Collectivity in e^+e^- Collisions

Yen-Jie Lee (MIT)

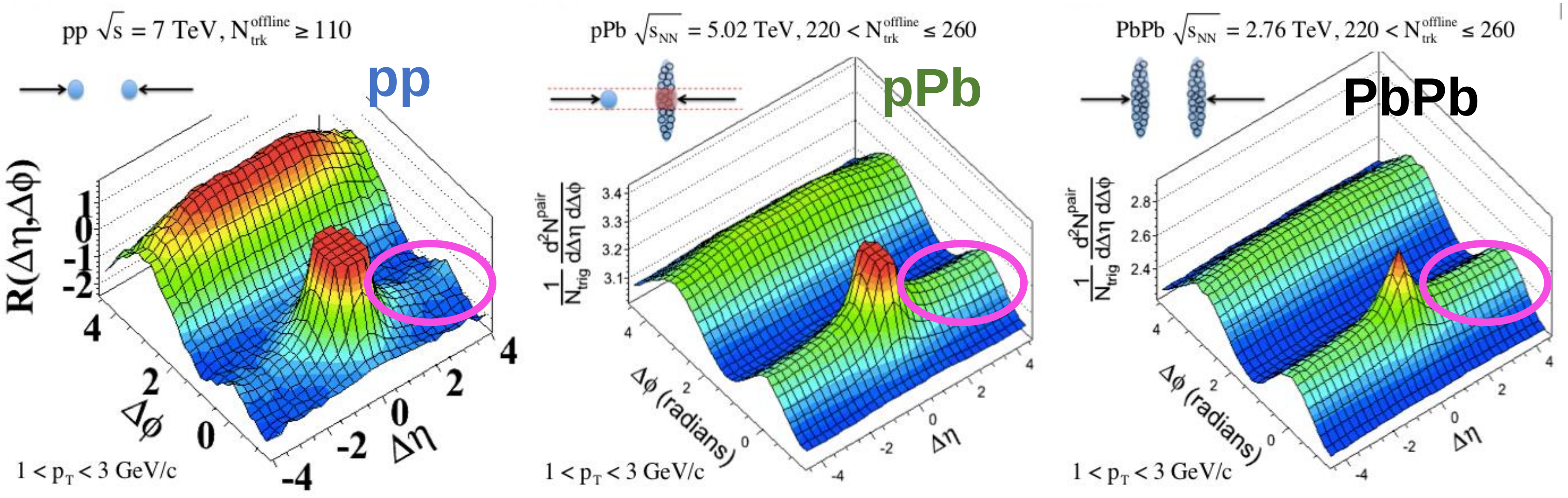
The 4th International Workshop on QCD Collectivity at the Smallest Scales

25 June, 2024

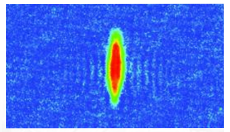
In Collaboration with Yu-Chen “Janice” Chen (MIT) ,Yi Chen (Vanderbilt U.), Anthony Badea (U. Chicago), Austin Baty (UIC) , Gian Michele Innocenti (MIT), Marcello Maggi (INFN Bari), Christopher McGinn (MIT), Michael Peters (MIT) , Tzu-An Sheng (MIT), Jesse Thaler (MIT)

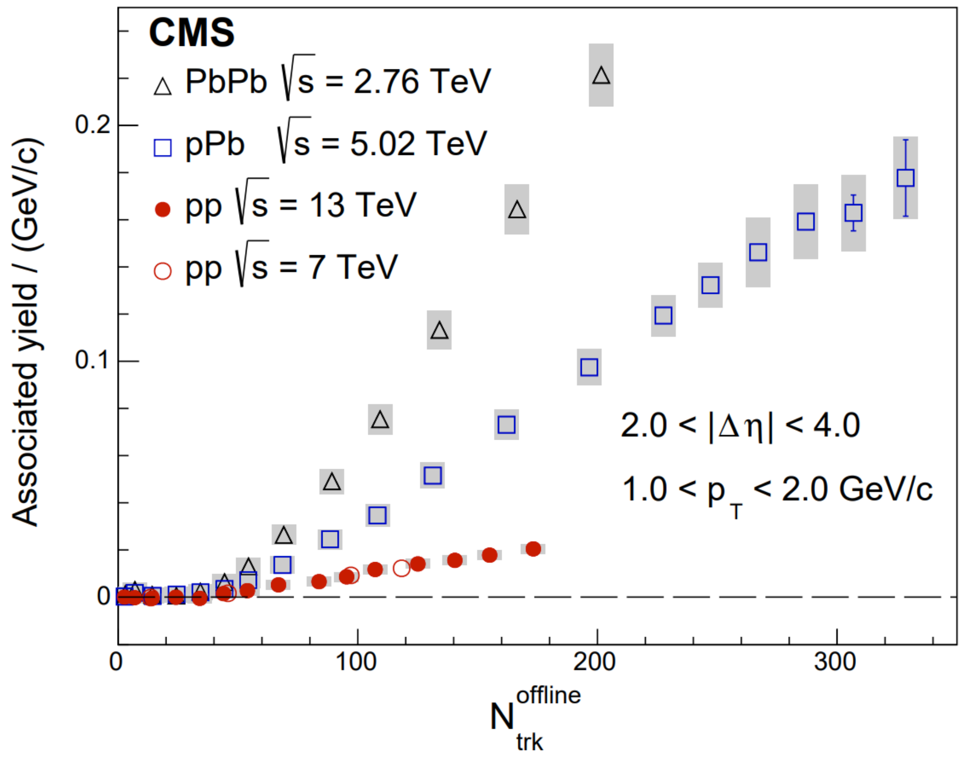
MIT HIG group's work was supported by US DOE-NP

Motivation



2010 **2012**





- **The first unexpected discovery at LHC: Ridge** in high multiplicity pp from CMS
- The origin may not necessary hydrodynamics, possible explanations includes:
  - Initial state effect (e.g. CGC)
  - Escape mechanism / Single or few scatterings (AMPT, PYTHIA with Rope Mechanism, Multi-parton rescattering…)
  - Final state effect due to mini-QGP
  - …

CMS JHEP 09 (2010) 091
CMS pPb PLB 718 (2013) 795-814

Physics Questions to be Addressed

- What are the minimum conditions for ridge signal in a small system?
- Can detectable collectivity arise from final state effects unrelated to the initial state?
- How does collectivity vary in different physics processes?
- Is the underlying physics the same in small and large systems?
- …

Physics Questions to be Addressed

- What are the minimum conditions for ridge signal in a small system?

  Vary the transverse size and multiplicity of the collision system

- Can detectable collectivity arise from final state effects unrelated to the initial state?

  Use electron beams that doesn’t have initial hadron structure

- How does collectivity vary in different physics processes?

  Select and study specific physics processes

- Is the underlying physics the same in small and large systems?

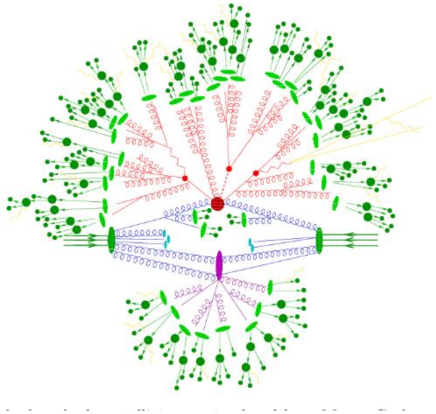
  By collection of all the experimental data and compare

- …

System Size

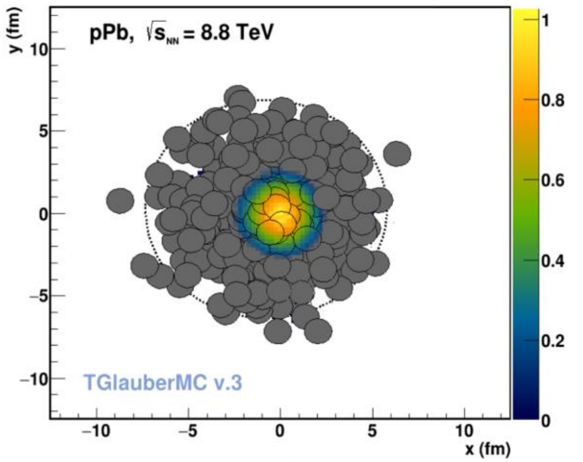
“Transverse Size” / MPI

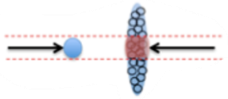
pp



~ O(1fm)

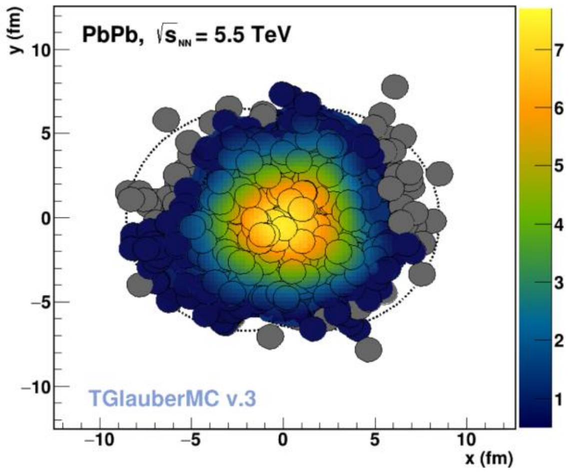
pA

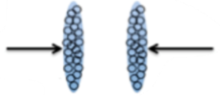




≥ O(1fm)

AA

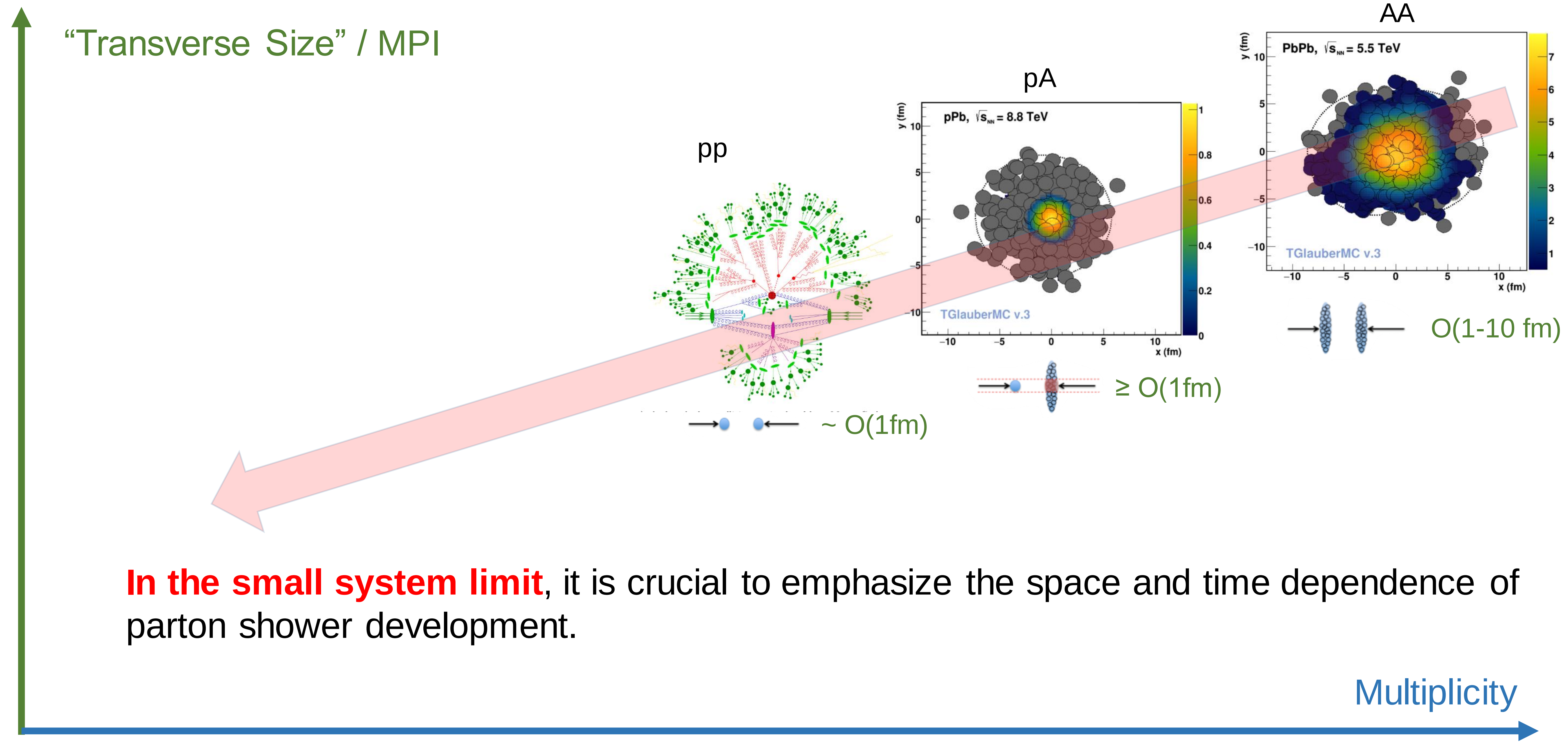




O(1-10 fm)

Multiplicity

System Size

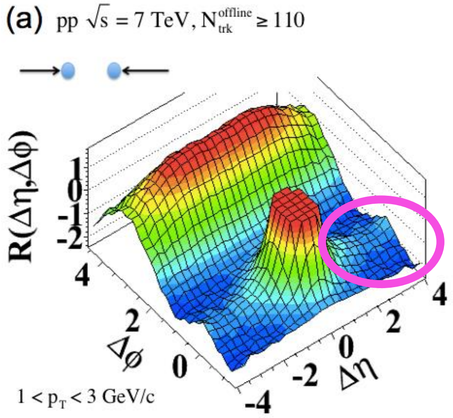


In the small system limit, it is crucial to emphasize the space and time dependence of parton shower development.

Smallest System: e^+e^-

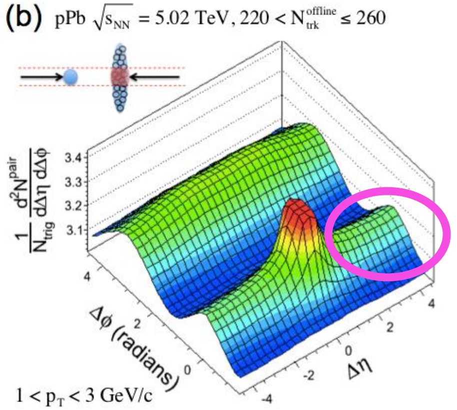
"Transverse Size" / MPI

High multiplicity pp

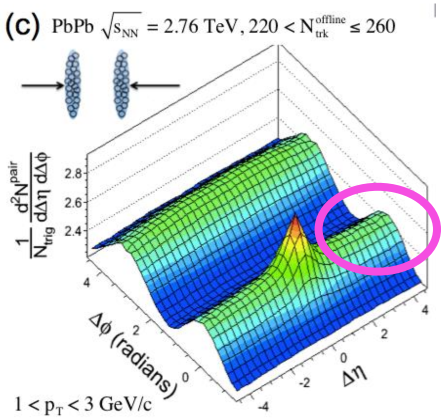


~ O(1fm)

High multiplicity pPb

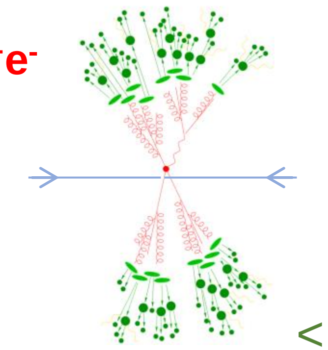


≥ O(1fm)



O(1-10 fm)

e^+e^-



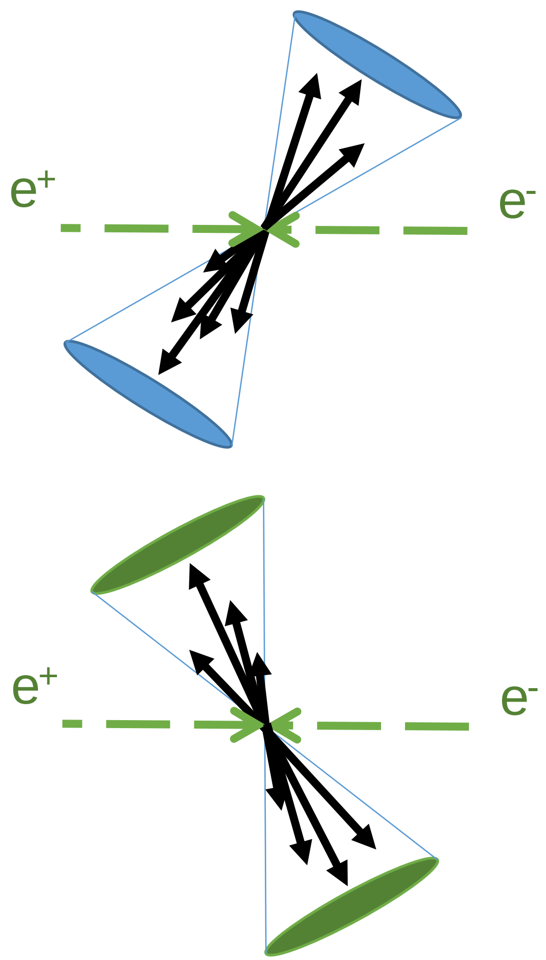
< 0.1 fm

- e^+e^- events: collisions with **well-defined initial conditions**
  - No complication from hadron structure
  - No multi-parton interaction
  - No gluonic initial state radiation

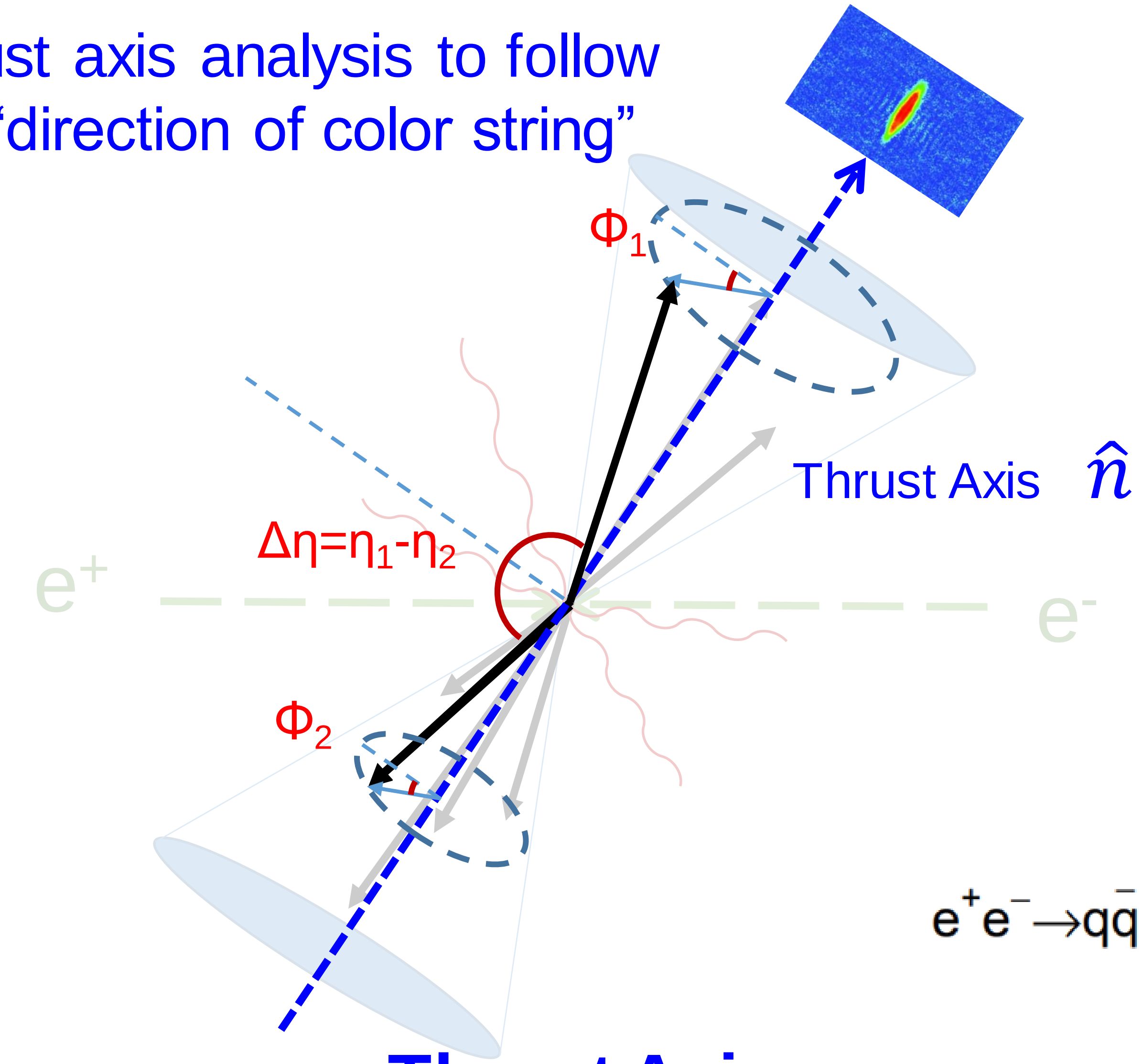
Multiplicity

Reference Axis for e^+e^-

Random orientation of the jets



Thrust axis analysis to follow the "direction of color string"

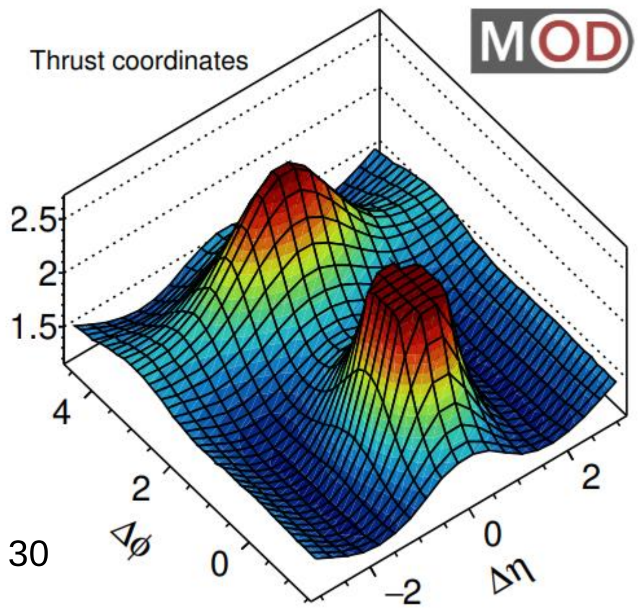


Thrust Axis

Sensitive to **"medium expansion"** perpendicular to the **Thrust axis**
(**Not necessary QGP**, it could be a few rescatterings of partons)

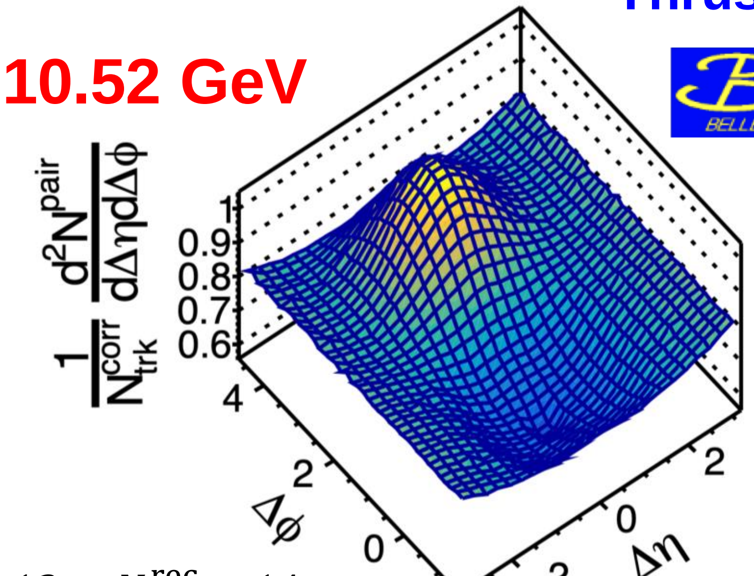
e^+e^- at 10.52 (Belle) and 91 GeV (ALEPH)

91 GeV



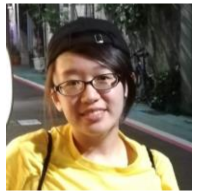
$N_{trk}^{rec} > 30$

10.52 GeV

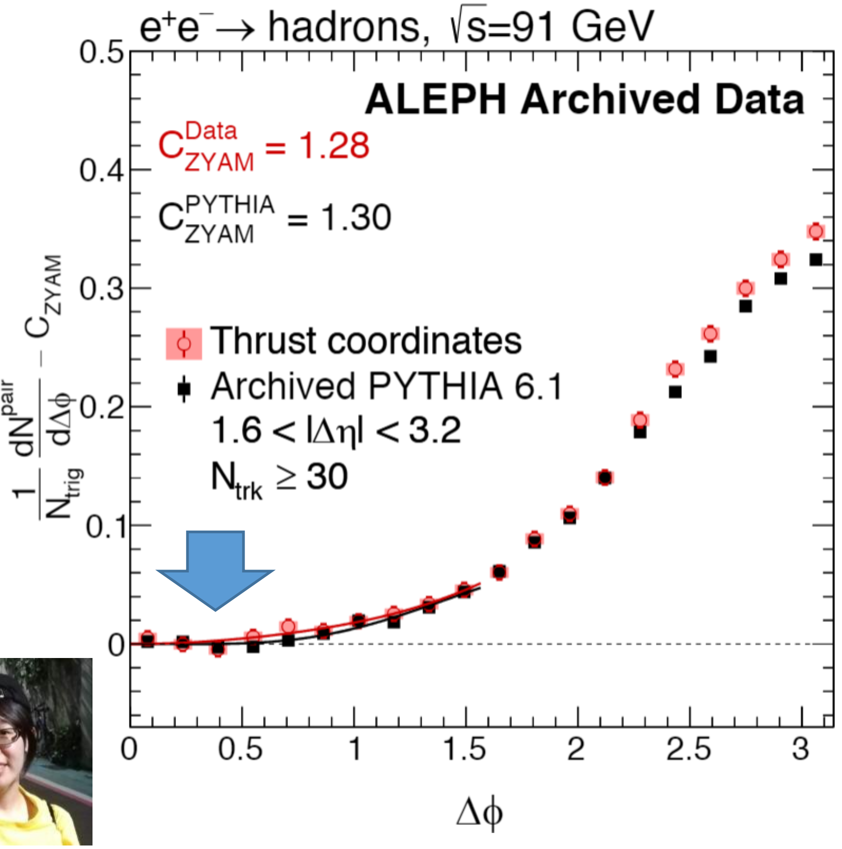


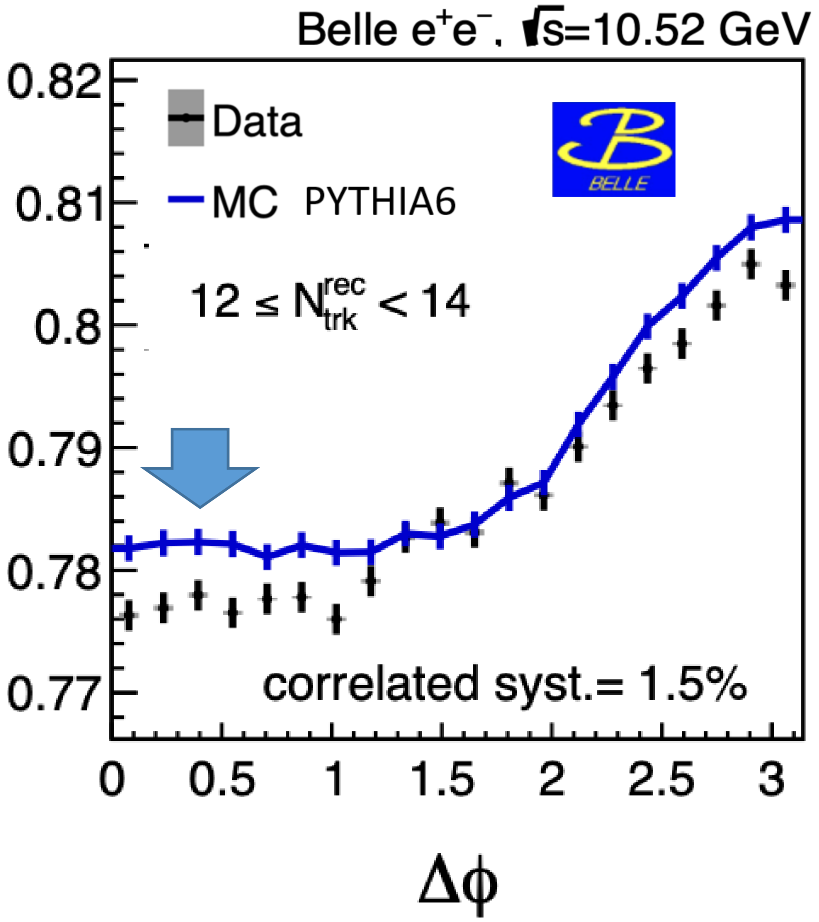
$12 \le N_{trk}^{rec} < 14$

Thrust



Janice Chen





- No sign of ridge signal in high multiplicity electron-positron collisions up to ~35 charged particles per event
- New reference to the collective behavior in small systems!

