

MIT HIG group's work was supported
by US DOE-NP

Long-range near-side correlation in e^+e^- collisions at 183-209 GeV with ALEPH archived data

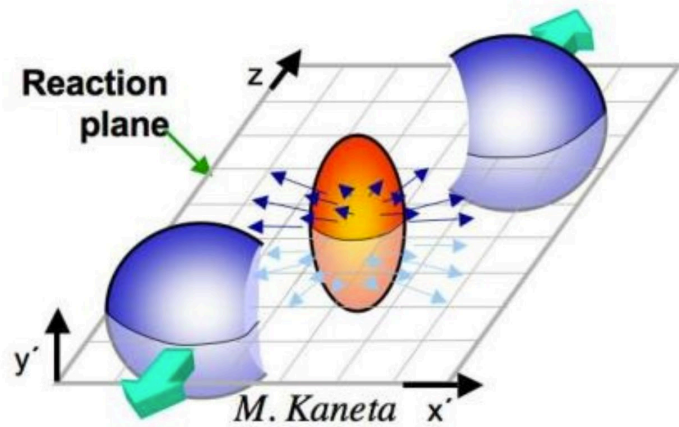
Michael Peters, in collaboration with Yu-Chen (Janice) Chen, Yi-Chen,
Pao-Ti Chang, Yen-Jie Lee, and Marcello Maggi, Austin Baty, Anthony
Badea, Chris McGinn, Jesse Thaler, Gian Michelle Innocenti, and Tzu-An
Sheng

arXiv: [2312.05084](https://arxiv.org/abs/2312.05084)

Analysis note: [2309.09874](https://arxiv.org/abs/2309.09874)

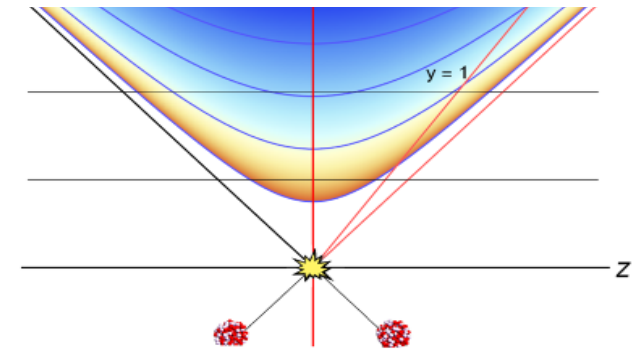
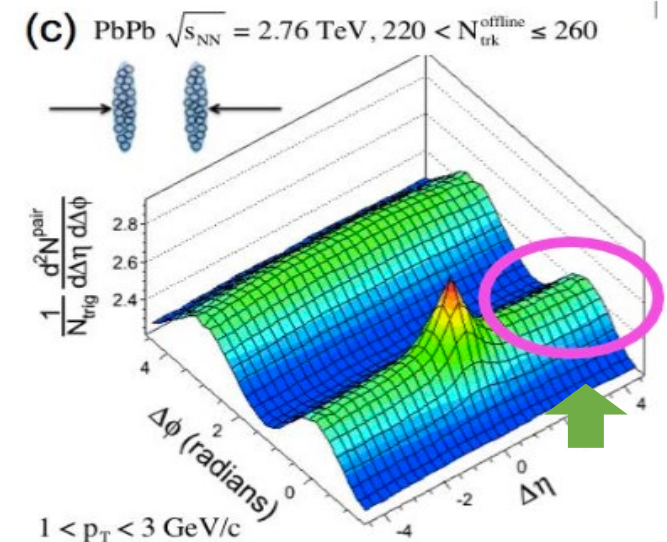
[\[Phys. Lett. B 856, 138957 \(2024\)\]](#)

Long-range near-side correlations: The “Ridge” in HI collisions



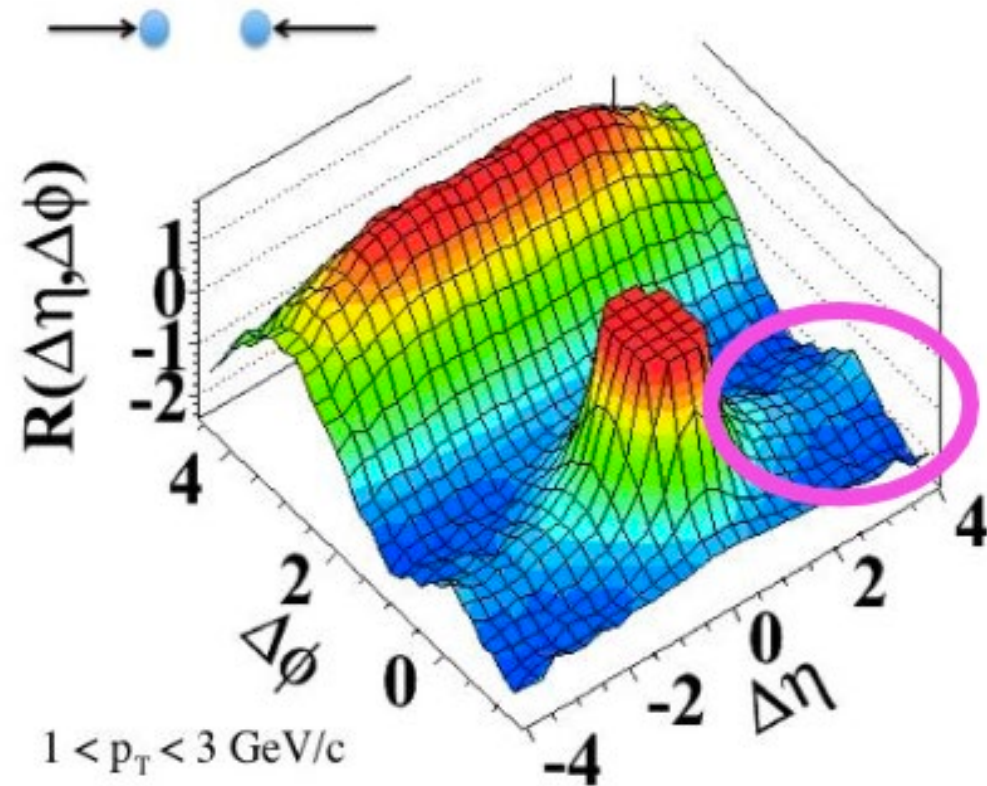
Ridge correlation:
long-range (large $\Delta\eta$)
near-side (small $\Delta\phi$)

- Large correlation for pairs of particles with large $\Delta\eta$ and small $\Delta\phi$
 - Large $\Delta\eta$ $\rightarrow$ causally disconnected for single point-like interaction, hence “long-range”
- Hints at existence of collective behavior, i.e. QGP



The “Ridge” in pp collisions

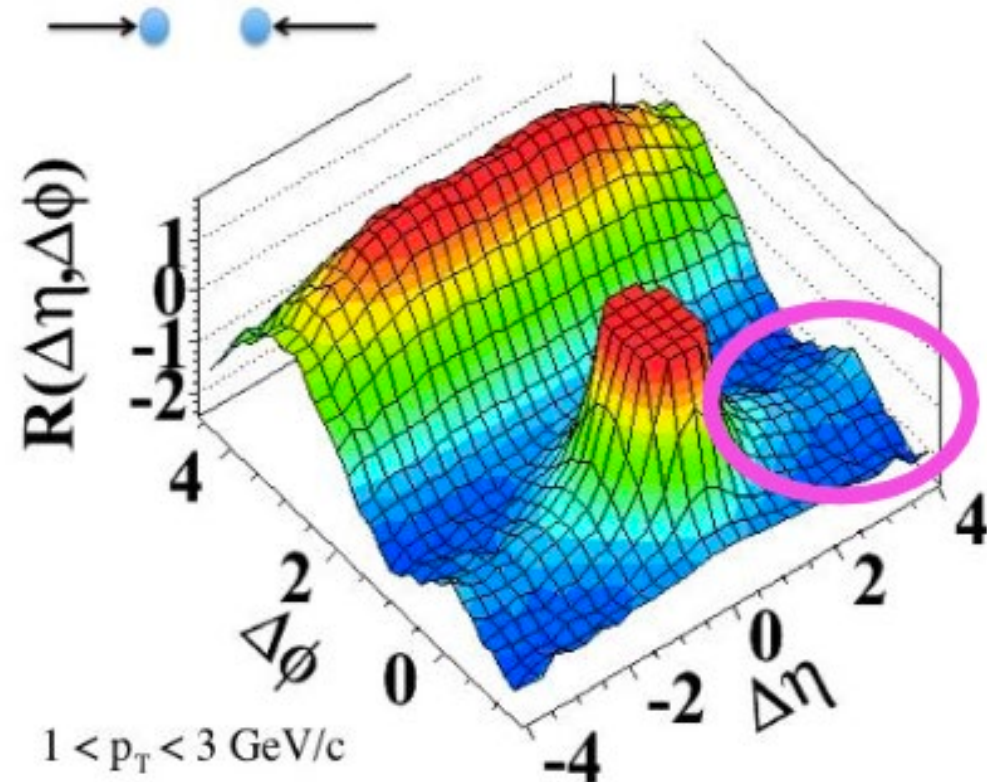
- Also observed in high-multiplicity pp collisions at the LHC in 2012
- Initial-state anisotropy may create ridge in this case
 - System thought to be too small to produce collective interactions



[CMS: [JHEP 1009 \(2010\) 091](#)]

The “Ridge” in pp collisions

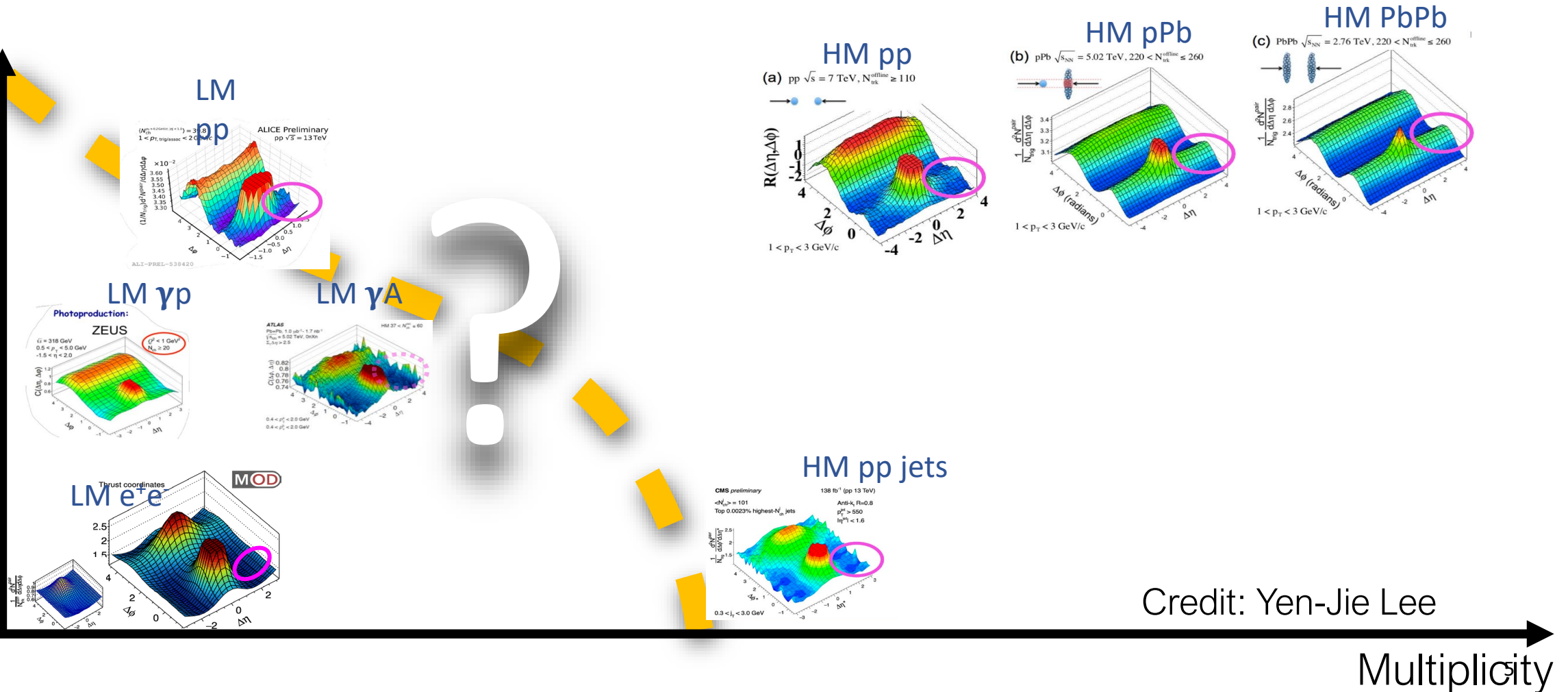
- Proposed explanations include:
 - Initial-stage effect (e.g. CGC)
 - Escape mechanism, after one or a few scatterings (AMPT, Pythia with Rope Mechanism, multiparton scattering...)
 - Final-state effect due to “mini-QGP”
 - Among others...



[CMS: [JHEP 1009 \(2010\) 091](#)]

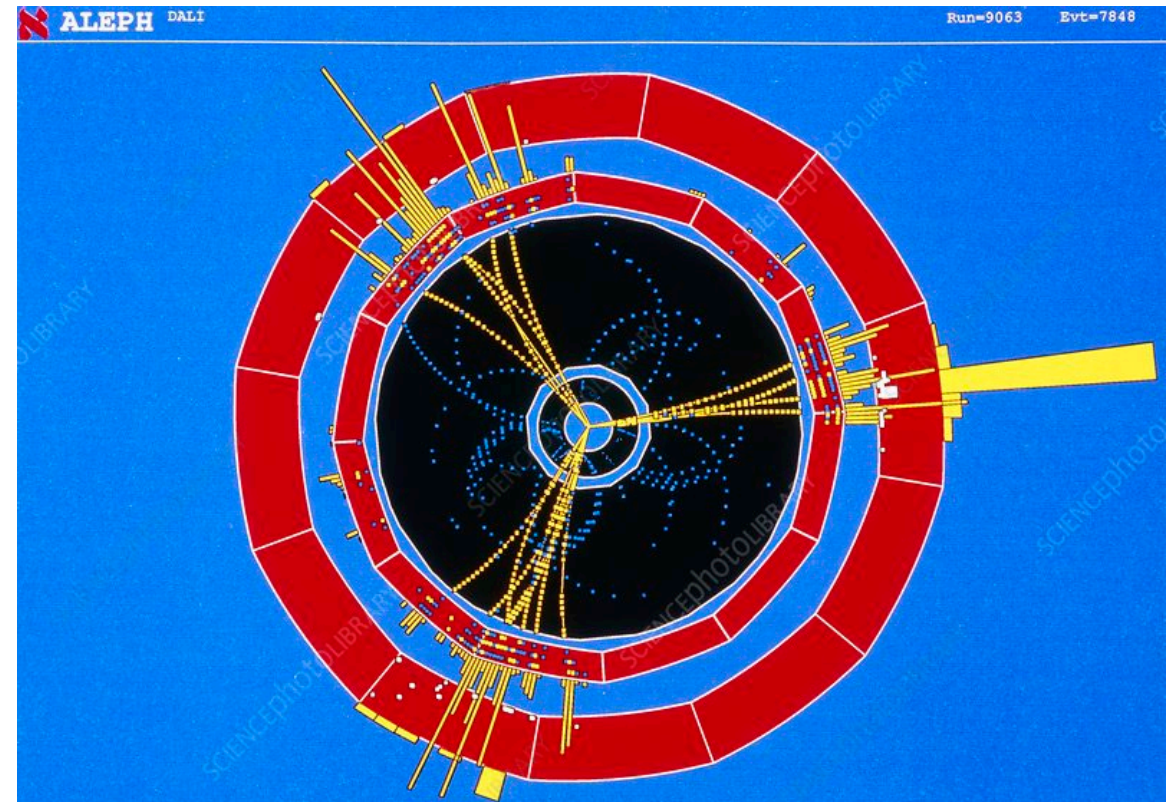
Emergence of “ridge-like” behavior?

