Spin-Independent Fragmentation in e^+e^- Annihilation

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"Fragmentation Functions in $e^+ e^-$"

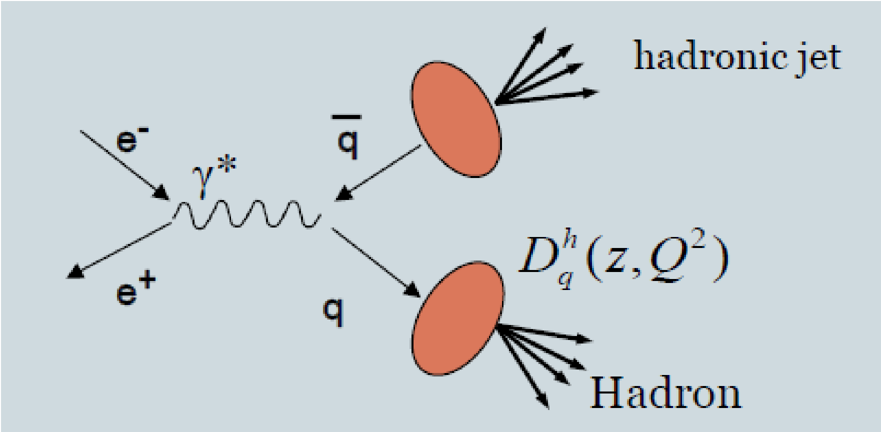
$$e^+ + e^- \rightarrow \gamma/Z \rightarrow h + X$$

- Functions characterizing hard scattering final-state particle distributions in general form:

$$\frac{1}{\sigma_0}\ \frac{d^2\sigma^h}{dxdcos(\theta}) = \frac{3}{8}(1+cos^2(\theta)F_T^h(x,s)+\frac{3}{4}sin^2(\theta)F_L^h(x,s)+\frac{3}{4}cos(\theta)F_A^h(x,s)$$

- The FFs most studied are the integrated (collinear) functions $D^h_{1,i}$ describing **fragmentation of an unpolarized parton type "i" into an unpolarized hadron type "h".**
- Below the Z mass where the coupling is the quark charge squared, and gluons contribute zero at LO

$$d\sigma(e^+e^- \rightarrow hX) \propto \sum_q e_q^2(D^h_{1,q}(z,Q^2)+D^h_{1,\bar{q}}(z,Q^2))$$



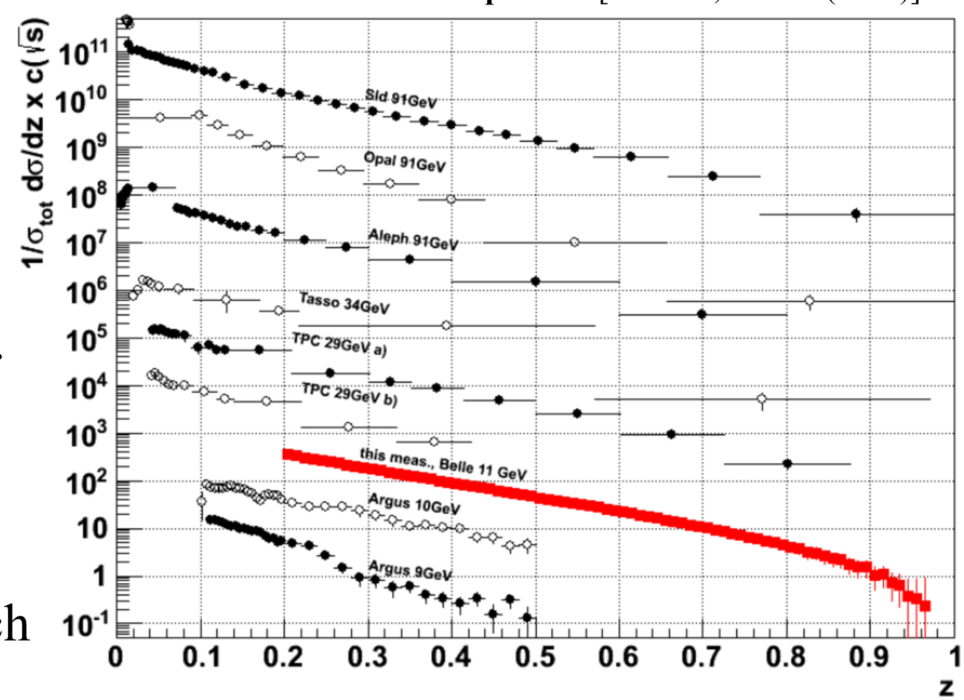
where z is the fraction of the parton's momenta carried by the hadron h

- These functions are like PDFs and transform under DGLAP evolution
- Universal: use in nucleon structure studies via hadronic reactions or SIDS

$e^+ e^-$ Measurements for FF's

- $e^+e^- \rightarrow q\bar{q}$ is the cleanest way to access fragmentation functions
  - EW physics known and initial parton showering can be calculated
  - data and hadronization models → global FF fitting
  - 2007: first unpolarized FF extraction w/ uncertainties and global analysis
- interesting history of e^+e^- colliders
  - $\sqrt{s} = M_{z^0}$ (weak coupling, not e_q)
  - PETRA, PEP (~30GeV); charm factories (CLEO-c, BES)
- generally. experimental data (π,K, etc.) limited in precision & coverage, and …
  - few data at high z
  - few data at low energy
- B factories bring new scale →
  - large integrated lumi & high z reach
  - closer in energy to SIDIS

Selected world data: **π multiplicities** [PRL111,062002 (2013)]

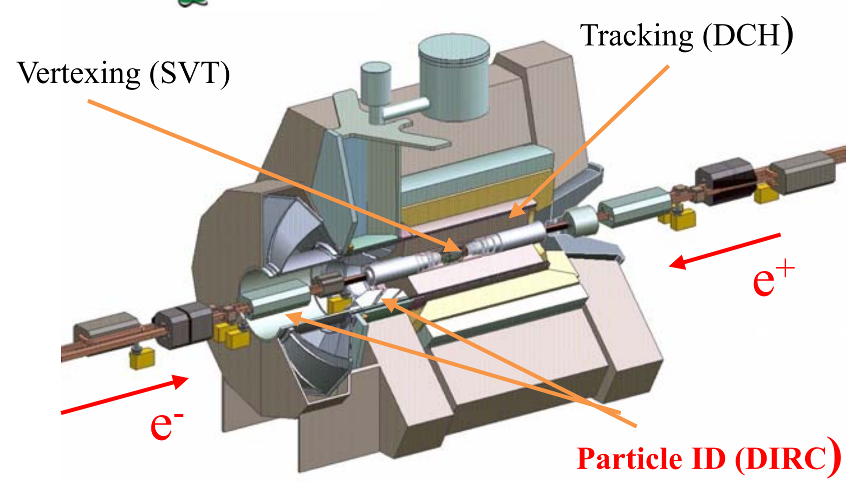


N.B. global analyses include (COMPASS, HERMES) SIDIS & hadron data from (pp) RHIC and the LHC. Various hyperon, charmed meson & baryon FF from Belle, Barbar & CLEO also exist.

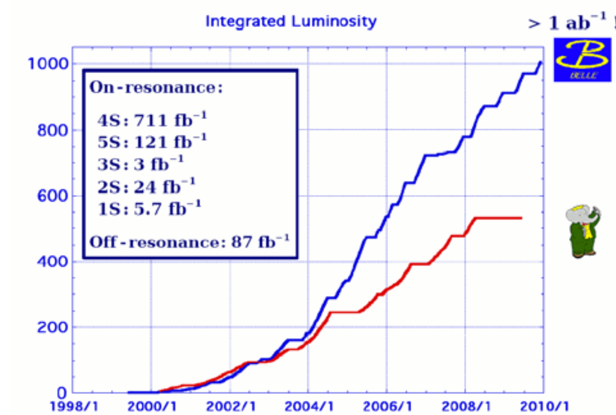
Talk Topics and Organization

- Introduction
- Single Hadron Measurements at Belle and BaBar
- di-Hadron Measurements at Belle
- Outlook and Summary

