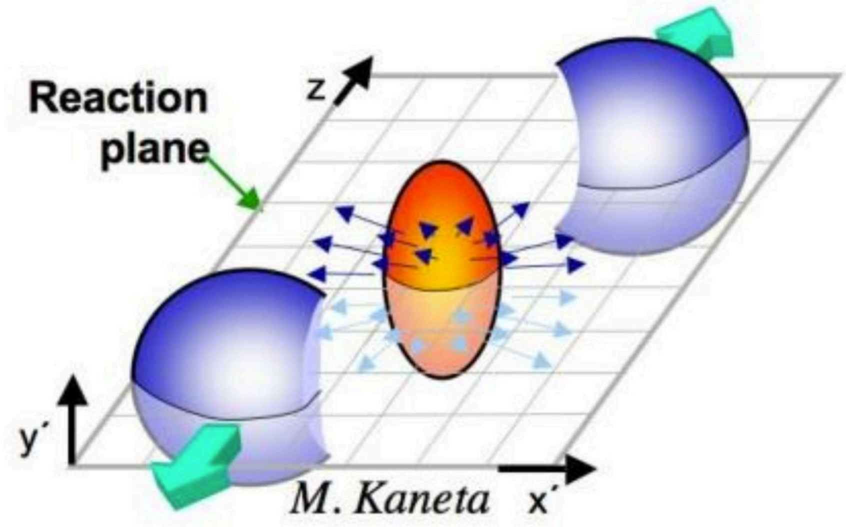
Long-range near-side correlation in e^+e^- collisions at 183-209 GeV with ALEPH archived data

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

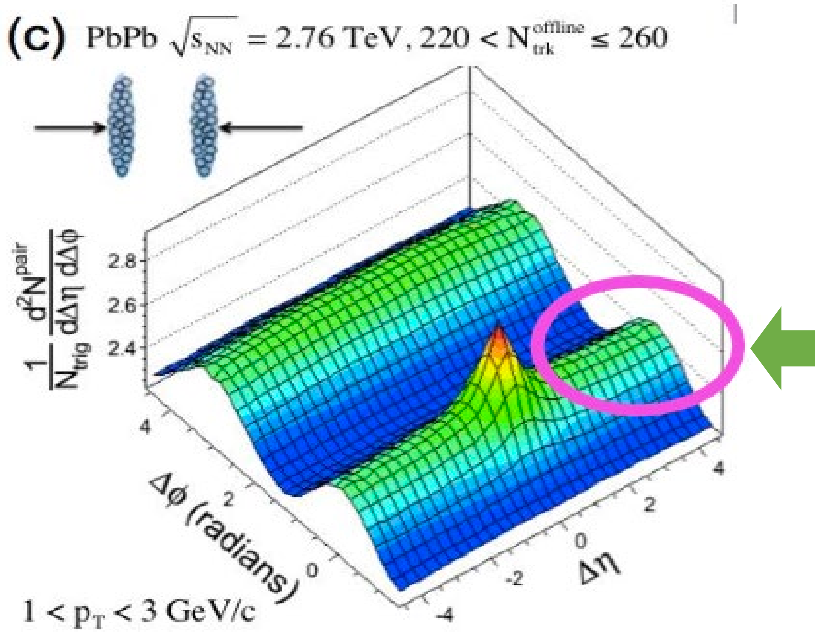
arXiv: 2312.05084
Analysis note: 2309.09874
[Phys. Lett. B 856, 138957 (2024)]

U.S. DEPARTMENT OF ENERGY
MITHIG group's work was supported by US DOE-NP

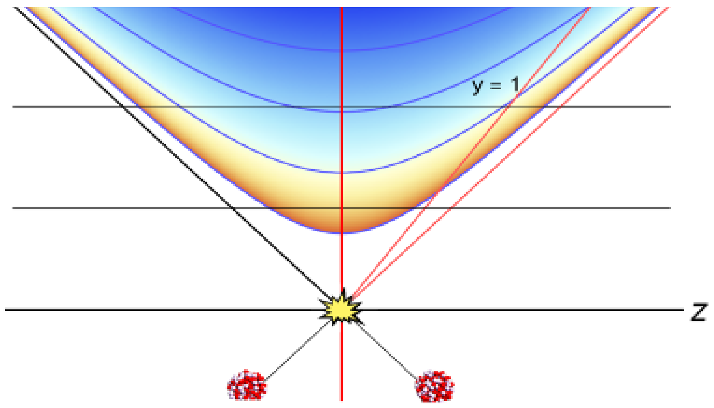
Long-range near-side correlations: The "Ridge" in HI collisions



Ridge correlation:
long-range (large Δη)
near-side (small Δϕ)

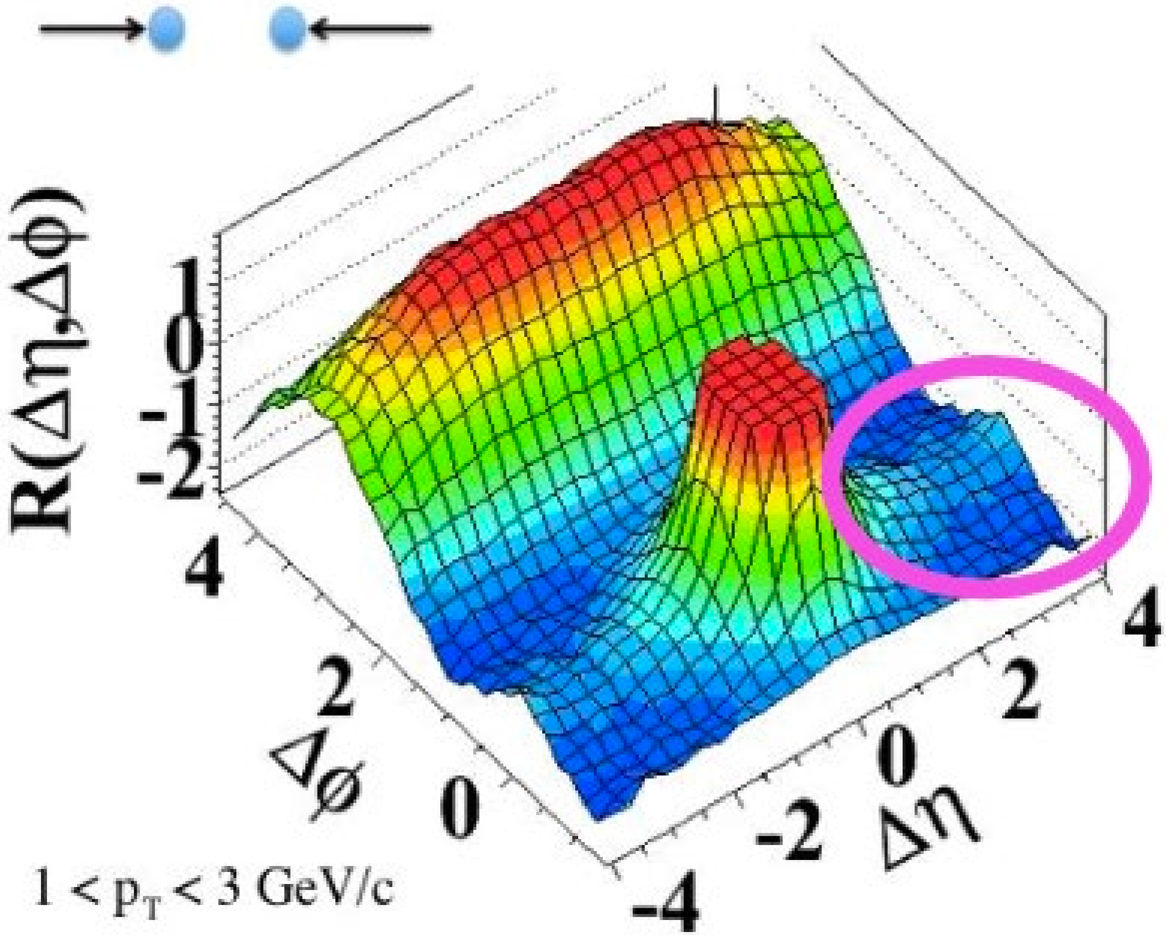


- Large correlation for pairs of particles with large $\Delta\eta$ and small $\Delta\phi$
  - Large $\Delta\eta$ -> causally disconnected for single point-like interaction, hence "long-range"
- Hints at existence of collective behavior, i.e. QGP



The “Ridge” in pp collisions

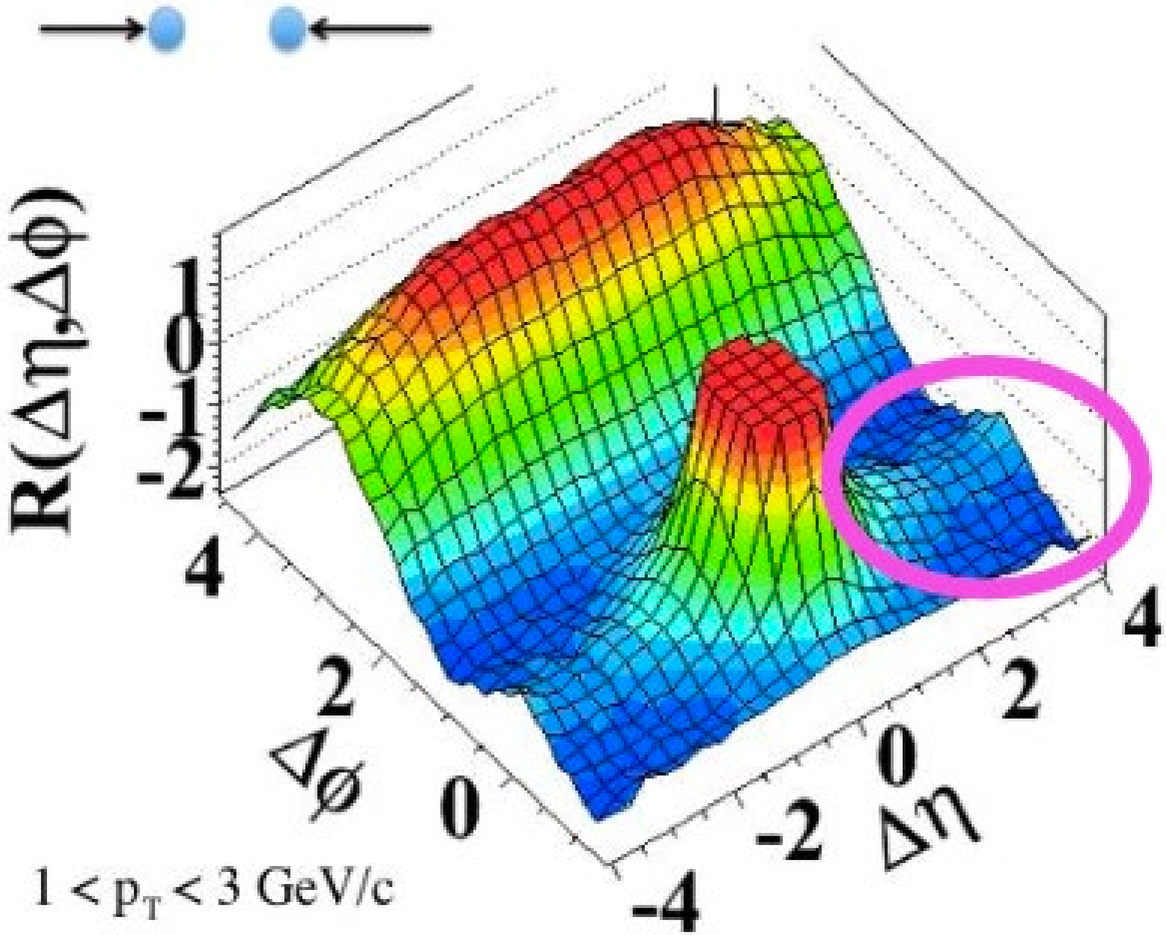
- Also observed in high-multiplicity pp collisions at the LHC in 2012
- Initial-state anisotropy may create ridge in this case
  - System thought to be too small to produce collective interactions



[CMS: JHEP 1009 (2010) 091]

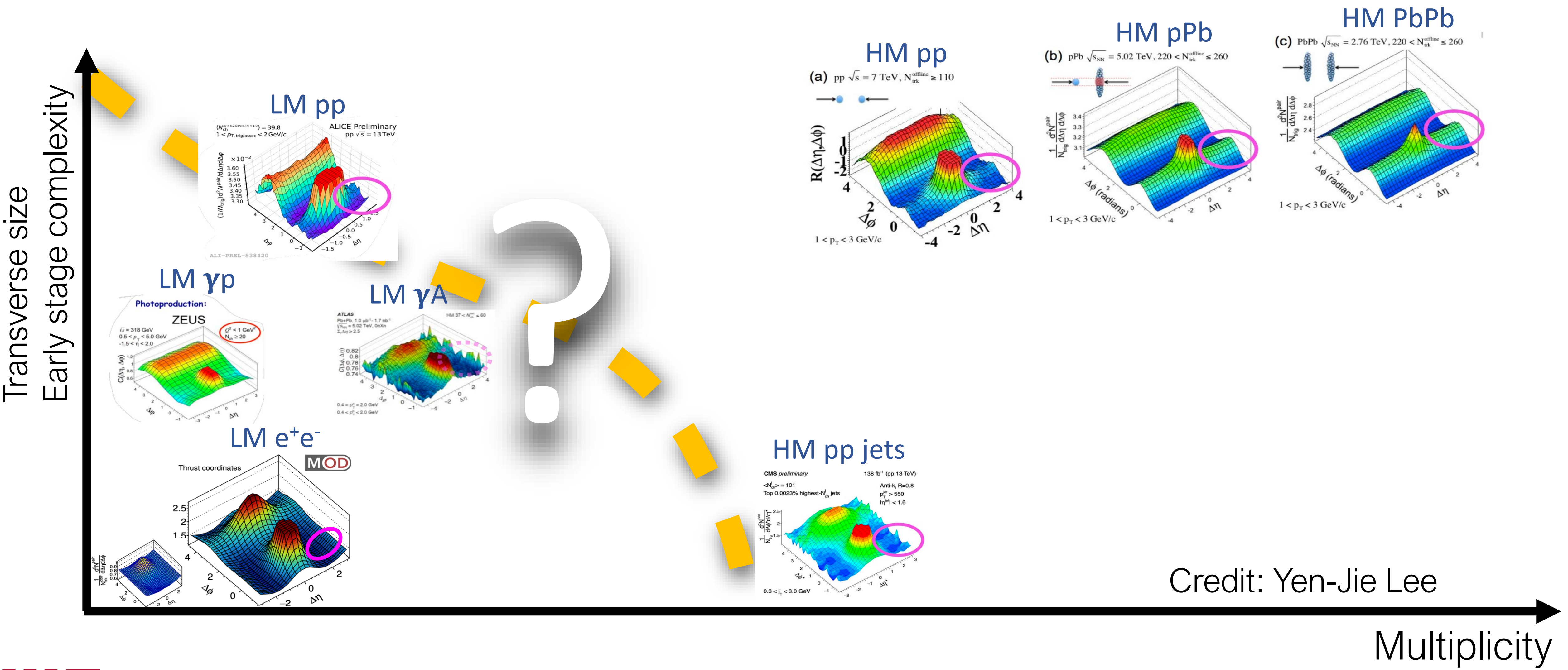
The “Ridge” in pp collisions

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



[CMS: JHEP 1009 (2010) 091]

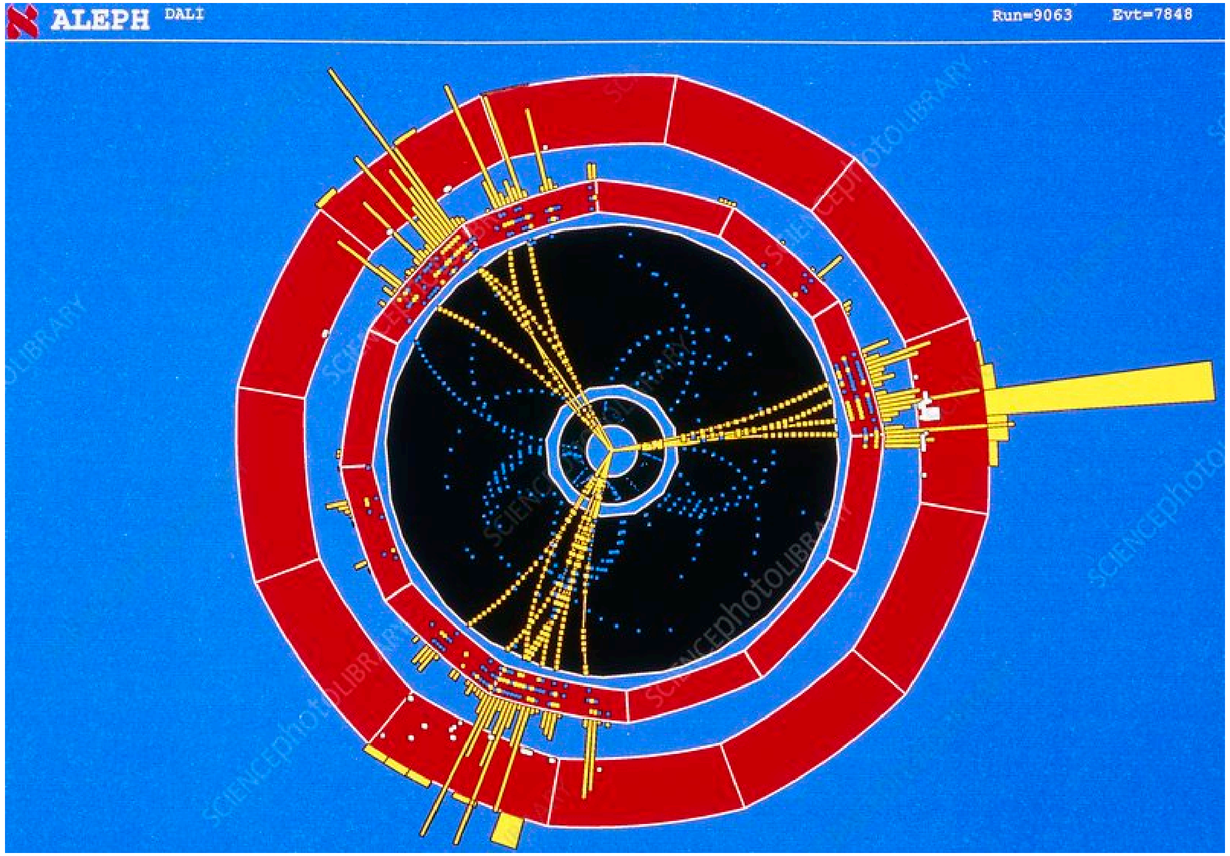
Emergence of “ridge-like” behavior?



