Two-Particle Correlations in e^+e^- Collisions

Yen-Jie Lee

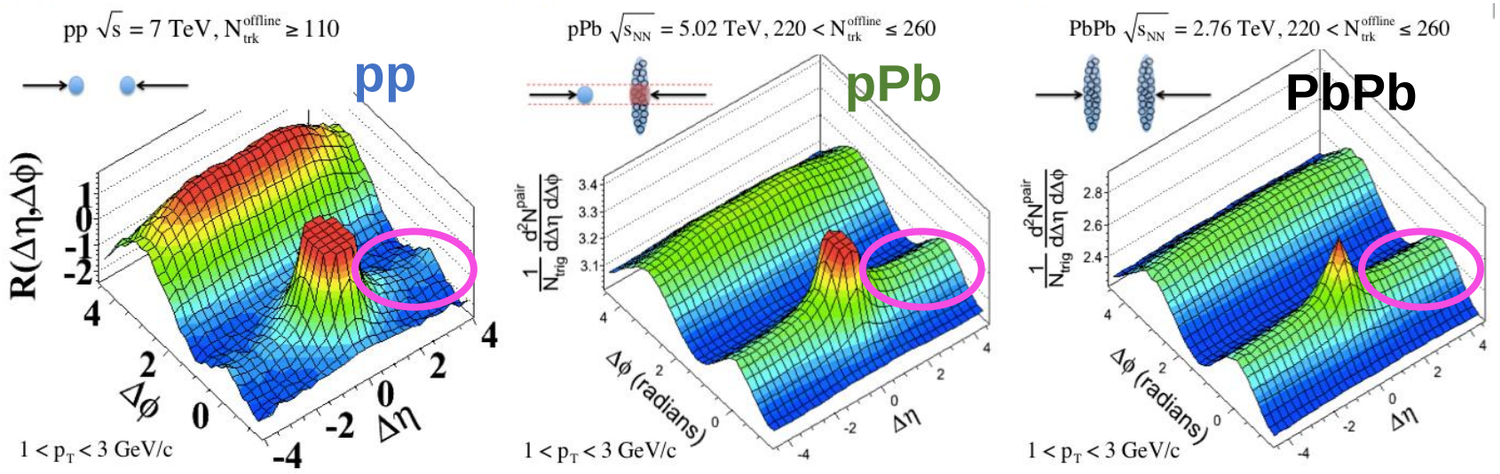
On the theory interpretation of multi-particle correlations in small collision systems, CERN, Switzerland

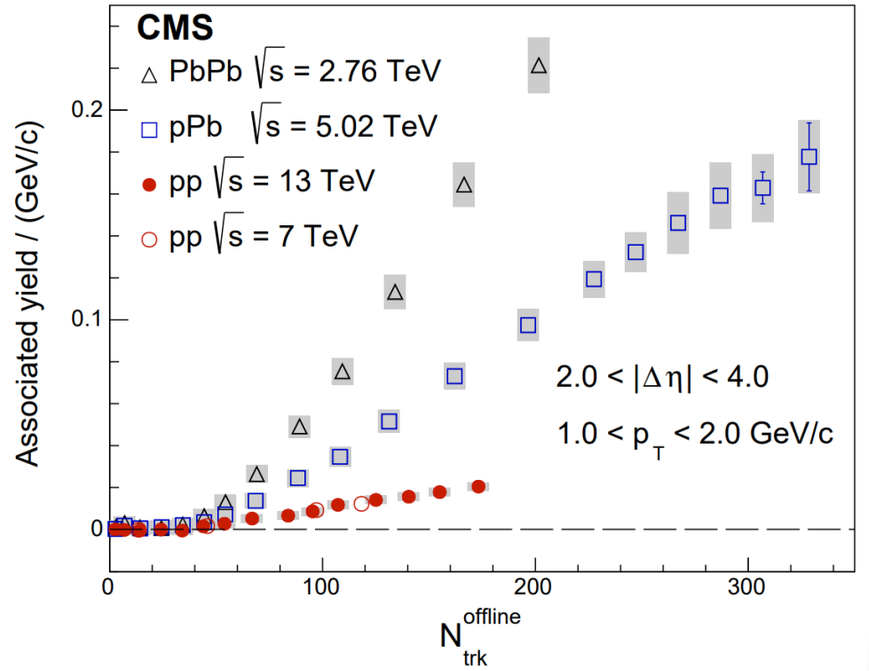
11 March, 2024

In Collaboration with Yu-Chen 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





- **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
  - …

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?

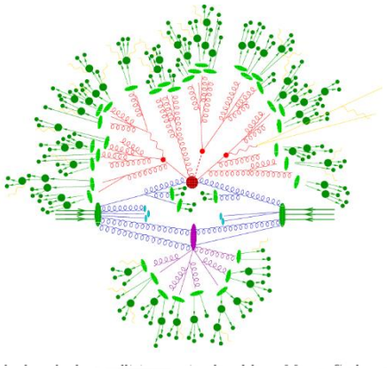
  By collection of all the experimental data and compare

- …

System Size

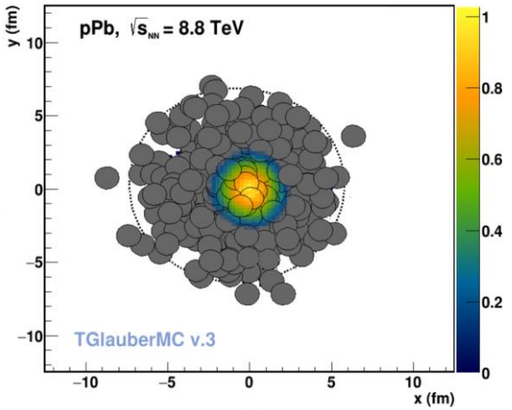
"Transverse Size" / MPI

pp



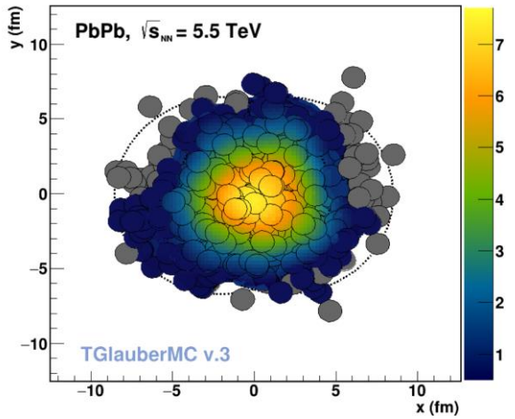
~ O(1fm)

pA



≥ O(1fm)

AA



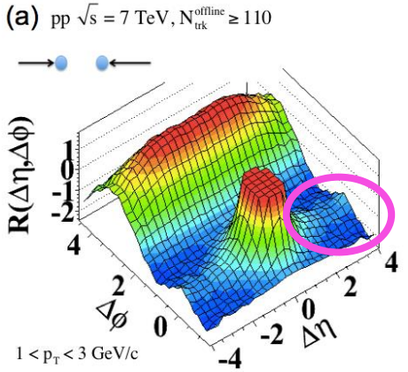
O(1-10 fm)

Multiplicity

Smallest System: e^+e^-

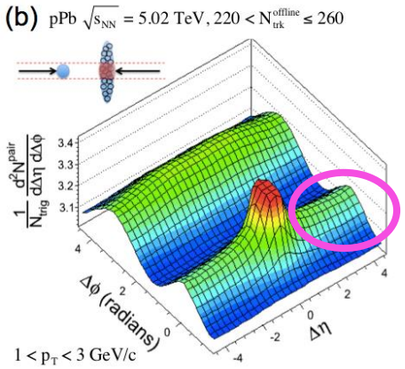
"Transverse Size" / MPI

High multiplicity pp

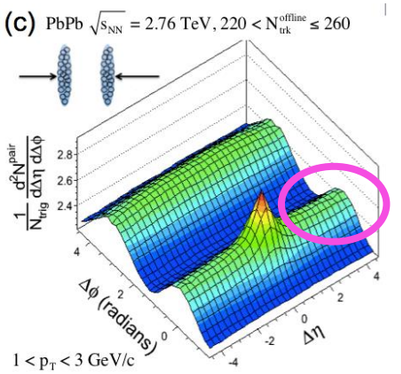


~ O(1fm)

High multiplicity pPb

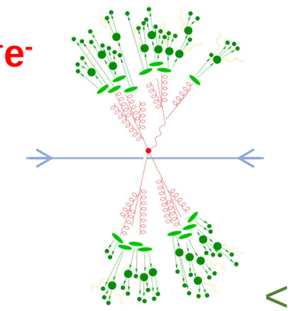


≥ O(1fm)



O(1-10 fm)

e^+e^-

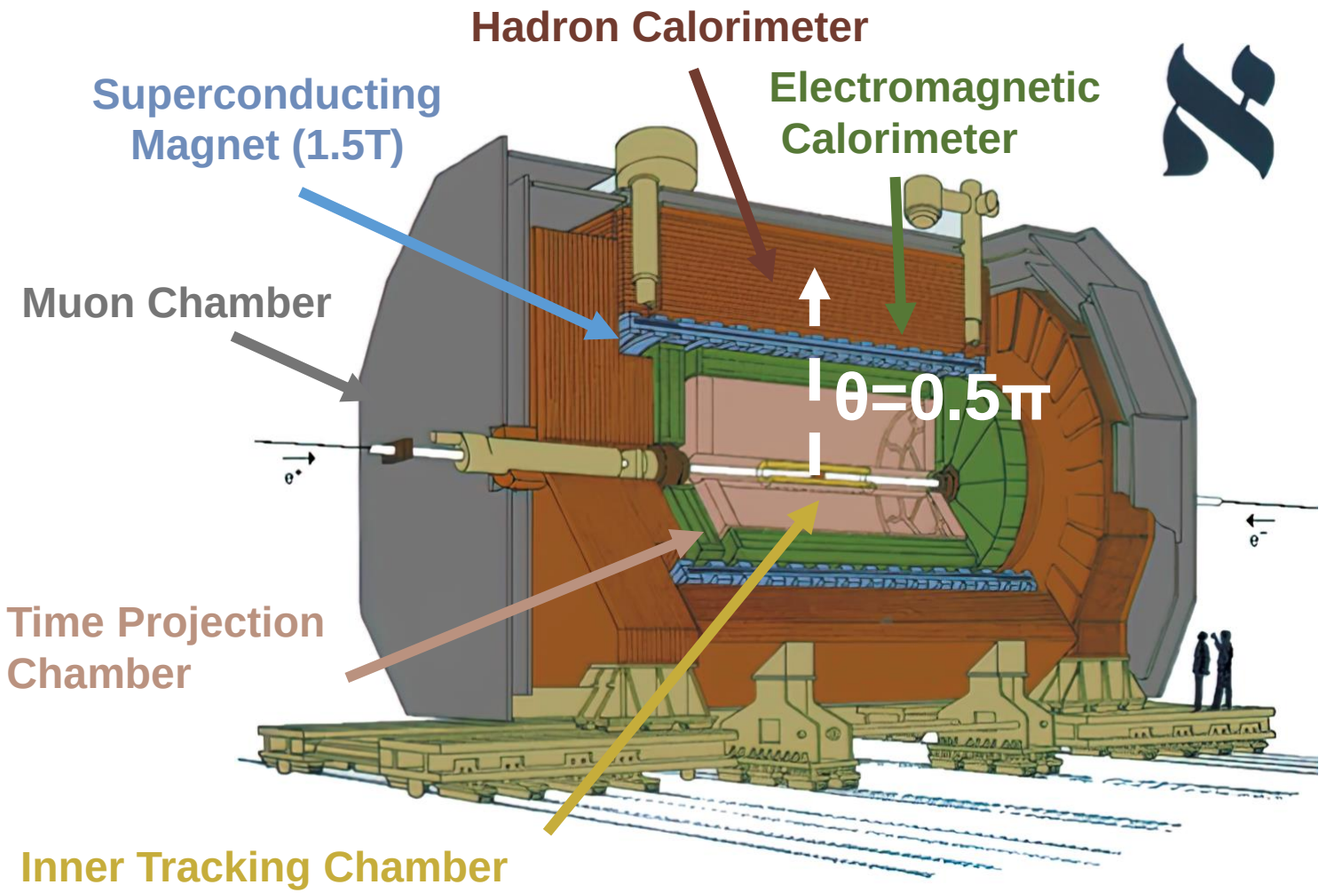


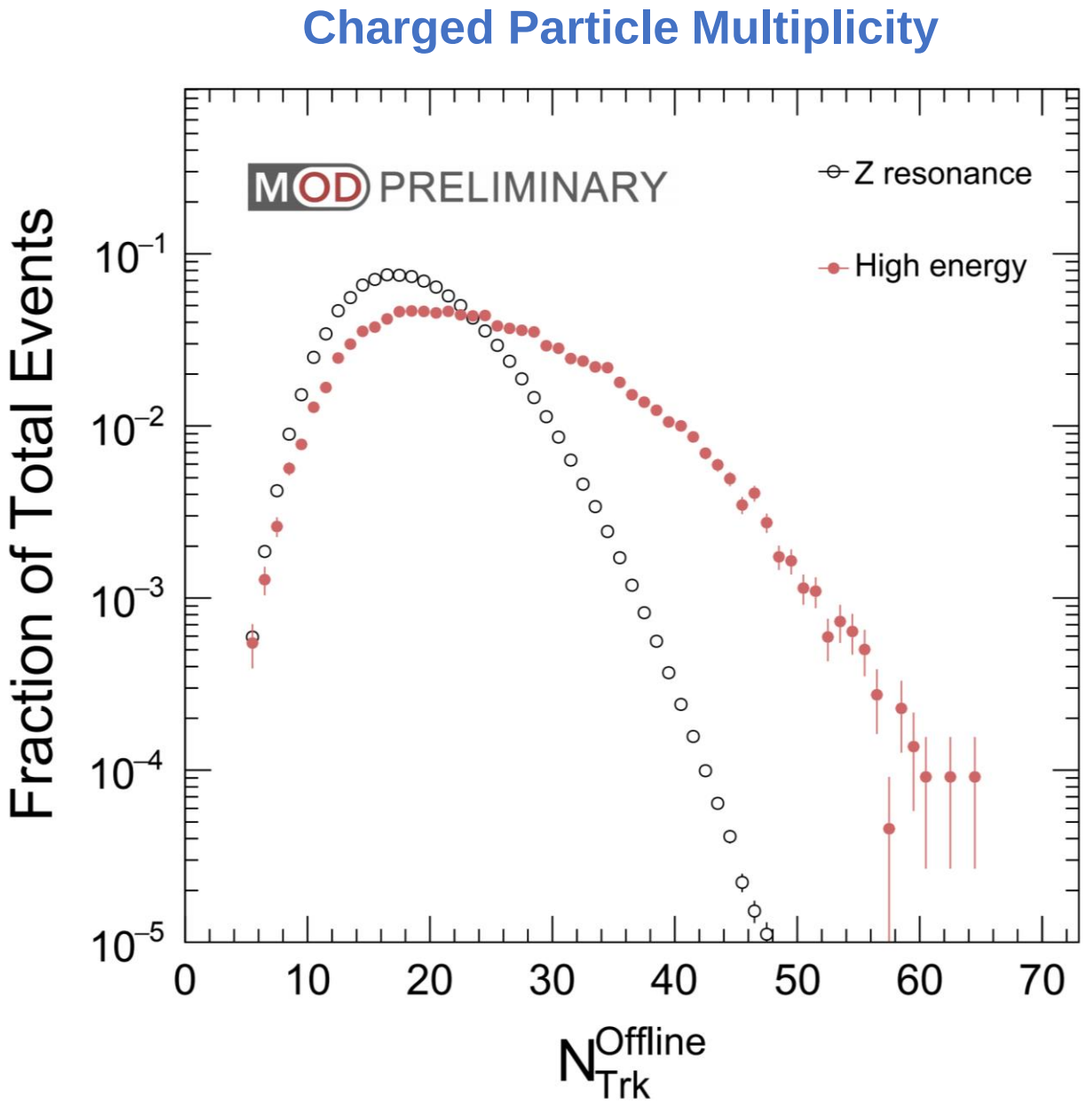
< 0.1 fm

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

Multiplicity

The ALEPH Detector

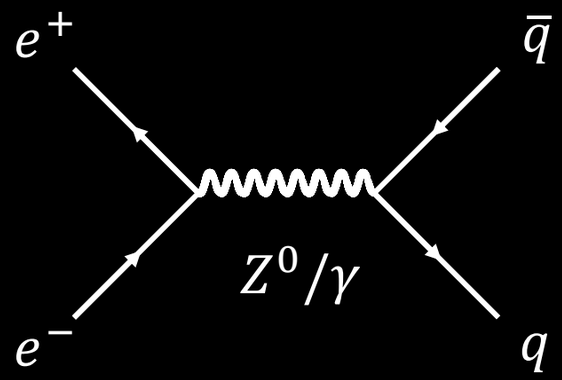




- LEP1 e^+e^- data at Z pole (91 GeV) taken between 1992-1995
- **LEP2 e^+e^- data above Z pole up 209 GeV**
  - ~ **RHIC** energy

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

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

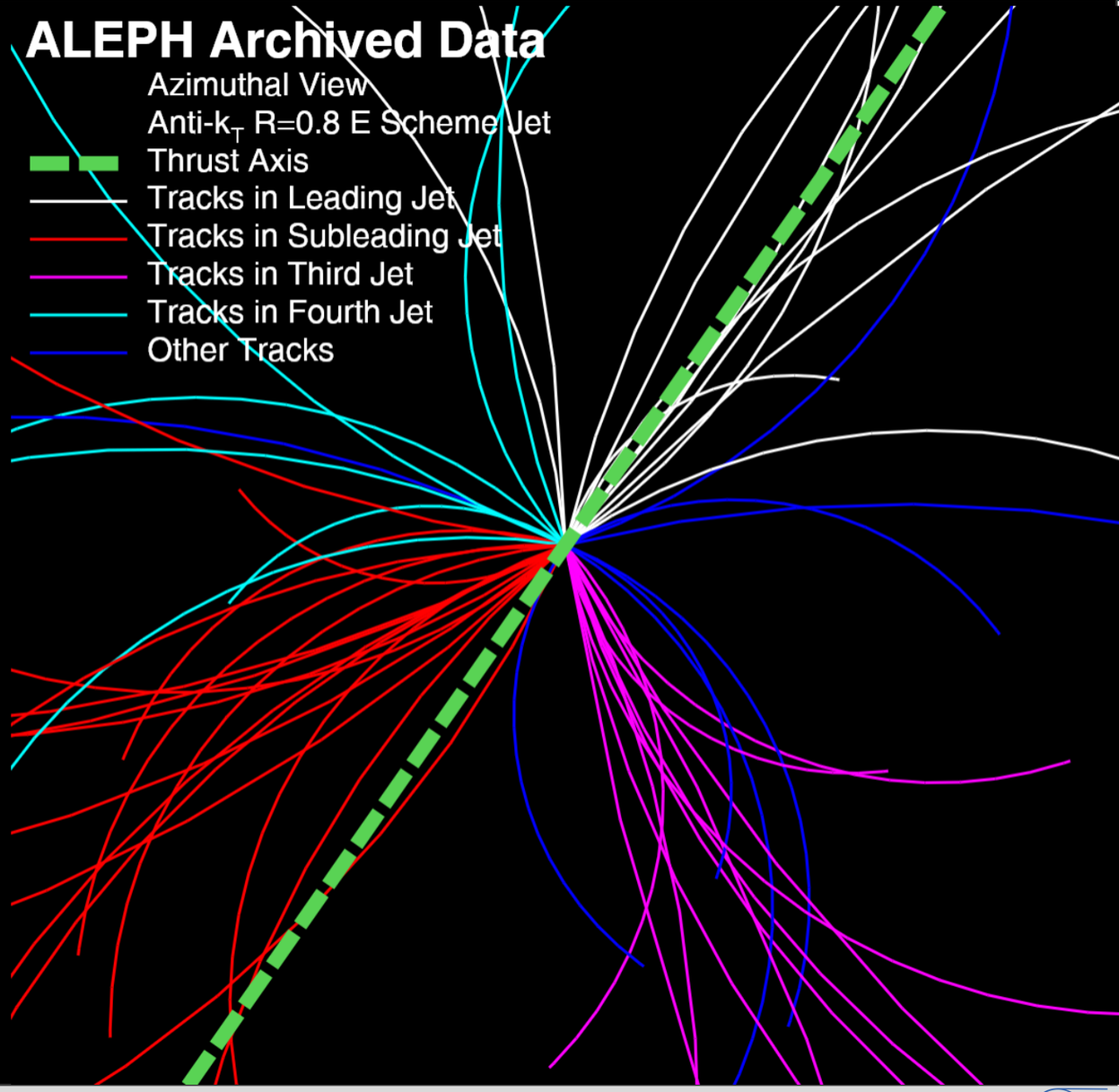


Anthony Badea, Austin Baty, Chris McGinn, Michael Peters, Jesse Thaler, Gian Michele Innocenti, Paoti Chang, Tzu-An Sheng

+ YJL

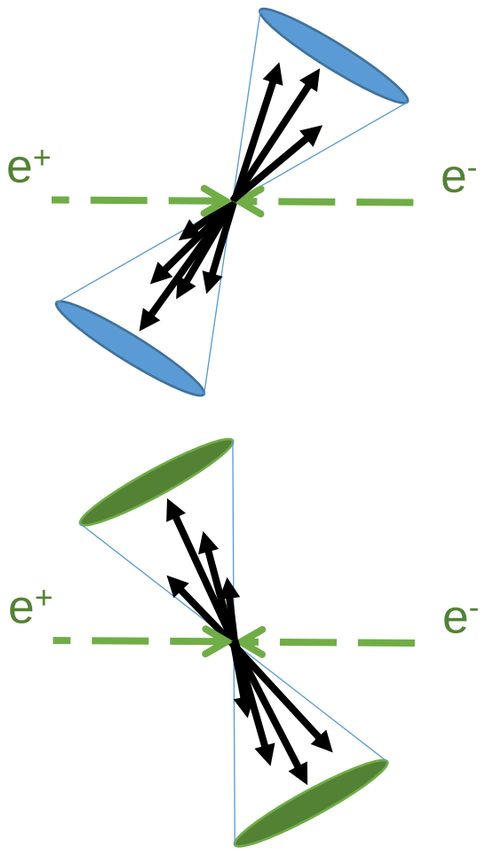
arXiv: 1906.00489
PRL 123, 212002 (2019)

55 Charged Particles
Thrust T=0.71

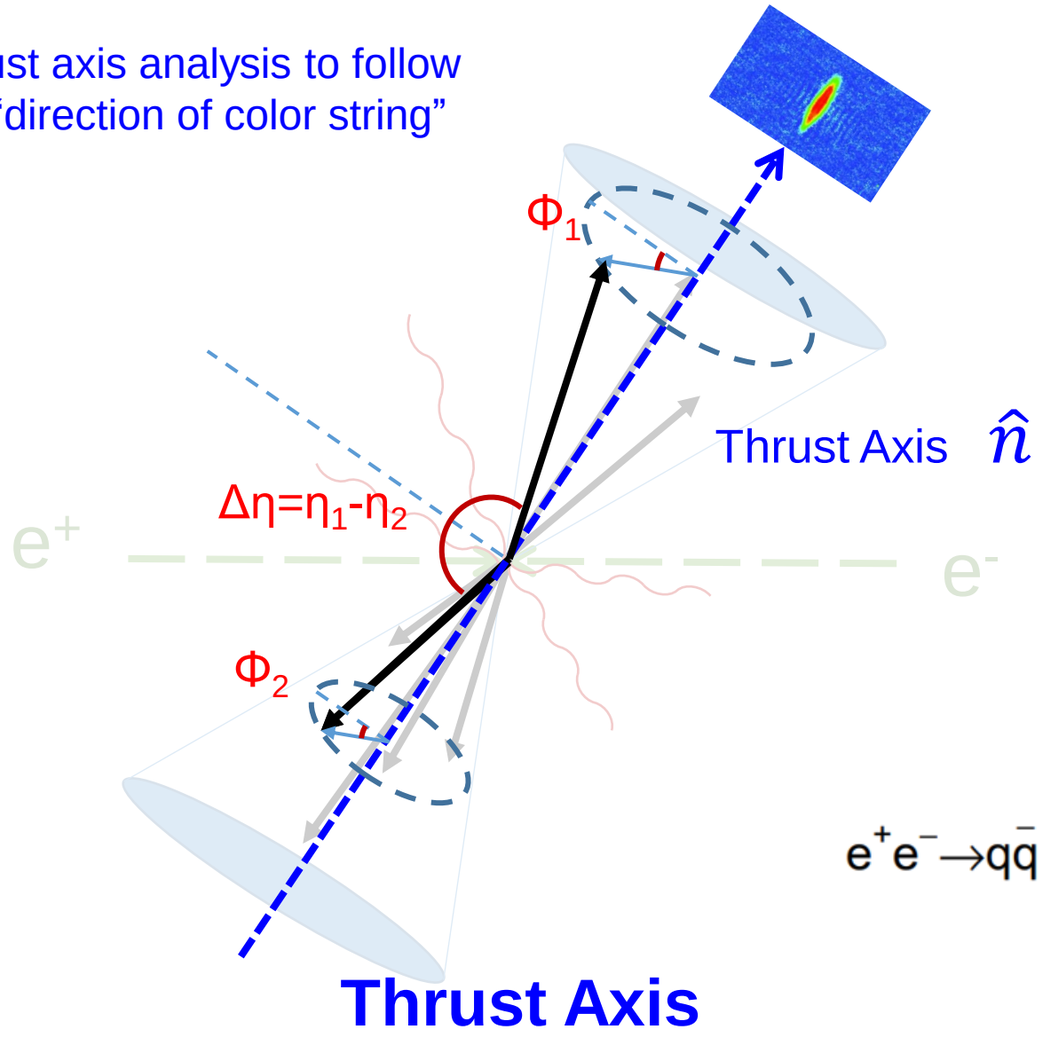


Reference Axis for e^+e^-

Random orientation of the jets



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

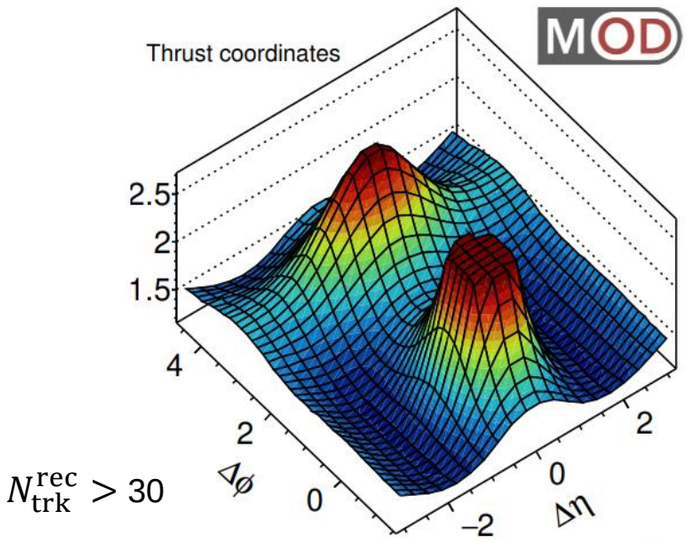


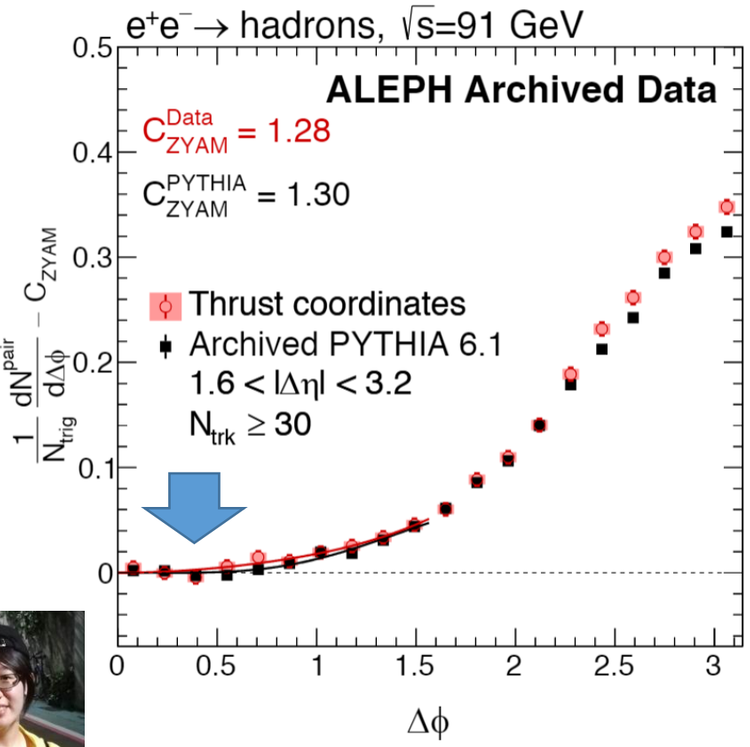
Thrust Axis

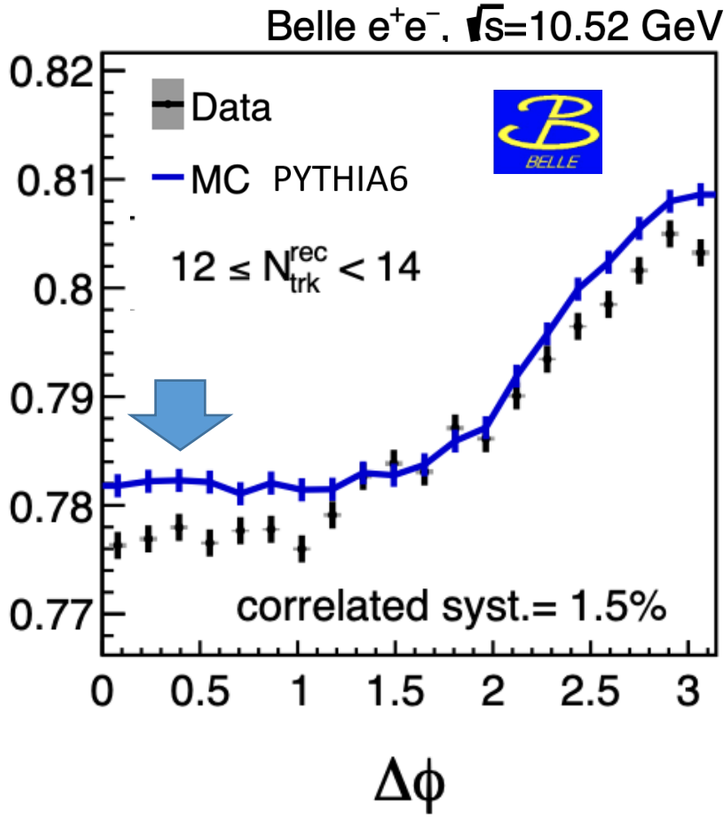
Sensitive to **"medium expansion"** perpendicular to the **Thrust axis**

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

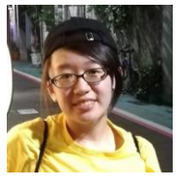
91 GeV





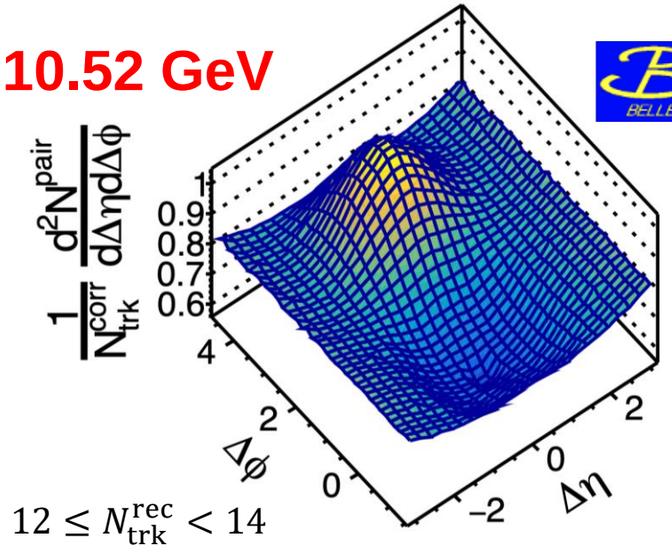


Thrust



Janice Chen

10.52 GeV



- 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!

