Transverse polarization of $\Lambda(\bar{\Lambda})$ at Belle and Belle II experiment

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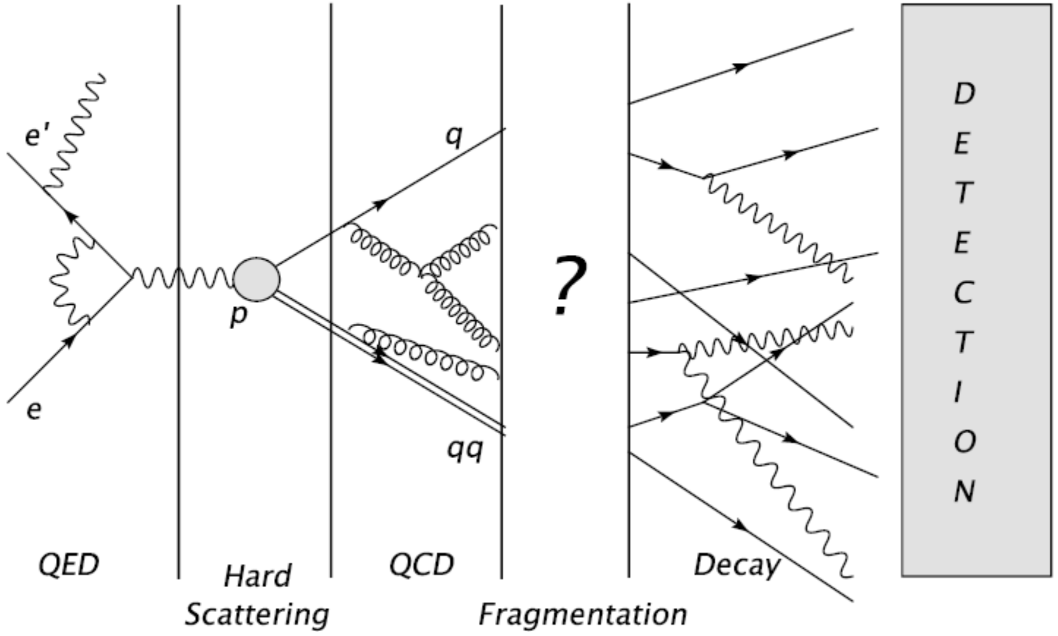
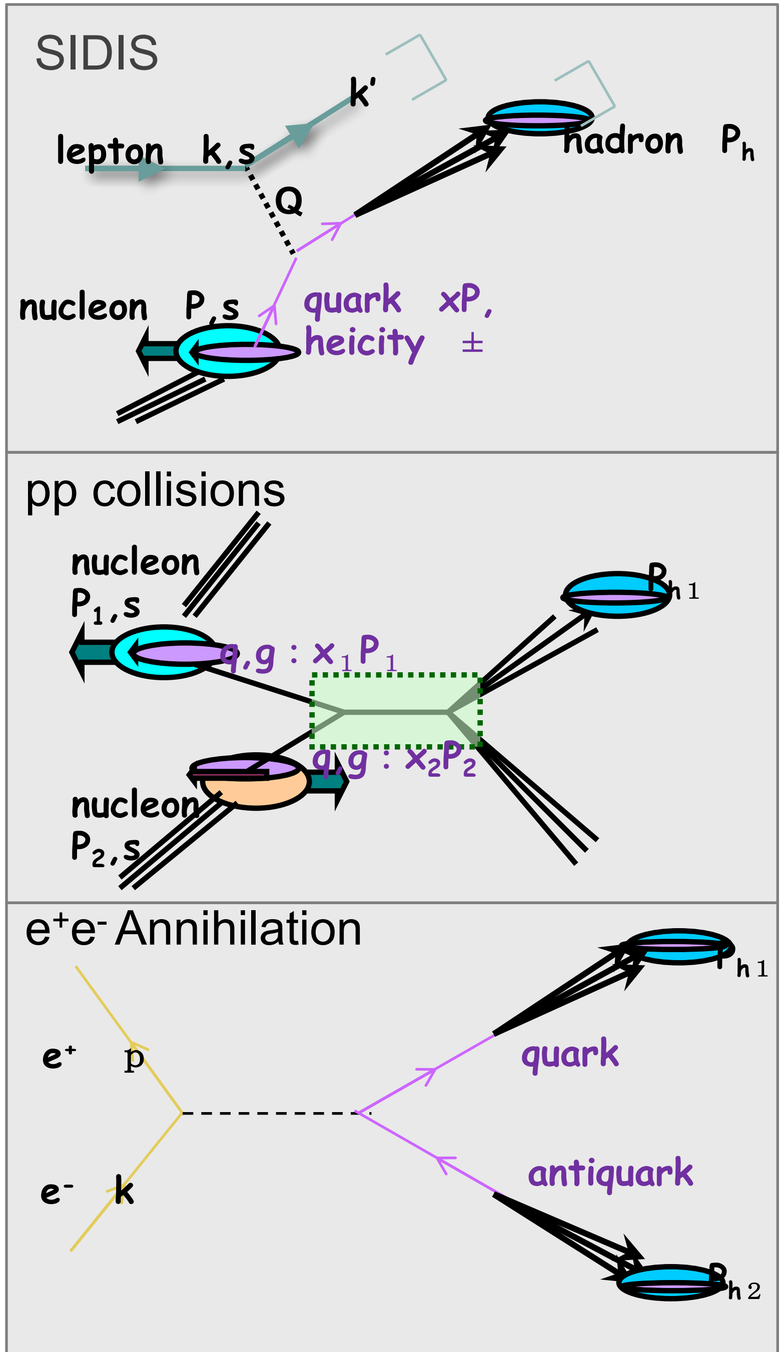
Quark fragmentation

- Quarks and gluons are confined into hadrons through the hadronization process.
- Consequence of confinement.
- Non-perturbative process.
- In factorized QCD: the hadronization process is described/parameterized using the Fragmentation Functions.
- **Field, Feynman (1977):** Fragmentation functions encode the information on how partons produced in hard-scattering processes are turned into an observed colorless hadronic bound final-state. [PRD 15 (1977) 2590]
- Complementary to the study of nucleon structure, Parton distribution functions (PDFs). In pp/SIDIS, PDFs and FFs are convoluted. FFs are needed to extract nucleon structure.



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
  - 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

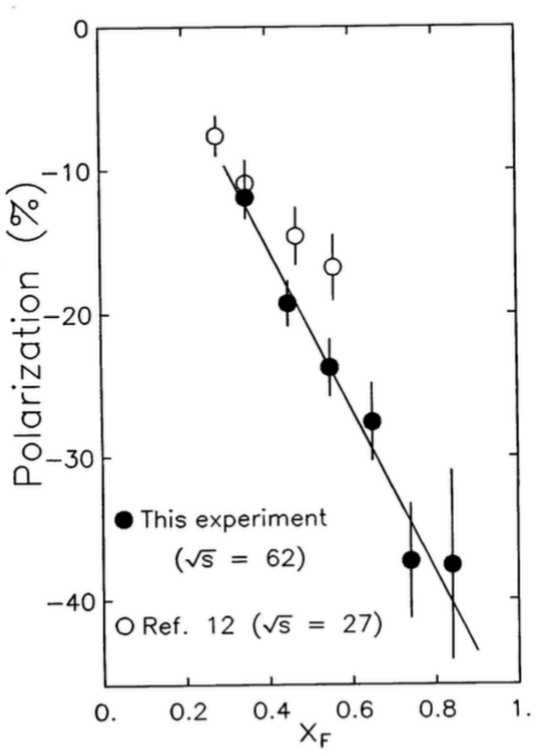
- e+e-:

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

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

Polarized Hyperon Production

- Large Λ transverse polarization was observed in unpolarized pp collision years ago. **PRL36, 1113 (1976); PRL41, 607 (1978)**
- In the absence of beam polarization, the observed transverse polarization is expected arising during the hadronization process.
- The corresponding Polarizing FF, $D_{1T}^{\perp}(z, p_{\perp}^{2})$. It describes an unpolarized quark fragmenting into a transversely polarized hadron.
- Question: is the hadronization the (only) effect?
- A measurement of the transverse polarization of in e+e- annihilation could indicate the extent to which final-state interactions contribute to the observed transverse polarization.
- OPAL experiment at LEP (e+e-) has been looking at transverse Λ polarization, no significant signal was observed. Statistical uncertainties are large. **Eur. Phys. J. C2, 49 (1998)**

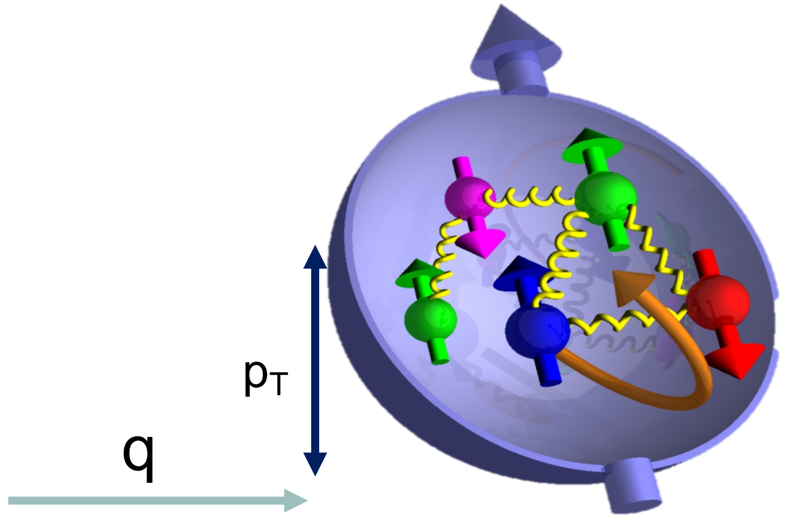


ISR data
(**Phys.Lett. B185 (1987) 209**)

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

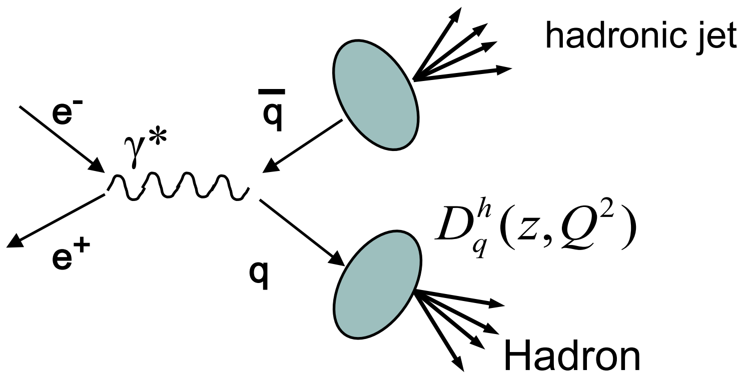
Hyperon production as a tool to study baryon spin structure

- Λ polarization allows to study spin-orbit correlation of quarks inside Baryon → counterpart of the Sivers parton distribution function (k_T dependence of quark distributions in transversely polarized proton)
- Check transverse polarization depending on p_T
- A non-vanishing Polarizing FF $D_{1T}^{\perp}$ could help to 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.
- Λ is similar with proton, but it is self-analyzing, angular distribution of its decay daughters encoded its polarization information.
- Polarizing FF is chiral-even, has been proposed as a unique test of universality. **PRL105,202001（2010）**