Credit: Yen-Jie Lee

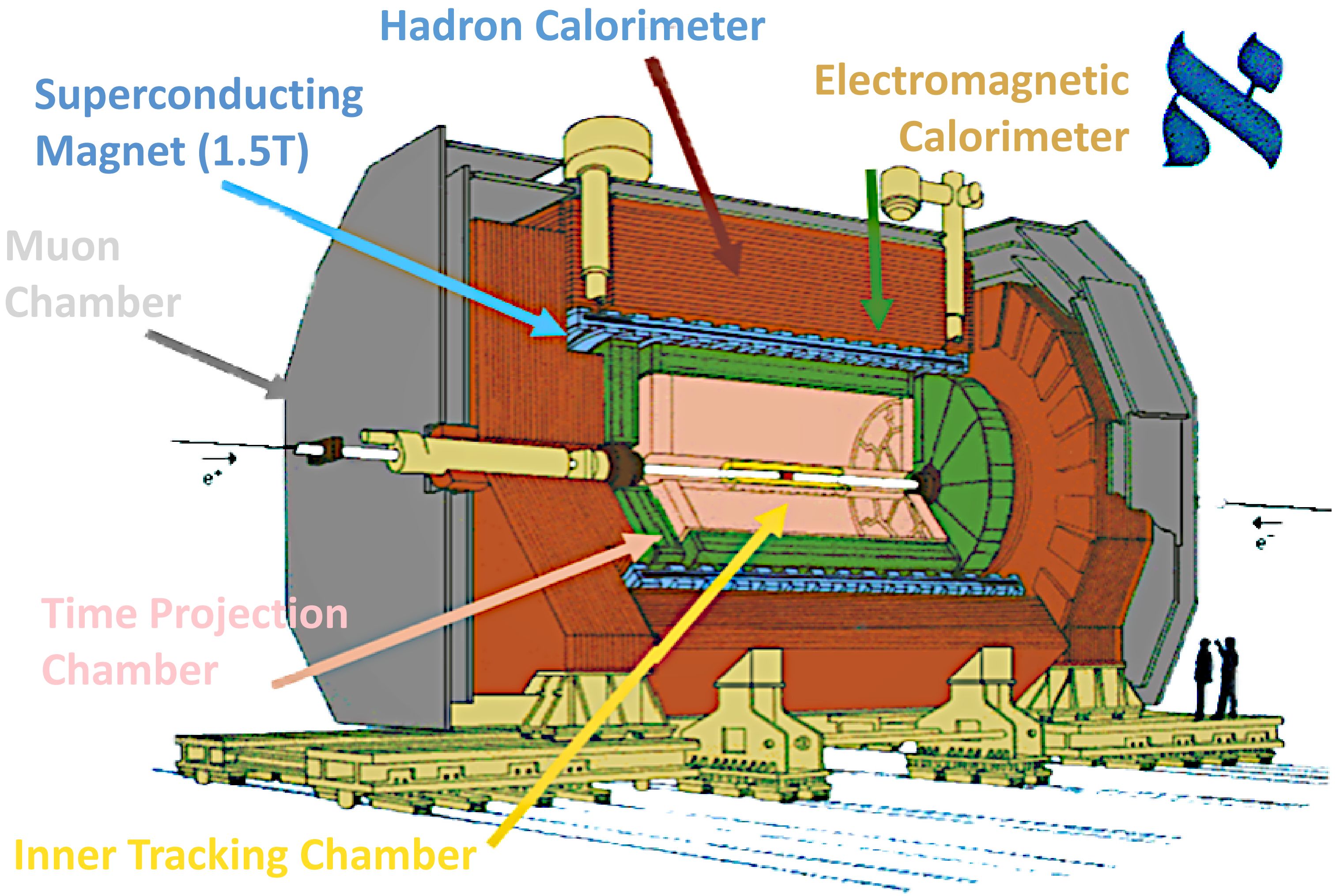
e+e- collisions: a QCD laboratory

- 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



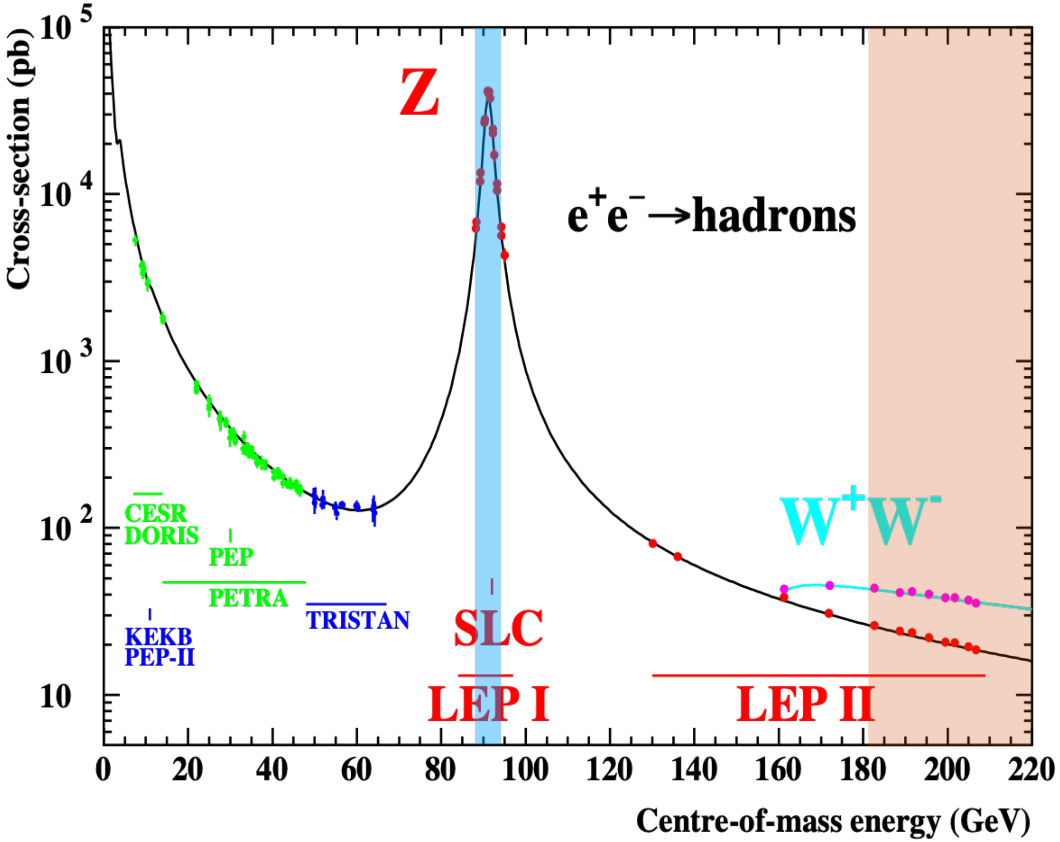
ALEPH data re-analysis

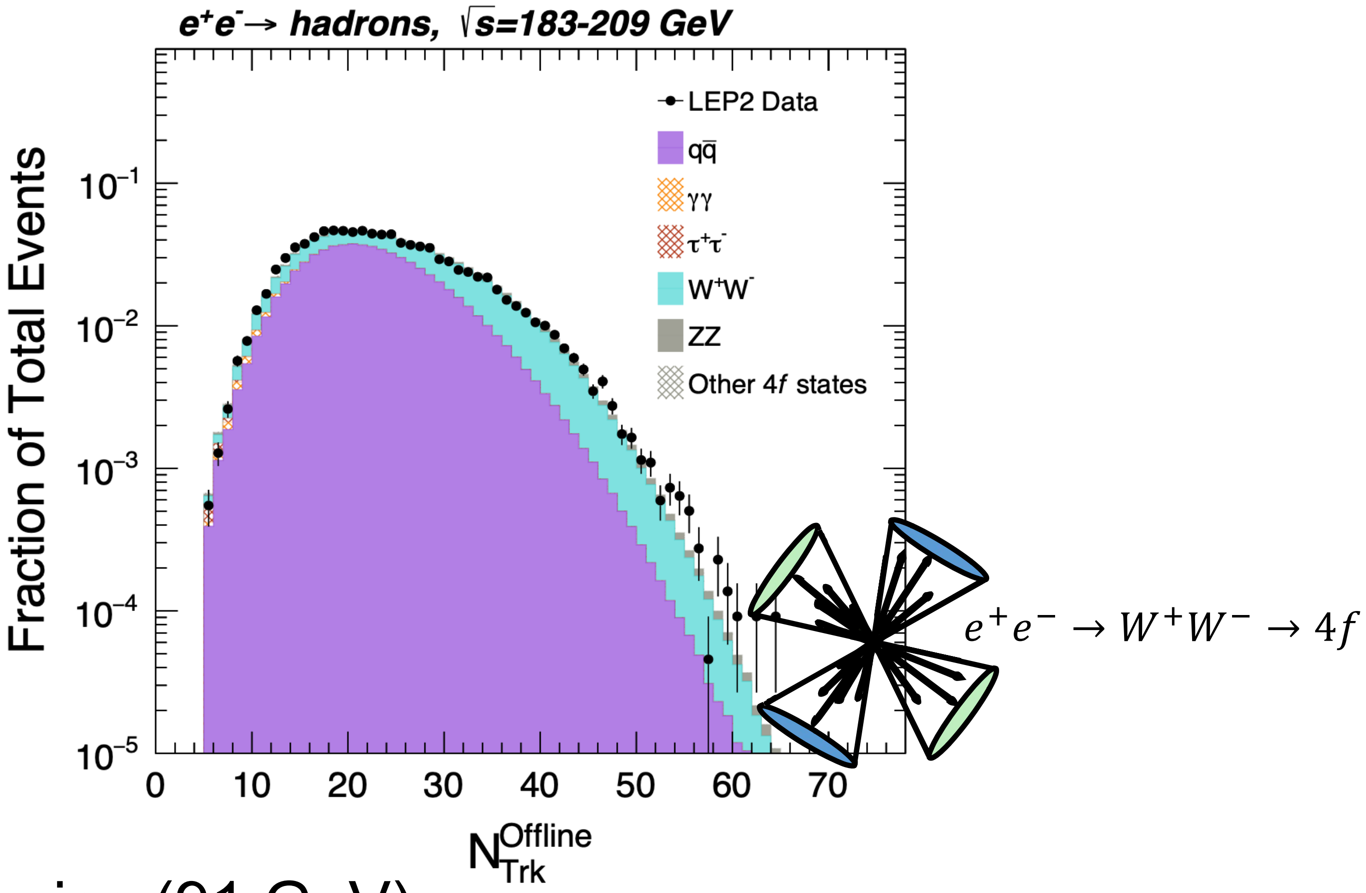
- Hermetic general-purpose detector on LEP collider
- Large e+e- datasets taken from 1989-2000
- Pythia6 MC archived along with data
- Re-analyzed using MIT Open Data Format MOD



*Acknowledgement:
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



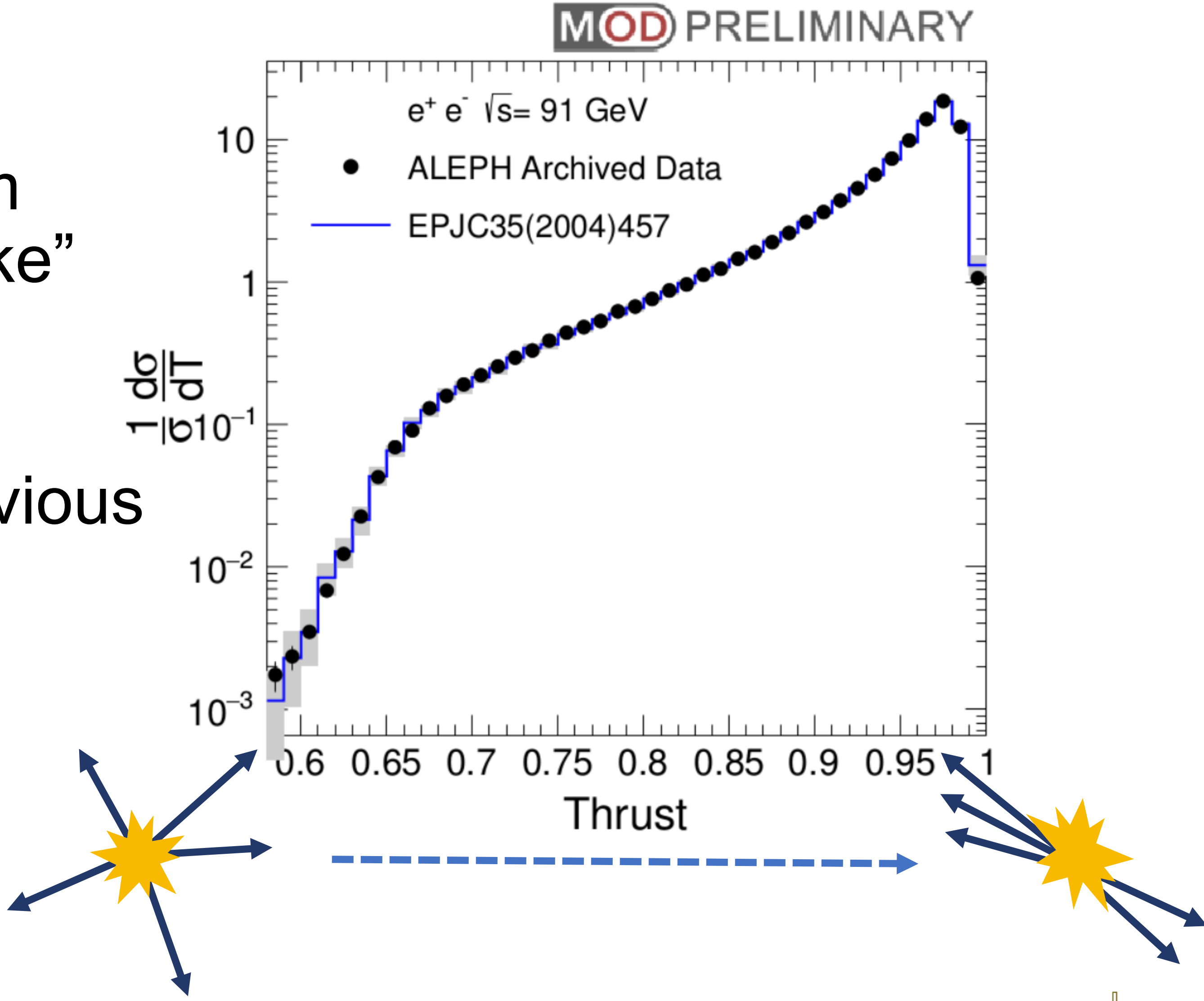


- LEP I dataset (1992-1995): Z-pole energies (91 GeV)
- LEP II dataset (1996-2000): higher energy (183-209 GeV), significant WW production
  - WW events dominate high-multiplicity data (two color strings instead of one)

