Energy-Energy Correlators in e^+e^-, pp and PbPb with ALEPH, DELPHI and CMS

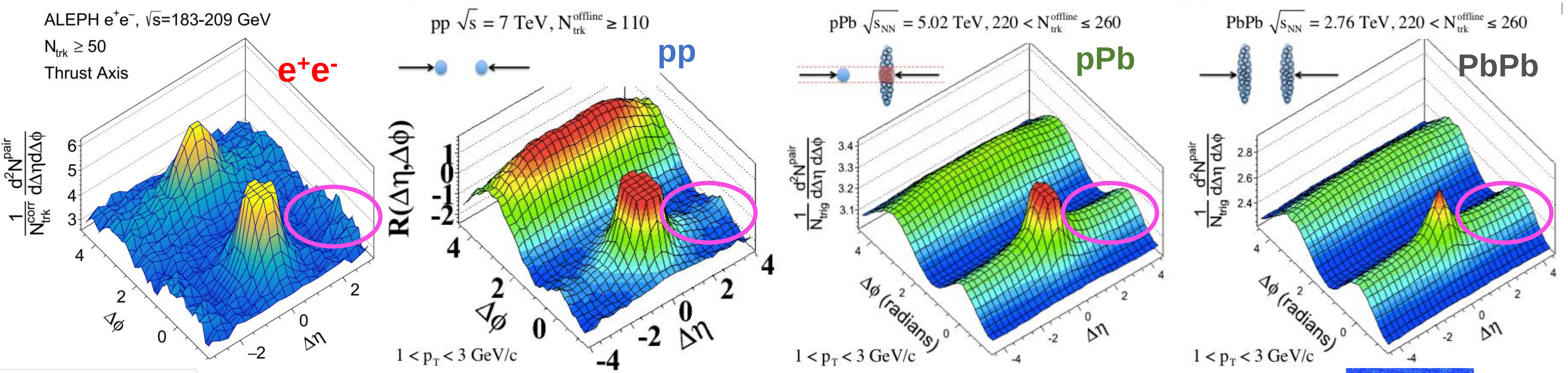
Yen-Jie Lee (MIT)

Taiwan EIC Meeting

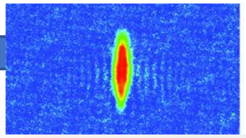
April 9th 2026

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

Motivation

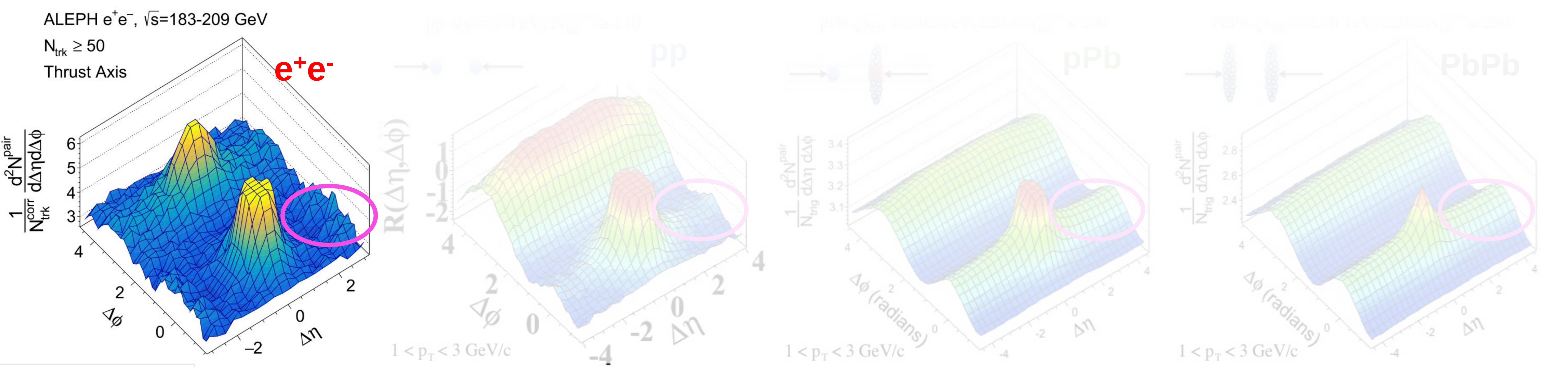


MIT-MOD-23-001
arXiv: 2312.05084
PLB 856 (2024) 138957



- Two-particle correlation functions have been studied in large collision systems.
- Recent efforts have been extended to **smaller and smaller** collision systems
- Comprehensive studies from e^+e^-, **pp** to **pA** and **AA** collisions:
  Understand how the strongly interacting medium in **AA** was produced
- **EEC** has been studied first in e^+e^- and now extended to **larger and larger** systems

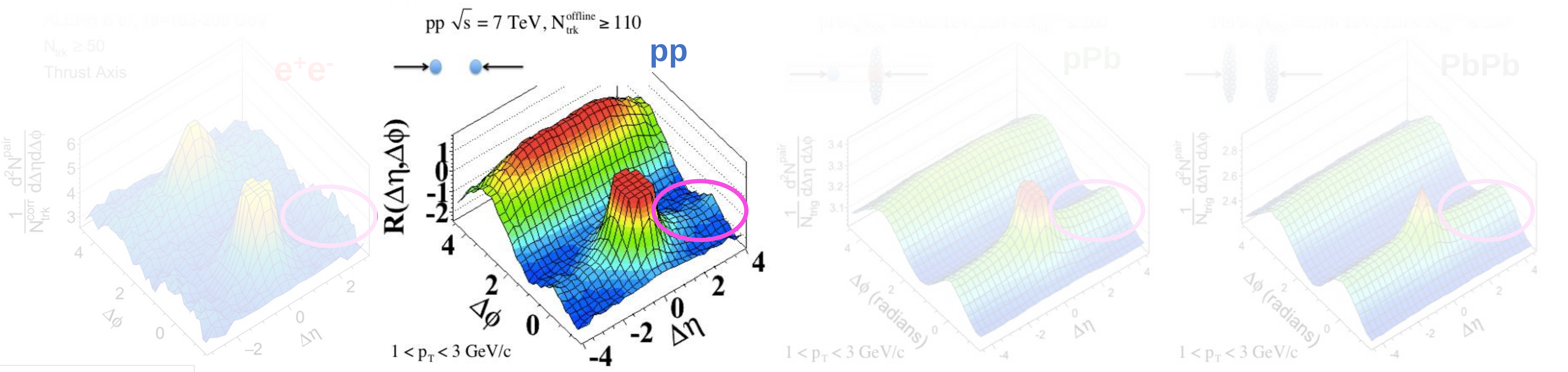
Motivation



MIT-MOD-23-001
arXiv: 2312.05084
PLB 856 (2024) 138957

- **Jet substructure and EEC in e^+e^-:**
  - Utilize the new **jet clustering tools** developed after LEP operation
  - New tool for α_s extraction
  - Revisit EEC with fine binning and extended it to full event
  - Further test of event generators, **precision QCD**, reference of pp
  - Important preparation for EIC analyses as its reference

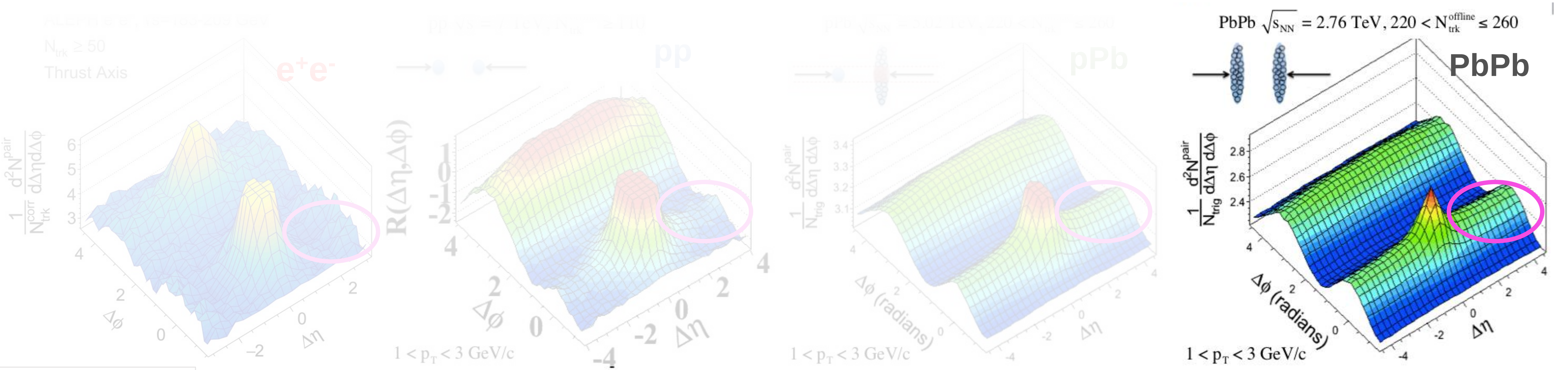
Motivation



MIT-MOD-23-001
arXiv: 2312.05084
PLB 856 (2024) 138957

- **EEC in pp:**
  - New tool for α_s extraction
  - Test on pQCD and compared to event generators, such as PYTHIA 6, PYTHIA 8, SHERPA and HERWIG are tuned with hadronic event shape observables and hadron spectra in $e^+ e^-$
  - Reference for pA and AA

Motivation



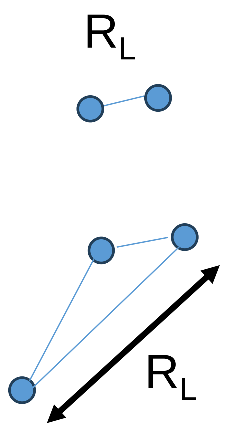
MIT-MOD-23-001
arXiv: 2312.05084
PLB 856 (2024) 138957

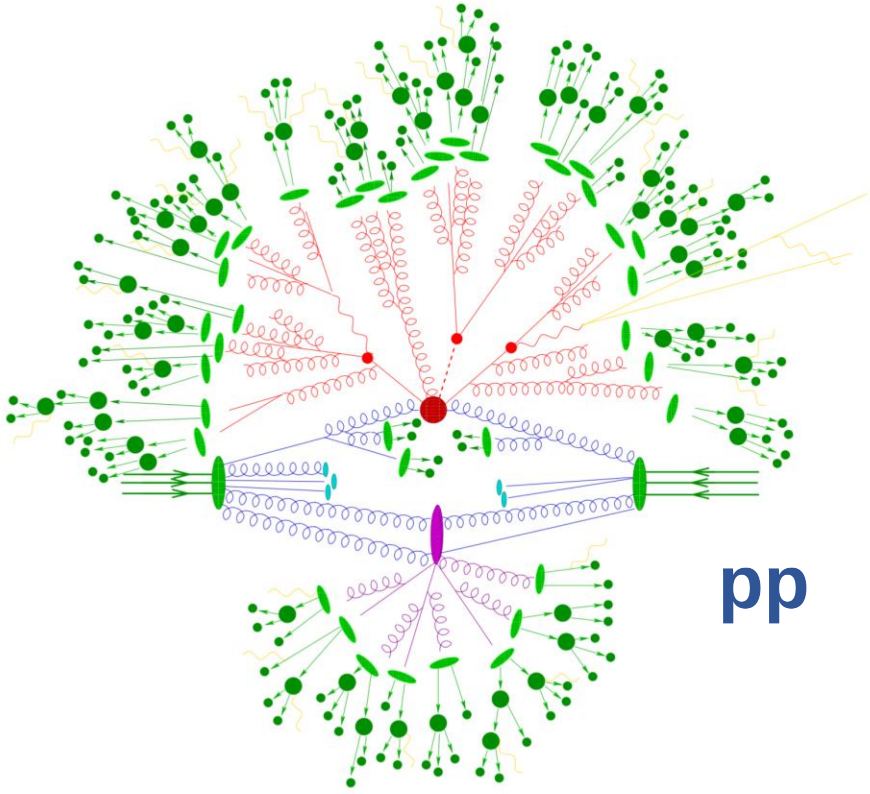
- **EEC in PbPb:**
  - Inclusive jet: reveal medium induced modification of EEC in jet
    - Jet quenching, medium induced momentum broadening, induced radiation and medium response
    - **First inclusive jet EEC in AA**
  - First Z-tagged EEC: access to full event, without jet selection bias

(1) Energy-energy correlators in CMS pp

$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$$

$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$





First Measurement of E3C and E3C/E2C in pp

Chen, Gao, Li, Xu, Zhang, and Zhu, arXiv:2307.07510

In QFT at LL, E3C/E2C is a linear function of α_s

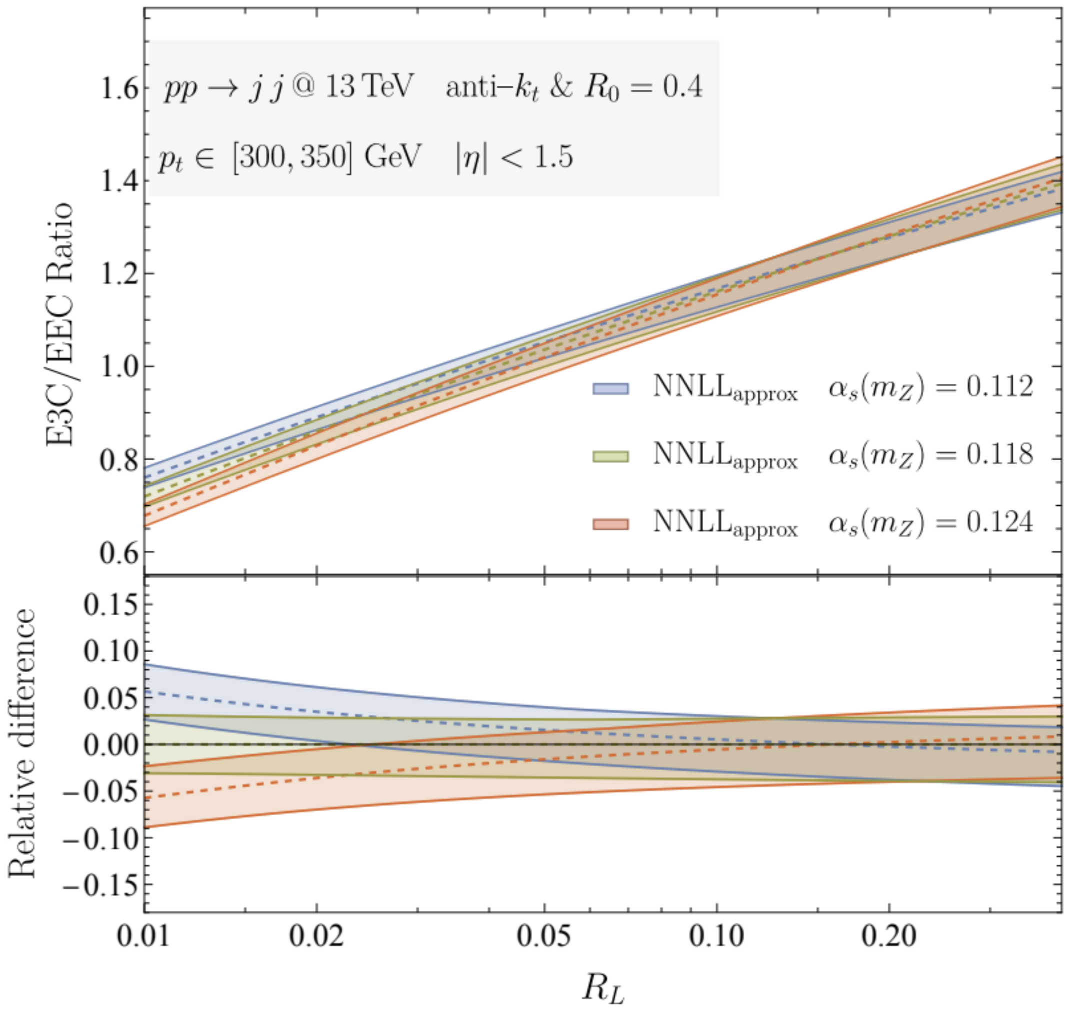

$$\propto \alpha_S(Q)\ln x_L + O(\alpha_S^2)$$

Difficulties in extracting α_s from jet substructure:

Degeneracy between q/g fraction and α_S: $\alpha_S * C_i$

Solution: E3C/E2C ratio mitigates the degeneracy

Former jet substructure α_s extraction: ~ 10%, arXiv:1808.07340



$\alpha_S(M_Z)\uparrow$ Slope $\uparrow$

Analysis Procedure (13 TeV)

Event selection:

Dijet events: large cross section

PF jet, $|\eta| < 2.1$, anti-kT with R = 0.4,

CHS (PU charged hadron subtraction)

Object selection:

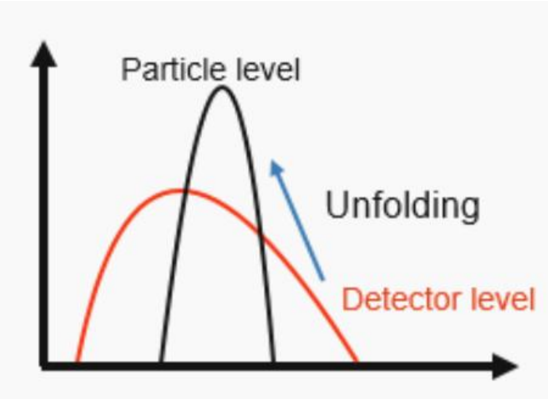
8 p_T^{jet} regions in 97 ~ 1784 GeV

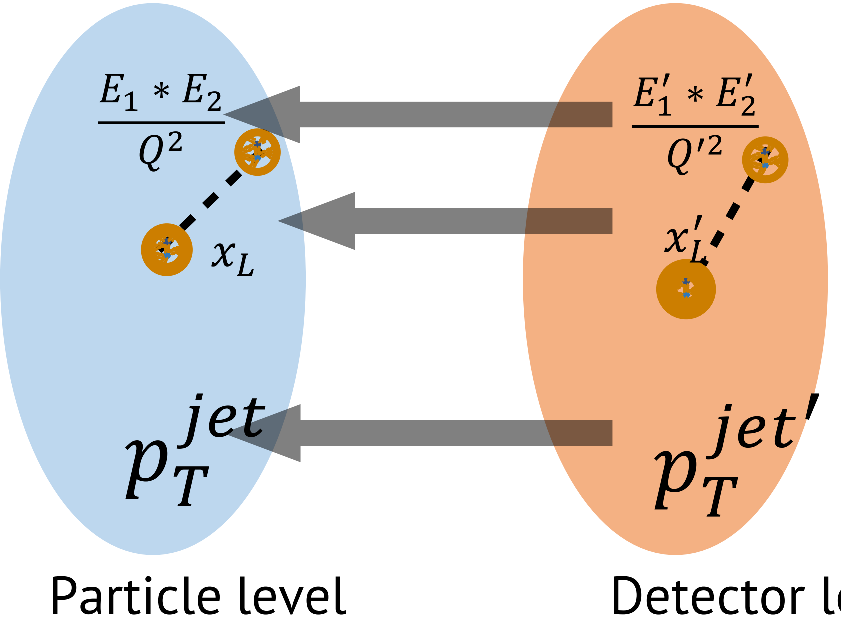
- Probe energy scale dependency

Neutral & charged particles with p_T > 1 GeV

- All particles included, direct comparison with theoretical calculation

Unfolding:





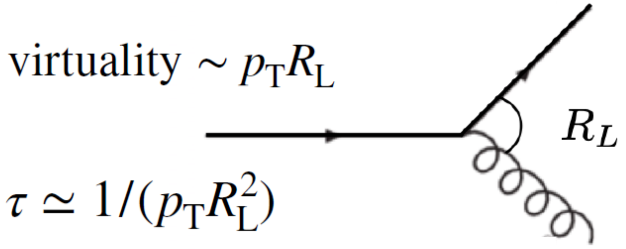
Unfolding: detector level -> particle level

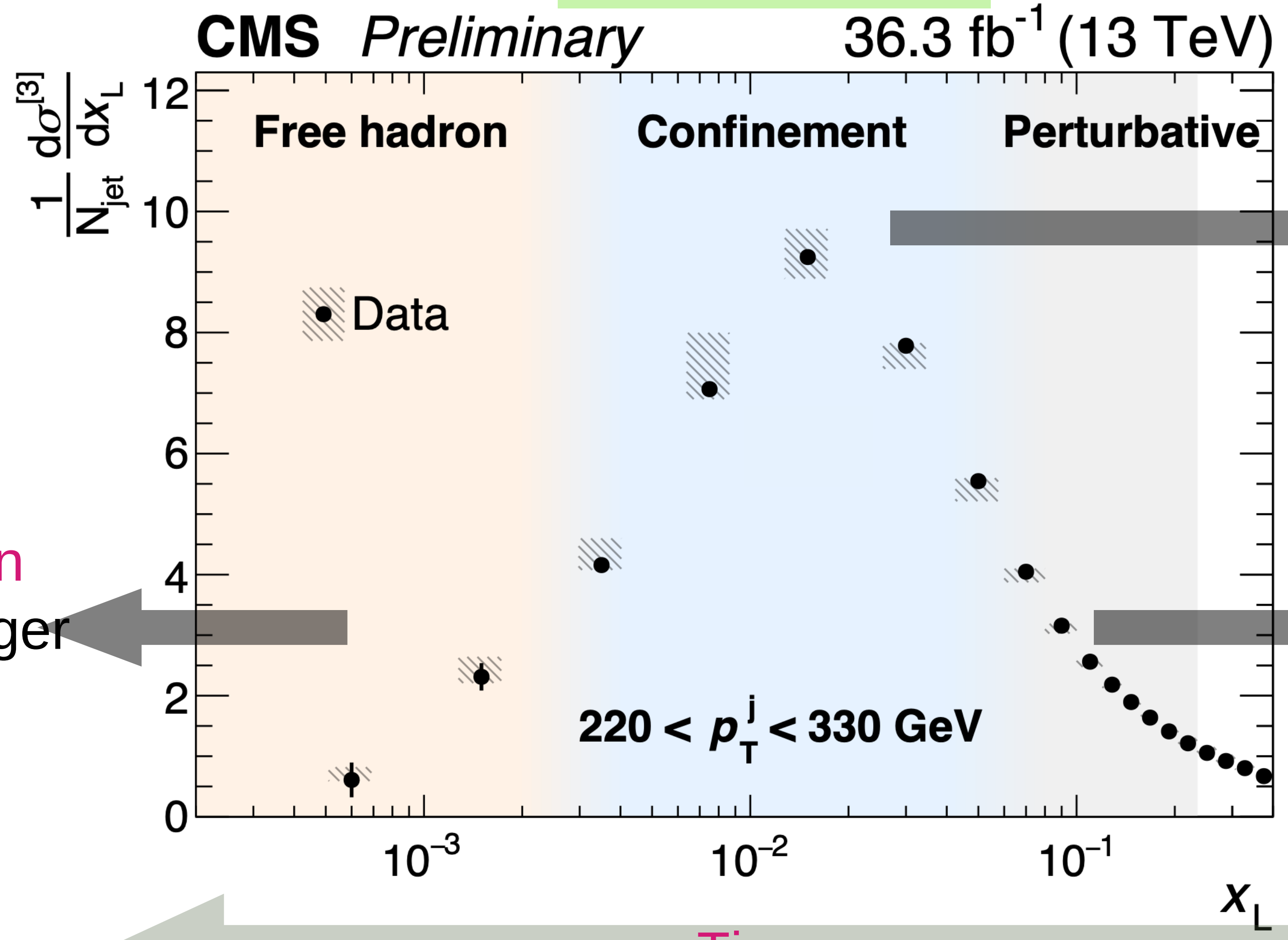
Unfold jet constituents instead of distribution:

- p_T^{jet}, x_L and energy weight, 3D unfolding
- $10 * 22 * 20 = 4400$ bins

•D'Agostini: iterative Bayesian unfolding

Unfolded E2C in pp at 13 TeV





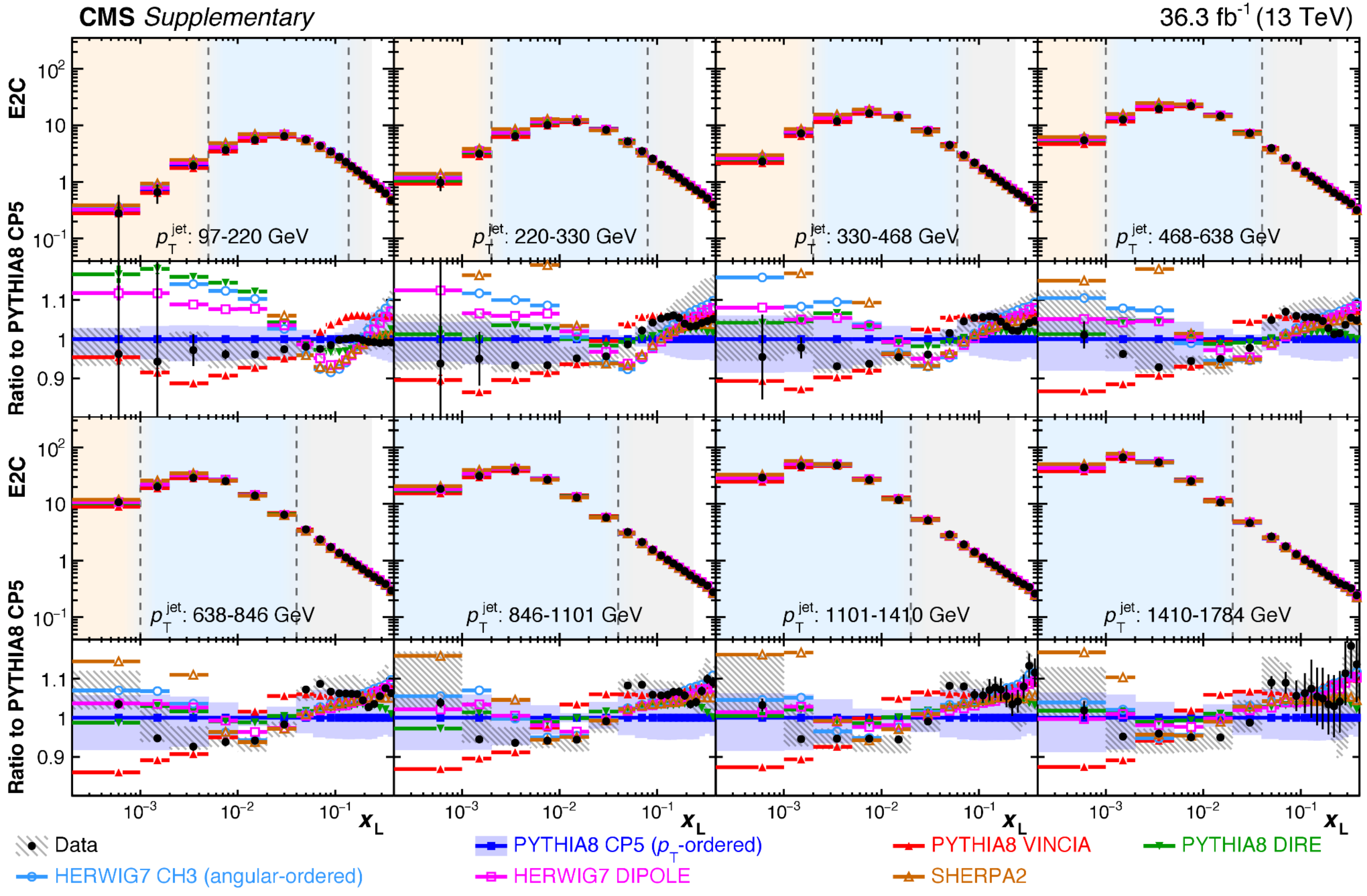
Phase transition from parton to hadron

Non-interacting hadron random distribution integer power-law scaling

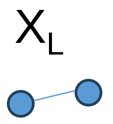
Interacting partons non-integer scaling

Time

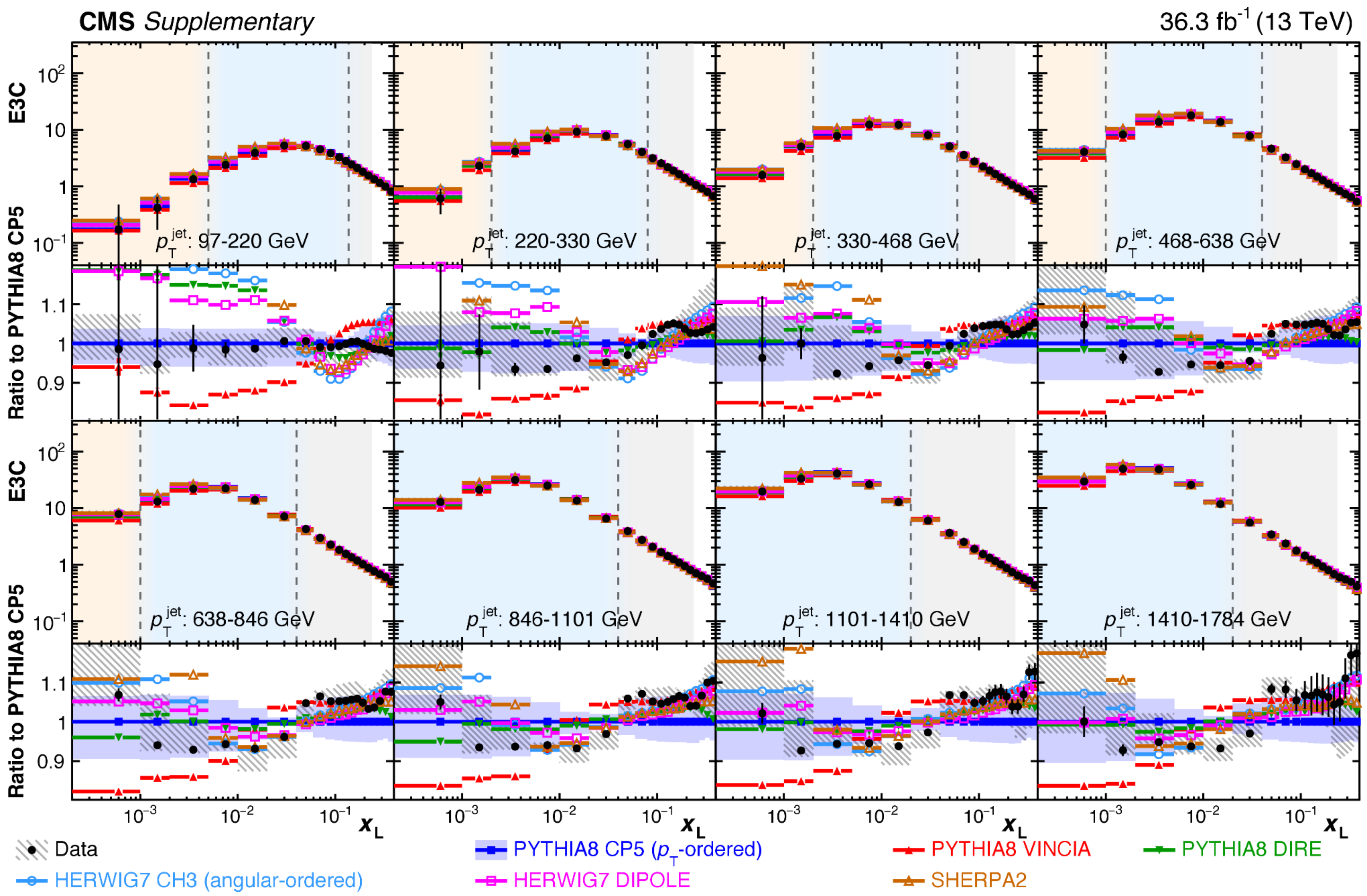
Unfolded **E2C** vs MC Generators in pp at 13 TeV



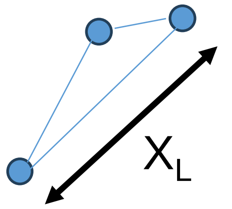
- Results compared to PYTHIA8, HERWIG and SHERPA2
- **None** of the generator fully describes the E2C data
- Spread of the predictions from generators at the 10-20% level
- Peak position at around $p_T X_L \sim$ 2-3 GeV



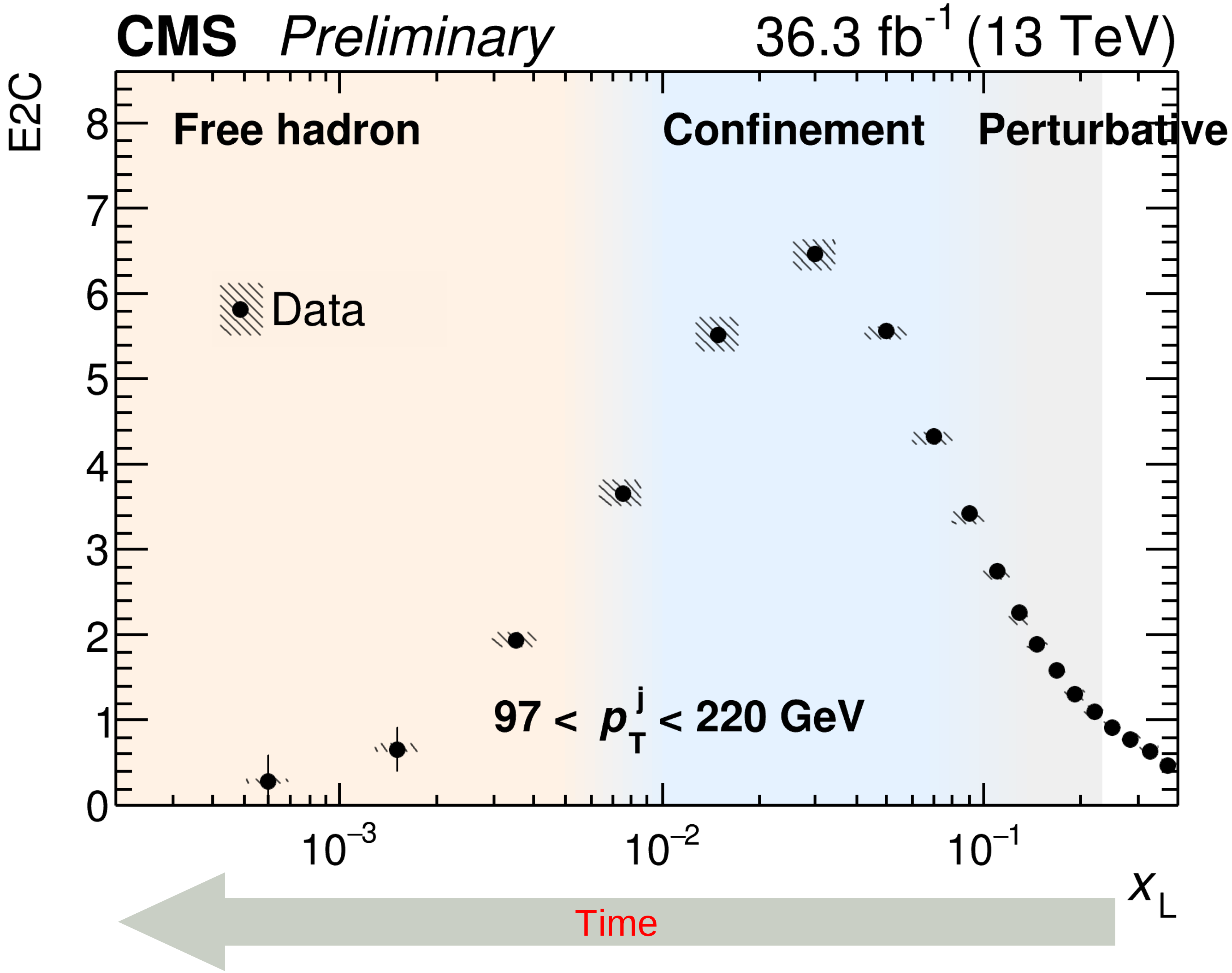
Unfolded **E3C** vs MC Generators in pp at 13 TeV



- Results compared to PYTHIA8, HERWIG and SHERPA2
- **None** of the generator fully describes the E3C data
- Spread of the predictions from generators at the 10-20% level



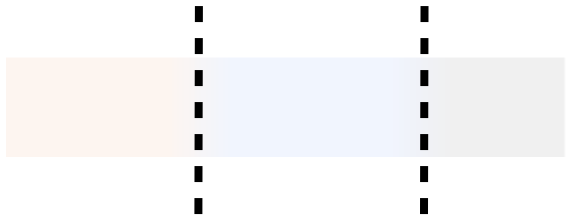
Unfolded E2C vs. Jet p_T



Boundary shifts with jet p_T

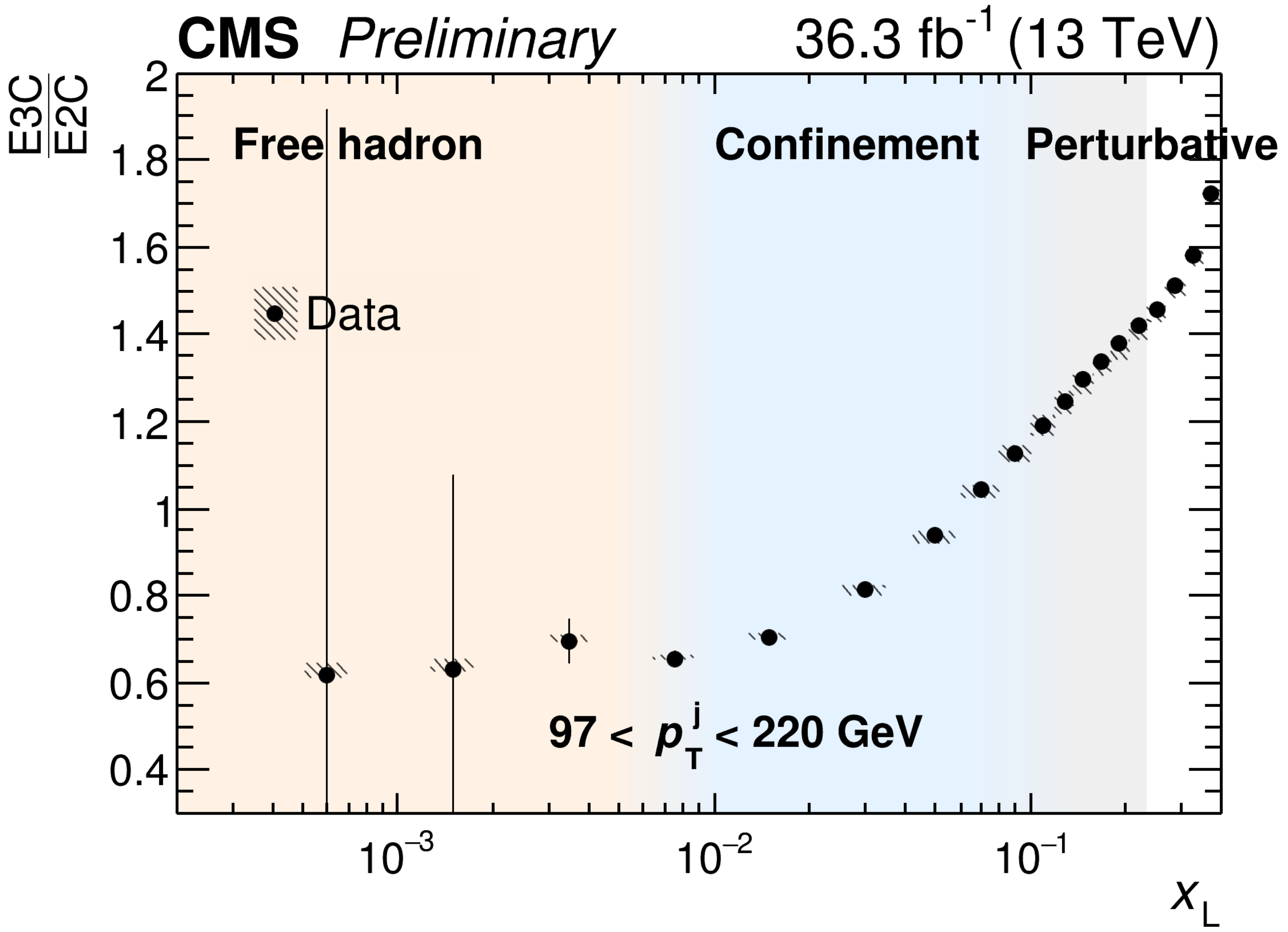
$Q \propto x_L * p_T^{jet}$

$p_T^{jet} \uparrow,\ x_L \downarrow$



$x_L \approx \frac{0.8}{p_T^{jet}}$ $x_L \approx \frac{20}{p_T^{jet}}$

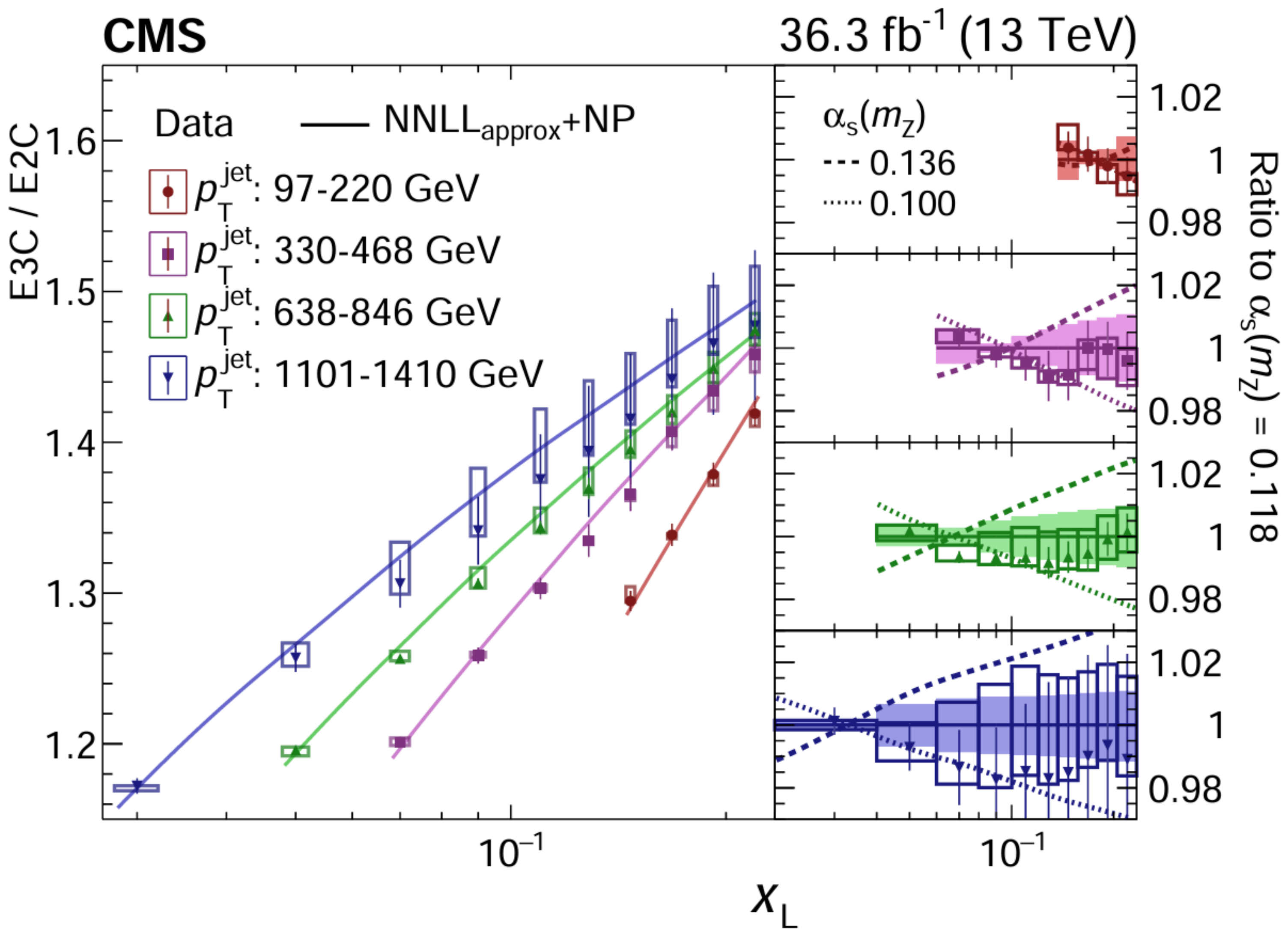
E3C/E2C ratios as a function of Jet p_T



p_T^{jet} ↑, Slope ↓

Extraction of α_s by data NNLL comparison

Perturbative Region



$\alpha_s(m_Z) = 0.118$

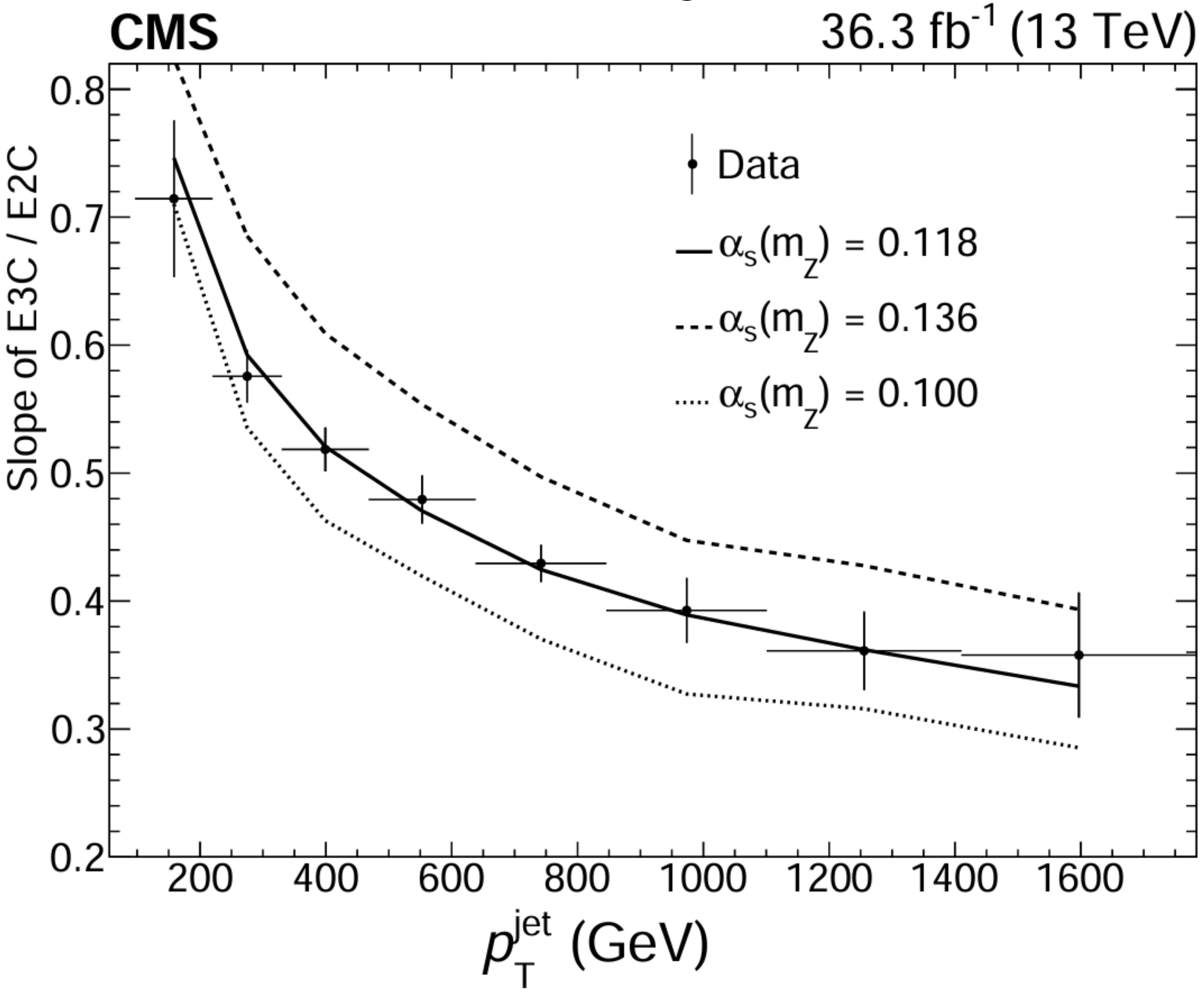
Shape of data agrees with within uncertainty

