Massachusetts Institute of Technology

Energy correlators as a probe of QCD from simple to complex systems

Hannah Bossi (MIT)

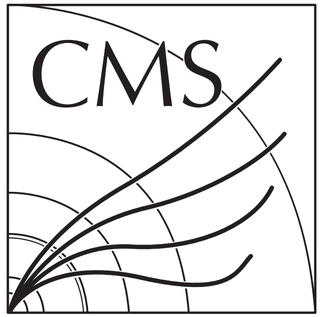
Nikhef Theory Seminar

Amsterdam, Netherlands

November 19th, 2024

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

Intro: What type of physics do I do?



Hard probes (Jets) in heavy-ion collisions

ML on FPGAs for fast triggering

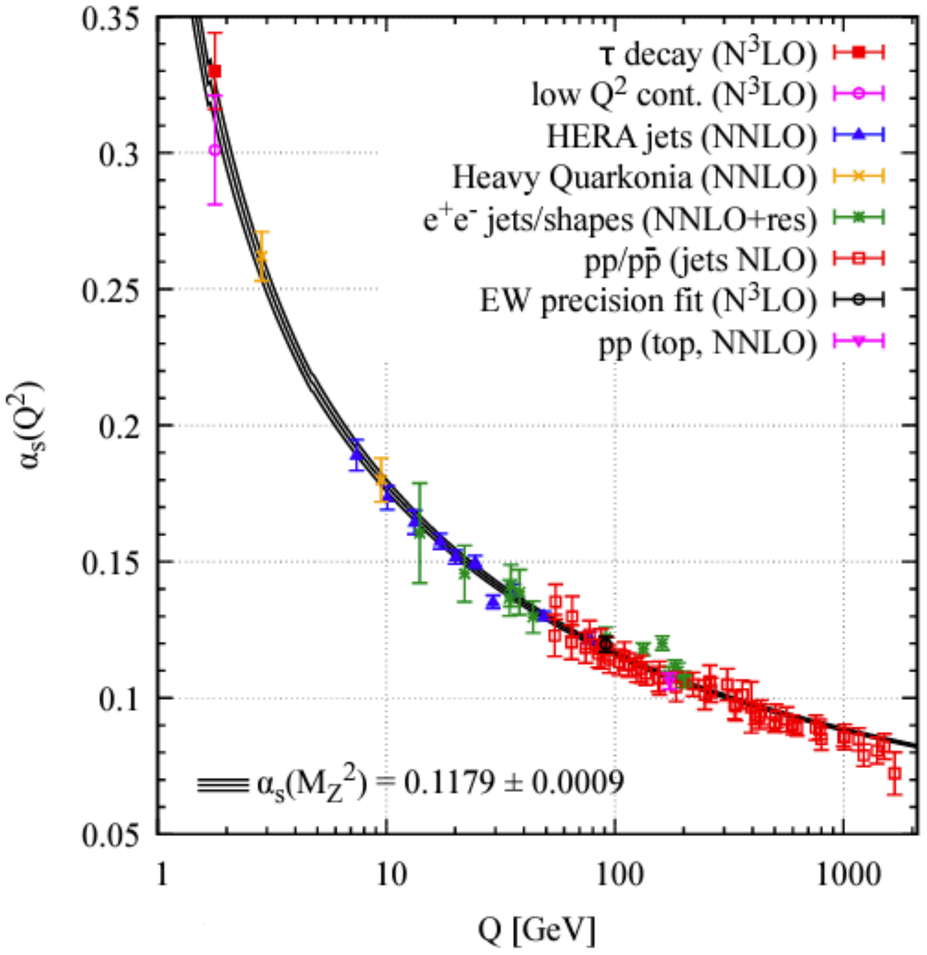
Re-analysis of archived data

…… + some phenomenological explorations

My overview of some things will be brief and biased!

Quantum Chromodynamics

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

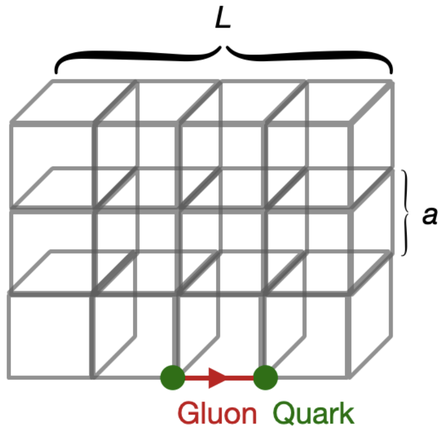


[Review of Particle Physics. PTEP, 2022:083C01, 2022]

Interaction strength dictated by the coupling constant α_s

Can solve QCD

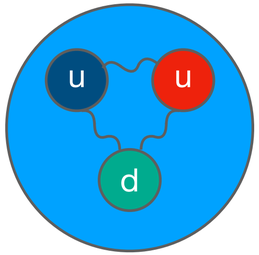
1. Using perturbative expansions in powers of α_s (perturbative QCD, $\alpha_s \ll 1$)
2. Using non-perturbative techniques (non-perturbative QCD, $\alpha_s \sim \mathcal{O}(1)$)



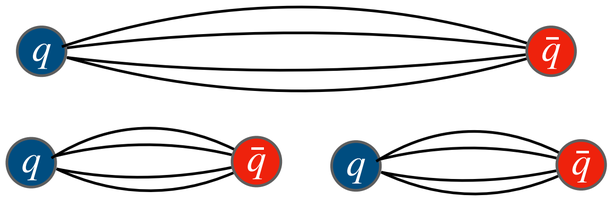
Ex: Lattice QCD

Defining features of QCD

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



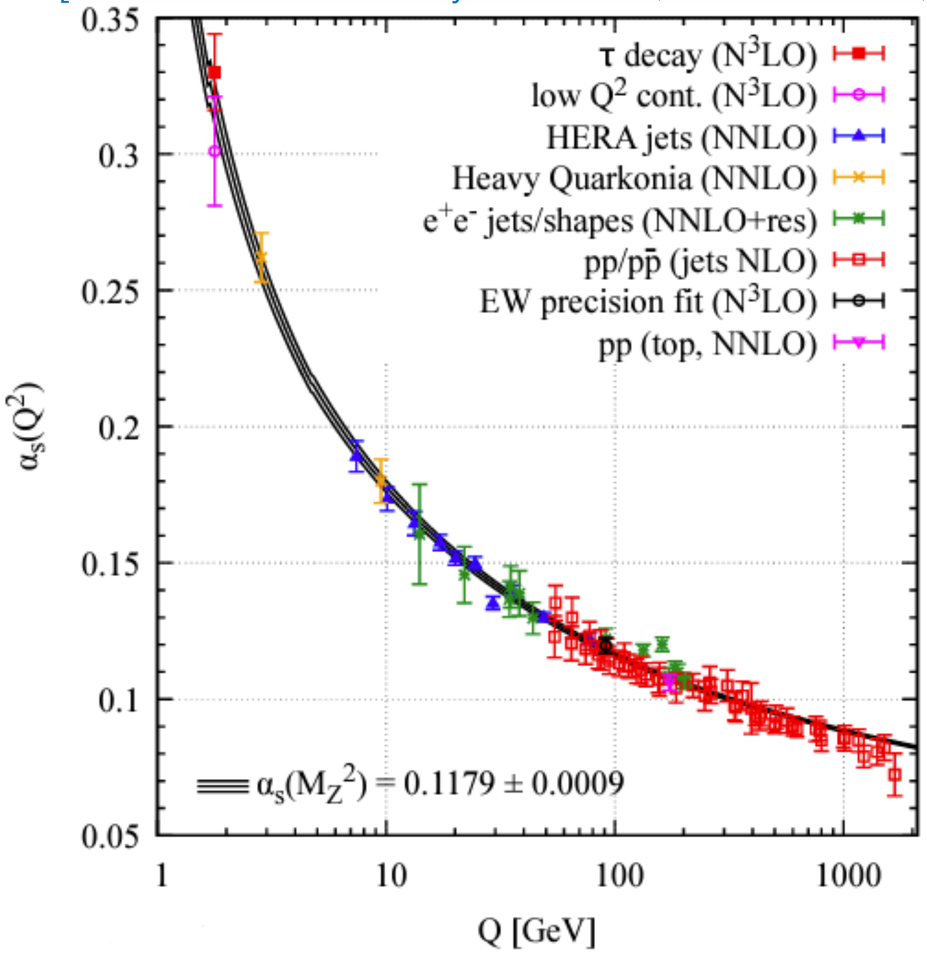
QCD potential grows as r increases



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

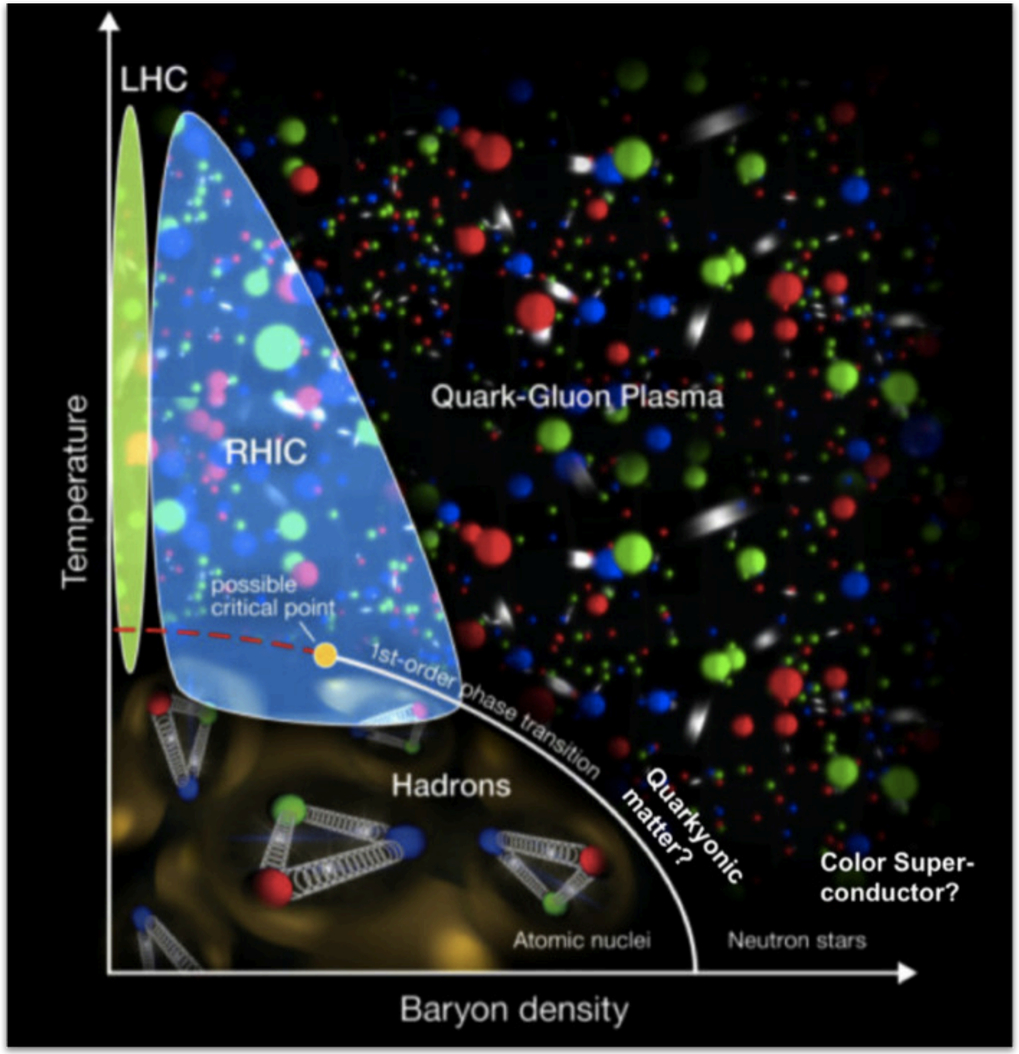
As you pull quarks apart at some point becomes favorable to form a new $q\bar{q}$ pair

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

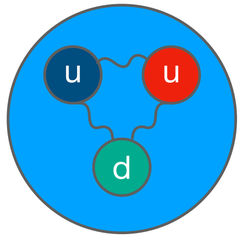


2 ***Asymptotic freedom:*** α_s decreases at high energies (high Q) and short distances

QCD Phase Diagram



[Image Credit: Brookhaven National Lab]



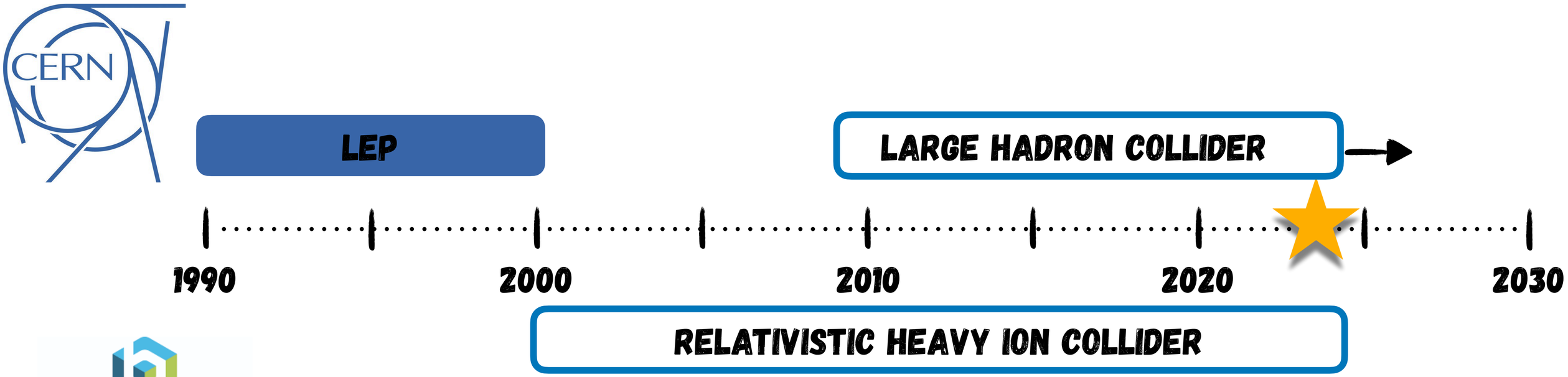
When temperature is hot enough QCD matter becomes a deconfined state of quarks and gluons called the **Quark-Gluon Plasma (QGP)**

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

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

Experimentally studying QCD

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

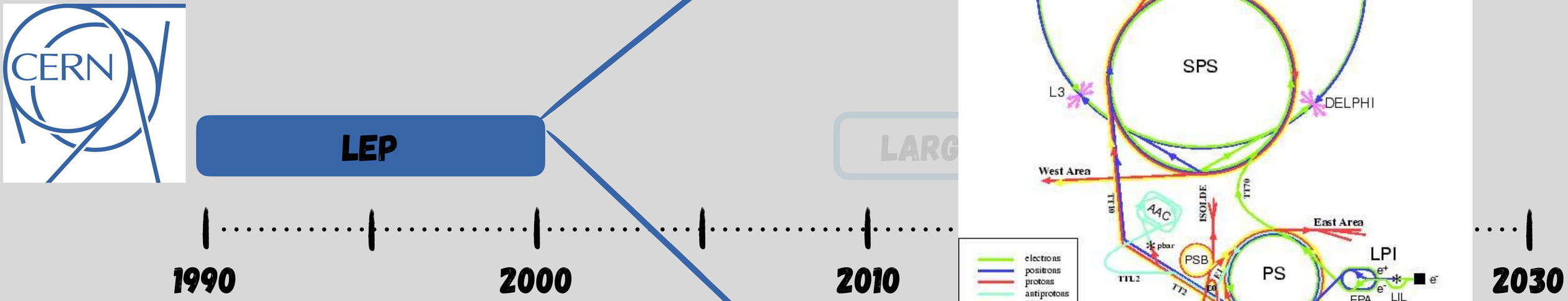


Electron-positron collider Hadron collider

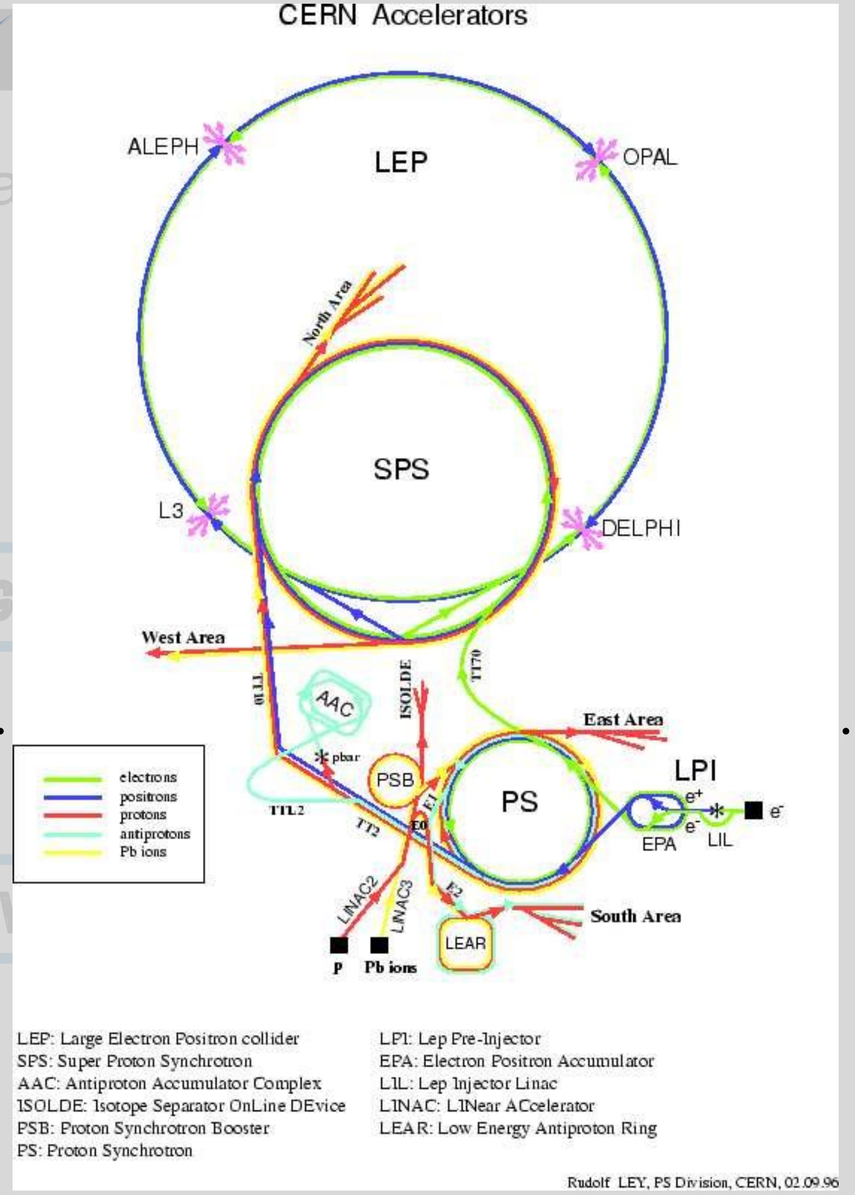
[See full list at Wikipedia]

Large Electron-Positron Collider (1989 - 2000)

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



Year	Beam energy [GeV]	Total luminosity [pb^{-1}]	Average luminosity rate [pb^{-1}/day]
1994	45.6	64	0.31
1995	45.6 – 70.0	47	0.23
1996	80.5 – 86.0	25	0.17
1997	91.0 – 92.0	75	0.66
1998	94.5	200	1.16
1999	96.0 – 101.0	254	1.35
2000	100.0 – 104.5	233	1.10

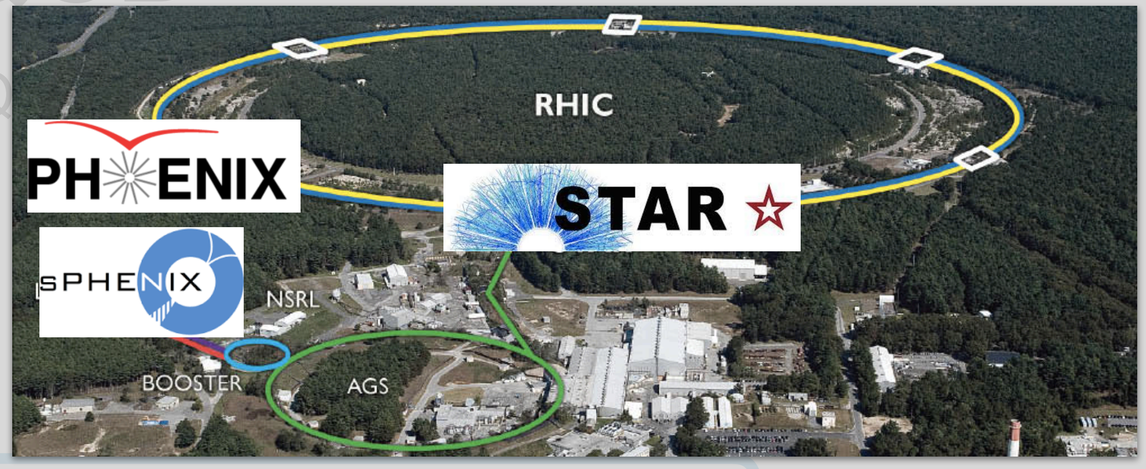


[See full list at Wikipedia]

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.



LEP

LARGE HADRON COLLIDER

1990 2000 2010 2020 2030

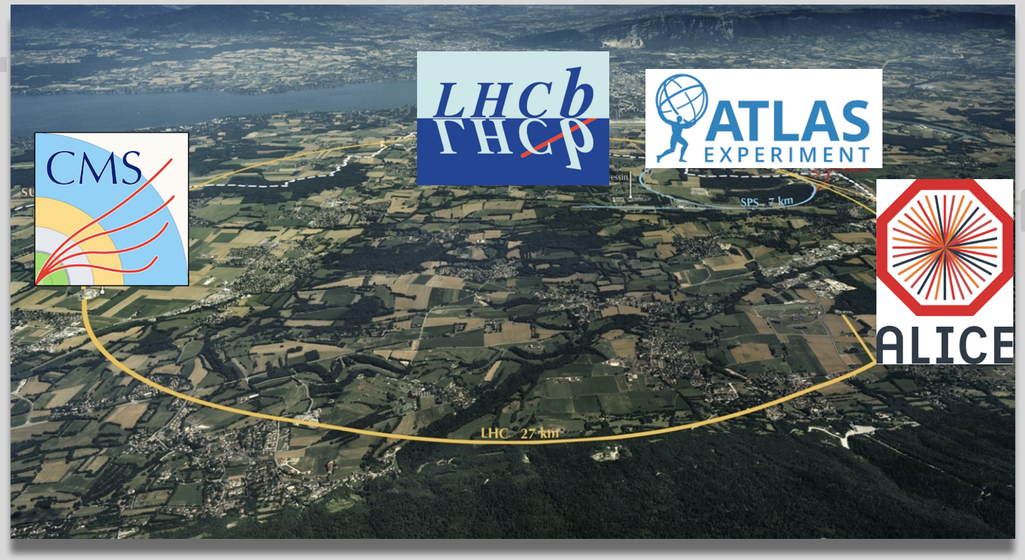
RELATIVISTIC HEAVY ION COLLIDER

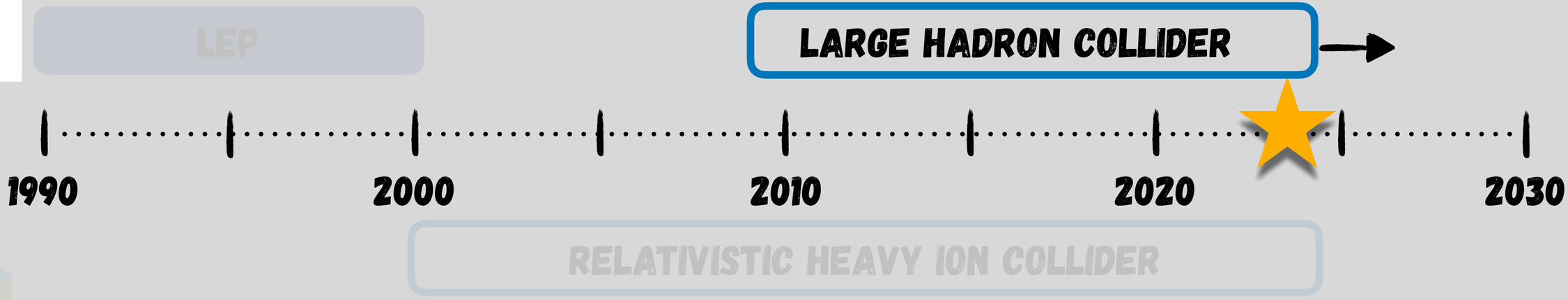
Brookhaven National Laboratory

[See full list at Wikipedia]

Exper… QCD

- This talk … f QCD at two facilities.