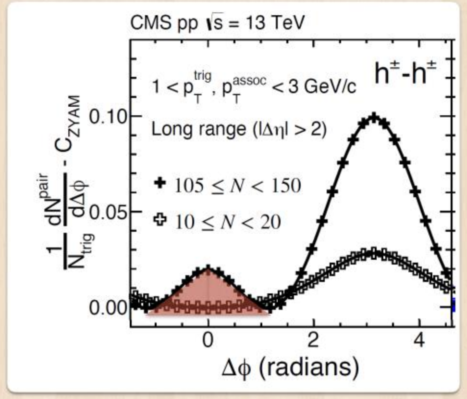
ALEPH archived data PRL 123, 212002 (2019)

Off Υ(4S) resonance, Belle PRL 128 (2022) 14, 142005

On Υ(4S) resonance, Belle JHEP 03 (2023) 171

Compilation of Ridge Yield Limit in e+e- collisions

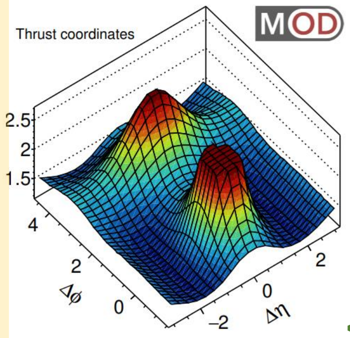
"Transverse Size"



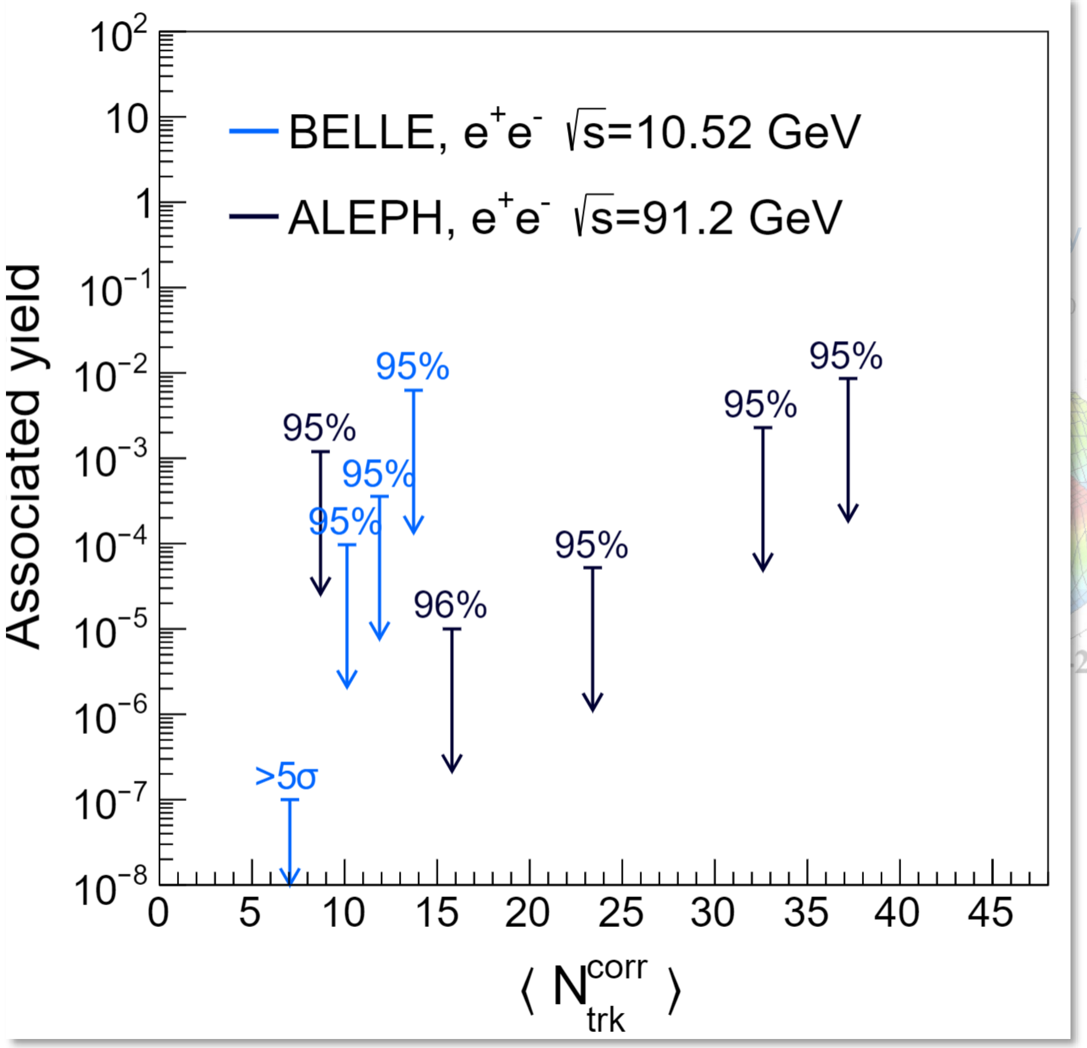
1. Find minimum point
2. Integrate area under it

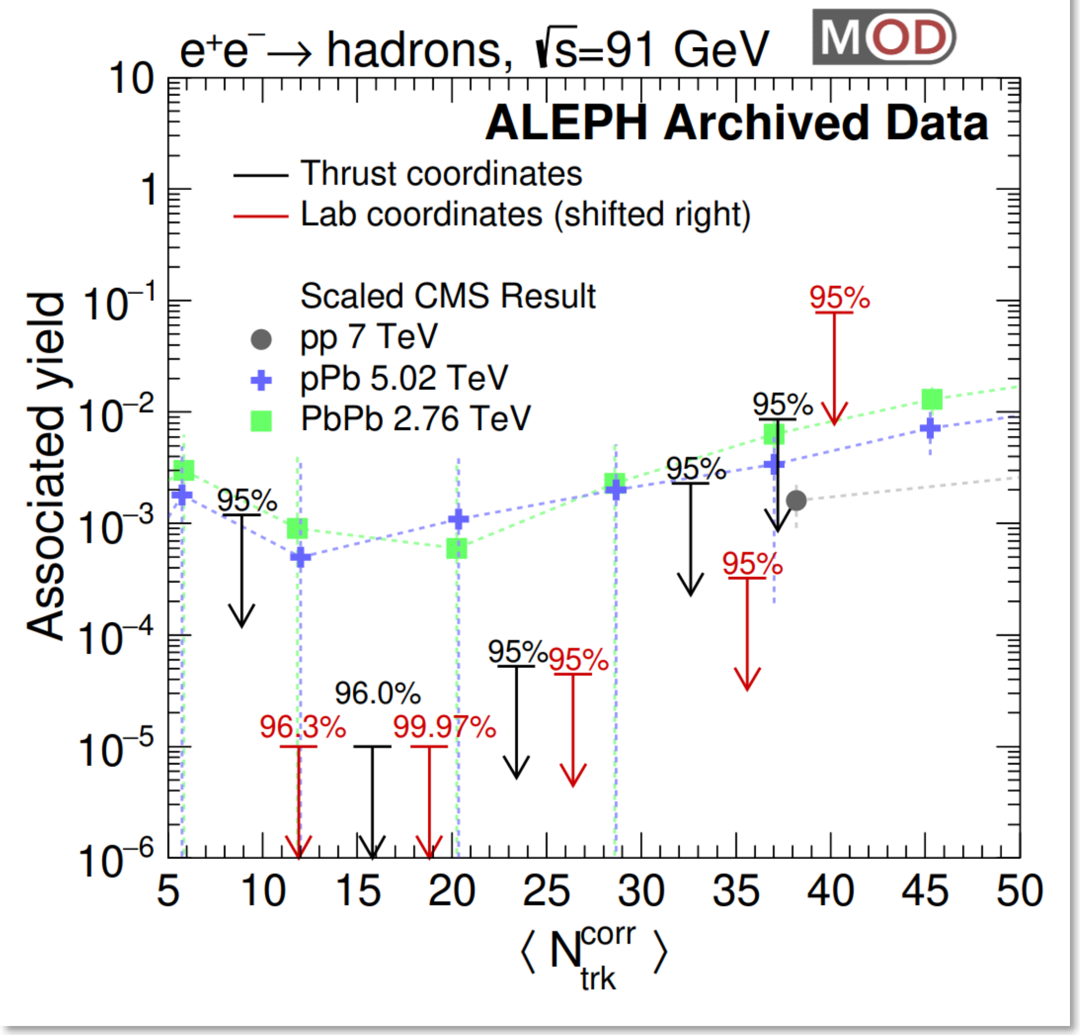
Yi Chen's slide

e^+e^-



<< 0.1 fm





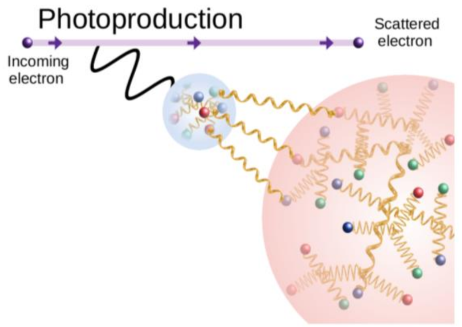
No significant ridge signal in $e^+e^- \rightarrow q\bar{q}$
from low to high multiplicity (up to ~35 particles)

Multiplicity

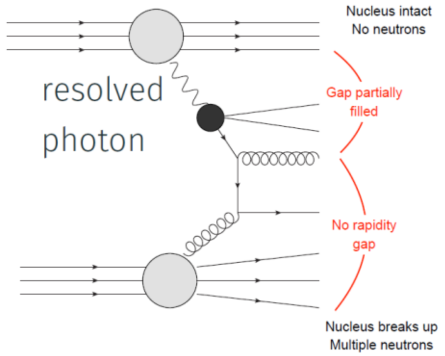
Searches with ZEUS, H1 and CMS γp

"Transverse Size" / MPI

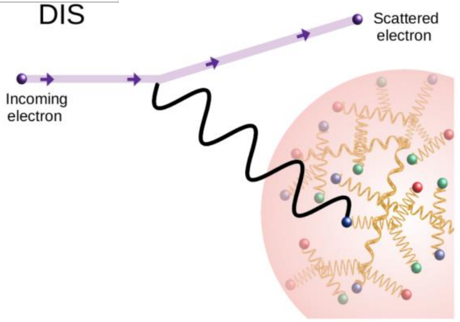
$1/\Lambda_{QCD}$ ~ 1 fm



(b) *Resolved photoproduction.*



DIS



(a) *Neutral current deep inelastic scattering.*

1/Q < 0.2 fm

<< 0.1 fm

High multiplicity pp

~ O(1fm)

High multiplicity pPb

≥ O(1fm)

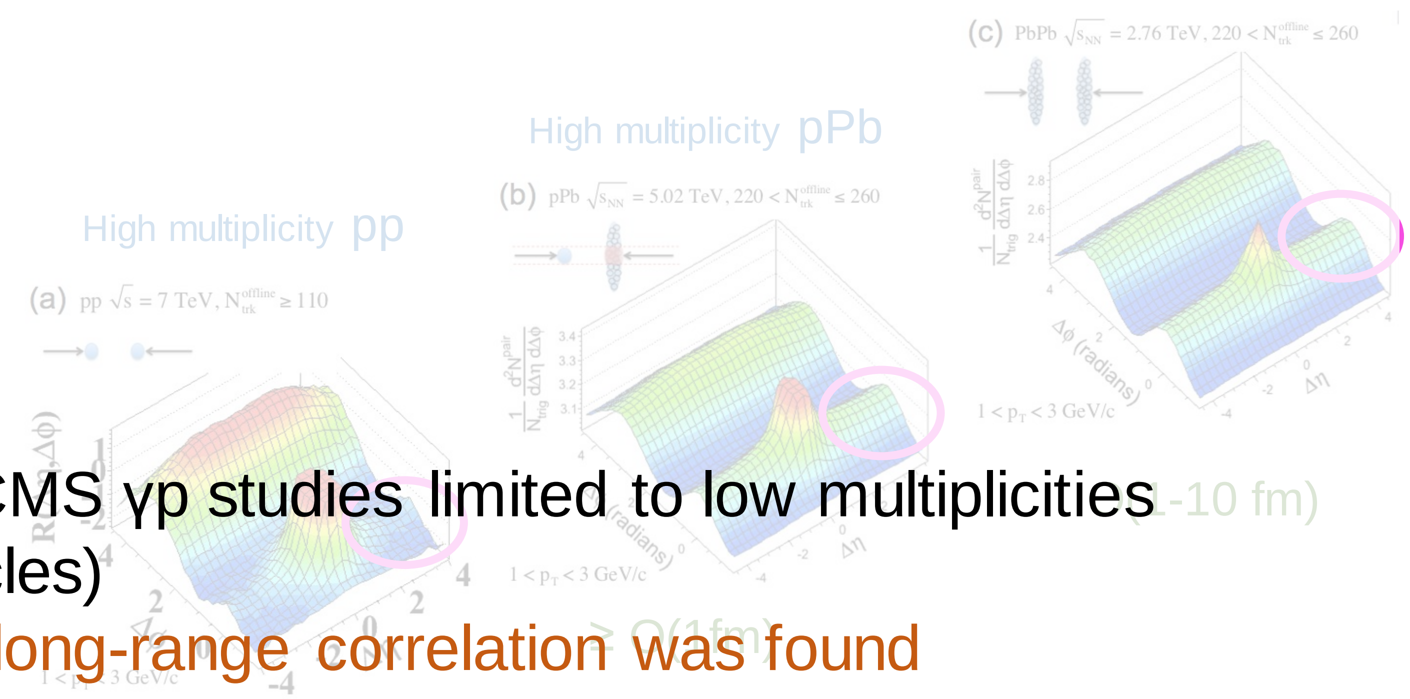
O(1-10 fm)

Multiplicity

Searches with ZEUS, H1 and CMS γp

“Transverse Size” / MPI

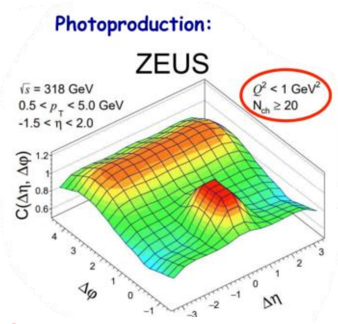
See Nicole Lewis’s talk in the workshop



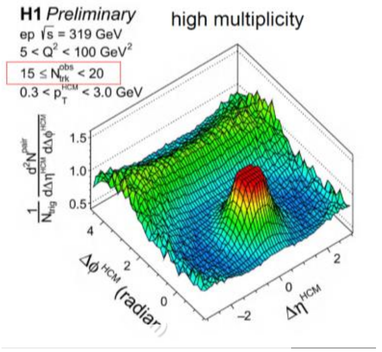
ZEUS, H1 and CMS γp studies limited to low multiplicities (Up to ~20 particles)

No indication of long-range correlation was found

ATLAS γPb shows no sign of ridge before subtraction



H1 DIS



MPI ≥ 1

“MPI”=1

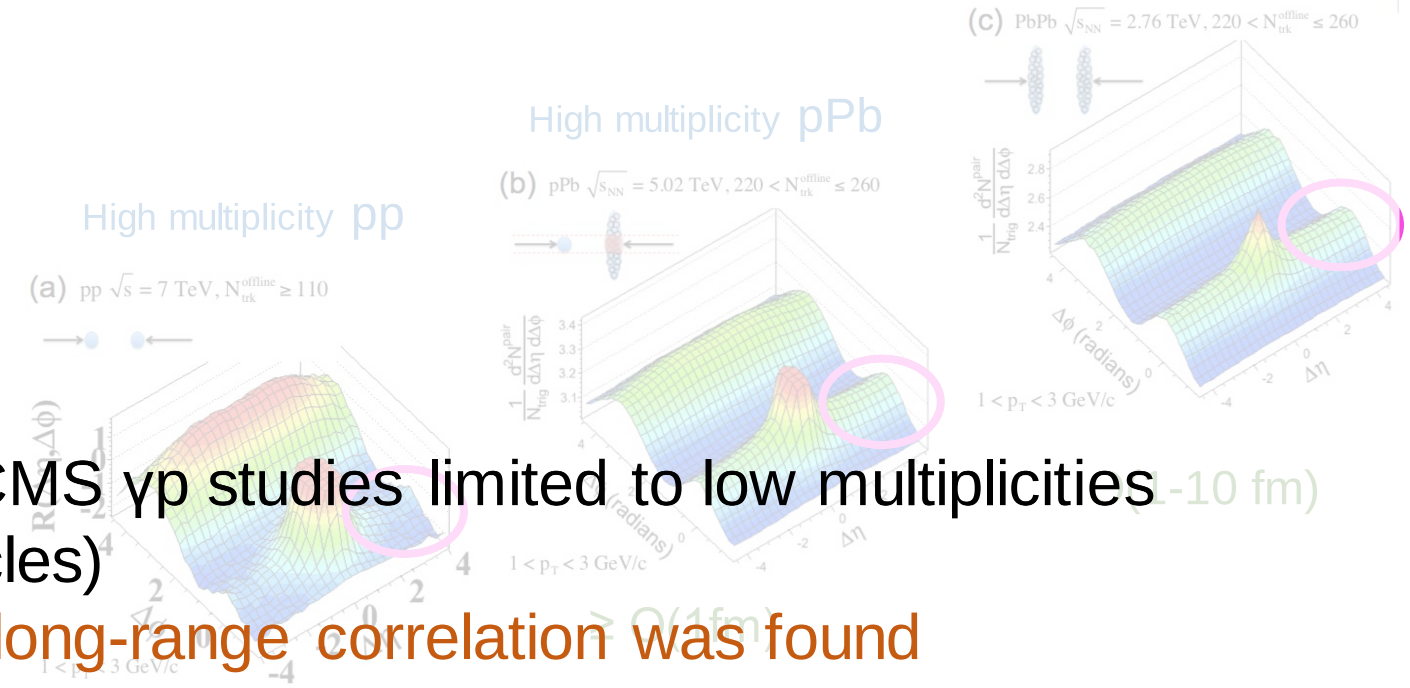
<< 0.1 fm

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
CMS pPb photonuclear: PLB 844 (2023) 137905
ATLAS PbPb photonuclear: PRC 104 (2021) 1, 014903

Multiplicity

System Size

“Transverse Size” / MPI

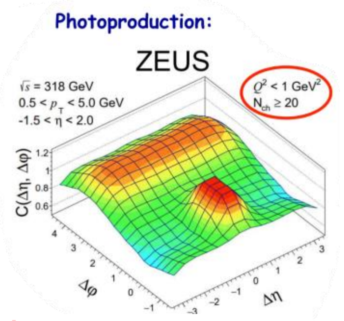


MPI>1

ZEUS, H1 and CMS γp studies limited to low multiplicities (Up to ~20 particles)

No indication of long-range correlation was found

~ O(1fm)



MPI ≥ 1

ATLAS γPb shows no sign of ridge before subtraction

Next steps: (1) Increase multiplicity

(2) Increase <MPI>

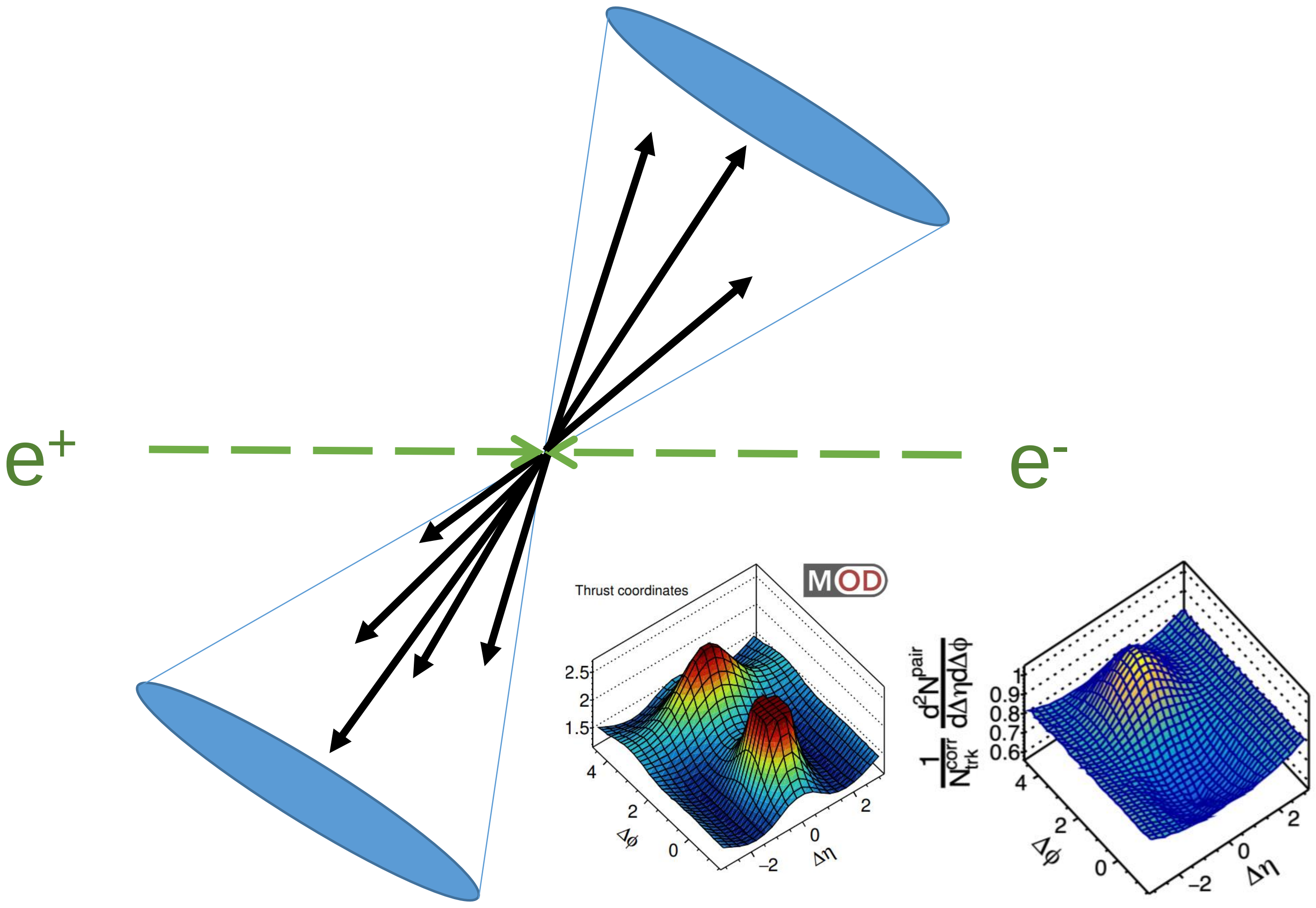
“MPI”=1

<< 0.1 fm

Multiplicity

Can We Overlap Two Color Strings?

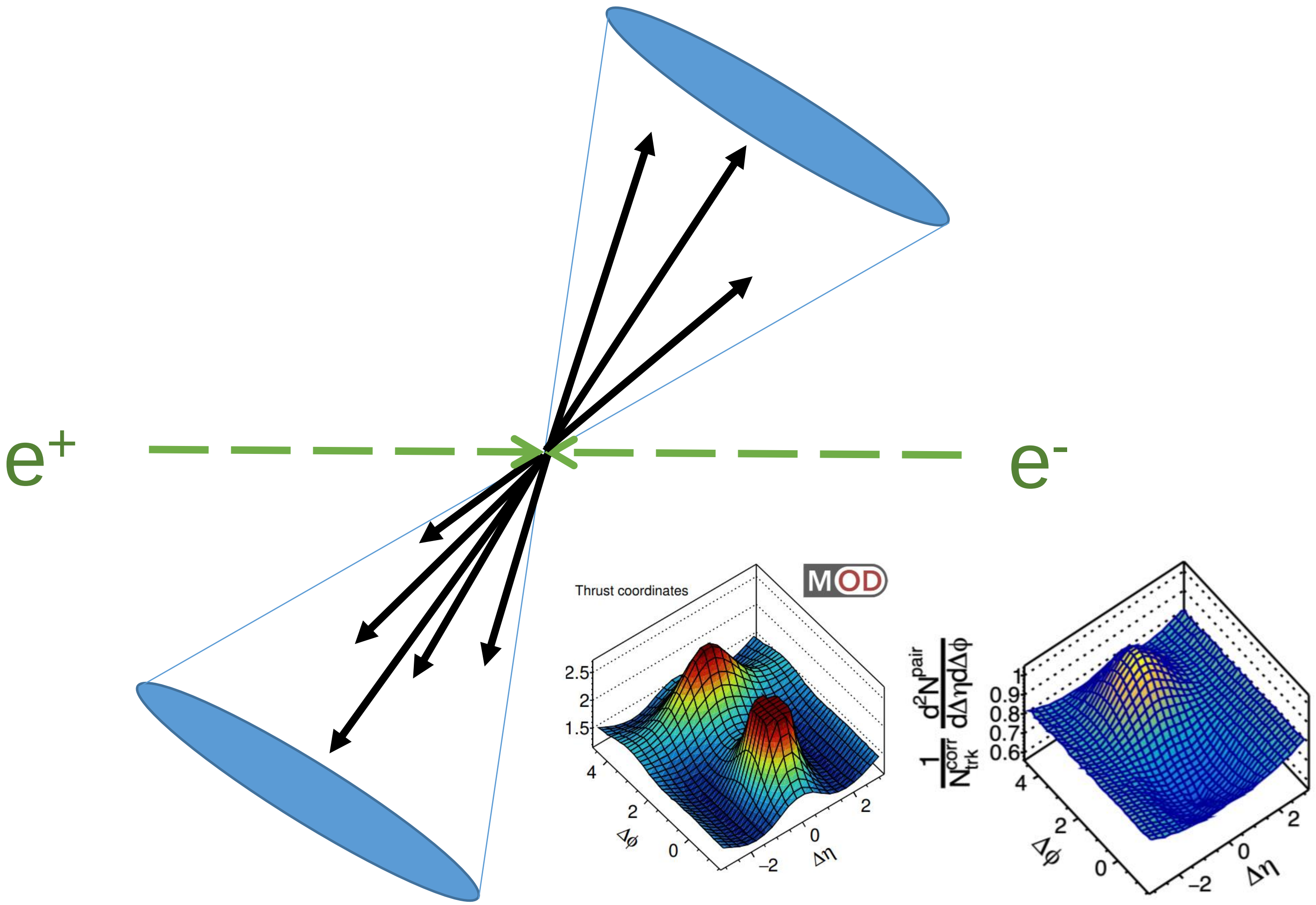
$$e^+e^- \rightarrow q\bar{q}$$



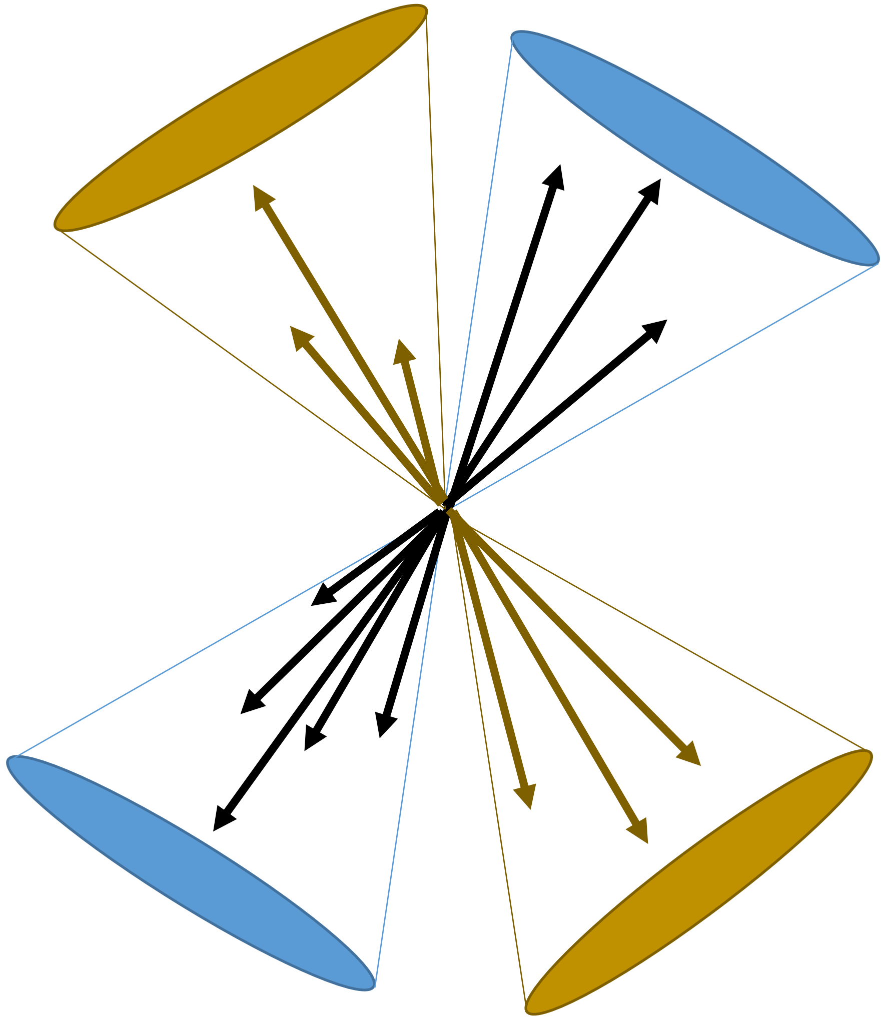
No ridge-like structure

Can We Overlap Two Color Strings?

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



No ridge-like structure

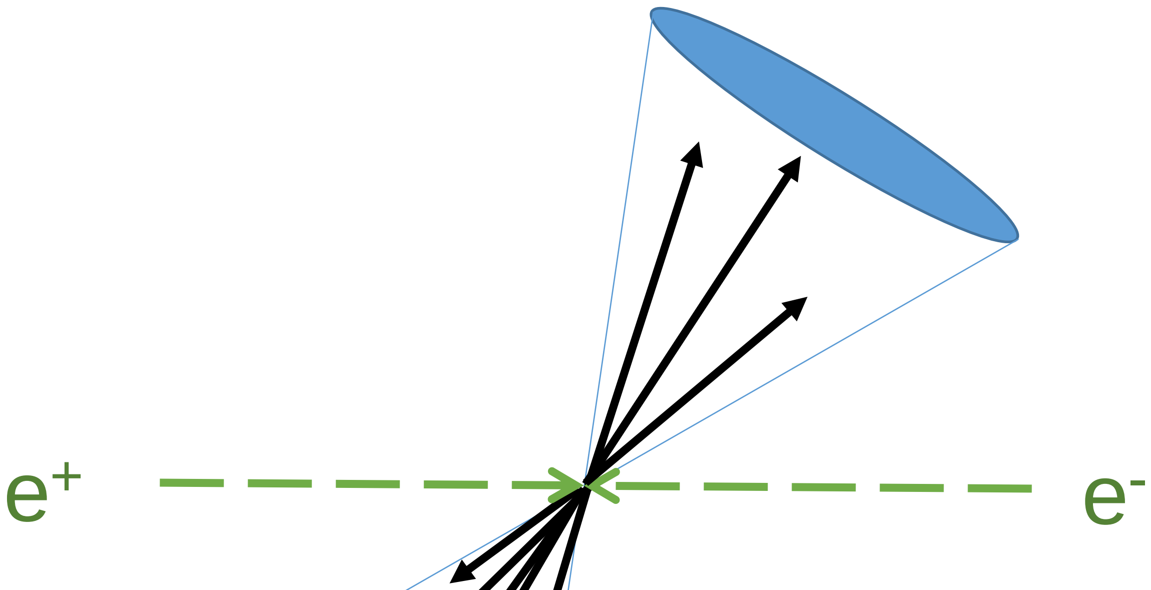


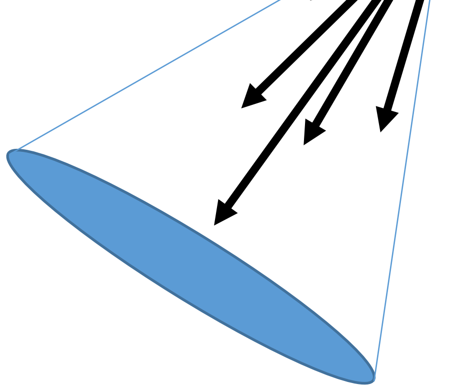
?

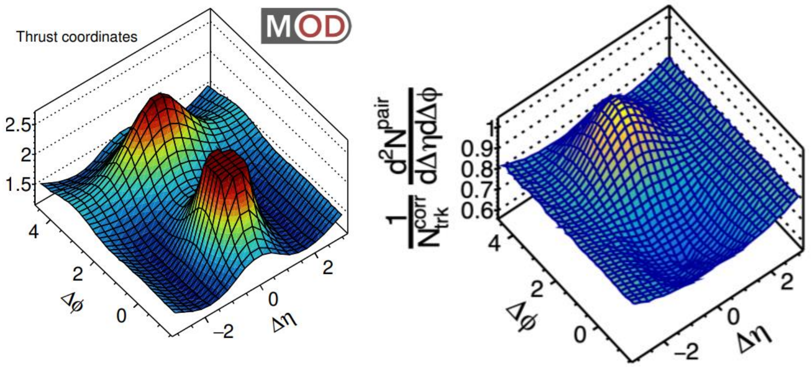
High Multiplicity e^+e^- Event at LEP 2 !!