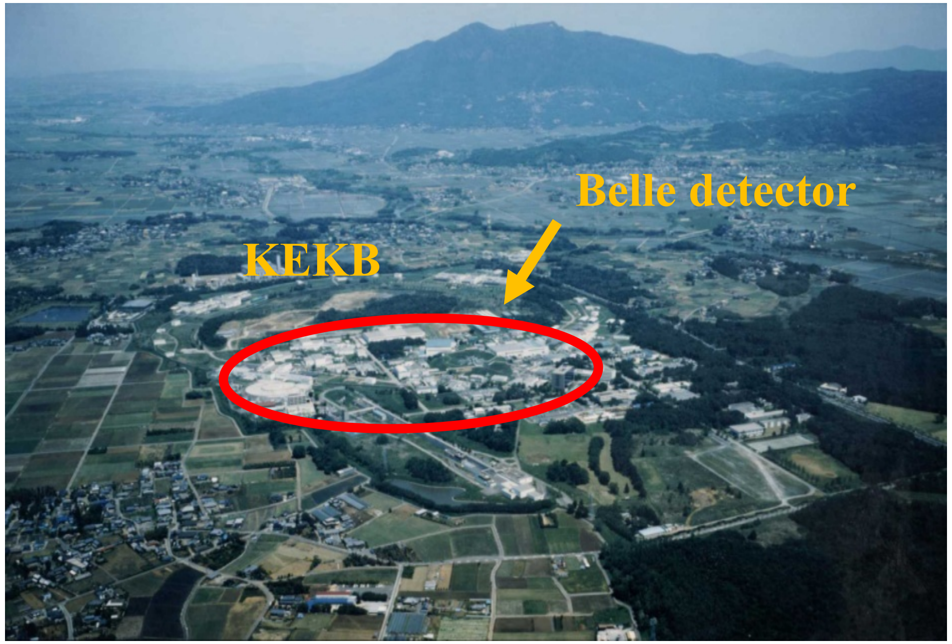


Easiest Process to access FFs

electron-positron collisions

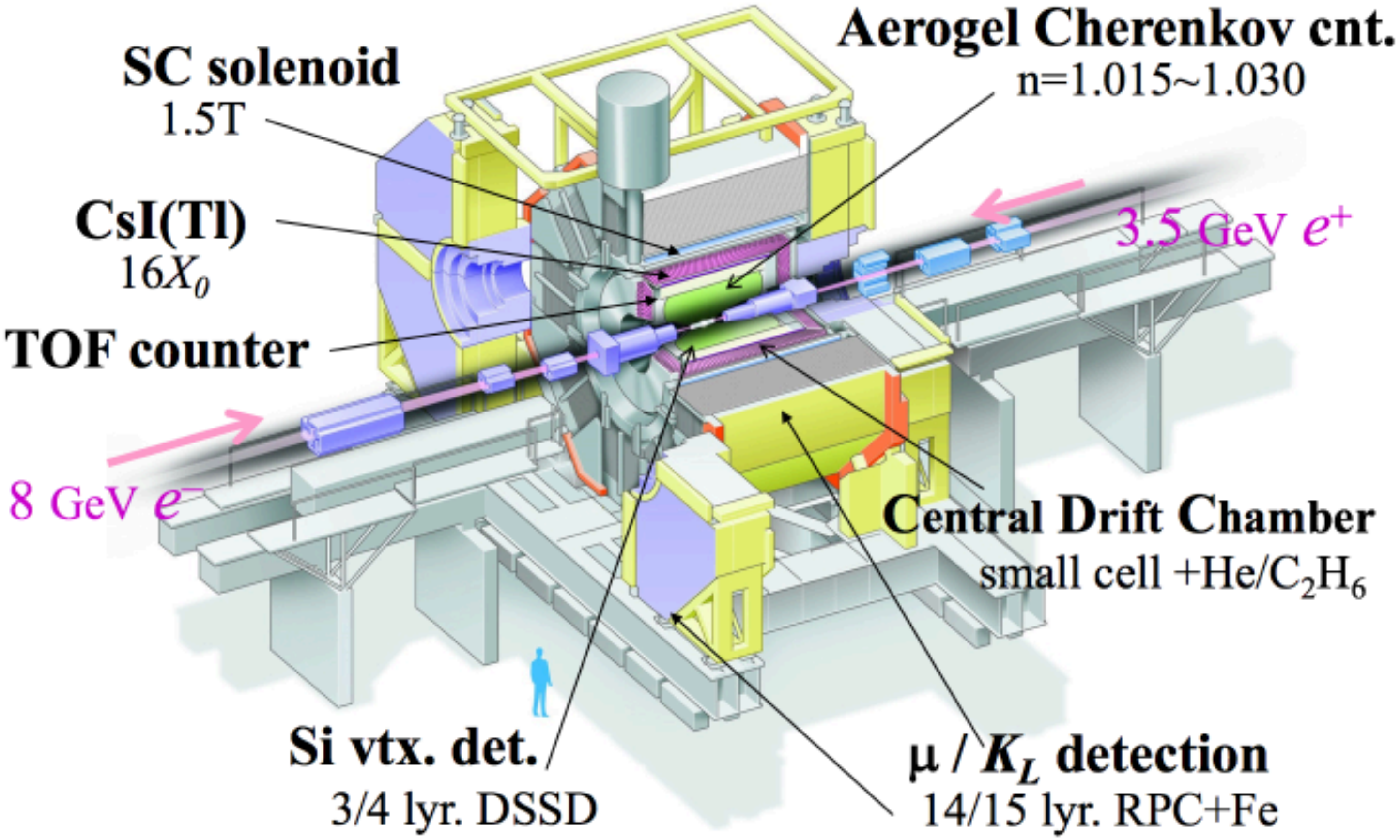


- B factories
  - Large integrated luminosity!
  - close in energy to SIDIS (100 GeV^2 vs 2-3 GeV^2)



KEKB@Tsukuba, Japan

Belle detector



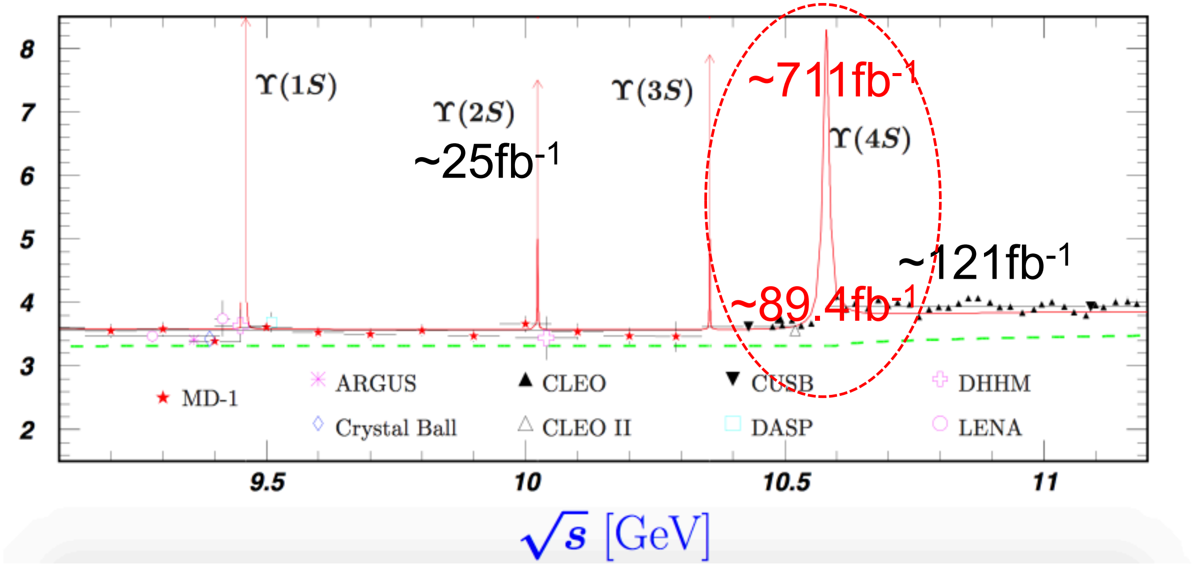
Nucl. Instrum. Meth. A479,117(2002)

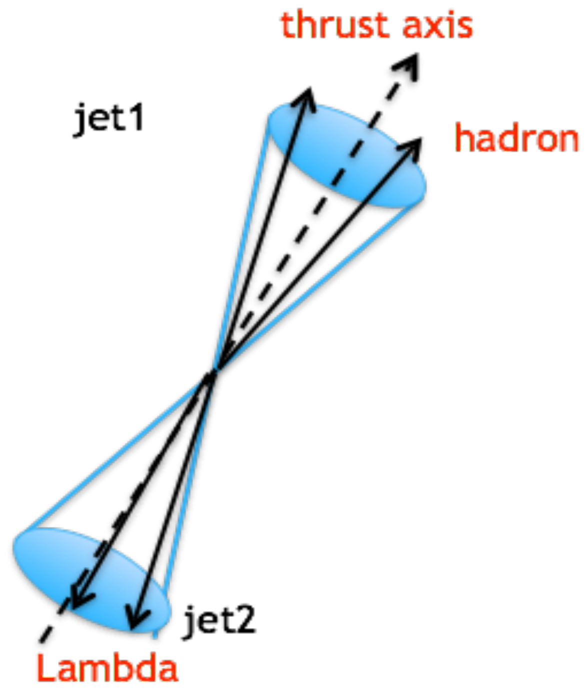
- e+e- annihilation, the easiest/cleanest process to access FFs

- Asymmetric collider: e^+ (3.5 GeV) e^- (8 GeV)
- $\sqrt{s}$ = 10.58 GeV, $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- $\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'
- Ideal detector for high precision measurements.
- High acceptance ($17^\circ \leqslant \theta \leqslant 150^\circ$), high resolution, good tracking (>95%), PID efficiency (Kaon ~85%).

Data set

- Data sets: ~ 800.4 fb^{-1} at or near $\sqrt{s}$ ~10.58 GeV

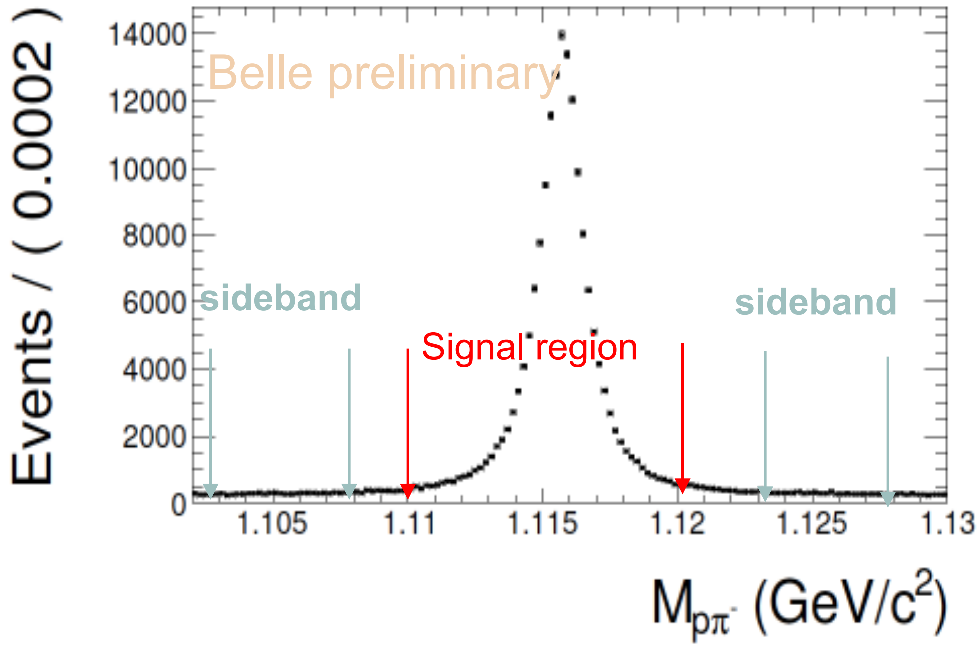




- Thrust axis $\hat{T}$ is the axis which maximizes the sum of all final particles' projection.
- Thrust value T>0.8 to select back-to-back event topology and suppress *B* decays to less than 1%.
- Thrust axis is the good approximation of the true qqbar direction but with detector resolution involved.

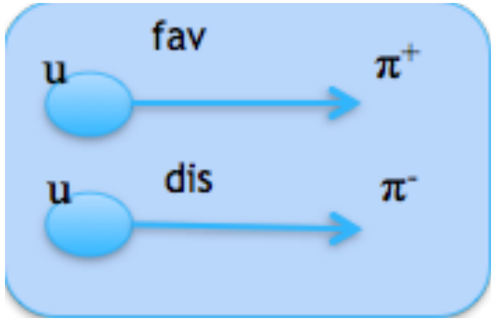
$$T = \mathrm{Max}\left[\frac{\sum_h |\mathbf{P_h}^{\mathrm{CMS}} \cdot \hat{\mathbf{T}}|}{\sum_h |\mathrm{P}_h^{\mathrm{CMS}}|}\right]$$

Λ reconstruction



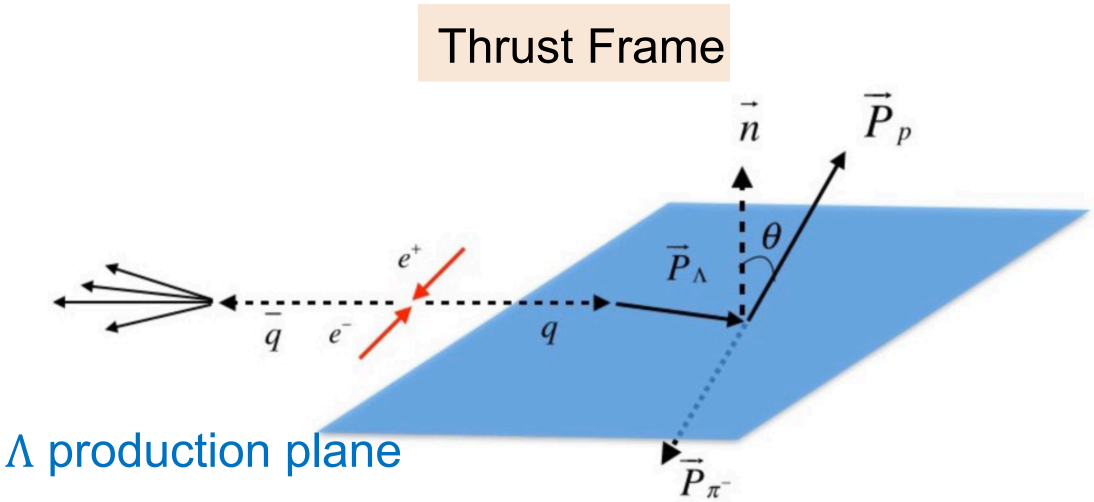
flavor tag!

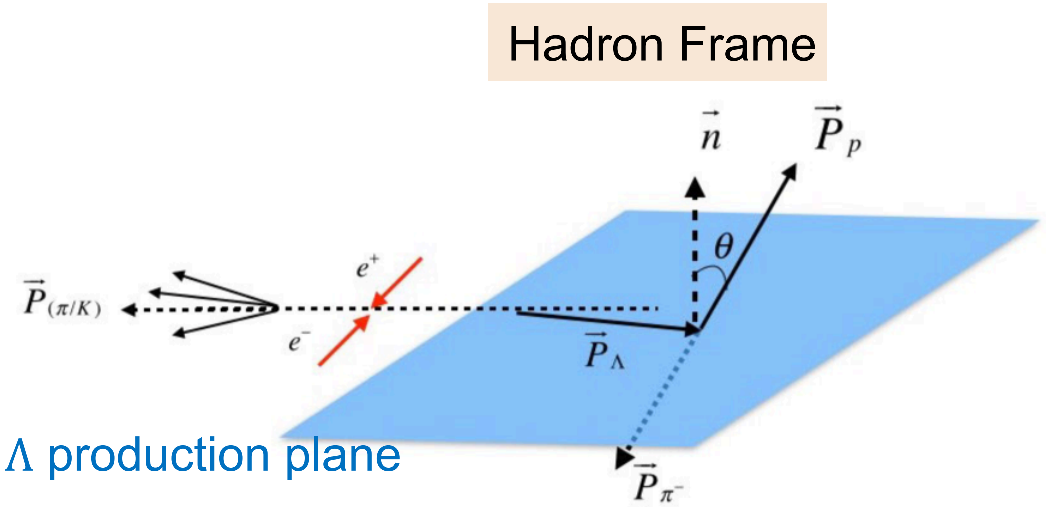
Λ(uds); π^+(u$\bar{d}$); K^+ (u$\bar{s}$)



- Signal process $\Lambda \to p\pi^-(\bar{\Lambda} \to \bar{p}\,\pi^+)$. Clear Λ peak.
- Sideband subtraction will be applied.
- There might be cancelation between different quark (u,d,s) contributions.
- By considering light hadron ($K^\pm, \pi^\pm$) in the opposite hemisphere, one can emphasize or suppress one kind of flavor which contributes to $\Lambda(\bar{\Lambda})$.
- In process $e^+e^- \to \Lambda + \pi^- + X$, the dominate process is expected as: u quark going to Λ and anti-u going to π^-.

