Jets in e^+e^- (TMD FFs in jets at the B-factories)

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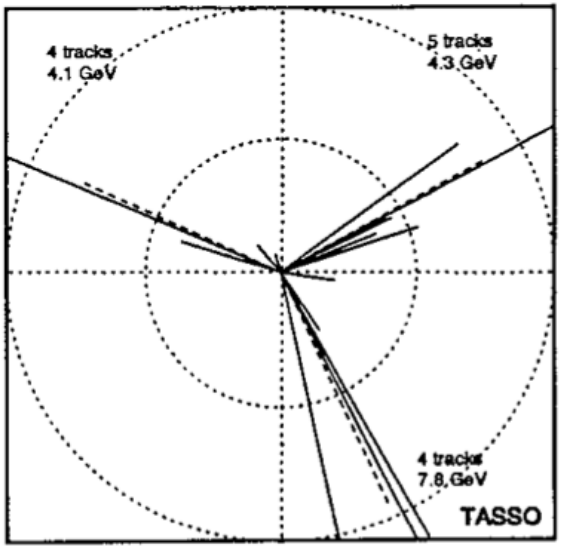
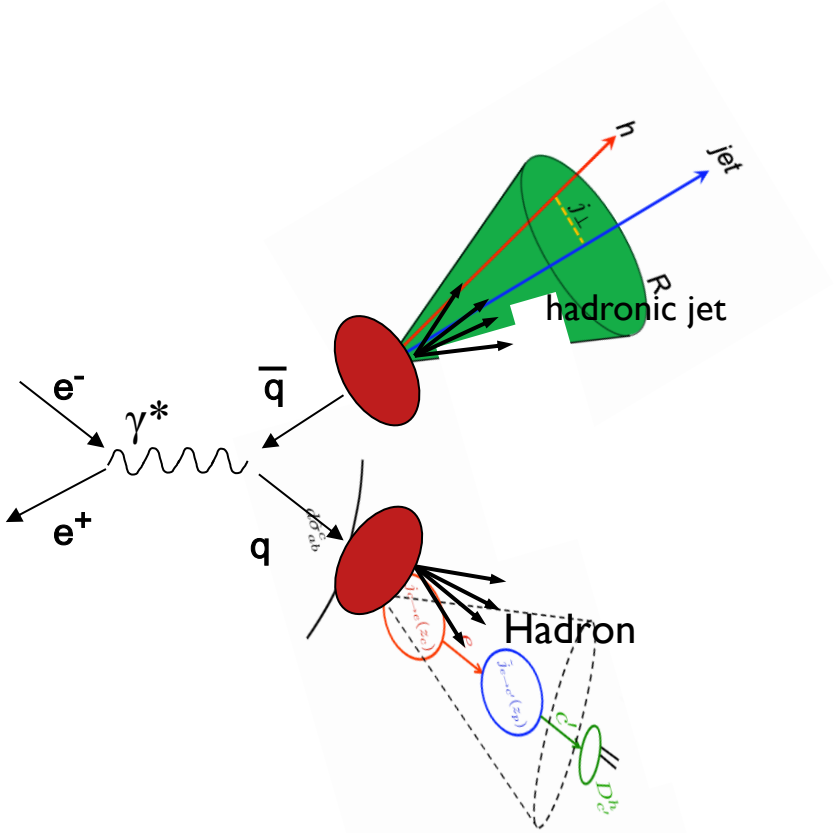
Long history of jet/hadronization studies in e^+e^- at DESY, SLAC, KEK, CERN

- Gluon discovery at TASSO, PLUTO, MARK-J, JADE at DESY
- Verification of LUND string model of fragmentation looking at activity between quarks and gluons
- α_S determination…
- Gluon vs quark jets…



Three jet event at TASSO

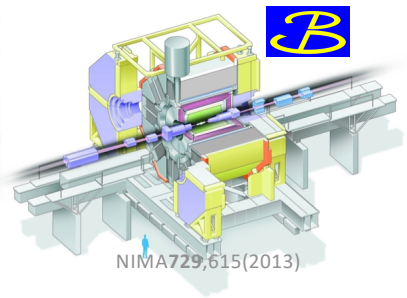
More recently: Interest in determining TMD FFs from Hadrons in Jets



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

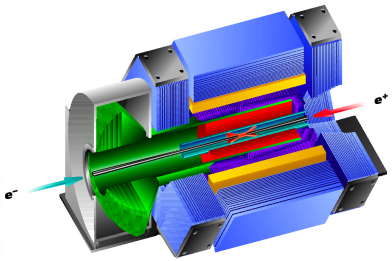
B-factories provide the necessary statistics…

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

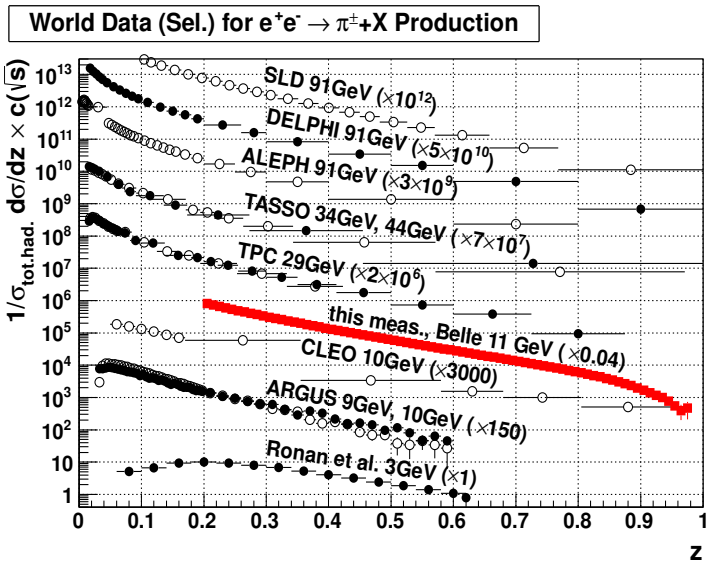


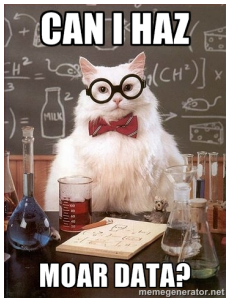
NIMA729,615(2013)

NIMA479,117(2002) BABAR



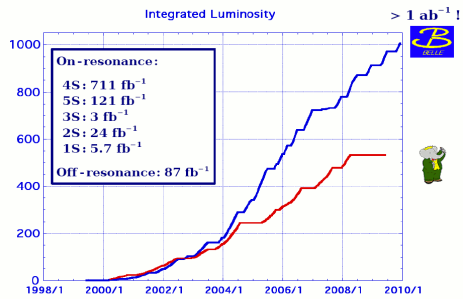
•Asymmetric-energy e^+e^- collider
• $\sqrt{s} \sim 10.6$ GeV ($\Upsilon(4S)$)
• $\beta\gamma=0.65$
• $L \sim 500$ fb^{-1}



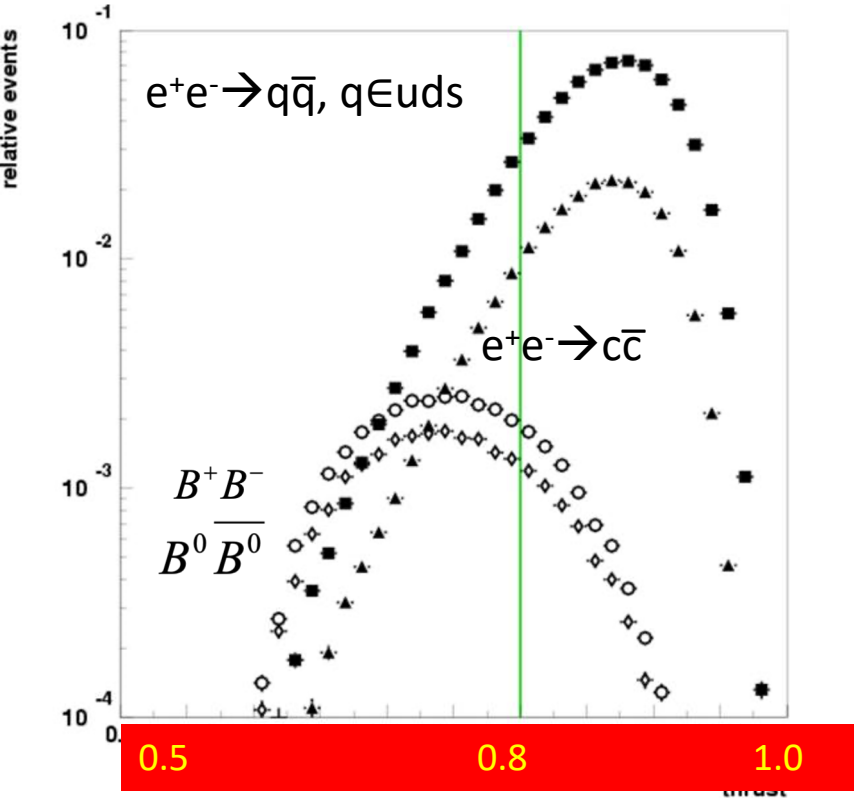


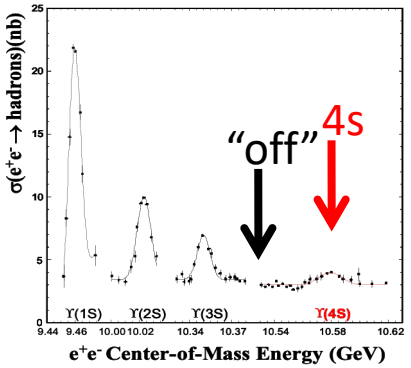
- Dominated by B factories
- Limited lever arm in $\sqrt{s}$ in particular at high z
- Precision data includes charged single hadrons π, K, p, D, Λ, charmed baryons…

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



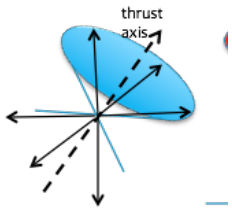
Lots of data off resonance, easy to remove resonance background



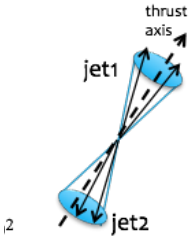


- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under Υ (4S) resonance
- ~100 fb^{-1} ➔ ~1000 fb^{-1}

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



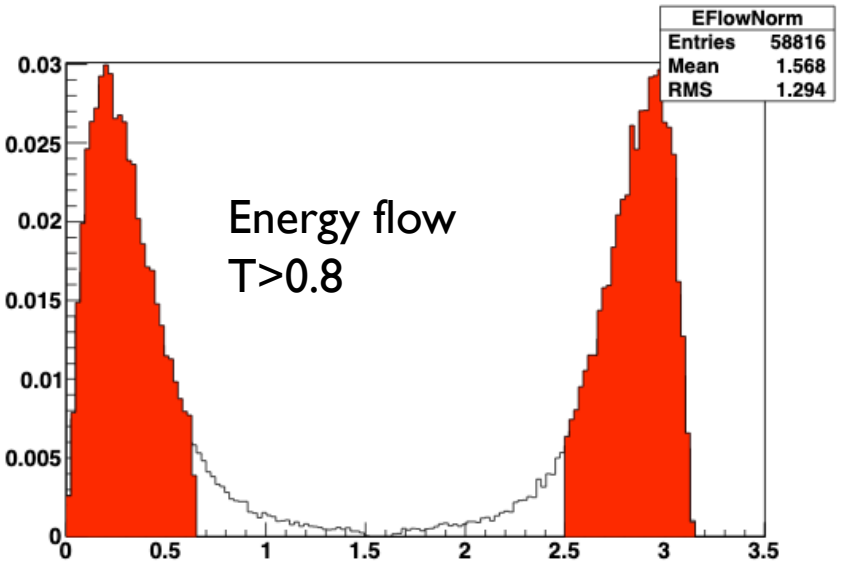
T~0.5

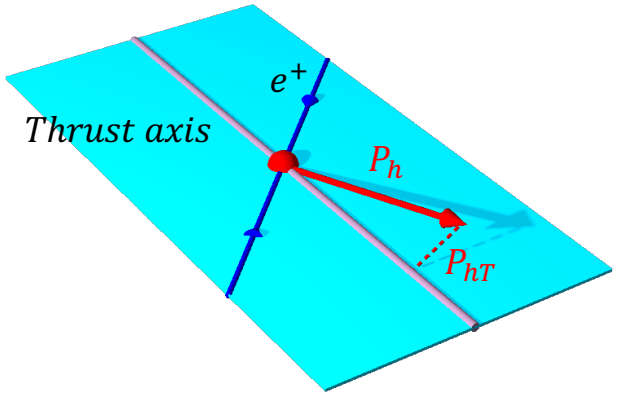


T~1

Use thrust as proxy to $q\bar{q}$ axis

- No phase space for >2 jet events
- **Transverse momentum measured with respect to thrust axis**



