Massachusetts Institute of Technology

First measurement of the energy-energy correlator from the collinear to the back-to-back limit in e^+e^- collisions with ALEPH

Hannah Bossi (MIT)

TH Heavy Ion Coffee

CERN, Geneva, Switzerland

November 22nd, 2024

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

Intro: What type of physics do I do?

CMS

sPHENIX

א

Hard probes (Jets) in heavy-ion collisions

ML on FPGAs for fast triggering

Today: Re-analysis of archived data

…… + some phenomenological explorations

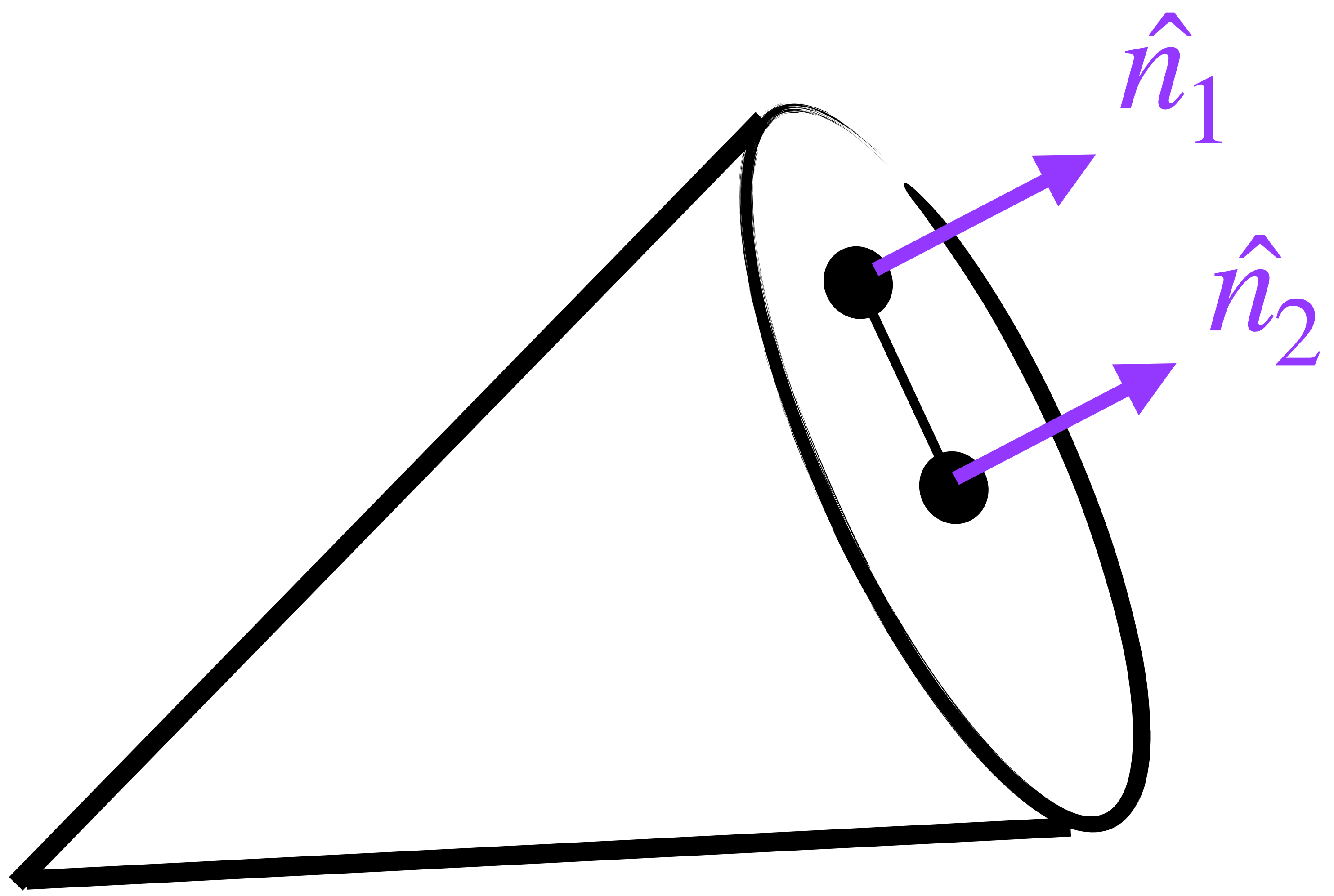
Main idea: I am not a theorist!

Energy Correlators

Energy flow in high-energy collisions can be characterized by energy correlators!

Define as the correlation of energy flow operator $\langle \Psi | \mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2)\cdots\mathscr{E}(\vec{n}_k) | \Psi \rangle$

where $\mathscr{E}(\vec{n}_1) = \lim_{r\to\infty} \int dt r^2 n_1^i T_{0i}(t, r\vec{n}_1)$



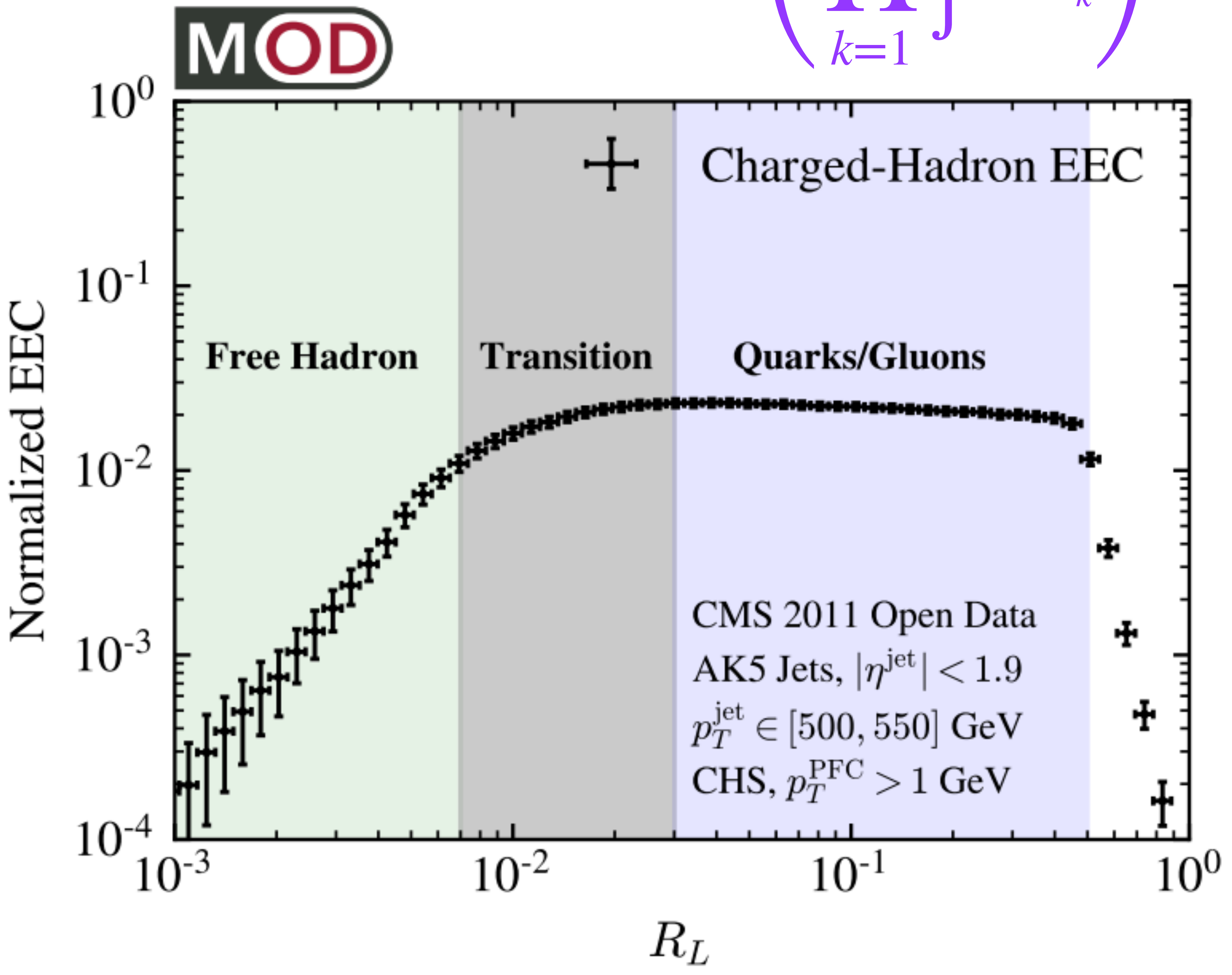
Characterizes the energy flux in the direction of $\hat{n}$

In hadron collider environments, instead of $\hat{n}_1$ use

$$\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$$

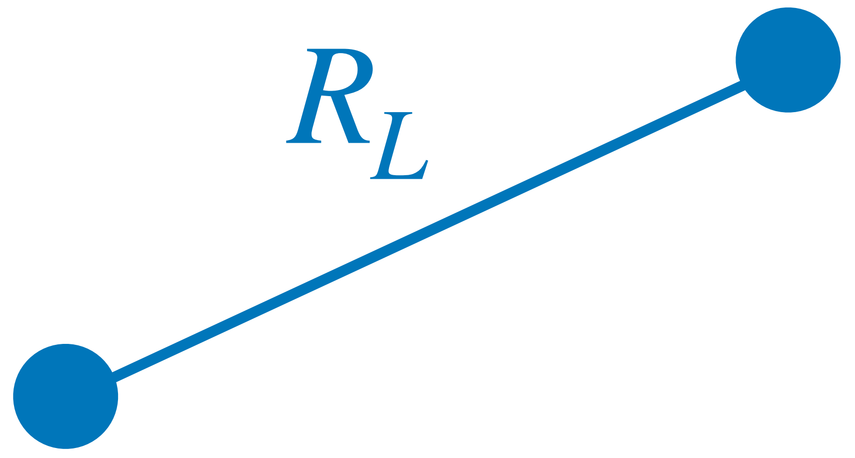
Projected N-point Correlators

$$\text{ENC}(R_L) = \left(\prod_{k=1}^{N}\int d\Omega_{\vec{n}_k}\right)\delta(R_L - \Delta\hat{R}_L)\cdot\frac{1}{(E_{\text{jet}})^{(n*N)}}\langle\mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\ldots\mathcal{E}^n(\vec{n}_N)\rangle$$



[PRL 130 (2023) 5, 051901]

- All shape information is integrated out, keep longest side R_L fixed

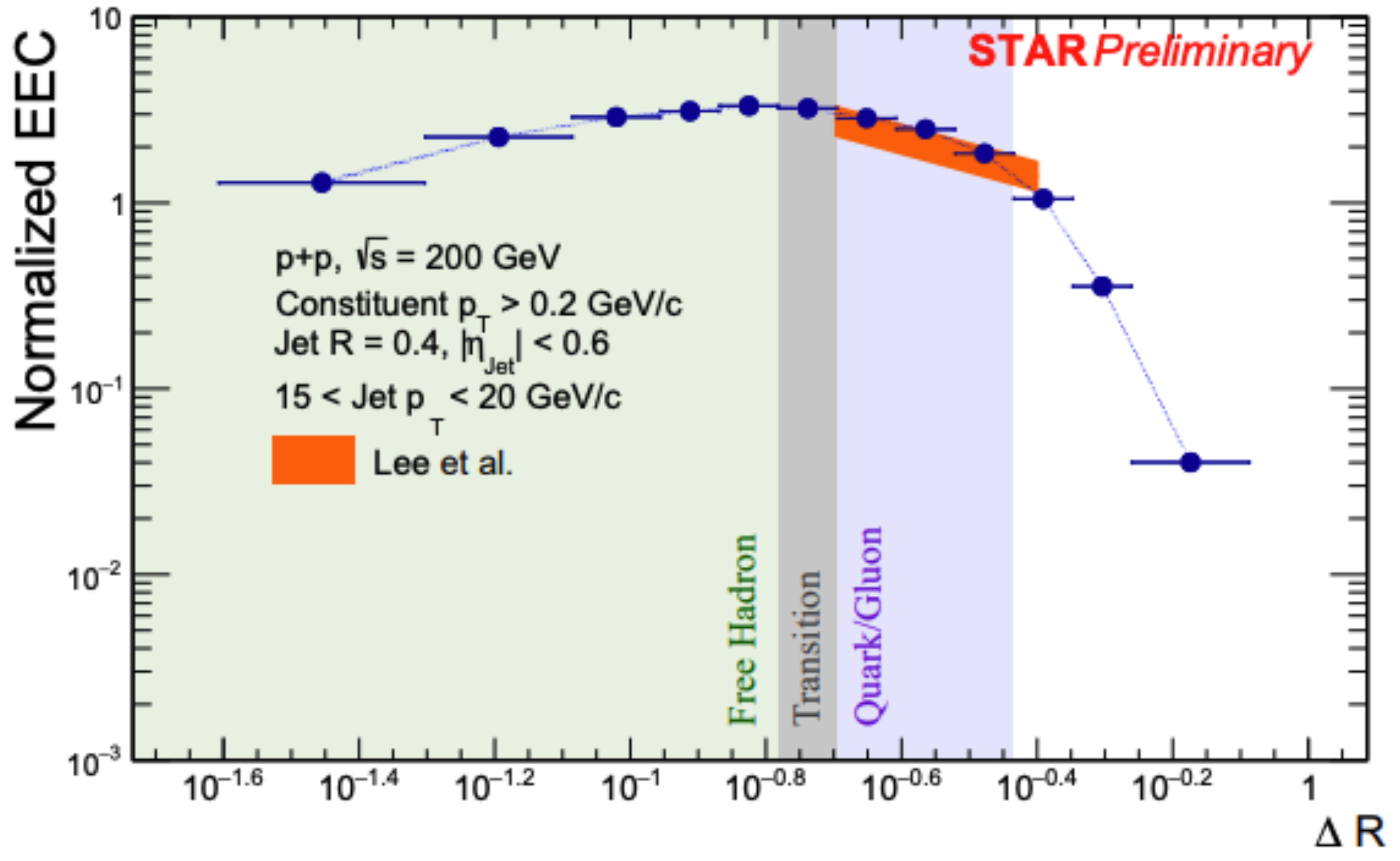


- ***Projected correlators are useful for isolating the scaling behavior!***

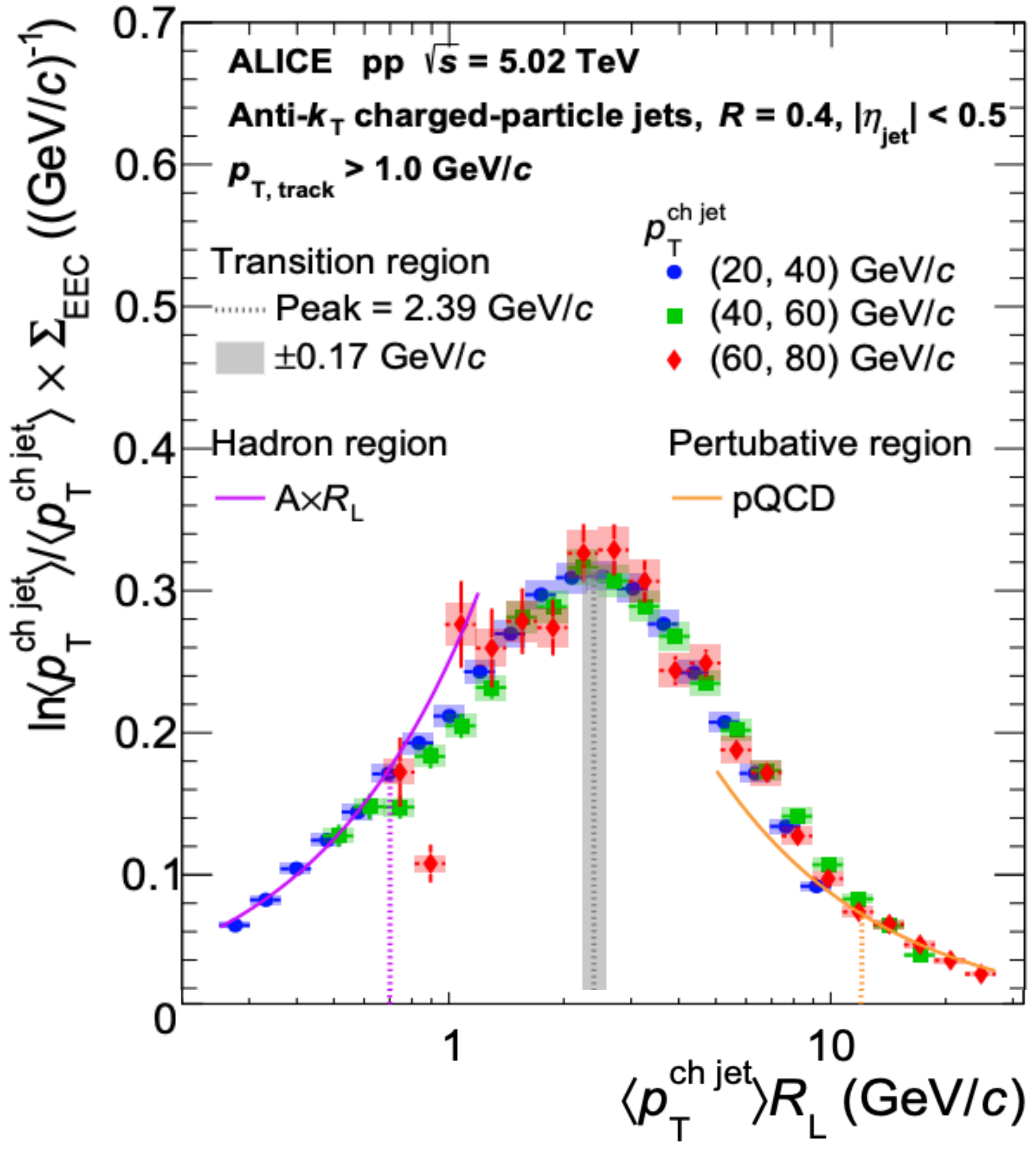
- Transition region happens roughly at $\Lambda_{\text{QCD}}/p_{\text{T,jet}}$

Measurements of E2Cs in pp collisions

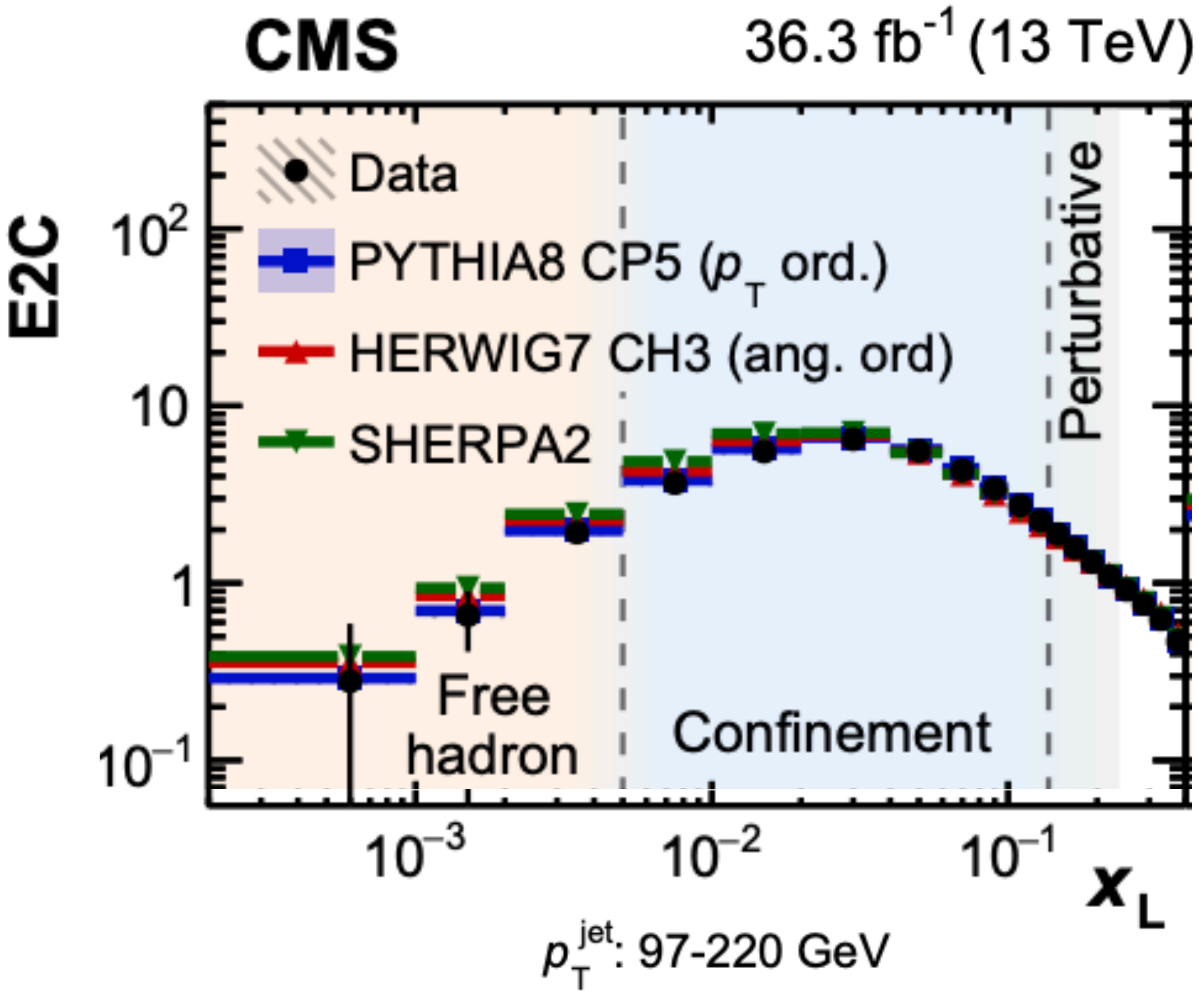
[arXiv:2309.05761]



[arXiv:2409.12687]



[PRL 133 (2024) 071903]

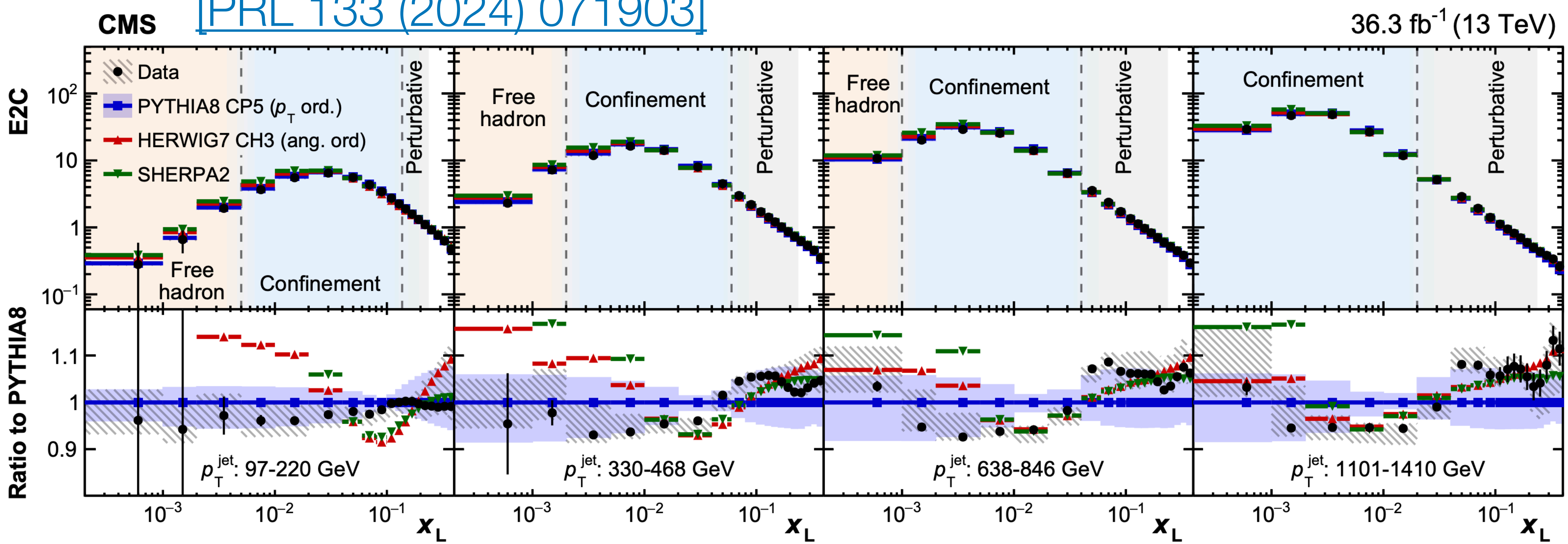


Increasing p_{T}

Transition region demonstrates remarkably universal behavior ($p_{\mathrm{T}}R_{\mathrm{L}} \sim 2-3$ GeV) across wide kinematic range from RHIC to the LHC!

EEC in pp comparisons to models

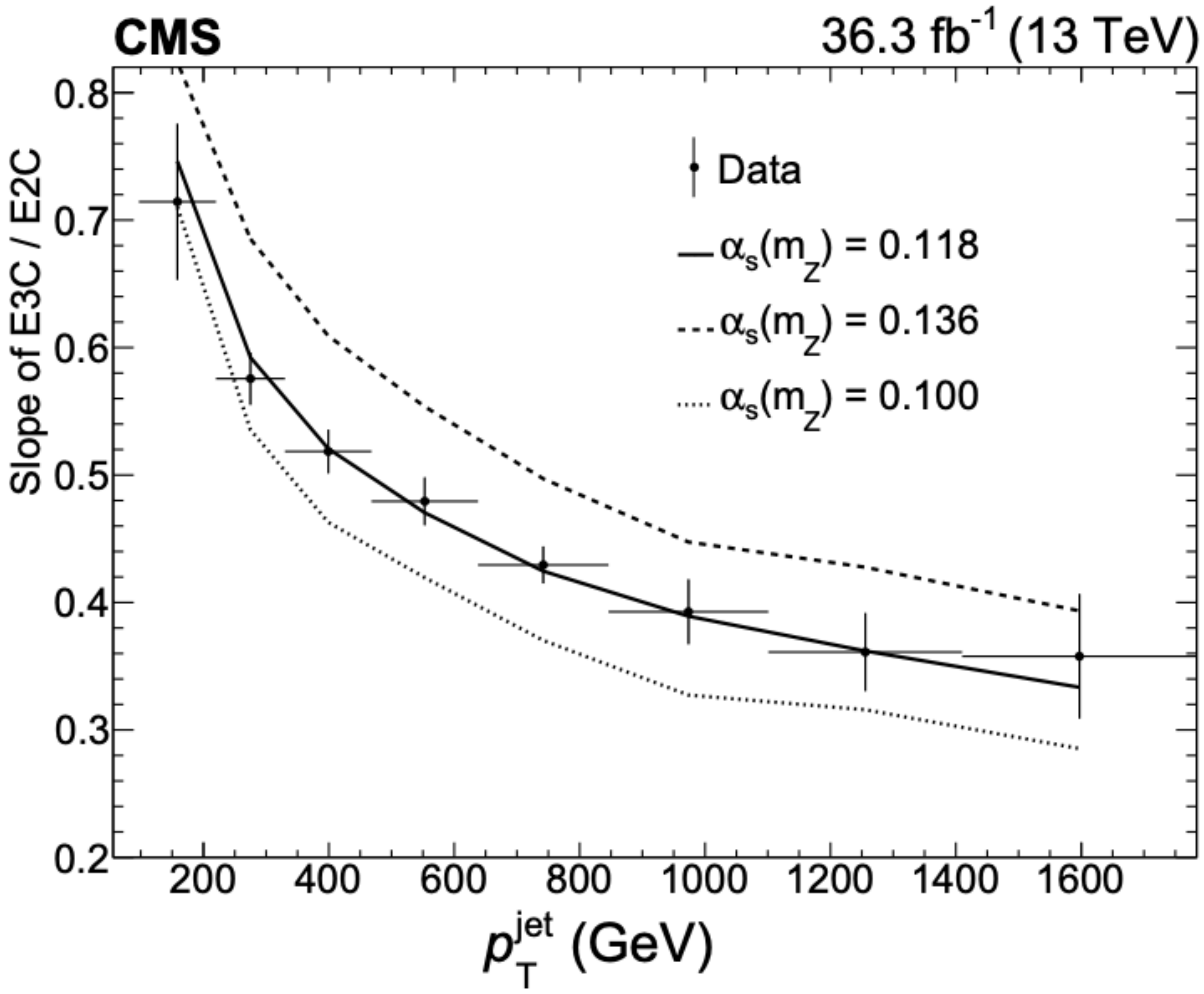
[PRL 133 (2024) 071903]



- Comparisons to PYTHIA 8, HERWIG, SHERPA with different settings.
- None of the generators fully describe the data across all measured regions of phase space.
  - Difference on the order of 10-20% level.
- **How can we understand these discrepancies with data? *(We'll get to this later)***

Extracting α_s

[PRL 133 (2024) 071903]

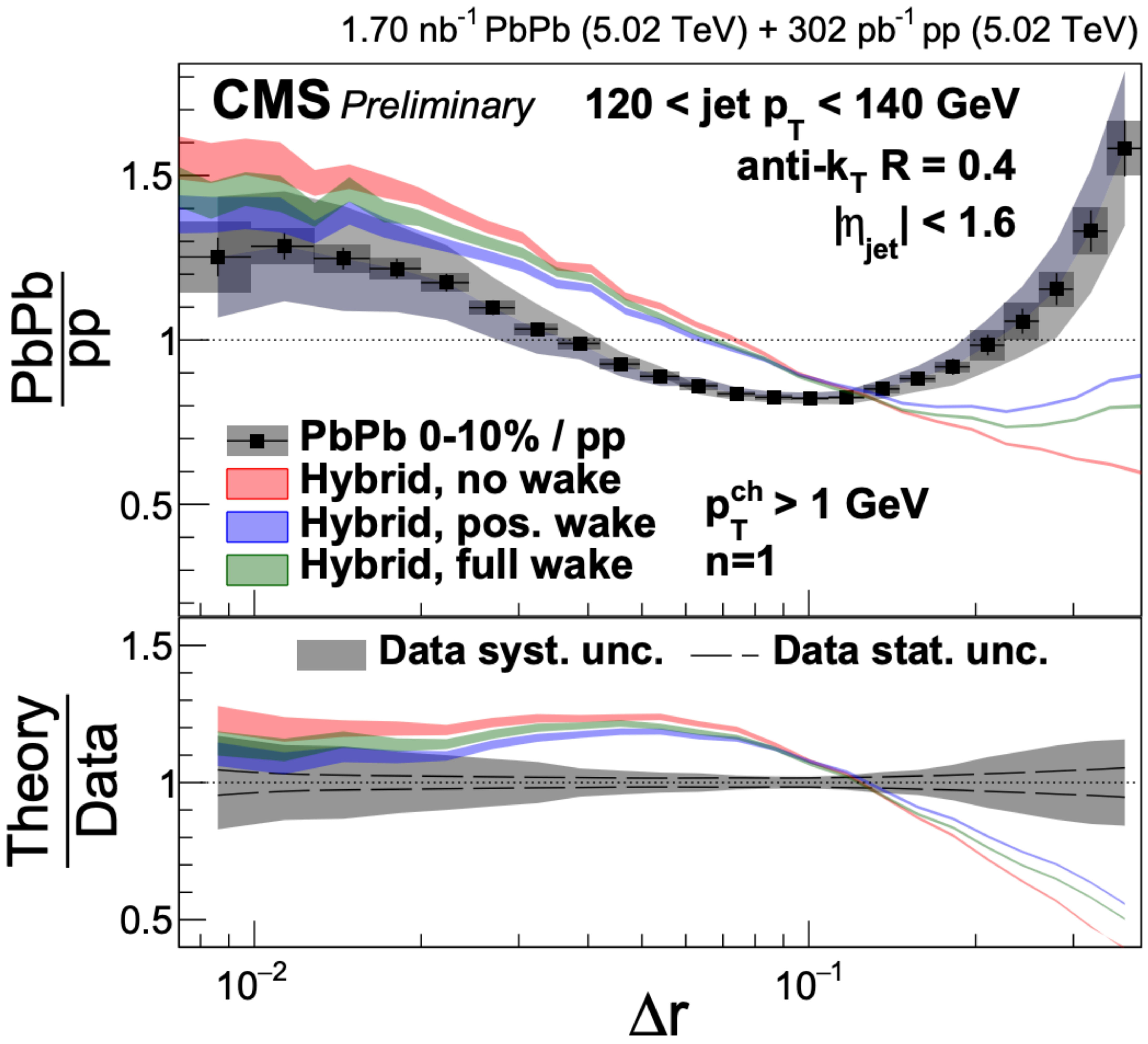


- Slope of the E3C/E2C ratio can be used in order to extract α_s [PRD 102, 054012 (2020)]
- Best fit value of $\alpha_s(m_Z)$ is $0.1229\,^{+0.0014}_{-0.0012}$(stat) $^{+0.0030}_{-0.0033}$(theo) $^{+0.0023}_{-0.0036}$(exp)
- Consistent with the world average of 0.1180 (see backup)

Most precise extraction of α_s from jet substructure to date!

EECs in heavy-ion collisions

[CMS-PAS-HIN-23-004]



- **First measurement of the EECs in heavy-ion collisions!**
- Peak position moves to the left in HIs due to jet quenching.
- Large enhancement at large Δr.
- Compared to many theoretical descriptions, hybrid model shown here (others in the backup). [JHEP 10 (2014) 019]

[See Jussi's talk at Hard Probes for more details!]

What else can we do with EECs?

Make precision measurements of “known” effects

Look for large qualitative signatures of relatively “unknown” effects

What else can we do with EECs?

Make precision measurements of “known” effects

Look for large qualitative signatures of relatively “unknown” effects

Check out arXiv:2407.13818 (to appear in JHEP) for one example of this approach!

Massachusetts Institute of Technology

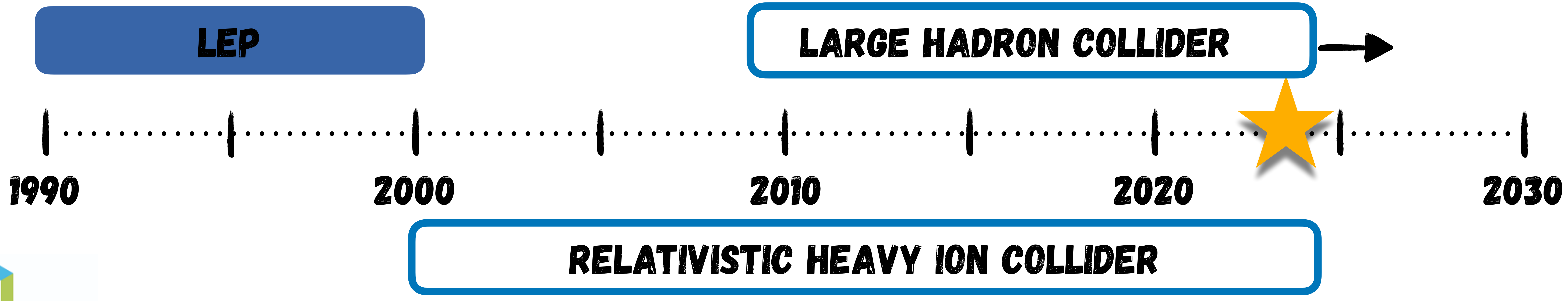
First measurement of fully-corrected E2C in e^+e^- LEP data

Work in collaboration with Janice Chen (MIT), Yi Chen (Vanderbilt) and Yen-Jie Lee (MIT)

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

Large Electron-Positron Collider

- This talk will focus on collider-based studies of QCD at LEP.

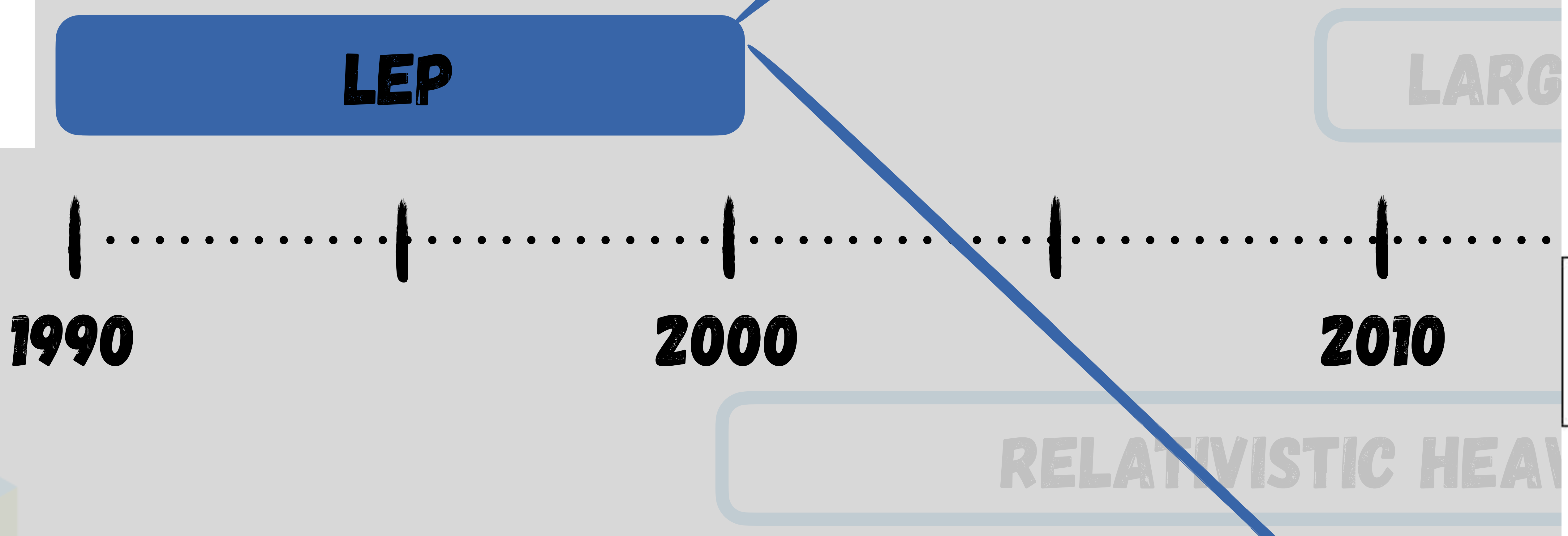


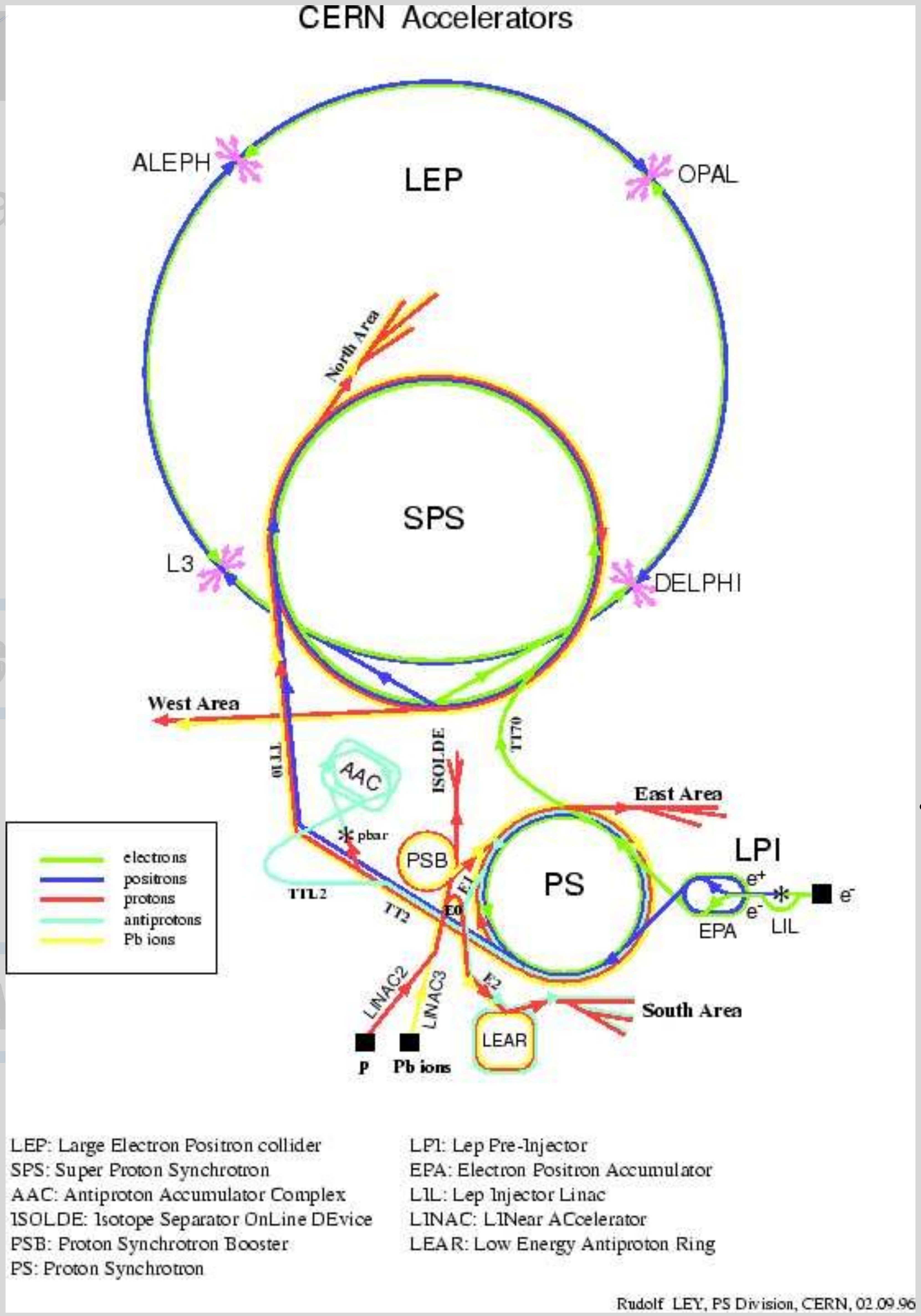
Electron-positron collider Hadron collider

[See full list of colliders at Wikipedia]

Large Electron-Positron Collider (1989 - 2000)

- **Experiments:** ALEPH, DELPHI, OPAL, L3





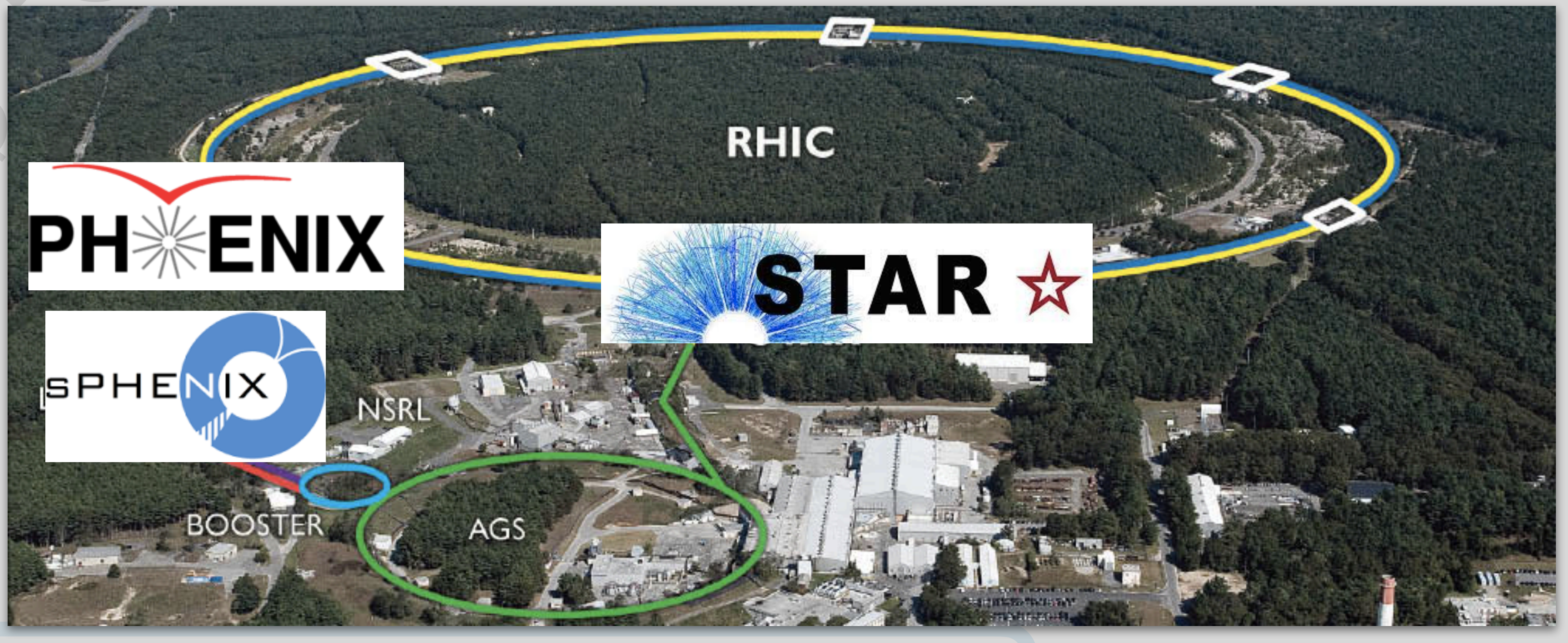
Variety of energies collected over the years!

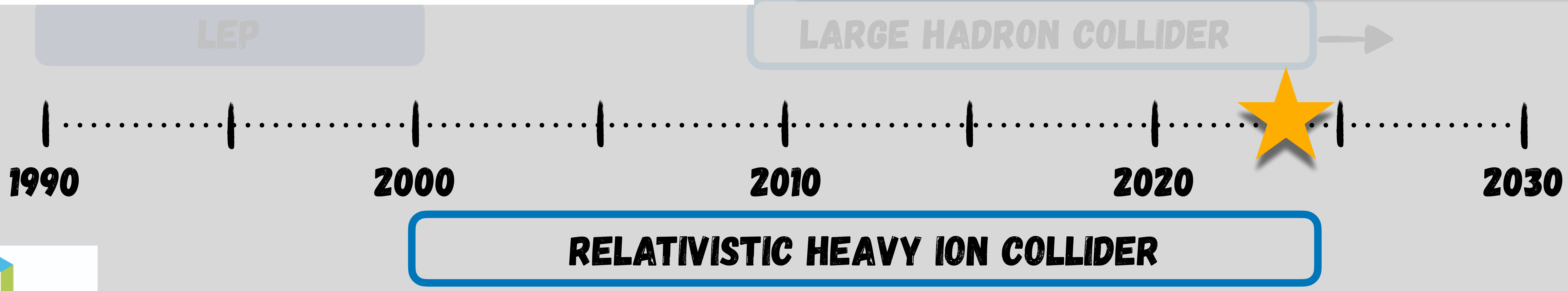
[See full list at Wikipedia]

Experimentally studying QCD

Relativistic Heavy Ion Collider (RHIC) (2000 - Present)

- Wide variety of species!
- PbPb at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV
- Future home of the EIC.



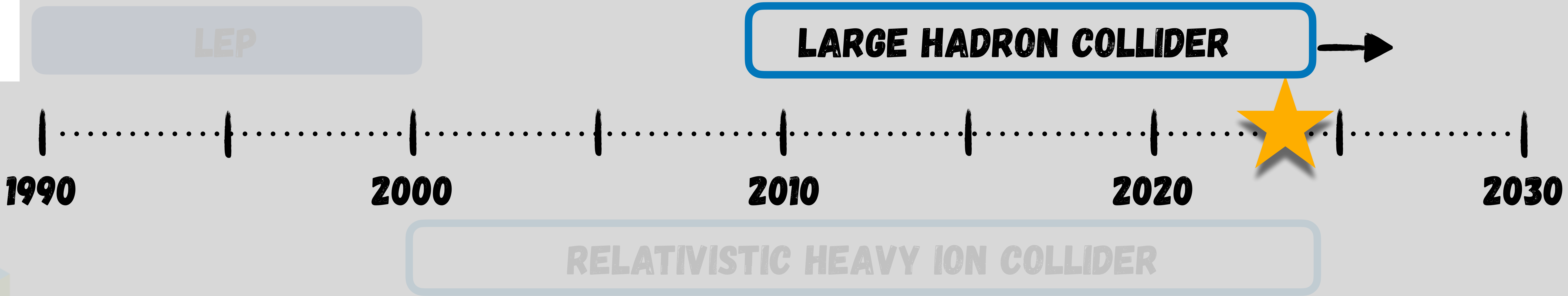


Brookhaven National Laboratory

[See full list at Wikipedia]

Exper... QCD

• This talk ... f QCD at two facilities.

