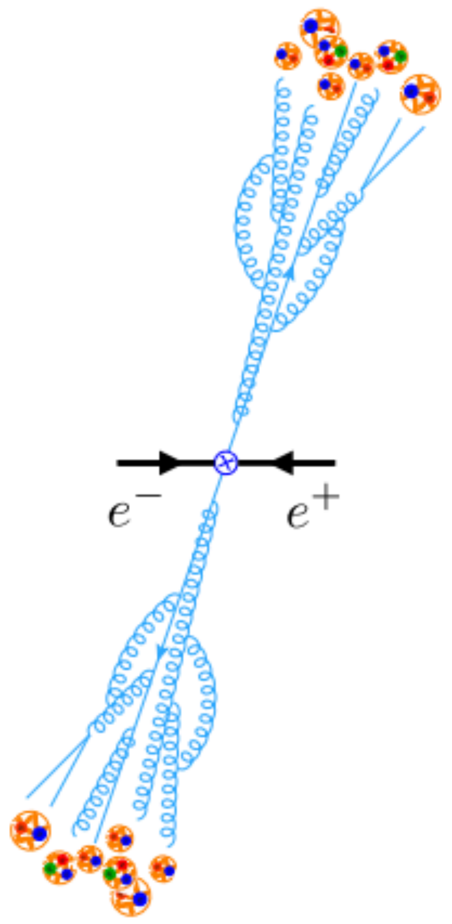
Reimagining Jet Substructure with Energy Correlators

