Hadronization Studies in e^+e^- annihilation at Belle

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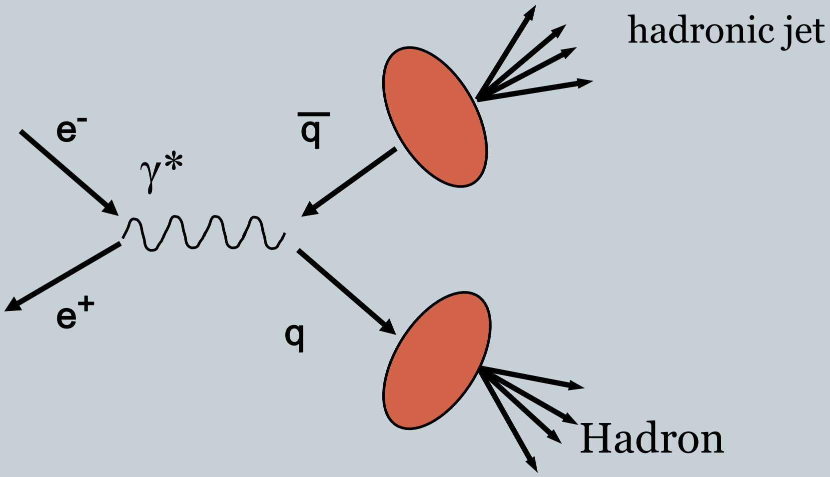
INDIANA UNIVERSITY

See A. Metz & A . Vossen,
“Parton Fragmentation Functions”,
arXiv:1607.02521

Seminar, Compass, CERN, 10/23/2016

Easiest Process to study QCD

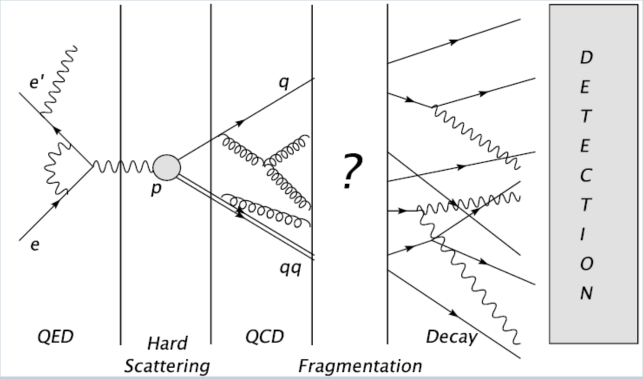
electron-positron collisions



time-like
virtual photon

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
- Consequence of confinement
- Questions to be asked
  - Macroscopic effect (distribution, polarization)of microscopic properties (quantum numbers)?
  - Effect of QCD vacuum the quark is traversing

Amsterdam notation for FFs with quark/hadron polarization

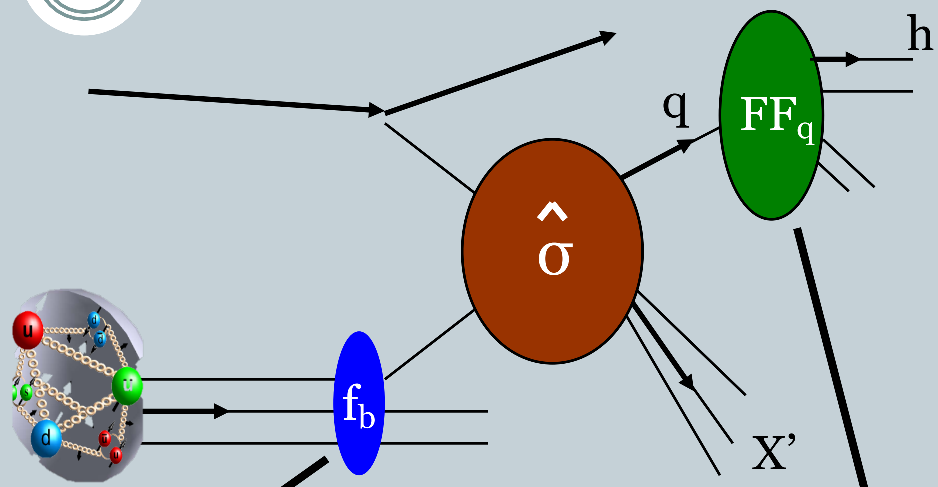
z: fractional energy of the quark carried by the hadron
$P_{h,T}$: transverse momentum of the hadron: **TMD FFs**

Parton polarization → Hadron Polarization ⇣	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z, p_T)$	$G_1^{h/q}(z, p_T)$	$H_1^{\perp h/q}(z, p_T)$
longitudinal			
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

Fragmentation Functions: Why should we bother?

- Proton Structure extracted using QCD factorization theorem
- FFs contribute to virtually all processes
- Particular important for transverse spin structure

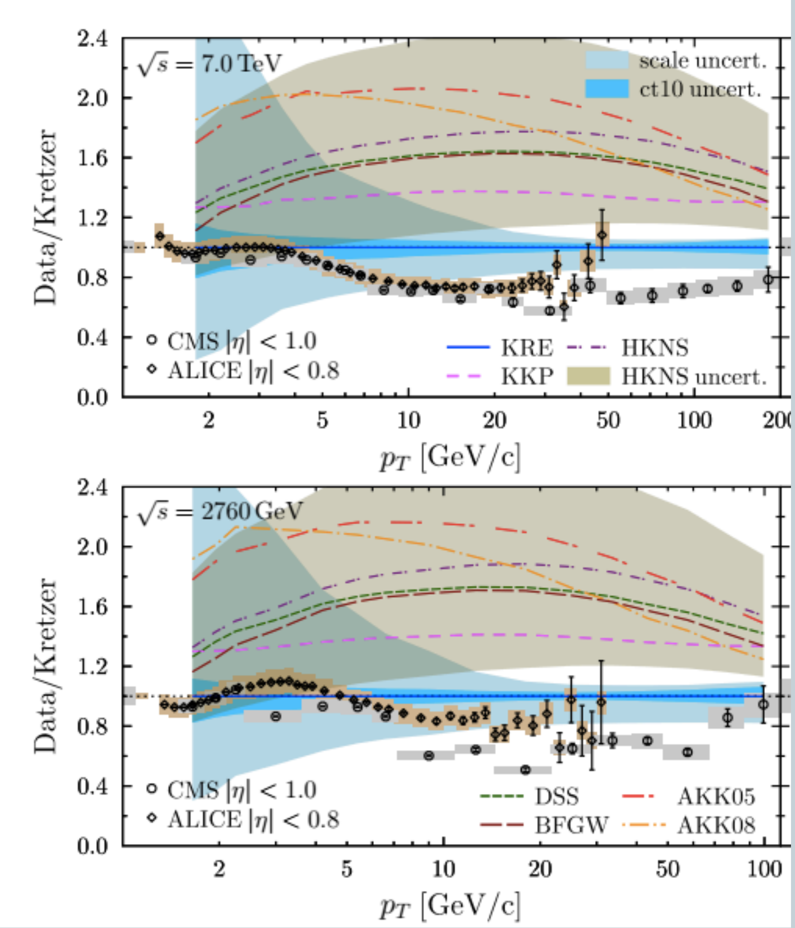


Proton Structure | pQCD | fragmentation function

$$\frac{d^3\sigma^\uparrow\left(pp^\uparrow \to \pi^+ X\right)}{dx_1 dx_2 dz} \propto q_i^\uparrow(x_1, k_{q,T}) \cdot G(x_2) \times \frac{d^3\hat{\sigma}^\uparrow(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k.l}}(z, p_{h,T})$$

Fragmentation Functions: Why should we bother?

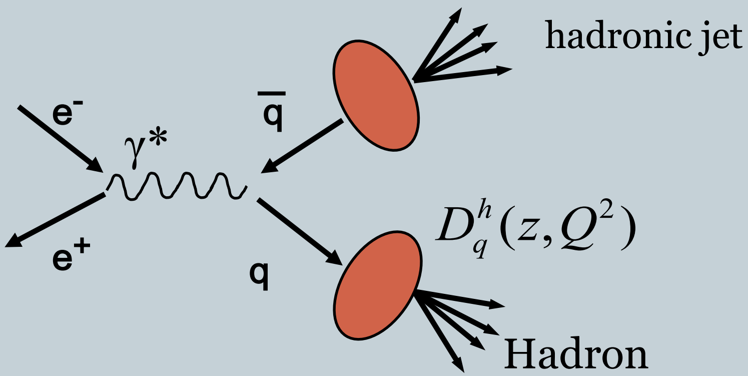
- Example:
  - Hadron Spectra at the LHC confronted with current FF sets
  - **Large disagreement!**

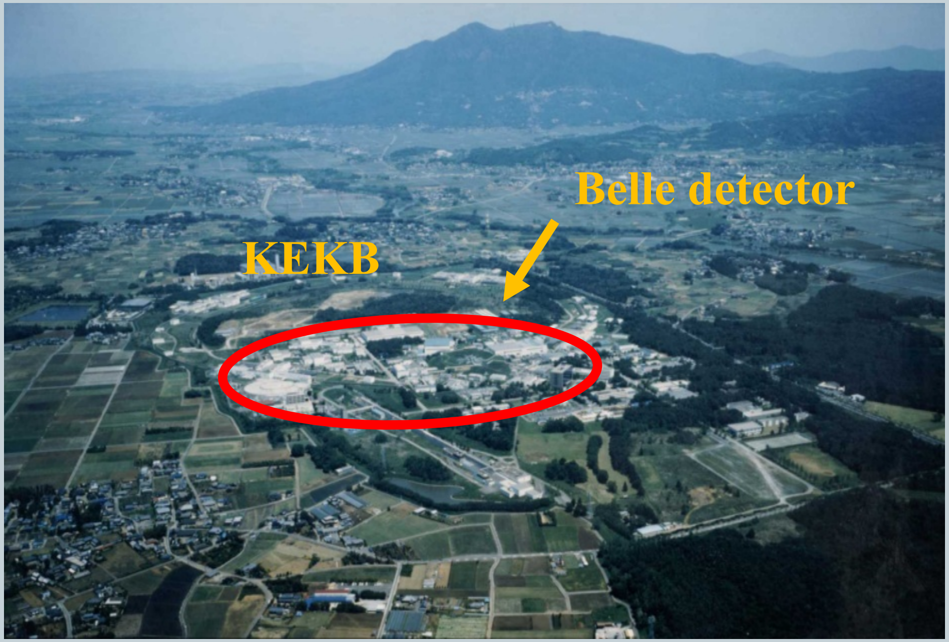


D. d'Enterria, K. J. Eskola, I. Helenius, H. Paukkunen, Nucl. Phys. B883 (2014) 615.

Where to Study?

- e^+e^- cleanest way to access FFs





- B factories
  - close in energy to SIDIS (100 GeV² vs 2-3 GeV²)
  - Large integrated lumi!, high z reach

Where to Study?

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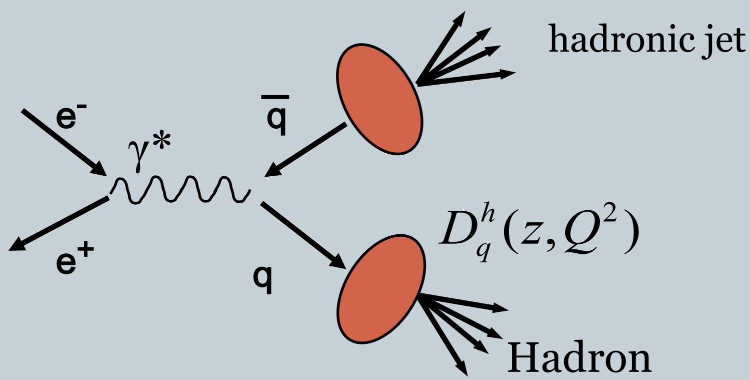

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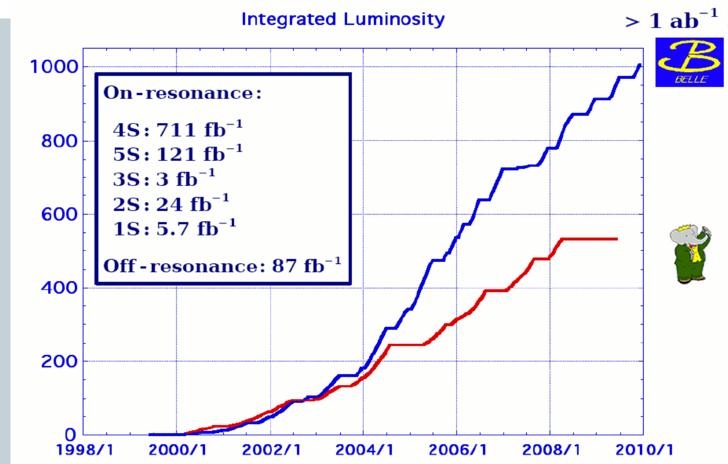
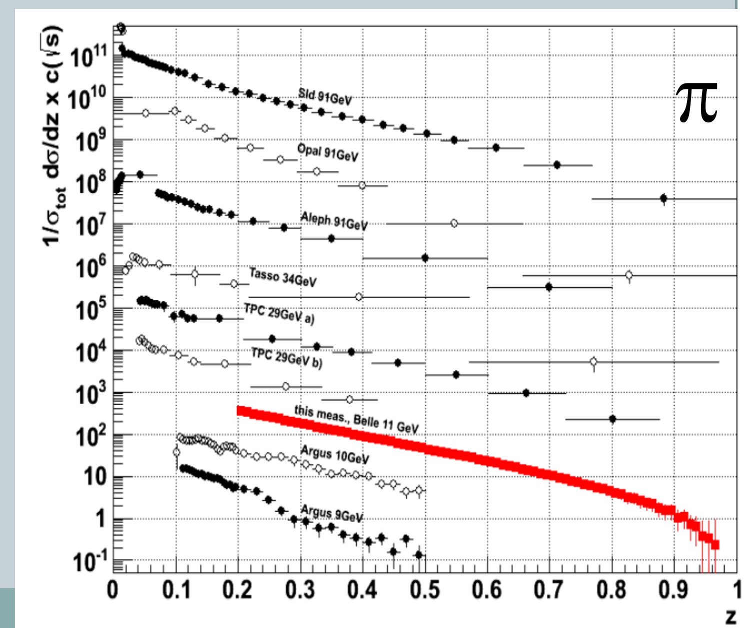




Belle, a typical e+e- Experiment of generation 2000

•Asym. e^+ (3.5 GeV) e^- (8 GeV) collider:

-√**s = 10.58 GeV,** e^+e^- →Y(4S)→B anti-B

-√**s** = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'

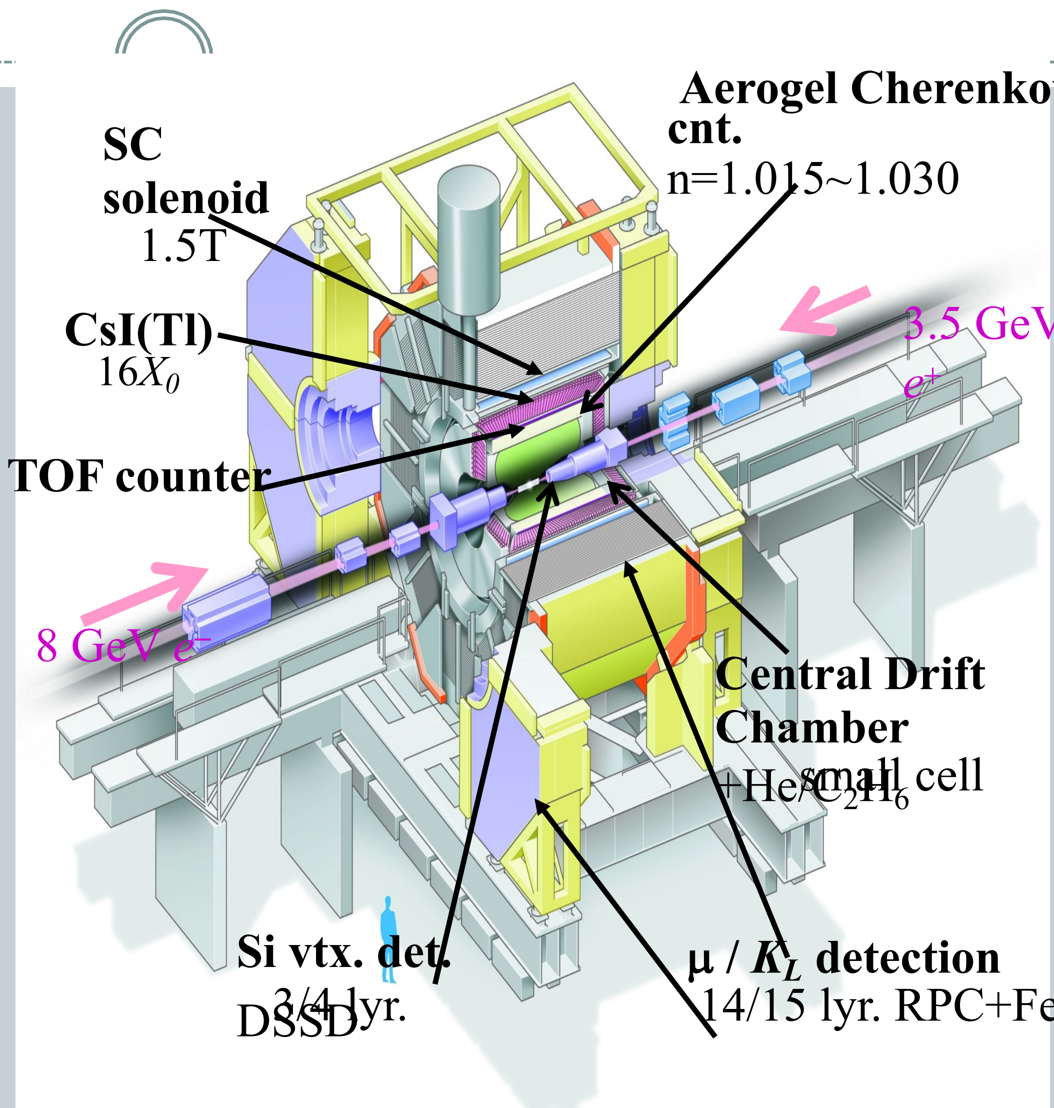
• ideal detector for high precision measurements:

- Azimuthally symmetric acceptance, high res. Tracking, PID: Kaon efficiency ~85%

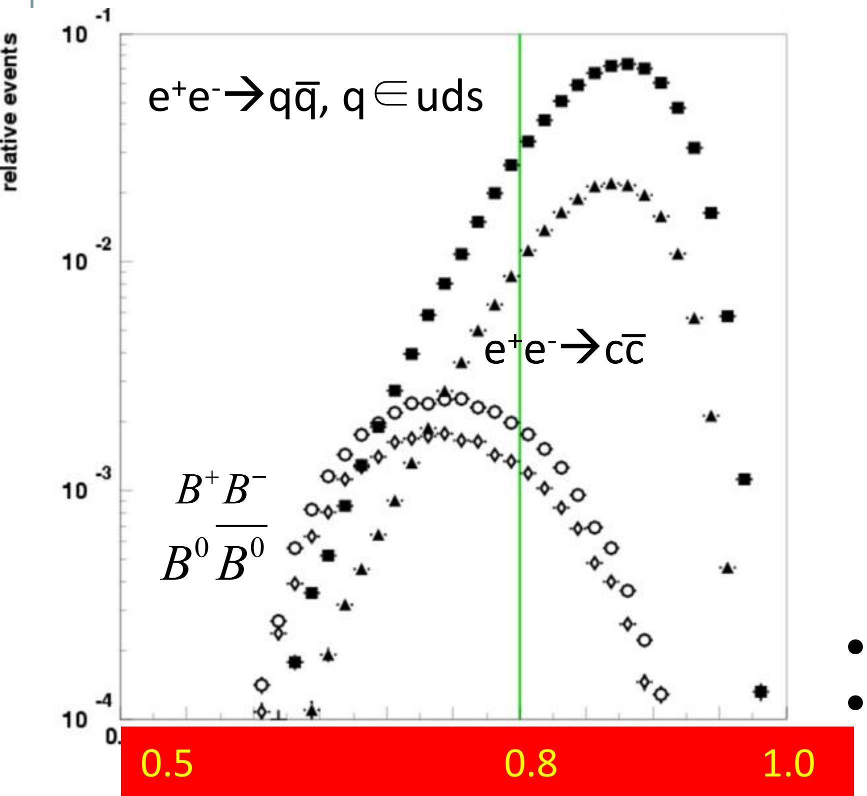
Available data:

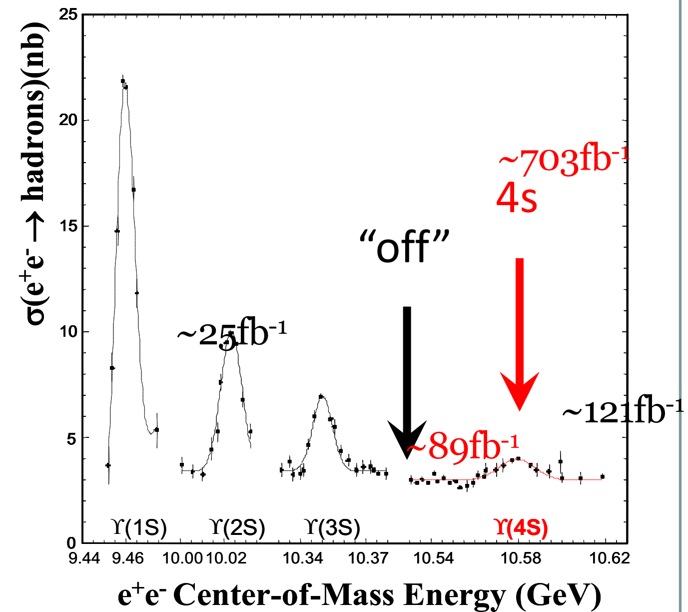
~1.8 $*10^9$ events at 10.58 GeV,

~220 $*10^6$ events at 10.52 GeV



Measuring Light Quark Fragmentation Functions on the ϒ(4S) Resonance

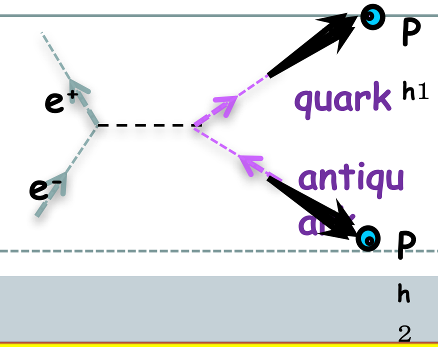




$$Thrust:\ T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under ϒ (4S) resonance
- 89 fb^{-1} ➔ 792 fb^{-1}

Baseline measurement D(z) from Cross-Section for identified Pions and Kaons

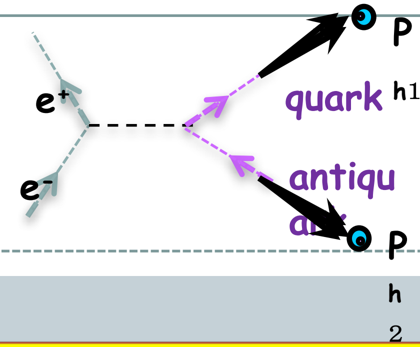


$$\sigma^h(z,Q^2,p_T) \propto \sum_q e_q^2 \left(D^h_{1,q}(z,Q^2,p_T) + D^h_{1,\bar{q}}(z,Q^2,p_T) \right)$$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}}$$

$$N^{j,raw}(z_m)$$

Baseline measurement D(z) from Cross-Section for identified Pions and Kaons



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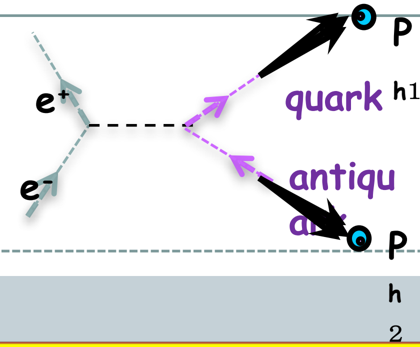
PID $i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \quad \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} \; N^{j,raw}(z_m)$$

- Smearing Corrections

- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low z, correct based on MC

Baseline measurement D(z) from Cross-Section for identified Pions and Kaons



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

PID $i = \pi, K$

$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \; \epsilon^i_{joint}(z) \; \epsilon^i_{ISR/FSR}(z) \, S^{-1}_{zz_m} \, \epsilon^i_{impu}(z_m) \, P^{-1}_{ij} \; N^{j,raw}(z_m)$$

- Correct for acceptance,
- ττ, 2γ,
- decay in flight,

< 10%

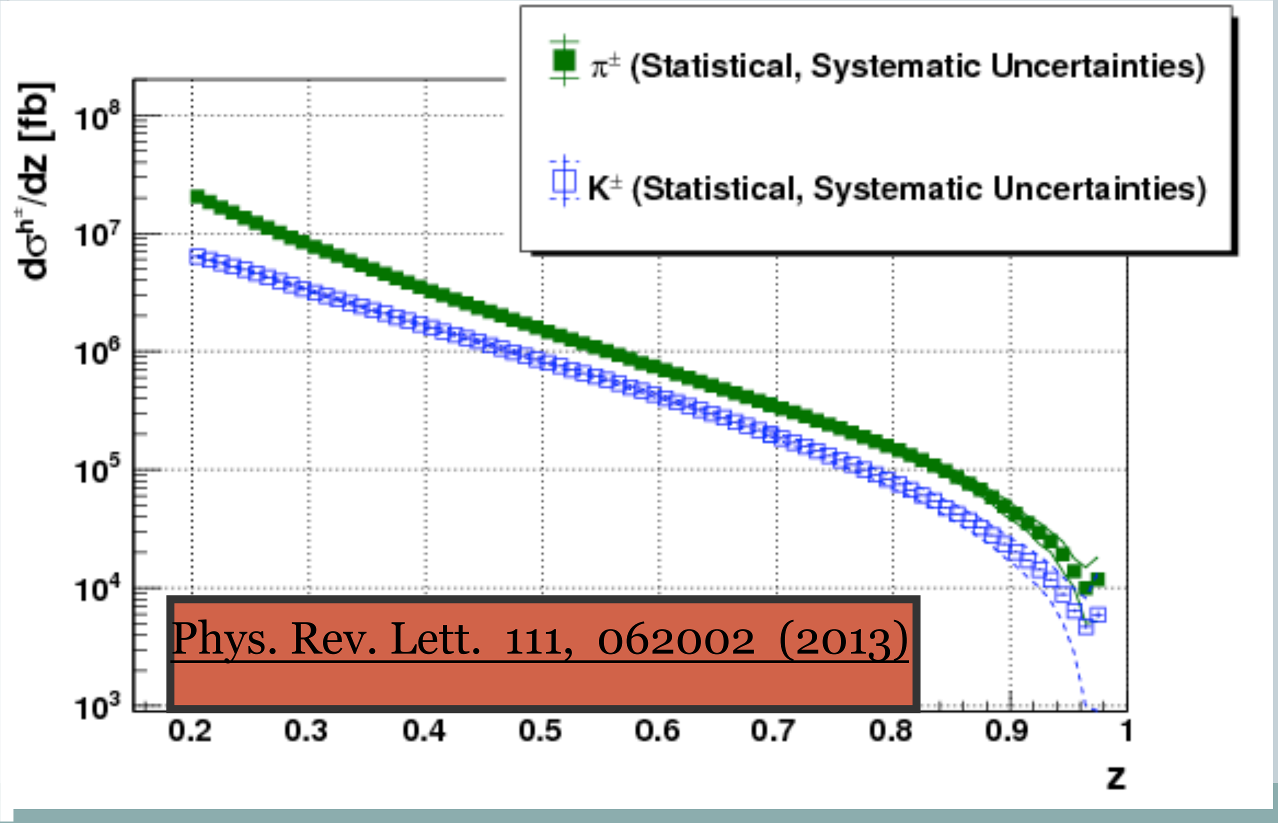
- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low z, correct based on MC

Smearing Corrections

Cross sections

$i = \pi, K$

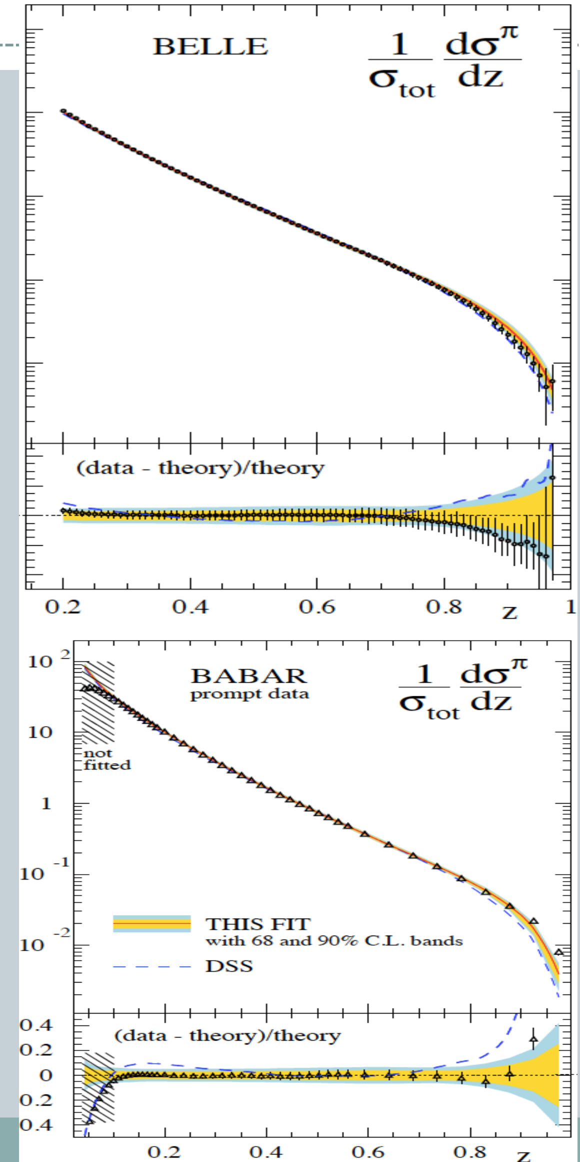
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\,\epsilon^i_{ISR/FSR}(z)\,S^{-1}_{zz_m}\,\epsilon^i_{impu}(z_m)\,P^{-1}_{ij}\,N^{j,raw}(z_m)$$



Phys. Rev. Lett. 111, 062002 (2013)

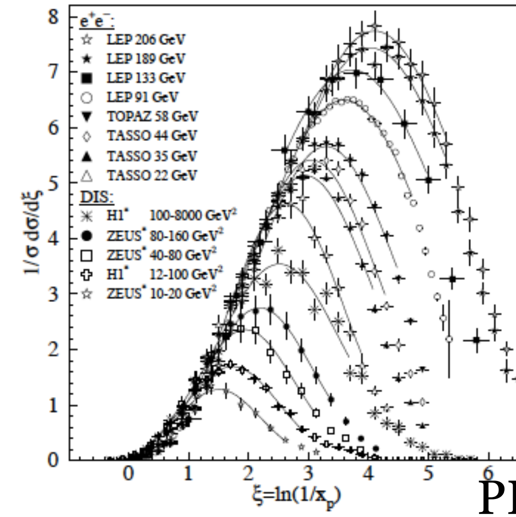
New DSS(E,H-P) Fit

- Fit includes pp, SIDIS data and BaBar e+e-
- From DSS:
  - Precise data at high z
  - Some info from scaling violations (Belle vs experiments at M_Z)
  - Some info on flavor due to charge weighting
- New NNLO calculations (only e+e-)
  - →Reduce theoretical uncertainty but χ^2 only marginally smaller
  - K factors at 10% (down from 40% for NLO/LO (at LEP energies only ~1%)
  - Still need high z resummation and target mass corrections

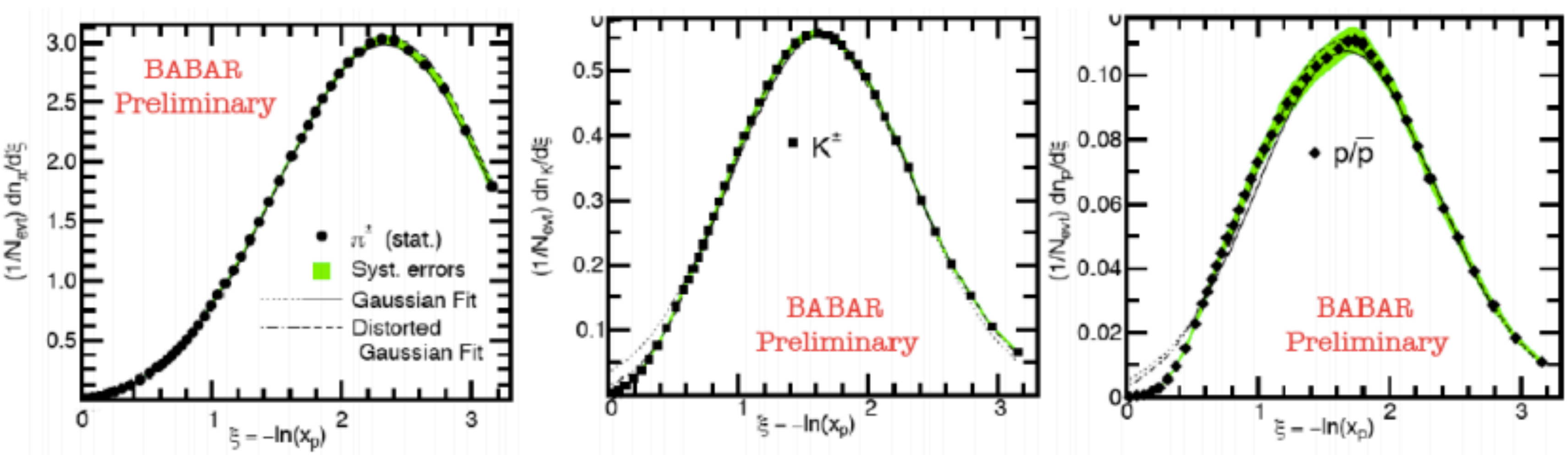


Perturbative QCD tests

- Time like splitting functions have singularities < 0.1 (unlike space like important for DIS)
- MLLA → test for resummation
- Observed shape consistent with QCD calculations
- Can be used to extract α_S

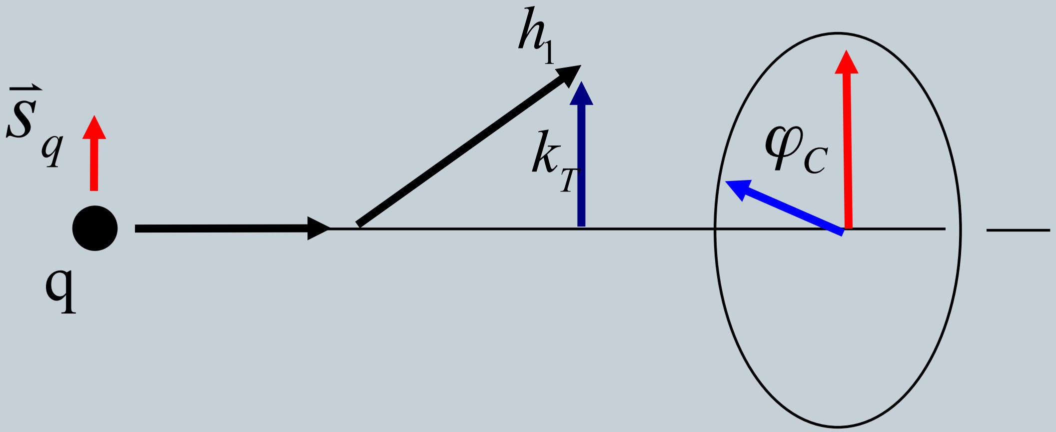


PDG



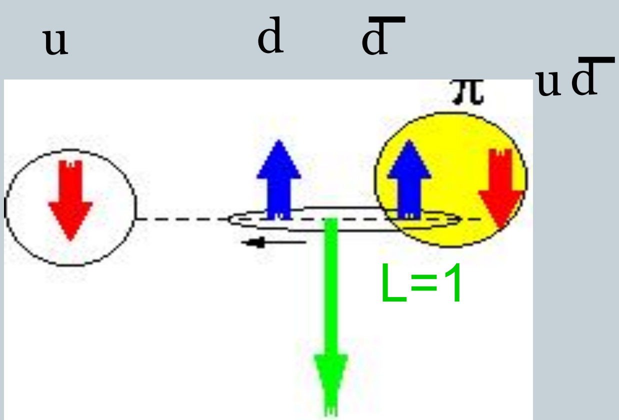
Can we measure quark polarization in FFs?

- Yes! →Collins fragmentation function
- Microscopic property (spin) leave footprint in macroscopic property (hadron azimuthal distributions)



The Collins Effect in the Artru Fragmentation Model

A simple model to illustrate that spin-orbital angular momentum coupling can lead to left right asymmetries in spin-dependent fragmentation:

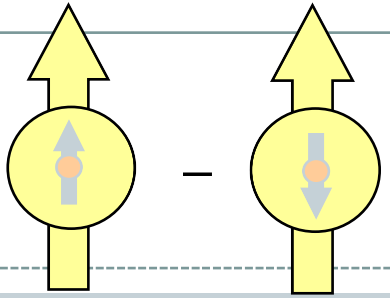


(favored)

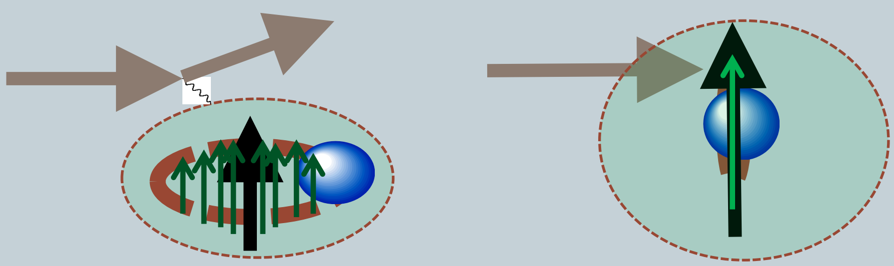
π^+ picks up L=1 to compensate for the pair S=1 and is emitted to the right.

