FRAGMENTATION STUDIES AT THE B-FACTORIES

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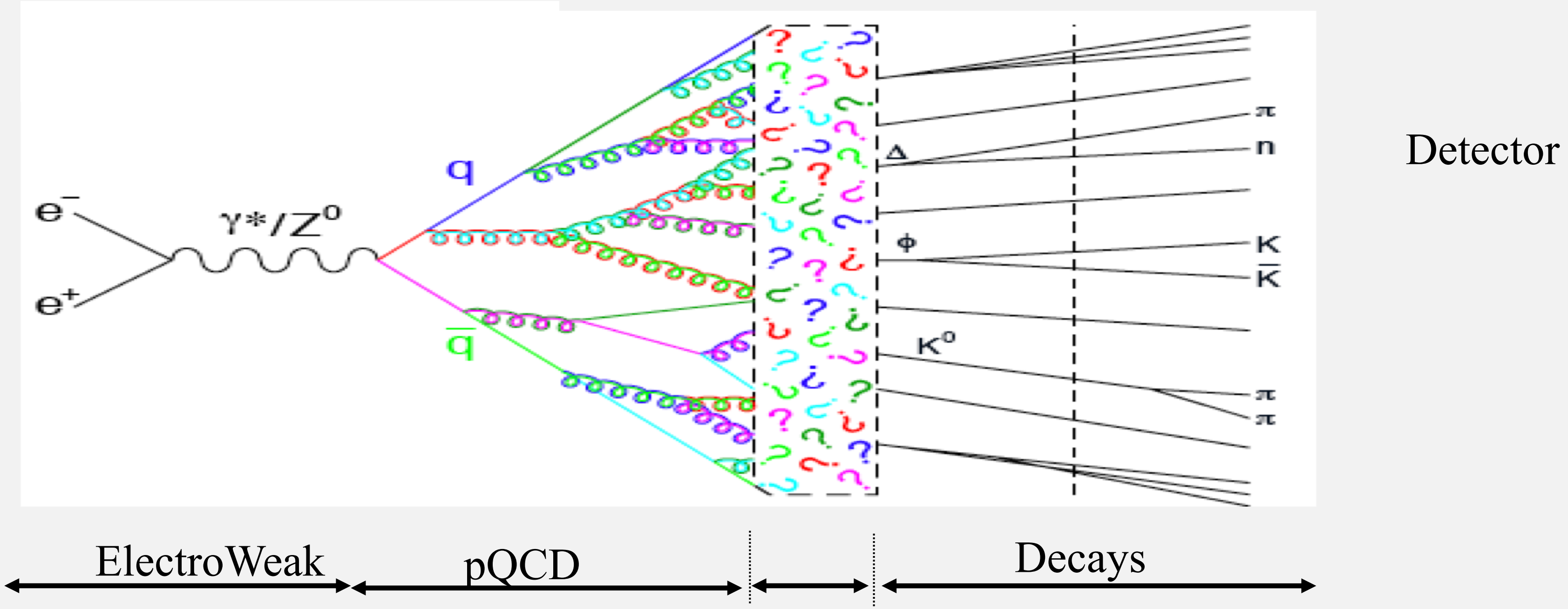
CIPANP 2018
June 1

FACTORIZED QCD: HADRONIZATION DESCRIBED BY 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]



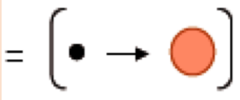
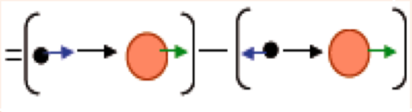
- Complementary to the study of nucleon structure (PDFs)
- Cannot be computed on the lattice
- Questions to be asked
  - Macroscopic effect (distribution, polarization)of microscopic properties (quantum numbers)?
  - Effect of QCD vacuum the quark is traversing
  - Study of the formation of hadrons →e.g. Phys.Rev. D97 (2018) no.7, 072005

AMSTERDAM NOTATION FOR FFS WITH QUARK/HADRON POLARIZATION

<u>Observables:</u>

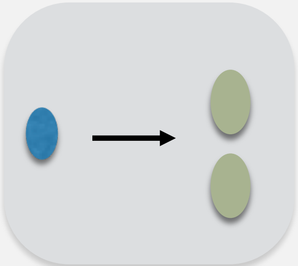
z: fractional energy of the quark carried by the hadron

$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → **Hadron Polarization ↓**	**Spin averaged**	**longitudinal**	**transverse**
spin averaged	$D_1^{h/q}(z, p_T)$ 		$H_1^{\perp h/q}(z, p_T)$ 
longitudinal		$G_1^{h/q}(z, p_T)$ 	
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z, p_T)$ 		$H_1^{q/\Lambda}(z, p_T)$ 

- Theoretically many more, in particular with polarized hadrons in the final state and transverse momentum dependence →similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay (Λ)
- Gluon FFs similar but with circular/linear polarization (not as relevant for e+e-)

DI-HADRON FRAGMENTATION FUNCTIONS



<u>Additional Observable:</u>

$\vec{R} = \overrightarrow{P_1} - \overrightarrow{P_2}$:

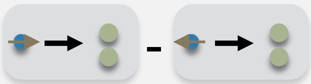
The relative momentum of the hadron pair is an additional degree of freedom:

<u>*the orientation of the two hadrons w.r.t. each other and the jet direction can be an indicator of the quark transverse spin*</u>

<u>*Do not need*</u>

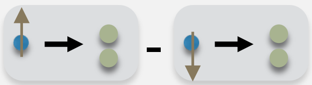
Small $\vec{R}$: non-perturbative object.

Parton polarization → Hadron Polarization ⇣	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h_1 h_2/q}(z, M)$	$G_1^{1\perp}(z, M, P_{hT})$	$H_1^{\measuredangle}(z, M)$



$G_1^{\perp}$: T-odd FF

- chiral-even function
- log. polarized q → two unp. Hadrons
- →connection to jet-handedness and (possibly) QCD vacuum structure

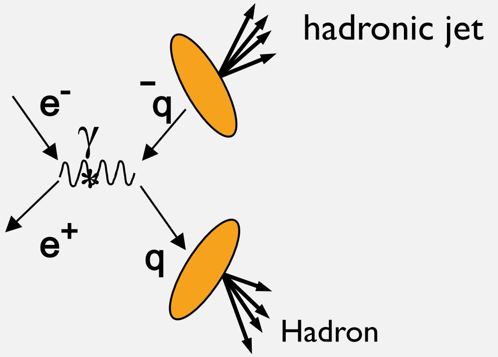


$H_1^{\measuredangle}$: T-odd FF

- Chiral-odd function
- Transv. polarized q → two unp. Hadrons
- →Collinear! (unlike Collins)

ACCESS OF FFS FOR LIGHT MESONS IN E^+E^- (SPIN AVERAGED CASE)

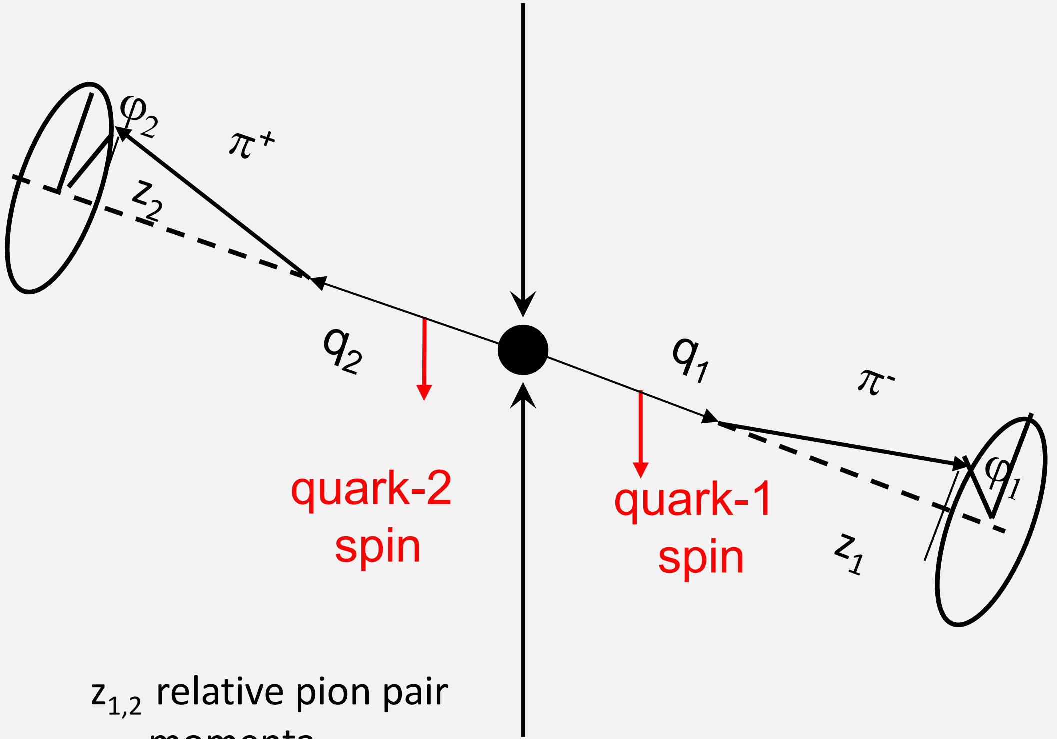
$$\frac{1}{\sigma_{\mathrm{tot}}}\frac{d\sigma^{e^+e^-\to hX}}{dz} = \frac{1}{\sum_q e_q^2}\left(2F_1^h(z,Q^2)+F_L^h(z,Q^2)\right),$$



$$2F_1^h(z,Q^2) \;=\; \sum_q e_q^2\left(D_1^{h/q}(z,Q^2)+\frac{\alpha_s(Q^2)}{2\pi}\left(C_1^q\otimes D_1^{h/q}+C_1^g\otimes D_1^{h/g}\right)(z,Q^2)\right)$$

- Cleanest process
- Clean environment, hermetic dectors → can reconstruct complex final states, differentiate from feed-down
- Well understood, calculations available at NNLO
- Limited access to flavor
  - Use different couplings to γ^* and Z^0
  - Use polarization (SLD) and parity violating coupling
  - Use back-to-back correlations for different flavor combinations → Phys.Rev. **D**92 (2015) no.9, 092007 (Belle)
- Limited access to gluon FF
  - From evolution
  - From three jet events (but theory treatment not clear)

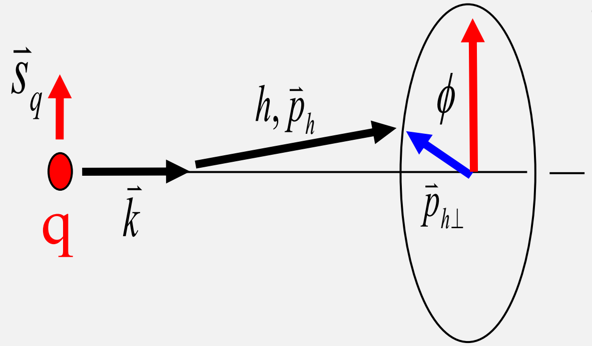
CORRELATION MEASUREMENTS IN E+E-



$z_{1,2}$ relative pion pair momenta

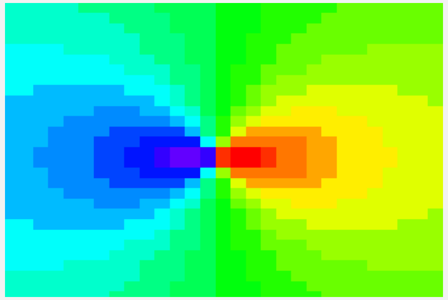
J. Collins, Nucl. Phys. B396, (1993) 161

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



Cross-section $e^+e^- \to (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

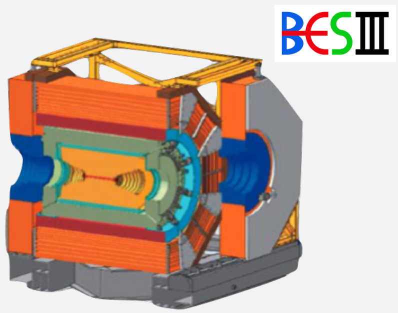
$$\propto D_1^{\perp}\,\overline{D_1^{\perp}} + H_1^{\perp}\,\overline{H_1^{\perp}}\cos(\phi_1+\phi_2)$$



- Access spin dependence and p_T dependence (convolution or in jet) without PDF complication
- Made possible by B-factory luminosities

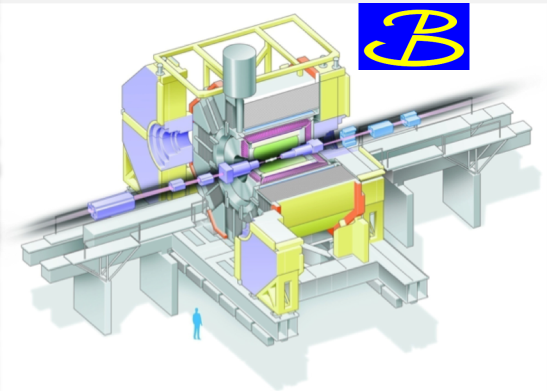
THE BESII, BELLE AND BABAR EXPERIMENTS

NIMA**614**,345(2010)



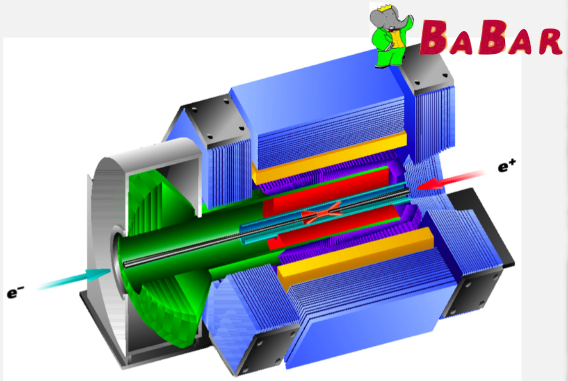
- Symmetric e^+e^- collider
- $\sqrt{s}$ = [2 - 4.6] GeV
- 62 pb^{-1} @ 3.65 GeV used for Collins studies
- Below open-charm threshold

- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma=0.425$
- $L \sim 1\ ab^{-1}$



NIMA**479**,117(2002)

NIMA**729**,615(2013)

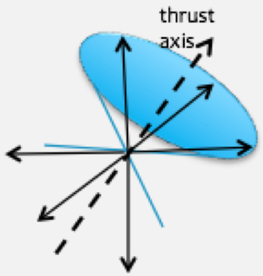


- Asymmetric-energy e^+e^- collider
- $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
- $\beta\gamma=0.65$
- $L \sim 500\ fb^{-1}$

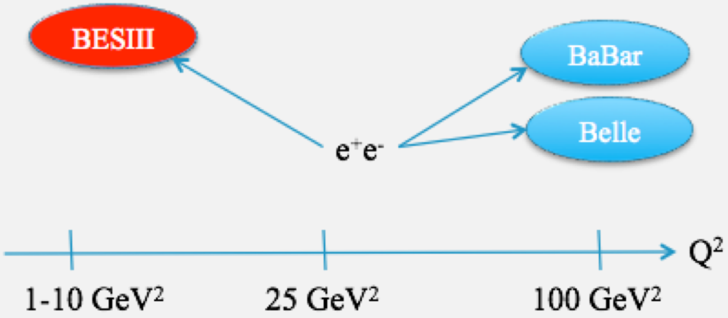
$$T = \sum_i \frac{|\mathbf{P} \cdot \hat{\mathbf{n}}|}{|P|}$$

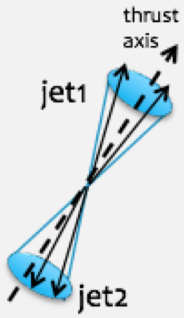
thrust axis $\equiv \hat{\mathbf{n}}$

$0.5 \leq T \leq 1$



T~0.5

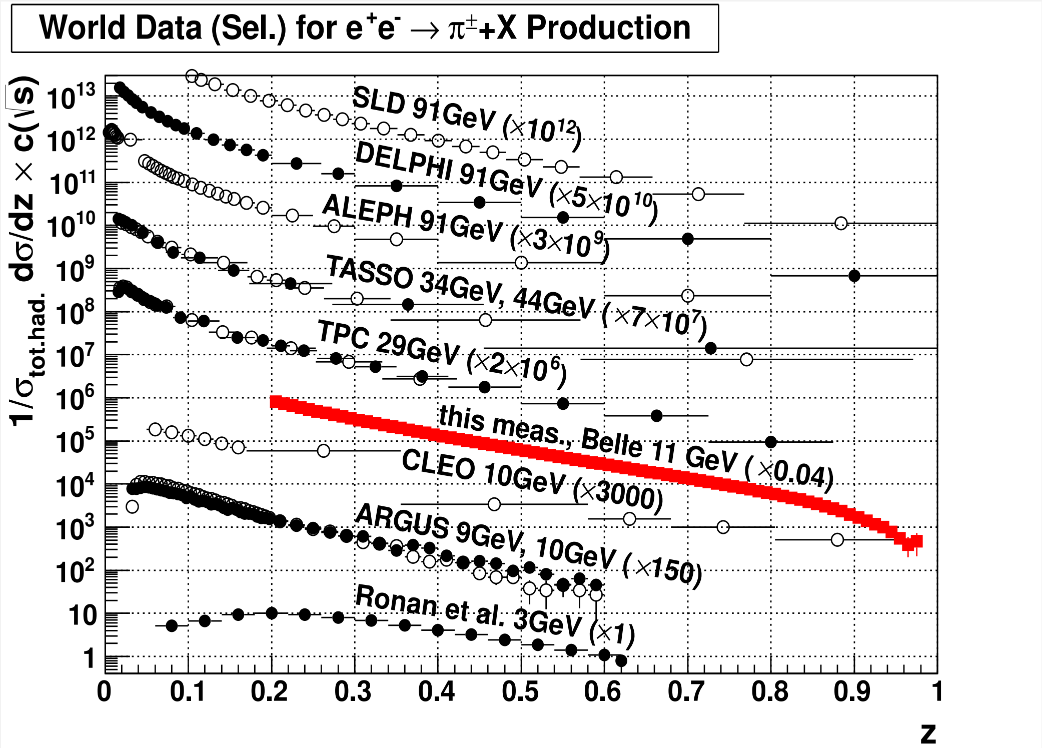


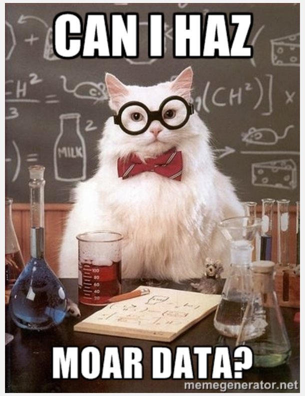


T~1

WORLD DATA ON E^+E^-

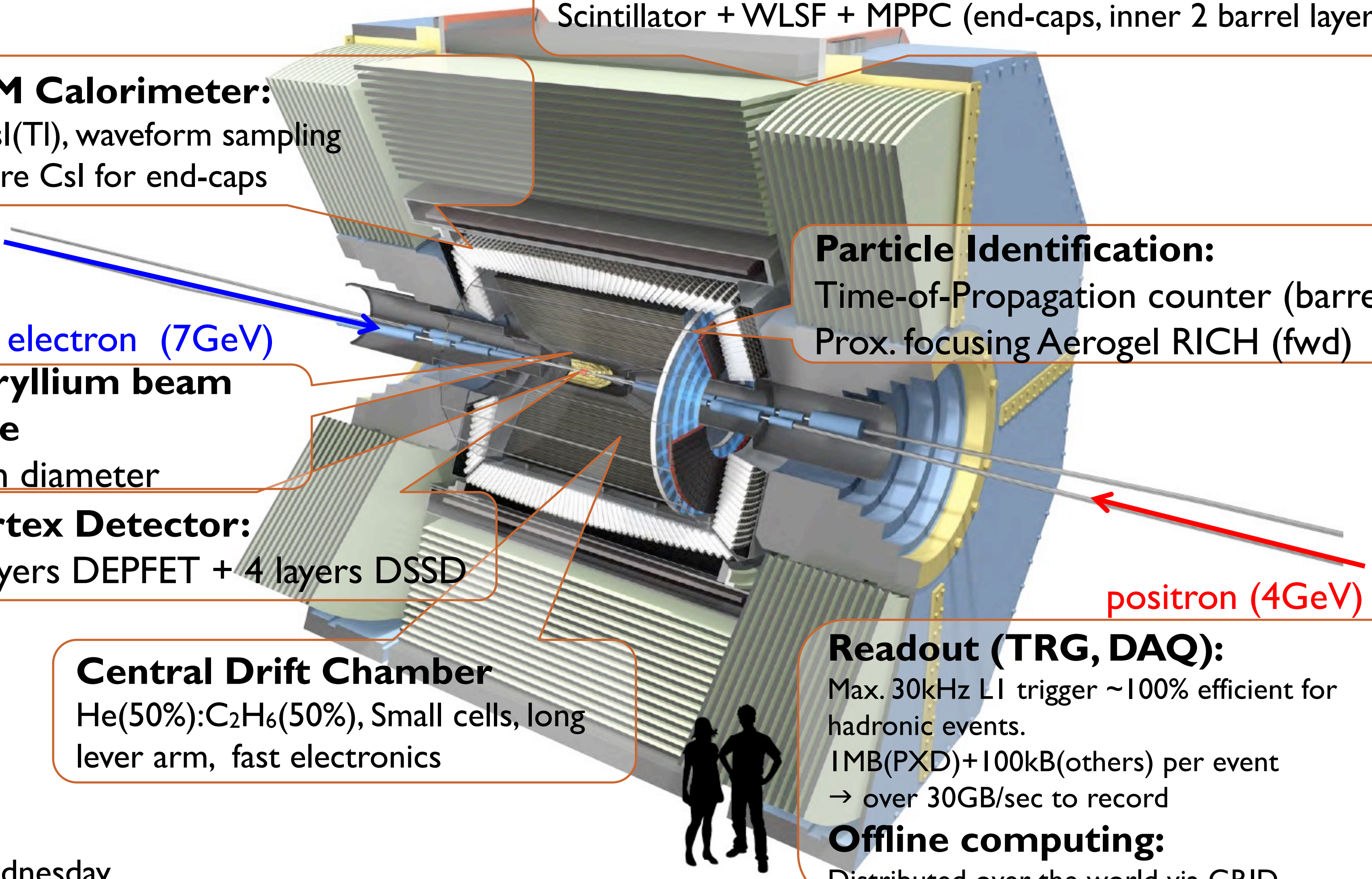
- Dominated by B factories
- Limited lever arm in $\sqrt{s}$ in particular at high z
- Precision data includes charged single hadrons π, K, p, $D^{(*)}$, Λ, charmed baryons…
- Pairs of π, K, p
- With B factory data theory and data uncertainties similar, good description by NNLO, some more work tbd at high and low z





Phys.Rev.Lett. 111 (2013) 062002 (Belle)
Phys.Rev. D88 (2013) 032011 (BaBar)

THE FUTURE: BELLE II AT SUPERKEKB (40X KEKB IN LUMINOSITY)



K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter:
CsI(Tl), waveform sampling
Pure CsI for end-caps

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector:
2 layers DEPFET + 4 layers DSSD

positron (4GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

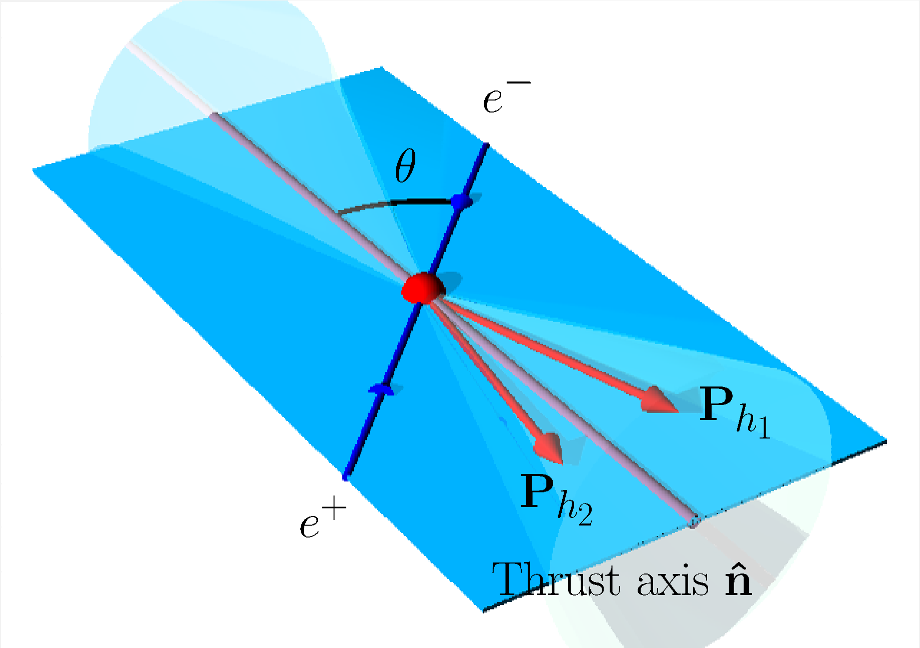
Readout (TRG, DAQ):
Max. 30kHz L1 trigger ~100% efficient for hadronic events.
1MB(PXD)+100kB(others) per event
→ over 30GB/sec to record

Offline computing:
Distributed over the world via GRID

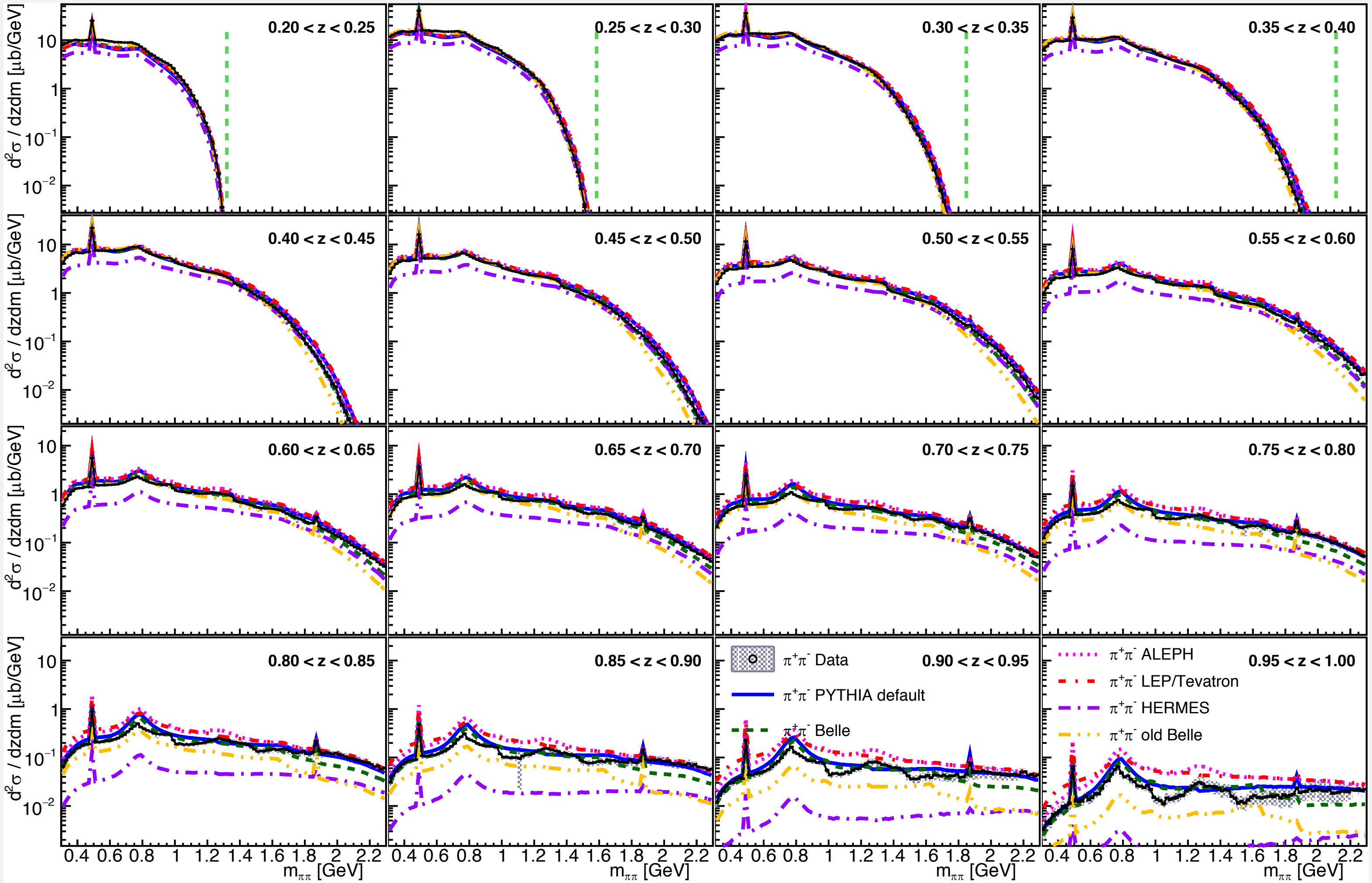
See my talk on Wednesday

MEASUREMENT OF DI-HADRON CROSS-SECTION TO EXTRACT $D_1^{h_1 h_2/q}(z, M)$ (Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005)

- From count rates to cross-sections and asymmetries
  - Particle (mis) identification
  - Smearing unfolding
  - Non-$\overline{qq}$ processes
  - Acceptance correction
  - QED radiation
  - Optional: weak decay removal
  - Asymmetries are corrected for ”false asymmetries” and thrust axis smearing if applicable

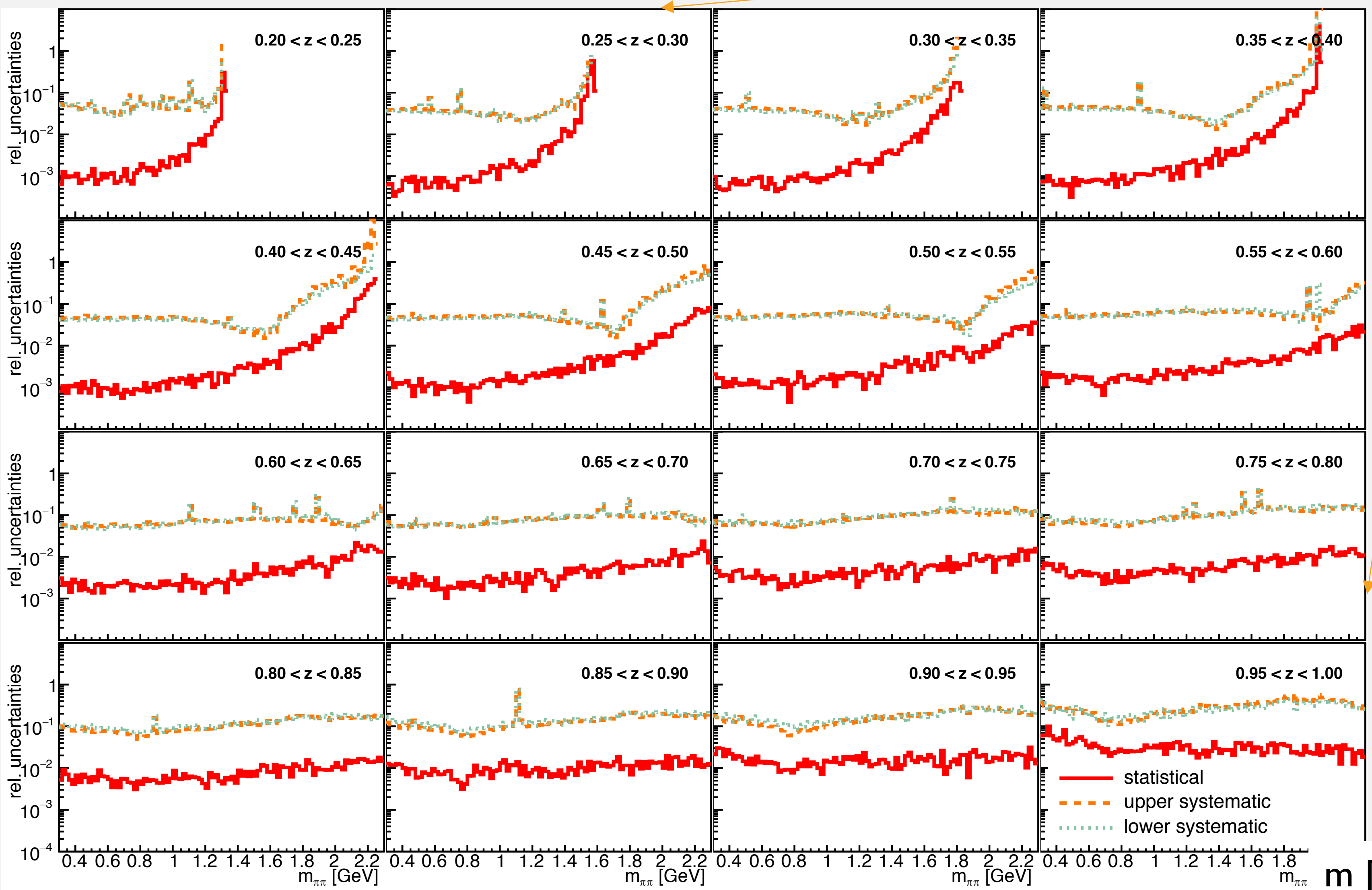


RESULTS COMPARED WITH MC



m [GeV]