Theory systematics includes:
(shape only, no normalization effect)

- QCD scale of NNLL prediction
- Hadronization factors
- QCD scale in hard scattering
- Underlying event + parton shower tune
- PDF

Extraction of α_s by data NNLL comparison

Perturbative Region



Shape of data agrees with within uncertainty

Theory systematics includes:
(shape only, no normalization effect)

- QCD scale of NNLL prediction
- Hadronization factors
- QCD scale in hard scattering
- Underlying event + parton shower tune
- PDF

Extracted coupling constant:

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

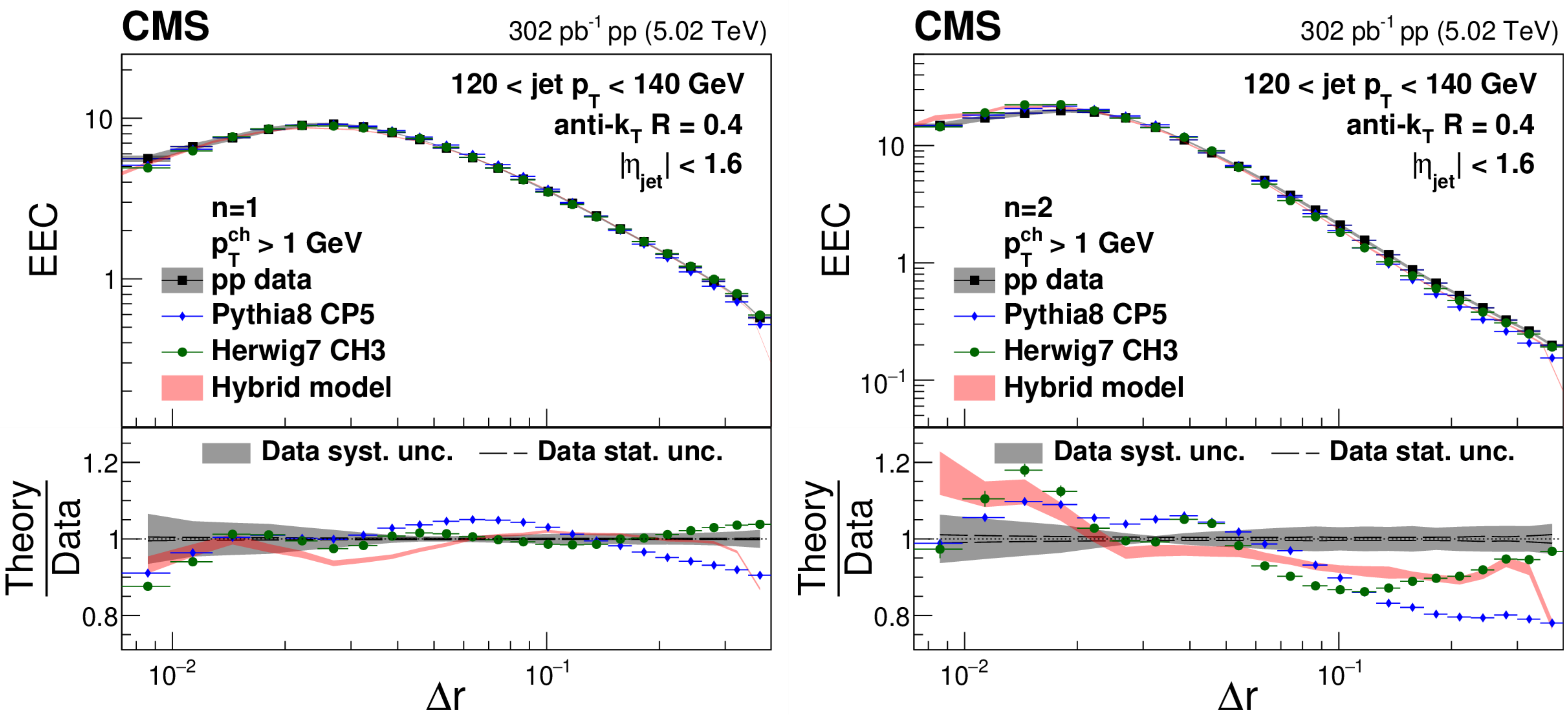
$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

Covariance matrix

QCD scale of *NNLLapprox*

Neutral hadron energy scale

Charged Hadron-Based E2C vs MC in pp at 5 TeV



- E2C calculated with charged particles only, fully corrected with resolution effects
- Compared to **Hybrid pp**, **Pythia 8** and **Herwig 7**
- None of the event generators describe the pp data at 5 TeV

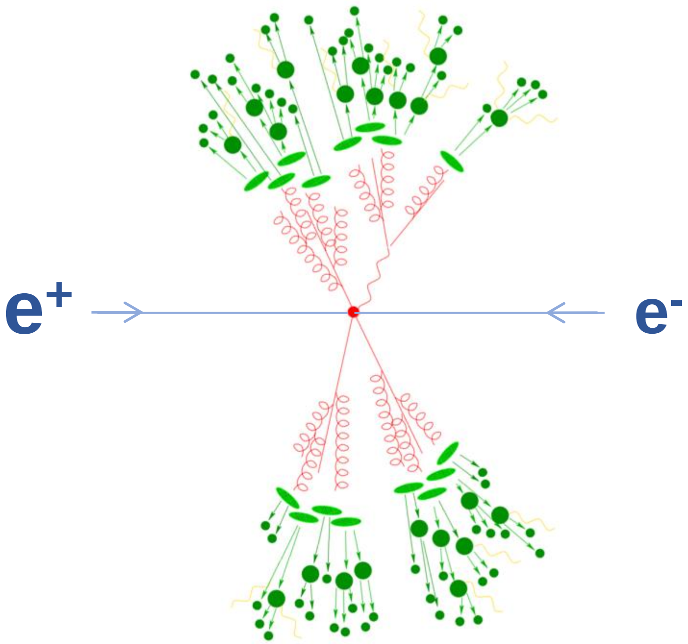
PLB 866 (2025) 139556

(2) Jets and energy-energy correlators in e^+e^-

Yi Chen (Vanderbilt U.)

Hannah Bossi (MIT)

Yu-Chen "Janice" Chen (MIT)

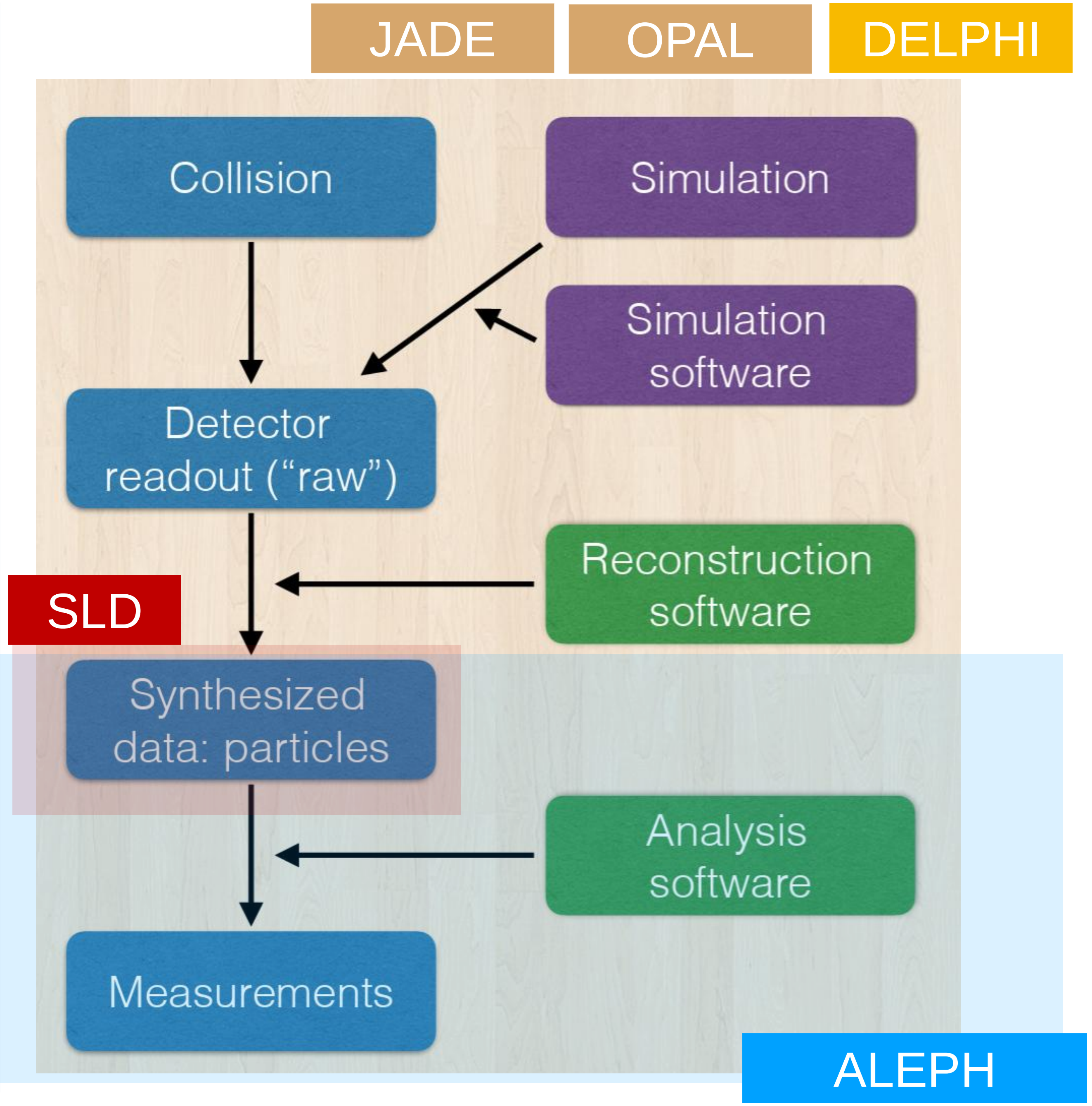


Electron Positron Alliance

Build a community that is actively working on the curation, standardizing and reanalysis of archived electron-positron collision data

Enable **direct collaboration** between **experimentalists, analyzers and theorists**

Weekly group analysis meeting since 2017
11 LEP notes and journal publications posted on arXiv
2 journal publications with the Belle Collaboration
> 70 presentations in conferences / workshops



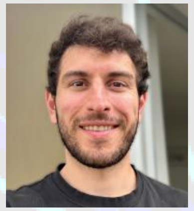
Electron-Positron Alliance


Janice Chen (MIT)


Austin Baty (UIC)

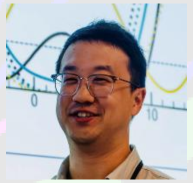

Chris McGinn (MIT)


Michael Peters (MIT)


Anthony Badea (UChicago)


Paoti Chang (NTU)


Cen Mo (SJTU)


Yulei Zhang (U. Washington)

Honey Khindri (IIT Madras)


Xiaoyuan Zhang (MIT)


Tzu-An Sheng (MIT)

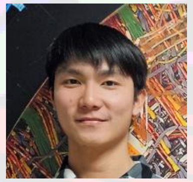

Ben Nachman (Stanford/SLAC)


Yi Chen (Vanderbilt)


Jingyu Zhang (Vanderbilt)


Luke Lu (Vanderbilt)


MJ Khan (Vanderbilt)


Chen-Hua Hsu (NTU)


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)

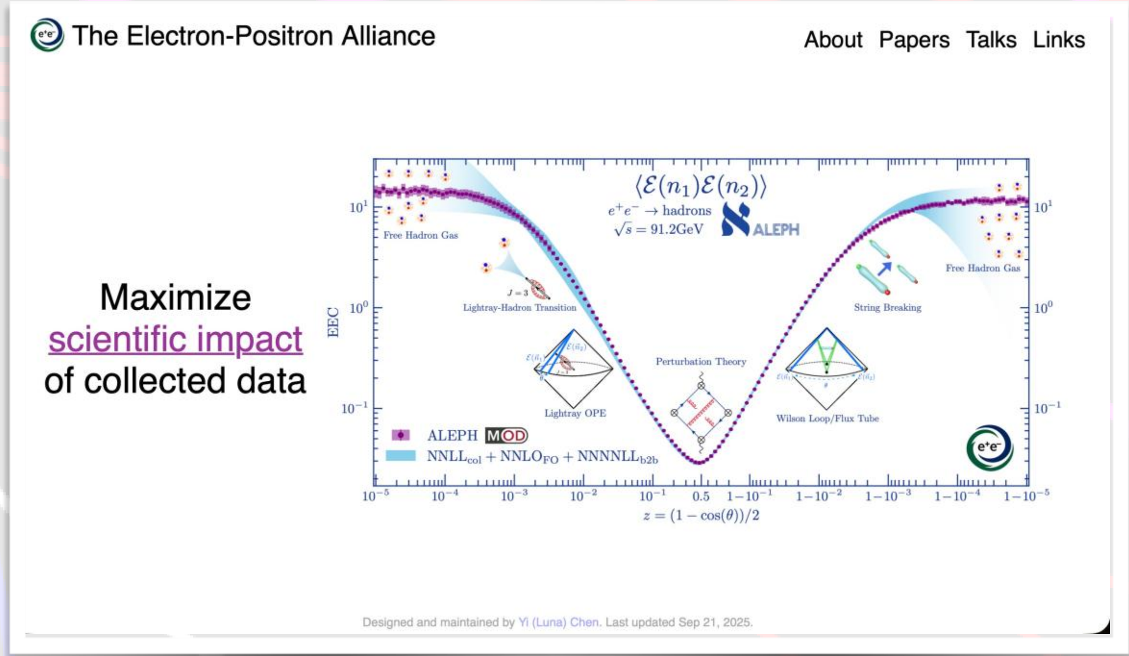
Sascha Diefenbacher (LBNL)

Bill Zhou (Vanderbilt)


Cristian Baldenegro (MIT)


Ting-Hsiang Hsu (NTU)


Prabhat Pujahari (IIT Madras)



https://ee-alliance.org

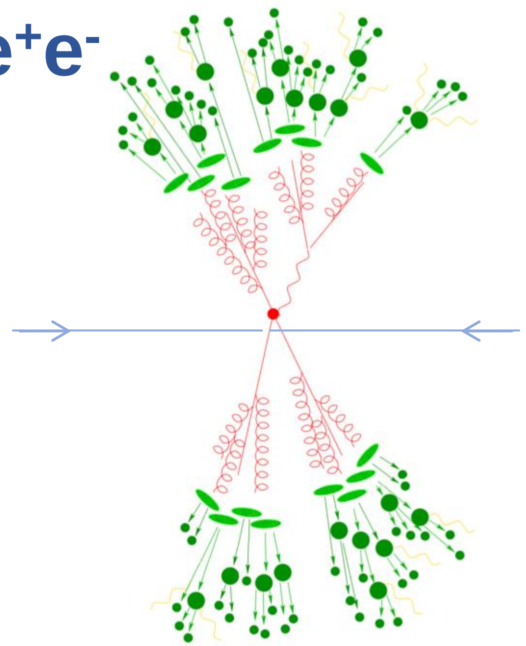
Jet in Electron-Positron Annihilation

- Jets in e^+e^- with identical algorithms as those used in hadron colliders are of great interest
  - No gluonic initial state radiation
  - No complications of parton distribution functions
  - No beam remnants and multi-parton interactions
  - → Cleanest test of pQCD and phenomenological models

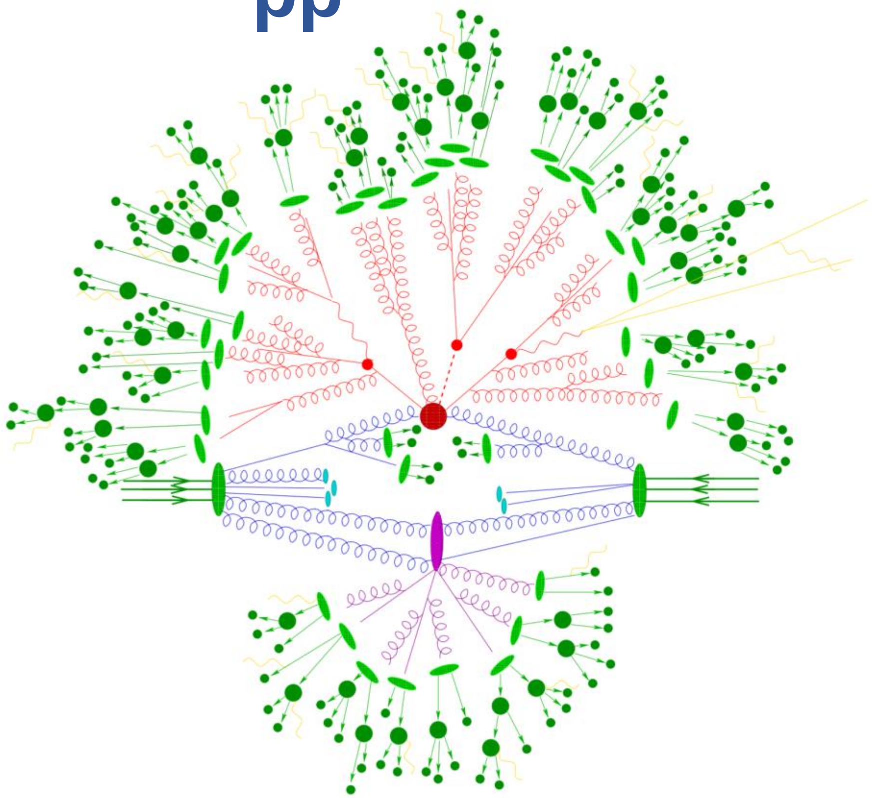
- Serve as a reference for the **pp** and future **EIC** measurements

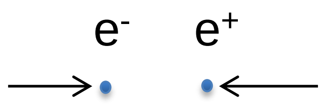
- Inform the QCD studies at the future FCC.

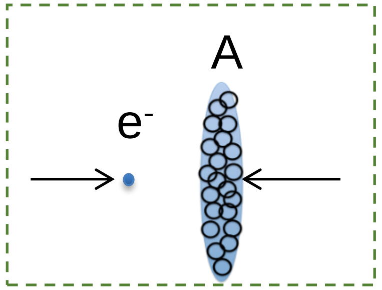
e^+e^-

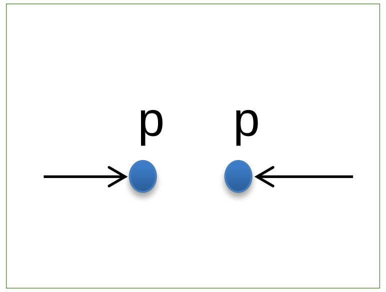


pp

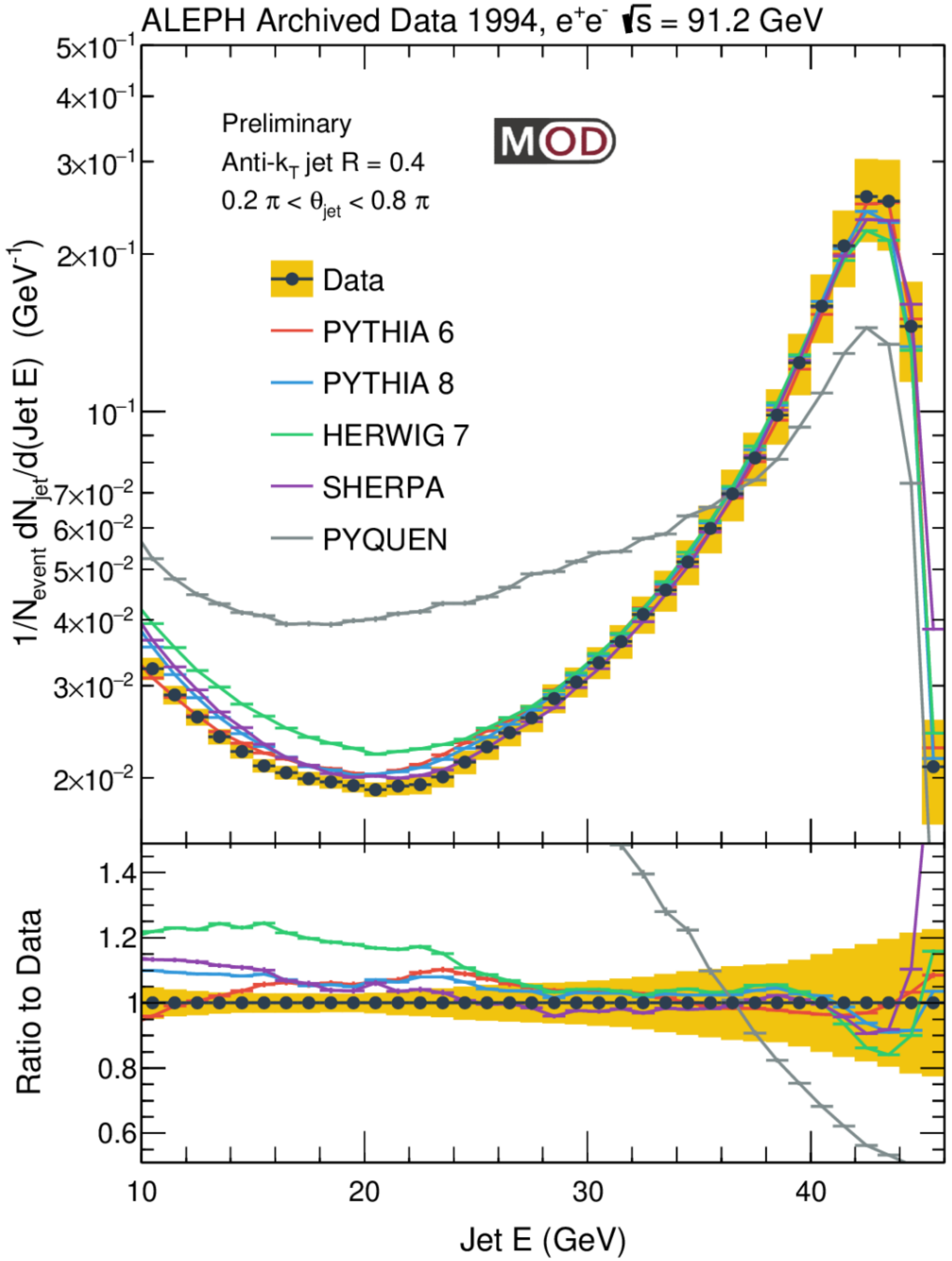






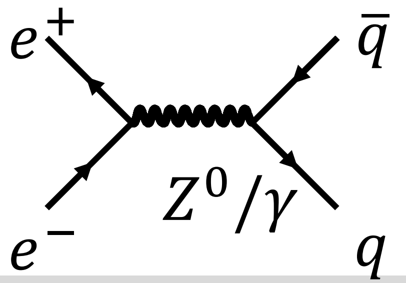


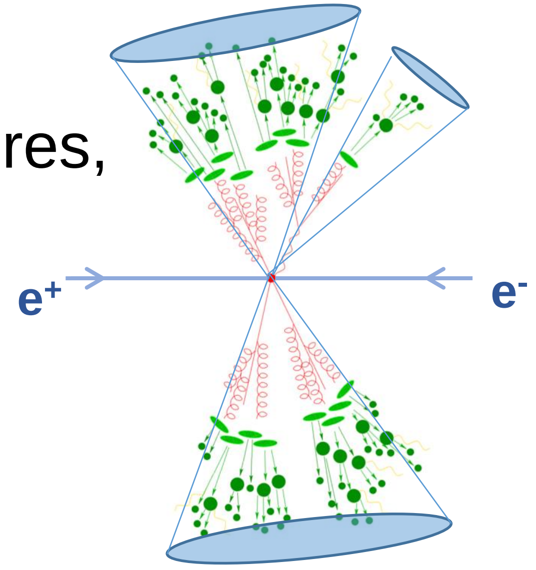
Inclusive Jet Spectrum vs. Generators



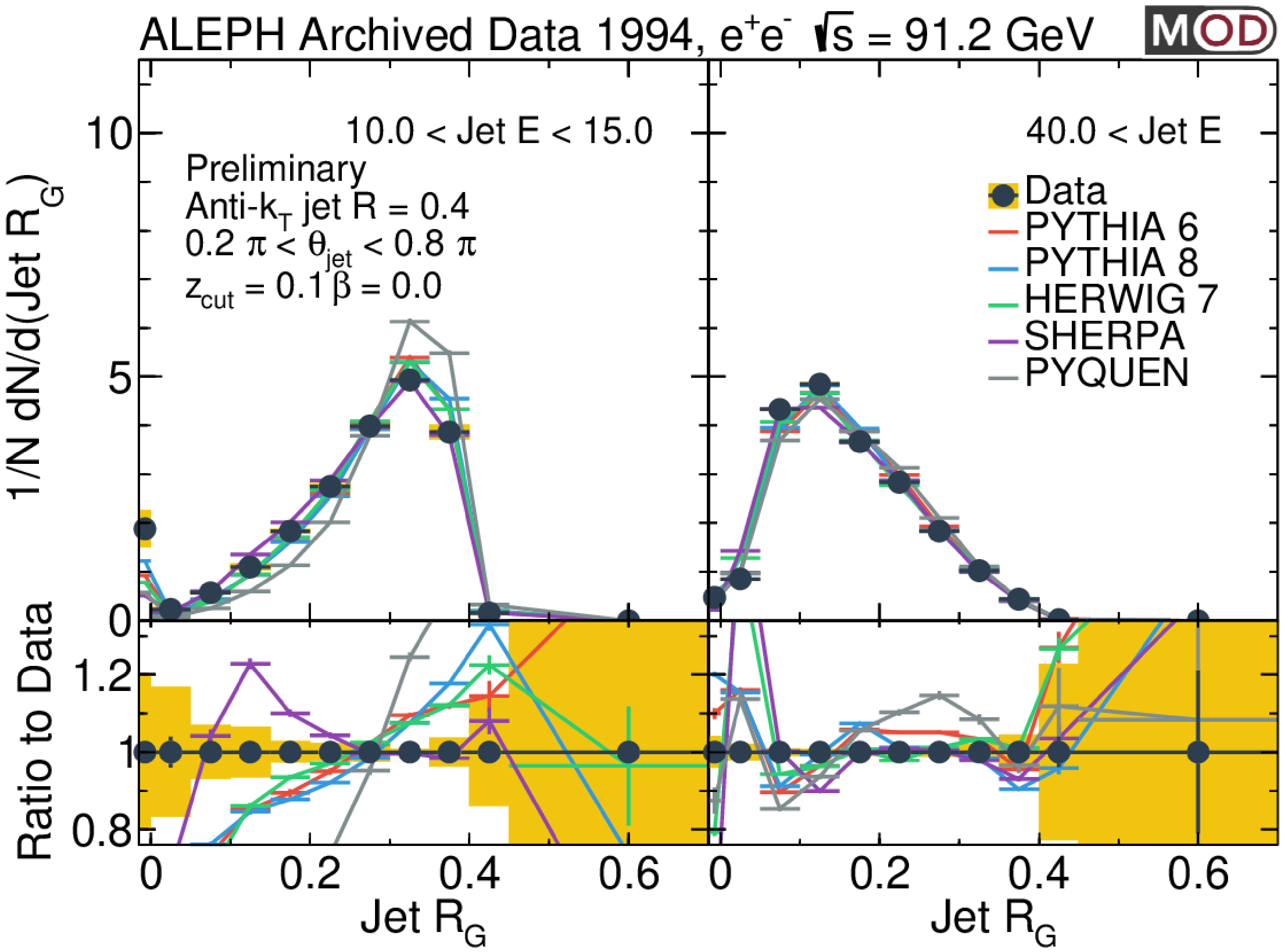
- The closest observable to the jet spectra analyses in hadron-hadron collisions!
- Peak at around 43 GeV: from $Z \to q\bar{q}$ and parton shower of the (anti-)quark **almost fully captured by the anti-k_T algorithm with R=0.4**
- Minimum at around 20 GeV
- At low E: increase due to a large number of jets from soft emissions or combinatorial
- Generators capture those general features, overpredict the spectra at low jet E

MITHIG-MOD-21-001
arXiv:2111.09914
JHEP 06 (2022) 008





Groomed Jet Radius R_G vs. Event Generators



Low jet E **High jet E**

- **High jet E** (mainly quark jets):
  - Peak at smaller R_G value
  - Generators give a better description of the data
- **Low jet E** (mainly from soft emissions and combinatorial):
  - Peak at larger R_G value as one would expect
  - SHERPA gives a better description of the data
  - PYTHIA 6, PYTHIA 8, HERWIG, and PYQUEN overpredict the R_G

MITHIG-MOD-21-001
arXiv:2111.09914
JHEP 06 (2022) 008

Definition of EEC in e^+e^-

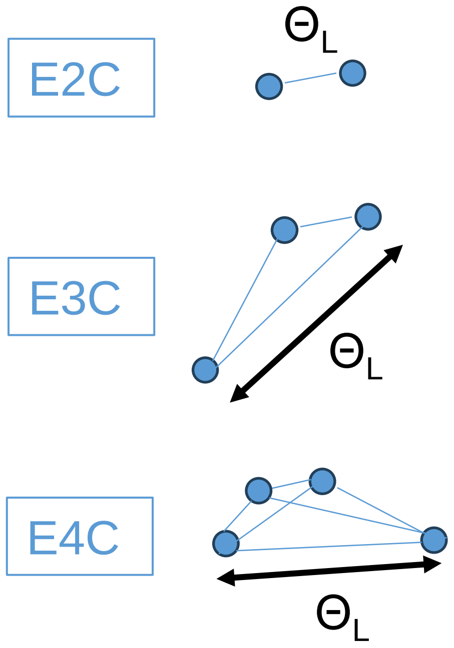
- No Jet reconstruction, Full event

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

Yi Chen (Vanderbilt U.)

  - 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.)** as opposed to the R_L or x_L which is eta-phi
  - Average over all events considered

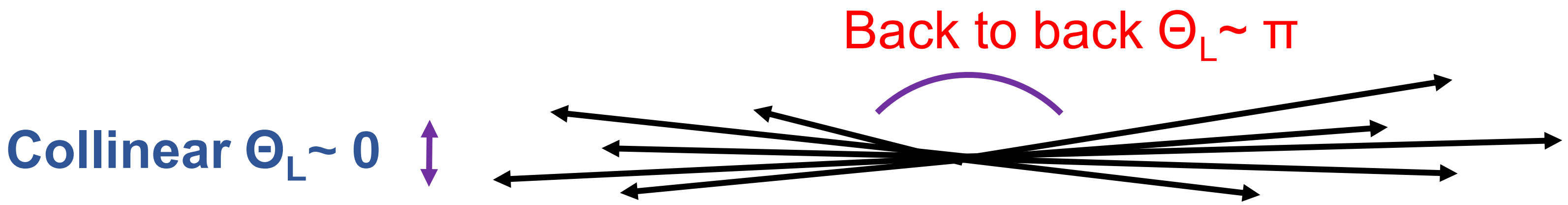
- Similar for 3-particle or higher correlators
  - For N-particle correlators, **Θ_L is defined as the largest angle of the pairs**

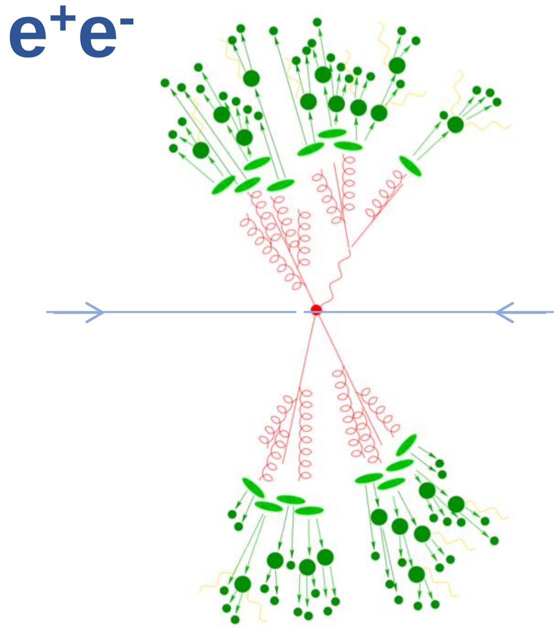


EEC in e^+e^-: Extending to back-to-back region

- Back-to-back (**Sudakov Limit**)
  - At $\Theta \sim \pi$
  - 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^-!
- Important ingredient into theory calculations to control non-perturbative effect
- Similar to collinear limit, this can also be used to study confinement transition and strong coupling constant

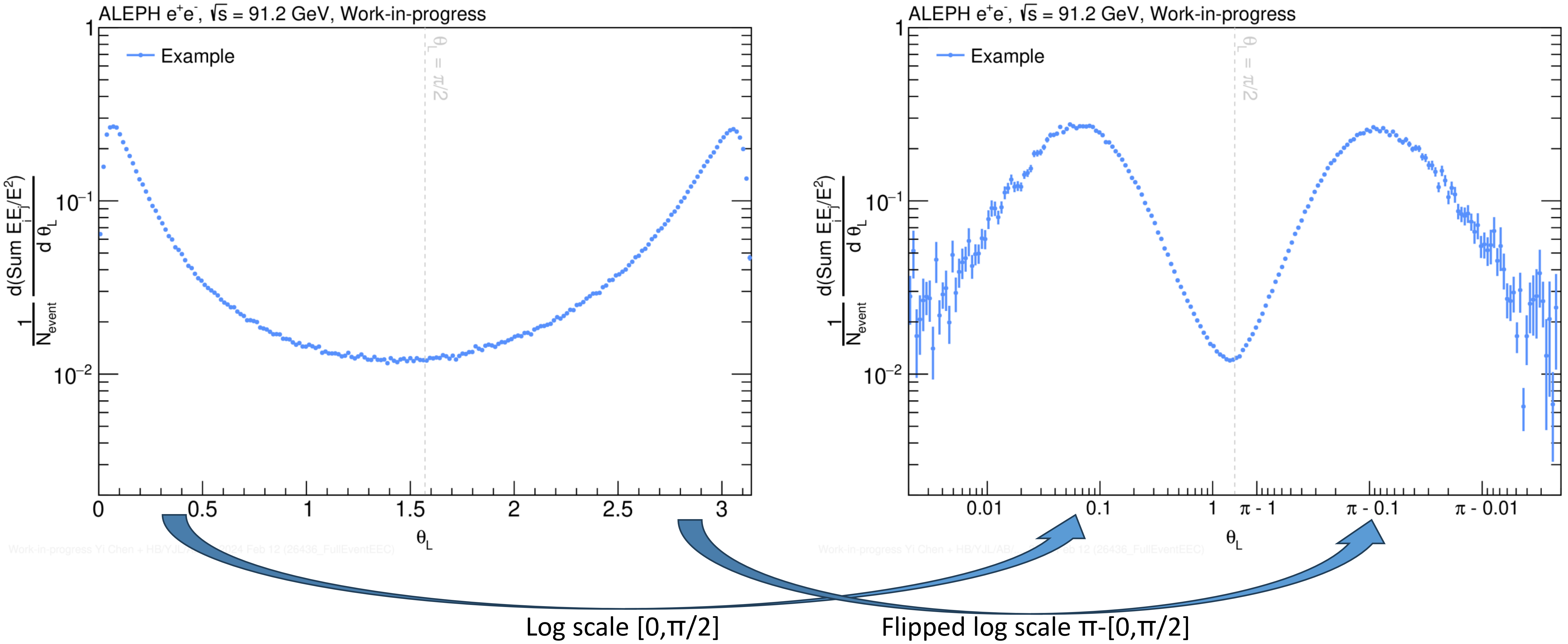
Yi Chen (Vanderbilt U.)