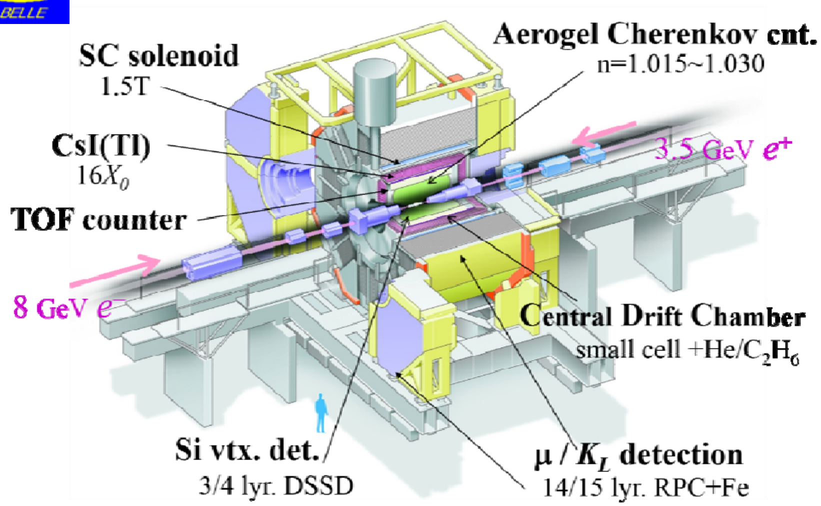
BABAR Detector



- PEP-II: L= 1.2×10^{34}cm^{-2}s^{-1} ; 9 GeV e^-+ 3.1 GeV e^+
- Totals: ~ 520 fb-1 ↔ 1.7 $\times10^9$ $e^+e^- \rightarrow q\bar{q}$ evts



Belle Detector



- KEKB: L>2.11×10^{34}cm^{-2}s^{-1} ; 8 GeV e^-+3.5 GeV e^+
- $\Upsilon(4S)$: 702.6 pb^{-1} on/ 89.5 pb^{-1} off
- Center-of-mass Energy 10.58/10.52 (on/off)

- PID: (dE/dx+aerogel+TOF) vs. (DIRC+dE/dx)

Single Hadron

- B-factory results: e^+e^- measurements near $\Upsilon(4S)$ 10.58 GeV
- Results from Belle and BaBar experiments (π, K, p/$\bar{p}$)
- Similar but different approaches in analysis and presentation
- Global analysis update for pions

Belle Single Hadron Analysis I

- cross sections for identified charged Pions and Kaons
- binning in z = 2Eh/$\sqrt{s}$ starting from 0.2 with width 0.01 out to 0.98
- events from 68.0 fb^{-1} off resonance; data from central detector region; beam/vertex cond's, 3 track min; HJM > 1.8 GeV; visible energy > 7 GeV (suppress $\tau^+\tau^-$ evts)

$$\frac{d\sigma^h}{dz} = \frac{1}{L_{tot}} \cdot \epsilon^i_{joint}(z) \cdot \epsilon^i_{ISR/FSR}(z) \cdot \epsilon_{acc}(z) \cdot \epsilon_{non-q\bar{q}}(z) \times S^{-1}_{smear}(z, z_{rec}) \cdot P^{-1}_{PID,hh'}(cos\theta_{lab}, p_{lab}) \cdot N^{h'}_{raw}(cos\theta_{lab}, p_{lab})$$

lost/gained hadrons (incl DIF) — $\epsilon^i_{joint}(z)$

initial/final state radiation — $\epsilon^i_{ISR/FSR}(z)$

acceptance — $\epsilon_{acc}(z)$

non-$q\bar{q}$ evts removal — $\epsilon_{non-q\bar{q}}(z)$

smearing corrections — $S^{-1}_{smear}(z, z_{rec})$

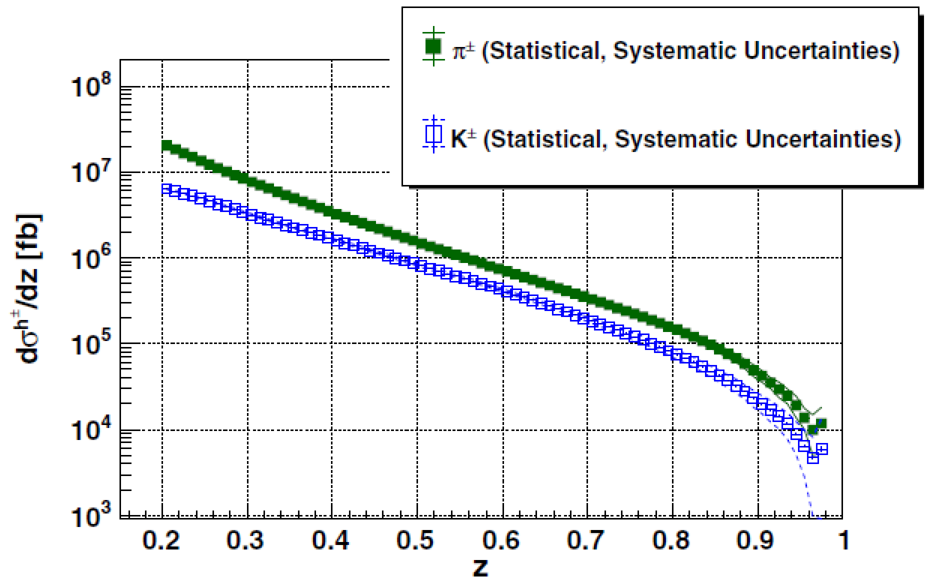
particle ID 5x5 corrections — $P^{-1}_{PID,hh'}(cos\theta_{lab}, p_{lab})$

initial raw yields (cut selection efficiency) — $N^{h'}_{raw}(cos\theta_{lab}, p_{lab})$

- ISR/FSR: exclude evts (MC estimate) when $\sqrt{s}/2$ changes by > 0.5% (~ DGLAP resolution)

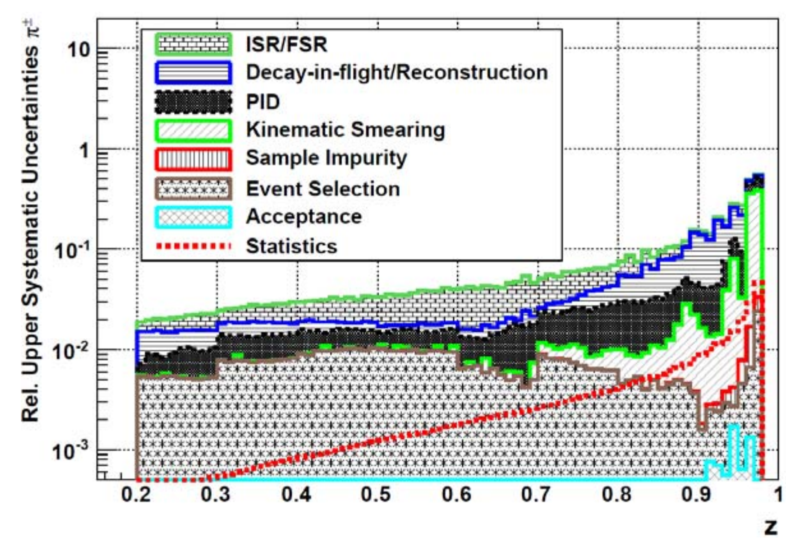
Belle Single Hadron Analysis II

M. Leitgab *et al.*, PRL 111, 062002 (2013)



- statistical + syst. uncertainties < 5% up to z ~ 0.65; rising to 15% (24%) for π's (K's) at z ~ 0.9, increasing at maximum z
- systematics dominate with ISR/FSR for z ≤ 0.5; near z ~ 1.0, PID, smearing and DIF and reconstruction dominate
- z ≤ 0.5 weakly produced π's (K's) are 30% (50%), vanishing toward z ~ 1.0

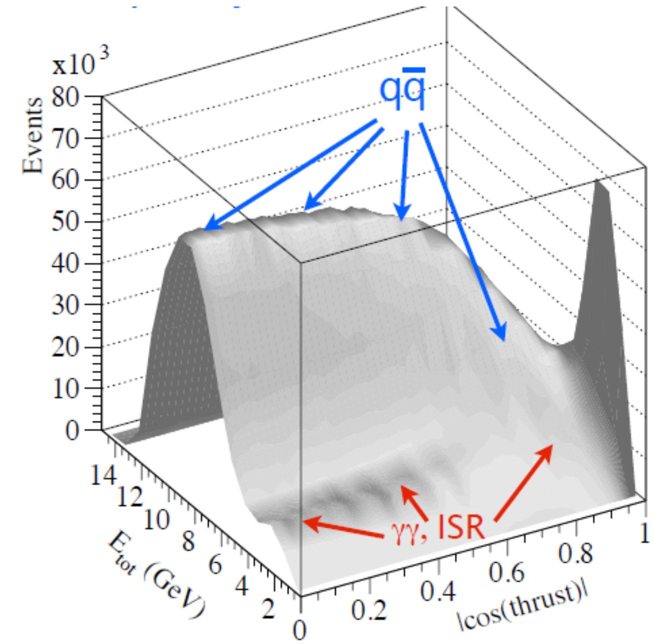
- final charge integrated $\pi^{+/-}$ and $K^{+/-}$ cross sections vs. z
- results includes all weakly produced π's and K's; all decayed π's and K's are recovered
- MC derived fractions of π's and K's from weak and strong decays in suppl. Material
- precision measurement with high z resolution; probes hadron production z-dependence in region ≥ 0.7