String breaks and a d$\bar{d}$-pair with spin -1 is inserted.

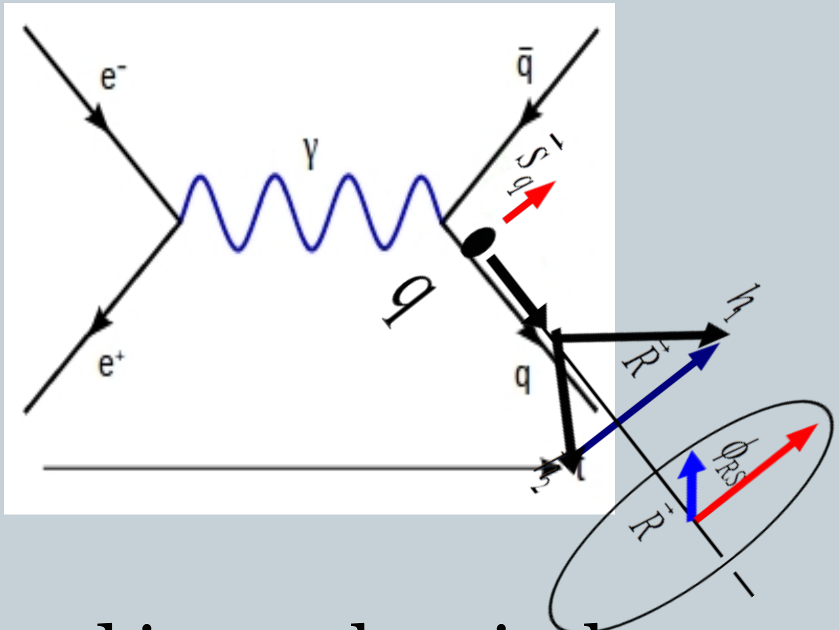
Application Transversity h:



- Tensor charge $g_T = \int_{-1}^{1} dx\, h(x)\;\; dx\, h(x)$ can be computed precisely on the lattice →Compare with first order QCD
- Important for low energy BSM physics e.g. in neutron β decay (tensor coupling)
- Cannot Measure in Inclusive Reactions
  - Naïve picture: leptonic probe too ‘fast’ to be sensitive to transverse polarization, need quark polarimeter:

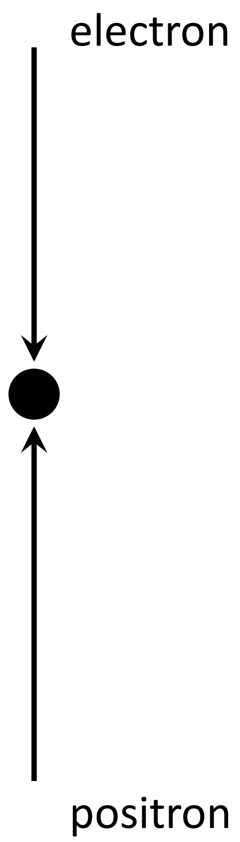


How to measure spin dependent FFs in (unpolarized) e^+e^-?



- Effect measured in one hemisphere averages out

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



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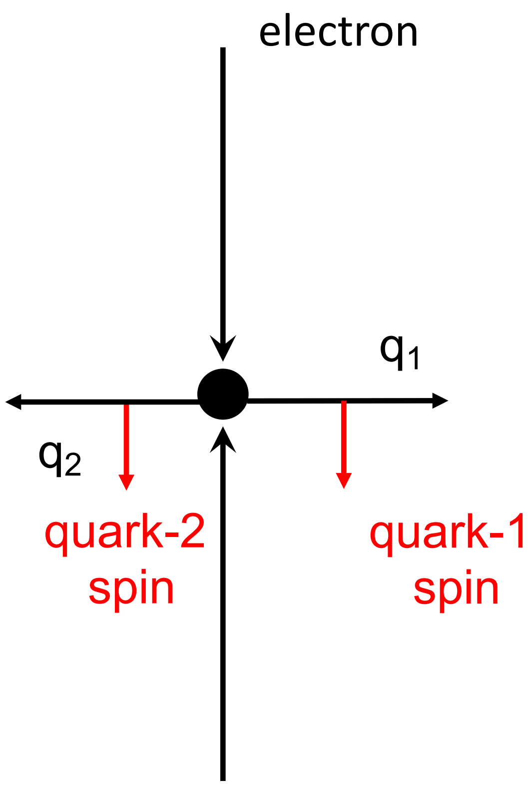
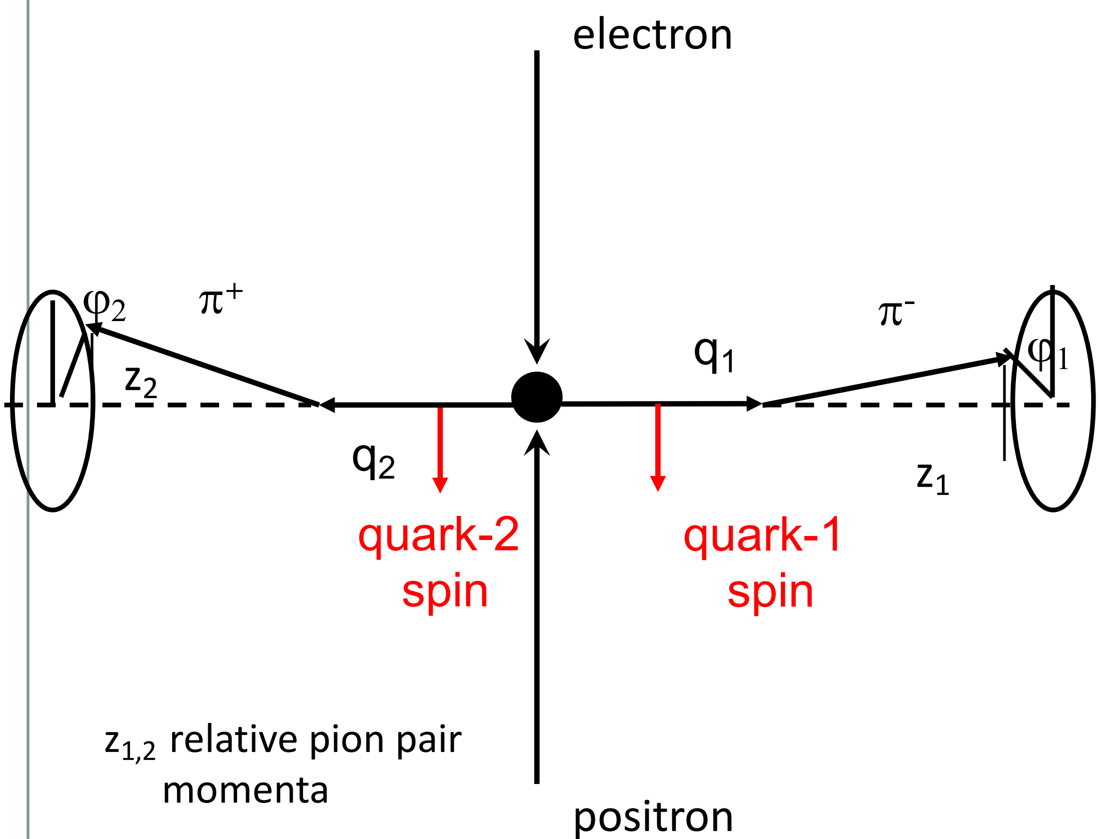


Measuring transverse spin dependent di-Hadron Correlations In unpolarized e^+e^- Annihilation into Quarks



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

Spin correlation will lead to azimuthal asymmetries in hadron pair correlation measurements!

Experimental requirements:

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

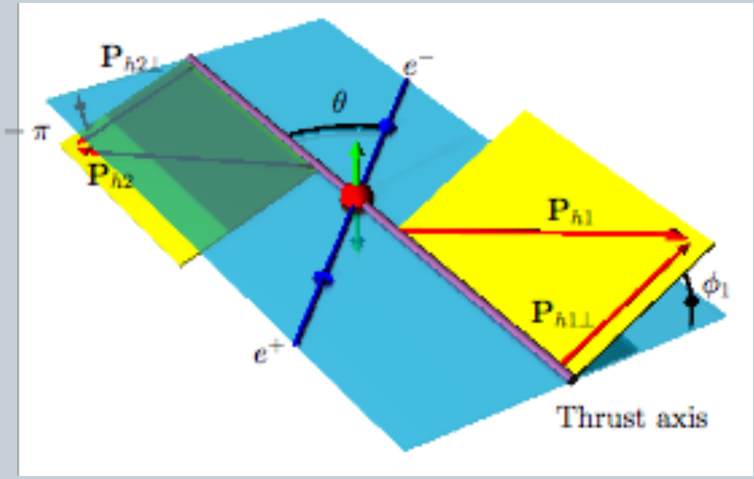
BELLE

There are two methods with two or one soft scale

D. Boer
Nucl.Phys.B806:23,2009

$\phi_1+\phi_2$ method:

hadron azimuthal angles with respect to the $q\bar{q}$ axis proxy

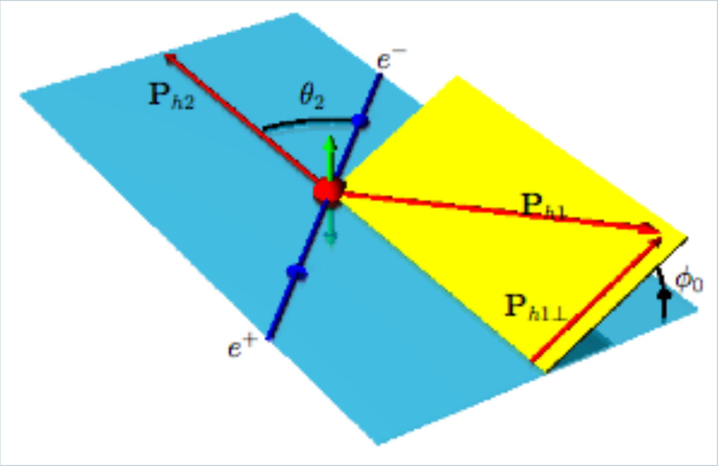


$$\sigma \sim \mathcal{M}_{12}\Big(1+\frac{\sin^2\theta_T}{1+\cos^2\theta_T}\cos(\phi_1+\phi_2)\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}\Big)$$

$$R_{12}^{U/L}=\frac{N(\varphi_1+\varphi_2)}{\langle N_{12}\rangle}$$

ϕ_0 method:

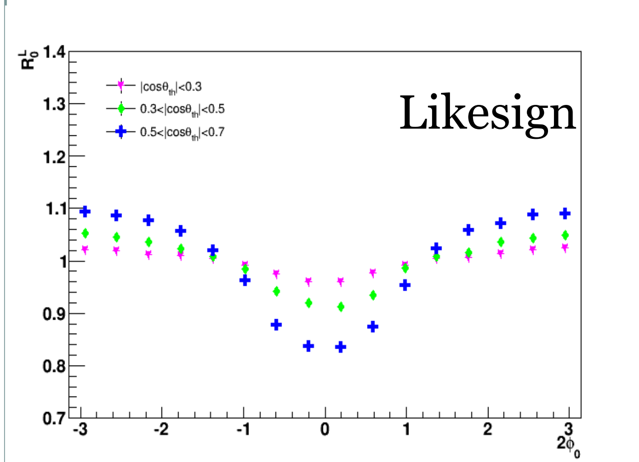
hadron 1 azimuthal angle with respect to hadron 2

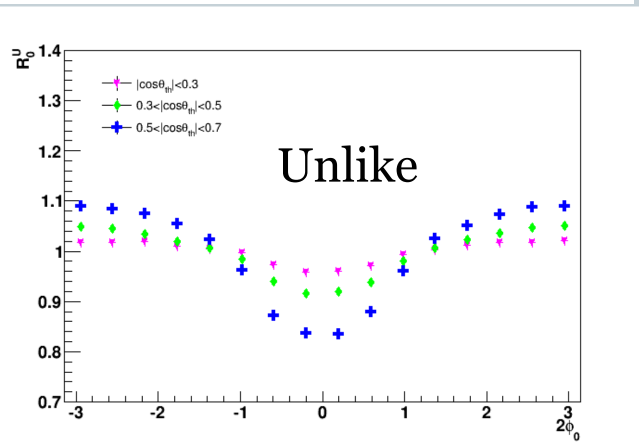


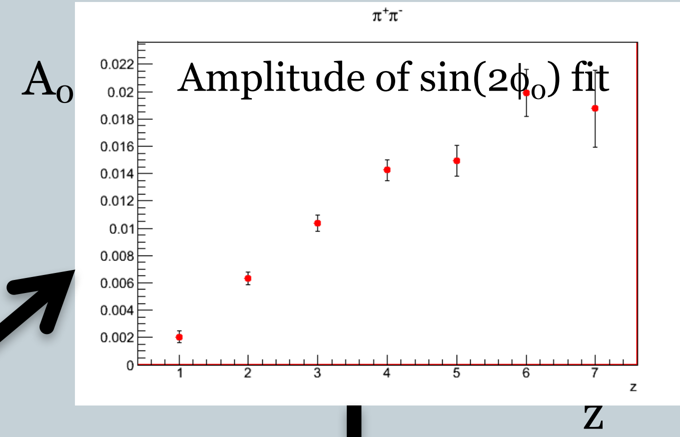
$$\sigma \sim \mathcal{M}_0\Big(1+\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_0)\mathcal{F}\Big[\frac{H_1^{\perp}(z_1)\bar{H}_1^{\perp}(z_2)}{D_1^{\perp}(z_1)\bar{D}_1^{\perp}(z_2)}\Big]\Big)$$

$$R_{0}^{U/L}=\frac{N(2\varphi_0)}{\langle N_{0}\rangle}$$

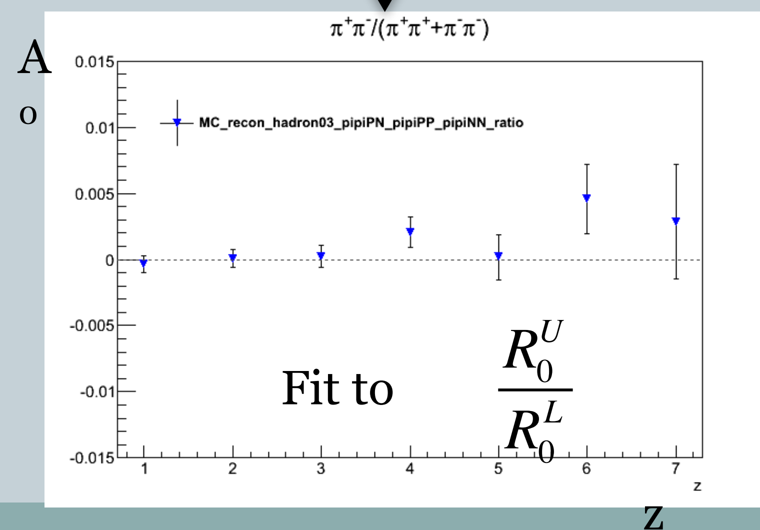
Use of Double Ratios







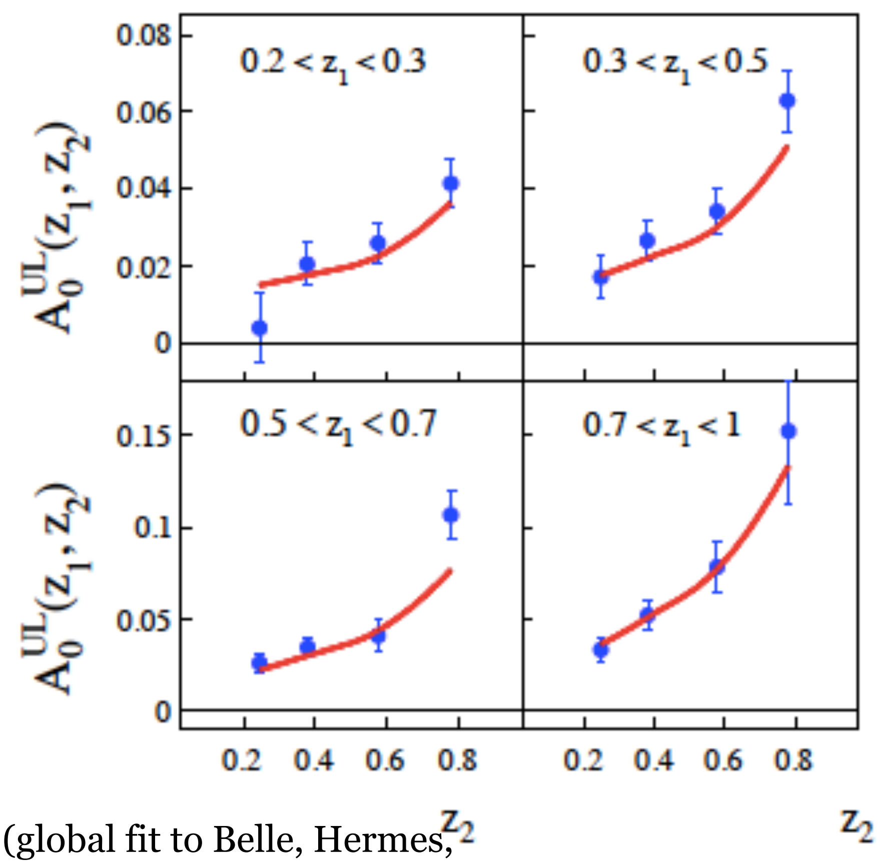
Use of "Double Ratios"



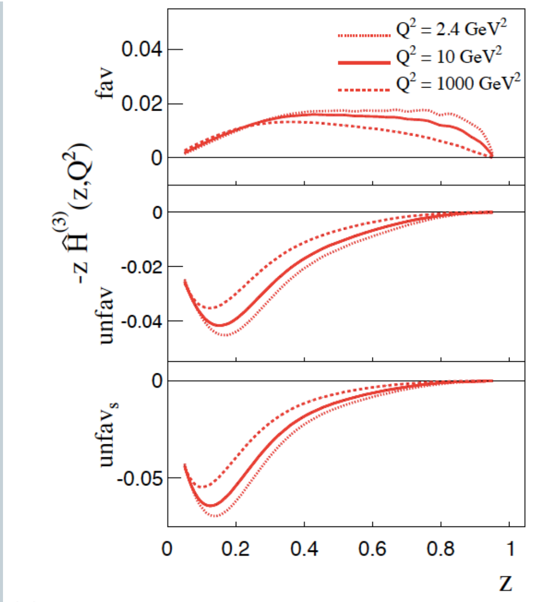
$$\frac{R_0^U}{R_0^L}$$

- False asymmetries due to Acceptance and QCD radiation
- Charge independent

Belle π Collins Results



(global fit to Belle, Hermes, Jlab & COMPASS data)

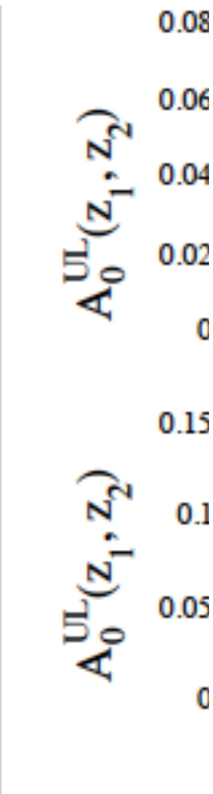


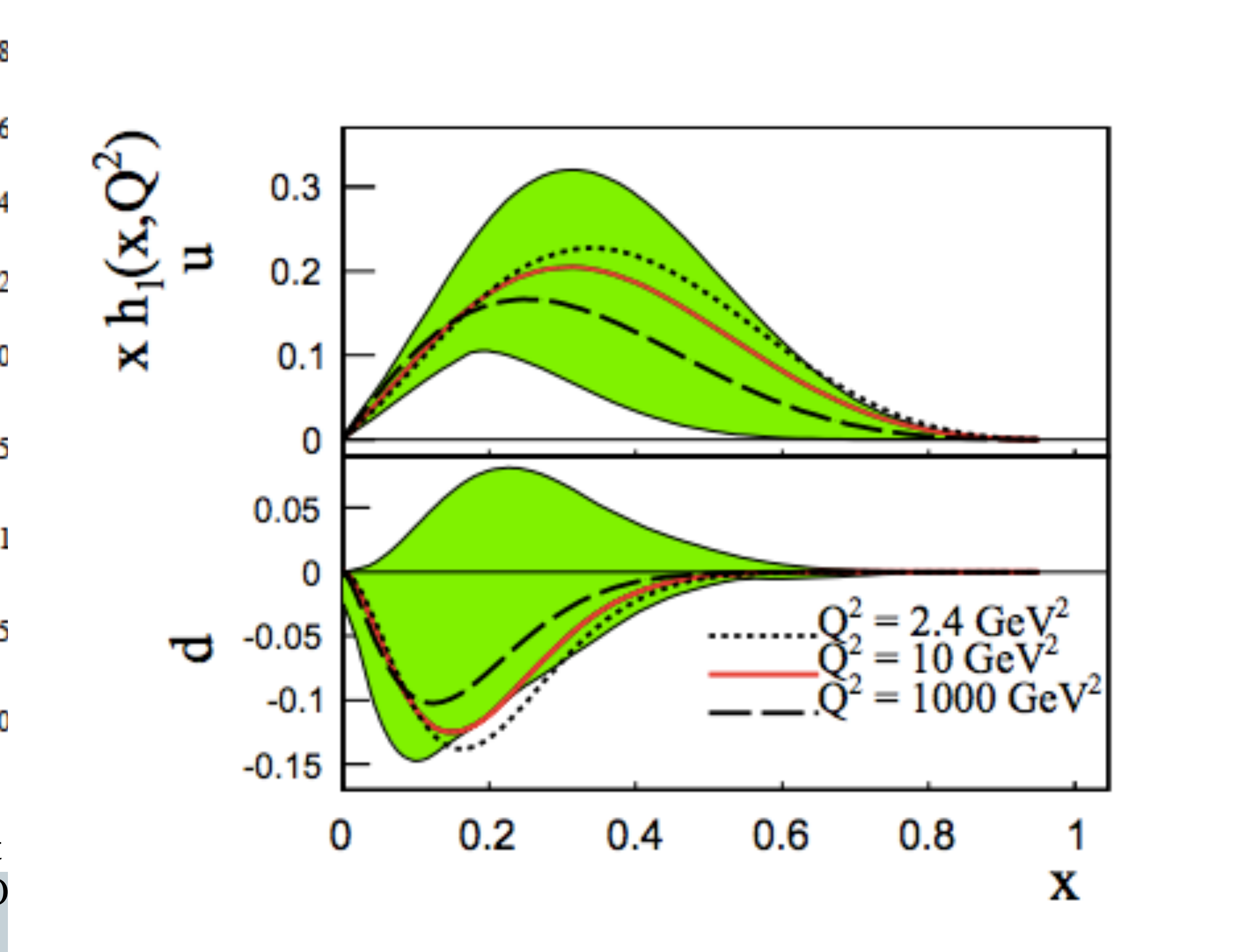
Extraction of Collins FF

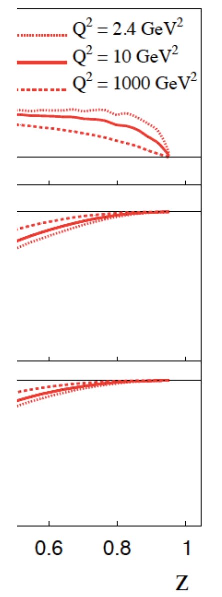
Kang, Prokudin, Sun, Yuan
Int.J.Mod.Phys.Conf.Ser. 37 (2015) 1560027

Belle Data:
Phys.Rev. D78 (2008) 032011

Extracted Transversity







ollins FF

n

(global fit

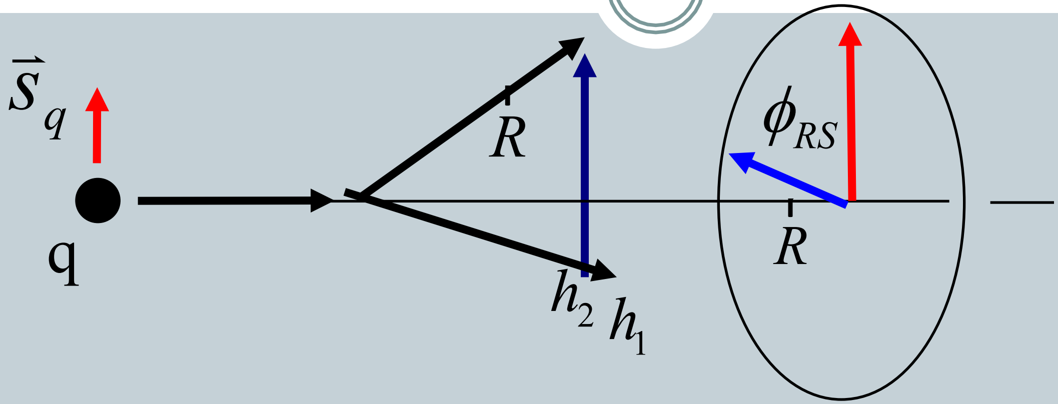
Jlab & CO

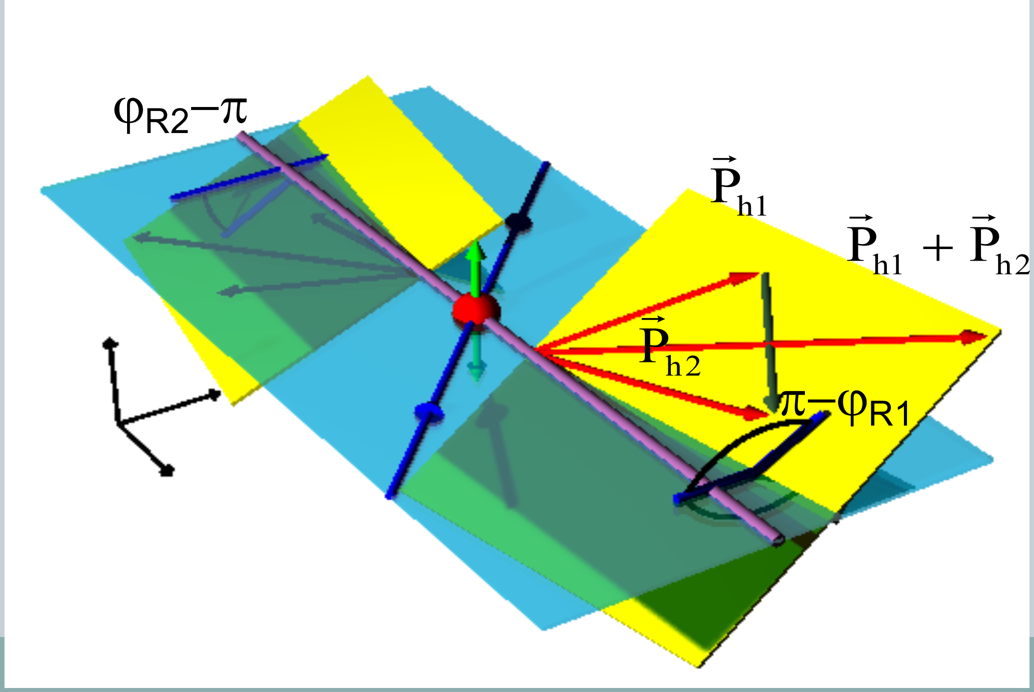
37 (2015) 156002

Belle Data:

Phys.Rev. D78 (2008) 032011

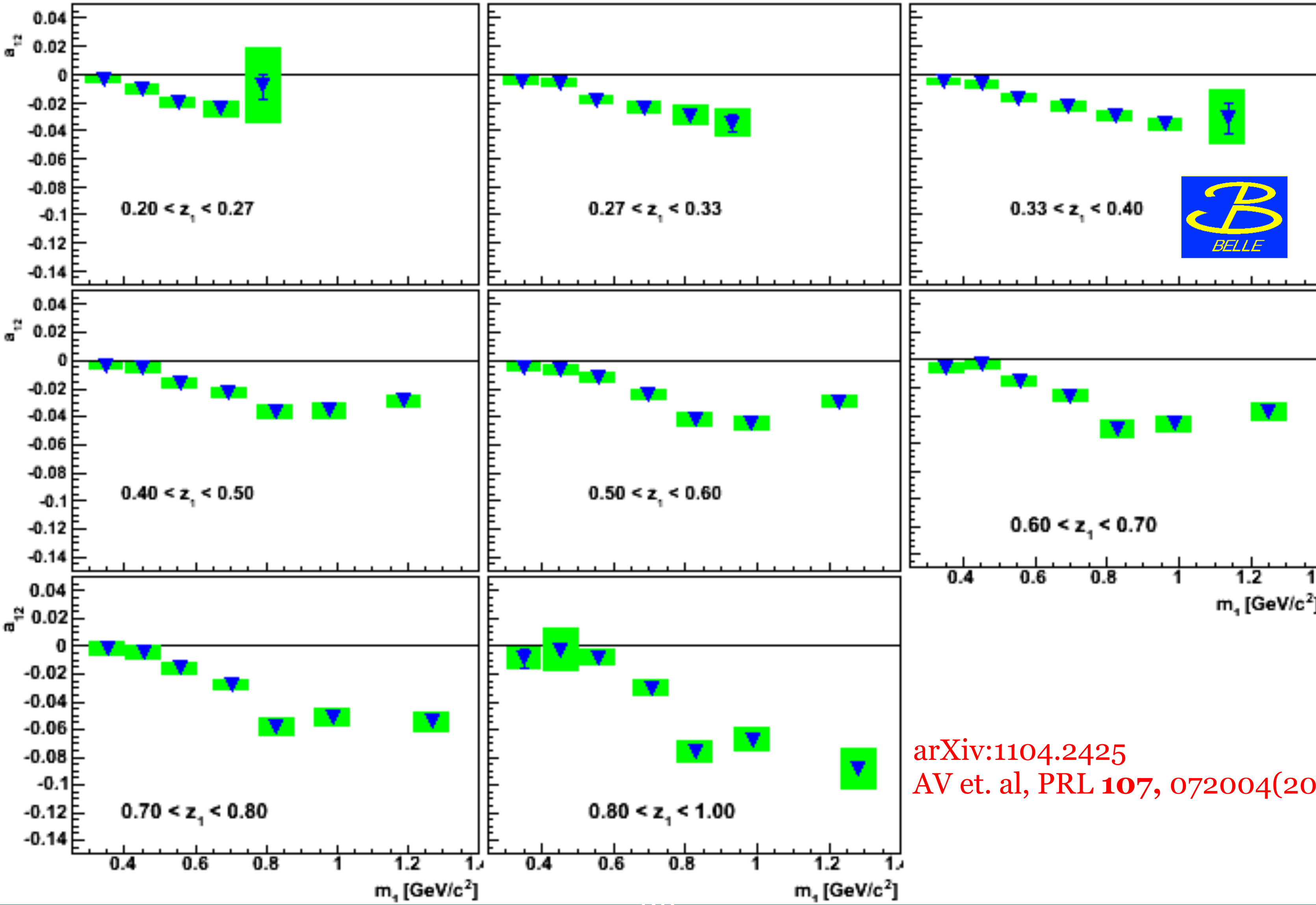
Di-Hadron Fragmentation





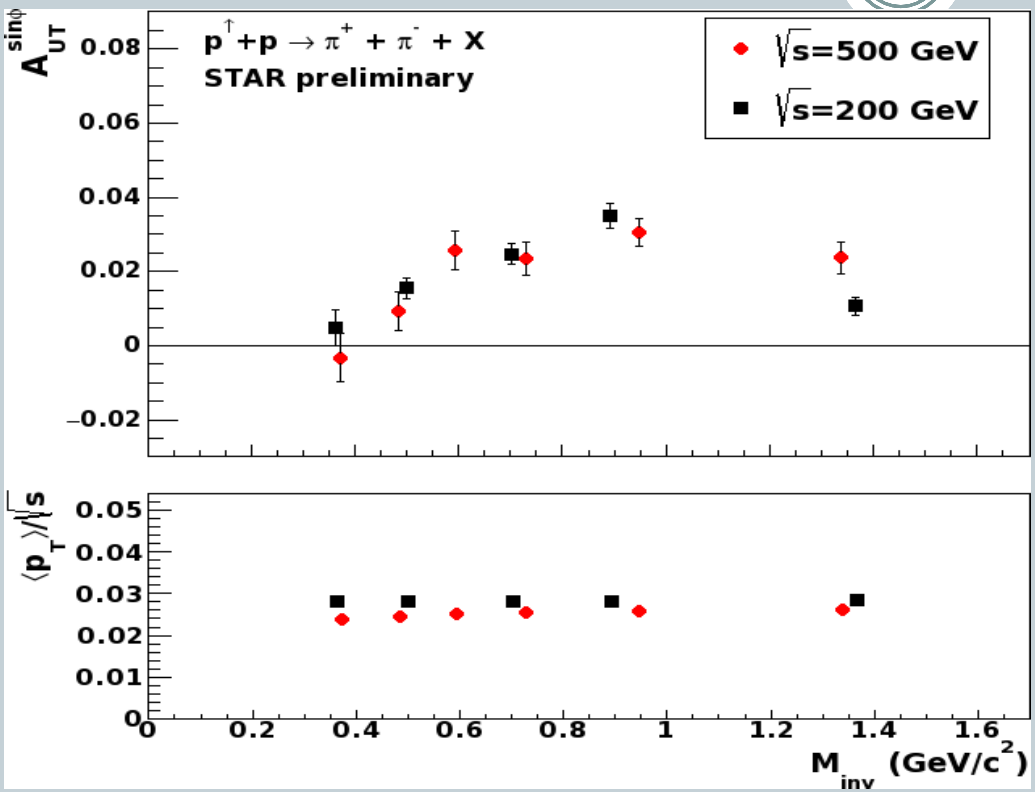
First measurement of Interference Fragmentation Function

$a_{12} \propto H_1^{<} * H_1^{<}$



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

”Easy” to measure in proton-proton!



