What Have We Learned from e^+e^-, ep, eA, MB pp and UPC Collectivity Experimental Searches?

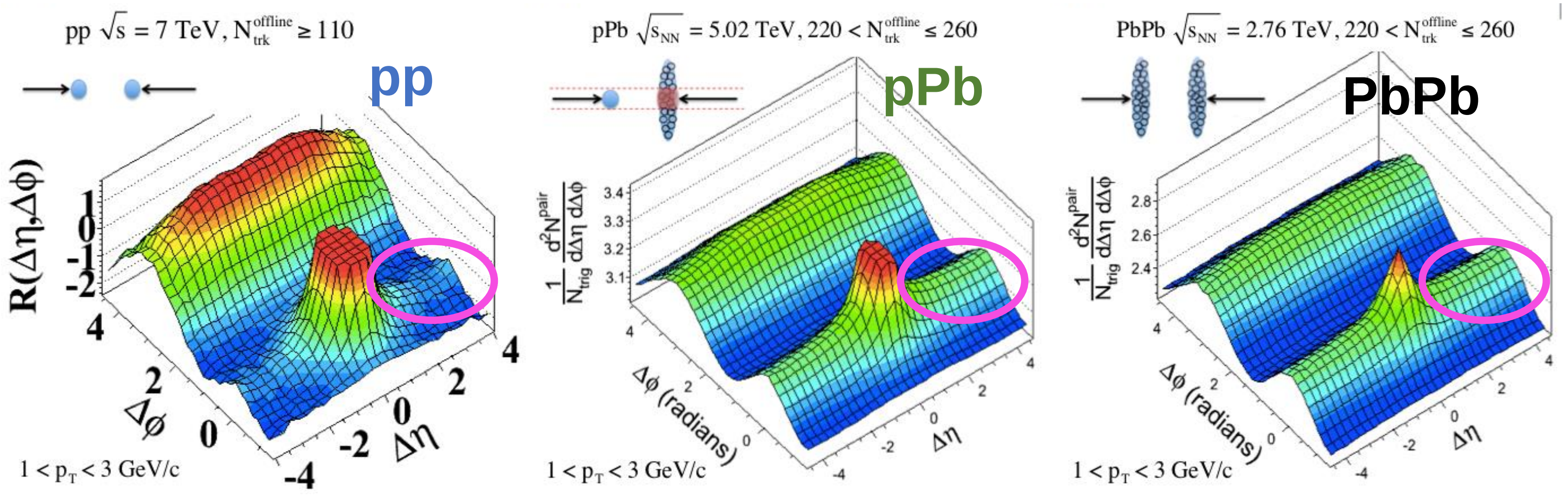
Yen-Jie Lee

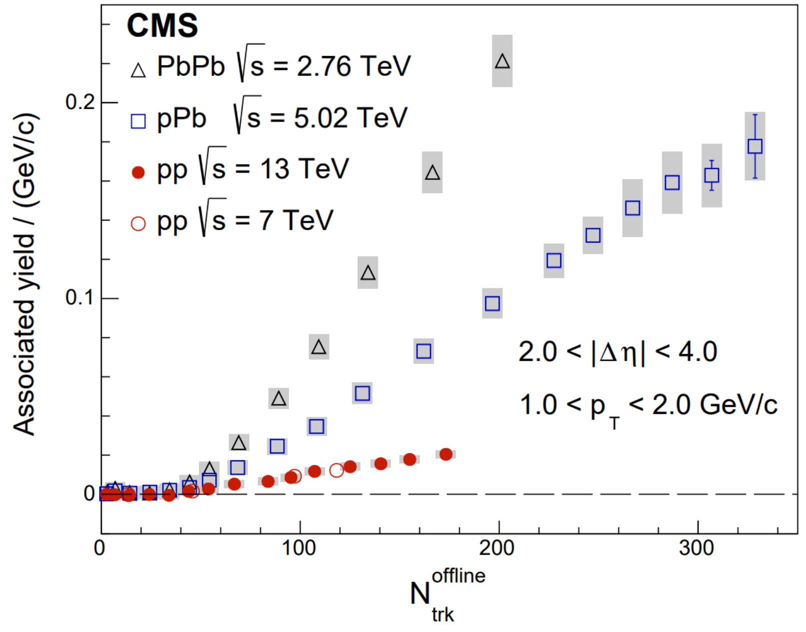
The VII-th International Conference on the Initial Stages of High-Energy Nuclear Collisions, Copenhagen, Denmark

22 June, 2023

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

Motivation





- **The first unexpected discovery at LHC: Ridge** in high multiplicity pp from CMS

* Debojit Sarkar's summary talk on recent results

- 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, …)
  - Final state effect due to mini-QGP
  - …

* Yuuka Kanakubo's talk on collectivity from few scatterings

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?

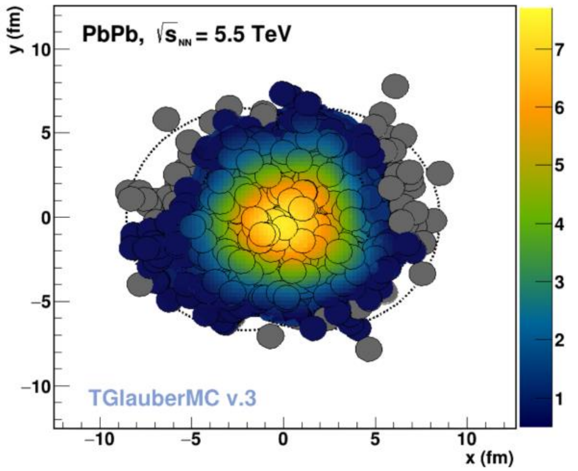
  By collection of all the experimental data and compare

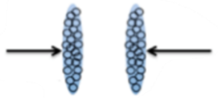
- …

System Size

"Transverse Size" / MPI

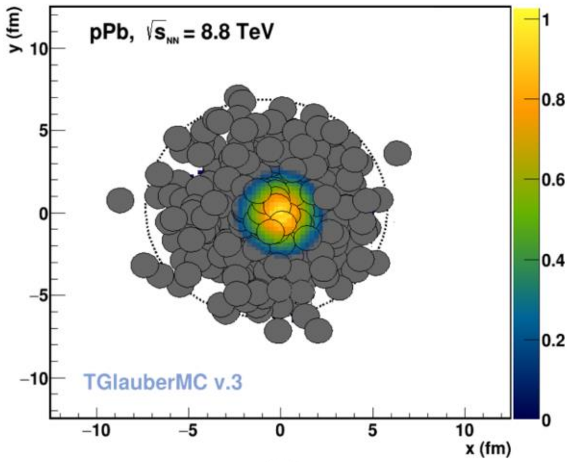
AA

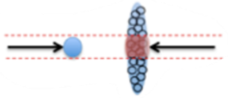




O(1-10 fm)

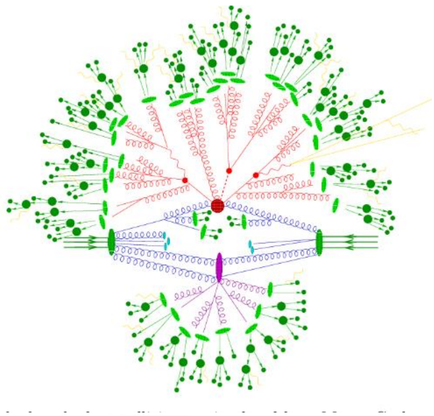
pA





≥ O(1fm)

pp



~ O(1fm)

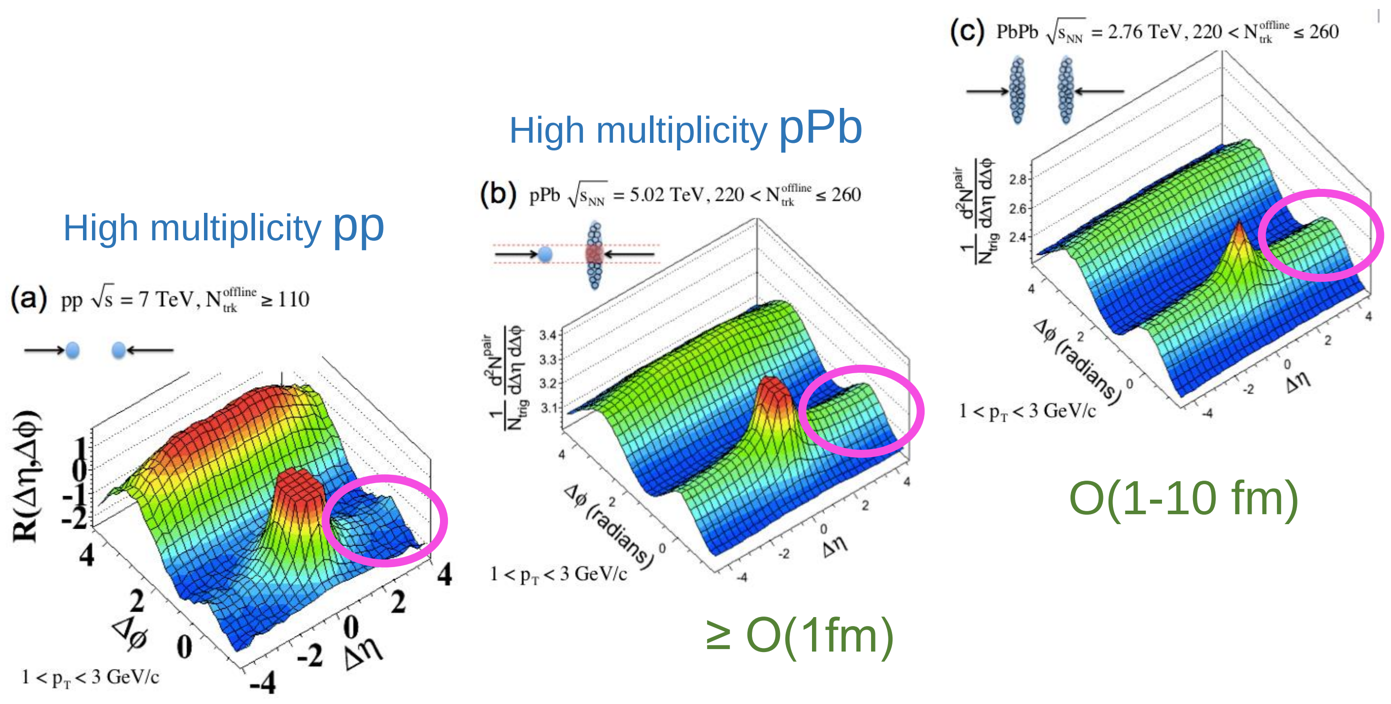
Multiplicity

Smallest System: e^+e^-

“Transverse Size” / MPI

High multiplicity pp

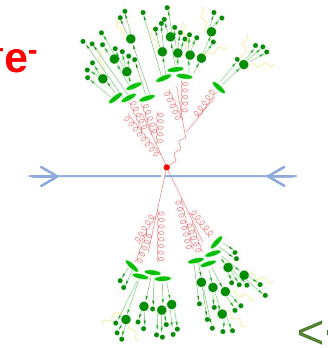
High multiplicity pPb



O(1-10 fm)

≥ O(1fm)

~ O(1fm)



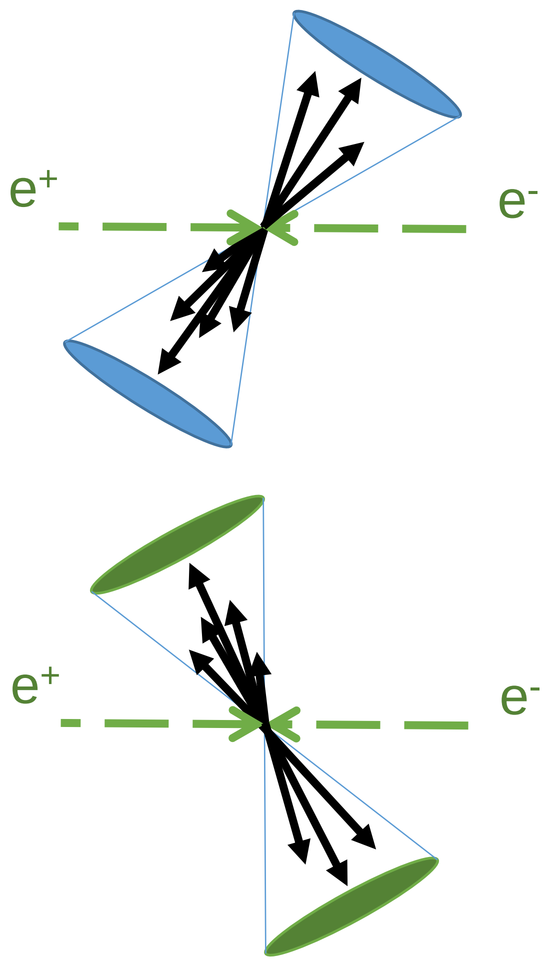
<< 0.1 fm

Multiplicity

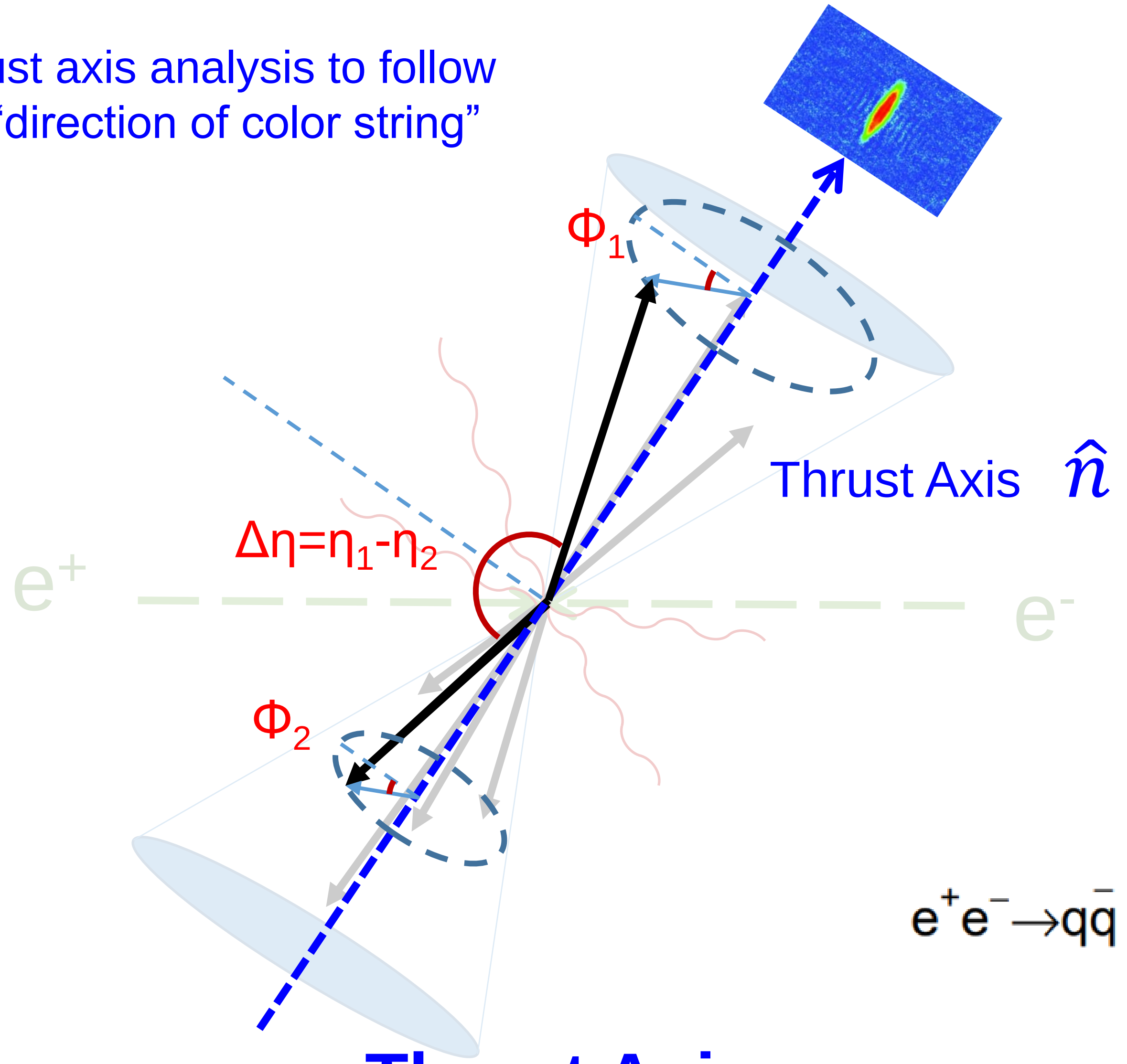
- e^+e^- events: collisions with **well-defined initial conditions**
  - No complication from hadron structure
  - No multi-parton interaction
  - No gluonic initial state radiation

Reference Axis for e^+e^-

Random orientation of the jets



Thrust axis analysis to follow the “direction of color string”

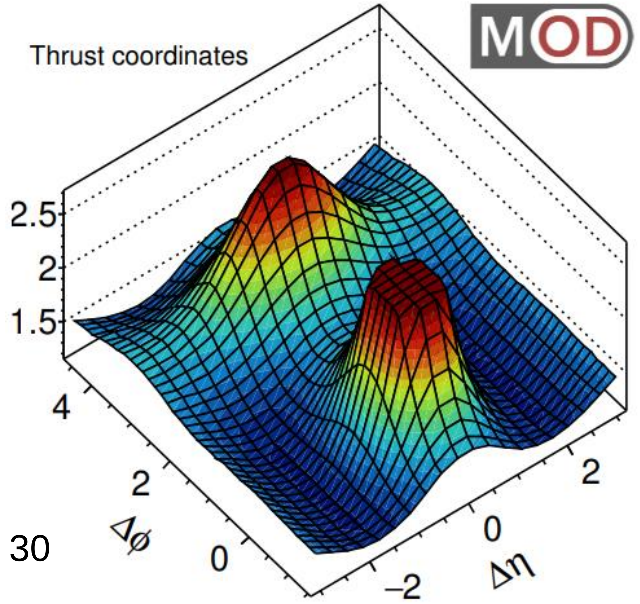


Thrust Axis

Sensitive to **“medium expansion”** perpendicular to the **Thrust axis**

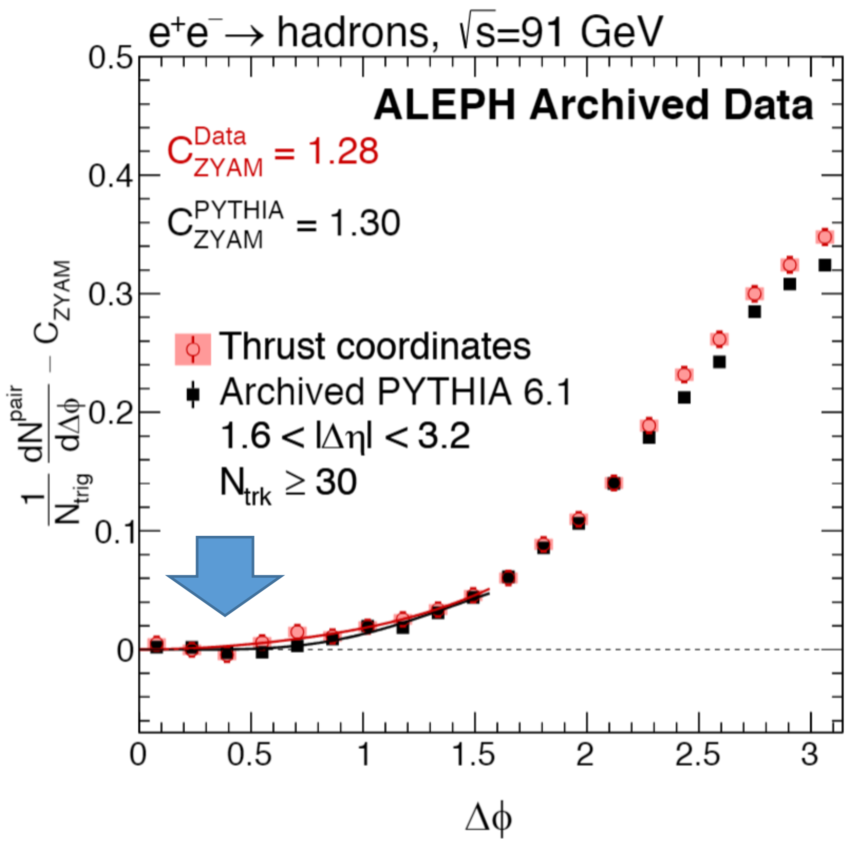
e^+e^- at 10.52 (Belle) and 91 GeV (ALEPH)

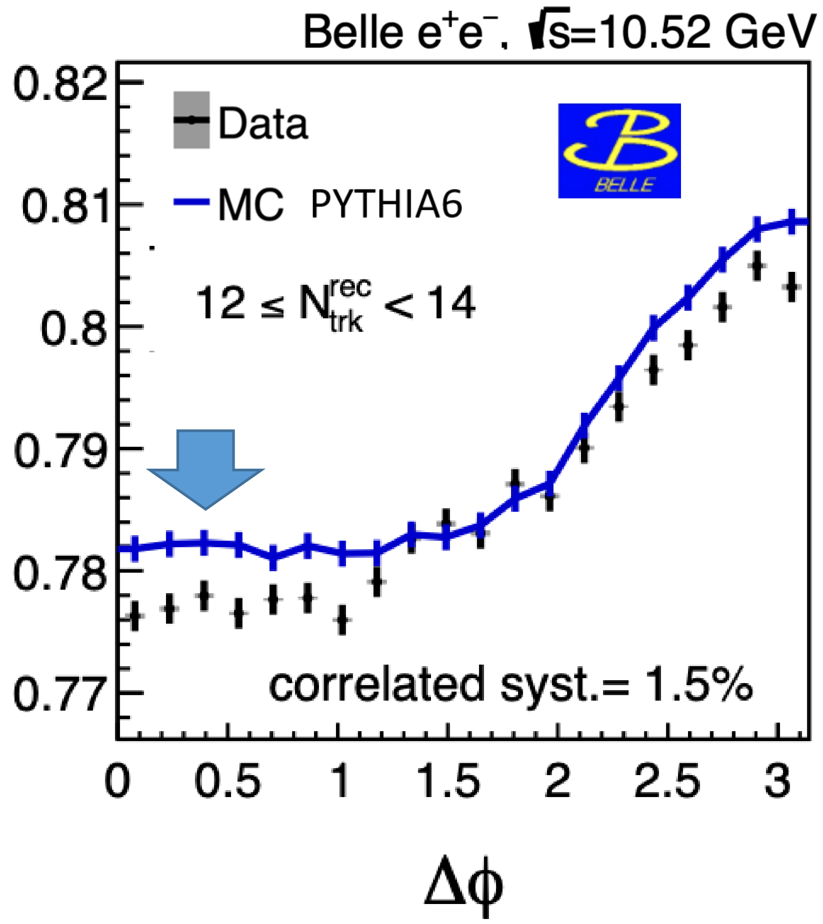
91 GeV



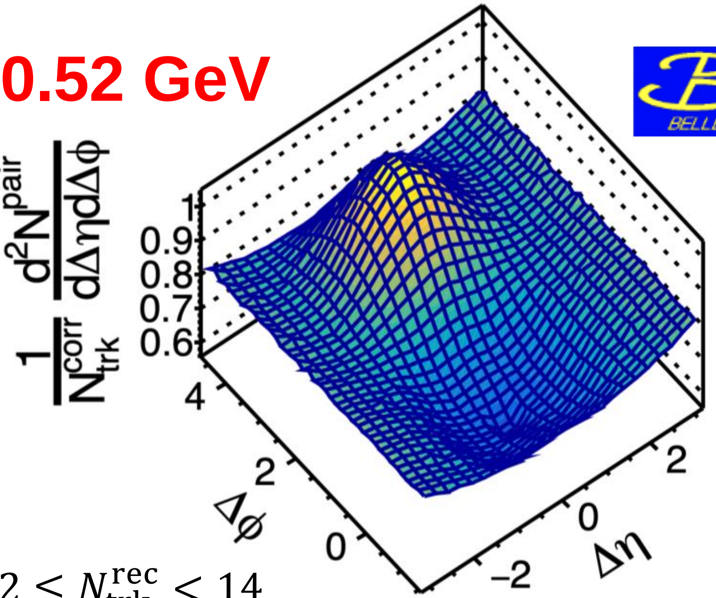
$N_{\mathrm{trk}}^{\mathrm{rec}} > 30$

Thrust





10.52 GeV



$12 \leq N_{\mathrm{trk}}^{\mathrm{rec}} < 14$

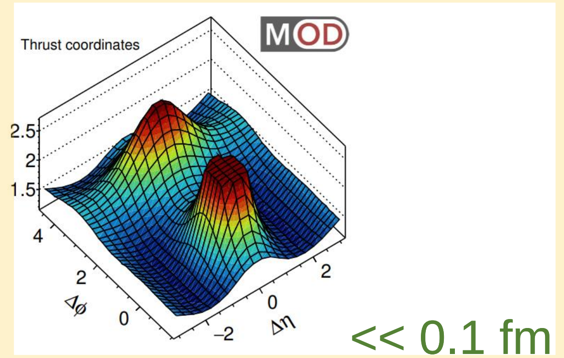
- No sign of ridge signal in high multiplicity electron-positron collisions up to ~35 charged particles per event
- New reference to the collective behavior in small systems!

ALEPH archived data PRL 123, 212002 (2019)

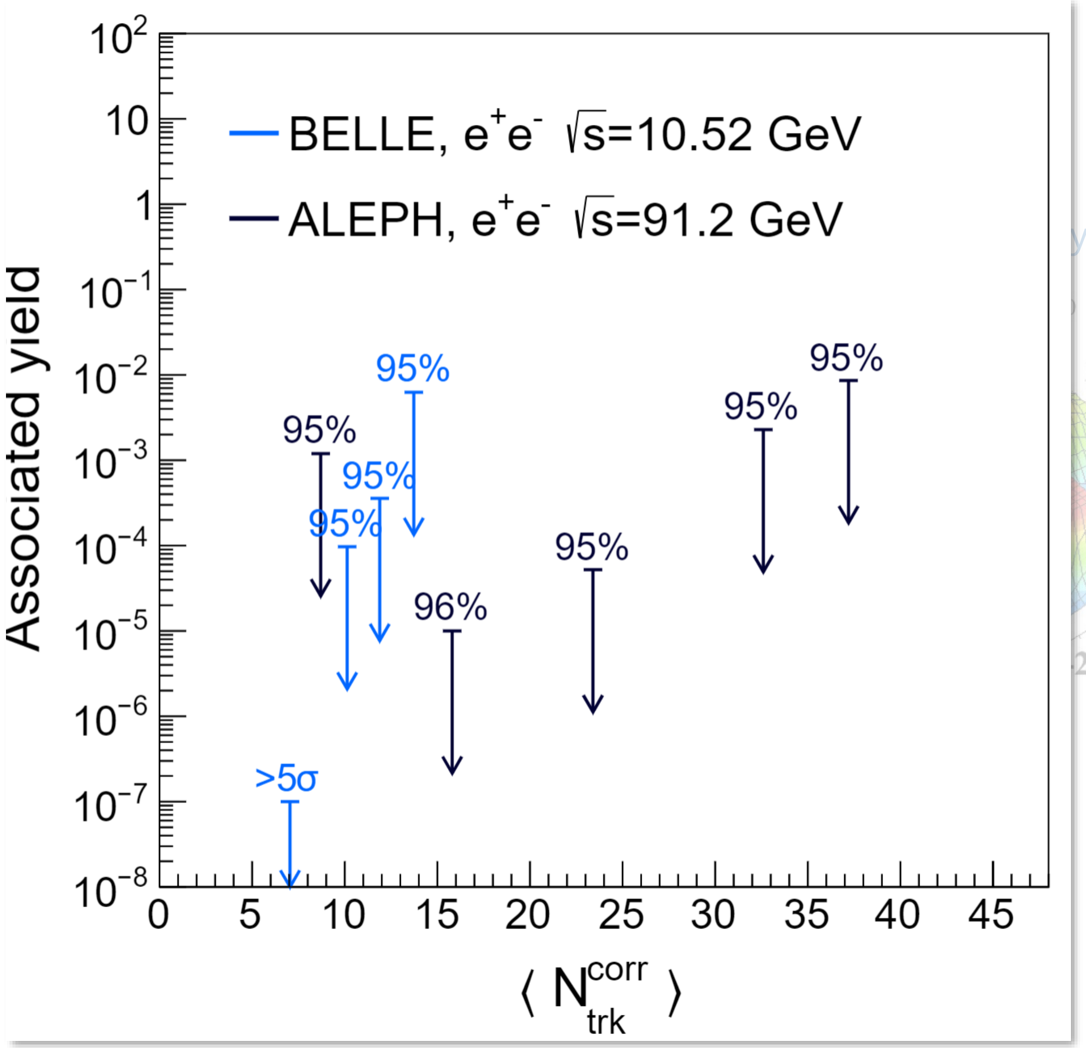
Compilation of Ridge Yield Limit in e^+e^- collisions

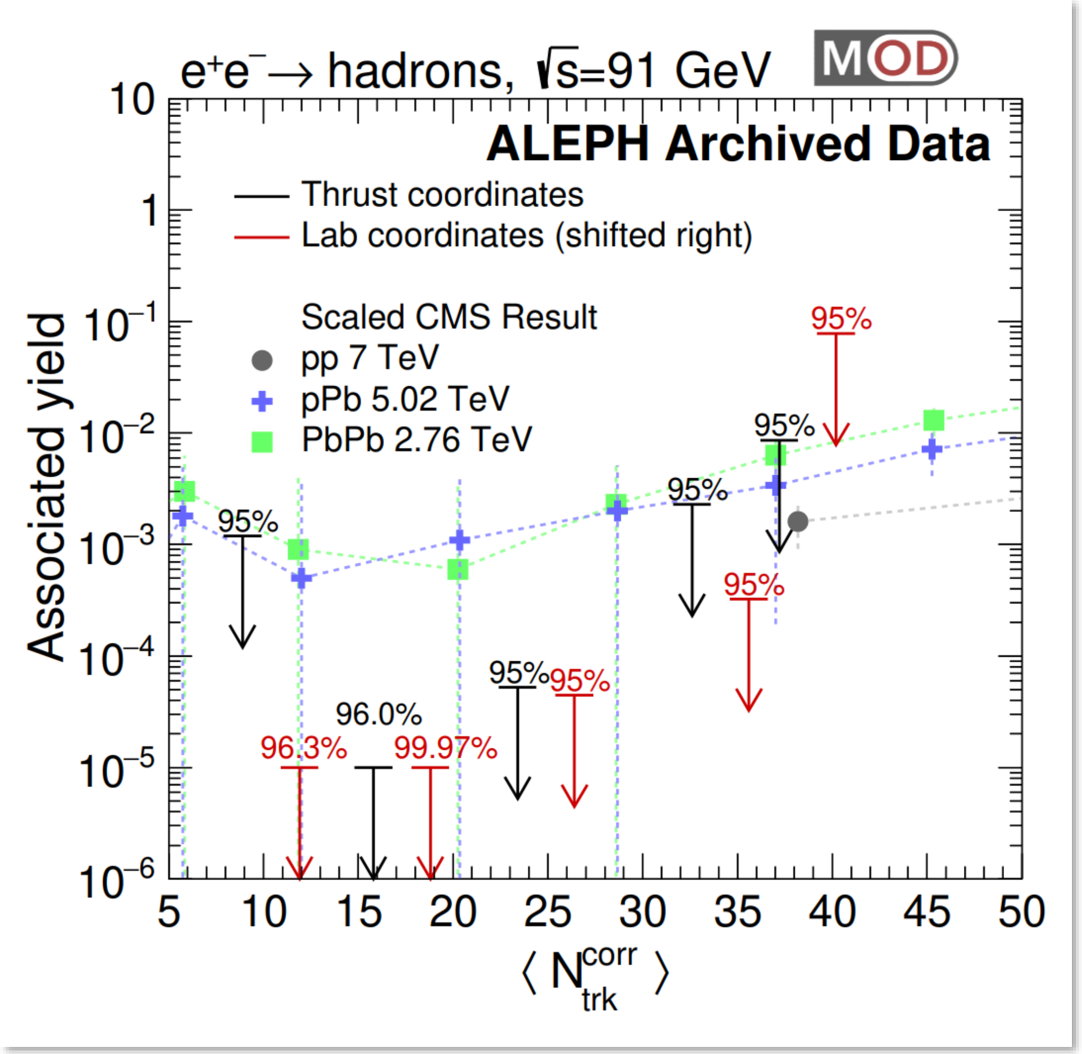
"Transverse Size"

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)

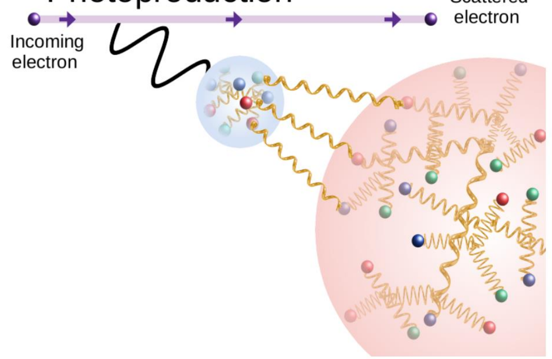
Multiplicity

System Size

"Transverse Size" / MPI

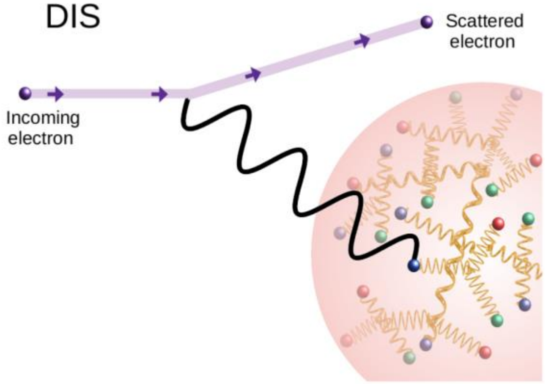
$1/\Lambda_{QCD}$ ~ 1 fm

Photoproduction



(b) *Resolved photoproduction.*

DIS



(a) *Neutral current deep inelastic scattering.*

1/Q < 0.2 fm

e^+e^-

<< 0.1 fm

High multiplicity pp

~ O(1fm)

High multiplicity pPb

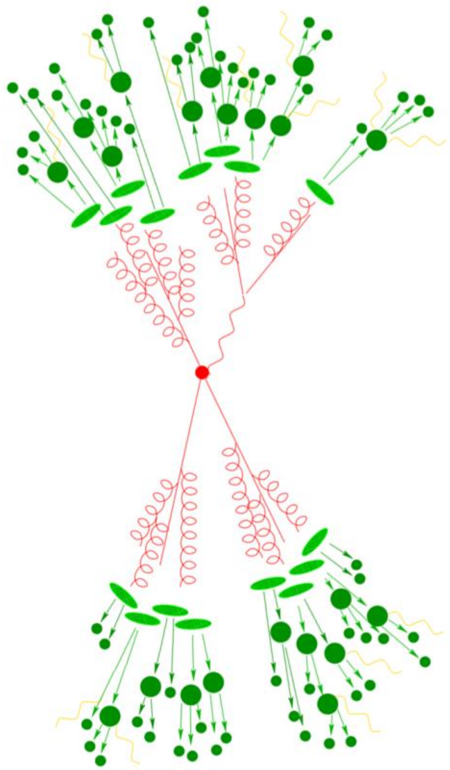
≥ O(1fm)

O(1-10 fm)

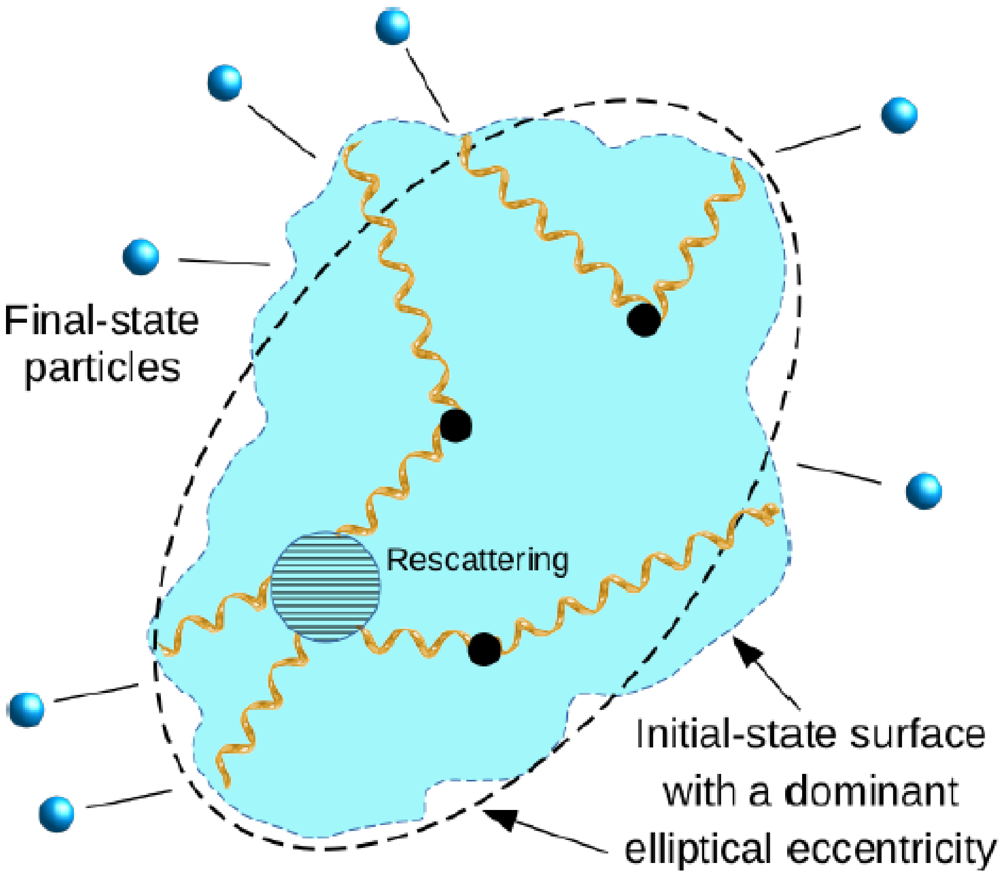
Multiplicity

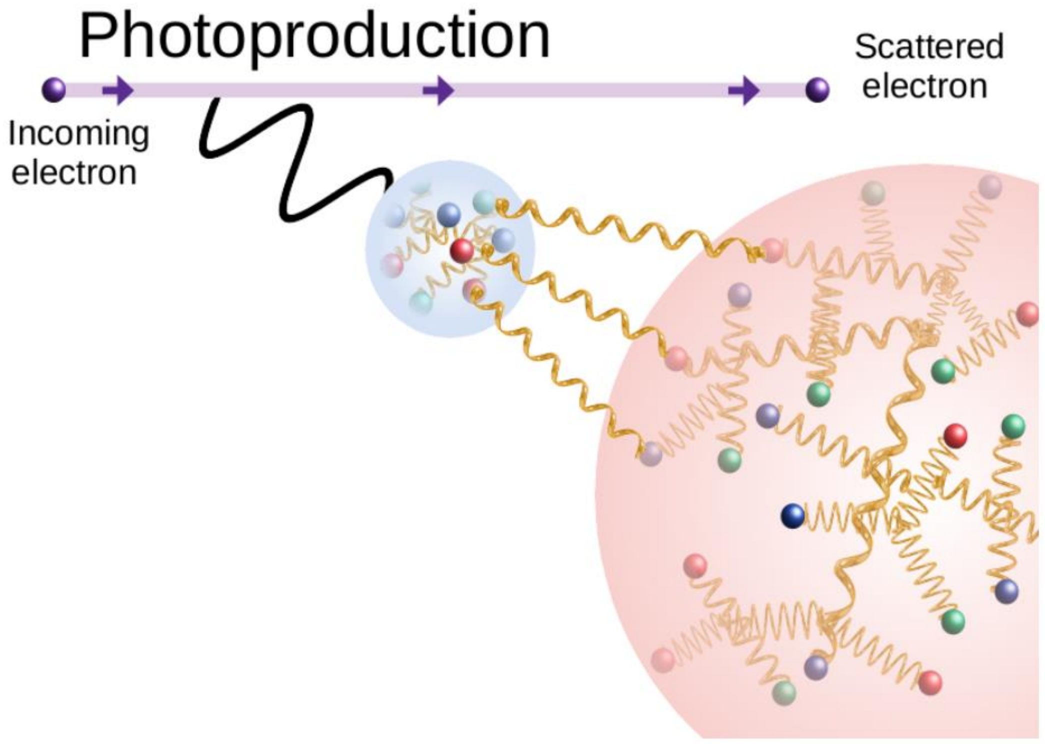
Multiple Parton Interaction (MPI)