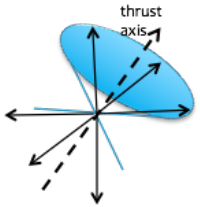


$$T = \sum_i \frac{|\mathbf{P} \cdot \hat{\mathbf{n}}|}{|P|}$$

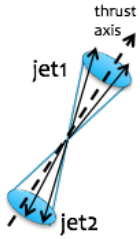
thrust axis $\equiv \hat{\mathbf{n}}$

$0.5 \leq T \leq 1$

θ_{CMS}



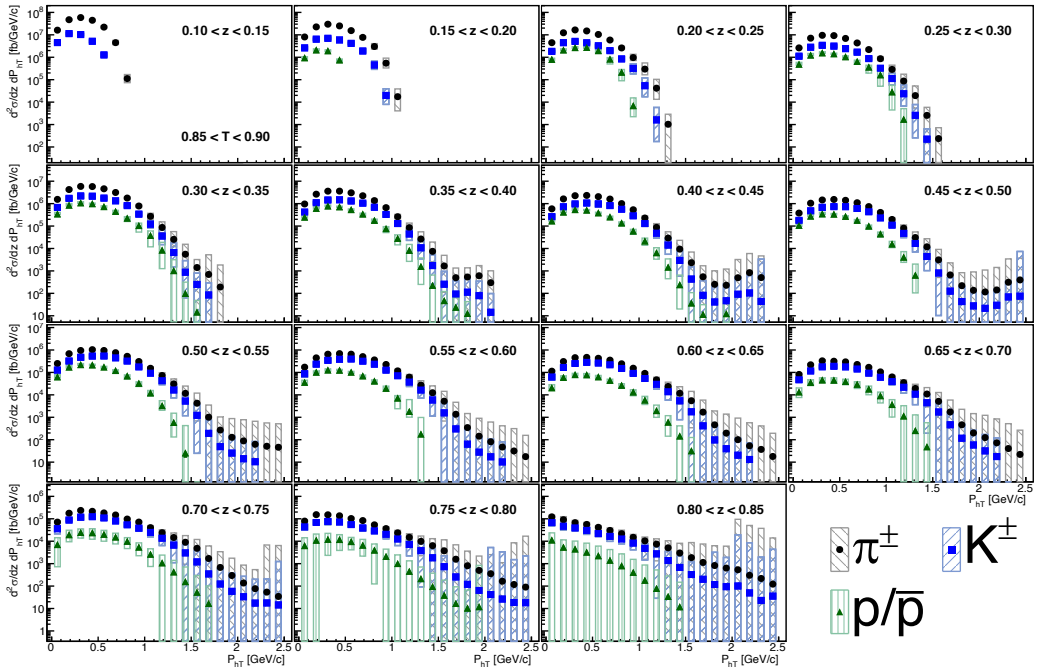
T~0.5



T~1

Transverse momentum distributions

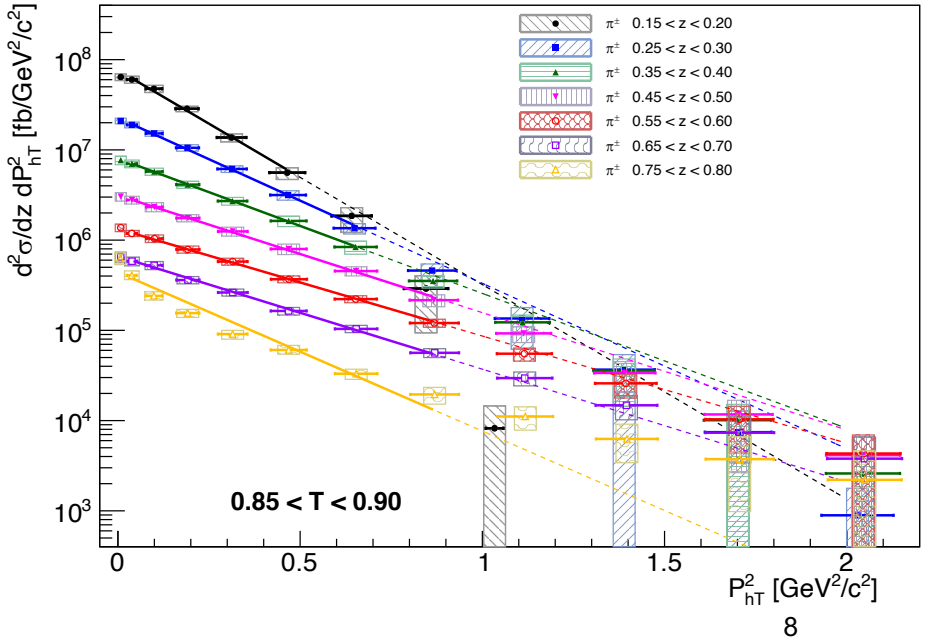
- 0.85< Thrust T < 0.9
  - Transverse momenta mostly Gaussian
  - Possible deviations for large P_{hT} tails, but also large uncertainties



Phys.Rev.D 99 (2019) 11, 112006

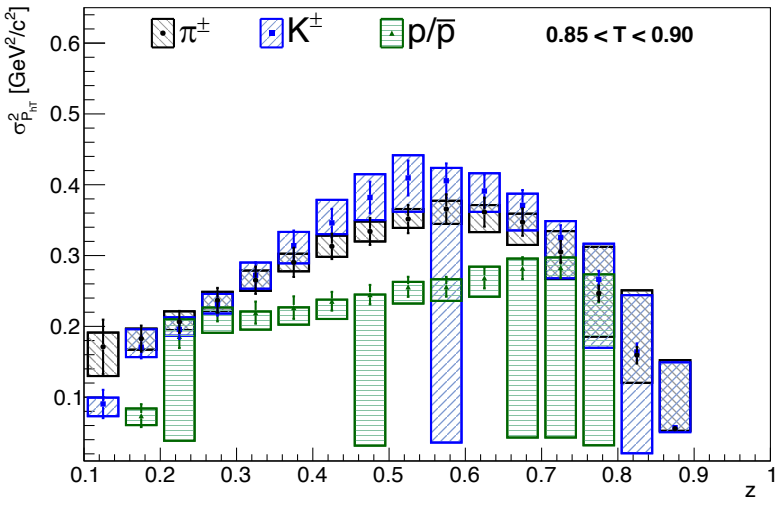
Transverse Momentum: Gaussian widths

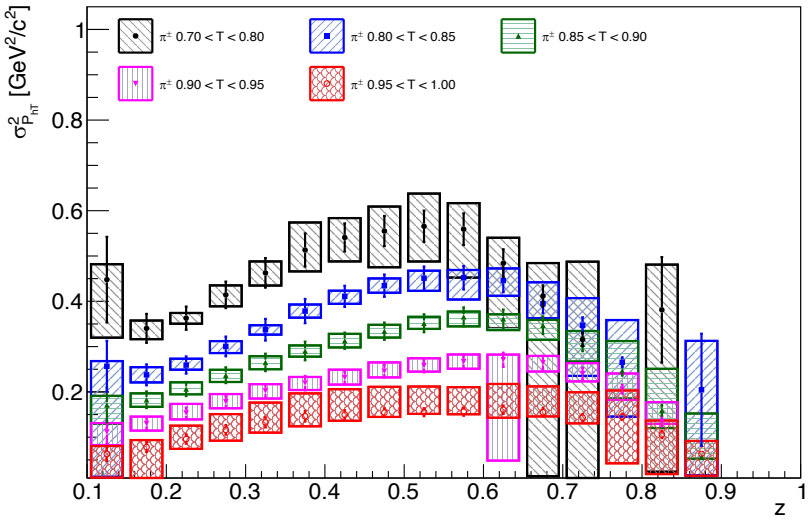
- 0.85 < T < 0.9
  - Fit Gauss to low P_{hT} data
  - Mostly well described with possible exception at high z
  - Deviation from Gauss at large P_{hT}
  - Clear increase in width with z for low values of z



Gaussian Width as a function of z and T

- General increase with z with turnover at larger values of z for mesons
- Protons with smaller width and more linear rise with z

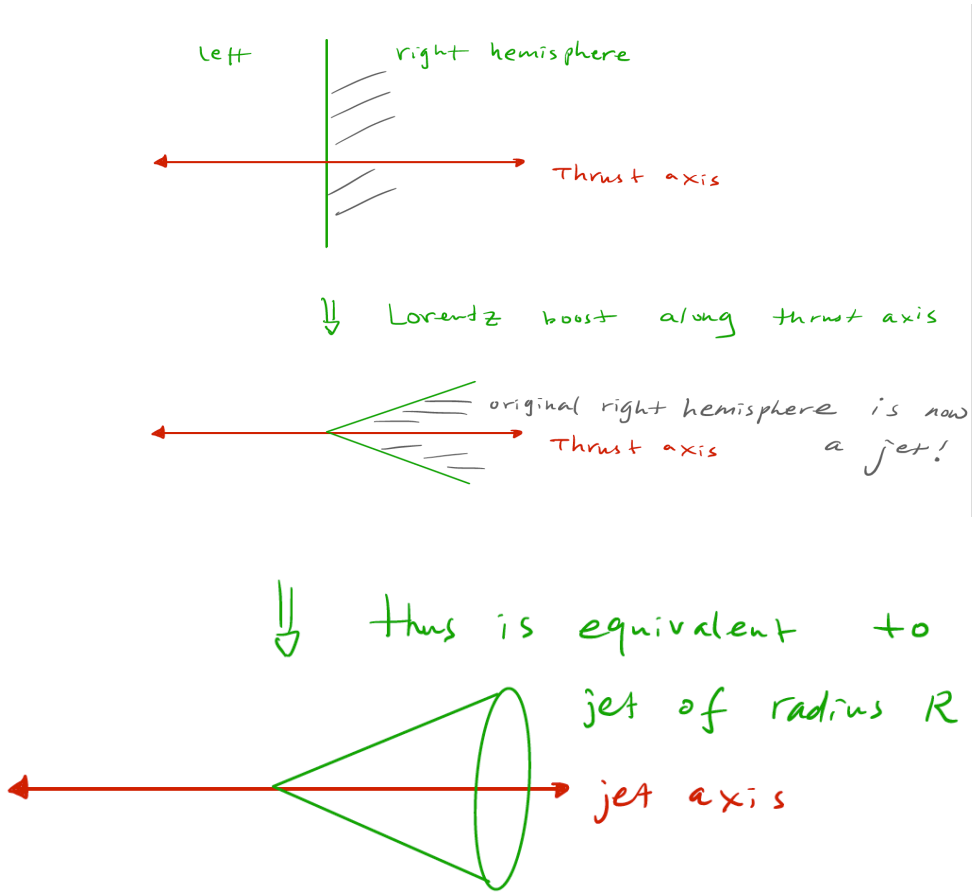




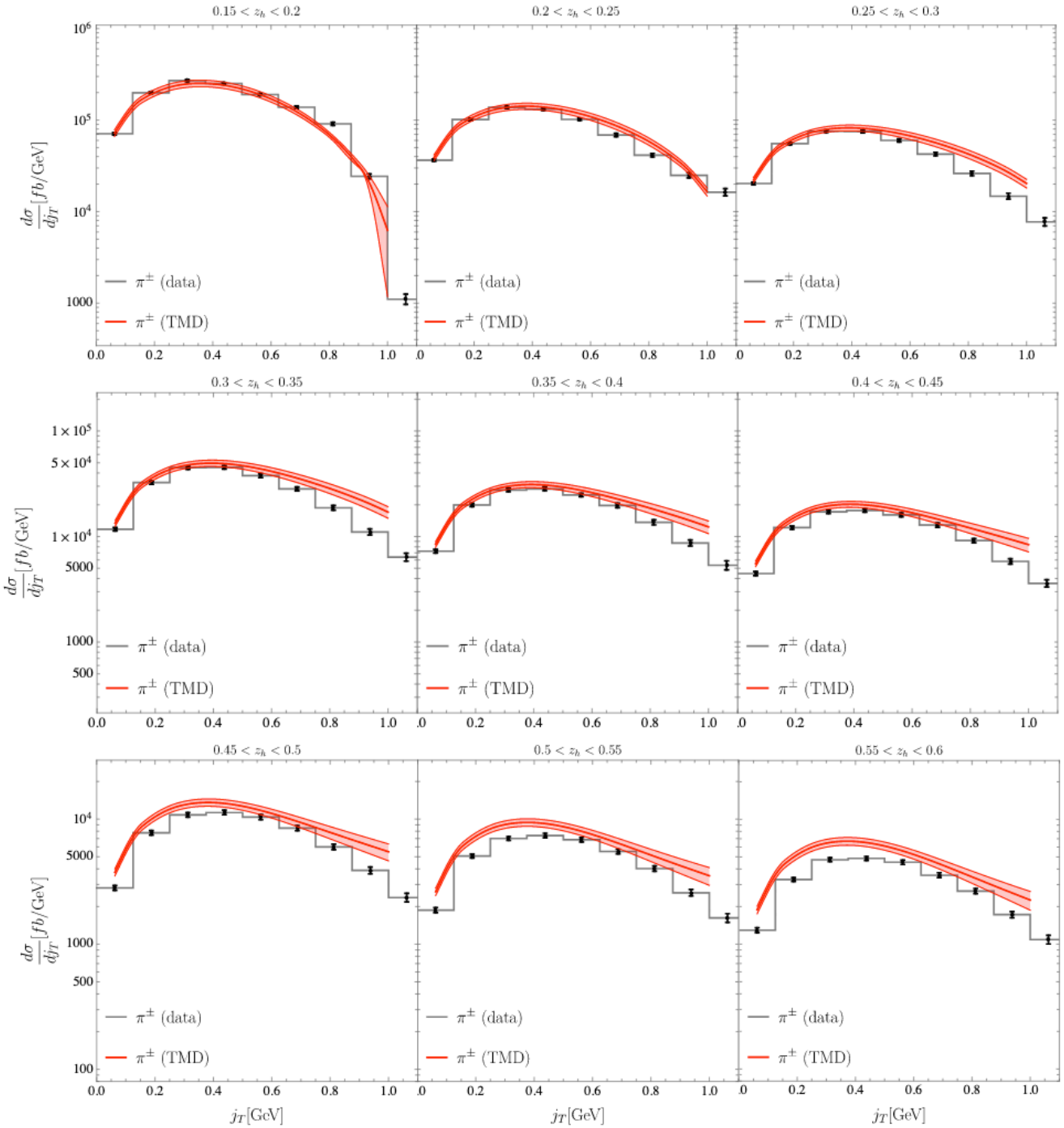
- General increase with z with turnover at larger values of z for mesons
- Clear decrease of widths with increase of T
  - Particles more and more collimated

New theoretical insights: Thrust and Jet measurements are closely related

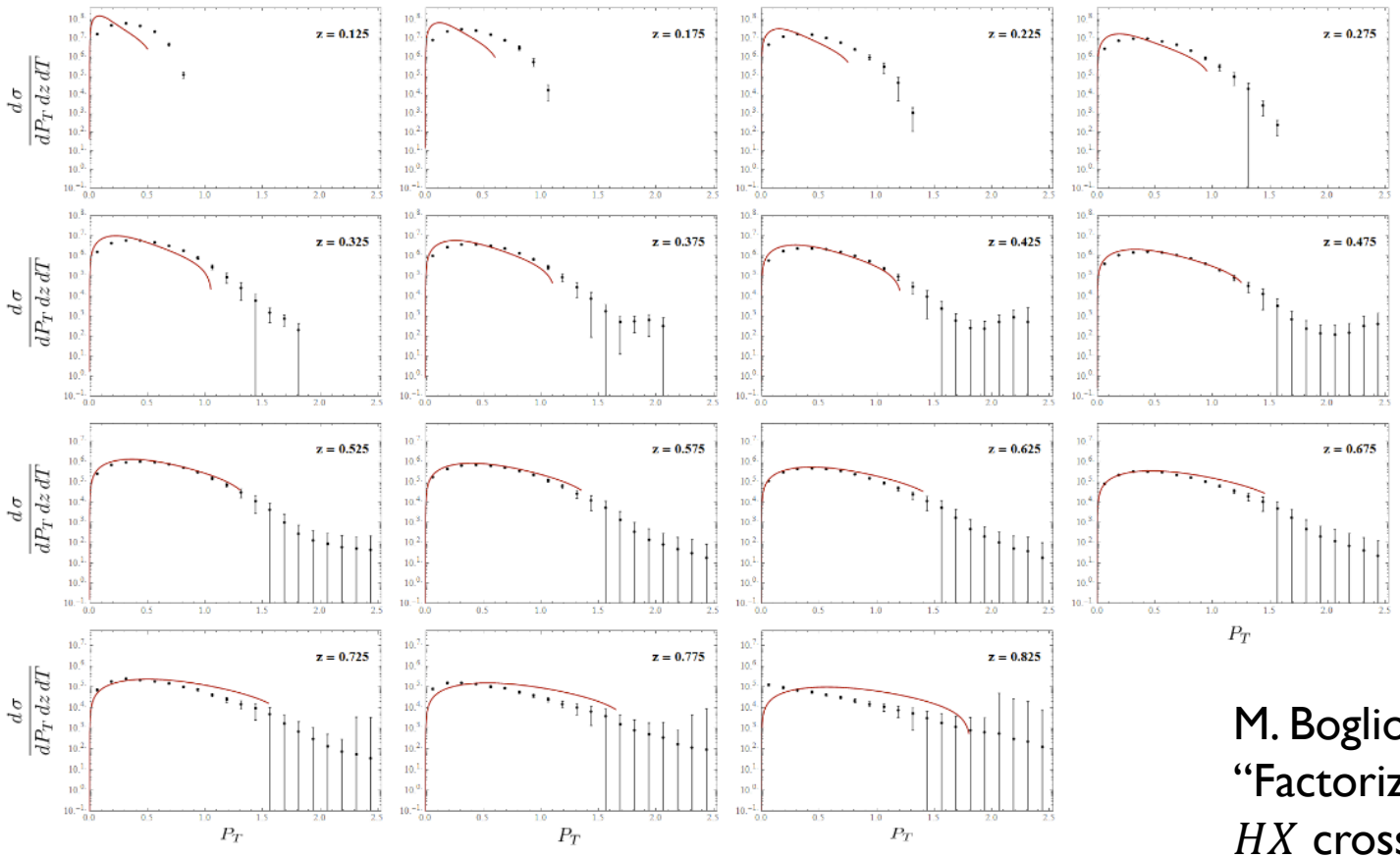
- Motivated by gaussian p_T spectrum as expected from jet measurement
- M. Boglione, A. Simonelli, "Factorization of $e^+e^- \to HX$ cross section, differential in z_h, P_T and thrust, in the 2-jet limit", 2011.07366 [hep-ph]
- Z. Kang, D. Shao, F. Zhao, "QCD resummation on single hadron transverse momentum distribution with the thrust axis", 2007.14425 [hep-ph]