RESULTS SYSTEMATICS DOMINATED

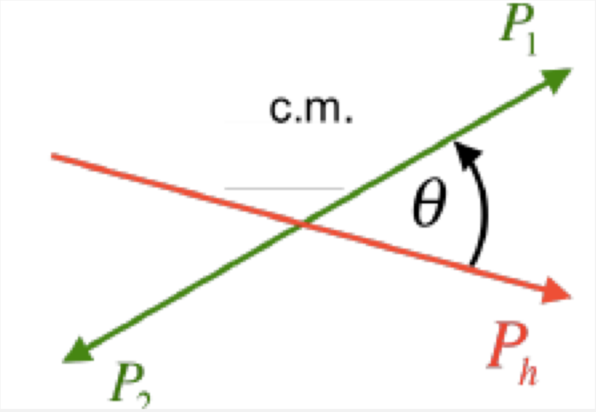


m [GeV]

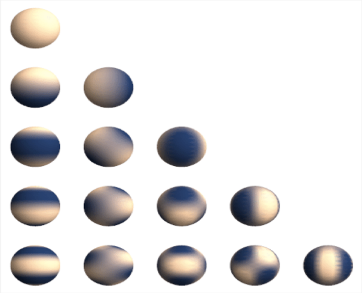
- Low z: Dominated by PID uncertainties
  Belle II prospects: Improved PID, higher statistics to improve uncertainties on PID
- High z: Dominated by ISR uncertainties
  Belle II prospects: better understanding of ISR radiation with better statistics
-

Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

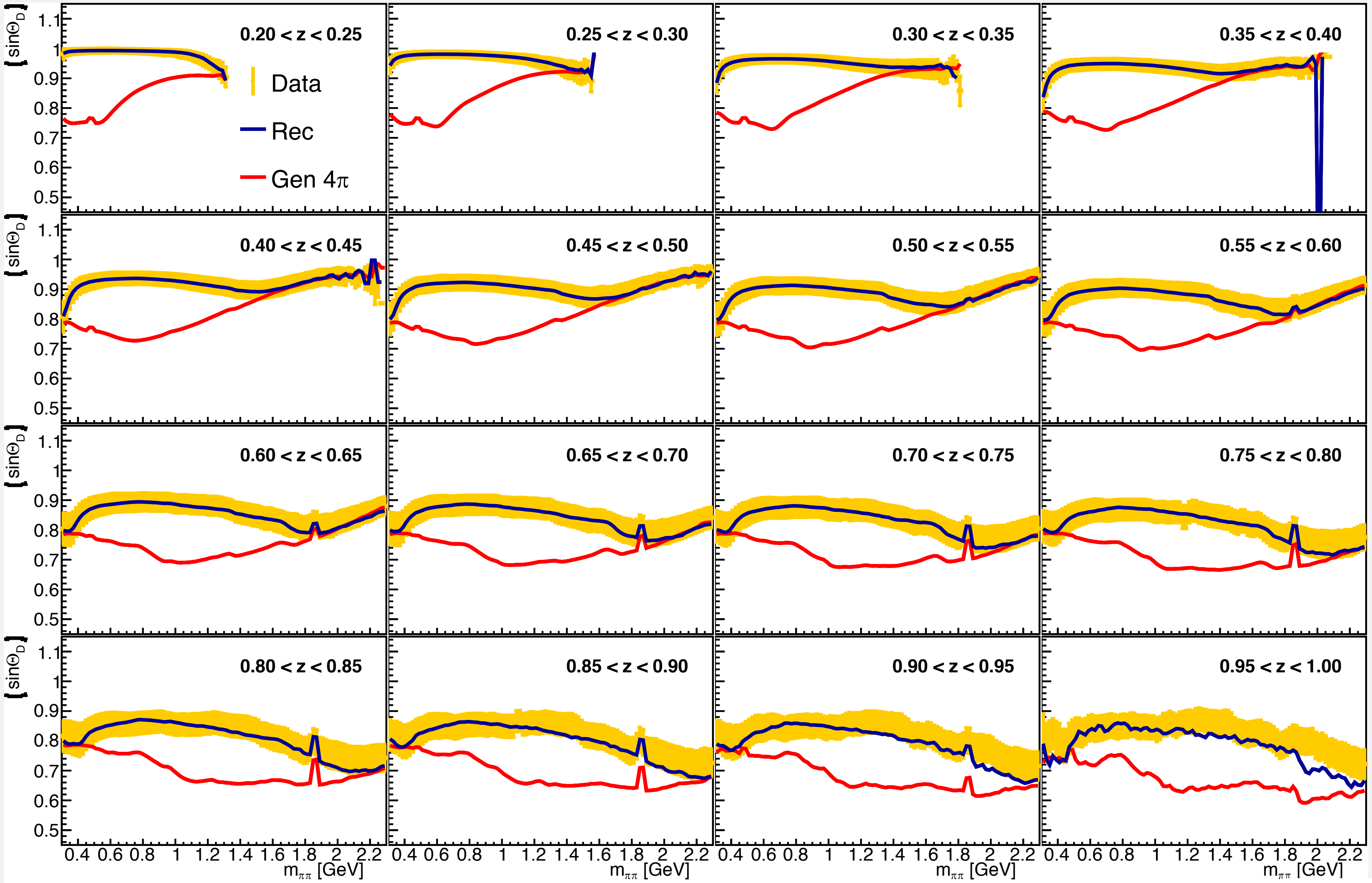
BELLE II PROSPECTS



- Partial Wave decomposition (more general: θ dependence)
- Higher order PWs lead to different moments in θ and ϕ
- In models, evolution of the different PWs different
- Important to have a full picture to understand mixing effects in ratios/partial integrals/acceptance
- Missing info from partial wave estimated to have effects up to 10% e.g. on extraction of transversity



ACCEPTANCE IMPACT ON PARTIAL WAVE COMPOSITION



m [GeV]

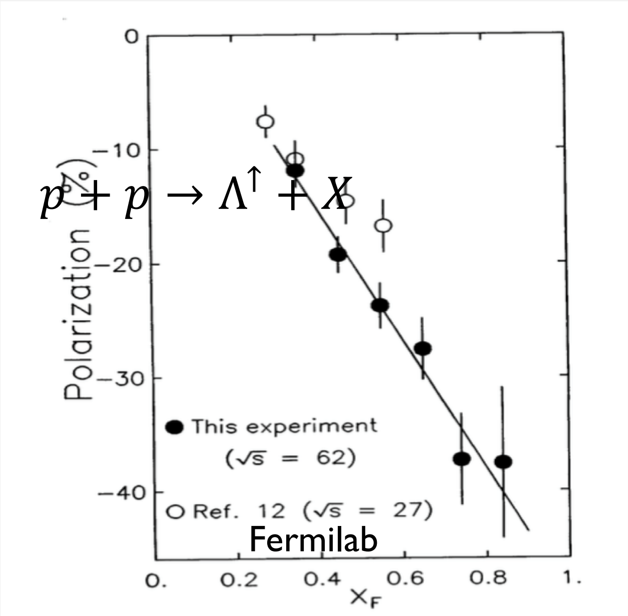
Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

- Belle II prospects: Sufficient statistics for full partial wave decomposition

POLARIZED HYPERON PRODUCTION

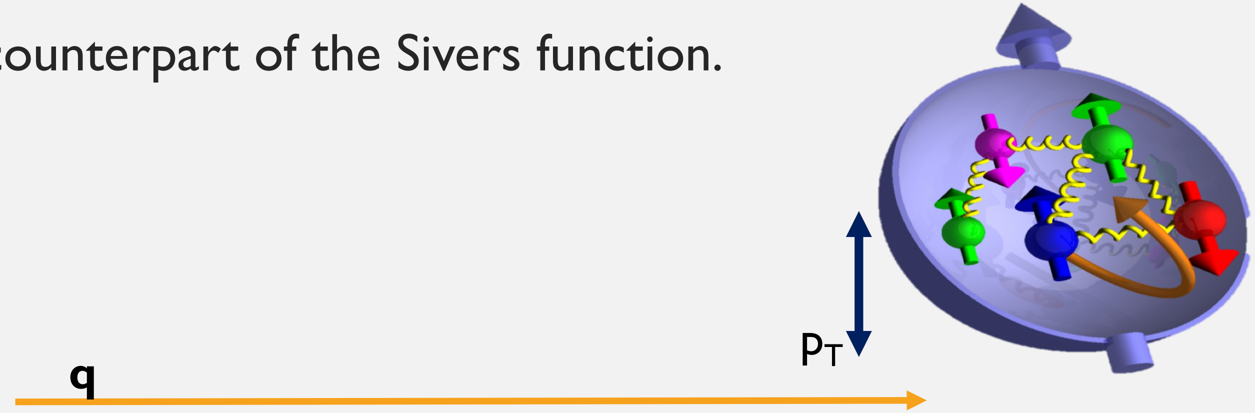
- Large Λ transverse polarization in unpolarized pp collision **PRL36, 1113 (1976); PRL41, 607 (1978)**
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- Polarizing FF is chiral-even, has been proposed as a test of universality. **PRL105,202001 (2010)**
- OPAL experiment at LEP has been looking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

$p + p \to \Lambda^{\uparrow} + X$

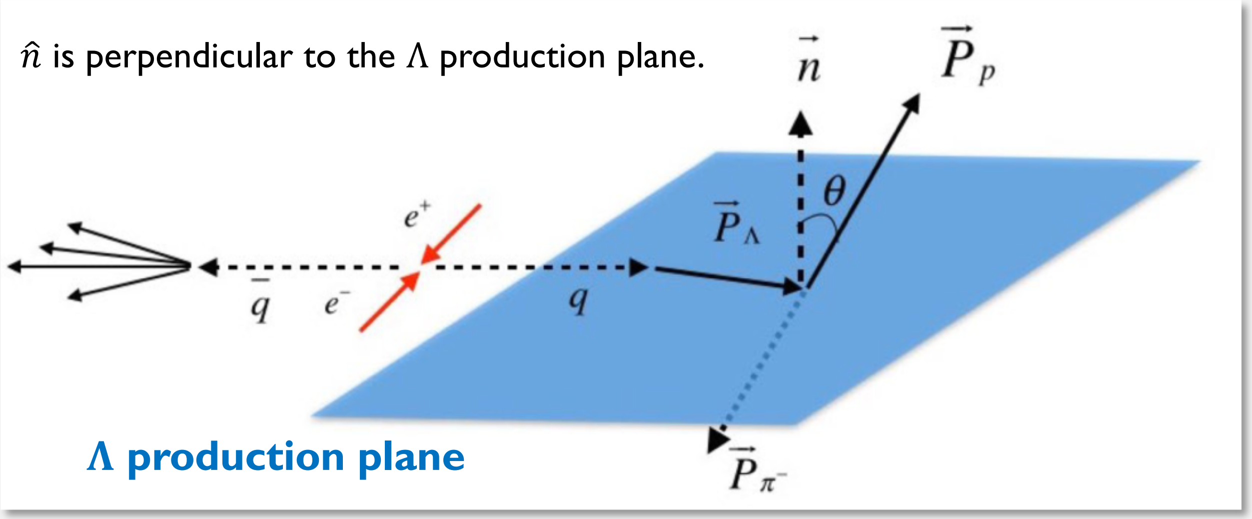


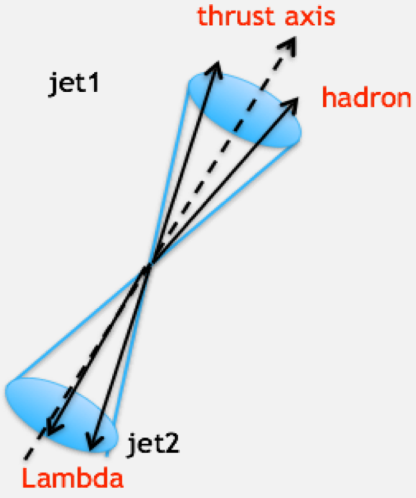
ISR data
(**Phys.Lett. B185 (1987) 209)**

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

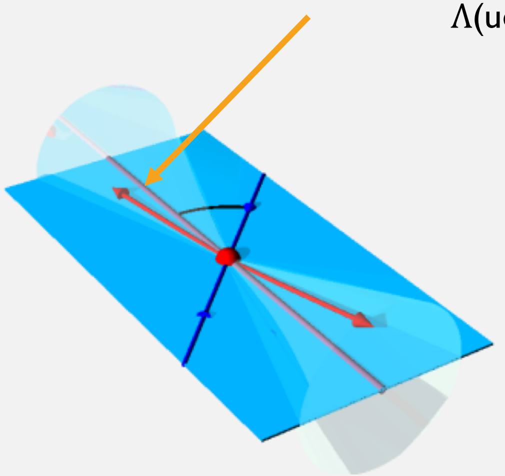


OBSERVABLES IN Λ RESTFRAME

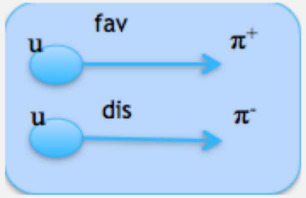




thrust axis



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



- Self-analyzing decay leads to polarization dependent distribution

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

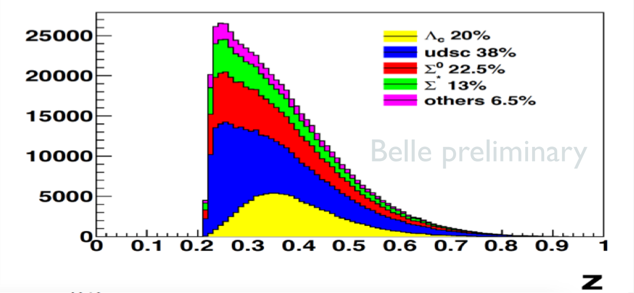
- where α is the decay parameter: α_+=0.642 $\pm$ 0.013 for Λ and α_-=-0.71 $\pm$ 0.08 for $\bar{\Lambda}$ (PDG).
- The p_t is measured as the transverse momentum of Λ relative to the **thrust axis**

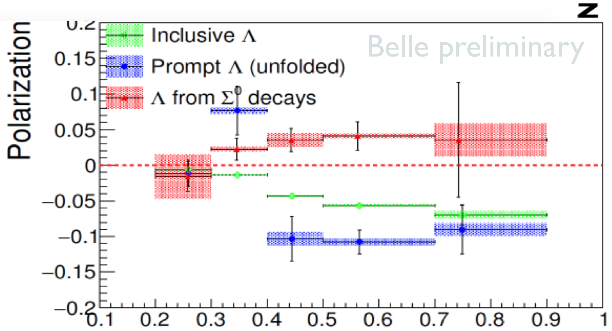
BACKGROUND UNFOLDING

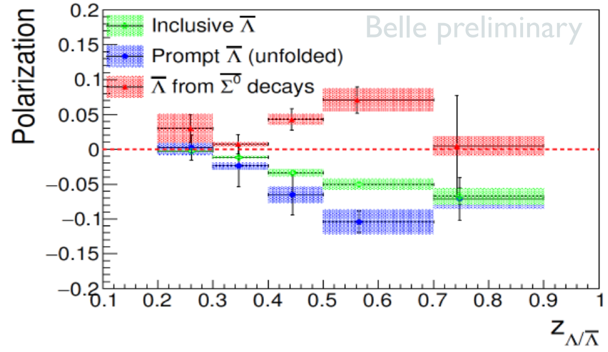
- Σ^* decays to Λ strongly, is included in the signal.
- Feed-down from Σ^0(22.5%), Λ_c(20%) decays need to be understood.
- The Σ^0-enhanced ($\Sigma^0 \rightarrow \Lambda + \gamma$) (Br~100%). and Λ_c-enhanced($\Lambda_c \rightarrow \Lambda + \pi^+$)(Br~1.07%) data sets are selected and studied.
-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

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

- 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.

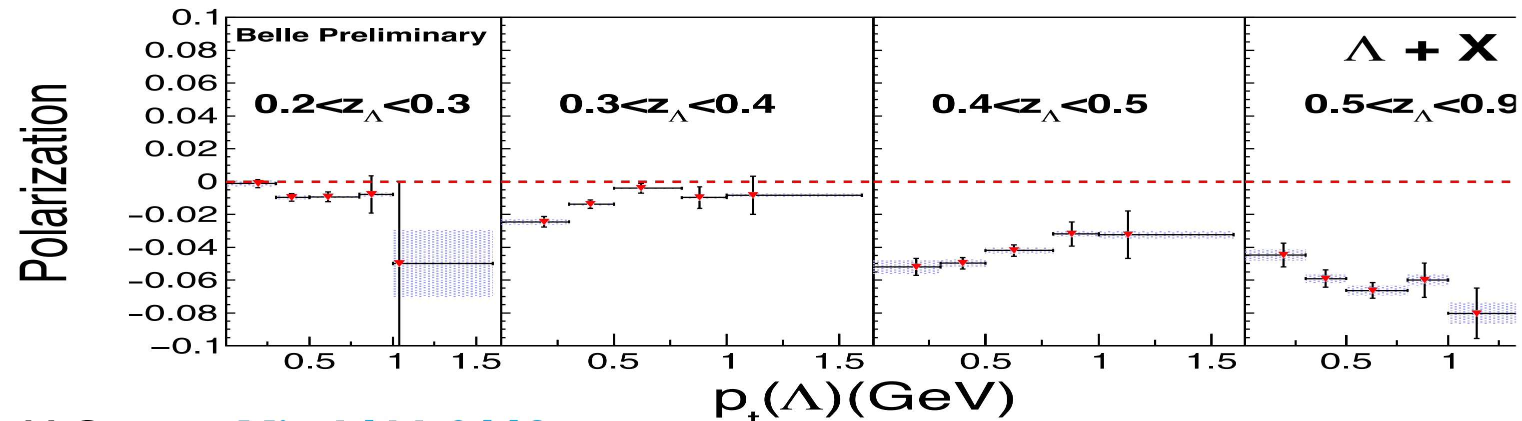




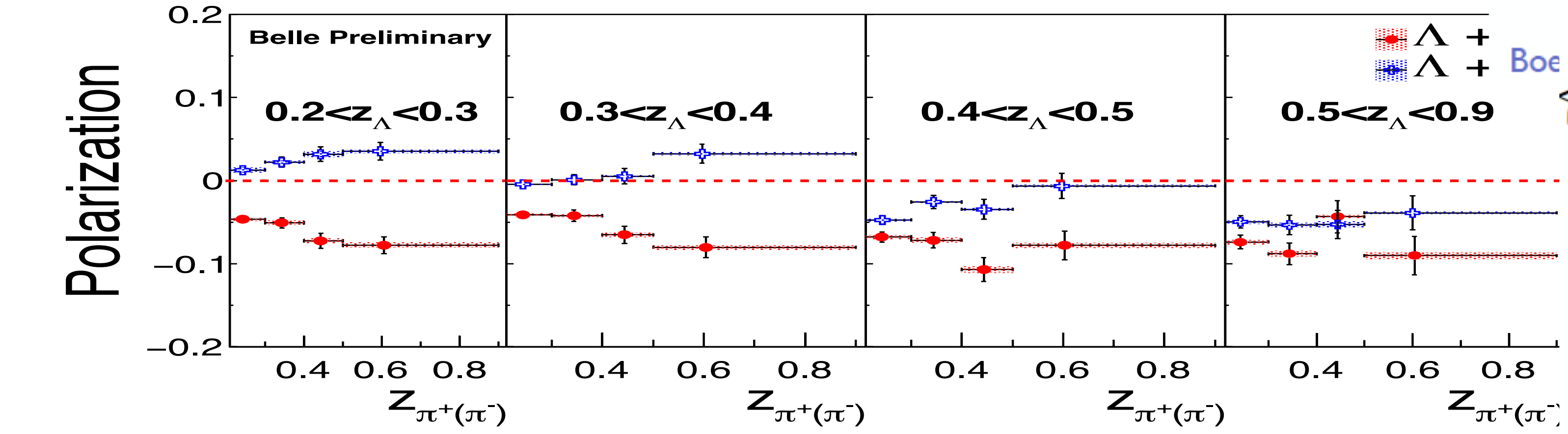


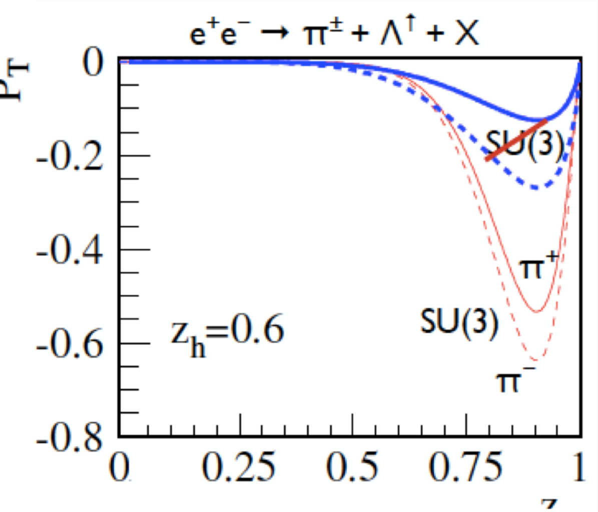
R. Gatto, Phys. Rev. 109, 610 (1958); Phys.Lett.B303,350(1993)

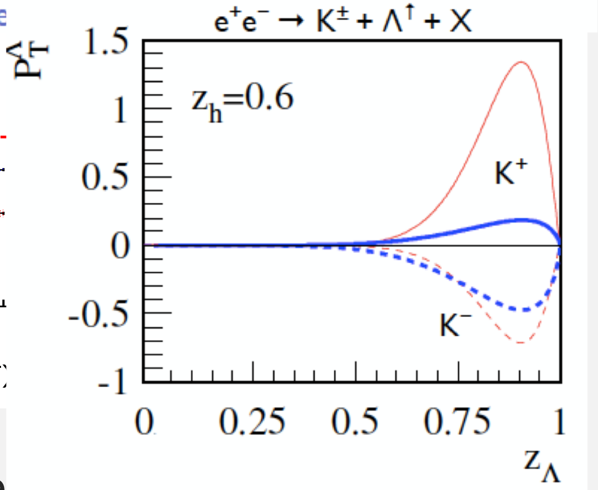
Z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION



Y. Guan, arXiv:1611.0668

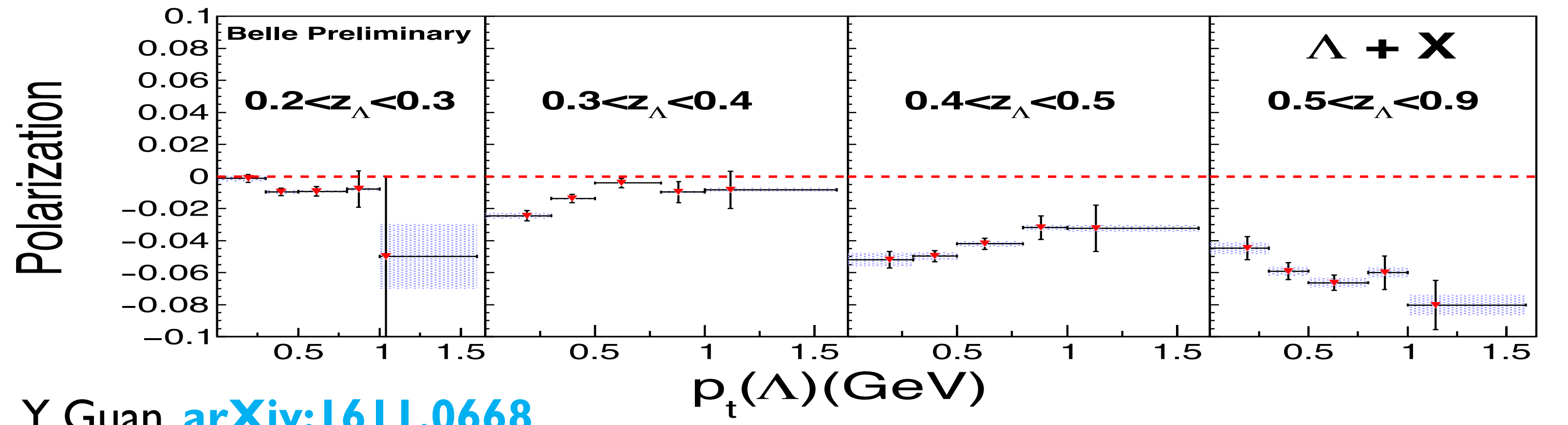






- Polarization rises with p_t in the lowest z_Λ and highest z_Λ bin. But the dependence reverses around 1 GeV in the intermediate z_Λ bins→**Unexpected!** (might be related to fragmenting quark flavor dependence on z_1,z_2)
- Correlation with opposite hemisphere light meson →quark flav/charge dependence

BELLE II PROSPECTS



Y. Guan, arXiv:1611.0668

- Explore low pT region with higher statistics and better tracking resolution
- Feed down correction for pT dependence and associated production
  - (currently only for z dependence, introduces large uncertainties)
  - $\Lambda^{\uparrow} - \Lambda^{\uparrow}$ correlations
  - ….

SUMMARY

- e^+e^- played and will play a crucial role in understanding hadronization and extracting fragmentation functions
- Important contributions to our knowledge of polarized and k_T dependent FFs
- Belle II started its physics program and will enable a new level of precision and the use of more rare probes
- Belle results on the horizon
  - k_T dependence of D_1
  - η/π^0 Collins

BACKUP

Collins Effect vs (z_1,z_2): comparisons

Unlike/**L**ikesign

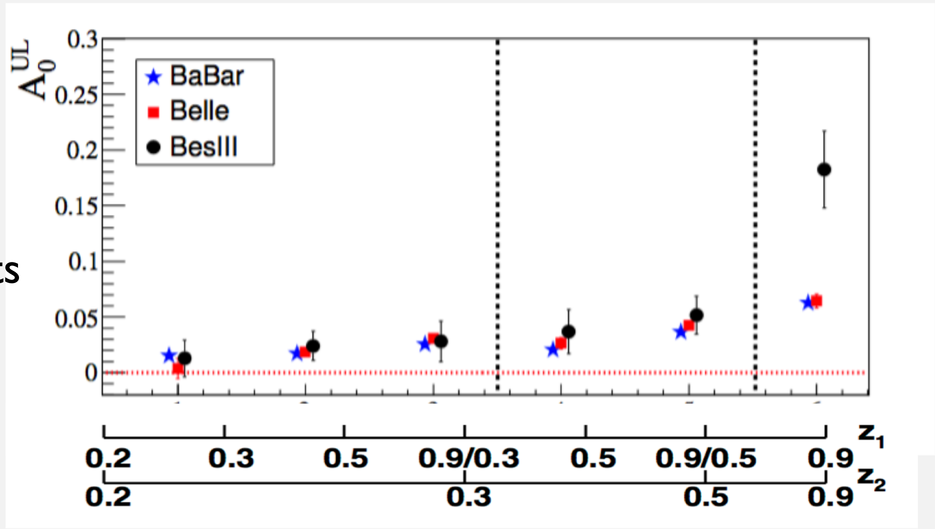
Ratios to cancel acceptance effects

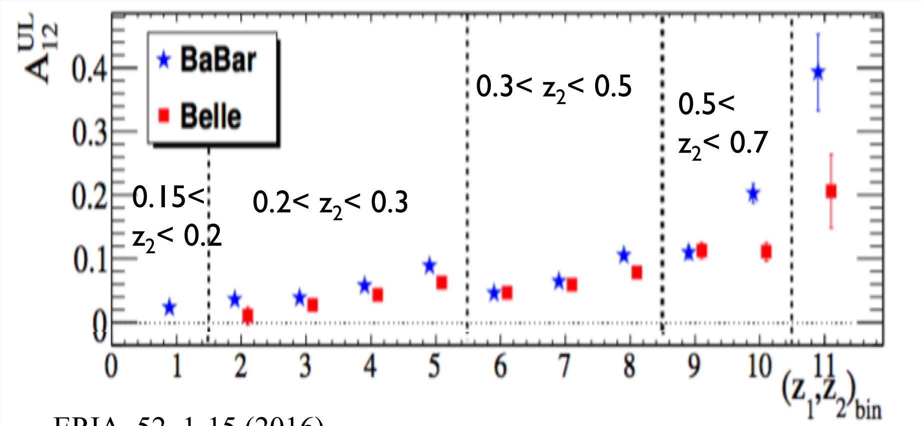
Unlike:

fav*fav+dis*dis

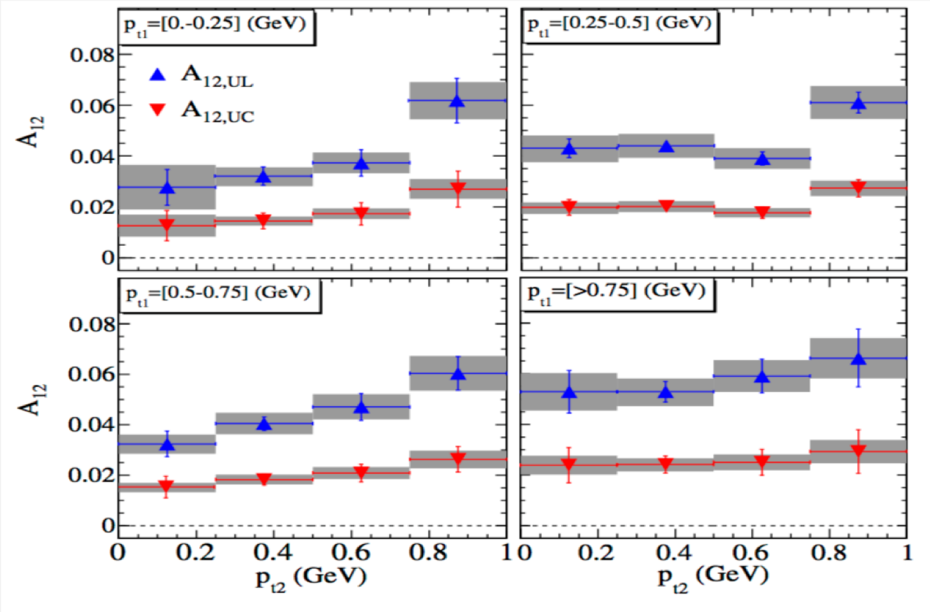
Like:

