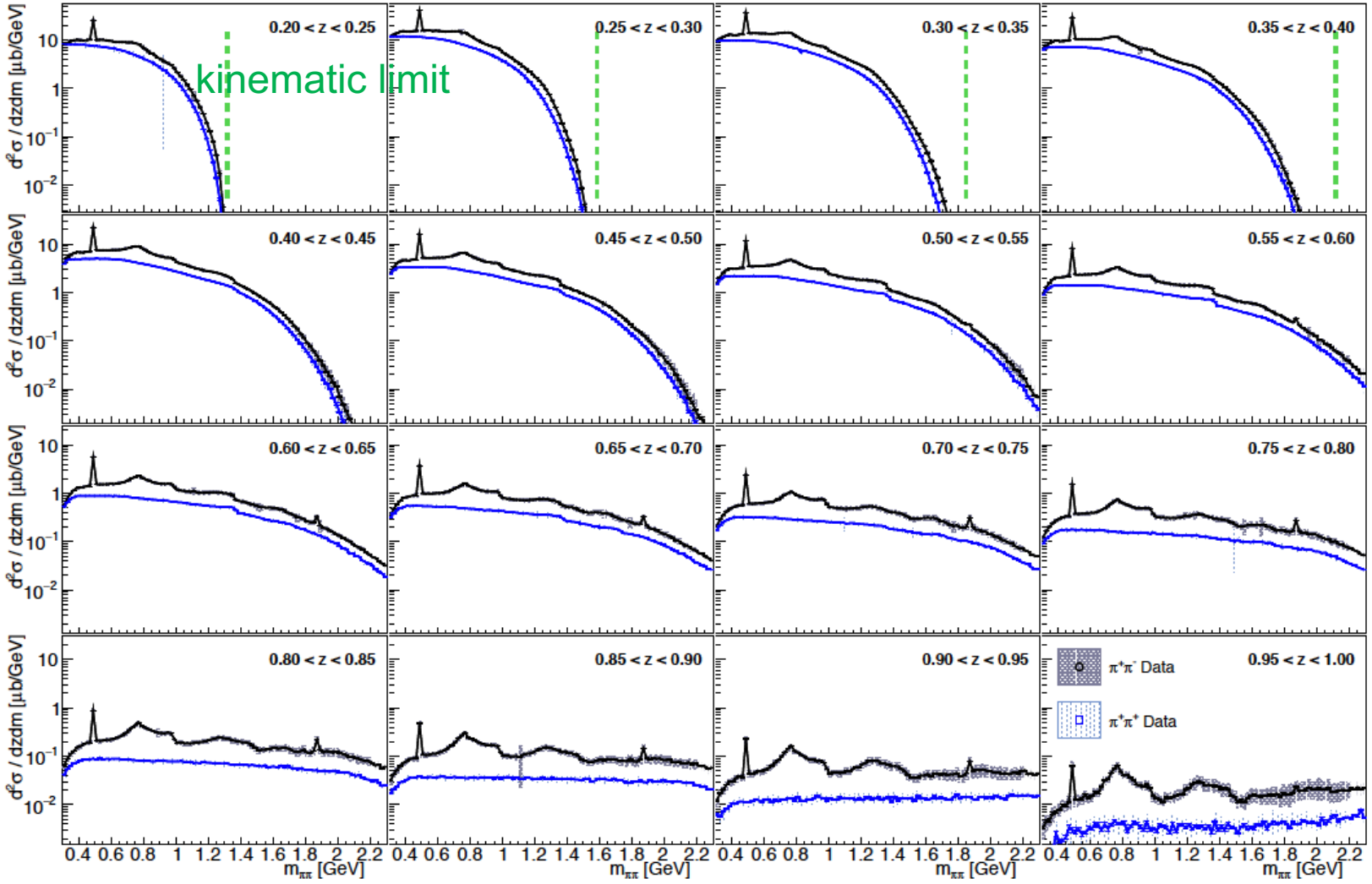
$$\sum_q e_q^2 \left(D_{1,q}^{h_1h_2}(z, m_{h_1h_2}) + D_{1,\bar{q}}^{h_1h_2}(z, m_{h_1h_2}) \right)$$

$$z = 2E_{h_1h_2}/\sqrt{s}$$

- Belle data sample 655 fb^{-1} (Υ(4S) peak) + 89 fb^{-1} ~60 MeV below (continuum) for comparison.
- Charged light hadron ($\pi^{\pm}$, K$^{\pm}$) pair, they are required to be in same hemisphere as defined by the thrust event-shape variable and its axis.
- Cross sections as a function of the total fractional energy z and invariant mass $m_{h_1h_2}$
- Various corrections: PID, momentum smearing, background, acceptance correction, and ISR correction
- Results with weak-decays-rmoved are also studied.

