Investigation of Flow-Like Signals in e^+e^- Collisions Using Jets, Two- and Multi-Particle Correlations

Yen-Jie Lee

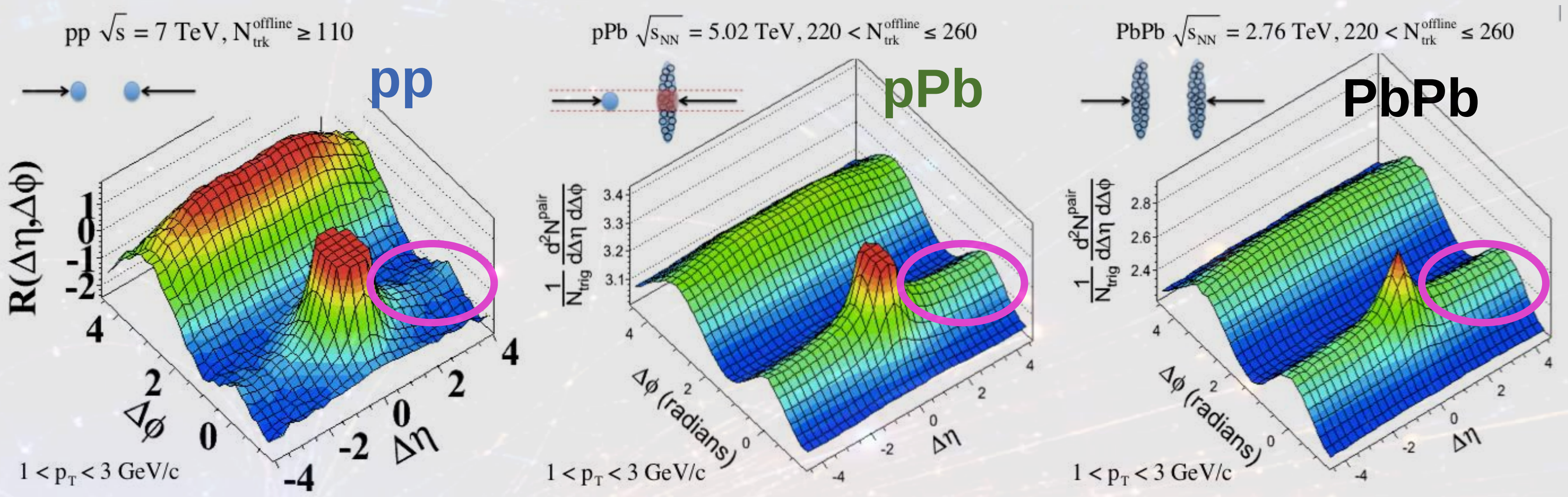
5th International Workshop on Emergent QCD Collectivity Across Scales: From Small System Collisions to Jets

Rice Global Paris Center, Paris, France

June 30, 2026

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

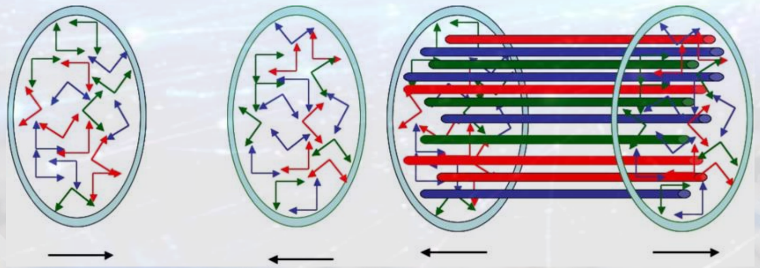
Interpretation of the Ridge Signal



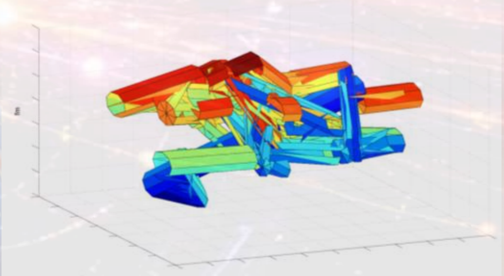
The origin may not be hydrodynamics, possible explanations include:

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

- Initial state effect (e.g. CGC)

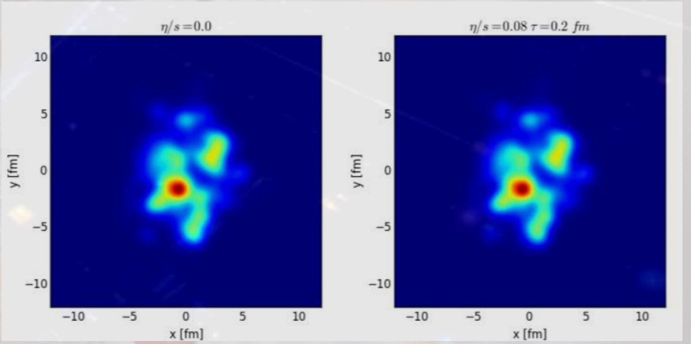


Overlapping strings in PYTHIA



- Escape mechanism / Single or few scatterings (AMPT, PYTHIA with Rope Mechanism, Multi-parton rescattering…)

Zi-Wei Lin's talk



- Final state effect due to mini-QGP production
- …

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 do not carry hadronic PDFs or beam remnants

- 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?

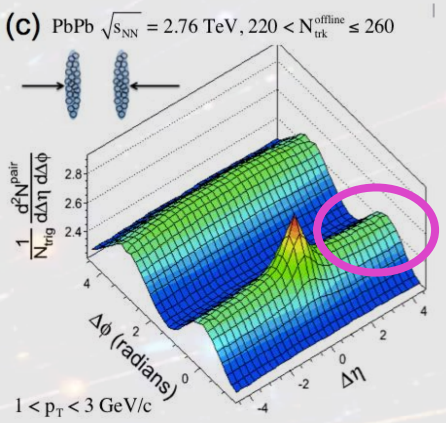
  Collect data across systems and compare systematically

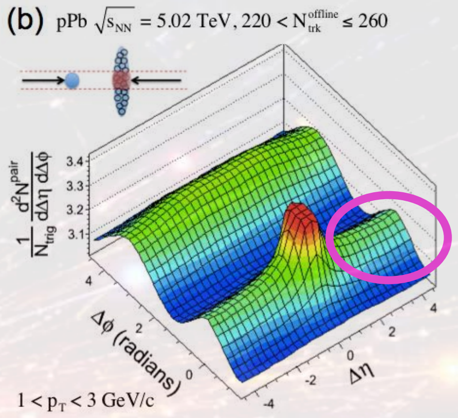
- …

Smallest System: e^+e^-

“Transverse Size” / MPI

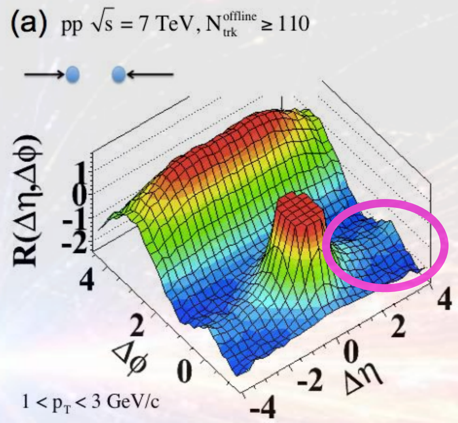
High multiplicity pPb





O(1-10 fm)

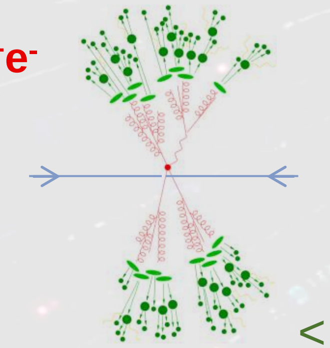
High multiplicity pp



≥ O(1fm)

~ O(1fm)

e^+e^-



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

< 0.1 fm

Multiplicity

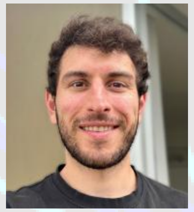
Electron-Positron Alliance


Janice Chen
(MIT)


Austin Baty
(UIC)

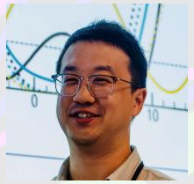

Chris McGinn
(MIT)


Michael Peters
(MIT)


Anthony Badea
(UChicago)


Paoti Chang
(NTU)


Cen Mo
(SJTU)


Yulei Zhang
U. Washington


Honey Khindri
(IIT Madras)


Tzu-An Sheng
(MIT)

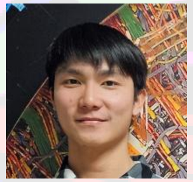

Ben Nachman
(Stanford/SLAC)

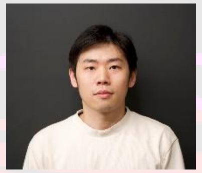

Yi Chen
(Vanderbilt)


Jingyu Zhang
(Vanderbilt)


Luke Lu
(Vanderbilt)

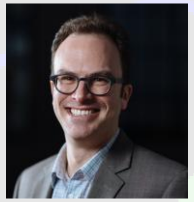

MJ Khan
(Vanderbilt)


Chen-Hua Hsu
(NTU)


Xiaoyuan Zhang
(MIT)


Hannah Bossi
(MIT)


Gian Innocenti
(MIT)

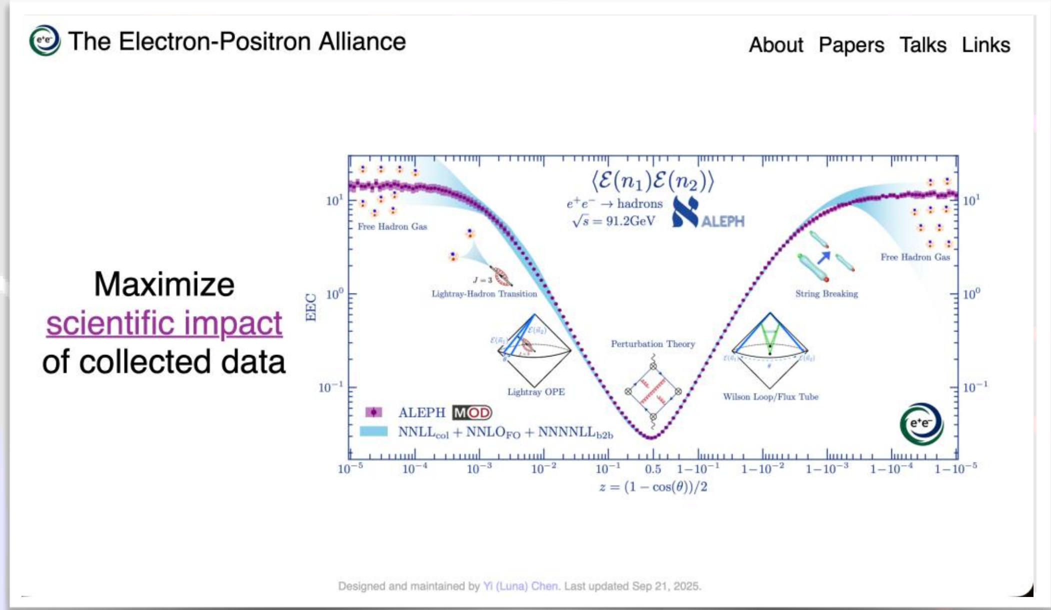

Jesse Thaler
(MIT)


Marcello Maggi
(INFN Bari)

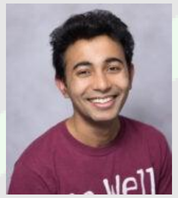

Günther Dissertori
(ETH Zürich)


Nishant Gaurav
(Vanderbilt)

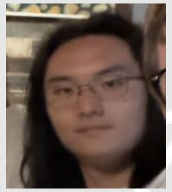

David d'Enterria
(CERN)




Yen-Jie Lee
(MIT)


Jeetendra Gupta
(UIC)

Sascha Diefenbacher
(LBNL)


Bill Zhou
(Vanderbilt)


Cristian Baldenegro
(MIT)


Ting-Hsiang Hsu
(NTU)


Prabhat Pujahari
(IIT Madras)

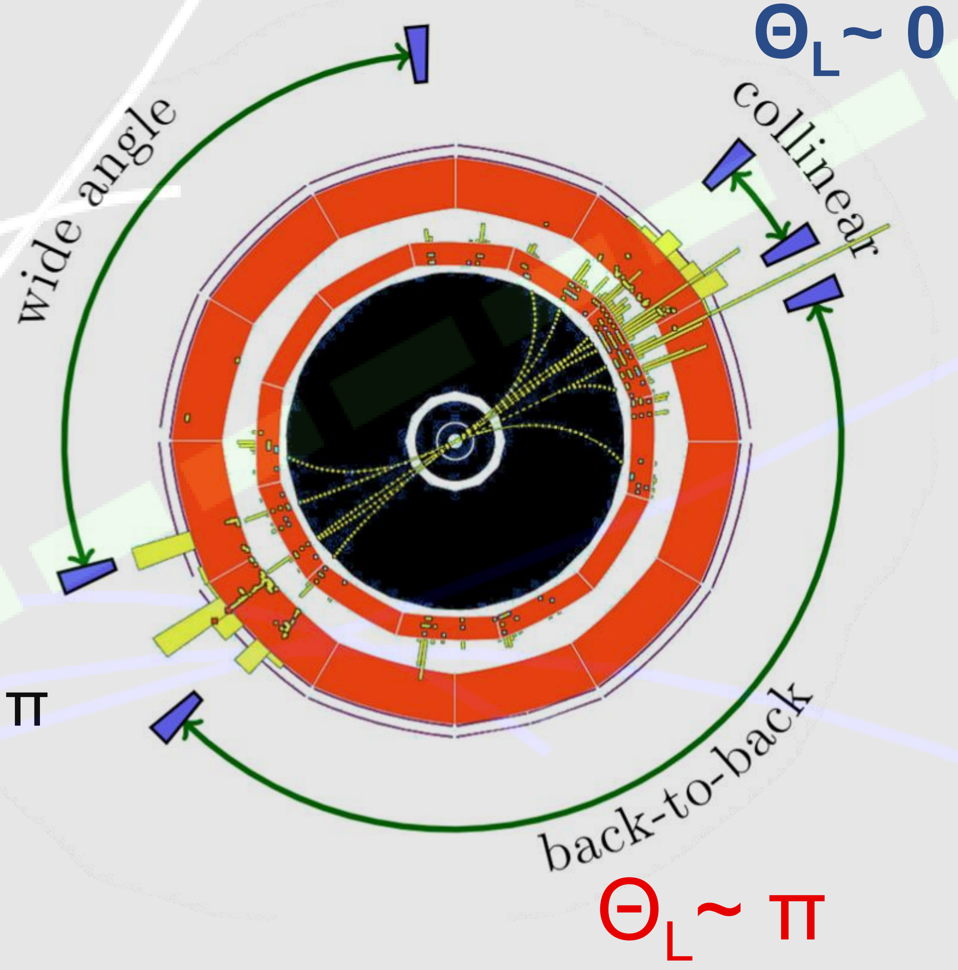
https://ee-alliance.org

Definition of Charged-Track EEC in e^+e^- Collisions

- No Jet reconstruction, Full event

$$\frac{1}{N_{event}} \frac{d(\sum E_i E_j / E^2)}{d\theta_L}$$

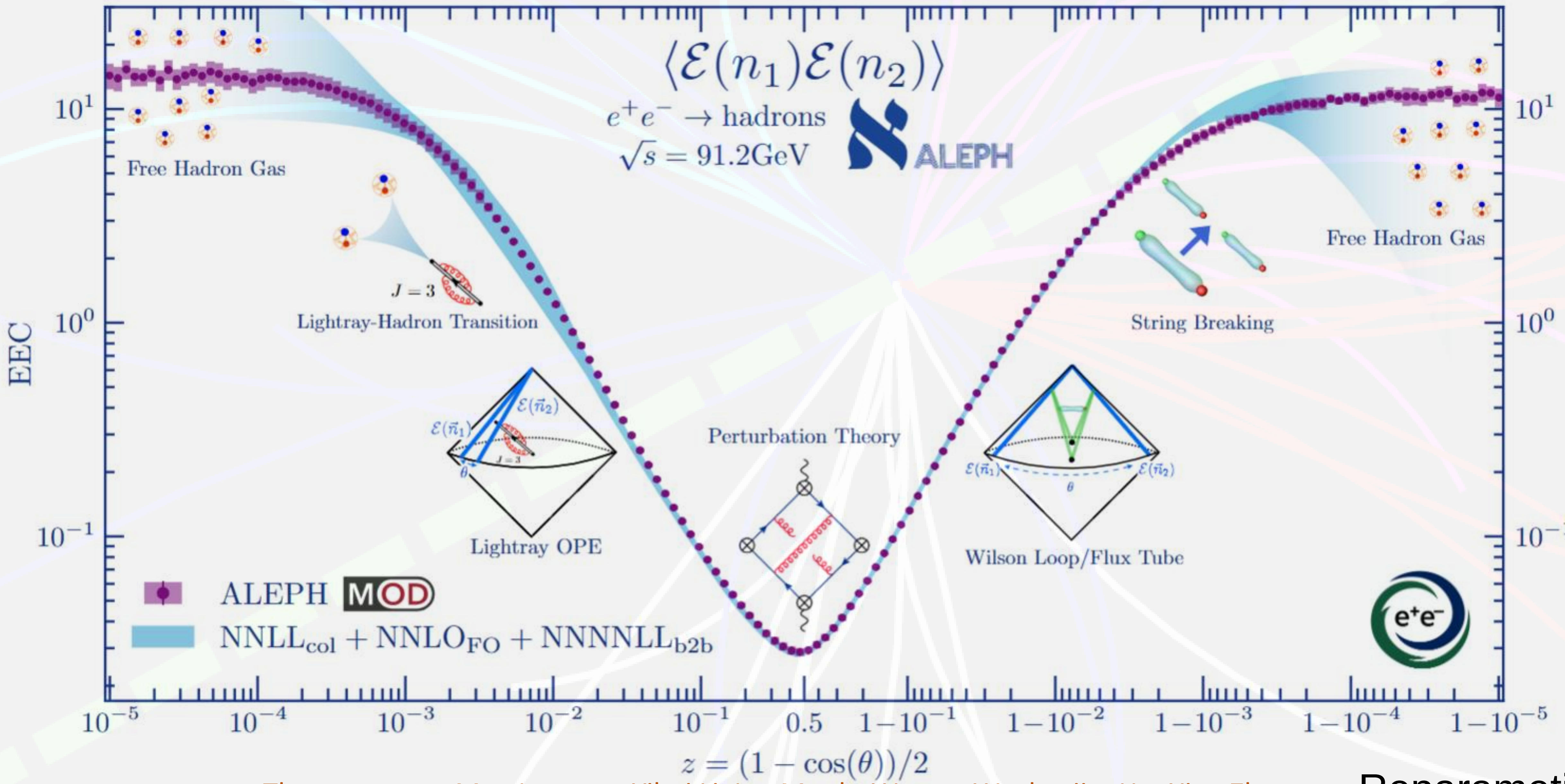
  - Sum over pairs of **charged particles** in the event
  - Normalize by total energy E in the event
    (91.2 GeV by definition in LEP1)
  - **Θ_L is the opening angle (in rad.)**
  - Observable naturally reaches the back-to-back region $\Theta_L \approx \pi$



- Back-to-back (**Sudakov Limit**)
  - At **$\Theta_L \sim \pi$**
  - Study correlations of the full set of particles, not just those within jets

- **Not possible to explore with jet substructure**
  - Presents a unique opportunity in e^+e^-!

Charged-Track EEC in e^+e^- vs. Theory



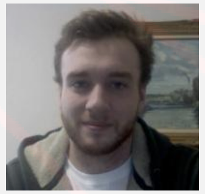
Theory curves: Max Jaarsma, Yibei Li, Ian Moult, Wouter Waalewijn, HuaXing Zhu

Electron-Positron Alliance arXiv:2511.00149

Hannah Bossi (MIT)

Yi Chen (Vanderbilt U.)

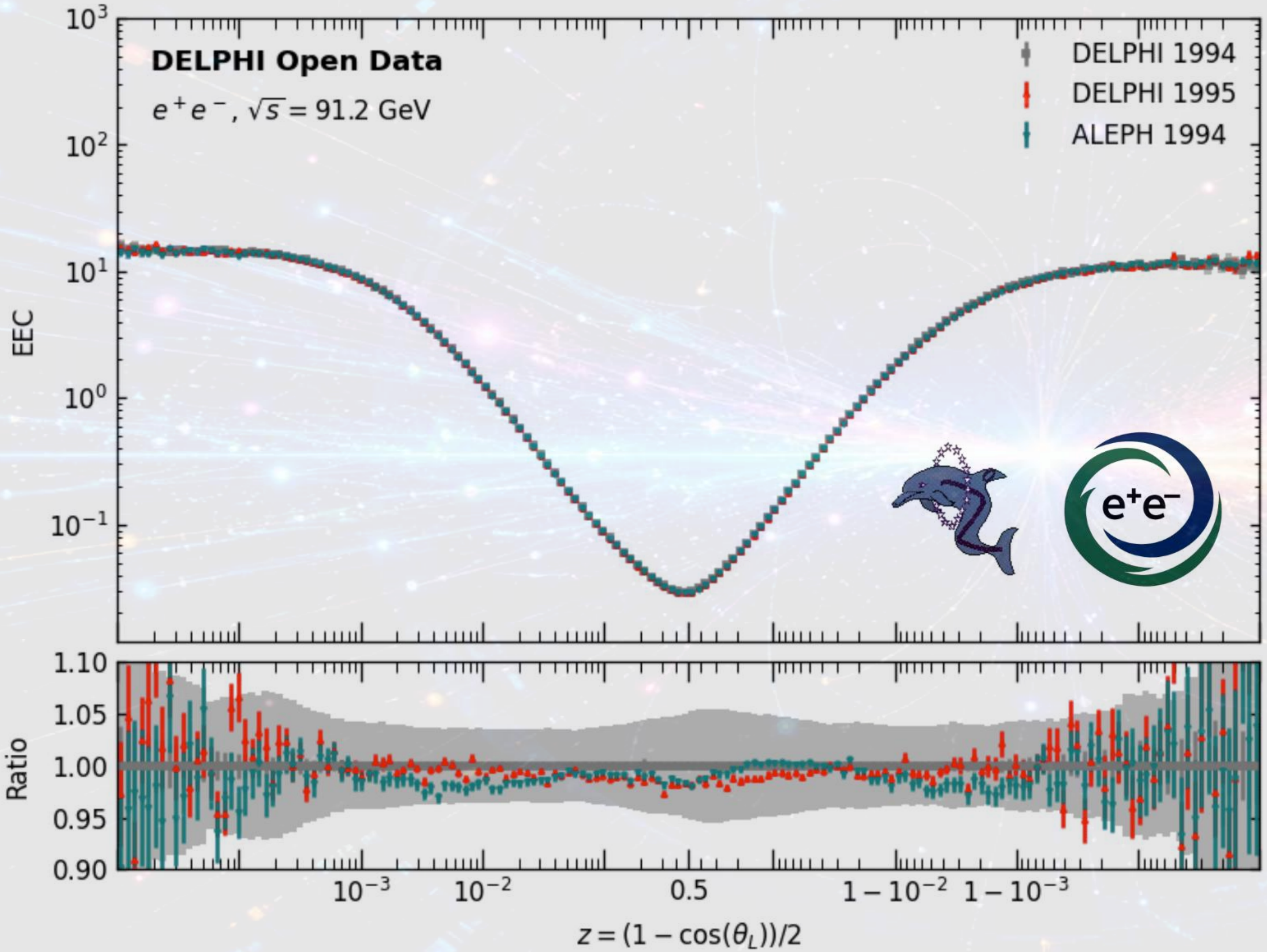
Yu-Chen "Janice" Chen (MIT)



Chris McGinn (MIT)

Reparametize θ to z=(1−cosθ)/2

Charged-Track EEC with DELPHI and ALEPH Data

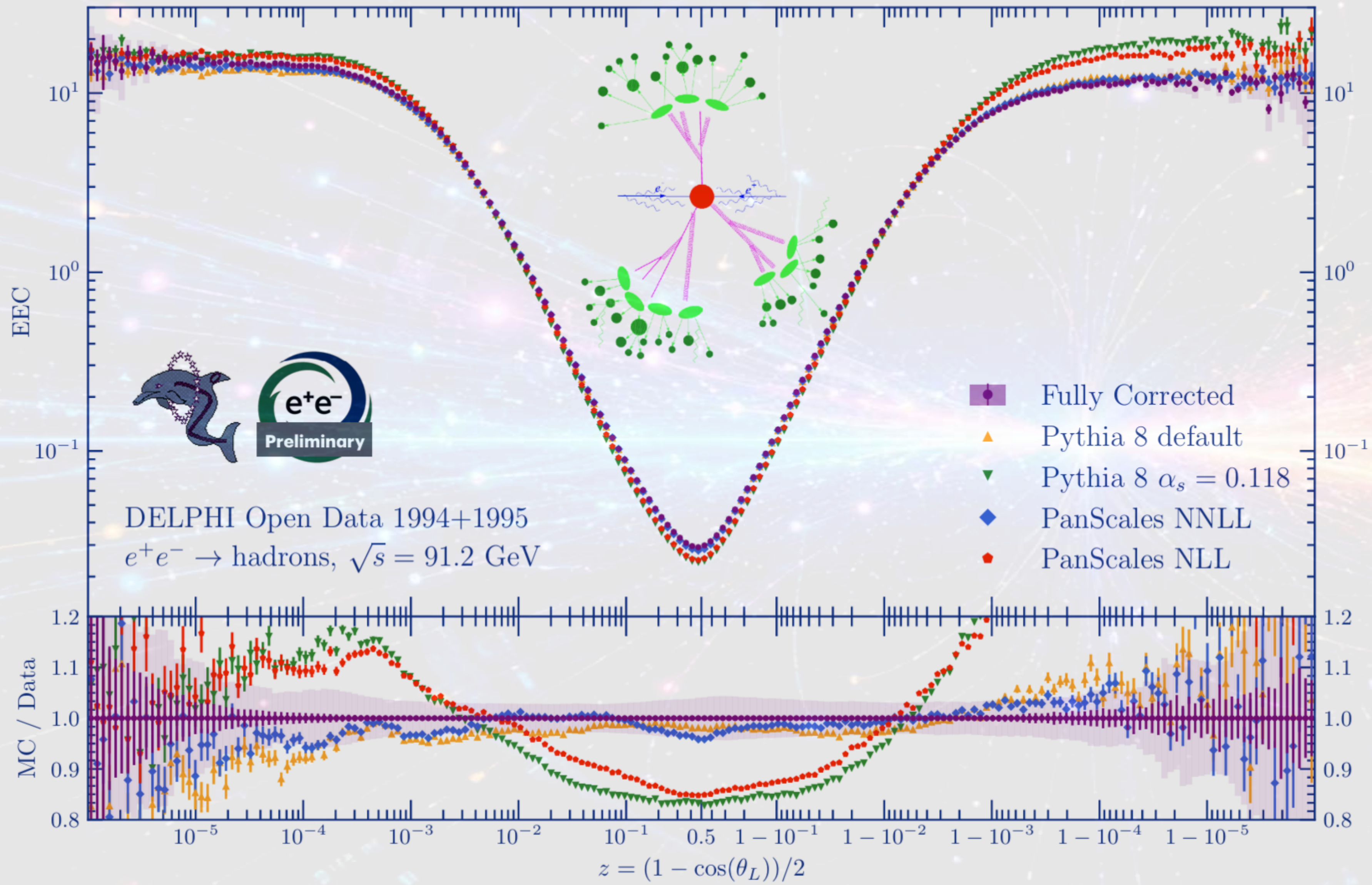


- Fully corrected **DELPHI** and **ALEPH** are in excellent agreement within a few percent.
- Power of the recycling frontier!!

Jingyu Zhang (Vanderbilt U.)

Electron-Positron Alliance
[DELPHI Analysis Note: arXiv:2510.18762]

Charged-Track EEC with DELPHI and ALEPH Data



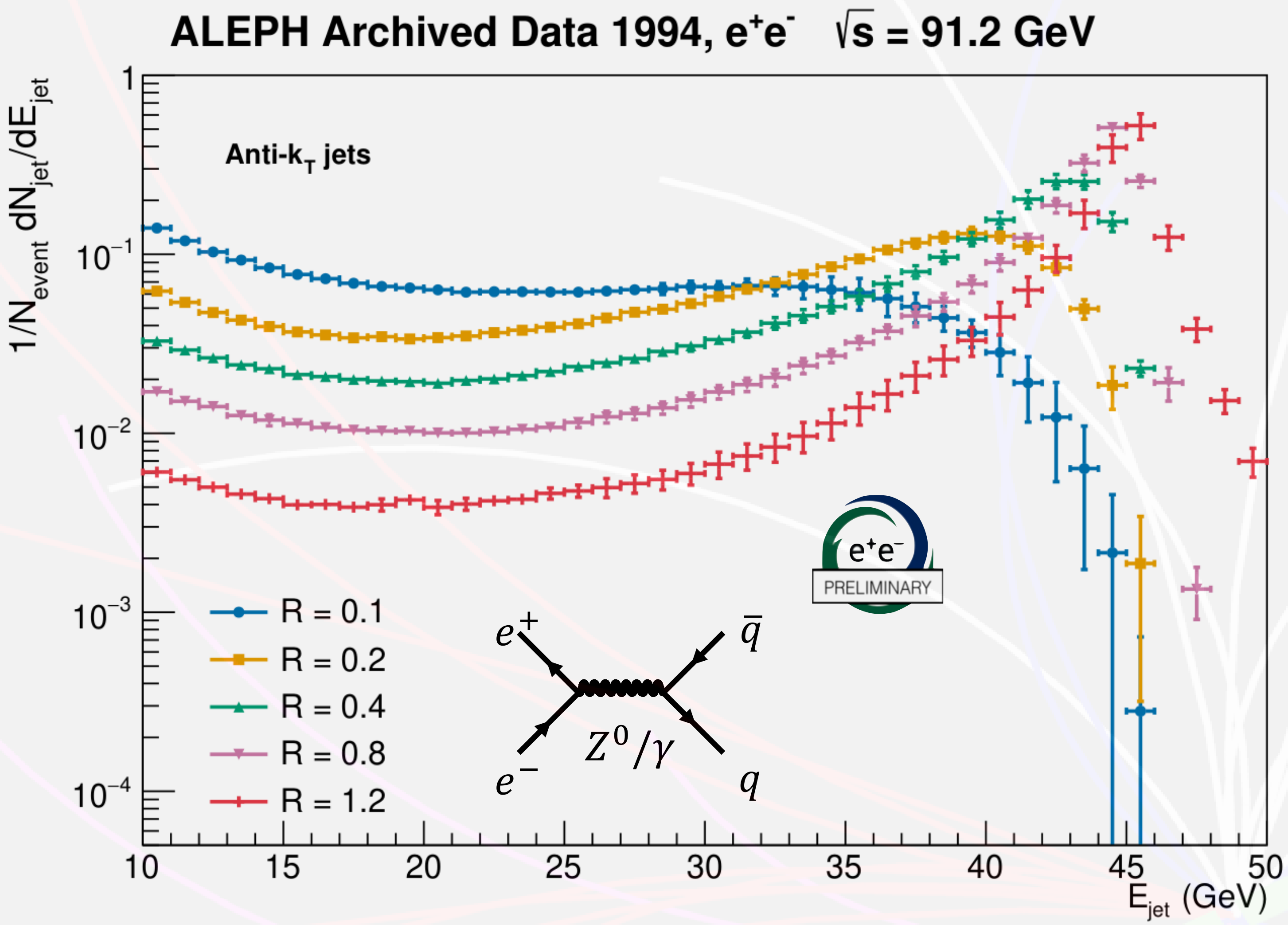
- Fully corrected **DELPHI** and **ALEPH** are in excellent agreement within a few percent.
- Power of the recycling frontier!!
- Results are better described by PanScales NNLL

Gavin Salam's talk

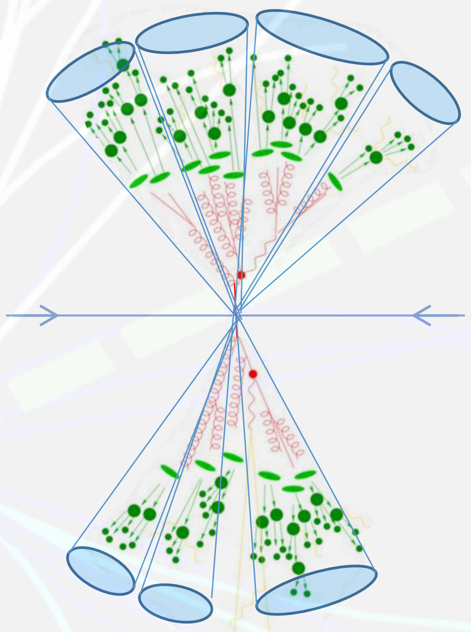
Jingyu Zhang (Vanderbilt U.)

Electron-Positron Alliance
[DELPHI Analysis Note: arXiv:2510.18762]

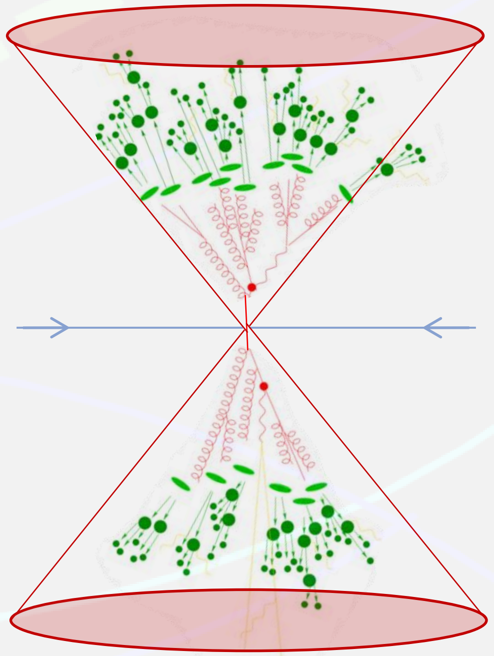
Inclusive Jet Spectra: Scanning the Parton Shower



- **New preliminary radius scan:** fully corrected energy spectra for R values from 0.1 to 1.2
- **Small R resolves the shower:** radiation is split into many narrow, lower-energy jets; the 45.6 GeV peak softens and moves to lower energy.
- **Large R captures the hemisphere:** radiation recombines into one jet near $E_{jet} \approx m_Z/2 \approx 45.6$ GeV.



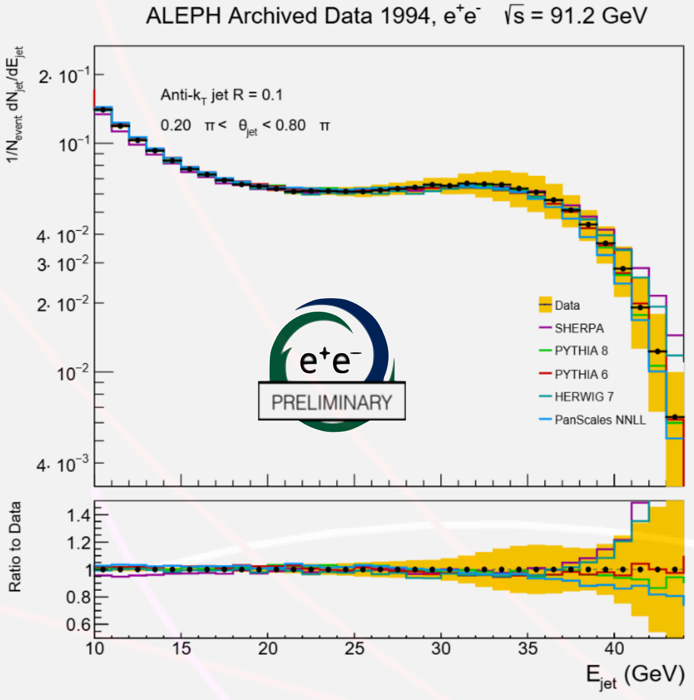
vs.



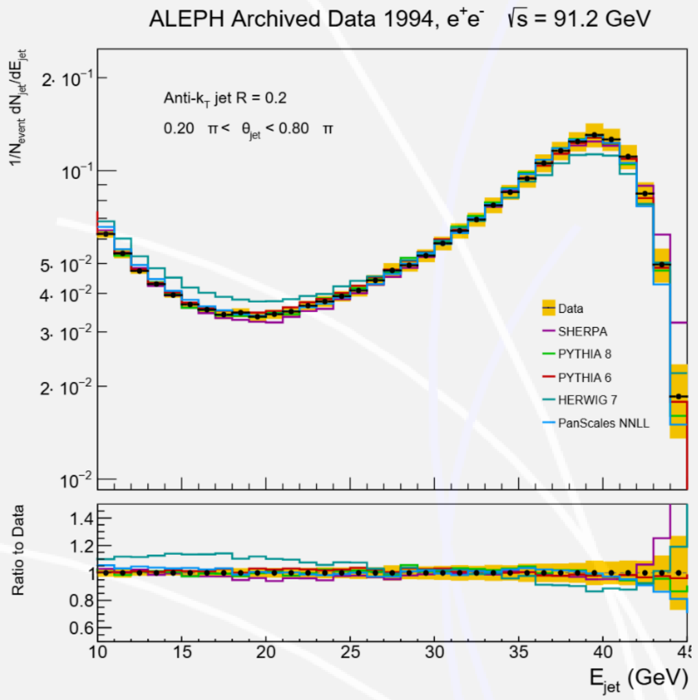
Bill Zhou (Vanderbilt)

R↓ resolves radiation → R↑ rebuilds the $m_Z/2$ peak

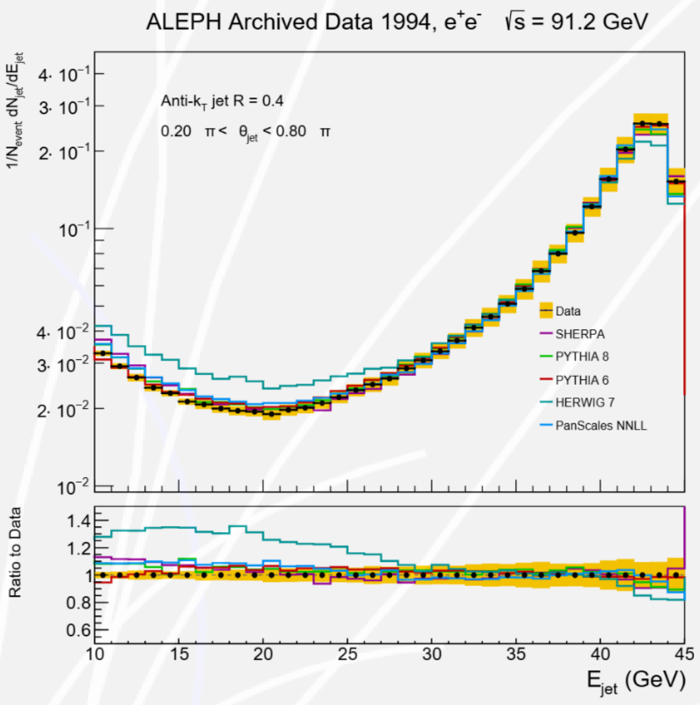
Inclusive Jet Spectrum vs. Jet Resolution Parameter



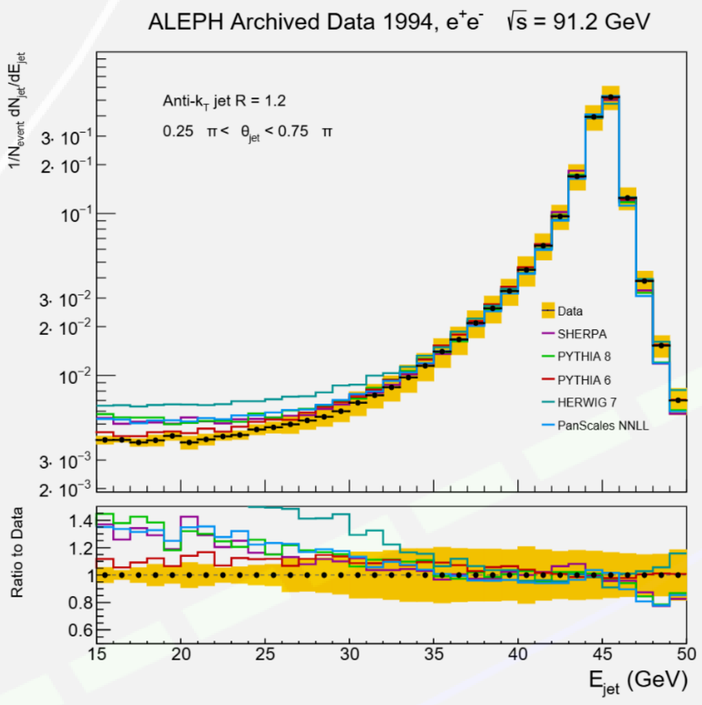
R = 0.1



R = 0.2

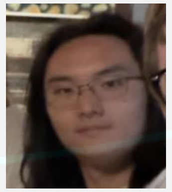


R = 0.4



R = 1.2

- Data compared to **PYTHIA6**, **PYTHIA8**, **SHERPA**, **HERWIG**, **and PanScales**
- Constrains both **parton shower evolution** and **hadronization modeling**
- **For R=1.2:** Data has **sharper peak** than predictions from event generators
- Most of the modern generators fail to describe the data

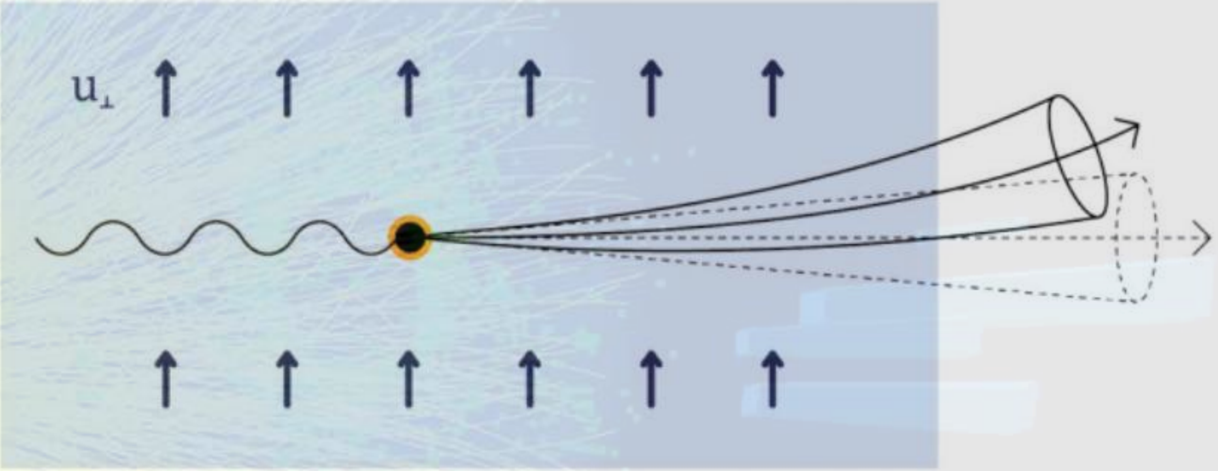


Bill Zhou
(Vanderbilt)

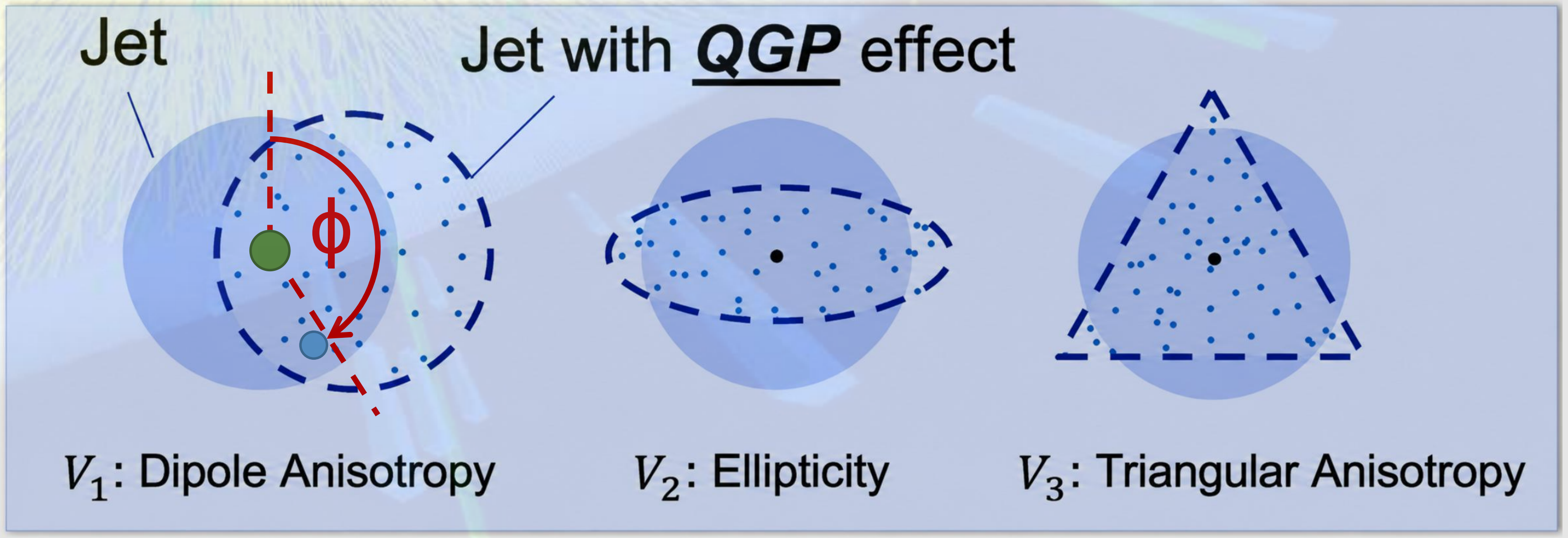
Data
SHERPA
PYTHIA 8
PYTHIA 6
HERWIG 7
PanScales NNLL