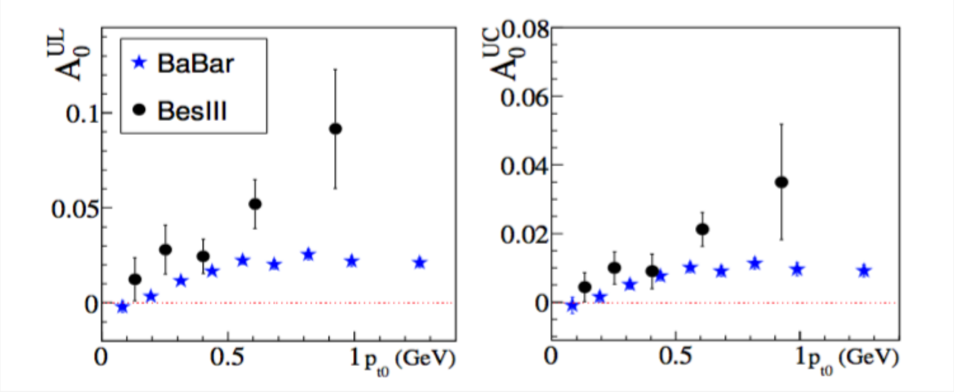
fav*dis





EPJA, 52, 1-15 (2016)





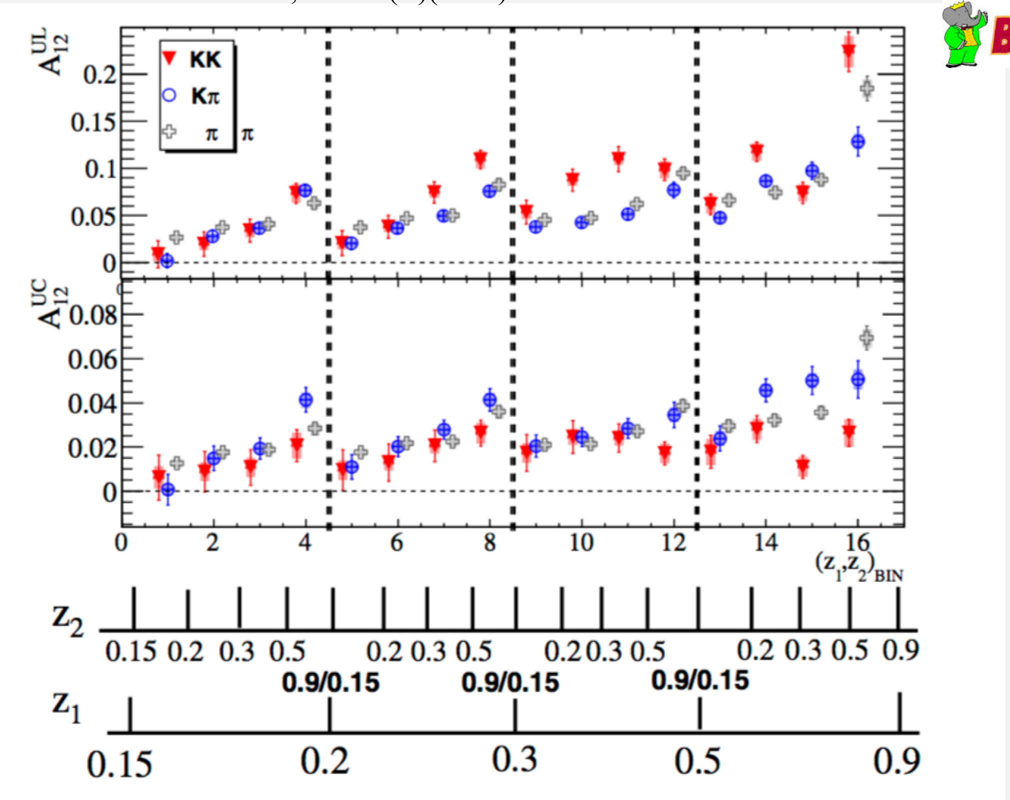
•First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ √s ~ 10.6 GeV (PRL 111,062002(2008), PRD 88,032011(2013)) leads to first extraction of transversity (Phys.Rev. D75 (2007) 054032) from SIDIS and e+e-

- Confirmed by BaBar @ √s ~ 10.6 GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
- Measured at BESIII @ √s = 3.65 GeV (PRL 116,42001(2016))

COLLINS EFFECT FOR KAON/PION PAIRS

Simultaneous measurement of KK, Kπ and ππ Collins asymmetries from BaBar data

PRD 92,111101(R)(2015)

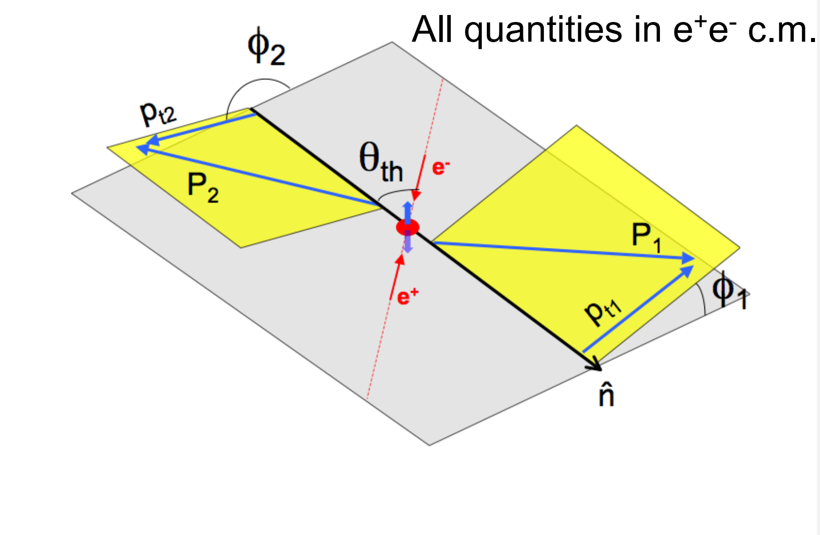


- Rise of the asymmetry as a function of *z*:
- A^{UL} KK asymmetry slightly higher than pion asymmetry for high z
- KK asymmetry consistent with zero at lower z
- ππ asymmetries consistent with previous measurements (PRD**90**, 052003)

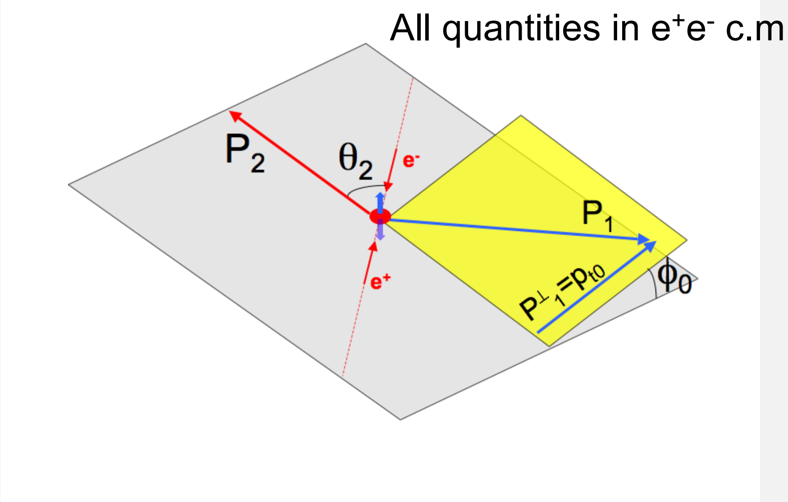
COLLINS EFFECT

RF12 or Thrust RF

BaBar
Belle
~~BESIII~~



RF0 or Second hadron momentum RF



BaBar
Belle
BESIII

- **Thrust axis** to estimate the $q\bar{q}$ direction
- $\varphi_{1,2}$ defined using thrust-beam plane

Normalized cross-section: $e^+e^- \to (h_1 h_2)(\overline{h_1}\ \overline{h_2}) + X$

$$\propto 1 + + H_1^\perp \cdot \overline{H_1^\perp} \cos(\phi_1 + \phi_2)$$

- Use **one track** in a pair
- Very clean experimentally (no thrust axis)

Normalized cross-section: $e^+e^- \to (h_1 h_2)(\overline{h_1}\ \overline{h_2}) + X$

$$\propto 1 + + H_1^\perp * \overline{H_1^\perp} \cos(2\phi_0)$$

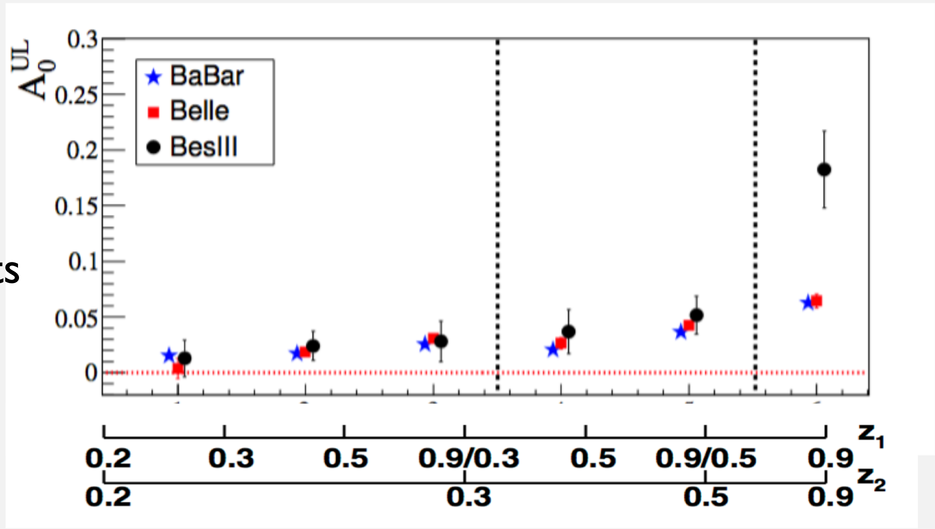
Collins Effect vs (z_1,z_2): comparisons

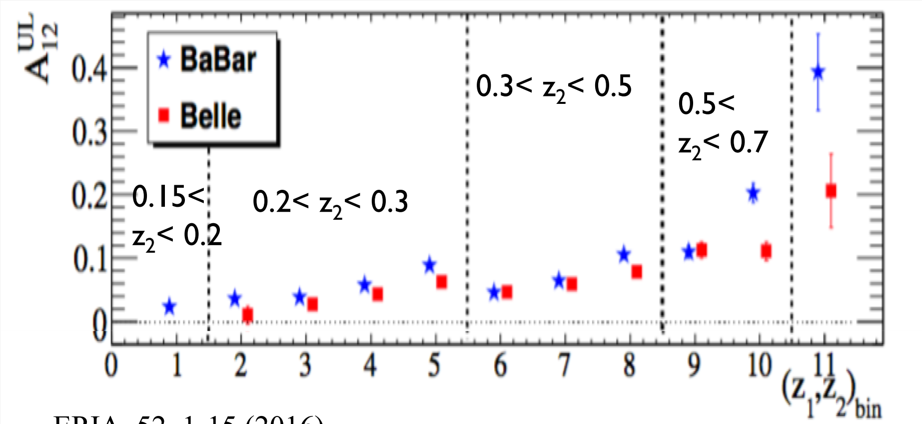
Unlike/**L**ikesign

Ratios to cancel acceptance effects

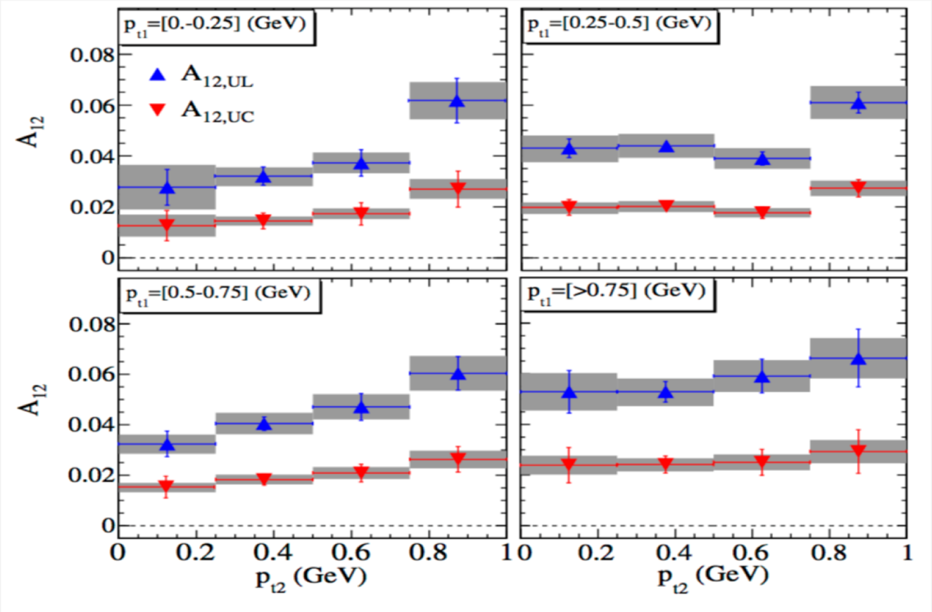
Unlike:
fav*fav+dis*dis

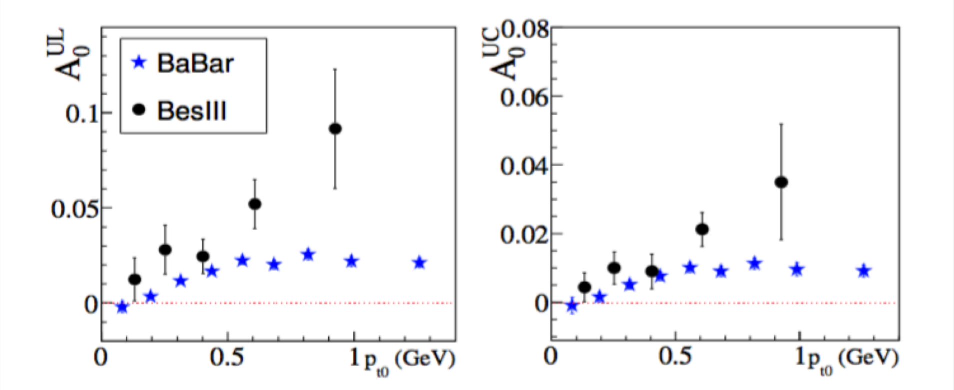
Like:
fav*dis





EPJA, 52, 1-15 (2016)





- First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ √s ~ 10.6 GeV (PRL 111,062002(2008), PRD 88,032011(2013)) leads to first extraction of transversity (Phys.Rev. D75 (2007) 054032) from SIDIS and e+e-
  - Confirmed by BaBar @ √s ~ 10.6 GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
  - Measured at BESIII @ √s = 3.65 GeV (PRL 116,42001(2016))

COLLINS EFFECT FOR KAON/PION PAIRS

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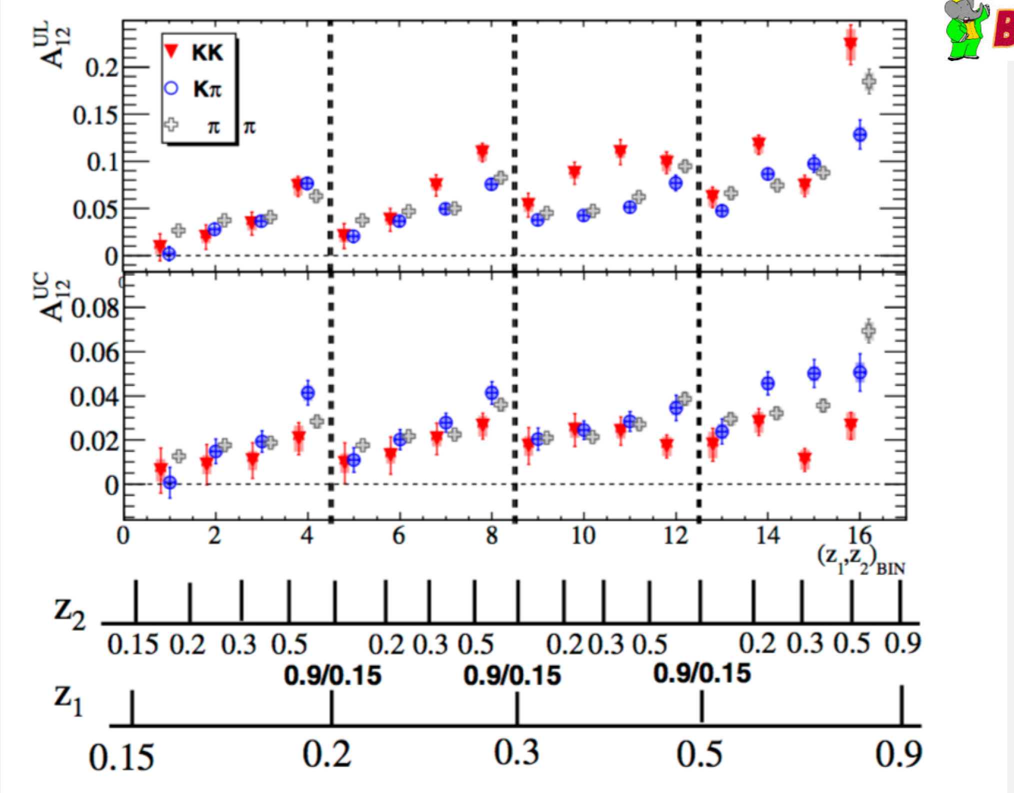

- Rise of the asymmetry as a function of *z*:
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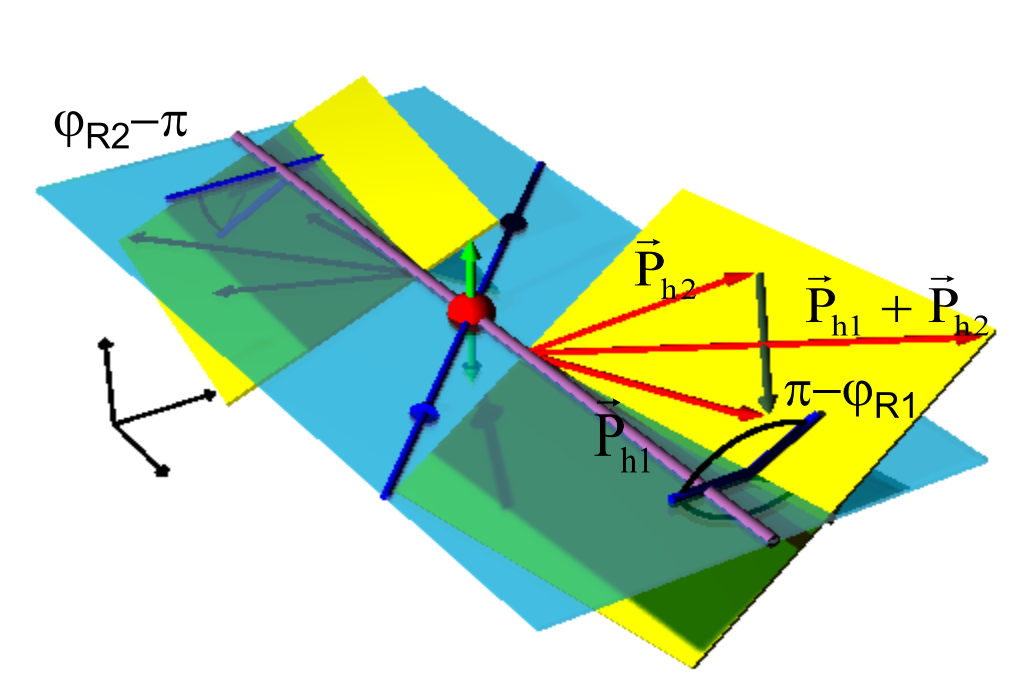
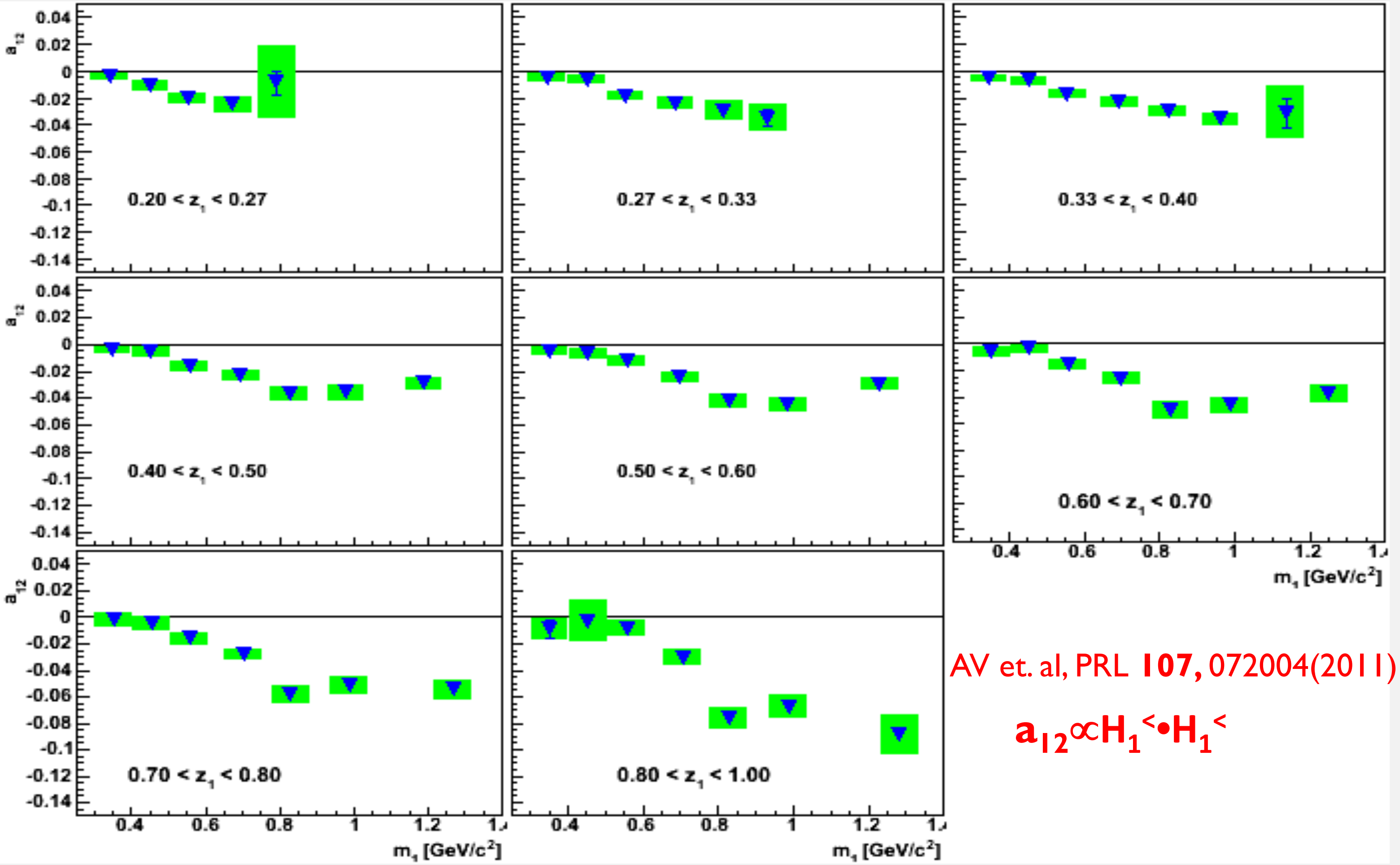
DI-HADRON ASYMMETRIES



- *Conceptually similar measurement as Collins with* $\overrightarrow{P_{h\perp}} \leftrightarrow \overrightarrow{R_\perp}$
- *Normalized cross section:*
  $e^+e^- \to (h_1 h_2)\left(\overline{h_1}\ \overline{h_2}\right) + X \propto 1 + H_1^\angle \overline{H_1^\angle}\cos(\phi_{R1} + \phi_{R2}) + G_1^\perp \overline{G_1^\perp}\cos(2(\phi_{R1} - \phi_{R2}))$
- See talks by Aram and Marco

Extraction of $\cos(\phi_{R_1} + \phi_{R_2})$
First measurement of Interference Fragmentation Function



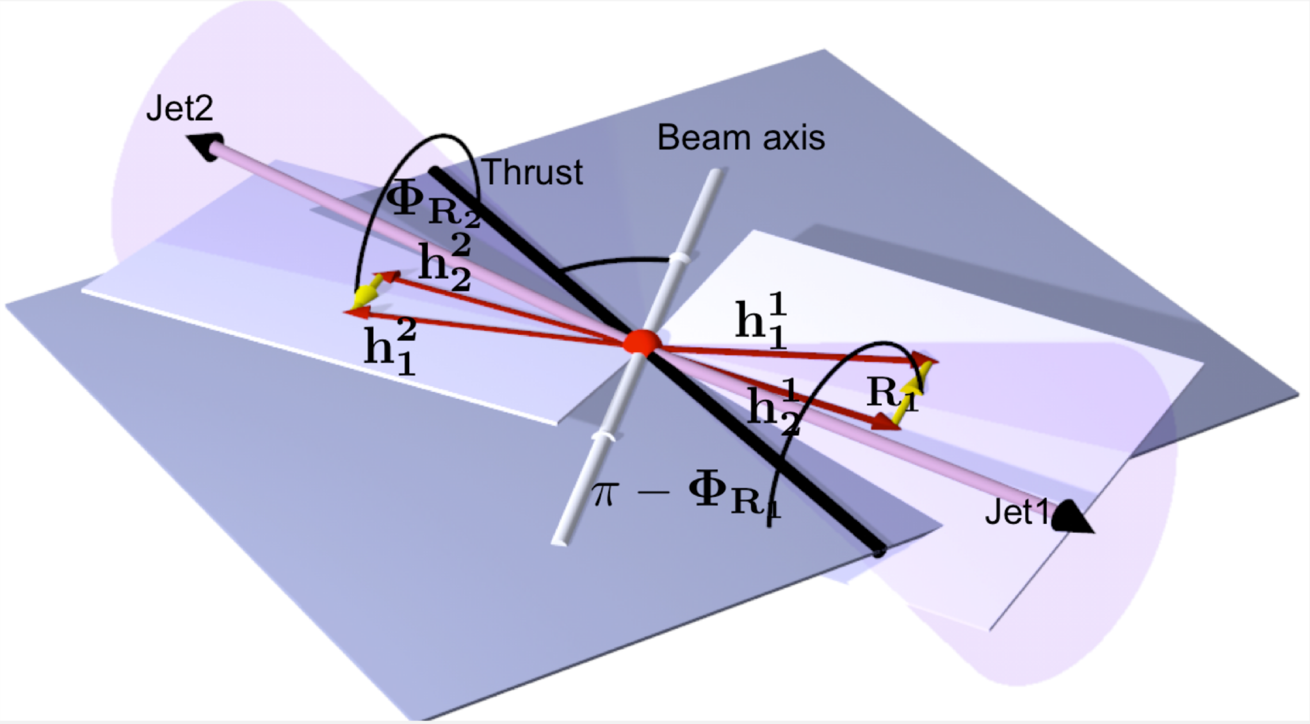
AV et. al, PRL **107,** 072004(2011)

$\mathbf{a_{12} \propto H_1^{\sphericalangle} \cdot H_1^{\sphericalangle}}$

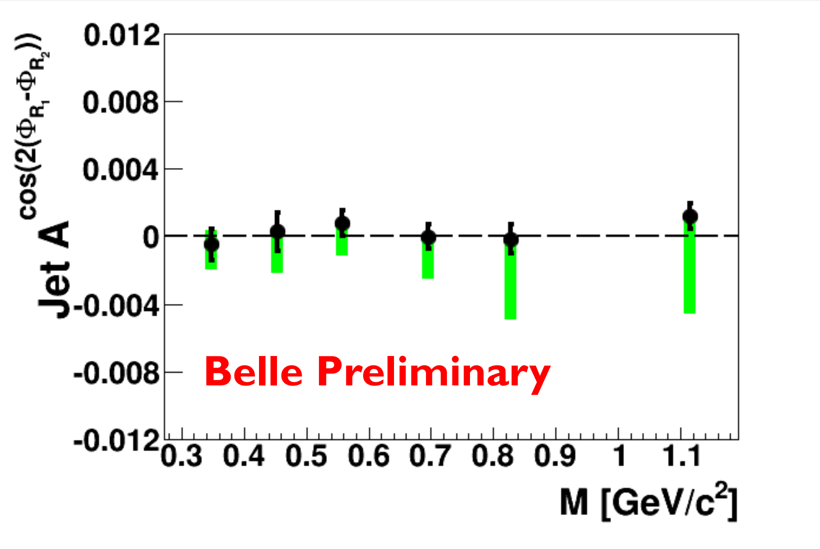
See Marco's talk about Transversity extraction From di-hadrons

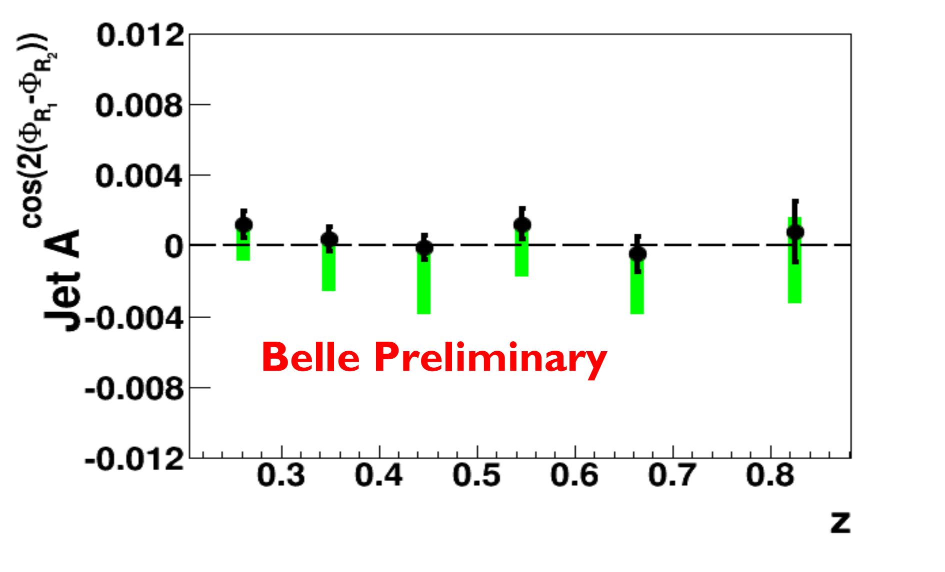
NEW: USE JET RECONSTRUCTION AT BELLE

- Robust vs. final state radiation
- **De-correlate axis between hemispheres**
  - We use anti-kT algorithm implemented in fastjet
  - Cone radius R=1.0
  - Min energy per jet 2.75 GeV→ suppress weak decays
- Only allow events with 2 jets passing energy cut (dijet events)
- Only particles that form the jet are
- Thrust cut of 0.8< T< 0.95



ASYMMETRIES FOR COS(2(ϕ_{R1}-ϕ_{R2})) ($G_1^{\perp}$) SMALL

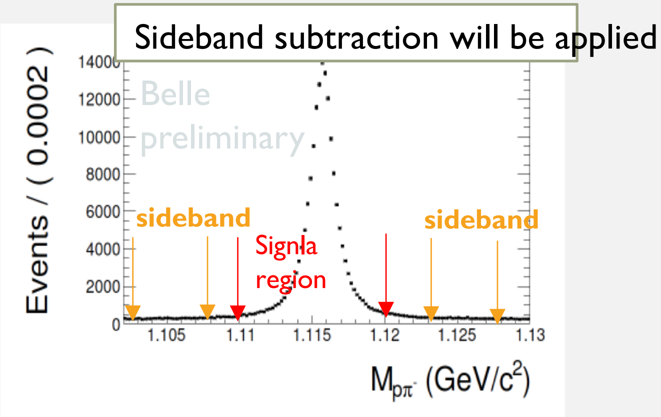


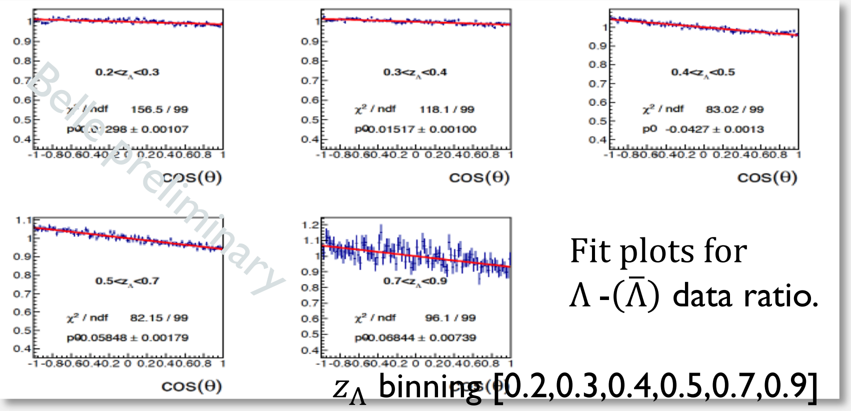


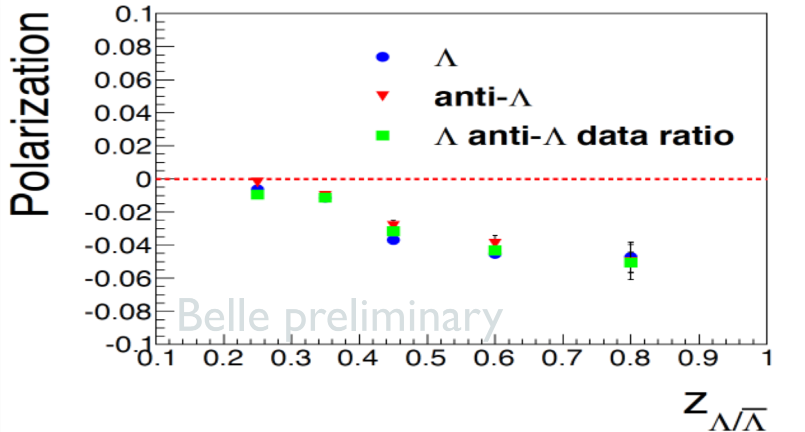
- No evidence of local p-odd effects yet
- Next step: partial wave analsyis
- See recent NJL model calculations by Matevosyan et al.
  - →G1T signal about half of IFF signal, produced by 'worm gear' splitting functions~g1T

FITS AND POLARIZATION EXTRACTION

- Fit the acceptance corrected cosθ 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 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, magnitude rises to about ~5% with $z_\Lambda = 2E_\Lambda/\sqrt{s}$.