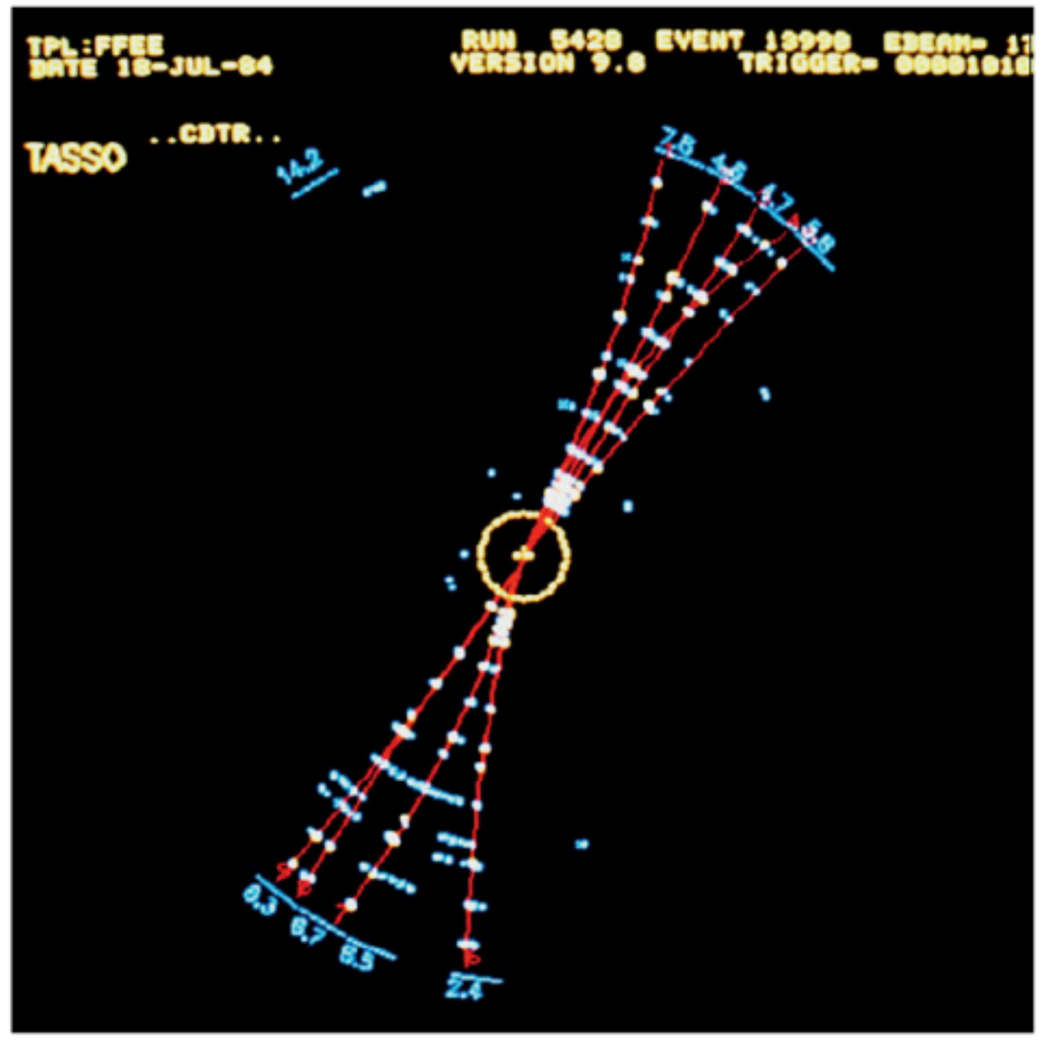
Kyle Lee
CTP, MIT

Jefferson Lab Theory Seminar 01/22/24

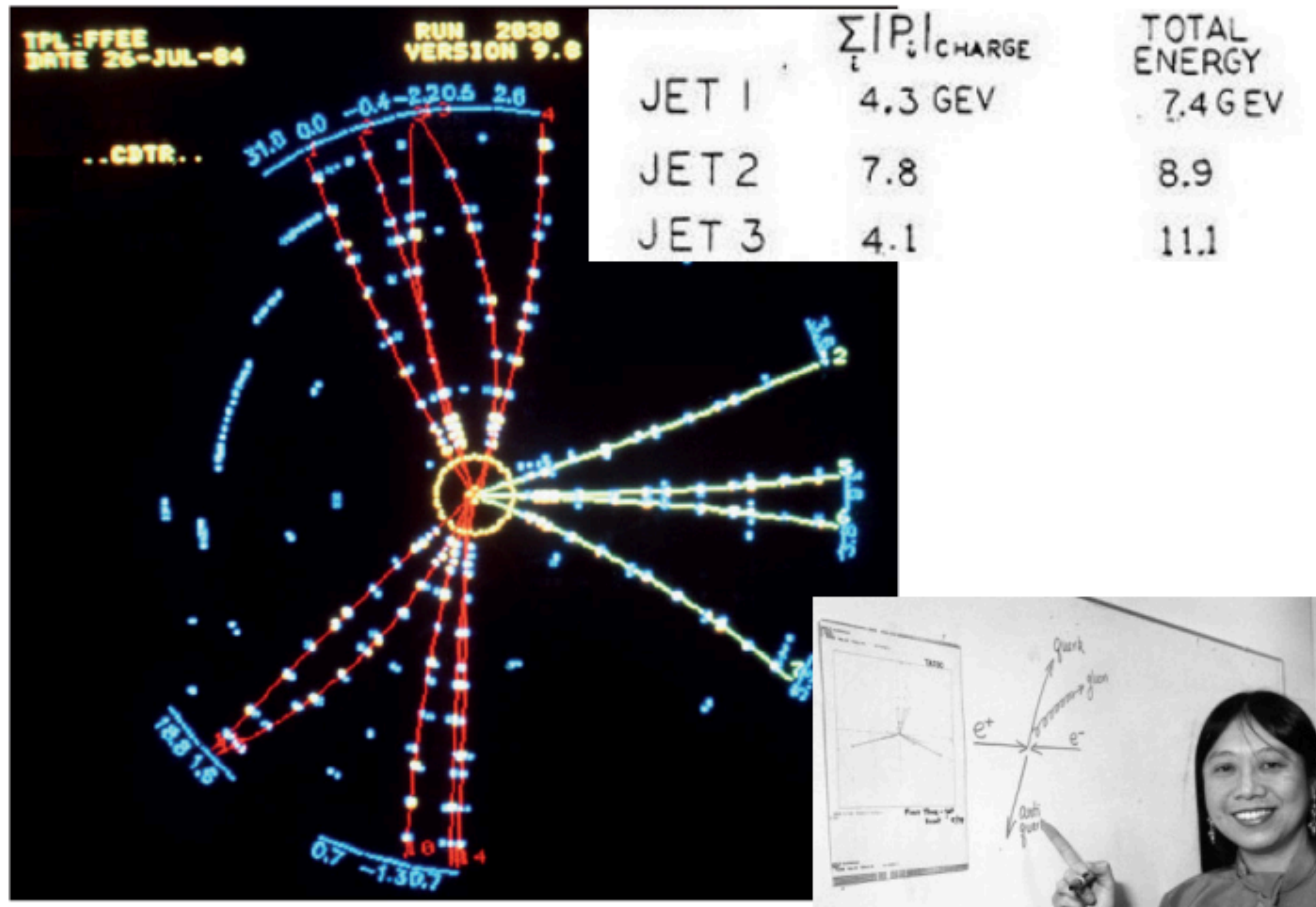
JETS — PROXIES FOR QUARKS AND GLUONS

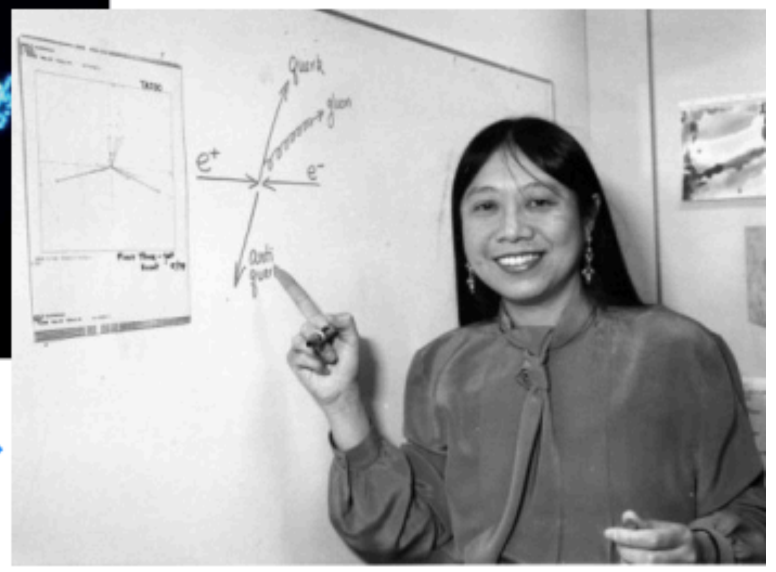


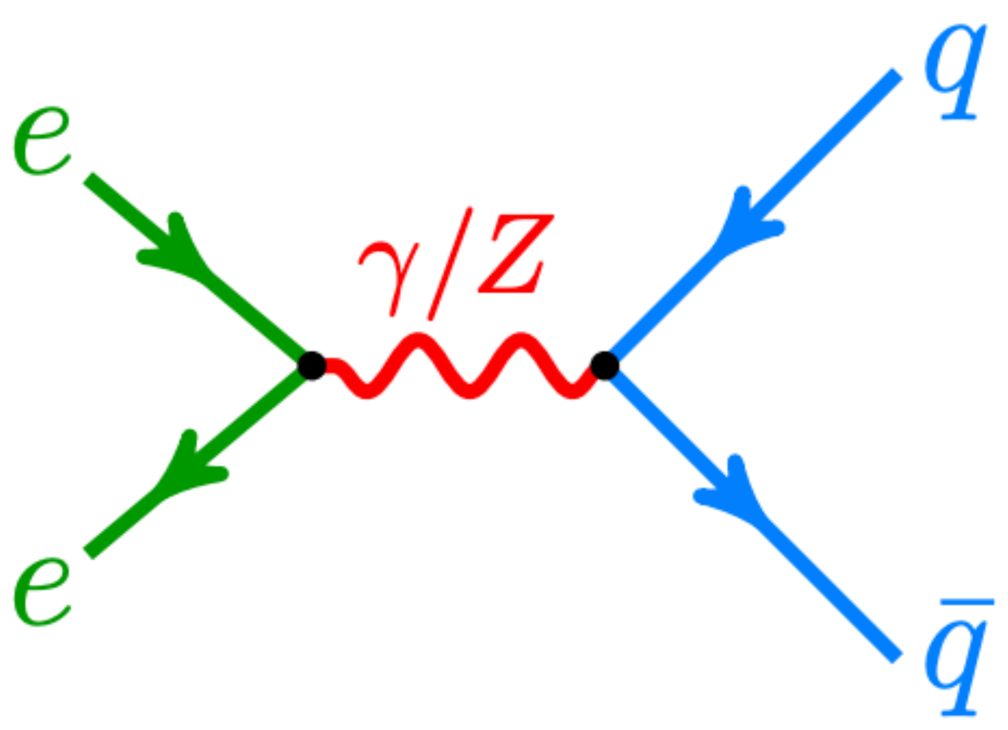
2-Jet Event

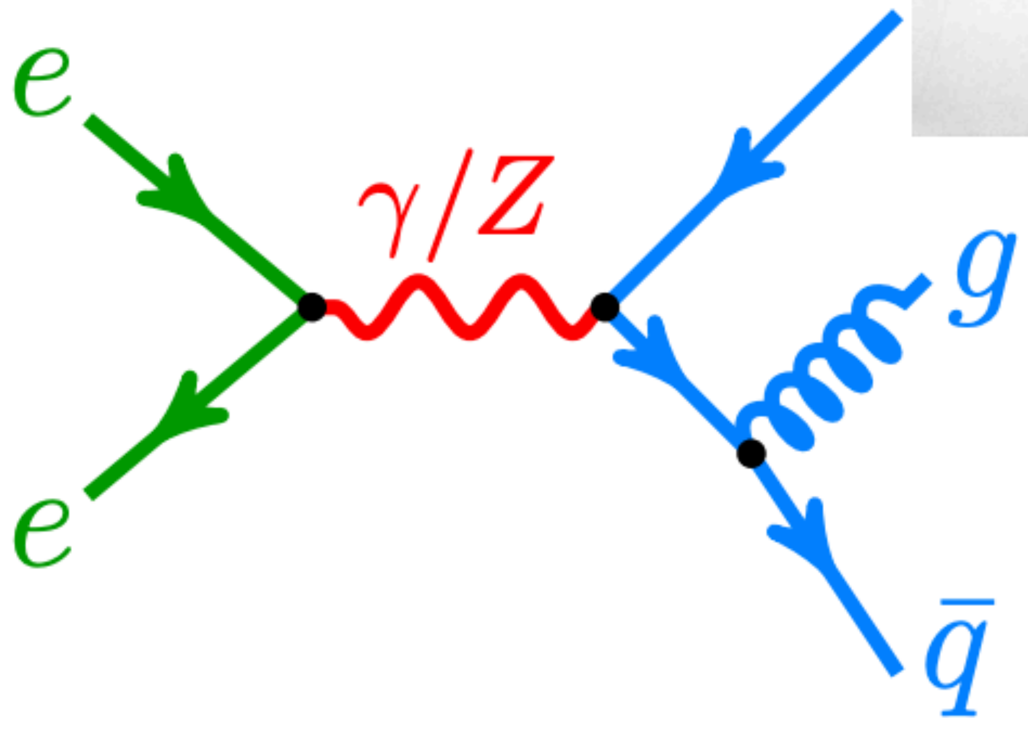


3-Jet Event



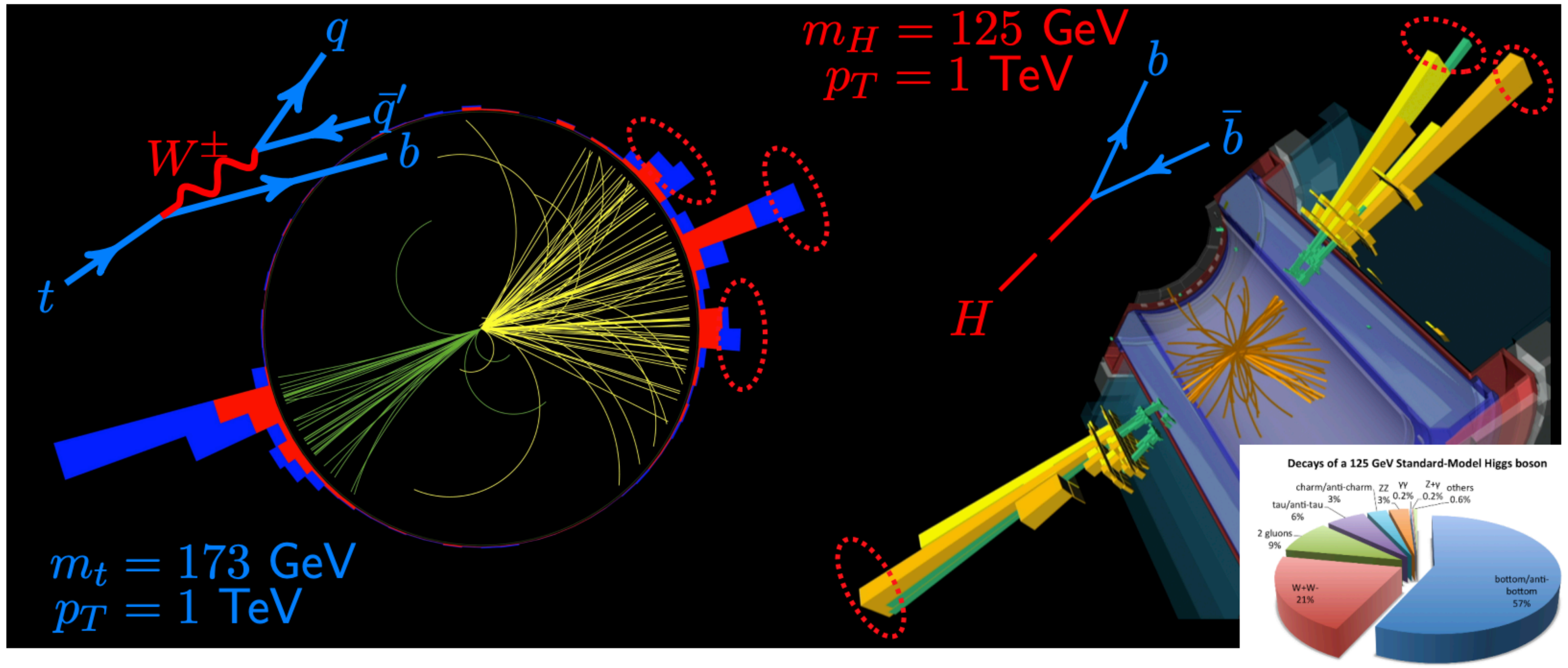


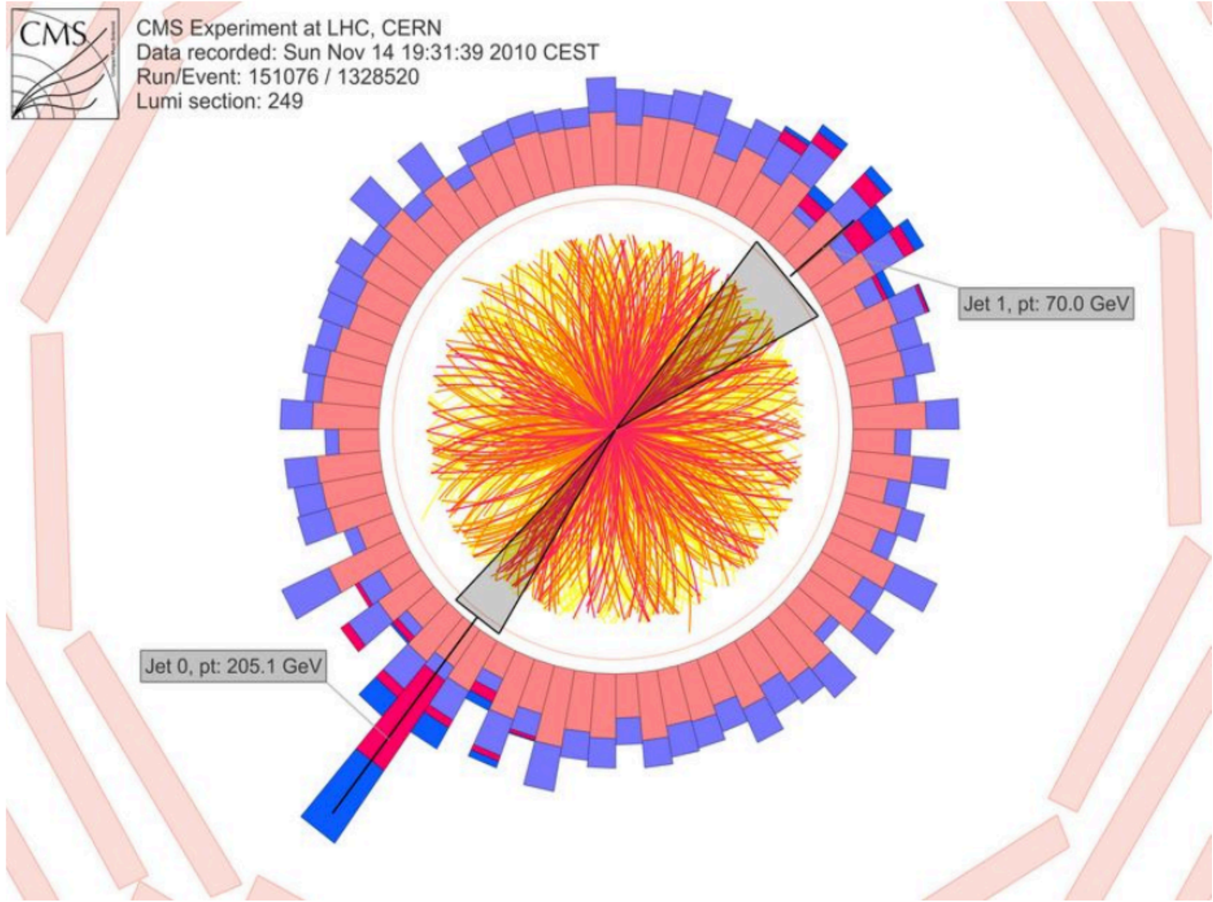


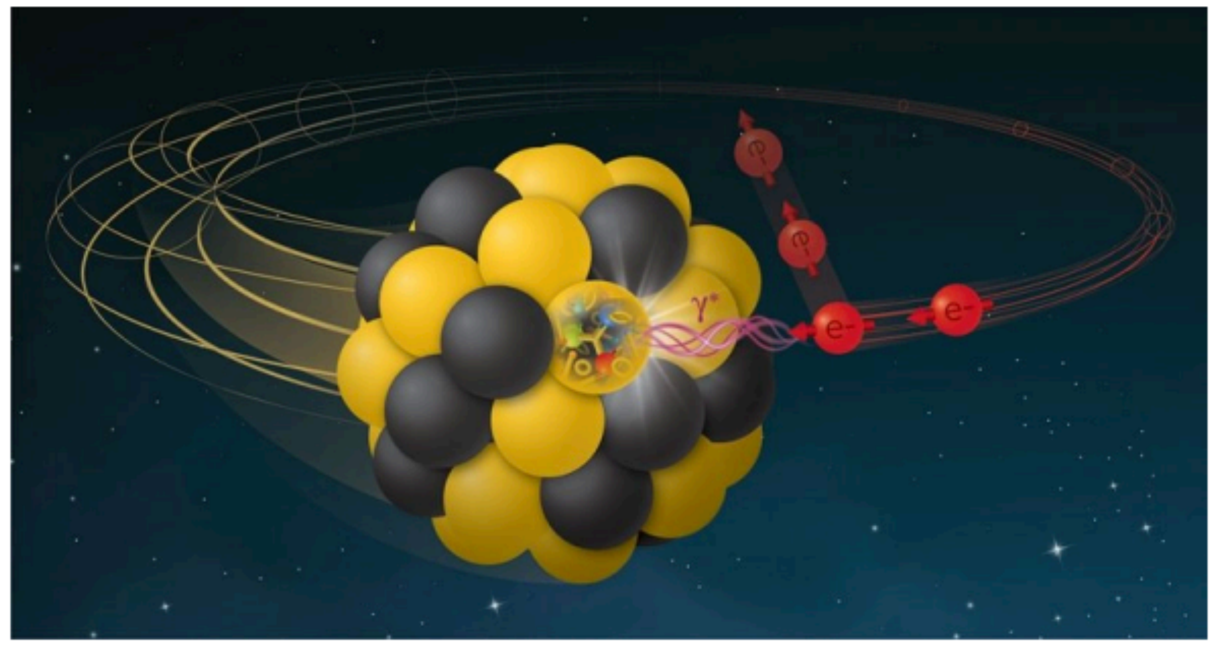


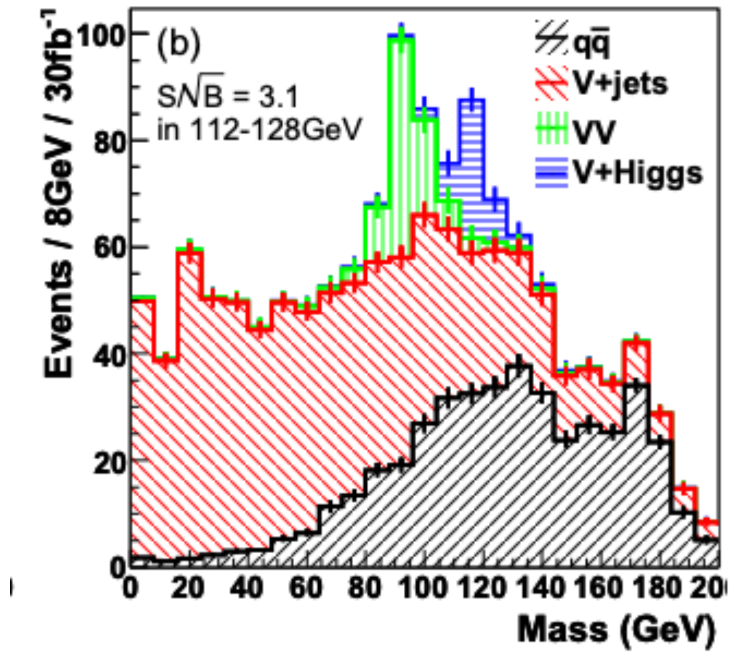
- **In the early years, jet served as proxies of the underlying partons from hard QCD interactions. This was particularly evident in the discovery of gluons, substantiated by the observation of three-jet events.**

JETS — IMPRINTING STANDARD MODEL DYNAMICS

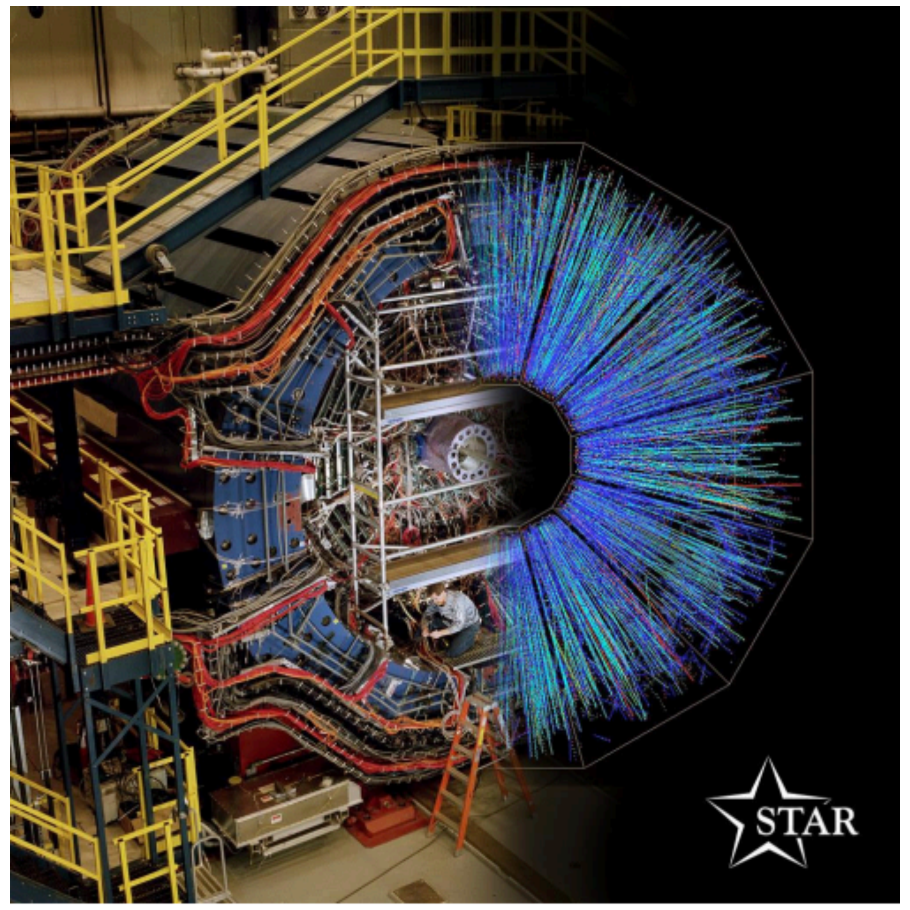


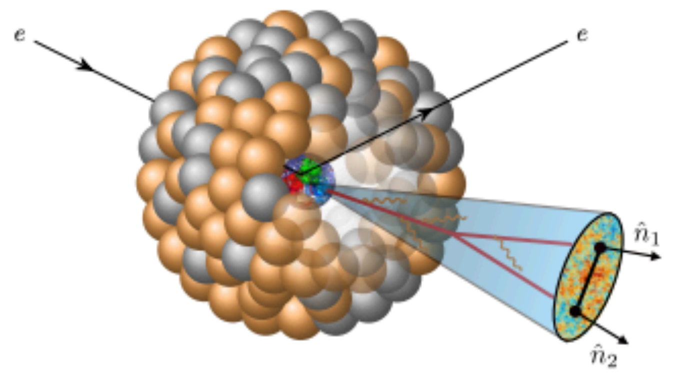






Butterworth, Davison, Rubin, Salam `08

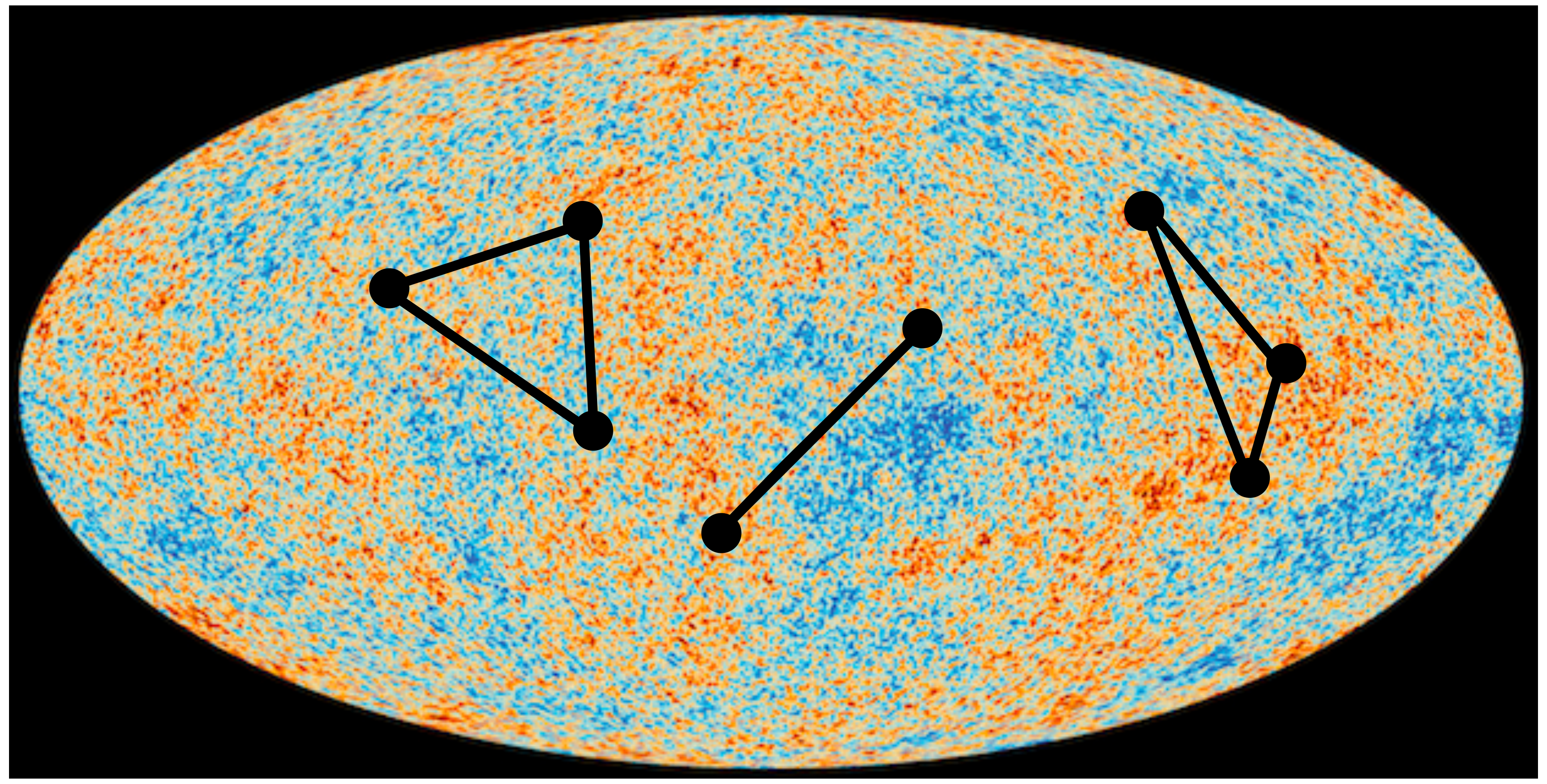


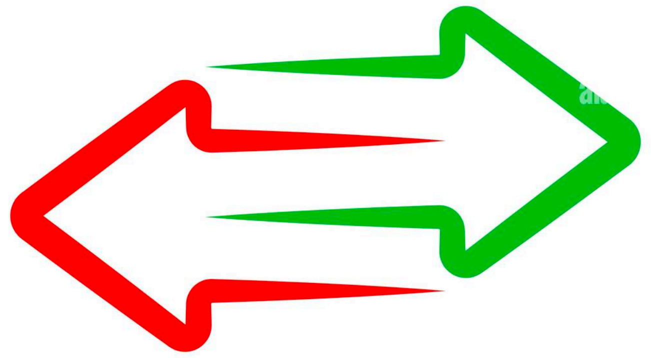


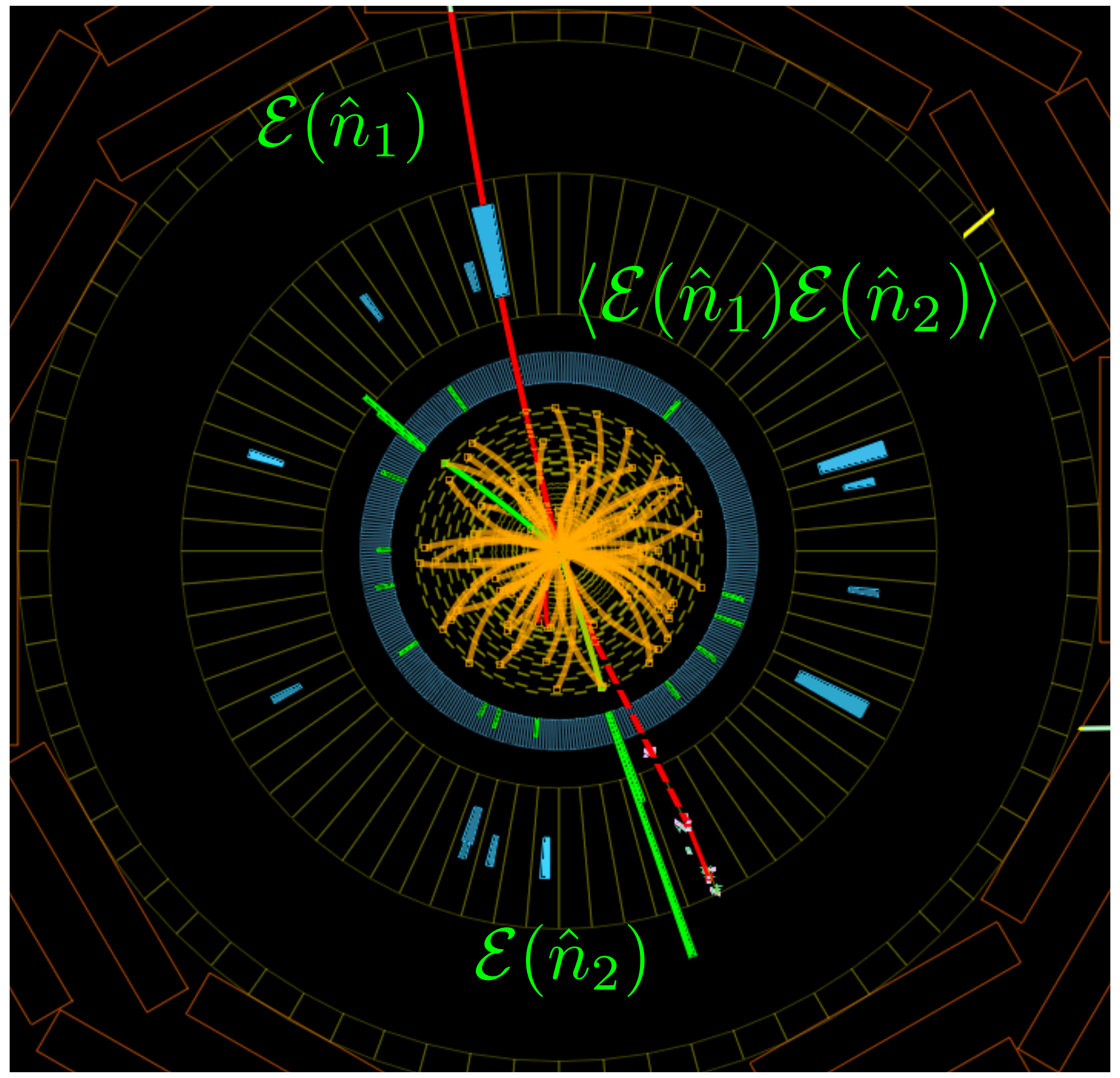
- **At the LHC, all standard model particles are produced with large boost, where EW scales also appear inside the boosted jets. Jet substructure study has evolved well beyond origin and has large impact in BSM, SM, high energy QCD, and nuclear physics.**

JET SUBSTRUCTURE AS CORRELATION FUNCTIONS

- In many fields, **correlation functions** are considered to be fundamental objects which encode the dynamics of the underlying theory.



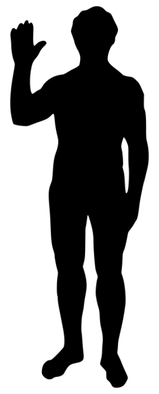




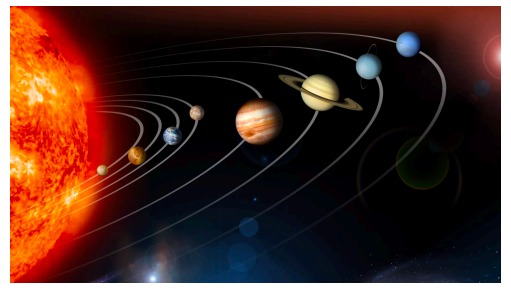
- Much like cosmology, we observe **asymptotic energy flux** at the detectors that are placed at **cosmic scale away** from where the events originated.

(Collision events happen at $\delta x \sim \frac{\hbar}{10\text{TeV}} \sim 2 \times 10^{-20}$ meters, and observed at ~ 10 meters away)

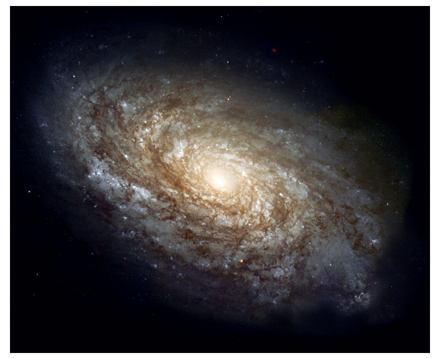
10^{21} **orders in distance!**



$\mathcal{O}(1)$ meters



$\mathcal{O}(10^{15})$ meters



$\mathcal{O}(10^{21})$ meters

JET SUBSTRUCTURE AS CORRELATION FUNCTIONS

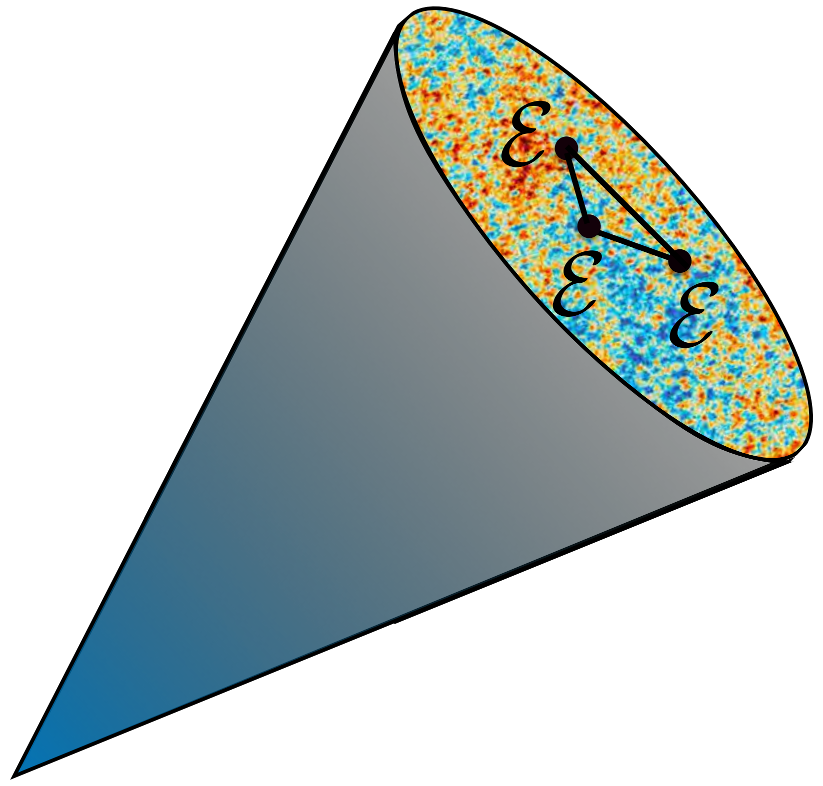
Theoretical definition of the calorimeter detectors

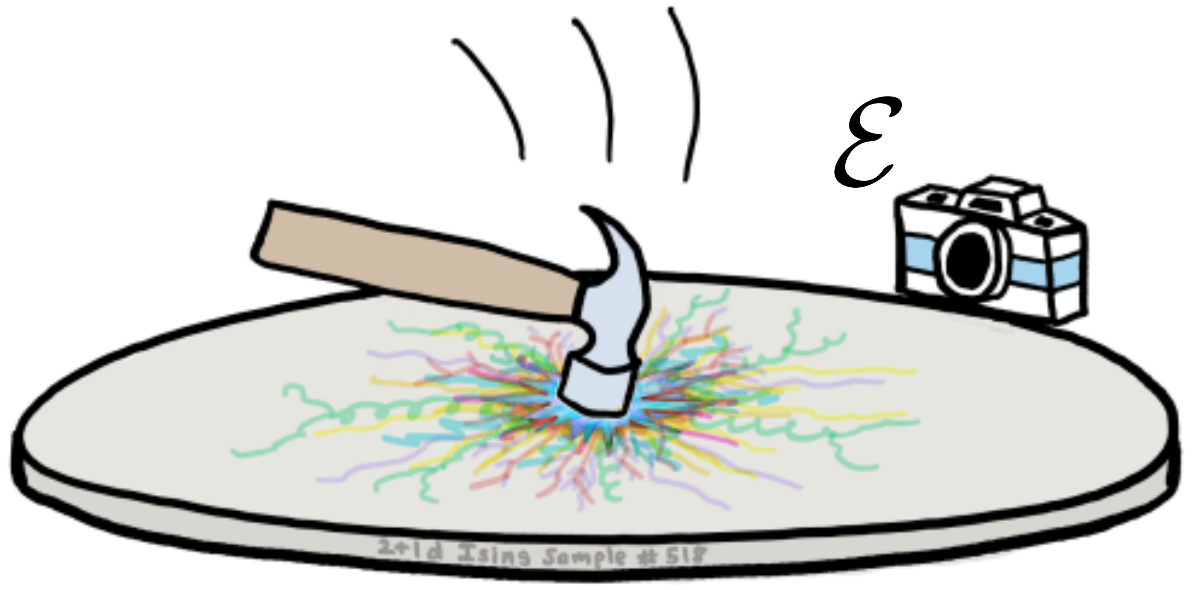
Energy Flow Operators (Light Ray Operators)