BaBar Single Hadron Analysis I

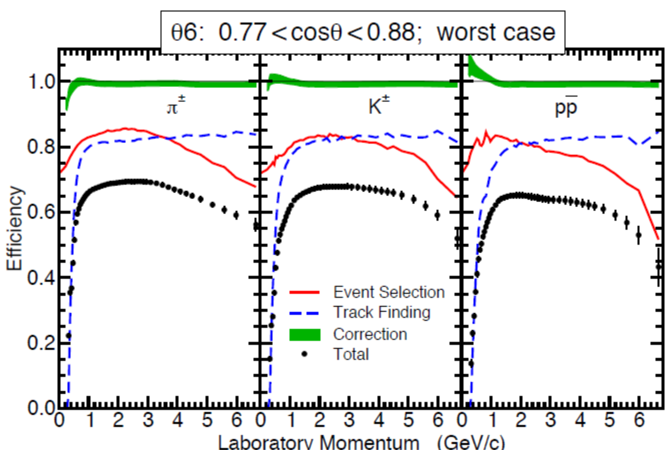
- production rates for $\pi^{+/-}$, $K^{+/-}$ and $p\bar{p}$ analysis and results

J.P Lee *et al*. Phys Rev D **78**, 032011 (2013)



Data Selection and Procedures

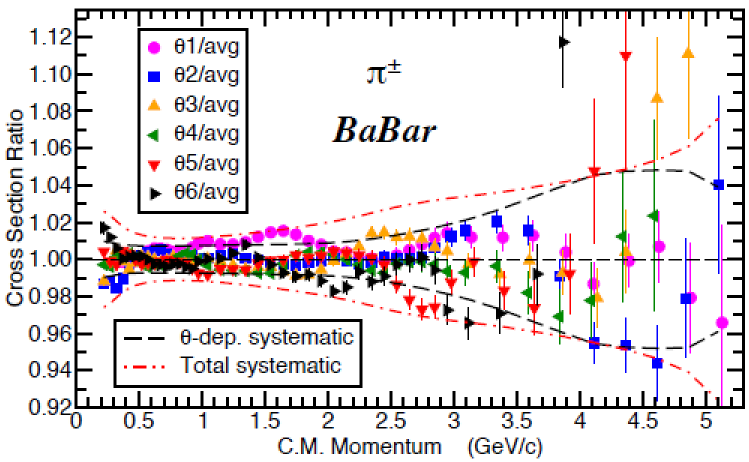
- use “only” very good runs of 1 fb^{-1} at 10.54 GeV (4 fb^{-1} on $\Upsilon(4S)$ at 10.58 GeV for calibrations)
- select clean e+e- $\rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ and $c\bar{c}$ events
  - evt vertex, topology, visible energy, $|\cos\theta^*_{thrust}|$
  - 2.2 million evts with 70% efficiency
  - understand backgrounds (< 5%)
- tracking: good drift chmbr and DIRC w/ pT > 0.2 GeV and within good detector acceptance/ops



- hadron definition:
  - no decay products of “stable” μ, π, K_L, n/$\bar{n}$
  - … or K_S, hyperons (Λ, Σ, etc.)
  - measure “prompt” production
  - Add back above for “conventional” production
- ISR: correct remaining effects (use JETSET?)

BaBar Single Hadron Analysis II

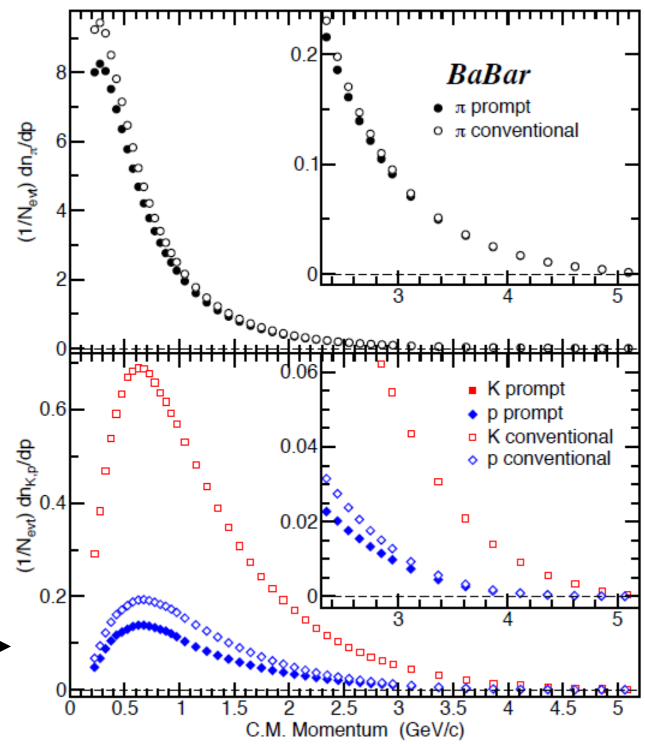
J.P Lee *et al*. Phys Rev D **78**, 032011 (2013)



- data divided into 6 polar angle subsamples
  - independent analysis in each with extensive systematic cross checks
  - similarly, studies of detector performance, MC corrections (mostly small)
- PID: likelihood from DIRC & drift chambers with efficiency matrix calibrated from data
- transform analysis to the center-of-mass frame

$$(\frac{1}{N_{evt}^{sel}})(\frac{dn_i}{dp}) \rightarrow (\frac{1}{N_{evt}^{had}})(\frac{dn_i}{dp^*})$$

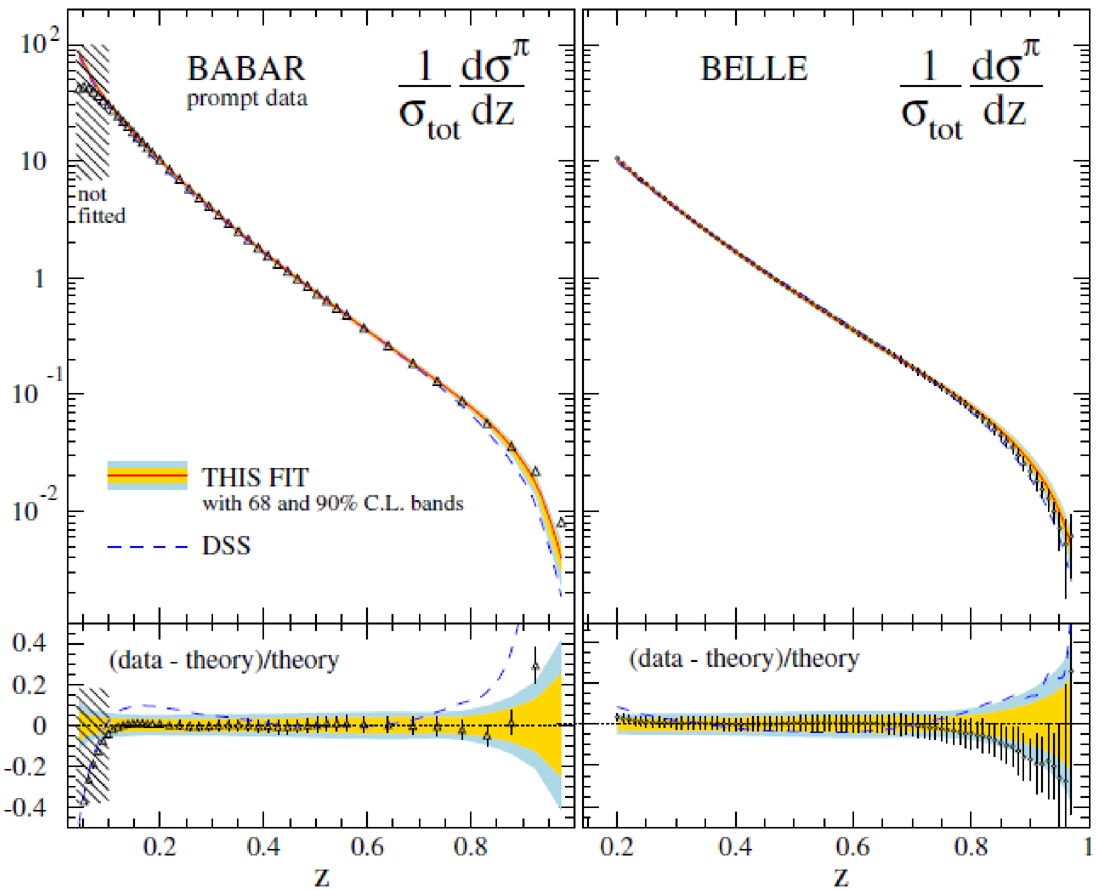
- transfer matrices sensitive to true θ*, p* distrs with additional cross checks
- final results average over θ regions; the overall normalization is to total hadron x-sec = 3.39 nb
- good coverage and precision for all species ⟶



Global Analysis: Parton to Pion Fragmentation

D. de Florian *et al.*, Phys. Rev. D **91**, 014035 (2015) – Parton-to-Pion Fragmentation Reloaded

- comprehensive update of DSS (2007) analysis at NLO, including new BaBar and Belle SIA, HERMES and COMPASS SIDIS and pp data from the LHC