Reference frames





- The reference vector $\hat{n}$ is perpendicular to the Λ production plane.
- The $z_\Lambda = 2E_\Lambda/\sqrt{s}$, is the fractional energy carried by the Λ. The p_t is defined as the transverse momentum of Λ relative to thrust axis in thrust frame and to hadron axis in hadron frame.
- Give a polarization of *P*, the yield of the events follow:

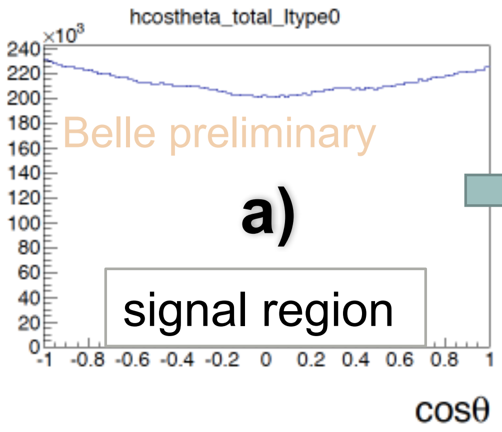
$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta$$

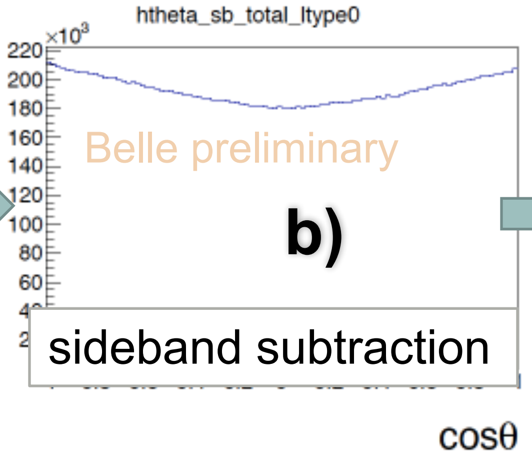
- where α is the decay parameter: α_+=0.642 $\pm$ 0.013 for Λ and α_-=-0.71 $\pm$ 0.08 for $\bar{\Lambda}$ (PDG).

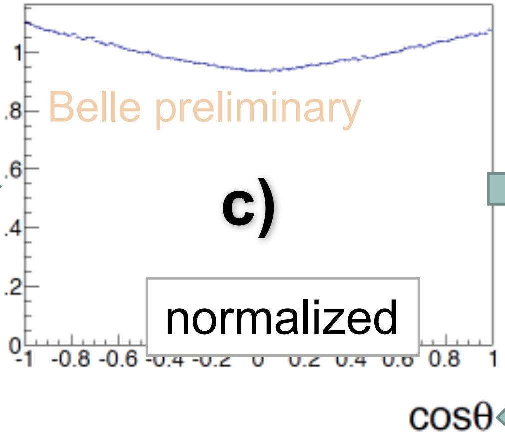
kinematic variables

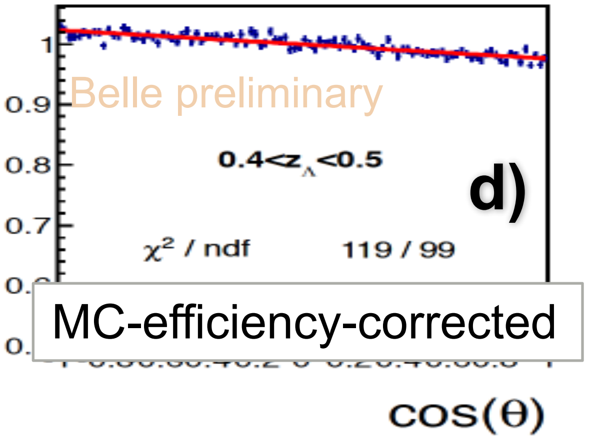
$\Lambda + X$	thrust frame	
variables	z_Λ , p_t	
$\Lambda + h + X$	thrust frame	hadron frame
variables	z_Λ, z_h, p_t	z_Λ, z_h, p_t

Analysis flow

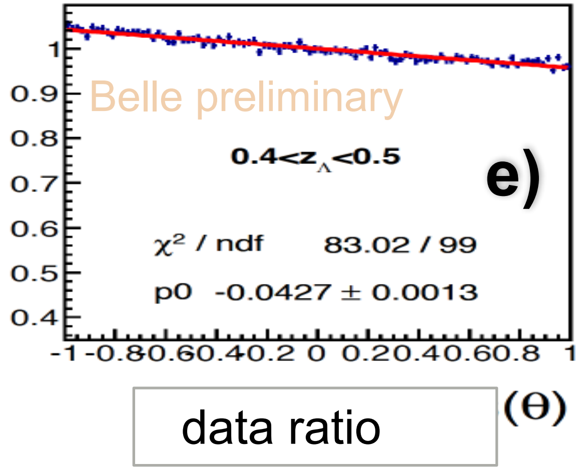






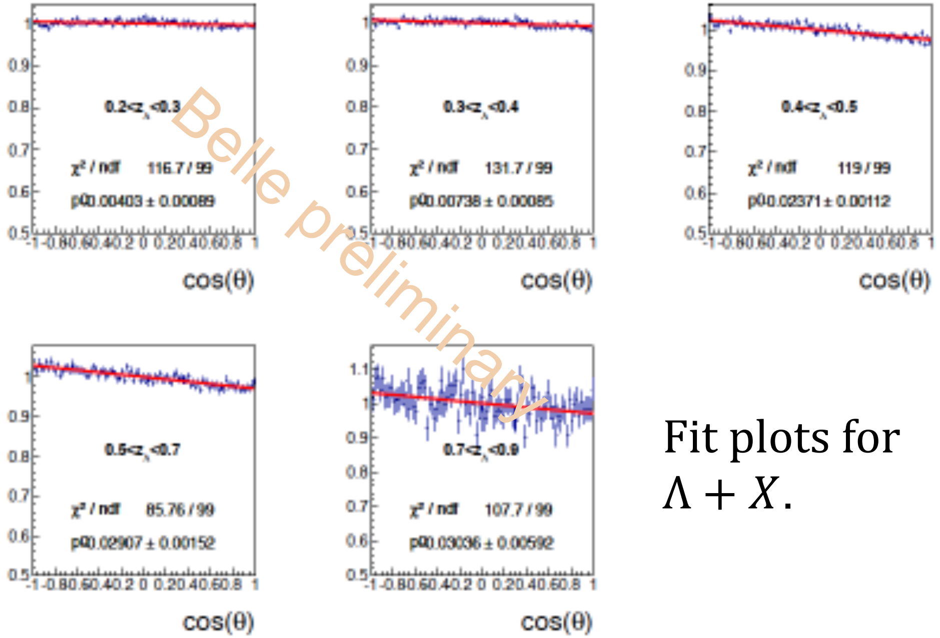


- Cosθ distribution in Λ signal region **a)** is subtracted by that in sideband region → **b)**
- Normalized by itself, as shown in **c).**
- The shape **c)** is divided by the corresponding shape from MC, so that we obtain the efficiency-corrected curve **d)**.
- Or **c)** shape of Λ events is divided 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.

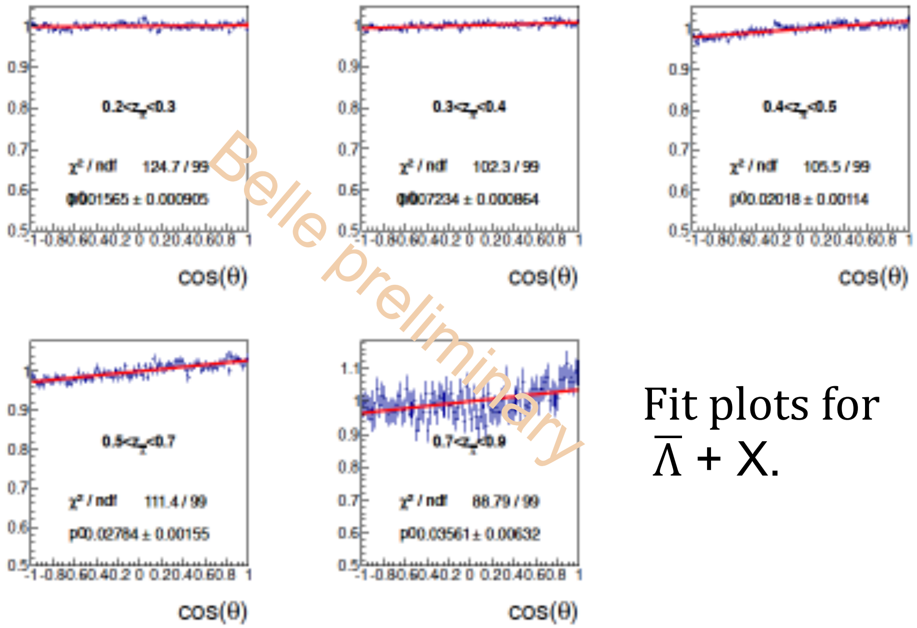


Fits and polarization extraction

z_Λ binning [0.2,0.3,0.4,0.5,0.7,0.9]



Fit plots for $\Lambda + X$.



Fit plots for $\overline{\Lambda}$ + X.

- Clear slope can be seen in the cosθ distributions, opposite slope for Λ and anti-Λ.
- Fit to the cosθ distributions with the simple function $1 + p_0 cos\theta$.
- The polarization is obtained from: p_0/α.

Fits to Data Ratio

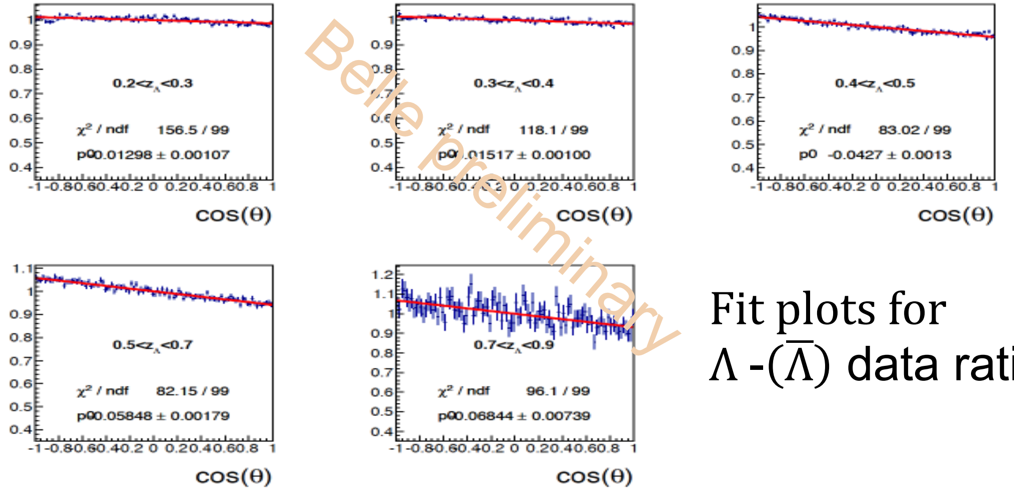
- In data ratios, the slope on the $\cos\theta$ distributions are about two times larger than that in MC-corrected ratios, the $(\alpha_+ - \alpha_-)$ is also about times larger than $\alpha_+(\alpha_-)$.

$$\frac{1+\alpha_+ P}{1+\alpha_- P}$$

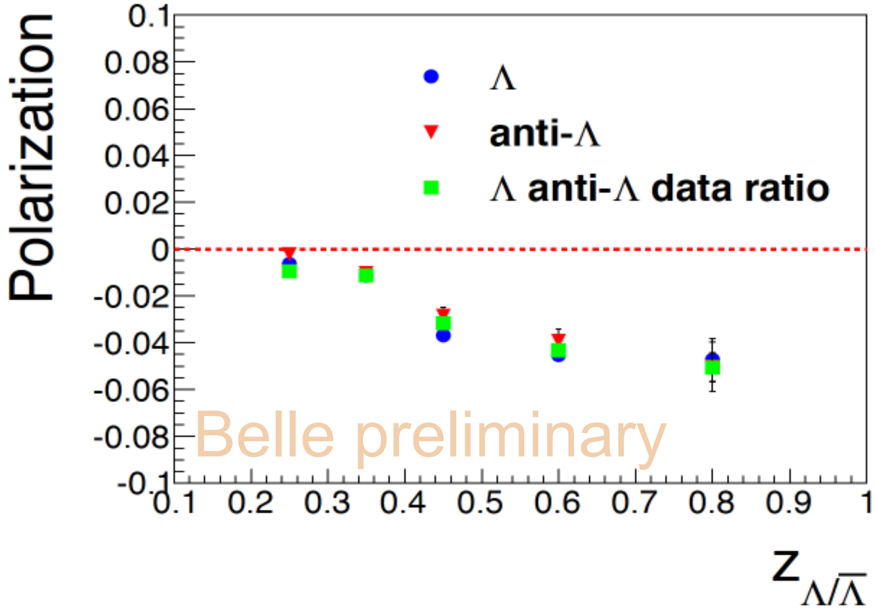
$$\approx 1 + (\alpha_+ - \alpha_-)P$$

- In the data ratio, polarization is obtained via $p_0/(\alpha_+ - \alpha_-)$.
- Results from MC-corrected ratio and data ratio are basically consistent with each other.
- Nonzero polarization can be seen, the magnitude grows with increasing fractional energy z_Λ, approaches ~5%.

