HADRONIZATION STUDIES AT BELLE AND BELLE II

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Entanglement 2018

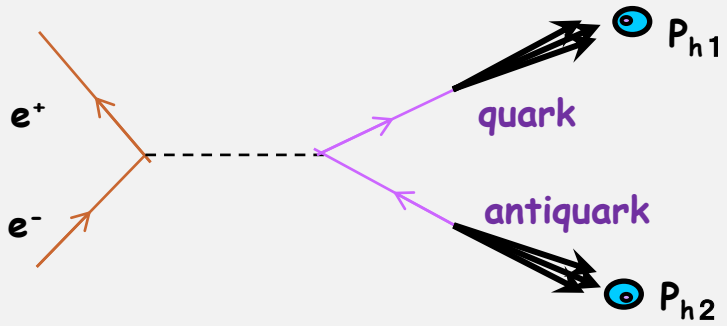
OUTLINE

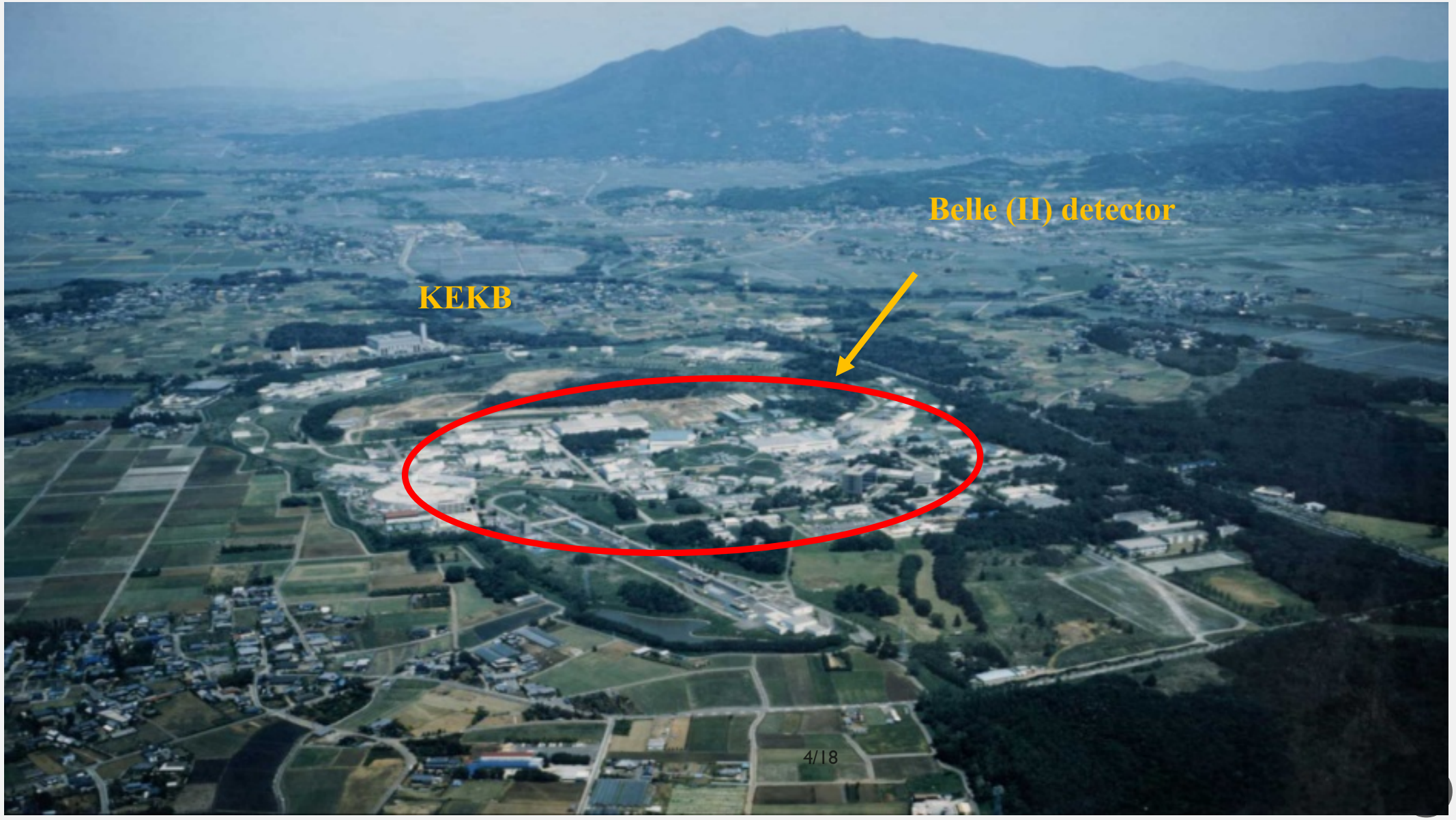
- Disclaimer: No research program on entanglement yet, this talk is mostly to point to opportunities and solicit input

- Motivation for hadronic physics at e+e-
- Belle Experiment and KEK
- Recent results and work in progress on hadronization of light quarks at Belle
  - Focus on single- and di-hadron cross-sections
  - →Connections to entanglement: Final state entropy, thermal behavior of sub-phase spaces (e.g. p_T)
- Belle II at SuperKEKB

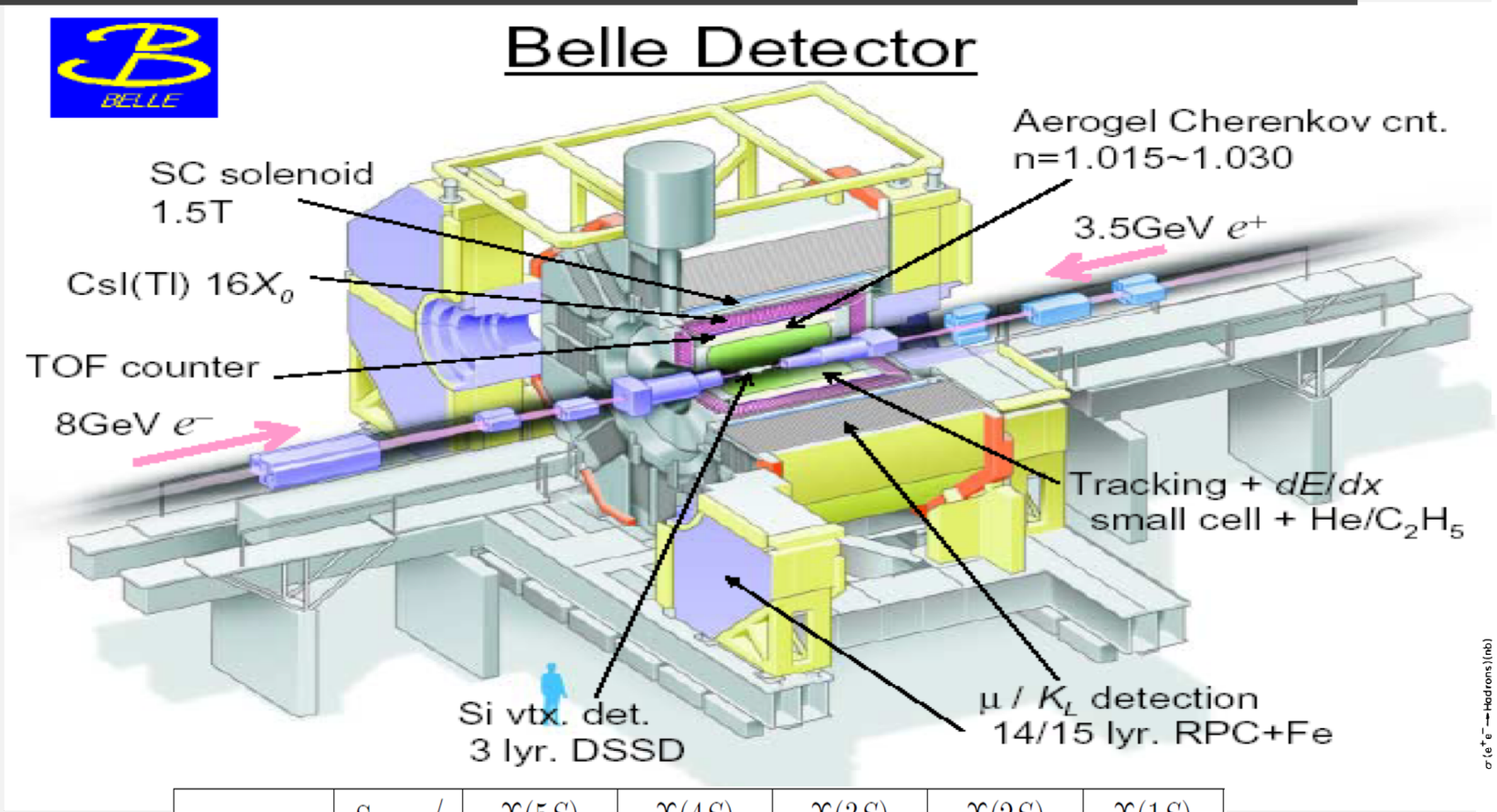
Why e^+e^-?

- Clean!
- Low density (no thermal behavior expected)
- Study of hadronization and global event properties
- Drawback:
  - Low multiplicities event-by-event studies more challenging
  - BUT: very high luminosity, can select high multiplicity events

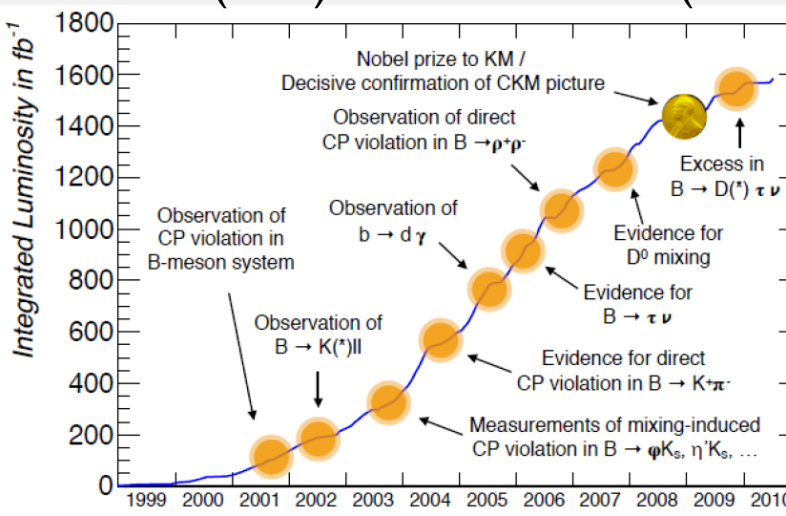


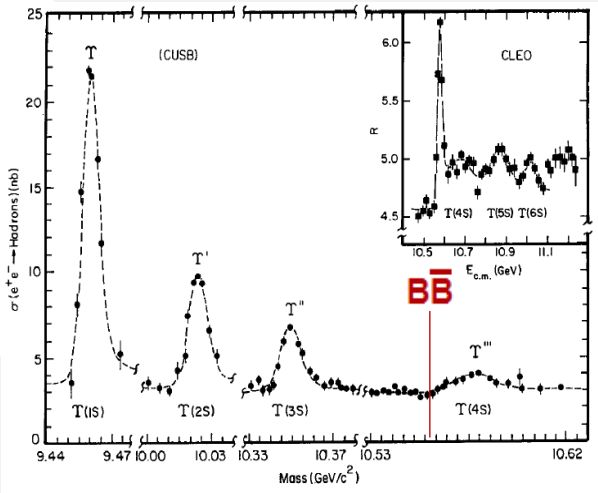

Belle (II) detector
KEKB

BELLE EXPERIMENT (1999 - 2010)



Belle/KEKB (KEK) and BaBar/PEP-II (SLAC

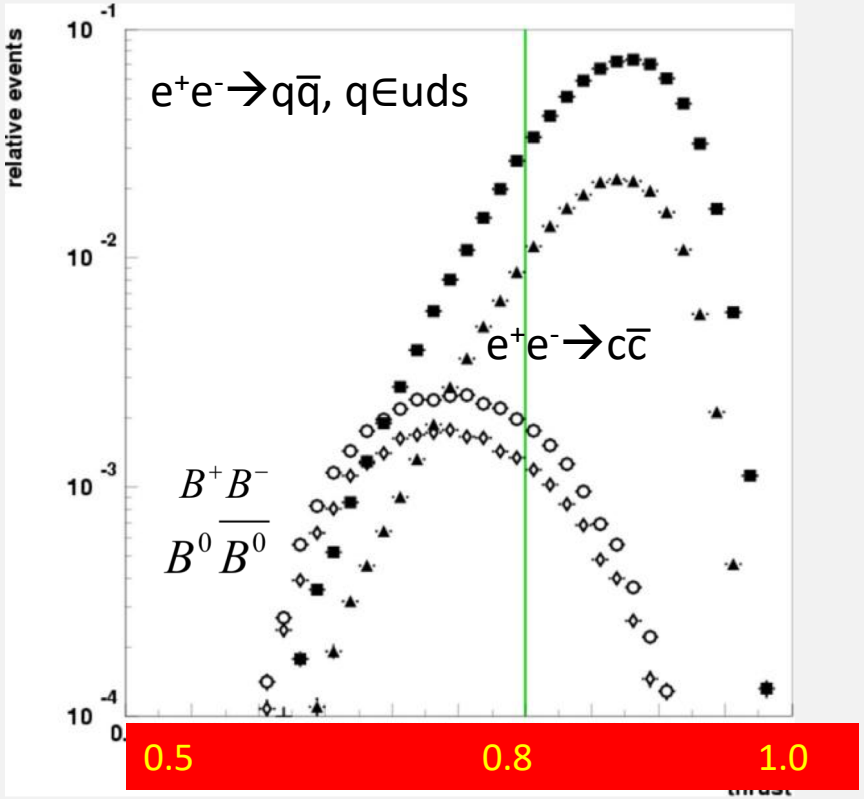




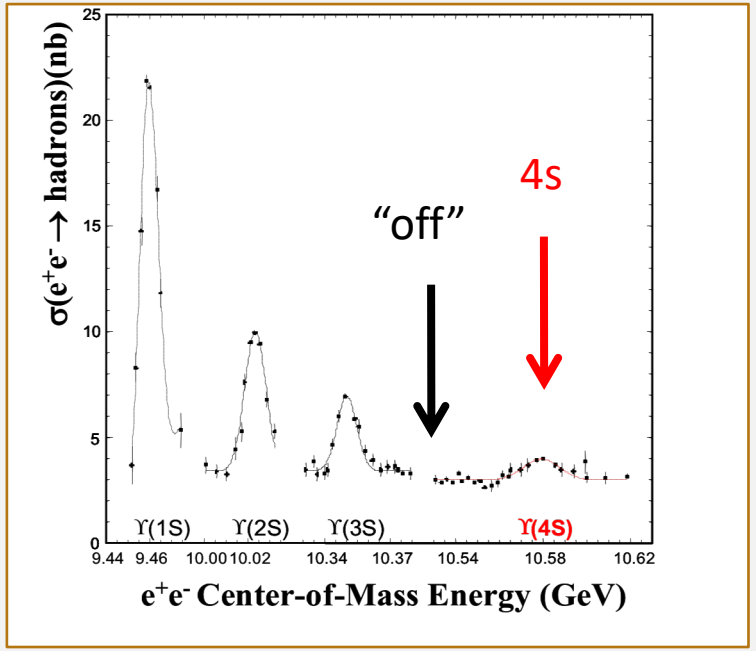
Experiment	Scans/ Off. Res. fb^{-1}	Υ(5S) 10876 MeV fb^{-1}	10^6	Υ(4S) 10580 MeV fb^{-1}	10^6	Υ(3S) 10355 MeV fb^{-1}	10^6	Υ(2S) 10023 MeV fb^{-1}	10^6	Υ(1S) 9460 MeV fb^{-1}	10^6
CLEO	17.1	0.4	0.1	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan		433	471	30	122	14	99	–	
Belle	100	121	36	711	772	3	12	25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