$\pi^+\pi^-$, $\pi^+\pi^+$ cross section

arXiv 1702.08348, accepted by Phy. Rev. D

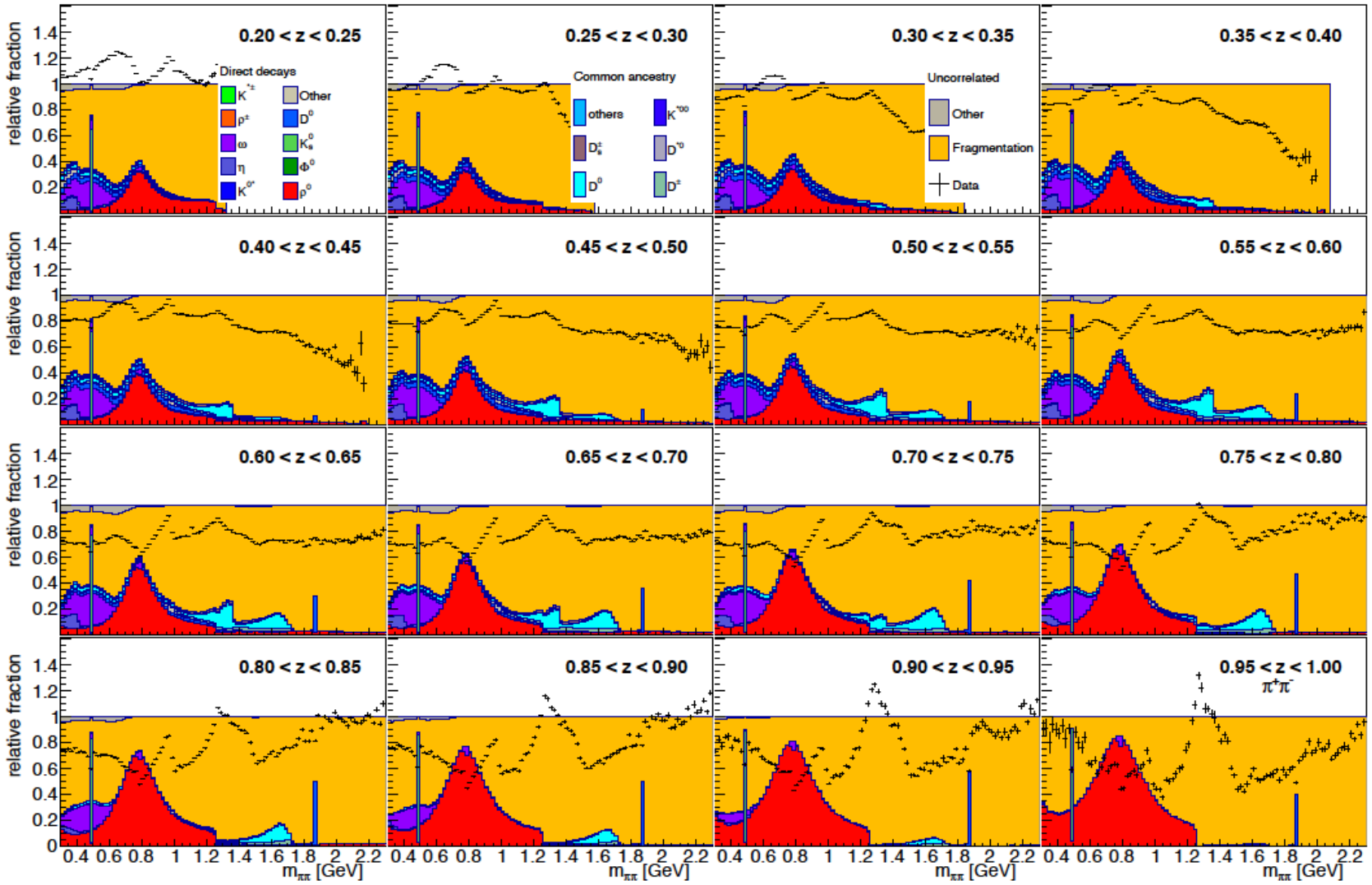


- Resonances seen are K_S^0, ρ^0, $f_0(980)$ and Cabibbo-suppressed D^0 decays. Below ρ^0 there are partially reconstructed ω, η
- Enhancements at ~1.35 GeV and 1.6 GeV can be identified as multi-body or indirect decay products of D mesons.
- Same-sign pion pairs generally display a continuous distribution with a slight enhancement at ~1.35GeV, caused by decay products of D mesons.