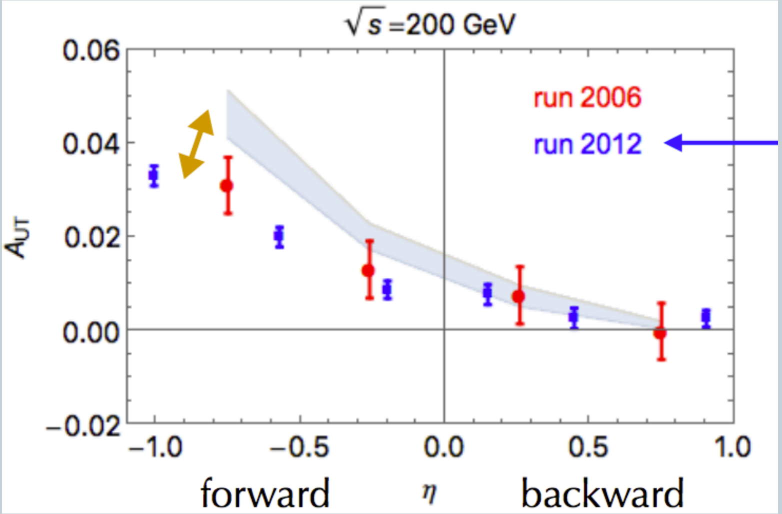
One p_T bin for which $p_T/\sqrt{s}$ similar

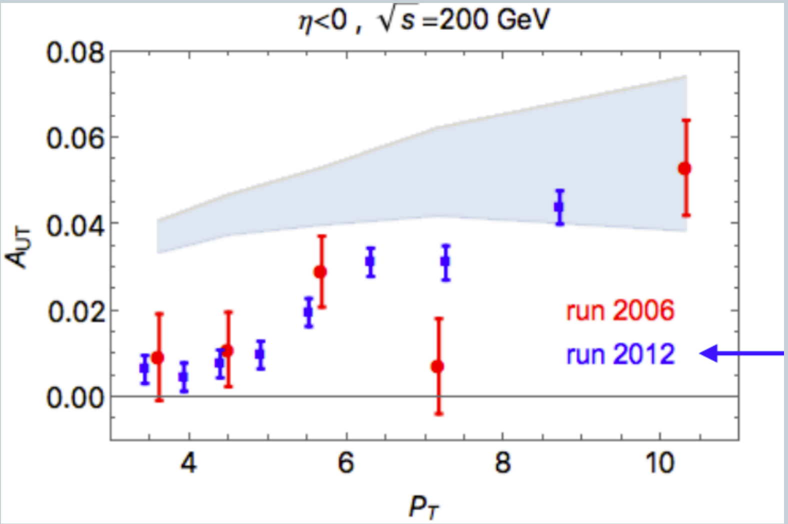
~x_{Bj}

See also **Phys.Rev.Lett. 115 (2015) 242501**

- Indeed: No Evolution, Gluons do not couple to transversity!
- Kinematic coverage and tests of universality
- 0.06< x < 0.35
- Still 3x (200 GeV) 15x (500 GeV) data on tape/to be taken next year →most precise determination of transversity before SoLID

Comparison of pp results with Theory Predictions based on SIDIS→Test of Universality

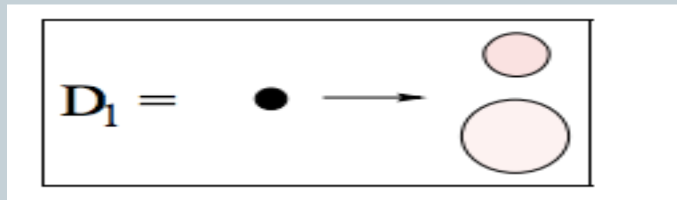


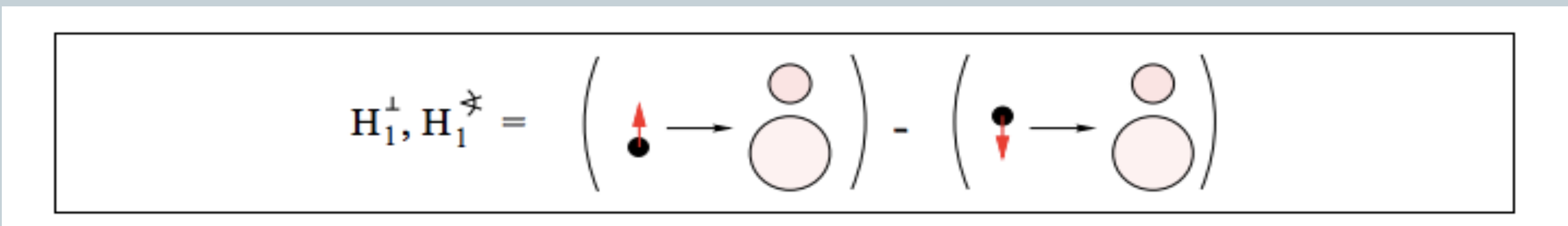


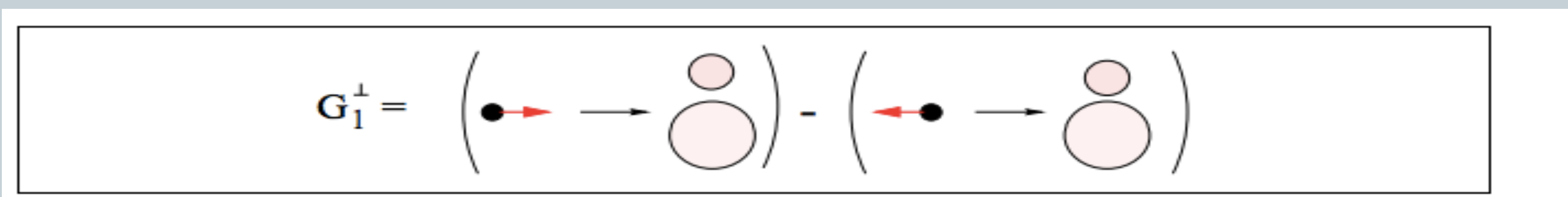
M. Radici at Spin2016

- Theory prediction in this region driven by one COMPASS datapoint outside the Soffer bound

Helicity Dependent FFs

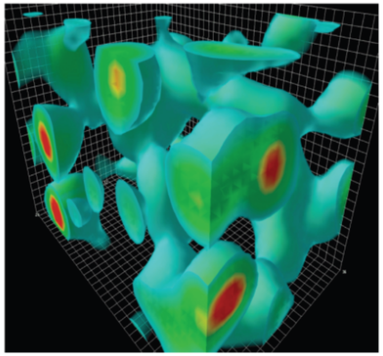


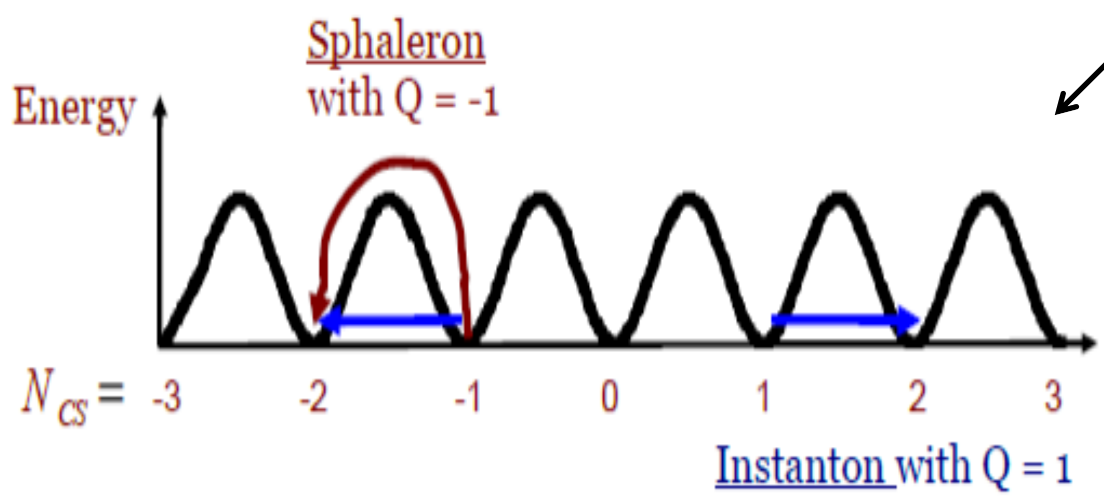




- Not needed for g1 but
  - Needs intrinsic transverse momentum to exist in FF → BM in the nucleon
  - Sensitive to local strong parity violating effects in the QCD vacuum

QCD Vacuum Transitions carry Chirality



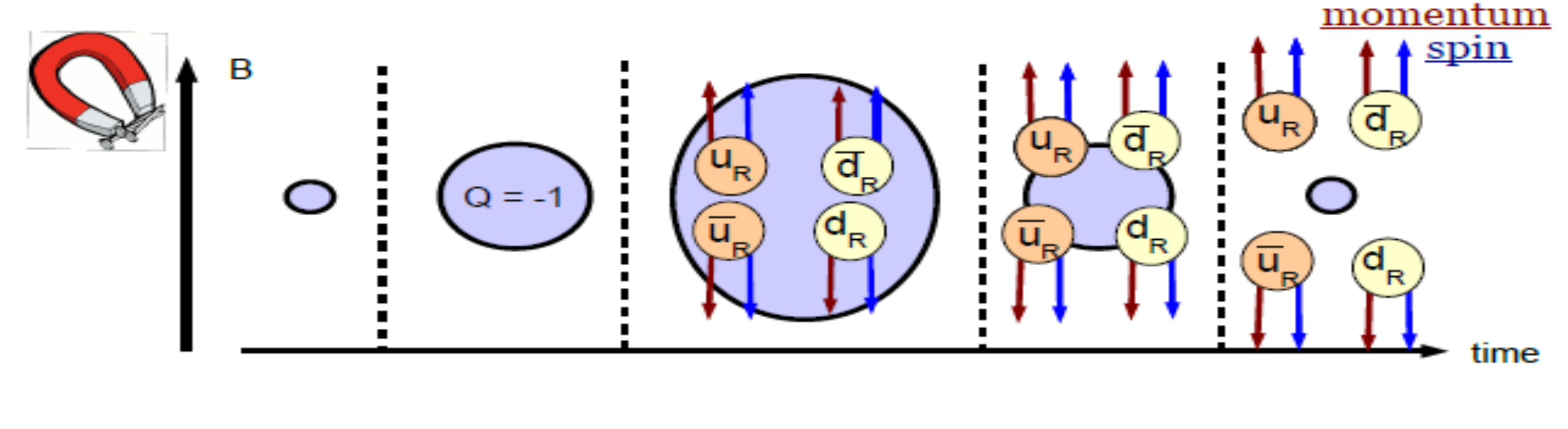


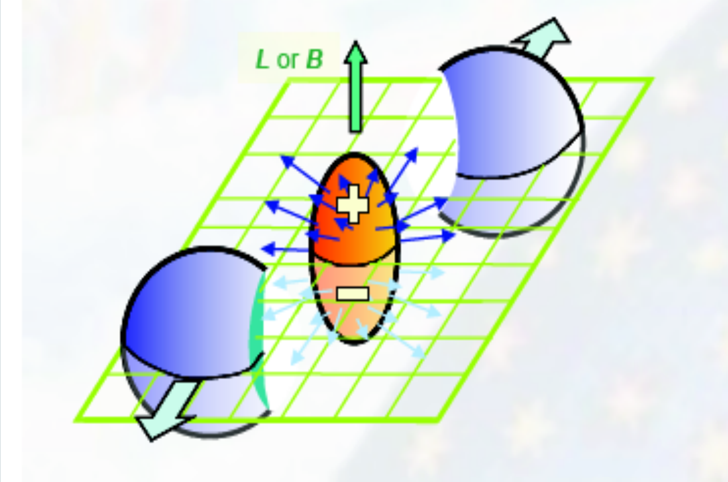
The QCD Vacuum

Difference in winding number:
Net chirality carried by
Instanton/Sphaleron

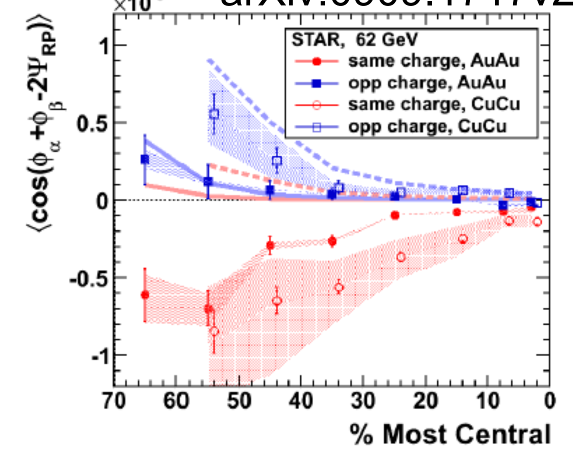
- Vacuum states are characterized by “winding number”
- Transition amplitudes: Gluon configurations, carry net chirality
- e.g. quarks: net spin momentum alignment
- Similar mechanism to EW baryogenesis

QCD Vacuum Transitions carry Chirality QN



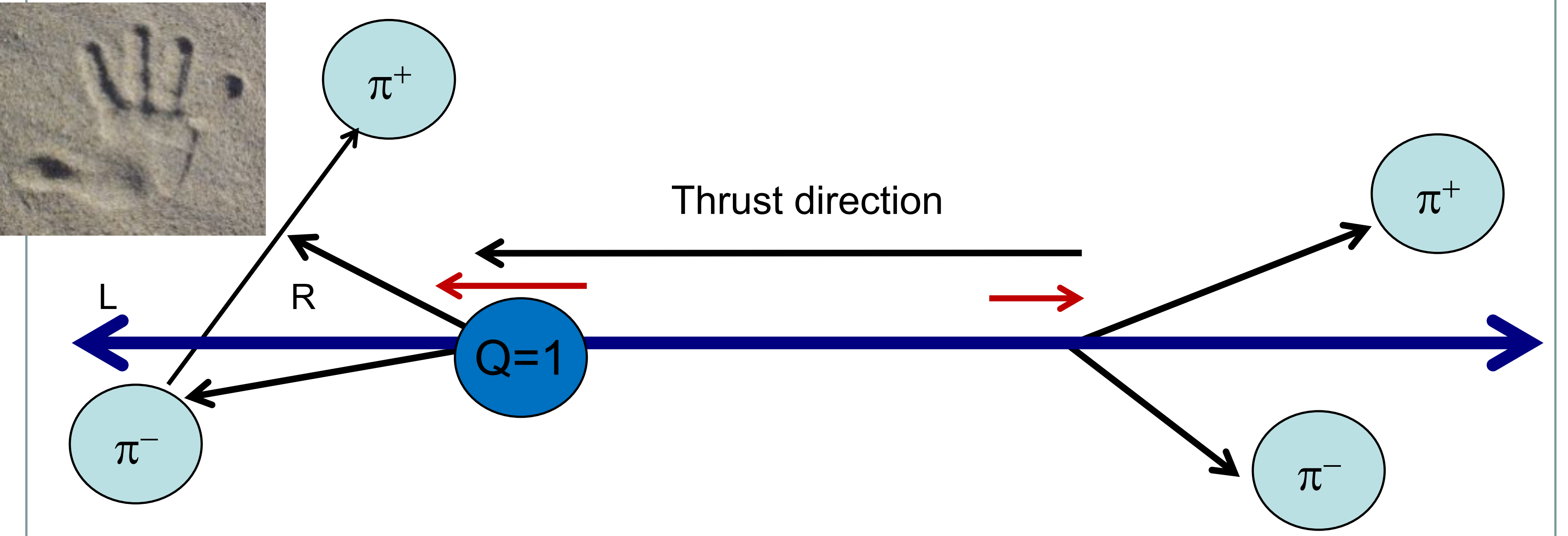


arXiv:0909.1717v2 [



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

Handedness Correlations



Di-Hadron Asymmetries

- Di-hadron Cross Section from Boer,Jakob,Radici[PRD 67,(2003) 094003]: Expansion of Fragmentation Matrix Δ: encoding possible correlations in fragmentation (k: $P_{h1}+P_{h2}$)

$$\frac{1}{32z}\int dk^+\,\Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\,\frac{1}{4}\Big\{D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\,n_-^\nu\,k_T^\rho\,R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\triangleleft\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\,n_-^\nu}{M_1+M_2} + H_1^{\perp\,a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\,n_-^\nu}{M_1+M_2}\Big\}\,.$$

$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\overline{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\overline{z},\overline{M}_h^2)\,.$$

$$\langle\cos(\phi_R+\phi_{\overline{R}}-2\phi^l)\rangle = \sum_{a,\overline{a}} e_a^2\,\frac{3\alpha^2}{Q^2}\,\frac{z^2\overline{z}^2\,B(y)}{(M_1+M_2)(\overline{M}_1+\overline{M}_2)}\,H_{1\,(R)}^{\triangleleft a}(z,M_h^2)\,\overline{H}_{1\,(R)}^{\triangleleft a}(\overline{z},\overline{M}_h^2)\,.$$

Measure Cos($\phi_{R1}+\phi_{R2}$), Cos($2(\phi_{R1}-\phi_{R2})$) Modulations!

Di-hadron Cross Section from Boer,Jakob,Radici

- Δ: Fragmentation Matrix, encoding possible correlations in fragmentation
- k: $P_{h1}+P_{h2}$

Helicity dependent correlation of Intrinsic transverse momentum with Di-hadron plane→Test of TMD framework

from Boer,Jakob,Radici[PRD 67,(2003) 094003]

$$\frac{1}{32z}\int dk^{+}\Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T}$$

$$= \frac{1}{4\pi}\frac{1}{4}\Big\{D_1^a(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\not{n}_- - G_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\,n_-^\nu\,k_T^\rho\,R_T^\sigma}{M_1M_2}\,\gamma_5$$

$$+ H_1^{\sphericalangle a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,R_T^\mu\,n_-^\nu}{M_1+M_2} + H_1^{\perp a}(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)\,\frac{\sigma_{\mu\nu}\,k_T^\mu\,n_-^\nu}{M_1+M_2}\Big\}\,.$$

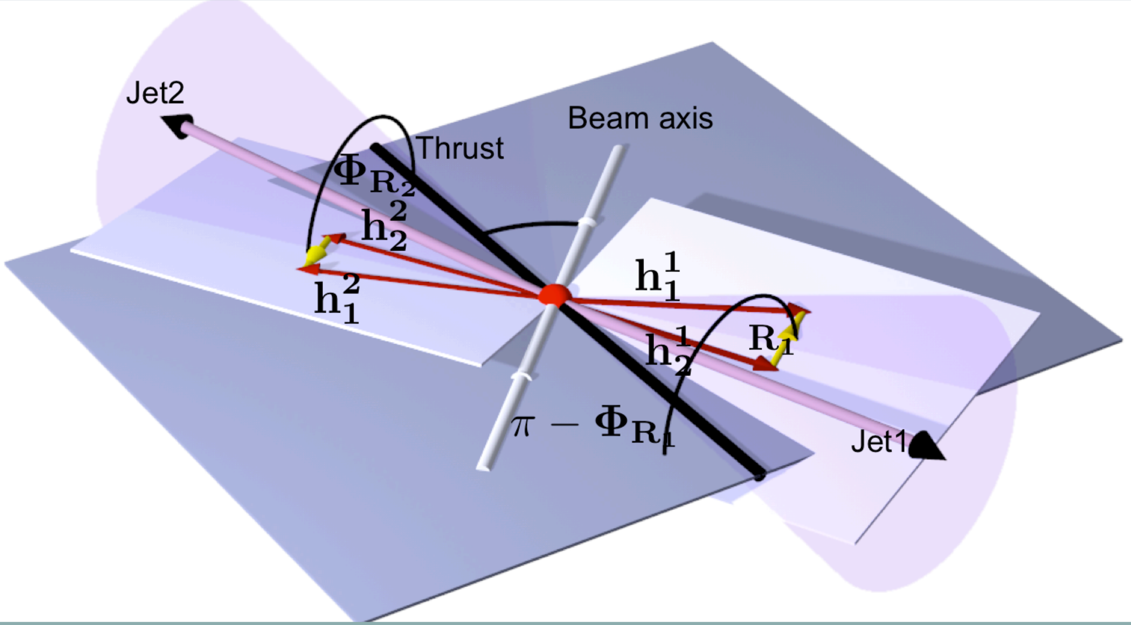
$$\langle\cos(2(\phi_R-\phi_{\overline{R}}))\rangle = \sum_{a,\bar{a}} e_a^2\,\frac{3\,\alpha^2}{2Q^2}\,z^2\bar{z}^2\,A(y)\,\frac{1}{M_1M_2\overline{M}_1\overline{M}_2}\,G_1^{\perp a}(z,M_h^2)\,\overline{G}_1^{\perp a}(\bar{z},\overline{M}_h^2)\,.$$

$$\langle\cos(\phi_R+\phi_{\overline{R}}-2\phi^l)\rangle = \sum_{a,\bar{a}} e_a^2\,\frac{3\alpha^2}{Q^2}\,\frac{z^2\bar{z}^2\,B(y)}{(M_1+M_2)(\overline{M}_1+\overline{M}_2)}\,H_{1\,(R)}^{\sphericalangle a}(z,M_h^2)\,\overline{H}_{1\,(R)}^{\sphericalangle a}(\bar{z},\overline{M}_h^2)\,.$$

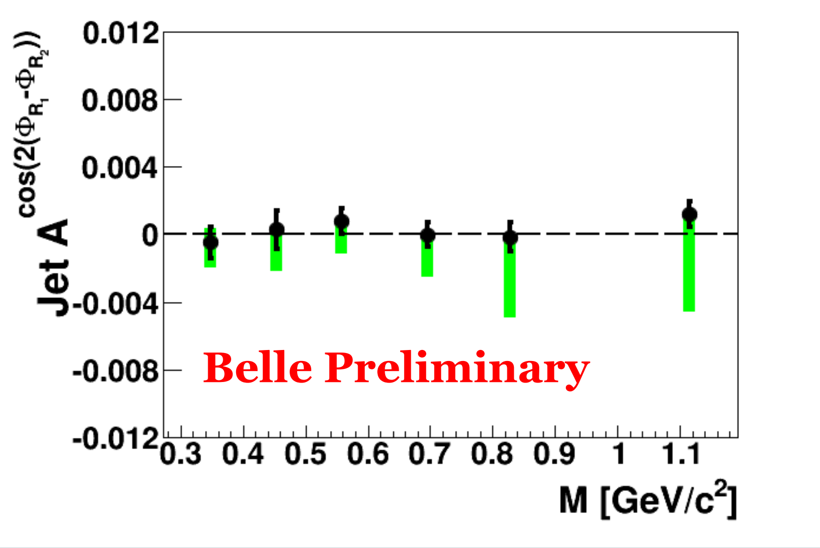
Measure $\cos(\phi_{R1}+\phi_{R2})$, $\cos(2(\phi_{R1}-\phi_{R2}))$ Modulations

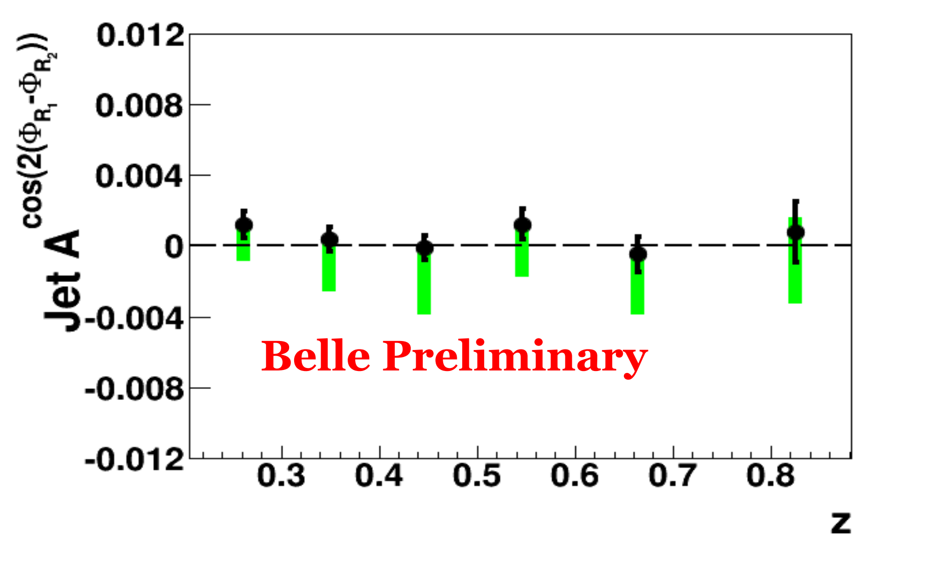
New: Use Jet Reconstruction at Belle

- 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 used in the asymmetry calculation
- Thrust cut of 0.8< T< 0.95



Asymmetries for Cos(2(ϕ_{R1}-ϕ_{R2})) ($G_1^\perp$) small

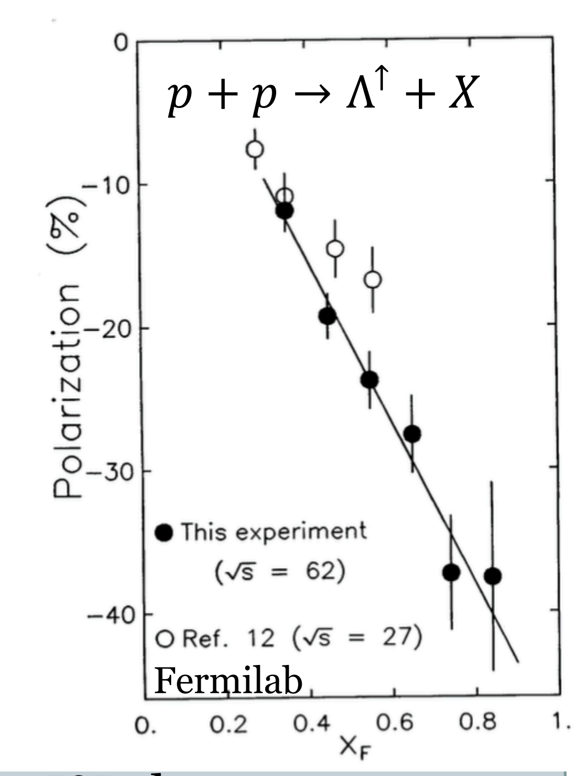




- No evidence of local p-odd effects yet
- Next step: partial wave analyis

Polarized Hyperon Production (see presentation by Y. Guan at Spin2016)

- Large Λ transverse polarization in unploarized 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)**

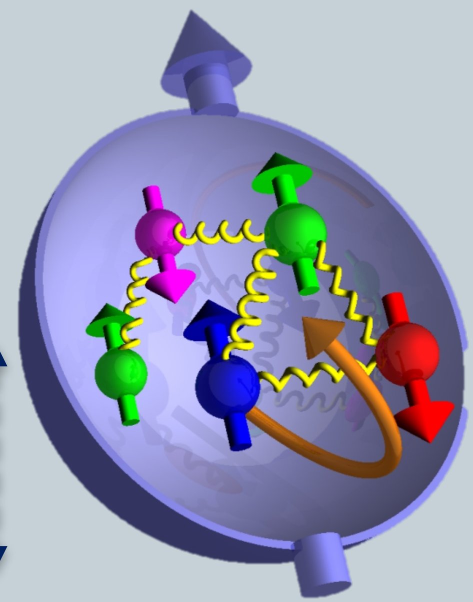


ISR data
(Phys.Lett. B185 (1987) 209)

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

Hyperon Production as a tool to study baryon spin structure

- 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

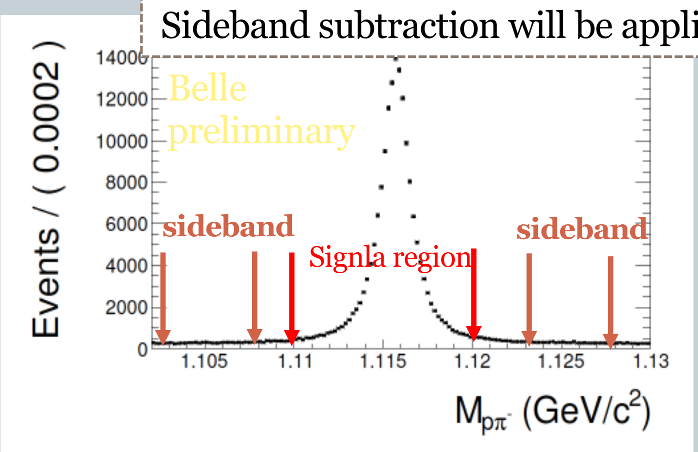


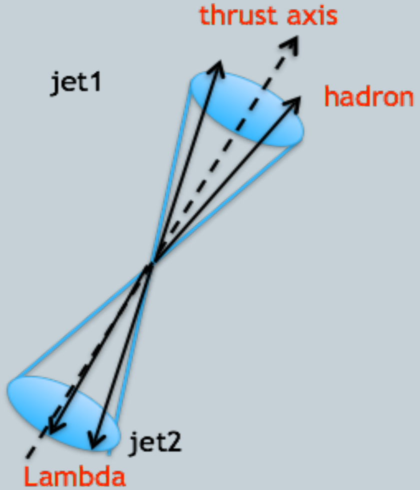
p_T

q

Lambda Reconstruction

Sideband subtraction will be applied

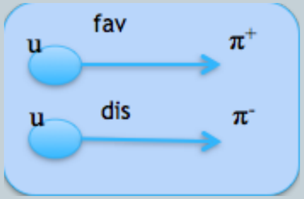




flavor tag

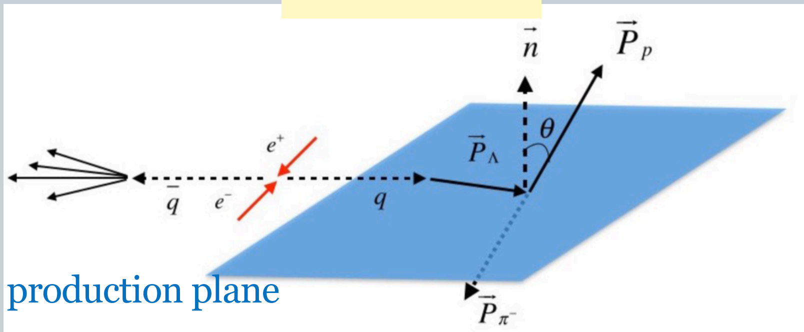
Λ(uds); $\pi^+(u\bar{d})$; K^+ $(u\bar{s})$

- 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 $\Lambda(\bar{\Lambda})$.

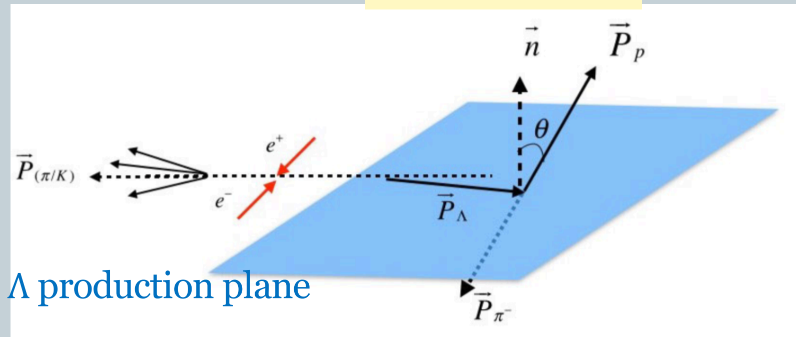


Reference frames

Thrust Frame



Hadron Frame



- The reference vector $\hat{n}$ is perpendicular to the Λ production plane.
- The p_t is defined as the transverse momentum of Λ relative to thrust axis in thrust frame and to hadron axis in hadron fram
- Give a polarization of P, the yield of the events follow:

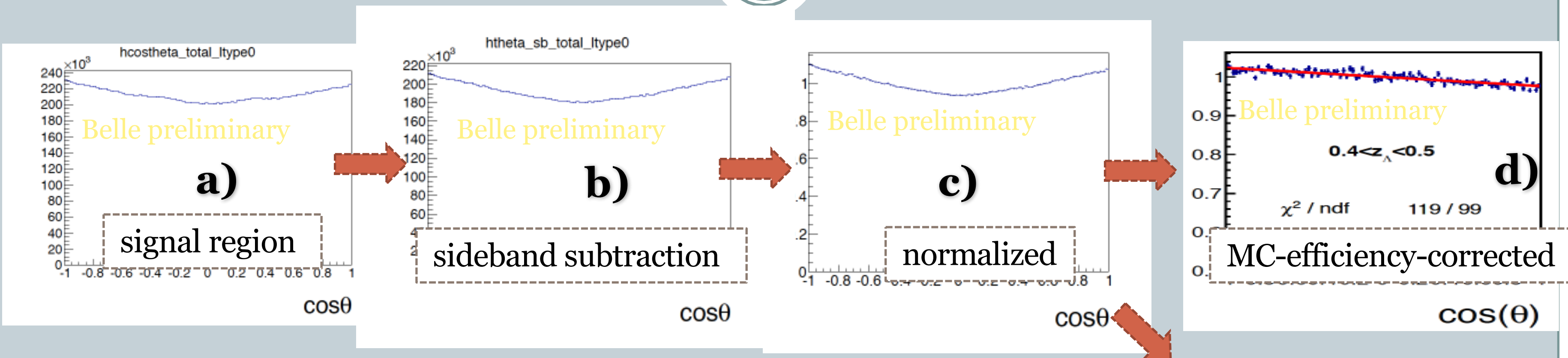
$$\frac{1}{N}\frac{dN}{d\cos\theta} = 1 + \alpha P \cos\theta$$

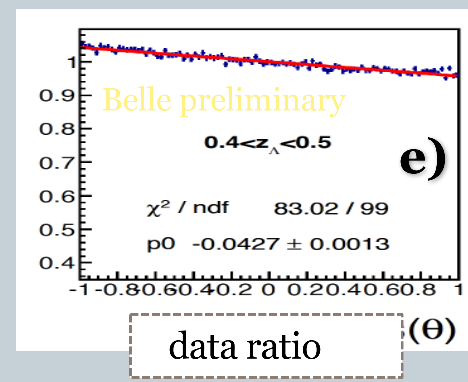
- where α is the decay parameter: α_+=0.642 ± 0.013 for Λ and α_-=-0.71 ± 0.08 for $\bar{\Lambda}$ (PDG).

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

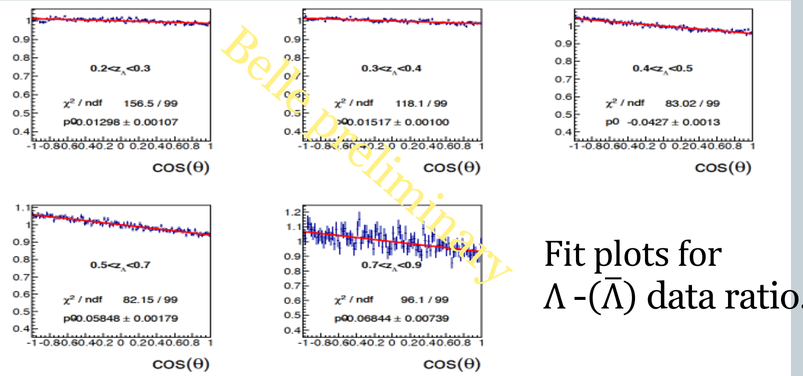




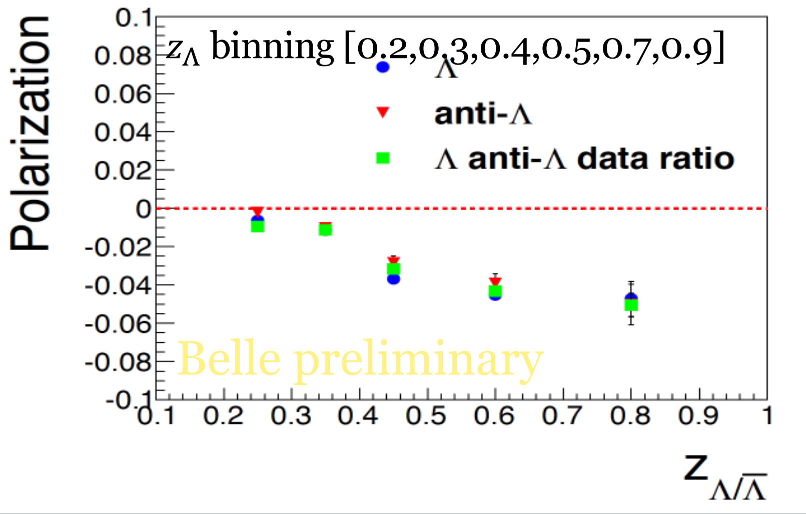
- Cosθ distribution in Λ signal region **a)** is corrected by sideband subtraction→ **b)**
- Normalized by itself, as shown in **c).**
- The shape **c)** is divided by the corresponding shape from MC, so that we obtain the efficiency-corrected curve **d).**
- Or **c)** shape of Λ events is divided by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

Fits and Extract polarization

- Fit to the cosθ distributions with $1 + p_0 cos\theta$.
- 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 times larger than $\alpha_+(\alpha_-)$.
- Results from MC-corrected ratio and data ratio are consistent with each other.
- Nonzero polarization, magnitude rises to about ~5% with $z_\Lambda = 2E_\Lambda/\sqrt{s}$.

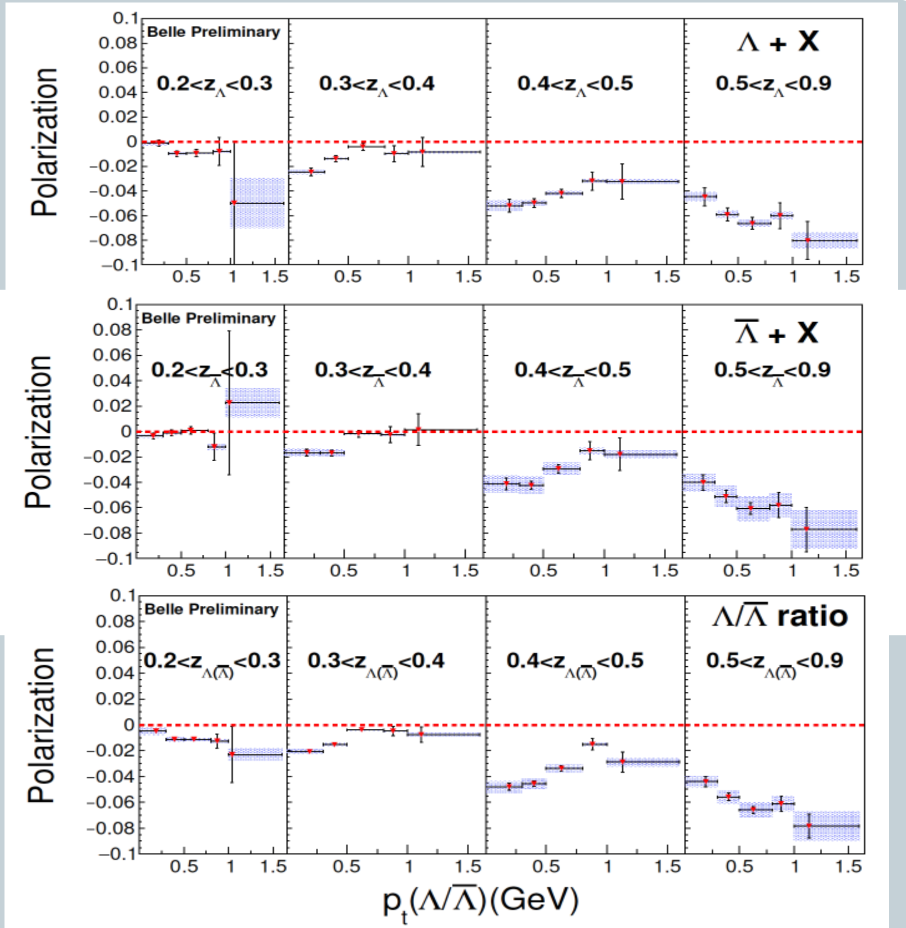


Fit plots for Λ -($\bar{\Lambda}$) data ratio.