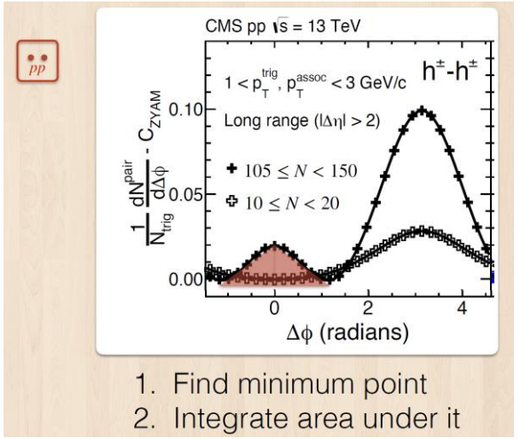
ALEPH archived data PRL 123, 212002 (2019)

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

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

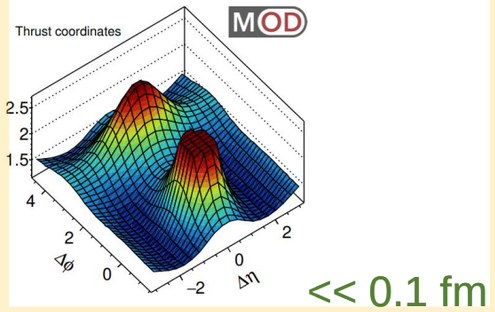
Compilation of Ridge Yield Limit in e^+e^- collisions

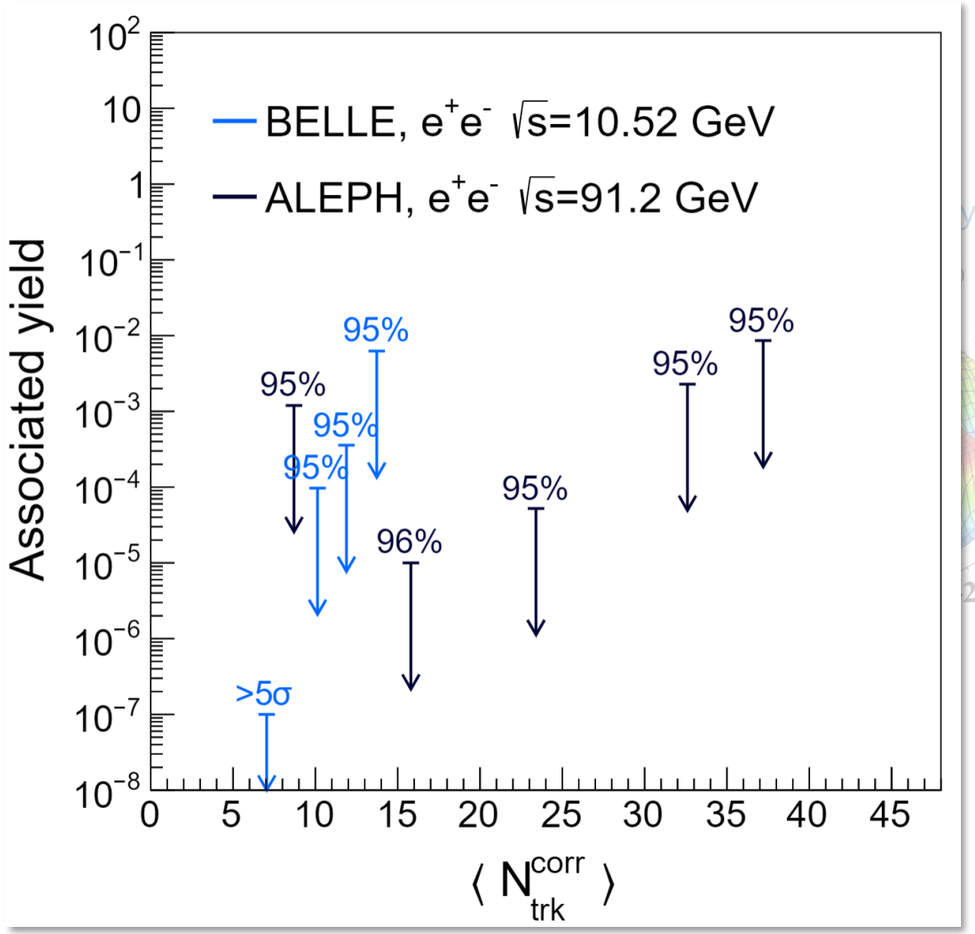
"Transverse Size"

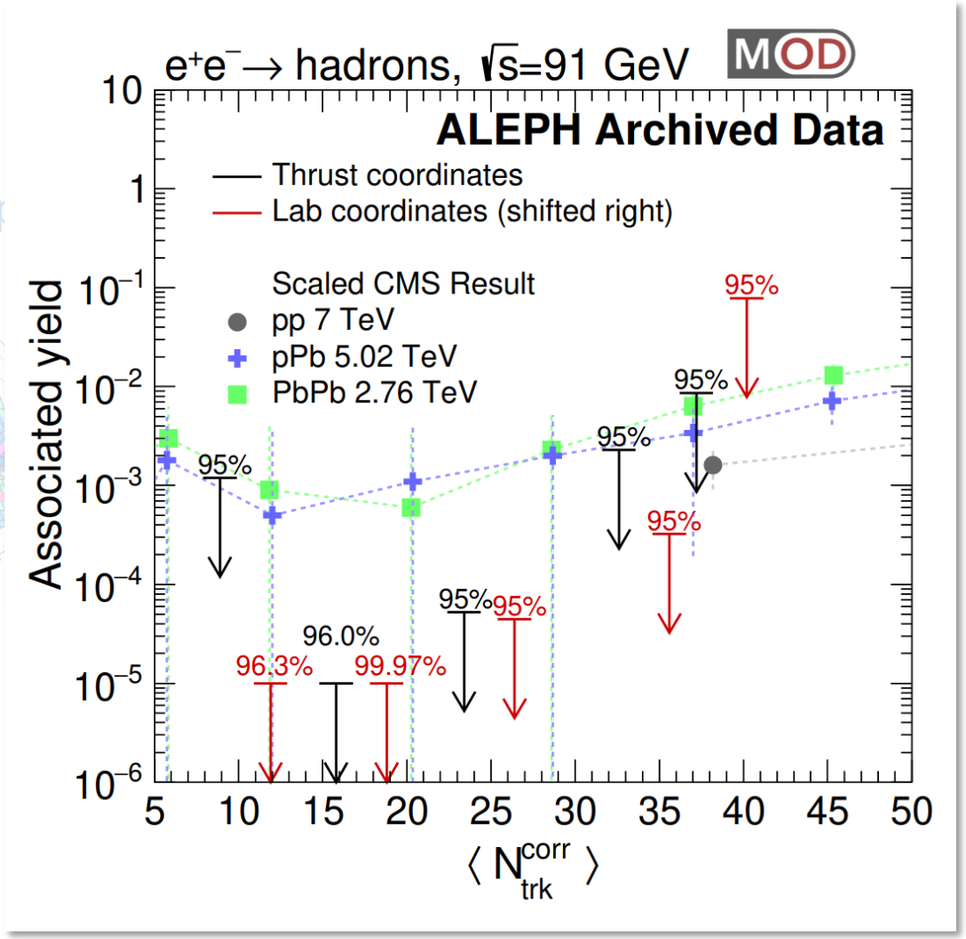


Yi Chen's slide

e^+e^-







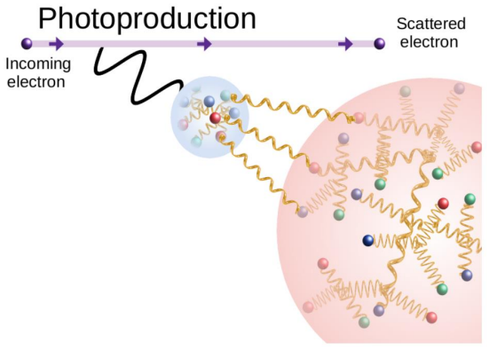
No significant ridge signal in $e^+e^- \to q\bar{q}$
from low to high multiplicity (up to ~35 particles)

Multiplicity

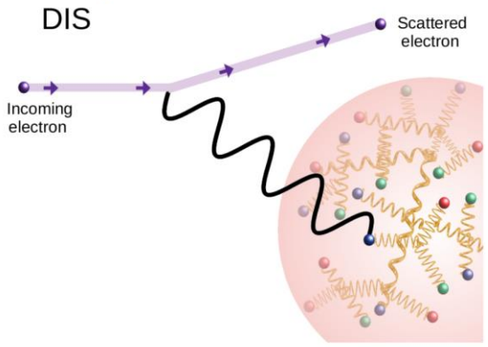
System Size

"Transverse Size" / MPI

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



(b) *Resolved photoproduction.*



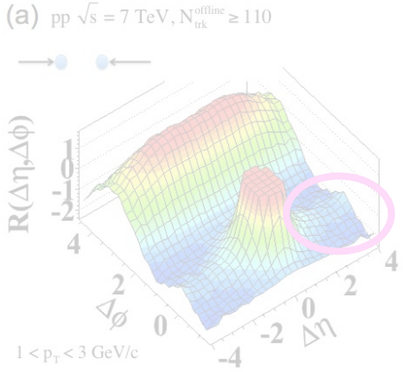
(a) *Neutral current deep inelastic scattering.*

$1/Q < 0.2$ fm

e^+e^-

<< 0.1 fm

High multiplicity pp



~ O(1fm)

High multiplicity pPb

≥ O(1fm)

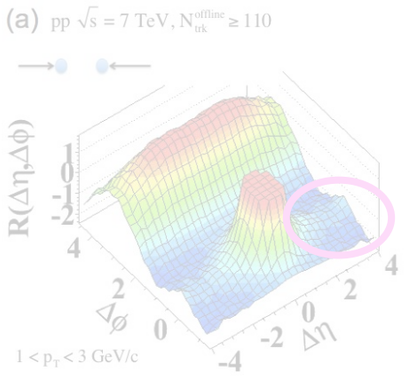
O(1-10 fm)

Multiplicity

System Size

"Transverse Size" / MPI

High multiplicity pp



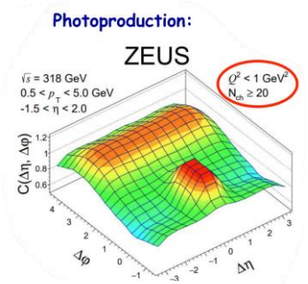
~ O(1fm)

High multiplicity pPb

≥ O(1fm)

O(1-10 fm)

MPI>1



MPI ≥ 1

"MPI"=1

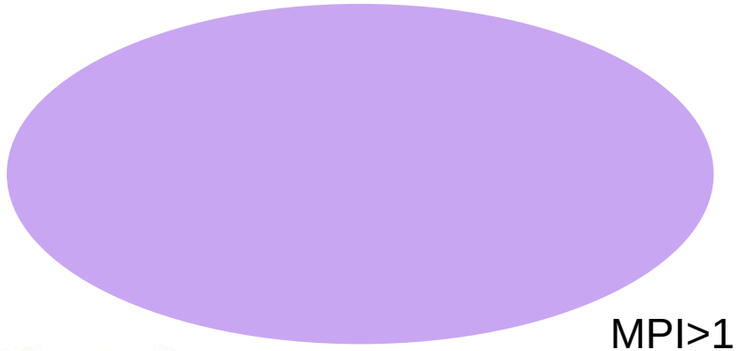
<< 0.1 fm

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

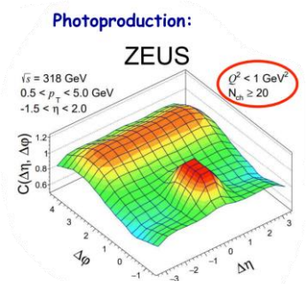
Multiplicity

System Size

"Transverse Size" / MPI



MPI>1

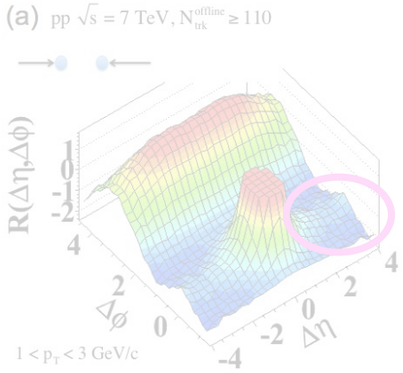


MPI ≥ 1

"MPI"=1

<< 0.1 fm

High multiplicity pp



~ O(1fm)

High multiplicity pPb

≥ O(1fm)

O(1-10 fm)

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

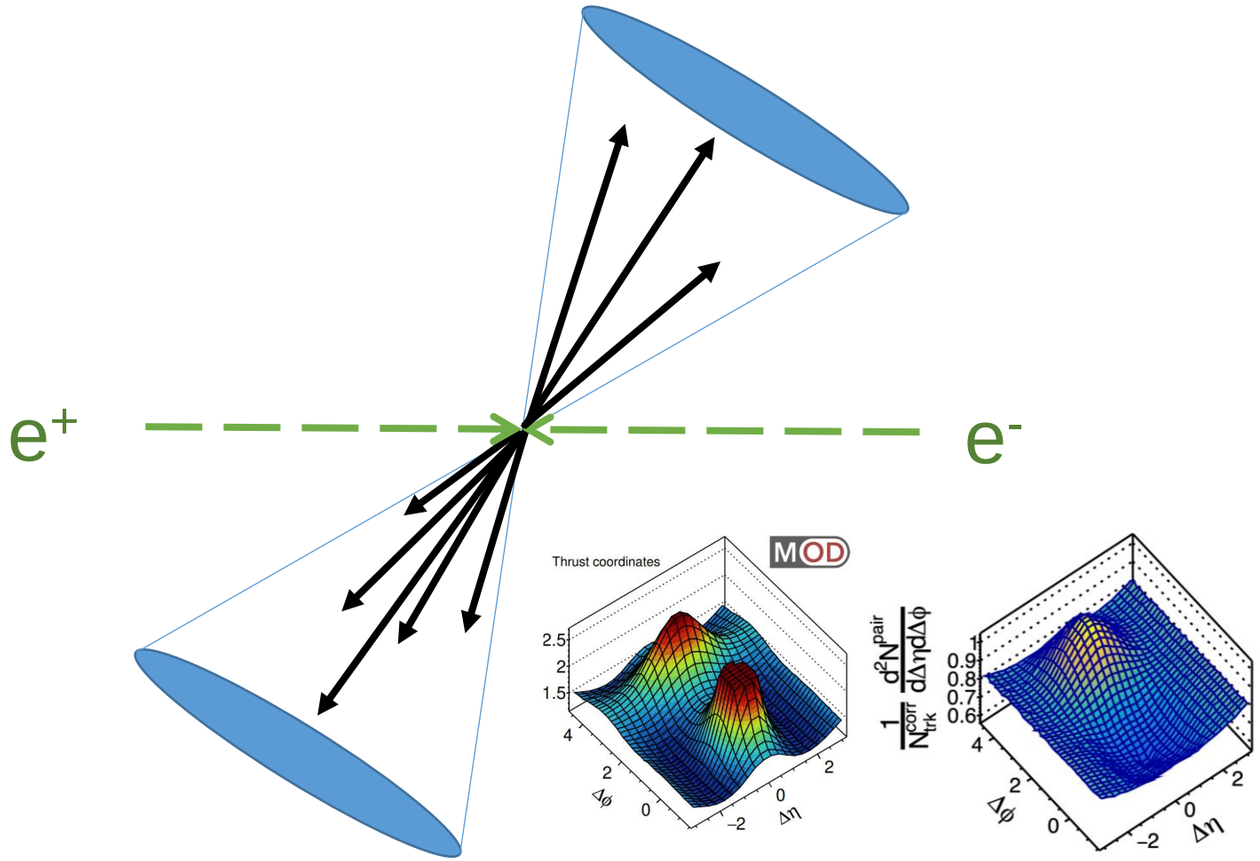
Next steps: (1) Increase multiplicity

(2) Increase <MPI>

Multiplicity

Can We Overlap Two Color Strings?

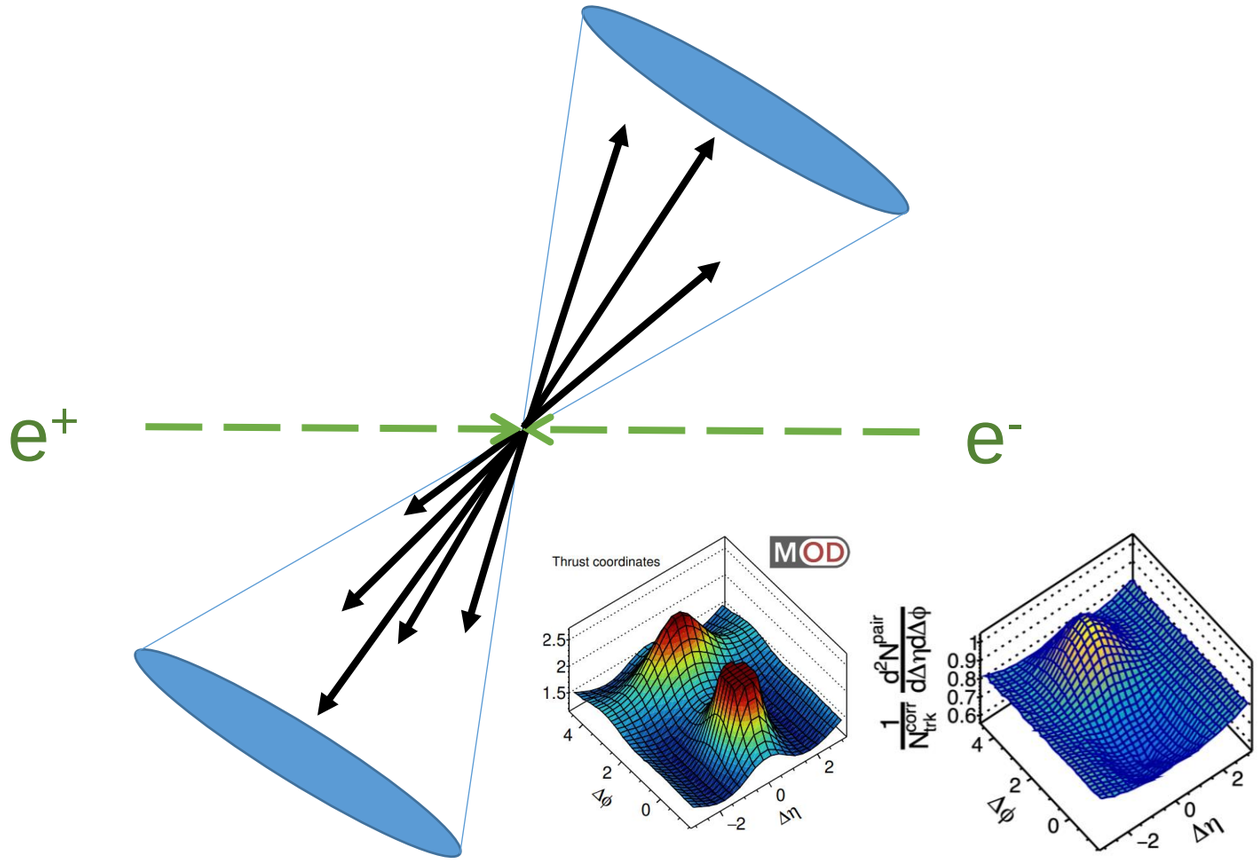
$$e^+e^- \to q\bar{q}$$



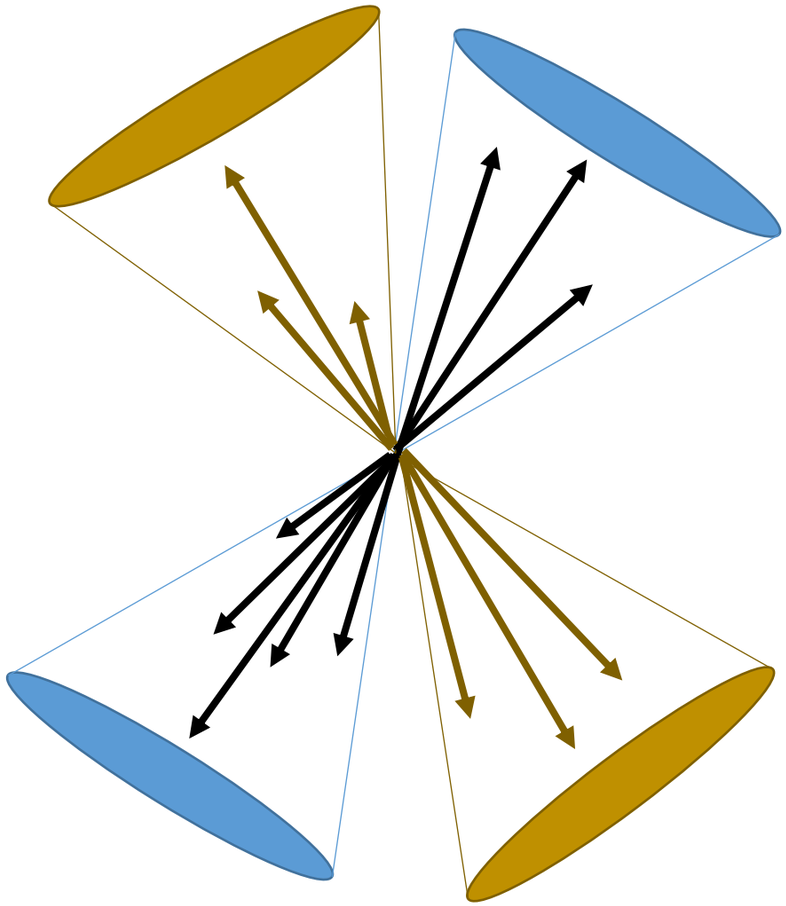
No ridge-like structure

Can We Overlap Two Color Strings?

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



No ridge-like structure

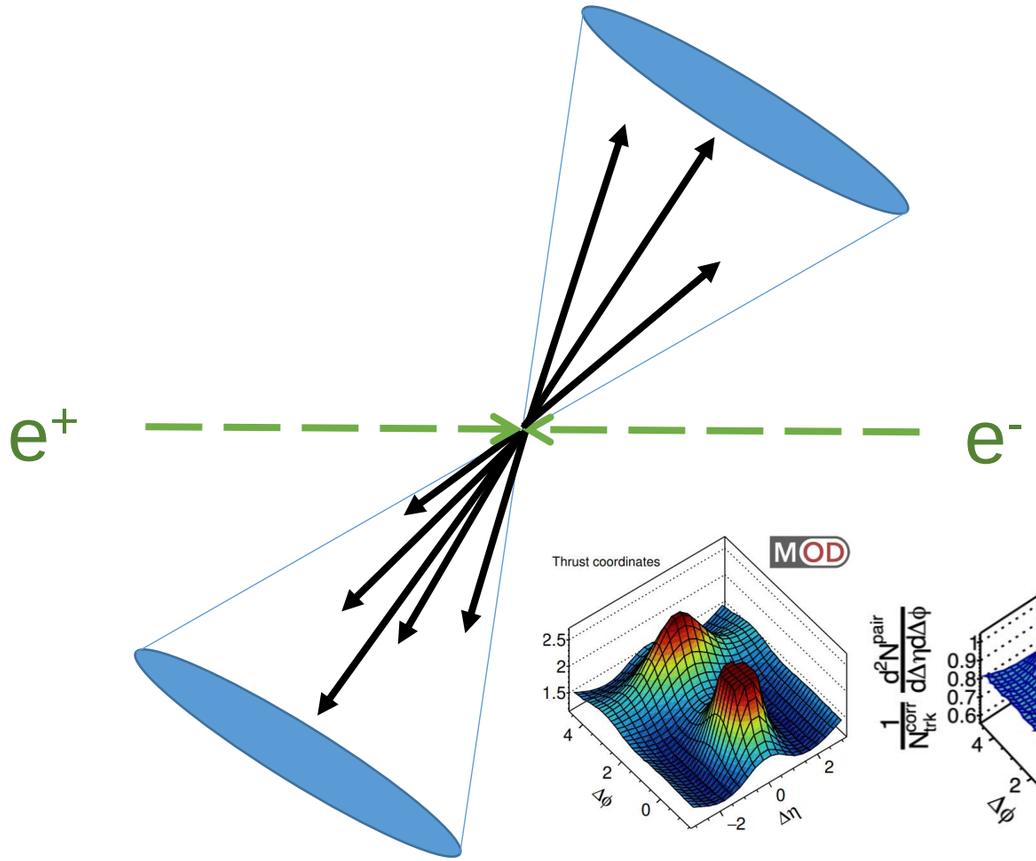


?

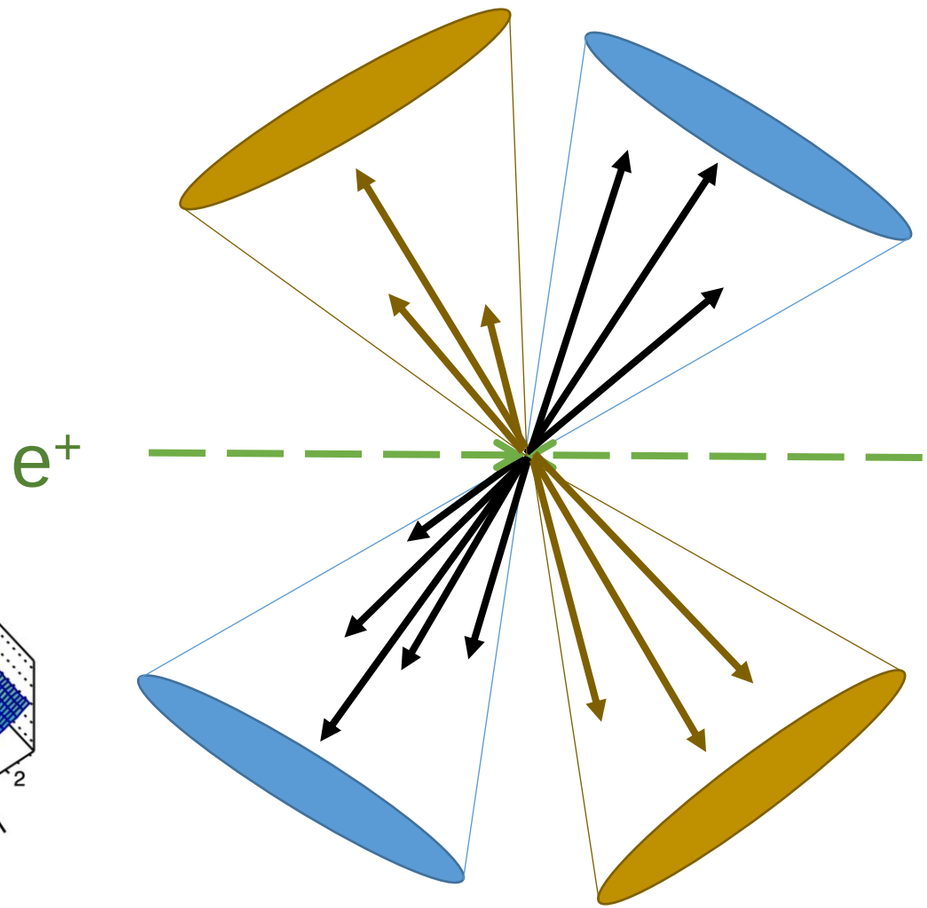
High Multiplicity e^+e^- Event at LEP 2

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

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



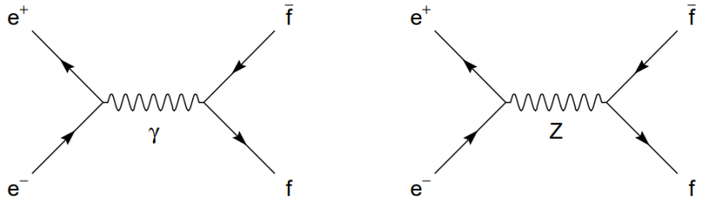
No ridge-like structure



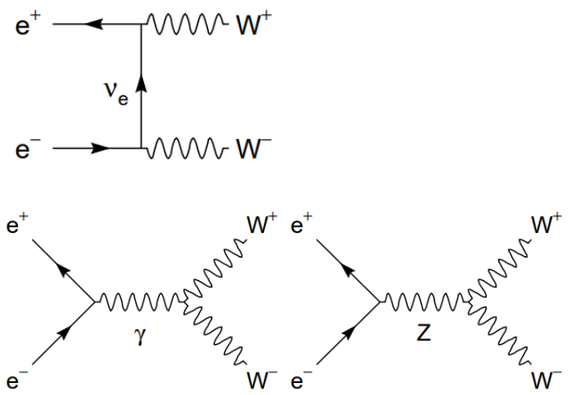
?