Drawing by Zhong-Bo Kang

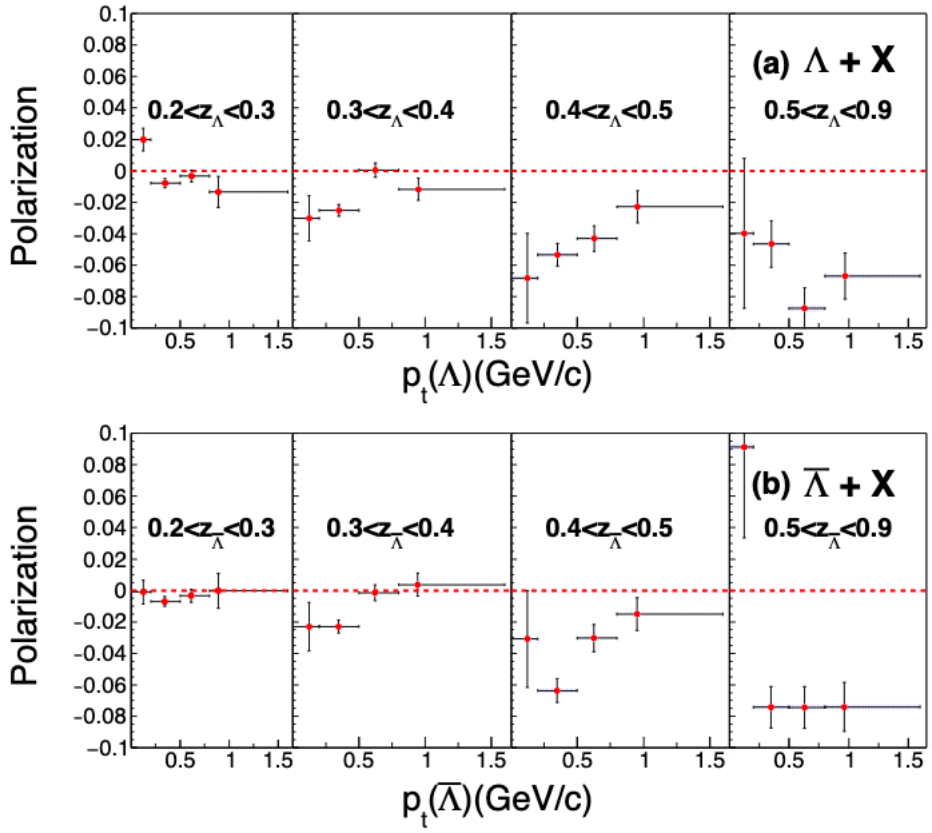


Z. Kang, D. Shao, F. Zhao, "QCD resummation on single hadron transverse momentum distribution with the thrust axis", 2007.14425 [hep-ph]



M. Boglione, A. Simonelli, "Factorization of $e^+e^- \to HX$ cross section, differential in z_h, P_T and thrust, in the 2-jet limit", 2011.07366 [hep-ph]

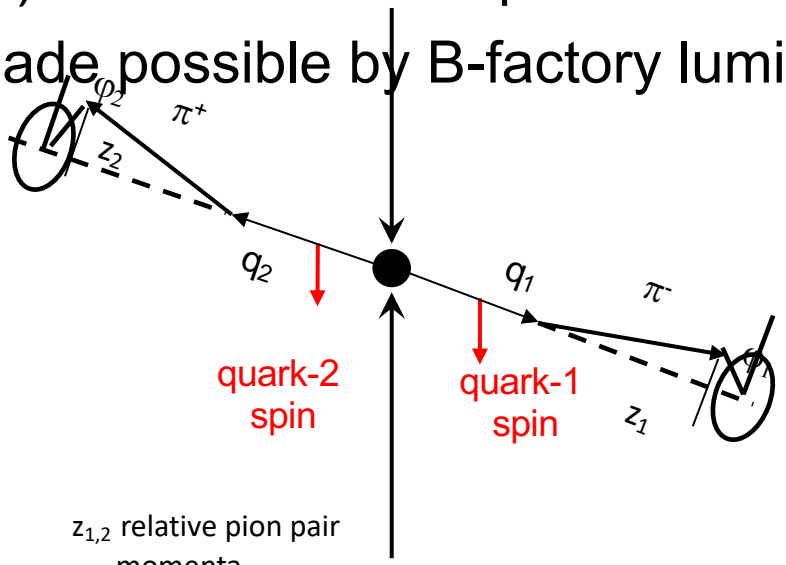
$\Lambda^{\uparrow}$ in jets



Phys.Rev.Lett. 122 (2019) 4, 042001

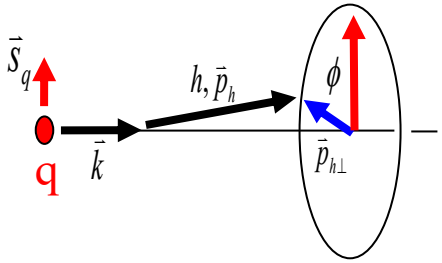
Polarized FFs from Correlation Measurements in e^+e^-

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



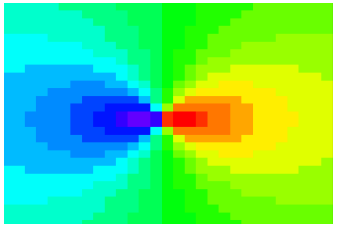
J. Collins, Nucl. Phys. B396, (1993) 161

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



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

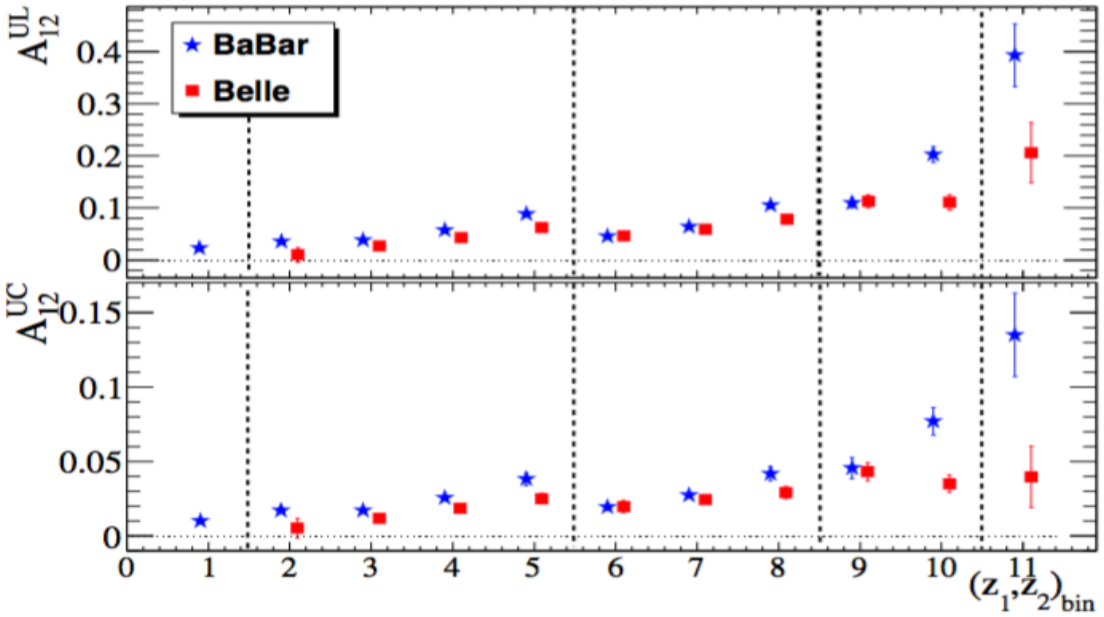
$\propto D_1^\perp \overline{D_1^\perp} + H_1^\perp \overline{H_1^\perp} \cos(\phi_1 + \phi_2)$



Collins Effect vs (z_1,z_2): comparisons

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

EPJA, 52, 1-15 (2016)



- Symmetric (z_1,z_2) bins are used for the comparisons: results falling in the same large (z_1,z_2) interval are averaged taking into account statistical and systematic uncertainties
- A_0 : very good agreement between BaBar and Belle data; larger asymmetry for BESIII in the last bin ($z_{1,2}$>0.5)
- A_{12}: some tensions between BaBar and Belle,
  - z<0.9 for BaBar, z<1 for Belle

•First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ $\sqrt{s}$ ~ 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 @ $\sqrt{s}$ ~ 10.6 GeV (PRD 90,052003 (2014); PRD 92,111101(R)(2015) for KK and Kπ)
- Measured at BESIII @ $\sqrt{s}$ = 3.65 GeV (PRL 116,42001(2016))

New Pt dependence from Belle

- Trend consistent with BaBar
- Direct comparison difficult due to different correction schemes (thrust vs $q\bar{q}$ −axis)

Unlike/**L**ikesign

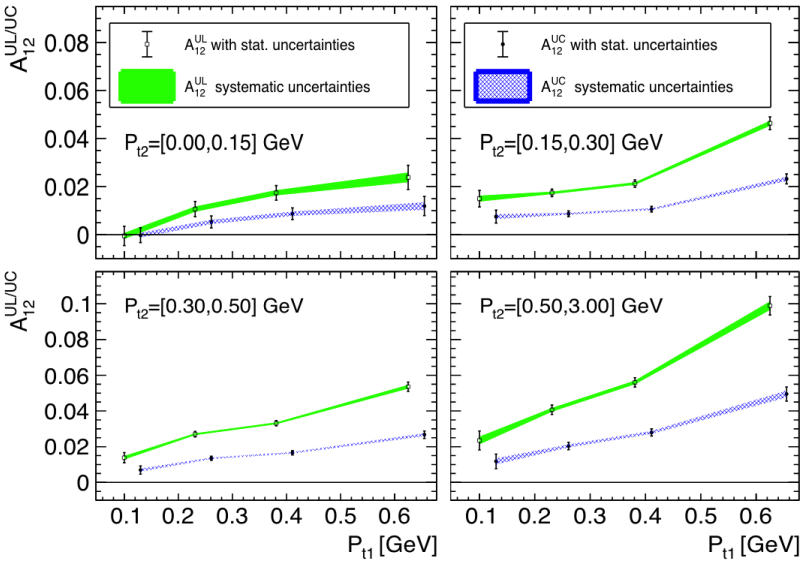
Ratios to cancel acceptance effects

Unlike:

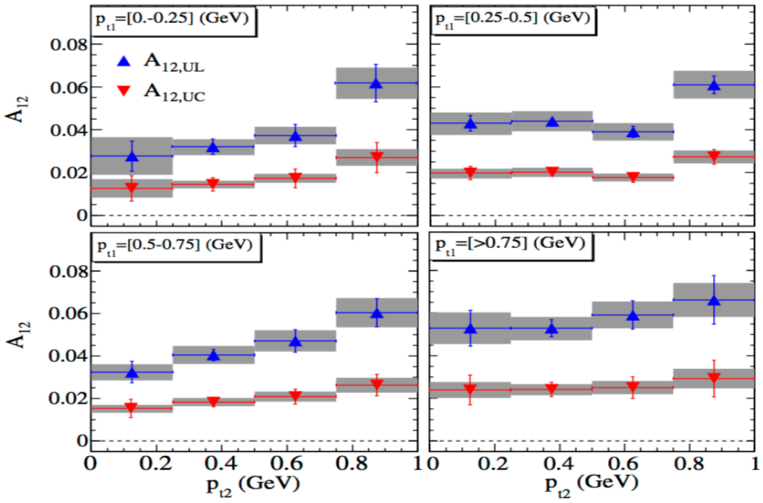
fav*fav+dis*dis

Like:

fav*dis



BaBar

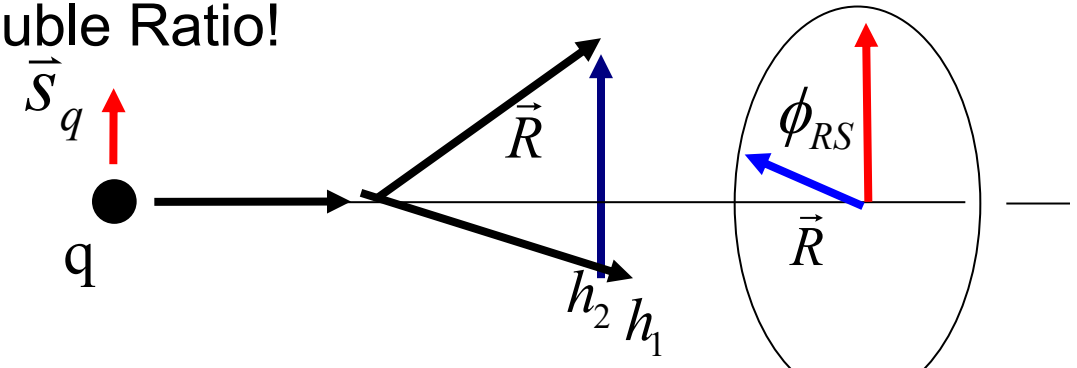


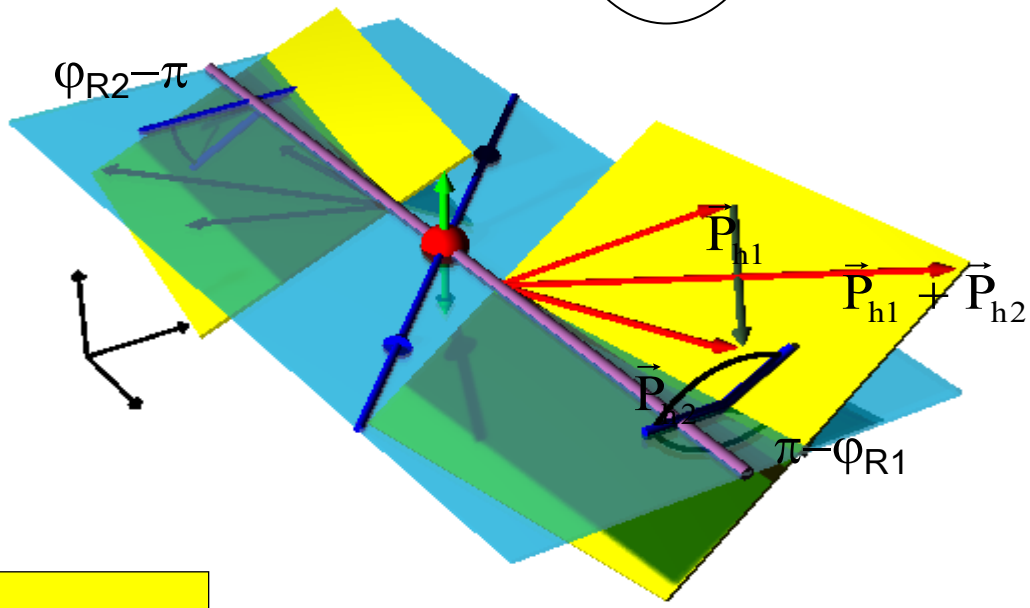
Phys.Rev.D 100 (2019) 9, 092008

Kaon, π^0, η, π^0-charged averaged also available (see backup)

Di-Hadron Fragmentation

- No Double Ratio!