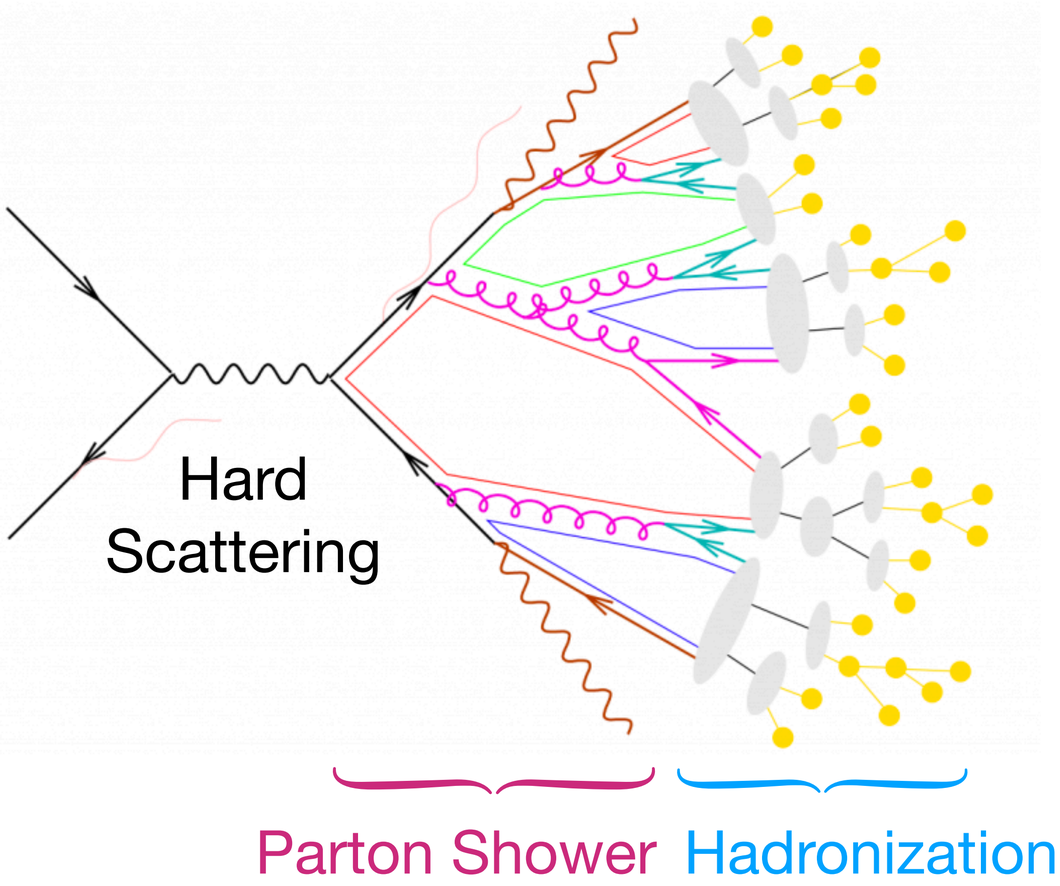


Large Hadron Collider (2008 - Present)

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

[See full list at Wikipedia]

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*.

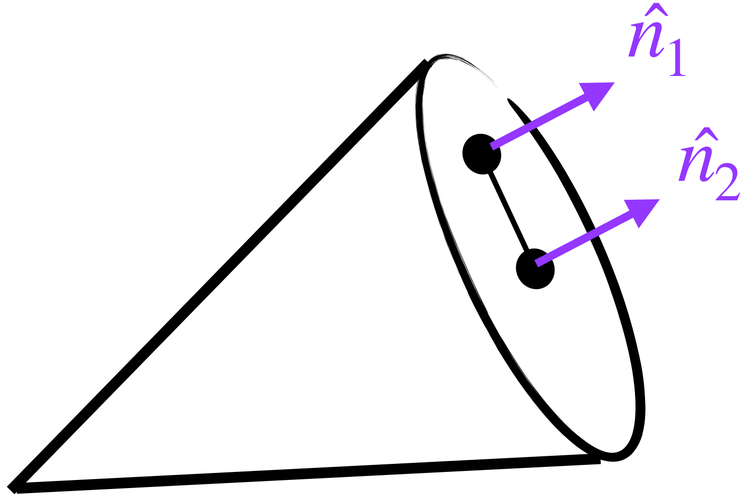
Jets are sensitive to physics information from many physics scales → great object to study these different processes!

Energy Correlators

Jets create energy flow that can be characterized by energy correlators!

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

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



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

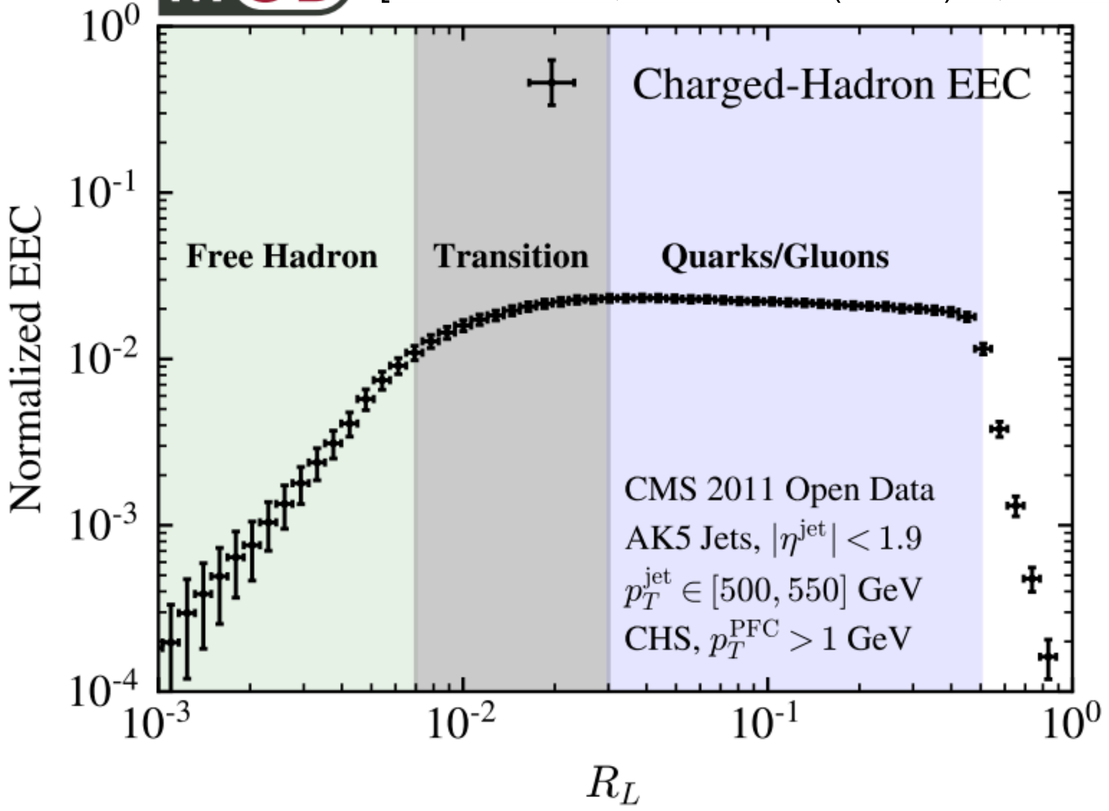
In hadron collider environments, instead of $\hat{n}_1$ use

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

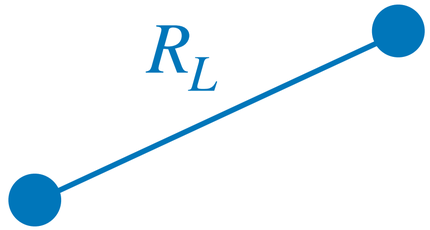
Projected N-point Correlators

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

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



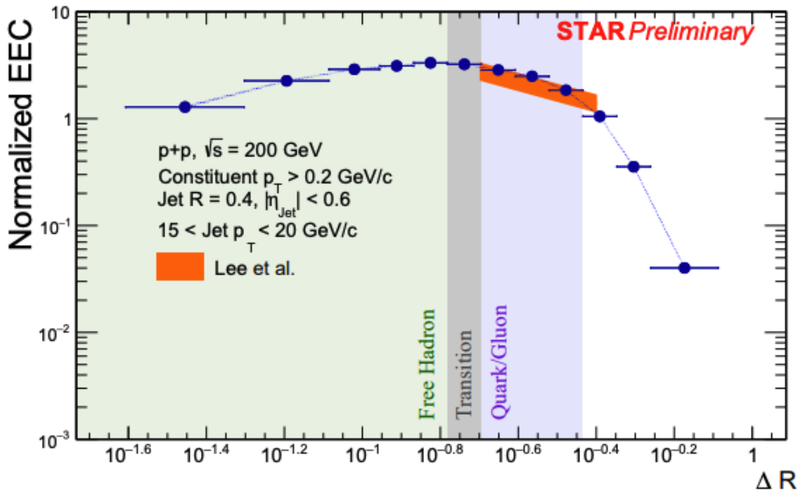
- All shape information is integrated out, keep longest side R_{L} fixed

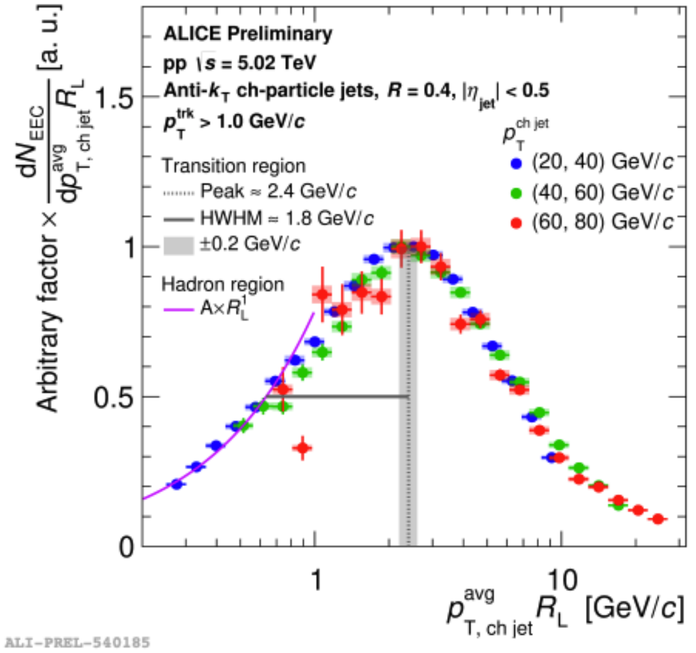


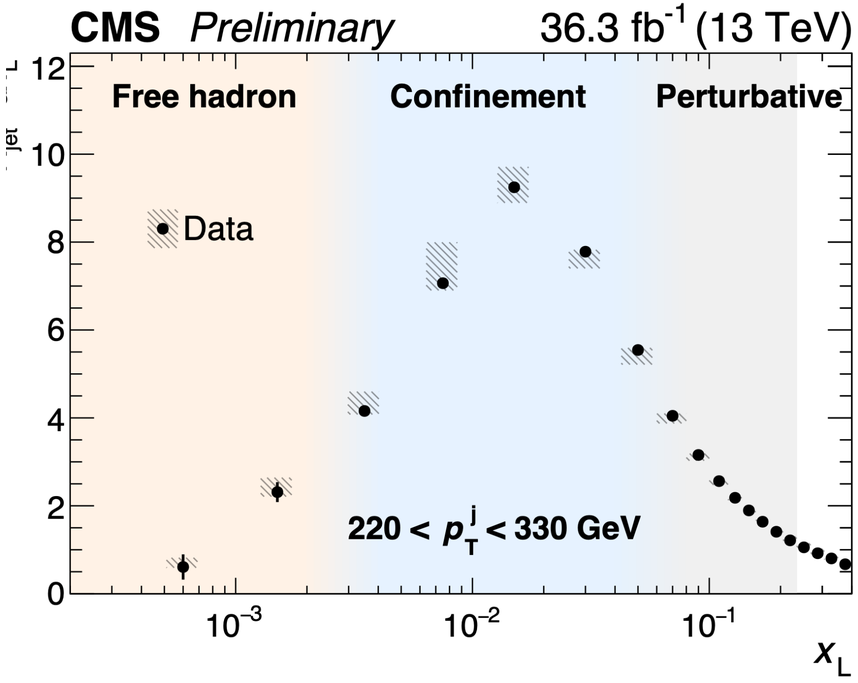
- ***Projected correlators are useful for isolating the scaling behavior!***

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

Measurements of E2Cs in pp collisions







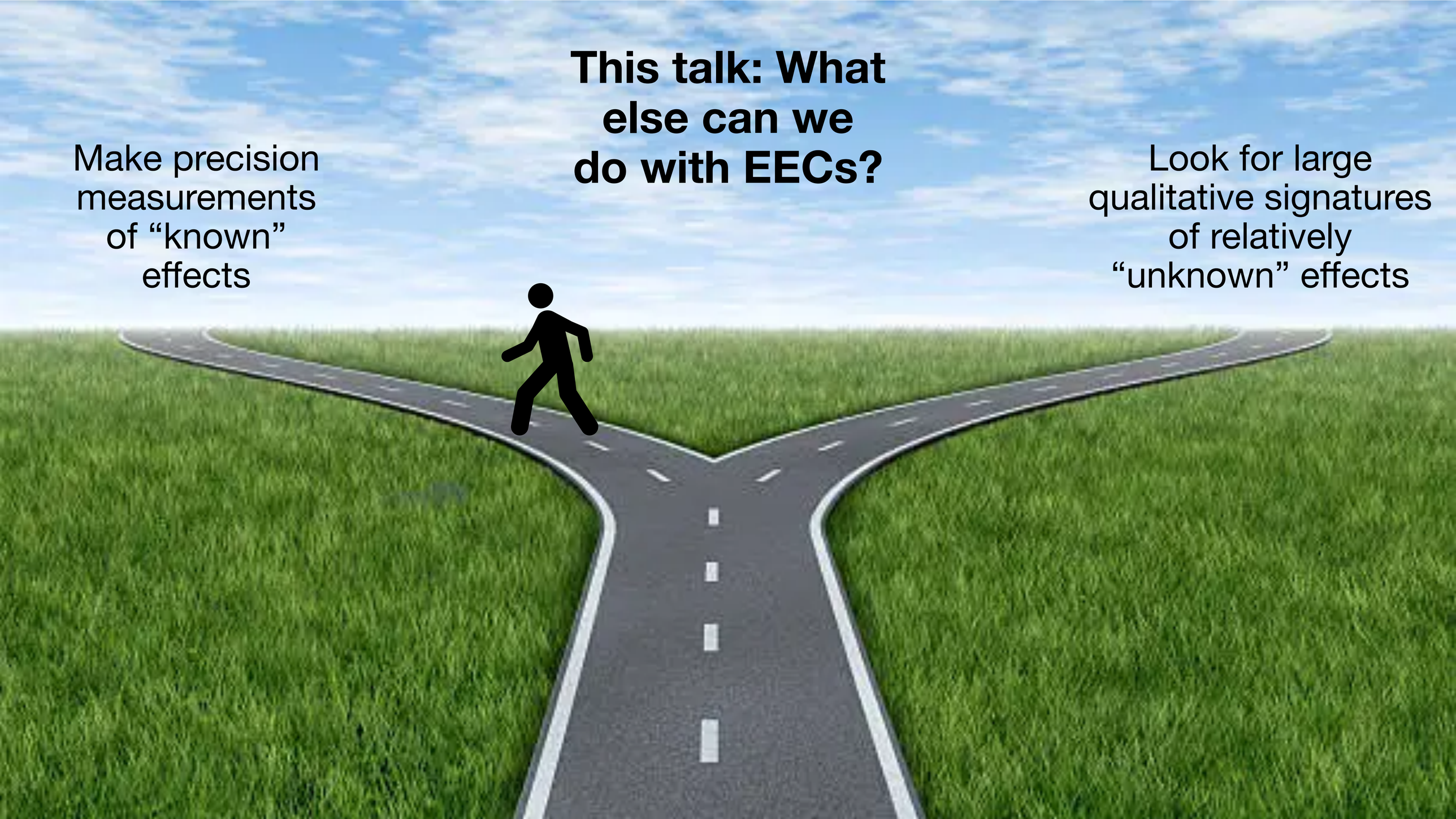
Increasing p_{T}

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!

This talk: What else can we do with EECs?

Make precision measurements of “known” effects

Look for large qualitative signatures of relatively “unknown” effects



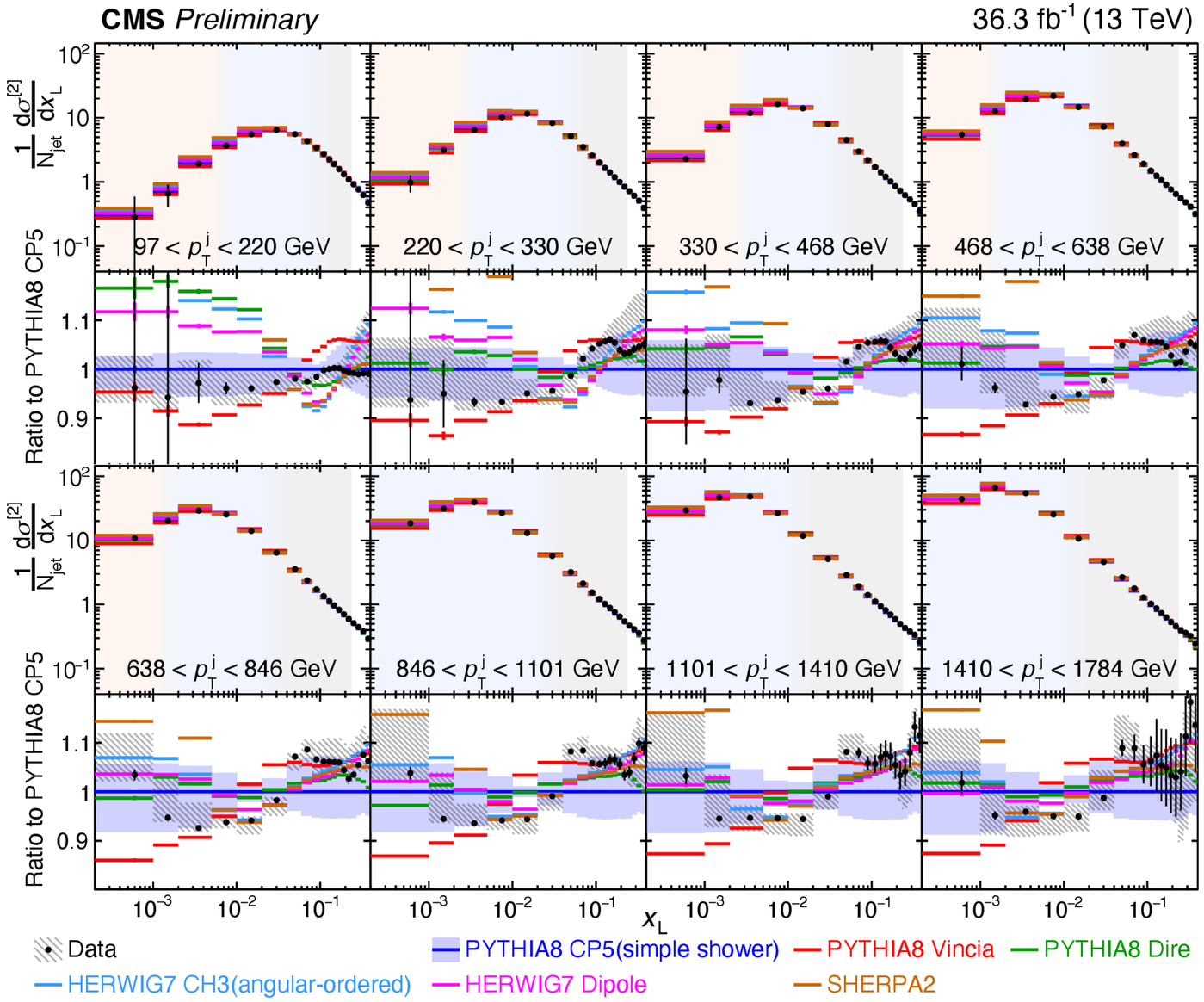
Massachusetts Institute of Technology

Part 1: First measurement of fully-corrected E2C in e^+e^- 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

EEC in pp comparisons to models



- Comparisons to PYTHIA 8, HERWIG, SHEPA 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?**

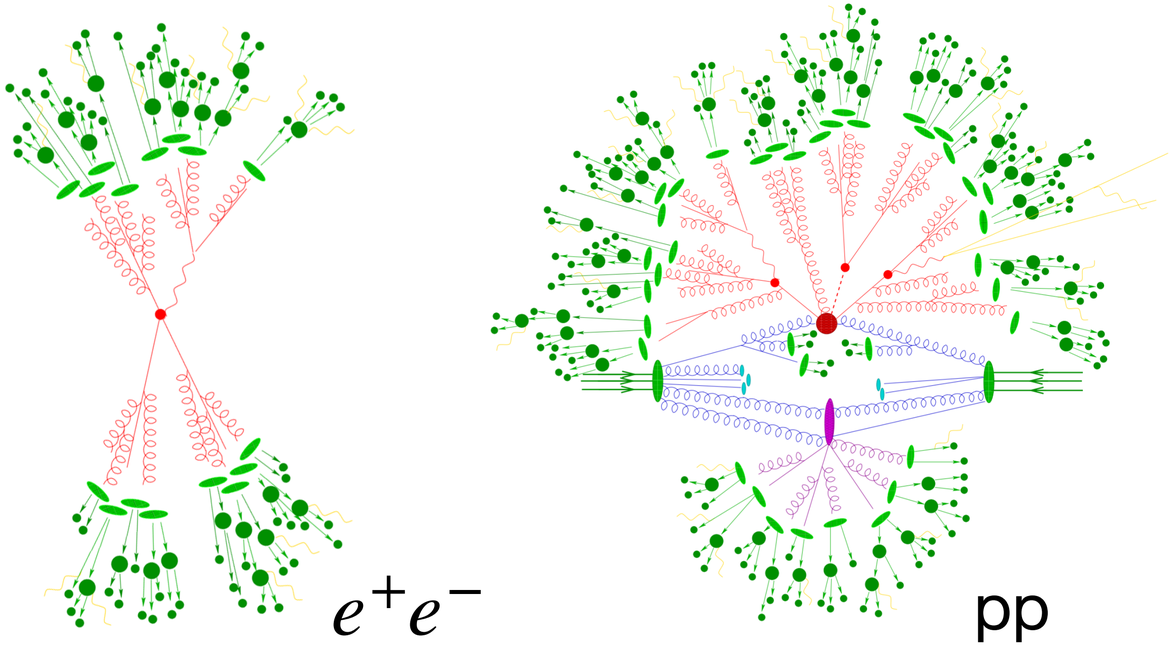
Going simpler! e^+e^-

- Archived LEP data presents a great opportunity to understand these discrepancies and explore new parts of phase space! *Much cleaner environment!*

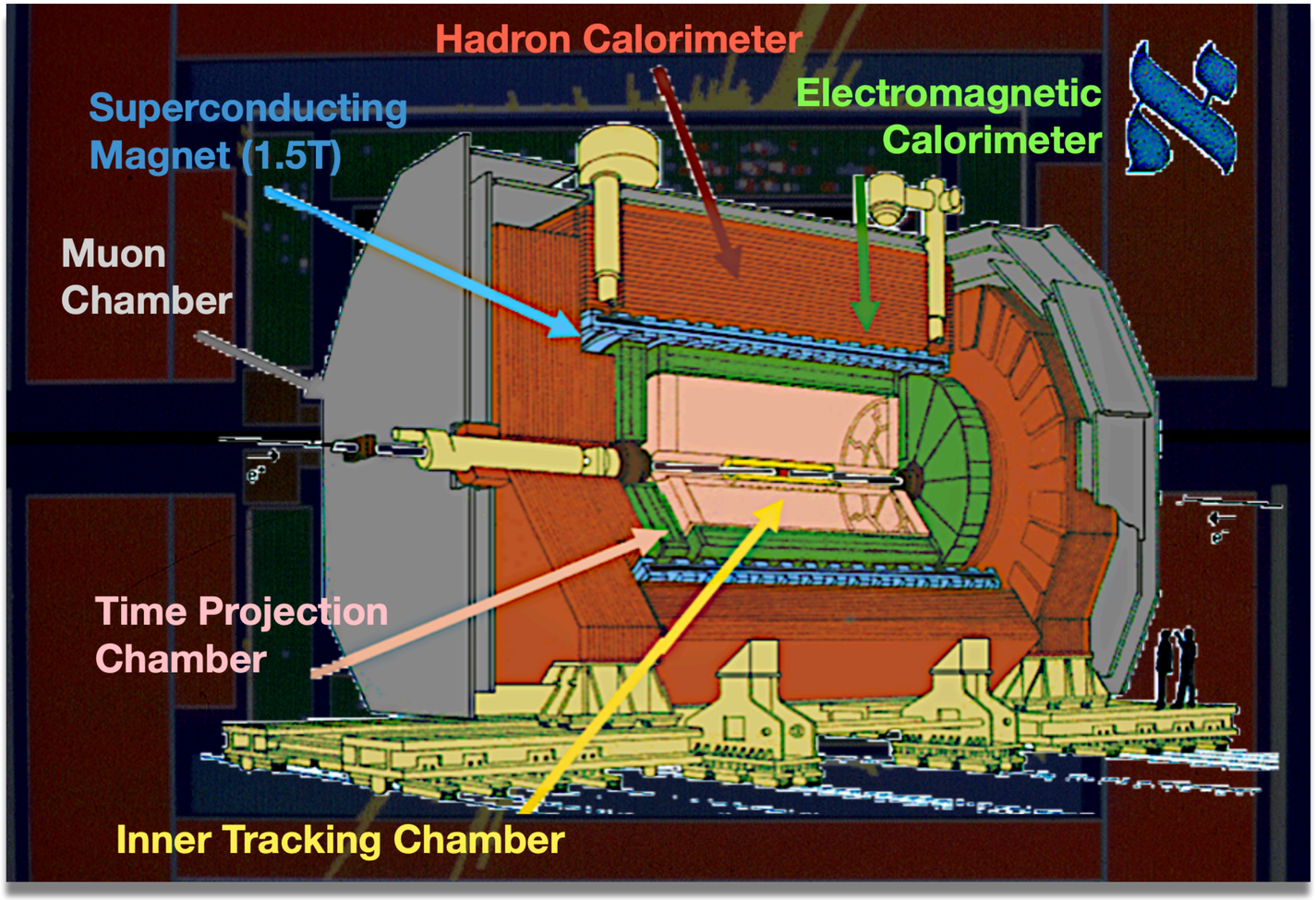
  - **Good background control**
    - No gluonic initial state radiation, no multi-parton interactions, negligible pileup.

  - **Structureless beam**
    - No complications of PDFs
    - Good final-state kinematic control.

Cleanest test of QCD and phenomenological models!