Single $q\bar{q}$ pair



MPI





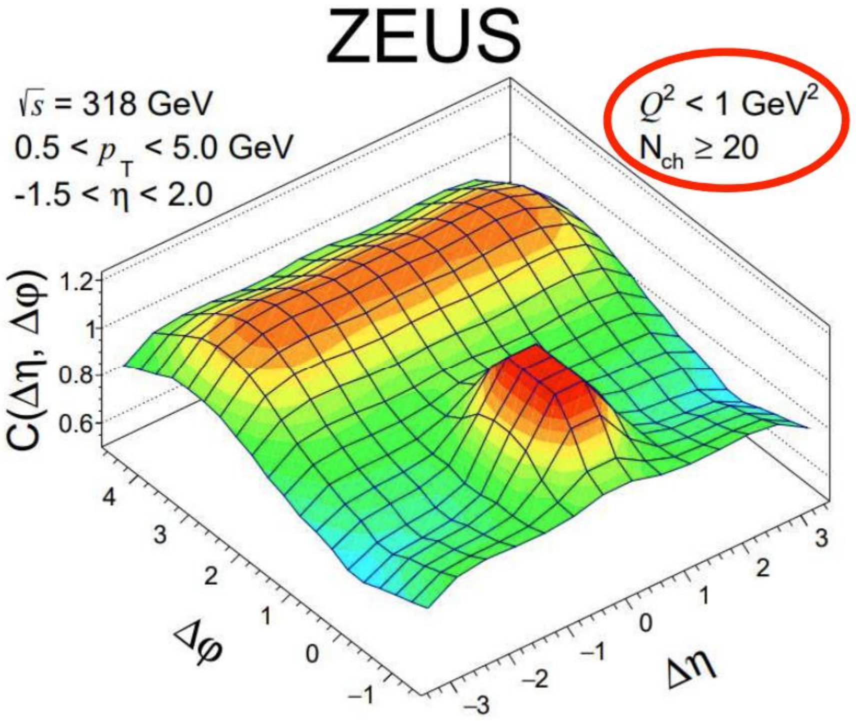
(b) *Resolved photoproduction.*

See for instance J. Nagle *et. al*, PRC 97 (2018) 2, 024909

Correlation Function in **ep** at 318 GeV with HERA

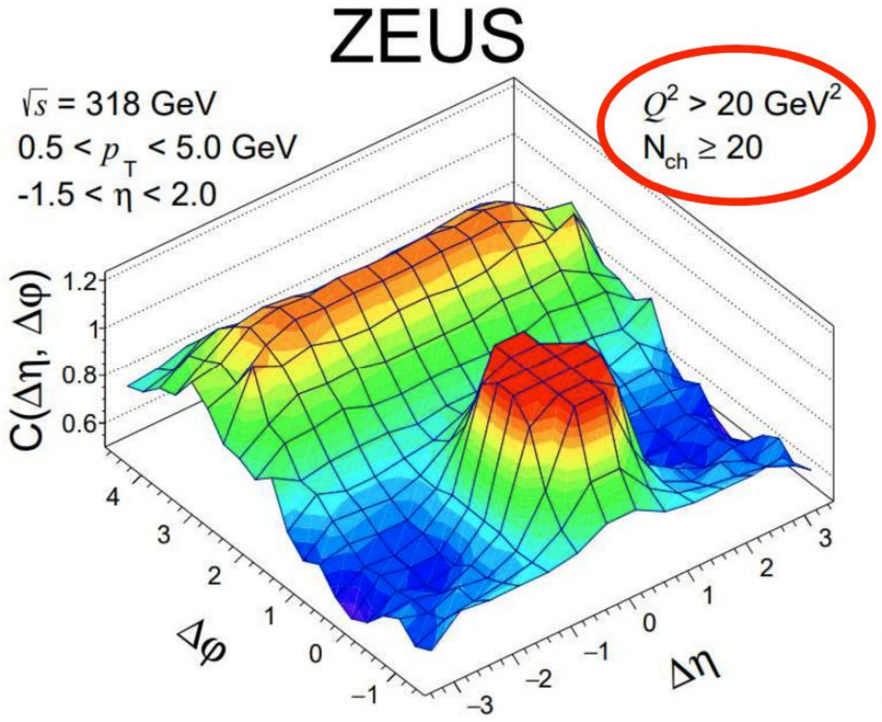
Photoproduction

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

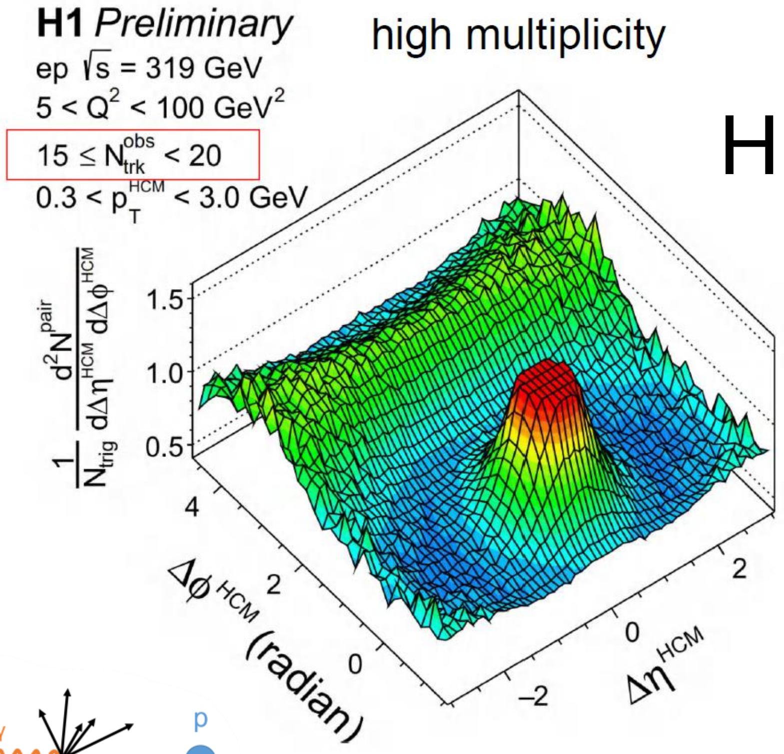


DIS

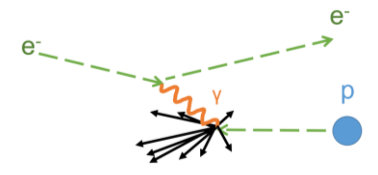
$1/Q < 0.2$ fm



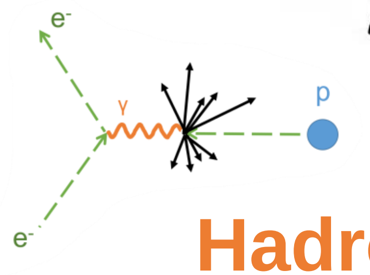
DIS



H1



Lab Frame



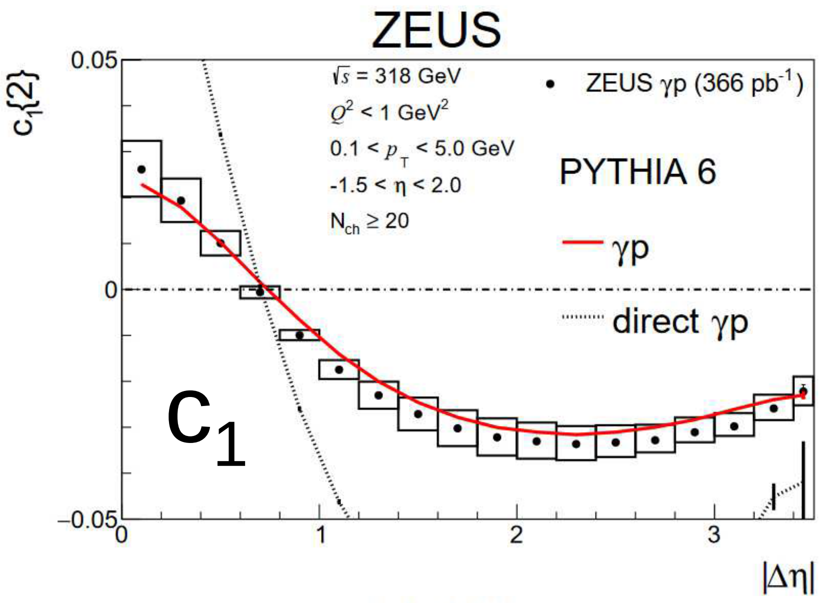
Hadronic CM Frame

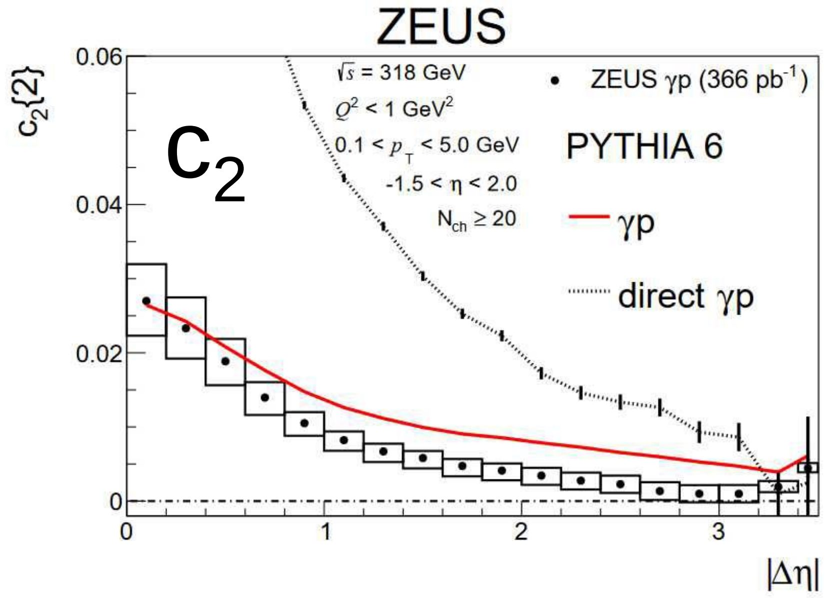
- ZEUS search in lab frame: No significant ridge-like signal in both photoproduction and DIS data with $N_{ch} > 20$

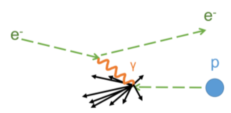
ZEUS DIS JHEP 04 (2020) 070
ZEUS Photoproduction JHEP 12 (2021) 102

- No significant ridge-like signal in H1 search in Hadronic CM Frame (Up to N_{ch} = 20)

Searches at HERA (ep Collisions) and CMS γp

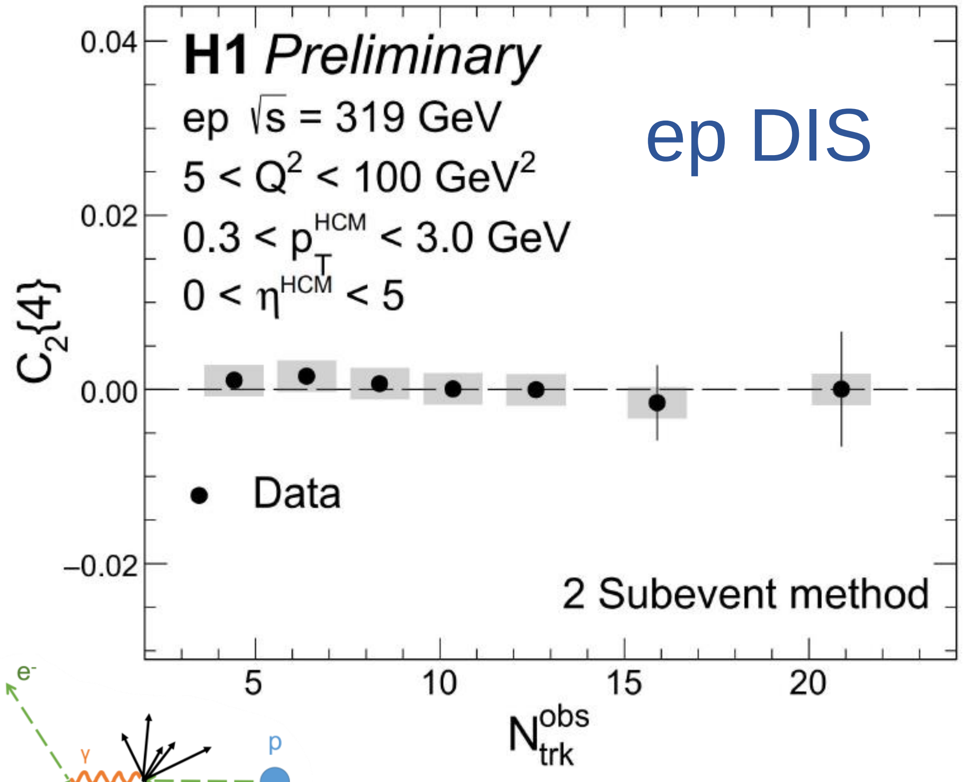


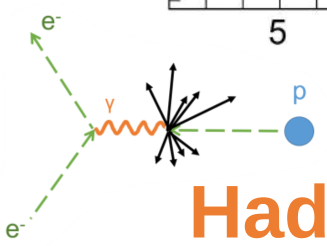




ep Photoproduction

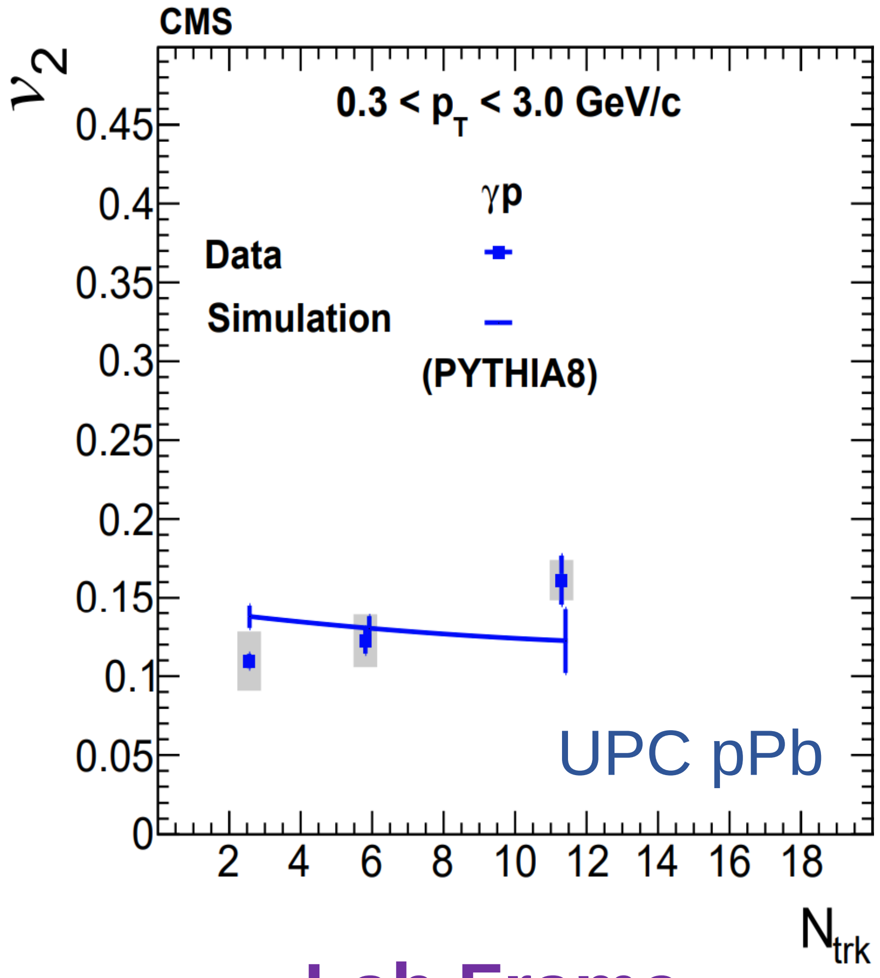
Lab Frame





Hadronic CMS Frame

- At high |Δη|: Large negative $c_1\{2\}$ in **ep**
- Different from the **PbPb** which features a **large v_2** compared to **v_1**
- No significant $c_2\{4\}$ in the investigated multiplicity range



Lab Frame

- γp in pPb UPC at 8.16 TeV
- PYTHIA8 describes the v_2 data at low N_{trk}

<MPI> vs. Multiplicity

Increase the MPI

High multiplicity pp

High multiplicity pPb

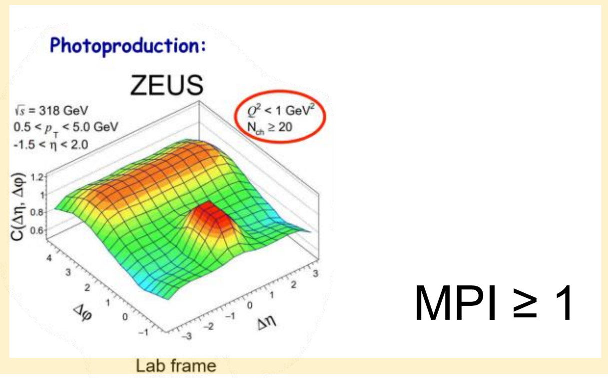
~ O(1fm)

≥ O(1fm)

O(1-10 fm)

Large MPI

.



MPI ≥ 1

"MPI"=1

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

Next steps: (1) Increase multiplicity

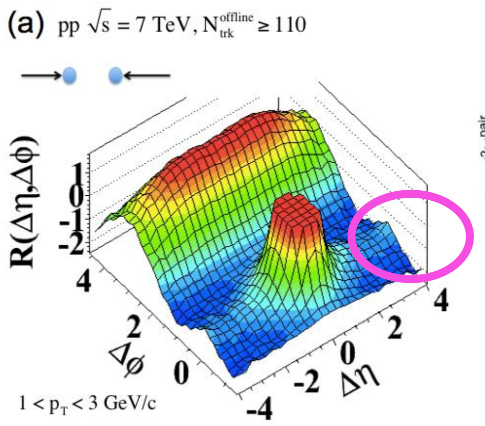
(2) Increase <MPI>

Larger multiplicity

Next Step

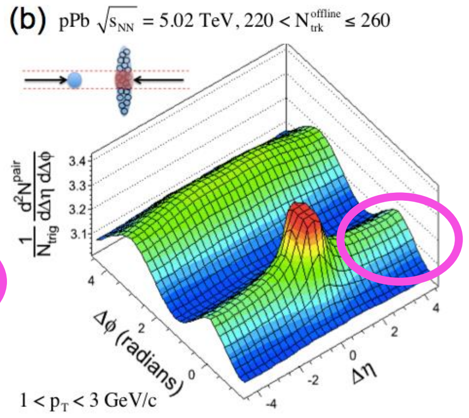
Increase the MPI

High multiplicity pp

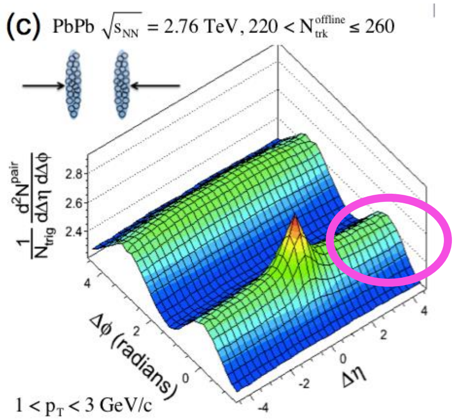


~ O(1fm)

High multiplicity pPb



≥ O(1fm)



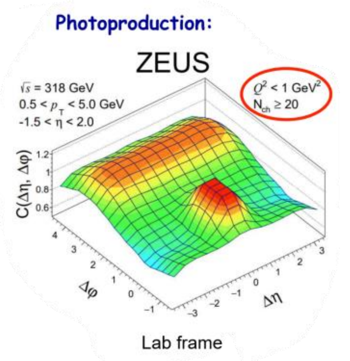
O(1-10 fm)

Large MPI

Low multiplicity pp

MPI>1

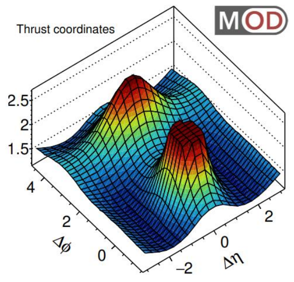
.



gamma Pb

Larger MPI than γp

MPI ≥ 1



Next steps: (1) Increase multiplicity
(2) Increase <MPI>

"MPI"=1

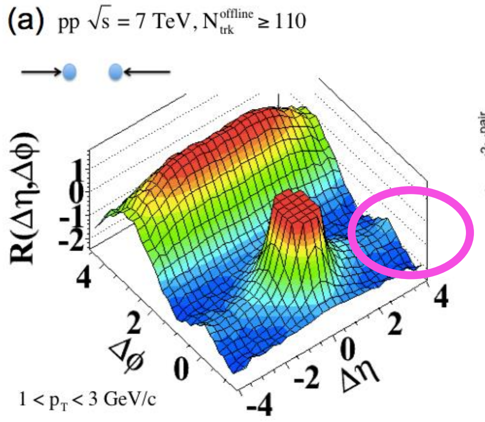
High Multiplicity Jet in pp

Larger multiplicity

(1) High Multiplicity Event with Single String Configuration

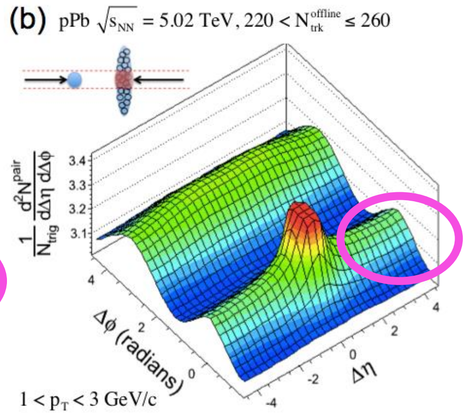
Increase the MPI

High multiplicity pp

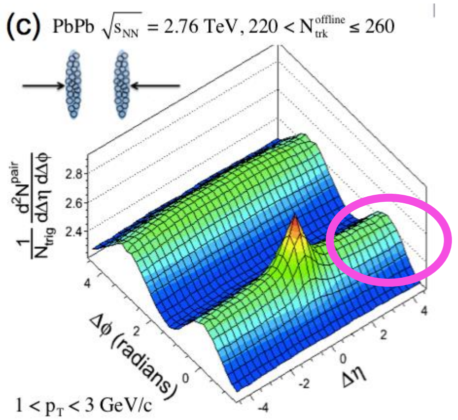


~ O(1fm)

High multiplicity pPb

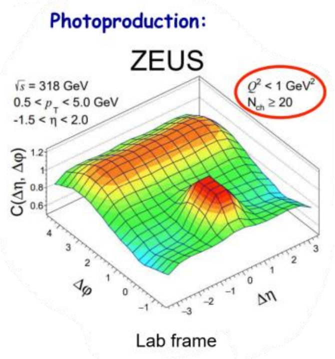


≥ O(1fm)

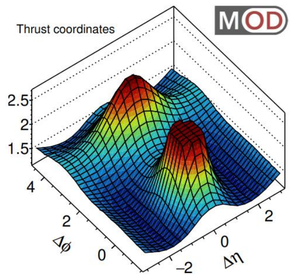


O(1-10 fm)

Large MPI



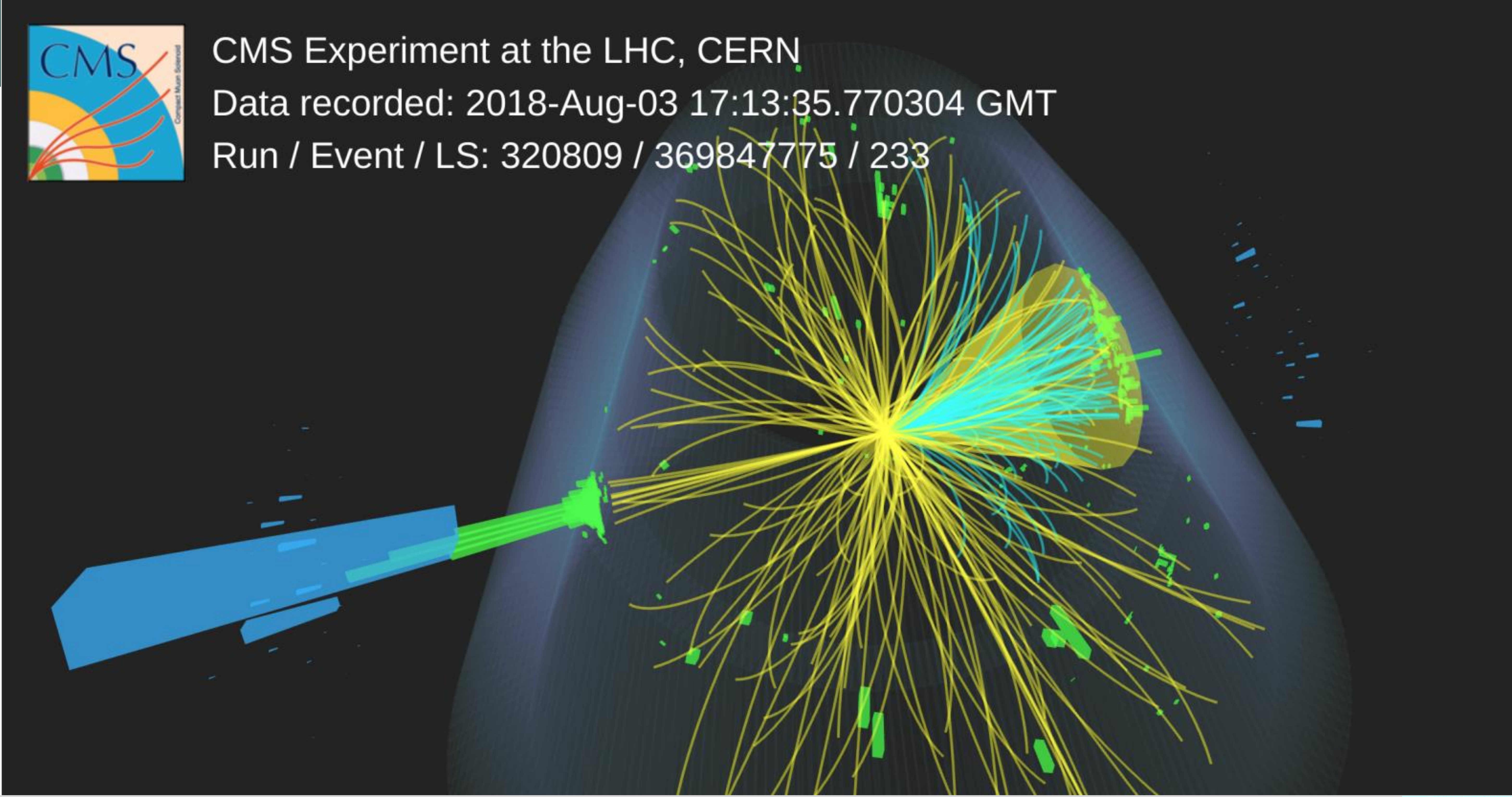
MPI ≥ 1



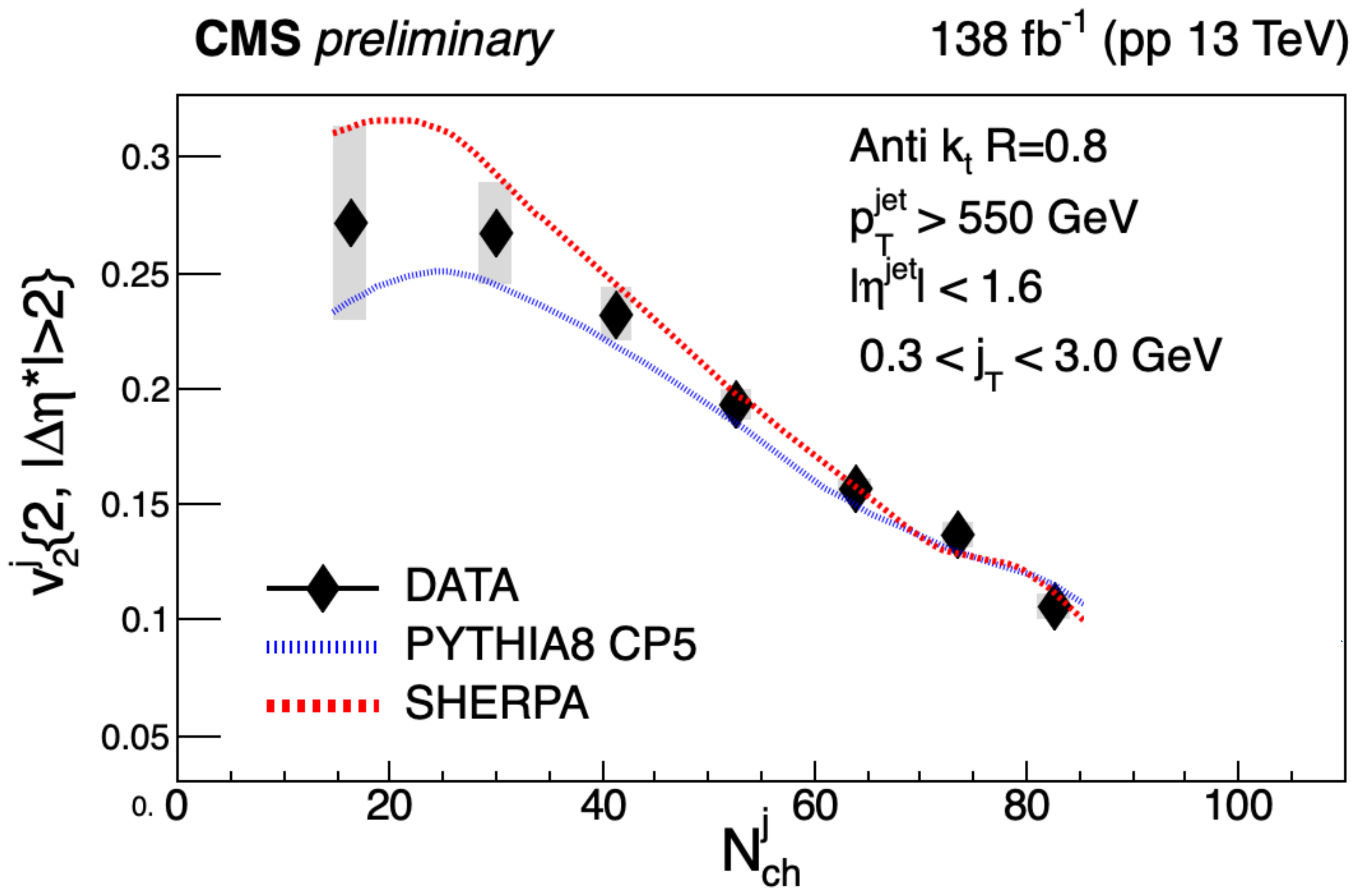
"MPI"=1

High Multiplicity Jet in pp

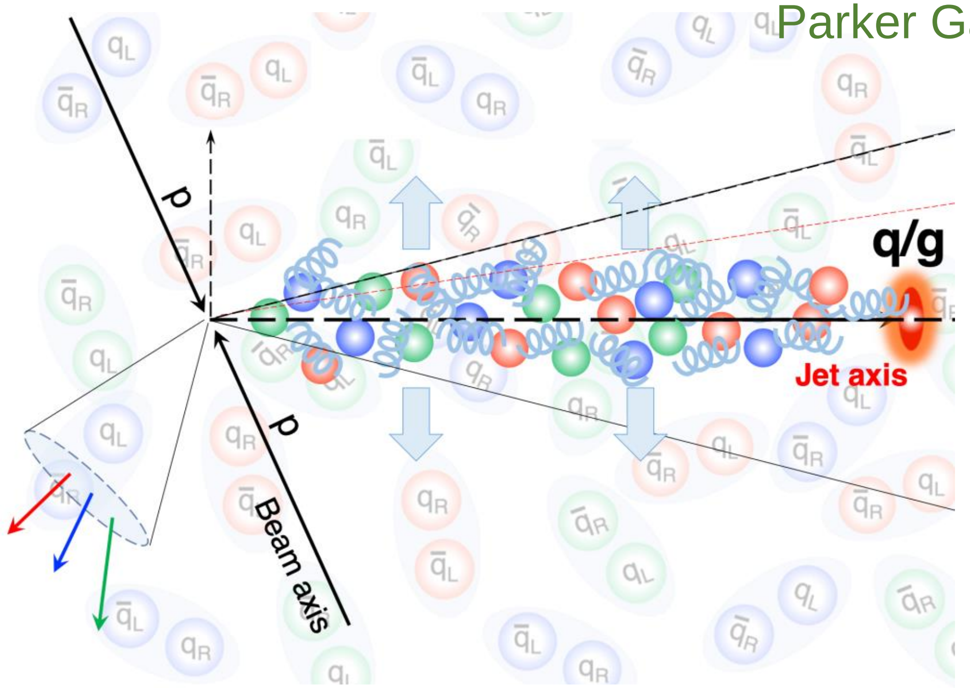
Larger multiplicity

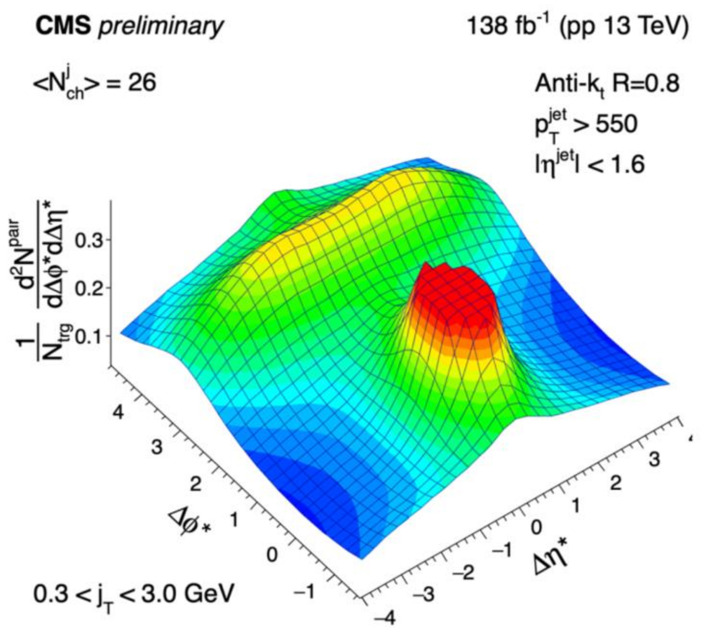

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2018-Aug-03 17:13:35.770304 GMT
Run / Event / LS: 320809 / 369847775 / 233