Charged Particle Multiplicity Distributions in LEP2 Data

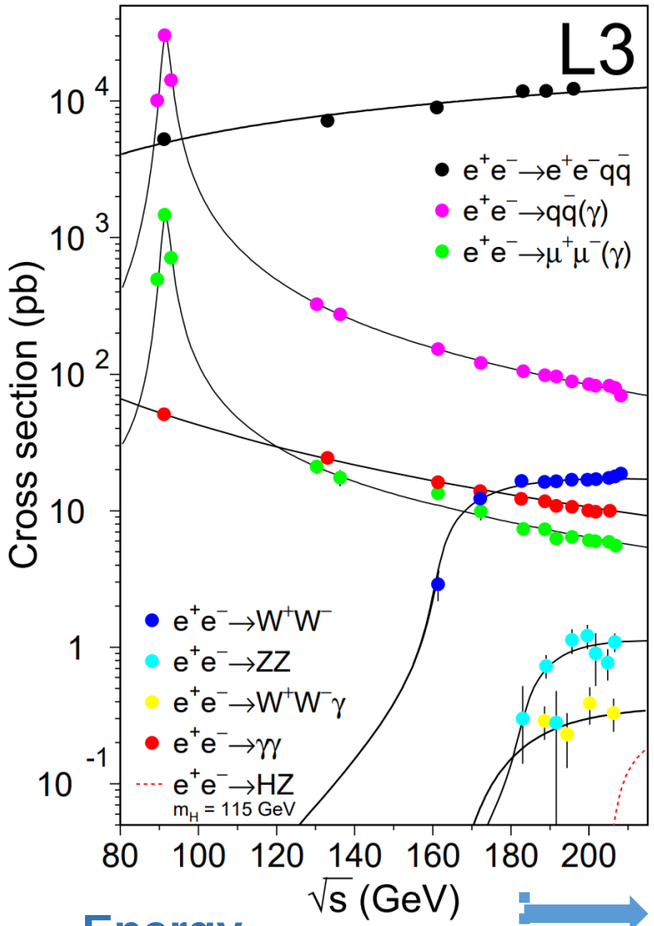
- $e^+e^- \to q\bar{q}(\gamma)$



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

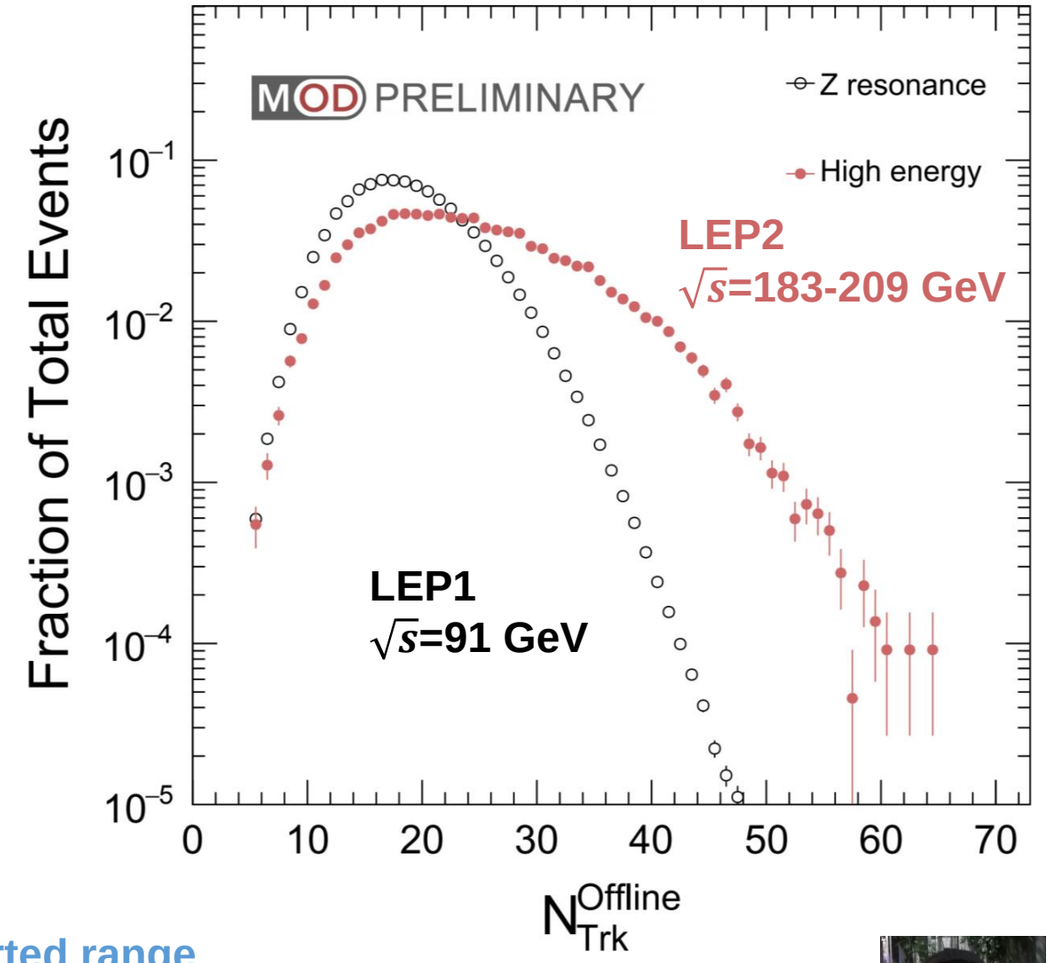


Phys. Rept. 532 (2013) 119-244



Energy

Reported range



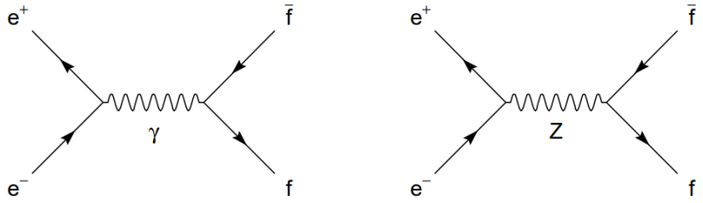
- **LEP2 energies** give access to also different physics processes

EPJC 63 611 (2009)

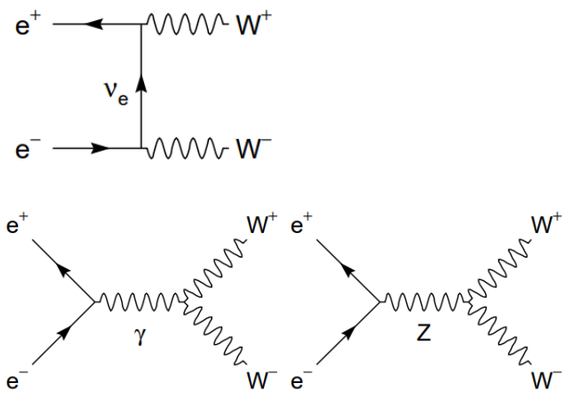
Yu-Chen "Janice" Chen (MIT)

Charged Particle Multiplicity Distributions in LEP2 Data

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



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



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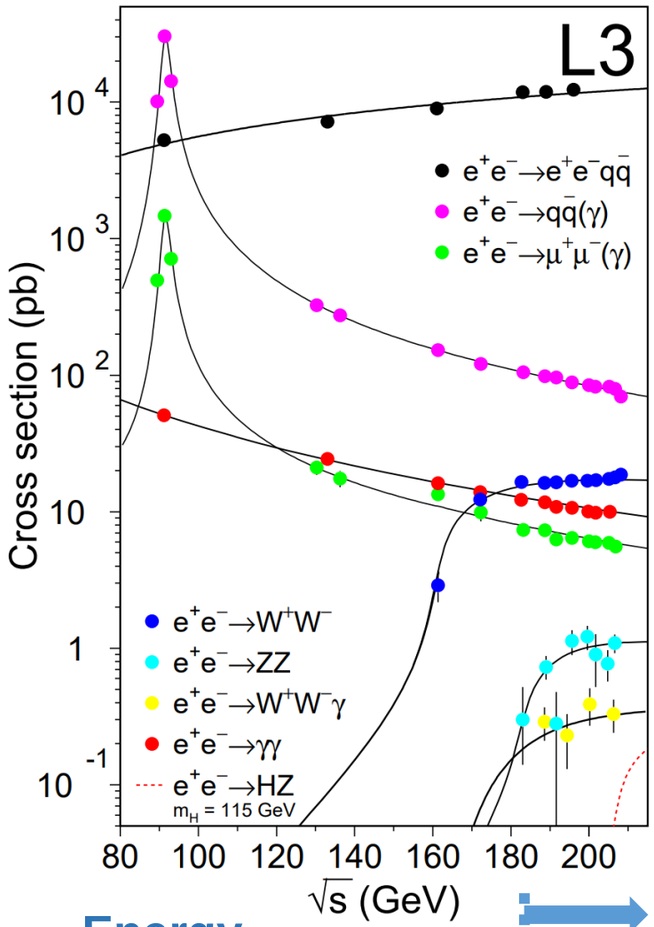
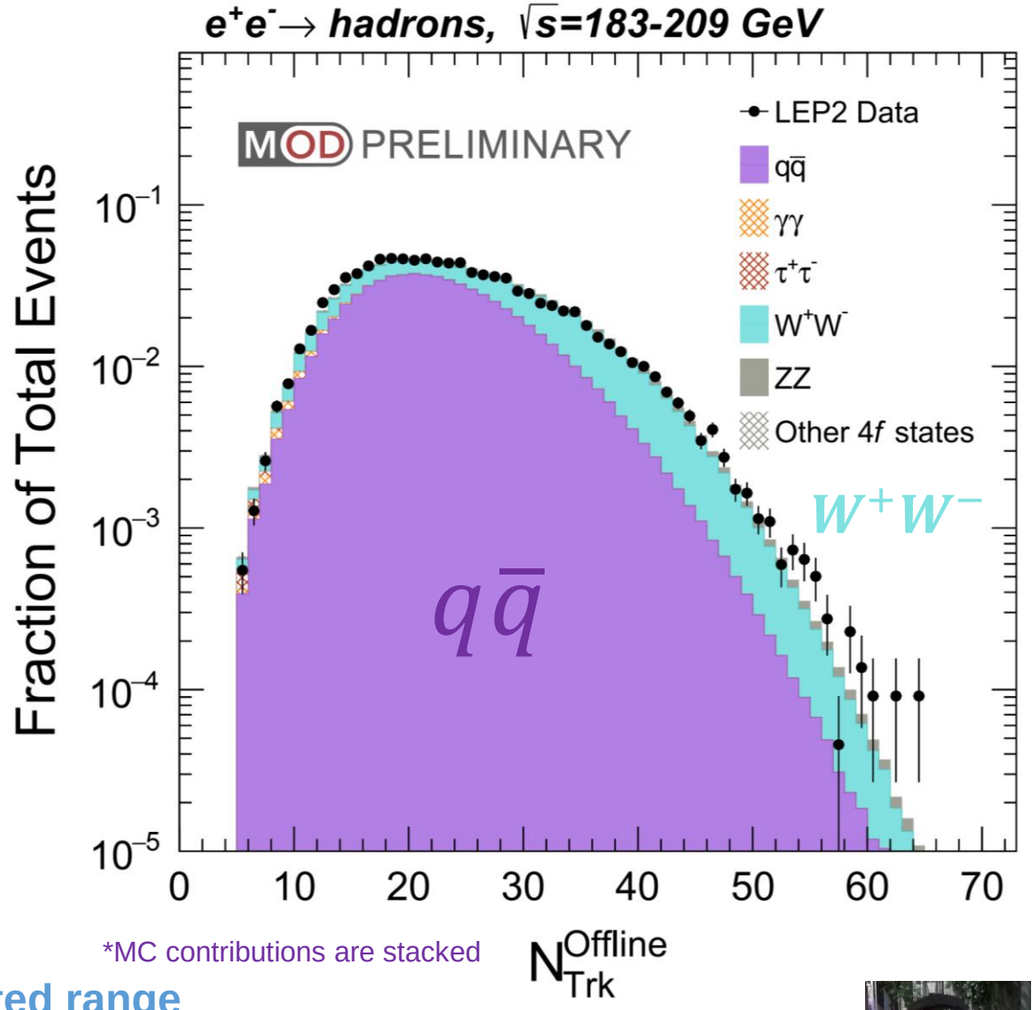


Energy



*MC contributions are stacked

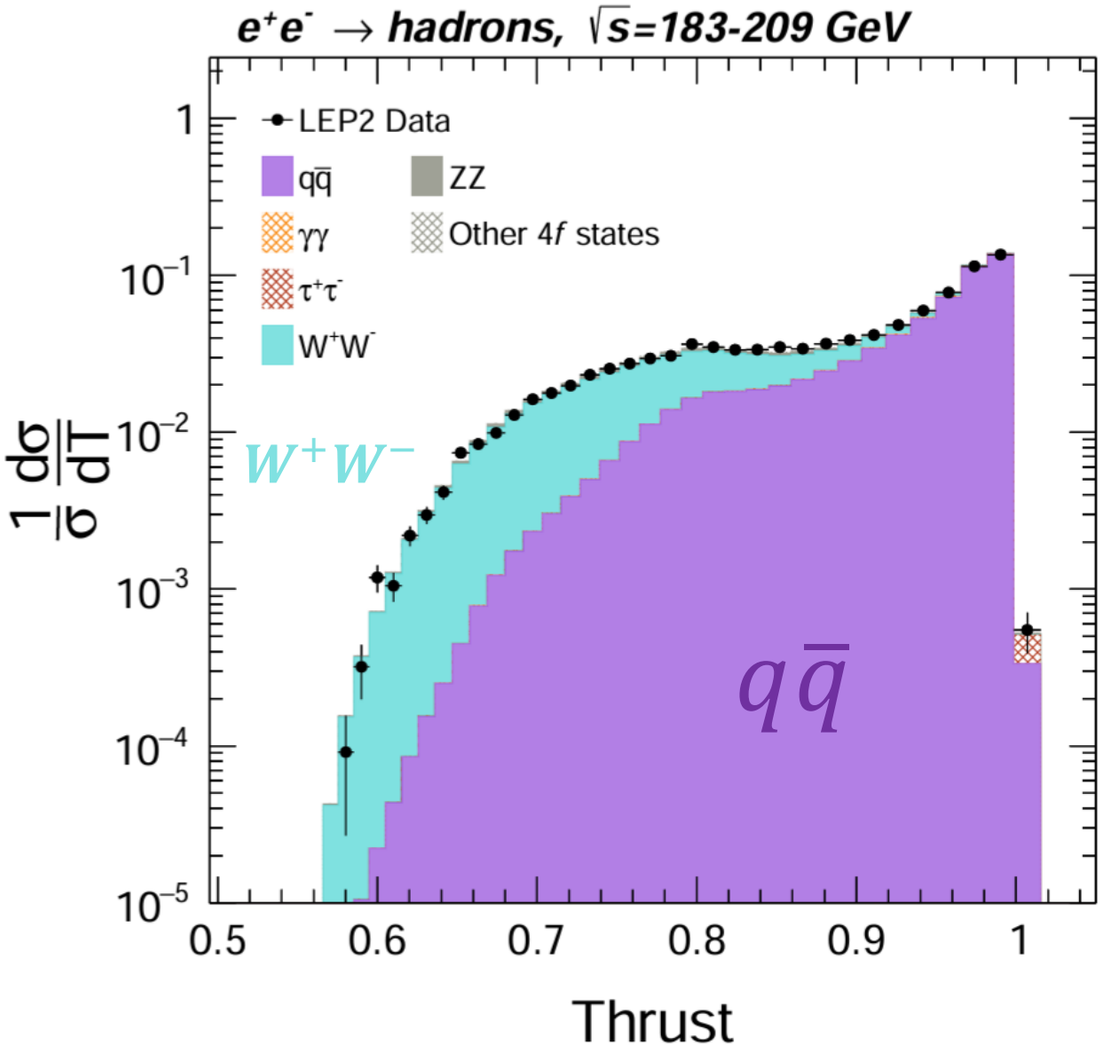
Reported range

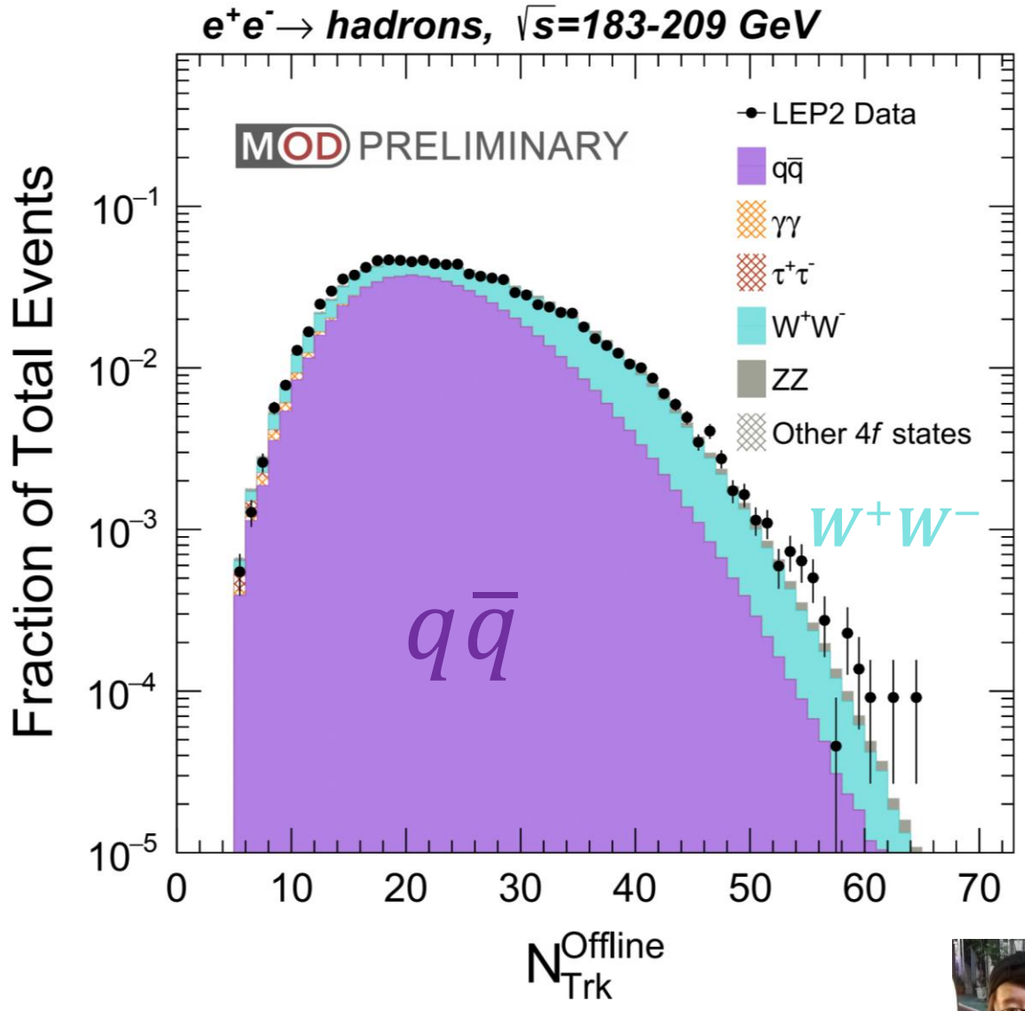
- **LEP2 energies** give access to also different physics processes
- At high multiplicity, W^+W^- contribution becomes significant

EPJC 63 611 (2009)

Yu-Chen "Janice" Chen (MIT)

Example validation study of archived data and MC

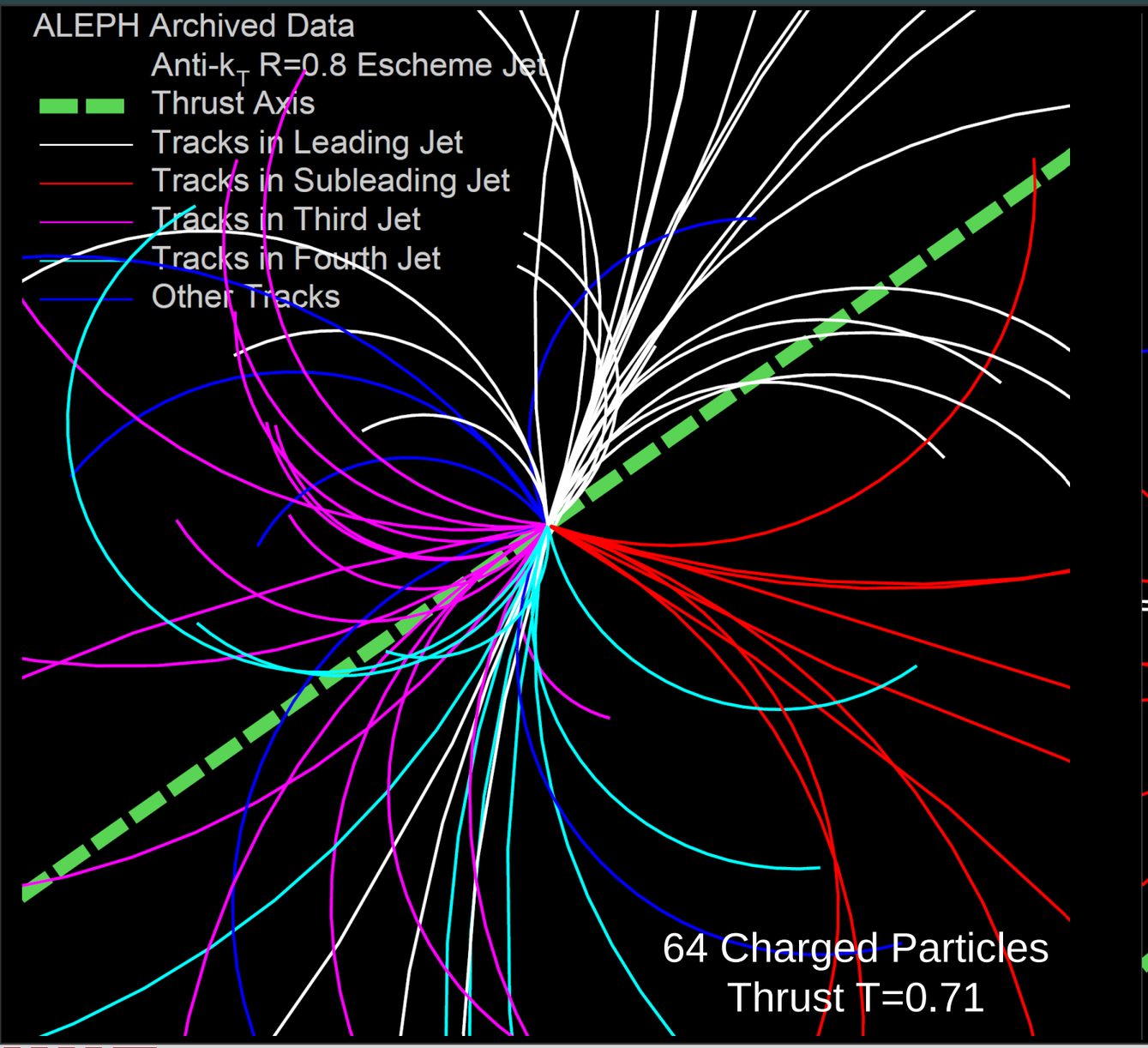


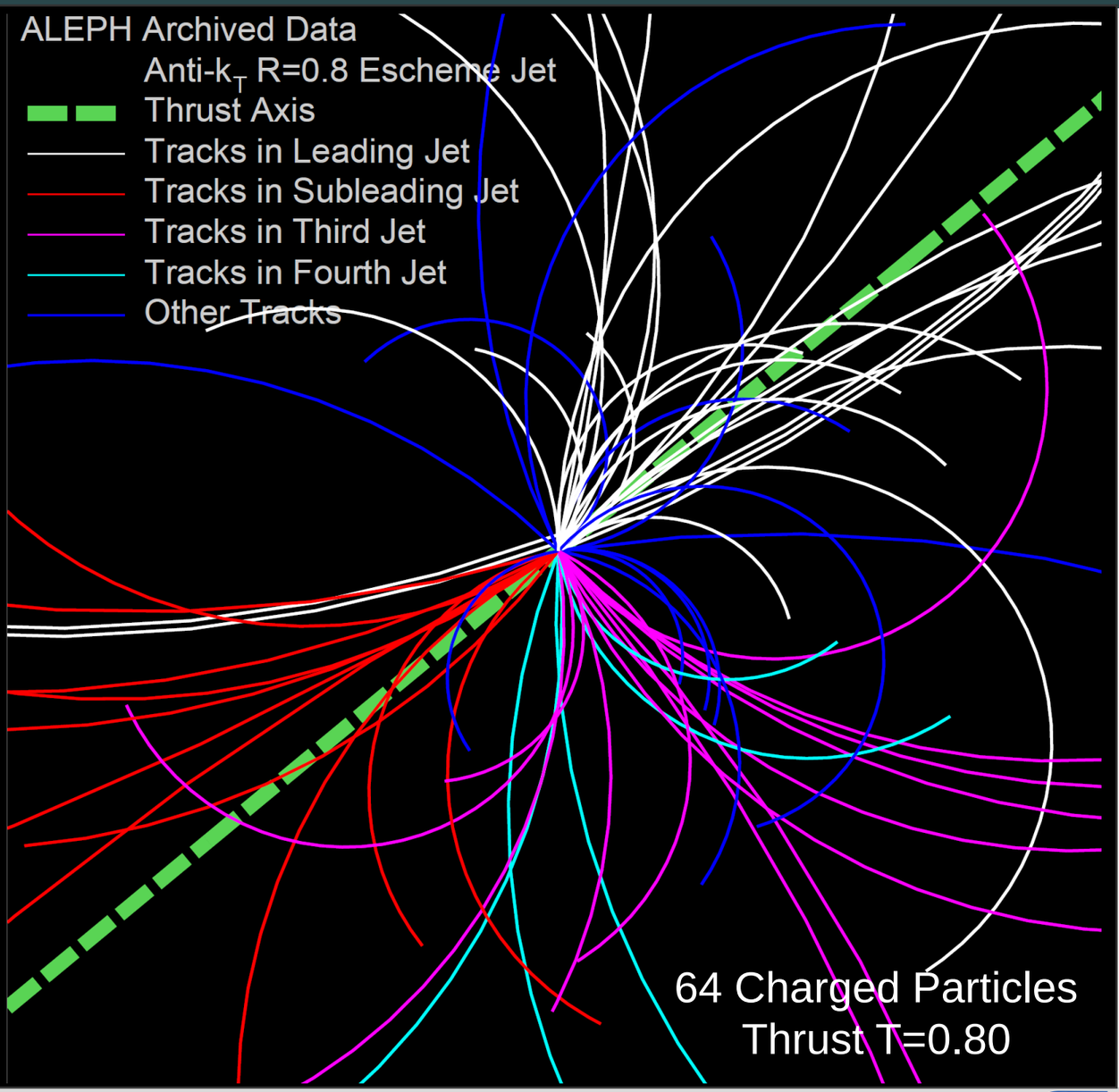


- Inspected thrust distributions (shown) and many other control plots (visible energies) year-by-year.
- Reasonable agreement between data and archived MC.

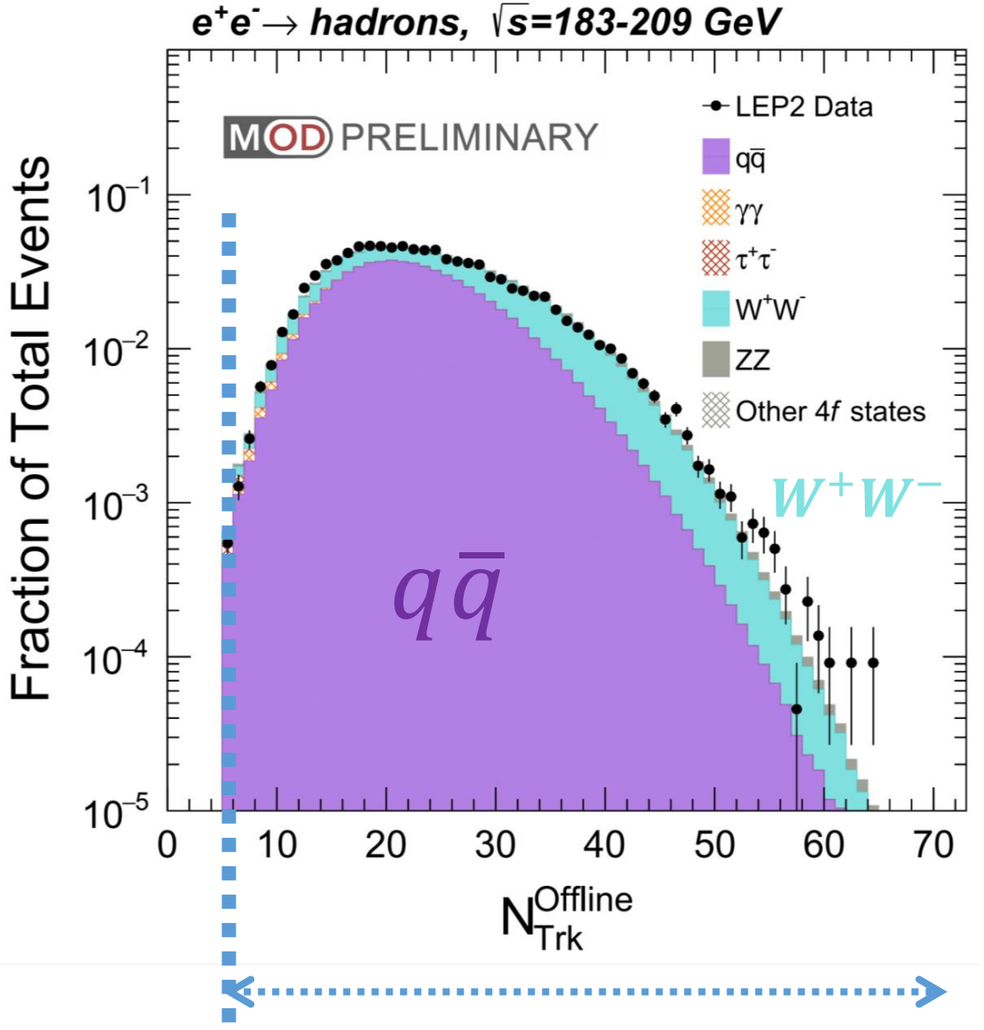
Yu-Chen “Janice” Chen (MIT)

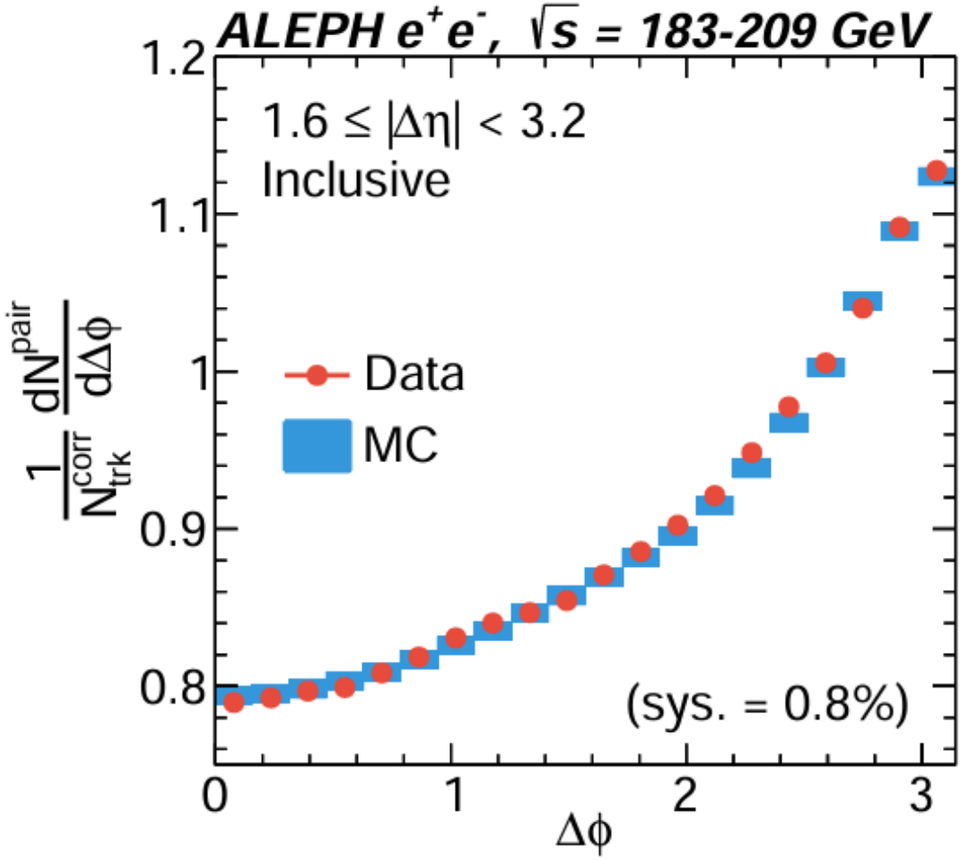
The Highest Multiplicity Events in Archived LEP2 Data