$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\; n^i T_{0i}(t, r\vec{n})$$

$$\mathcal{E}(\hat{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\hat{n})$$

$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$





Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin`22

- **Energy Flow Operator provides theoretical meaning of what is a detector in field theory, sharpening the connection between experimentally measurable observables and the underlying field theory.**

Basham, Brown, Ellis, Love, `78-79
Sveshnikov,Tkachov, `95
Korchemsky, Sterman, `01

$$j_a(\Omega) = \sum_{i=1}^{n_a} \eta_i \delta(\Omega - \omega_i)$$

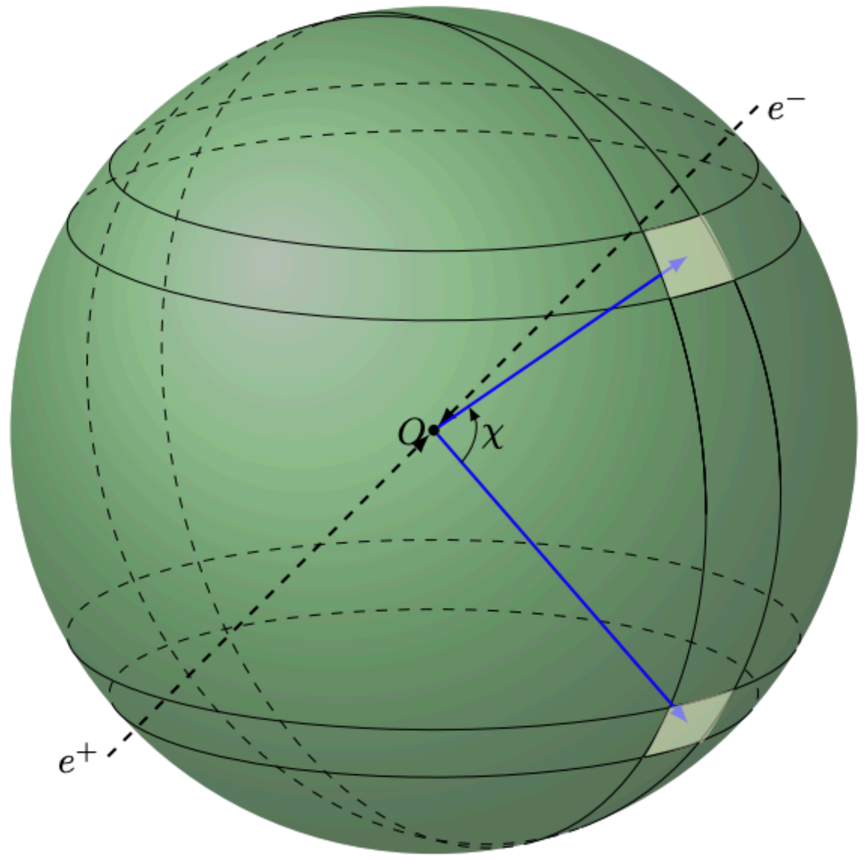
Sterman `75

"Energy flow becomes the focus of computability"

JET SUBSTRUCTURE AS CORRELATION FUNCTIONS

- **Indeed, energy-energy correlators are one of the very first studied event shape (or correlations) observables in QCD**

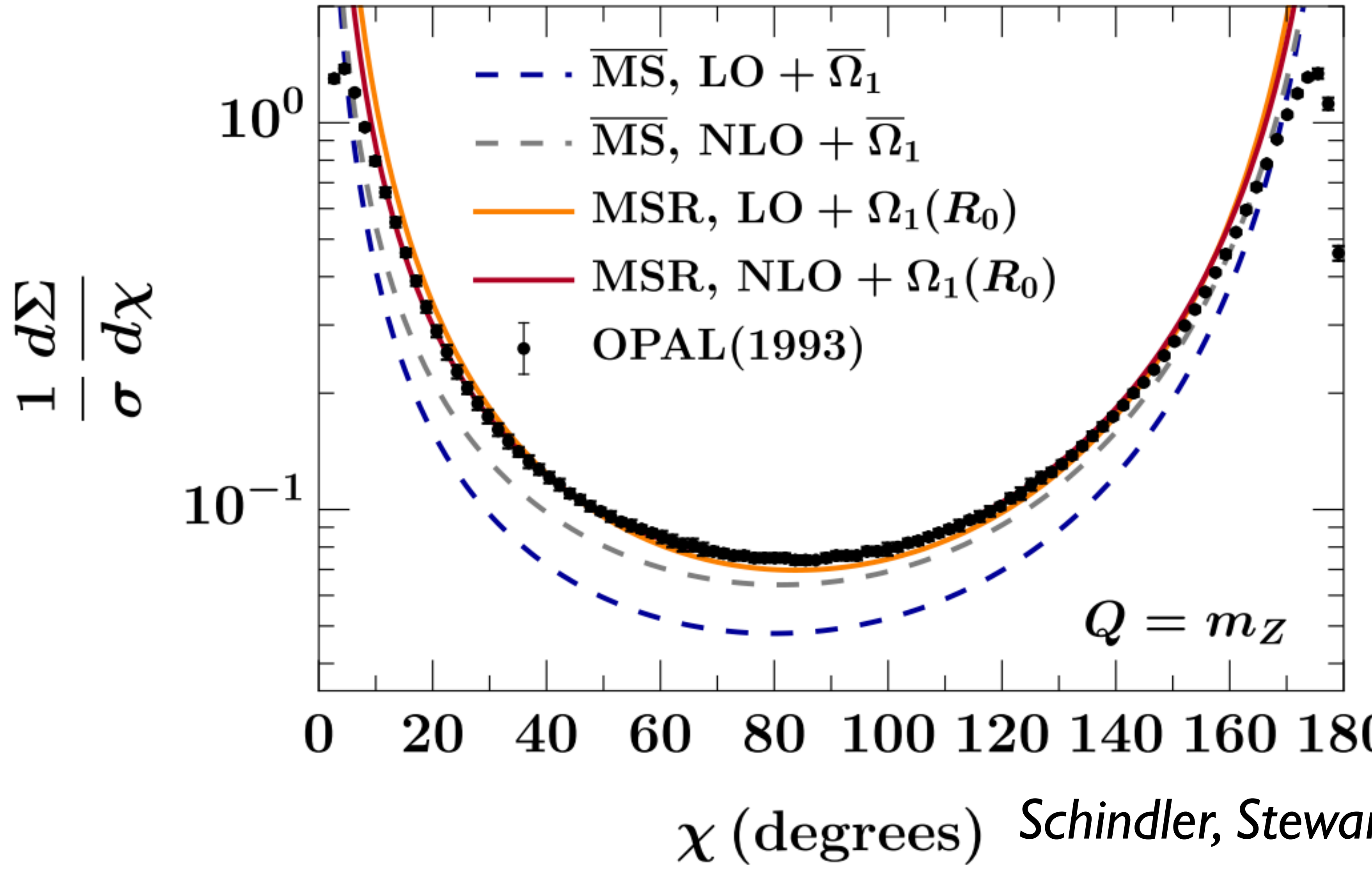
Basham, Brown, Ellis, Love, `78-79



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta} \sim \langle \Psi | \mathcal{E}(\hat{n}_1)\, \mathcal{E}(\hat{n}_2) | \Psi \rangle$$

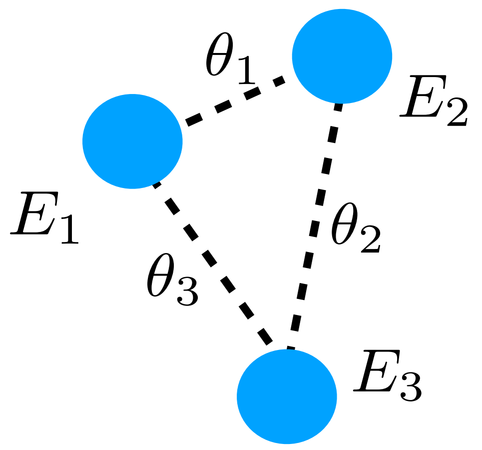
Many precise calculations!

Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov `13
Dixon, Luo, Shtabovenko, Yang, Zhu `18
Luo, Shtabovenko, Yang, Zhu `19
Henn, Sokatchev, Yan, Zhiboedov `19

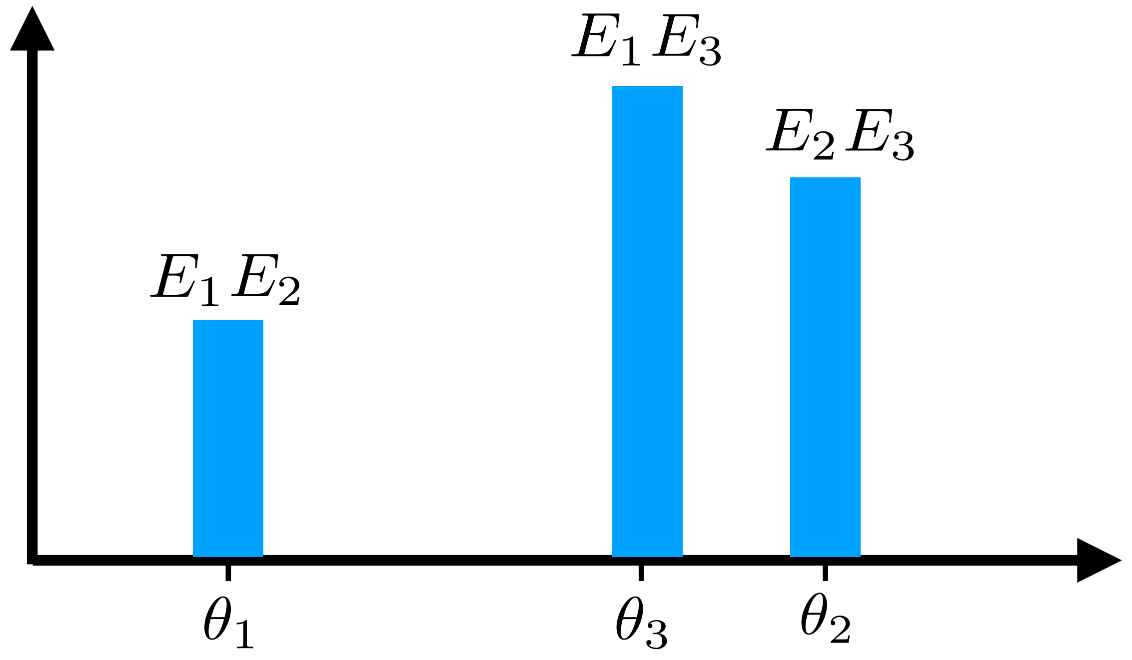


Schindler, Stewart, Sun `23

Impressive agreements from recent calculation, without any fits!



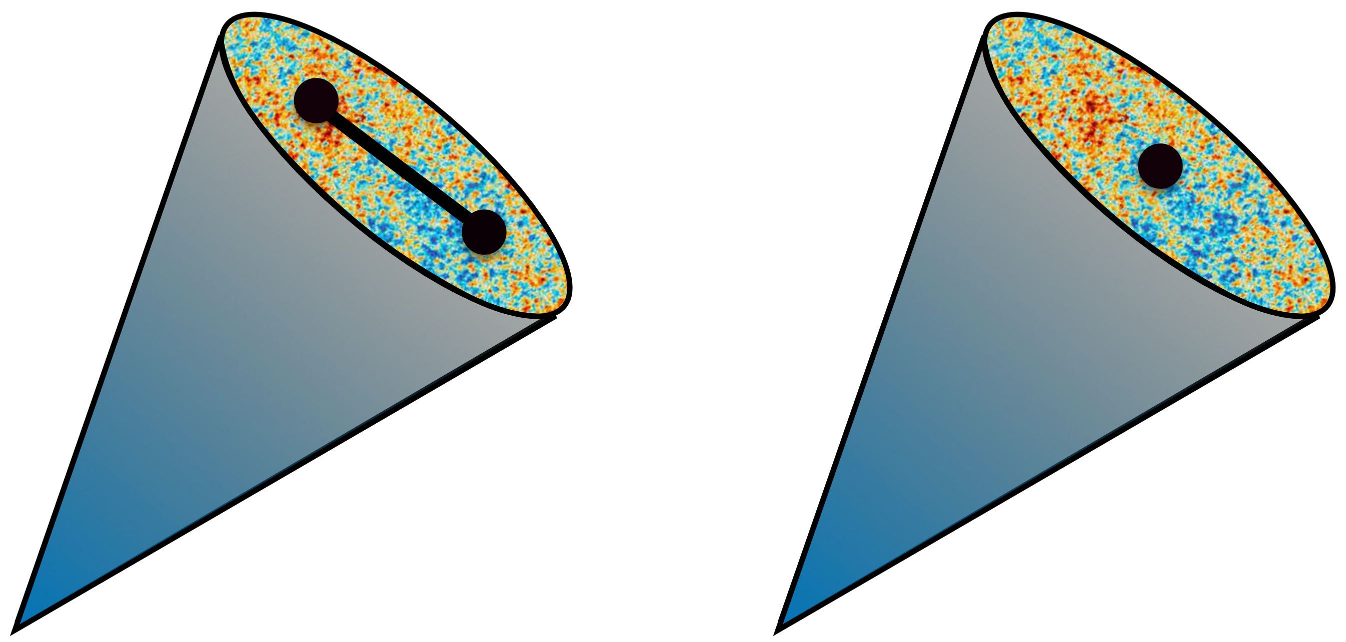
$\Longrightarrow$



$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta} = \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta\left(\theta - \theta_{ij}\right) \sim \langle \Psi | \mathcal{E}(\hat{n}_1)\, \mathcal{E}(\hat{n}_2) | \Psi \rangle$$

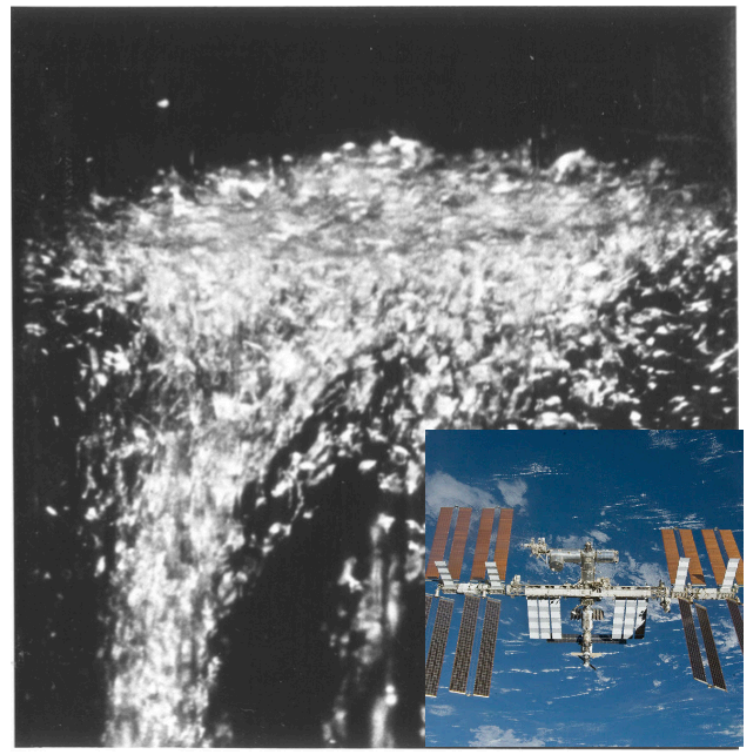
Weighted cross-section, or, ensemble averaged observable

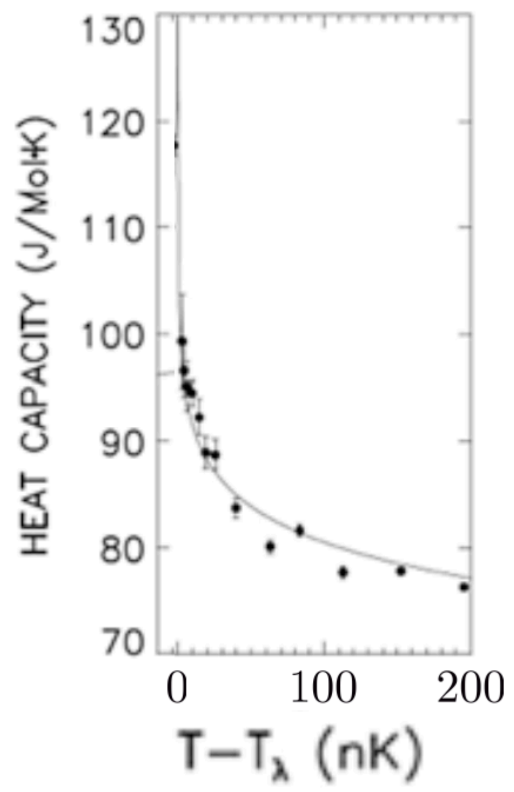
JET SUBSTRUCTURE AS CORRELATION FUNCTIONS



- **Jet limit corresponds to the collinear limit (OPE limit) of the correlation functions of the Energy Flow Operators**

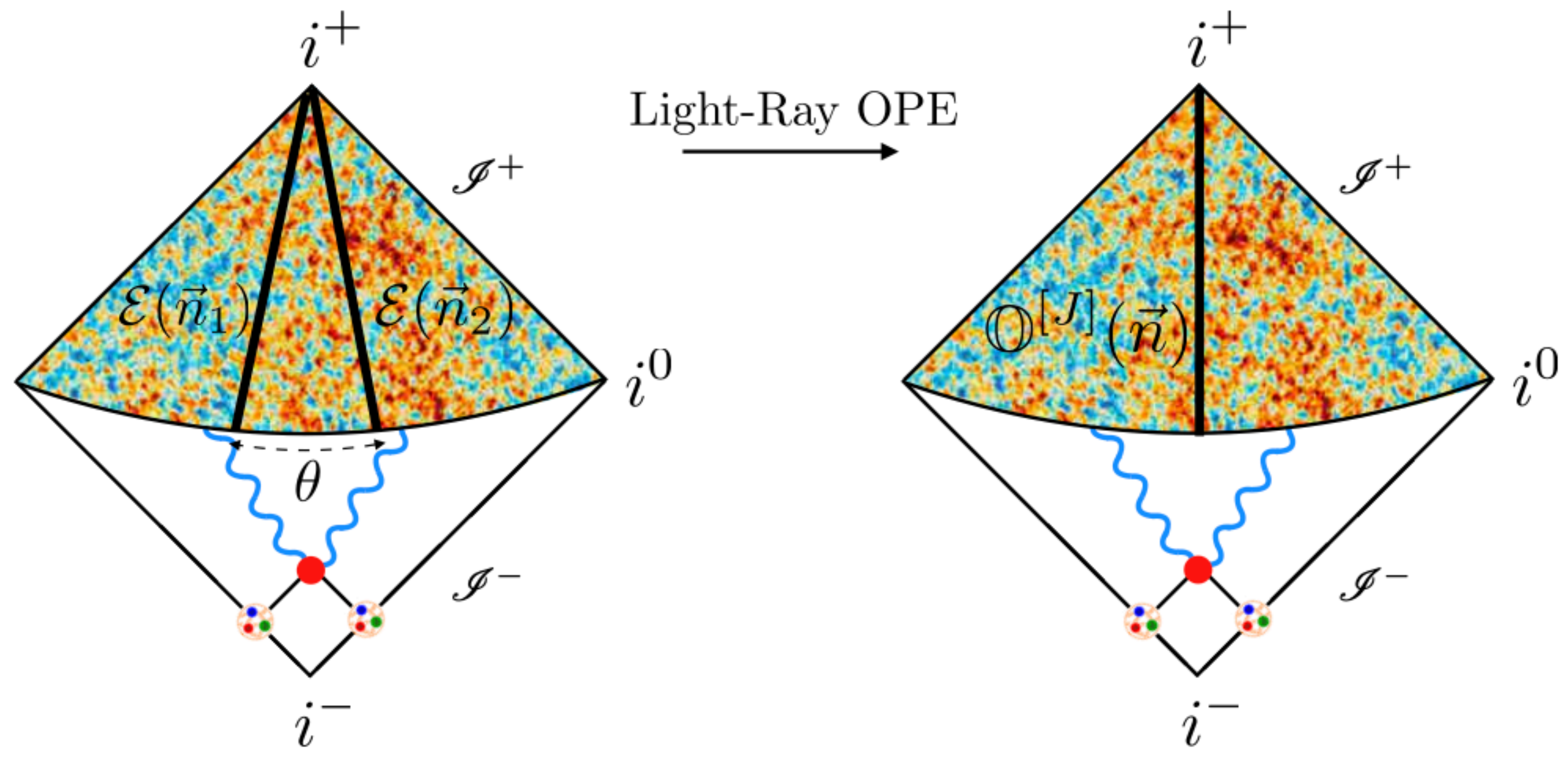
- **Field theory often predicts universal scaling as operators approach each other**





$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

$\Leftrightarrow$



$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\,\mathbb{O}_i(\hat{n}_1)$$