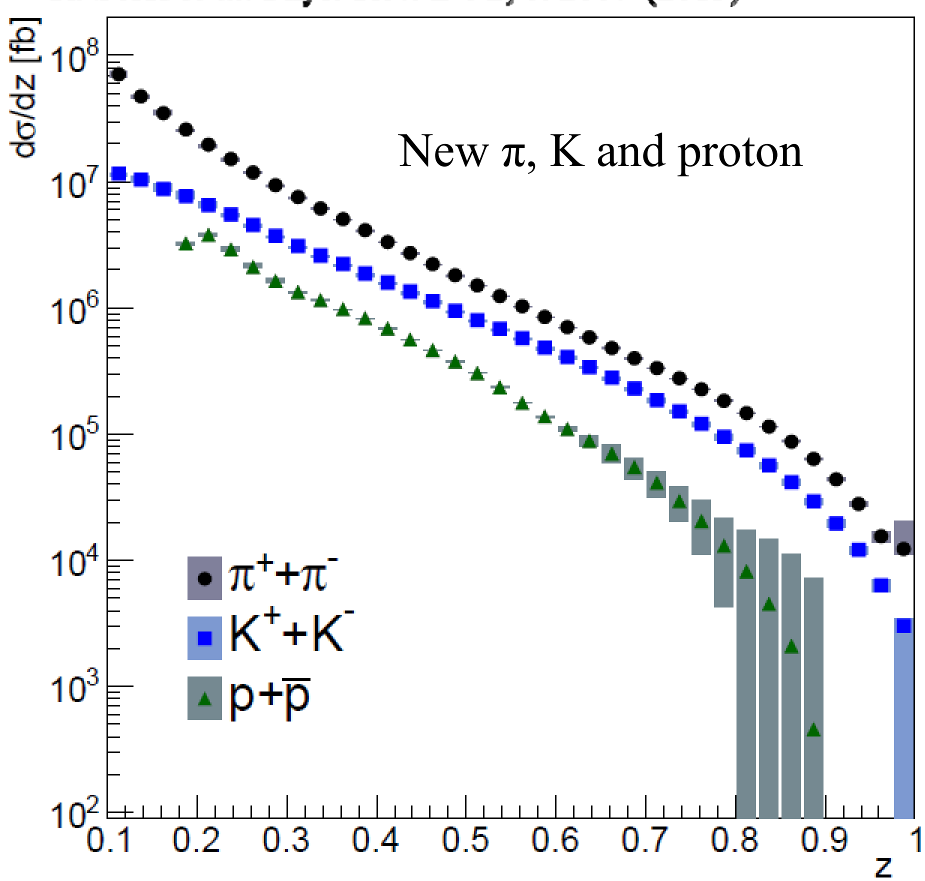


- Belle, Babar $z \leq 1.0$ analyzed; $n_f = 4$, NLO cross section; norm =1.04, 1.05, respectively
- fine binned Belle data below fit at high z, trend not visible with more sparse BaBar data
- at $z \geq 0.8$ large log corrections may need resum/investigation?
- possible experimental issues: treatment of weak decay and for Belle, ISR correction.
- overall fits to data set are good and Belle/Babar fit in “nicely”

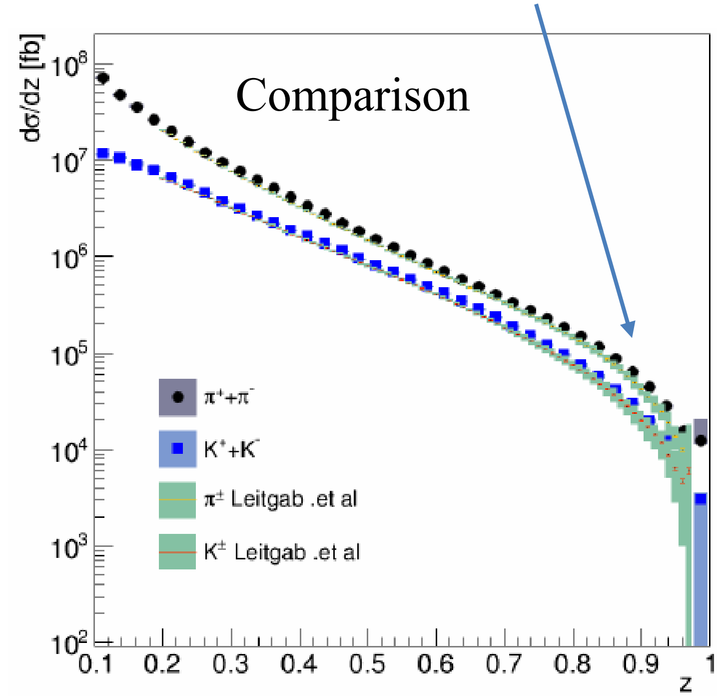
Most Recent Belle Single Hadron Results

- di-hadron analysis was used to extract **new single proton results** (from 109 fb^{-1}) with good replication of the previous Belle (Leitgab) charged pions and kaons

R. Seidl *et al.* Phys. Rev. D 92, 092007 (2015)



- $\pi^{+/-}$ and $K^{+/-}$ points now extend down to z = 0.1 (previous cutoff z = 0.2); overall coarser binning
- new π, K data slightly more "stiff" at highest z but within syst. errors

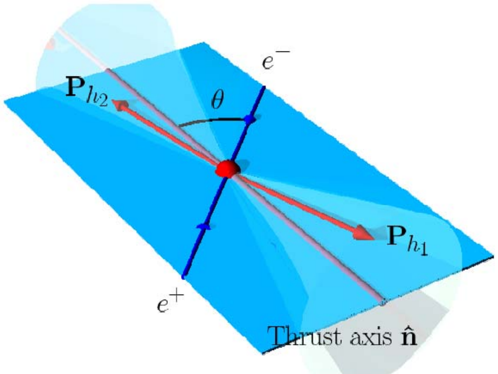


- proton results from 1st accessible bin (z ~ 0.19) extracted w/ high precision; syst, grow at high z

di-Hadron

- Recent Belle e^+e^- measurements at Υ(4S) 10.58 GeV and off resonance checks
- Systematics of opposite and same hemisphere fragmentation

Use di-Hadrons to Access Flavor Structure

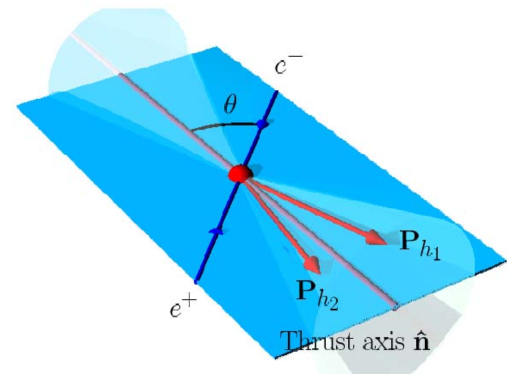


- Inclusive single hadron measurements sum over all flavors of quarks and anti-quarks
- **di-hadron** fragmentation into **opposite hemispheres** provides access to favored vs. unfavored combinations (e.g, jets are not independent); cross section at LO is a **product of FFs**

$$u\bar{u} \rightarrow \pi^+\pi^- X \quad \propto \quad D^{\pi^+}_{u,fav}(z_1,Q^2)\cdot D^{\pi^-}_{\bar{u},fav}(z_2,Q^2)+D^{\pi^+}_{\bar{u},dis}(z_1,Q^2)\cdot D^{\pi^-}_{u,dis}(z_2,Q^2)$$

$$u\bar{u} \rightarrow \pi^+\pi^+ X \quad \propto \quad D^{\pi^+}_{u,fav}(z_1,Q^2)\cdot D^{\pi^+}_{\bar{u},dis}(z_2,Q^2)+D^{\pi^+}_{\bar{u},dis}(z_1,Q^2)\cdot D^{\pi^+}_{u,fav}(z_2,Q^2)$$

- **same hemisphere** measurements of di-hadrons most likely come from the same parton (mixed perhaps with some multi-single hadron processes)
- the **latter** measurements should therefore be described by di-hadron fragmentation functions DiFF $D_{1,q}^{h_1h_2}(z,Q^2)$



- **any Hemisphere**: no thrust or any hemisphere assignment; full statistics and dominate features (will show some of these results)

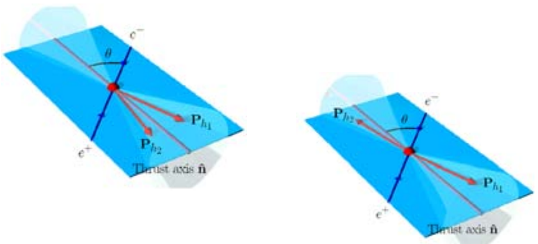
Di-Hadron Fragmentation Analysis Setup

Data Set

- 665 fb^{-1} (109 fb^{-1}) collected by Belle at (60 MeV below) the Υ(4S) resonance