Transverse size
Early stage complexity



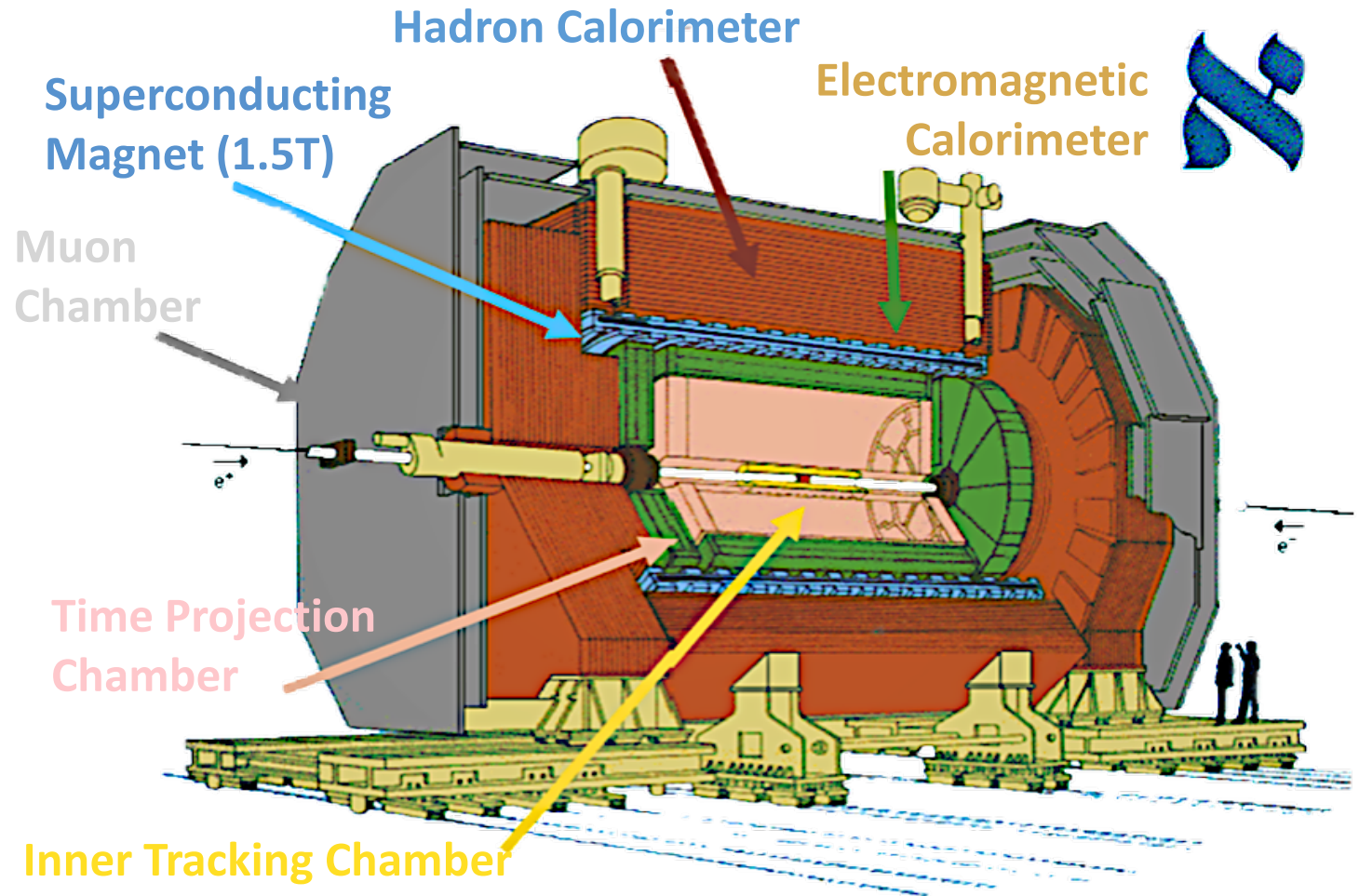
Electron-positron collisions: a QCD laboratory

- Many advantages as a reference system for correlation studies:
 - No gluon ISR, no beam remnant
 - Structureless beam (no beam PDF, no MPI)
 - Point-like collisions (good kinematic control for final states)
 - Colorless initial state
 - Parton shower and hadronization occur in vacuum



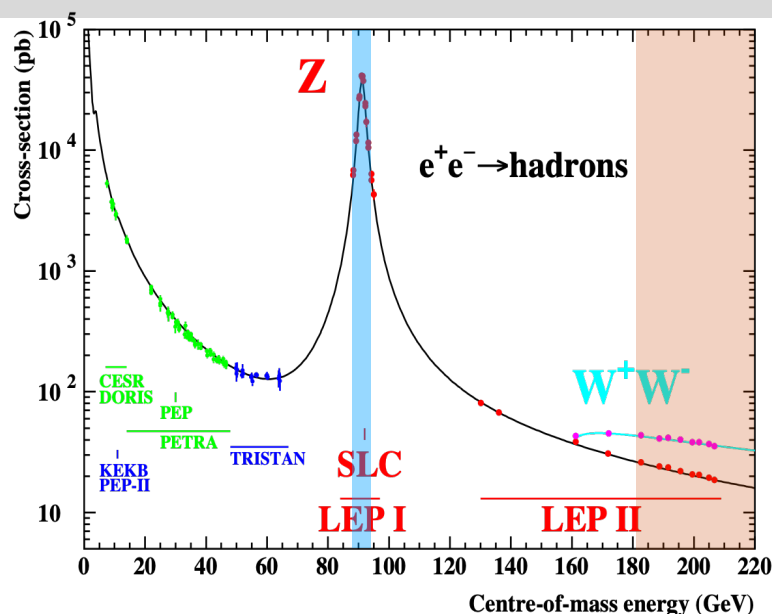
ALEPH data re-analysis

- Hermetic general-purpose detector on LEP collider
- Large e^+e^- datasets taken from 1992-2004
- Pythia6 MC archived along with data
- Re-analyzed using MIT Open Data Format

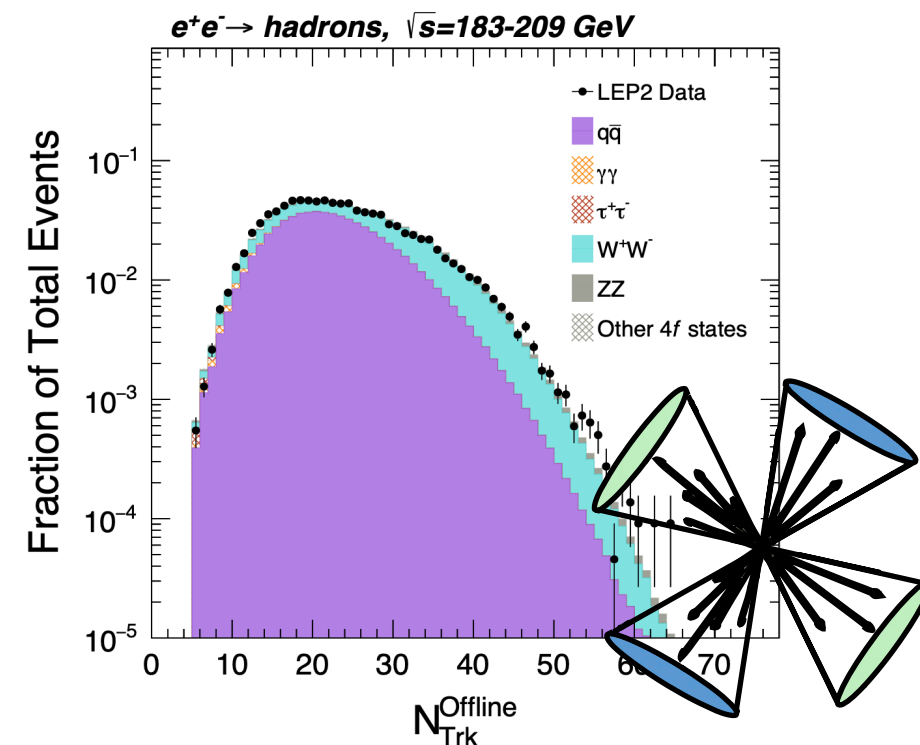


*Acknowledgement:
we would like to thank Roberto Tenchini and Guenther Dissertori from the ALEPH collaboration
for the useful comments and suggestions on the use of ALEPH data

LEP I and LEP II datasets



- LEP I dataset (1992-1995): Z-pole energies (91 GeV)
- LEP II dataset (1996-2000): higher energy (183-209 GeV), significant WW production
 - WW events dominate high-multiplicity data (two color strings instead of one)

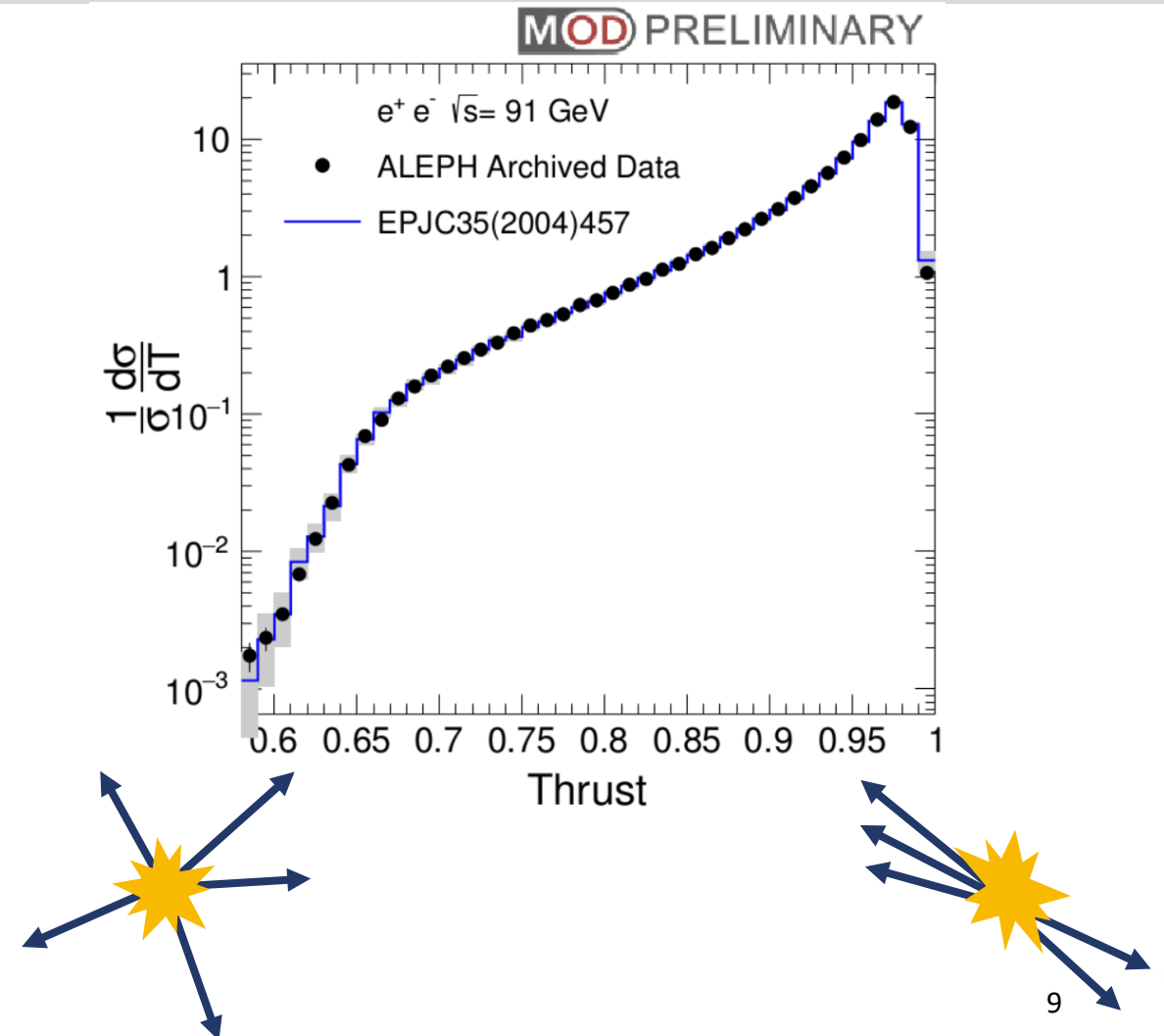


$$e^+e^- \rightarrow W^+W^- \rightarrow 4f$$

Thrust Distribution

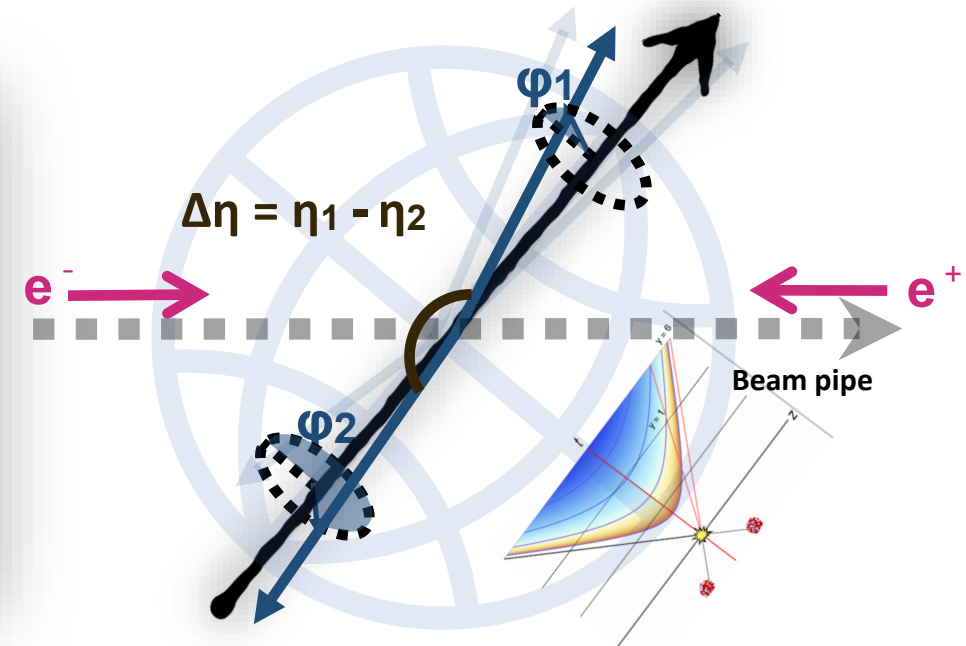
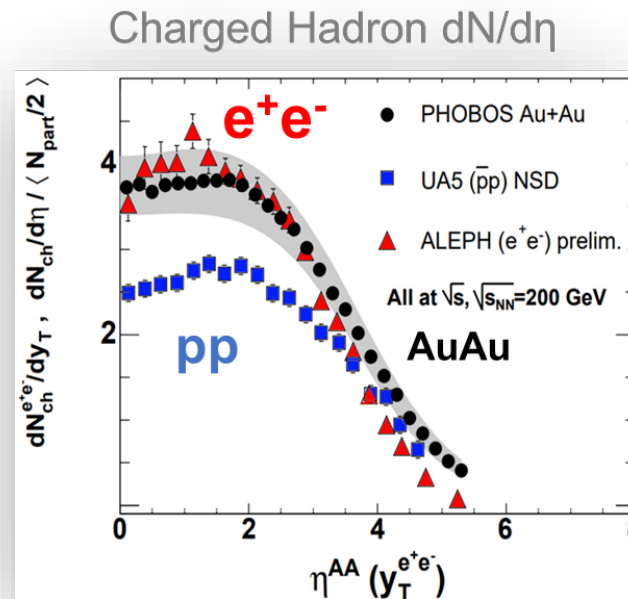
- Thrust measures event shape, from “spherical” (thrust=0.5) to “pencil-like” (thrust=1)
- Good agreement between thrust distribution in this analysis and previous ALEPH Collaboration analyses