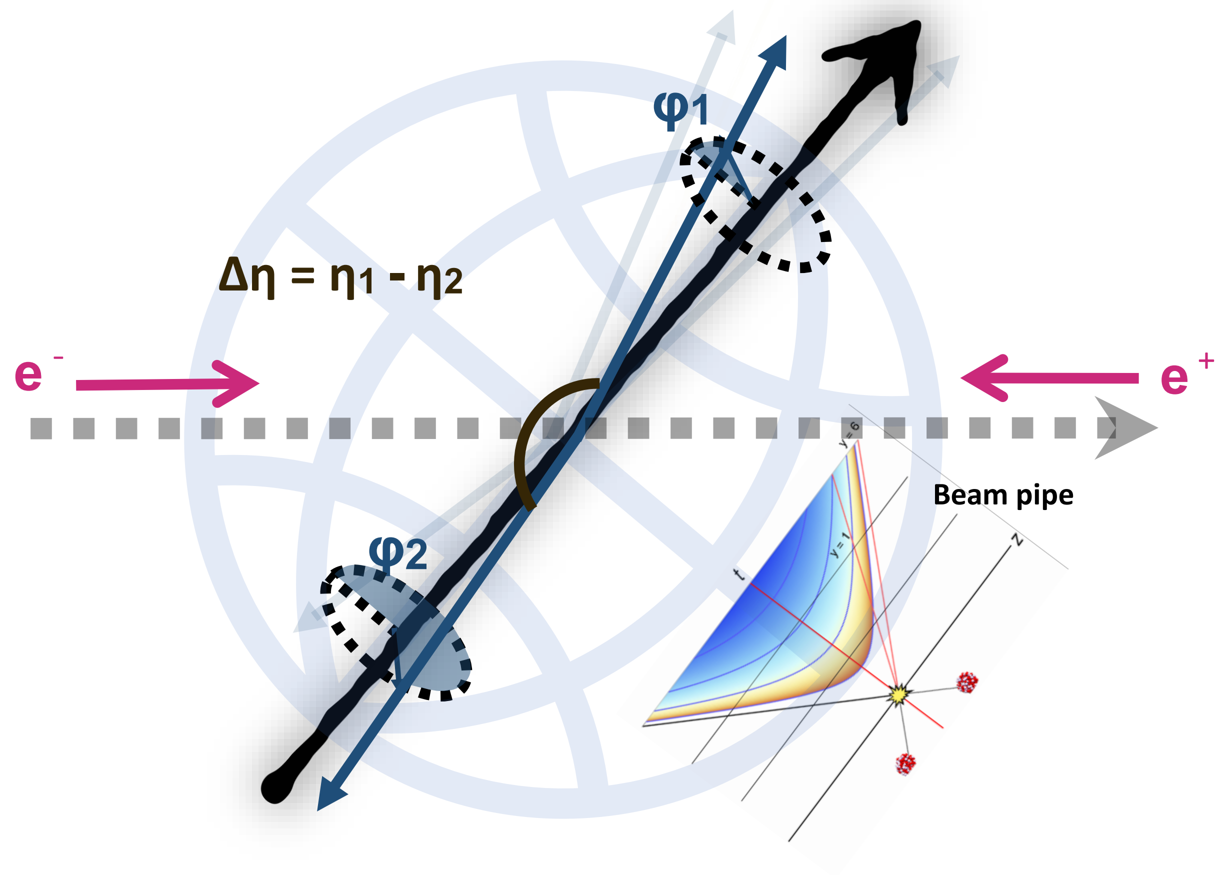
Thrust Distribution

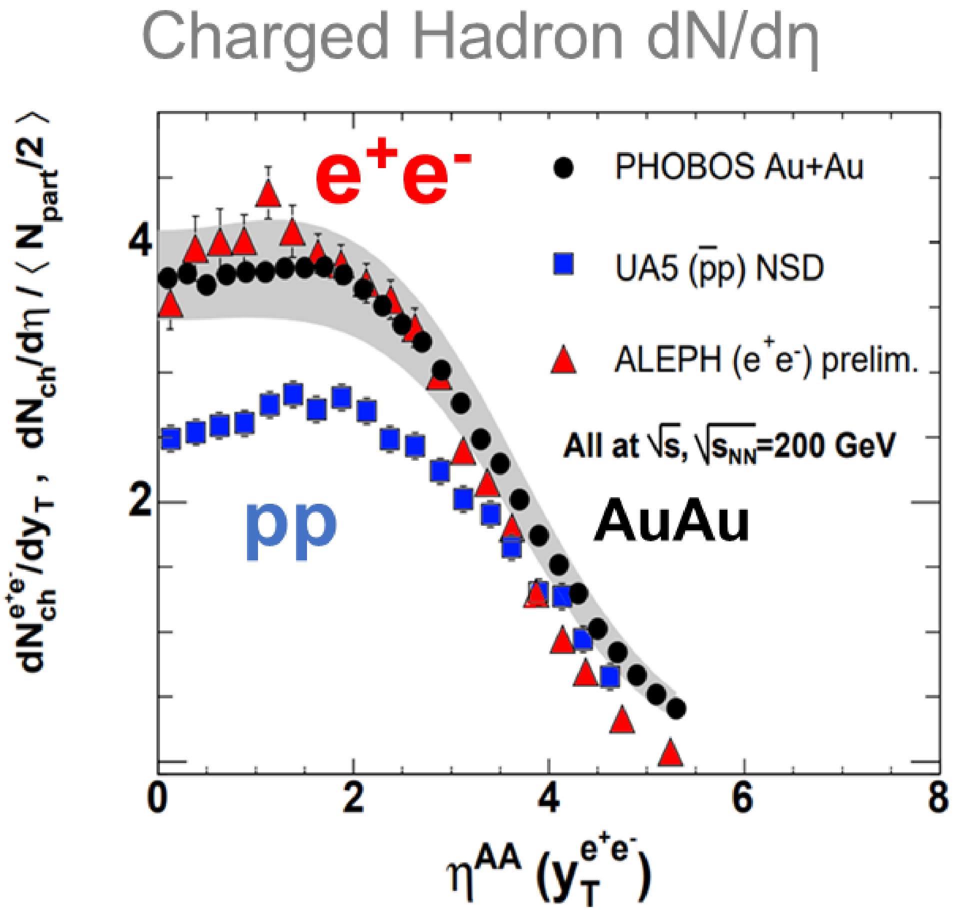
- Thrust measures event shape, from “spherical” (thrust=0.5) to “pencil-like” (thrust=1)
- Good agreement between thrust distribution in this analysis and previous ALEPH Collaboration analyses

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



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





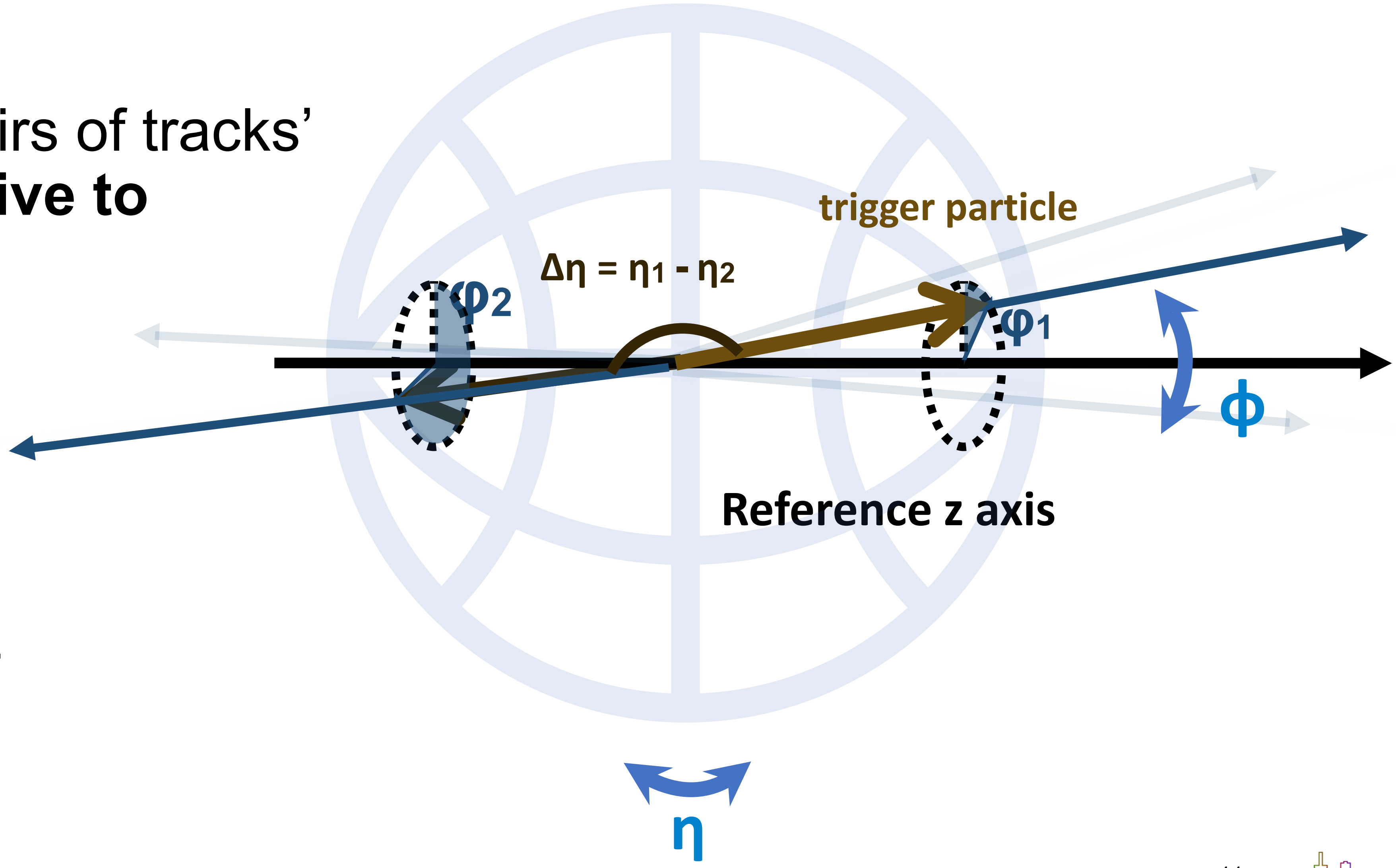
Thrust axis used as reference to focus on medium expanding perpendicular to outgoing final-state axis

Cross-check: $dN/d\eta$ in e+e- relative to thrust axis similar to pp and AuAu results relative to beam axis

Two-particle correlation: the observable

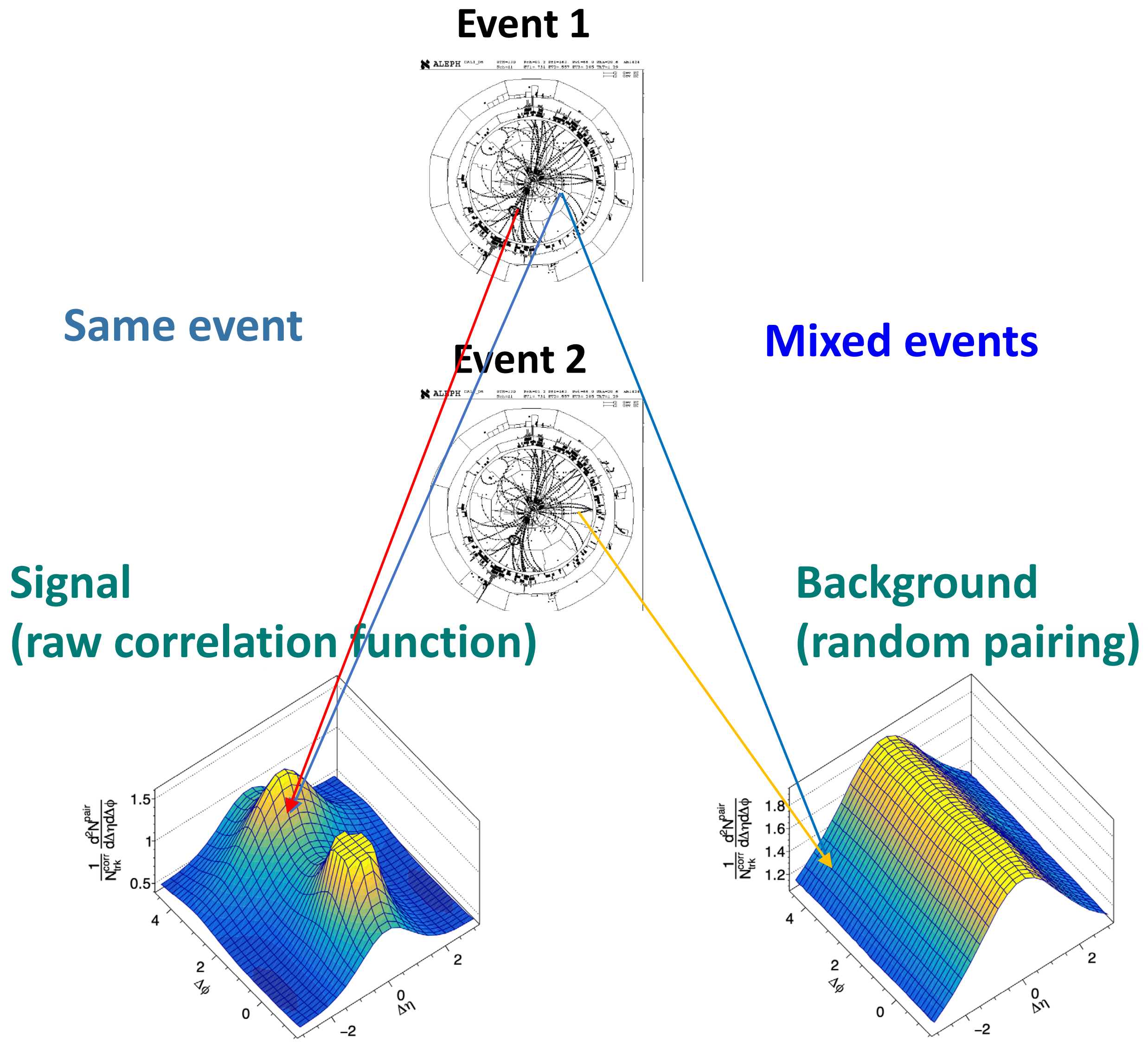
Correlation between pairs of tracks' (η, ϕ) coordinates **relative to thrust axis:**

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



Background reduction via event-mixing

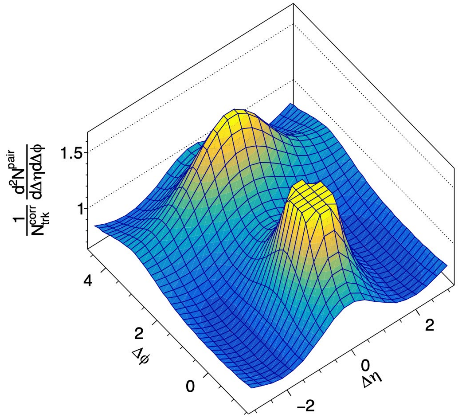
- Background from random pairing determined using pairs of tracks from two different events
  - Different events → uncorrelated by construction
  - Both events coming from same sample → realistic background magnitude as well as shape



Extraction of observable

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

Observable



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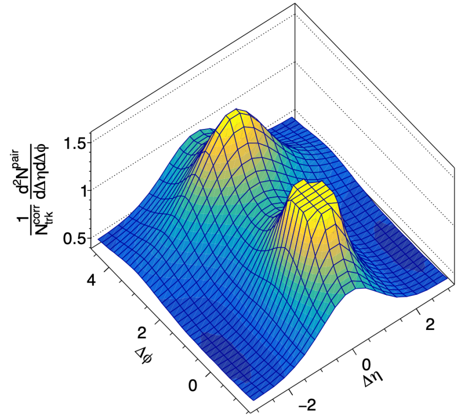
Raw correlation function



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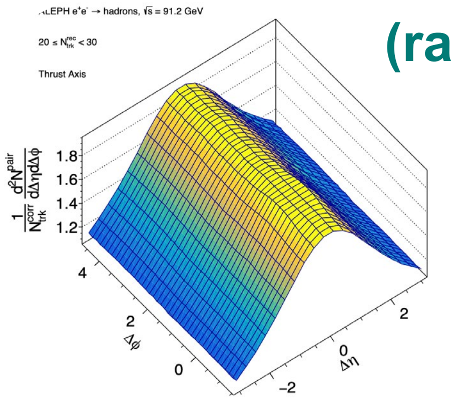
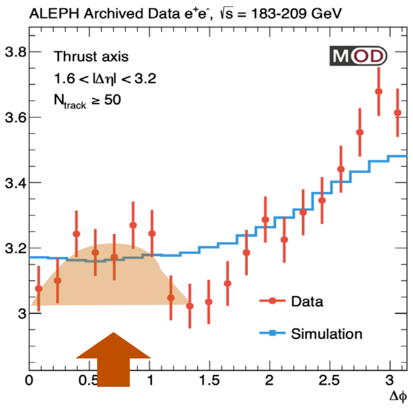
Background (random pairing)