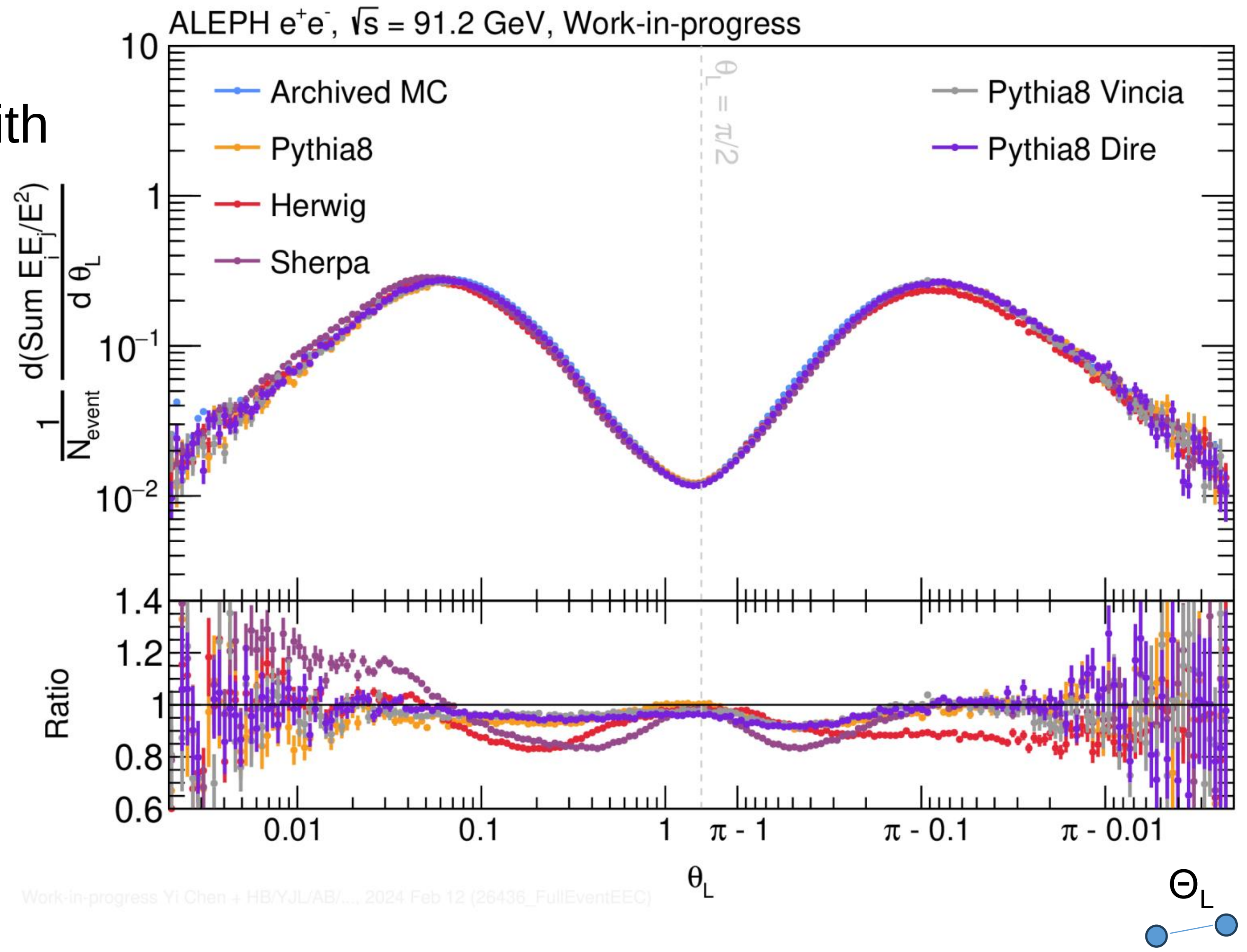
2-Particle EEC (E2C) from Archived MC

- Presented in double-log-x scale to focus on the tail region



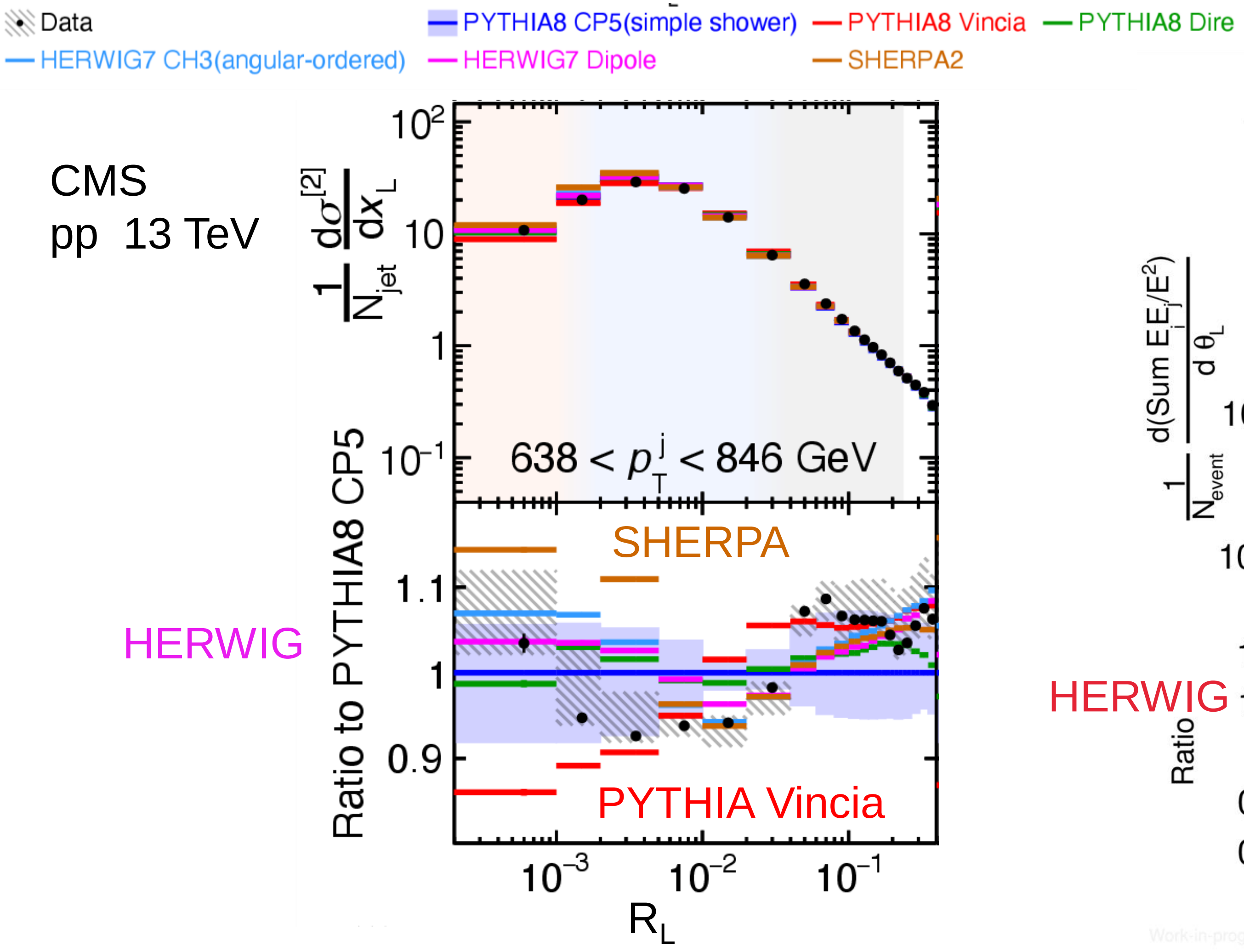
E2C from MC Generators

- Dominant structures
  - Dijet back to back
  - Left peak is what people are familiar with
  - No reason to be symmetric a priori
- Left peak (collinear)
  - Parton shower region
    - Different shower, different slope
  - Hadronization region
    - MCs roughly parallel to each other
  - Peak location
    - Correspond to 45 GeV scale
    - Different MC are a bit different
- Right peak (back-to-back)
  - Also a peak and transition between Sudakov limit and parton shower

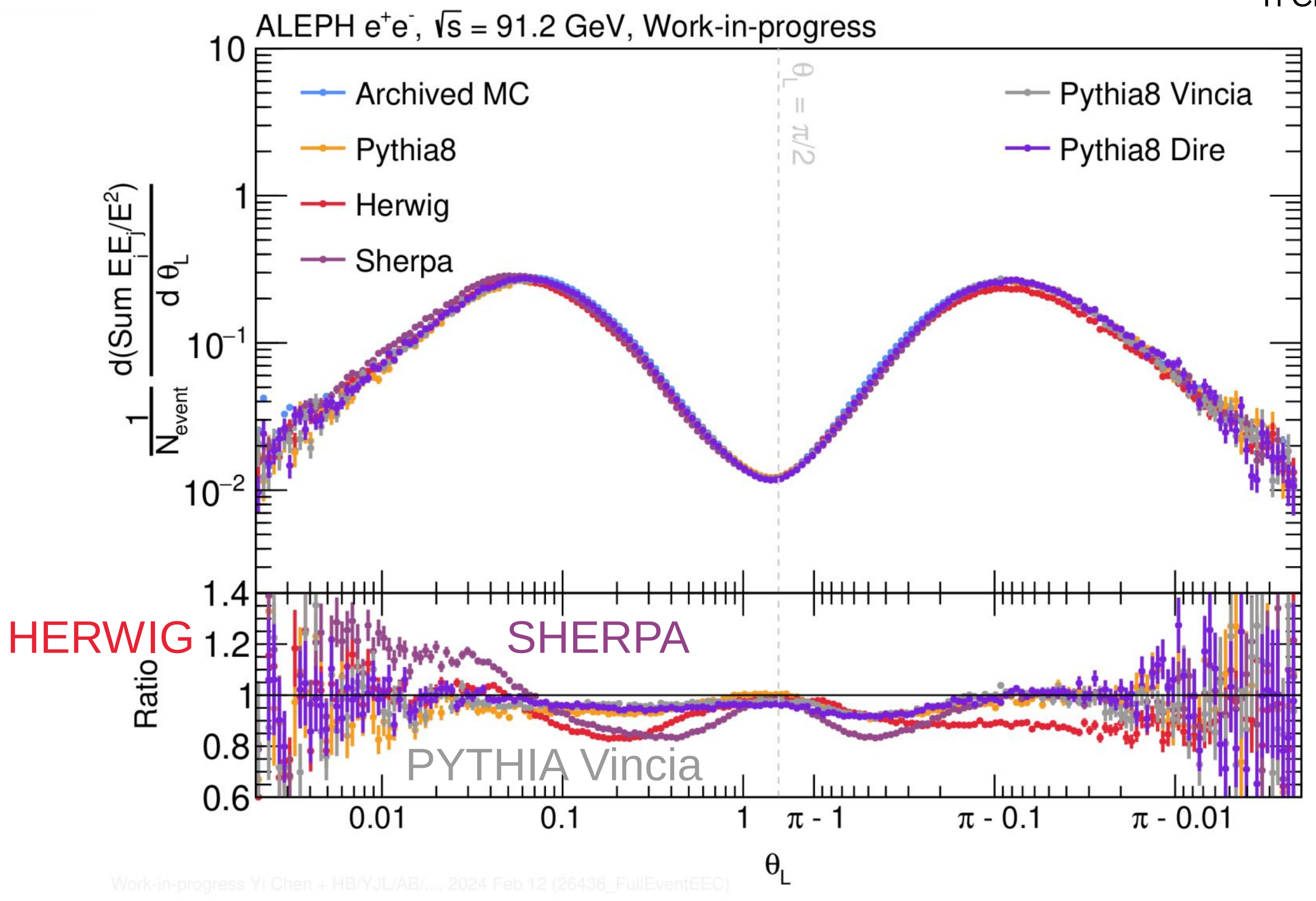


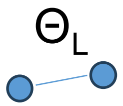
E2C from MC in pp and e^+e^-

- Similar MC hierarchy between e^+e^- generators and pp generators (SHERPA→HERWIG→PYTHIA)
- Larger x_L not comparable due to jet boundary effects in pp measurement



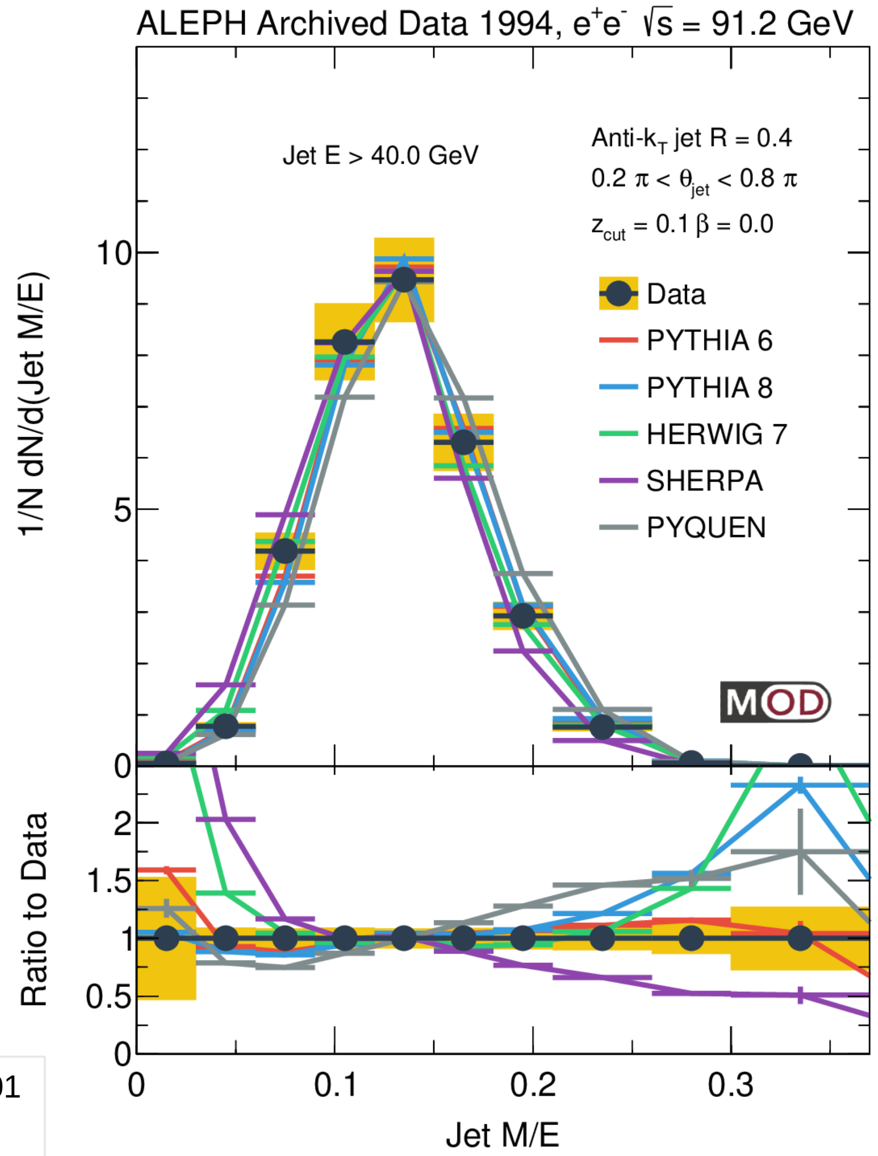
Yi Chen (Vanderbilt U.)



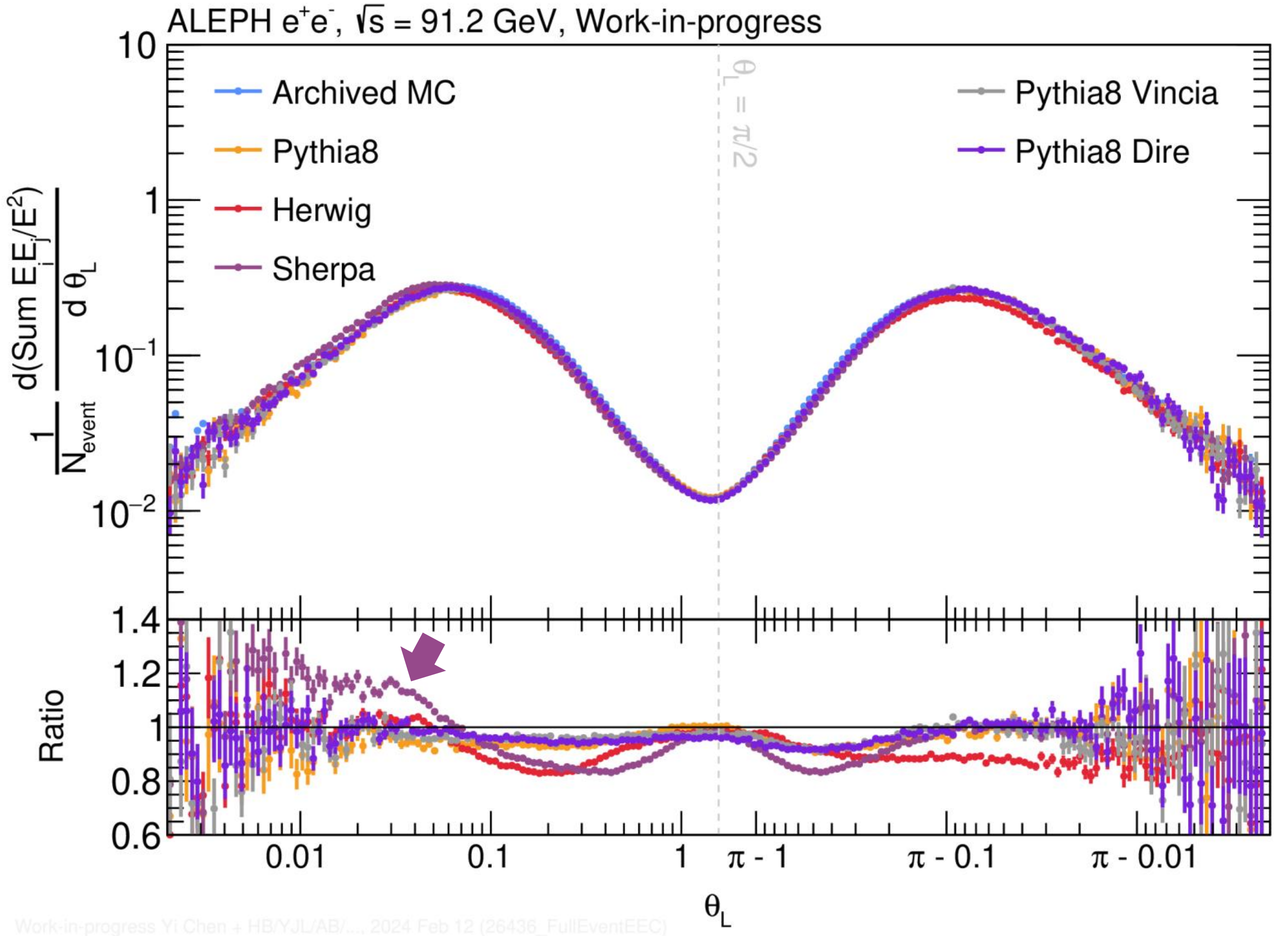


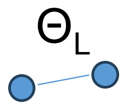
Comparison between E2C with Jet Mass

- Mass scale for SHERPA is smaller → smaller SHERPA angular scale in EEC

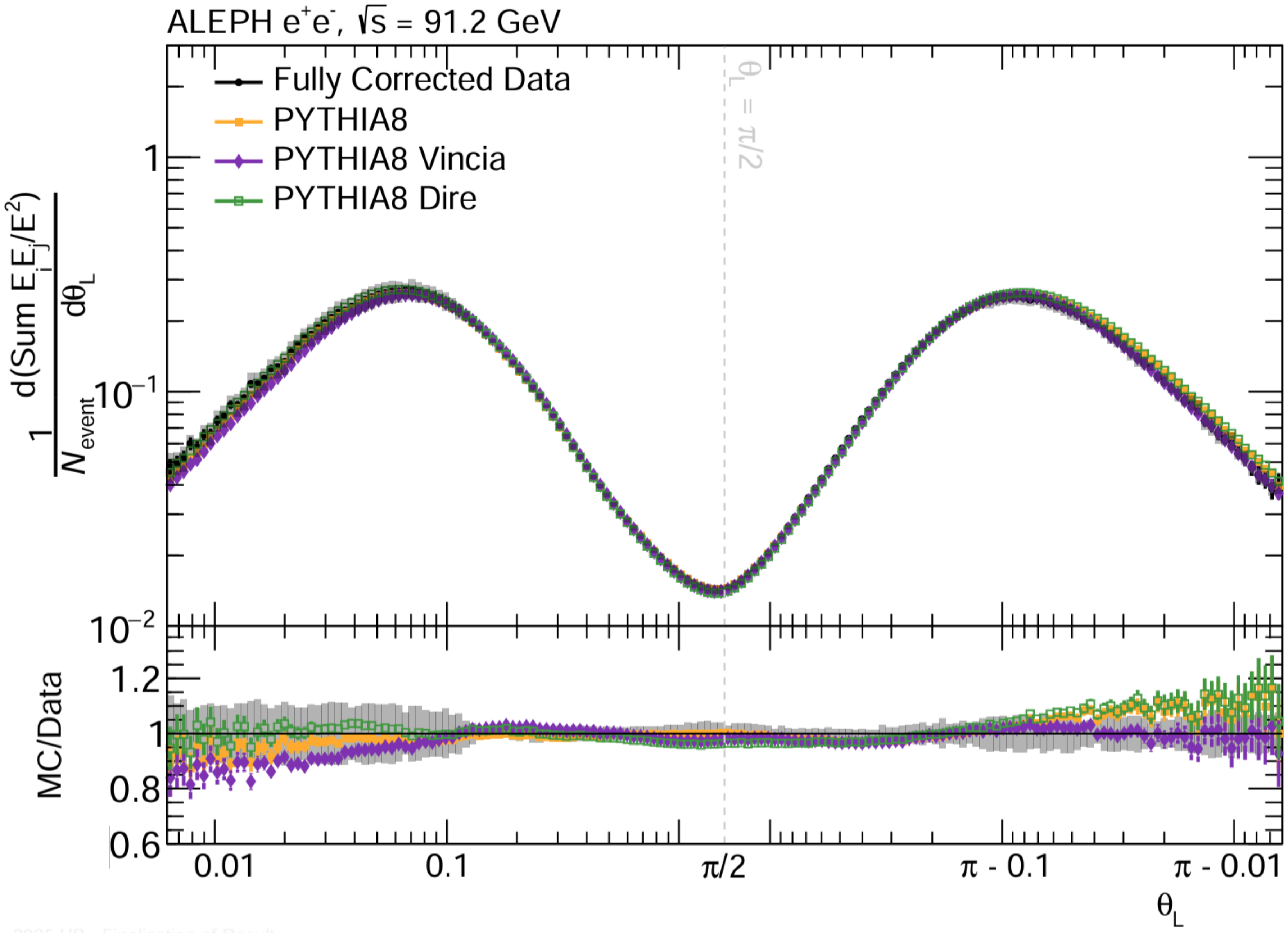


MITHIG-MOD-21-001
[arXiv:2111.09914](https://arxiv.org/abs/2111.09914)
JHEP 06 (2022) 008





Result: Fully Corrected EEC in e^+e^-



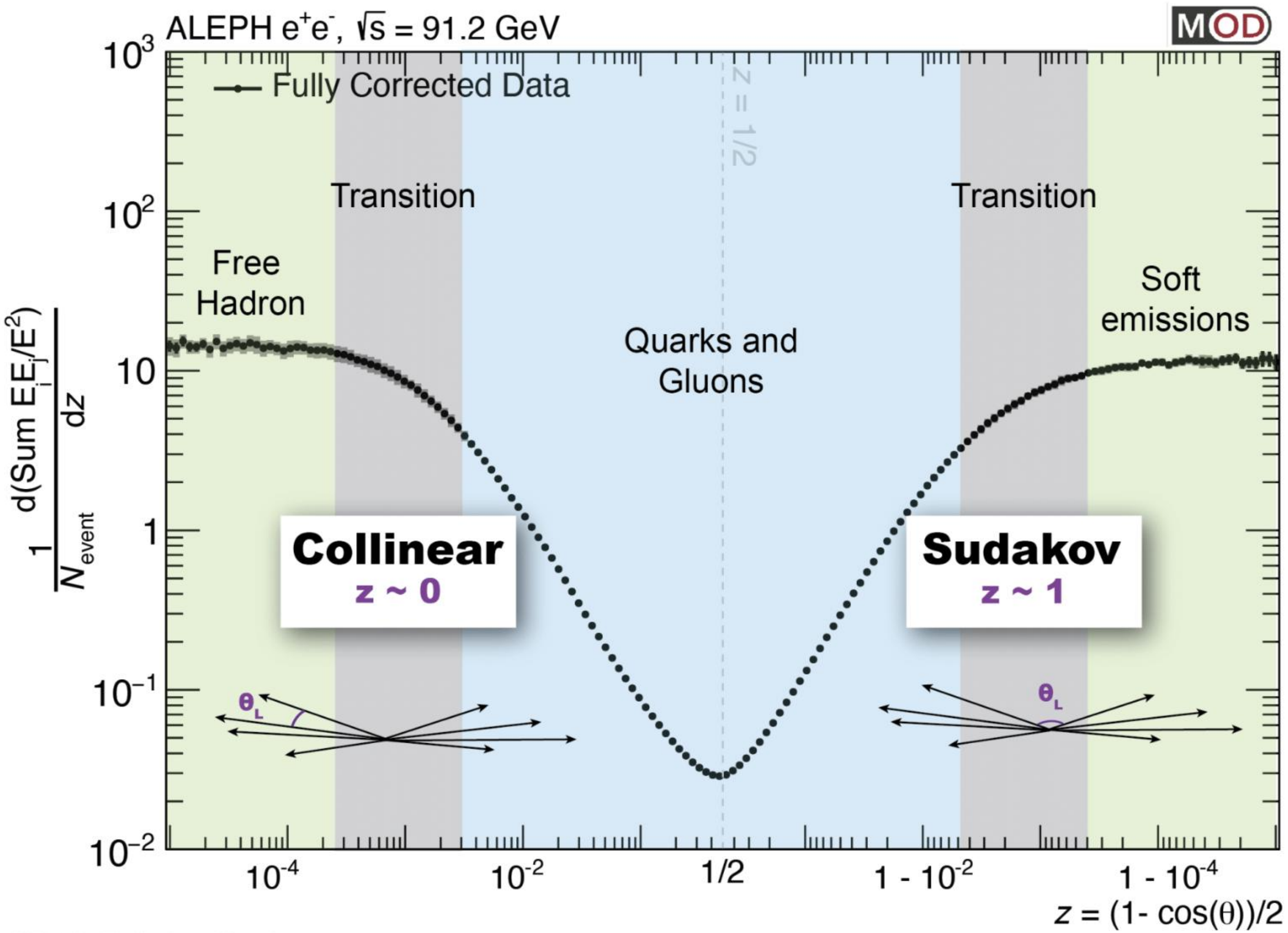
Hannah Bossi (MIT)

Yi Chen (Vanderbilt U.)

Yu-Chen "Janice" Chen (MIT)

2025 HB - Finalization of Result

Result: Fully Corrected EEC in e^+e^-



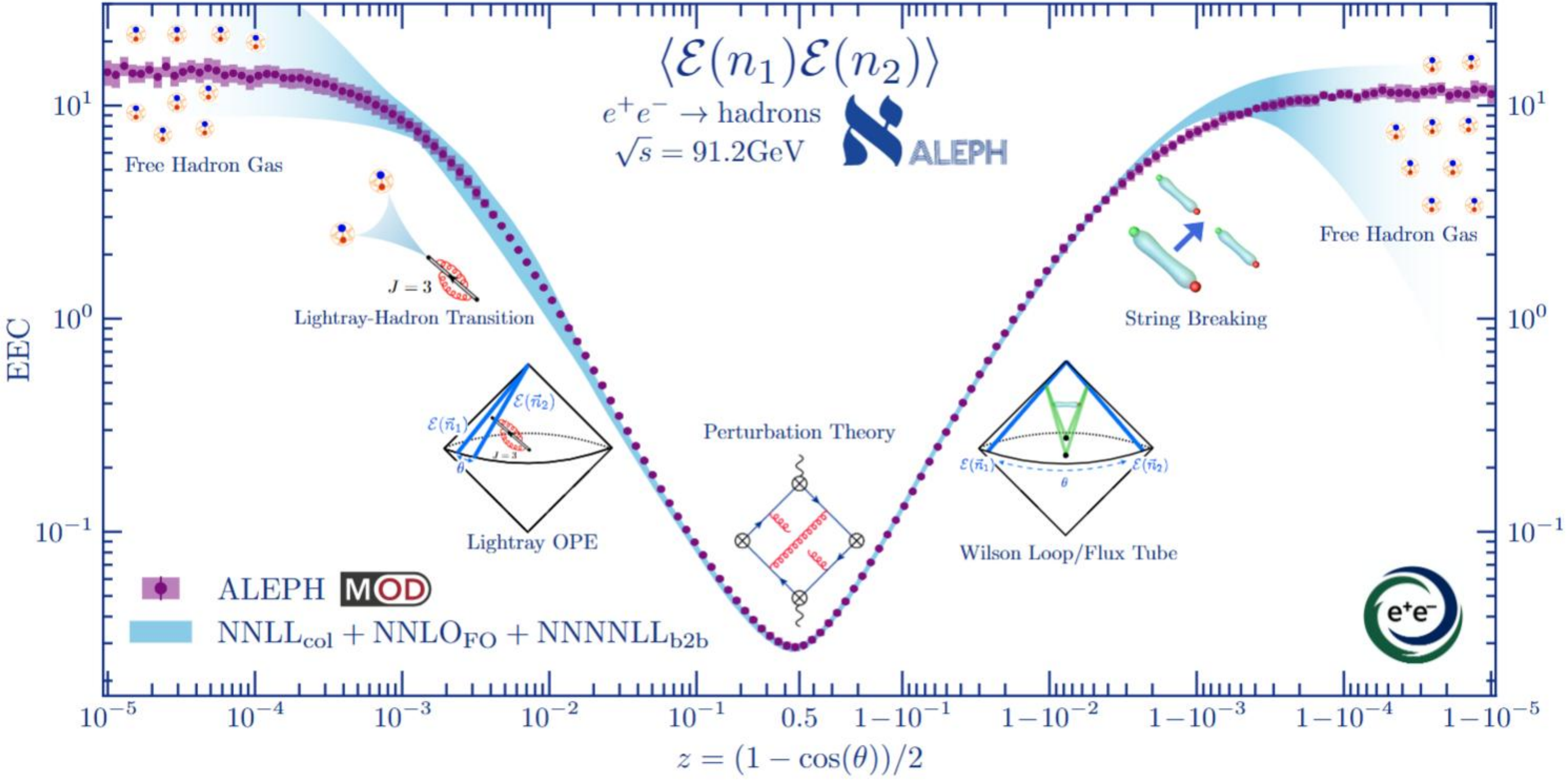
Hannah Bossi (MIT)

Yi Chen (Vanderbilt U.)

Yu-Chen "Janice" Chen (MIT)

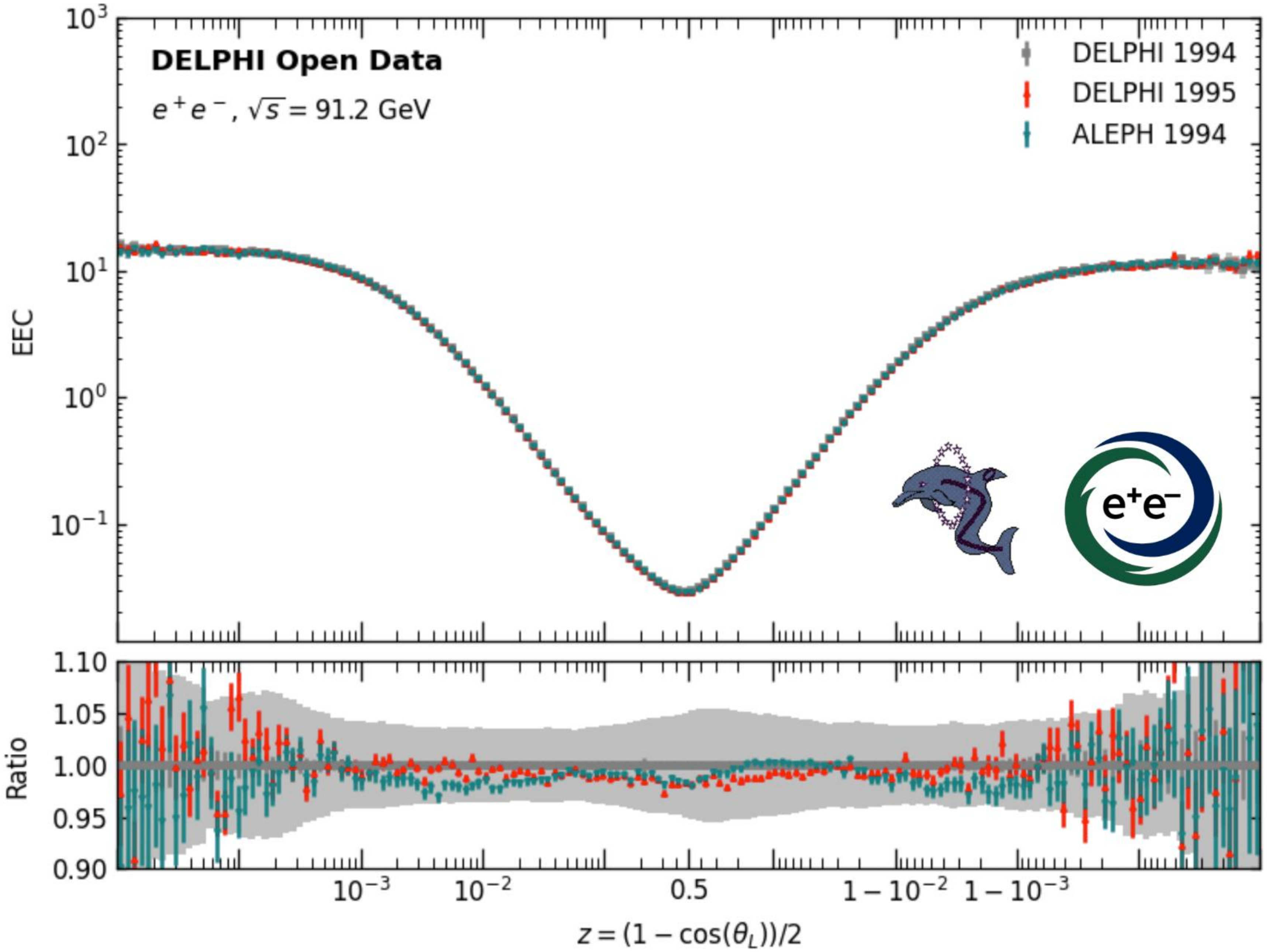
Reparameterize θ to $z=(1-\cos\theta)/2$

Result: Fully Corrected EEC in e^+e^- vs theory



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

Reanalysis with DELPHI and ALEPH Data



[ee alliance, DELPHI Analysis Note: arXiv:2510.18762]

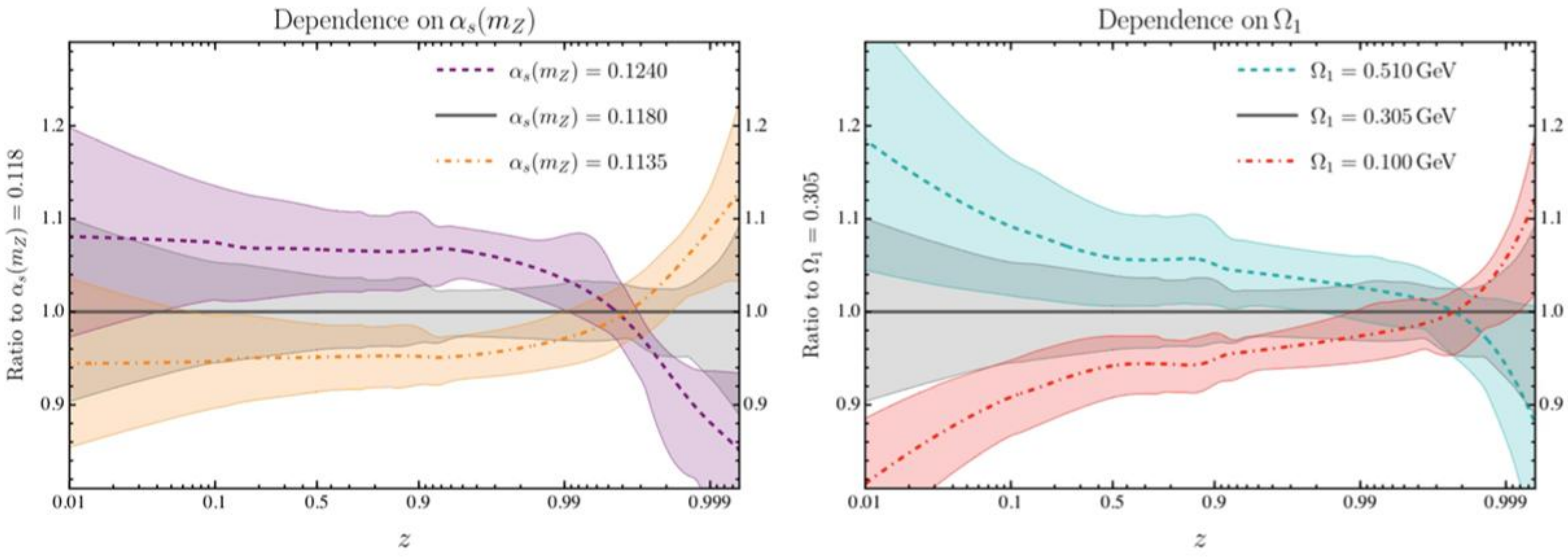
- Can also compare to the 2-point energy correlator for all charged particles using archived e^+e^- data from DELPHI.
- Access to original DELPHI GEANT simulation, can perform much better tests of prior dependence, etc.
- **Power of the recycling frontier!!**

Yi Chen (Vanderbilt U.)

Sensitivity to Strong Coupling Constant

Breaking degeneracy in (Ω_1, α_s)

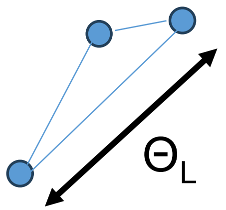
- Precision theory calculation in both kinematic limits breaks the degeneracy.



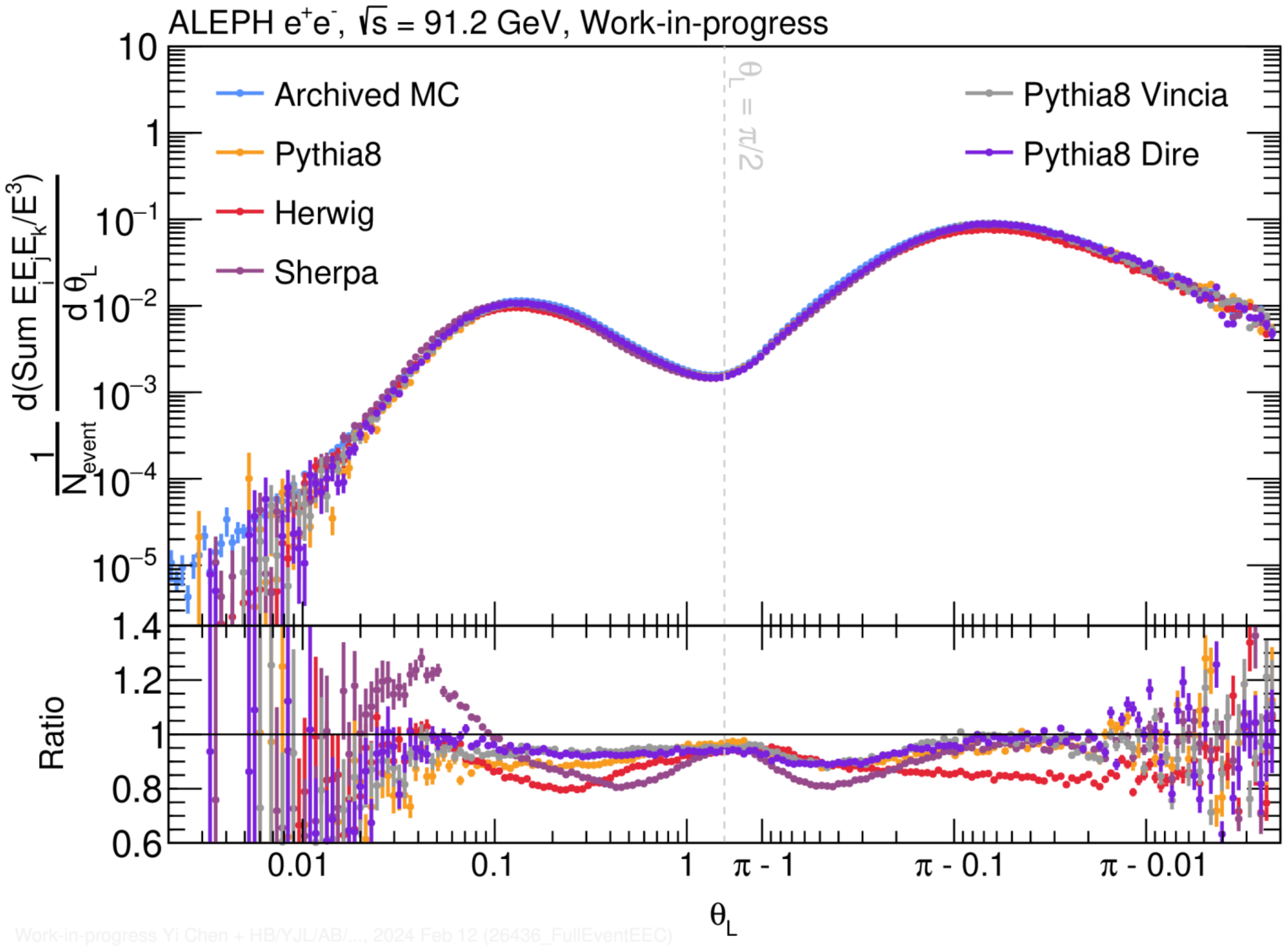
Full-range track EEC, Yibei Li 10 RAS2025, CERN

3-particle EEC (E3C) from MC in e^+e^-

- E3C is by definition not symmetric
  - Due to intrinsic max(pair)
  - Other variants of E3C are possible
- At the away-side
  - Dominant contribution from **dijet**
  - Higher peak value due to Θ_L definition
  - Mostly 1 particle from one shower + 2 particles from the other shower
- Agreement between MC generators similar to E2C:
  - The predictions differ by up to 20%!

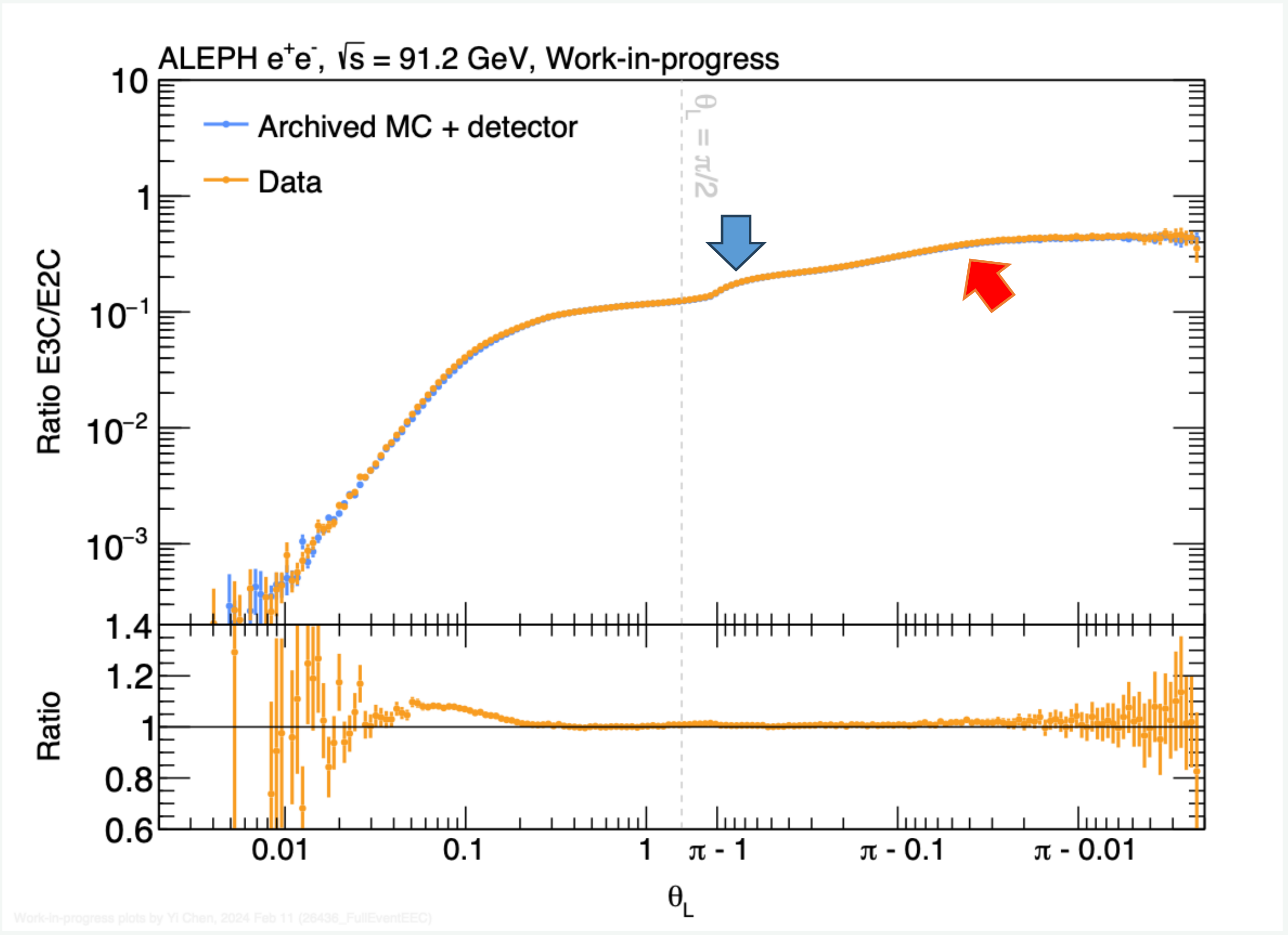


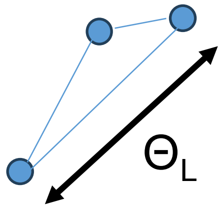
Yi Chen (Vanderbilt U.)



E3C / E2C in e^+e^- at 91 GeV

- Observe non-trivial slope in the hadronization region
  - Away-side ($\Theta_L > \pi/2$) region: roughly flat
  - A small structure around $2\pi/3$:
    - Reject **3-jet** event removes this particular structure
  - Further increase beyond $2\pi/3$: **di-jet**
- Overall excellent agreement between archived MC and data

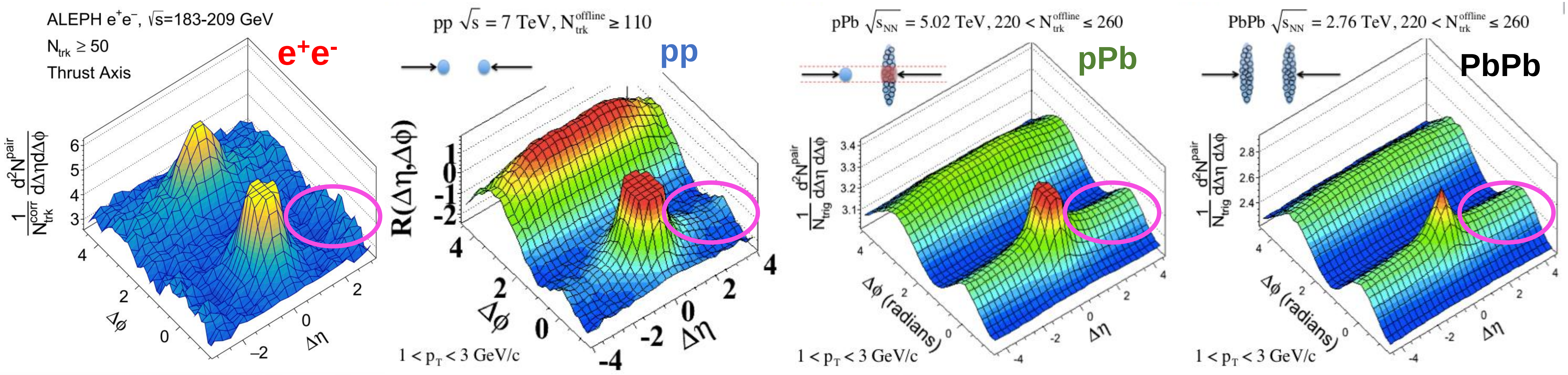





Yi Chen (Vanderbilt U.)