Single High Multiplicity Jet



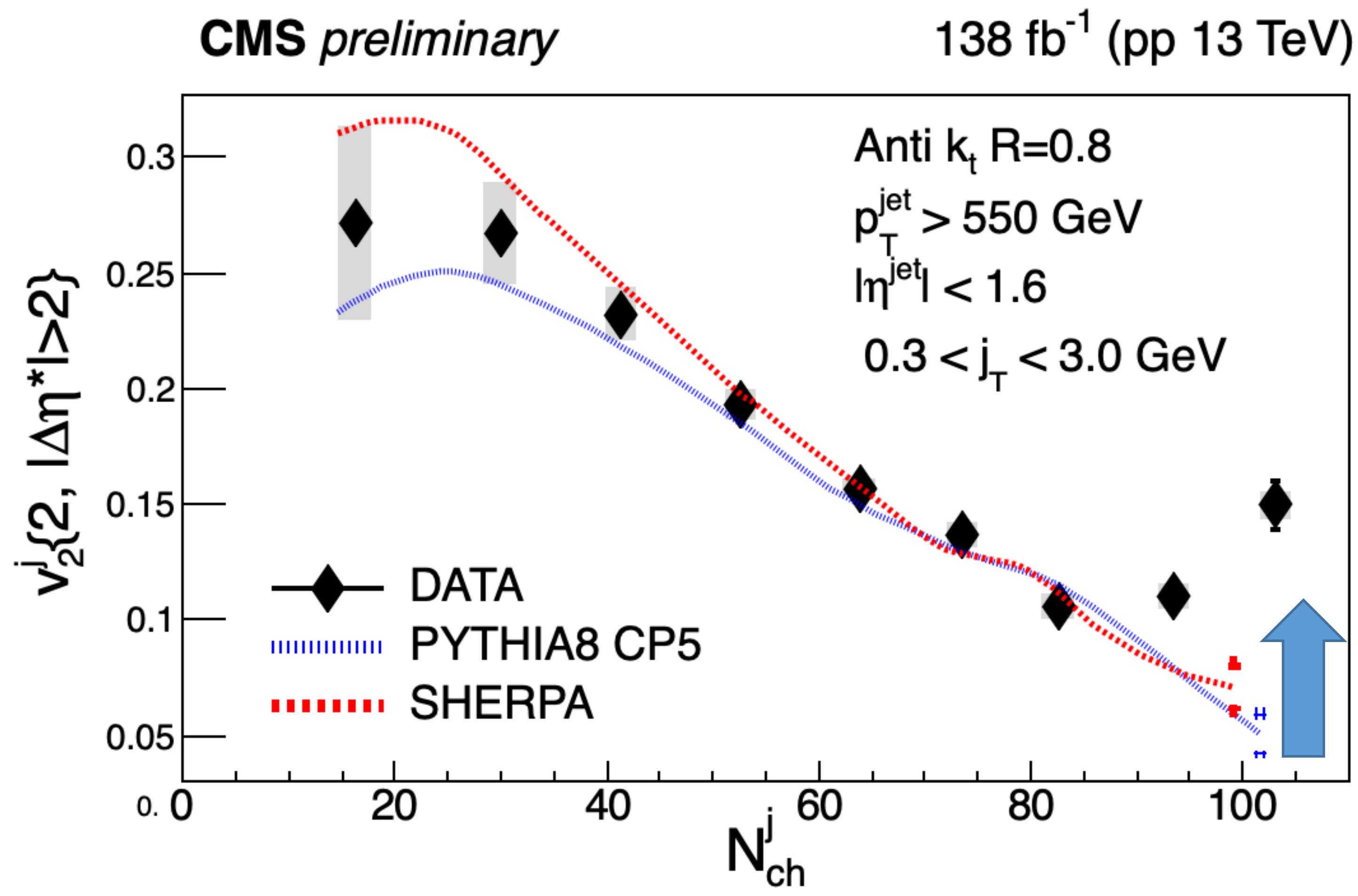
Parker Gardner (Rice)



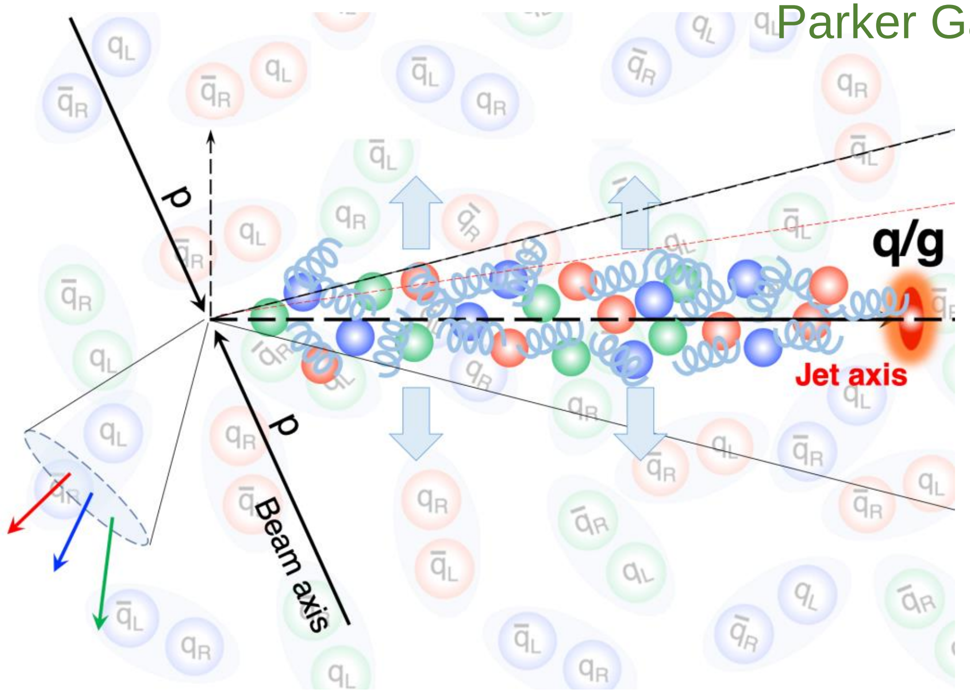


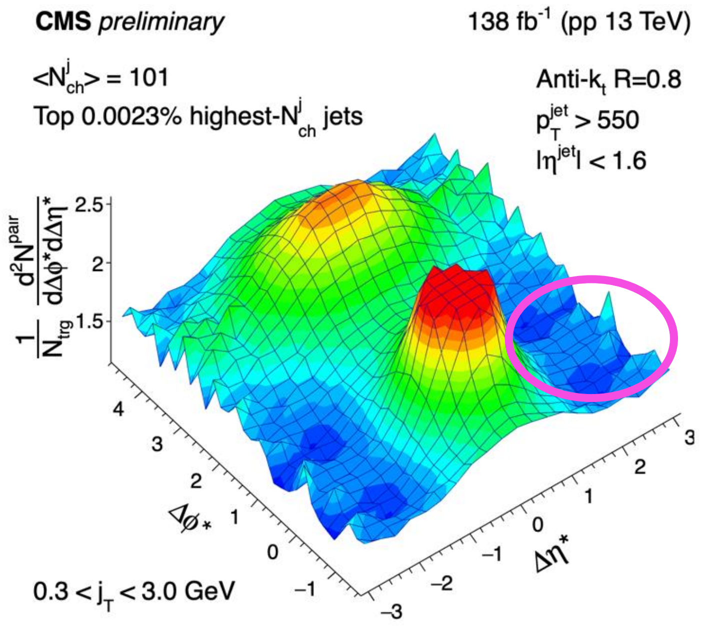
- N_{ch} < 90: **PYTHIA8** and **SHERPA** can effectively describe the data.

Single High Multiplicity Jet



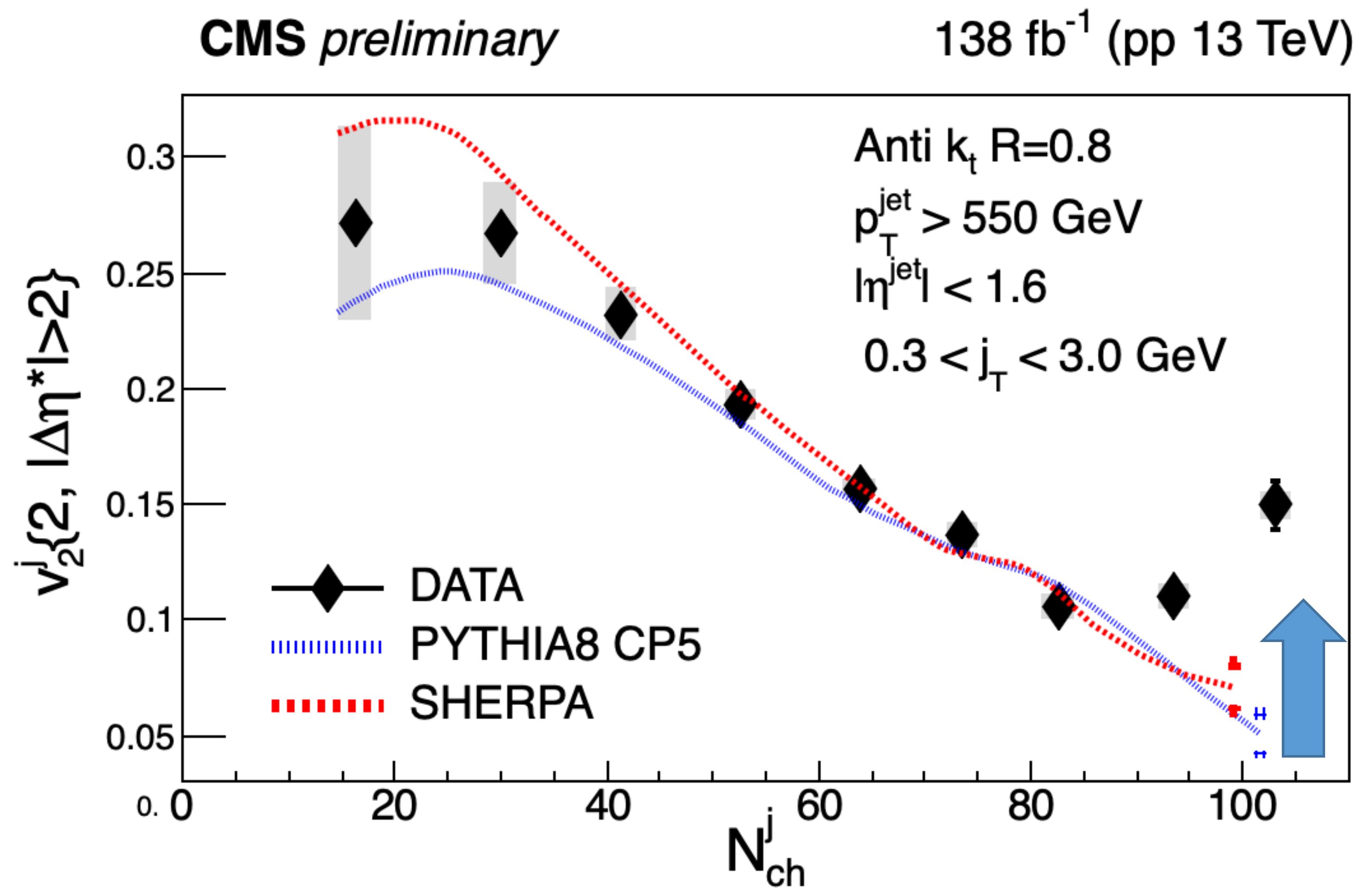
Parker Gardner (Rice)

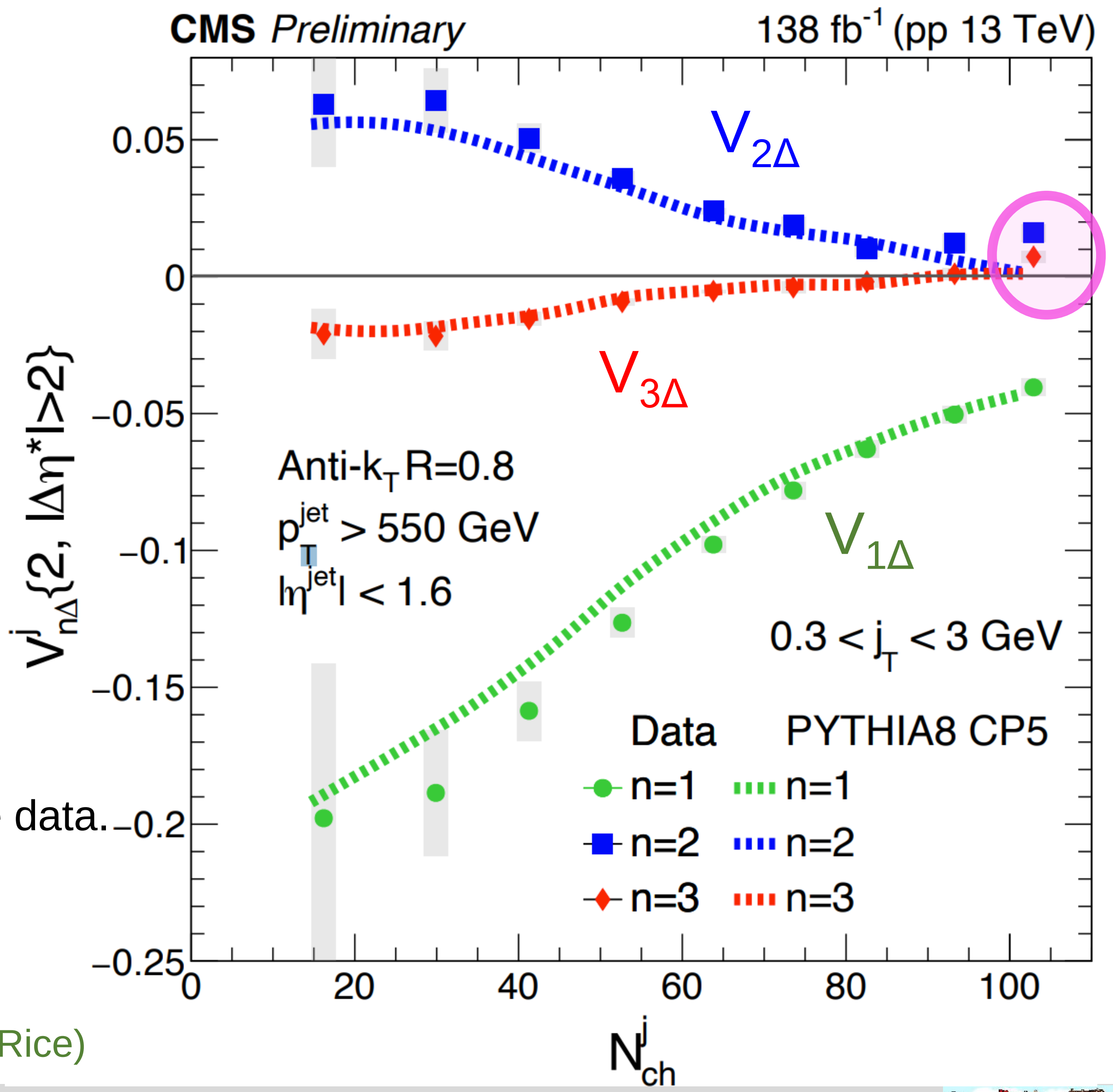




- N_{ch} < 90: **PYTHIA8** and **SHERPA** can effectively describe the data.
- At high multiplicity (N_{ch} > 90), the data v_2 deviates from the decreasing trend observed in the MC

Single High Multiplicity Jet





- N_{ch} < 90, **PYTHIA8** and **SHERPA** can effectively describe the data.
- At high multiplicity (N_{ch} > 90), the data v_2 deviates from the decreasing trend observed in the MC
- **v_3** become **positive** in data

Parker Gardner (Rice)

(1) High Multiplicity Event with Single String Configuration

Increase the MPI

High multiplicity pp

High multiplicity pPb

~ O(1fm)

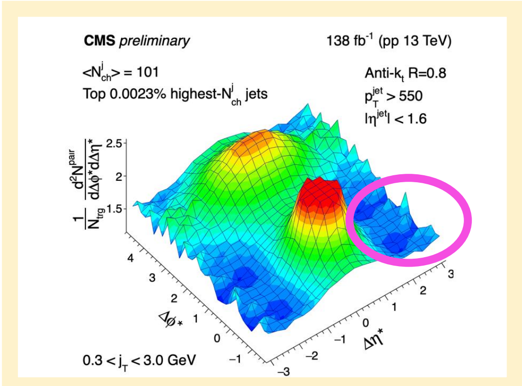
≥ O(1fm)

O(1-10 fm)

Large MPI

MPI ≥ 1

"MPI"=1



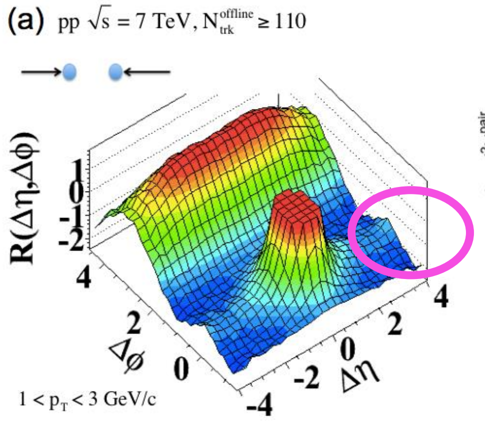
A single string configuration can generate a ridge-like structure at high multiplicity

Increase multiplicity

(2) Look into Events with Larger <MPI>

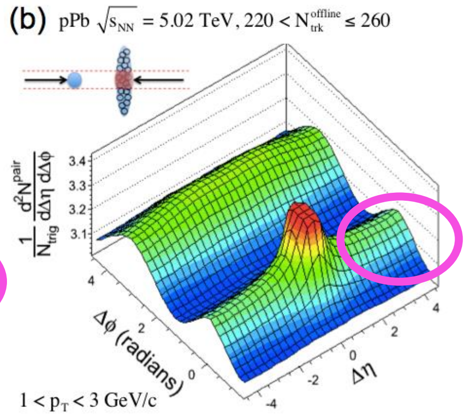
Increase the MPI

High multiplicity pp

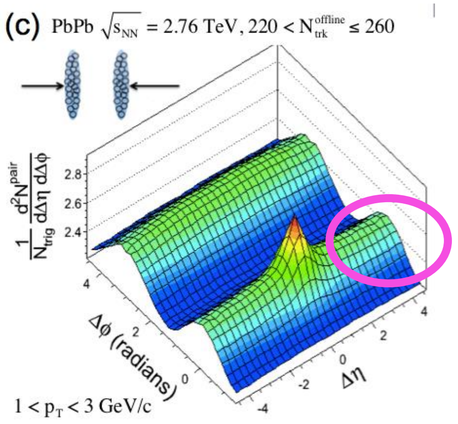


~ O(1fm)

High multiplicity pPb



≥ O(1fm)

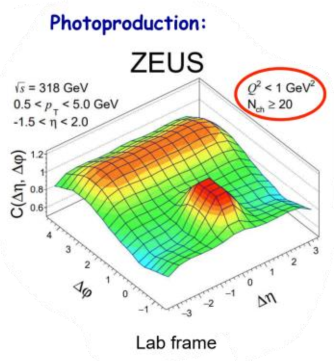


O(1-10 fm)

Large MPI

Low multiplicity pp

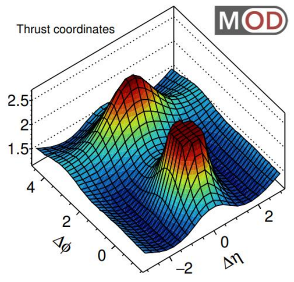
MPI>1



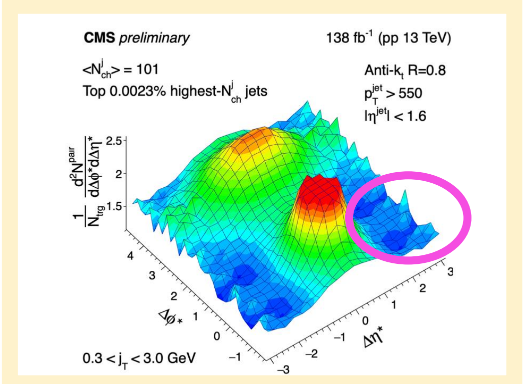
gamma Pb

MPI ≥ 1

Larger MPI than γp



"MPI"=1

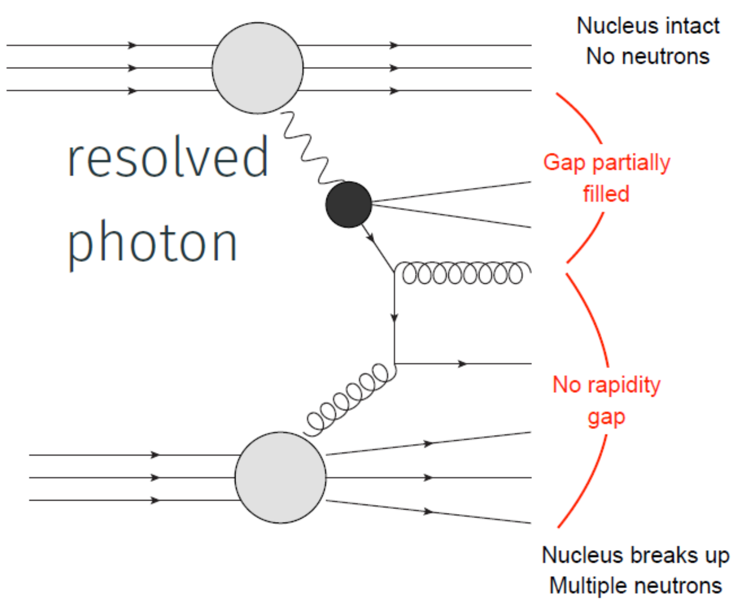


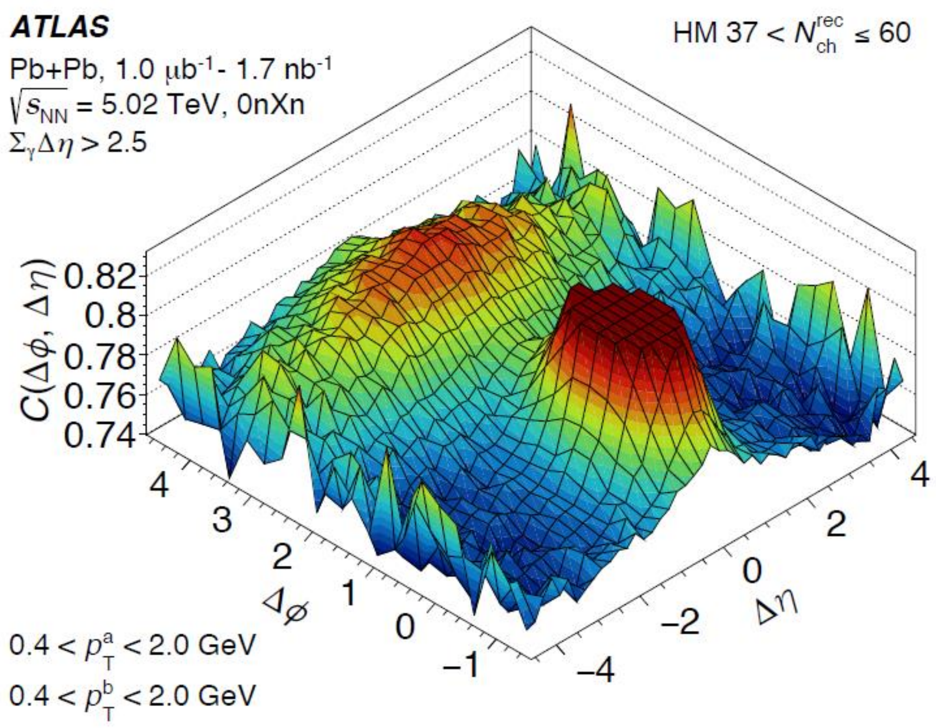
A single string configuration can generate a ridge-like structure at high multiplicity

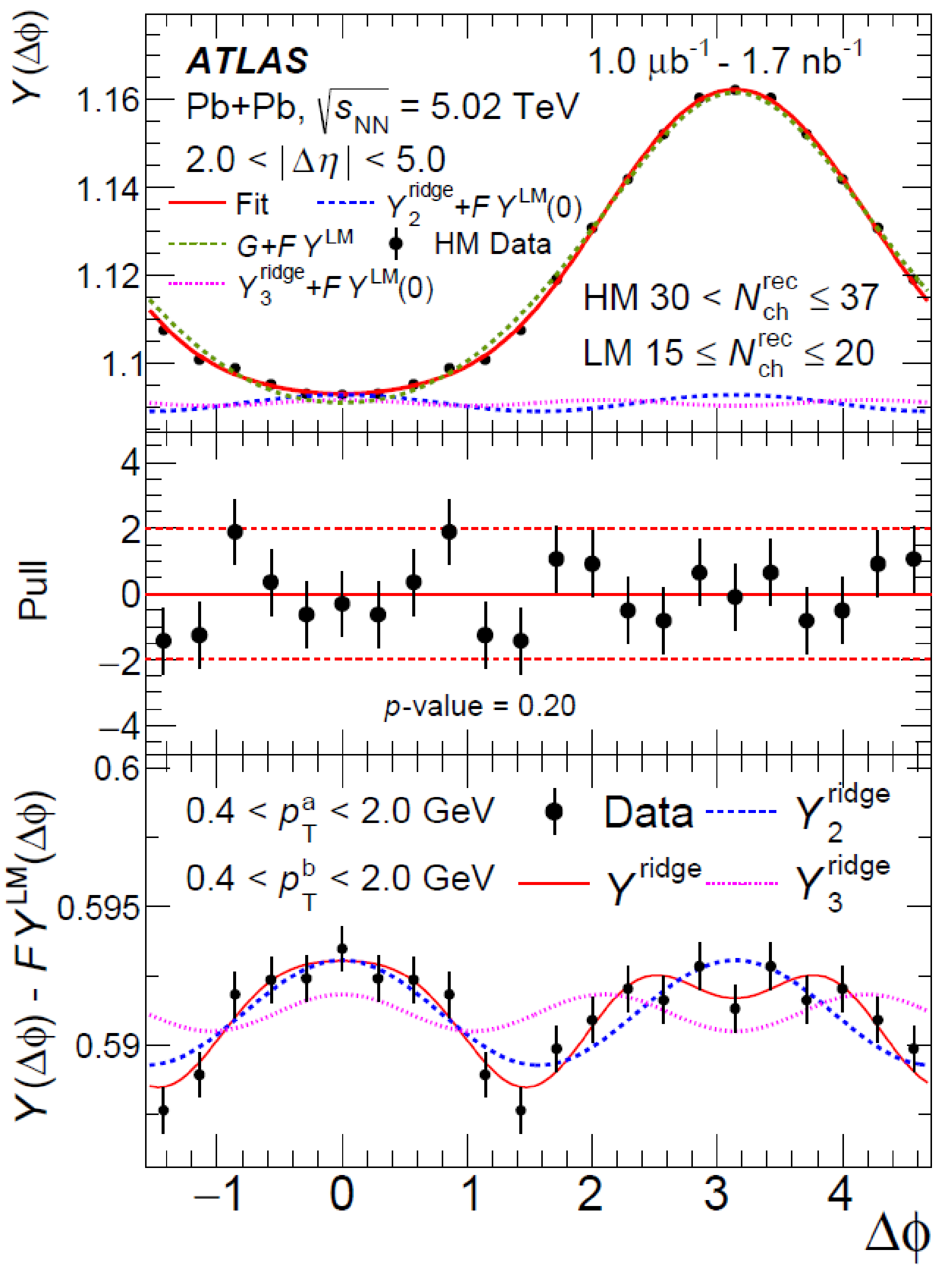
Increase multiplicity

Photonuclear Collisions with PbPb UPC at the LHC

Photonuclear collision enriched sample

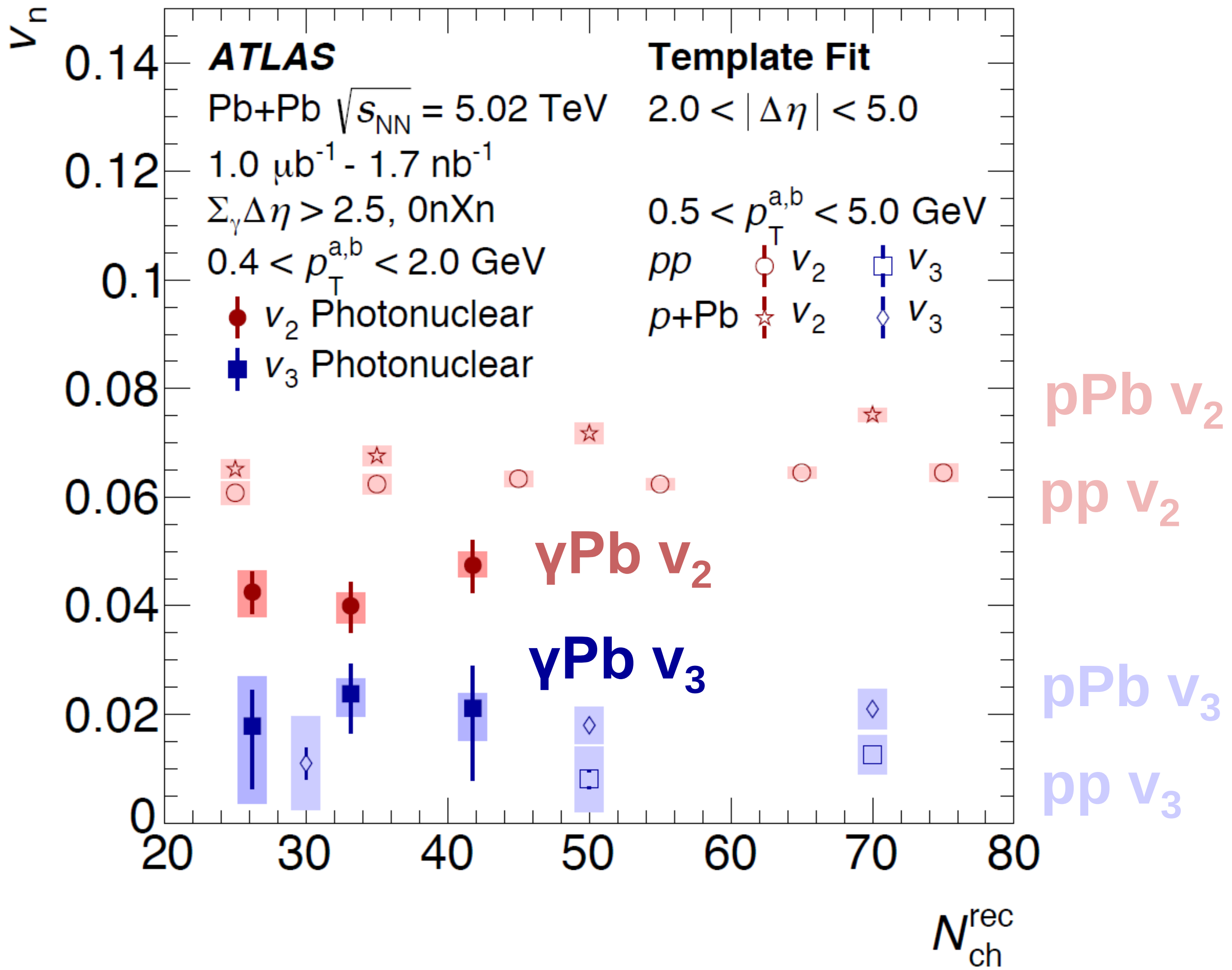


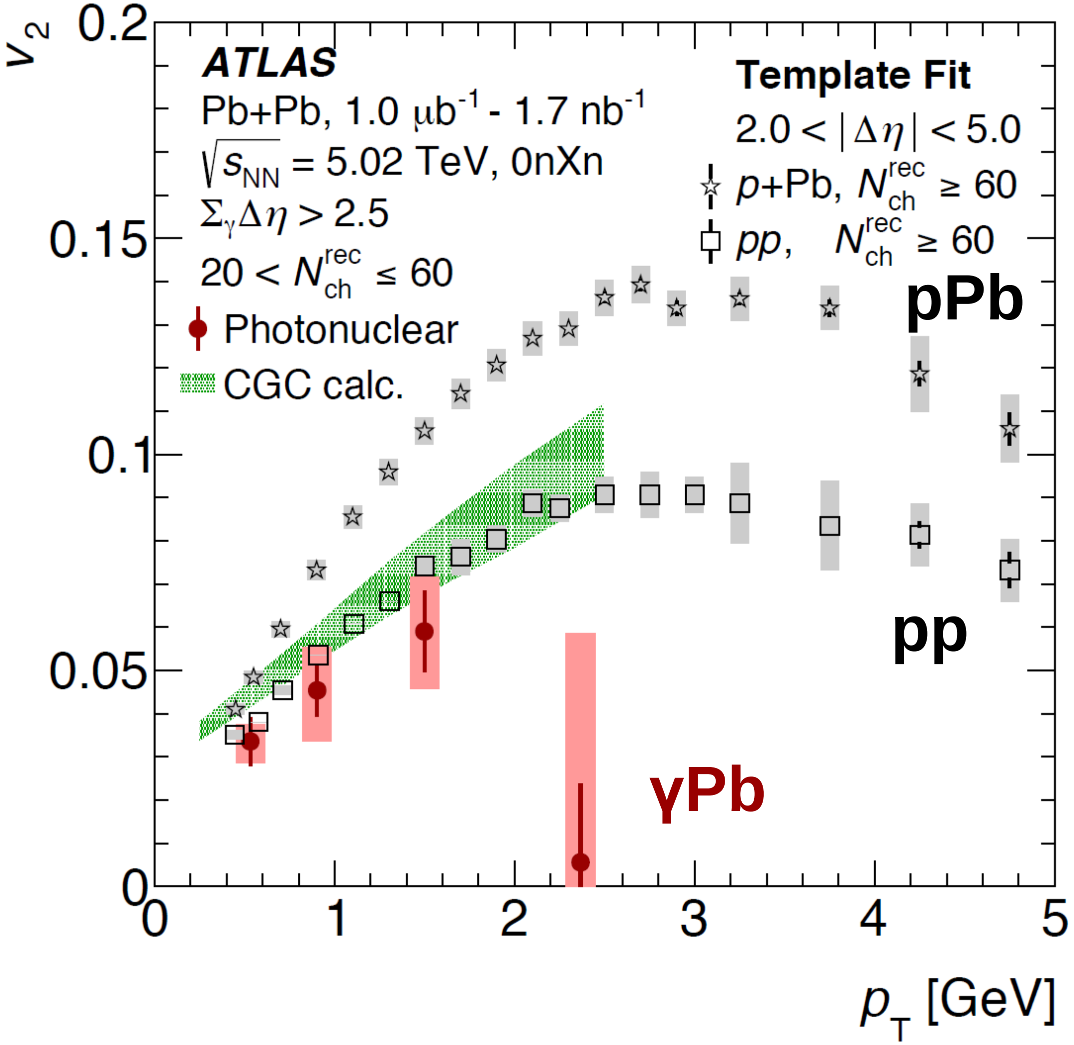




- No ridge-like signal in the correlation function up to N_{ch} = 60,
- ATLAS observed a flow-like modulation through low-multiplicity event subtraction (**90%** amplitude subtracted)

v_2 and v_3 after Low Multiplicity Event Subtraction

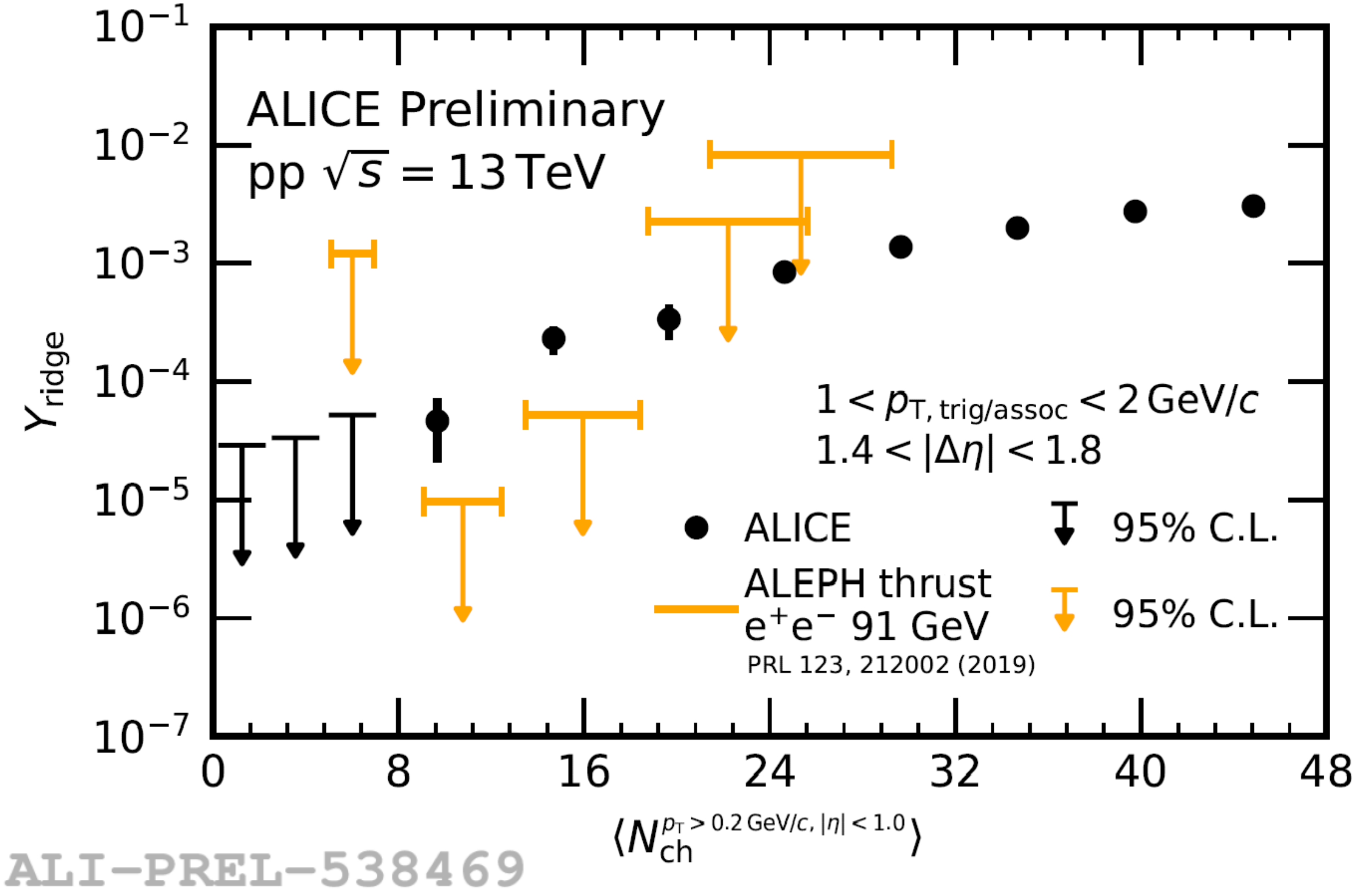


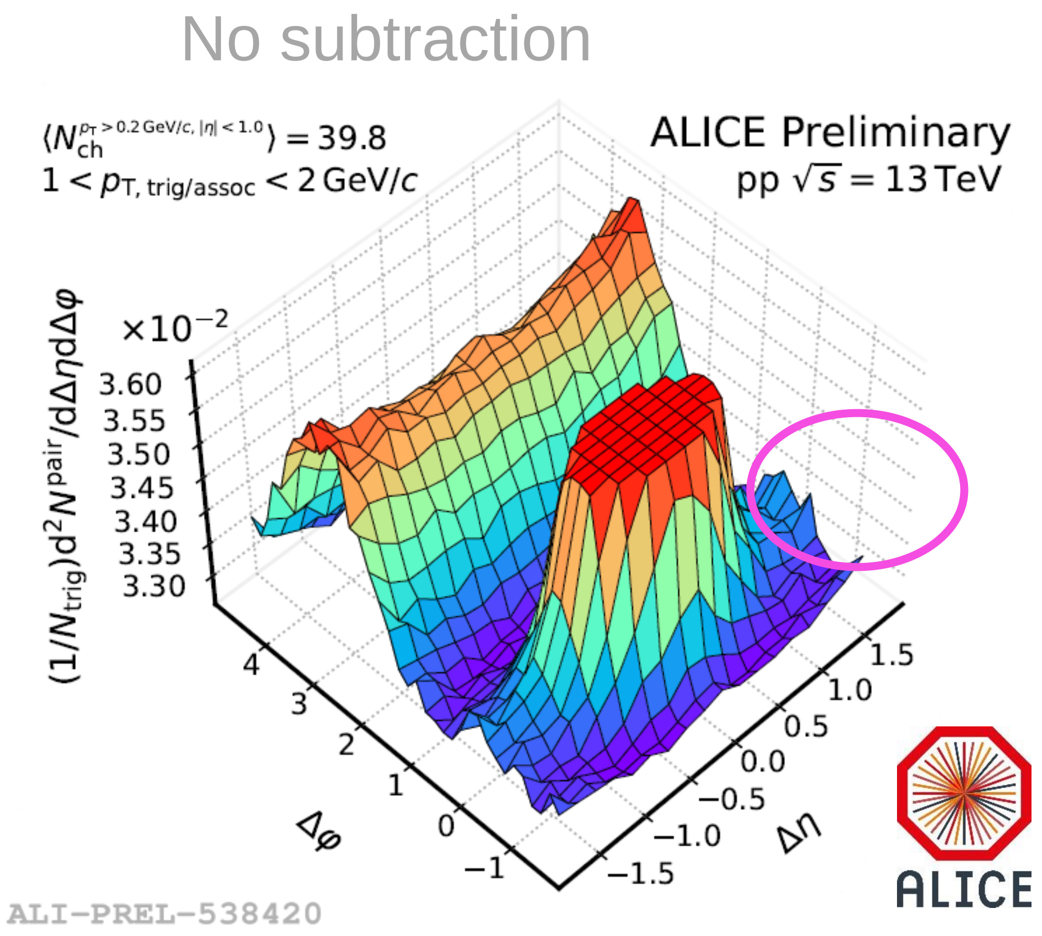


- **Positive v_2** and **v_3** after subtraction with lower multiplicity events
- Largely independent of N_{ch}