Jet Drift in e^+e^- and Heavy Ion Collisions

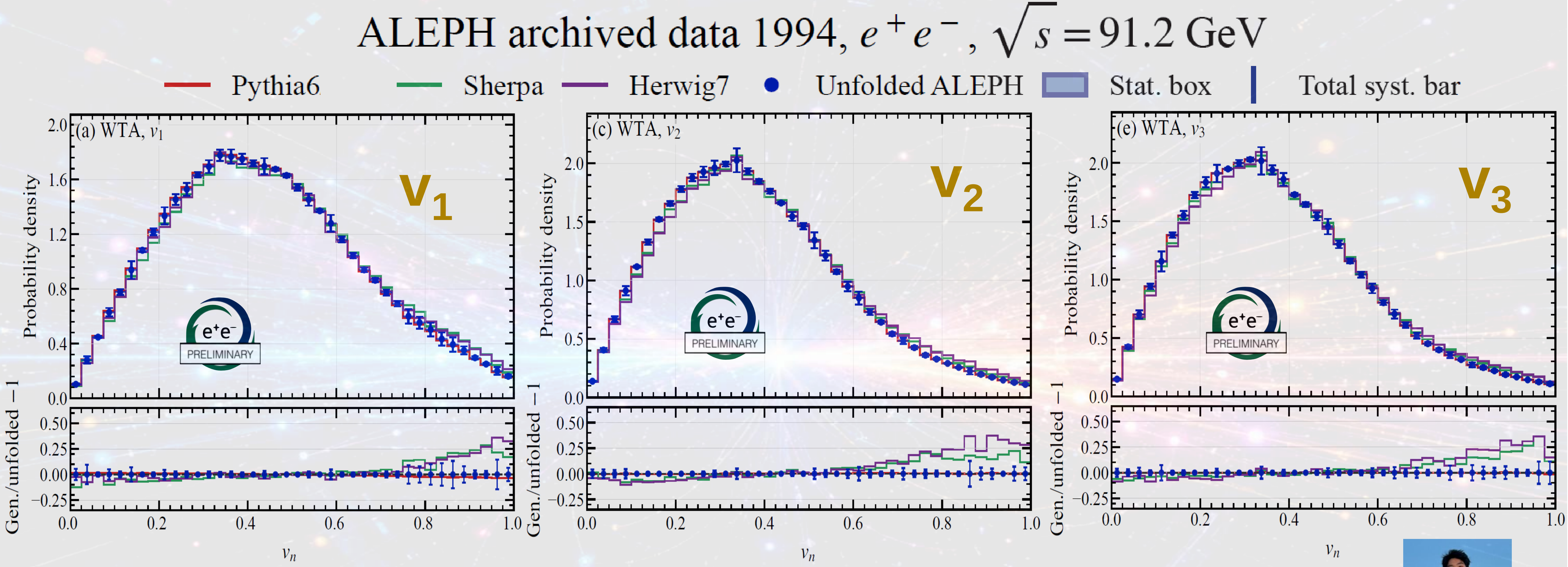
- In heavy ion collisions, jet drift is sensitive to jet-medium interaction
- Azimuthal angle measured around the jet WTA axis
- Quantify the azimuthal anisotropy with Fourier decomposition
- Establish a vacuum baseline with e^+e^- data



Luke Lu
(Vanderbilt)



Jet Drift in e^+e^- Collisions

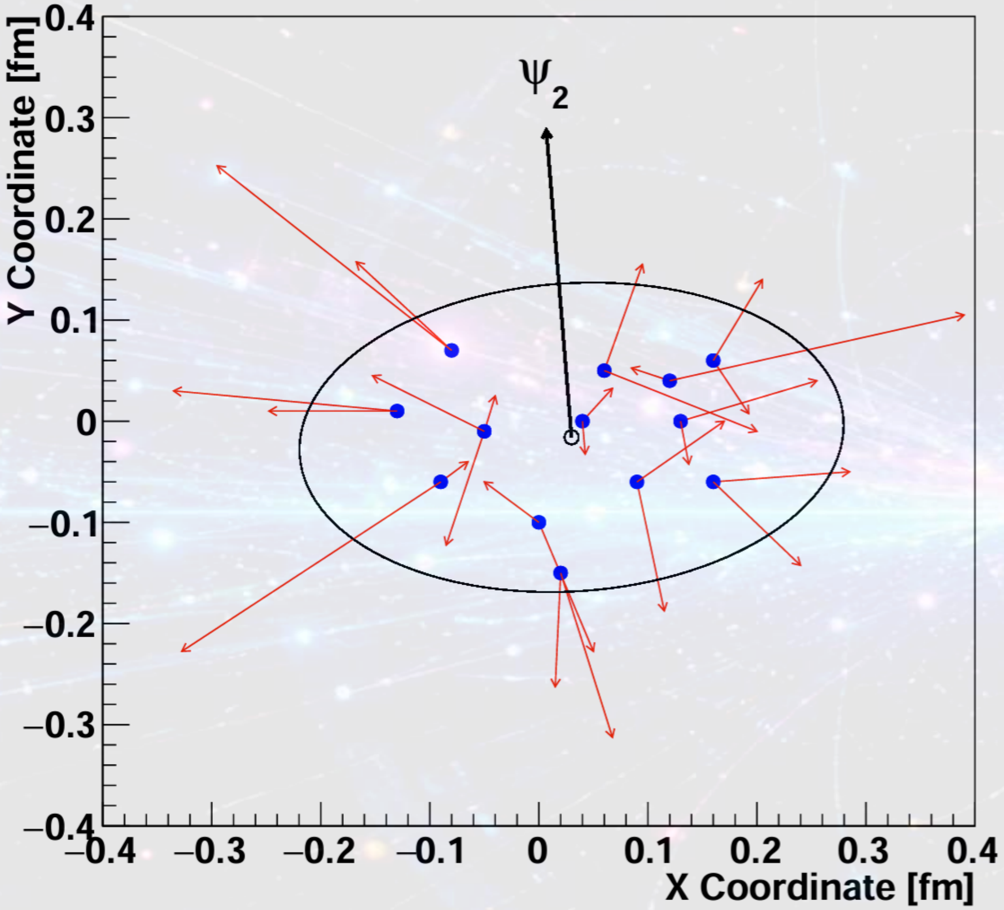


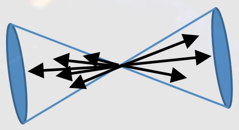
- **Nonzero v_1, v_2 and v_3** already in vacuum e^+e^- jets through vacuum showering, hadronization, and jet-axis response.
- **HERWIG7** and SHERPA over predict the anisotropy
- QGP signal must be additional deformation relative to the vacuum spectra

Luke Lu
(Vanderbilt)
Poster

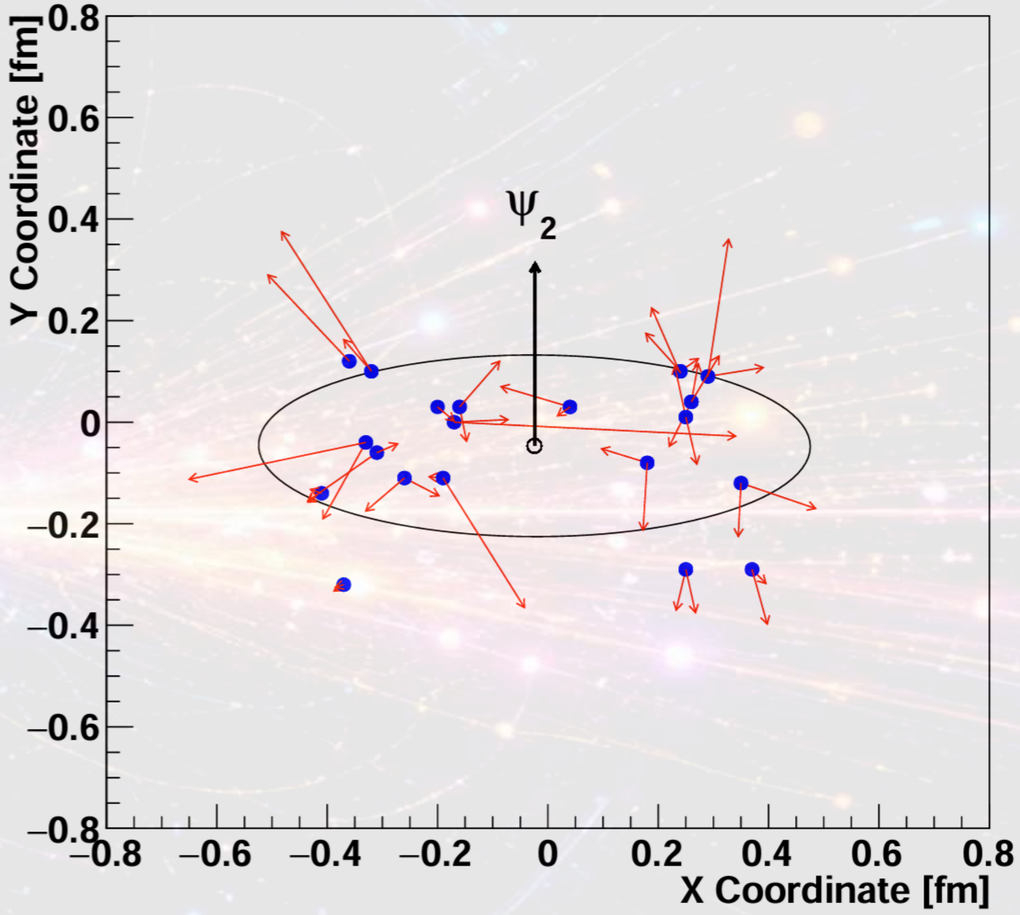
e^+e^- Study with AMPT (A Multi-Phase Transport Model)

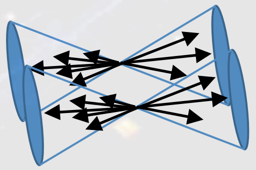
Single-String Configuration





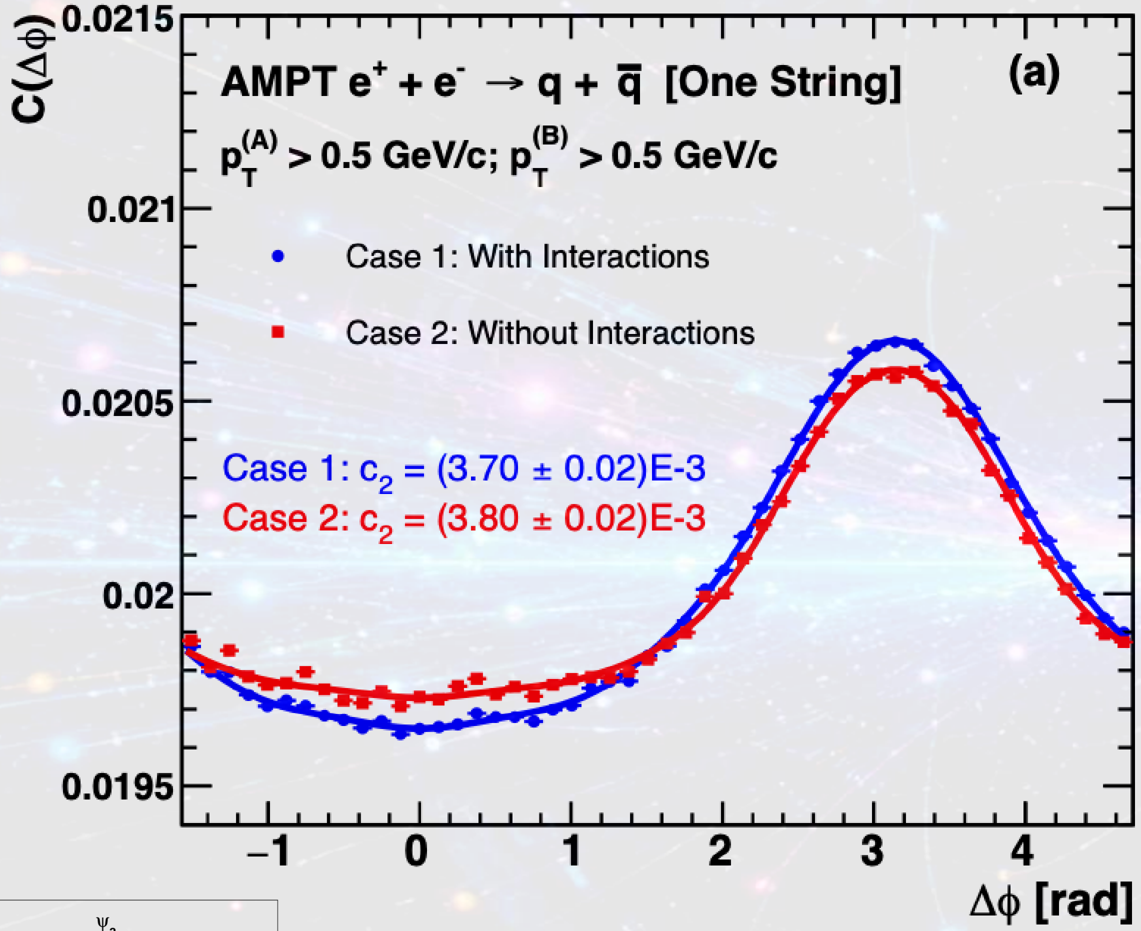
Two-String Configuration

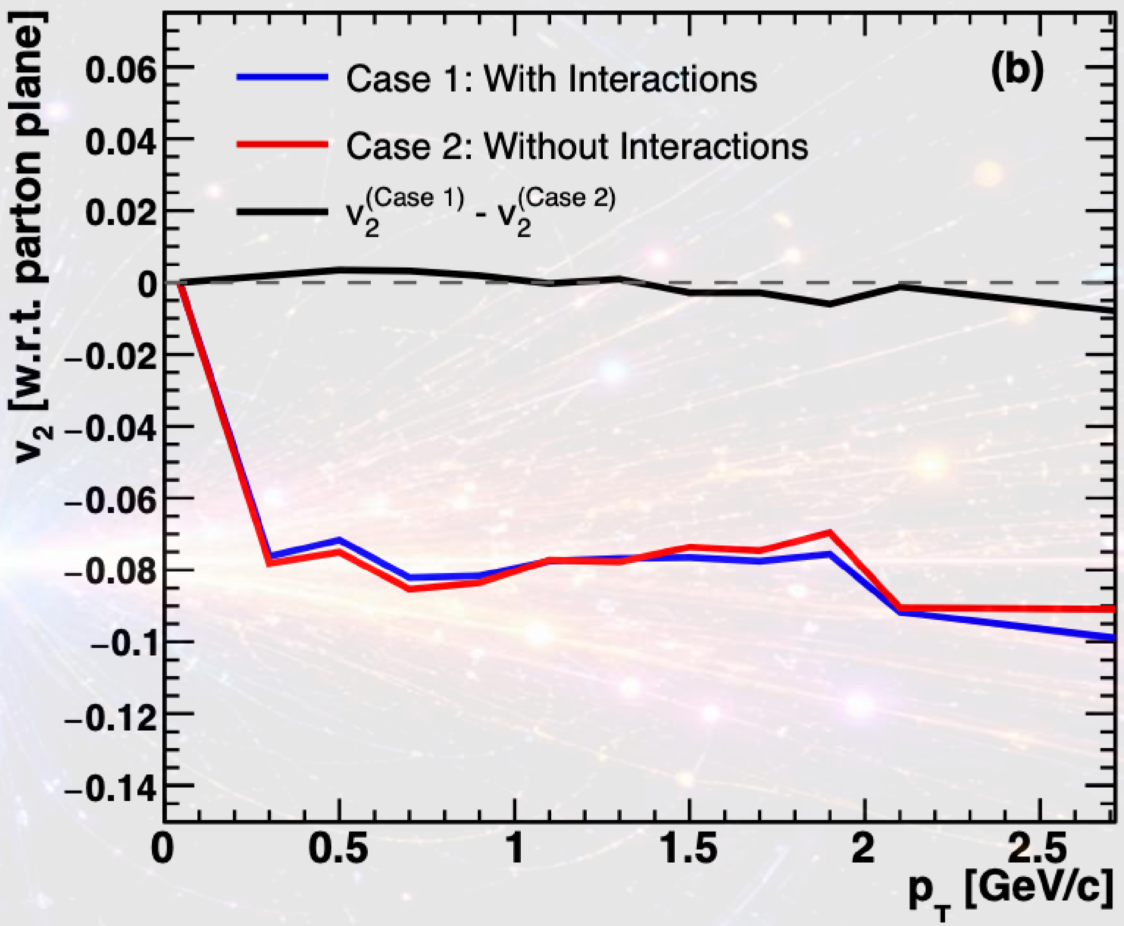


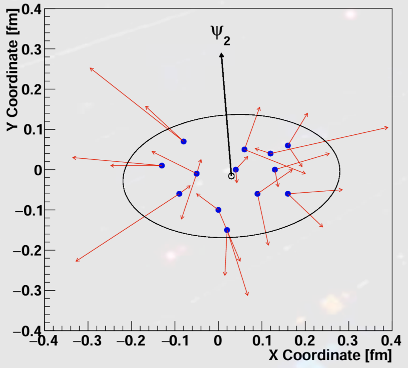


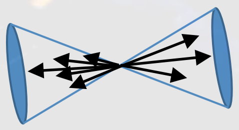
Jamie Nagle, Zi-Wei Lin, et al, PRC 97 (2018) 2, 024909

Example: One String Configuration Study with AMPT





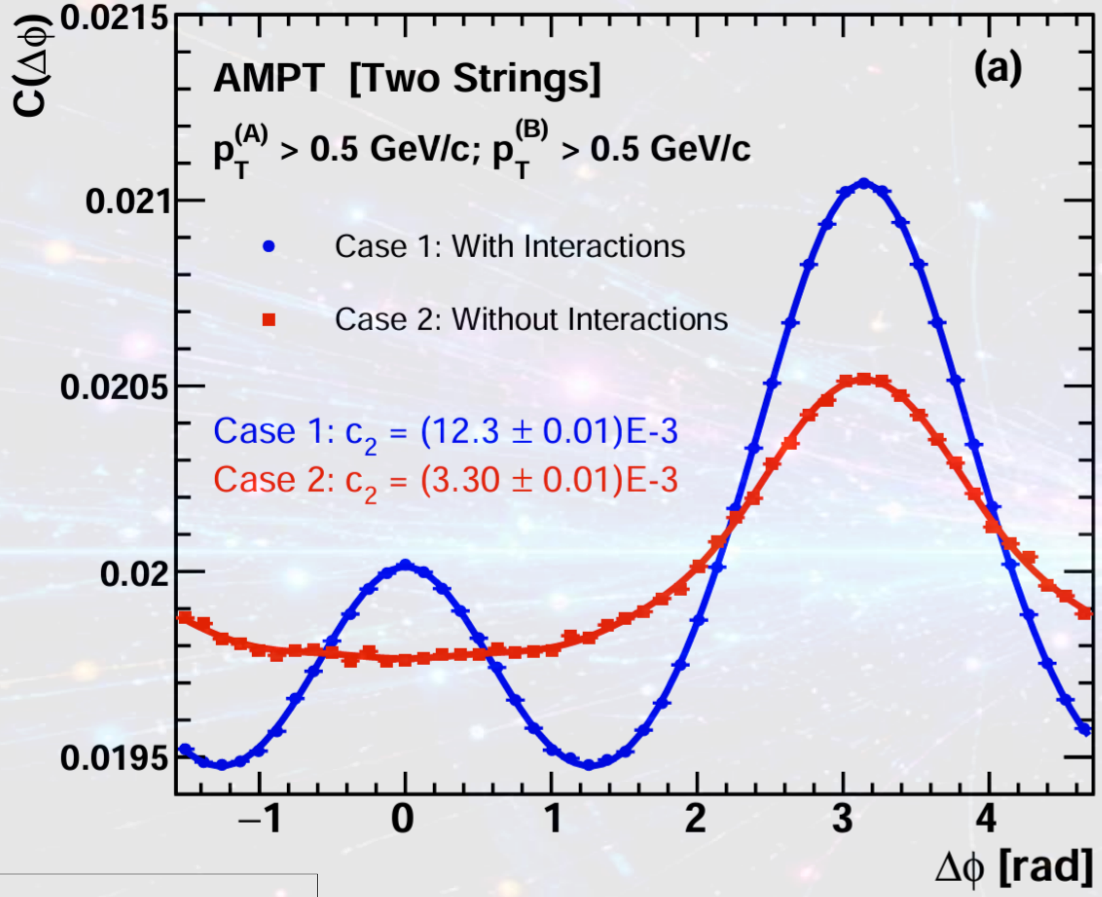


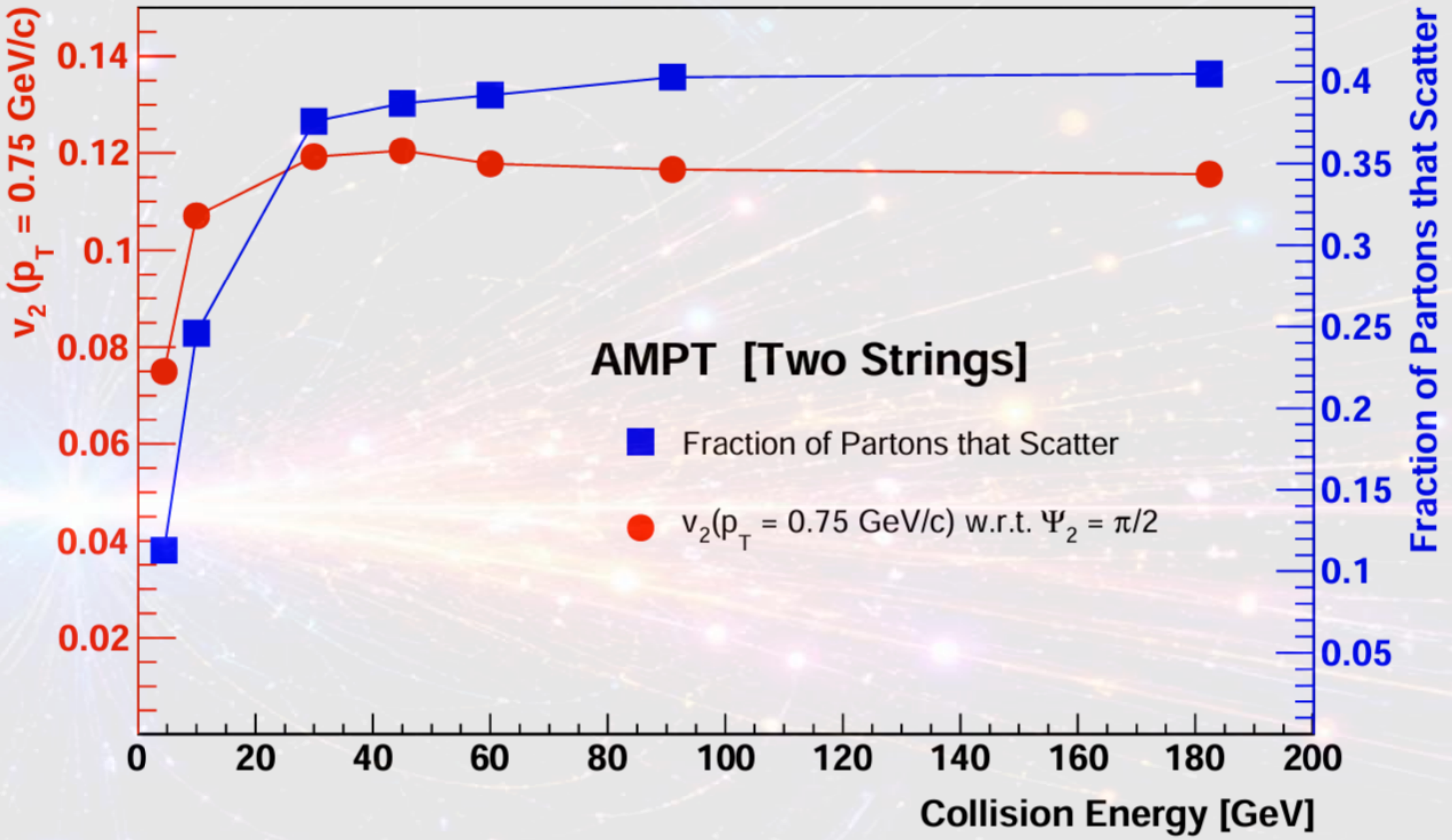


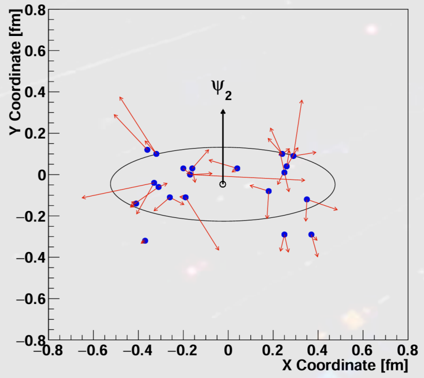
- With Interaction: A significant reduction of v_2
- v_2 becomes smaller than the reference without interaction

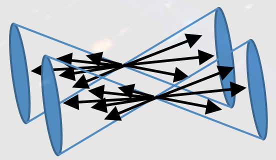
Jamie Nagle, Zi-Wei Lin, et al, PRC 97 (2018) 2, 024909

Example: Two Strings Configuration Study with AMPT







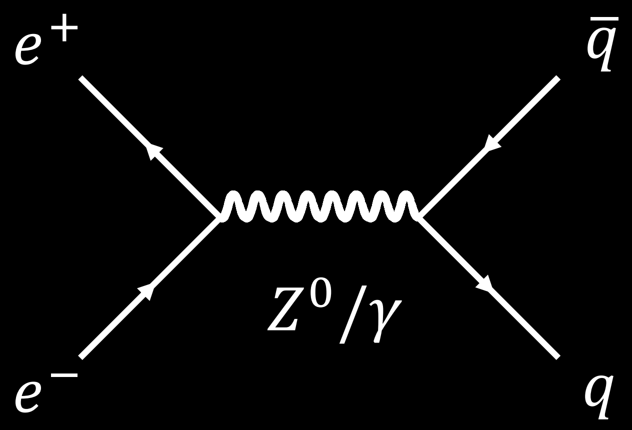


- With Interaction: A significant enhancement of v_2
- Little change in terms of v_3 magnitude (from a Fourier decomposition fit to the data in the figure)

Jamie Nagle, Zi-Wei Lin, et al, PRC 97 (2018) 2, 024909

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

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

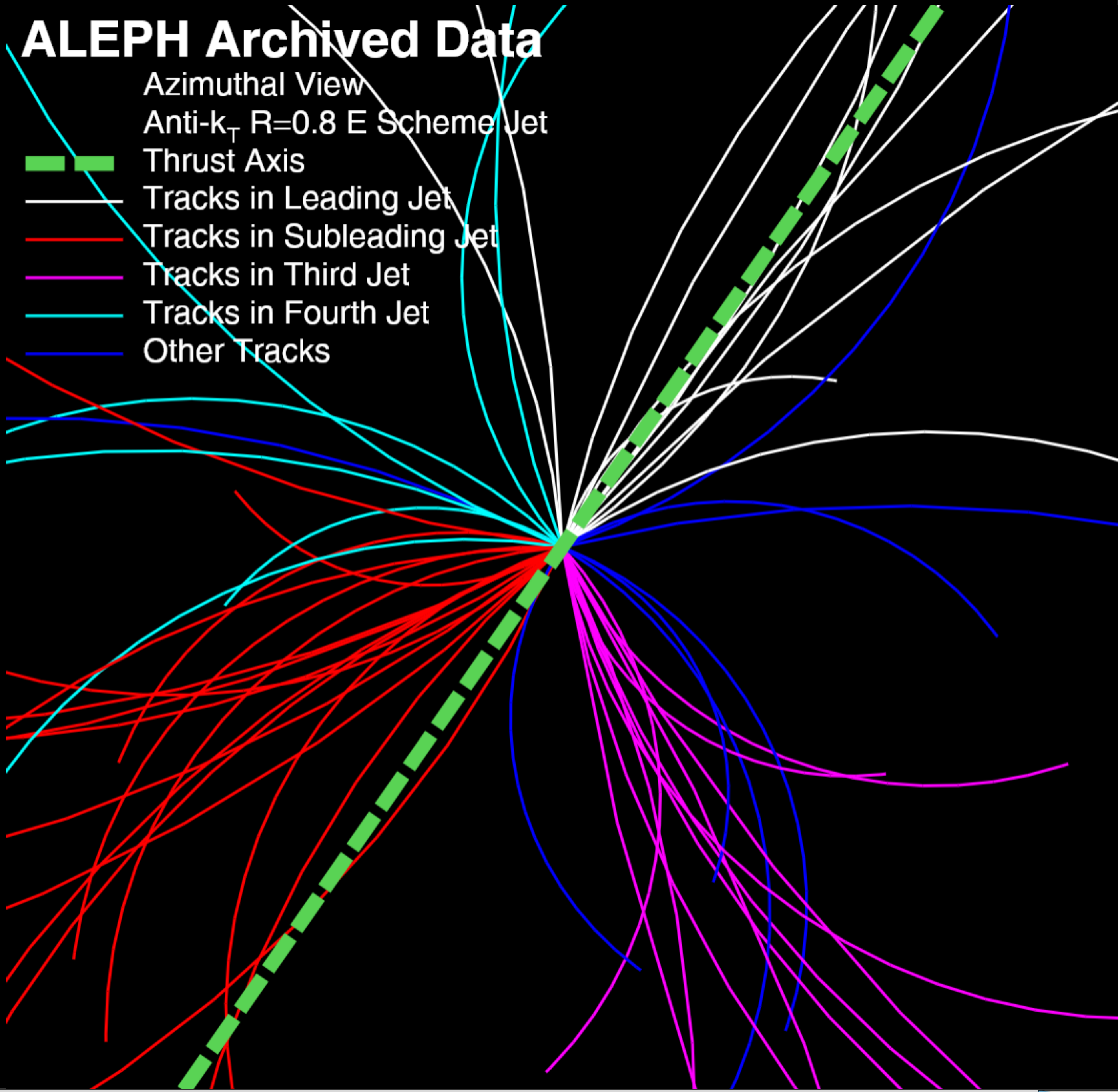


Anthony Badea, Austin Baty, Chris McGinn, Michael Peters, Jesse Thaler, Gian Michele Innocenti, Paoti Chang, Tzu-An Sheng

+ YJL

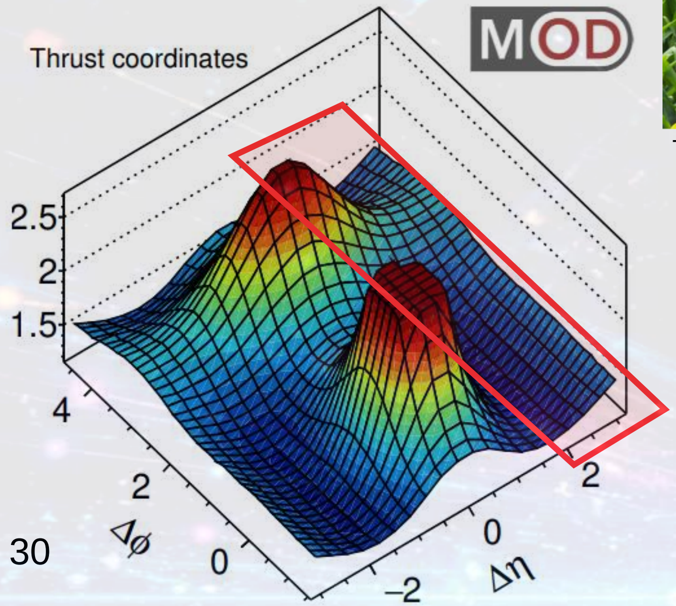
arXiv: 1906.00489
PRL 123, 212002 (2019)

55 Charged Particles
Thrust T=0.71



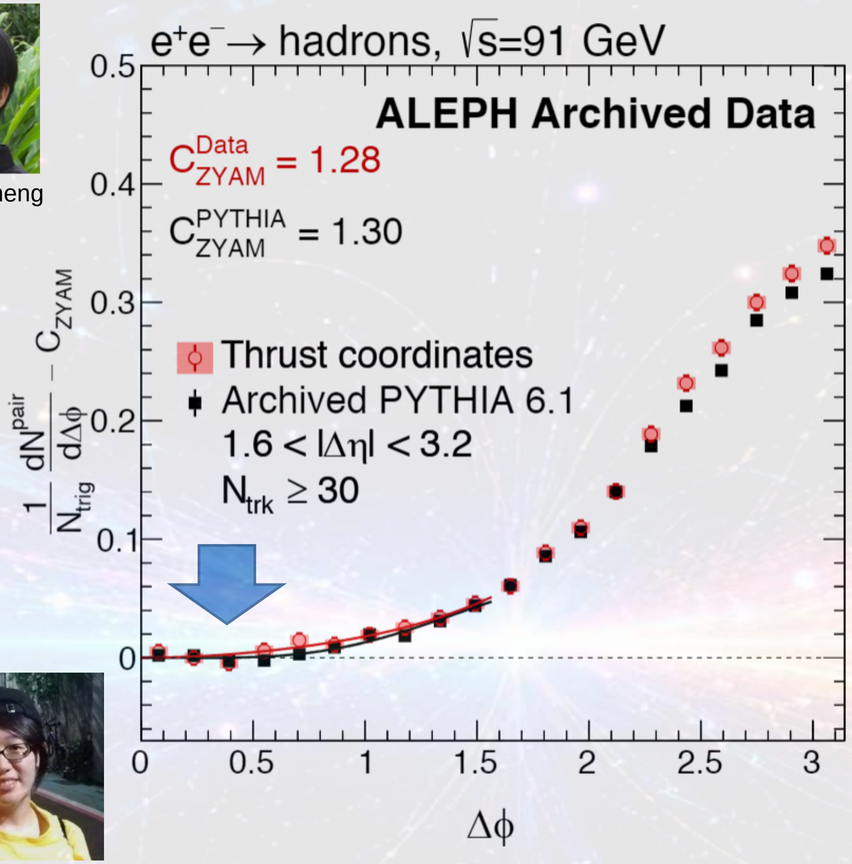
e^+e^- at 10.52 (Belle) and 91 GeV (ALEPH)

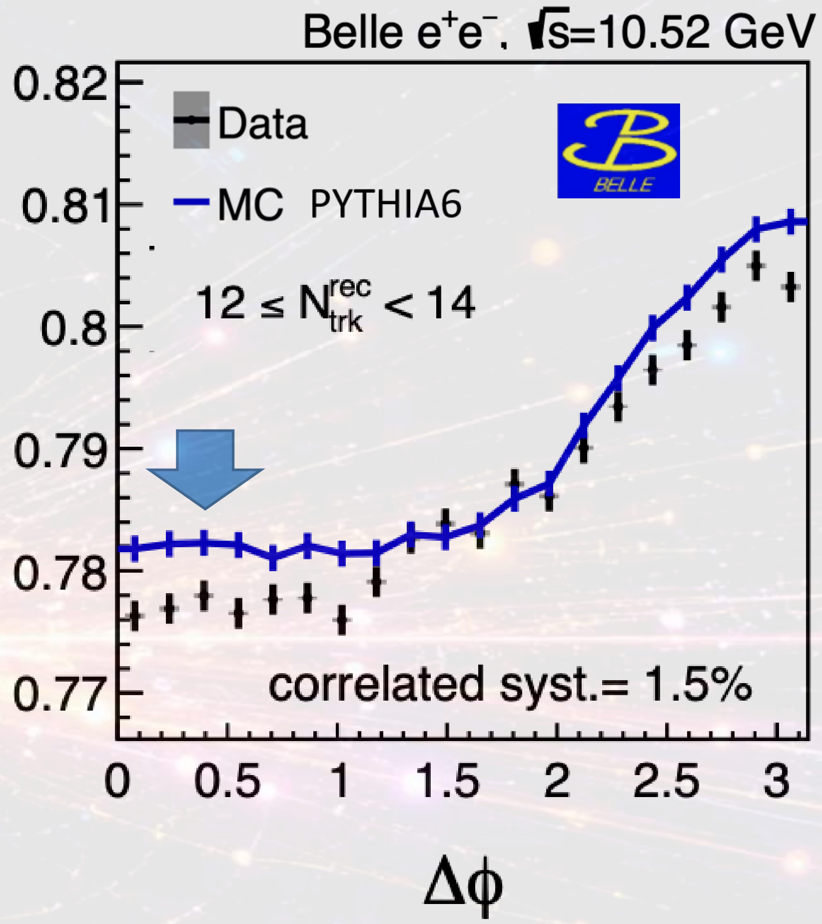
91 GeV



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

Tzu-An Sheng

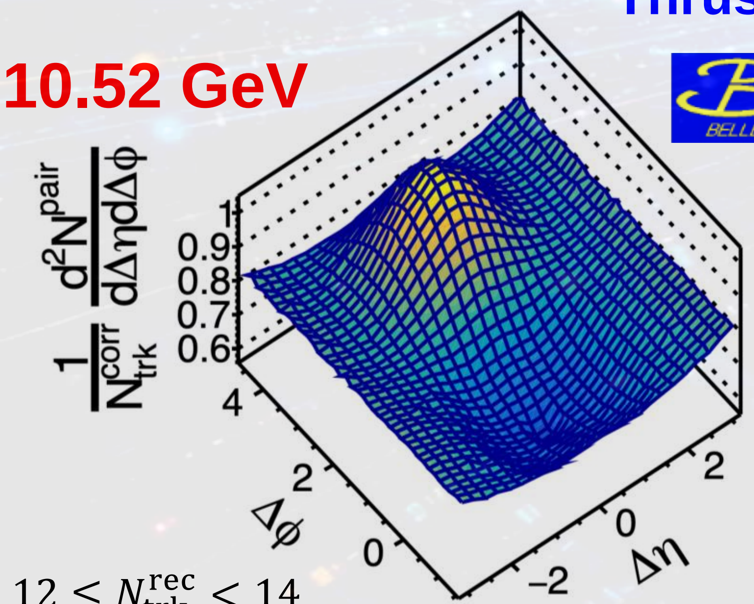




Thrust

Yu-Chen "Janice" Chen

10.52 GeV



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

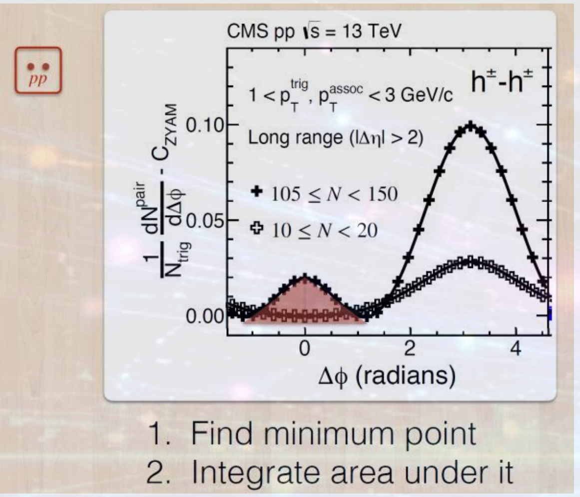
- No sign of ridge signal in high multiplicity electron-positron collisions up to ~35 charged particles per event
- New reference to the collective behavior in small systems!

ALEPH archived data PRL 123, 212002 (2019)

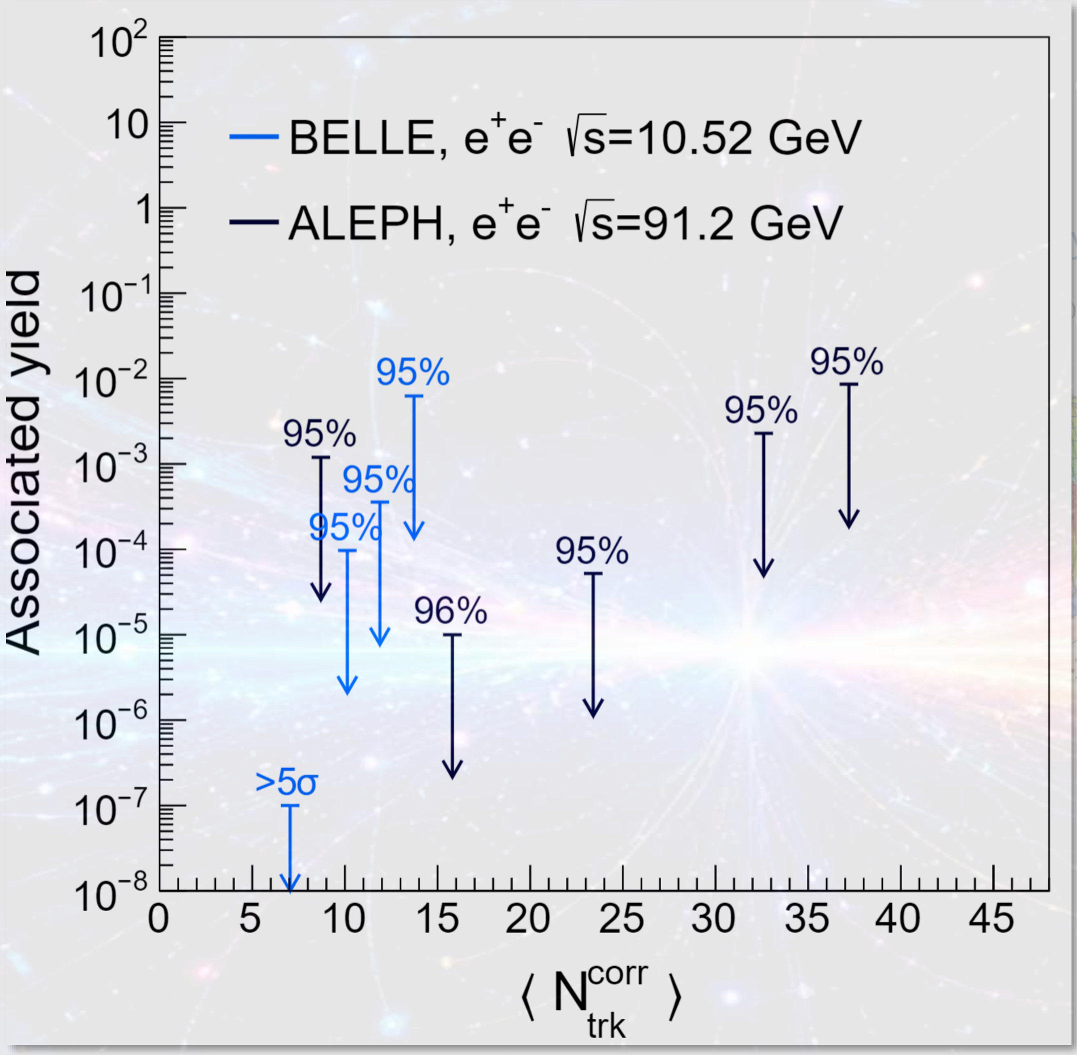
Off Y(4S) resonance, Belle PRL 128 (2022) 14, 142005

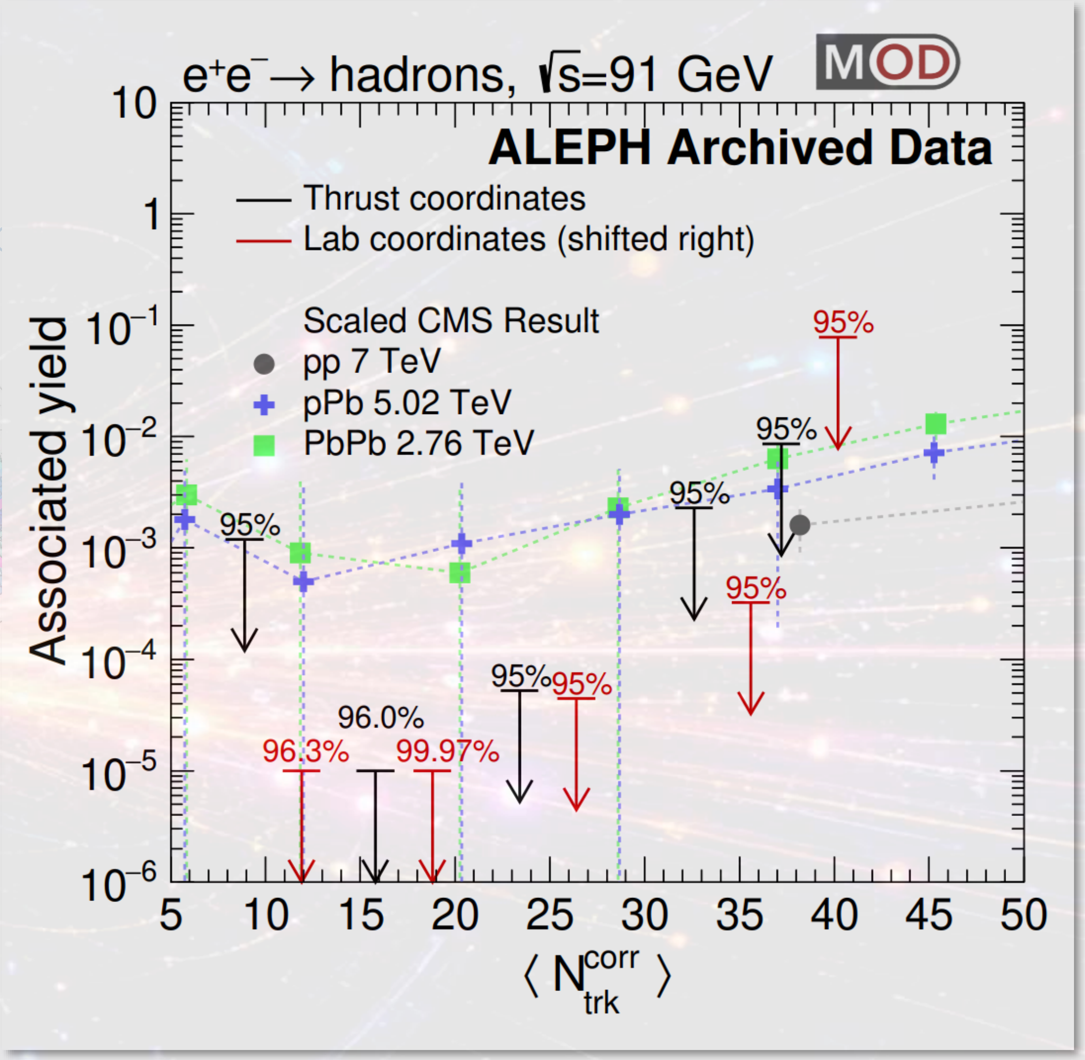
On Y(4S) resonance, Belle JHEP 03 (2023) 171

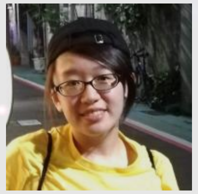
Compilation of Ridge Yield Limit in e^+e^- collisions



Yi Chen's slide







Yu-Chen "Janice" Chen

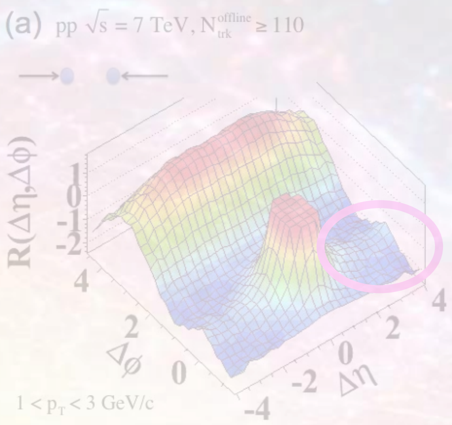
No significant ridge signal in $e^+e^- \to q\bar{q}$
from low to high multiplicity (up to ~35 particles)