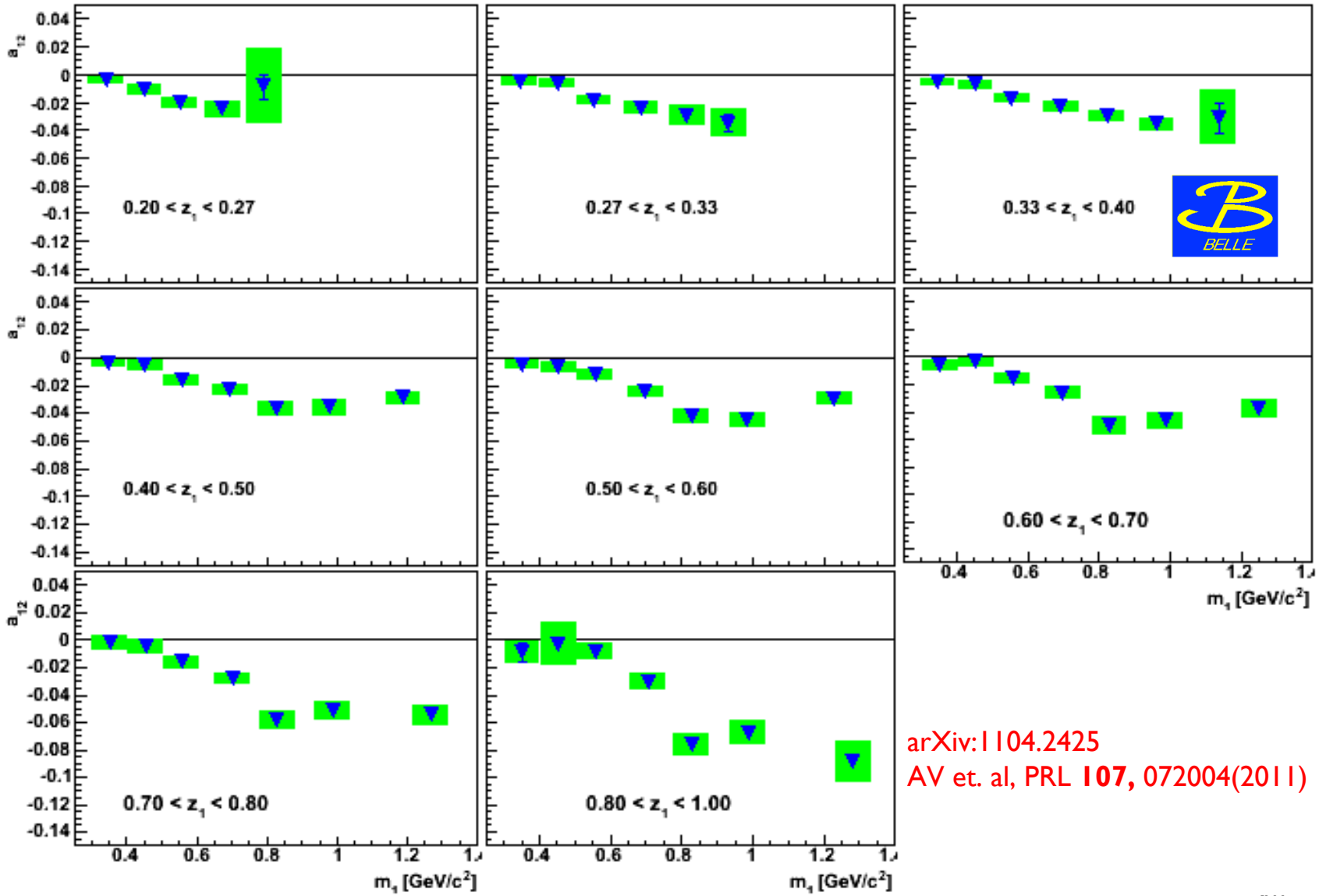




$$\sigma \propto H_1^{\angle} \cdot \bar{H}_1^{\angle}$$

First measurement of Interference Fragmentation Function

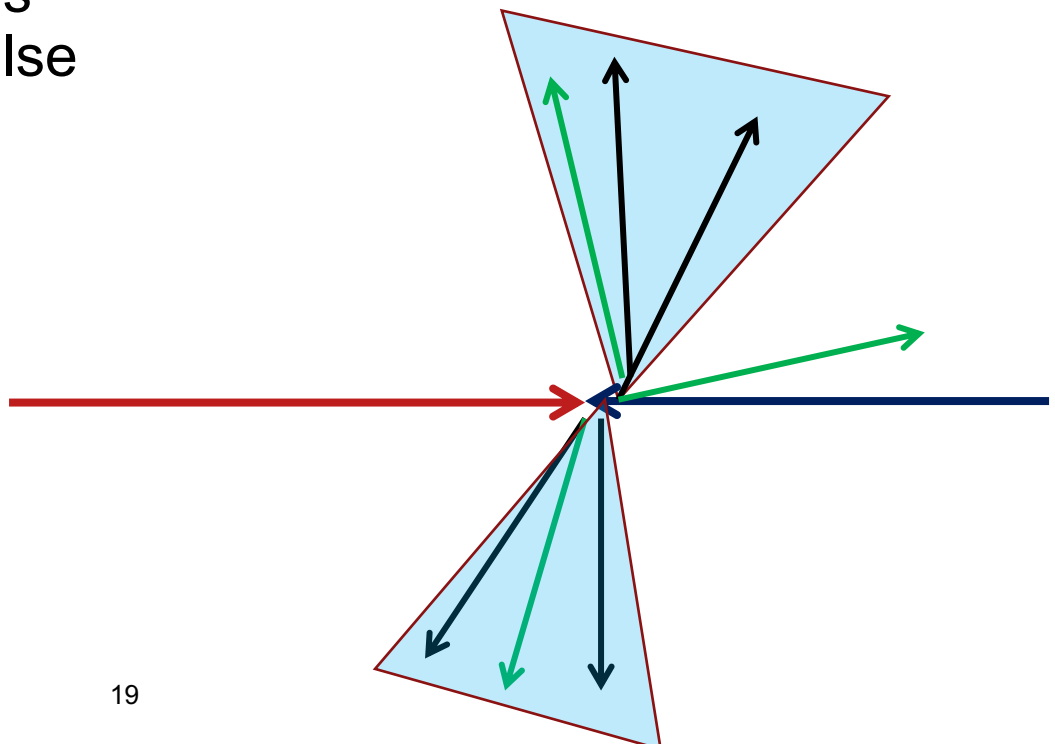
$a_{12} \propto H_1^{<} * H_1^{<}$



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

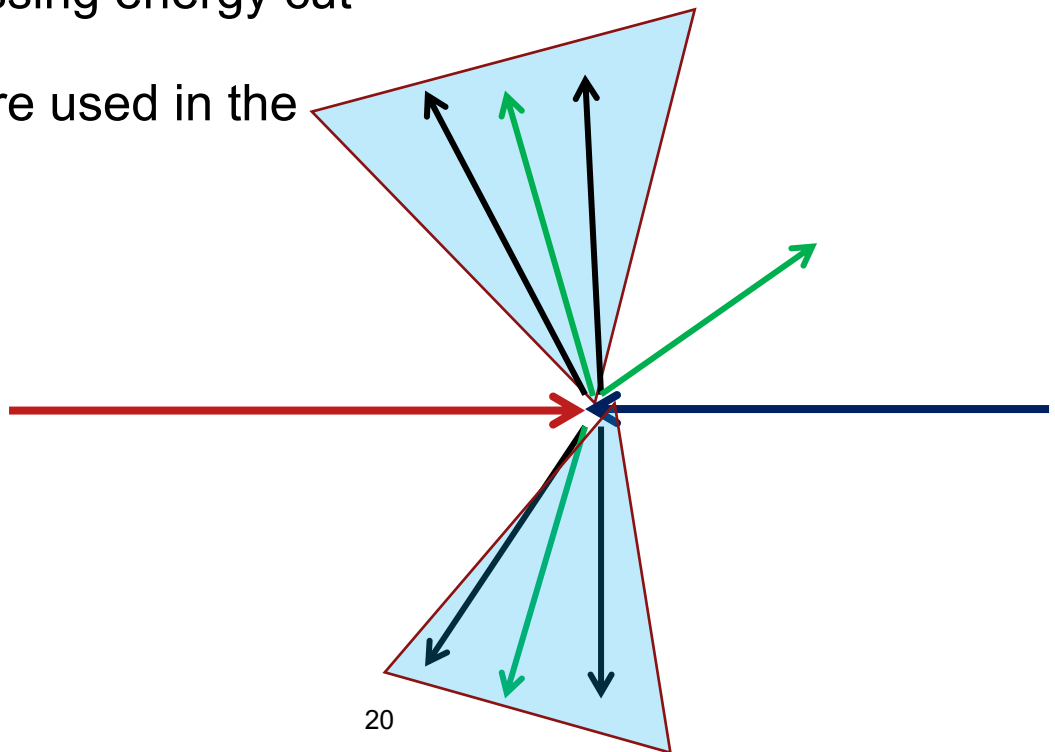
Extraction of $\phi_1 - \phi_2$ Asymmetries

- *Phys.Rev.D* 67 (2003) 094003: $\cos\big(2(\phi_1 - \phi_2)\big)$ asymmetries are proportional to $G_1^{\perp} \cdot \bar{G}_1^{\perp}$
- Fixed thrust axis correlates hemispheres leading to false asymmetries



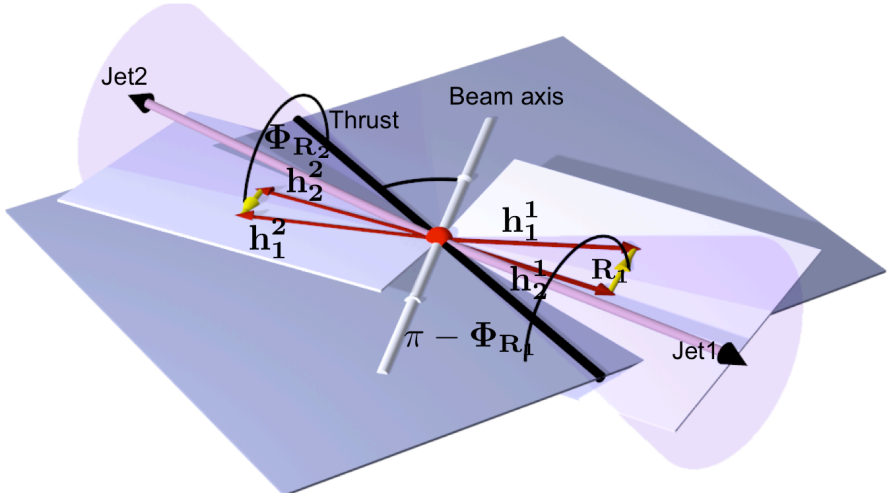
Jet Reconstruction at Belle

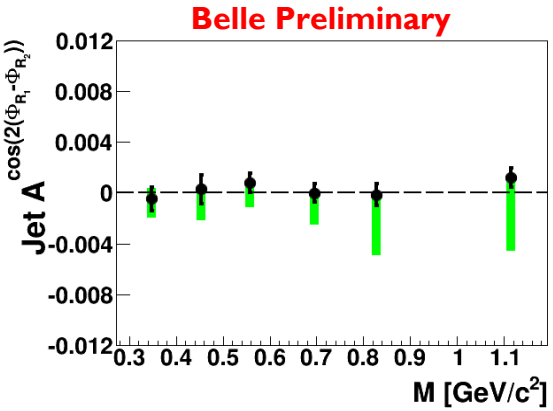
- Robust vs. final state radiation
- **De-correlate axis between hemispheres**
- We use anti-kT algorithm implemented in fastjet
- Cone radius R=1.0
- Min energy per jet 3.75 GeV→ suppress weak τ decays
- Only allow events with 2 jets passing energy cut (dijet events)
- Only particles that form the jet are used in the asymmetry calculation