error boxes represent the systematic uncertainties

$\pi^+\pi^-$ MC decomposition

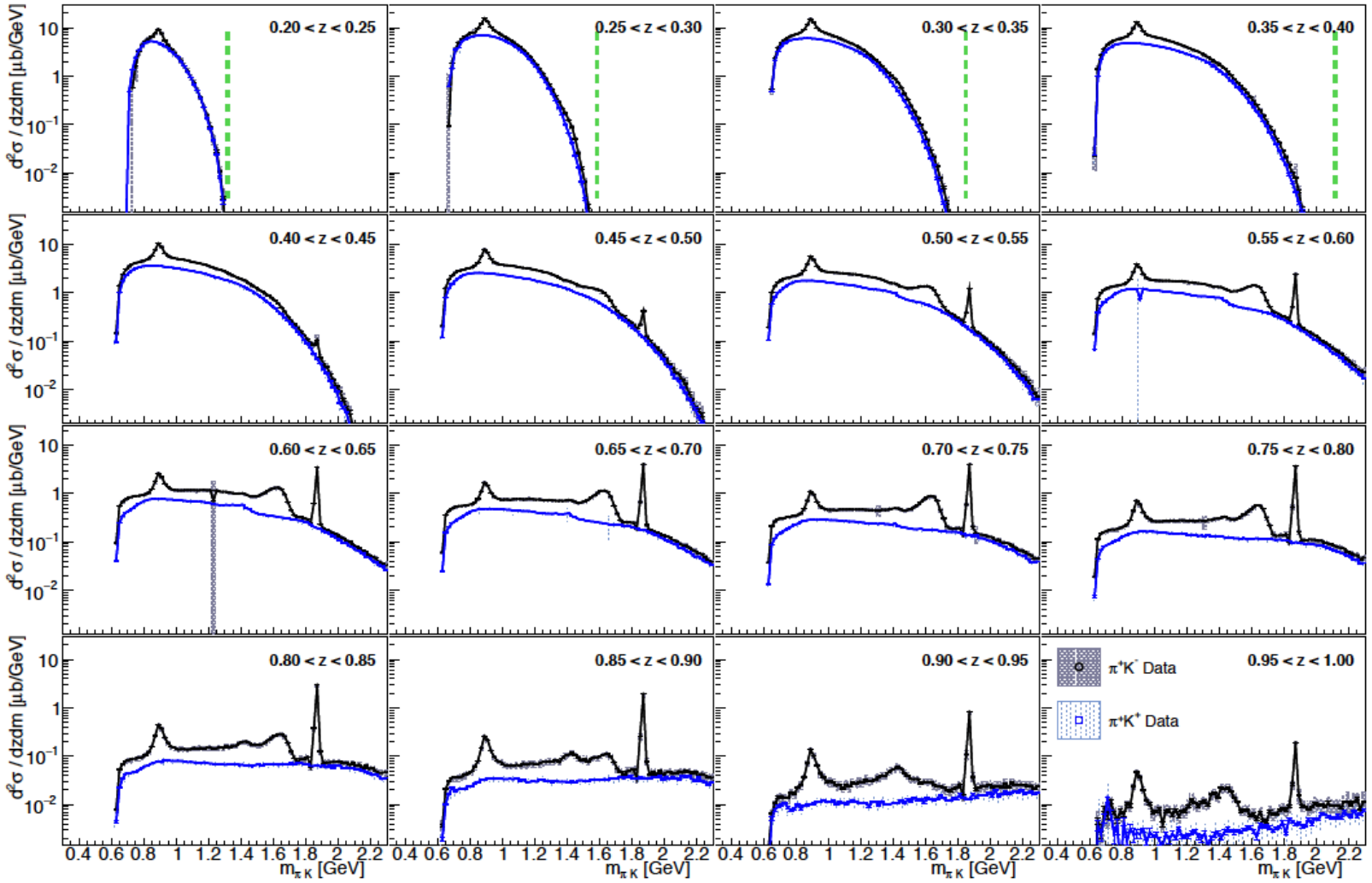
arXiv 1702.08348, accepted by Phy. Rev. D



- A substantial fraction of pion pairs have no common ancestor: they originate directly from the fragmentation chain.
- See clearly several of direct two- or three-body decays such as K_S^0, ρ^0, D^0, η etc., and pions from different steps in D mesons.
- Cross sections after weak decays removal are also shown in the paper: arXiv 1702.08348.