ALEPH



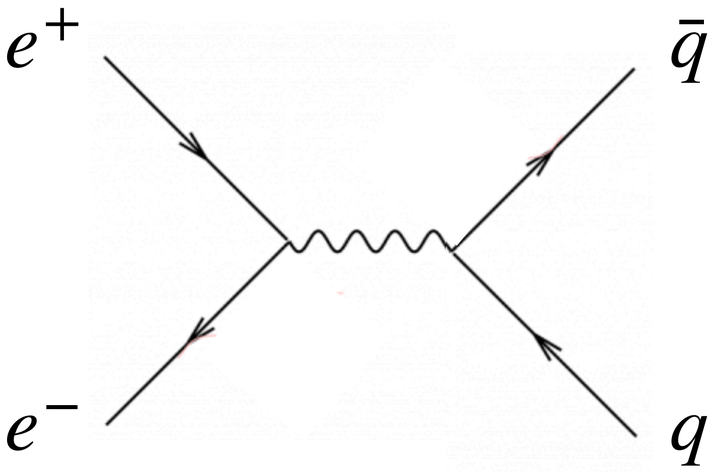
- ALEPH was located at IP4 of LEP.
- Now 25-30 years after data was collected, the data is preserved and able to be analyzed thanks to the MIT Open data format.
- Archived PYTHIA 6 MC with detector simulation also available.

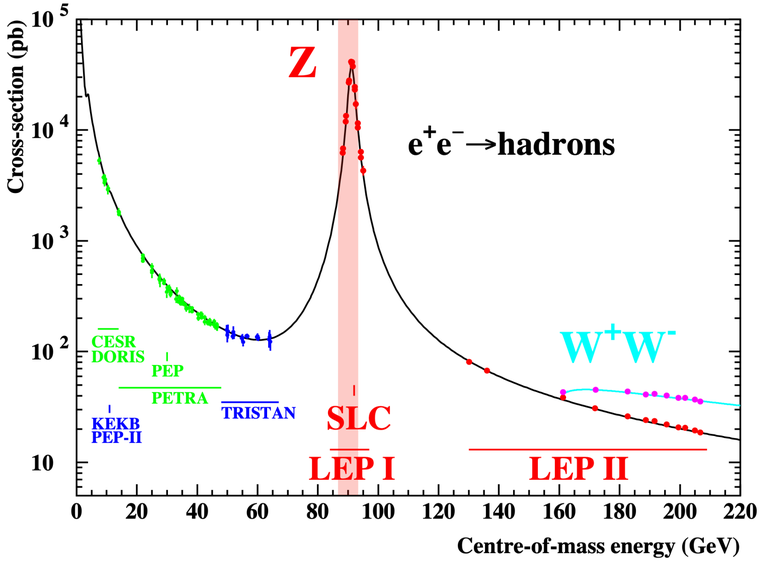
Archived data can now be reanalyzed and reimagined with new experimental tools!

Special thanks to Roberto Tenchini and Guenther Dissertori for their help in making this archival effort possible through their advice and expertise with ALEPH data.

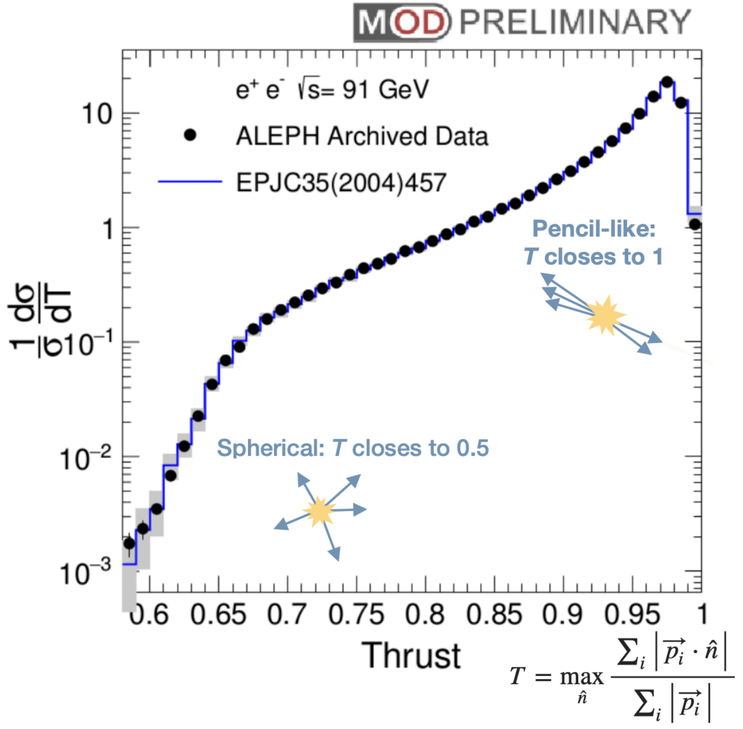
LEP 1 (1992 - 1995)

- Data taken at the Z-pole $\sqrt{s} = 91.2$ GeV



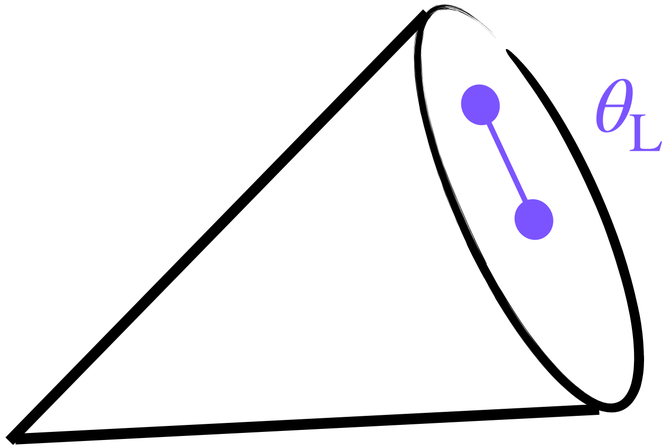


- Analysis of MIT Open Data (MOD) format agrees well with original analysis of the thrust (jet shape variable).

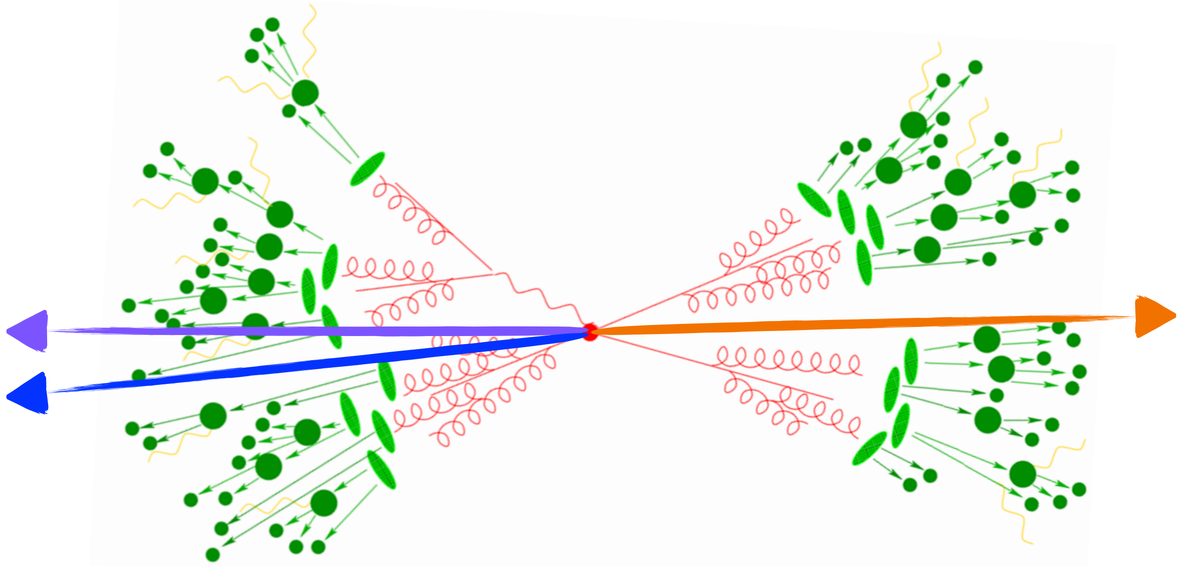


EECs in e^+e^-

- In this first analysis, we use the variables θ_L and $z = \frac{1-\cos(\theta_L)}{2}$
  - Function of the opening angle in radians (θ_L)



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



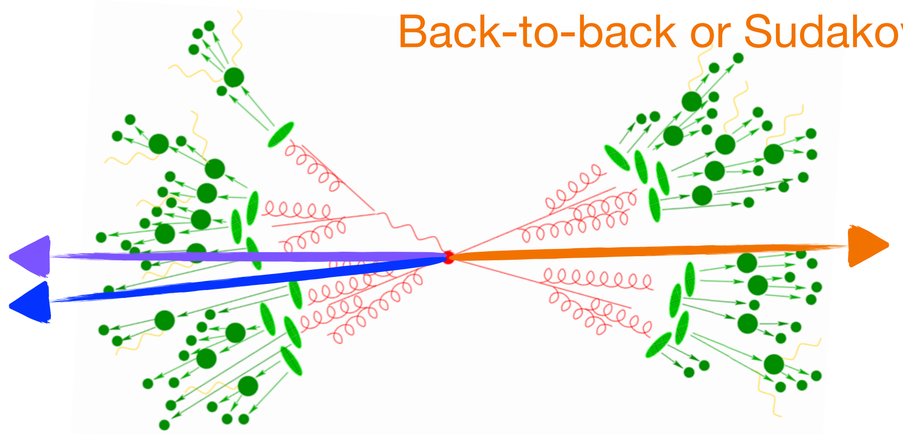
Collinear ($\theta_L \sim 0$)

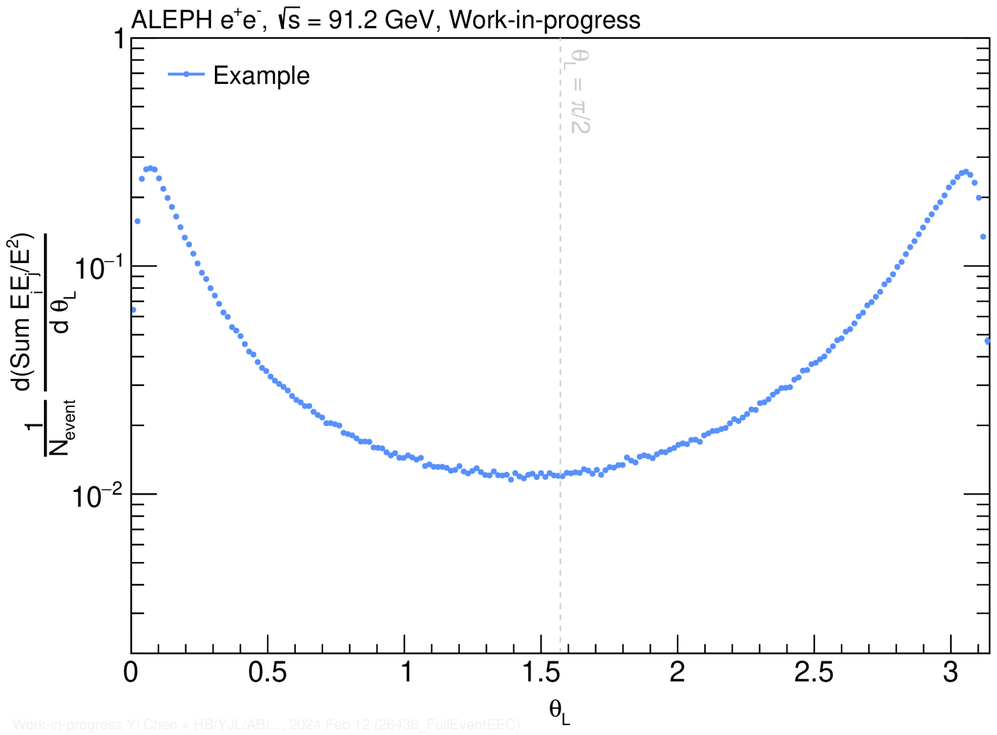
Back-to-back or Sudakov ($\theta_L \sim \pi$)

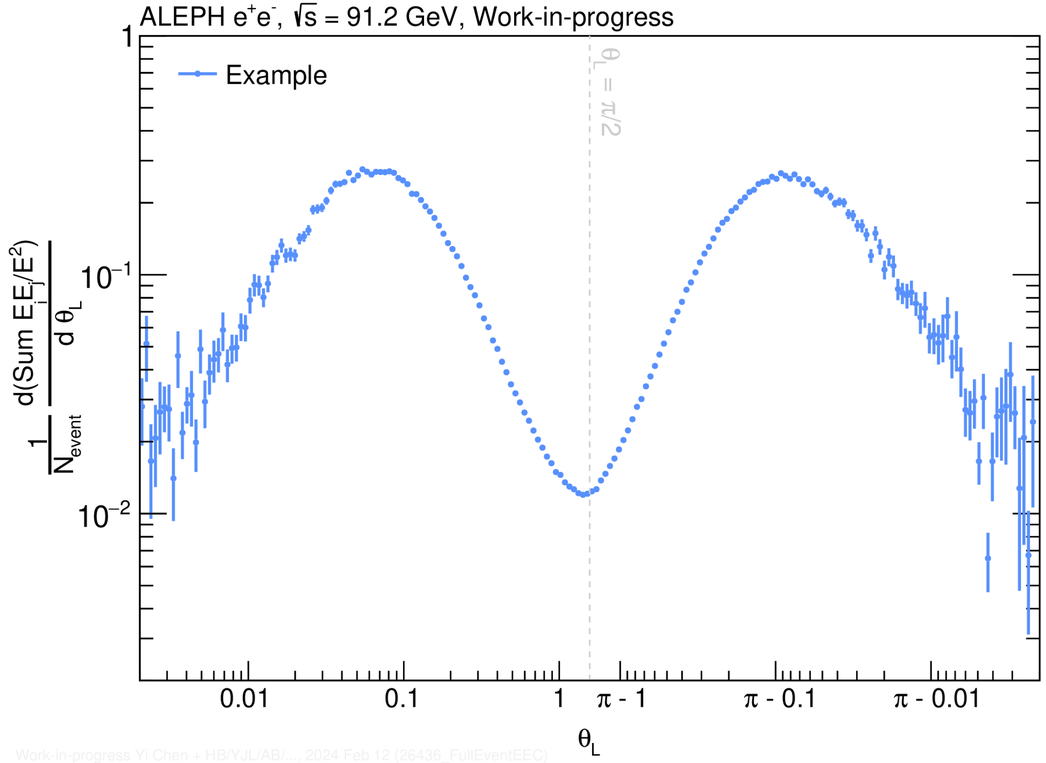
$$\text{E2C}(z) = \sum_{i,j}^{n} d\sigma \frac{E_i E_j}{E^2} \delta(z - z_{ij})$$

EECs in e^+e^-

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

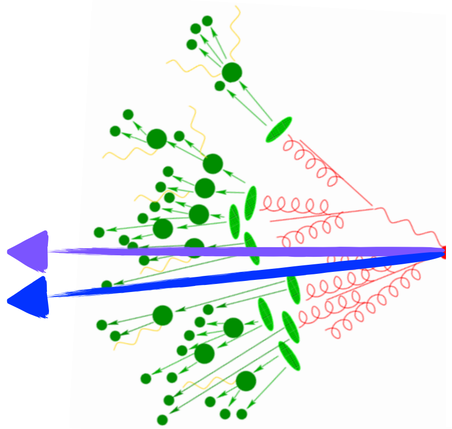




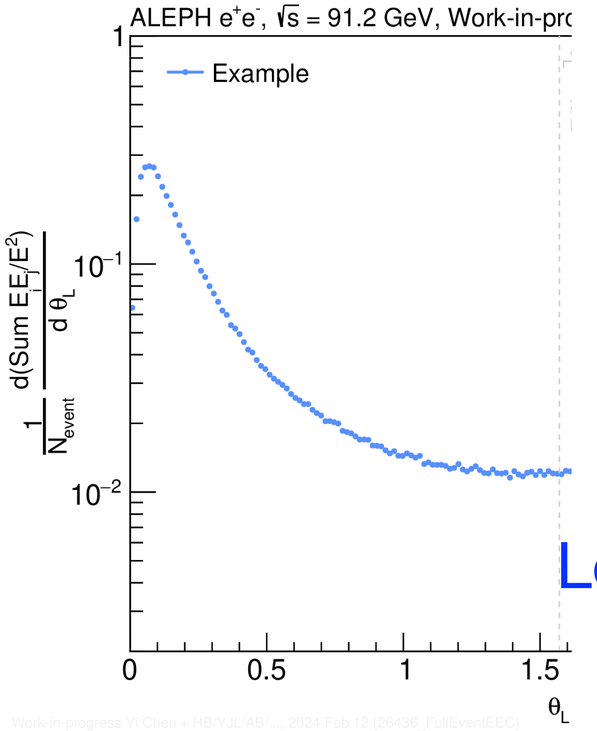


EECs in e^+e^-

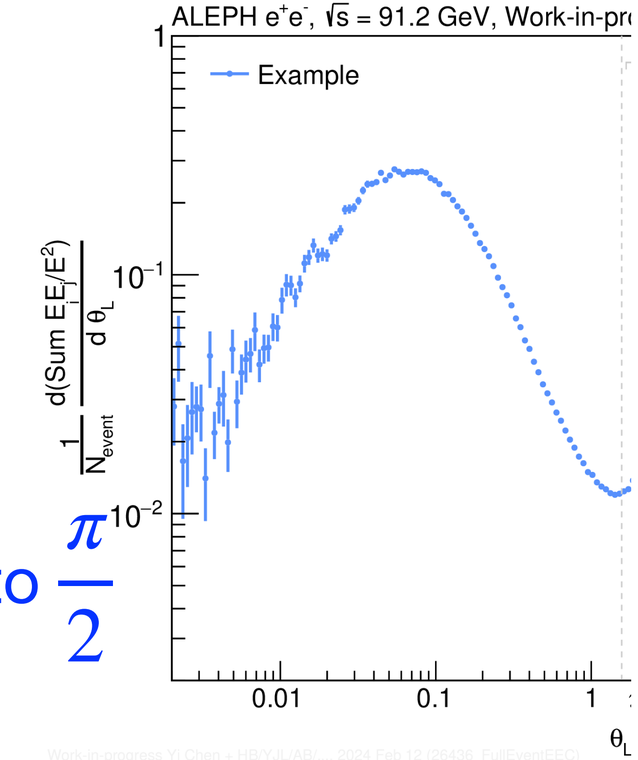
- Example using archived MC.
- Plot this in a double log style.



Collinear ($\theta_L \sim 0$)

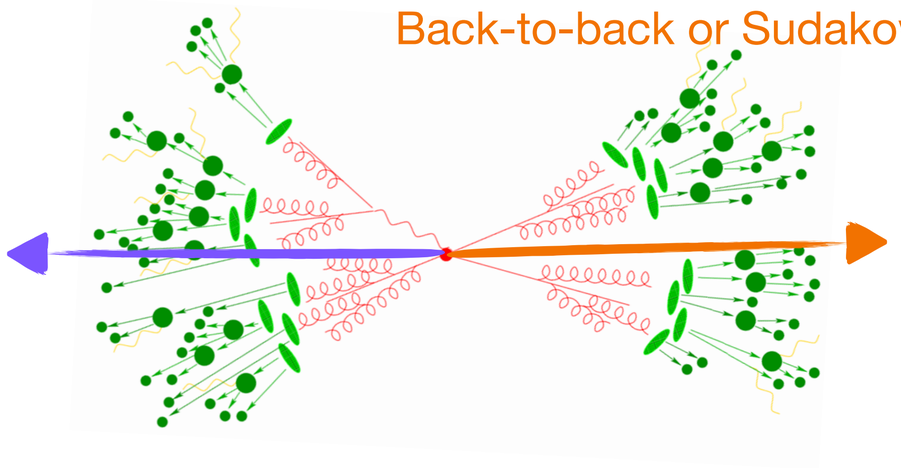


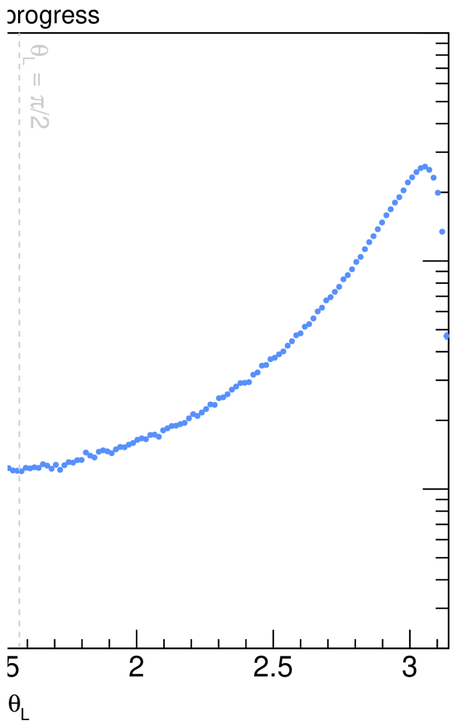
Log scale from 0 to $\frac{\pi}{2}$



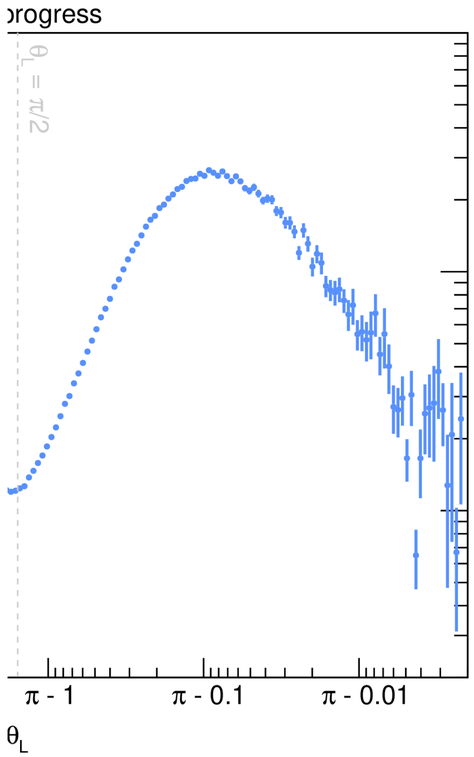
EECs in e^+e^-

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



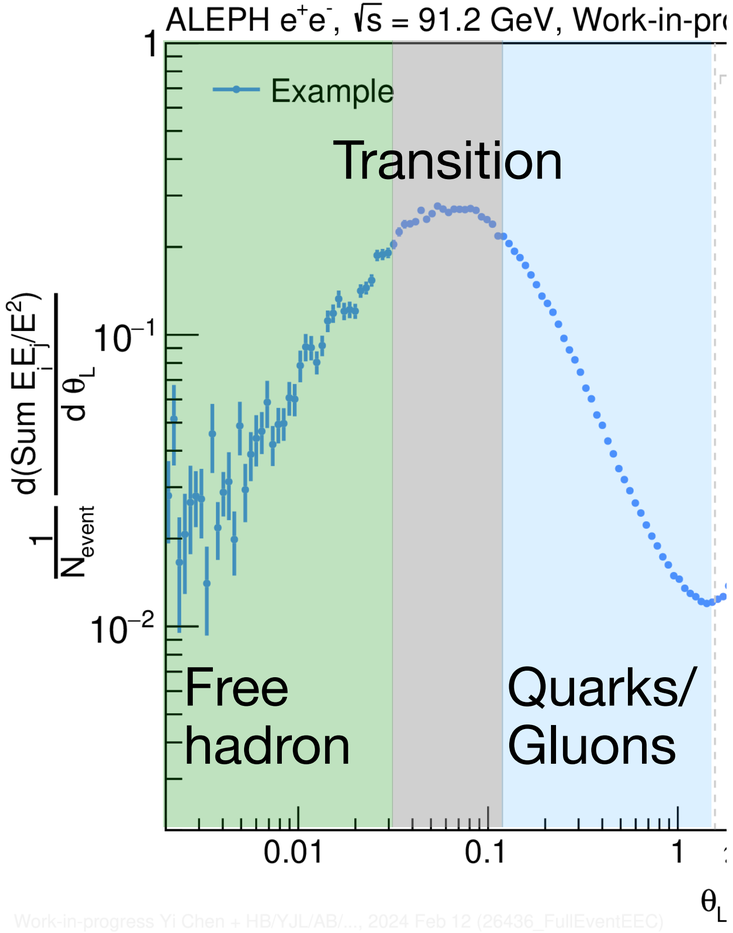


"Flipped" Log scale from π to $\pi - \frac{\pi}{2}$

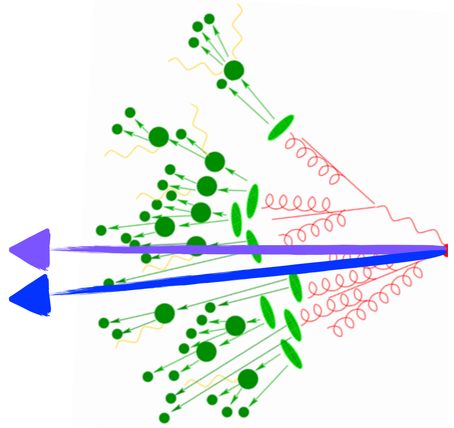


EECs in e^+e^-

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

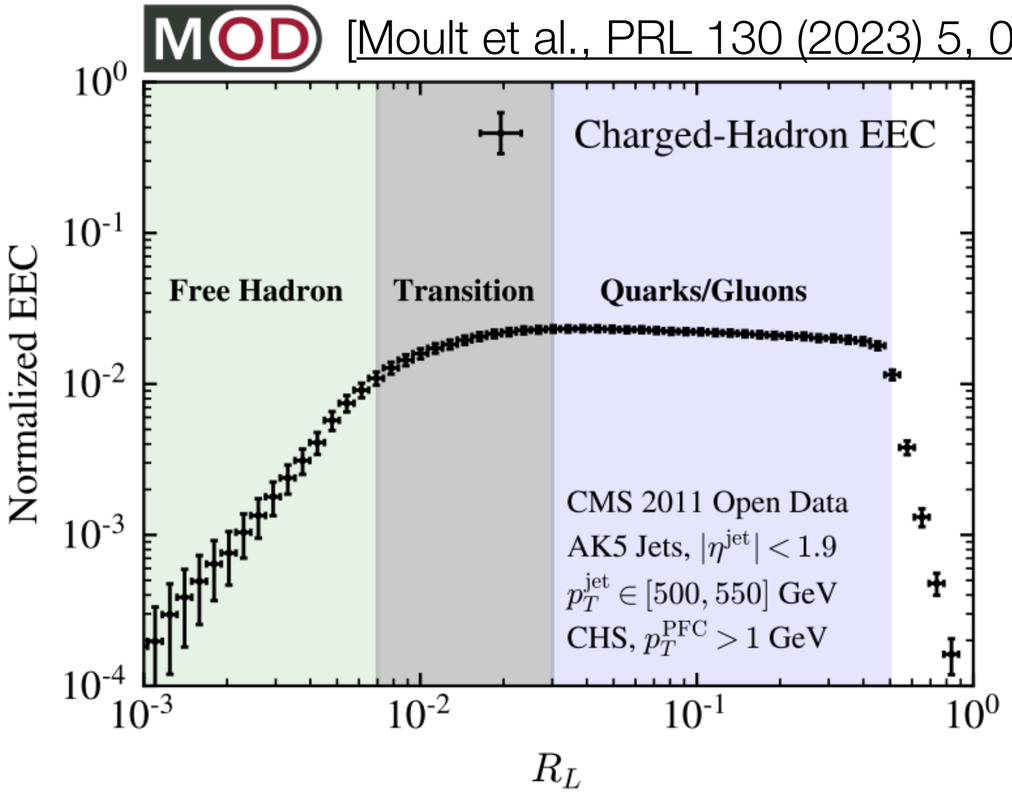


Collinear region is the E2C we are already familiar with!