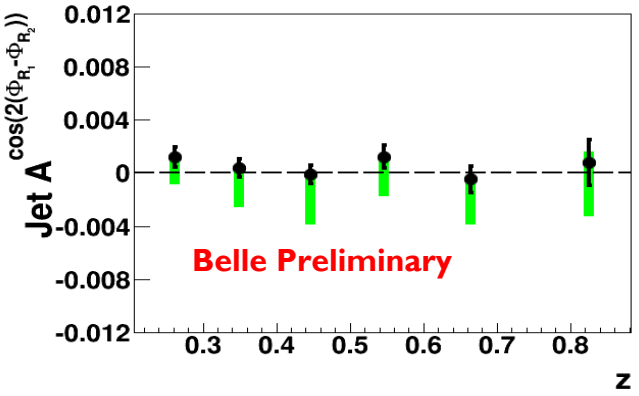


Asymmetries for Cos(2(ϕ_{R1}-ϕ_{R2})) ($G_1^{\perp}$) small

- Turned out that the asymmetry is projected to be $\equiv 0$

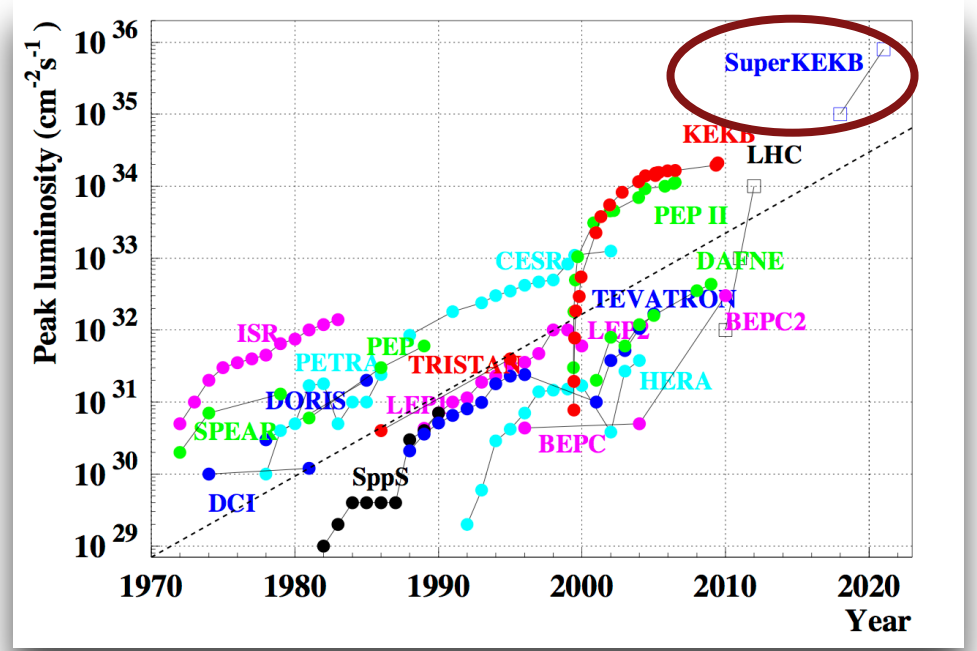




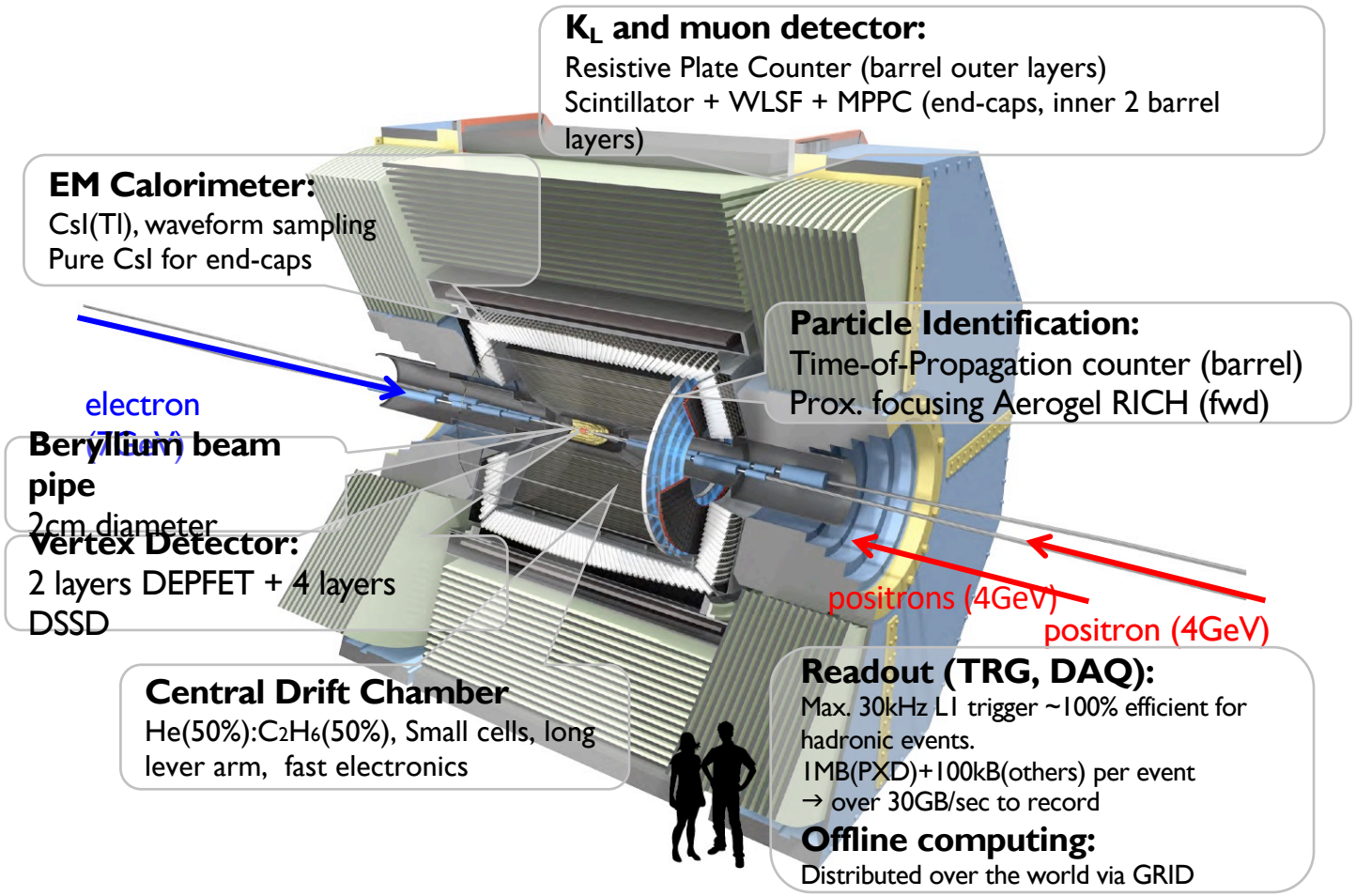


1505.08020 [hep-ex]

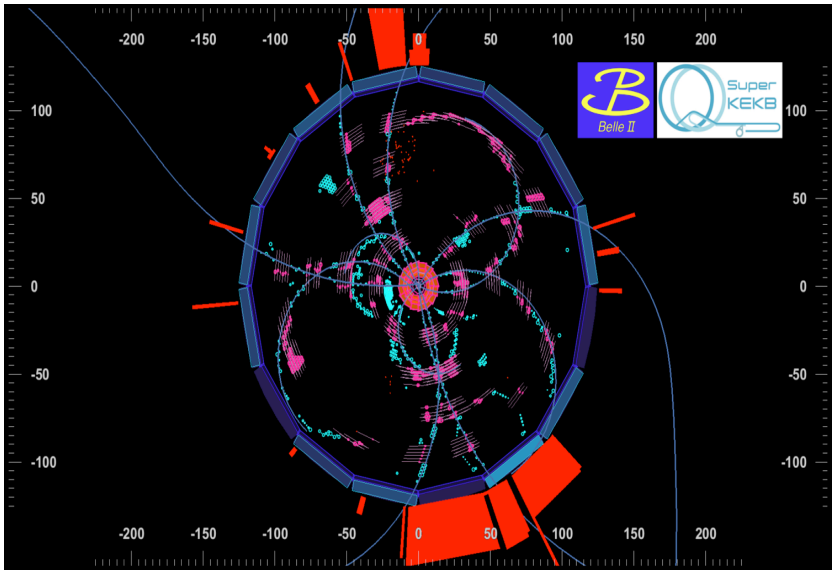
The future is now: Next Generation B factory SuperkeB

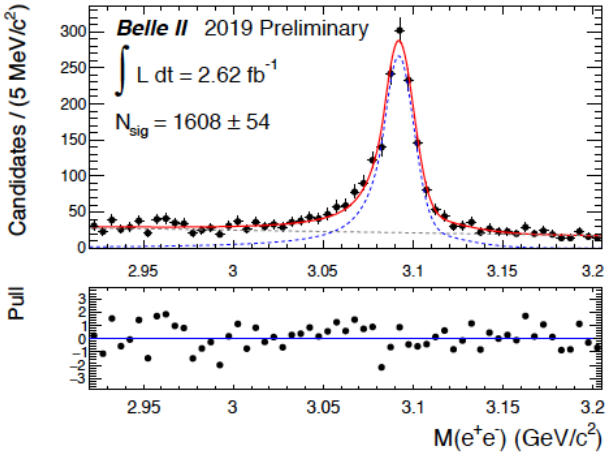


Cut view of Belle II Detector



2019: First Collisions in Phase 3, the Physics Run

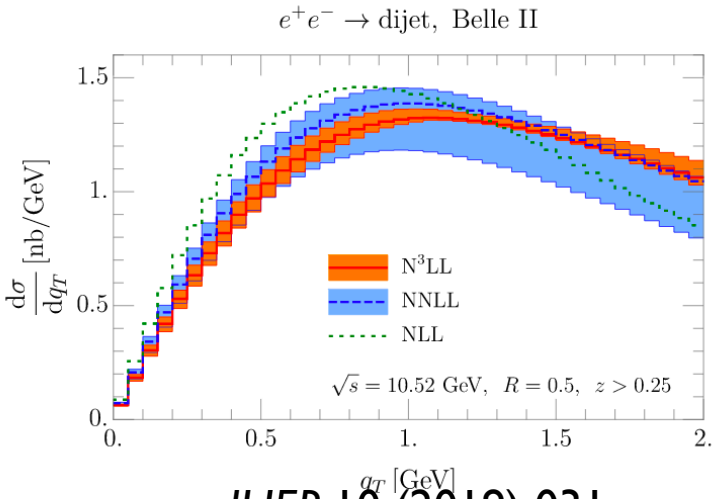




Clear signals for B→J/ψ X in ~1/2 of Phase 3 data.

Summary

- (Super) B-factories great place to study jets
- Focus so far on in-jet fragmentation using thrust axis
  - Unpolarized, p_T dependence
  - $\Lambda^{\uparrow}$ in jet
  - Collins/IFF
- First dijet measurement extracting $A^{\cos(2(\phi_1-\phi_2))}$
- Future: dedicated program on jets at Belle II
  - E.g. measuring dijet correlations



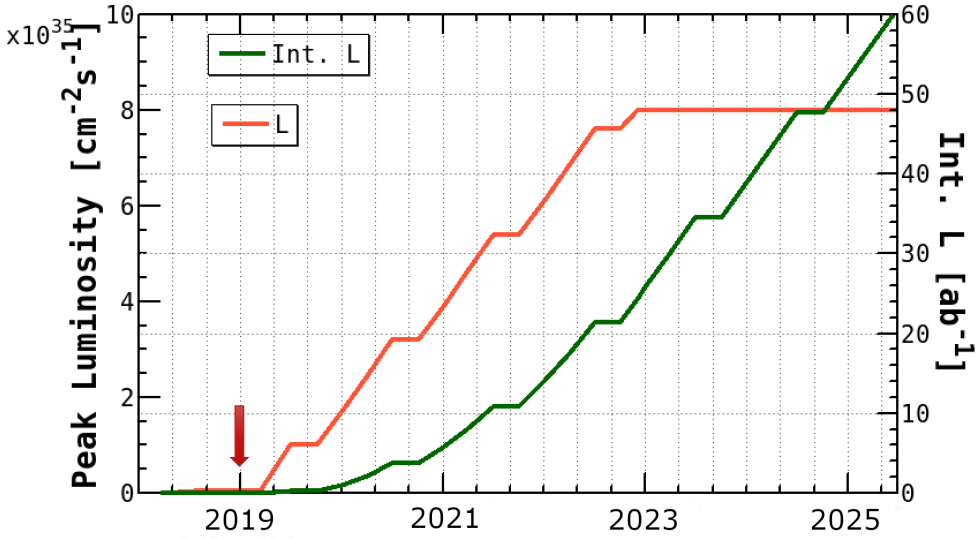
JHEP 10 (2019) 031

SuperKEKB/Belle II Luminosity Profile

Beam currents *only* a factor of two higher than KEKB (~PEPII)

"nano-beams" are the key; vertical beam size is 50nm at the IP

Belle/KEKB recorded ~1000 fb^{-1} . Now have to change units on the y-axis to ab^{-1}



Invitation to participate in the Snowmass Whitepaper

Snowmass 2021 Letter of Interest:
QCD and Hadronization Studies at Belle II

on behalf of the U.S. Belle II Collaboration

Corresponding Author:
Anselm Vossen (Duke University), anselm.vossen@duke.edu

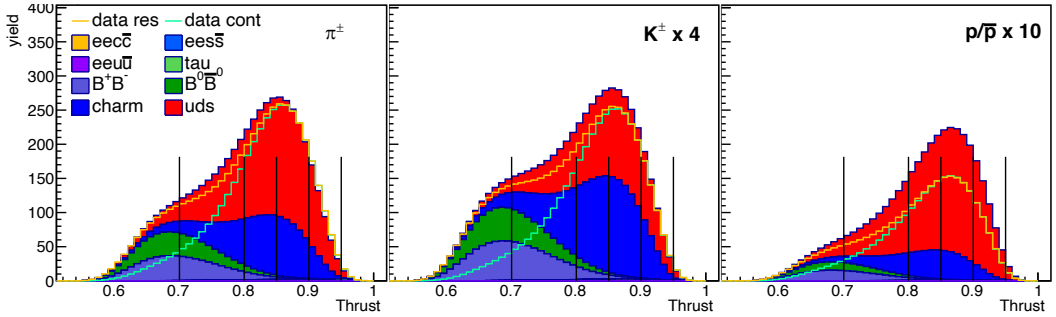
Thematic Area(s):

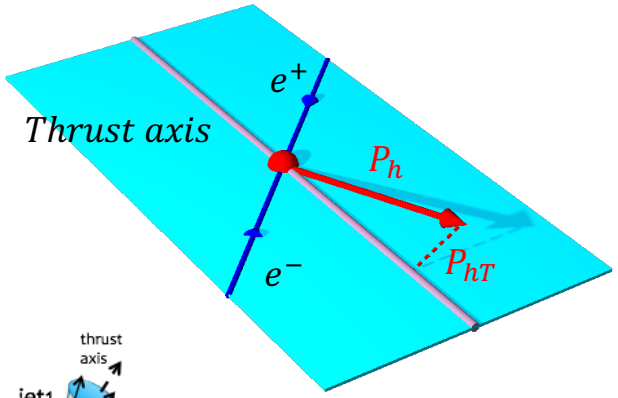
- (EF05) QCD and strong interactions: Precision QCD
- (EF06) QCD and strong interactions: Hadronic structure and forward QCD
- (RF03) Fundamental Physics in Small Experiments