π^+K^-, π^+K^+ cross section

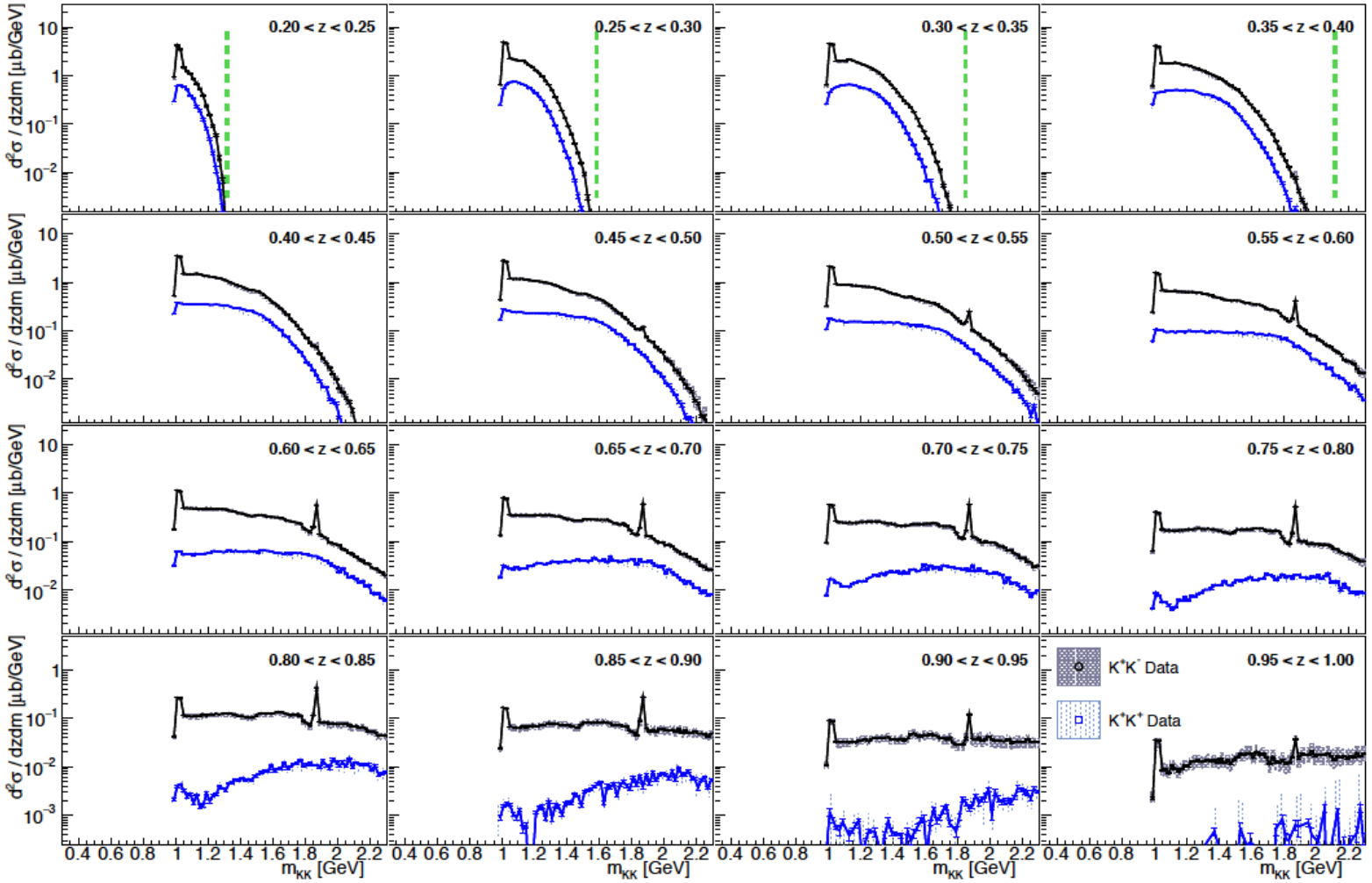
arXiv 1702.08348, accepted by Phy. Rev. D



- The corresponding K^* resonance and the Cabibbo-favored D^0 meson decay are very clearly visible.
- The enhancement at 1.6GeV is predominantly caused by D meson decays.
- The same-sign pion-kaon pairs again show a predominately smooth distribution from direct fragmentation.

K^+K^-, K^+K^+ cross section

arXiv 1702.08348, accepted by Phy. Rev. D



- The ϕ and the Cabibbo-suppressed D^0 meson decay are clearly visible.
- Some enhancements around the D^0 mass can be assigned to D mesons decays
- Same-sign kaon pair cross section is mostly a smooth function of the invariant mass and is increasingly suppressed with z.
- Small enhancement close to mass threshold is related to D^0 decays into a kaon and another hadron, which can further decays into more kaons.

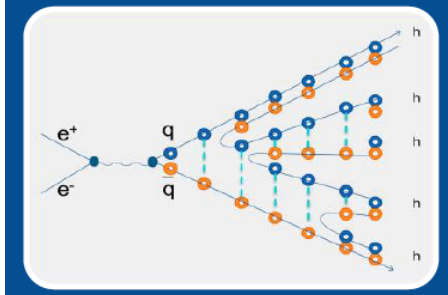
Summary

- The study on the transverse polarization of $\Lambda(\bar{\Lambda})$ in the inclusive process $e^+ e^- \rightarrow \Lambda(\bar{\Lambda}) + X$ and $e^+ e^- \rightarrow \Lambda(\bar{\Lambda}) + K^{\pm}(\pi^{\pm}) + X$ is performed at Belle. arXiv:1611.06648 BELLE-CONF-1611
  - Nonzero transverse polarizations of $\Lambda(\bar{\Lambda})$ is observed for the first time at $e^+ e^-$ annihilation. Its magnitude as a function of z_{Λ} and p_{t} was presented.
  - By selecting identified light hadrons ($K^{\pm}, \pi^{\pm}$) in the opposite hemisphere we also obtain sensitivity to the flavor dependence.
- Di-hadron ($e^+ e^- \rightarrow \mathrm{h_1 h_2} + X$) mass dependent cross sections were measured at Belle arXiv:1706.08348, accepted by Phy. Rev. D
  - provides the very important input for the measurements related to the spin-dependent di-hadron fragmentation functions.