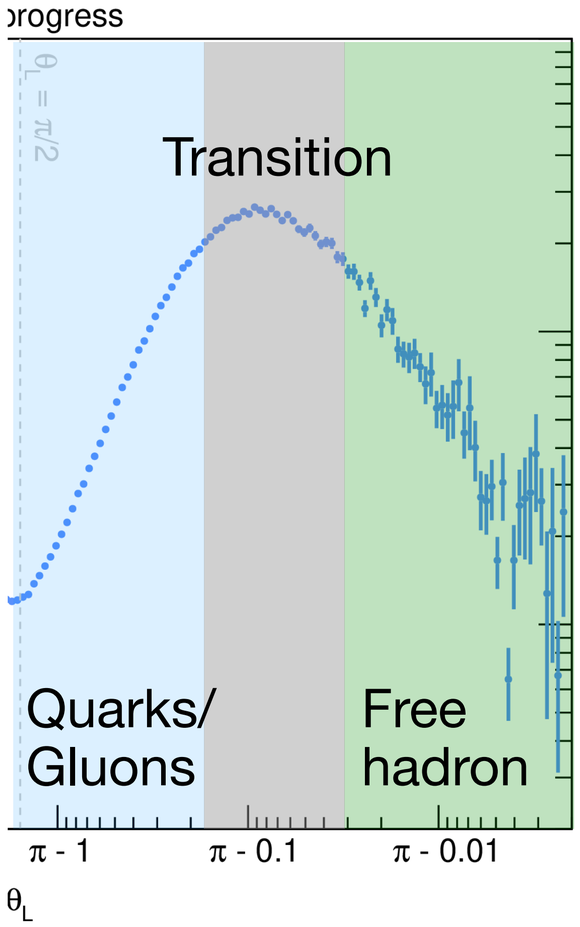
Collinear ($\theta_L \sim 0$)

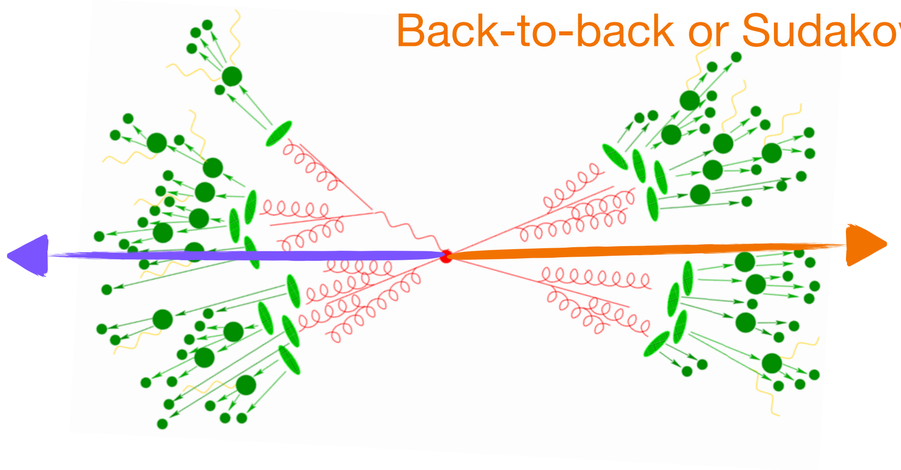
MOD [Moult et al., PRL 130 (2023) 5, 051901]



EECs in e^+e^-

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



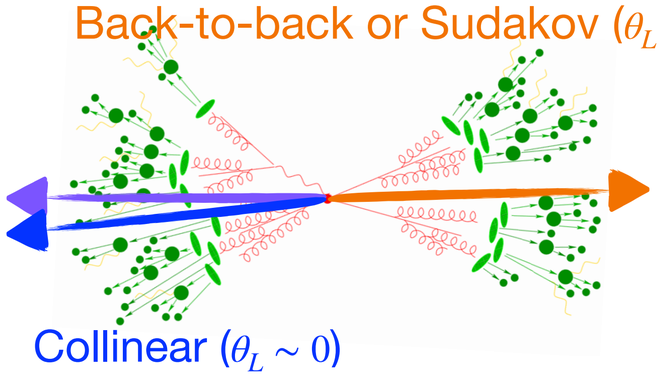


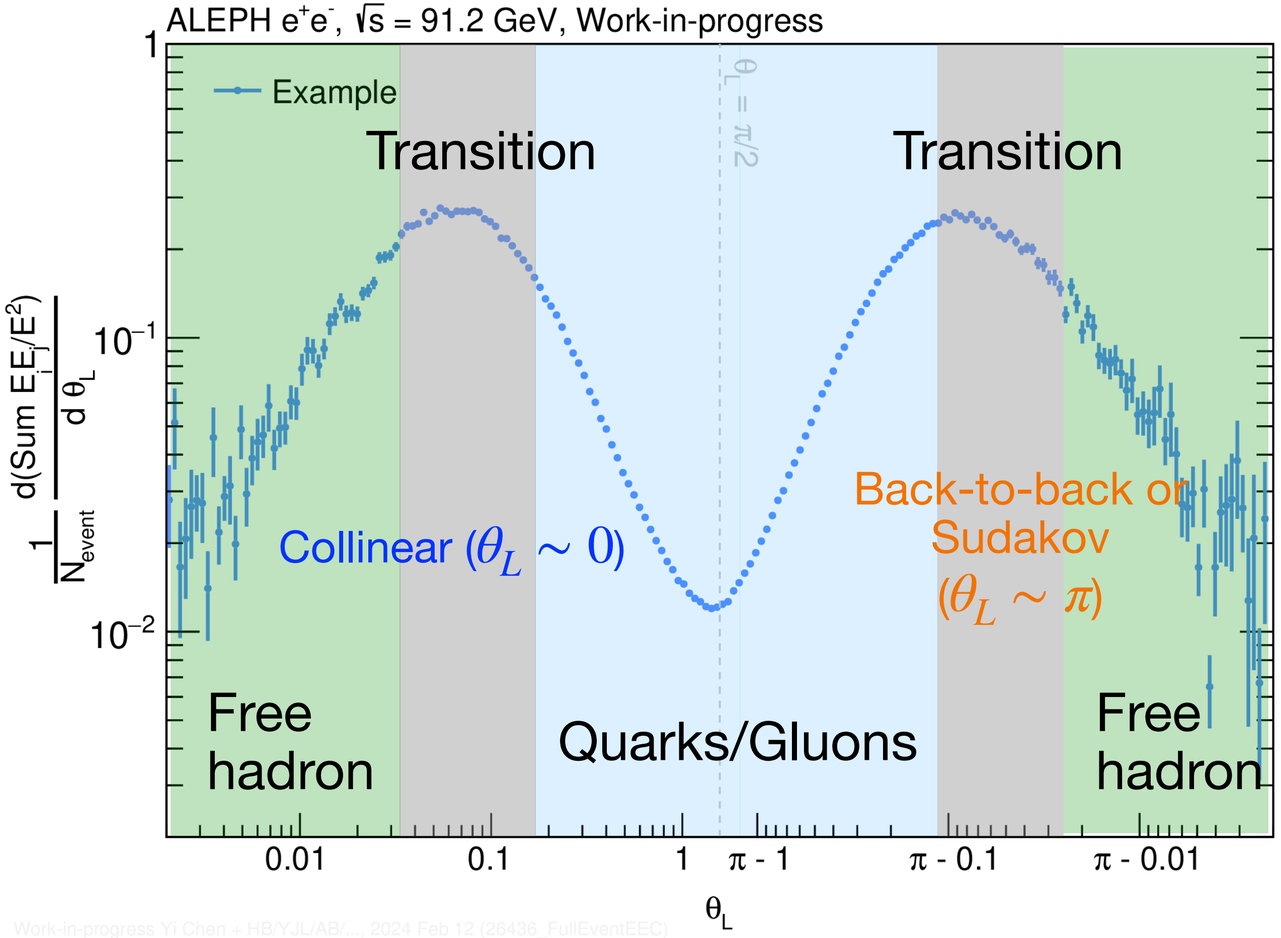
Back-to-back limit has similar regions!

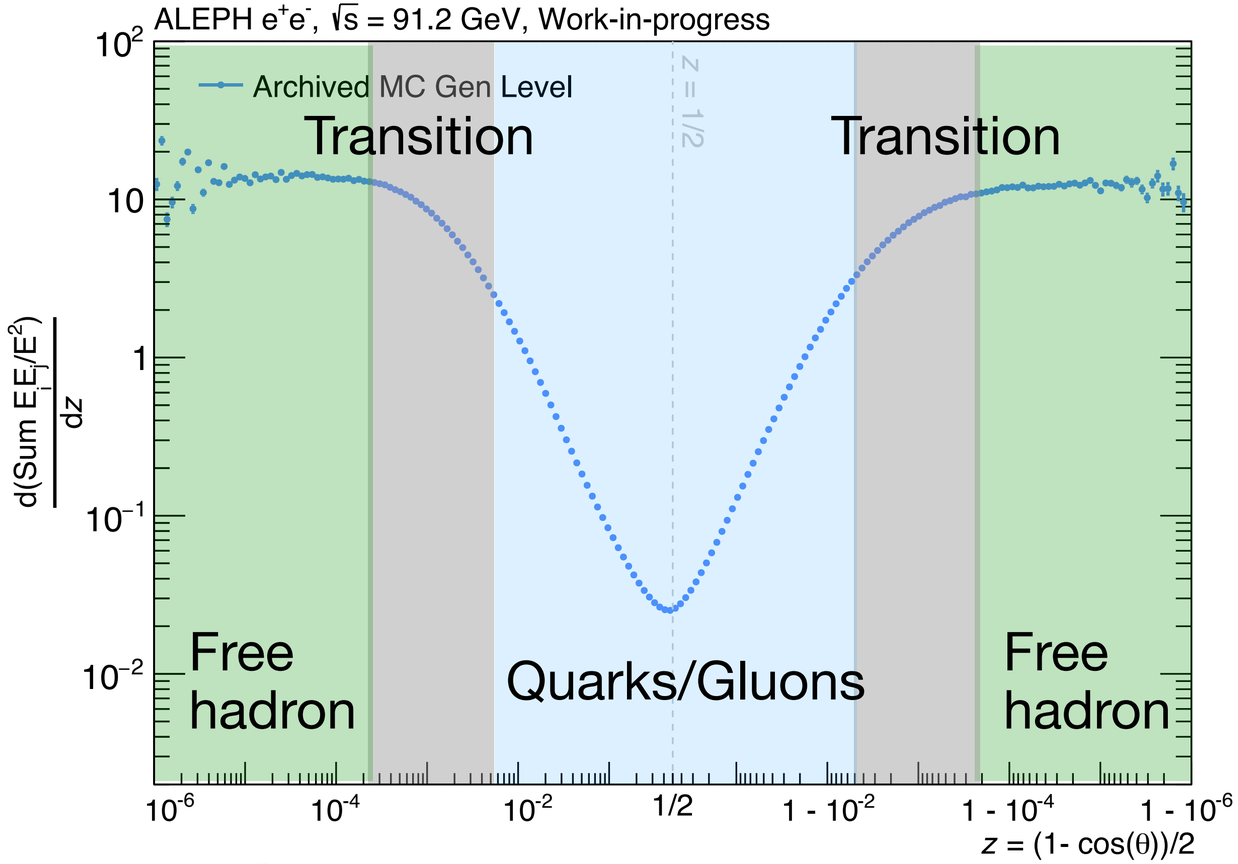
- Can be used to probe the universality of free hadron region (z-variable useful for this)

EECs in e^+e^-

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

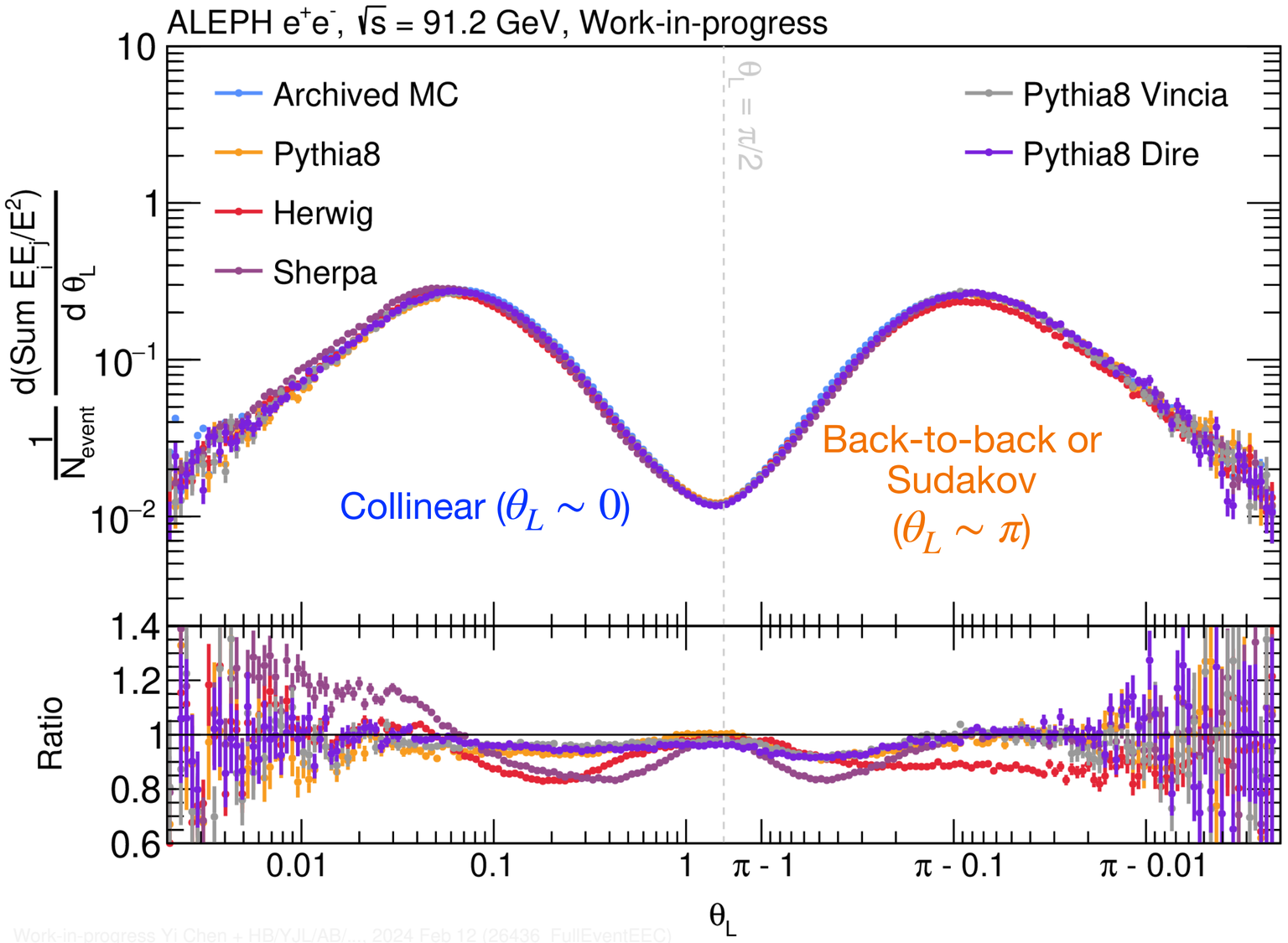


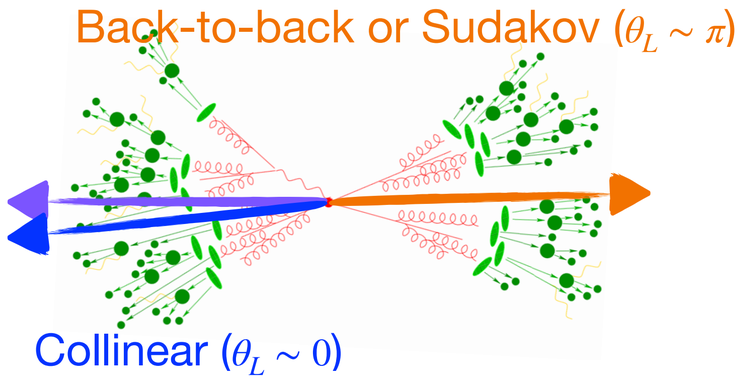




Work-in-progress Yi Chen + HB/YJL/AB/..., 2024 Feb 12 (26436_FullEventEEC)
Work-in-progress, 2024 Jul 16 HB

E2Cs in models

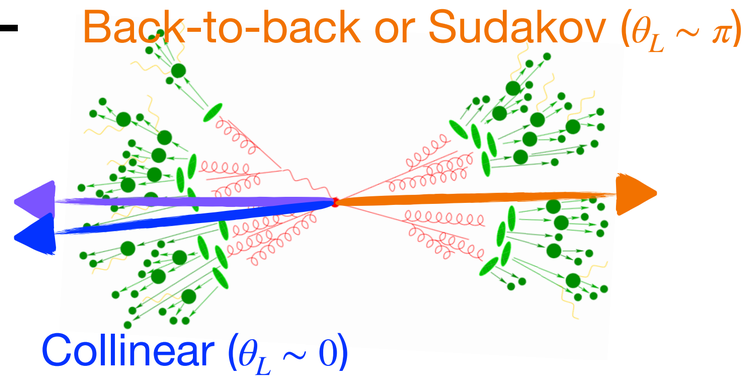




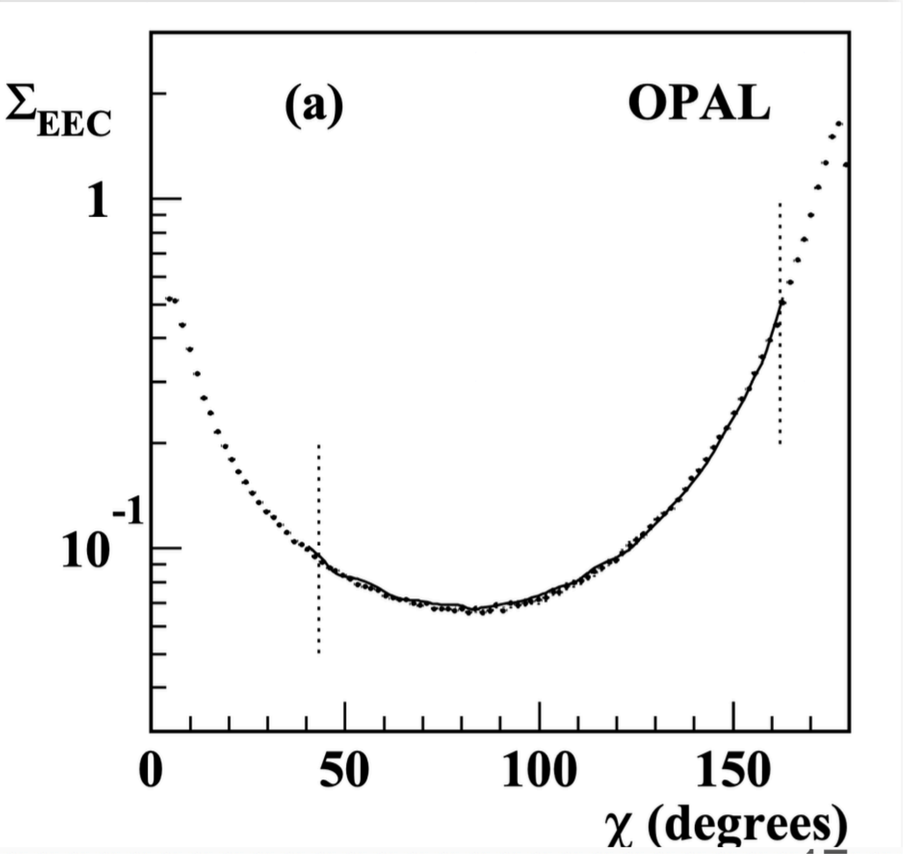
- Similar differences between models as seen in e^+e^- as in the pp case.
  - Larger θ_L not comparable (outside the jet)
- In free hadron region, models are roughly parallel to one another.
- In Quark/Gluon region different showers give a different slope.

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

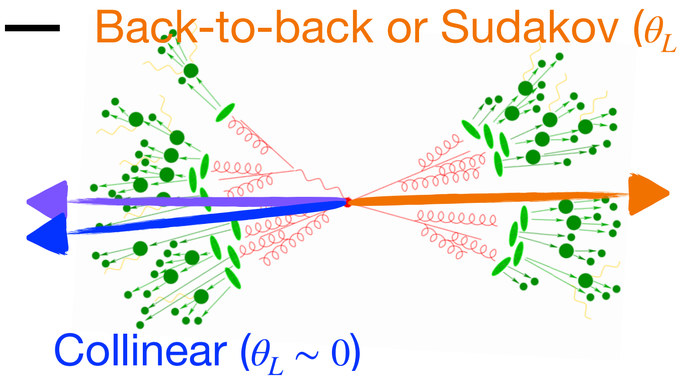
$$\mathrm{E2C}(z) = \sum_{\mathrm{i,j}}^{n} d\sigma \frac{E_\mathrm{i}E_\mathrm{j}}{E^2}\delta(z - z_\mathrm{ij})$$

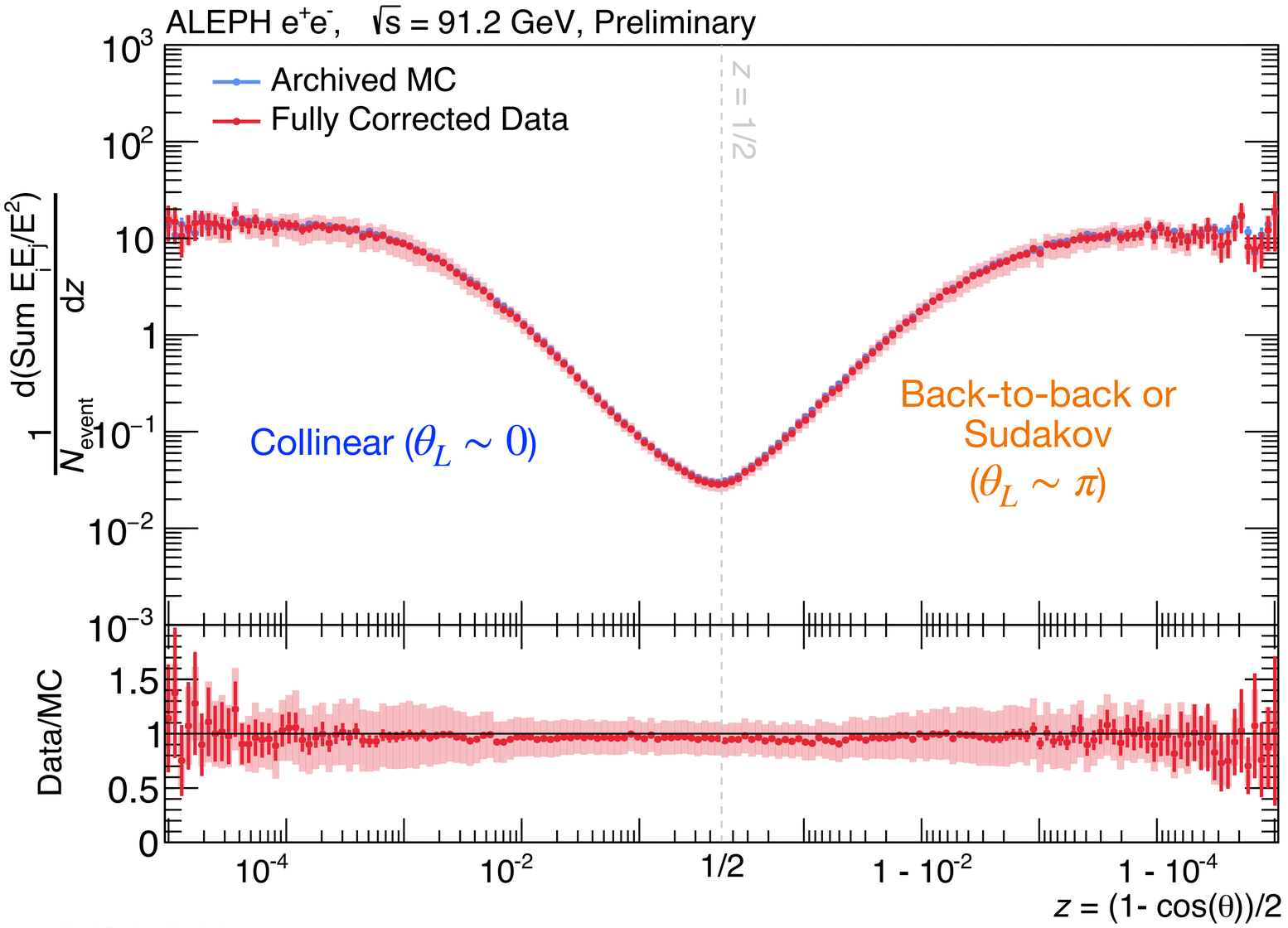


- Can do this in a fully-corrected way, unfolding in two dimensions.
  - z or θ_L axis
  - $E_\mathrm{i}E_\mathrm{j}$ axis
- Huge advantage of doing this in e^+e^- is that E = 91.2 GeV is fixed! Normally, would need to do three-dimensional correction, also correcting for the energy scale.
- First of its kind in e^+e^-! There was an OPAL measurement, but not unfolded and limited binning especially in the edges of the distribution!