1 Hadron and Jet Fragmentation Studies at Belle II as input for the EIC

Use thrust as proxy to $q\bar{q}$ axis

- No phase space for >2 jet events
- **Transverse momentum measured with respect to thrust axis**

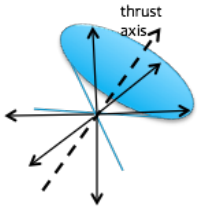




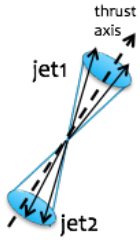
$$T = \sum_i \frac{|\mathbf{P} \cdot \hat{\mathbf{n}}|}{|P|}$$

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

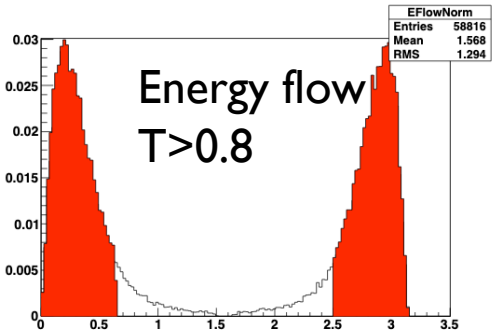
$0.5 \leq T \leq 1$



T~0.5



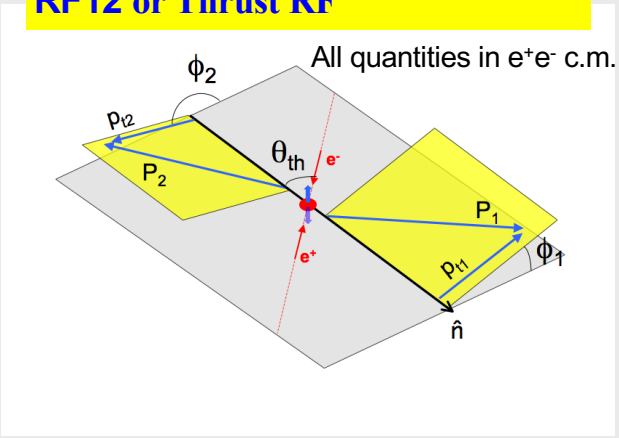
T~1



Collins Effect

BaBar
Belle
~~BESIII~~

RF12 or Thrust RF

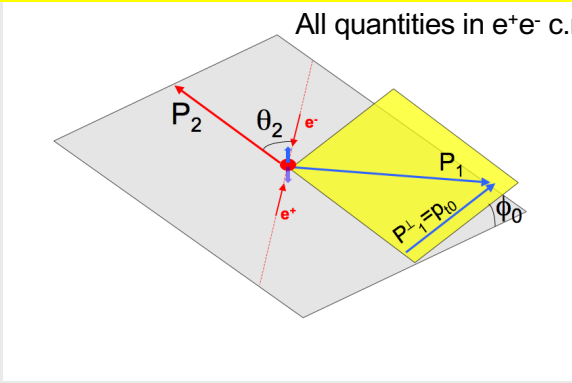


- **Thrust axis** to estimate the $q\bar{q}$ direction
- $\varphi_{1,2}$ defined using thrust-beam plane

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

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

RF0 or Second hadron momentum RF



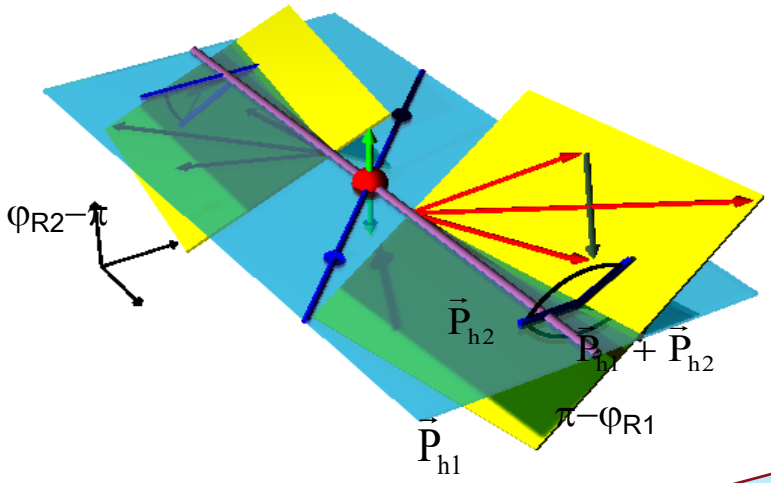
BaBar
Belle
BESIII

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

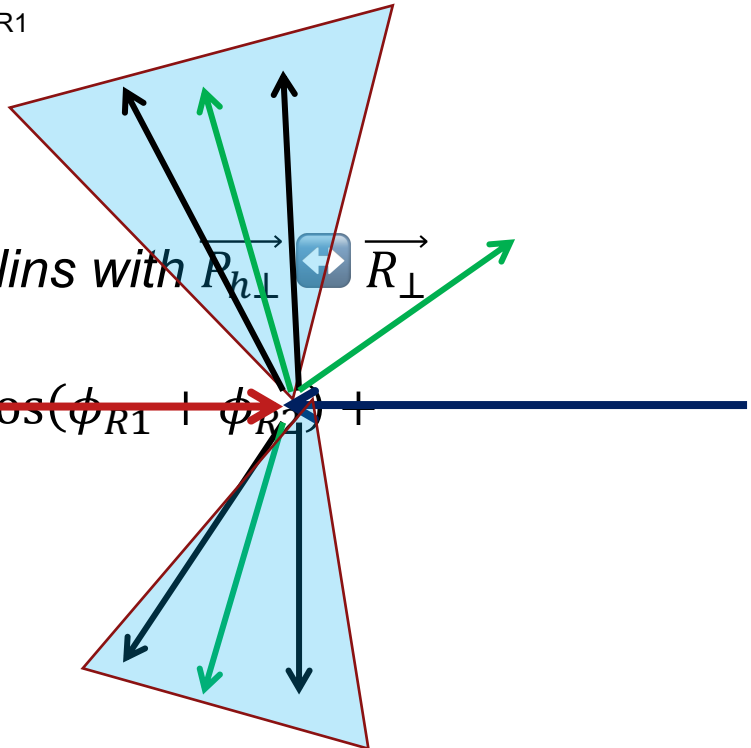
Normalized cross-section: $e^+e^- \to (h_1 h_2)(\overline{h_1}\,\overline{h_2}) + X$

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

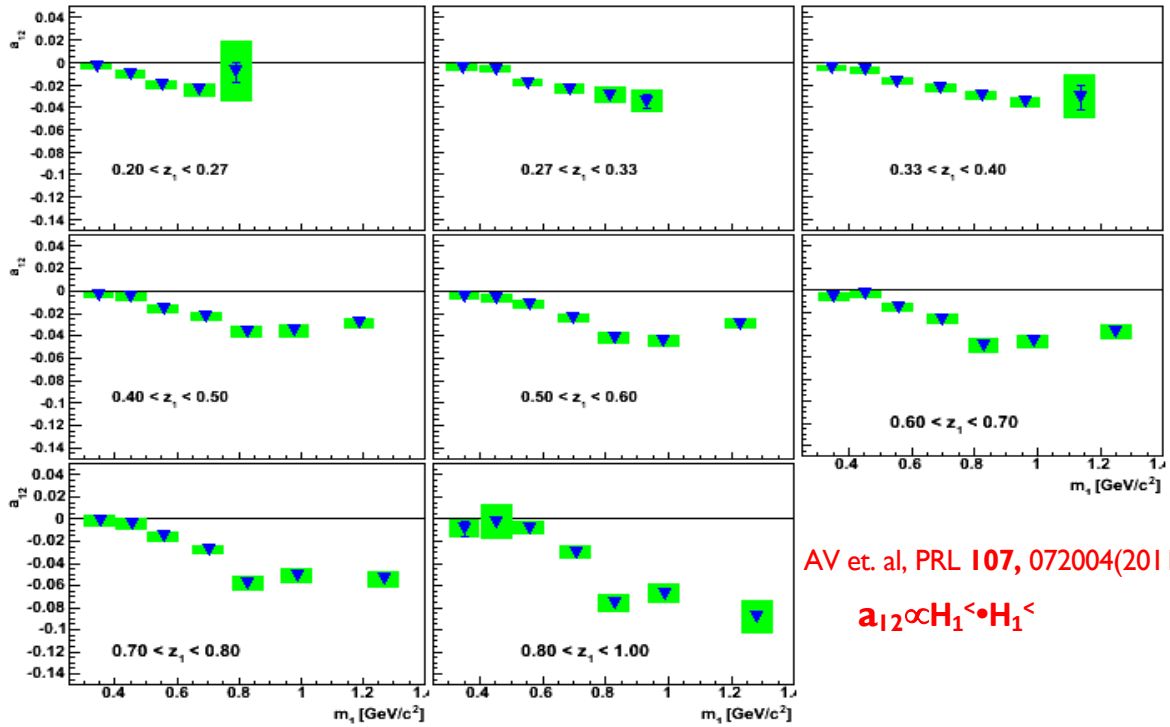
Di-hadron asymmetries



- *Conceptually similar measurement as Collins with* $\overrightarrow{P_{h\perp}}$ $\overrightarrow{R_\perp}$
- *Normalized cross section:*
  $e^+e^- \to (h_1h_2)(\overline{h_1}\,\overline{h_2}) + X \propto 1 + H_1^\sphericalangle \overline{H_1^\sphericalangle}\cos(\phi_{R1} + \phi_{R2}) + G_1^\perp \overline{G_1^\perp}\cos(2(\phi_{R1} - \phi_{R2}))$
- See talks by Aram and Marco



First measurement of Interference Fragmentation Function



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

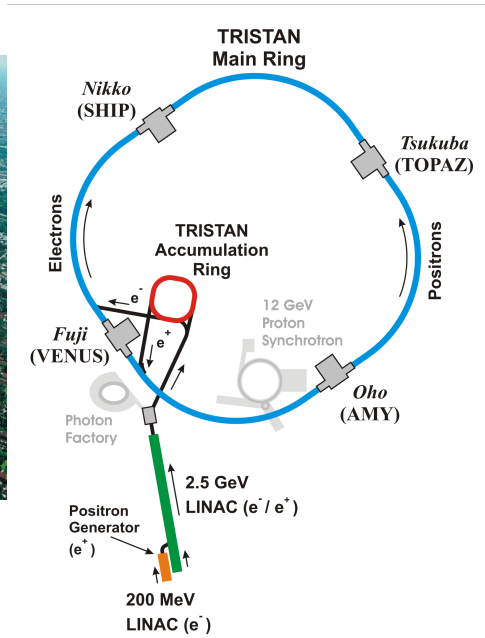
$a_{12} \propto H_1^{<} \bullet H_1^{<}$

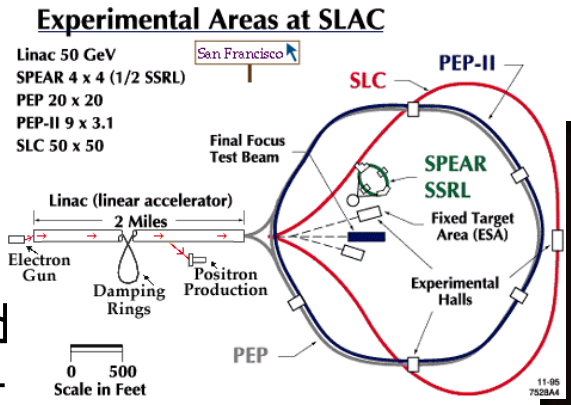
See Marco's talk about Transversity extraction From di-hadrons

Backup

Long history of e+e- colliders: First generation for FF measurements

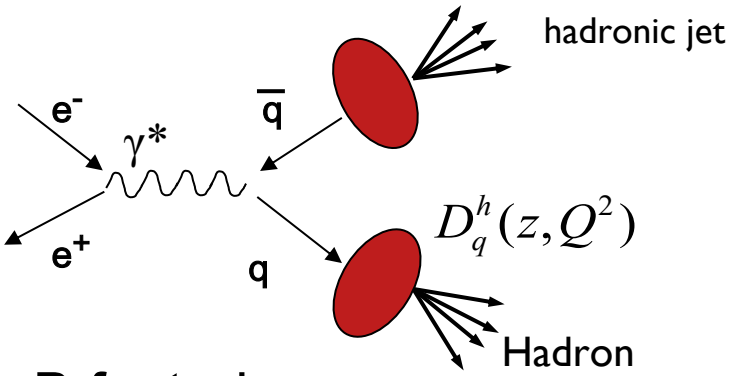
- DESY:
  - DORIS I (3-5) DORIS II (7-10 GeV)
  - PETRA 14-46 GeV (1978-86) : TASSO (34pb^{-1} (34/44 GeV)
- SLAC:
  - PEP@29GeV 1980-1990 (TPC 140 pb^{-1}), HRS, MARK
- KEK:
  - Tristan @ 50-64 : TOPAZ, AMY (278pb^{-1})
- SLC @ M_Z ($20p^{-1}$)
- SLD+MARK II @M_Z (500k evts $Z \rightarrow qq$), long polarized
- LEP I : 160pb^{-1}, LEP-II 700pb^{-1}
  - ~50x SLC

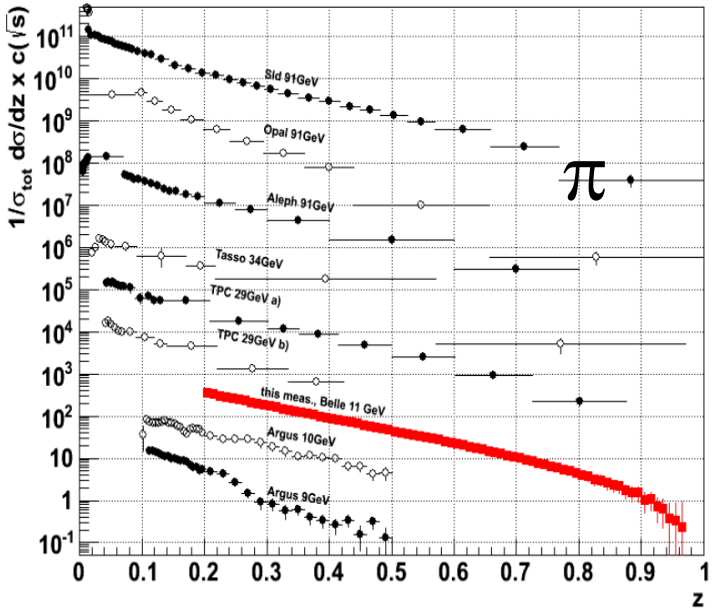




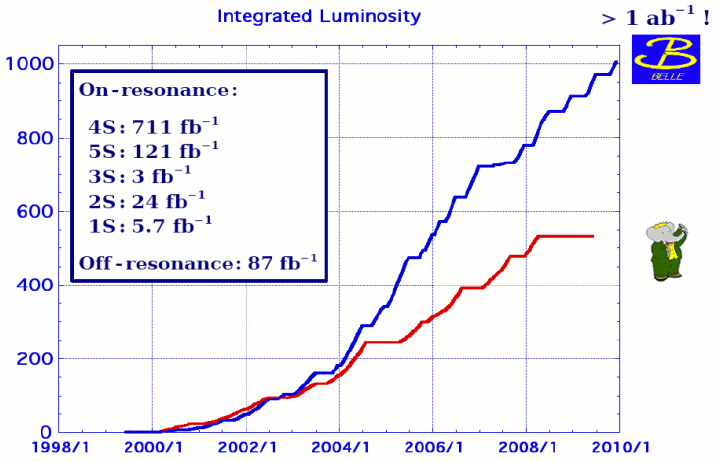
Where to Study?