NEW!

Long-range Correlation in e^+e^- collisions

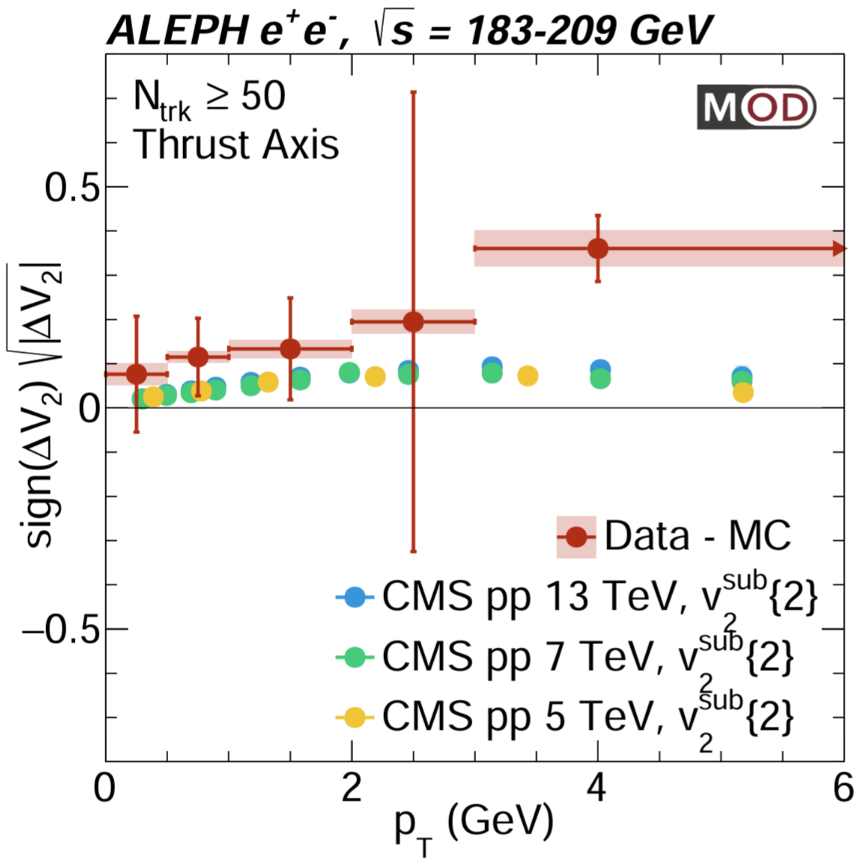


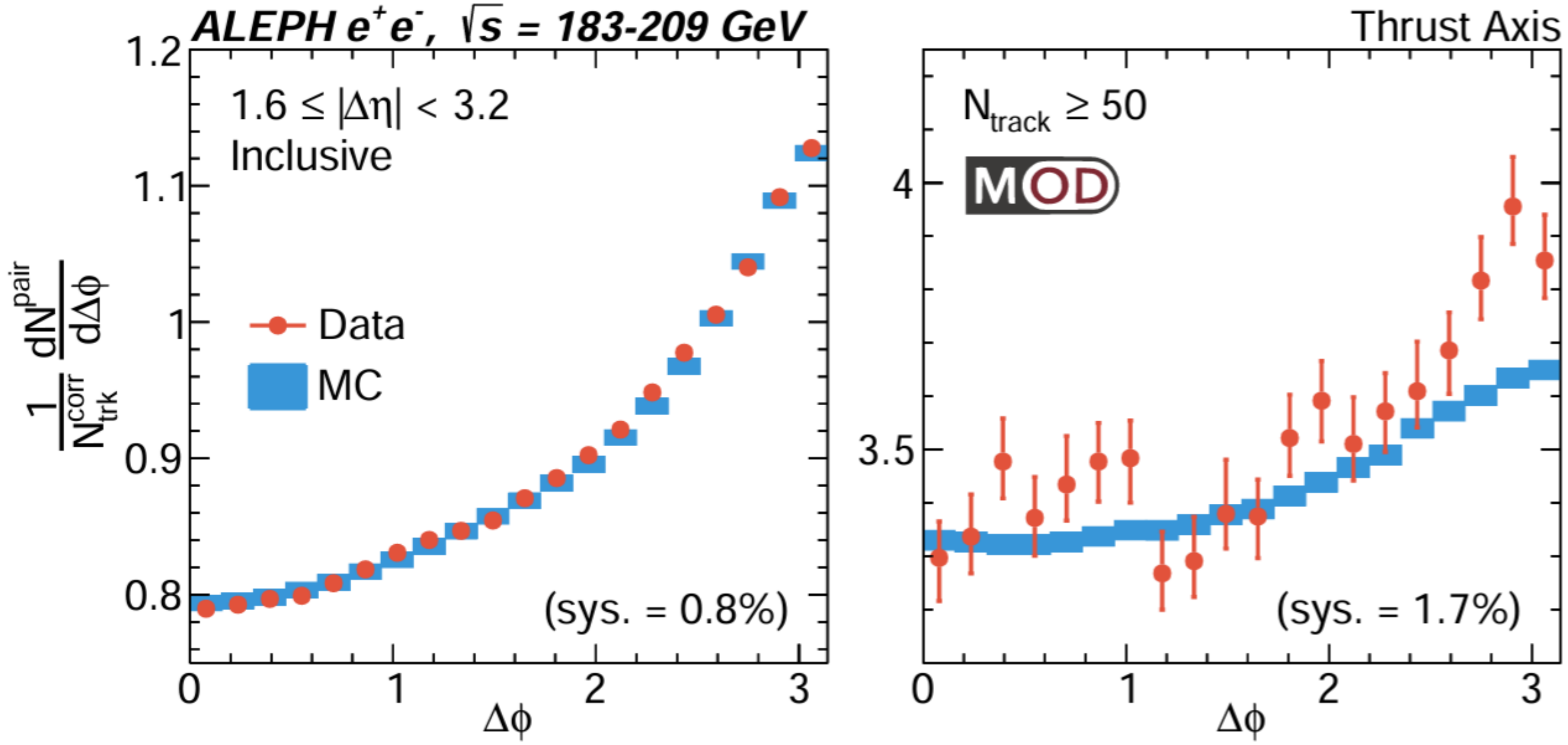
- In PbPb Collisions, long-range ridge-like correlation in two-particle correlation function is interpretated as hydrodynamics flow of QGP
- Recent Excitement:
  Long-range correlation in e^+e^- collisions!
  - Not described by ALEPH archived MC

MIT-MOD-23-001
arXiv: 2312.05084
PLB 856 (2024) 138957

Yu-Chen "Janice" Chen (MIT)

Flow-like Correlation in e^+e^- at LEP2 Energies





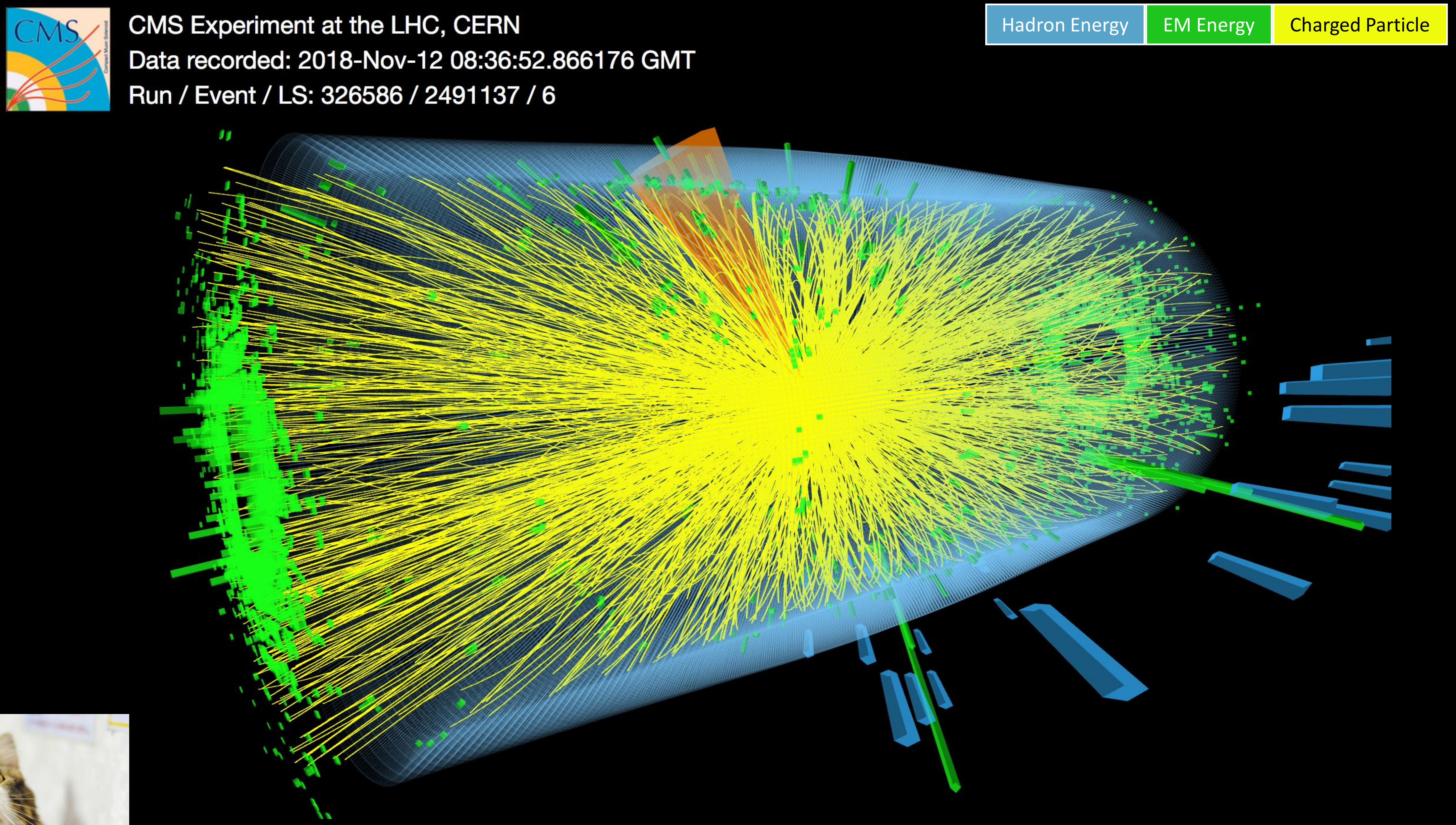
- Long-range correlation in e^+e^- collisions!
  - Not described by ALEPH archived MC

→ Interesting to study EEC the difference between archived data and MC in different multiplicity intervals

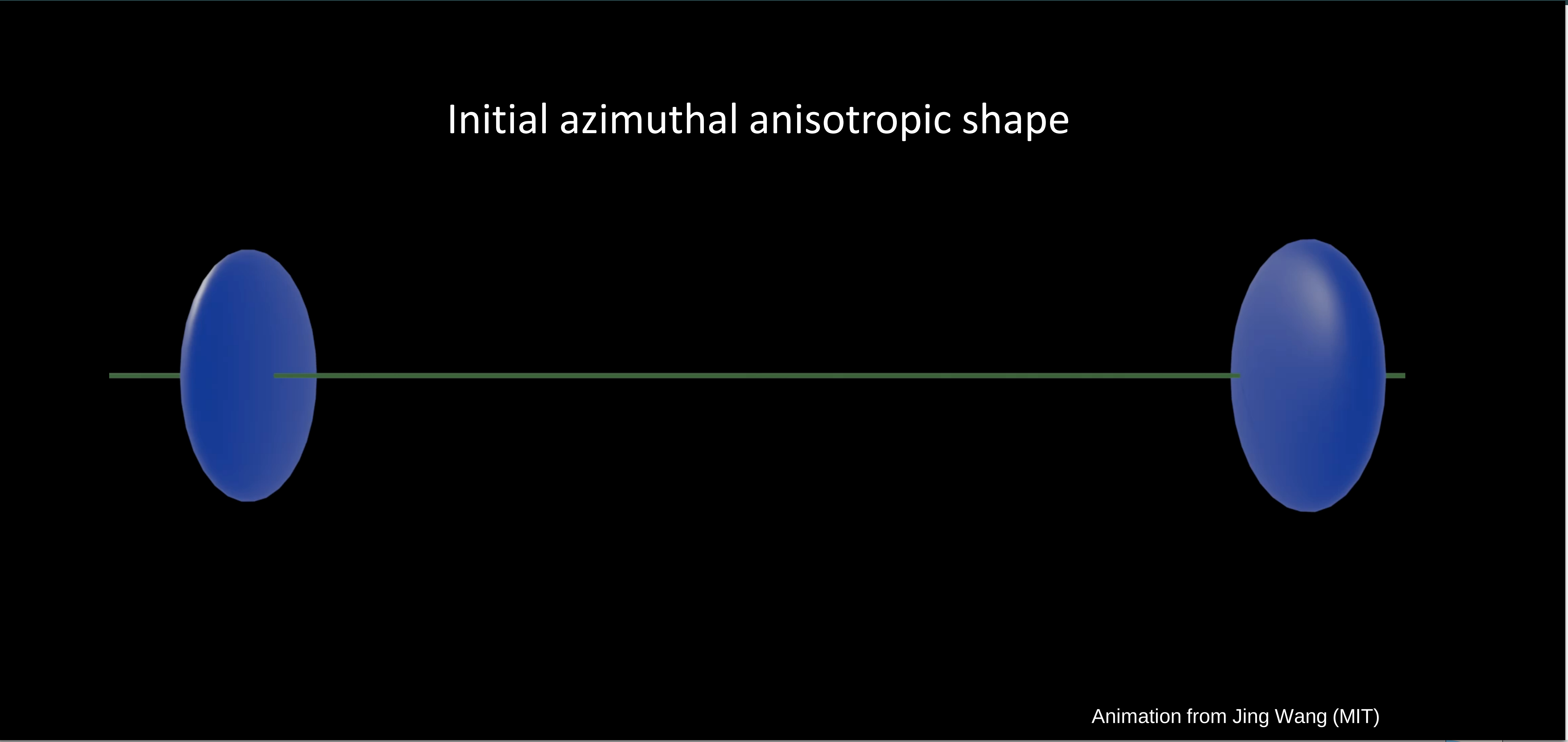
MIT-MOD-23-001
arXiv: 2312.05084
PLB 856 (2024) 138957

Yu-Chen "Janice" Chen
(MIT)

(3) EEC in PbPb Collisions

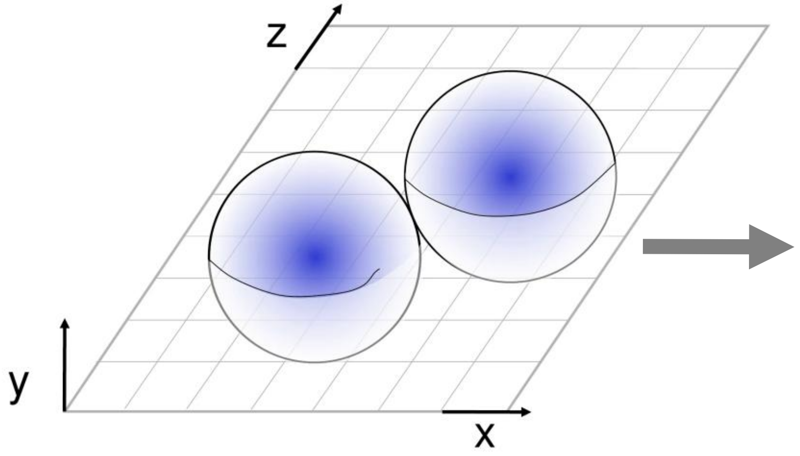


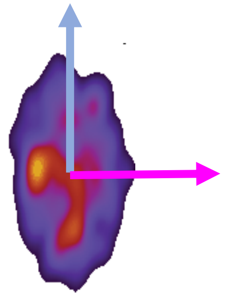
Initial Shape Before Expansion

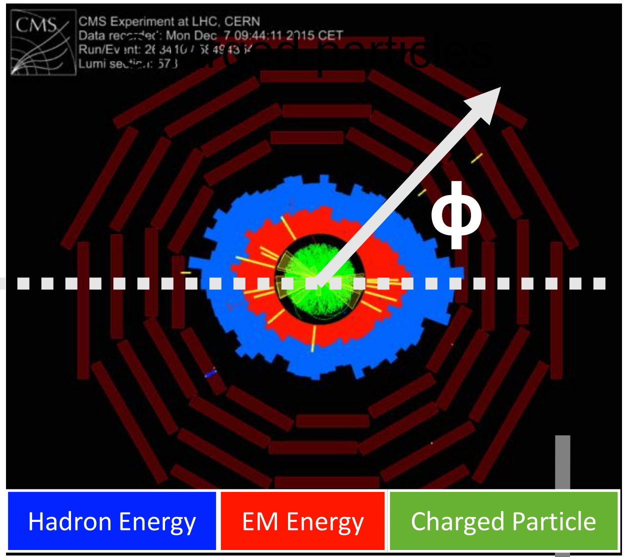


Animation from Jing Wang (MIT)

Pressure Driven Expansion of the Quark Soup

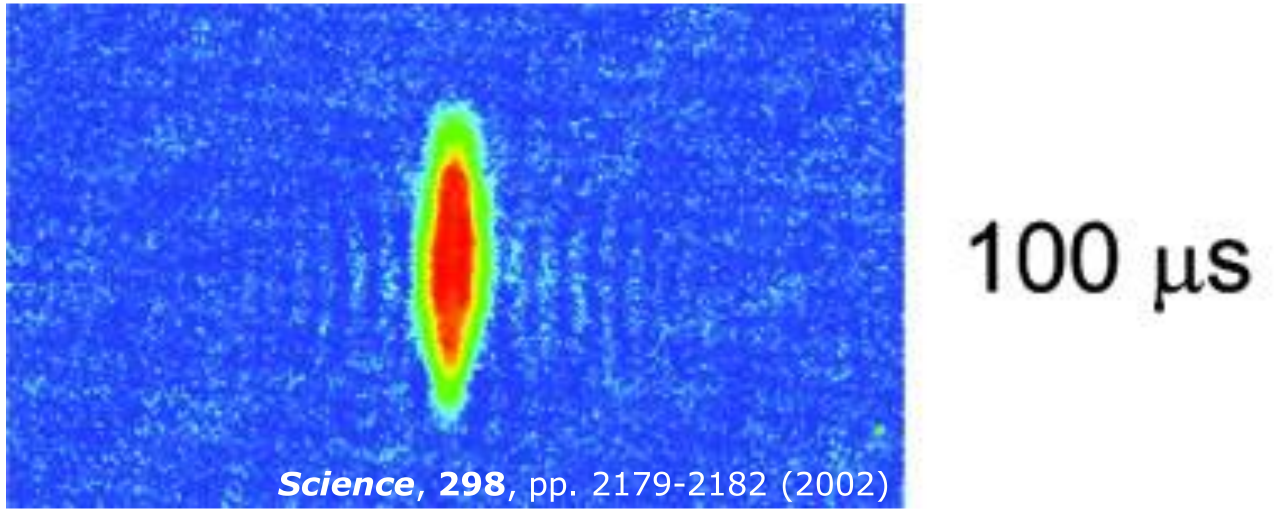


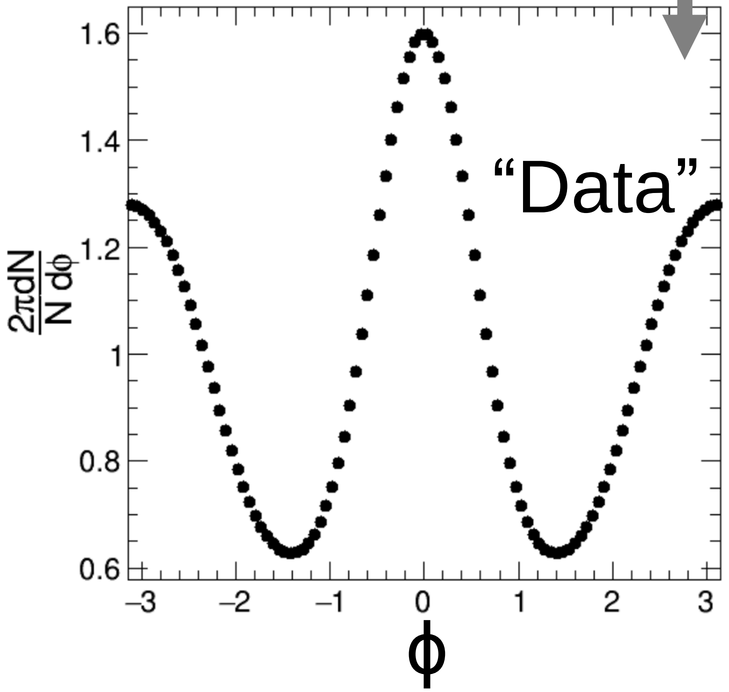




Event plane angle

Expansion of **Ultra-cold atoms (Li-6)** released from laser trap





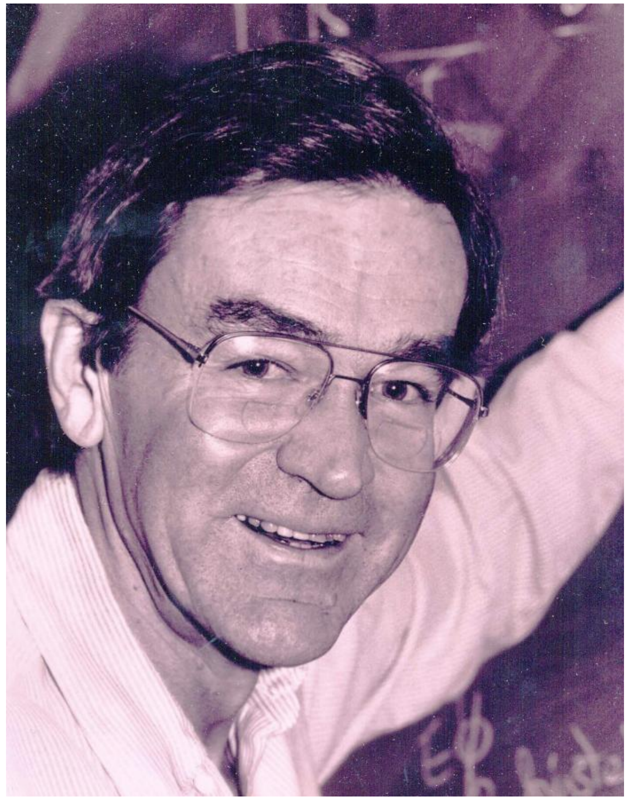
Hydrodynamics Simulations

Collective motion is observed

→ **Early hydrodynamization!**

Particle Azimuth Angle Distribution

Hard Probes of Quark Gluon Plasma

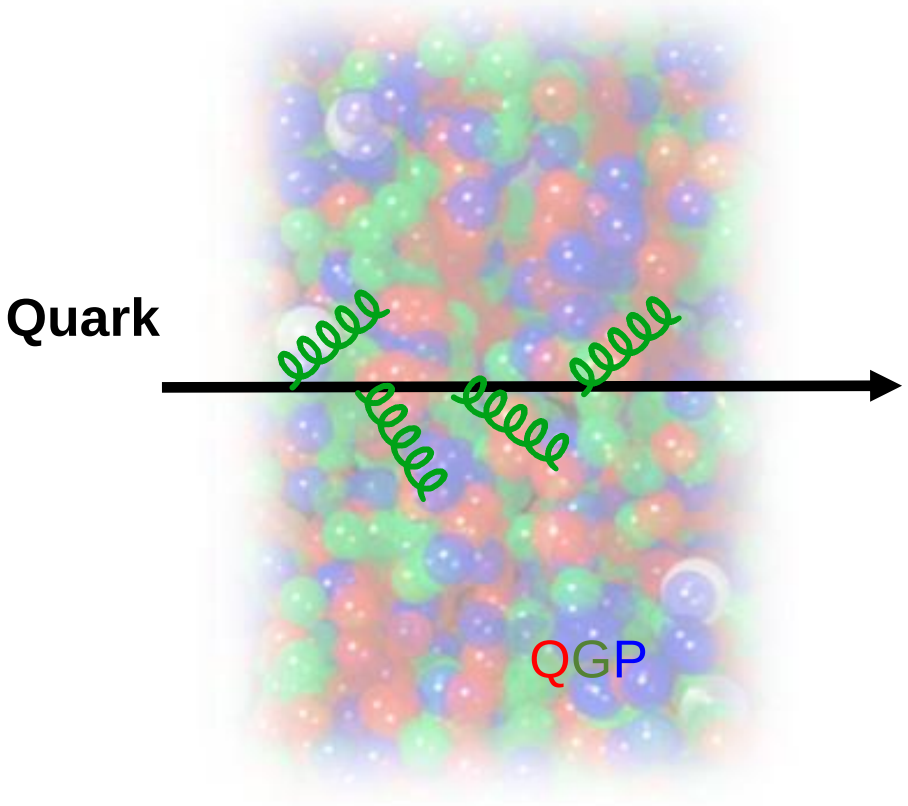


James Bjorken (1982)

FERMILAB-PUB-82-059-T

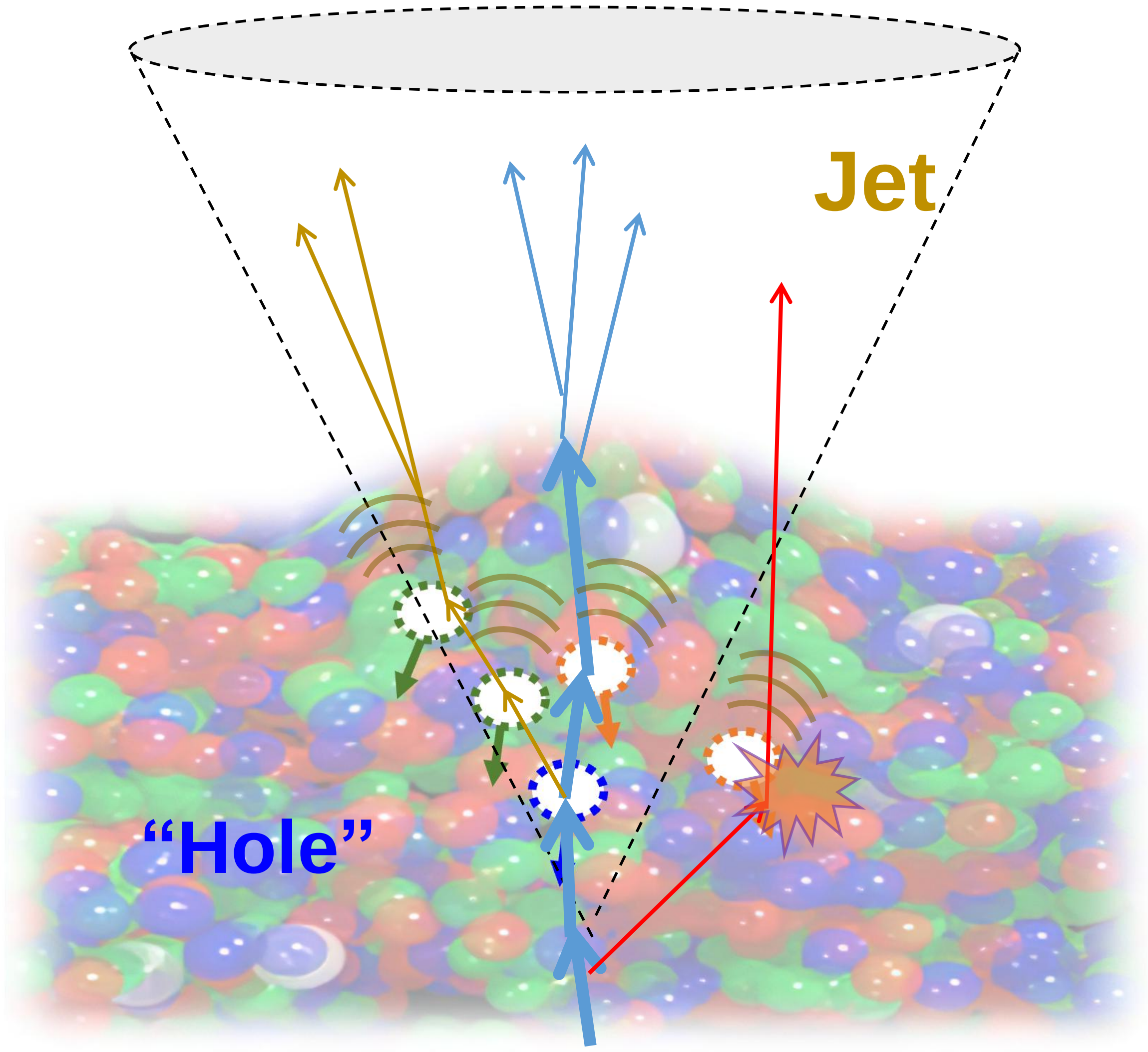
Jet Quenching

Lifetime O(10^{-24}s)



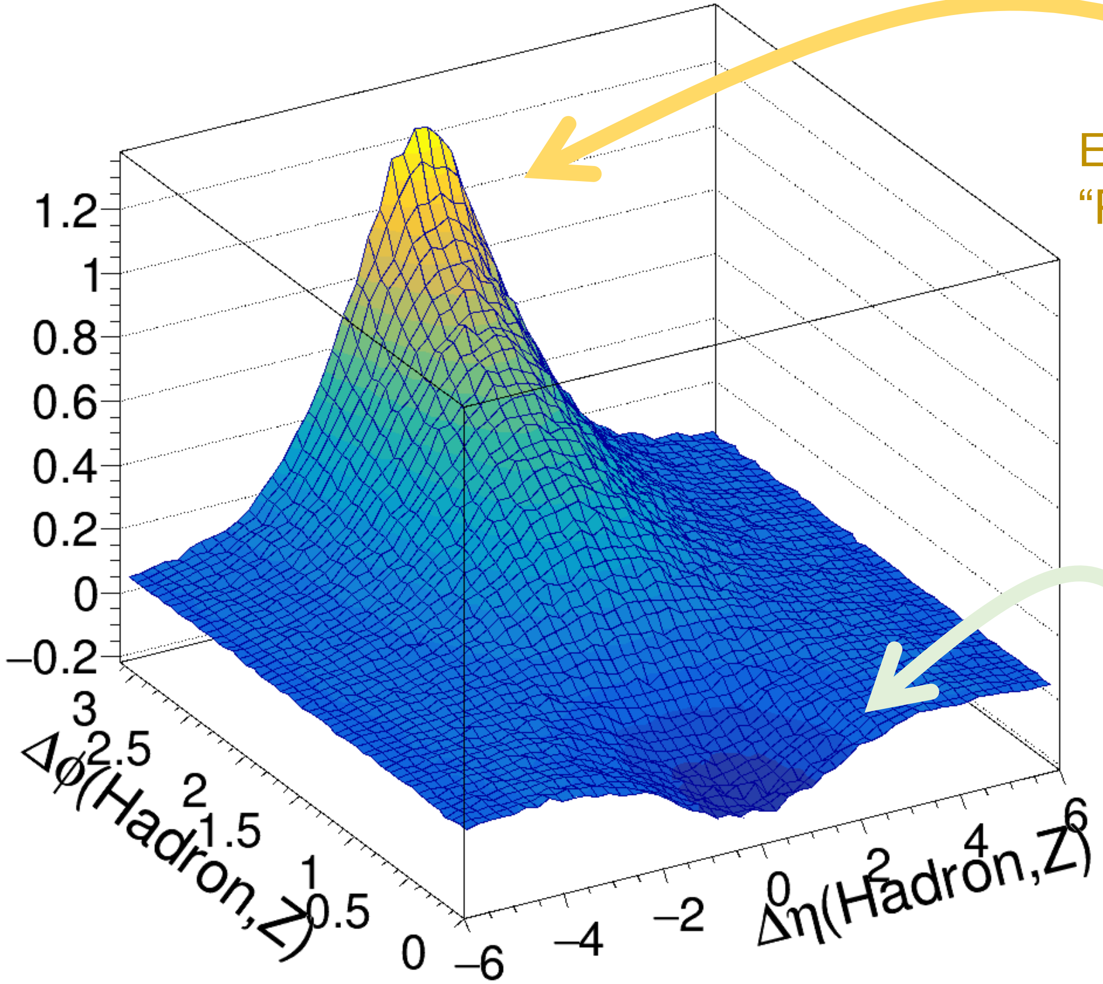
Use **Energetic Quarks** to reveal
QGP structure at various length scales

QGP Transport Properties and Structure with Jets

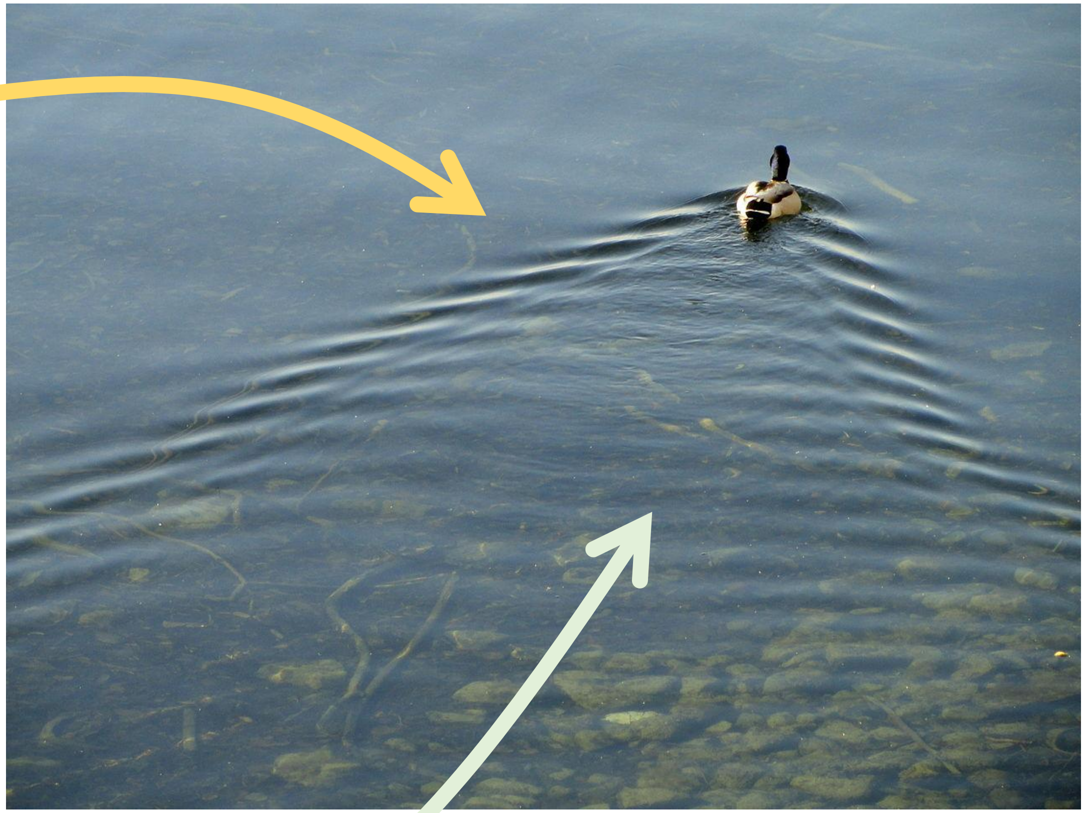


- Jet broadening effects from multiple soft scattering ($\hat{q}$) and induced radiation
- Contribution from medium response
- Reveal medium recoil (the propagation of QGP holes)
- With the precise understanding of the phenomena above, one could reveal the QGP structure with Moliere scattering

Reveal Wake Contribution With Z-tagged Jets and Hadrons



Enhancement of particle
"Positive wake"



Depletion of particle
"Recoil"
"QGP hole"
"Negative wake"

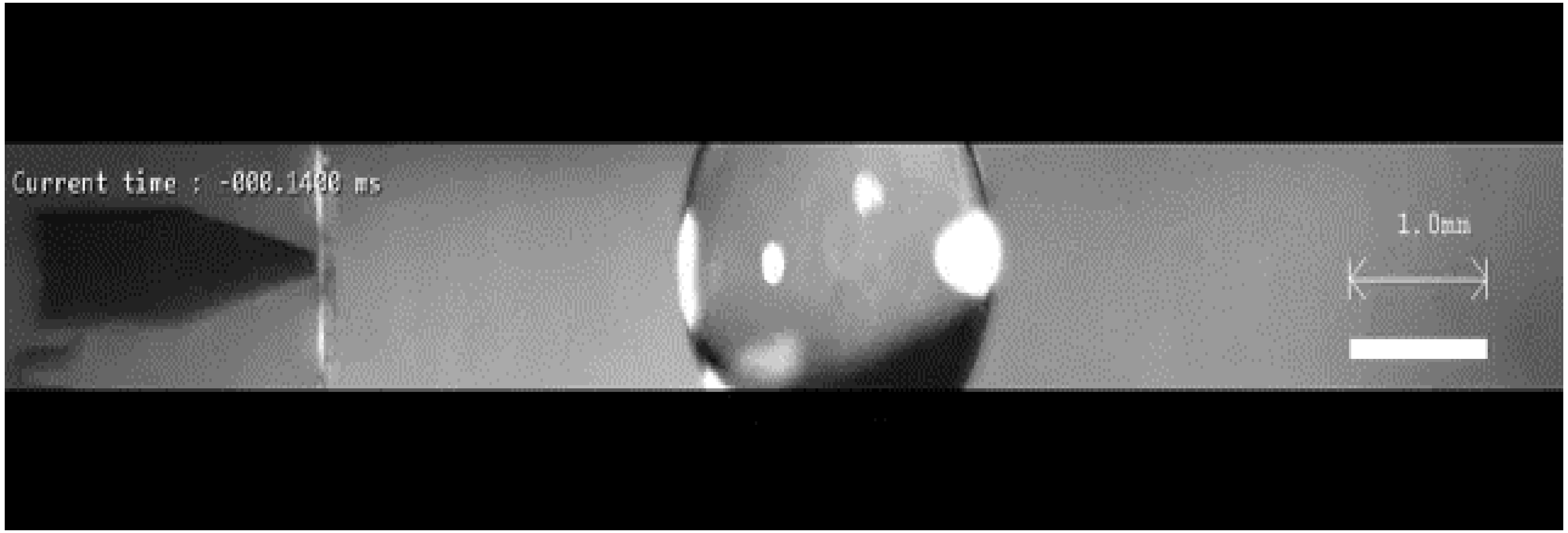
Position space

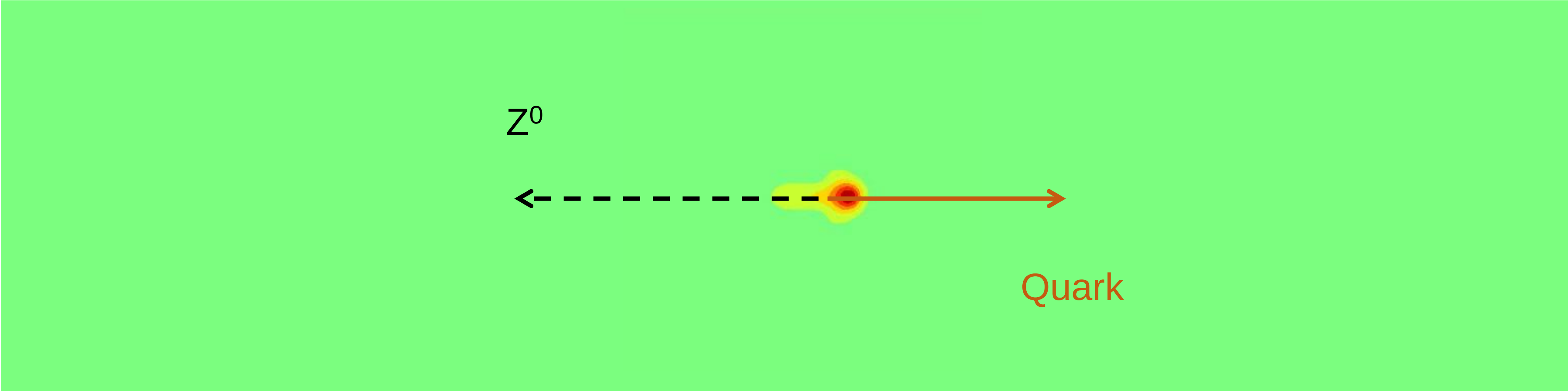
Z^0 and **wake hadron** correlation in Hybrid model

Daniel Pablo, Krishna Rajagopal, YJL

Momentum space

Z^0 Boson as a tag of the Quark direction

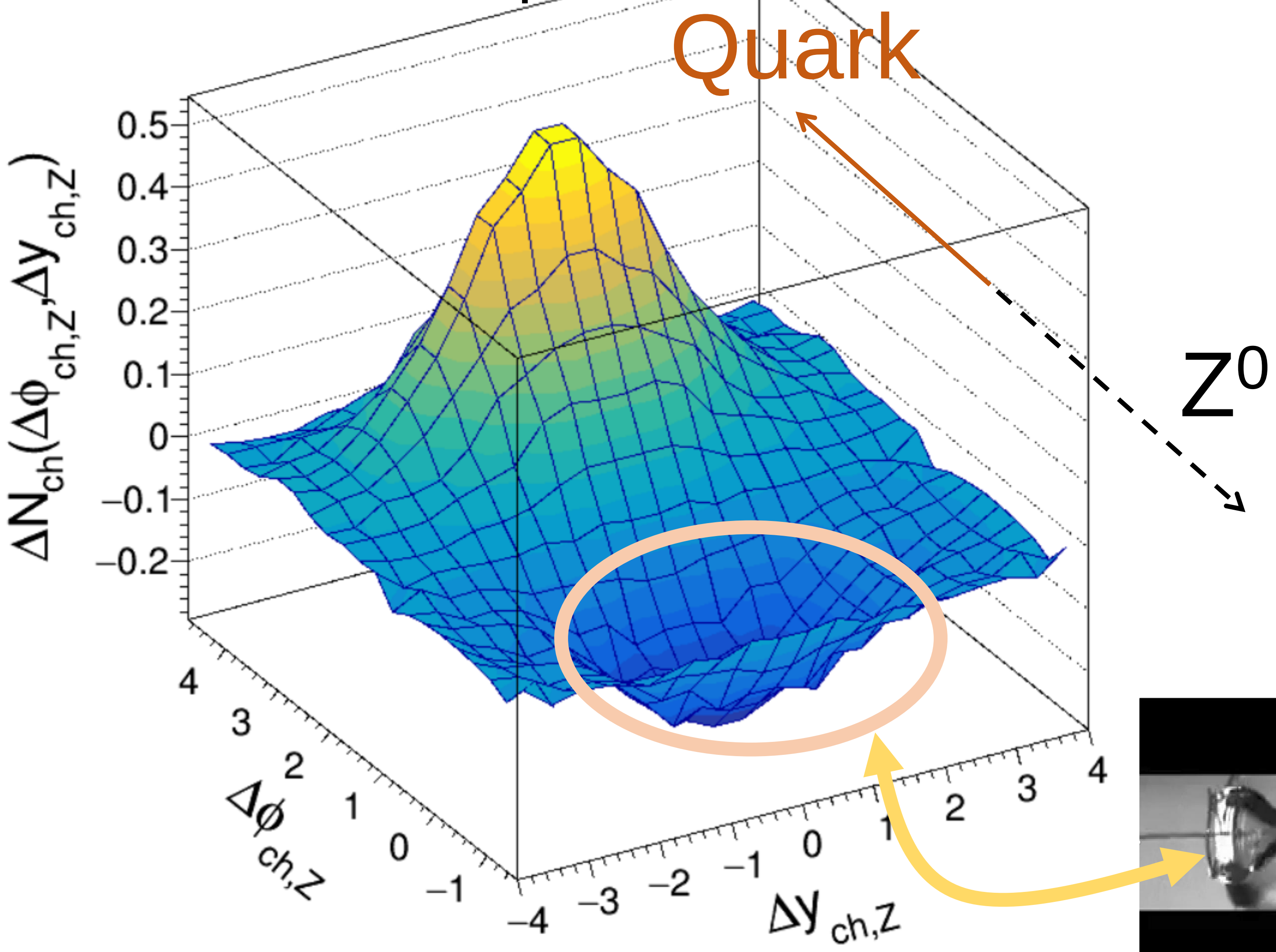


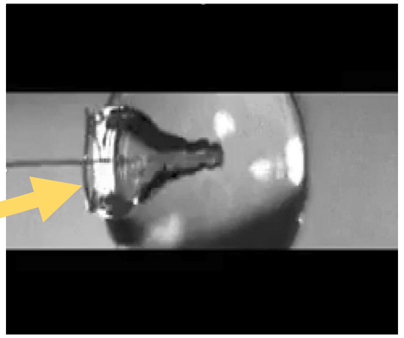


We use Z^0 bosons (**colorless** probe) to tag the original quark direction:
Z^0 **escapes unaffected**; the jet plows through the quark soup