Extracted observables

- use 4x4 hadron combinations of π, K in different charge combinations
- look at 3 hemisphere combinations
  - same hemisphere (thrust > 0.8)
  - opposite hemisphere (thrust > 0.8)
  - any combination (e.g., no thrust selection)



- 16 equidistant bins in z_1 z_2 between [0.2, 1.0]

Methodology

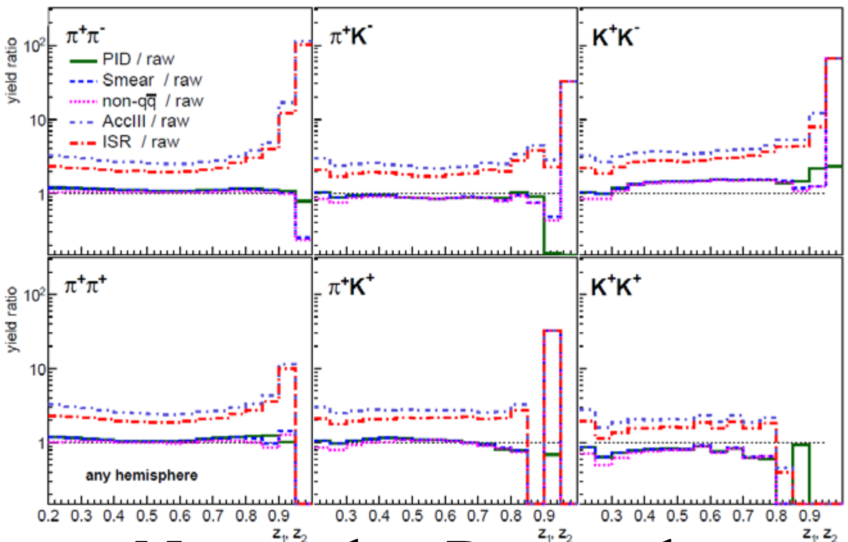
- use single hadron analysis approach but adapted to di-hadron analysis
- in particular, ensure cuts and analsyis techniques allow for use of large data set taken on resonance with cross checks to below resonance data

di-hadron Correction Chain (similar to singles)

Correction	Method	Systematics
PID mis-id	PID matrices (5x5 for cos θ_{lab} and p_{lab})	MC sampling of inverted matric element uncertainties
Momentum smearing	MC based smearing matrices (256x256), SVD unfold	SVD unfolding vs analytically inverted matrix, reorganized binning, MC statistics
Non-qqbar BG removal	eeuu, eess, eecc, tau MC subtraction	Variation of size, MC statistics
Acceptance I (cut efficiency)	In barrel reconstucted vs udsc generated in barrel	MC statistics
Acceptance II	udsc Gen MC barrel to 4pi	MC statistics
Weak decay removal (optional)	udcs check evt record for weak decays	Compare to other Pythia settings
Acceptance III	Extrapolation to $\|\cos\theta\| \rightarrow 1$ in (Fit to MC)	Fit uncertainties
ISR	Keep event fraction with E> 0.995 E_{cms}	

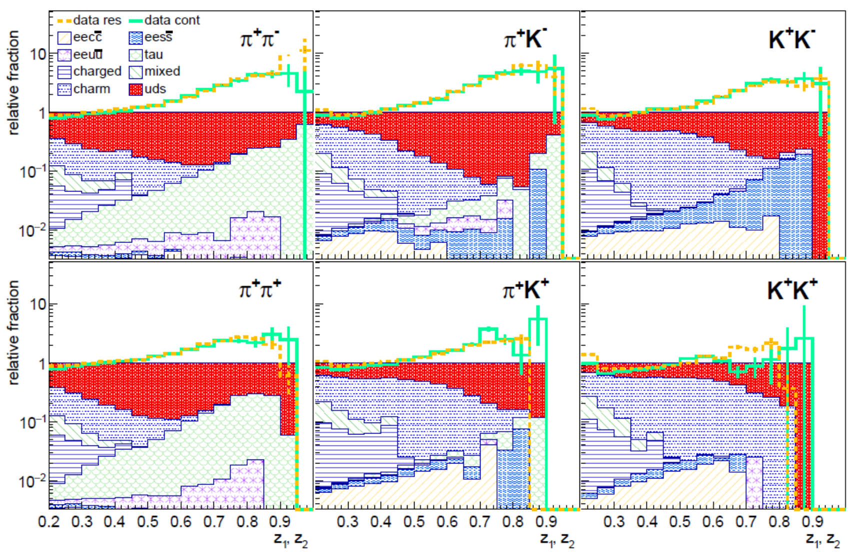
Corrections to Yields & Error Estimates

Total Corrections

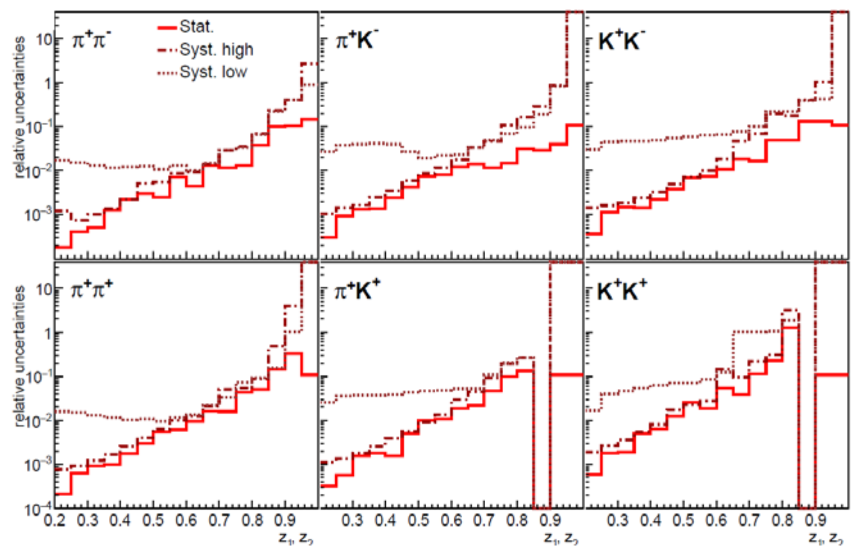


- biggest corrections to the raw yields are at large z and due to smearing and acceptance (diagonal z_1,z_2 bins shown)
- remove non "u,d,s,c" pair events:
  - Remaining τ pairs
  - decays from ϒ(4S)
  - 2 photon to quark processes
- systematic errors generally dominate