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

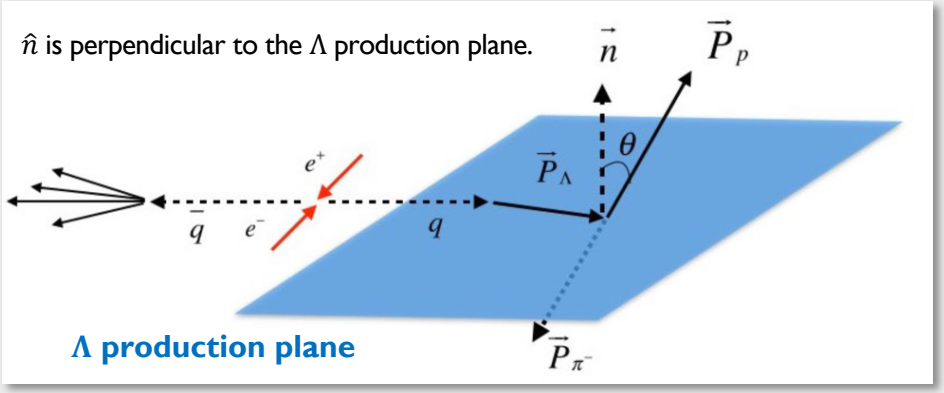


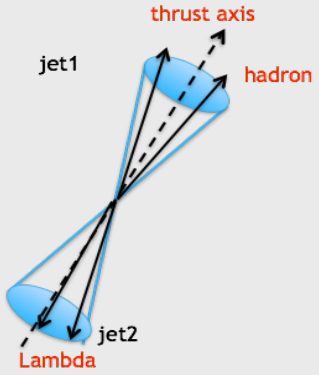


- B factories
  - close in energy to SIDIS (100 GeV^2 vs $\hat{s}$ [illegible])
  - Large integrated lumi!, high z reach



Observables in Λ Restframe

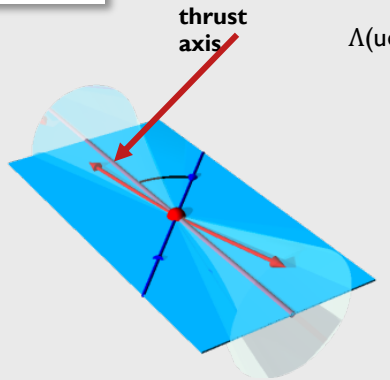




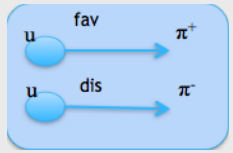
- Self-analyzing decay leads to polarization dependent distribution

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

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



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



Thrust

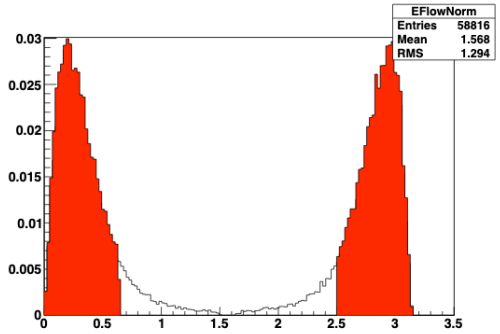
- →at Belle energies 2 jet events, connection to di-jet events

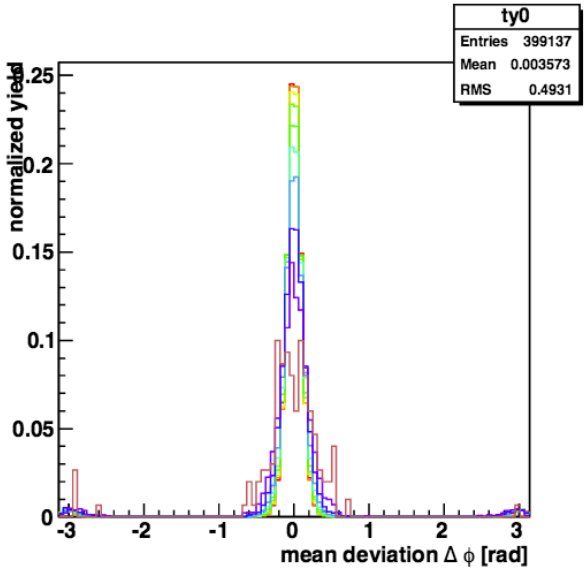
Seminal measurements, Collins IFF

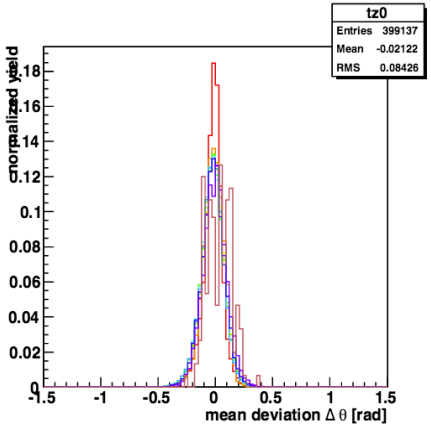
G1\perp

Jet vs Thrust vs $q\bar{q}$ axis

- Non-negligible resolution effects
- In terms of k_T multiply by ~z*0.5√s, e.g. for typical RMS 0f 0.1 rad RMS ~100 MeV RMS for p_T (Similar as BaBar)







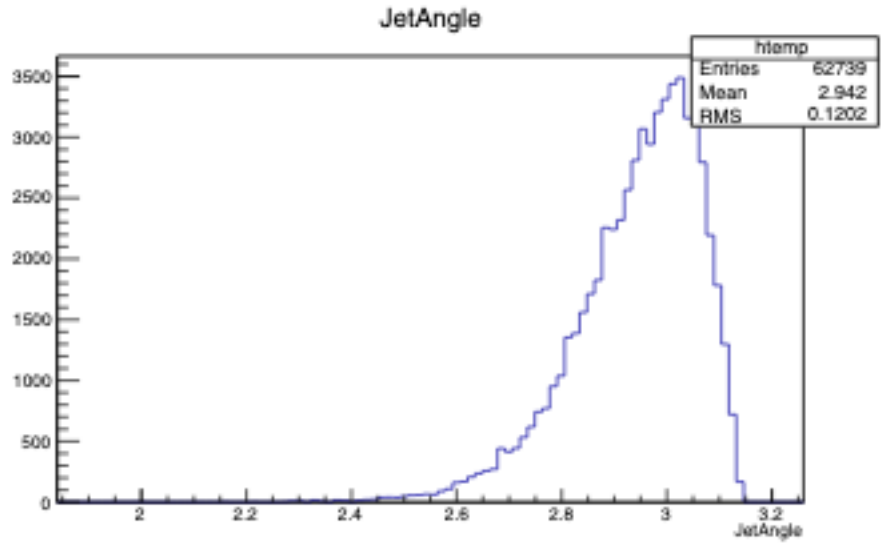


FIG. 12. The angle between two jets in 4π Monte Carlo simulation.

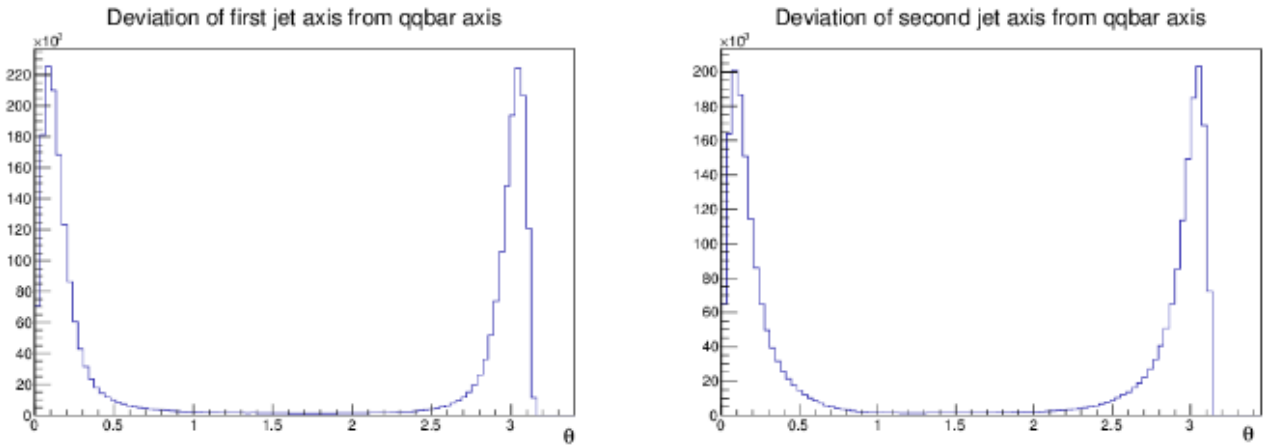
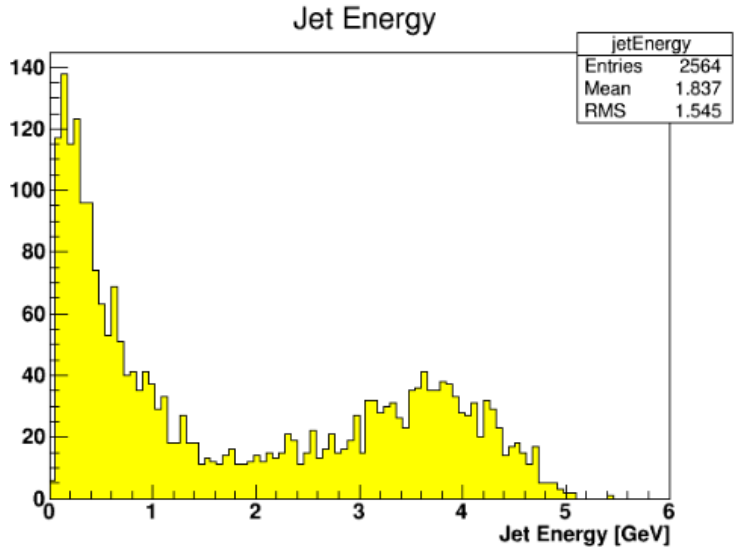
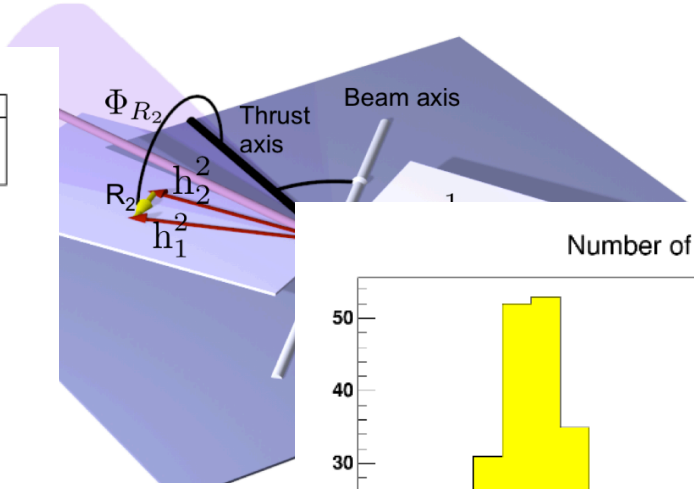
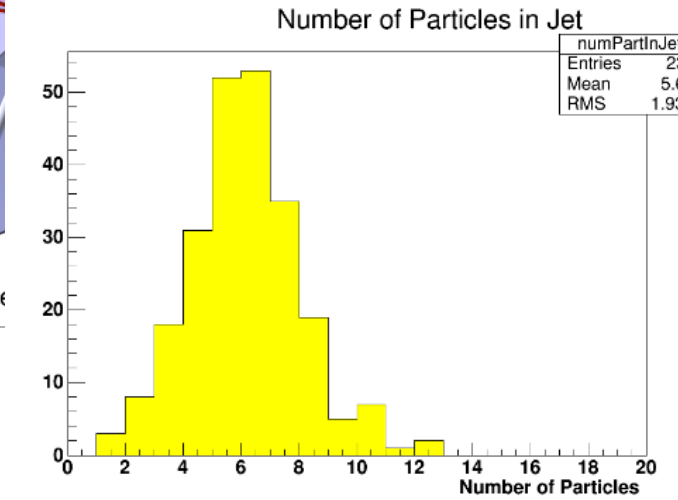
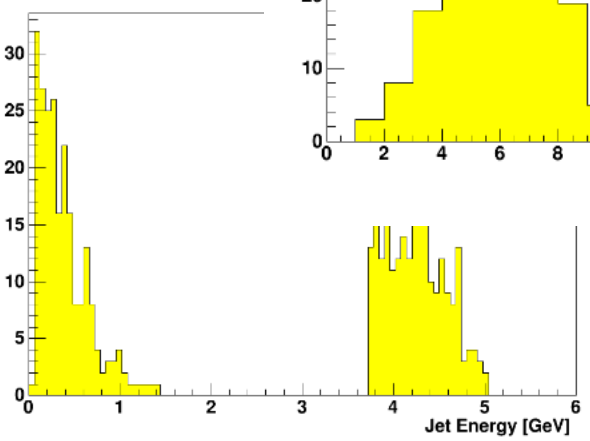


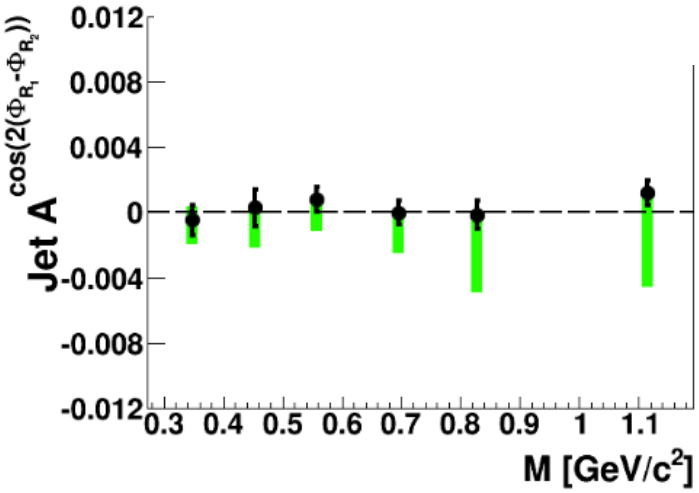
FIG. 14. The angle between jet and initial $q\bar{q}$-pair axes. The left plot shows the deviation for the jet with the higher momentum in the pair and the right one with the lower momentum. The deviation for the lower momentum jet is larger, since less energy of the parent quark is reconstructed in the jet. In the analysis the order is randomly assigned.