- Smaller v_2 in **γPb** compared to **pPb** and **pp**
- Initial state effect of Pb could be relevant

Even Higher <MPI>: Minimum-Bias pp Events





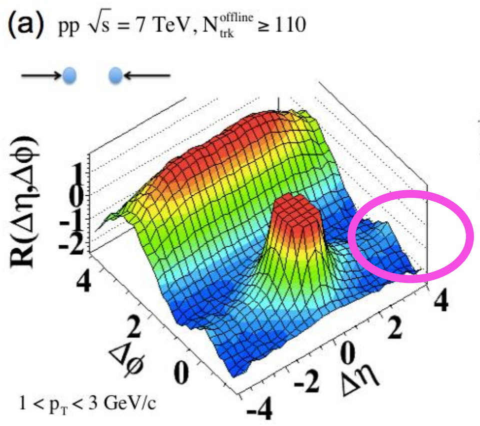
- Searches in **low multiplicity pp**
- Ridge yield in pp collisions is higher (**3.2σ**) than in **e^+e^- at the Z pole**, given **the same multiplicity**
- Data from larger acceptance CMS/ATLAS and multi-particle correlation would be highly intriguing

<MPI> vs. Multiplicity

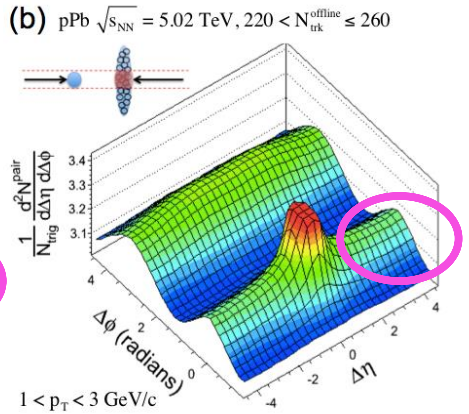
Increase the MPI

High multiplicity pp

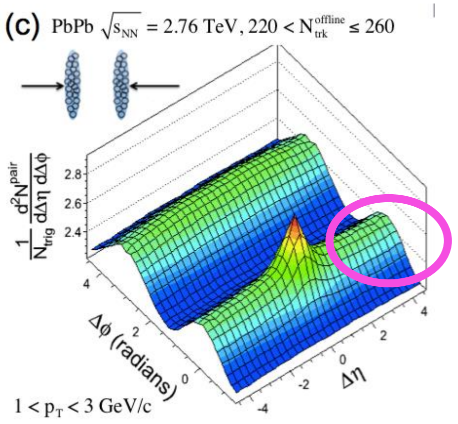
High multiplicity pPb



~ O(1fm)

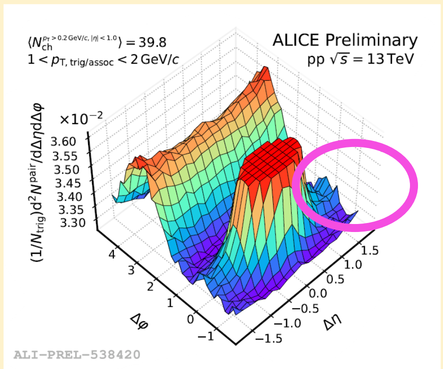


≥ O(1fm)

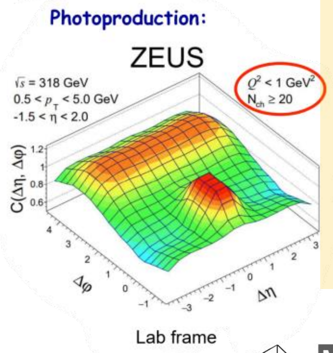


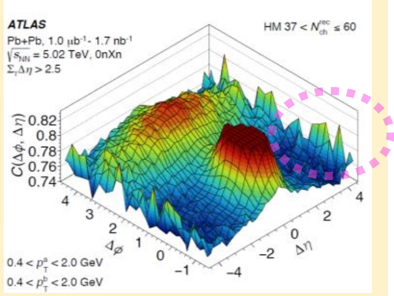
O(1-10 fm)

Large MPI



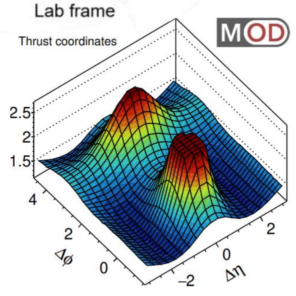
MPI>1



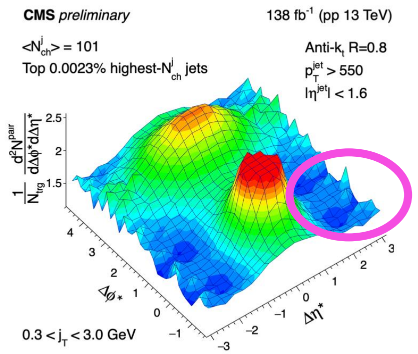


MPI ≥ 1

Larger MPI than γp

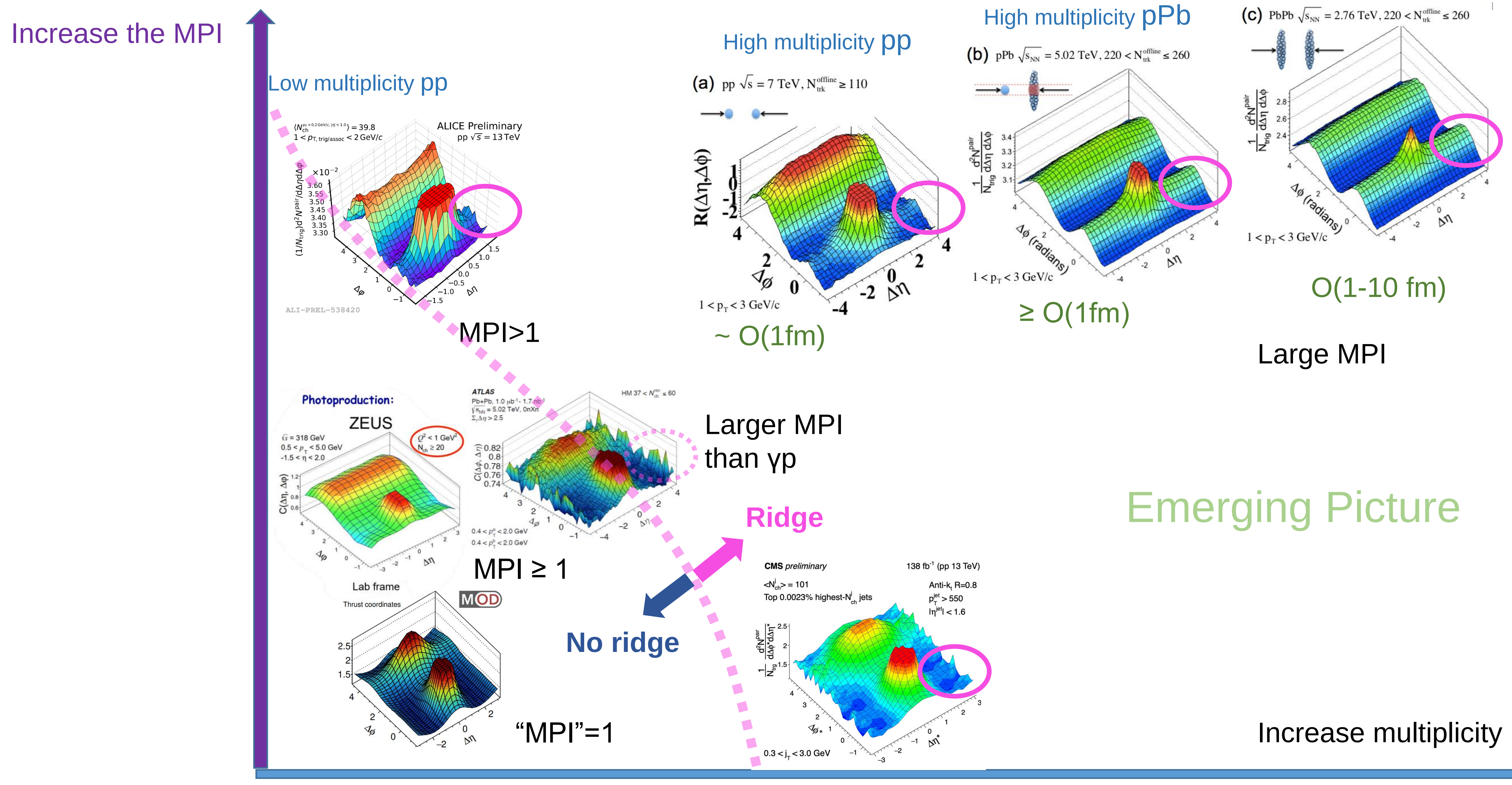


"MPI"=1



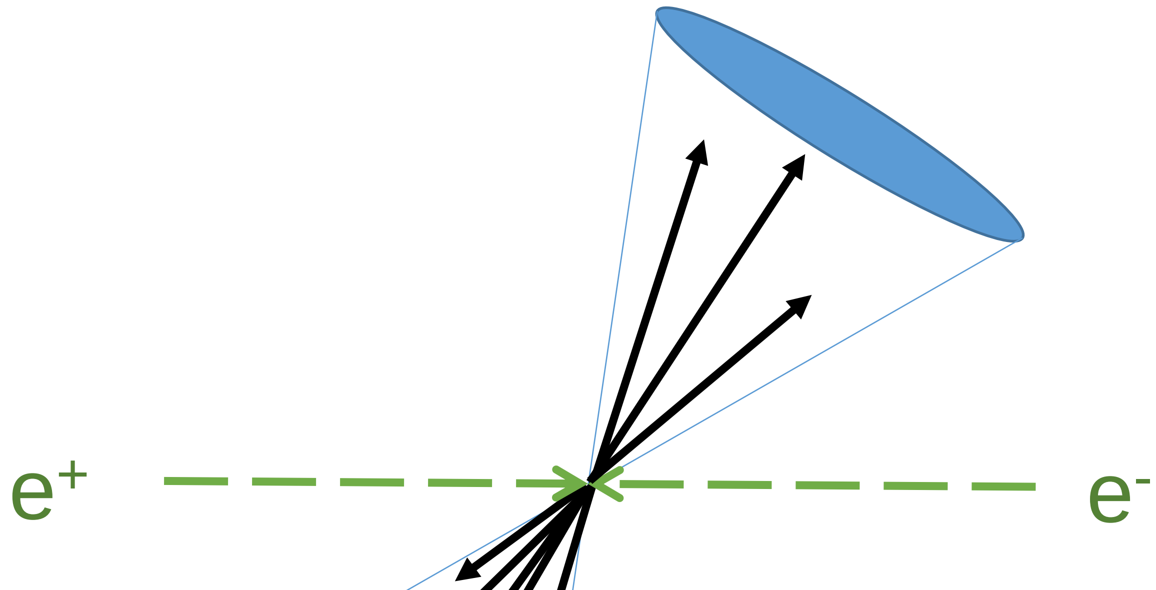
Increase multiplicity

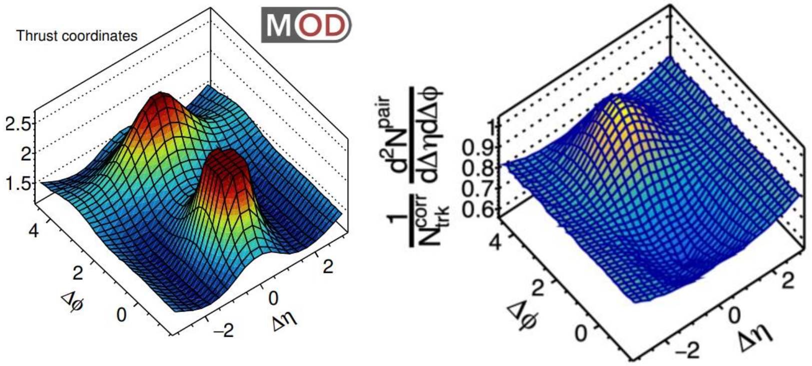
<MPI> vs. Multiplicity



Can We Overlap Two Pairs of Color Strings?

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

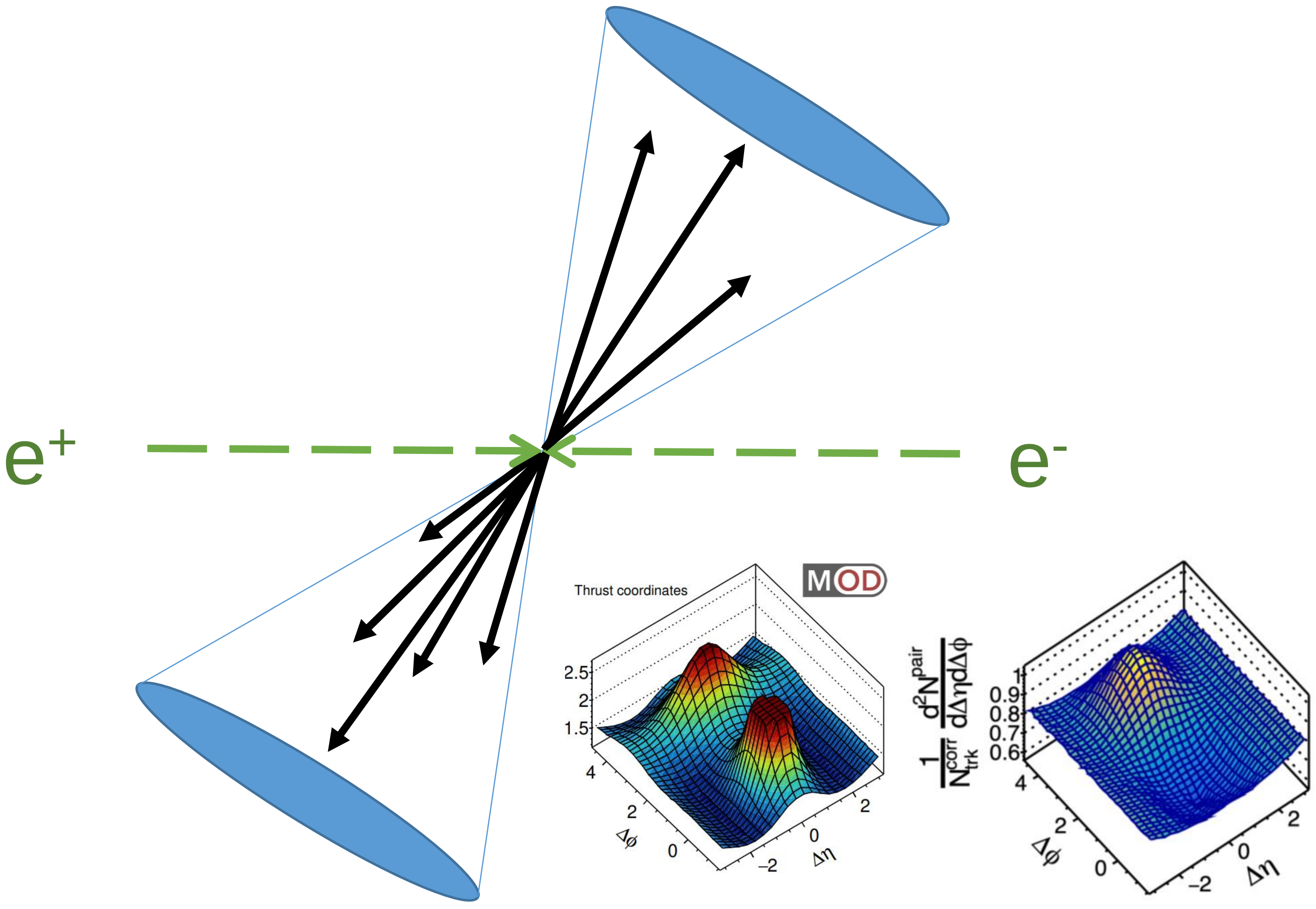




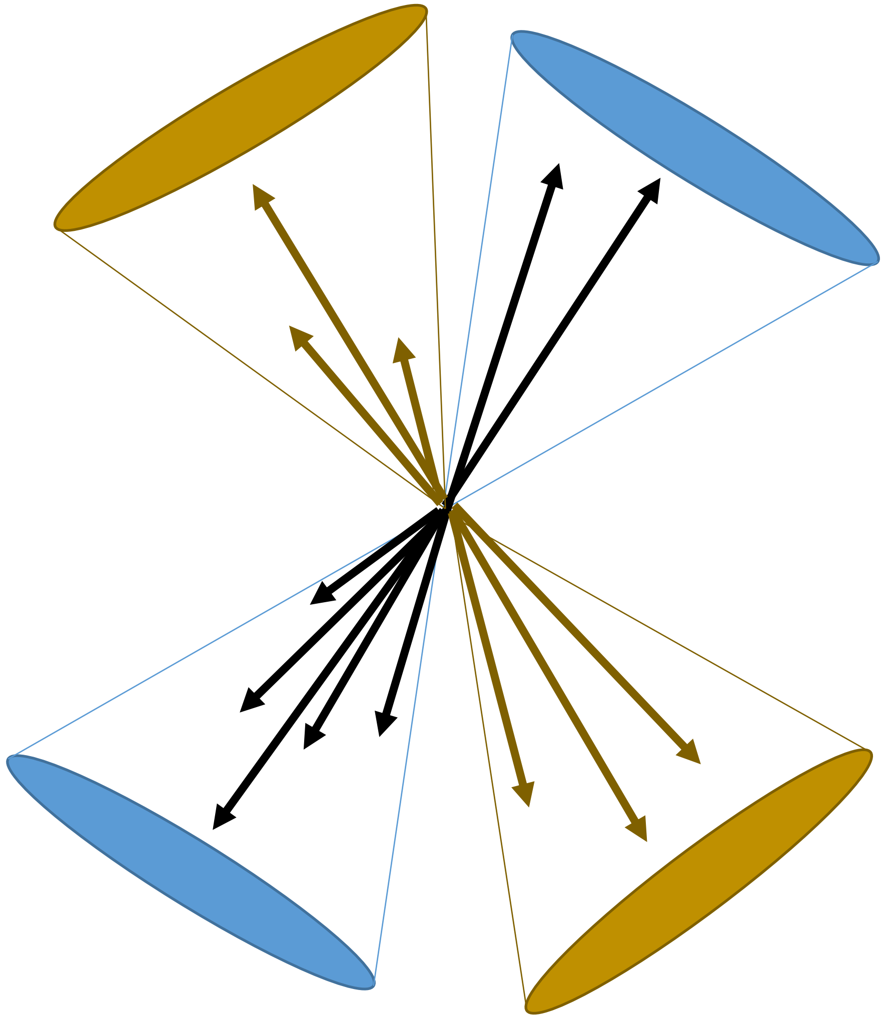
No ridge-like structure

Can We Overlap Two Pairs of Color Strings?

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



No ridge-like structure

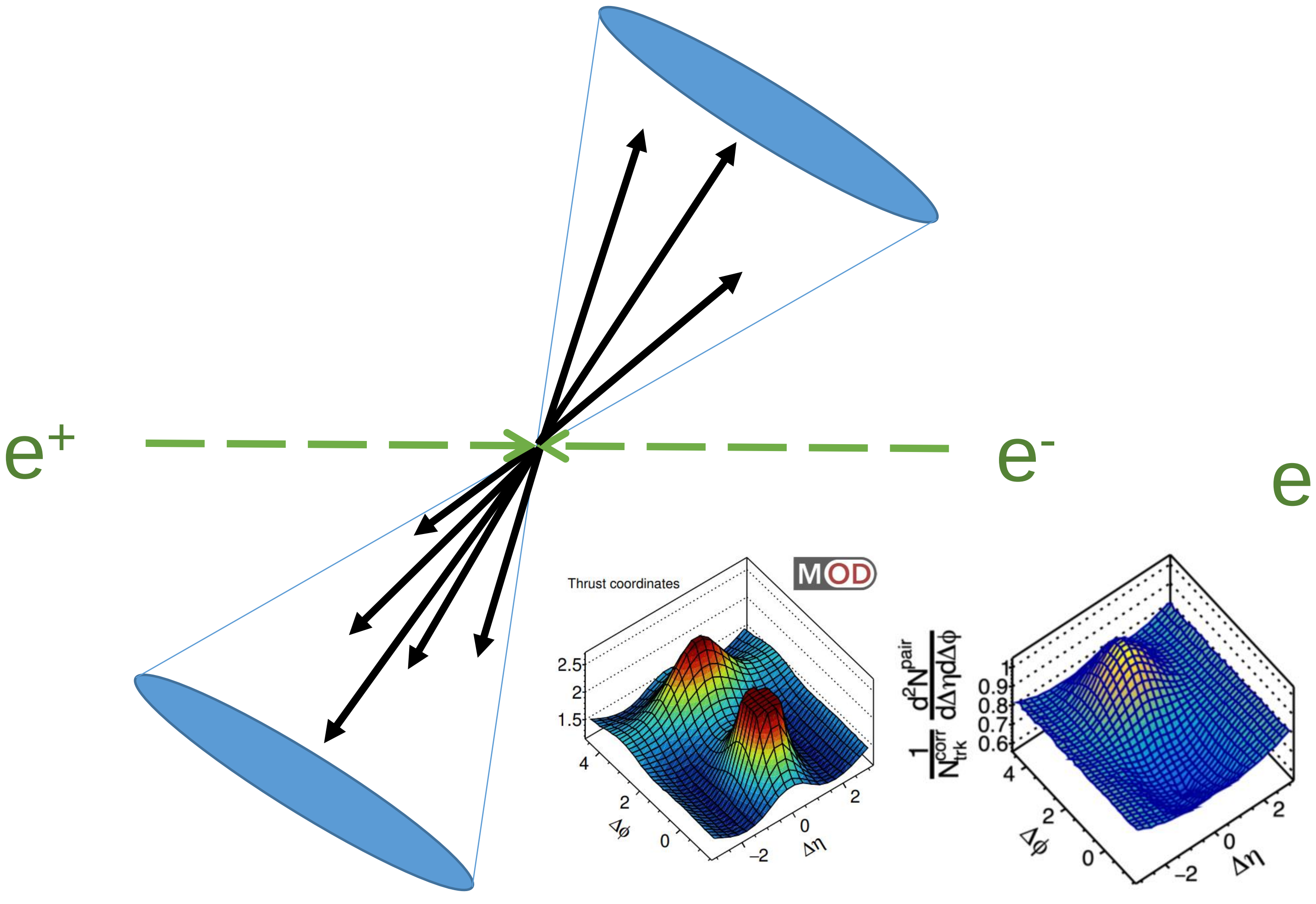


?

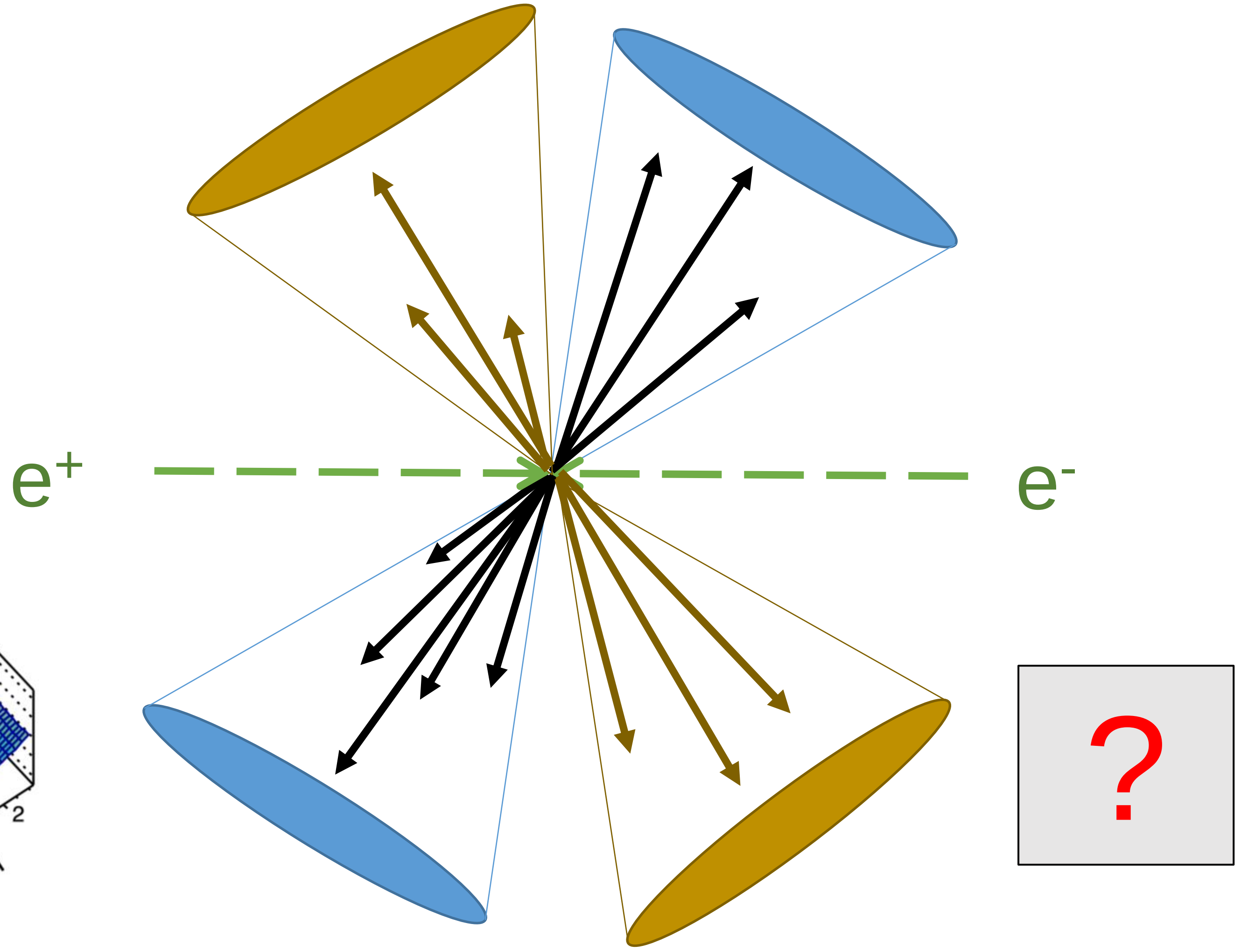
LEP2 High Multiplicity Event

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

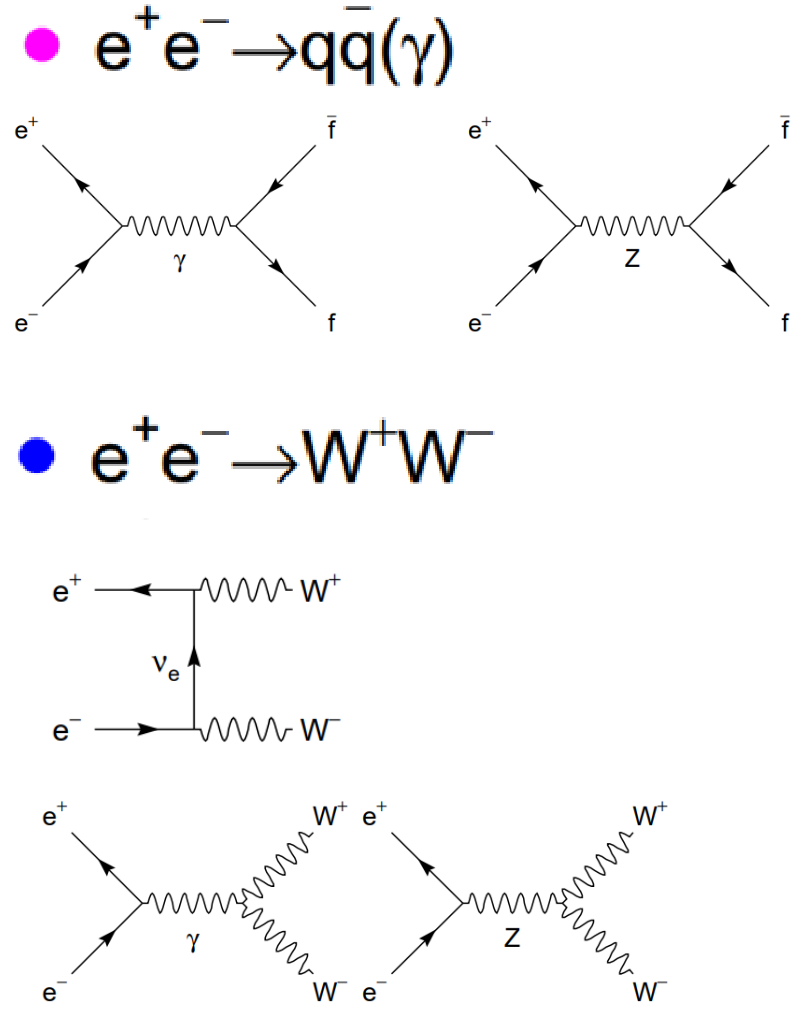
$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$



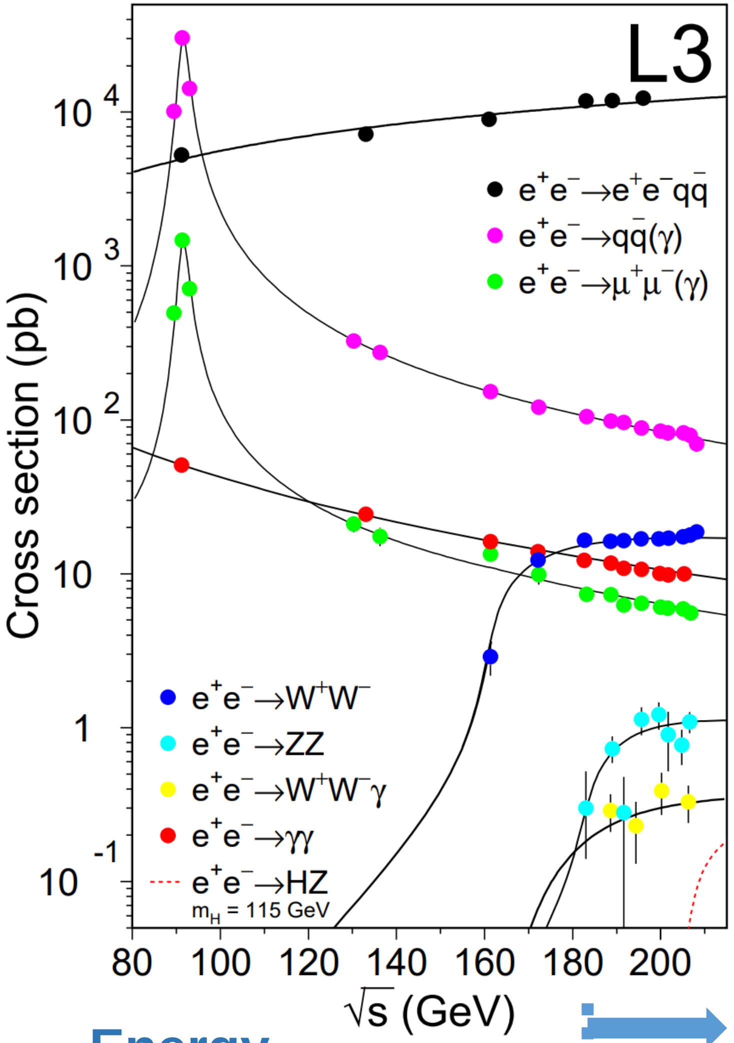
No ridge-like structure



Charged Particle Multiplicity Distributions in LEP2 Data

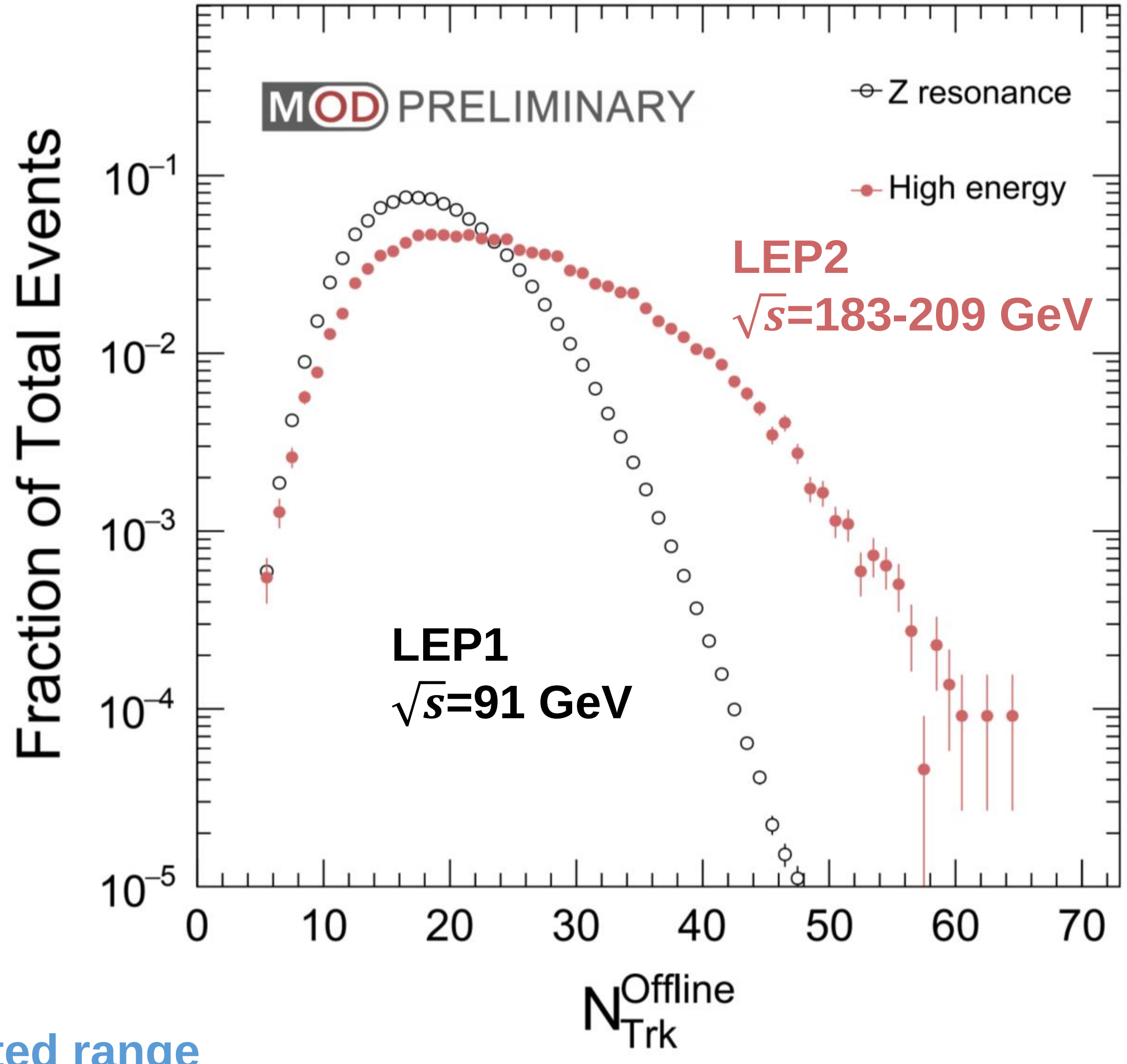


Phys. Rept. 532 (2013) 119-244



Energy

Reported range

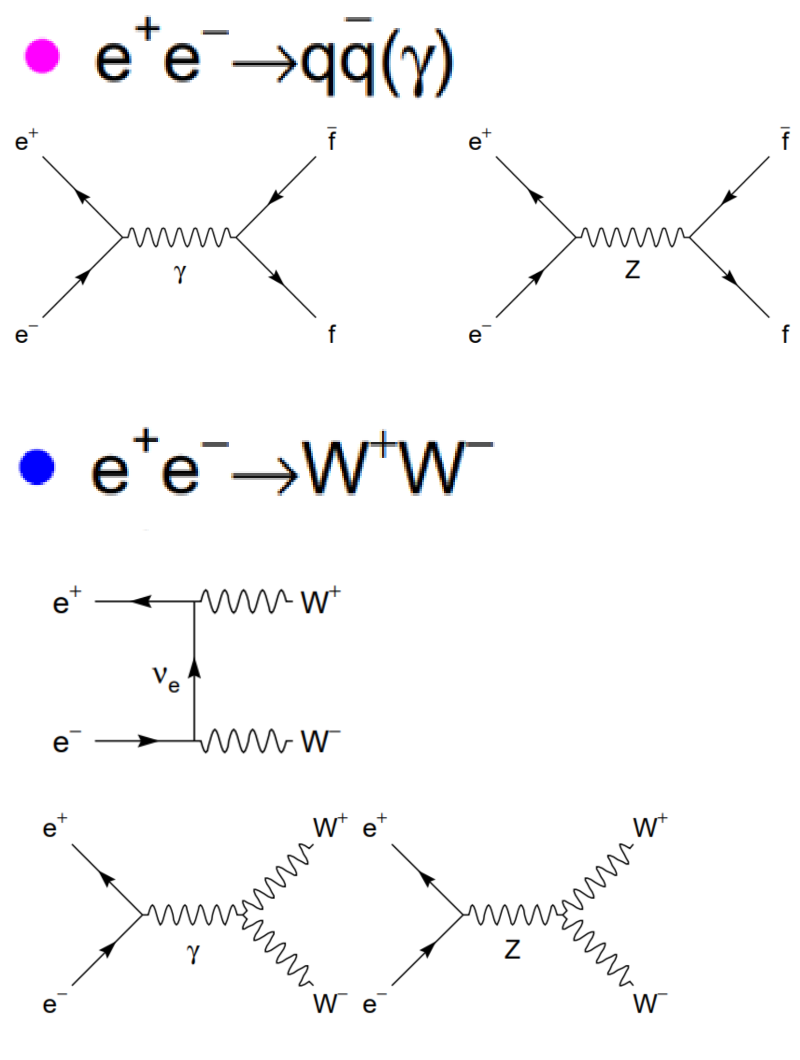


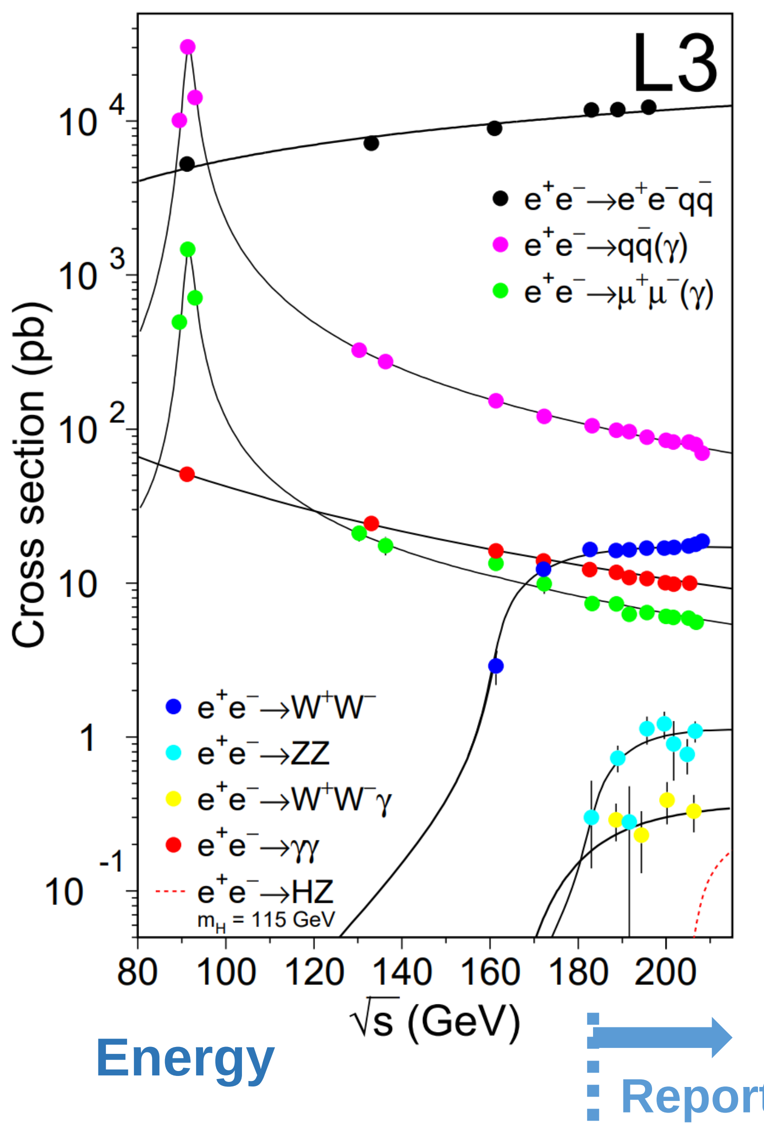
- **LEP2 energies** give access to also different physics processes