Tzu-An Sheng

Emerging Picture

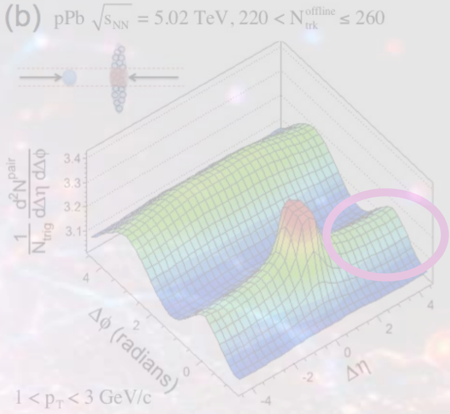
"Transverse Size" / "MPI"

High multiplicity pp

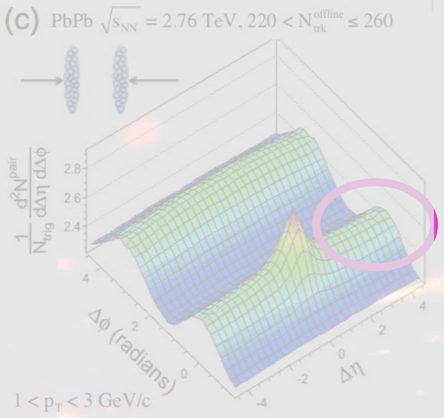


~ O(1fm)

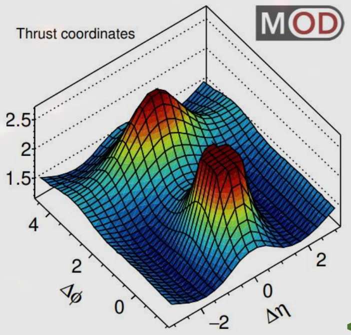
High multiplicity pPb



≥ O(1fm)



O(1-10 fm)



e^+e^-

"MPI"=1

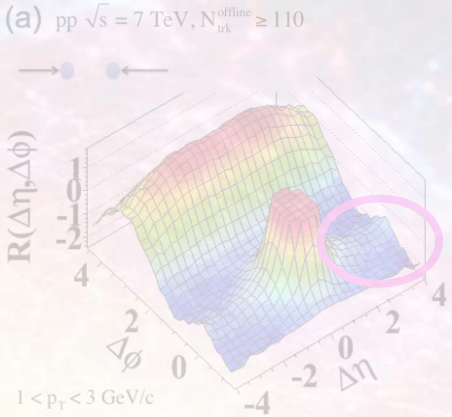
<< 0.1 fm

Multiplicity

Emerging Picture

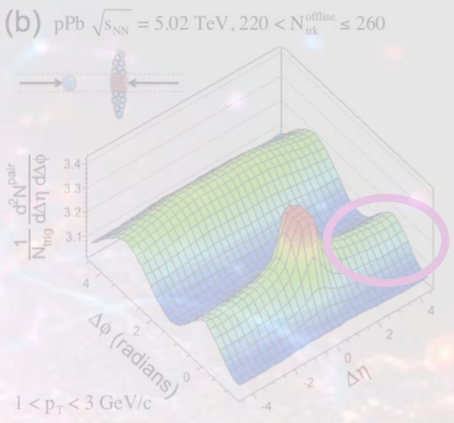
“Transverse Size” / “MPI”

High multiplicity pp

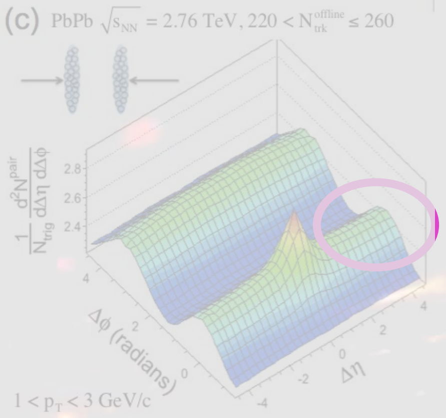


~ O(1fm)

High multiplicity pPb

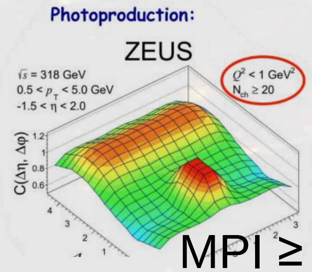


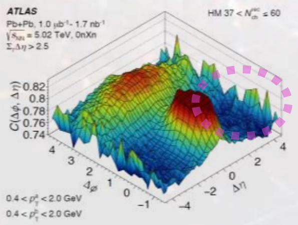
≥ O(1fm)



O(1-10 fm)

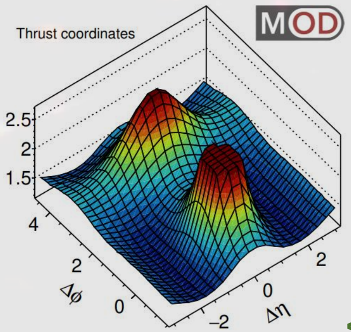
HERA Data





MPI ≥ 1

Larger MPI
than γp



e^+e^-

“MPI”=1

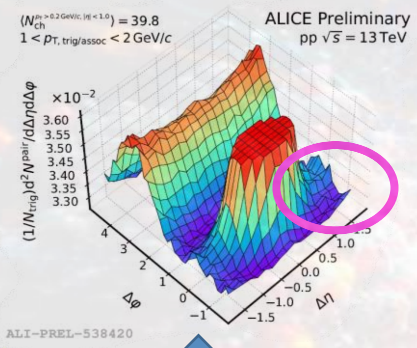
<< 0.1 fm

Multiplicity

Emerging Picture

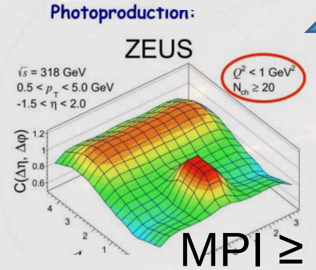
“Transverse Size” / “MPI”

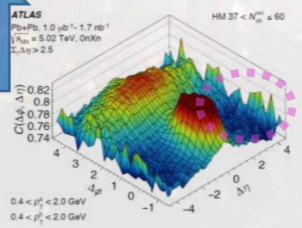
ALICE Low multiplicity pp signal



MPI>1

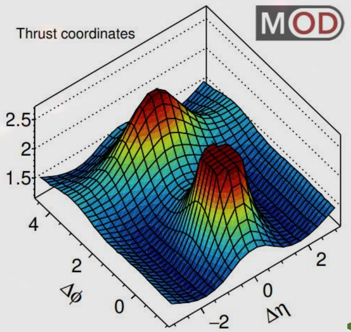
Photoproduction:





MPI ≥ 1

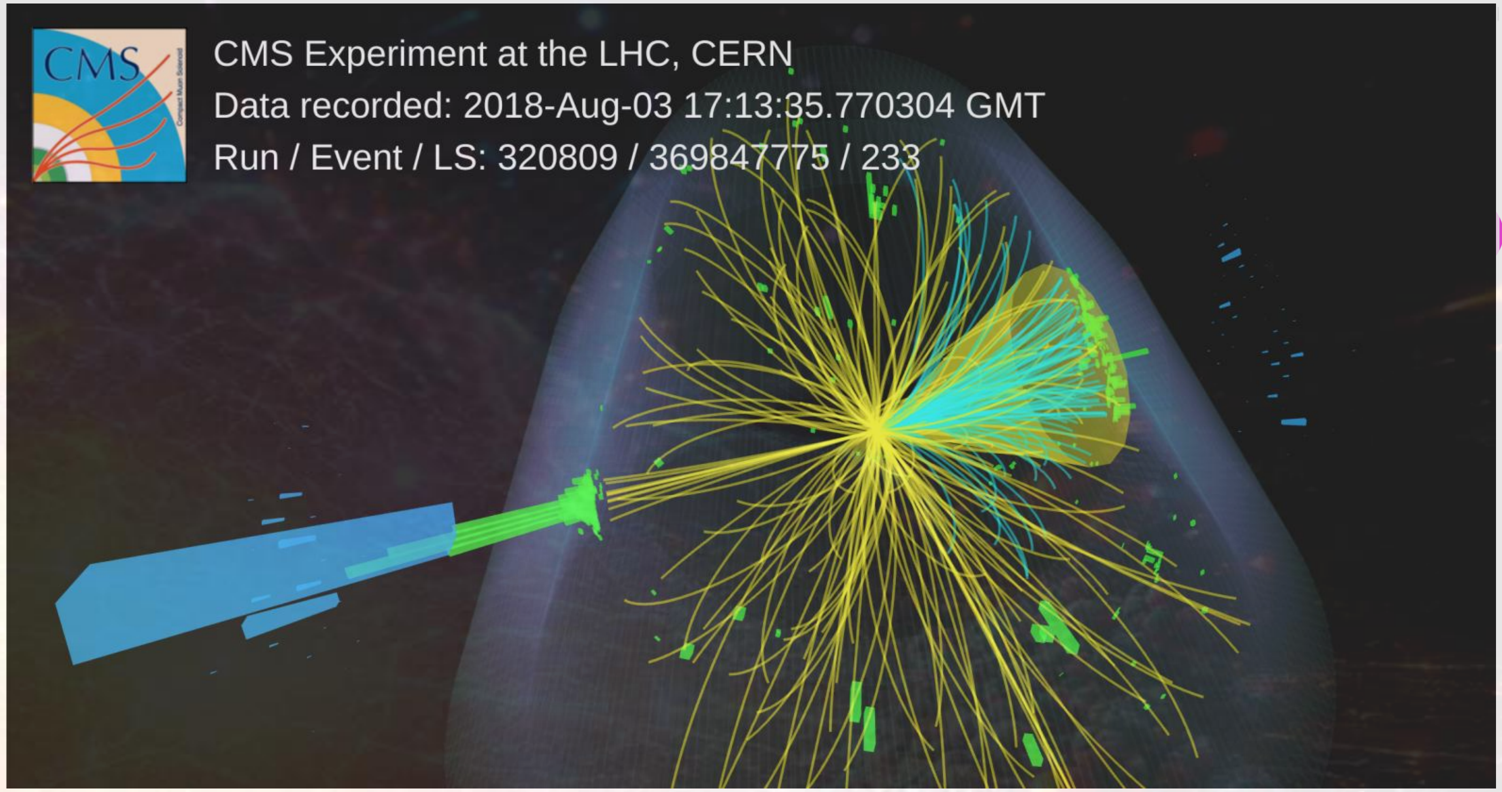
Larger MPI than γp

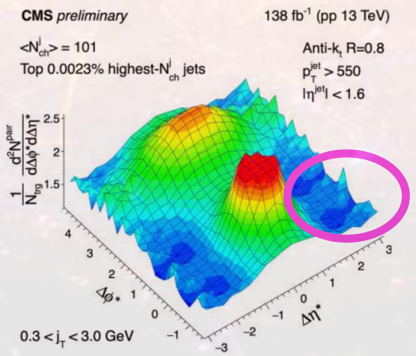


e^+e^-

“MPI”=1

<< 0.1 fm





CMS High Multiplicity Jet

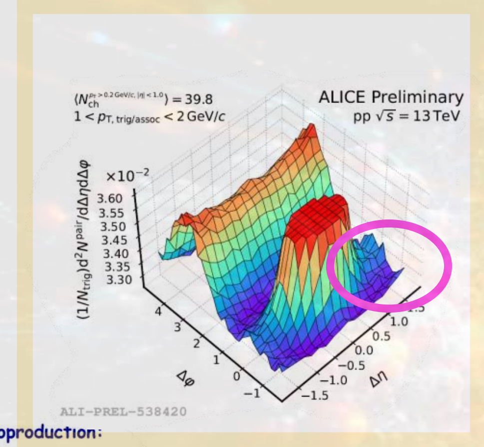
Xiaoyu Liu’s talk

Multiplicity

Emerging Picture

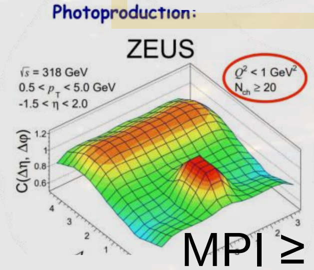
“Transverse Size” / “MPI”

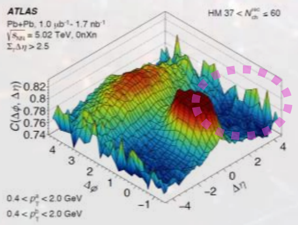
ALICE Low multiplicity pp signal



MPI>1

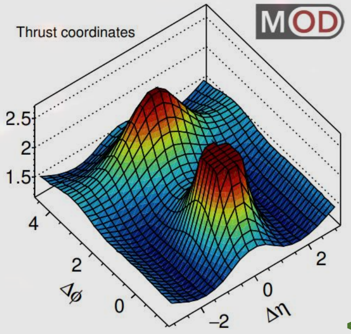
Photoproduction:





MPI ≥ 1

Larger MPI than γp



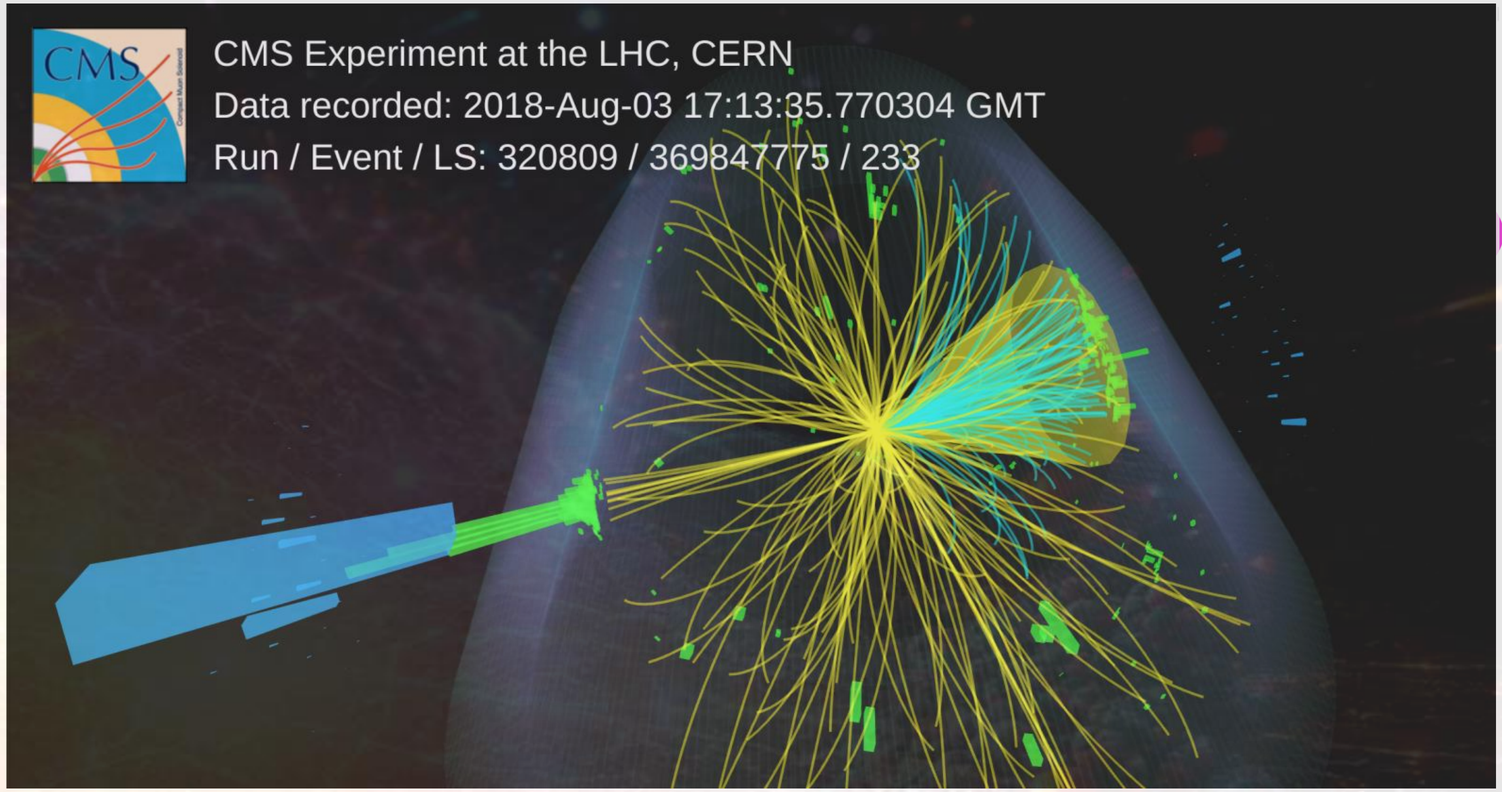
MOD

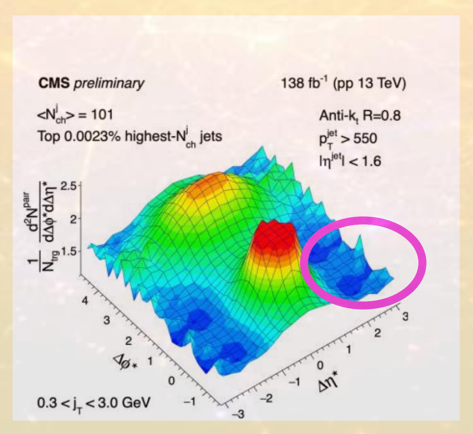
e^+e^-

“MPI”=1

<< 0.1 fm

?





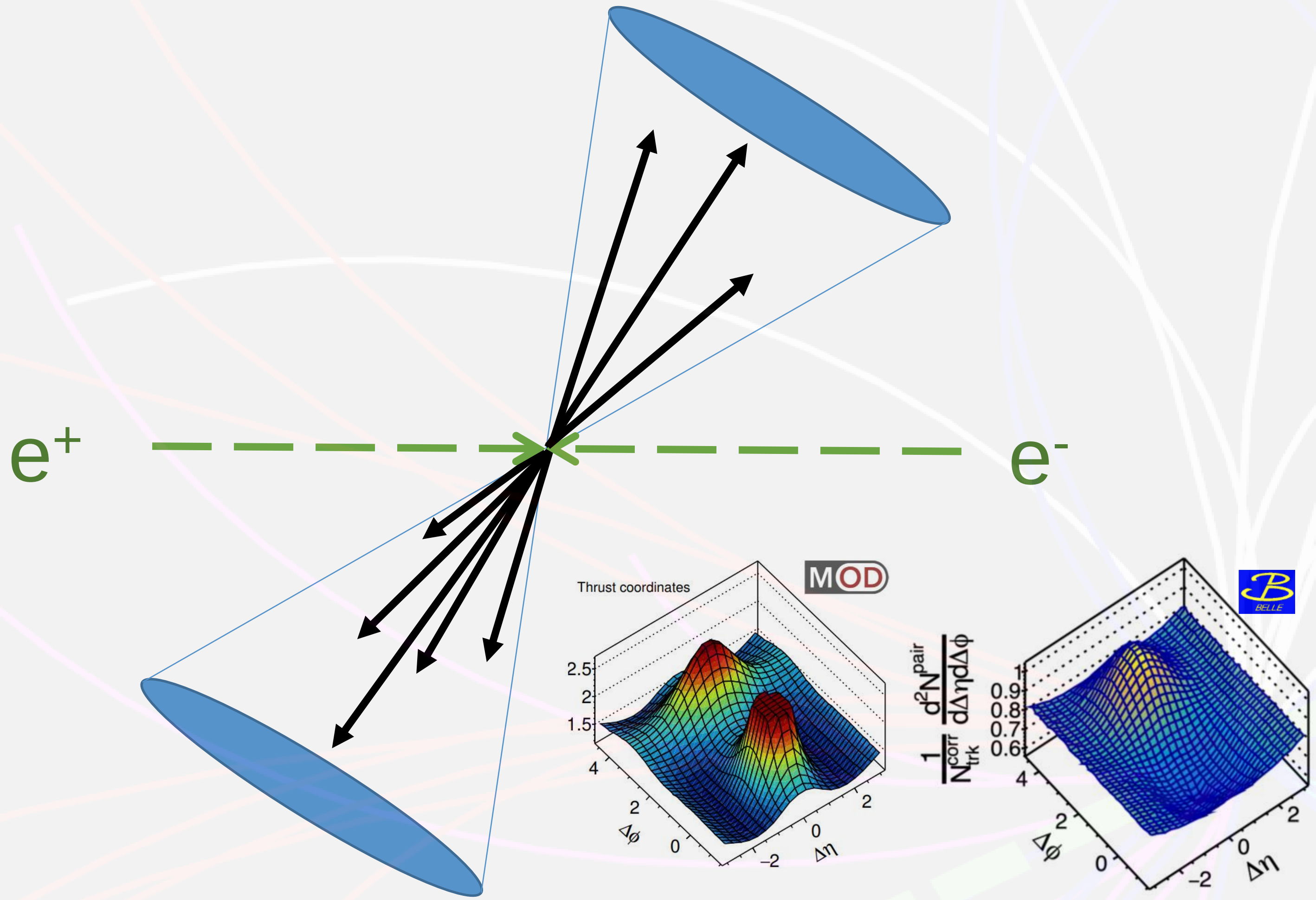
CMS High Multiplicity Jet

Xiaoyu Liu’s talk

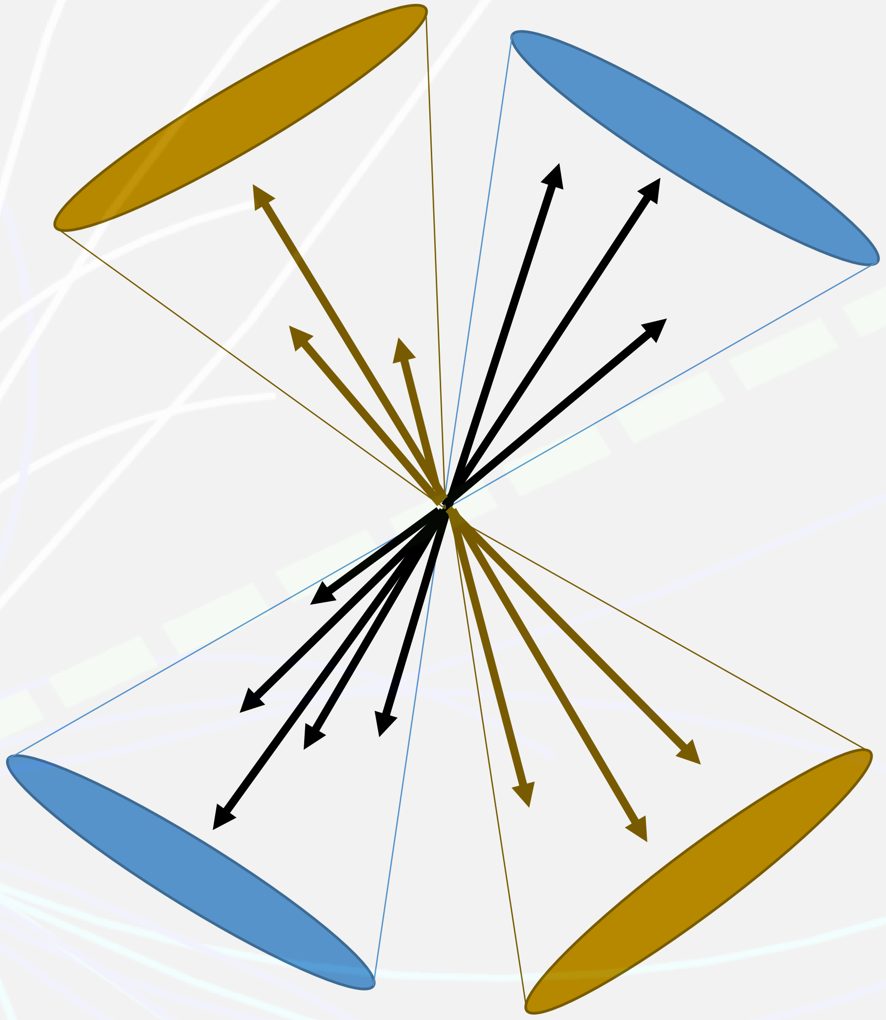
Multiplicity

Can We Overlap Two Color Strings?

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



No ridge-like structure



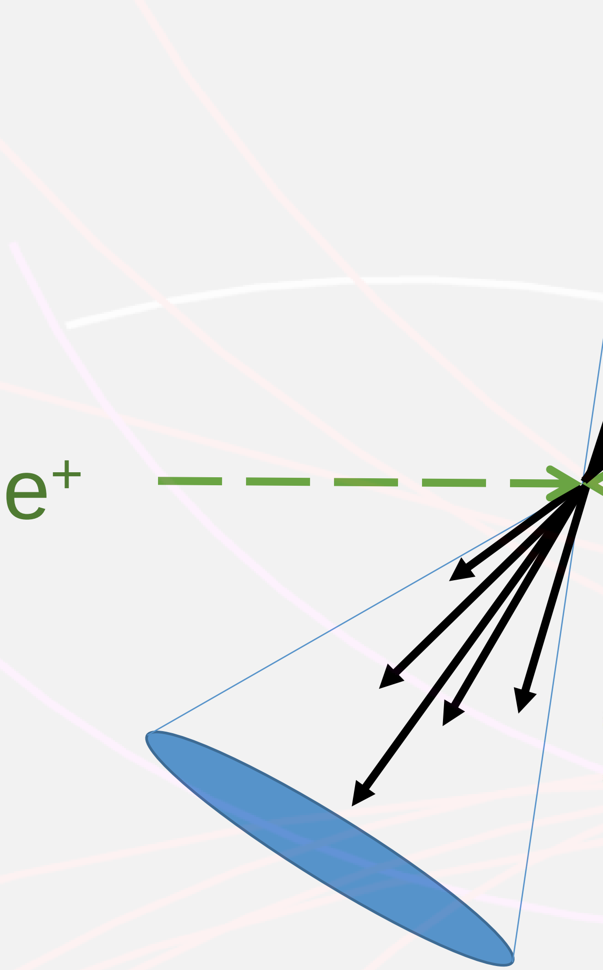
?

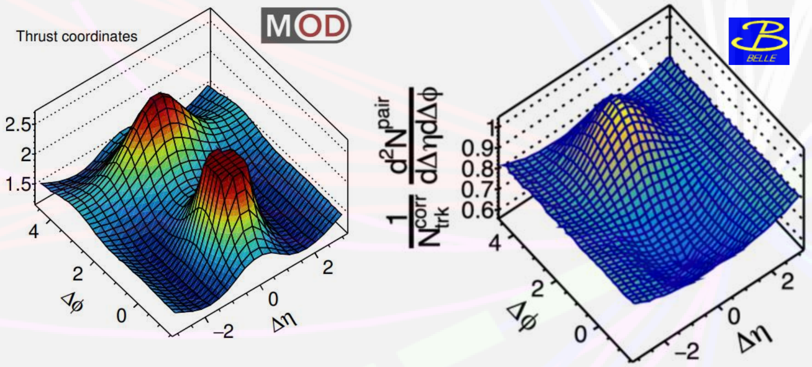
High Multiplicity e^+e^- Event at LEP 2 !!

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

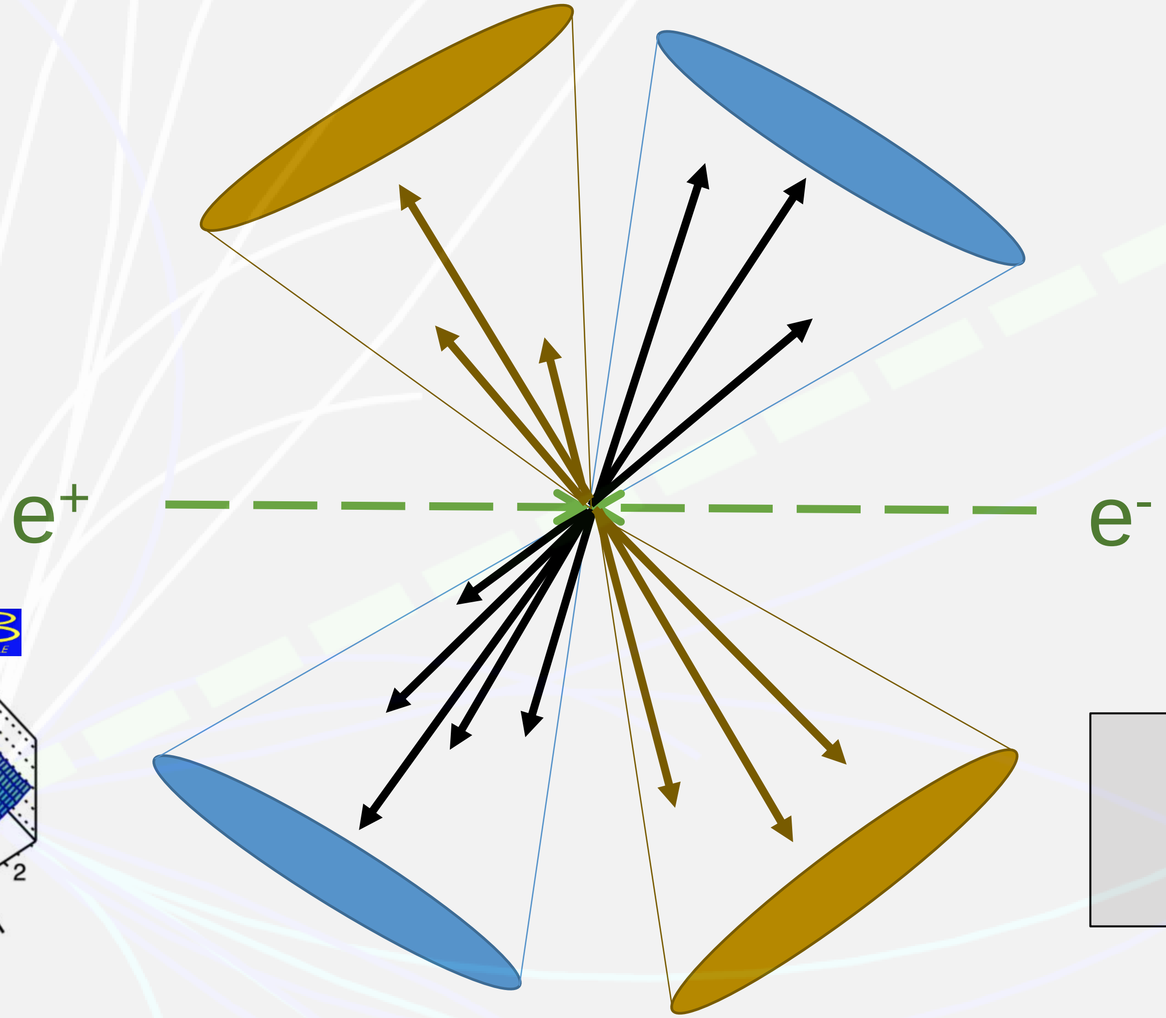
$$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$$

$$L \sim \beta\gamma c\tau \approx 0.07 \text{ fm}$$





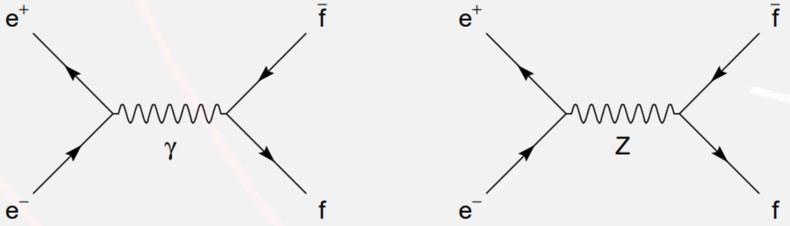
No ridge-like structure



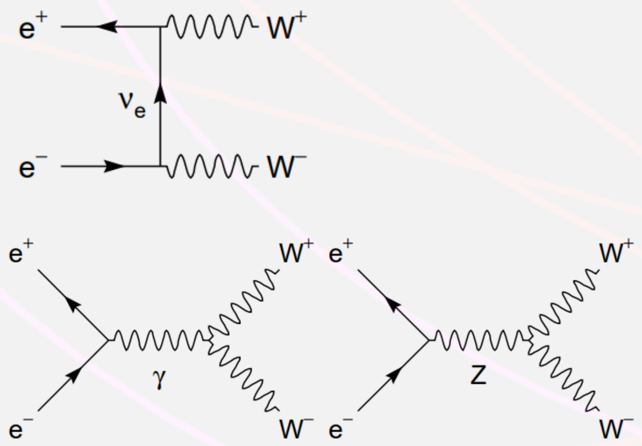
?

Charged Particle Multiplicity Distributions in LEP2 Data

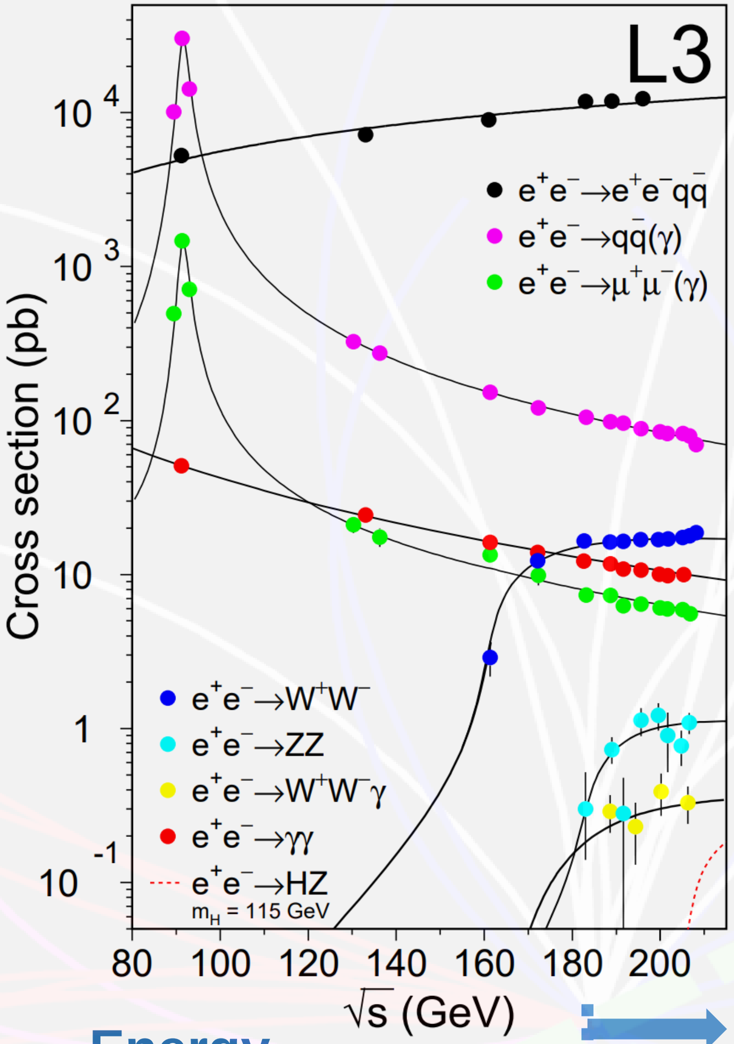
- $e^+e^- \rightarrow q\bar{q}(\gamma)$



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



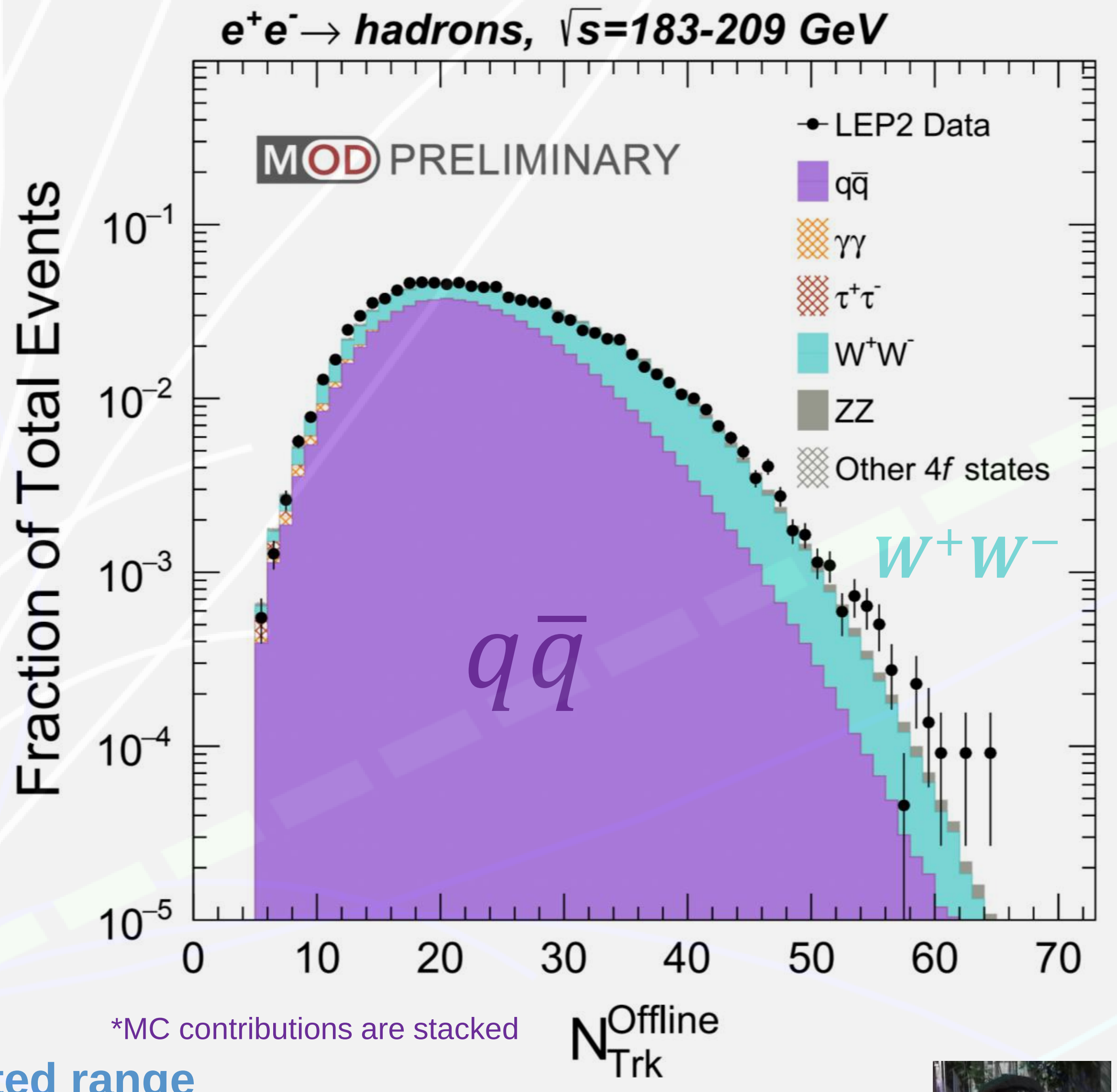
Phys. Rept. 532 (2013) 119-244



Energy

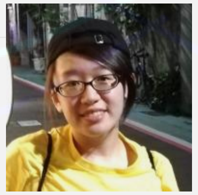
EPJC 63 611 (2009)

Reported range



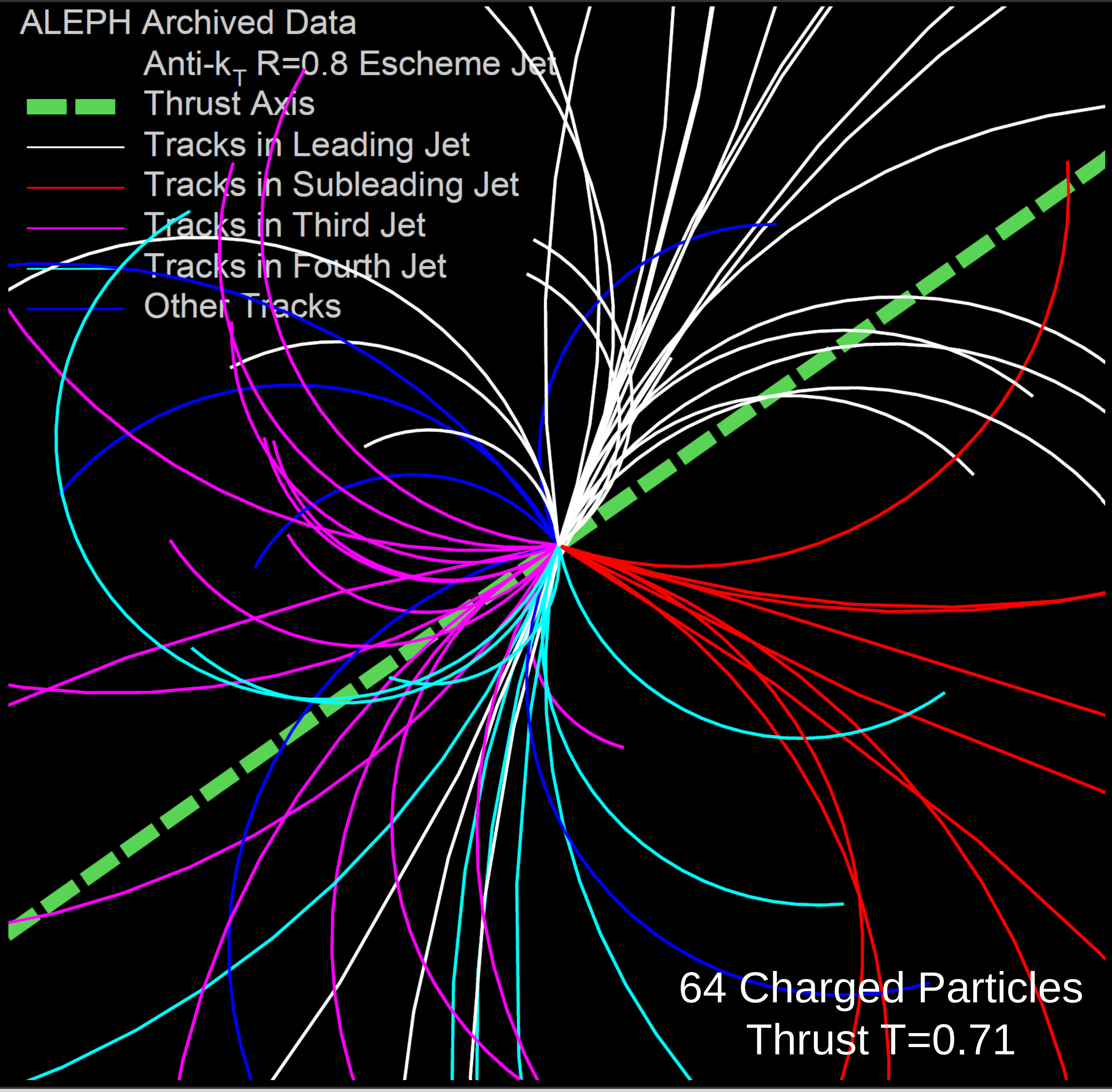
*MC contributions are stacked

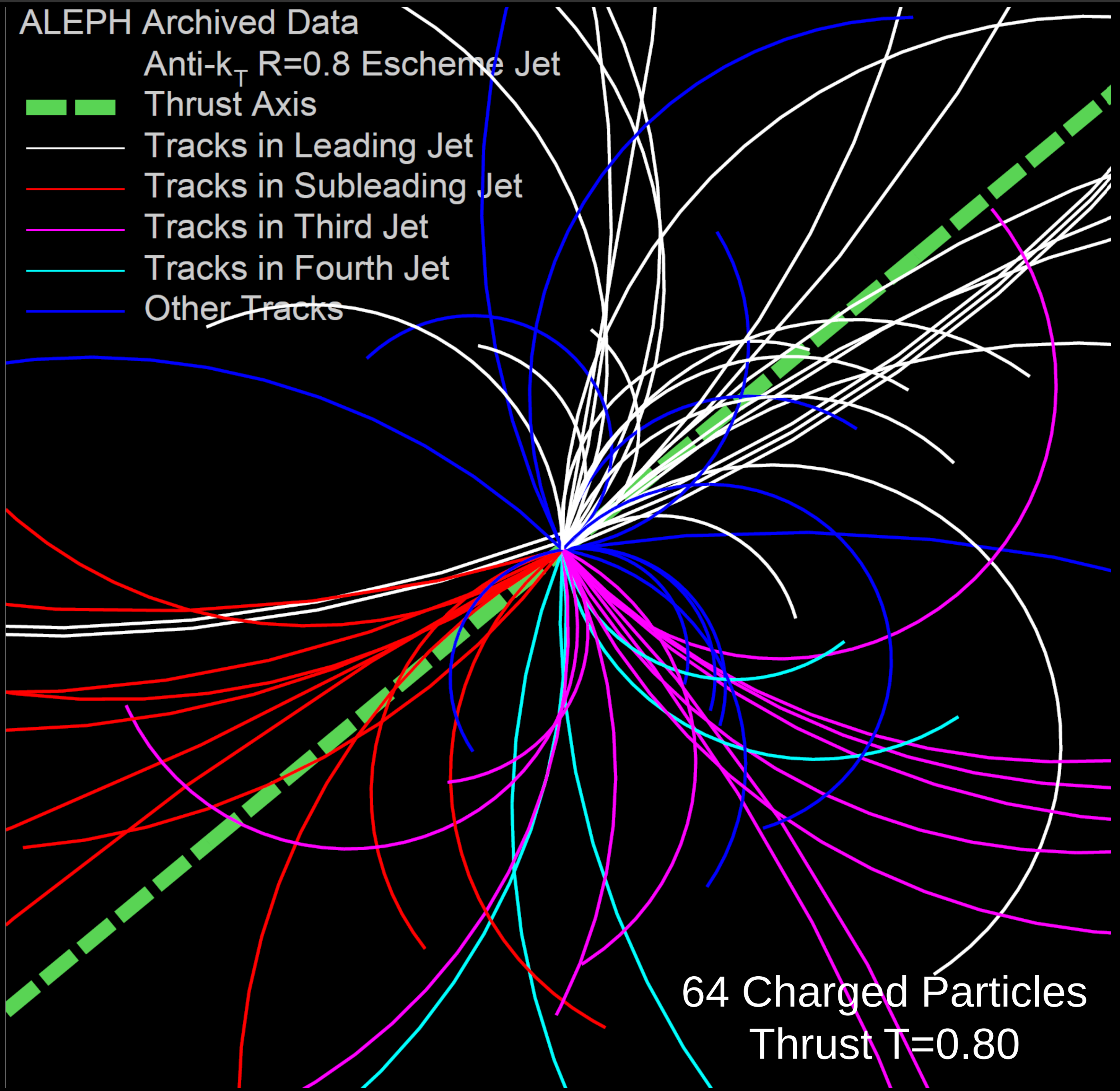
- **LEP2 energies** also give access to different physics processes
- At high multiplicity, W^+W^- contribution becomes significant