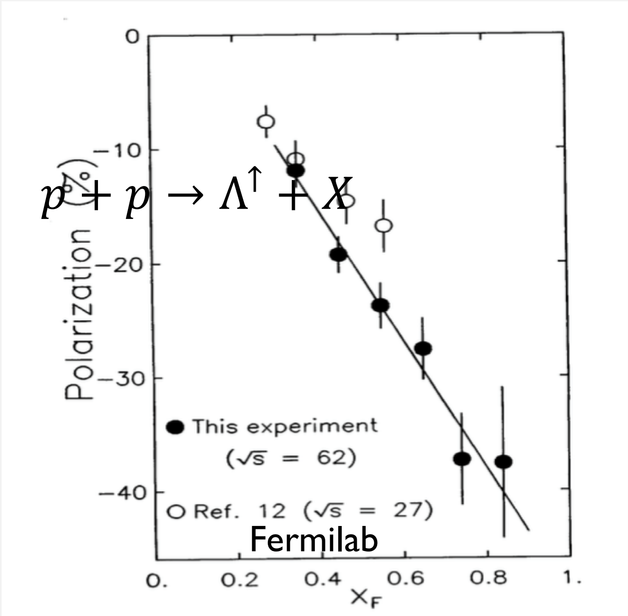






POLARIZED HYPERON PRODUCTION

- 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)**
- FF counterpart of the Sivers function.

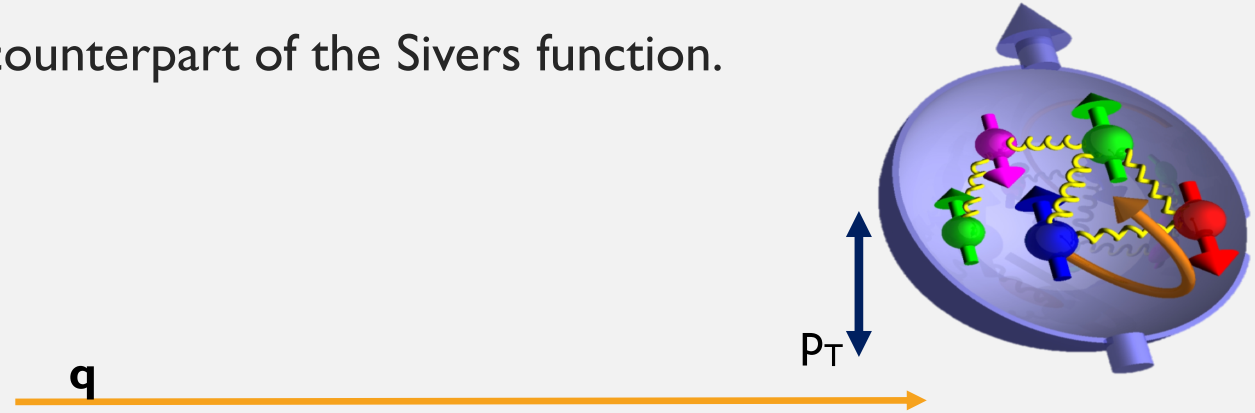


$p + p \to \Lambda^{\uparrow} + X$

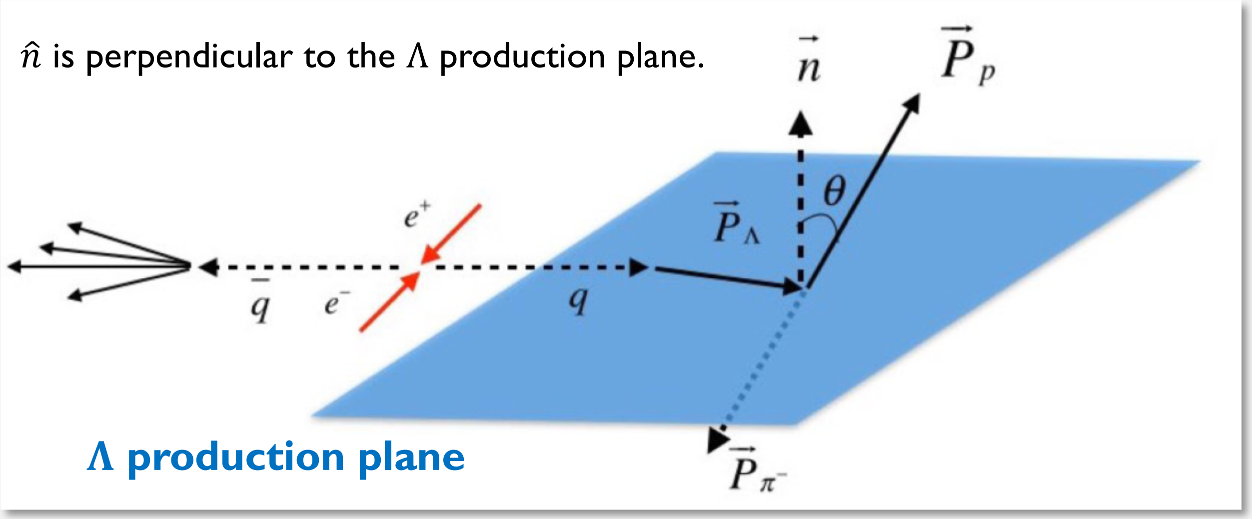
ISR data

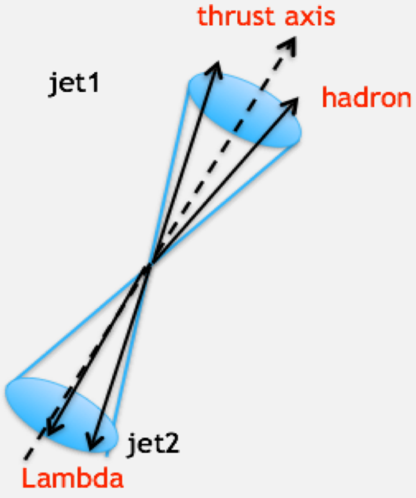
(**Phys.Lett. B185 (1987) 209**)

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

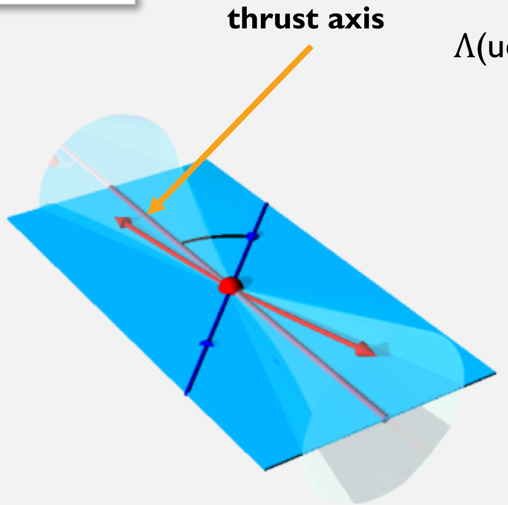


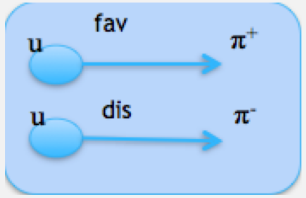
OBSERVABLES IN Λ RESTFRAME





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





- 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 POLARIZATION EXTRACTION

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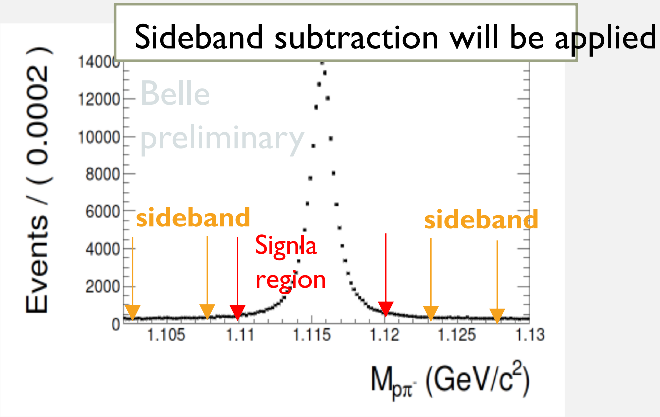
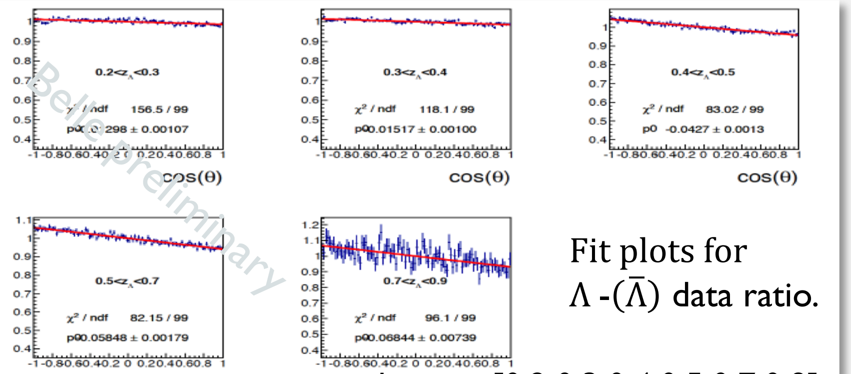
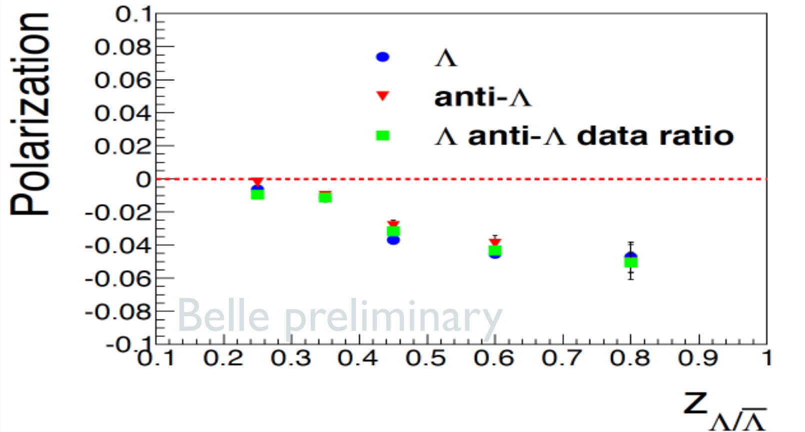




Fit plots for Λ -($\bar{\Lambda}$) data ratio.
z_Λ binning [0.2,0.3,0.4,0.5,0.7,0.9]

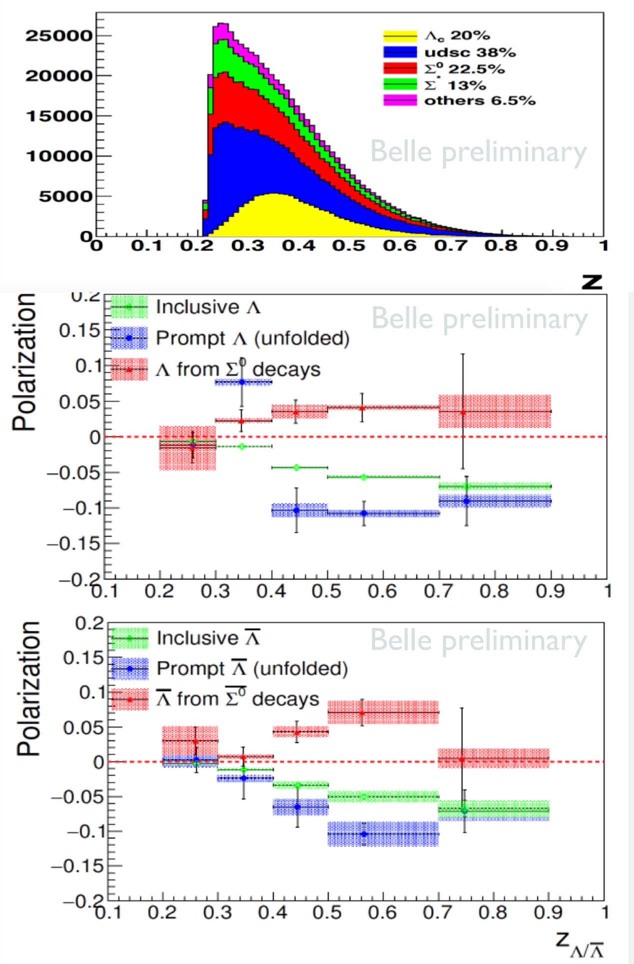


BACKGROUND UNFOLDING

- 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:

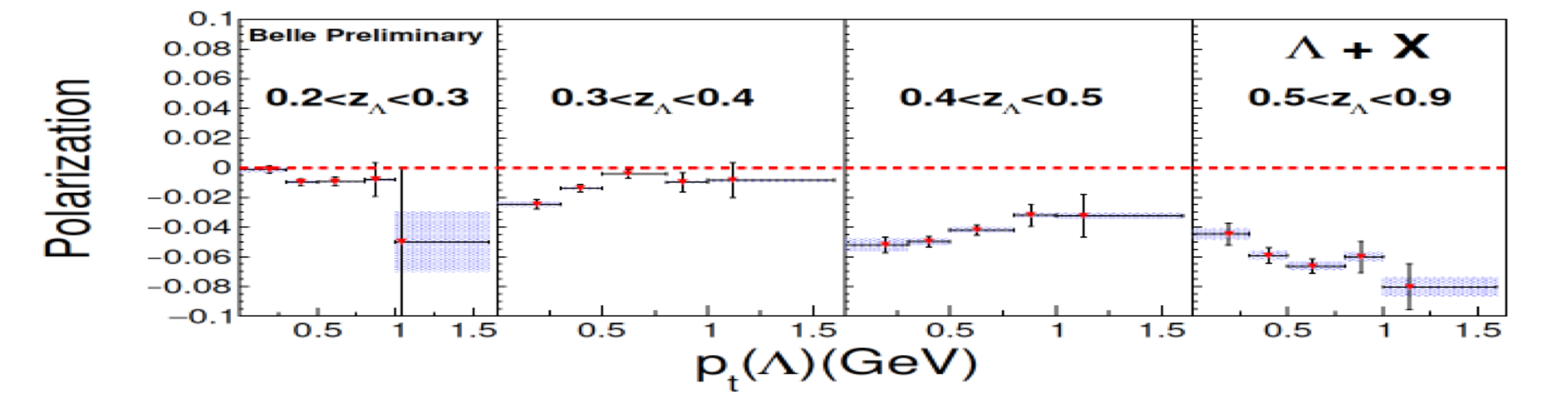
$$P^{mea.} = (1 - \sum_i \boxed{F_i}) P^{true} + \sum_i \boxed{F_i} P_i,$$

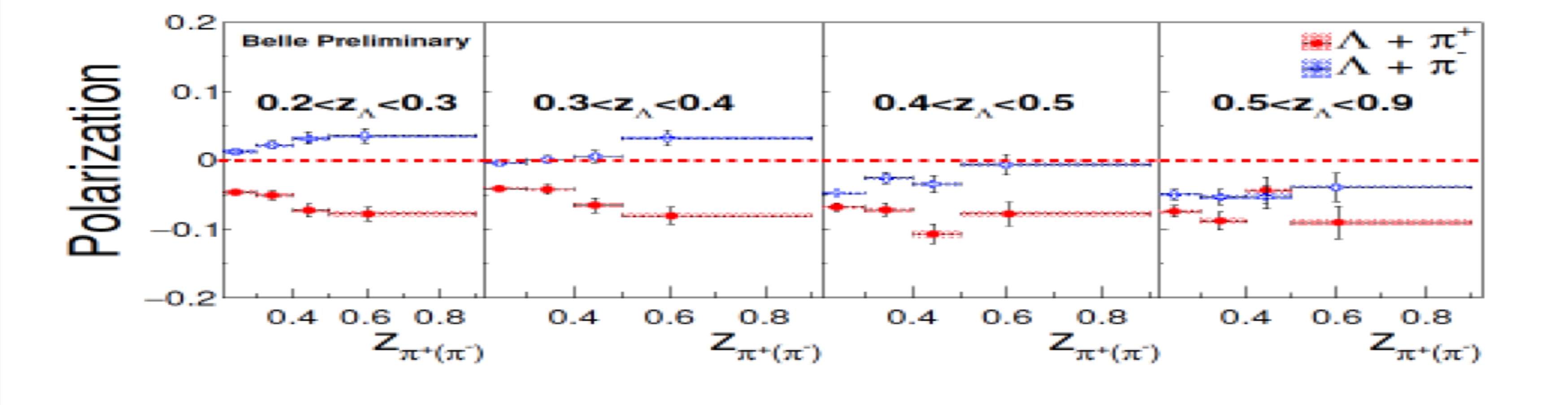
- F_i is the fraction of feed-down component i, estimated from MC. P_i is polarization of component i.
- Polarization of Λ from Σ^0 decays is found has opposite sign with that of inclusive Λ.



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

z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION





- Polarization rises with p_t in the lowest z_Λ and highest z_Λ bin. But the dependence reverses around 1 GeV in the intermediate z_Λ bins→**Unexpected!** (might be related to fragmenting quark flavor dependence on z_1,z_2)
- Correlation with opposite hemisphere light meson →quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge cf Sivers

SUMMARY

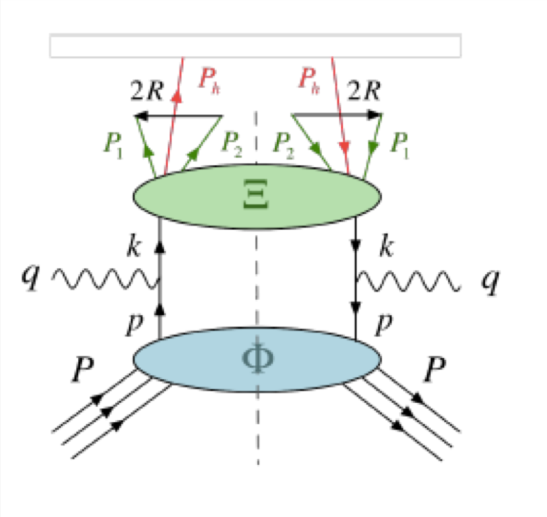
- **FF programs at Belle, BaBar and BES III has provided key measurements leading to new insights into the spin structure of the nucleon and QCD in general!**
- Results on the horizon include p_T dependence of D_1, Collins FF for η,π^0
- Belle II will start data taking next year and will quickly surpass Belle data with superior data quality
  - High statistics, multidimensional extraction of $H_1^{\perp h/q}$, LPV effects in high multiplicity events …
  - Quantification of the impact of precision FF measurements on Jlab12 and EIC program would be helpful to bolster FF program at Belle II

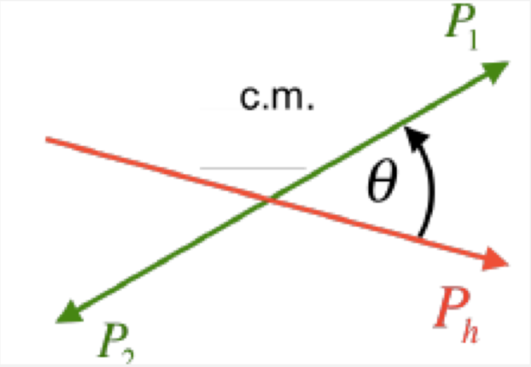
FRAGMENTATION FUNCTIONS WITH ADDITIONAL DEGREES OF FREEDOM: NOVEL PROBES OF THE NUCLEON STRUCTURE AND HADRONIZATION

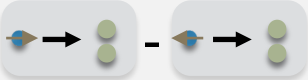
- Di-hadron fragmentation functions
- Polarized Hyperons

DI-HADRON FRAGMENTATION FUNCTIONS

- Additional degree of freedom ($\vec{R} = \vec{P_1} - \vec{P_2}$)
  - Plus z, P_T
- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs
  - Analogue of 1h production with spin in final state
- Transverse polarization dependence in collinear framework
- Makes 'new' FFs possible, such as $G_1^{\perp}$:T-odd chiral even. In 1h case, this needs polarized hadron in the final state →**See H. Matevosyan's talk!**
- **Similar to Λ FF,chiral-even,T-odd: Important to check factorization**







EXAMPLE, ACCESS OF e(x) in SIDIS X-SECTION

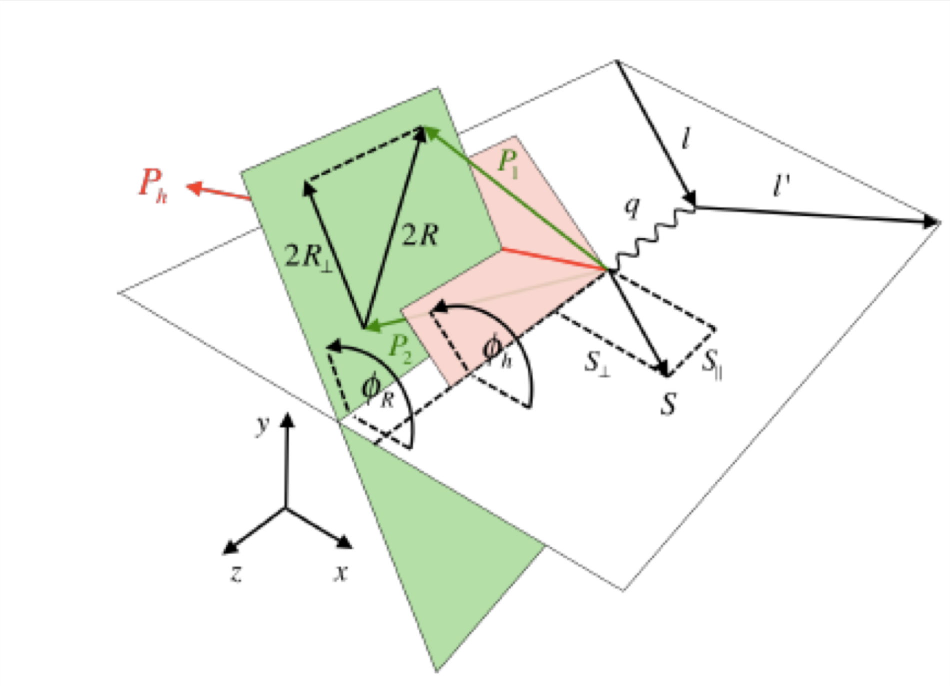
- Di-hadron cross section

WW Approximation

$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\,x\,e^q(x)\,H_1^{\sphericalangle q}(z,\cos\theta,m_{hh}) + \cancel{\frac{1}{z}\,f_1^q(x)\,\widetilde{G}^{\sphericalangle q}(z,\cos\theta,m_{hh})}\right],$$

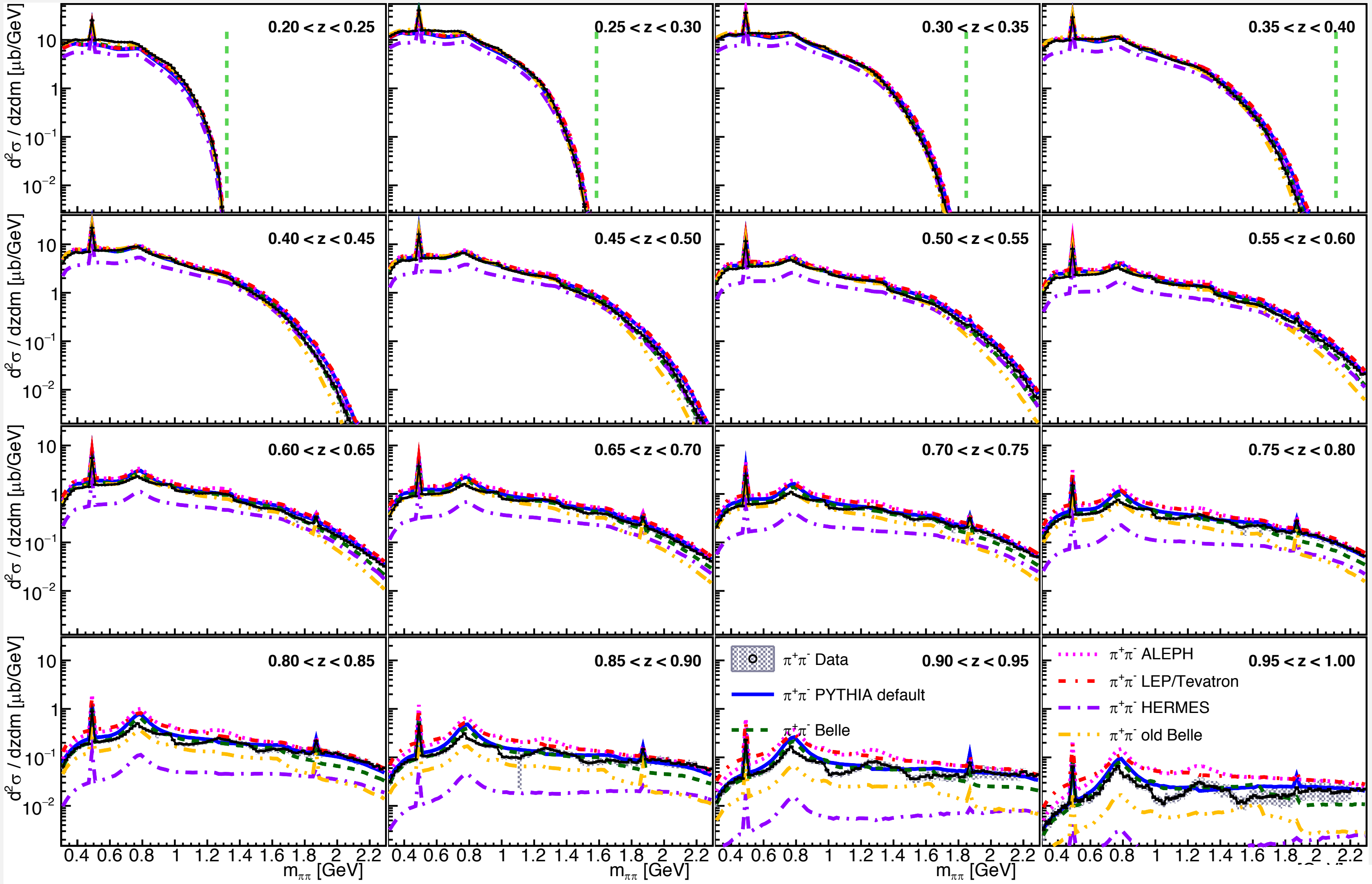
- Single hadron cross-section: mixes other contributions:

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q}\mathcal{I}\Big[-\frac{\boldsymbol{k}_T\hat{\boldsymbol{P}}_{h\perp}}{M_h}\Big(xeH_1^\perp + \cancel{\frac{M_h}{Mz}f_1\tilde{G}^\perp}\Big) + \frac{\boldsymbol{p}_T\hat{\boldsymbol{P}}_{h\perp}}{M}\Big(xg^\perp D_1 + \cancel{\frac{M_h}{Mz}h_1^\perp\tilde{E}}\Big)\Big]$$

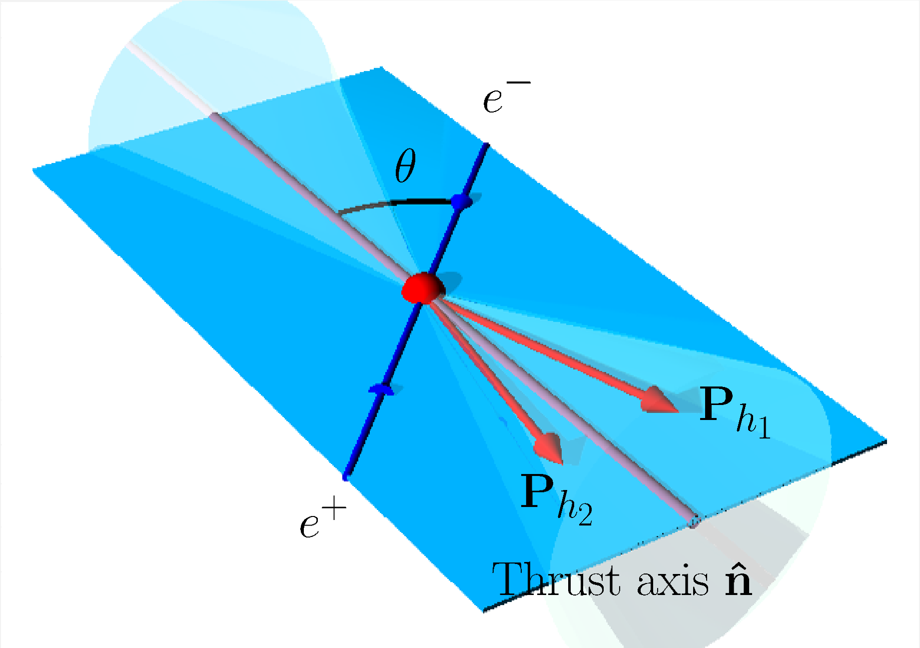


RECENT BELLE RESULT

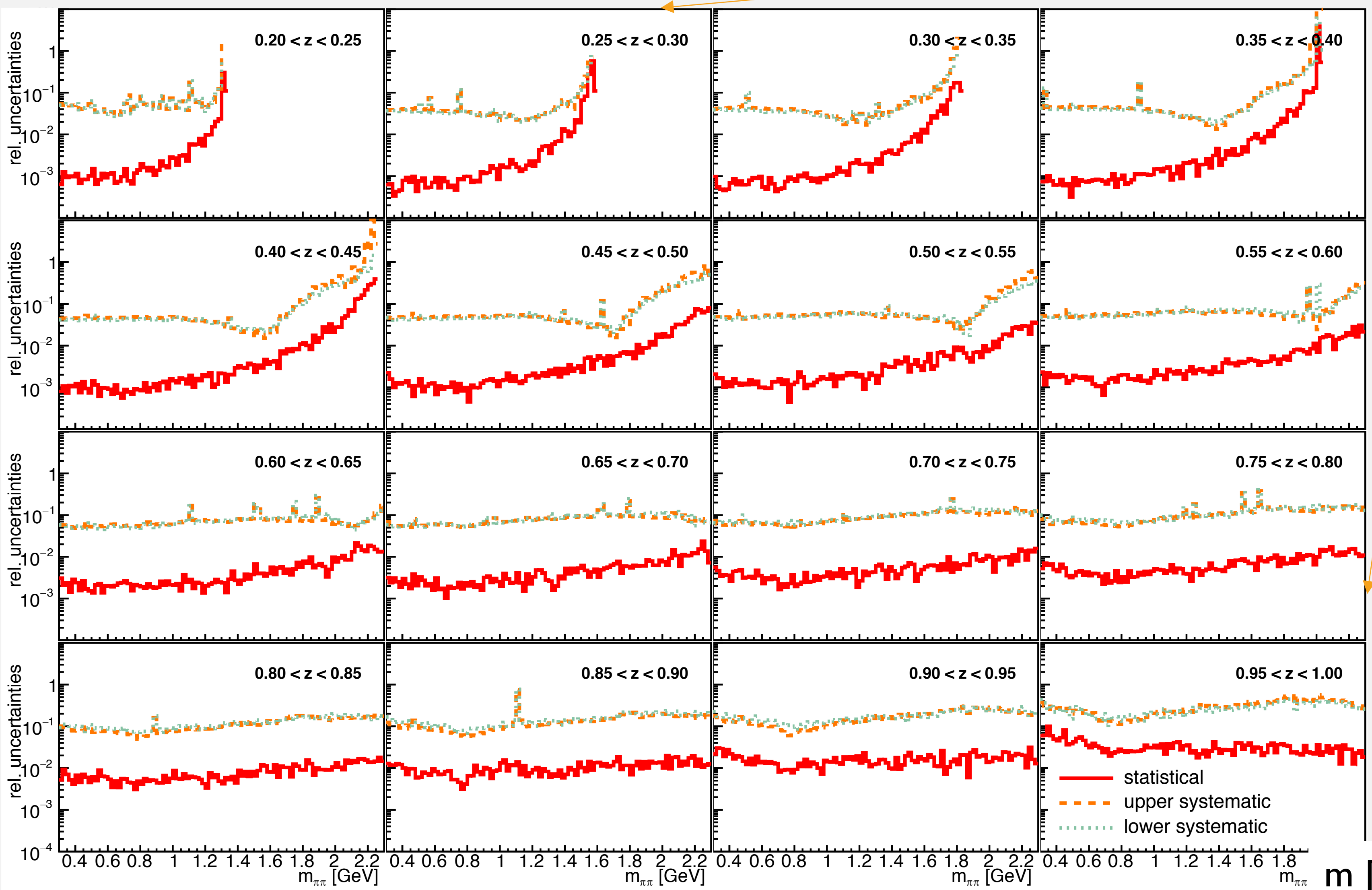
(Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005)



m [GeV]