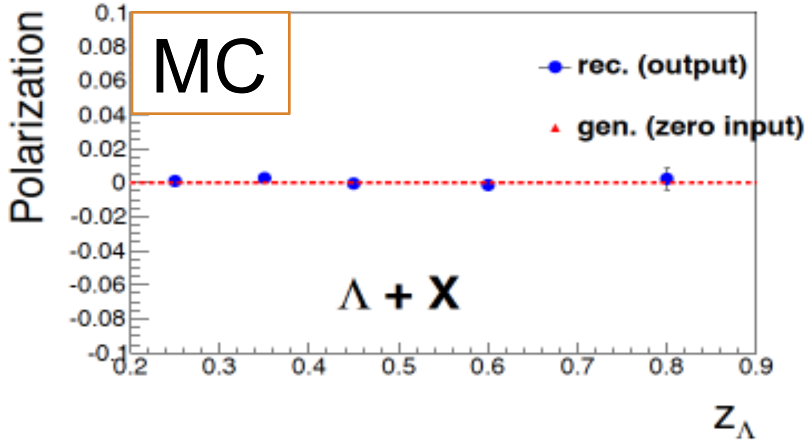
z_Λ binning [0.2,0.3,0.4,0.5,0.7,0.9]

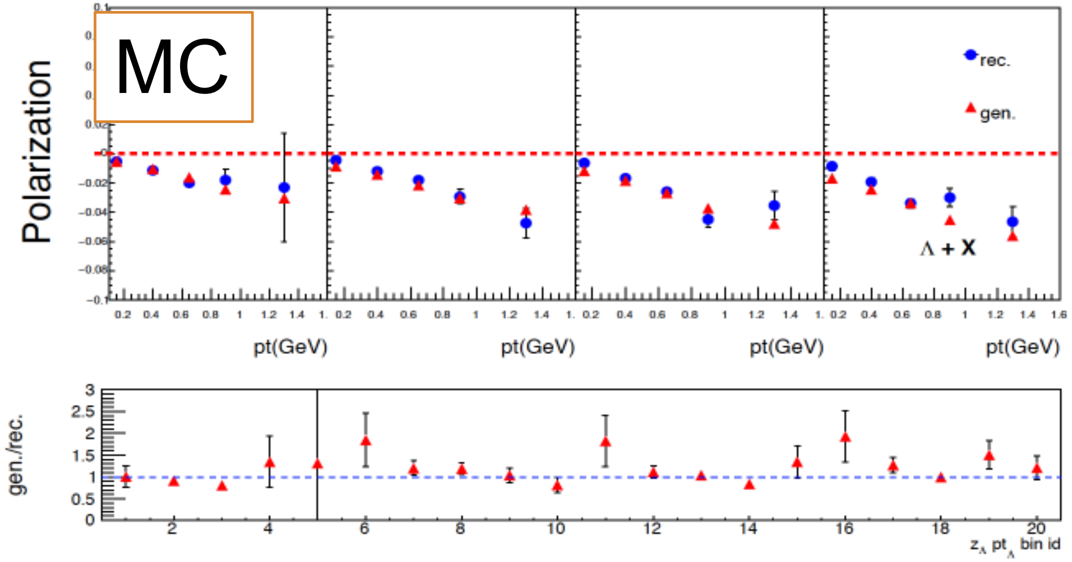


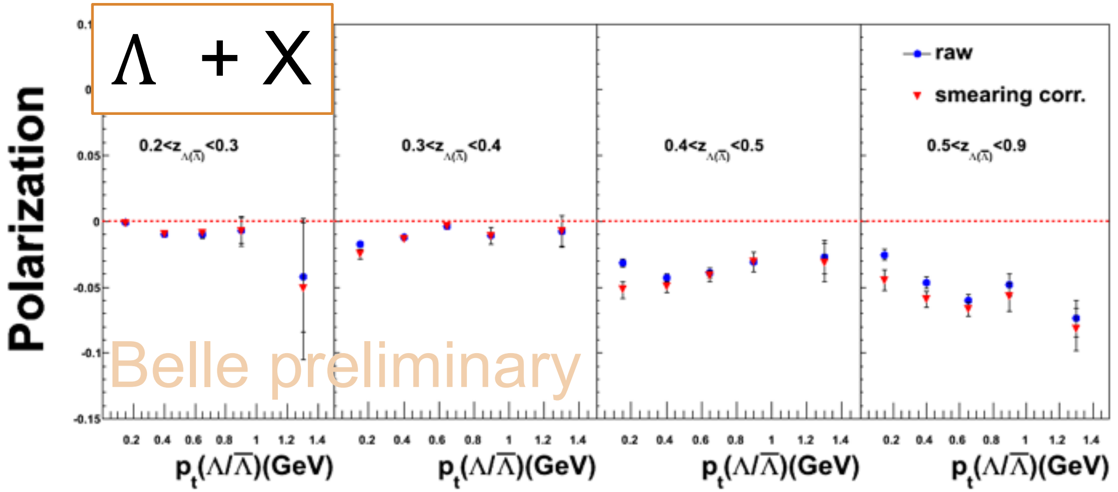
Fit plots for Λ -($\bar{\Lambda}$) data ratio.



MC validation & Smearing correction



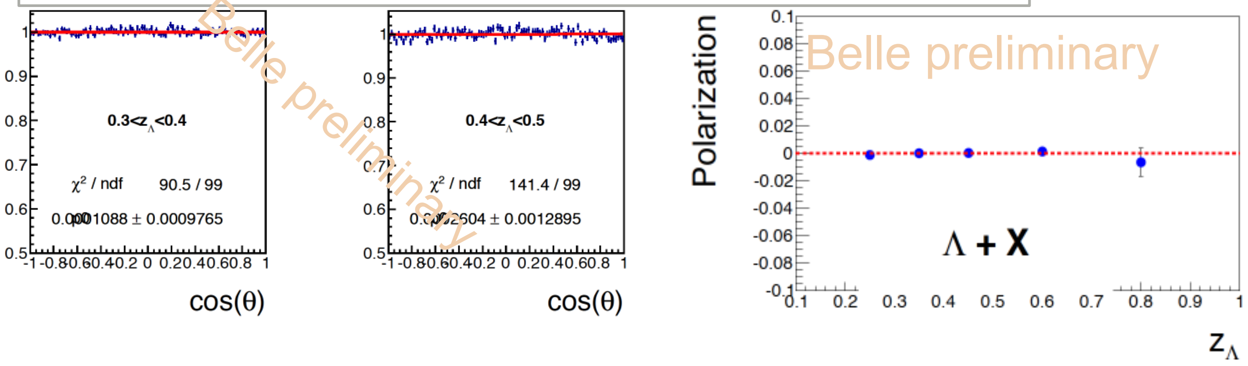




- Zero polarization is observed in MC, as expected.
- Smearing effects caused by the detector acceptance and resolution are estimated using the weighted-MC with nonzero polarization input.
- In thrust frame, the polarization is found underestimated in reconstruction, correction factors ranges 1.0-1.3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

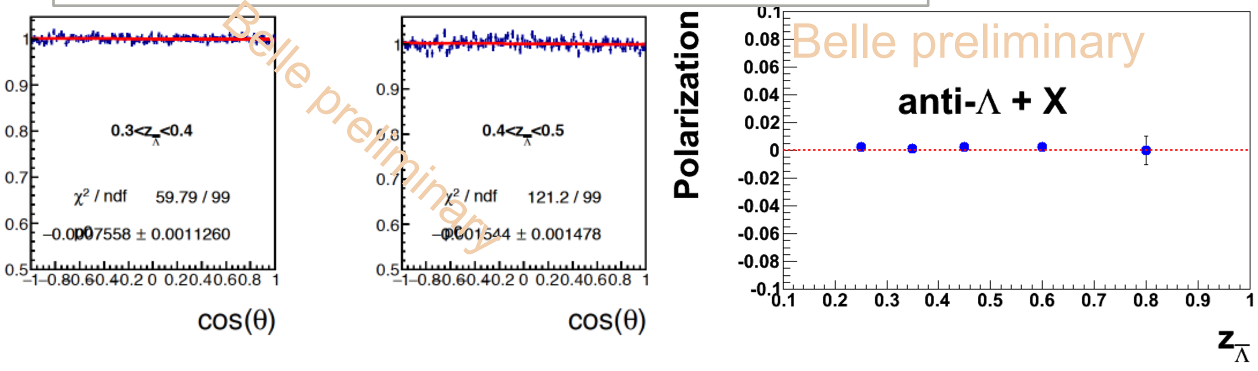
Systematics

fake angle θ in production plane



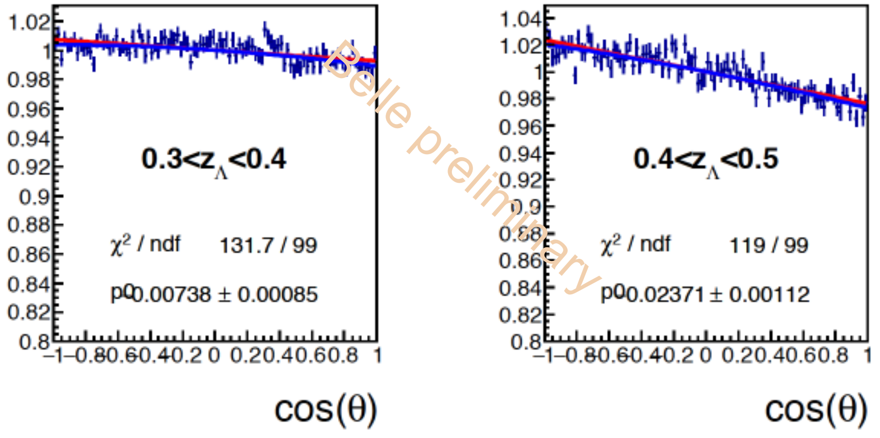
- Change the reference vector $\hat{n}$ to be in the Λ production plane. But still normal to $\vec{p}_\Lambda$.