Thank you!

Backup slides

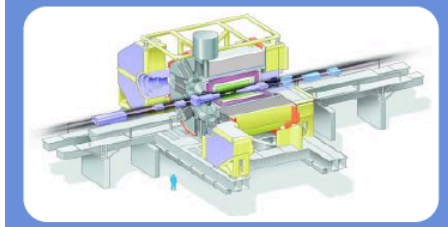
What are fragmentation functions?



How do quasi-free partons fragment into confined hadrons ?

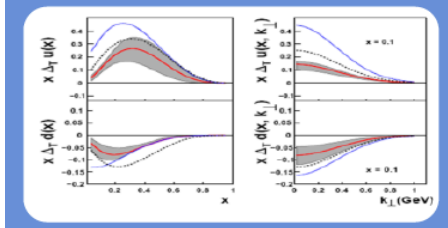
- Does spin play a role ? Flavor dependence?
- What about transverse momentum (and its Evolution) ?

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 :

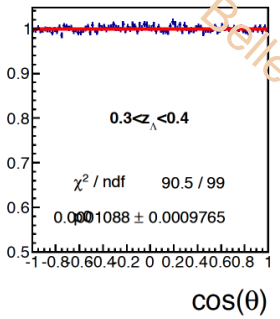


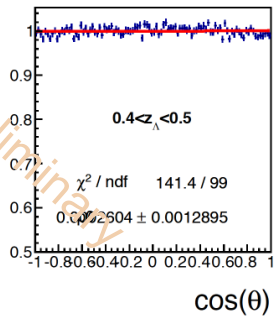
- Pol FFs necessary input to transverse spin SIDIS und pp measurements to extract Transversity distributions function
- Flavor separation of all Parton distribution functions (PDFs) via FFs (including unpolarized PDFs)
- Baseline for any Heavy Ion measurement
- Access to exotics?

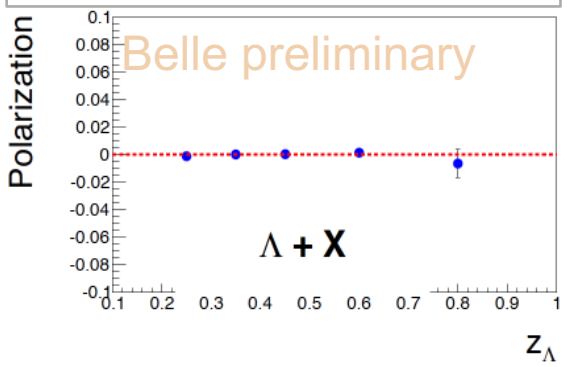
Credit:
Ralf. Seidl

Systematics

Build fake angle θ

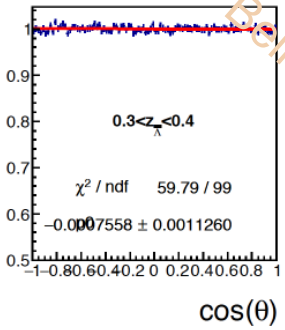


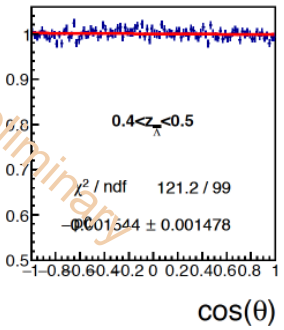


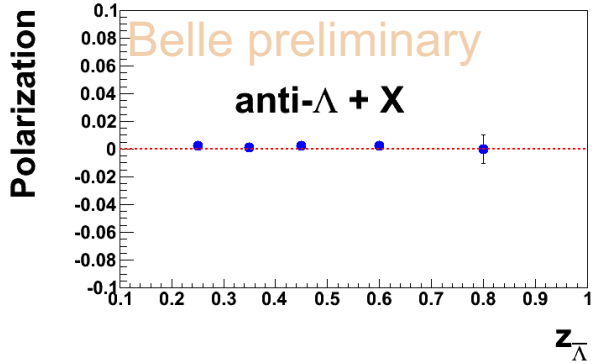


- Change the reference vector $\hat{n}$ to be in the Λ production plane. But still normal to $\vec{p}_{\Lambda}$.