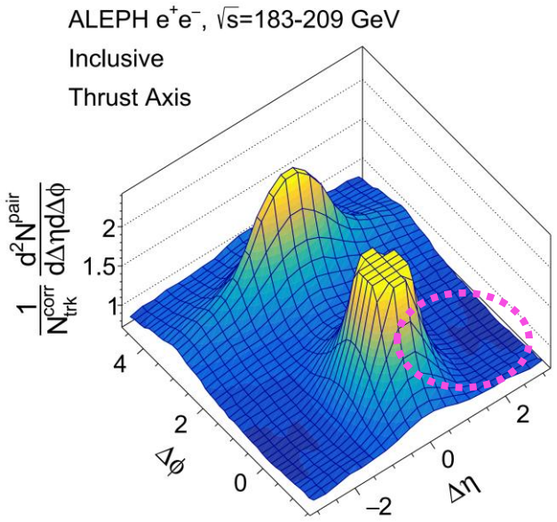


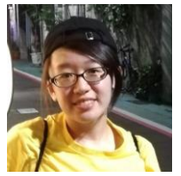


Inclusive Hadronic e^+e^- Events at LEP 2 ($N_{ch} \geq 5$)







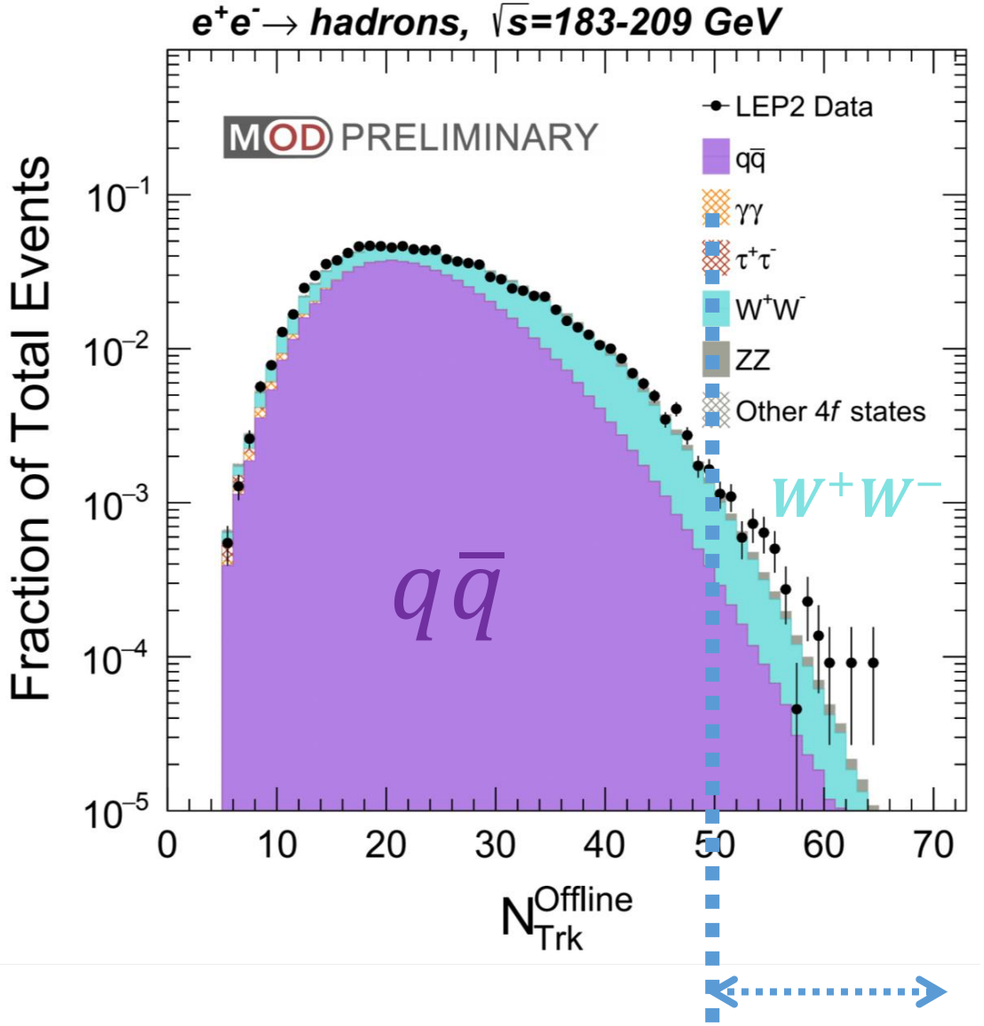


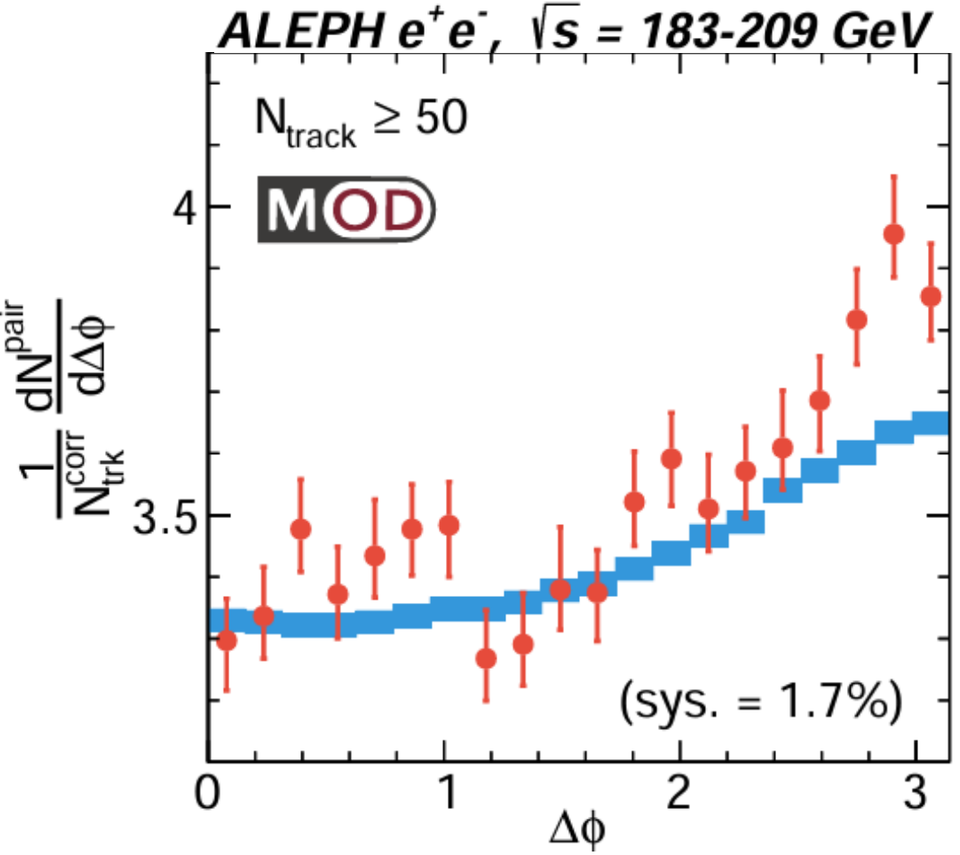
Yu-Chen "Janice" Chen (MIT)

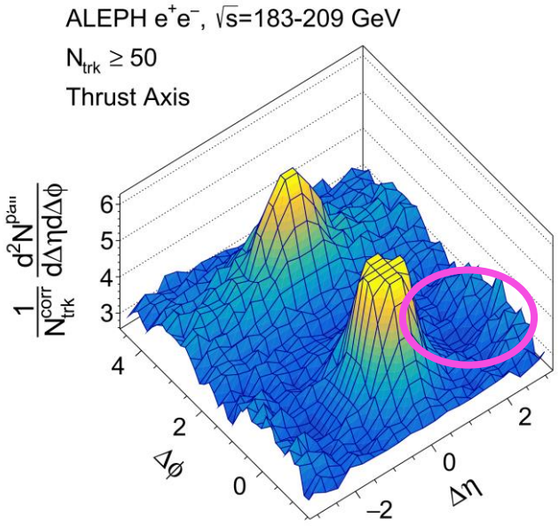
- Excellent agreement between **data** and **simulation (Archived MC)**

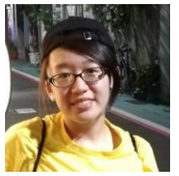
arXiv:2312.05084 submitted to PRL

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









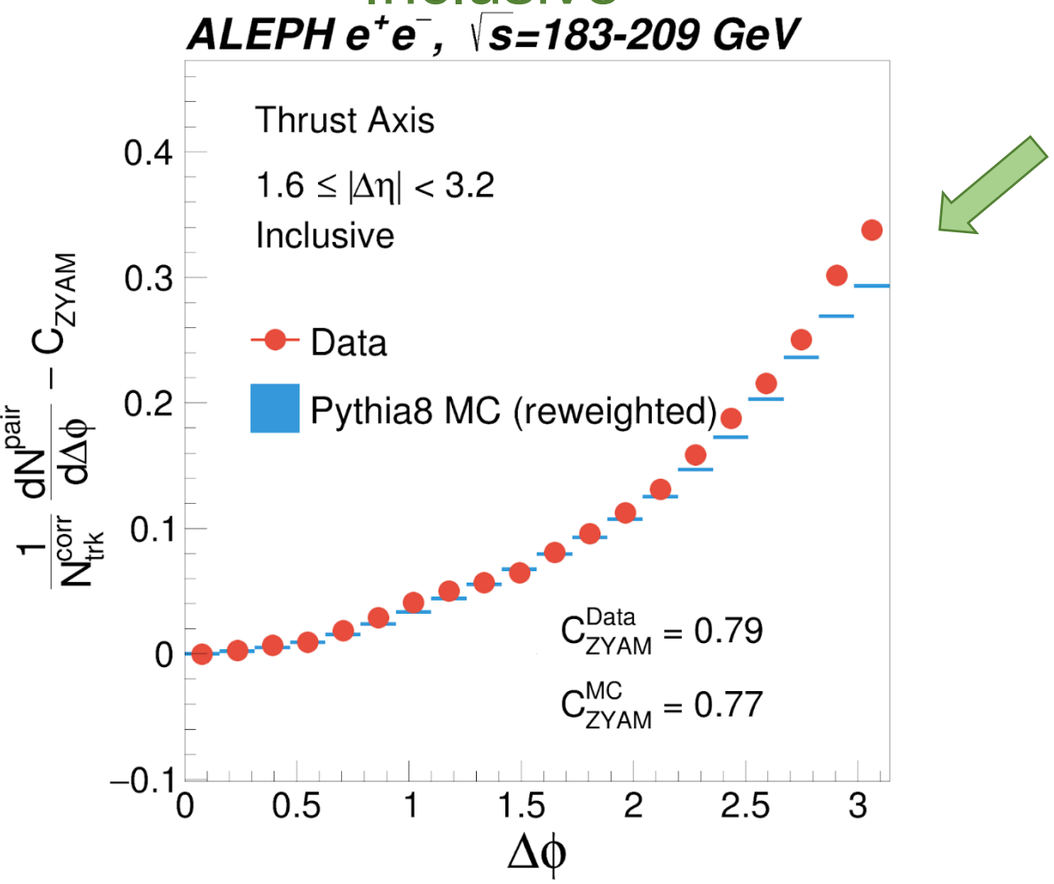
Yu-Chen "Janice" Chen (MIT)

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

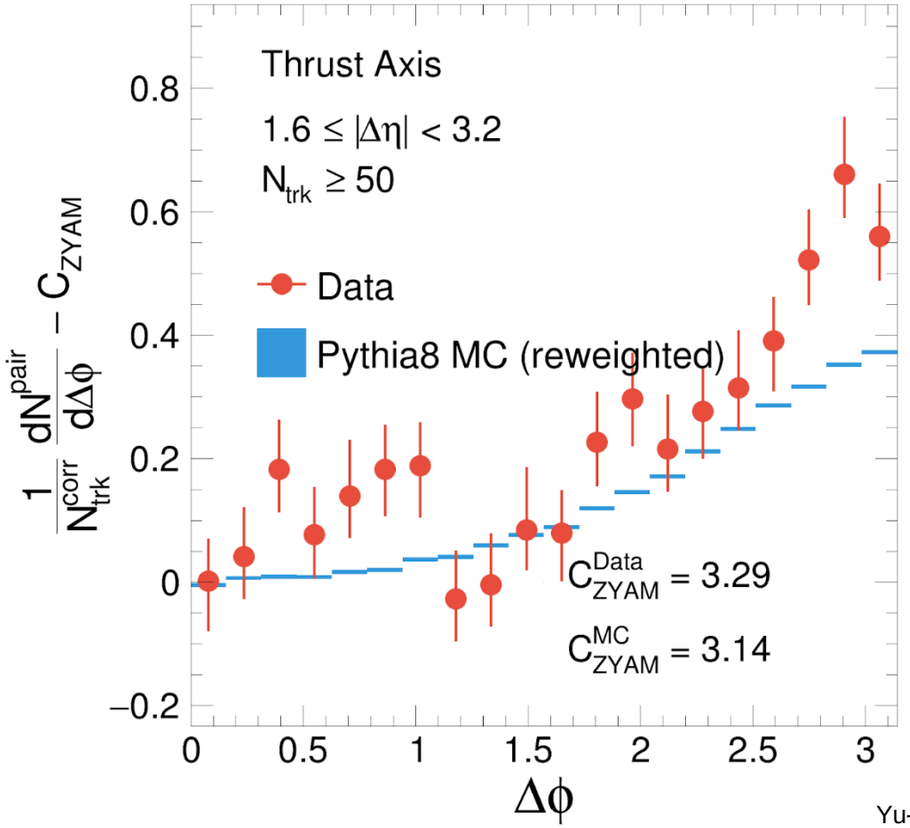
arXiv:2312.05084 submitted to PRL

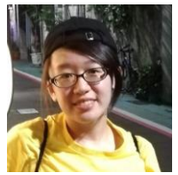
Comparison to Prediction from PYTHIA8

Inclusive



High Multiplicity



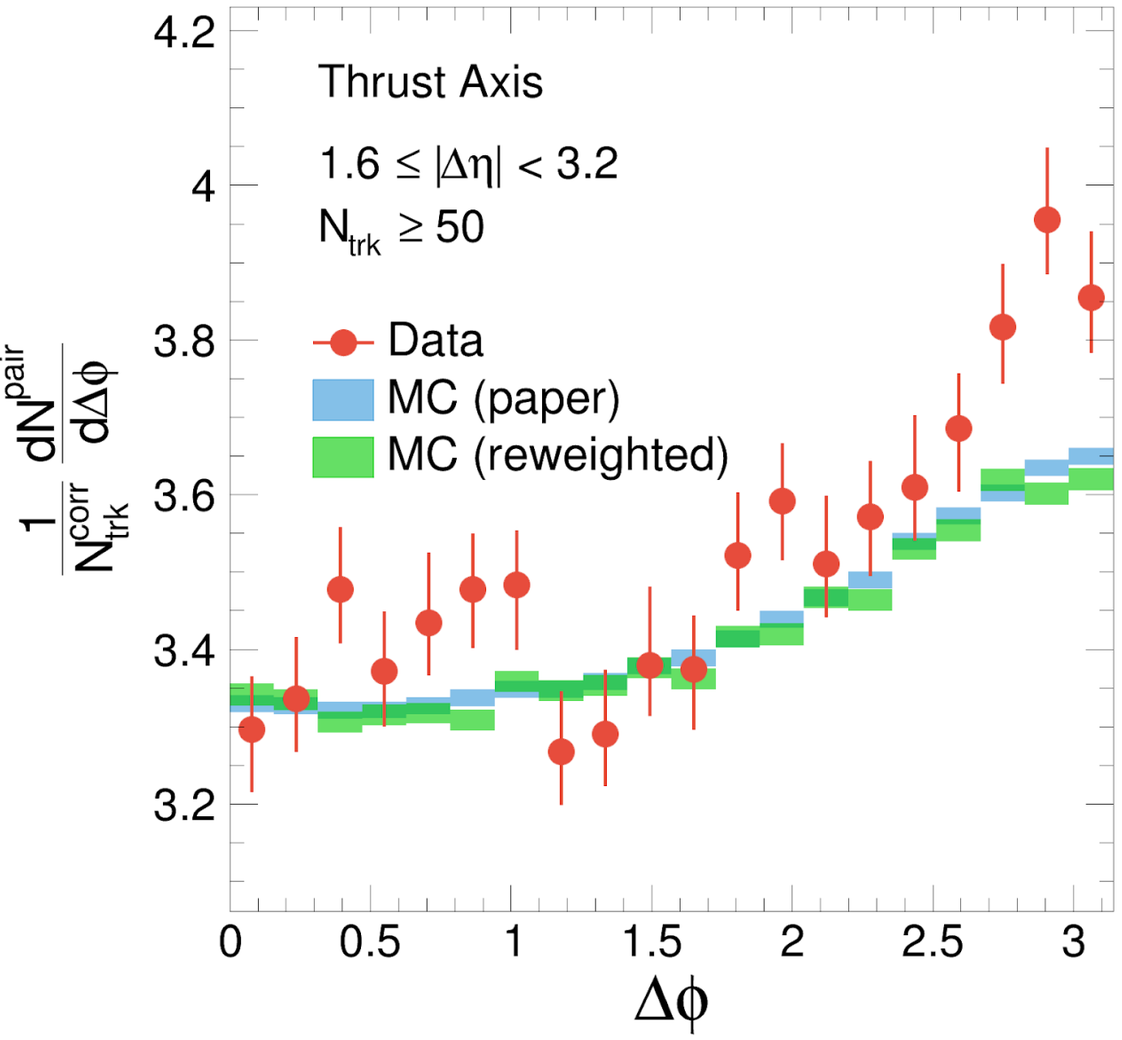


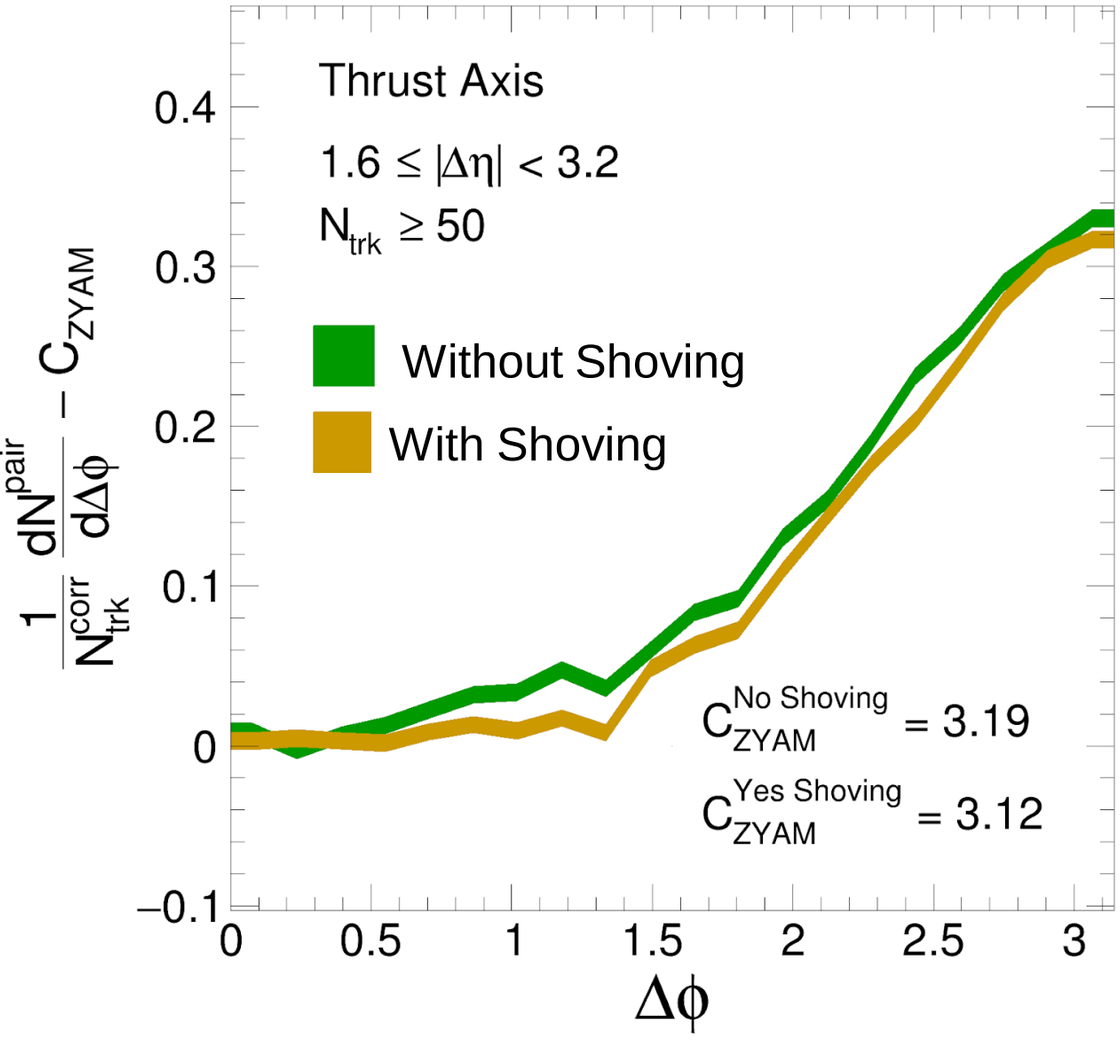
Yu-Chen “Janice” Chen (MIT)

- 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 submitted to PRL

Additional Cross-checks at High Multiplicity





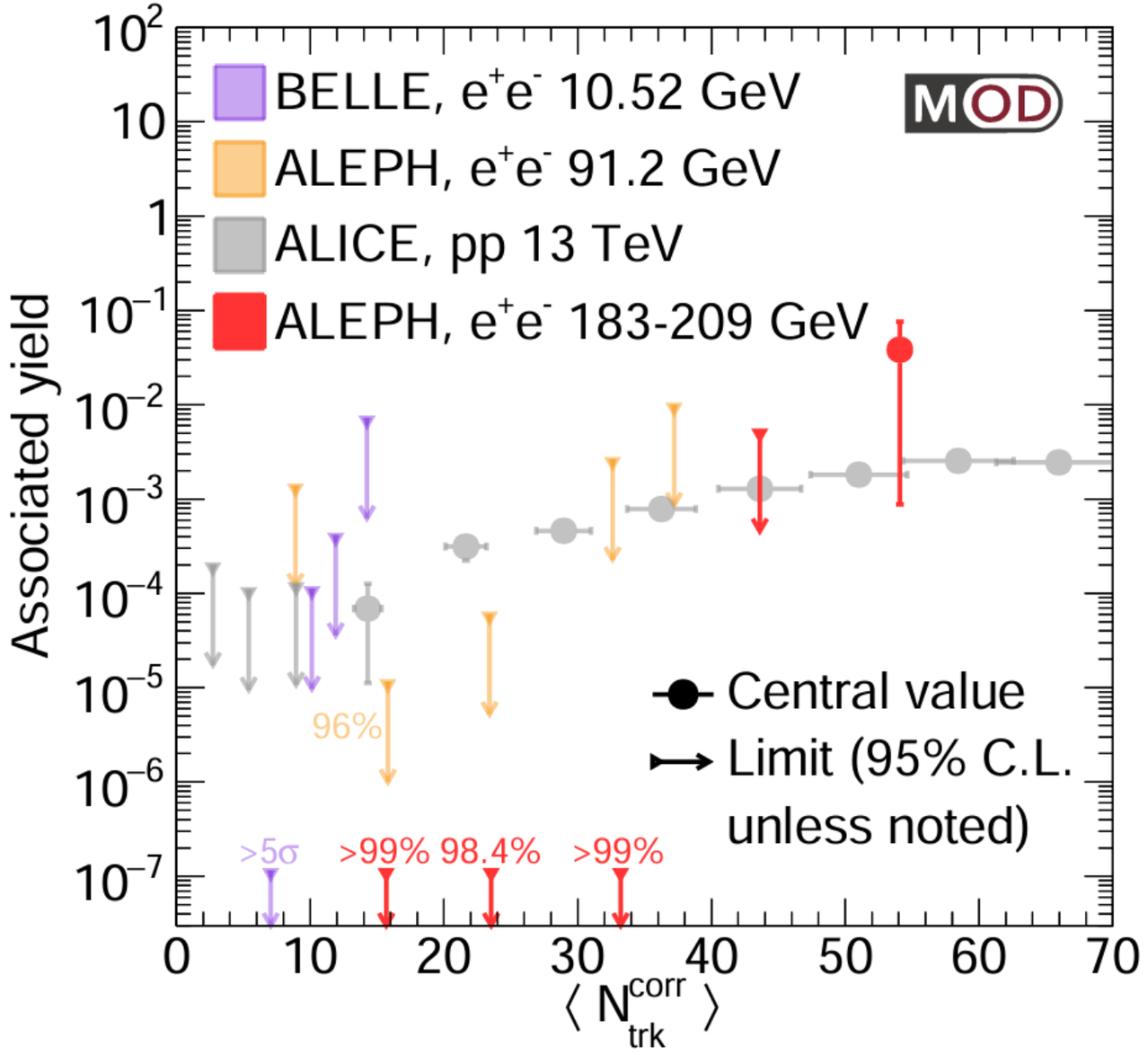
- Reweight the MC to match the data multiplicity
- Effect of reweighting is small

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

arXiv:2312.05084 submitted to PRL

Associated Yield as a Function of Multiplicity

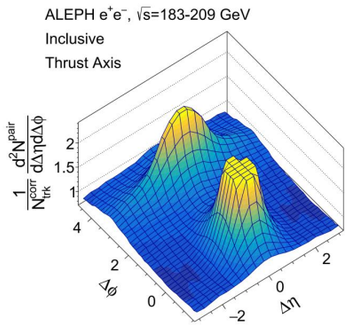
- Very tight upper limit set with **Belle**, **LEP1** and **LEP2** data set at low multiplicity (<40), lower than **ALICE** pp results
- Indication of an increasing trend at high multiplicity in LEP2 data
- Non-zero central value reported at the highest multiplicity bin with large statistical uncertainty