Results in thrust frame

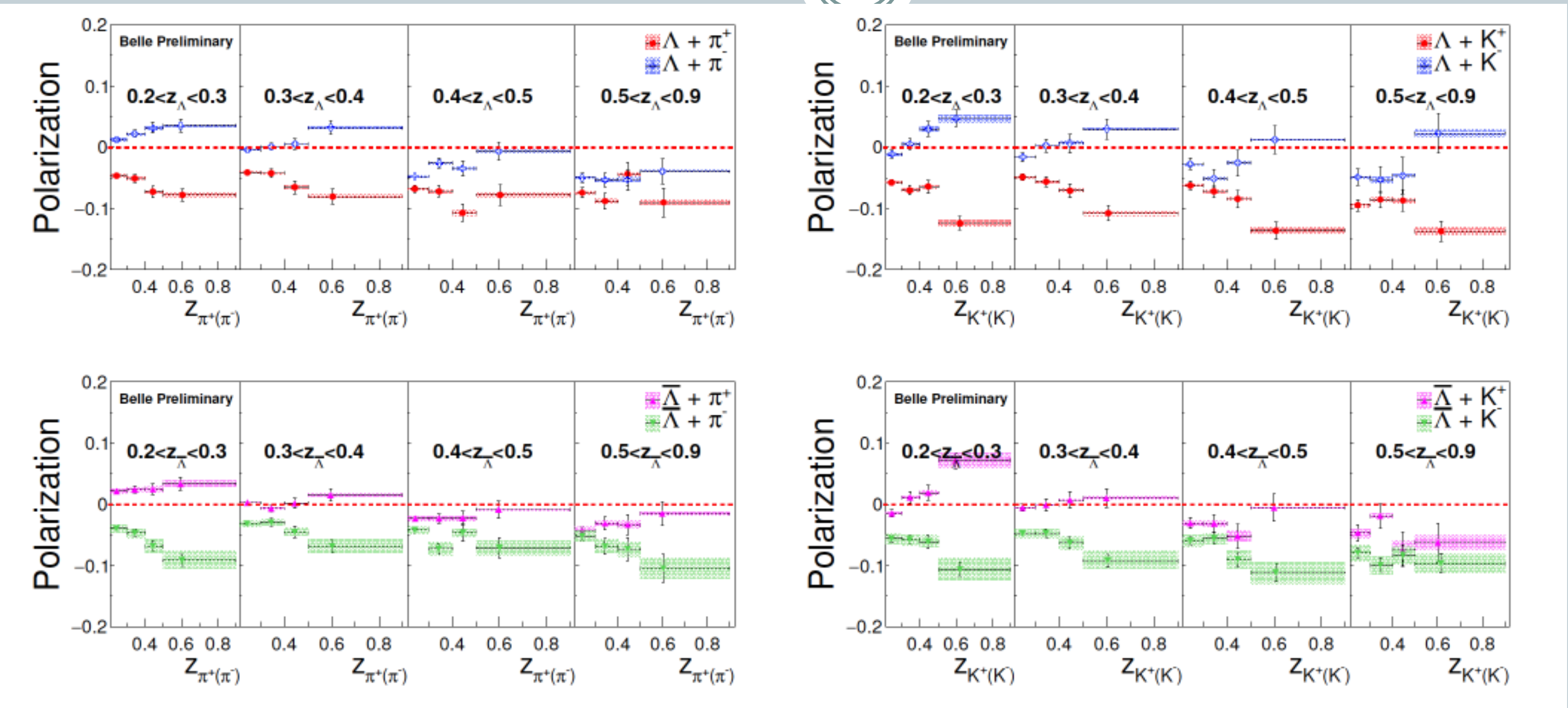
vs. (z, p_t)



- Four z bins and five p_t bins are used: 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 the dependence 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

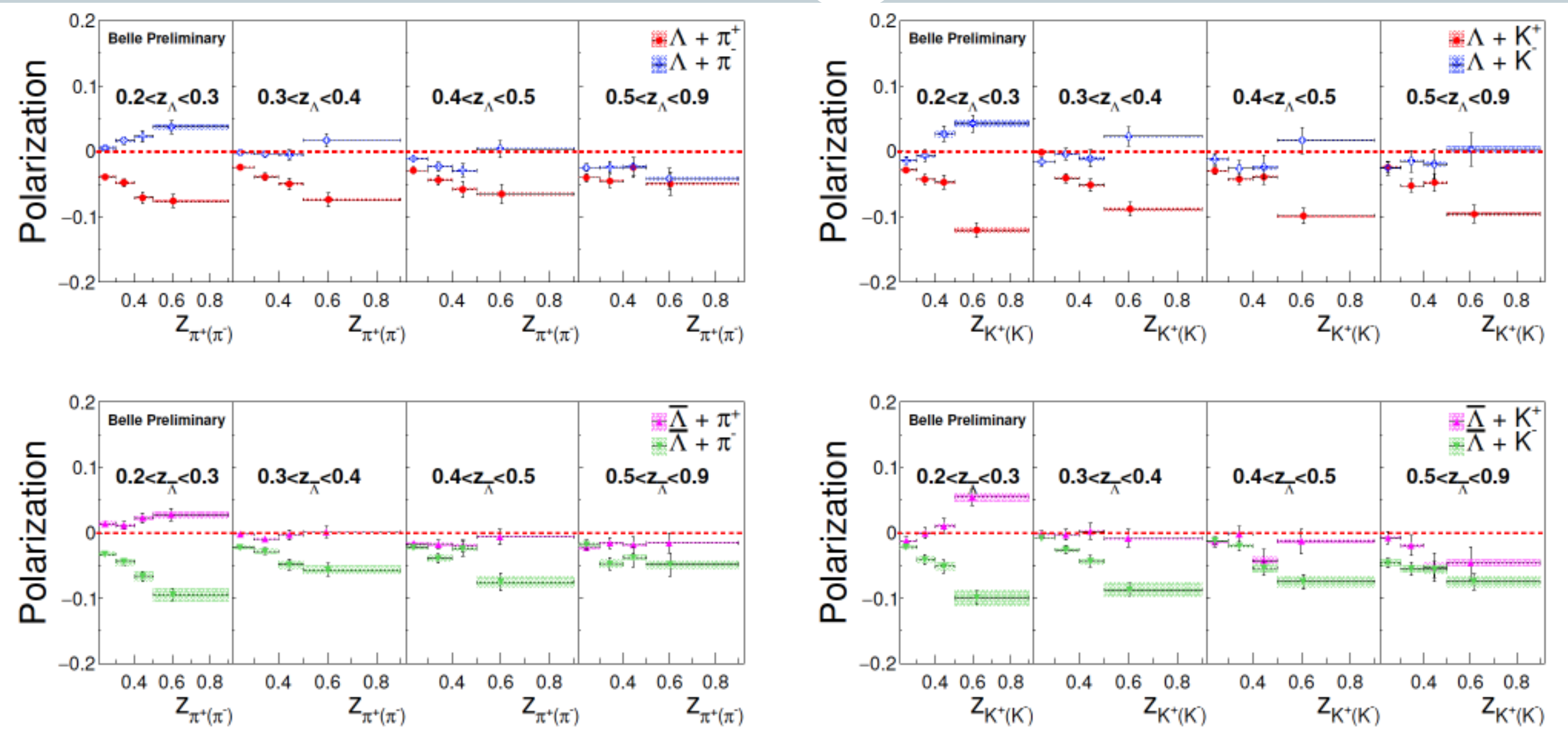
vs. (z_Λ, z_h)



- 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

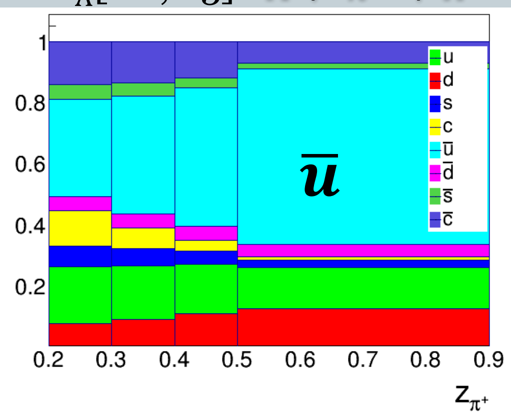
vs. (z_Λ, z_h)



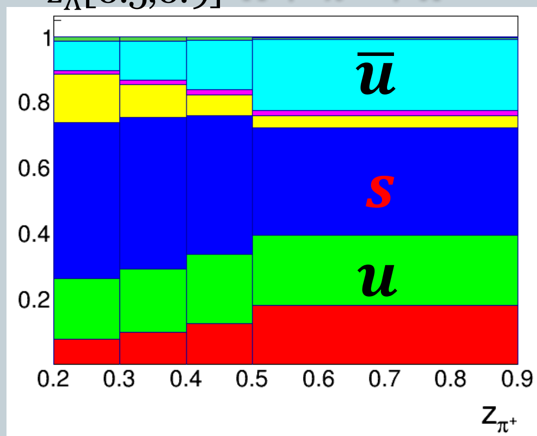
- Similar results with that in the thrust frame.
- Results from charge-conjugate modes are consistent with each other.

Quark flavor tag by the light hadron

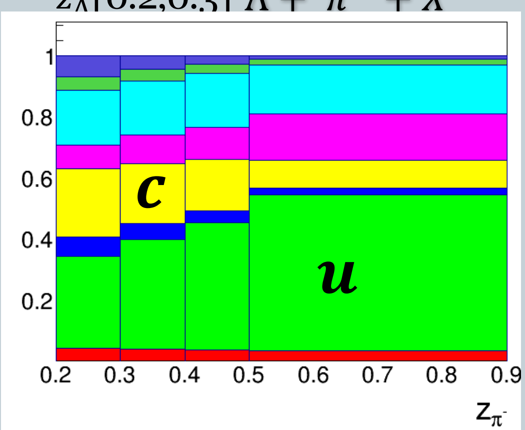
$z_\Lambda[0.2,0.3]$ $\Lambda + \pi^+ + X$



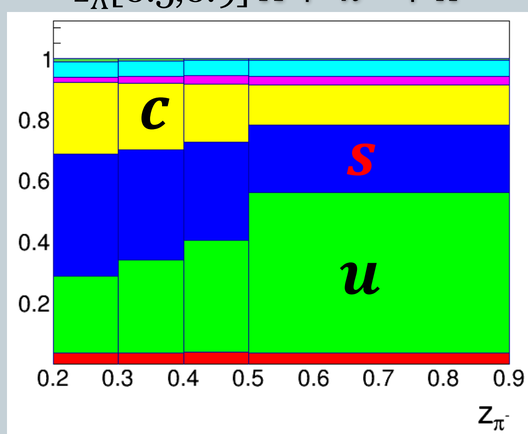
$z_\Lambda[0.5,0.9]$ $\Lambda + \pi^+ + X$



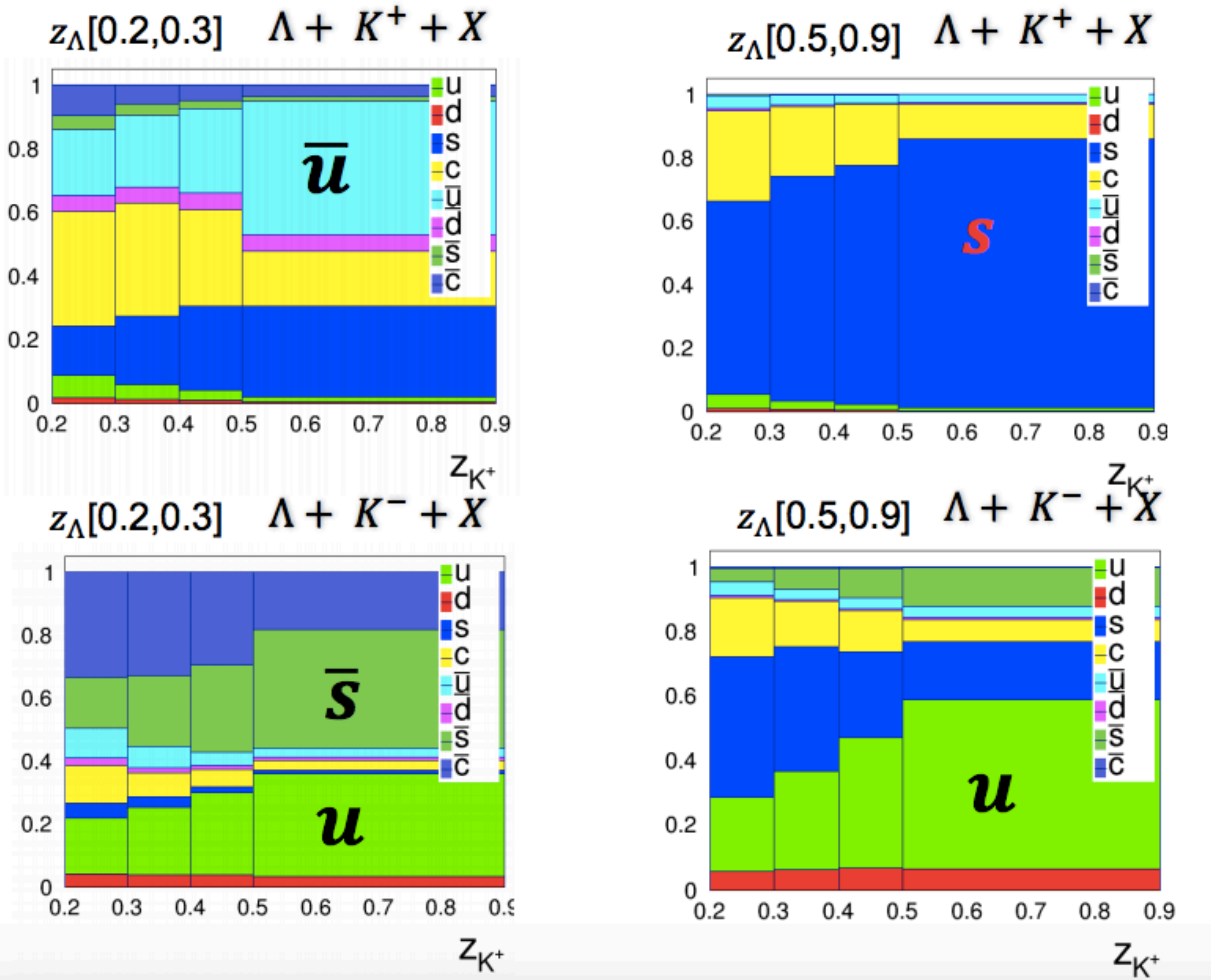
$z_\Lambda[0.2,0.3]$ $\Lambda + \pi^- + X$



$z_\Lambda[0.5,0.9]$ $\Lambda + \pi^- + X$



- 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.



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

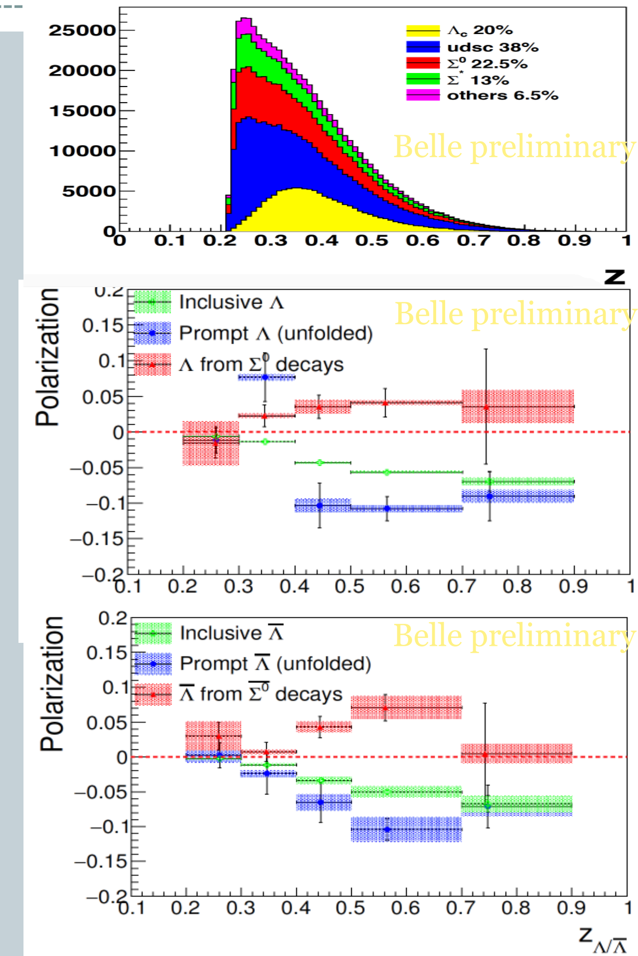
Background unfolding

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

○ The measured polarization can be expressed as:

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

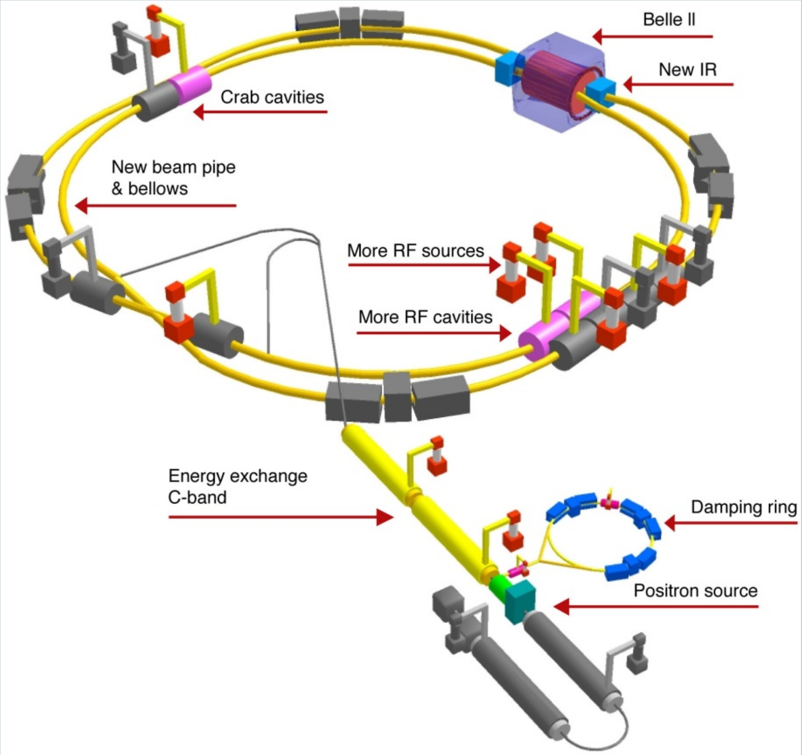
- F_i is the fraction of feed-down component i, estimated from MC. P_i is polarization of component i.
- Polarization of Λ from Σ^0 decays is found has opposite sign with that of inclusive Λ.

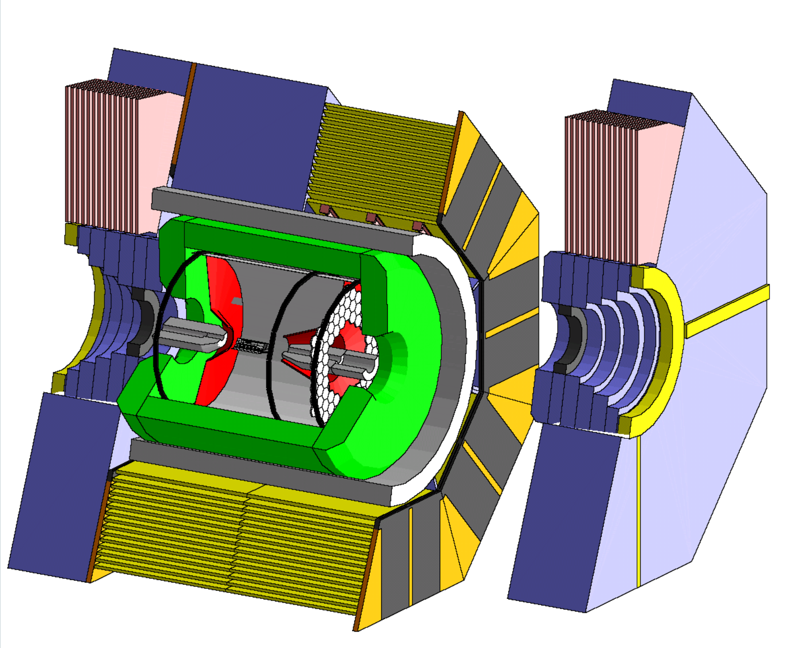


R. Gatto, Phys. Rev. 109, 610 (1958); Phys.Lett.B303,350(1993)

KEKB/Belle→SuperKEKB, Belle II Upgrade

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

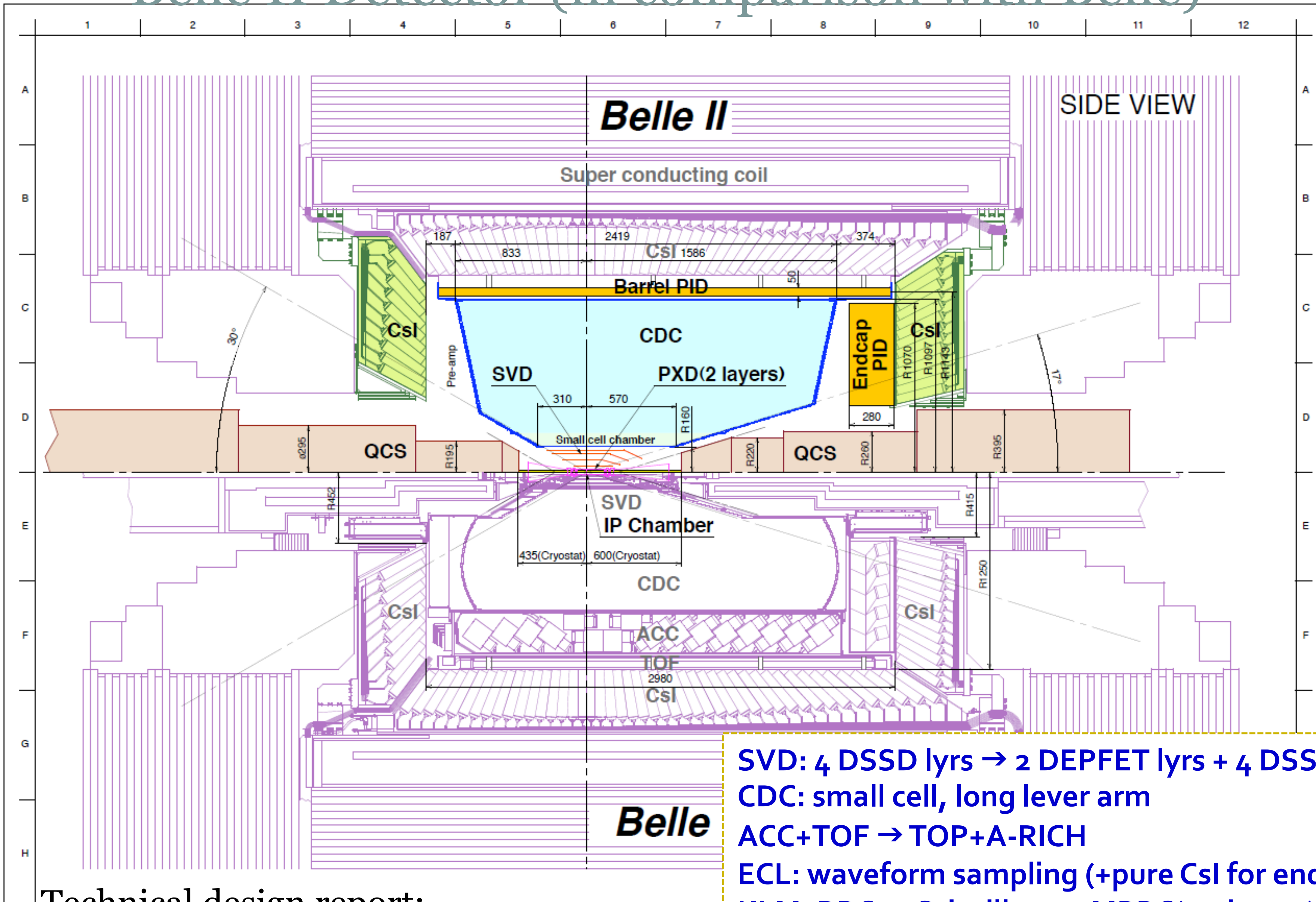




http://belle2.kek.jp

Start of comissioning in 2016

Belle II Detector (in comparison with Belle)



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

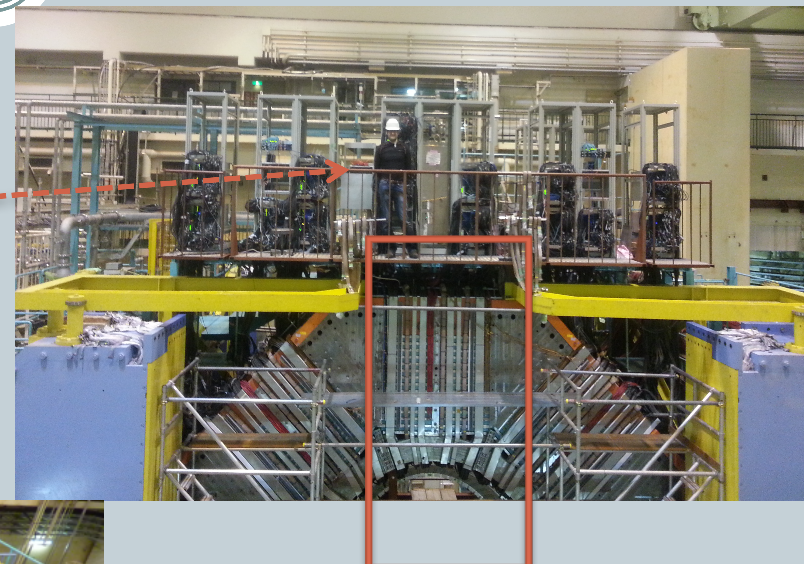
Technical design report:
arXiv:1011.0352

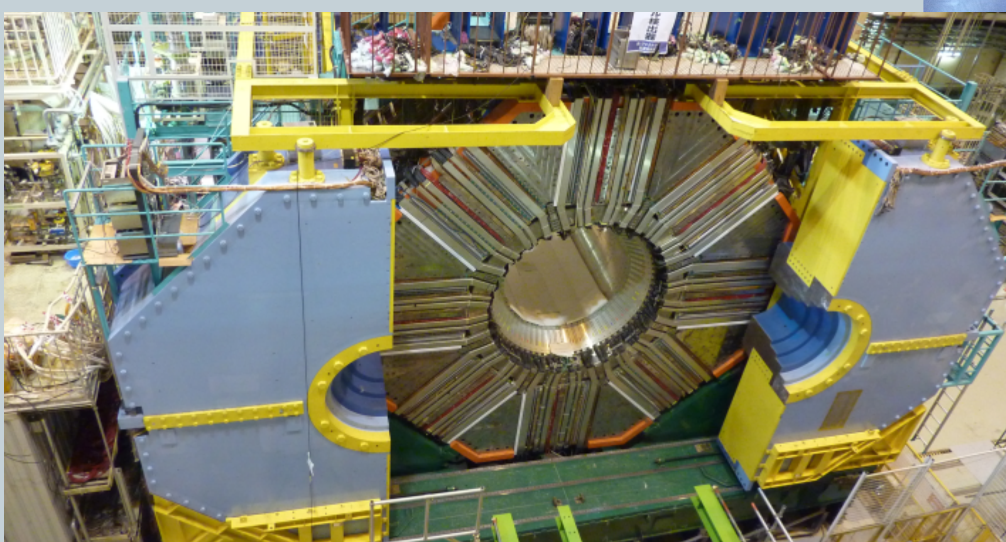
QCD studies at Belle II

- Precision study of local strong parity violation to probe the QCD vacuum
- Hadronization studies in transverse momentum-spin correlations (Λ)/Fragmentation function
- Precision studies of fragmentation functions needed for JLab12 program
  - Precision
  - Charm suppresion
  - Kaon ID

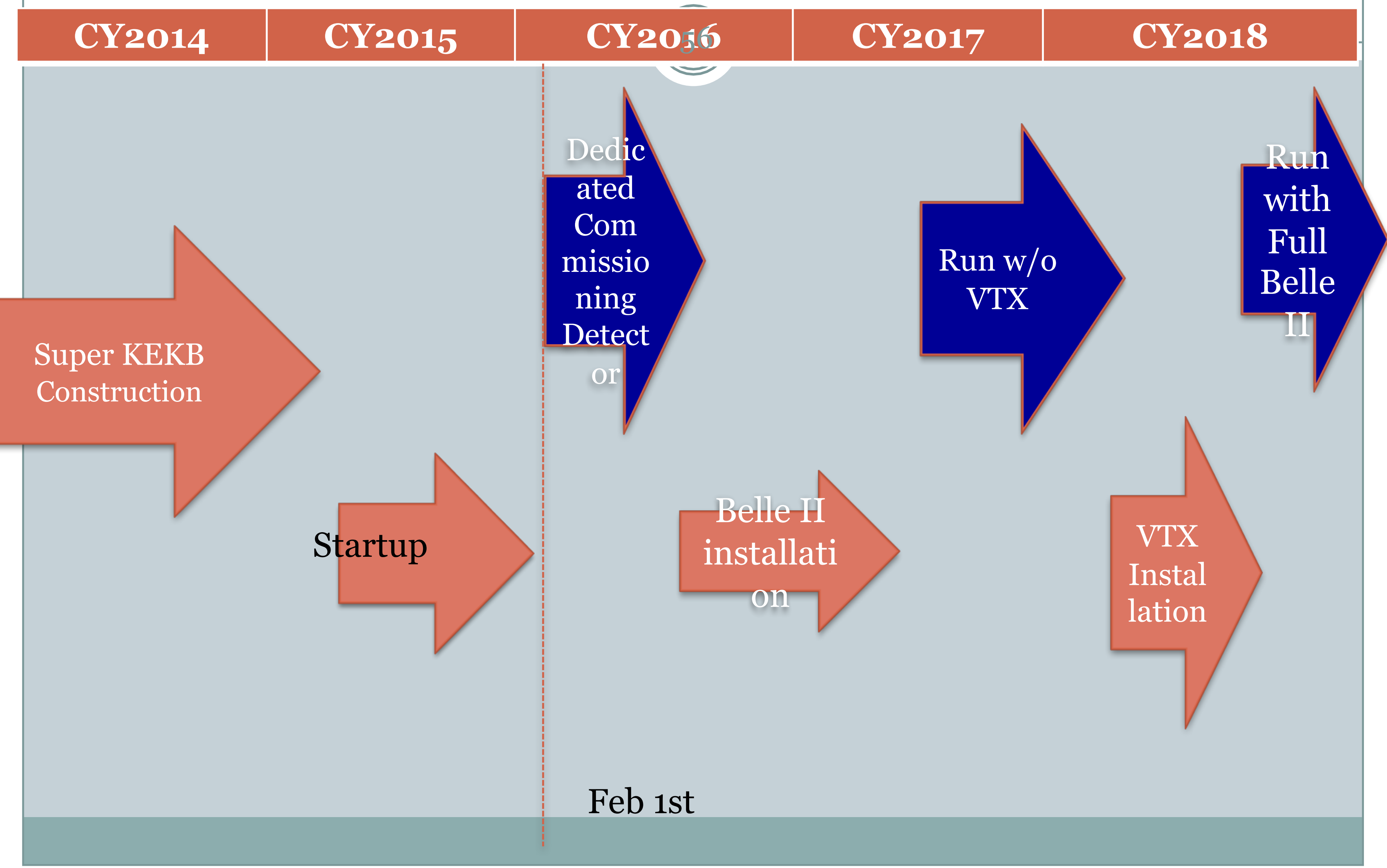
Status of Belle II Installation

Sector Test of KLM
(B Kunkler from IU)





Current SuperKEKB/Belle II Schedule

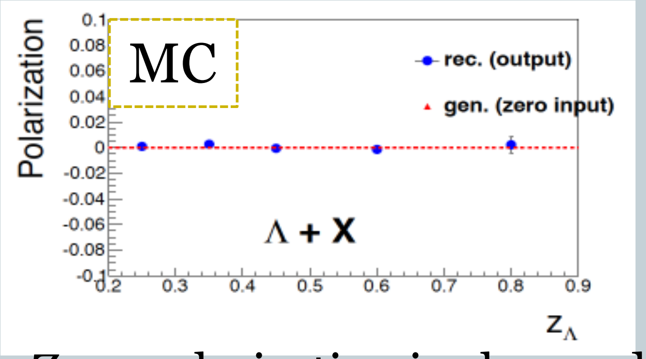


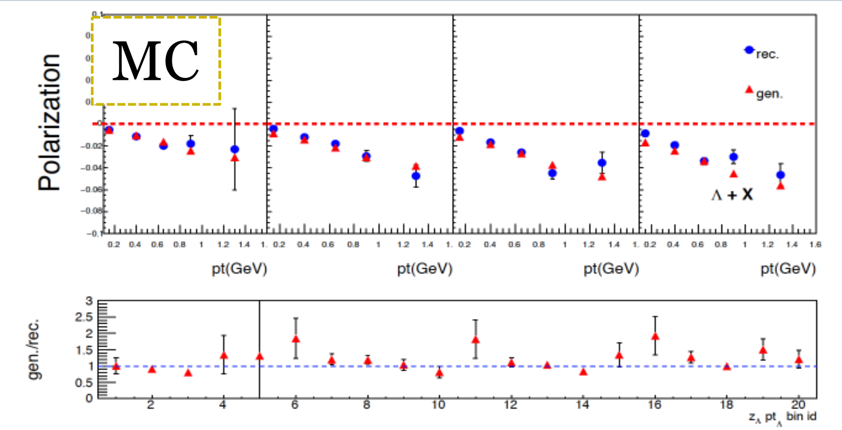
Conclusion/Outlook

- Hadronization Studies in e+e- provide a complimentary access to non-perturbative QCD
- Exciting new results with respect to polarized and polarizing FFs
- k_T dependent FFs on the horizon
- Belle II will provide ample new opportunities

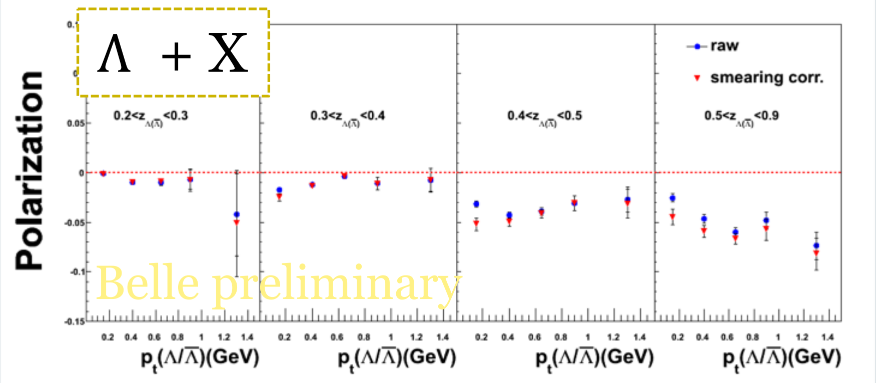
Backup

MC validation & Smearing correction

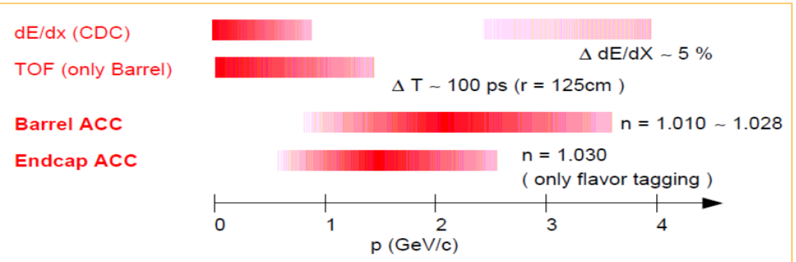




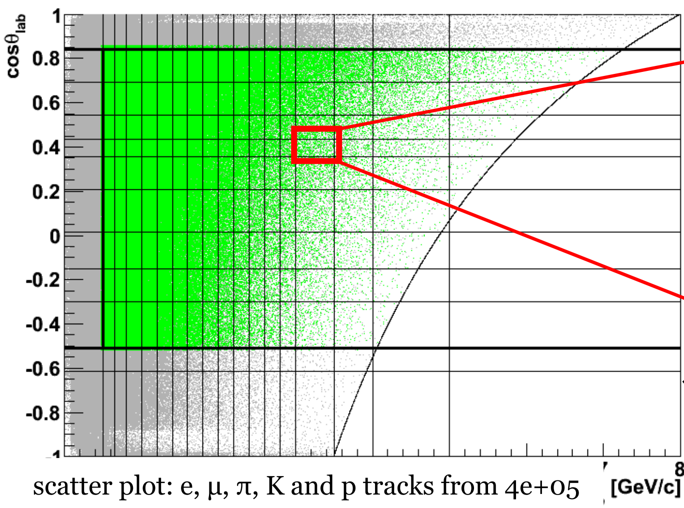
- Zero polarization is observed in MC, as expected.
- Smearing effects caused by the detector acceptance and resolution are estimated using weighted-MC with nonzero polarization input.
- In thrust frame correction factors are 1.0-1.3 depending on the [z,p_t].
- No Correction needed for hadron frame



PID Corrections from Data: Significant improvements compared to previous experiments



ToF forward geometry acceptance limit



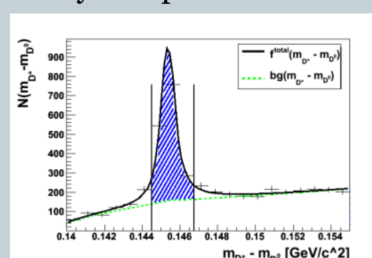
scatter plot: e, μ, π, K and p tracks from 4e+05 events

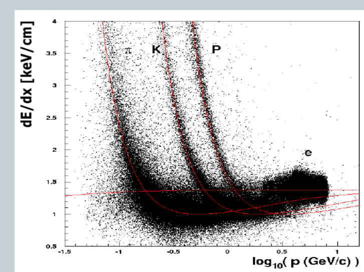
fill matrix of PID probabilities for each single bin from real data calibration- need large statistics

$$[P]_{ij\,(p_{lab},\,\cos\theta_{lab})} = \begin{pmatrix} p(e\to\tilde{e}) & p(\mu\to\tilde{e}) & p(\pi\to\tilde{e}) & p(K\to\tilde{e}) & p(p\to\tilde{e}) \\ p(e\to\tilde{\mu}) & p(\mu\to\tilde{\mu}) & p(\pi\to\tilde{\mu}) & p(K\to\tilde{\mu}) & p(p\to\tilde{\mu}) \\ p(e\to\tilde{\pi}) & p(\mu\to\tilde{\pi}) & p(\pi\to\tilde{\pi}) & p(K\to\tilde{\pi}) & p(p\to\tilde{\pi}) \\ p(e\to\tilde{K}) & p(\mu\to\tilde{K}) & p(\pi\to\tilde{K}) & p(K\to\tilde{K}) & p(p\to\tilde{K}) \\ p(e\to\tilde{p}) & p(\mu\to\tilde{p}) & p(\pi\to\tilde{p}) & p(K\to\tilde{p}) & p(p\to\tilde{p}) \end{pmatrix}$$

ToF backward geometry acceptance limit

e.g. $D^* \to D^0 \pi^+_{slow}$, $D^0 \to K^- \pi^+_{fast}$



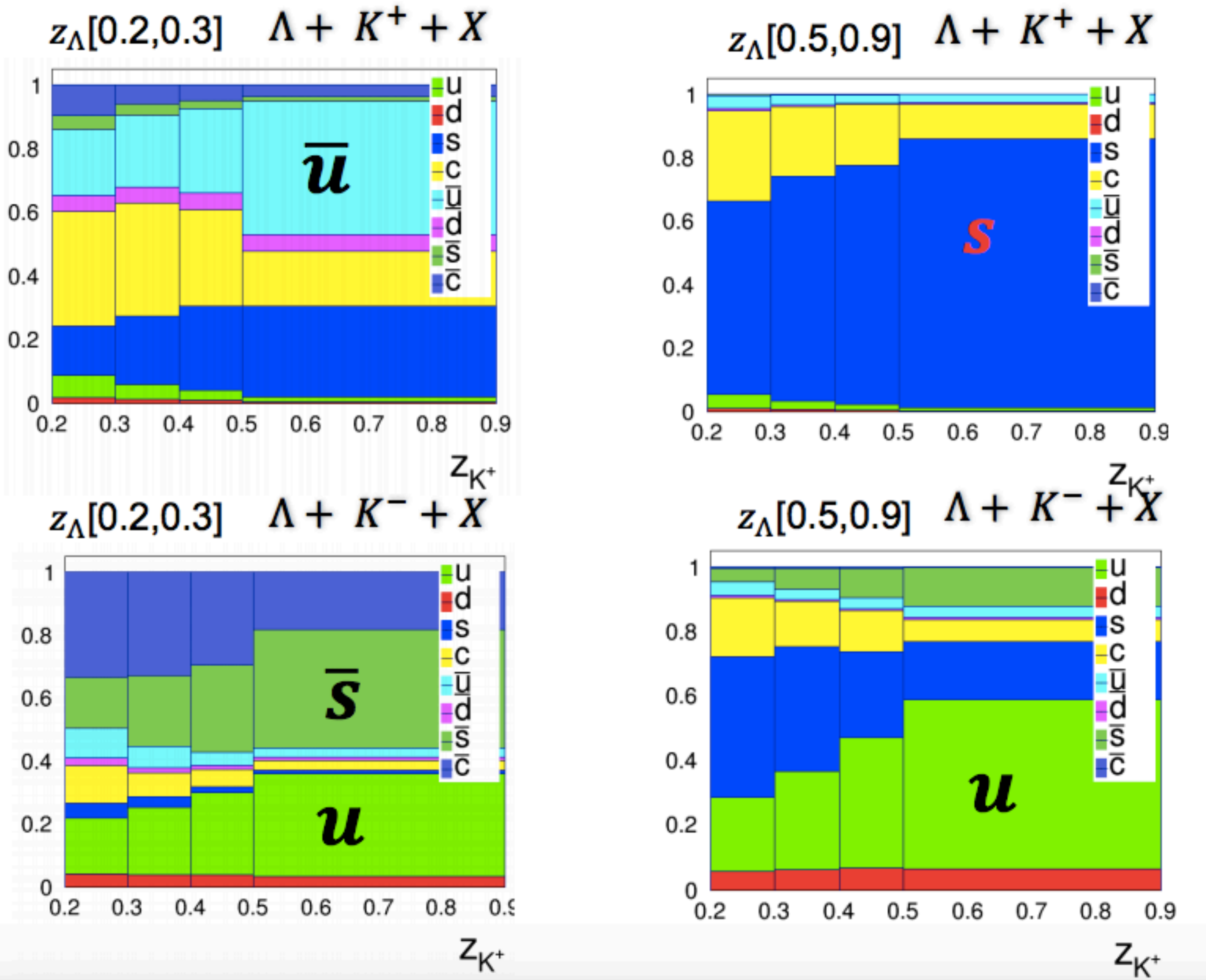


- Misidentification π→K up to 15%, K→π up to 20%

What we can learn by studying Hadronization

- Hadronization is the process by which colored objects (quarks/gluons) form hadrons in the final state
  - Cannot be calculated from first principles in QCD from the lattice → Measurements needed!