Non q-qbar Removal



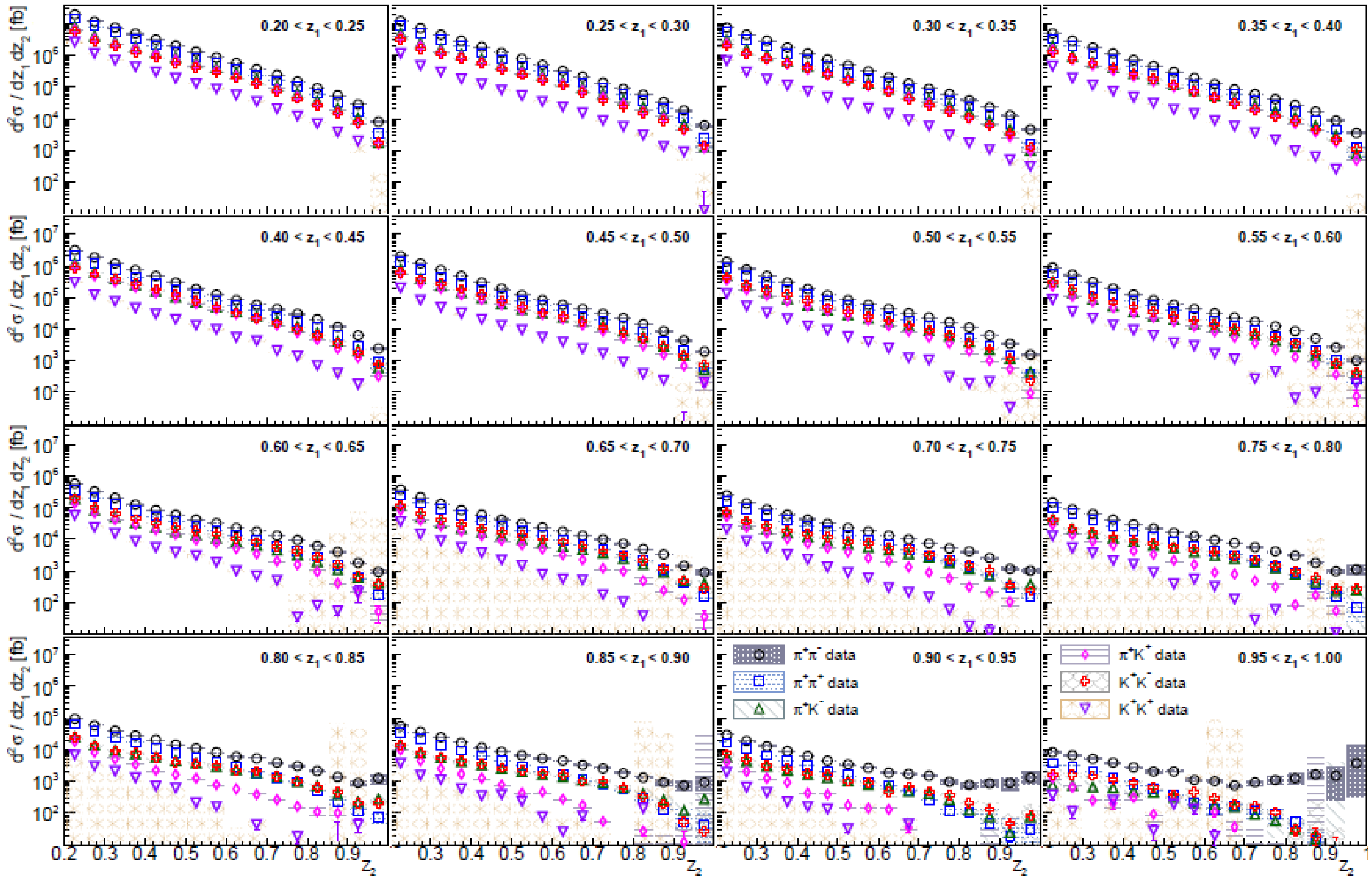
Error Budget



Full Results: Hadron Pairs w/ any Topology

(as a function of z_2 for various ranges of z_1)

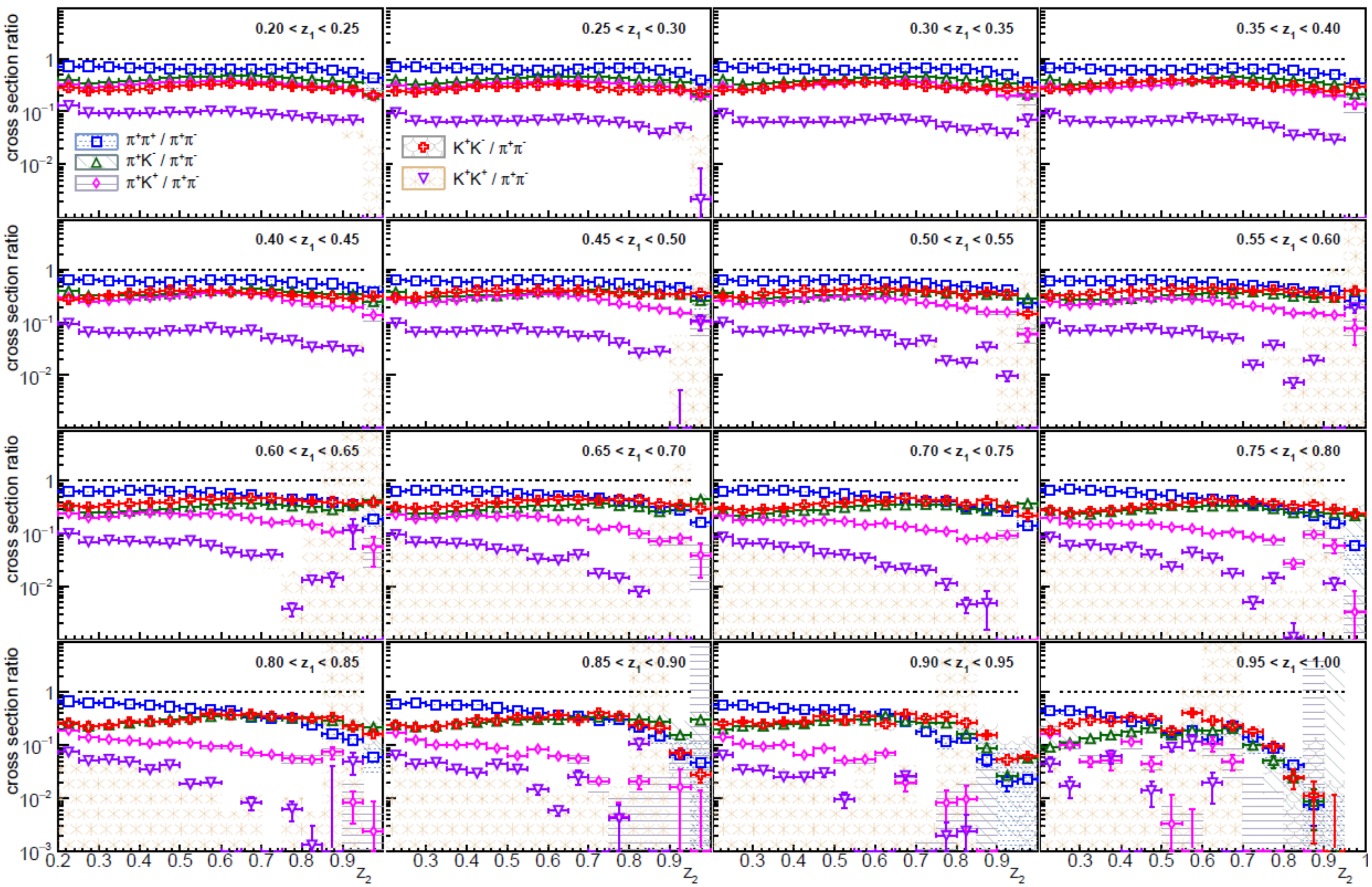
R. Seidl *et al.* Phys. Rev. D **92,** 092007 (2015)



- unlike-sign π (like-sign K) pair cross section largest (smallest) at all z_1, z_2 combo's
- consistent with dominate role of u-quark , favored vs. unfavored fragmentation and suppression of strange quark production

Hadron Pair Ratios to $\pi^+\pi^-$ (any Topology)

- ratio $\pi^+\pi^+/\pi^+\pi^-$ □ has favored & disfavored combinations; favored ~ unfavored at low z; disfavored decreasing toward the higher z values with ratio < 1

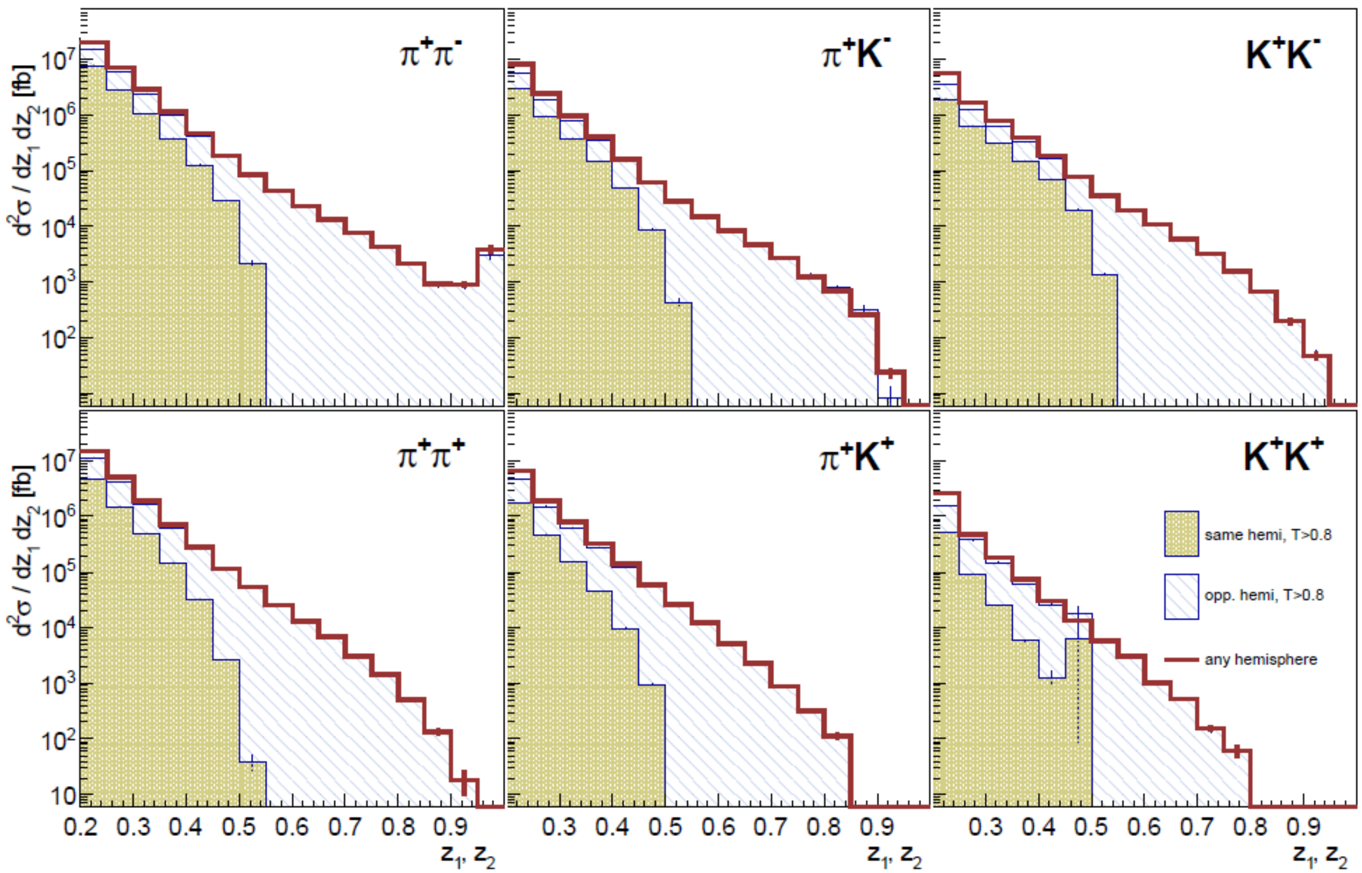


R. Seidl *et al.* Phys. Rev. D **92**, 092007 (2015)

- same sign K and K-π: less than same sign π at low z → strangeness suppression
- at large z, opposite sign K and K−π become comparable / larger than same-sign π → disfavored vs. strangeness