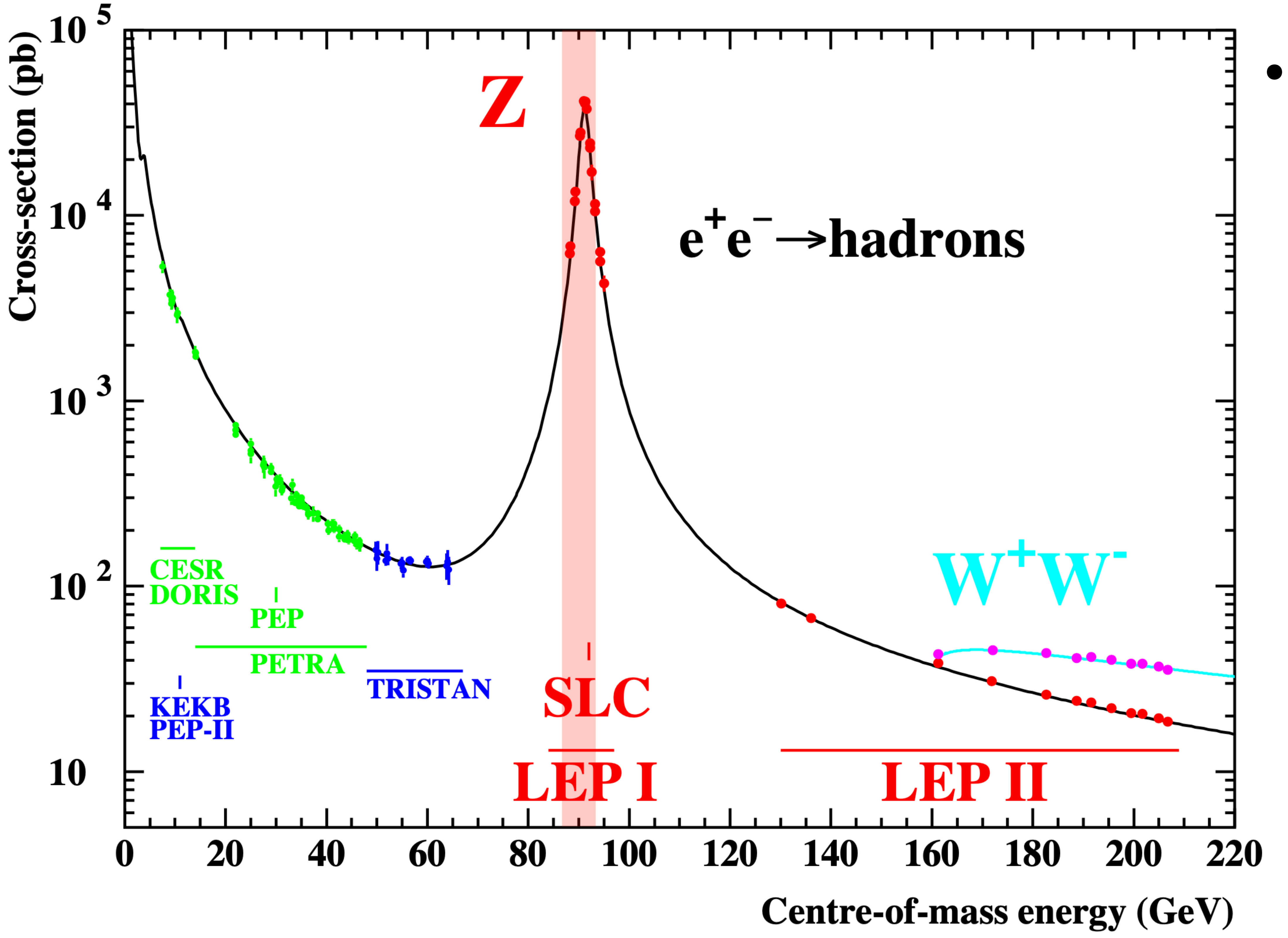


<u>Large Hadron Collider (2008 - Present)</u>

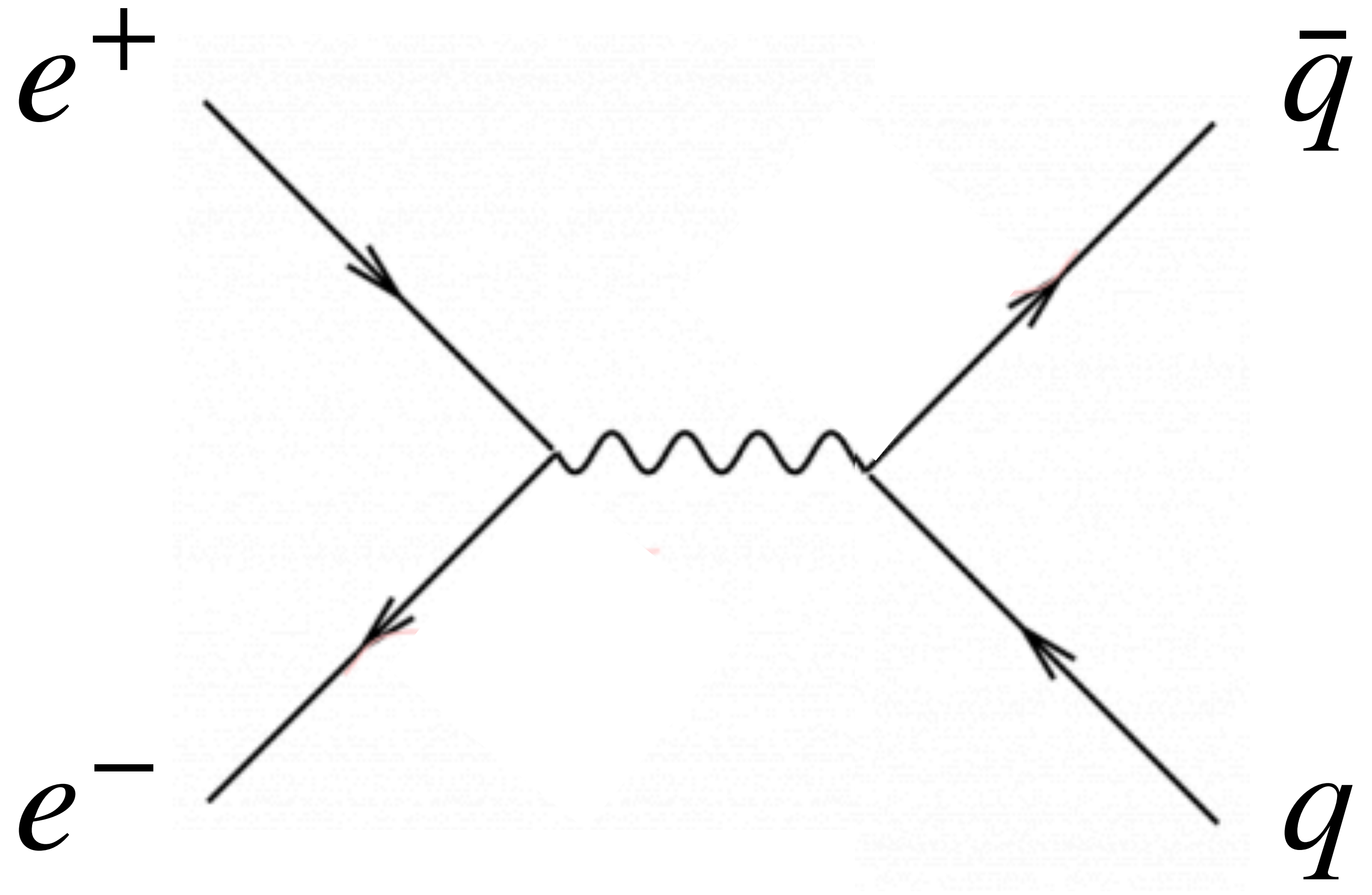
- Largest machine ever built by human hands
- Proton-Proton, Proton-Lead, Lead-Lead and Xenon-Xenon collisions

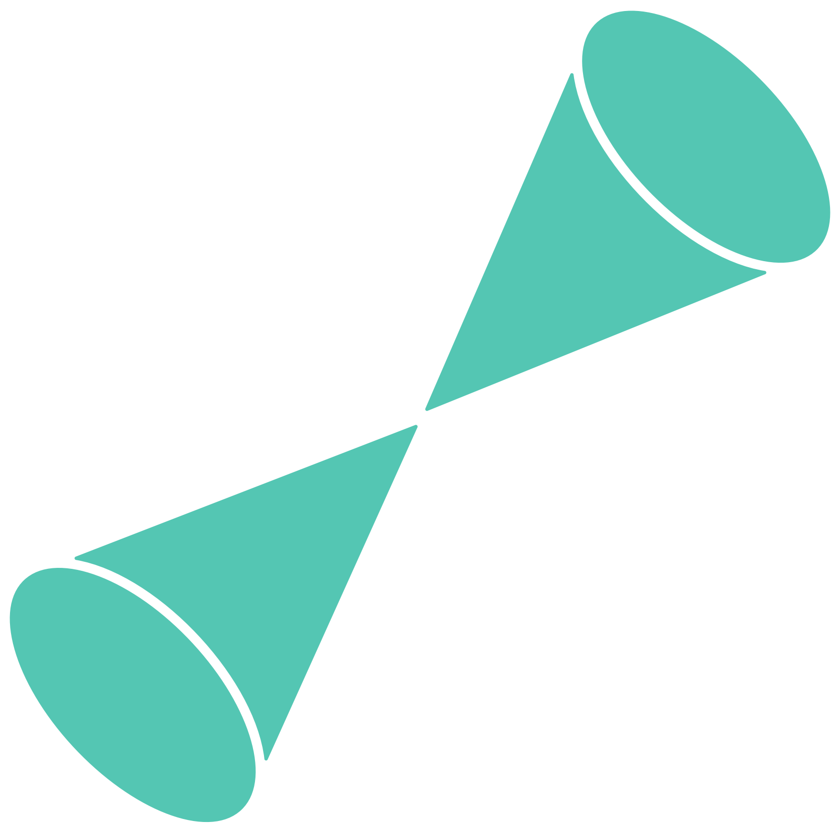
[See full list at Wikipedia]

LEP over the years



- **LEP 1:** data taken at 91.2 GeV from 1992 - 1995
  - Z-pole, $e^+e^- \rightarrow q\bar{q}$ dominant in hadronic data



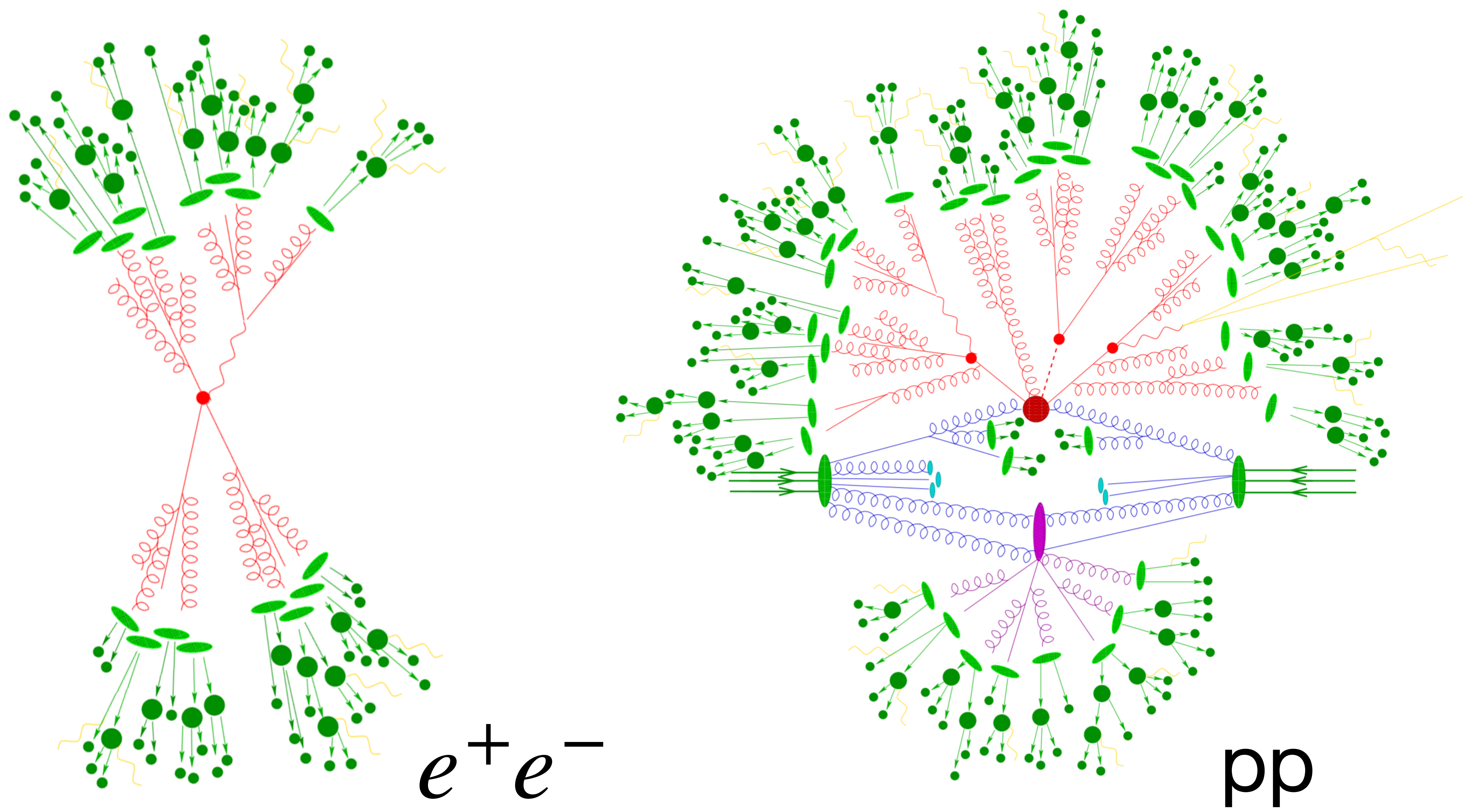


- **LEP 2:** data taken at higher energies ($\sqrt{s} - 183 - 209$ GeV)
  - $e^+e^- \rightarrow W^+W^- \rightarrow 4f$
  - W^+W^- dominates in the high-multiplicity hadronic data

Why LEP?

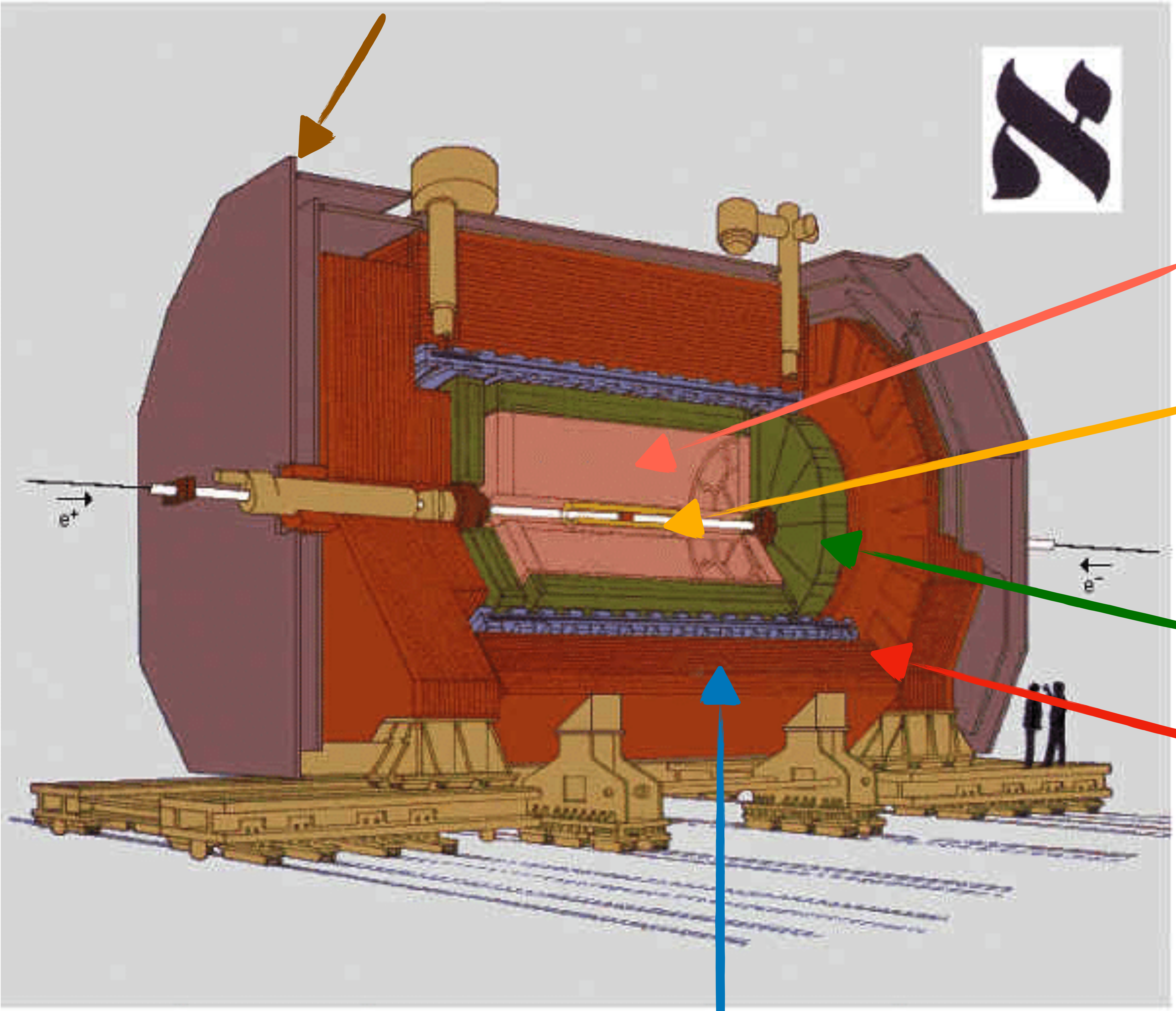
- Archived LEP data presents a great opportunity to understand these discrepancies and explore new parts of phase space! *Much cleaner environment!*
  - **Good background control**
    - No gluonic initial state radiation, no multi-parton interactions, negligible pileup.
  - **Structureless beam**
    - No complications of PDFs
    - Good final-state kinematic control.

Cleanest test of QCD and phenomenological models!



Apparatus for LEp PHysics (ALEPH)

Muon chambers



- ALEPH was located at IP4 of LEP.

Time projection chamber

Inner tracking chamber

Tracking

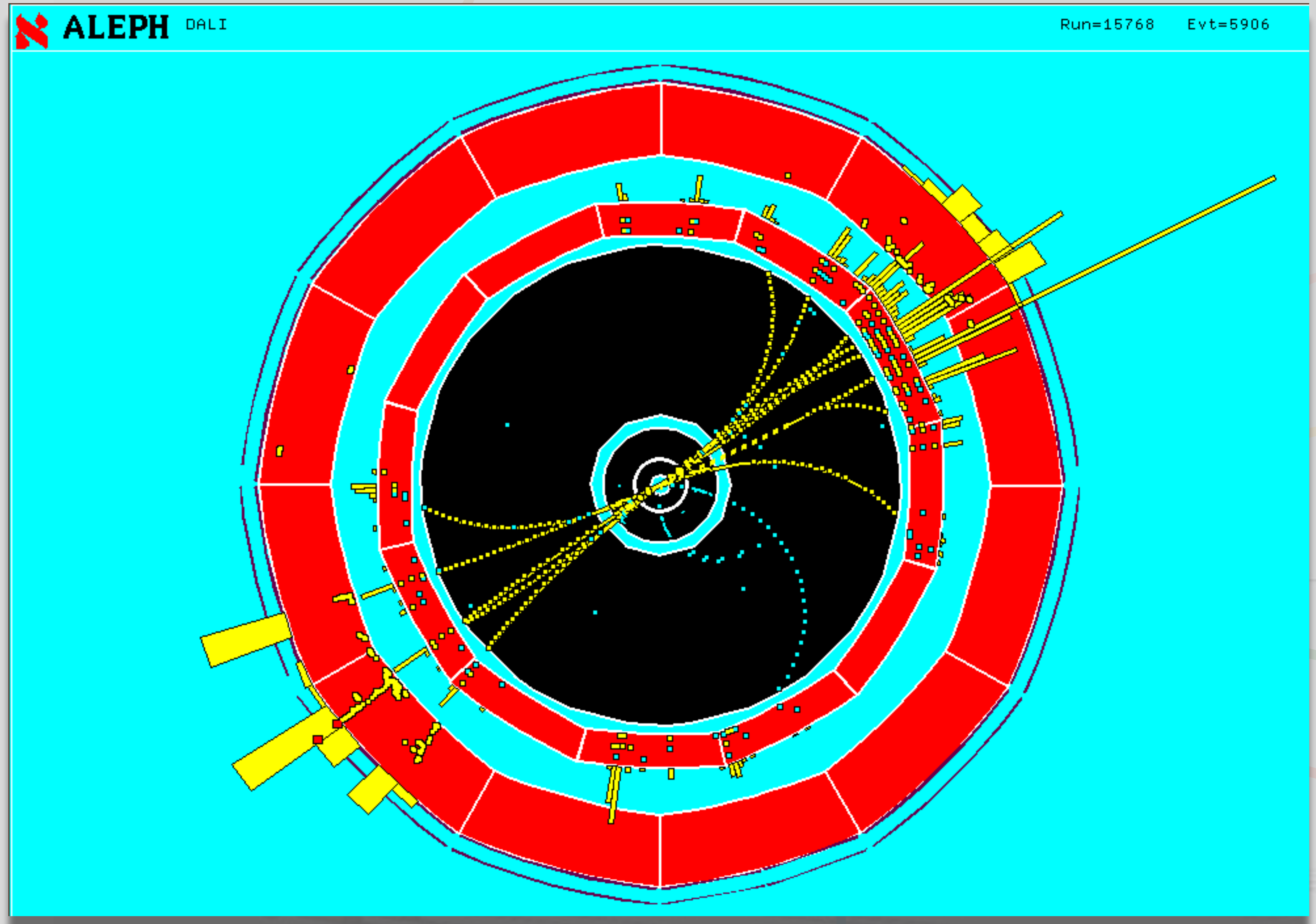
Electromagnetic Calorimeter

Hadron Calorimeter

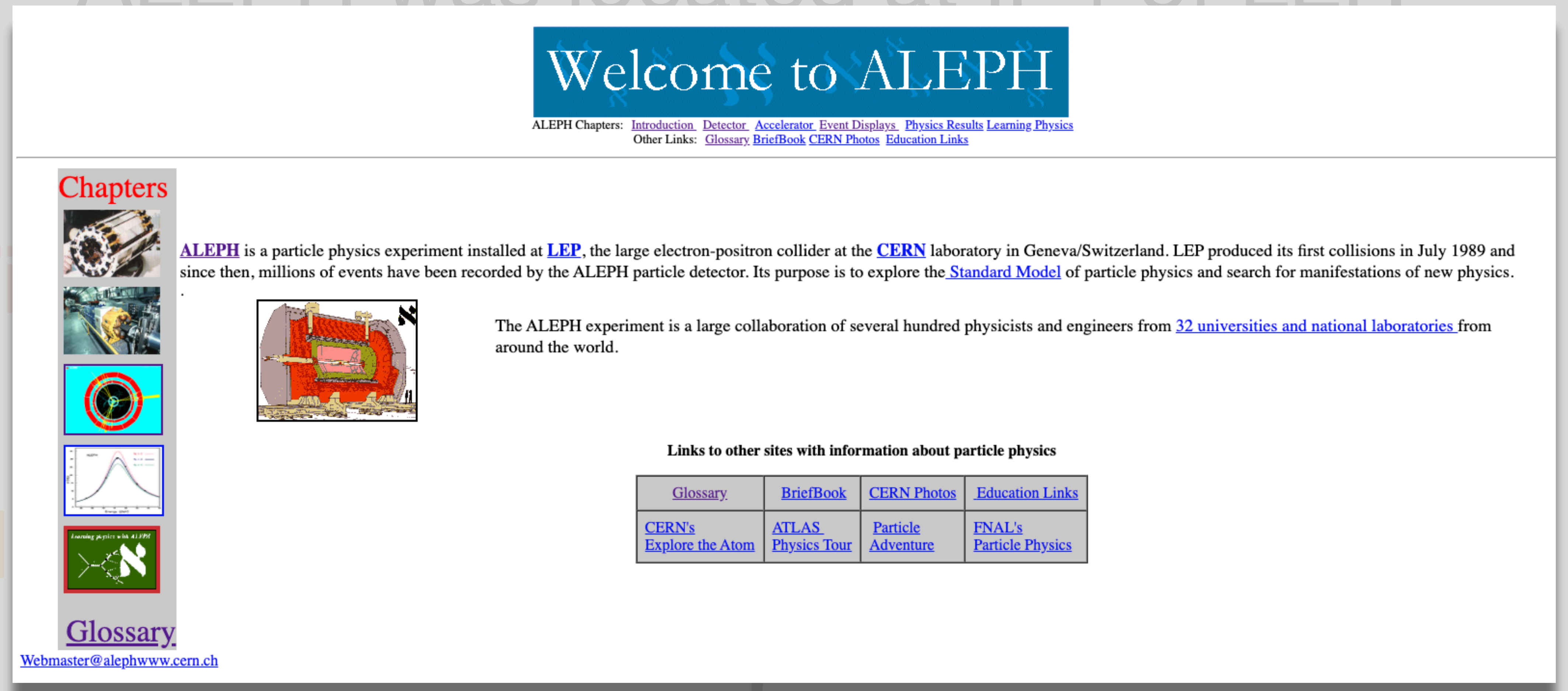
Calorimetry

Superconducting Magnet (1.5 T)

Apparatus for LEp PHysics (ALEPH)



Z-boson decay into hadrons



ALEPH Website

Strong motivation to reanalyze and reimagine old data with new experimental tools (ex: jet reco)

But many things outdated - how did we go about this???

ALEPH Archived Data

FEB 2017

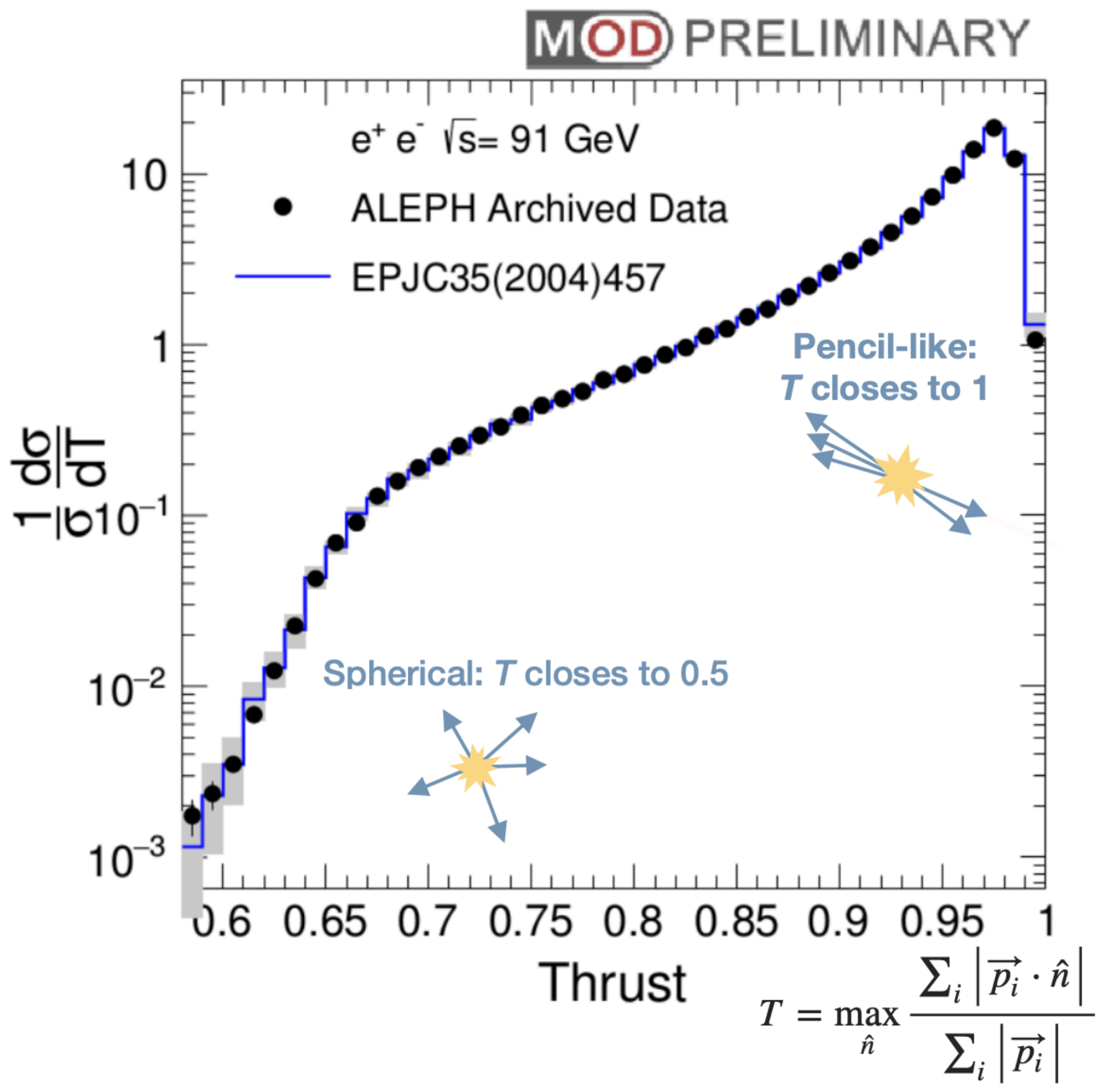
- Yen-Jie Lee (MIT) contacted Gigi Rolandi and Roberto Technici about the use of archived data and PYTHIA 6 MC w/ detector simulation.
  - Marcello Maggi also helped extract energy flow information.
  - Guenther Dissertori provided analysis code for QCD paper.

THANK YOU

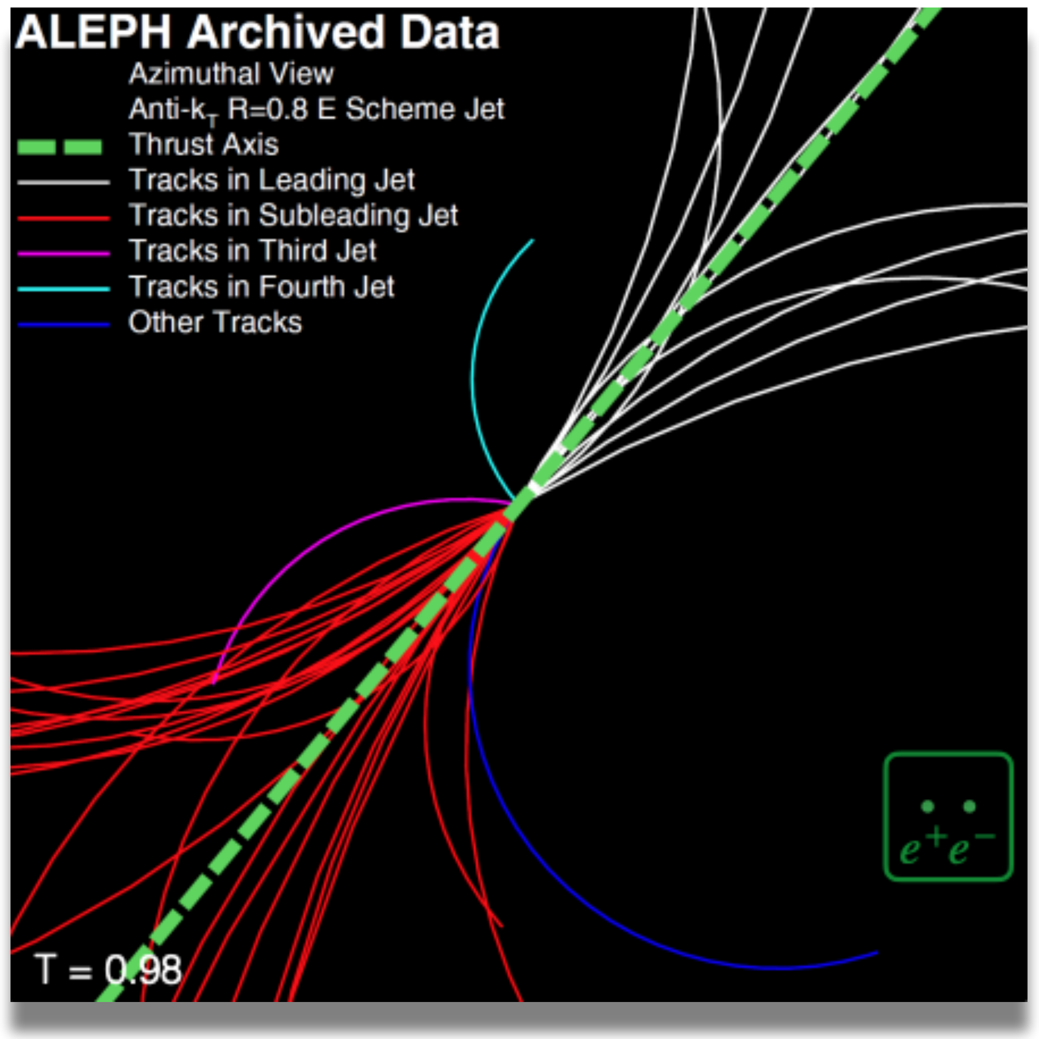
MID 2017

- All samples converted to MIT Open data format MOD

MAR 2018

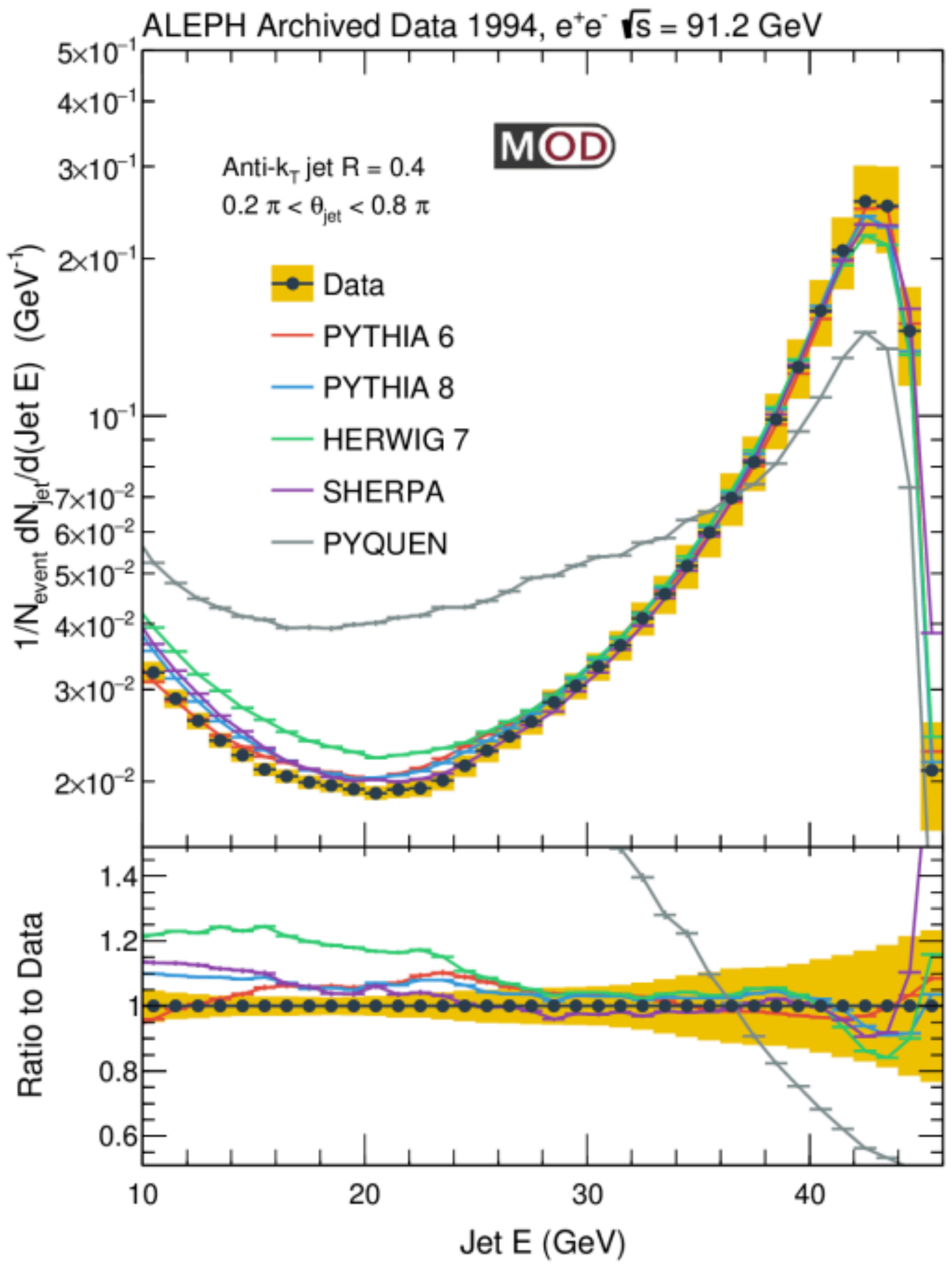


- Successfully reproduced corrected thrust distribution from 2004, validating archival.



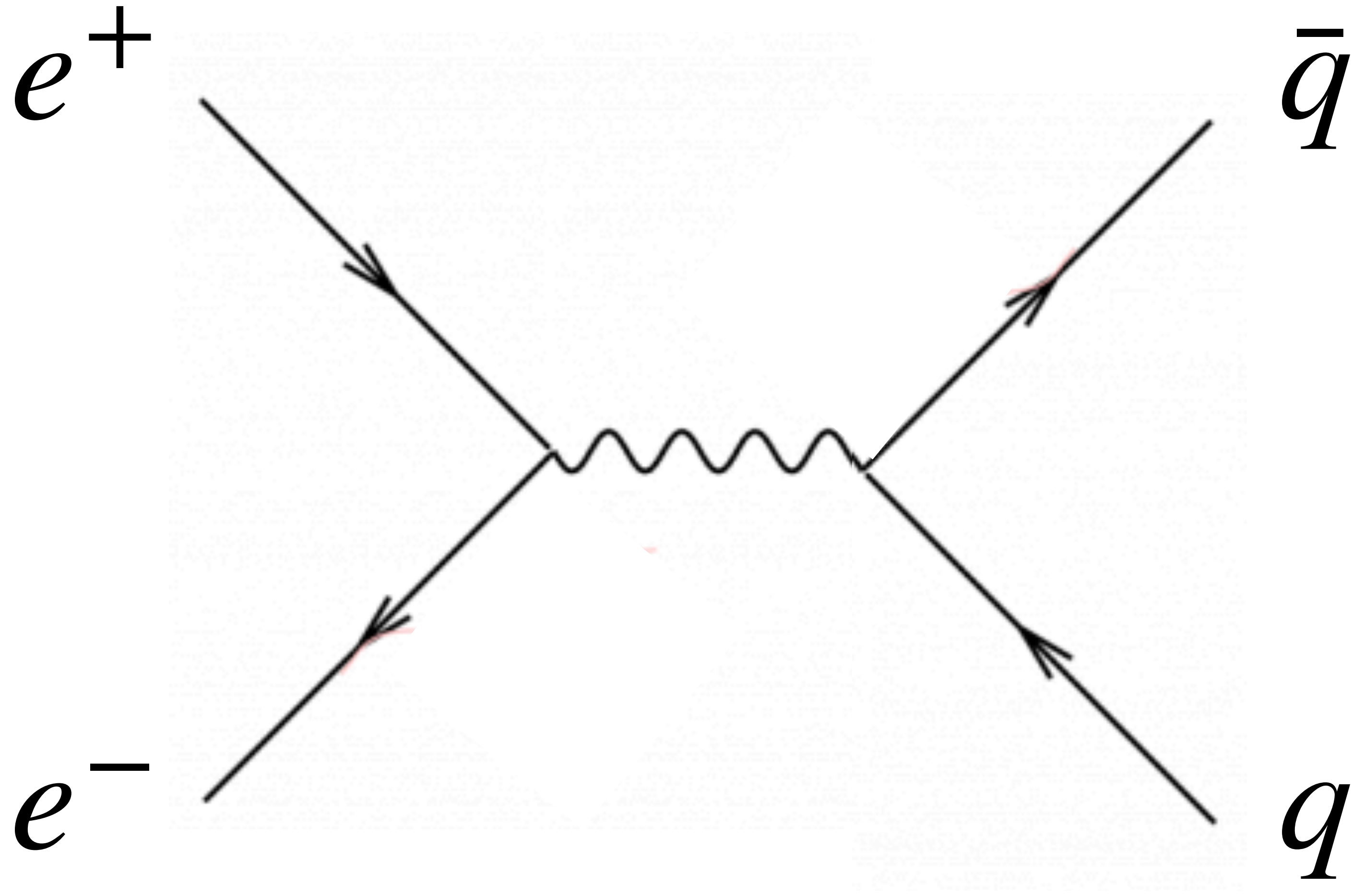
Gold mine for new re-analysis with new tools and techniques!

What has been done so far?



[JHEP 06 (2022) 008]

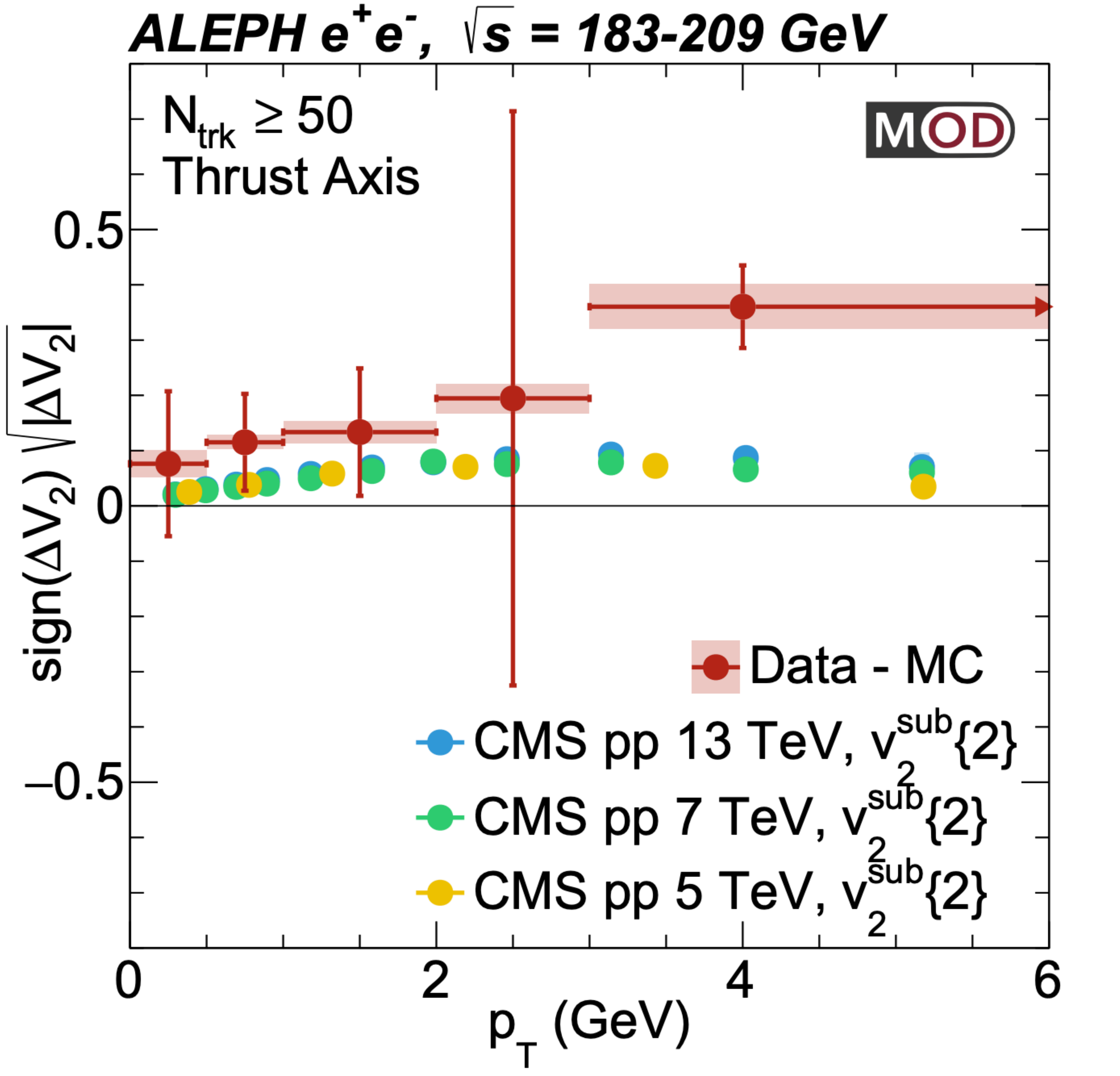
- Measure jet spectra and jet substructure at 91.2 GeV



- Peak around 43 GeV, meaning that a majority of the shower is captured by an R = 0.4 anti-k_T jet.

- Generally good description with models, some deviations at lower jet E.

What has been done so far?



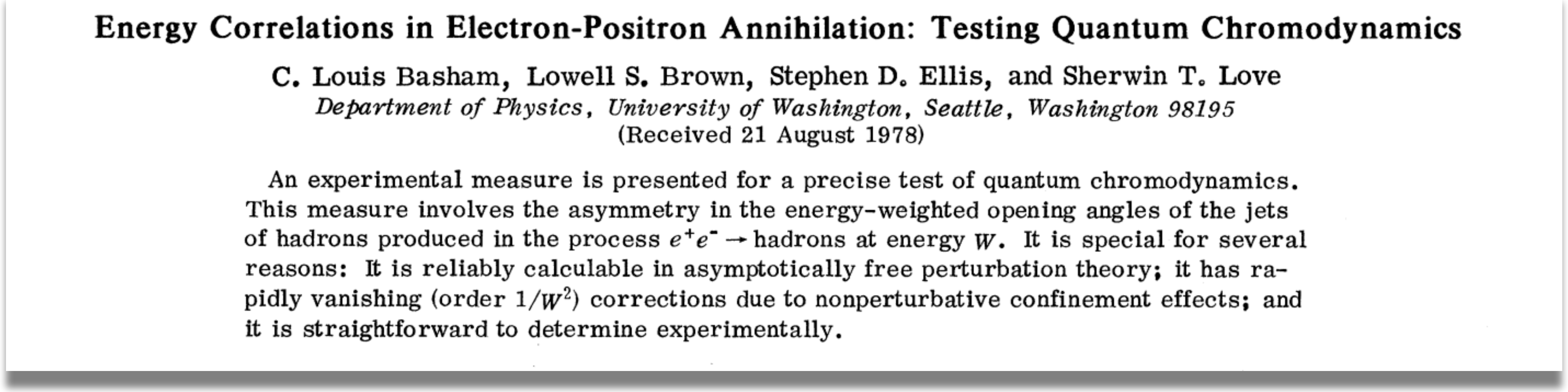
[Phys.Lett.B 856 (2024) 138957]

- Measurement of long-range near-side correlations in e^+e^- data from LEP 2.

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

- v_2(data) − v_2(MC)
- Excess observed in the high multiplicity interval ($N_{\mathrm{trk}} \geq 50$) not seen in the MC.

History of EECs in e^+e^-


Energy Correlations in Electron-Positron Annihilation: Testing Quantum Chromodynamics

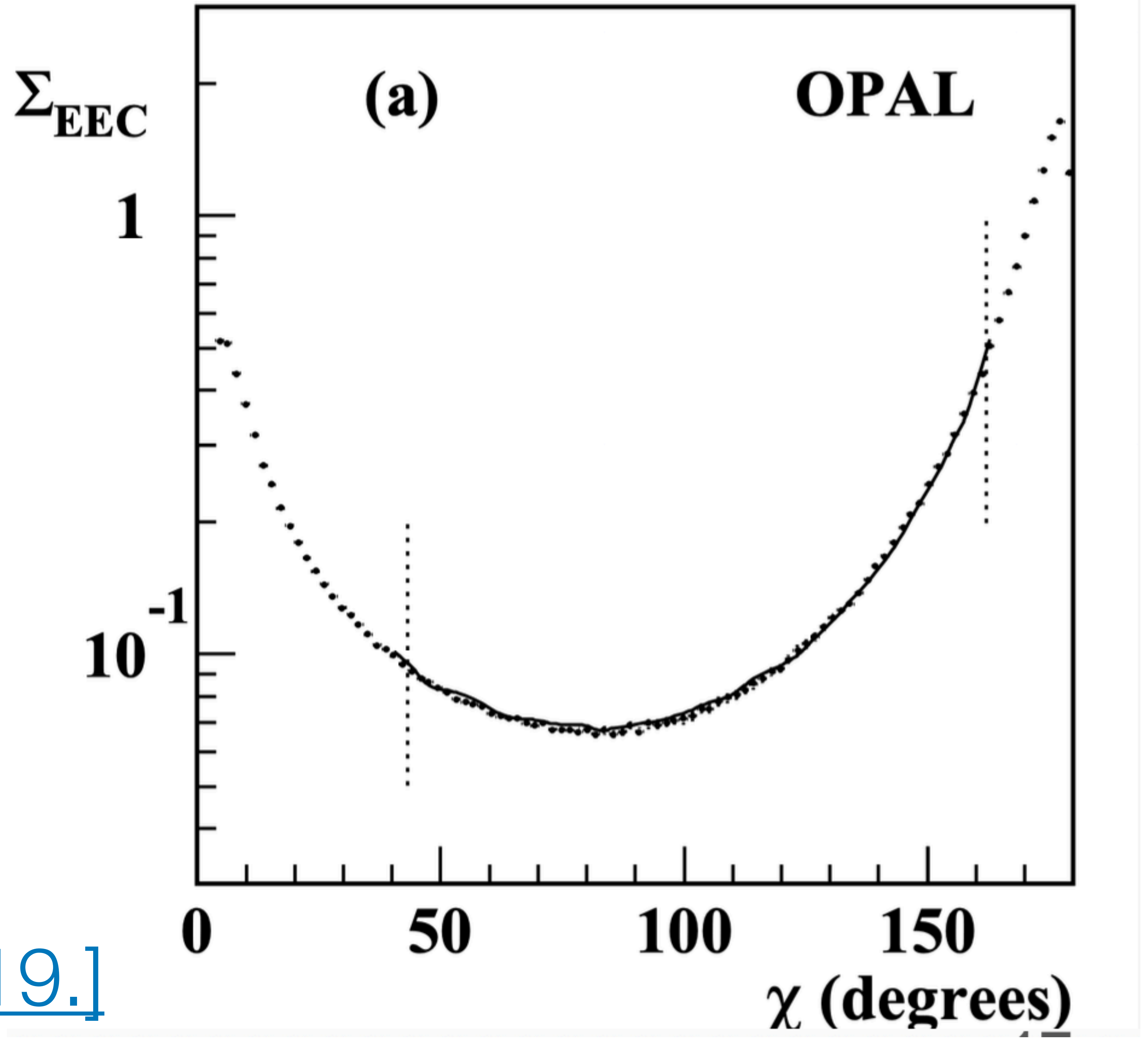
C. Louis Basham, Lowell S. Brown, Stephen D. Ellis, and Sherwin T. Love
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 21 August 1978)

An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process $e^+e^- \to$ hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order $1/W^2$) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

- Not a new idea theorists worked on this long ago!