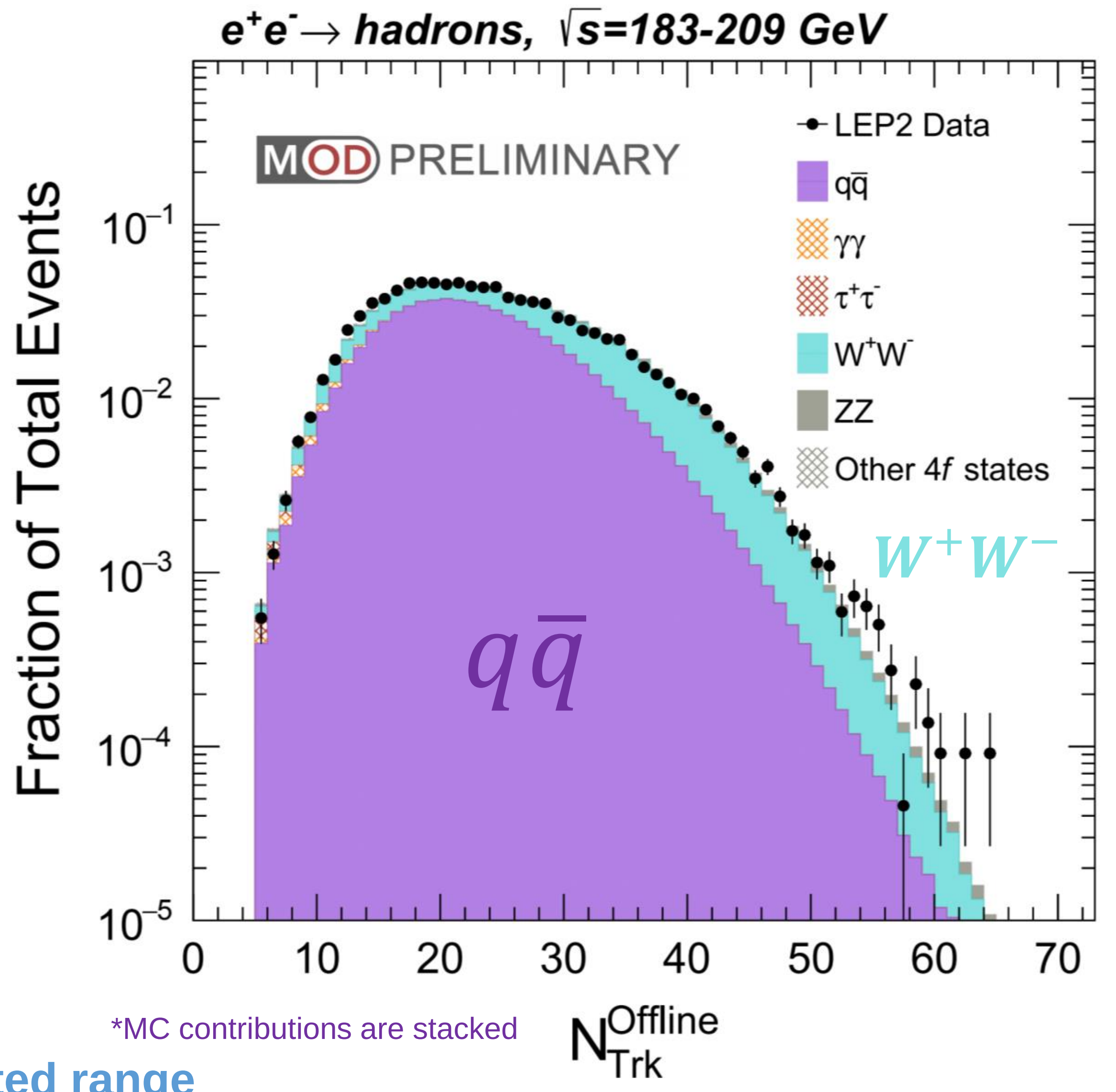
Yu-Chen "Janice" Chen (MIT)

EPJC 63 611 (2009)

Charged Particle Multiplicity Distributions in LEP2 Data





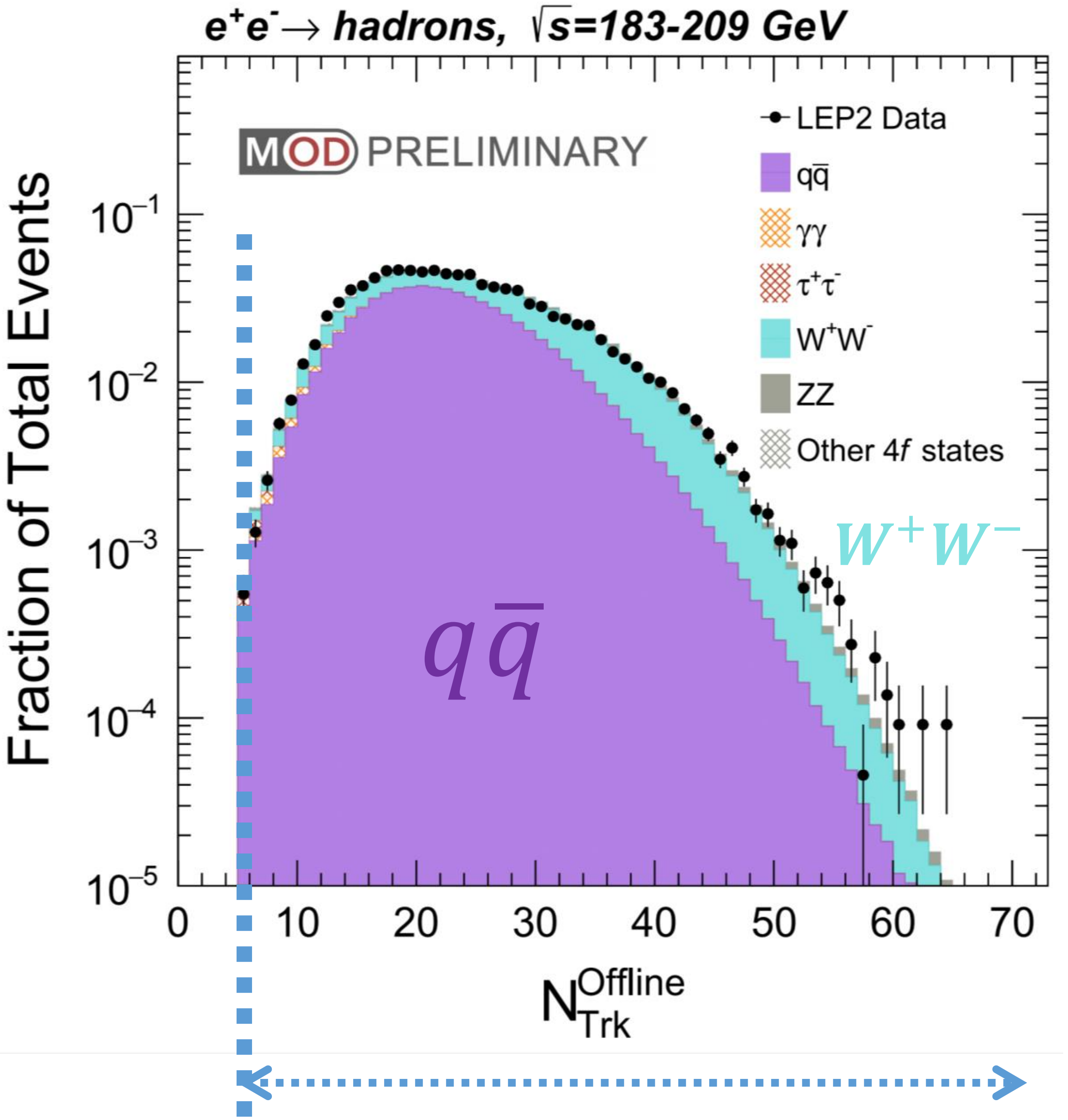


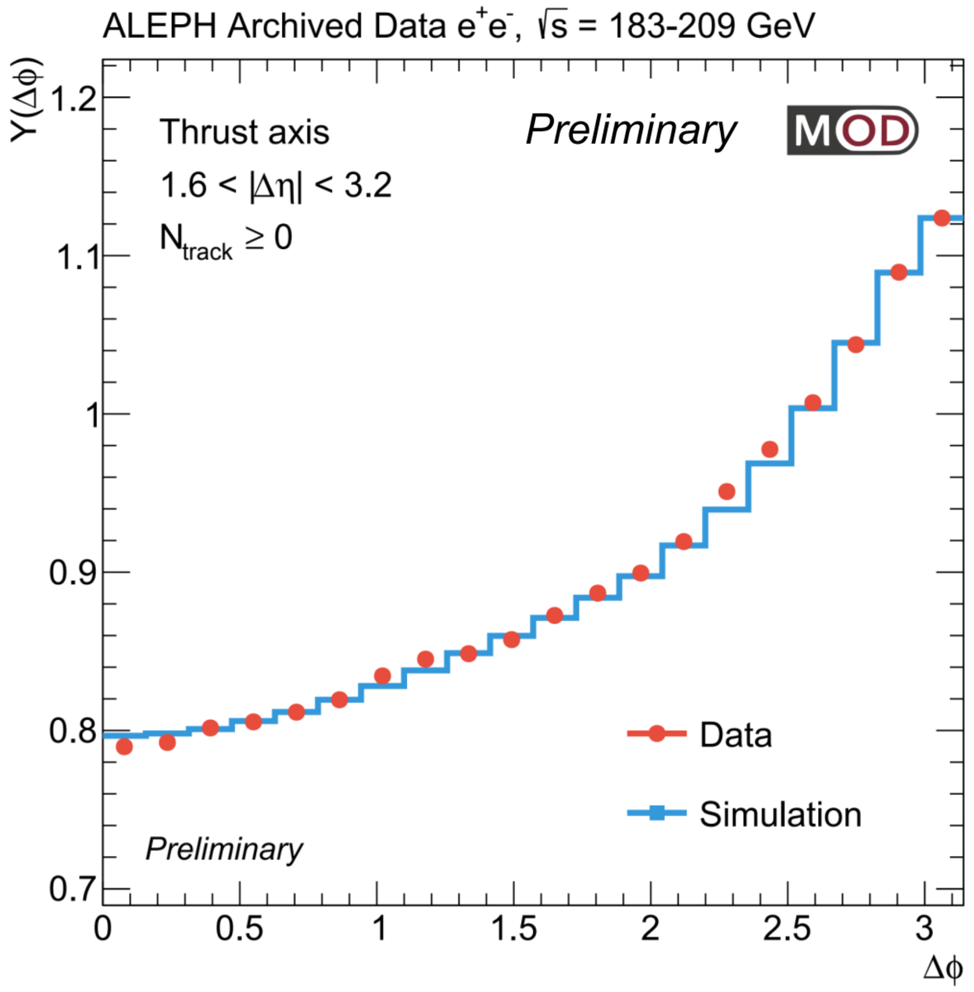
- **LEP2 energies** give access to also different physics processes
- At high multiplicity, W^+W^- contribution becomes significant

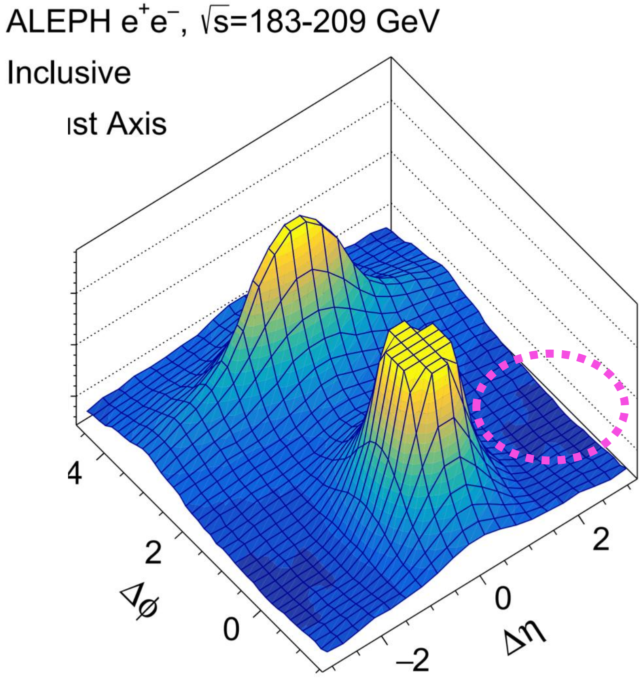
Yu-Chen "Janice" Chen (MIT)

EPJC 63 611 (2009)

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



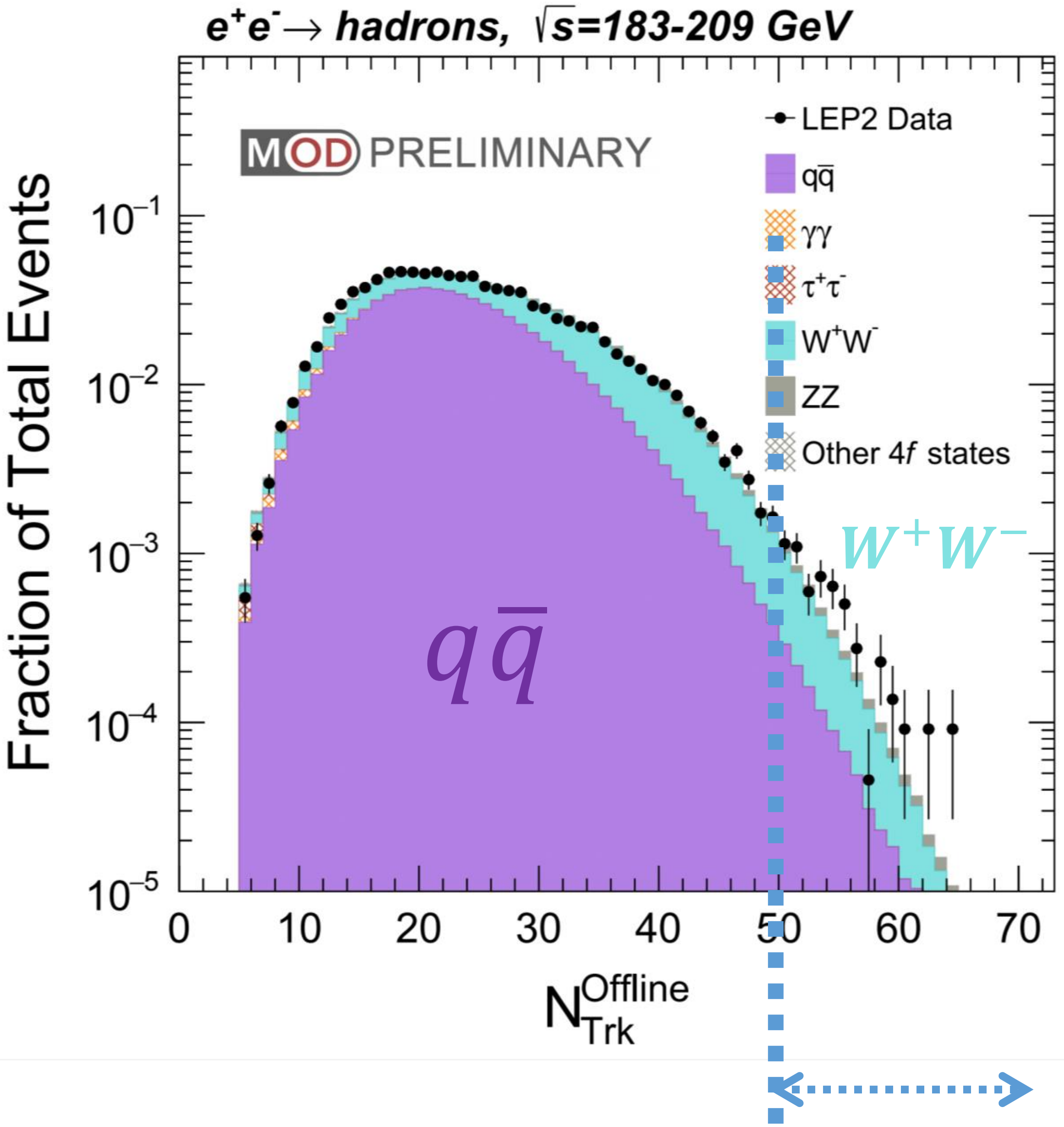


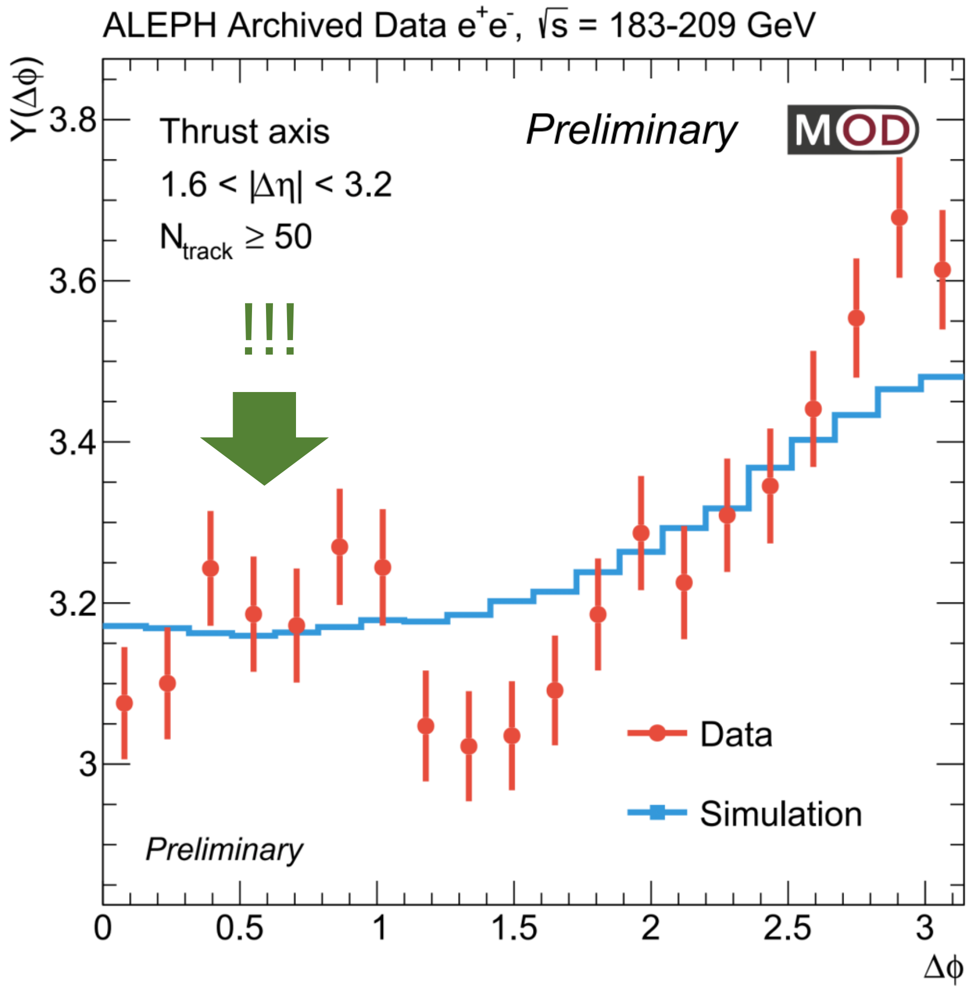


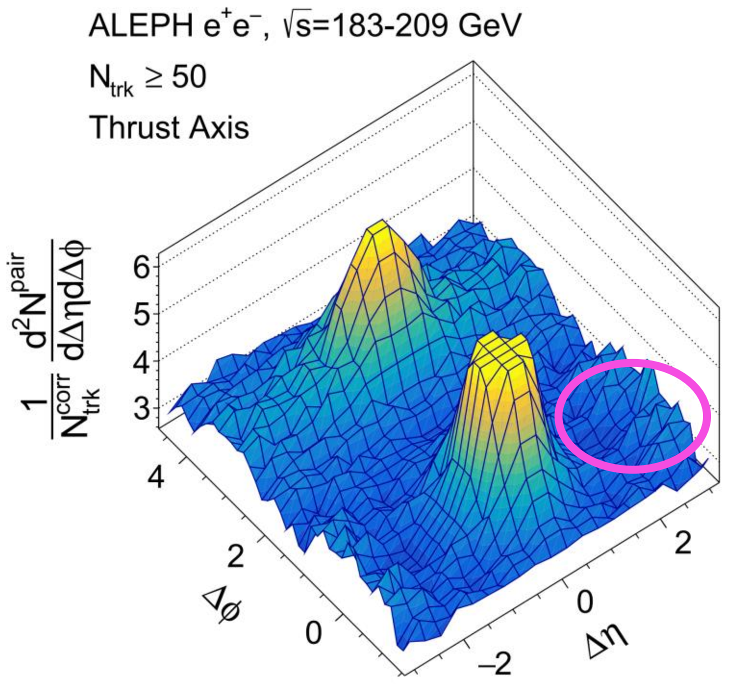
- Excellent agreement between **data** and **simulation (Archived MC)**

Yu-Chen "Janice" Chen (MIT)

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





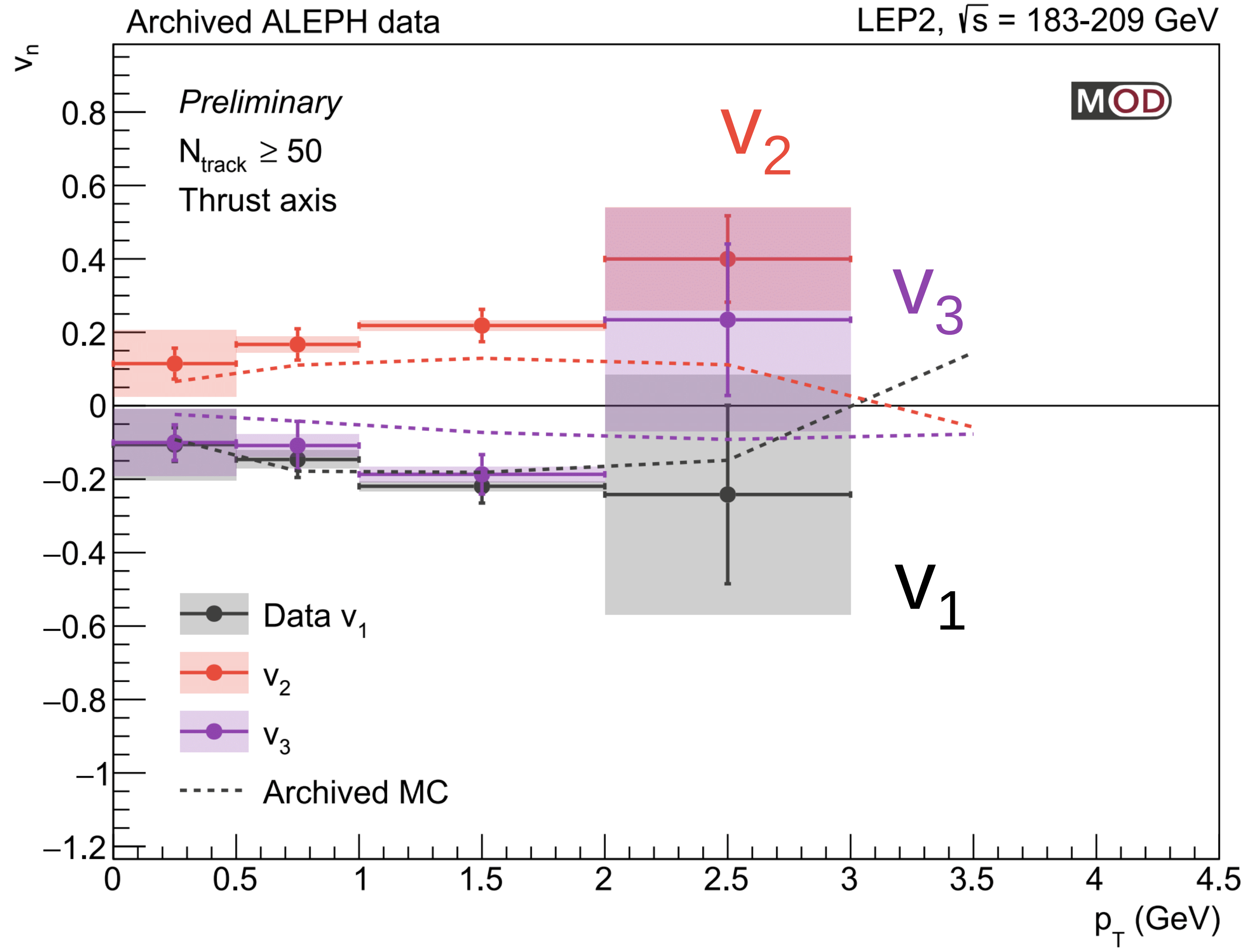


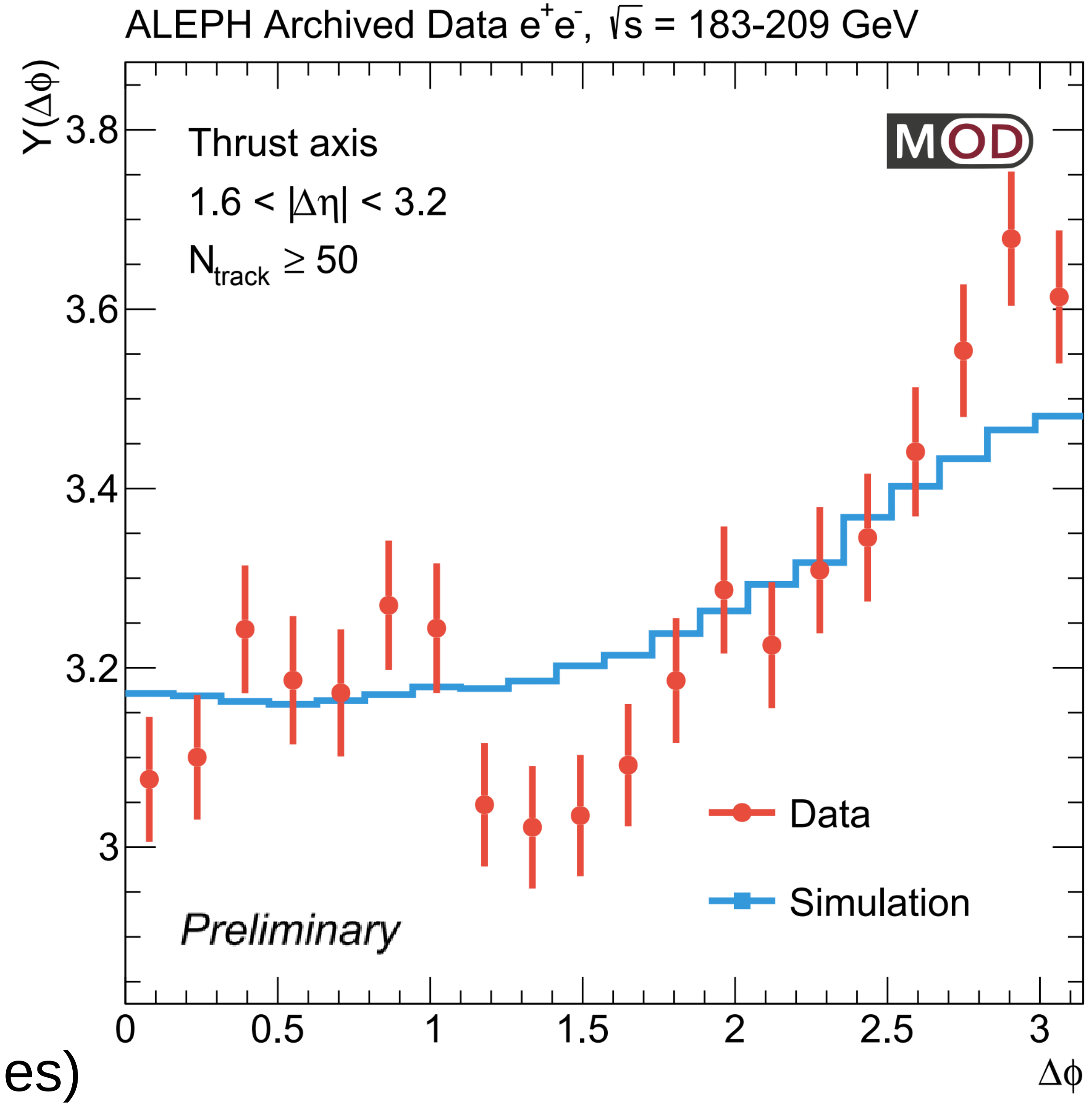
- A long-range near-side correlation signal shows up at high multiplicity!
- Data also feature a narrower away-side spectrum at Δϕ~π

Yu-Chen "Janice" Chen (MIT)

Extracted v_n vs. Charged Particle p_T

High multiplicity $N_{track} \geq 50$

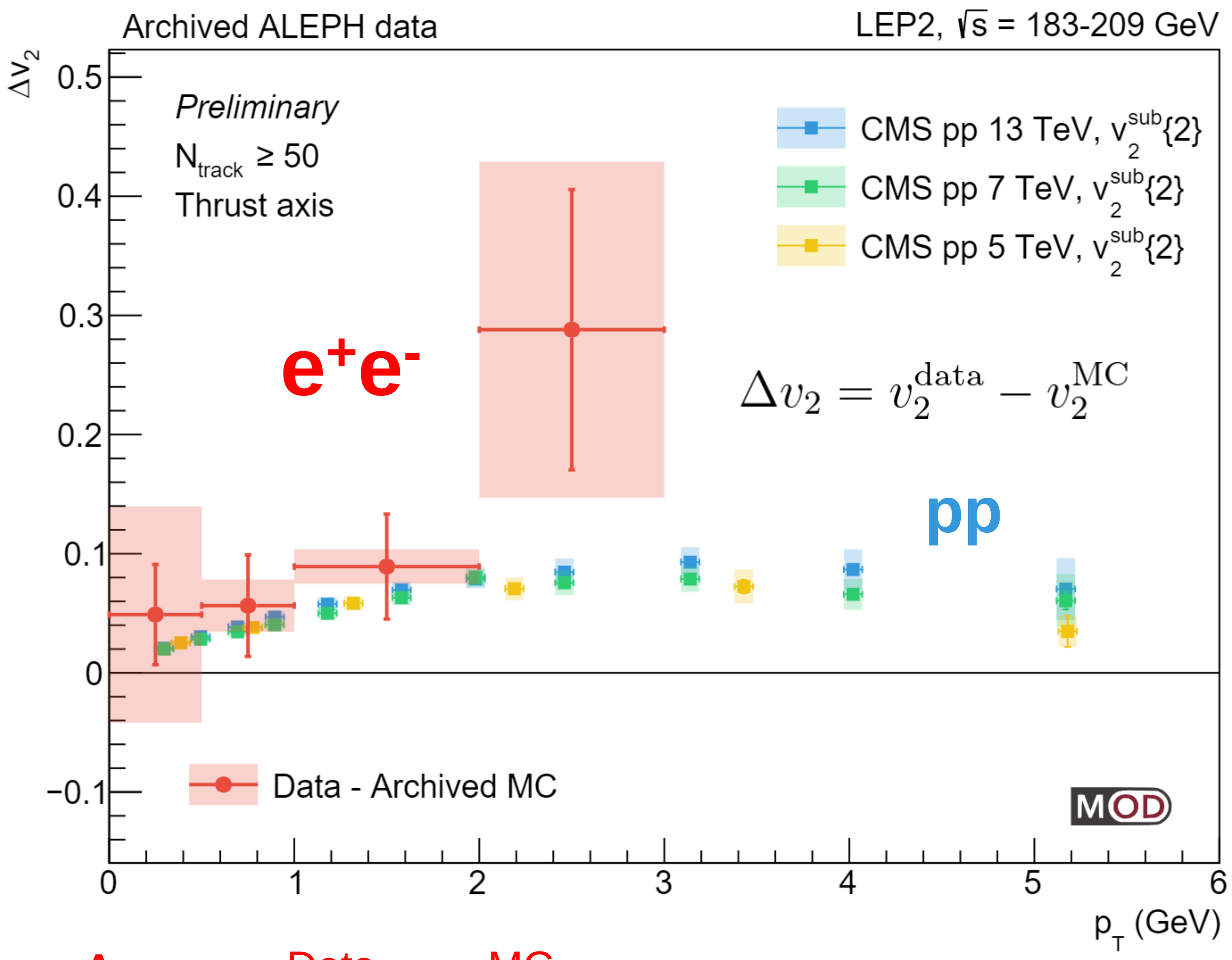


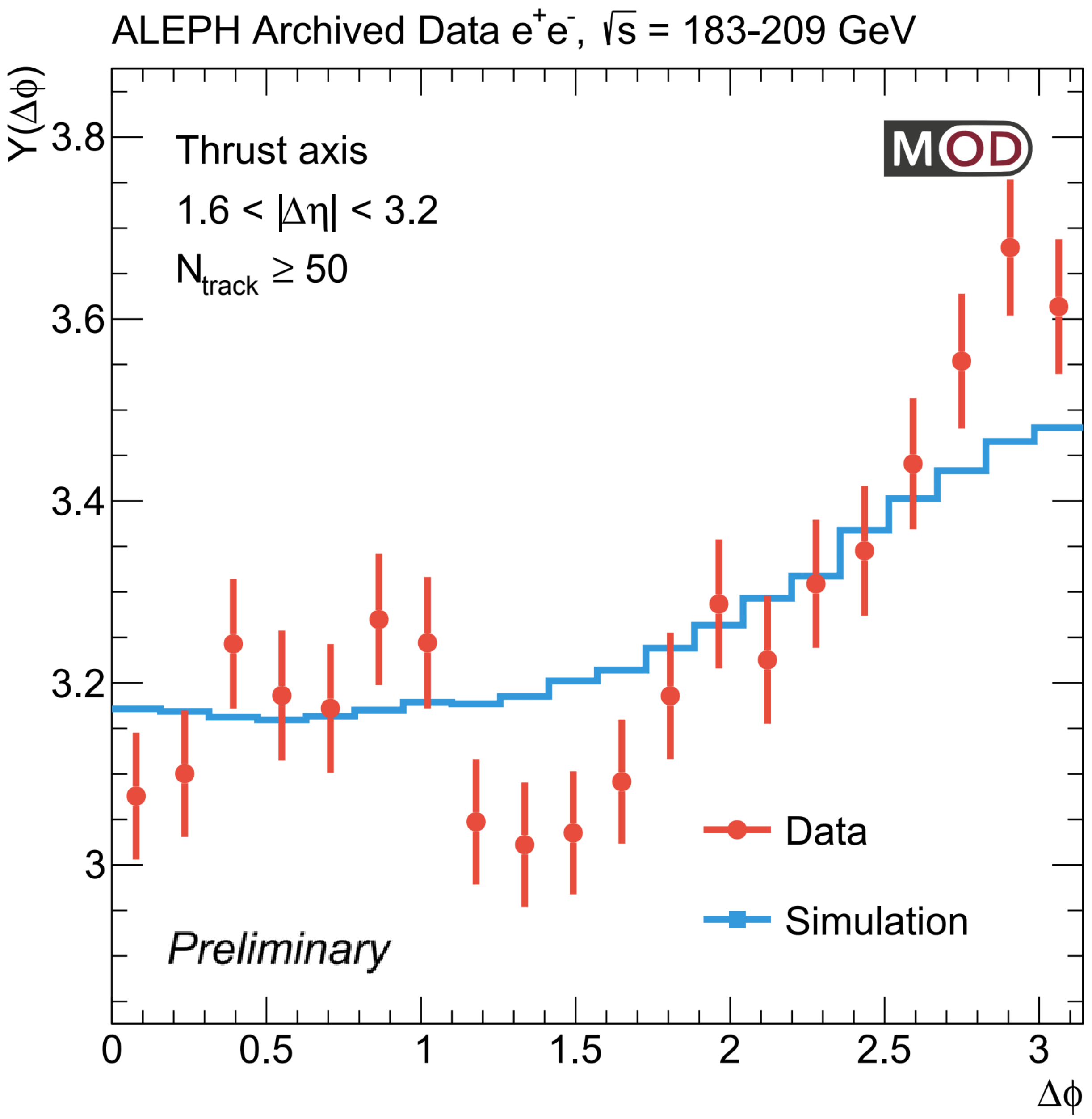


Larger v_2 and v_3 magnitudes than MC (dash lines)

Yu-Chen "Janice" Chen (MIT)

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





- $\Delta v_2 = v_2^{Data} - v_2^{MC}$
- Similar trend between e^+e^- and pp data

Yu-Chen "Janice" Chen (MIT)

Lessons Learned from e^+e^-, ep, eA, MB pp and UPCs

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

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

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

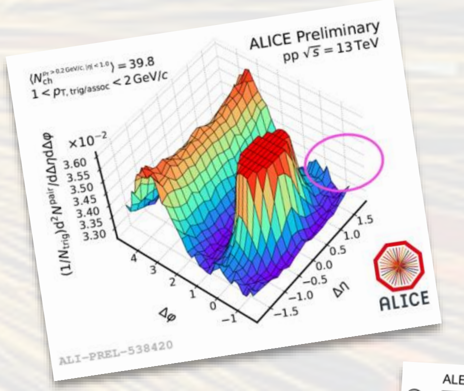
  Indication of final state effects from CMS high multiplicity single jet and ALEPH LEP2 data

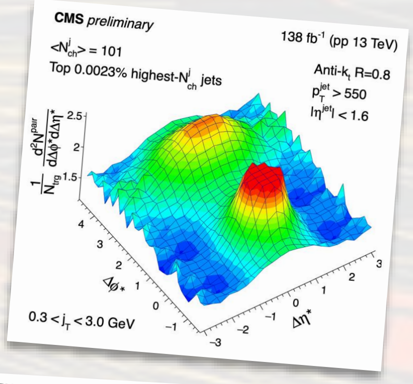
- How does collectivity vary in different physics processes?