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

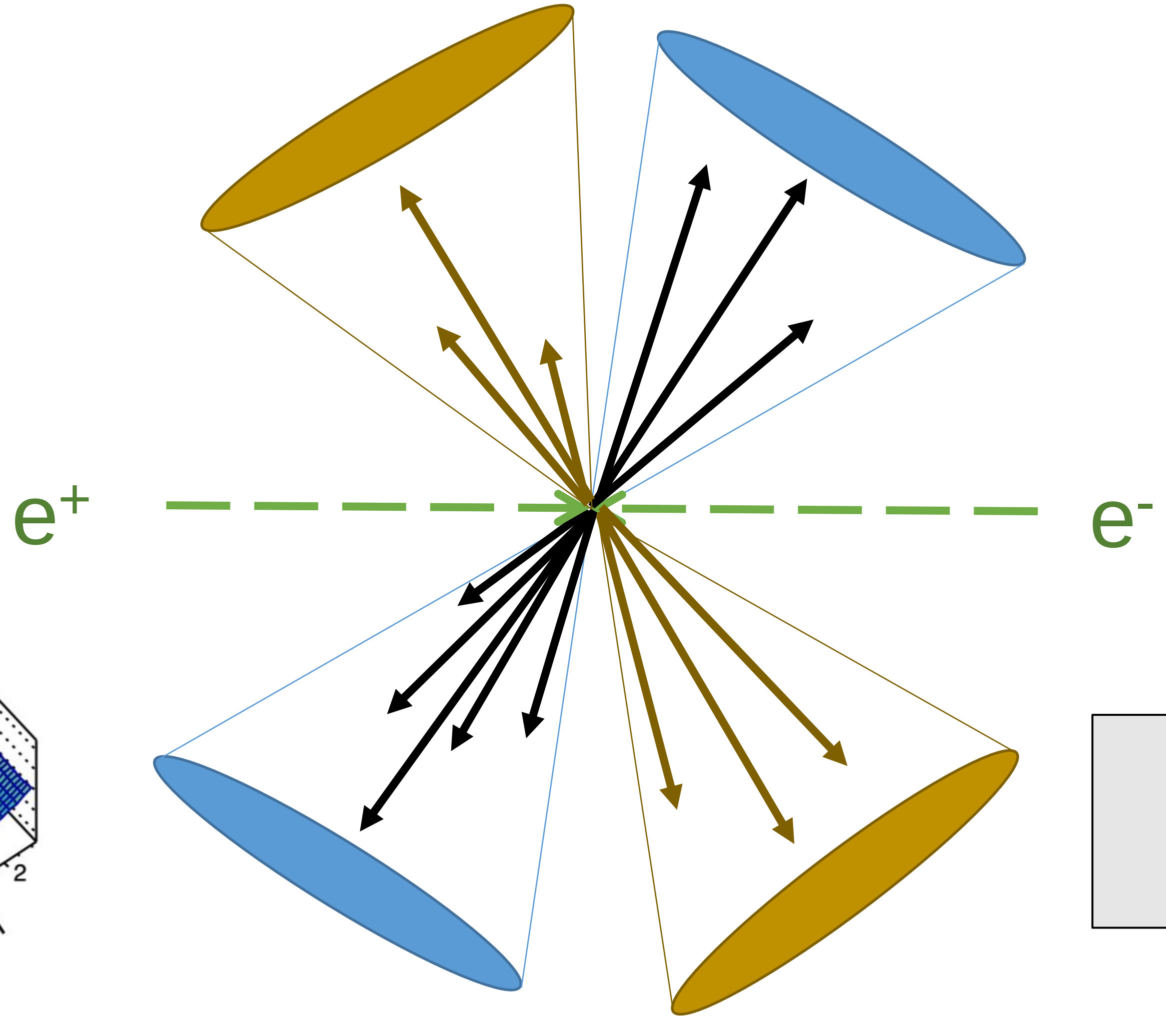
$$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$$







No ridge-like structure



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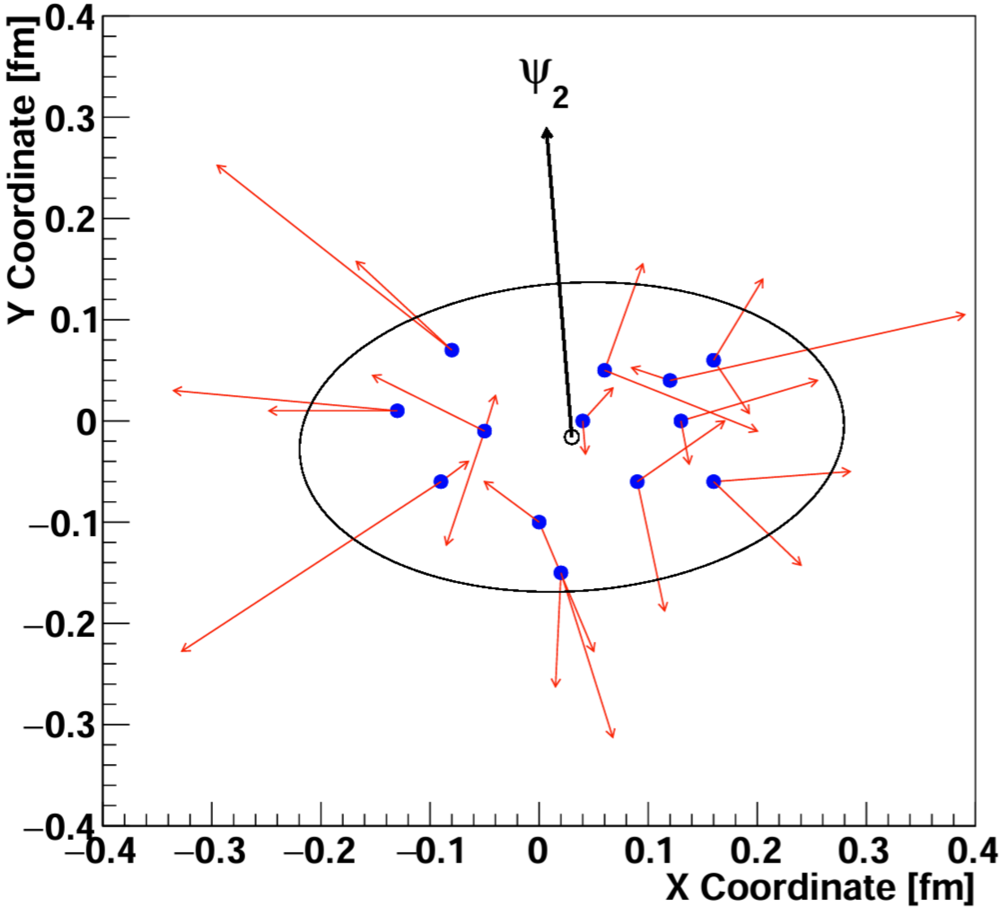
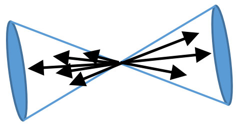
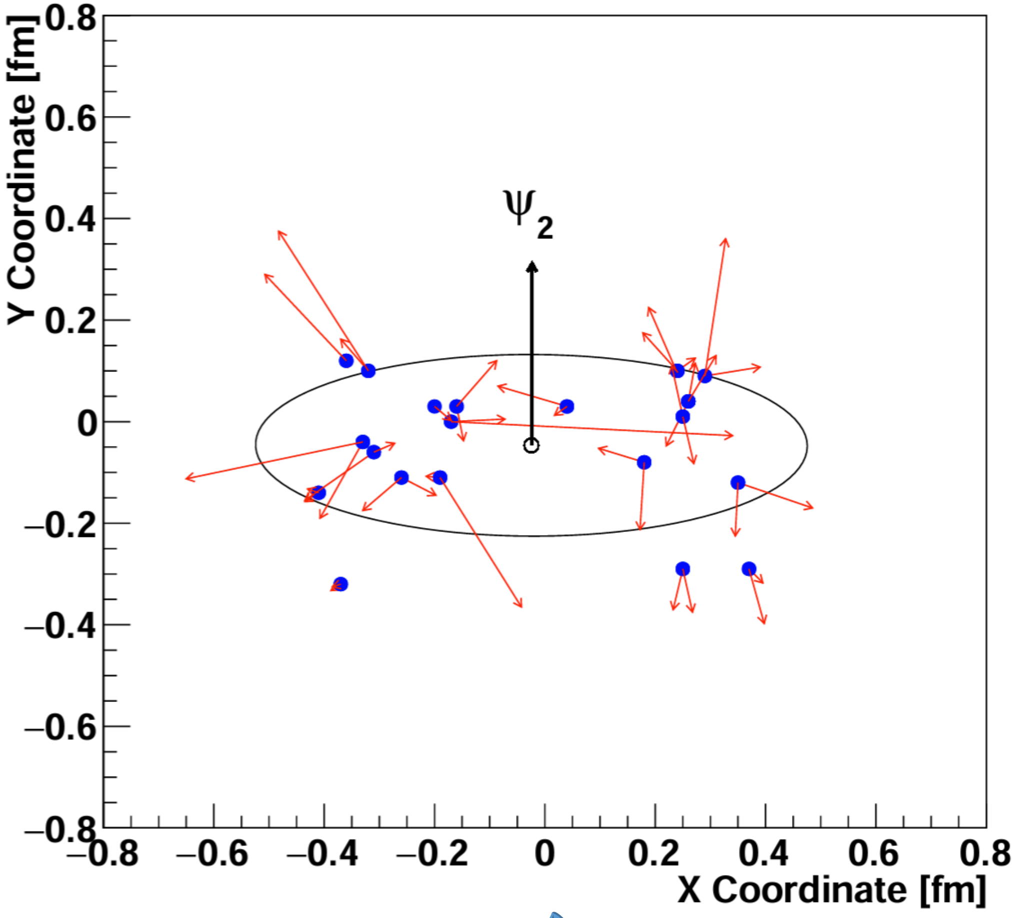
Example Study with AMPT

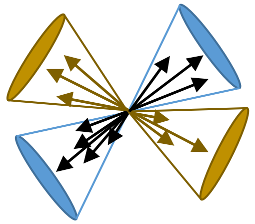
Single-String Configuration





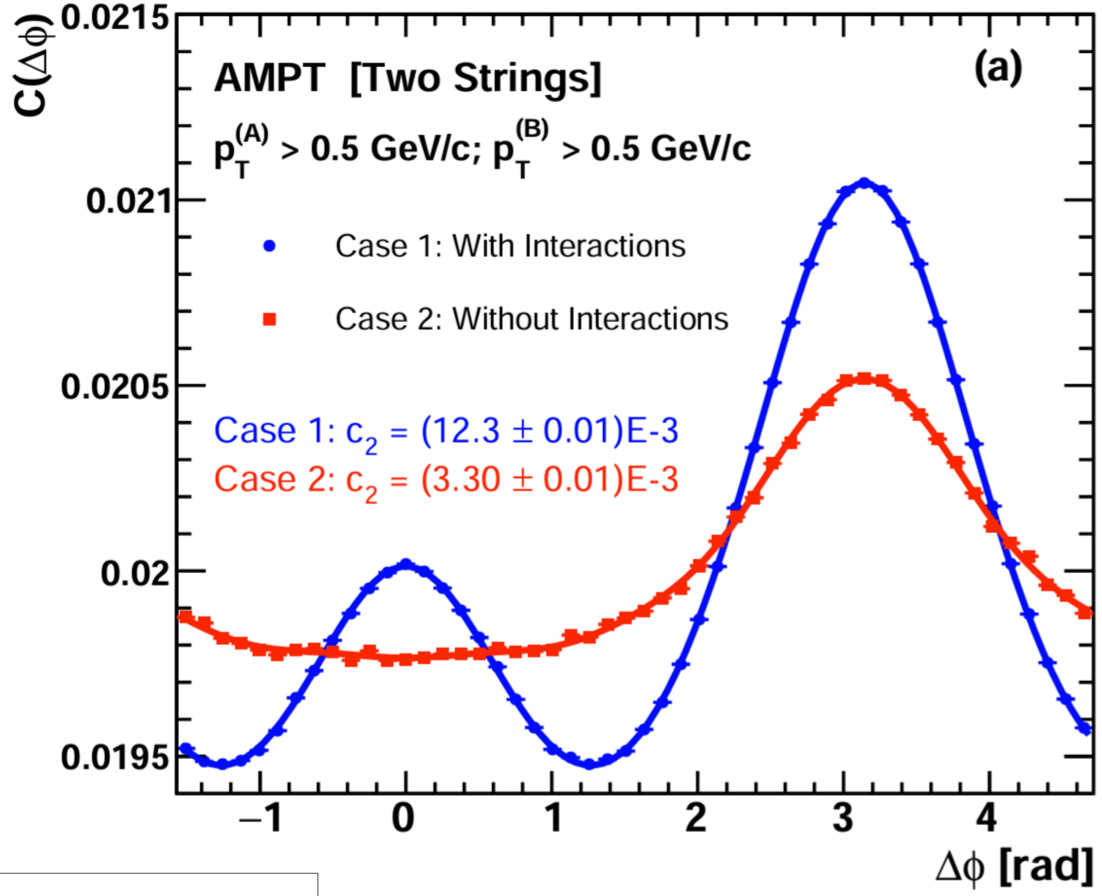
Two-String Configuration

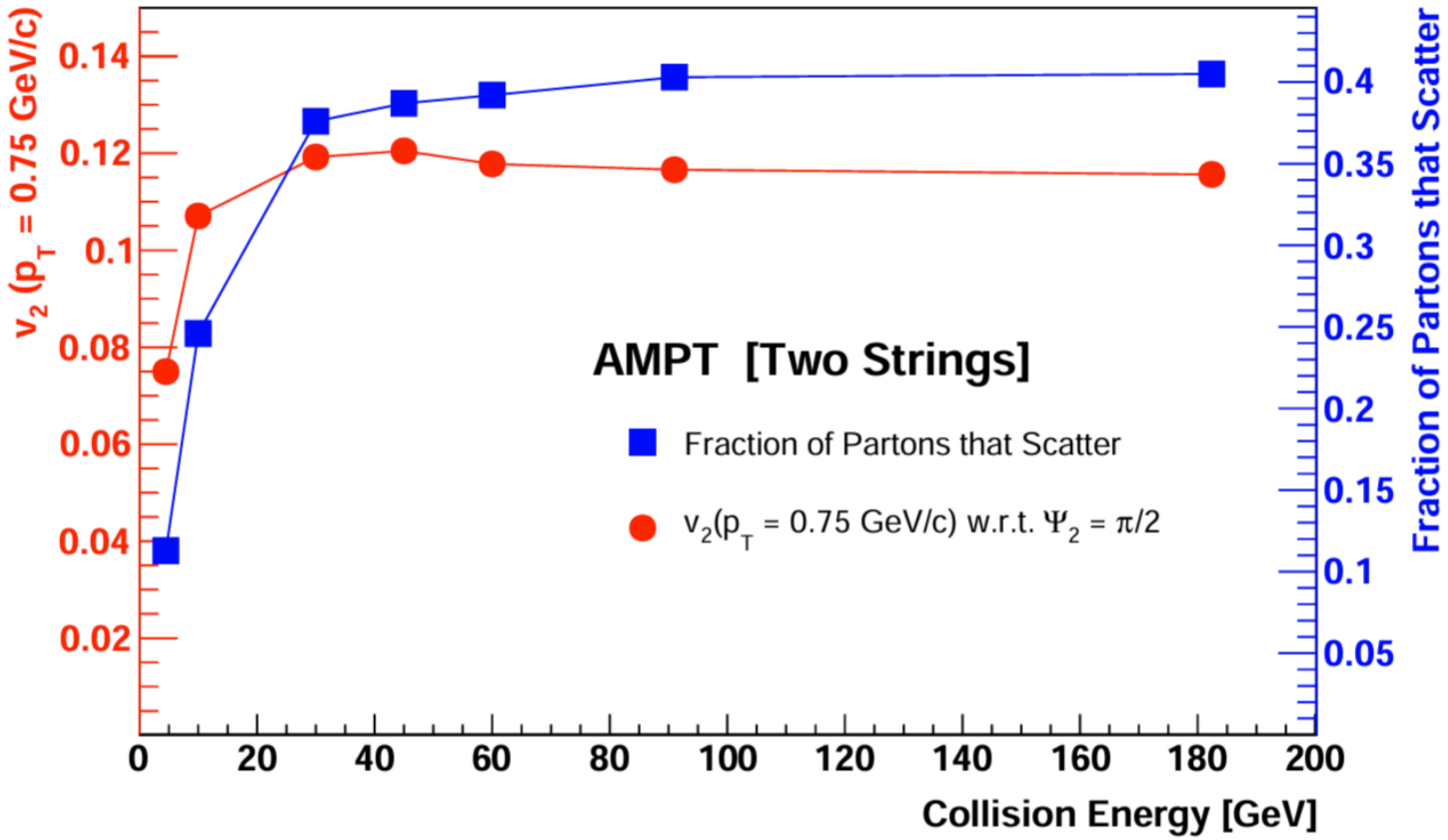


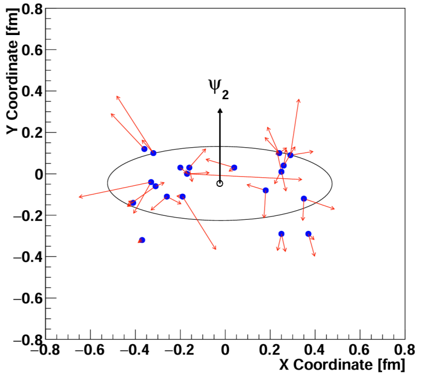


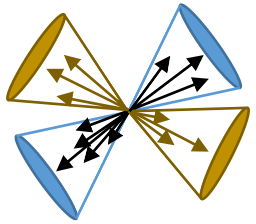
J. Nagle et al, PRC 97 (2018) 2, 024909

Example: Two Strings Configuration Study with AMPT







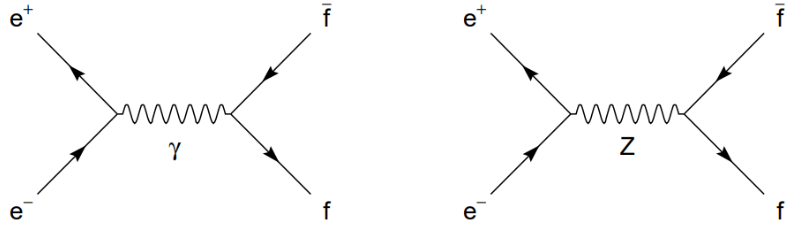


- With Interaction: A significant enhancement of v_2
- Little change in terms of v_3 magnitude (from a Fourier decomposition fit to the data in the figure)

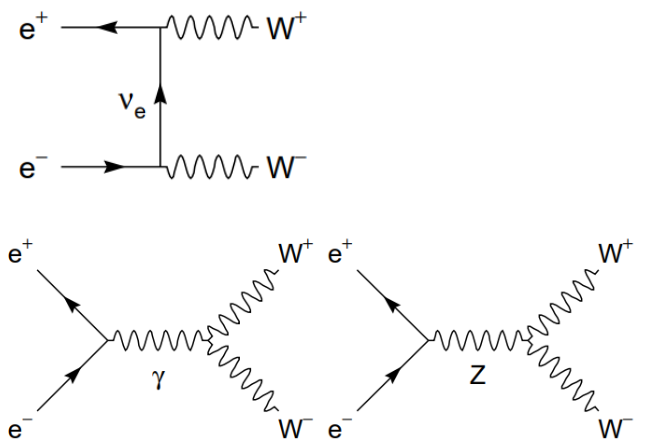
J. Nagle et al, PRC 97 (2018) 2, 024909

Charged Particle Multiplicity Distributions in LEP2 Data

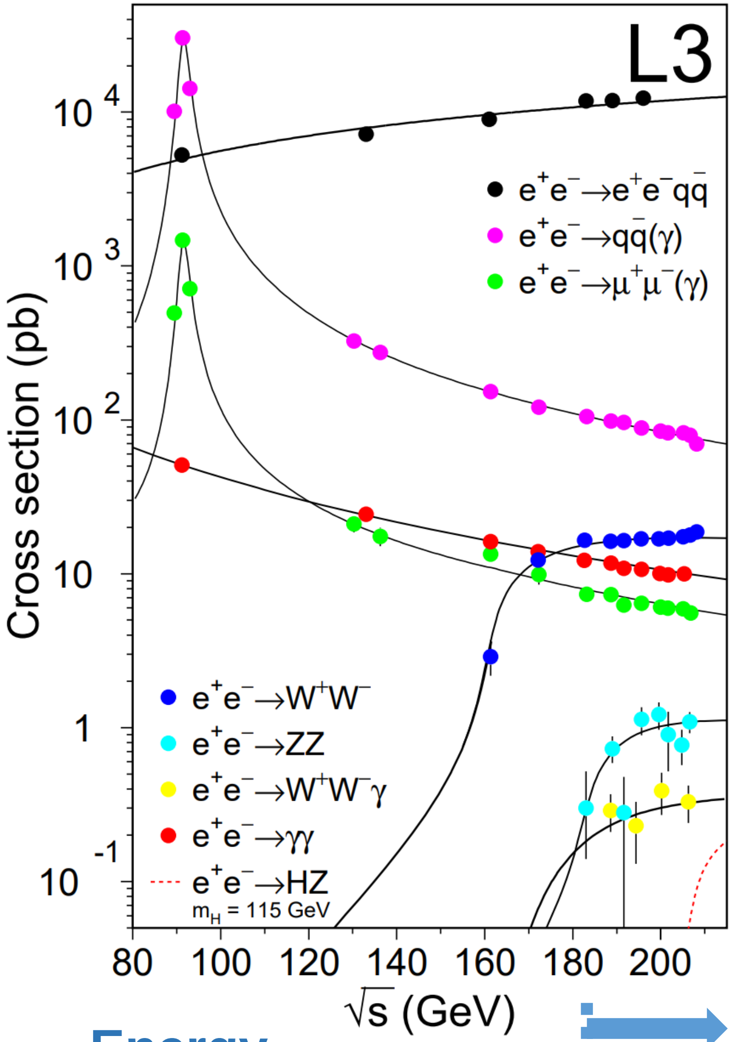
- $e^+e^- \rightarrow q\bar{q}(\gamma)$



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



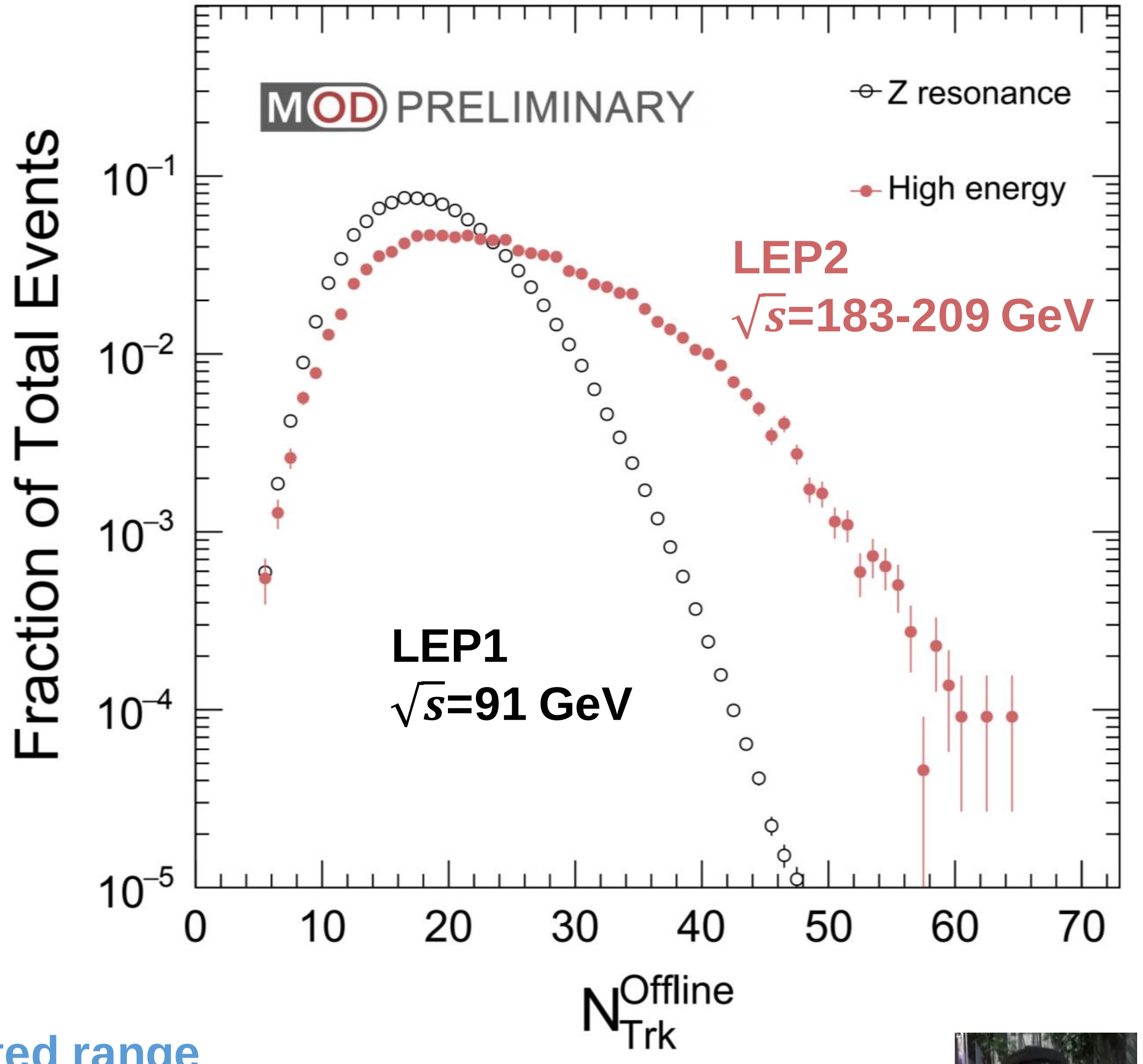
Phys. Rept. 532 (2013) 119-244



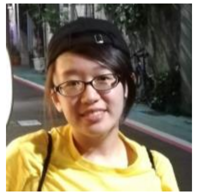
Energy

EPJC 63 611 (2009)

Reported range



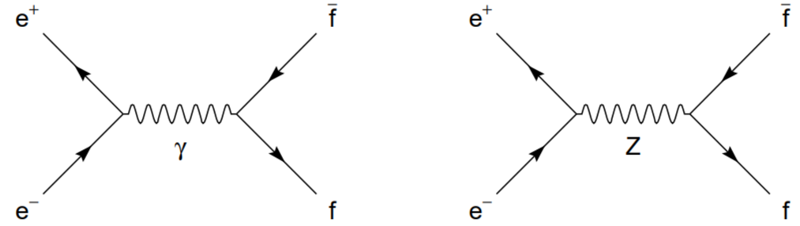
- **LEP2 energies** also give access to different physics processes



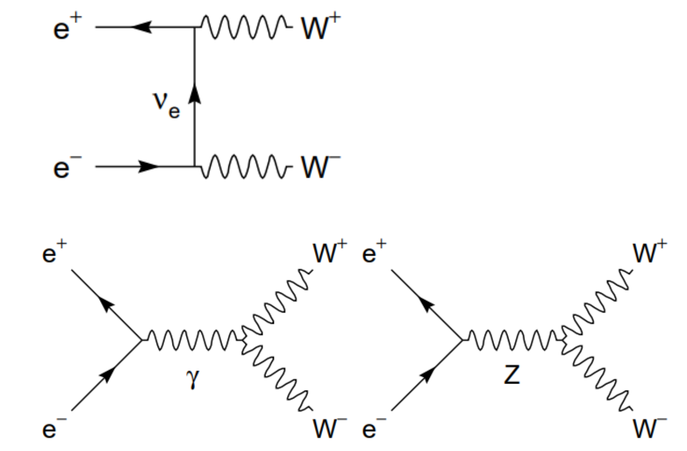
Yu-Chen "Janice" Chen (MIT)