[PRL 41, 1585 (1978)]

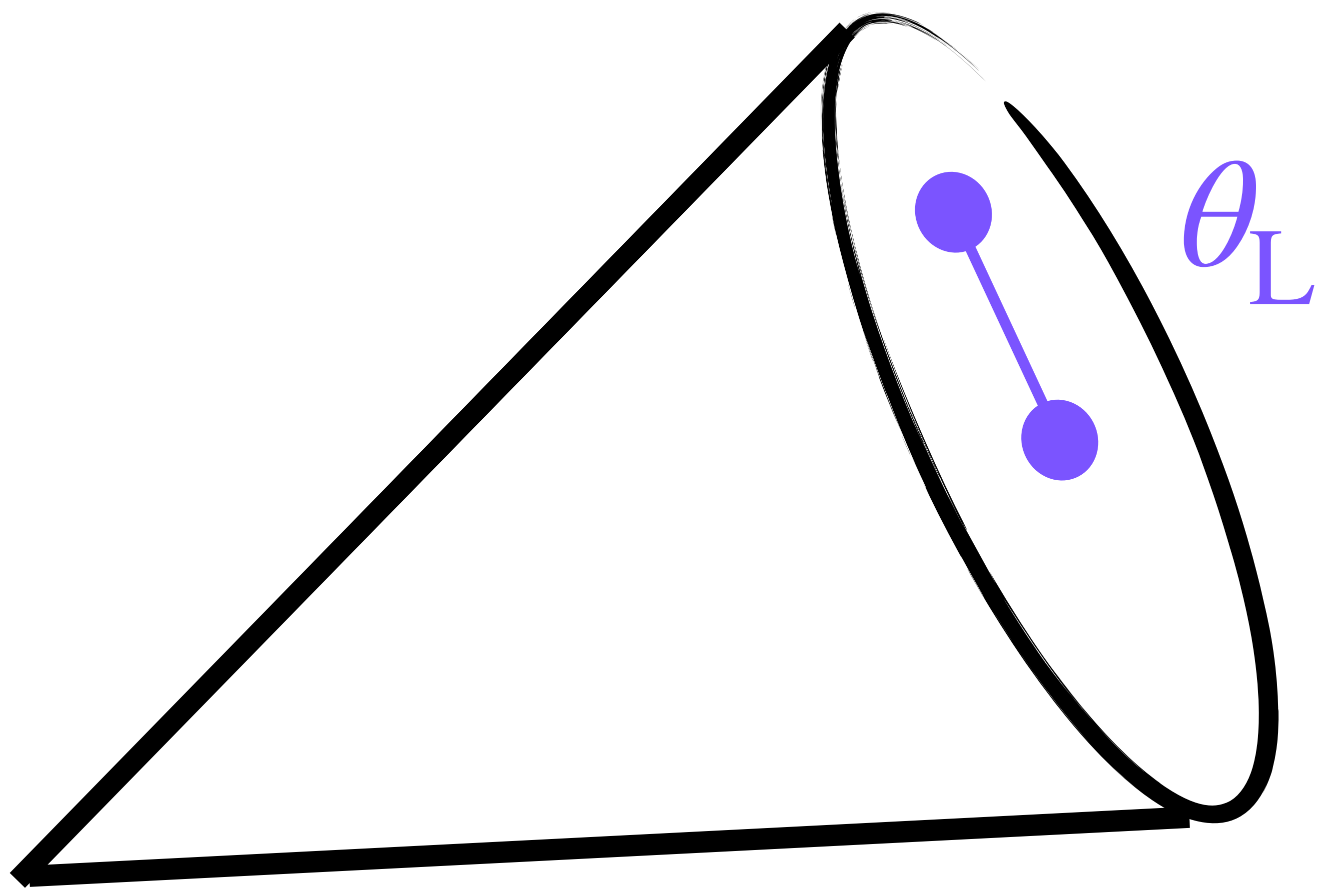
- Not new for experimentalists either!
- Measured in OPAL data
  - Only a bin-by-bin correction (no advanced unfolding)
  - with limited binning (especially in the small and large angle regions).



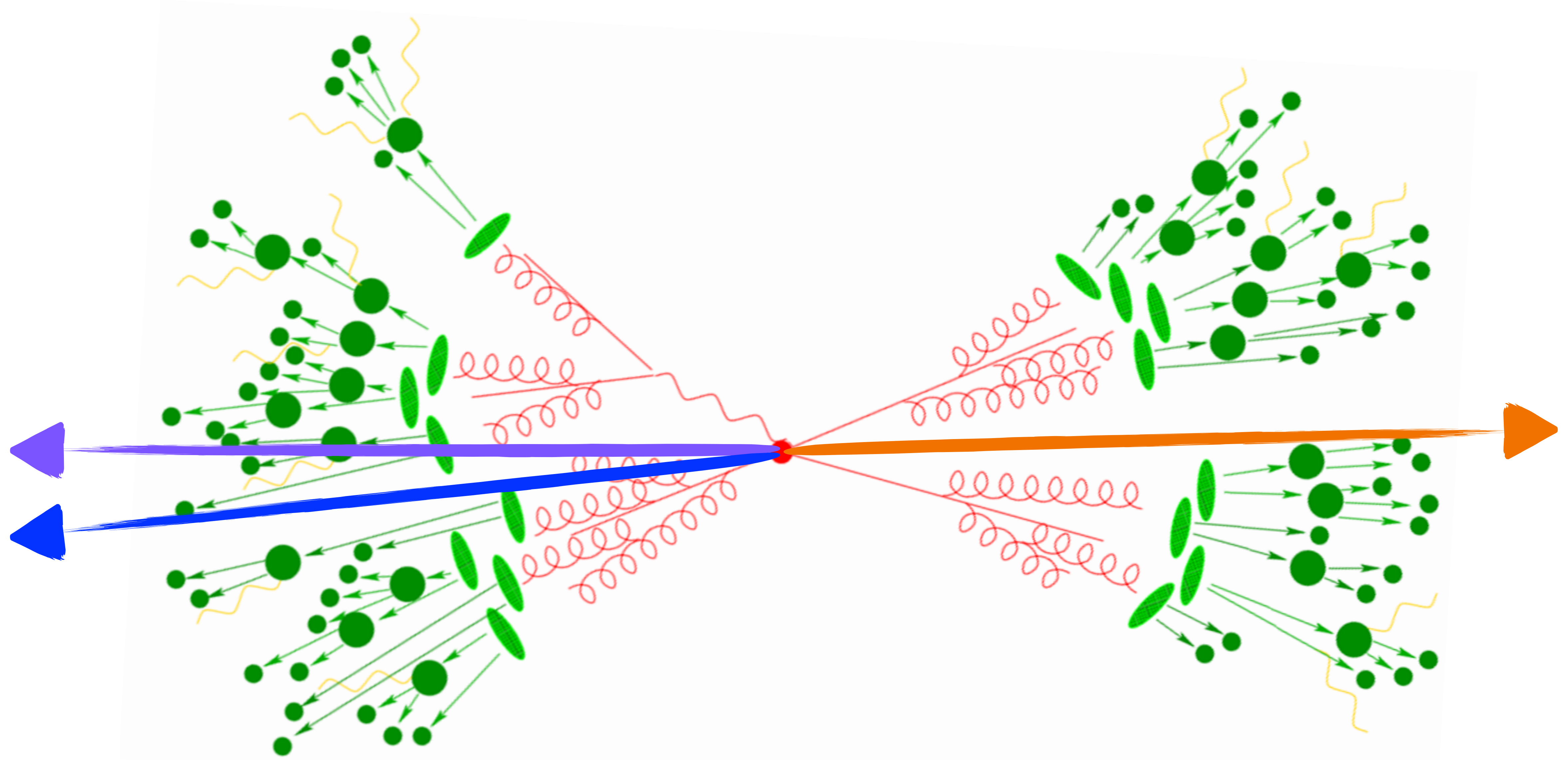
[Zeitschrift für Physik C Particles and Fields 59 (1993): 1-19.]

EECs in e^+e^-

- In this first analysis, we use the variables $\theta_{\rm L}$ and $z = \dfrac{1 - \cos(\theta_{\rm L})}{2}$
  - $\theta_{\rm L}$ = opening angle in radians



- **Use all particles in an event, allows us to probe QCD from the collinear to the back-to-back region!**



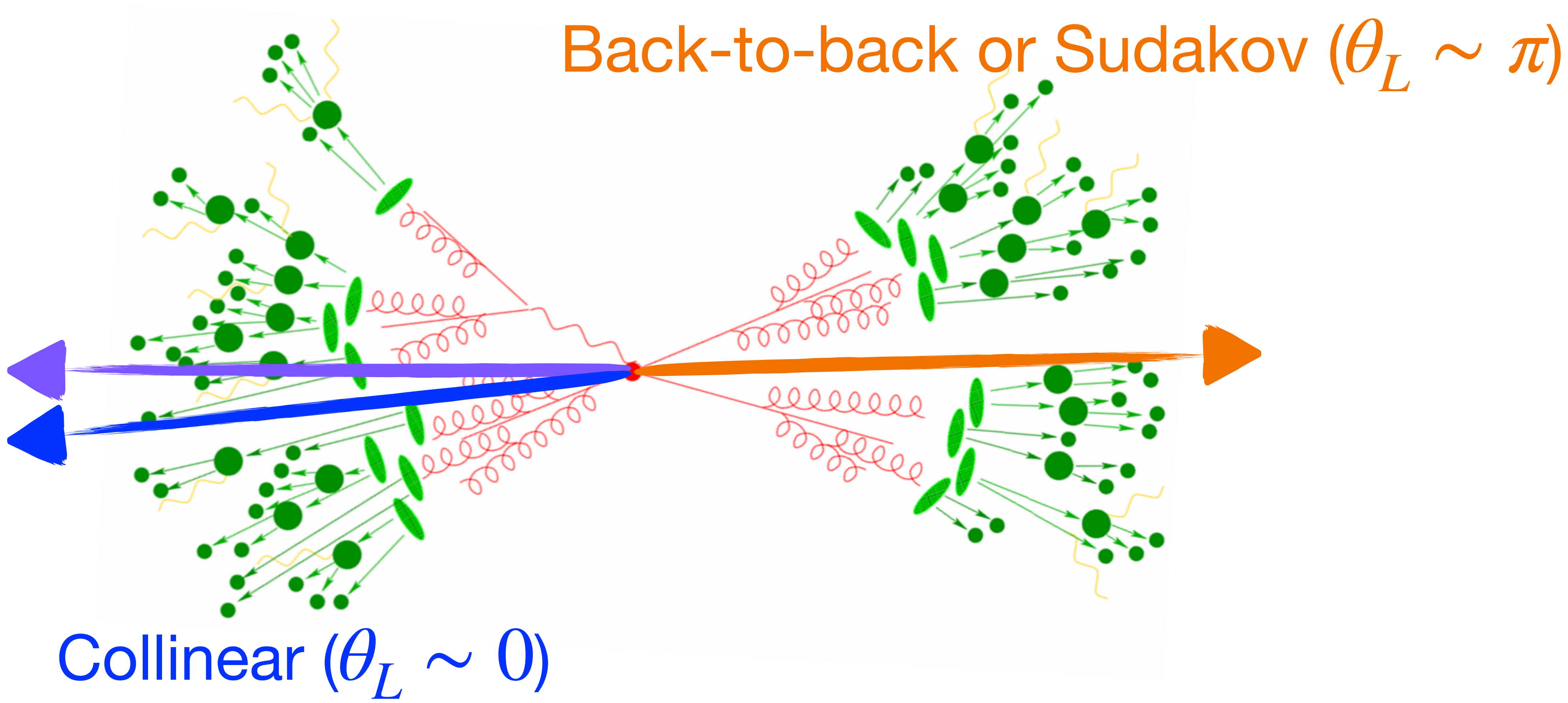
$$\text{E2C}(z) = \sum_{\rm i,j}^{n} d\sigma \frac{E_{\rm i}E_{\rm j}}{E^2}\delta(z - z_{\rm ij})$$

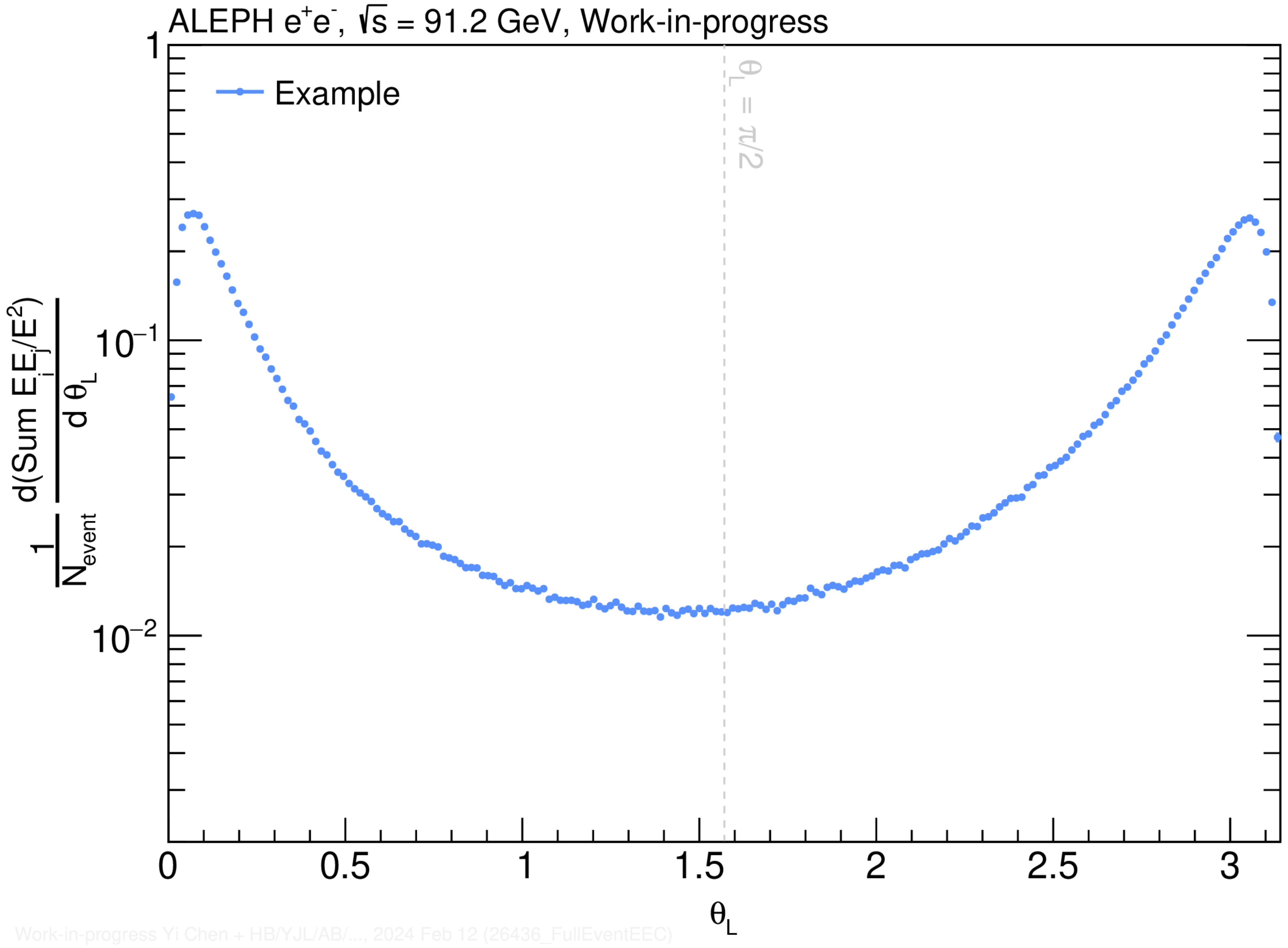
$$\text{E2C}(\theta_{\rm L}) = \sum_{\rm i,j}^{n} d\sigma \frac{E_{\rm i}E_{\rm j}}{E^2}\delta(\theta_{\rm L} - \theta_{\rm ij})$$

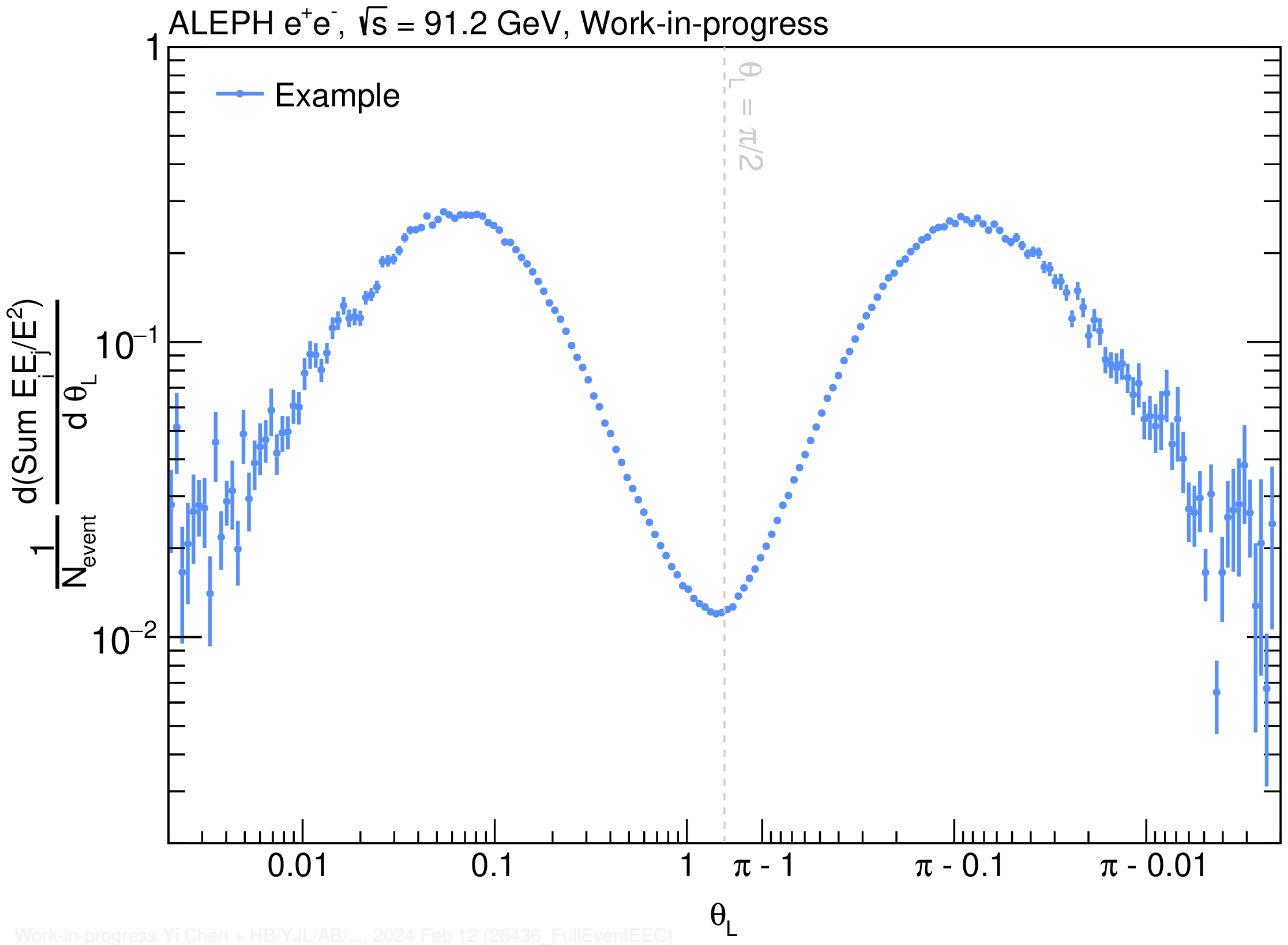
Collinear ($\theta_L \sim 0$) Back-to-back or Sudakov ($\theta_L \sim \pi$)

EECs in e^+e^-

- Example using archived MC.
- Plot this in a double log style.







EECs in e^+e^-

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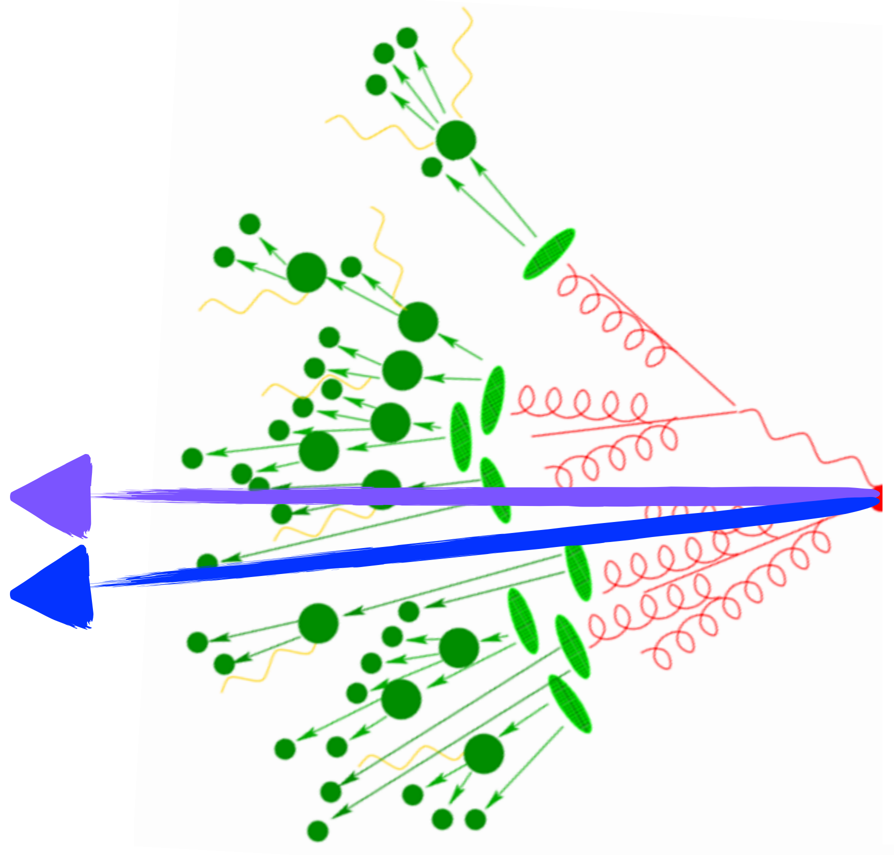
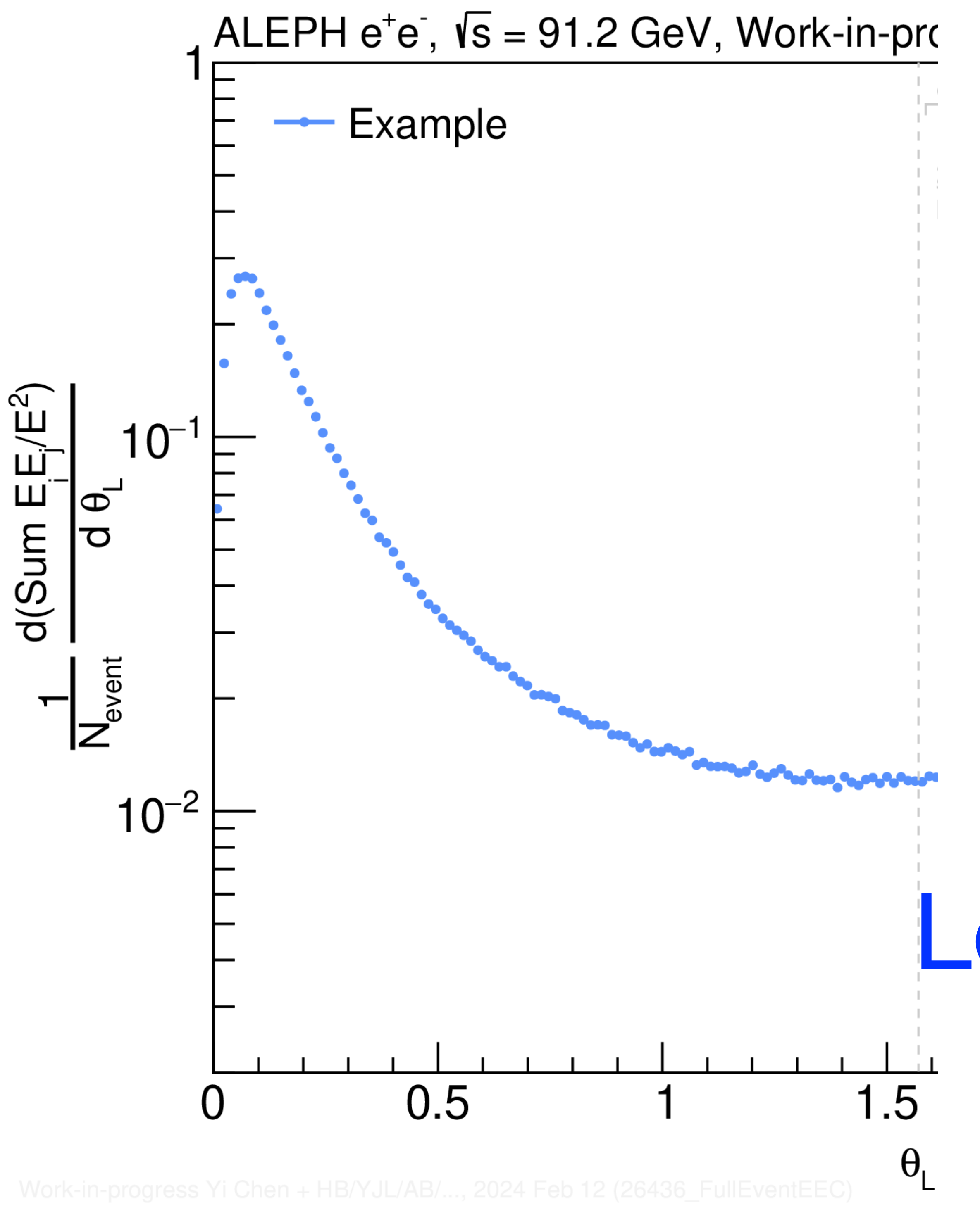
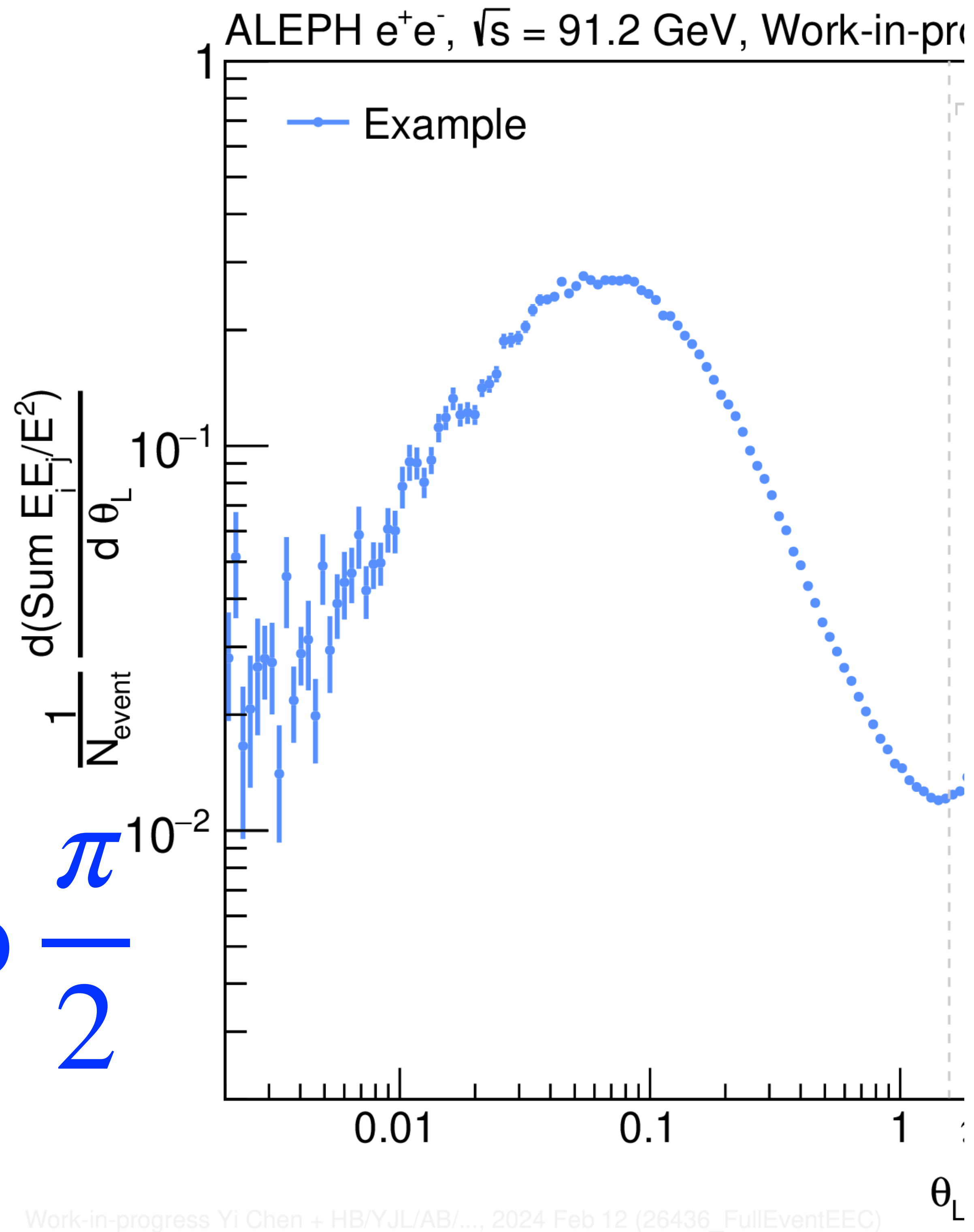


Collinear ($\theta_L \sim 0$)

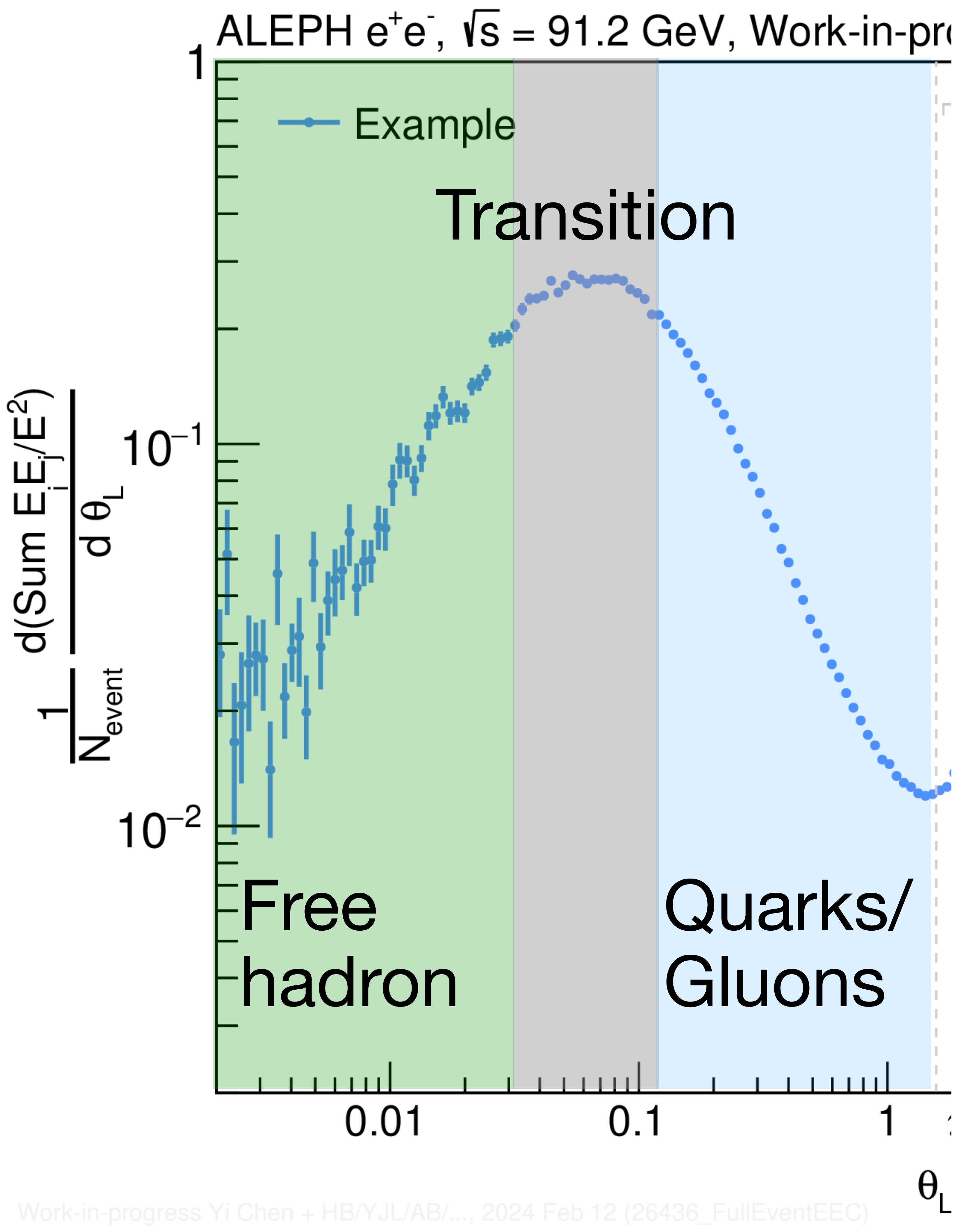




Log scale from 0 to $\frac{\pi}{2}$

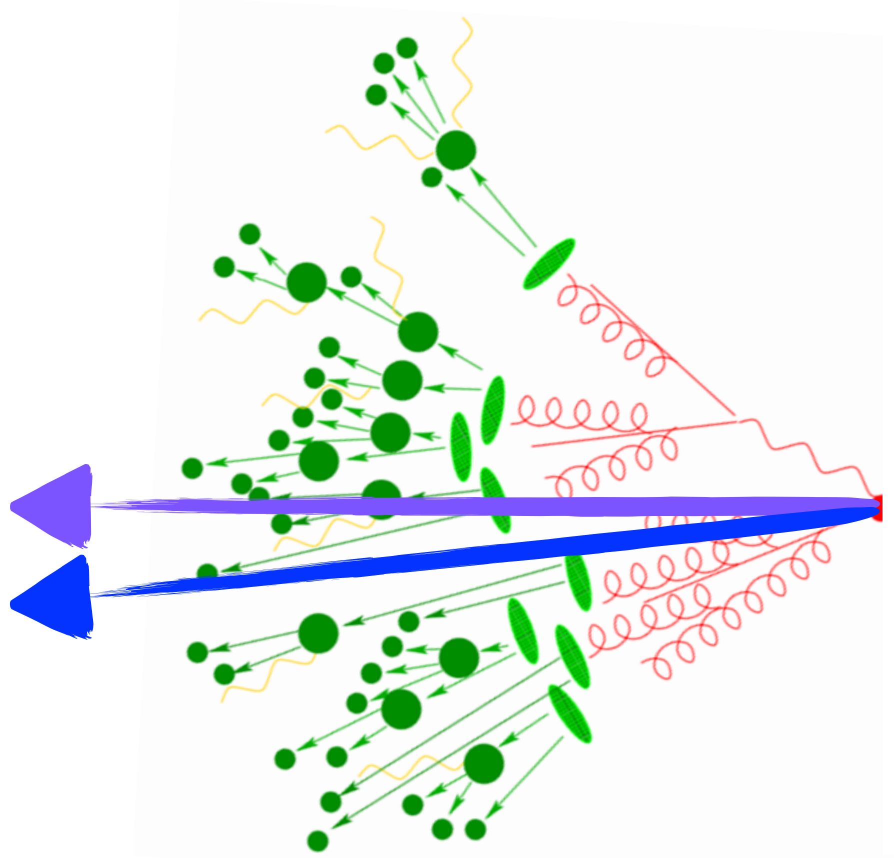
EECs in e^+e^-

- Example using archived MC.
- Plot this in a double log style.



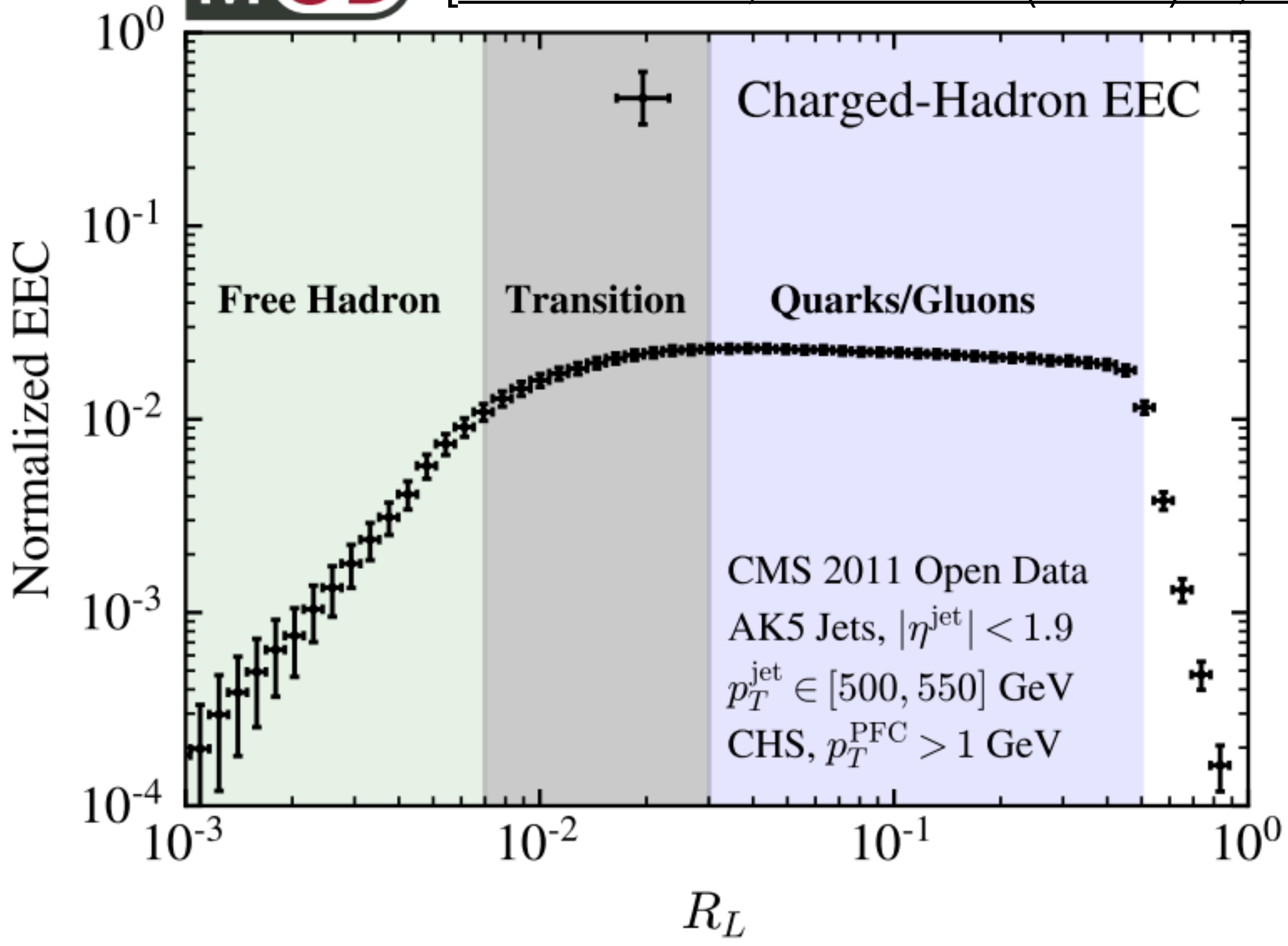
Collinear region is the E2C we are already familiar with!

(with a different jacobian)



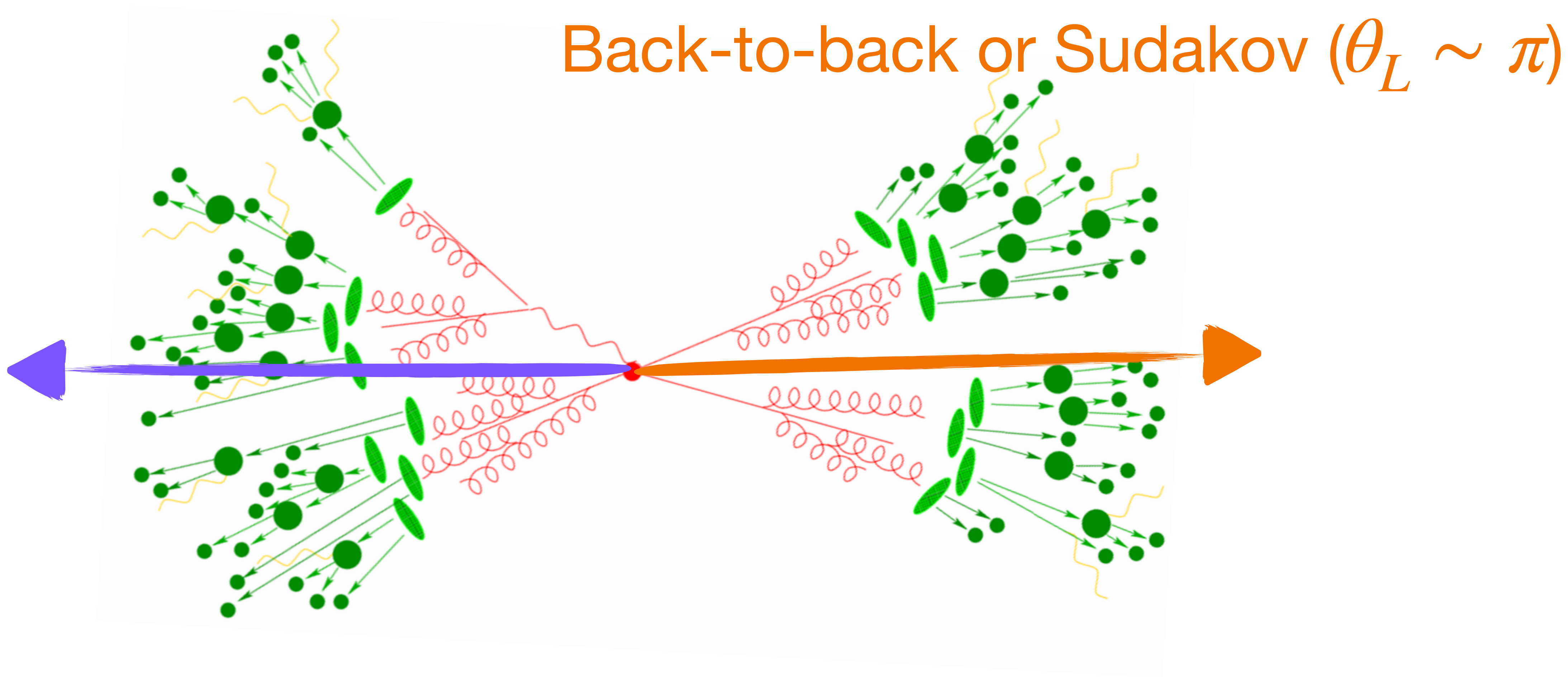
Collinear ($\theta_L \sim 0$)

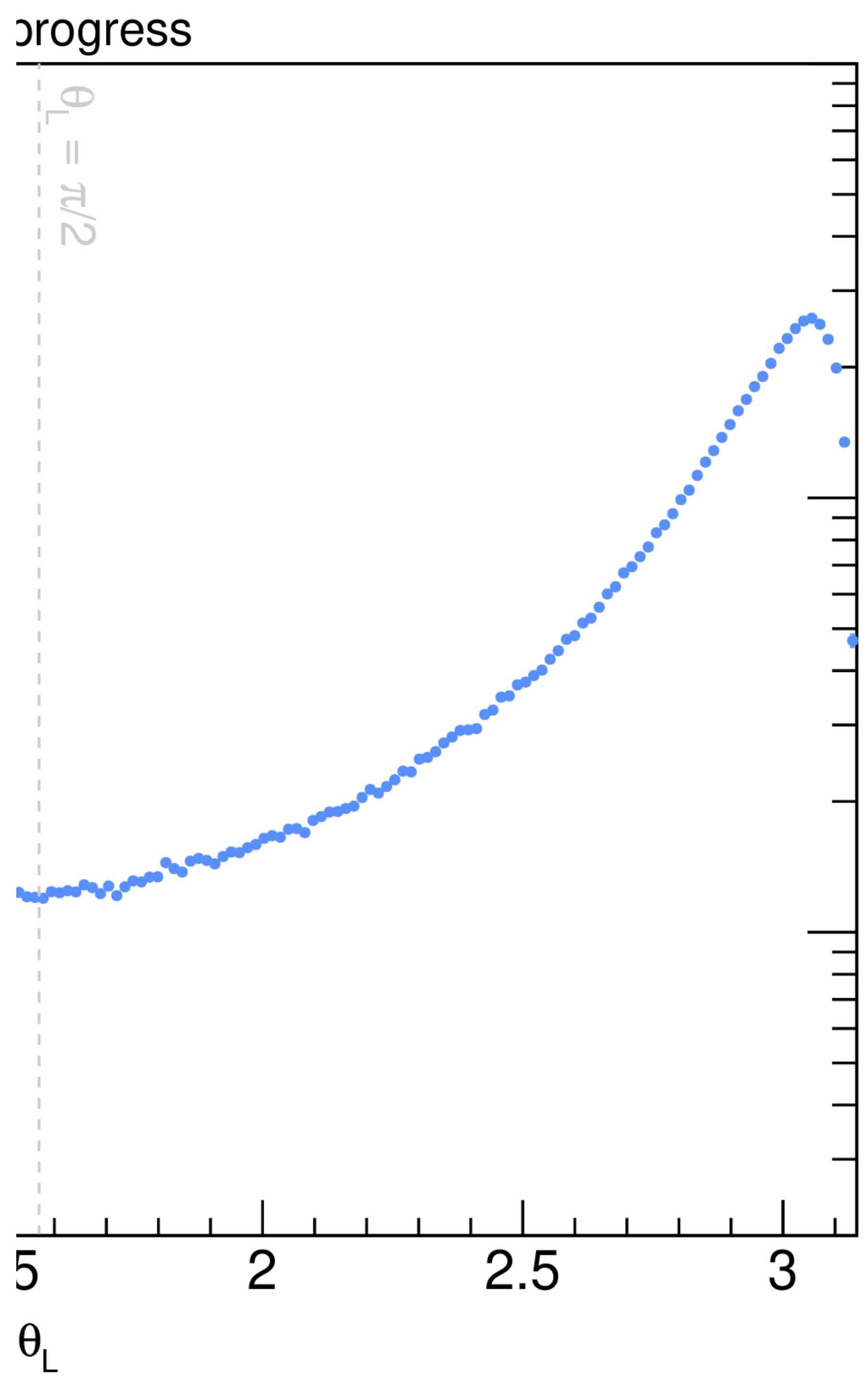
MOD [Moult et al., PRL 130 (2023) 5, 051901]



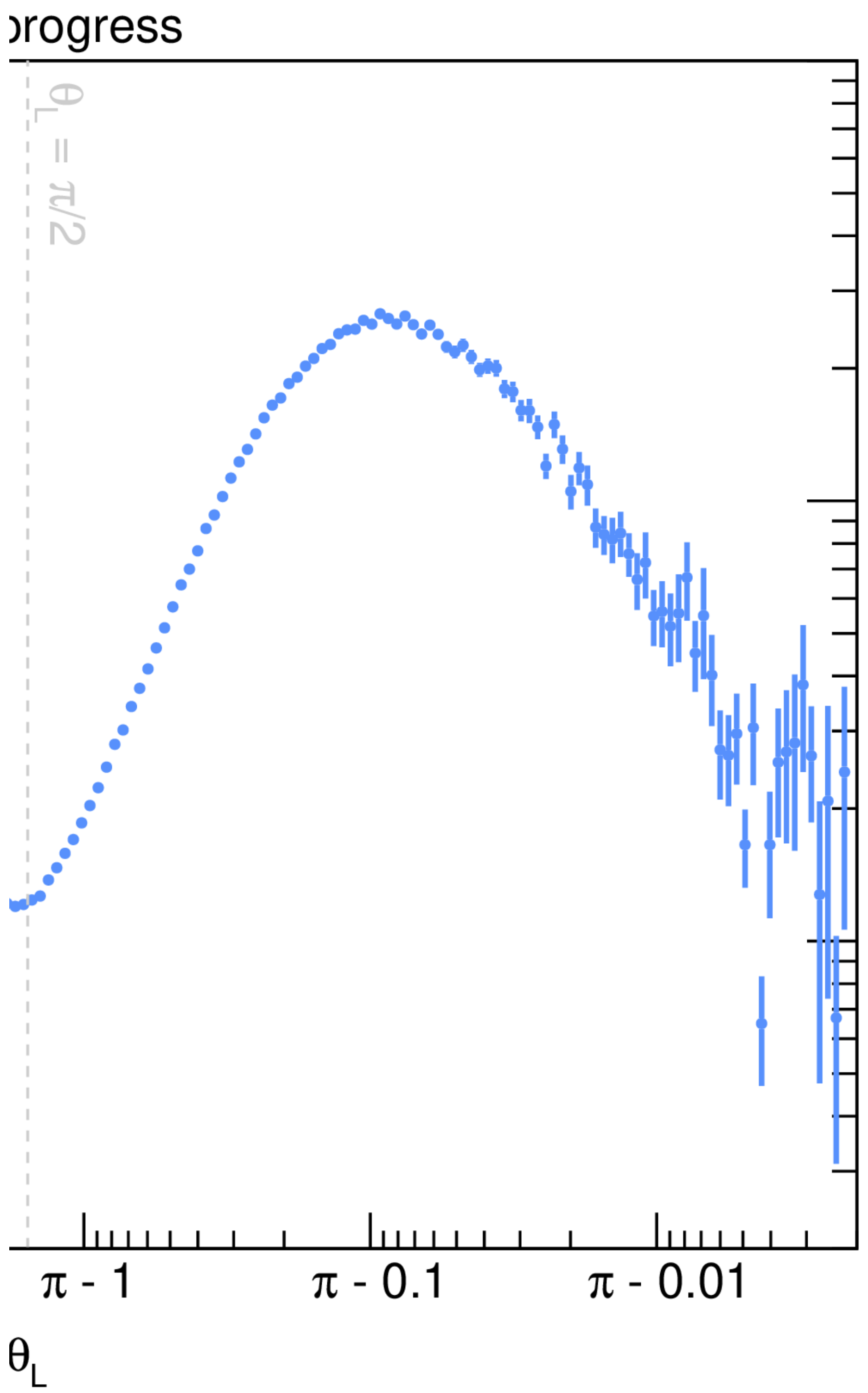
EECs in e^+e^-

- Example using archived MC.
- Plot this in a double log style.