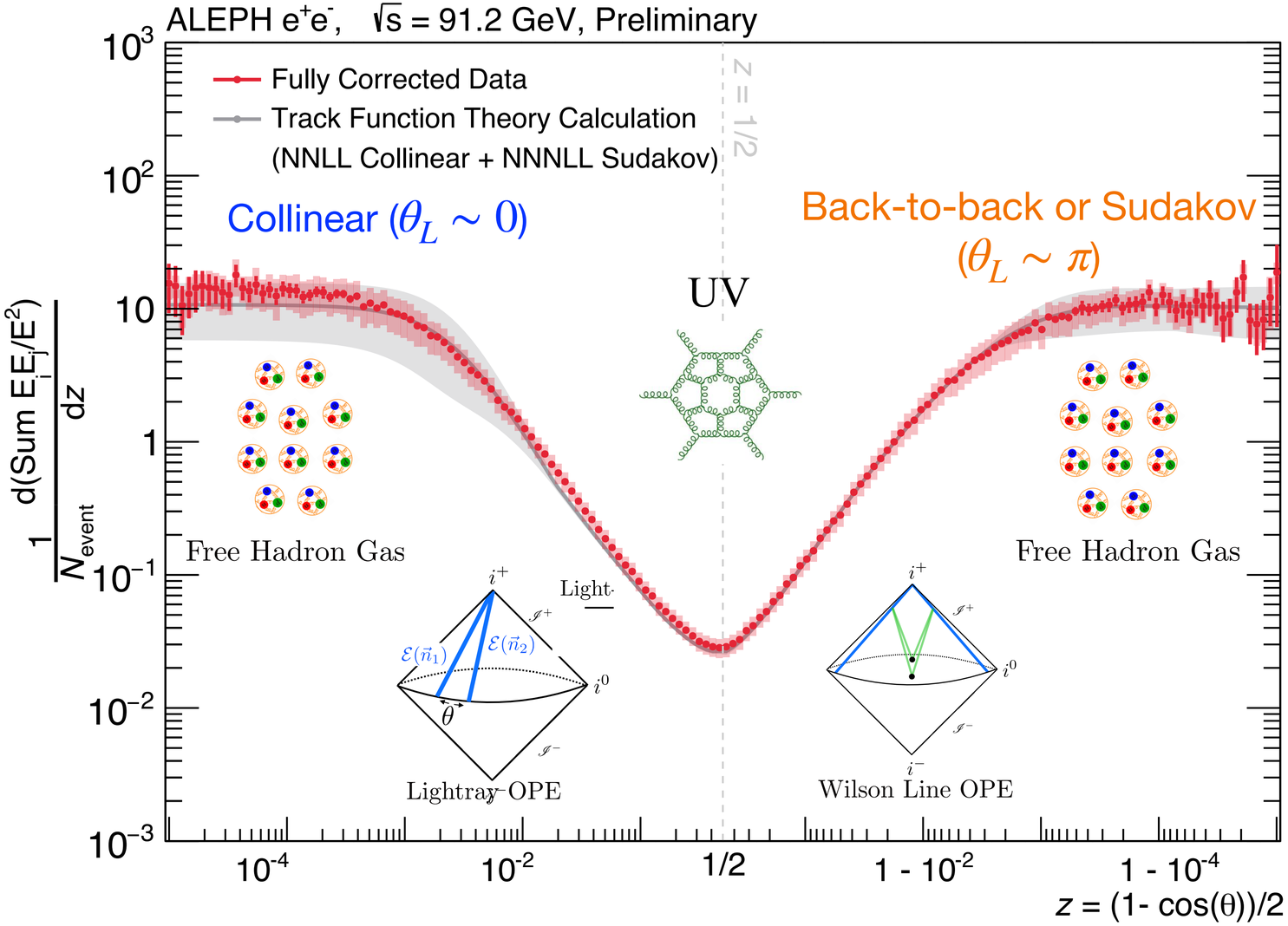
First fully-corrected E2Cs in e^+e^-



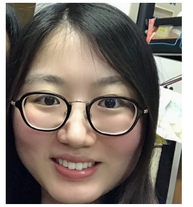


- For this first look, systematics are conservative.
- Shows good agreement with Archived PYTHIA 6 MC across all parts of phase space!
- Able to achieve unprecedented binning and kinematic reach!
- At first look collinear and back-to-back regions look comparable.

Comparison with theory calculation



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



Yibei Li

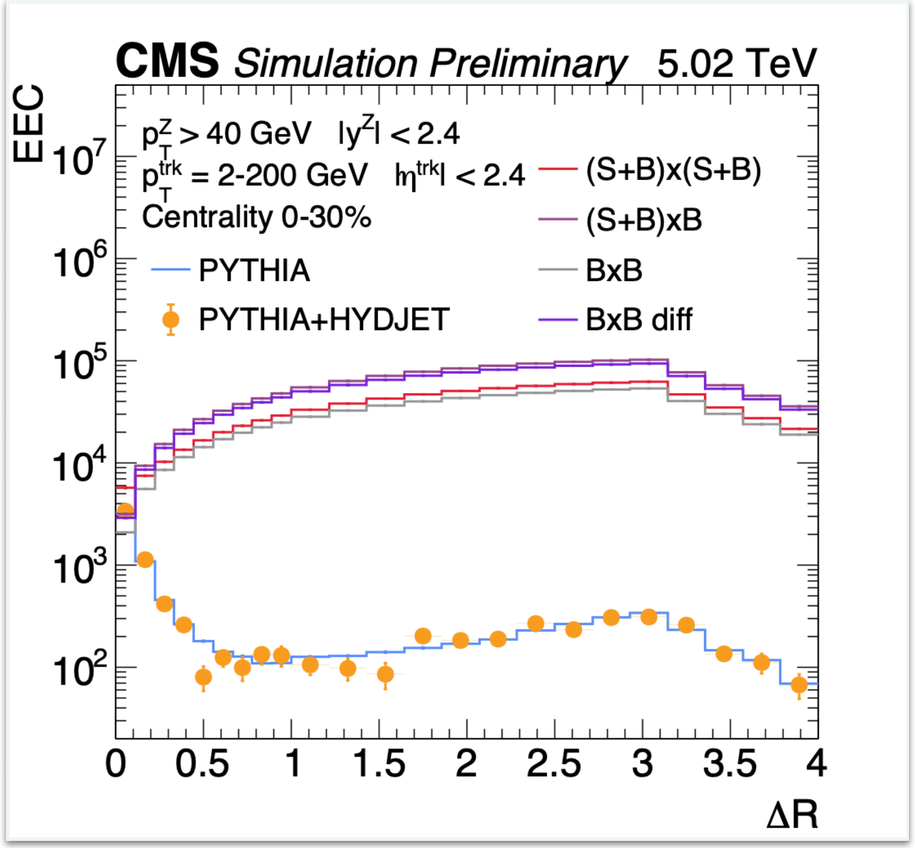
Max Jaarsma

- 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!**

Where can we go from here?

- Path #1: Measure the E2C with all particles in the event in other systems!



- 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*!

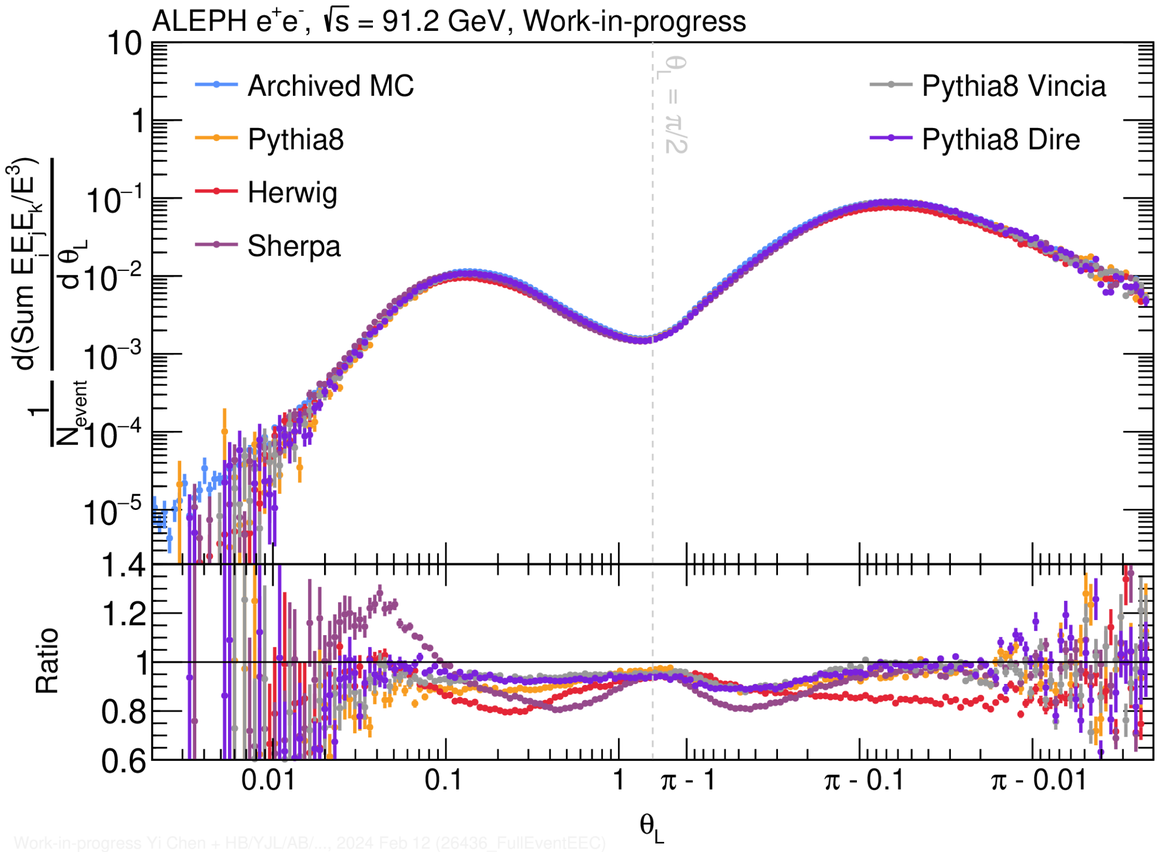
Orange: Detector level following background subtraction

Blue: Generator level pp

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

Where can we go from here?

- Path #2: Go to higher orders and take the ratio with lower orders.
  - Useful for the extraction of α_s.



- Higher orders 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]

Massachusetts Institute of Technology

Part 2: Imaging the wakes of jets with EEECs

Based on arXiv:2407.13818 (to appear in JHEP) with Ian Moult (Yale), Dani Pablos (Santiago), Ananya Rai (Yale), Krishna Rajagopal (MIT), and Arjun Srinivasan Kudinoor (Cambridge)

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

Jet quenching

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

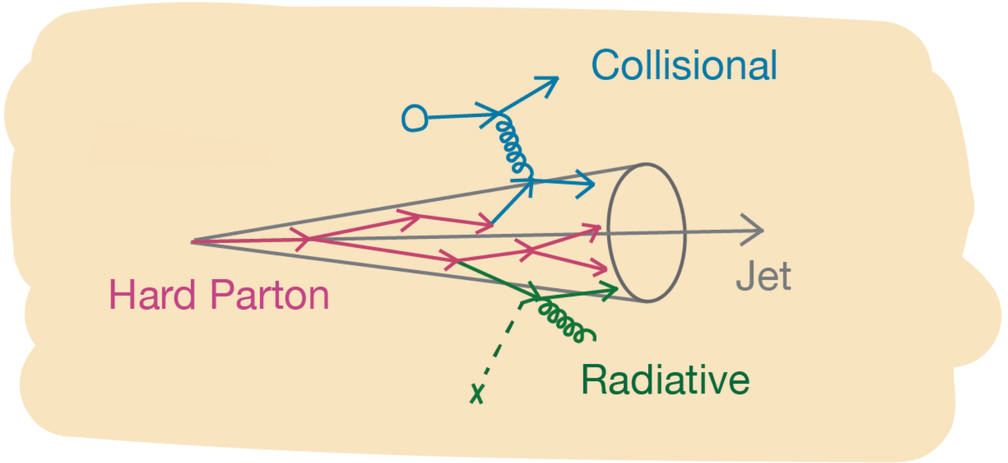
① Impact of the medium on the jet → jet energy loss

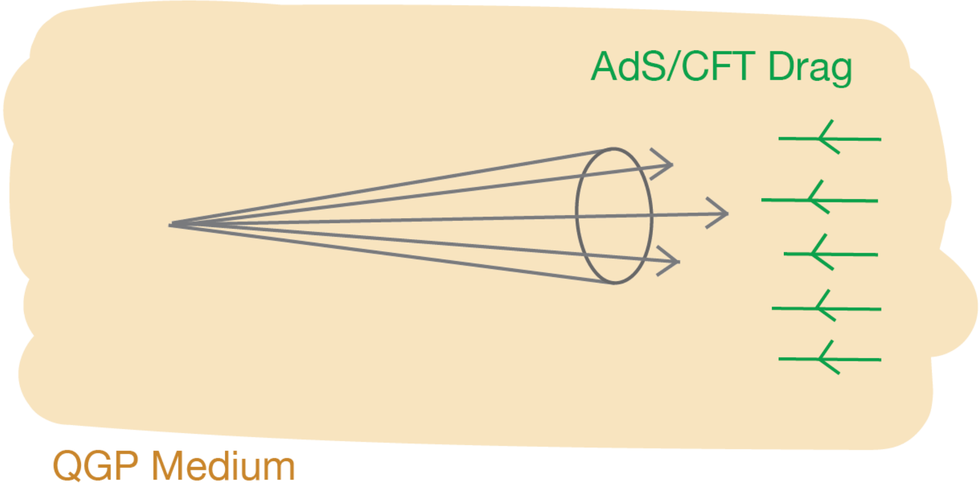
Ⓐ Weak coupling limit

- ❃ 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.*

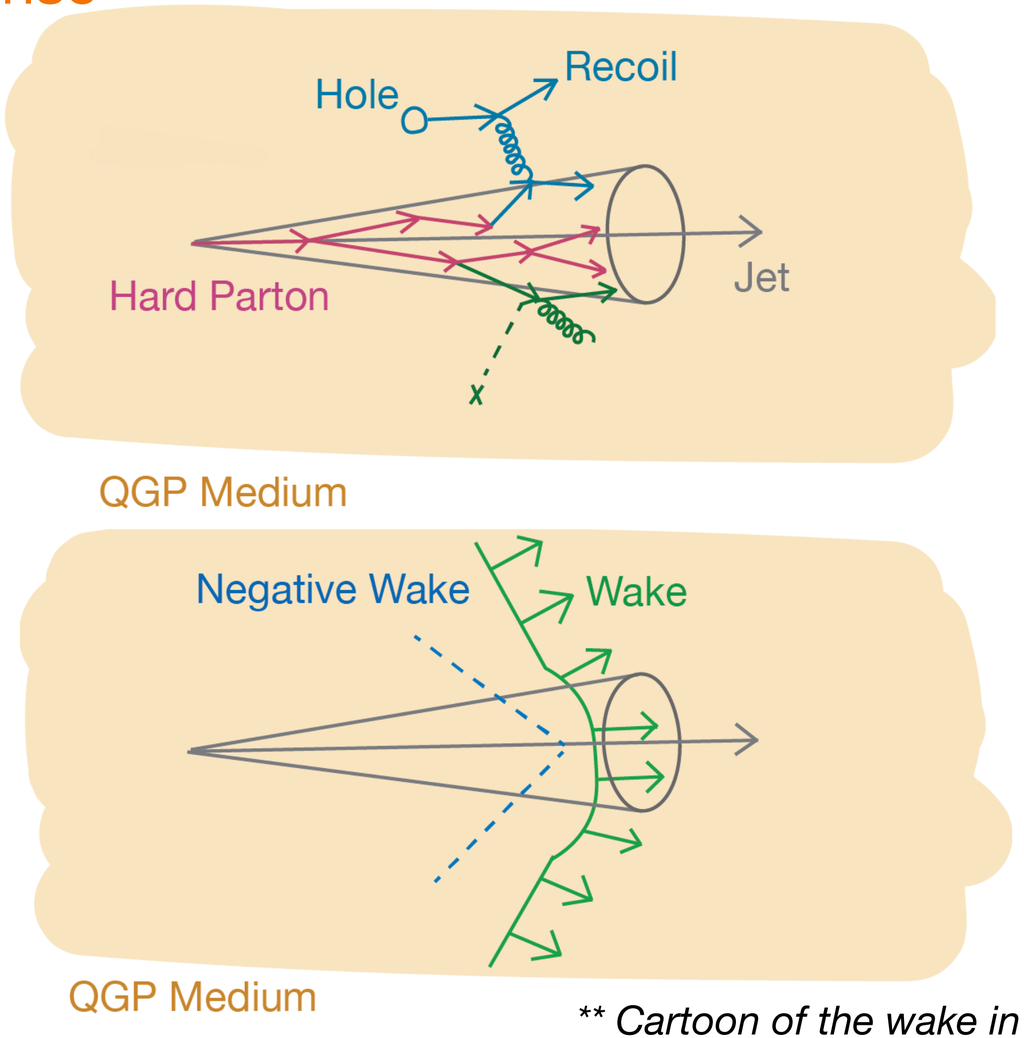
② Impact of the jet on the medium → medium response

Ⓐ Weak coupling limit

- Recoils (Kinetic based approach)

Ⓑ Strong coupling limit

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



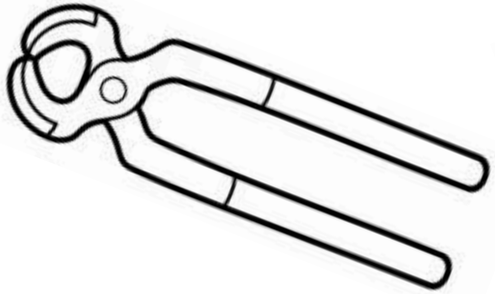
*** Cartoon of the wake in position space*

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

Tools to search for the medium response

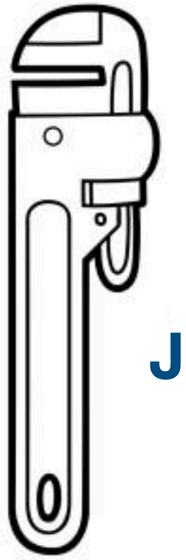
What tools exist to study the medium response?

Z-hadron

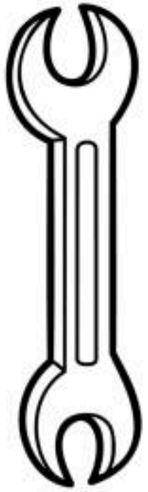


γ/Z-jet

(Groomed) jet substructure



Jet Shapes



R-dependent inclusive jet measurements

Jet-Hadron correlations

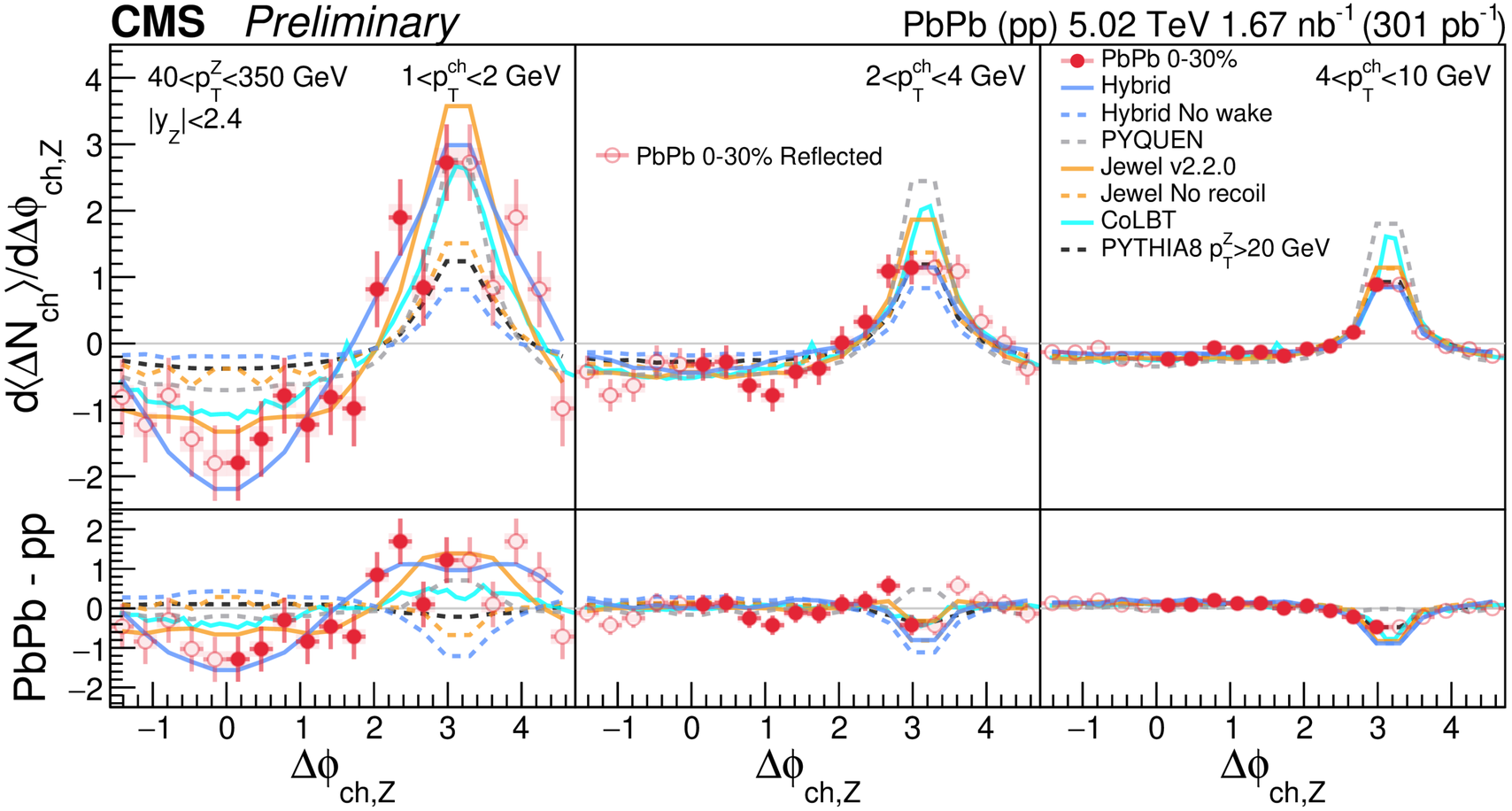
Baryon-to-Meson ratio near jets

Some tools are better than others!

New tools or a combination often needed!