+About 4x10^6 events per fb in continuum

LOTS OF DATA OFF RESONANCE, EASY TO REMOVE RESONANCE BACKGROUND



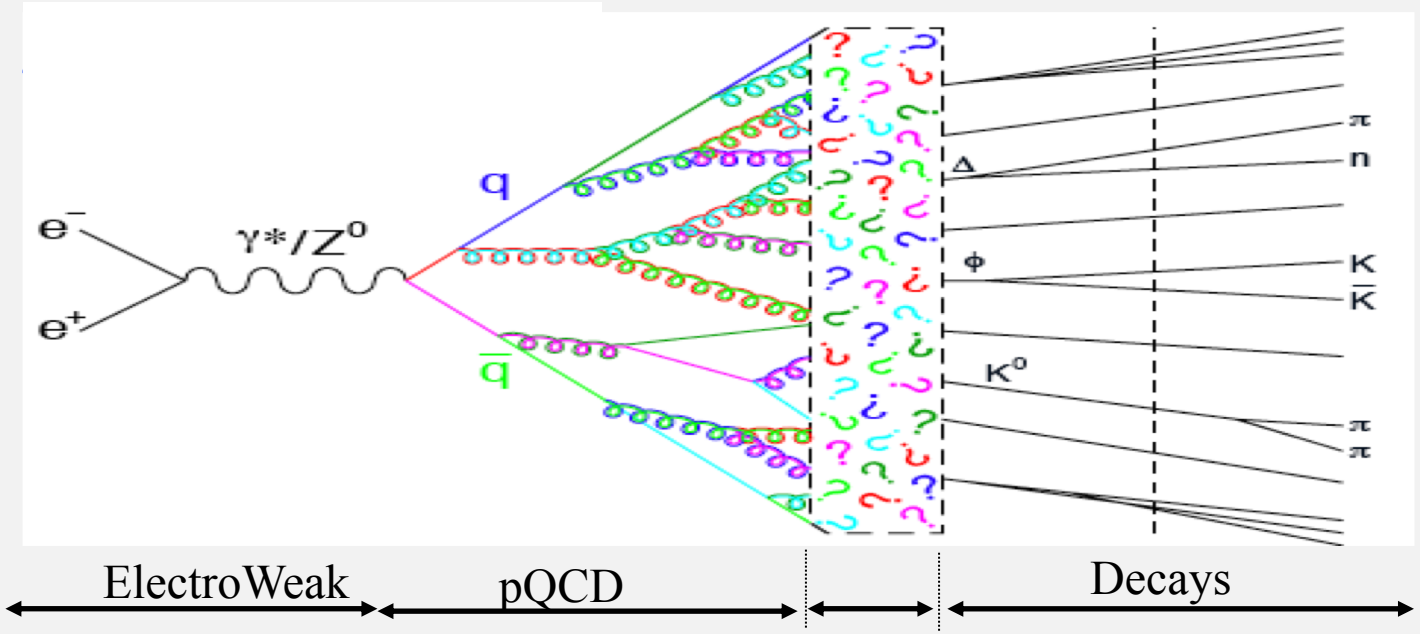
$$Thrust: T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$



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

FACTORIZED PICTURE OF E+E- →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]

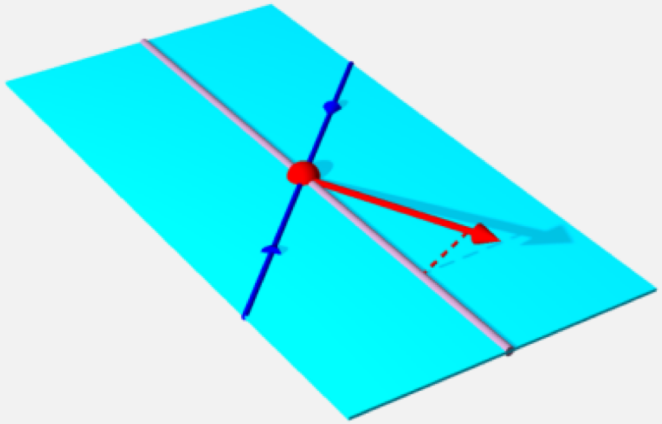


Detector

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

- Earlier machines (including LEP) focused on observables like jet structure
- High statistics/PID + progress in SIDIS →B-factory program focuses on fragmentation functions (and spectroscopy)

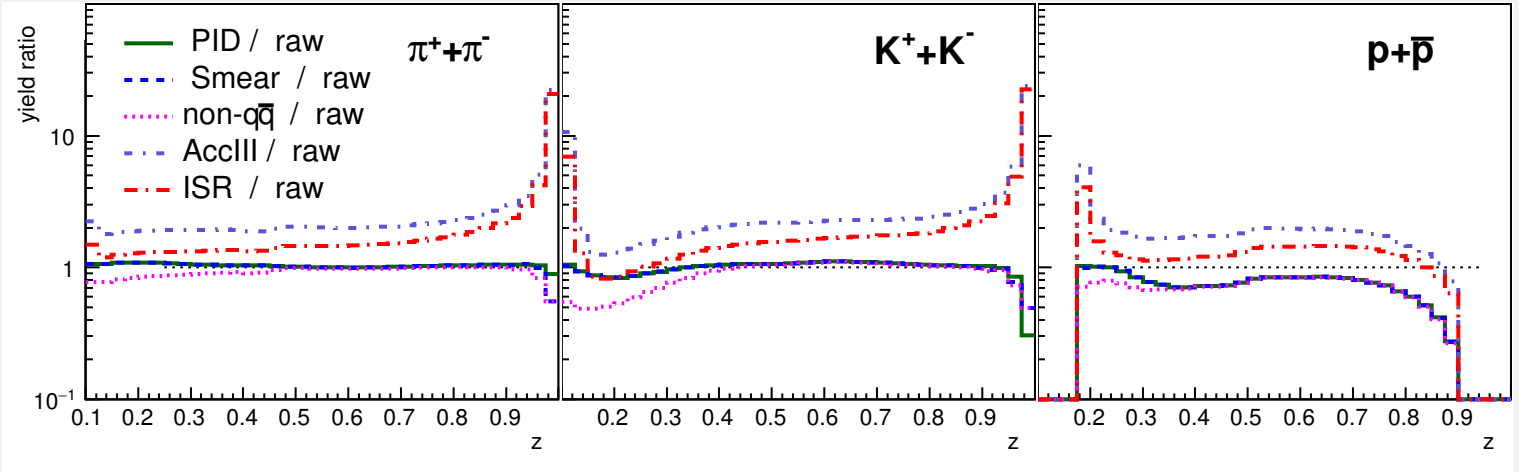
SPIN AVERAGED FFs FROM X-SECTION MEASUREMENTS FOR CHARGED PION, KAONS AND PROTONS



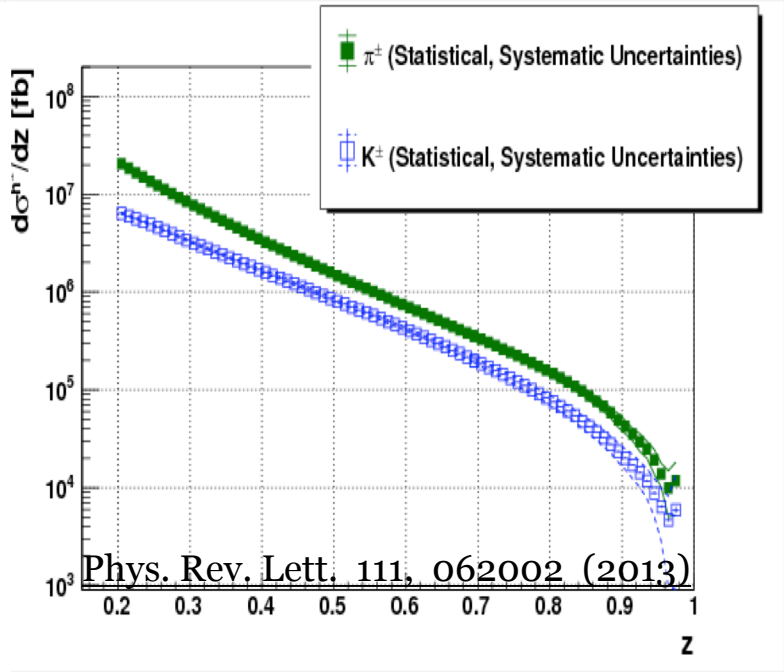
$$\sigma^h(z, Q^2, p_T) \propto \sum_q e_q^2 \left(D^h_{1,q}(z, Q^2, p_T) + D^h_{1,\bar{q}}(z, Q^2, p_T) \right)$$

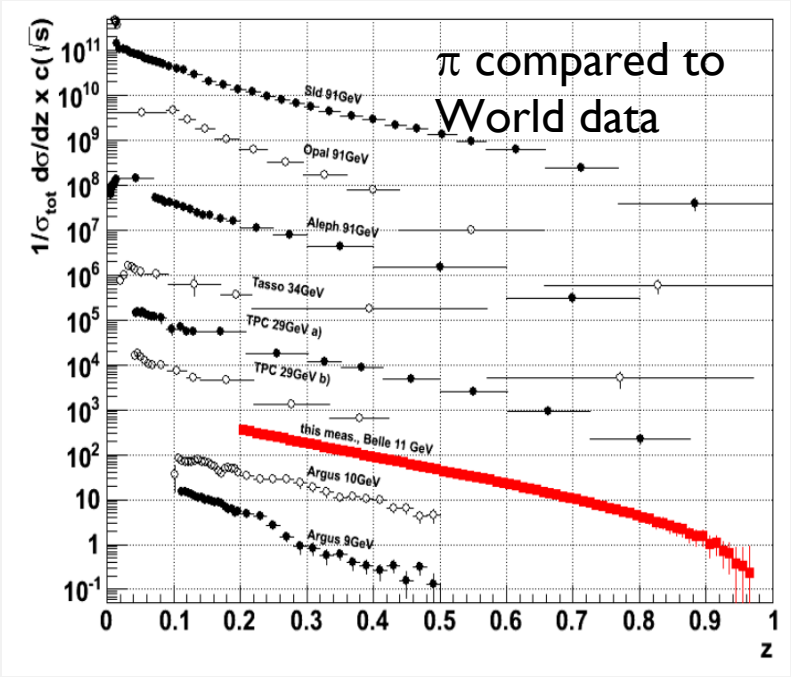
FROM YIELDS TO CROSS-SECTIONS

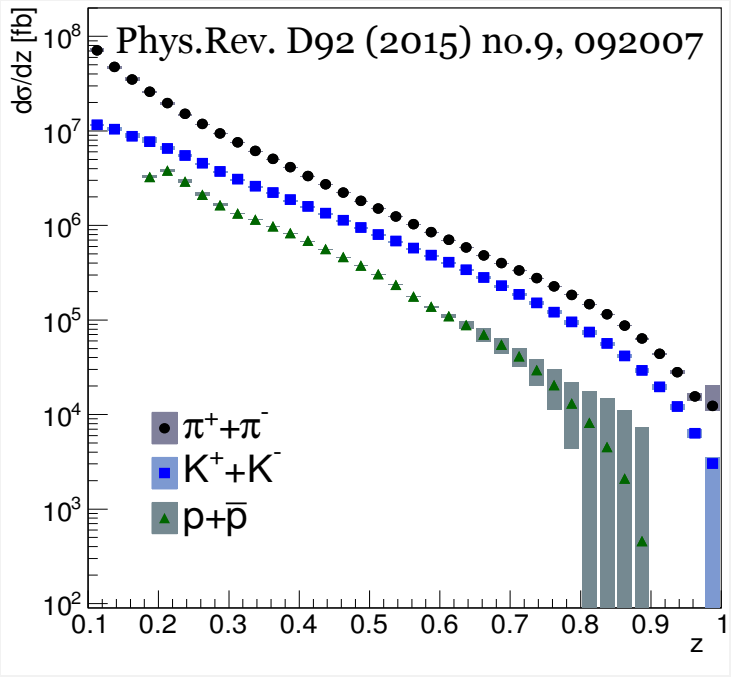
- Hadron yields undergo a number of corrections
  - Particle (mis) identification [e. g., not every identified pion was a pion]
  - smearing unfolding [e.g., measured and true momentum might differ]
  - non-qq processes [e.g., two-photon processes, Y-> BB, …]
  - 4π" correction [selection criteria and limited geometric acceptance]
  - QED radiation [initial-state radiation (ISR)]
  - optional: weak-decay removal (e.g., "prompt fragmentation")
- Collins asymmetries also corrected for false asymmetries and maybe for qq-axis (mis)reconstruction
- partially different approaches in different experiments/analyses