Charged Particle Multiplicity Distributions in LEP2 Data

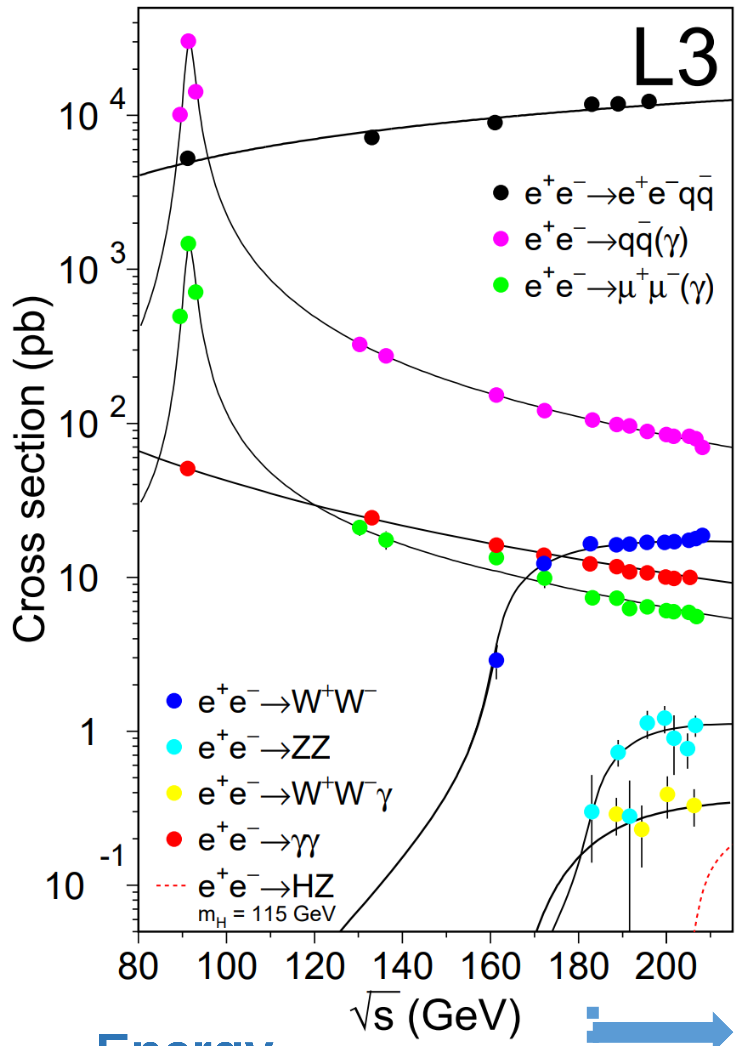
● $e^+e^- \to q\bar{q}(\gamma)$



● $e^+e^- \to W^+W^-$



Phys. Rept. 532 (2013) 119-244



Energy

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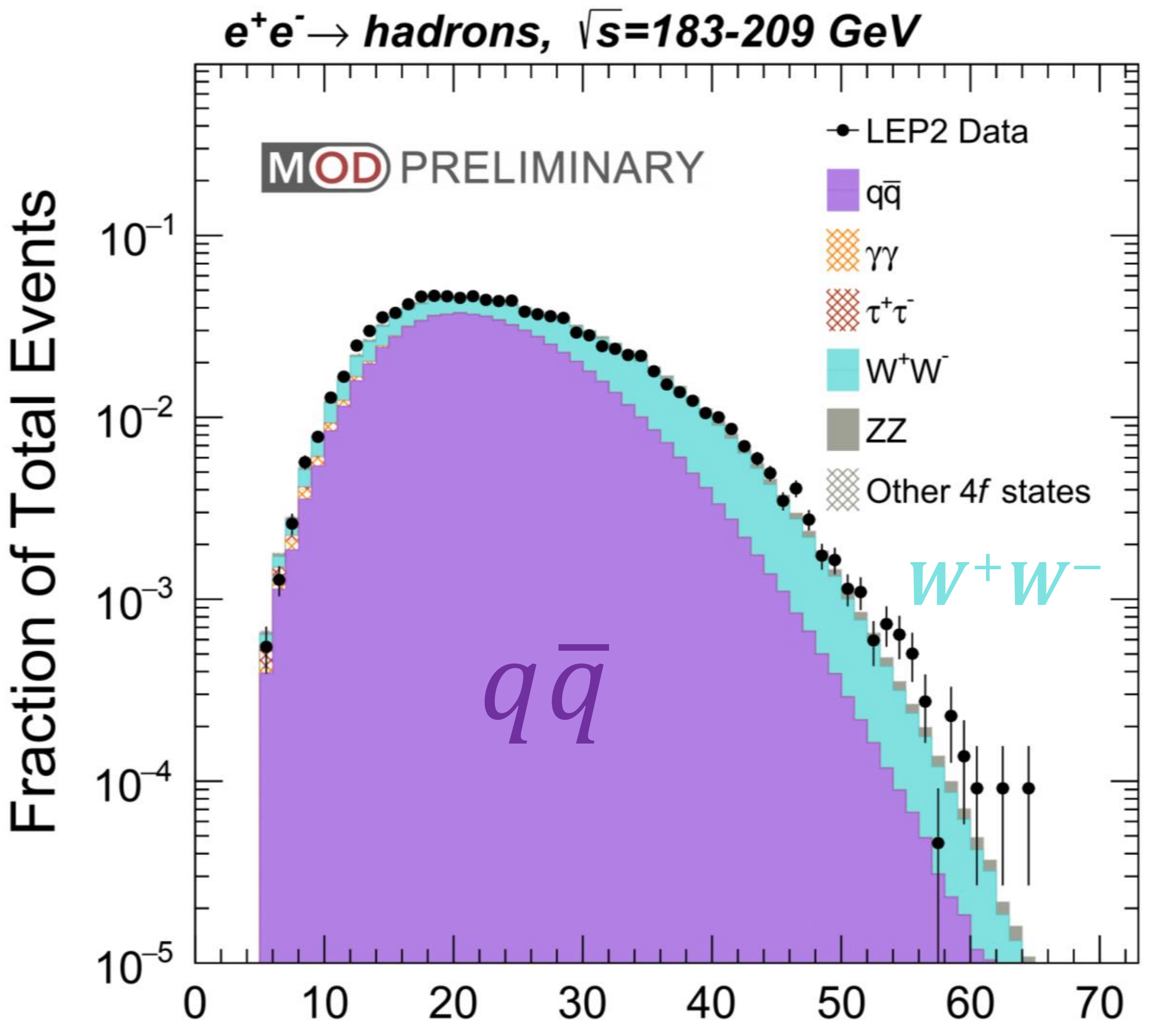
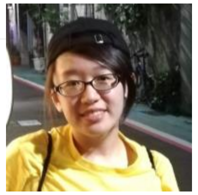
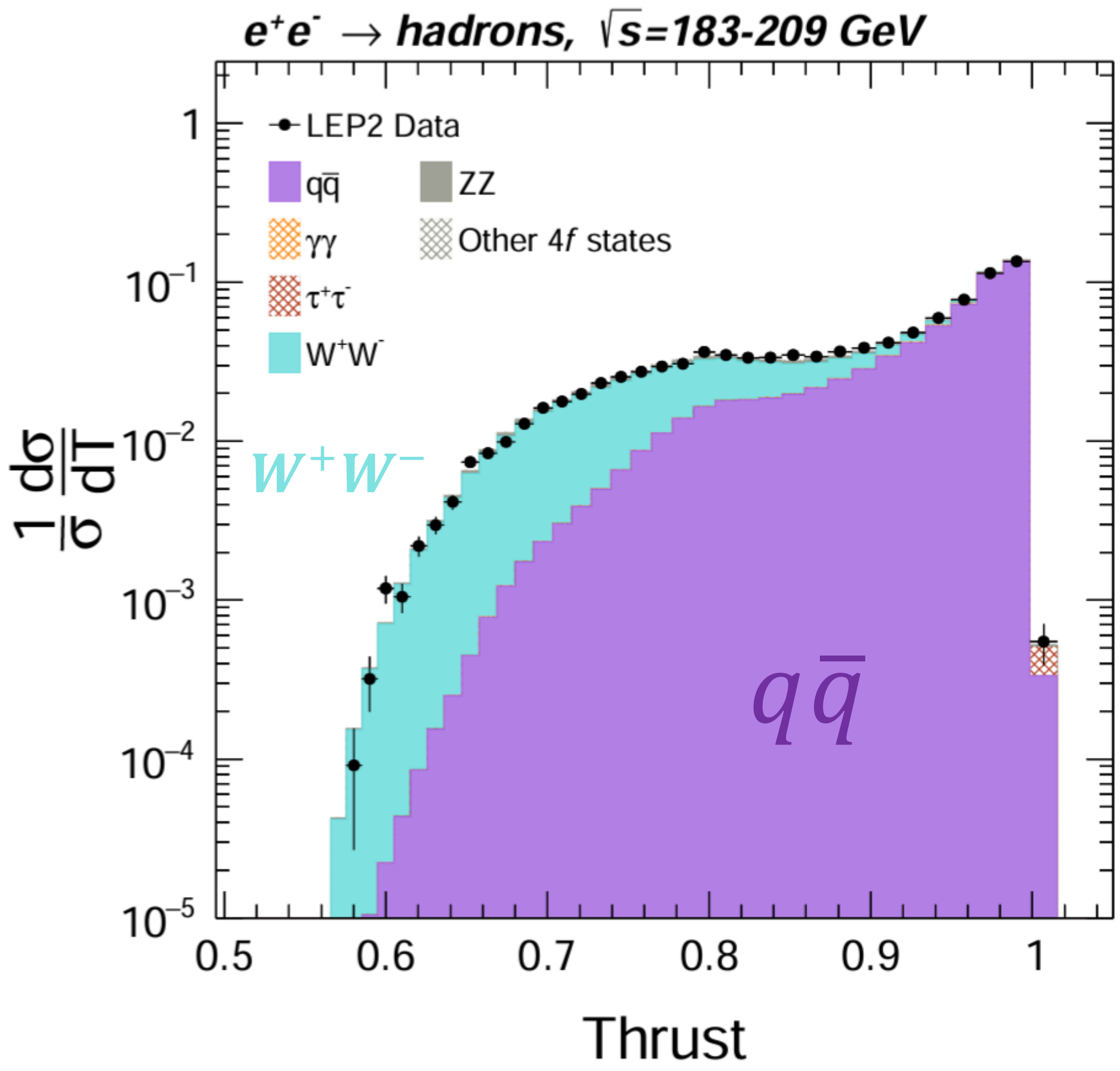


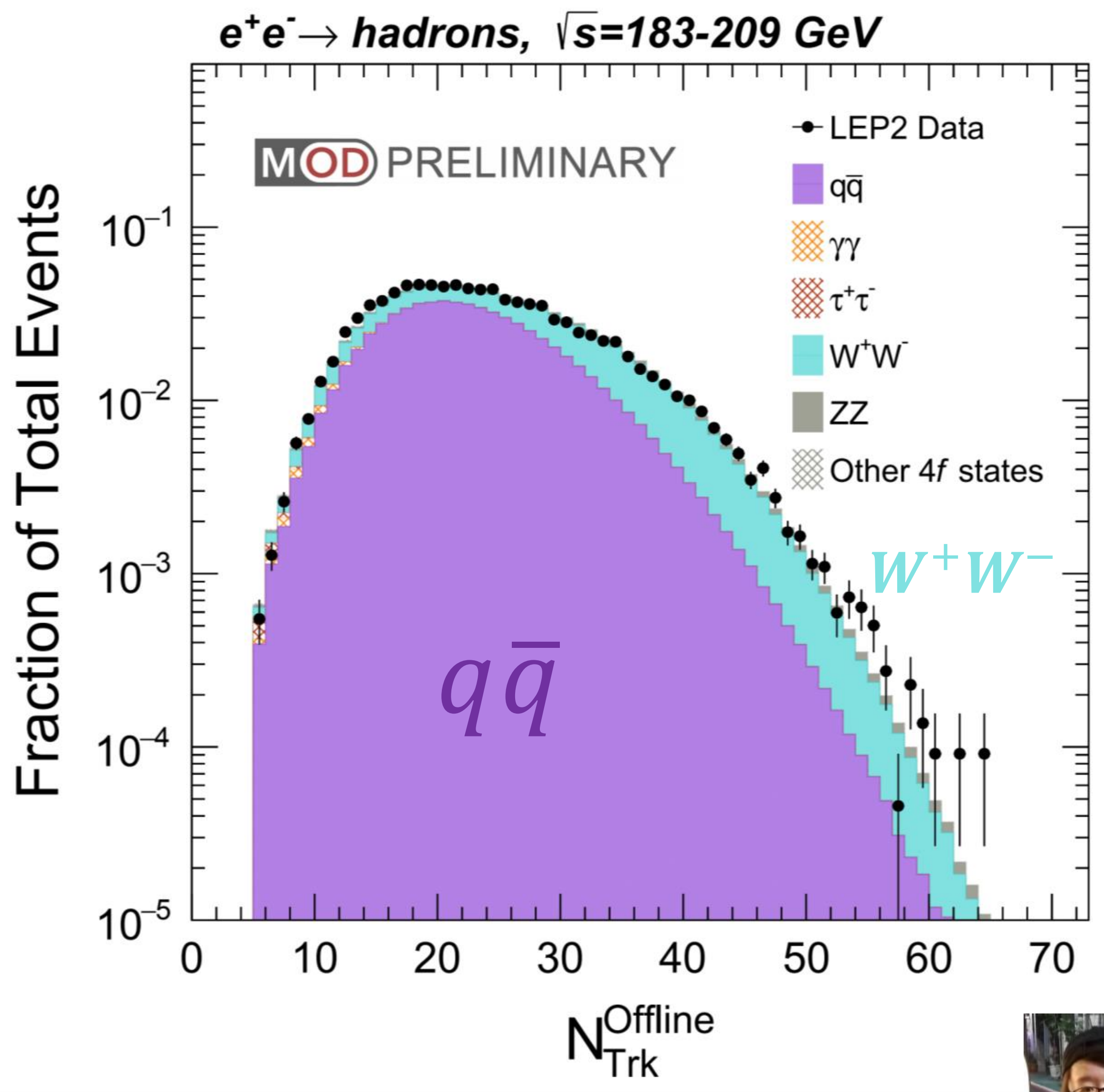


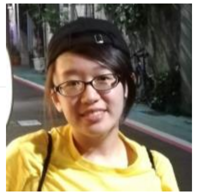
Yu-Chen "Janice" Chen (MIT)

- **LEP2 energies** also give access to different physics processes
- At high multiplicity, W^+W^- contribution becomes significant

Example validation study of archived data and MC



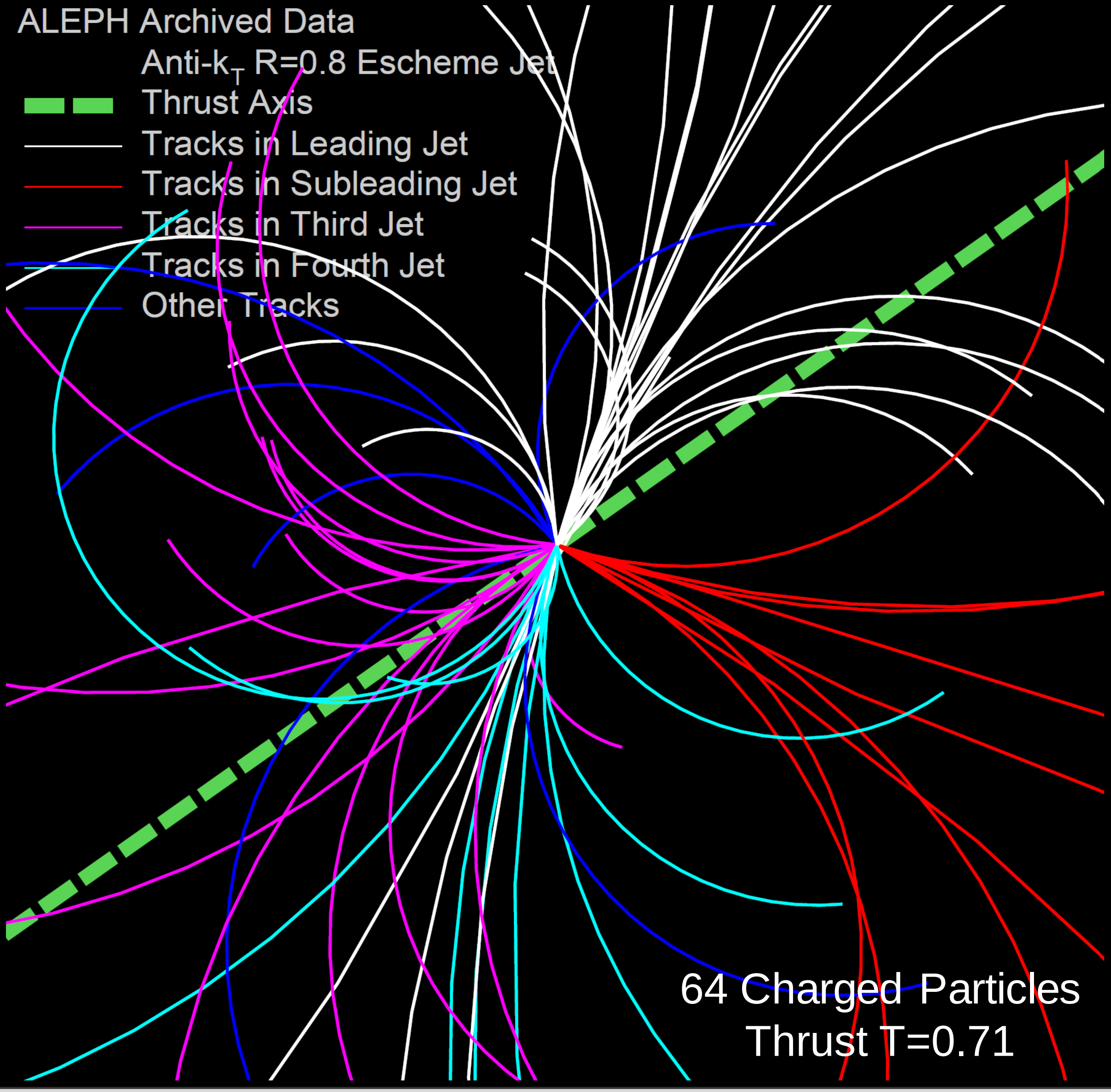


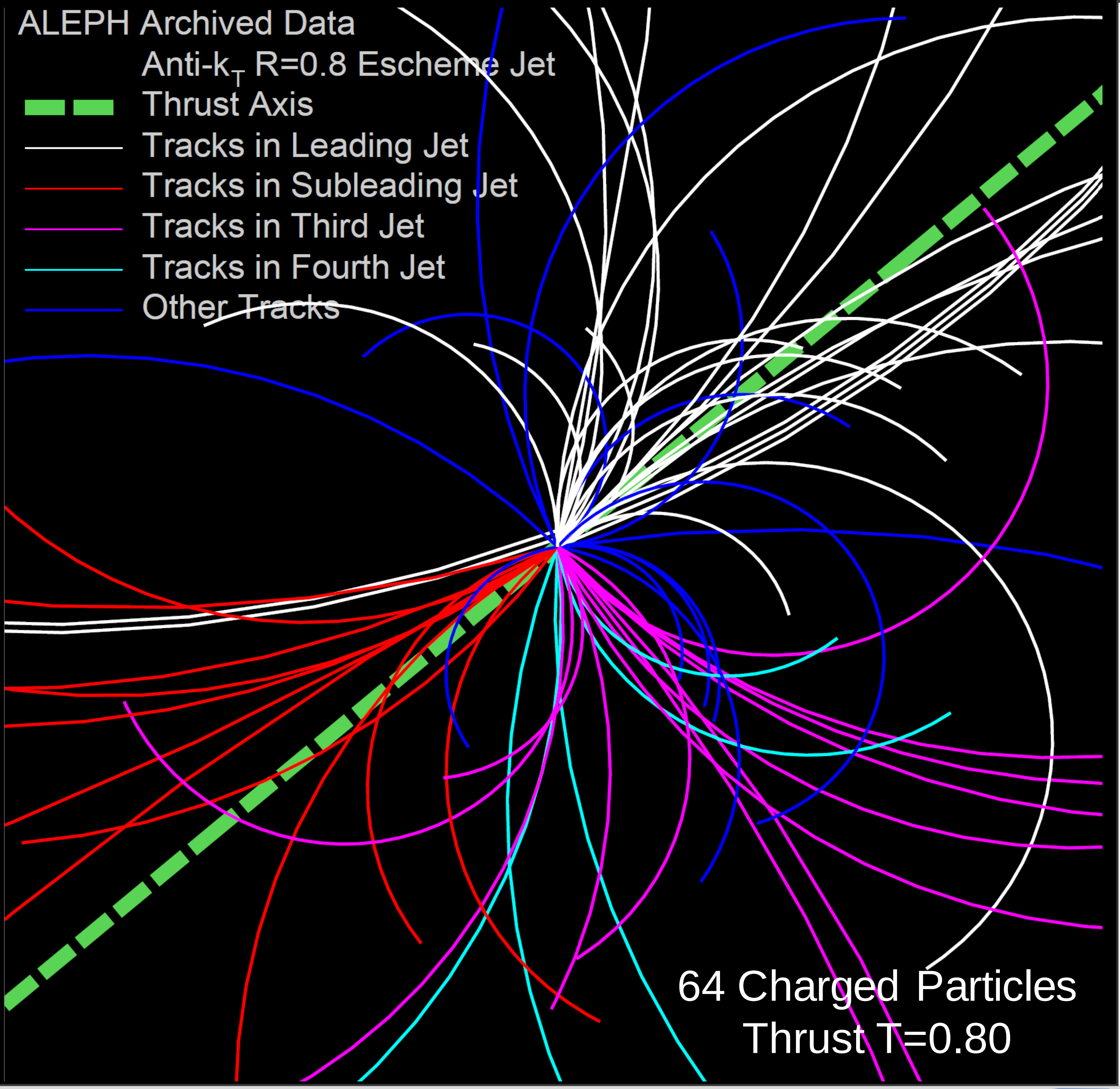


Yu-Chen “Janice” Chen (MIT)

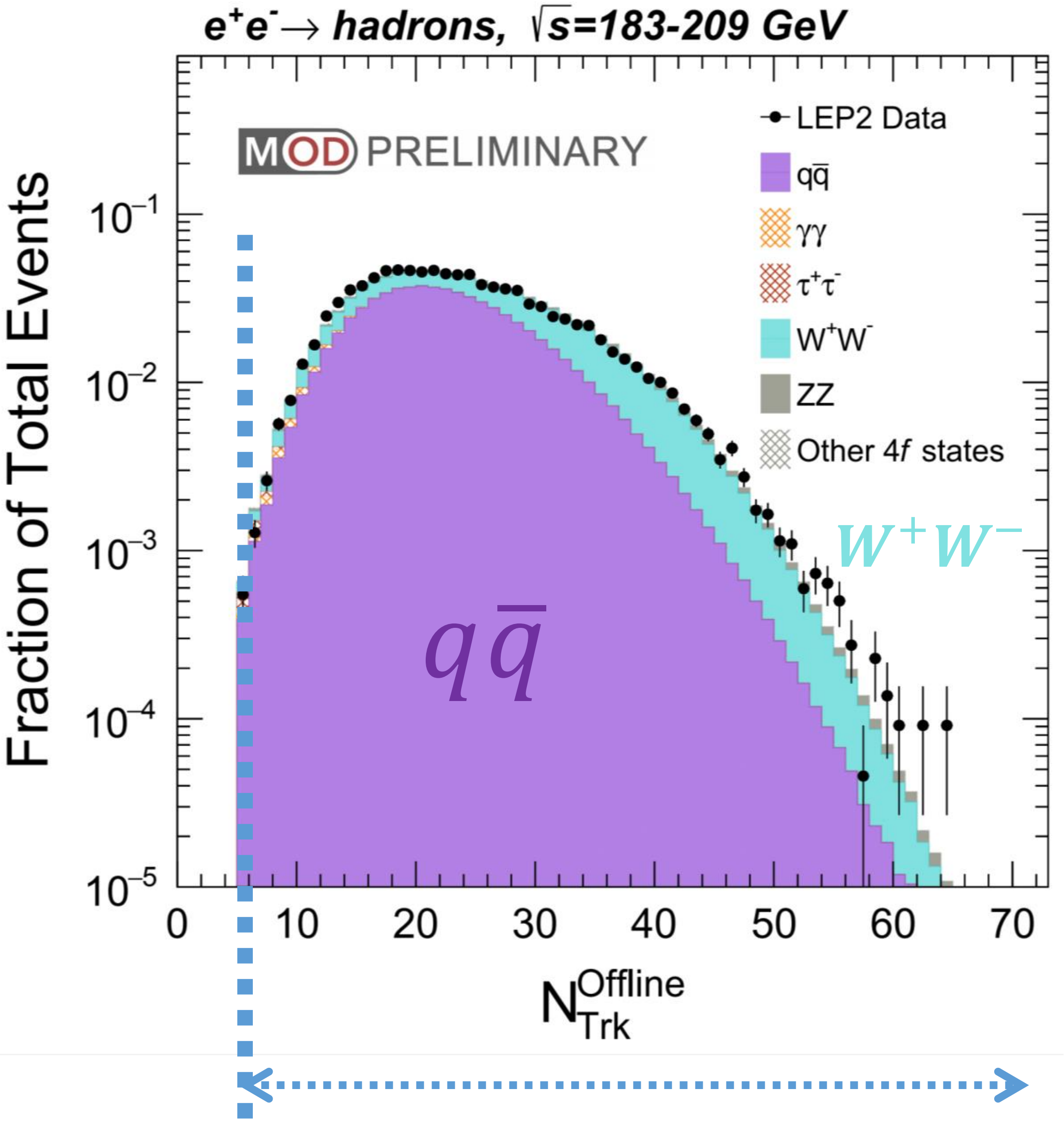
- Inspected thrust distributions (shown) and many other control plots (visible energies) year-by-year.
- Reasonable agreement between data and archived MC.

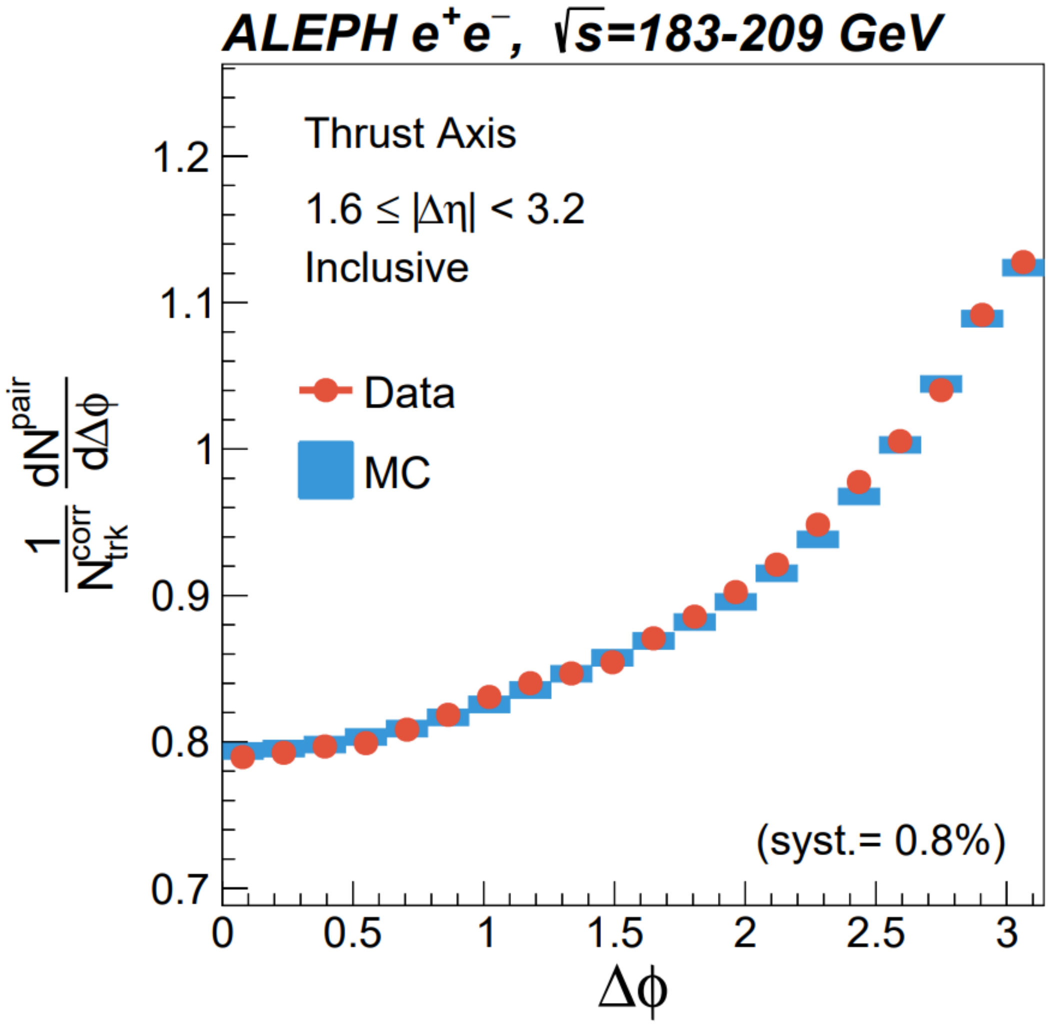
The Highest Multiplicity Events in Archived LEP2 Data

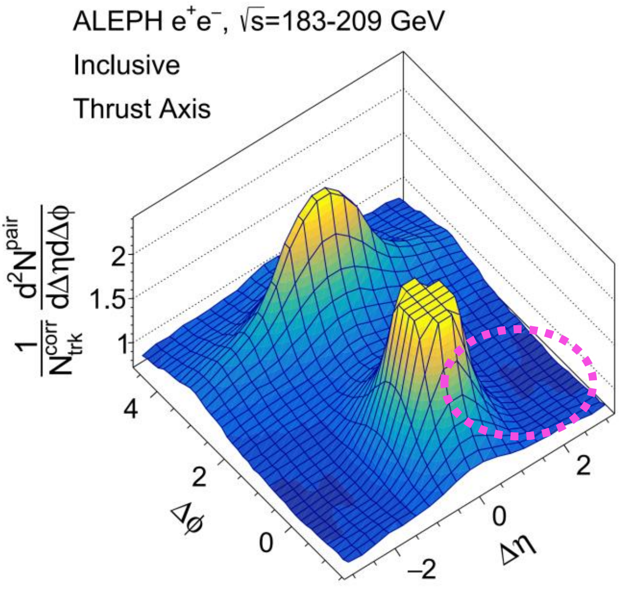


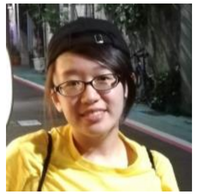


Inclusive Hadronic e^+e^- Events at LEP 2 ($N_{ch} \geq 5$)