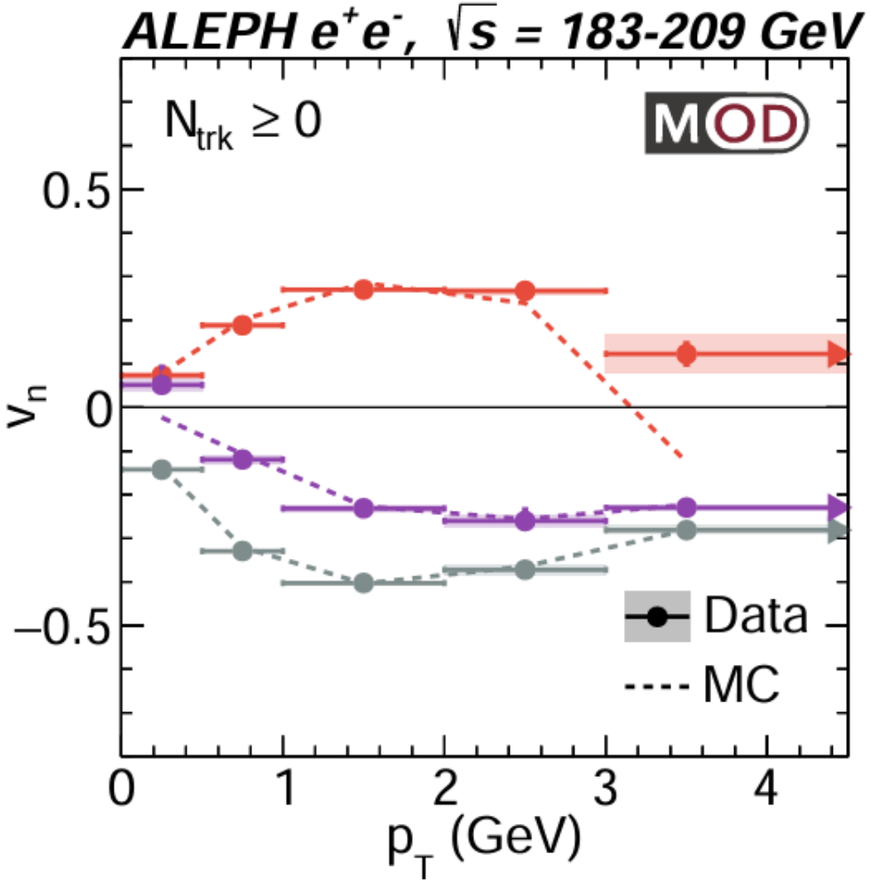
arXiv:2312.05084 submitted to PRL

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

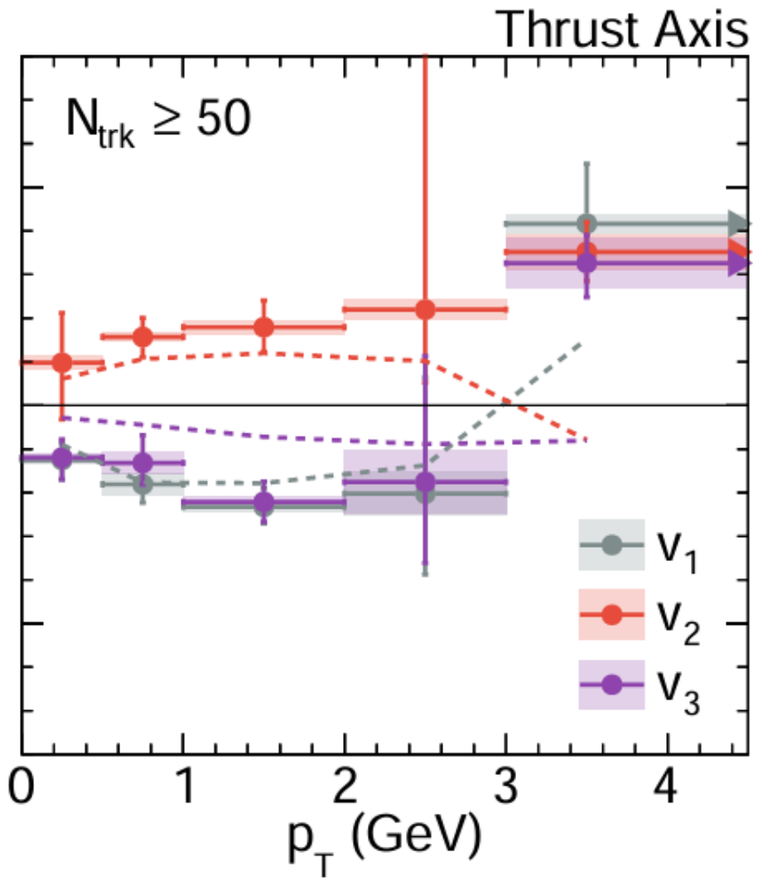
Extracted v_n vs. Charged Particle p_T

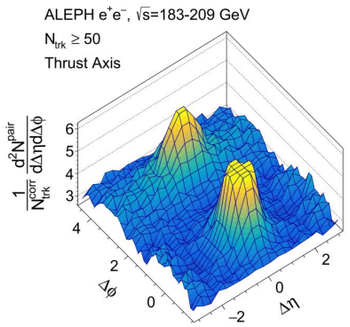


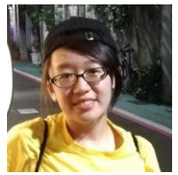
Inclusive



High Multiplicity





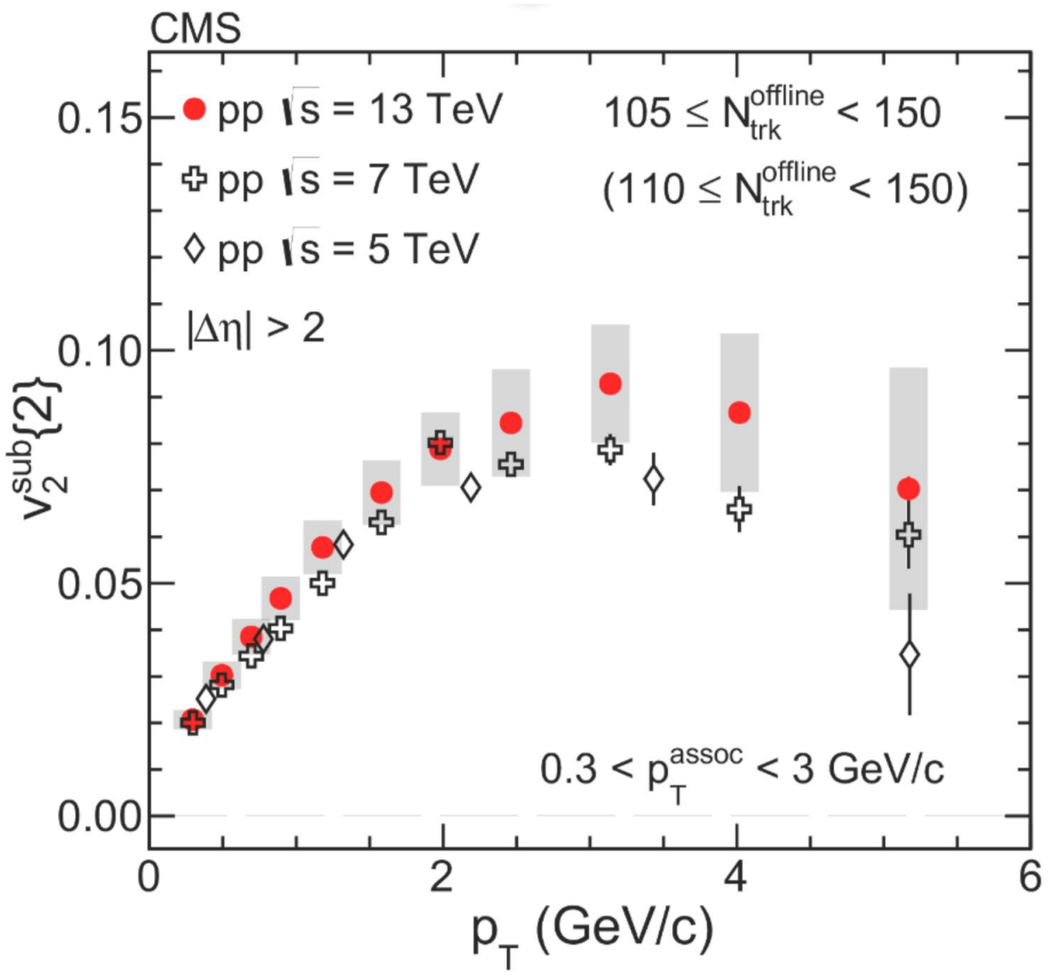


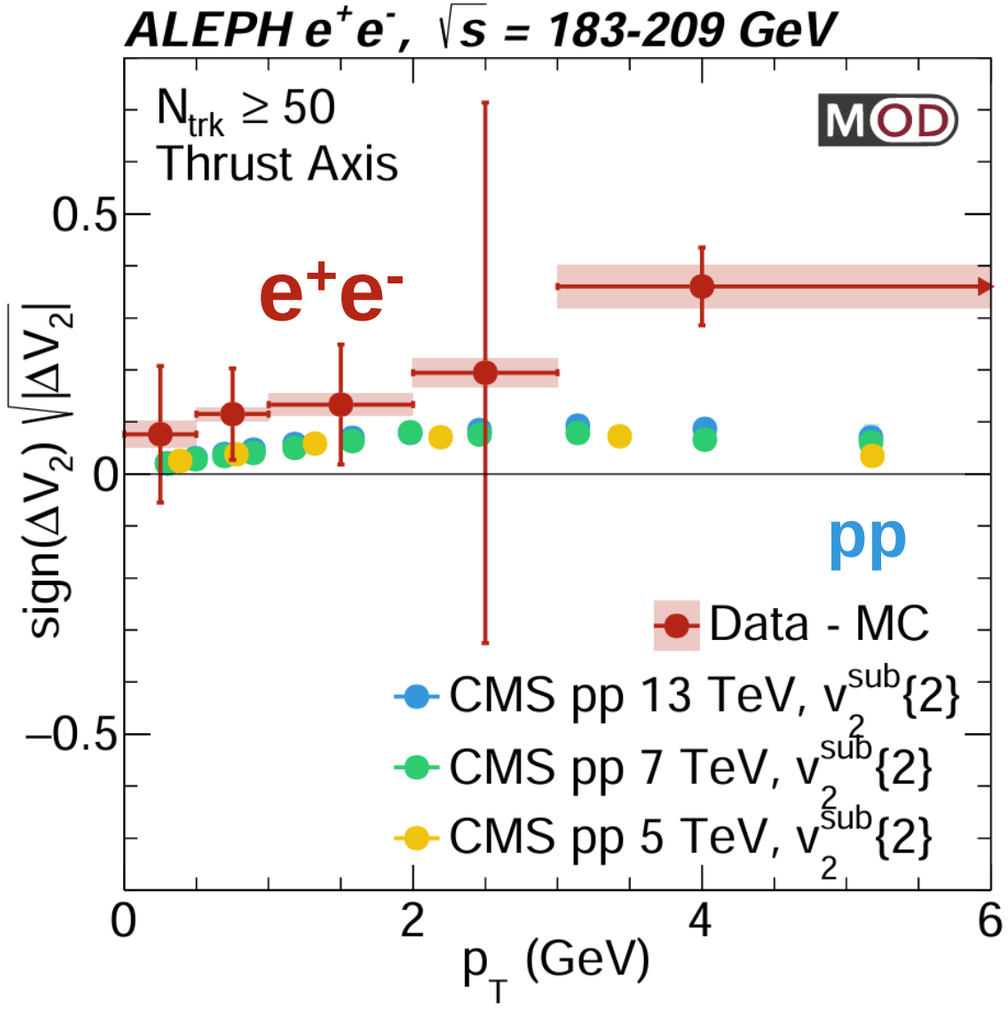
Yu-Chen “Janice” Chen (MIT)

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

arXiv:2312.05084 submitted to PRL

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

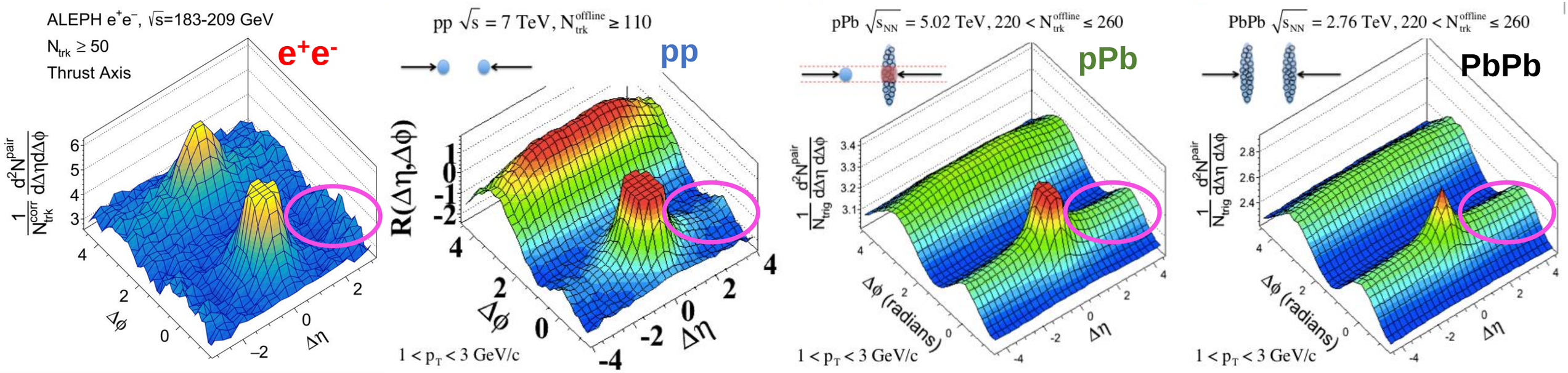




- MC based "Non-flow subtraction": $\Delta v_2 = v_2^{Data} - v_2^{MC}$
- Similar increasing trend in **e^+e^-** and **pp** data as a function of p_T

arXiv:2312.05084 submitted to PRL

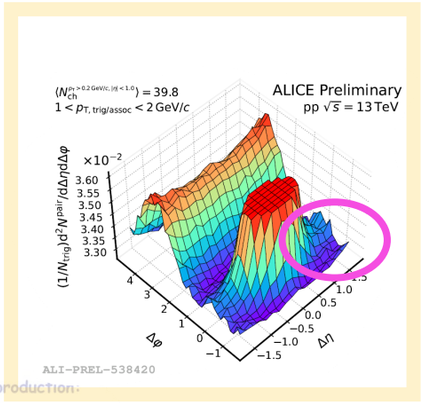
Emerging Picture



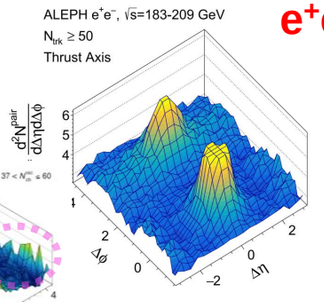
Emerging Picture

“Transverse Size” / “MPI”

Jasper Parkkila’s talk

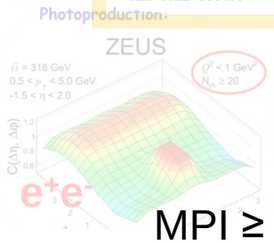


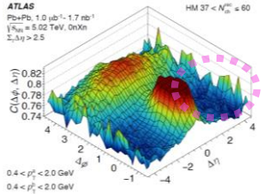
MPI>1



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

“MPI”=2



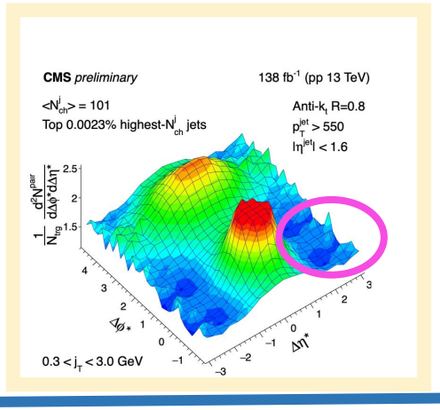


MPI ≥ 1

Larger MPI than γp

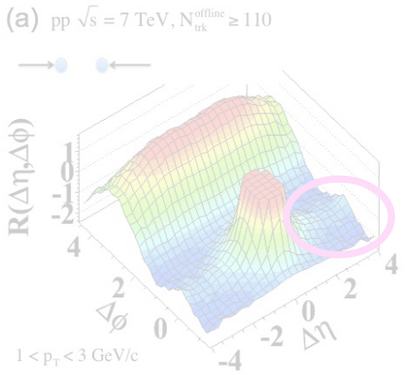
“MPI”=1

<< 0.1 fm



Wei Li’s talk

High multiplicity pp



~ O(1fm)

High multiplicity pPb

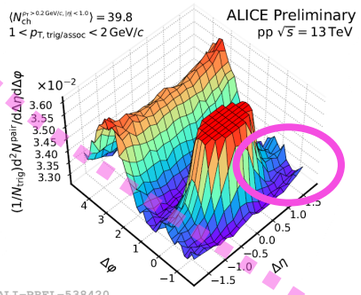
≥ O(1fm)

O(1-10 fm)

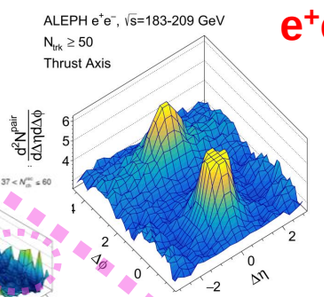
Multiplicity

Emerging Picture (Artist's impression)

"Transverse Size" / "MPI"

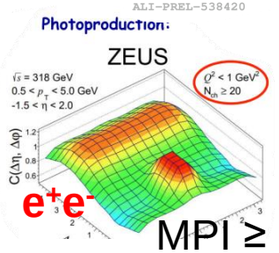


MPI>1



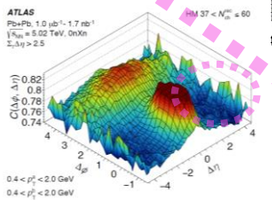
$e^+e^- \rightarrow W^+W^-$

"MPI"=2



e^+e^-

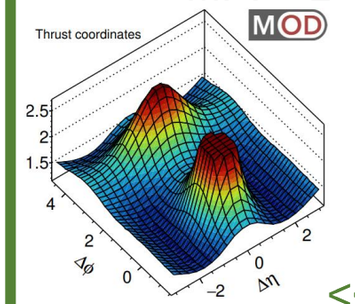
MPI ≥ 1



Larger MPI than γp

Ridge

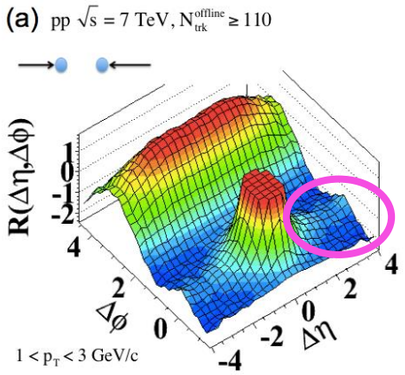
No ridge



"MPI"=1

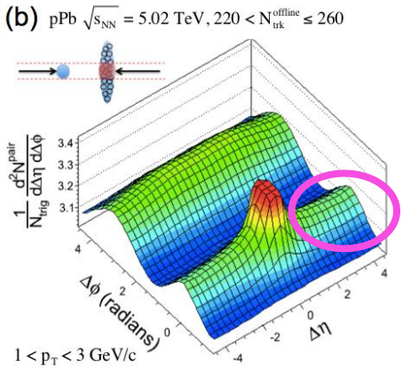
<< 0.1 fm

High multiplicity pp

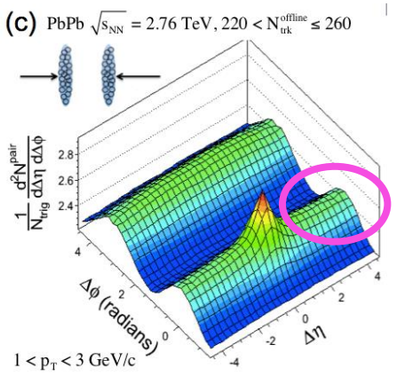


~ O(1fm)

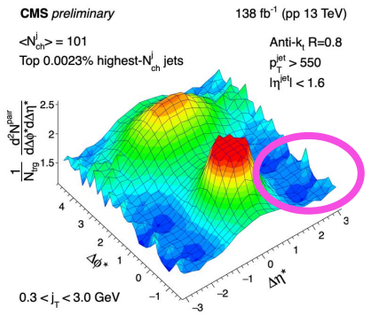
High multiplicity pPb



≥ O(1fm)



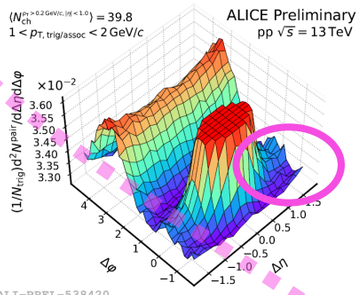
O(1-10 fm)



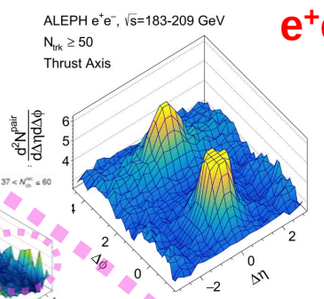
Multiplicity

Emerging Picture (Artist's impression)

"Transverse Size" / "MPI"

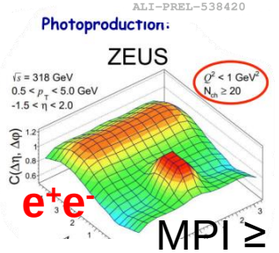


MPI>1

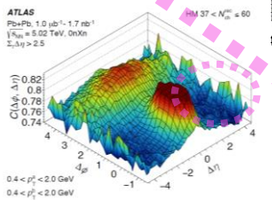


$e^+e^- \rightarrow W^+W^-$

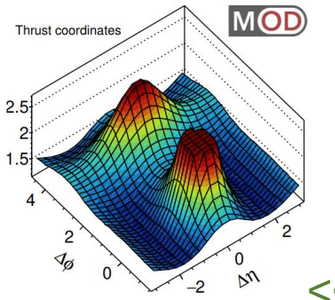
"MPI"=2



MPI ≥ 1



Larger MPI than γp

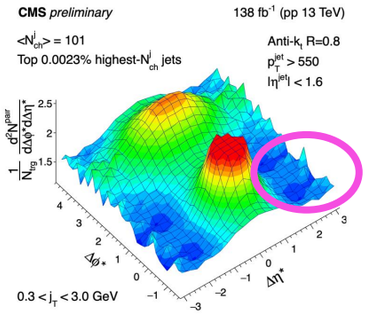


"MPI"=1

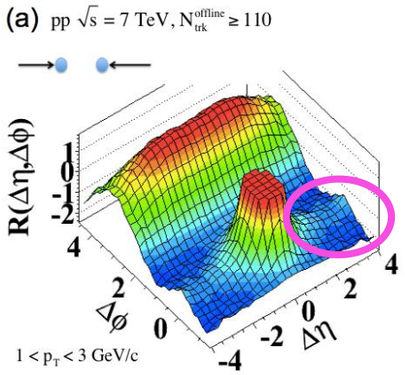
<< 0.1 fm

Ridge

No ridge

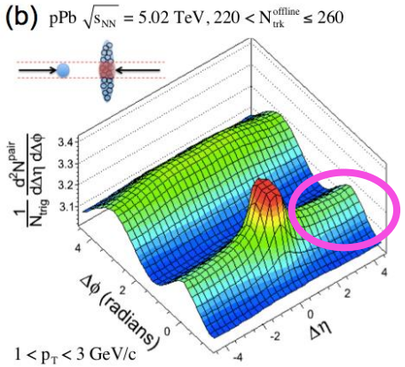


High multiplicity pp

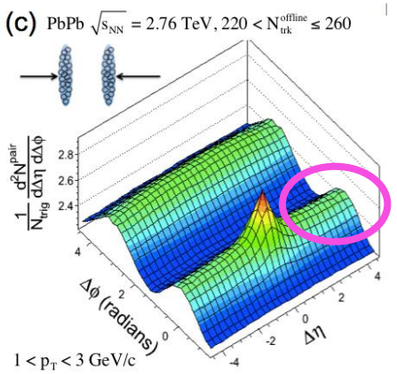


~ O(1fm)

High multiplicity pPb



≥ O(1fm)



O(1-10 fm)

Future program with

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

(2) UPC AA data

(3) Investigation with EIC data

Multiplicity

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 $V_{1\Delta}$ and directly reveal the ridge

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

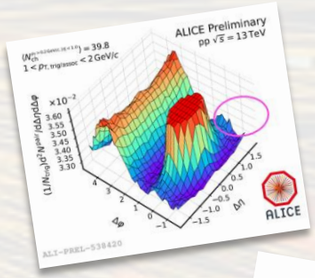
  Indication of final state effects from CMS high multiplicity single jet and ALEPH LEP2 data

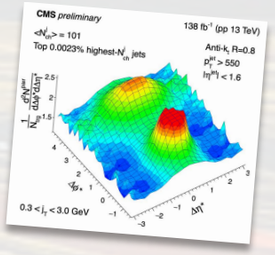
- How does collectivity vary in different physics processes?

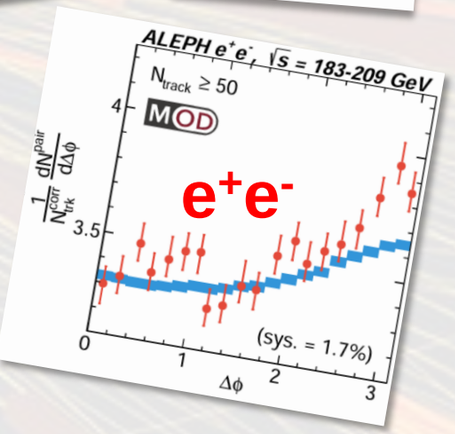
  Long-range near-side correlations vary in different physics processes in LEP data

- 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.







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(MIT, BELLE/CMS)

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(NTU, BELLE)

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(MIT, CMS)

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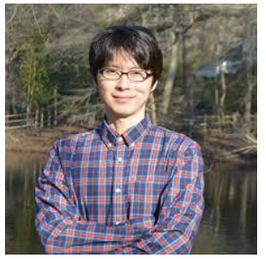
(MIT, CTP)

Eric Metodiev
(MIT, CTP)

Jing Wang
(MIT, CMS)

Ben Nachman
(LBNL, ATLAS)

Yi Chen
(MIT, CMS)

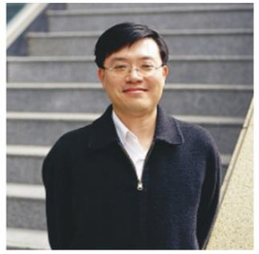


Yang-Ting Chien
(GSU)

Yen-Jie Lee
(MIT, CMS)

Gian Innocenti
(CERN, ALICE)

Jesse Thaler
(MIT, CTP)



Paoti Chang
(NTU, BELLE/CMS)

Marcello Maggi
(INFN, CMS)

Günther Dissertori
(ETH Zürich, CMS)

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 (Y(4S)): — JHEP 03 (2023) 171

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

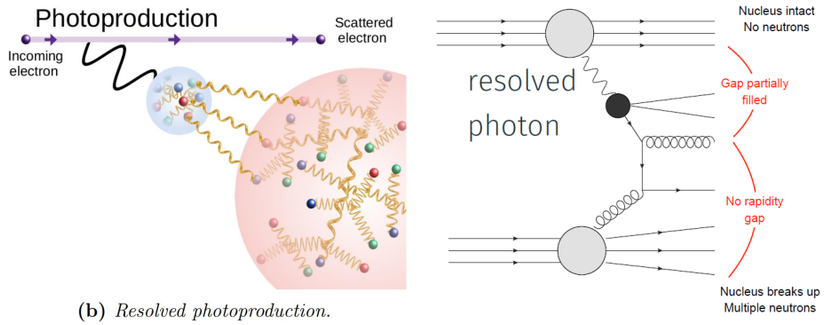
- **γPb**
  - ATLAS PbPb photonuclear: — PRC 104 (2021) 1, 014903

- **pp**
  - ALICE MB: — https://arxiv.org/pdf/2311.14357.pdf
  - CMS Single Jet in pp: — (preliminary) CMS-PAS-HIN-21-013

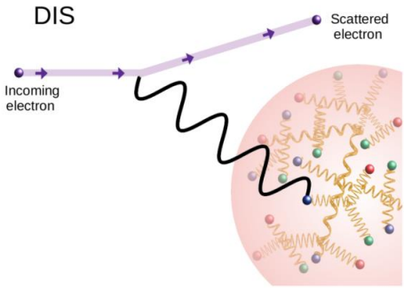
System Size

"Transverse Size"

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

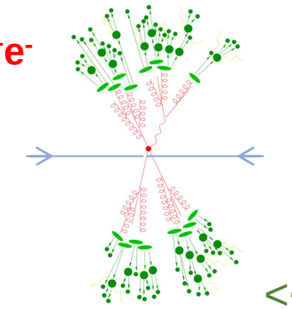


(b) *Resolved photoproduction.*



(a) *Neutral current deep inelastic scattering.*

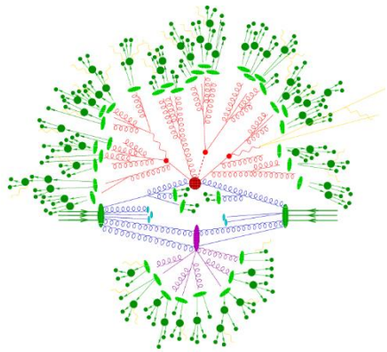
e^+e^-



<< 0.1 fm

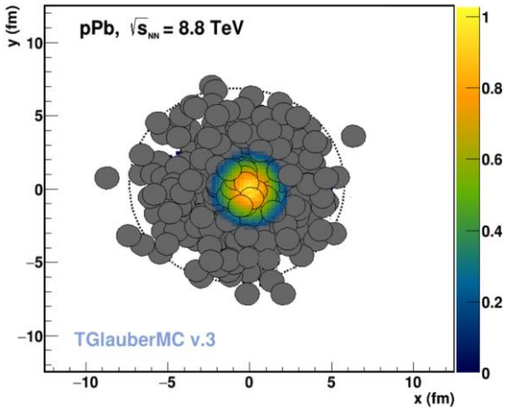
1/Q < 0.2 fm

pp



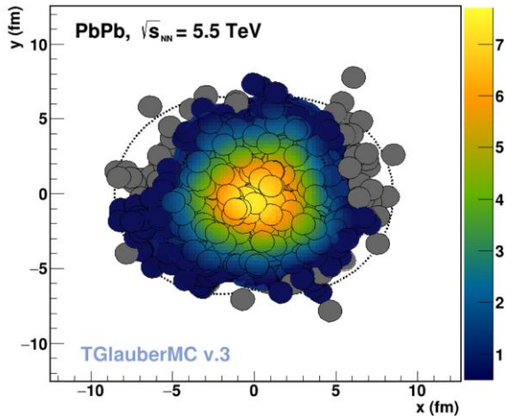
~ O(1fm)

pA

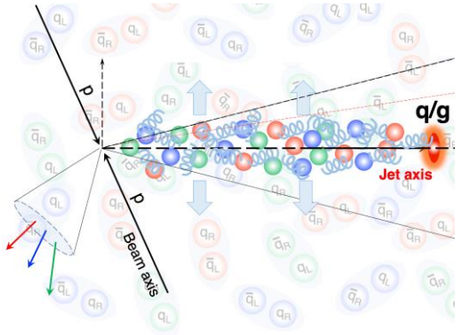


≥ O(1fm)

AA



O(1-10 fm)



Multiplicity

Backup Slides

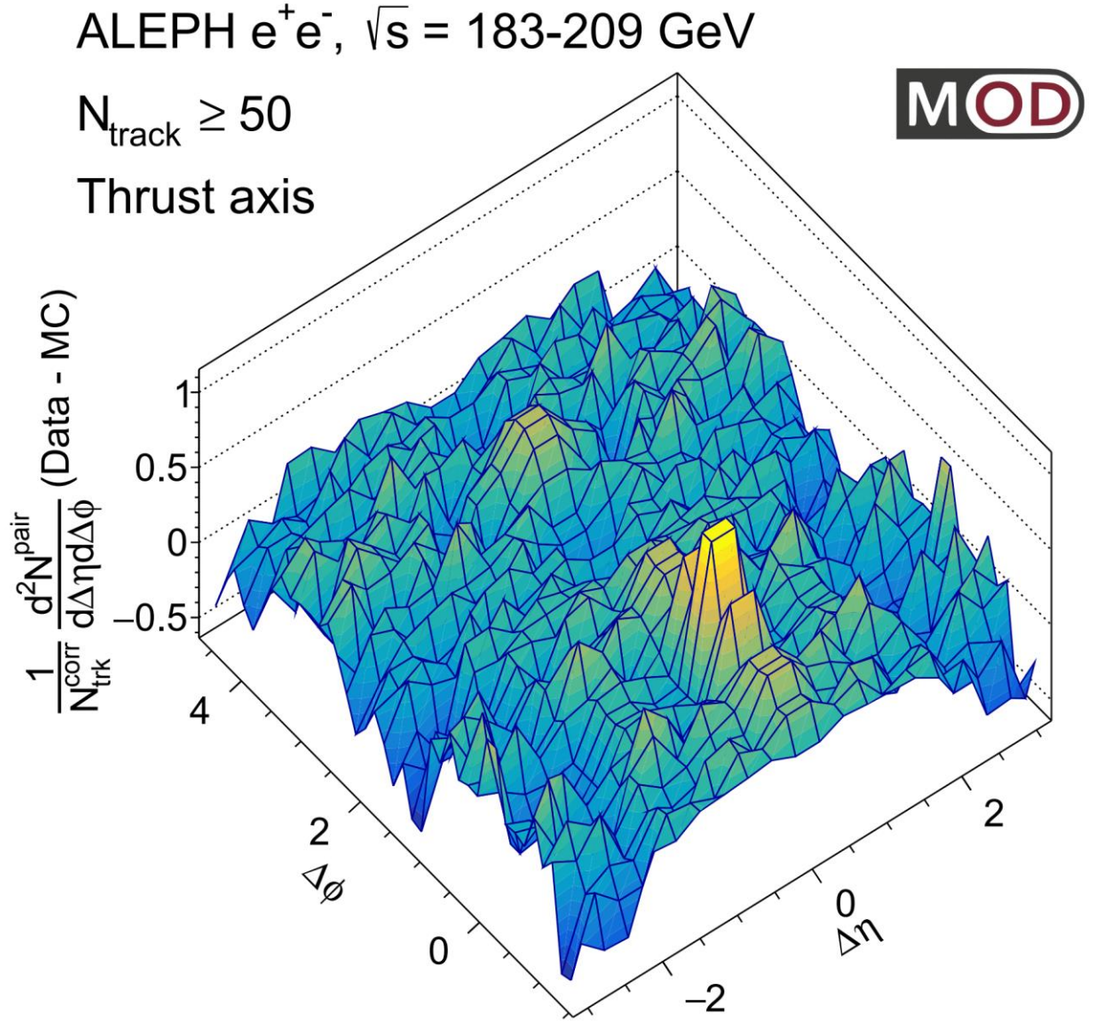
Hadronic Event Selection

- **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.