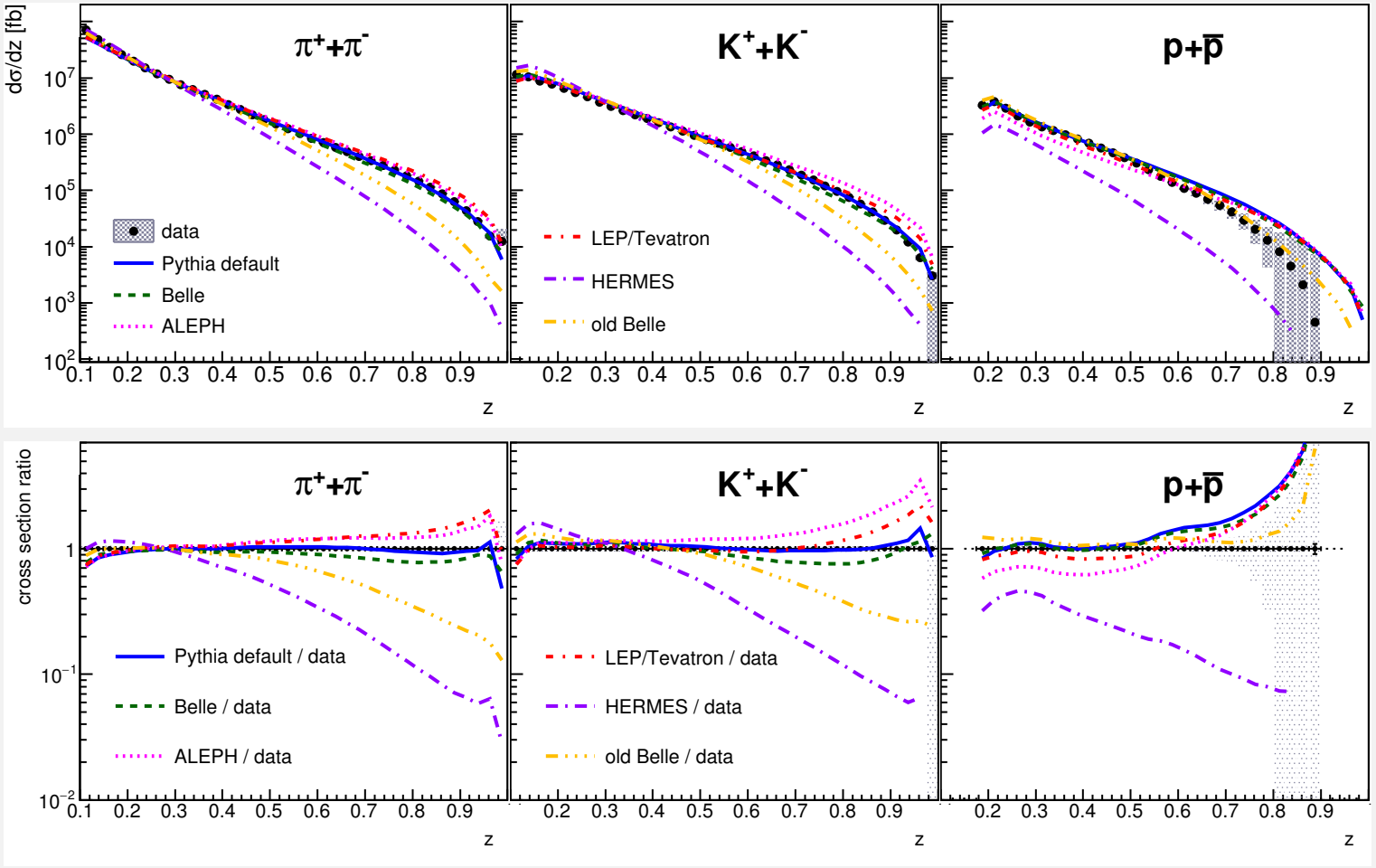
CROSS SECTIONS FOR SINGLE HADRONS

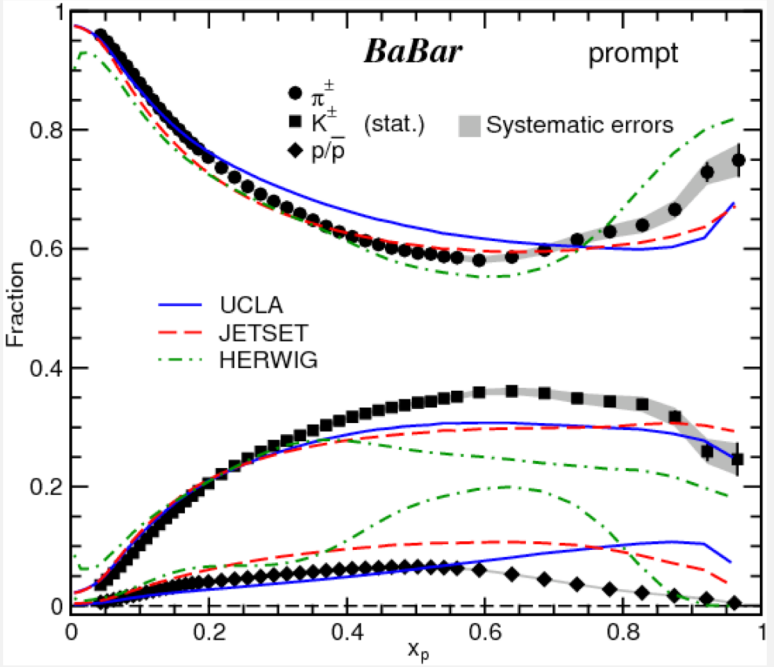






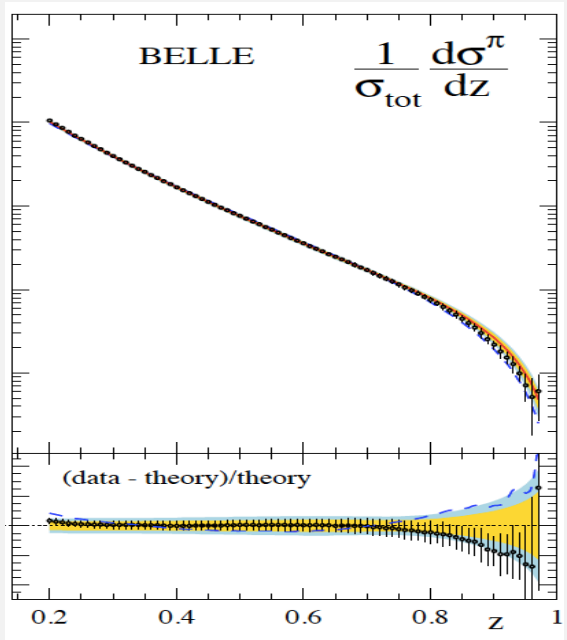
COMPARISON TO MC

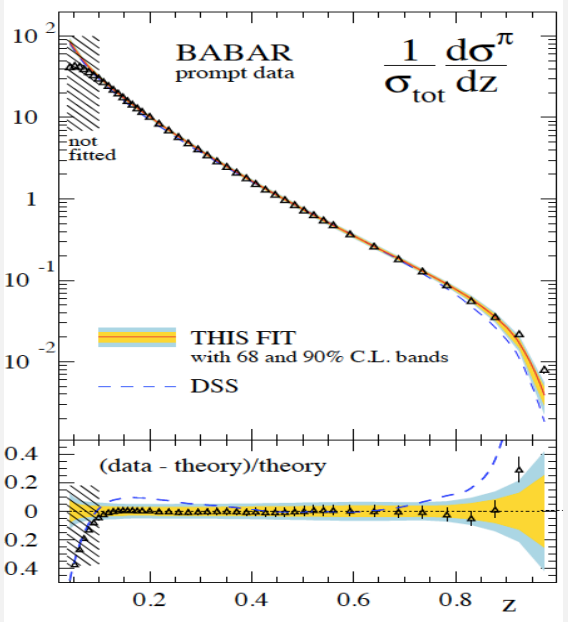




- Agreement with Belle MC reasonable with the exception of high z K/p

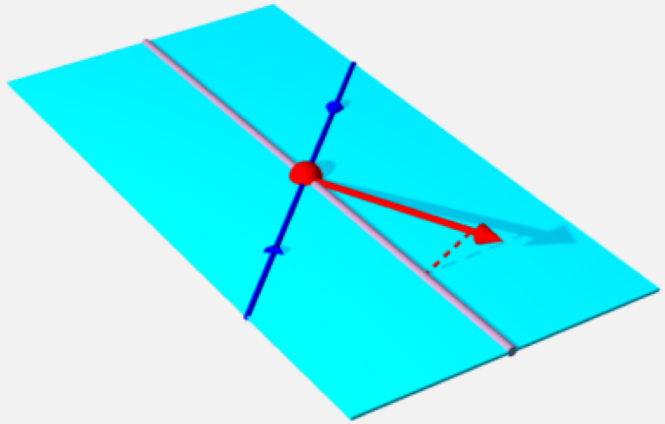
DSS(E,H-P) Fit

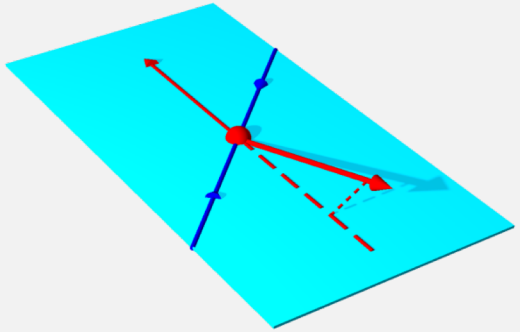




- pQCD fit at NLO
- Good agreement between Belle and BaBar however, there seems to be a trend away from the fit for the Belle data at high z
- Low z data from BaBar also agrees with Modified Leading Log predictions

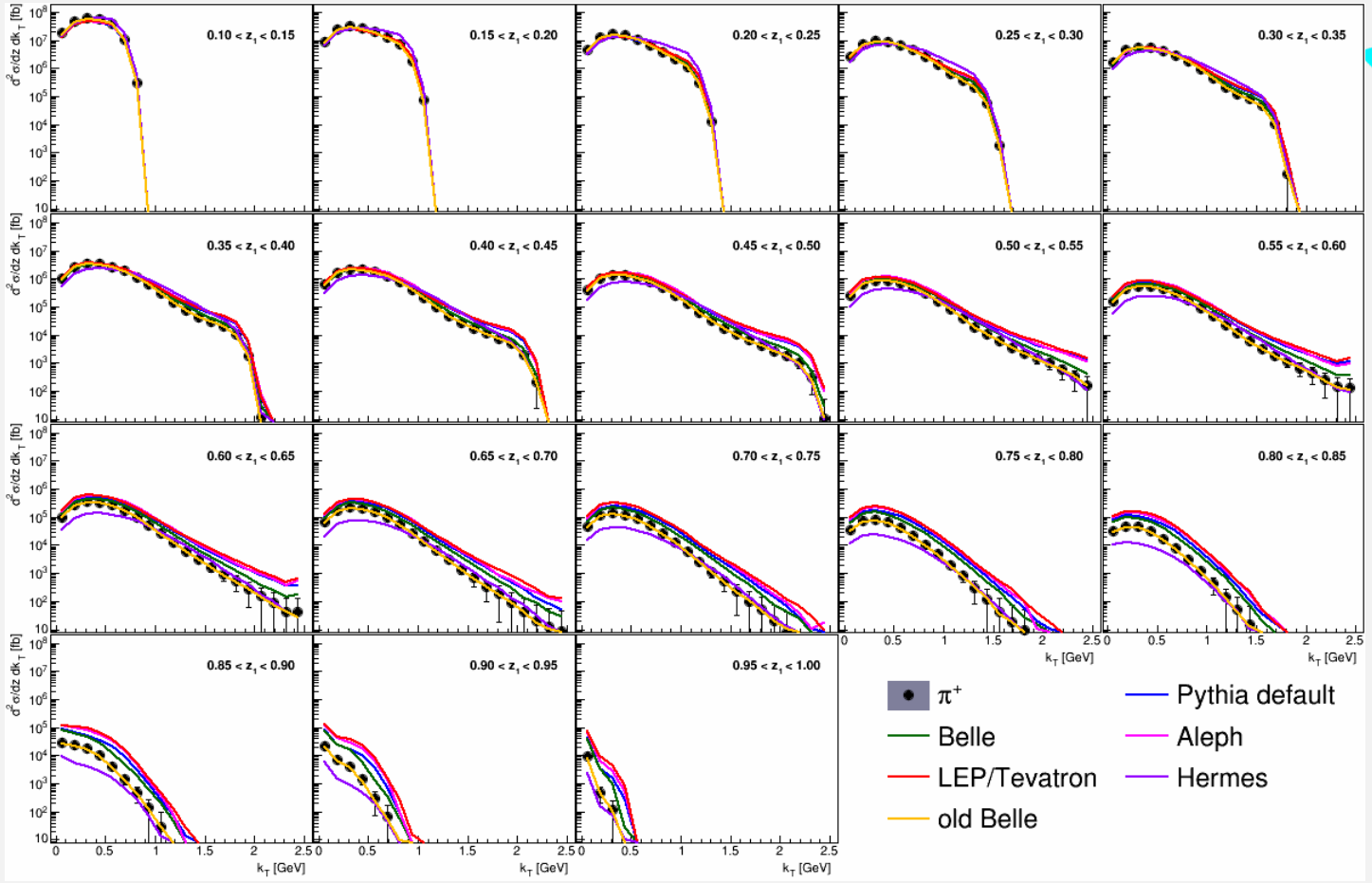
TRANSVERESE MOMENTUM DEPENDENCE

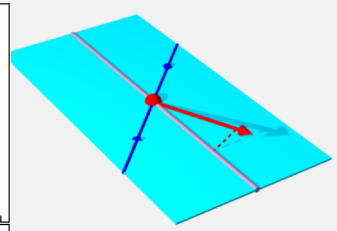




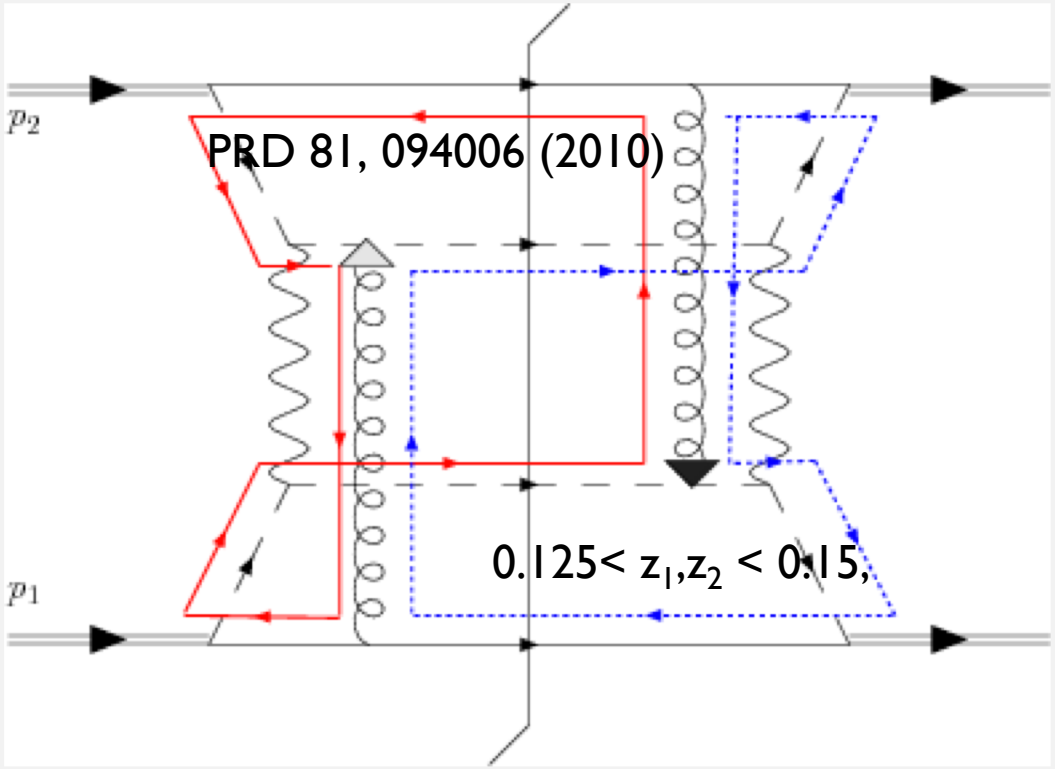
- Two different defininitons
  - Vs thrust direction
  - Relative in back-to-back hadrons (related: q_T, relative transv. momentum of γ^*)

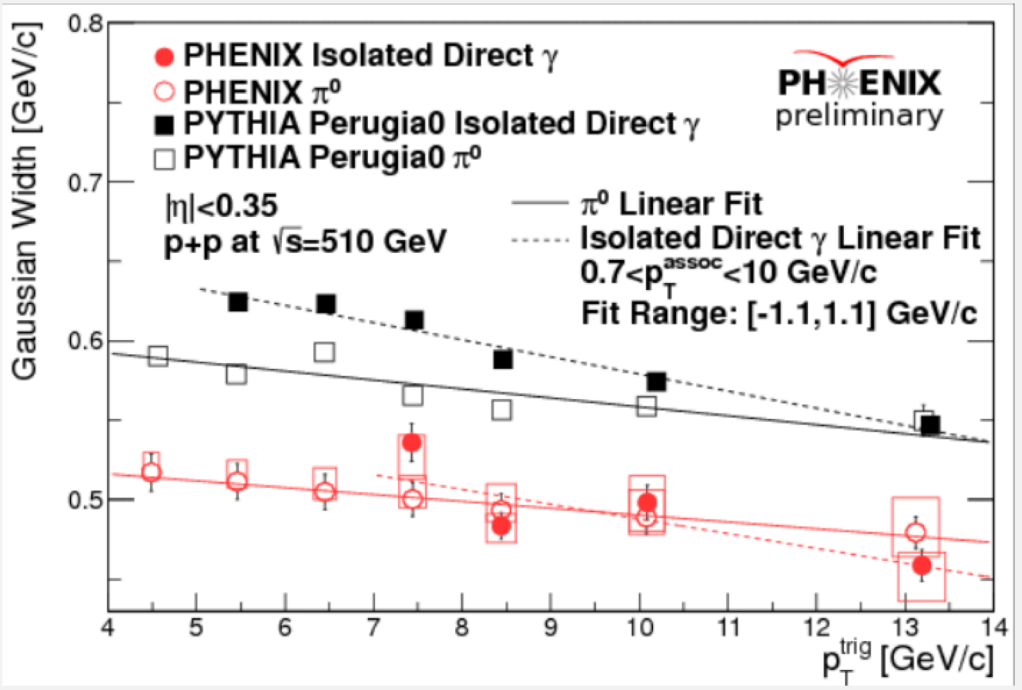
MC EXAMPLE OF K_T SENSITIVITIES

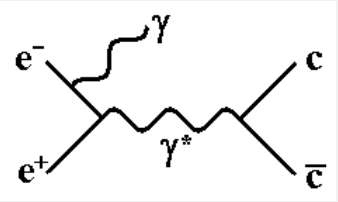




CONNECTION TO COLOR ENTANGLEMENT?

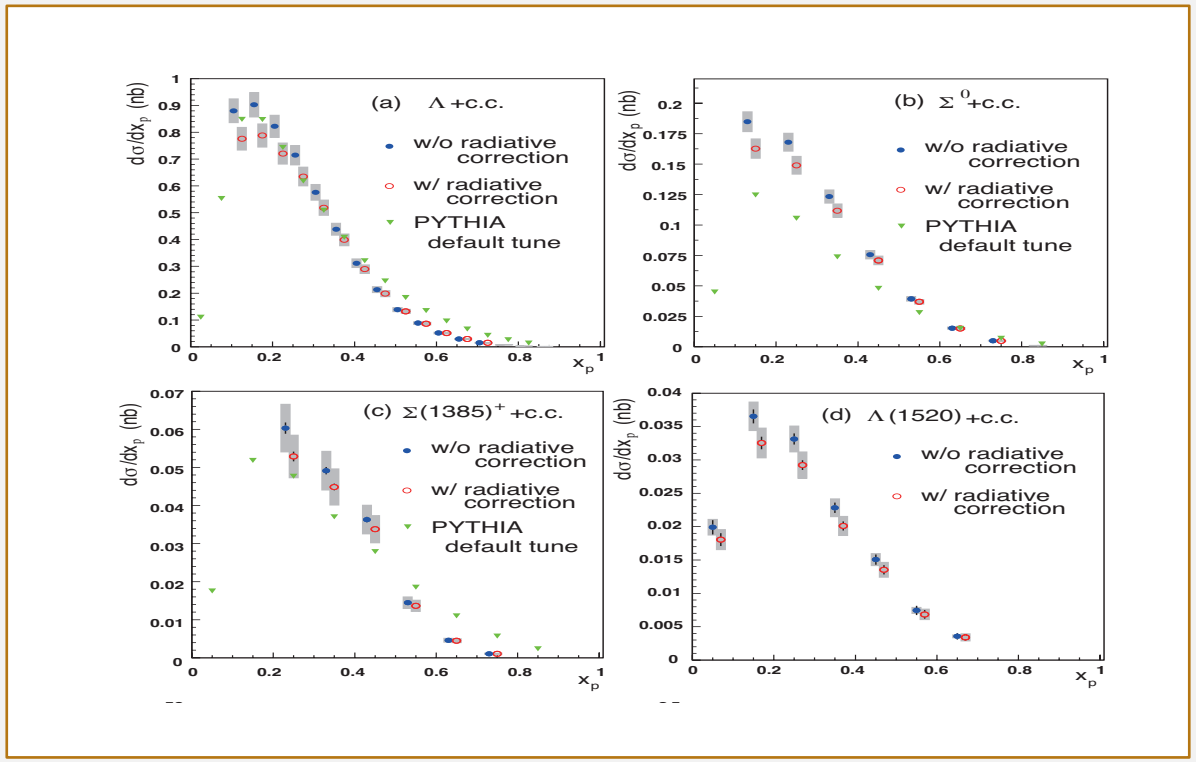


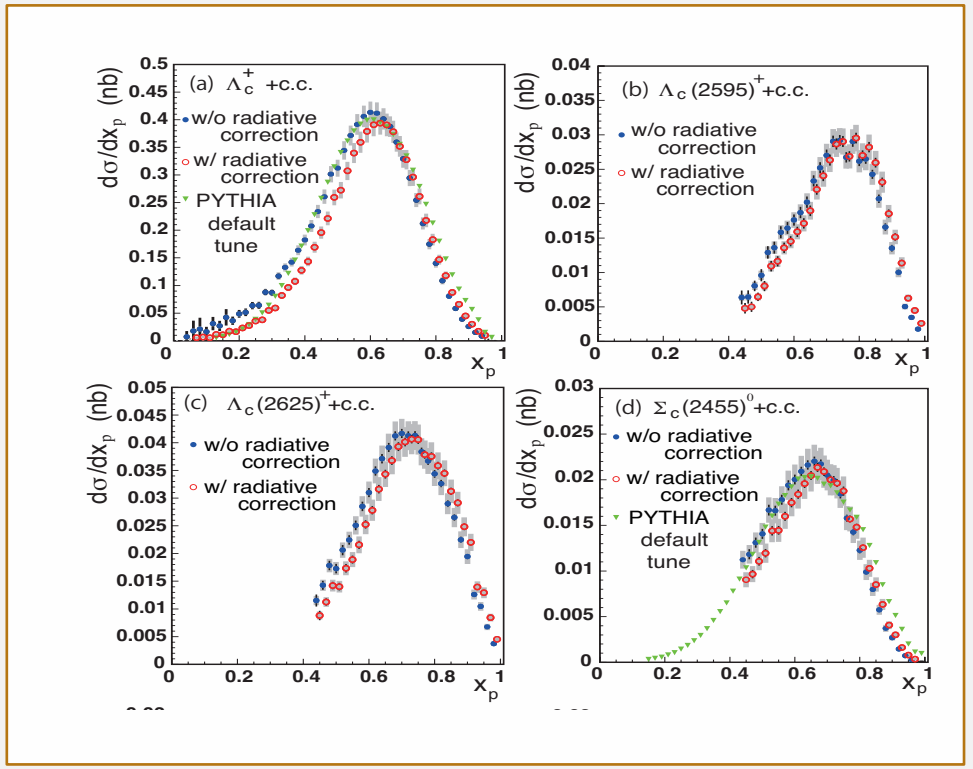




- Color entanglement might lead to factorization breaking
- p_T 'narrowing' observed at RHIC, at variance with pQCD but in good agreement with Pythia
- At Belle can study transverse momentum distribution as a function of Q^2 using ISR