$$T = \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$$



Two-particle correlation w.r.t. the thrust axis

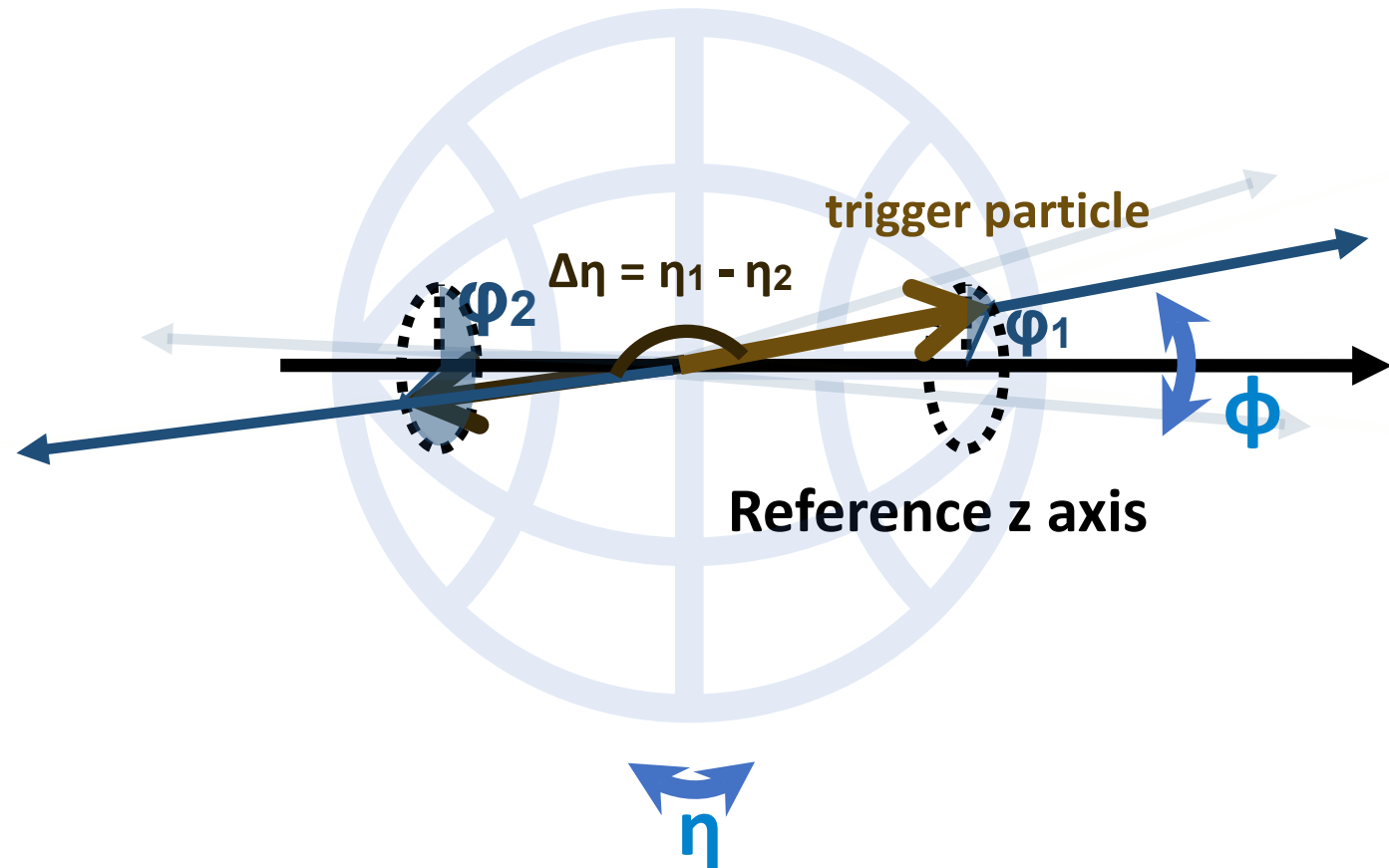
- Thrust axis used as reference to focus on medium expanding perpendicular to outgoing final-state axis
- $dN/d\eta$ distributions in e^+e^- relative to thrust axis similar to those in pp and AuAu relative to beam axis



Two-particle correlation: the observable

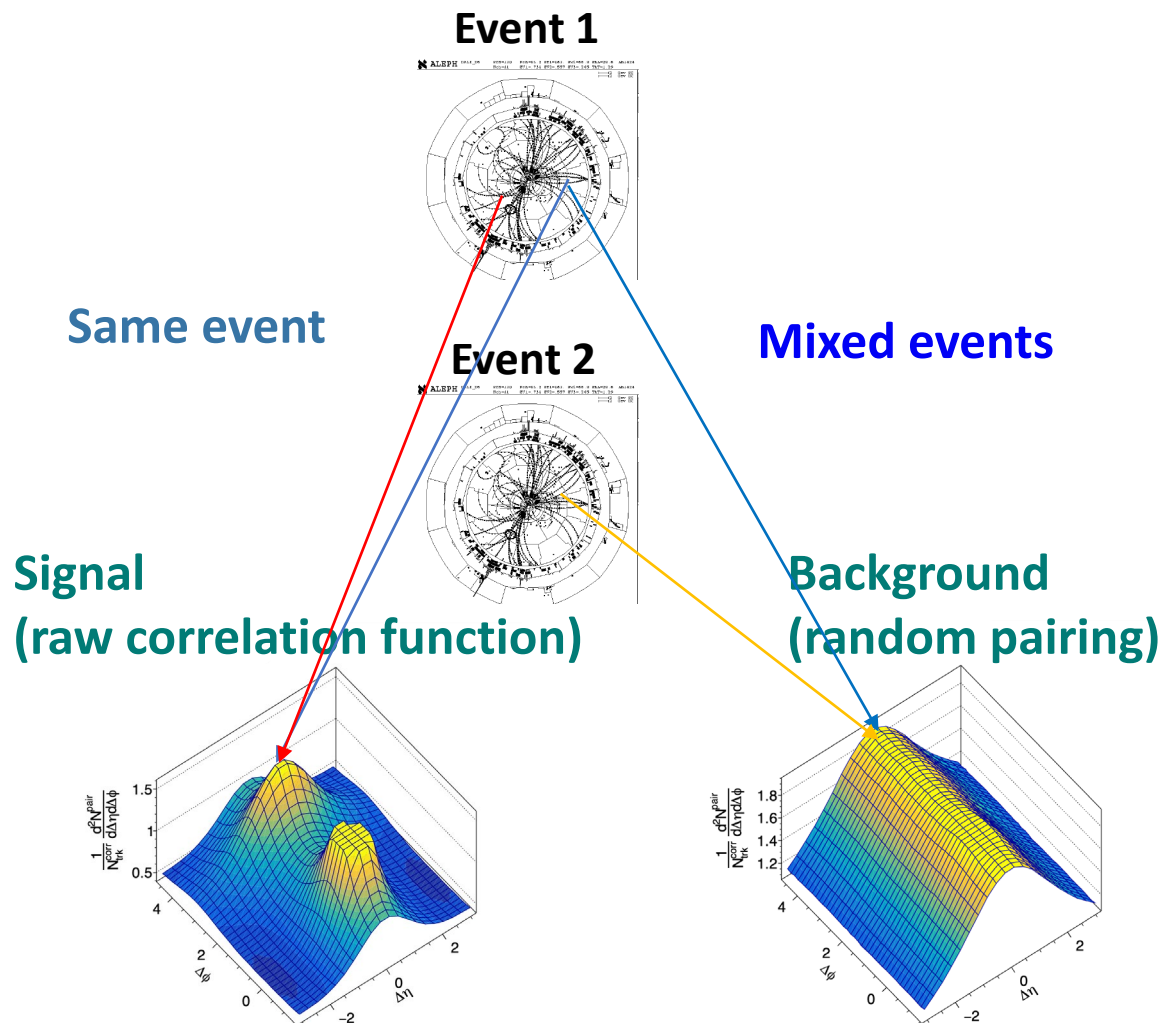
- Correlation between pairs of tracks' (η, ϕ) coordinates relative to thrust axis

$$\frac{1}{N_{\text{trk}}^{\text{corr}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi}$$



Background reduction via event-mixing

- Background from random pairing recovered using pairs of tracks from two different events

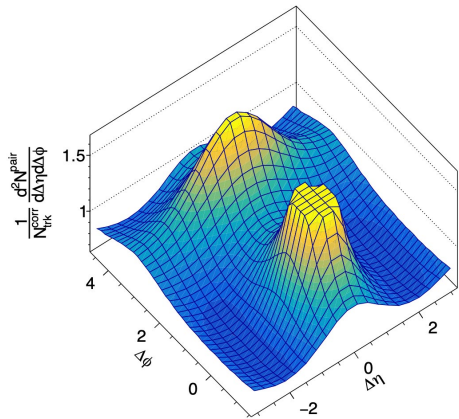


Extraction of observable

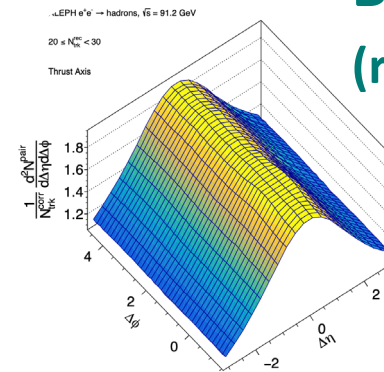
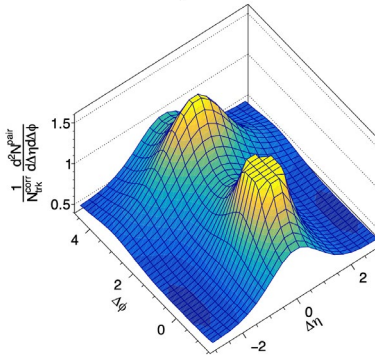
$$\frac{1}{N_{\text{trk}}^{\text{corr}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0,0) \times \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

Signal
(raw correlation function)

Background
(random pairing)



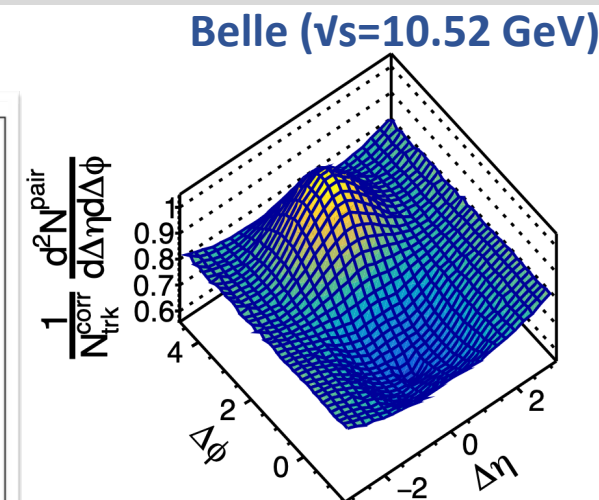
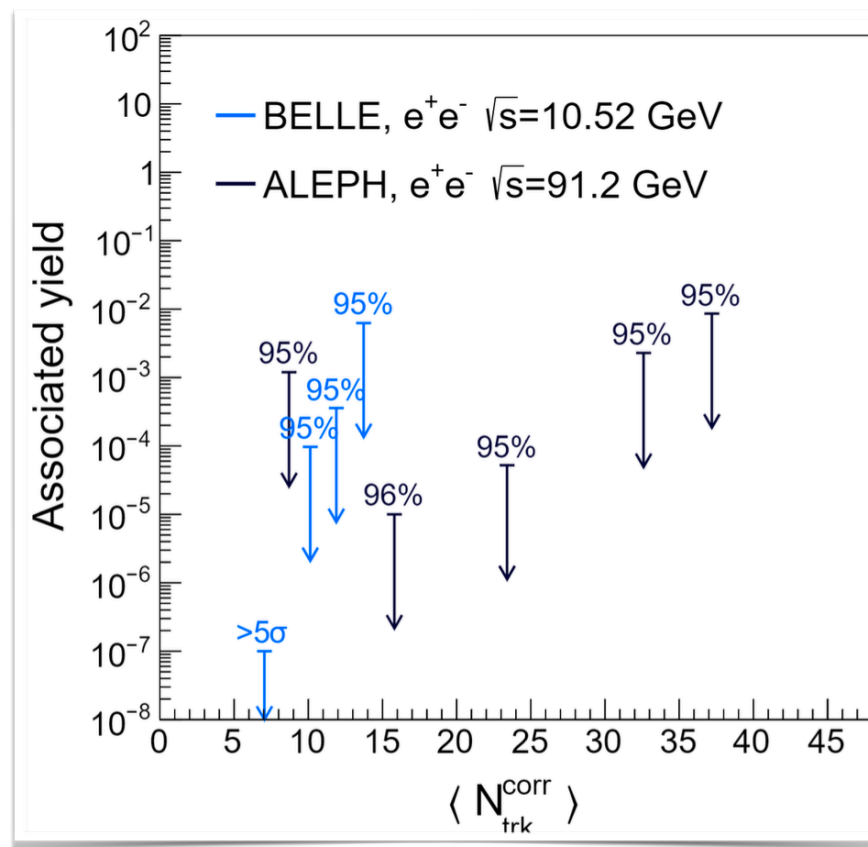
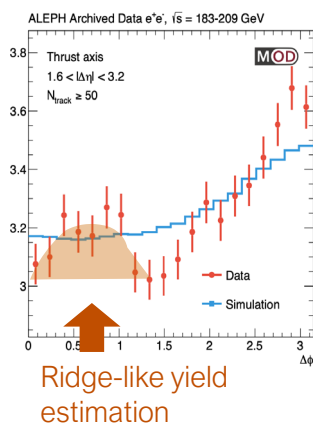
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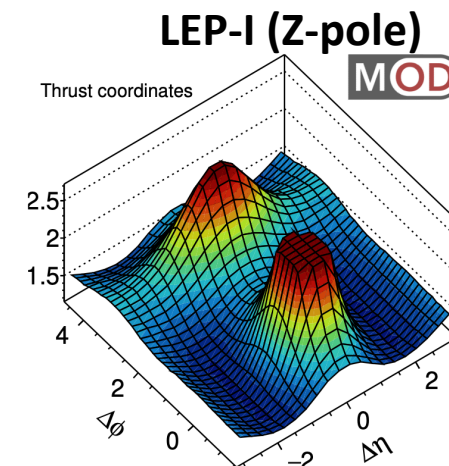
Normalization of $B(\Delta\eta, \Delta\phi)$

Previous two-particle correlation results

- 2019 re-analysis of LEP I data showed no significant yield associated with “ridge” feature
- 2022 BELLE analysis agreed

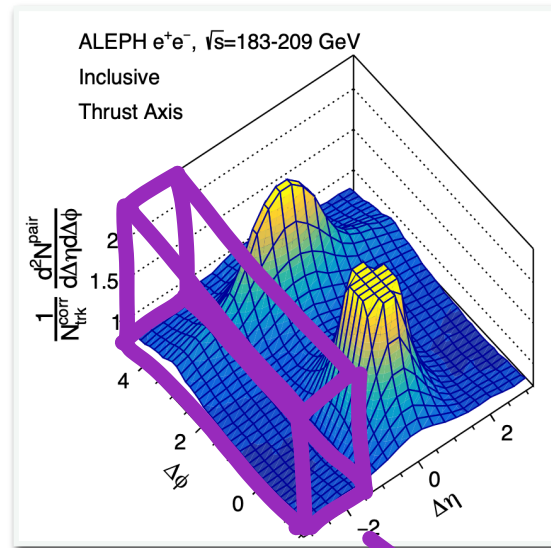


[Phys. Rev. Lett. 128, 142005 (2022)]