Mixed events

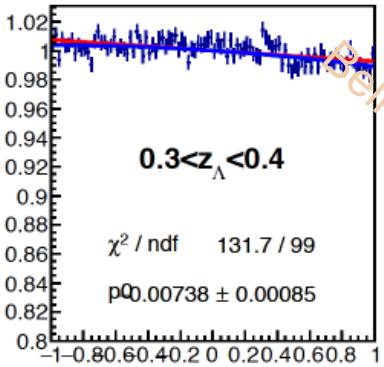


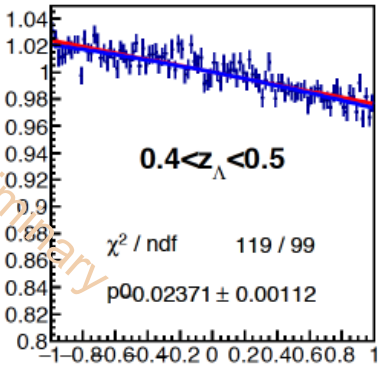




- Combine a proton in one event and pion in the other event to form a false Λ.

Vary the fit function



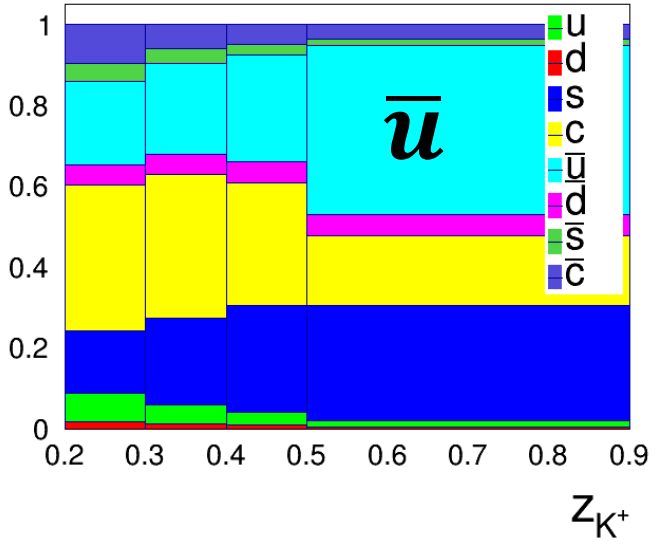


- The second order term was added in the fit function $1 + p_0 cos\theta + p_1 \, cos^2\theta$

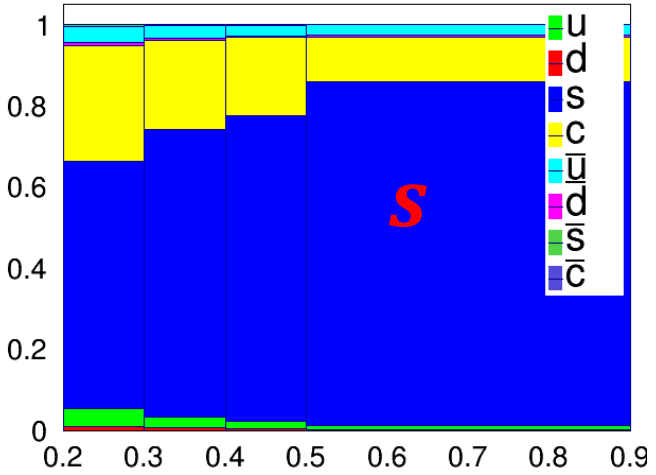
- Besides, uncertainties from smearing correction factors and sideband subtractions are included in systematics errors.
- Uncertainties of decay parameters are assigned as systematic errors.