di-Hadron Hemispheric Composition

R. Seidl *et al.* Phys. Rev. D **92**, 092007 (2015)

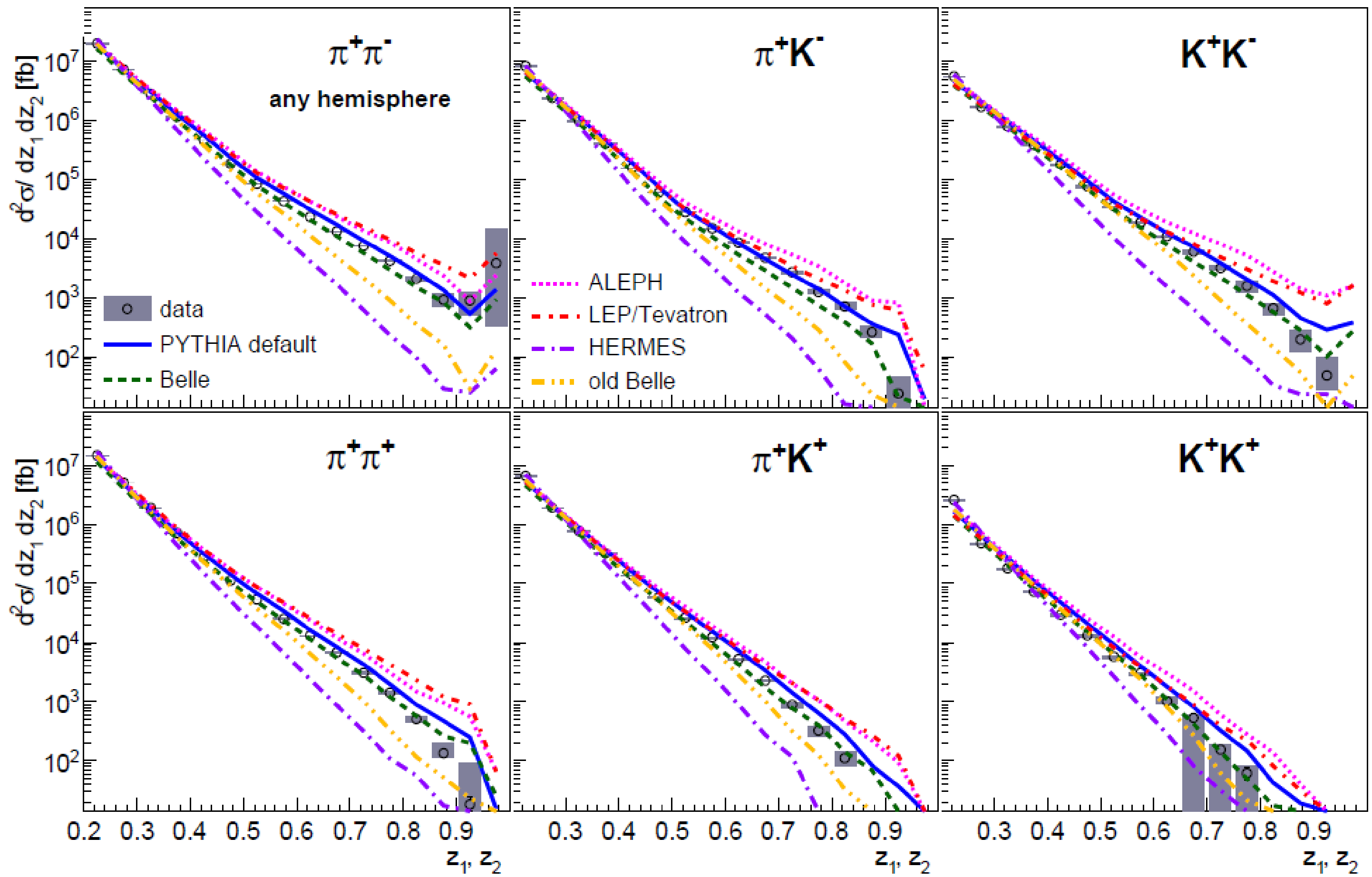


- same hemisphere cross sections drop off rapidly with z_1, z_2 binning
- consistent with LO expectation of:
  - same hemisphere: single quark → di-hadron FF: ($z_1 + z_2 < 1$)
  - small amount of data > 0.5 due to thrust axis smearing, etc.
  - opposite hemisphere: single quark → single hadron

di-Hadron Results for Diagonal z_1 z_2 Bins

Pythia default and current "Belle" settings generally describe new hadron pair data, except at the larger z values

- low z region dominates yield and all tunes agreed in this region
- high z region has not been well measured (esp. at these energies), hence larger spread in tunes



di-Hardon Fragmentation: Takeaways

- **first cross sections** for pairs of charged hadron from e^+e^- annihilation extracted from Belle data
- **pion pair ordering consistent** (opposite hemispheres) with suppression of disfavoured fragmentation, e.g., same-sign pairs fall more rapidly with z than opposite-sign pairs
- creation of **strangeness is suppressed** in e^+e^- fragmentation
- **same hemisphere pairs yields drop**/vanish rapidly: consistent with LO expectation: single quark → di-hadron fragmentation ($z_1+z_2 < 1$)
  [opposite hemisphere: single quark → single hadron fragmentation]
- new precise **input to global analyses re: flavor separation** of light hadron fragmentation
- **default Pythia** fragmentation settings do a reasonable job describing new data

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N.B. the polarized counterpart of the same hemisphere DiFF are the interference fragmentation functions (IFF) used in conjunction w/ SIDIS to access transversity. The present **unpolarized DiFF serve as the baseline** z dependence

Outlook & Future I

Analyses in progress

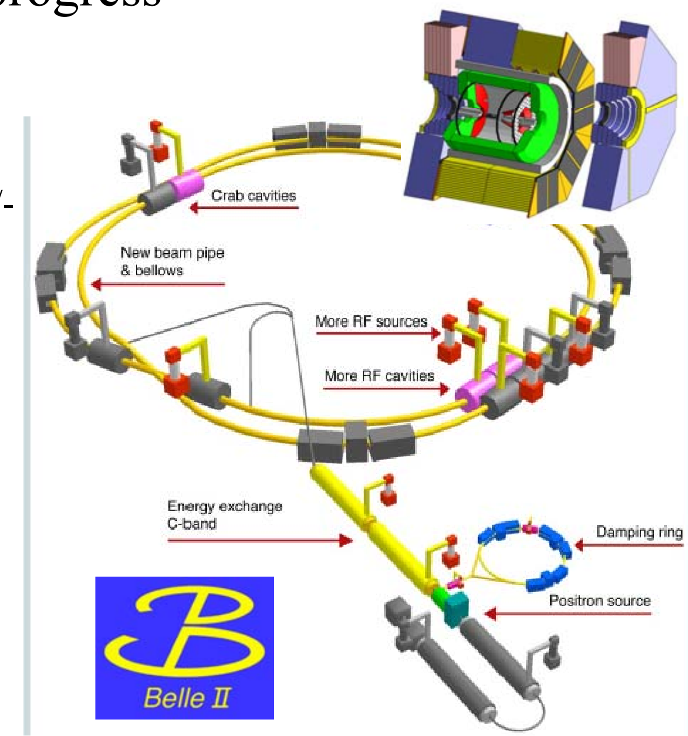
- di-hadron in same hemisphere in progress (Seidl/Belle)
  - base line for quark transversity via di-hadron fragmentation
- back-to-back hadron P_T imbalance in progress (van Huse + Vossen/Belle)
  - quark intrinsic k_T vs. transverse momentum from the fragmentation
- k_T relative to thrust axis from single hadron analysis (Seidl/Belle)
  - thrust smearing and low k_T Gauss fitting in progress