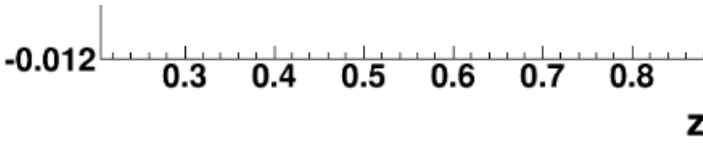

Jet Energy
jetEnergy
Entries 2564
Mean 1.837
RMS 1.545
Jet Energy [GeV]


Φ_{R_2}
Thrust axis
Beam axis
R_2
h_2^2
h_1^2


Number of Particles in Jet
numPartInJe
Entries
Mean
RMS
Number of Particles


Jet Energy [GeV]


Jet A
$\cos(2(\Phi_{R_1}-\Phi_{R_2}))$
M [GeV/c²]



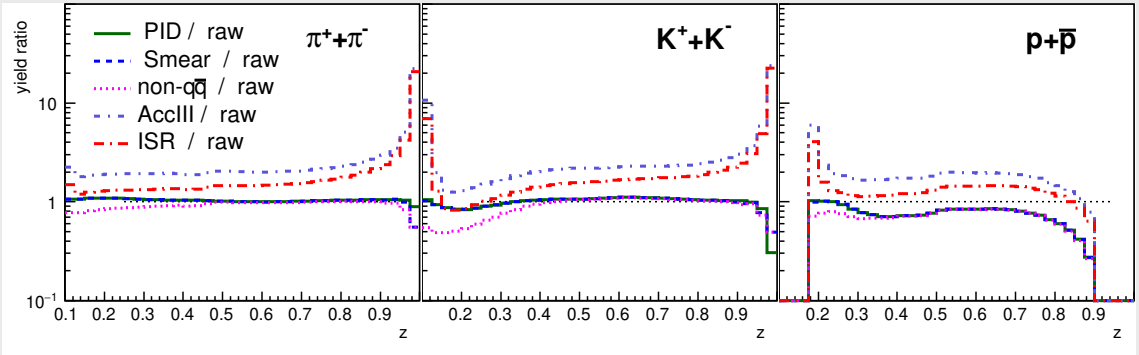
Latest: TMD FF

From Hadron yields to Cross-sections

- **Hadron yields undergo a series of corrections**
  - Particle (mis) identification [e.g. not every identified pion was a pion]
  - Smearing unfolding [e.g. measured and true momentum might differ]
  - Non $\bar{q}q$-processes [e.g. two photon processes, $\Upsilon \rightarrow B\bar{B}\ldots$)
  - "4π"-correction [selection criteria and limited acceptance]
  - QED radiation [initial-state radiation (ISR)]
- **Collins asymmetries also corrected for false asymmetries and axis (mis)recontruction**

From Hadron yields to Cross-sections

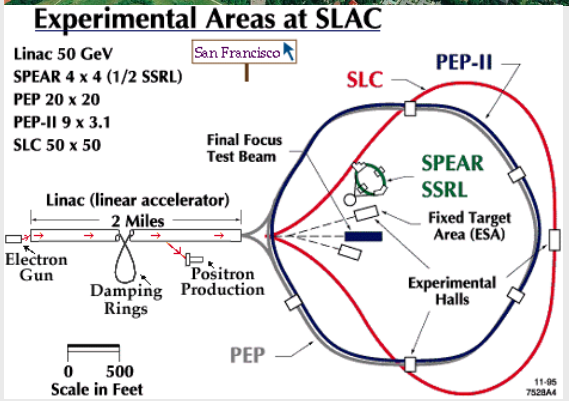
- **Example: single hadron inclusive cross-sections**
  - Largest effect for mesons **from acceptance** and **ISR corrections**
  - Larger PID correction for protons than for mesons

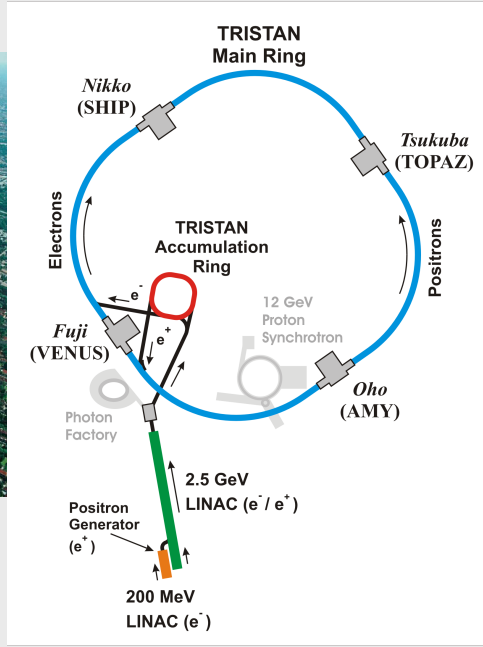


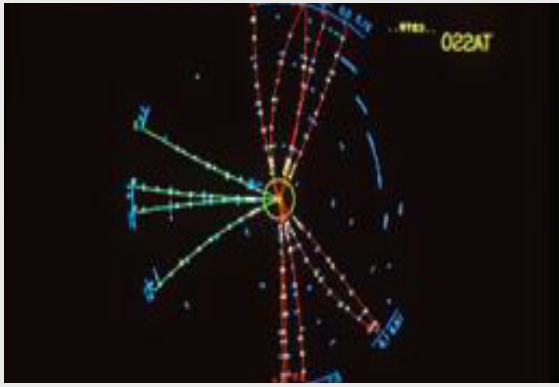
Phys.Rev. D92 (2015) no.9, 092007

Long history of e+e- colliders: First generation for FF measurements

- X-section below M_{Z0}
- DESY:
  - DORIS I (3-5) DORIS II (7-10 GeV)
  - PETRA 14-46 GeV (1978-86) : TASSO (34pb^{-1} (34/44 GeV)
- SLAC:
  - PEP@29GeV 1980-1990 (TPC 140 pb^{-1}), HRS, MARK I
- KEK:
  - Tristan @ 50-64 : TOPAZ, AMY (278pb^{-1})

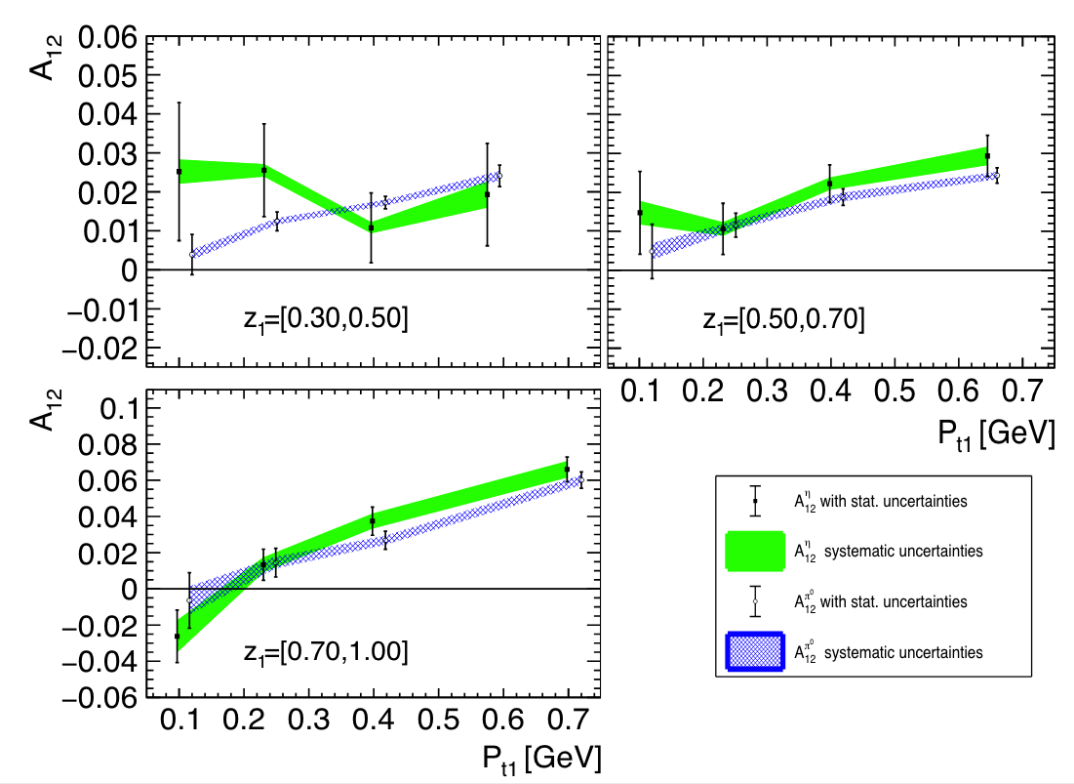






Outlook to Belle II

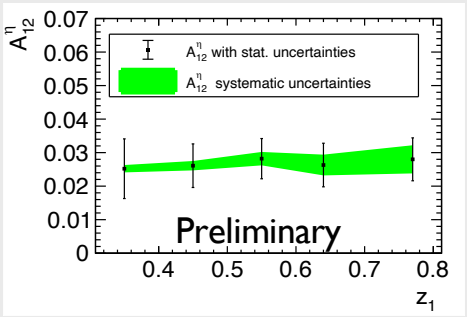
New π^0/η from Belle



$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} = \frac{\pi^0\pi^+ + \pi^0\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

$$\mathcal{R}_{12}^{\eta} = \frac{R_{12}^{\eta\pm}}{R_{12}^{L}} = \frac{\eta\pi^+ + \eta\pi^-}{\pi^+\pi^+ + \pi^-\pi^-}$$

- **Rise with $z_{1,2}$, similar to charged pions**

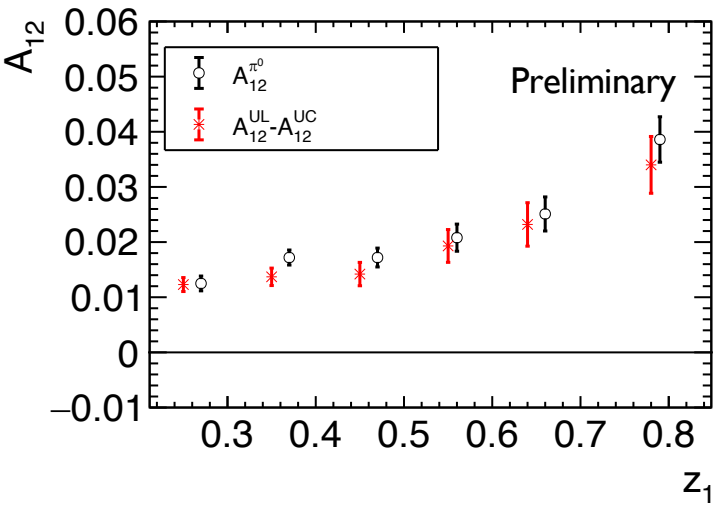


- η almost flat except large z

Consistency between Neutral and charged pions

$$\mathcal{R}_{12}^{\pi^0} = \frac{R_{12}^{0\pm}}{R_{12}^{L}} \approx 1 + \cos(\phi_{12}) \frac{\sin^2(\theta)}{1+\cos^2(\theta)} \times \left\{ \frac{5(H_1^{\perp,fav} + H_1^{\perp,dis}) \otimes (H_1^{\perp,fav} + H_1^{\perp,dis}) + 4H_{1,s\to\pi}^{\perp,dis} \otimes H_{1,s\to\pi}^{\perp,dis}}{5(D_1^{fav} + D_1^{dis}) \otimes (D_1^{fav} + D_1^{dis}) + 4D_{1,s\to\pi}^{dis} \otimes D_{1,s\to\pi}^{dis}} - \frac{10H_1^{\perp,fav} \otimes H_1^{\perp,dis} + 2H_{1,s\to\pi}^{\perp,dis} H_{1,s\to\pi}^{\perp,dis}}{10D_1^{fav} \otimes D_1^{dis} + 2D_{1,s\to\pi}^{dis} \otimes D_{1,s\to\pi}^{dis}} \right\}.$$

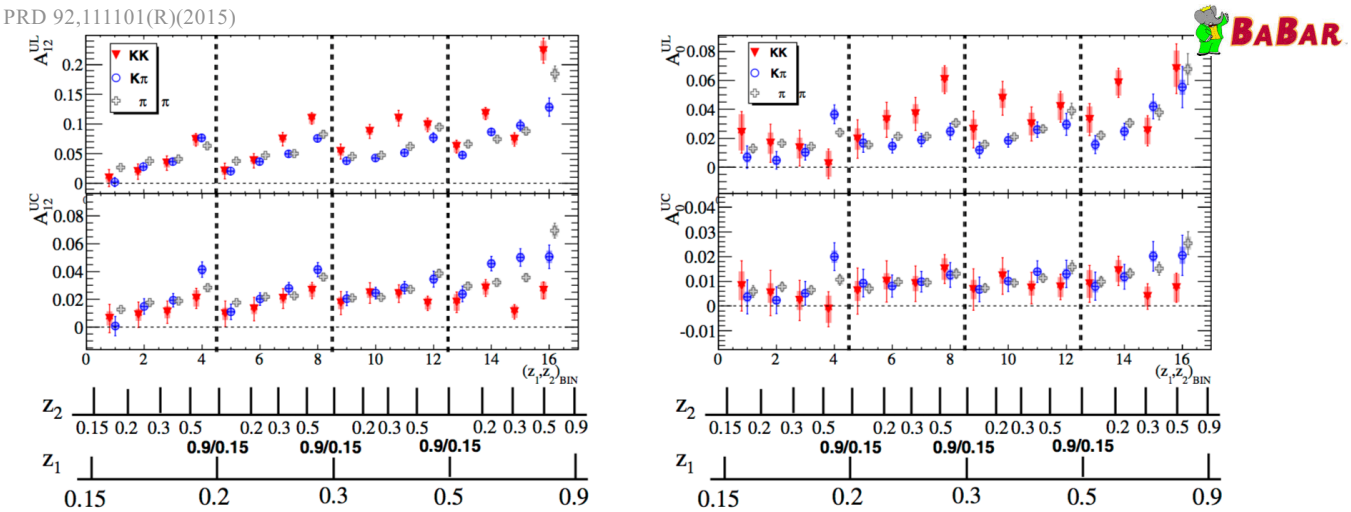
$$= A_{12}^{UL} - A_{12}^{UC} \ (Isospin)$$



Collins effect for kaon/pion pairs

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

PRD 92,111101(R)(2015)



- Rising of the asymmetry as a function of *z*:
  - more pronounced for U/L
- 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)

- Analysis performed differentially in bins of $z, P_{hT}, Thrust$ $(18\times20\times6)$