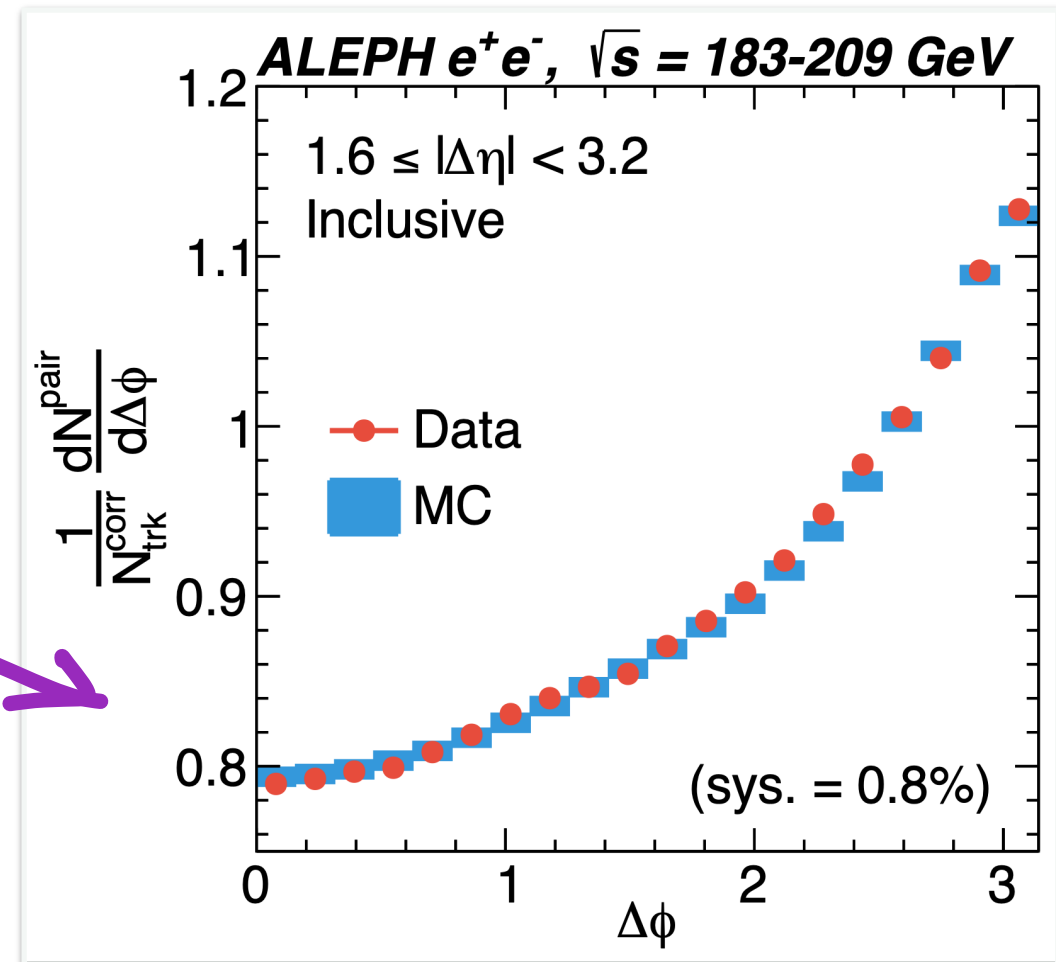


[Phys. Rev. Lett. 123, 212002 (2019)]

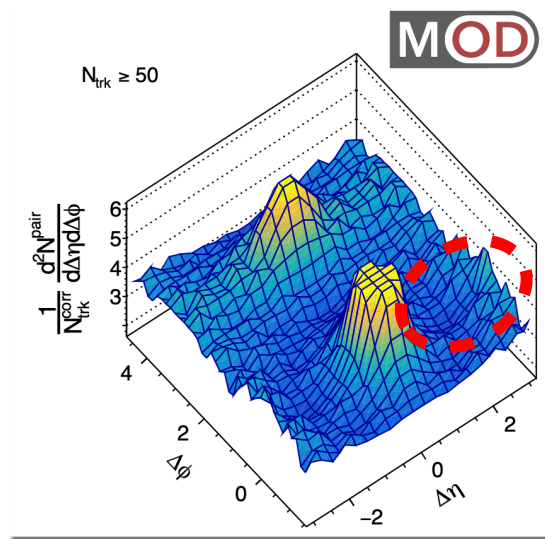
Two-particle correlation >183 GeV at LEP II



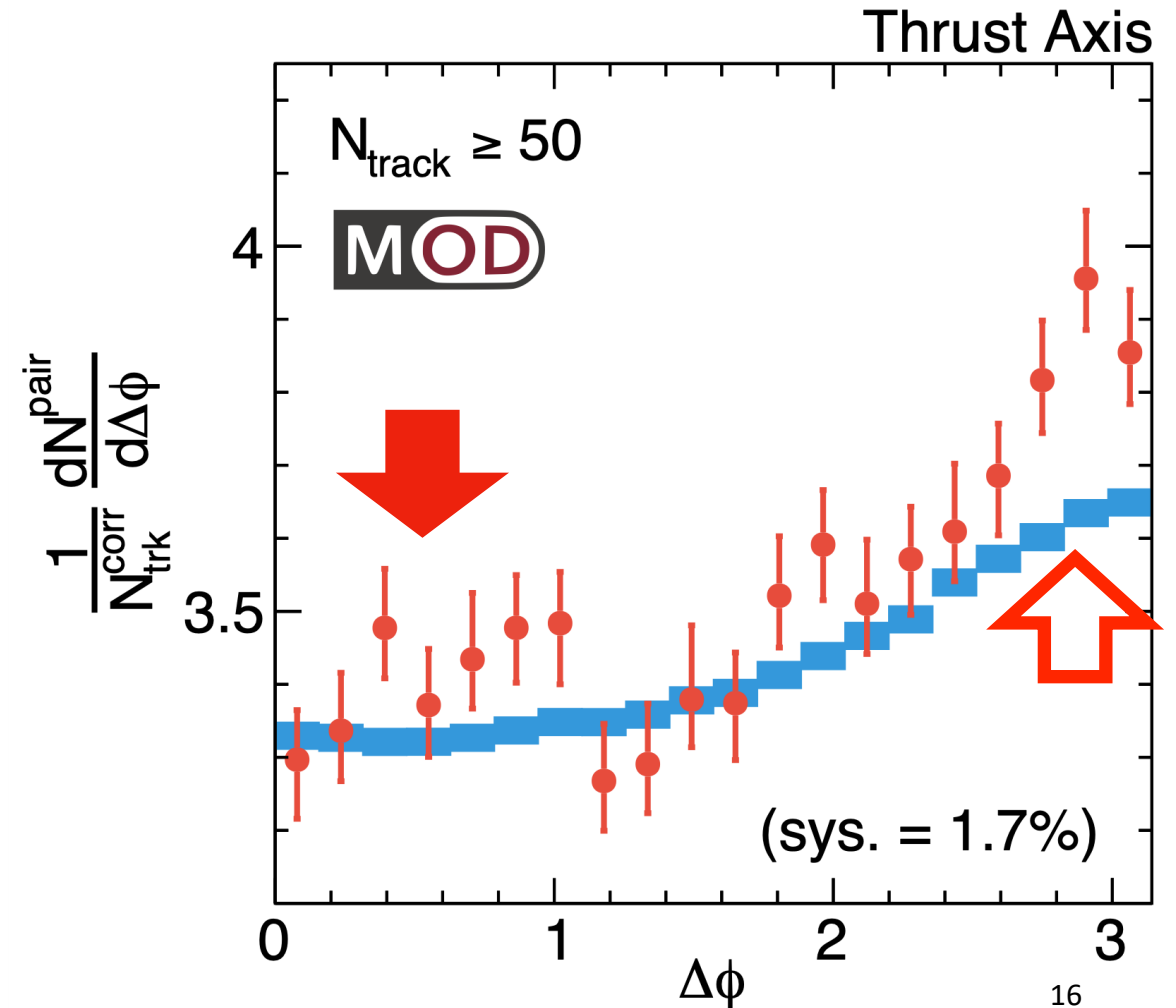
- Generally good agreement between data and MC for LEP II re-analysis



High-multiplicity ($N_{\text{track}} \geq 50$) LEP II results



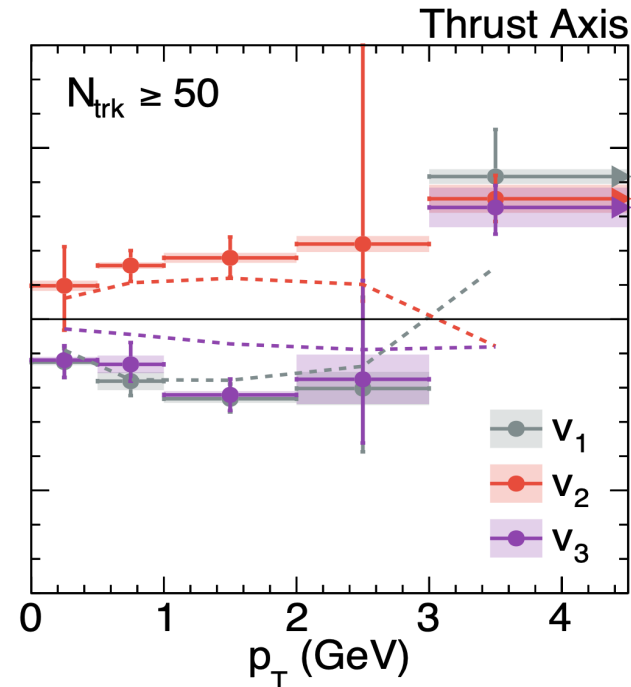
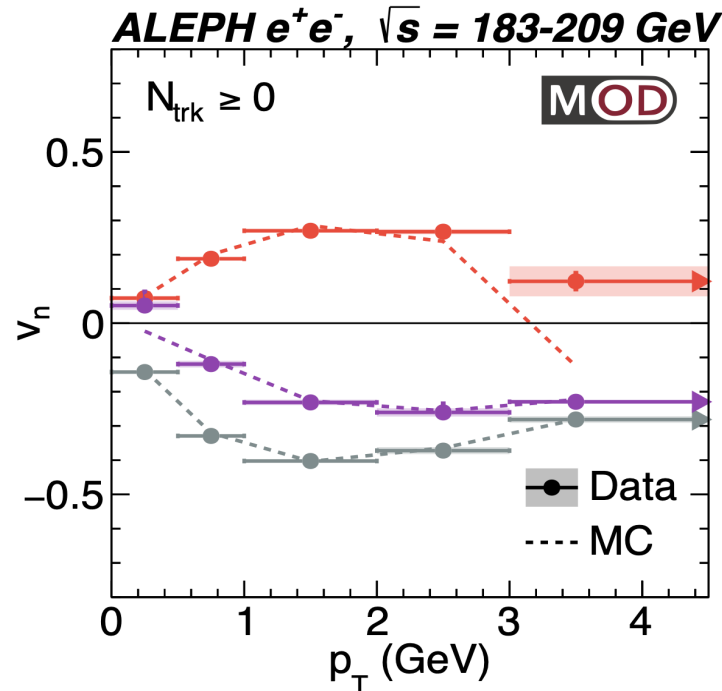
- Interesting features in high-multiplicity long-range near-side correlations
- Possible hint of excess over MC



“Flow-like trend” coefficients

Inclusive N_{Trk}

High-multiplicity



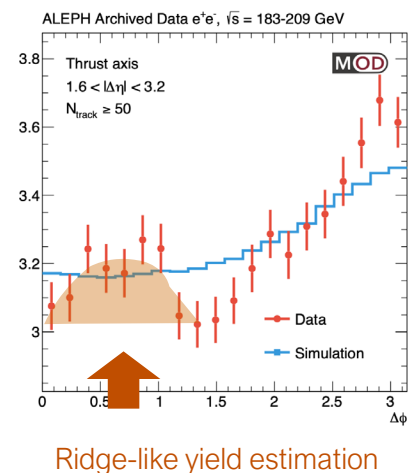
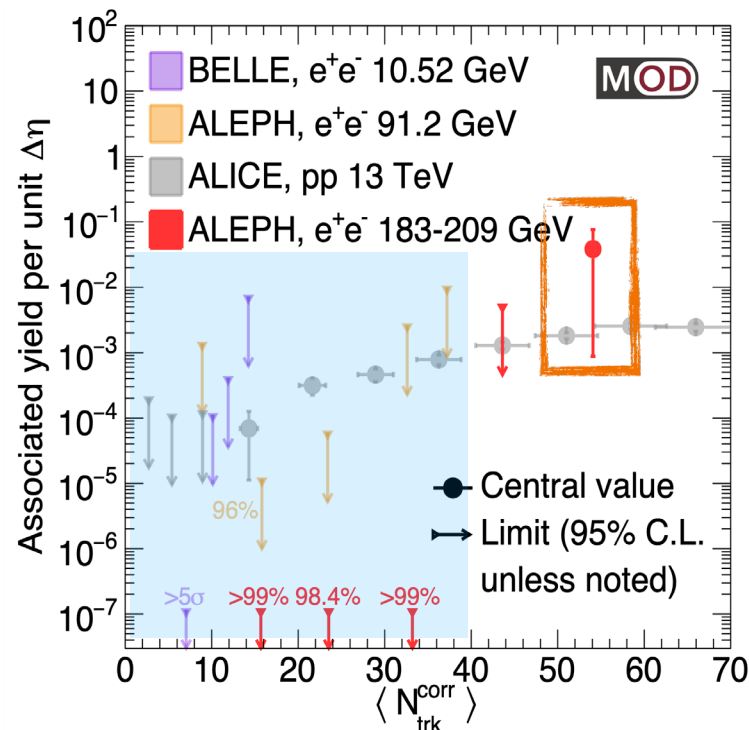
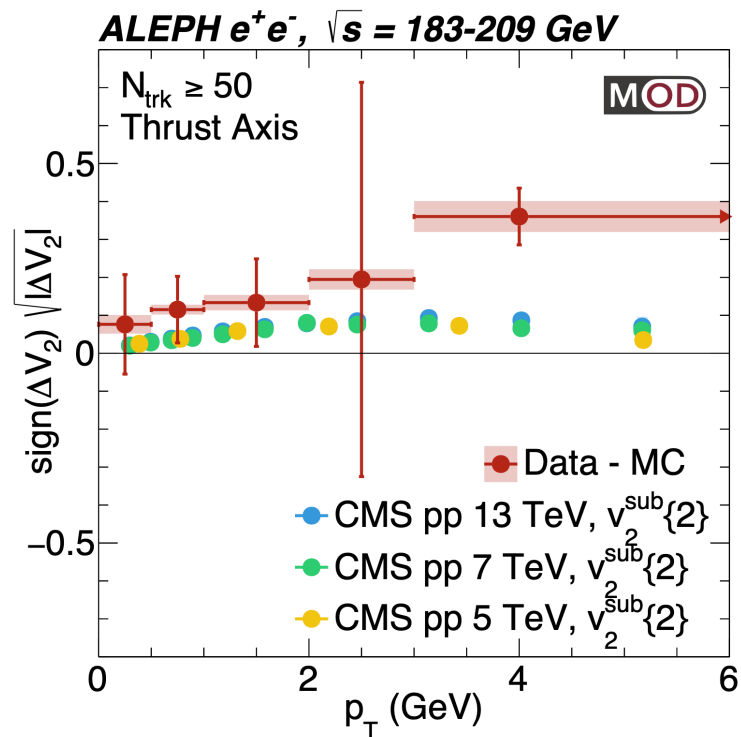
Sign change for v_2 and v_3

- Coefficients found by taking Fourier transform of yield

$$Y(\Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{dN^{\text{pairs}}}{d\Delta\phi} = \frac{N^{\text{assoc}}}{2\pi} \left(1 + \sum_{n=1}^{n_{\text{max}}} 2V_{n\Delta} \cos(n\Delta\phi) \right)$$

- Assuming factorization: $v_n\{2, 1.6 < |\Delta\eta| < 3.2\} = \text{sign}(V_{n\Delta}) \sqrt{V_{n\Delta}}$