- Hadronization is tied to confinement →Crucial property of QCD which we are still trying to understand
  - **Provide data to extract fragmentation functions parametrizing Hadronization for use in factorized expression**
  - Study the formation and dynamics of short lived particles
  - Study QCD in a process complementary to looking at nucleon structure
  - Study non-perturbative QCD effects

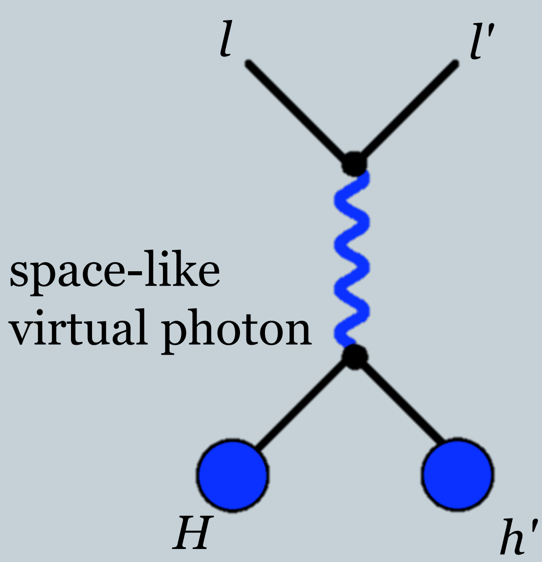


z_Λ[0.2,0.3] $\Lambda + K^+ + X$
$\bar{u}$
z_{K^+}
z_Λ[0.5,0.9] $\Lambda + K^+ + X$
s
z_{K^+}
z_Λ[0.2,0.3] $\Lambda + K^- + X$
$\bar{s}$
u
z_{K^+}
z_Λ[0.5,0.9] $\Lambda + K^- + X$
u
z_{K^+}
u
d
s
c
$\bar{u}$
$\bar{d}$
$\bar{s}$
$\bar{c}$
0
0.2
0.4
0.6
0.8
1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Easiest Process to study QCD

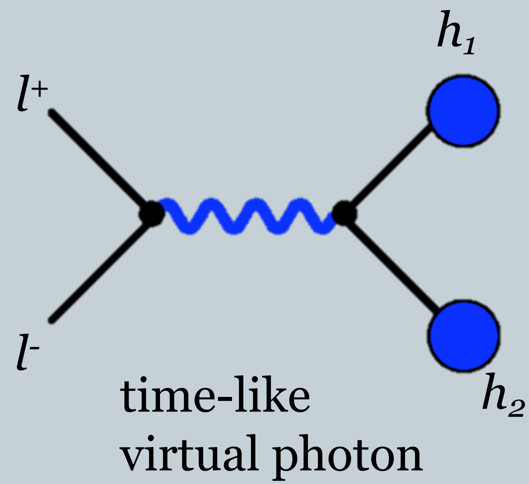
DIS

$DF \otimes FF$



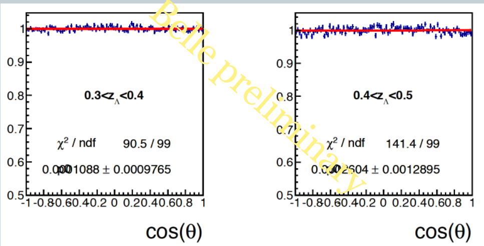
electron-electron collisions

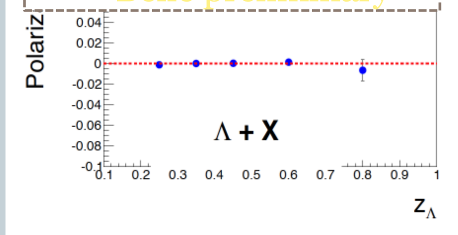
$FF \otimes FF$



Systematics

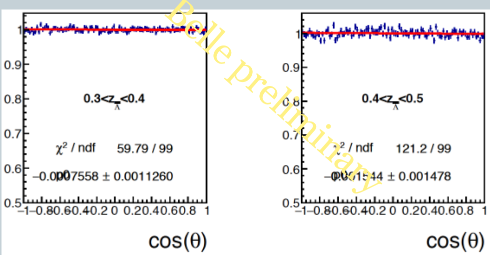
Build fake angle θ

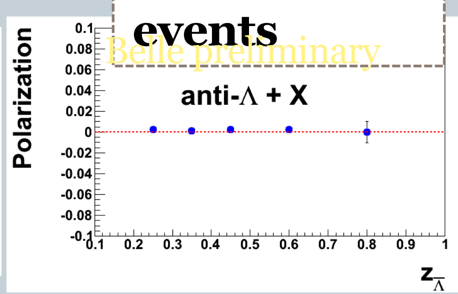




- Change the reference vector $\hat{n}$ to be in the Λ production plane. But still normal to $\vec{p}_{\Lambda}$.

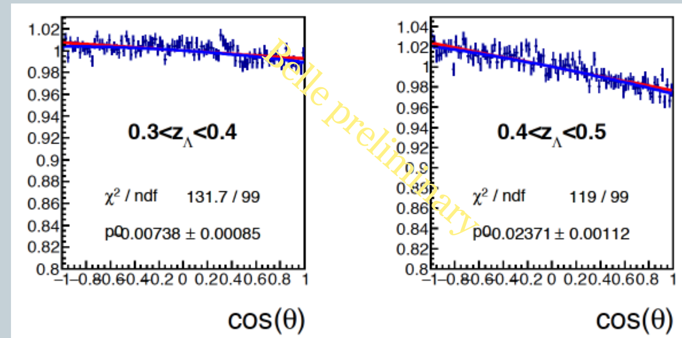
Mixed events





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

Vary the fit function

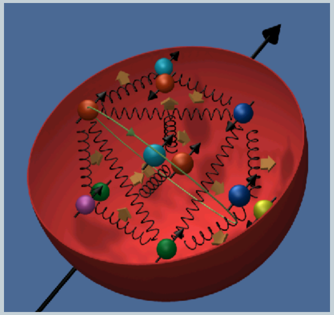


- The second order term was added in the fit function $1 + p_0 cos\theta + p_1\ cos^2\theta$

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

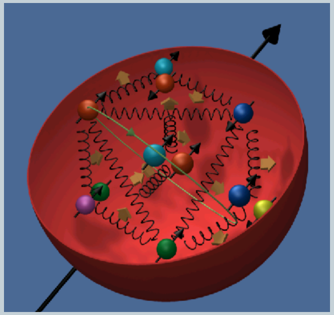
QCD is hard…

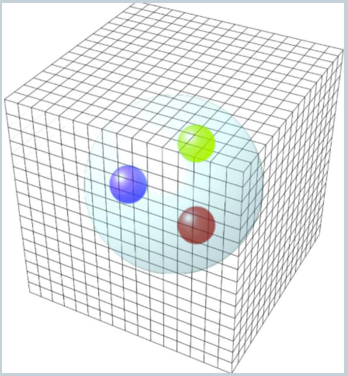
- QCD has glue-glue interaction and strong coupling
  - Binding energy/constituent mass ~10^2 in proton, 10^{-8} in hydrogen atom
- ➔Much more difficult to compute

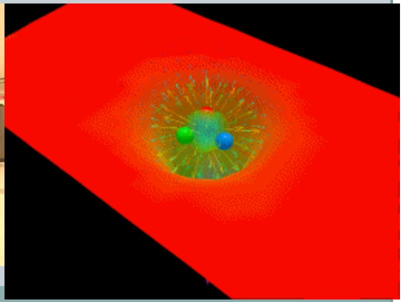


… but signficant progress in first order calculations from the lattice

- QCD has glue-glue interaction and strong coupling
  - Binding energy/constituent mass ~10^2 in proton, 10^{-8} in hydrogen atom
  - Much more difficult to compute
- Advances in Computational QCD (lattice)
  - Need experimental input
  - Cannot compute hadronization







Spin, the death of many theories

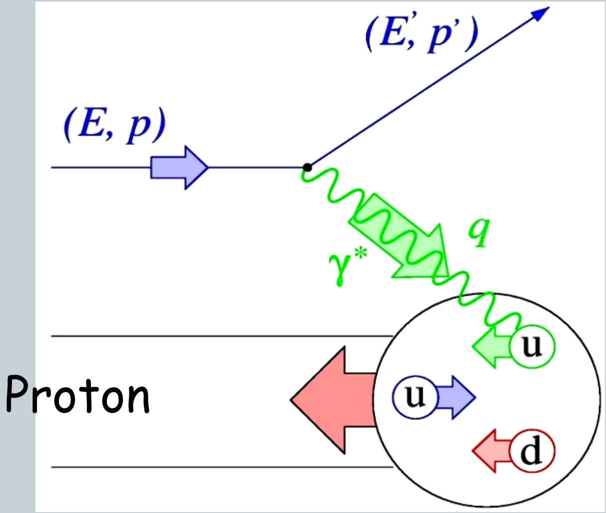
- "Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection - J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes,St. Croix, Virgin Islands (1987)."
- "Experiments with spin have killed more theories than any other single physical parameter" - Elliot Leader, Spin in Particle Physics, Cambridge U. Press (2001)

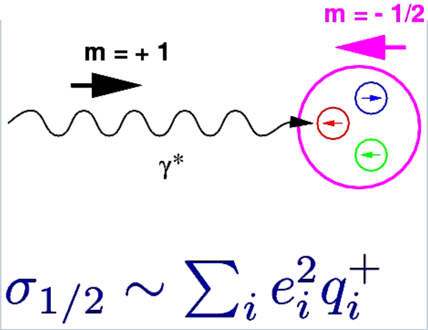
Example: Role of spin in the particle masses of mesons:

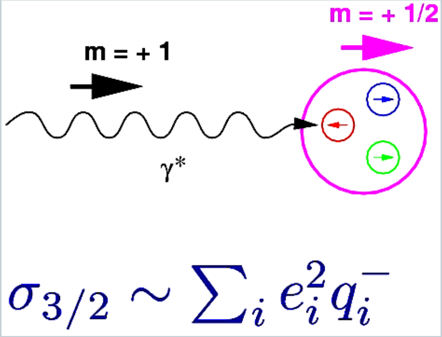
Mesons $q\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1

Probes to Study Polarized Proton Structure

Inclusive polarized deep inelastic scattering (DIS)

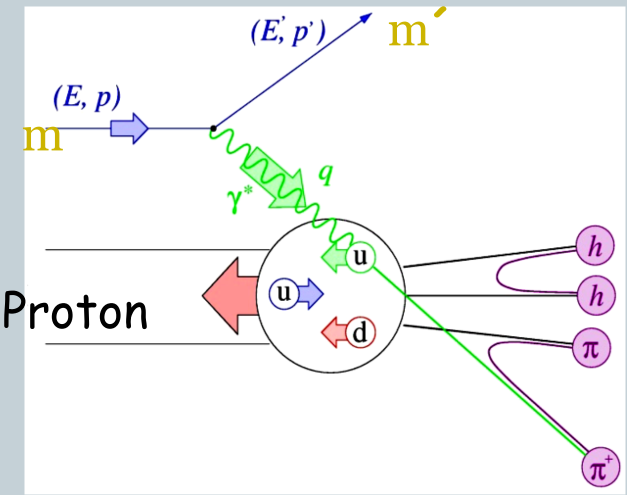


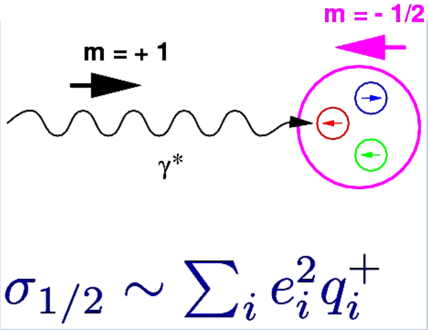


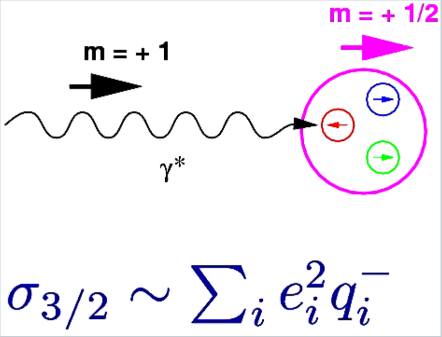


Probes to Study Polarized Proton Structure

Semi-Inclusive polarized deep inelastic scattering (DIS)





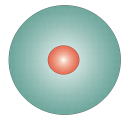


Fragmentation Process:
Outgoing quark forms hadrons

Parton Distribution Functions

The three leading order, collinear PDFs

$f_1^q(x)$

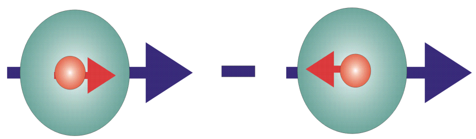


unpolarized PDF

quark with momentum $x = p_{quark}/p_{proton}$ in a nucleon

well known – unpolarized DIS

$g_1^q(x)$

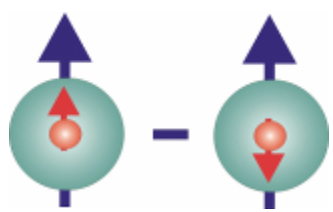


helicity PDF

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

known – polarized DIS

$h_1^q(x)$



transversity PDF

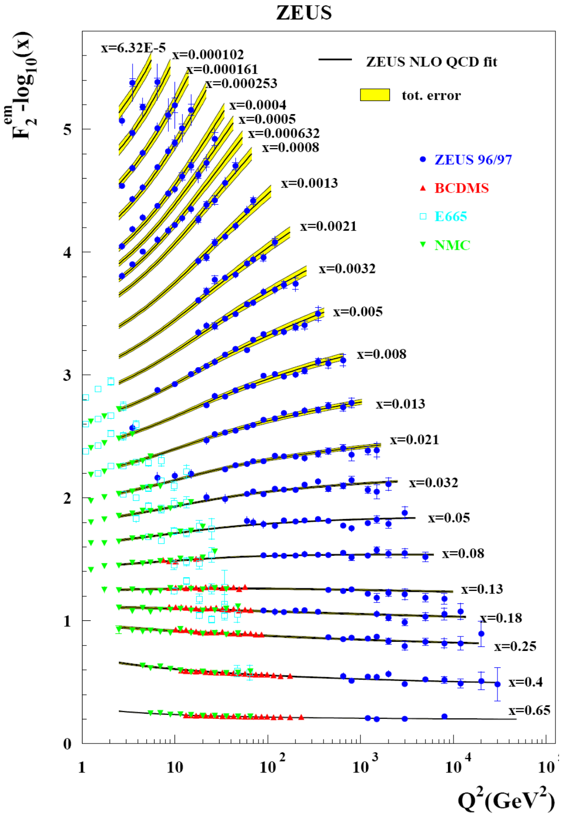
quark with spin parallel to the nucleon spin in a transversely polarized nucleon
Helicity – transversity: measurement of the nonzero angular momentum components in the protons wavefunction

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

Current Status of Distribution Functions

$f_1 =$ 

Unpolarized

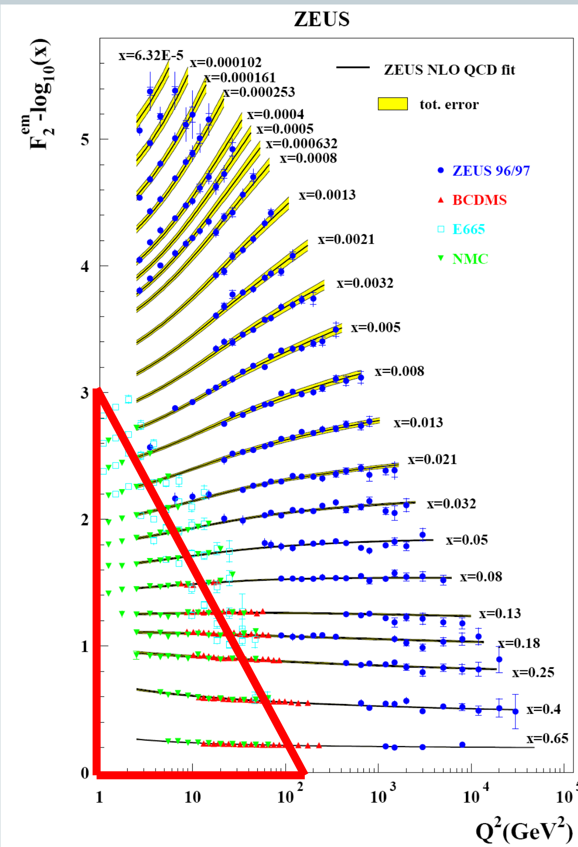


$$F_2 \propto \sum_q x e_q^2 f_1^q$$

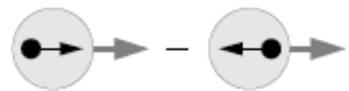
Current Status of Distribution Functions

$f_1 =$ 

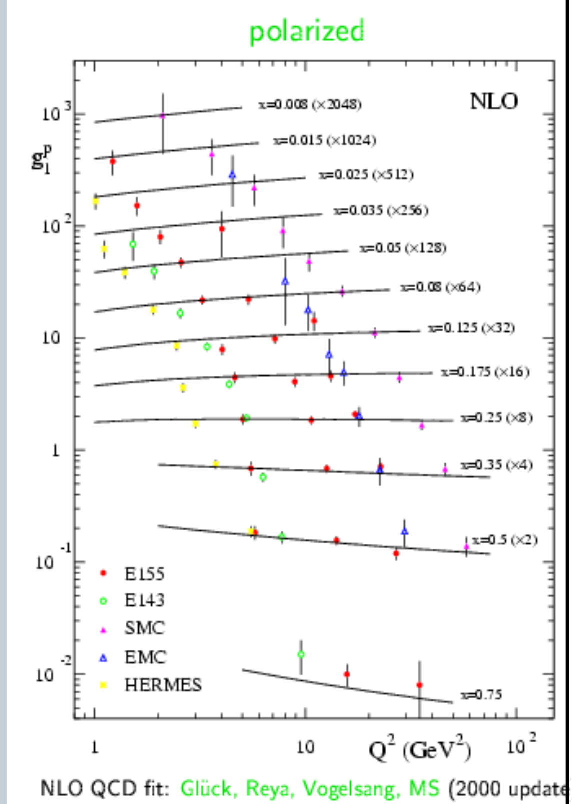
Unpolarized



$$F_2 \propto \sum_q x e_q^2 f_1^q$$

$g_1 =$ 

Longitudinally Polarized



$$g_1 \propto \sum_q e_q^2 g_1^q$$

Current Status of Distribution Functions

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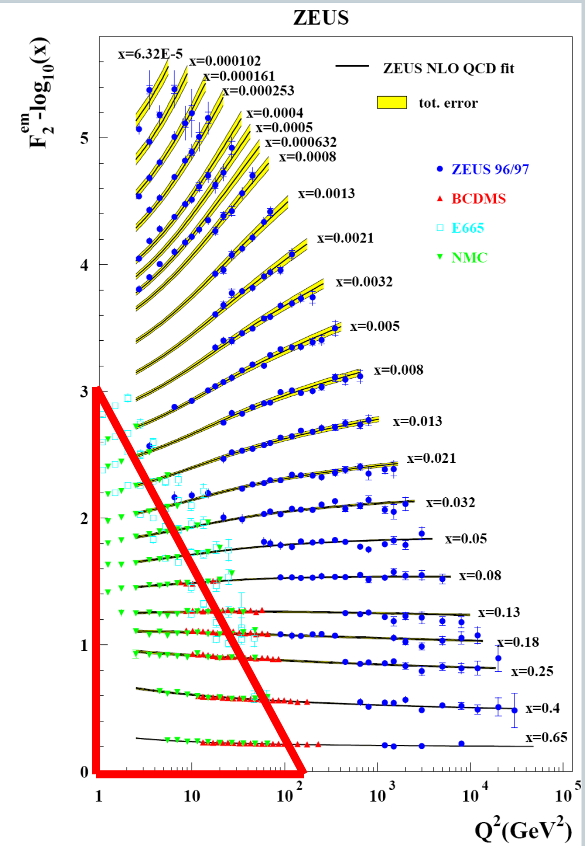

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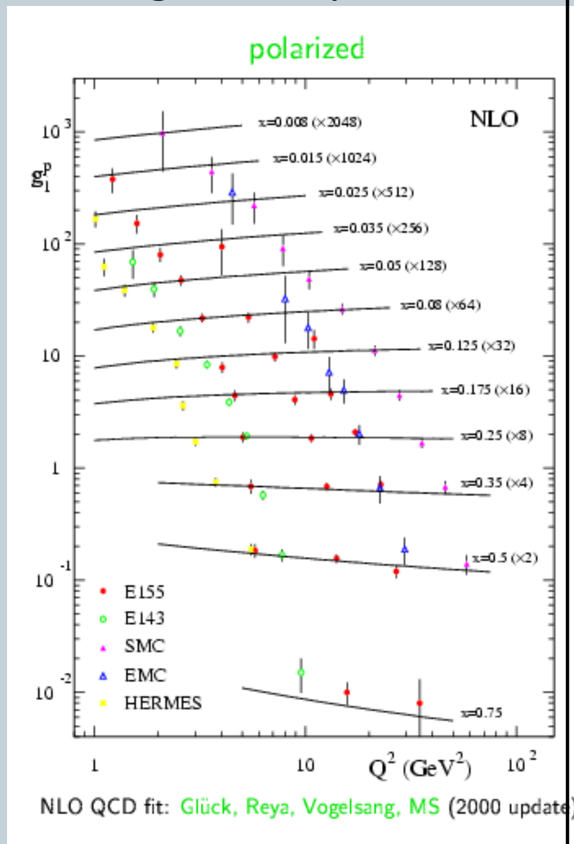
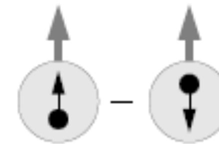
$g_1 =$ 

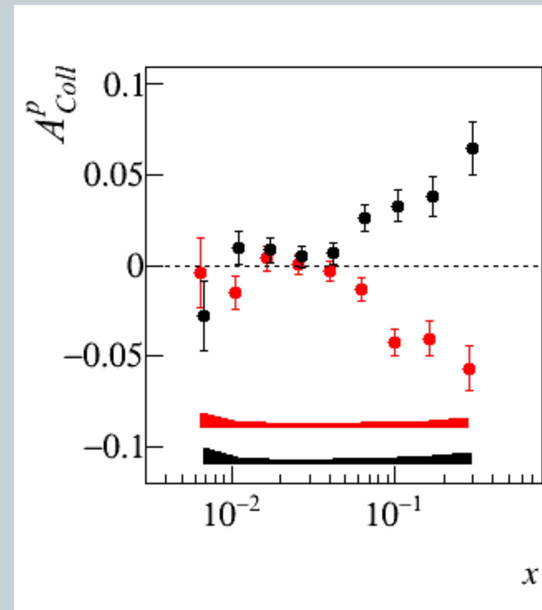
Longitudinally Polarized



$$g_1 \propto \sum_q e_q^2 g_1^q$$

$h_1 =$ 

Transversely Polarized



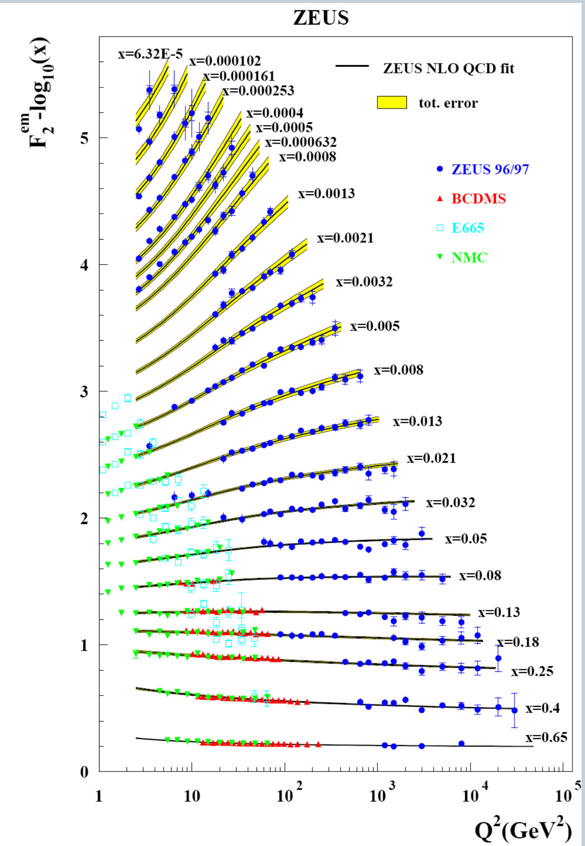
$$A^{\text{Collins}} \propto \frac{\sum_q e_q^2 h_1^q(x) * H_1^{\perp}}{\sum_q e_q^2 q_q^q(x) * D_q^h(z)}$$

Chiral odd -
cannot be measured inclusively

Current Status of Distribution Functions

$f_1 =$ 

Unpolarized



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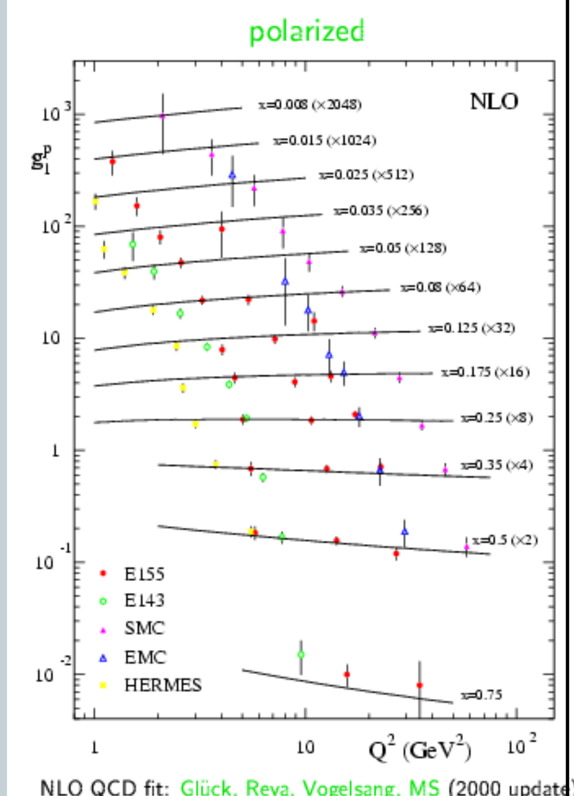

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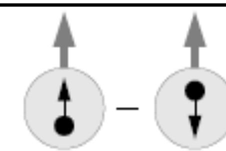
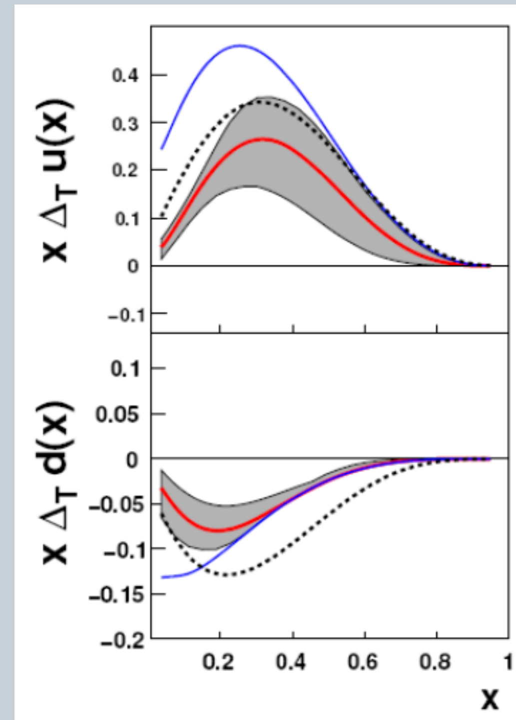
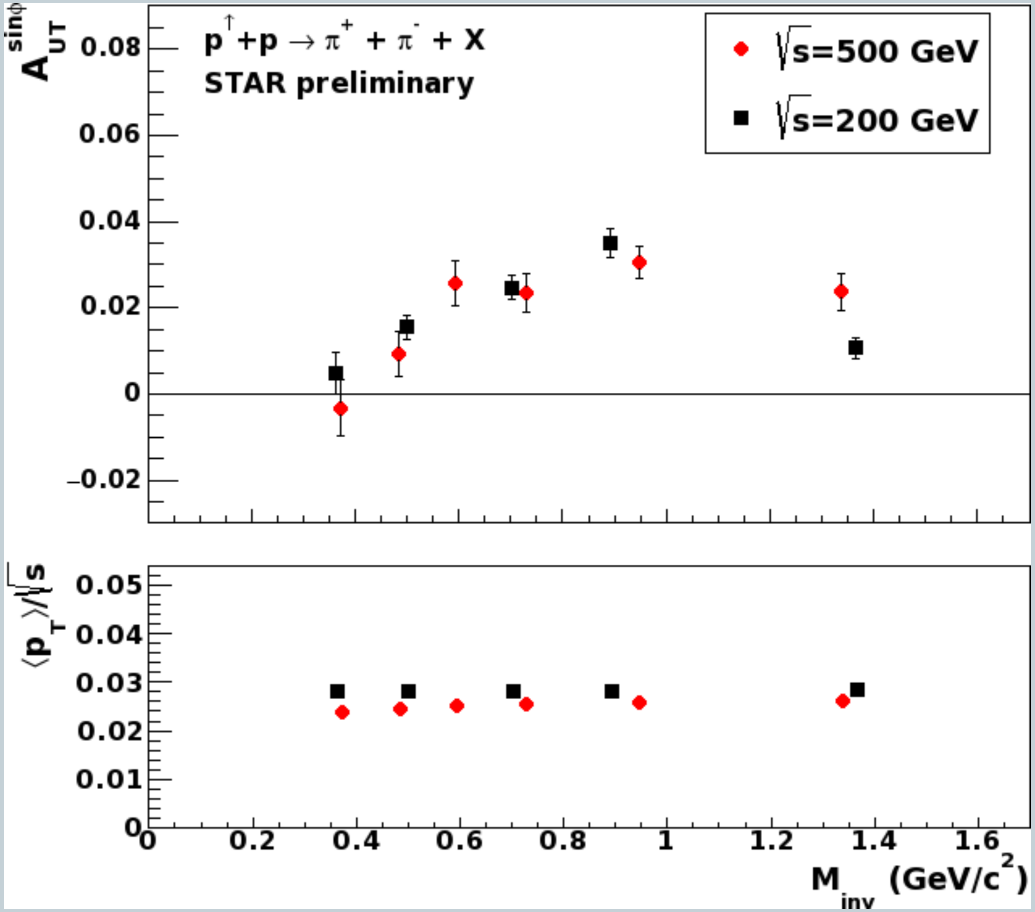
$h_1 =$ 

Transversely Polarized



Anselmino et al

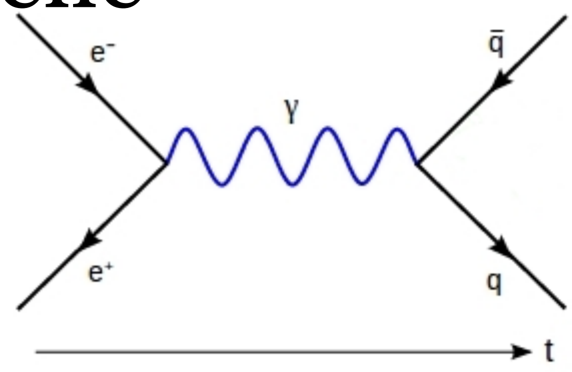
Comparison between 0.2 and 0.5 TeV: Consistent and no Sign of Evolution



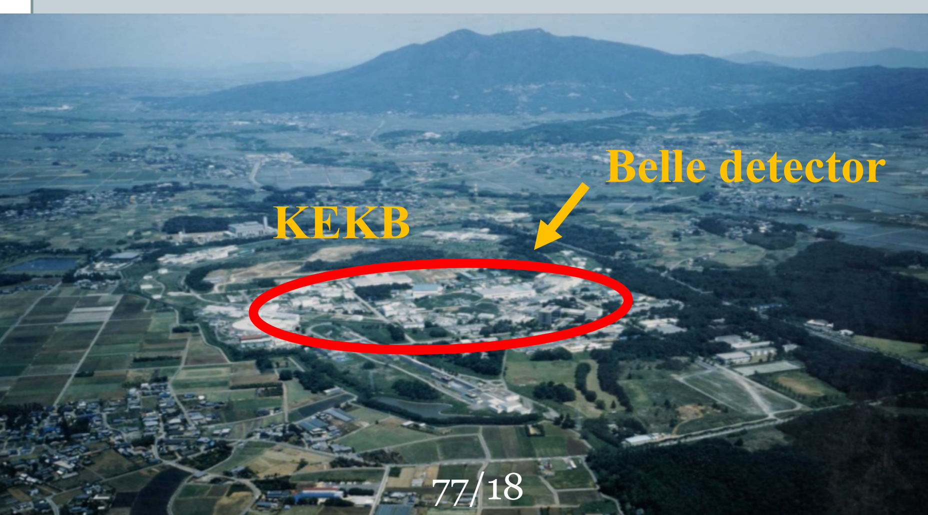
~x_{Bj}

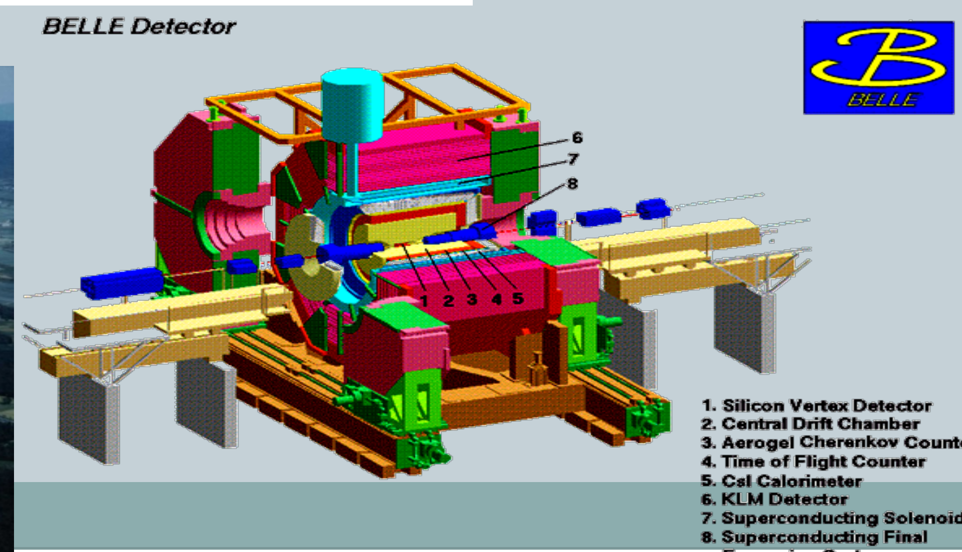
Indeed: No Evolution, Gluons do not couple to transversity!