Mixed events, false Λ



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

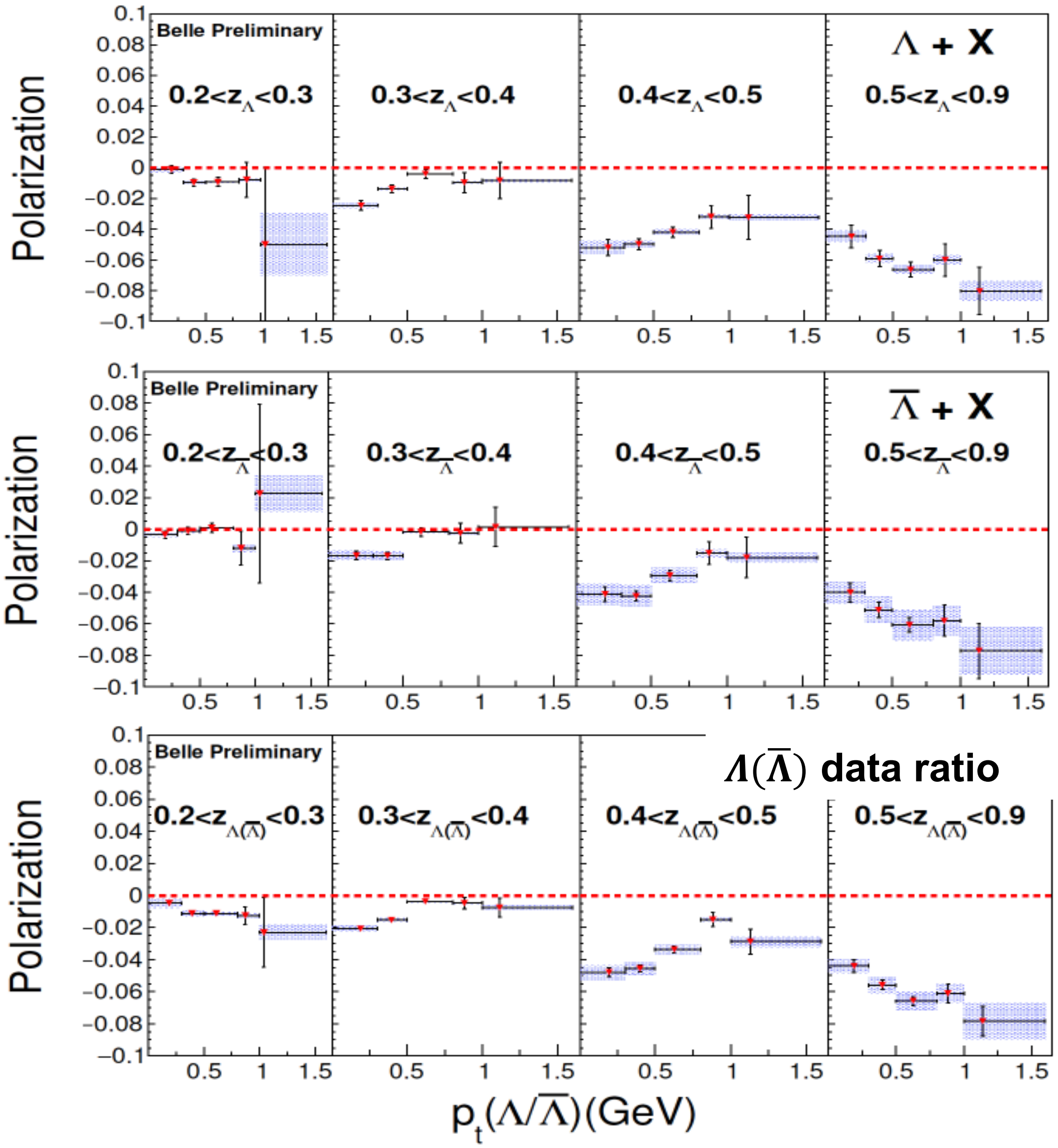
Check on the fit function



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

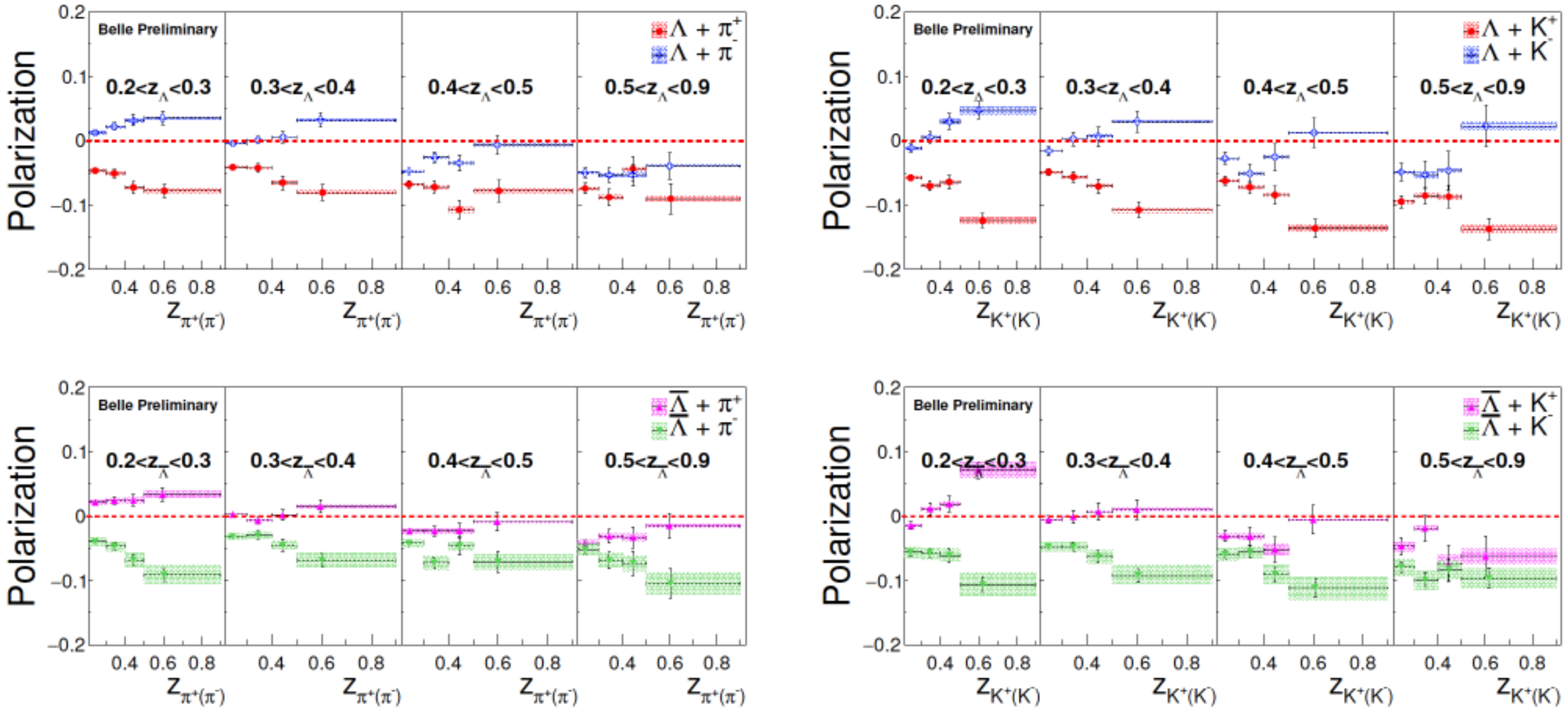
- Besides, uncertainties from smearing correction factors and sideband subtractions are included in systematics errors.
- Uncertainties of decay parameters are assigned as systematic errors.

Results in thrust frame vs. (z,p_t)



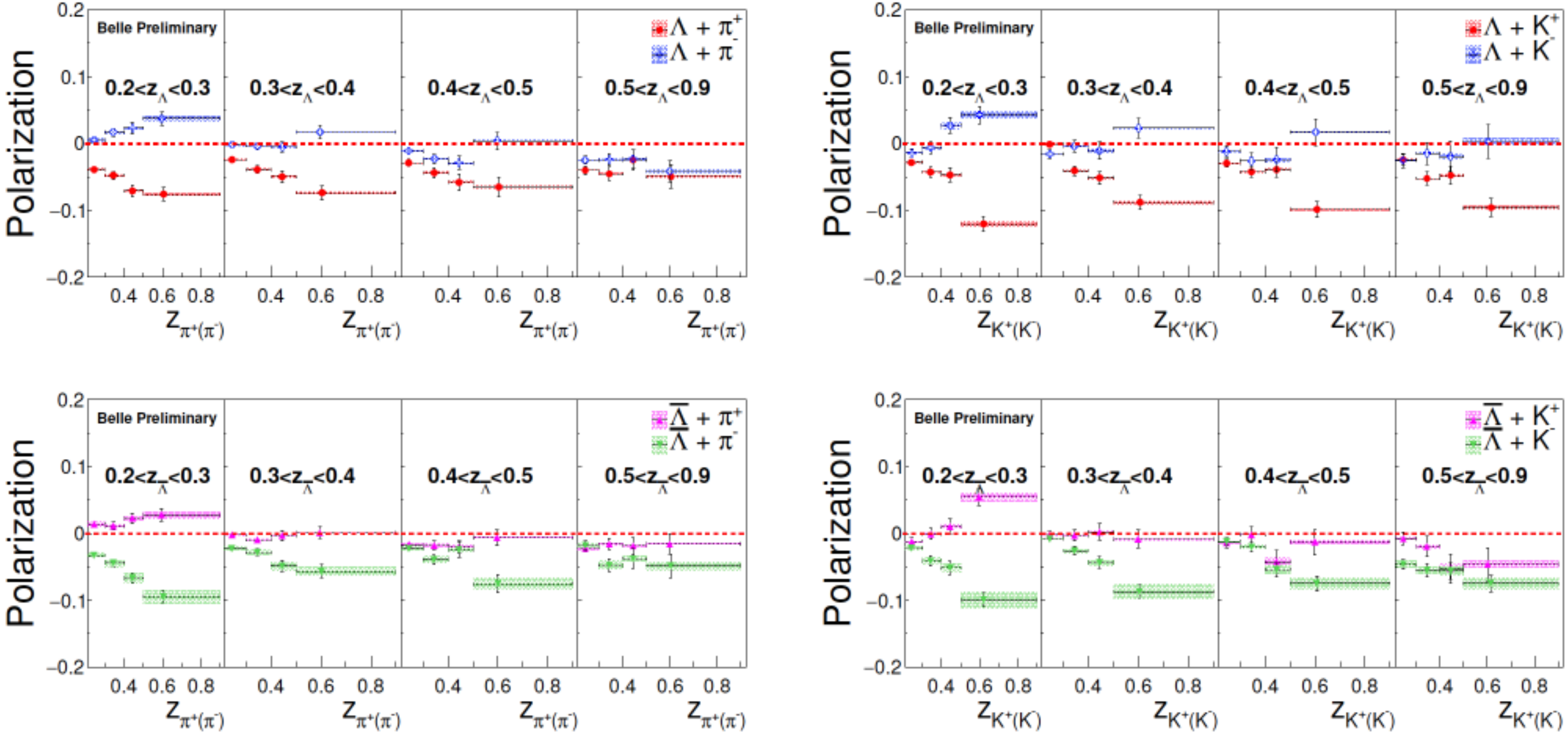
- Four z bins and five p_t bins are applied: z_Λ=[0.2,0.3,0.4,0.5,0.9]; p_t=[0.0,0.3,0.5,0.8,1.0,1.6] GeV
- Error bars are statistical uncertainties and shaded areas show the systematic uncertainties.
- Nonzero polarization was observed. Interesting shape as a function of (z_Λ, p_t).
- The polarization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

Results in thrust frame vs. (z_Λ, z_h)



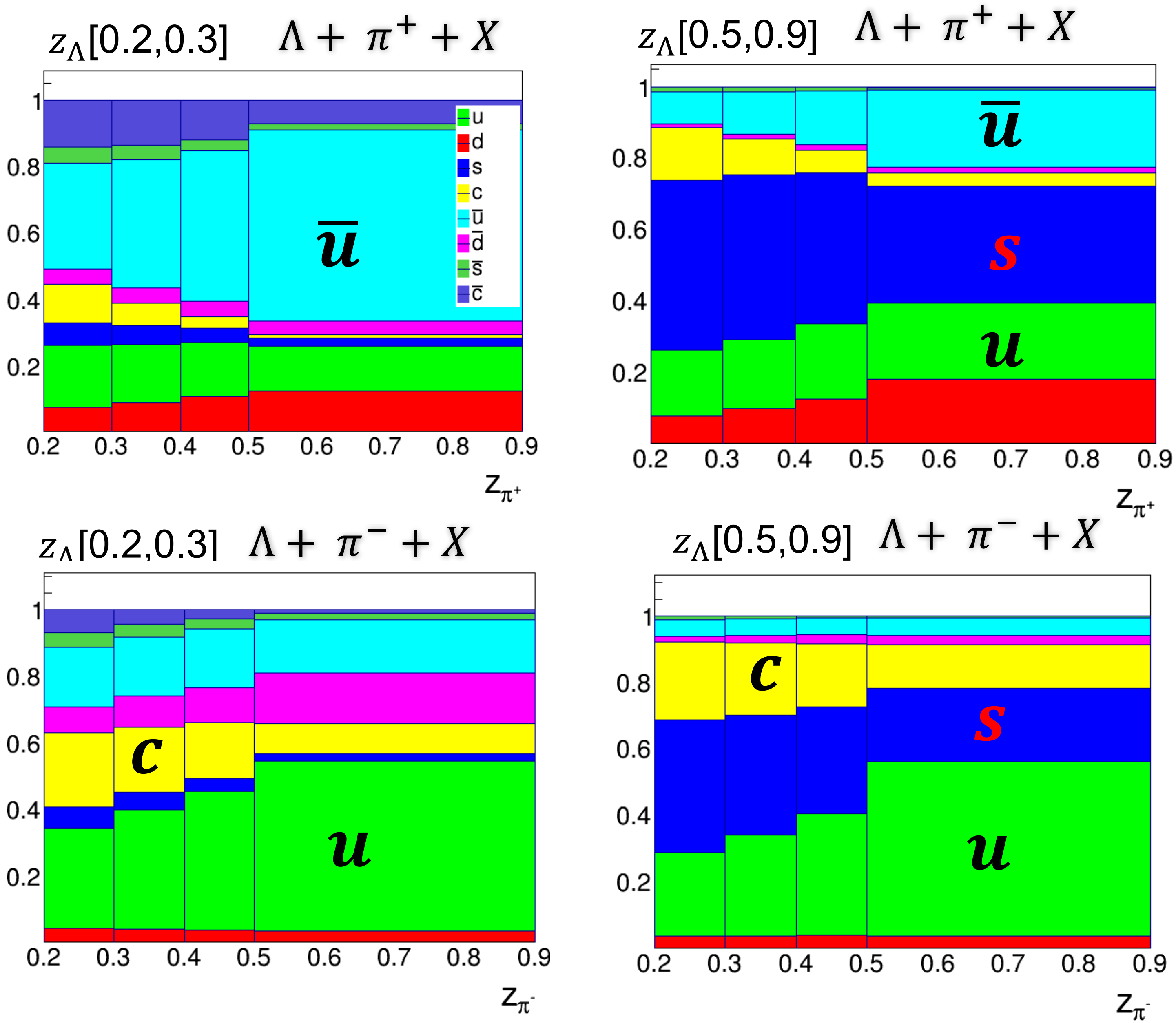
- At low z_Λ, polarization in $\Lambda + h^+$ and $\Lambda + h^-$ have opposite sign. The magnitude increases with higher z_{h}.
- At large z_Λ, the differences between $\Lambda + h^+$ and $\Lambda + h^-$ reduce. Small deviations can still be seen and depend on z_{h}.

Results in hadron frame vs. (z_Λ, z_h)



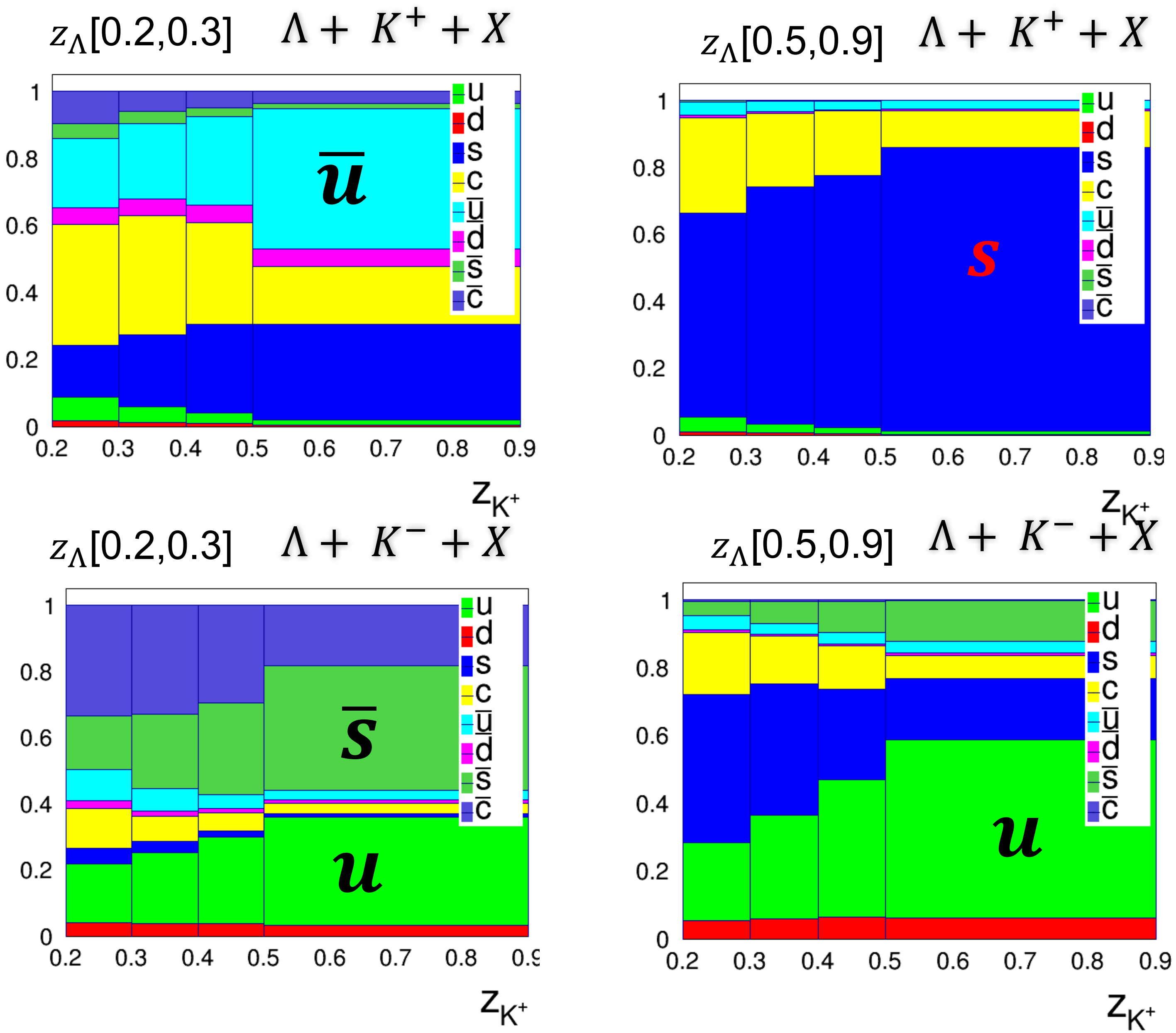
- Very similar results with that in the thrust frame.
- Results from charge-conjugate modes are consistent with each other.