Quark flavor tag by the Kaon

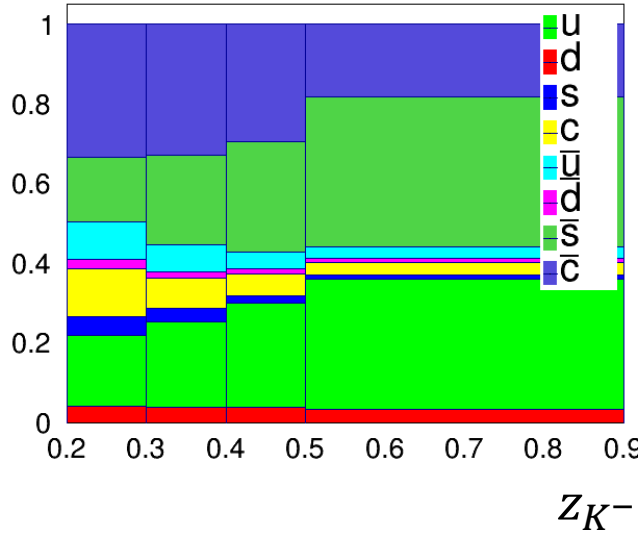
z_Λ[0.2,0.3] $\Lambda + K^+ + X$



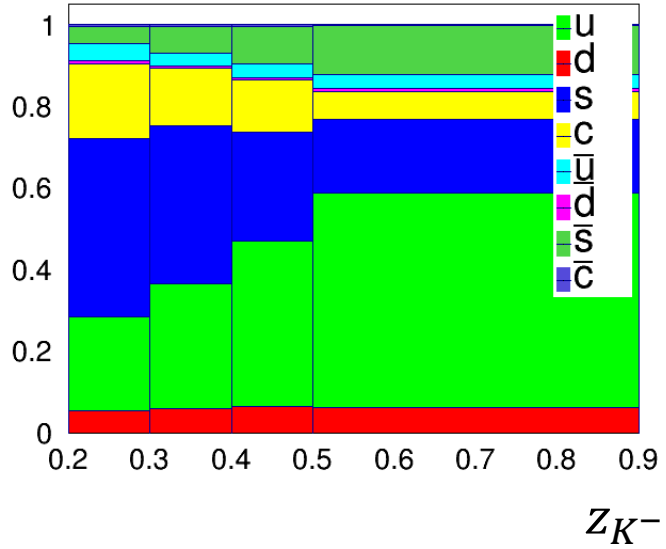
z_Λ[0.5,0.9] $\Lambda + K^+ + X$



z_Λ[0.2,0.3] $\Lambda + K^- + X$

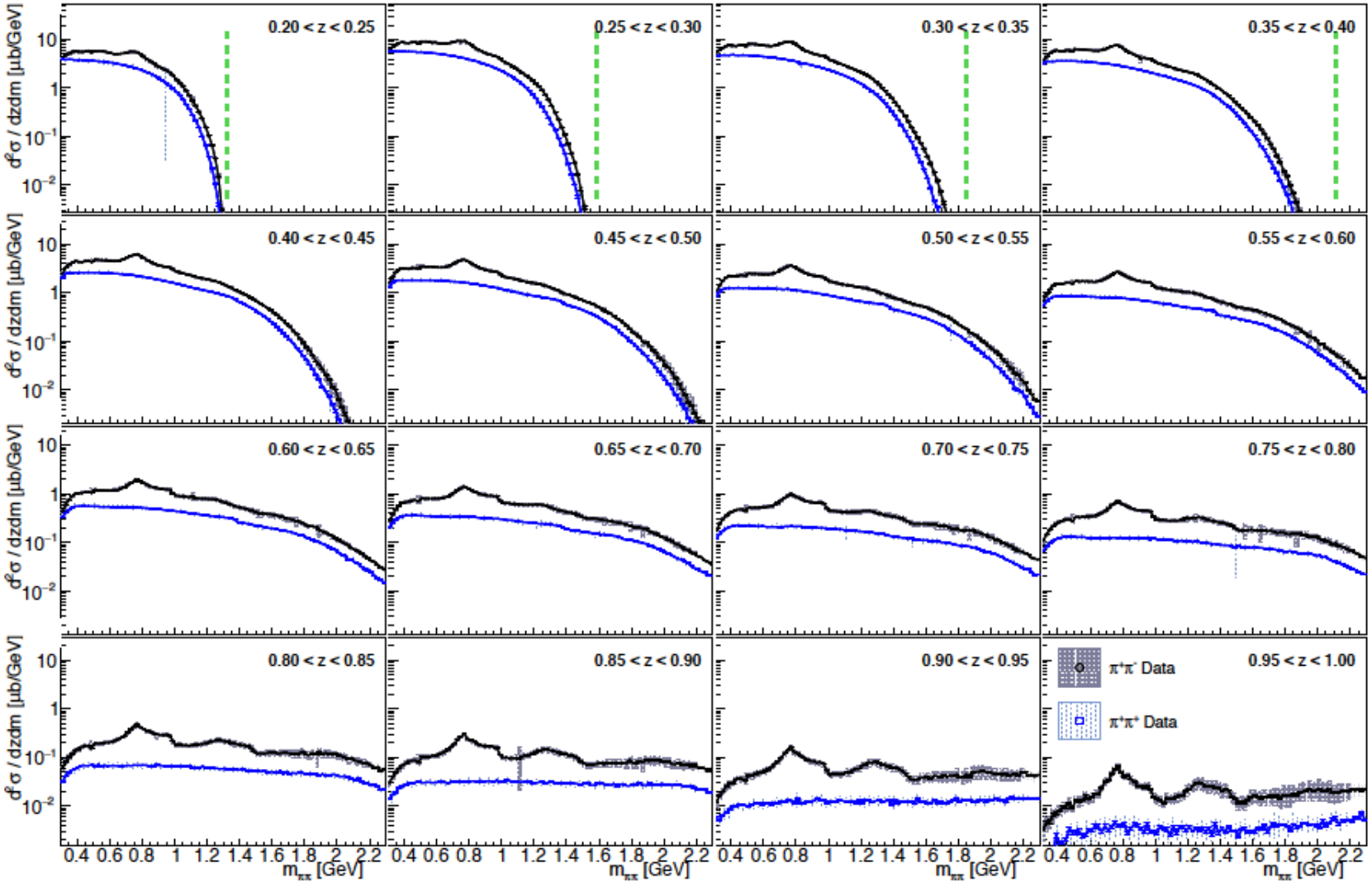


z_Λ[0.5,0.9] $\Lambda + K^- + X$