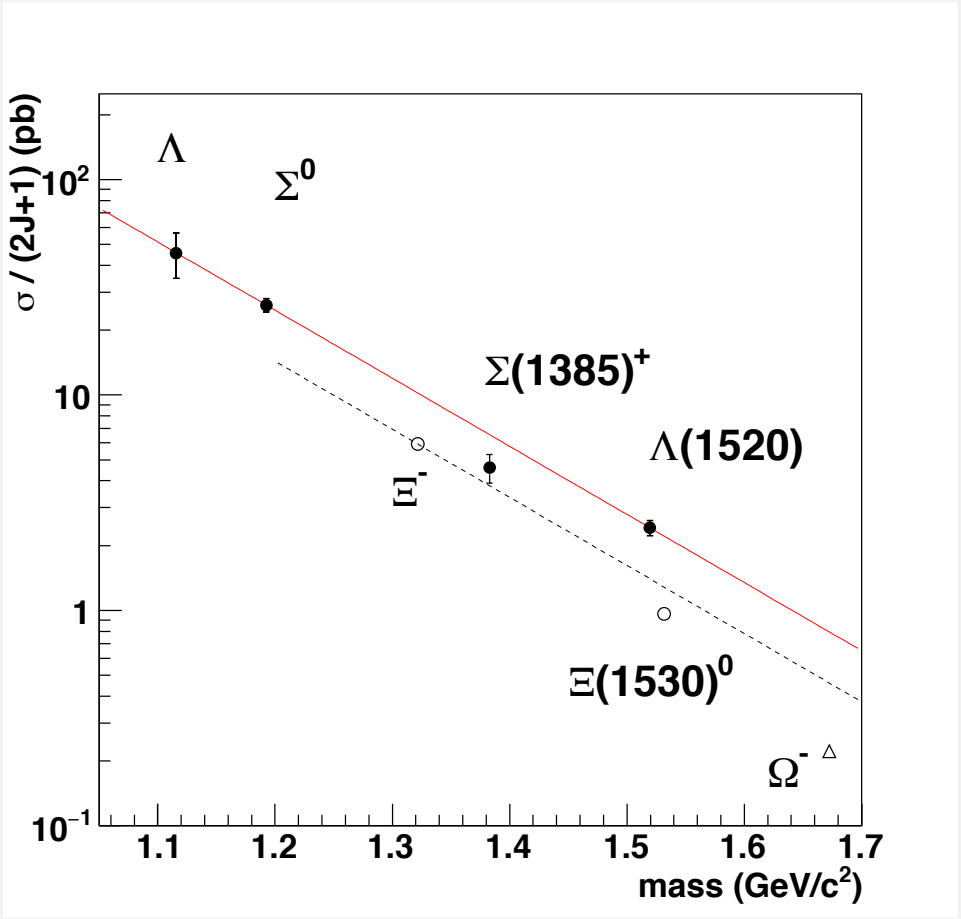
PRODUCTION OF CHARMED AND NON CHARMED BARYONS AS A TEST OF FRAGMENTATION MODELS

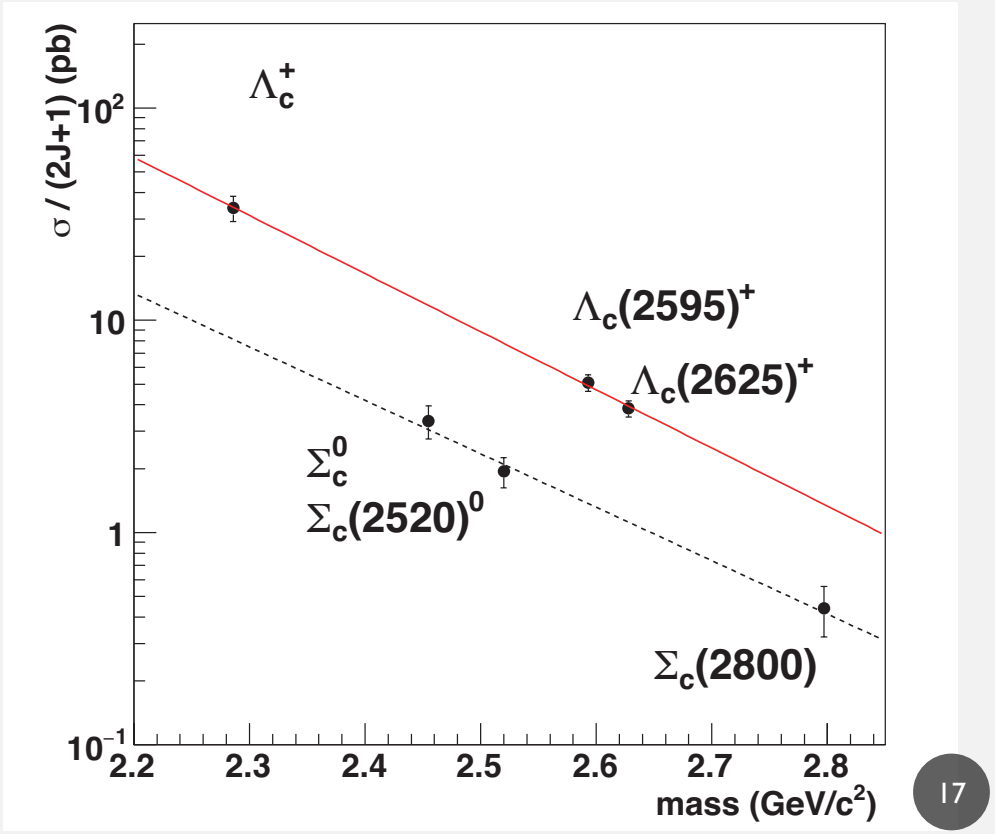




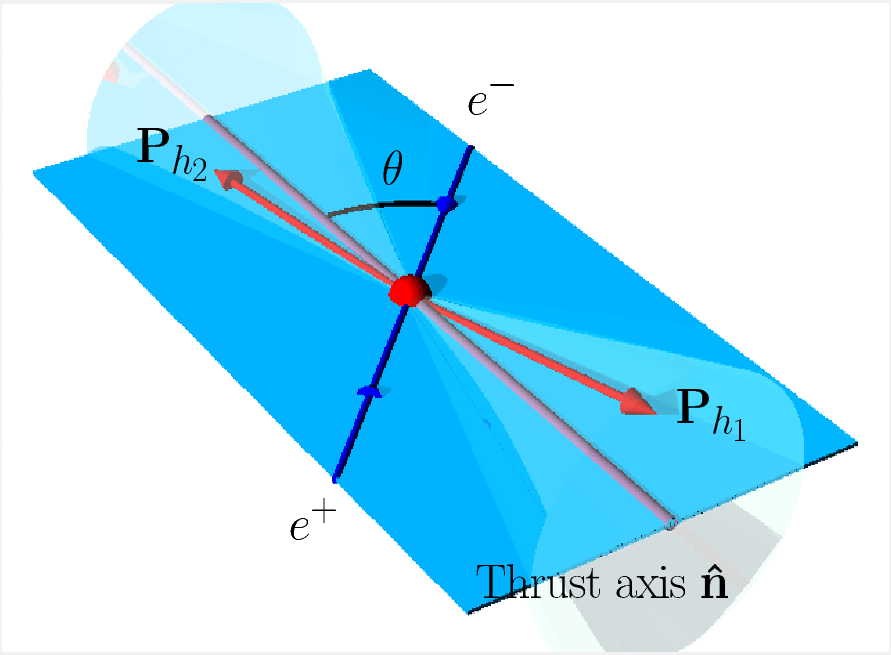
- Ξ^-, $\Xi(1530)$, Ω^- Σ_c, Ω_c, Ξ_c not shown

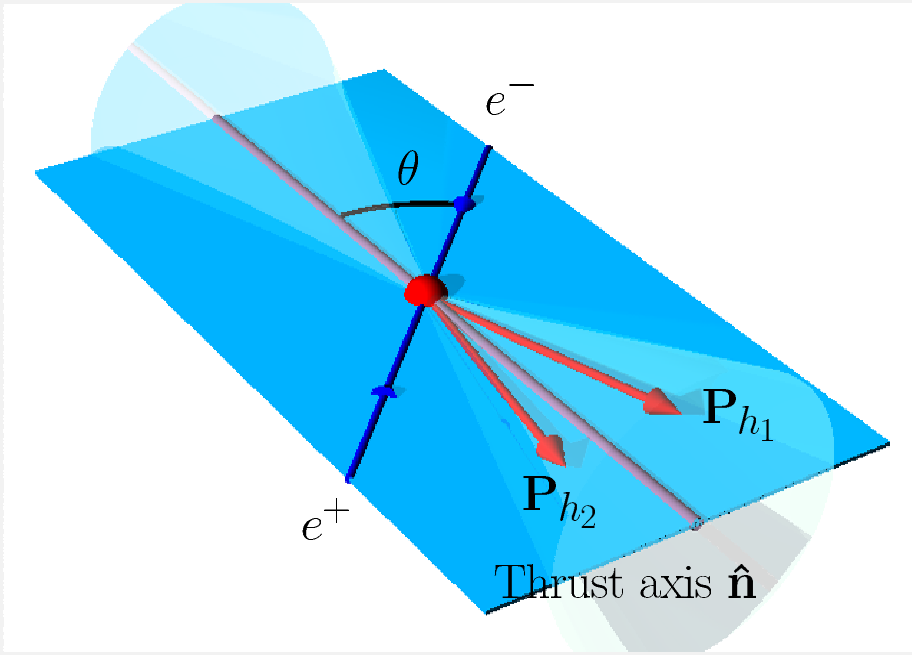
MASS DEPENDENCE CONFIRMS DIQUARK MODEL





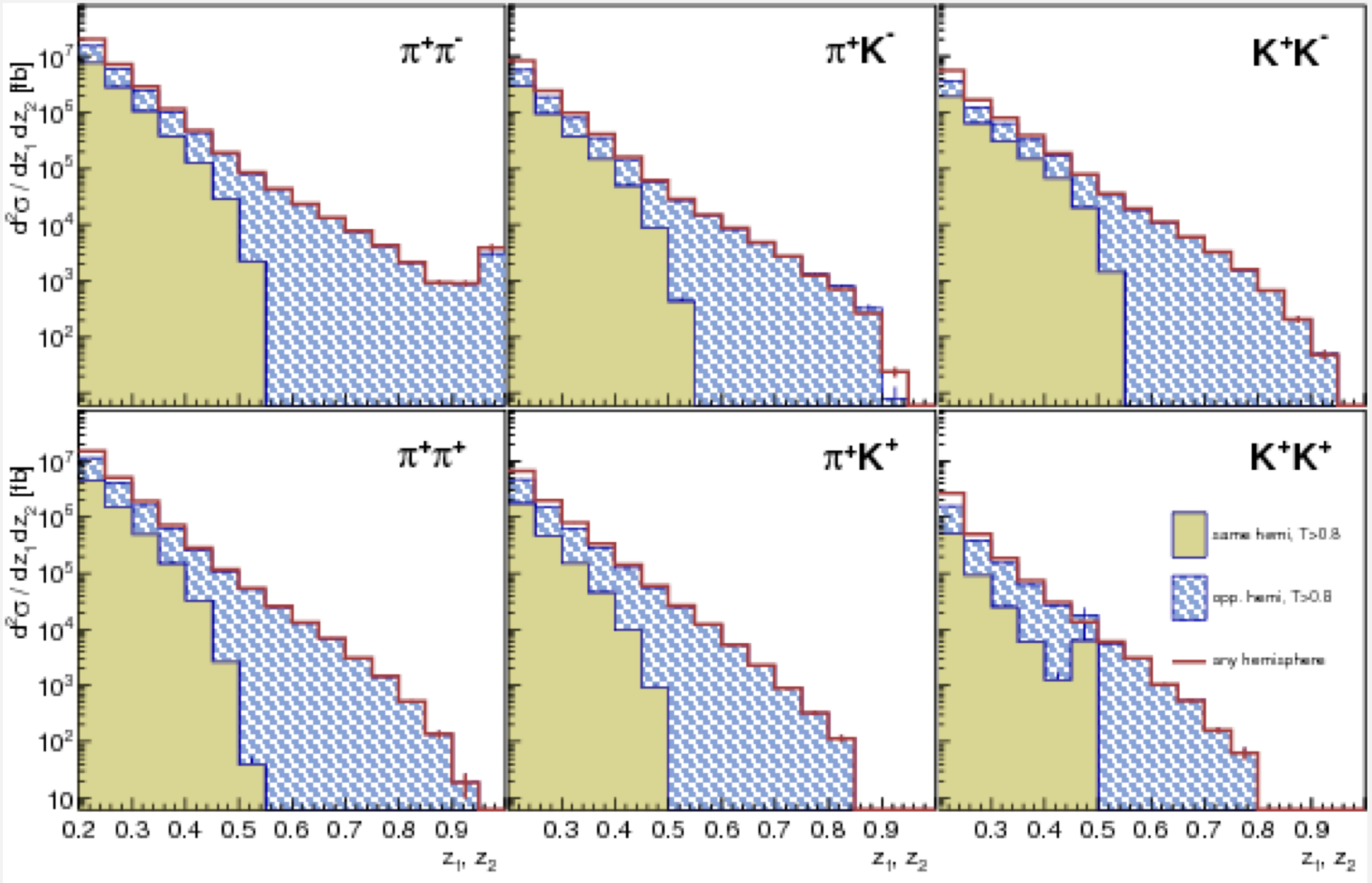
PRODUCTION OF HADRON PAIRS



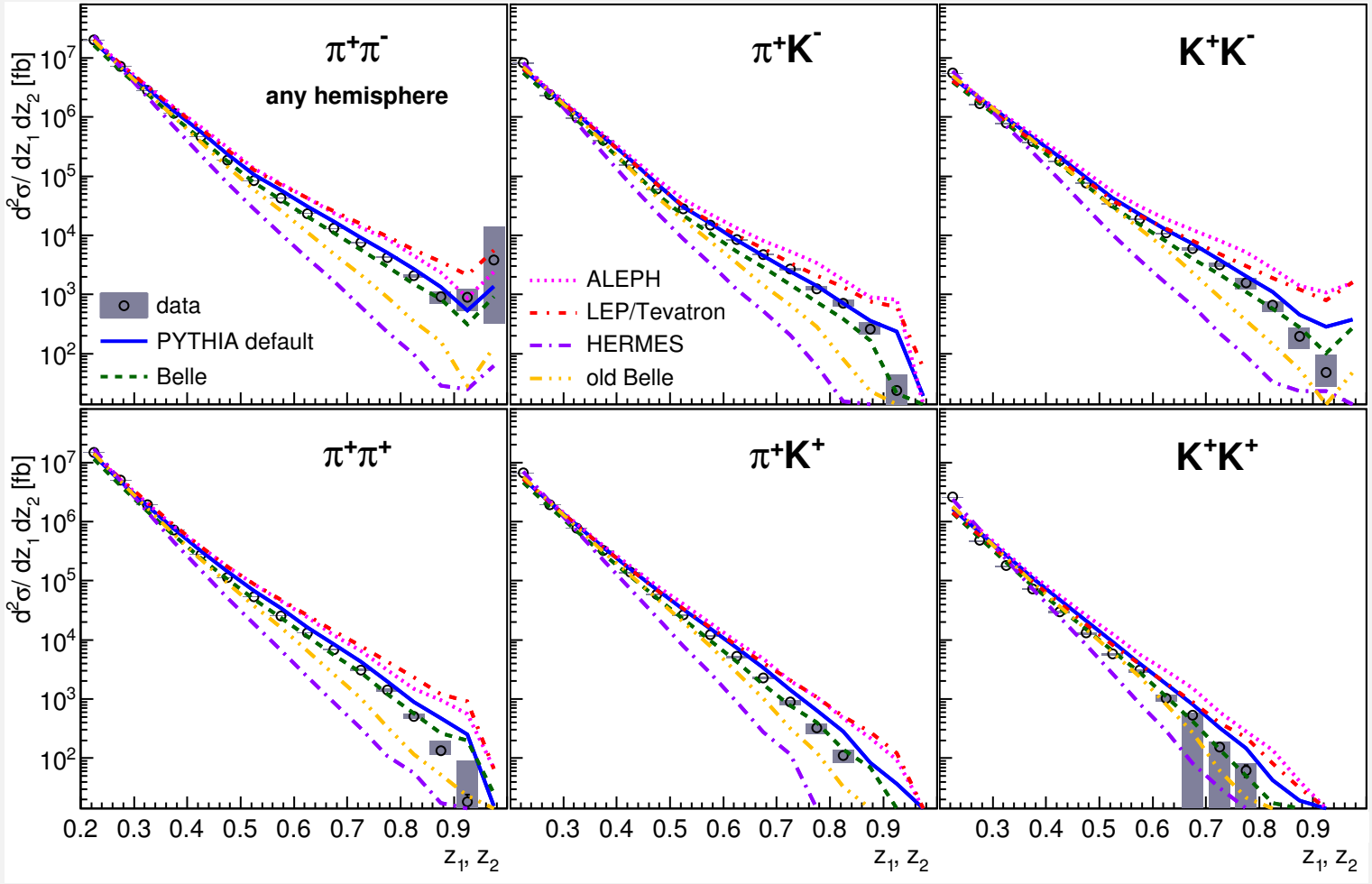


- From Phys.Rev. **D**92 (2015) no.9, 092007 and Phys.Rev. **D**96 (2017) no.3, 032005