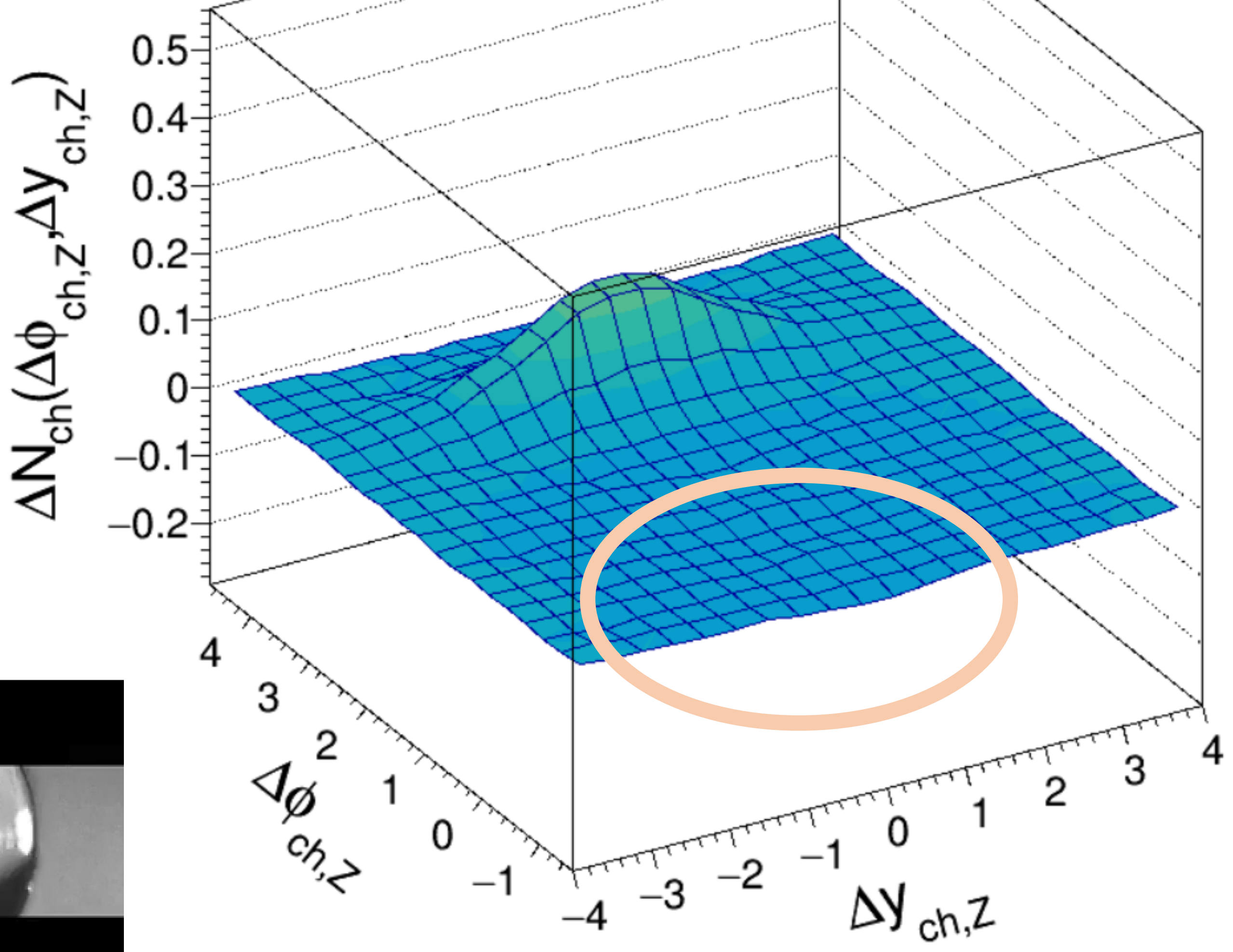
Z^0 Boson as a tag of the Quark direction

Simulation ***with*** quark wake



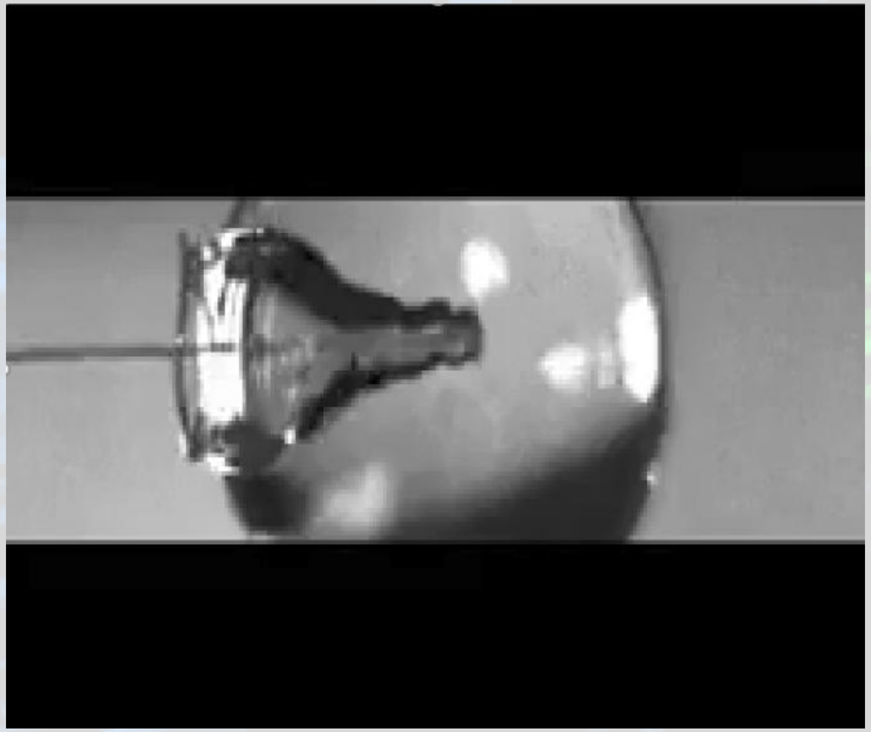


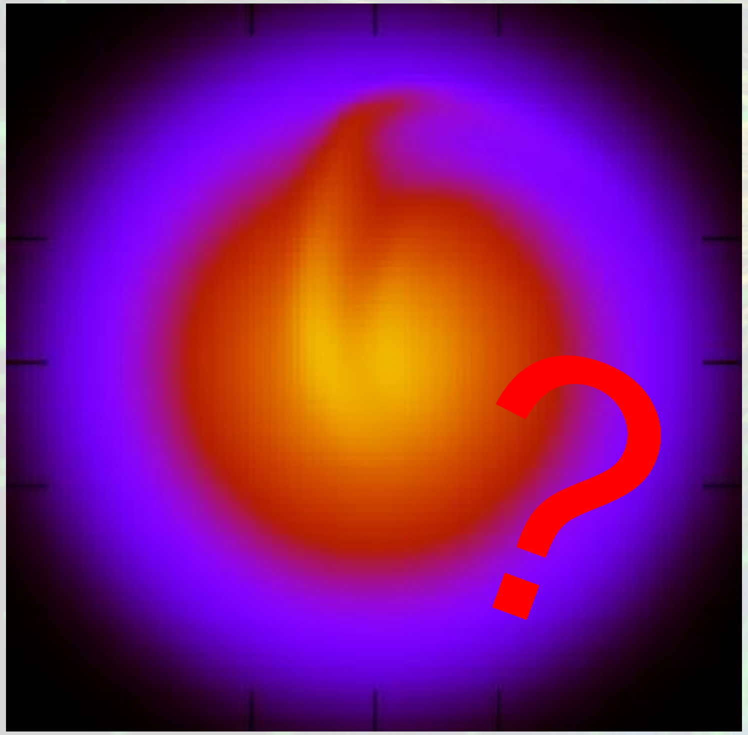
Simulation ***without*** quark wake



- **Hybrid Model**: **QGP** wake creates a **Z^0-side dip structure** and significantly enhance the jet peak

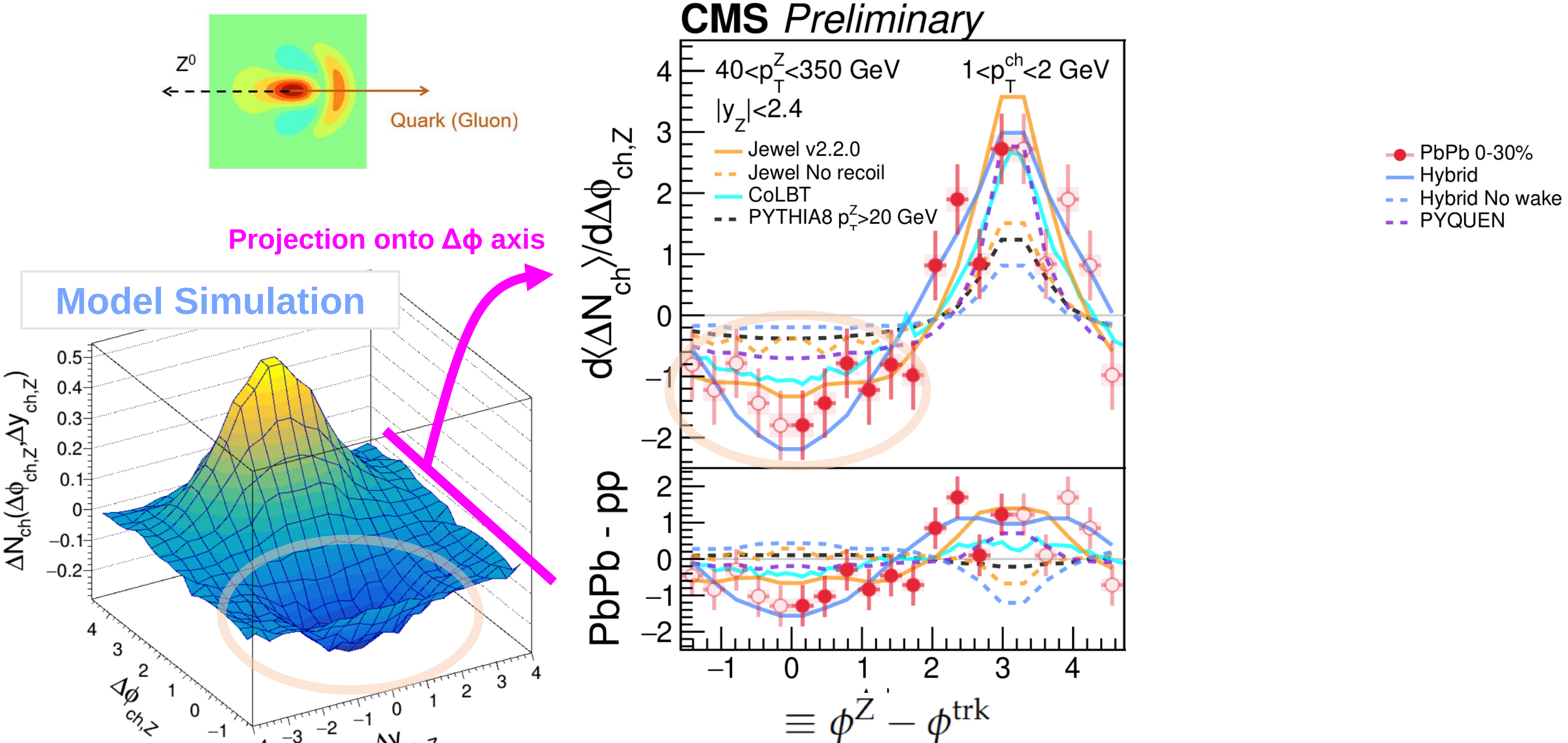
Results





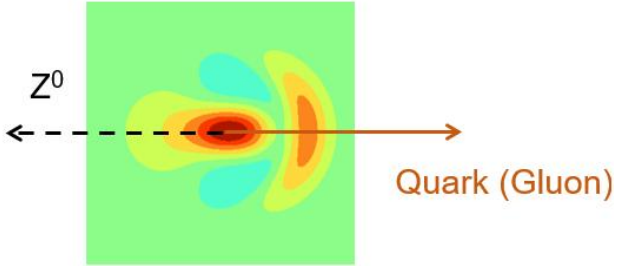
Can we see an unambiguous evidence of the QGP **wake** created by a fast moving quark?

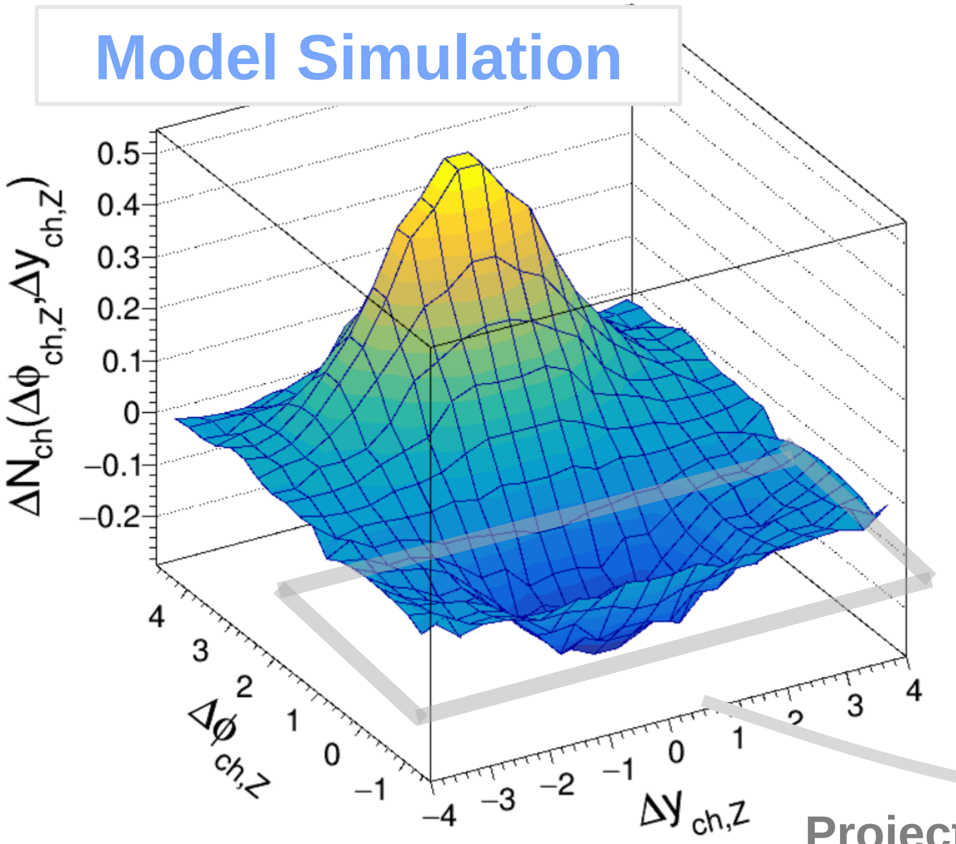
Direct Evidence of Medium Response



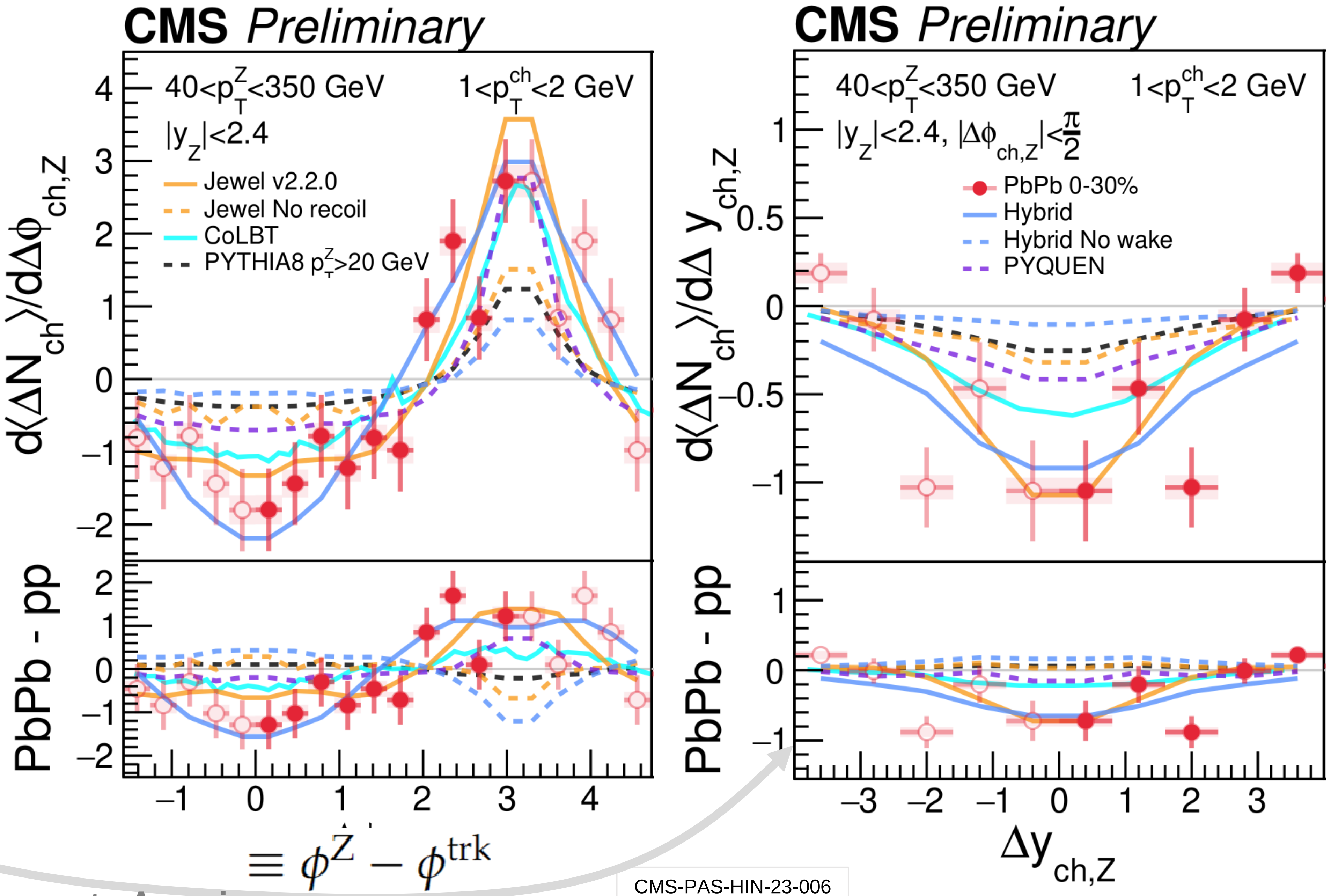
Projection onto Δy axis

Direct Evidence of Medium Response





Projection onto Δy axis



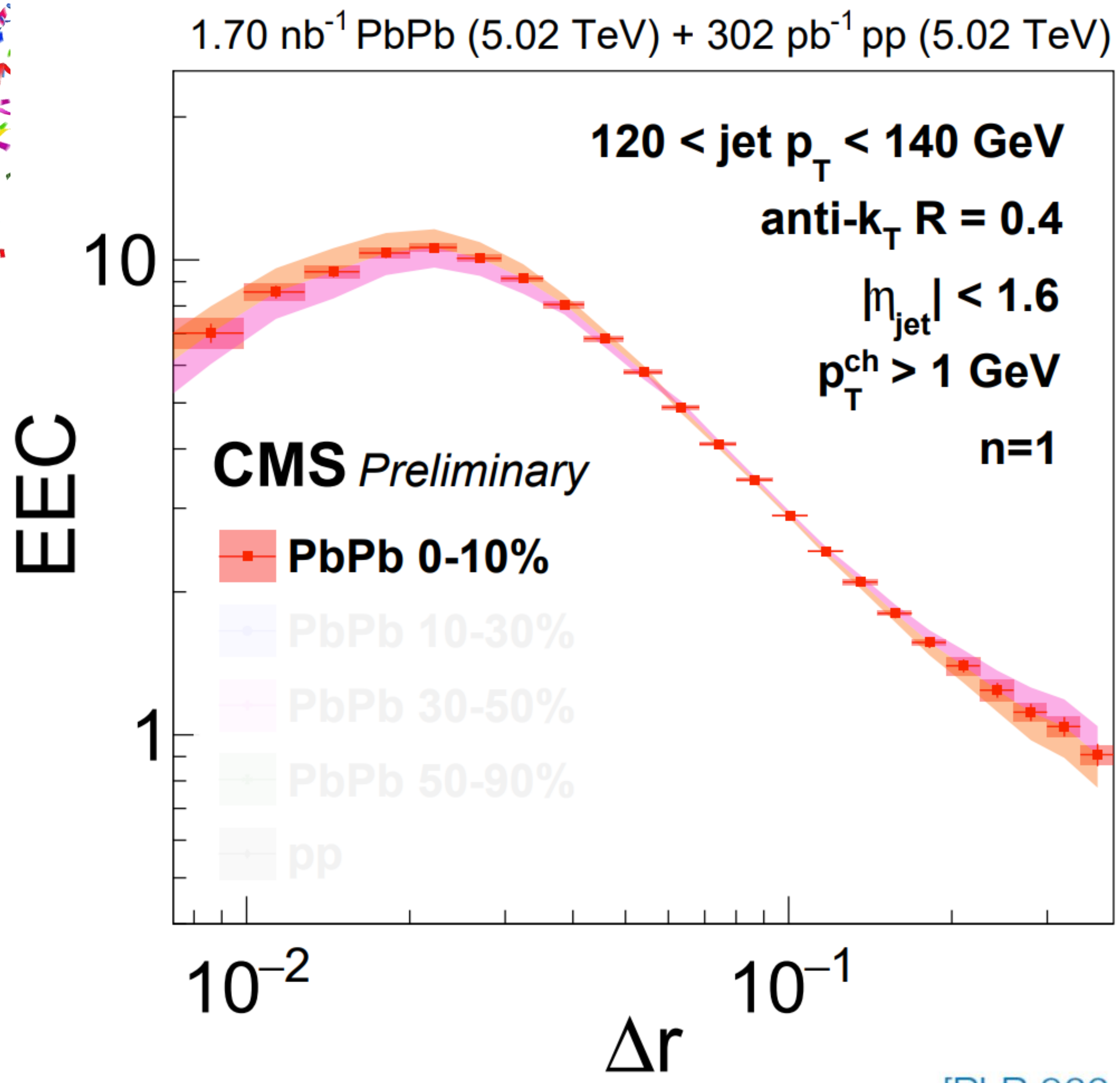
CMS-PAS-HIN-23-006

Inclusive Jet EEC in PbPb Collisions

- **CMS is releasing the PbPb results**

- Background subtraction method: Identical to Z-tagged EEC, with jet replacing the role of Z boson
- Technical details are in Jussi's talk on Friday
- Peak at around Δr =0.02
- Exciting to see the "**Free Hadron**" "**Confinement**" and "**Perturbative**" regions in PbPb 0-10% results!

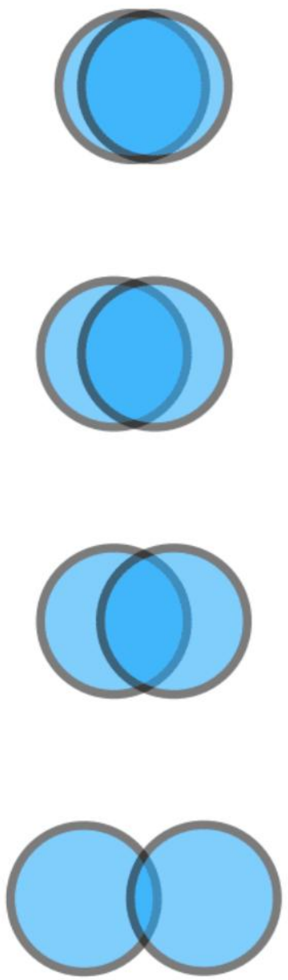
$$\mathrm{EEC}(\Delta r) = \frac{1}{W_{\mathrm{pairs}}} \sum_{\mathrm{jets} \in [p_{\mathrm{T},1}, p_{\mathrm{T},2}]} \sum_{\mathrm{pairs}} \left(p_{\mathrm{T},i}\, p_{\mathrm{T},j}\right)^n$$

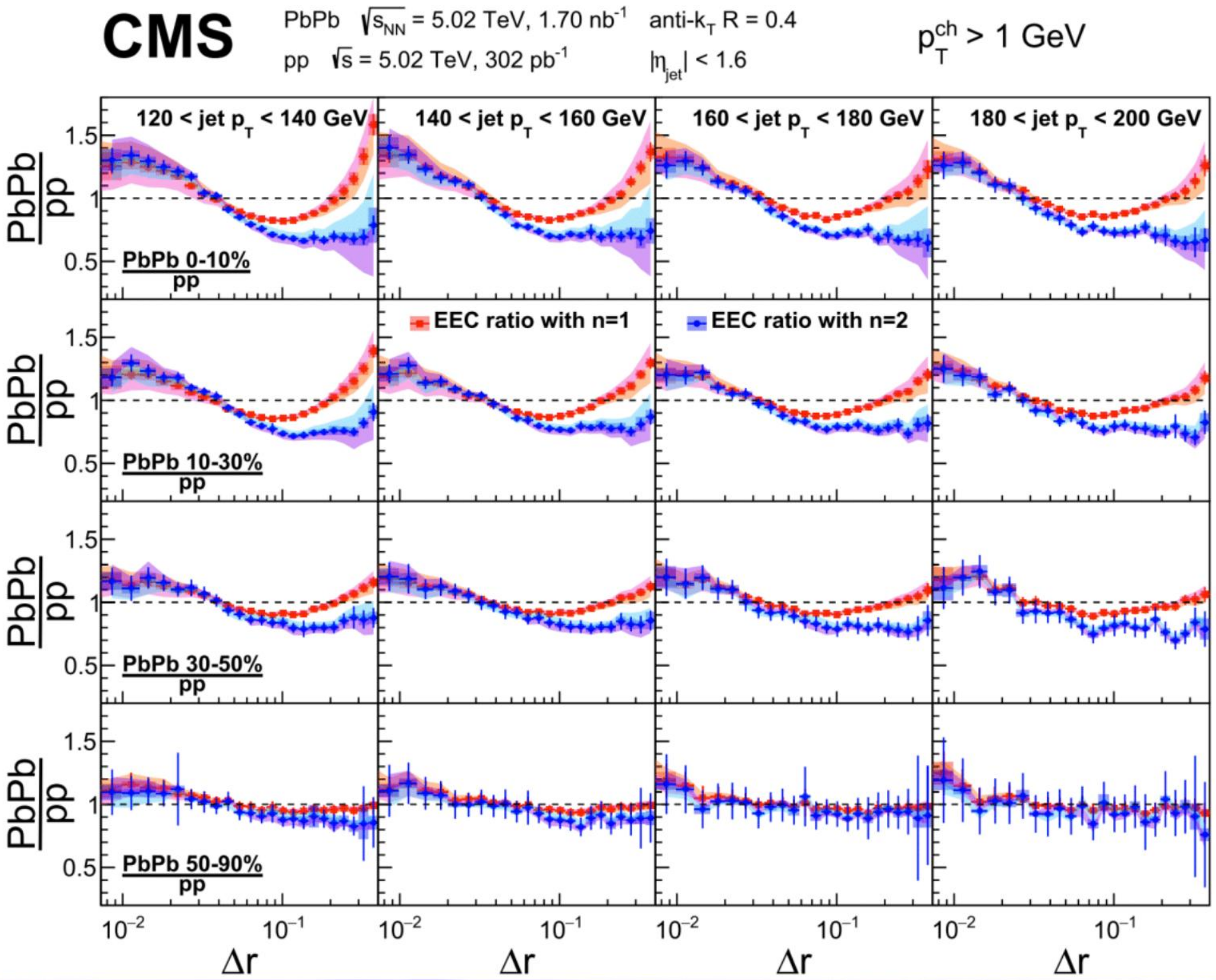


Jussi Viinikainen (Vanderbilt U)

[PLB 866 (2025) 139556]

Inclusive Jet EEC in PbPb Collisions



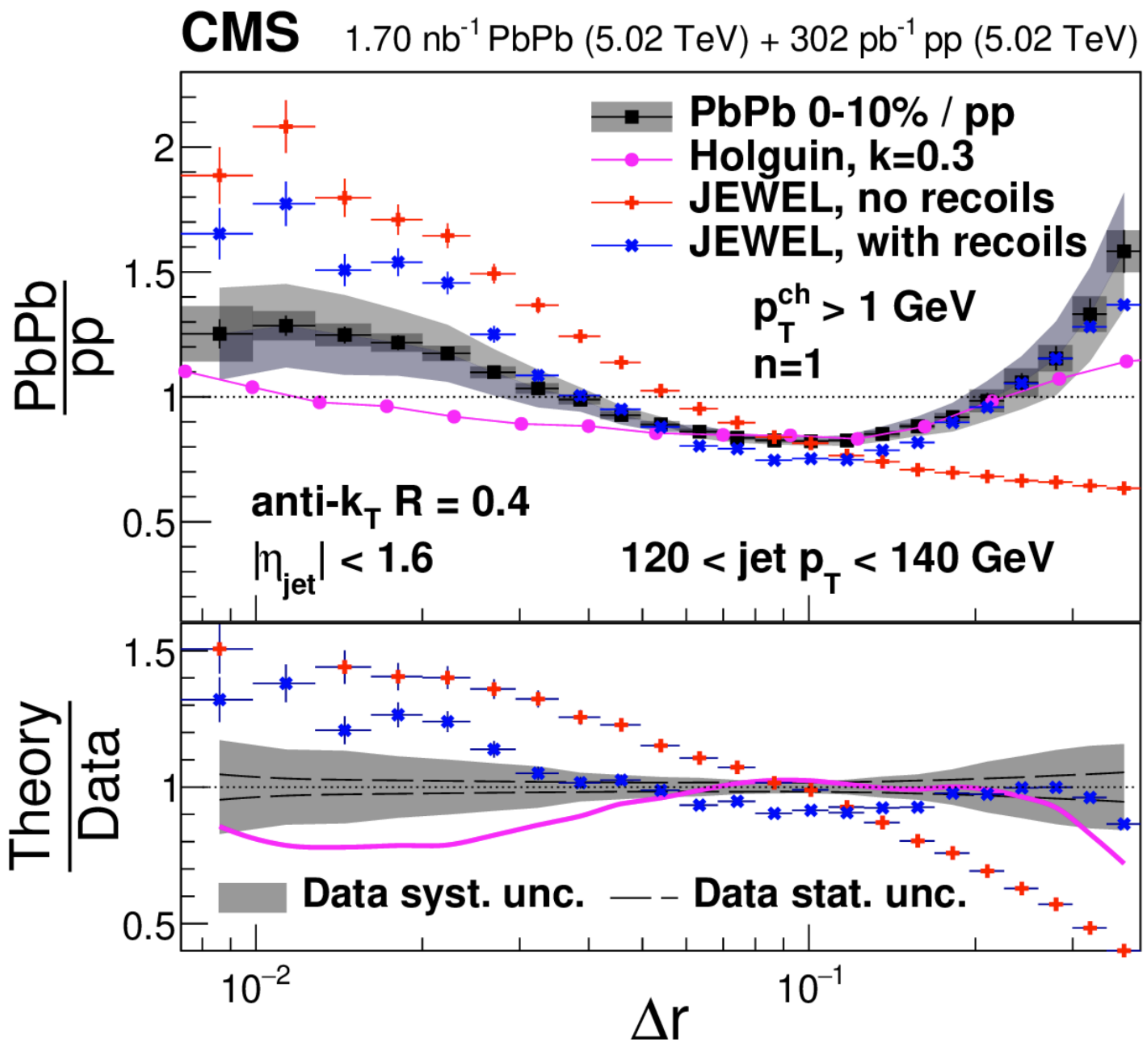


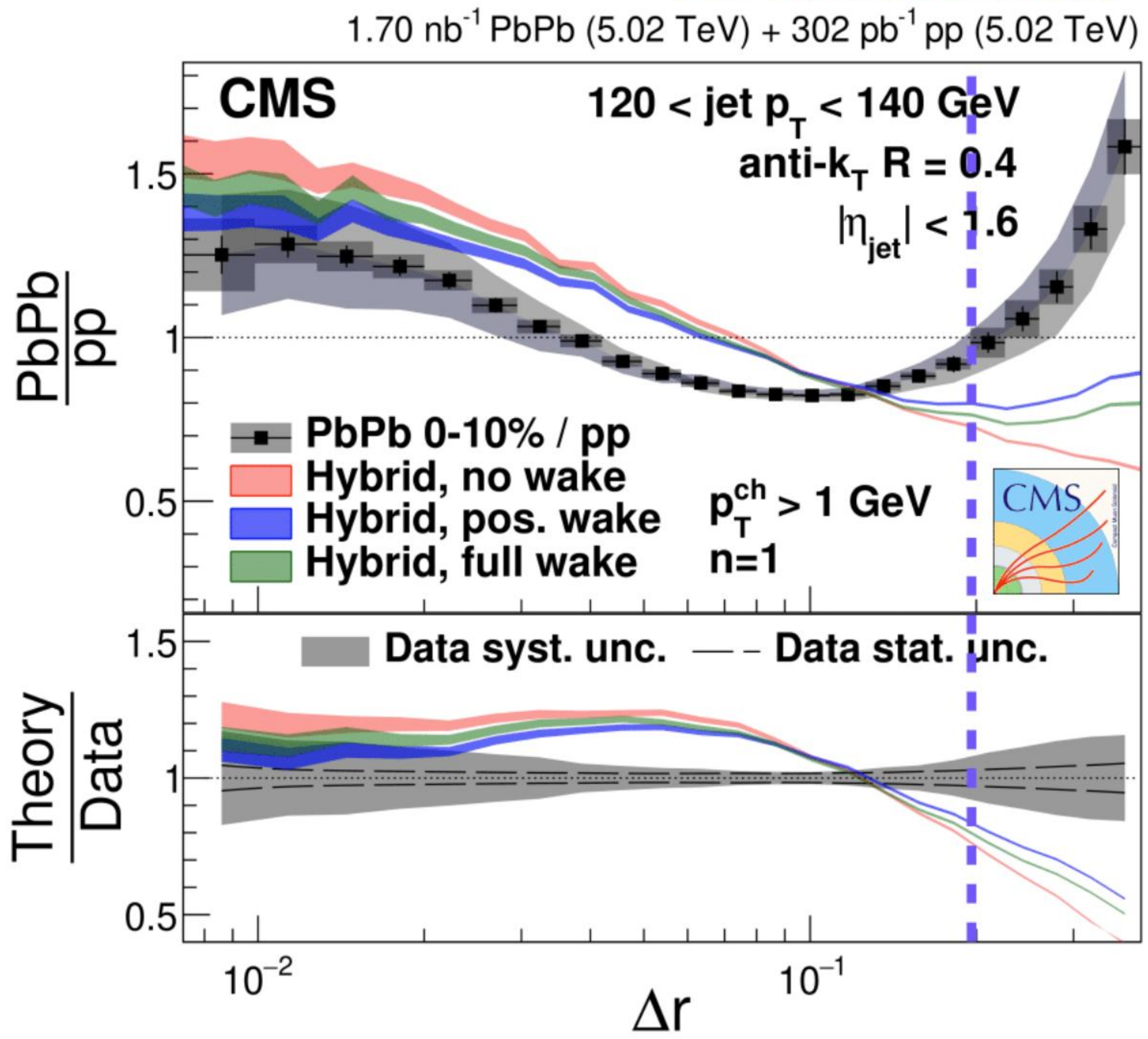
- Incredibly differential result!
- Degree of modification depends on these parameters
- Energy weighting changes modification.

Increasing $p_{T,\mathrm{jet}}$

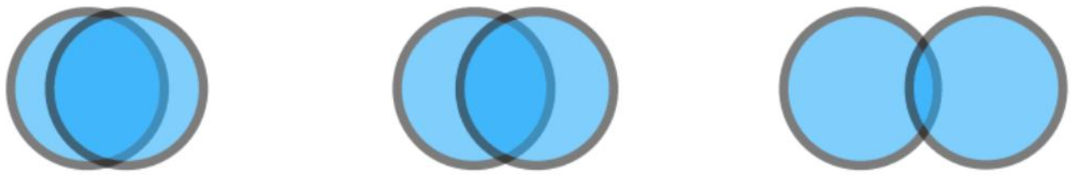
PbPb EEC vs Theory

[PLB 866 (2025) 139556]



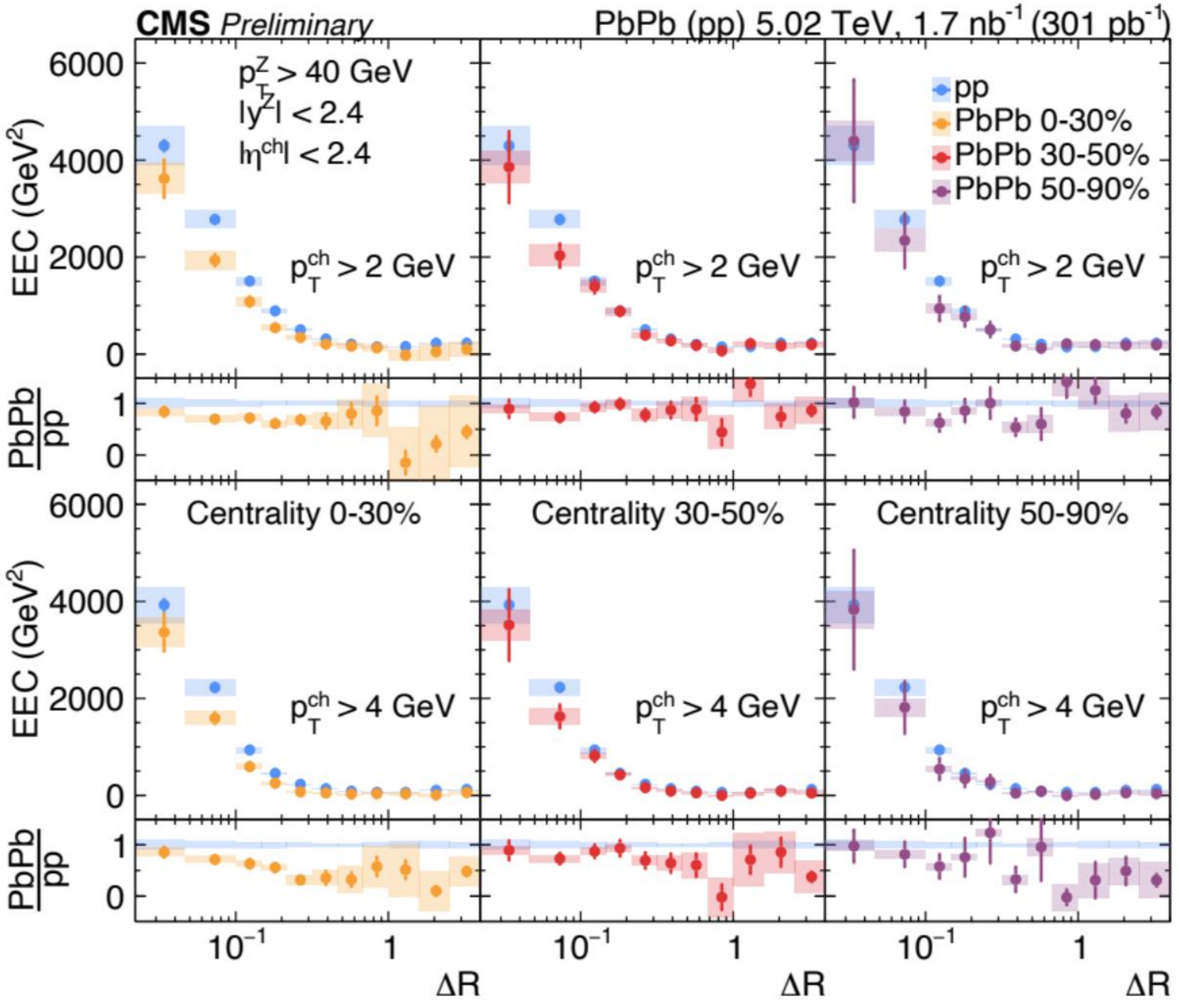


Z-Tagged Jet EEC in PbPb and pp collisions



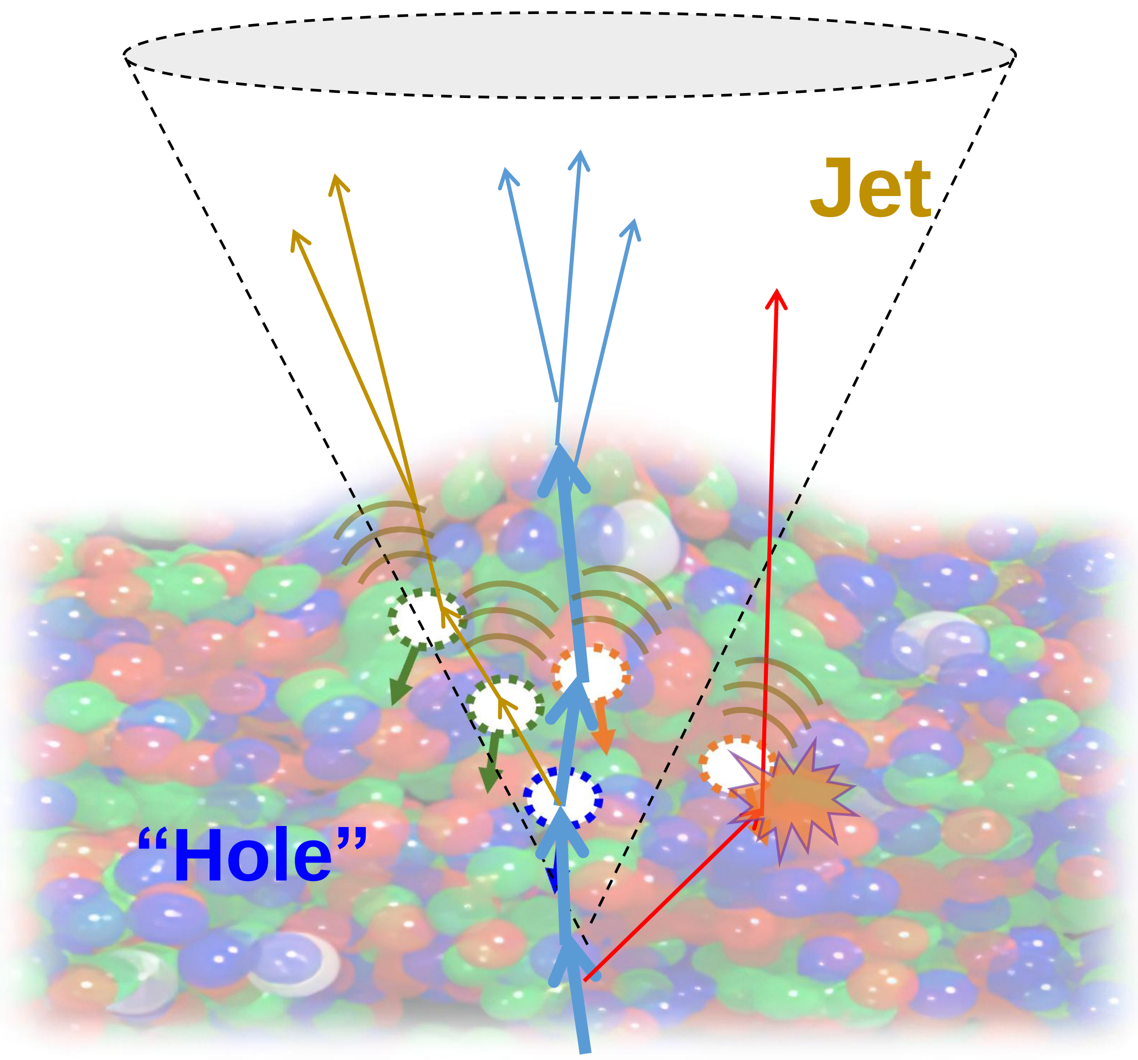
$p_T^{ch} > 2$ GeV

$p_T^{ch} > 4$ GeV

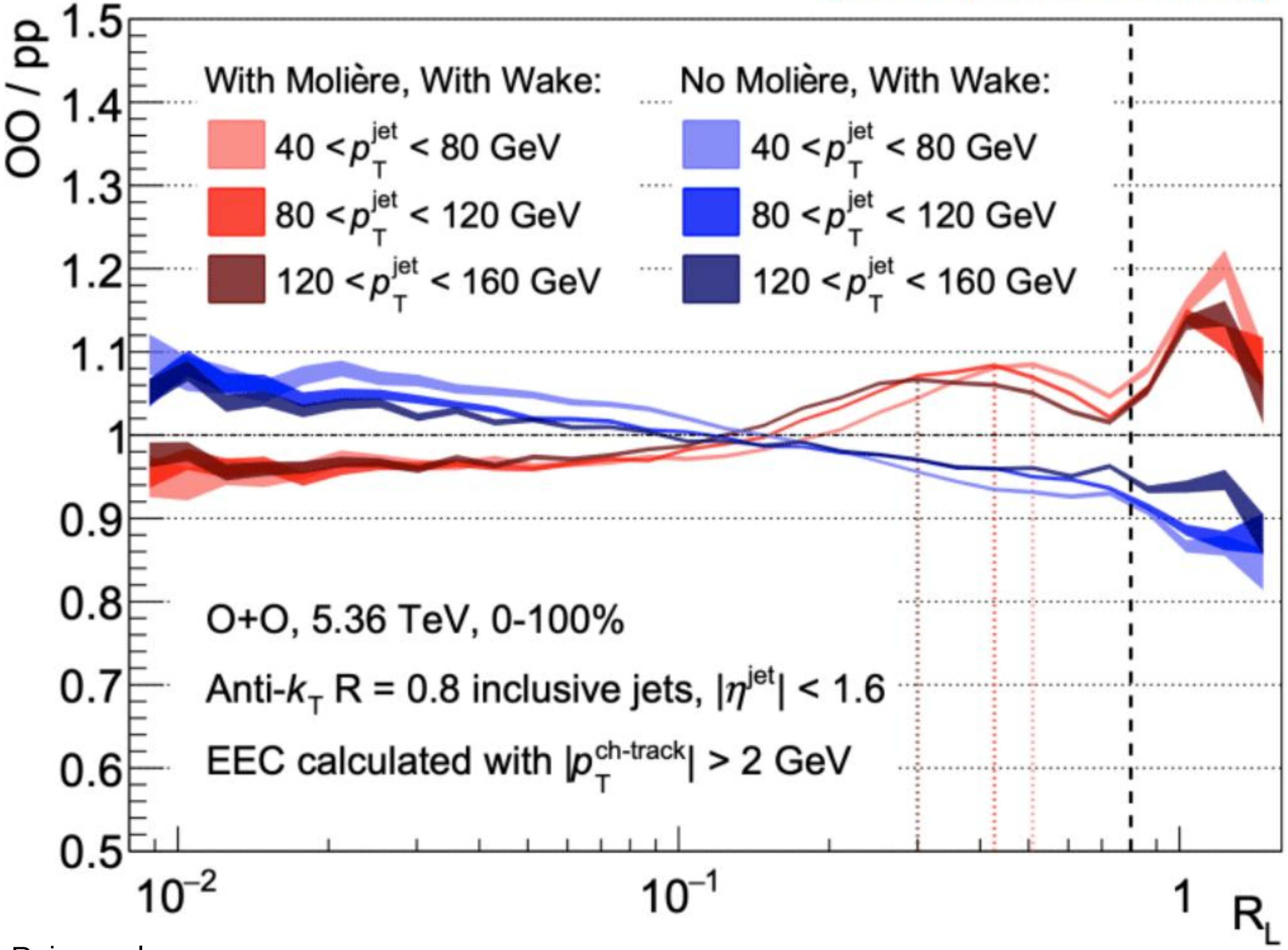


- Go beyond the jet using the full-event EEC with Z-boson tagging.
- Clean, ideal, avenue for looking at medium modifications, relatively free from selection bias effects.