Hofman, Maldacena, `08

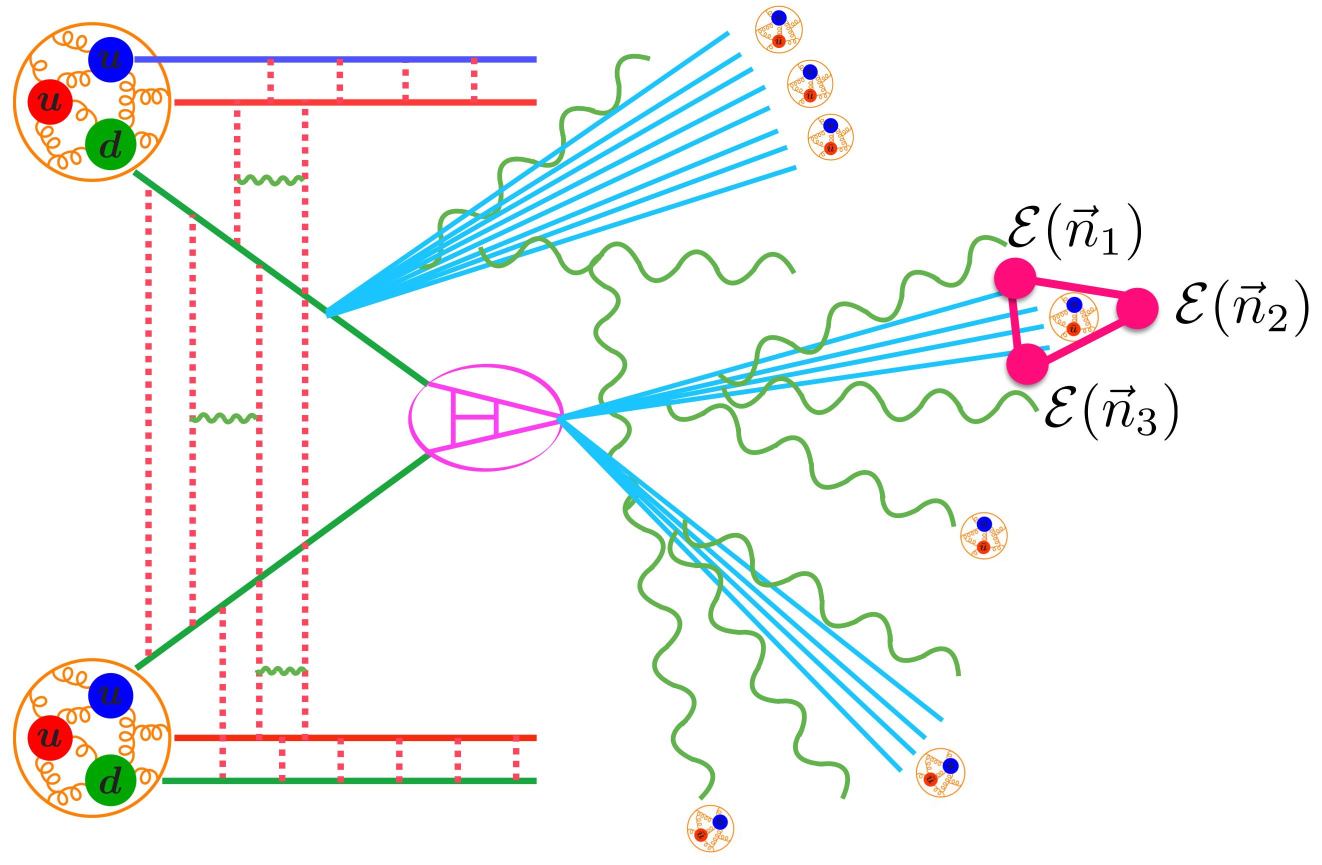
Much interests from the formal theory:

Kravchuk, Simmons Duffin, `18
Henn, Sokatchev, Yan, Zhiboedov, `19
Korchemsky, `19
Belin, Hofman, Mathys, `19
Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, `13
Kologlu, Kravchuk, Simmons Duffin, Zhiboedov, `19
Chang, Kologlu, Kravchuk, Simmons-Duffin, `20
Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin, `22

CAN THIS UNIVERSAL SCALING OF THE FIELD THEORY BE OBSERVED IN JETS AT THE LHC???

CONFORMAL COLLIDERS MEET THE HIGH ENERGY COLLIDERS

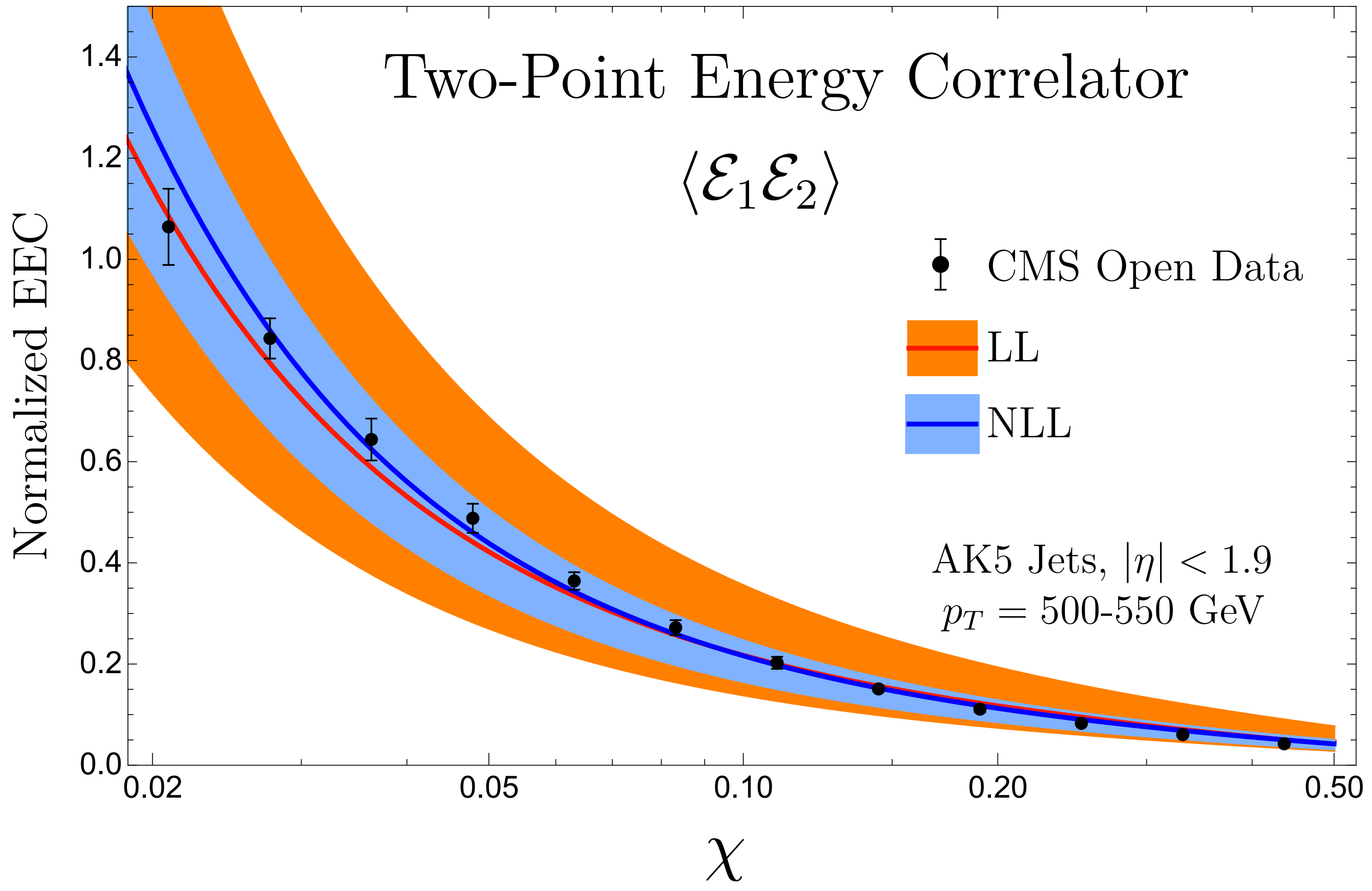
2019/2020



Rethinking Jets with Energy Correlators

Chen, Moult, Zhang, Zhu `20
Dixon, Moult, Zhu `19

2022



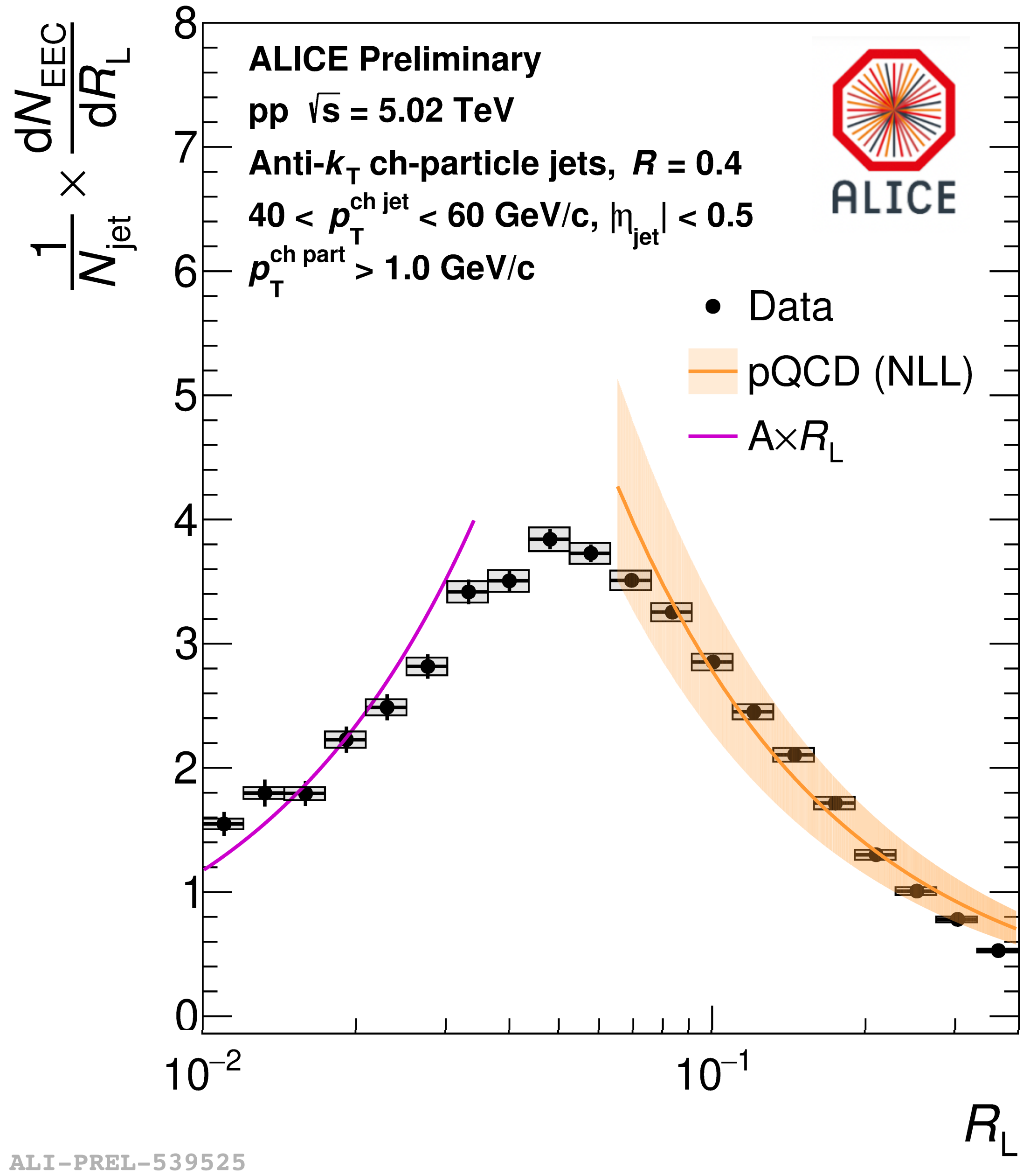
Open data analyses and QCD Factorization

KL, Meçaj, Moult `22
Komiske, Moult, Thaler, Zhu `22

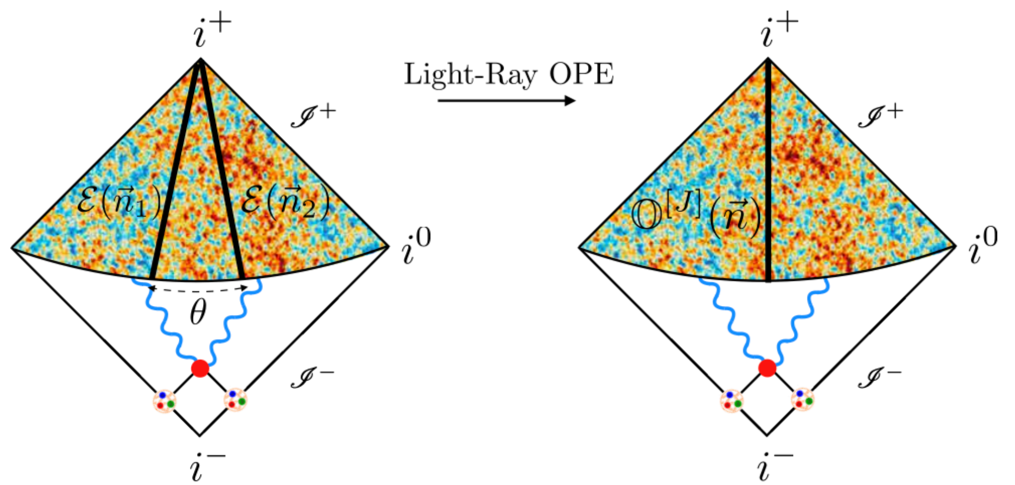
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\,\mathbb{O}_i(\hat{n}_1)$$

2023

ALICE `23

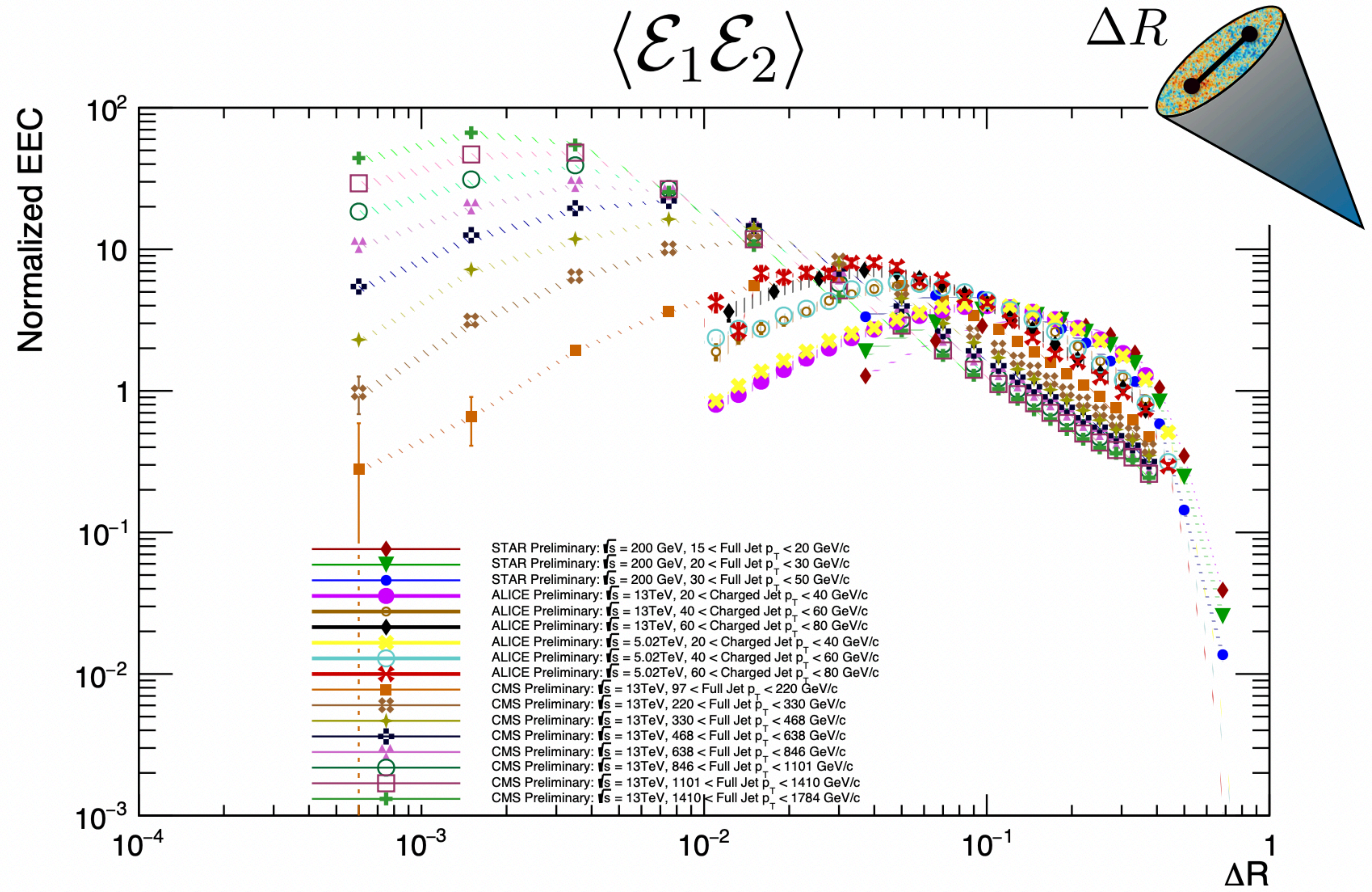


Real Data analyses at the LHC

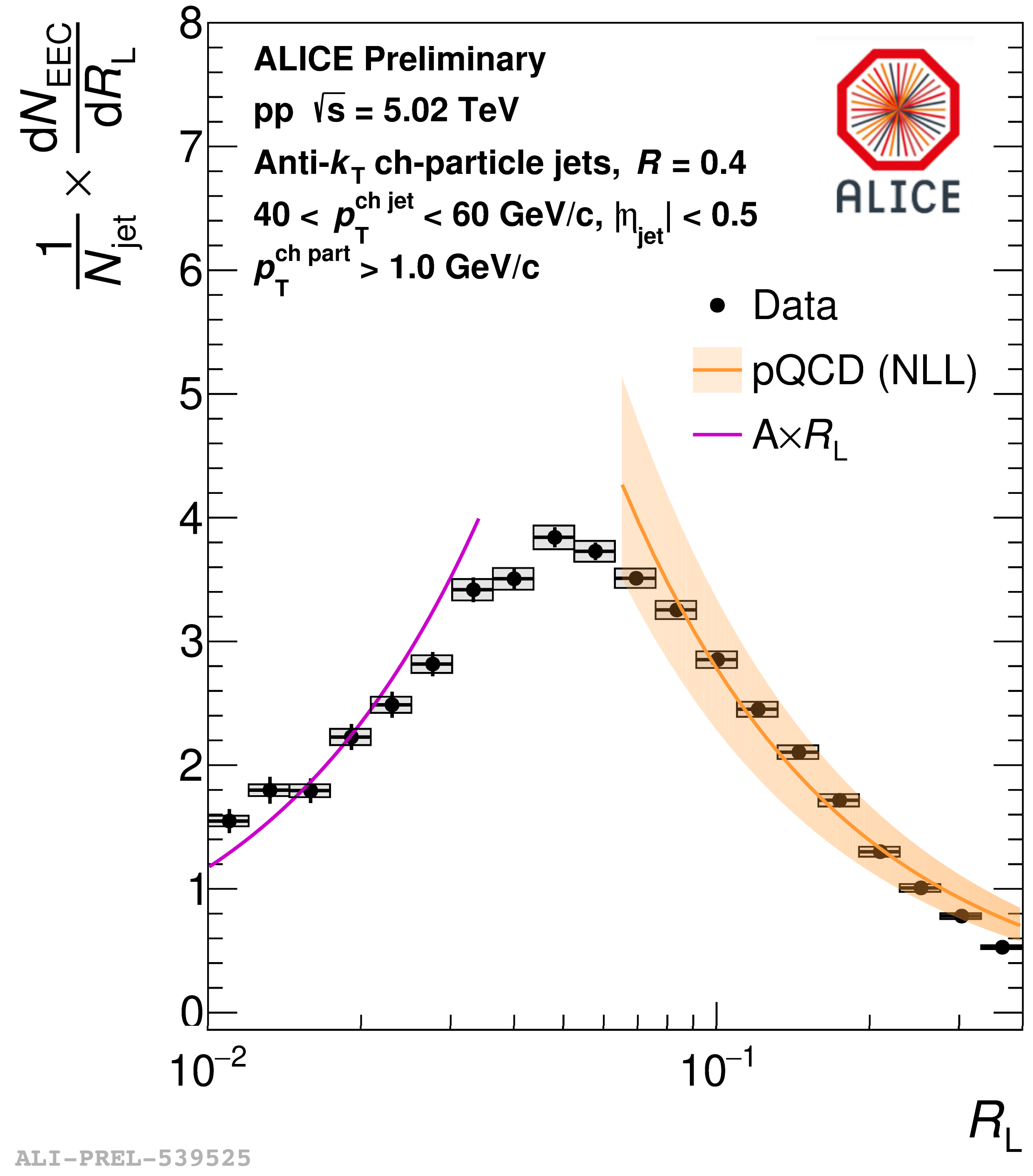


Observation of the universal of QCD predicted at the operator levels from the light-ray operator product expansion!