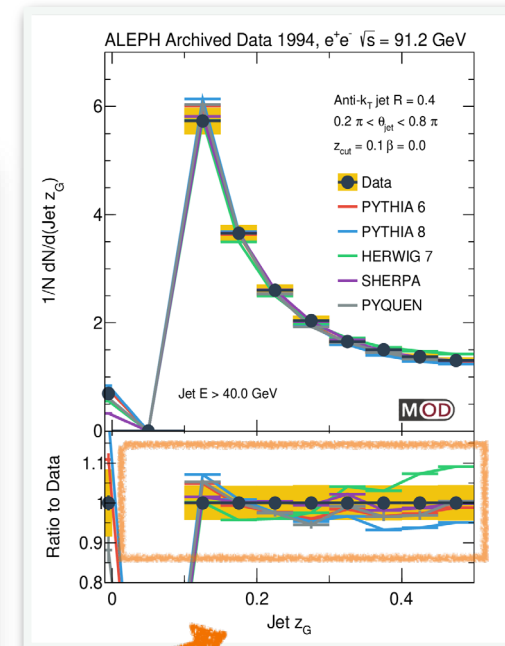
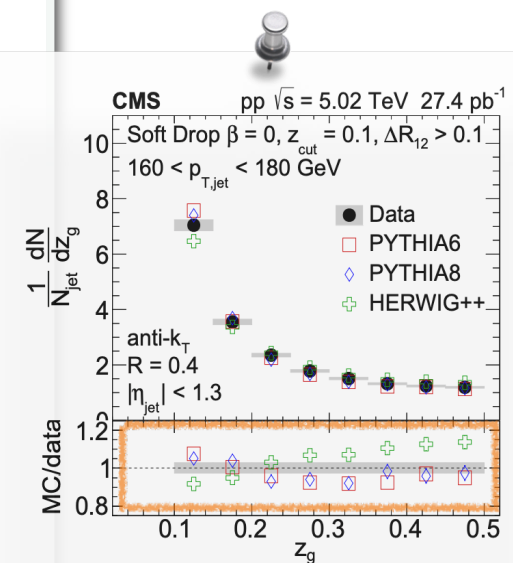
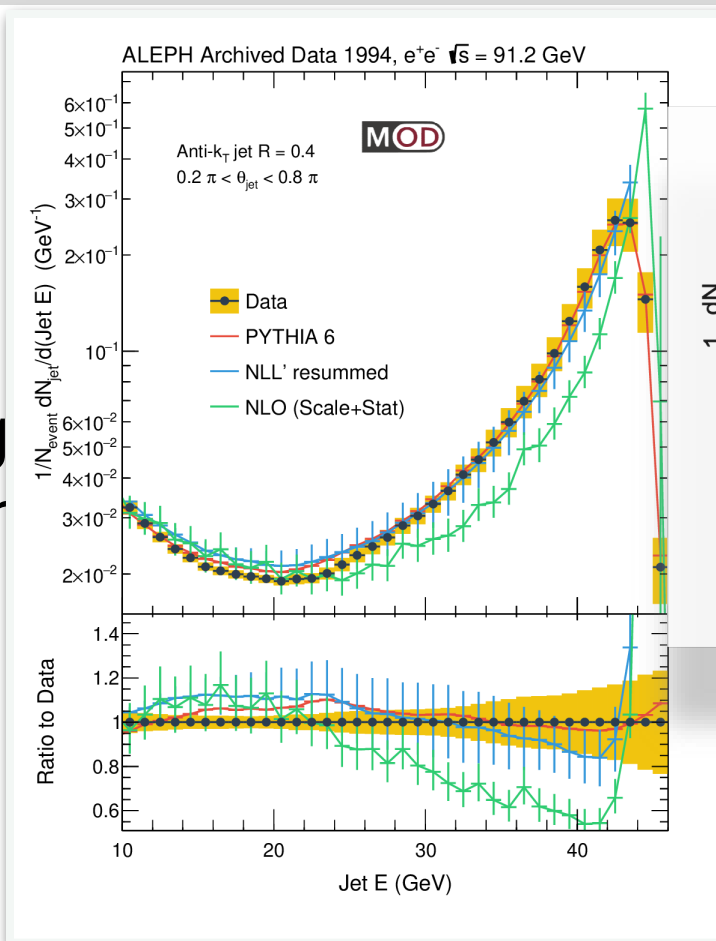
Similarity to low-multiplicity pp collisions?



- Measured coefficients seem to be similar to CMS and ALICE measurements in low-multiplicity pp collisions at a variety of beam energies

Other observables: Jet Substructure

- Rising edge of jet energy spectrum sensitive to jet function
- Jet energy sharing (z_g) shows similar trend between e+e- and pp collisions

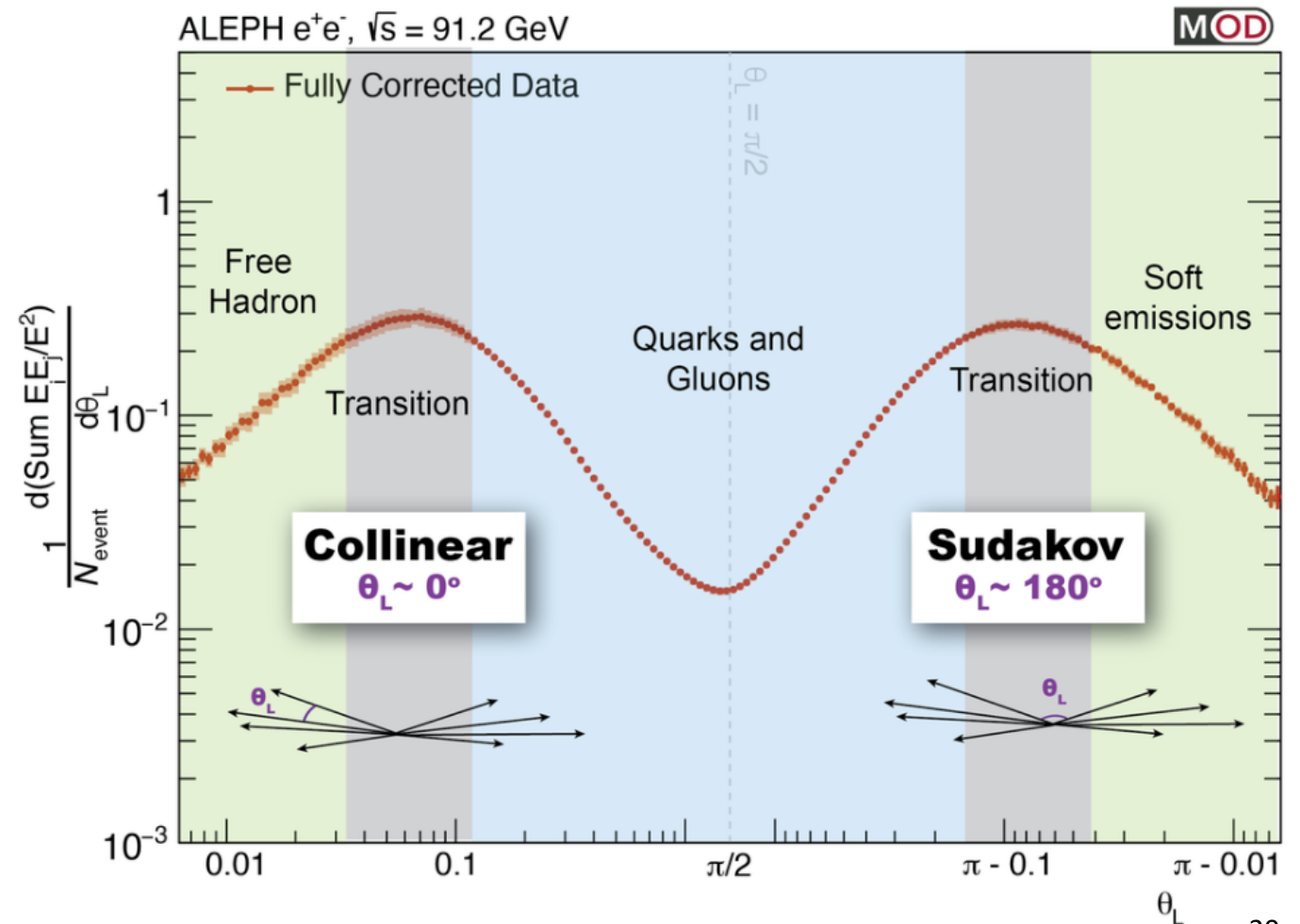


ALEPH jet

[JHEP 06 (2022) 008]

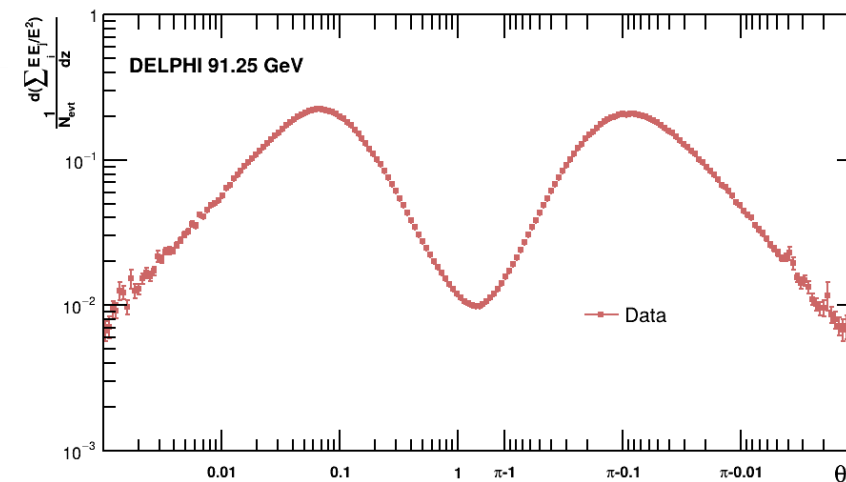
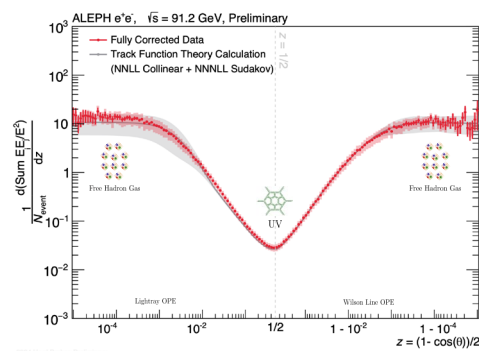
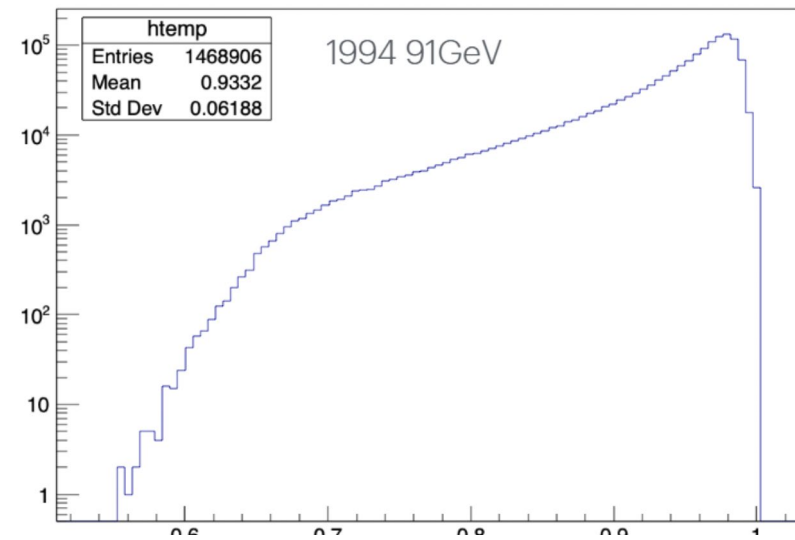
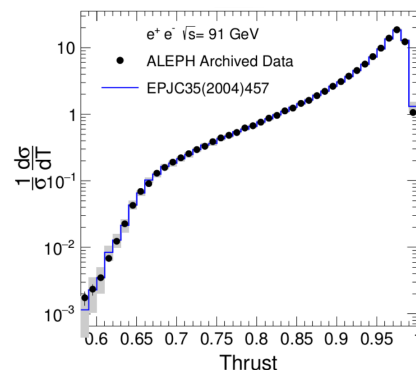
Other observables: Energy-Energy Correlator

- Theorists (Ian Mould + collaborators, Iain Stewart, et al.) interested in this quantity in particular:
 - Directly sensitive to theory parameters (ex: α_S)
 - Constraining non-perturbative parameters in lattice QCD
- Unique opportunity in e^+e^- to access the 2-point correlator from collinear to back-to-back limit
- Excellent agreement between archived data and theory calculation
- Analysis currently in internal review



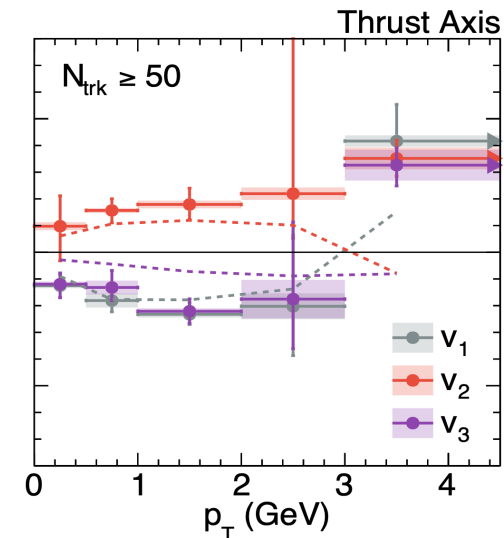
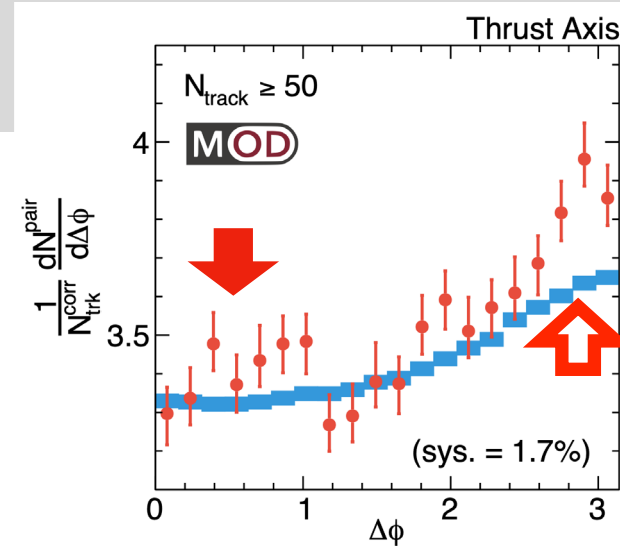
Other datasets: DELPHI archived data

- Extremely useful as a cross-check of ALEPH re-analyses
- Re-analysis actively in progress
 - Thrust distribution already substantially similar to ALEPH, EEC corrections under active development



Conclusions

- Electron-positron collisions allow for investigation of smallest possible collision systems for flow-like characteristics
- Re-analysis of LEP II data reveals possible signs of an excess long-range near-side yield relative to MC
 - Hints at a “bridge” between pure hard scattering and flow in pp collisions
- Plenty of avenues for further use of electron-positron collision data as a versatile laboratory for QCD investigation

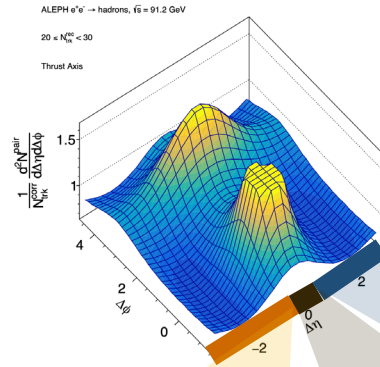


Backup

Azimuthal differential associated yield $Y(\Delta\phi)$

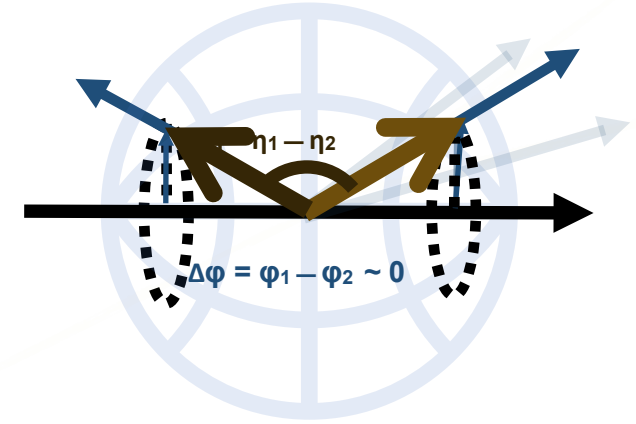
Two-particle correlation function
(per-trigger-particle associated yield)