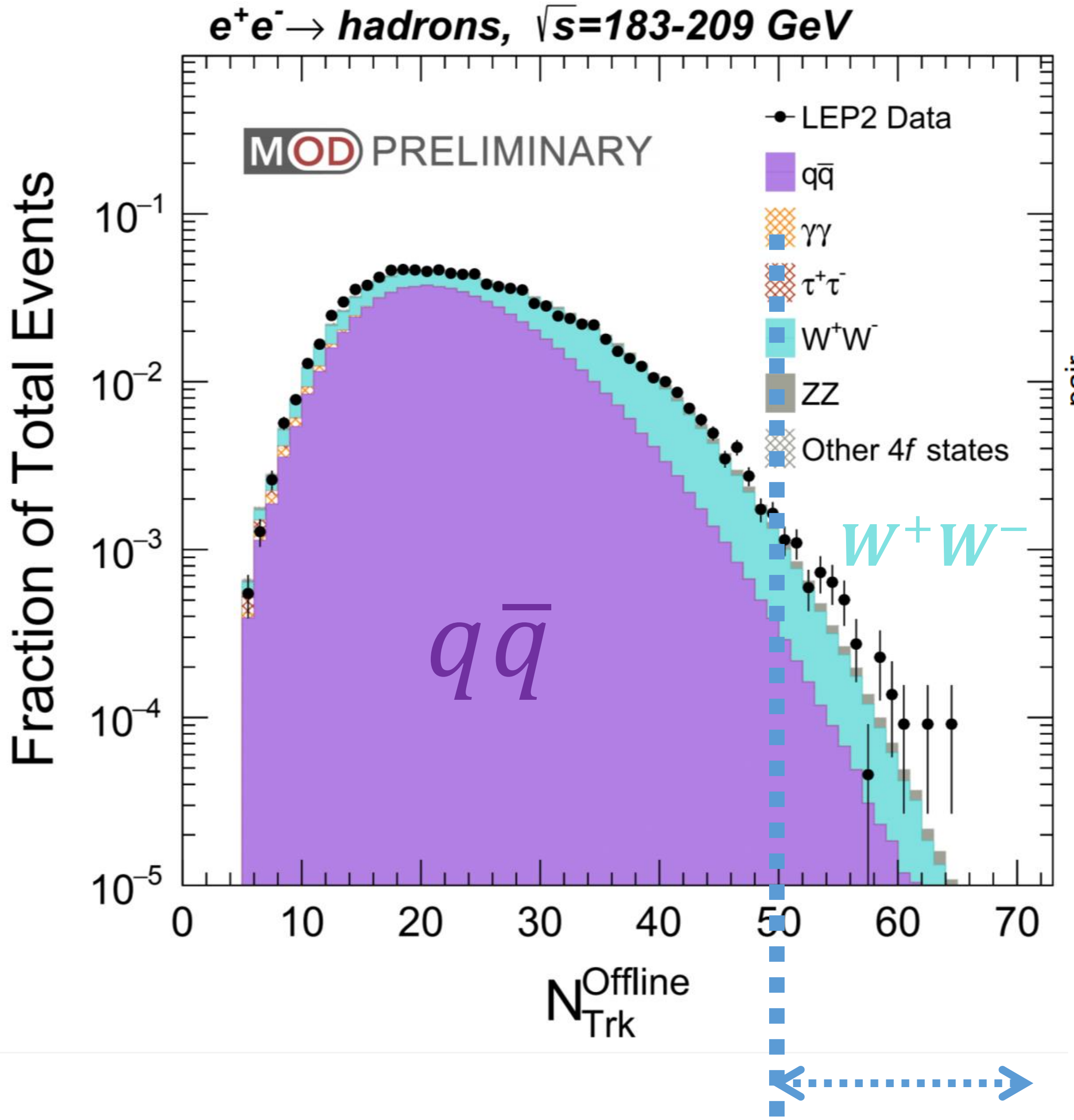


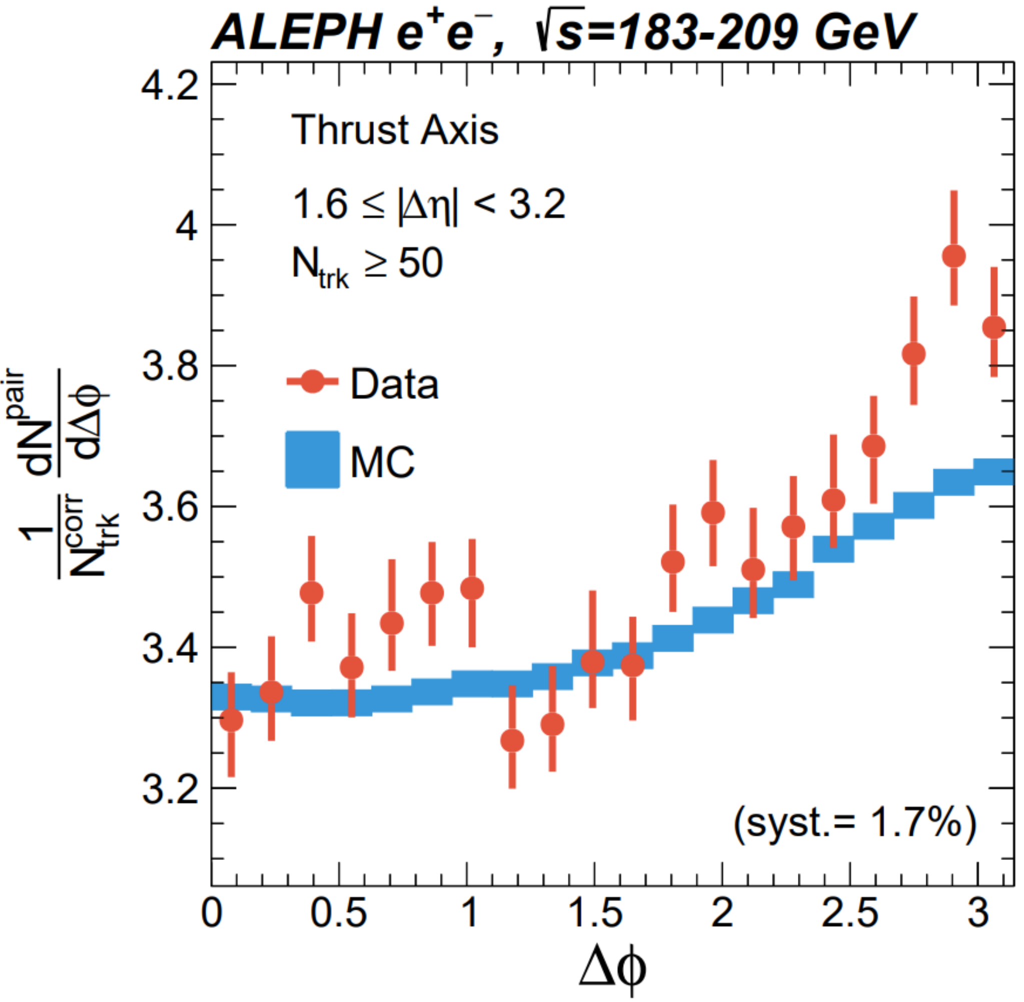
Yu-Chen "Janice" Chen (MIT)

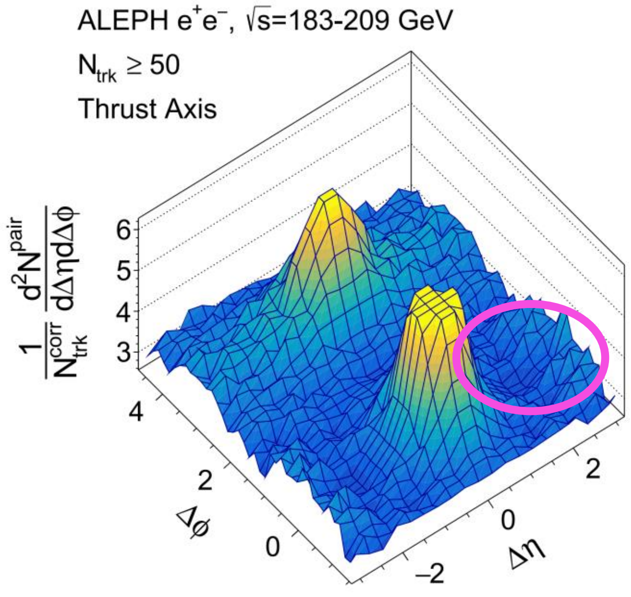
- Excellent agreement between **data** and **simulation (Archived MC)**

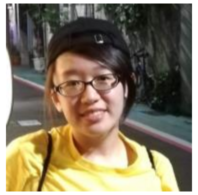
arXiv:2312.05084

High Multiplicity e^+e^- Events at LEP 2 ($N_{trk} \geq 50$)









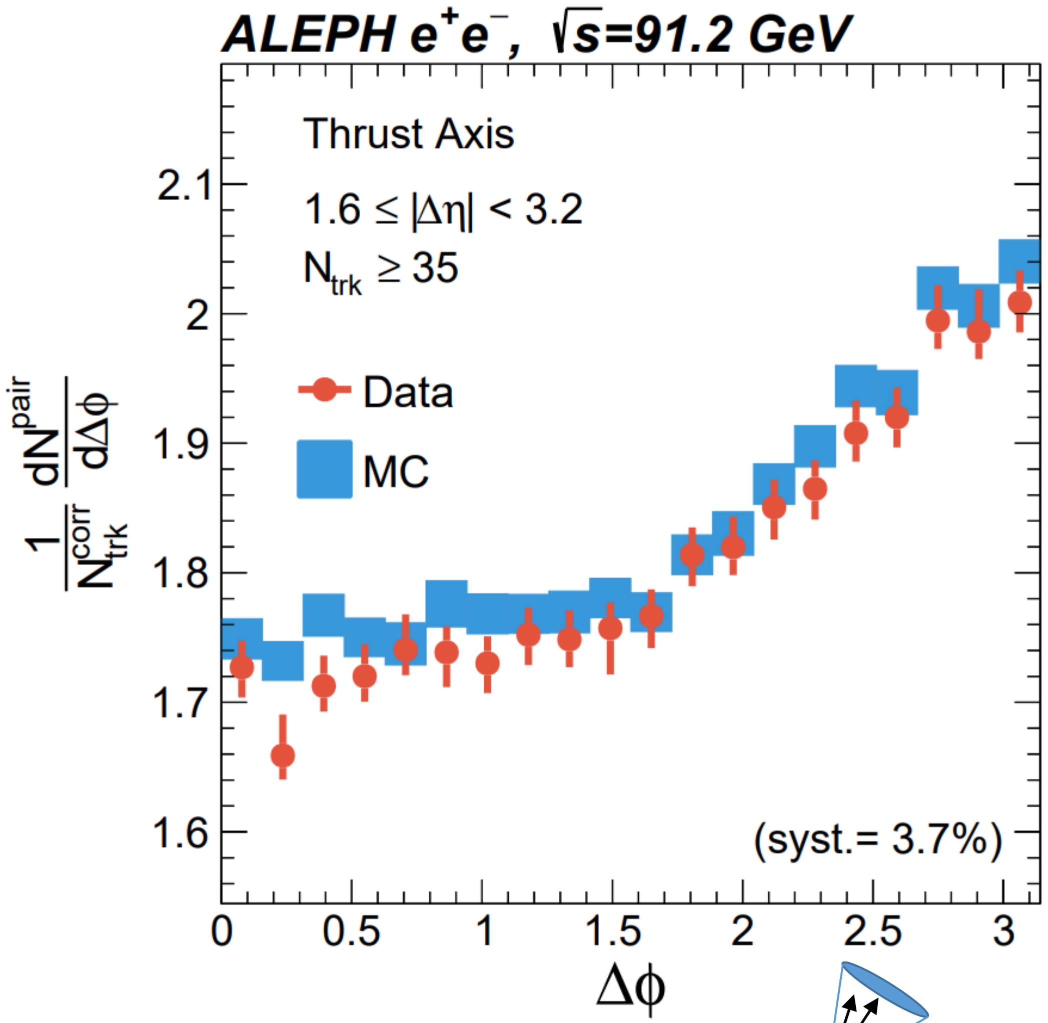
Yu-Chen "Janice" Chen (MIT)

- A long-range near-side correlation signal shows up at high multiplicity!
- Data also feature a narrower away-side spectrum at $\Delta\phi \sim \pi$

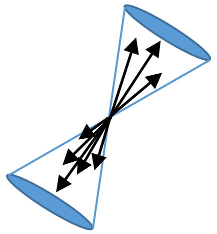
arXiv:2312.05084

High Multiplicity e^+e^- Events at LEP1 vs LEP 2

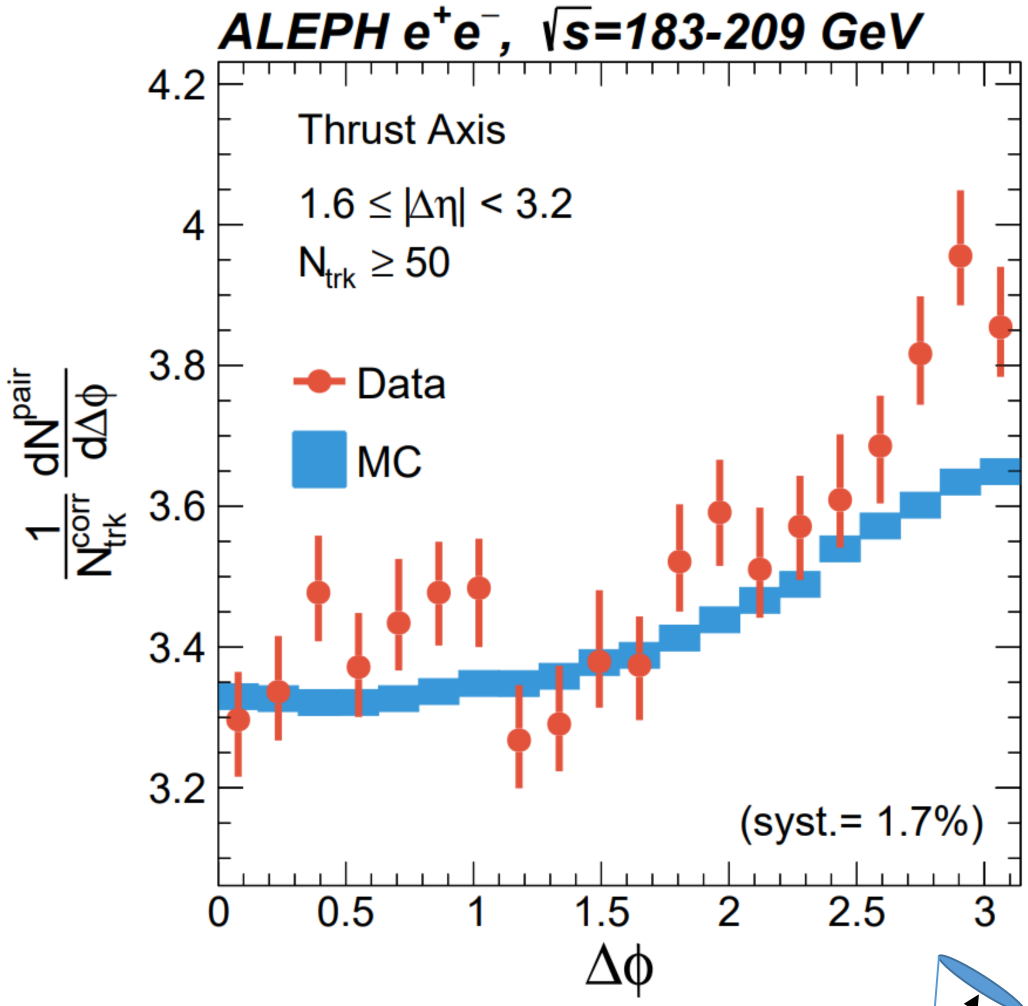
LEP1 N_{trk}>35



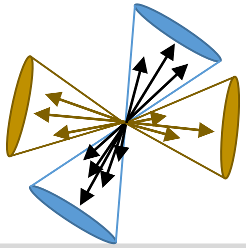
$e^+e^- \rightarrow q\bar{q}(\gamma)$

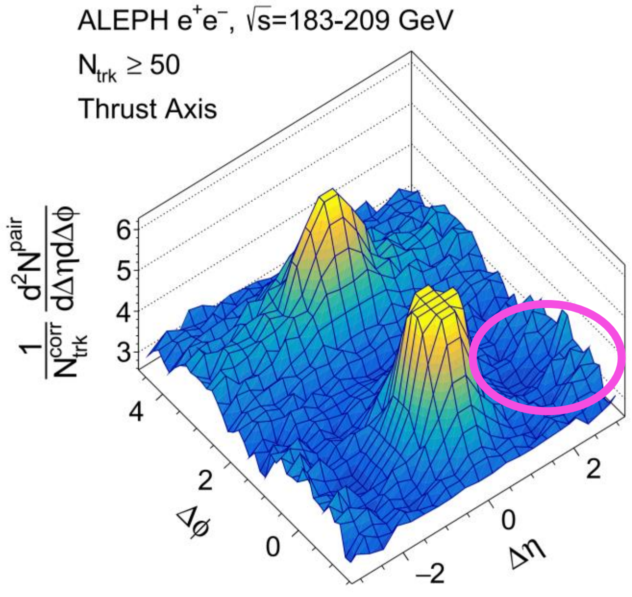


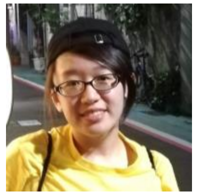
LEP2 N_{trk}>50



$e^+e^- \rightarrow W^+W^-$ enriched



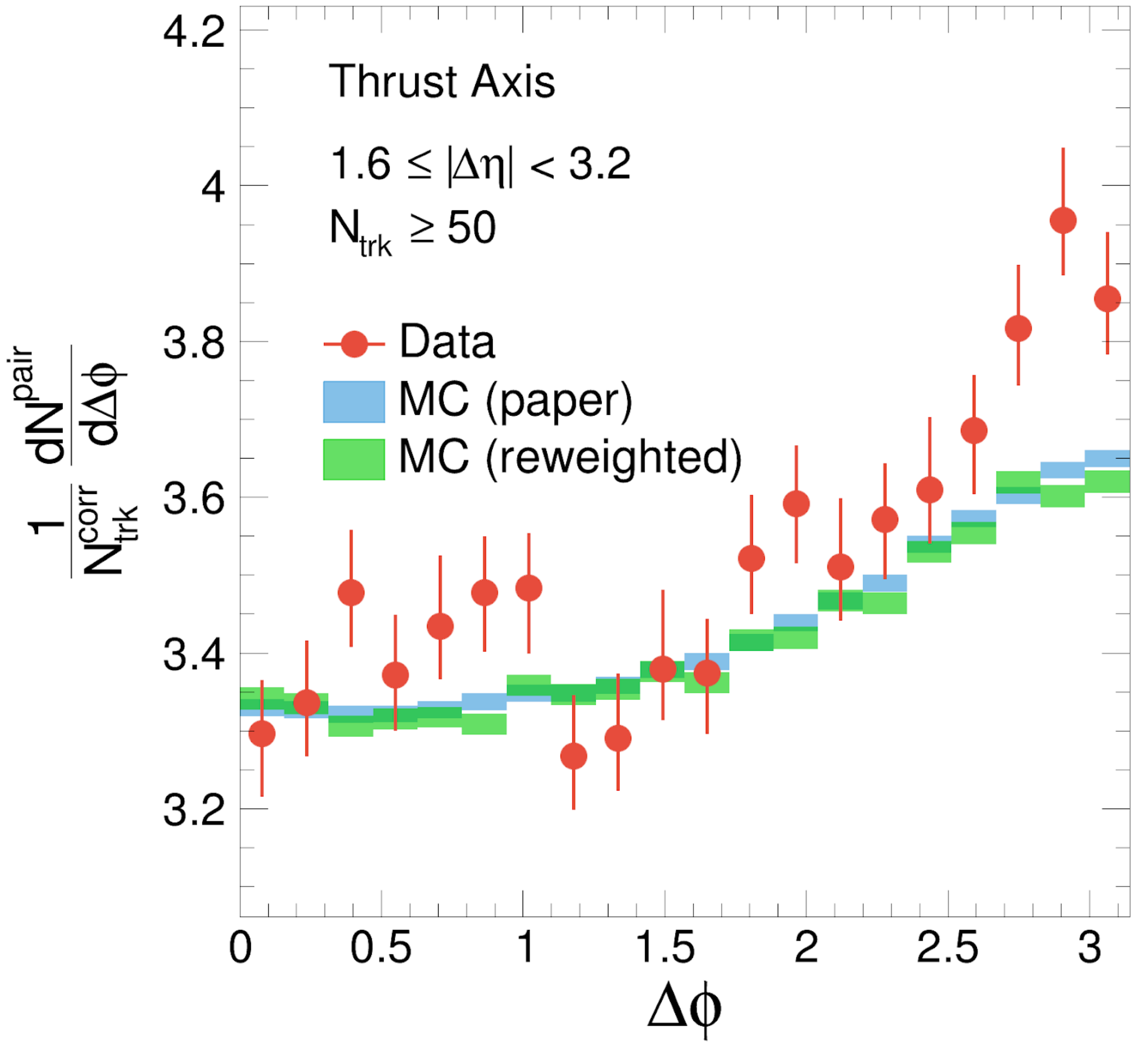


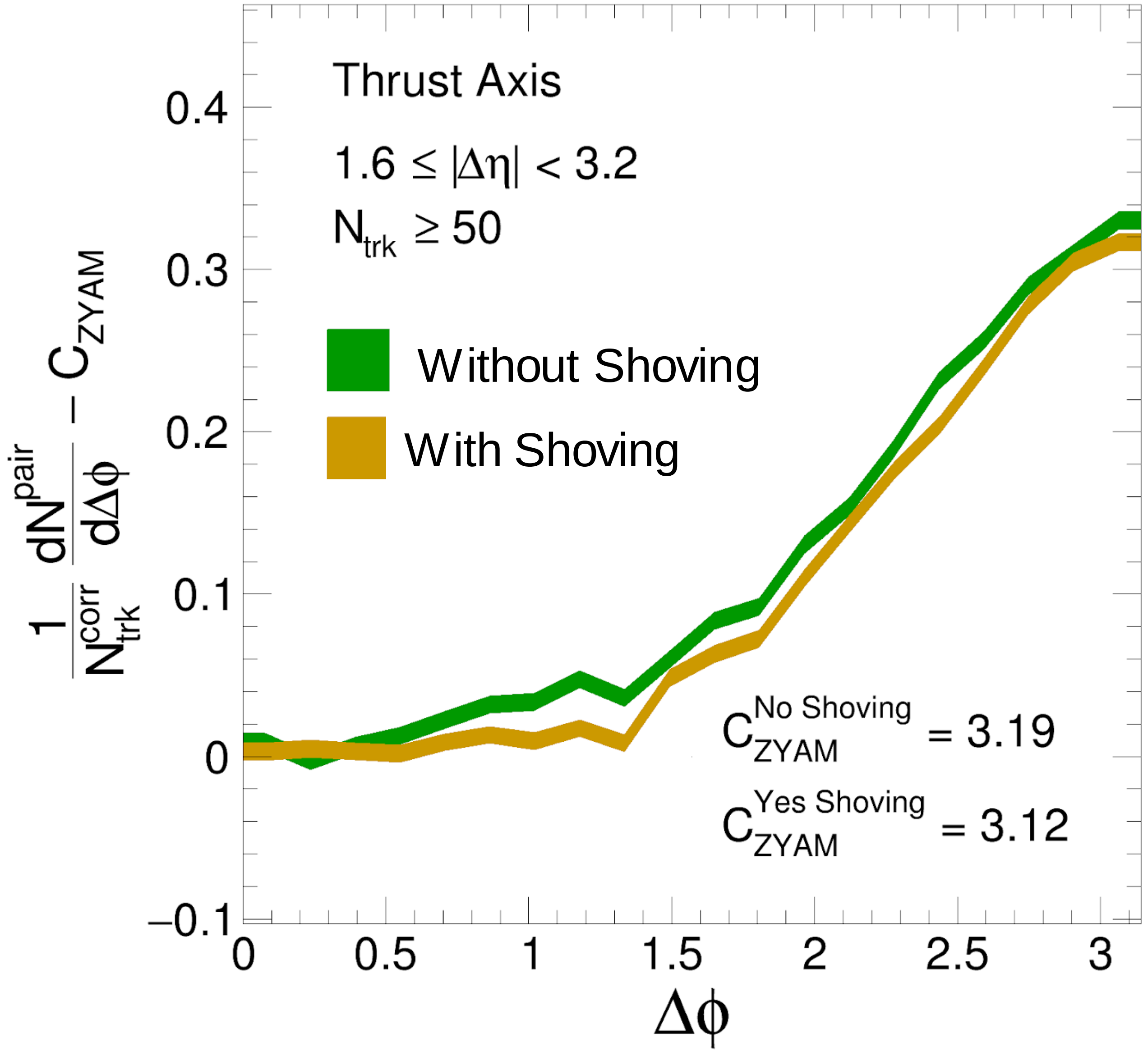


Yu-Chen "Janice" Chen (MIT)

arXiv:2312.05084

Additional Cross-checks at High Multiplicity





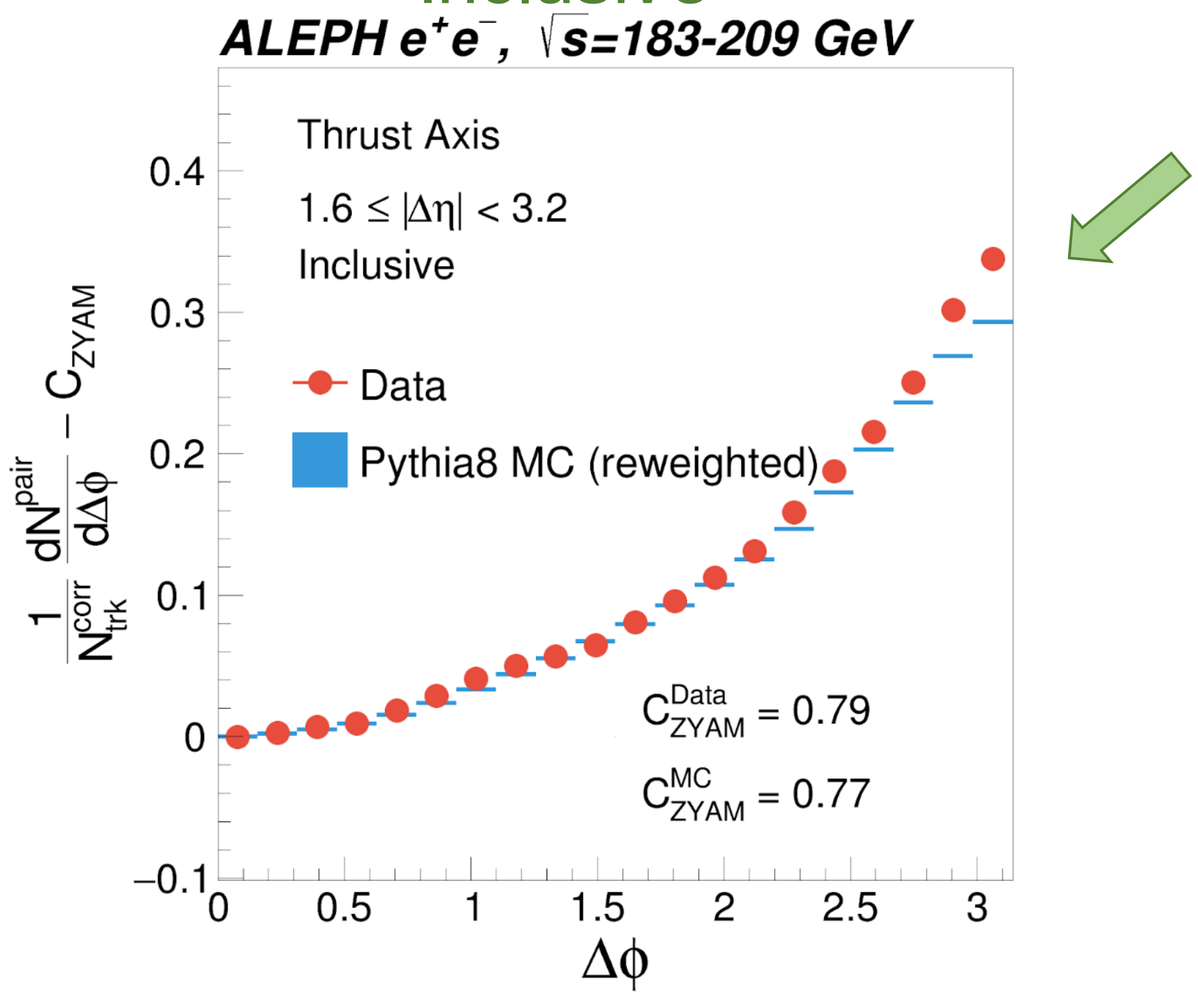
- Reweight the MC to match the data multiplicity spectrum
- Effect of reweighting is small

- **PYTHIA8 with shoving** changes the correlation function
- Doesn't produce a near-side excess

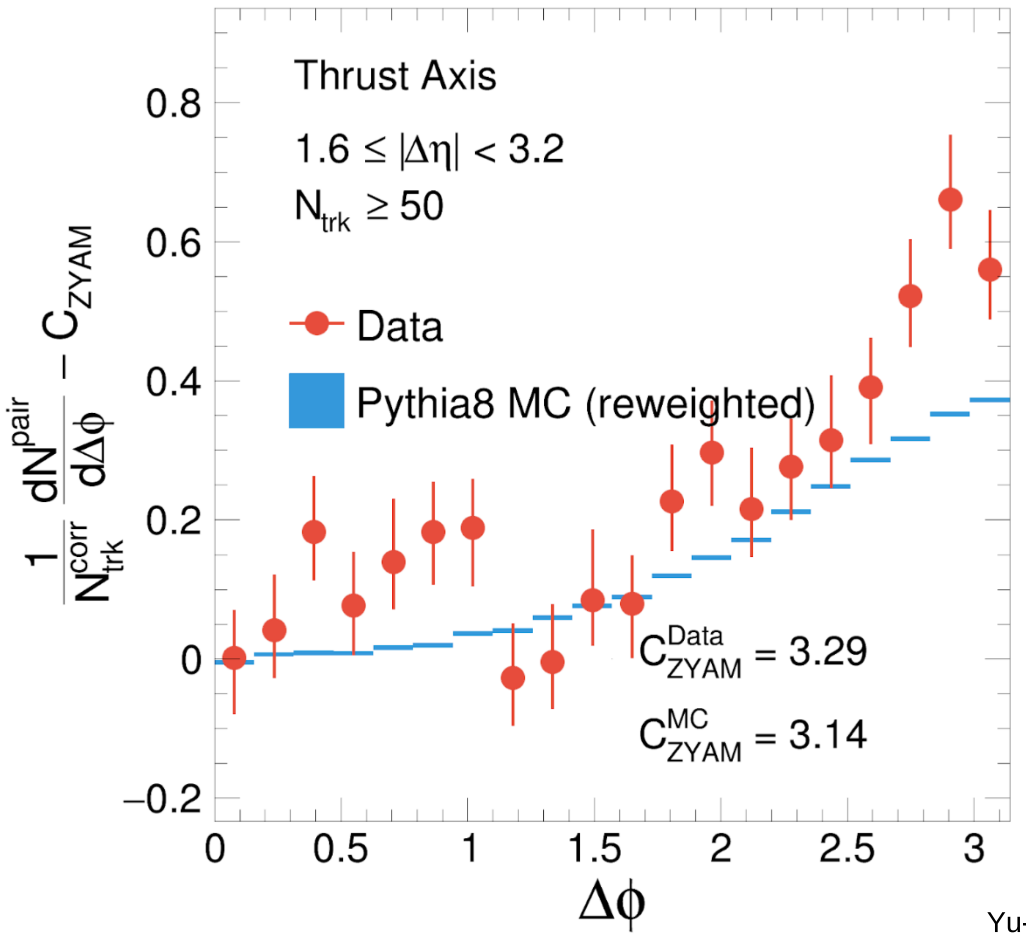
arXiv:2312.05084

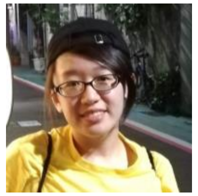
Comparison to Prediction from PYTHIA8

Inclusive



High Multiplicity





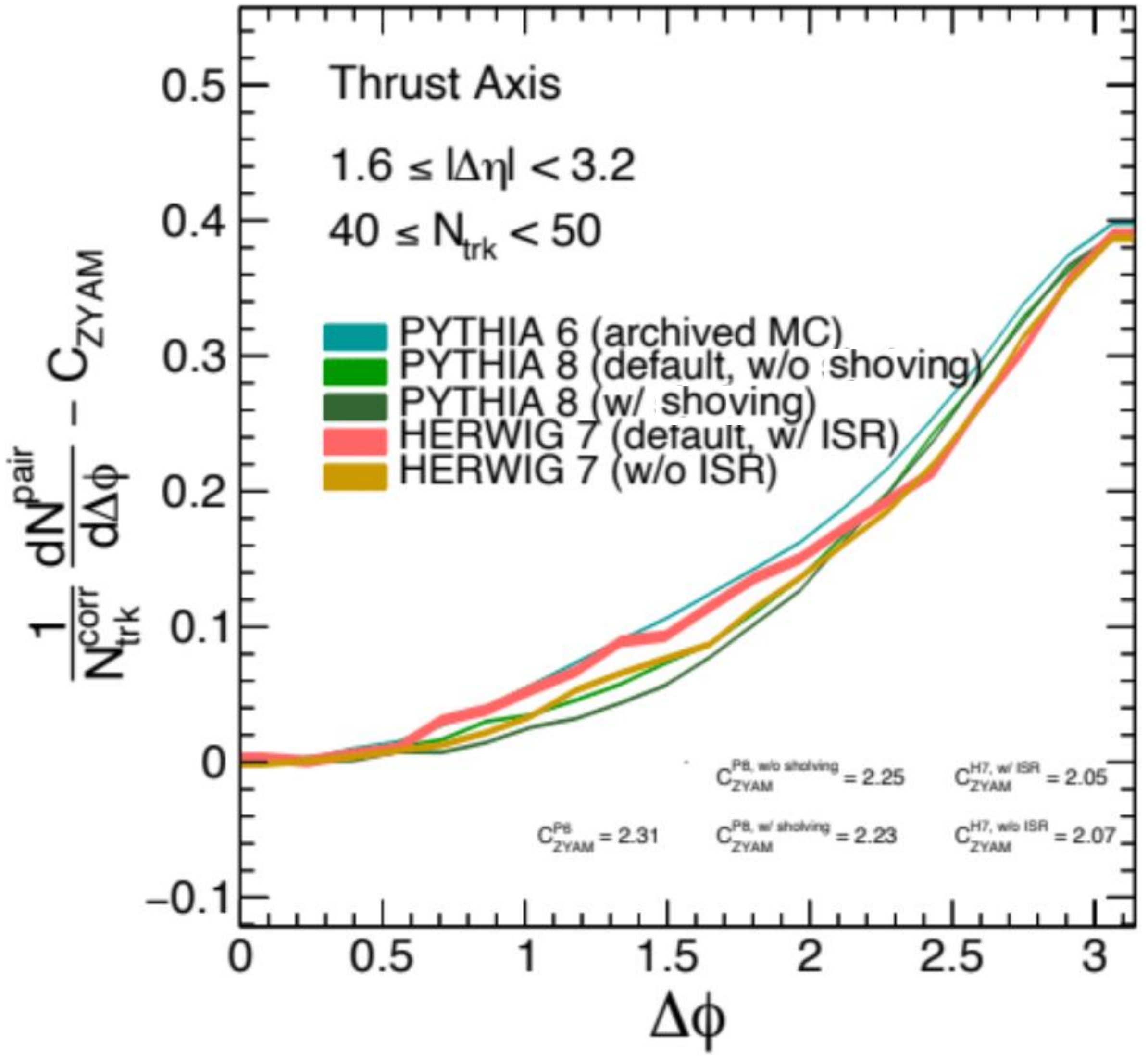
Yu-Chen "Janice" Chen (MIT)