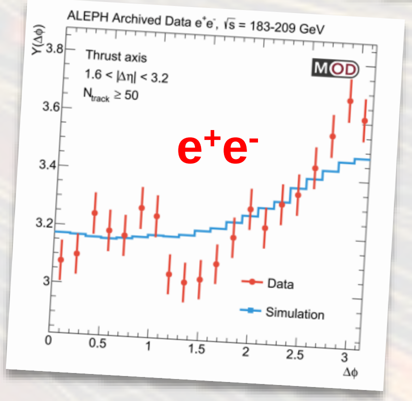
  Ridge signals vary in different physics processes

- 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







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 archived data.

I would like to thank **Janice Chen, Jurgen Schukraft, Jiangyong Jia, Wei Li, Yi Chen, Jing Wang, Austin Baty, Gian Michele Innocenti, Fuqiang Wang, Wilke van der Schee, Christian Bierlich, Guilherme Milhano, Carlos Salgado** for the useful discussions

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

Selected List of Analyses

- **e^+e^-**
  - ALEPH LEP1 (91 GeV) — PRL 123 (2019) 21, 212002
  - ALEPH LEP2 (183-209 GeV): — (preliminary) https://arxiv.org/pdf/2211.11995.pdf
  - Belle Off-resonance 10.52 *GeV* : — PRL 128 (2022) 14, 142005
  - Belle On-resonance (Υ(4S)): — JHEP 03 (2023) 171

- **γp**
  - CMS pPb photonuclear: — https://arxiv.org/pdf/2204.13486
  - 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

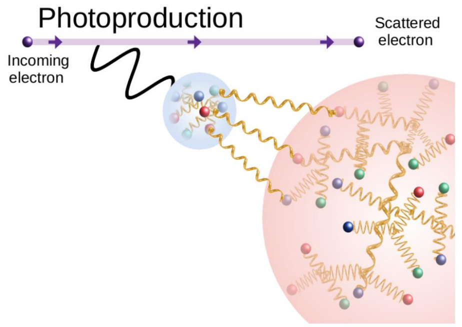
- **pp**
  - ALICE MB: — (preliminary) https://arxiv.org/pdf/2306.04808.pdf
  - CMS Single Jet in pp: — (preliminary) CMS-PAS-HIN-21-013

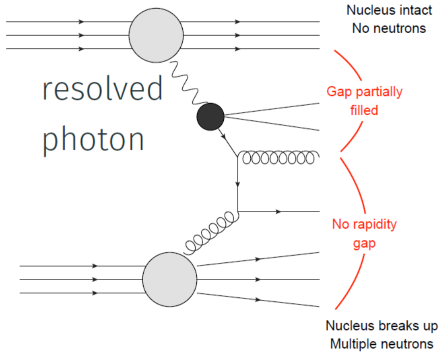
System Size

"Transverse Size"

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

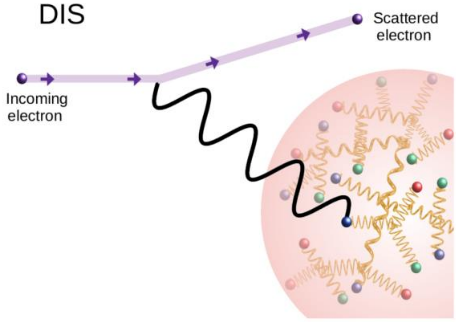
Photoproduction





(b) *Resolved photoproduction.*

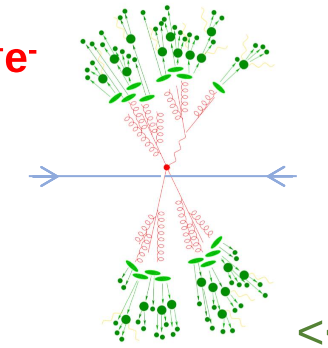
DIS



(a) *Neutral current deep inelastic scattering.*

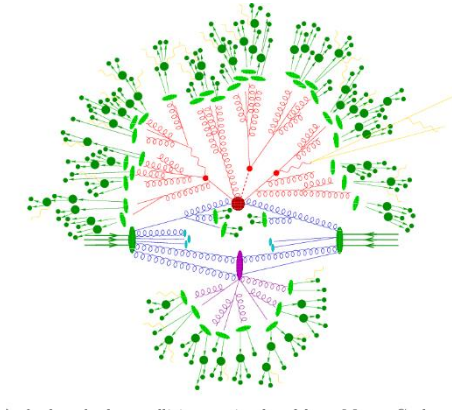
1/Q < 0.2 fm

e^+e^-



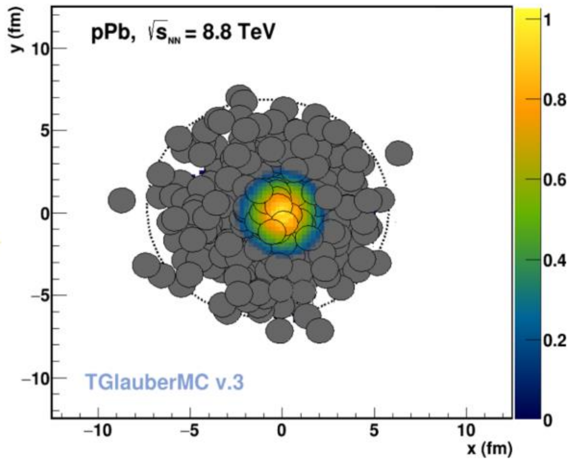
<< 0.1 fm

pp



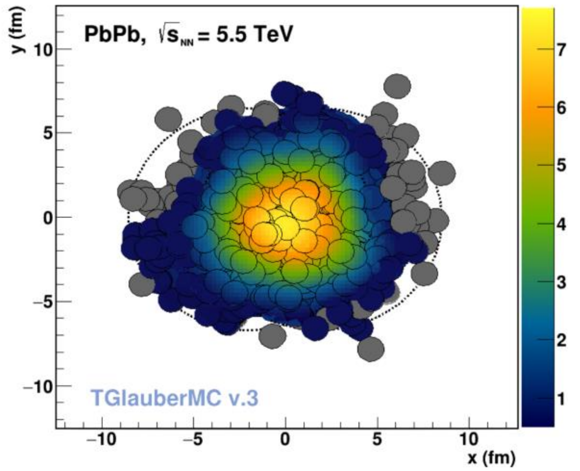
~ O(1fm)

pA

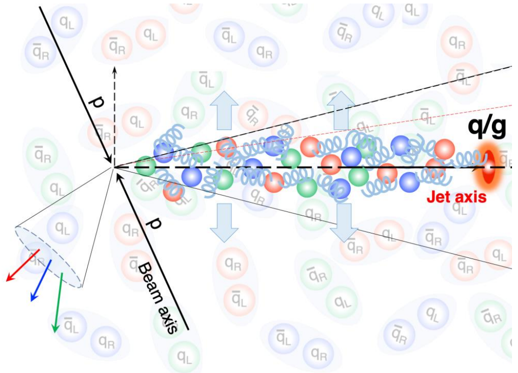


≥ O(1fm)

AA



O(1-10 fm)



Multiplicity

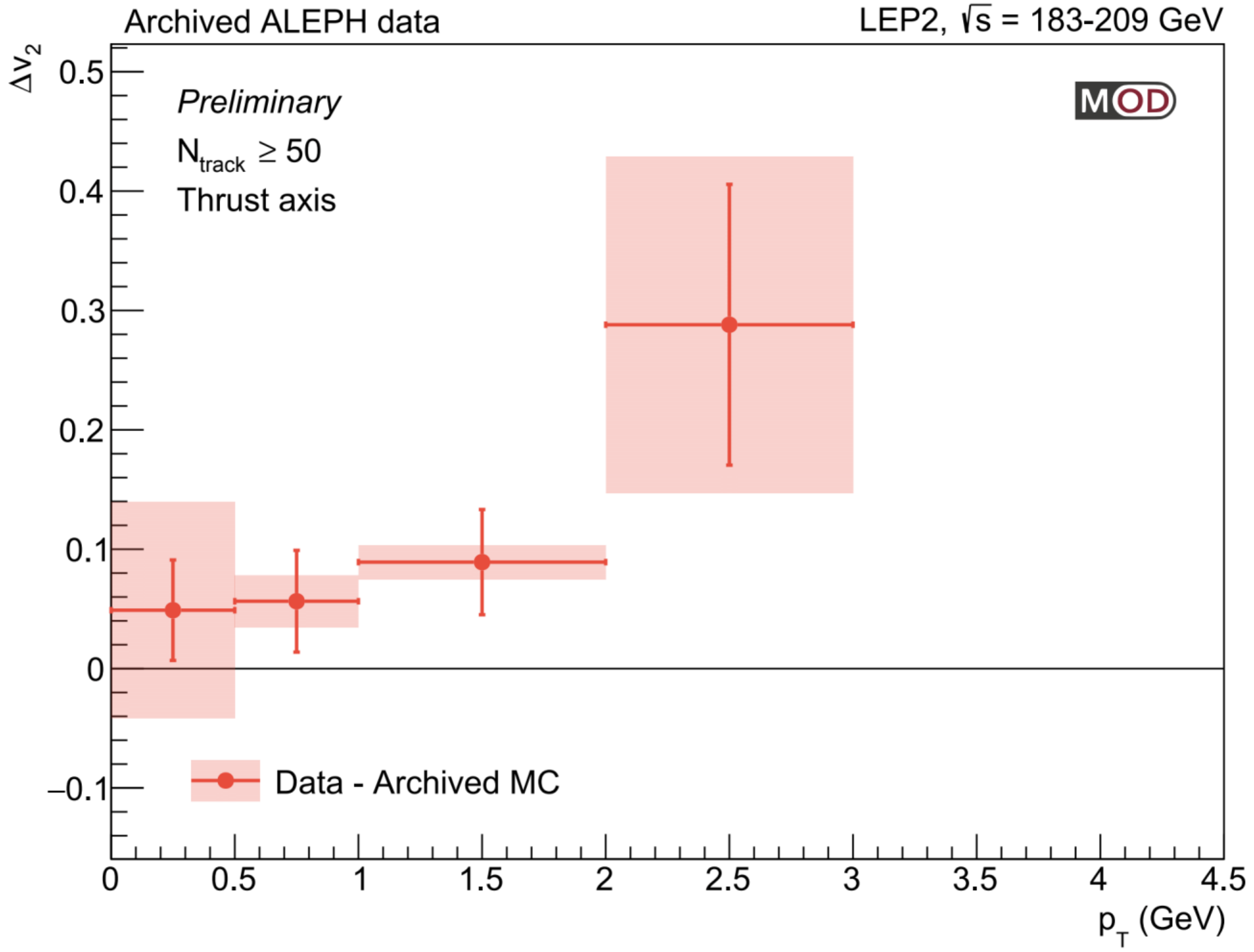
Backup Slides

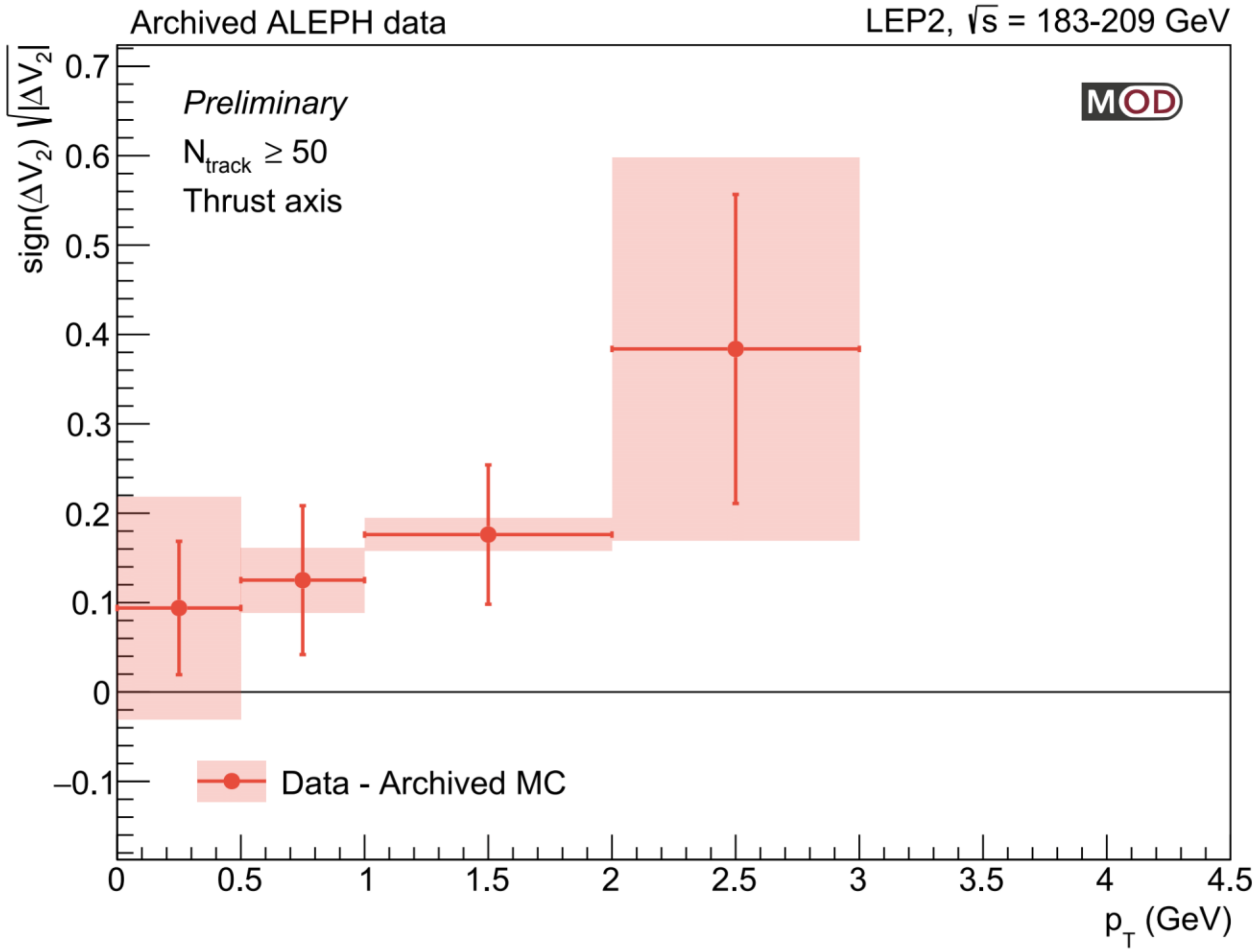
Difference between Data and Archived MC

$$\Delta v_2 = v_2^{\text{data}} - v_2^{\text{MC}}$$

$$sign(\Delta V_2)\sqrt{\Delta V_2}$$

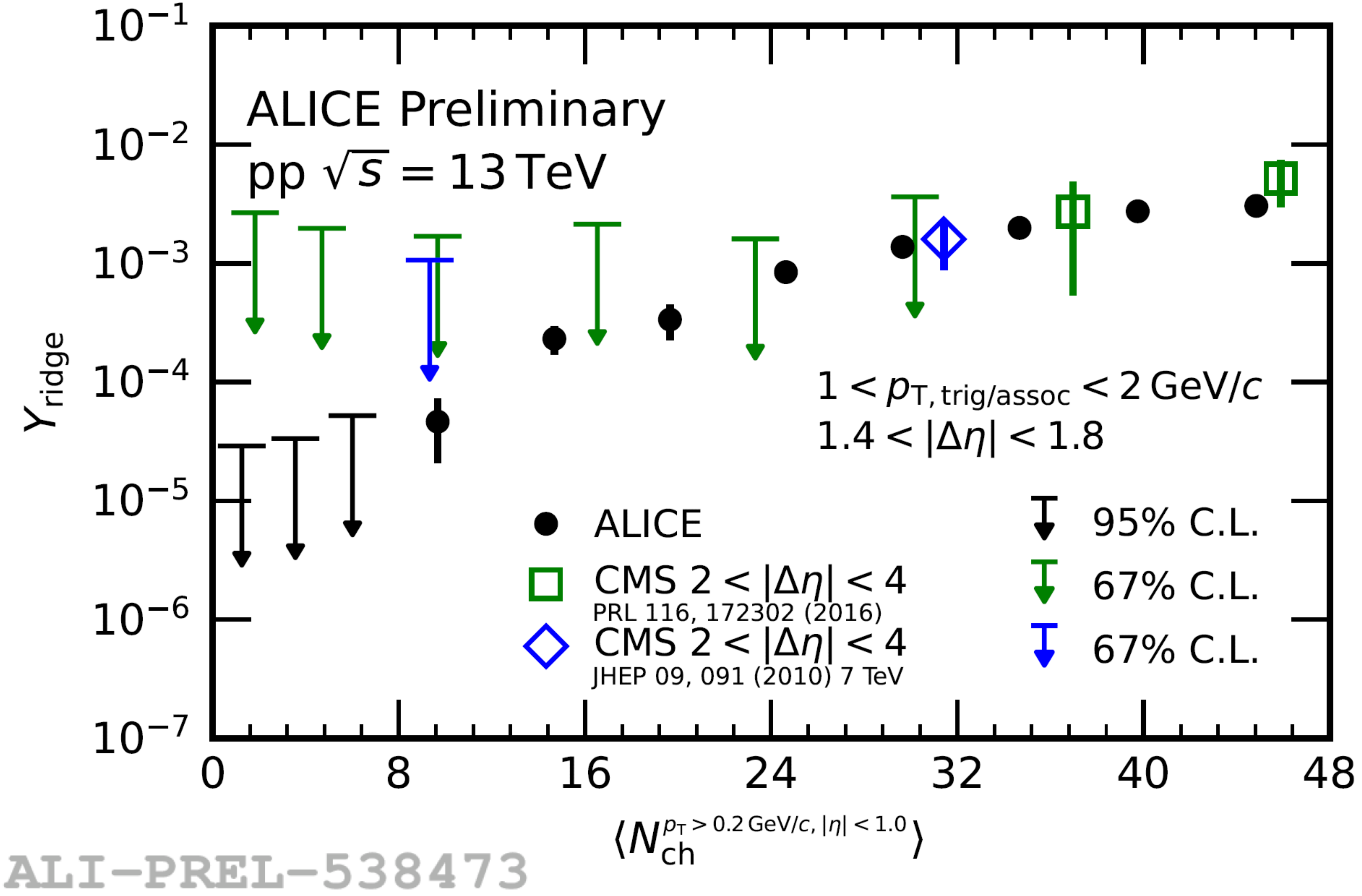
$$\Delta V_2 = V_2^{\text{data}} - V_2^{\text{MC}}$$



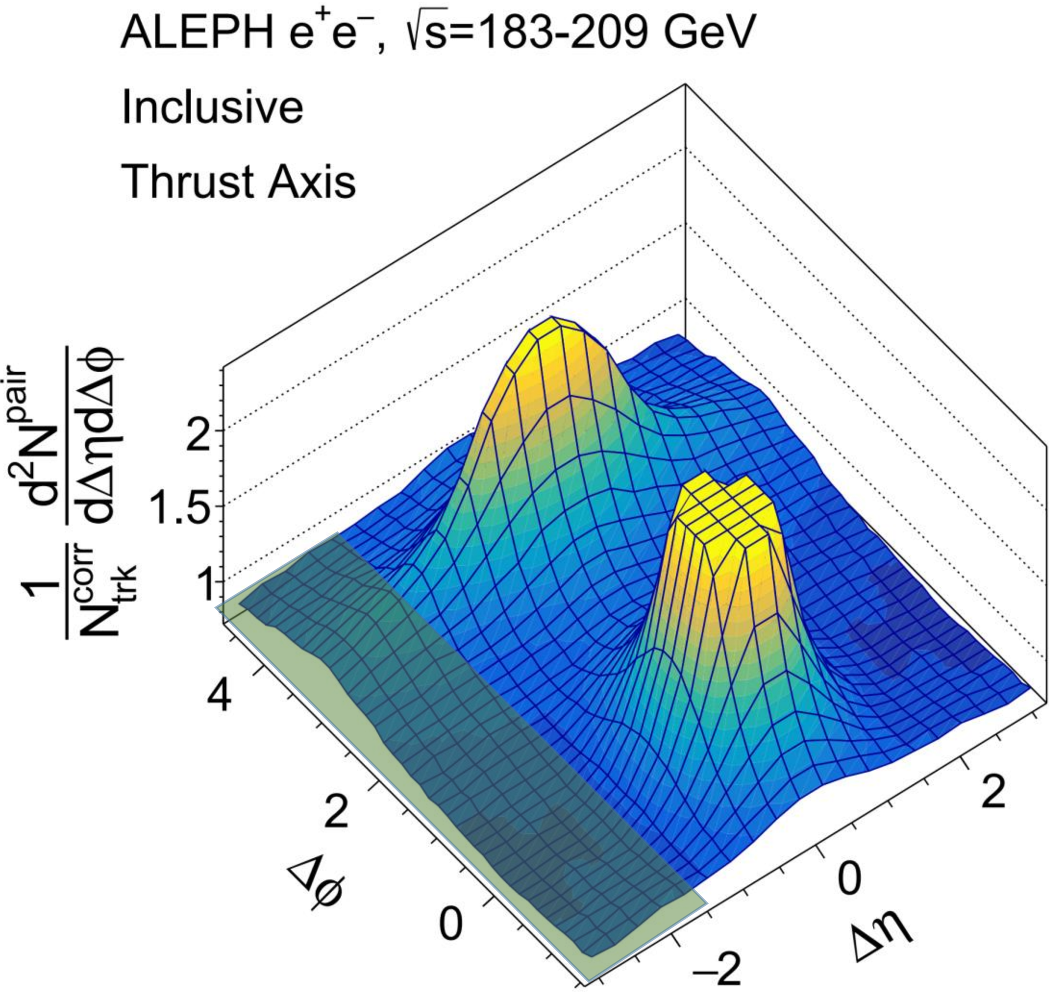


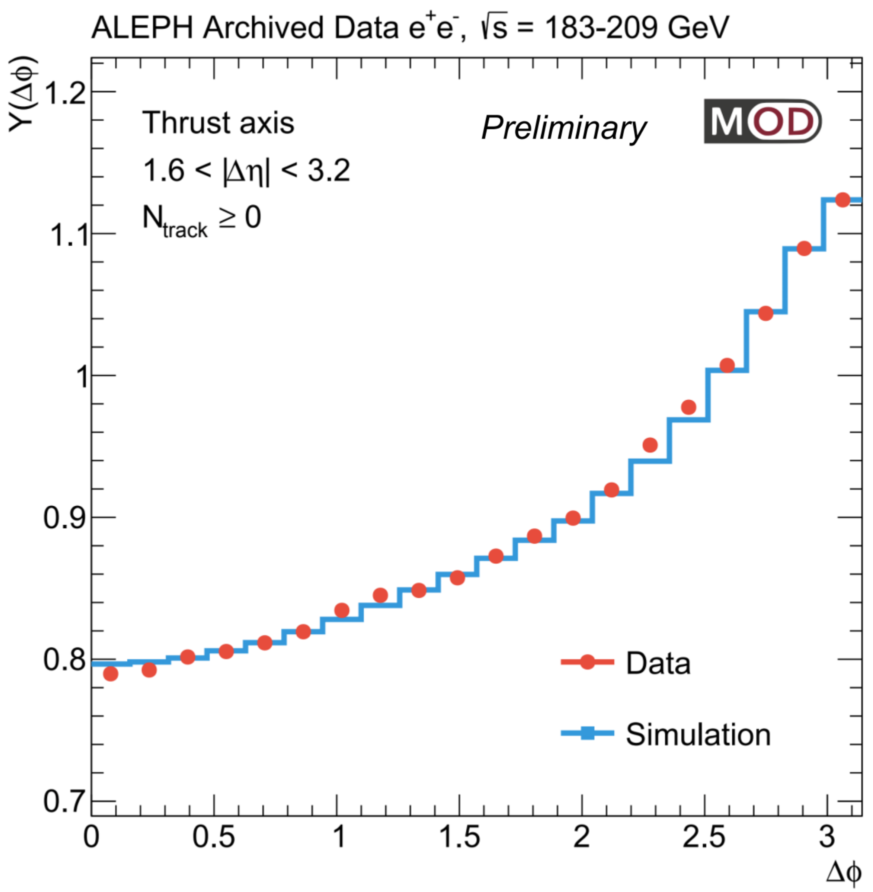
- Difference between data and MC v_2 is studied differentially in p_T bins*
- Data v_2 is systematically higher than MC simulation between $0<p_T<3$ GeV
- Significance of this signal is under investigation

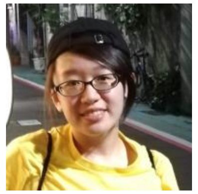
* p_T calculated with respect to thrust axis


ALICE Preliminary
pp $\sqrt{s} = 13$ TeV
$1 < p_{T,\,trig/assoc} < 2$ GeV/c
$1.4 < |\Delta\eta| < 1.8$
ALICE
CMS $2 < |\Delta\eta| < 4$
PRL 116, 172302 (2016)
CMS $2 < |\Delta\eta| < 4$
JHEP 09, 091 (2010) 7 TeV
95% C.L.
67% C.L.
67% C.L.
Y_{ridge}
$\langle N_{ch}^{p_T > 0.2\,GeV/c,\,|\eta| < 1.0} \rangle$
ALI-PREL-538473

Two-Particle Correlation Function: 1D Projection

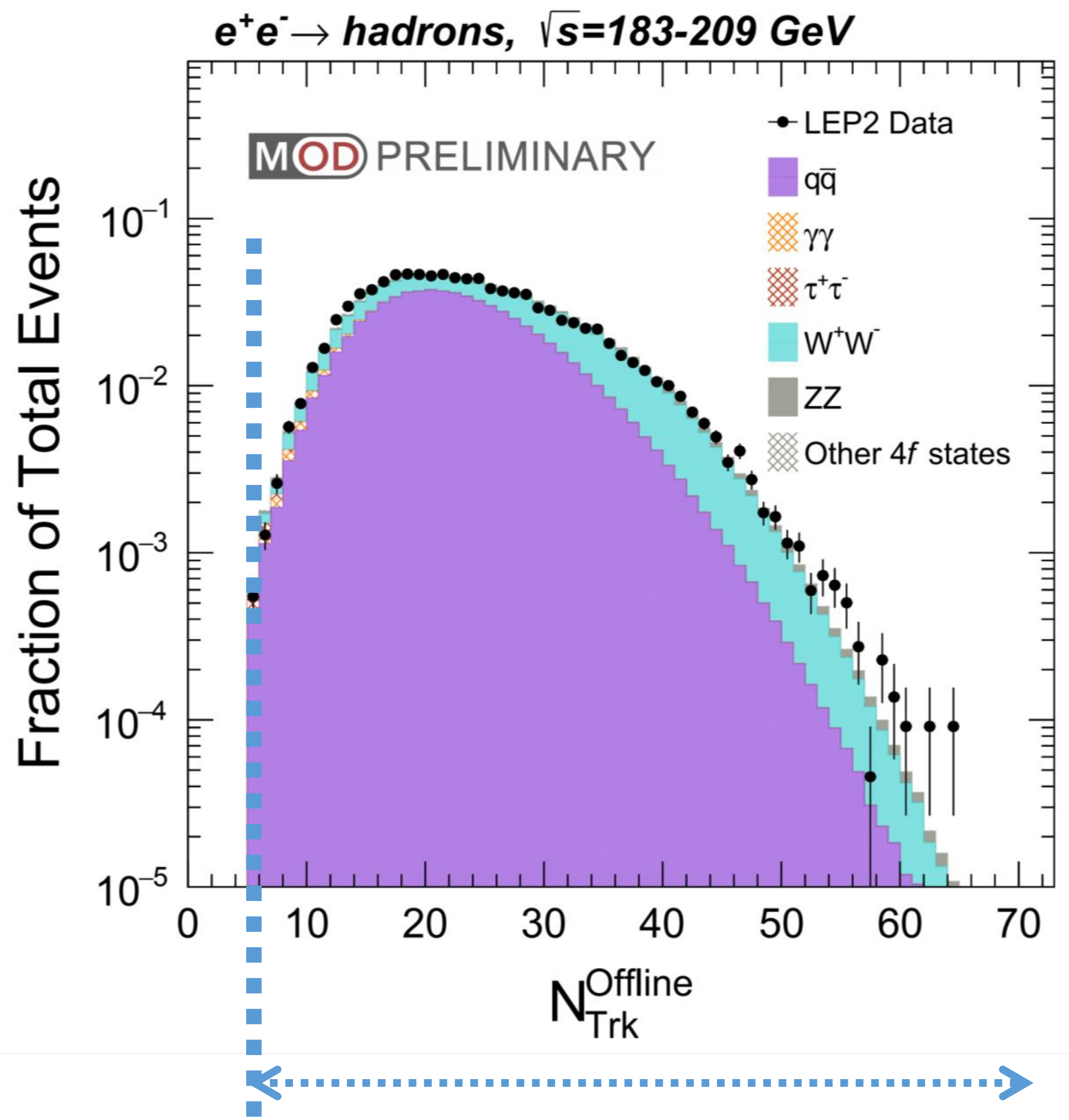


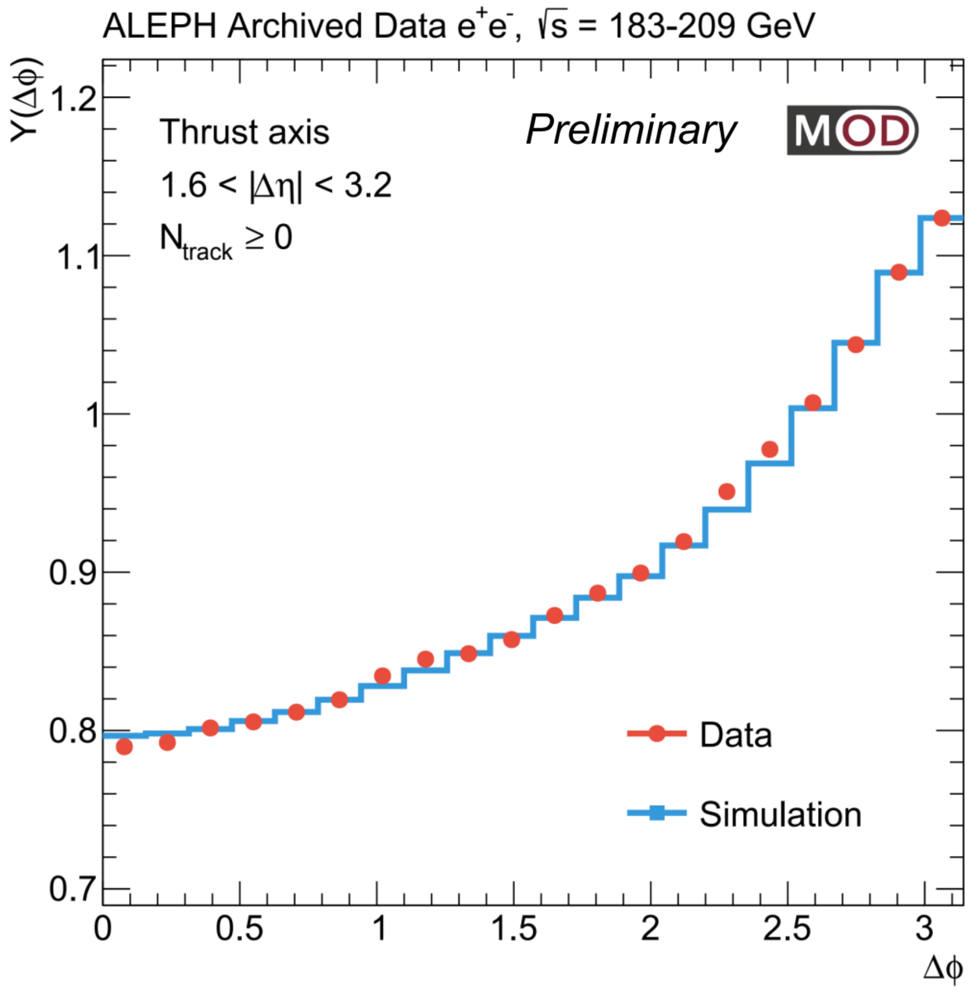


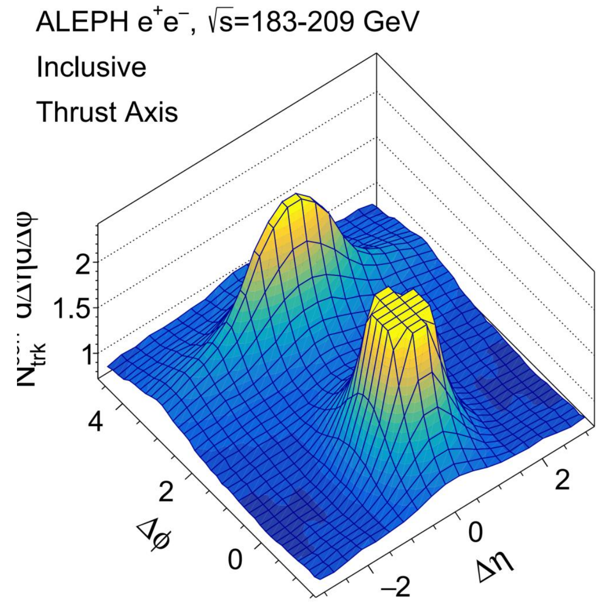


Janice Chen

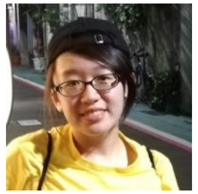
Hadronic e⁺e⁻ Events at LEP 2 (no multiplicity cut)