CONFORMAL COLLIDERS MEET THE HIGH ENERGY COLLIDERS



2023

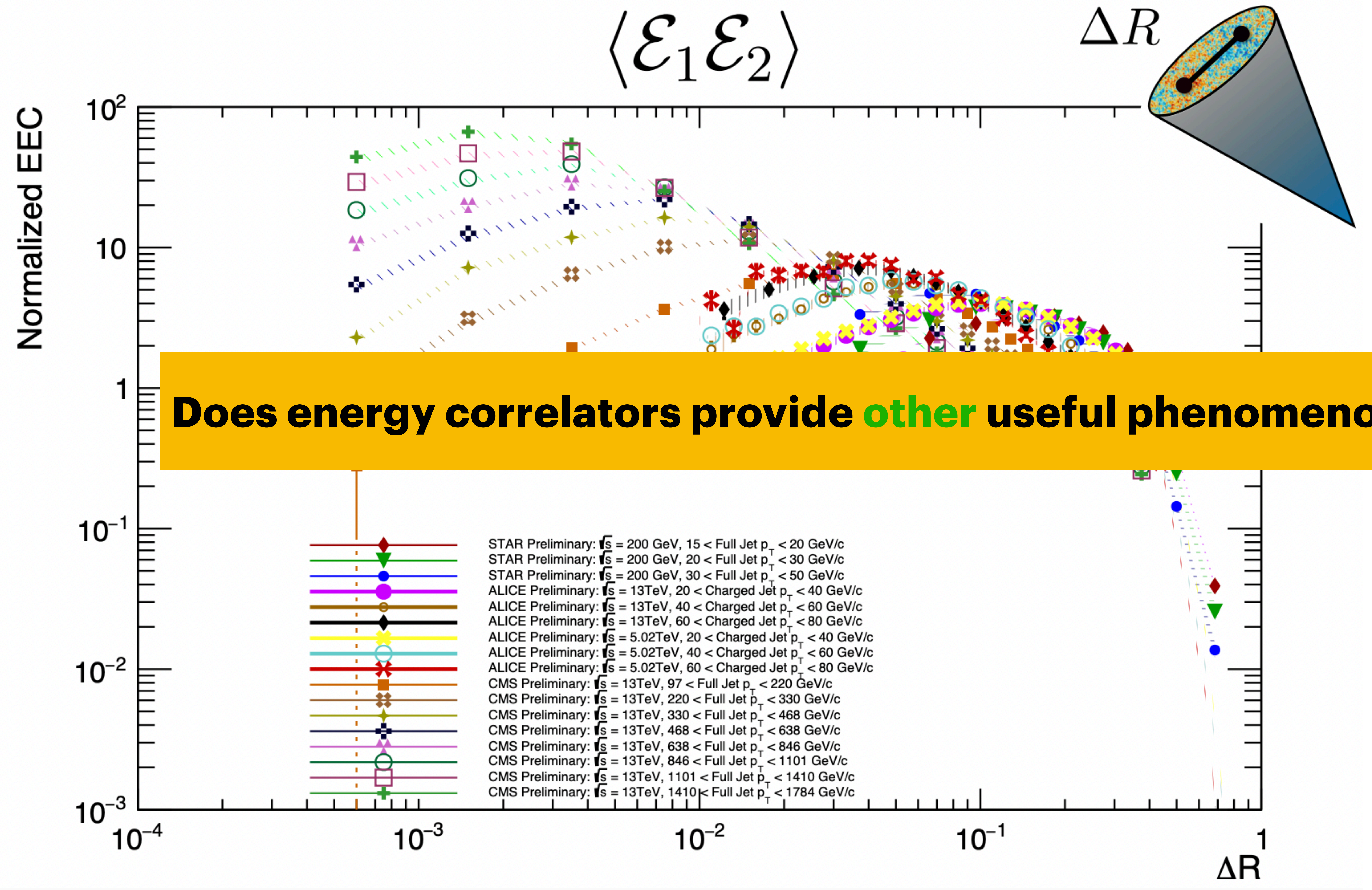


Real Data analyses at the LHC

$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\, \mathbb{O}_i(\hat{n}_1)$$

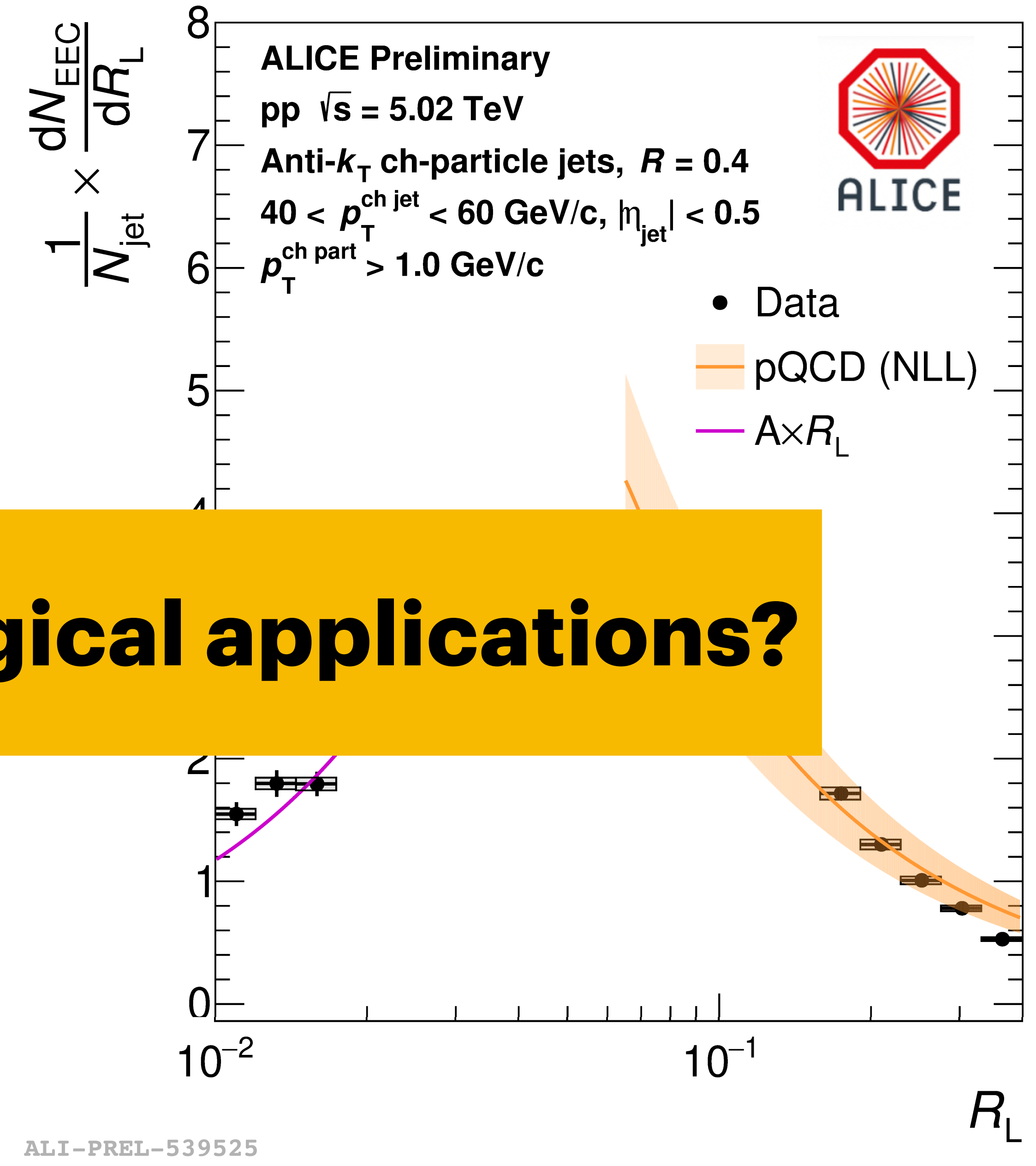
- **Universal scaling measured in real data from ALICE, CMS, and STAR from 15 GeV to 1784 GeV!**

CONFORMAL COLLIDERS MEET THE HIGH ENERGY COLLIDERS



Does energy correlators provide other useful phenomenological applications?

2023



Real Data analyses at the LHC

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Standard-model physics (QCD and electroweak)
100 MeV - 4 TeV
New physics searches
100 GeV - 8 TeV
Top-quark physics
170 GeV - O(TeV)
Heavy flavor physics (beauty and charm)
1 - 5 GeV
Higgs physics
125 GeV - 500 GeV
Heavy-ion physics
100 MeV - 500 GeV
Heart
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV


Standard-model physics
(QCD and electroweak)
100 MeV - 4 TeV
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170 GeV - O(TeV)
Heavy flavor physics
1 - 5 GeV
Higgs physics
125 GeV - 500 GeV
Heavy-ion physics
100 MeV - 500 GeV
Heart
Rethinking jet substructure using energy correlators provide powerful
framework for phenomenological applications!
100 MeV
1 GeV
10 GeV
1 TeV
10 TeV

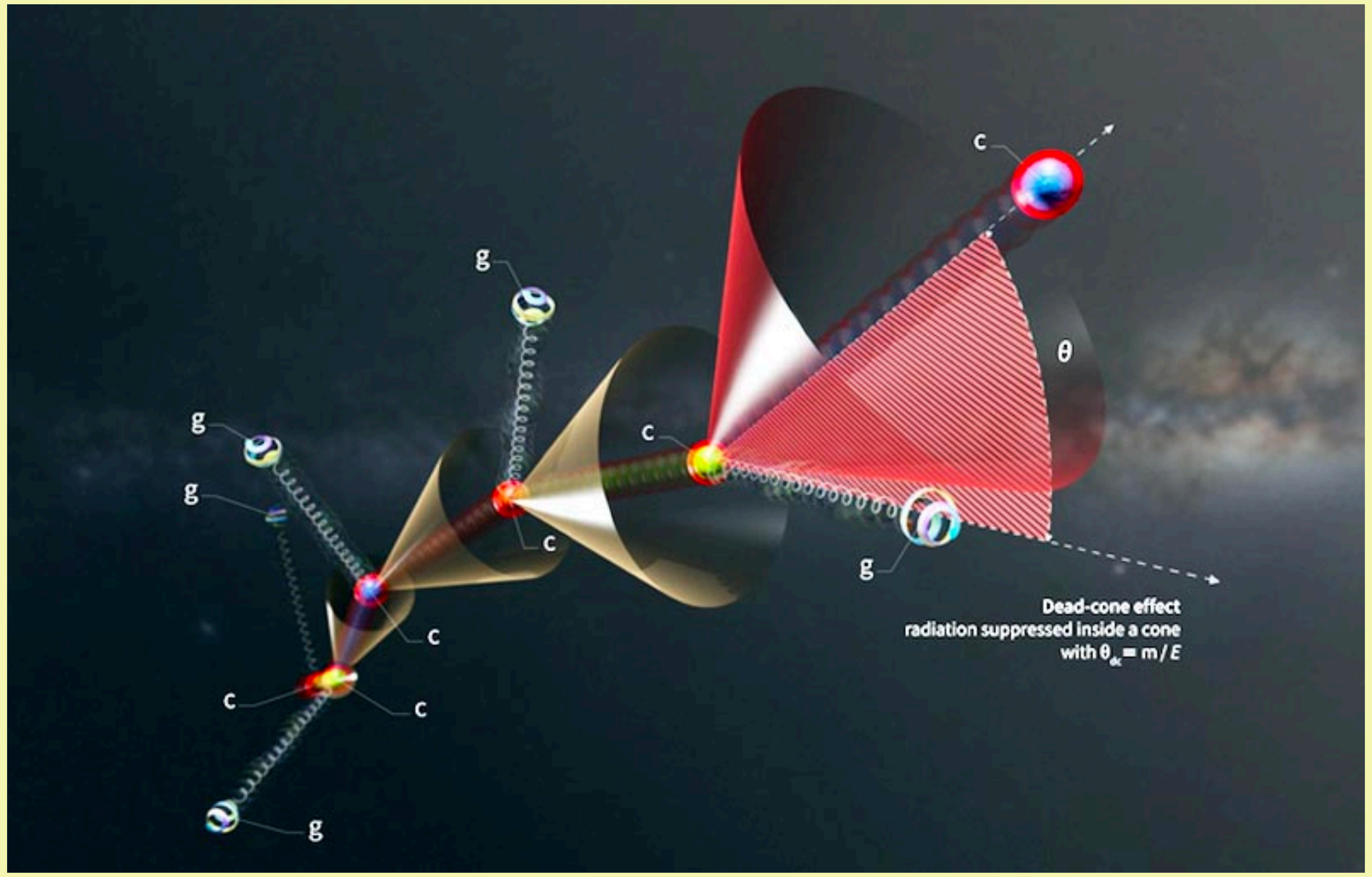
Heavy flavor physics
(Beauty and charm)

1 - 5 GeV

GOAL

HOW DO WE UNDERSTAND HEAVY FLAVOR PHYSICS?

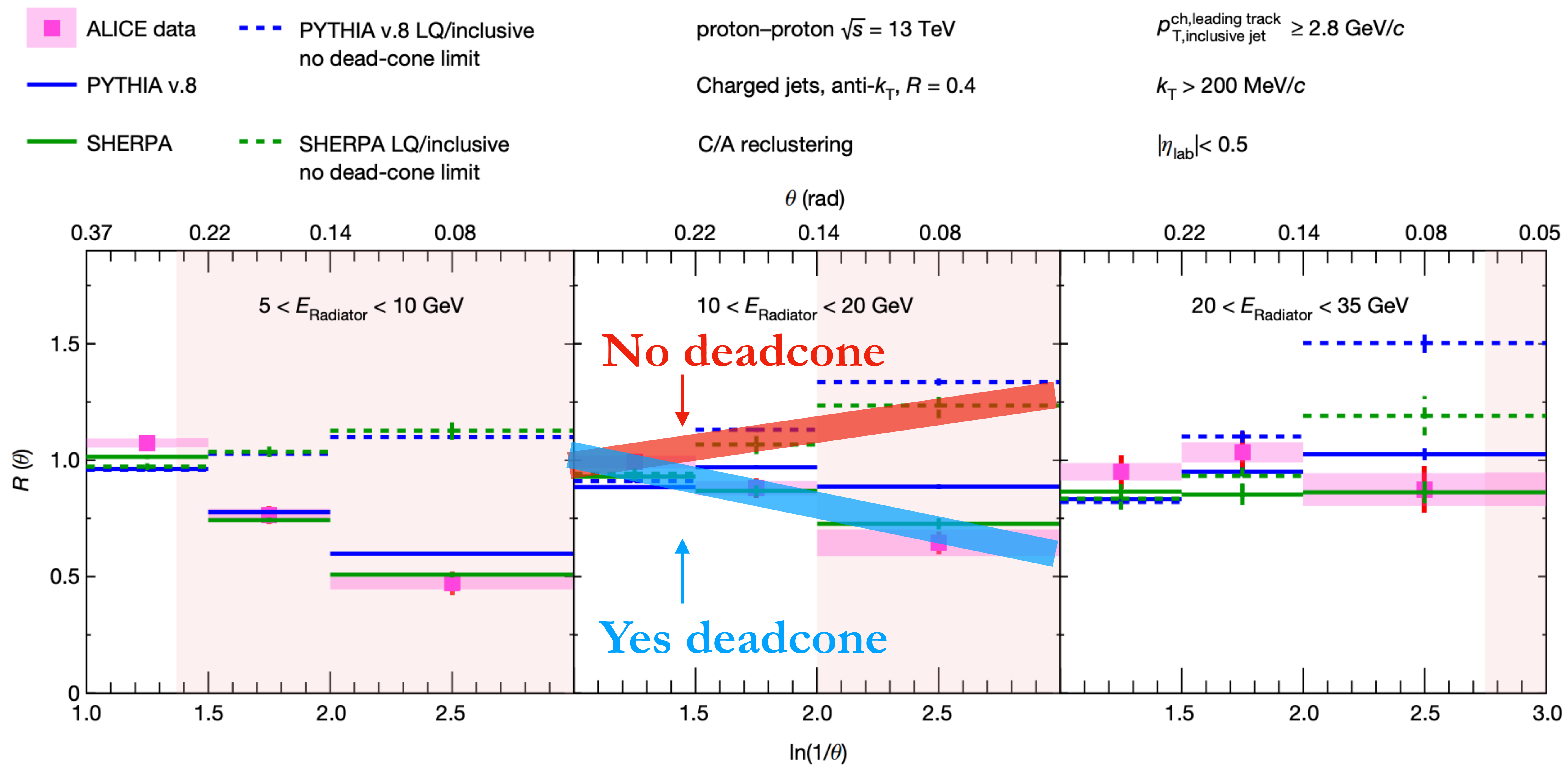
IMPROVING OUR UNDERSTANDING OF MASS EFFECTS

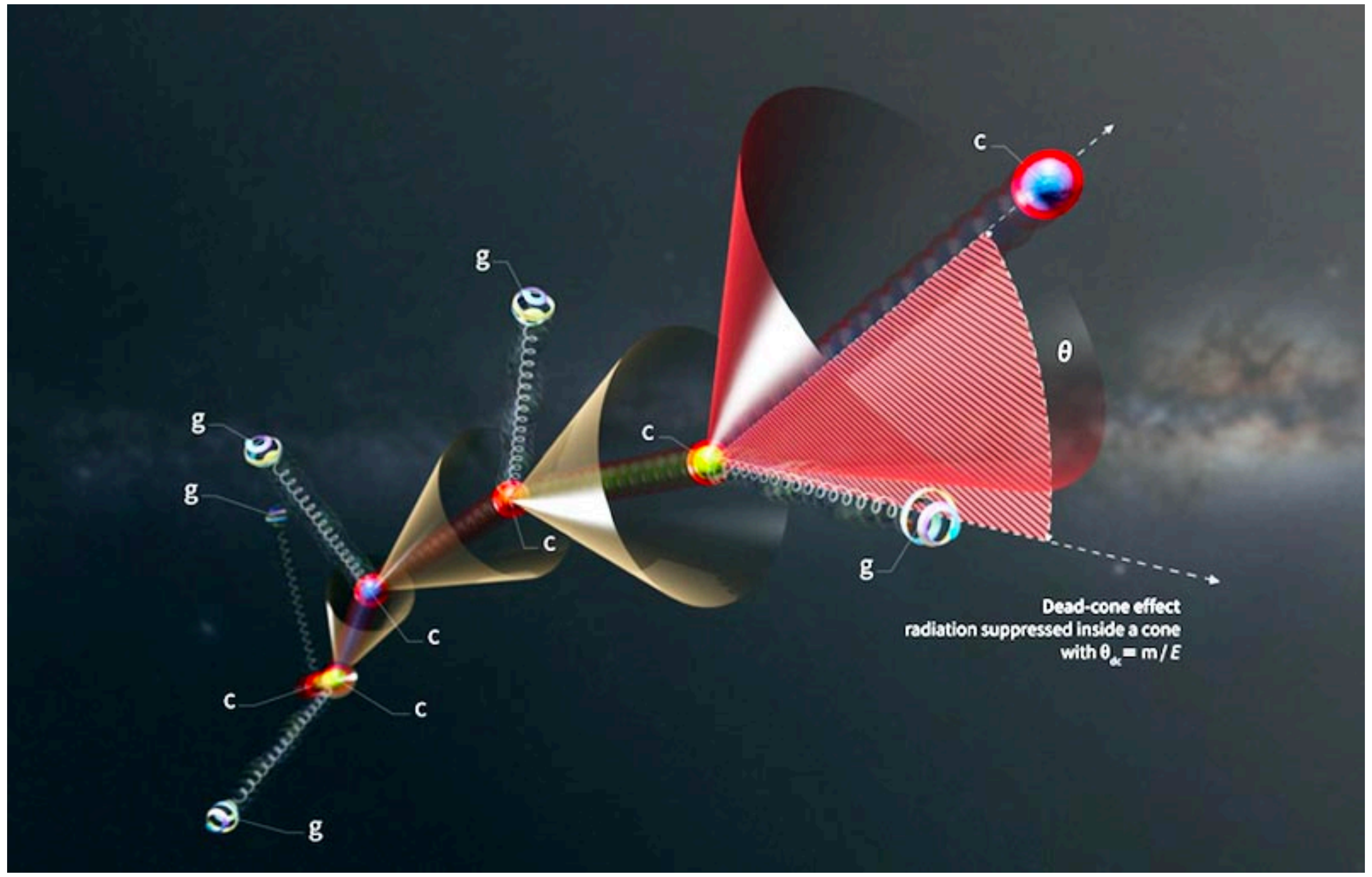


VERY FIRST DIRECT DETECTION OF DEADCONE

- **Fundamental predictions of our gauge theory— directly observed for the very first time last year!**