Search for Moliere Scattering with EEC in OO



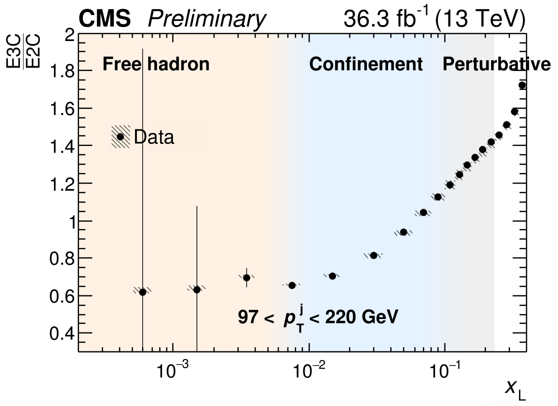
[arXiv:2603.23596]

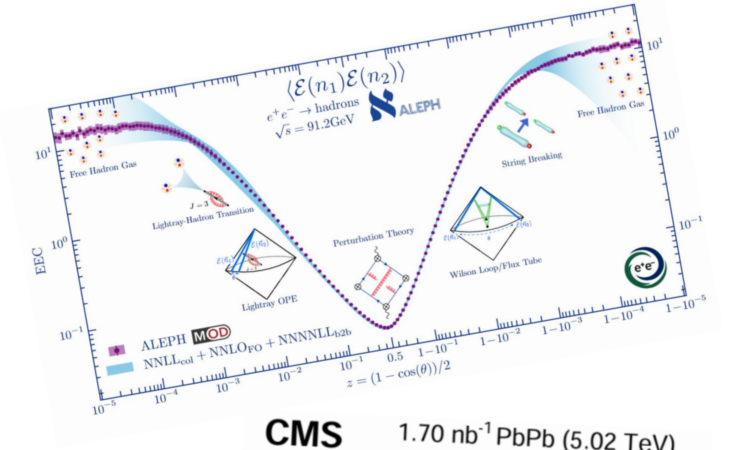


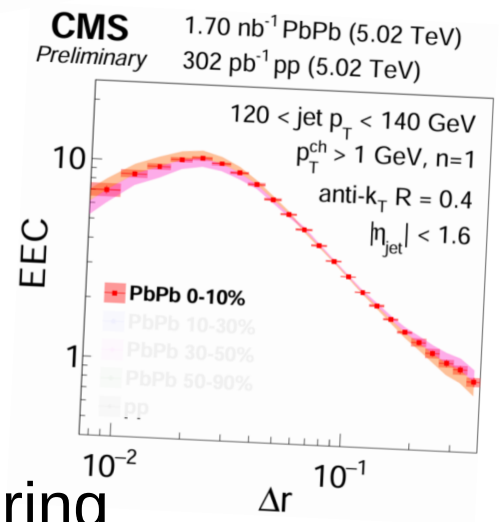
Prediction from Arjun Kudinoor, Arthur Yi-Ting Lin, Daniel Pablos, Krishna Rajagopal

Summary

- CMS pp EEC
  - Widest p_T^{jet} range measurement of E2C, the first measurement on E3C
  - Multi-dimensional unfolding: accounts for correlation between variables
  - Features of QCD observed: color confinement, asymptotic freedom
  - α_s Uncertainty ~ 4%, "most precise extraction from jet-substructure"
- e^+e^- EEC with archived ALEPH and DELPHI data
  - Progress on data MC comparison and unfolding
  - Full event analysis without jet: exploration of the back-to-back region
  - Up to 20% spread across MC generators
    - Identify interesting length scales related to Z mass, 2 and 3 jet event
    - Collinear regions are consistent with our understanding in pp
  - "Highest precision test of pQCD calculation"
- CMS PbPb EEC:
  - First measurement of PbPb EEC with **inclusive** and **Z-tagged** jet
  - Reveal jet quenching, medium induced radiation and medium response
  - **Promising tool** for revealing the substructure of QGP through Moliere scattering







Acknowledgement

We would like to thank **Roberto Tenchini** and **Guenther Dissertori** from the ALEPH collaboration for the useful comments and suggestions on the use of ALEPH archived data.

We would like to thank **Ian Moult, Felix Ringer**, **Jesse Thaler, Andrew Lakoski, Liliana Apolinário, Ben Nachman, Camelia Mironov, Jing Wang, Ian Moult, Krishna Rajagopal, Daniel Pablos Alfonso, Jussi Viinikainen, Hannah Bossi** for the useful discussions on the analysis and presentation.

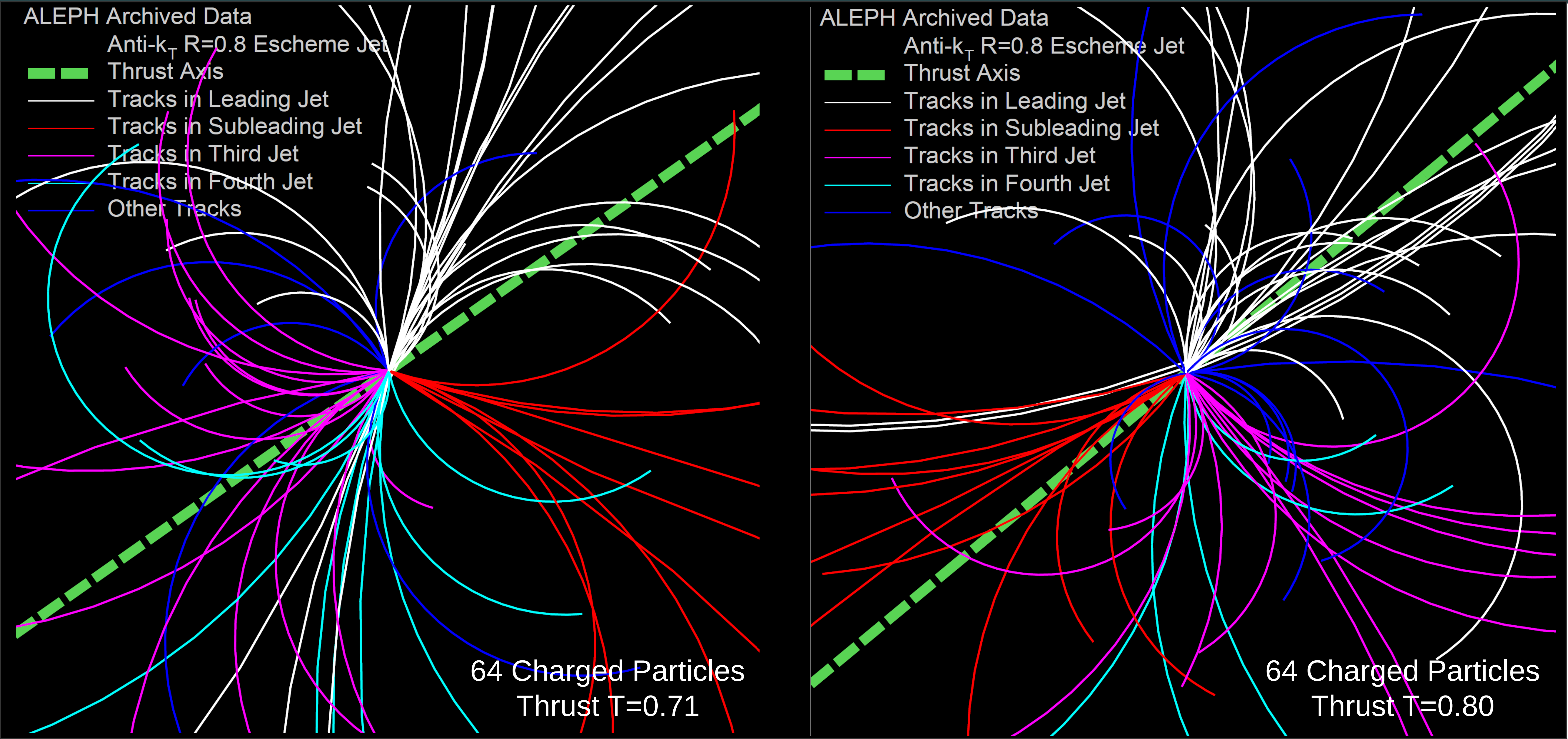
The MIT group's work was supported by US DOE-NP

Backup slides

Observable Wishlist in e^+e^-

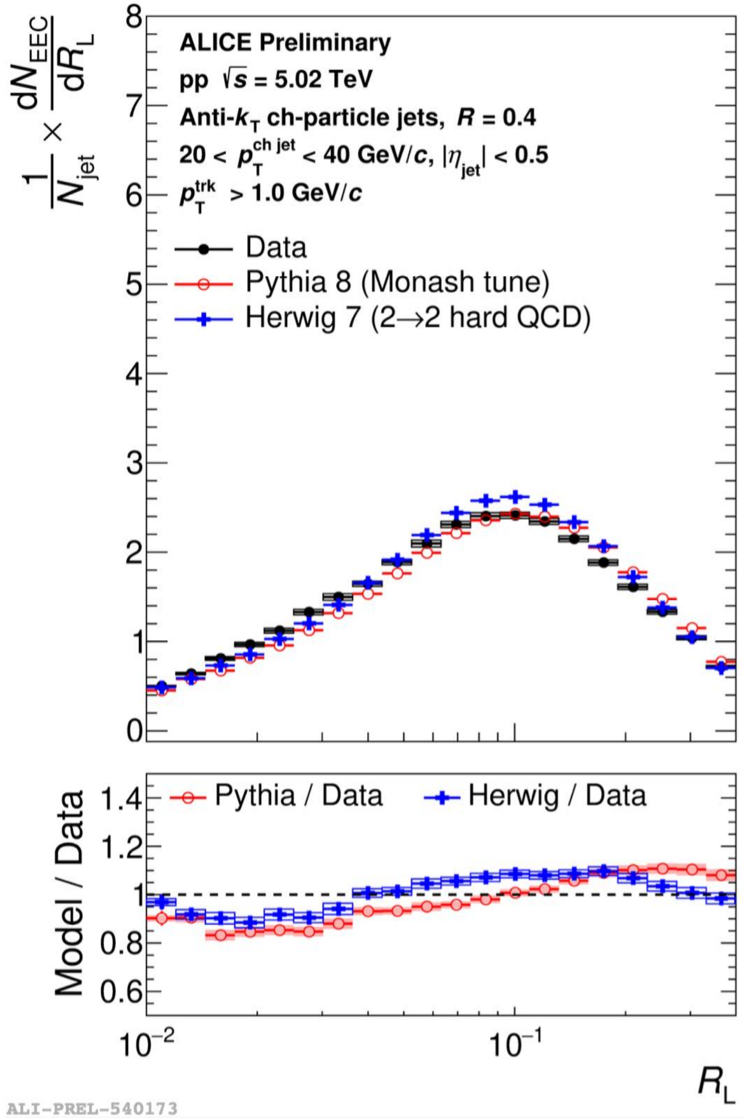
- Two point and higher particle correlator (EnC) and their ratios
  - How high can we go??
- Charged Correlators (plus/minus) and Charge-Weighted Correlators
  - Probes correlations between charges, modification of scaling behavior, and changes in hadronization transitions
- E^nE^m Correlators
  - Potentially useful for suppressing soft radiation & studying transition region
- … also a lot of other possibilities
  - (As usual we have way too many interesting observables to measure)

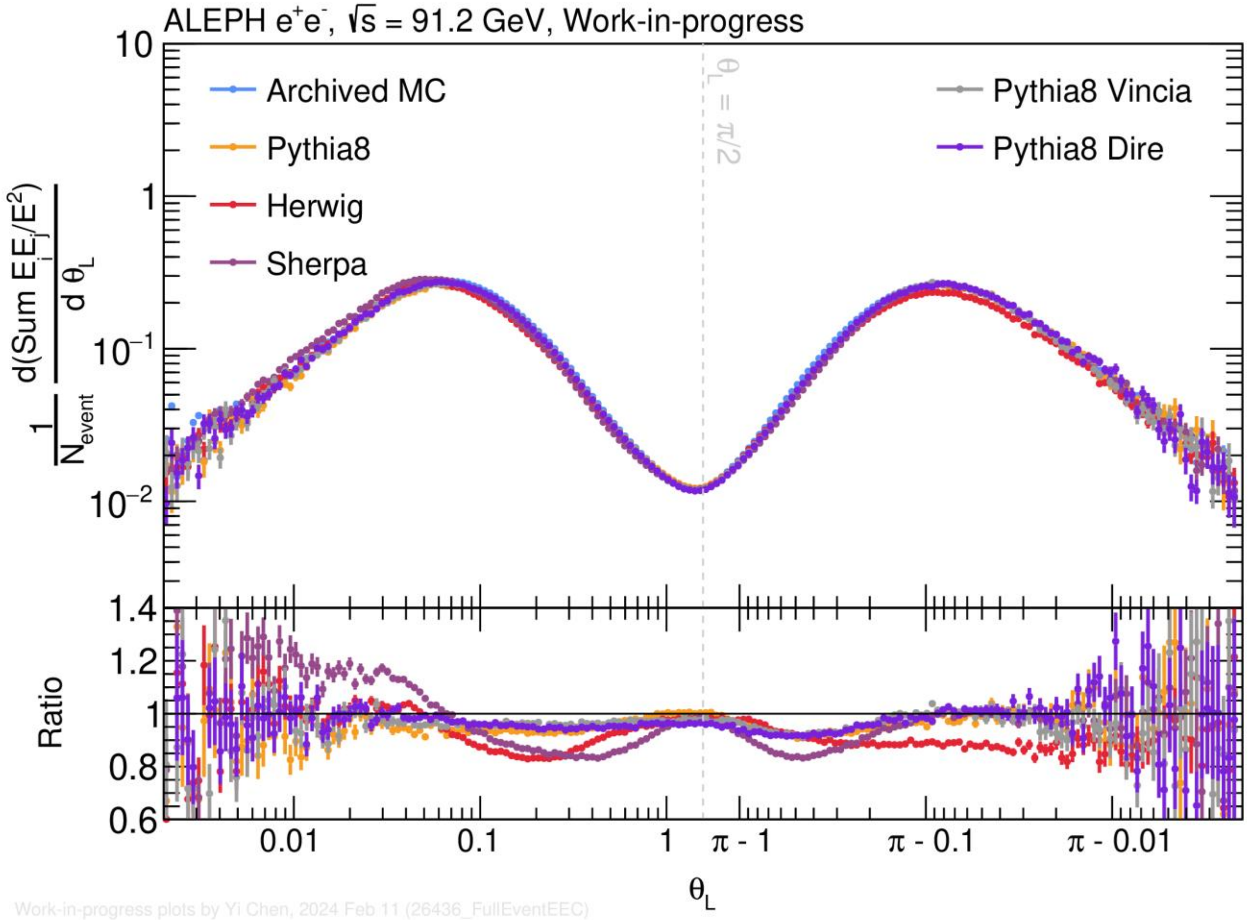
The Highest Multiplicity Events in Archived LEP2 Data



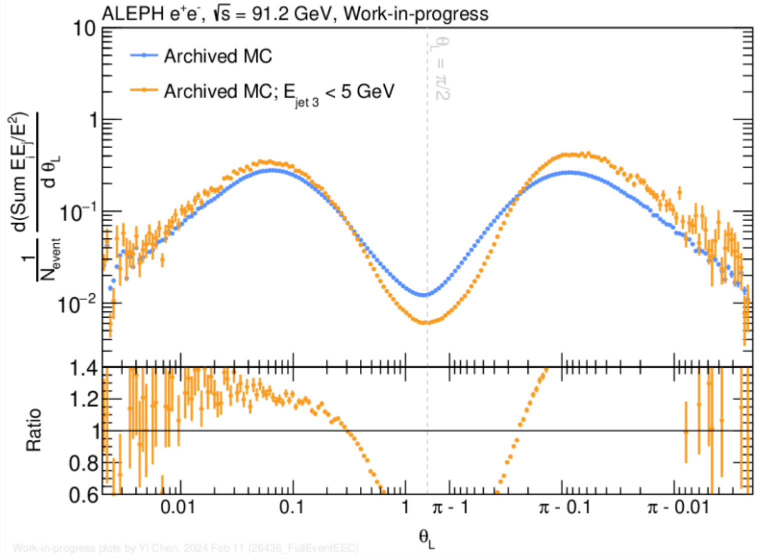
Comparison with ALICE pp

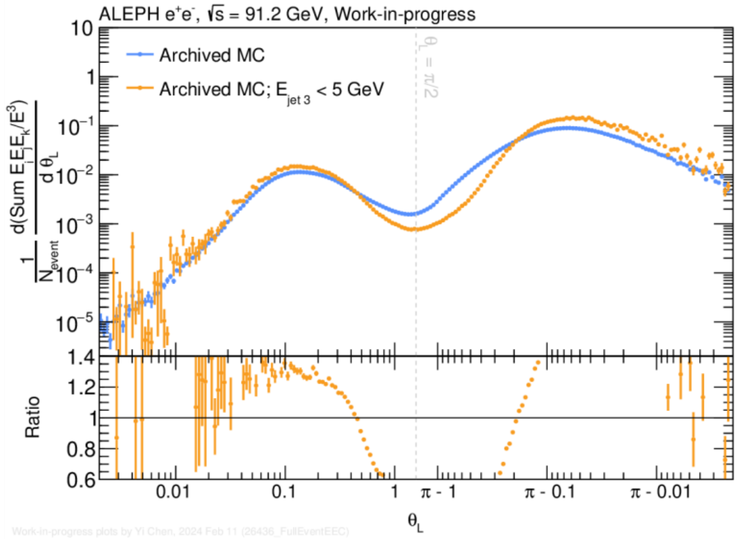
- Mostly similar story from MC comparisons

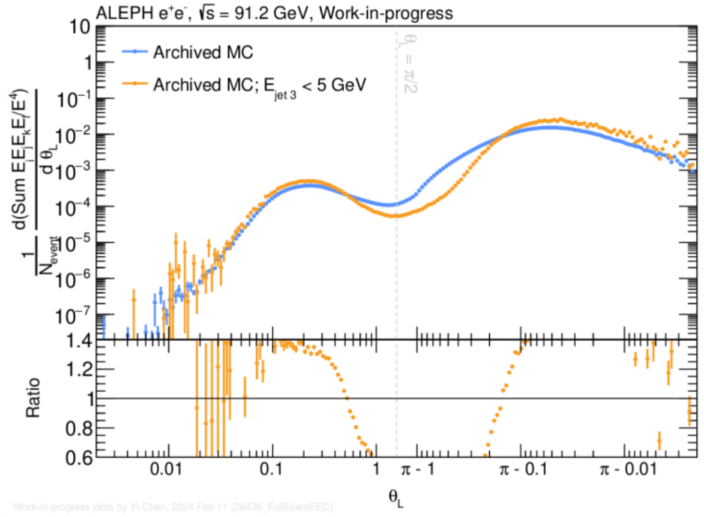


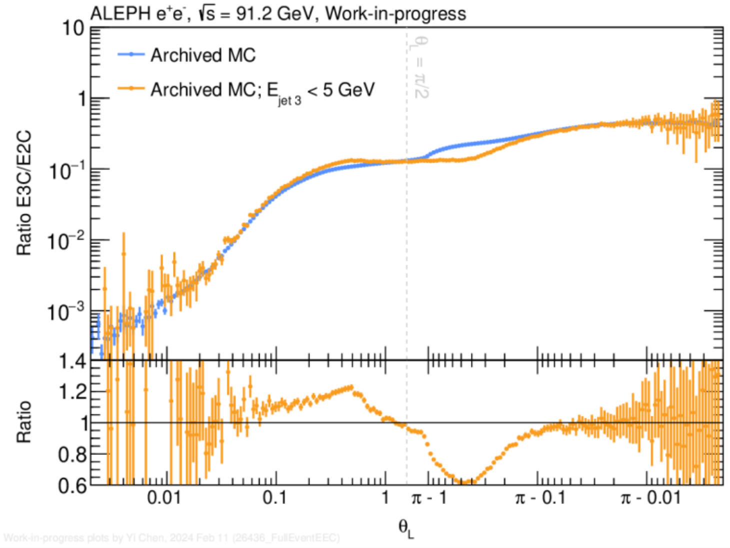


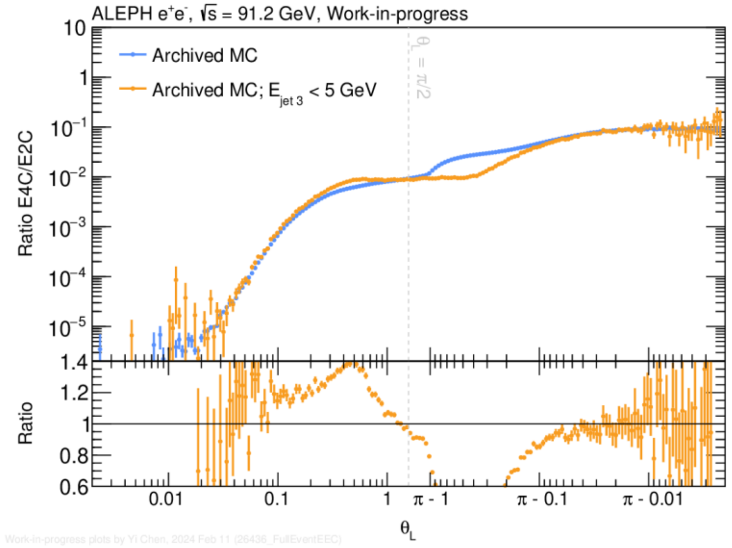
Rejecting 3-jet events in EEC's



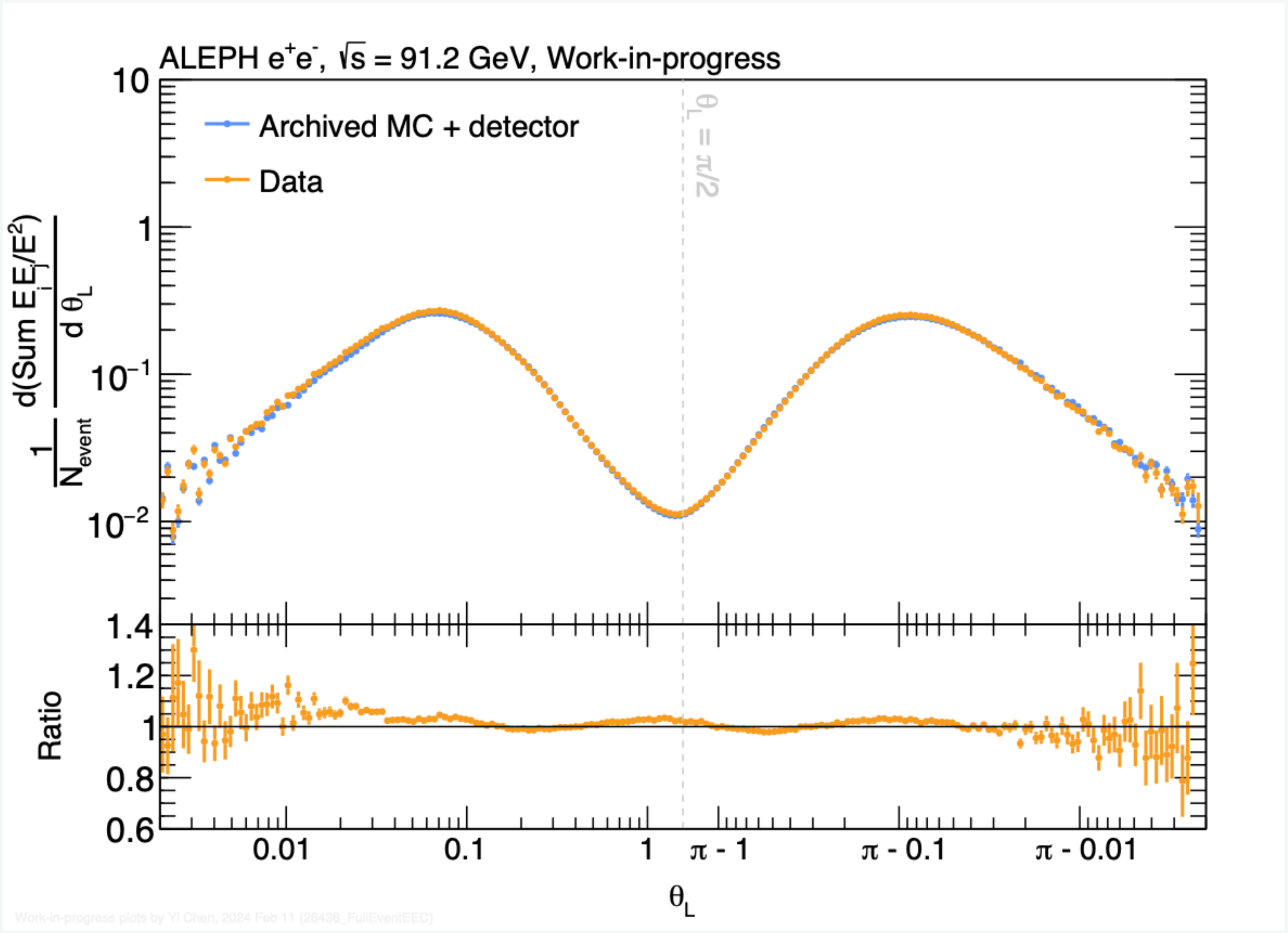






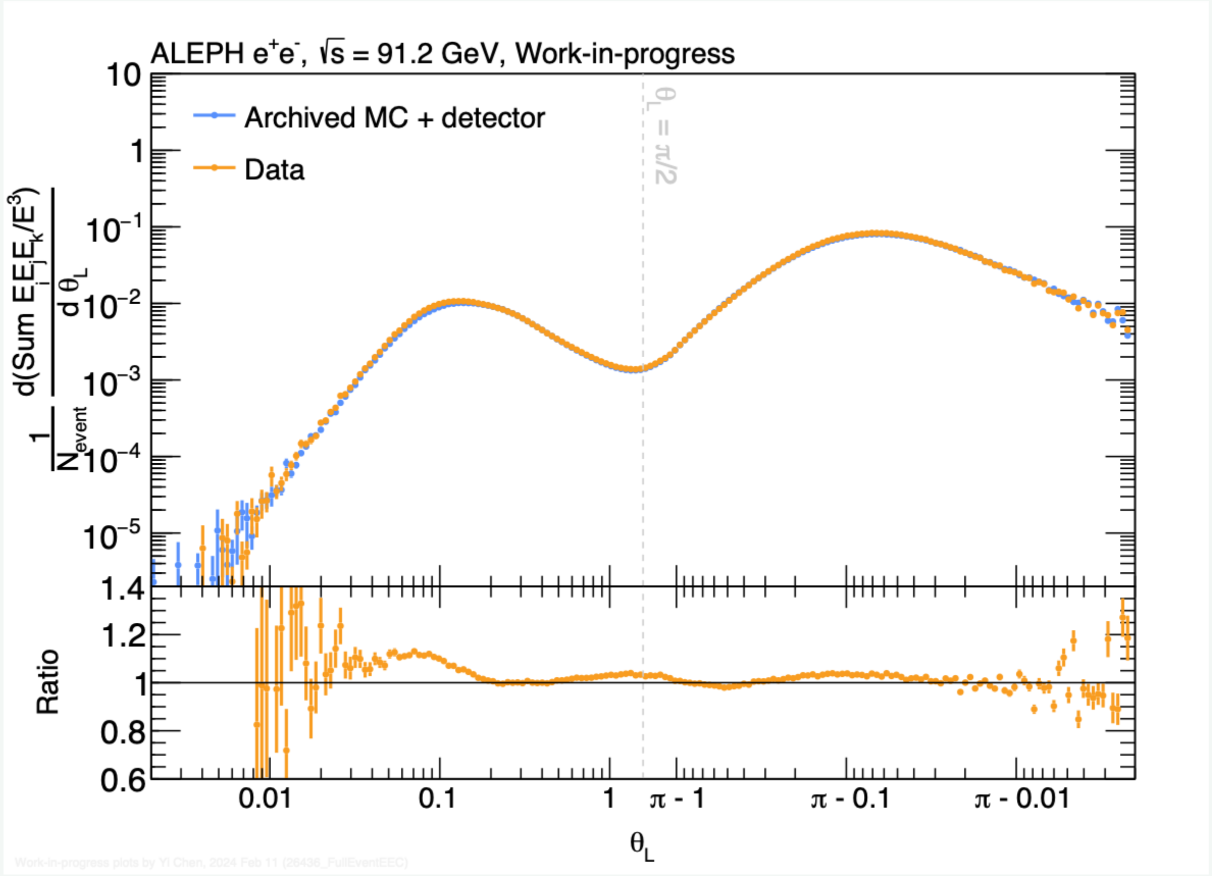


E2C

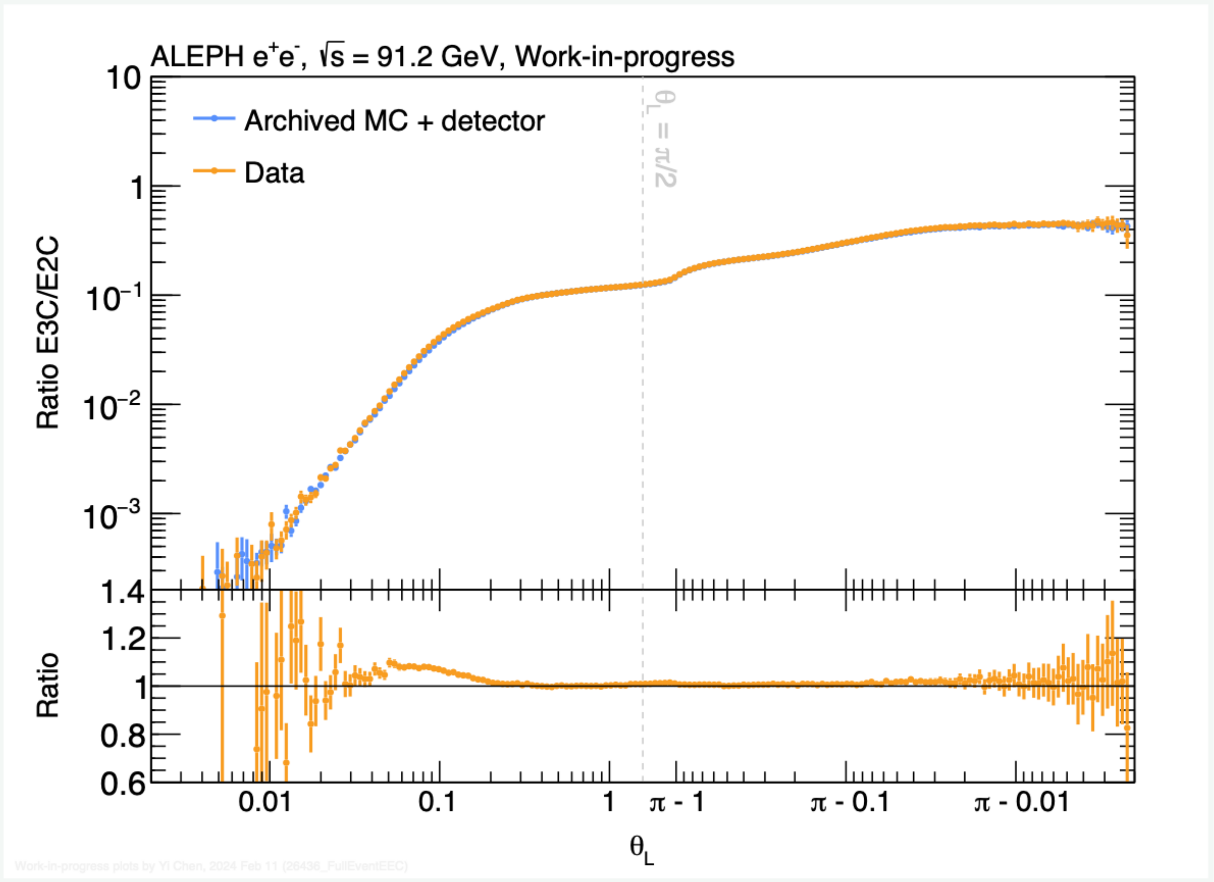


ALEPH e+e-, √s = 91.2 GeV, Work-in-progress
Archived MC + detector
Data
θL = π/2
1/Nevent d(Sum EiEj/E2)/d θL
Ratio
θL
0.01
0.1
1
π - 1
π - 0.1
π - 0.01

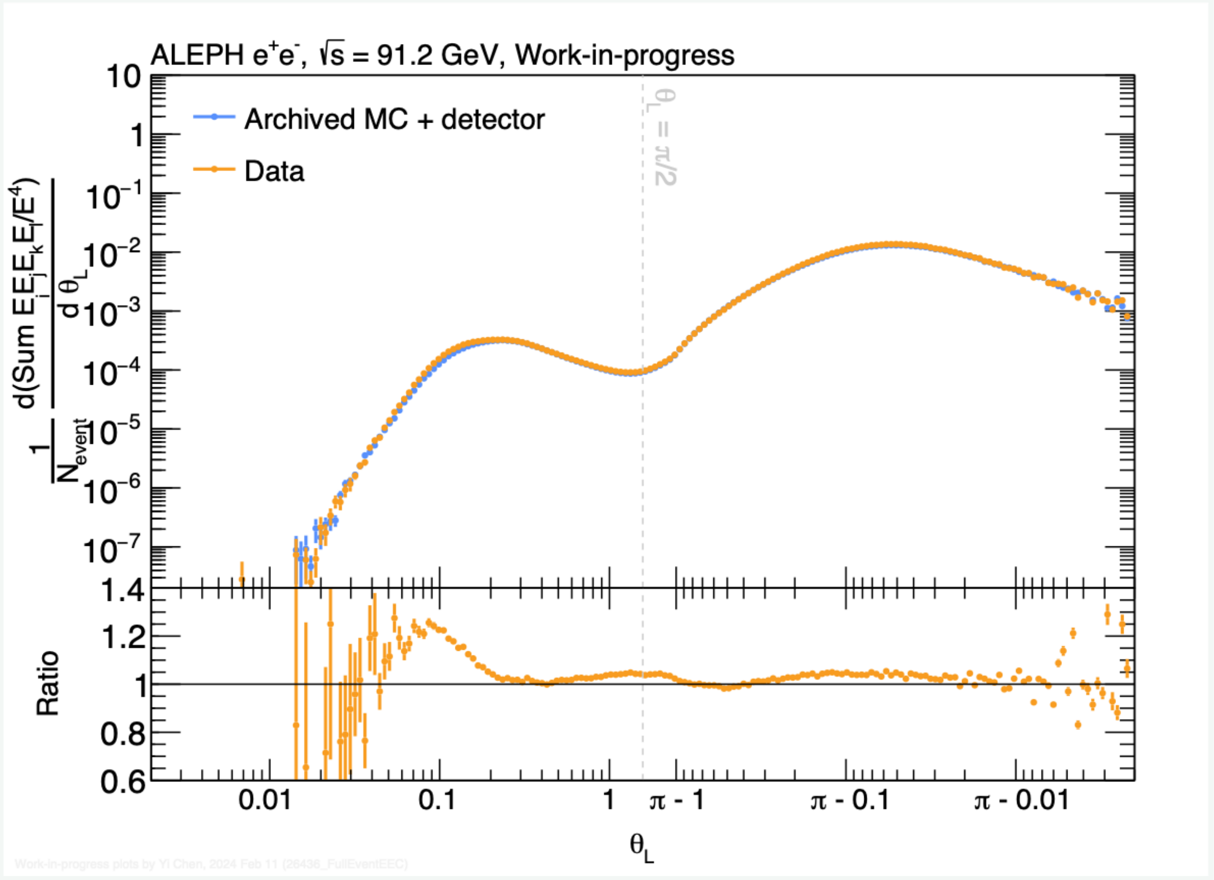
E3C


ALEPH e+e-, √s = 91.2 GeV, Work-in-progress
Archived MC + detector
Data
θL = π/2
Ratio
0.01
0.1
1
π - 1
π - 0.1
π - 0.01
θL

E3C/E2C

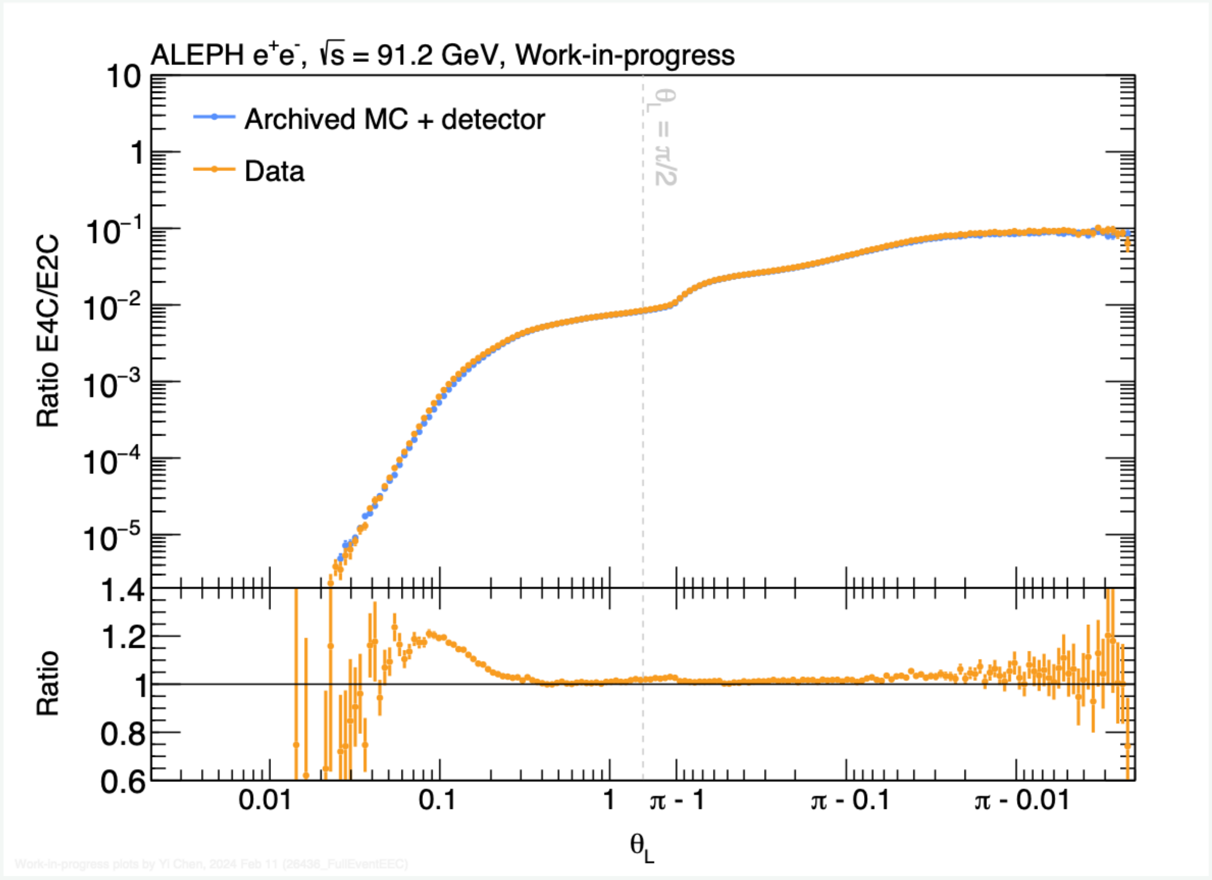

ALEPH e⁺e⁻, √s = 91.2 GeV, Work-in-progress
Archived MC + detector
Data
θL = π/2
Ratio E3C/E2C
Ratio
10
1
10⁻¹
10⁻²
10⁻³
1.4
1.2
1
0.8
0.6
0.01
0.1
1
π - 1
π - 0.1
π - 0.01
θL