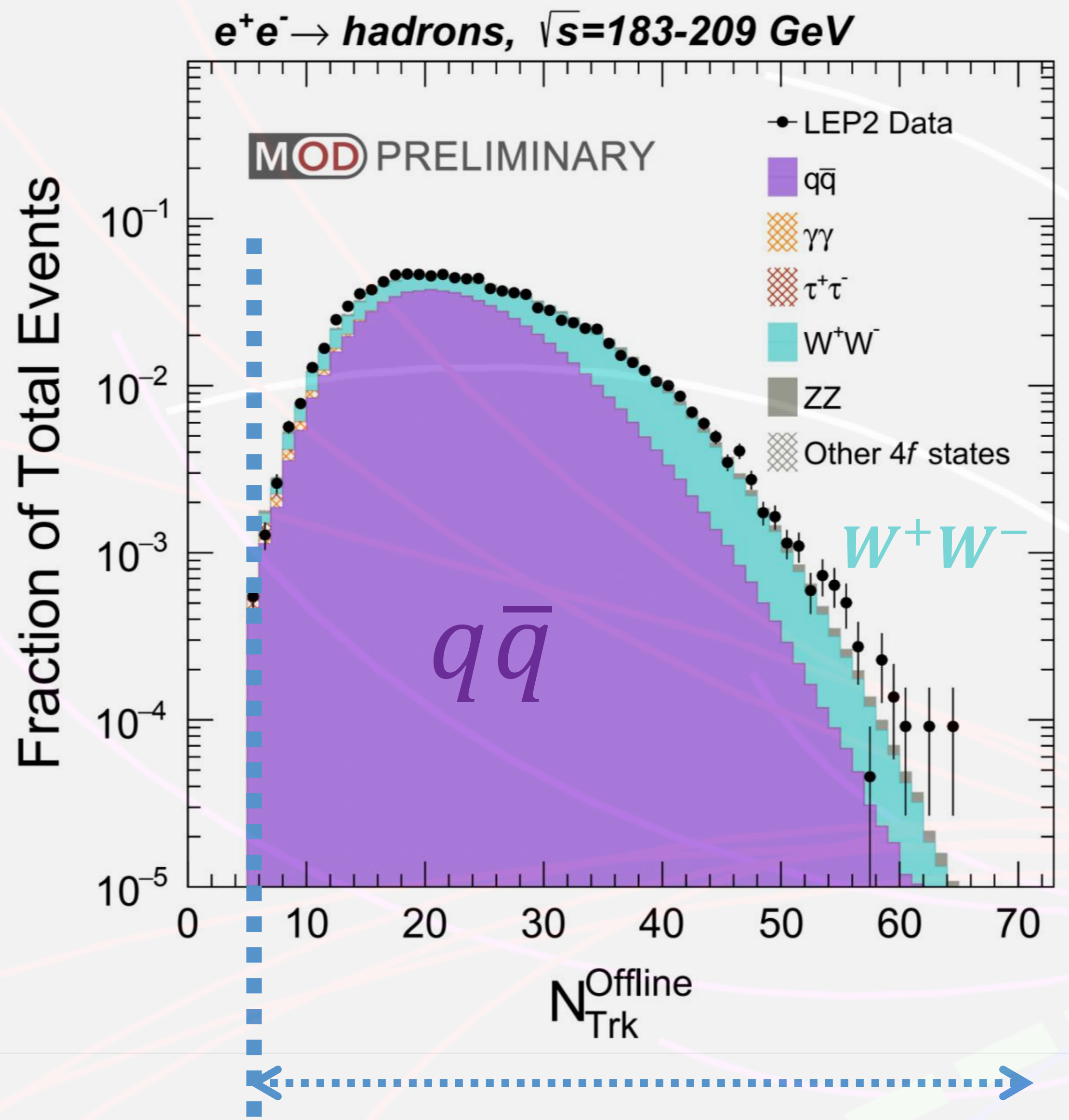
Yu-Chen "Janice" Chen (MIT)

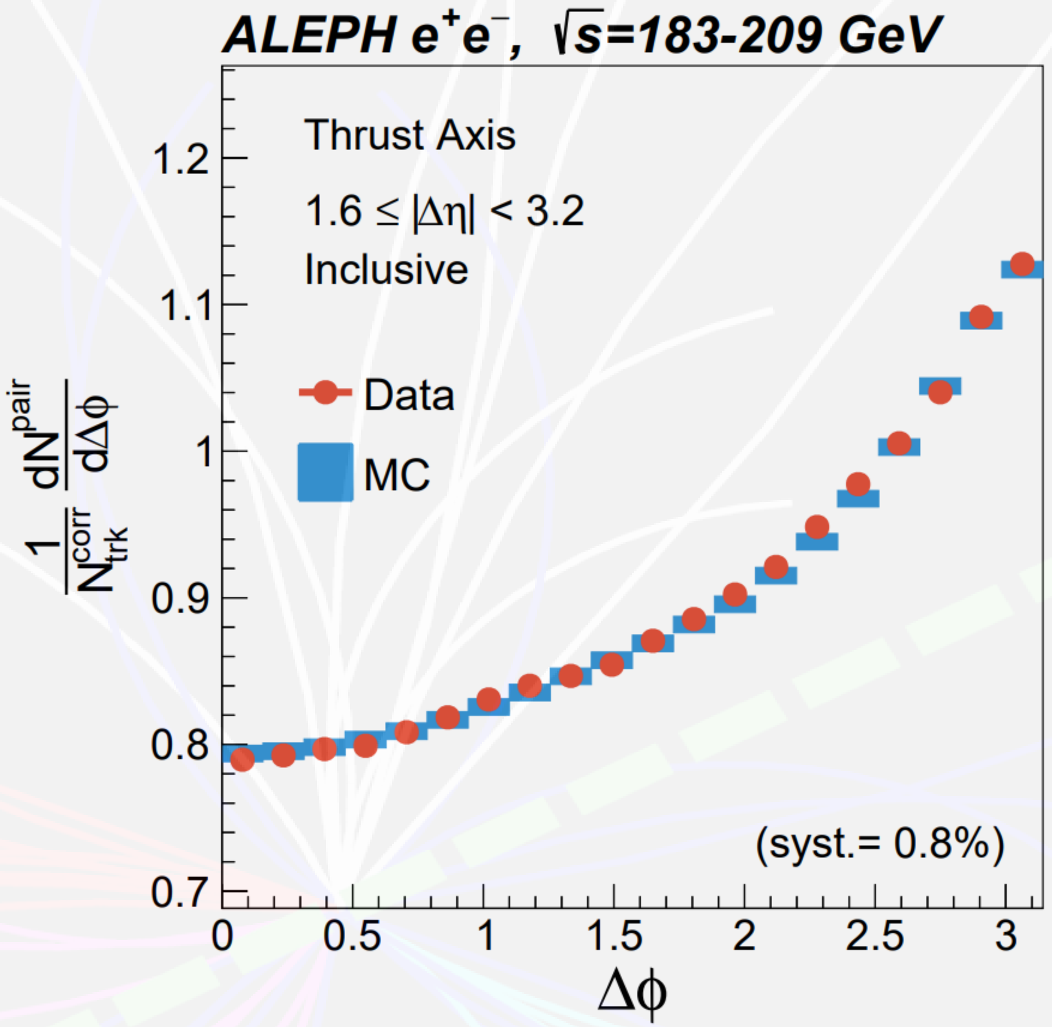
The Highest Multiplicity Events in Archived LEP2 Data

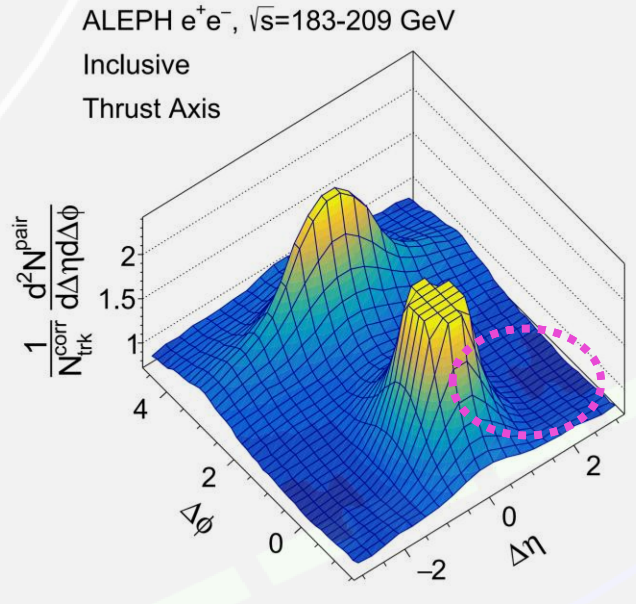




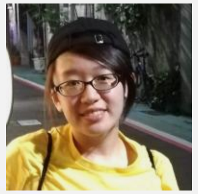
Inclusive Hadronic e^+e^- Events at LEP 2 ($N_{ch} \geq 5$)







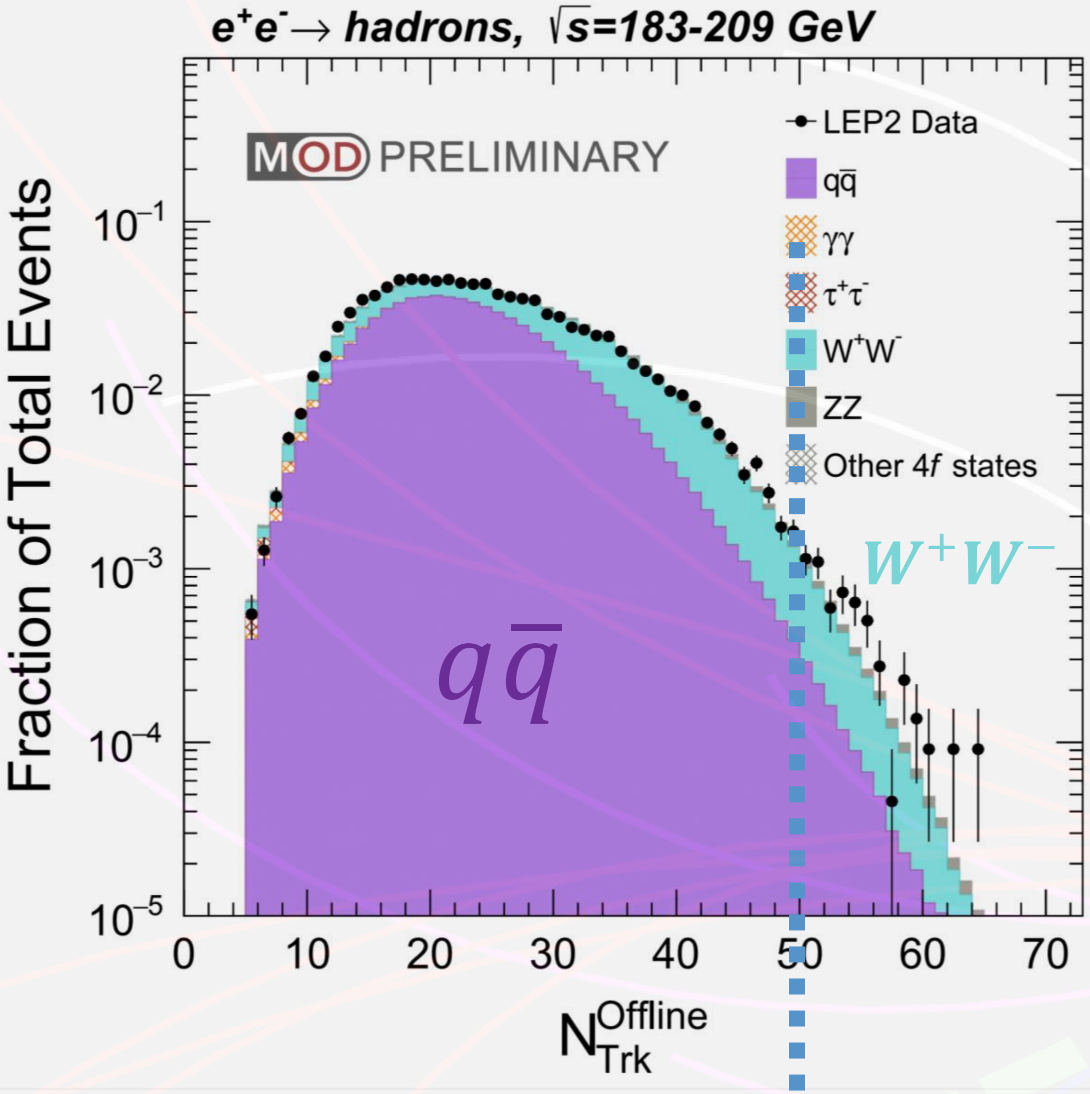
arXiv:2312.05084 PLB 856 (2024) 138957

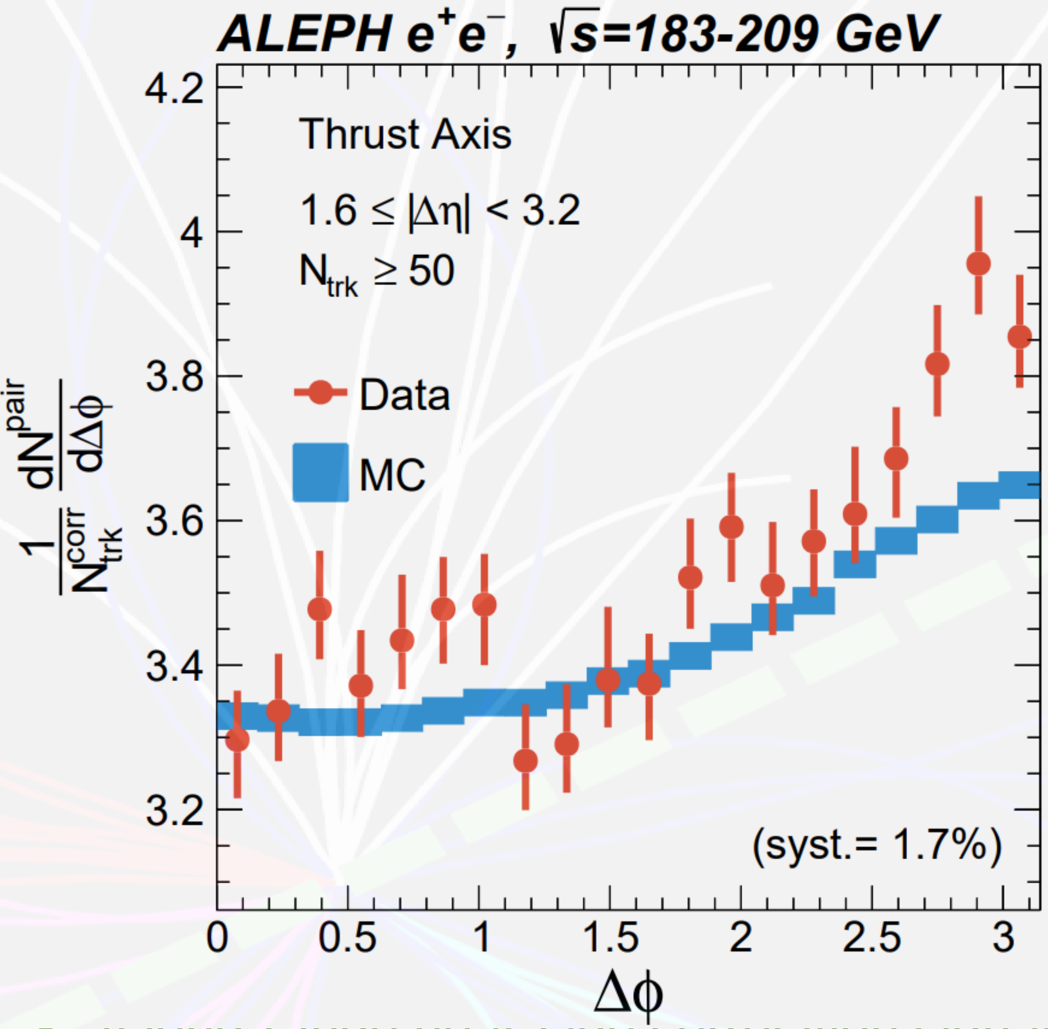


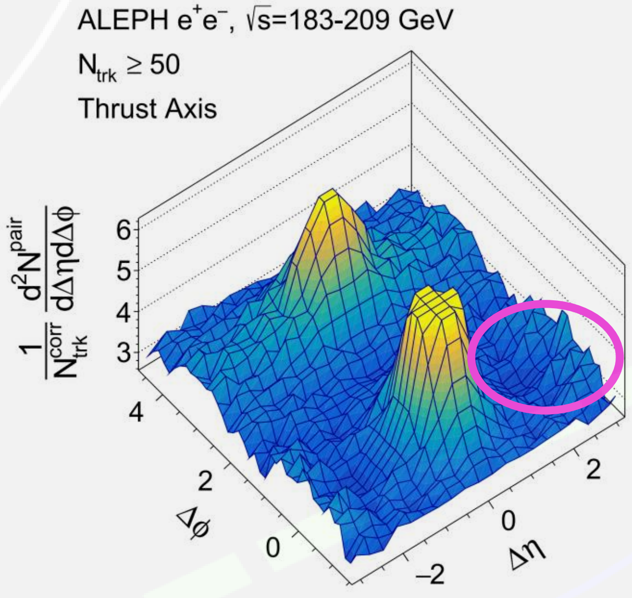
Yu-Chen "Janice" Chen (MIT)

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

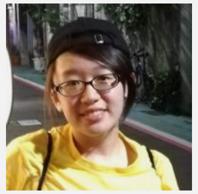
High Multiplicity e^+e^- Events at LEP 2 ($N_{trk} \geq 50$)







arXiv:2312.05084 PLB 856 (2024) 138957

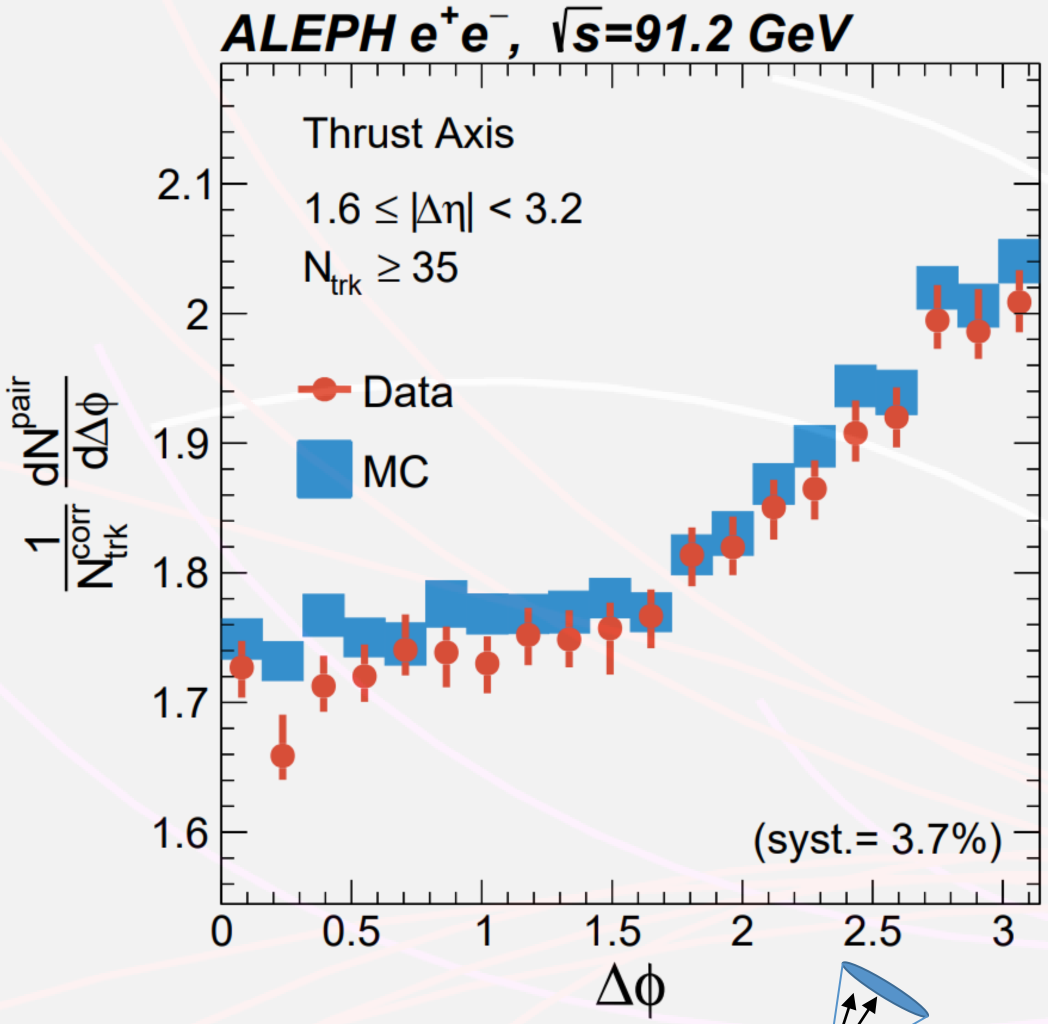


Yu-Chen "Janice" Chen (MIT)

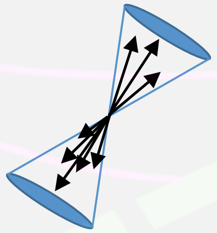
- A long-range near-side correlation signal shows up at high multiplicity!
- Data also feature a narrower away-side spectrum at $\Delta\phi \sim \pi$

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

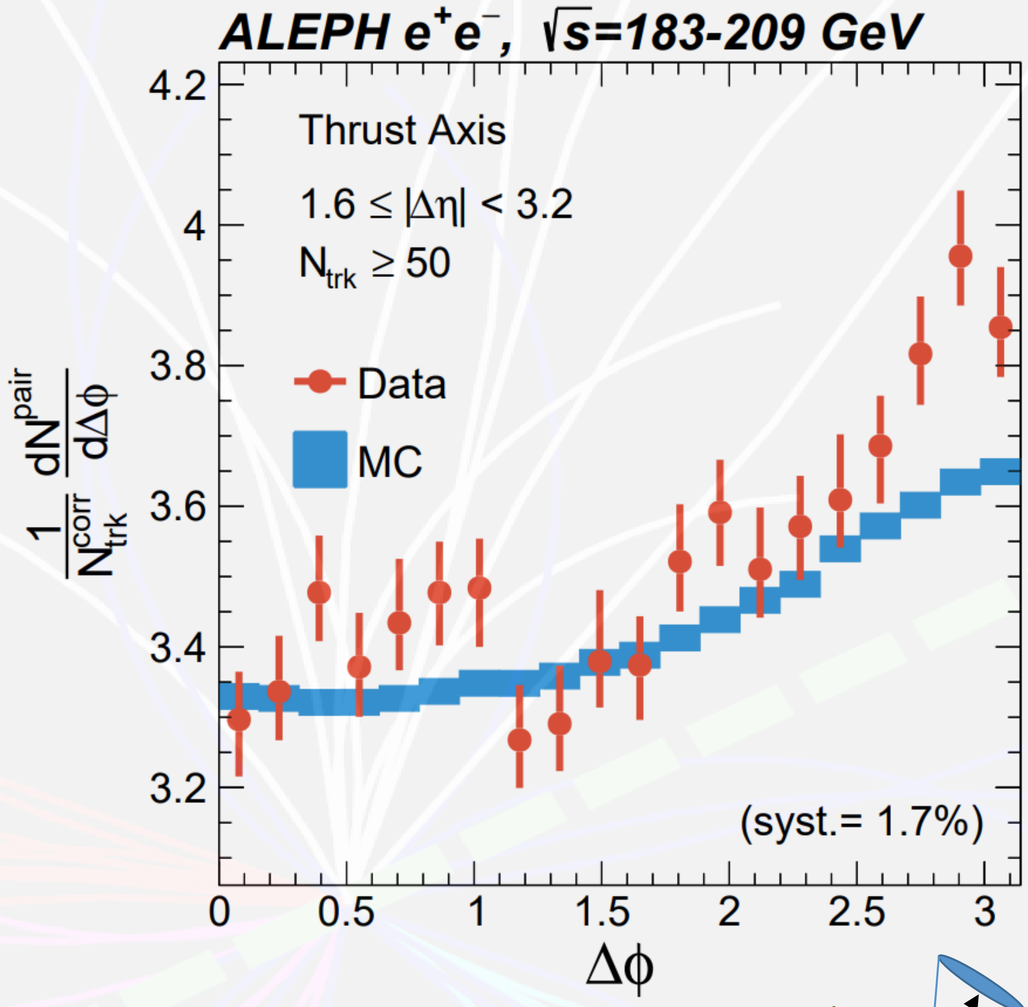
LEP1 N_{trk}>35



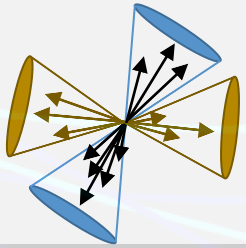
$e^+e^- \rightarrow q\bar{q}(\gamma)$

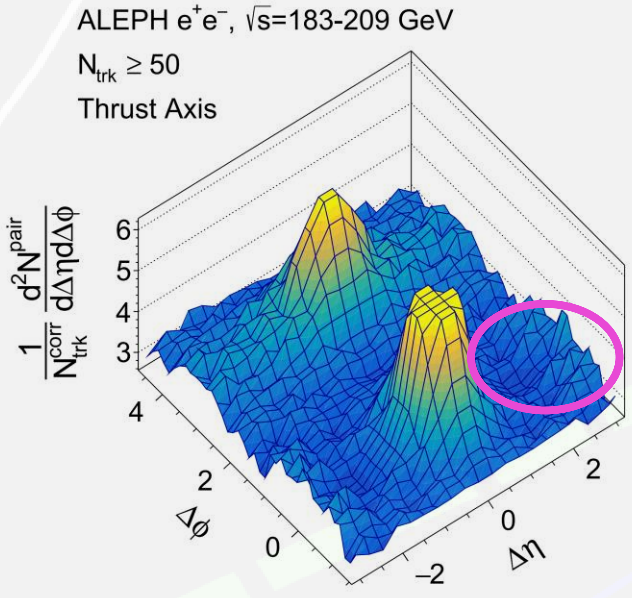


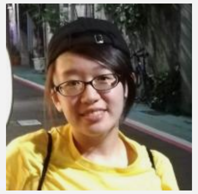
LEP2 N_{trk}>50



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





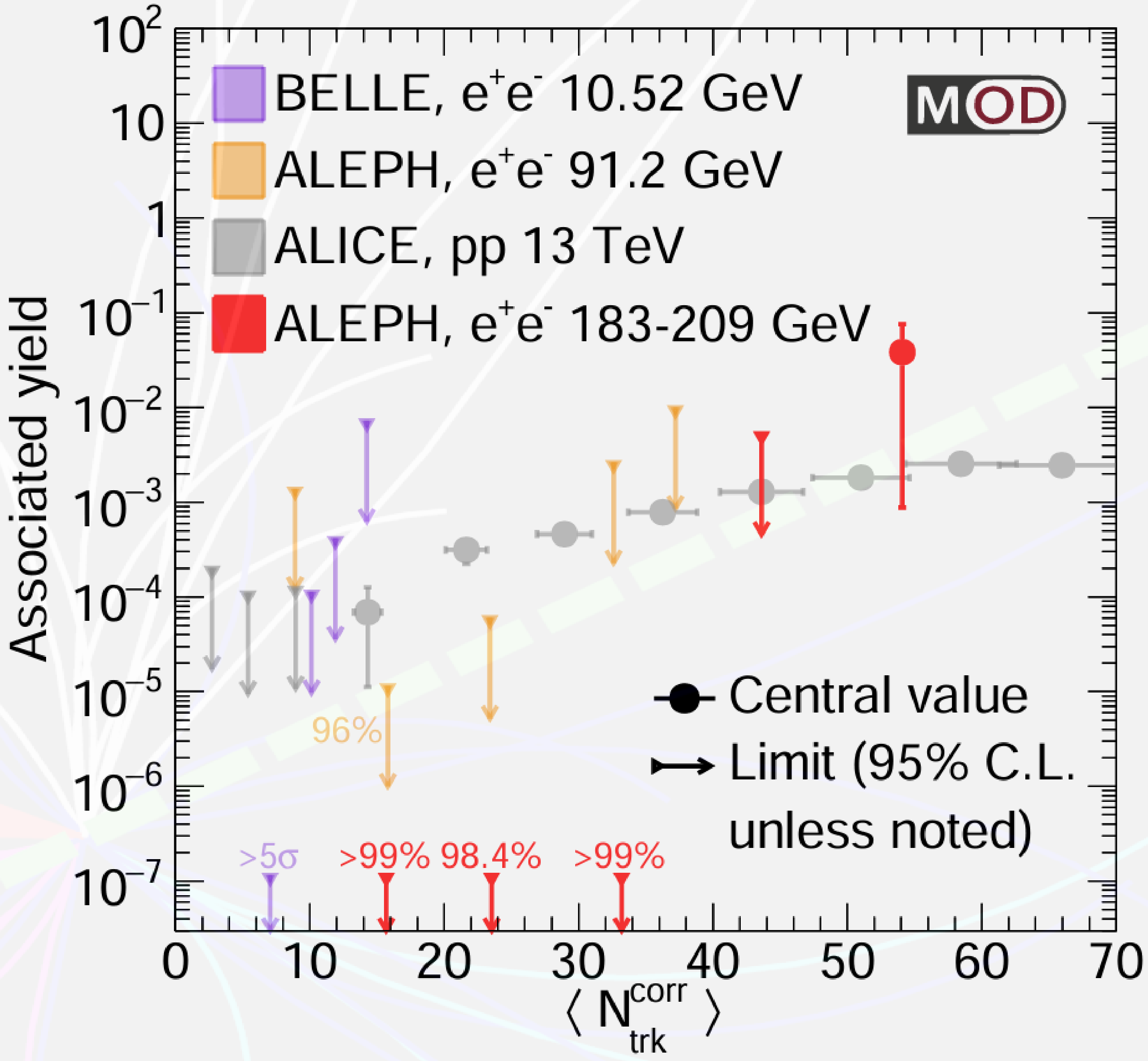


Yu-Chen "Janice" Chen (MIT)

arXiv:2312.05084
PLB 856 (2024) 138957

Associated Yield as a Function of Multiplicity

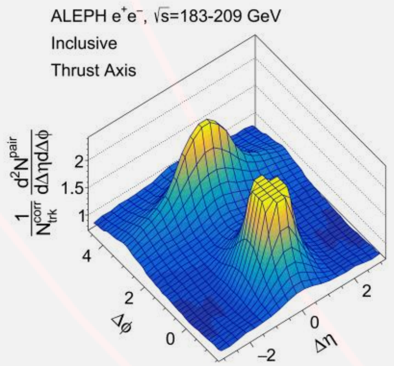
- Very tight upper limit set with **Belle**, **LEP1** and **LEP2** data set at low multiplicity (<40), lower than **ALICE** pp results
- Indication of an increasing trend at high multiplicity in LEP2 data
- Non-zero central value reported at the highest multiplicity bin with large statistical uncertainty



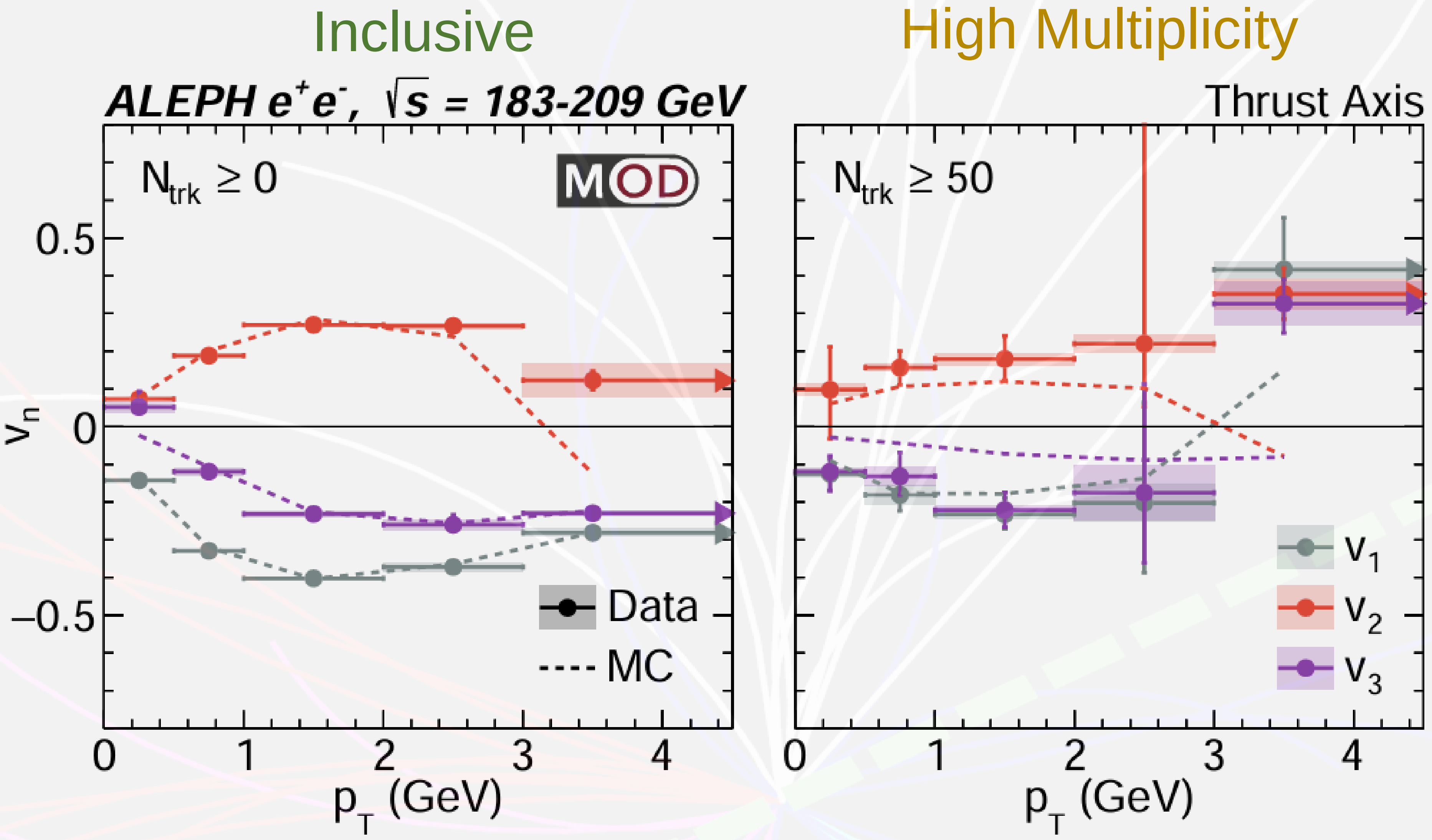
arXiv:2312.05084 PLB 856 (2024) 138957

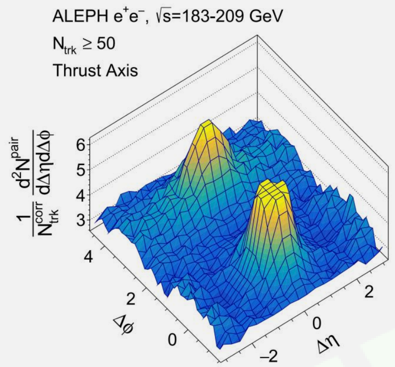
Analysis note: MITHIG-MOD-NOTE-23-011 (arXiv:2309.09874)

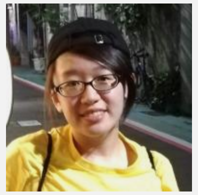
Extracted v_n vs. Charged Particle p_T



Inclusive | High Multiplicity





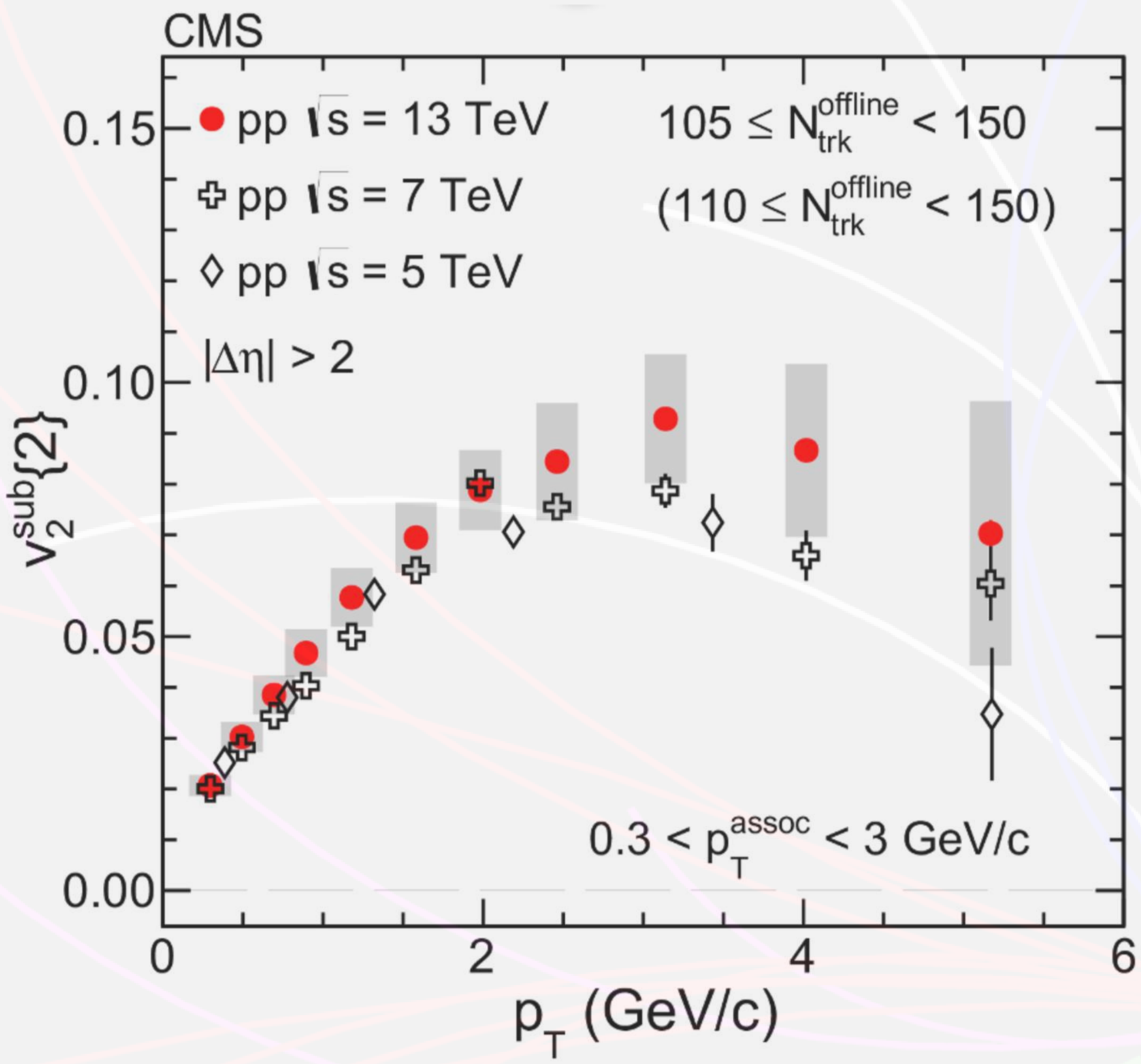


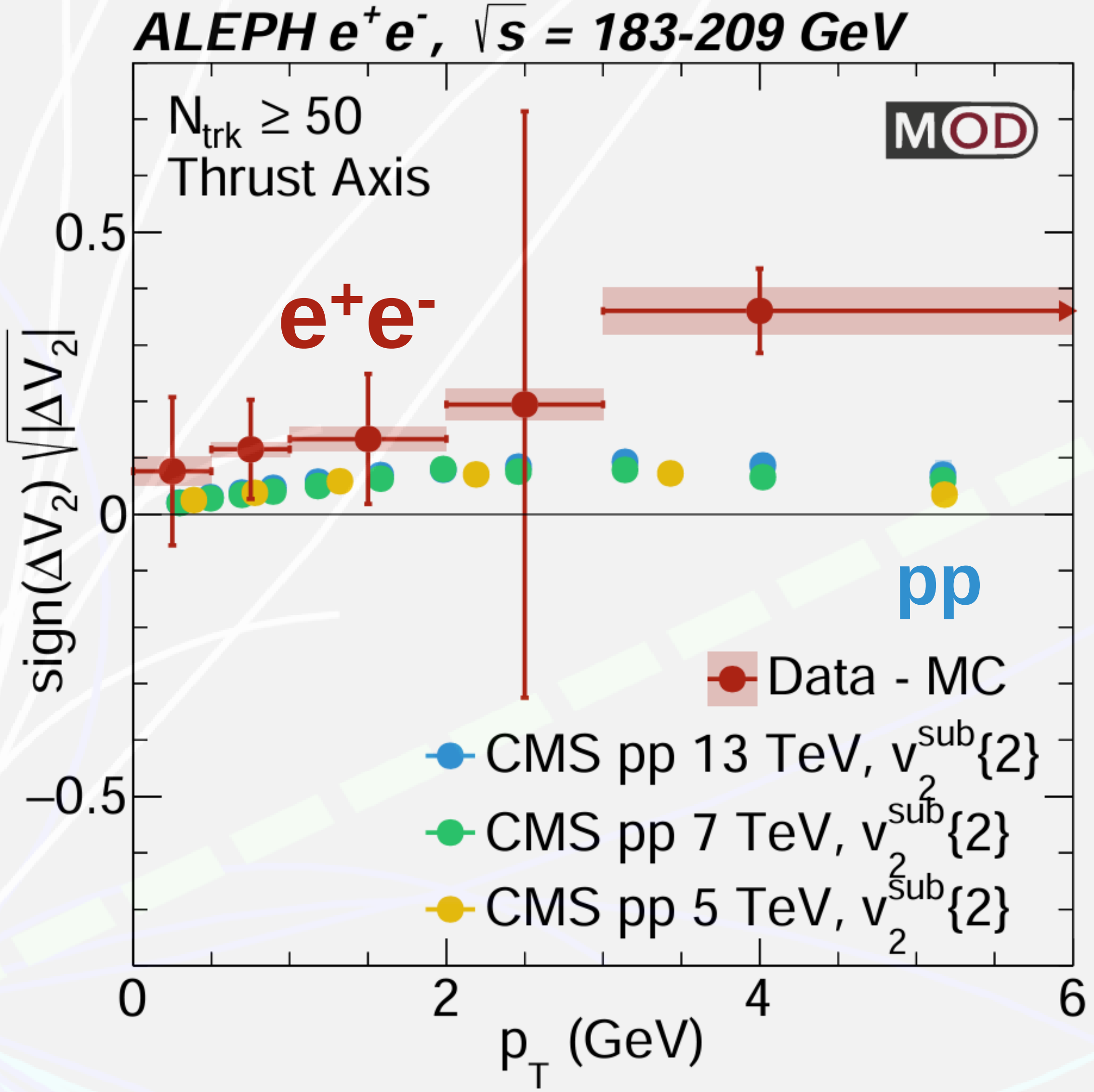
Yu-Chen "Janice" Chen (MIT)

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

arXiv:2312.05084
PLB 856 (2024) 138957

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

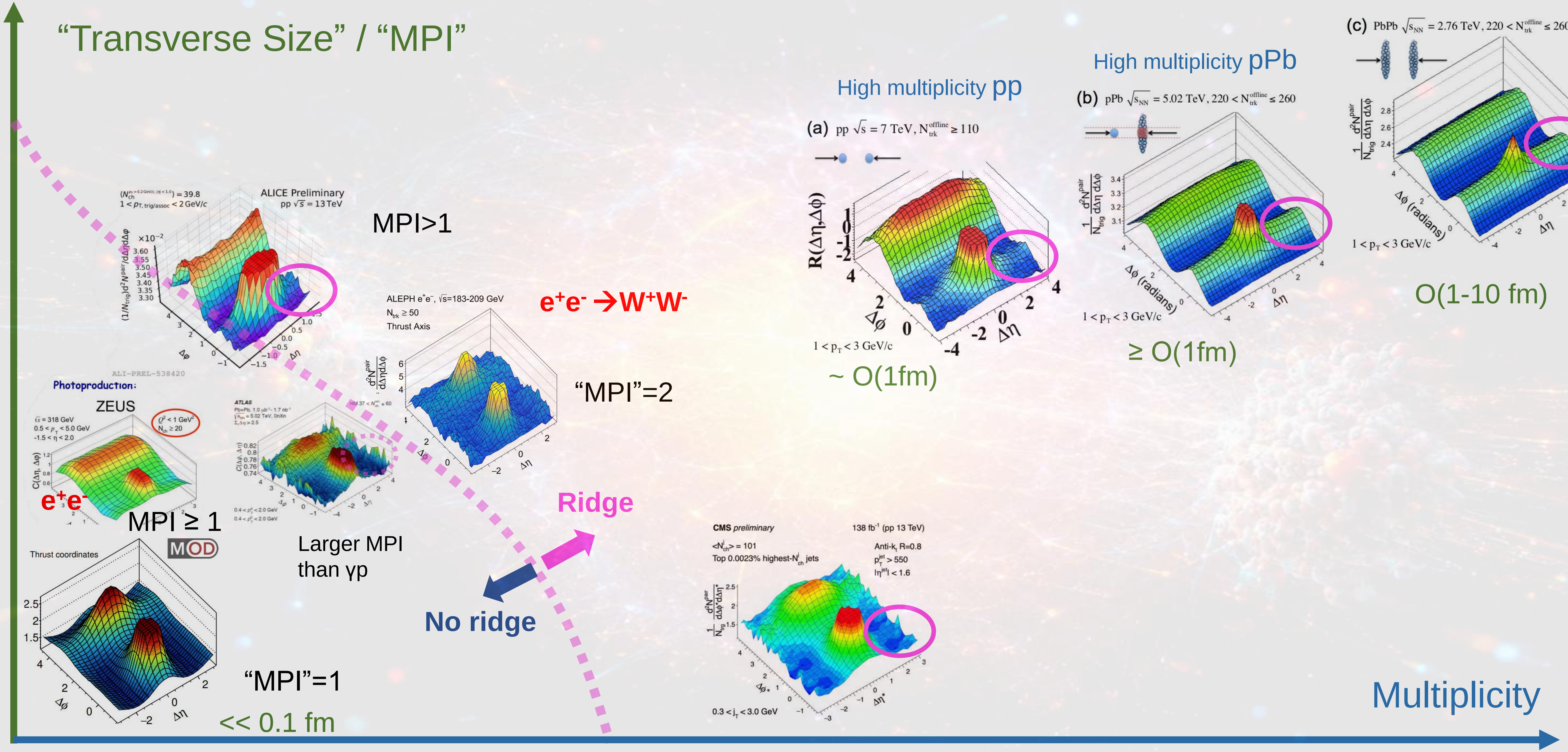




- MC based "Non-flow subtraction": $\Delta v_2 = v_2^{Data} - v_2^{MC}$
- Similar increasing trend in e^+e^- and pp data as a function of p_T

arXiv:2312.05084
PLB 856 (2024) 138957

Emerging Picture (Artist's impression)