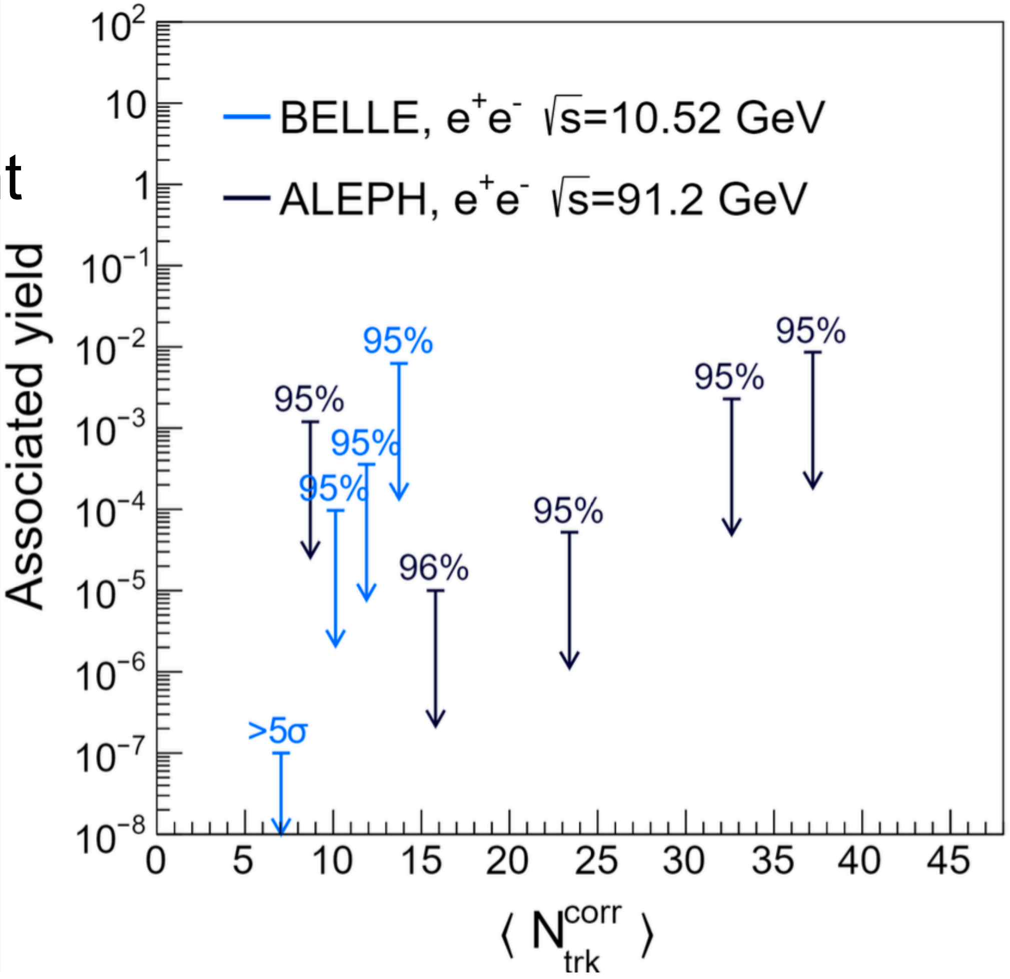
Normalization of $B(\Delta\eta,\Delta\phi)$

Previous two-particle correlation results

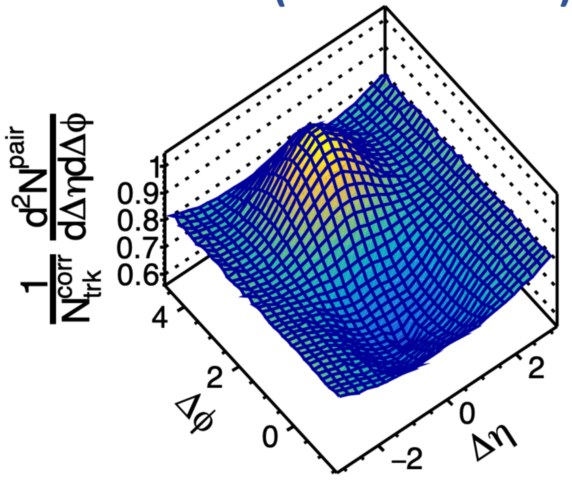
- 2019 re-analysis of LEP I data showed no significant yield associated with "ridge" feature
- 2022 BELLE analysis agreed



Ridge-like yield estimation

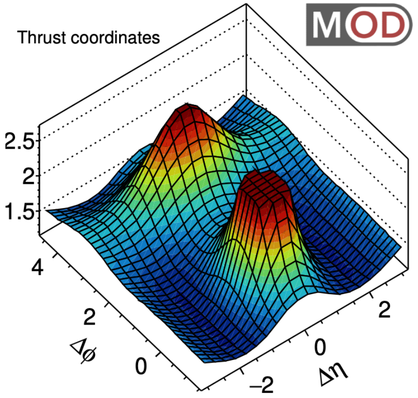


Belle (√s=10.52 GeV)



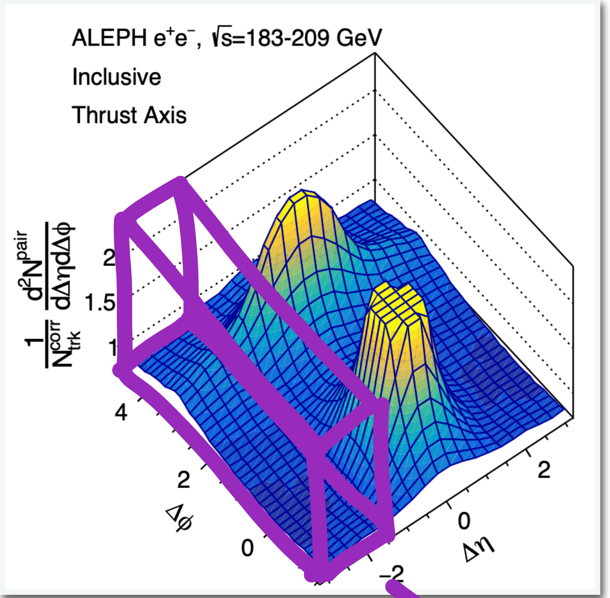
[Phys. Rev. Lett. 128, 142005 (2022)]

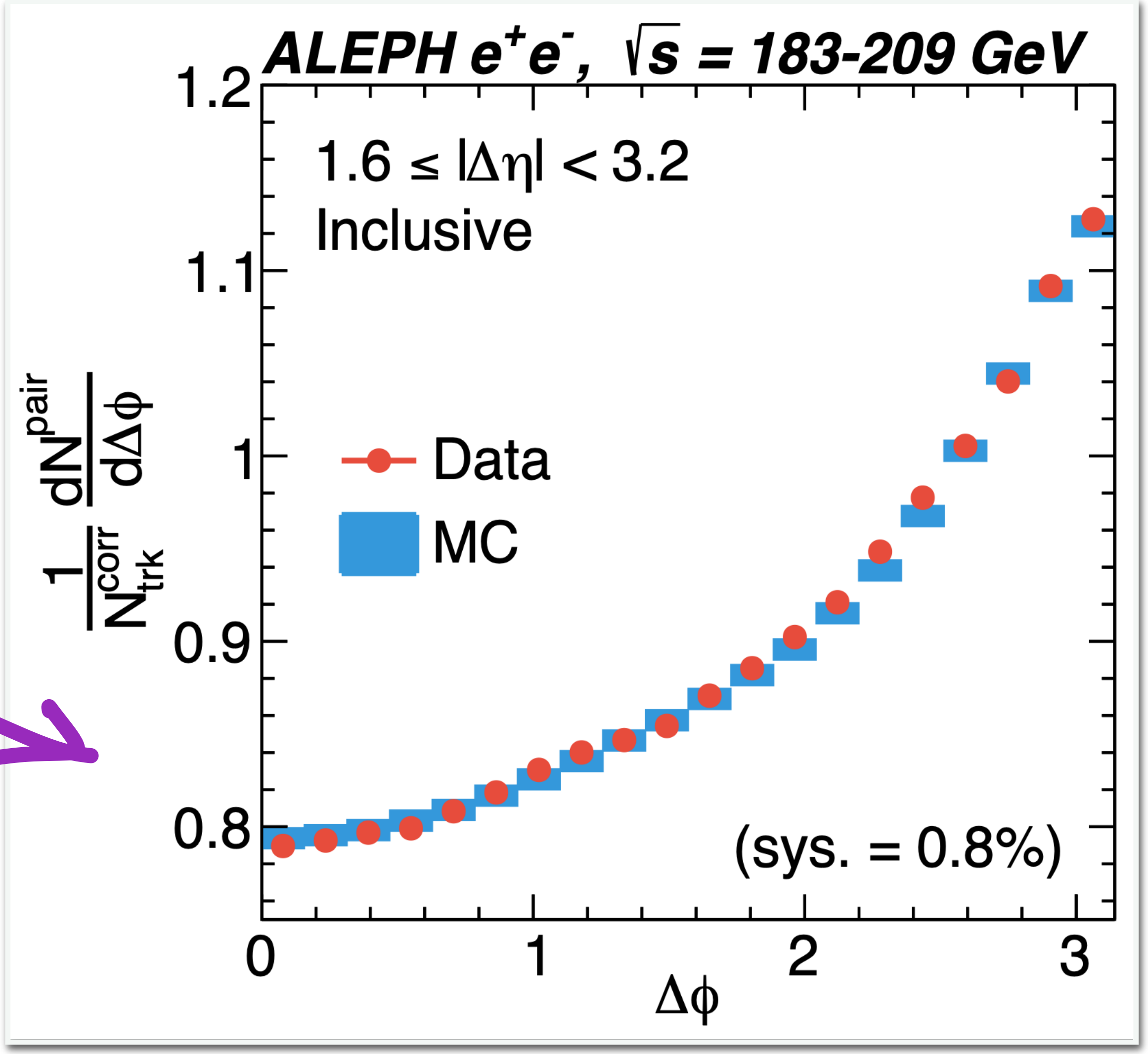
LEP-I (Z-pole)



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

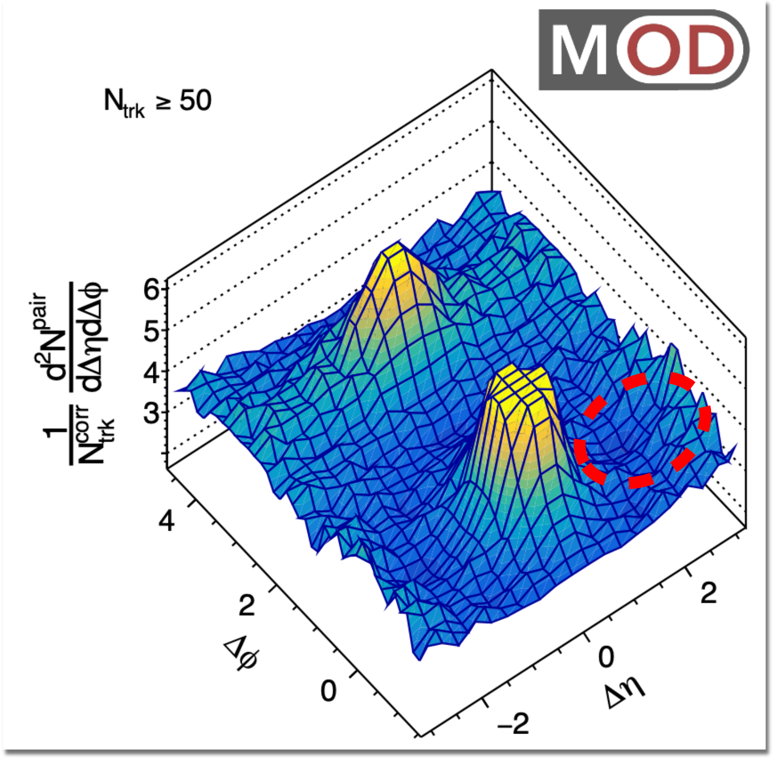
Two-particle correlation >183 GeV at LEP II

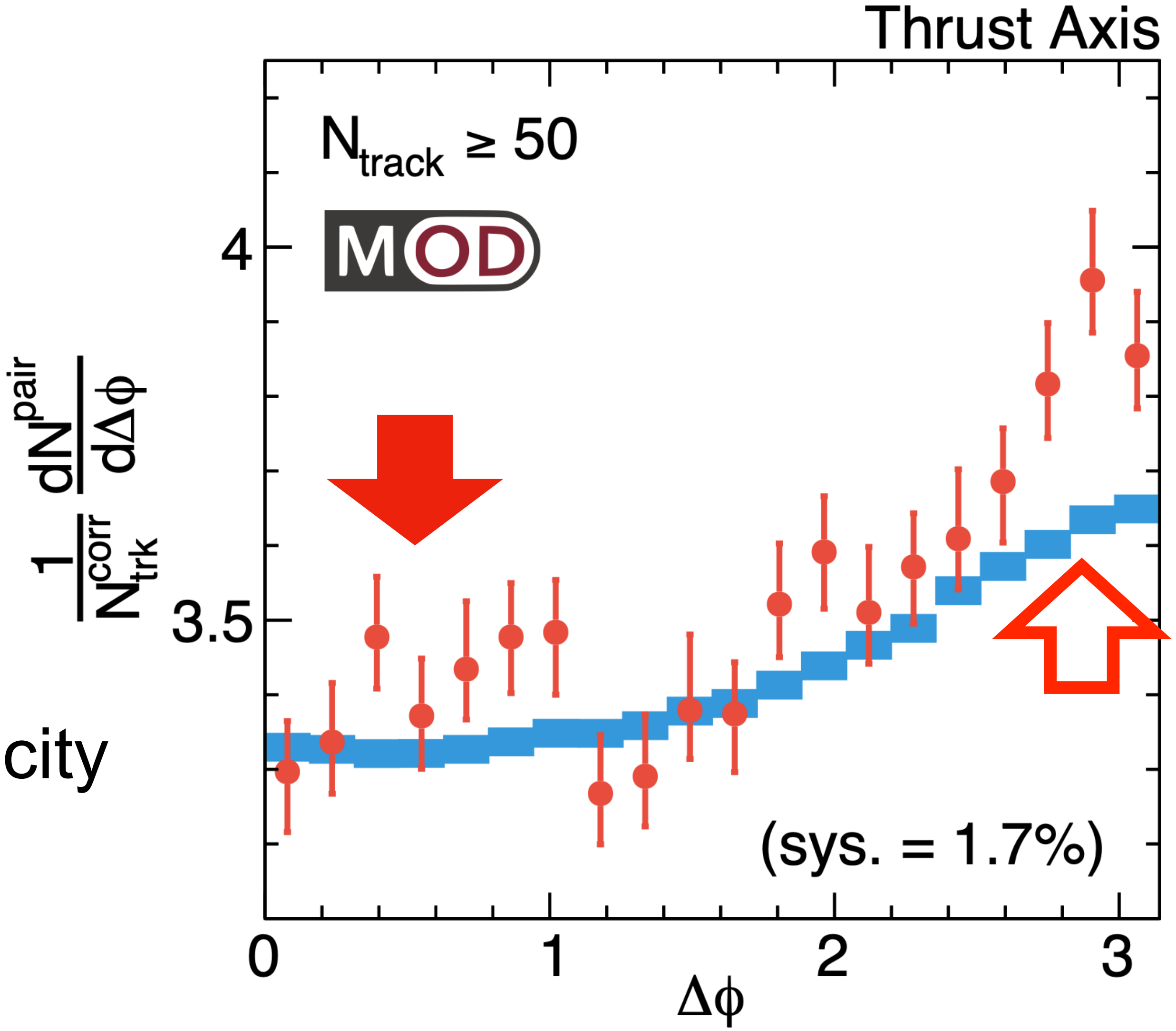




Generally **good agreement** for **inclusive** sample between data and MC for LEP II re-analysis