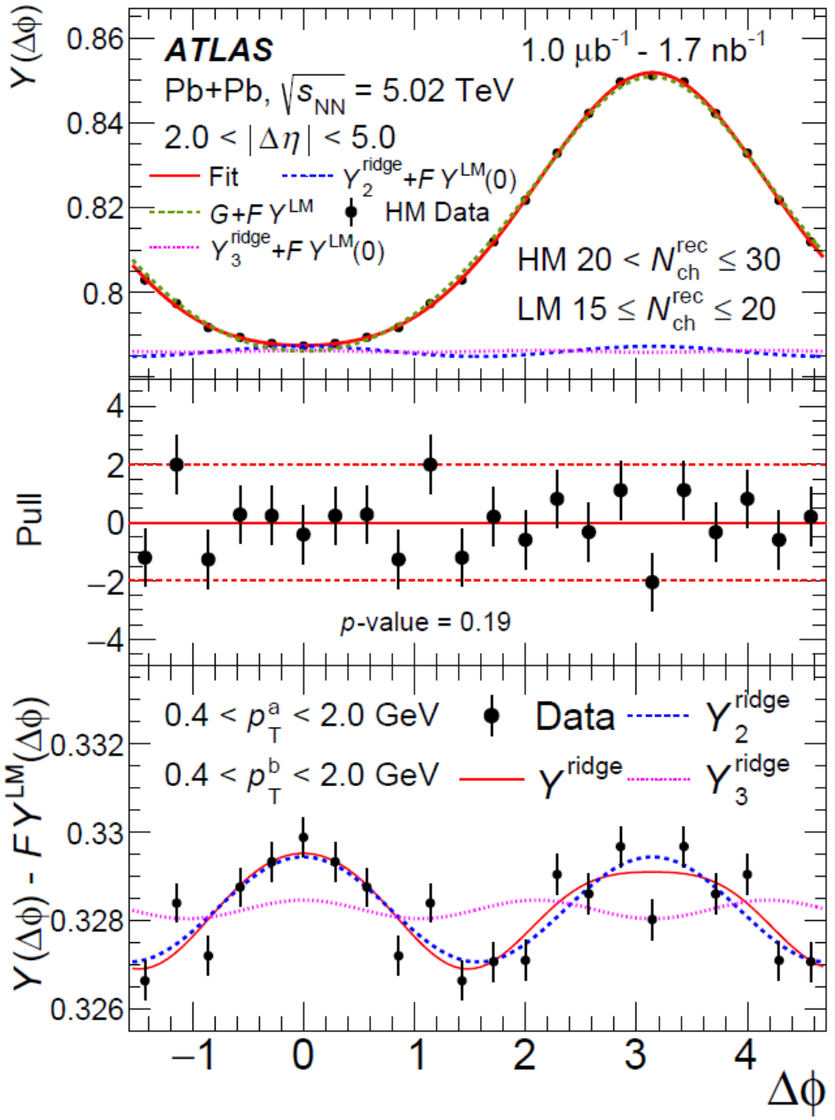
- **Neutral Hadron Selection:**
  - Particle Flow Candidate 4, 5 (ECAL / HCAL object)
  - E> 0.4 GeV
  - |cosθ|<0.98

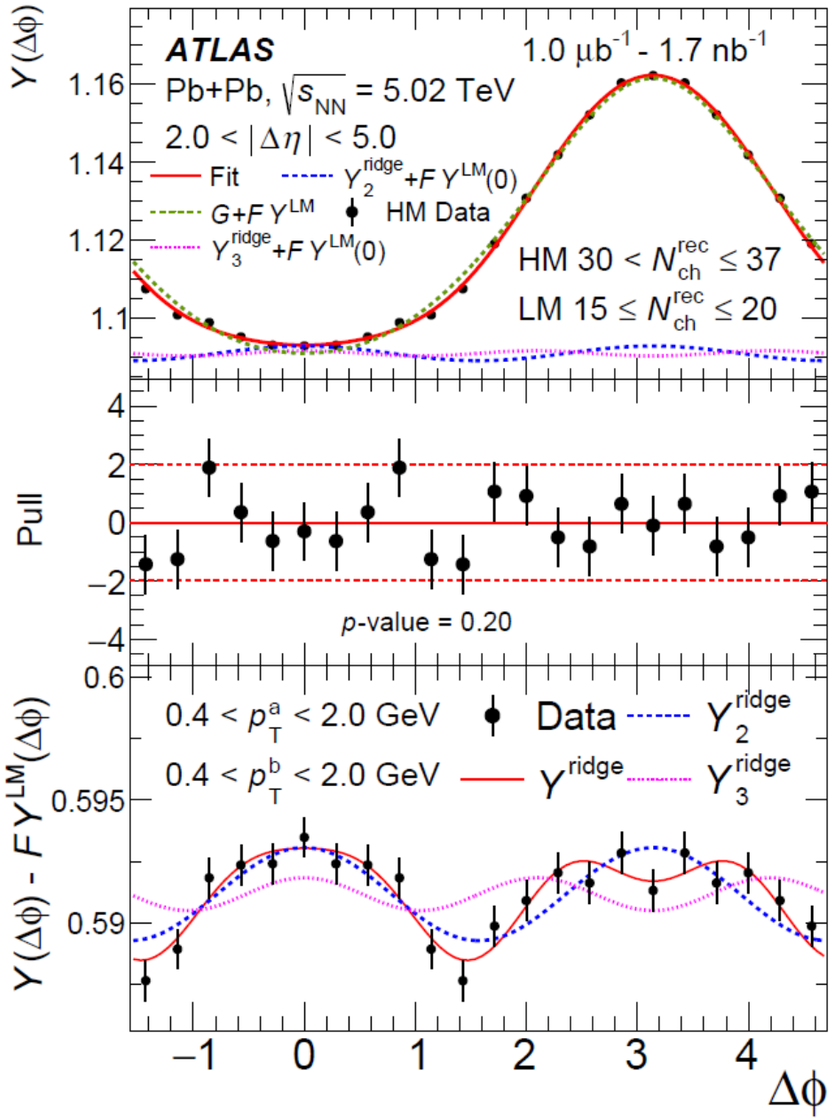
- **Event Selection:**
  - Number of good charged particles >= 5 (including charged hadrons and leptons)
  - Number of good ch+neu. Particles >= 13
  - $E_{charged}$ > 15 GeV
  - $|\cos(\theta_{sphericity})|$<0.82

Difference between Data and MC



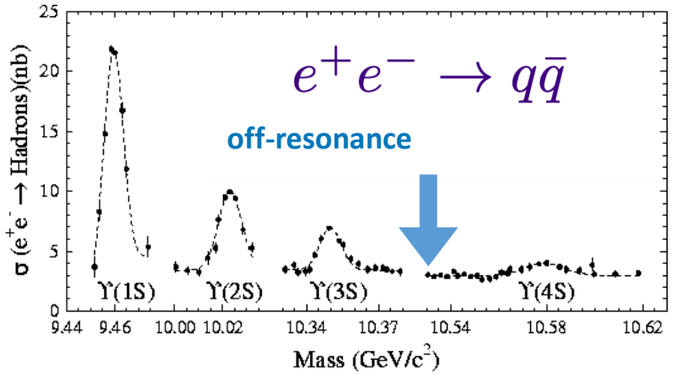
Photonuclear at the LHC





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

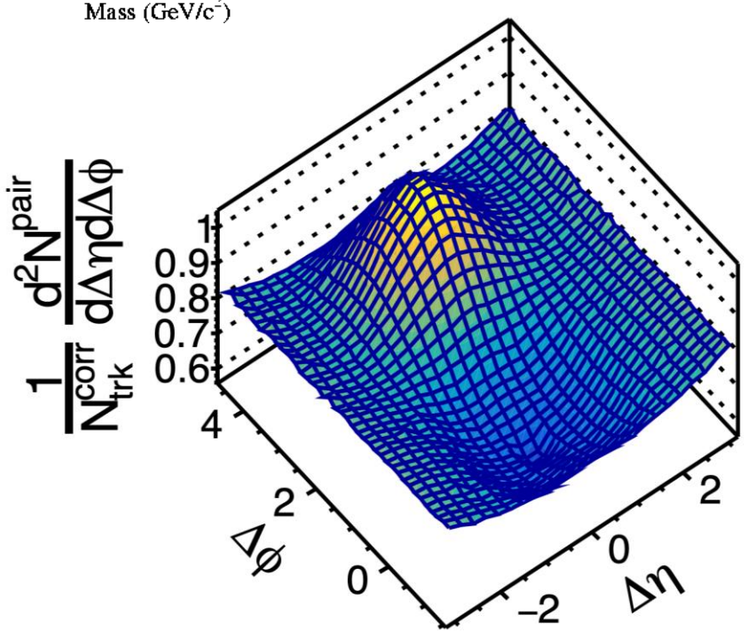
Reasonable data and MC agreements!



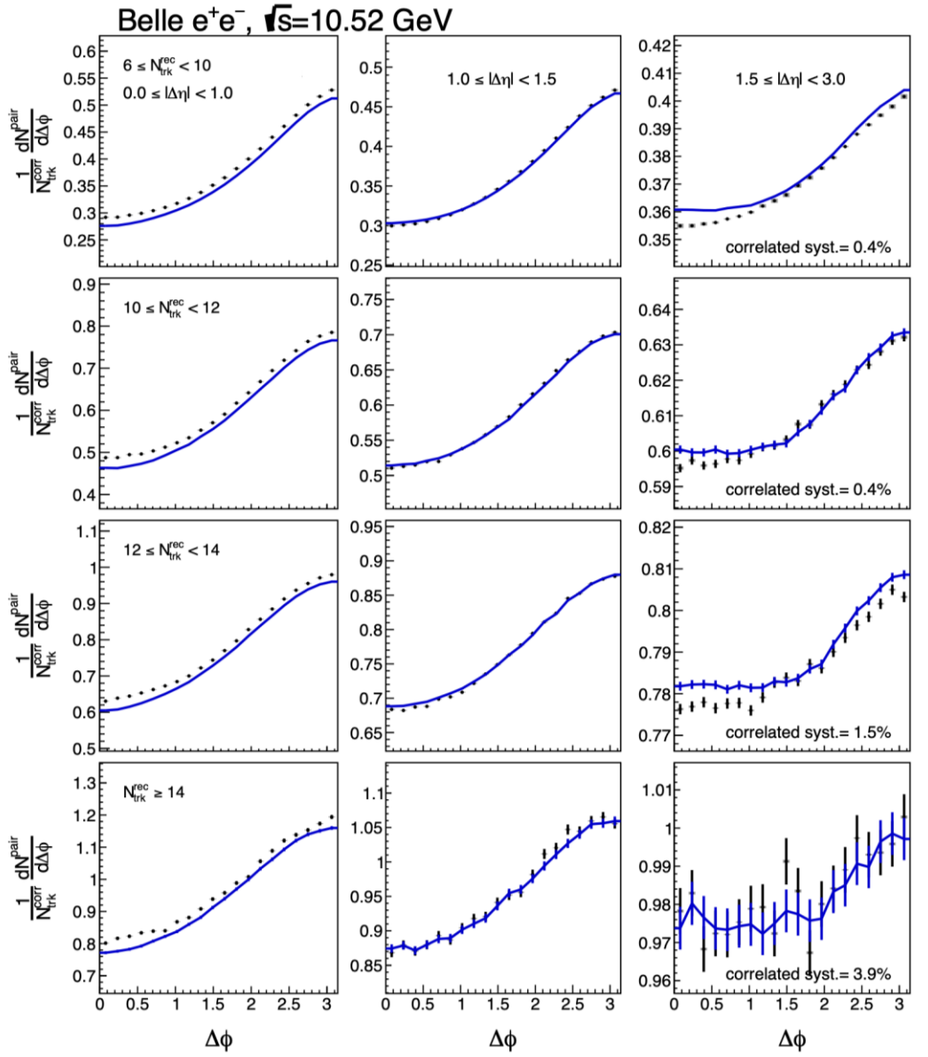
Data

MC PYTHIA6

High-multiplicity



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



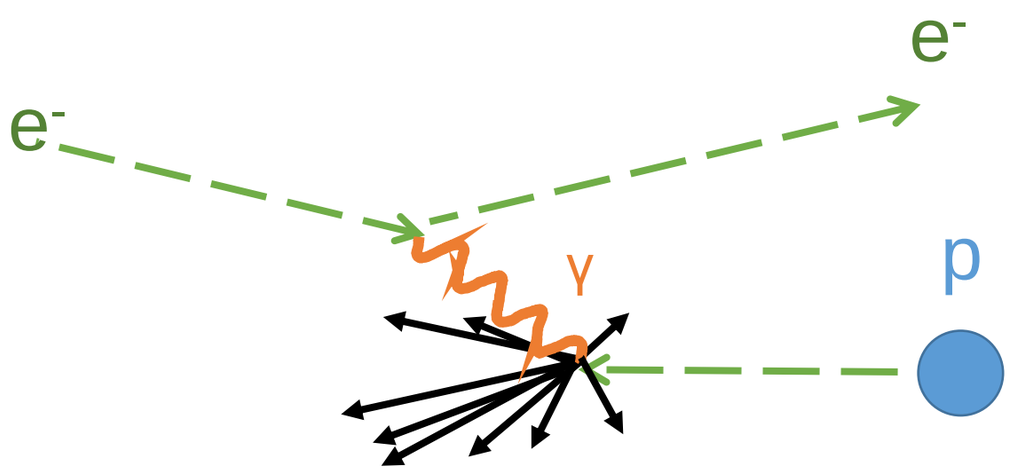
Short Range ($0 \leq |\Delta\eta| < 1$)

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

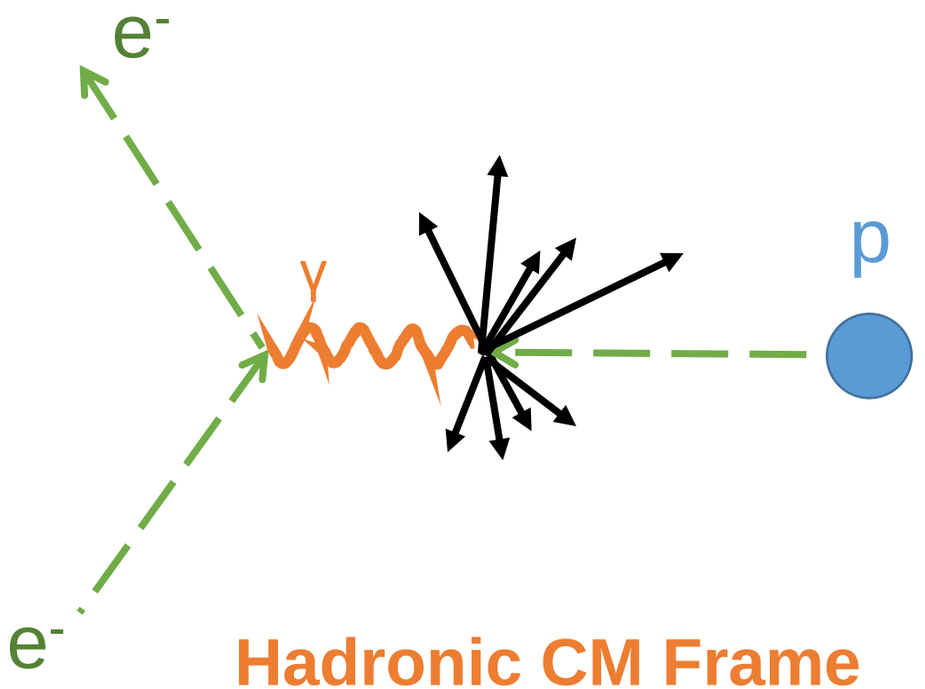
Long Range ($1.5 \leq |\Delta\eta| < 3.0$)

[PRL 128 (2022) 142005]

Lab vs. Hadronic CM Frame



Lab Frame



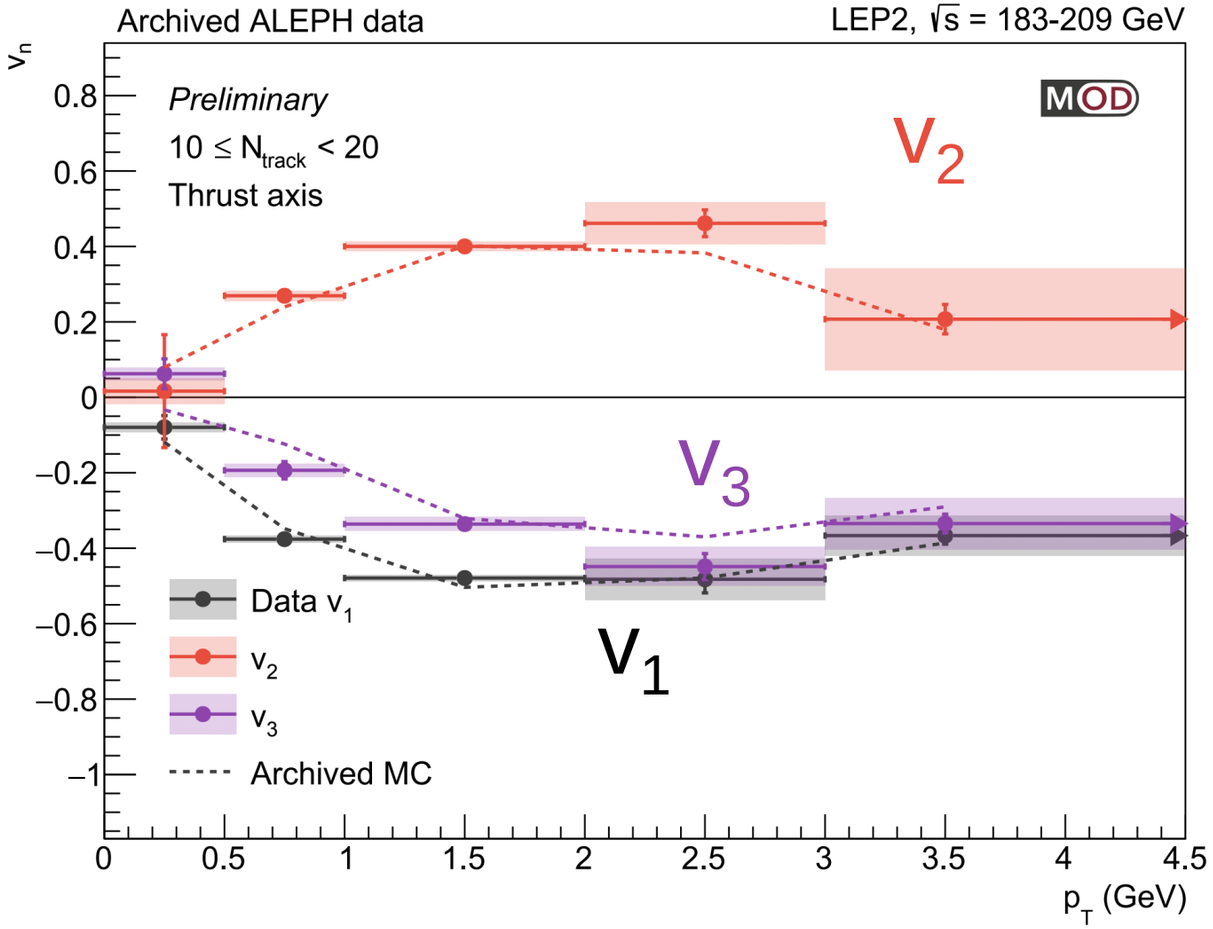
Hadronic CM Frame

Used in ZEUS analysis

Used in H1 analysis

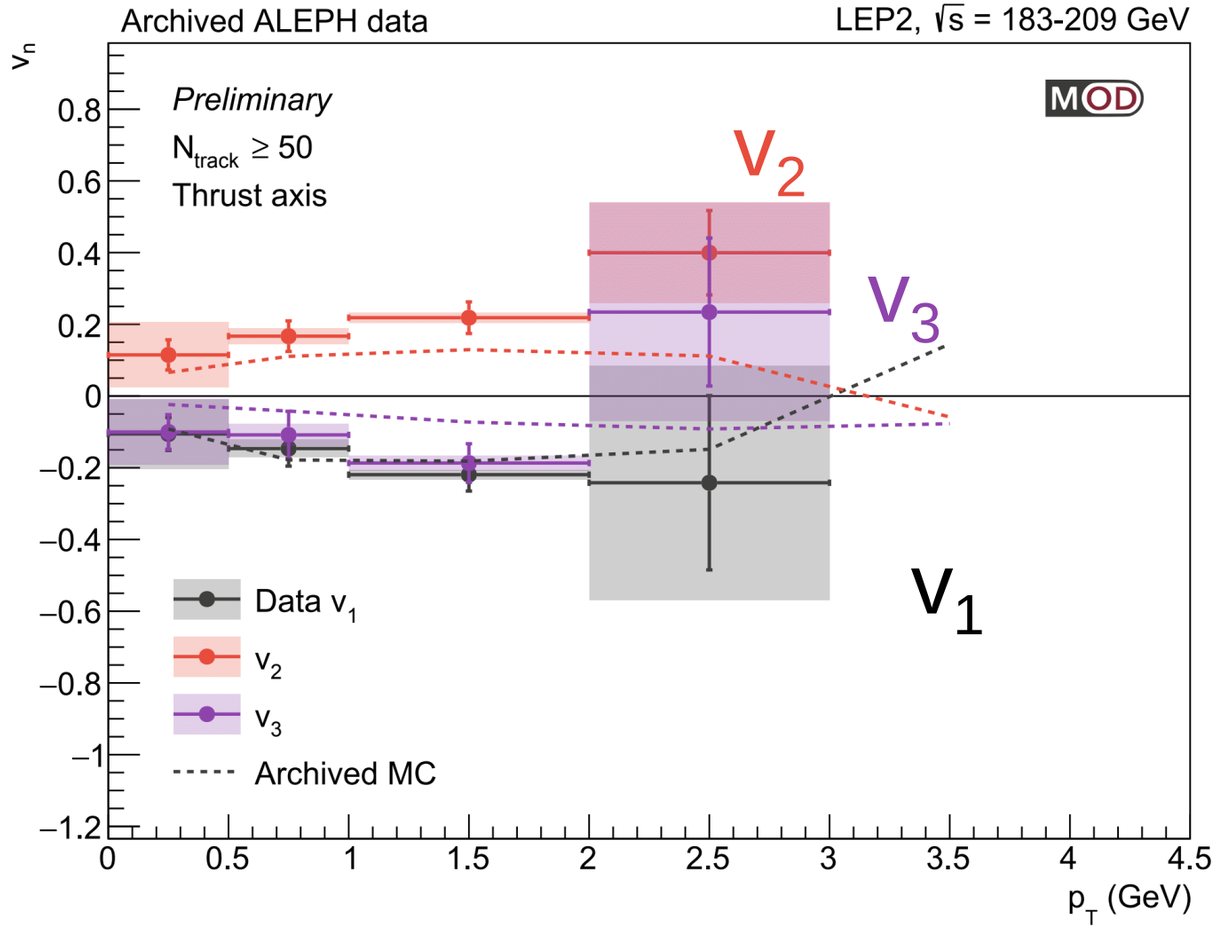
Extracted v_n vs. Charged Particle p_T

Low multiplicity 10 $\leq N_{track} <$ 20



Good agreement between data and MC

High multiplicity $N_{track} \geq 50$

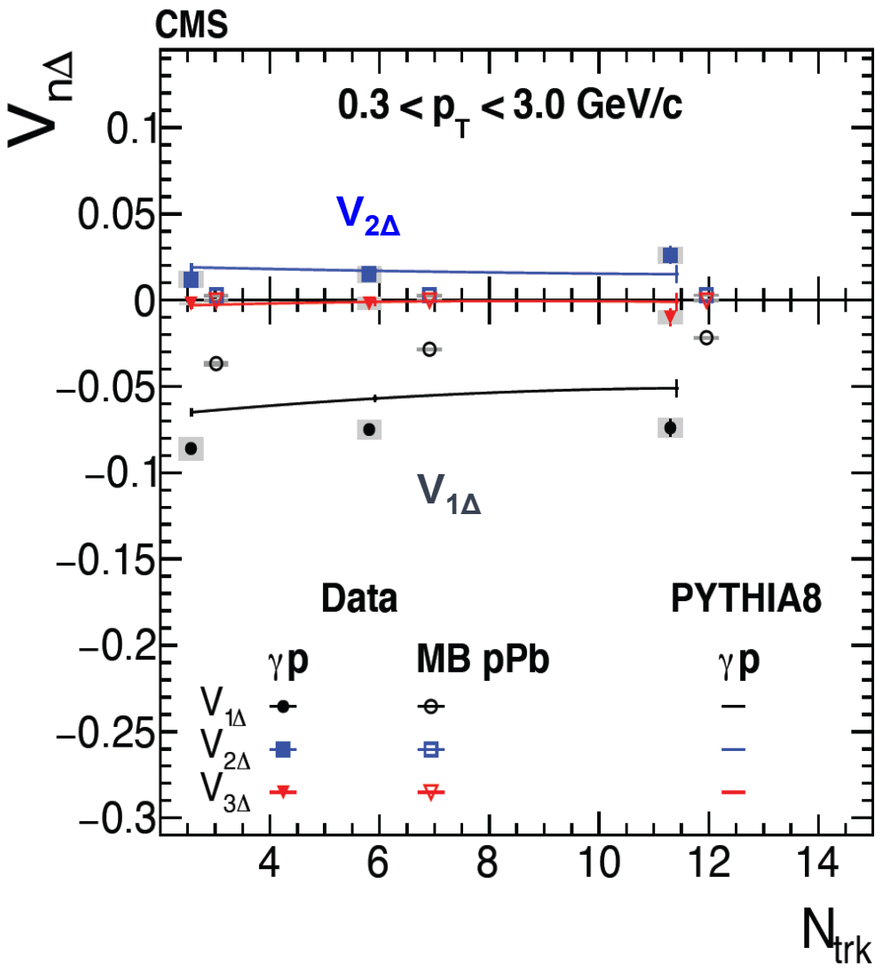


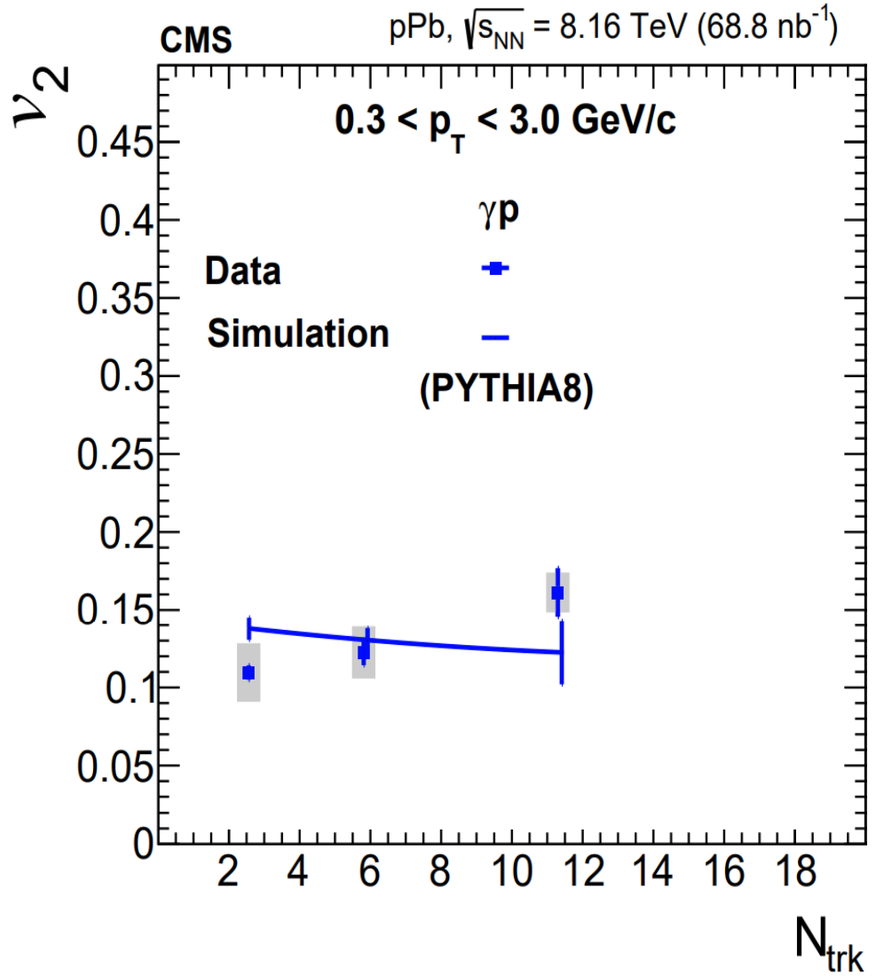
Larger v_2 and v_3 magnitudes than MC

CMS γp in pPb Collisions at 8.16 TeV

No low multiplicity event subtraction

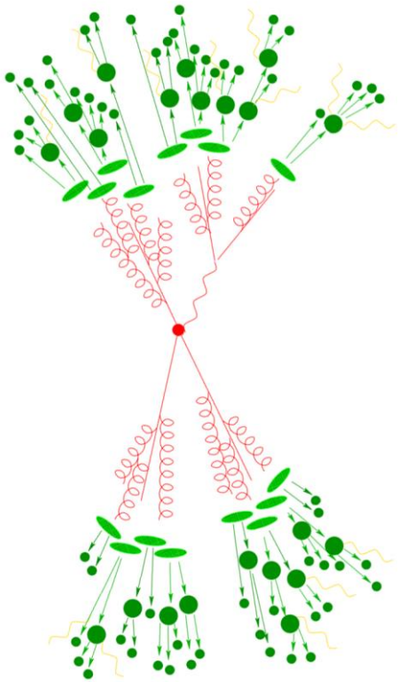
- Positive $\mathbf{V_{2\Delta}}$ and negative $\mathbf{V_{1\Delta}}$ indicate a significant influence of jet-like correlations
- $V_{2\Delta}$ and $V_{1\Delta}$ magnitudes in γp are larger than those in MB pPb
- PYTHIA8 describe the v_2 data at low N_{trk}



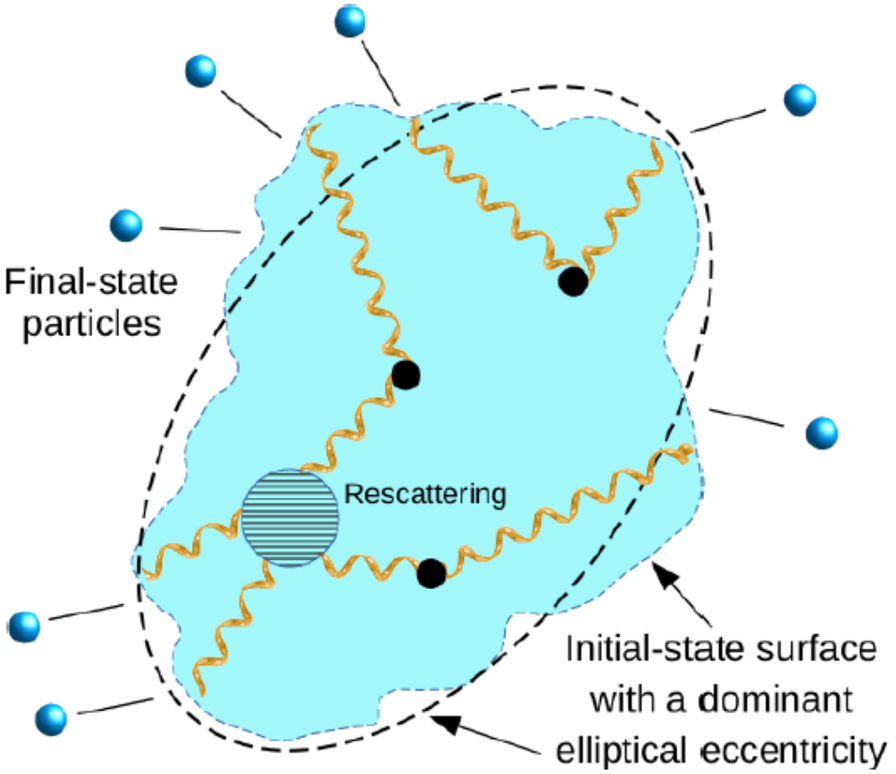


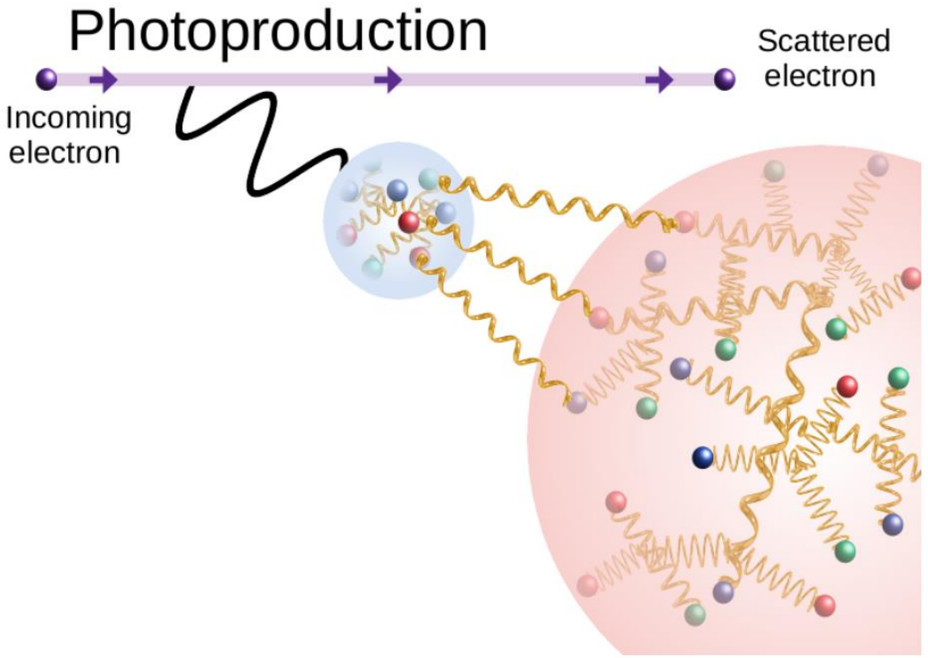
Multiple Parton Interaction (MPI)