Measurements of Fragmentation Functions in e+e- at Belle

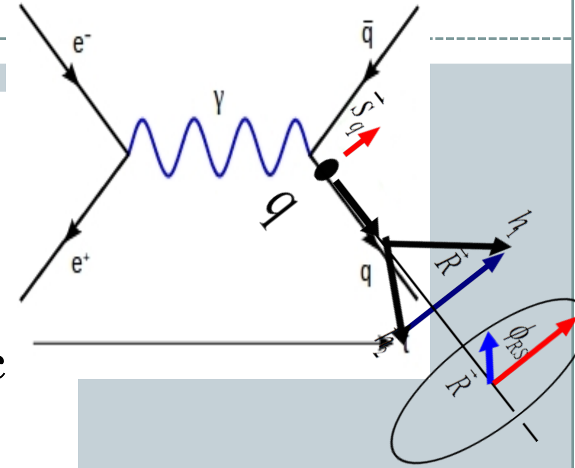


- KEK-B: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - **$\sqrt{s}$ = 10.58 GeV,** $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\ \bar{B}$
  - $\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'
- ideal detector for high precision measurements:
  - tracking acceptance θ [17 °;150°]: Azimuthally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





Measurements of Fragmentation Functions in e+e- at Belle



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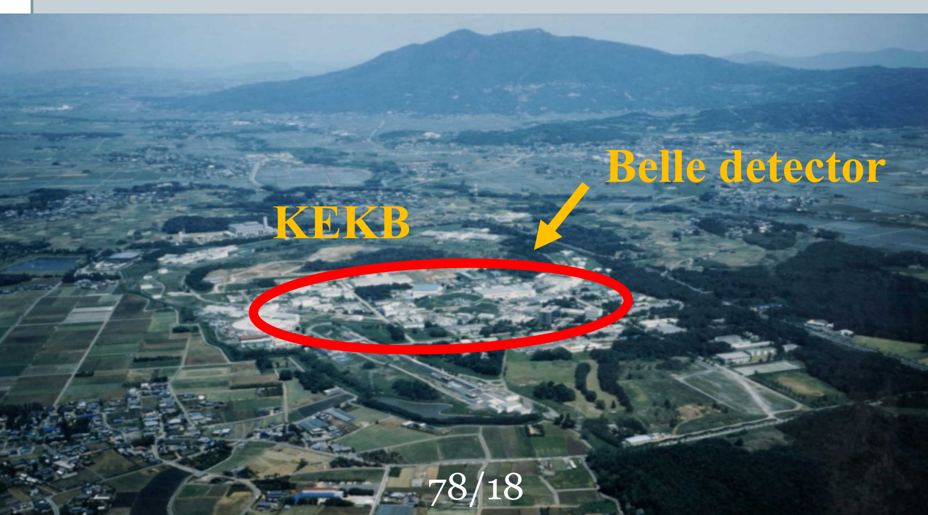
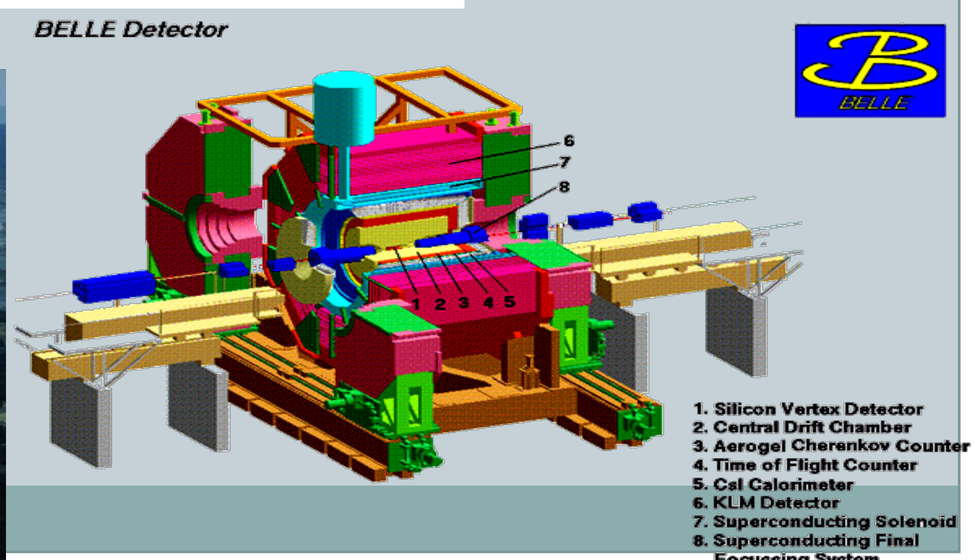
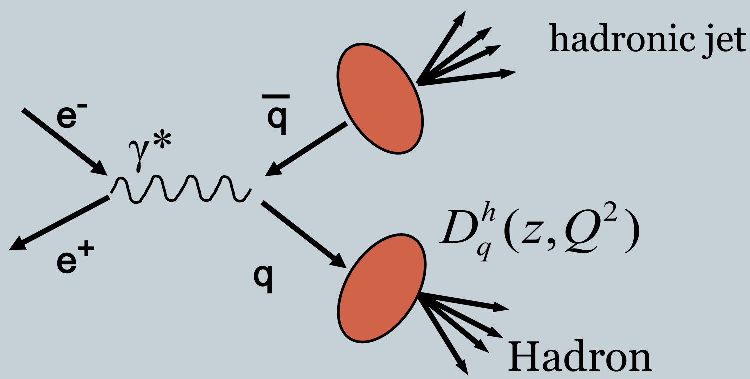


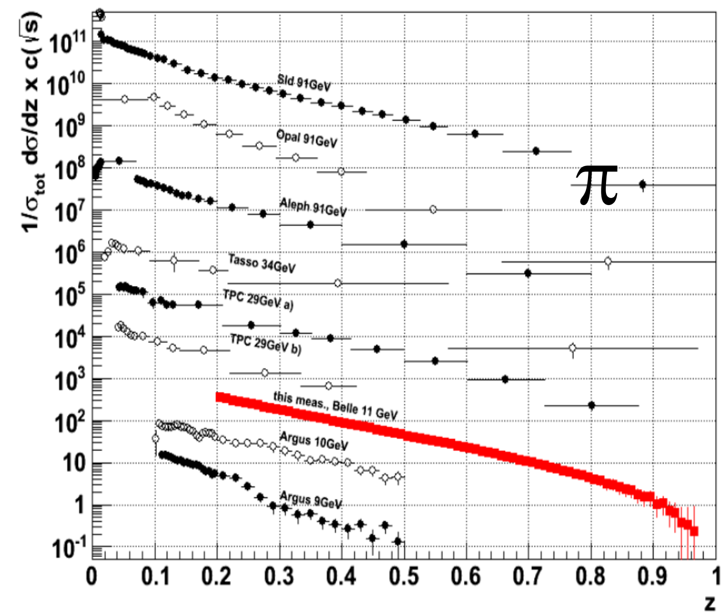


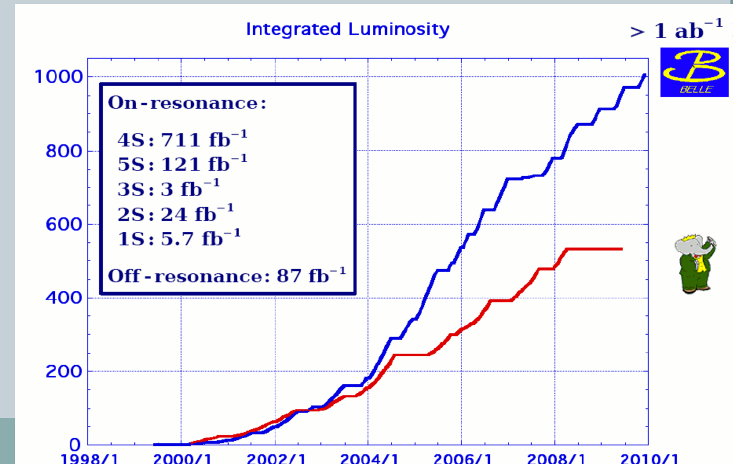
Where to Study?

- e^+e^- cleanest way to access FFs



- B factories
  - close in energy to SIDIS (100 GeV² vs 2-3 GeV²)
  - Large integrated lumi!, high z reach





Measurements of Fragmentation Functions in e+e- at Belle

•Asym. e^+ (3.5/3.1 GeV) e^- (8/9 GeV) collider:

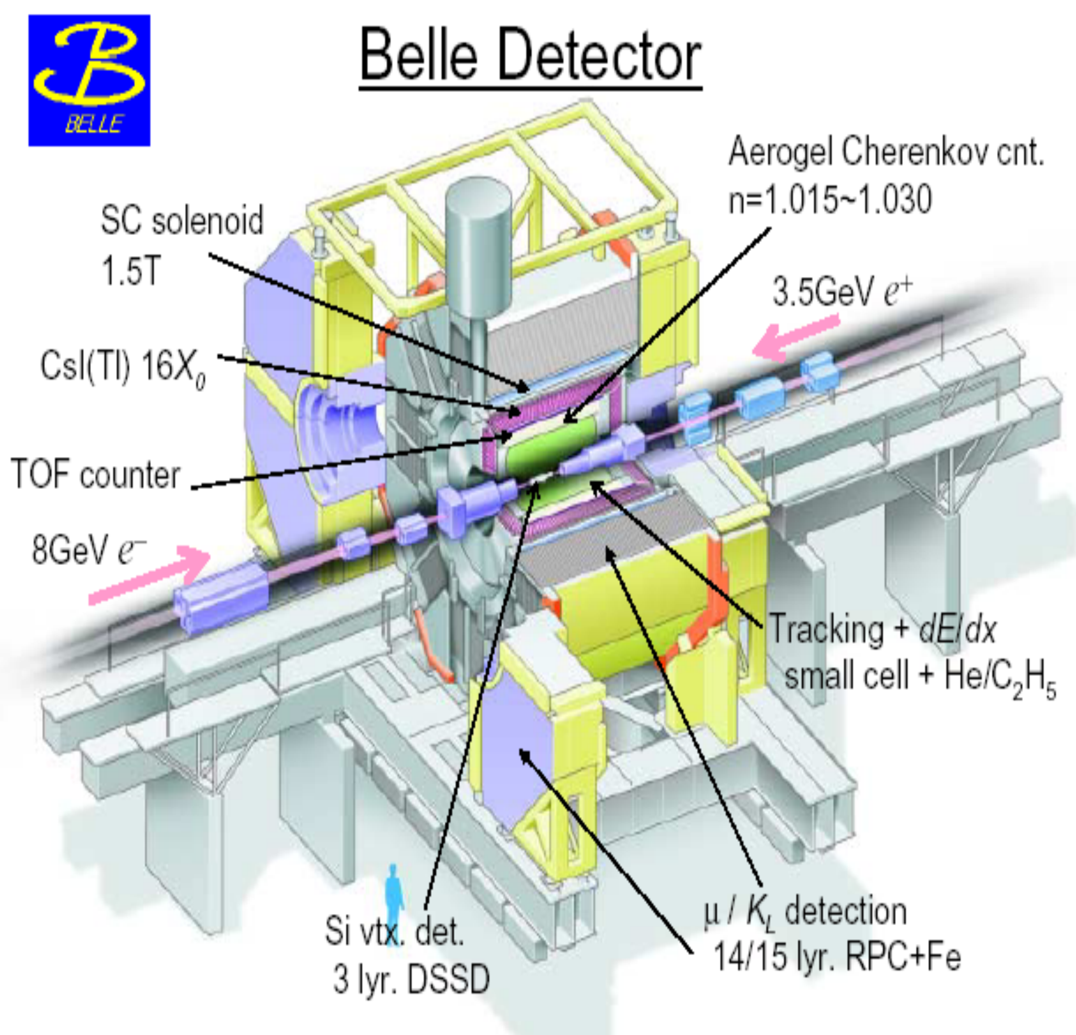
- **-$\sqrt{s}$ = 10.58 GeV,** e^+e^- →Y(4S)→B anti-B
- **-$\sqrt{s}$** = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'

• ideal detector for high precision measurements:

- Azimuthally symmetric acceptance, high res. Tracking, PID

Available data:

~1.8 *10^9 events at 10.58 GeV,
~220 *10^6 events at 10.52 GeV



Cross-Section for identified Pions and Kaons

- Initial State Radiation
- Exclude events where CME/2 changes by more than 0.5%
- Large at low z, correct based on MC

PID

$i = \pi, K$

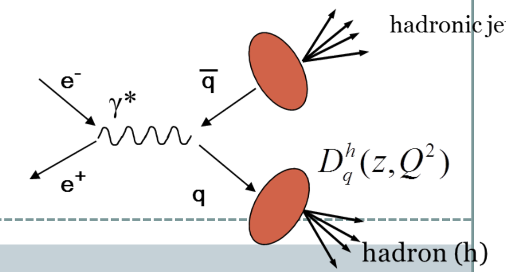
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$

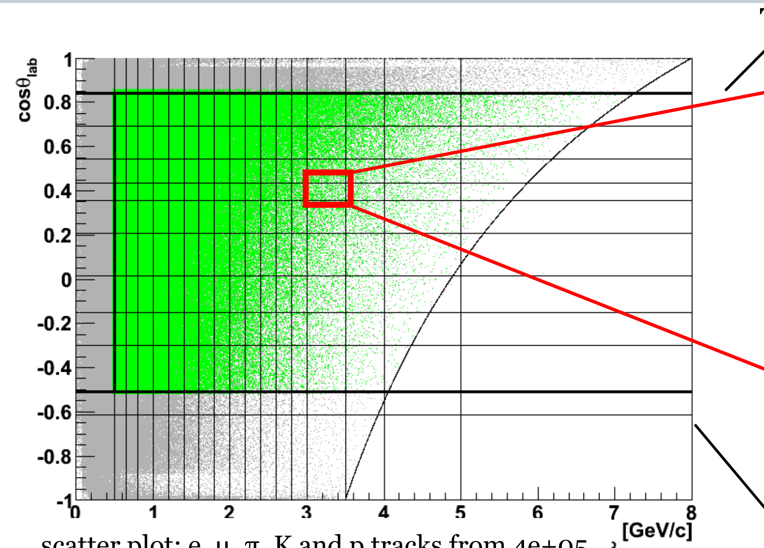
- Correct for acceptance,
- ττ, 2γ,
- decay in flight,

< 10%

- Smearing Corrections

PID Corrections from Data





scatter plot: e, μ, π, K and p tracks from 4e+05 events

ToF forward geometry acceptance limit

ToF backward geometry acceptance limit

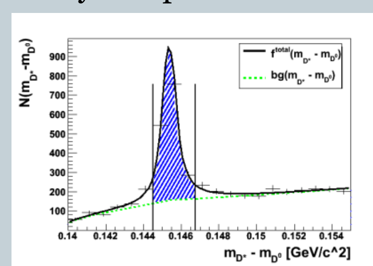
fill matrix of PID probabilities for each single bin from real data calibration- need large statistics

$$[P]_{ij}\,(p_{lab},\cos\theta_{lab}) = \begin{pmatrix} p(e\to\tilde{e}) & p(\mu\to\tilde{e}) & p(\pi\to\tilde{e}) & p(K\to\tilde{e}) & p(p\to\tilde{e}) \\ p(e\to\tilde{\mu}) & p(\mu\to\tilde{\mu}) & p(\pi\to\tilde{\mu}) & p(K\to\tilde{\mu}) & p(p\to\tilde{\mu}) \\ p(e\to\tilde{\pi}) & p(\mu\to\tilde{\pi}) & p(\pi\to\tilde{\pi}) & p(K\to\tilde{\pi}) & p(p\to\tilde{\pi}) \\ p(e\to\tilde{K}) & p(\mu\to\tilde{K}) & p(\pi\to\tilde{K}) & p(K\to\tilde{K}) & p(p\to\tilde{K}) \\ p(e\to\tilde{p}) & p(\mu\to\tilde{p}) & p(\pi\to\tilde{p}) & p(K\to\tilde{p}) & p(p\to\tilde{p}) \end{pmatrix}$$

e.g. $D^* \to D^0 \to K^-$

$D^* \to \pi^+_{slow}$

$D^0 \to \pi^+_{fast}$

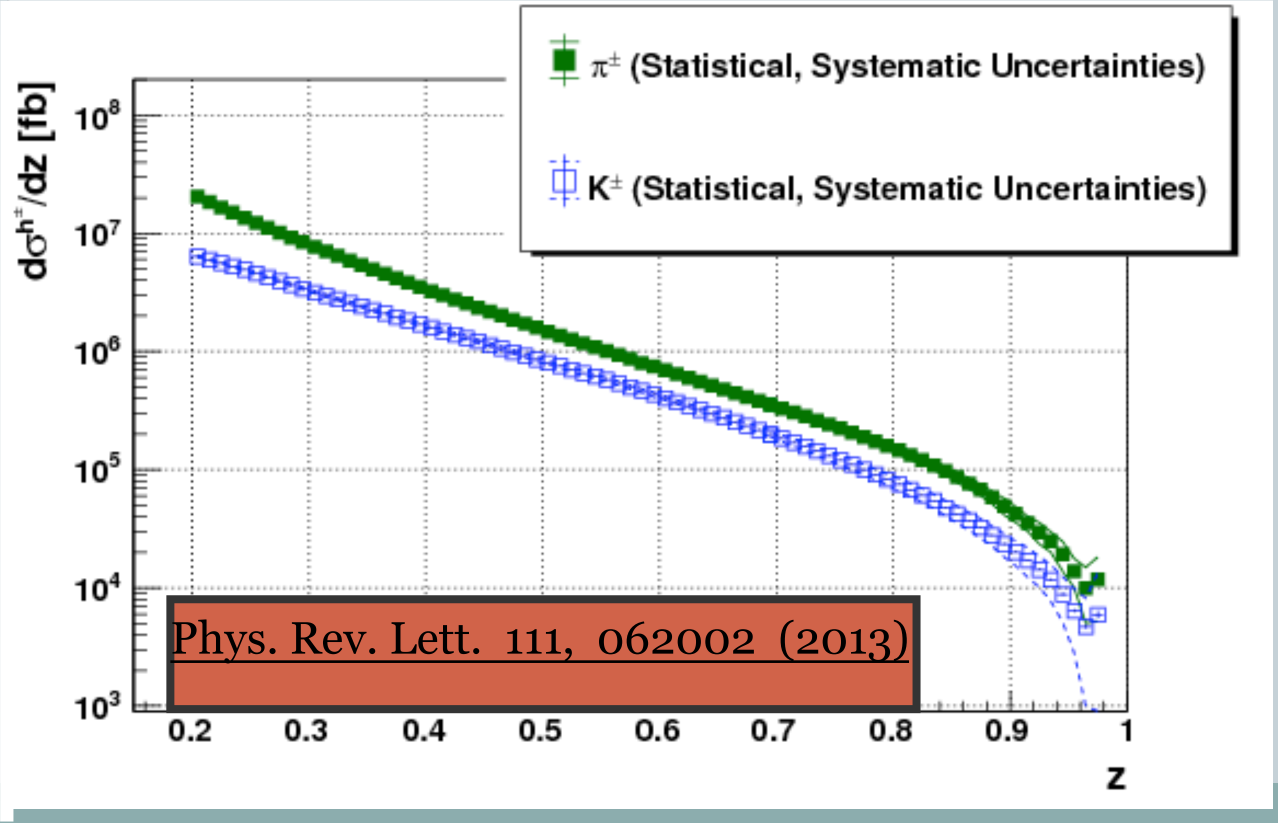


- Misidentification π→K up to 15%, K→π up to 20%

Cross sections

$i = \pi, K$

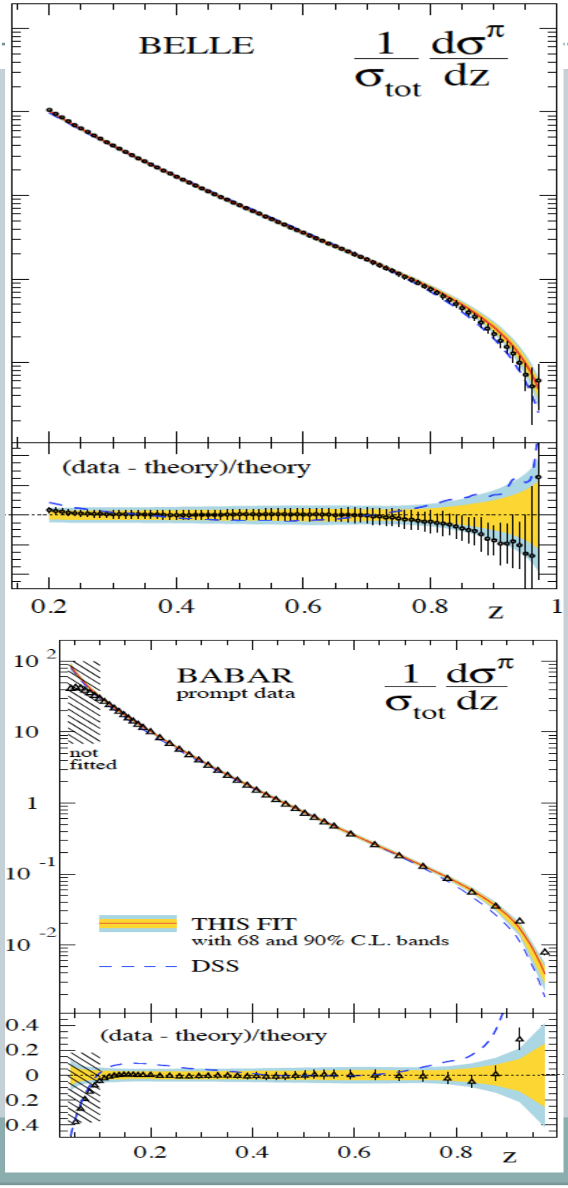
$$\frac{d\sigma_i}{dz} = \frac{1}{L_{tot}} \epsilon^i_{joint}(z)\, \epsilon^i_{ISR/FSR}(z)\, S^{-1}_{zz_m}\, \epsilon^i_{impu}(z_m)\, P^{-1}_{ij} N^{j,raw}(z_m)$$



Phys. Rev. Lett. 111, 062002 (2013)

New DSS(E,H-P) Fit

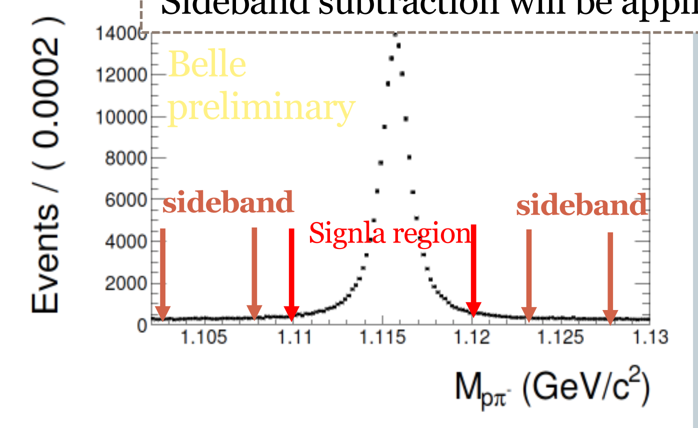
- Good agreement, however, there seems to be a trend away from the fit for the Belle data at high z
- Babar low z data needs resummation
- From DSS:
  - Precise data at high z
  - Some info from scaling violations (Belle vs experiments at M_Z)
  - Some info on flavor due to charge weighting



Data set

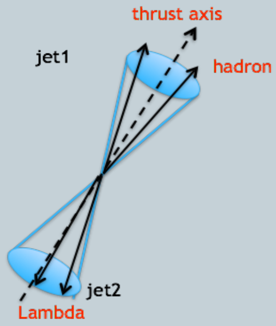
- Data sets: ~792 fb^{-1} at or near $\sqrt{s}$ ~10.58 GeV

Sideband subtraction will be applied



- 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 $\Lambda(\bar{\Lambda})$.

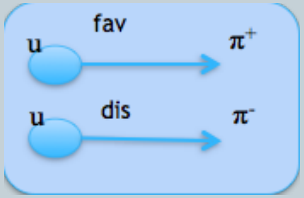
PRL105,202001 (2010)



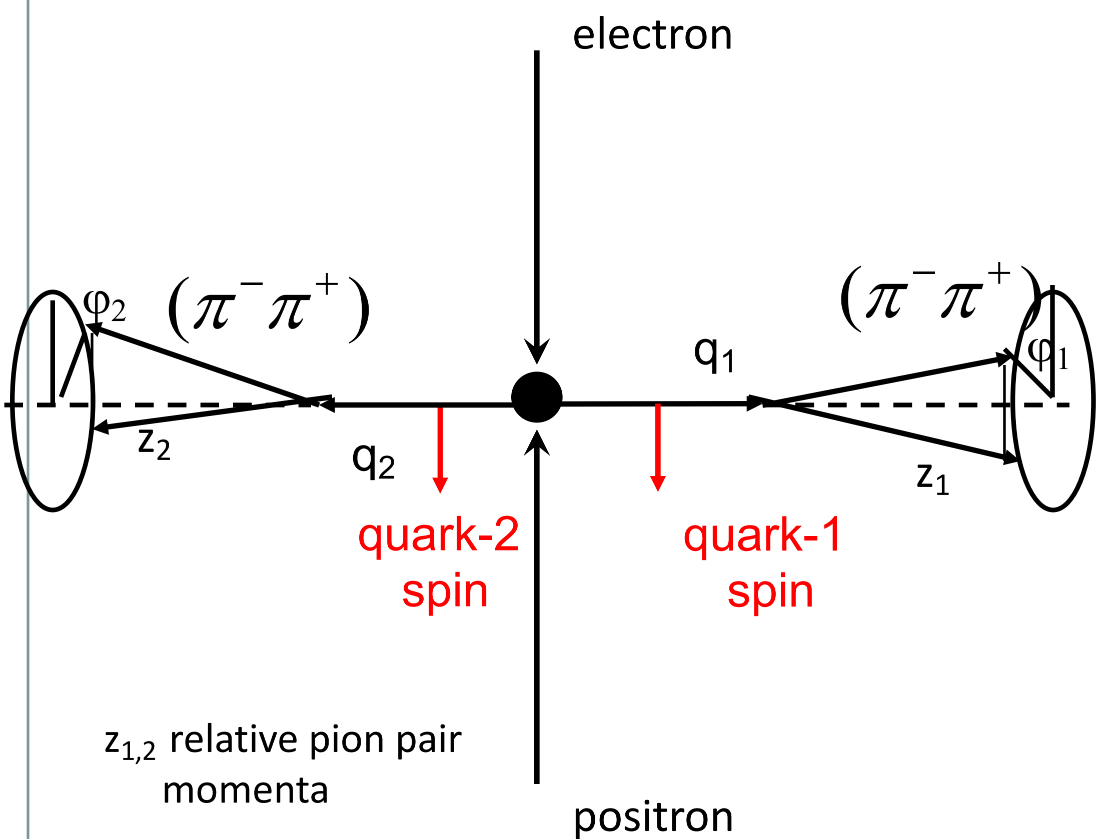
$$T = \mathrm{Max}\left[\frac{\sum_h |\mathbf{P}_h^{CMS} \cdot \hat{\mathbf{T}}|}{\sum_h |\mathbf{P}_h^{CMS}|}\right]$$

flavor tag

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



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!

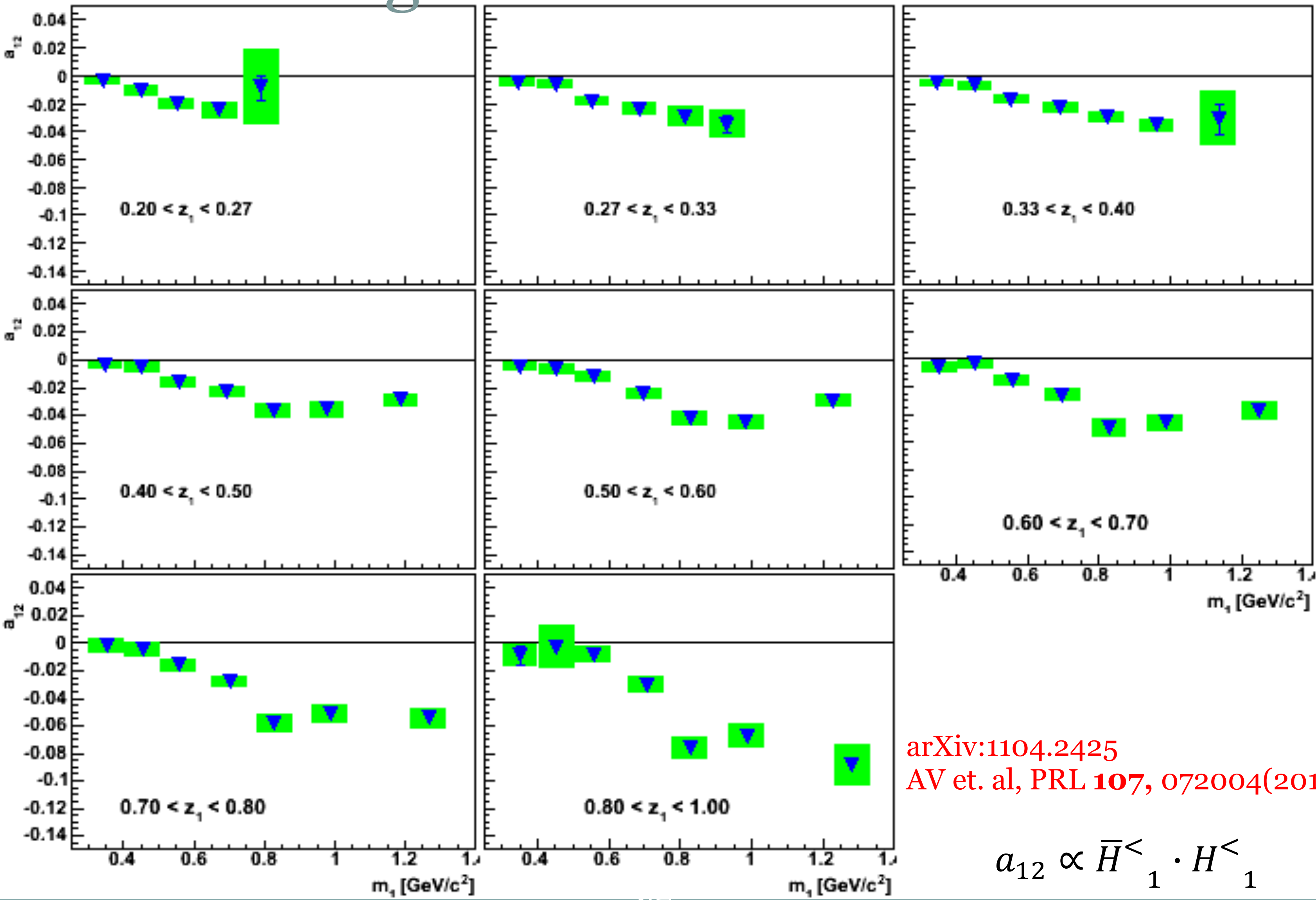
Experimental requirements:

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

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

BELLE

First measurement of Interference Fragmentation Function

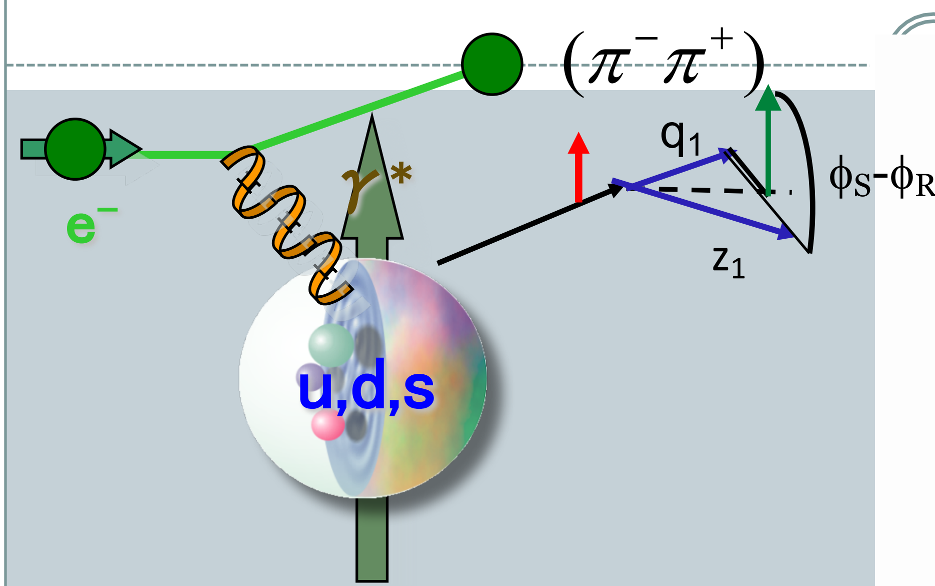


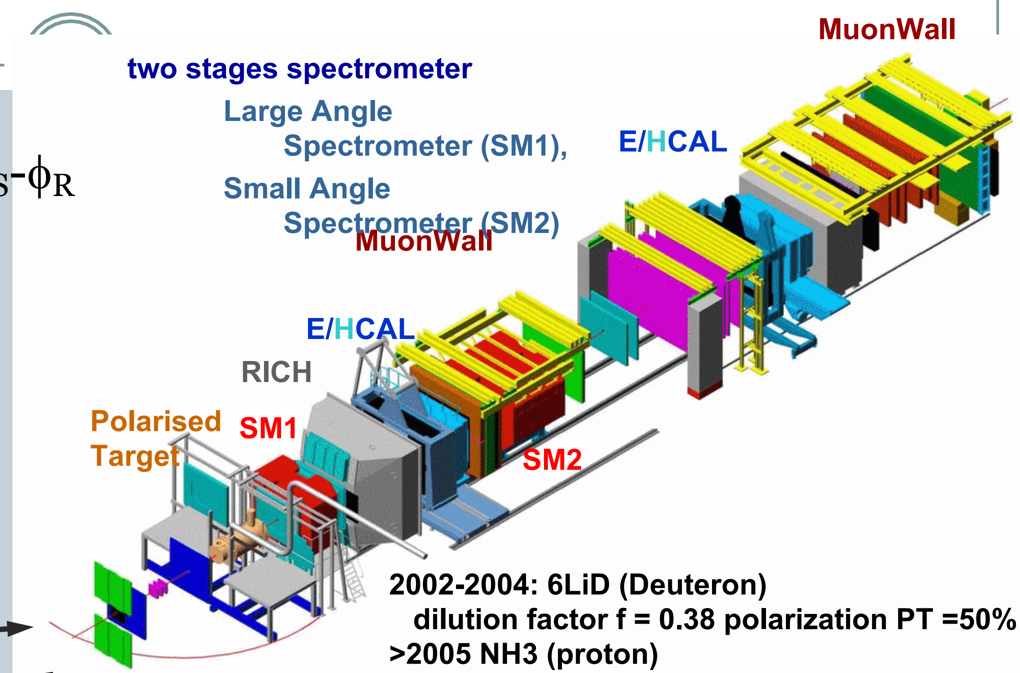
arXiv:1104.2425

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

$$a_{12} \propto \overline{H}^{<}{}_{1} \cdot H^{<}{}_{1}$$

COMPASS 2004 Setup



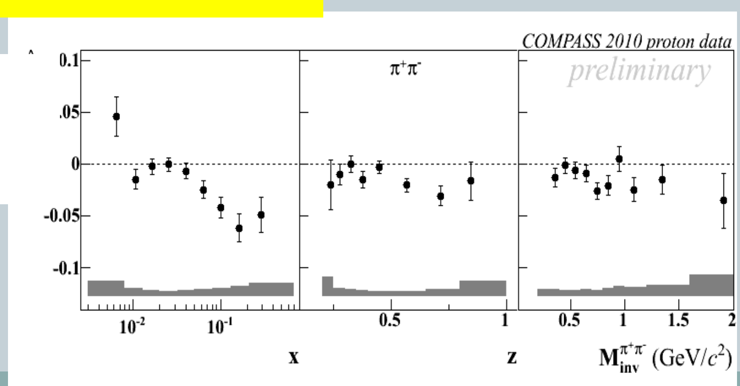


μ
beam

2002-2004: 6LiD (Deuteron)
dilution factor f = 0.38 polarization PT =50%
>2005 NH3 (proton)
3 target cells with opposite polarization,90% polarization, 16% dilution