nature



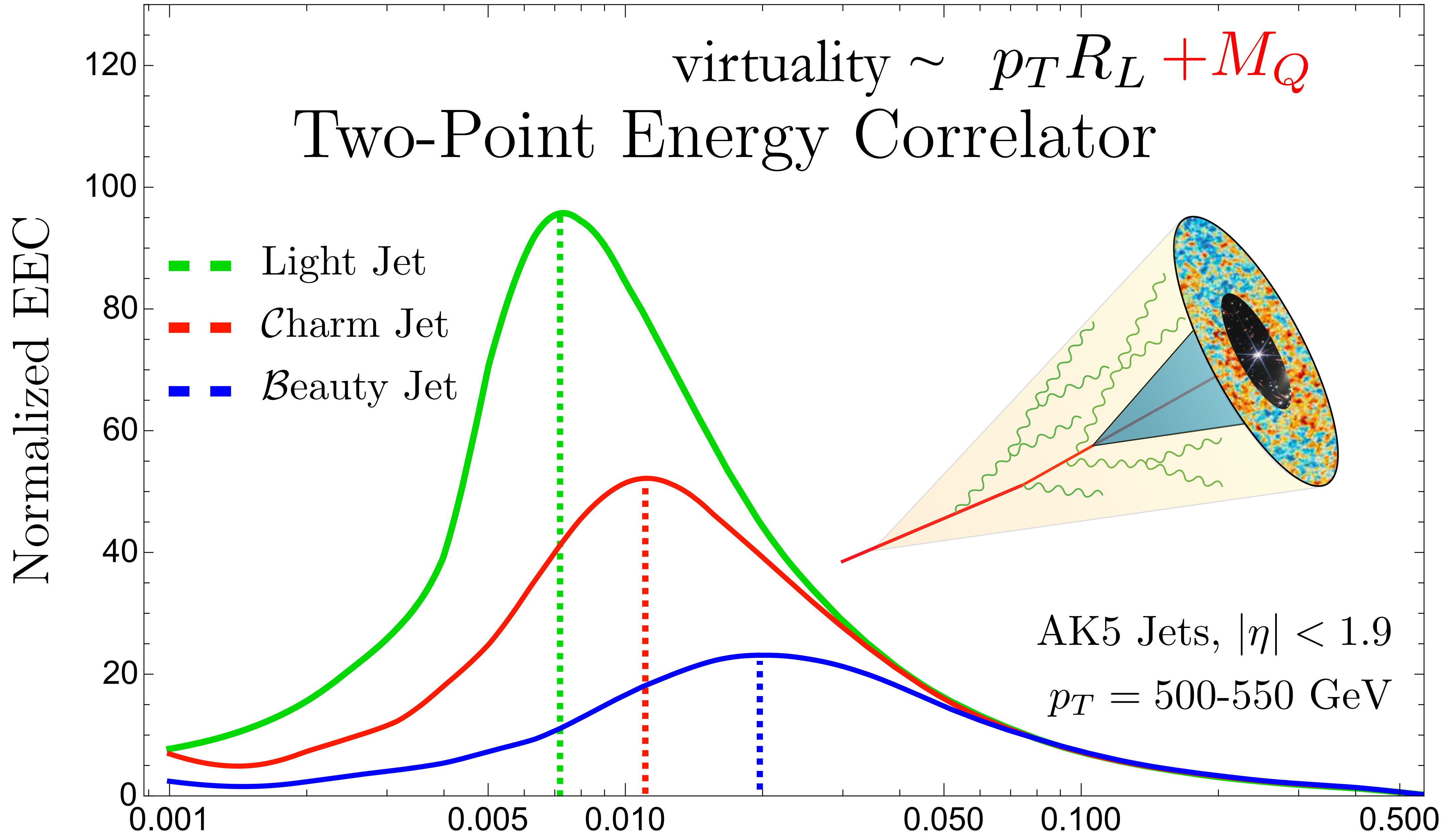


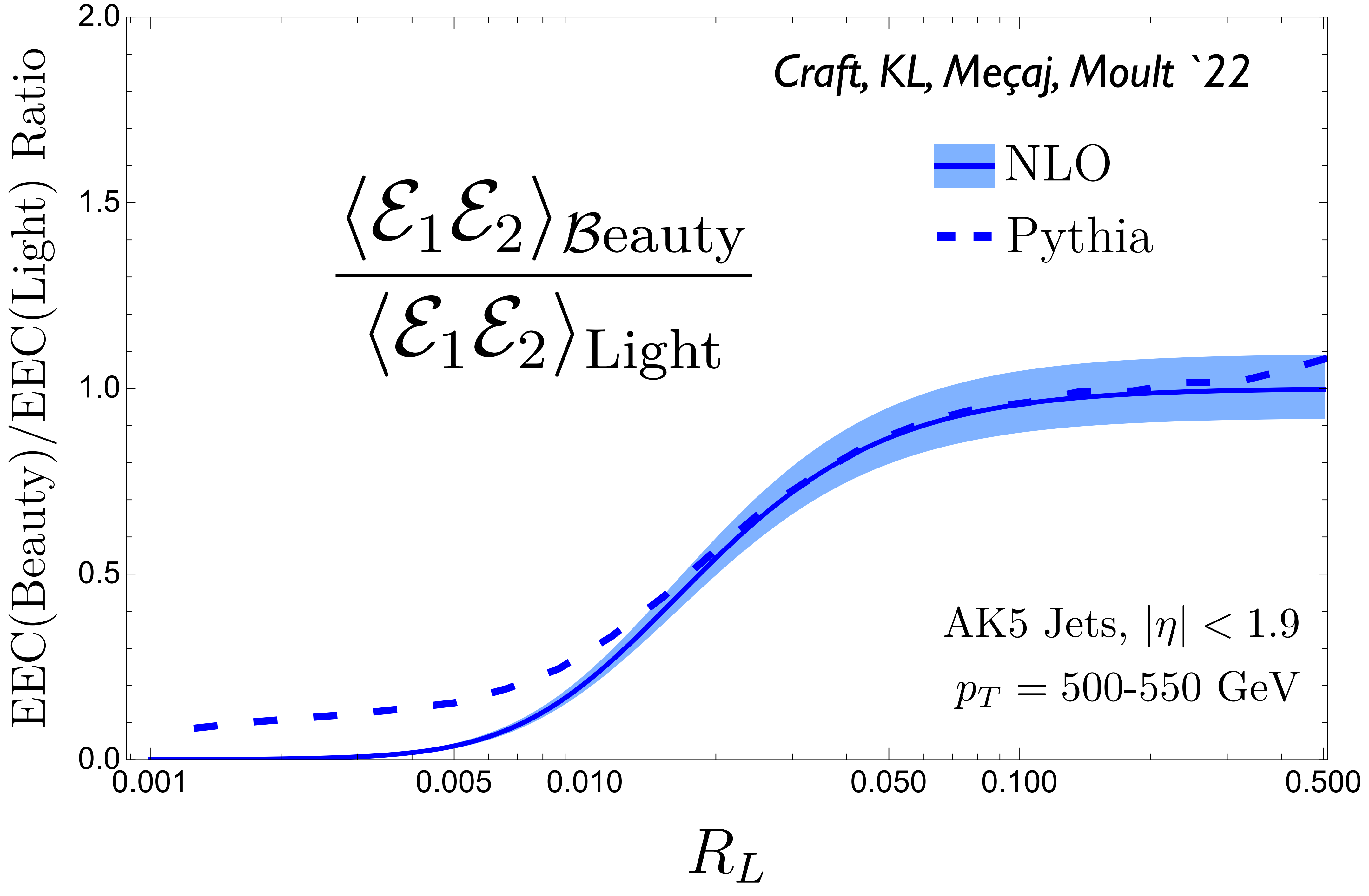
[ALICE 2022]

BEAUTIFUL AND CHARMING ENERGY CORRELATORS

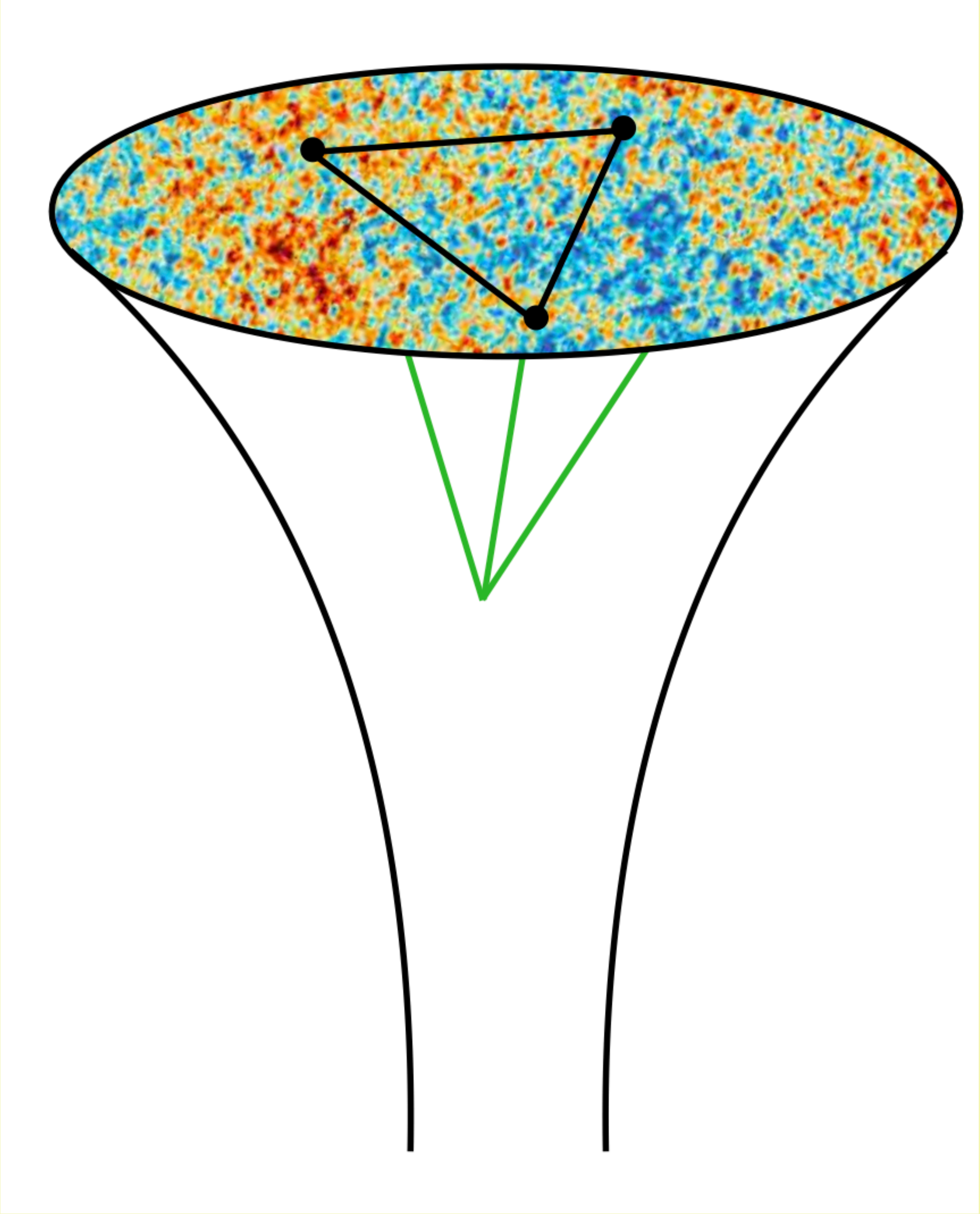
- **One can statistically measure the gluon suppression (dead cone) within the heavy jets as compared to the light jets by taking the ratio of energy correlators.**

scale knob  **EEC gives angular scale** $\mu \sim p_T \theta_{ij}$



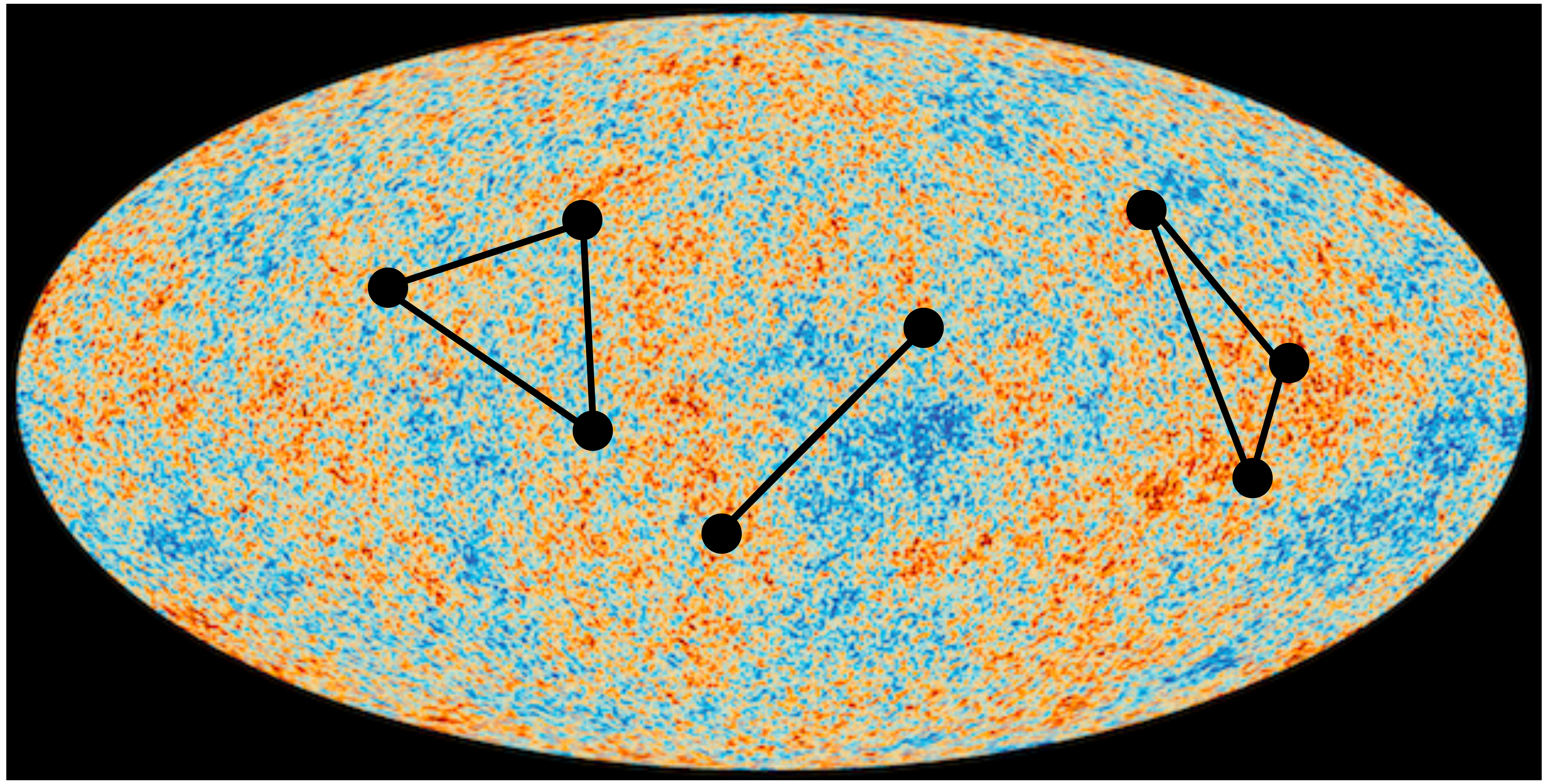


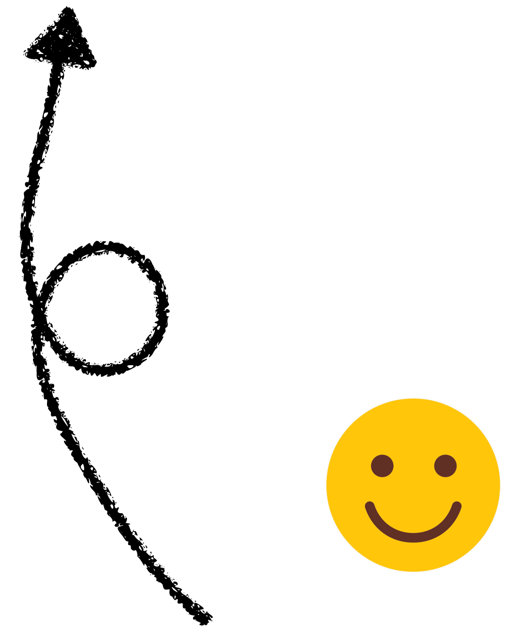
NON-GAUSSIANITIES /HIGHER POINTS IN PARTICLE COLLIDER



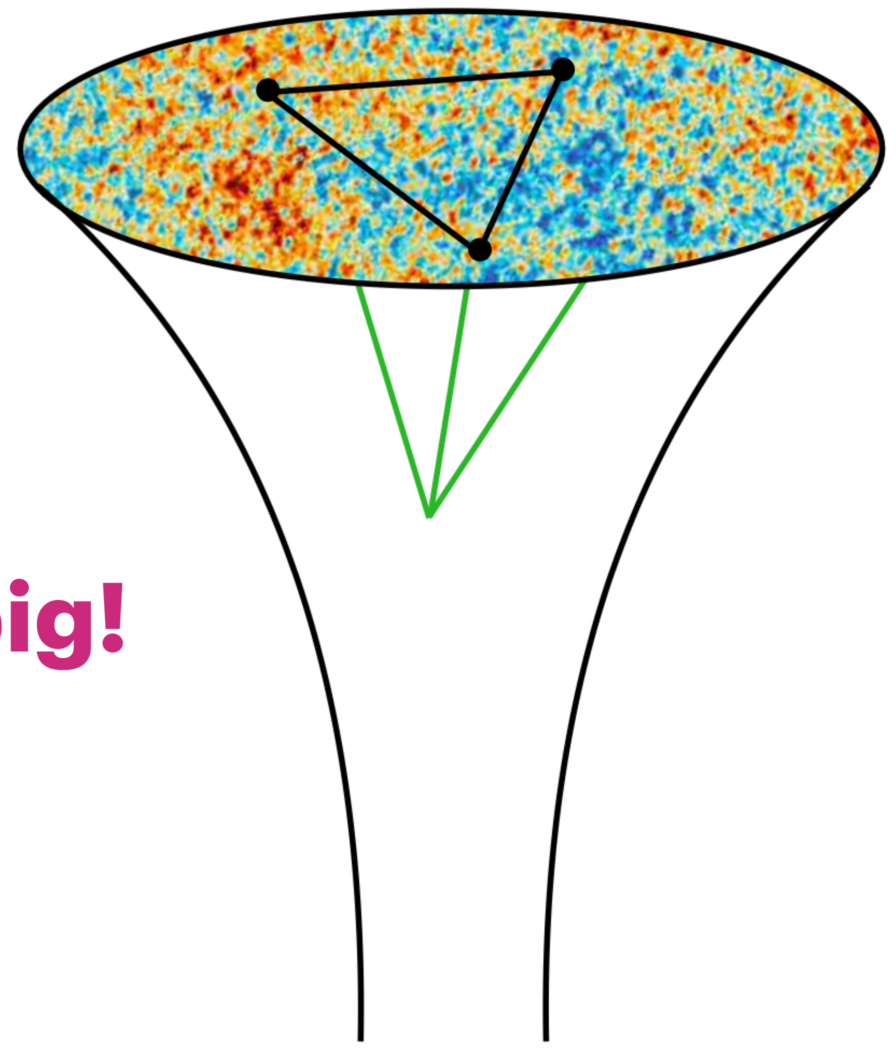
PROBING HIGHER POINT STRUCTURE

- **Higher-point correlators probe more detailed aspects of interactions.**
- **Hunting for non-gaussianities to distinguish the models of inflation.**
  Maldacena `02, Komatsu `10
  Cabass, Pajer, Stefanyszyn, Supel `21,…
  Extremely interesting physics detail hiding under the 1 part in 100000 non-gaussianity in CMB!