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi}$$



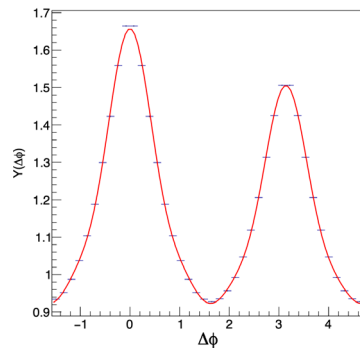
Associated yield vs. $\Delta\phi$

$$Y(\Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{1}{\Delta\eta_{\text{max}} - \Delta\eta_{\text{min}}} \int_{\Delta\eta_{\text{min}}}^{\Delta\eta_{\text{max}}} \frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi} d\Delta\eta$$



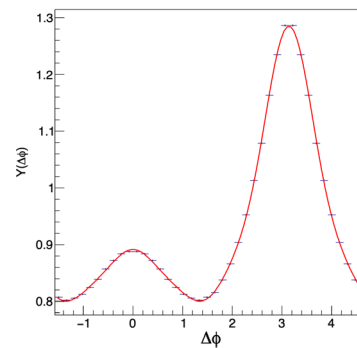
Short Range

$\Delta\phi, \Delta\eta (0.0, 1.0)$, Multiplicity (20, 30)



Middle Range

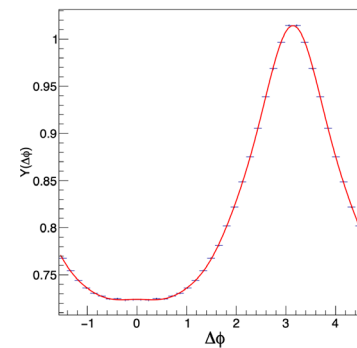
$\Delta\phi, \Delta\eta (1.0, 1.6)$, Multiplicity (20, 30)



Long Range

$(1.6 \leq |\Delta\eta| < 3.2)$

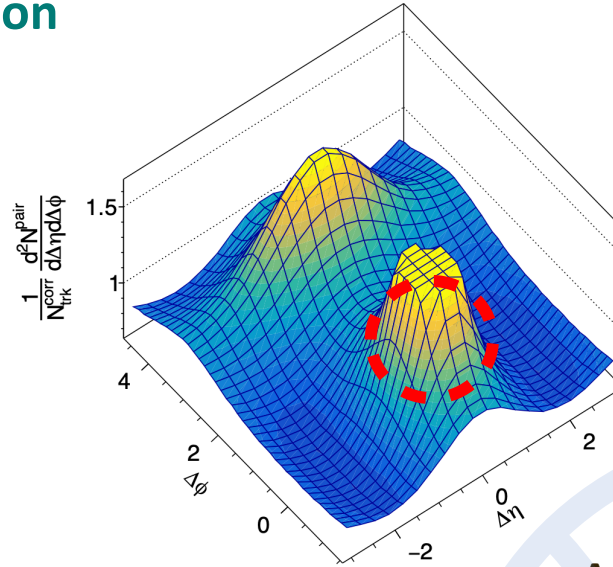
$\Delta\phi, \Delta\eta (1.6, 3.2)$, Multiplicity (20, 30)



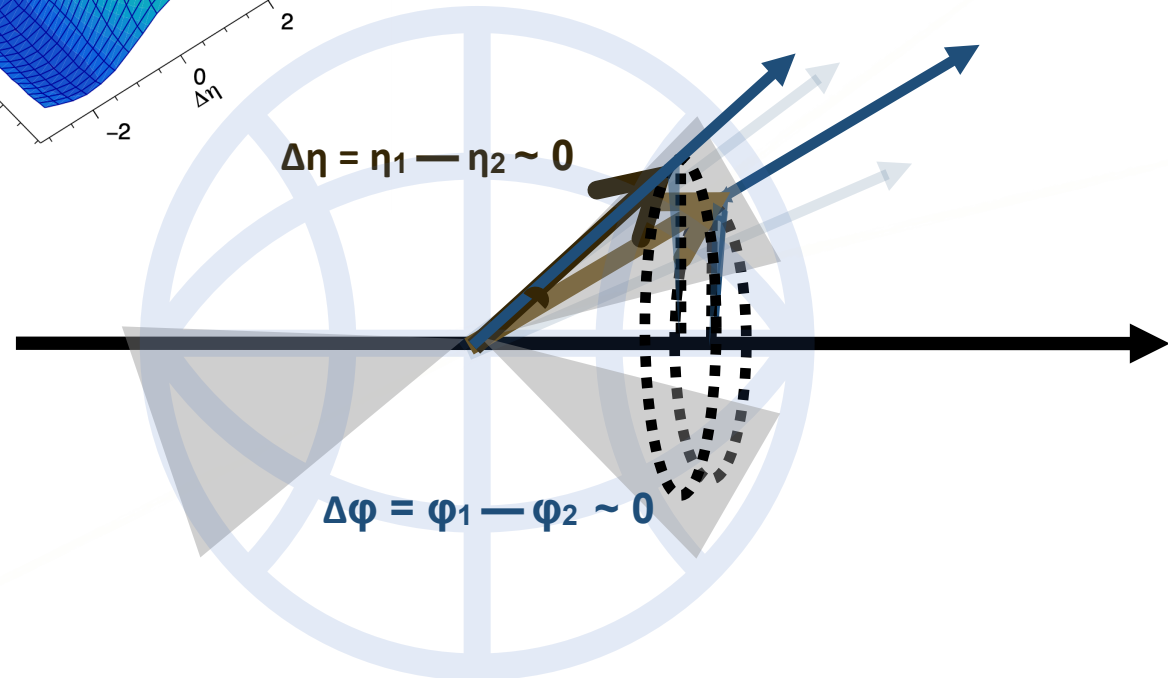
Understanding 2PC in e^+e^- — Intra-jet correlations

Two-particle correlation function
(per-trigger-particle associated yield)

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi}$$



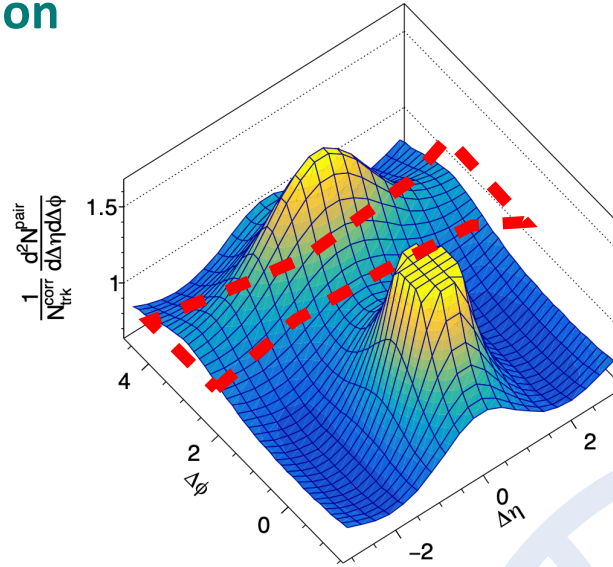
Origin-peak intra-jet correlations
@ near side $(\Delta\eta, \Delta\phi) \sim (0, 0)$



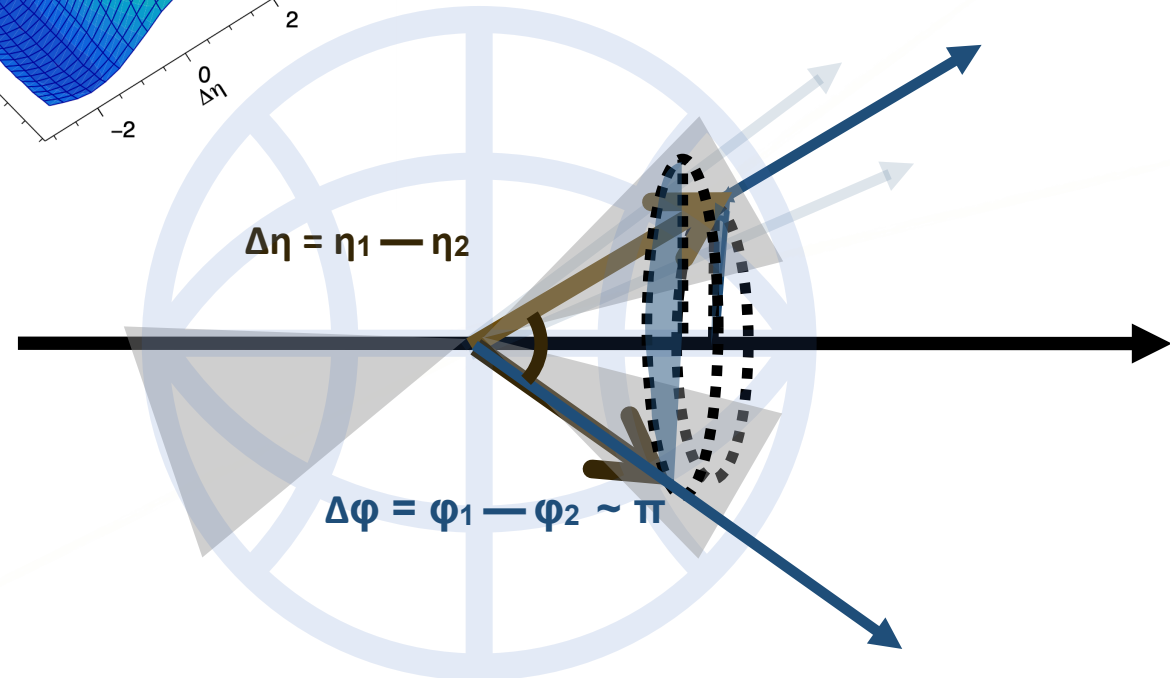
Understanding 2PC in e^+e^- — Inter-jet correlations

Two-particle correlation function
(per-trigger-particle associated yield)

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi}$$



Inter-jet correlations
@ away side ($\Delta\phi \sim \pi$)

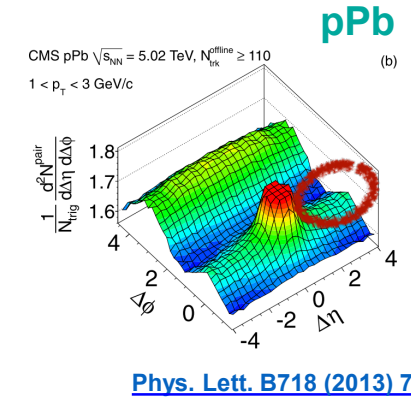
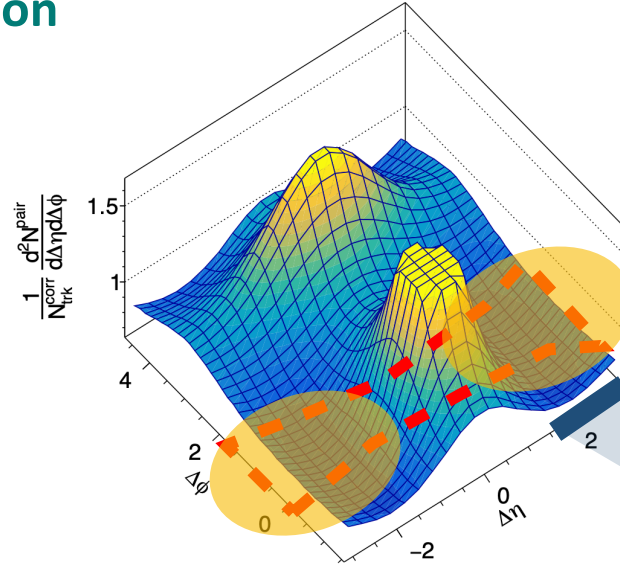


Understanding 2PC in e^+e^- — Ridge(-like) correlations

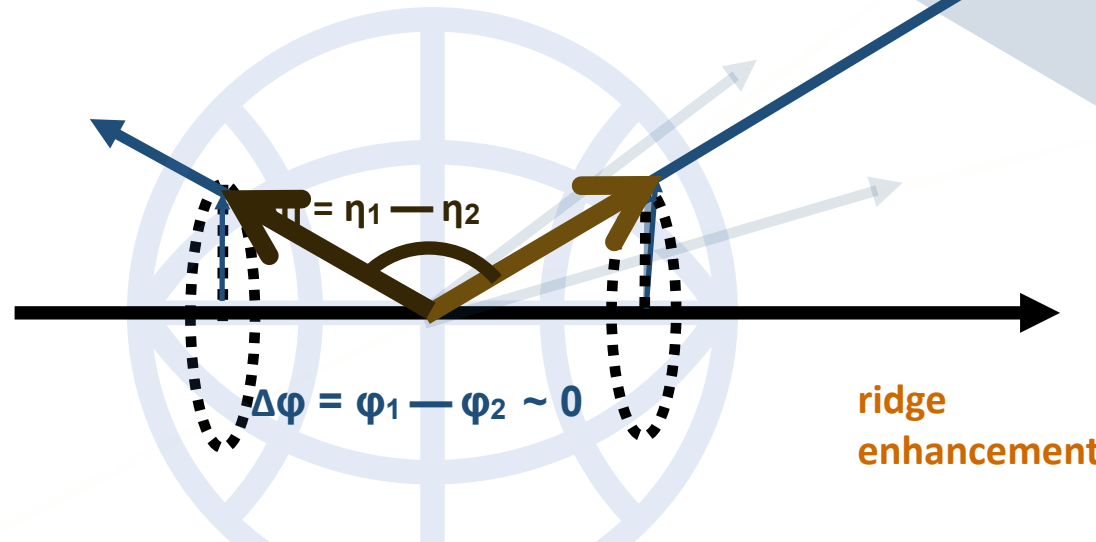
Two-particle correlation function
(per-trigger-particle associated yield)

$$\frac{1}{N_{\text{trig}}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi}$$

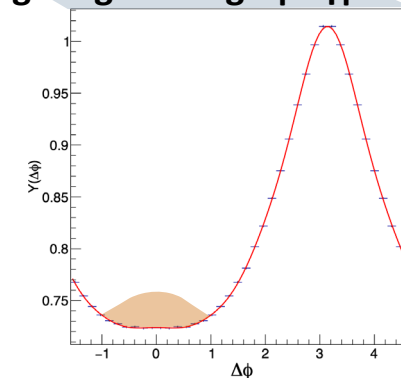
Ridge correlations
@ long range, near side



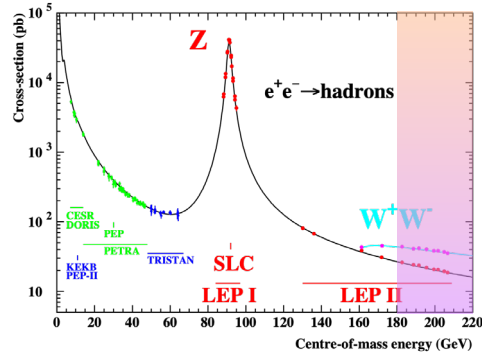
814



long range in large $|\Delta\eta|$



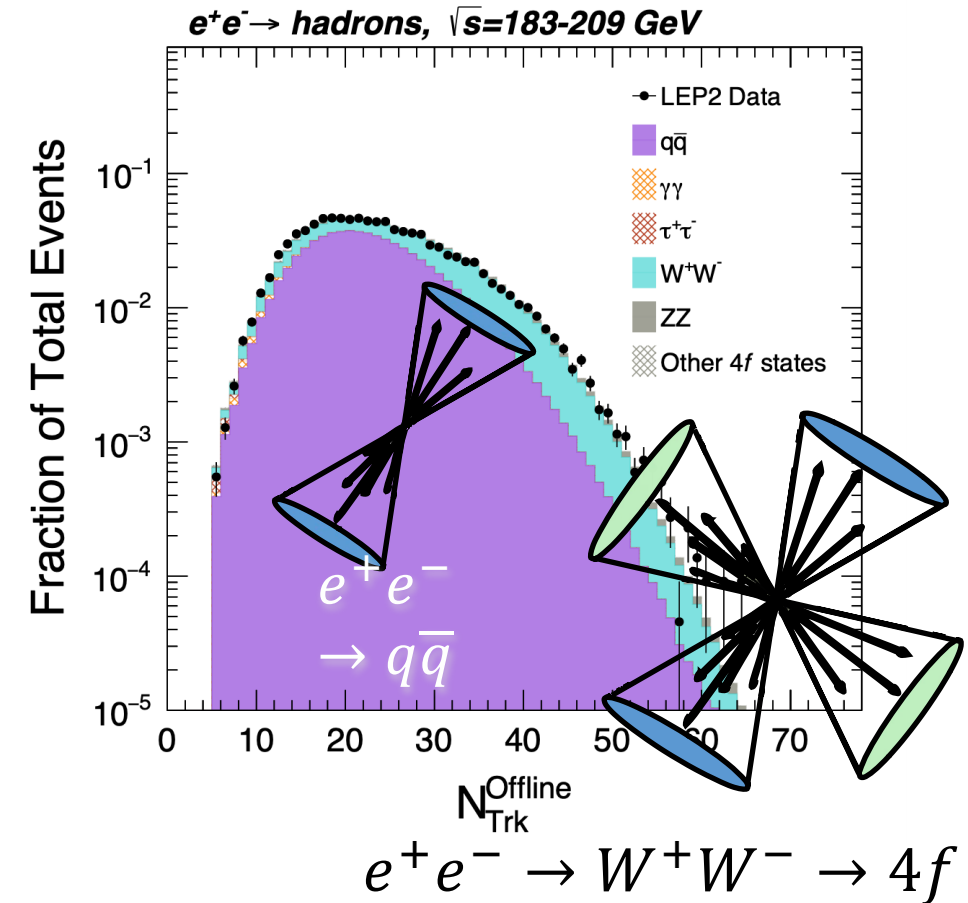
Searching for emergence of azimuthal correlation in e^+e^-



$\sqrt{s} \geq 183 \text{ GeV}$

What will happen in higher energy LEP-II sample?