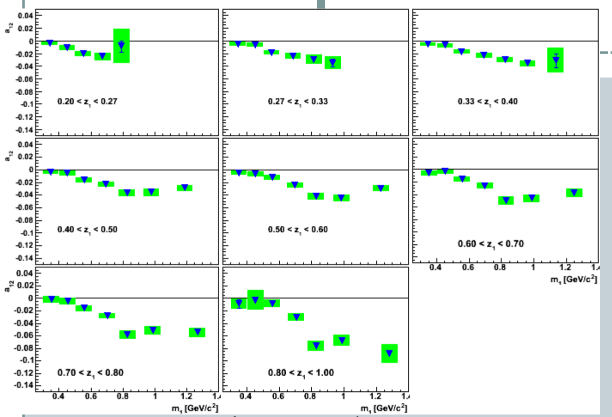
$$\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}(\phi_S-\phi_R) = A_{UT}\sin(\phi_S-\phi_R)$$

$$A_{UT} \propto h_1 \cdot H^{<}{}_1$$



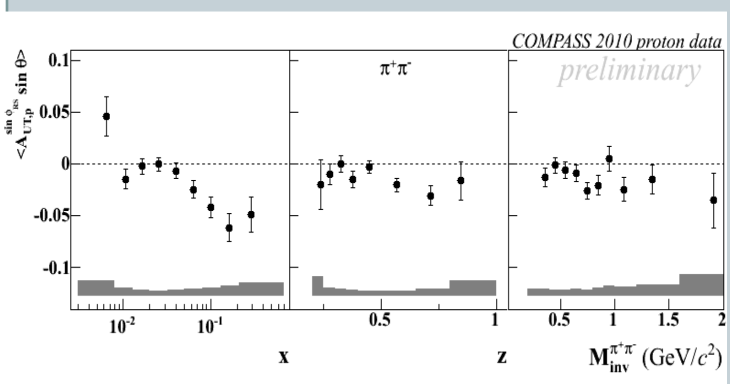
- high energy beam
- Large angular acceptance
- Broad kinematical range

Measurement at Belle leads to first point by point extraction of Transversity



$a_{12} \propto \bar{H}^{<}{}_{1} \cdot H^{<}{}_{1}$

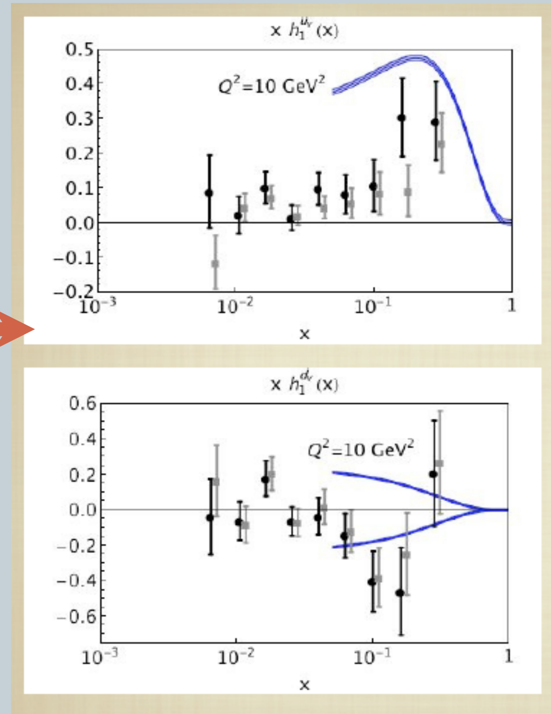
+



$A_{UT} \propto h_1 \cdot H^{<}{}_{1}$

M. Radici at FF workshop, RIKEN, 11/2012

See also: Courtoy: Phys. Rev. Lett. 107:012001,2011



Future Plans at Star/Belle:

Better sensitivity to d transversity

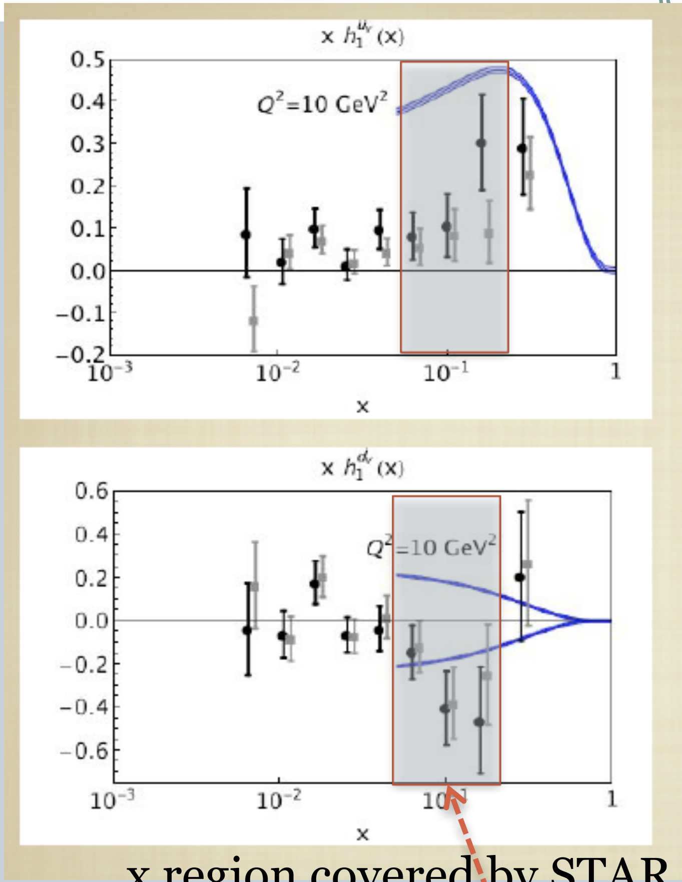
From $\pi^0/\pi^{+/-}$ combinations

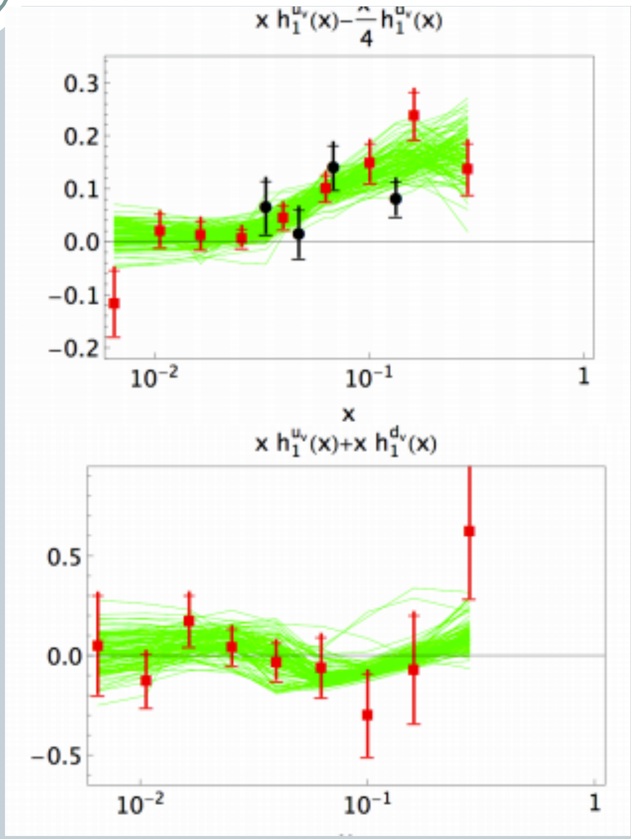
Increase x range

Is Soffer Bound violated?

h(x)<|f(x)+g(x)|/2

Predictions for STAR

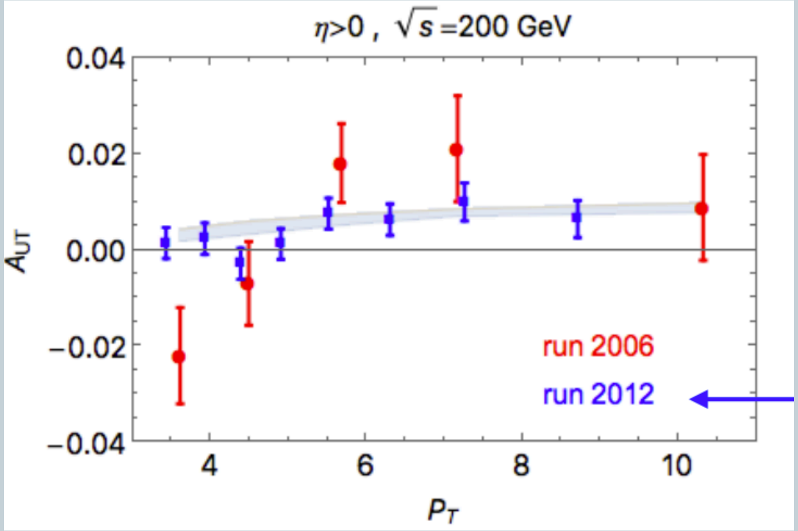




x region covered by STAR

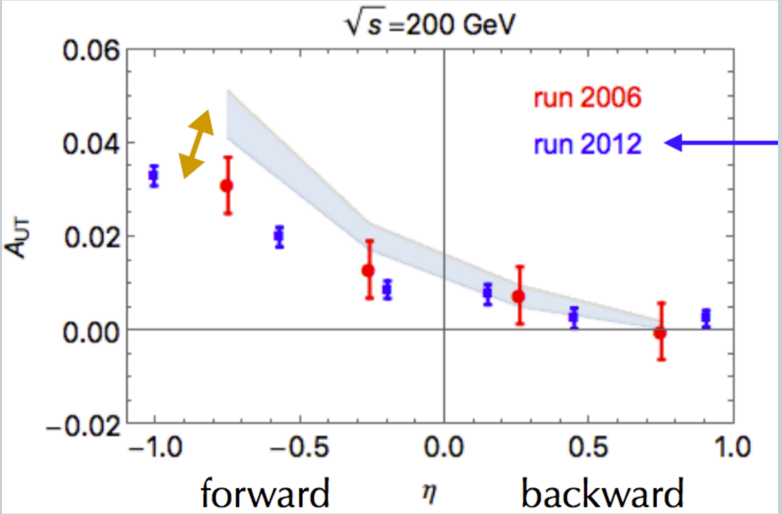
M. Radici at

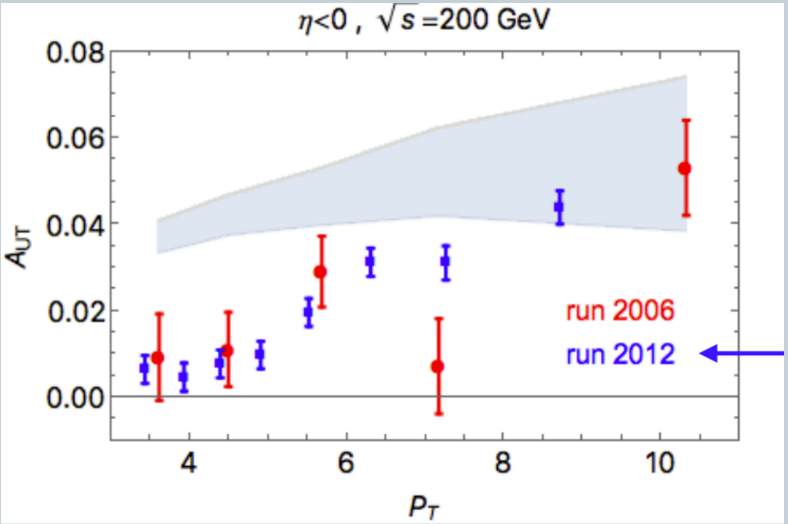
Good Agreement in Backwards Region



- Gluons under control?

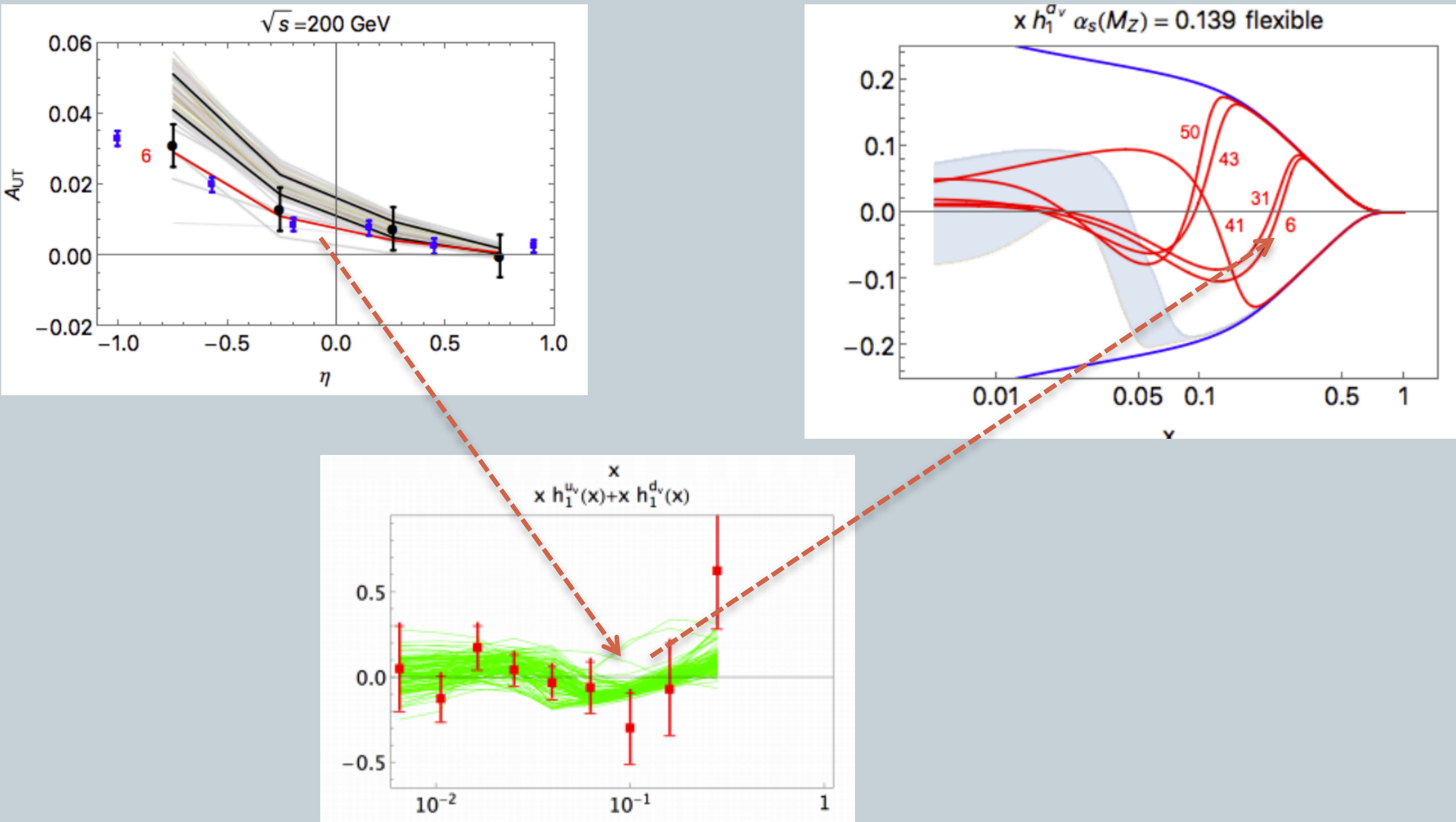
Mismatch at low pT and high η



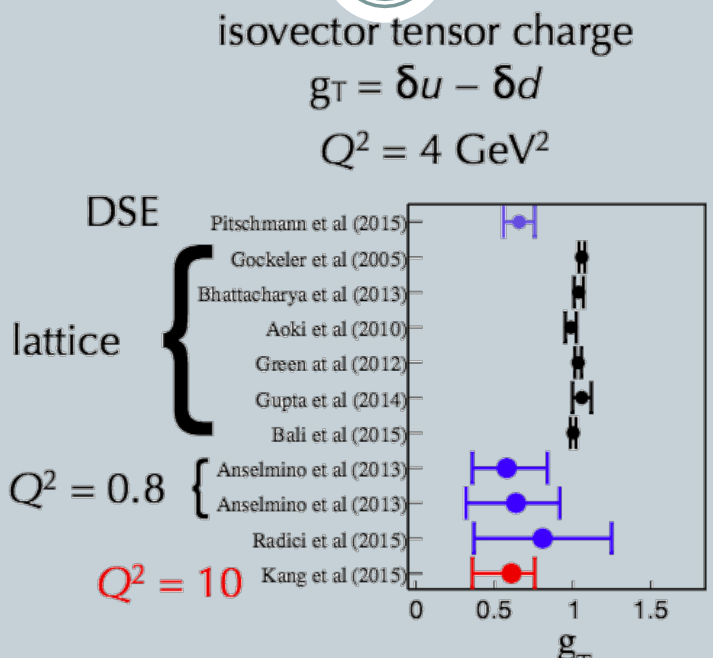


- Theory prediction in this region driven by one Compass datapoint outside the Soffer bound

STAR data prefers "more reasonable" transversity



Tensor Charge



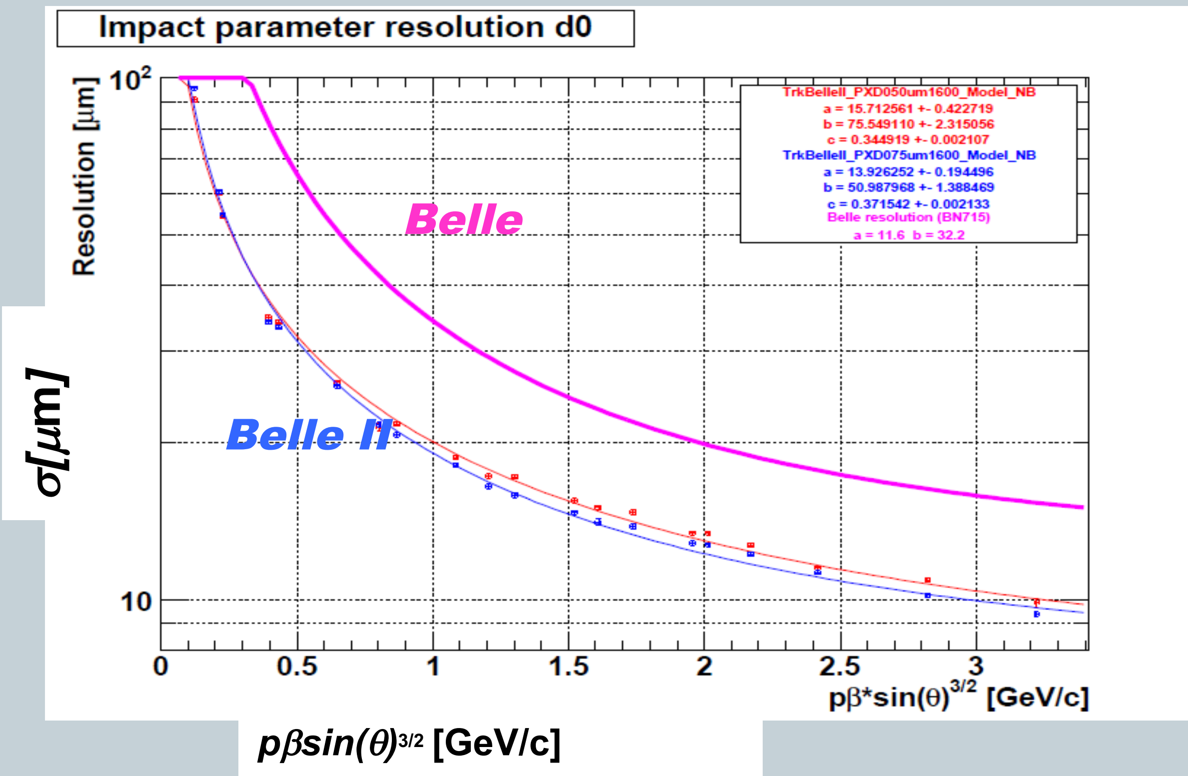
- Still a lot to do to get experimental precision to lattice/model predictions
- STAR data will provide higher precision and Q^2 leverage
- JLAB12 will give high precision at high x
- Belle II will provide comparable precision for fragmentation function measurements

Summary and Outlook

- Precision measurements of the proton's spin structure important step to ab-initio solutions to QCD
- Combining p-p scattering, SIDIS and e+e- data allows to extract protons transversity
- Belle and Belle II data will provide further inside into hadronization, confinement and the structure of the QCD vacuum

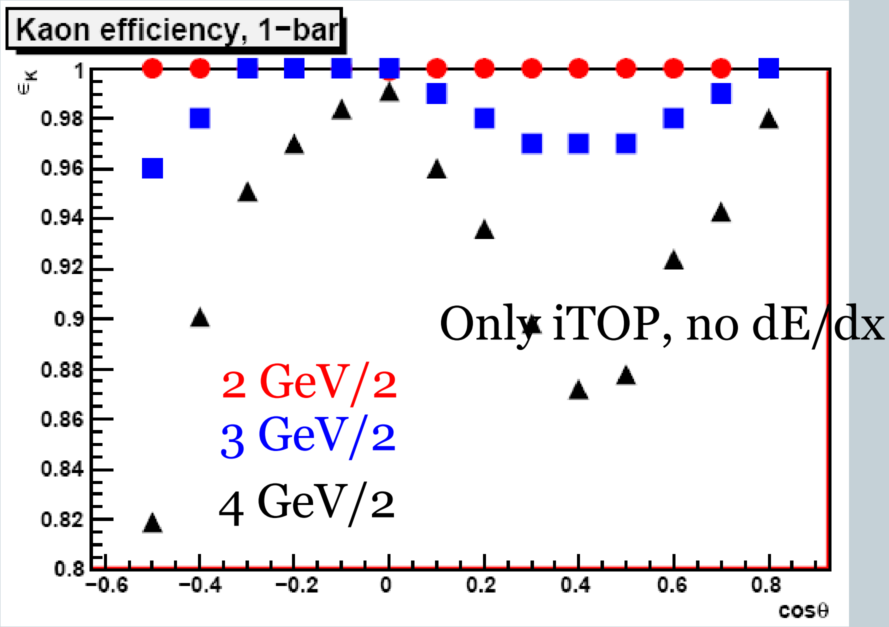
Backup

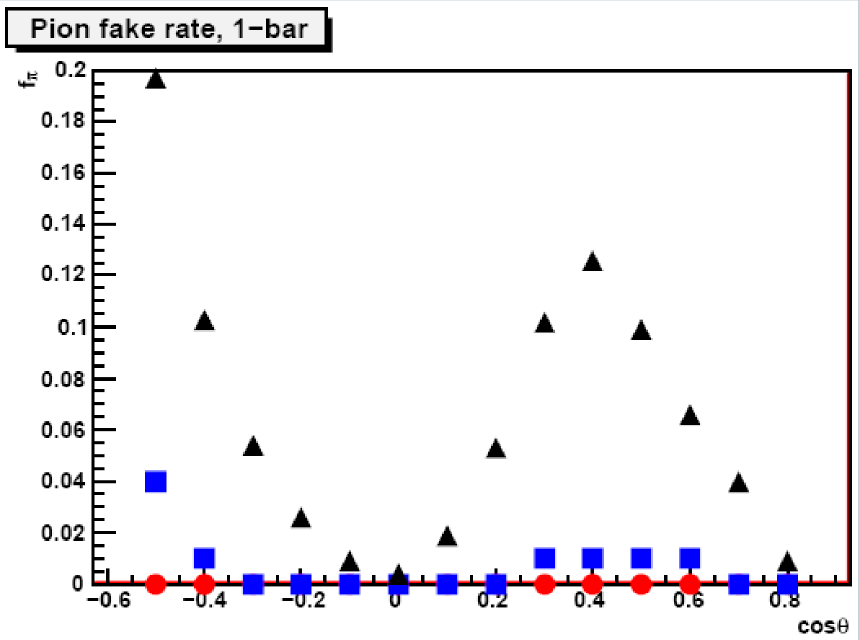
Improve Charm Discrimination with SVD&PXD



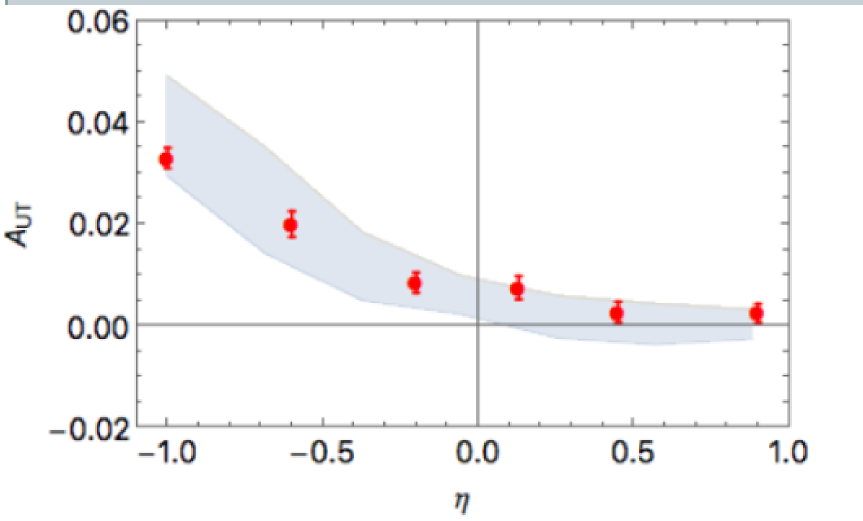
PID improvement with iTOP

- Compare with ~85% efficiency for Belle





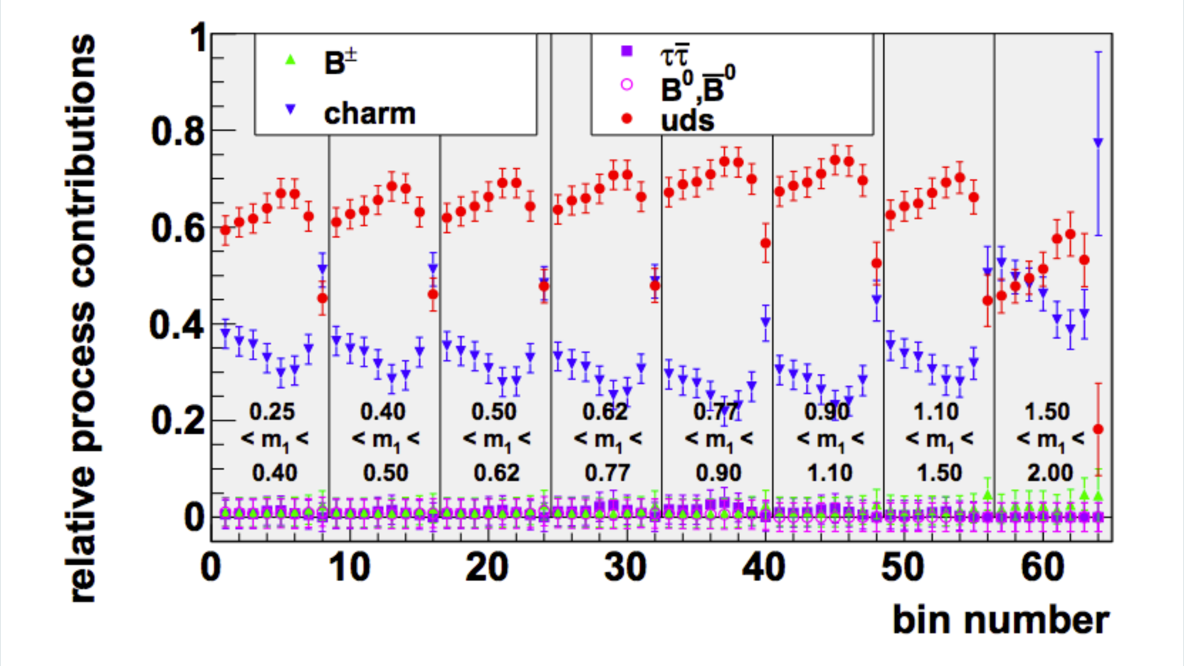
Add more stuff from Marco here…



Comparison of prediction based
on fit to SIDIS and e+e- IFF data
& STAR IFF asymmetry data in p-p

Belle II

- Ueberleitung? Need for charm discrimination etc



Summary

Transversity from di-Hadron SSA

p+p c.m.s. = lab frame

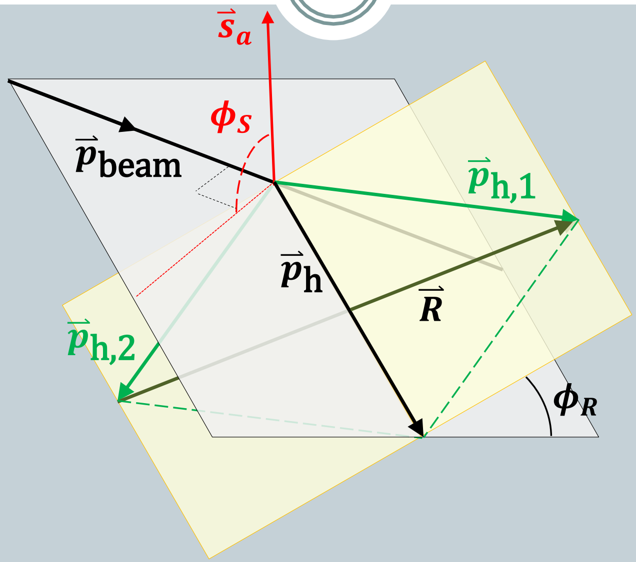
$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation



ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C}\, |\mathbf{S}_{BT}| \sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a\, dx_b}{16\pi z_c} f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat{\sigma}_{ab^\uparrow \to c^\uparrow d}}{d\hat{t}}\, H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

Unpolarized quark distribution
Known from DIS

Transversity
to be extracted

Hard scattering cross section
from pQCD

IFF + Di-hadron FF
measured in e+e at Belle-

Backup

Collins Extraction of Transversity: model dependence from Transverse Momentum Dependences!

$$A_{UT}^{Collins} = \frac{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp h(x,k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z,p_\perp) \sin(\phi_S + \phi + \phi_q^h) \sin(\phi_S + \phi_h)}{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z,p_\perp)}$$

transversity — Collins FF — quark pdf — hadron FF

$k_\perp$ transverse quark momentum in nucleon
$p_\perp$ transverse hadron momentum in fragmentation

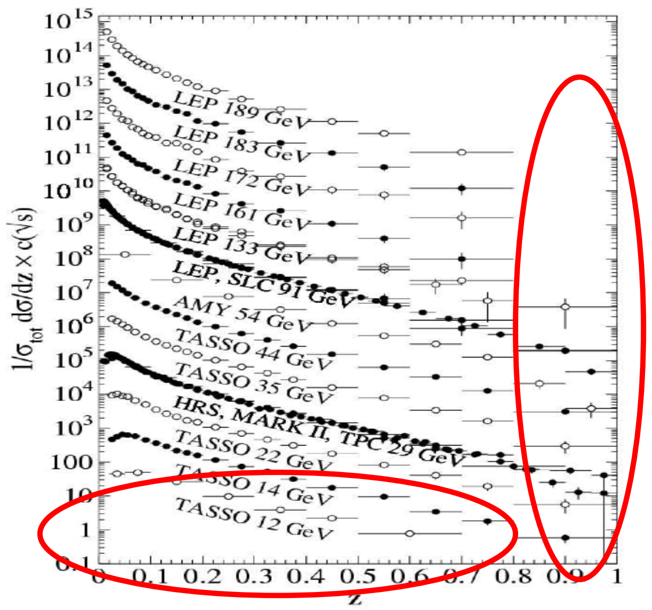
Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk
Phys. Rev. D75:054032,2007

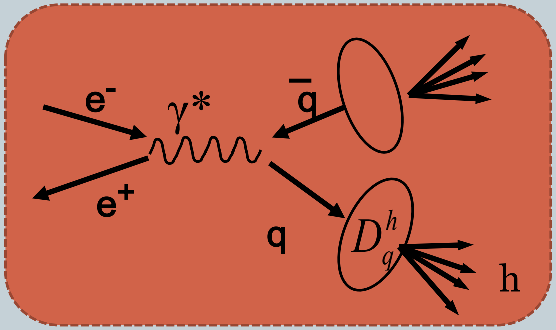
The transverse momentum dependencies are still unknown
Need p_T dependent FFs from Belle to extract transversity and test TMD framework

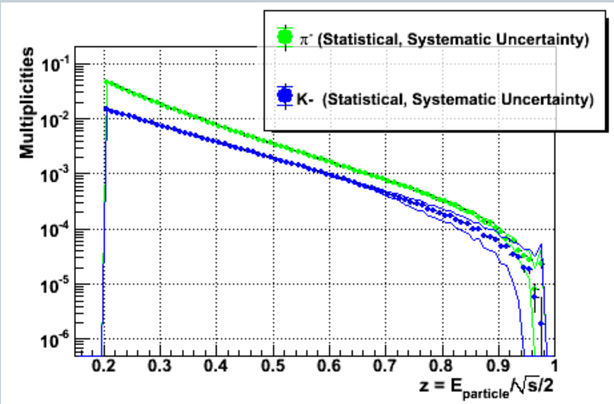
Unpolarized Fragmentation Functions

- Precise knowledge of upol. FFs necessary for virtually all SIDIS measurements

Lack of data at high z, lower CMS





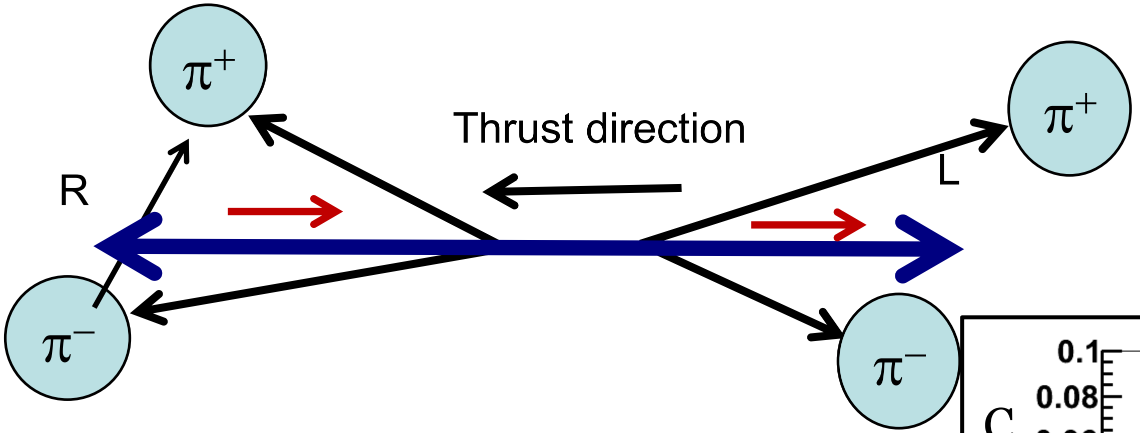


Submitted to PRL
arXiv:1301.6183

- π^0, η fragmentation function under way
- In particular important at RHIC

Handedness Correlations

- Handedness Correlations expected to be zero in factorized approach
- Non-zero asymmetries predicted in factorized approach for azimuthal asymmetries sensitive to $G^{\perp}{}_1$
- Several suggestions how interactions with QCD vacuum can lead to non-zero asymmetries
- SLD: Upper bound from 90k hadronic Z events: 7%

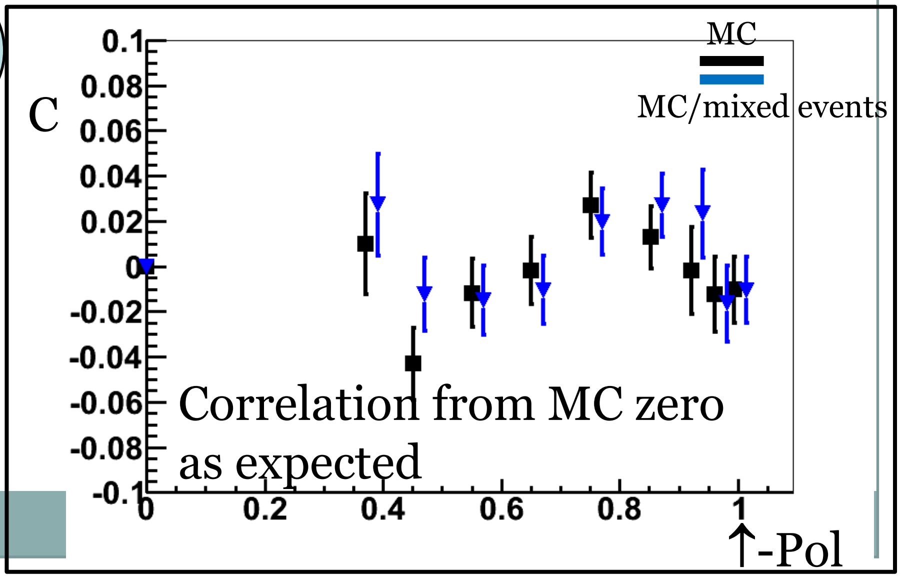


Handedness: $\frac{(\overrightarrow{k_+} \times \overrightarrow{k_-}) \cdot \vec{t}}{|k_+||k_-|} >^{?} 0 \Rightarrow$ L/R

Jet

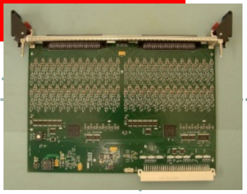
handedness: $\frac{N_R - N_L}{N_R + N_L}$