Excellent agreement between **data** and **simulation**



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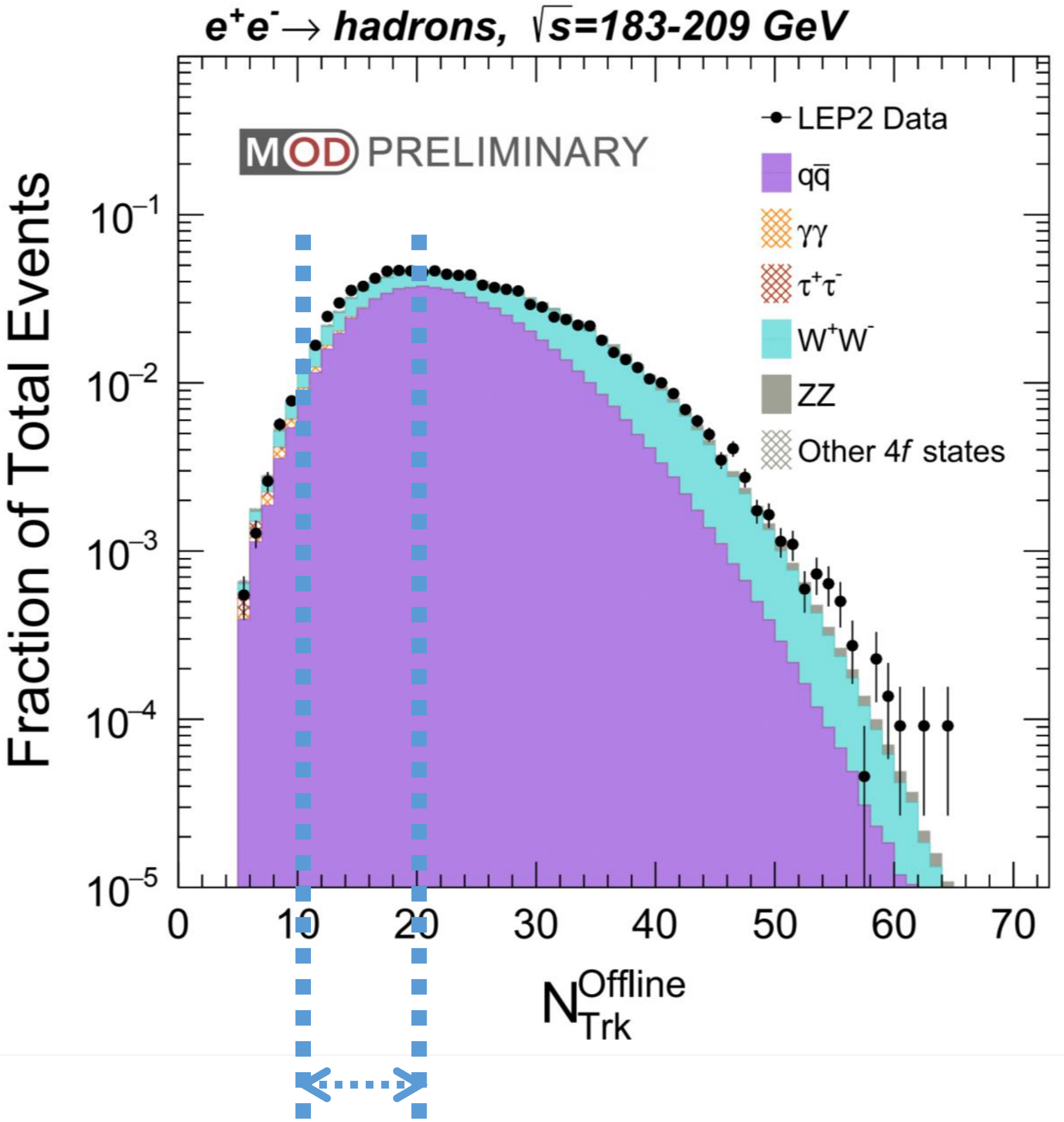
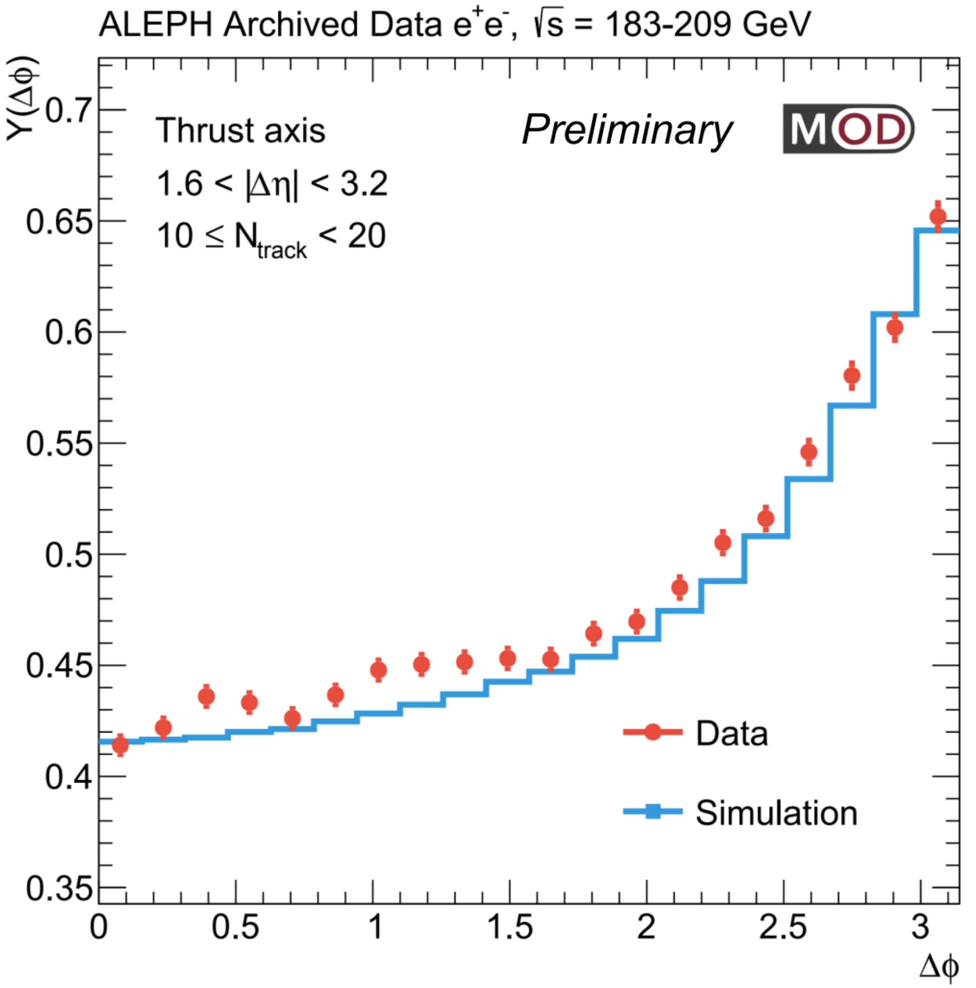
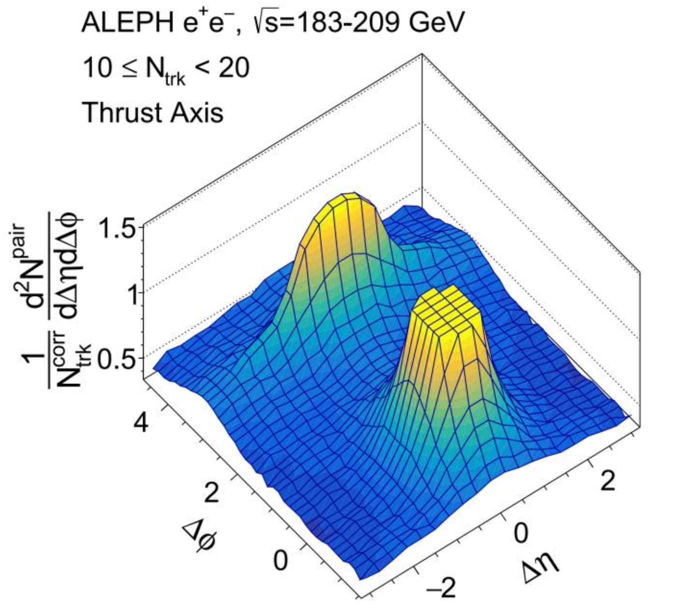
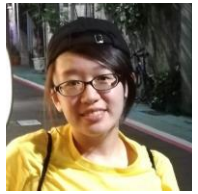
Hadronic e^+e^- Events at LEP 2 ($10<=N_{trk}<20$)







Good agreement between **data** and **simulation** except a shift in baseline



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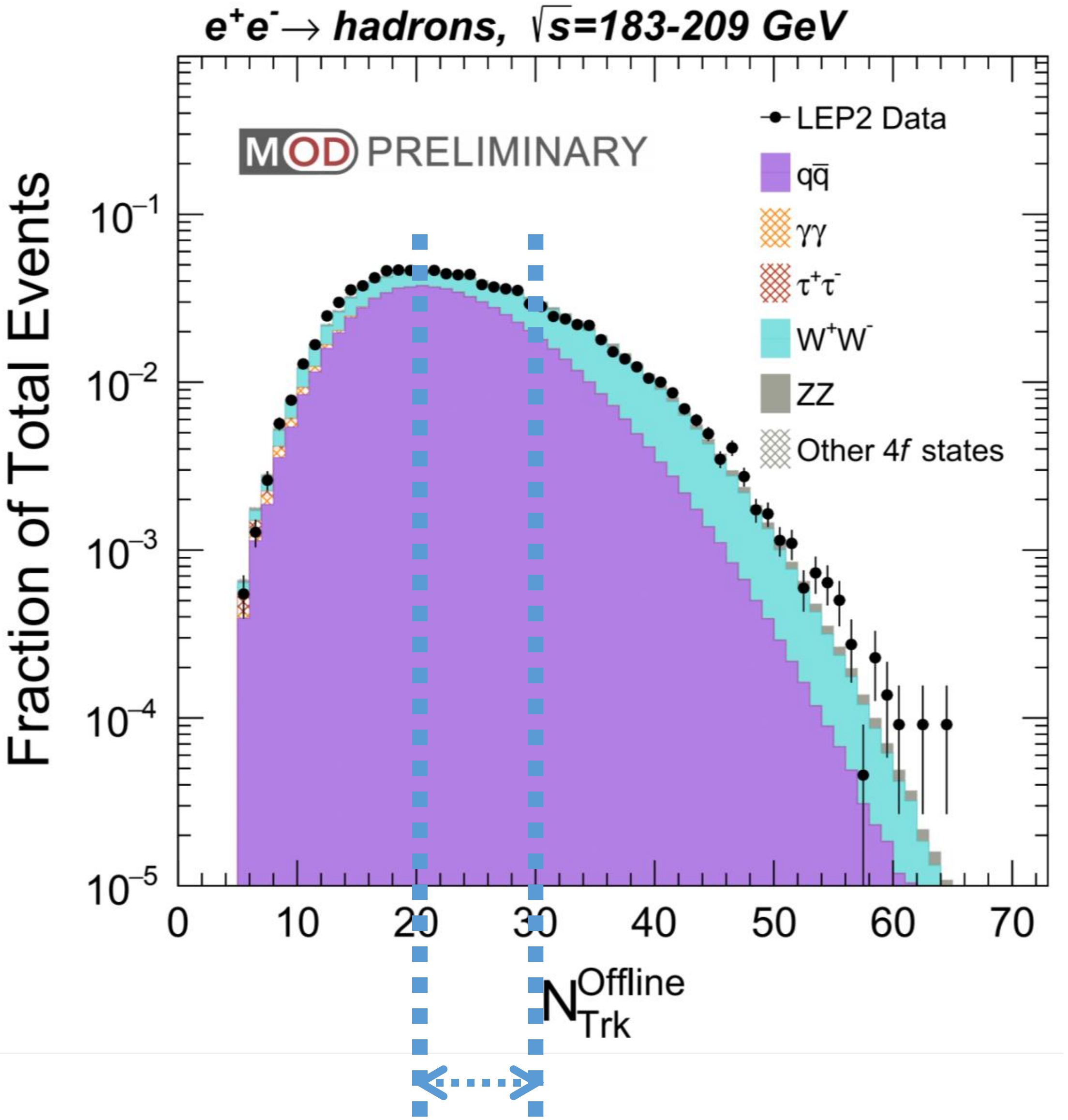
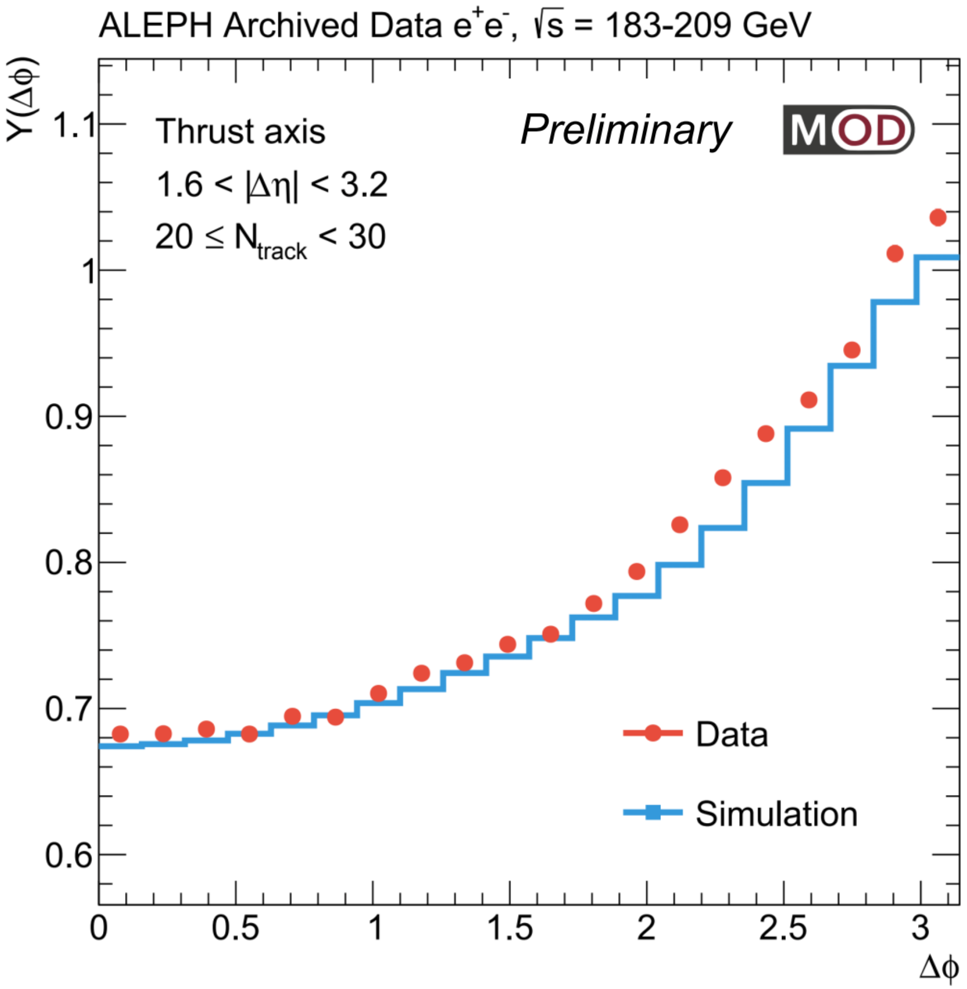
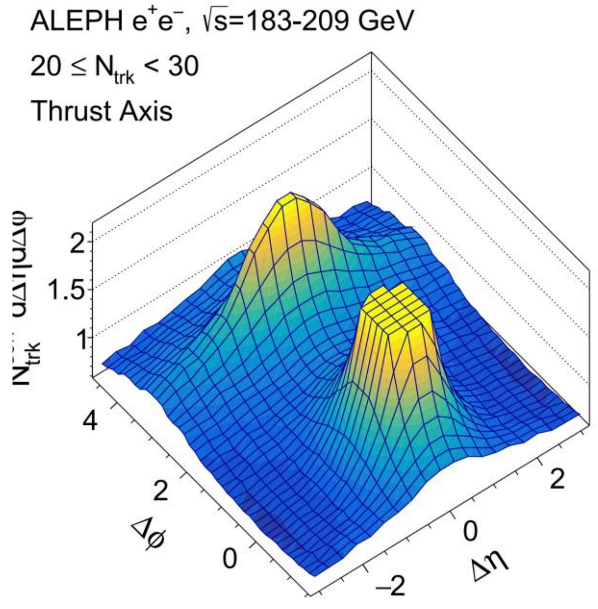
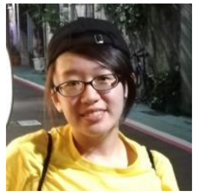
Hadronic e^+e^- Events at LEP 2 ($20<=N_{trk}<30$)







Reasonable agreement between **data** and **simulation** except a shift in baseline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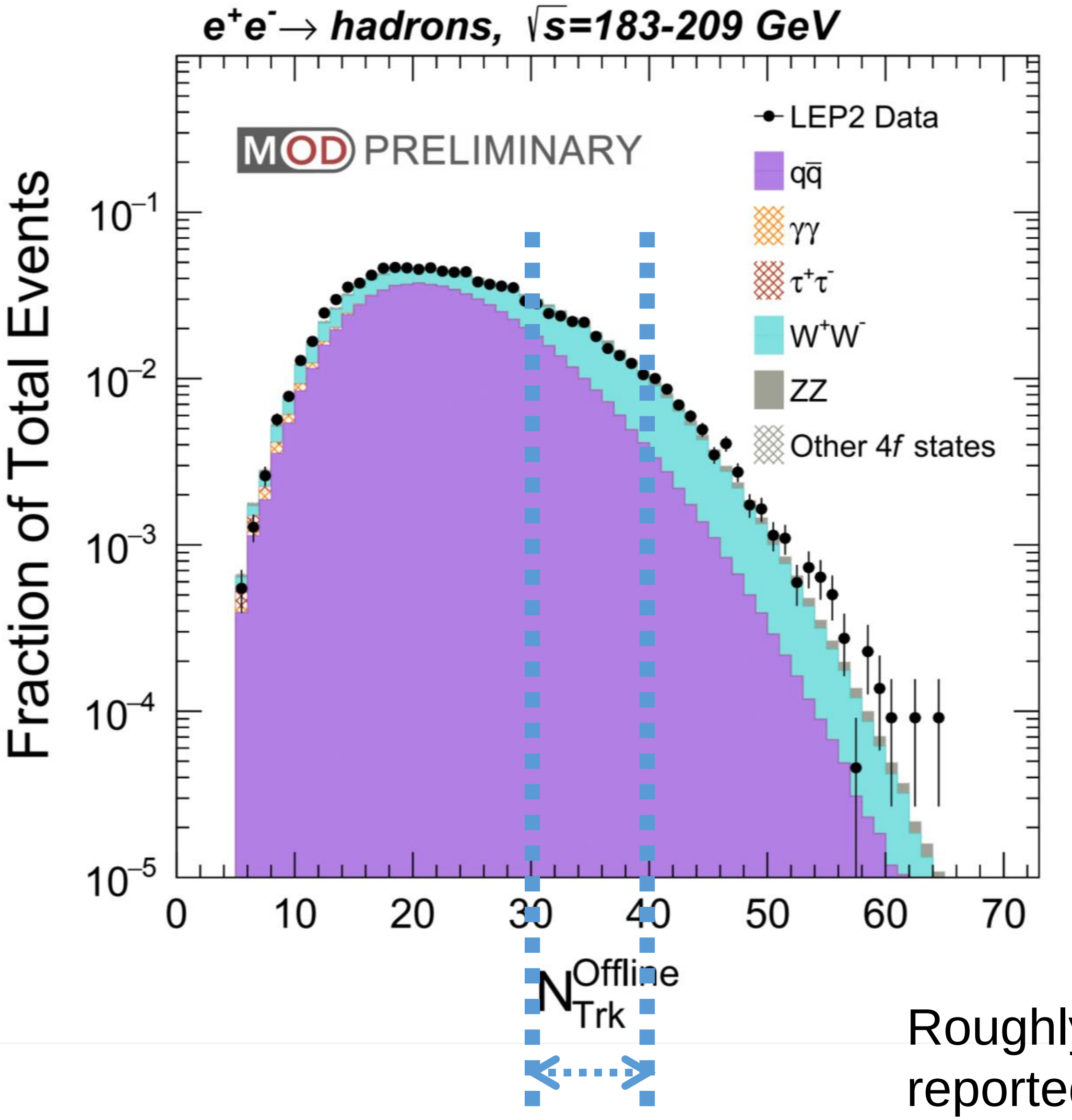
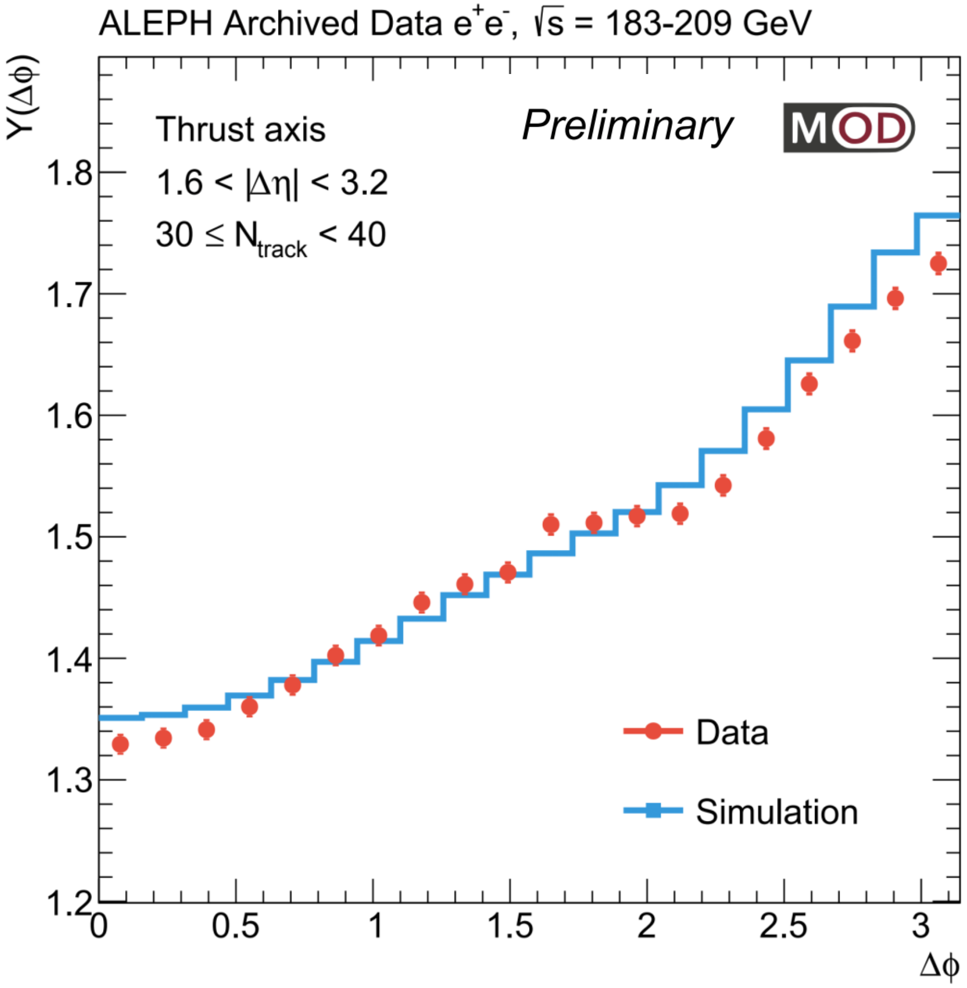
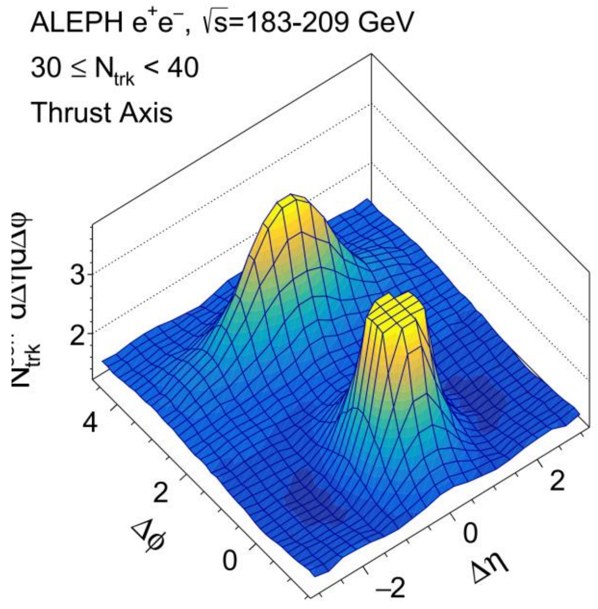
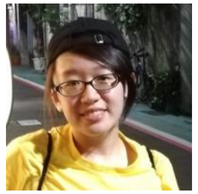
Hadronic e^+e^- Events at LEP 2 ($30<=N_{trk}<40$)







Roughly correspond to the highest multiplicity LEP1 result reported (with $N_{trk}>=35$)



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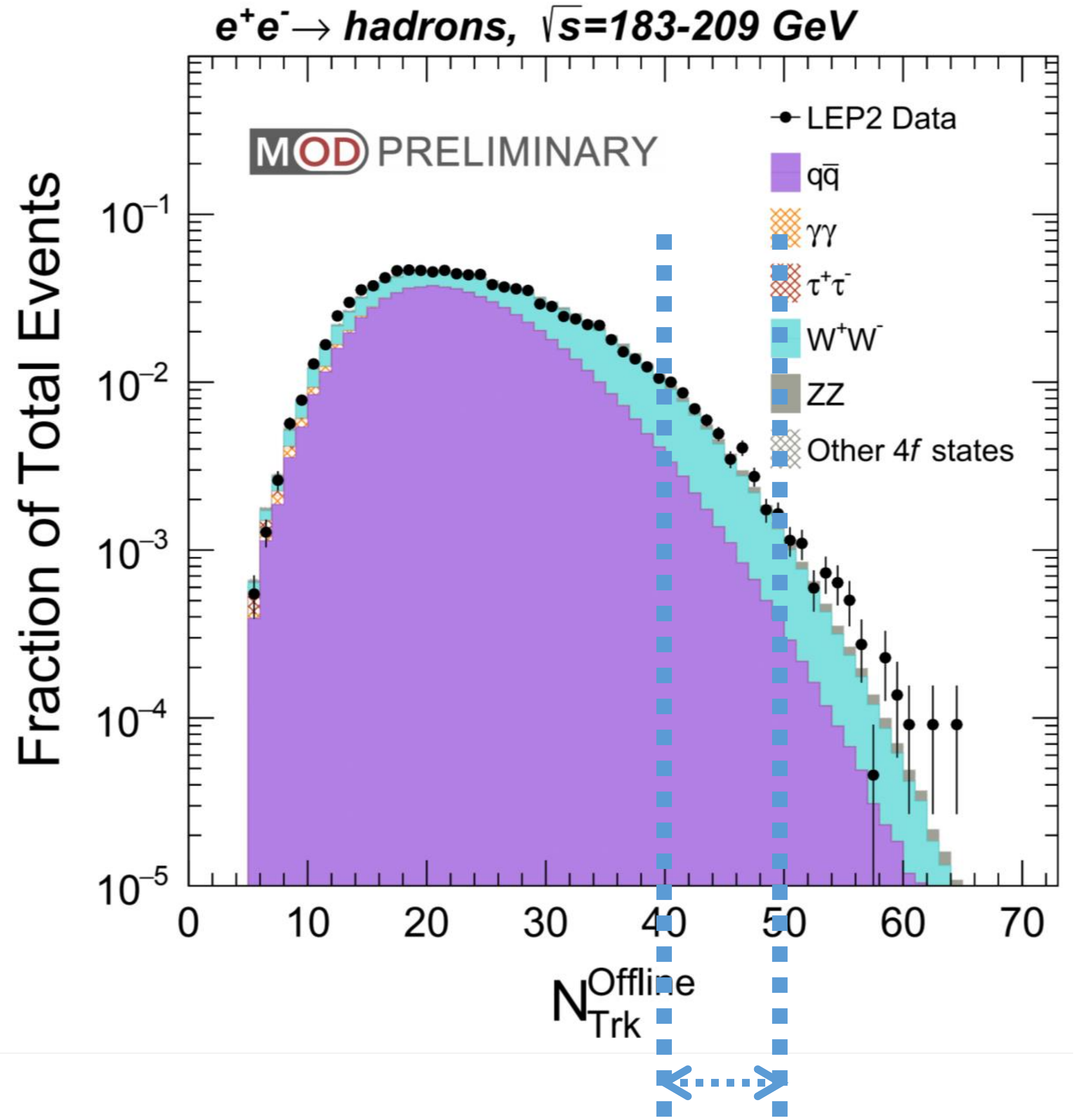
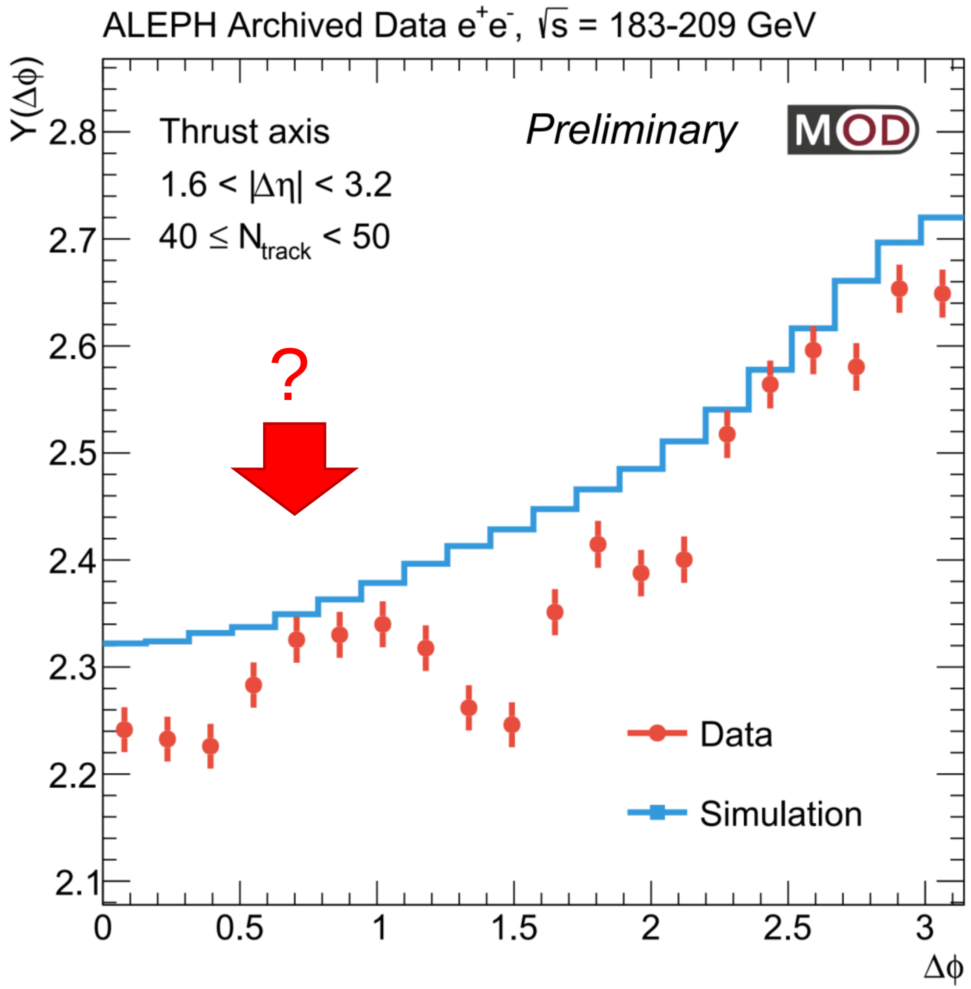
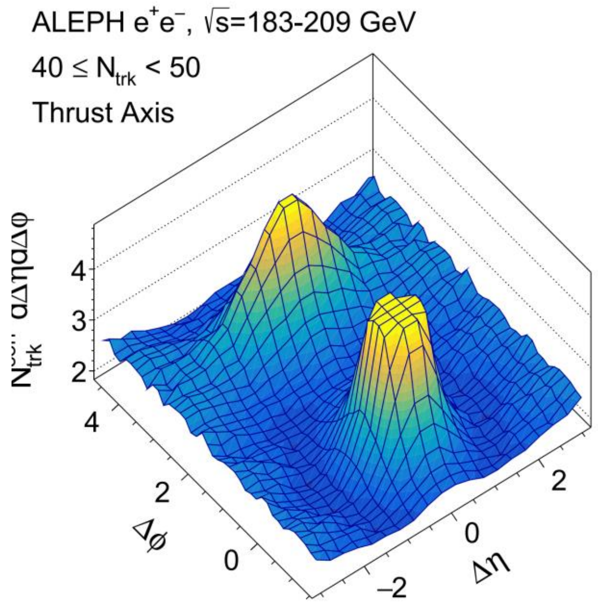
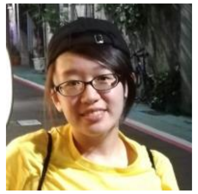
Hadronic e^+e^- Events at LEP 2 ($40 \le N_{trk} < 50$)









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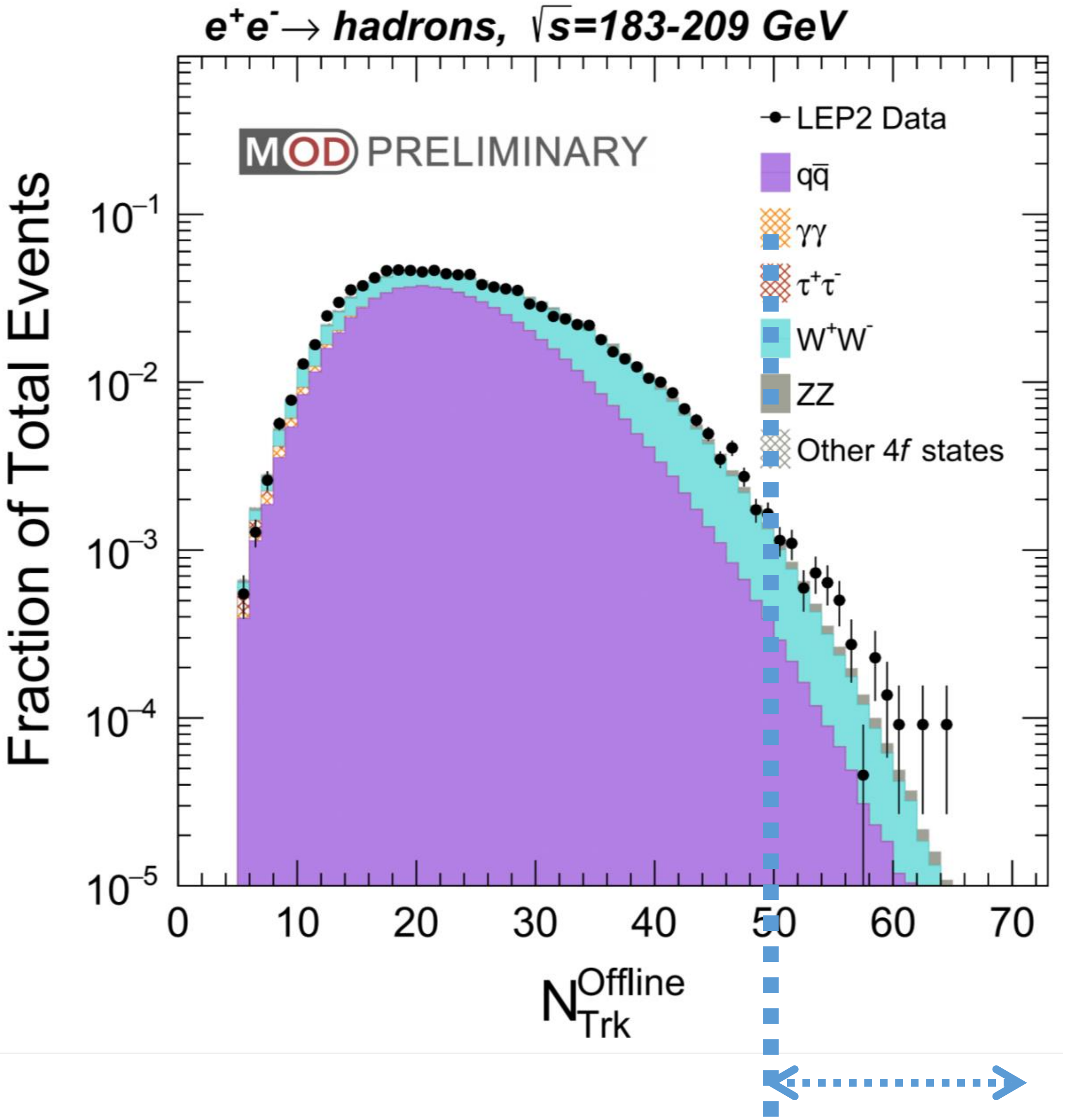
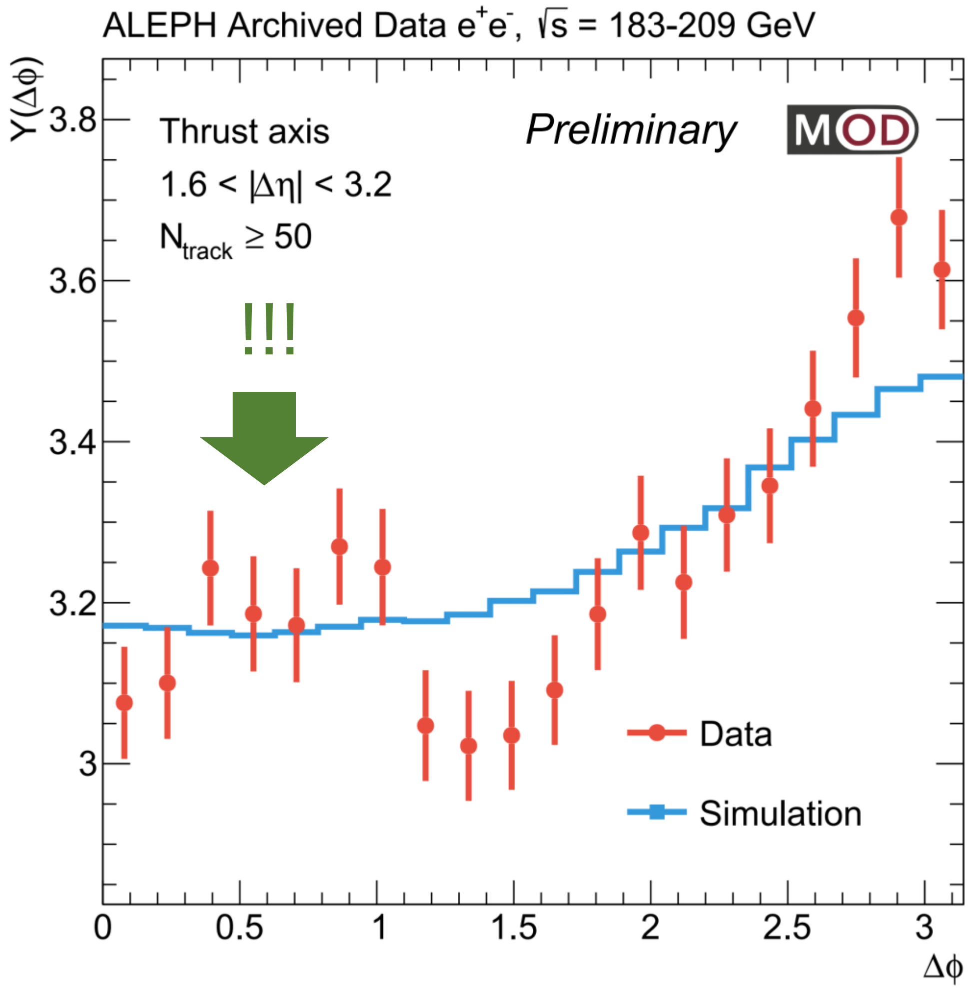
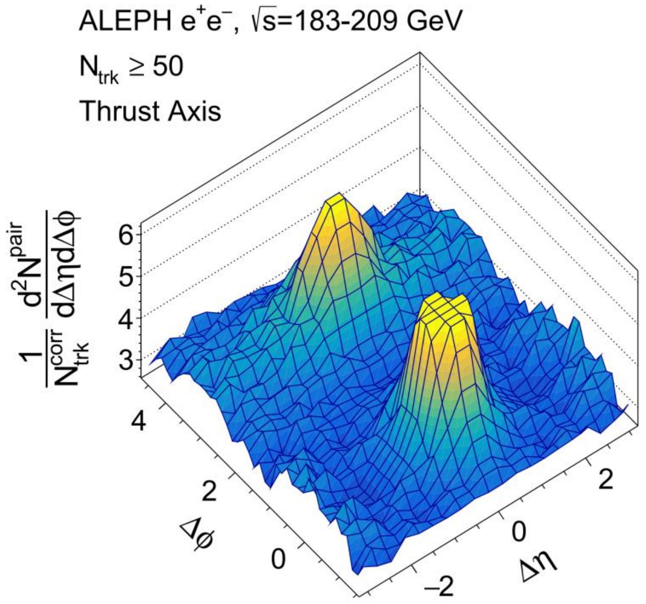
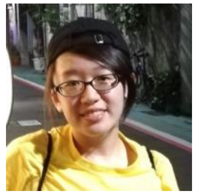
Hadronic e^+e^- Events at LEP 2 (N_{trk}>=50)