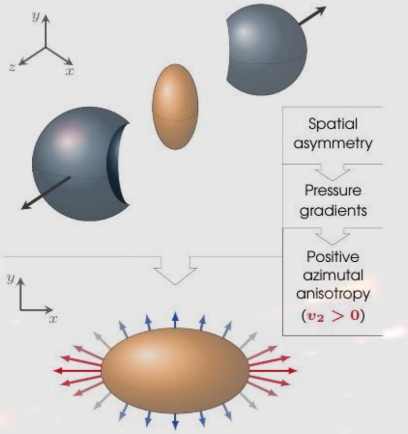
Going Against the Flow

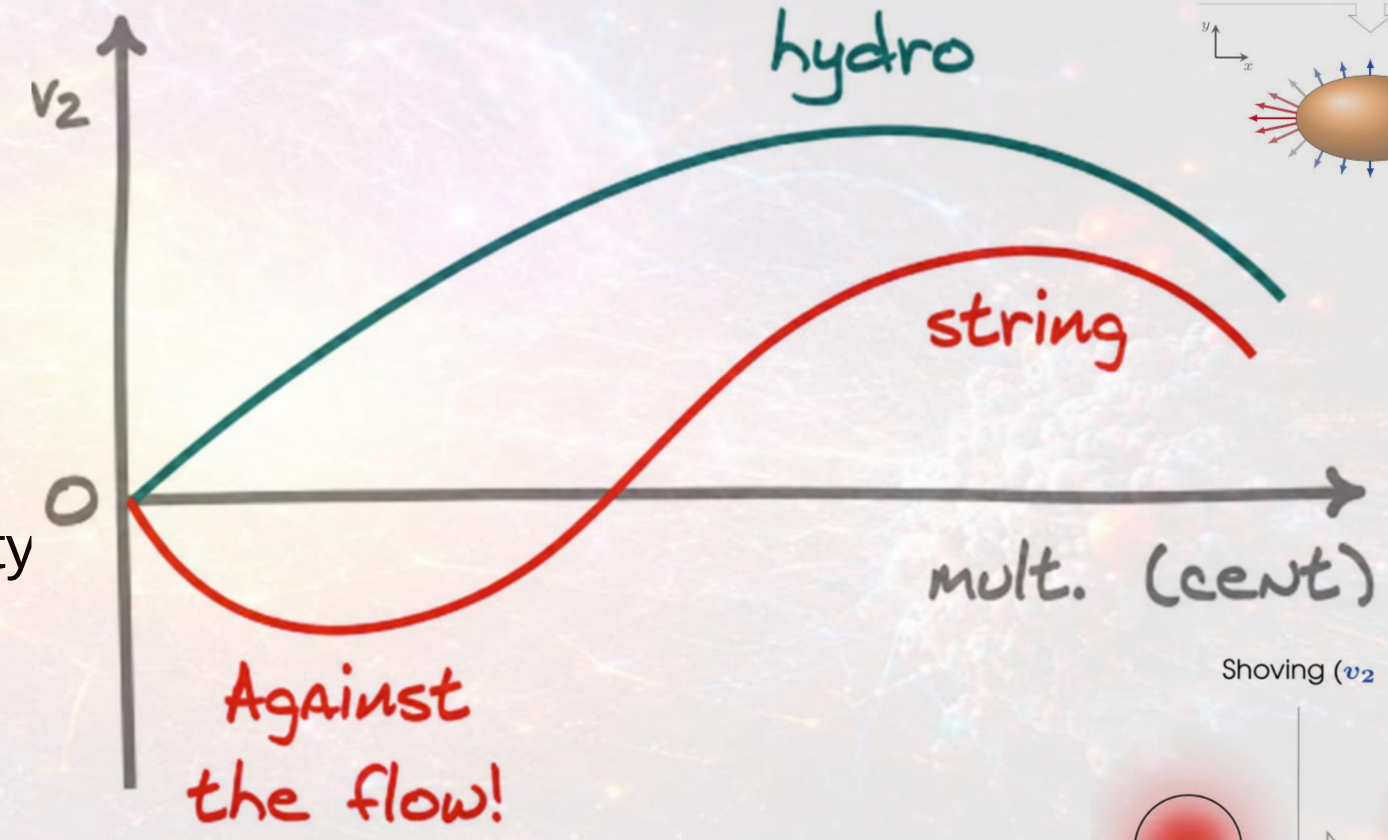
- **Going against the flow:**

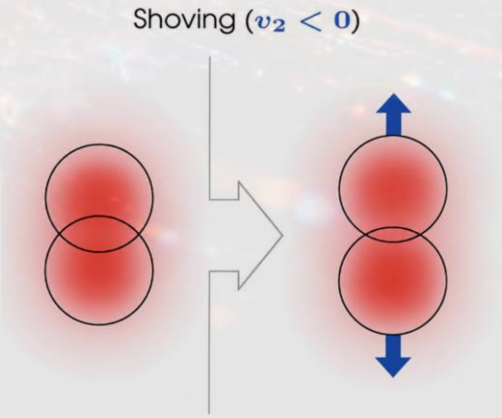
  negative v_2 prediction in small system size, contrary to hydrodynamic picture

- **Repulsion between string-like fields** can generate momentum anisotropy along the major axis, yielding $v_2<0$

- Sign-changing v_2 with system size/multiplicity is predicted by string-shoving and kinetic-theory calculations

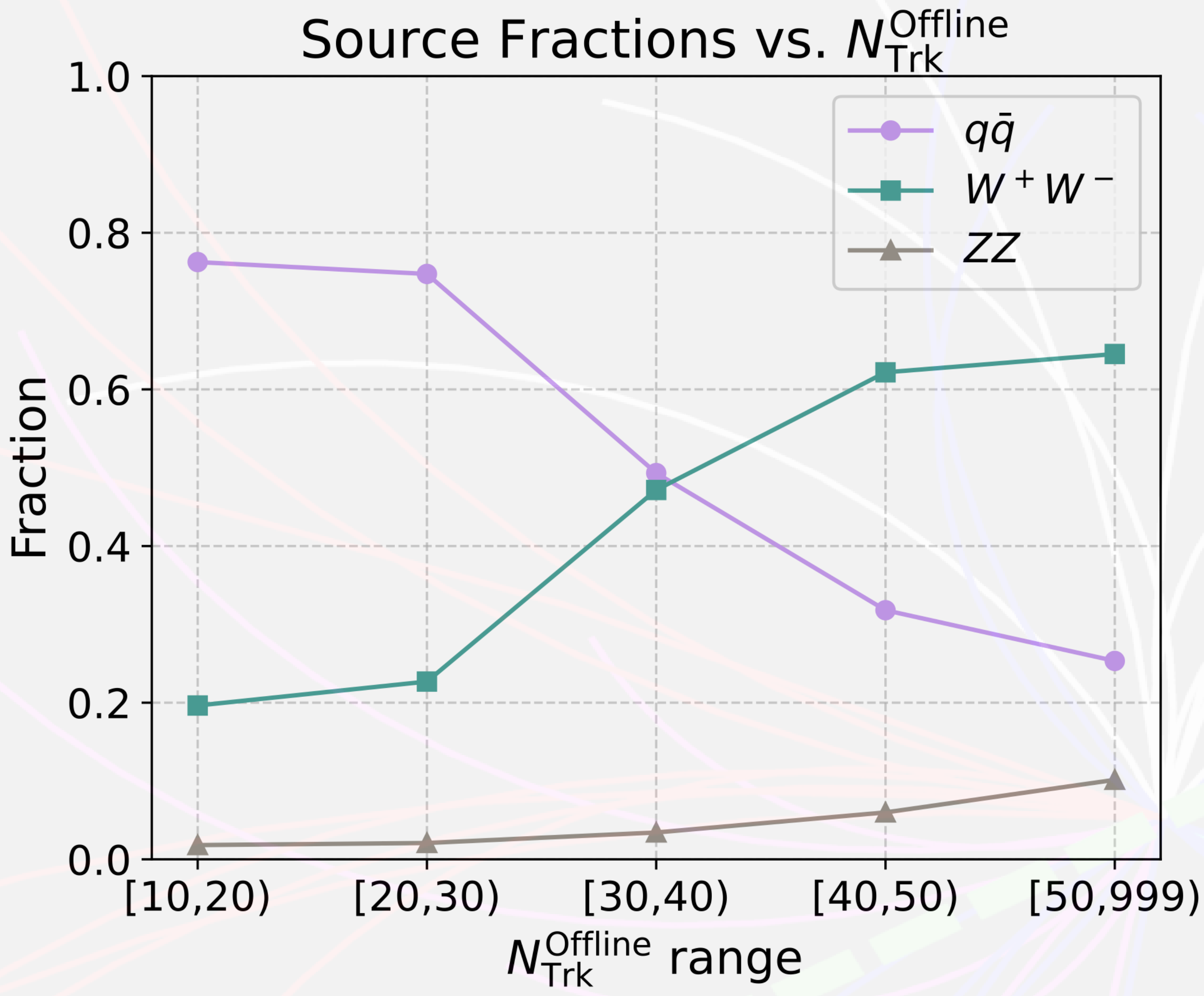




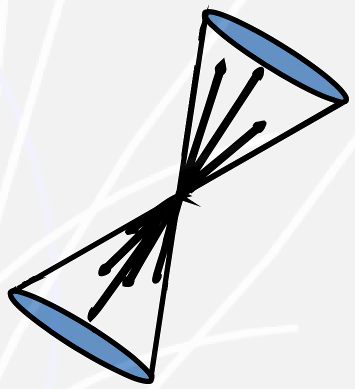


[arXiv:2409.16093](https://arxiv.org/abs/2409.16093)
[Phys.Lett.B 874 (2026) 140216]()

What does e^+e^- resolve parton configurations mean?

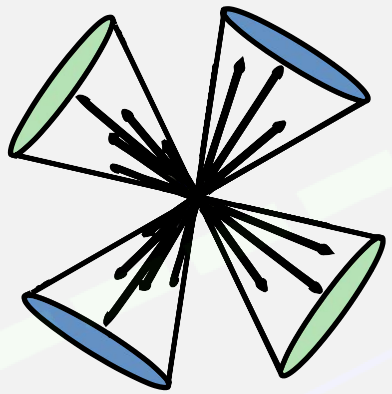


Single string baseline



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

Two strings collectivity test



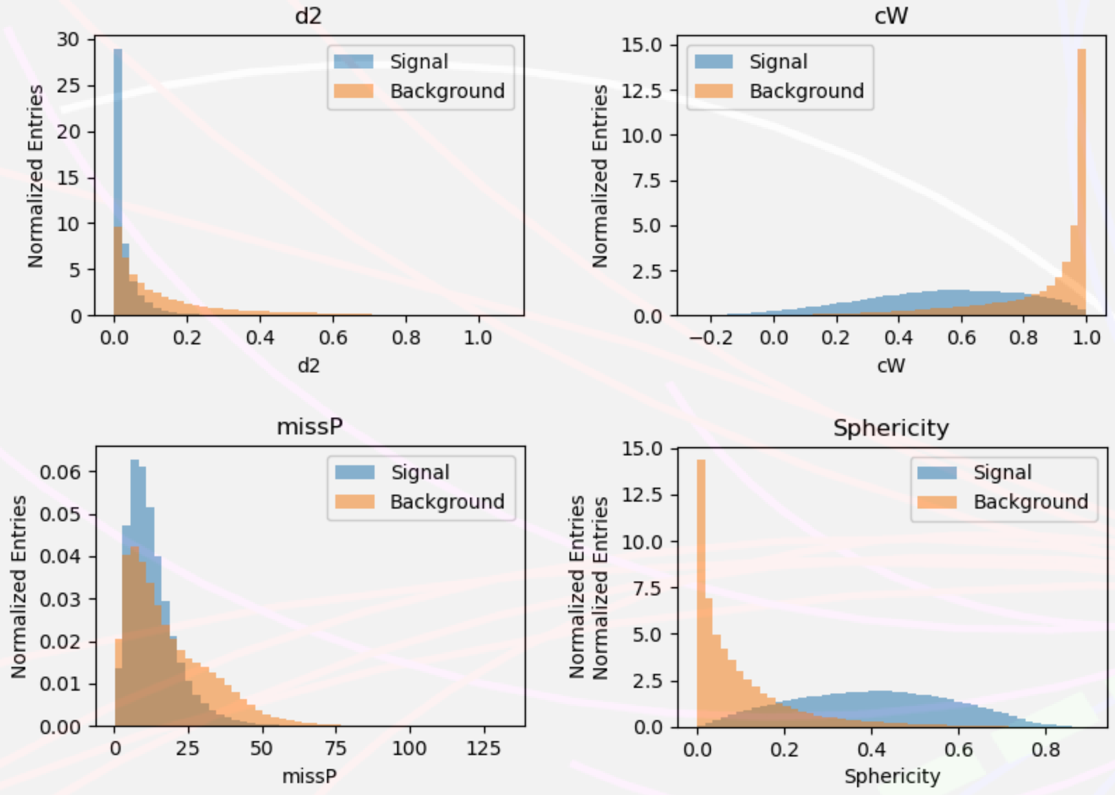
$$e^+e^- \rightarrow W^+W^- \rightarrow 4f$$

This event-by-event partonic-geometry handle is unavailable in pp/pA

Enrichment of 2-string purity with BDT

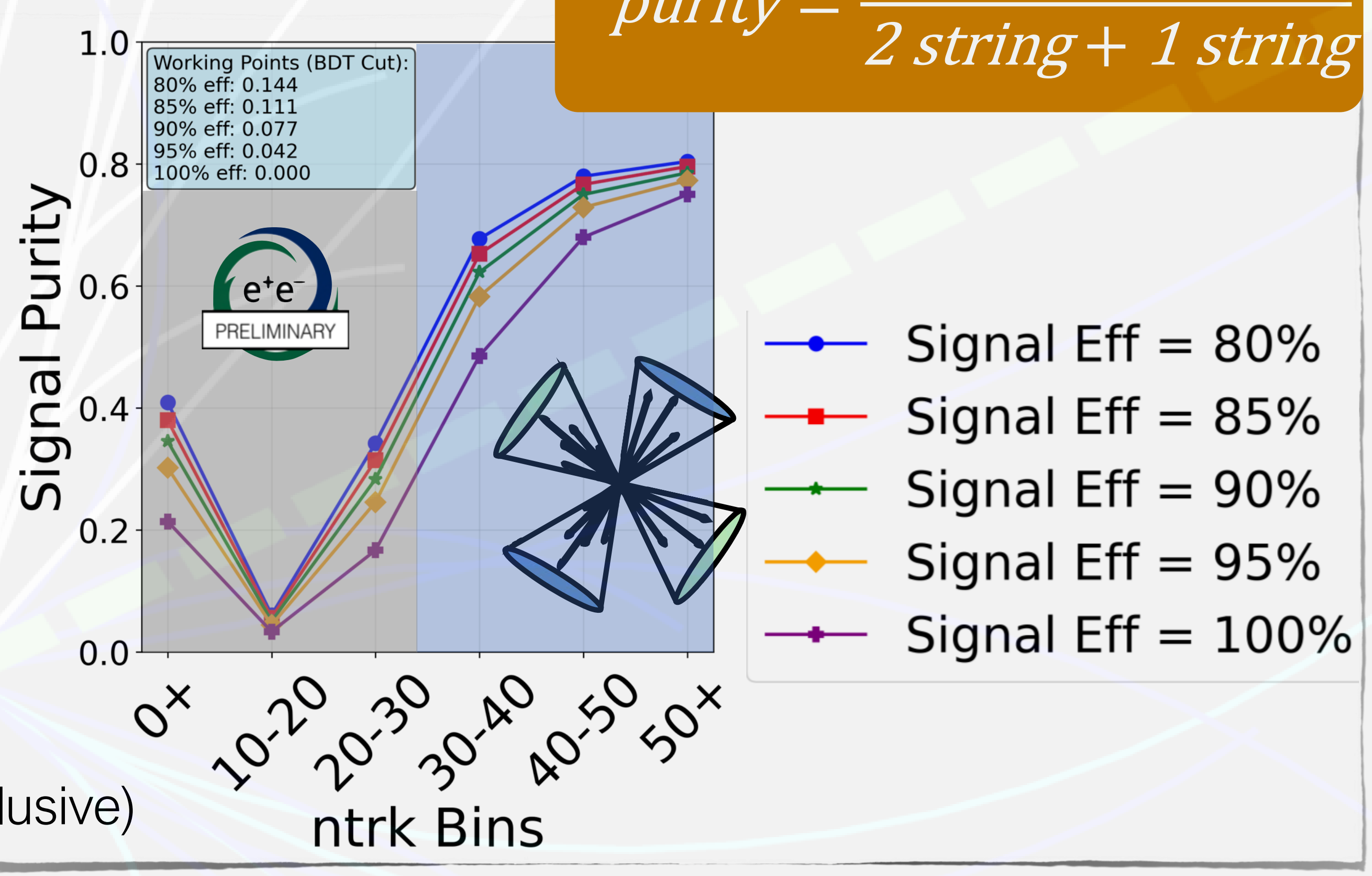
- Separate WW→4q (signal) from $q\bar{q}$ (background)

Input discriminants:
kinematics, 4-jet clustering



- Scan BDT working points to test ridge observables as **two-string purity** increases

$$purity = \frac{2\ string}{2\ string + 1\ string}$$

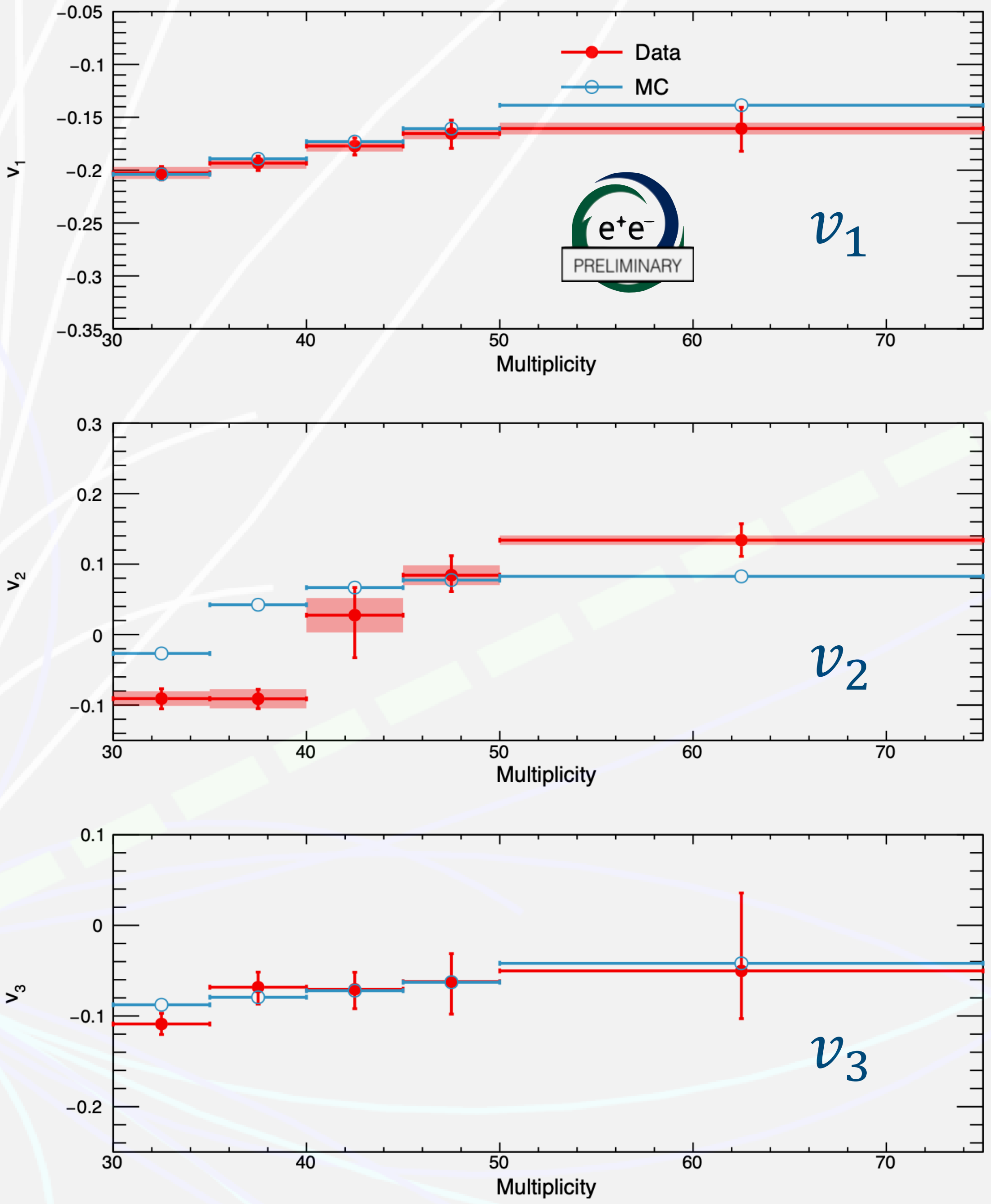


v_n extraction with WW-enhanced dataset

- Flow coefficients $v_n(2, 1.6 < |\Delta\eta| < 3.2)$ extracted from long-range correlation
  - v_1, v_3: Decreasing magnitude as multiplicity grows; data and MC show good agreement
  - v_2: Data visibly flips sign, more drastic than MC

$$v_2^{\mathrm{sgn}} = \mathrm{sign}(V_{2\Delta})\sqrt{|V_{2\Delta}|}$$

arXiv:2606.21094

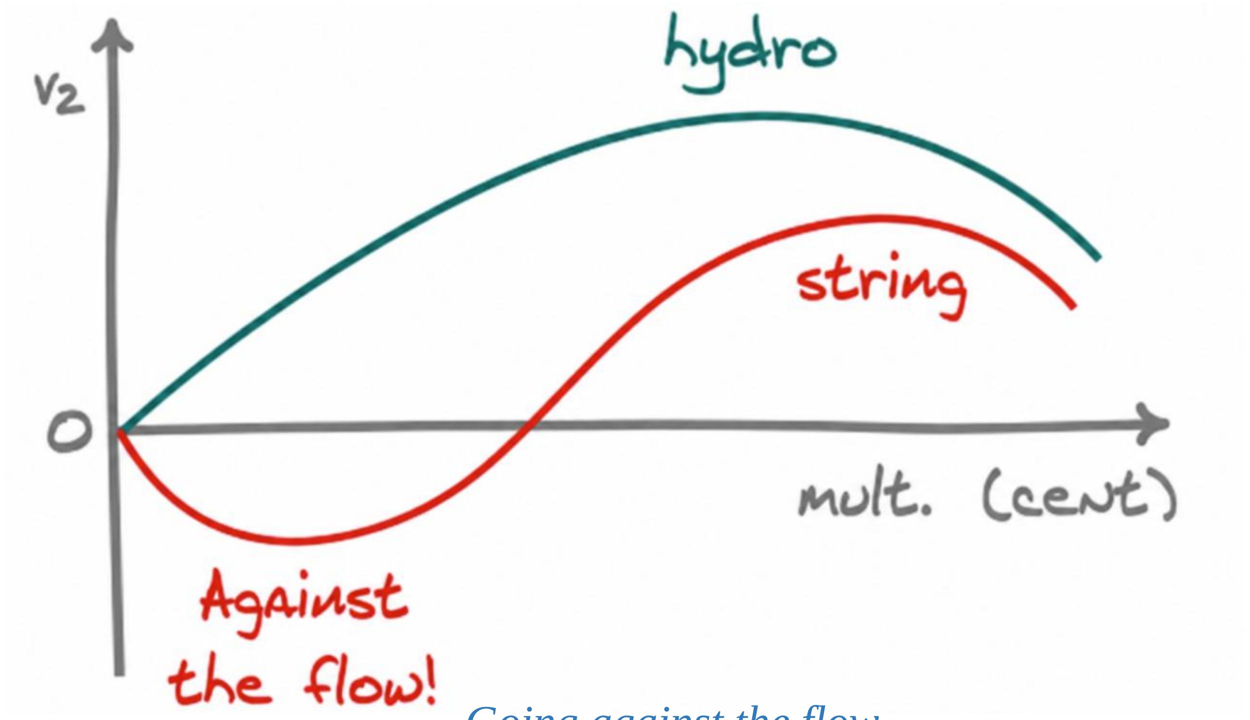


Sign-changing v_2 as a function of NTrk

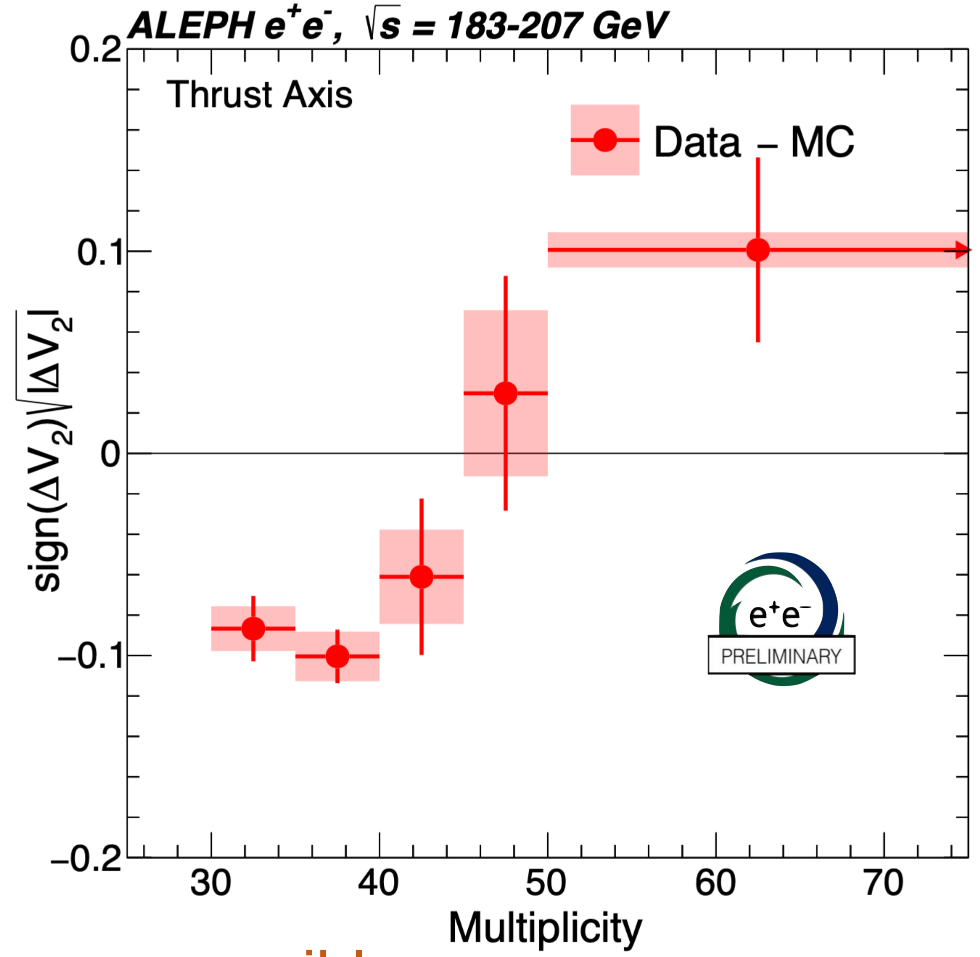
- v_2 modulation is quantified by $\mathrm{sign}(\Delta V_2)\sqrt{|\Delta V_2|}$: $\Delta V_2 = V_2^{Data} - V_2^{MC}$

  A **sign change** in data-MC ΔV_2 proxy is observed!

  Note that this doesn't necessary mean we observe negative v_2 since this is a two particle correlation measurement



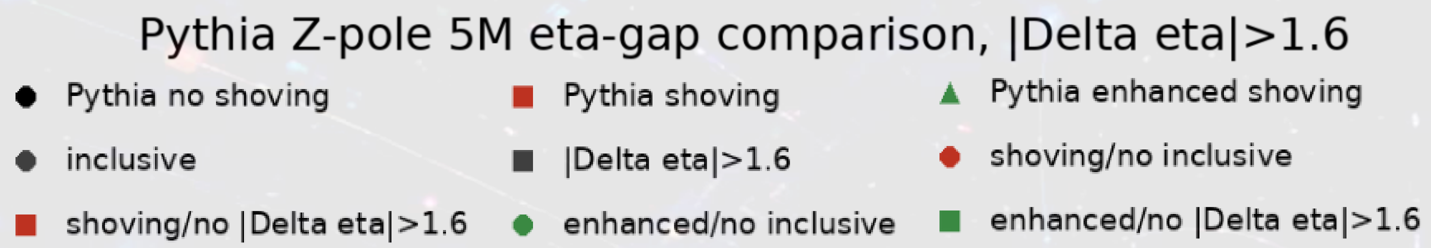
Going against the flow
arXiv:2409.16093

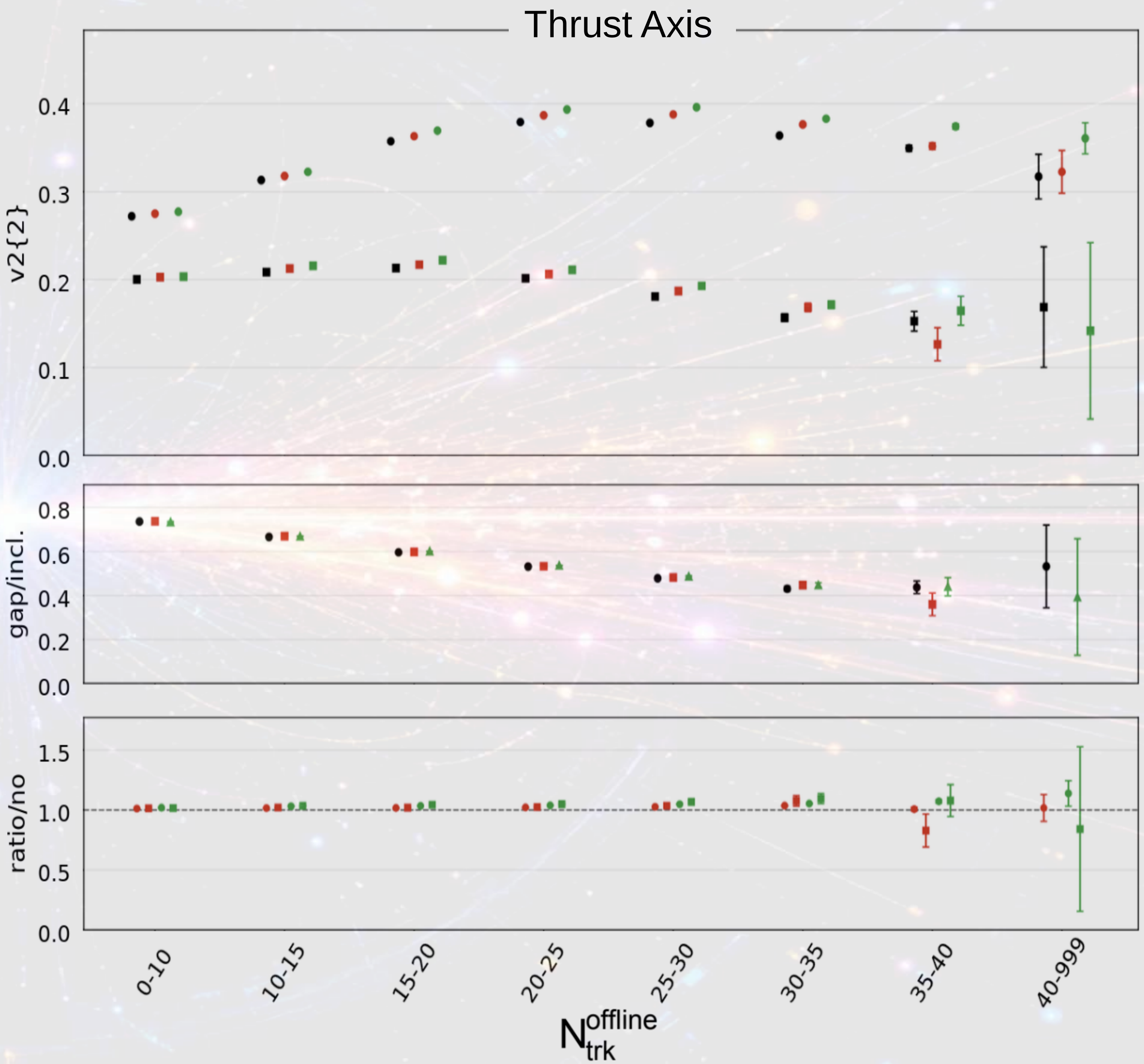


- Independent cross-checks with DELPHI & OPAL data are possible

arXiv:2606.21094

String-shoving Response in Two-Particle Cumulants

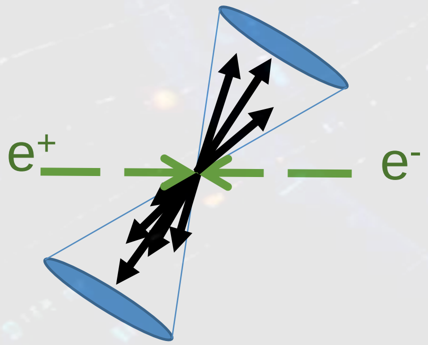


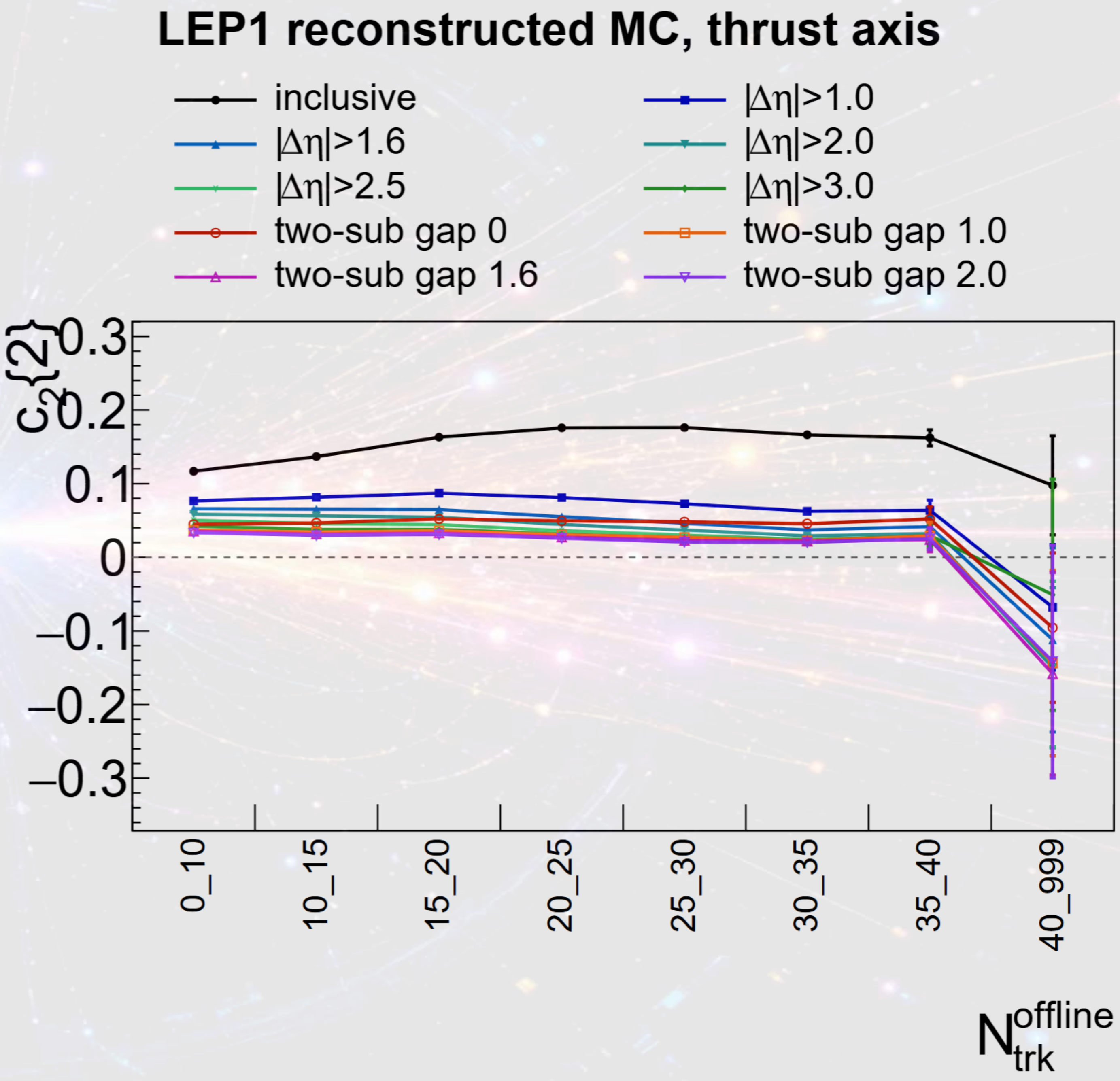


- PYTHIA8 string-shoving branch: Gleipnir models repulsive interactions between color strings (private communication)
- Configs: **No shoving** / **Nominal** / **Enhanced**
  - Nominal: repulsionFactor = 0.25;
  - Enhanced: 0.50
- Effect: small beam-axis changes, larger **thrust-axis** v_2 shifts

Next: Collectivity with Subevent

- Subevent method and large rapidity gap could suppress $c_2\{2\}$
- Combination of large rapidity gap and subevents could suppress the nonflow
- However, significant nonzero $c_2\{2\}$ still present in the largest rapidity gap setting

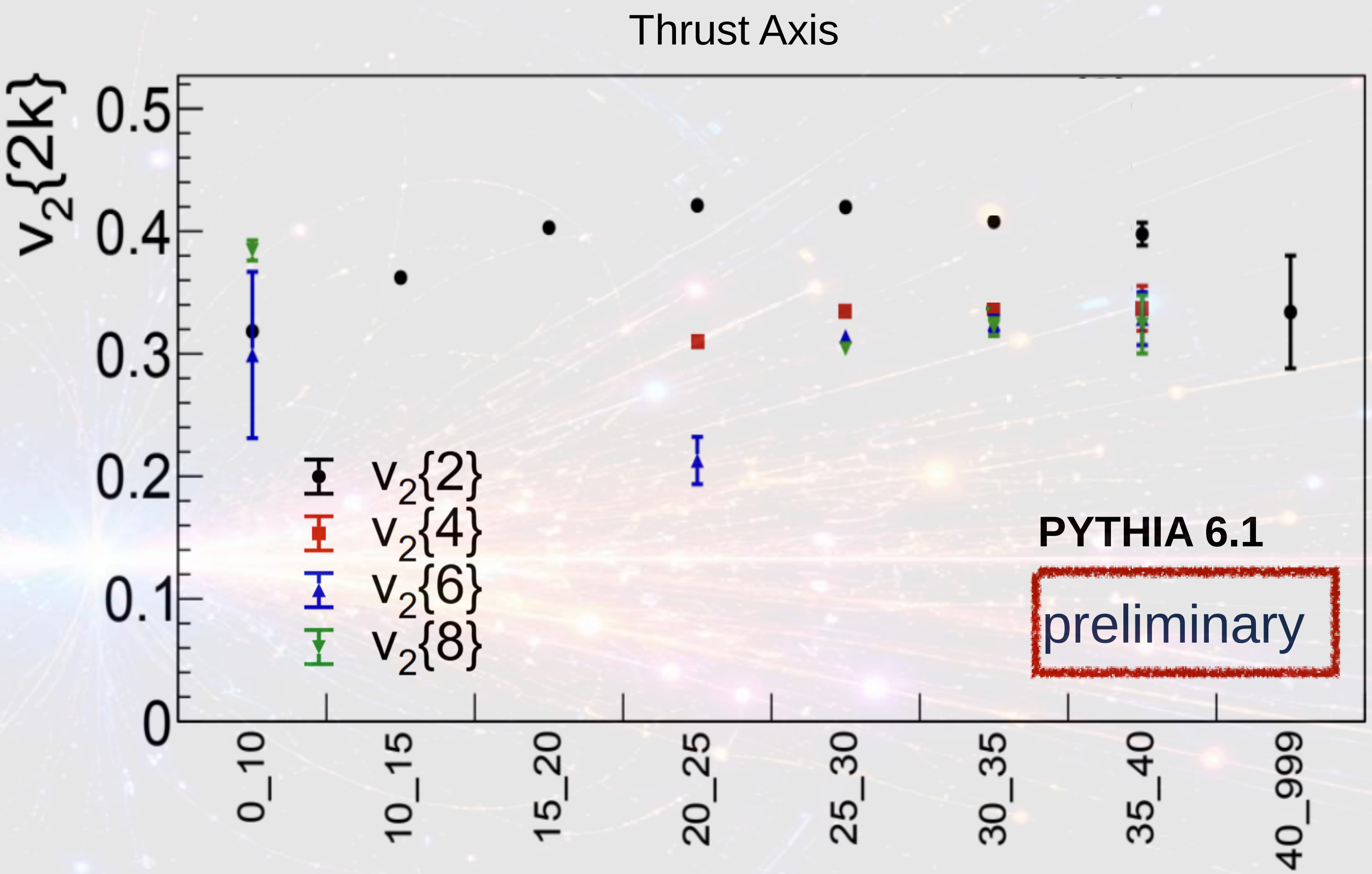


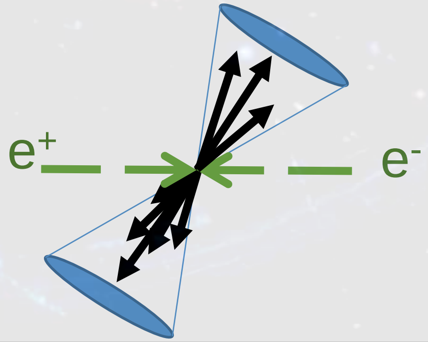


Next: Collectivity with Multi-particle Cumulant

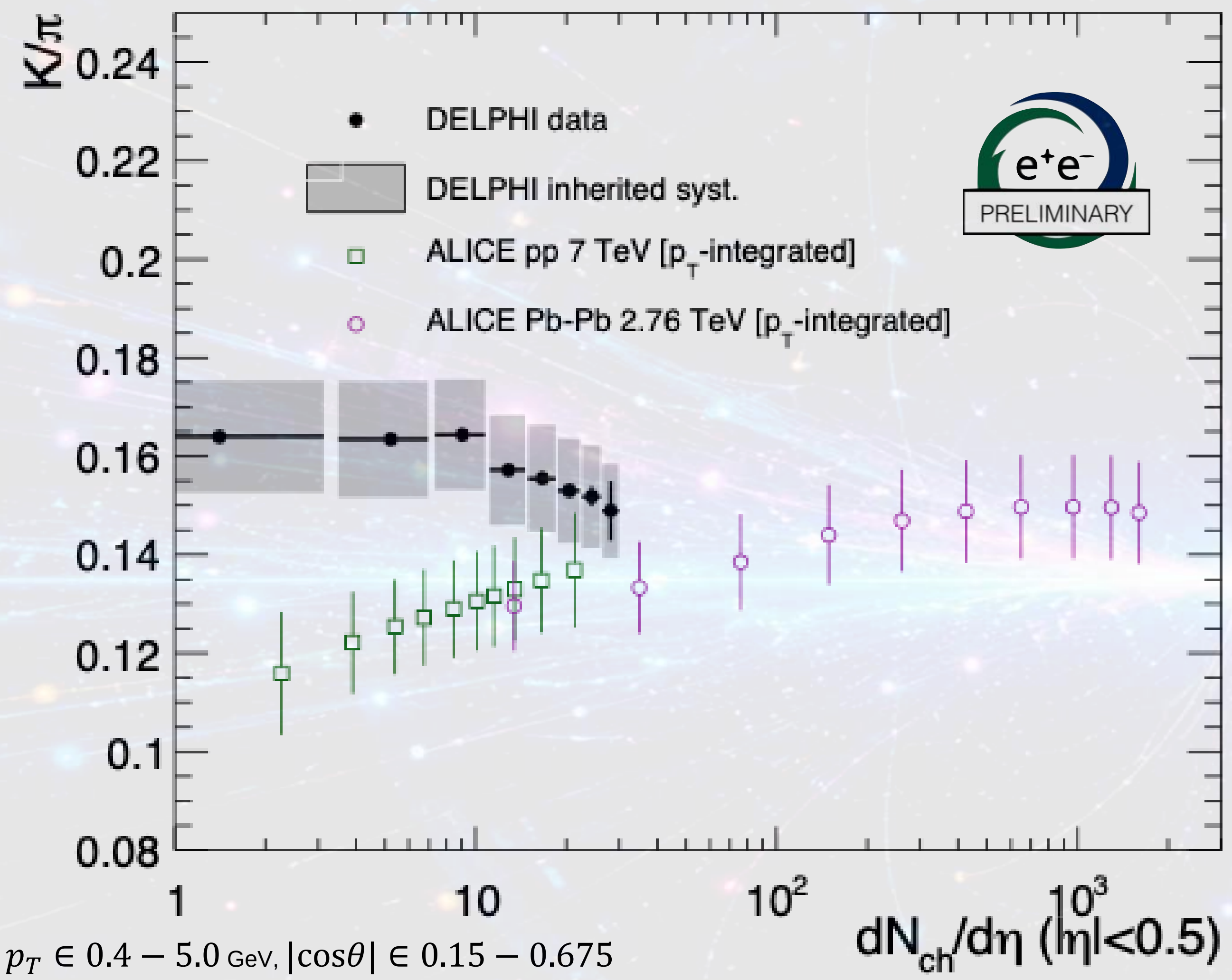
- Multi-particle cumulants could provide a more stringent test of collectivity behavior
- Current exploration with generator-level LEP1 MC:
  - Sufficient statistics enables up to $v_2\{8\}$ extraction with LEP1 statistics
  - Non-zero high-order cumulants can arise even in MC sample without hydrodynamic collectivity

➡ What is the appropriated nonflow-suppressed observable, or non-flow subtraction technique to assess collectivity?