Single $q\bar{q}$ pair



MPI





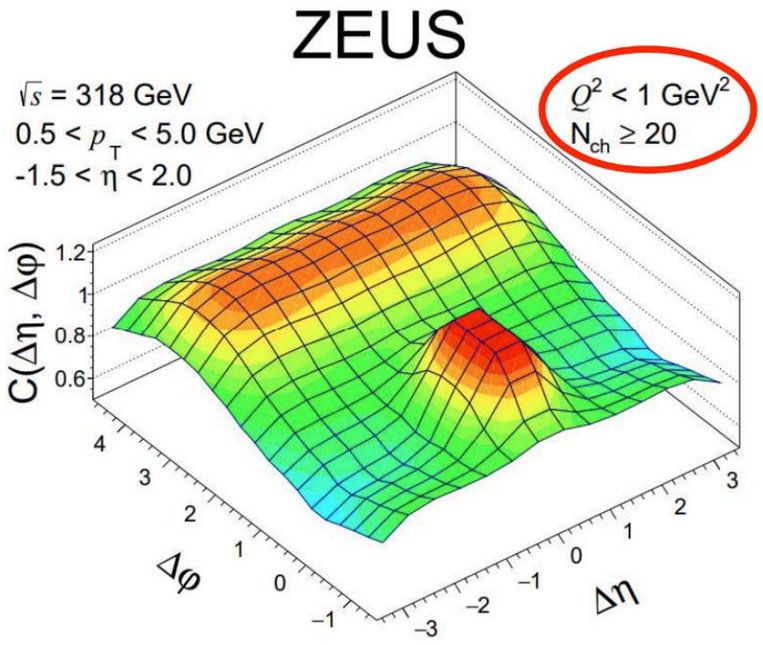
(b) *Resolved photoproduction.*

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

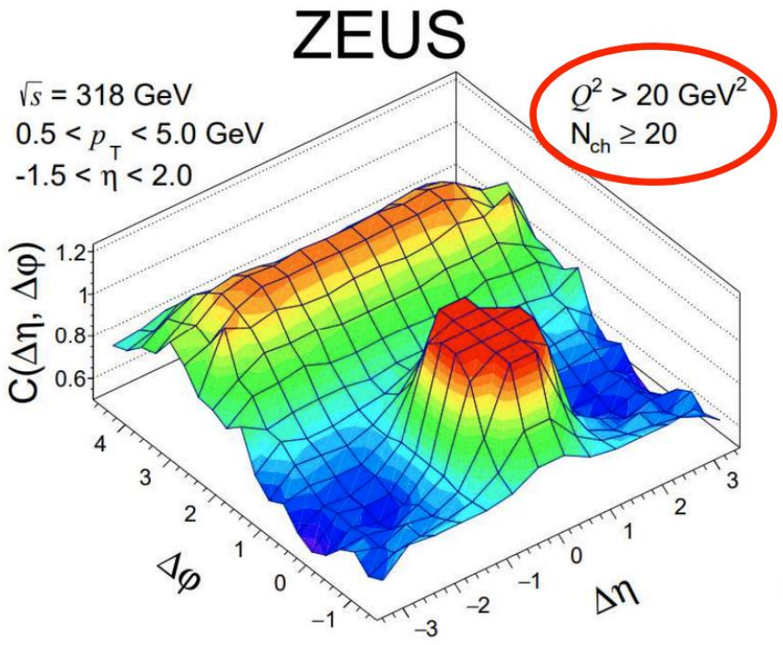
Correlation Function in **ep** at 318 GeV with HERA

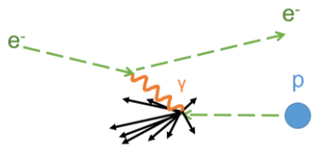
Photoproduction

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



DIS

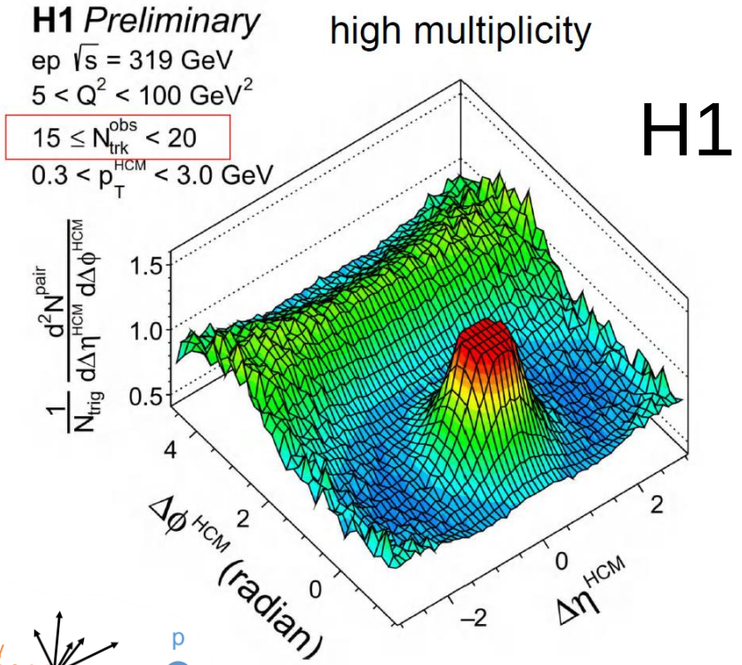


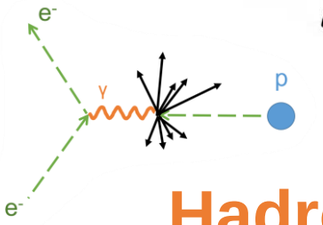


Lab Frame

DIS

1/Q < 0.2 fm





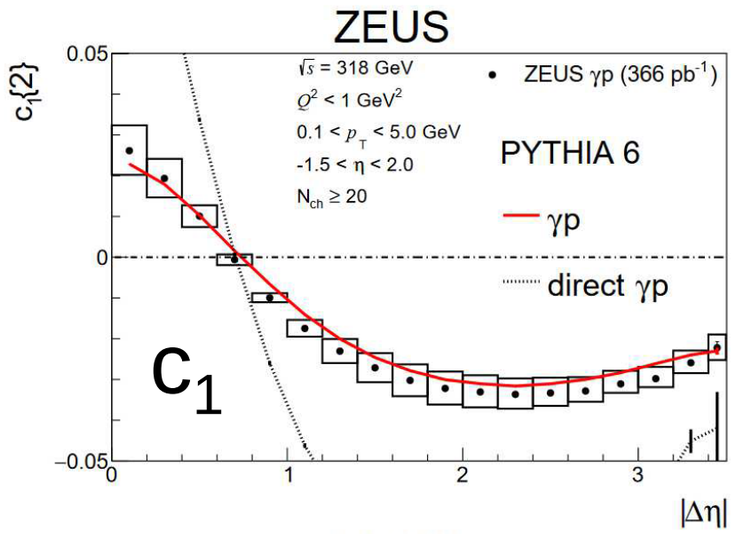
Hadronic CM Frame

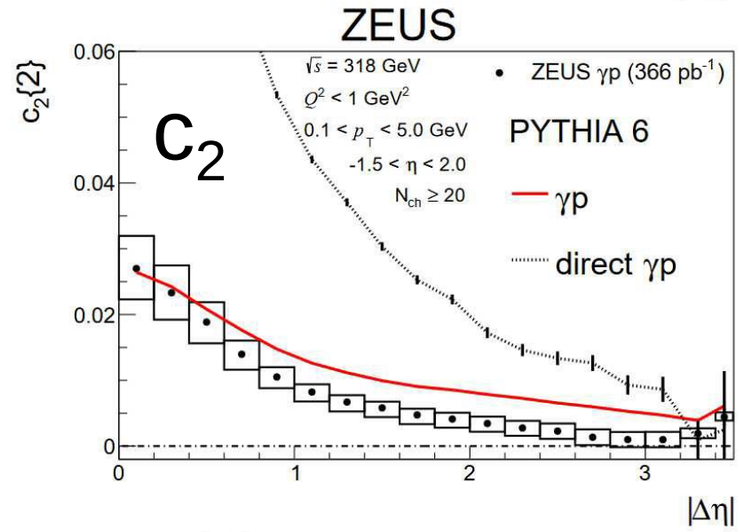
- ZEUS search in lab frame: No significant ridge-like signal in both photoproduction and DIS data with $N_{ch} > 20$

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

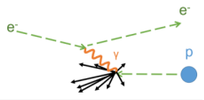
- No significant ridge-like signal in H1 search in Hadronic CM Frame (Up to $N_{ch} = 20$)

Searches at HERA (ep Collisions) and CMS γp

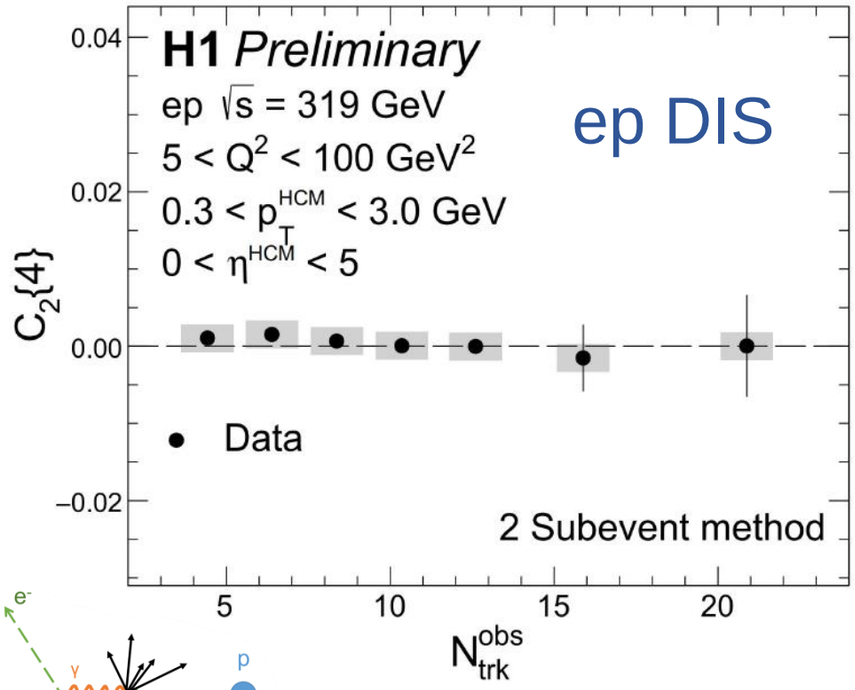


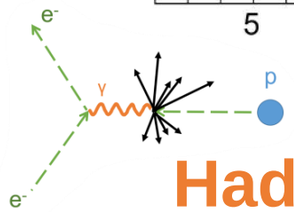


ep Photoproduction



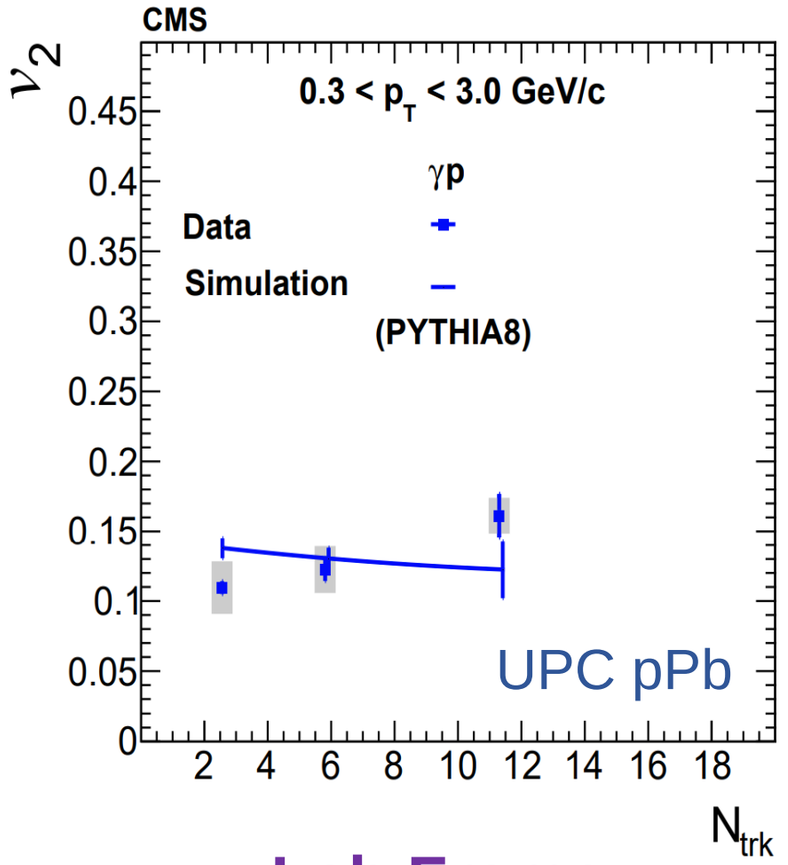
Lab Frame





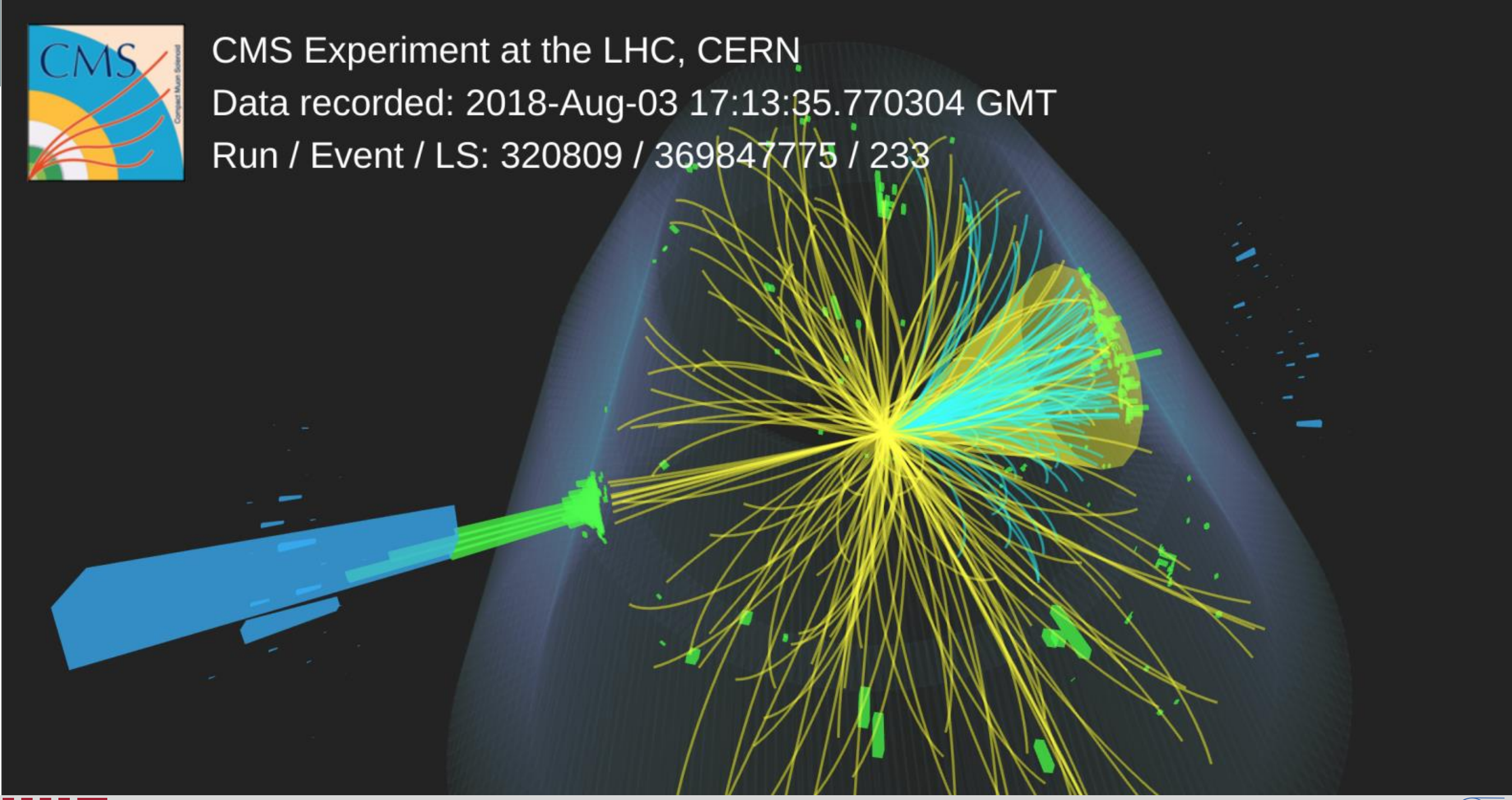
Hadronic CMS Frame

- 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



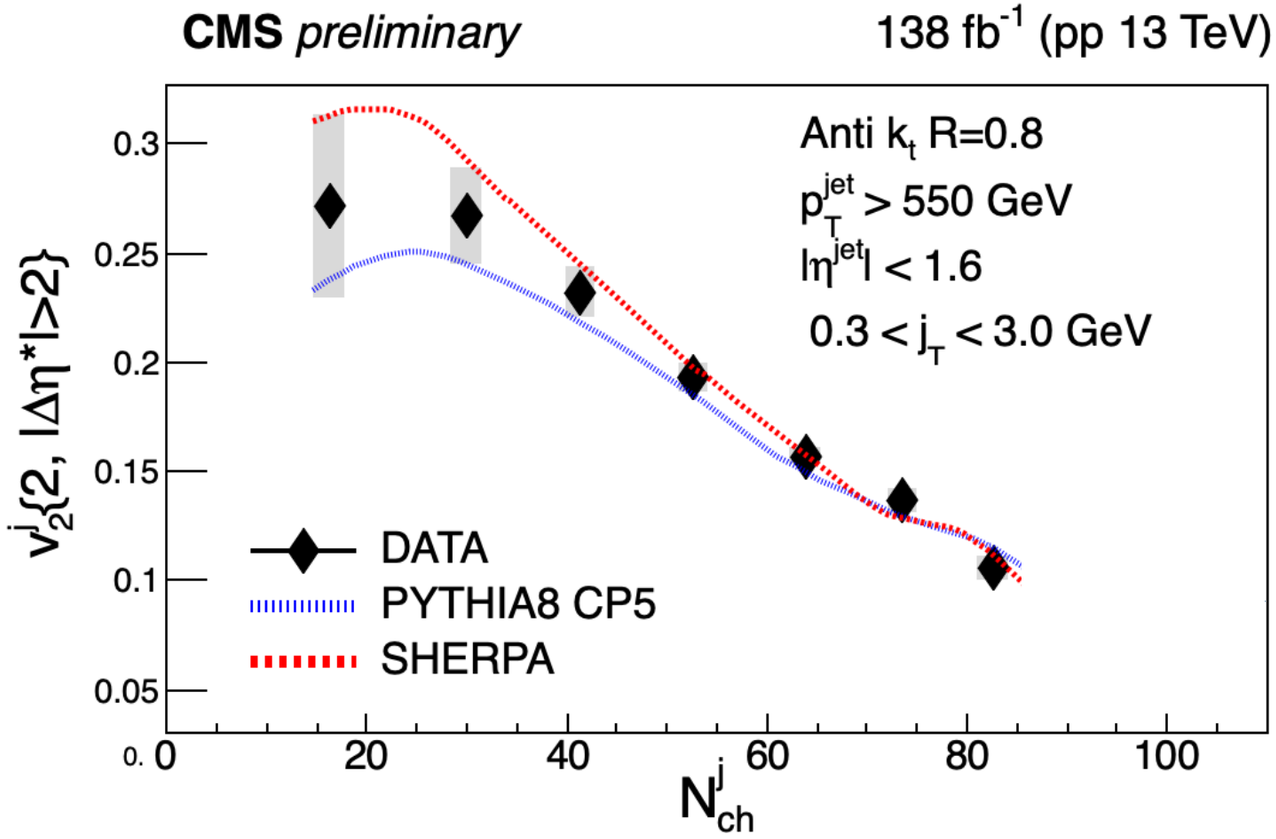
Lab Frame

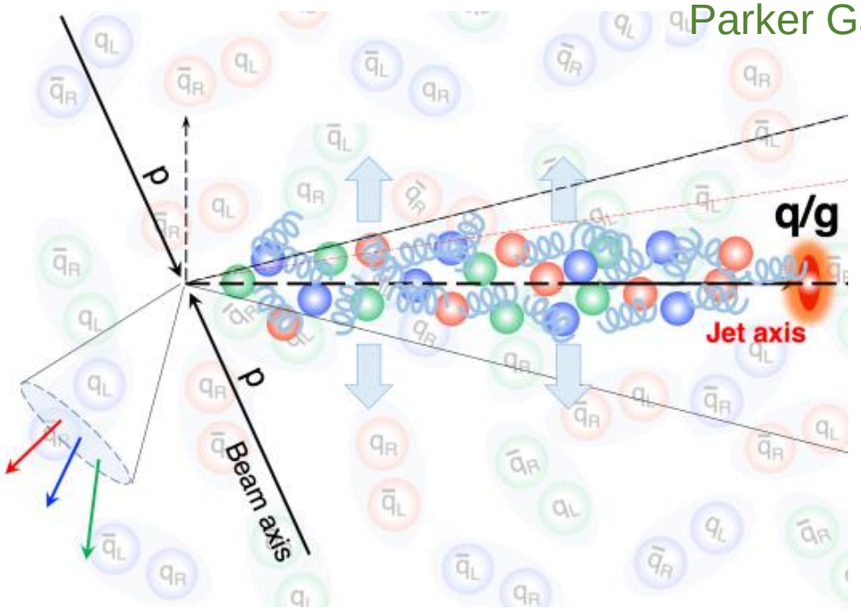
- γp in pPb UPC at 8.16 TeV
- PYTHIA8 describes the v_2 data at low N_{trk}

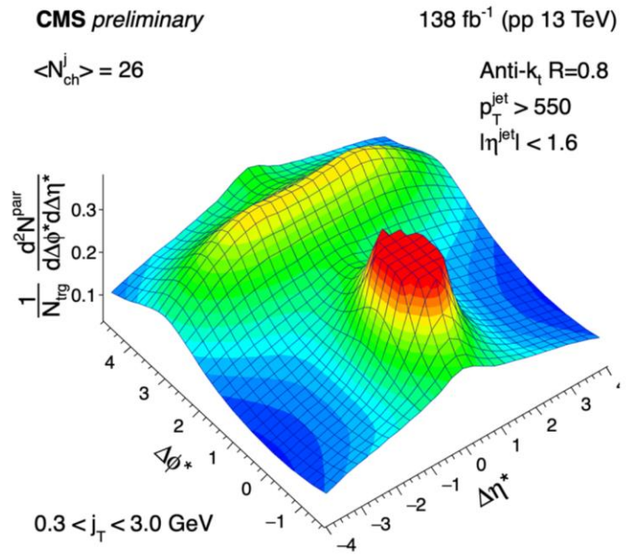

CMS Experiment at the LHC, CERN
Data recorded: 2018-Aug-03 17:13:35.770304 GMT
Run / Event / LS: 320809 / 369847775 / 233

Single High Multiplicity Jet

Parker Gardner (Rice)



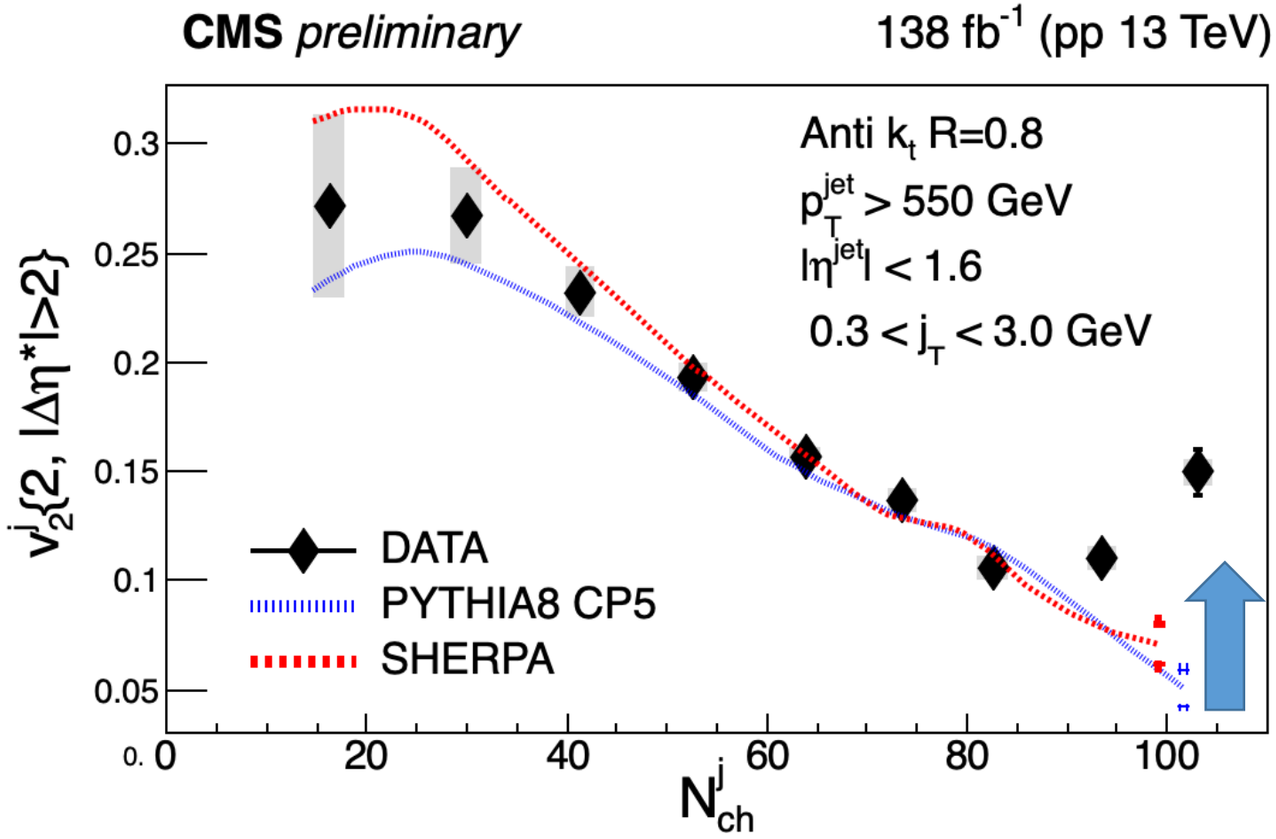


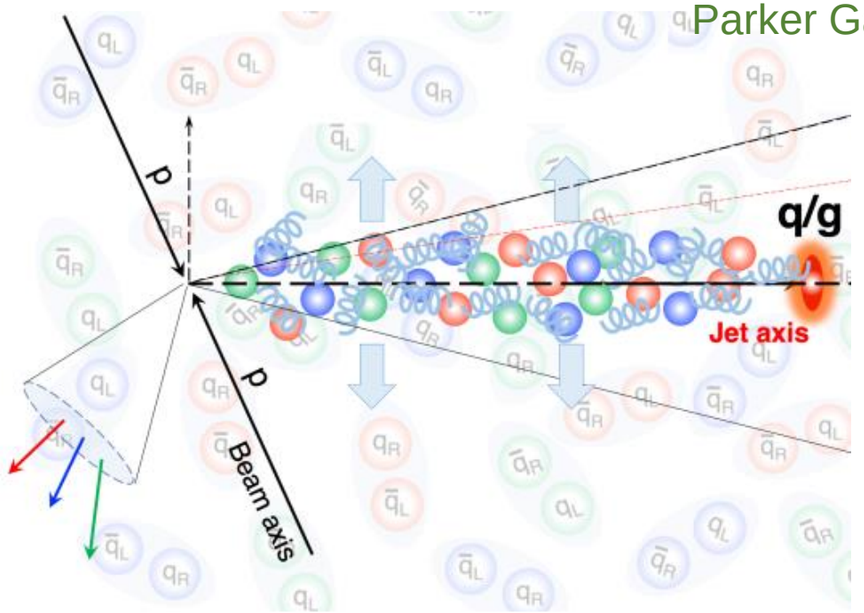


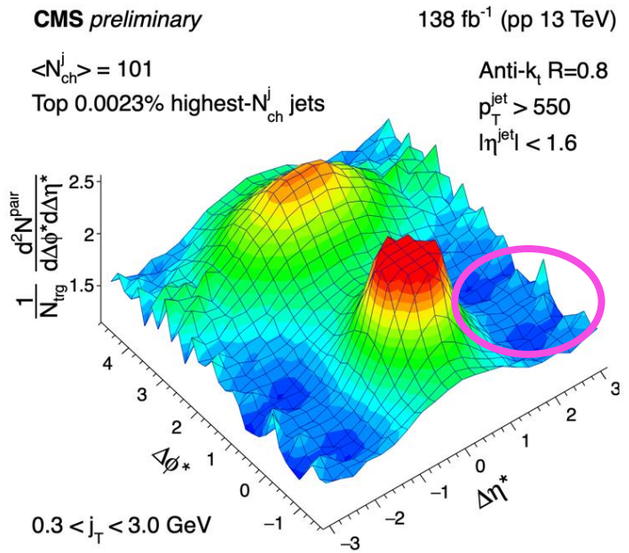
- N_{ch} < 90: **PYTHIA8** and **SHERPA** can effectively describe the data.