RESULTS SYSTEMATICS DOMINATED



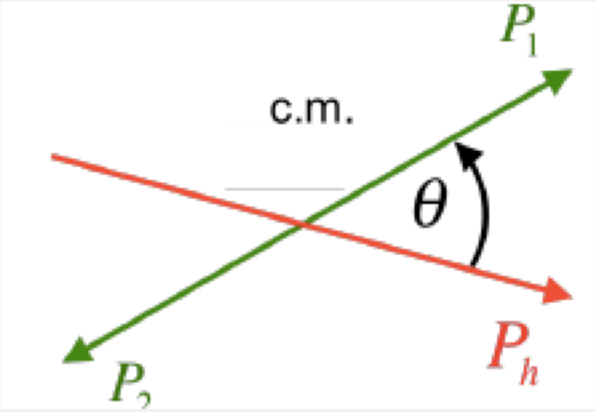
m [GeV]

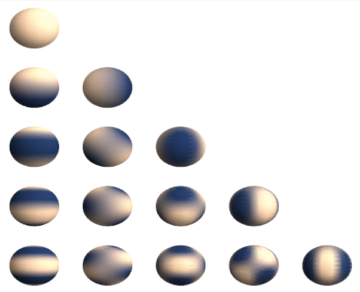
- Low z: Dominated by PID uncertainties
  Belle II prospects: Improved PID, higher statistics to improve uncertainties on PID
- High z: Dominated by ISR uncertainties
  Belle II prospects: better understanding of ISR radiation with better statistics
-

Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

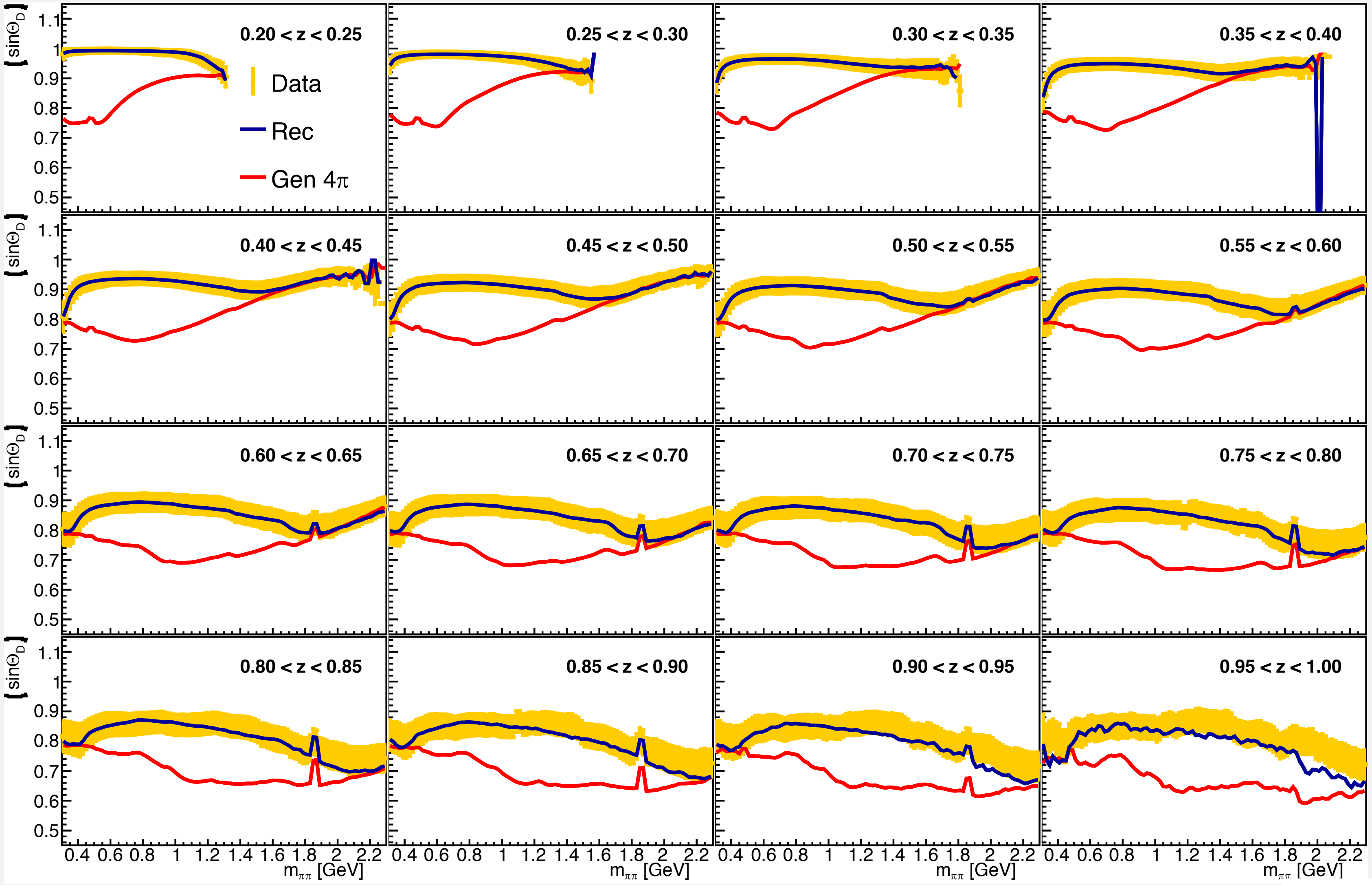
BELLE II PROSPECTS

- Partial Wave decomposition (more general: θ dependence)
- Higher order PWs lead to different moments in θ and ϕ
- In models, evolution of the different PWs different
- Important to have a full picture to understand mixing effects in ratios/partial integrals/acceptance
- Missing info from partial wave estimated to have effects up to 10% e.g. on extraction of transversity





ACCEPTANCE IMPACT ON PARTIAL WAVE COMPOSITION



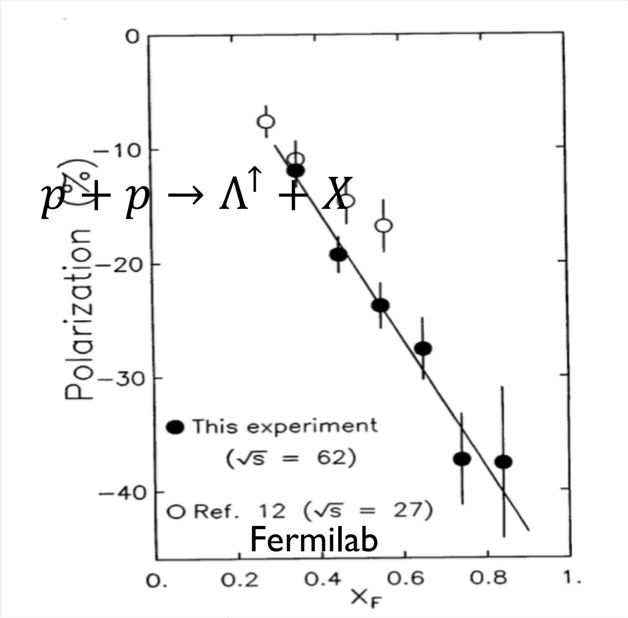
m [GeV]

- Belle II prospects: Sufficient statistics for full partial wave decomposition

Seidl et. al. Phys.Rev. D96 (2017) no.3, 032005

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 studied transverse Λ polarization, no significant signal was observed. **Eur. Phys. J. C2, 49 (1998)**
- FF counterpart of the Sivers function.



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

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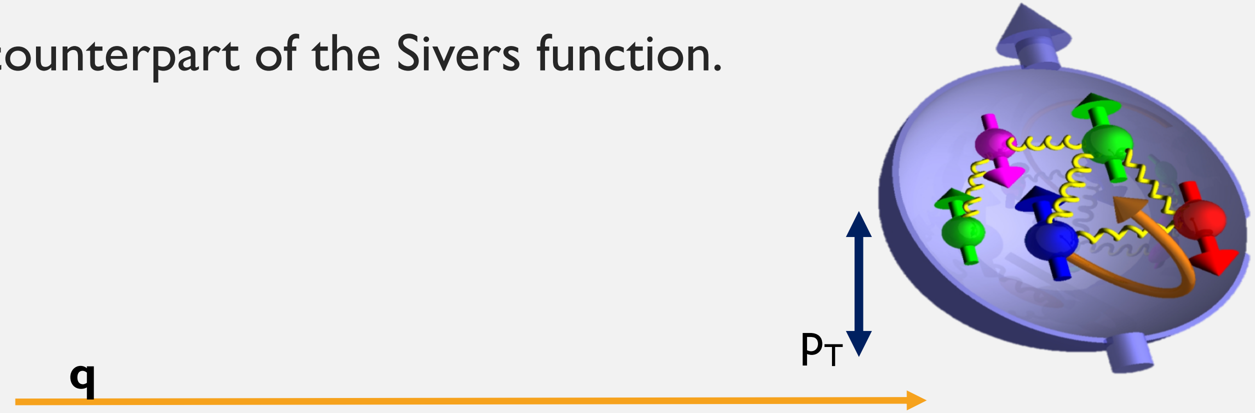
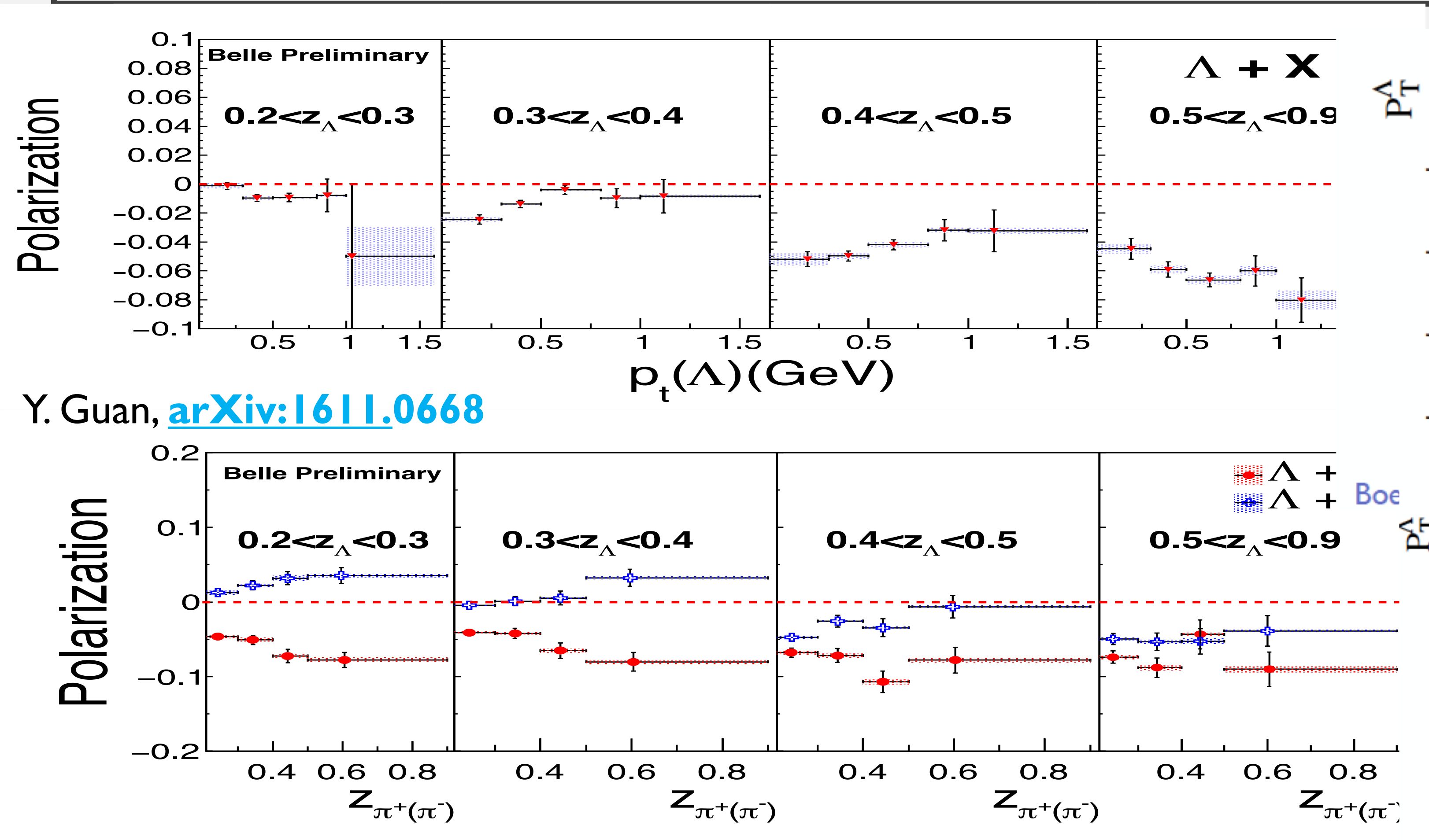
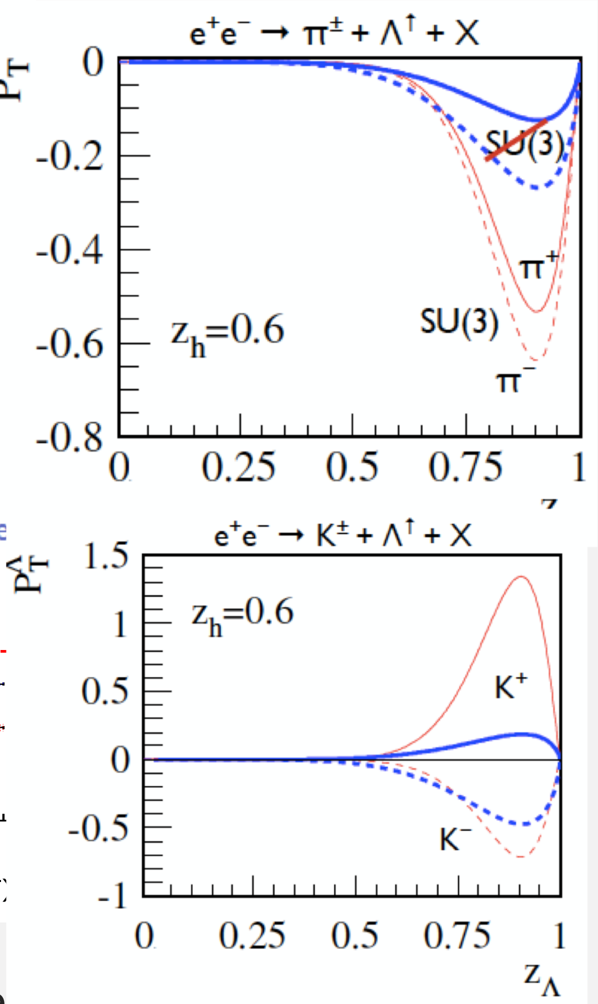


Z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION





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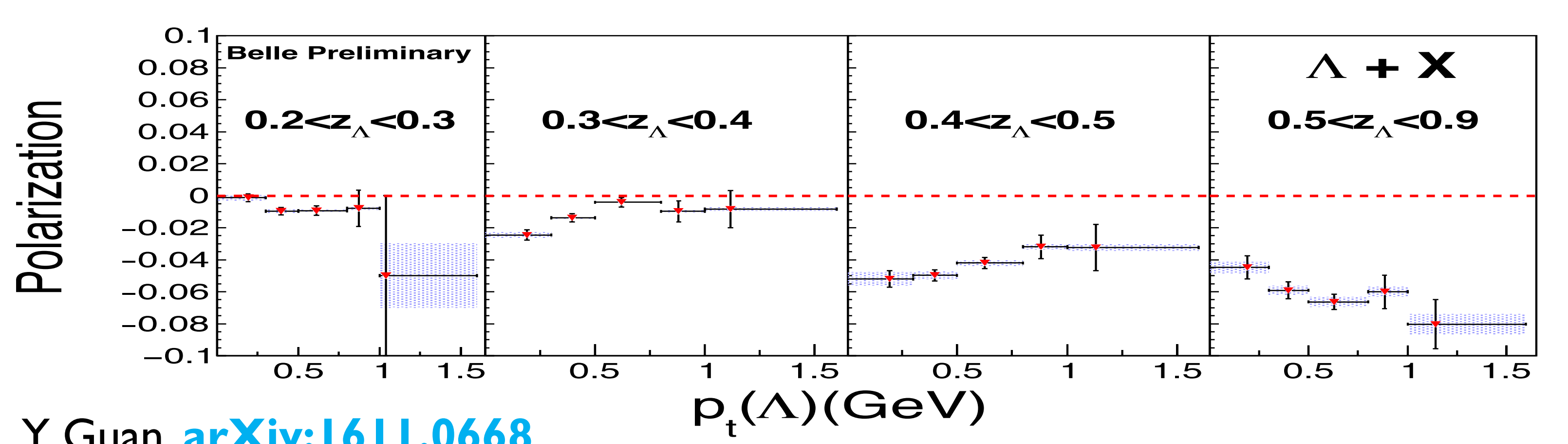


Y. Guan, arXiv:1611.0668

- Explore low pT region with higher statistics and better tracking resolution
- Feed down correction for pT dependence and associated production
  - (currently only for z dependence, introduces large uncertainties)
  - $\Lambda^{\uparrow} - \Lambda^{\uparrow}$ correlations
  - ….

KEKB →SUPERKEKB: DELIVER INSTANTANEOUS LUMI X 40

Belle II

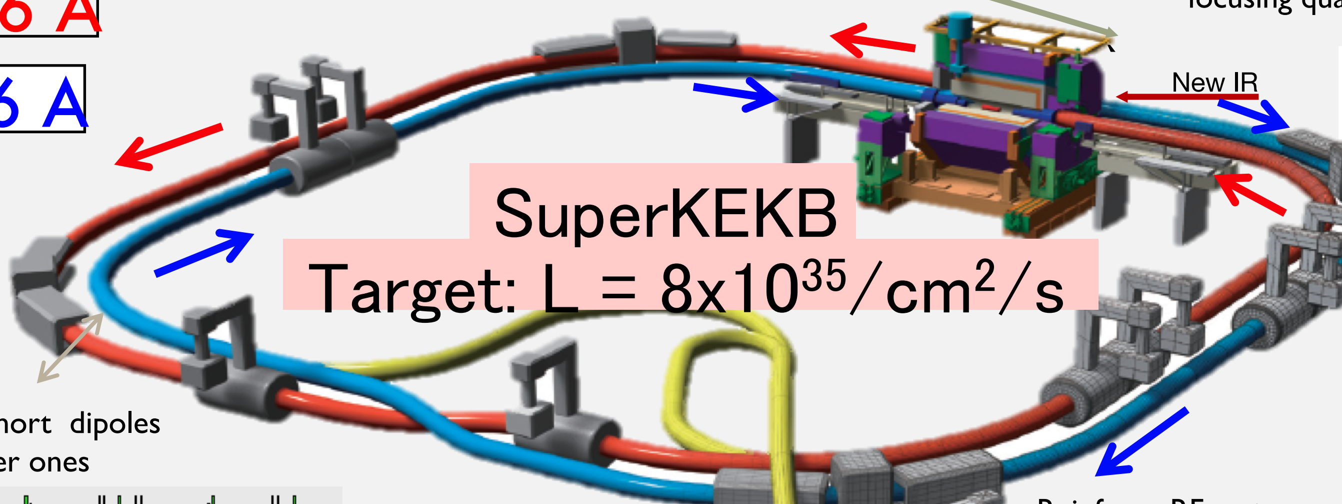
e^+ 4GeV 3.6 A

e^- 7GeV 2.6 A

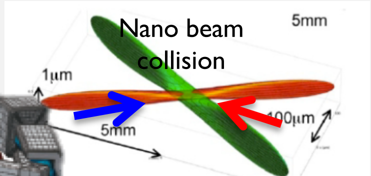
(~2x KEKB)

New superconducting final focusing quads (QCS) near the IP

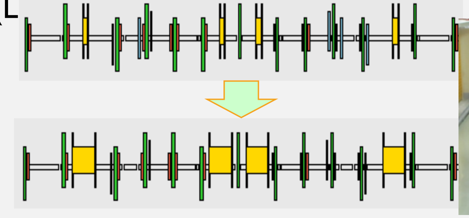
New IR



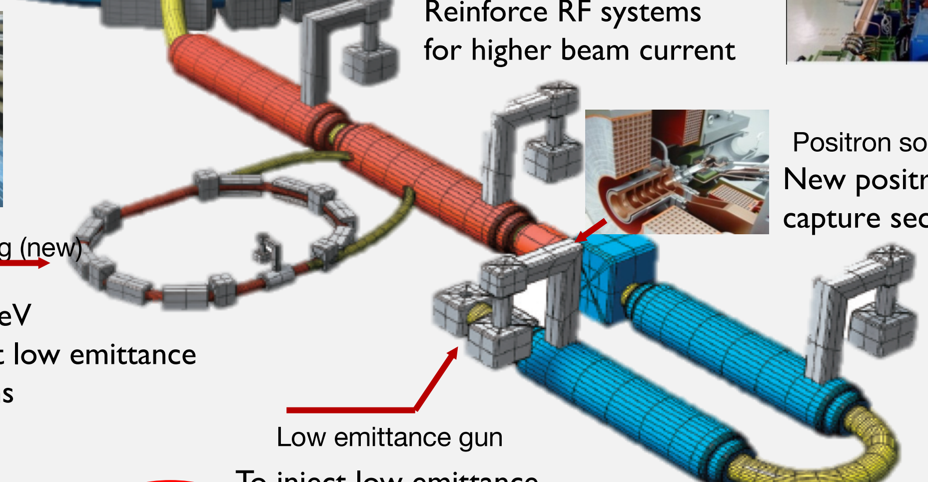
SuperKEKB
Target: L = $8x10^{35}/cm^2/s$



Replace short dipoles with longer ones
(L



Reinforce RF systems for higher beam current



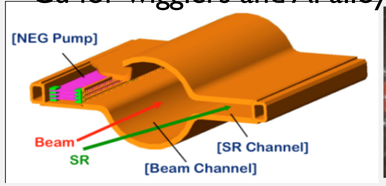
Positron source
New positron target / capture section

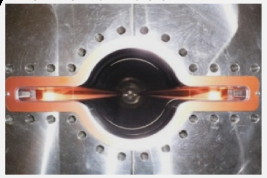
Redesign the lattices of HER & LER to squeeze the emittance

Damping ring (new)

@1.1 GeV
To inject low emittance positrons

TiN-coated beam pipe with antechambers
Cu for wigglers and Al alloy for the rest

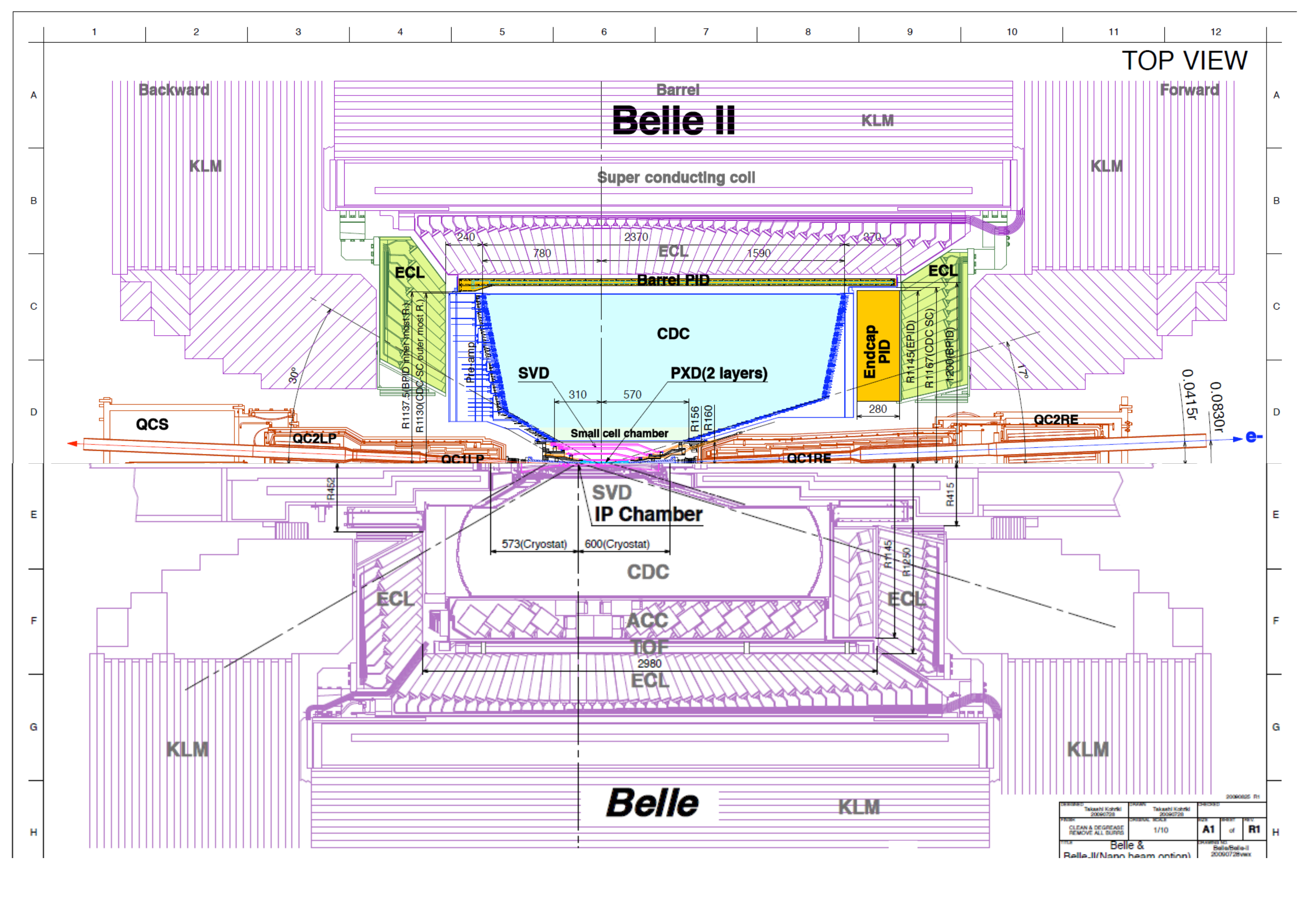




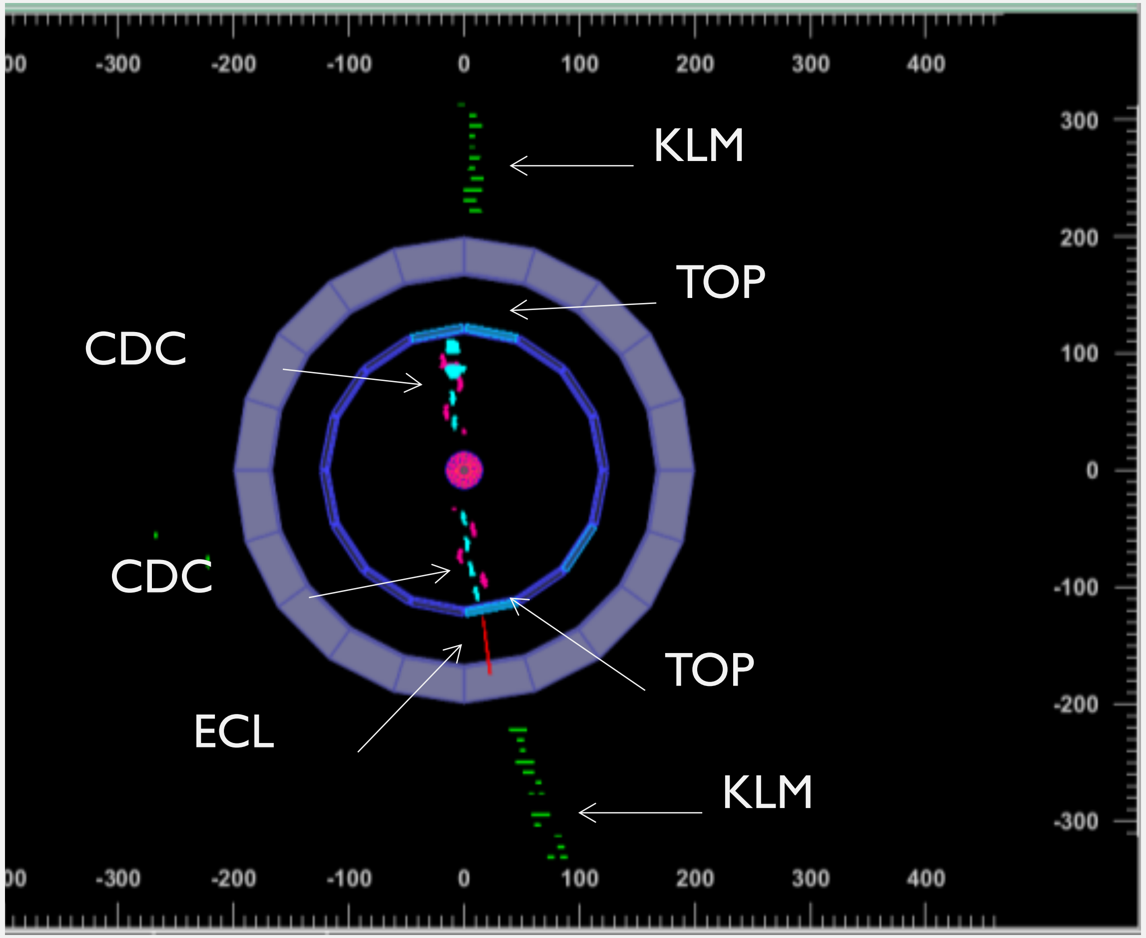
Low emittance gun
To inject low emittance electrons