High-multiplicity (Ntrack>=50) LEP II results

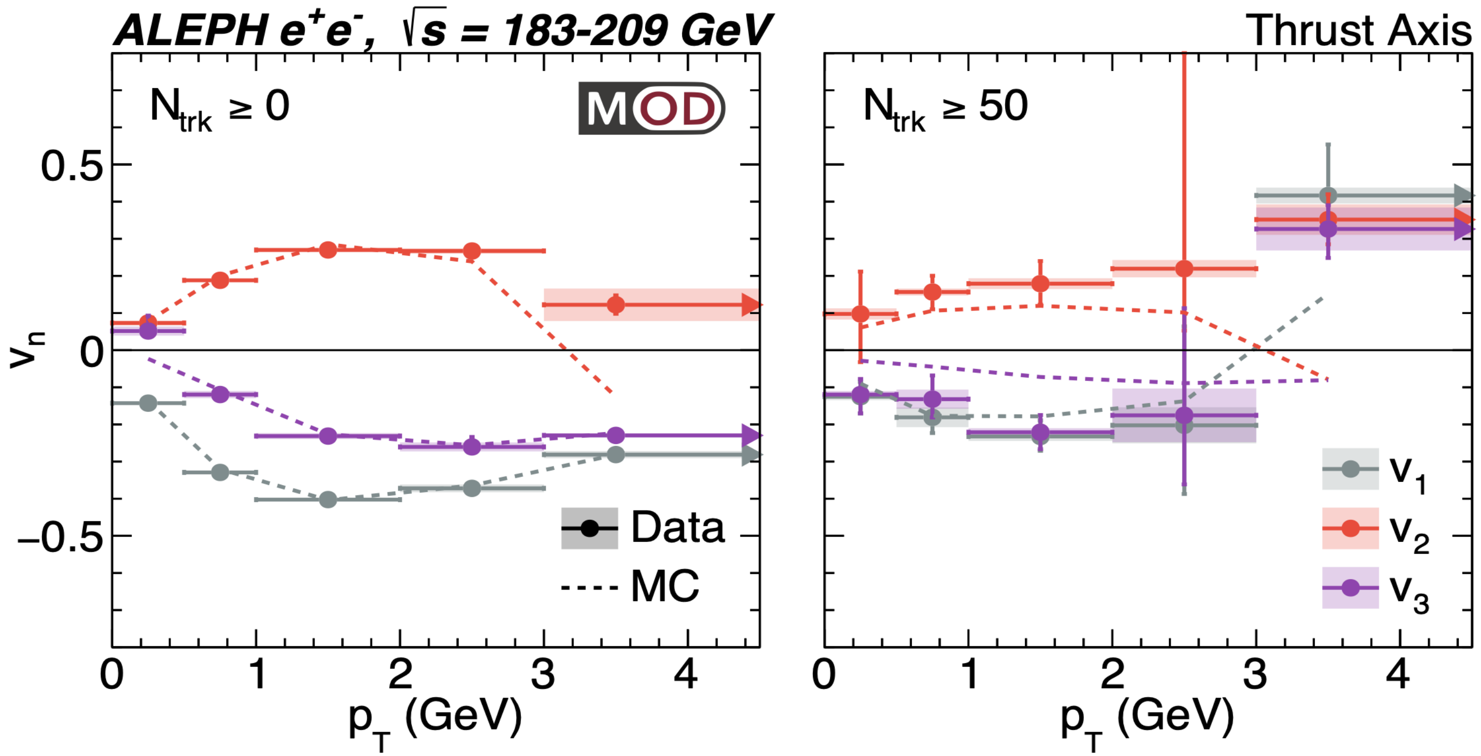




- Interesting features in high-multiplicity long-range near-side correlations
- Possible signs of excess over MC

"Flow-like trend" coefficients

Inclusive NTrk | High-multiplicity



Sign change for v_2 and v_3!

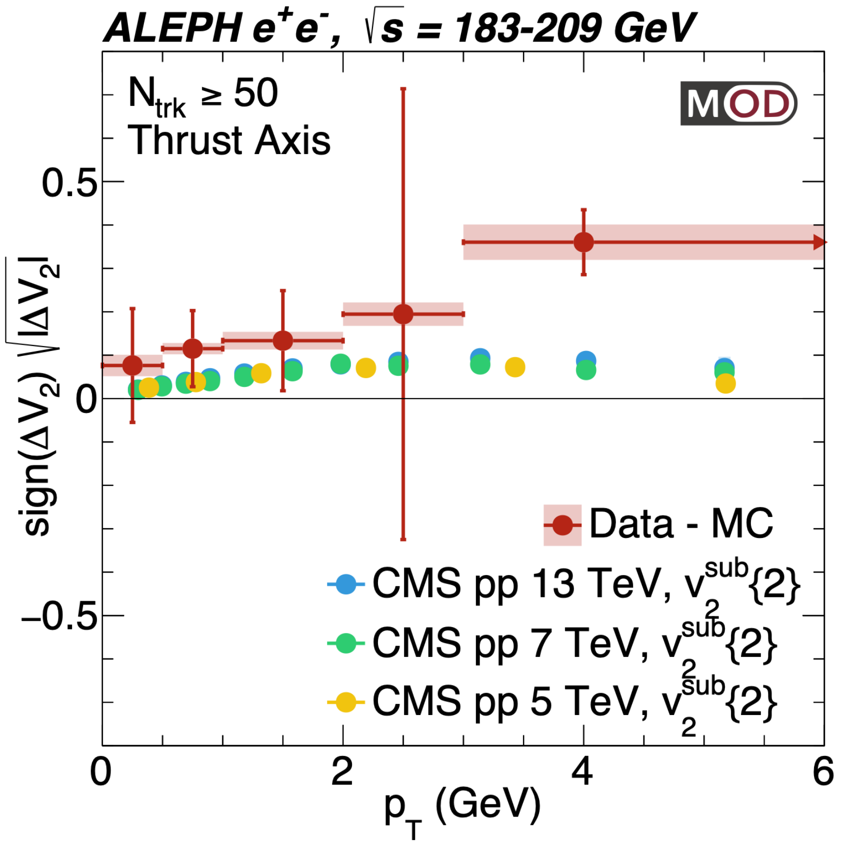
Coefficients found by taking Fourier transform of yield:

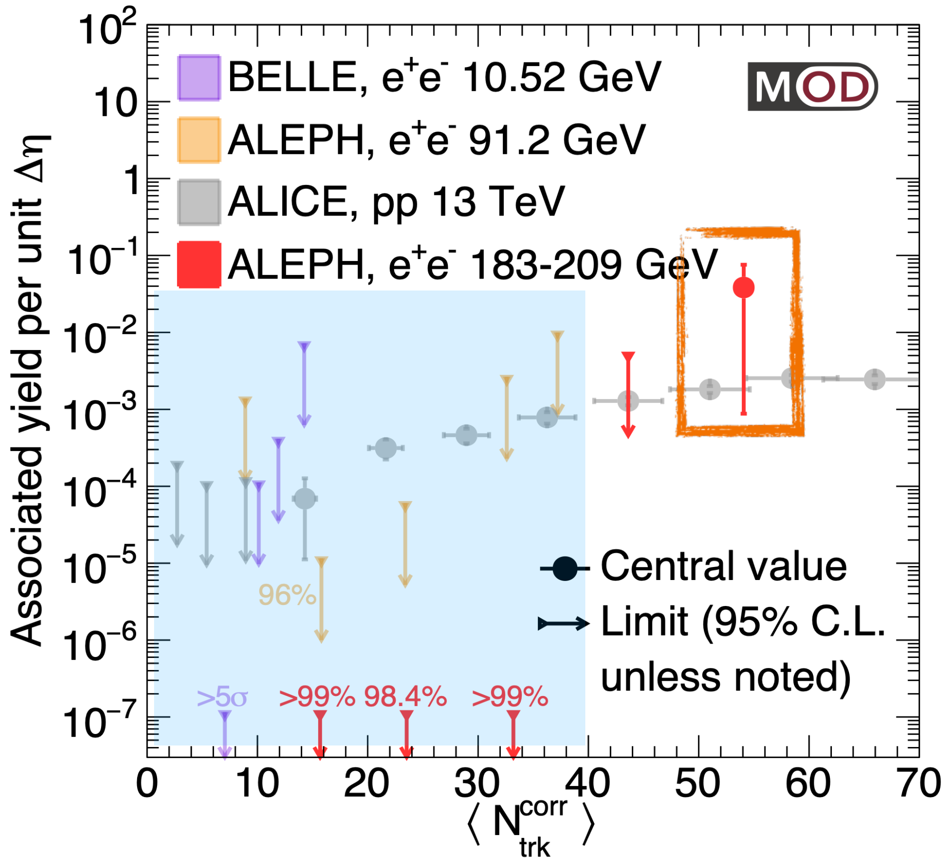
$$Y(\Delta\phi) = \frac{1}{N_{\text{trig}}}\frac{dN^{\text{pairs}}}{d\Delta\phi} = \frac{N^{\text{assoc}}}{2\pi}\left(1 + \sum_{n=1}^{n_{\max}} 2V_{n\Delta}\cos(n\Delta\phi)\right)$$

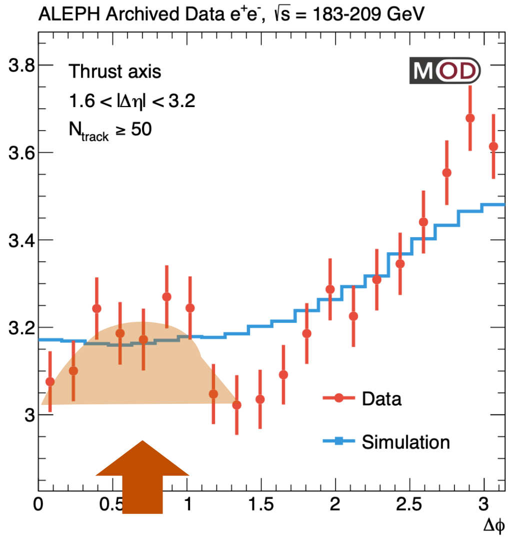
Assuming factorization:

$$v_n\{2, 1.6 < |\Delta\eta| < 3.2\} = \text{sign}(\text{V}_{\text{n}\Delta})\sqrt{\text{V}_{\text{n}\Delta}}$$

Similarity to low-multiplicity pp collisions





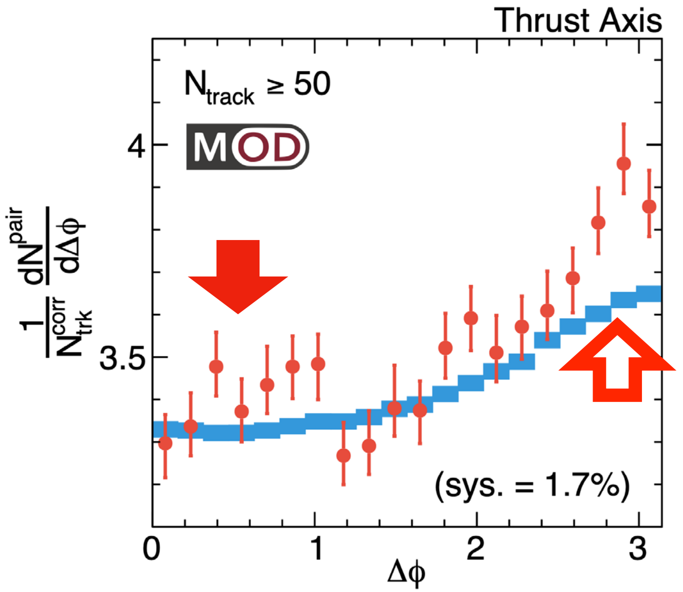


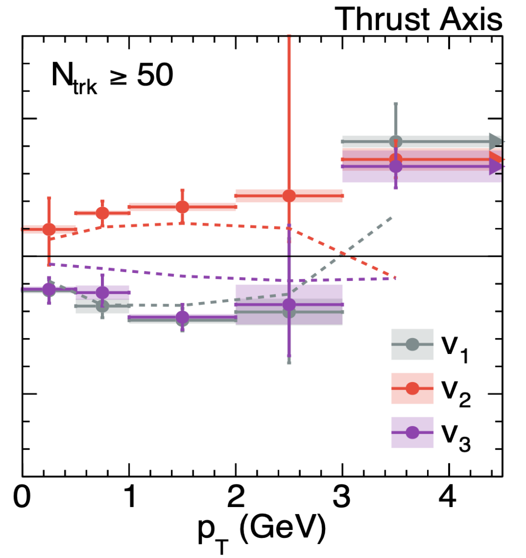
Ridge-like yield estimation

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

Conclusions

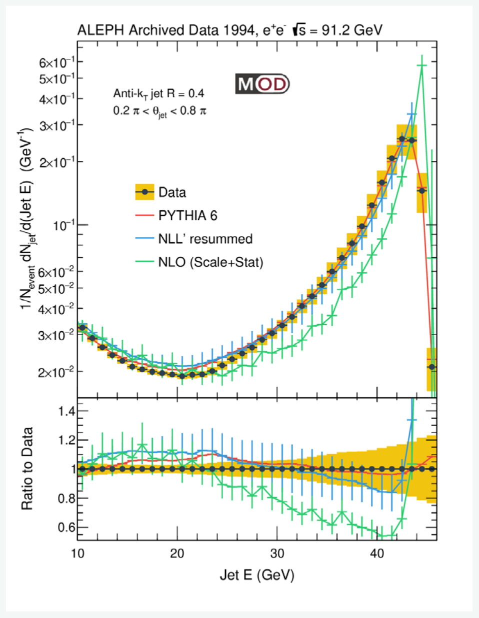
- e+e- collisions allow for investigation of smallest possible collision systems for flow-like characteristics
- Re-analysis of LEP II data reveals possible signs of an excess long-range near-side yield relative to MC
  - Hints at a "bridge" between pure hard scattering and flow in pp collisions
- Plenty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

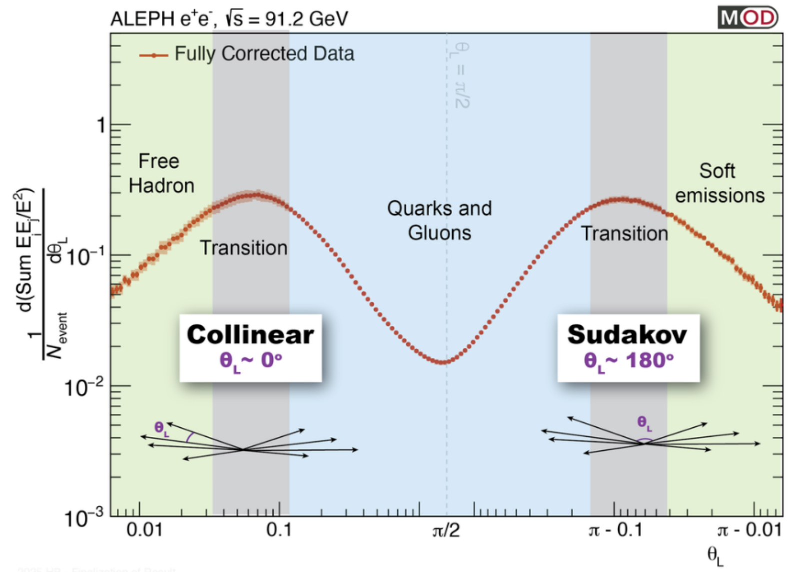


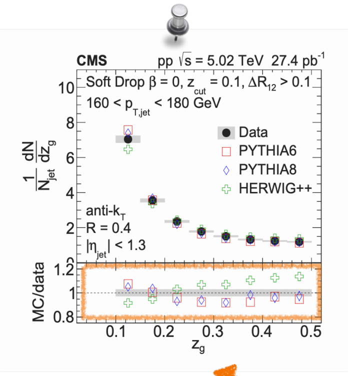


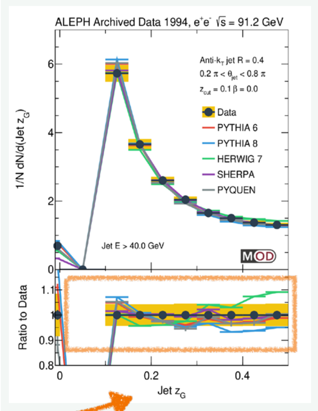
Other Results, Here and Elsewhere

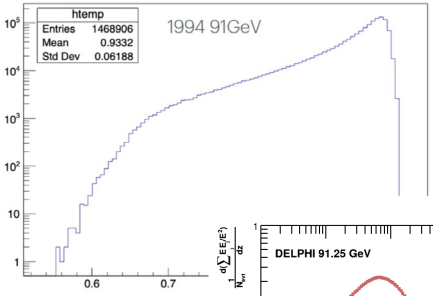
- Yen-Jie Lee's **poster** at this conference (https://indi.to/Dz7rM)
  - "Measurement of the N-point energy-energy correlator from the collinear limit to the back-to-back limit in e+e- collisions at 91 GeV with the ALEPH experiment"
- Jet substructure measurements [JHEP 06 (2022) 008]
- Re-analysis of DELPHI data (under construction, stay tuned!)