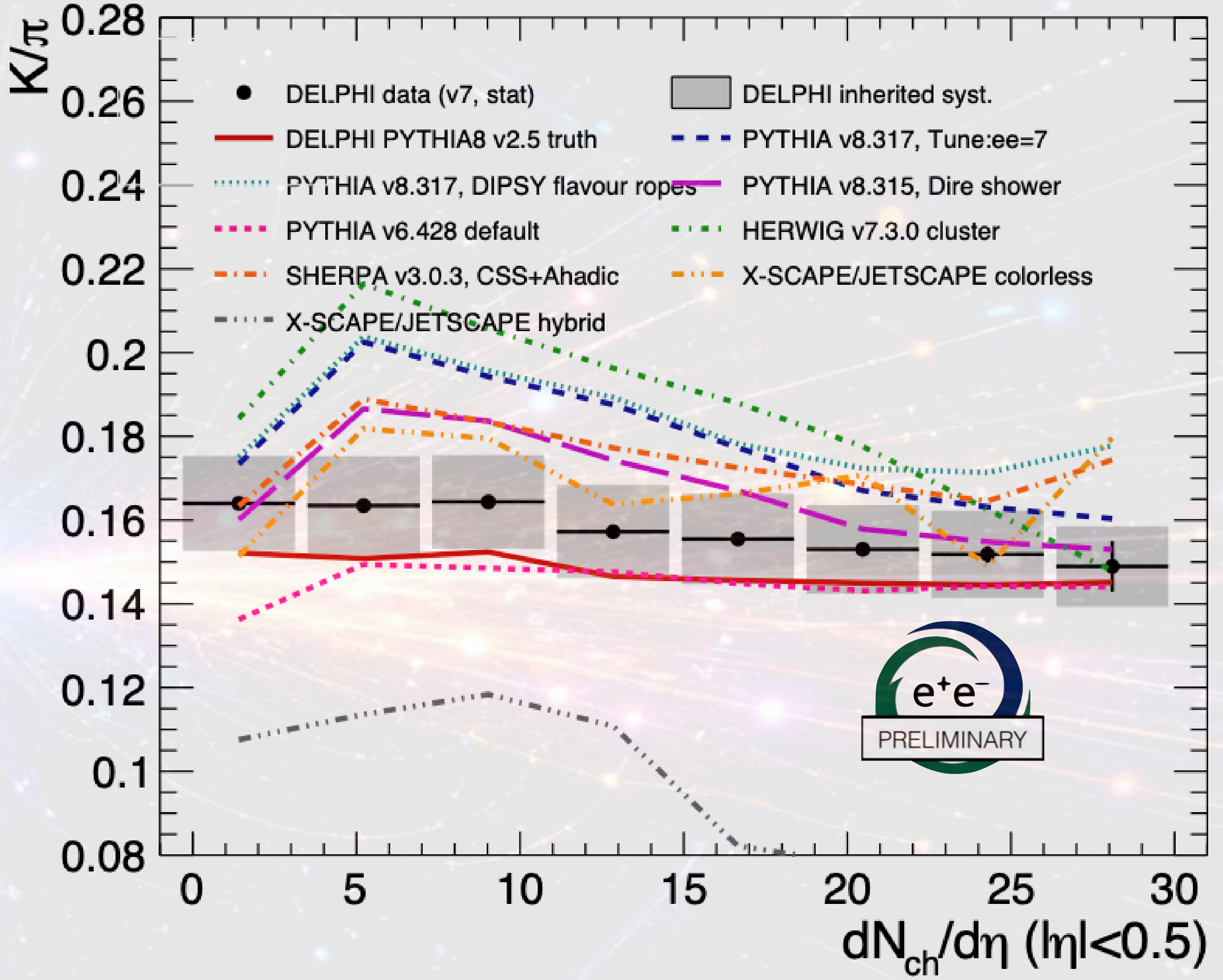




K/π Ratio vs. Event Multiplicity in Z→Dijet Events



$p_T \in 0.4-5.0$ GeV, $|\cos\theta| \in 0.15-0.675$



- Doesn't follow the **pp** and **PbPb** trend
- Higher dN/dη: quark fragments into more partons → reduced number of strange quarks.

- Generators predict the decreasing trend
- Different results from various generators → new input to generator tuning

Lessons Learned from Collectivity Searches

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

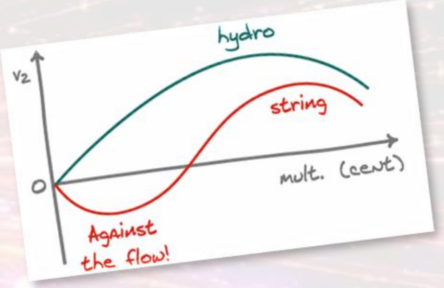
  Large MPI and/or high multiplicity events help reducing the $\mathbf{V_{1\Delta}}$ and directly reveal the ridge

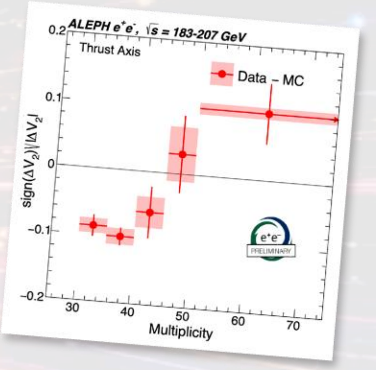
- Can detectable collectivity arise from final state effects unrelated to the initial state?

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

- How does collectivity vary in different physics processes?

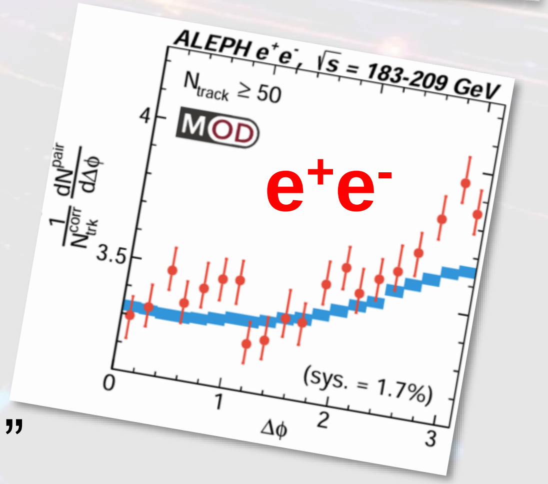
  Single-string $e^+e^- \rightarrow qq$ gives the null baseline.
  Two-string LEP2 $e^+e^- \rightarrow W^+W^-$ is the cleanest final-state geometry test





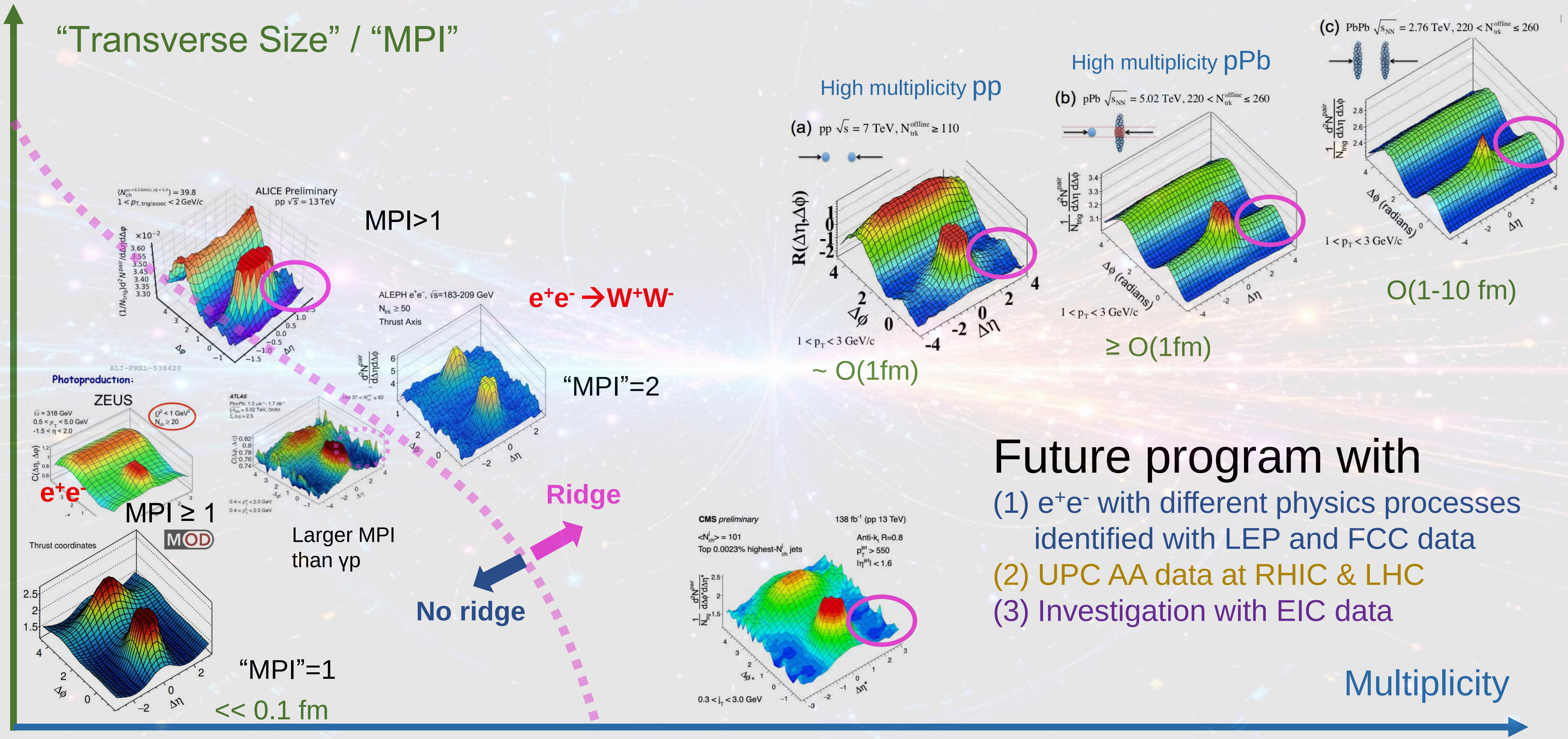
- Is the underlying physics the same in small and large systems?

  Data suggest that small systems lacking hadronic initial state effects could still yield a ridge-like signal.



These data suggest final-state collectivity-like correlations can emerge even without hadronic initial-state structure; the mechanism remains to be determined."

Emerging Picture (Artist's impression)



Future program with

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

(2) UPC AA data at RHIC & LHC

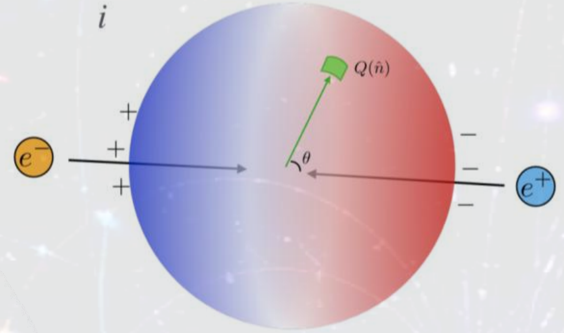
(3) Investigation with EIC data

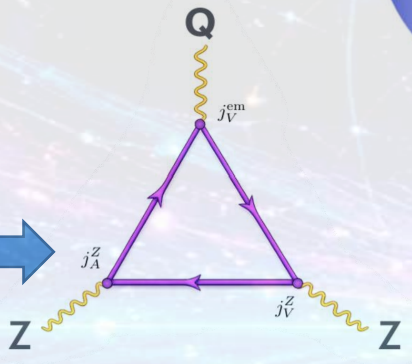
Backup Slides

Agentic Analysis of Charge Flux in e^+e^- Collisions

Start from a blackboard drawing in KITP UCSB presenting the calculation to us

$$Q(\theta) = \sum_i q_i \delta(\theta - \theta_i)$$





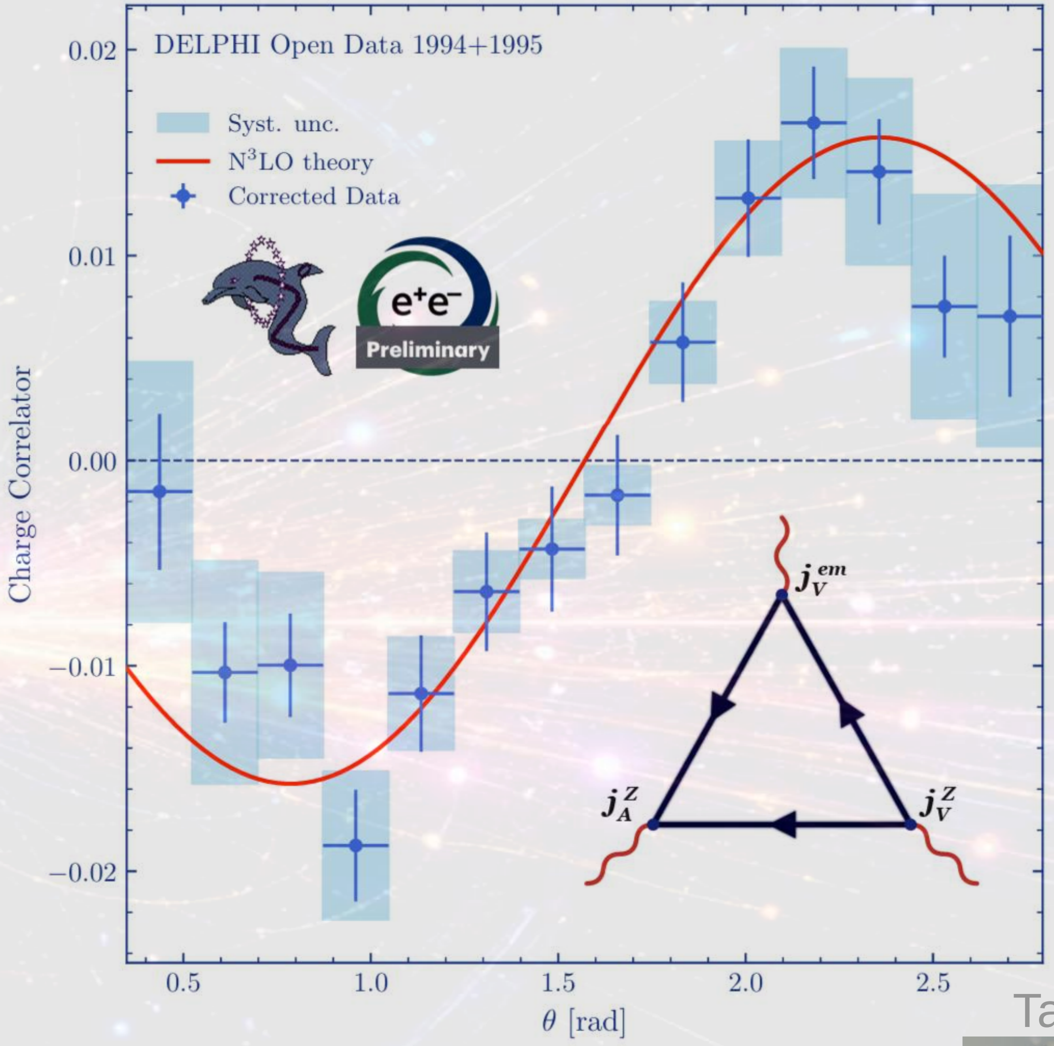
K. Lee
(Argonne)

I. Moult
(Yale)

It took just **3 days** for agentic AI to extract the first result with estimated systematics

Kyle and Ian are "in the loop" via comments in overleaf where the agents are programmed to check periodically the comment section

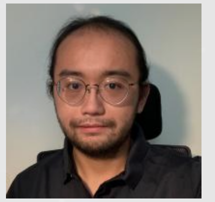
Agentic AI was able to identify data and MC difference on anti-proton modeling. However, **failed to produce a fully data-driven correction**



Human carried out results are consistent with agentic AI with a sophisticated $Z \rightarrow \tau^+ \tau^-$ based data-driven correction

Preliminary results are shown in **LHCP 2026**

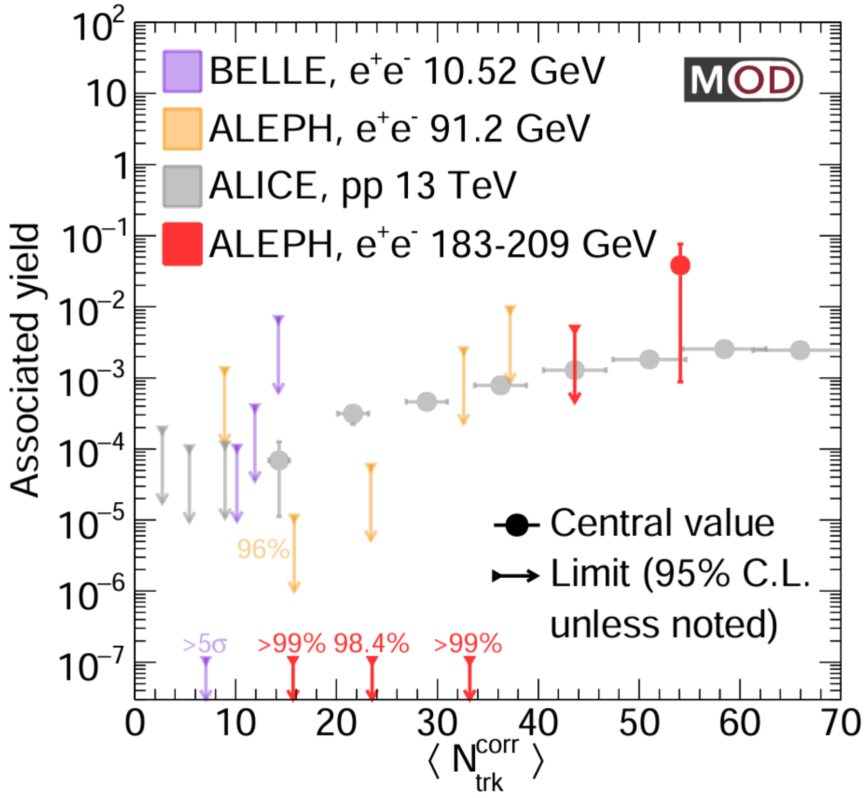
Talk

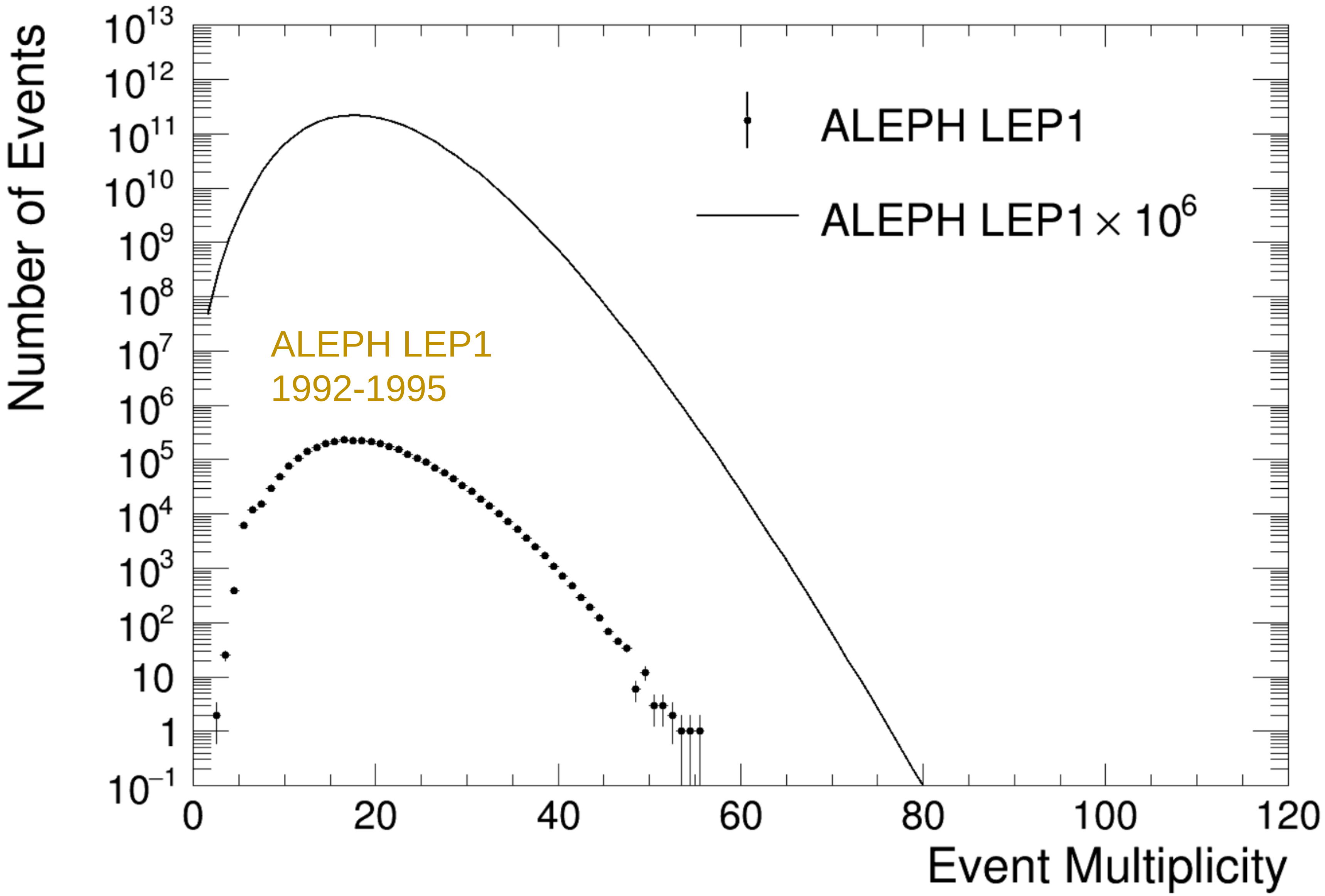


Jingyu Zhang
(Vanderbilt)

Long term future: Projection to FCC-ee

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



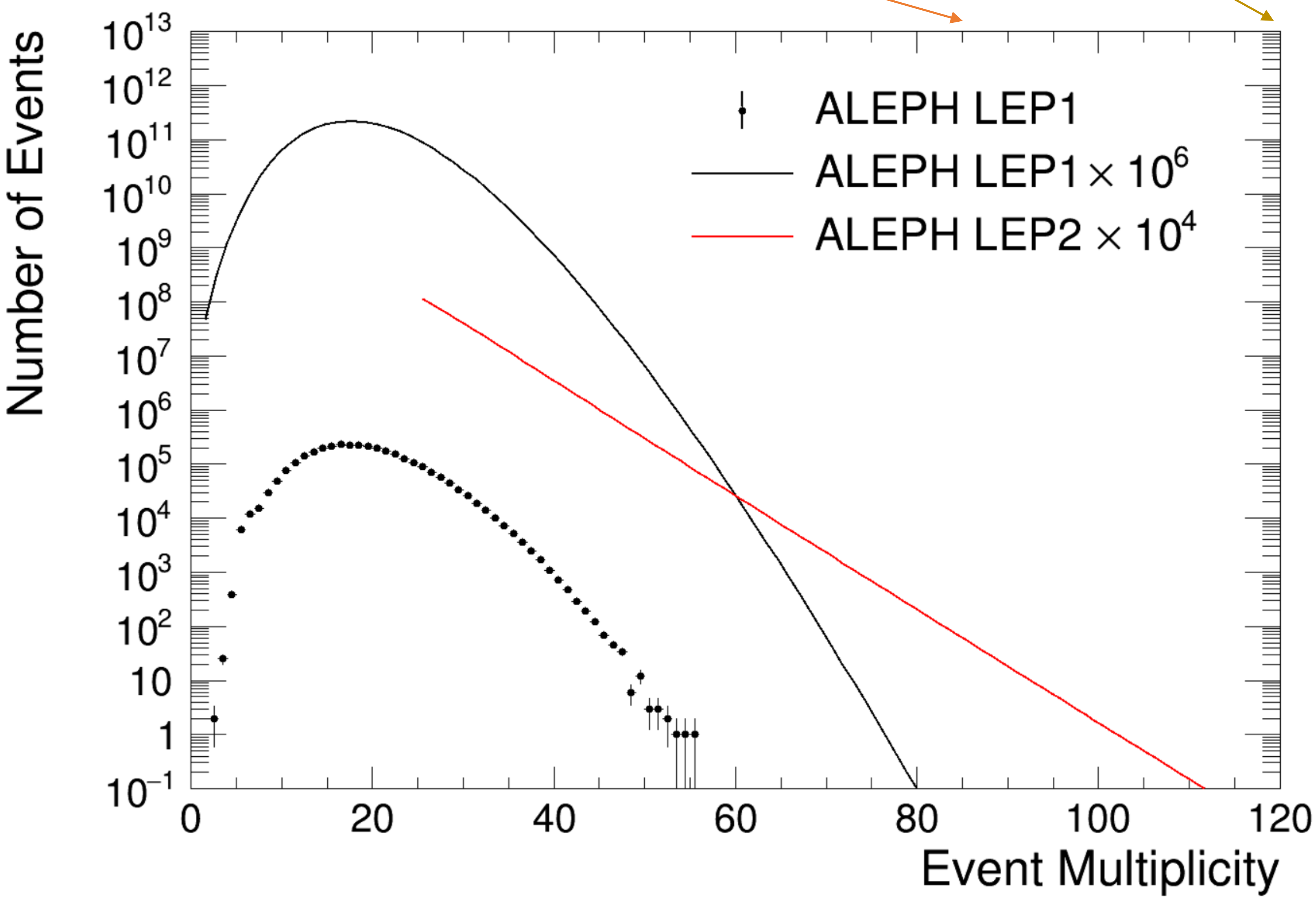


Projection to FCC-ee

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

p-Pb 10-20% at 5 TeV

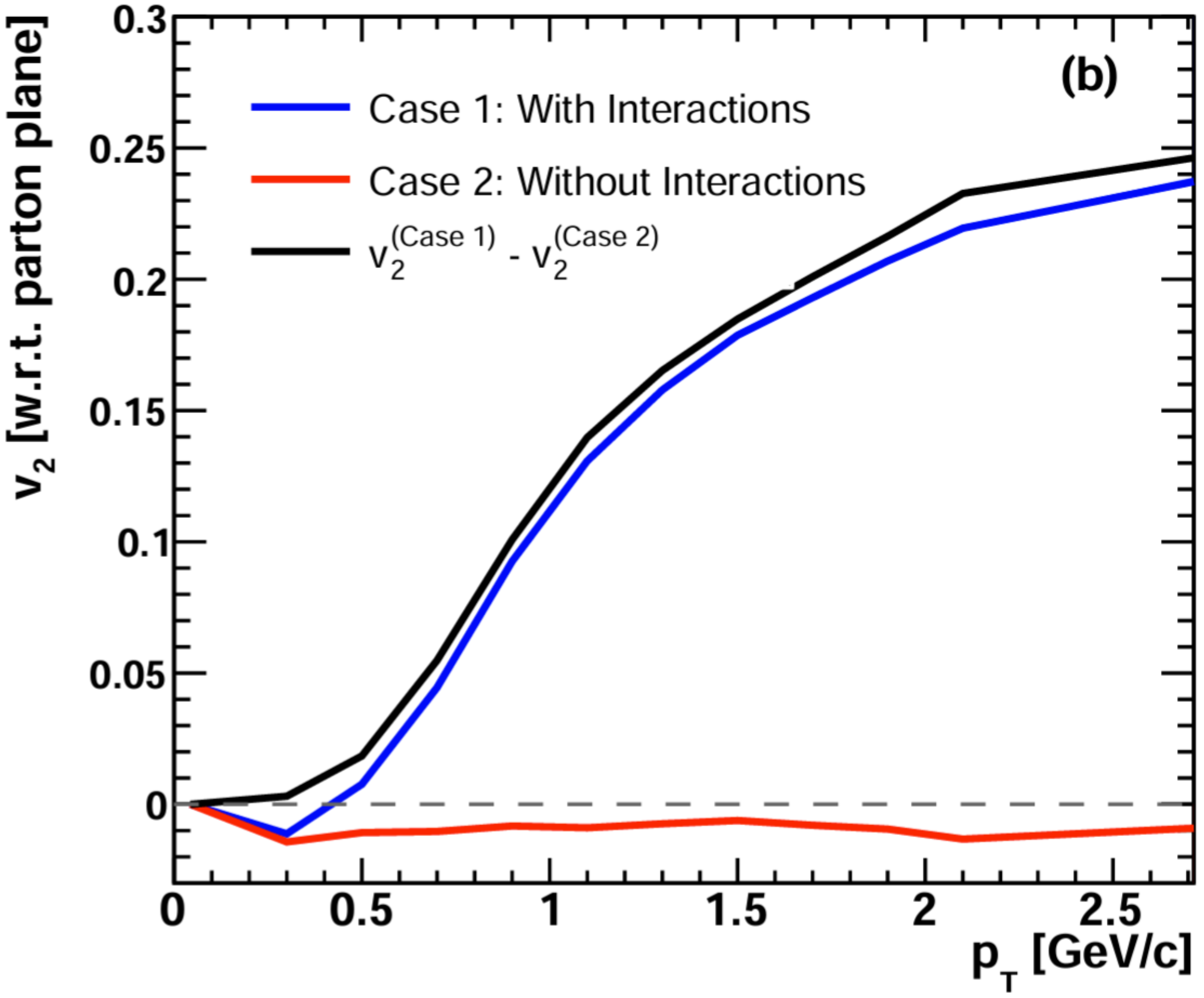
p-Pb 0-10% at 5 TeV

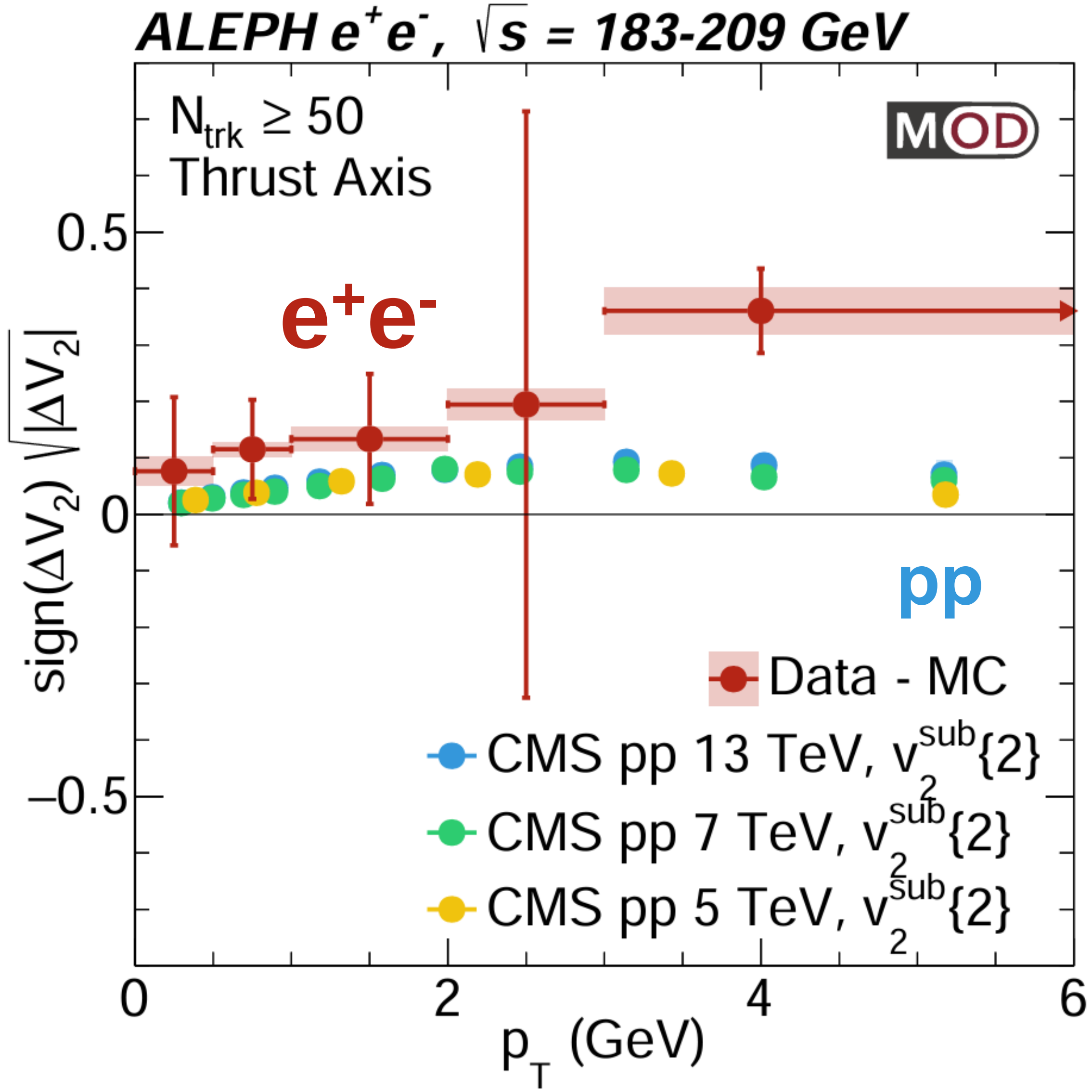


Selected List of Analyses

- e^+e^-
  - ALEPH LEP1 (91 GeV) PRL 123 (2019) 21, 212002
  - ALEPH LEP2 (183-209 GeV): https://arxiv.org/pdf/2312.05084
  - Belle Off-resonance (10.52 GeV) : PRL 128 (2022) 14, 142005
  - Belle On-resonance (Υ(4S)): JHEP 03 (2023) 171
- γp
  - CMS pPb photonuclear: PLB 844 (2023) 137905
  - ZEUS ep neutral current DIS: JHEP 04 (2020) 070
  - ZEUS ep photonuclear: JHEP 12 (2021) 102
  - H1 ep neutral current DIS: (preliminary) H1prelim-20-033
- γPb
  - ATLAS PbPb photonuclear: PRC 104 (2021) 1, 014903
- pp
  - ALICE MB: https://arxiv.org/pdf/2311.14357.pdf
  - CMS Single Jet in pp: CMS-HIN-21-013 arXiv:2312.17103

Δv_2 in e^+e^-





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

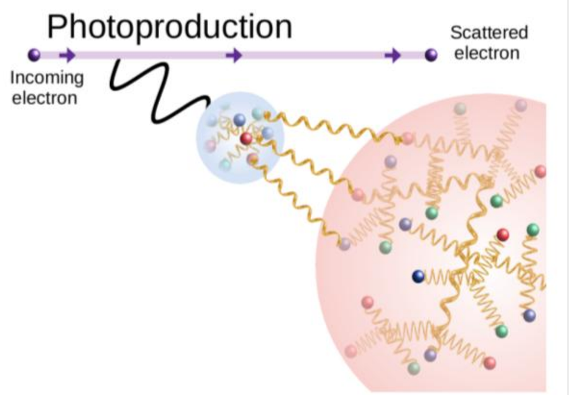
Jamie Nagle, Zi-Wei Lin, et al, PRC 97 (2018) 2, 024909

arXiv:2312.05084 PLB 856 (2024) 138957

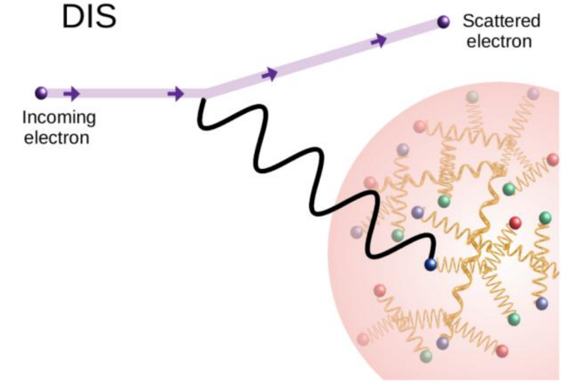
System Size

"Transverse Size" / MPI

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



(b) *Resolved photoproduction.*



(a) *Neutral current deep inelastic scattering.*

1/Q < 0.2 fm

High multiplicity pp

~ O(1fm)

High multiplicity pPb

≥ O(1fm)

O(1-10 fm)

e^+e^-

<< 0.1 fm

Multiplicity

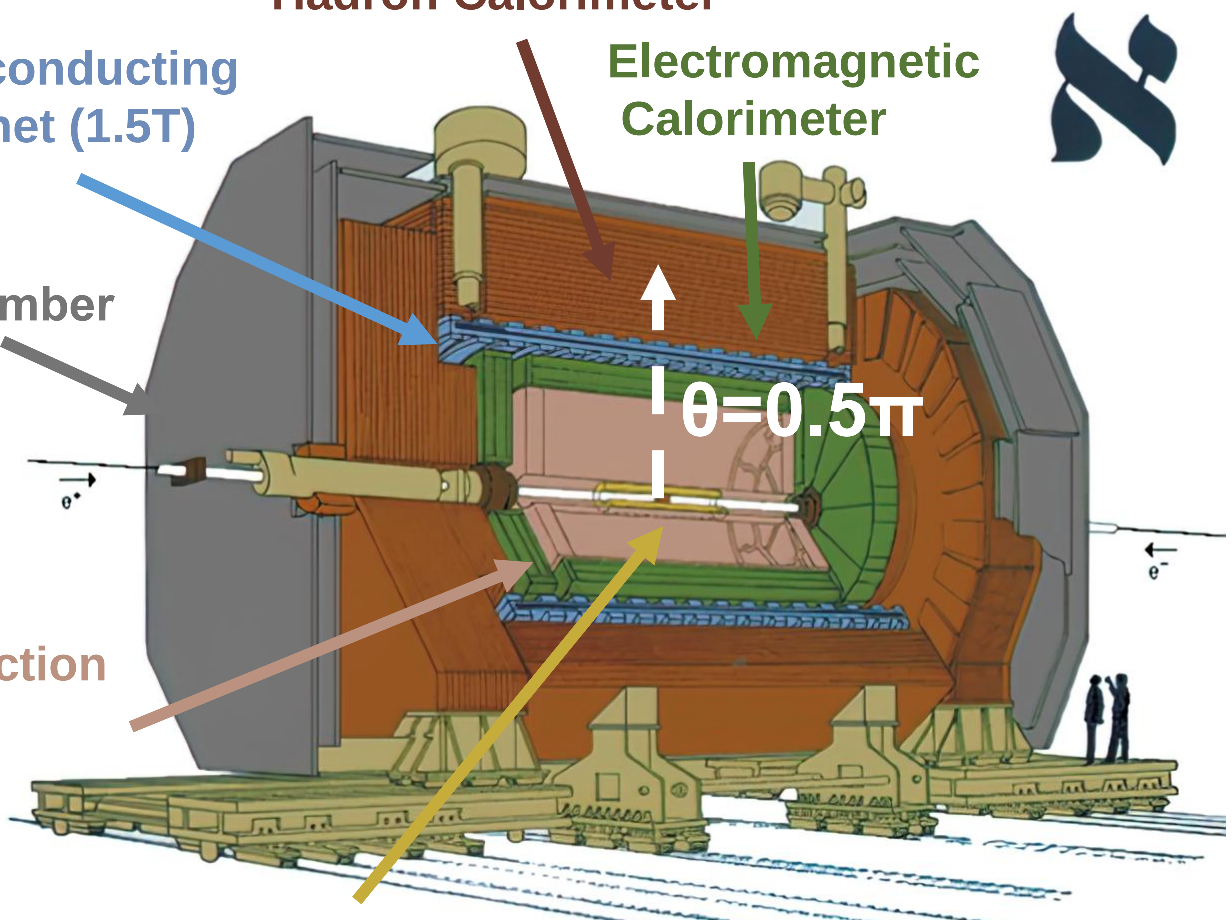
Hadronic Event Selection

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

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

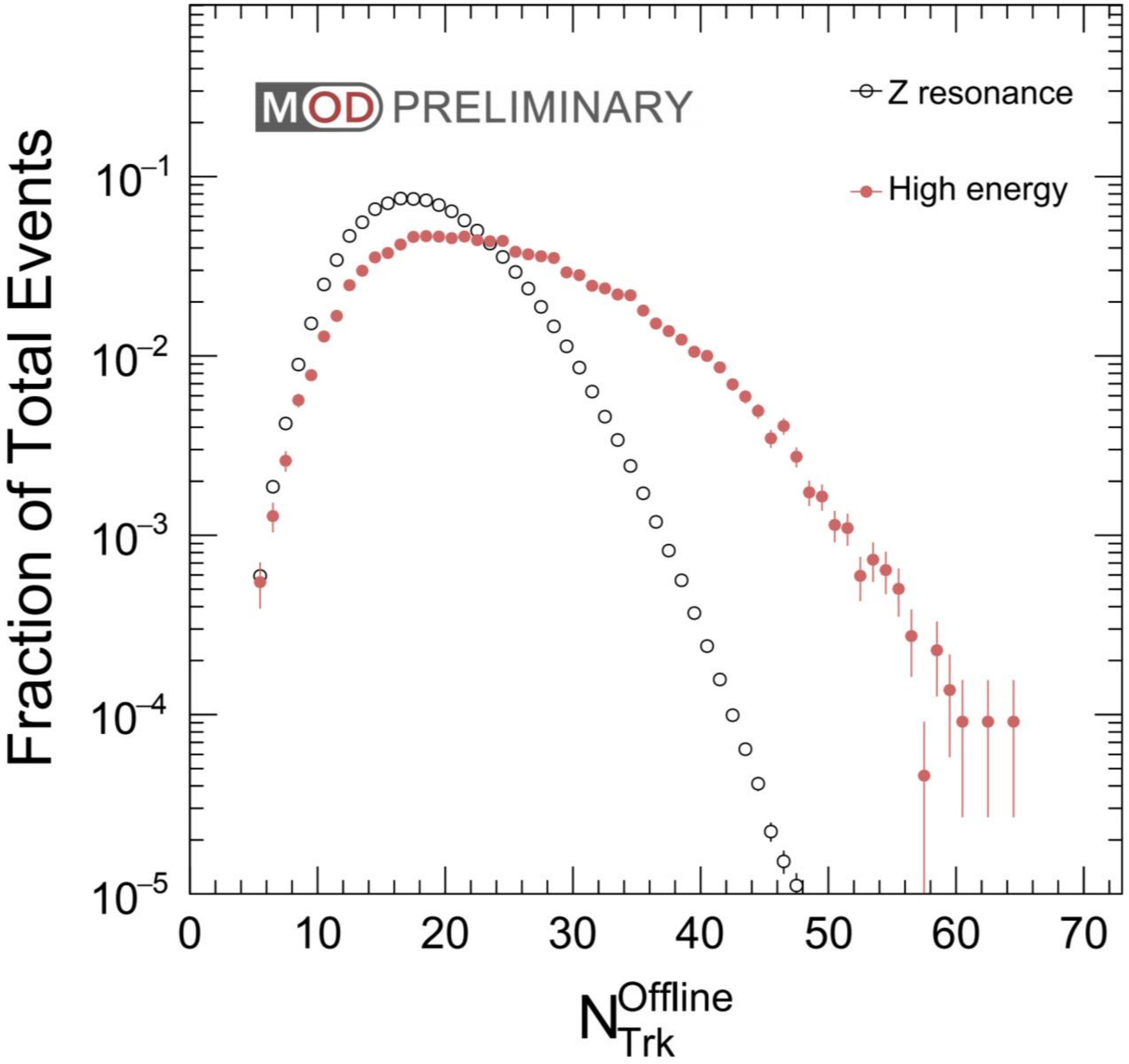
- **Event Selection:**
  - Number of good charged particles >= 5 (including charged hadrons and leptons)
  - Number of good ch+neu. Particles >= 13
  - $E_{charged}$ > 15 GeV
  - $|\cos(\theta_{sphericity})|<0.82$

The ALEPH Detector

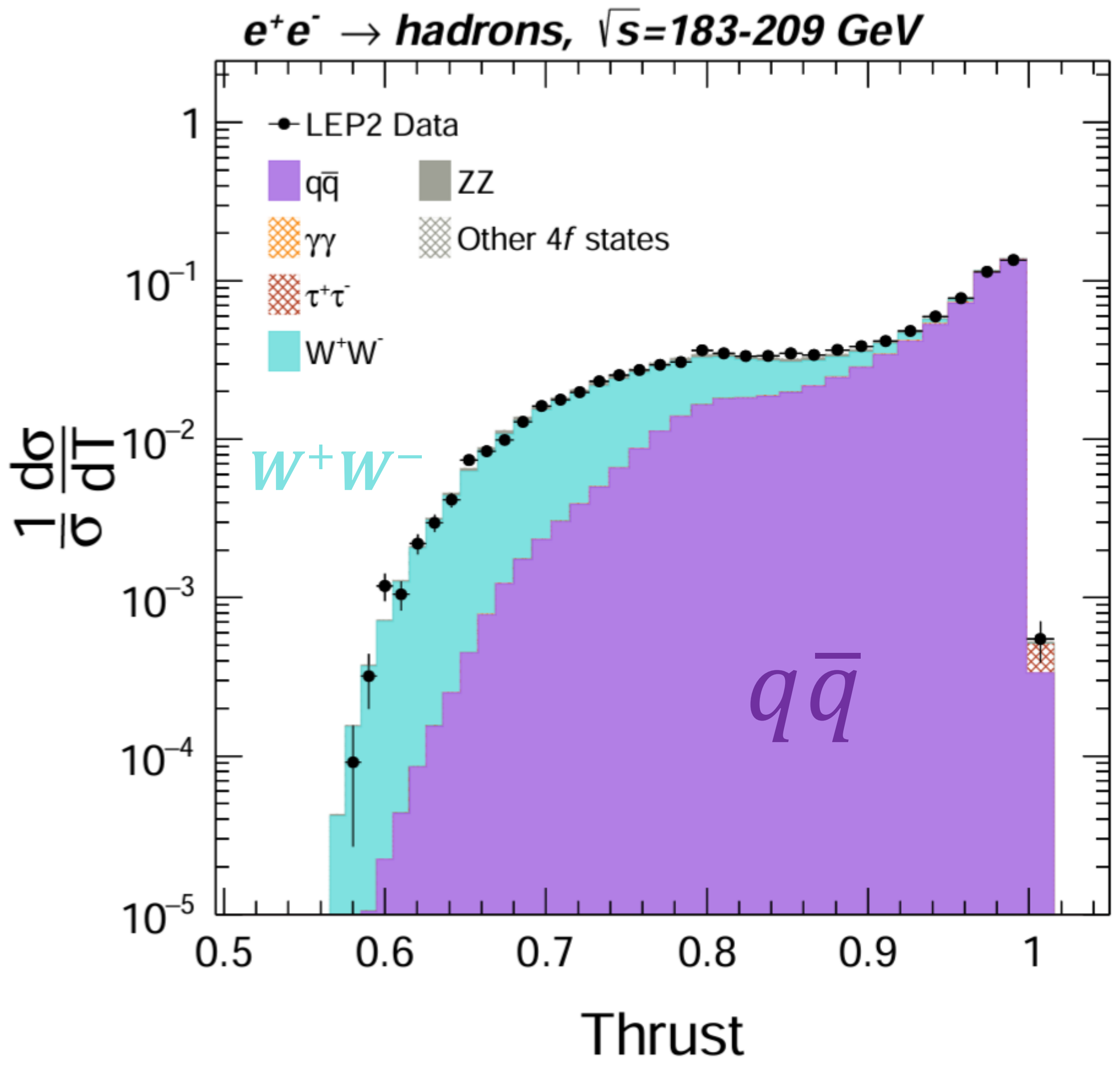


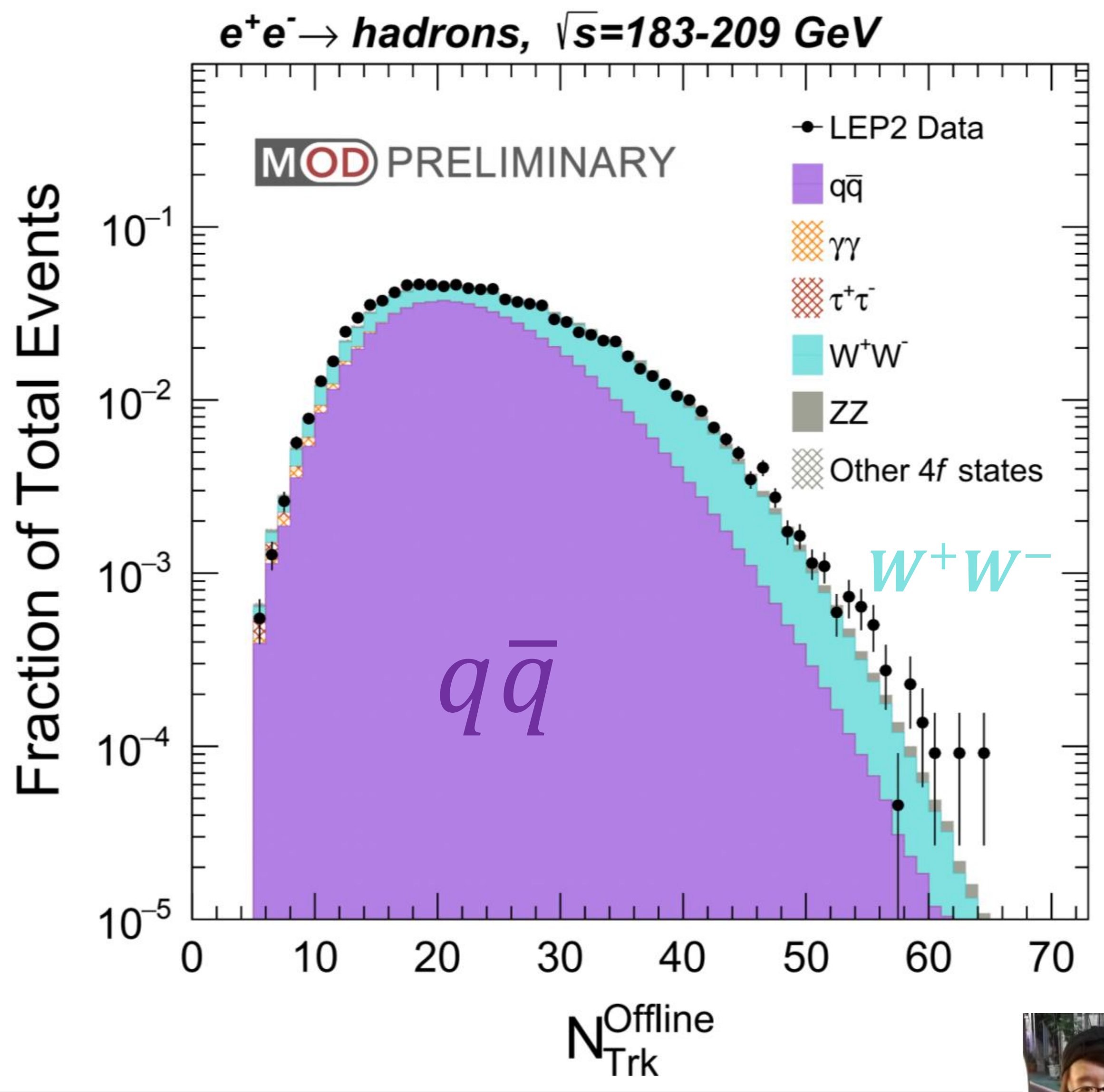
- LEP1 e^+e^- data at Z pole (91 GeV) taken between 1992-1995
- **LEP2 e^+e^- data above Z pole up 209 GeV**
  - ~ **RHIC** energy

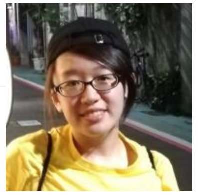
Charged Particle Multiplicity



Example validation study of archived data and MC





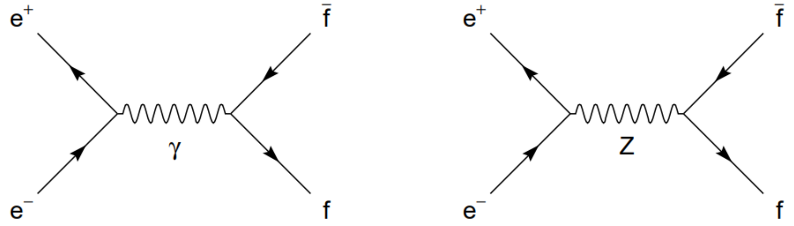


Yu-Chen “Janice” Chen (MIT)

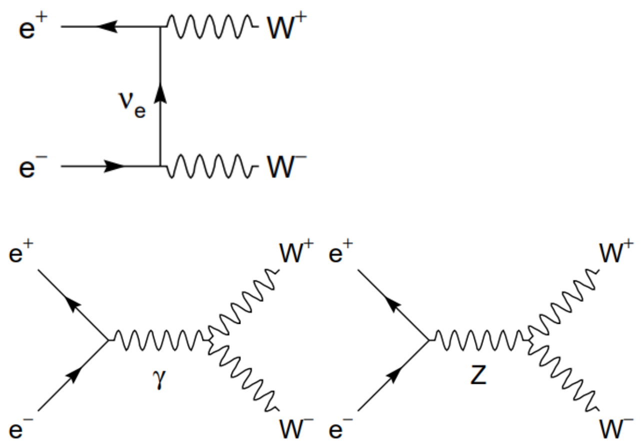
- Inspected thrust distributions (shown) and many other control plots (visible energies) year-by-year.
- Reasonable agreement between data and archived MC.