$\pi^+\pi^-$, $\pi^+\pi^+$ weak-decay-removed

arXiv 1702.08348, accepted by Phy. Rev. D



π^+K^-, π^+K^+ weak-decay-removed

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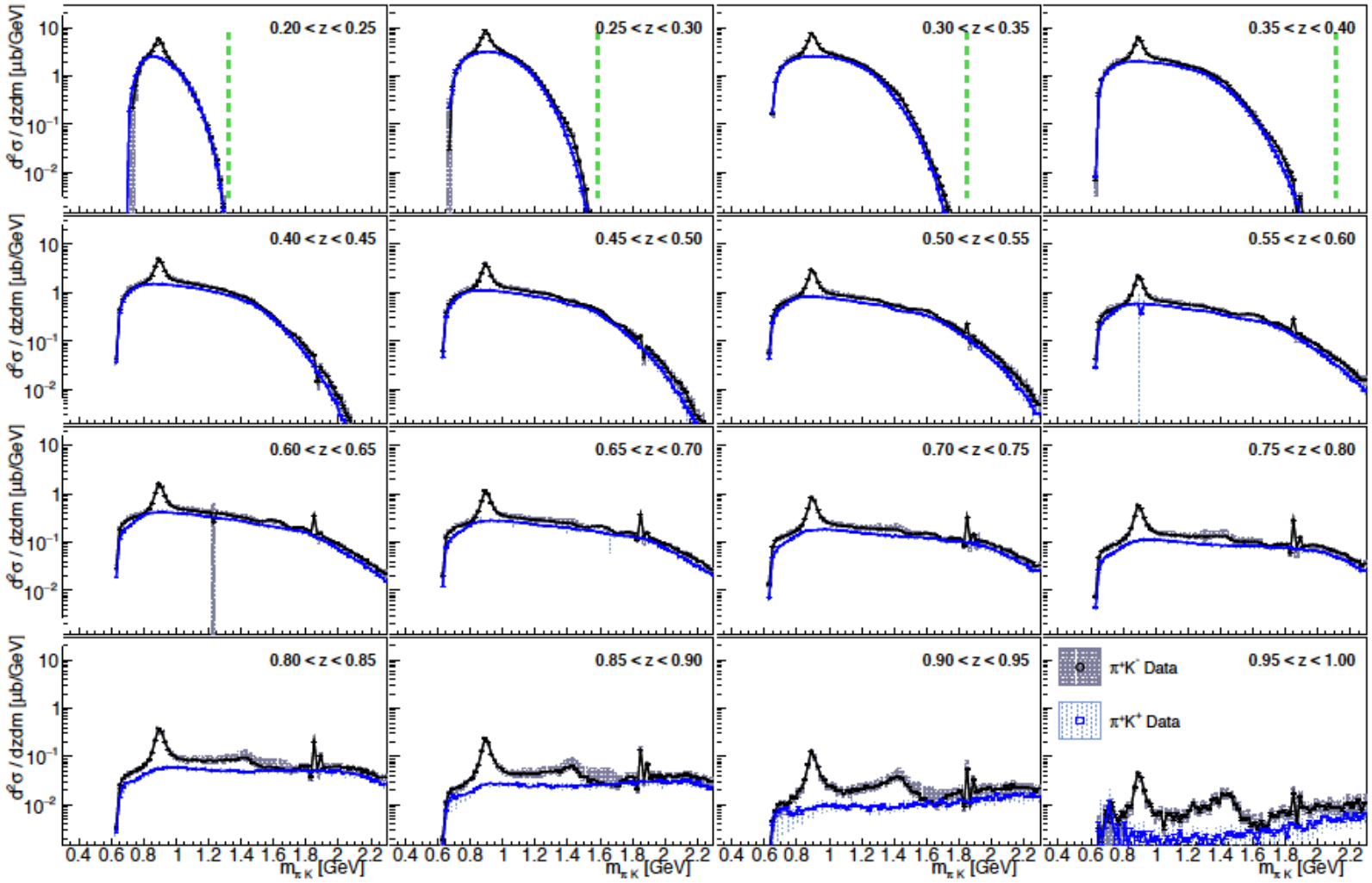

K^+K^-, K^+K^+ weak-decay-removed

arXiv 1702.08348, accepted by Phy. Rev. D