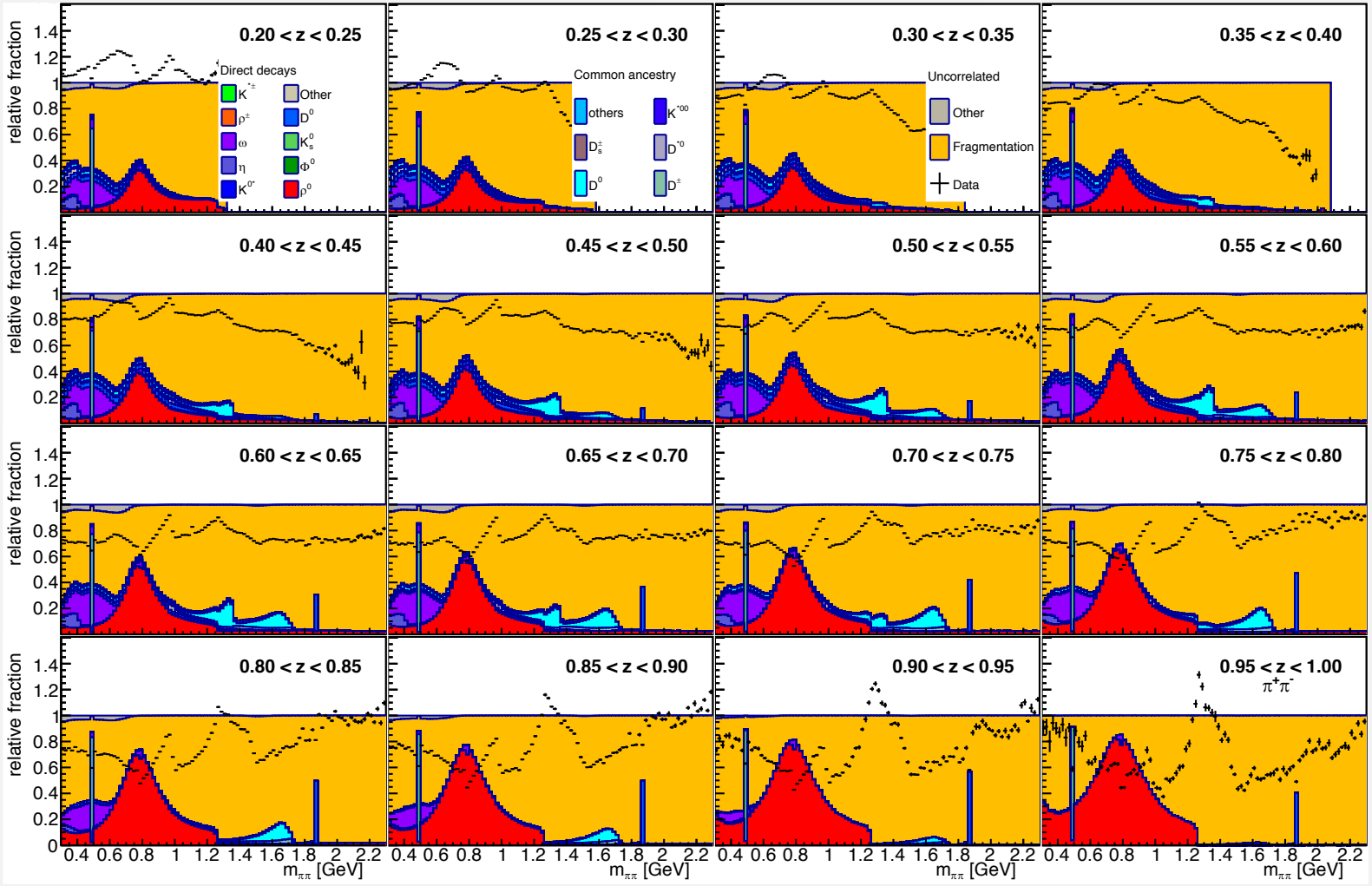
TOPOLOGY: SAME HEMISPHERE VS OPPOSITE HEMISPHERES



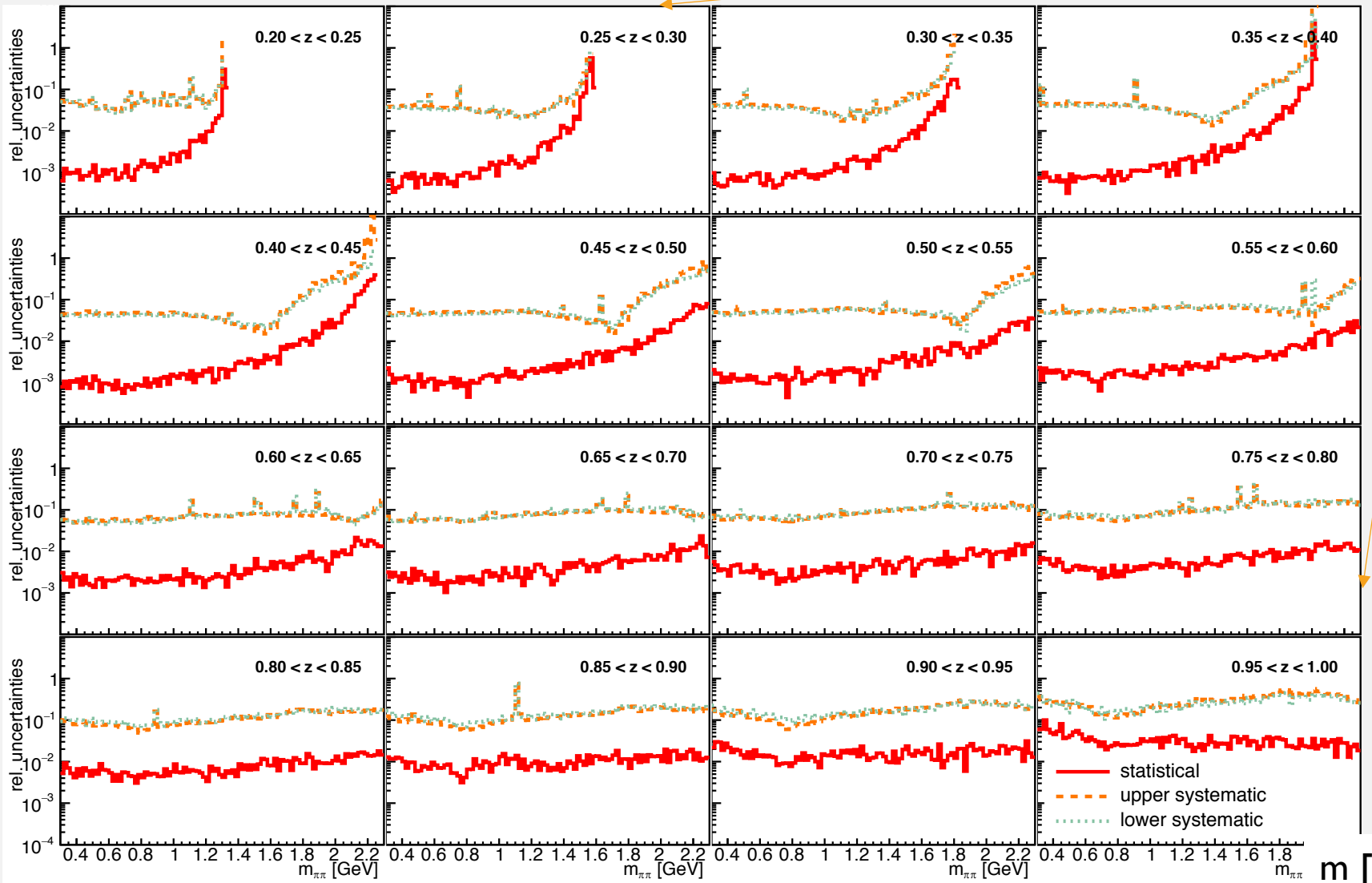
CROSS-SECTION COMPARED TO MC



DECOMPOSITION ACCORDING TO PYTHIA



RESULTS SYSTEMATICS DOMINATED

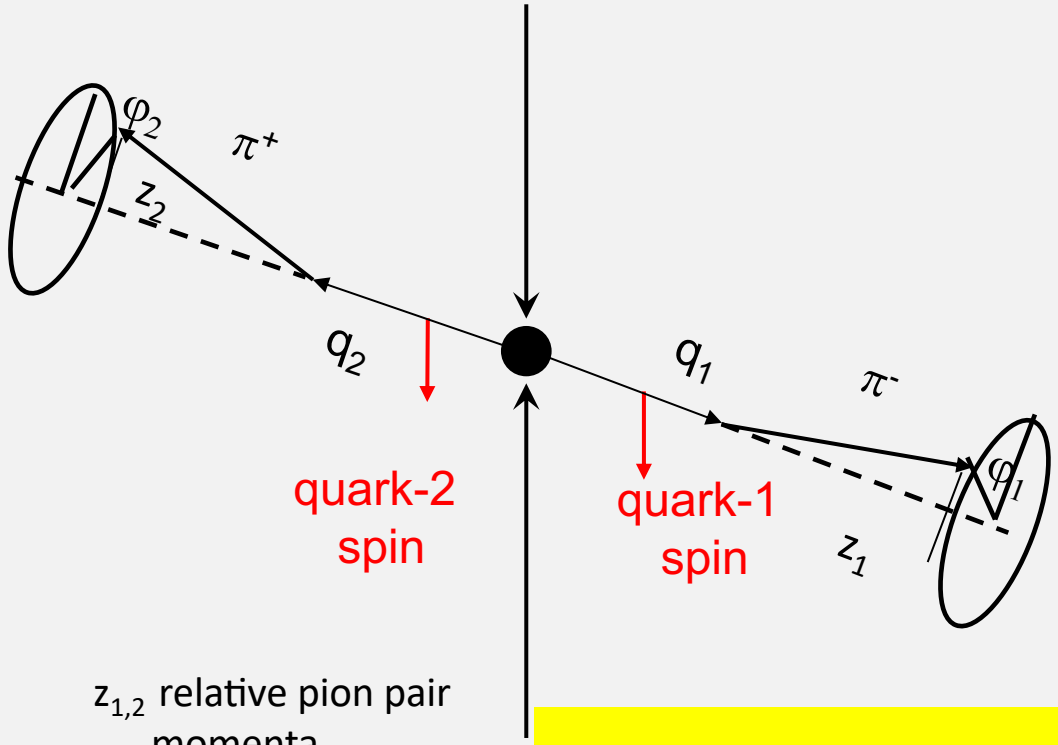


- Low z: Dominated by PID uncertainties
  Belle II prospects: Improved PID, higher statistics to improve uncertainties on PID
- High z: Dominated by ISR uncertainties
  Belle II prospects: better understanding of ISR radiation with better statistics
-

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

m [GeV]

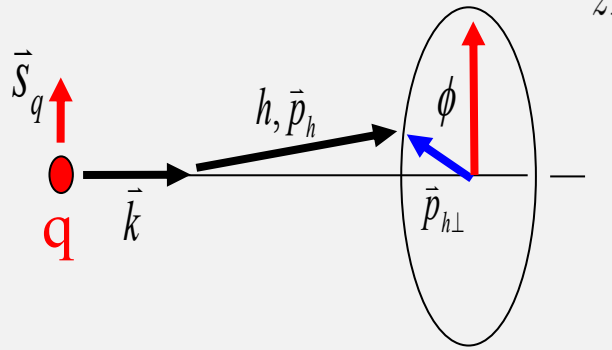
CORRELATION MEASUREMENTS IN E+E-



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

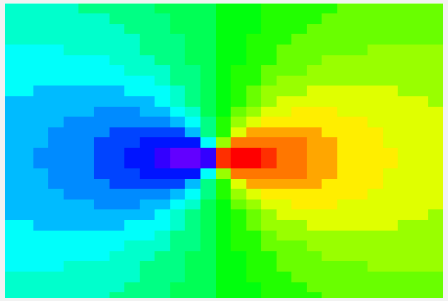
J. Collins, Nucl. Phys. B396, (1993) 161

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



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

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



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

Collins Effect vs (z_1,z_2): comparisons

Unlike/**L**ikesign

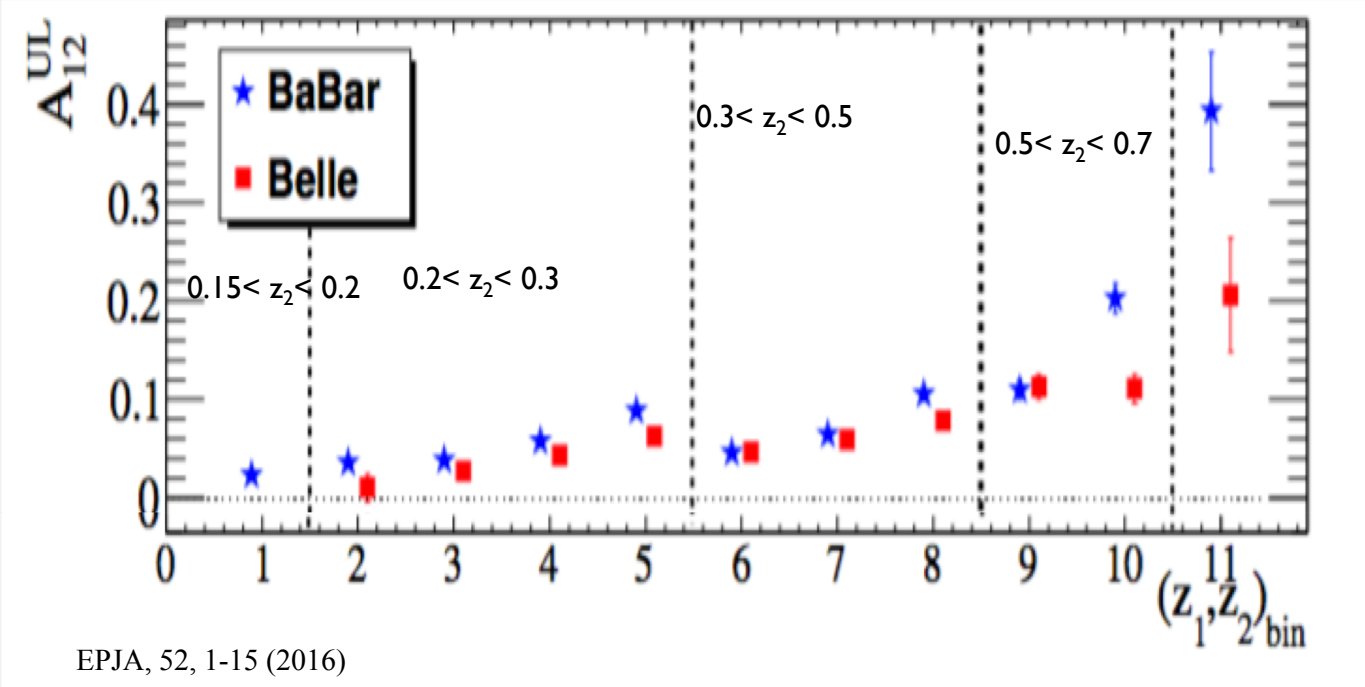
Ratios to cancel acceptance effects

<u>Unlike:</u>

fav*fav+dis*dis

<u>Like:</u>

fav*dis



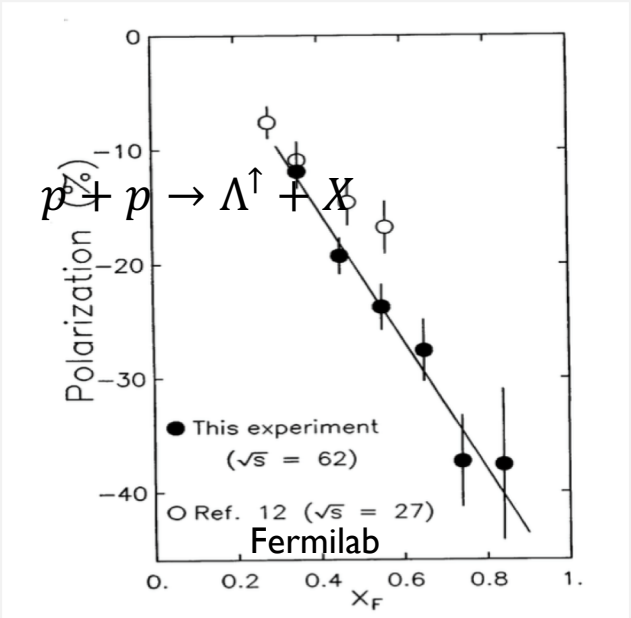
EPJA, 52, 1-15 (2016)