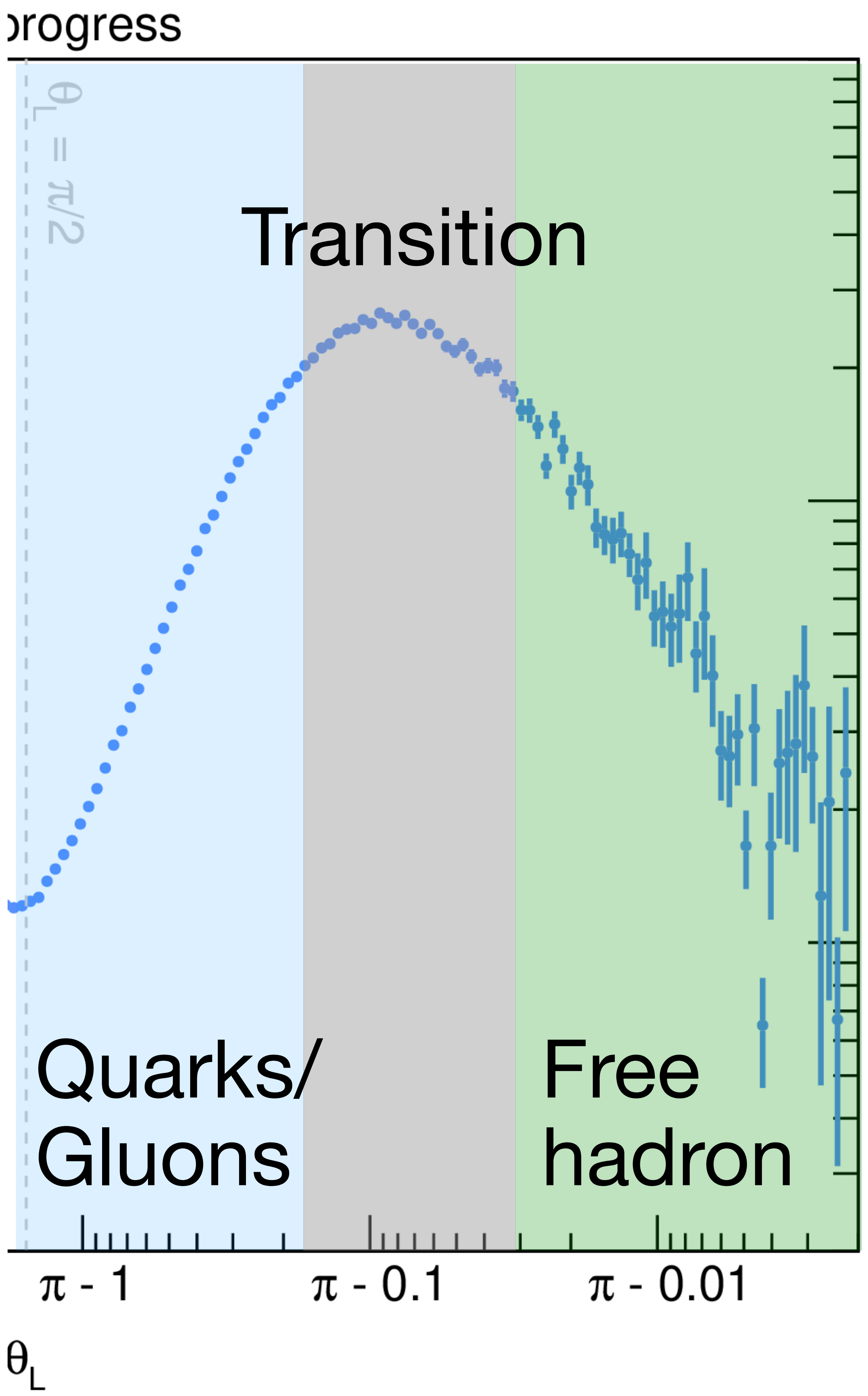


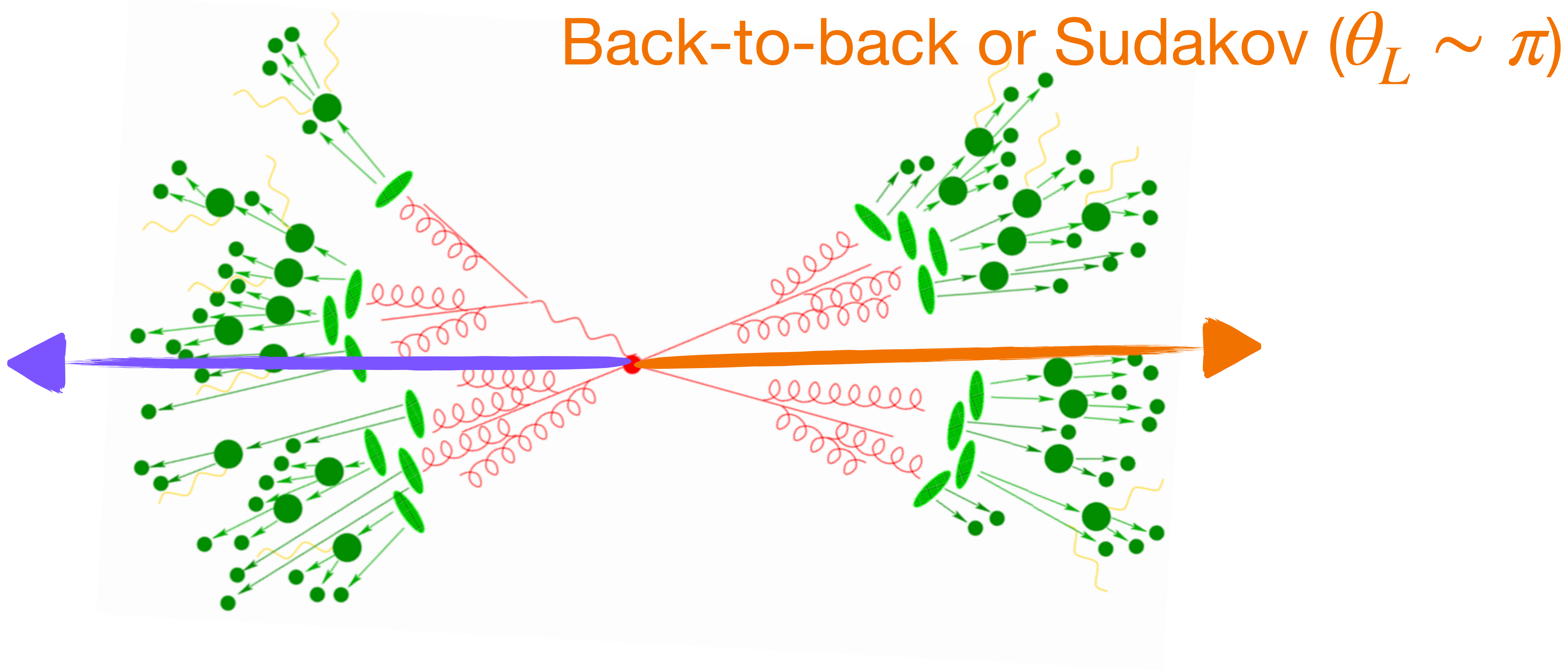
“Flipped” Log scale from π to $\pi - \frac{\pi}{2}$



EECs in e^+e^-

- Example using archived MC.
- Plot this in a double log style.



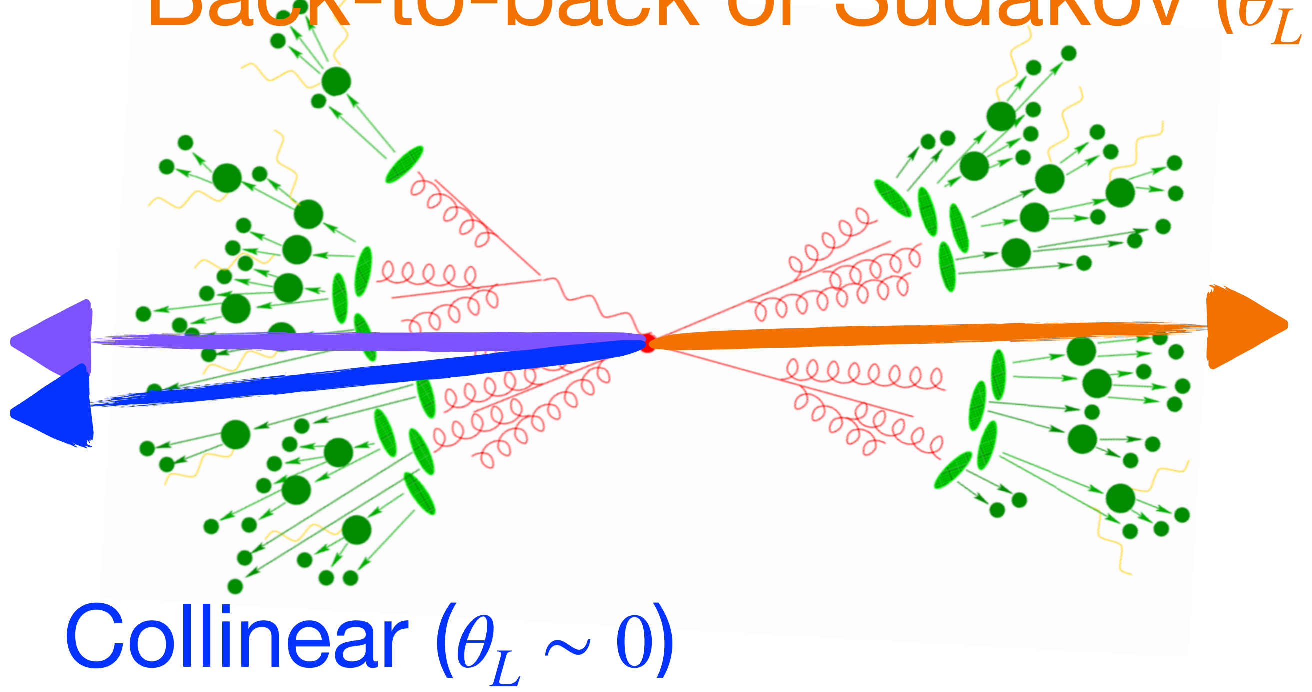


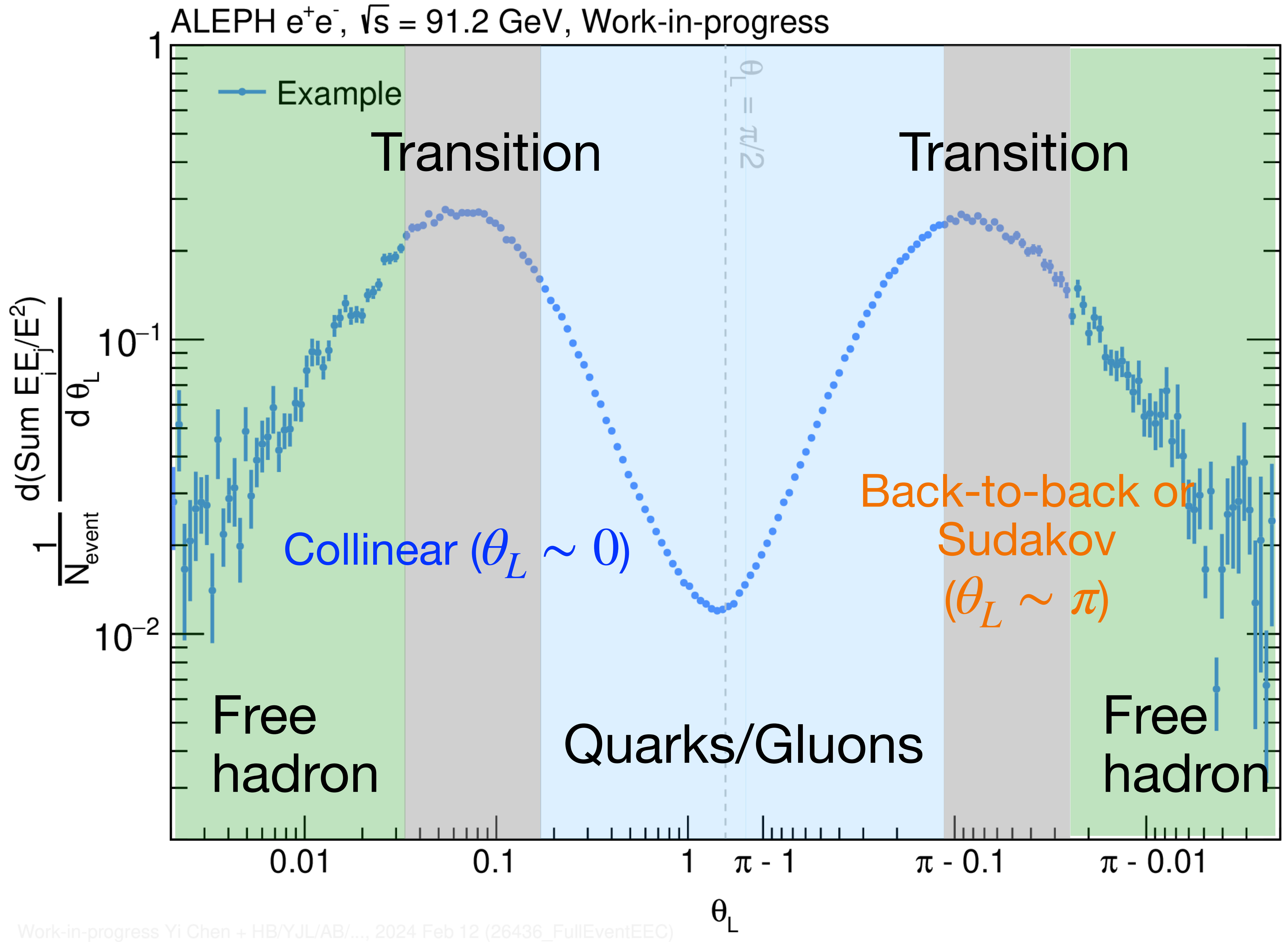
Back-to-back limit has similar regions!

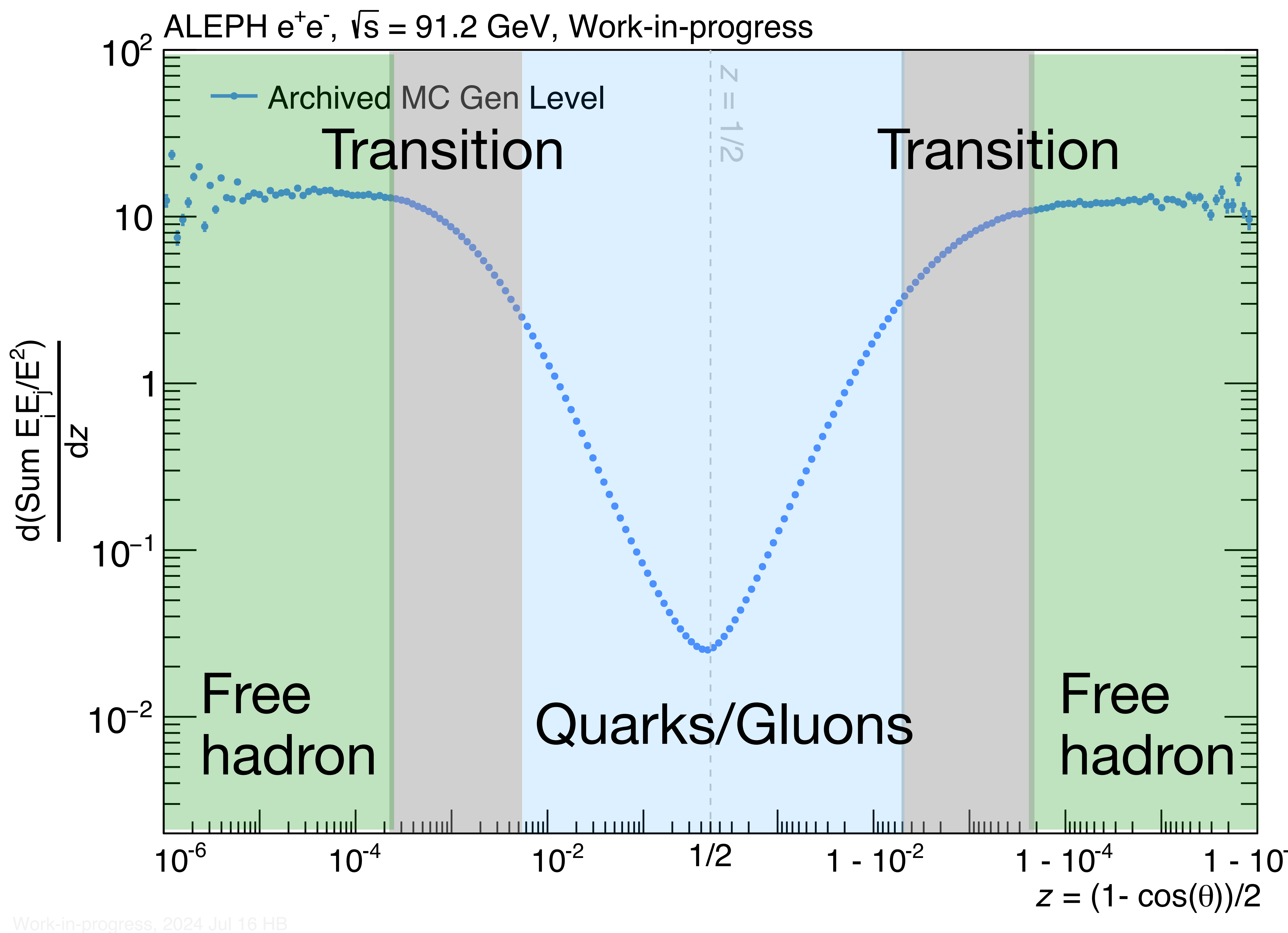
- Can be used to probe the universality of free hadron region (z-variable useful for this)

EECs in e^+e^-

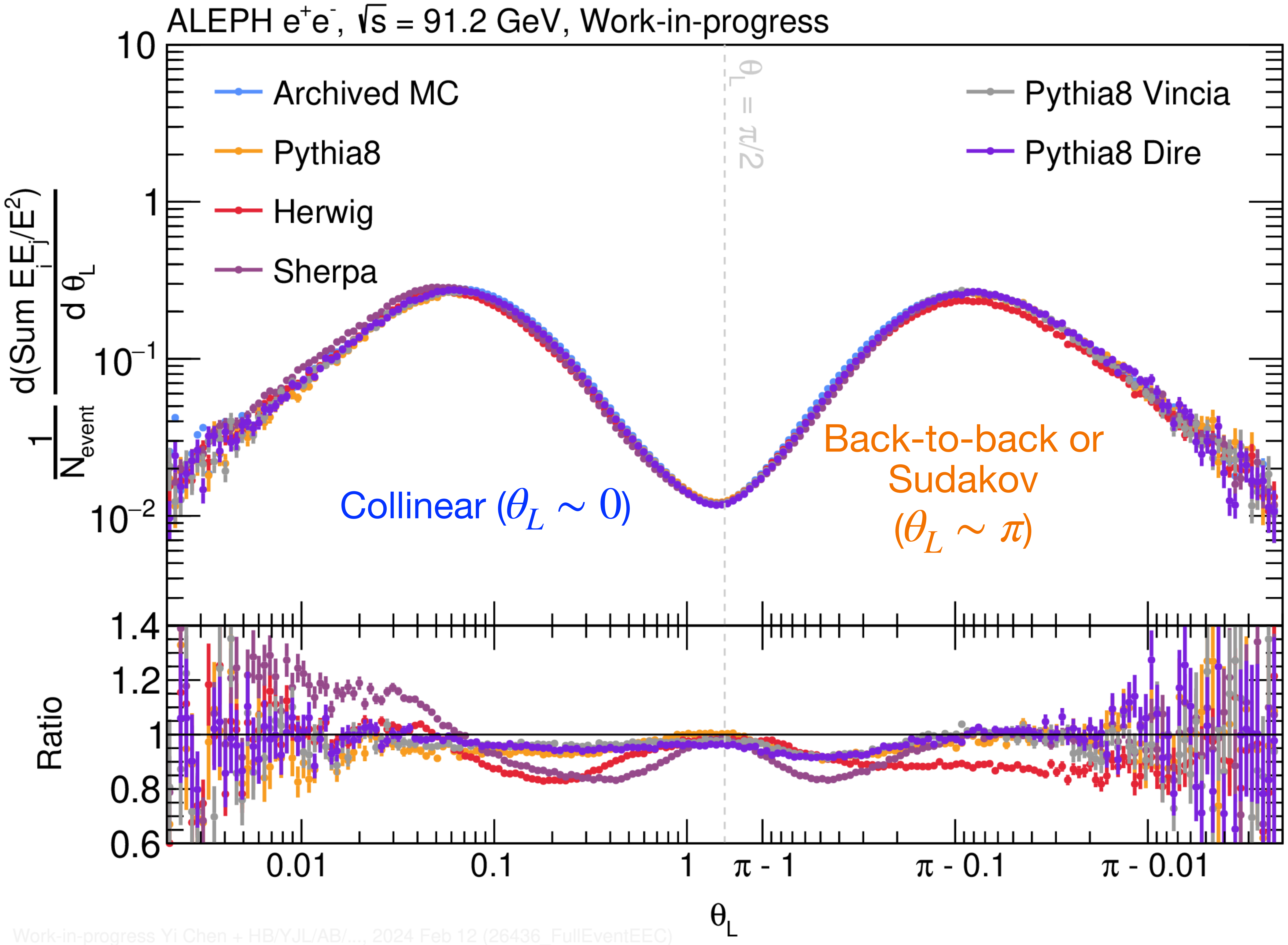
- Example using archived MC.
- Plot this in a double log style.

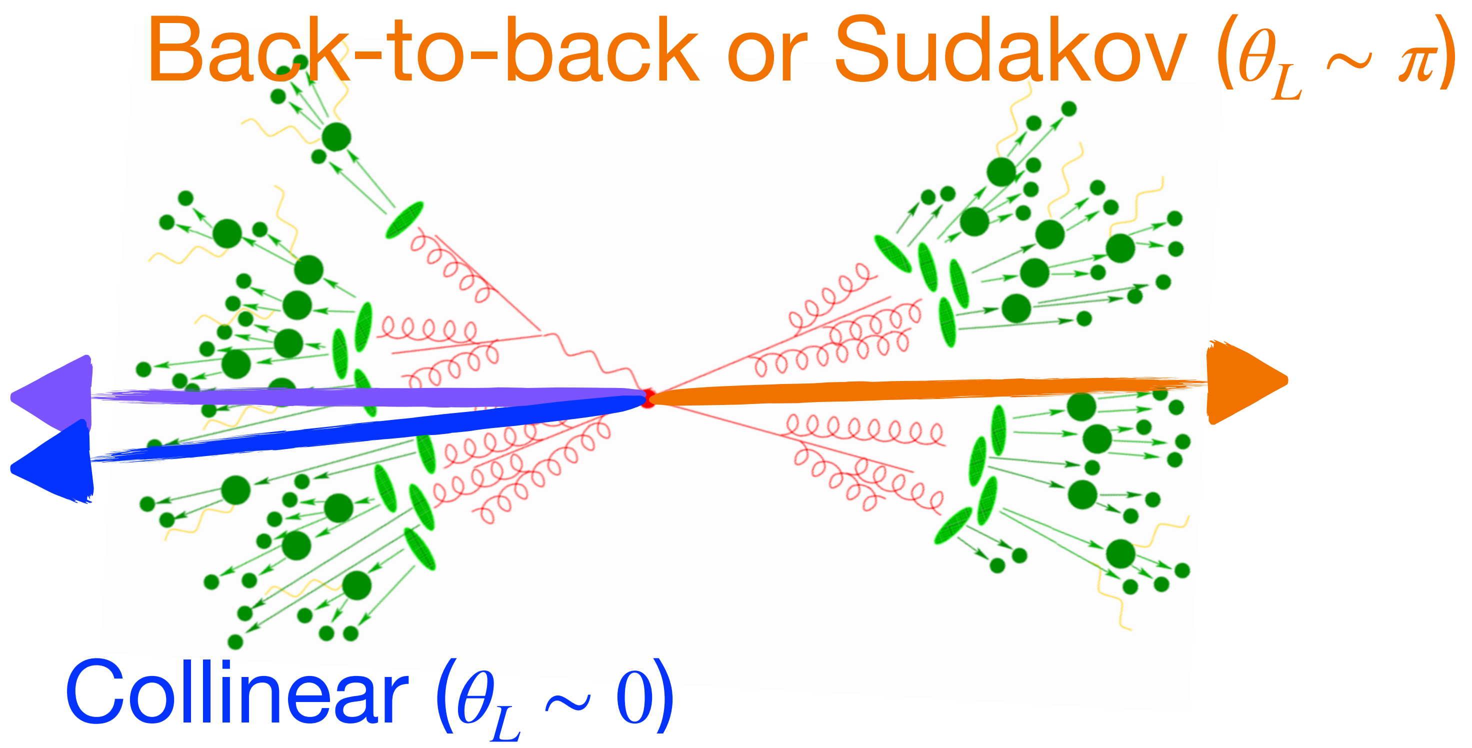






E2Cs in models

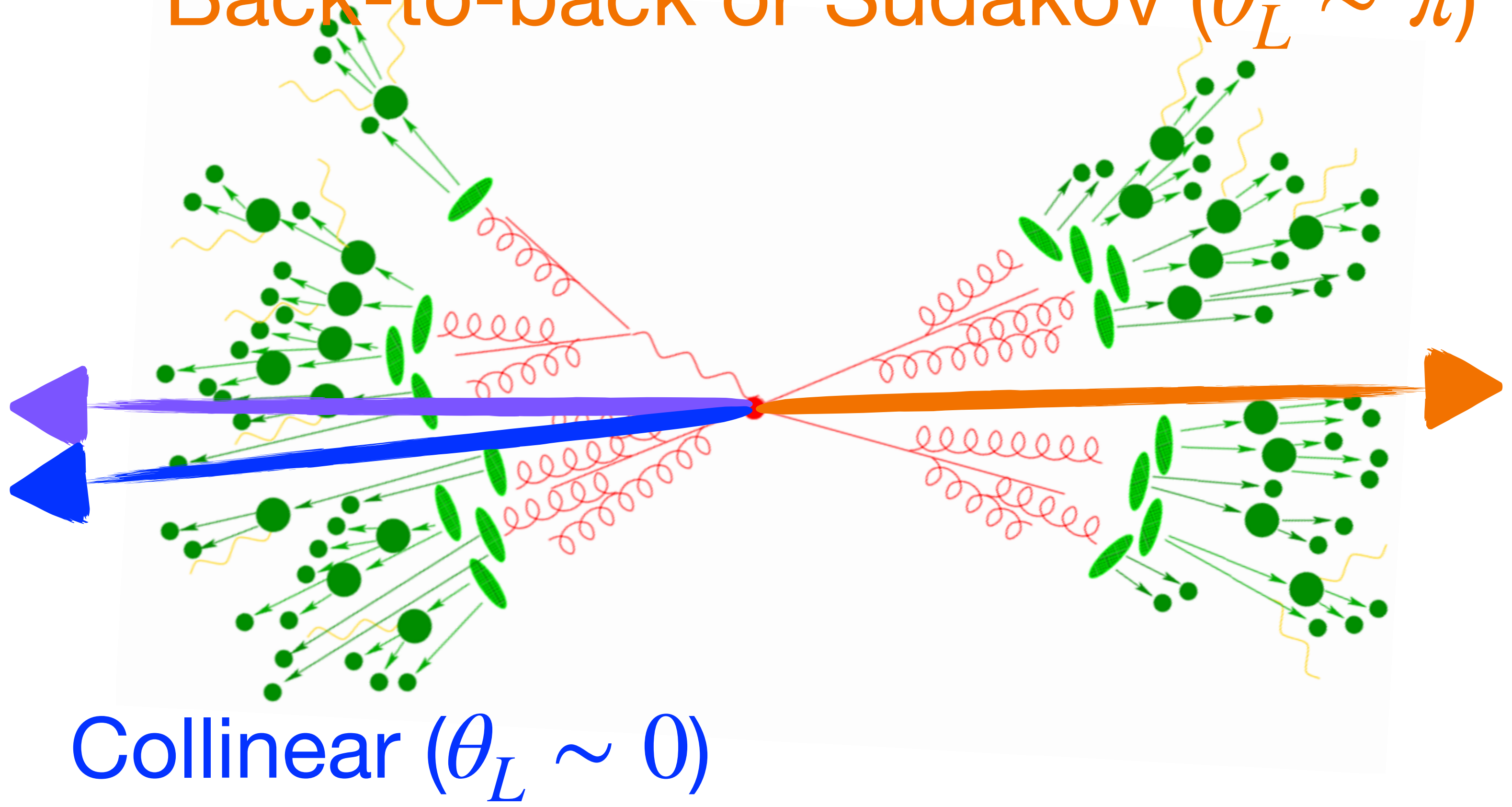




- Similar differences between models as seen in e^+e^- as in the pp case.
  - Larger θ_{L} not comparable (outside the jet)
- In free hadron region, models are roughly parallel to one another.
- In Quark/Gluon region different showers give a different slope.

First fully-corrected E2Cs in e^+e^-

$$\text{E2C}(z) = \sum_{\text{i,j}}^{n} d\sigma \frac{E_\text{i} E_\text{j}}{E^2} \delta(z - z_{\text{ij}})$$



- Can do this in a fully-corrected way, unfolding in two dimensions using archived PYTHIA 6 for the response matrix.
  - z or θ_L axis
  - $E_\text{i}E_\text{j}$ axis
- Huge advantage of doing this in e^+e^- is that E = 91.2 GeV is fixed! Normally, would need to do three-dimensional correction, also correcting for the energy scale.
- **First of its kind in e^+e^-!**

Event selection

- Select on hadronic events

Event selection	
Hadronic events	at least five good tracks
	total reconstructed charged-particle energy ≥ 15 GeV
Acceptance	$7\pi/36 \leq \theta_{\text{sphericity}} \leq 29\pi/36$

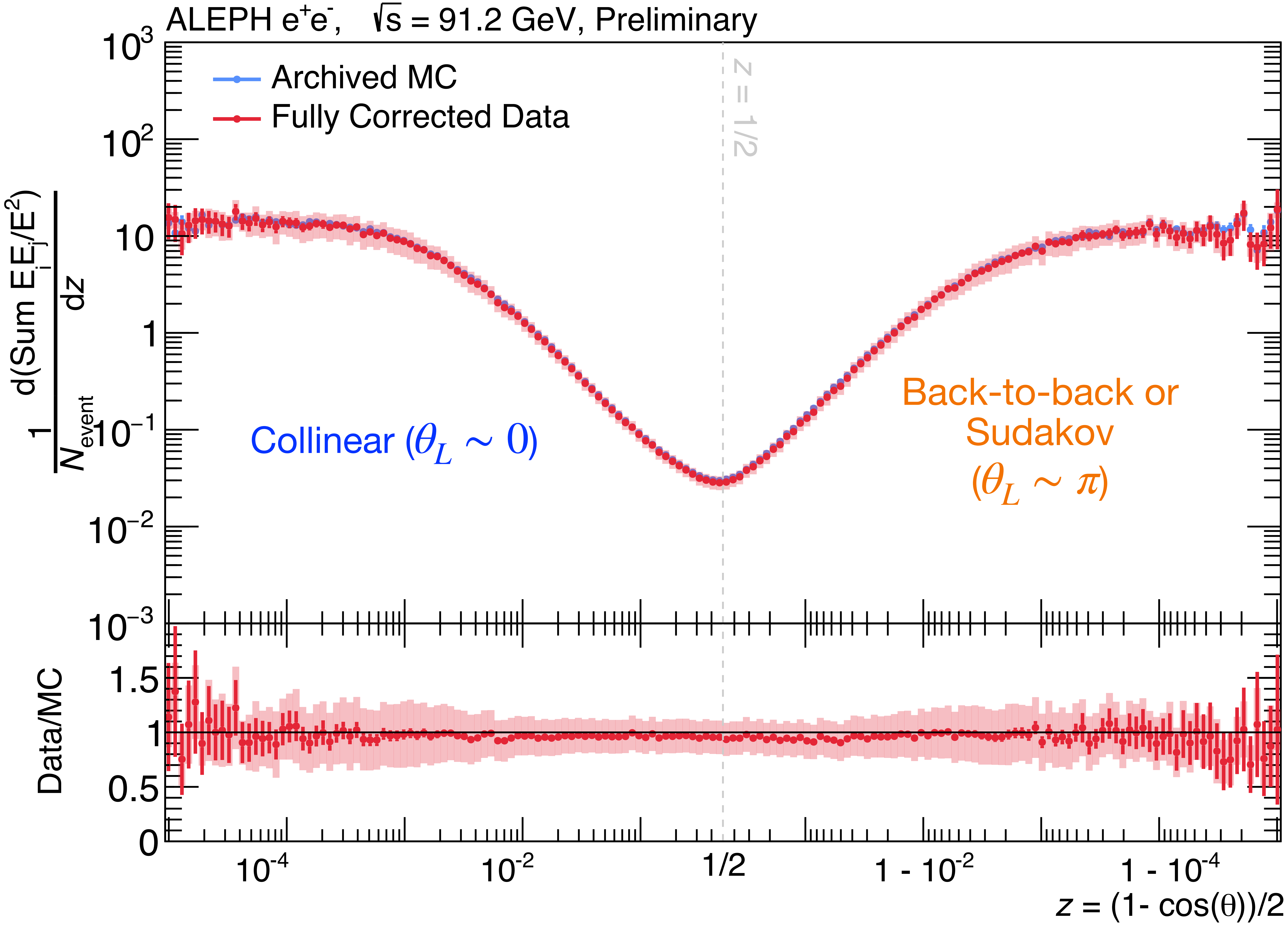
- For this measurement, we use charged particles only.

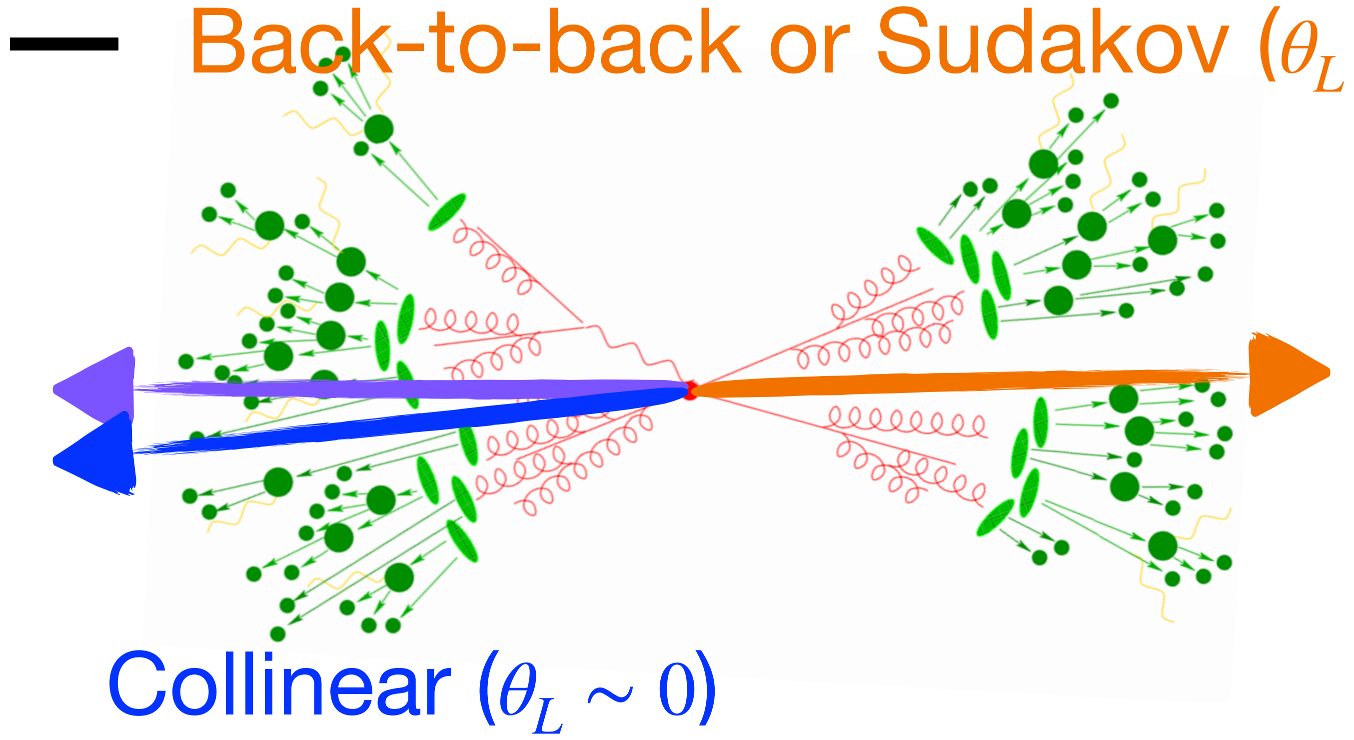
Charged particles	
Acceptance	$\lvert\cos\theta\rvert < 0.94$
High quality tracks	$p_{\mathrm{T}} \geq 0.2$ GeV ← Min p_{T} cutoff (reco)
	at least 4 TPC hits
Impact parameter	$d_0 < 2$ cm, $z_0 < 10$ cm

Systematic Uncertainties

- First look at the systematics designed to be *conservative*!
  - Expect the final systematics to be greatly reduced from here!
- **Number of TPC hits:**
  - ≥ 4 (nominal) varied to ≥ 7
- **Unfolding systematics (dominant)**
  - Chosen to be conservative, including number of iterations, choice of binning, prior variation etc.
- **Matching**
  - Vary the matching method used to match true

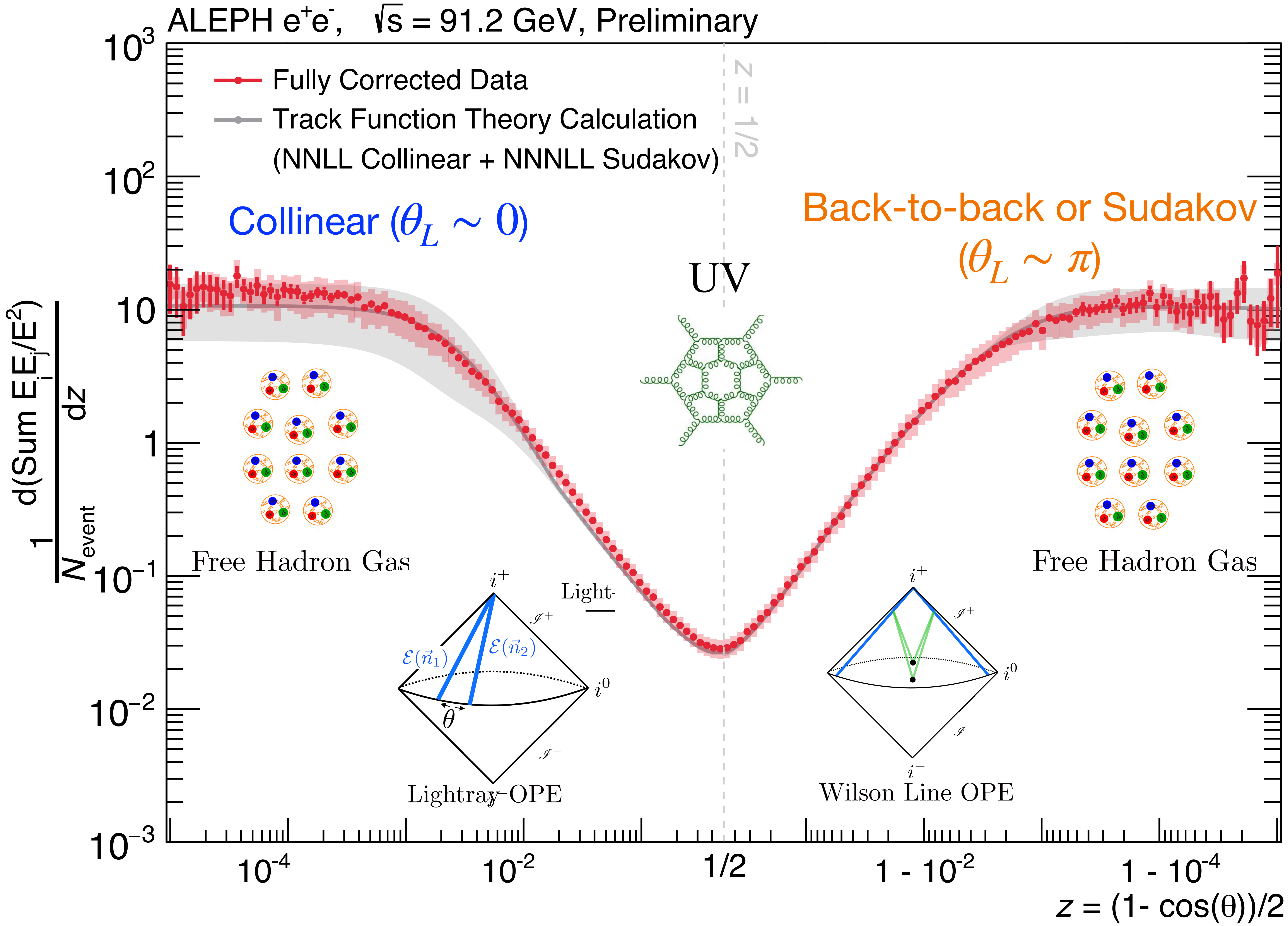
First fully-corrected E2Cs in e^+e^-



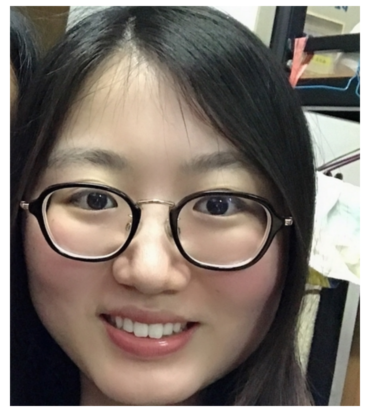


- For this first look, systematics are conservative.
- Shows good agreement with Archived PYTHIA 6 MC across all parts of phase space!
- Able to achieve unprecedented binning and kinematic reach!
- At first look collinear and back-to-back regions look comparable.

Comparison with theory calculation



Thank you to Max Jaarsma, Yibei Li, Ian Moult, Wouter Waalewijn, HuaXing Zhu for providing the theory curves!



Yibei Li

Max Jaarsma

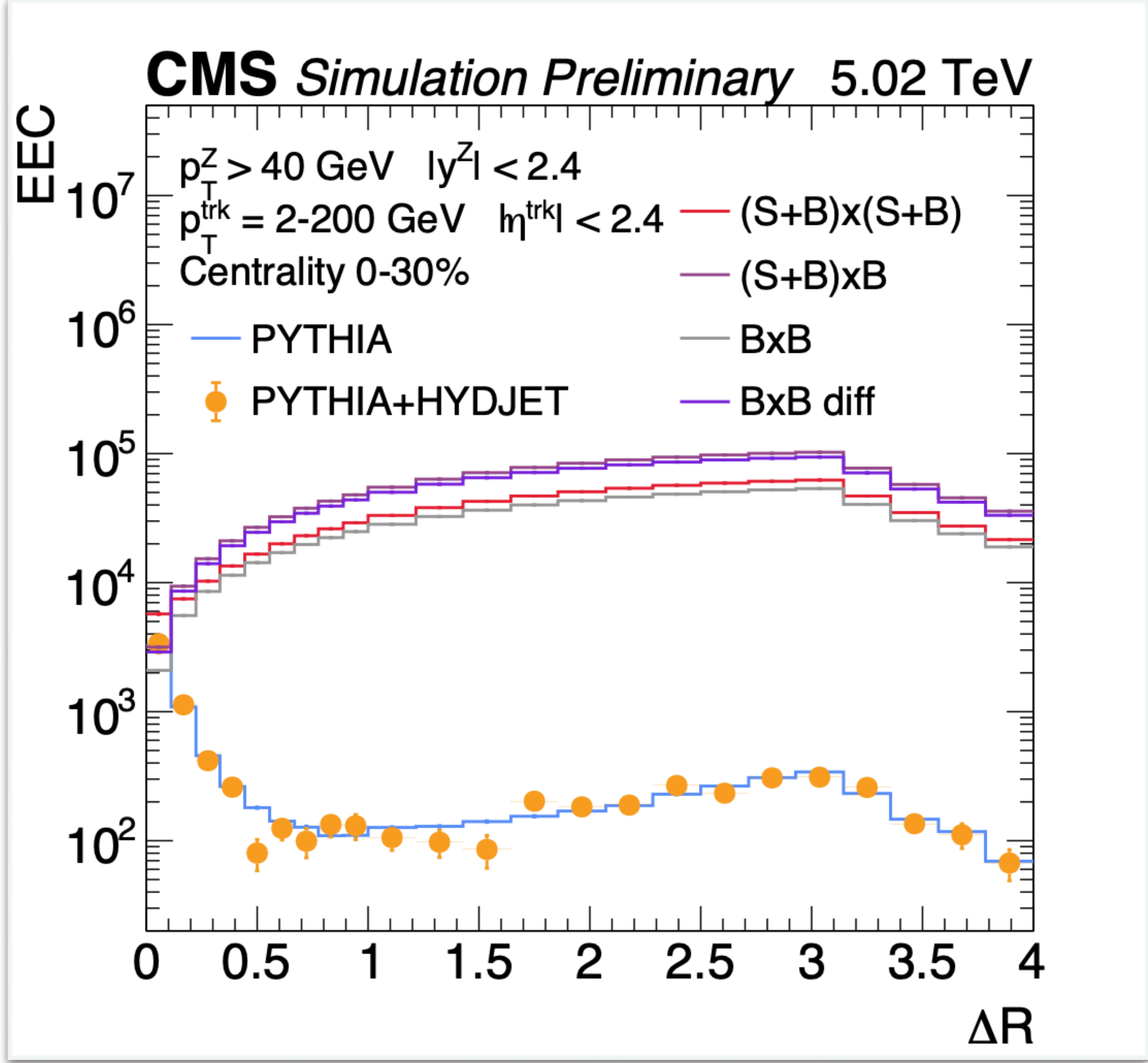
- Compared to theoretical calculation with the following ingredients.
- **Collinear:** NNLL collinear resumption
- **Sudakov:** NNNLL Sudakov Resummation, Collins-Soper Kernel extracted from lattice QCD
- In both cases non-perturbative Ω parameter extracted from the thrust.

- **Excellent agreement! New measurements help further constrain error bars!**
- **This is just the beginning!!!**


Where do we go from here?
Make precision measurements of “known” effects
Look for large qualitative signatures of relatively “unknown” effects
I will list some ideas, other ideas also welcome!!

Extend techniques here to other systems!