Charged Particle Multiplicity Distributions in LEP2 Data

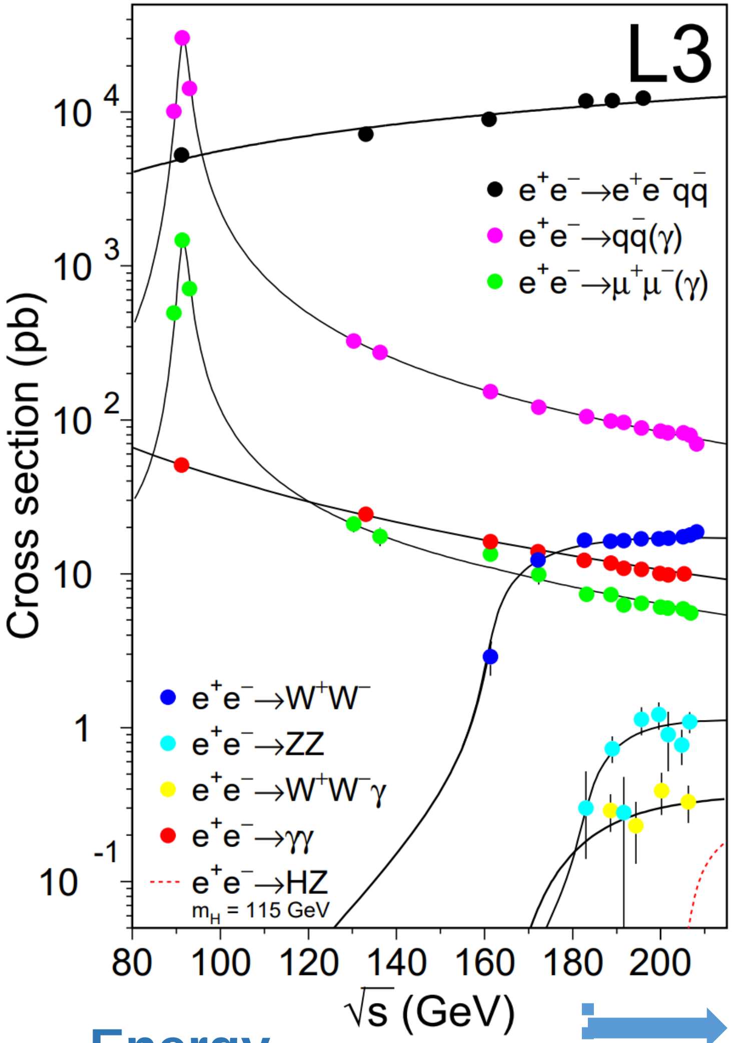
- $e^+e^- \rightarrow q\bar{q}(\gamma)$



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



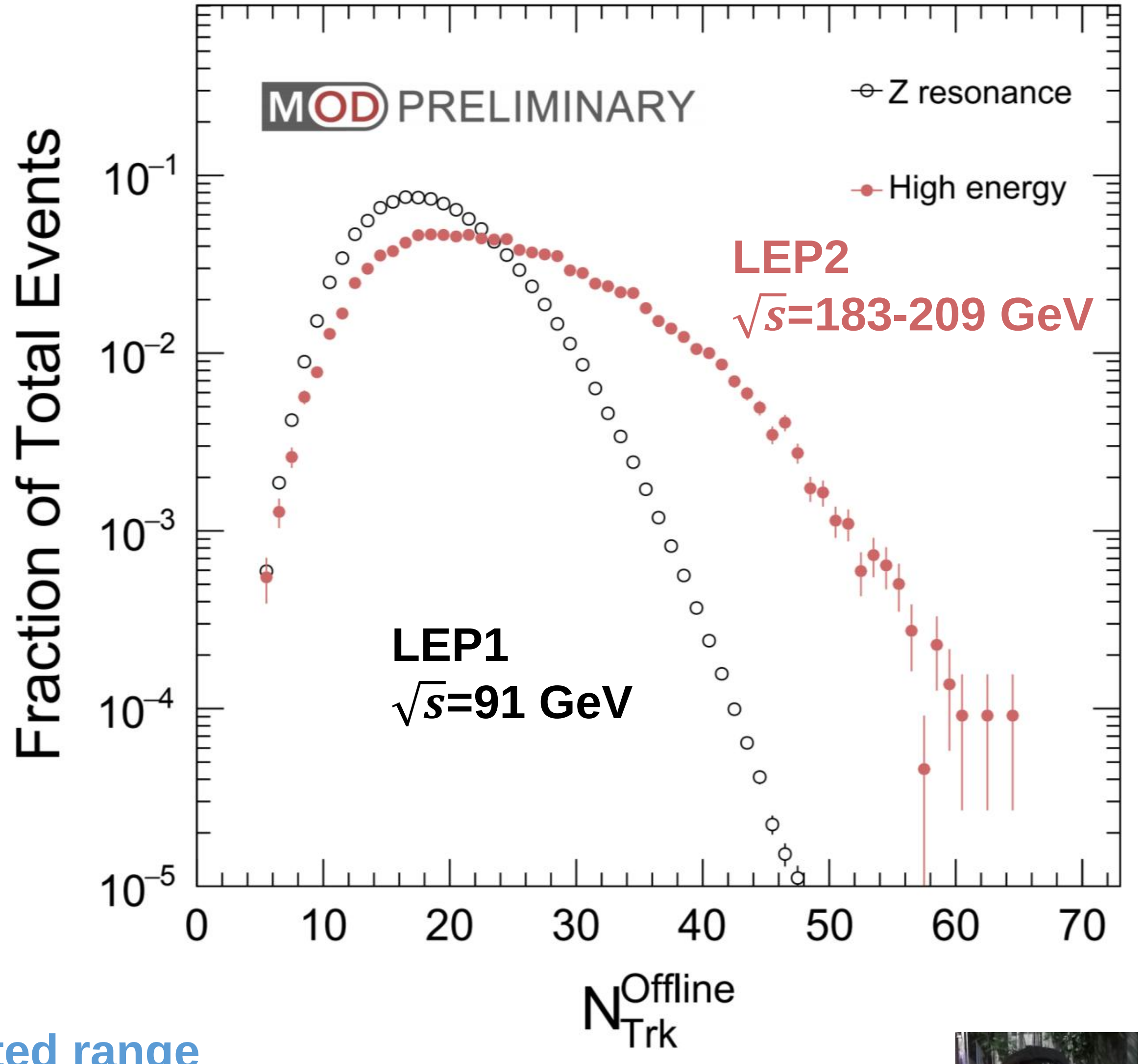
Phys. Rept. 532 (2013) 119-244

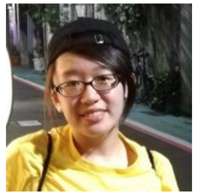


Energy

EPJC 63 611 (2009)

Reported range

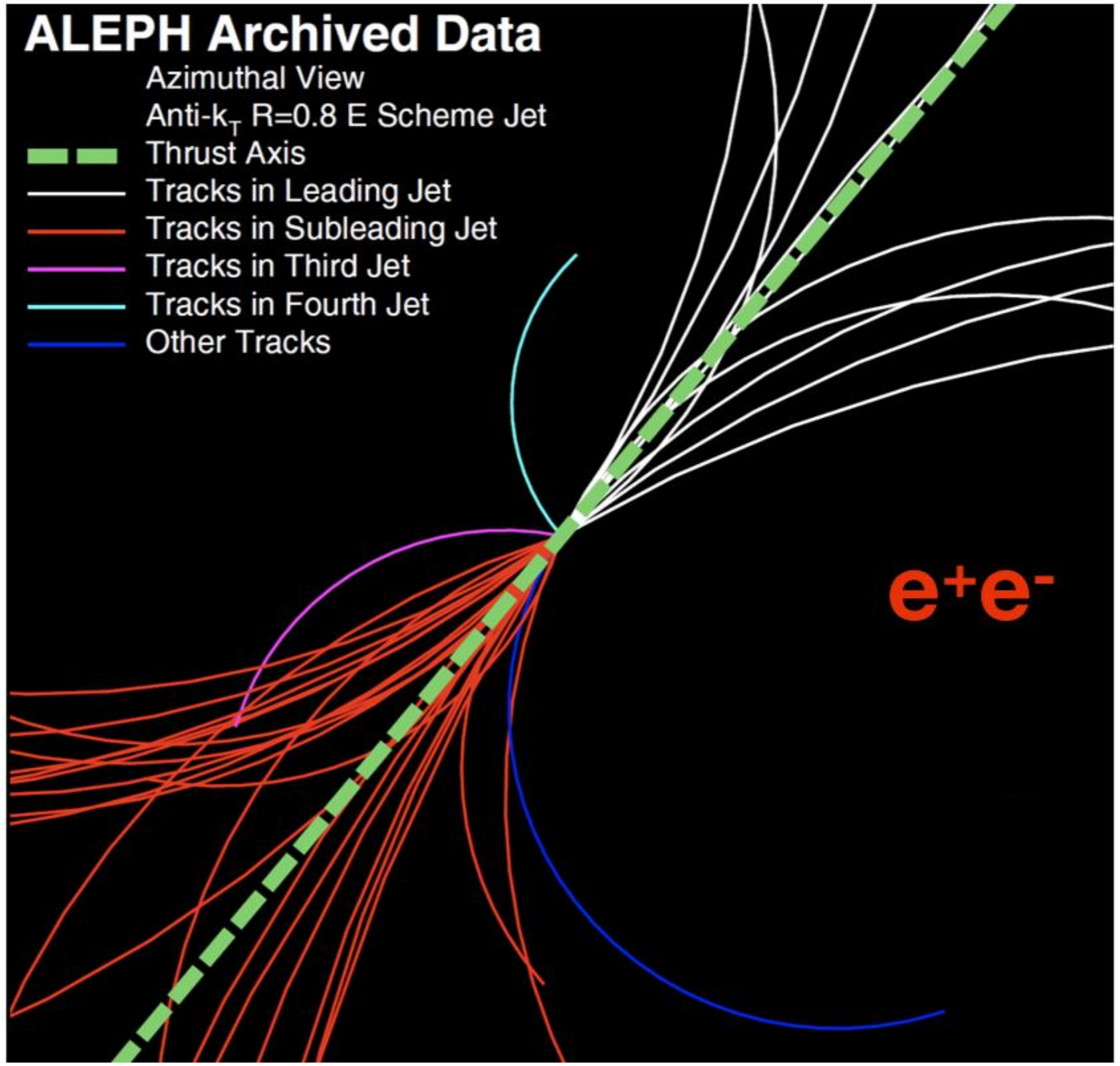




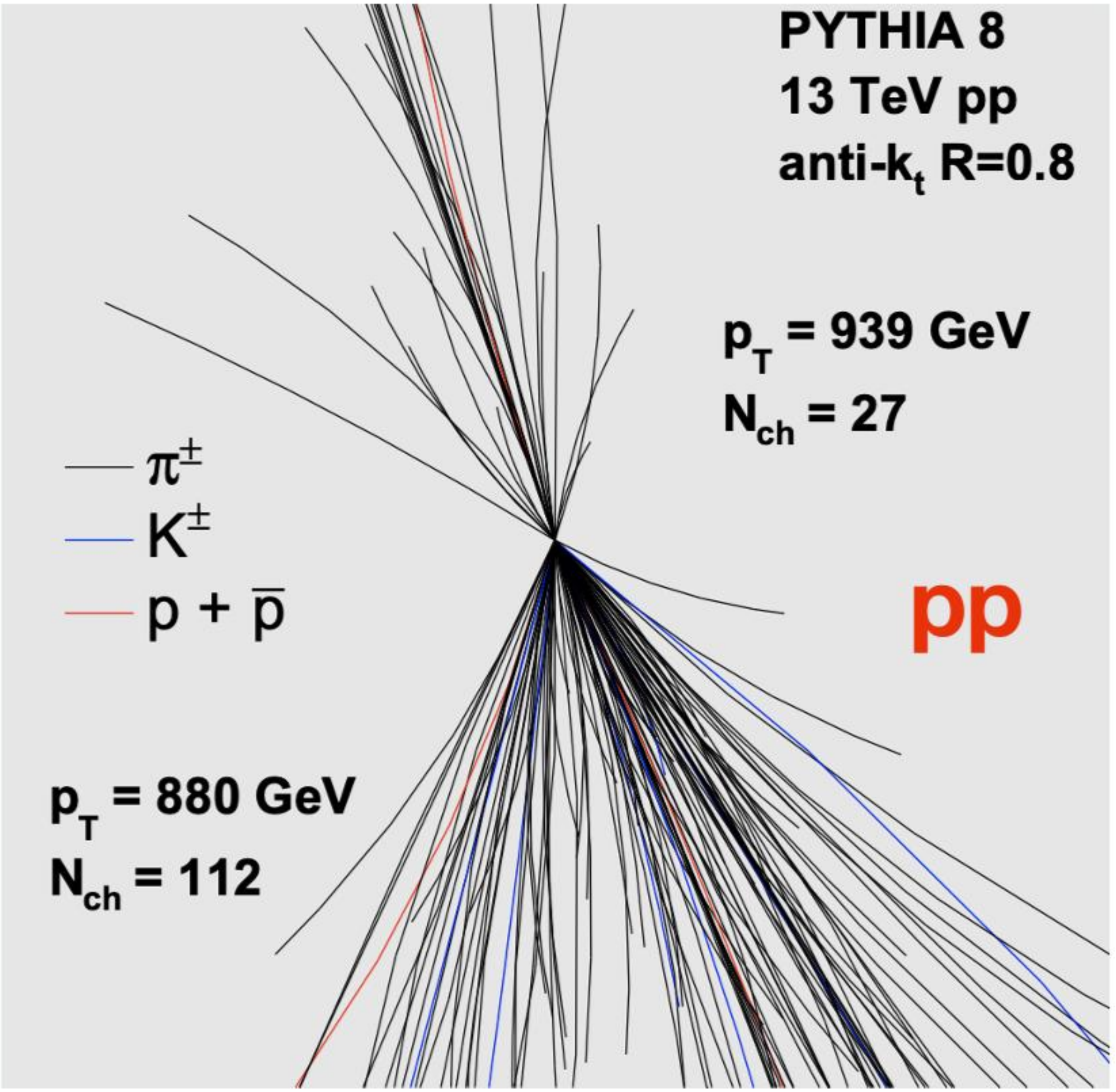
Yu-Chen "Janice" Chen (MIT)

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

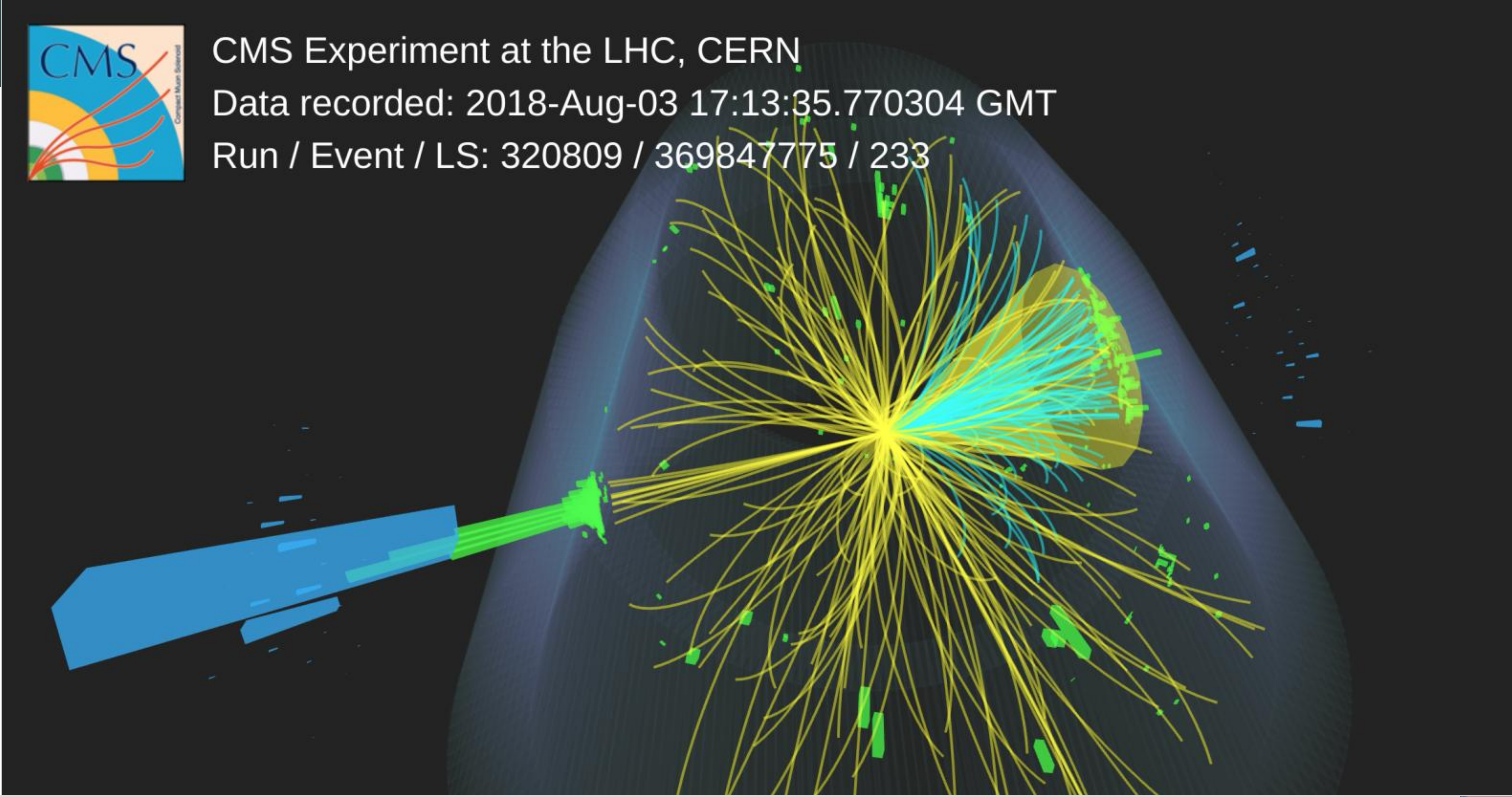
“Single String Configuration”: High Multiplicity Jet



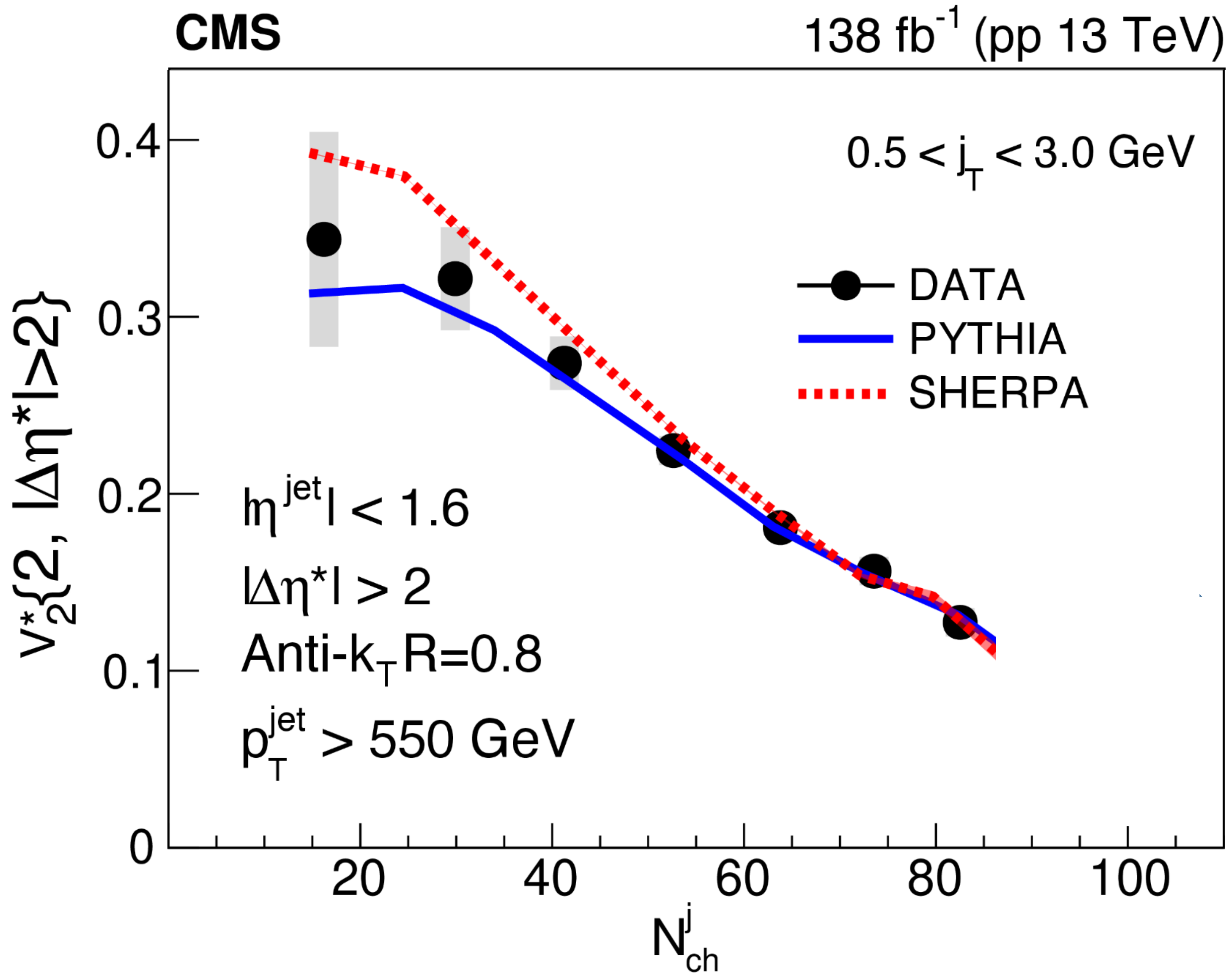
ALEPH archived data PRL 123, 212002 (2019)

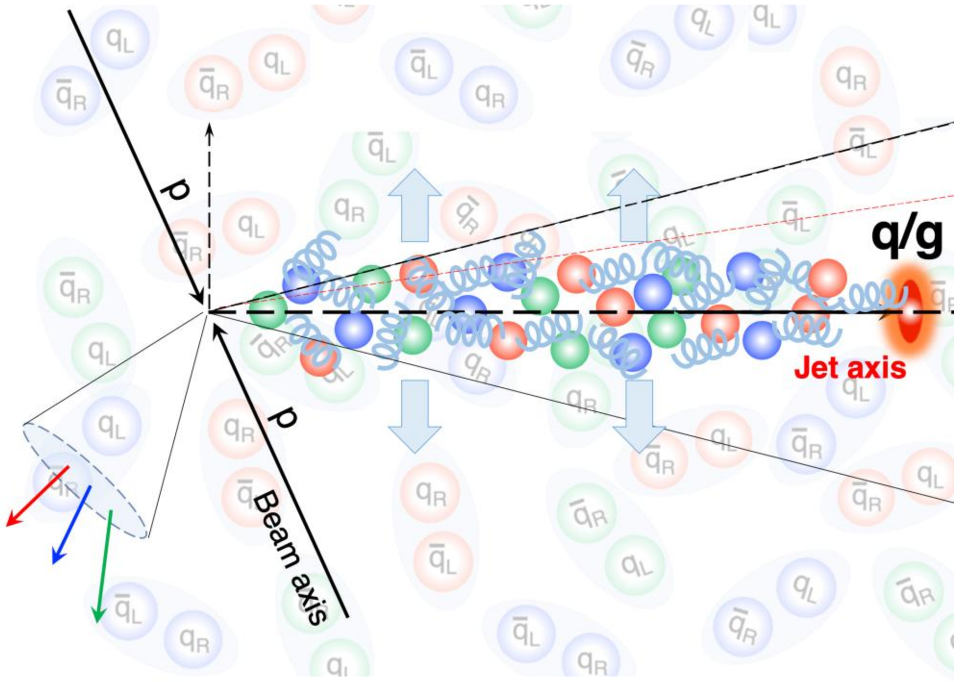


Austin Baty, Gardner P., Li W. PRC 107, 064908 (2023)

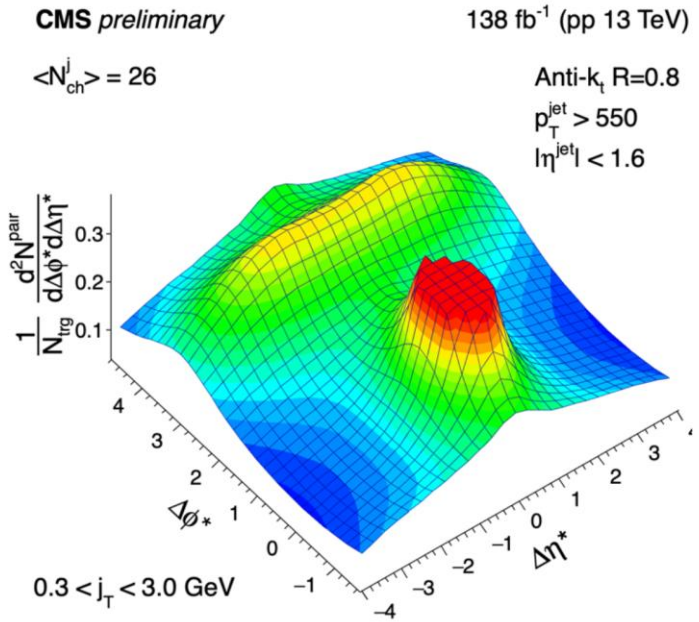

CMS
CMS Experiment at the LHC, CERN
Data recorded: 2018-Aug-03 17:13:35.770304 GMT
Run / Event / LS: 320809 / 369847775 / 233

Two-Particle Correlation with Particles in Jet





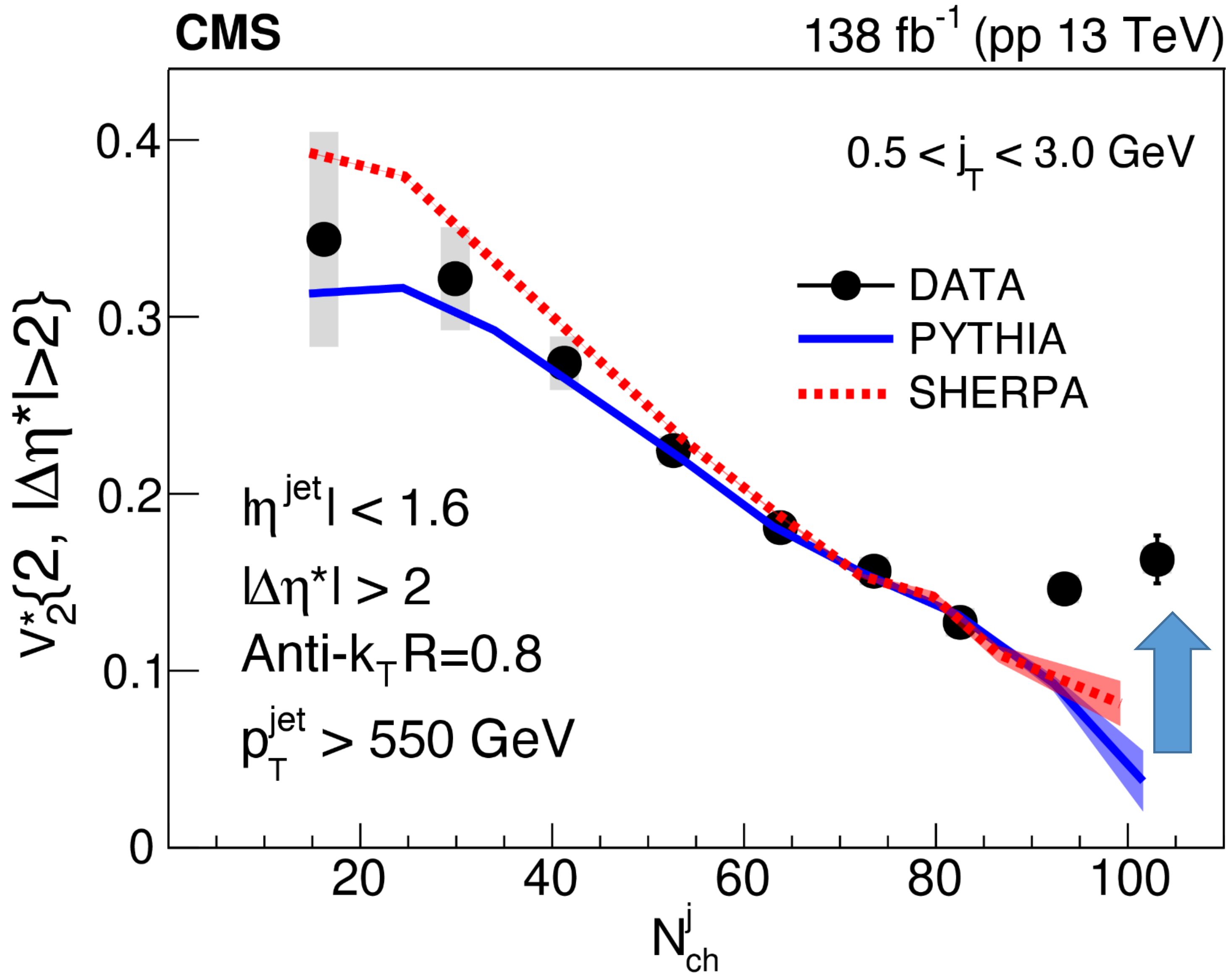
Austin Baty

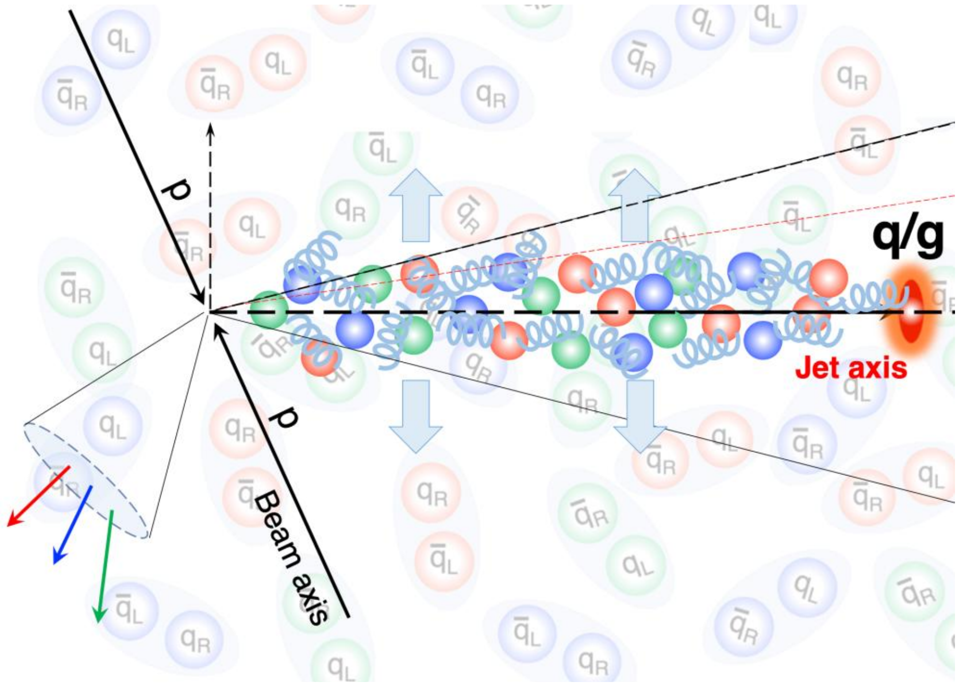


- $N_{ch} < 90$: **PYTHIA8** and **SHERPA** can effectively describe the data.

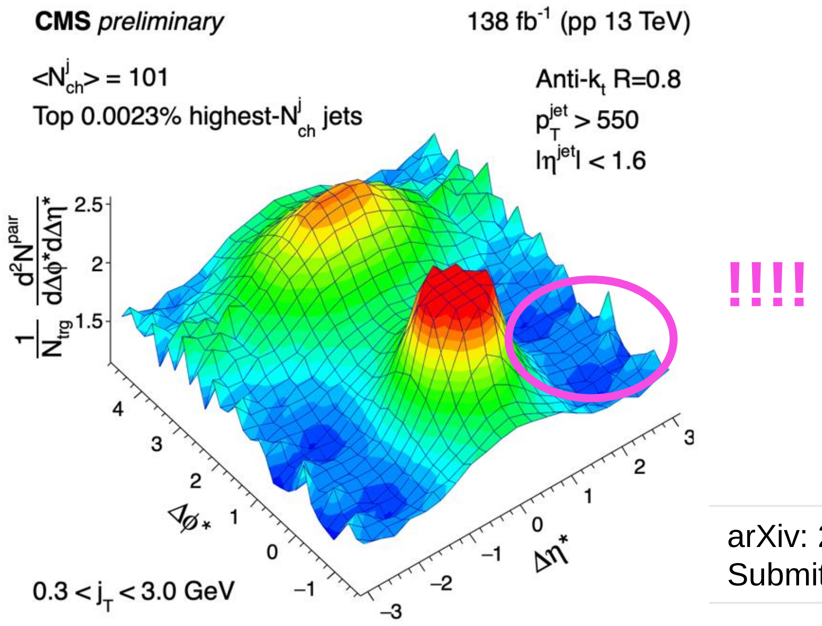
arXiv: 2312.17103
Submitted to PRL

Two-Particle Correlation in **High Multiplicity Jet**





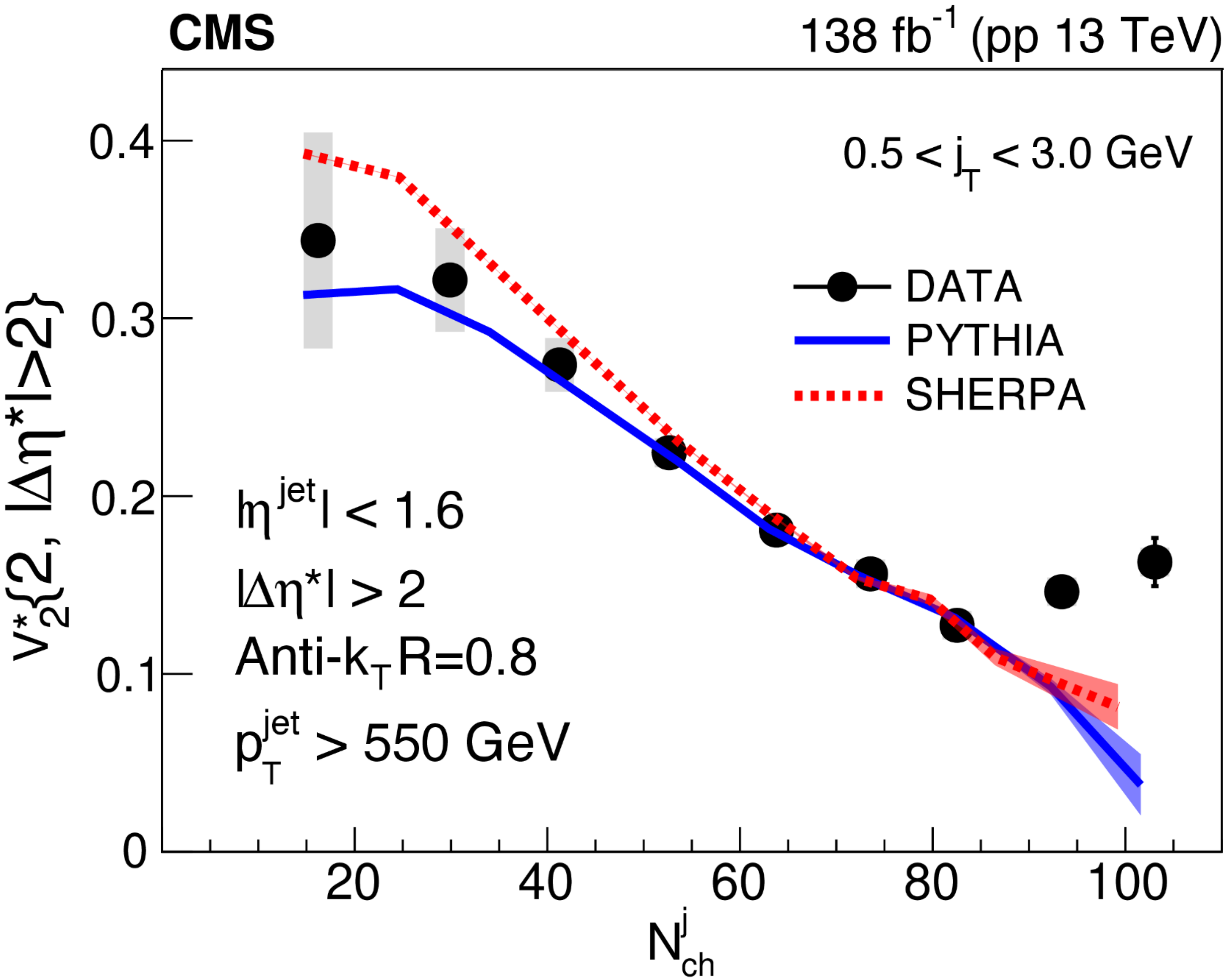
Austin Baty

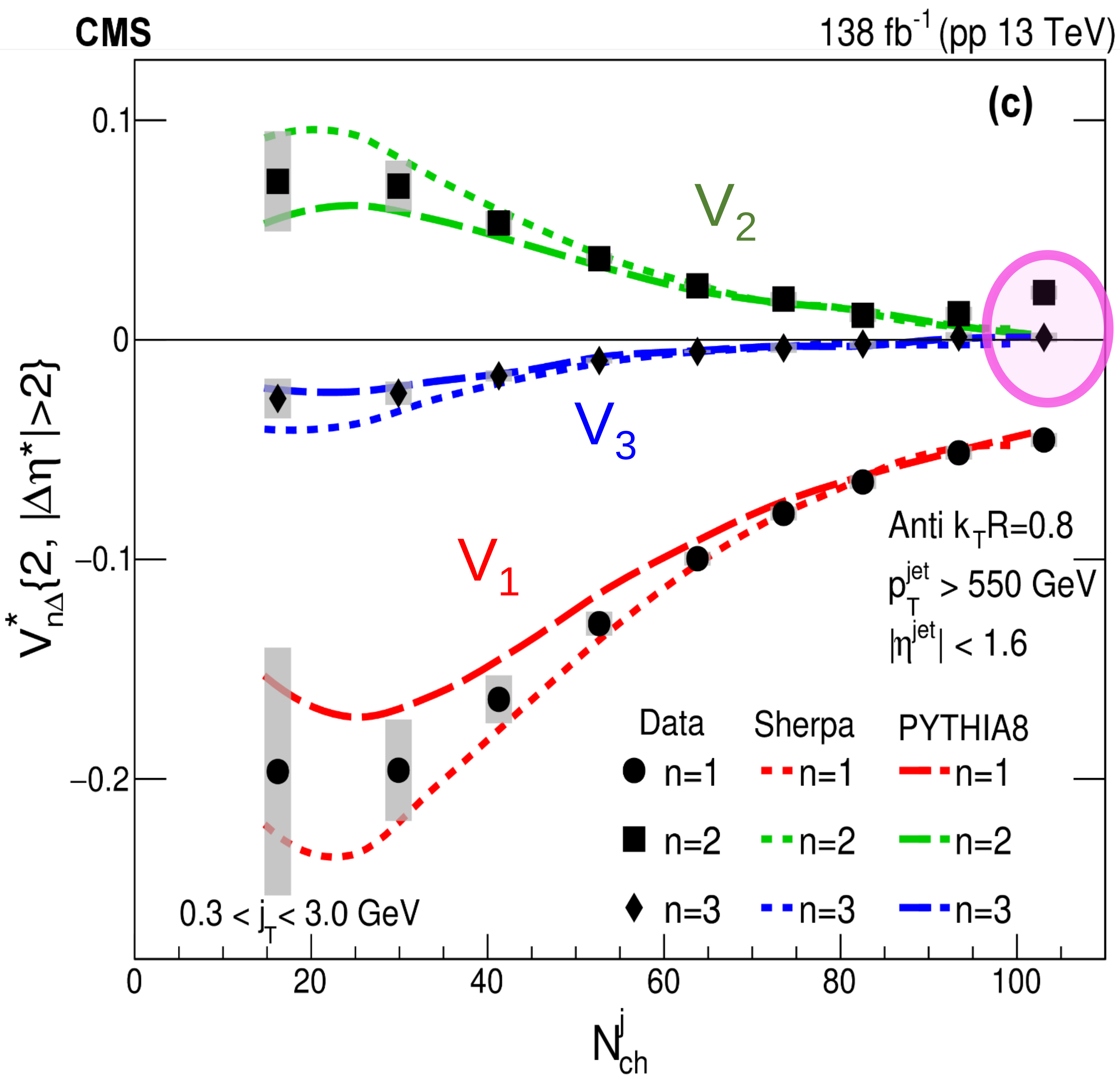


arXiv: 2312.17103
Submitted to PRL

- At high multiplicity (N_{ch} > 90), the data v_2 deviates from the decreasing trend observed in the MC!