Single High Multiplicity Jet

Parker Gardner (Rice)

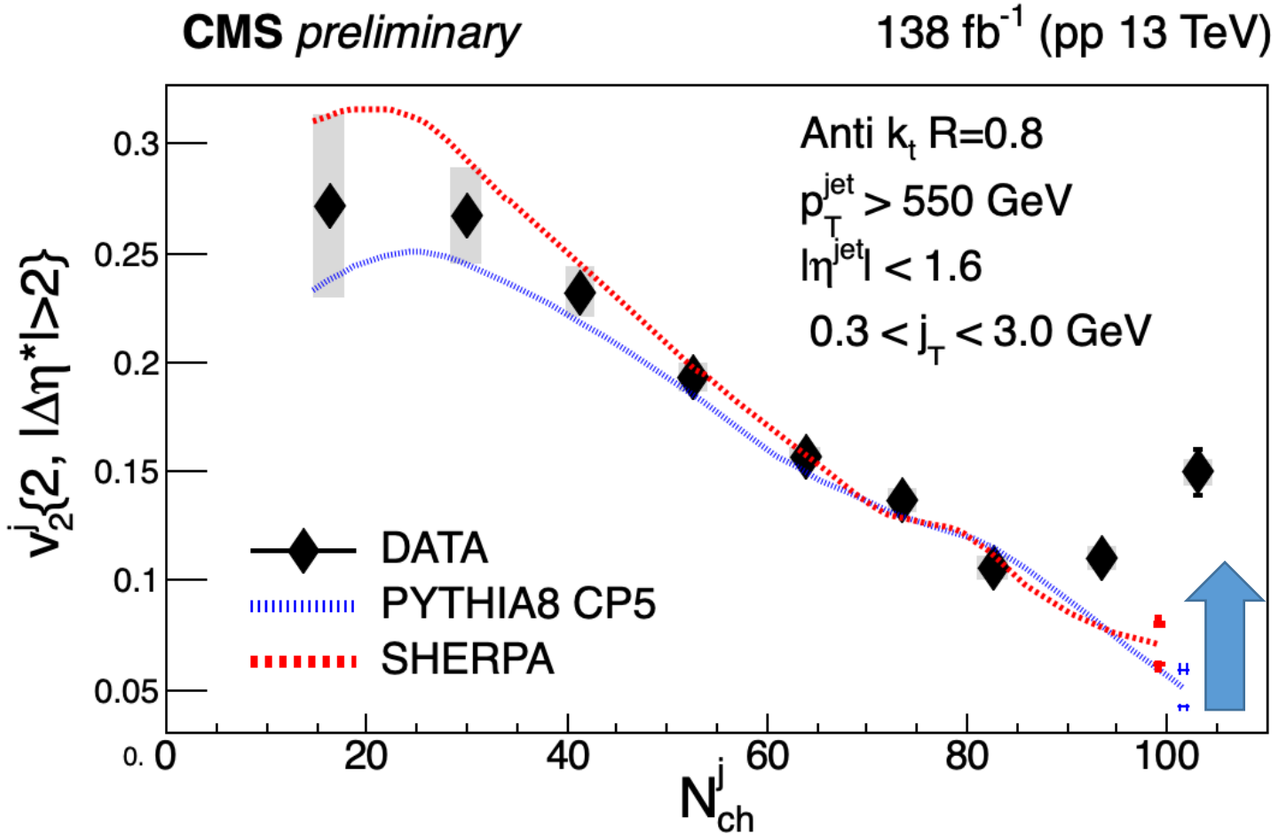


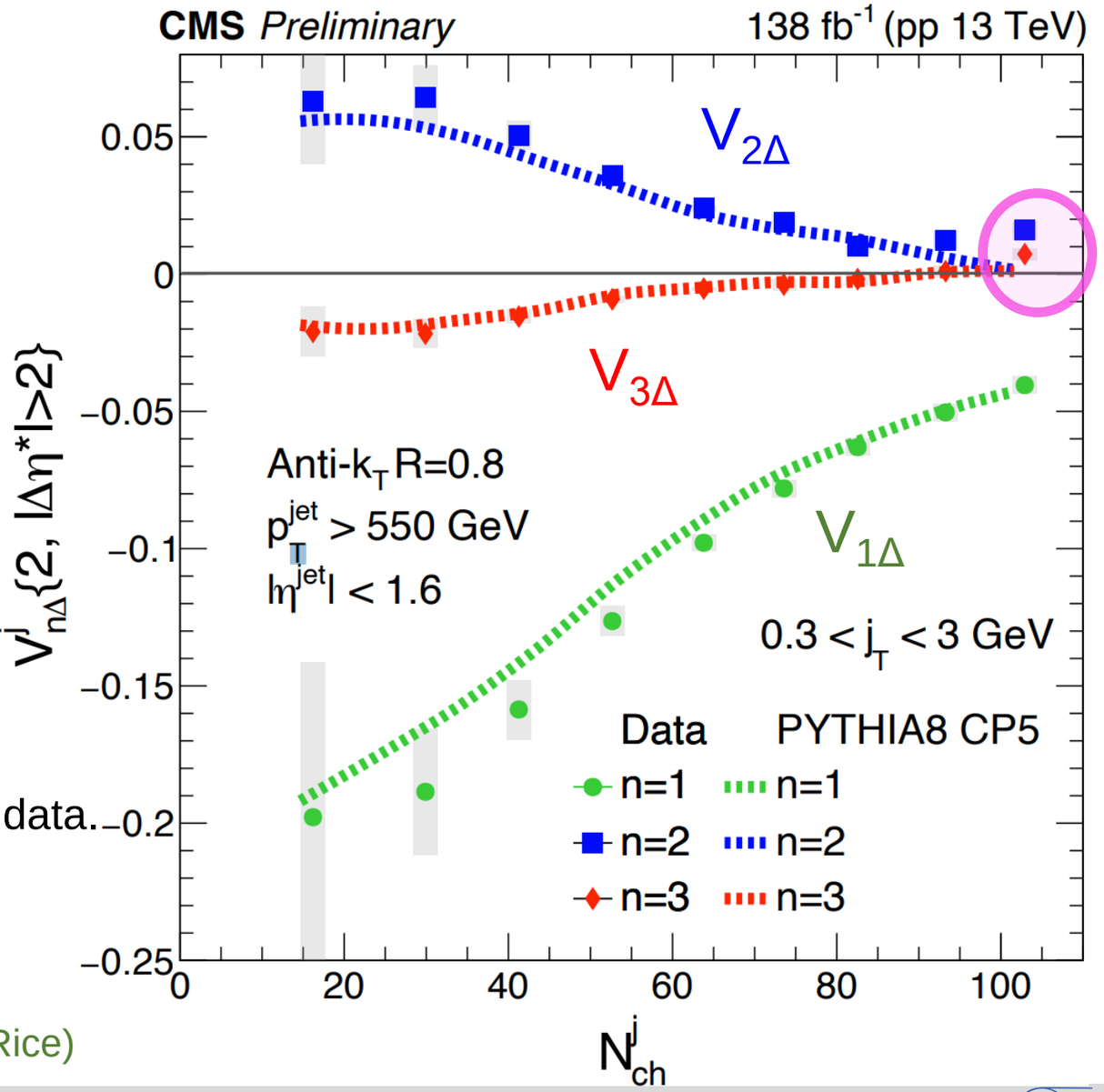




- N_{ch} < 90: **PYTHIA8** and **SHERPA** can effectively describe the data.
- At high multiplicity (N_{ch} > 90), the data v_2 deviates from the decreasing trend observed in the MC

Single High Multiplicity Jet





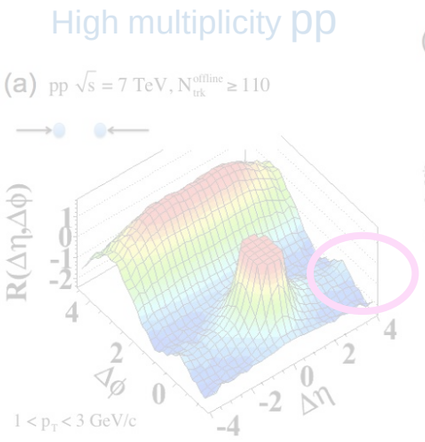
- N_{ch} < 90, **PYTHIA8** and **SHERPA** can effectively describe the data.
- At high multiplicity (N_{ch} > 90), the data v_2 deviates from the decreasing trend observed in the MC
- **v_3** become **positive** in data

Parker Gardner (Rice)

(1) High Multiplicity Event with Single String Configuration

Increase the MPI

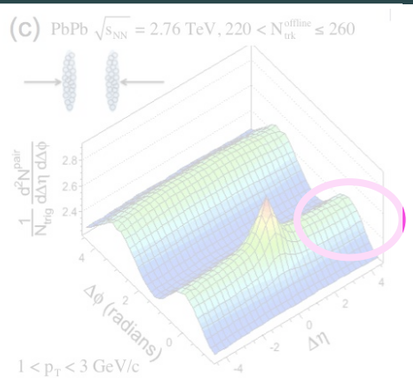
High multiplicity pp



~ O(1fm)

High multiplicity pPb

≥ O(1fm)



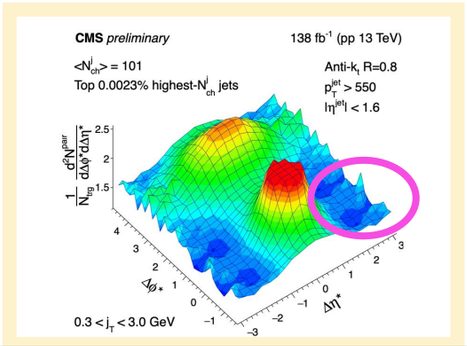
O(1-10 fm)

Large MPI

Photoproduction:

MPI ≥ 1

"MPI"=1



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

Increase multiplicity

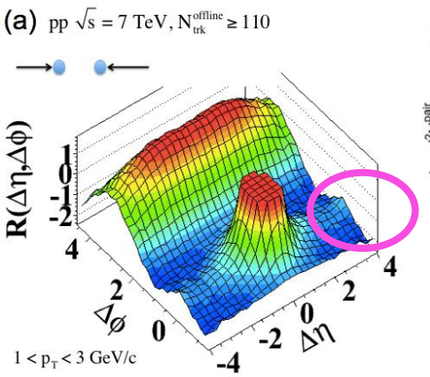
(2) Look into Events with Larger <MPI>

Increase the MPI

Low multiplicity pp

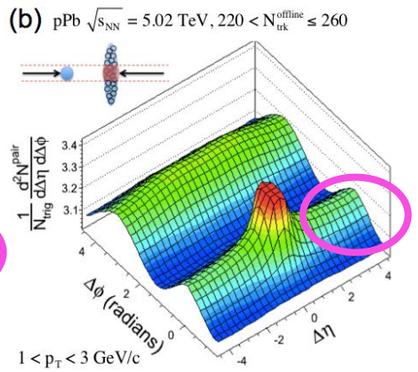
MPI>1

High multiplicity pp

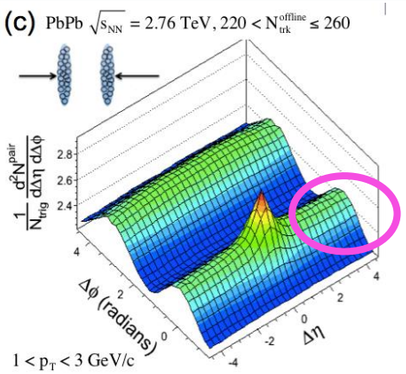


~ O(1fm)

High multiplicity pPb



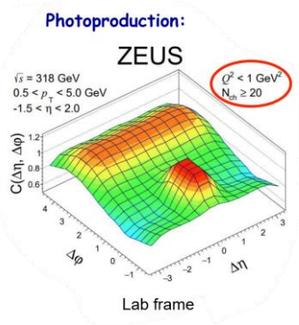
≥ O(1fm)

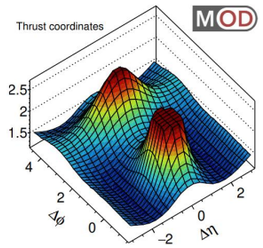


O(1-10 fm)

Large MPI

gamma Pb

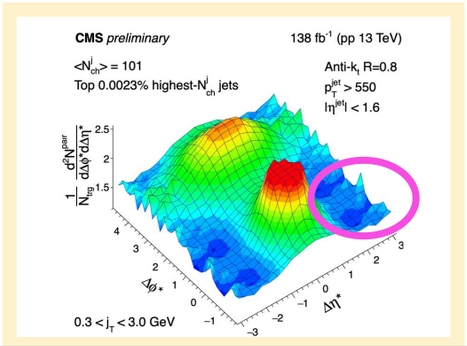




MPI ≥ 1

“MPI”=1

Larger MPI than γp

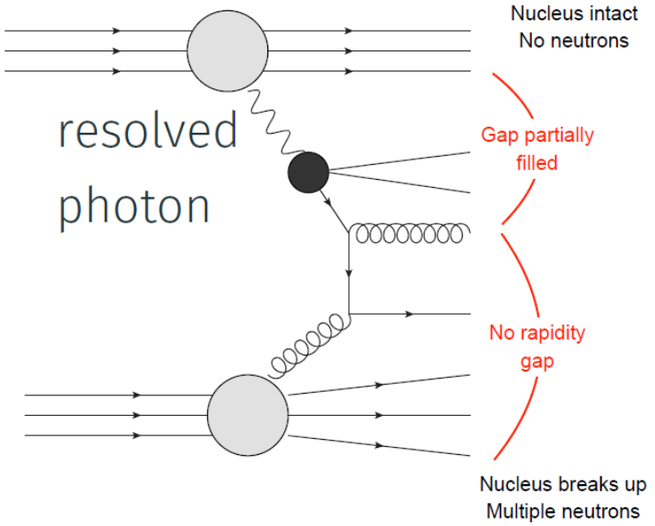


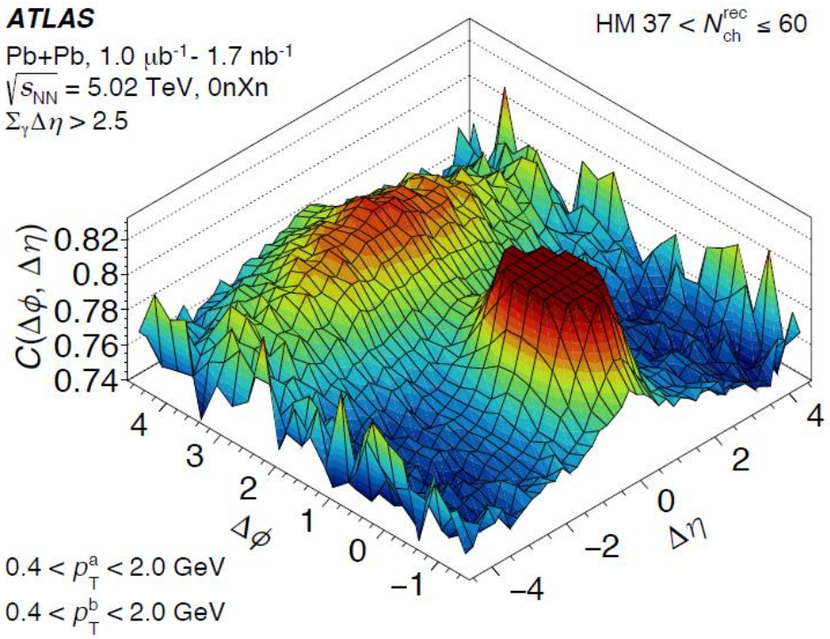
A single string configuration can generate a ridge-like structure at high multiplicity

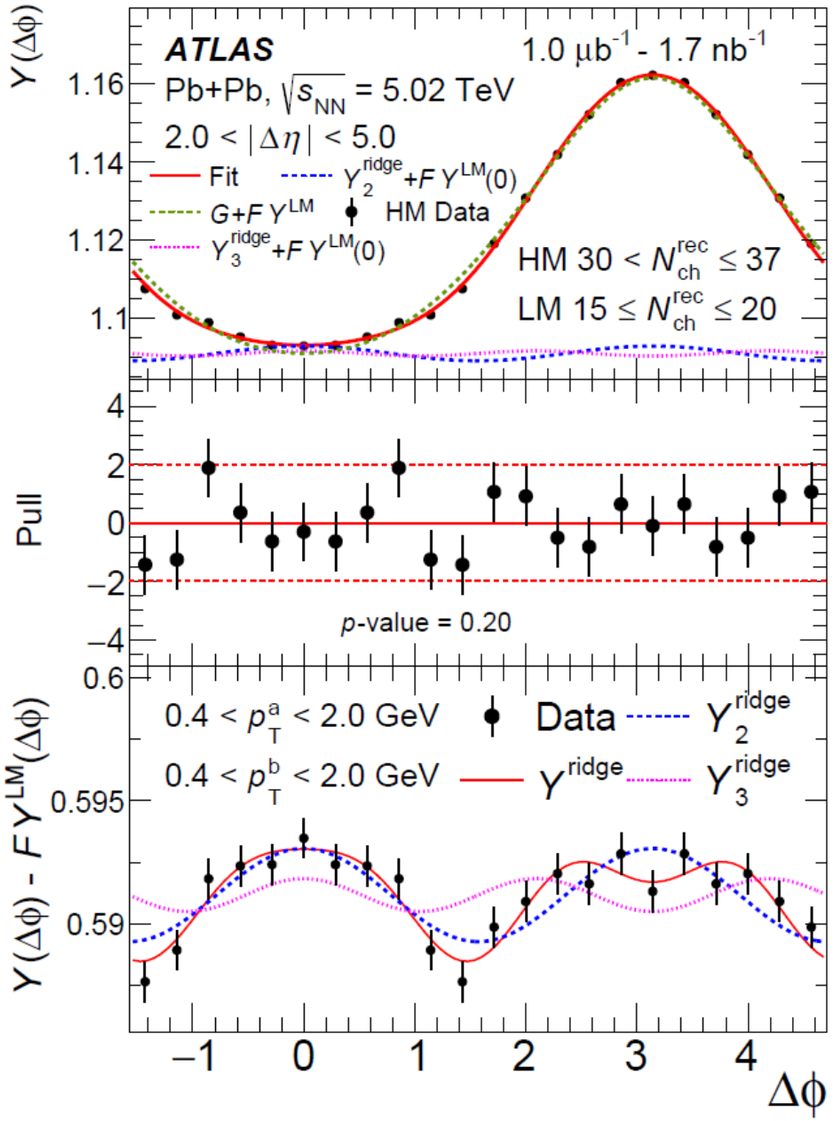
Increase multiplicity

Photonuclear Collisions with PbPb UPC at the LHC

Photonuclear collision enriched sample

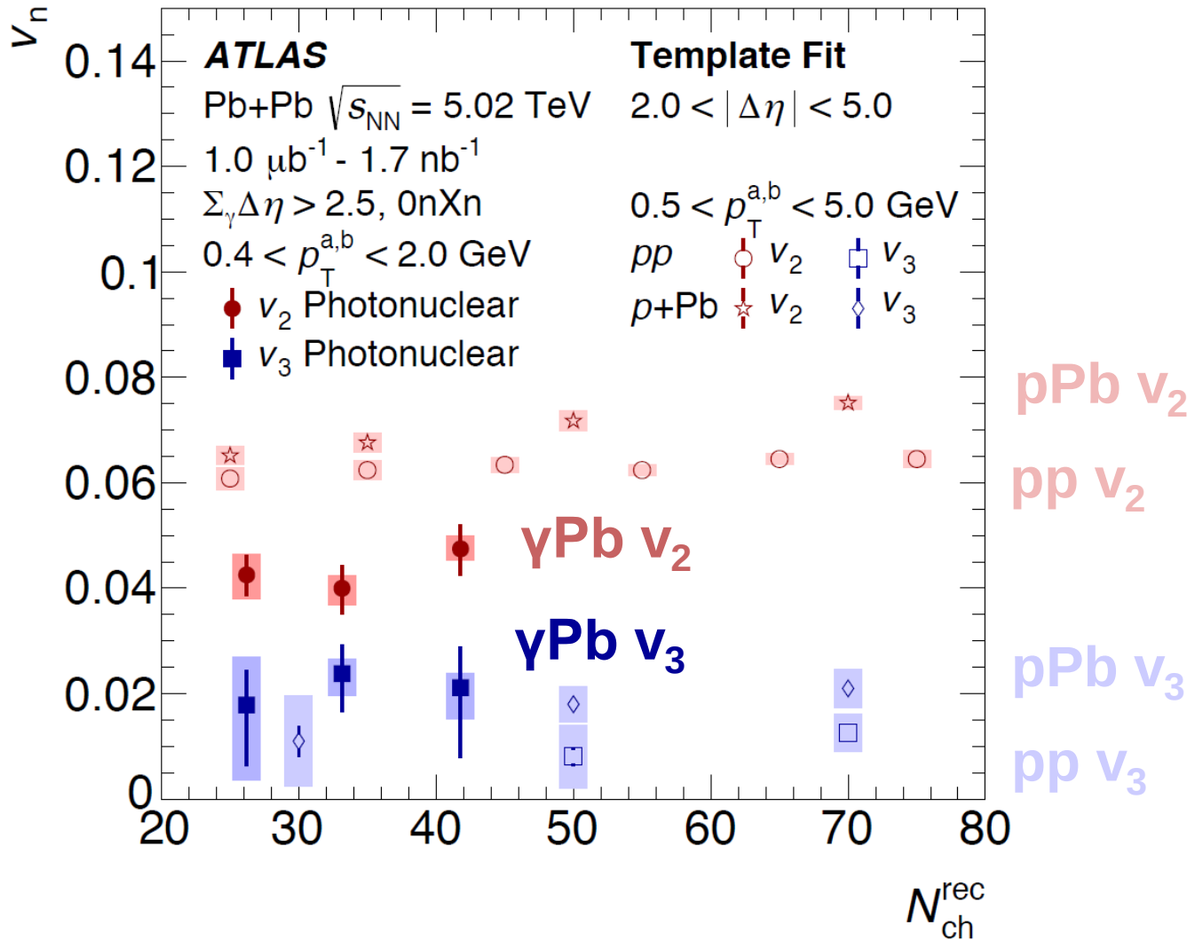




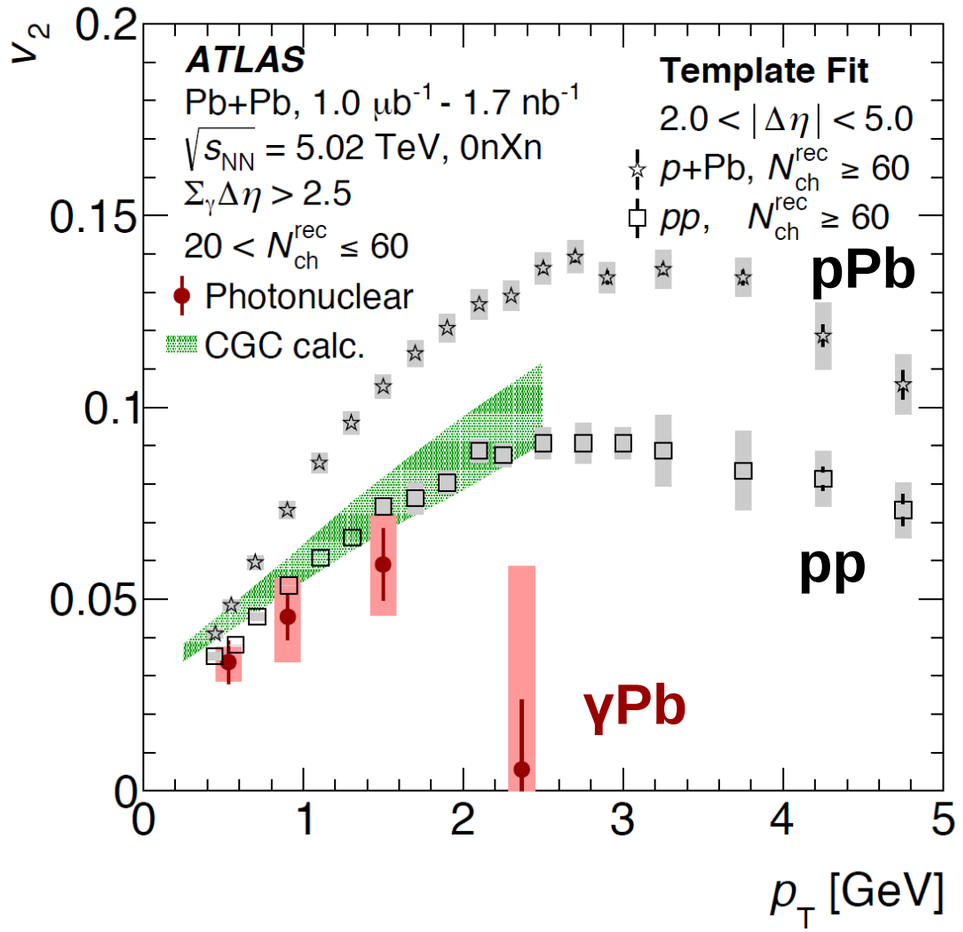


- No ridge-like signal in the correlation function up to N_{ch} = 60,
- ATLAS observed a flow-like modulation through low-multiplicity event subtraction (**90%** amplitude subtracted)

v_2 and v_3 after Low Multiplicity Event Subtraction

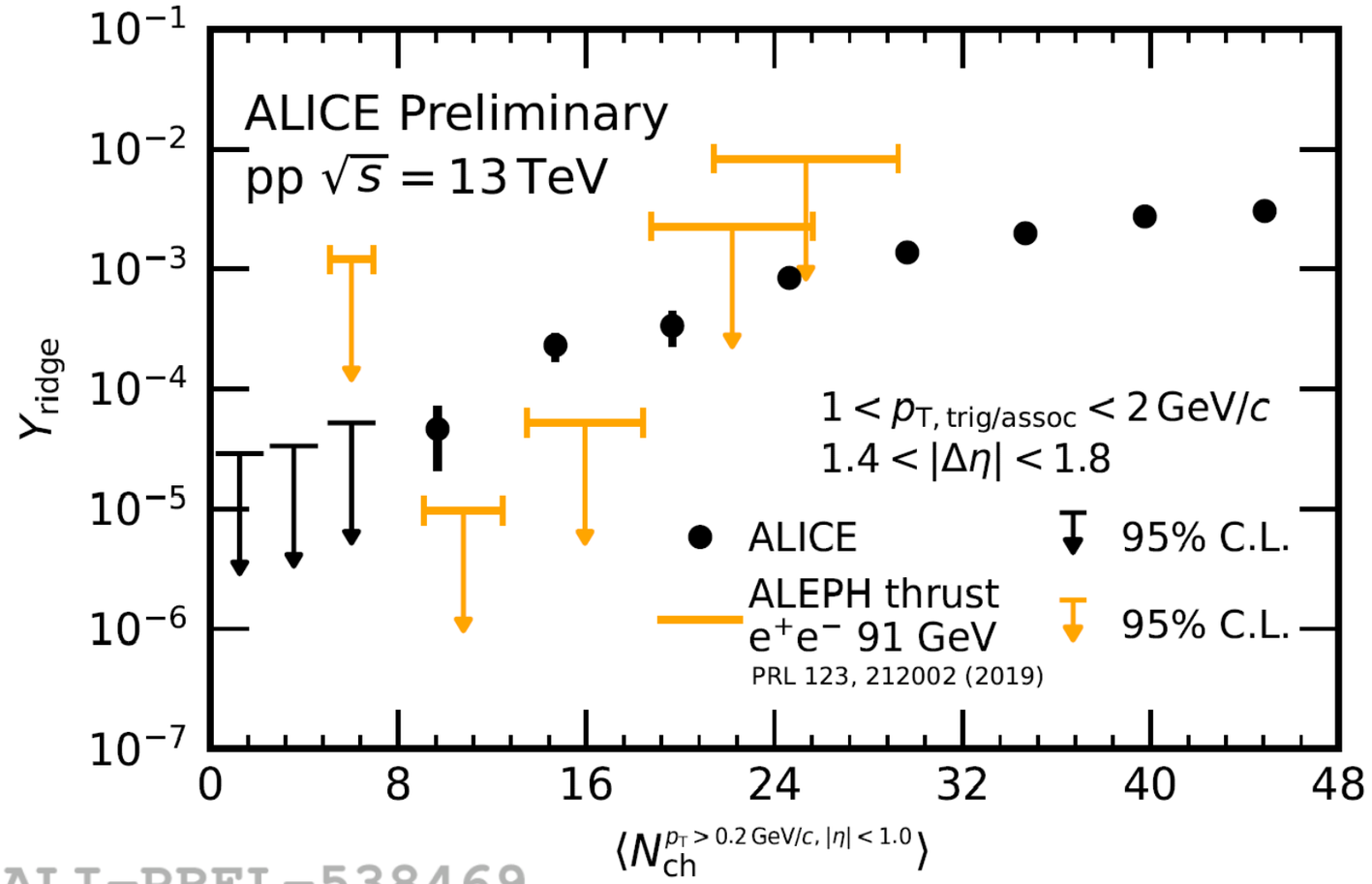


- **Positive v_2** and **v_3** after subtraction with lower multiplicity events
- Largely independent of N_{ch}

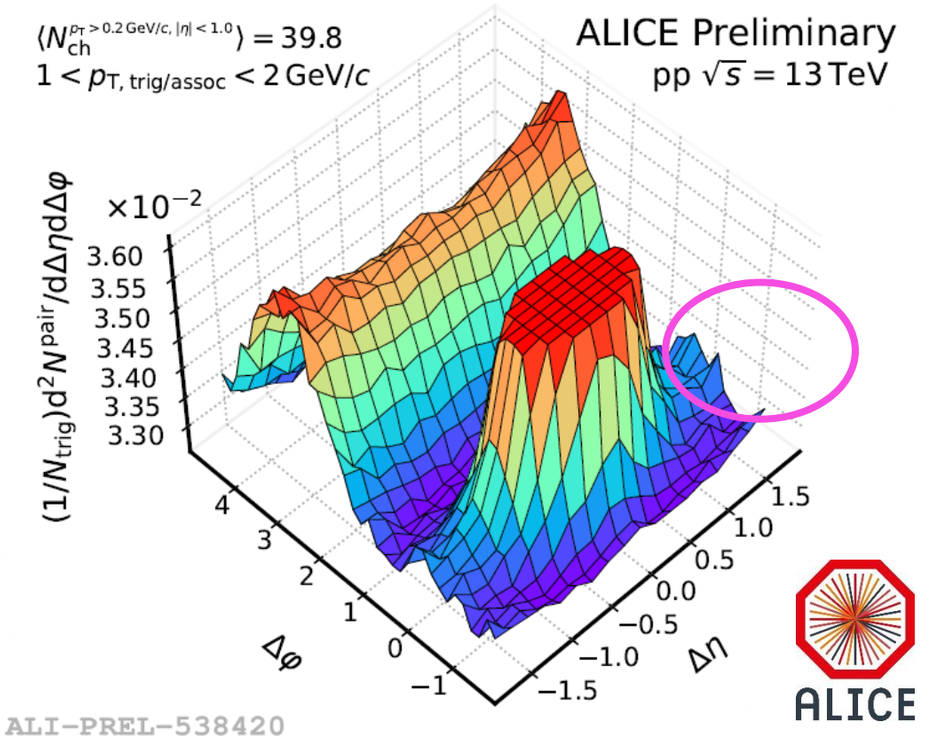


- Smaller v_2 in **γPb** compared to **pPb** and **pp**
- Initial state effect of Pb could be relevant

Even Higher <MPI>: Minimum-Bias pp Events



No subtraction



- 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