- **Path #1:** Measure the E2C with all particles in the event in other systems!
  - In principle no barrier to doing this!



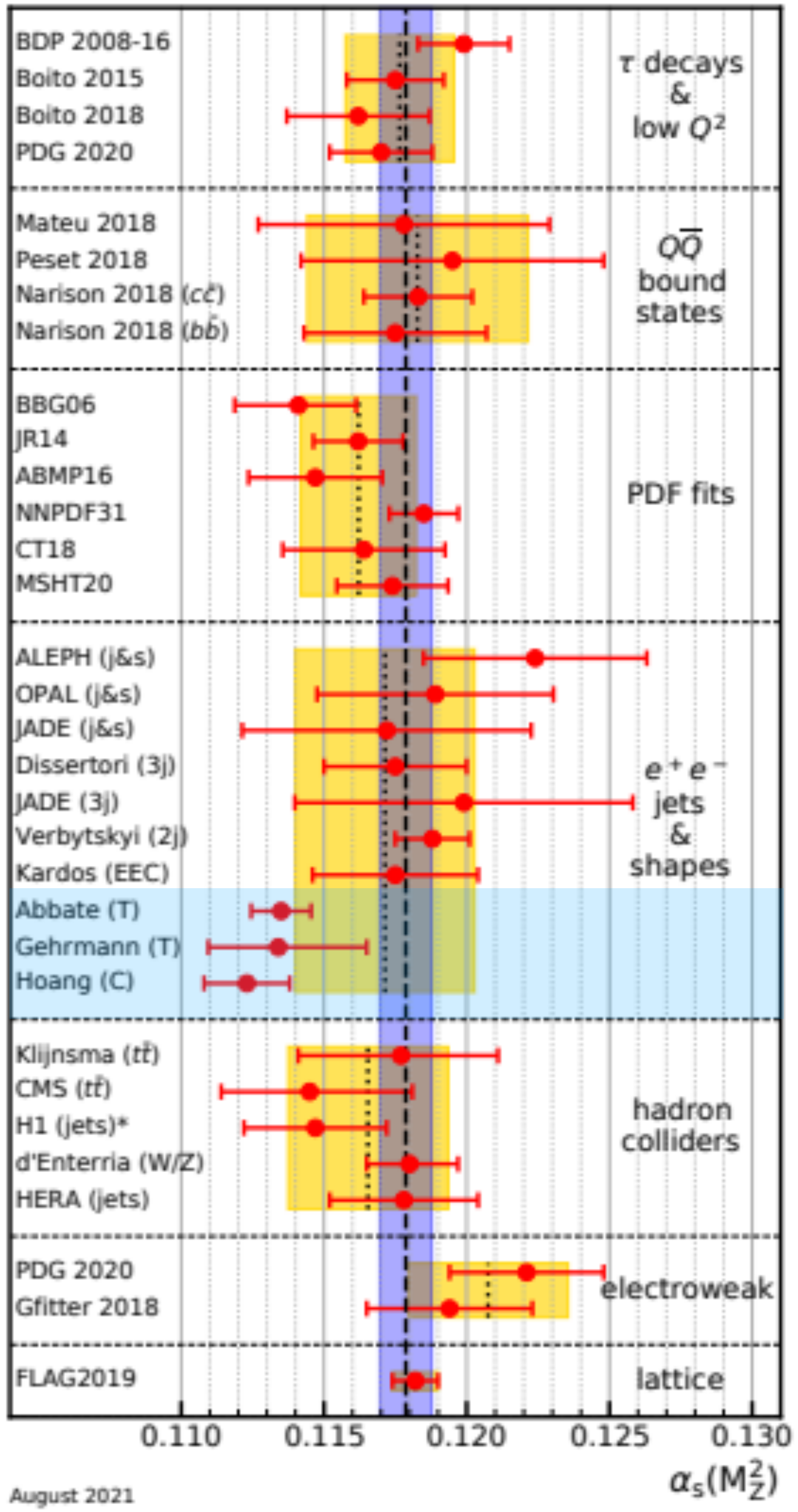
- Work ongoing to do this in heavy-ion collisions with Z-tagged events!
  - Background is a major limitation for measuring EECs in heavy-ions, but *event-mixing strategy looks promising*!

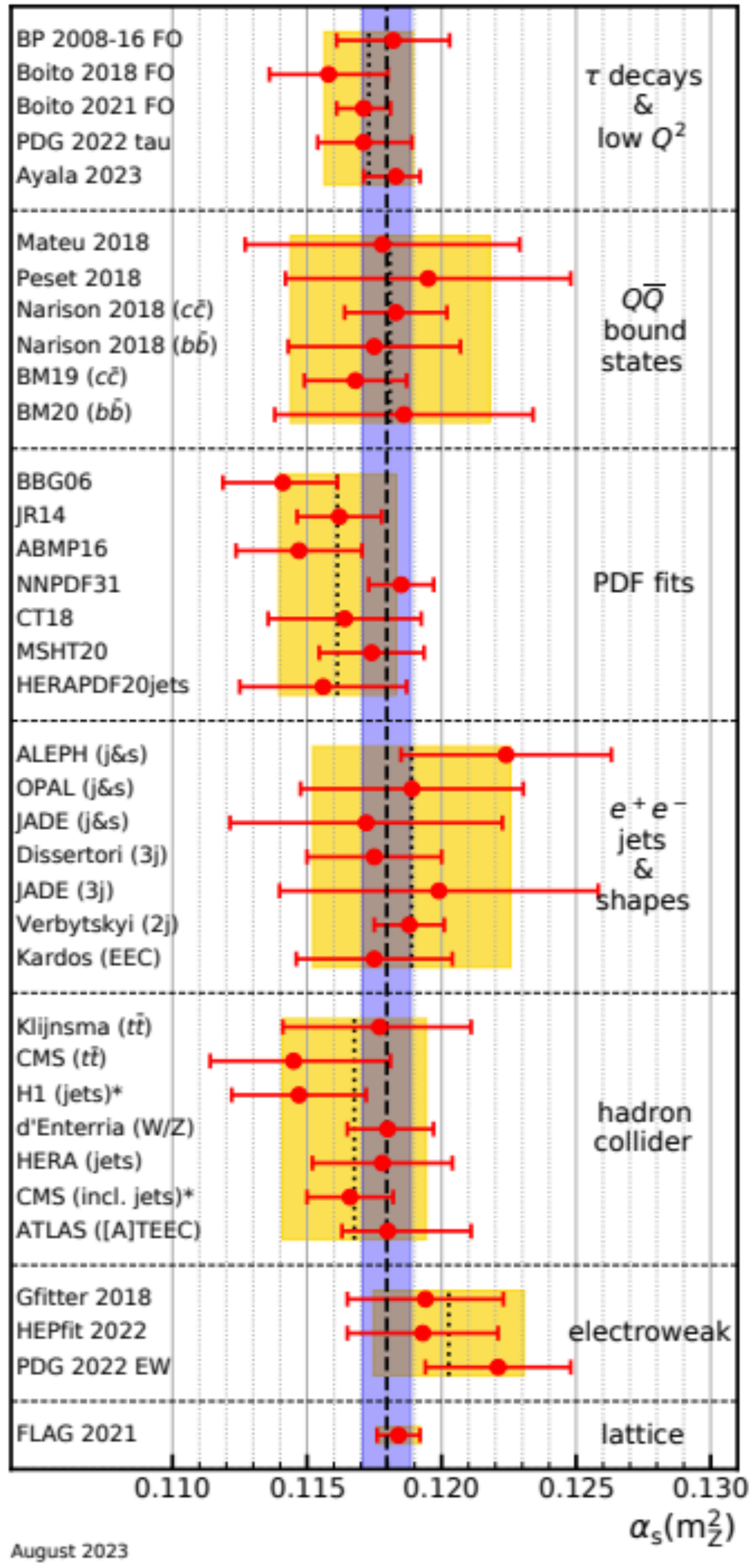
Orange: Detector level following background subtraction

Blue: Generator level pp

[See talk at HP by Yi Chen for more details.]

Opportunities of Higher-point correlators





- **Path #2:** Measure higher-point correlators and take the ratio with lower point correlators.
  - Useful for the extraction of α_s.
- α_s fits from e^+e^- event shapes and analytic hadronization characterization removed recently from world average
- **Extracting from e^+e^- EEC can be useful here!**

[PDG QCD Review 2021]

[PDG QCD Review 2023]

Challenges of higher point correlators

- Higher point correlators are more difficult to measure.
  - Computation takes more time, making unfolding to high precision very time intensive.
  - There are potential solutions for this!

FastEEC: Fast Evaluation of *N*-point Energy Correlators

Ankita Budhraja[a], Wouter J. Waalewijn[a,b]

[a] *Nikhef, Theory Group, Science Park 105, 1098 XG, Amsterdam, The Netherlands*
[b] *Institute of Physics and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, The Netherlands*

[arXiv:2406.08577]

New Angles on Energy Correlators

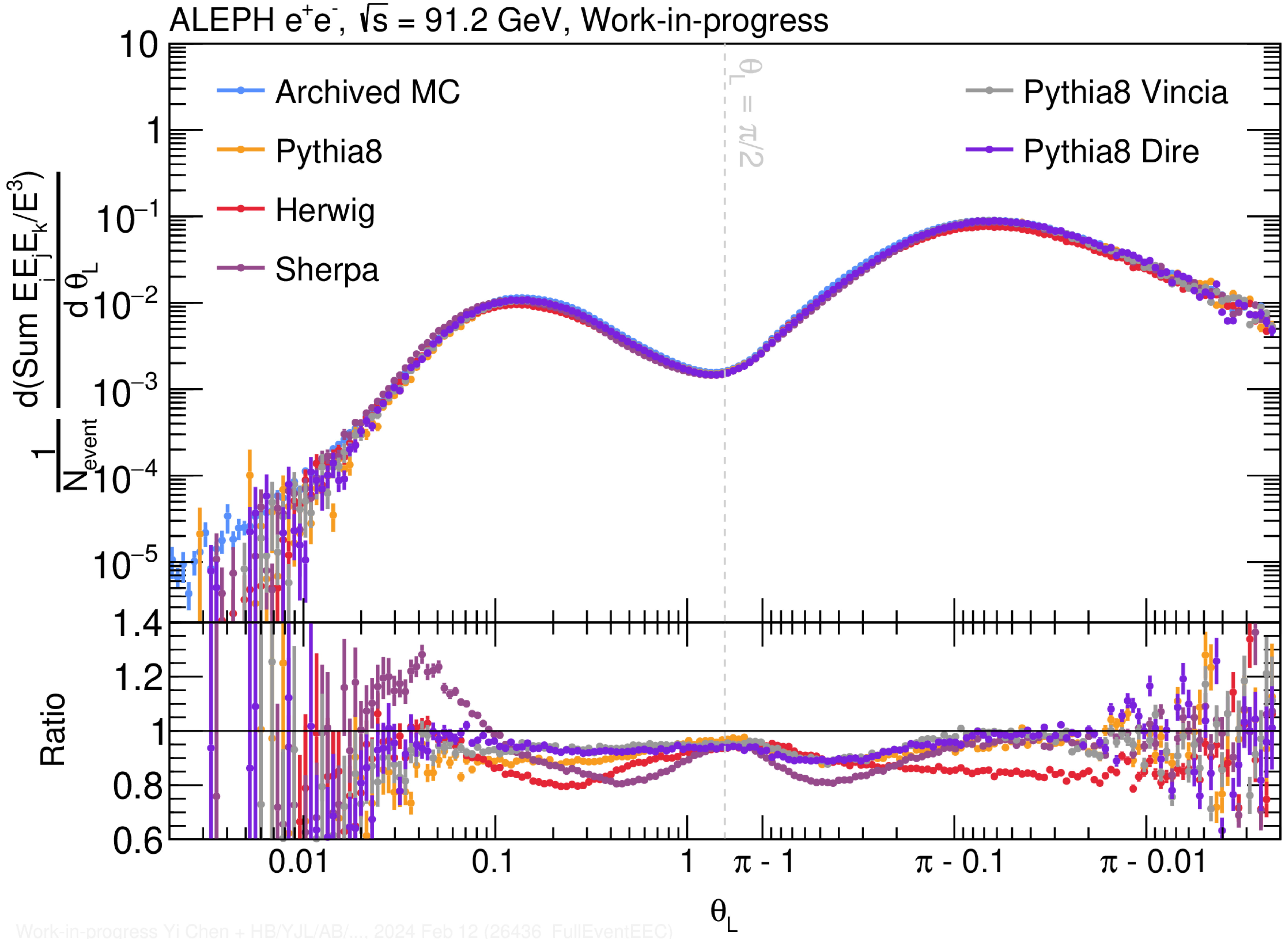
Samuel Alipour-fard,[1,*] Ankita Budhraja,[2,†] Jesse Thaler,[1,‡] and Wouter J. Waalewijn[2,3,§]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Nikhef, Theory Group, Science Park 105, 1098 XG, Amsterdam, The Netherlands*
[3] *Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

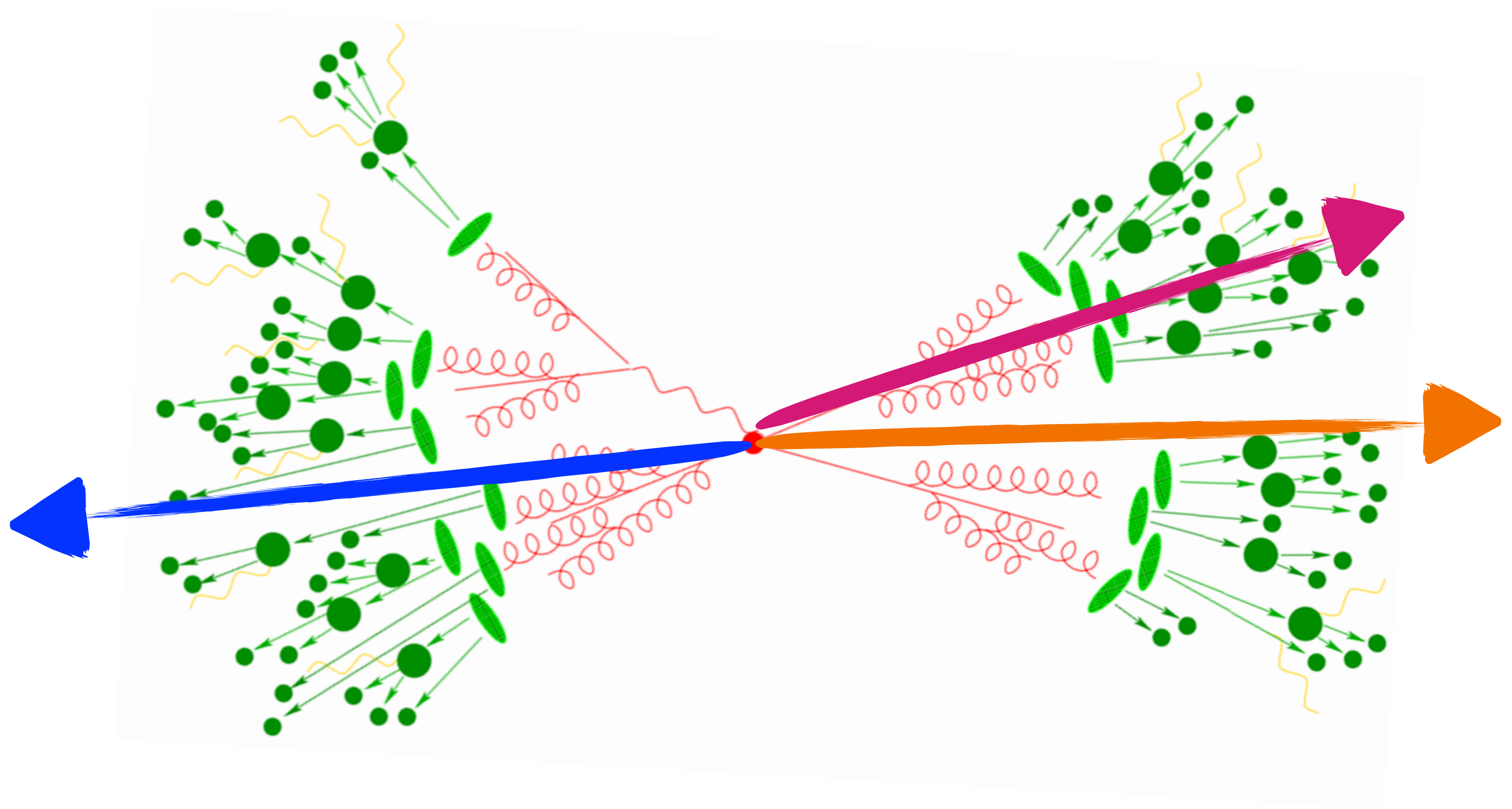
[arXiv:2410.16368]

- **What would higher point correlators look like? Can already take a peak in MC!**

Features of the E3C

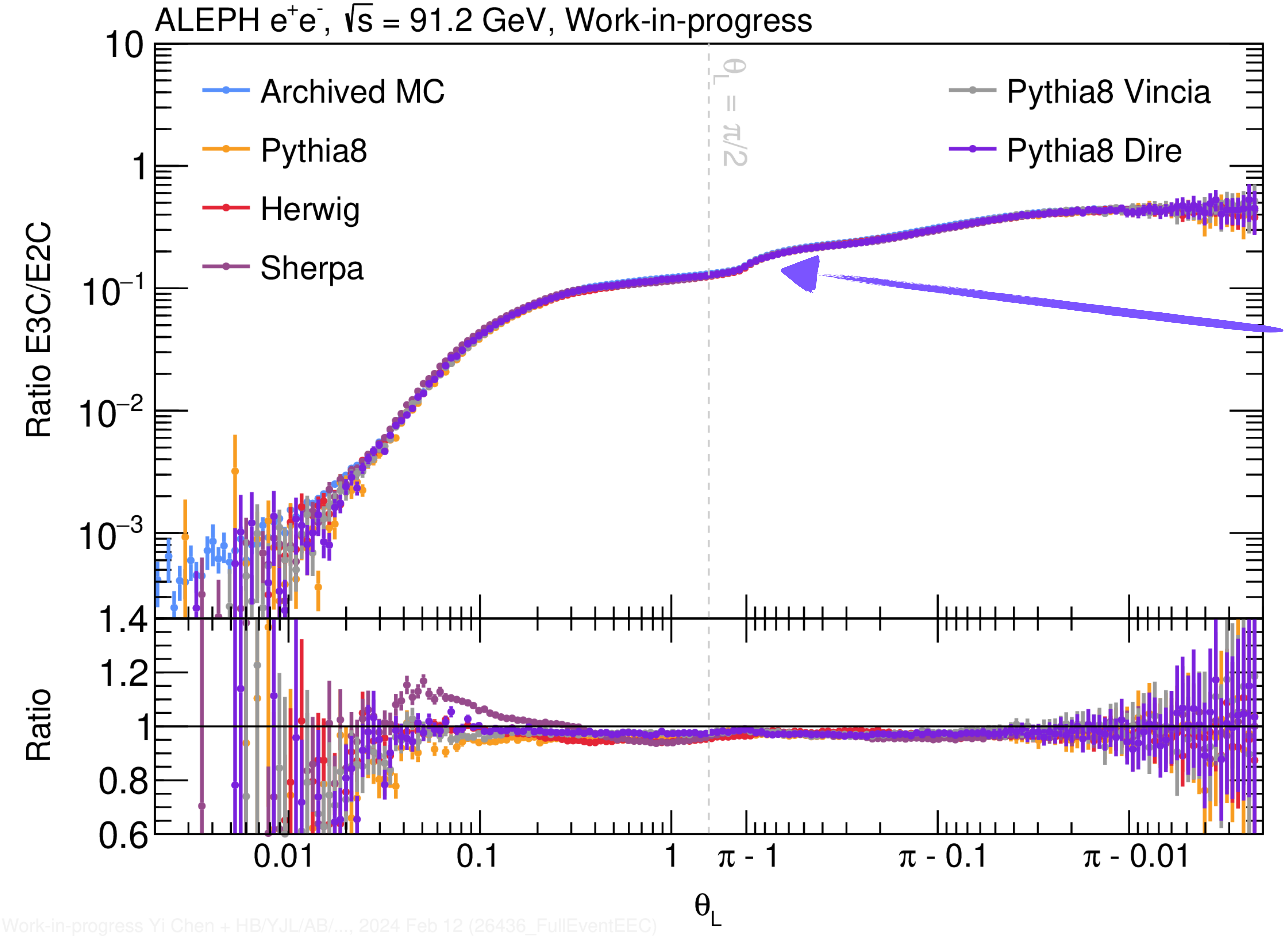


- Asymmetry in the heights of the peaks appears because we choose the max distance.
  - Dominated by configurations with 2 particles from one shower and one particle from the other.

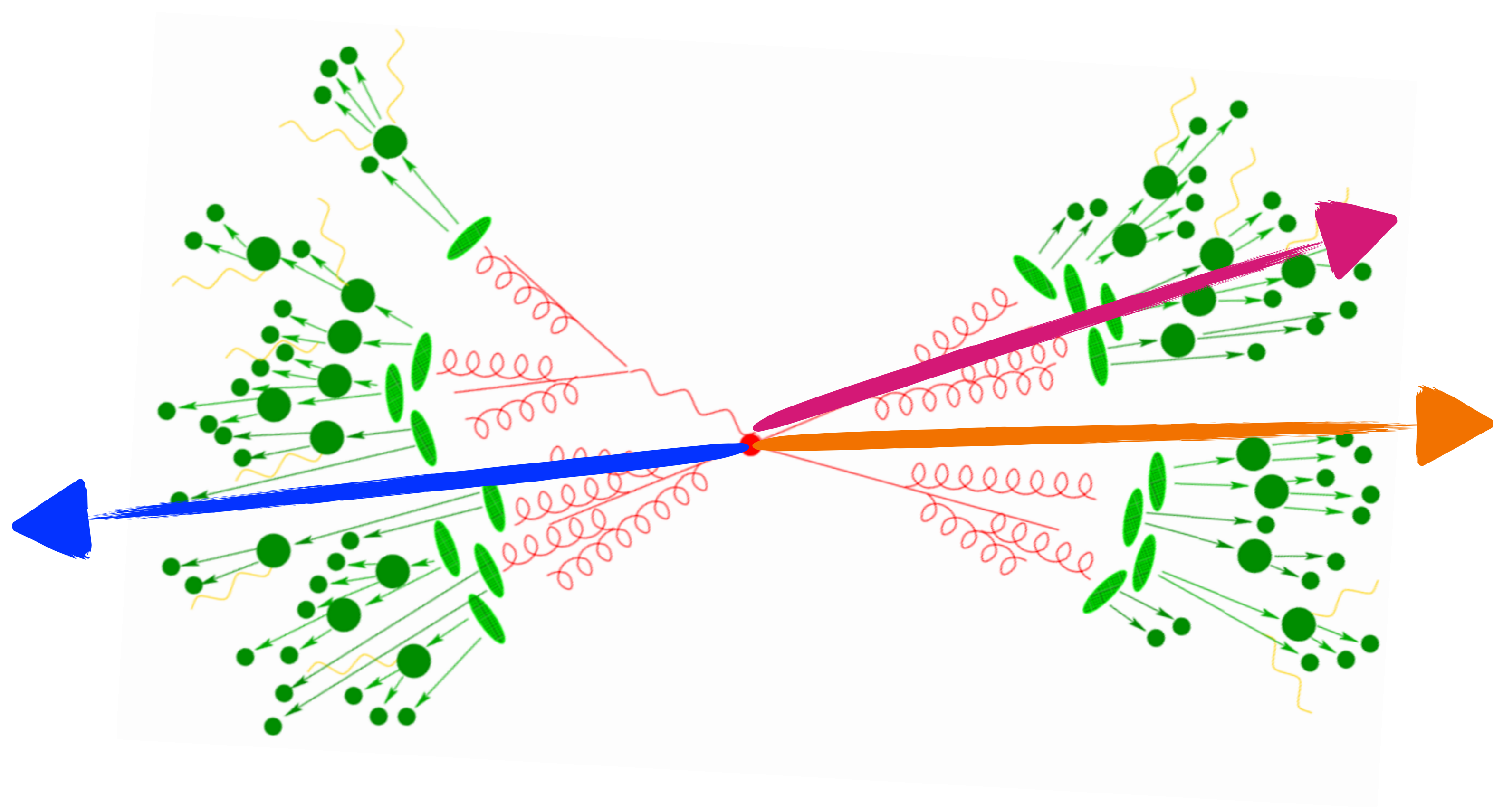


Generators differ by the same 10-20% seen in E2C!

Features of the E3C

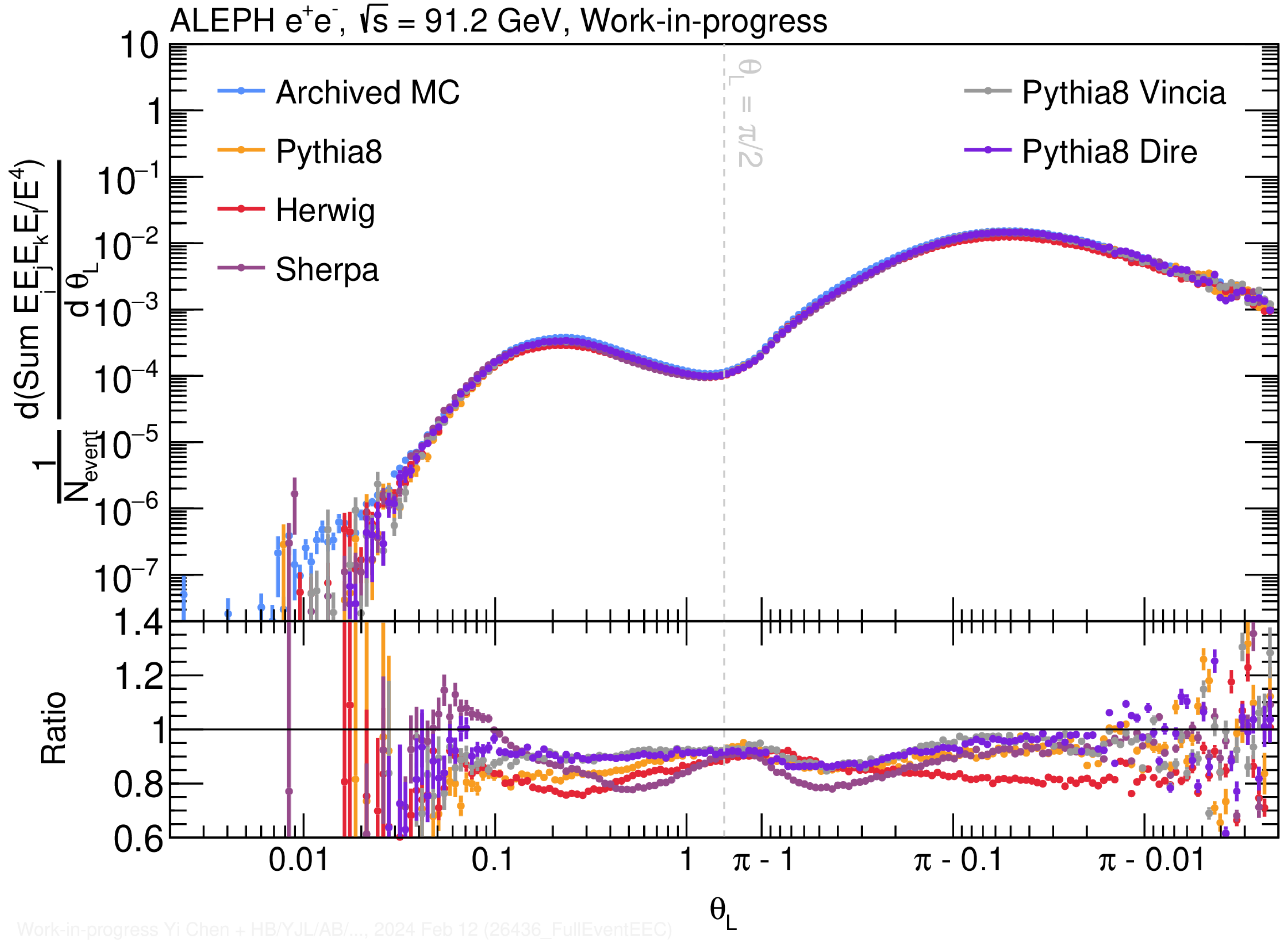


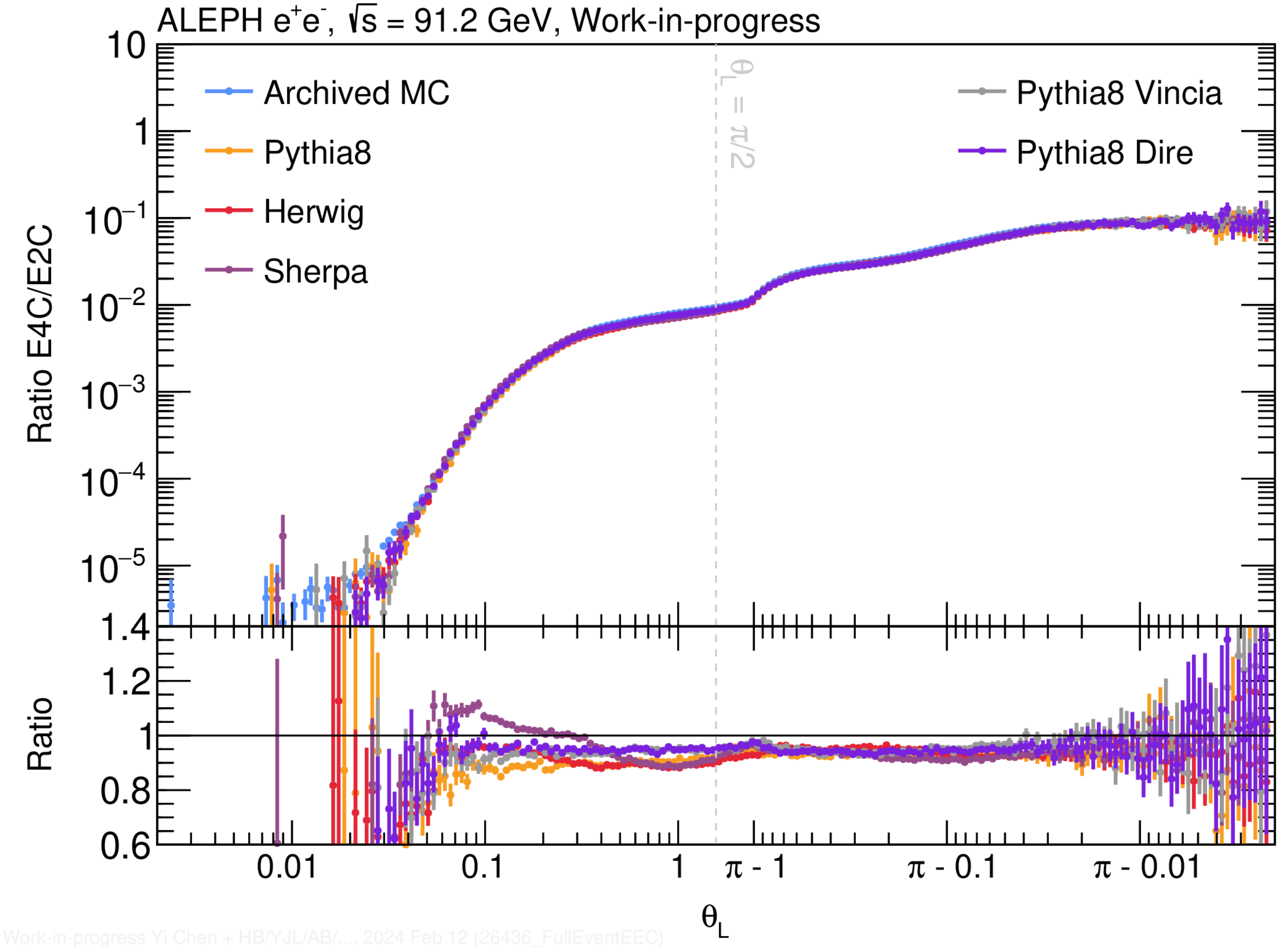
- See a slope change in the E3C/E2C ratio.
- Rejecting 3-jet events removes this structure.



- MCs typically agree upon the ratio, except SHERPA in the small angle region

E4C in ALEPH

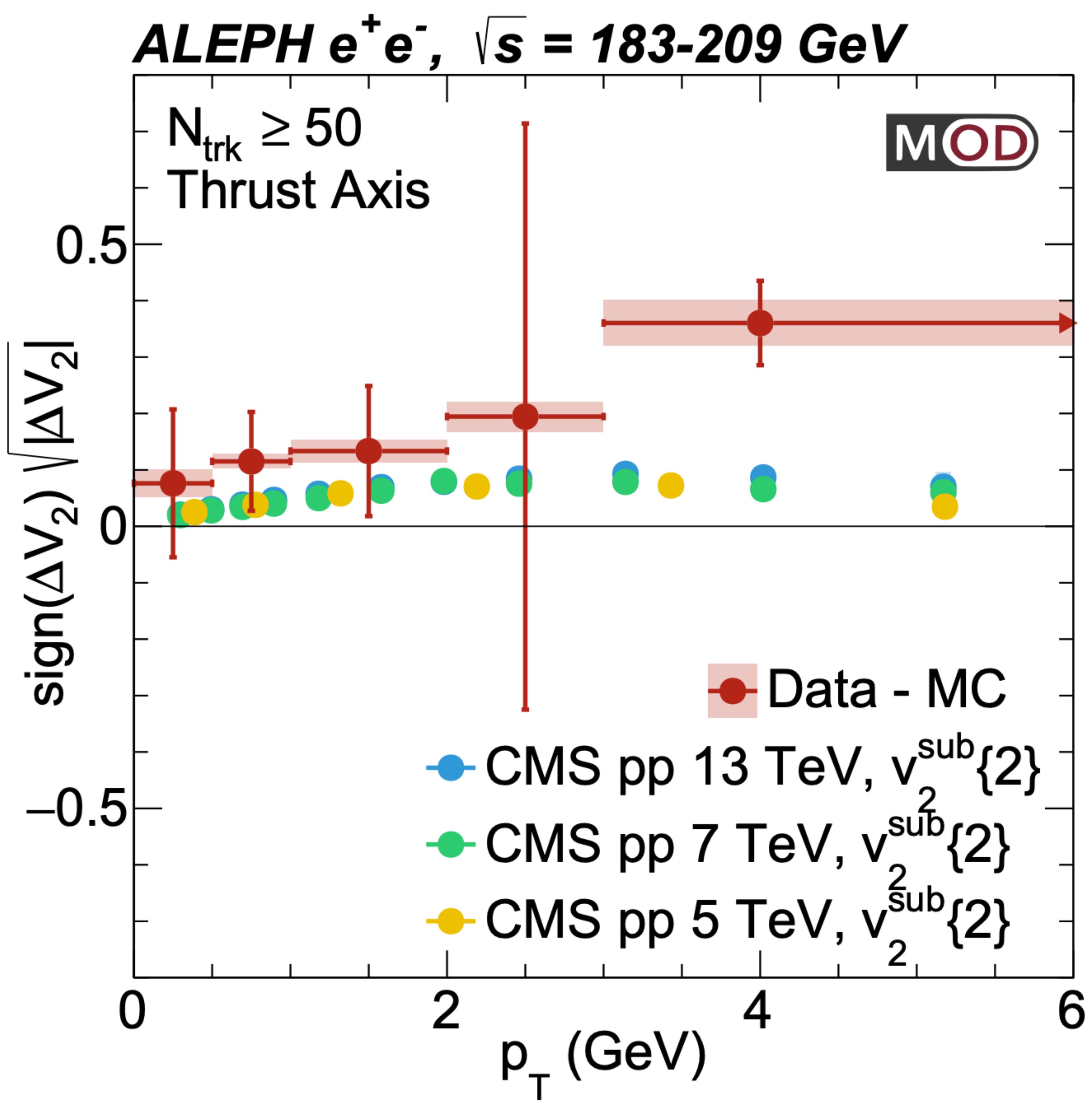




- **Similar trends also seen in the E4C and the ratio of E4C/E2C.**

Look at the multiplicity dependence

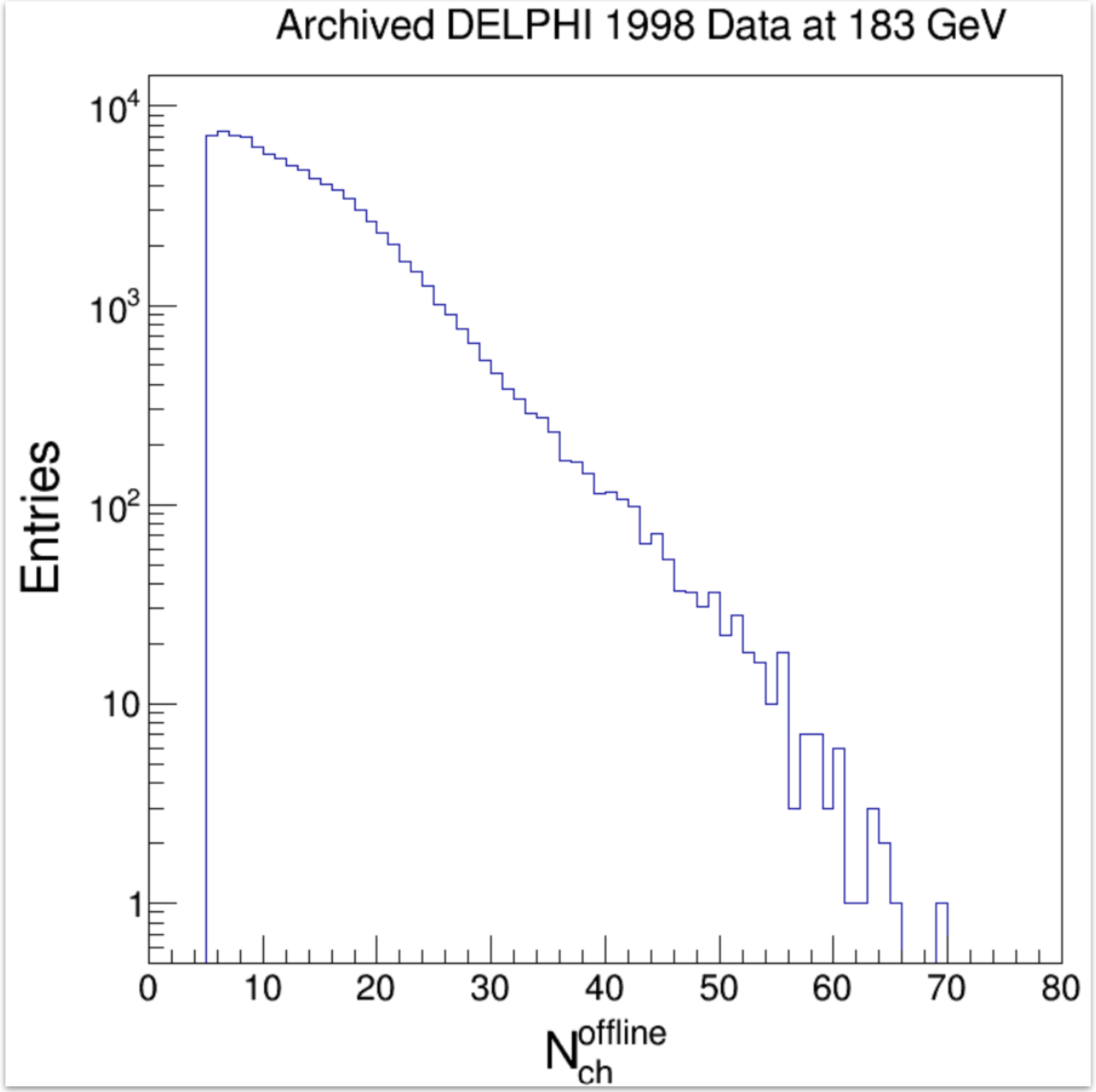
- May be also interesting to study the EEC in different multiplicity intervals to investigate investigate long-range near side excess seen in high multiplicity e^+e^- not seen in Archived MC.



[Phys.Lett.B 856 (2024) 138957]

Possibility discussed in "Light Ions at the LHC" workshop last week!

What about other LEP experiments?



- Yesterday, Yen-Jie took open data from DELPHI (publicly available here) and drew the multiplicity distribution.
- **Challenge:** code is outdated, need knowledge of Fortran, etc.
- Maybe we can grow our available archived datasets!

DELPHI collision data hadr98_e1

DELPHI

Dataset | Collision | DELPHI | 181-210 GeV | e+e- | CERN-LEP

Description

XShort DSTs,hadronic events for analysis; 98 data, 5th proc. Fix 1

Dataset characteristics

216319 events. **32** files. **4.9 GiB** in total.

How were these data selected?

The data was recorded by the DELPHI detector in the year 1998. It was then reconstructed by the detector reconstuction program DELANA and the physics DST program PXDST (Version v98e1).

Summary and conclusions

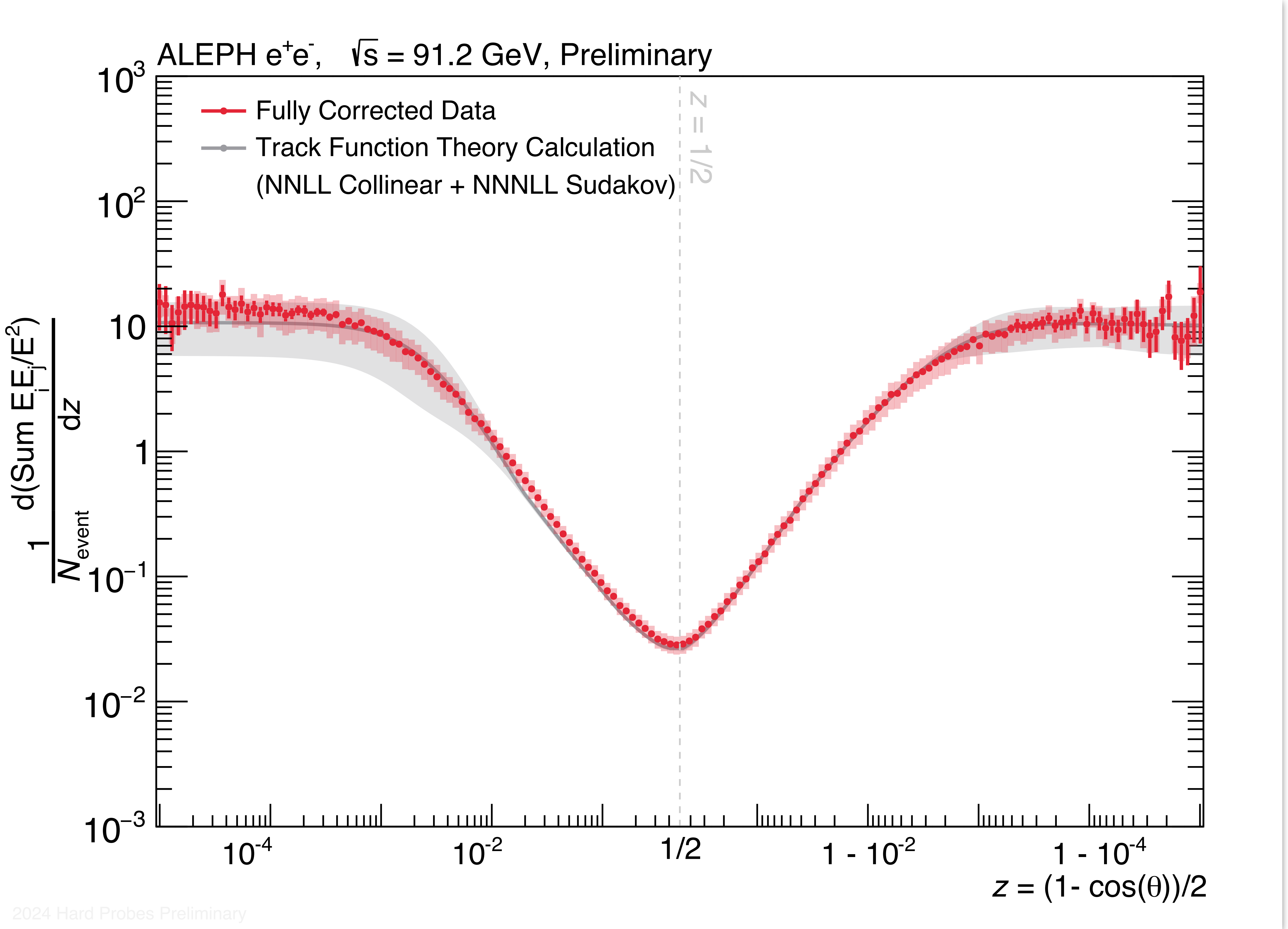
Energy correlators are powerful tools that can be useful for different types of QCD studies.

- **Performing precision measurements**

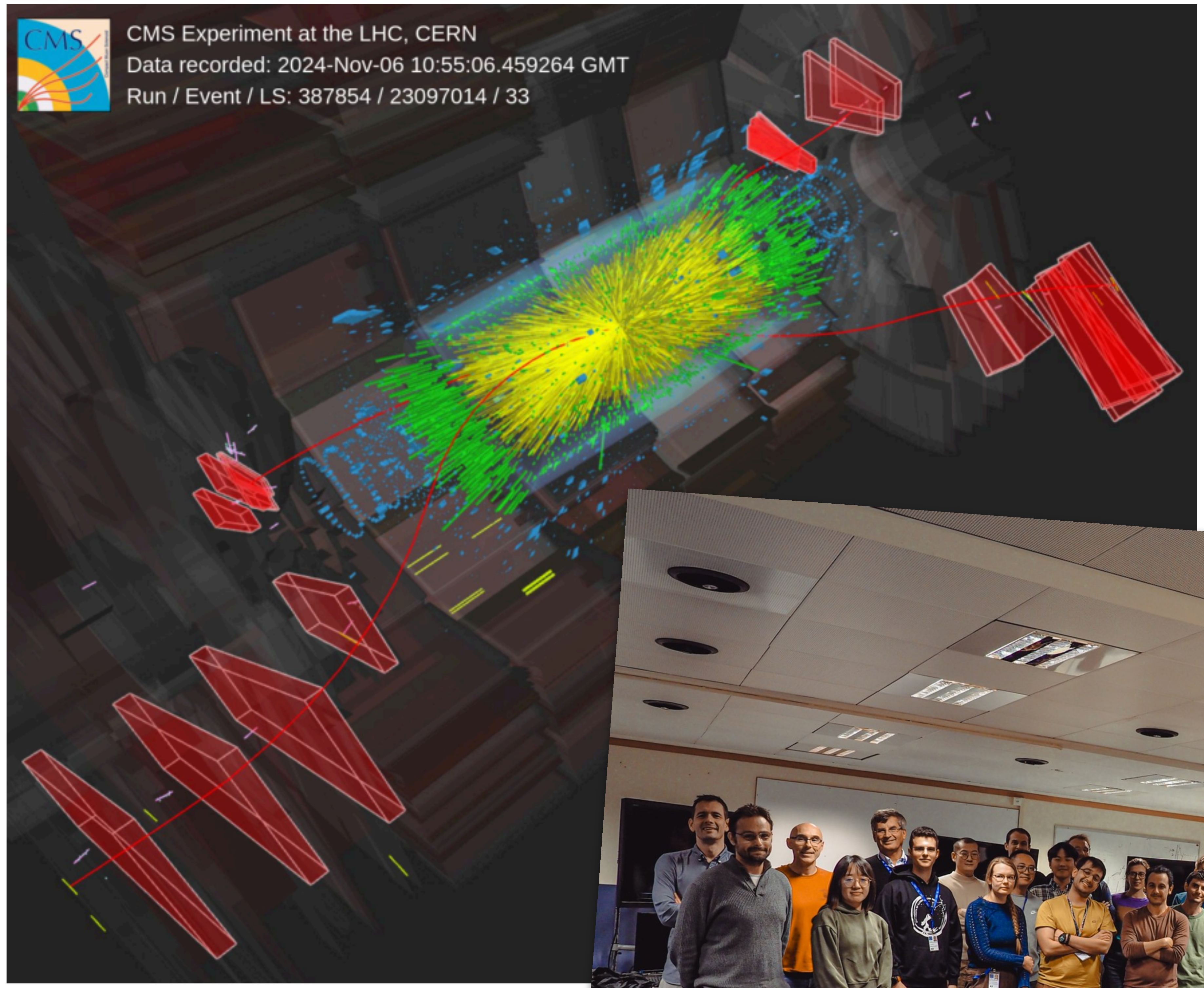
- First fully-corrected measurement of EECs from collinear to the back-to-back region using ALEPH archived data.