Search for the medium response

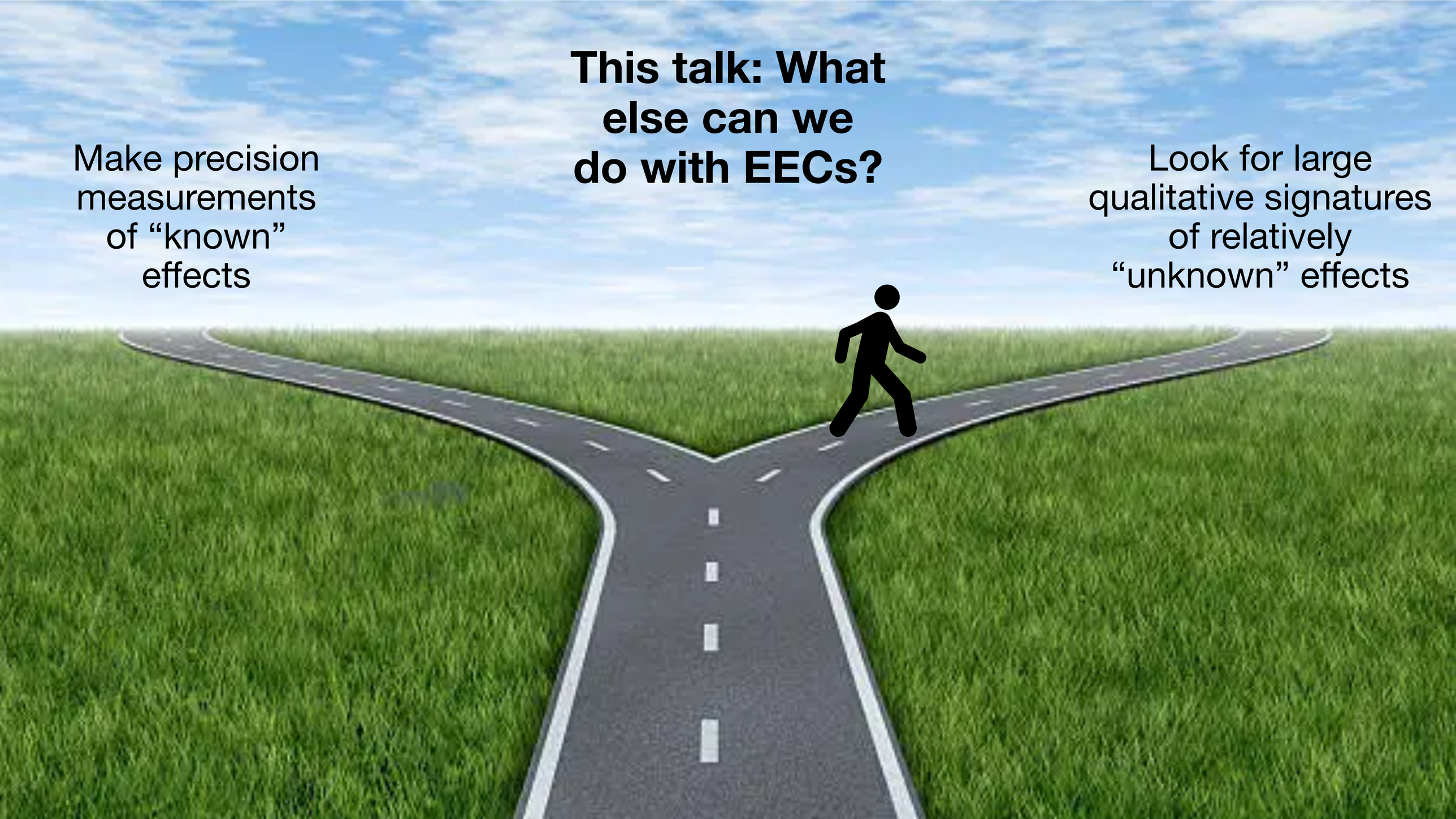
[CMS-PAS-HIN-23-006]



- 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

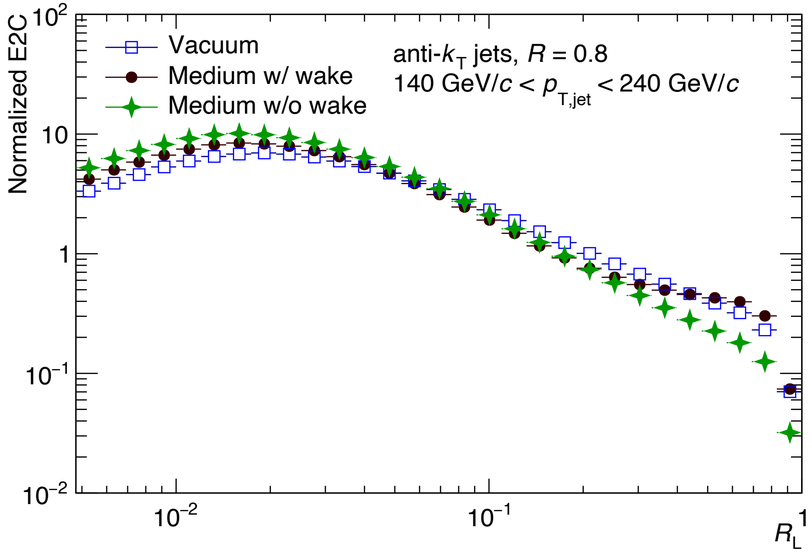
Can we use EECs?

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

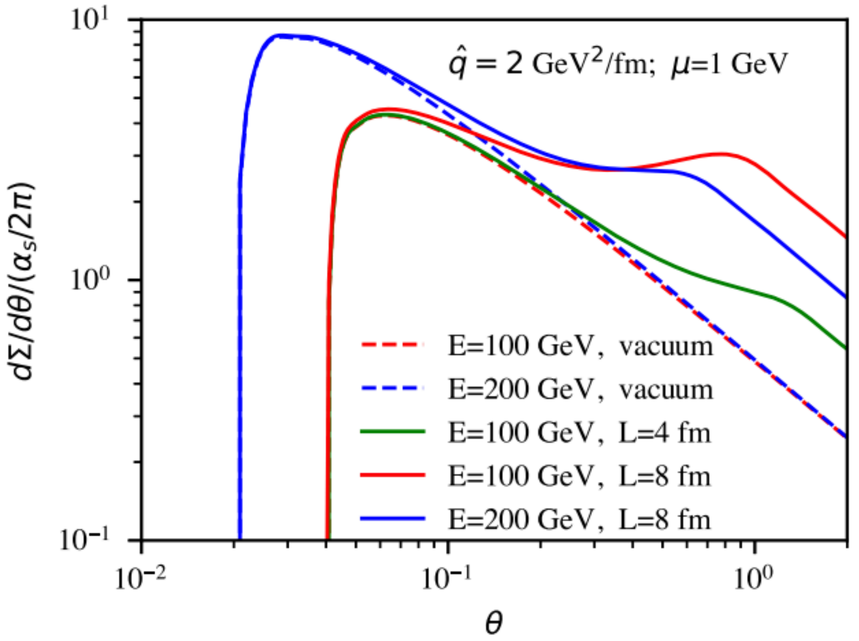
Yes! Many applications so far …

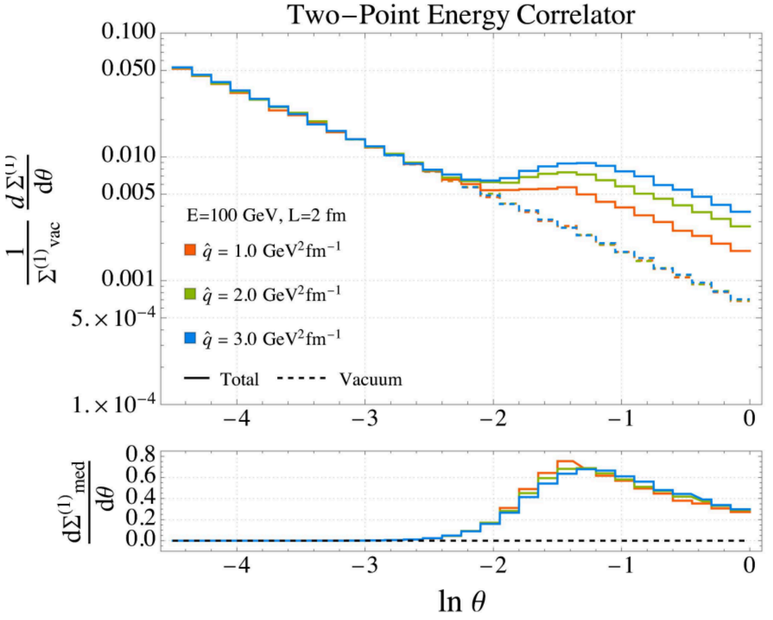
[Andres et al. Phys. Rev. Lett. 130, 262301]

[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.

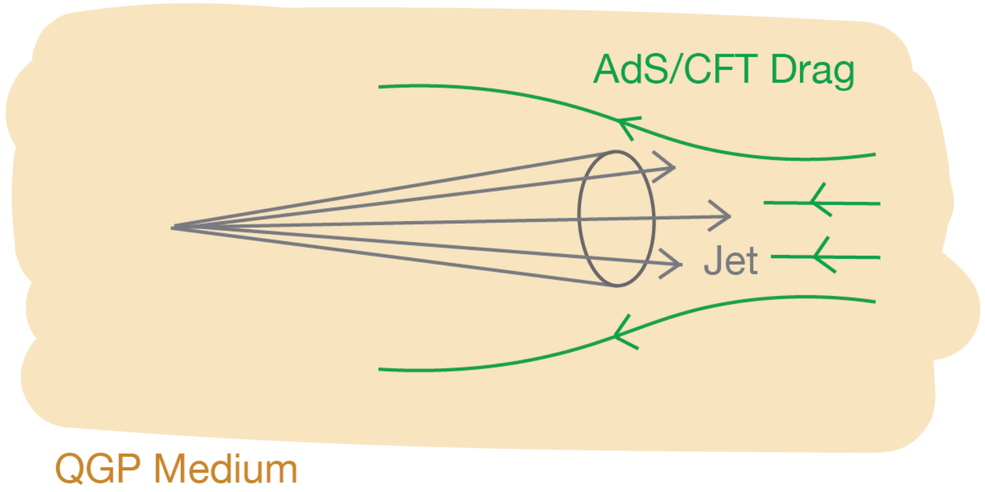
Can we distinguish these different physical mechanisms? What about higher orders of N? What if we also included the full shape information?

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

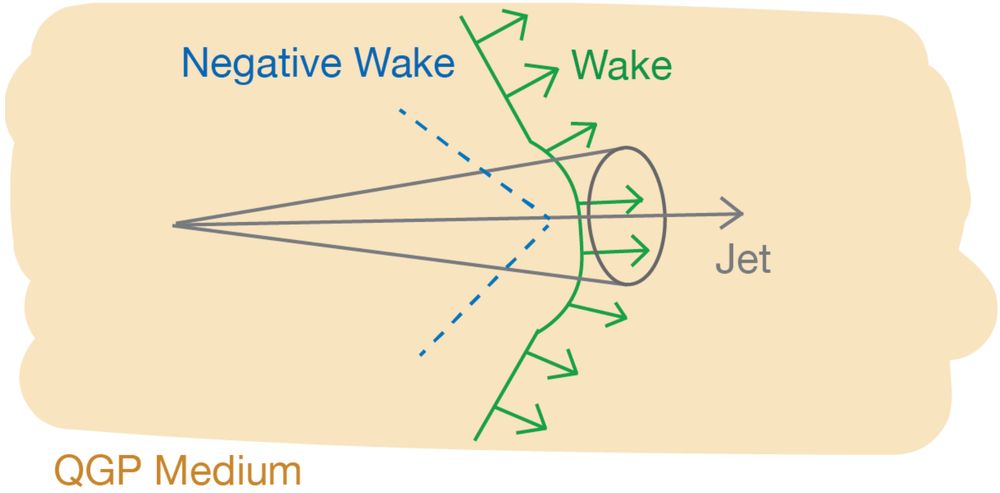


Strong coupling limit

- AdS/CFT drag force

Impact of the jet on the medium →

medium response



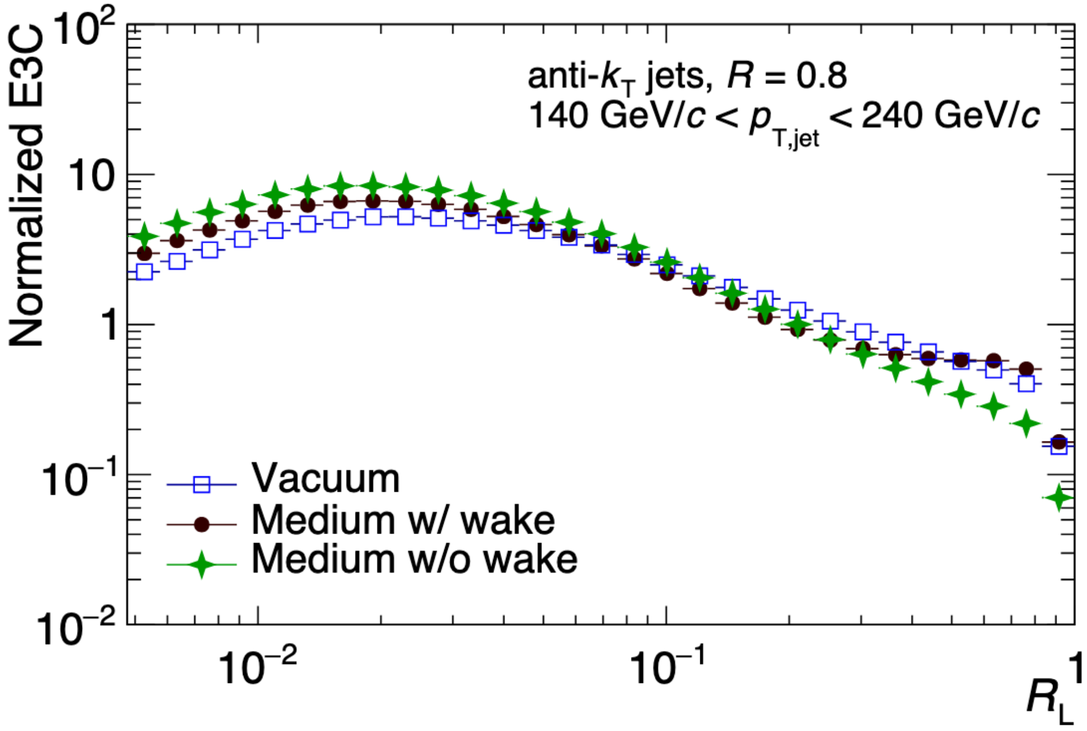
Strong coupling limit

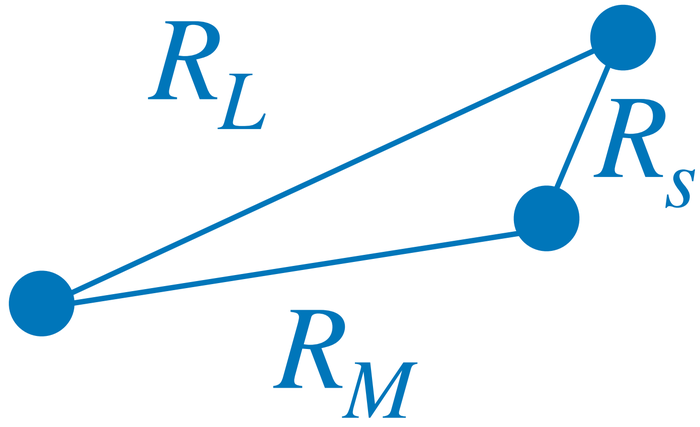
Wake (Hydrodynamics based approach)

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.

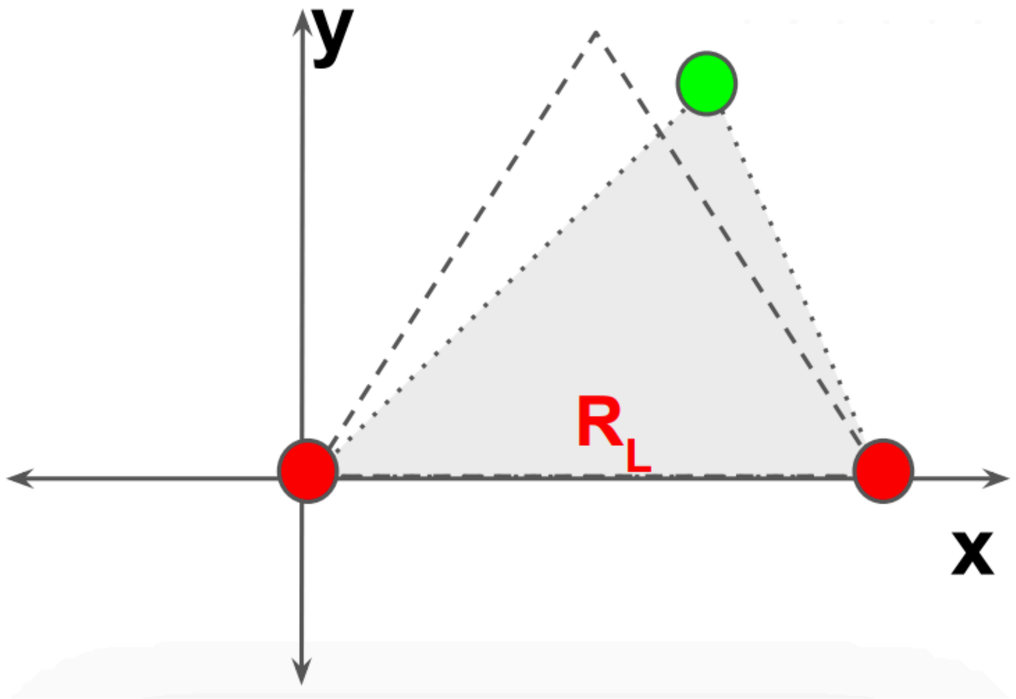
We can get more information by studying the shape (full correlator, EEEC)!

❃ 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!

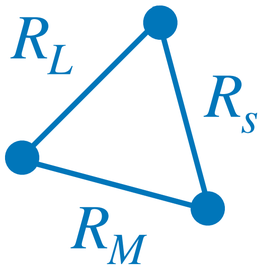


- Fix the longest side (R_L) on the x axis placing one of the particles at the origin.
- Set $R_L = 1$ and rescale the rest of the triangle accordingly.
- Fill the EEEC in bins (x,y) for the third particle in the triplet!

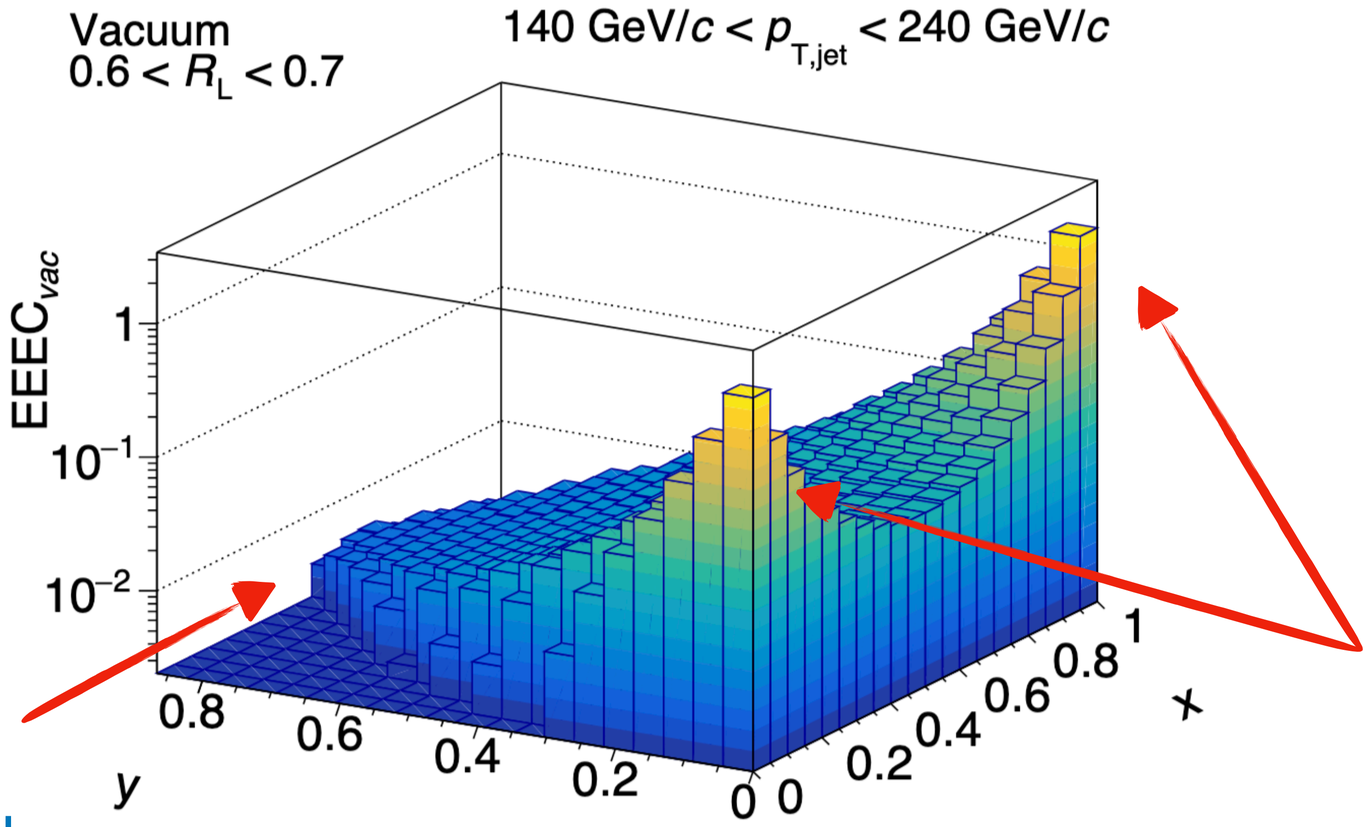
Coordinates chosen to have a flat Jacobian such that there is no preference for a single region based on coordinate choices alone.

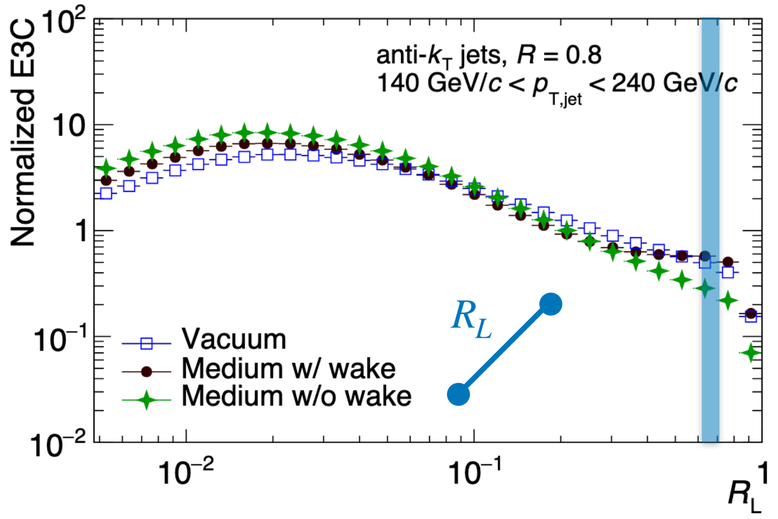
Shape dependence in vacuum

Look at distribution for an R_{L} slice



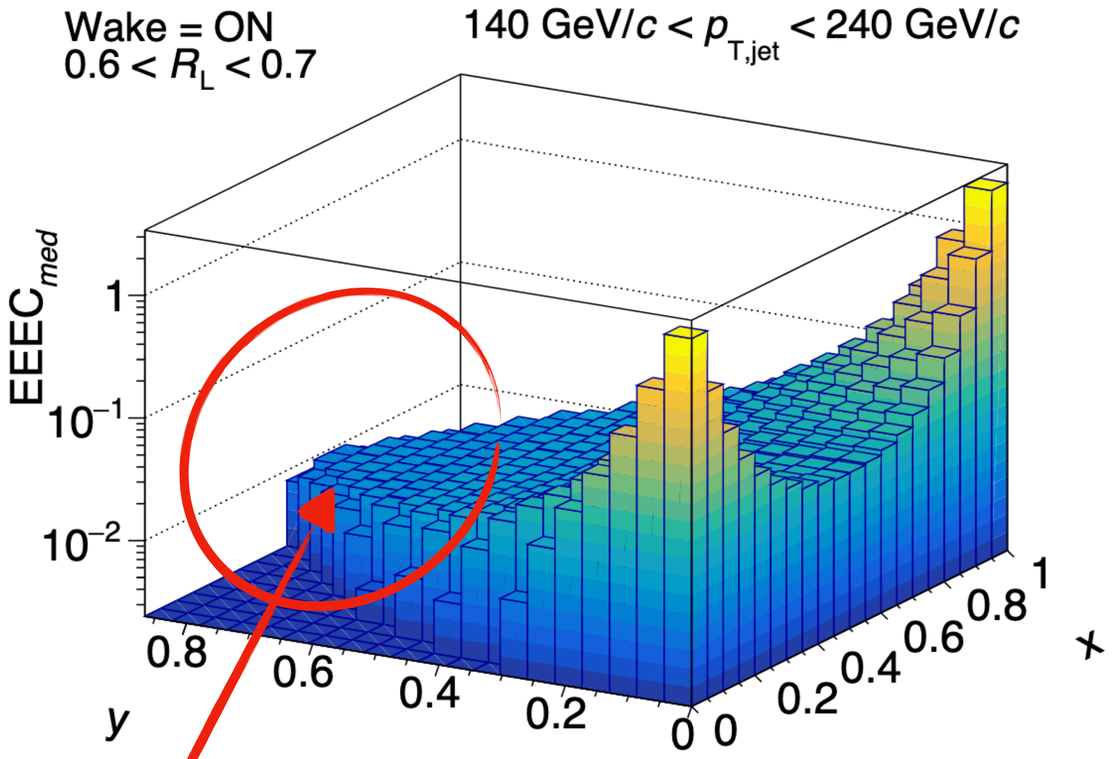
Equilateral region relatively unpopulated

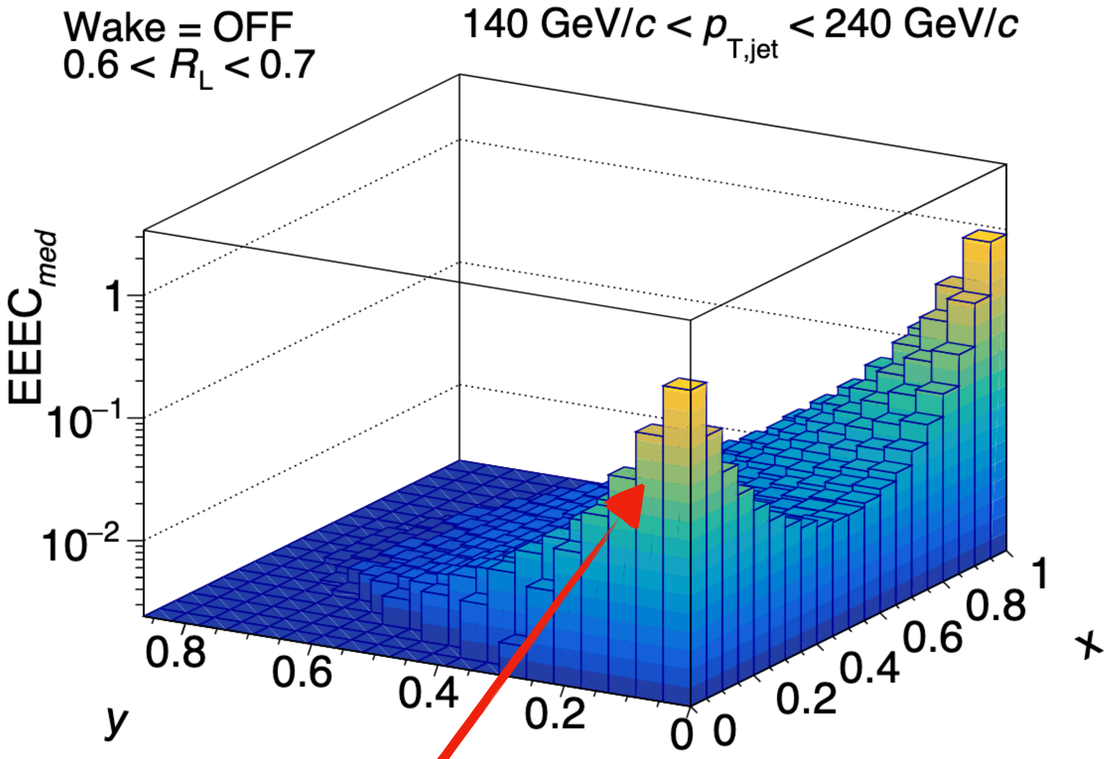


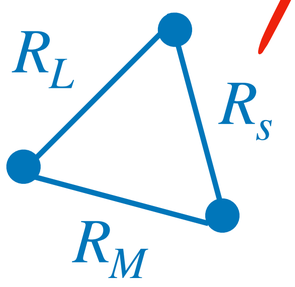


Dominant shapes when all emissions are correlated with the same source (parton shower)