- A long-range near-side correlation signal shows up at high multiplicity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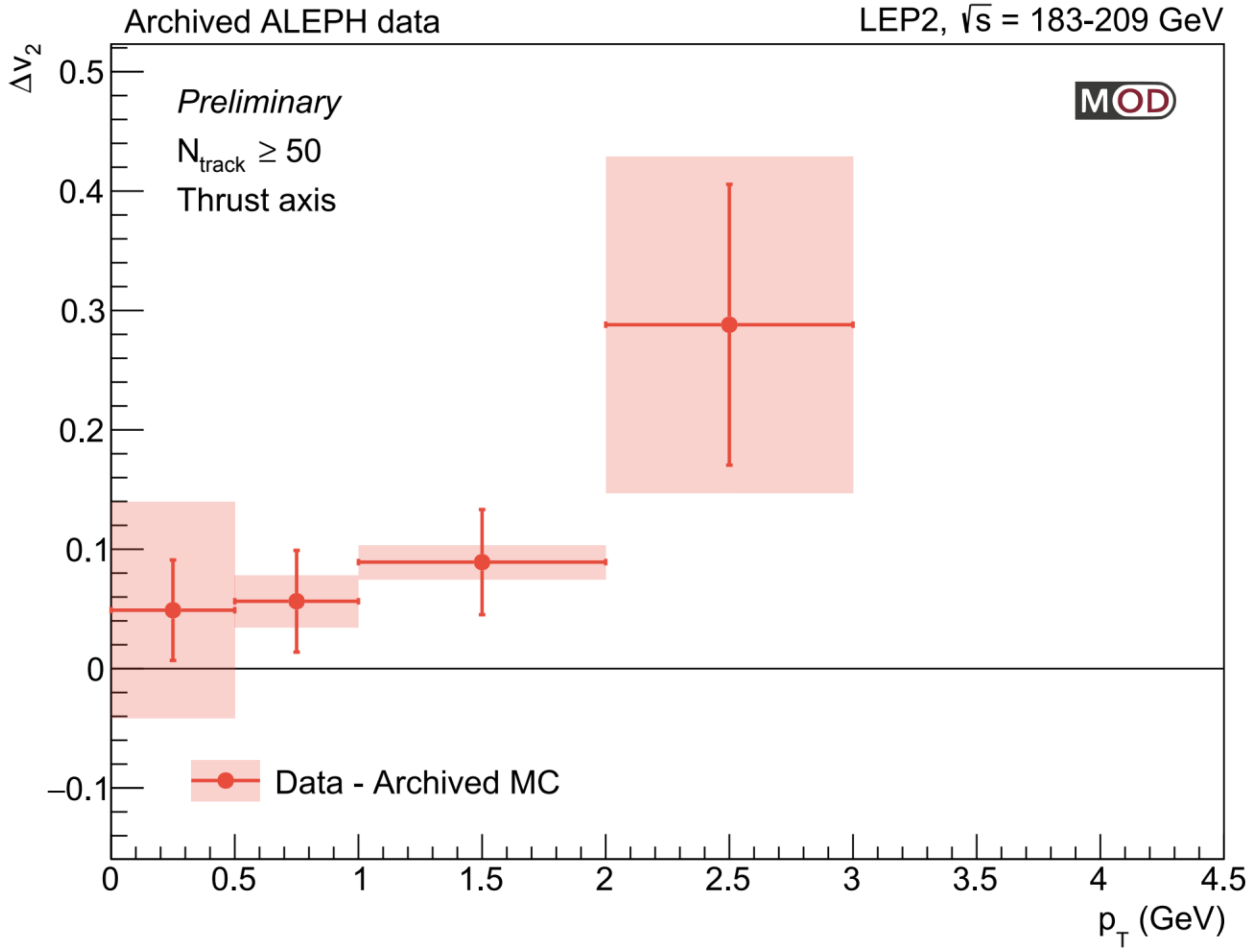
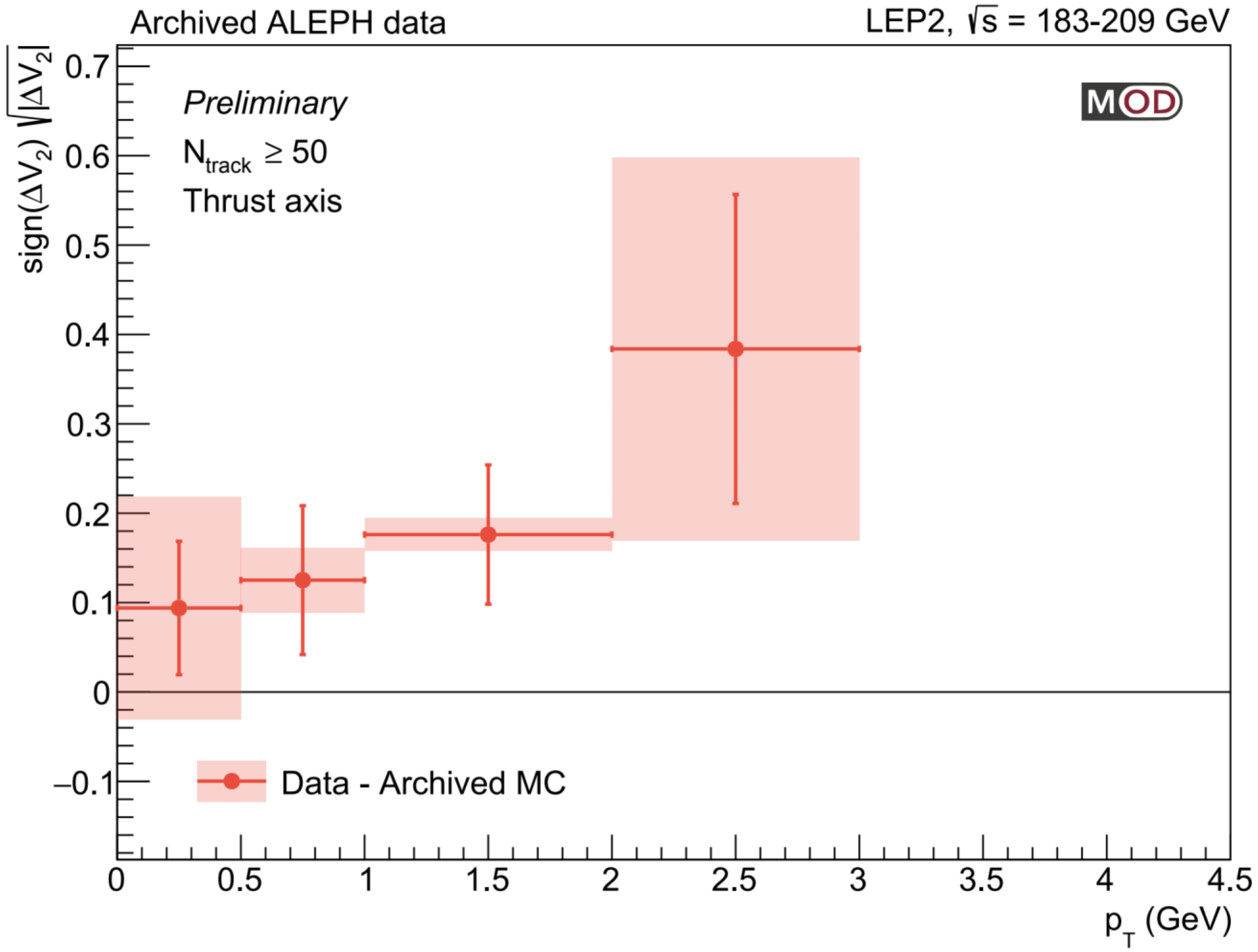
Difference between Data and Archived MC

$$\Delta v_2 = v_2^{\mathrm{data}} - v_2^{\mathrm{MC}}$$



$$sign(\Delta V_2)\sqrt{\Delta V_2}$$

$$\Delta V_2 = V_2^{\mathrm{data}} - V_2^{\mathrm{MC}}$$



- Difference between data and MC v_2 is studied differentially in p_T bins*
- Data v_2 is systematically higher than MC simulation between $0<p_T<3$ GeV
- Significance of this signal is under investigation

* p_T calculated with respect to thrust axis

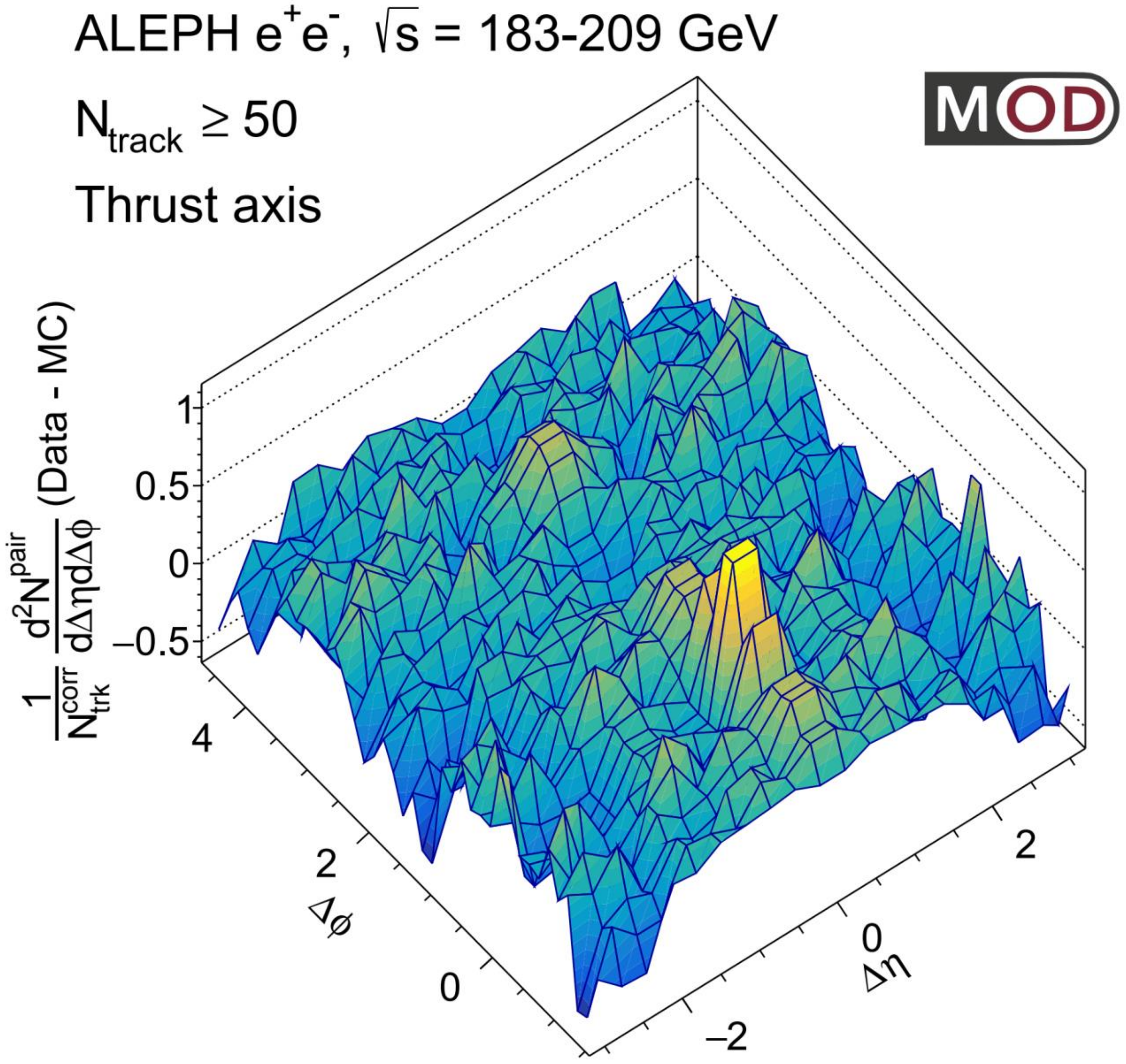
Hadronic Event Selection

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

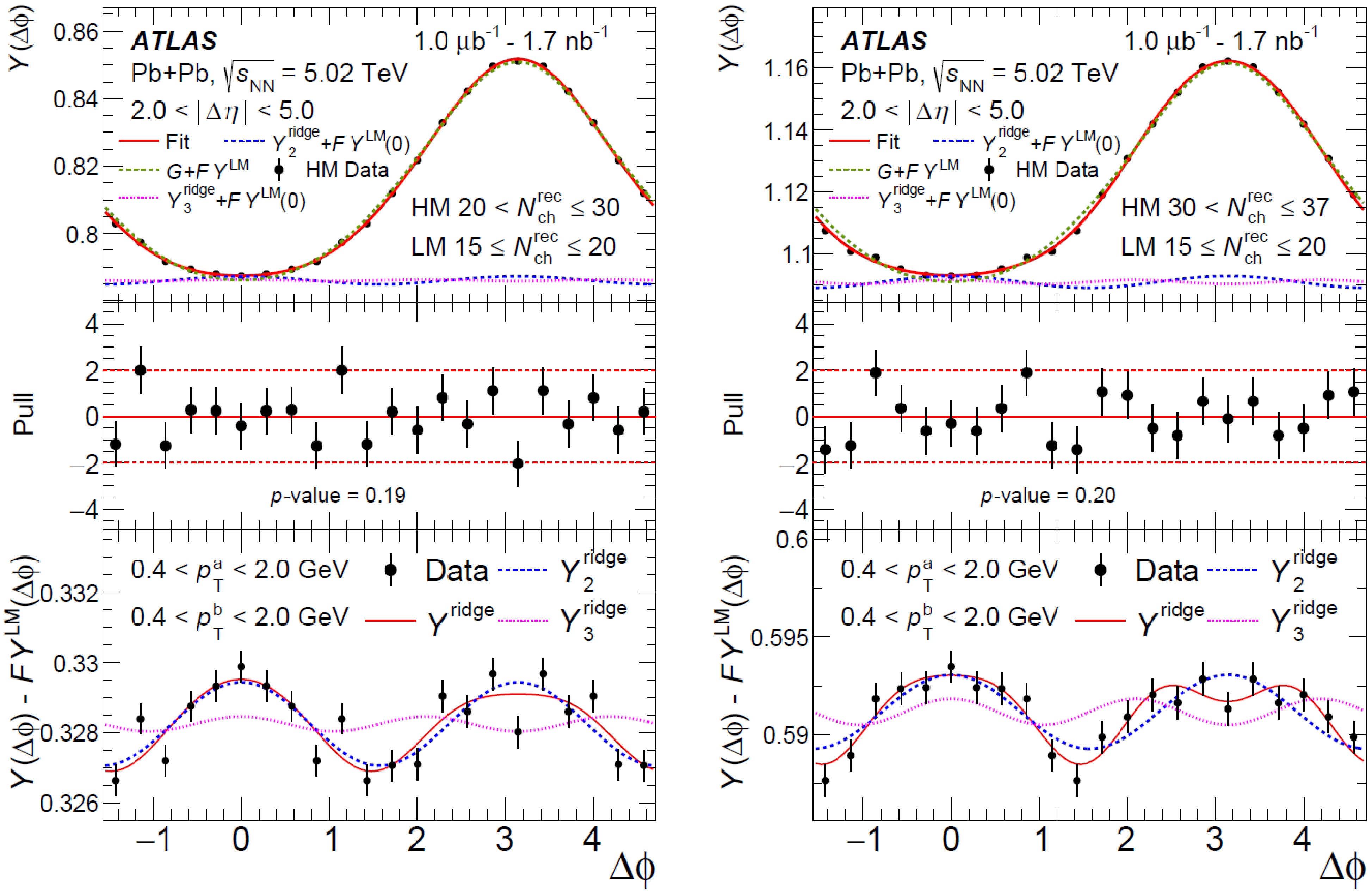
- **Neutral Hadron Selection:**
  - Particle Flow Candidate 4, 5 (ECAL / HCAL object)
  - E> 0.4 GeV
  - |cosθ|<0.98

- **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

Difference between Data and MC

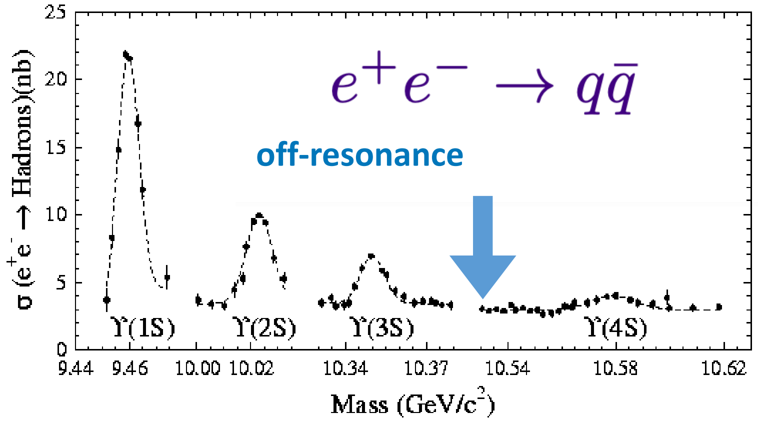


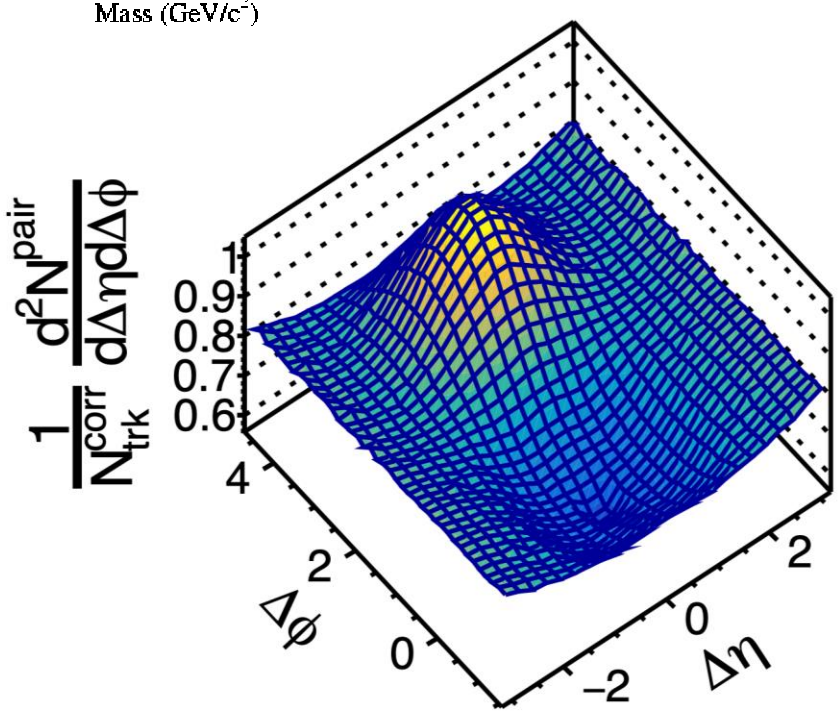
Photonuclear at the LHC



Belle e$^+$e$^-$ at 10.52 GeV (Off-Resonance)

Reasonable data and MC agreements!



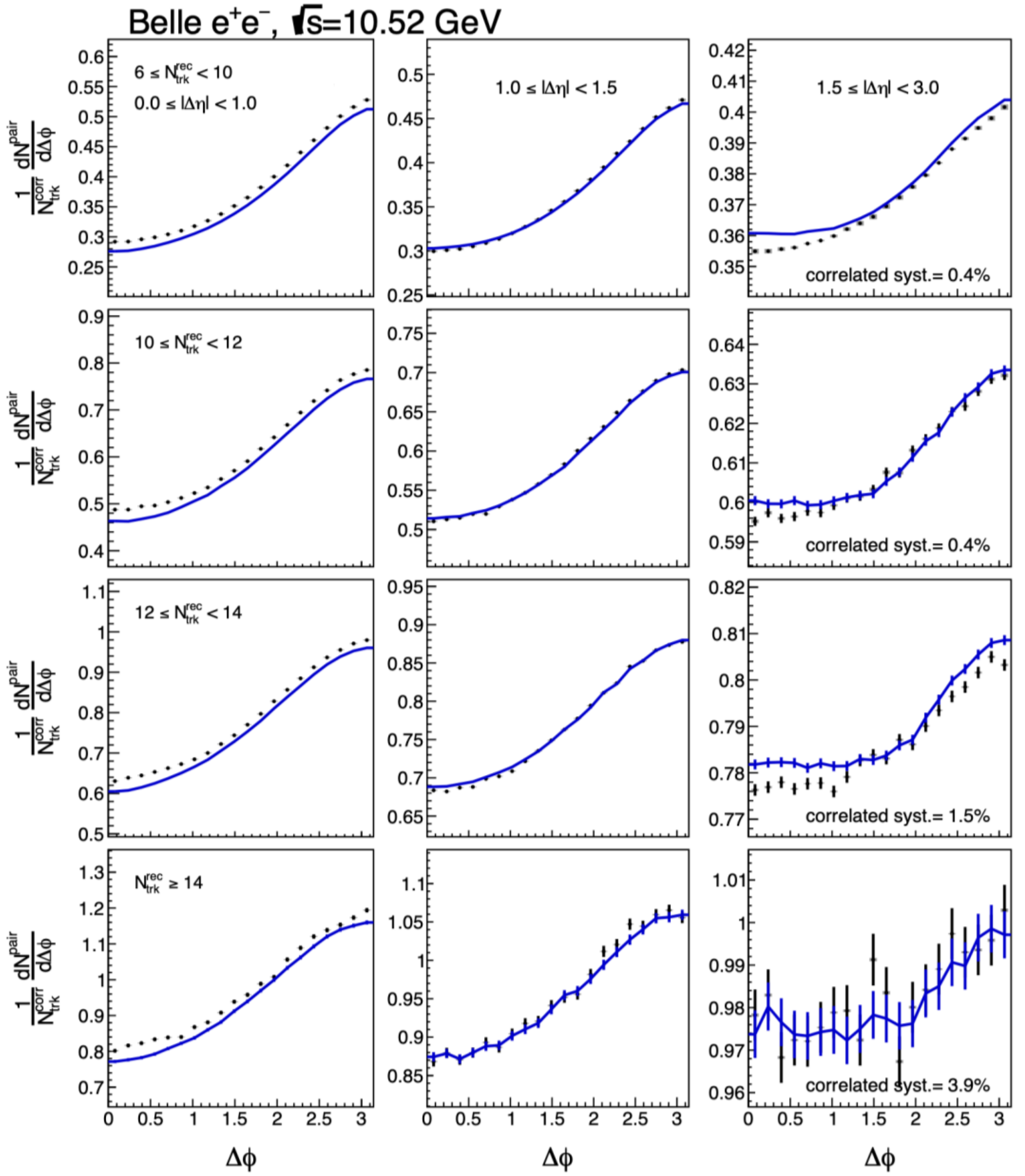


$12 \leq N_{trk}^{rec} < 14$

Data

MC PYTHIA6

High-multiplicity



Short Range ($0 \leq |\Delta\eta| < 1$)

Middle Range ($1 \leq |\Delta\eta| < 1.5$)

Long Range ($1.5 \leq |\Delta\eta| < 3.0$)

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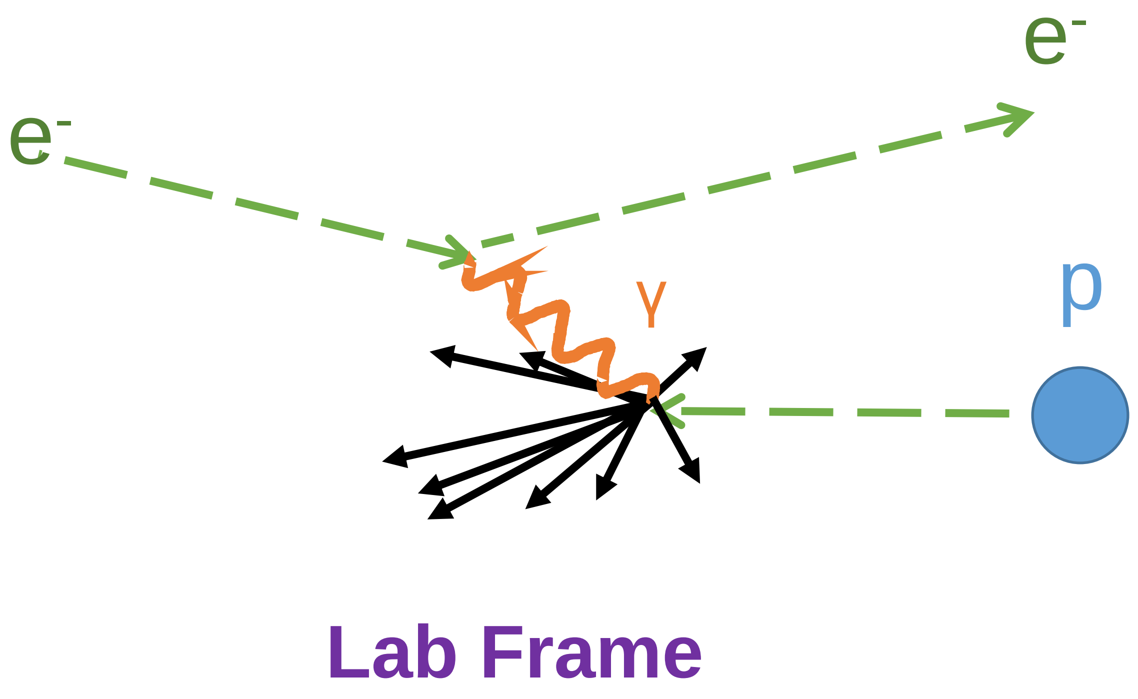
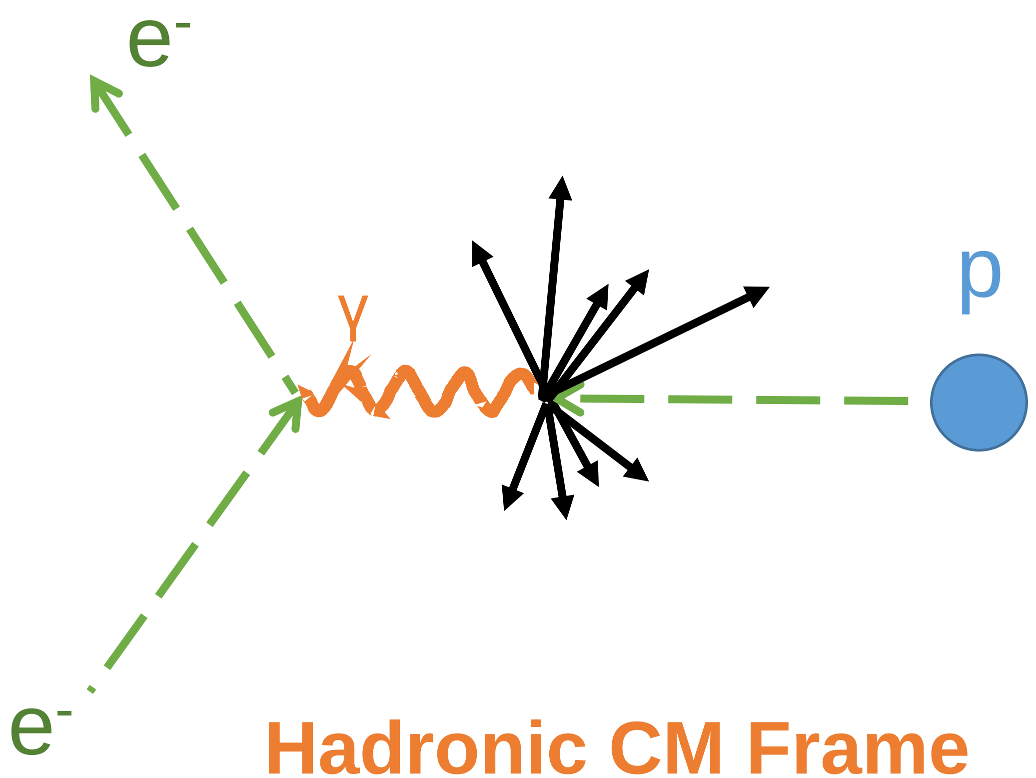
Lab vs. Hadronic CM Frame



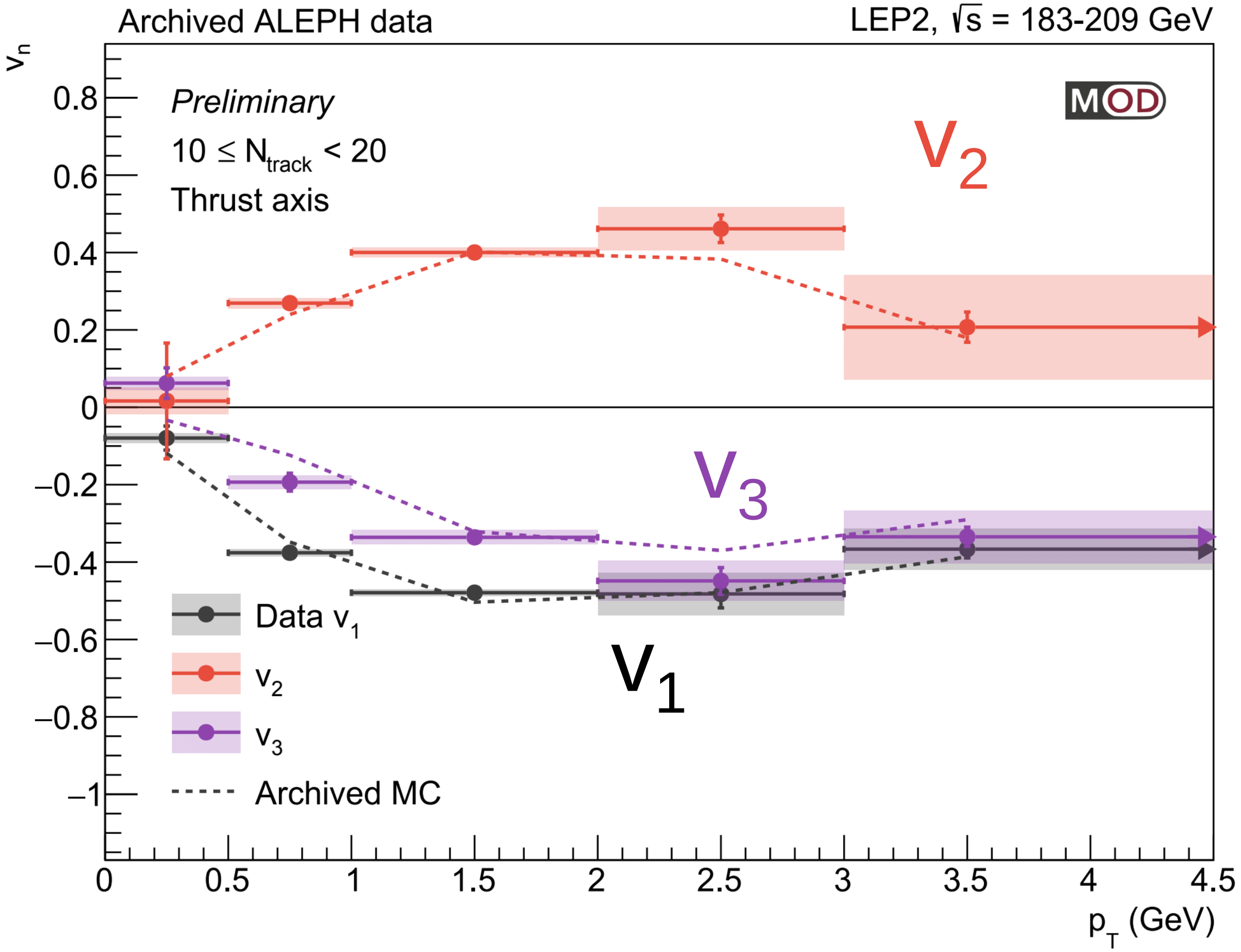


Used in ZEUS analysis

Used in H1 analysis

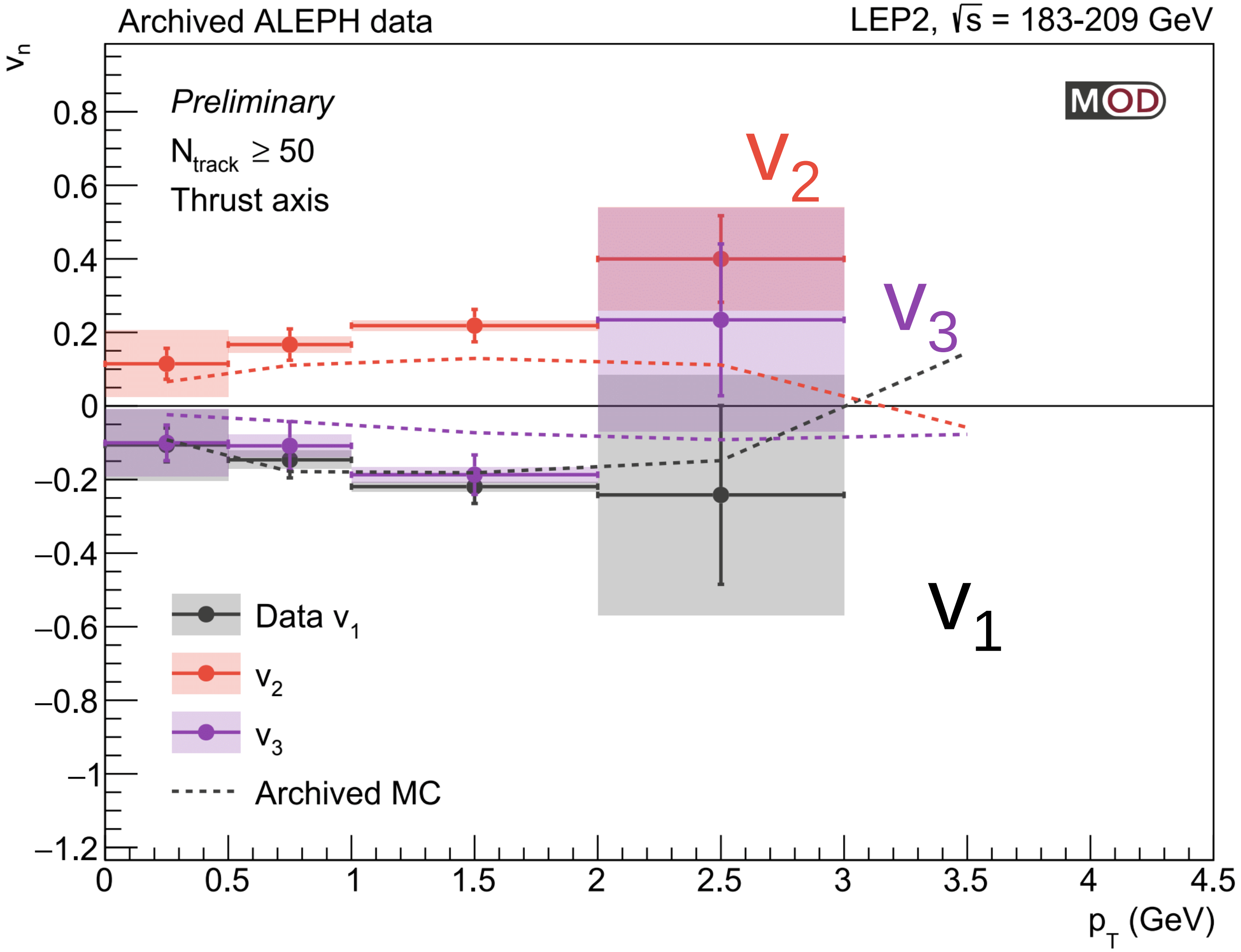
Extracted v_n vs. Charged Particle p_T

Low multiplicity 10 ≤N_{track} < 20



Good agreement between data and MC

High multiplicity N_{track}≥50



Larger v_2 and v_3 magnitudes than MC

CMS γp in pPb Collisions at 8.16 TeV

No low multiplicity event subtraction

- Positive $V_{2\Delta}$ and negative $V_{1\Delta}$ indicate a significant influence of jet-like correlations
- $V_{2\Delta}$ and $V_{1\Delta}$ magnitudes in γp are larger than those in MB pPb
- PYTHIA8 describe the v_2 data at low N_{trk}