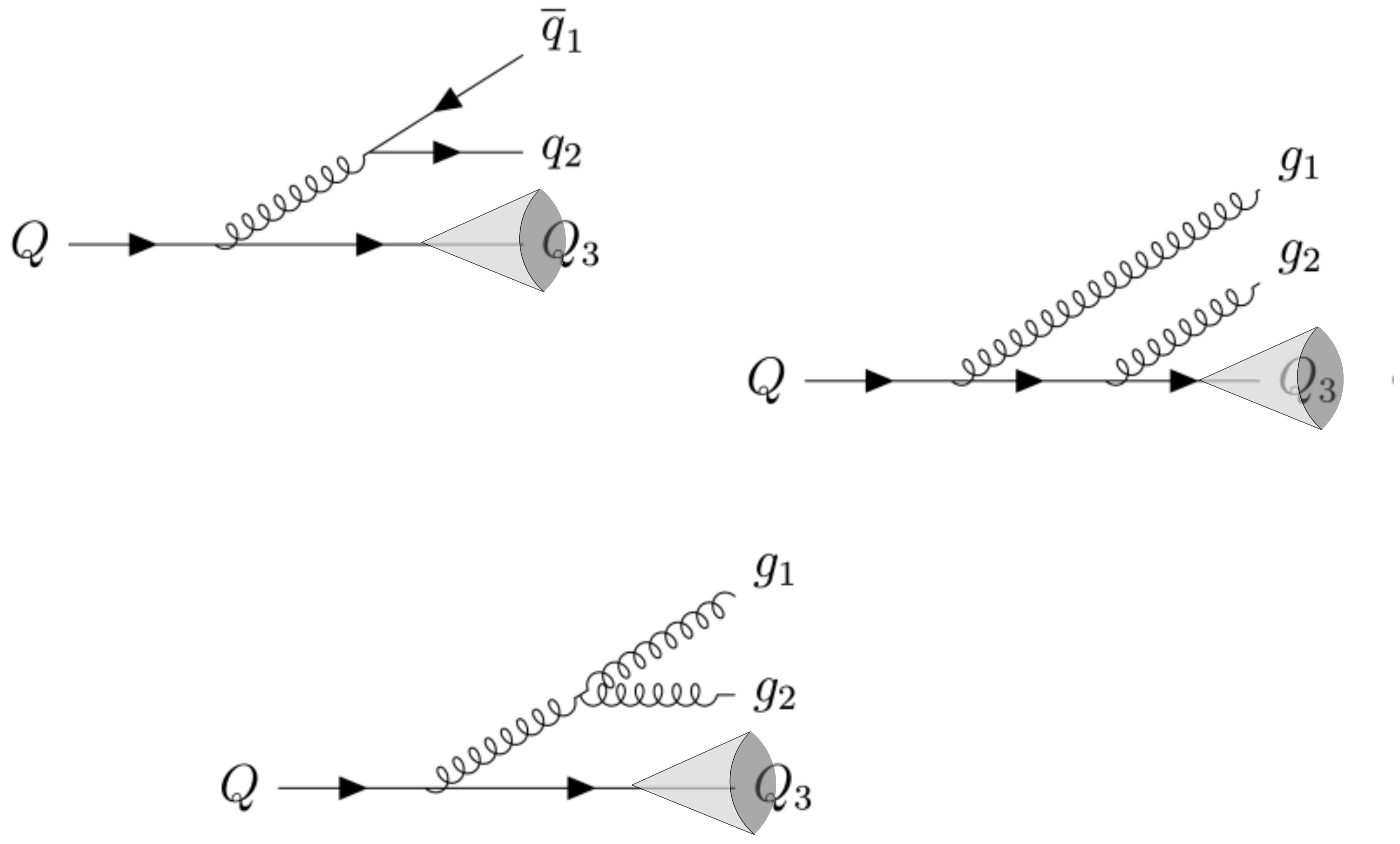


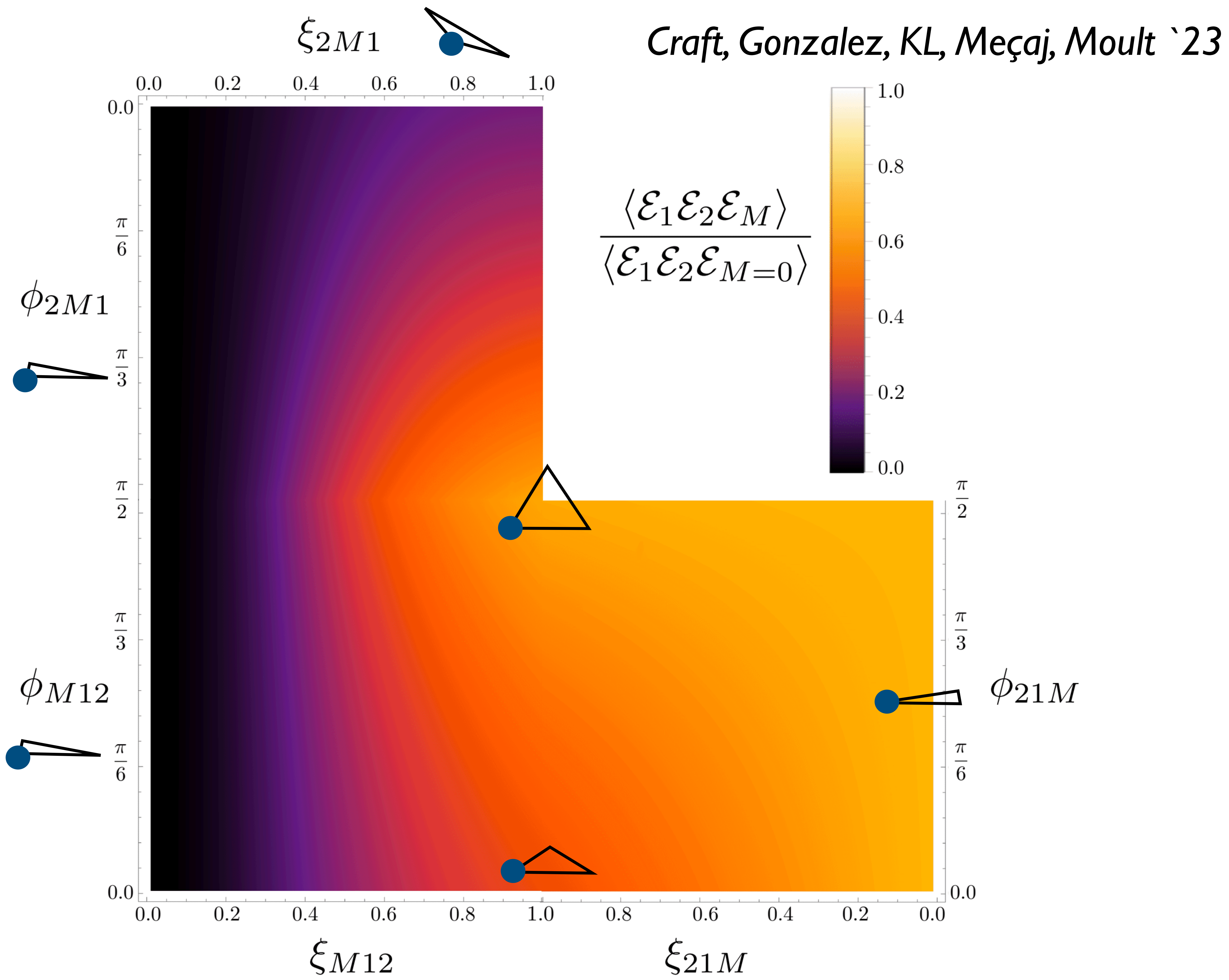
We must also dream big!



BEAUTIFUL AND CHARMING ENERGY CORRELATORS

Triple collinear interactions





Higher-point structure provides nontrivial shape information of the heavy flavor dynamics

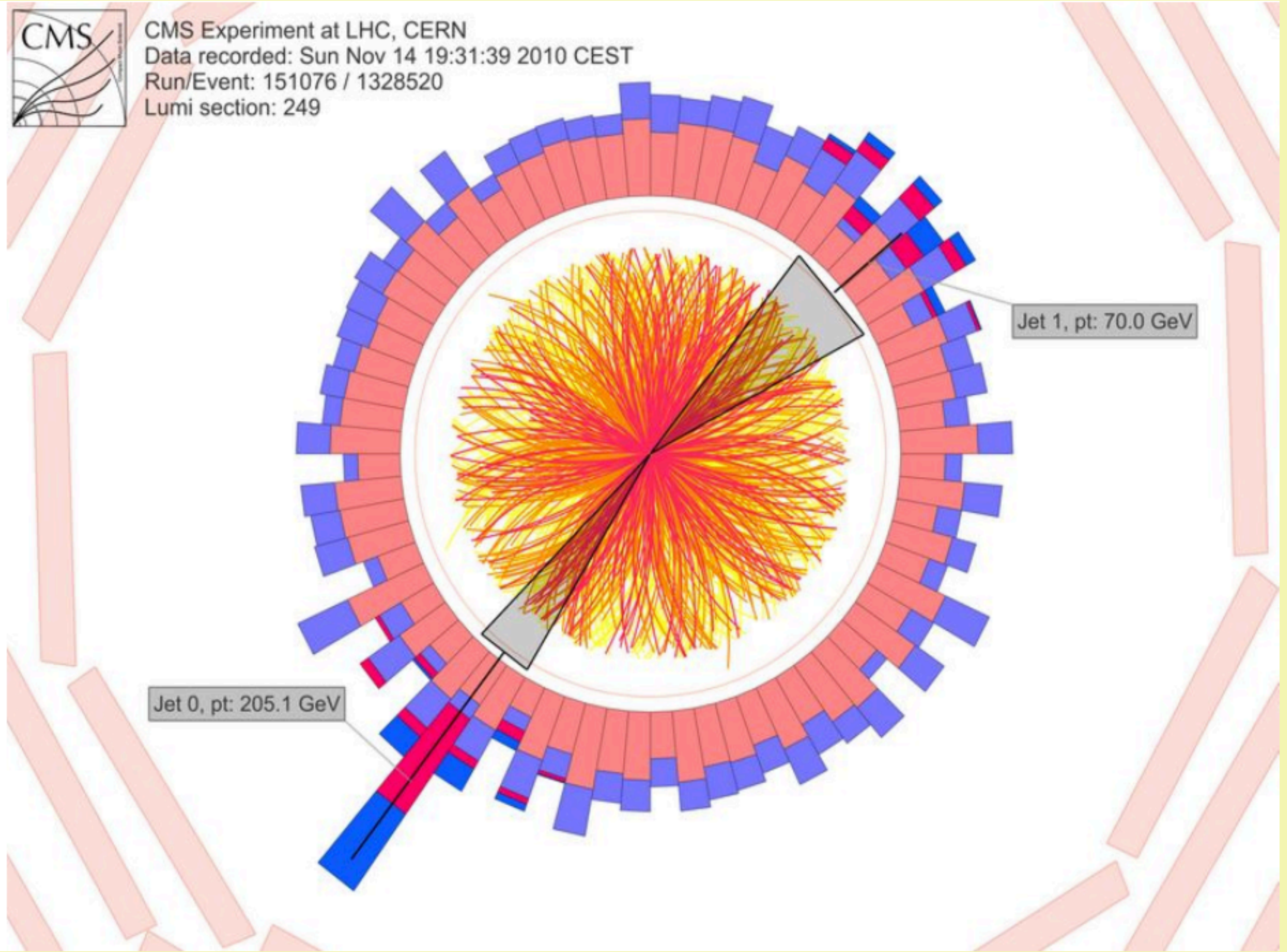
Heavy-ion physics

100 MeV - 500 GeV

GOAL

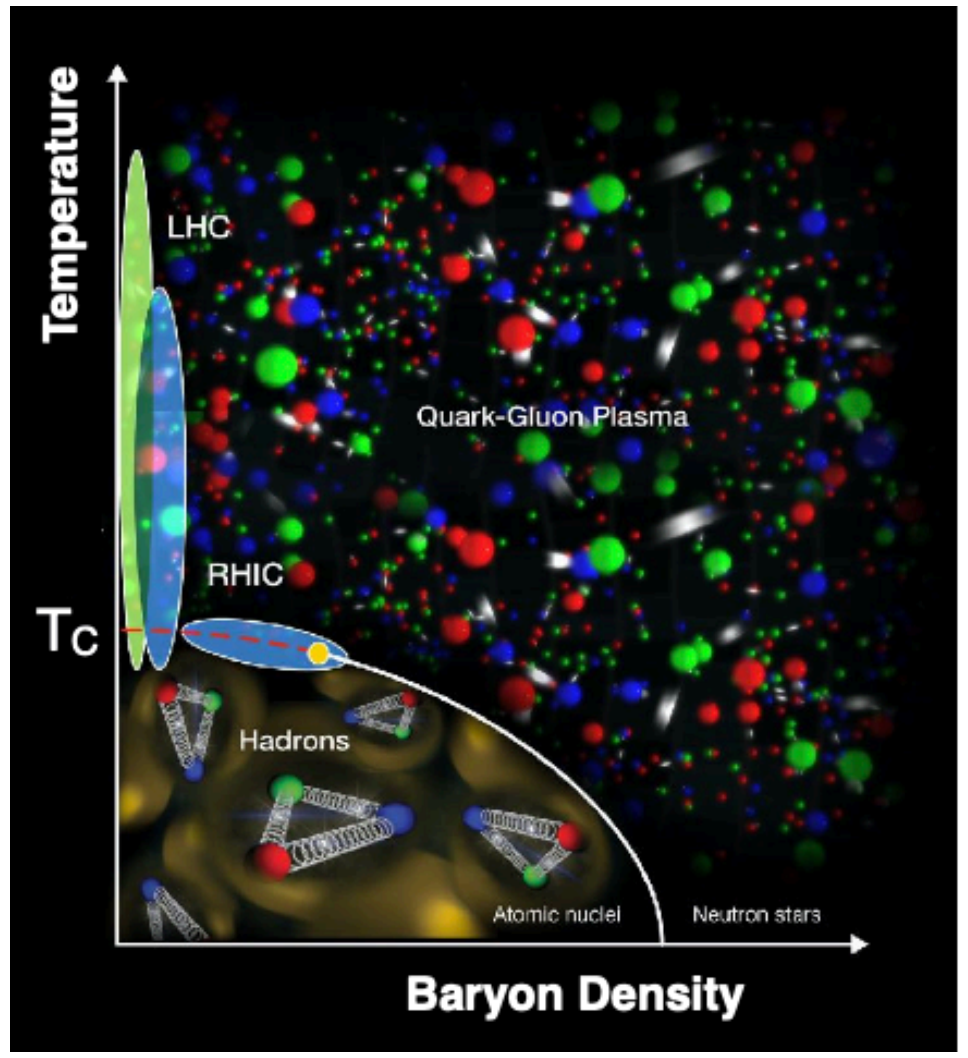
WHAT IS THE CONDITION OF OUR EARLY UNIVERSE?

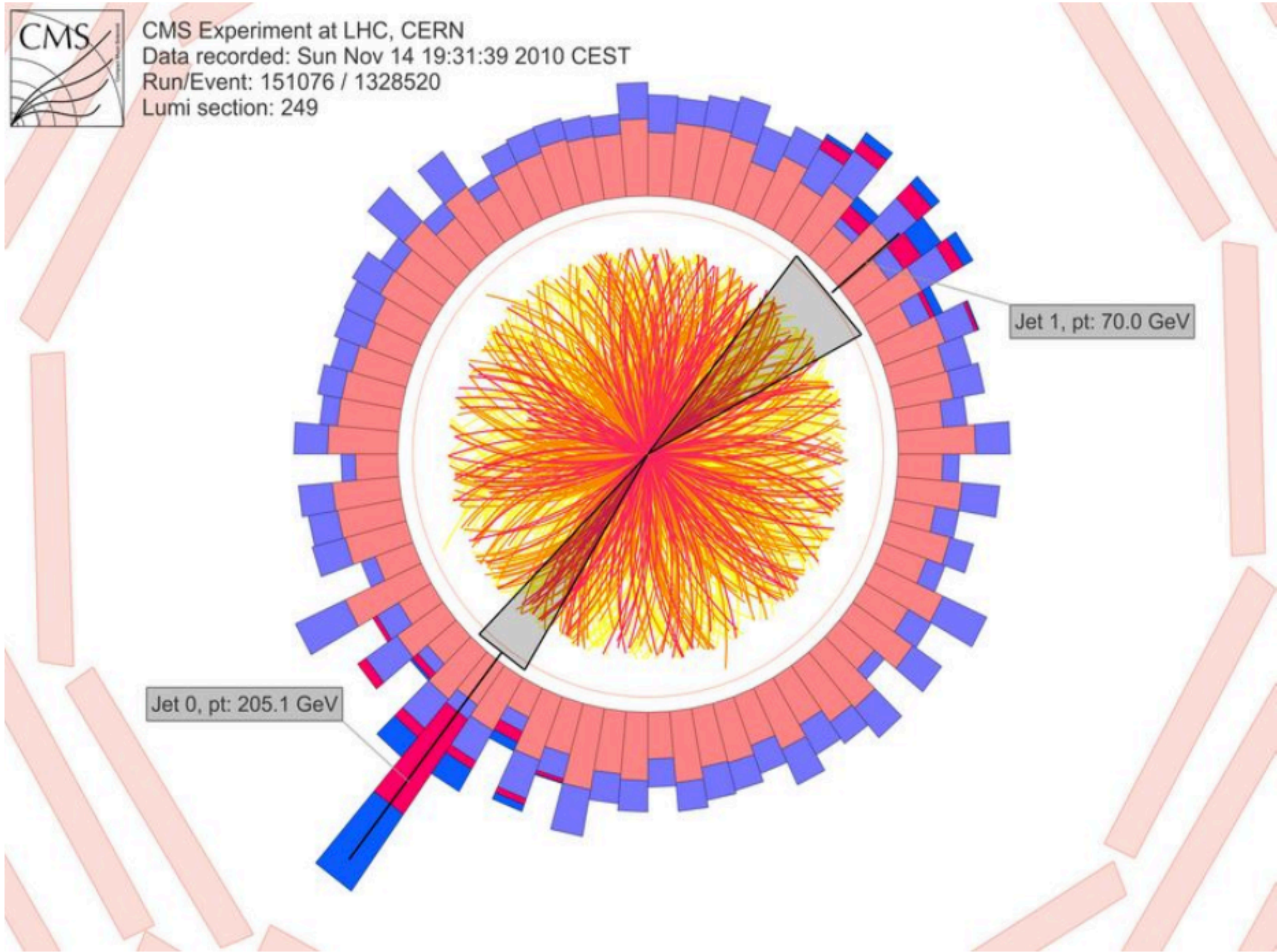
IMPROVING OUR UNDERSTANDING OF MEDIUM PROPERTIES

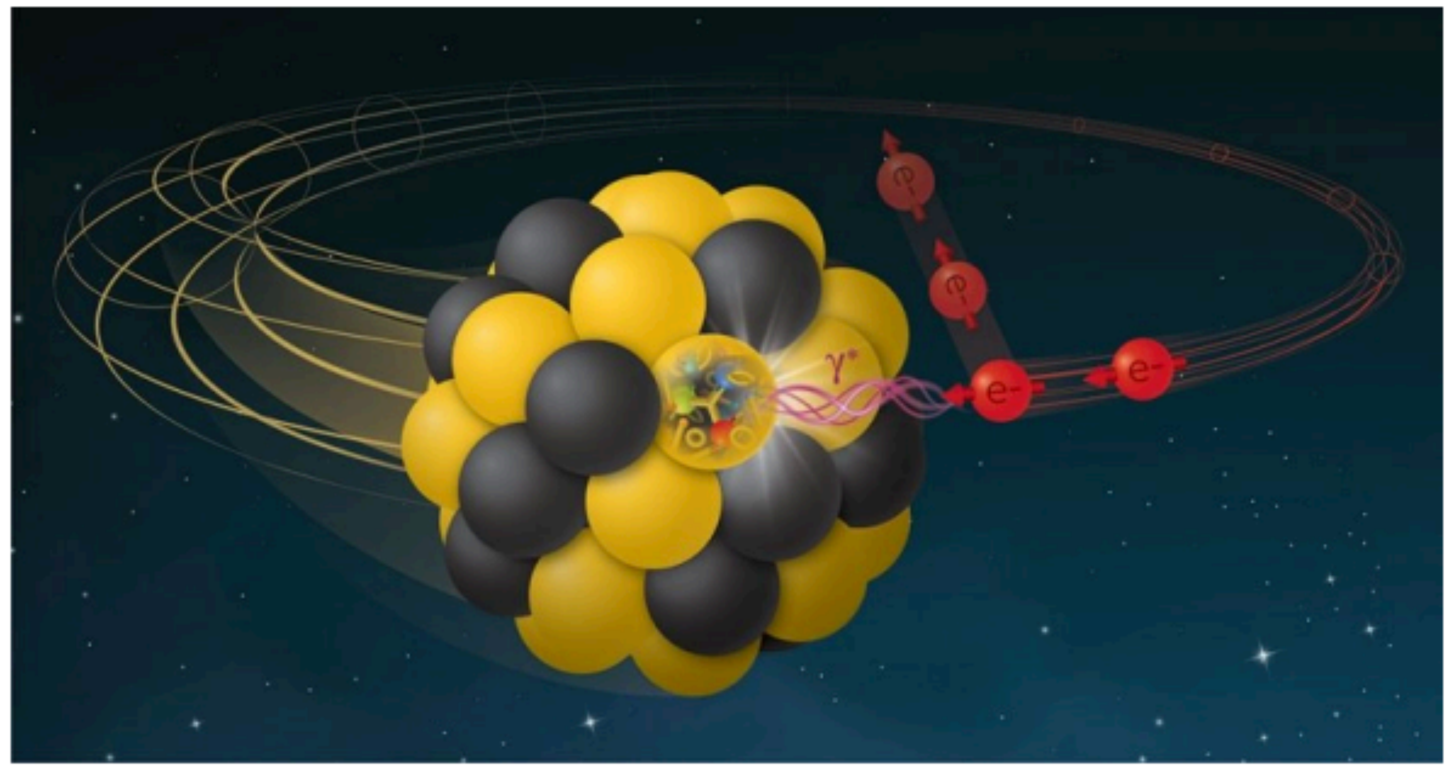


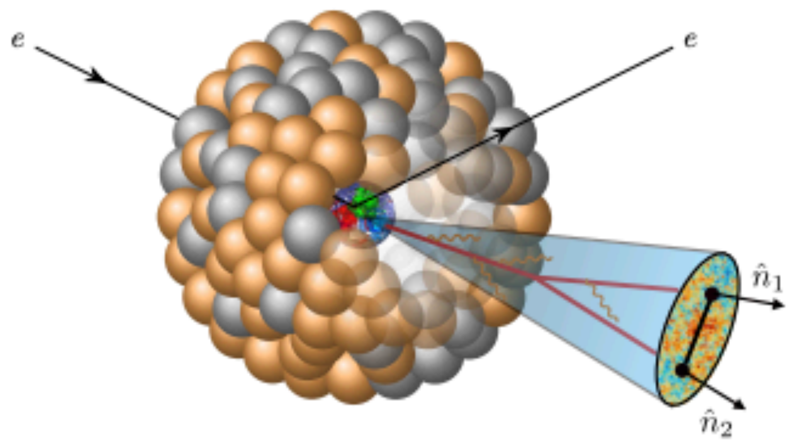
CREATING BIG BANG MATTER ON EARTH

- **Heavy Ion Collisions at the LHC recreate in laboratory conditions the plasma of quarks and gluons that is thought to have existed shortly after the Big Bang**
- **Jets are used as the hard probe to study medium properties by studying their energy loss as they propagate through the medium.**