Shape dependence in medium







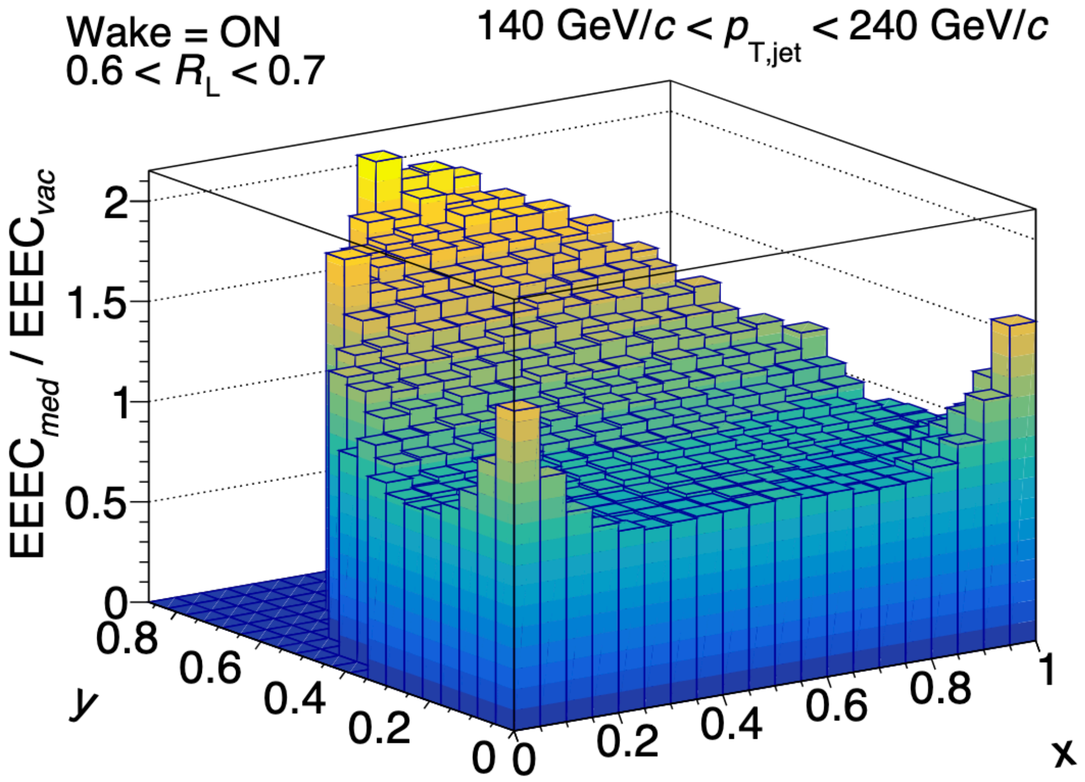
Medium, With Wake

Medium, No Wake

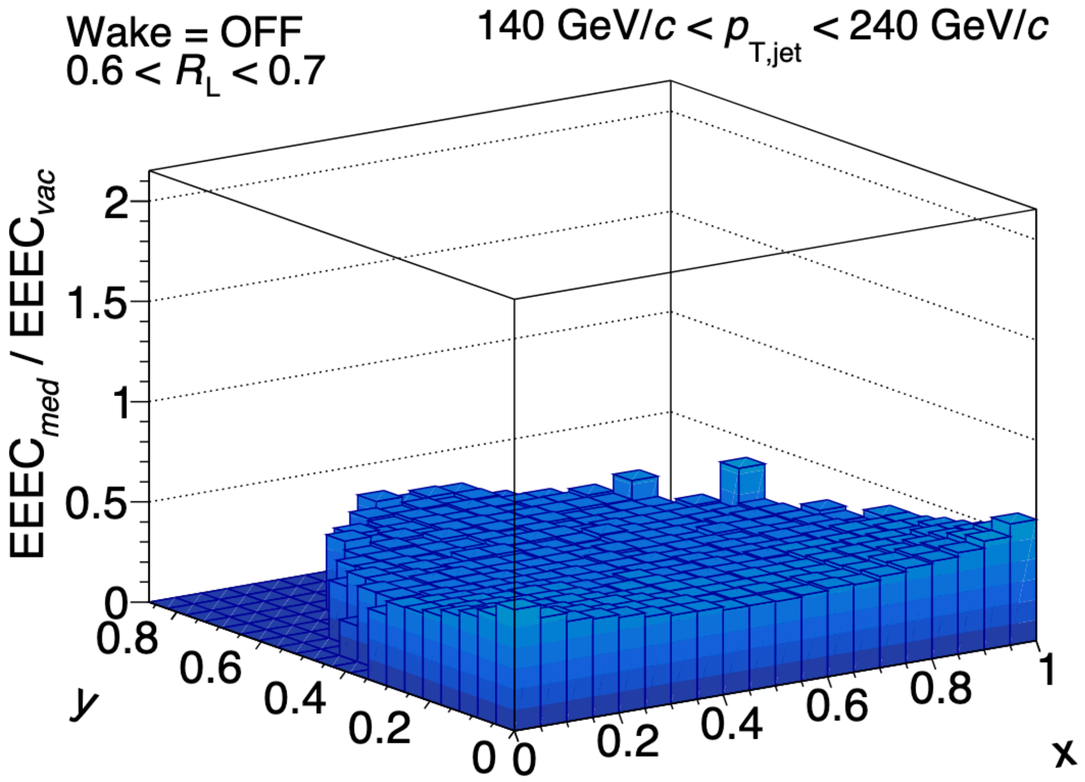
Jet quenching alone reduces peak

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

Ratios to vacuum



Wake / vacuum



No wake / vacuum

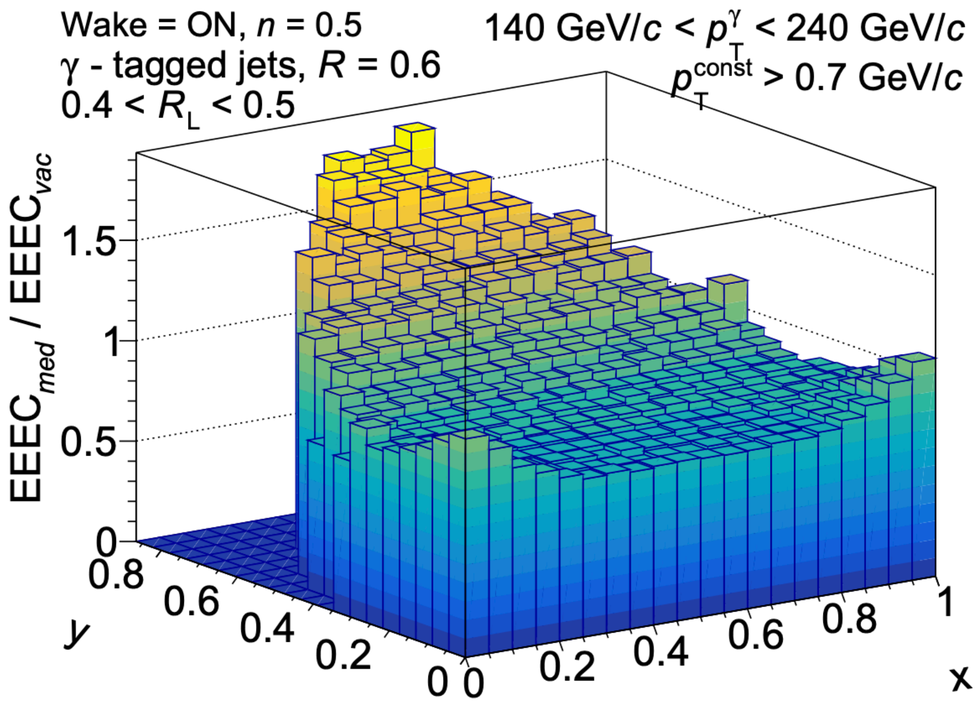
Wake leaves clear signatures in comparison to vacuum! Dramatically different from the no wake case

❃ Shape of medium response is encoded in these ratios!

Where can we go from here?

Ultimate goal is to measure this large signal in data!

- Background subtraction and correction for detector effects is a barrier for this!
- Potential solution: Start with regions of phase space where background is easier to deal with!



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

- γ -tagged jets with R = 0.6
- Includes a cut on the constituent p_{T} of 0.7 GeV
- Change n to be 0.5 to amplify medium response.

Stay tuned!!!

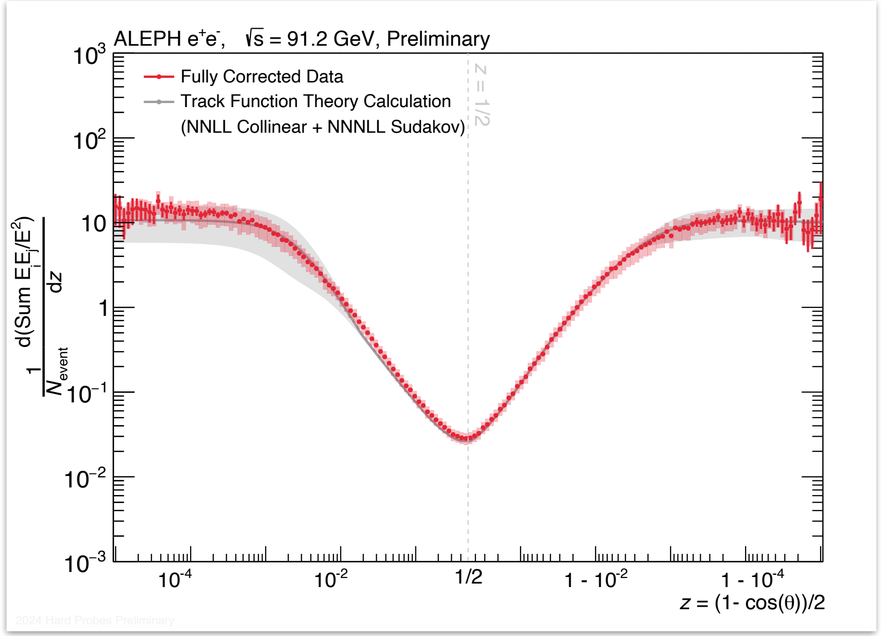
Summary and conclusions

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!

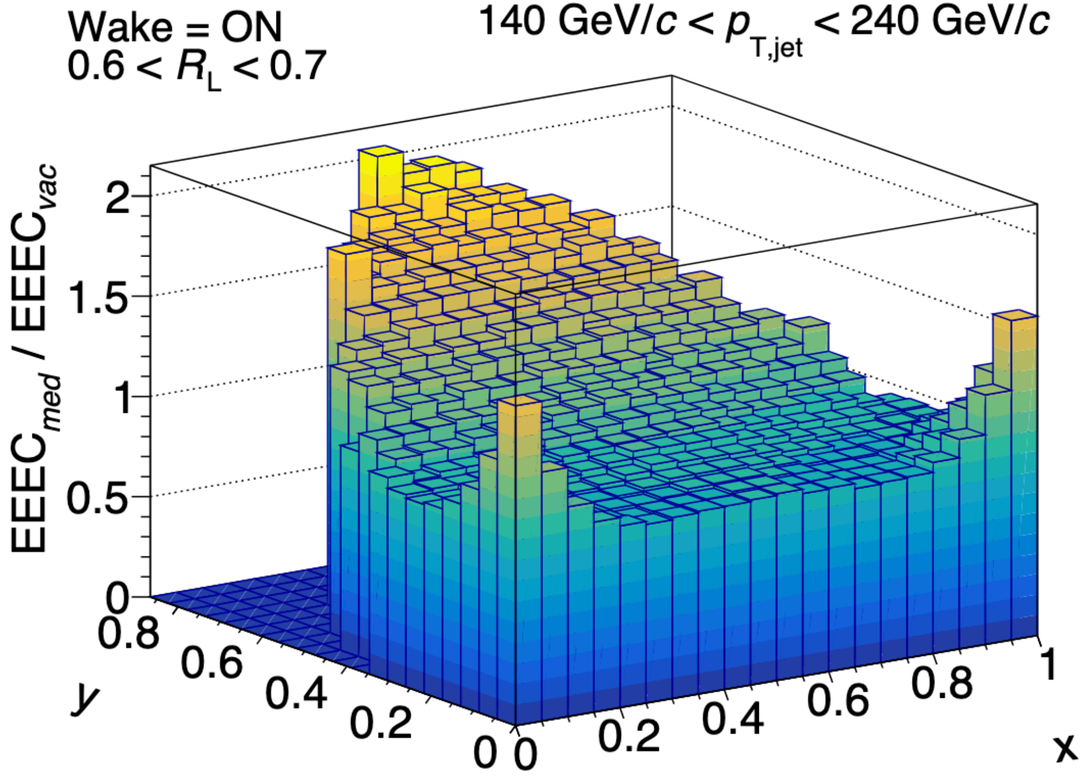


Summary and conclusions

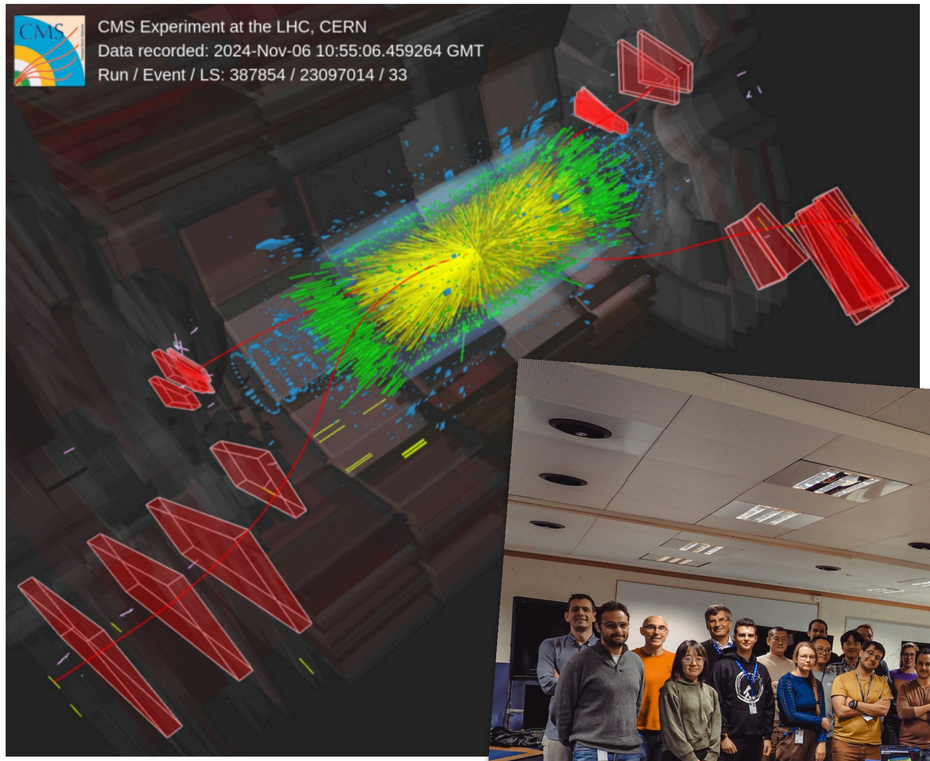
Energy correlators are powerful tools that can be useful for different types of QCD studies.

- **Searching for large qualitative signatures of (relatively unknown effects)**

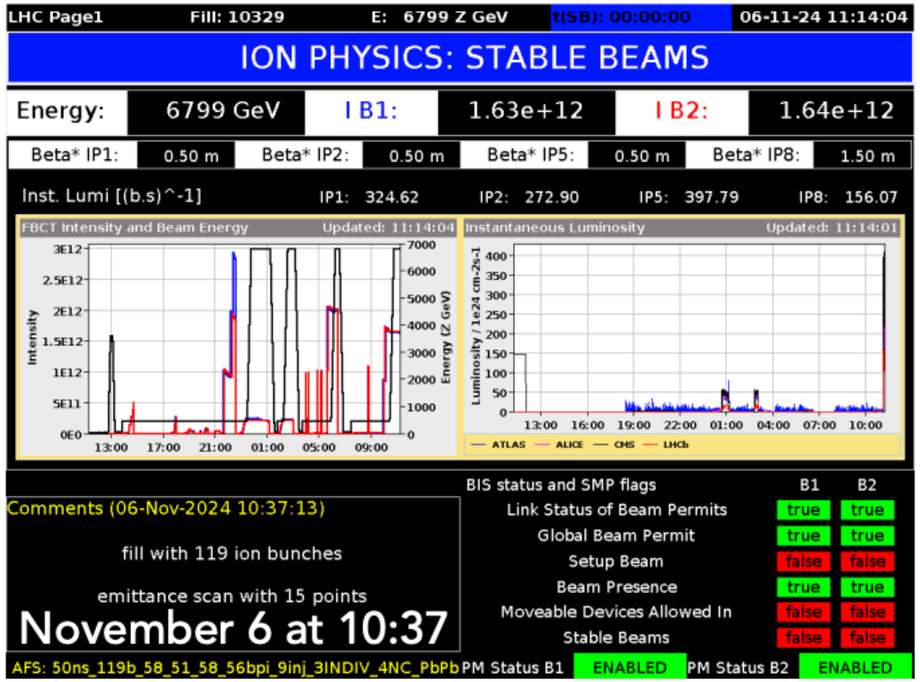
- First exploration of the full shape-dependent EEEC in heavy-ions
  - Leaves clear wake signatures in equilateral region using the hybrid model!



Lots to look forward to!



2024 HI Run of the LHC currently ongoing!

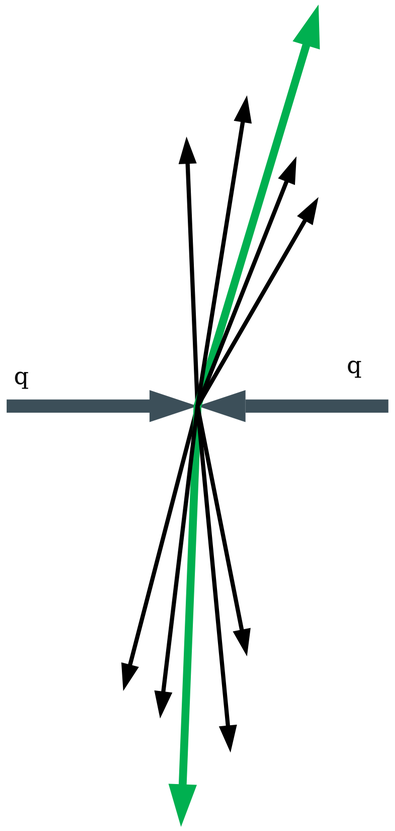


Massachusetts Institute of Technology

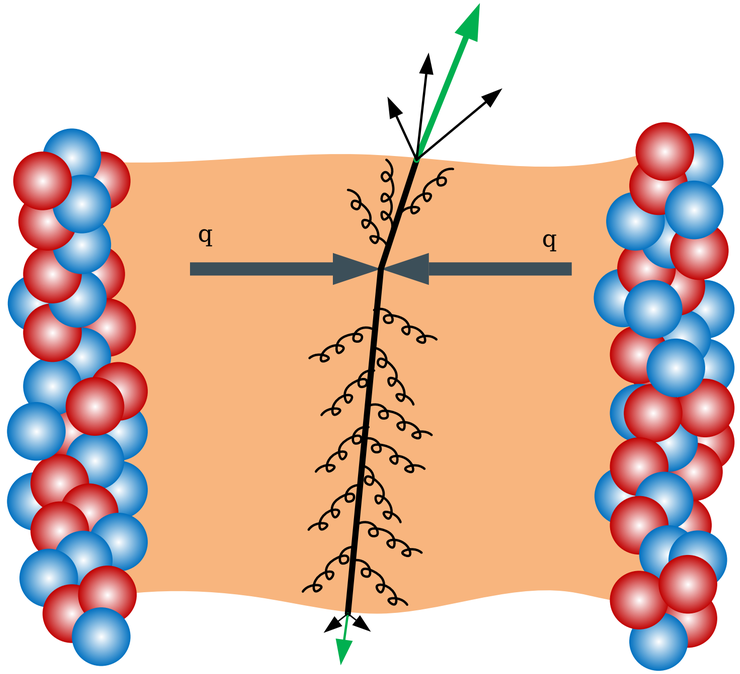
Backup

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

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!

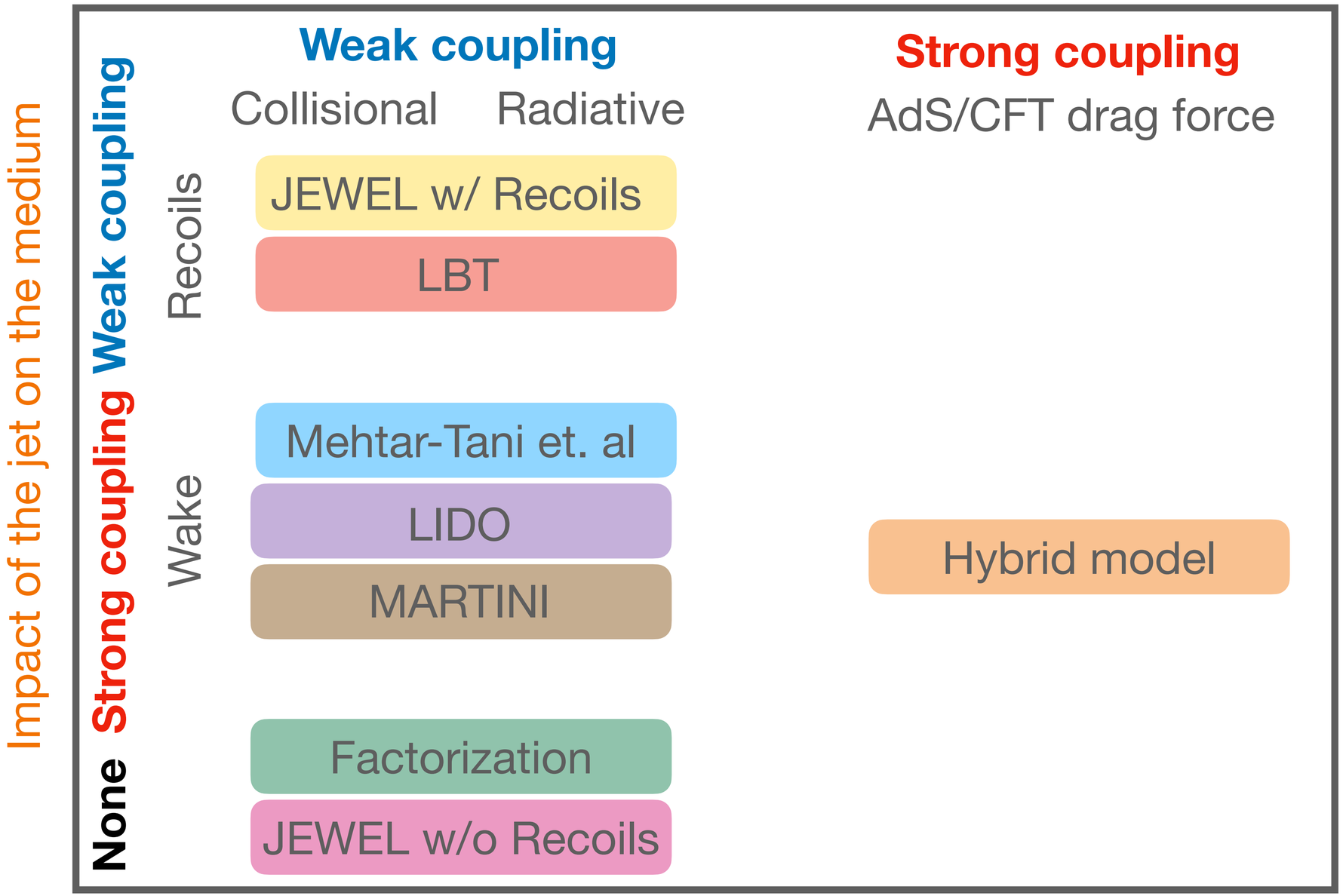
→ Use pp, where jets are measured in vacuum, as a reference for no QGP.

Jet quenching models

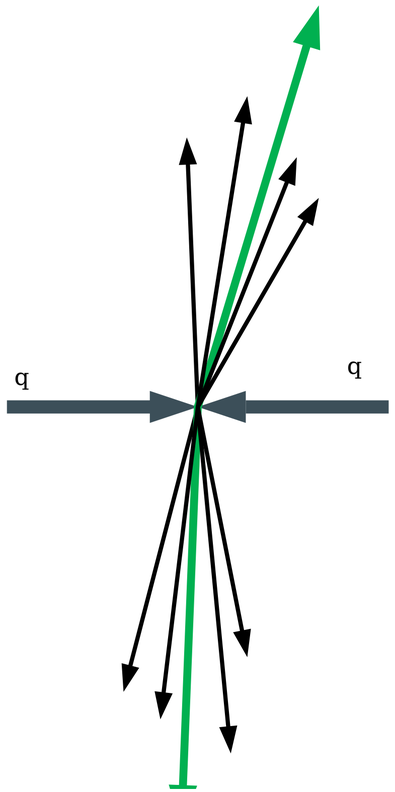
As of now, no clear winner for best description of jet quenching effects!