C: $\frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$



Belle II Detector at SuperKEKB (L x 40)

and IU contributions to Barrel Particle ID

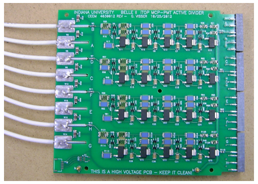


- Barrel PID instrumental for fragmentation function measurements

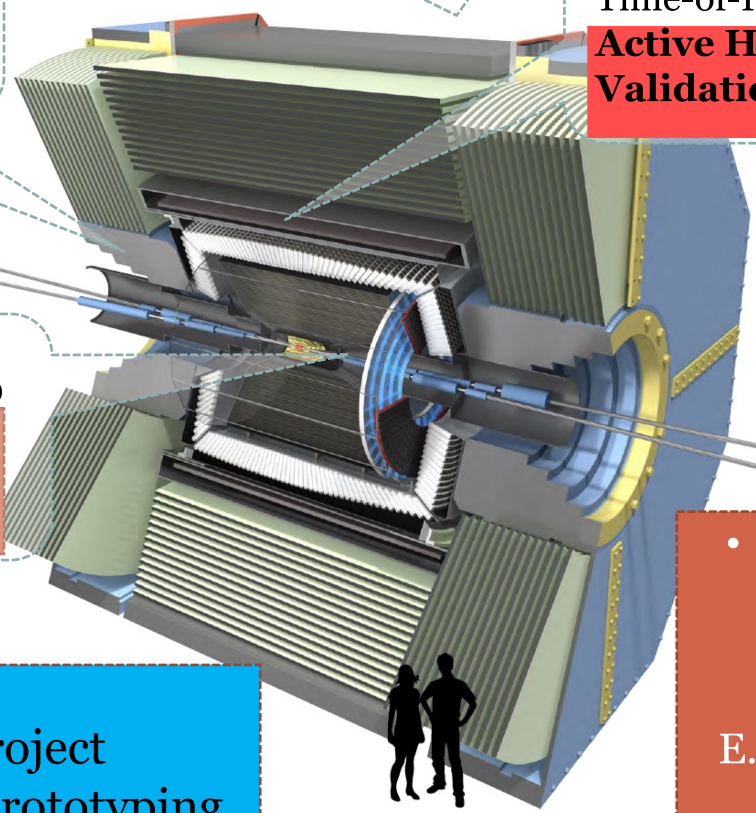
K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)
RPC Front End Electronics, Concentrator boards for barrel and endcap scintillator layers

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

Particle Identification
Time-of-Propagation counter (barrel)
Active HV Divider board for MCP-PMT
Validation of FPGA code of iTOP



e- (7GeV)



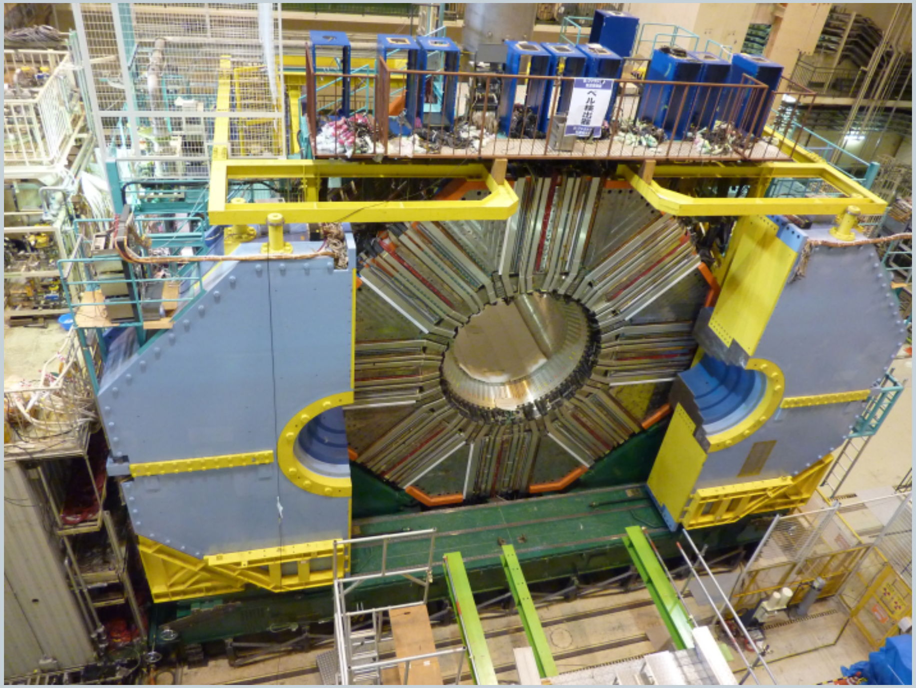
Vertex Detector
2 layers DEPFET + 4 layers DSSD
Vertex resolution improved by order of magnitude: Separate charm/uds

e+ (4GeV)

- RPC test stand at IU to test electronics: E. Zarndt, S. Arnold

$90k + $700k Grant
From DOE US Belle II project
+~$100k from NSF for prototyping

Belle II Status



Outlook over Next 5 Years

- Analysis:
  - e: existing dataset
    - Extraction of Di-hadron FF from Belle with π-K final states
    - Di-hadron correlations at Belle to test TMD framework and probe local parity violating effects
    - Current Student Hairong Li: π^0/η unpolarized and Collins FF
  - dataset:
    - Explore charm rejection for π^+/π^- IFF
  - Jefferson Lab
    - Transverse spin physics at SoLID, di-hadron correlations at CLAS
- Instrumentation:
  - Jefferson Lab
    - Participation in detector upgrades (experience with GEM detector and building RPCs),
    - Investigating Transversely polarized target option at CLAS
  - Belle II
    - Readout electronics. Currently PI on ~$90k grant, MoU for ~$700k dependent on US-Congress

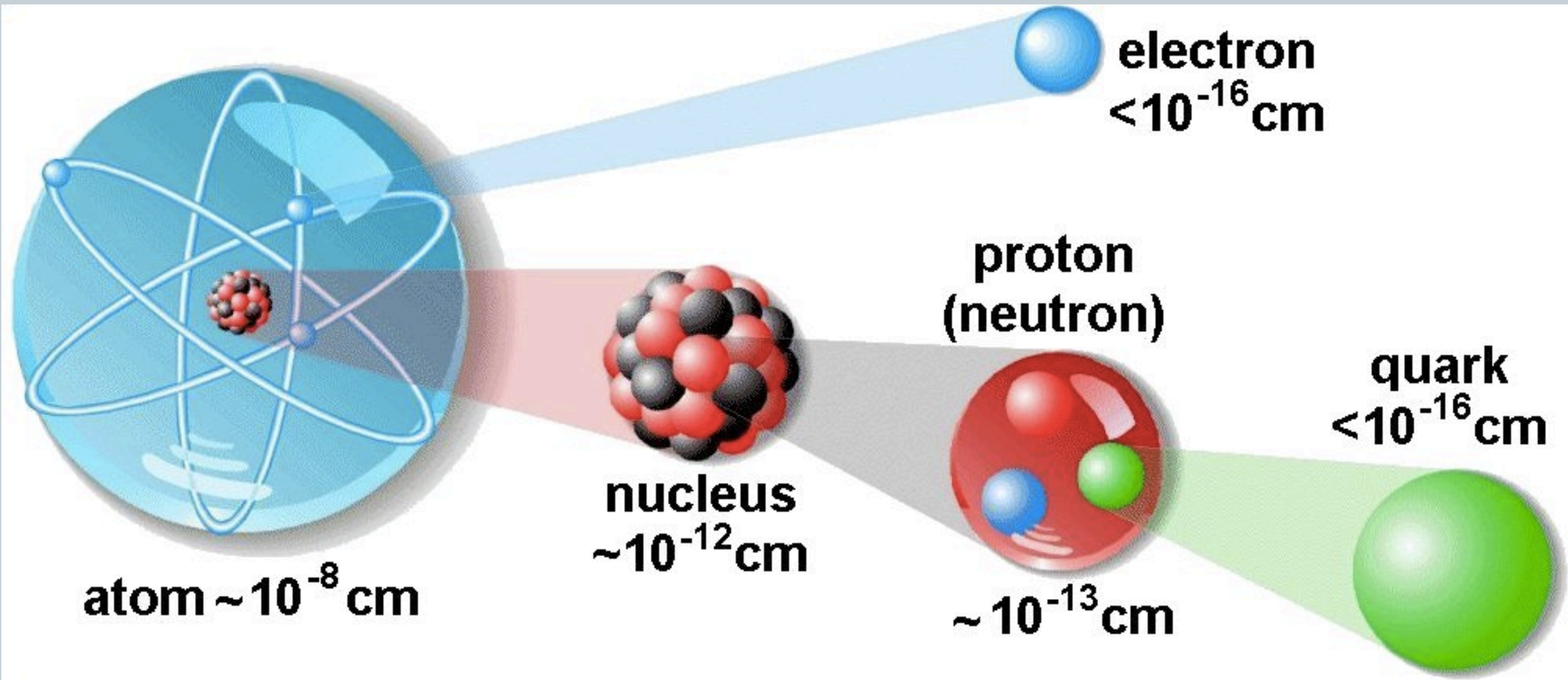
Long Term Outlook

- Fragmentation Extraction at Belle II
  - Transverse spin dependent FFs with Kaons in final state
  - p_T dependent FFs
  - Reduce systematic effects by removing charm
- EIC?

Summary

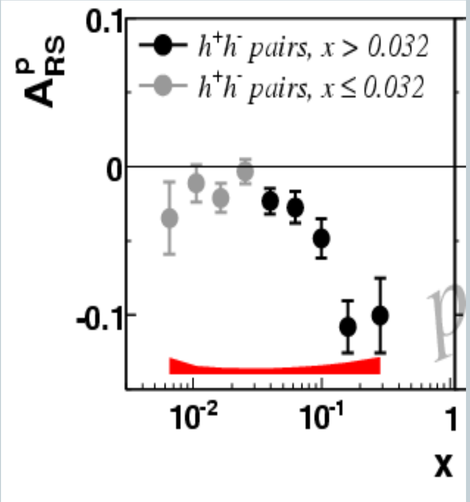
- Breakthrough Measurements of Proton Structure underway: How does QCD work inside the Nucleon?
- Di-hadron Correlations best way to access transversity in p+p, SIDIS
- Needed to describe spin structure of the proton, derive tensor charge
- Corresponding Fragmentation Functions measured at Belle

- Outlook
  - CLAS, SoLID @JLab: Transversity measurements on helium3, proton, high x, p_T dependence, wide kinematic range
  - Di-hadron correlations of π-K to access higher twist distribution functions
  - TMD x-sections
  - Belle II: Continuation of FF measurements with improved Kaon ID and vertex reconstruction
  - Test TMD framework
  - Probe QCD vacuum polarization
  - Precision measurements at Belle (II) crucial for success of Jlab program

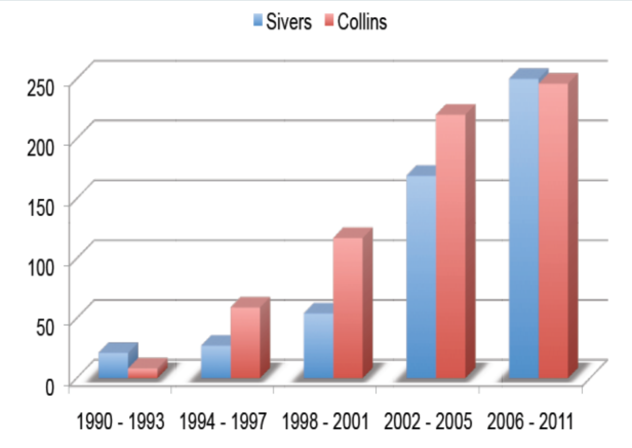

electron
<10-16cm
proton
(neutron)
quark
<10-16cm
nucleus
~10-12cm
atom ~ 10-8 cm
~ 10-13cm

Di-Hadron correlations allow model independent extraction of transversity

- Ab-initio contact to the tensor charge
- Transverse momentum is integrated
  - Collinear factorization
    - No assumption about k_t in evolution
    - evolution known, collinear scheme can be used
    - Universal function: directly applicable to semi-inclusive DIS and pp
    - No ambiguity due to Sudakov suppression



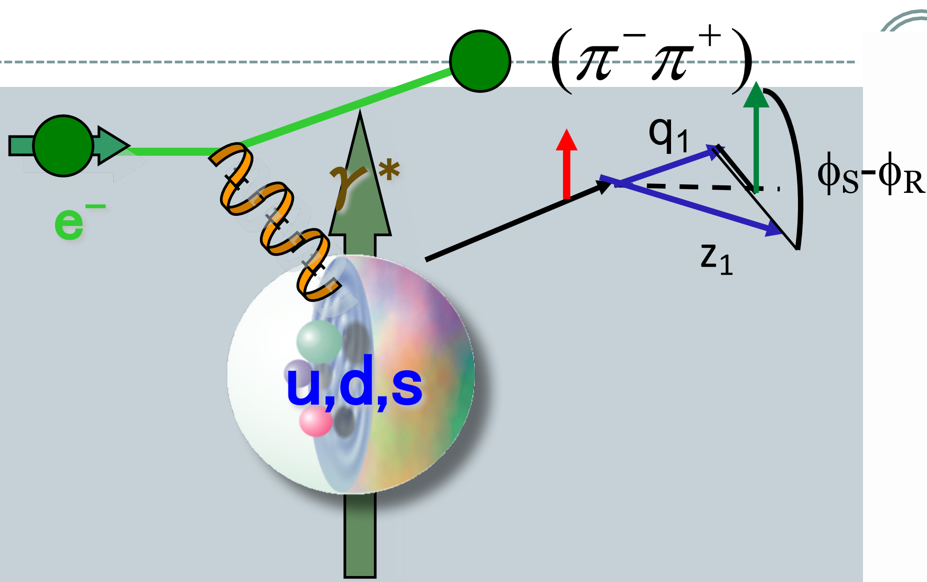
- SIDIS experiment show that the effect is large
- Interest in transverse spin physics in the theoretical community is growing rapidly

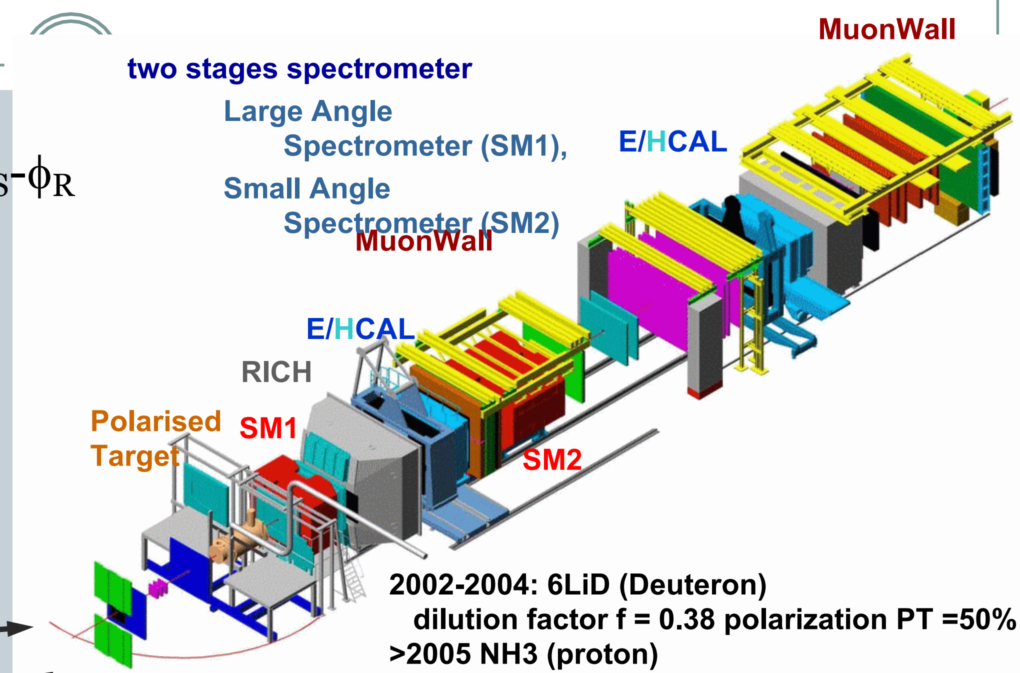


In p+p:

- No jet reconstruction necessary, better systematics: "Easier" measurement
- No u-quark dominance

COMPASS 2004 Setup

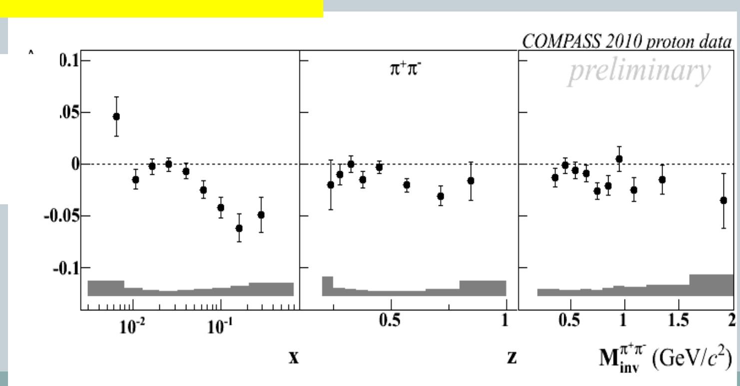




2002-2004: 6LiD (Deuteron)
dilution factor f = 0.38 polarization PT =50%
>2005 NH3 (proton)
3 target cells with opposite polarization,90% polarization, 16% dilution

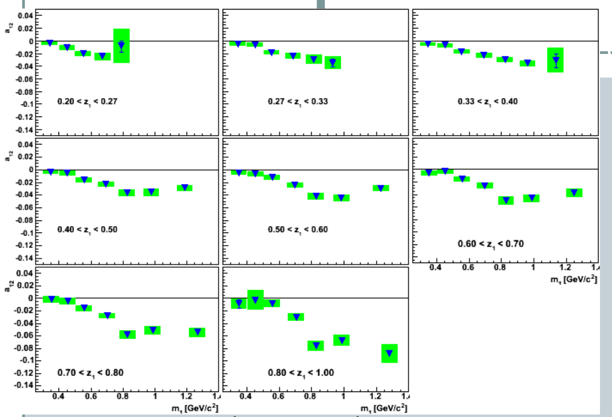
$$\frac{\sigma^\uparrow-\sigma^\downarrow}{\sigma^\uparrow+\sigma^\downarrow}(\phi_S-\phi_R) = A_{UT}\sin(\phi_S-\phi_R)$$

$$A_{UT} \propto h_1 \cdot H^{<}{}_1$$



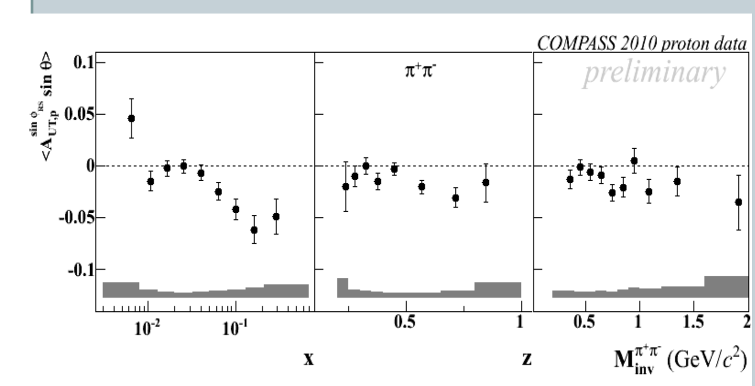
- high energy beam
- Large angular acceptance
- Broad kinematical range

Measurement at Belle leads to first point by point extraction of Transversity



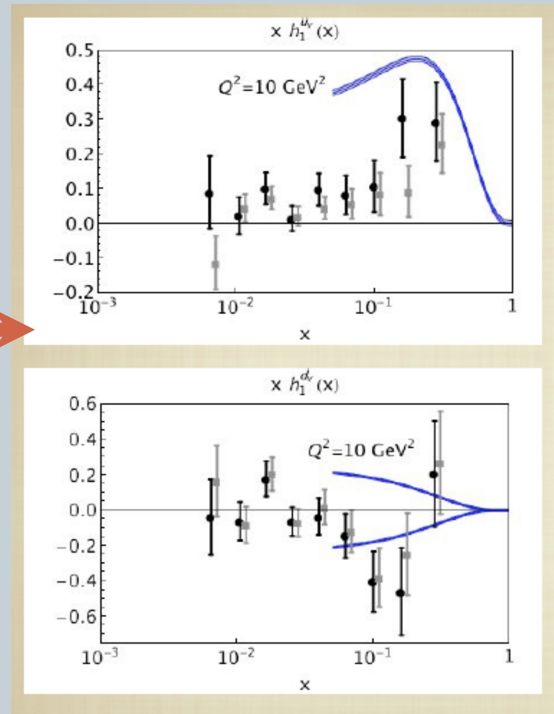
$a_{12} \propto \bar{H}^{<}{}_{1} \cdot H^{<}{}_{1}$

+



$A_{UT} \propto h_1 \cdot H^{<}{}_{1}$

M. Radici at FF workshop, RIKEN, 11/2012
See also: Courtoy: Phys. Rev. Lett. 107:012001,2011



Future Plans at Star/Belle:

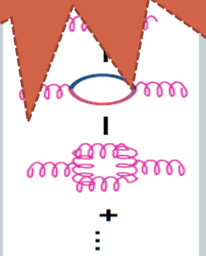
Better sensitivity to d transversity
From $\pi^0/\pi^{+/-}$ combinations

Increase x range

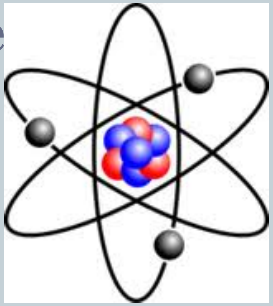
Is Soffer Bound violated?
h(x)<|f(x)+g(x)|/2

Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

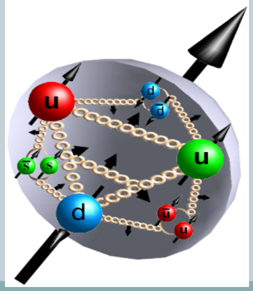
Millenium Prize



- QCD successful in describing high energy reactions, Asymptotic freedom, Nobel 2004
- **BUT** No consistent description of hadronic sector
  - →No consistent description of fundamental bound state of the theory
  - QCD binding energy : most of the visible mass in the universe
  - Spin is fundamental Quantum Number: What role does it play? Use transverse spin as precision probe.



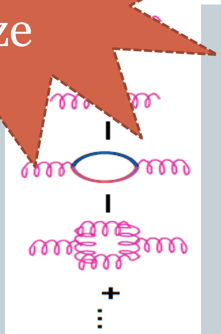
x60,000

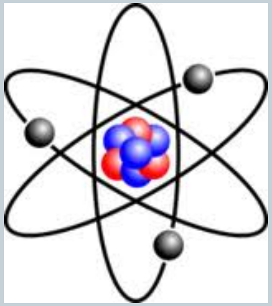


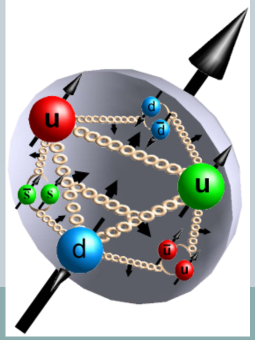
Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

Millenium Prize

- QCD successful in describing high energy reactions
- **BUT** No consistent description of hadronic sector
  - →No consistent description of fundamental bound state of the theory : proton
  - QCD binding energy : most of the visible energy in the universe
  - Spin is fundamental Quantum Number: What role does it play? Use transverse spin as precision probe
- Compare to QED:
  - Bound state: QED: atom
  - Stringent tests of QED from study of spin structure of hydrogen
    - Lamb shift (Nobel prize 1955)
  - →Atomic physics, QCD?

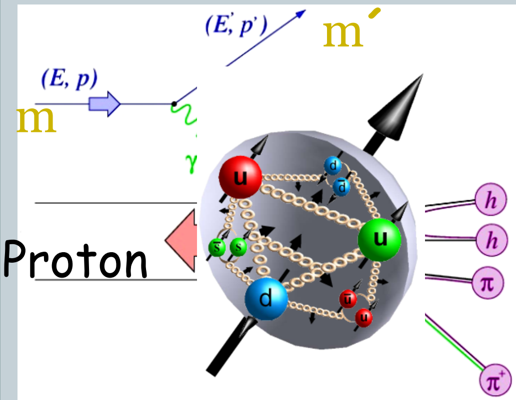






QCD Factorization Theorem needed to Access Nucleon Structure

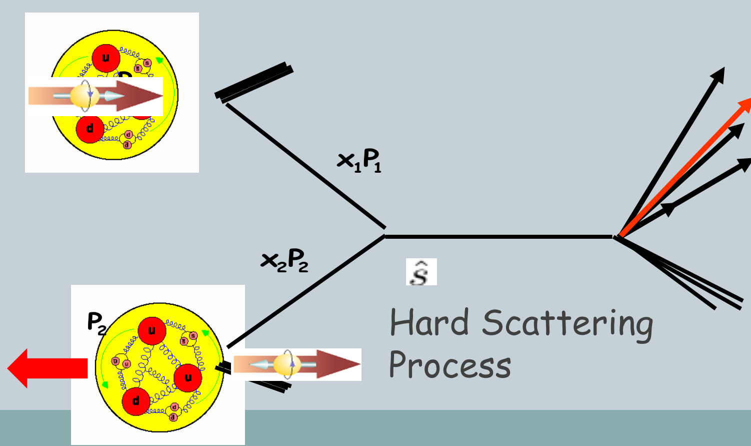
(semi) Inclusive polarized deep inelastic scattering (DIS)



F time sigma times FF

Describes probability to find a quark
In the nucleon with a specific polarization state

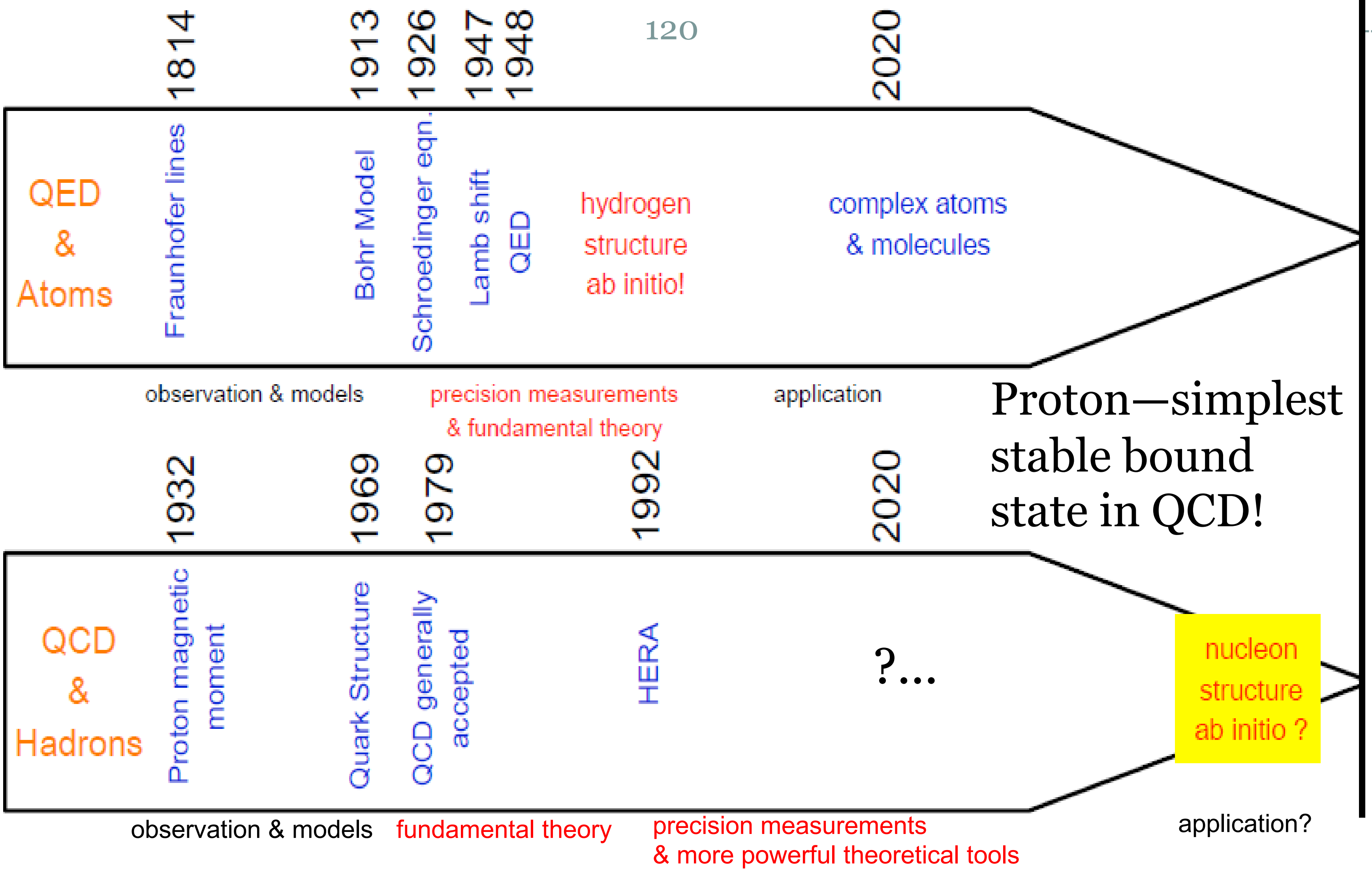
polarized pp scattering



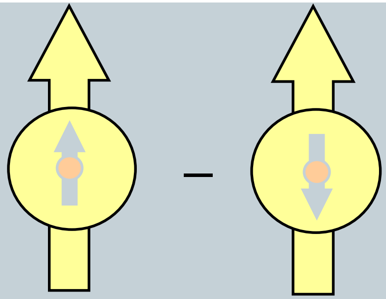
Hard x section

FF

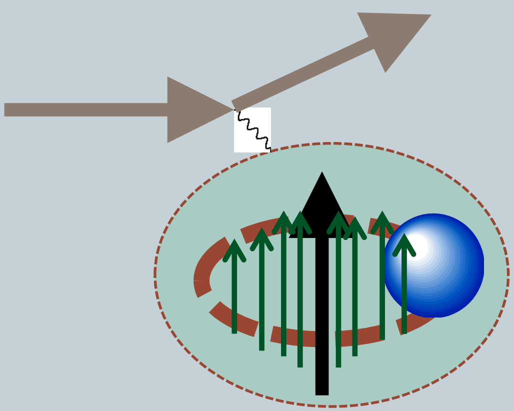
The proton as a QCD "laboratory"

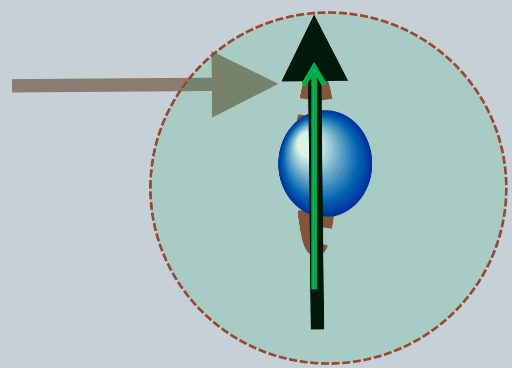


Transversity:

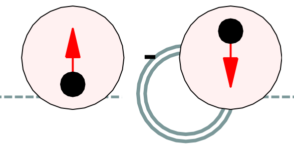
Why is  so hard to measure?

- Naïve picture: leptonic probe too ‘fast’ to be sensitive to transverse polarization

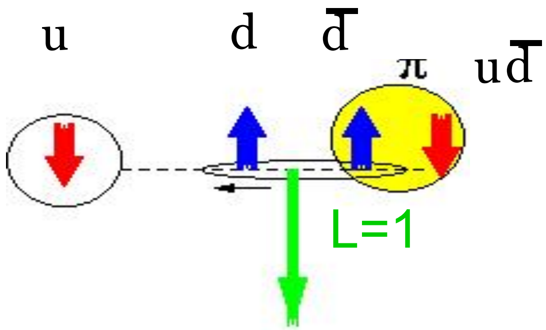




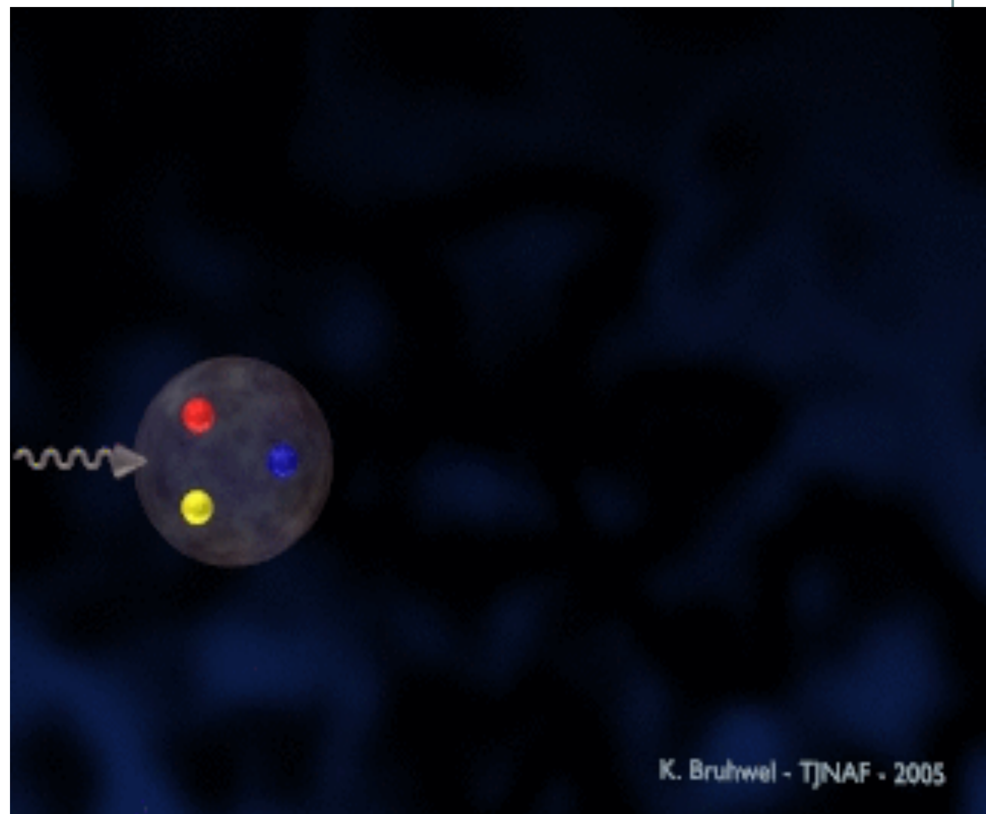
Mechanisms for SSA

Collins Fragmentation $H_1^\perp =$ 

fragmentation of transversely polarized quarks into unpolarized hadrons



(favored)



Orbital momentum generated in string breaking and pair creation produces left-right asymmetry from transversely polarized quark fragmentation (Artru-93)

- L/R SSA generated in fragmentation
- Unfavored SSA with opposite sign
- No effect in target fragmenation

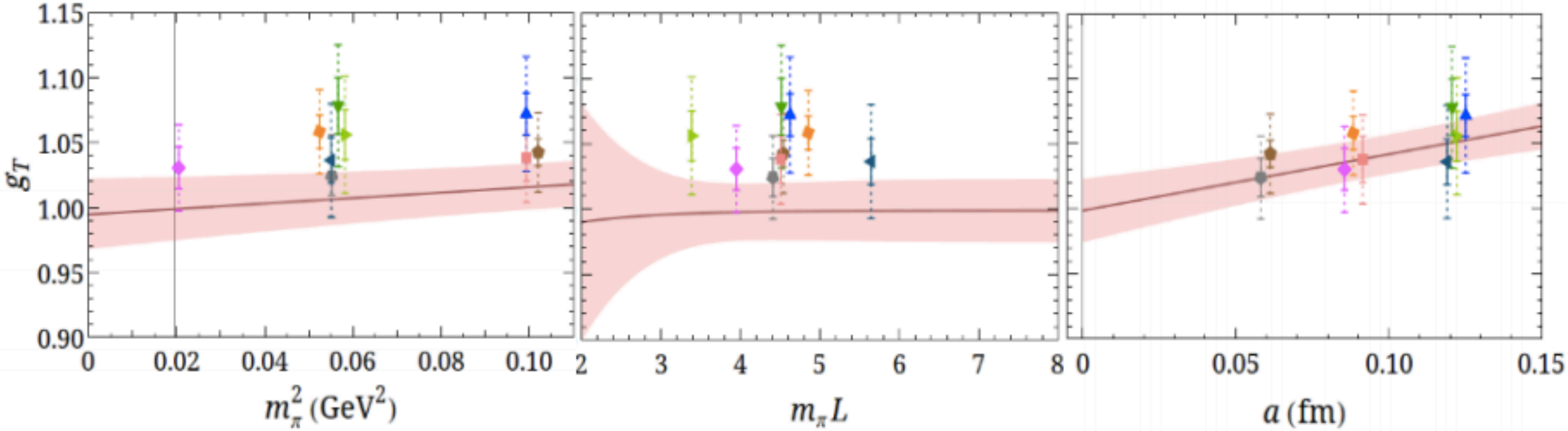
§ g_T: zeroth moment of transversity $\Gamma = \sigma_{\mu\nu}$

§ A state-of-the art calculation (PNDME)

$$g_T = \int_{-1}^{1} dx\, \delta q(x)$$

- Extrapolate to the physical limit

$$g_T(a, m_\pi, L) = c_1 + c_2 m_\pi^2 + c_3 a + c_4 e^{-m_\pi L}$$



First extrapolation to the physical limit
of a nucleon matrix element!