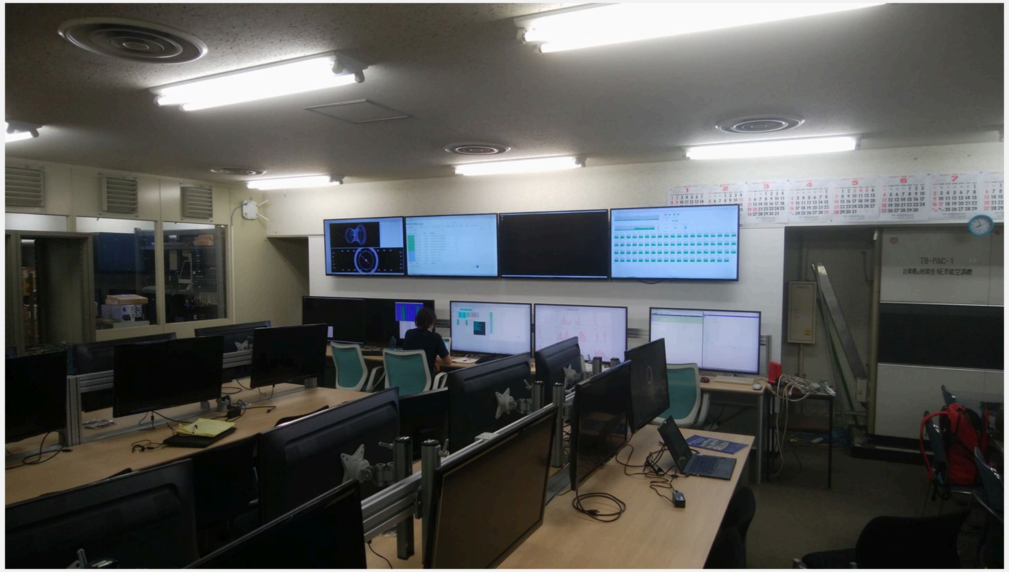
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

BELLE II DETECTOR (COMP. TO BELLE)



READOUT INTEGRATION



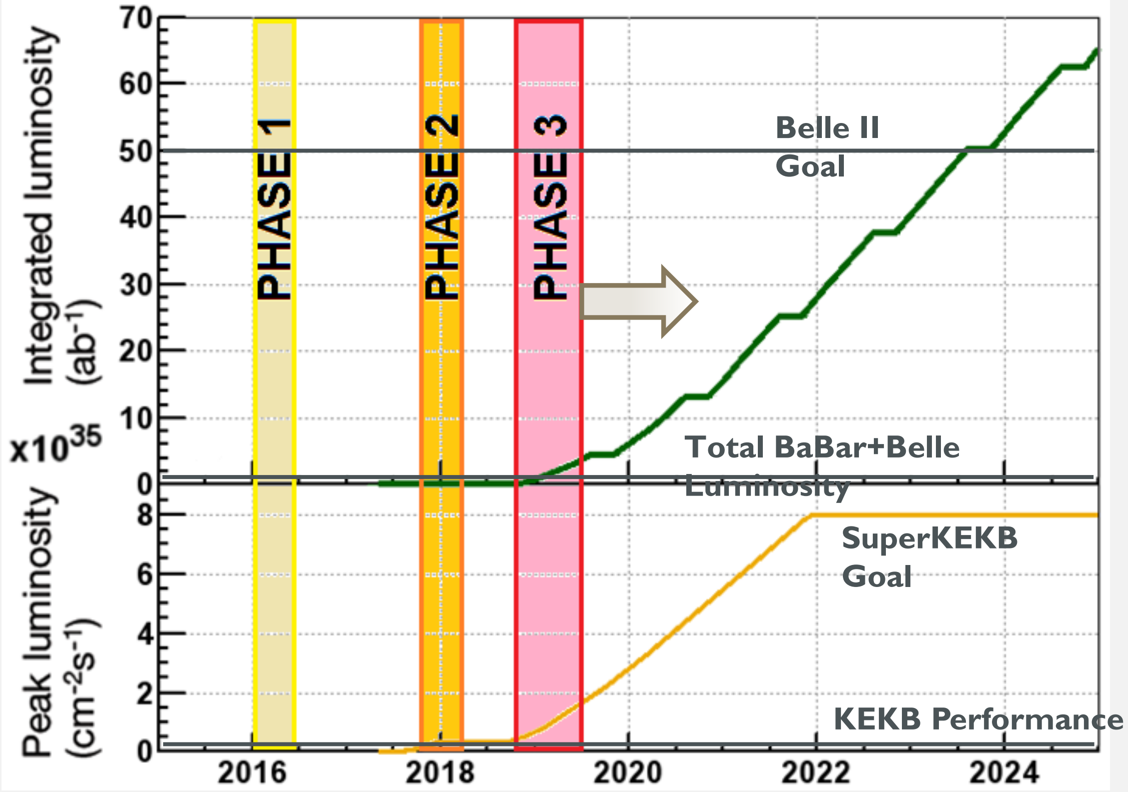


Belle II Control Room

- Readout integration of installed sub-detectors and central DAQ is in progress.
- Combined data taking established in cosmic running

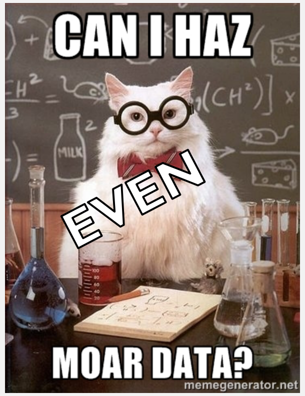
CURRENT STATUS AND SCHEDULE

- Phase 1 (complete)
  - Accelerator commissioning
- Phase 2 (early 2018)
  - First collisions (20±20 fb^{-1})
  - Partial detector
  - Background study
  - Physics possible
- Phase 3 ("Run 1", early 2019)
  - Nominal Belle II start
- **Ultimate goal: 50 ab^{-1}**



- **Search for New Physics via precision measurements**
  - CPV, (semi-)leptonic/penguin decays, LFV, dark sector, …

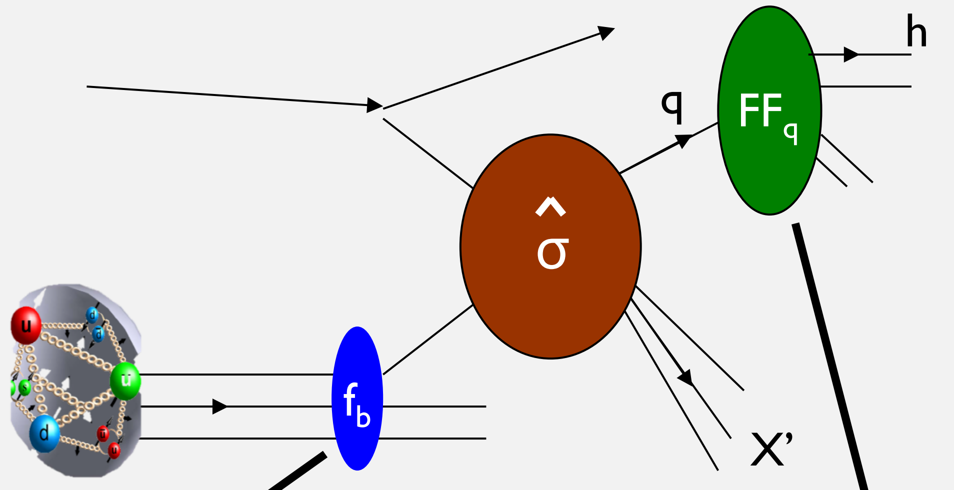
FF PROGRAM AT BELLE II



- High Precision measurements of spin dependent Fragmentation Functions
  - Precision back-to-back correlations of less copious hadrons (e.g. Λ)
  - Precision should be on par with anticipated SIDIS data from JLab12
  - LPV effects in high multiplicity events helped by statistics and increased acceptance for low multiplicity tracks
- State of the Art Detector
  - PID: increase efficiency of e.g. multi kaon final states
  - Vertexing: More efficient charm rejection for FF studies
  - Reduce systematics (in particular charm) and improve PID

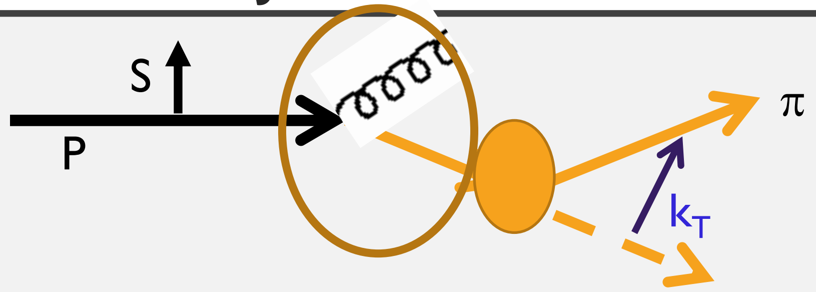
FRAGMENTATION FUNCTIONS APPEAR ALMOST ALWAYS WHEN ACCESSING PARTONIC STRUCTURE OF THE NUCLEON

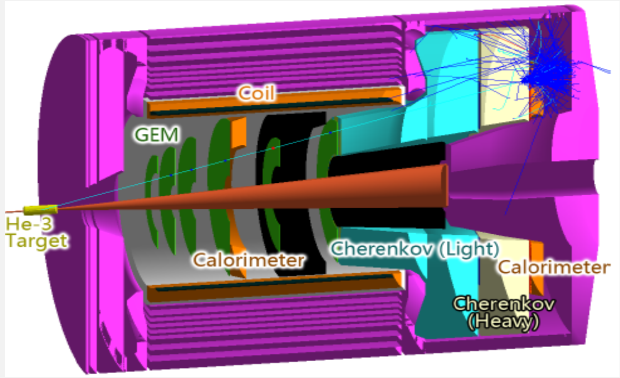
- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes:
- Particular important for transverse spin structure
  →need detailed understanding of FFs to use as 'quark polarimeter' and tag the flavor of the struck quark

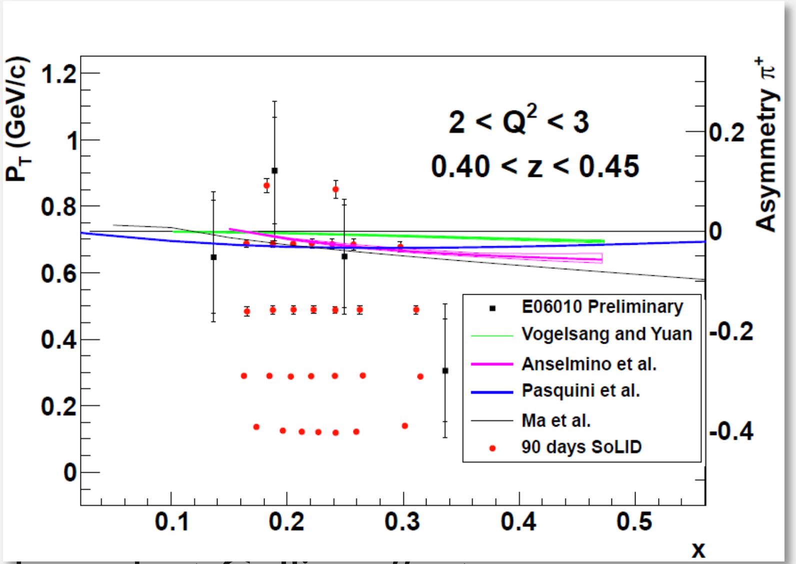


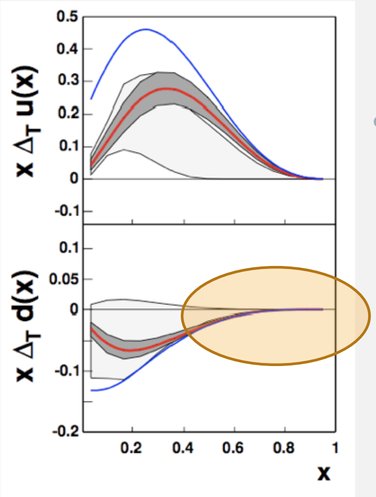
$$\frac{d^2\sigma(ep\to\pi X)}{dx\,dz} \propto \overbrace{q(x,k_T)}^{\text{Proton Structure}}\times \overbrace{\frac{d\sigma^2(e\,q\to e'q')}{dx}}^{\text{pQCD}}\times \overbrace{FF(z,p_T)}^{\text{fragmentation function}}$$

TRANSVERSITY AT HIGH X FROM POLARIZED HE3 AT SOLID WITH 12 GEV UPGRADE AT JLAB



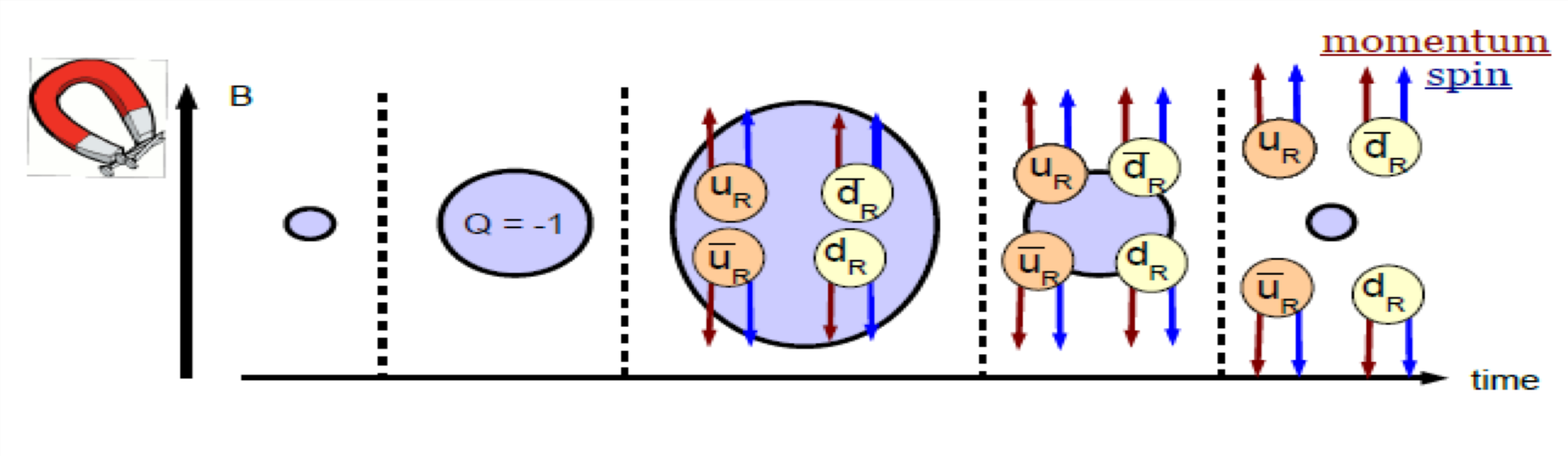


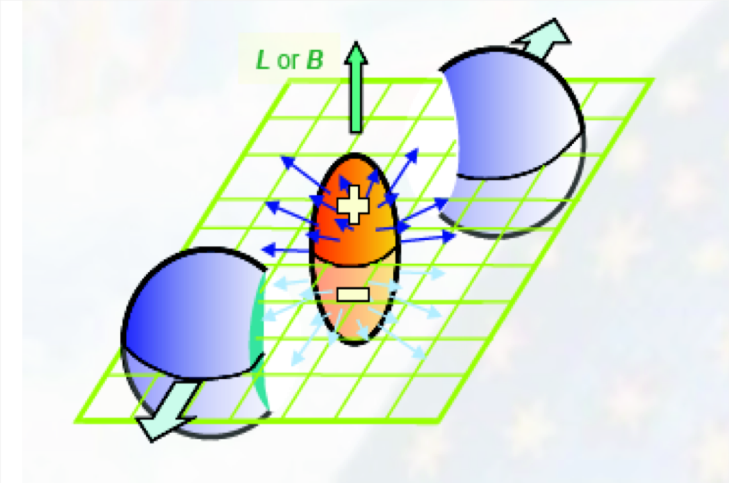


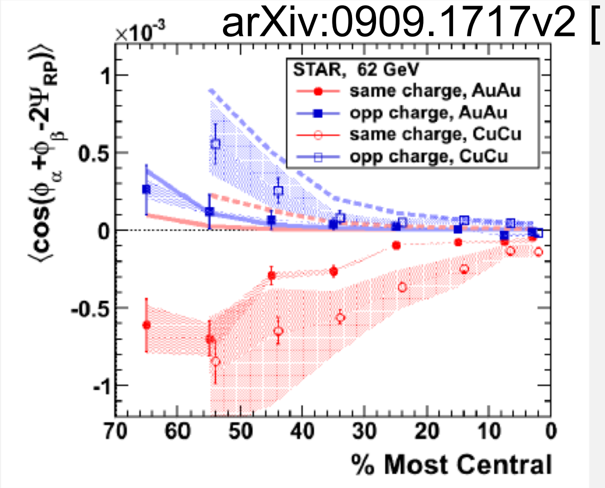


- Precise measurement of p_T dependent Collins effect
  - Needs precise measurement of Collins and spin averaged p_T dependent fragmentation functions!

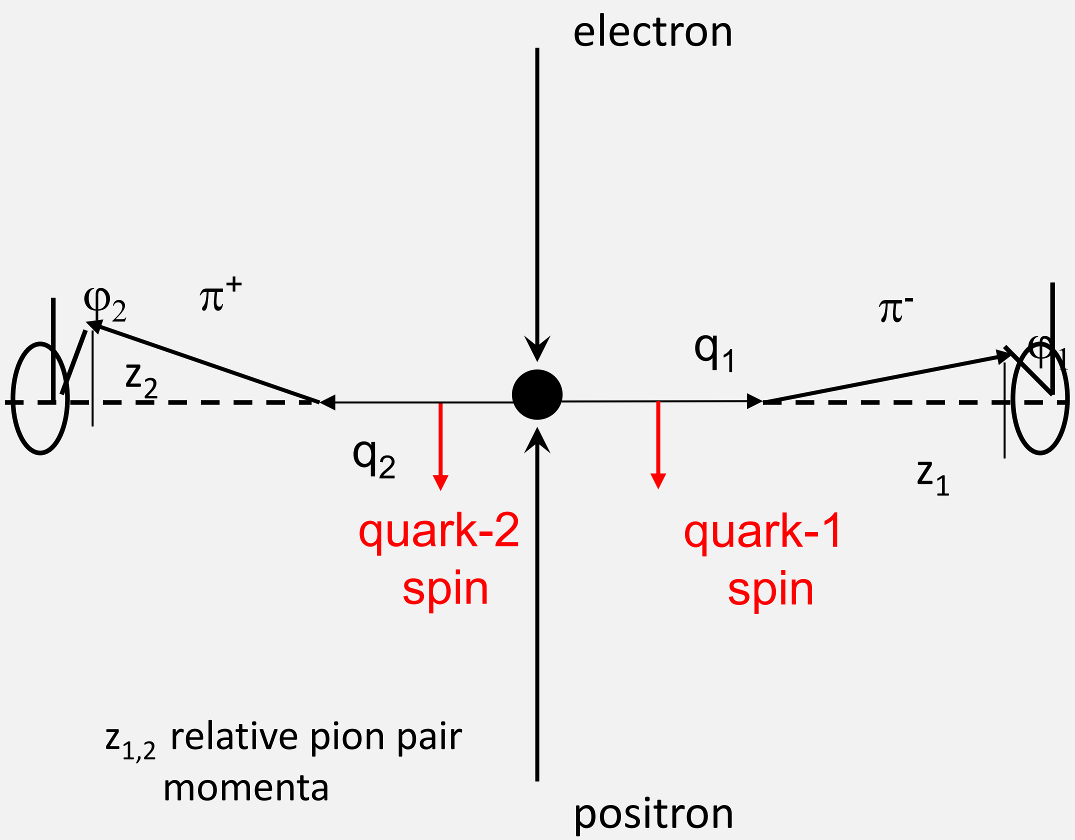
QCD VACUUM TRANSITIONS CARRY CHIRALITY





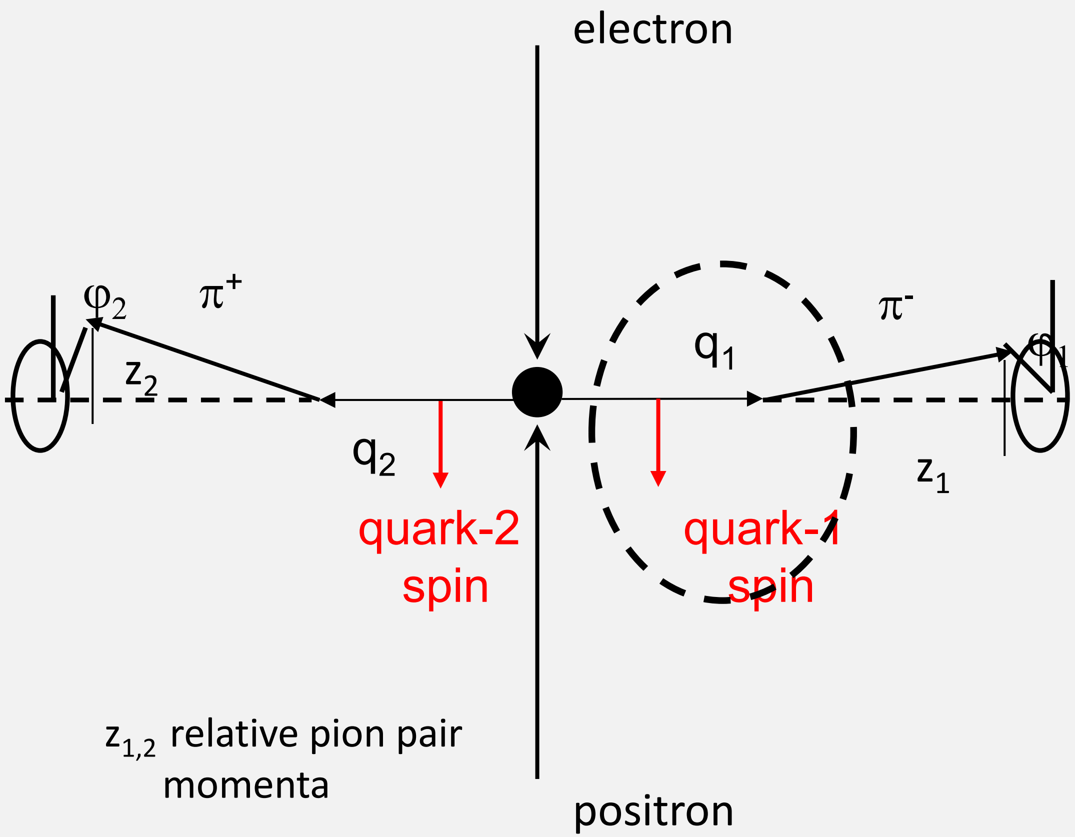


Kharzeev, McLerran and Warringa, arXiv:0711.0950,
Fukushima, Kharzeev and Warringa, arXiv:0808.3382

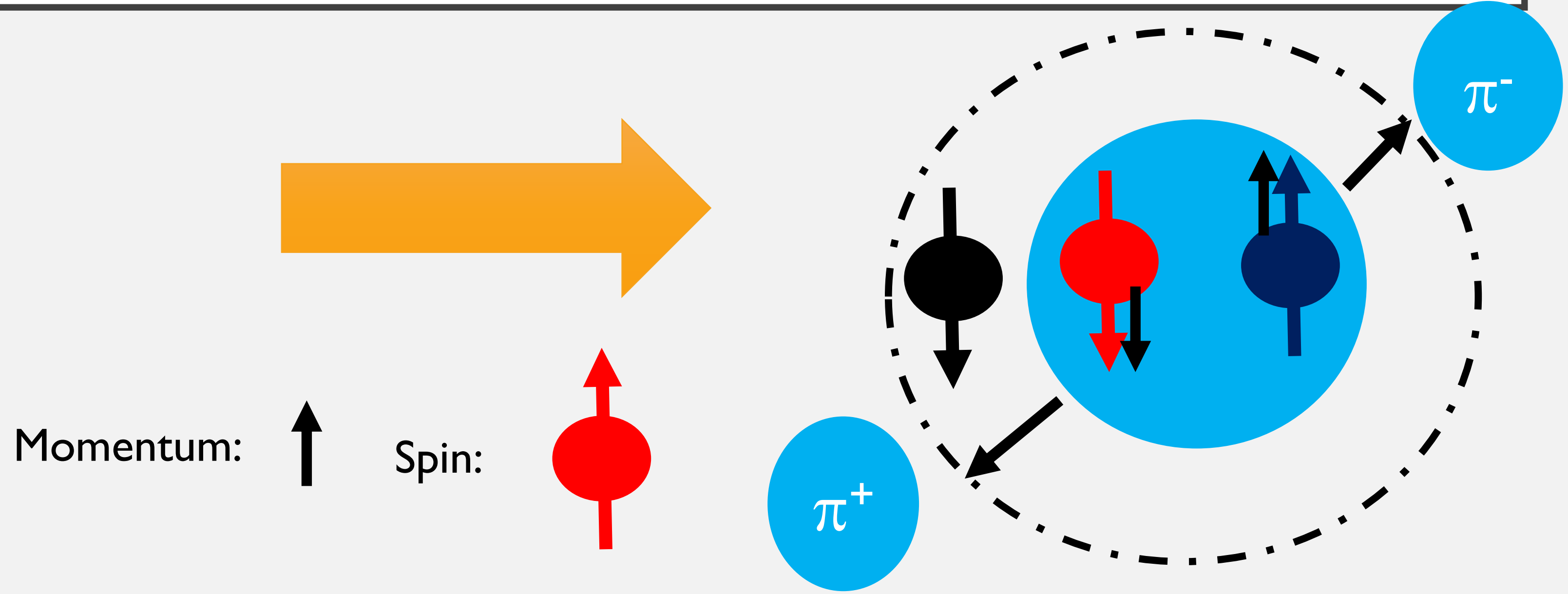


$z_{1,2}$ relative pion pair momenta

$$\sigma \propto H_1^{\perp}\,(z_1)\overline{H}_1^{\perp}\,(z_2)\cos(\phi_1+\phi_2)+C$$

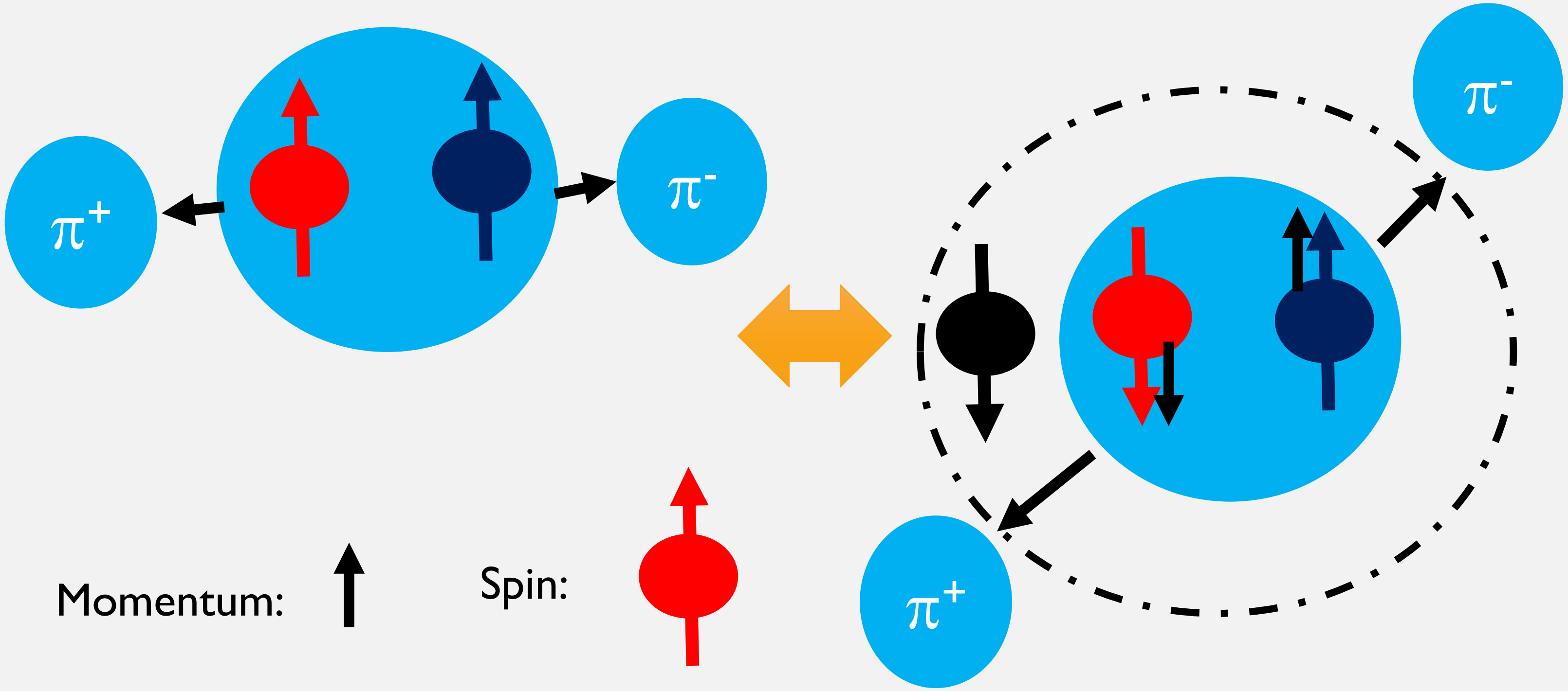


$$\sigma \propto H_1^{\perp}\,(z_1)\bar{H}_1^{\perp}\,(z_2)\cos(\phi_1+\phi_2)+C$$



- Fragmentation in P-odd bubble leads spin-momentum correlation
- Difference in 'Winding number' gives effective increment in chirality
- Spin alignment via chromomagnetic-electric effect → FF $\widetilde{H}_1$

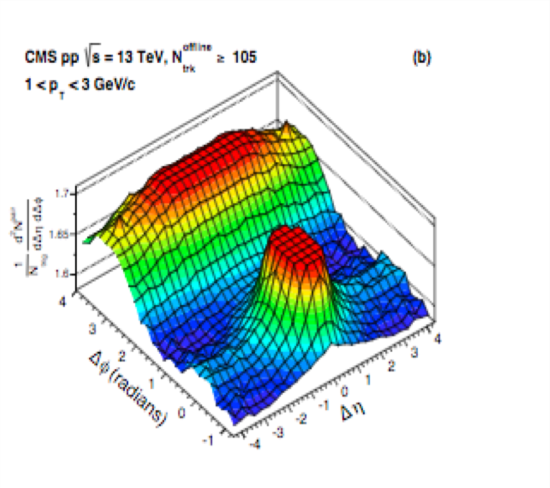
MIX OF P-ODD FF WITH COLLINS FF LEADS TO EVENT-BY-EVENT ASYMMETRY



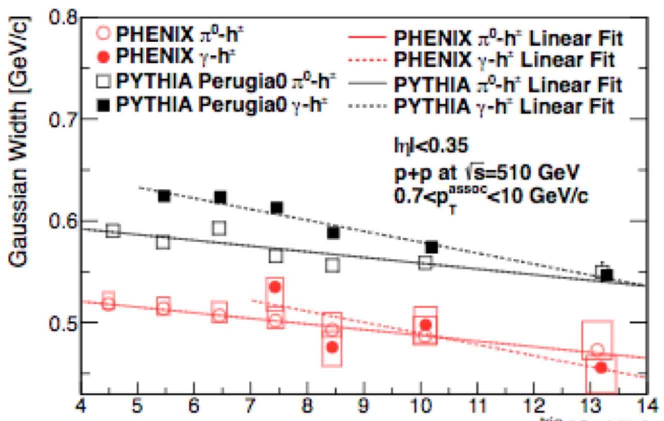
- Fragmentation in P-odd bubble leads spin-momentum correlation (both fragmenting quarks in the 'bubble' → $G_1^\perp$/jet handedness like effect (but conserving parity))
- Difference in 'Winding number' gives effective increment in chirality
- Spin alignment via chromomagnetic-electric effect
- Azimuthal **event by event** modulation → **sin(ϕ_1+ϕ_2) modulation →needs large dataset of high multiplicity events →Belle II**
- See Kang, Kharzeev, Phys.Rev.Lett. 106 (2011) 042001