•First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ $\sqrt{s} \sim 10.6$ 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 @ $\sqrt{s} \sim 10.6$ 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))

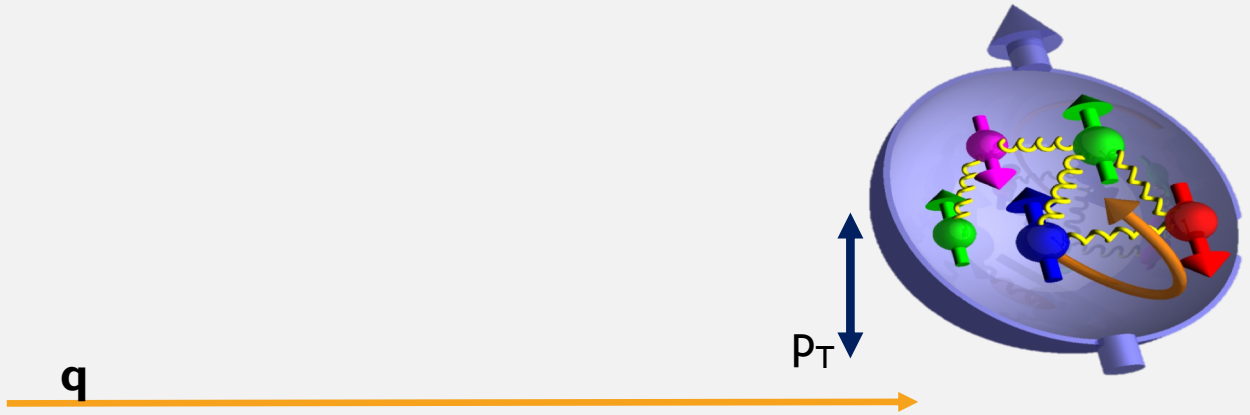
POLARIZED HYPERON PRODUCTION

- Large Λ transverse polarization in unpolarized pp collision **PRL36, 1113 (1976); PRL41, 607 (1978)**
- Caused by polarizing FF $D_{1T}^{\perp}(z, p_{\perp}^2)$?
- Polarizing FF is T-odd andchiral-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)**

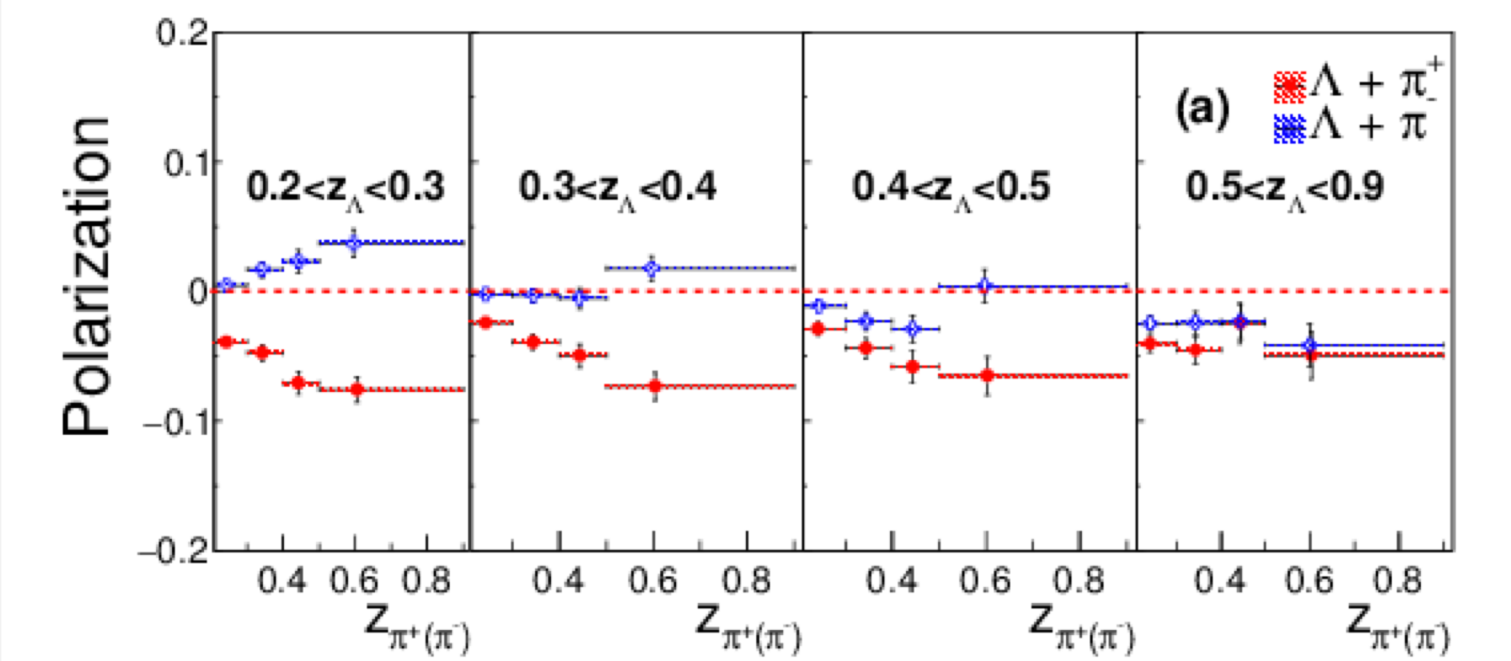


ISR data
(**Phys.Lett. B185 (1987) 209**)

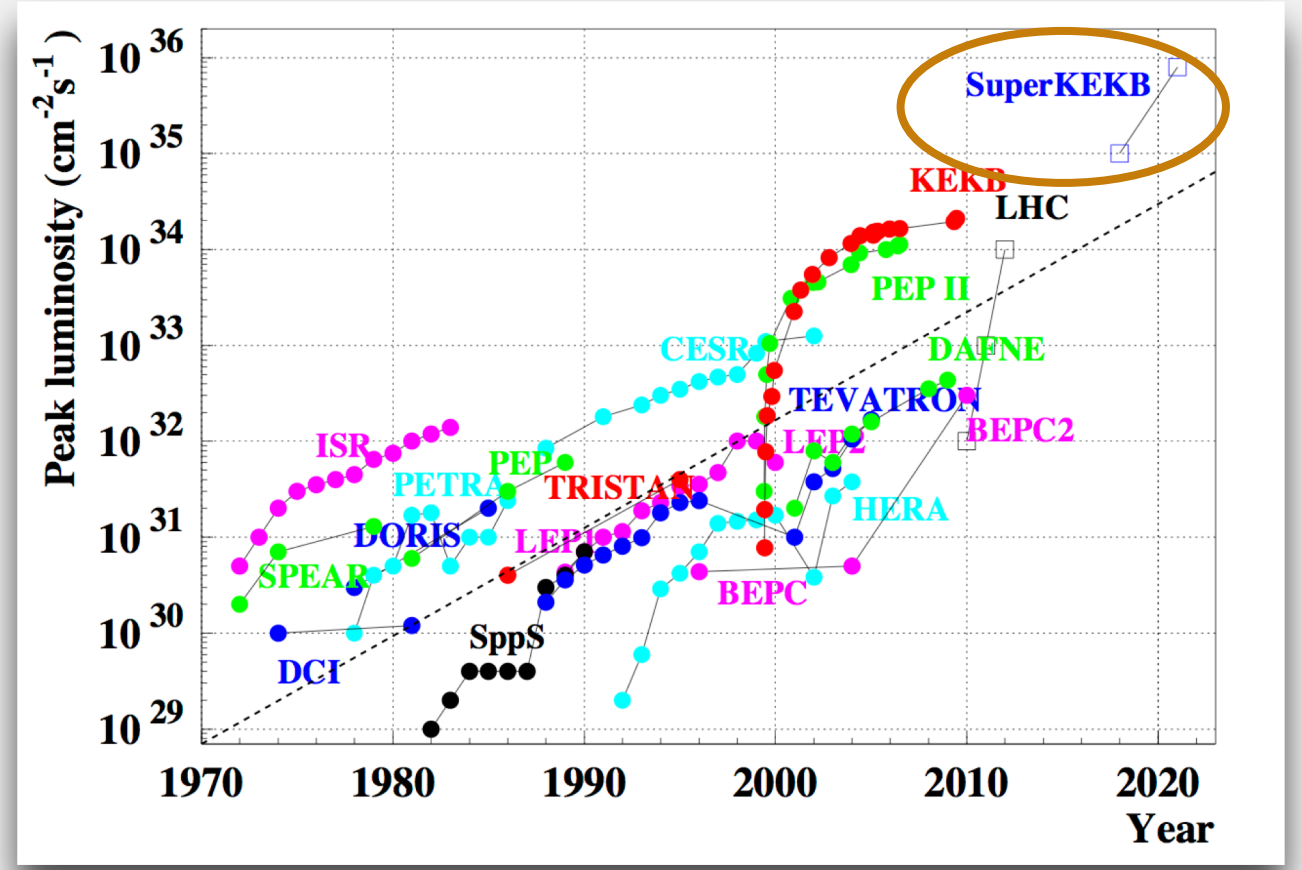
$$x_F = p_L / \max p_L{\sim}_{LO} x_1 - x_2{\sim}_{forward} x_1$$



FIRST OBSERVATION OF TRANSVERSE Λ POLARIZATION IN E+E-

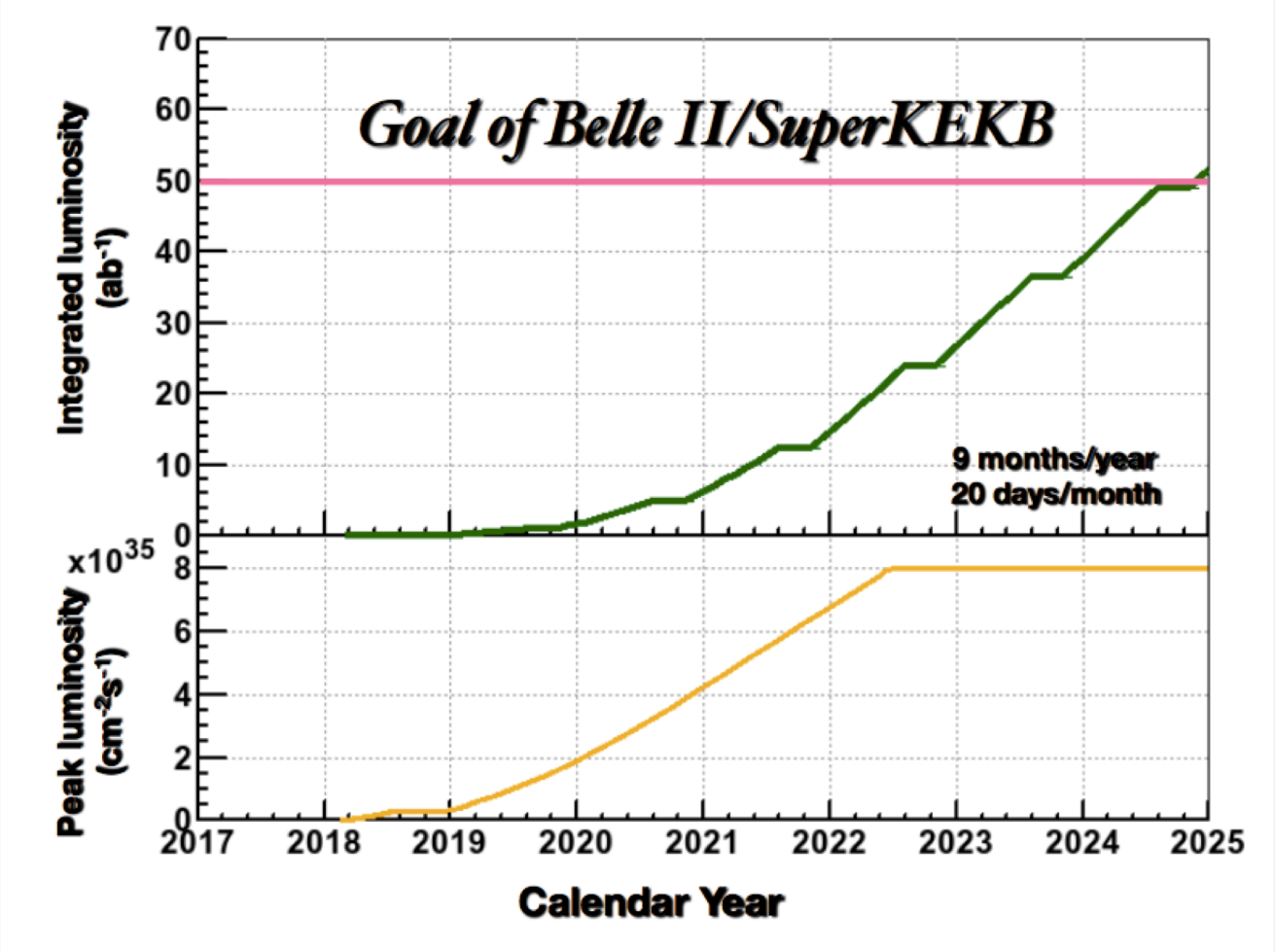


LUMINOSITY HISTORY OF E+E- (AND PP) MACHINES

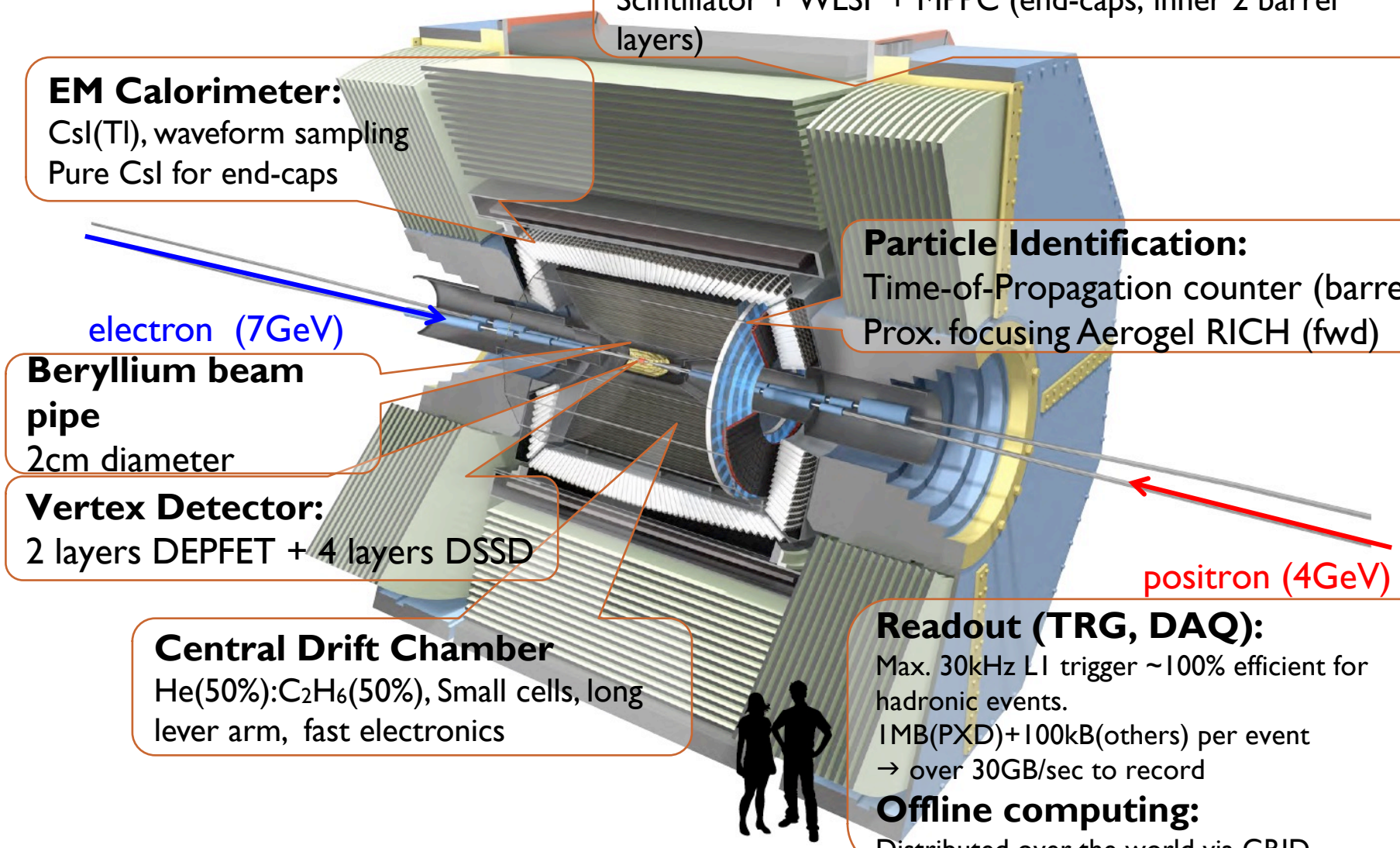


CURRENT STATUS AND SCHEDULE

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



CUT VIEW OF BELLE II DETECTOR



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

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

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

electron (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector:
2 layers DEPFET + 4 layers DSSD