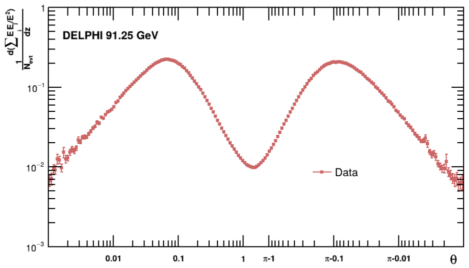










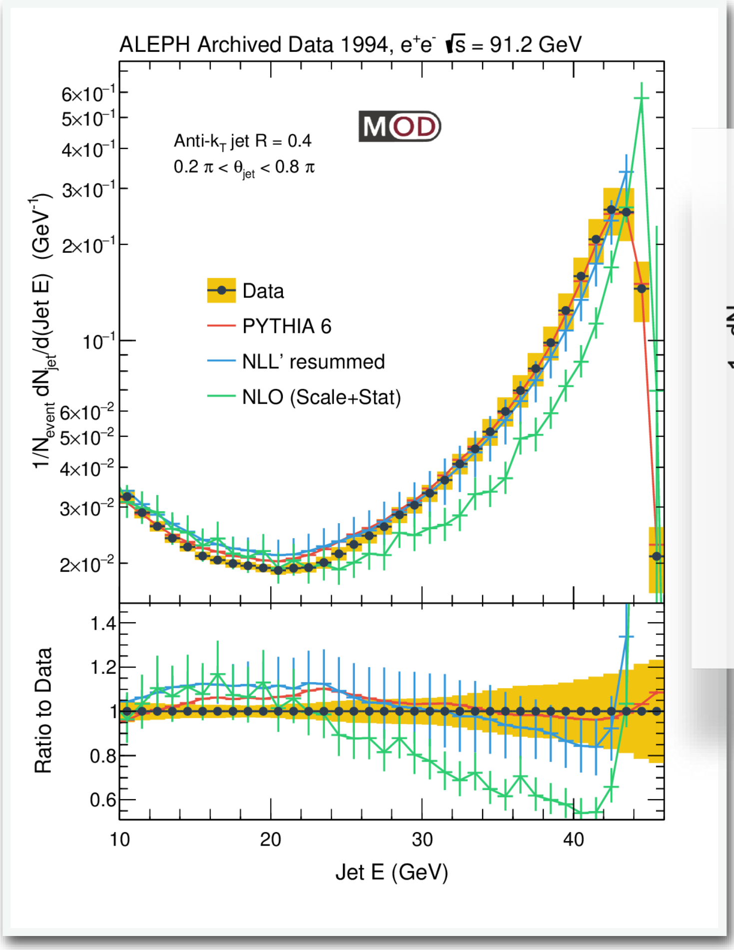


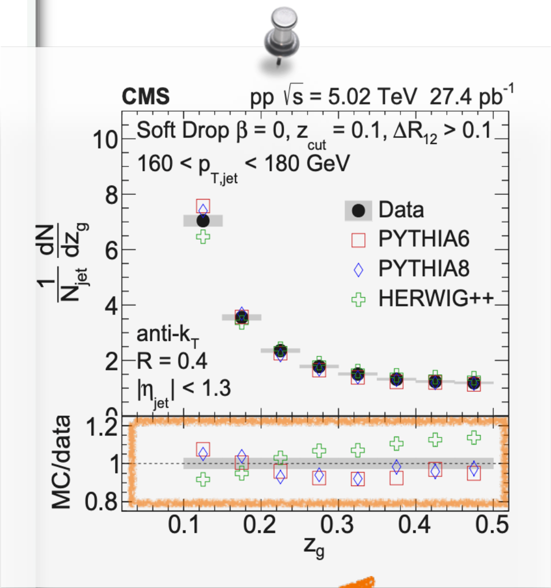
Thank you!

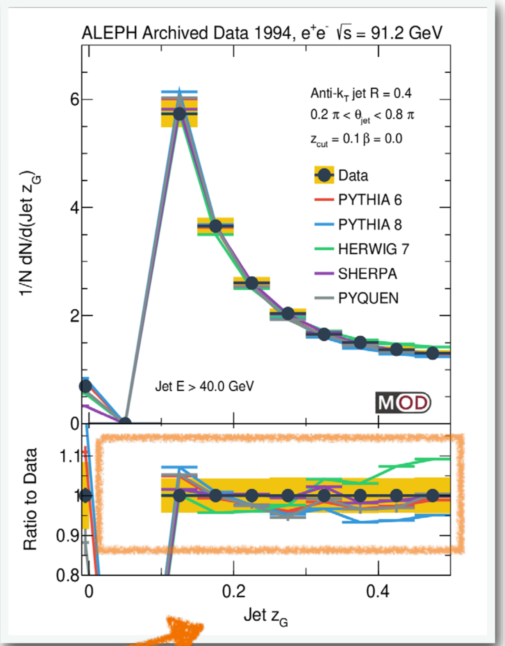
Backup

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





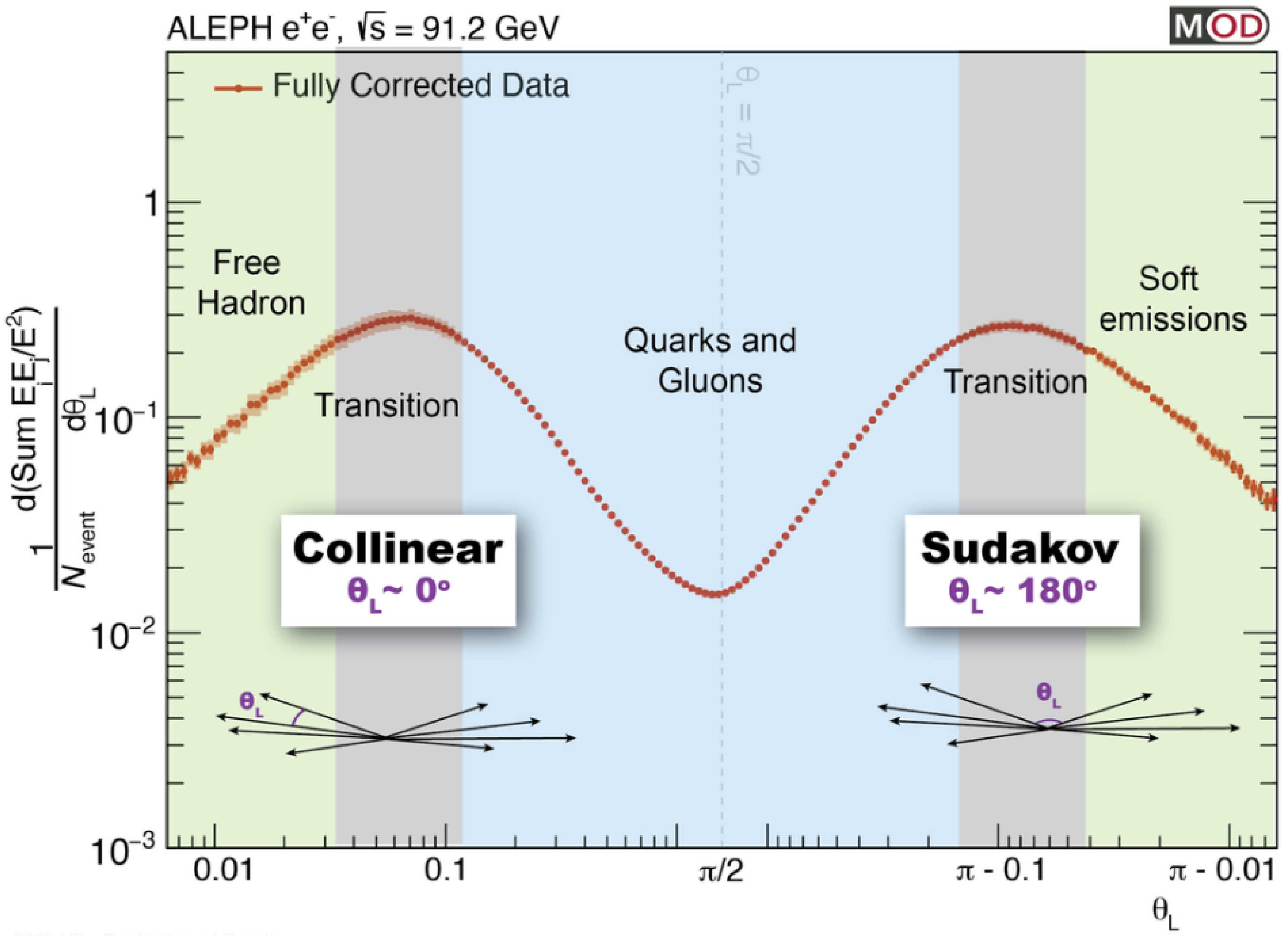


ALEPH jet

[JHEP 06 (2022) 008]

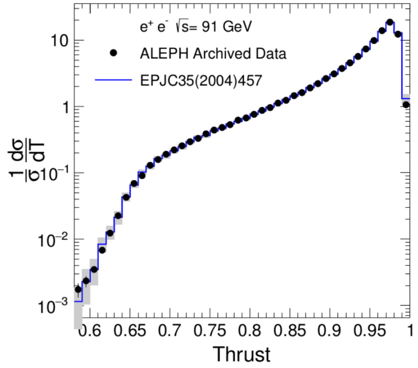
Other observables: Energy-Energy Correlator

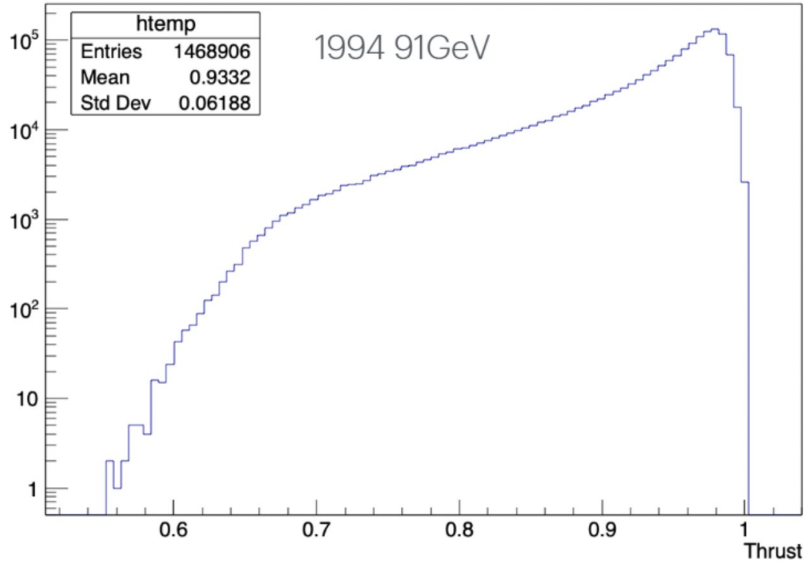
- Theorists (Ian Moult + collaborators, Iain Stewart, et al.) interested in this quantity in particular:
  - Directly sensitive to theory parameters (ex: α_S)
  - Constraining non-perturbative parameters in lattice QCD
- Unique opportunity in e^+ e^− to access the 2-point correlator from collinear to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

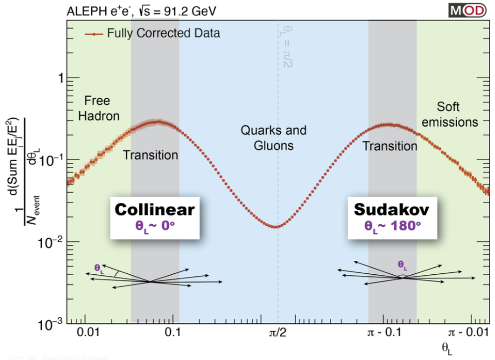


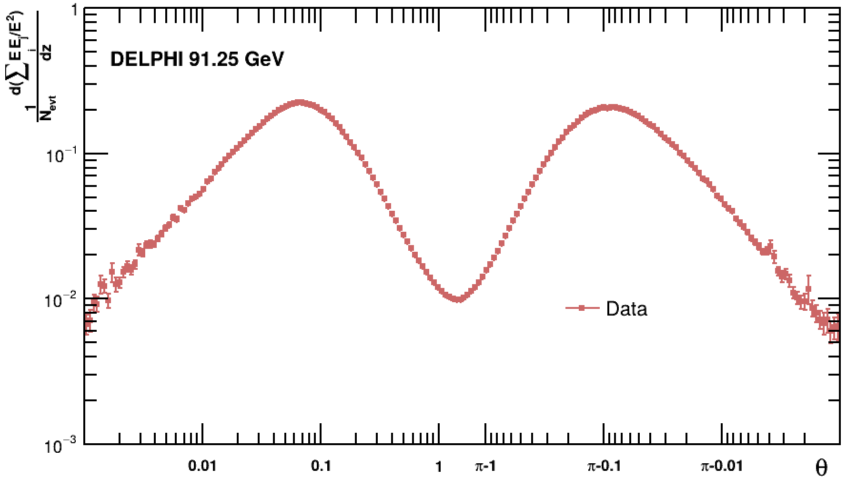
Other datasets: DELPHI archived data

- 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







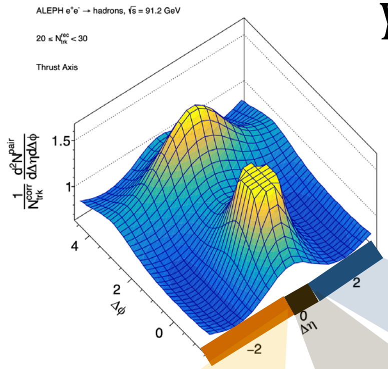


Azimuthal differential associated yield $Y(\Delta\phi)$

Two-particle correlation function

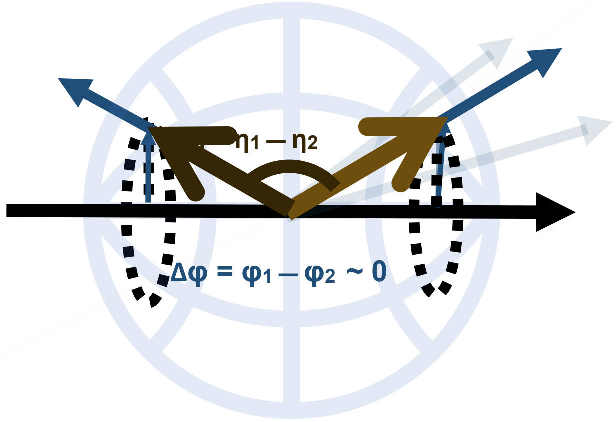
(per-trigger-particle associated yield)

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



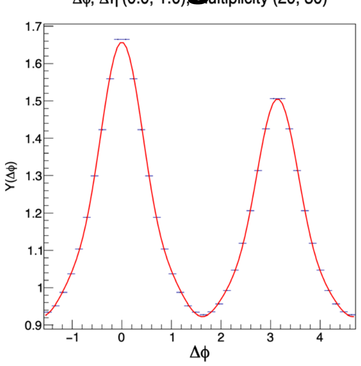
Associated yield vs. Δϕ

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

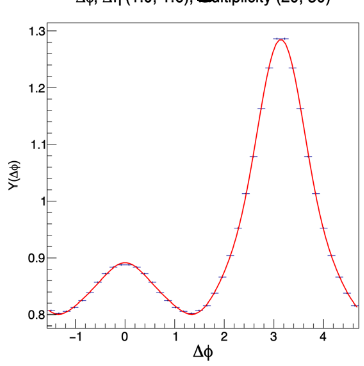


Long Range

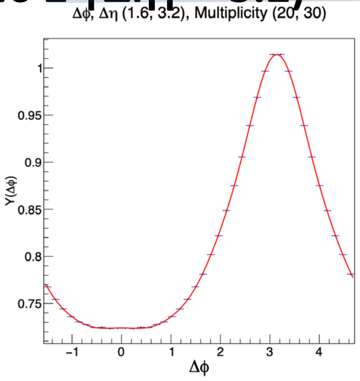
Short Range



Middle Range



(1.6 ≤ |Δη| < 3.2)