E+E- AS A BASELINE FOR HADRONIC COLLISIONS

Acta Phys.Polon.Supp. 9 (2016) 207-211

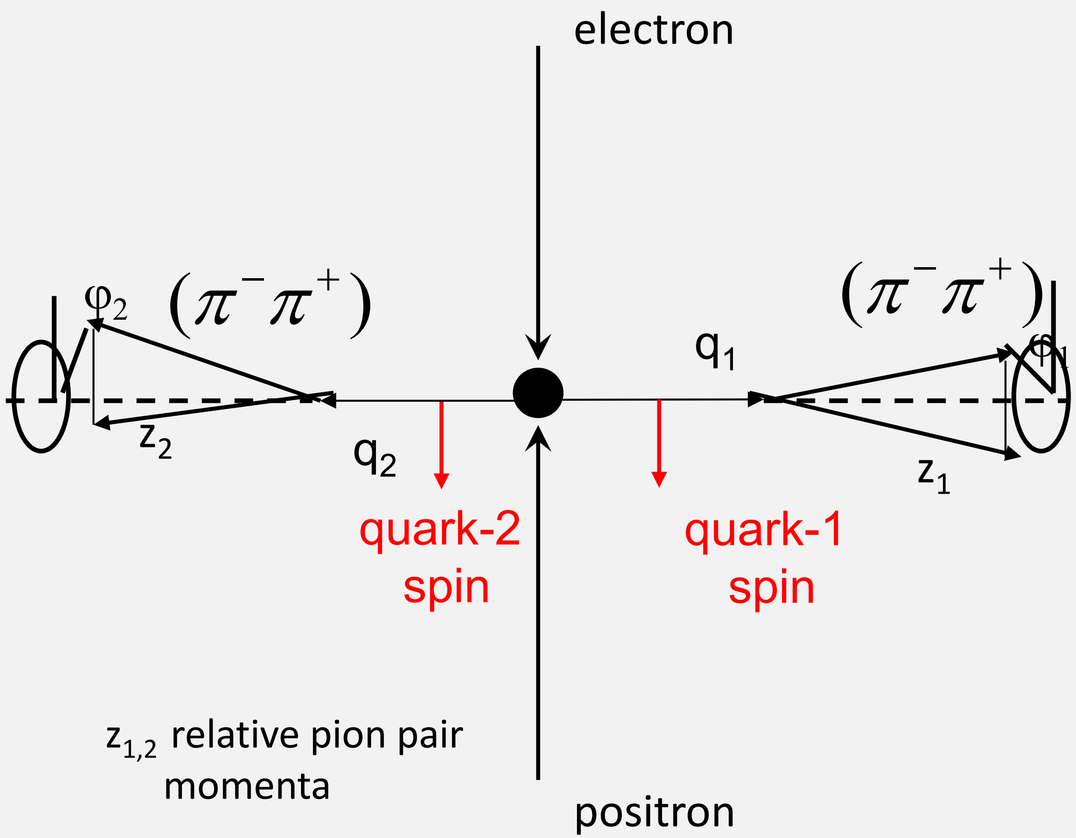


- Beyond pQCD there are new phenomena emerging in hadronic collisions
  - Ridge in high multiplicity hadronic collisions
  - pT broadening in back-to-back production
  - …
- e+e- can provide baseline
- More statistics needed to select e.g. high multiplicity events



Phys.Rev. D95 (2017) no.7, 072002

Measuring transverse spin dependent di-Hadron Correlations In unpolarized e^+e^- Annihilation into Quarks



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

Interference effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

Experimental requirements:

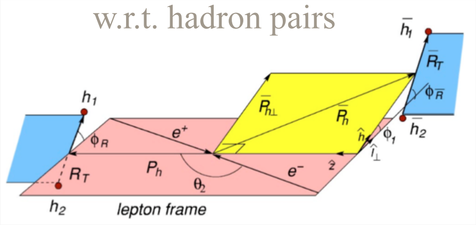
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

Di-hadron Fragmentation Functions

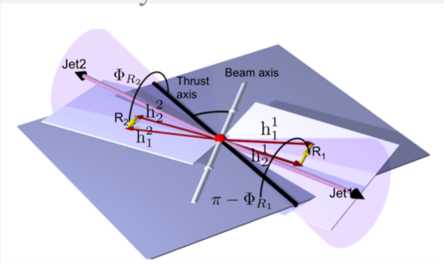
Starting from the fully integrated e^+e^- cross section into four unpolarized hadrons with two leading hadrons in each jet, authors of ref. PRD**67**, 094003 explicitly derive the asymmetry:

$$A(y, z, \bar{z}, M_h^2 \overline{M}_h^2) = \frac{\langle \cos(2(\phi_R - \phi_{\overline{R}})) \rangle}{\langle 1 \rangle} = \frac{\sum_{a,\bar{a}} e_a^2 \frac{3\alpha^2}{2Q^2} z^2 \bar{z}^2 A(y) \frac{1}{M_1 M_2 \overline{M}_1 \overline{M}_2} G_1^{\perp a}(z, M_h^2) \overline{G}^{\perp a}(\bar{z}, \overline{M}_h^2)}{\sum_{a,\bar{a}} e_a^2 \frac{6\alpha^2}{Q^2} A(y) z^2 \bar{z}^2 D_1^a(z, M_h^2) \overline{D}_1^a(\bar{z}, \overline{M}_h^2)}$$

PRD67,094003
asymmetric frame
w.r.t. hadron pairs



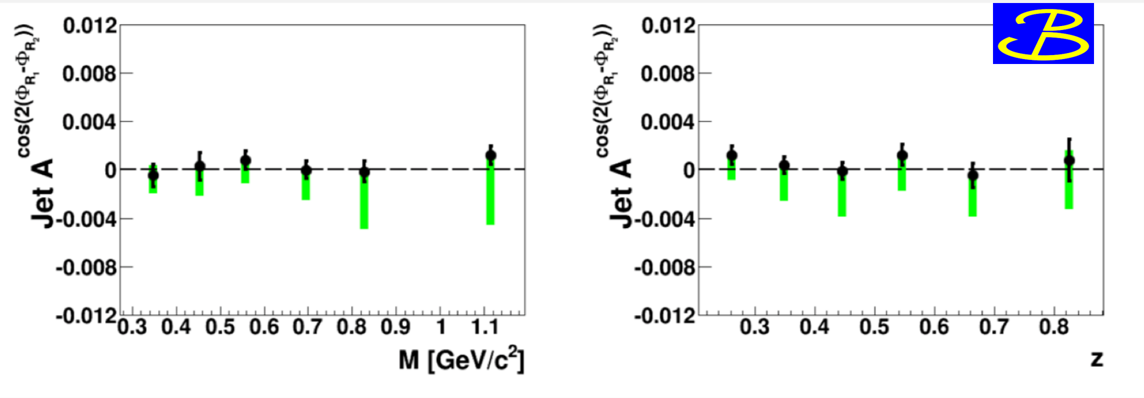
arXiv:1505.08020
symmetric frame



- longitudinally polarized quark IFF $G_1^\perp$
- chiral-even function related to the jet handedness
- asymmetric reference frame
- experimentally: switch to a symmetric frame
  - Belle preliminary: arXiv:1505.08020
  - angles are computed using the jet axis of di-jet event
  - jet axes reconstructed using anti-kT jet algorithm JHEP**0804**, 063

Two-dimensional χ^2 fit is performed to the normalized di-pion pairs:

$$1 + A^{\cos(\phi_{R1}+\phi_{R2})} \cos(\phi_{R1} + \phi_{R2}) + A^{\cos(2(\phi_{R1}-\phi_{R2}))} \cos(2(\phi_{R1} - \phi_{R2}))$$



NO SIGNAL observed at Belle

BUT more investigations about the thrust axis method and jet-axes reconstruction are needed

Summary and Conclusions

- Spin-dependent fragmentation functions provide key informations for understanding the hadronic structure and can also be used as a tool for the extraction of parton distribution functions
- e^+e^- annihilation experiments offer the ideal conditions to access FFs

one hadron FF	without k_T	with k_T
spin-0	D_1	$H_1^{\perp}$
spin-1/2	D_1, G_1, H_1	$D_{1T}^{\perp}$, $H_1^{\perp}$, G_{1T}, $H_{1L}^{\perp}$, $H_{1L}^{\perp}$
spin-1	D_1, D_{1LL}, G_1, H_1, H_{1LT}	$D_{1T}^{\perp}$, $H_1^{\perp}$, G_{1T}, $H_{1L}^{\perp}$, $H_{1L}^{\perp}$, $D_{1T}^{\perp}$, D_{1LT}, D_{1TT}, G_{1LT}, G_{1TT}, $H^{\perp}_{1LL}$, H'_{1LT}, $H^{\perp}_{1LT}$

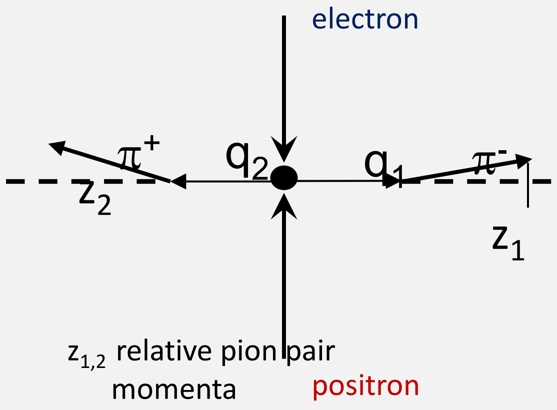
two hadrons FF	without k_T	with k_T
spin-0	D_1, $H_1^{\sphericalangle}$	$G_1^{\perp}$, $H_1^{\perp}$

higher twist

T-odd

OTHER PROCESSES NEEDED FOR FLAVOR SEPARATION AND GLUON FF

- e^+e^-
  - back-to-back: flavor and p_T dependence

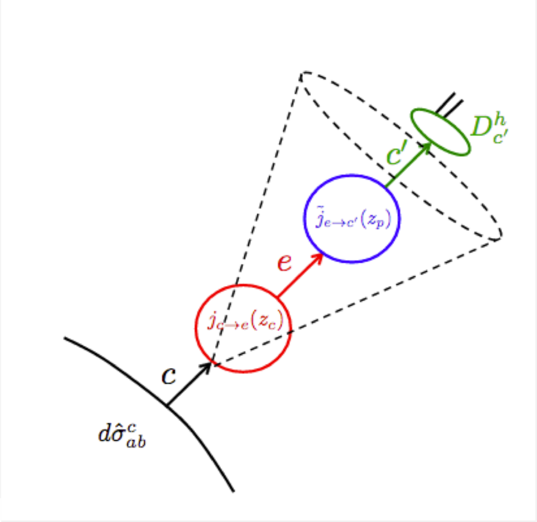


- SIDIS
  - Inclusive hadrons

$$2F_1^h(x,z,Q^2) = \sum_q e_q^2 \Big(f_1^{q/p} D_1^{h/q} + \frac{\alpha_s(Q^2)}{2\pi}\Big(f_1^{q/p}\otimes C_1^{qq}\otimes D_1^{h/q} + f_1^{q/p}\otimes C_1^{gq}\otimes D_1^{h/g} + f_1^{g/p}\otimes C_1^{qg}\otimes D_1^{h/q}\Big)\Big]$$

- pp
  - Inclusive

$$\frac{d^3\sigma^{pp\to(h,\mathrm{jet})X}}{dP_T^{\mathrm{jet}}\,d\eta^{\mathrm{jet}}\,dz} \propto \sum_{i,j,k} f_1^{i/p_a}(x_a)\otimes f_1^{j/p_b}(x_b)\otimes \hat{\sigma}^{ij\to k\mathrm{jet}}\otimes D_1^{h/p_k}\left(\frac{z}{z_k}\right)$$

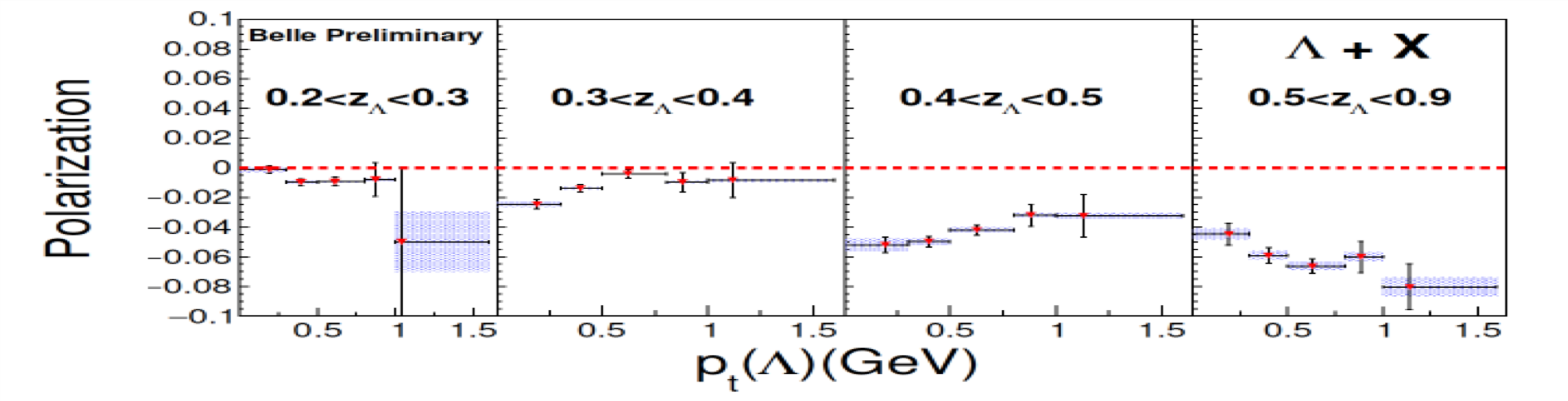


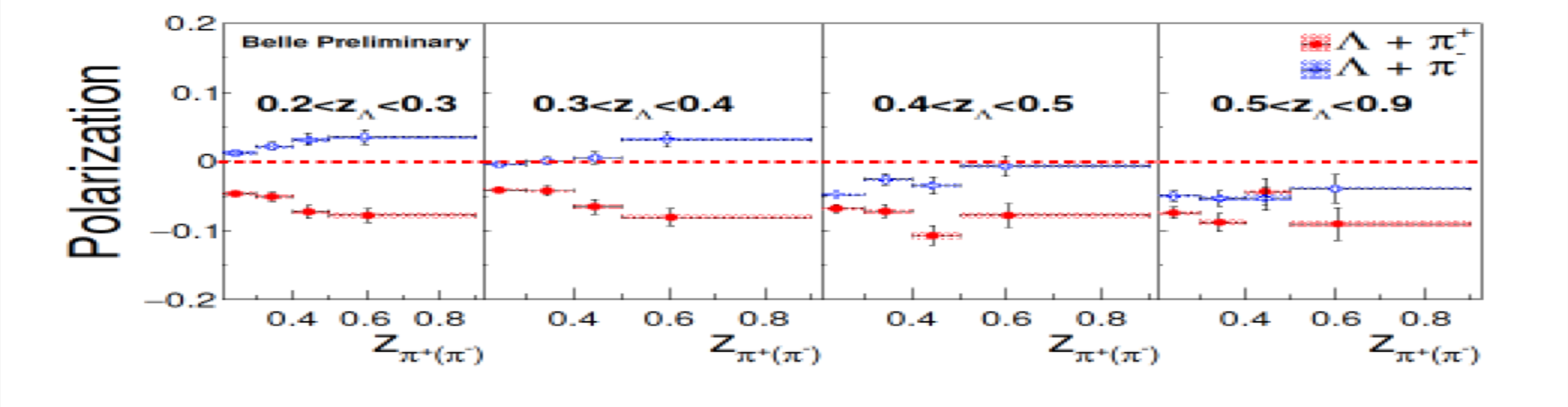
  - h-h, Jet-hadron (back-to-back)
  - γ-hadron (back-to-back)
  - Hadron in jet

$$\frac{E_h\, d^3\sigma^{pp\to hX}}{d^3P_h} = \sum_{i,j,k,l}\int\frac{dx_a}{x_a}\int\frac{dx_b}{x_b}\int\frac{dz}{z^2} f_1^{i/p_a}(x_a)\, f_1^{j/p_b}(x_b)\, D_1^{h/k}(z)\,\hat{\sigma}^{ij\to kl}\,\delta(\hat{s}+\hat{t}+\hat{u}),$$

Kaufmann, Mukherjee, Vogelsang,
Phys.Rev. D92 (2015) no.5, 054015

Z_Λ, P_T DEPENDENCE OF OBSERVED Λ POLARIZATION

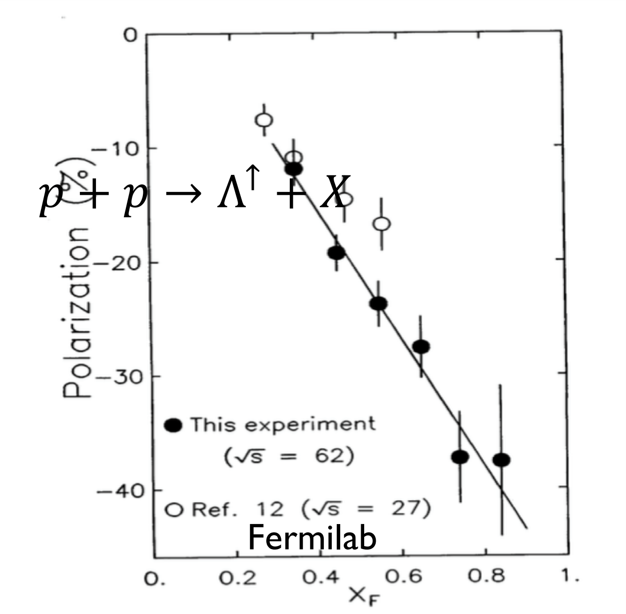




- Polarization rises with p_t in the lowest z_Λ and highest z_Λ bin. But the dependence reverses around 1 GeV in the intermediate z_Λ bins→**Unexpected!** (might be related to fragmenting quark flavor dependence on z_1,z_2)
- Correlation with opposite hemisphere light meson →quark flav/charge dependence
  - Sign of asymmetry dependent on quark charge cf Sivers

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 studied transverse Λ polarization, no significant signal was observed. **Eur. Phys. J. C2, 49 (1998)**
- FF counterpart of the Sivers function.



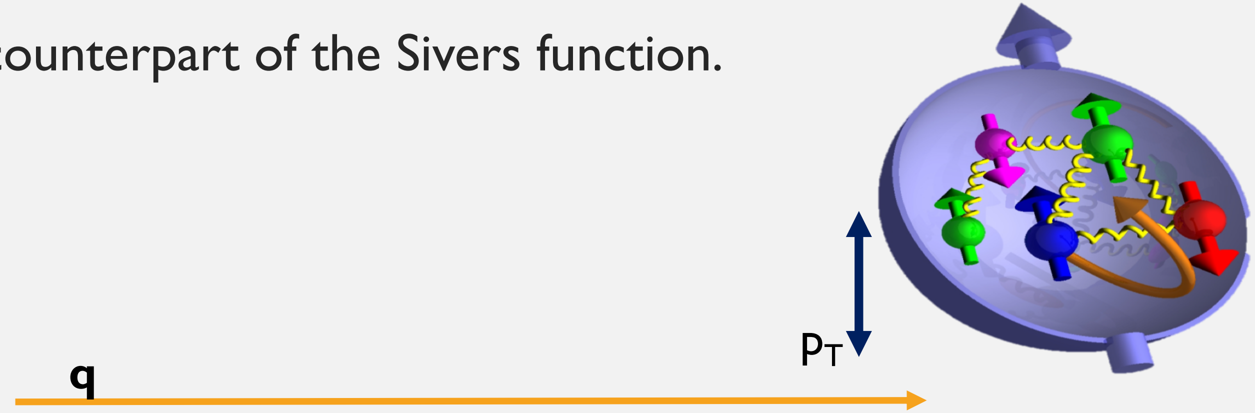
$p + p \to \Lambda^{\uparrow} + X$

Fermilab

ISR data

(Phys.Lett. B185 (1987) 209)

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



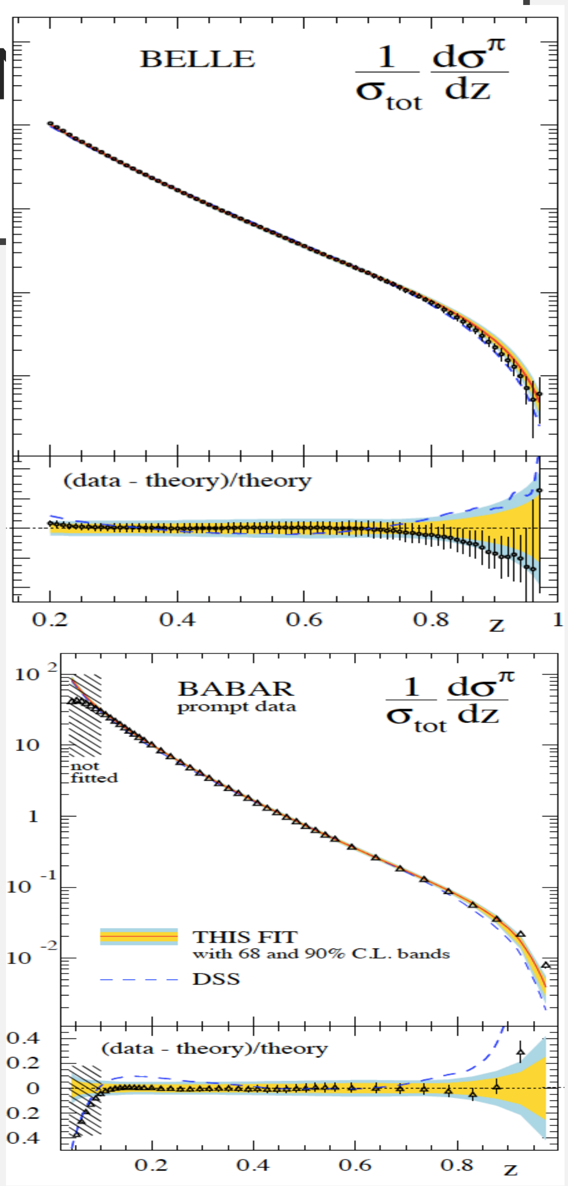
ADVANTAGES OF E+E-

- Reconstruct complex final states (e.g. lambda) with feed-down contributions etc
- Correlations dependent on initial quark spin (not known if quark comes from proton)
- Correlations dependent on pT

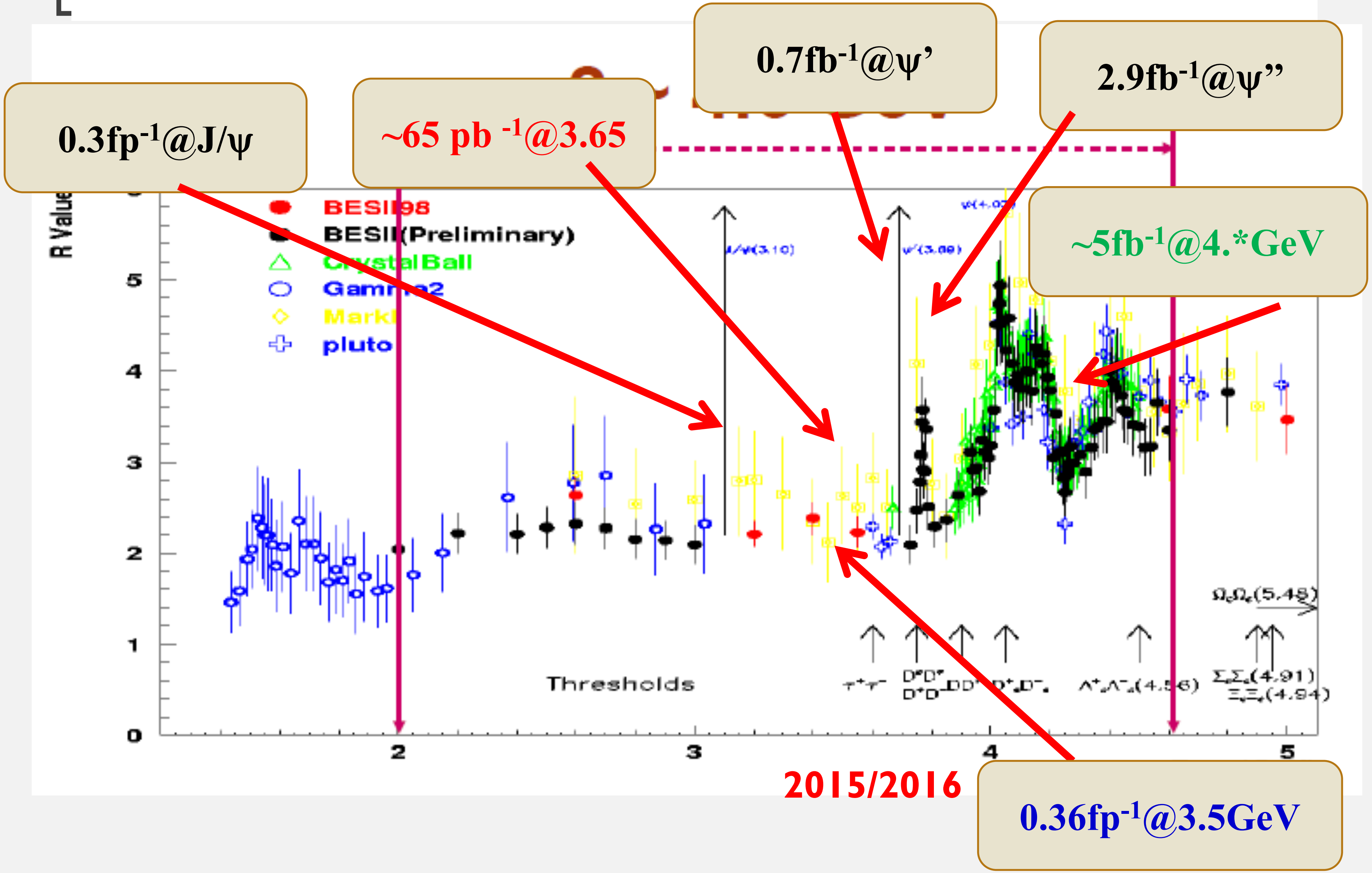
- Null-test for back-to-back correltions in pp, HI colissions

COMPARE TO E+E-: AGREEMENT GOOD

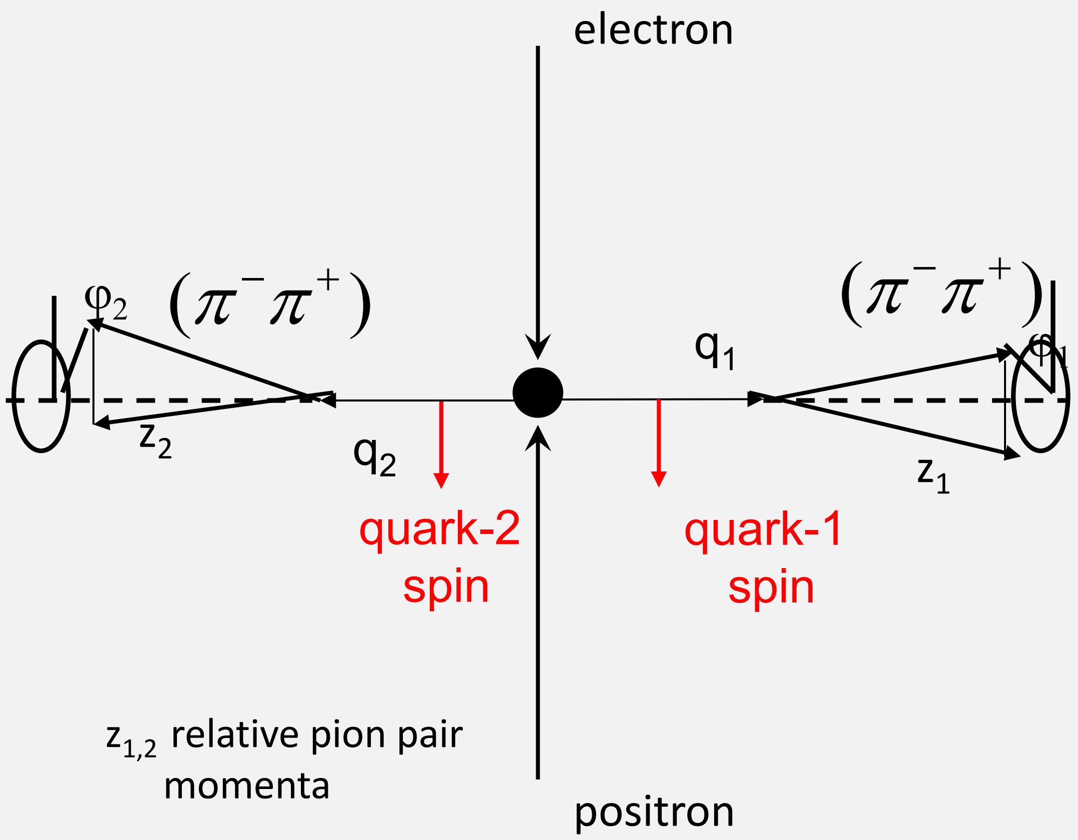
- Fit includes pp, SIDIS data and BaBar e+e-
- New NNLO calculations (only e+e-)
  - See talk tomorrow
  - Still need high z resummation and target mass corrections → see also JAM fits
  - Target mass corrections mitigated by high energy at FCC-ee



Data samples we (will) have



Measuring transverse spin dependent di-Hadron Correlations In unpolarized e^+e^- Annihilation into Quarks



Interference effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

Experimental requirements:

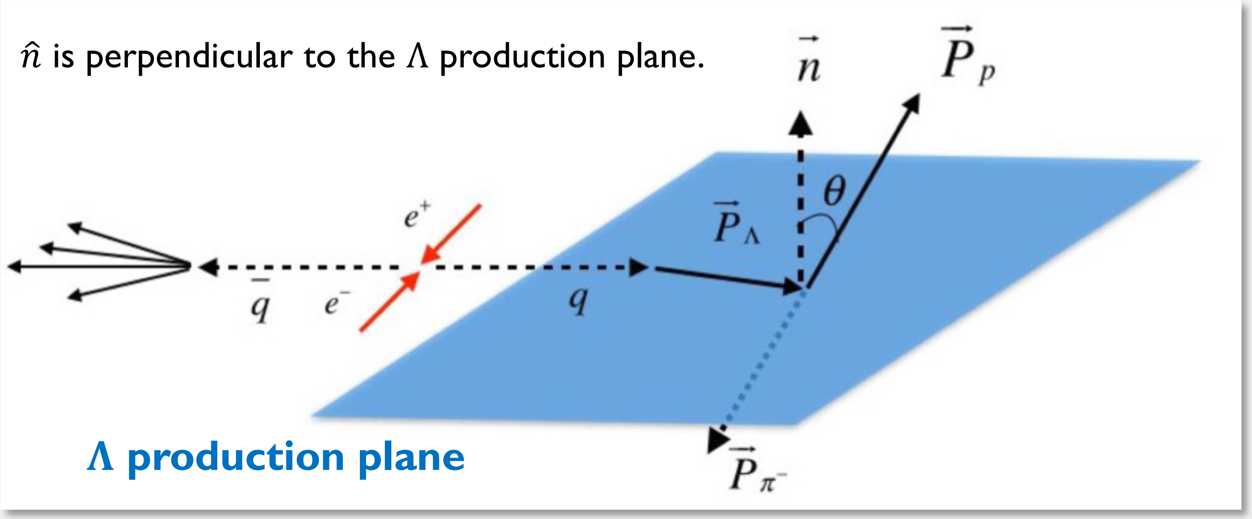
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