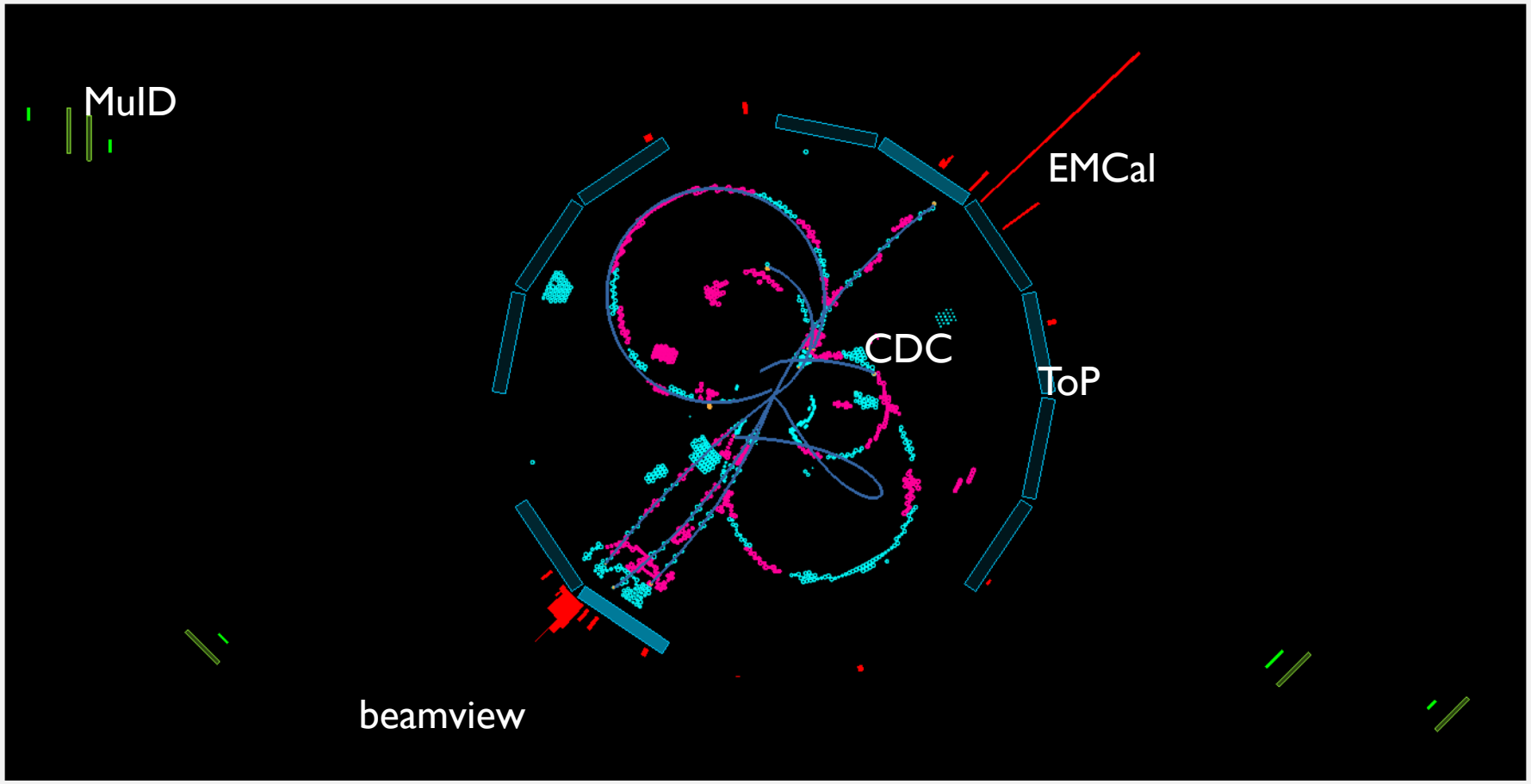
positron (4GeV)

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

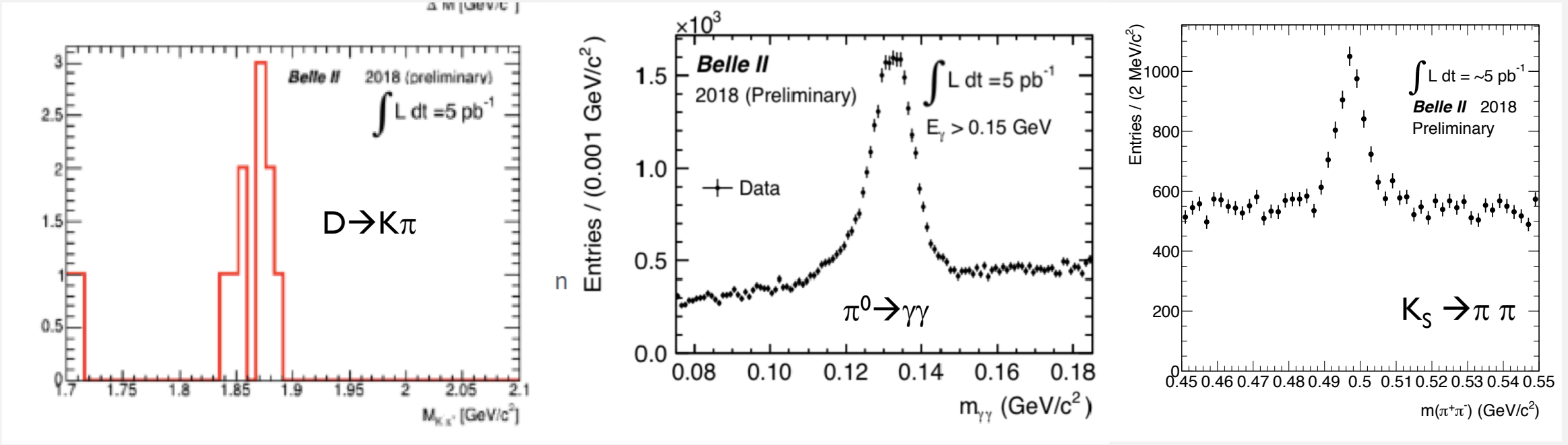
Readout (TRG, DAQ):
Max. 30kHz L1 trigger ~100% efficient for hadronic events.
1MB(PXD)+100kB(others) per event
→ over 30GB/sec to record

Offline computing:
Distributed over the world via GRID

26 APRIL 2018 00:38 GMT+09:00: FIRST COLLISIONS



FIRST BUMPS


Belle II 2018 (preliminary)
∫ L dt =5 pb-1
D→Kπ
Belle II
2018 (Preliminary)
∫ L dt =5 pb-1
Eγ > 0.15 GeV
Data
π0→γγ
Entries / (0.001 GeV/c2)
mγγ (GeV/c2)
∫ L dt = ~5 pb-1
Belle II 2018
Preliminary
Entries / (2 MeV/c2)
KS →π π
m(π+π-) (GeV/c2)

CONCLUSION

- B-factories provide world record statistics to study e+e- annihilation final states
- Rich physics program on fragmentation function studies already exists
- Extension to entanglement studies would be very interesting

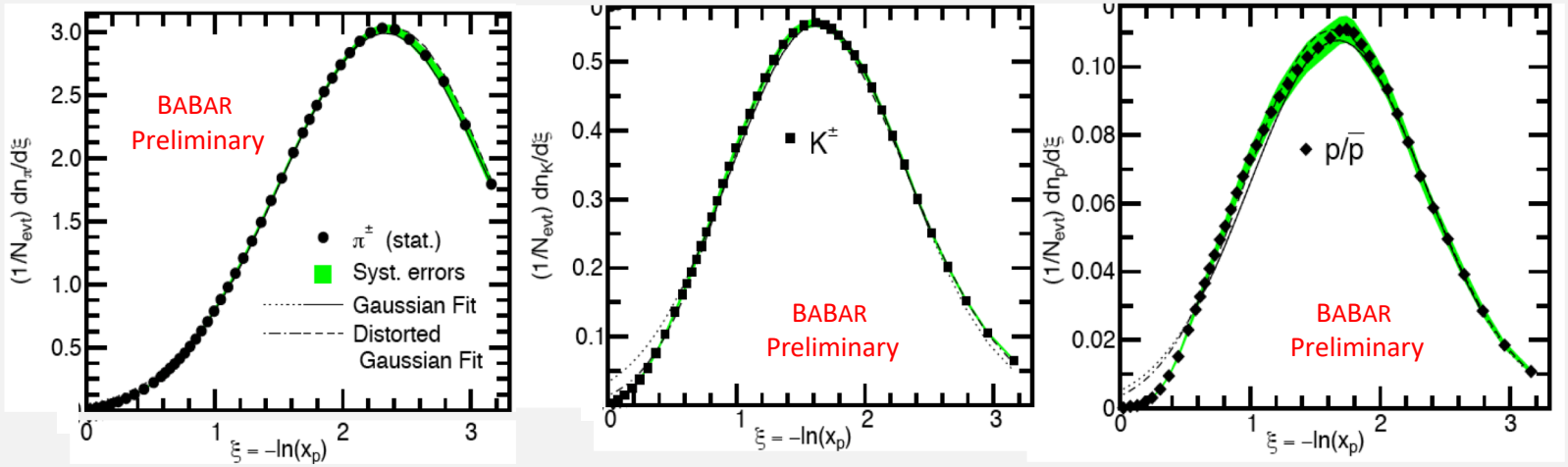
TEST OF MLLA AND LOC. PARTON-HADRON DUALITY

Test of QCD prediction

Modified Leading Logarithm Approximation (MLLA) with Local Parton-Hadron Duality (LPHD) ansatz: ==> a Gaussian function should provide a good description of these spectra

==> the peak position ξ^* should **decrease exponentially with increasing hadron mass at a given E_{cm}**

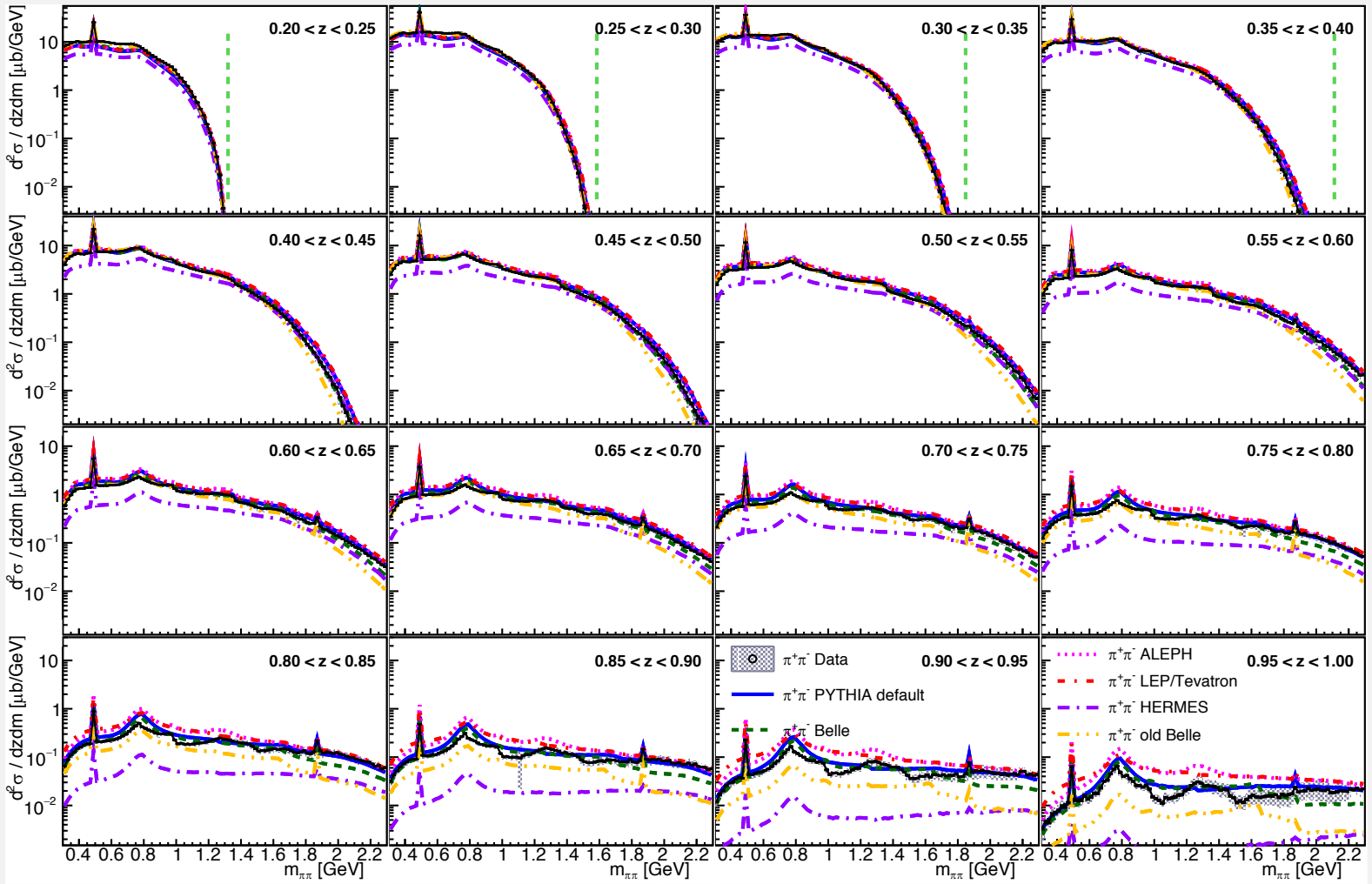
==> should **increase logarithmically with E_{cm} for a given hadron type**



- Fit the spectra with a (distorted) Gaussian function ==> **reasonable description of the data**
- ξ^*_{π} is higher than ξ^*_{K} in agreement with the predicted drop, but ξ^*_{p} is not lower than ξ^*_{K}
- Similar behavior observed at higher energies

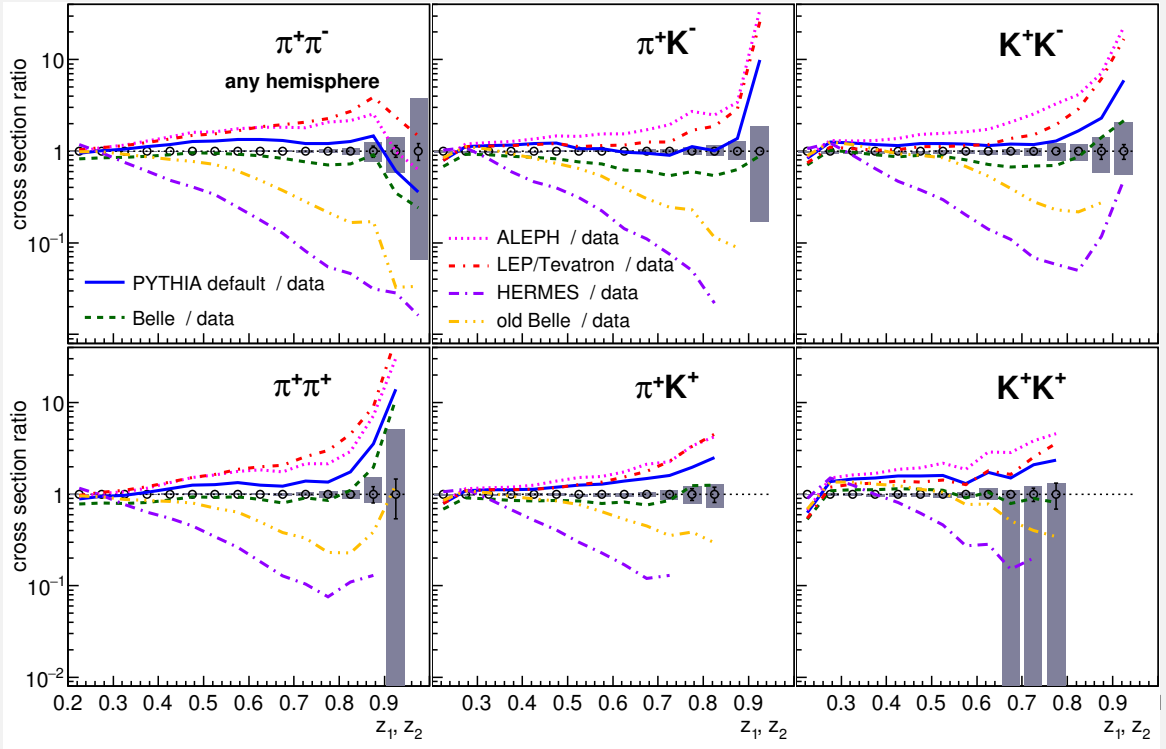
Material from I. Garzia, QCD Evolution 2013

INVARIANT MASS DISTRIBUTION COMPARED TO MC



m [GeV]

RATIO TO MC


$\pi^+\pi^-$
any hemisphere
π^+K^-
K^+K^-
$\pi^+\pi^+$
π^+K^+
K^+K^+
cross section ratio
PYTHIA default / data
Belle / data
ALEPH / data
LEP/Tevatron / data
HERMES / data
old Belle / data
z_1, z_2