- Smear PYTHIA8 with detector tracking efficiency from archived MC
- Reweight multiplicity to match with data
- Worse description of the inclusive sample than archived MC
- No peak structure at $\Delta\phi$~0

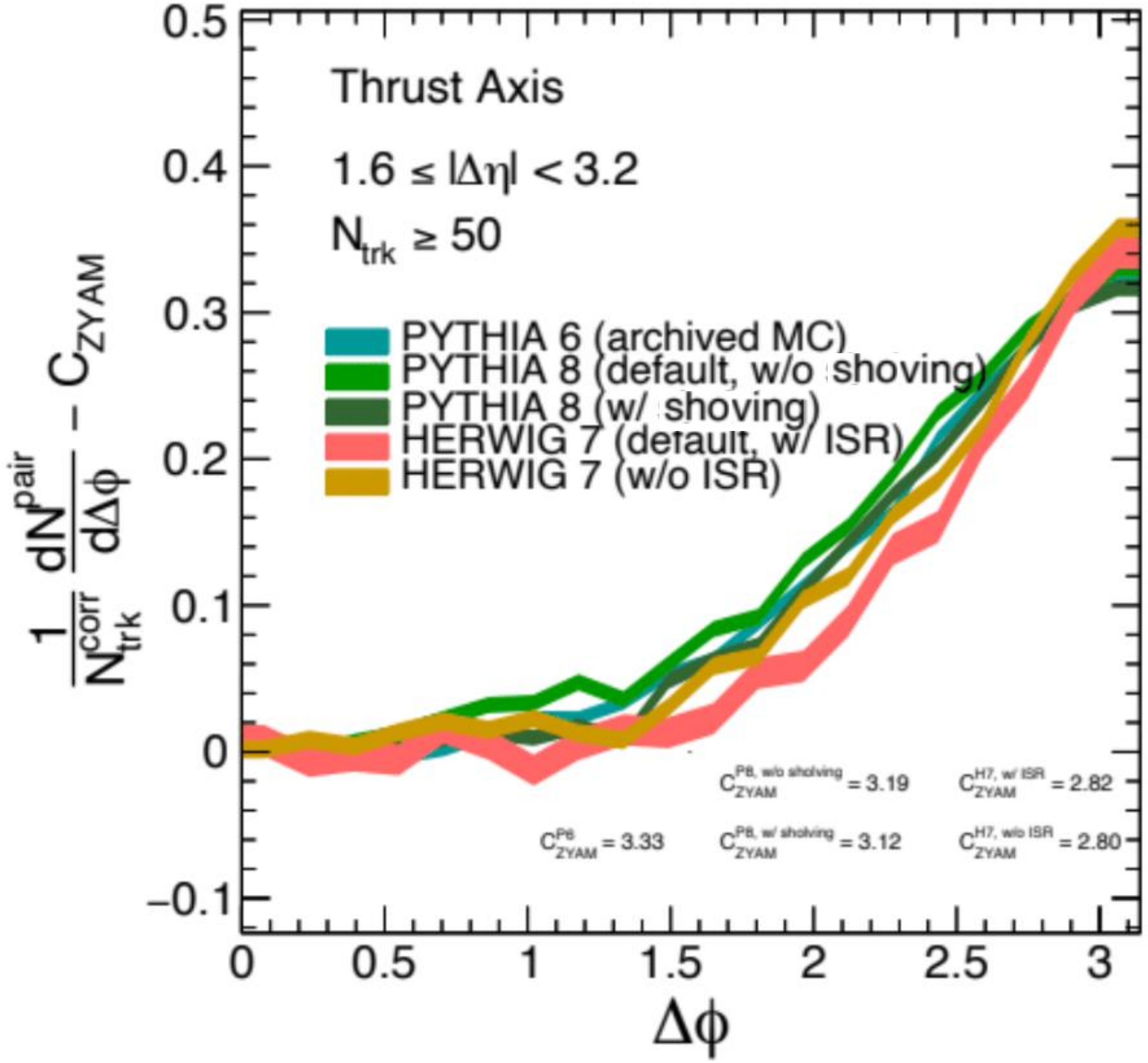
arXiv:2312.05084

PYTHIA and HERWIG Generator Studies

$40 < N_{trk} < 50$



$N_{trk} > 50$



- **HERWIG7** (with or without ISR) and PYTHIA8 (with or without shoving)
- No near-side enhancement observed

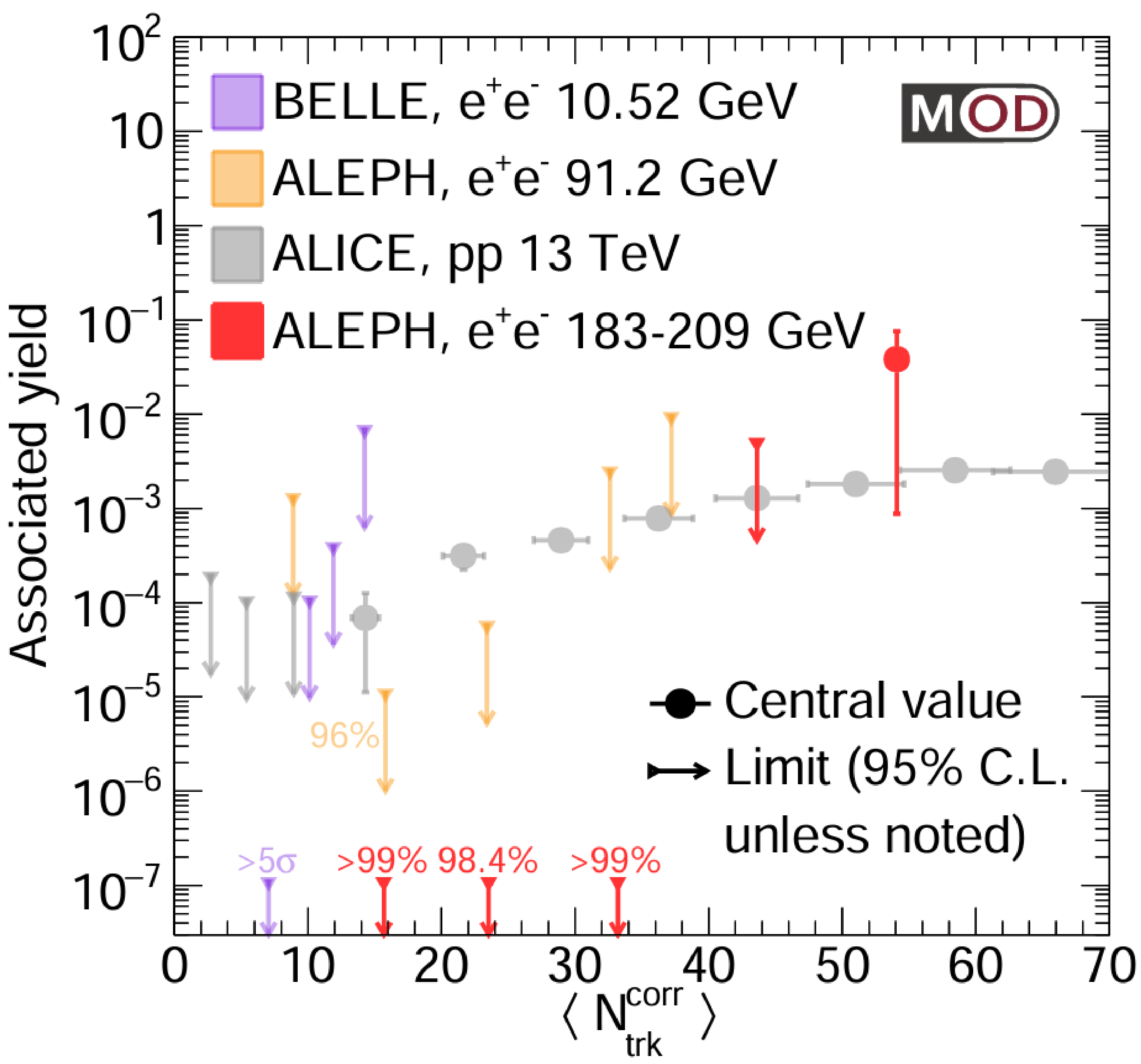
Associated Yield as a Function of Multiplicity

- Very tight upper limit set with **Belle**, **LEP1** and **LEP2** data set at low multiplicity (<40), lower than **ALICE** pp results

See You Zhou's talk

- Indication of an increasing trend at high multiplicity in LEP2 data

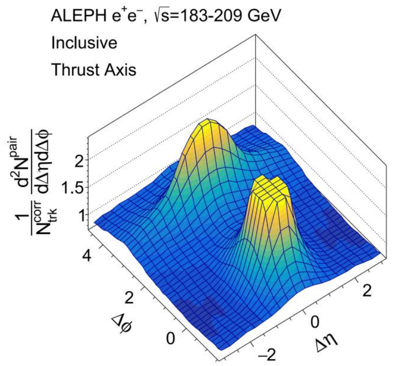
- Non-zero central value reported at the highest multiplicity bin with large statistical uncertainty



arXiv:2312.05084

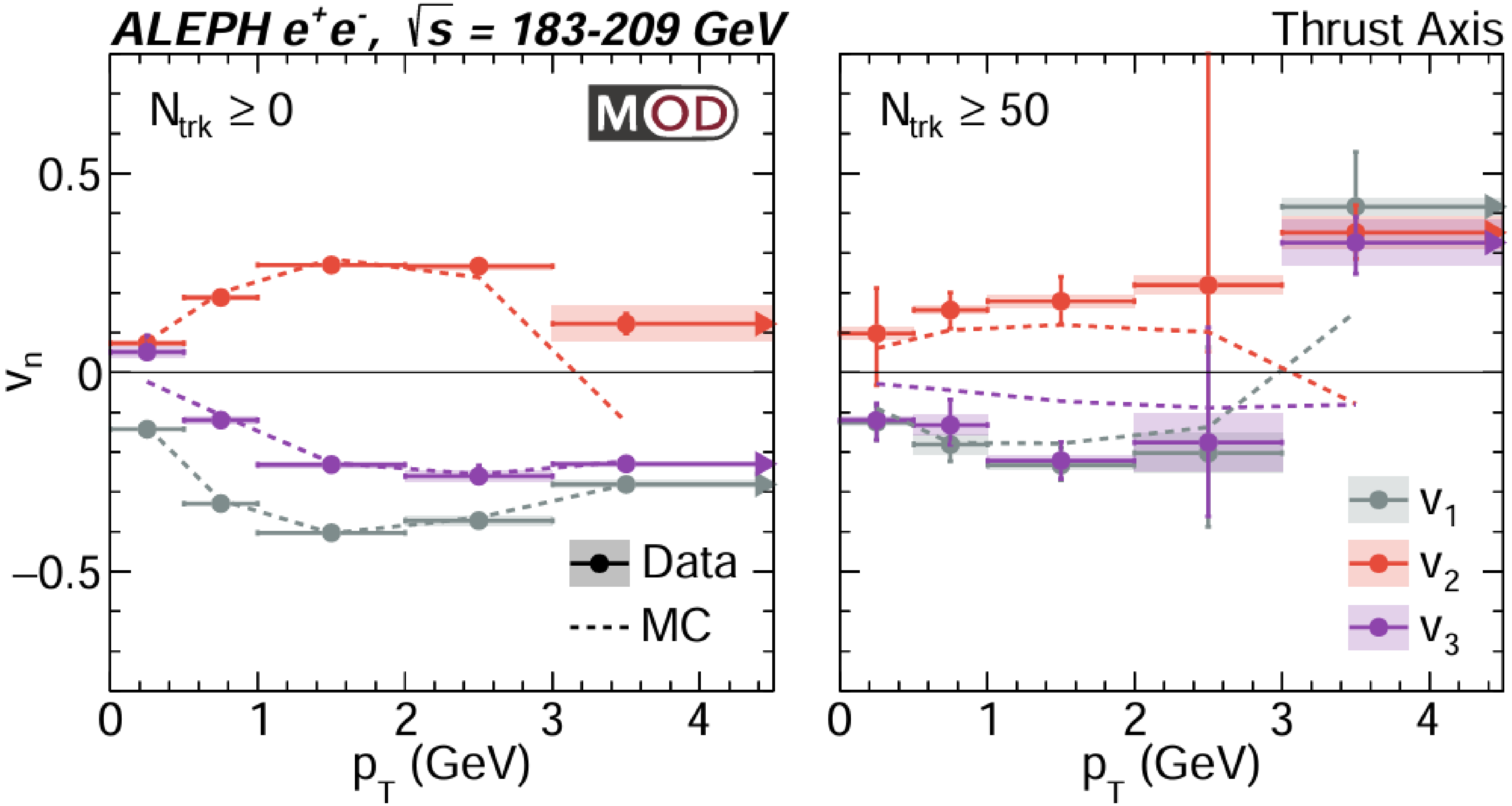
Analysis note: MITHIG-MOD-NOTE-23-011 (arXiv:2309.09874)

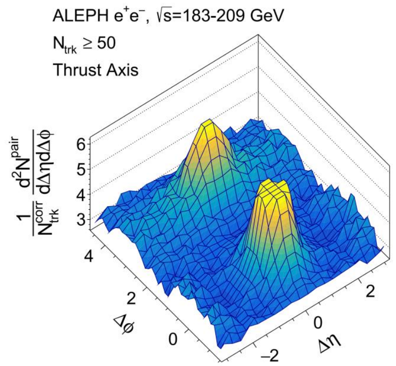
Extracted v_n vs. Charged Particle p_T

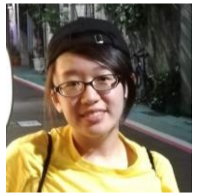


Inclusive

High Multiplicity





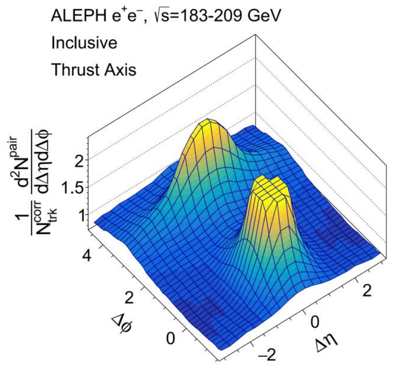


Yu-Chen “Janice” Chen (MIT)

- Reasonable agreement between Inclusive data and MC (Left)
- At High Multiplicity (Right): Larger v_2 and v_3 magnitudes than MC (dash lines)

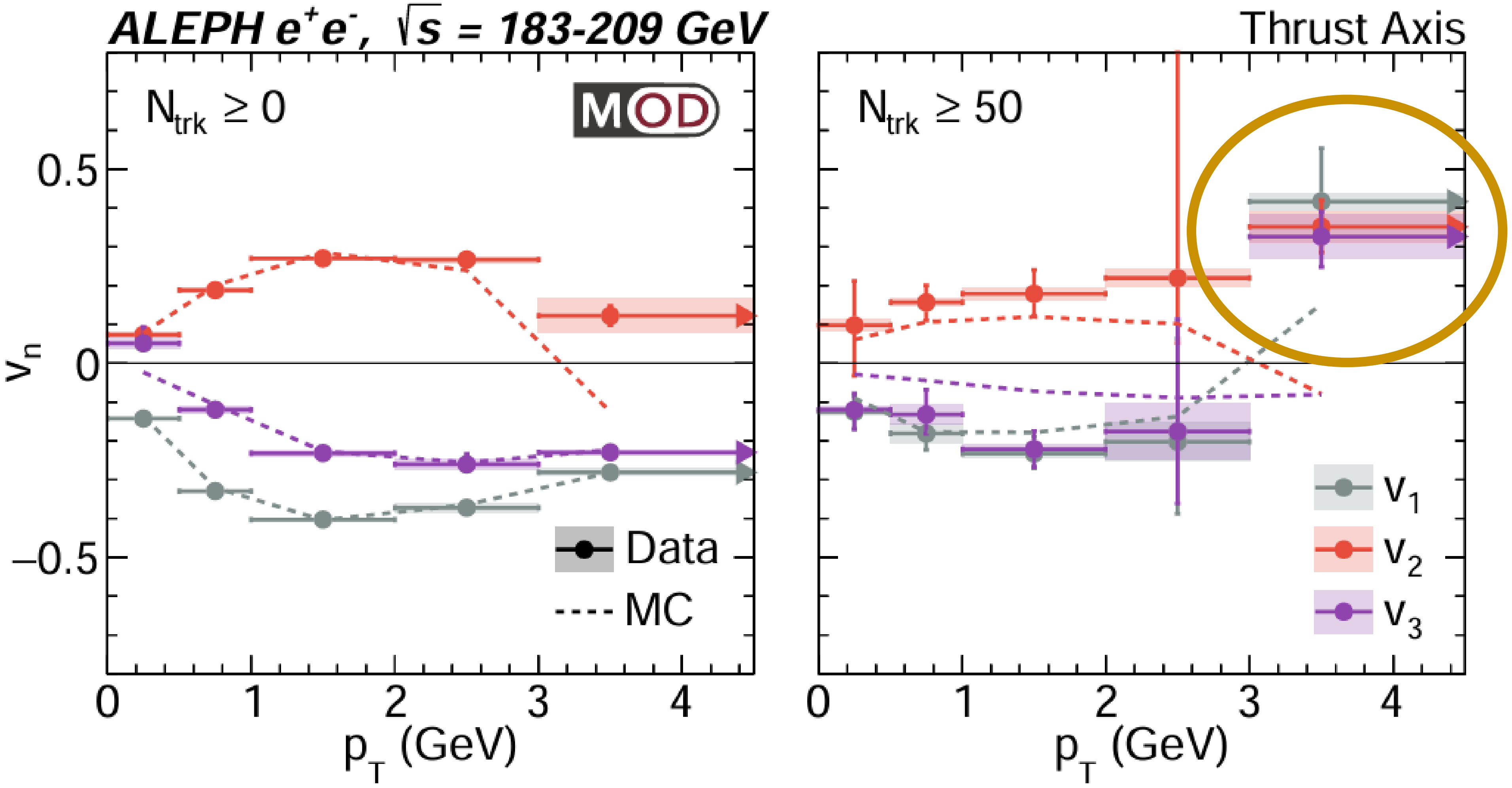
arXiv:2312.05084

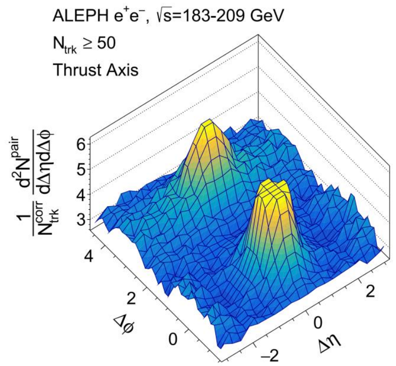
Extracted v_n vs. Charged Particle p_T

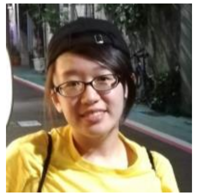


Inclusive

High Multiplicity





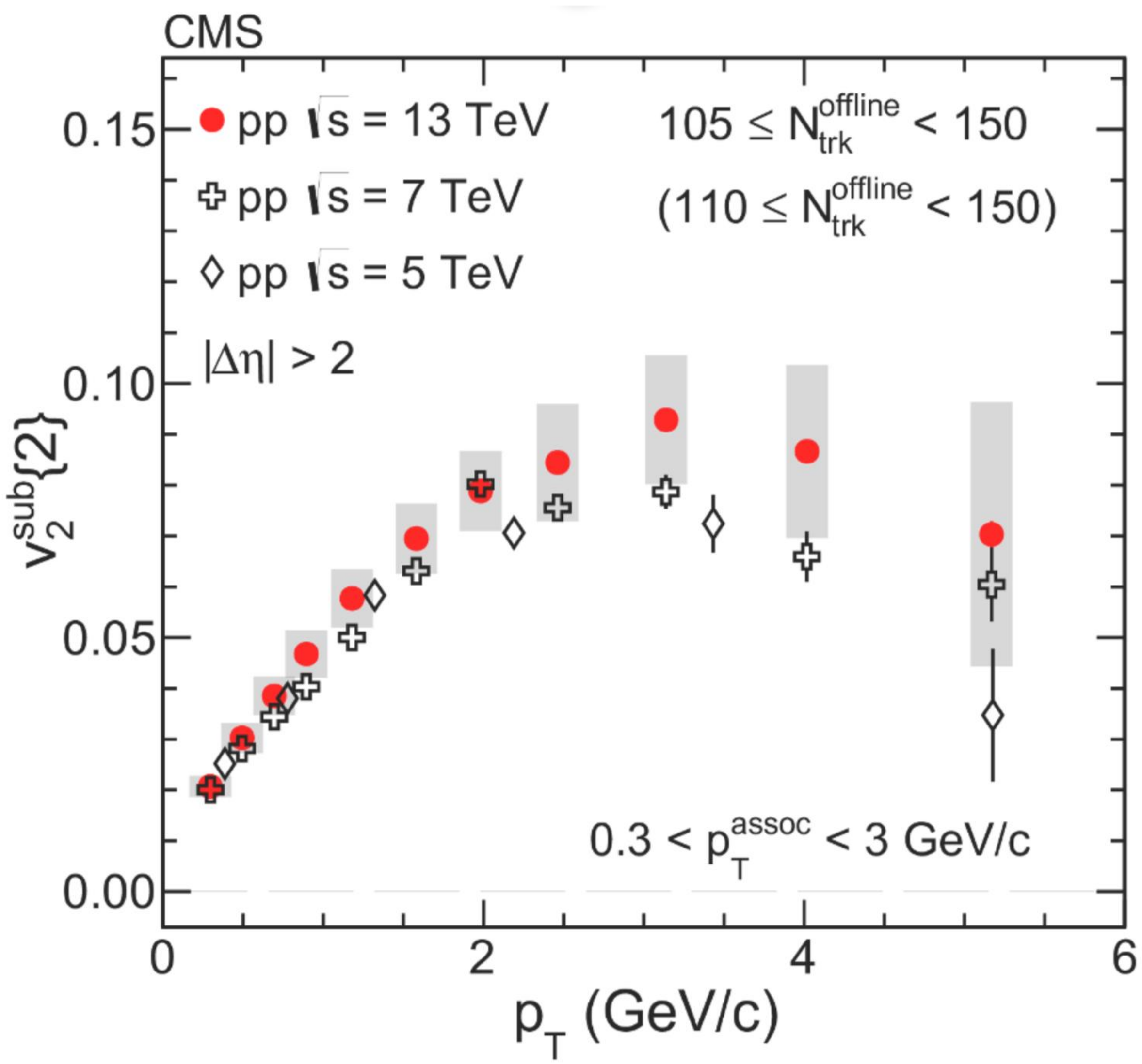


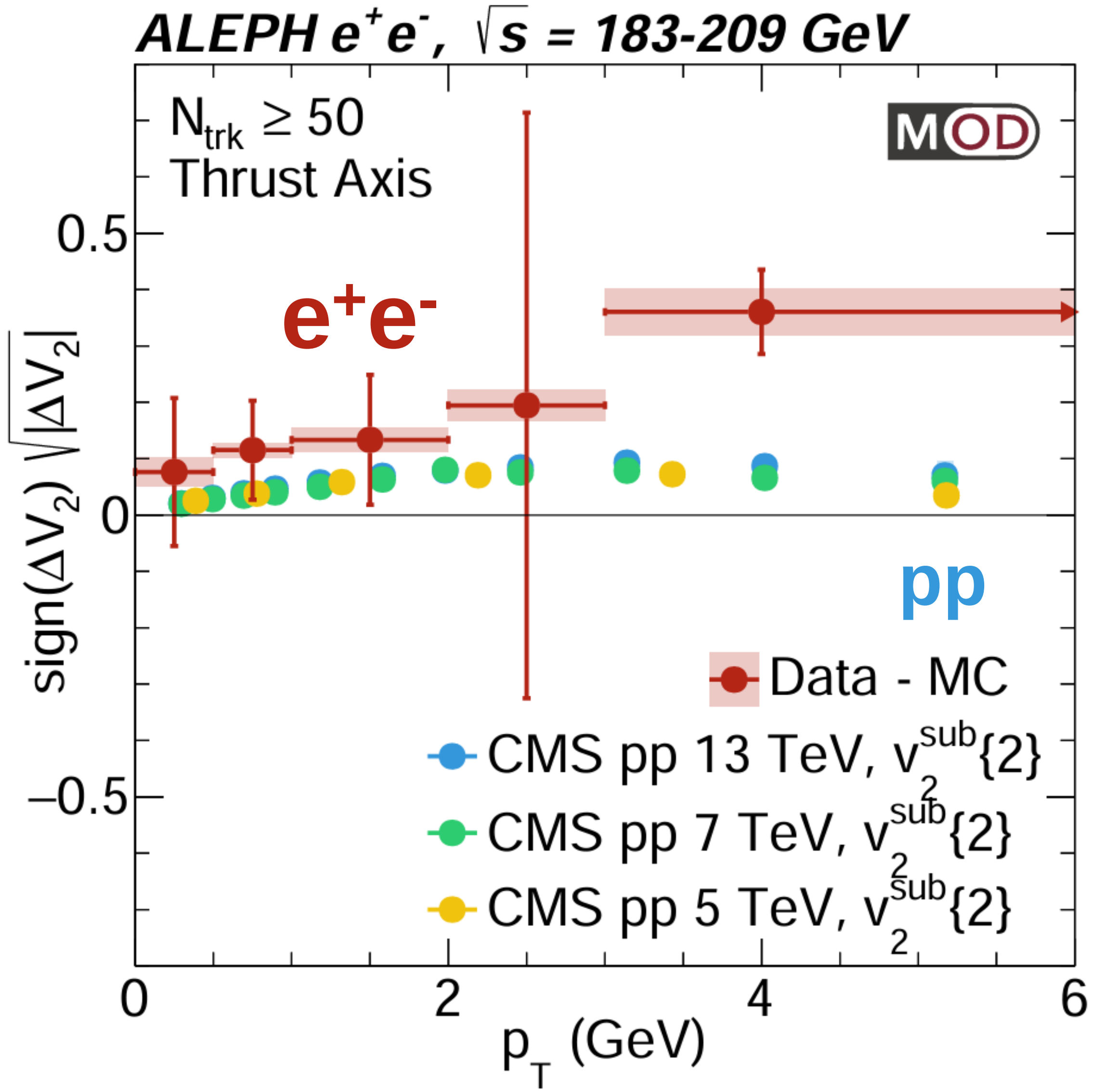
Yu-Chen “Janice” Chen (MIT)

- Reasonable agreement between Inclusive data and MC (Left)
- At High Multiplicity (Right): Larger v_2 and v_3 magnitudes than MC (dash lines)
- v_1, v_3 change sign at high p_T

arXiv:2312.05084

Δv_2 in e^+e^- Compared to v_2^{sub} in pp Collisions

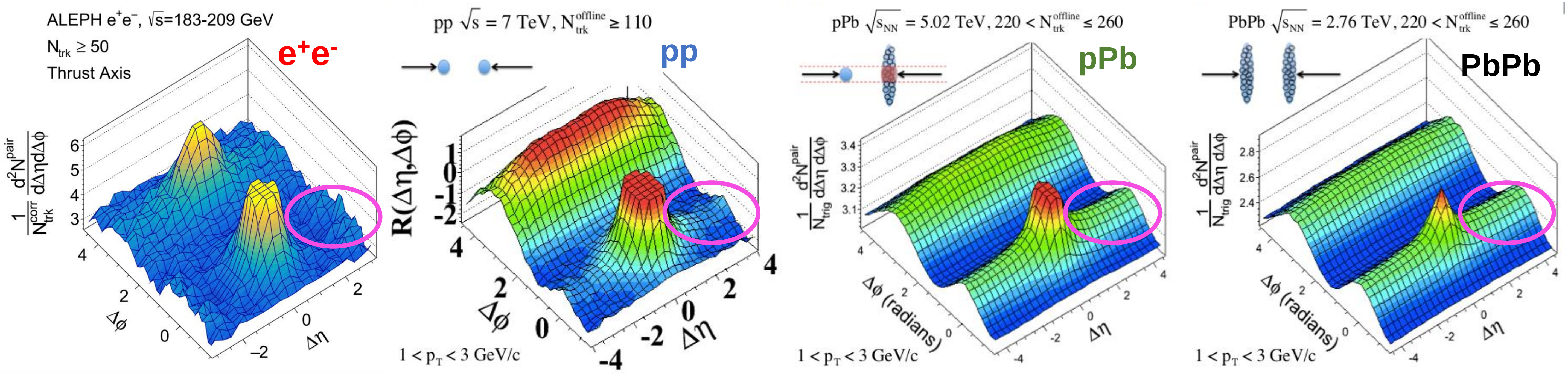




- MC based "Non-flow subtraction": $\Delta v_2 = v_2^{Data} - v_2^{MC}$
- Similar increasing trend in e^+e^- and pp data as a function of p_T

arXiv:2312.05084

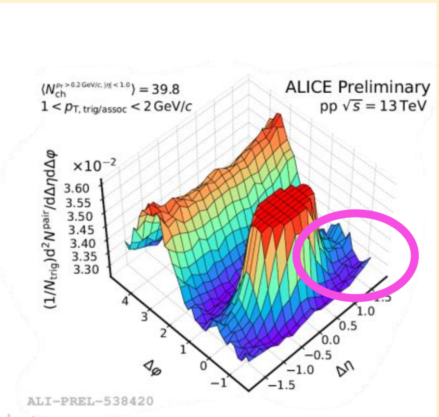
Emerging Picture



Emerging Picture

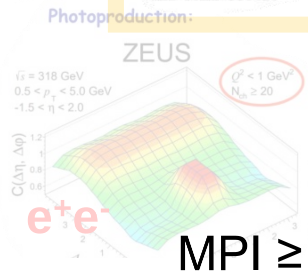
"Transverse Size" / "MPI"