Different models are different!

We will come back to these later!



Jets in Vacuum



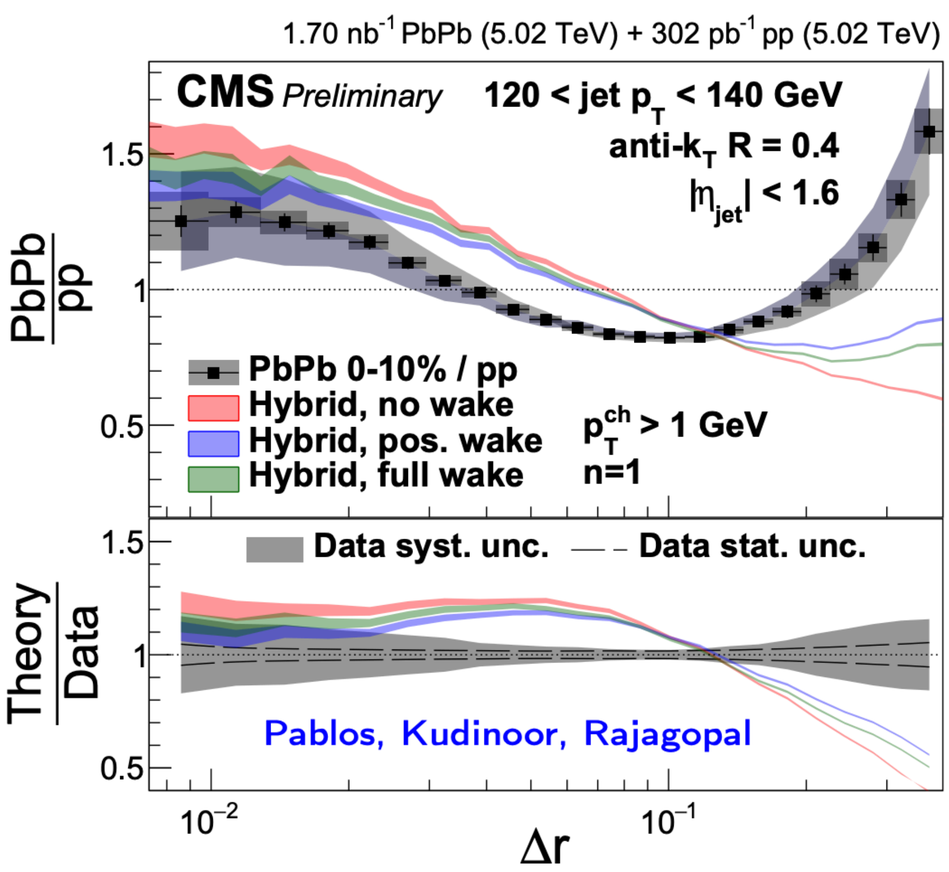
p+p

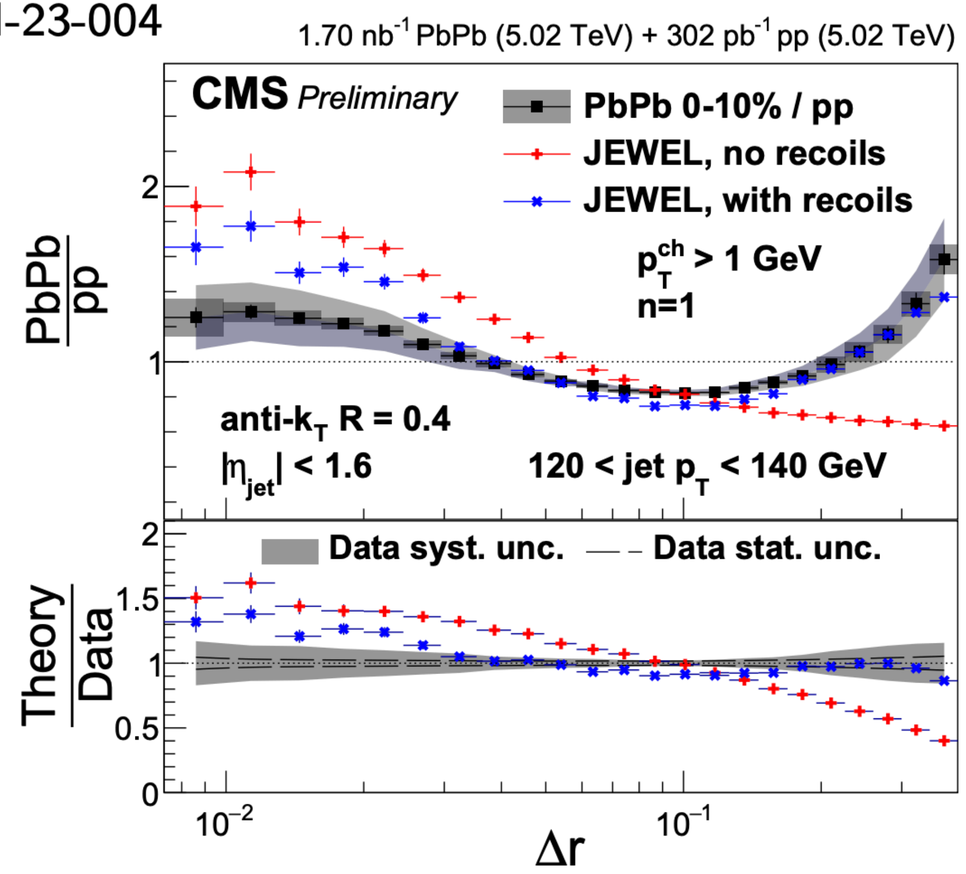
- In vacuum a majority of hard scatterings are 2→2, resulting in high transverse momentum (p_{T}) partons traveling back to back in the transverse plane.
- Production of partons calculable in perturbative QCD (pQCD).
  - Jets in vacuum useful for testing fundamental QCD properties.

What about jets in heavy-ion collisions??

EECs in heavy-ion collisions

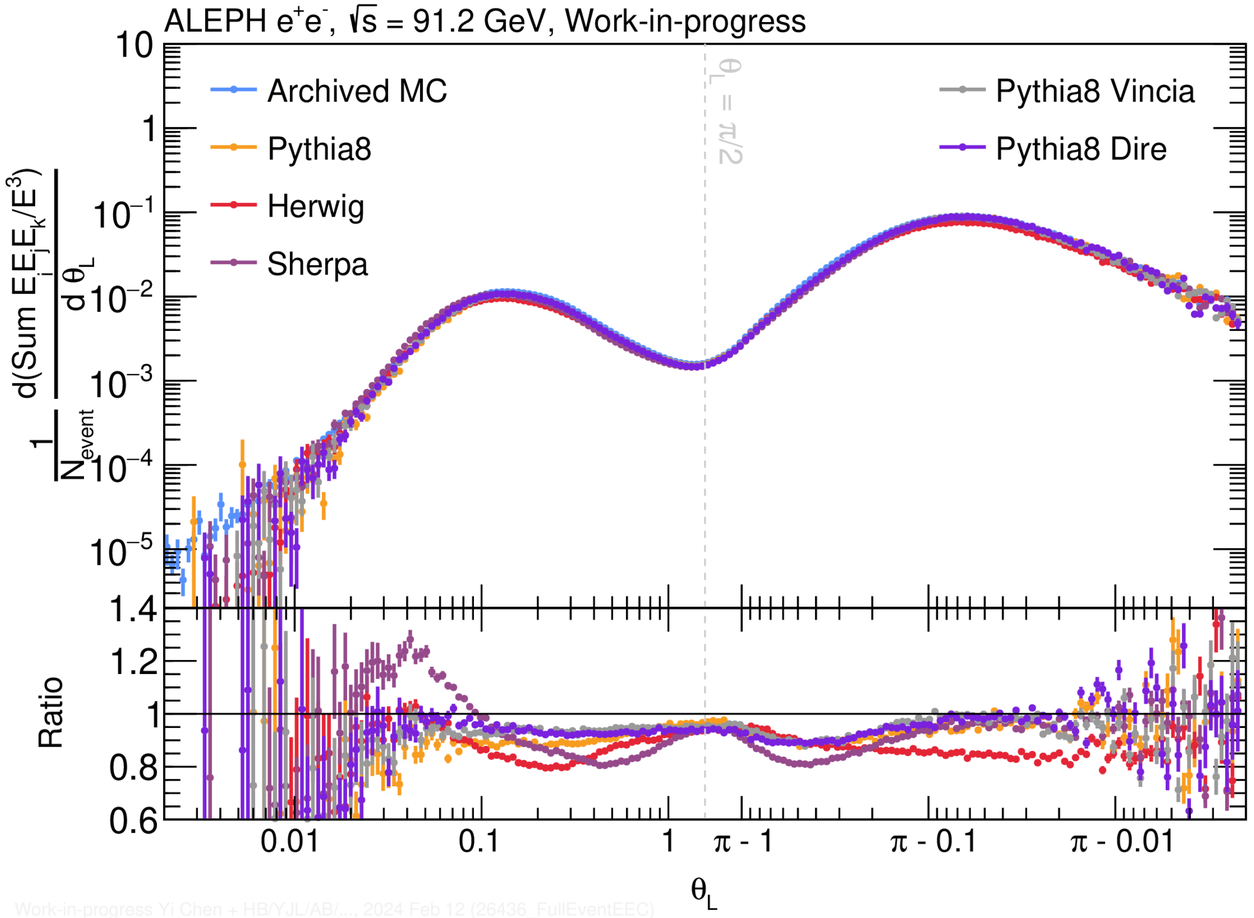
CMS-PAS-HIN-23-004

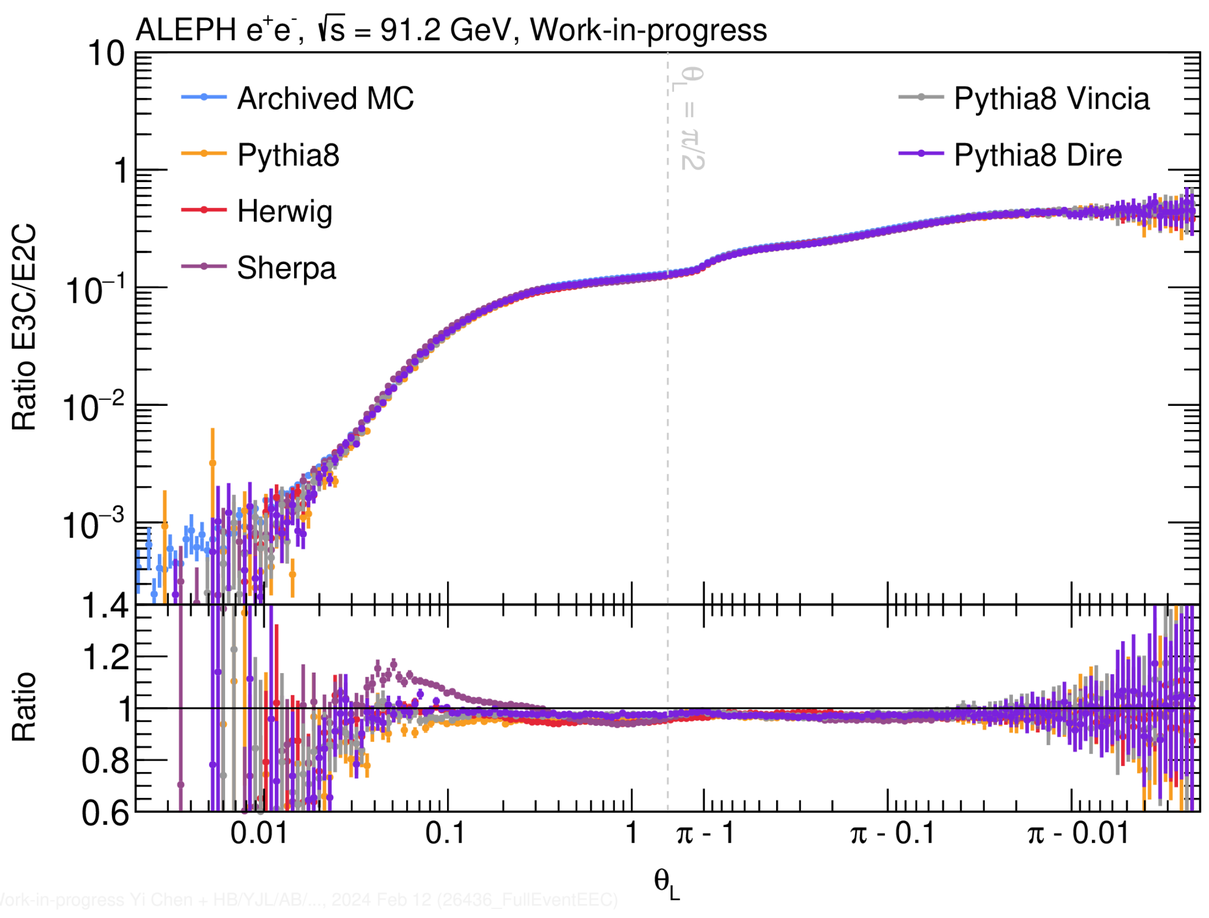




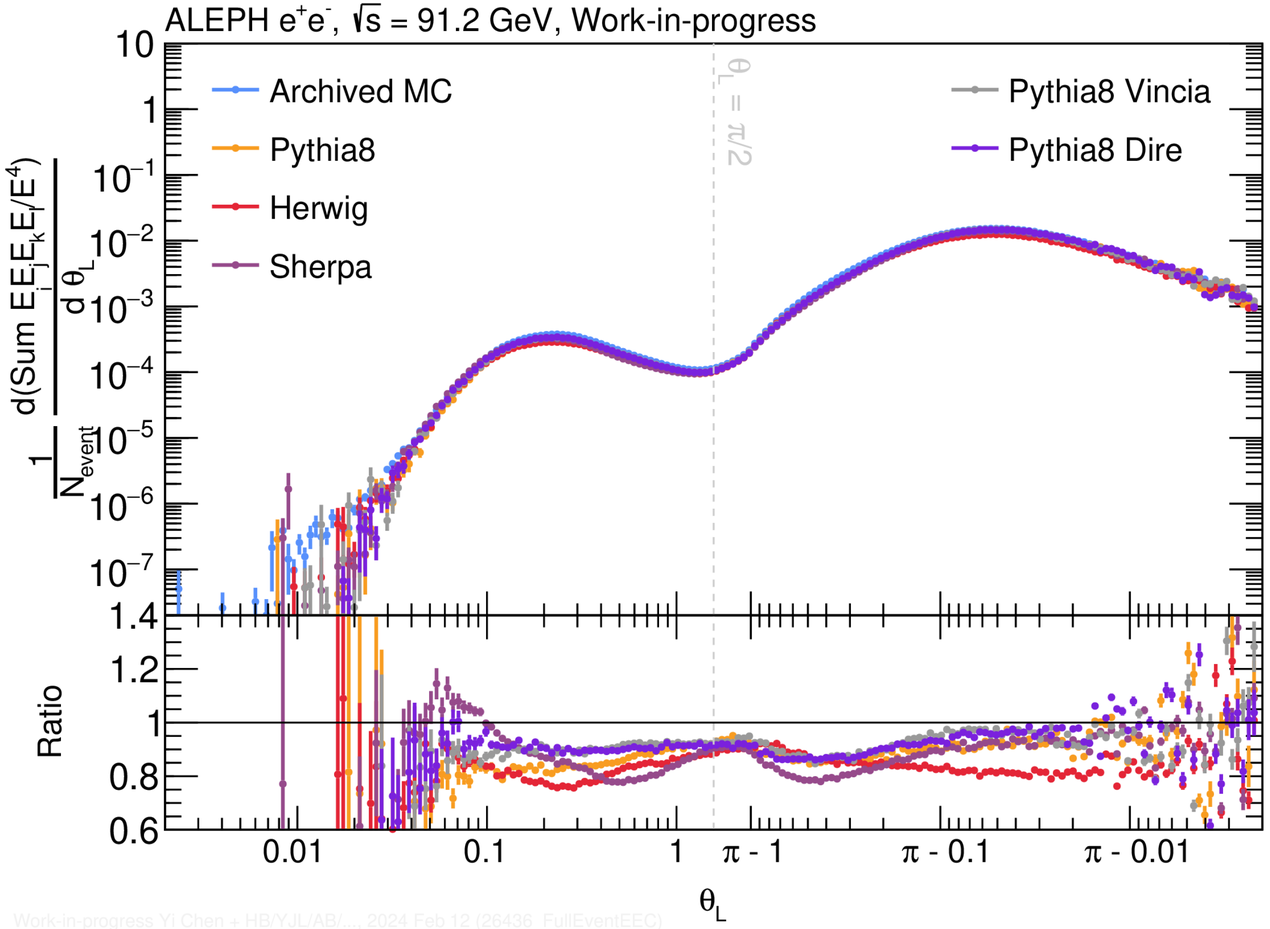
[See Jussi's talk at Hard Probes for more details!]

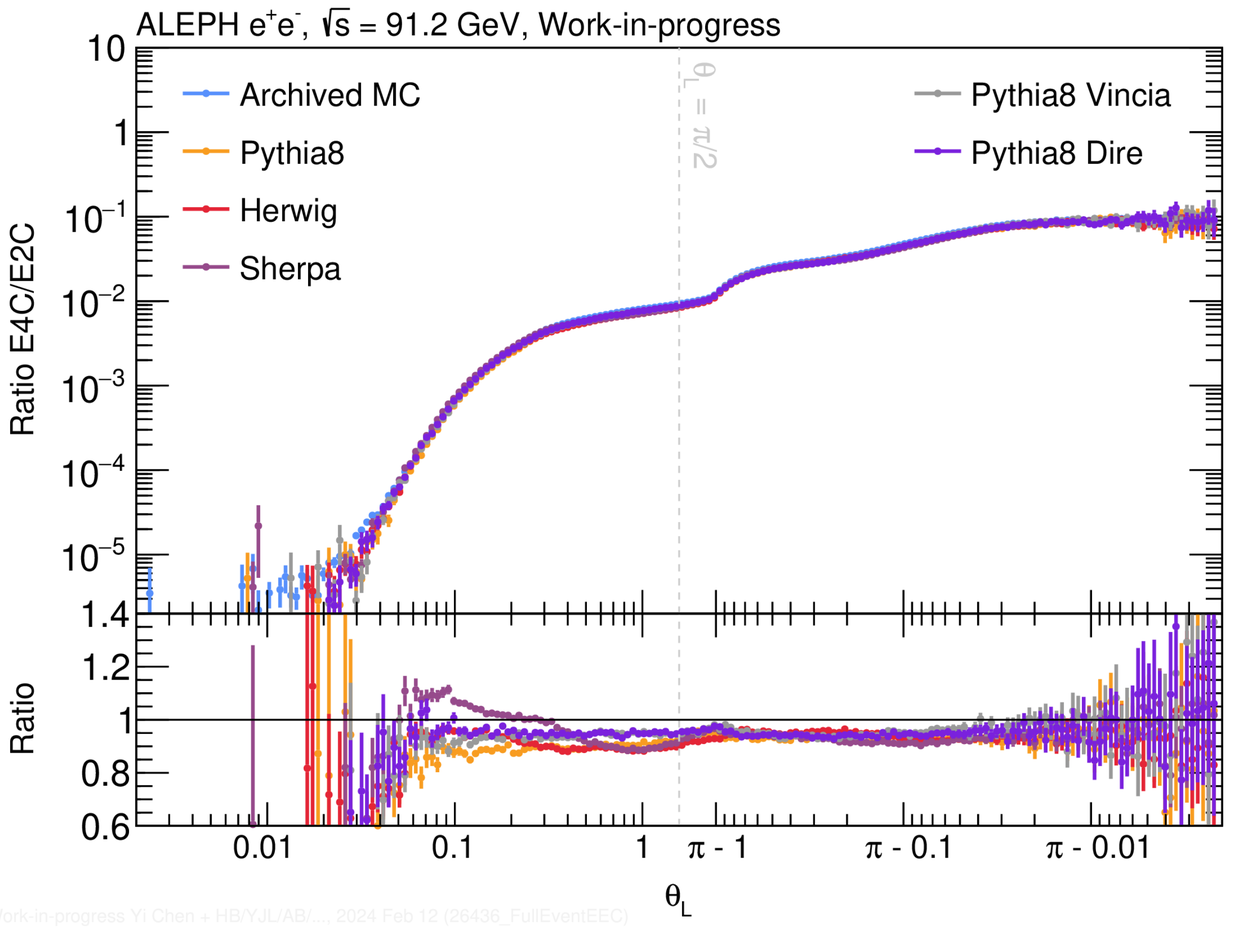
E3C in ALEPH

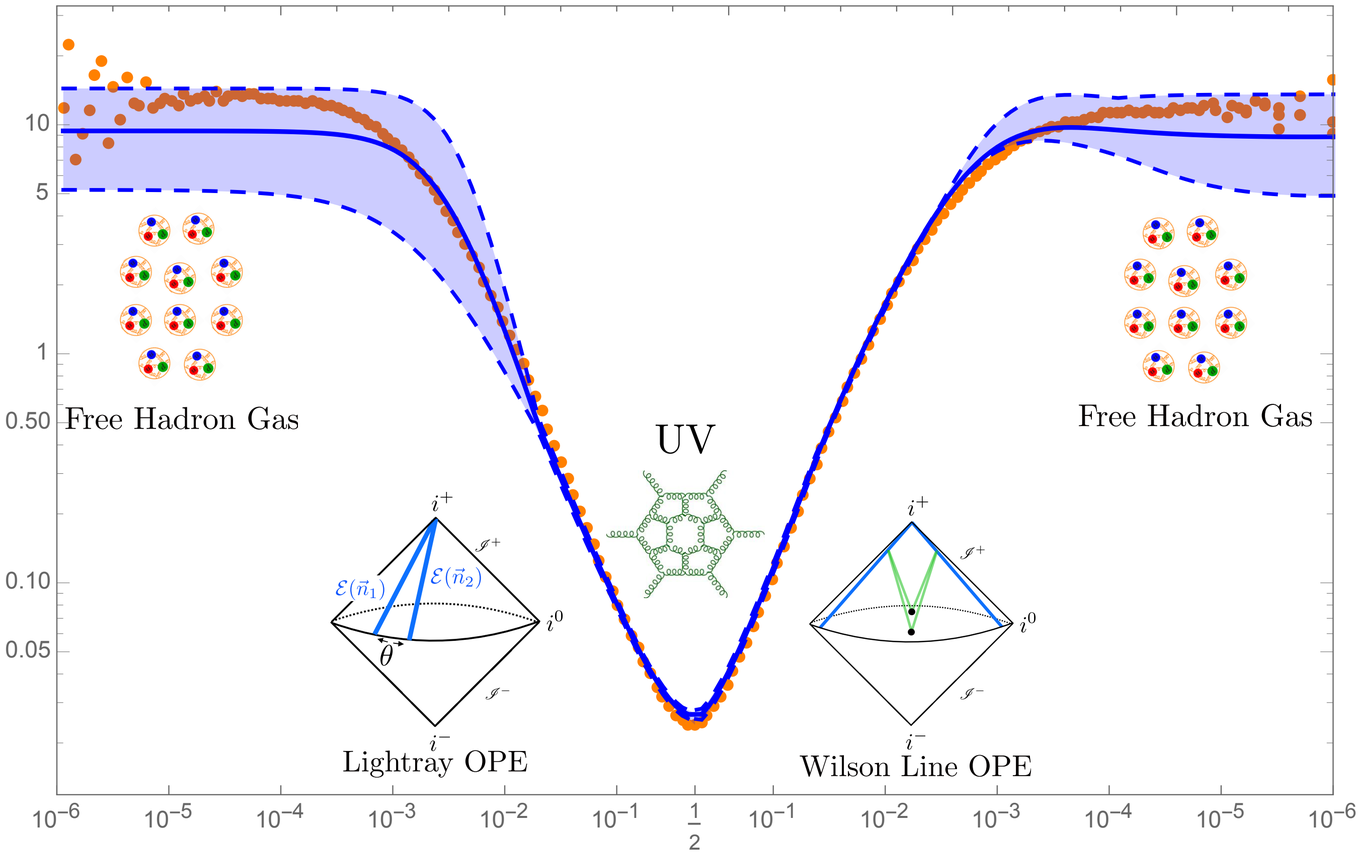

ALEPH e+e-, √s = 91.2 GeV, Work-in-progress
Archived MC
Pythia8
Herwig
Sherpa
Pythia8 Vincia
Pythia8 Dire
θL = π/2
1/Nevent d(Sum EEiEjEk/E3)/d θL
Ratio
θL
0.01
0.1
1
π - 1
π - 0.1
π - 0.01
Work-in-progress Yi Chen + HB/YJL/AB/..., 2024 Feb 12 (26436_FullEventEEC)


ALEPH e+e-, √s = 91.2 GeV, Work-in-progress
Archived MC
Pythia8
Herwig
Sherpa
Pythia8 Vincia
Pythia8 Dire
θL = π/2
Ratio E3C/E2C
Ratio
θL
0.01
0.1
1
π - 1
π - 0.1
π - 0.01
Work-in-progress Yi Chen + HB/YJL/AB/..., 2024 Feb 12 (26436_FullEventEEC)

E4C in ALEPH


ALEPH e+e-, √s = 91.2 GeV, Work-in-progress
Archived MC
Pythia8
Herwig
Sherpa
Pythia8 Vincia
Pythia8 Dire
θL = π/2
1/Nevent d(Sum EEjEkEl/E4) / d θL
Ratio
θL
Work-in-progress Yi Chen + HB/YJL/AB/..., 2024 Feb 12 (26436_FullEventEEC)


ALEPH e+e-, √s = 91.2 GeV, Work-in-progress
Archived MC
Pythia8
Herwig
Sherpa
Pythia8 Vincia
Pythia8 Dire
θL = π/2
Ratio E4C/E2C
Ratio
θL
Work-in-progress Yi Chen + HB/YJL/AB/..., 2024 Feb 12 (26436_FullEventEEC)



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.