- Allowing for higher event multiplicity up to $N_{\text{Trk}} \geq 50$
- Opening up more complicated color-string configuration
Dominant W^+W^- event at high multiplicity showcases a 2-color-string configuration



Selected list of analyses

e^+e^-

- ALEPH LEP1 (91 GeV) [PRL 123 \(2019\) 21, 212002](#)
- ALEPH LEP2 (183-209 GeV): [Phys. Lett. B 856, 138957 \(2024\)](#)
- Belle Off-resonance 10.52 GeV : [PRL 128 \(2022\) 14, 142005](#)
- Belle On-resonance (Y(4S)): [JHEP 03 \(2023\) 171](#)

γp

- CMS pPb photonuclear: [PLB 844 \(2023\) 137905](#)
- ZEUS ep neutral current DIS: [JHEP 04 \(2020\) 070](#)
- ZEUS ep photonuclear: [JHEP 12 \(2021\) 102](#)
- H1 ep neutral current DIS: (preliminary) [H1prelim-20-033](#)

γPb

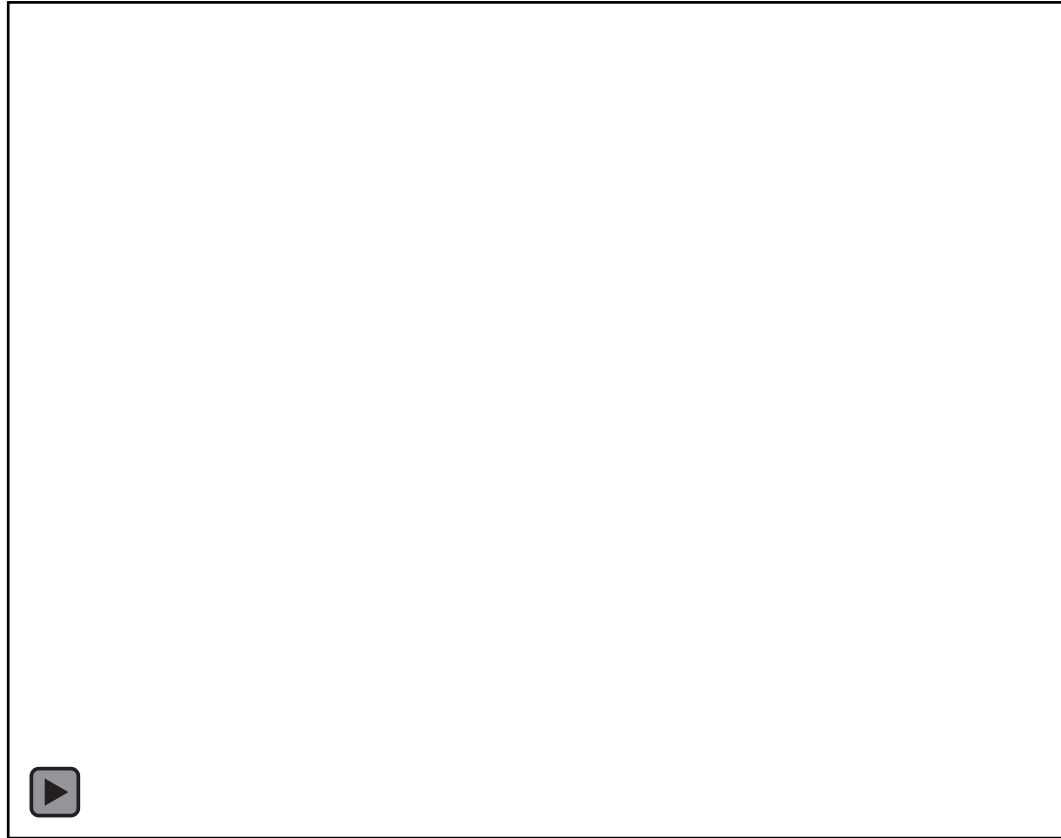
- ATLAS PbPb photonuclear: [PRC 104 \(2021\) 1, 014903](#)

pp

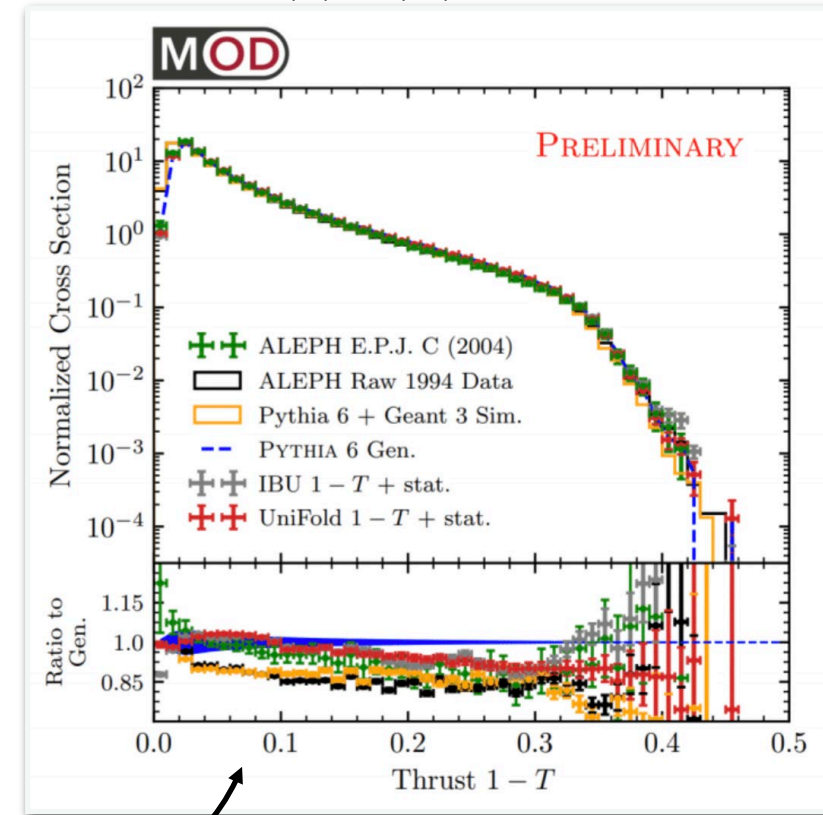
- ALICE MB: <https://arxiv.org/pdf/2311.14357.pdf>
- CMS Single Jet in pp: [CMS-HIN-21-013 arXiv:2312.17103](#)

High quality archived data

(slides from BOOST
2022
by Yi Chen)



Badea, Komiske, Metodiev, Thaler, Nachman, Lee,
paper in preparation



ALEPH: EPJC 35 (2004) 456

Published results can be reproduced

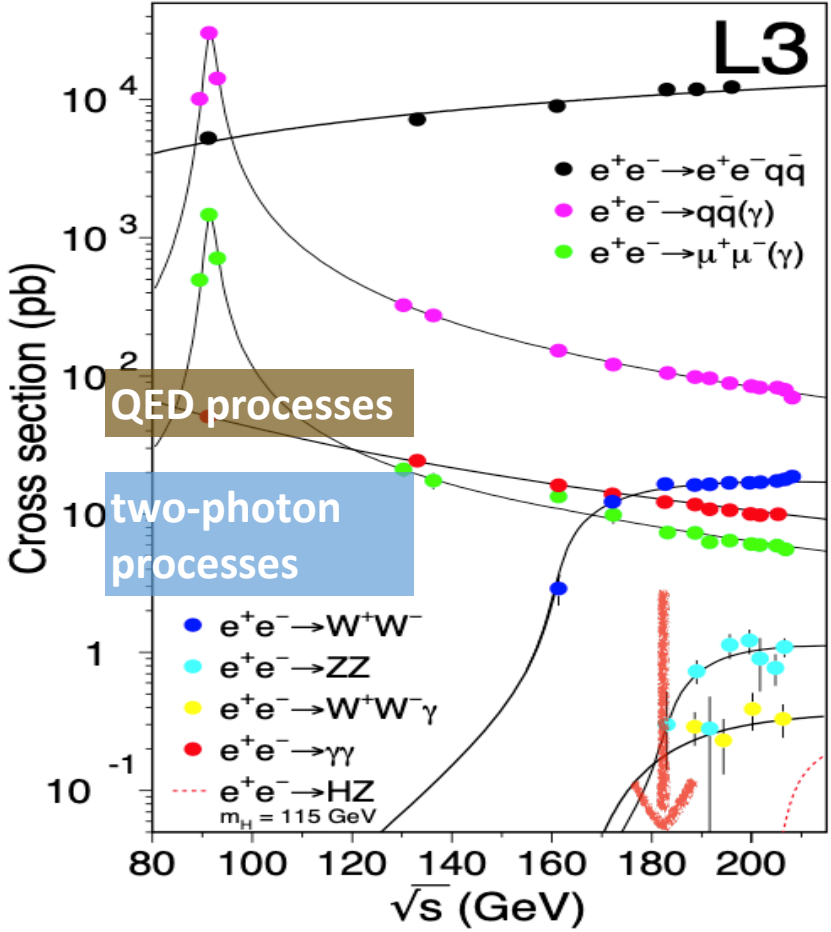
Big thanks to ALEPH collaboration and MIT open data

LEP-II data & MC processes

Year $\sqrt{s}$. $\sqrt{s}$. $\sqrt{s}$. int. L

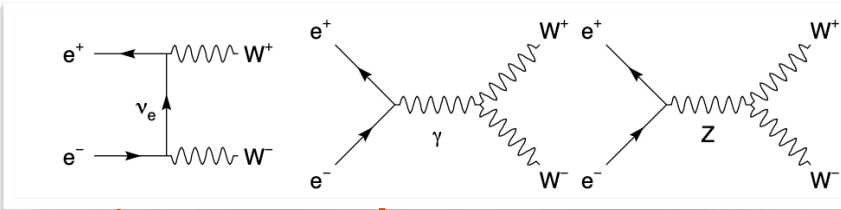
Year	Mean energy $\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
1995, 1997	130.3	6
	136.3	6
	140.2	1
1996	161.3	12
	172.1	12
1997	182.7	60
1998	188.6	180
1999	191.6	30
	195.5	90
	199.5	90
	201.8	40
2000	204.8	80
	206.5	130
	208.0	8
Total	130 – 209	745