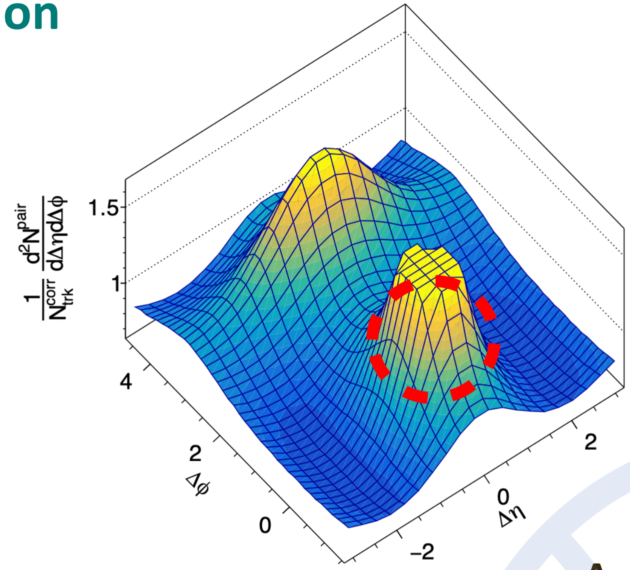


Understanding 2PC in e^+e^-— Intra-jet correlations

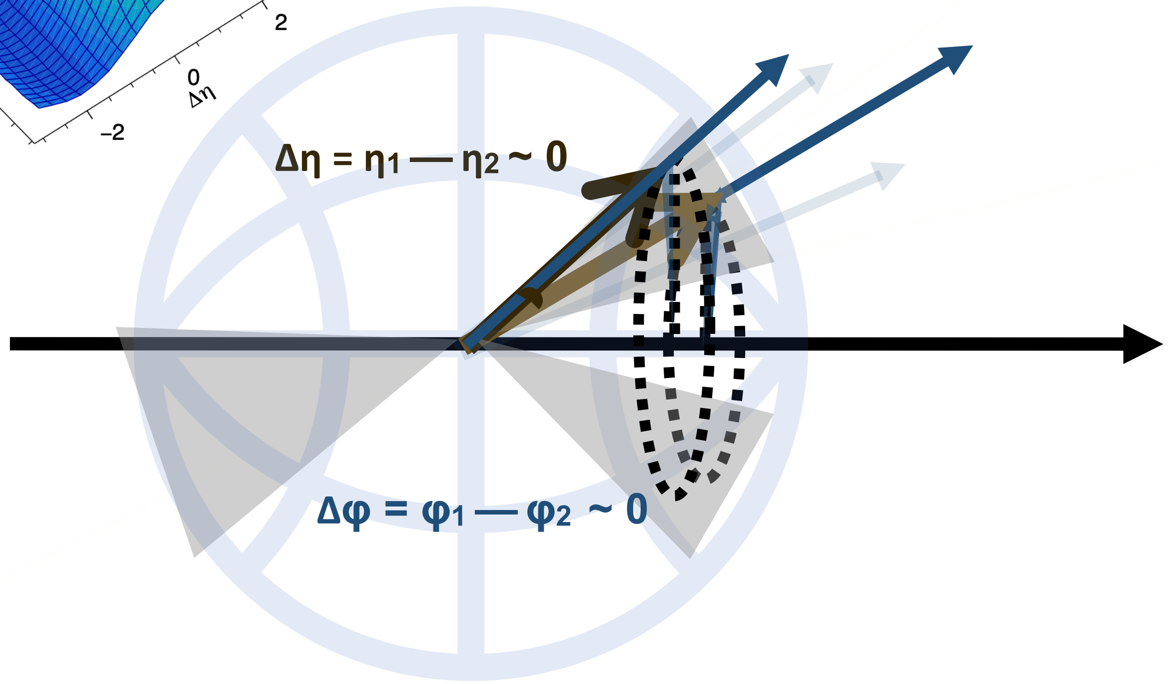
Two-particle correlation function

(per-trigger-particle associated yield)

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



Origin-peak intra-jet correlations @ near side (Δη,Δϕ)~(0,0)

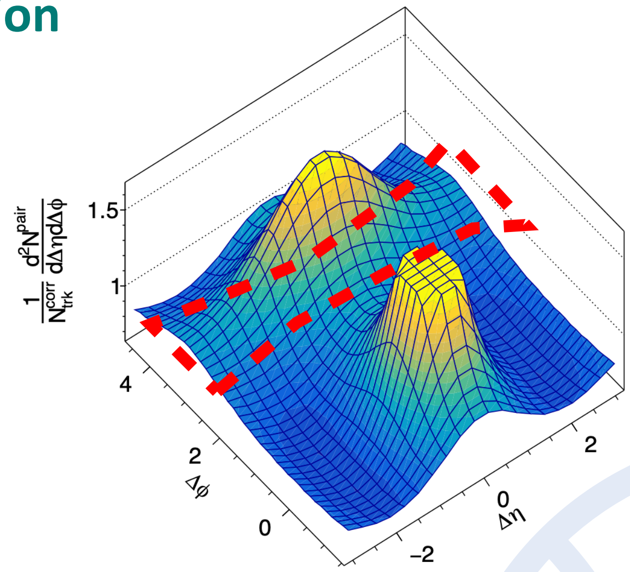


Understanding 2PC in e^+e^-— Inter-jet correlations

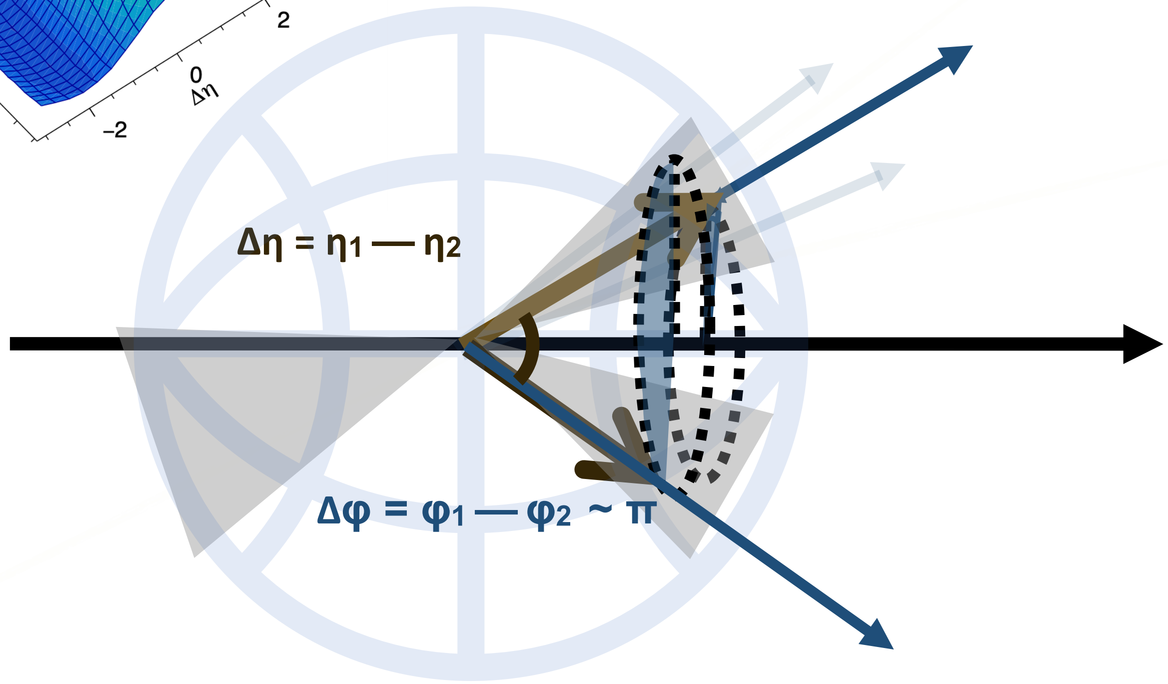
Two-particle correlation function

(per-trigger-particle associated yield)

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



Inter-jet correlations
@ away side (Δϕ~π)

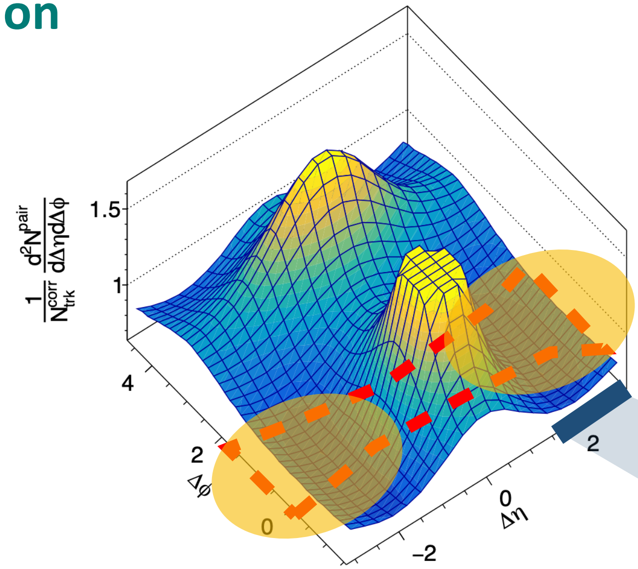


Understanding 2PC in e^+e^- — Ridge(-like) correlations

Two-particle correlation function

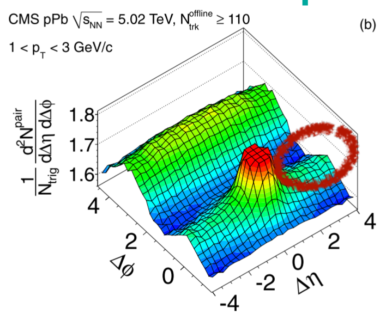
(per-trigger-particle associated yield)

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

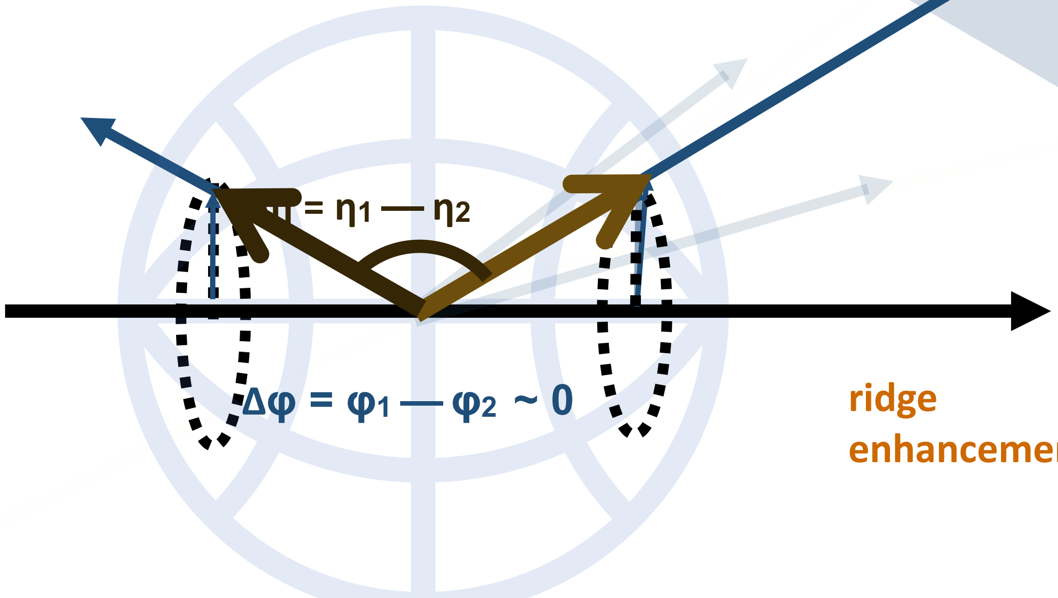


Ridge correlations
@ long range, near side

pPb

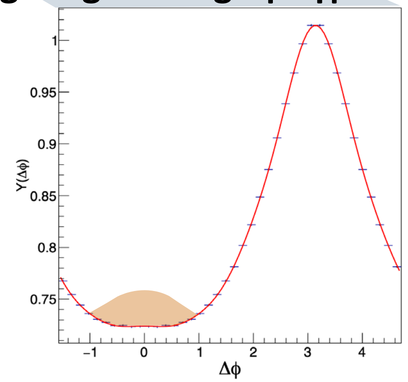


[Phys. Lett. B718 (2013) 795-814]

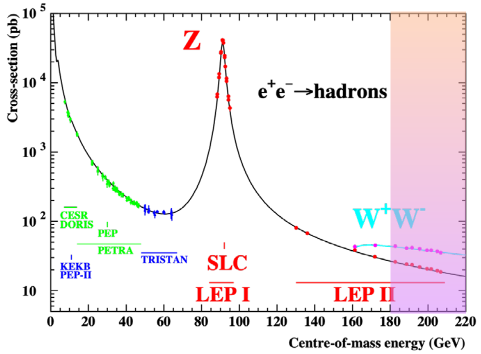


ridge enhancement

long range in large |Δη|



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

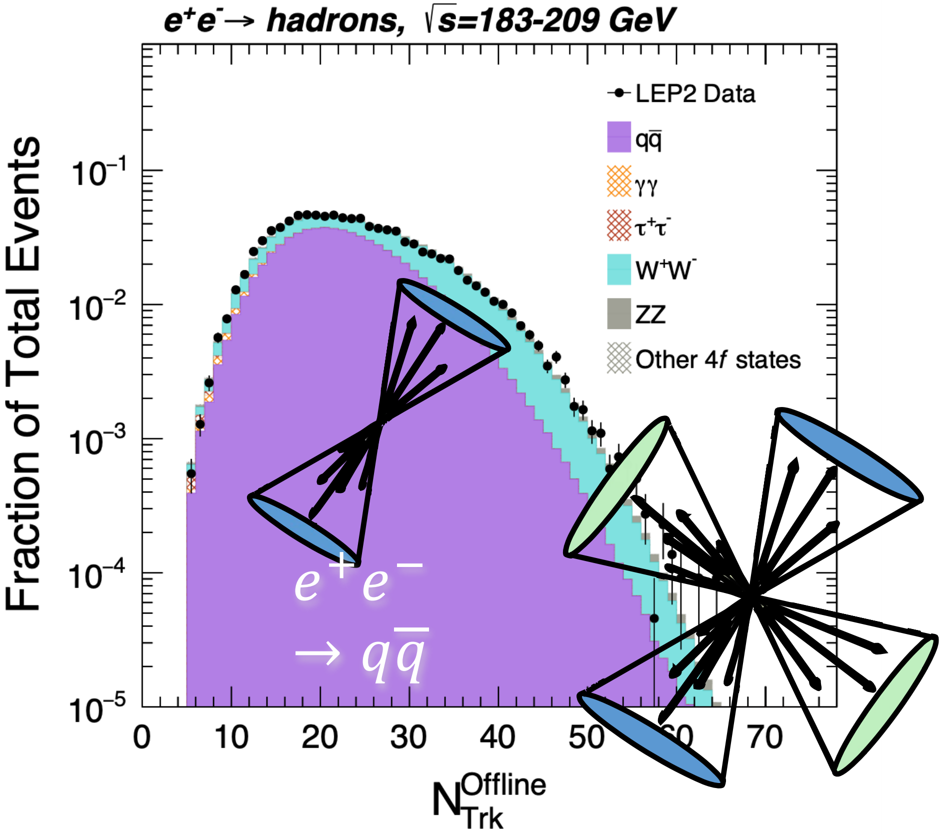


$\sqrt{s} \geq 183$ GeV

What will happen in higher energy LEP-II sample?

- Allowing for higher event multiplicity up to $N_{Trk} \geq 50$
- Opening up more complicated color-string configuration

  Dominant W^+W^- event at high multiplicity showcases a 2-color-string configuration



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

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 (Υ(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

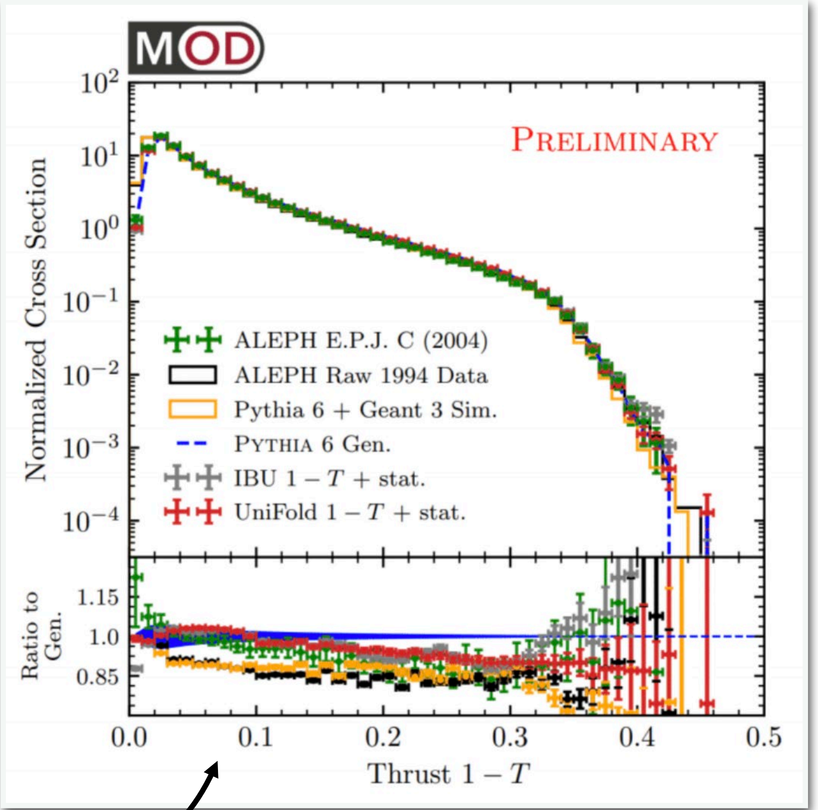
pp

- 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

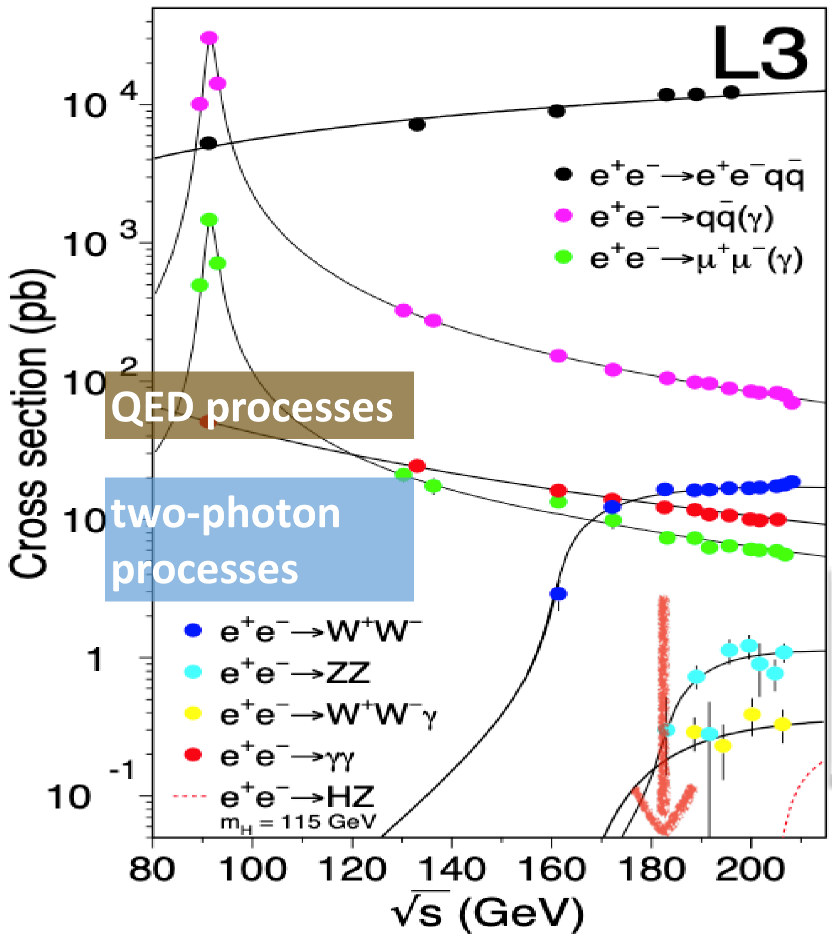
Big thanks to ALEPH collaboration and MIT open data