E4C



ALEPH e⁺e⁻, √s = 91.2 GeV, Work-in-progress
Archived MC + detector
Data
θ_L = π/2
Ratio
θ_L
0.01
0.1
1
π - 1
π - 0.1
π - 0.01

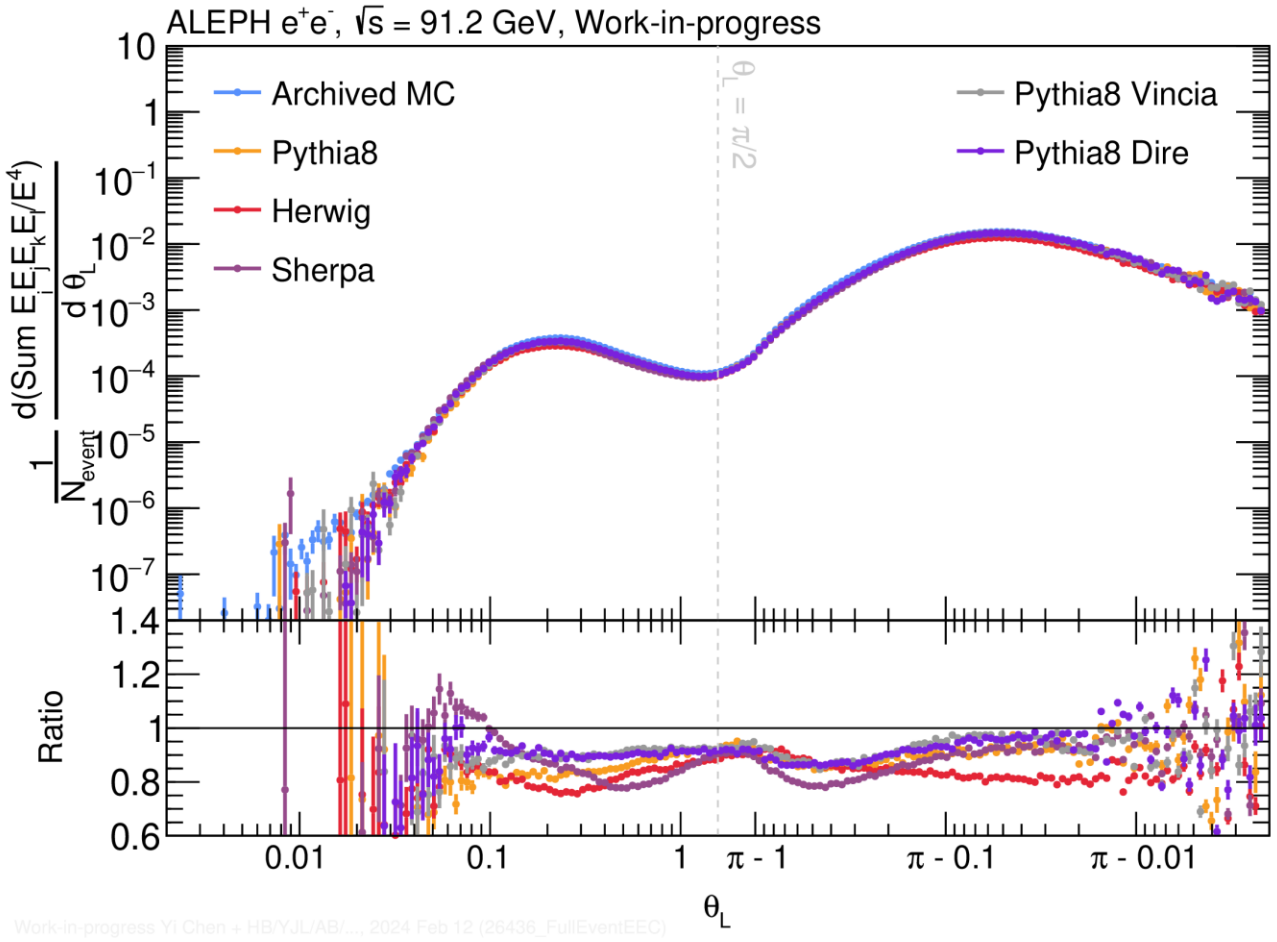
E4C/E2C

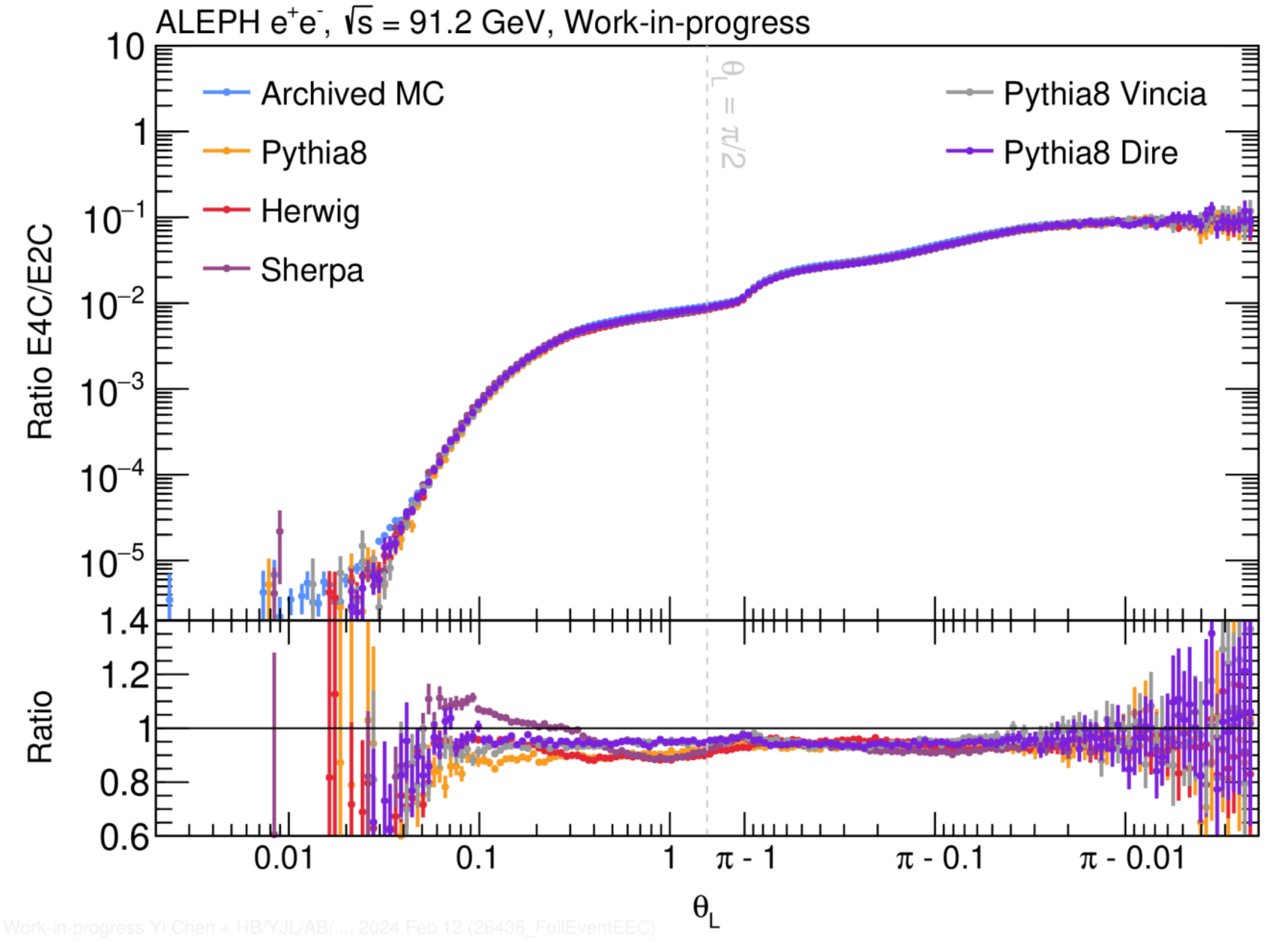


ALEPH e+e-, √s = 91.2 GeV, Work-in-progress
Archived MC + detector
Data
θL = π/2
Ratio E4C/E2C
Ratio
10
1
10−1
10−2
10−3
10−4
10−5
1.4
1.2
1
0.8
0.6
0.01
0.1
1
π - 1
π - 0.1
π - 0.01
θL

E4C and E4C/E2C ratio in e^+e^-

- Predictions of E4C and E4C/E2C from event generators



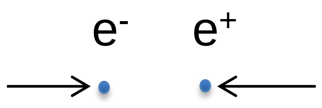


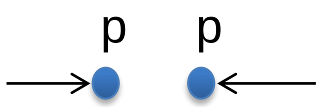
Motivation

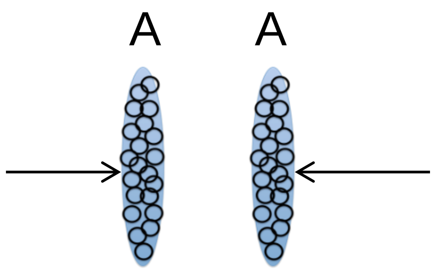
- Monte Carlo generators such as PYTHIA 6, PYTHIA 8, SHERPA and HERWIG are tuned with hadronic event shape observables and hadron spectra in $e^+ e^-$
  - Then used to predict the jet spectra and substructure in more complicated hadron collisions

- **EEC in pp:**
  - New tool for α_s extraction
  - Test on pQCD and compared to event generators.
  - Reference for AA

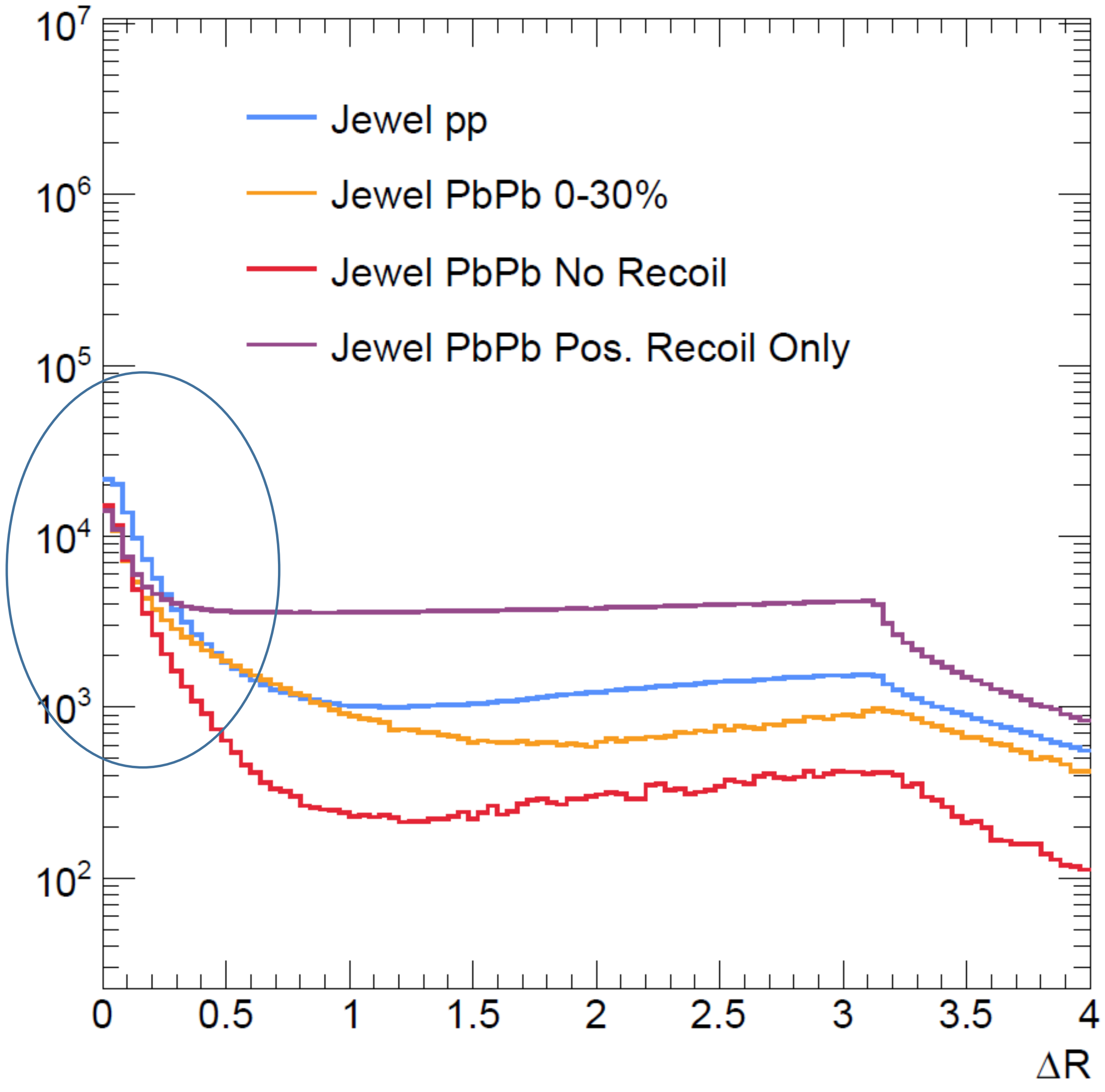
- **Jet substructure and EEC in e^+e^-:**
  - Utilize the new jet clustering tools developed after LEP operation
  - Revisit EEC with fine binning and extended it to full event.
  - Further test of event generators, reference of pp

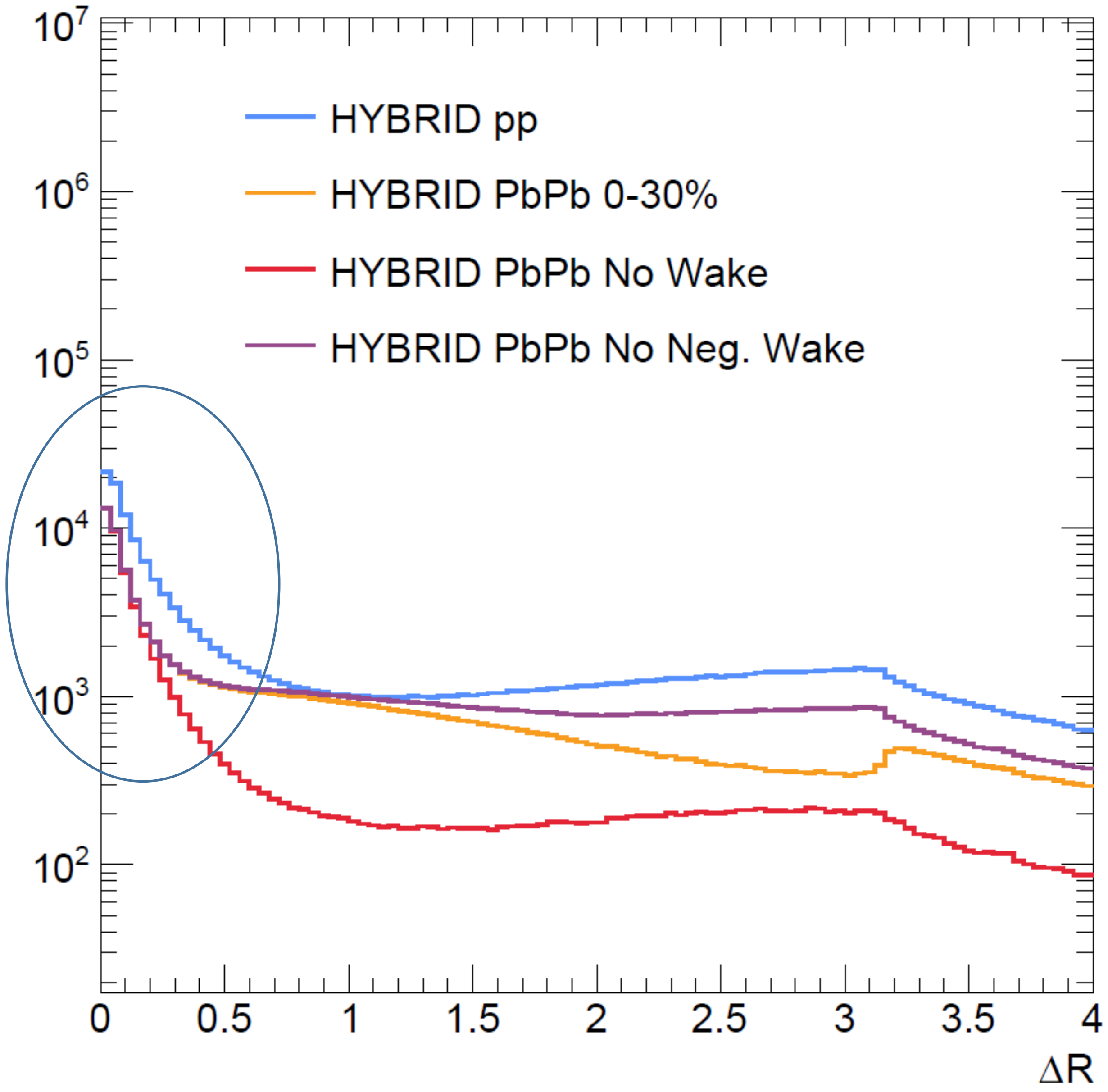




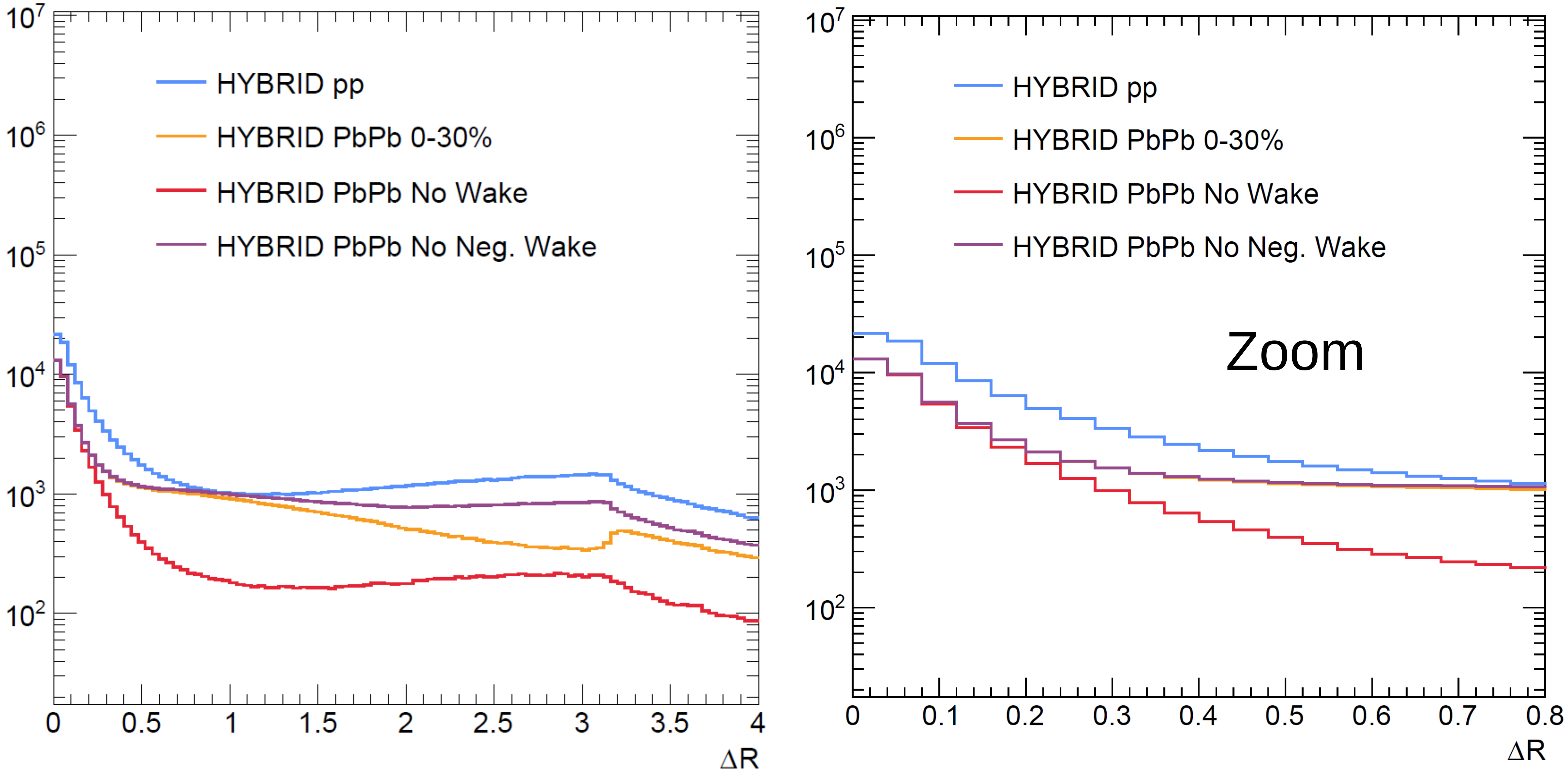


JEWEL vs HYBRID (All Hadrons)



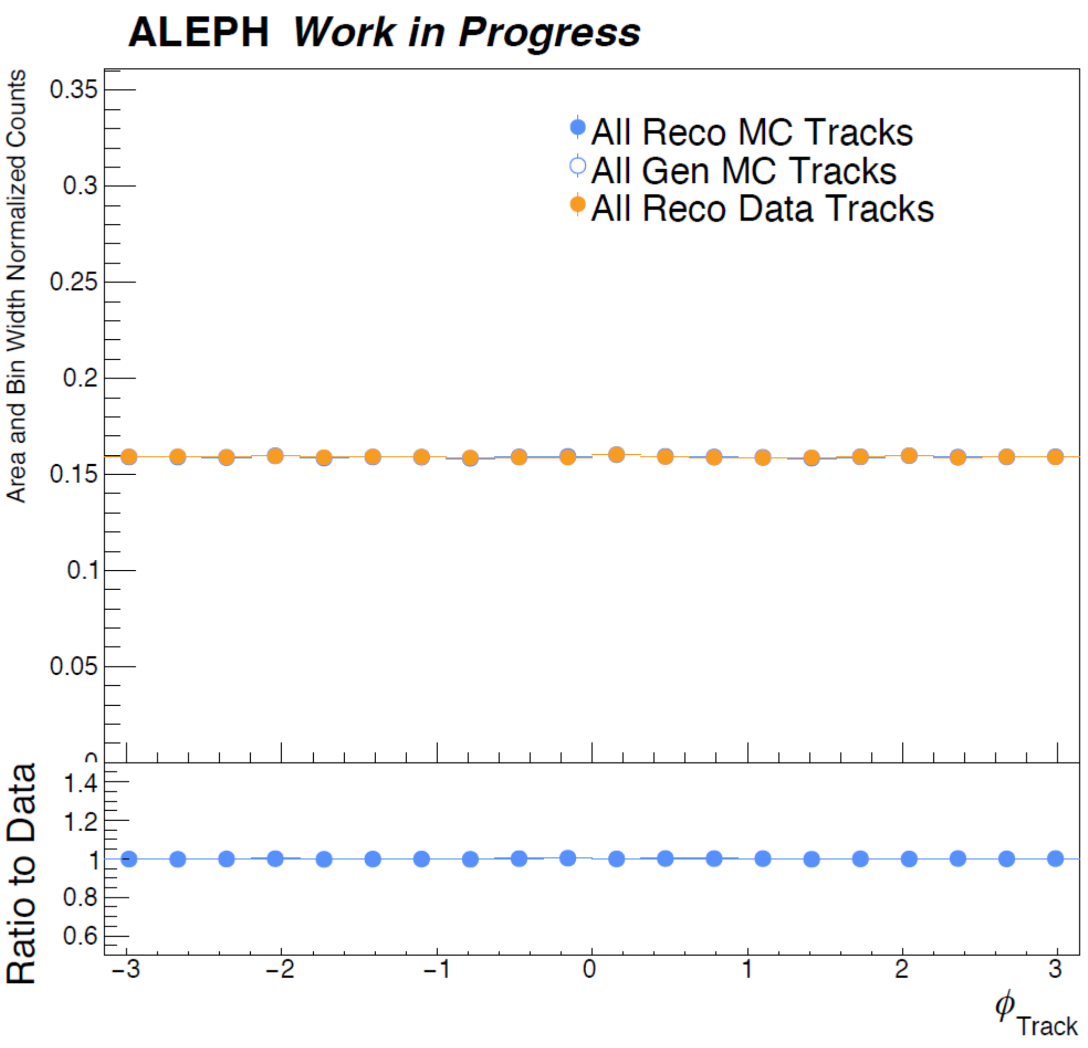


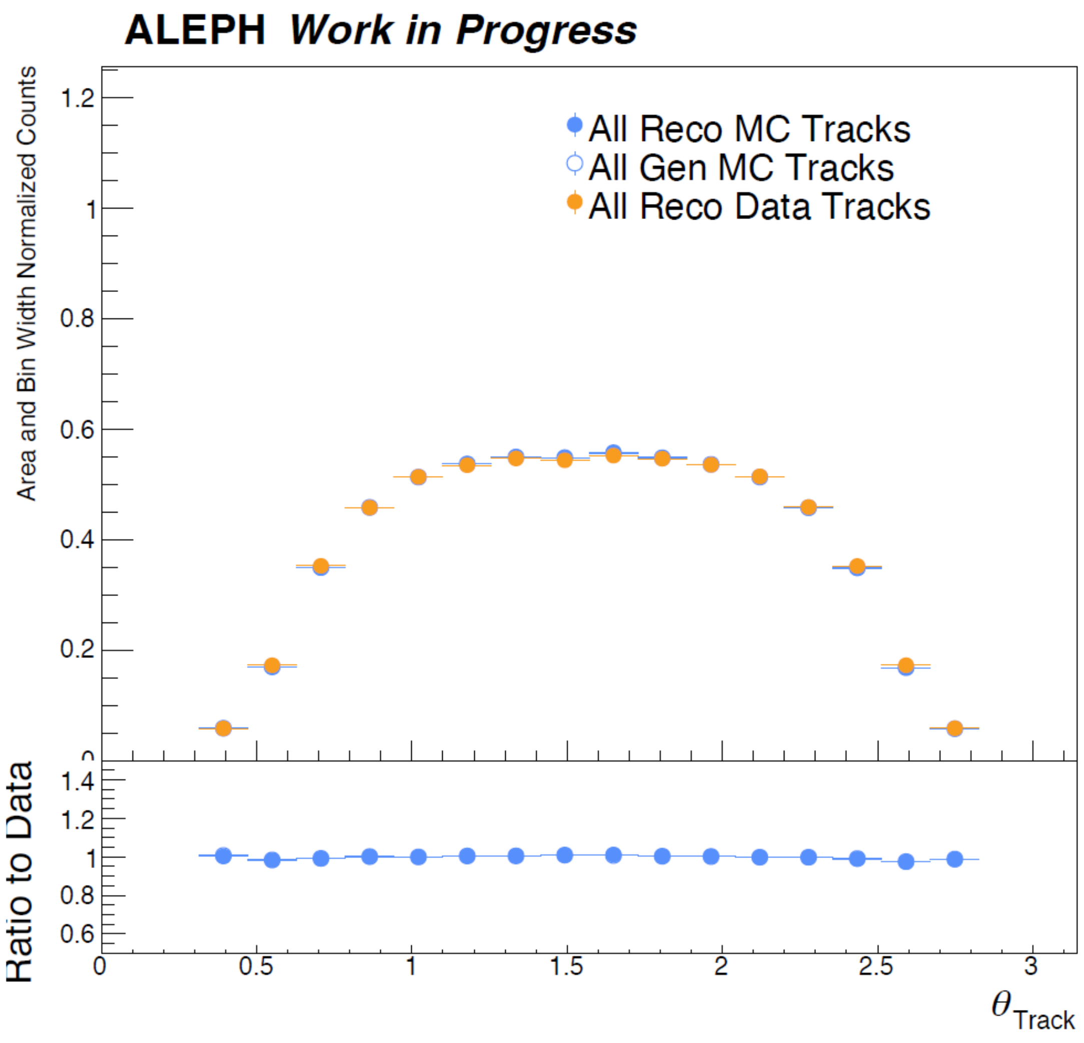
Z-Tagged E2C in HYBRID Model (All Hadrons)



Daniel Pablo, Krishna Rajagopal, Yi Chen, YJL

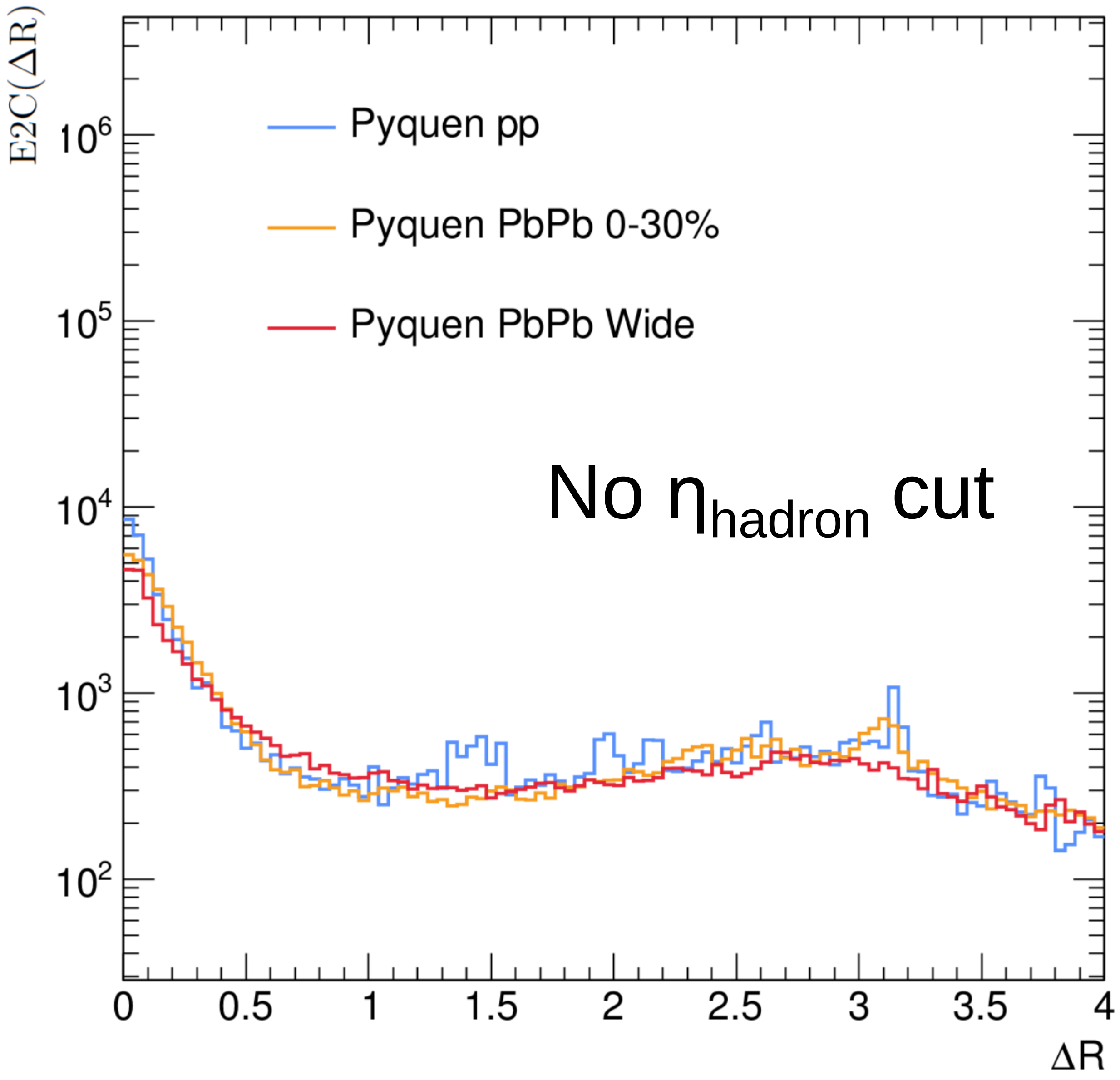
Track-based EEC in e^+e^- Collisions





Hannah Bossi (MIT)

Z-Tagged E2C in PYQUEN (Charged Hadrons)



- PYQUEN model which use a simple implementation jet quenching mechanism without conservation of energy shows little modification of the shape
- Jet Quenching shows as area change and E2C broadening effect
- At small ΔR: sensitive to wide angle radiation

→ Lead to further suppression at large angle as well as broadening of the E2C correlation function

Can we measure Z-tagged EnC in the actual AA data?

$$E2C(\Delta R) = \frac{1}{N_Z} \sum_{Z \in [p_T^Z > 40 GeV]} \sum_{pairs\ \Delta R_{i,j} \in \Delta R\ bin} (w_i\ w_j\ p_{T,i}\ p_{T,j})$$

Yi Chen, YJL

Background Subtraction of Z-Tagged Hadron Spectra

PbPb Z event:
Z-Jet + **UE**

Minimum-bias PbPb Event

MC: should reproduce pp Z event
Data: Subtracted event

Correlated hadrons with Z (**S1**)
Uncorrelated hadrons with Z (**B1**)

–

Uncorrelated hadrons with Z (**B2**)

=

Correlated hadron with Z (**S1**)

We can then compare this with pp

For Z-tagged Hadron Spectrum, we could calculate S1 by

(**S1** + **B1**) – (**B2**) ~ **S1** **(if we do a statistical subtraction <B1> = <B2>)**

Background Subtraction of Z-Tagged E2C

PbPb Z event:
Z-Jet + **UE**

Minimum-bias
PbPb Event

MC: should reproduce pp Z event
Data: Subtracted event

PbPb Z event		Minimum-bias PbPb Event		Subtracted event
Correlated hadrons with Z (**S1**)				Correlated hadron with Z (**S1**)
Uncorrelated hadrons with Z (**B1**)	−	Uncorrelated hadrons with Z (**B2**)	=	

We want to measure **S1** x **S1** and compare this with pp

$$\mathrm{E2C}(\Delta R) = \frac{1}{N_Z} \sum_{Z \in [p_T^Z > 40\,\mathrm{GeV}]} \sum_{\mathrm{pairs}\ \Delta R_{i,j} \in \Delta R\ \mathrm{bin}} (w_i\, w_j\, p_{T,i}\, p_{T,j})$$

Experimentally, we could calculate (**S1** x **S1**) by …

[Z event]^2: (**S1** + **B1**) x (**S1** + **B1**) = **S1** x **S1** + **2** **S1** x **B1** + **B1** x **B1**
[Z event x MB]: (**S1**+ **B1**) x **B2** = **S1** x **B2** + **B1** x **B2**

However, cross terms **B1** x **B2** won't cancel **B1** x **B1** due to correlations in UE particles

Background Subtraction of Z-Tagged E2C

PbPb Z event:
Z-Jet + **UE**

Minimum-bias
PbPb Event

MC: should reproduce pp Z event
Data: Subtracted event

PbPb Z event		Minimum-bias PbPb Event		Subtracted
Correlated hadrons with Z (**S1**)				Correlated hadron with Z (**S1**)
Uncorrelated hadrons with Z (**B1**)	−	Uncorrelated hadrons with Z (**B2**)	=	

We want to measure **S1** x **S1** and compare this with pp

Experimentally, we could calculate (**S1** x **S1**) by all the following mixed-event pairs:

[Z event]^2: (**S1** + **B1**) x (**S1** + **B1**) = **S1** x **S1** + **2** **S1** x **B1** + **B1** x **B1**
[Z event x MB]: (**S1**+ **B1**) x **B2** = **S1** x **B2** + **B1** x **B2**
[MB]^2: **B1** x **B1**
[MB1 x MB2]: **B1** x **B2**

Background Subtraction of Z-Tagged E2C

PbPb Z event:
Z-Jet + **UE**

Minimum-bias
PbPb Event

MC: should reproduce pp Z event
Data: Subtracted event

Correlated hadrons with Z (**S1**)
Uncorrelated hadrons with Z (**B1**)

–

Uncorrelated hadrons with Z (**B2**)

=

Correlated hadron with Z (**S1**)

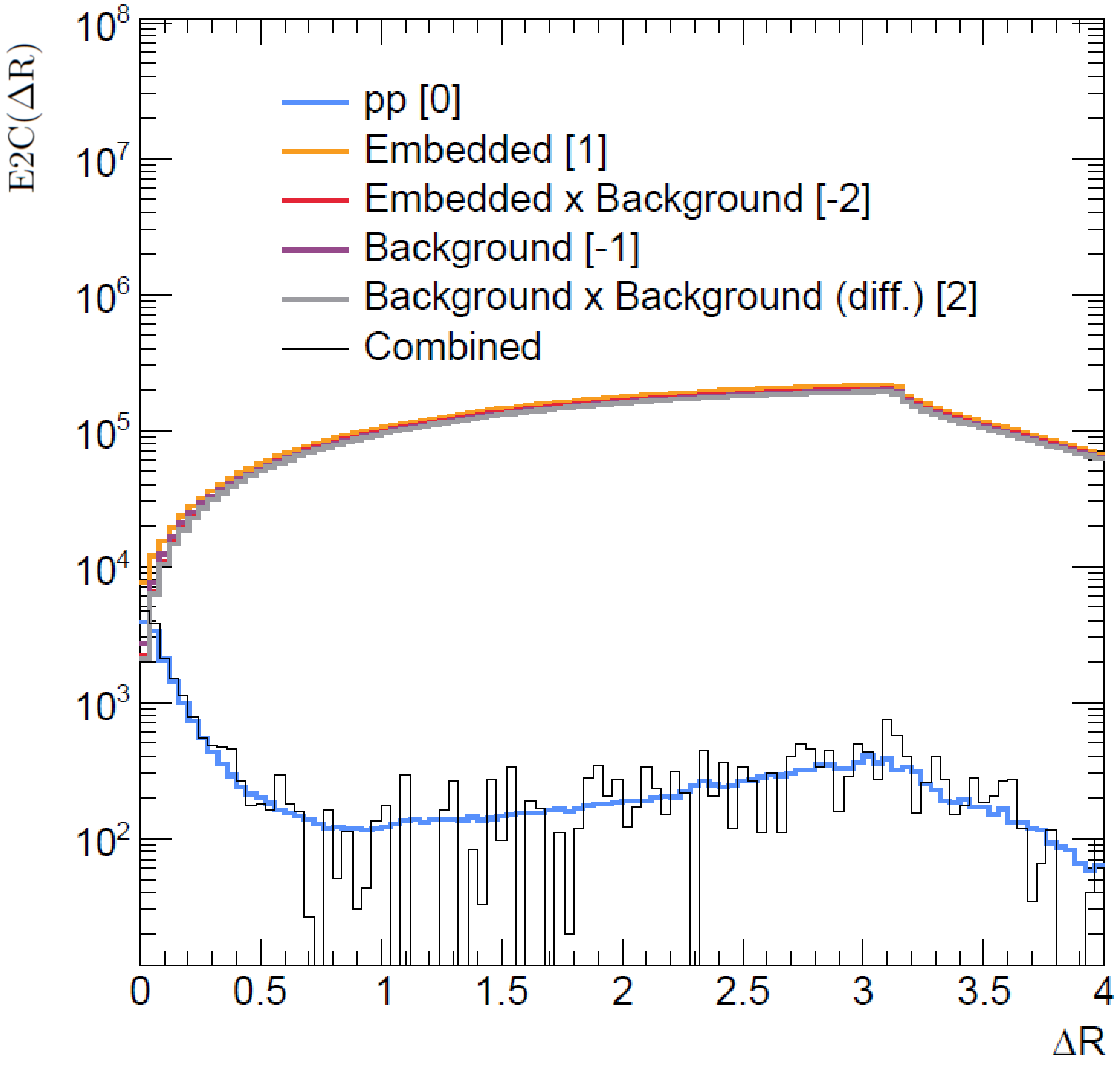
We want to measure **S1** x **S1** and compare this with pp

Experimentally, we could calculate (**S1** x **S1**) by all the following mixed-event pairs:

[Z event]^2: (**S1** + **B1**) x (**S1** + **B1**) = **S1** x **S1** + **2** **S1** x **B1** + **B1** x **B1**
[Z event x MB]: (**S1**+ **B1**) x **B2** = **S1** x **B2** + **B1** x **B2**
[MB]^2: **B1** x **B1**
[MB1 x MB2]: **B1** x **B2**

Signal = **S1** x **S1**
= [Z event]^2 - **2** [Z event x MB] – [MB]^2 + **2** [MB1 x MB2]

Background Subtraction Closure Test



Yi Chen, YJL

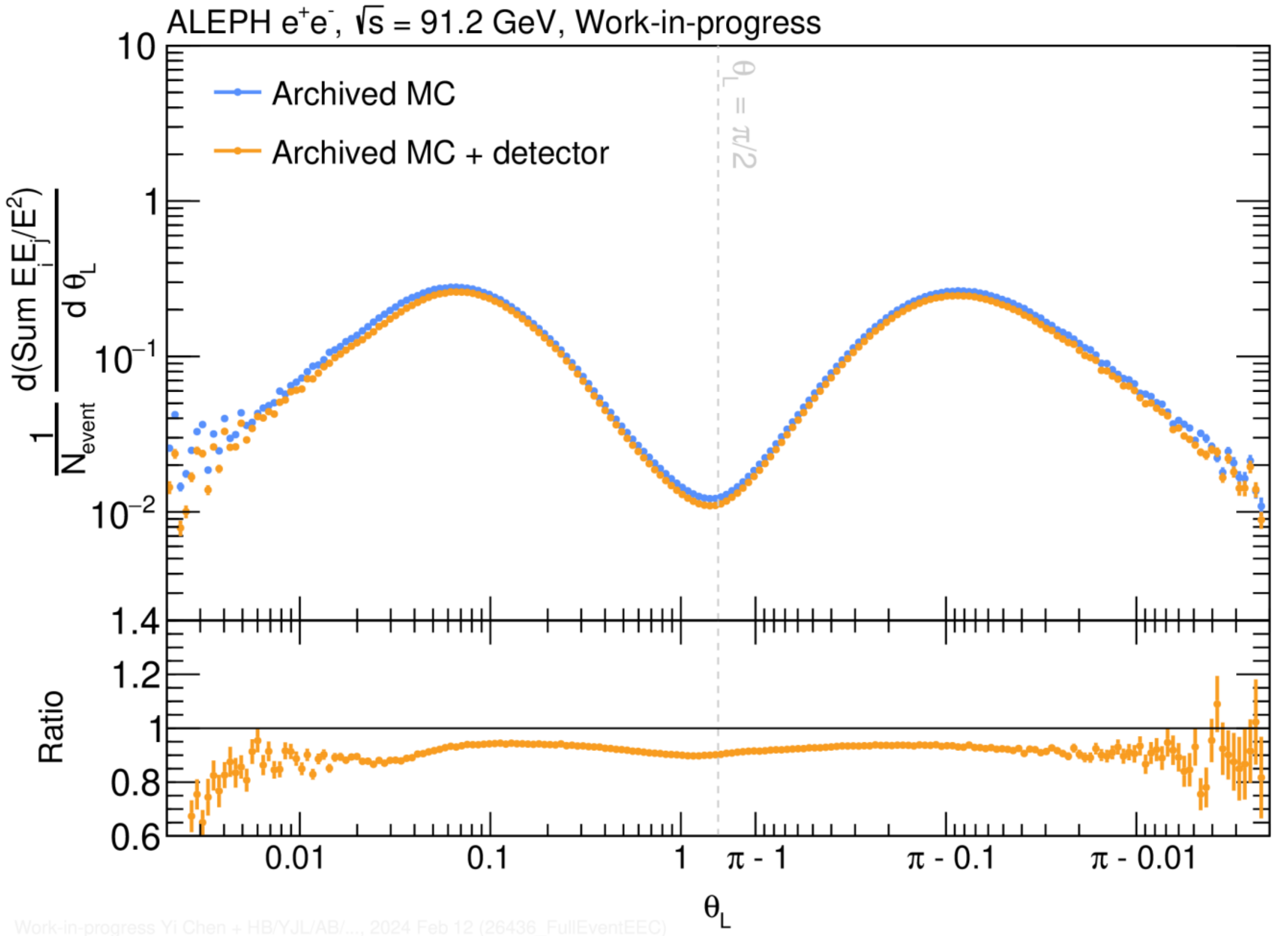
- Closure test with Embedded (PYTHIA + HYDJET) for E2C
- Following the event-mixing and subtraction scheme:

Combined = [Z event]^2 - **2** [Z event x MB] – [MB]^2 + **2** [MB1 x MB2]

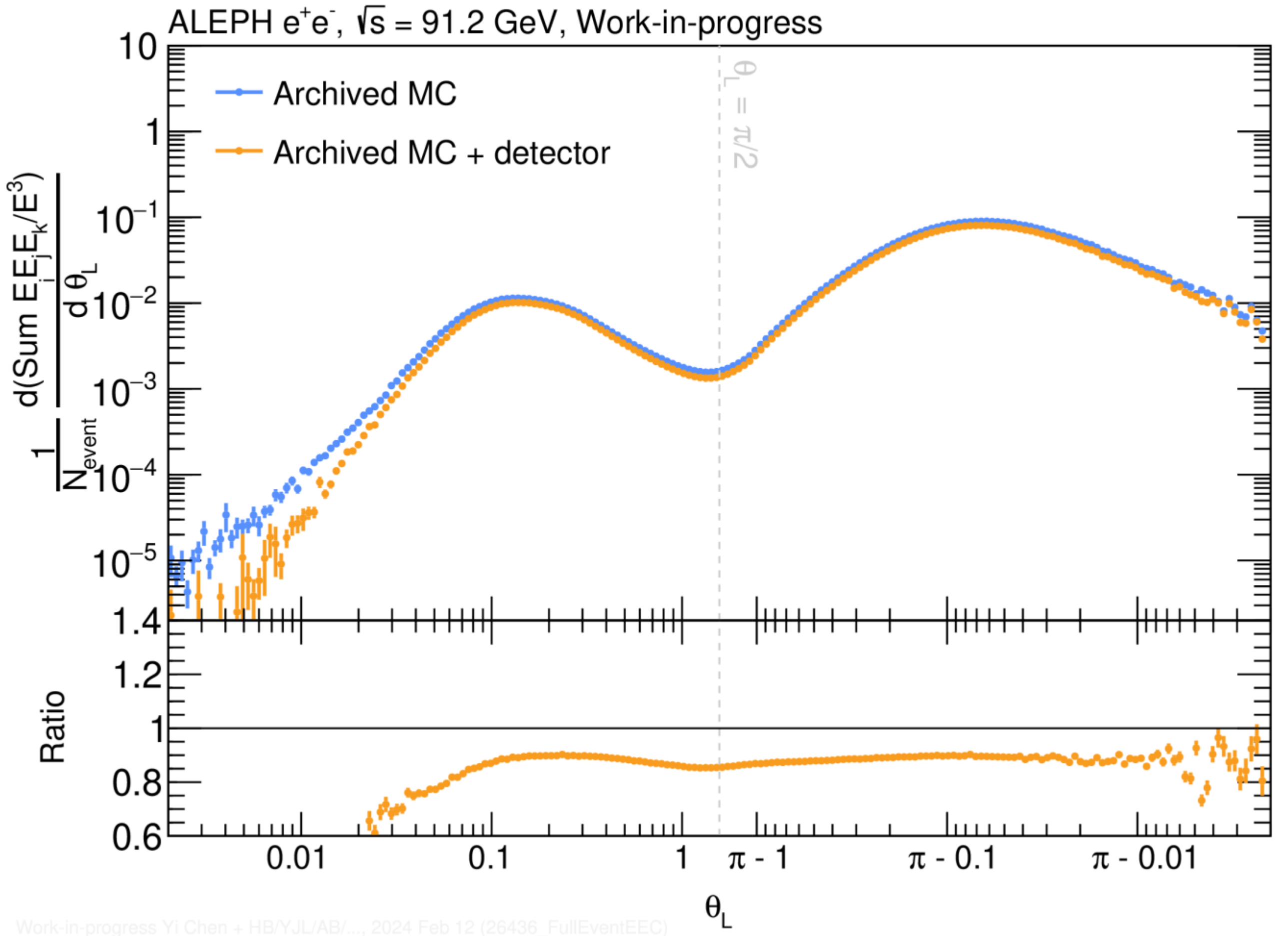
- Reproduce the embedded pp signal with the proposed fully data-driven method
- Used in inclusive jet and Z-tagged EEC in CMS PbPb analyses
- Extension to **EnC** with similar ideas

Detector Effects based on Archived ALEPH MC

- Will we be able to measure the correlators? **Yes!**
- Generator- and detector-level results are similar over a large phase space

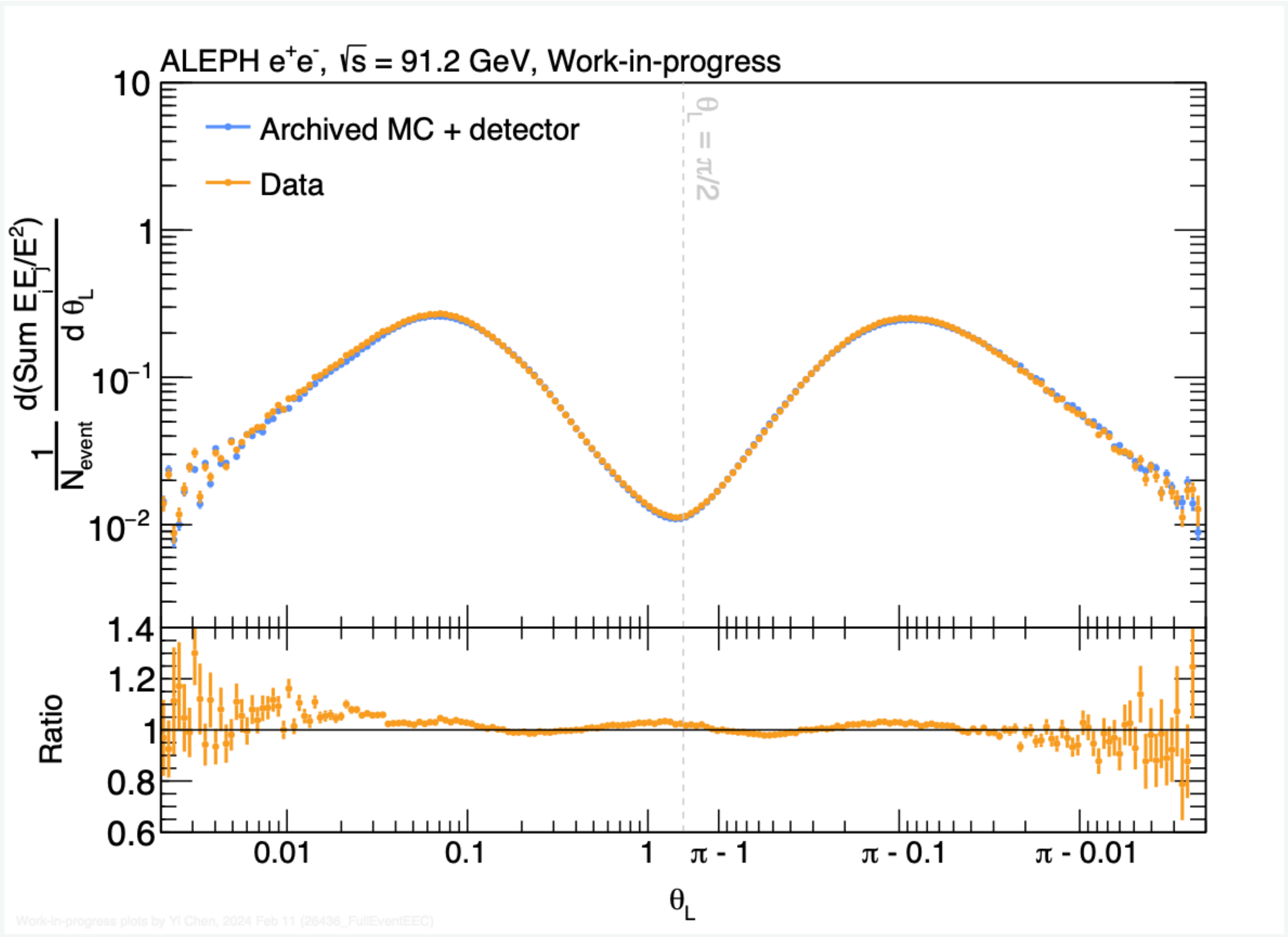


E2C

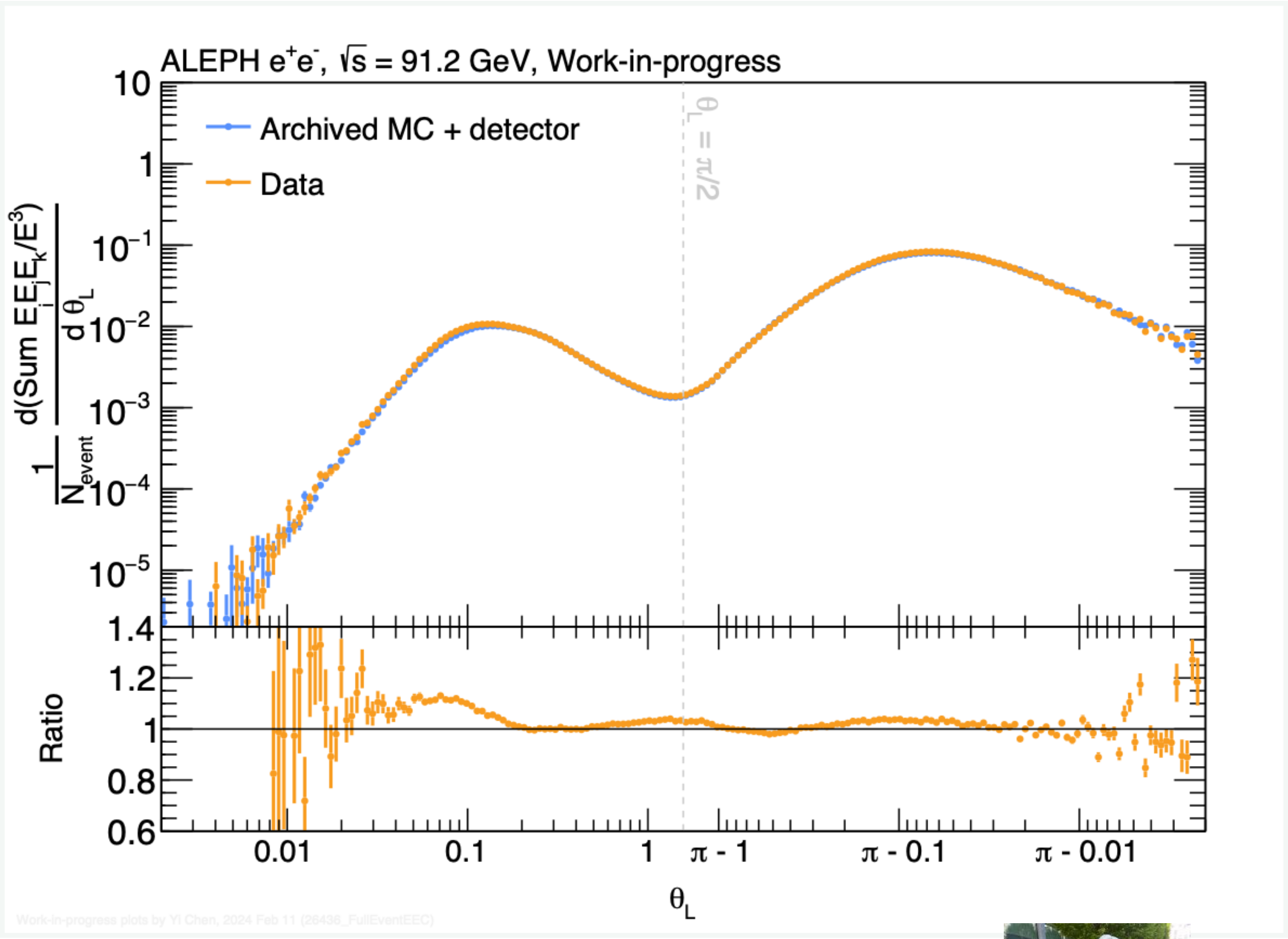


E3C

Detector Level MC vs Data in E2C and E3C



E2C



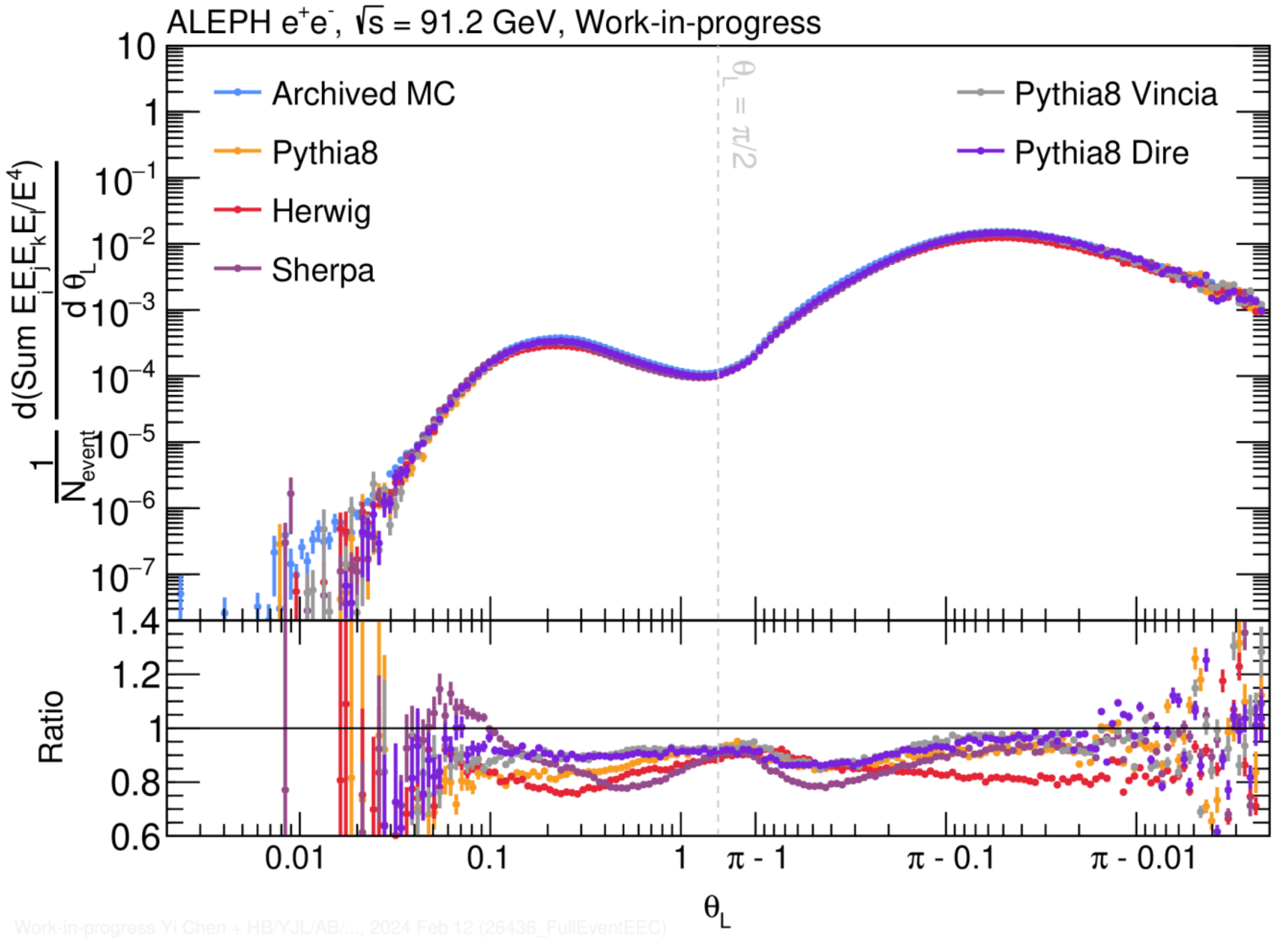
E3C

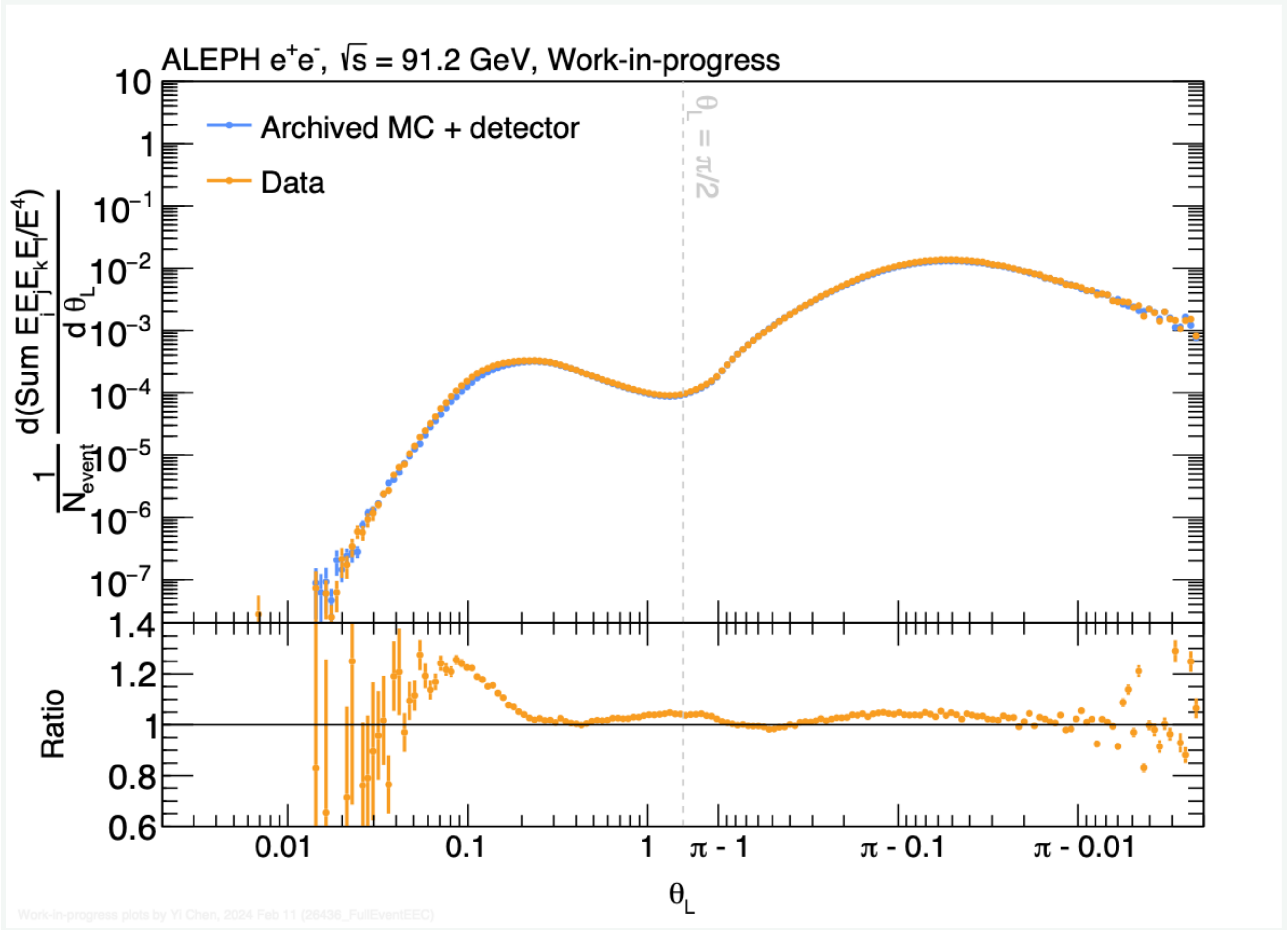
- Comparison between detector level archived **PYTHIA 6.1 MC** and Data
- Reasonable description of the **E2C** and **E3C** data

NEW! Yi Chen (Vanderbilt U.)

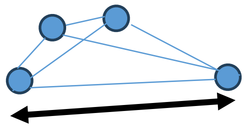
E4C and E4C/E2C ratio in e^+e^-

- Predictions of E4C and E4C/E2C from event generators





E4C



NEW!

Z Tagged E2C in Event Generators

Event selection:

Z Boson 60 < M_Z < 120 GeV

Z p_T > 40 GeV, $|y_z|$<2.4

No jet reconstruction

Object selection:

All Hadron analysis: all neutral & charged final state particles with p_T > 1 GeV included

Charged Hadron analysis: only charged final state particles with p_T > 1 GeV included

Wake / Recoil particle:

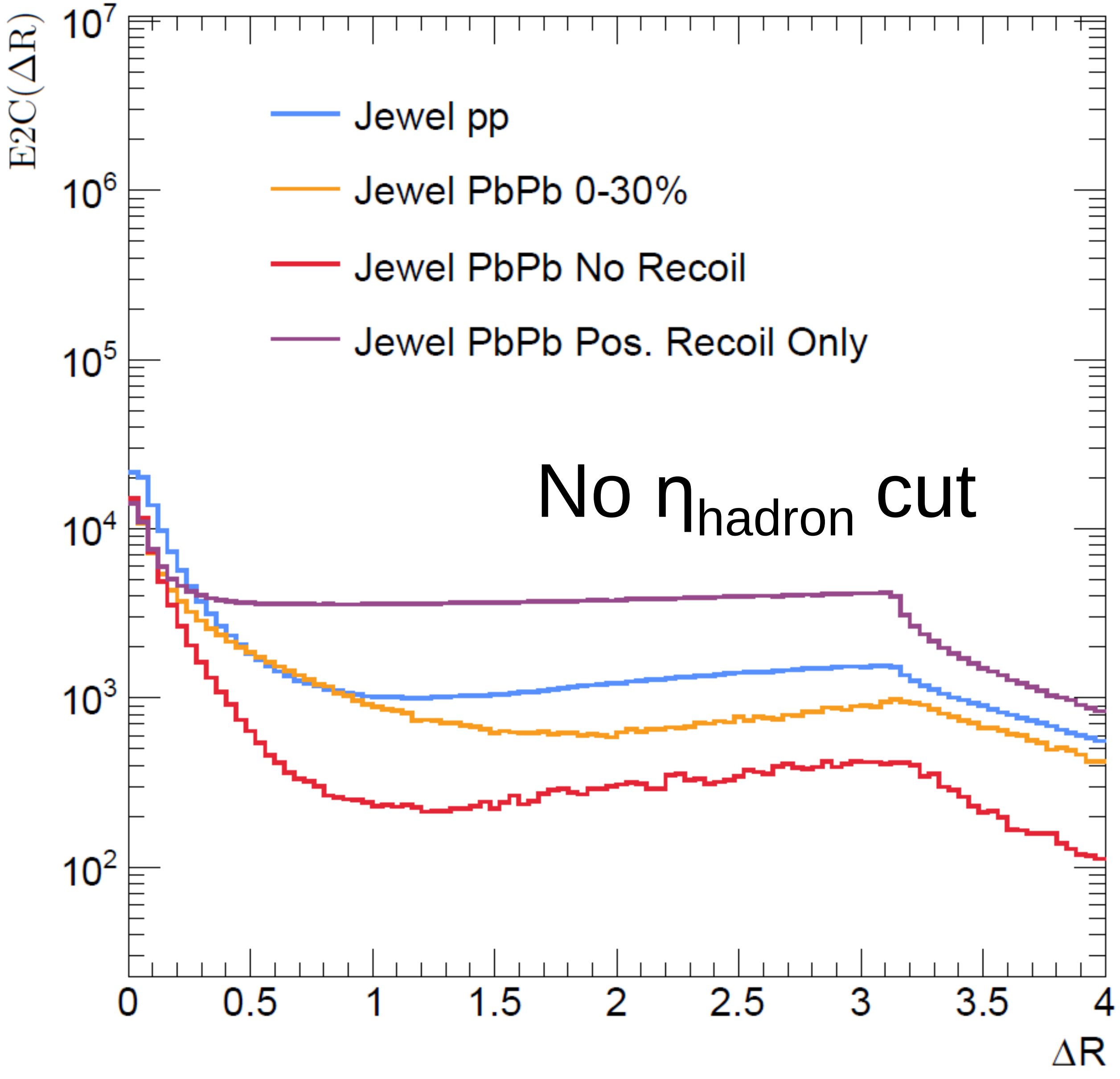
Weight (W_i) the **negative wake** (Hybrid model) and
parton hole (Jewel model) by a factor of **-1** in the $P_{T,1}$ x $P_{T,2}$ calculation

Normalization:

Normalization by number of Z

$$\mathrm{E2C}(\Delta R) = \frac{1}{N_Z} \sum_{Z \in [p_T^Z > 40\mathrm{GeV}]} \sum_{\text{pairs } \Delta R_{i,j} \in \Delta R \text{ bin}} (w_i\, w_j\, p_{T,i}\, p_{T,j})$$

JEWEL (All Hadrons)



- At small ΔR, **PbPb 0-30%** is lower than **pp reference**

→ Jet Quenching

- **Shower only result** shows a larger suppression in the phase space ΔR> 0.1

→ There is a characteristic scale of the medium recoil effect

- Large cancellation effect between **Positive Recoil** and Hole Contributions

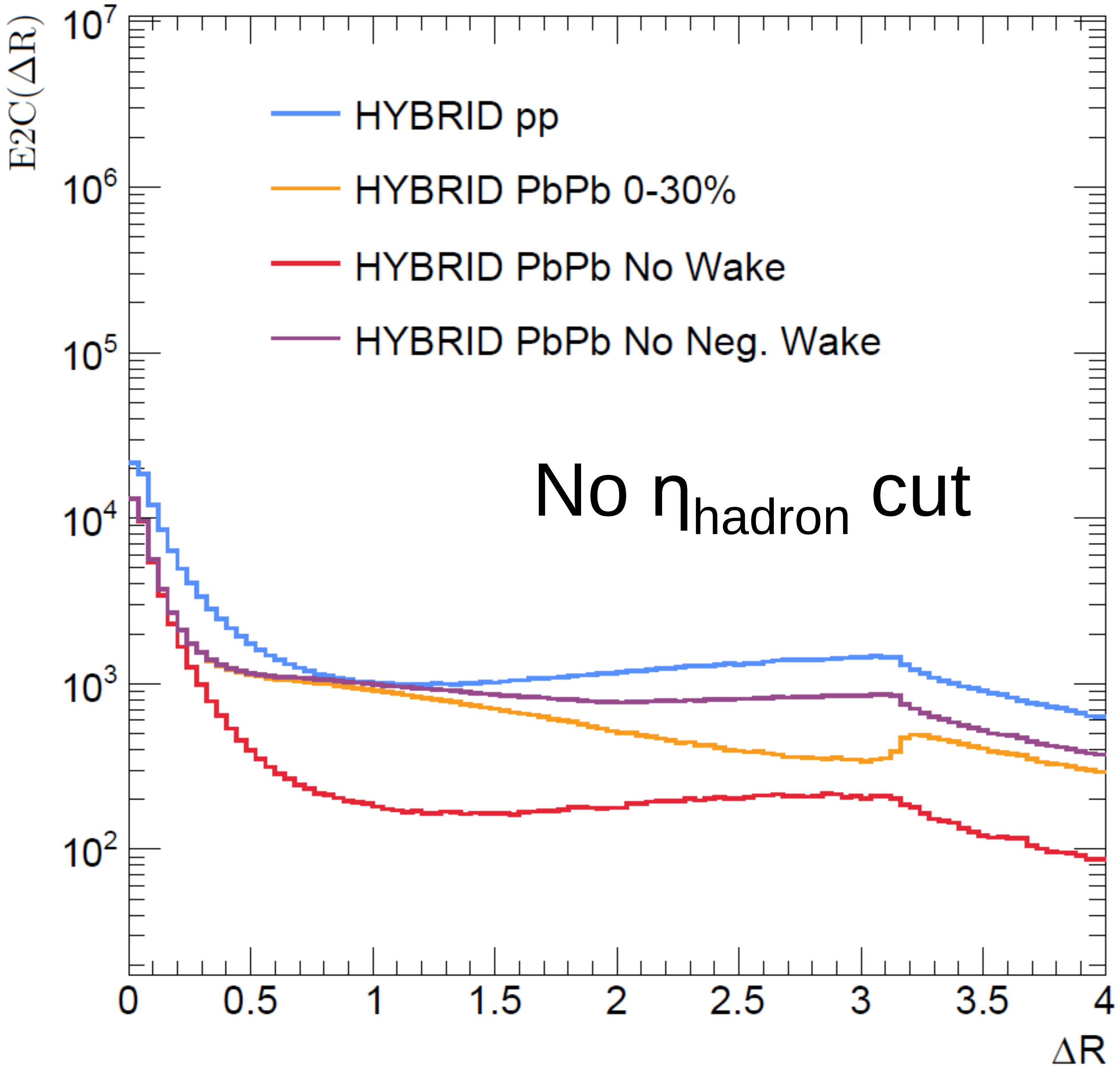
- Note that hole partons are not hadronized in this calculation

$$E2C(\Delta R) = \frac{1}{N_Z} \sum_{Z \in [p_T^Z > 40 GeV]} \sum_{\text{pairs } \Delta R_{i,j} \in \Delta R \text{ bin}} (w_i \, w_j \, p_{T,i} \, p_{T,j})$$

Yi Chen, YJL

Z-Tagged E2C in HYBRID Model (All Hadrons)

VERY preliminary results



Daniel Pablo, Krishna Rajagopal, Yi Chen, YJL

- At small ΔR, **PbPb 0-30%** is lower than **pp reference**

→ Jet Quenching

- **Shower only result (no Wake)** shows a larger suppression in the phase space ΔR> 0.1

→ There is a characteristic scale of the medium wake effect

- At ΔR=π, **PbPb 0-30%** shows a kink structure

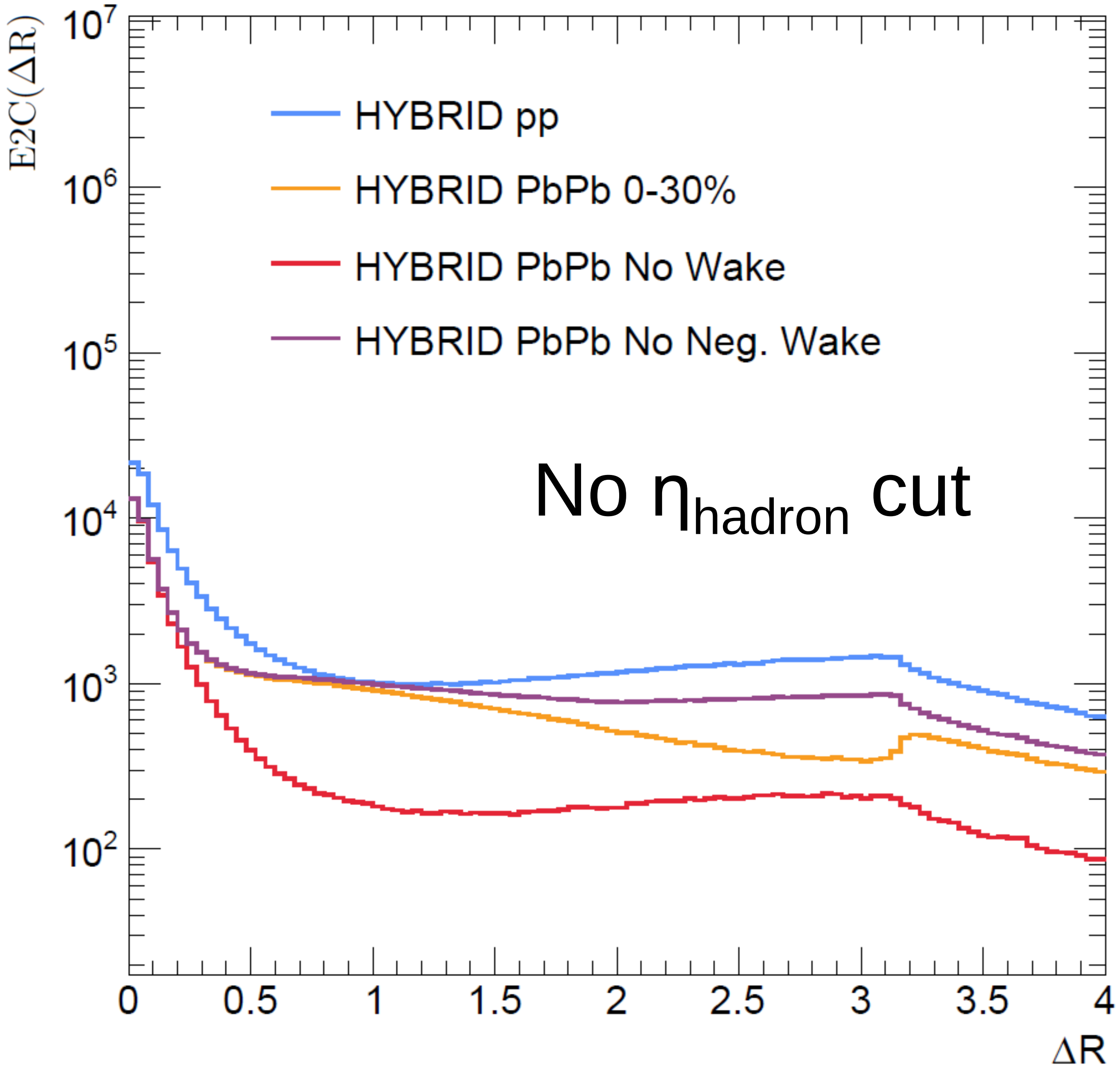
→ Associated with the angular scale between positive and negative wake contribution

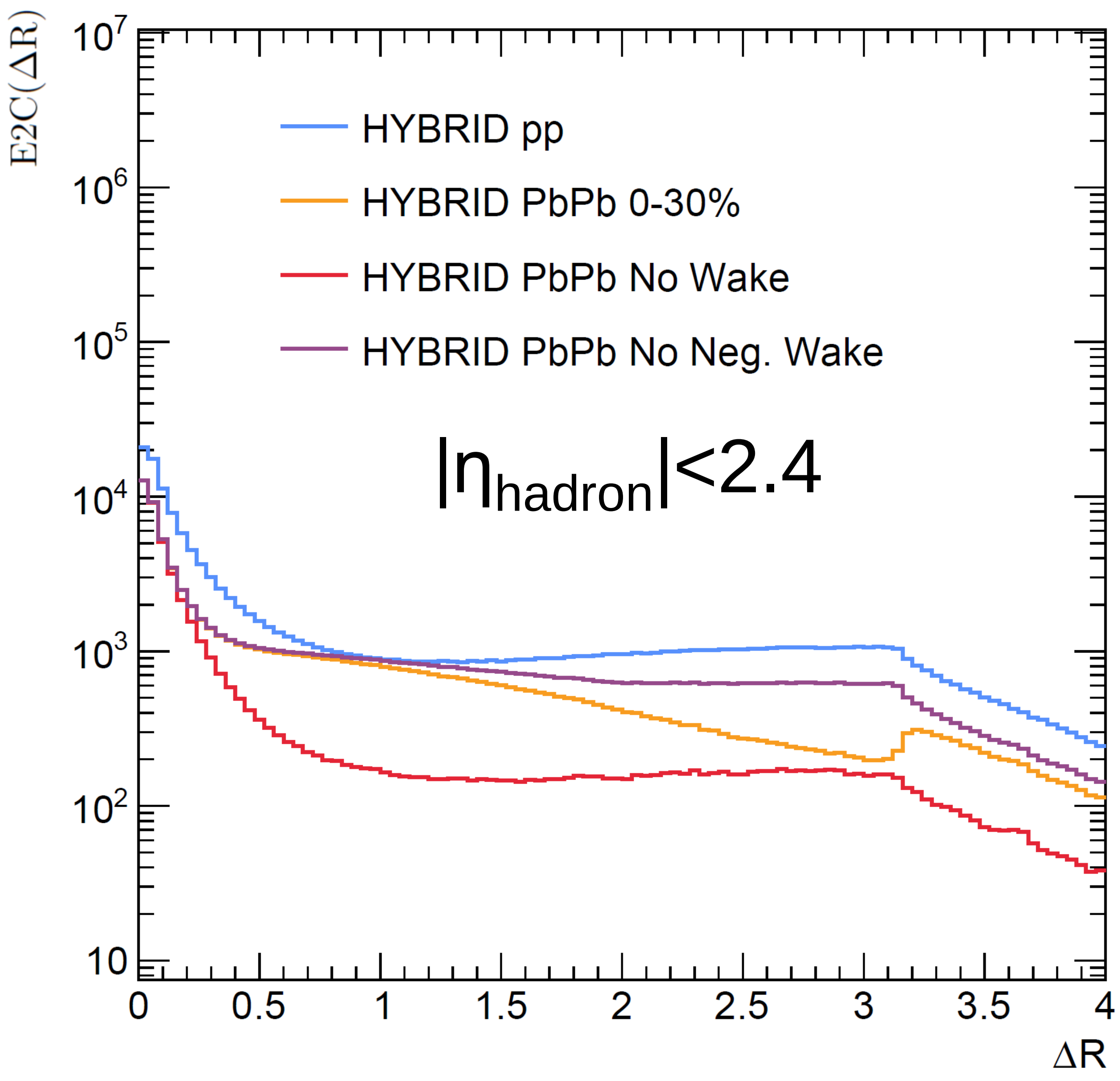
- **Without Negative wake**, the structure at ΔR=π is gone

$$E2C(\Delta R) = \frac{1}{N_Z} \sum_{Z \in [p_T^Z > 40 GeV]} \sum_{pairs\ \Delta R_{i,j} \in \Delta R\ bin} (w_i\, w_j\, p_{T,i}\, p_{T,j})$$

Z-Tagged E2C in HYBRID Model (All Hadrons)

VERY preliminary results



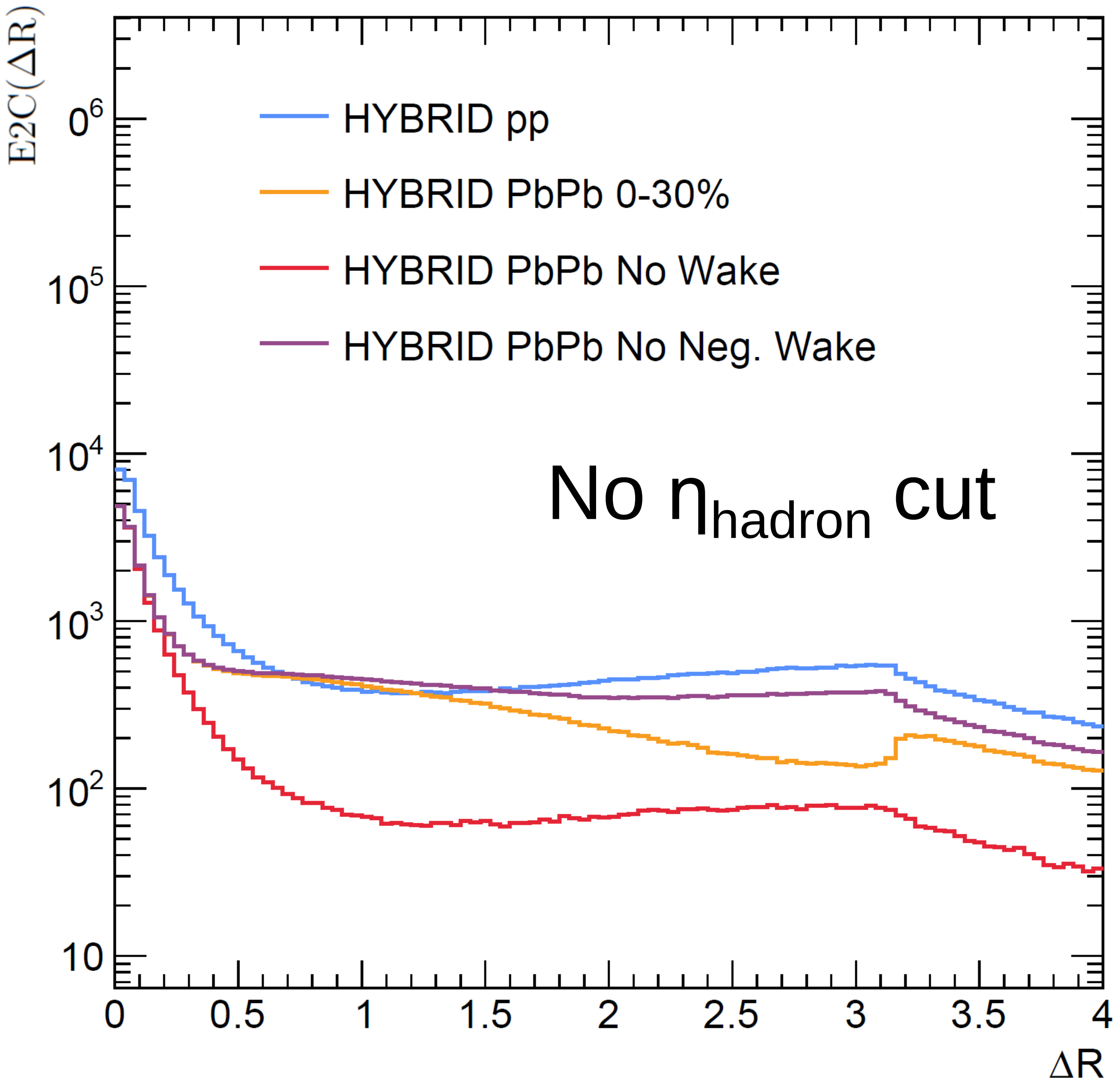


Daniel Pablo, Krishna Rajagopal, Yi Chen, YJL

CMS acceptance cut keep essential physics

Z-Tagged E2C in HYBRID Model (Charged Hadrons)

VERY preliminary results



Daniel Pablo, Krishna Rajagopal, Yi Chen, YJL

- Hybrid Model is fully hadronized

→ Results with charged hadrons only could be calculated

- E2C based on charged hadron keeps all the physics message with inclusive hadron
- Significantly simplify the experimental measurement and enable statistical subtraction with mixed event

$$E2C(\Delta R) = \frac{1}{N_Z} \sum_{Z \in [p_T^Z > 40\text{GeV}]} \sum_{\text{pairs } \Delta R_{i,j} \in \Delta R \text{ bin}} (w_i \, w_j \, p_{T,i} \, p_{T,j})$$