$\sqrt{s}$ $\sqrt{s}$. X-section



Hadronic $q\bar{q}$ production

Four fermion processes



Diverse decay channels above $\sqrt{s} = 180 \text{ GeV}$

LEP-II event selections

Acceptance

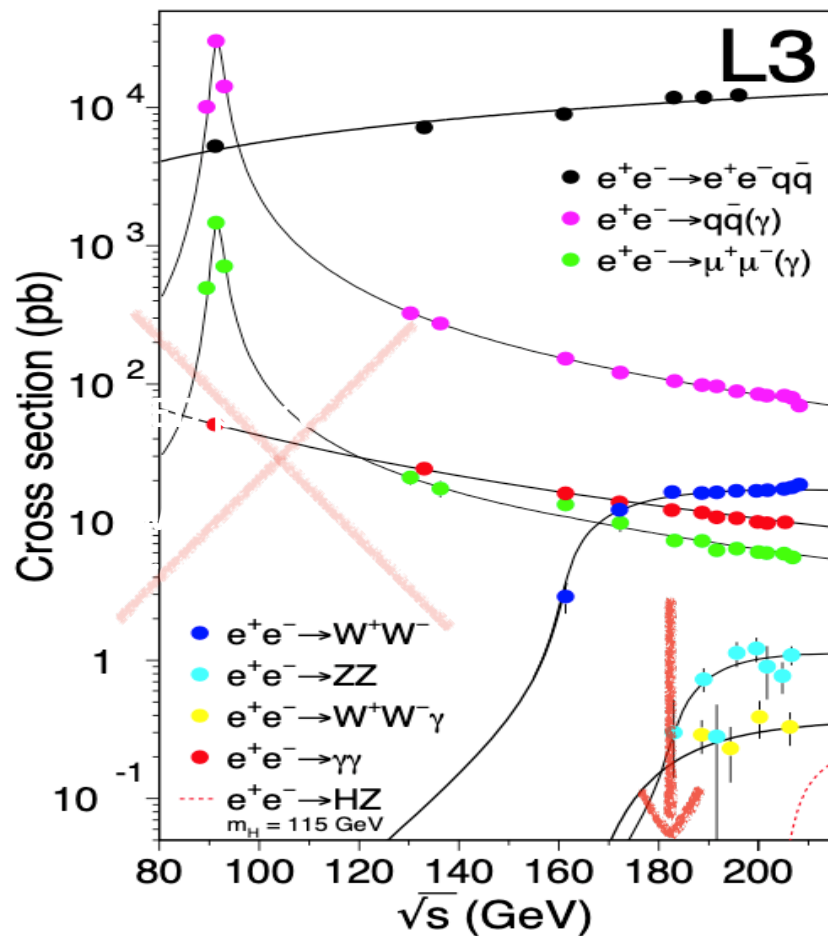
Polar angle of sphericity

axis: $7\pi/36 < \theta_{\text{lab}} < 29\pi/36$

Hadronic event selection

≥ 5 tracks

$E_{\text{chgd.}} \geq 15\text{GeV}$



LEP-II event selections

Acceptance

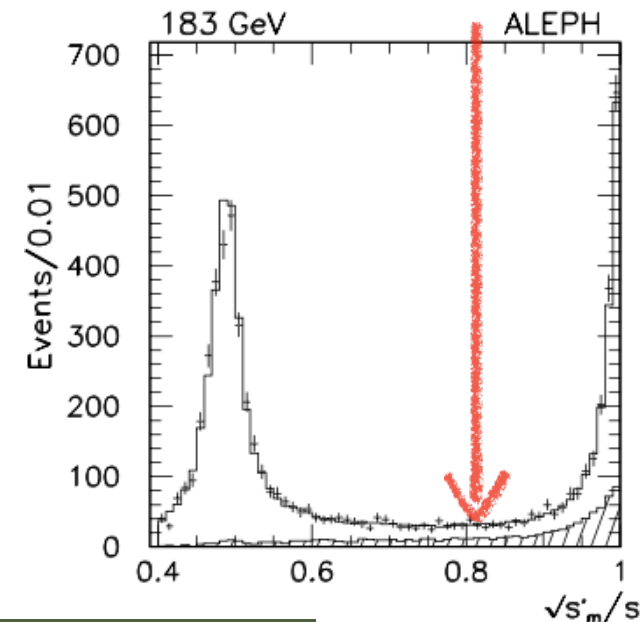
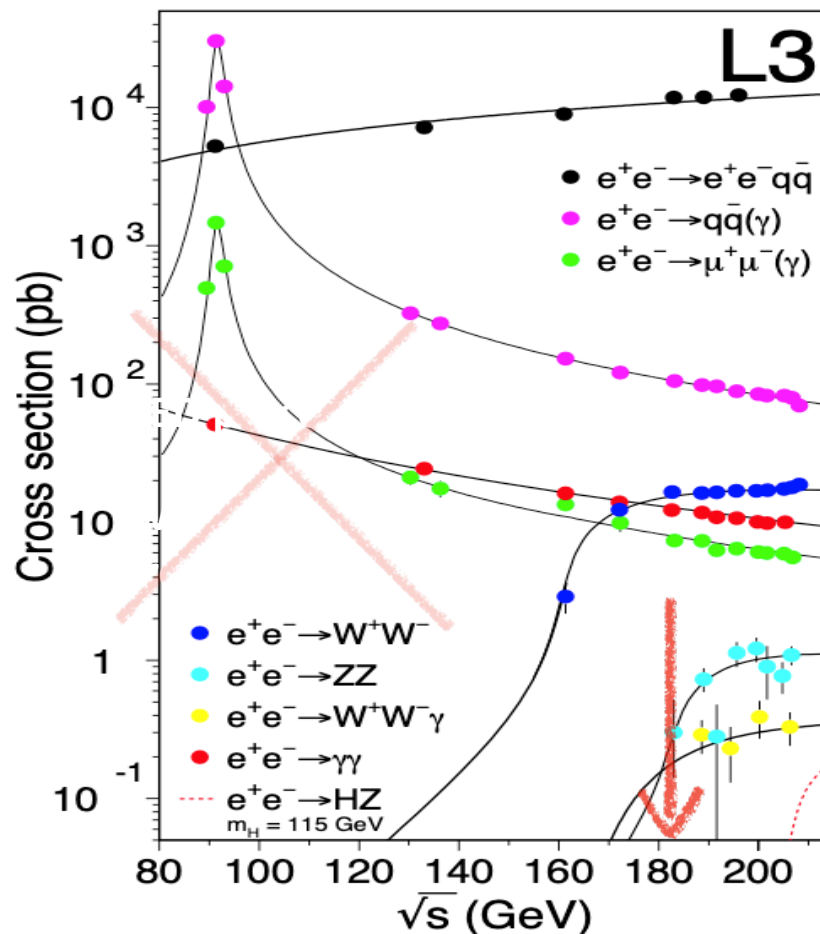
Polar angle of sphericity
axis: $7\pi/36 < \theta_{\text{lab}} < 29\pi/36$

Hadronic event selection

≥ 5 tracks

$E_{\text{chgd.}} \geq 15\text{GeV}$

Radiative return to
the $Z_{\sqrt{s}} \sim 90\text{ GeV}$



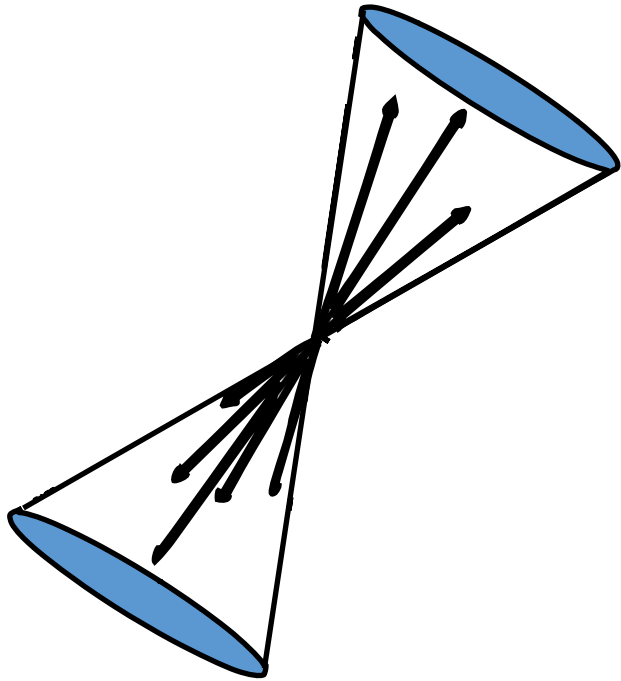
Hadronic $q\bar{q}$ production

[Ref: hep-ex/9904011](http://hep-ex/9904011)

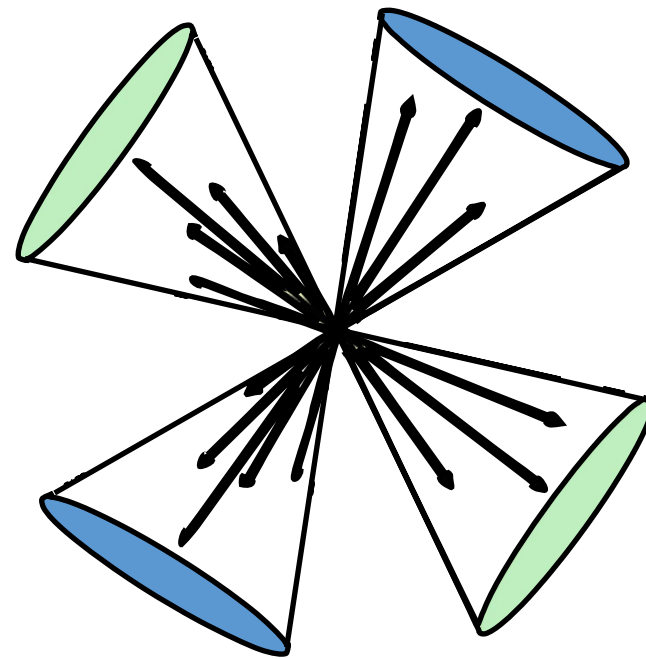
Four fermion processes
ISR cut

Required on the visible mass and
the reconstructed center-of-mass
energy

LEP-II physics processes



$$e^+e^- \rightarrow q\bar{q}$$



$$e^+e^- \rightarrow W^+W^- \rightarrow 4f$$

Selection

Selection

Two-particle
correlations

Residual MC
correction

- **Track Selection:**
 - Particle flow candidate 0, 1, 2 (charged hadron / $e^\pm$ / $\mu^\pm$)
 - Number of TPC hits for a charged tracks (N_{TPC}) ≥ 4 , $\chi^2/\text{ndf} < 1000$
 - $|d_0| < 2$ cm
 - $|z_0| < 10$ cm
 - $|\cos\theta| < 0.94$
 - $p_T > 0.2$ GeV (transverse momentum with respect to beam axis)
- **Neutral Hadron Selection:**
 - Particle flow candidate 4, 5 (ECAL / HCAL object)
 - $E > 0.4$ GeV
 - $|\cos\theta| < 0.98$
- **Event Selection:**
 - Number of good charged particles ≥ 5 (including charged hadrons and leptons)
 - Number of good ch+neu. particles ≥ 13
 - $E_{\text{charged}} > 15$ GeV
 - $|\cos(\theta_{\text{sphericity}})| < 0.82$

Corrections

- To calibrate the nonuniform detection efficiency and misconstruction bias
- Reconstructed tracks are weighted by the inverse of the efficiency correction factor:

$$\varepsilon(p_T, \theta, \phi, N_{\text{trk}}^{\text{rec}}) = \left[\frac{d^3 N^{\text{reco}}}{dp_T d\theta d\phi} / \frac{d^3 N^{\text{gen}}}{dp_T d\theta d\phi} \right]_{N_{\text{trk}}^{\text{rec}}}$$

- A closure test is performed by comparing the p_T , θ , ϕ distributions of the generator level and those of the corrected reconstructed level

Selection &
efficiency
correction

Two-particle
correlations

1. Efficiency
correction
2. Residual MC
correction

Corrections

Selection &
efficiency
correction

Two-particle
correlations

1. Efficiency
correction
2. Residual MC
correction

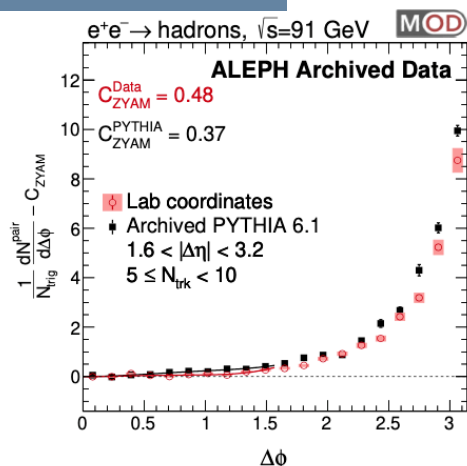
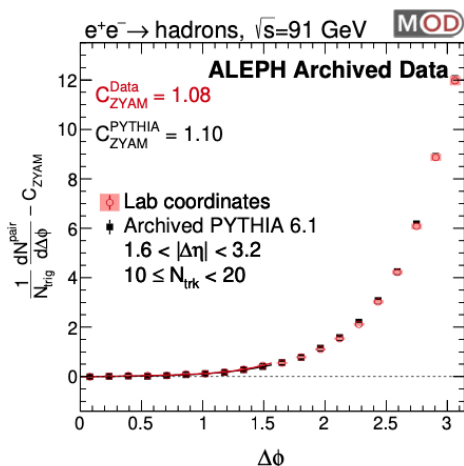
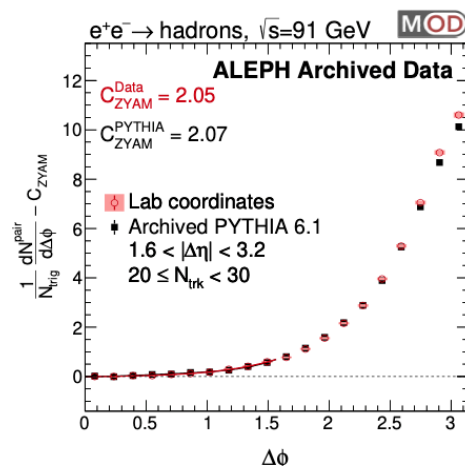
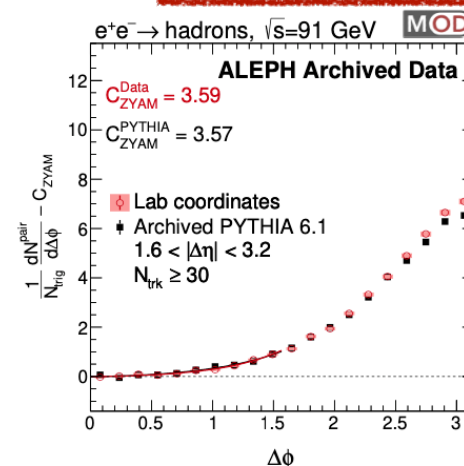
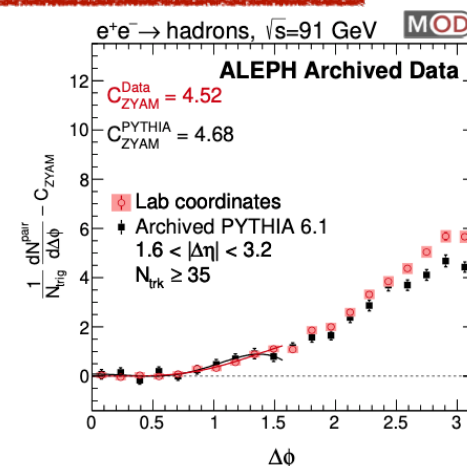
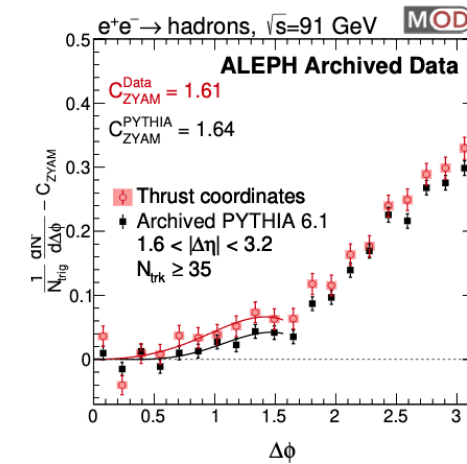
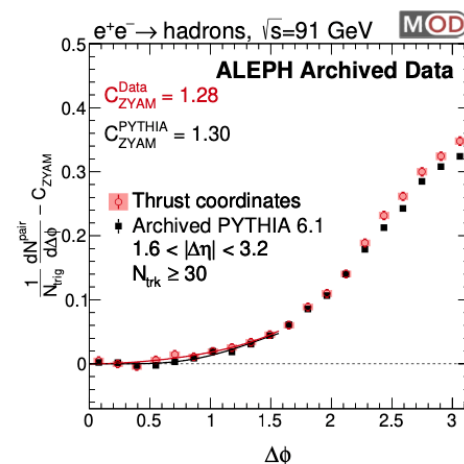
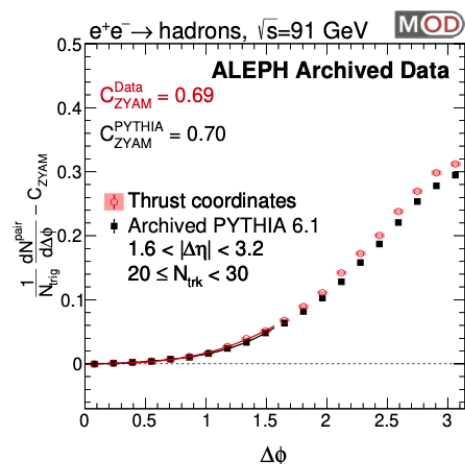
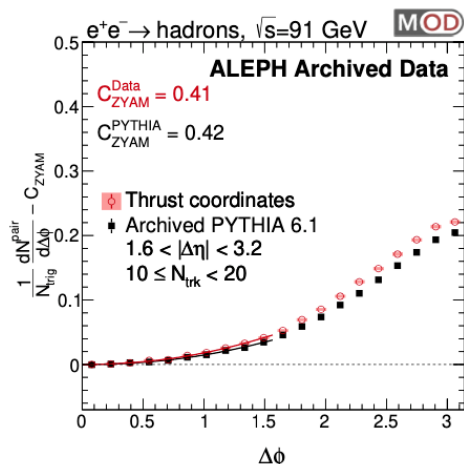
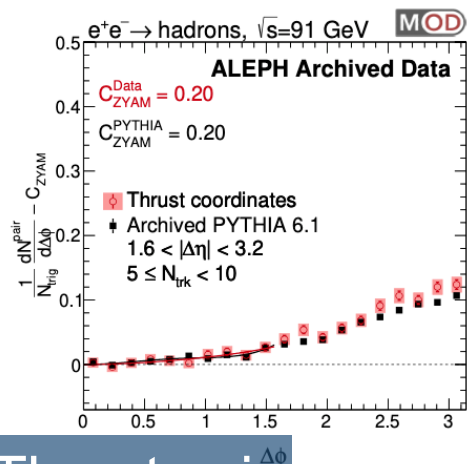
- To deal with remaining possible reconstruction effects
- Bin-by-bin correction: the correction factor is derived from the histogram ratio of MC correlation functions at the reconstruction and generator level as $C(\Delta\phi)$

$$= \frac{Y(\Delta\phi)_{\text{gen},i_g}}{Y(\Delta\phi)_{\text{reco},i_r}}$$

- Final data correlation results are obtained from the multiplication of the original correlation function with the bin-by-bin correction factor

Beam axis

Good agreement with MC!

 $5 \leq N_{\text{trk}} < 10$  $10 \leq N_{\text{trk}} < 20$  $20 \leq N_{\text{trk}} < 30$  $N_{\text{trk}} \geq 30$  $N_{\text{trk}} \geq 35$ 

Thrust axis