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.
- In process $\Lambda + \pi^+ + X$, at low z_Λ, u quark is most likely carried away by π^+. But at high z_Λ, the case is different. There is more s/u quark contribution.
- In process $\Lambda + \pi^- + X$, seems u quark is dominate, at high z_Λ, more s quark contribution.

Quark flavor tag by the Kaon



- In $\Lambda + K^+(u\,\bar{s}) + X$, at low z_Λ, there is anti-u quark contribution. At high z_Λ, s quark dominates.
- In $\Lambda + K^-(\bar{u}s) + X$, at low z_Λ, u/$\bar{s}$ dominate and at high z_Λ, s/u dominate.
- MC indicates that the tag of the quark flavors is more effective at low z_Λ and high z_h. It might explain why at low z_Λ and high z_h, polarization in $\Lambda + h^+$ and $\Lambda + h^-$ have opposite sign.
- Note that charm contribution is not excluded out.

Backgrounds

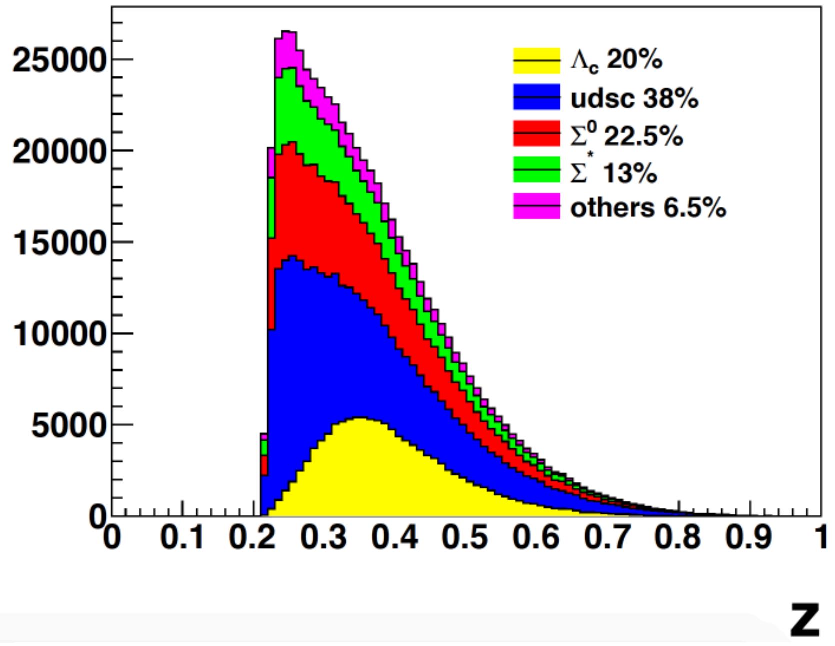


Table 2: The fraction of various sources of Λ in each z bin.

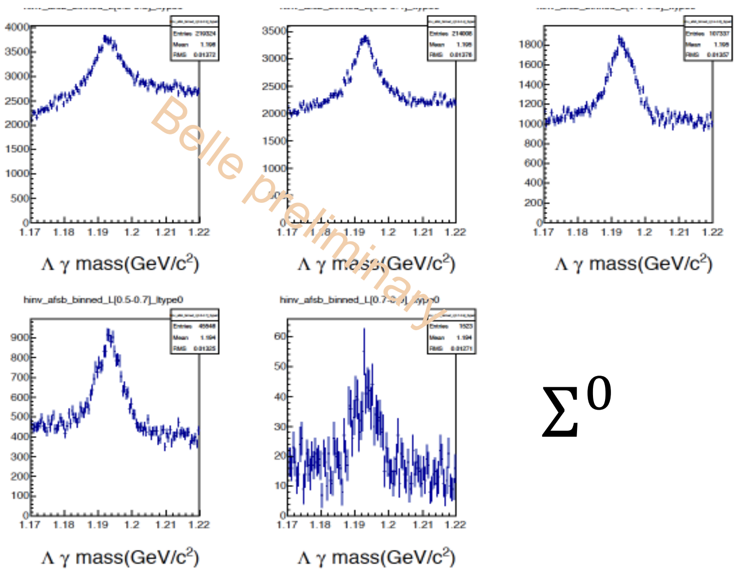
z bin	[0.2, 0.3]	[0.3,0.4]	[0.4, 0.5]	[0.5, 0.7]	[0.7, 0.9]
$q\bar{q}$	45.0	33.8	32.3	38.7	57.4
Σ^0	23.5	21.9	21.9	21.8	18.3
Σ^*	15.0	12.3	12.4	12.7	10.2
Λ_c	9.0	25.9	27.6	21.1	9.8
others	7.5	6.1	5.8	5.7	4.2

- Non-Λ backgrounds are excluded out in the sideband subtraction.
- Σ^* decays to Λ strongly, is included in the signal process.
- Feed-down from Σ^0(22.5%), Λ_c(20%) decays need to be understood.
- The measured polarization includes contribution from backgrounds:

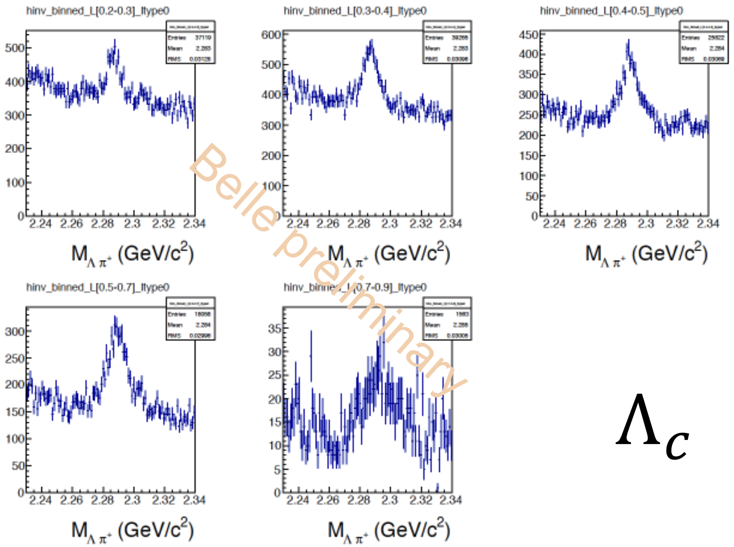
$$P^{mea.} = (1 - \sum_i F_i) P^{true} + \sum_i F_i P_i,$$

- F_i is the fraction of component i, can be estimated from MC. P_i is the polarization of Λ in background component i.

Σ^0/Λ_c-enhanced sample

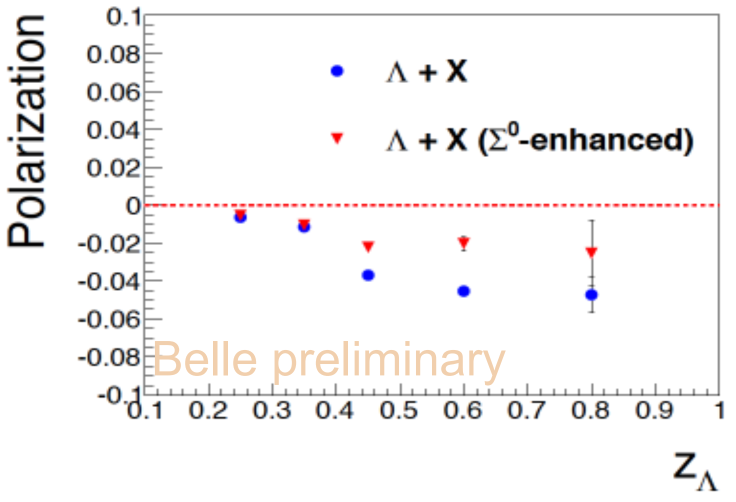


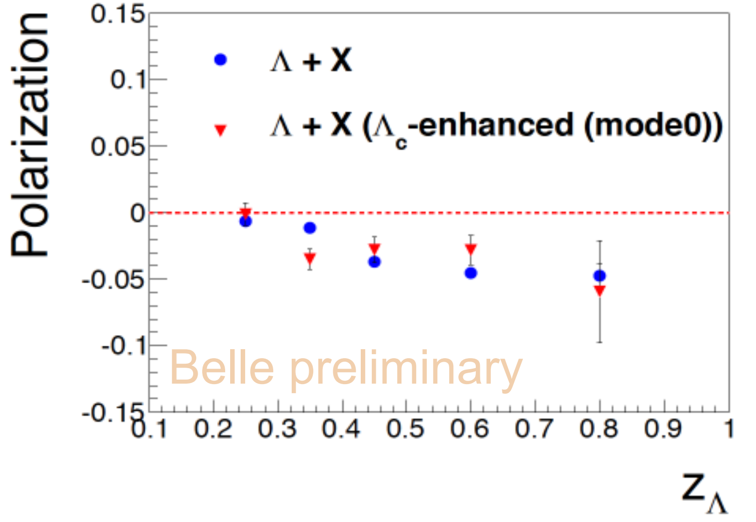
Σ^0



Λ_c

- 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 $\Lambda_c \to \Lambda + \pi^+$ was used as the representative of all Λ_c→ Λ + X. Not prefect.
- Smaller magnitude of polarization in the Σ^0-enhanced sample.
- Λ_c-enhanced sample is consistent with inclusive Lambda within statistics.

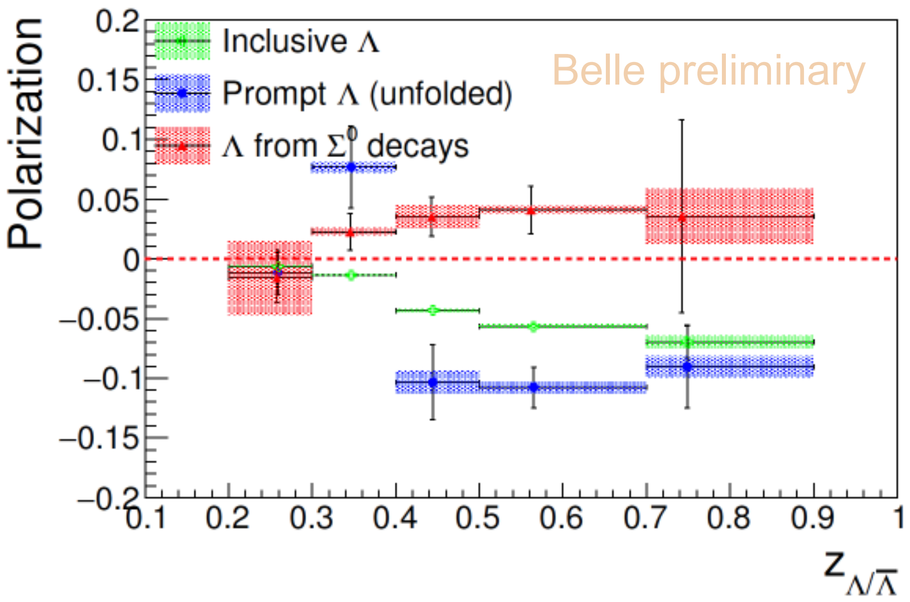


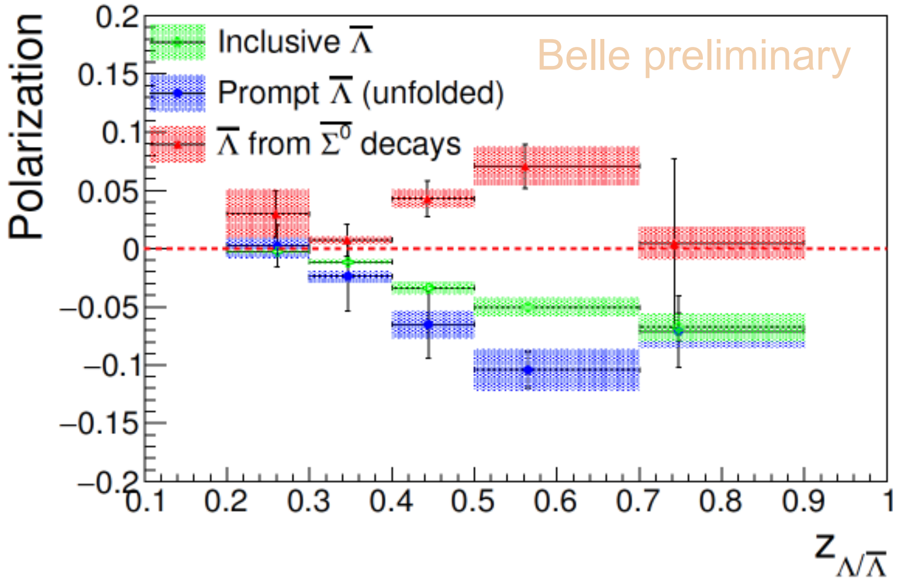


Backgrounds Unfolding

- We have three times of measurements and three unknown parameters.
- The unfolding was done according to: $$P^{mea.} = (1 - \sum_i F_i) P^{true} + \sum_i F_i P_i,$$
- Polarization of Λ from Σ^0 decays is found has opposite sign with that of inclusive Λ.
- The spin transfer between Σ^0 and Λ is assumed as -1/3 in some models.

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

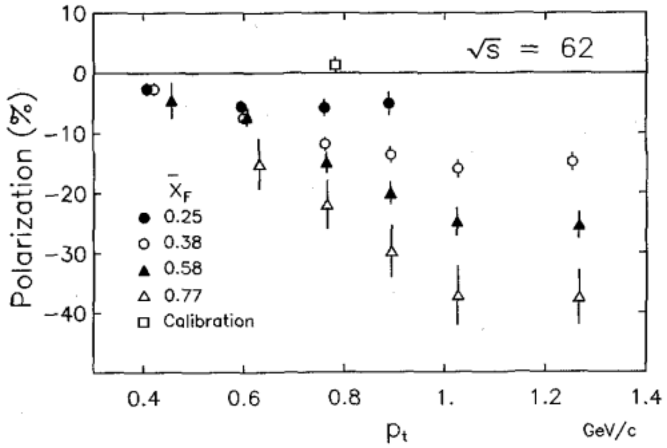




Discussion (1)

Comparing to pp?