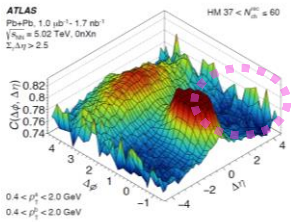
ALICE Low multiplicity pp signal

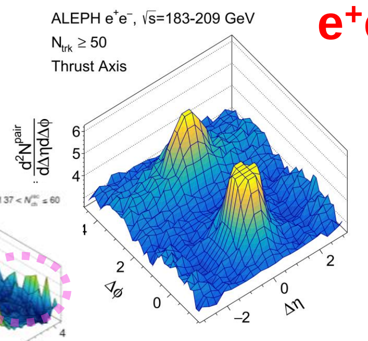


See You Zhou's talk

MPI>1







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

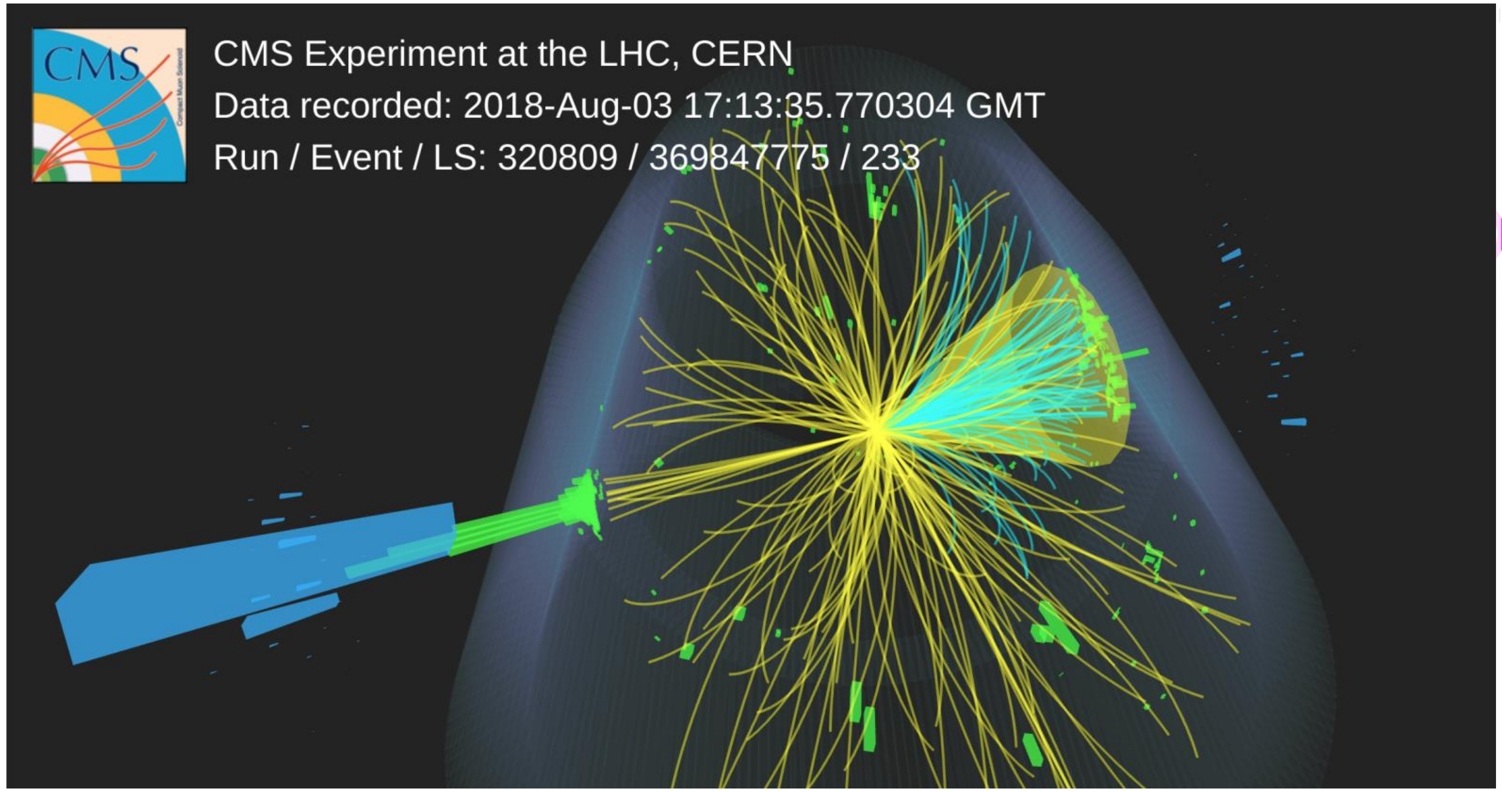
"MPI"=2

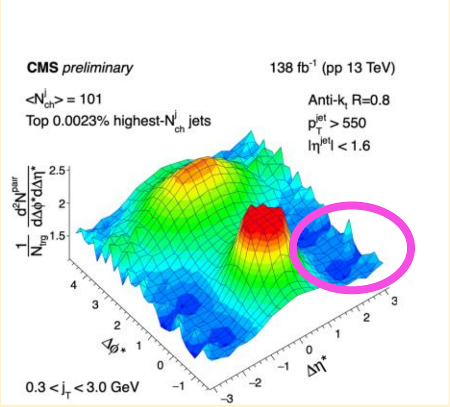
MPI ≥ 1

Larger MPI than γp

"MPI"=1

<< 0.1 fm



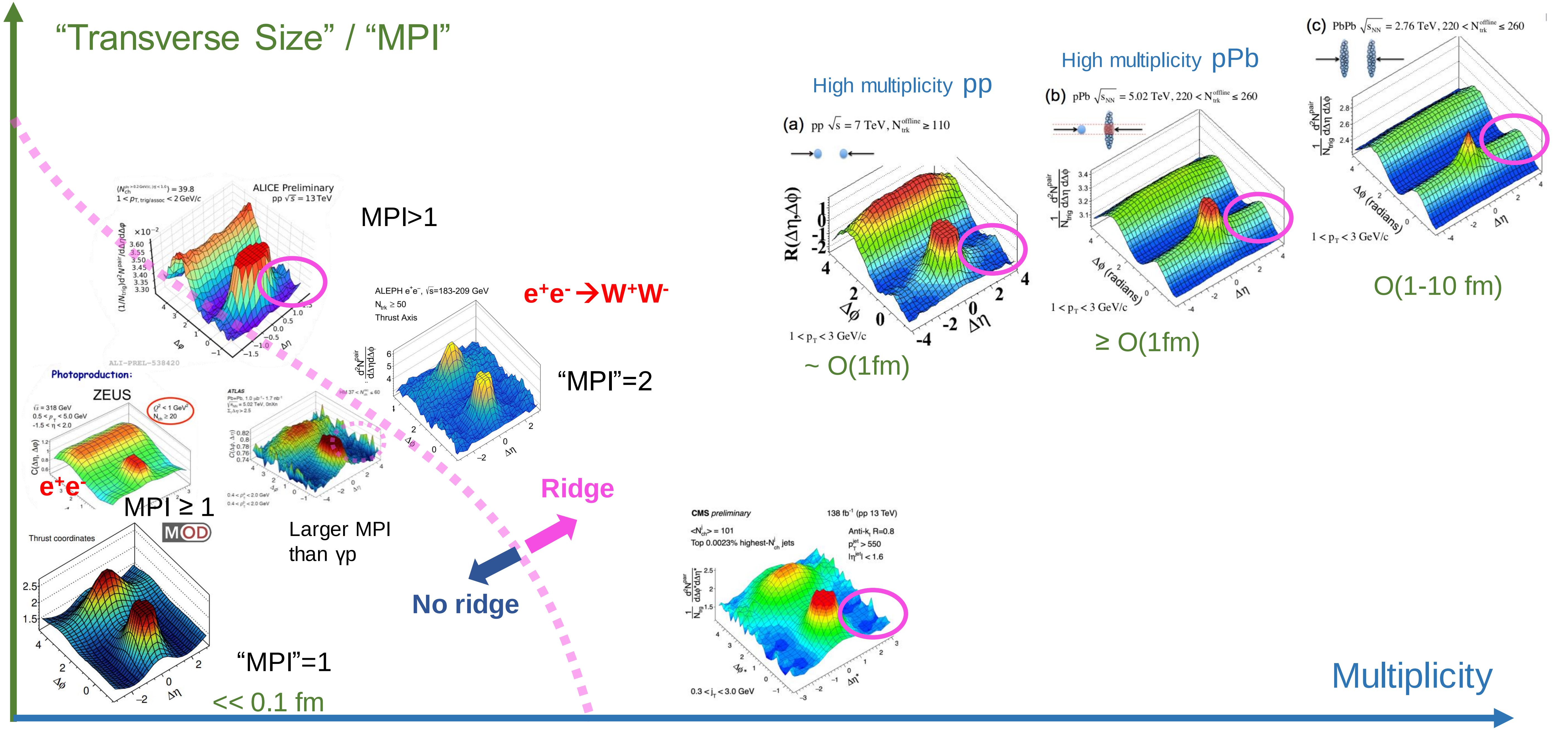


CMS High Multiplicity Jet

See Austin Baty's talk

Multiplicity

Emerging Picture (Artist's impression)



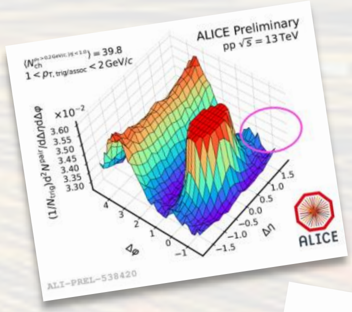
Lessons Learned from Collectivity Searches

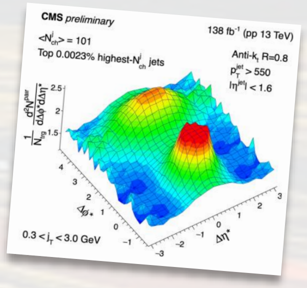
- What are the minimum conditions for ridge signal in a small system?

Large MPI and/or multiplicity events help reducing the $\mathbf{V_{1\Delta}}$ and directly reveal the ridge

- Can detectable collectivity arise from final state effects unrelated to the initial state?

Indication of final state effects from CMS high multiplicity single jet and ALEPH LEP2 data



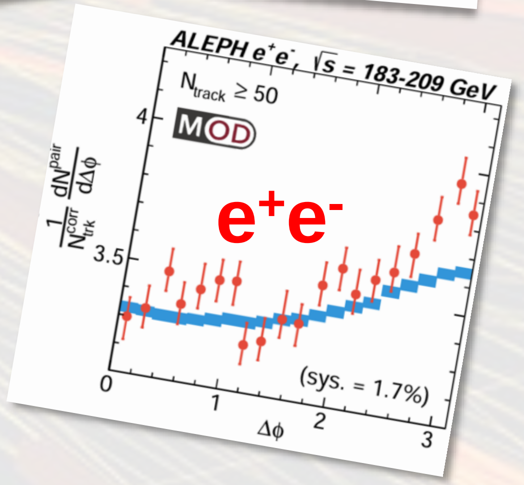


- How does collectivity vary in different physics processes?

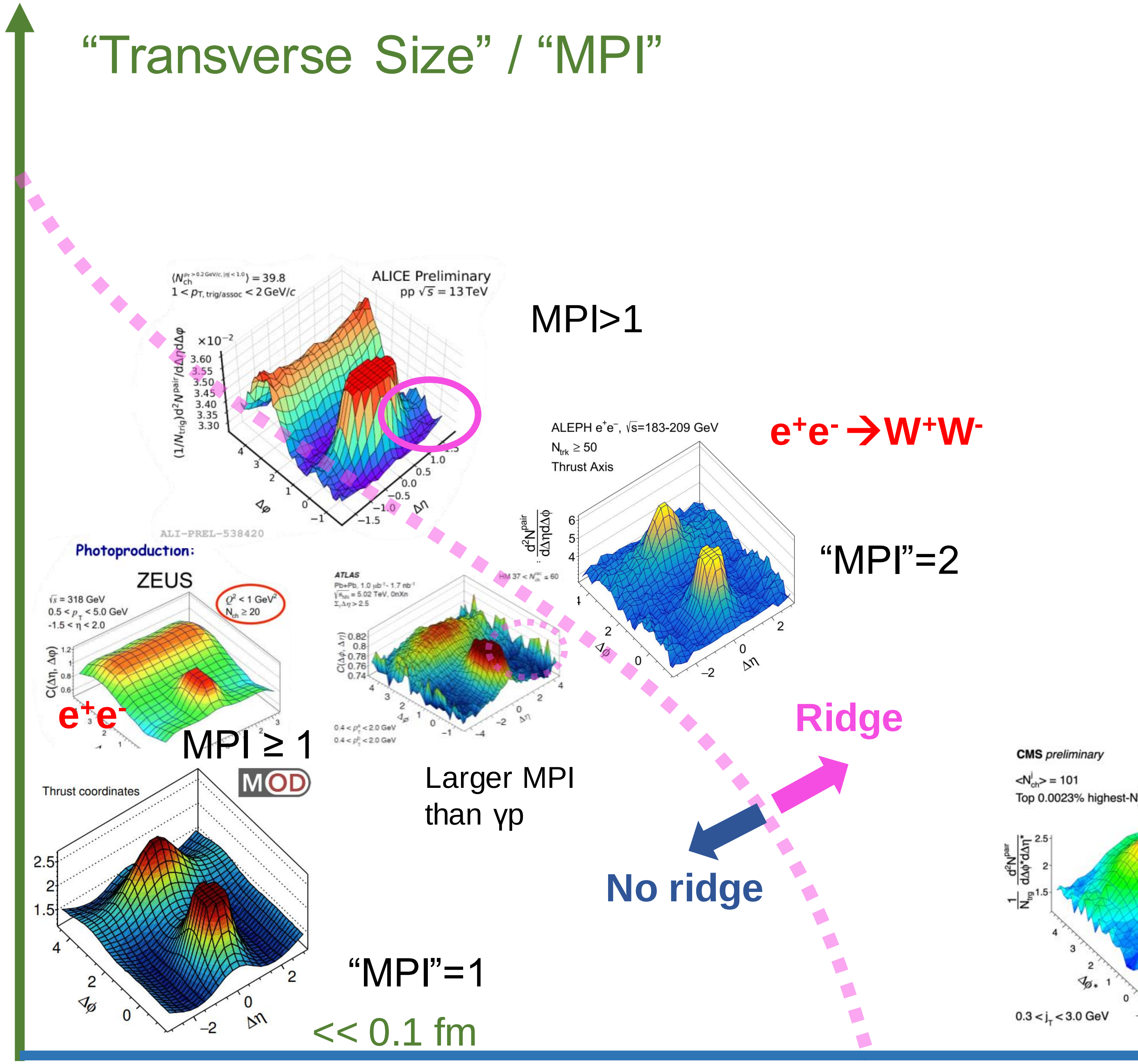
Long-range near-side correlations vary in different physics processes in LEP data

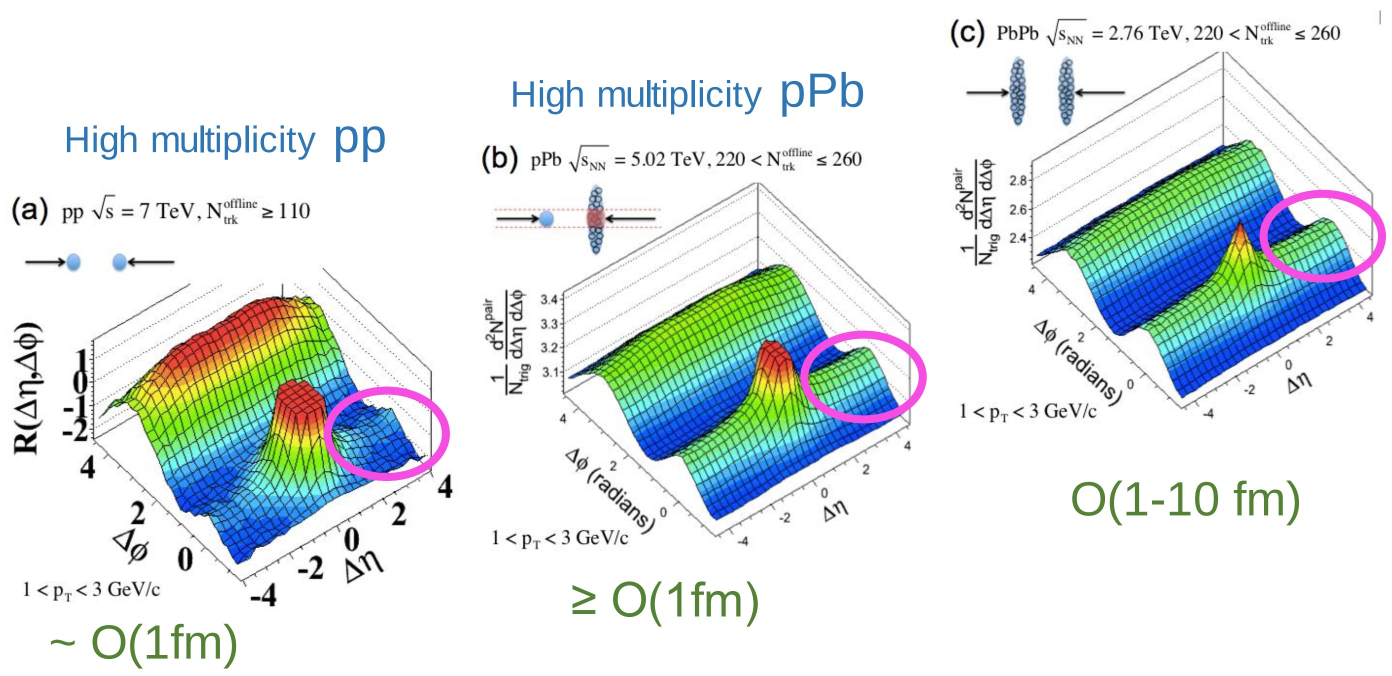
- Is the underlying physics the same in small and large systems?

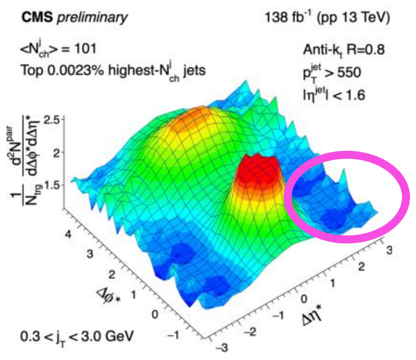
Data suggest that small systems lacking hadronic initial state effects could still yield a ridge-like signal. Nature of the correlation to be understood.



Emerging Picture (Artist's impression)







Future program with

(1) e^+e^- with different physics processes identified with LEP and FCC data

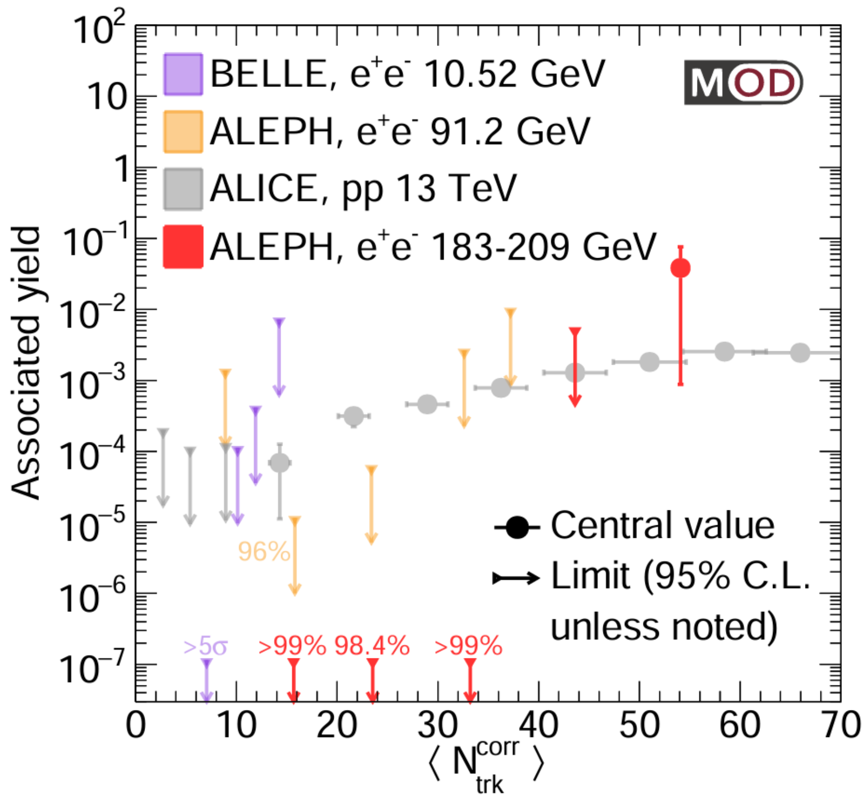
(2) UPC AA data at RHIC & LHC

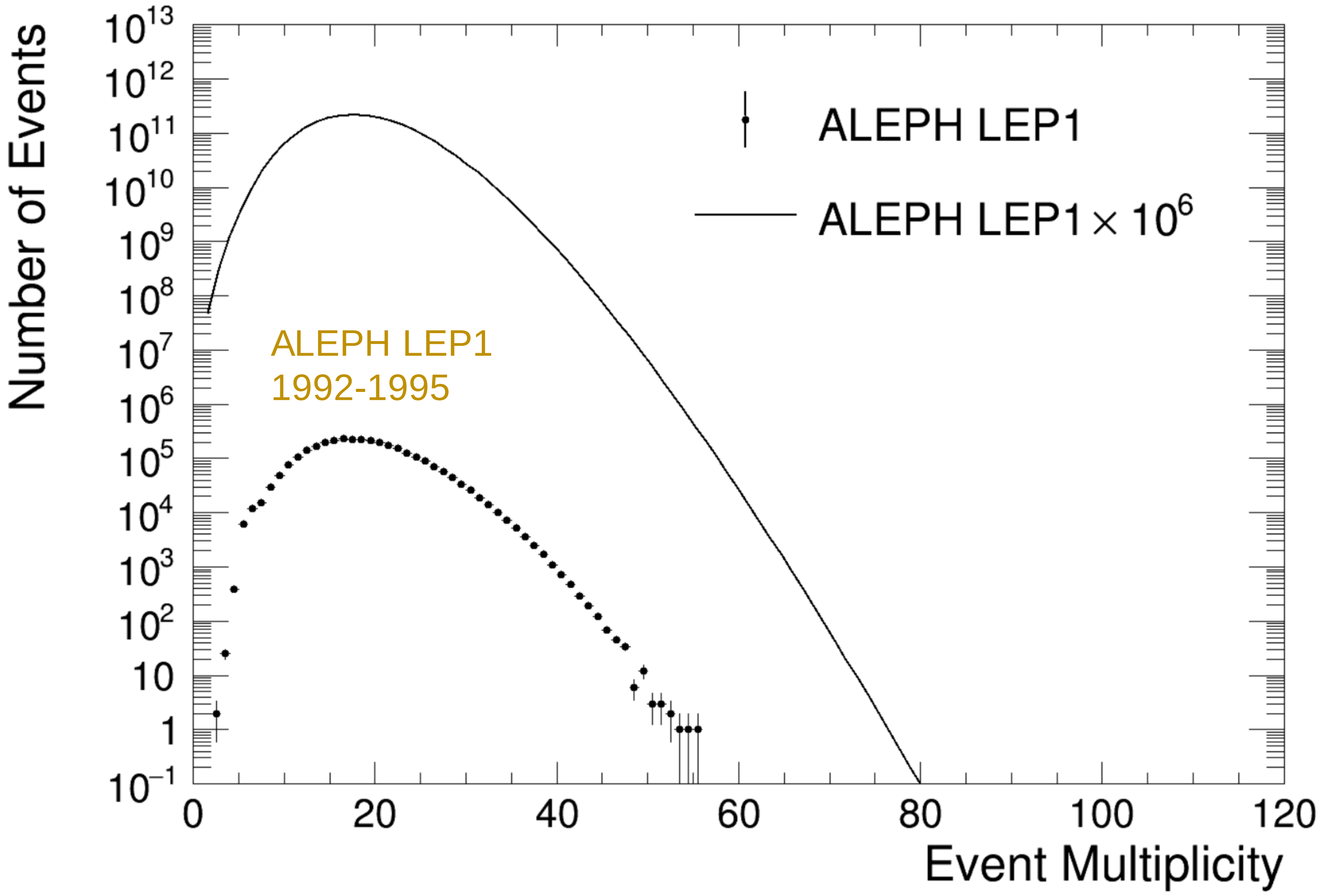
(3) Investigation with EIC data

Multiplicity

Projection to FCC-ee

- Estimation with ALEPH archived data
- Extrapolation with NBD fit to the archived data
- Significantly higher reach up to event multiplicity of around 75 particles

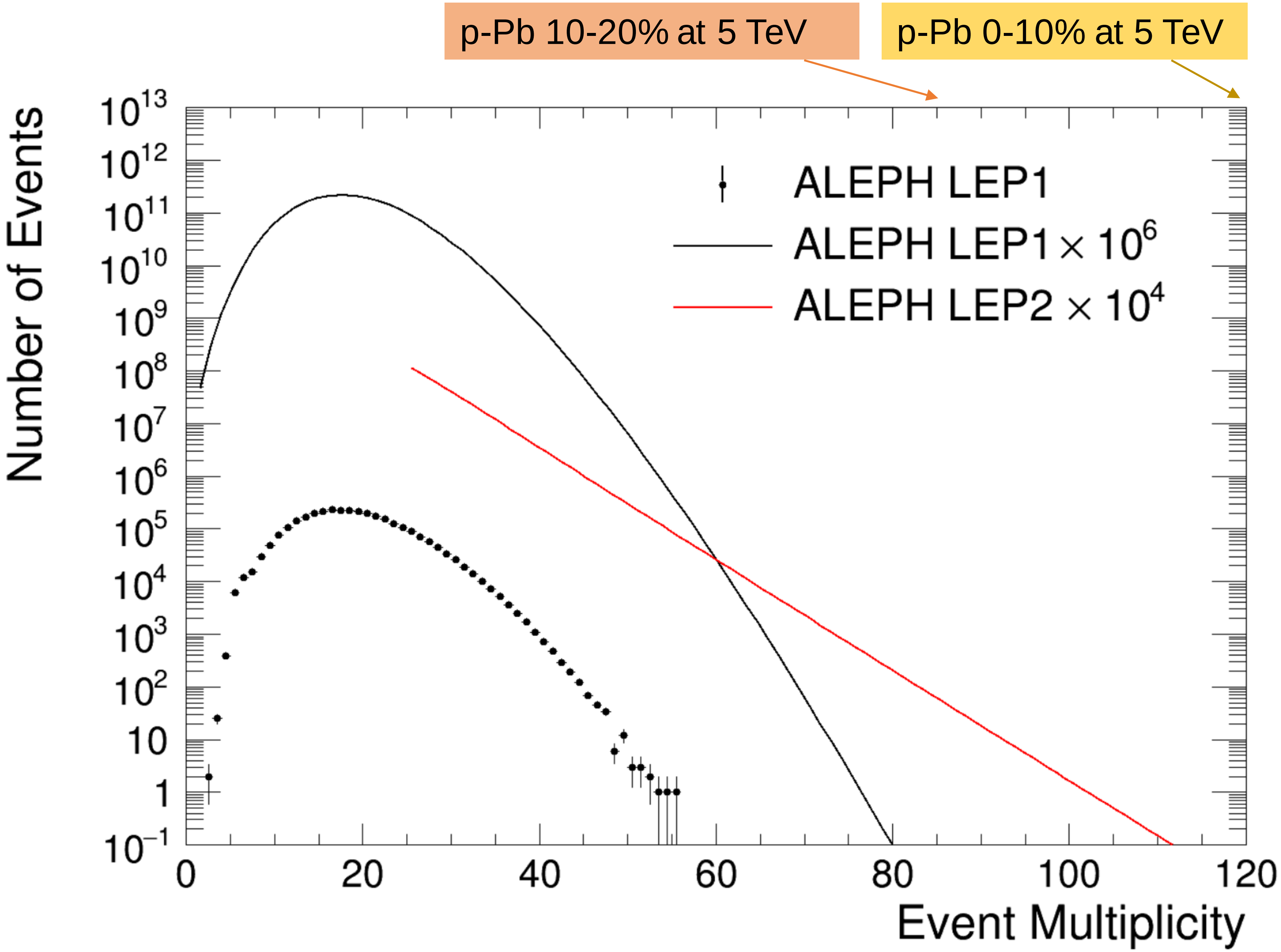




Projection to FCC-ee

- Extrapolation with archived LEP2 data
- Significant increase in multiplicity reach:
  ~ central proton-lead collisions
- Large statistics will enable new analyses which are not yet accessible:
  - 3-particle and multi-particle correlation analyses
  - Strangeness enhancement
  - Charm baryon to meson ratio enhancement
  - Studies of its process dependence
  - High multiplicity jet substructure
  - High multiplicity event energy-energy-correlators

  - … many other ideas to come!