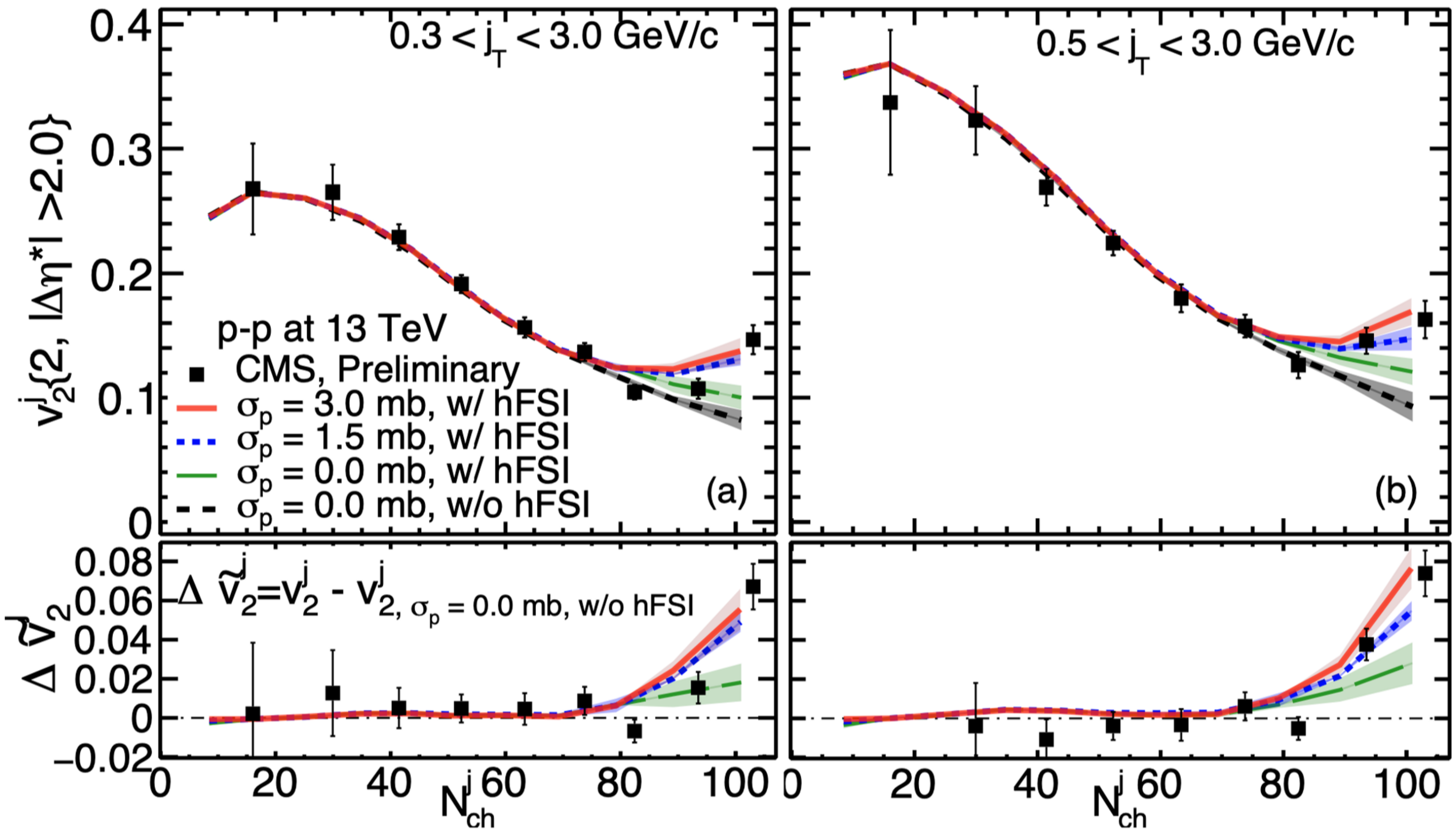
Azimuthal Anisotropy in High Multiplicity Jet





- At high multiplicity (N_{ch} > 90), V_1 is significantly reduced.
- V_3 become positive in data!

Final State Iinteraction (FSI) Model Calculation



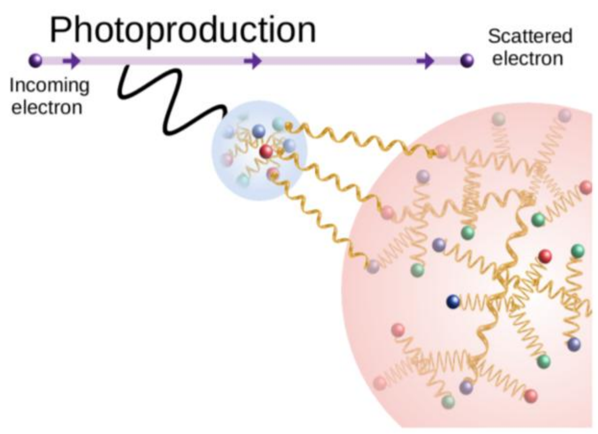
- PYTHIA + UrQMD FSI could explain the jet data
- Potential extension to e^+e^- data

W. Zhao, Zi-Wei Lin and Xin-Nian Wang
arXiv:2401.13137

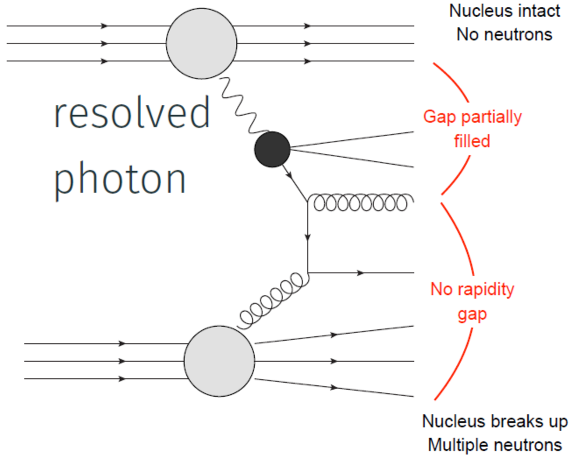
Searches with ZEUS, H1 and CMS γp

“Transverse Size” / MPI

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

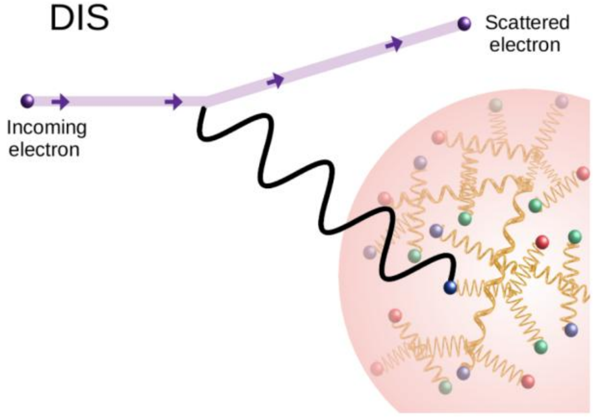


(b) *Resolved photoproduction.*



DIS

MI



(a) *Neutral current deep inelastic scattering.*

1/Q < 0.2 fm

High multiplicity pp

~ O(1fm)

High multiplicity pPb

≥ O(1fm)

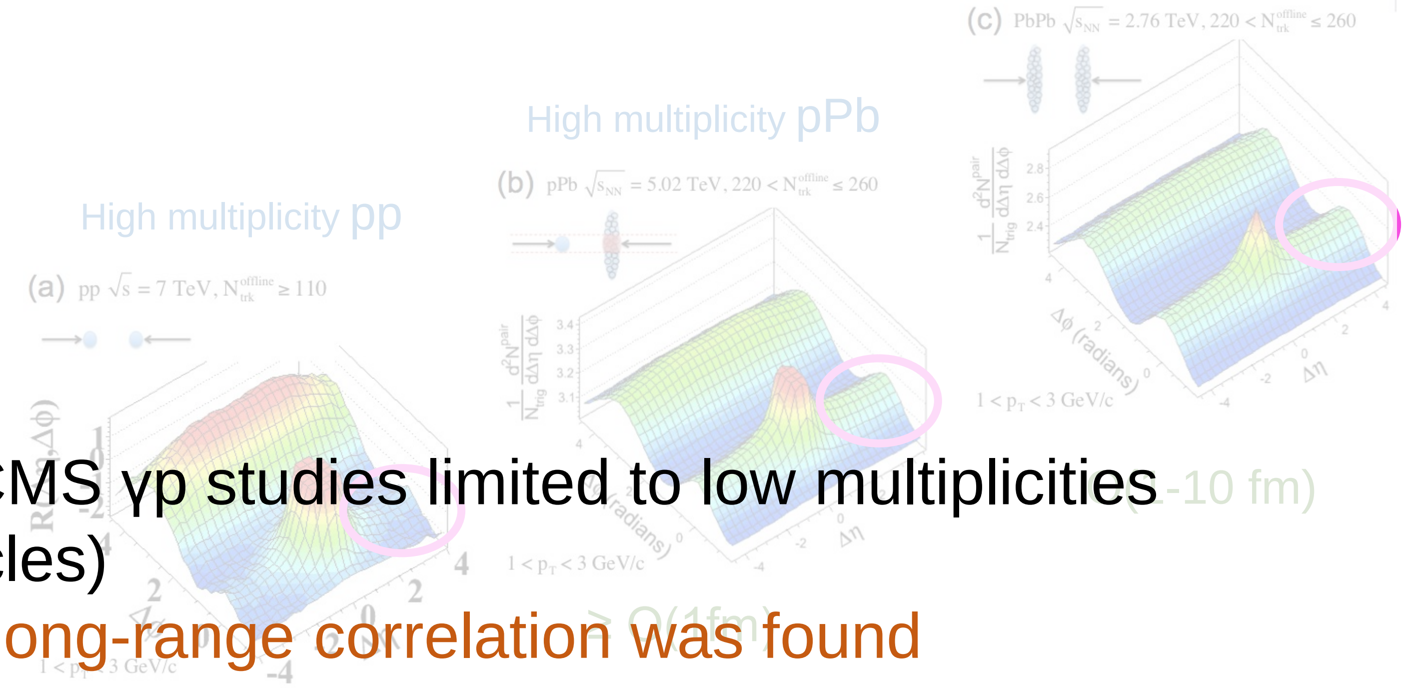
O(1-10 fm)

<< 0.1 fm

Multiplicity

Searches with ZEUS, H1 and CMS γp

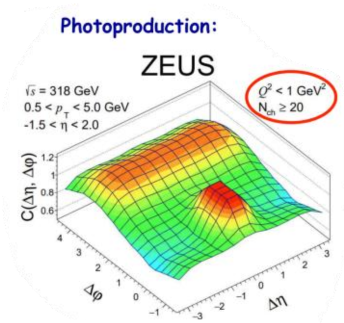
“Transverse Size” / MPI



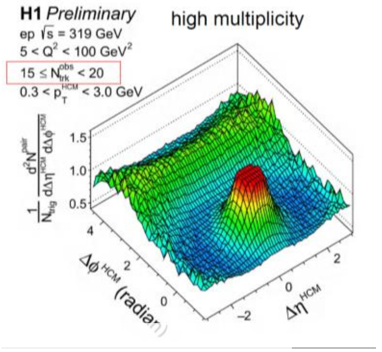
ZEUS, H1 and CMS γp studies limited to low multiplicities (Up to ~20 particles)

No indication of long-range correlation was found

ATLAS γPb shows no sign of ridge before subtraction



H1 DIS



MPI ≥ 1

“MPI”=1

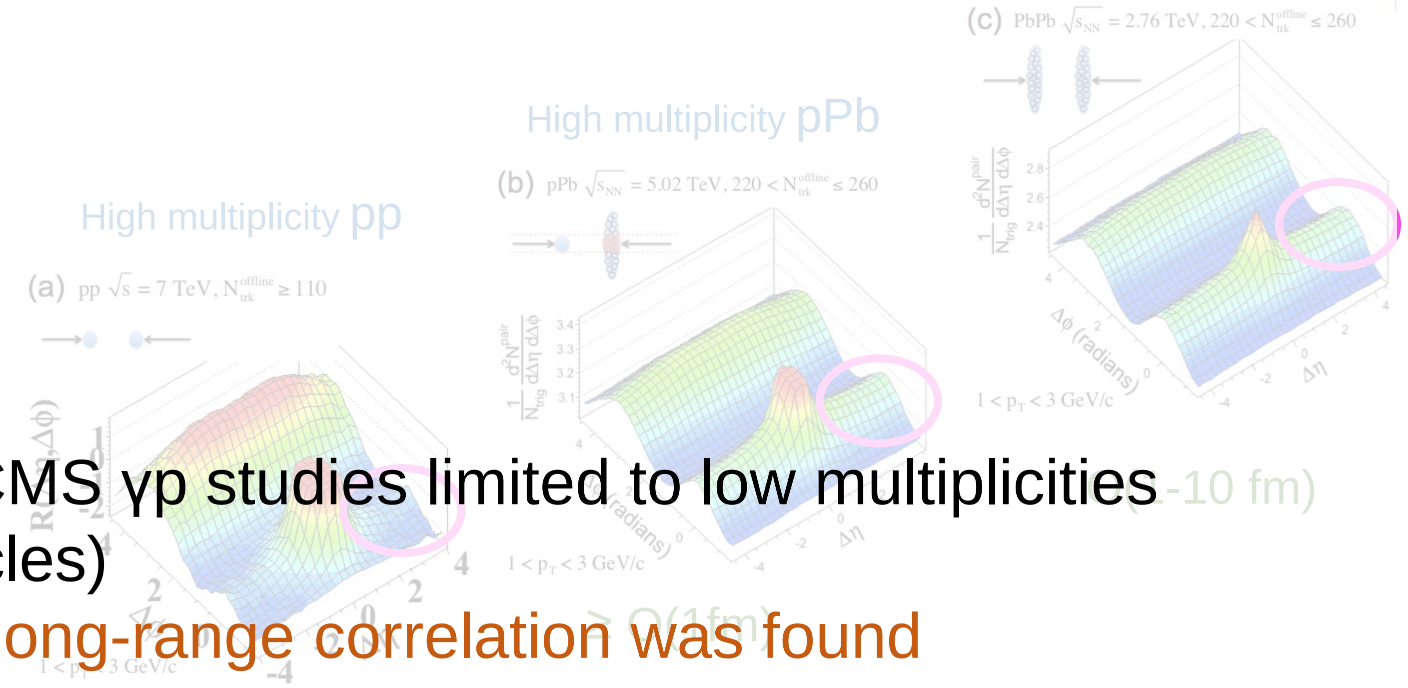
<< 0.1 fm

ZEUS ep neutral current DIS: JHEP 04 (2020) 070
ZEUS ep photonuclear: JHEP 12 (2021) 102
H1 ep neutral current DIS: (preliminary) H1prelim-20-033
CMS pPb photonuclear: PLB 844 (2023) 137905
ATLAS PbPb photonuclear: PRC 104 (2021) 1, 014903

Multiplicity

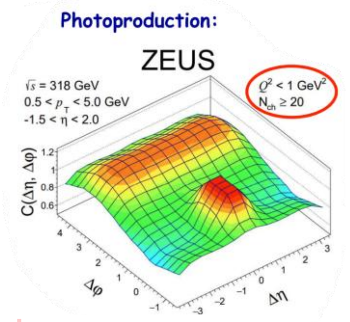
System Size

“Transverse Size” / MPI



ZEUS, H1 and CMS γp studies limited to low multiplicities
MPI>1 (Up to ~20 particles)
No indication of long-range correlation was found

~ O(1fm)



MPI ≥ 1

ATLAS γPb shows no sign of ridge before subtraction

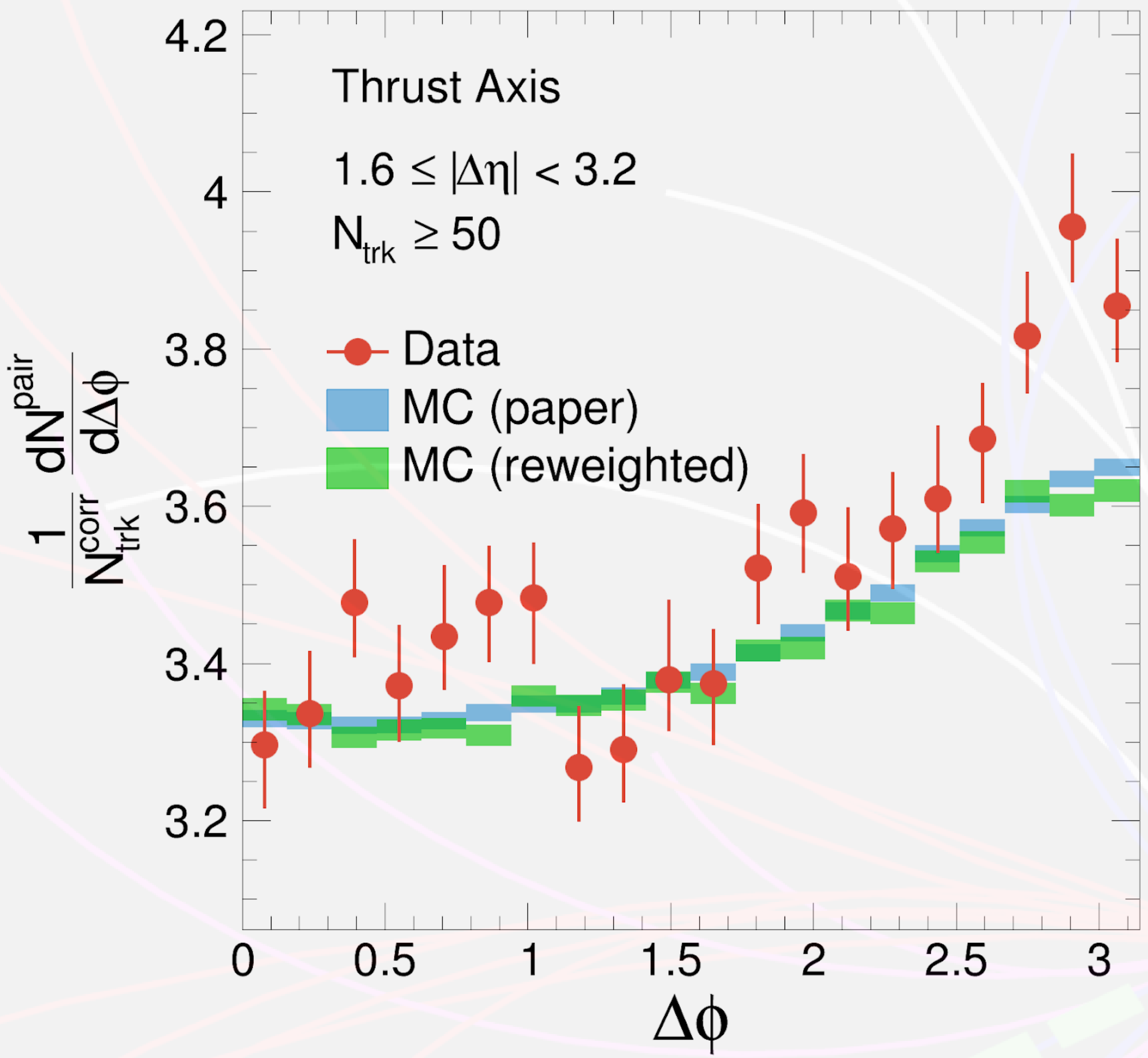
Next steps: (1) Increase <MPI>
(2) Increase multiplicity

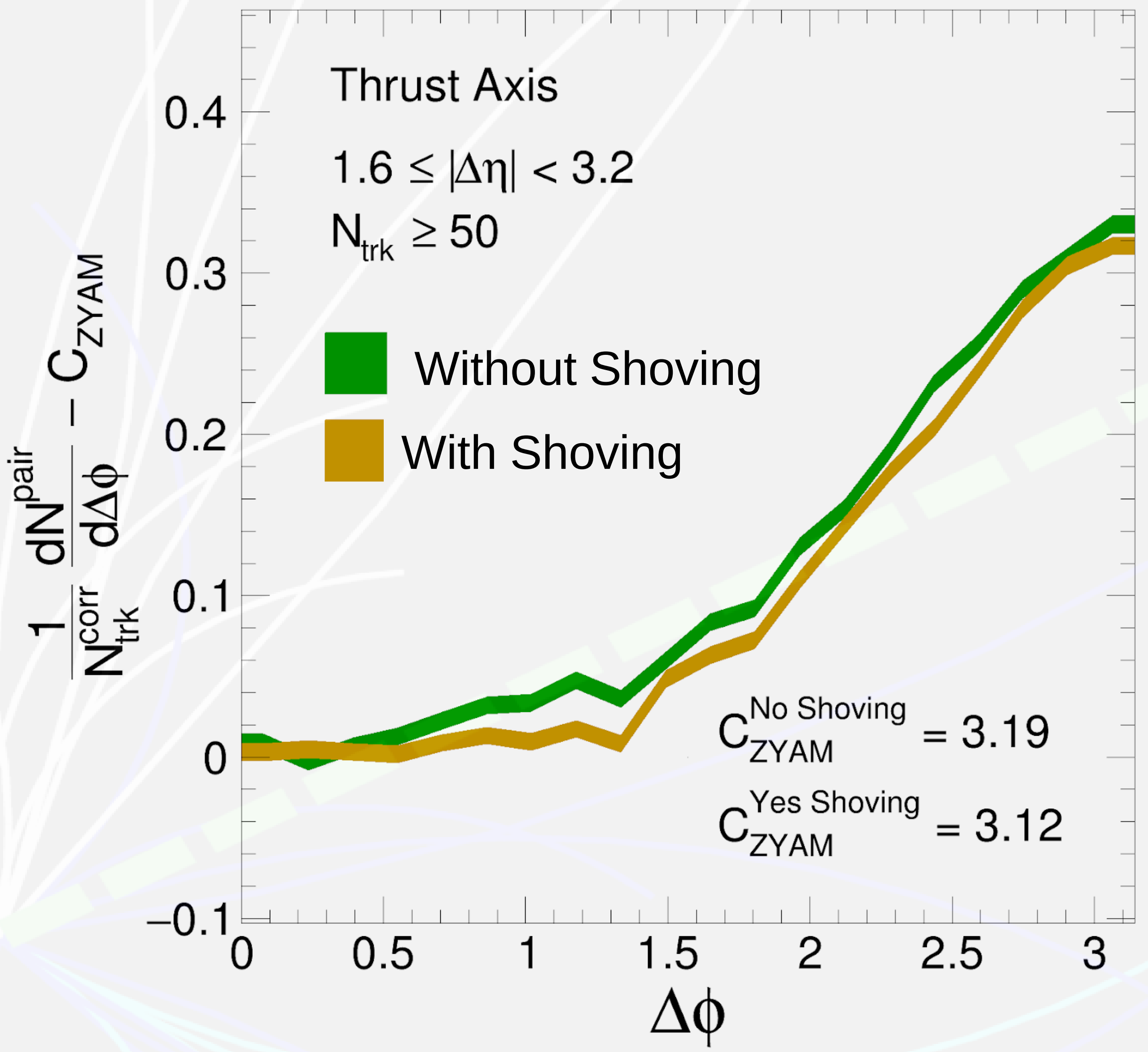
“MPI”=1

<< 0.1 fm

Multiplicity

Additional Cross-checks at High Multiplicity



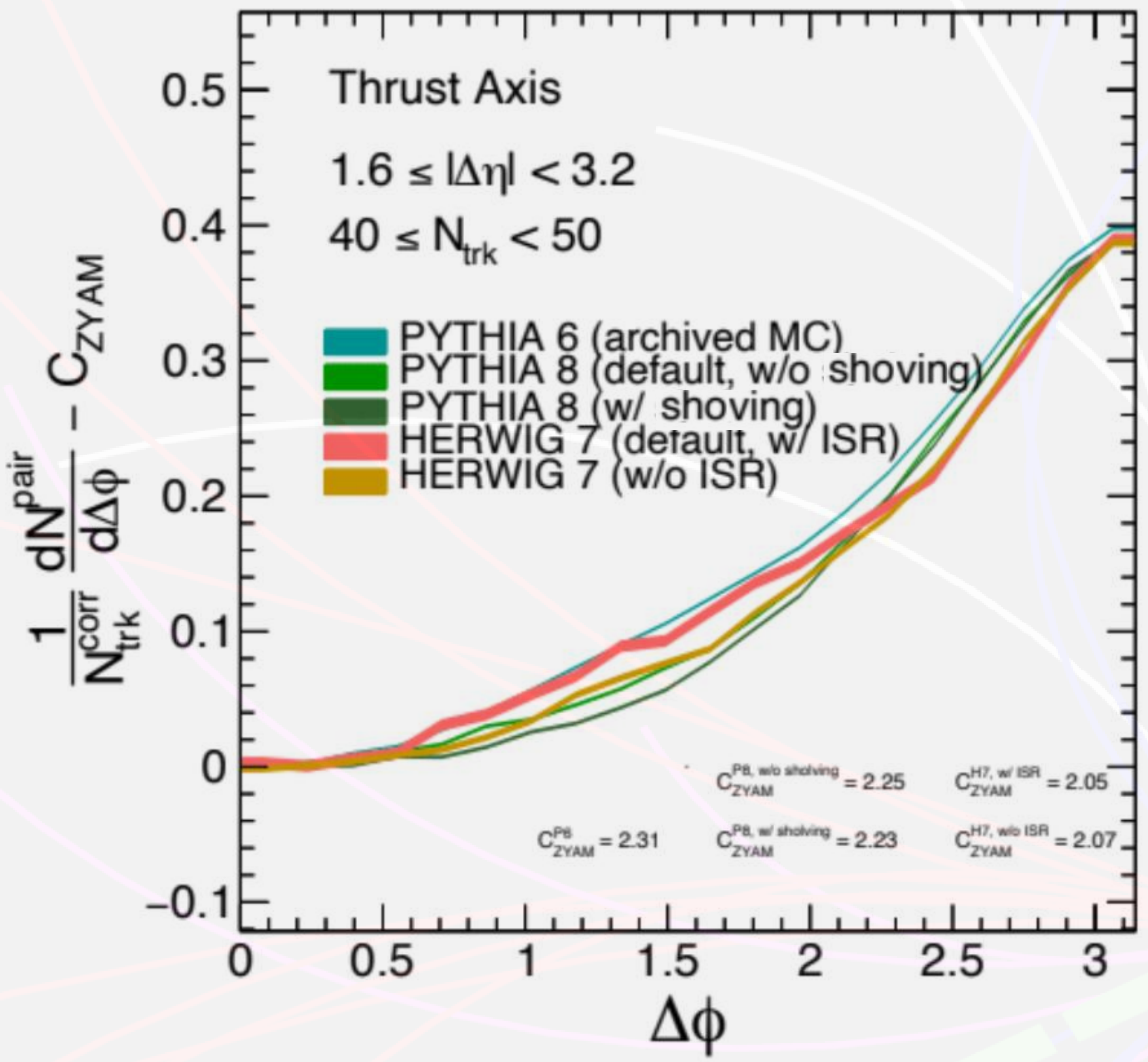


- Reweight the MC to match the data multiplicity spectrum
- Effect of reweighting is small

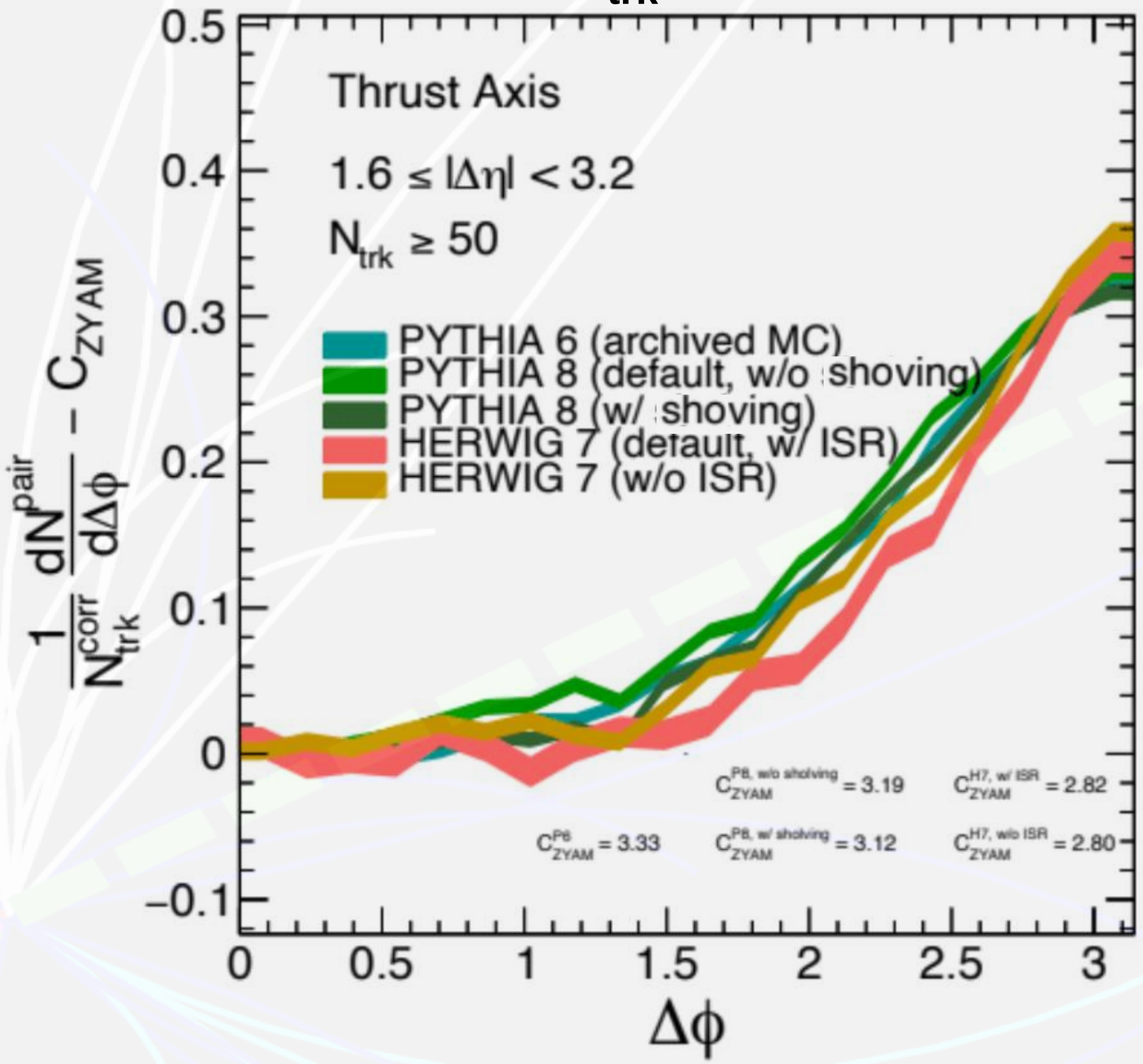
- **PYTHIA8 with shoving** changes the correlation function
- Doesn't produce a near-side excess

PYTHIA and HERWIG Generator Studies

$40 < N_{trk} < 50$



$N_{trk} > 50$



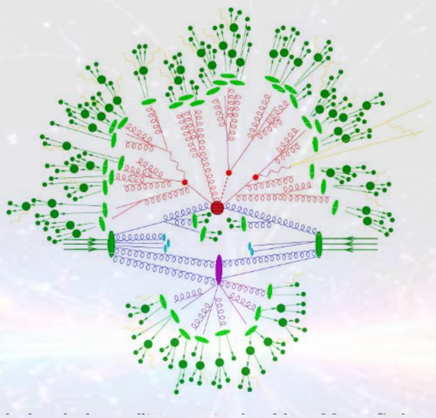
- **HERWIG7** (with or without ISR) and PYTHIA8 (with or without shoving)
- No near-side enhancement observed

arXiv:2312.05084
PLB 856 (2024) 138957

System Size

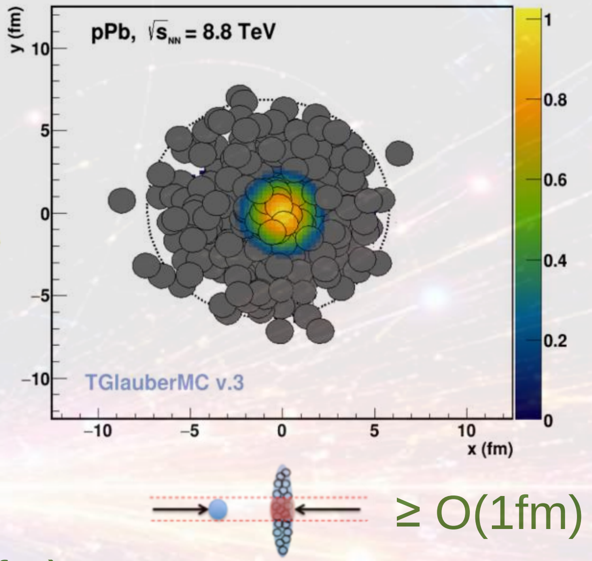
"Transverse Size" / MPI

pp



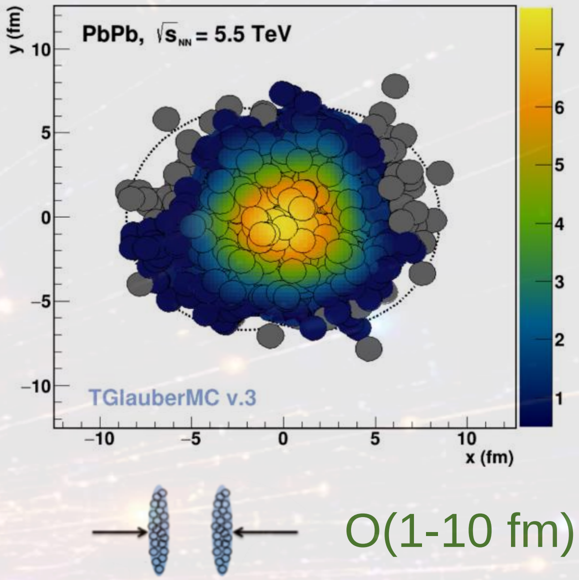
~ O(1fm)

pA



≥ O(1fm)

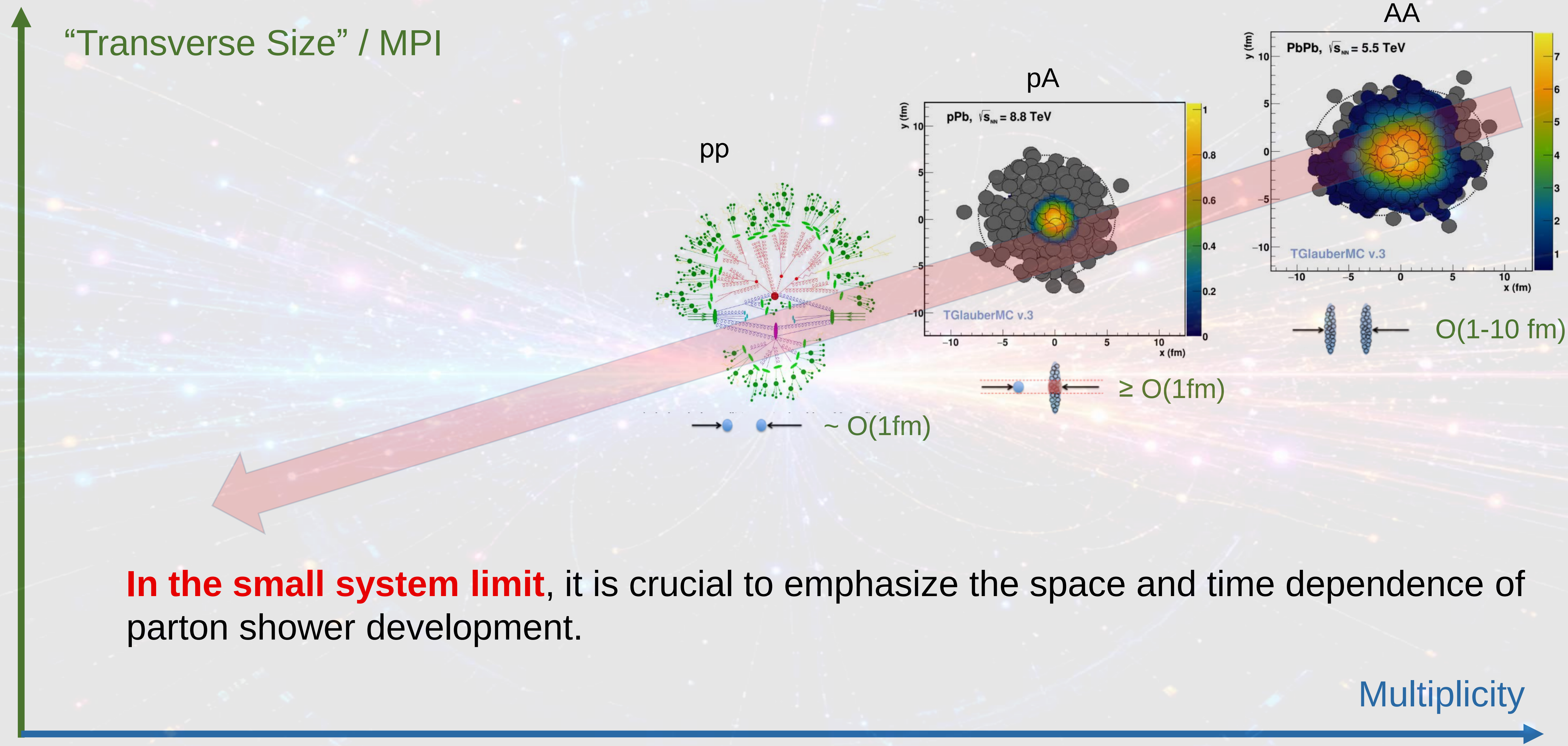
AA



O(1-10 fm)

Multiplicity

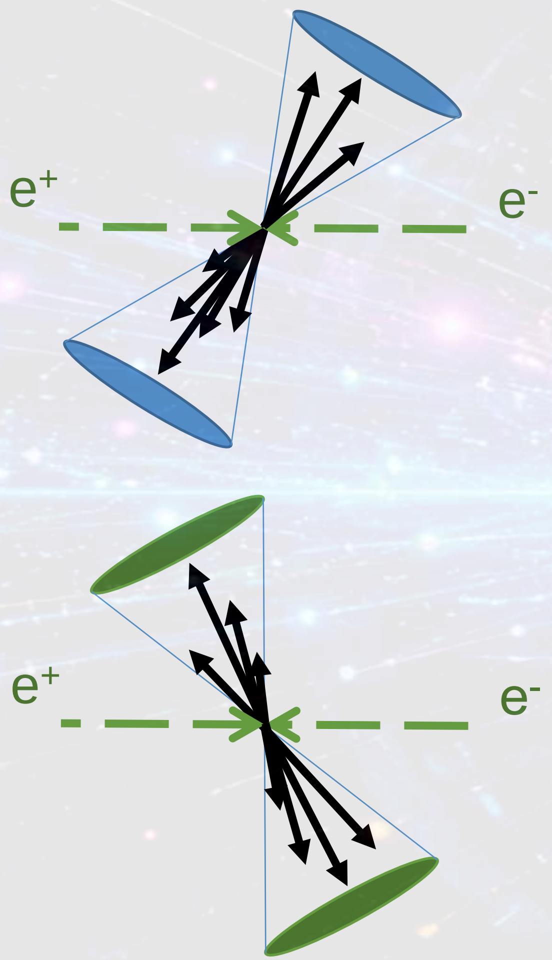
System Size



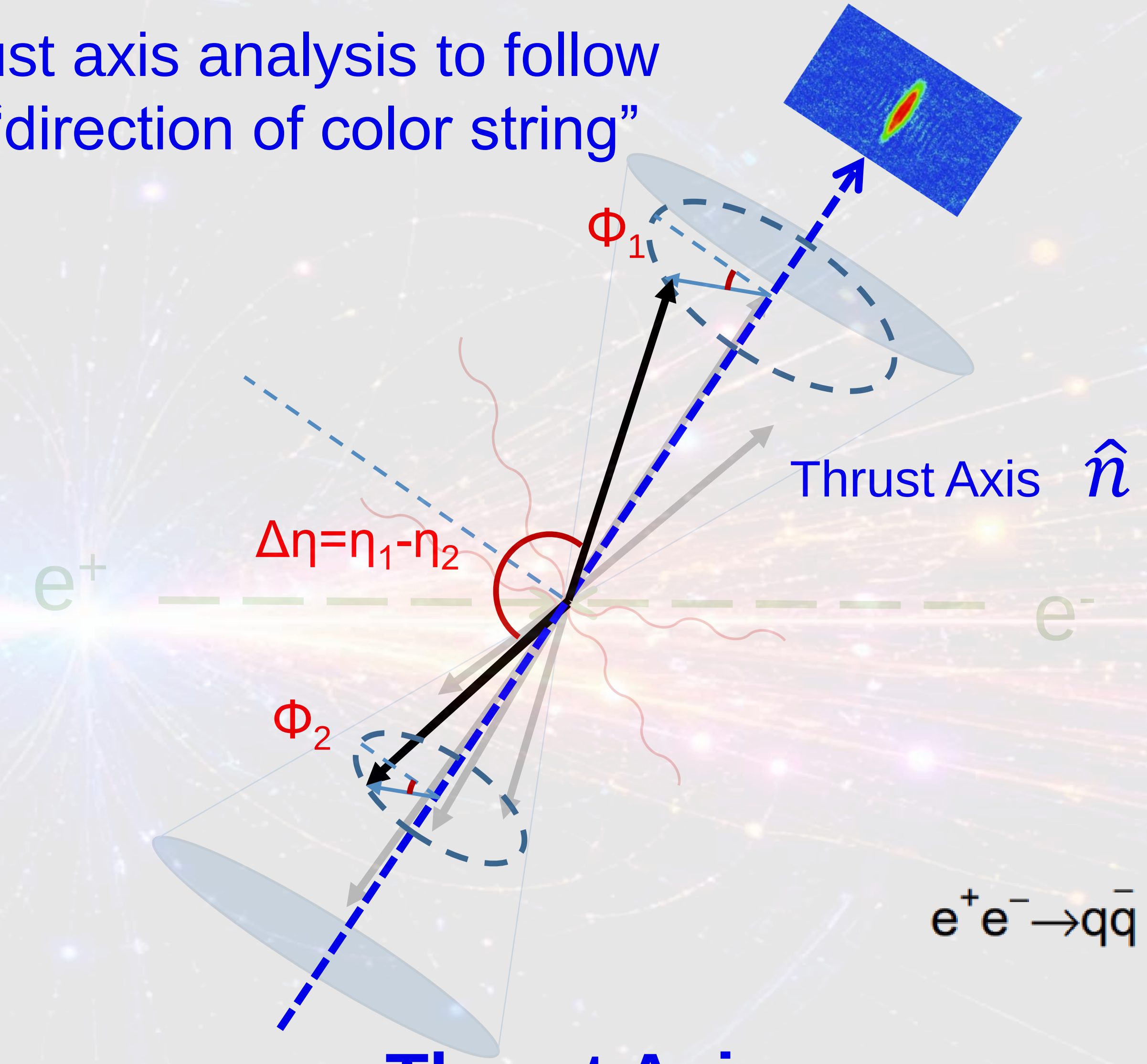
In the small system limit, it is crucial to emphasize the space and time dependence of parton shower development.

Reference Axis for e^+e^-

Random orientation of the jets



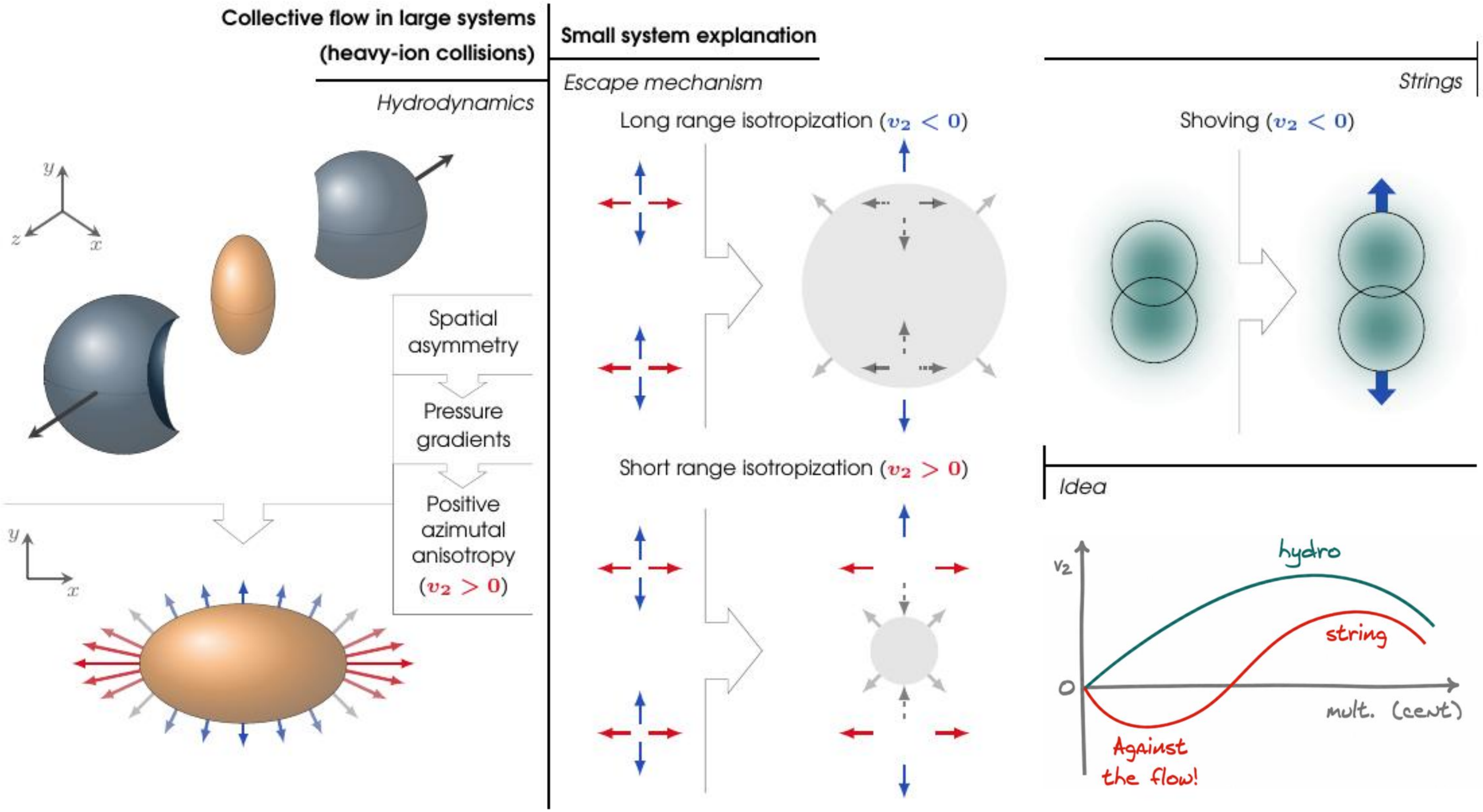
Thrust axis analysis to follow
the "direction of color string"



Thrust Axis

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

Going Against the Flow



At low multiplicity, similar conclusion as AMPT study

arXiv:2409.16093
Phys.Lett.B 874 (2026) 140216