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



- In pp, the magnitude is quite large, especially at large x_F, approaches -40%.
- Comprehensive studies considering the kinematics (with theoretical calculations) might draw more serious conclusions.

Comparing to high energy ?

OPAL@Z_0, Eur. Phys. J. C2, 49 (1998)

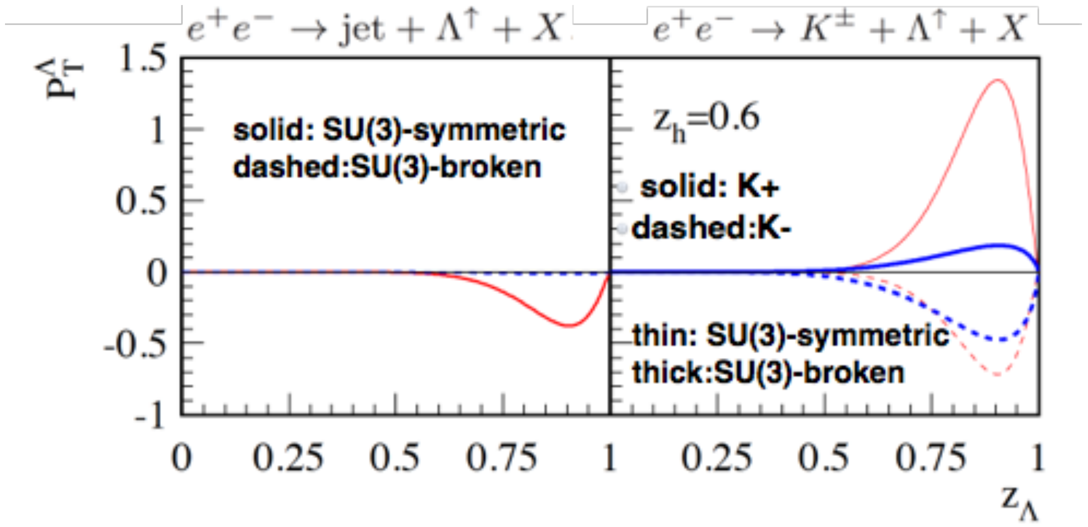
p_T (GeV/c)	P_T^Λ (%)
< 0.3	$-1.8 \pm 3.1 \pm 1.0$
$0.3 - 0.6$	$0.4 \pm 1.8 \pm 0.7$
$0.6 - 0.9$	$1.0 \pm 1.9 \pm 0.7$
$0.9 - 1.2$	$0.8 \pm 2.2 \pm 0.6$
$1.2 - 1.5$	$0.0 \pm 2.7 \pm 0.6$
> 1.5	$1.8 \pm 1.6 \pm 0.5$
> 0.3	$0.9 \pm 0.9 \pm 0.3$
> 0.6	$1.1 \pm 1.0 \pm 0.4$

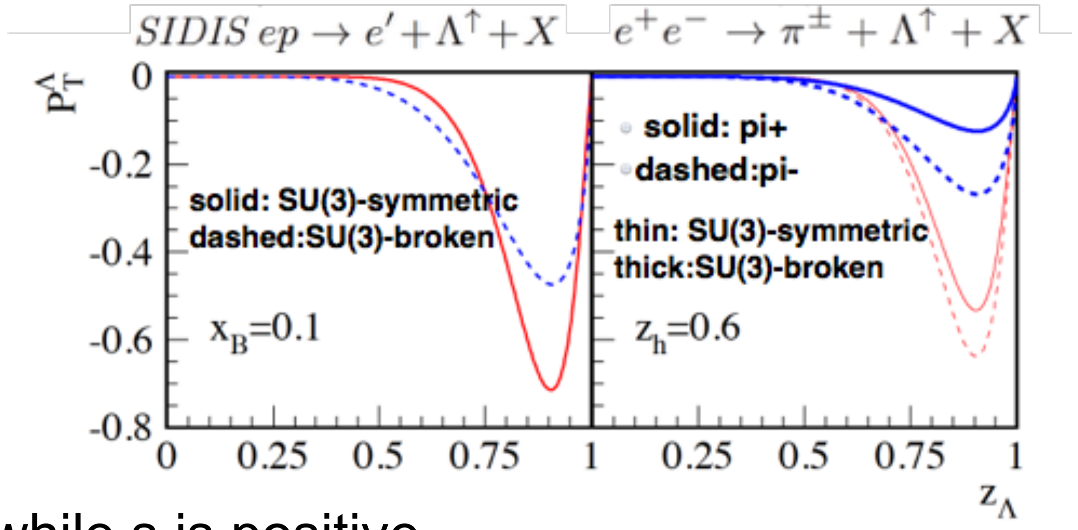
- OPAL: less statistics, larger energy @ Z_0 (90GeV)
- We see larger magnitude @10.6GeV.
- QCD evolution?

Discussion (2)

Comparing to theoretical prediction?

Phys.Rev.Lett.105:202001,2010

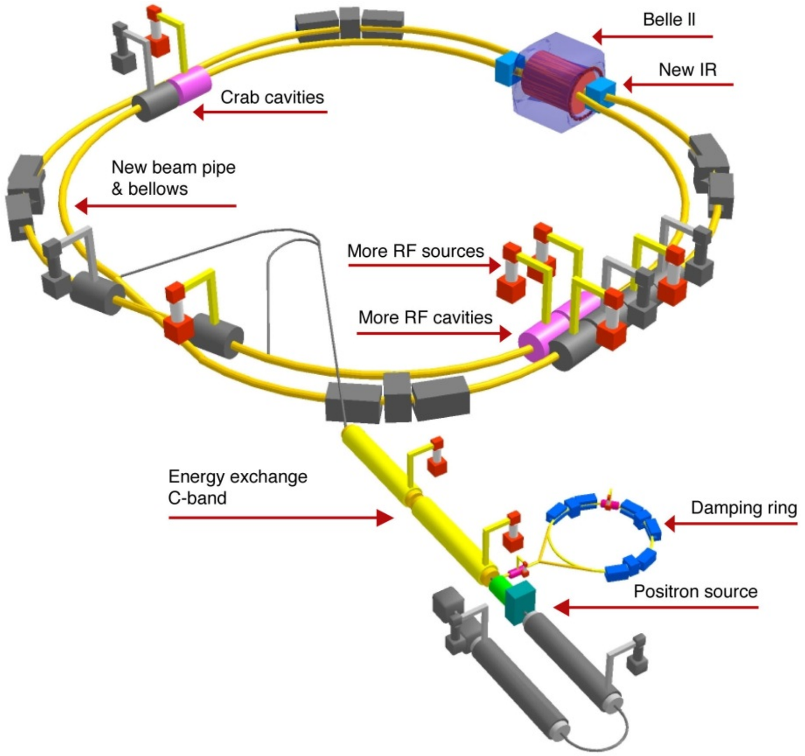




- In the prediction, u/d are assumed negative while s is positive.
- The data polarization results agree with negative sign predictions for $\Lambda + X$.
- For $\Lambda + \pi^{+/-} + X$, the magnitude in data is not as large as that in prediction.
- For $\Lambda + K^{+/-} + X$, in data we don't see clear opposite sign in K^+ and K^- at large z_Λ, z_h.
- There are large uncertainties in the predictions as said by authors. Important constrains from real data for the various flavor contribution/cancelation.
- Also be worth investigating in SIDIS.

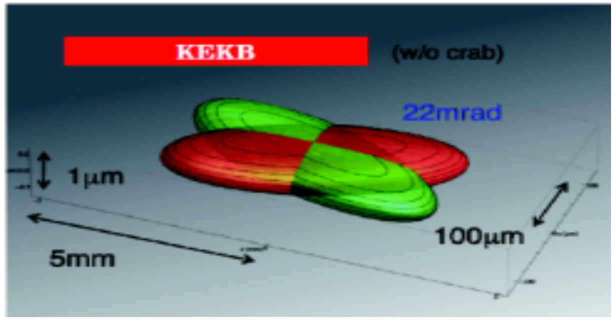
KEKB/Belle→SuperKEKB/BelleII

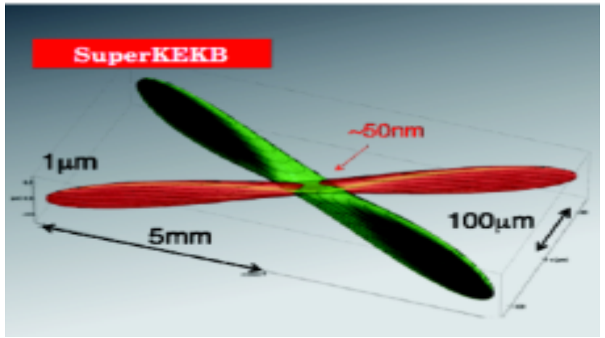
- Aim: super-high luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$ (~40x KEK/Belle)
- Upgrades of Accelerator (Nano-beams + Higher currents) and Detector (Vertex detector, better PID system, modern DAQ, higher rates)
- Significant US contribution.



Target Luminosity

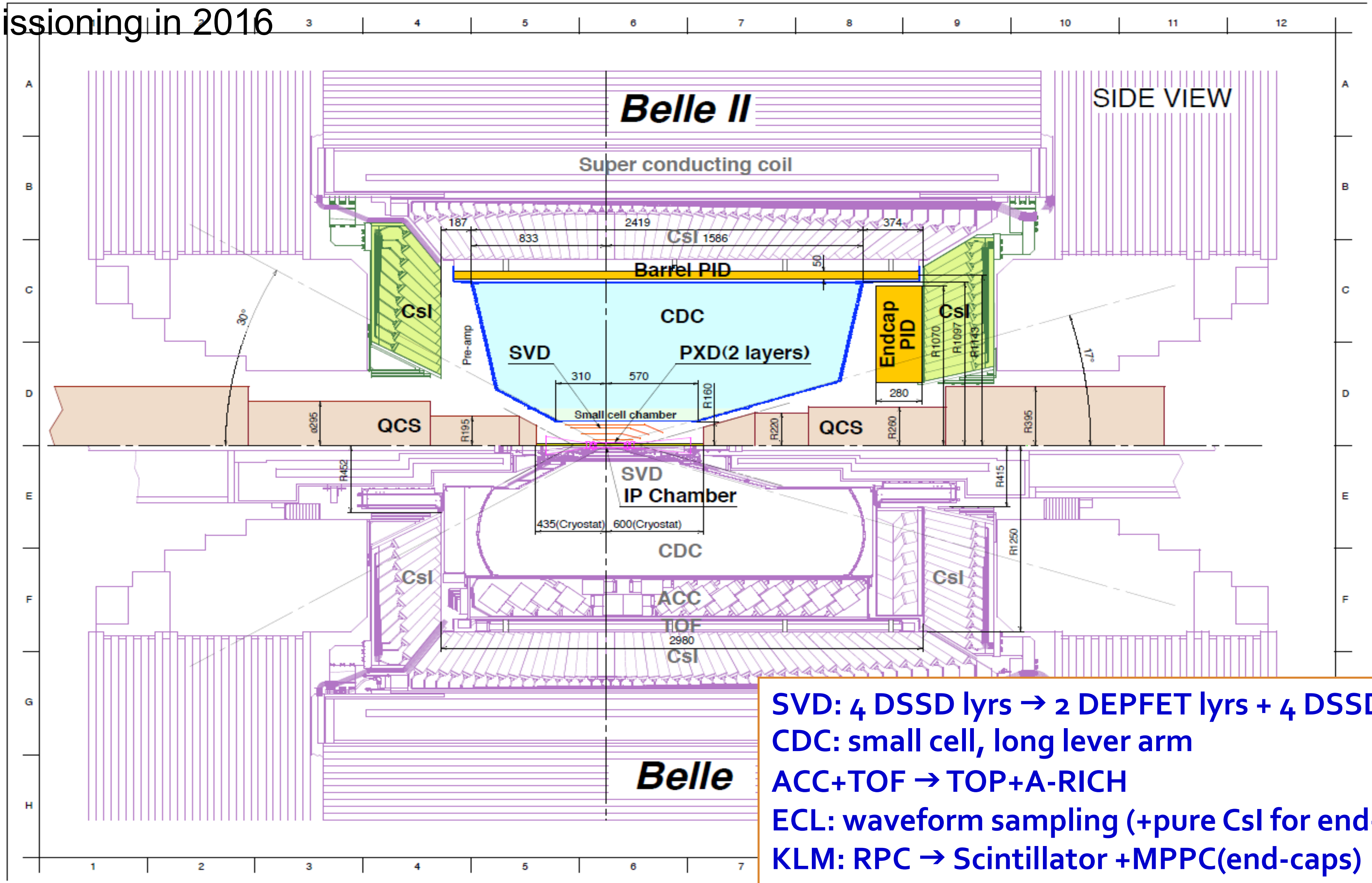
- L_{int} > 50 ab^{-1} by 2020s (50x Belle)
- L_{peak} = 8 × $10^{35}cm^{-2}s^{-1}$ (40x KEKB)





Belle II Detector (in comparison with Belle)