KEKB →SUPERKEKB: DELIVER INSTANTANEOUS LUMINOSITY X 40

Belle II

e^+ 4GeV 3.6 A

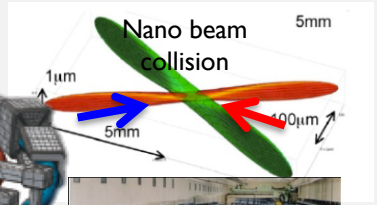
e^- 7GeV 2.6 A

(~2x KEKB)

SuperKEKB
Target: $L = 8 \times 10^{35}/cm^2/s$

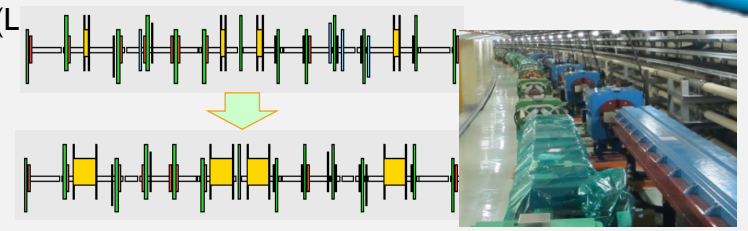
New superconducting final focusing quads (QCS) near the IP

New IR



Reinforce RF systems for higher beam current

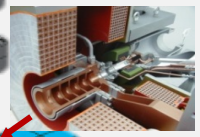
Replace short dipoles with longer ones (L



Redesign the lattices of HER & LER to squeeze the emittance

Damping ring (new)

@1.1 GeV
To inject low emittance positrons



Positron source
New positron target / capture section

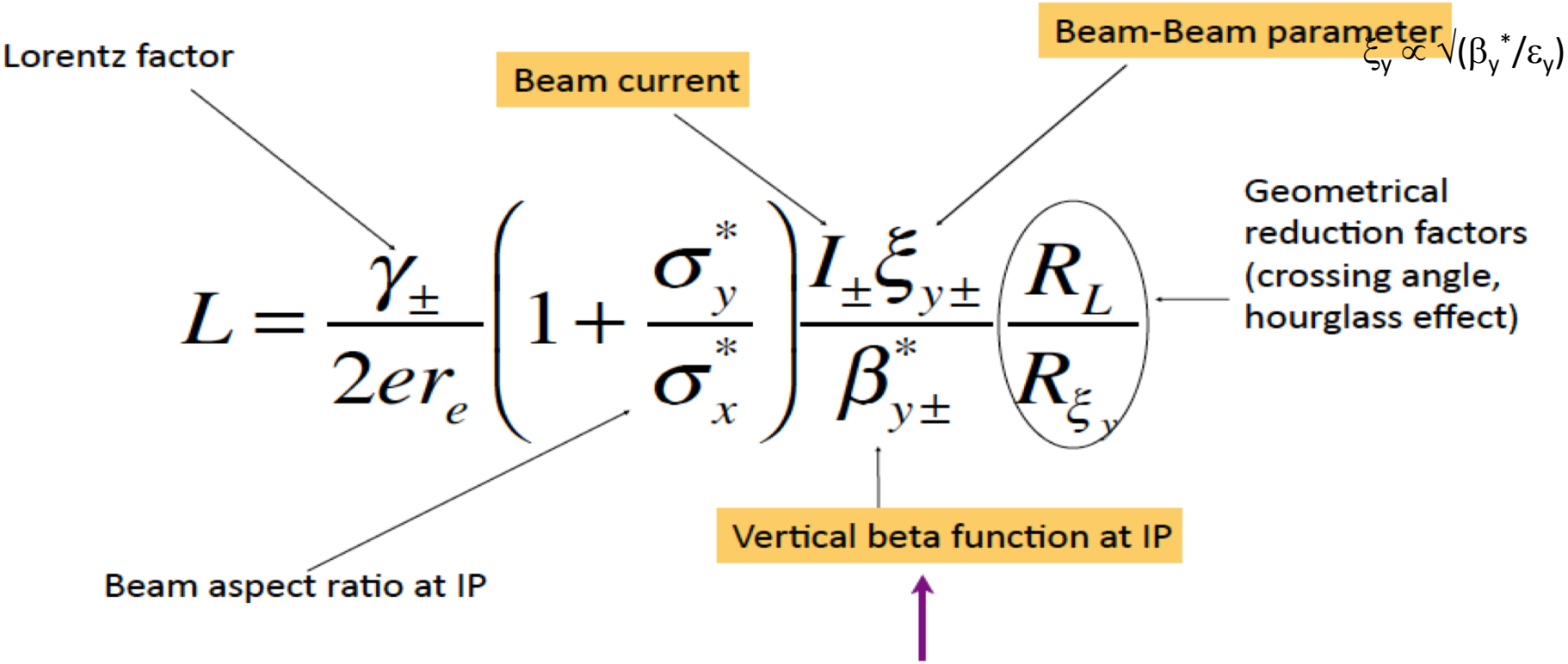
Low emittance gun

To inject low emittance electrons

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

ACCELERATOR DESIGN: NANO BEAM SCHEME

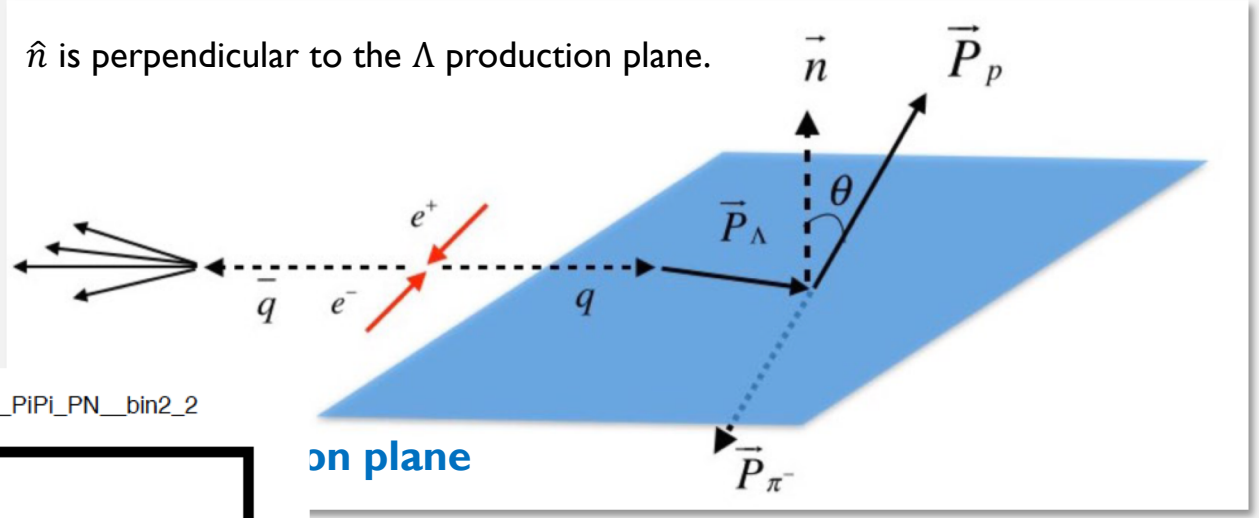
Invented by Pantaleo Raimondi for SuperB



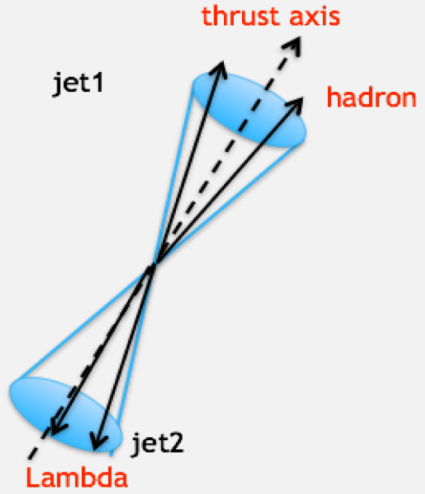
	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

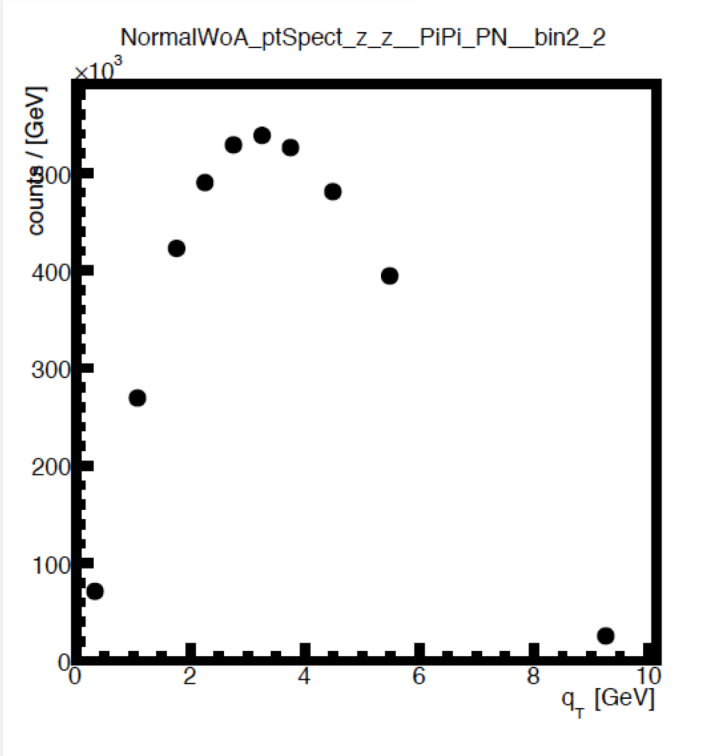
OBSERVABLES IN Λ RESTFRAME

$\hat{n}$ is perpendicular to the Λ production plane.



on plane



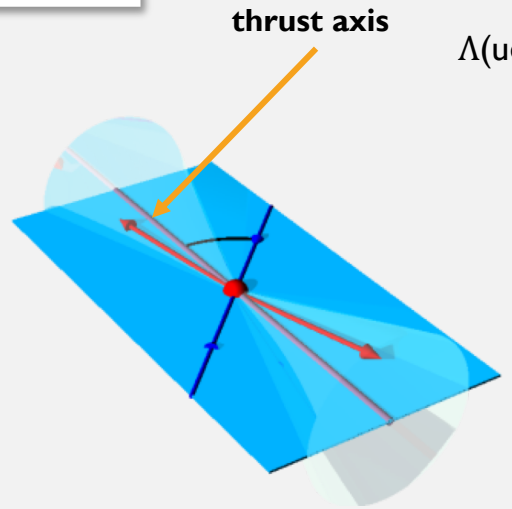


polarization dependent distribution

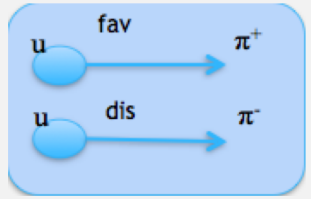
$$+ \alpha P \cos\theta$$

neter: α_+=0.642 ± 0.013 for Λ and
G).

ransverse momentum of Λ relative to the



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



Collins Effect vs (z_1,z_2): comparisons

Unlike/**L**ikesign

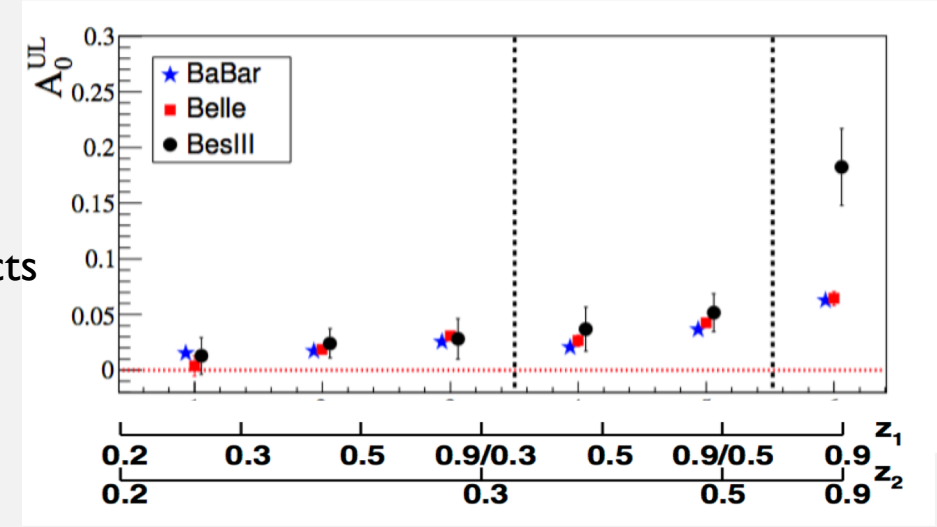
Ratios to cancel acceptance effects

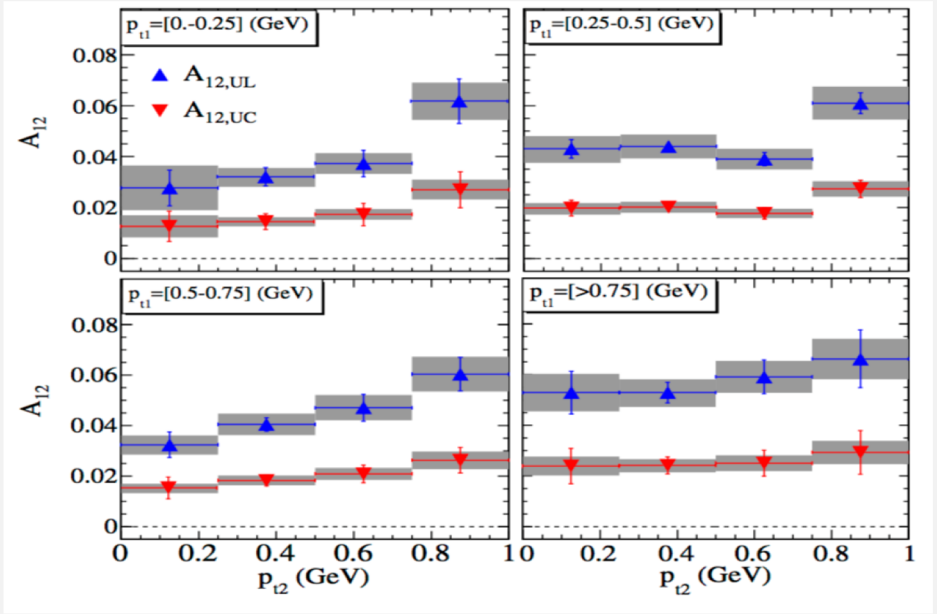
<u>Unlike:</u>

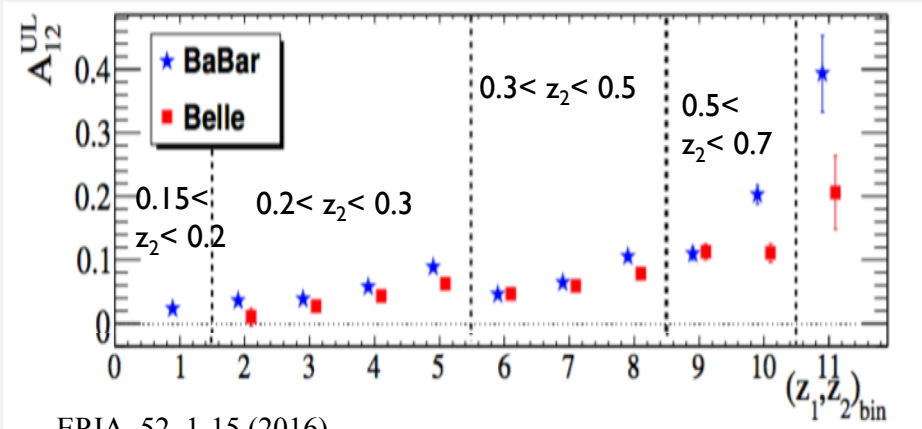
fav*fav+dis*dis

<u>Like:</u>

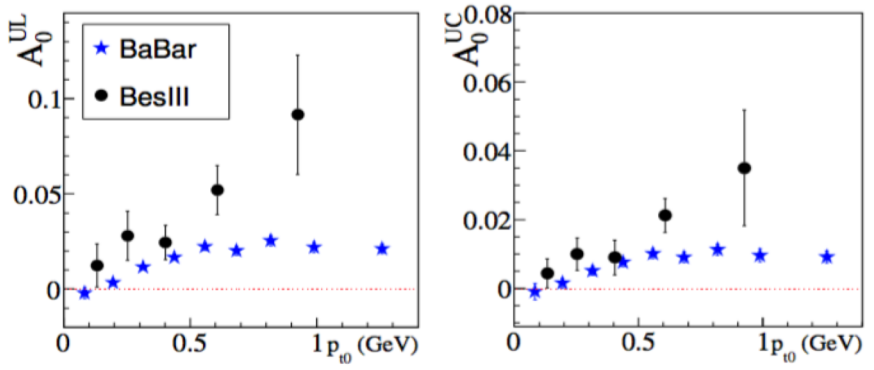
fav*dis







EPJA, 52, 1-15 (2016)



•First non-zero independent measurement of the Collins effect for pion pairs in e^+e^- annihilation by Belle Collaboration @ $\sqrt{s} \sim 10.6$ 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 @ $\sqrt{s} \sim 10.6$ 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))