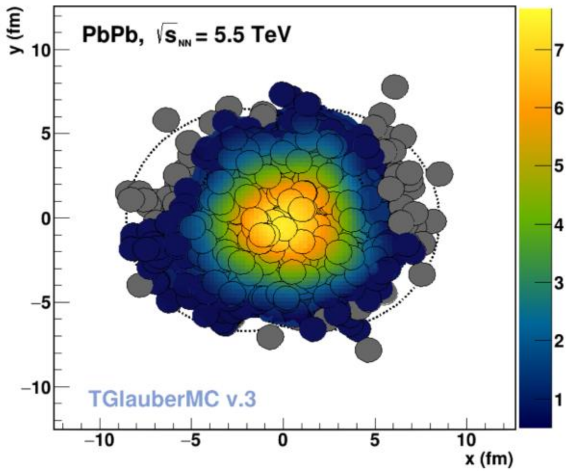
Selected List of Analyses

- **e^+e^-**
  - ALEPH LEP1 (91 GeV) PRL 123 (2019) 21, 212002
  - ALEPH LEP2 (183-209 GeV): https://arxiv.org/pdf/2312.05084
  - 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

System Size

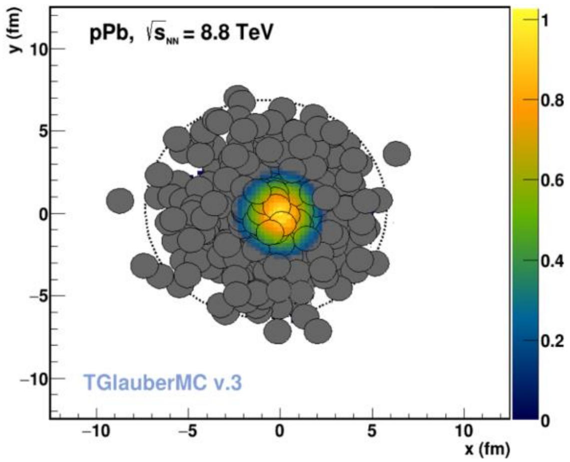
“Transverse Size” / “MPI”

AA



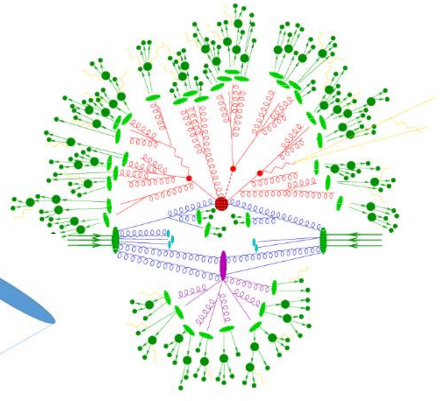
O(1-10 fm)

pA



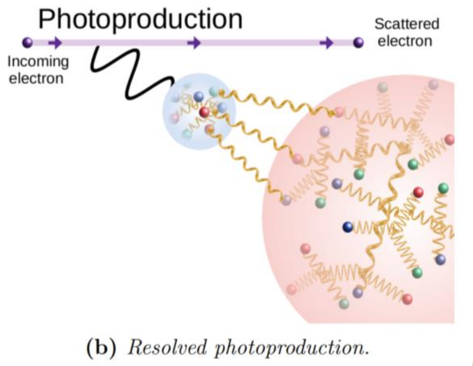
≥ O(1fm)

pp

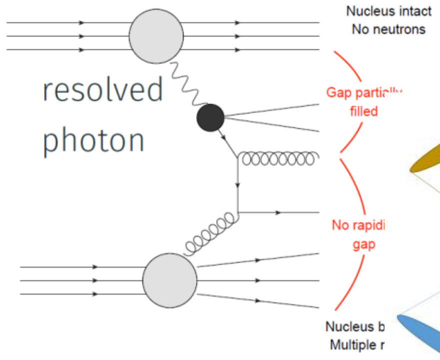


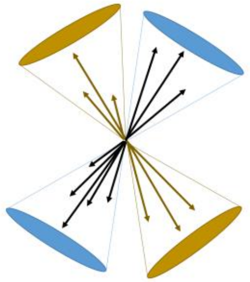
~ O(1fm)

$1/\Lambda_{QCD}$ ~ 1 fm



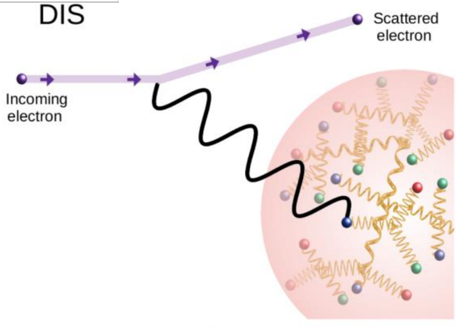
(b) *Resolved photoproduction.*





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

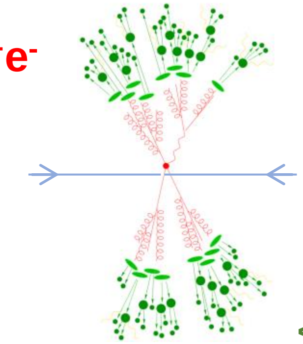
DIS



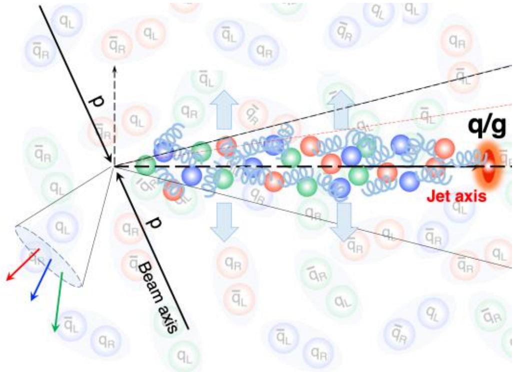
(a) *Neutral current deep inelastic scattering.*

1/Q < 0.2 fm

e^+e^-



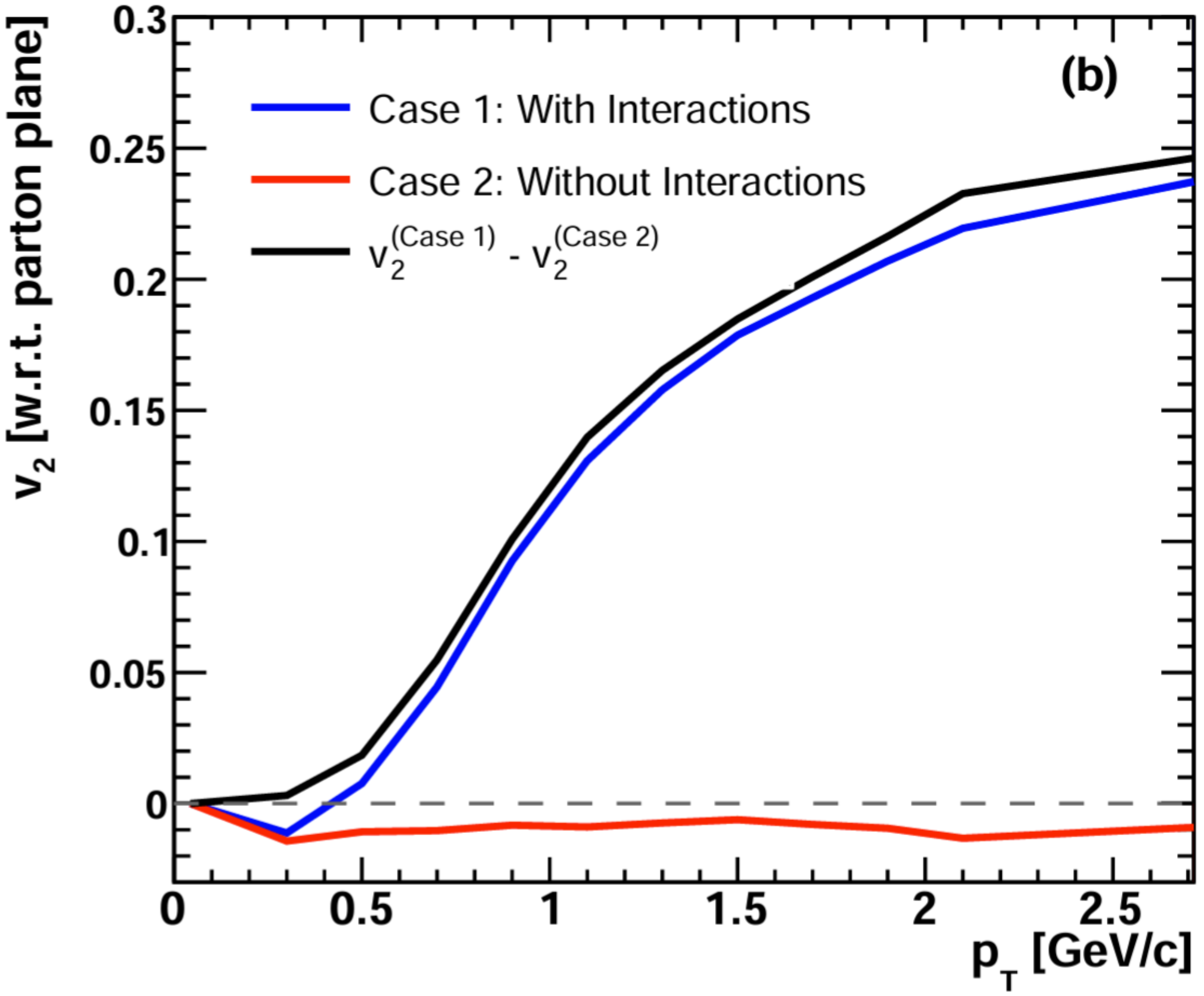
<< 0.1 fm

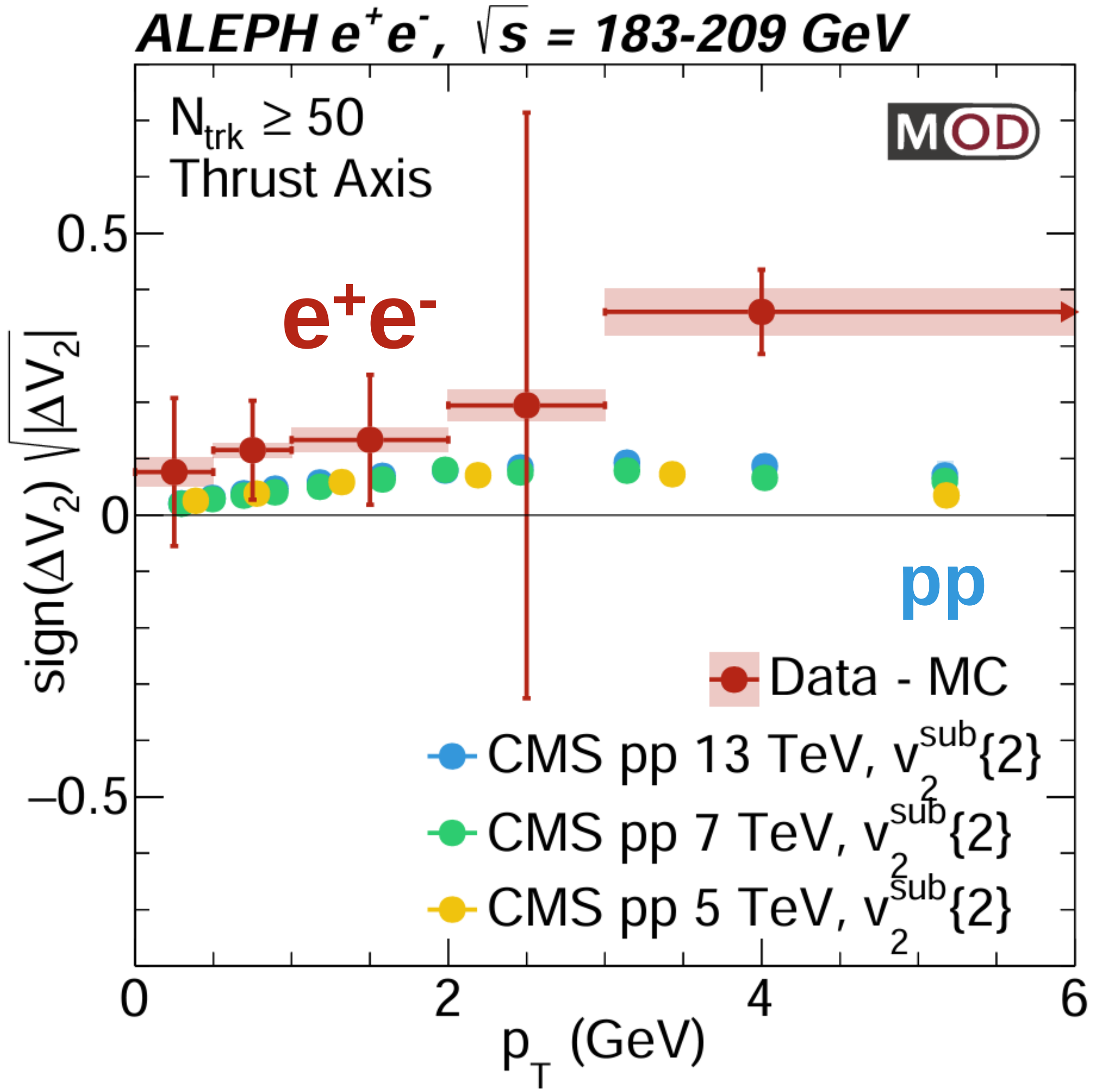


Multiplicity

Backup Slides

Δv_2 in e^+e^-





- MC based "Non-flow subtraction": $\Delta v_2 = v_2^{Data} - v_2^{MC}$

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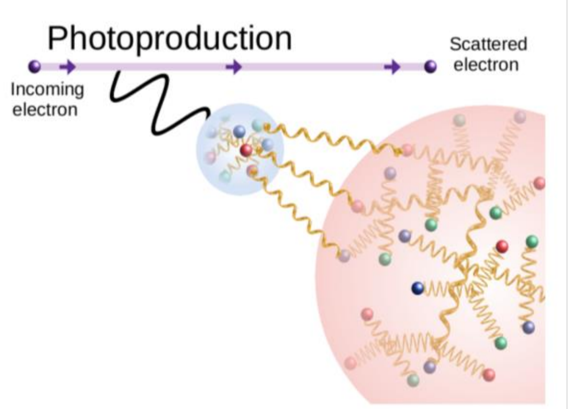
arXiv:2312.05084

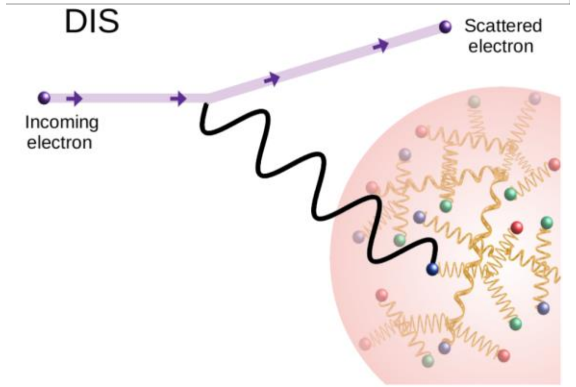
System Size

"Transverse Size" / MPI

$1/\Lambda_{QCD}$ ~ 1 fm



(b) *Resolved photoproduction.*



(a) *Neutral current deep inelastic scattering.*

1/Q < 0.2 fm

e^+e^-

<< 0.1 fm

High multiplicity pp

~ O(1fm)

High multiplicity pPb

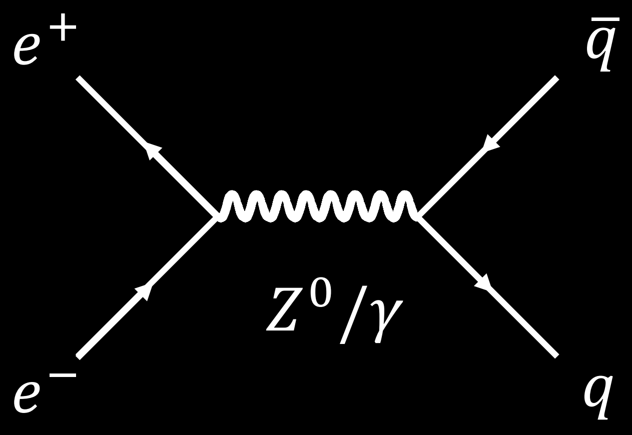
≥ O(1fm)

O(1-10 fm)

Multiplicity

High Multiplicity Event in e^+e^- Collisions in LEP1

Highest multiplicity event in ALEPH LEP1 data
Collision Energy = 91 GeV

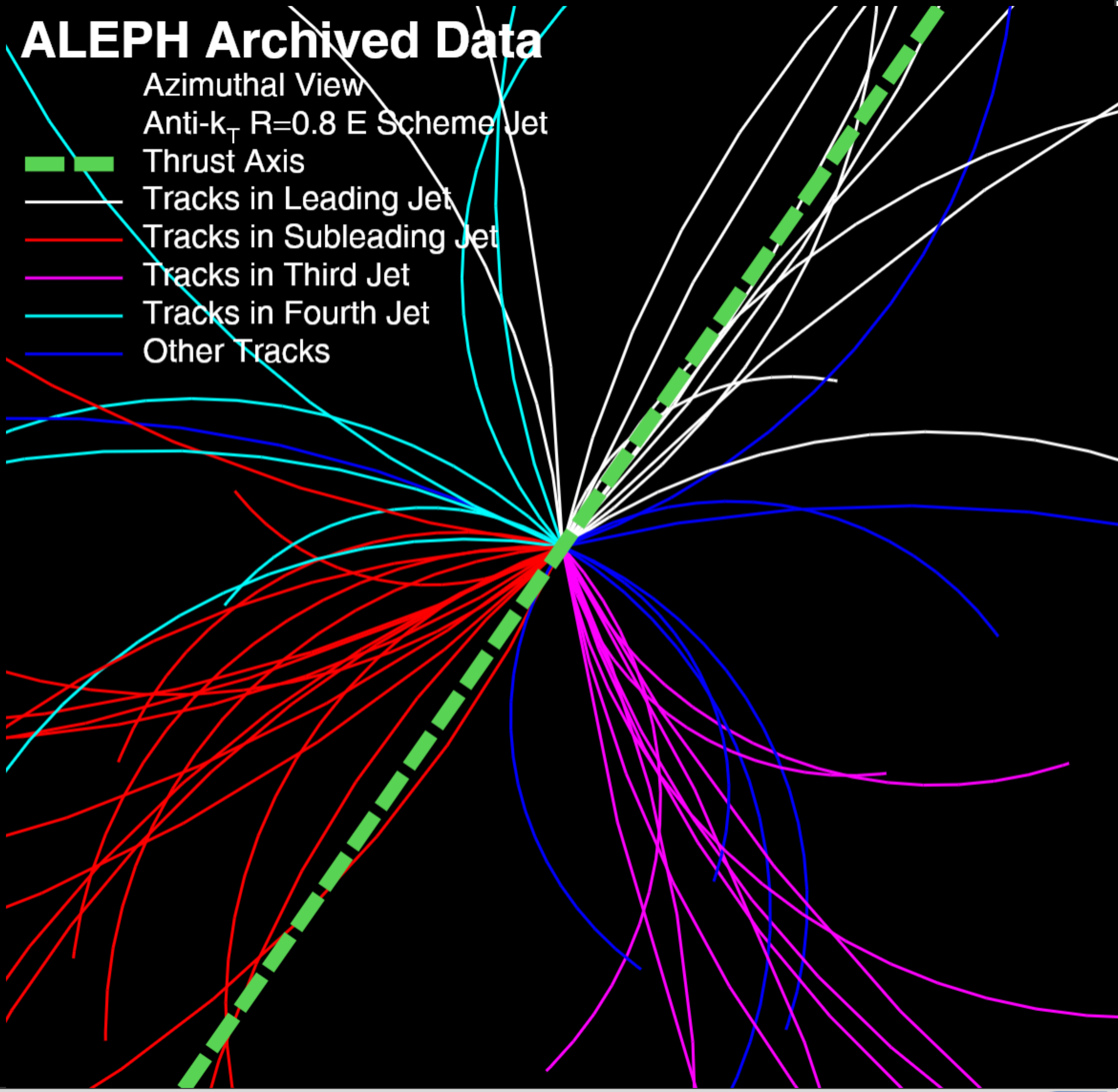


Anthony Badea, Austin Baty, Chris McGinn, Michael Peters, Jesse Thaler, Gian Michele Innocenti, Paoti Chang, Tzu-An Sheng

+ YJL

arXiv: 1906.00489
PRL 123, 212002 (2019)

55 Charged Particles
Thrust T=0.71



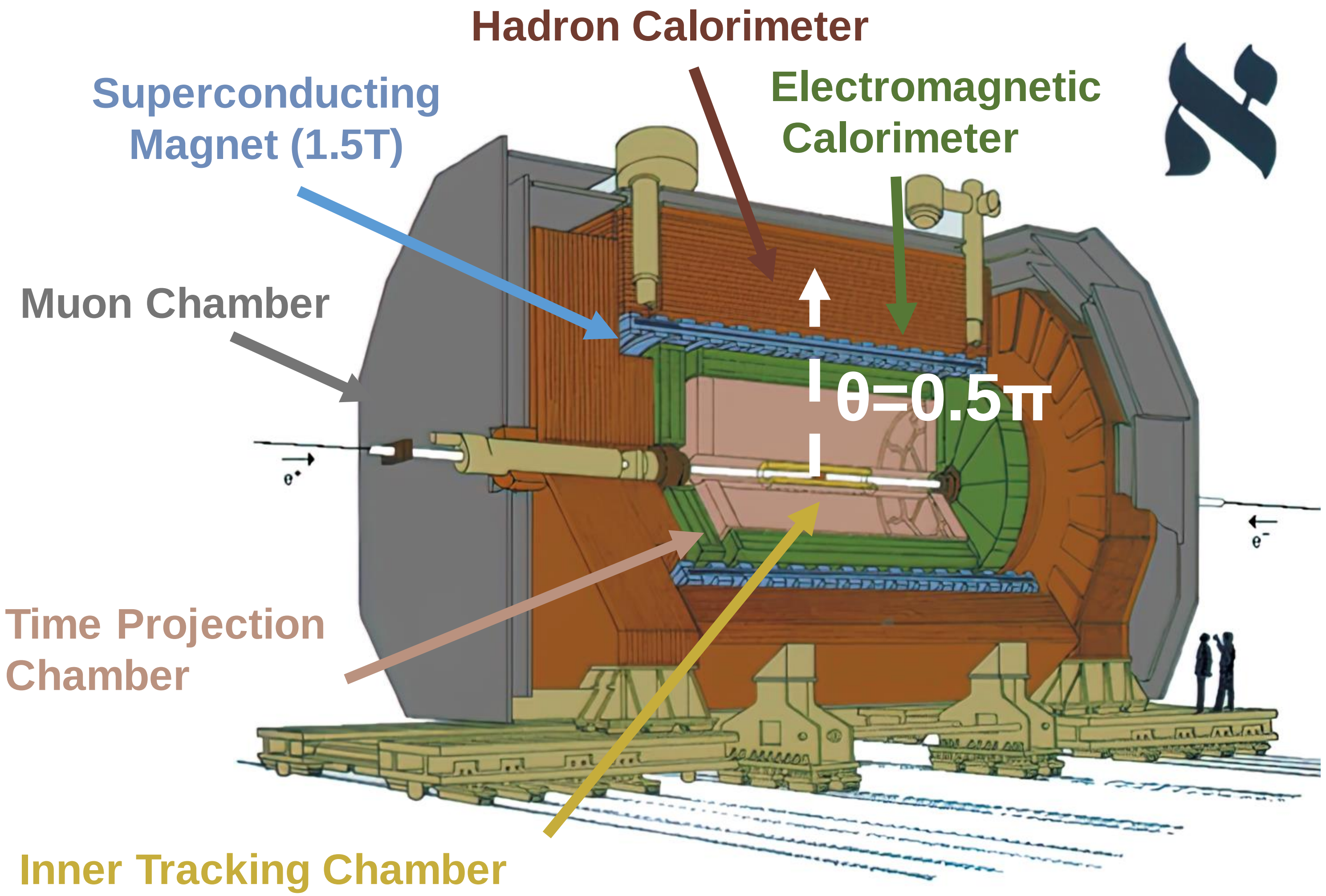
Hadronic Event Selection

- **Track Selection:**
  - Particle Flow Candidate 0, 1, 2
  - Number of TPC hits for a charged tracks >= 4
  - |d0| < 2 cm
  - |z0|< 10 cm
  - $|\cos\theta|<0.94$
  - p_T> 0.2 GeV (transverse momentum with respect to beam axis)
  - N_{TPC} >=4
  - x^2/ndf < 1000.

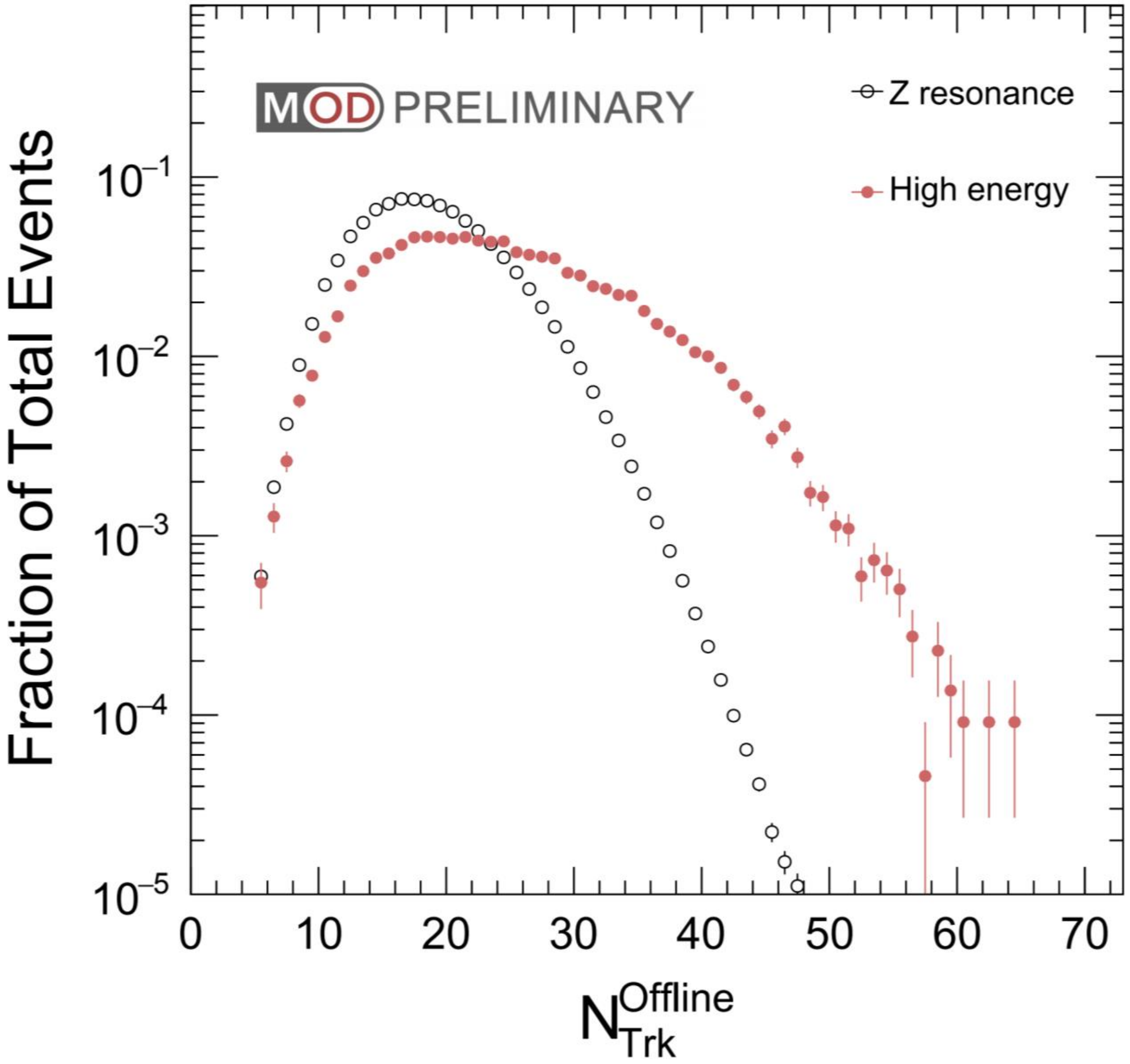
- **Neutral Hadron Selection:**
  - Particle Flow Candidate 4, 5 (ECAL / HCAL object)
  - E> 0.4 GeV
  - $|\cos\theta|<0.98$

- **Event Selection:**
  - Number of good charged particles >= 5 (including charged hadrons and leptons)
  - Number of good ch+neu. Particles >= 13
  - $E_{charged}$ > 15 GeV
  - $|\cos(\theta_{sphericity})|<0.82$

The ALEPH Detector

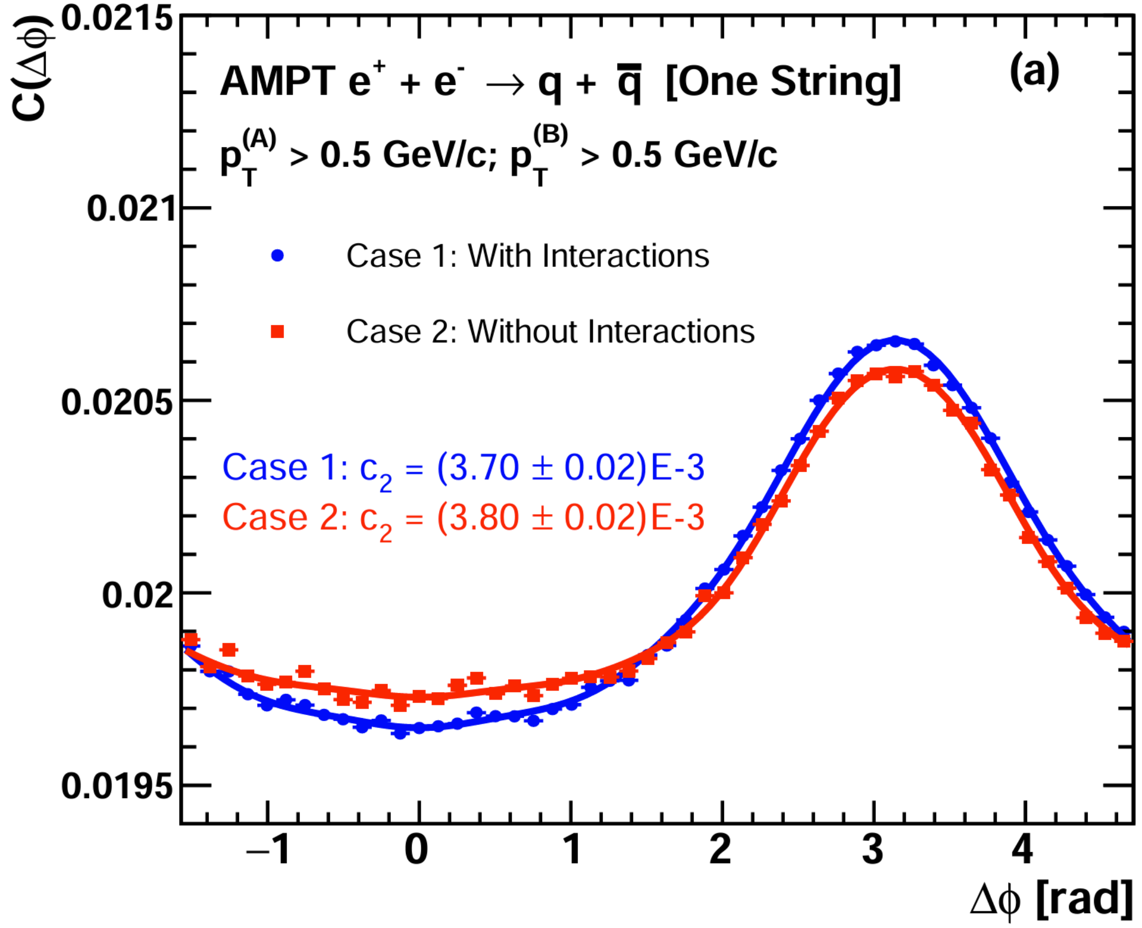


Charged Particle Multiplicity



- LEP1 e^+e^- data at Z pole (91 GeV) taken between 1992-1995
- **LEP2 e^+e^- data above Z pole up 209 GeV**
  - ~ **RHIC** energy

Example: One-String Configuration Study with AMPT



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