Start of comissioning in 2016



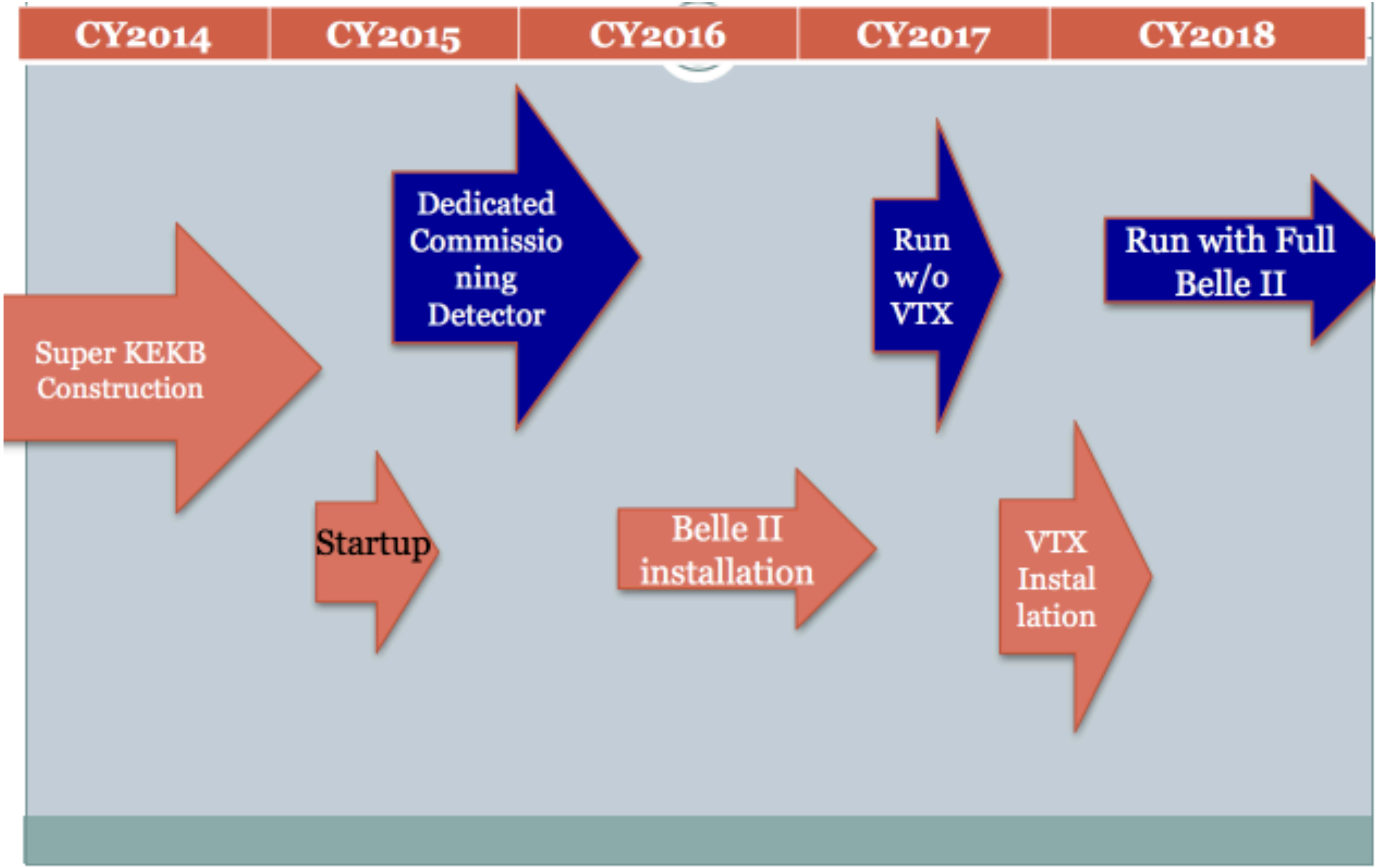
SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for end-caps)
KLM: RPC → Scintillator +MPPC(end-caps)

Technical design report: arXiv:1011.0352

QCD studies at Belle II

- Hadronization studies in transverse momentum-spin correlations (Λ)/Fragmentation functions
- Precision studies of fragmentation functions needed for Jlab@12GeV program
  - much more statistics, better precision
  - better hadron (K/pi) identification performance
  - better charm suppression/corrections
- Precision study of local strong parity violation to probe the QCD vacuum.
- More others, also important
  - New physics beyond Standard Model
  - New CP violation phase
  - ….

Belle II Schedule



Summary & Outlook

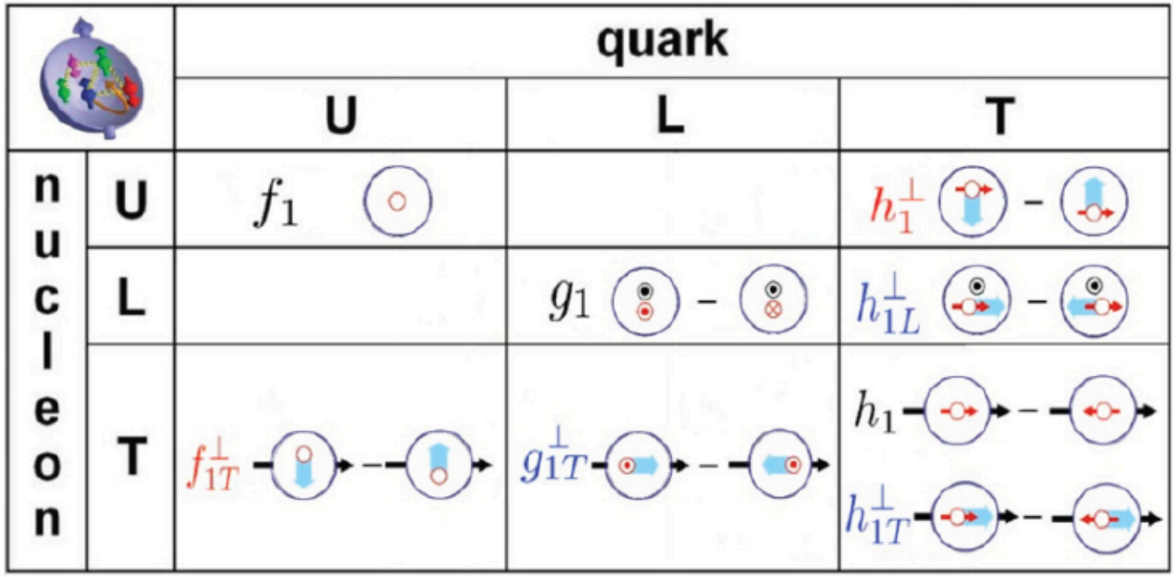
- The measurement of the transverse polarization of $\Lambda(\bar{\Lambda})$ in the inclusive process $e^+e^- \to \Lambda(\bar{\Lambda}) + X$ and $e^+e^- \to \Lambda(\bar{\Lambda}) + K^{\pm}(\pi^{\pm}) + X$ is performed at Belle.
- Nonzero transverse polarizations of $\Lambda(\bar{\Lambda})$ is observed 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.

- Outlook
  - More correlation can be explored: $e^+e^- \to \Lambda + \bar{\Lambda} + \mathrm{X}$ ...
  - The SuperKEKB and Belle-II detector are under construction. Physics runs are expected from 2018. New opportunities at Belle II.

Thank you！

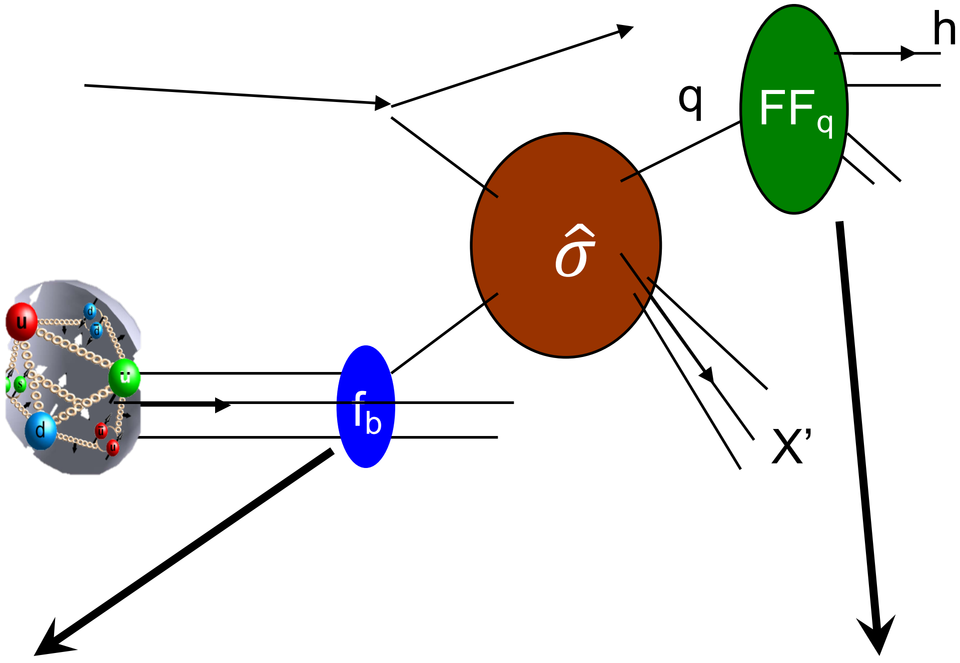
32 Backup slides

Parton distribution function



Fragmentation Functions: Why should we bother?

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes, needed to extract nucleon structure
- FFs non-perturbative QCD objects



Proton Structure

pQCD

fragmentation function

$$\frac{d^3 \quad (pp \qquad {}^+X)}{dx_1 dx_2 dz} \quad q_i\,(x_1, k_{q,T})\ \ G(x_2) \quad \frac{d^3\ \hat{}\ \ (q_i q_j \qquad q_k q_l)}{dx_1 dx_2} \quad FF_{q_{k,l}}(z, p_{h,T})$$

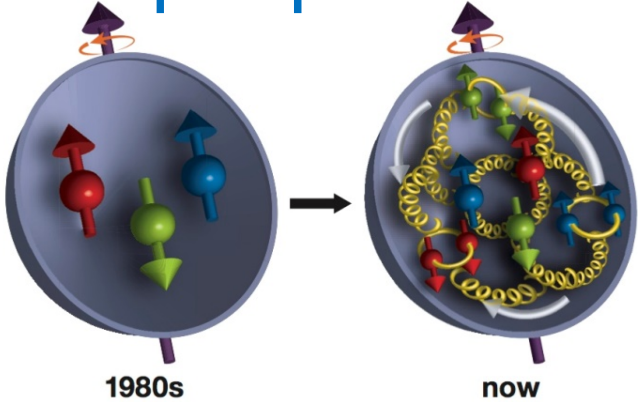
Unsolved questions/puzzles

- Where does the mass come from?
  - The Higgs boson only gives mass to some very simple particles.
  - The vast majority of mass comes from the energy needed to hold quarks together inside nuclei.
- Why are quarks confined in hadrons?
- How is the nucleon‘s spin is distributed amongst its constituent partons?
- …..
- Strong interaction sector of the Standard Model, QCD, *is not well understood.*

mass?

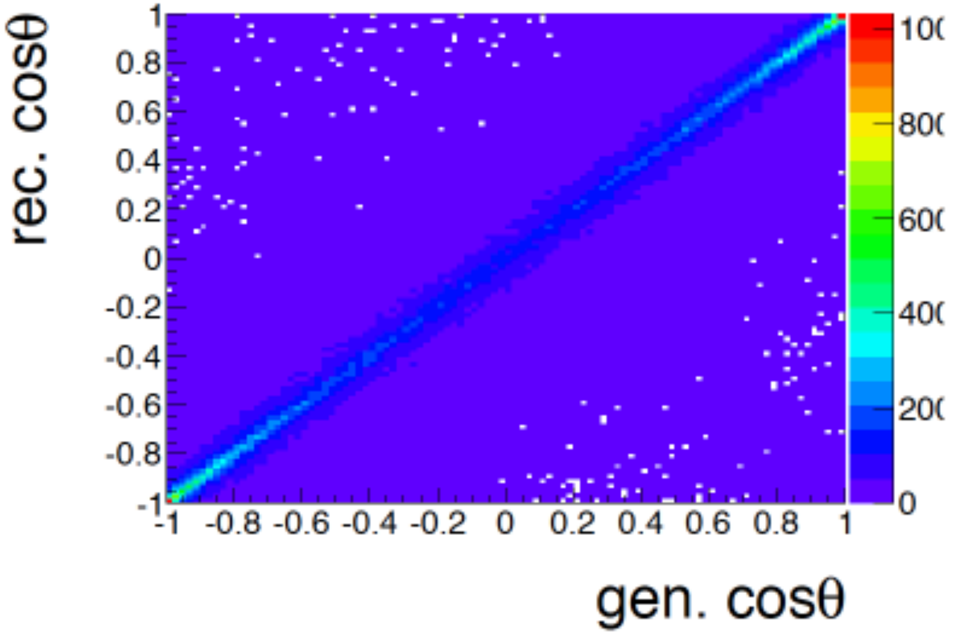
confinement

spin puzzle

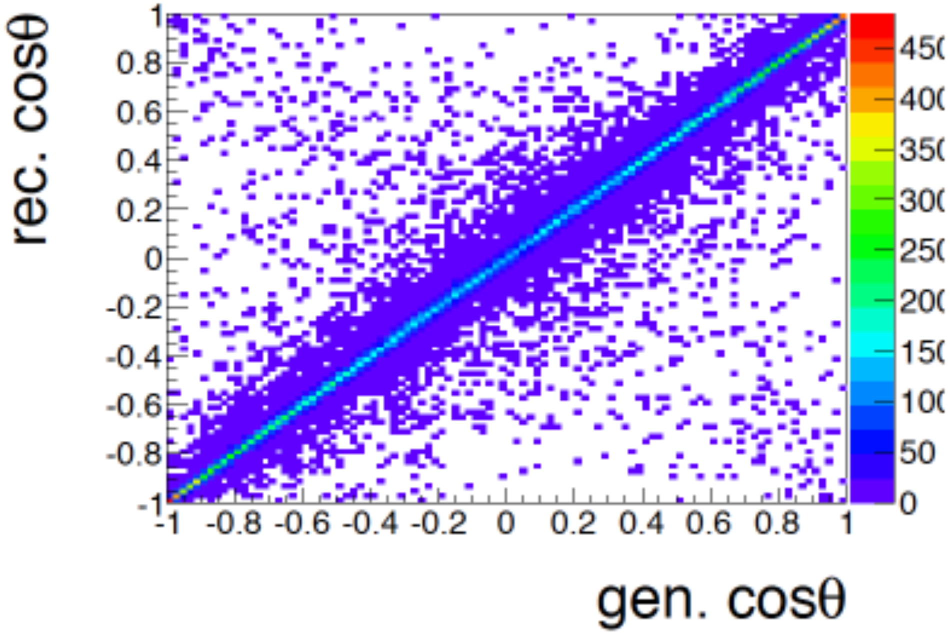


Reference Frames (rec. vs. gen.)

Thrust Frame



Hadron Frame



- Smearing effects caused the detector resolutions.
- The hadron frame has better performance, because the resolution of a light hadron is better than the thrust axis.
- The dilution caused the smearing will be estimated from MC and used to correct results from data.