Analyses planned

- single hadron data at lower energy with BESIII have π^0, K_s (2.-3.65 GeV), plan to do $\pi^{+/-}$ and $K^{+/-}$
  - will provide low-Q^2 overlap with JLAB, COMPASS and HERMES expt's
  - connect via evolution to higher scale

Near Future capabilities

- the SuperKEKB, Belle II upgrade will enable a new era of precision / quality measurements in the upcoming years →



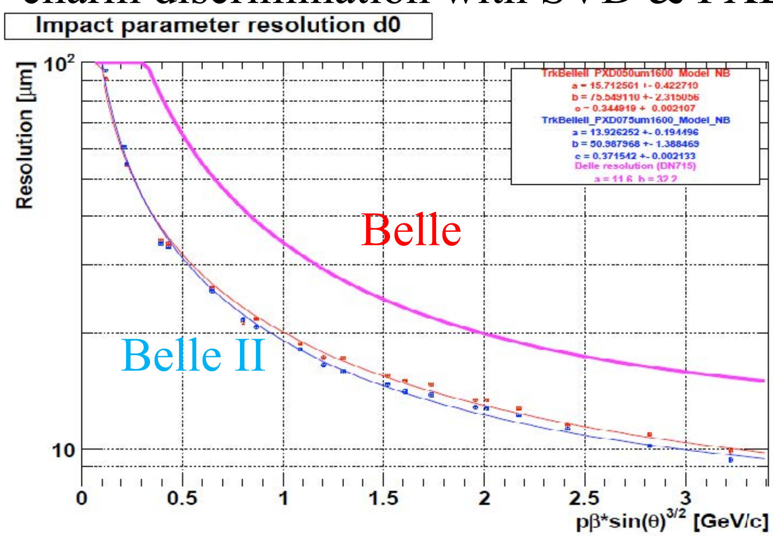
Outlook & Future II

Near future capabilities (cont)

- aim: super-high luminosity ~ 10^{36} $cm^{-2}s^{-1}$ (~ 40x KEK/Belle); expect to integrate 50 ab^{-1} over a ~ 7 year period starting with first data in 2017
- upgrades of Accelerator: nano-beams + higher currents
- detector upgrades: vertexing, PID, higher rates and modern DAQ

- for fragmentation studies: detector capability to tag charm events (current large systematic for Belle/Babar) and provide better Kaon identification

charm discrimination with SVD & PXL



May 20, 2016 final TOP module install

- Feb 2016: first turns observed at SuperKEKB (4 GeV e+'s and 7 GeV e-'s)

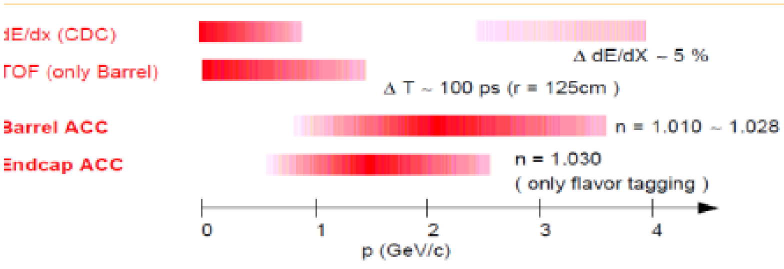
Summary and Conclusions

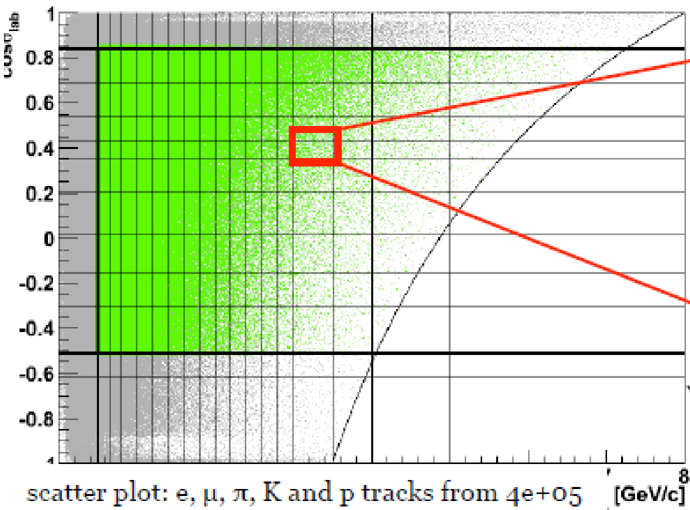
- **single hadron:** e^+e^- annihilation results from Belle and Barbar
  - $\pi^{+/-}$, $K^{+/-}$ and $p\bar{p}$ data expanded the kinematic range (esp. Belle high z) with high precision data near 10.58 GeV
  - data for pions incorporated into global analyses
- **di-hadron:** results from Belle … first cross sections extracted
  - sensitive to favored vs. unfavored fragmentation in the opposite hemisphere topology
  - same hemisphere: primarily fragmentation from a single quark
  - new precise data for better flavor separation in global analyses
- **outlook**: ongoing analyses for: same hemisphere di-hadrons; k_T studies via back-to-back hadron P_T imbalance; single hadron k_T relative to thrust axis
  - New era of precision coming with Belle II
- big **thanks** to Belle FF collaborators as well as colleagues in this field for discussions, slides, etc.!

Thank you!

Backup Slides

PID Corrections from Data (Single Hadron Analysis)





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

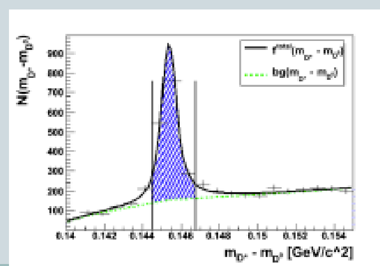
ToF forward geometry acceptance limit

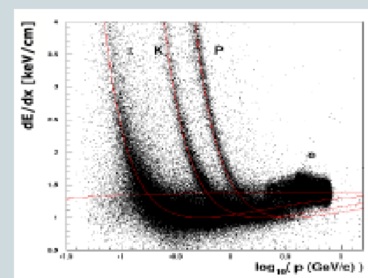
ToF backward geometry acceptance limit

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

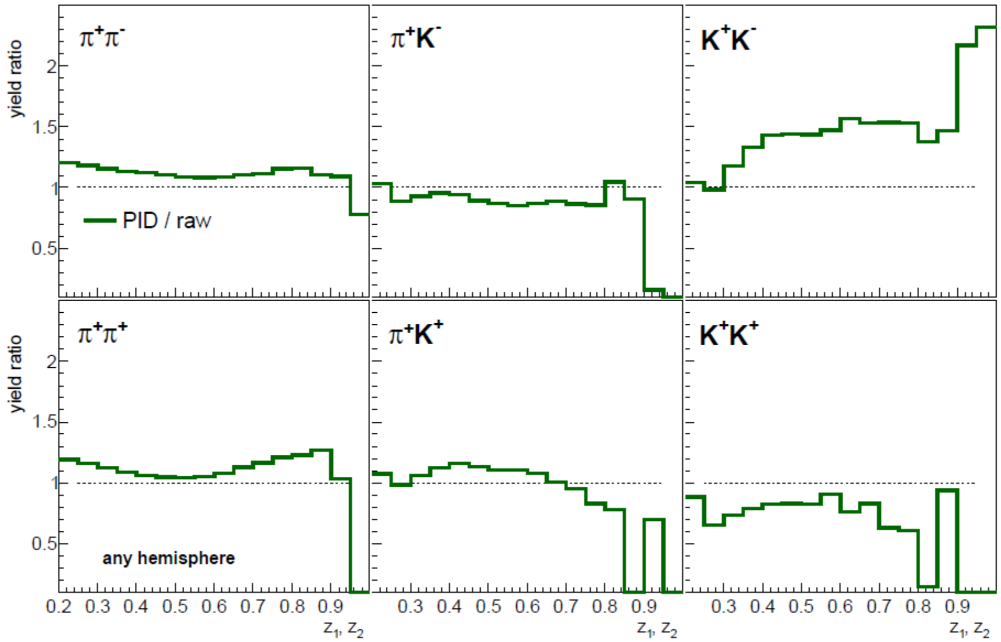
$$[P]_{ij\,(p_{lab},\,\cos\theta_{lab})} = \begin{pmatrix} p(e\to\tilde{e}) & p(\mu\to\tilde{e}) & p(\pi\to\tilde{e}) & p(K\to\tilde{e}) & p(p\to\tilde{e}) \\ p(e\to\tilde{\mu}) & p(\mu\to\tilde{\mu}) & p(\pi\to\tilde{\mu}) & p(K\to\tilde{\mu}) & p(p\to\tilde{\mu}) \\ p(e\to\tilde{\pi}) & p(\mu\to\tilde{\pi})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

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%



di-hadron yield ratios "after to before" PID correction

di-hadron (any topo) fraction originating from weak and strong decays