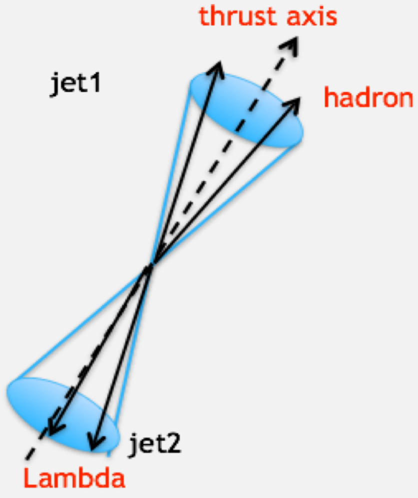
BELLE

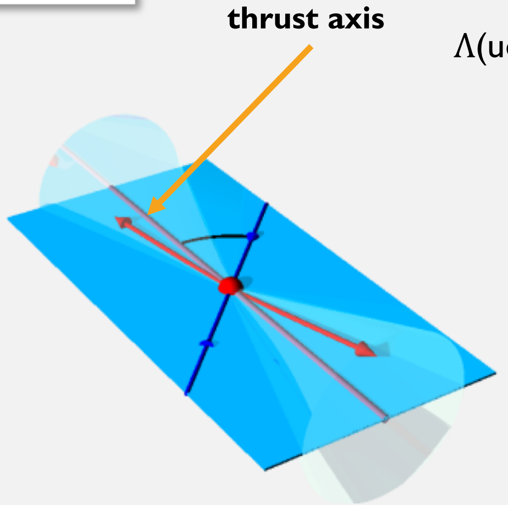
Normalized cross section $e^+e^- \rightarrow (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

$$\propto 1 + H_1^{\angle}\,\overline{H_1^{\angle}}\cos(\phi_1 + \phi_2) + G_1^{\perp}\overline{G_1^{\perp}}\cos(2(\phi_1 - \phi_2))$$

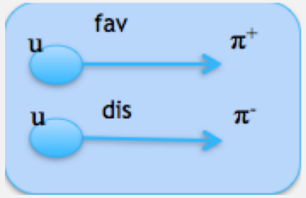
OBSERVABLES IN Λ RESTFRAME







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



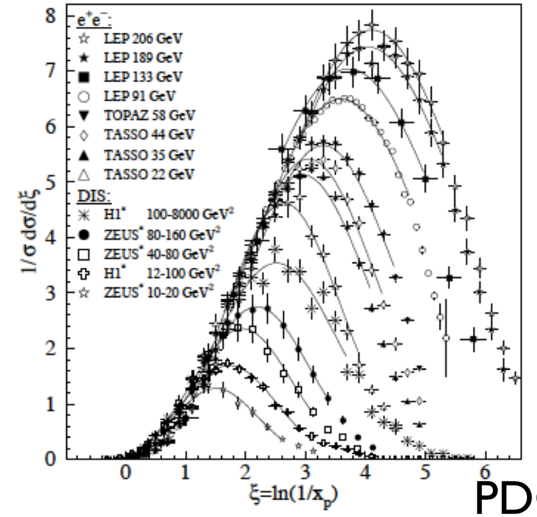
- Self-analyzing decay leads to polarization dependent distribution

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

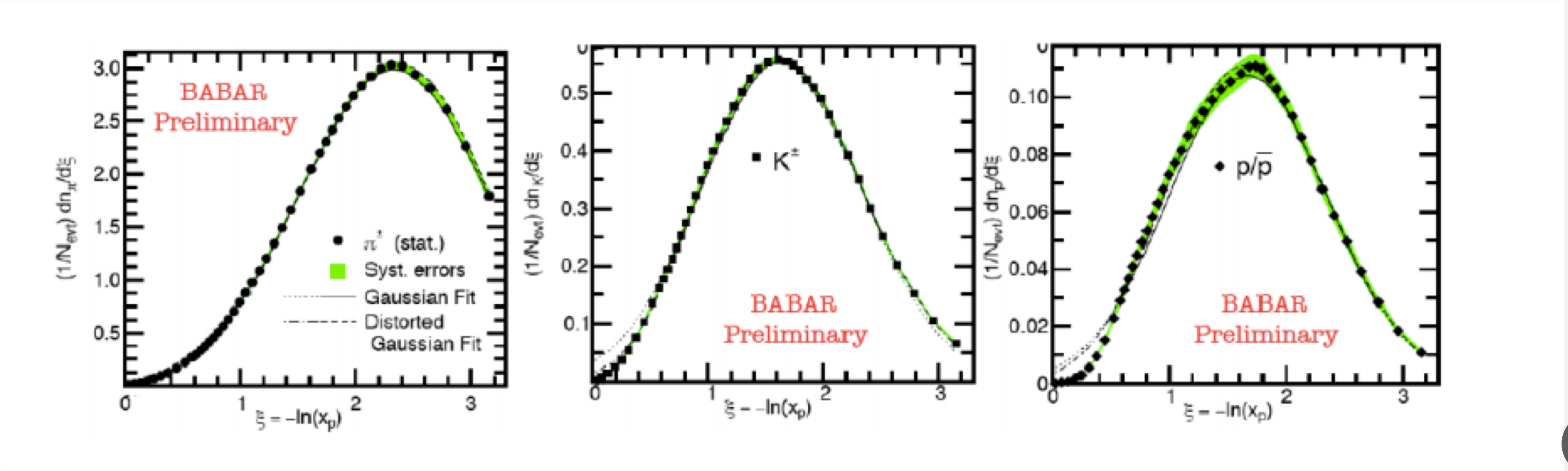
- where α is the decay parameter: α_+=0.642 $\pm$ 0.013 for Λ and α_-=-0.71 $\pm$ 0.08 for $\bar{\Lambda}$ (PDG).
- The p_t is measured as the transverse momentum of Λ relative to the **thrust axis**

PERTURBATIVE QCD

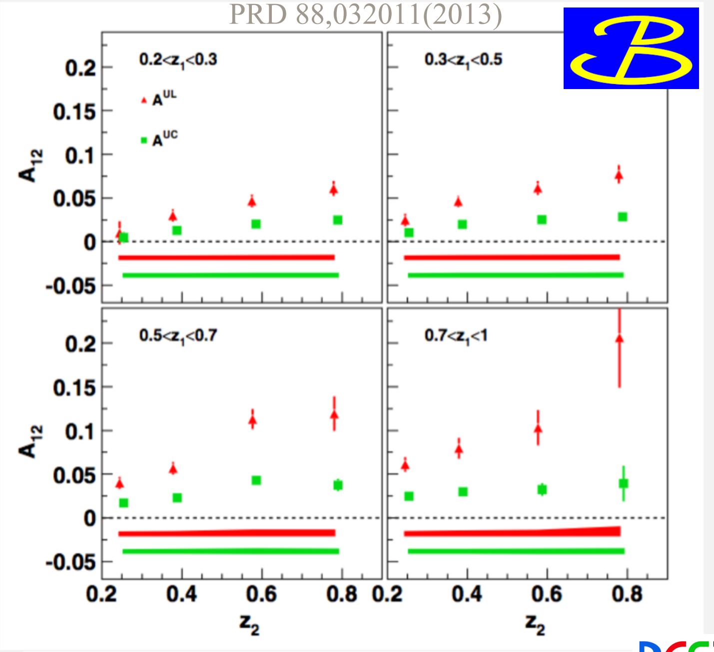
- Time like splitting functions have singularities < 0.1 (unlike space like important for DIS)
- MLLA → test for resummation
- Observed shape consistent with QCD calculations (access to α_S)
- FCC-ee might go to lower z. Impact?

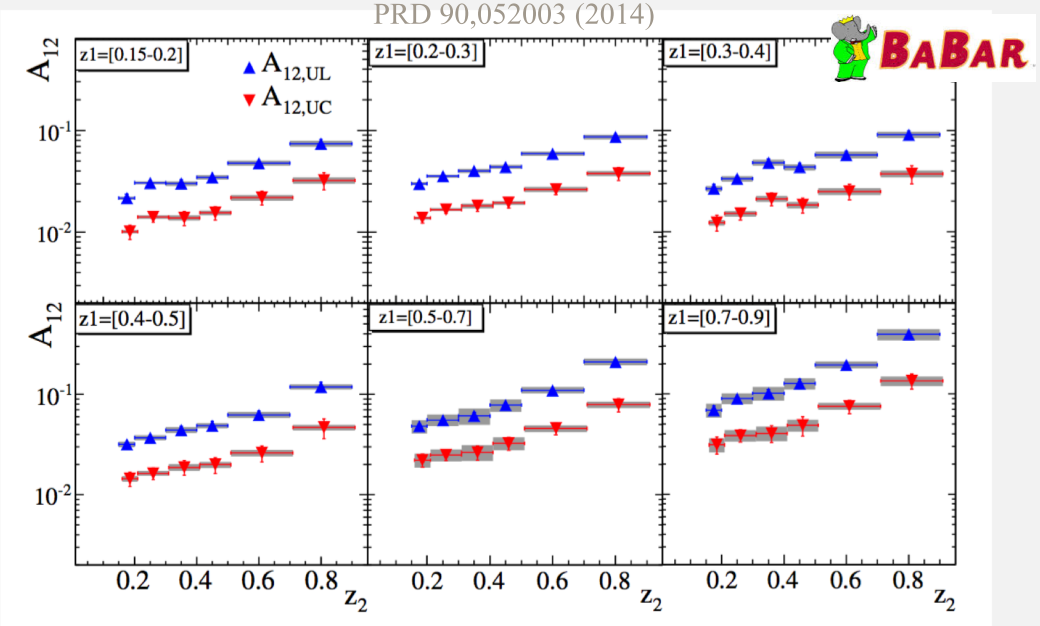


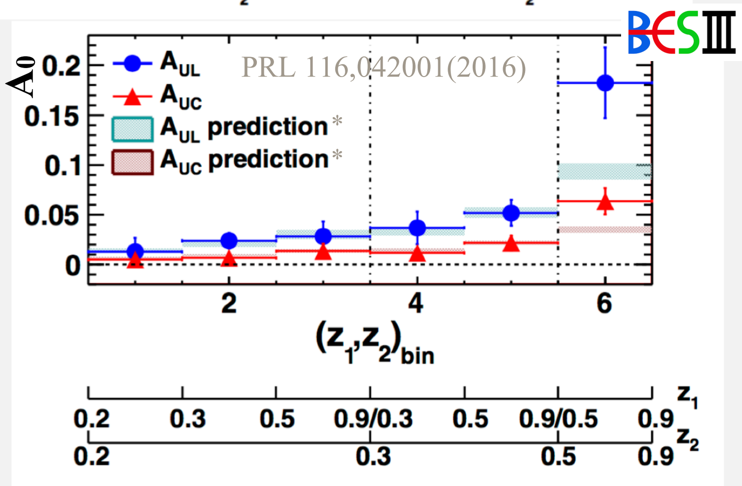
PDG



Collins Effect vs (z_1,z_2)





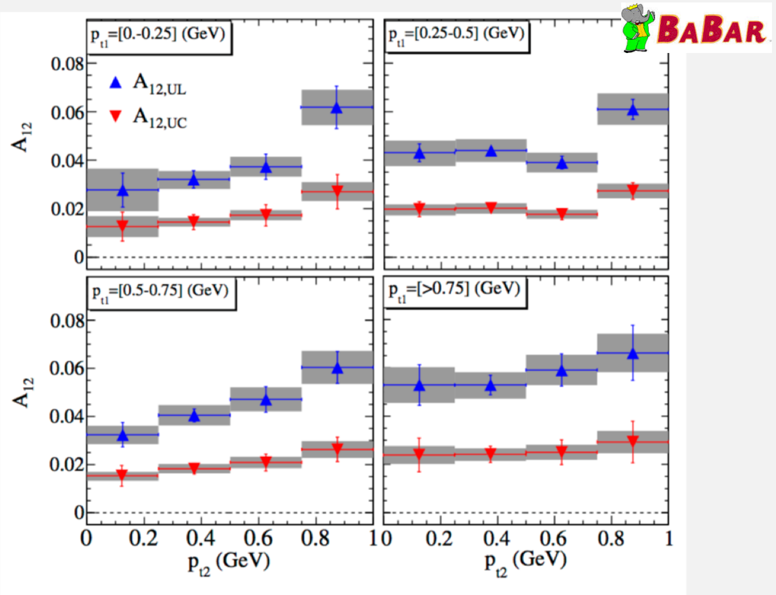


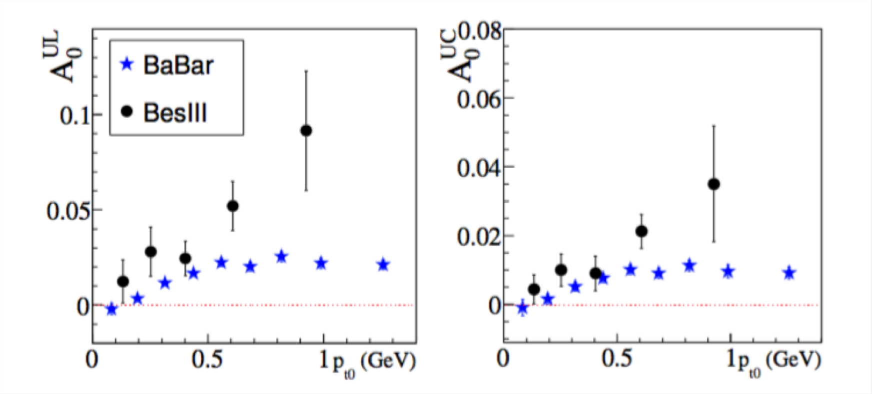
- Significant non-zero asymmetries A_{12}, A_0 in all bins
- Strong dependence on (z_1,z_2) observed in all the experiments
- $A_{UC}<A_{UL}$ as expected; complementary informations about favored and disfavored fragmentation processes

*PRD 93,014009(2016)

COLLINS EFFECT VS PT AND THRUST POLAR ANGLE

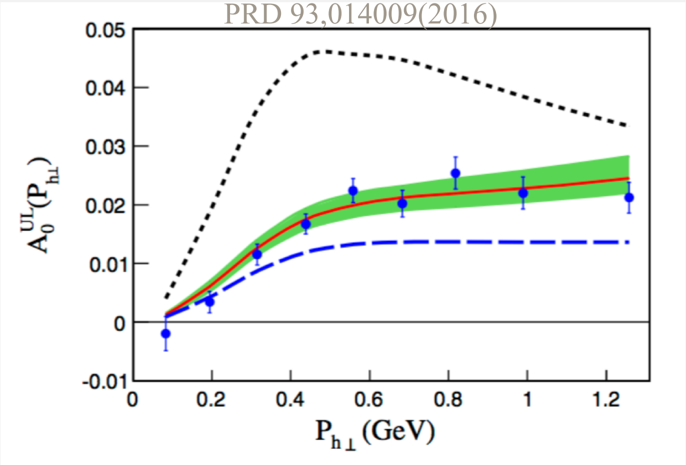
Unlike/**L**ikesign
Unlike/**C**harged
Ratios to cancel acceptance effects
Unlike:
fav*fav+dis*dis
Like:
fav*dis





The asymmetries increase for increasing p_t:

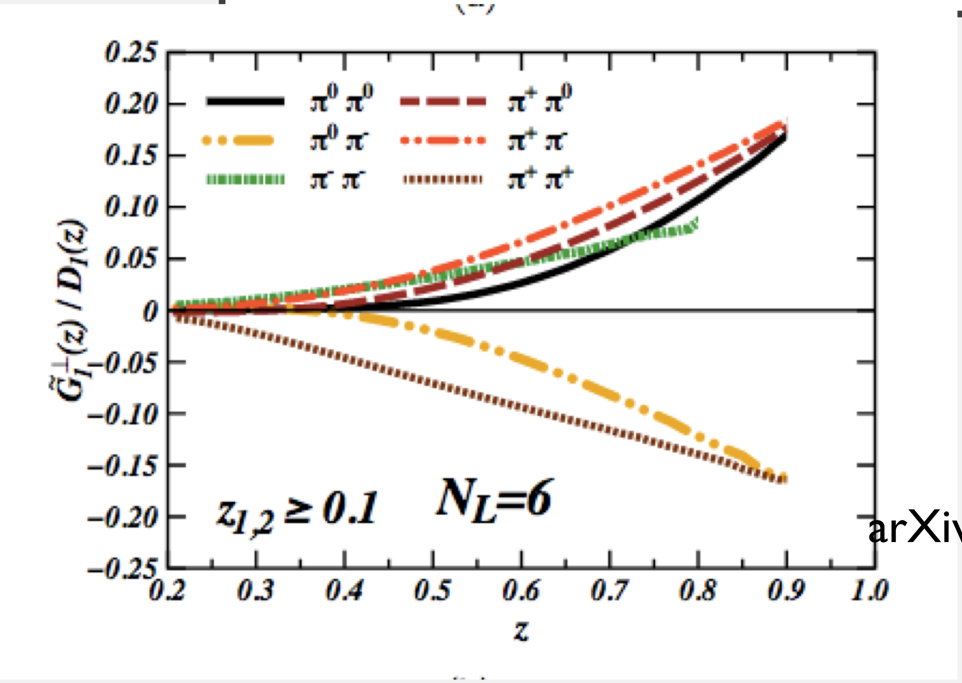
- less pronounced for A_{12}, but large uncertainties due to the p_t resolution
- steeper p_t dependence for BESIII
  - different kinematic regions: $\langle z \rangle_{BESIII} > \langle z \rangle_{BaBar}$



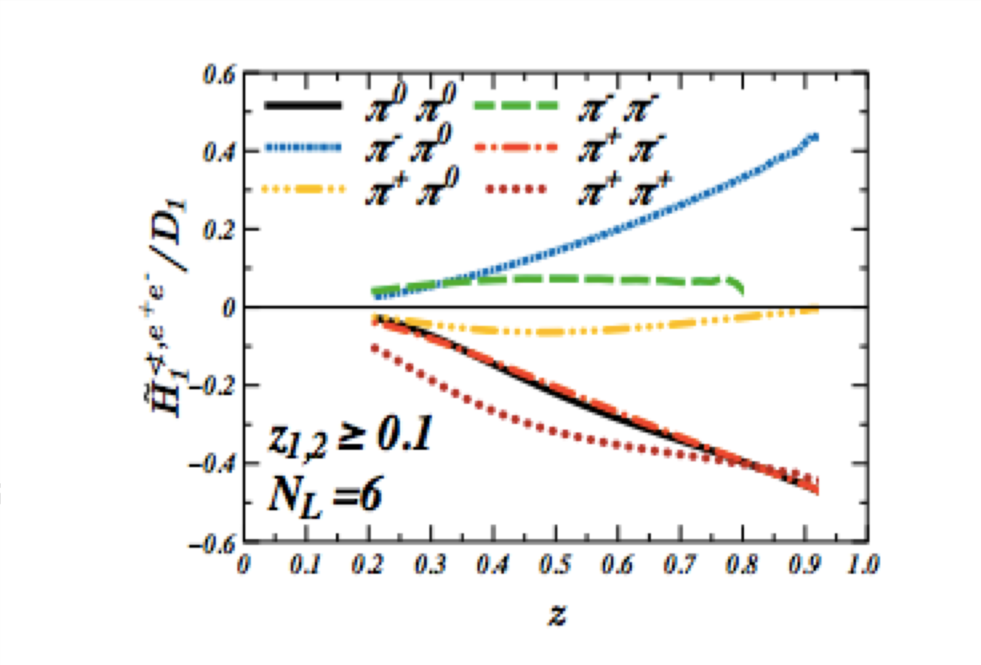
NLL’: next-to-leading-logarithm approximation
LL: leading logarithmic calculation
No TMD evolution
Calculation performed with fixed parameters from Table I in PRD93,014009

- A^{UL} and A^{UC} asymmetries are described very well
- TMD evolution at NLL’ describes e^+e^- and SIDIS data adequately well
- better description including higher orders: improvement of the theoretical uncertainties

ASYMMETRIES FOR COS(2(ϕ_{R1}-ϕ_{R2})) ($G_1^\perp$) SMALL

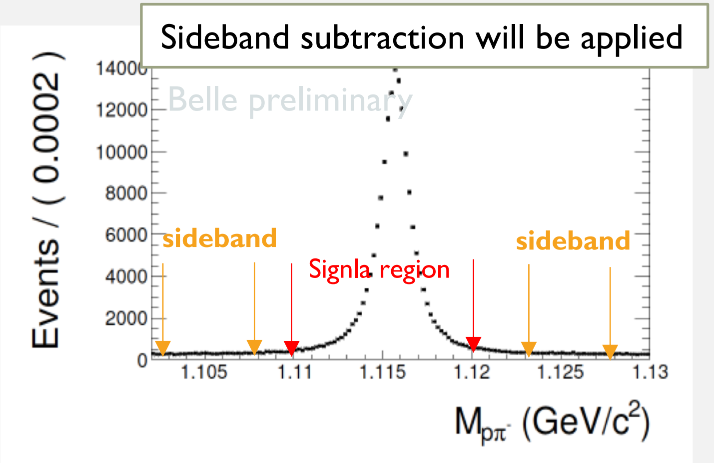


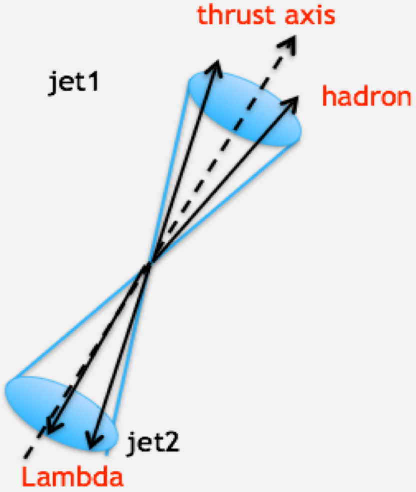
arXiv:17



- See recent model calculations by Matevosyan et al. → 'worm gear' type splitting function (cmp to g1t pdf)

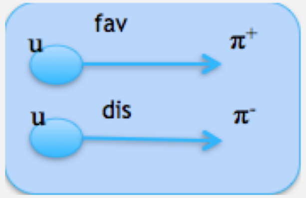
LAMBDA RECONSTRUCTION





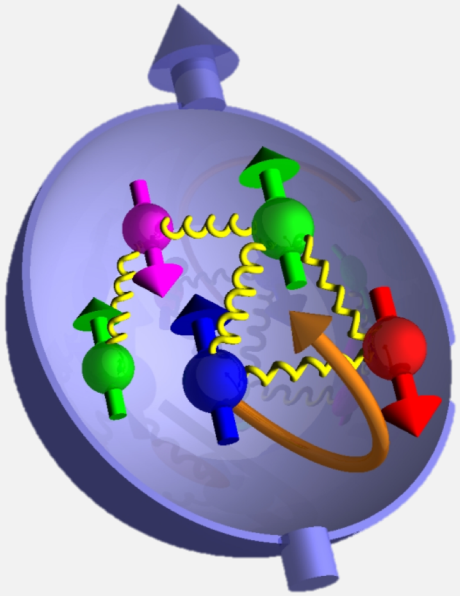
- Signal process $\Lambda \to p\pi^-(\bar{\Lambda} \to \bar{p}\,\pi^+)$. Clear Λ peak.
- Detect light hadron $(K^{\pm}, \pi^{\pm})$ in the opposite hemisphere→ enhance or suppress different flavors fragmenting in $\Lambda(\bar{\Lambda})$.

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



HYPERON PRODUCTION AS A TOOL TO STUDY BARYON SPIN STRUCTURE

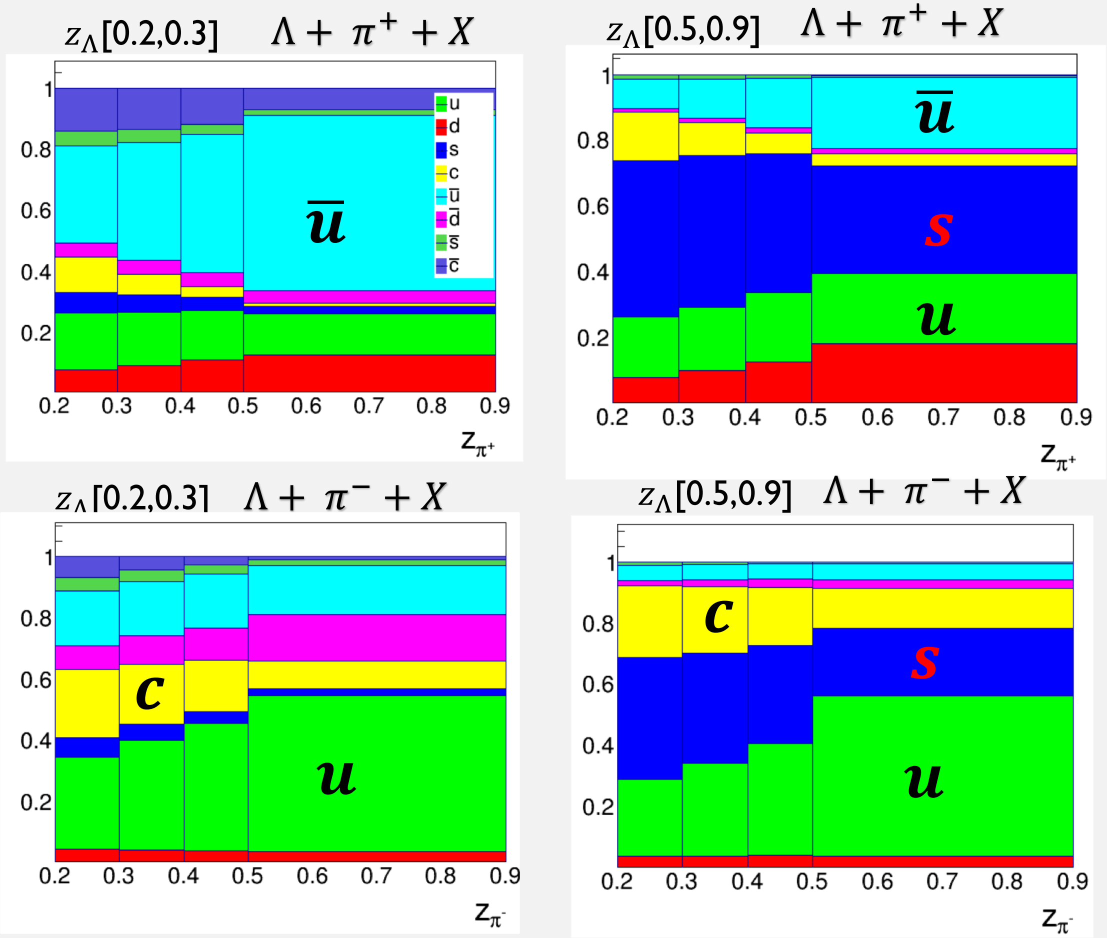
- Lambda polarization allows to study spin-orbit correlation of quarks inside Baryon → counterpart of the Sivers parton distribution function (k_T dependence of quark distributions in transversely polarized proton)
- A non-vanishing $D_{1T}^{\perp}$ could help to shed light on the spin structure of the Λ, especially about the quark orbital angular momentum, a missing part of the spin puzzle of the nucleon.
- Produce Lambda with certain p_T
- Check Transverse Polarization depending on p_T and flavor
- Analogue of the Sivers effect in the Similar Universality checks (T-odd but not chiral odd) allows to fix sign



p_T

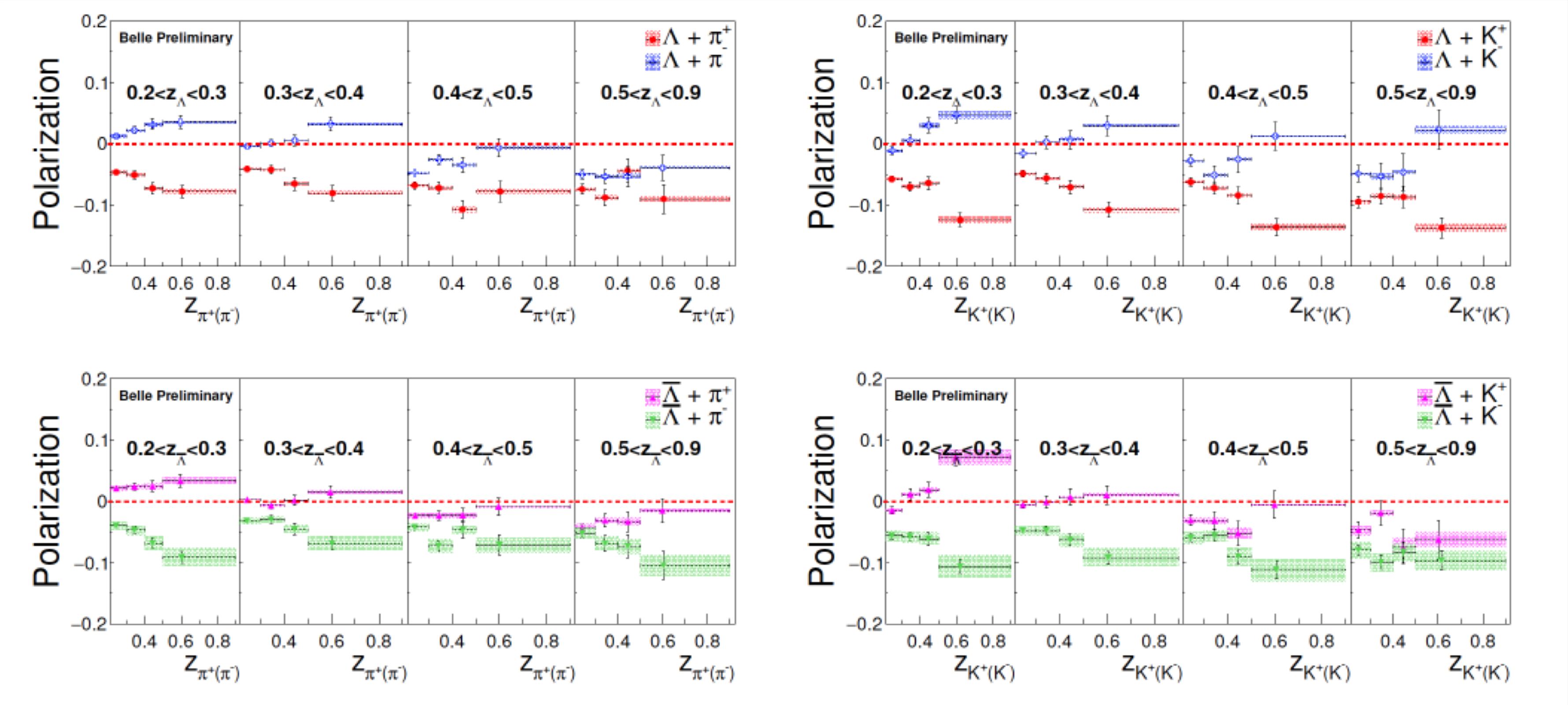
q

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 $[z_\Lambda\ z_\mathrm{h}]$ 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.

Π/K TAG IN OPPOSITE HEMISPHERE



- 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.

Before Belle II there was BELLE

- KEKB: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - $\sqrt{s}$ = **10.58 GeV,** $e^+e^- \to \Upsilon(nS) \to B/\bar{B}$ + continuum
  - $\sqrt{s}$ = 10.52 GeV, e+e- → qqbar (u,d,s,c) 'continuum'
- Ideal (at the time) detector for high precision measurements:
  - tracking acceptance θ [17 °;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - ~1 ab^{-1} total
  - ~1.8 *10^9 events at 10.58 GeV,
    ~220 *10^6 events at 10.52 GeV

Experiment	Scans/ Off. Res.	$\Upsilon(5S)$ 10876 MeV		$\Upsilon(4S)$ 10580 MeV		$\Upsilon(3S)$ 10355 MeV		$\Upsilon(2S)$ 10023 MeV		$\Upsilon(1S)$ 9460 MeV	
	fb^{-1}	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6	fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
Belle	100	121	36	711	772	3	12	25	158	6	102

BELLE Detector (took data till 2010)