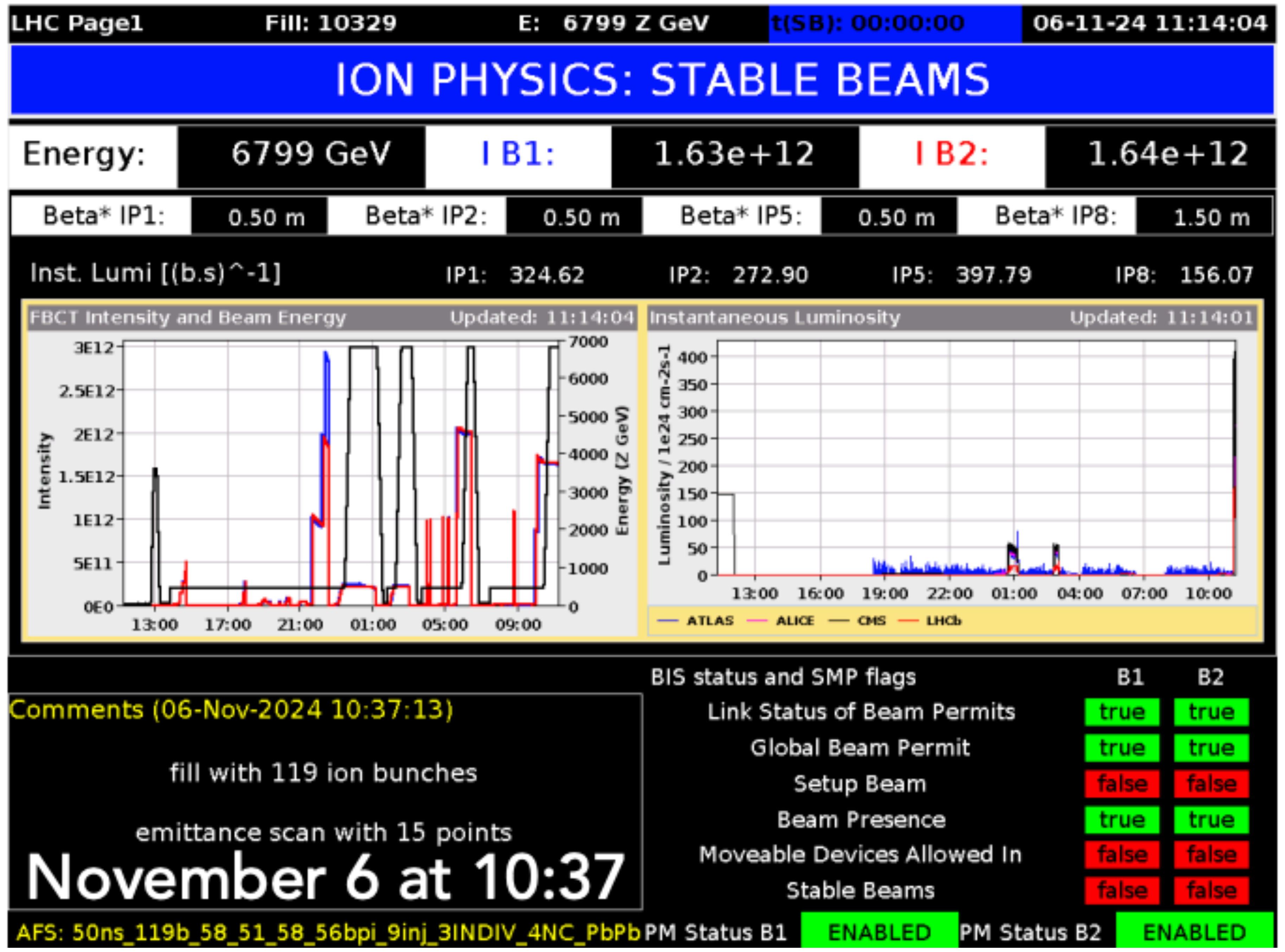
    - Crucial for testing QCD and phenomenological models. Data provides first constraints in the back-to-back region!

- Check out the data here!



Lots to look forward to!





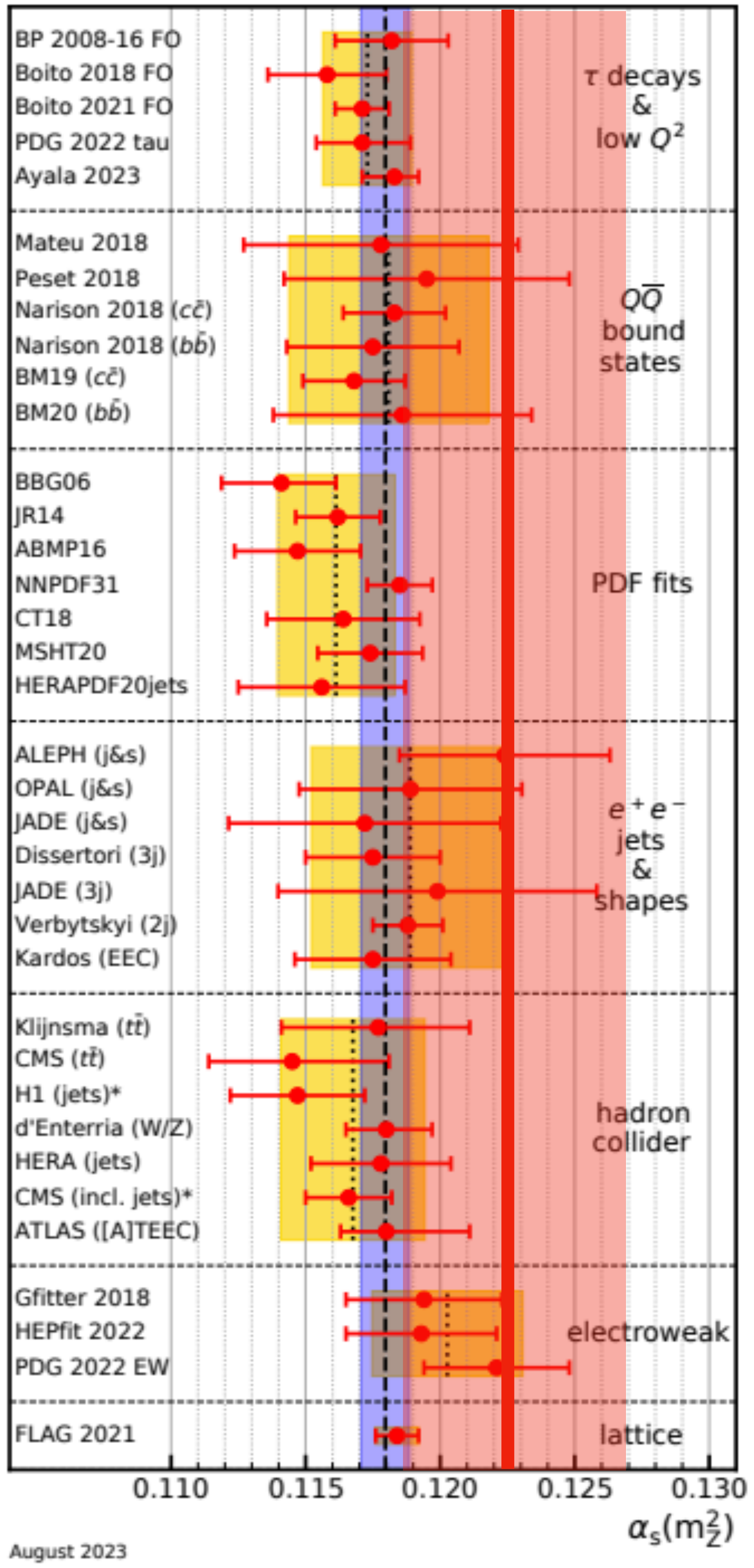
2024 HI Run of the LHC currently ongoing (until Sunday)!

Massachusetts Institute of Technology

Backup

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

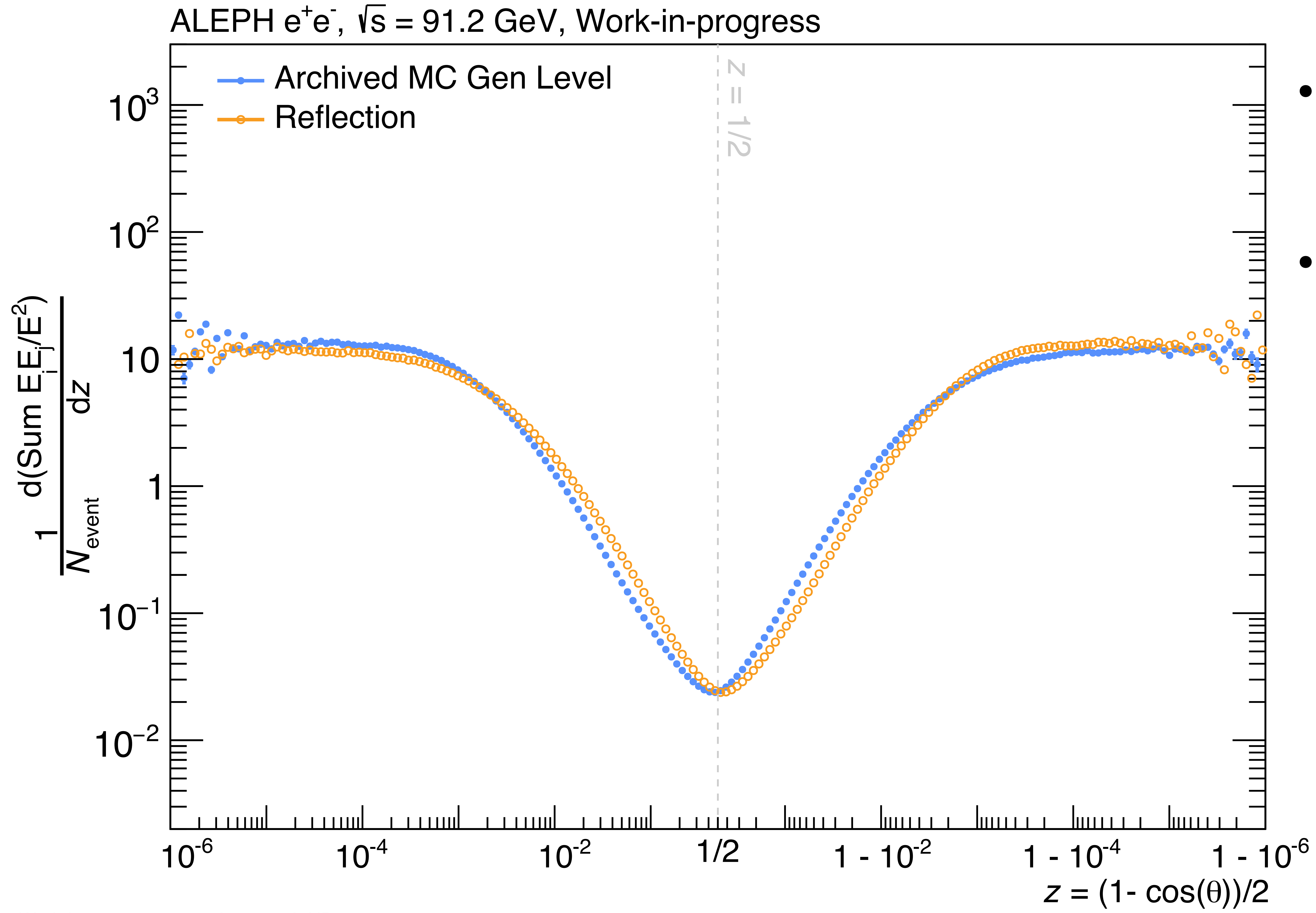
α_s from CMS compared to world average



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

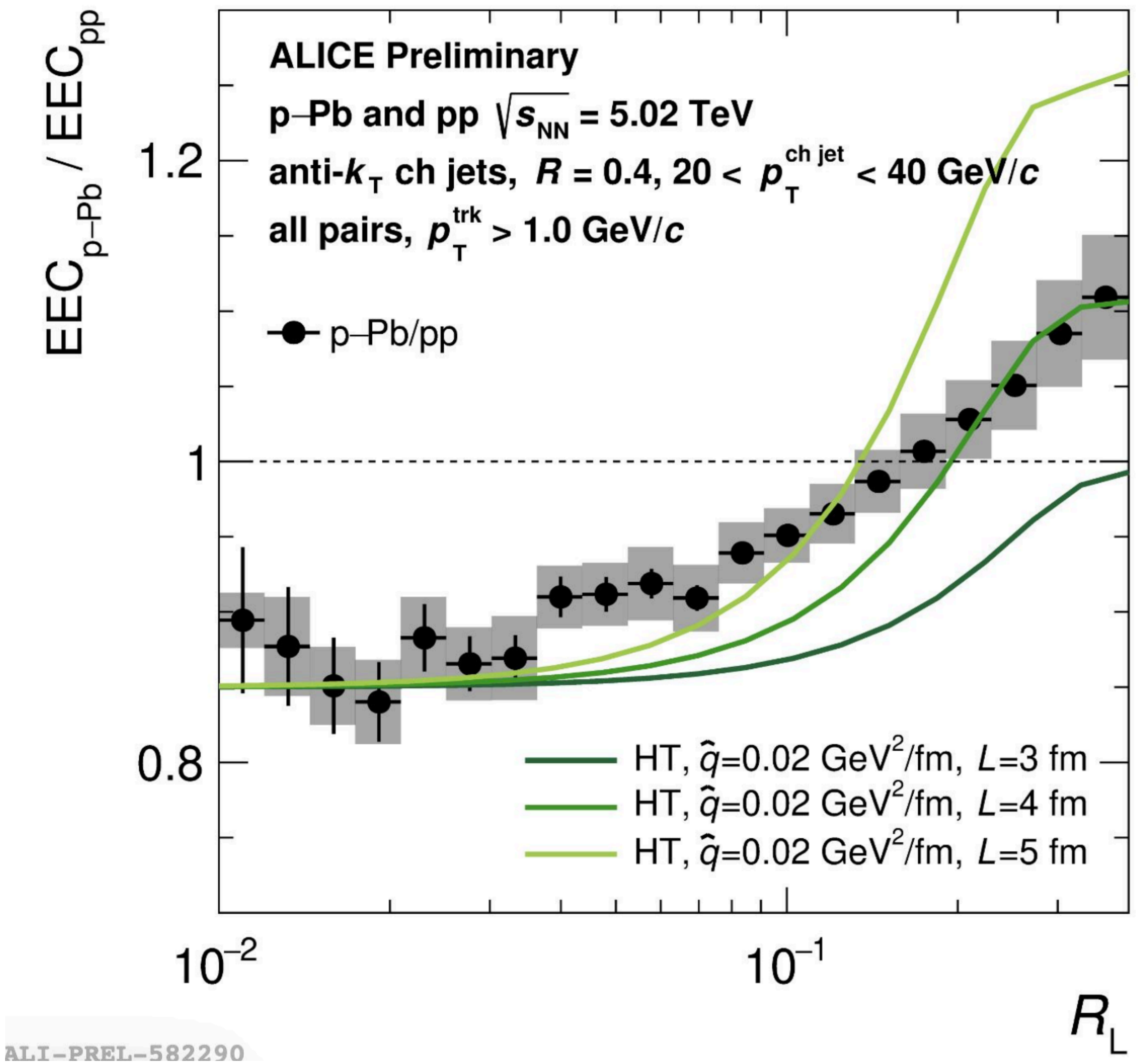
$$0.1229\ ^{+0.0040}_{-0.0050}\text{(combined)}$$

How “flat” is the E2C(z)?



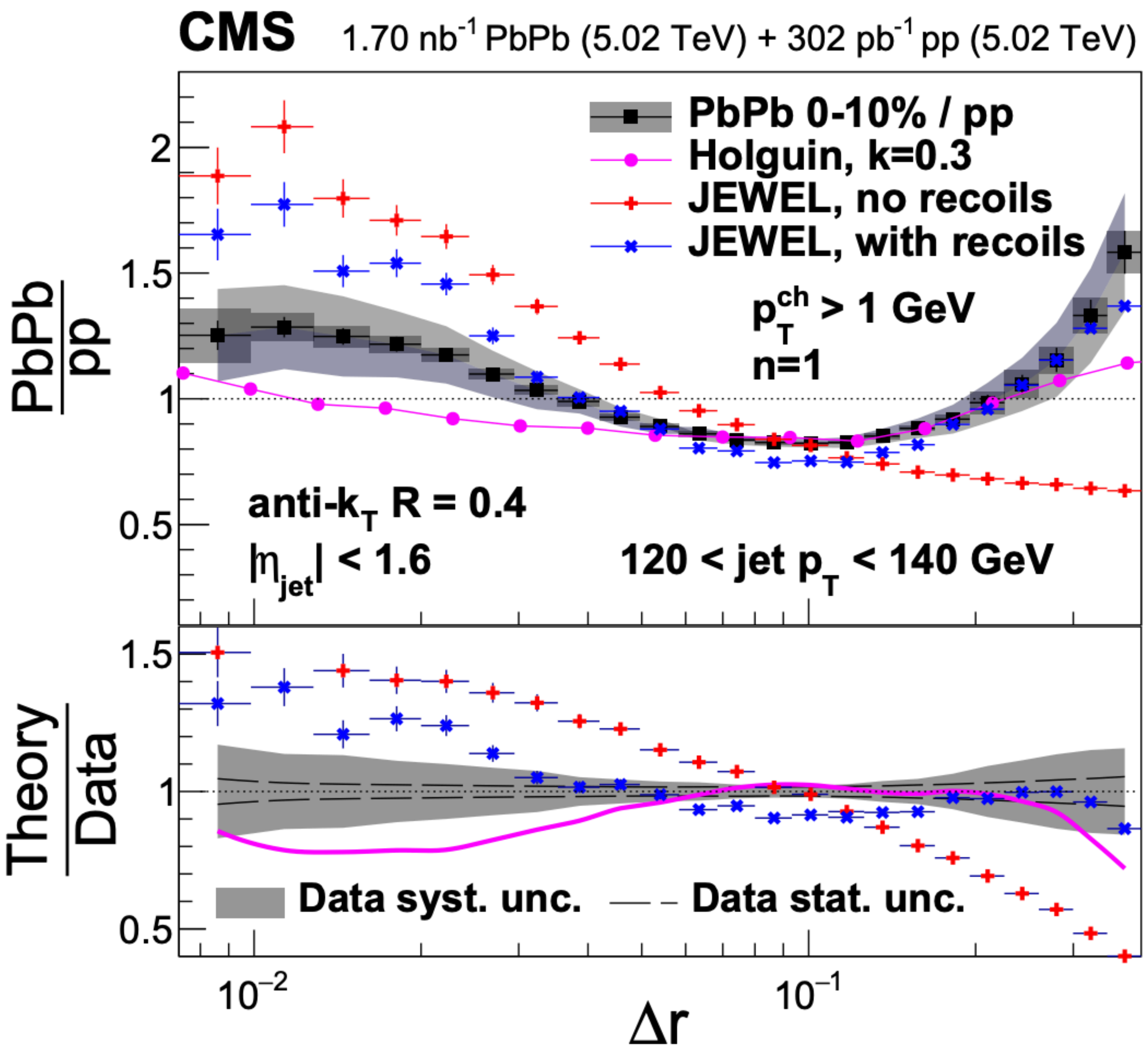
- Take distribution and reflect it, comparing it to itself.
- Focus on the free hadron region.

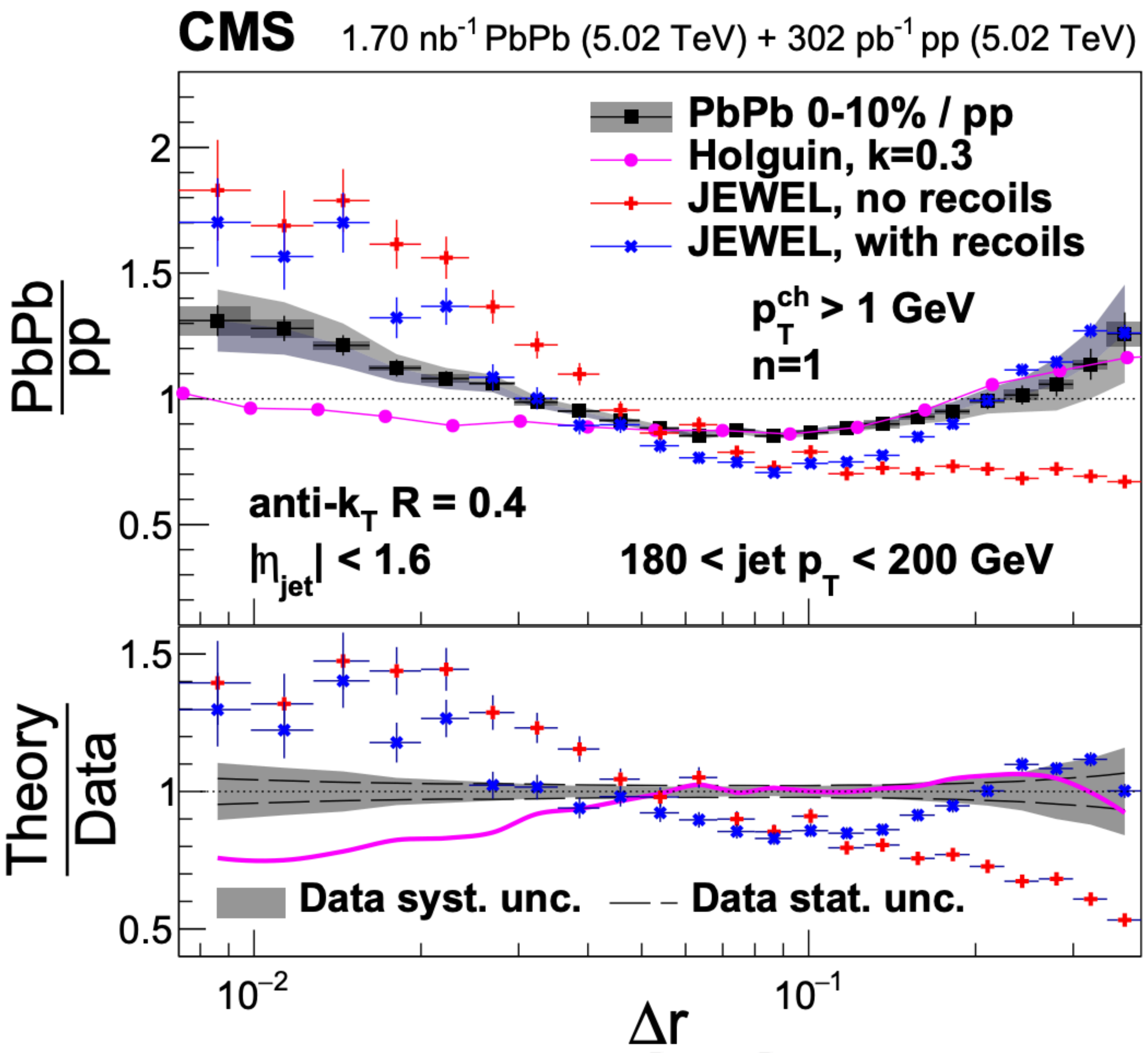
EECs in pPb collisions



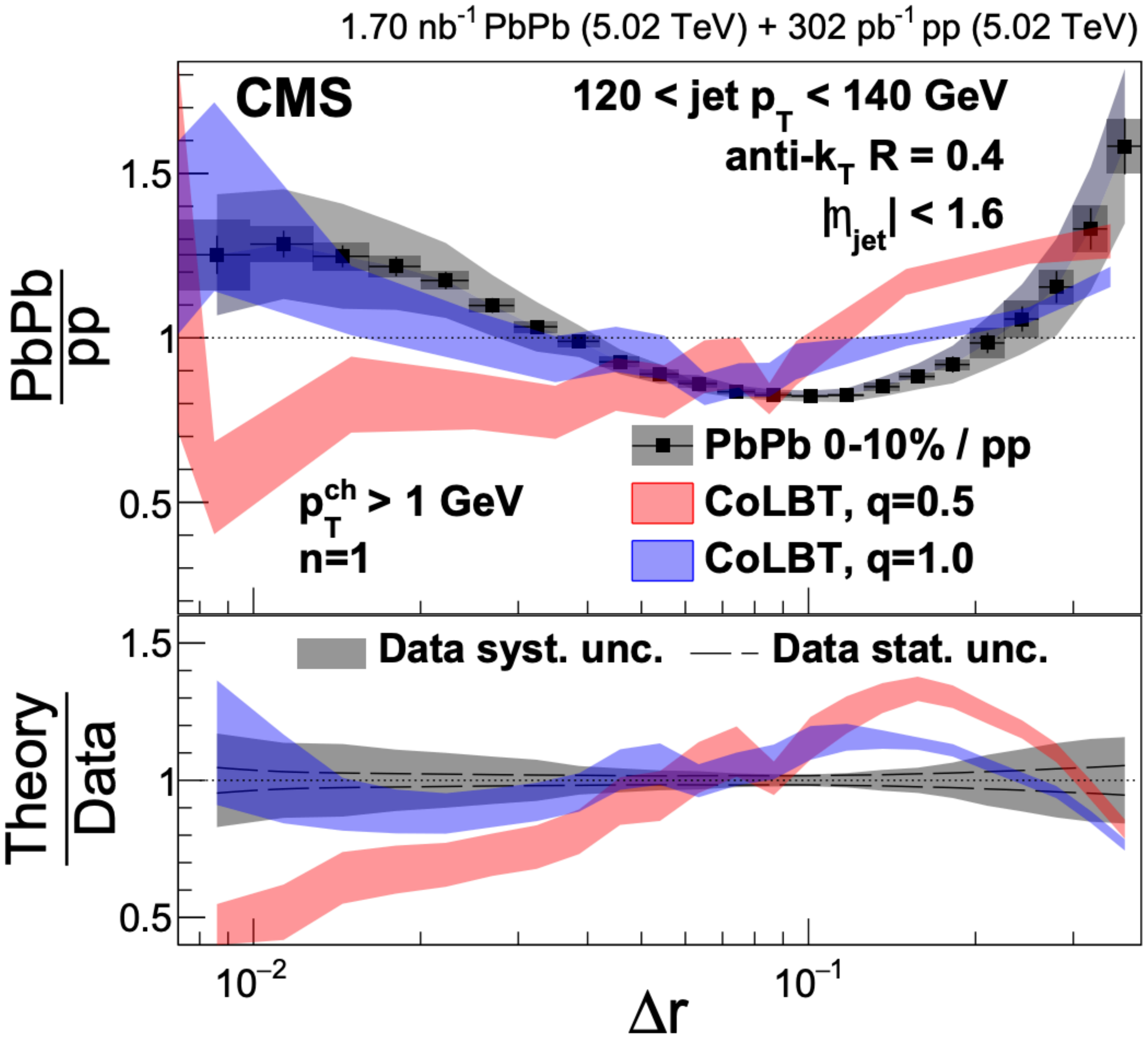
[See Anjali's talk at HP for more details!]

EEcs in heavy-ions model comparisons

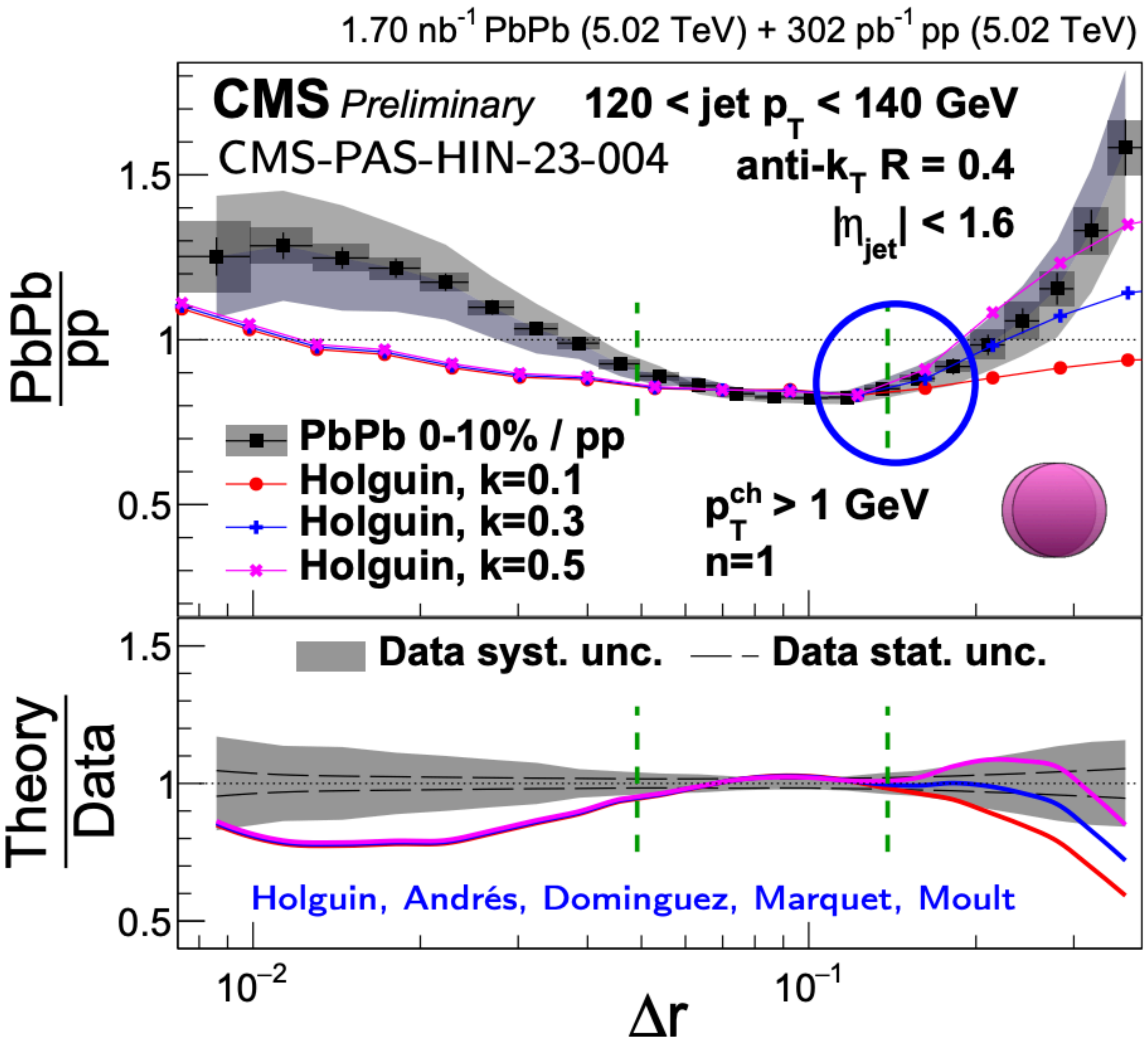


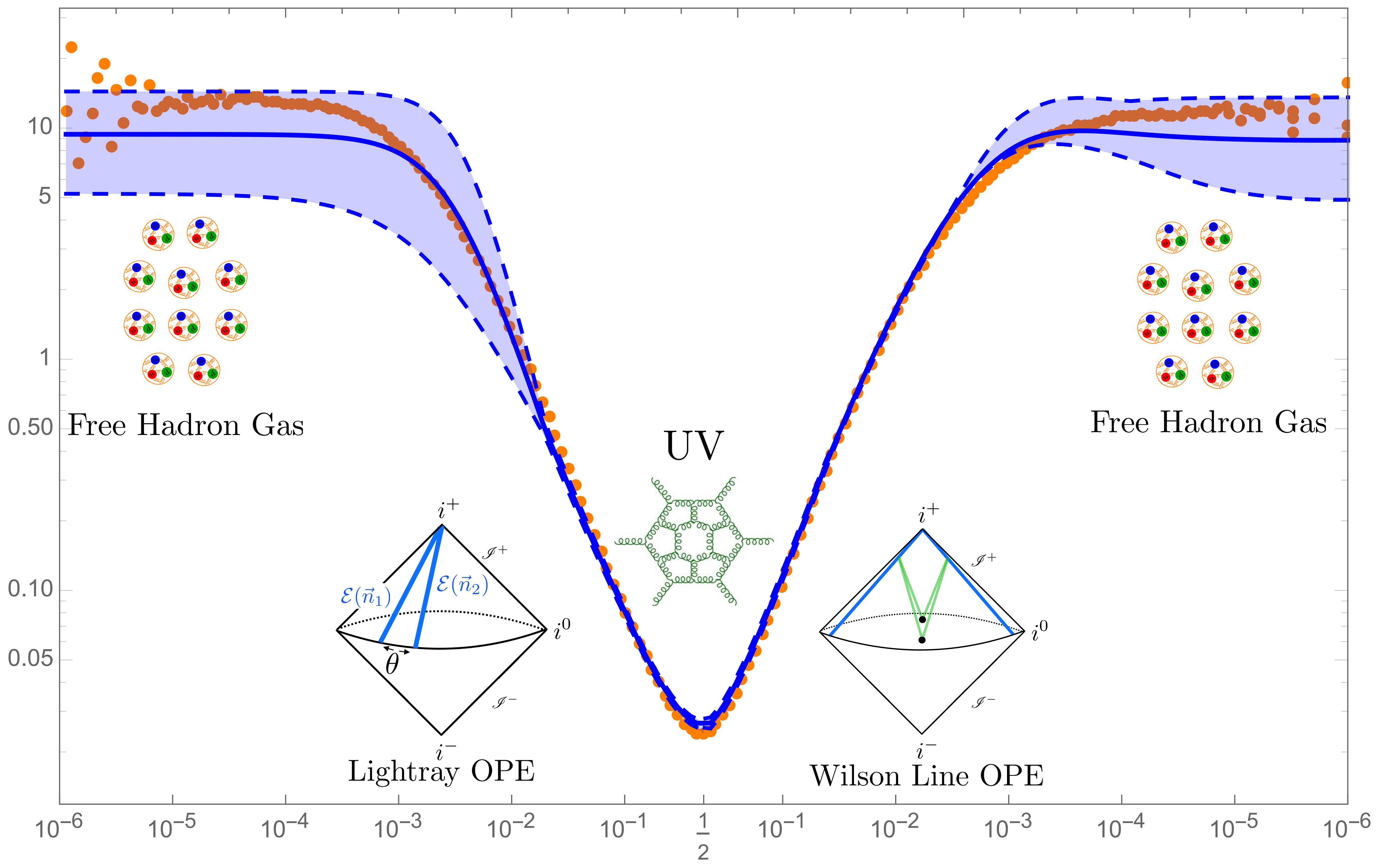


EECs in heavy-ions model comparisons



EECs in heavy-ions model comparisons

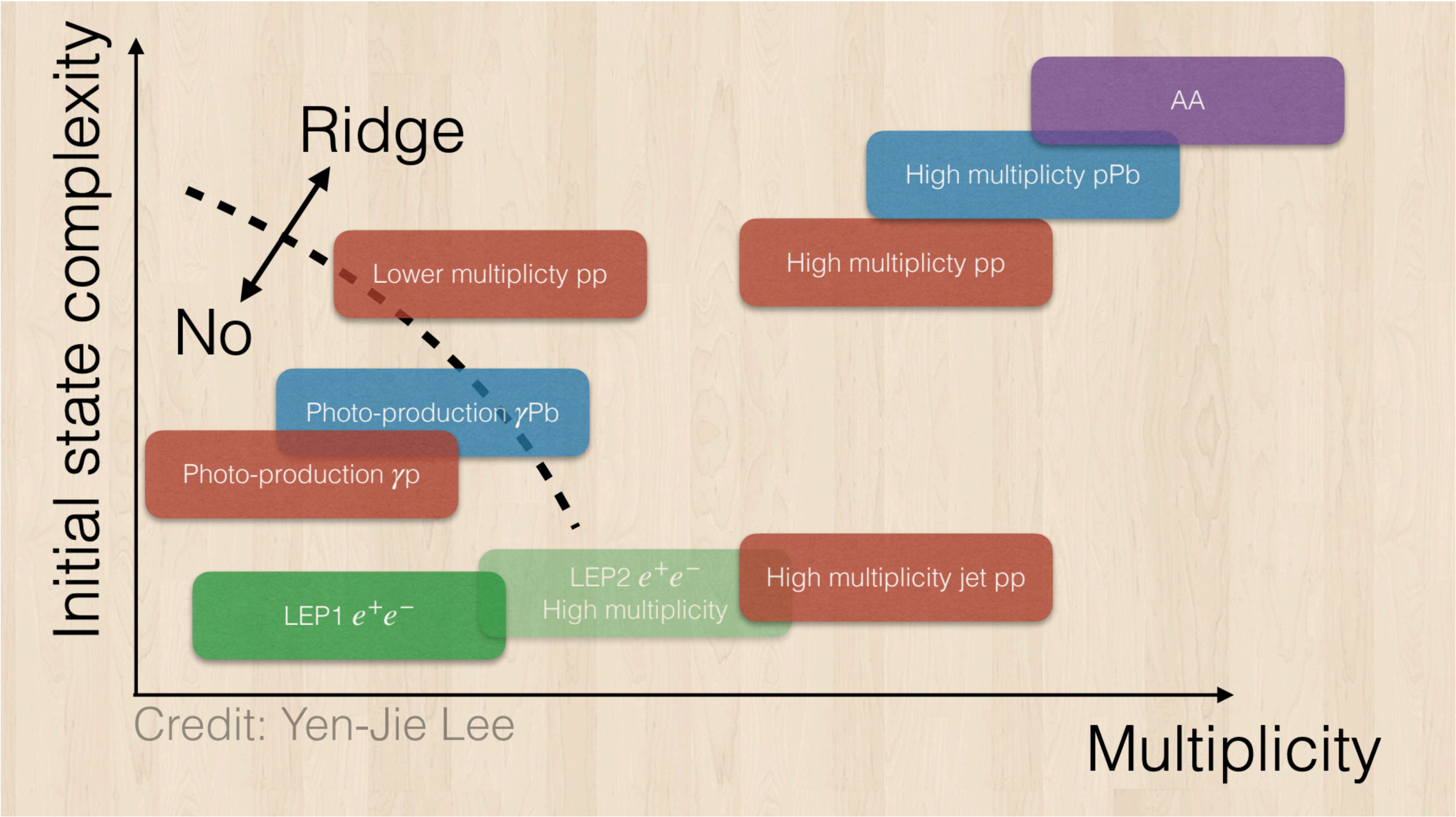




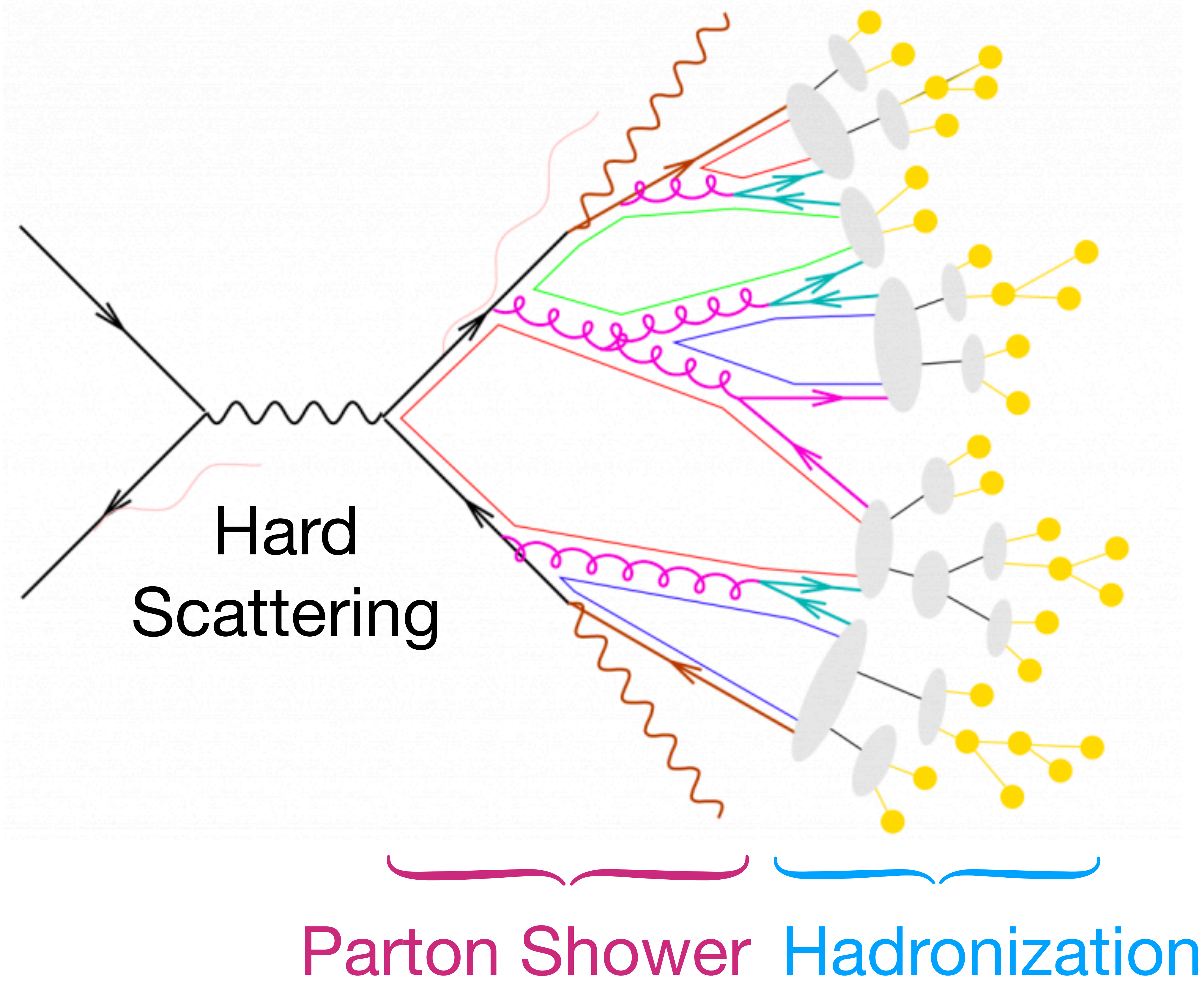
Collinear Limit:
-NNLL Collinear Resummation (Three Loop DGLAP Evolution)
- **Non-Perturbative Parameter Ω extracted from thrust**

Back-to-Back Limit:
-NNNLL Sudakov Resummation
- **Non-Perturbative Parameter Ω**
- **extracted from thrust**
- **Collins-Soper Kernel extracted from lattice QCD**

Uncertainty band is a combination of perturbative scale variation, and variation of non-perturbative parameters. Large error bars in the flat “plateau” regions are due to non-perturbative physics. Measurement constrains these regions.


Initial state complexity
Ridge
No
AA
High multiplicty pPb
High multiplicty pp
Lower multiplicty pp
Photo-production γPb
Photo-production γp
LEP2 e^+e^-
High multiplicity
High multiplicity jet pp
LEP1 e^+e^-
Credit: Yen-Jie Lee
Multiplicity

Studying QCD with jets

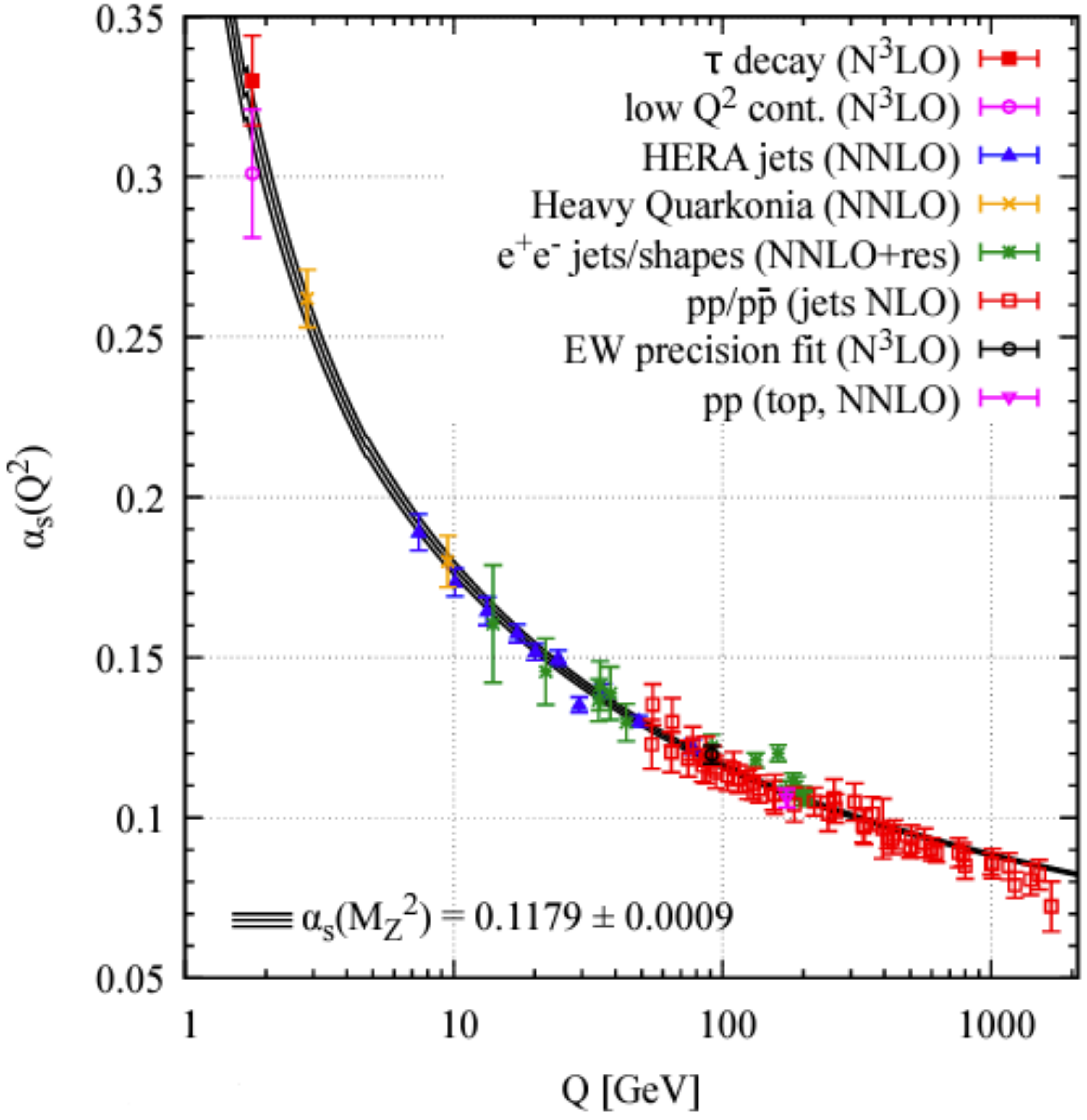


- In hadronic collisions, partons will hard-scatter.
- In e^+e^- collisions annihilate producing a quark/anti-quark pair.
- A jet is the spray of particles that results from the fragmentation and hadronization of an outgoing parton.
- Defined by specific algorithms that cluster particles roughly into a cone of radius *R*.

Jets are sensitive to physics information from many physics scales → great object to study these different processes!

Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the theory of the strong force

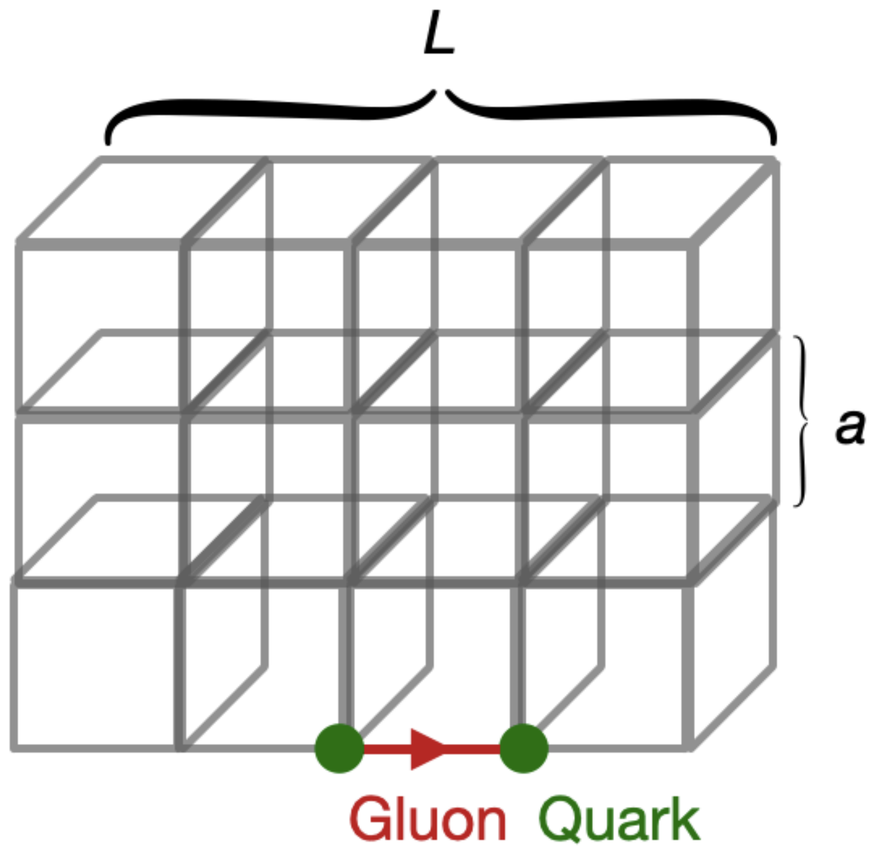


[Review of Particle Physics. PTEP, 2022:083C01, 2022]

Interaction strength dictated by the coupling constant α_s

Can solve QCD

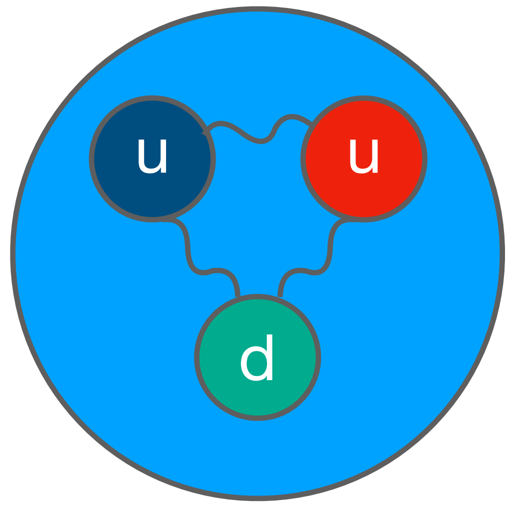
1. Using perturbative expansions in powers of α_s (perturbative QCD, $\alpha_s \ll 1$)
2. Using non-perturbative techniques (non-perturbative QCD, $\alpha_s \sim \mathcal{O}(1)$)



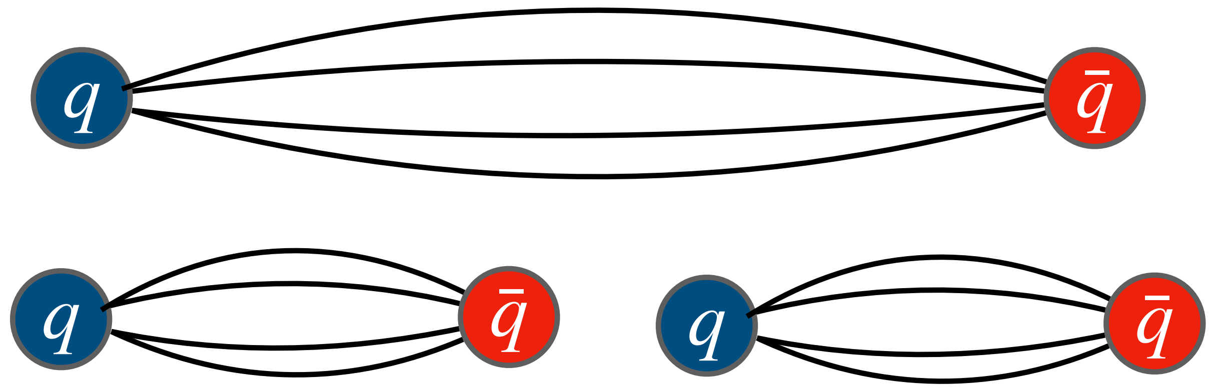
Ex: Lattice QCD

Defining features of QCD

① ***Color confinement:***
Colored partons have never been observed in isolation



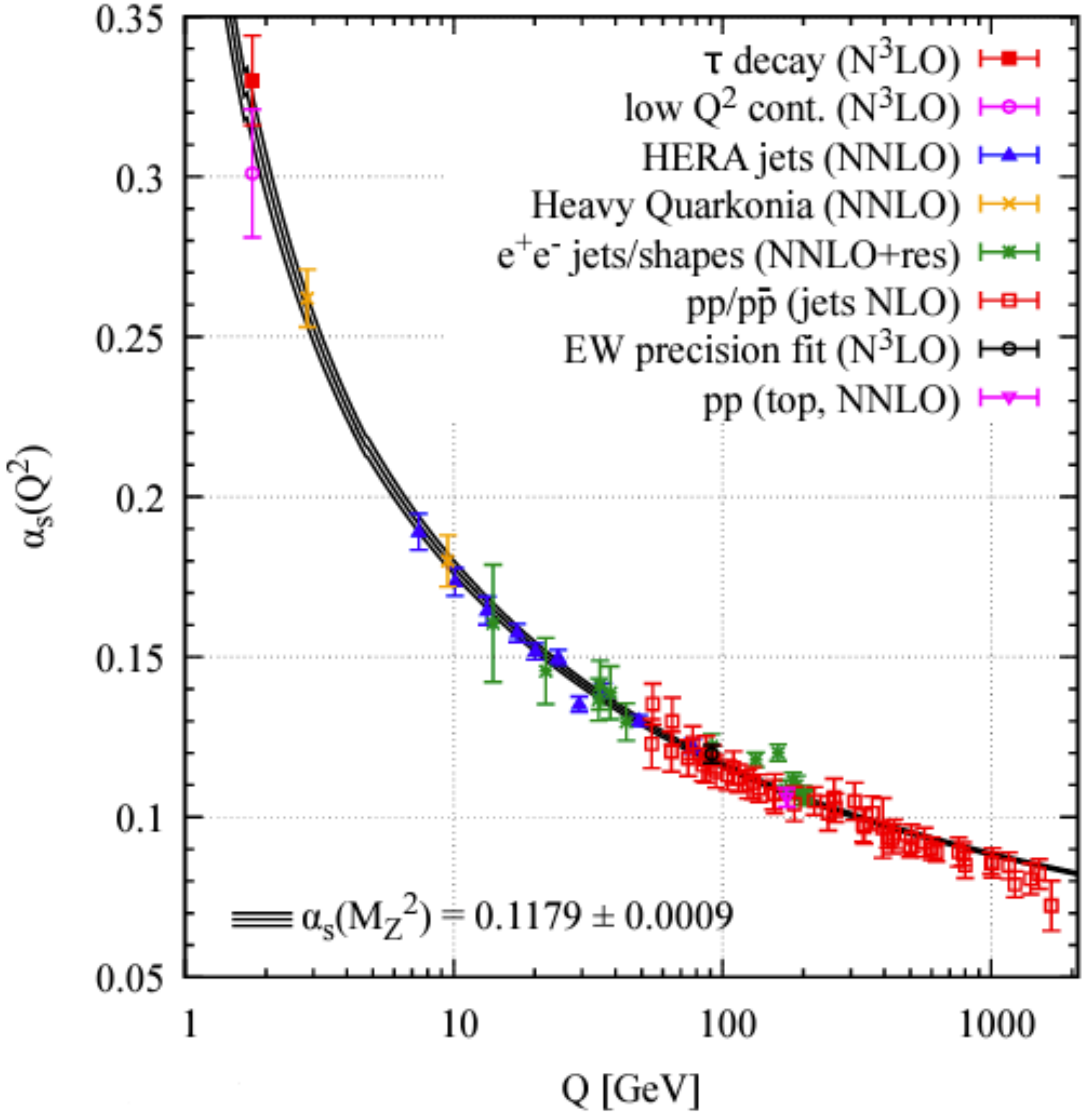
QCD potential grows as r increases



$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

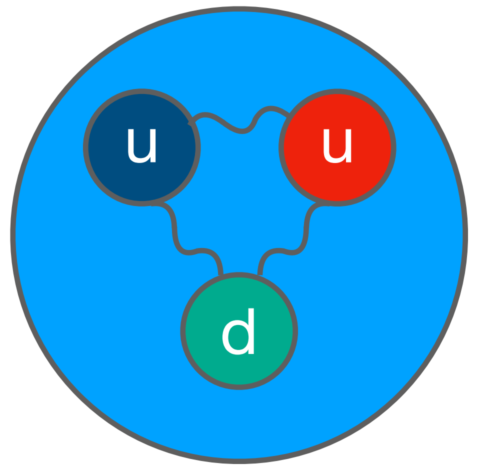
As you pull quarks apart at some point becomes favorable to form a new $q\bar{q}$ pair

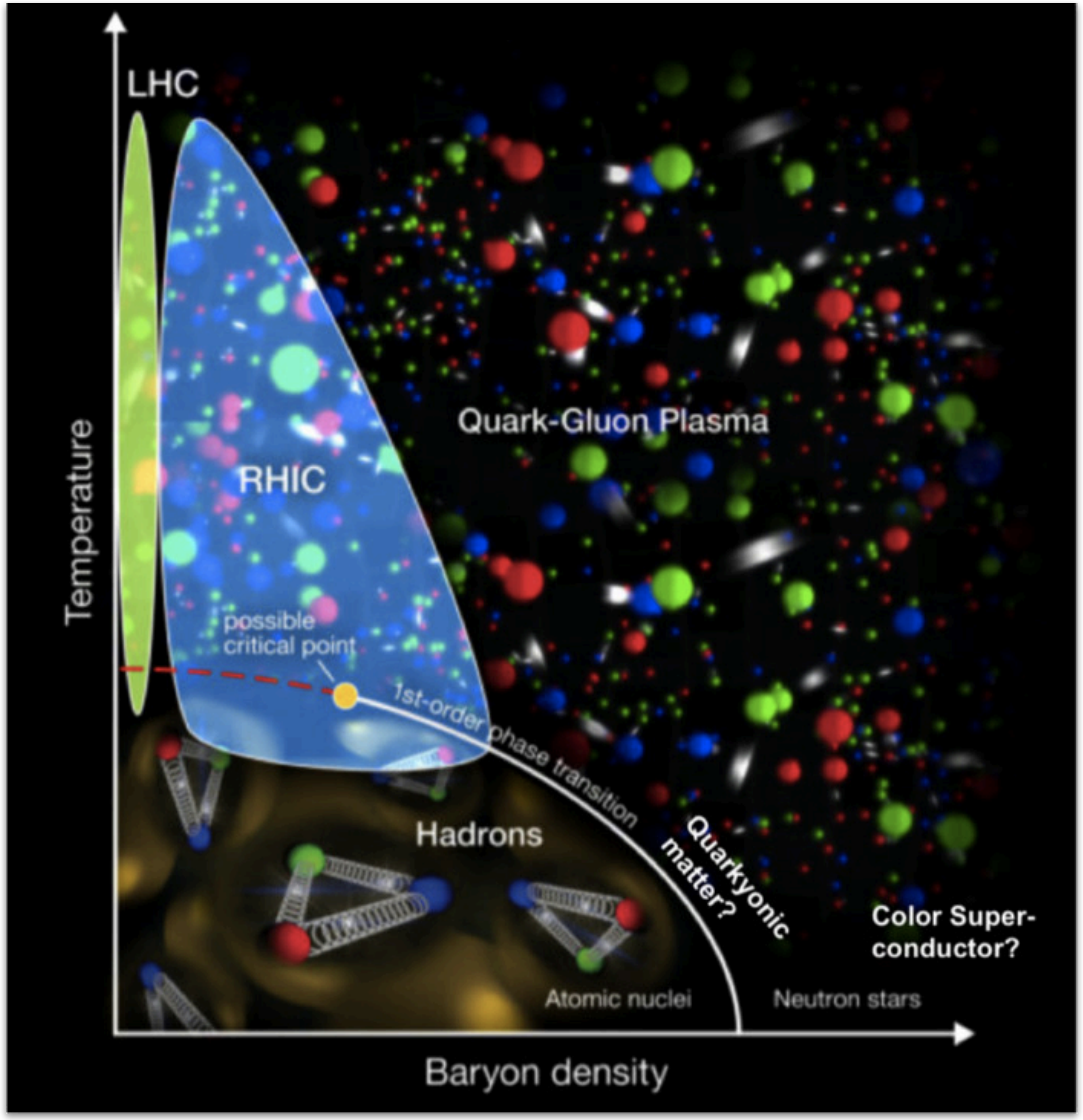
[Review of Particle Physics. PTEP, 2022:083C01, 2022]



② ***Asymptotic freedom:*** α_s decreases at high energies (high Q) and short distances

QCD Phase Diagram





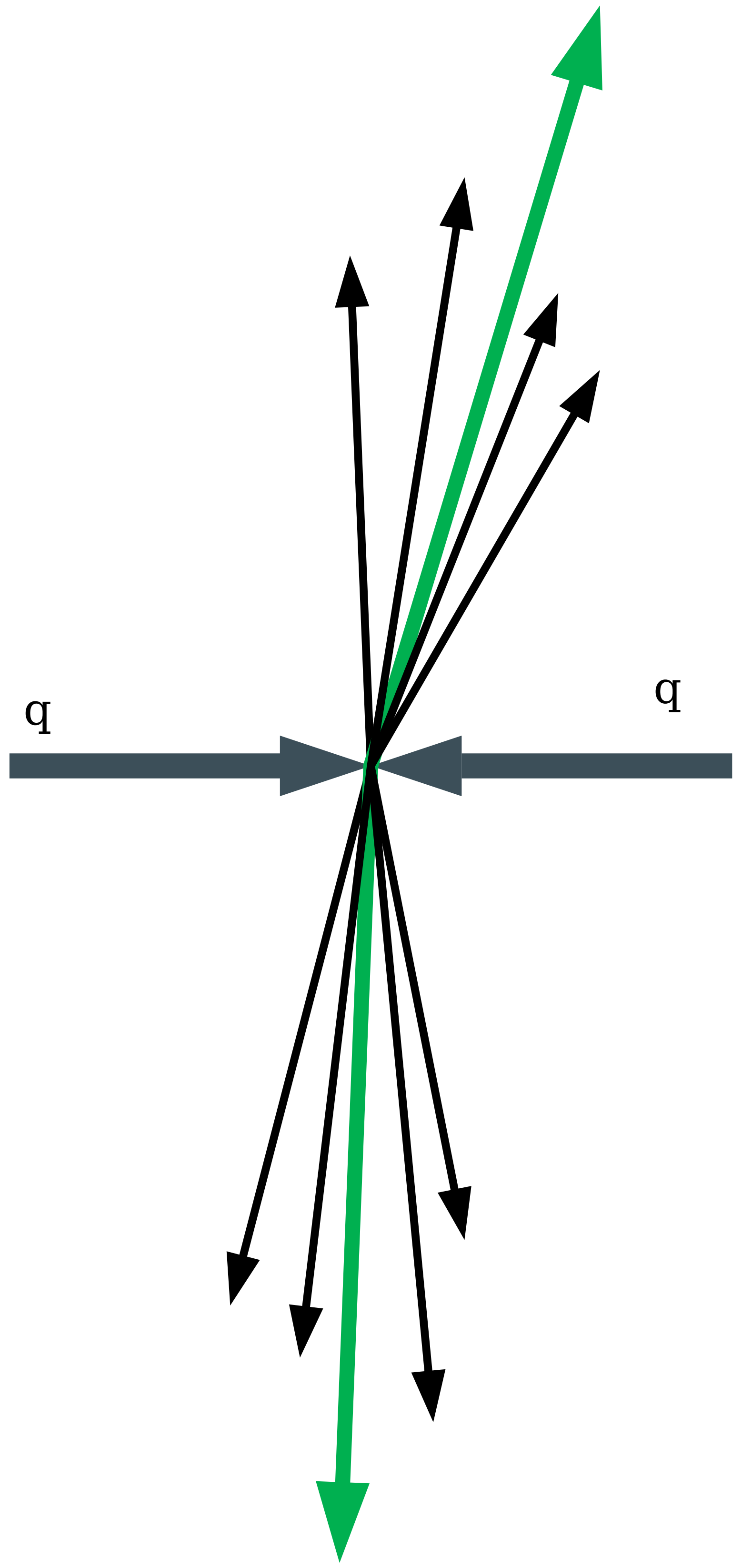
[Image Credit: Brookhaven National Lab]

When temperature is hot enough QCD matter becomes a deconfined state of quarks and gluons called the **Quark-Gluon Plasma (QGP)**

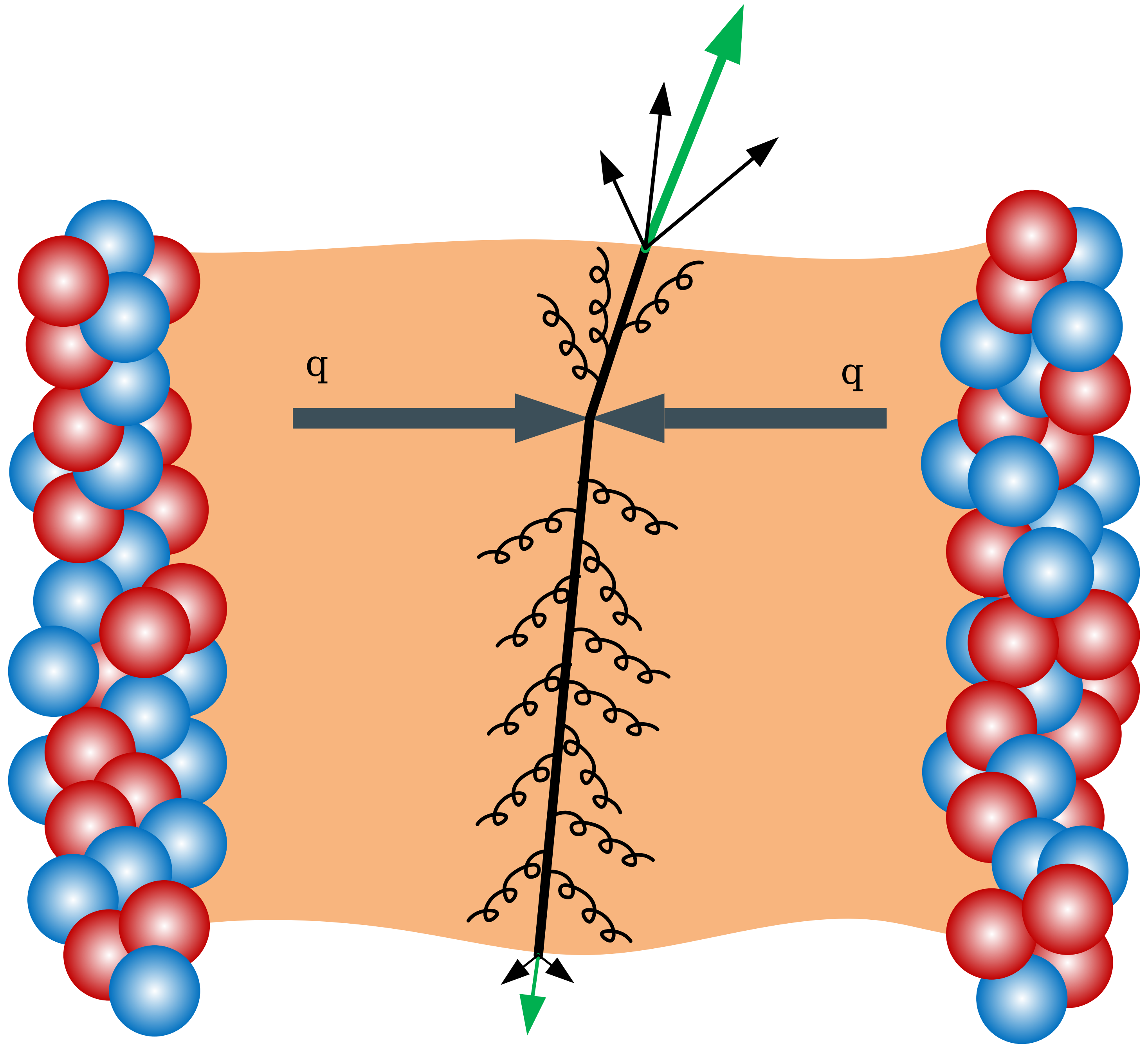
Lattice QCD predicts smooth crossover at $\mu_B = 0$ and $T_c \sim 150$ MeV ($\sim 10^{12}$ K).

Can recreate similar conditions in ultra-relativistic heavy-ion collisions.

Jets in heavy-ion collisions



pp



Heavy-Ions (Pb—Pb)

→ High p_{T} parton is expected to lose energy in interactions with the hot and dense medium in heavy-ion collisions **(jet quenching)**.

→ Jets are a colored probe of the colored QGP medium!

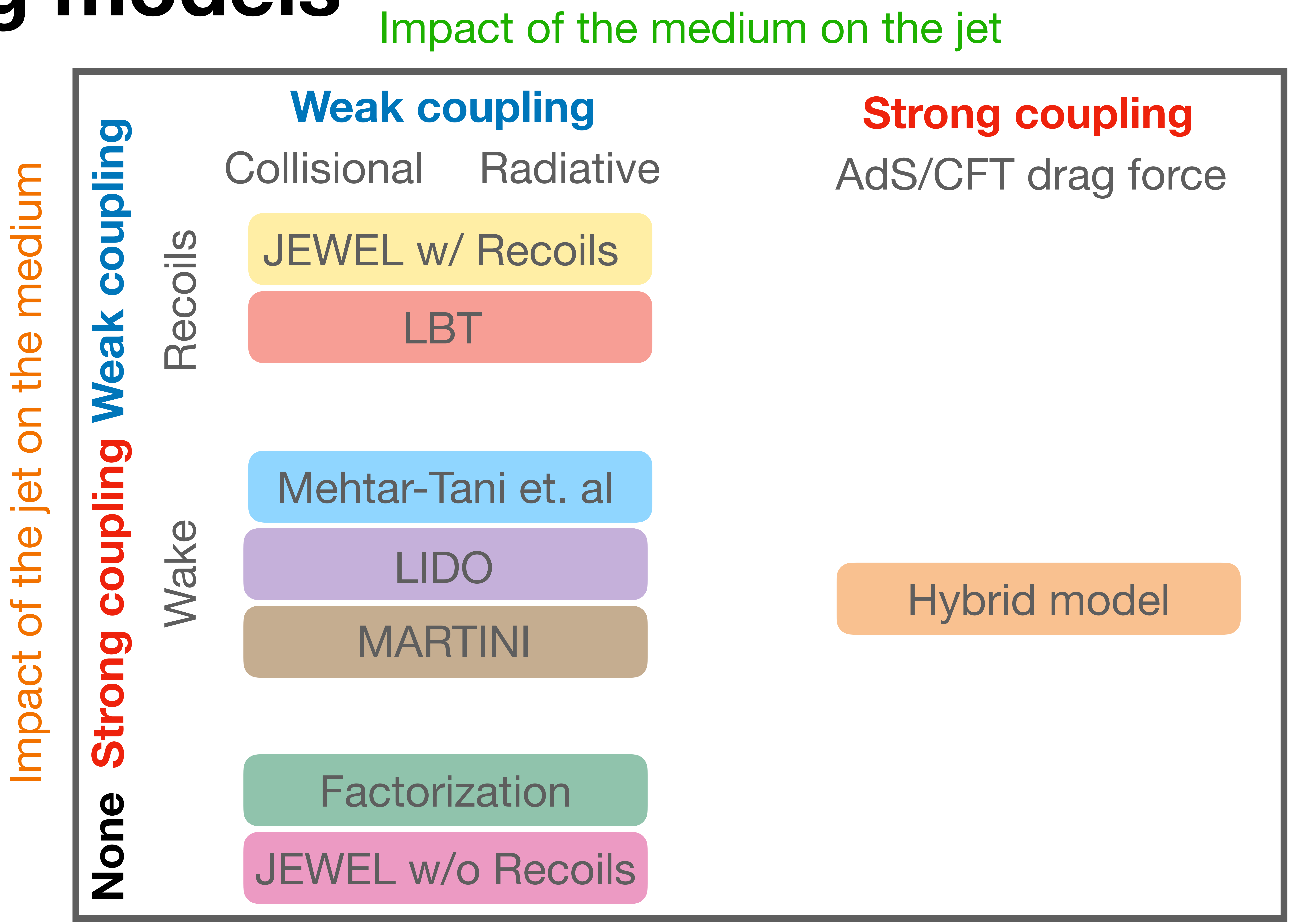
→ Use pp, where jets are measured in vacuum, as a reference for no QGP.

Jet quenching models

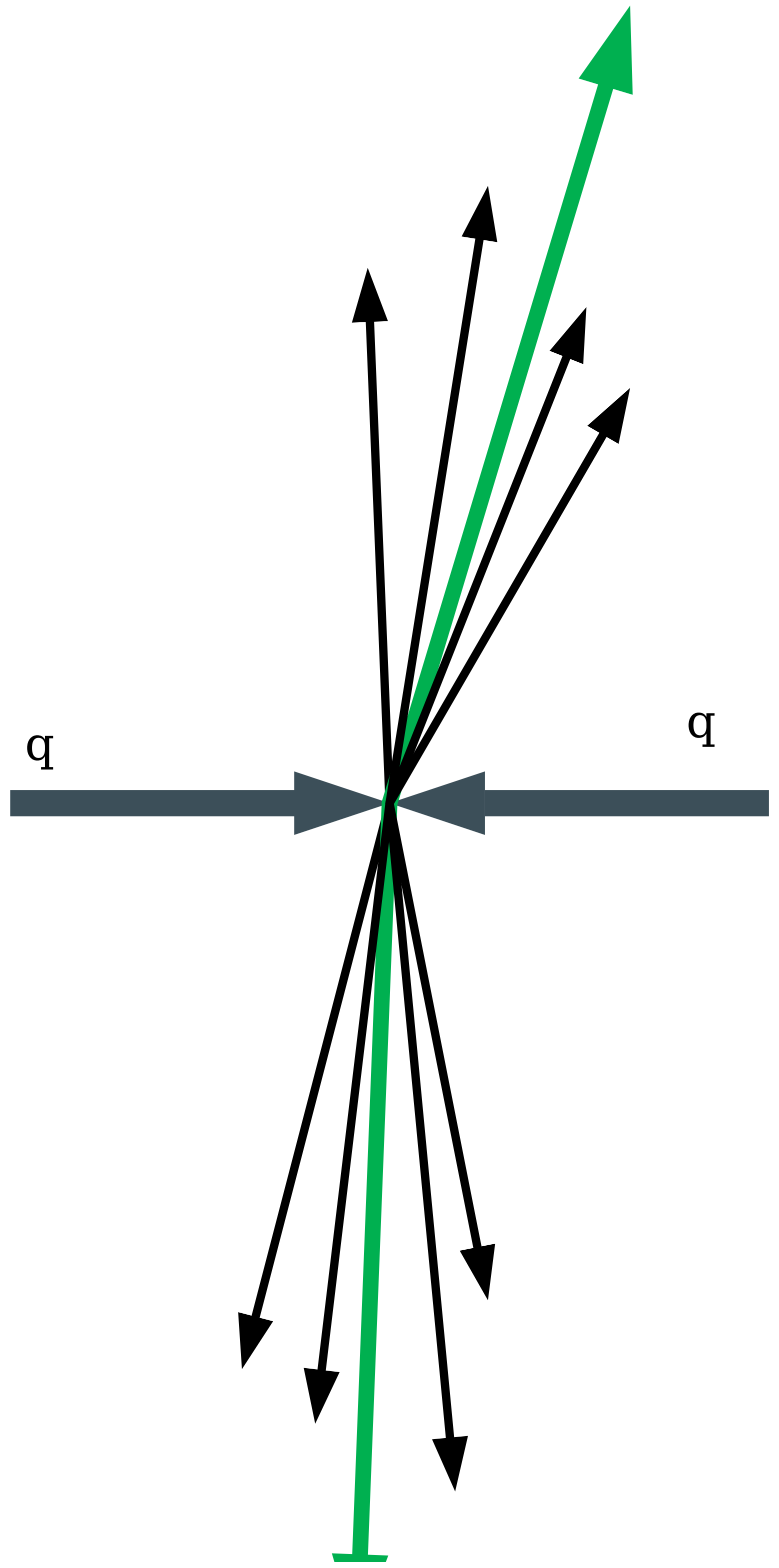
As of now, no clear winner for best description of jet quenching effects!

Different models are different!

We will come back to these later!



Jets in Vacuum



p+p

- In vacuum a majority of hard scatterings are 2→2, resulting in high transverse momentum (p_{T}) partons traveling back to back in the transverse plane.

- Production of partons calculable in perturbative QCD (pQCD).
  - Jets in vacuum useful for testing fundamental QCD properties.

What about jets in heavy-ion collisions??

Jet quenching

***This categorization scheme is largely based off of great talk by Jing Wang.*

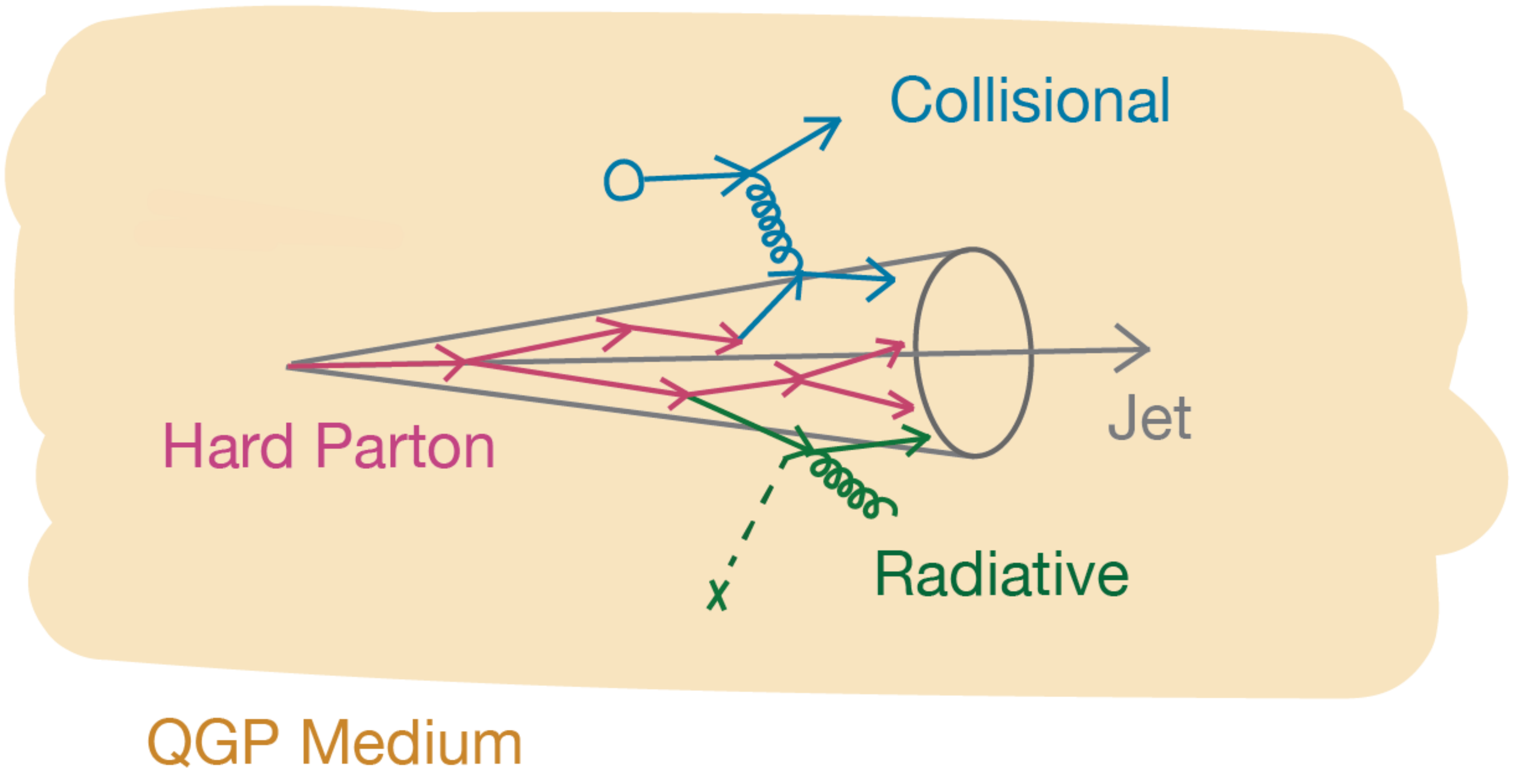
① Impact of the medium on the jet → jet energy loss

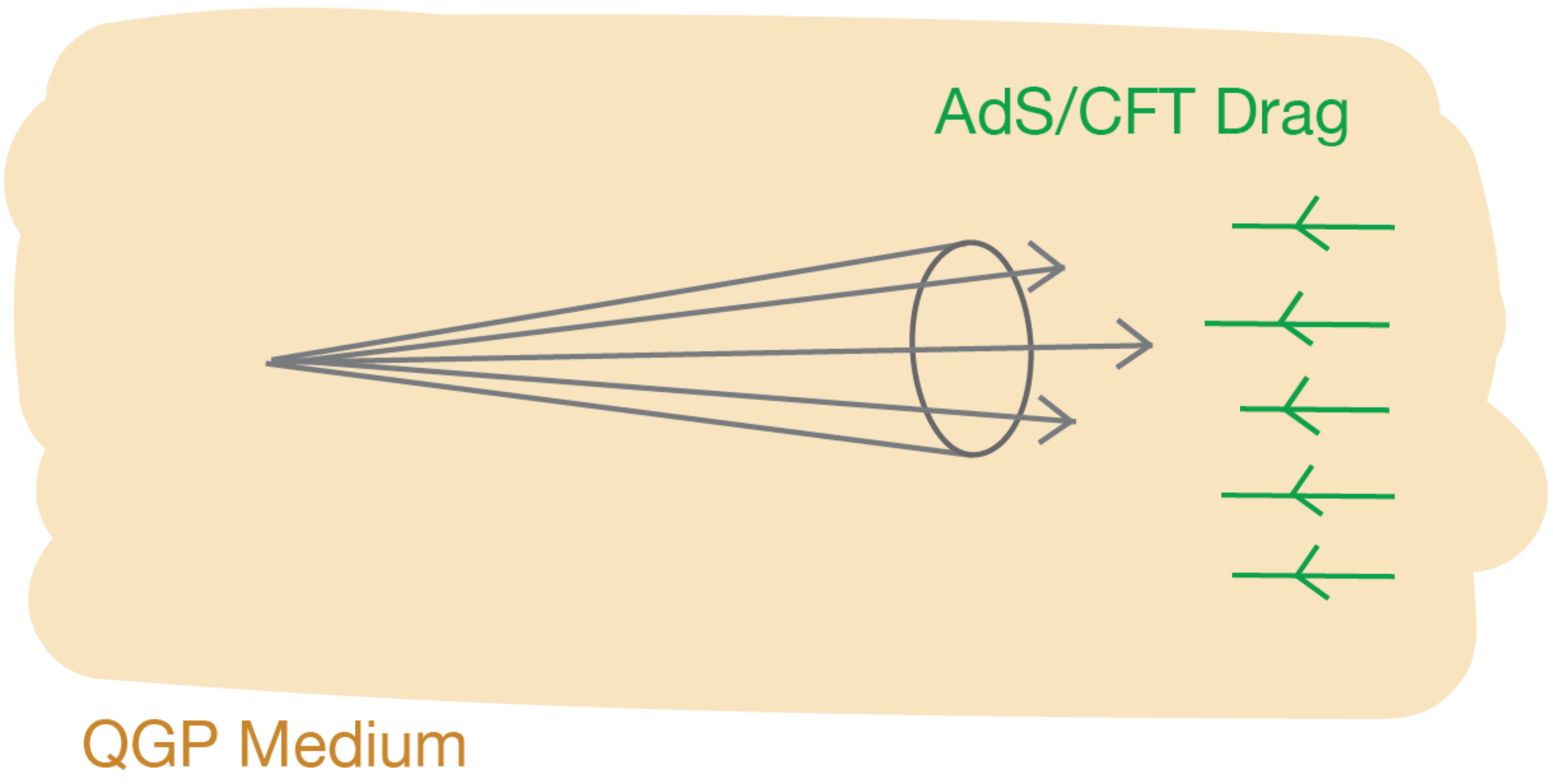
Ⓐ Weak coupling limit

- ✽ Collisional
- ✽ Radiative

Ⓑ Strong coupling limit

- ✽ AdS/CFT drag force





Variety of ways to implement each category →all theories won't behave the same!

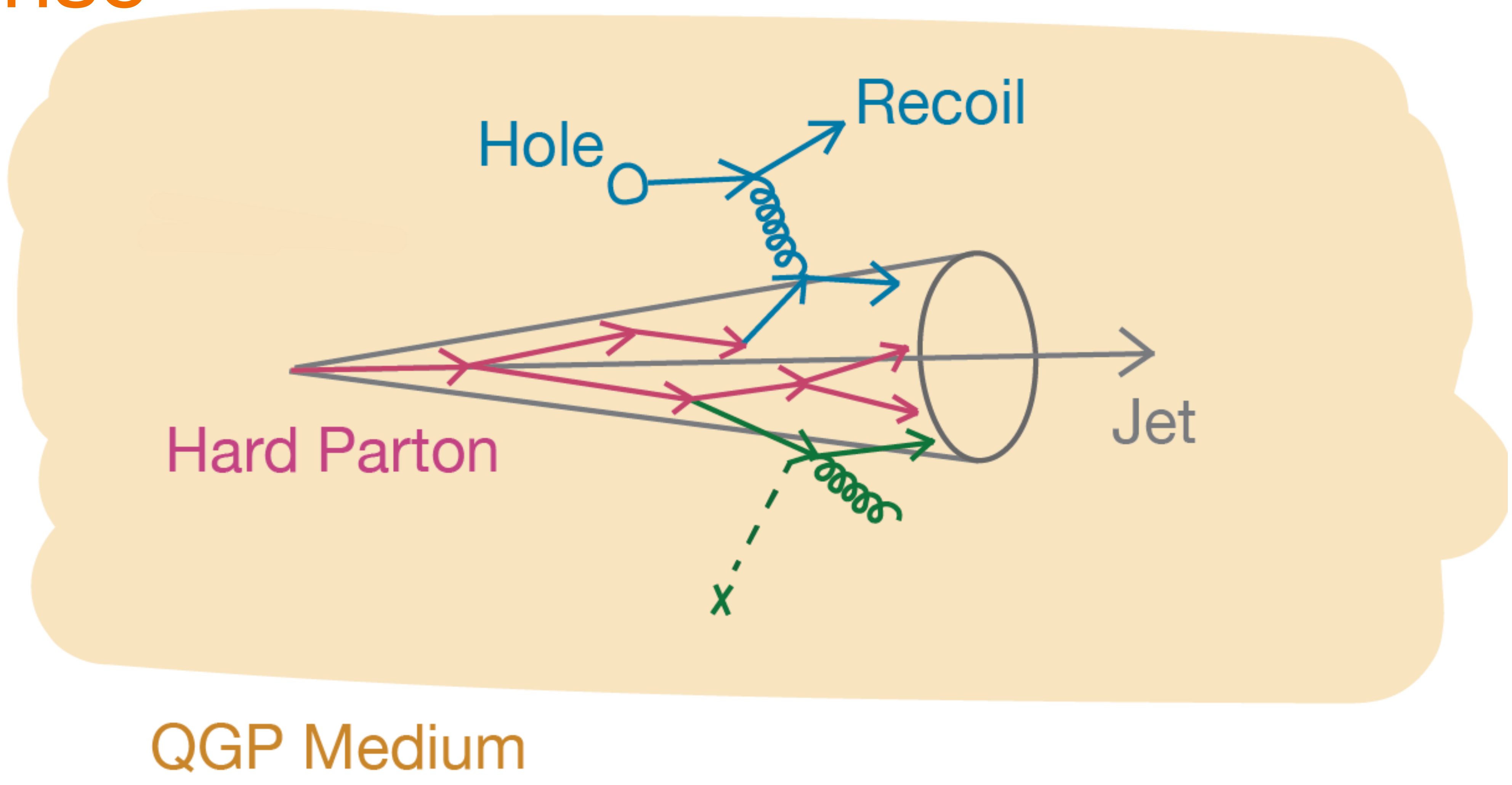
Jet quenching

***This categorization scheme is largely based off of great talk by Jing Wang.*

② Impact of the jet on the medium → medium response

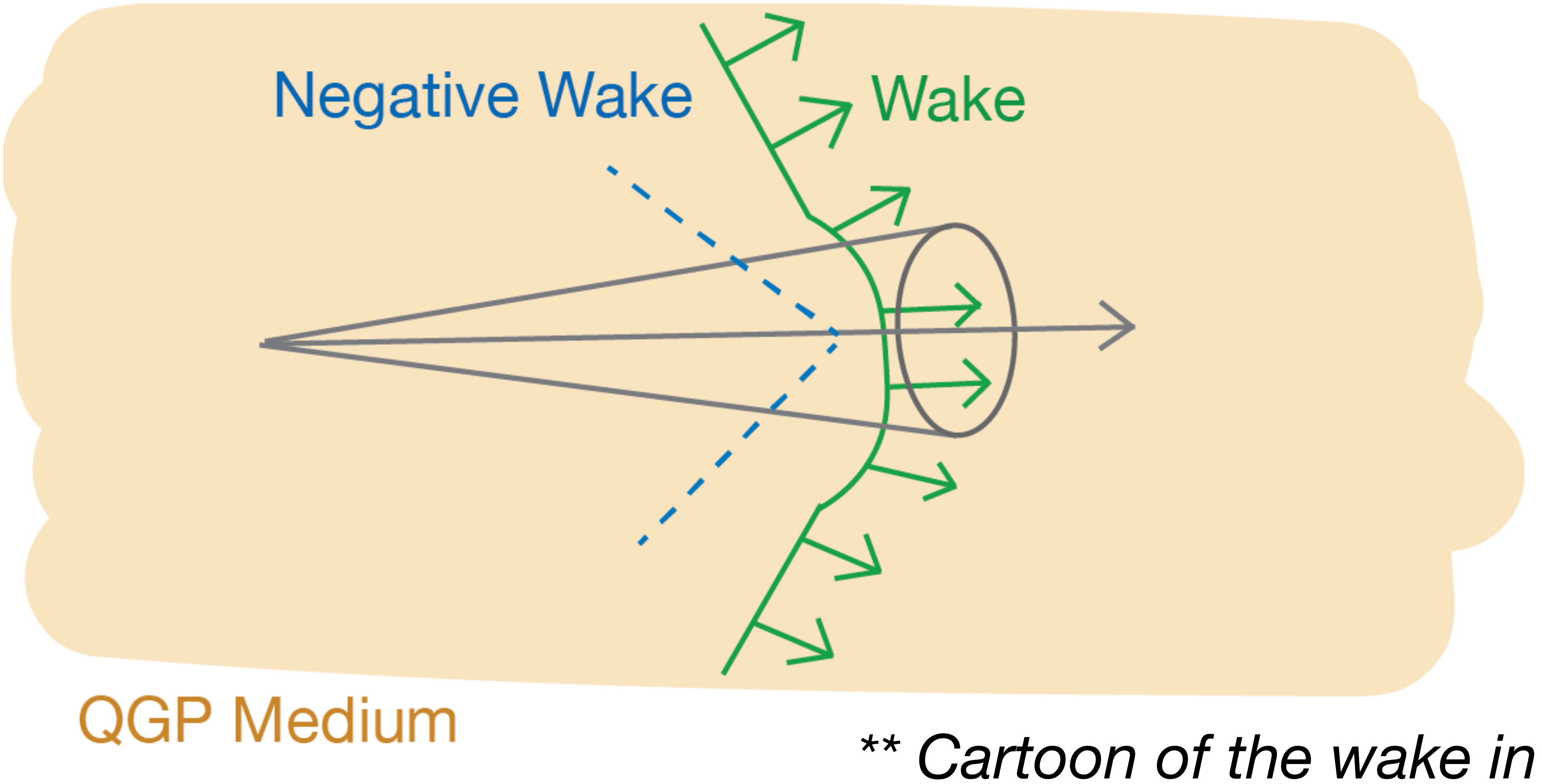
Ⓐ Weak coupling limit

- ❃ Recoils (Kinetic based approach)



Ⓑ Strong coupling limit

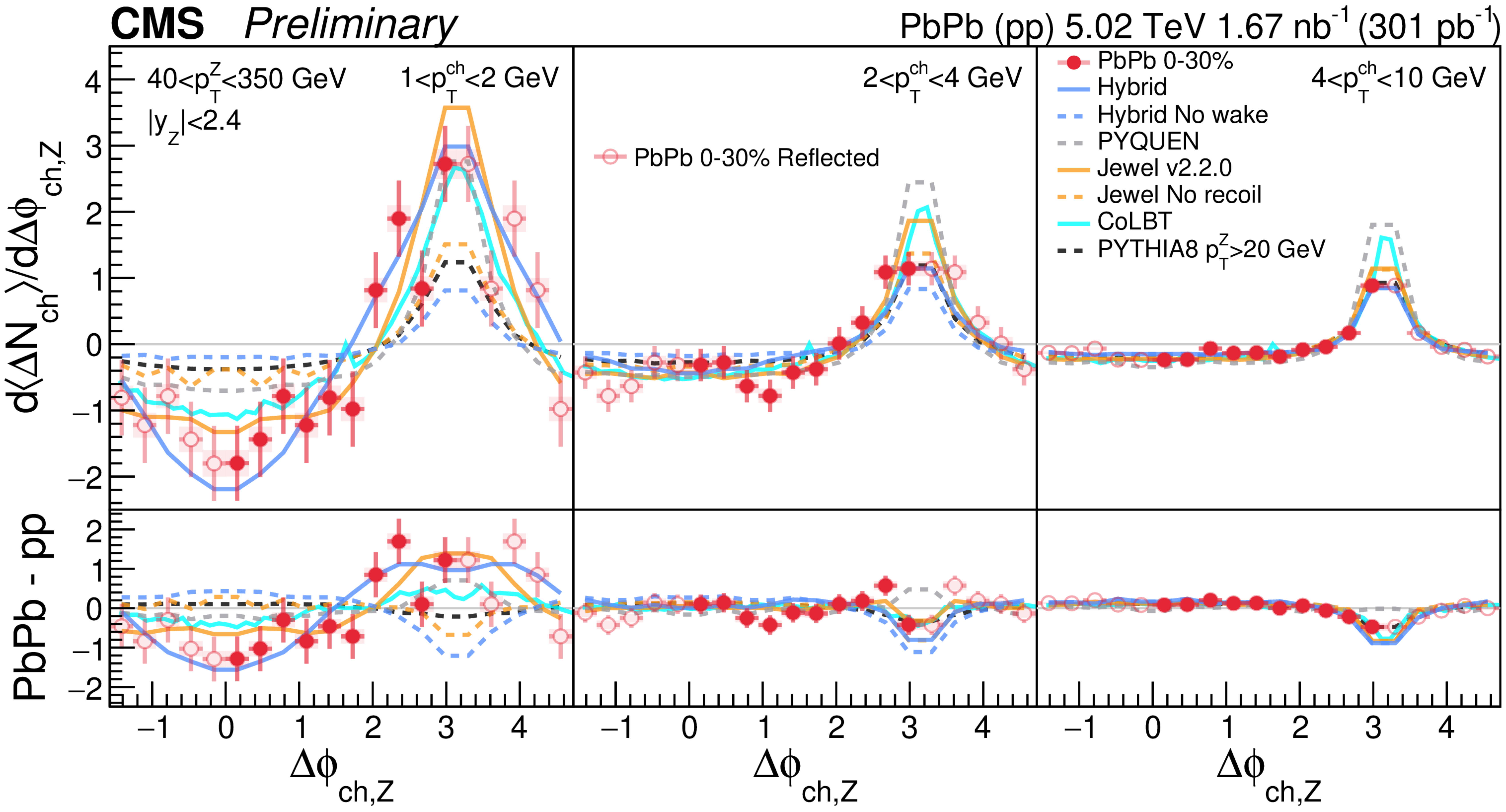
- ❃ Wake (Hydrodynamics based approach)
- ❃ Includes positive and negative contributions



*** Cartoon of the wake in position space*

What tools are there to search for these medium response effects?

Search for the medium response [CMS-PAS-HIN-23-006]



- Use p_{T}-differential measurement of the Z-hadron correlation in azimuthal angle (ϕ) and rapidity.
- See evidence of the medium response in the QGP!
- Different medium response mechanisms appear similarly.

See talk by Yen-Jie Lee at Hard Probes for more details!

How do we begin to characterize the medium response further??

This talk: What else can we do with EECs?