LEP-II data & MC processes

Year vs. √s vs. int. L

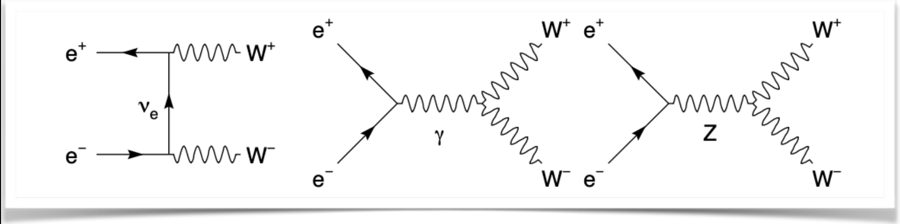
Year	Mean energy $\sqrt{s}$ [GeV]	Luminosity [pb^{-1}]
1995, 1997	130.3	6
	136.3	6
	140.2	1
1996	161.3	12
	172.1	12
1997	182.7	60
1998	188.6	180
1999	191.6	30
	195.5	90
	199.5	90
	201.8	40
2000	204.8	80
	206.5	130
	208.0	8
Total	130 – 209	745

√s v.s. X-section



Hadronic $q\bar{q}$ production

Four fermion processes

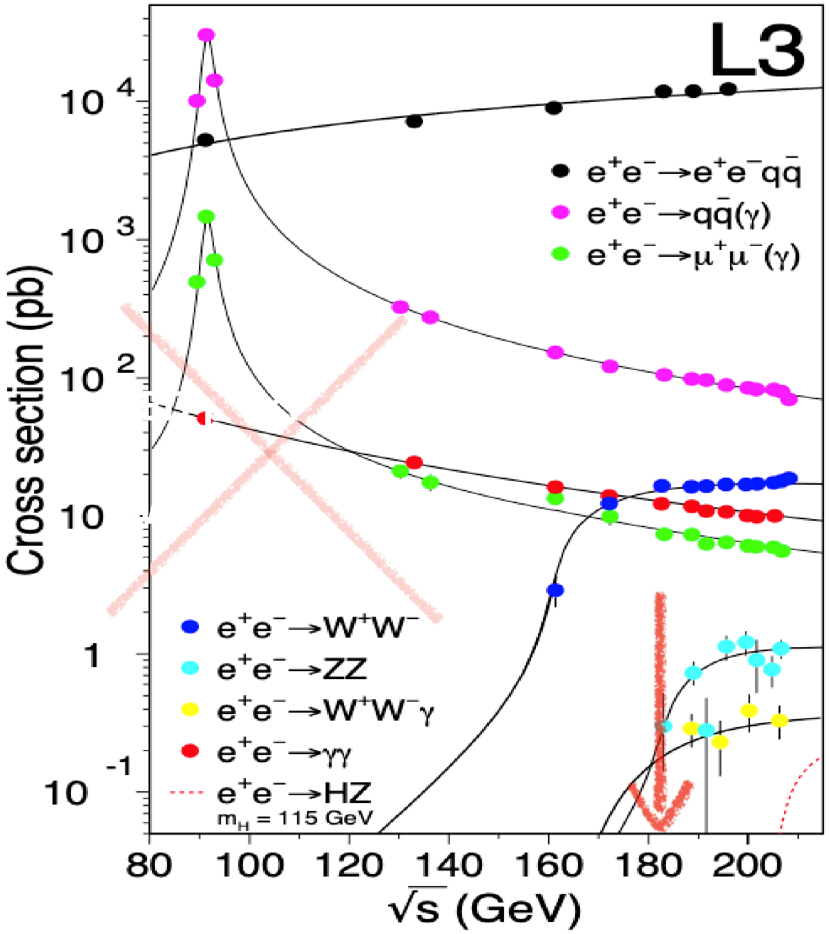


Diverse decay channels above $\sqrt{s}$ = 180 GeV

LEP-II event selections

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

Hadronic event selection
≥ 5 tracks
$E_{\text{chgd.}} \geq 15\text{GeV}$

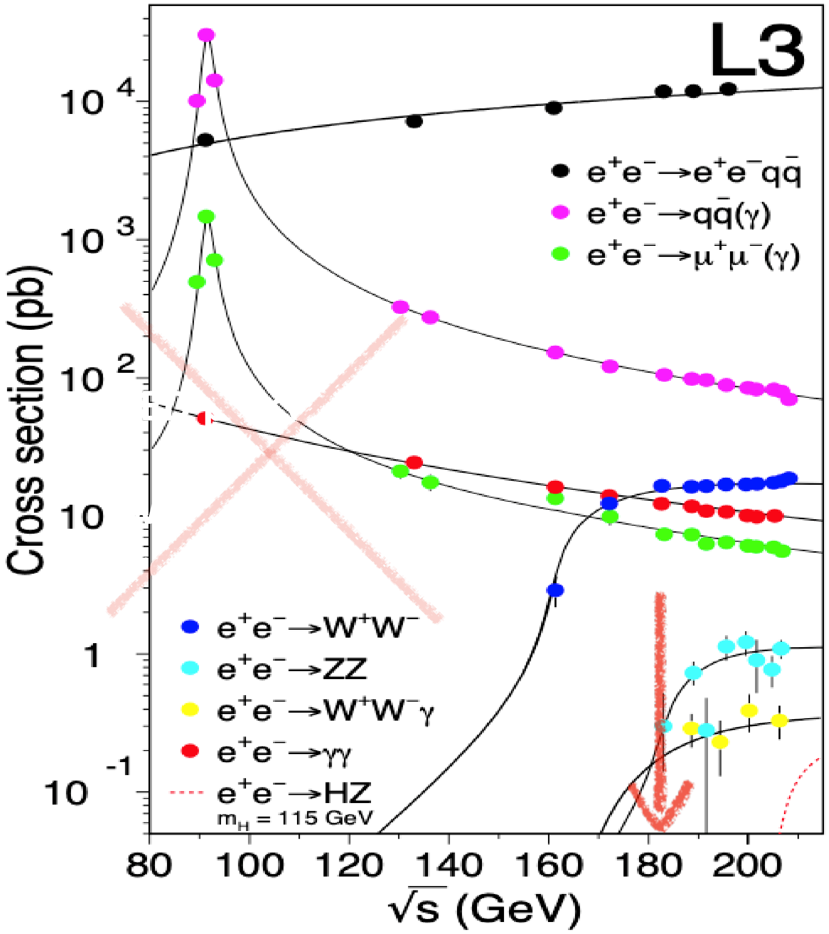


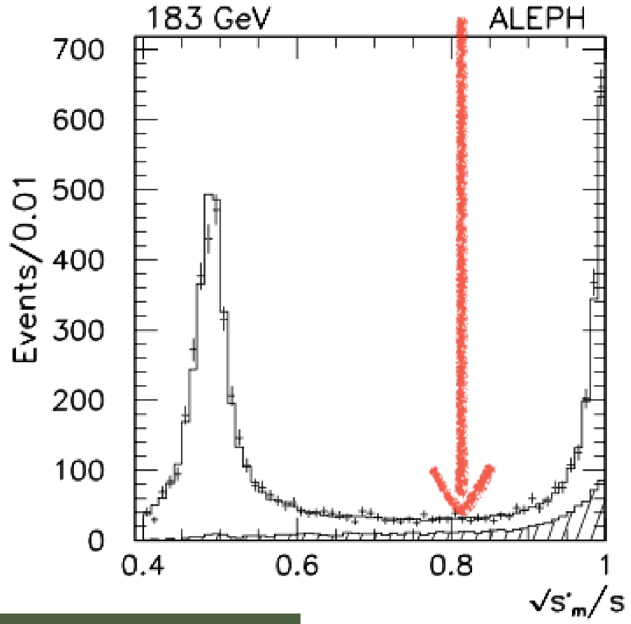
LEP-II event selections

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 $Z_{\sqrt{s}}$ ~ 90 GeV





Hadronic $q\bar{q}$ production

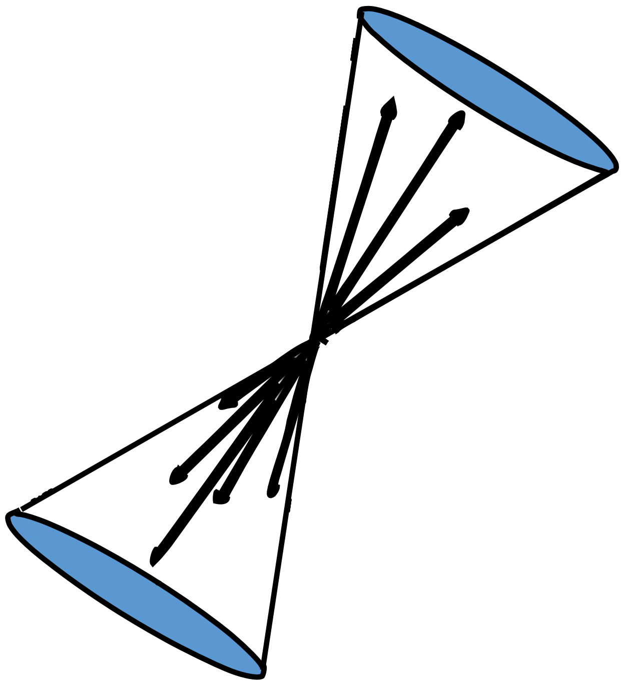
Ref: hep-ex/9904011

Four fermion processes

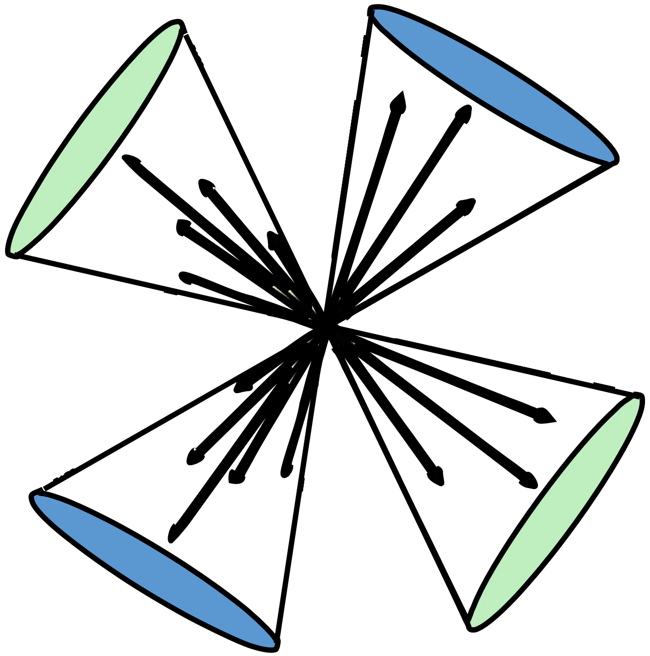
ISR cut

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

LEP-II physics processes



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



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

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, χ^2/ndf < 1000
  - |d0| < 2 cm
  - |z0|< 10 cm
  - |cosθ|<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
  - |cosθ|<0.98
- **Event Selection:**
  - Number of good charged particles >= 5 (including charged hadrons and leptons)
  - Number of good ch+neu. particles >= 13
  - $E_{charged}$ > 15 GeV
  - $|\cos(\theta_{sphericity})|$<0.82

Corrections

Selection & efficiency correction

Two-particle correlations

1. Efficiency correction
2. Residual MC correction

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

$$\varepsilon(p_{\mathrm{T}}, \theta, \phi, \mathrm{N}_{\mathrm{trk}}^{\mathrm{rec}}) = \left[\frac{d^3\mathrm{N}^{\mathrm{reco}}}{dp_{\mathrm{T}}d\theta d\phi} \Big/ \frac{d^3\mathrm{N}^{\mathrm{gen}}}{dp_{\mathrm{T}}d\theta d\phi}\right]_{\mathrm{N}_{\mathrm{trk}}^{\mathrm{rec}}}$$

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

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

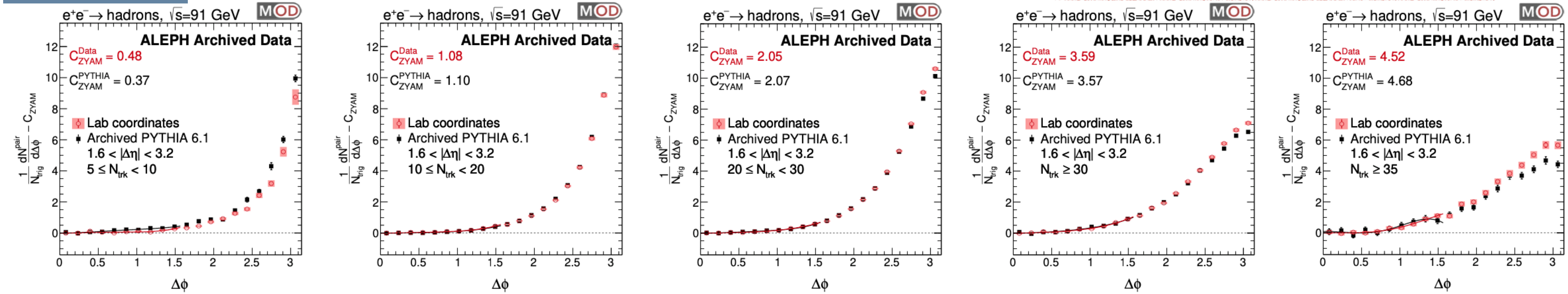
$$C(\Delta\phi) = \frac{Y(\Delta\phi)_{\mathrm{gen},i_g}}{Y(\Delta\phi)_{\mathrm{reco},i_r}}$$

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

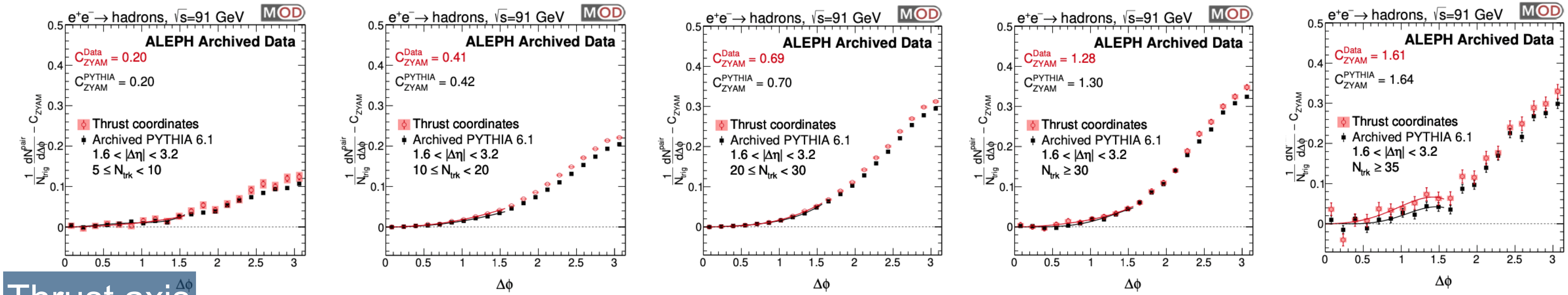
LEP1 Long-range correlations (c.f. MC)

Beam axis

Good agreement with MC!



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



Thrust axis