Make precision measurements of “known” effects

Look for large qualitative signatures of relatively “unknown” effects

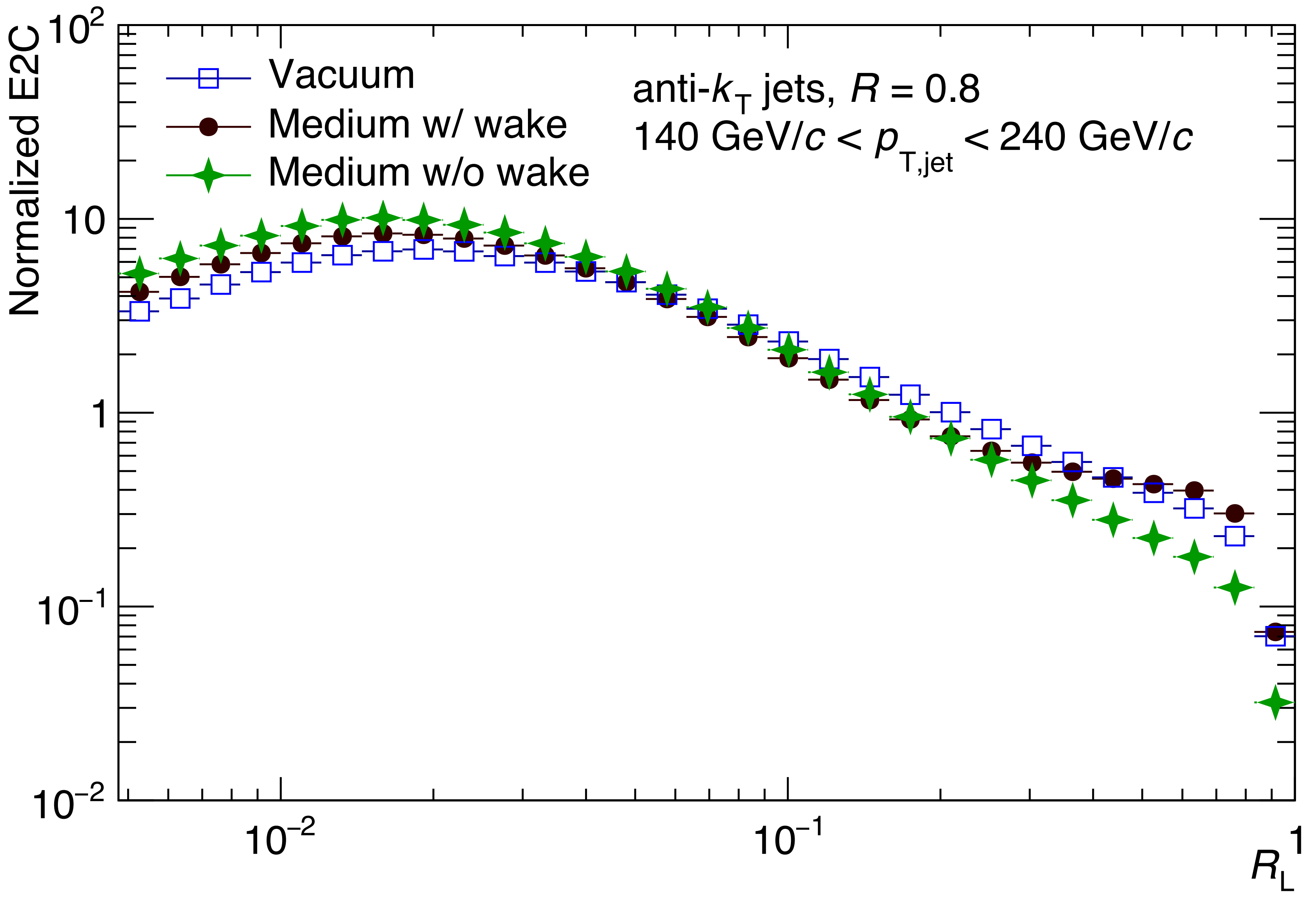
Can we use EECs?

$$\text{ENC}(R_L) = \left(\prod_{k=1}^{N}\int d\Omega_{\vec{n}_k}\right)\delta(R_L - \Delta\hat{R}_L)\cdot\frac{1}{(E_{\text{jet}})^{(n*N)}}\langle\mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\ldots\mathcal{E}^n(\vec{n}_N)\rangle$$

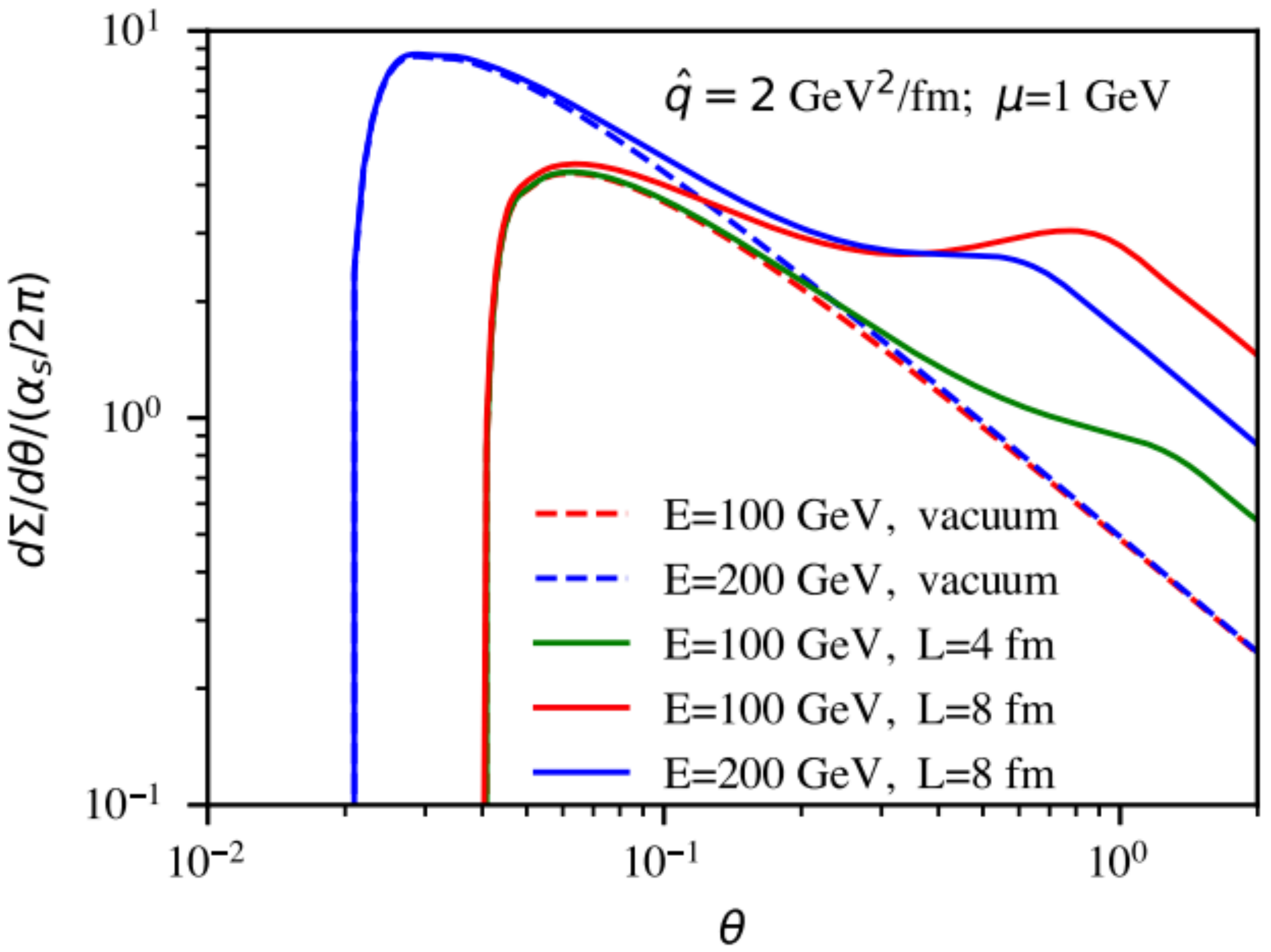
Yes! Many applications so far …

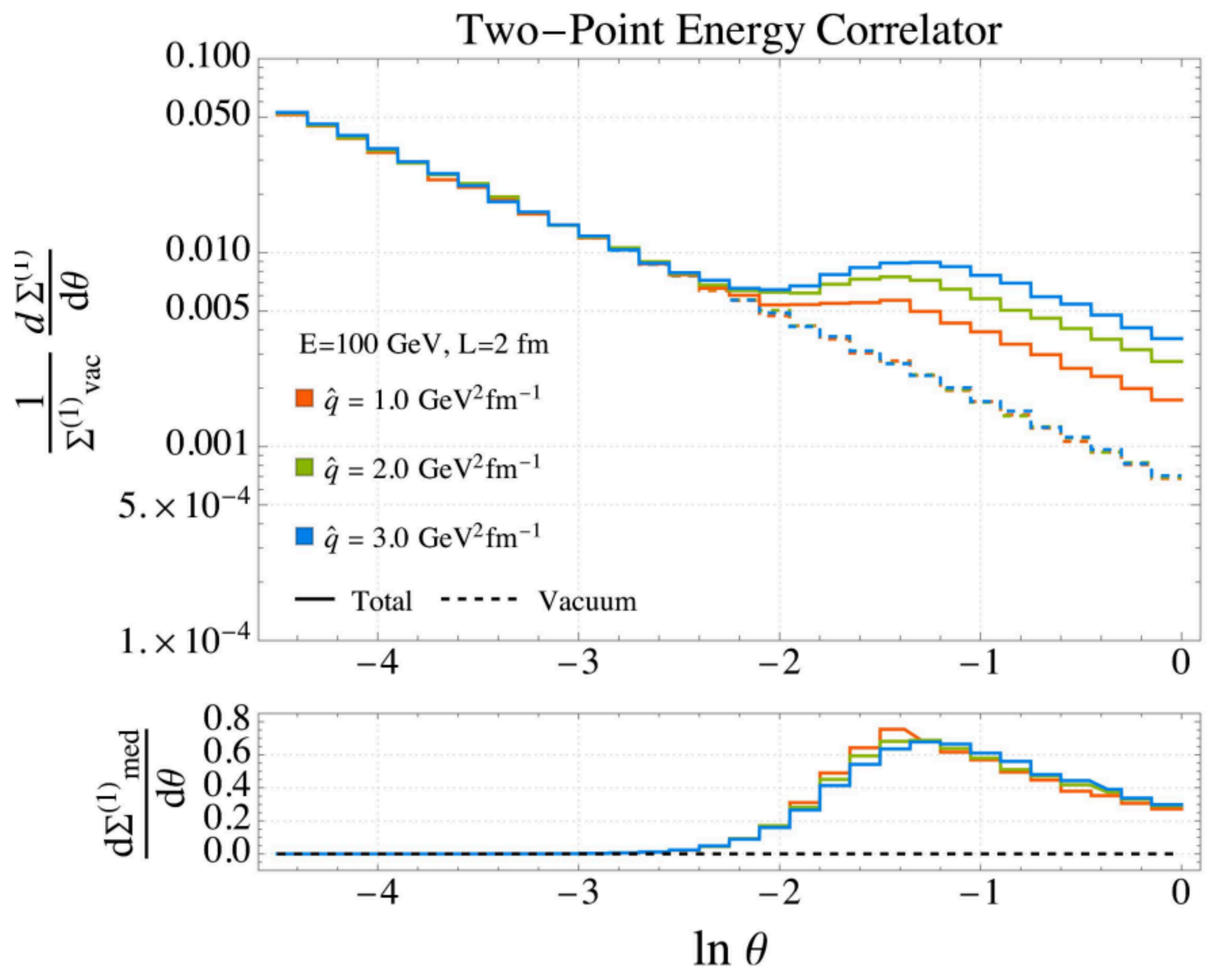
[Andres et al. Phys. Rev. Lett. 130, 262301]

[HB et al arXiv:2407.13818]



[Yang et al., Phys. Rev. Lett. 132, 011901]





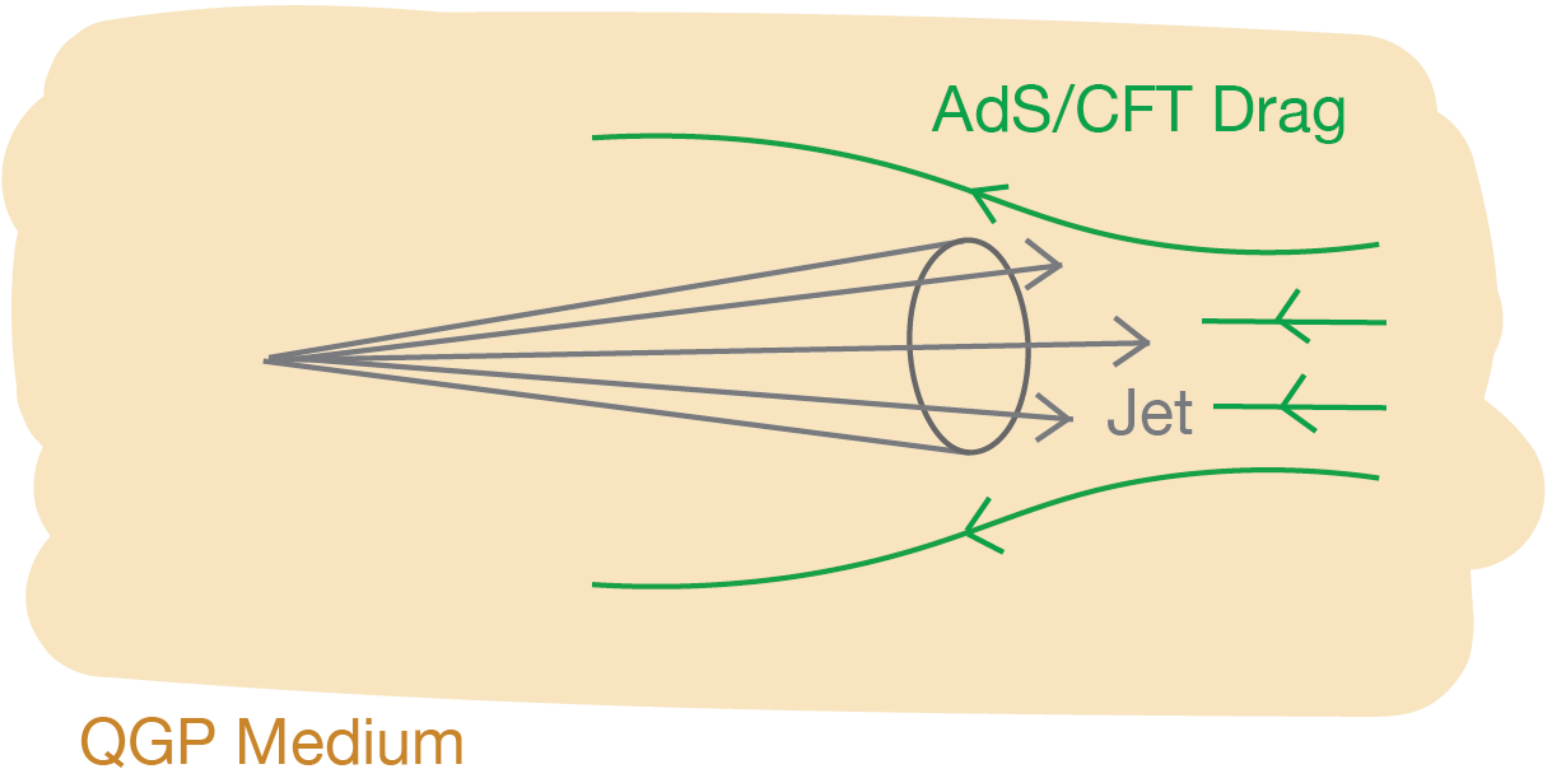
- Medium effects appear at a similar characteristic scale in the projected correlators regardless of the physical mechanism driving these medium effects.

Can we distinguish these different physical mechanisms? What about higher orders of N? What if we also included the full shape information?

Exposing the wake with 3-point correlators

Idea: Study one type of medium response (wake) via its scaling dependence in the projected correlator (E3C) and its distinct shape dependence in the full 3-point correlator (EEEC). For this use the **Hybrid Model** [JHEP 10 (2014) 019]

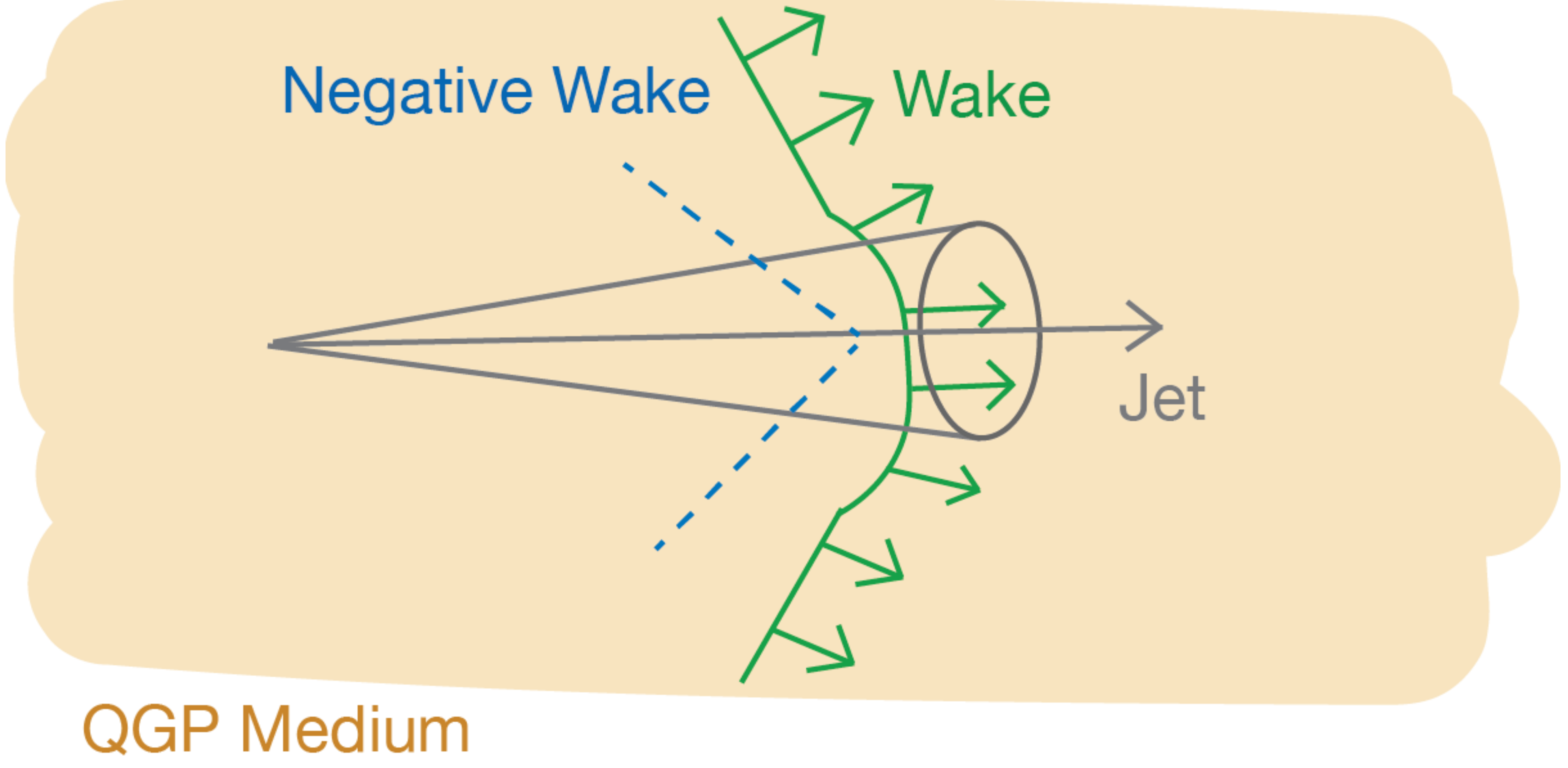
Impact of the medium on the jet → jet energy loss



Strong coupling limit

- AdS/CFT drag force

Impact of the jet on the medium → medium response



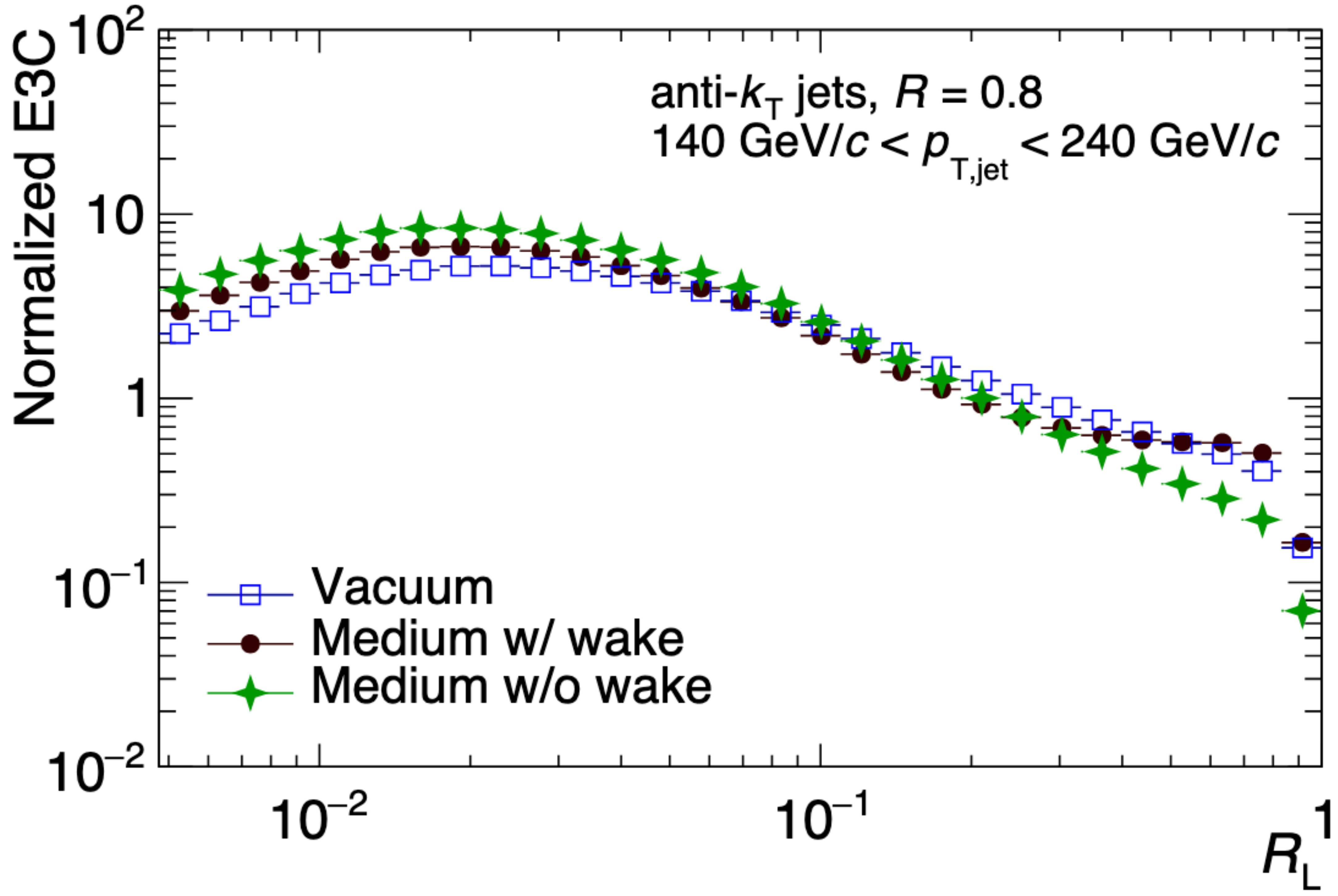
Strong coupling limit

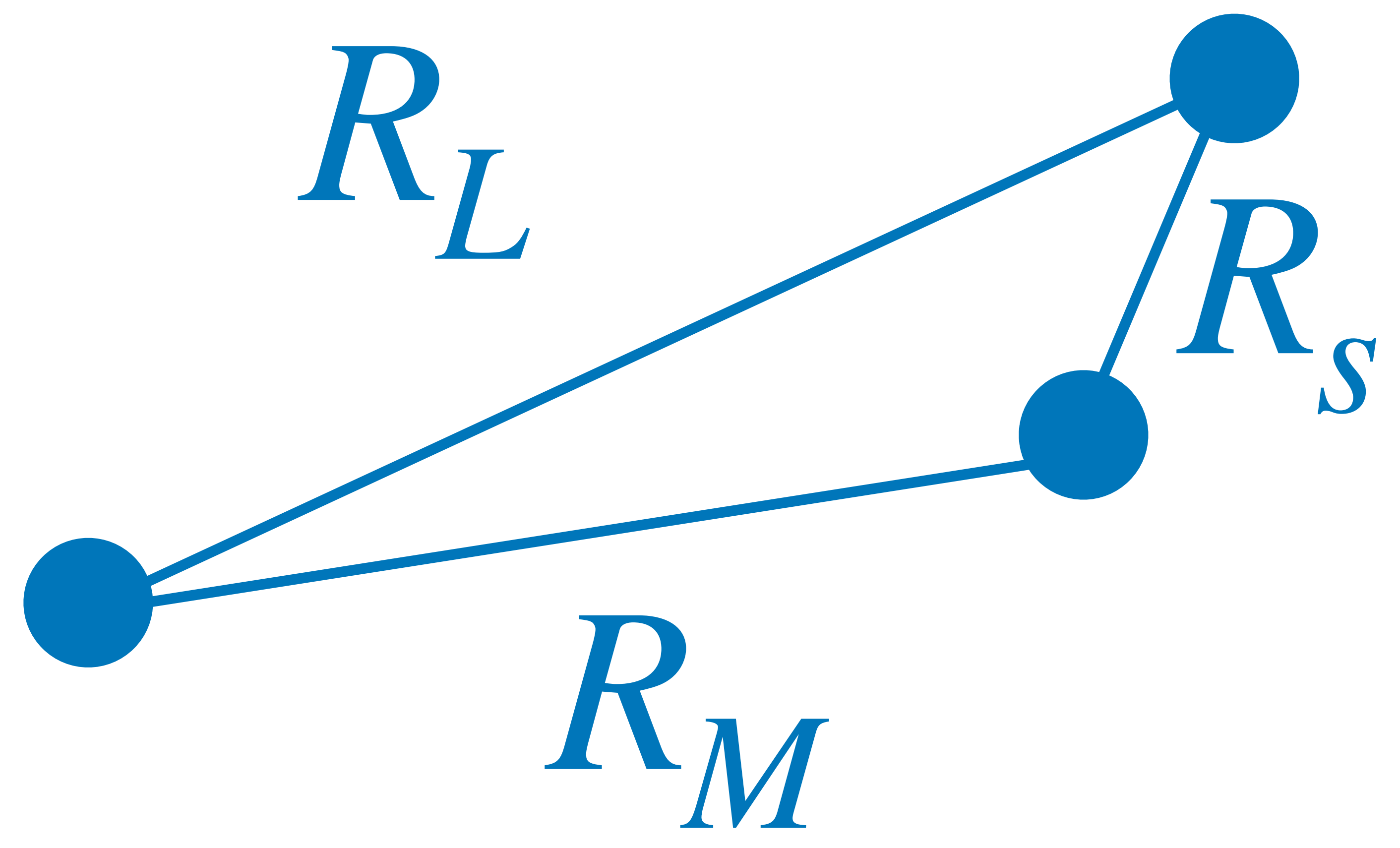
Wake (Hydrodynamics based approach)

Projected 3-point correlators

Can first use higher-point projected correlators (ENC) correlators to study the scaling of wake effects.

[HB et al arXiv:2407.13818]





- Wake effects prominent at large R_{L}.
- Shift in the peak position due to jet energy loss.

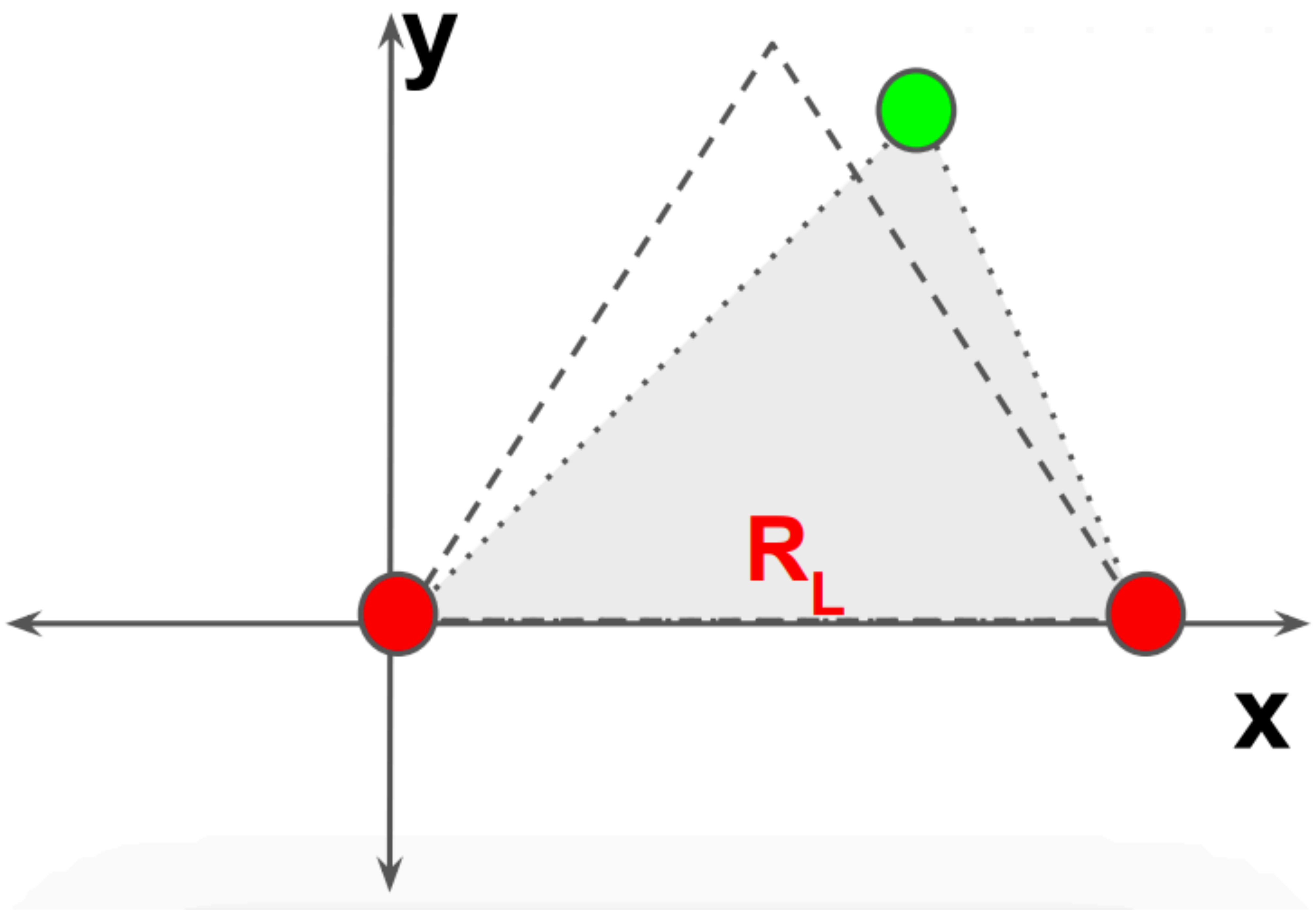
We can get more information by studying the shape (full correlator, EEEC)!

- When $N > 2$ there are non-trivial shape dependencies in collinear limit.

Coordinate system for EEECs

How do we visualize the full 3-point energy energy correlators (EEECs)?

- Use a 3D space with the following coordinate setups!

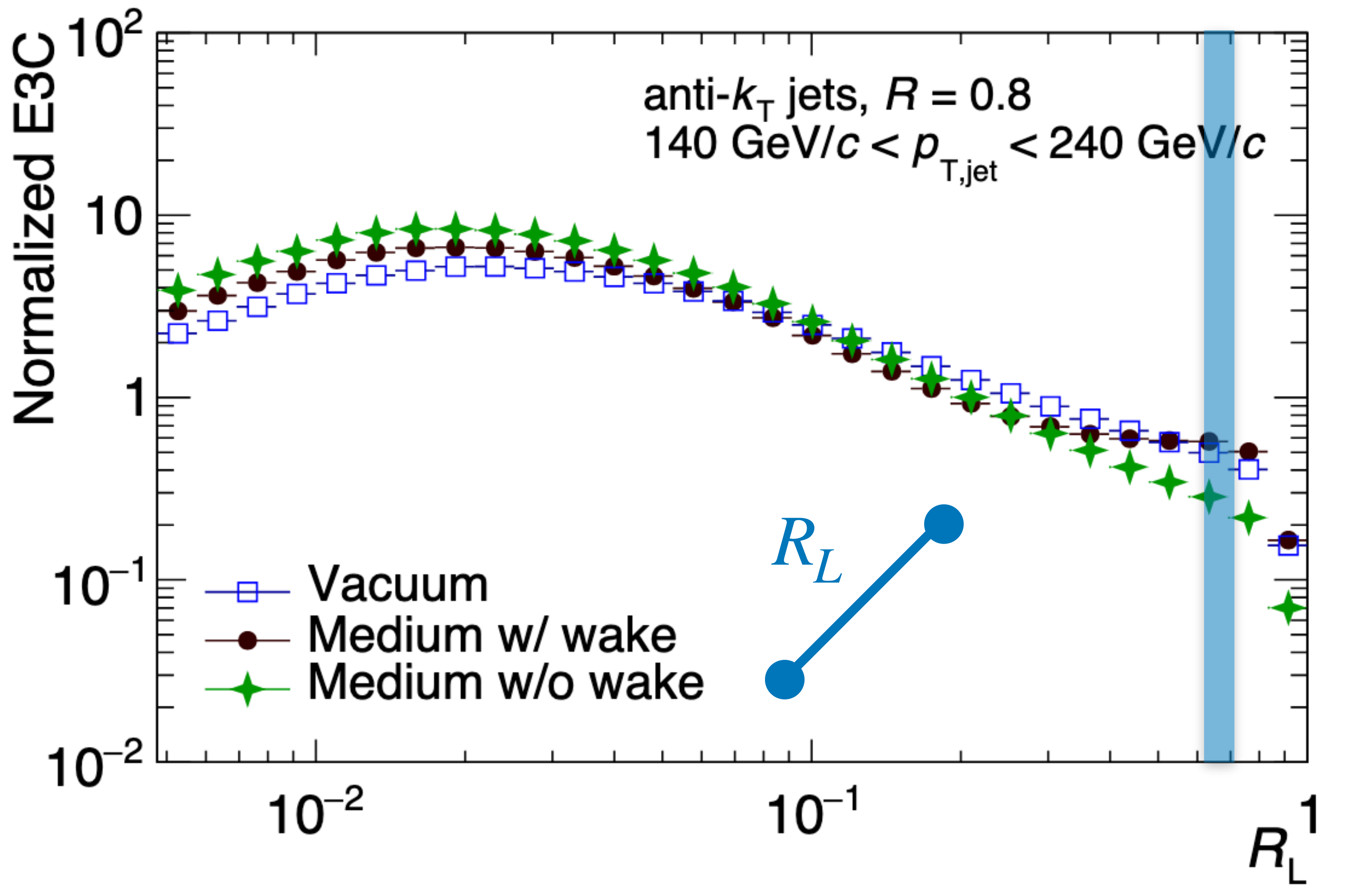


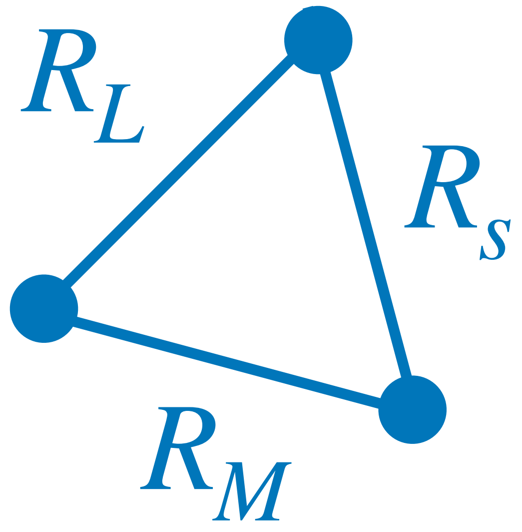
- Fix the longest side (R_{L}) on the x axis placing one of the particles at the origin.
- Set $R_{\mathrm{L}} = 1$ and rescale the rest of the triangle accordingly.
- Fill the EEEC in bins (x,y) for the third particle in the triplet!

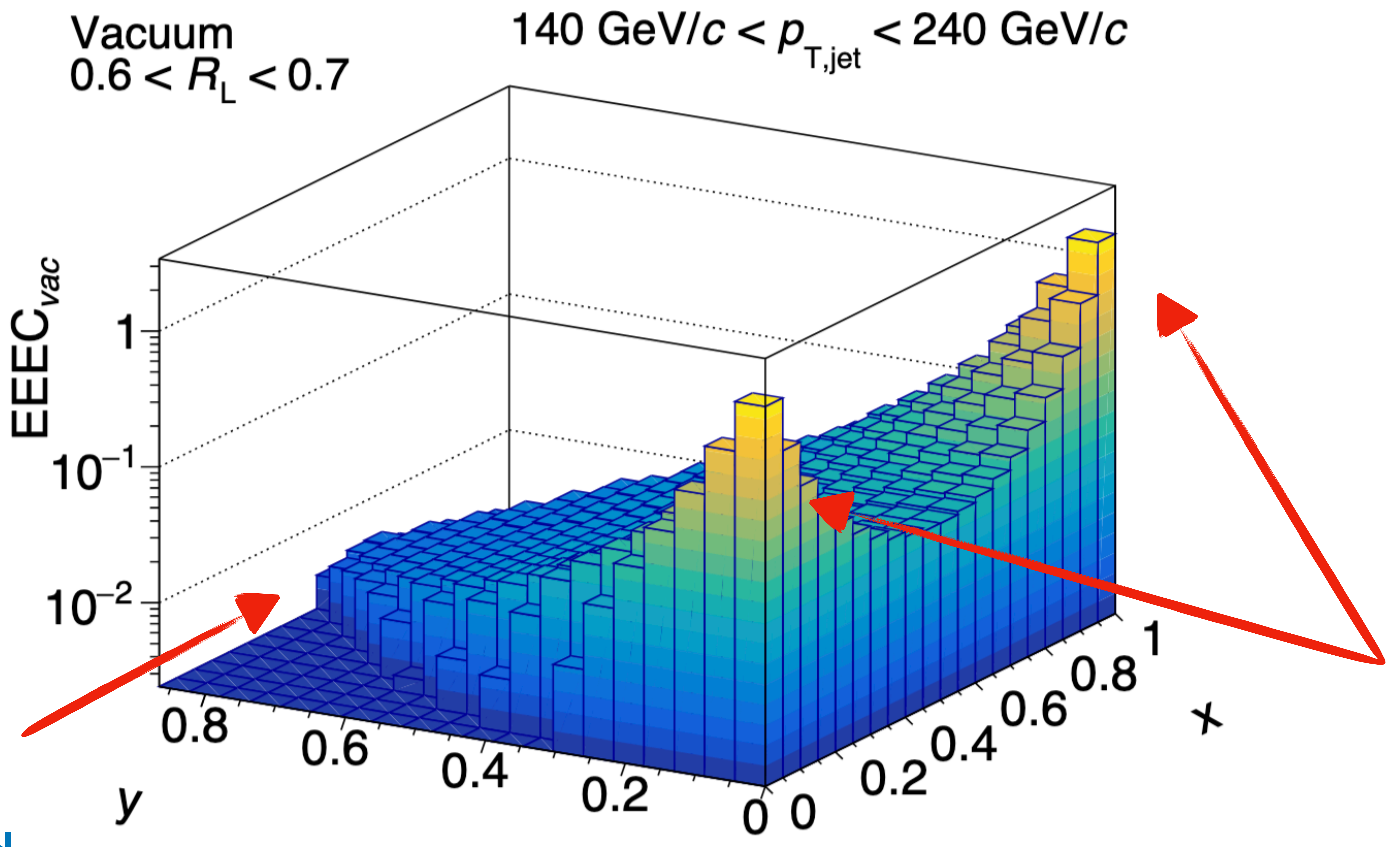
Coordinates chosen to have a flat Jacobian such that there is no preference for a single region based on coordinate choices alone.

Shape dependence in vacuum

Look at distribution for an R_L slice



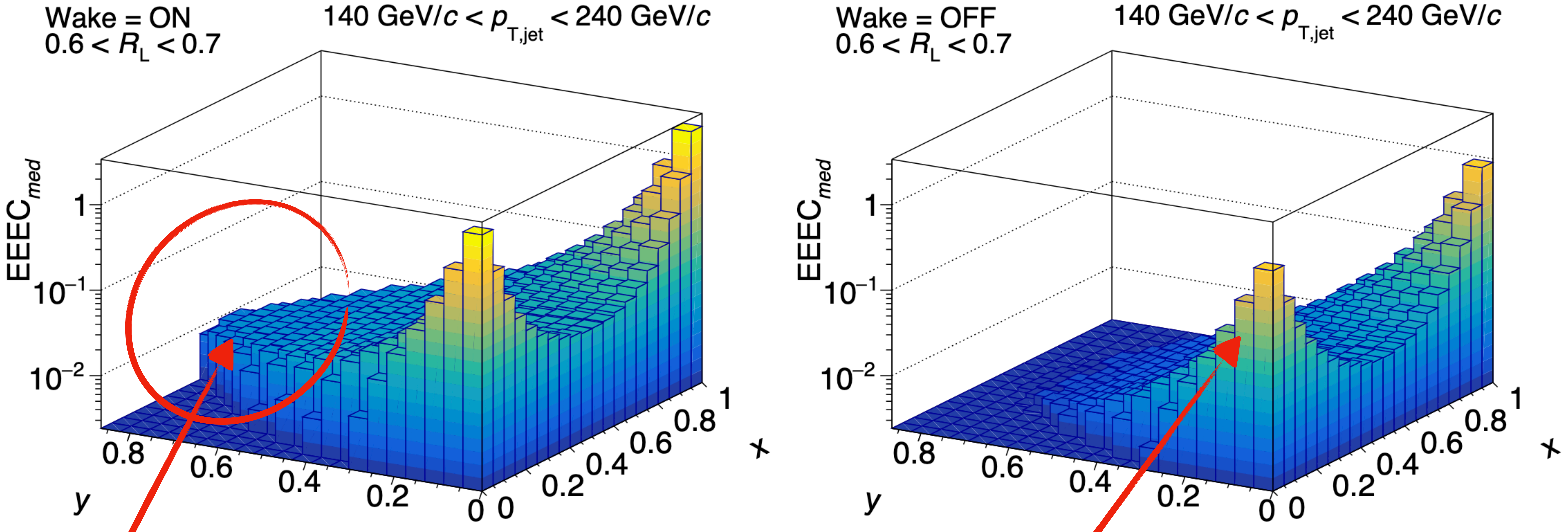


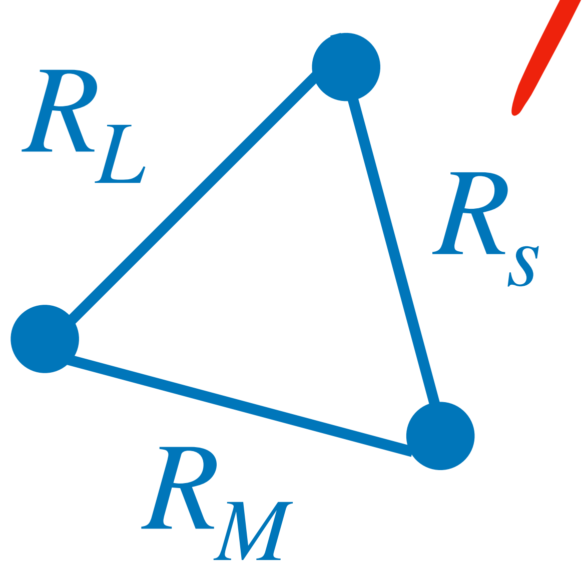


Equilateral region relatively unpopulated

Dominant shapes when all emissions are correlated with the same source (parton shower)

Shape dependence in medium





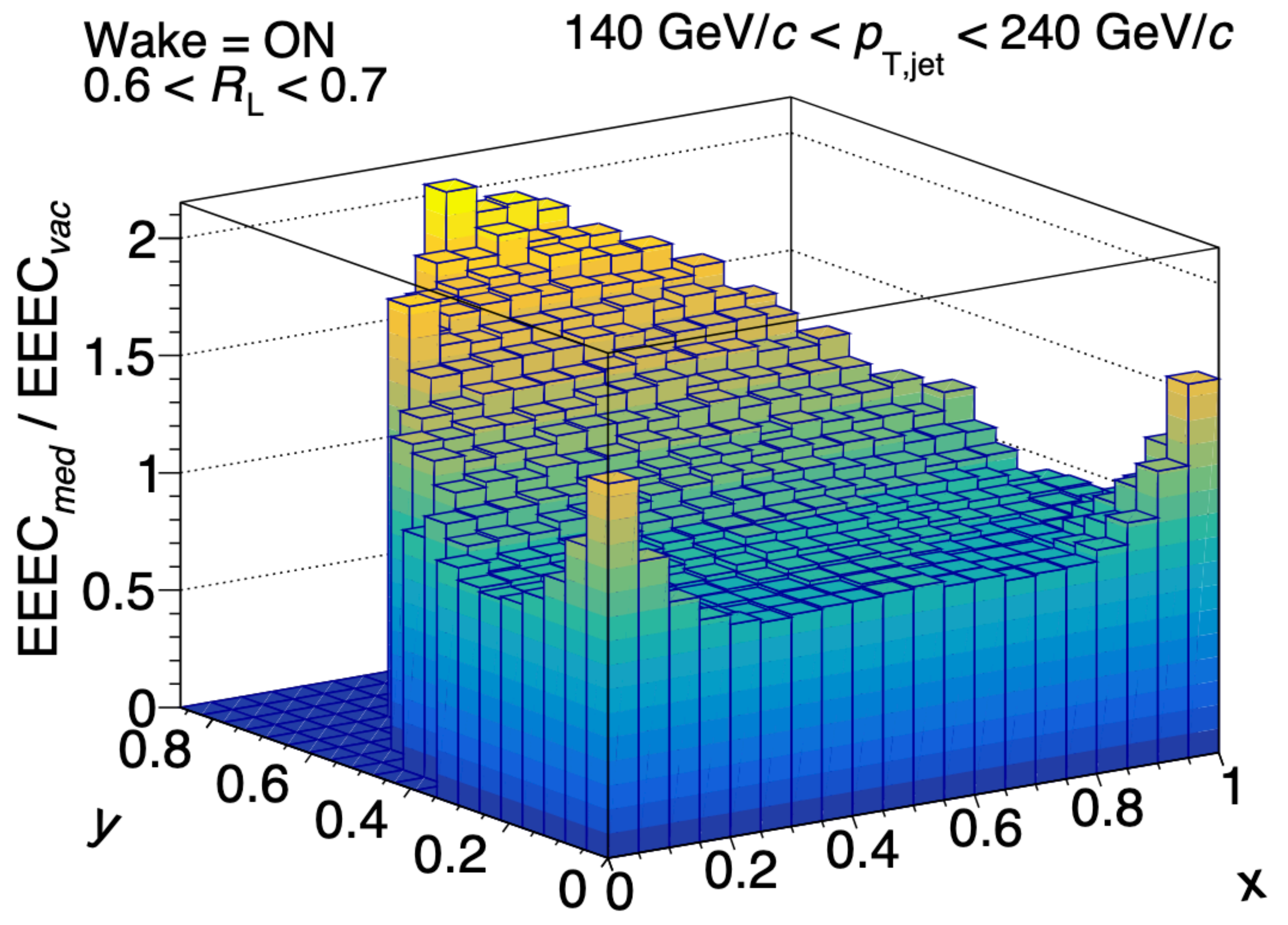
Medium, With Wake

Medium, No Wake

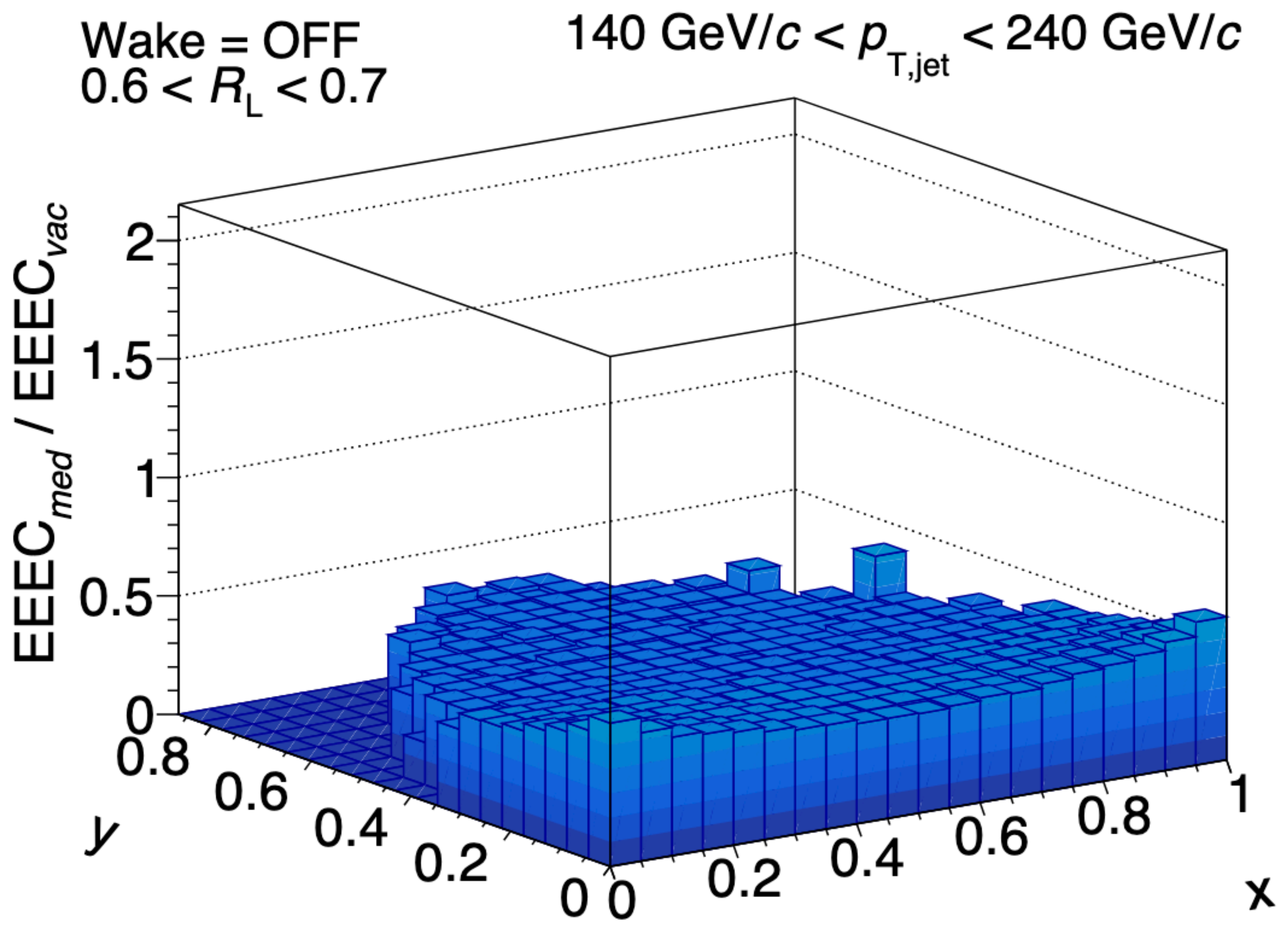
Jet quenching alone reduces peak

Rise in equilateral and collinear structures due to the presence of the uncorrelated wake!

Ratios to vacuum



Wake / vacuum



No wake / vacuum

Wake leaves clear signatures in comparison to vacuum! Dramatically different from the no wake case

- ✽ Shape of medium response is encoded in these ratios!