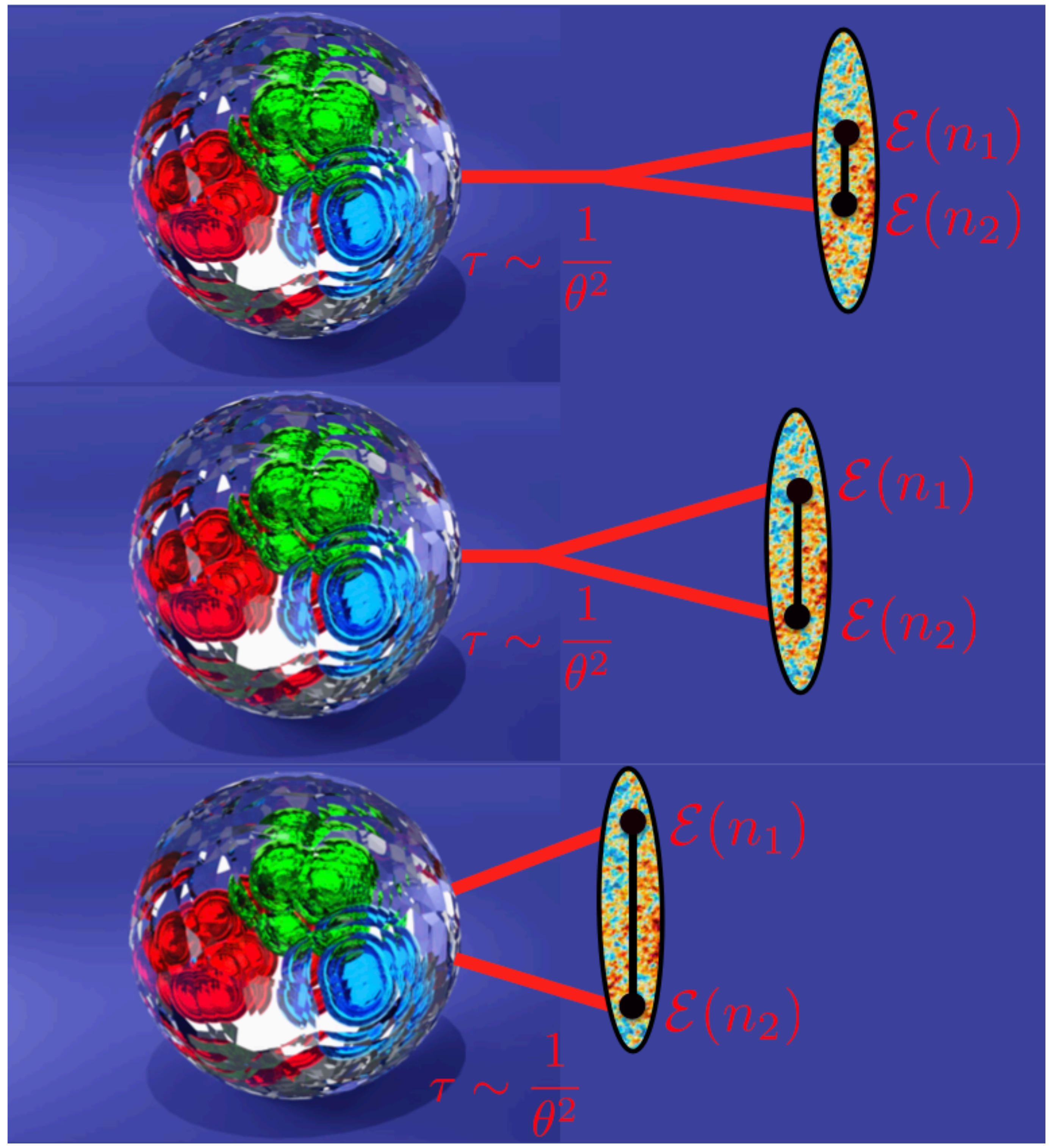


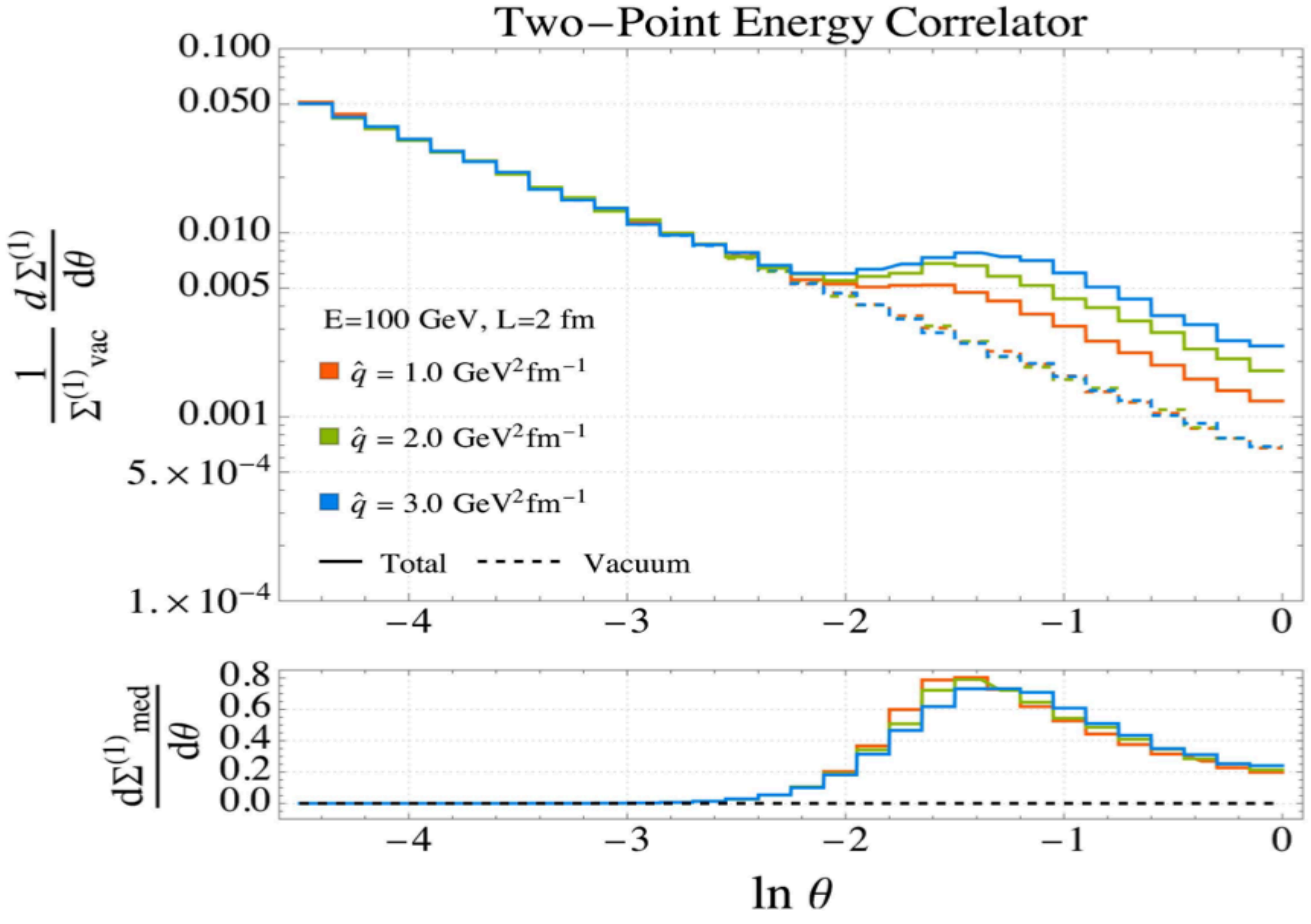


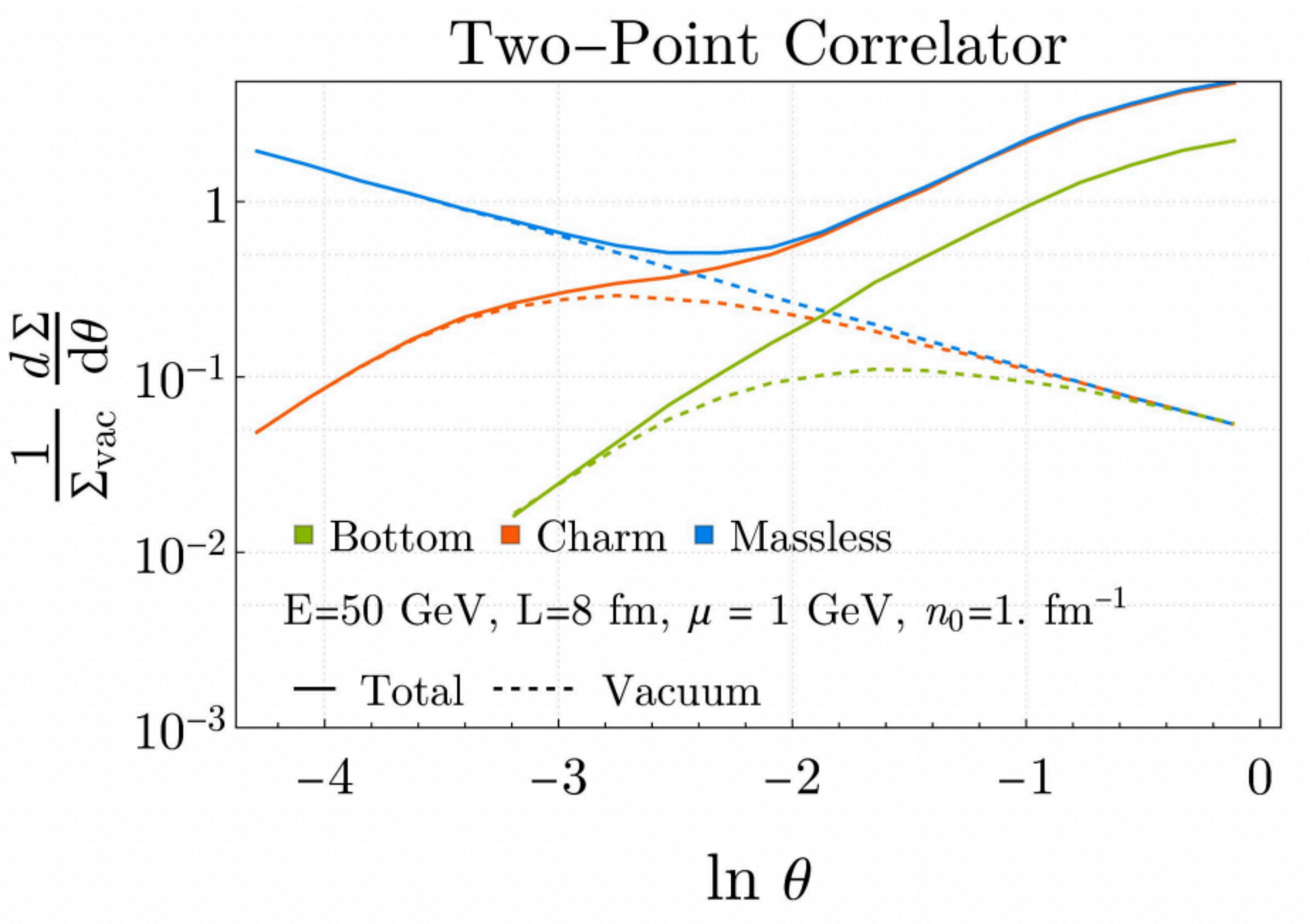
RESOLVING THE QGP USING ENERGY CORRELATORS

- **The standard energy loss corresponds to the measurement of the one-point energy correlator**
- **Two-point energy correlators clearly identify the scale at which the energy loss occurs, and gives robust prediction across different models!**

EEC gives angular scale $\mu \sim p_T \theta_{ij}$



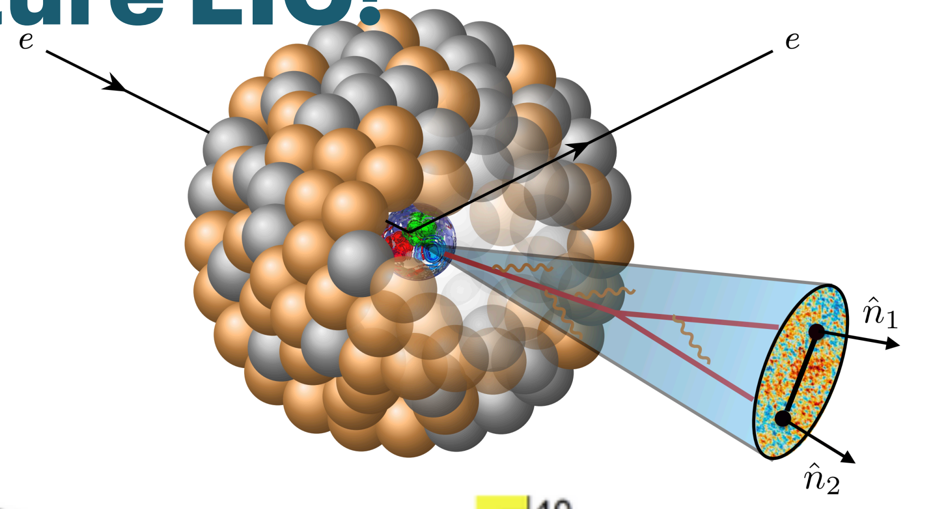


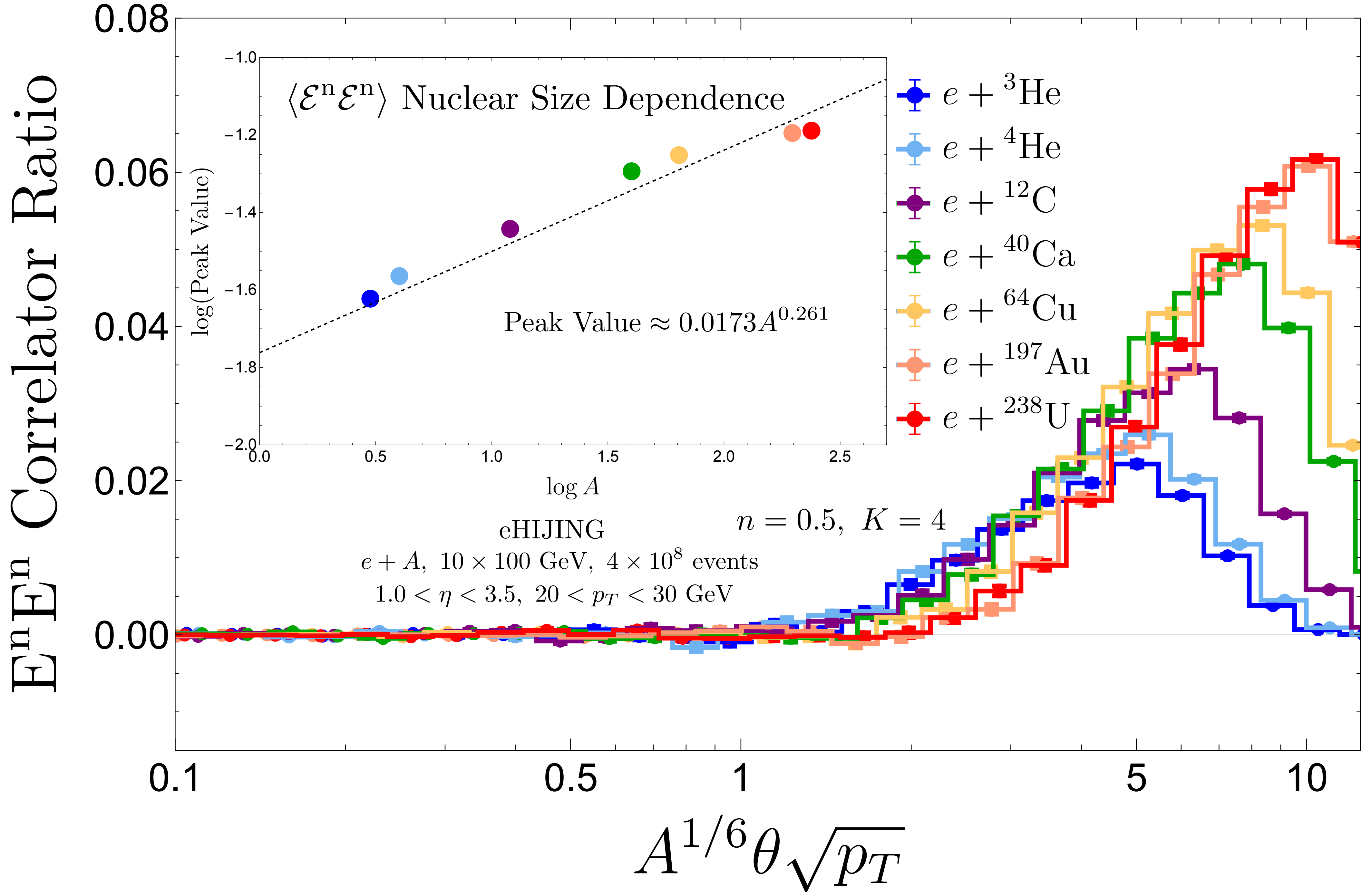


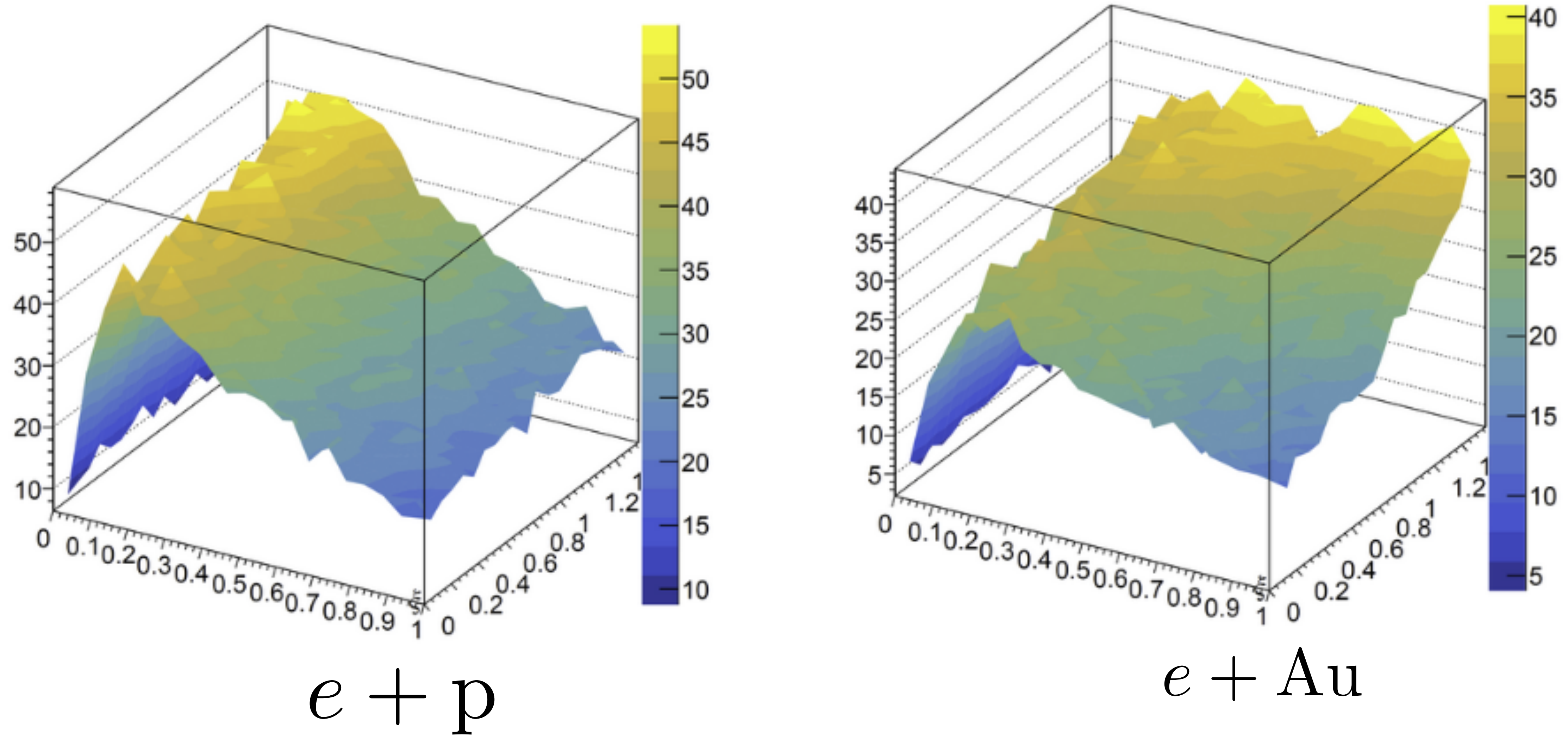
Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult `22
Andres, Dominguez, Holguin, Marquet, Moult `23
Barata, Mehtar-Tani `23

COLD NUCLEAR EFFECTS AND JET SUBSTRUCTURE

- Jet substructure enables us to study image **cold nuclear matter effects** at the future EIC!







- We must also dream big and try to probe higher point structure.
  Higher point structure provides us deeper insight into medium modification!

Devereaux, Fan, Ke, KL, Moult `23
Chen, Moult, Thaler, Zhu `22

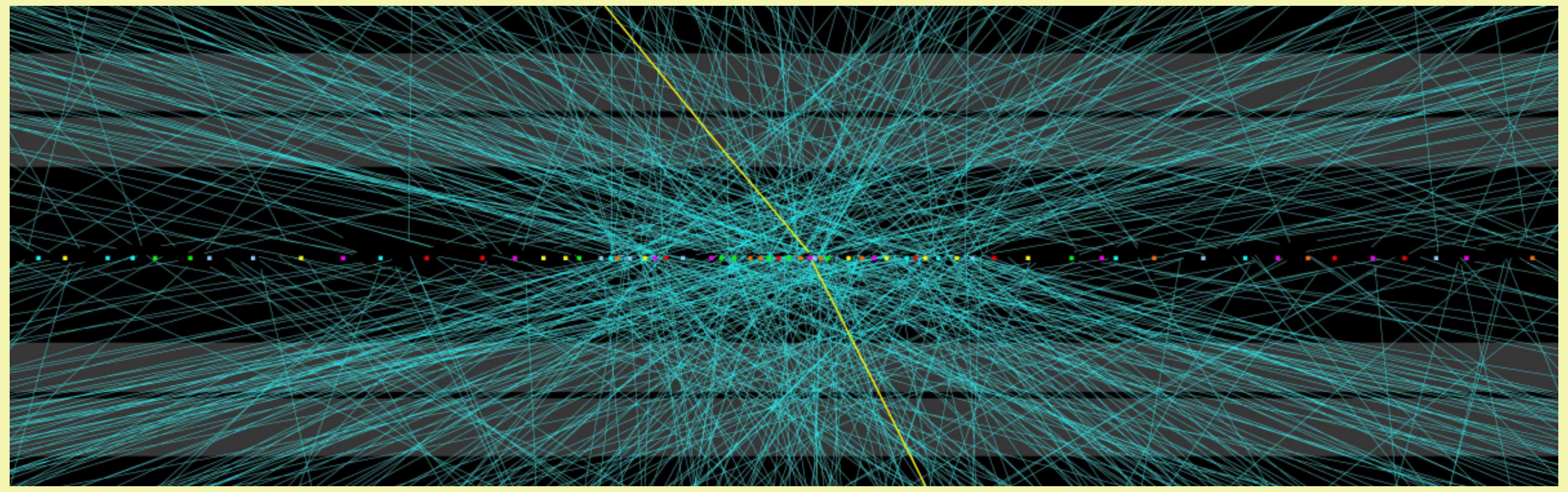
Standard-model physics (QCD and electroweak)

100 MeV - 4 TeV

GOAL

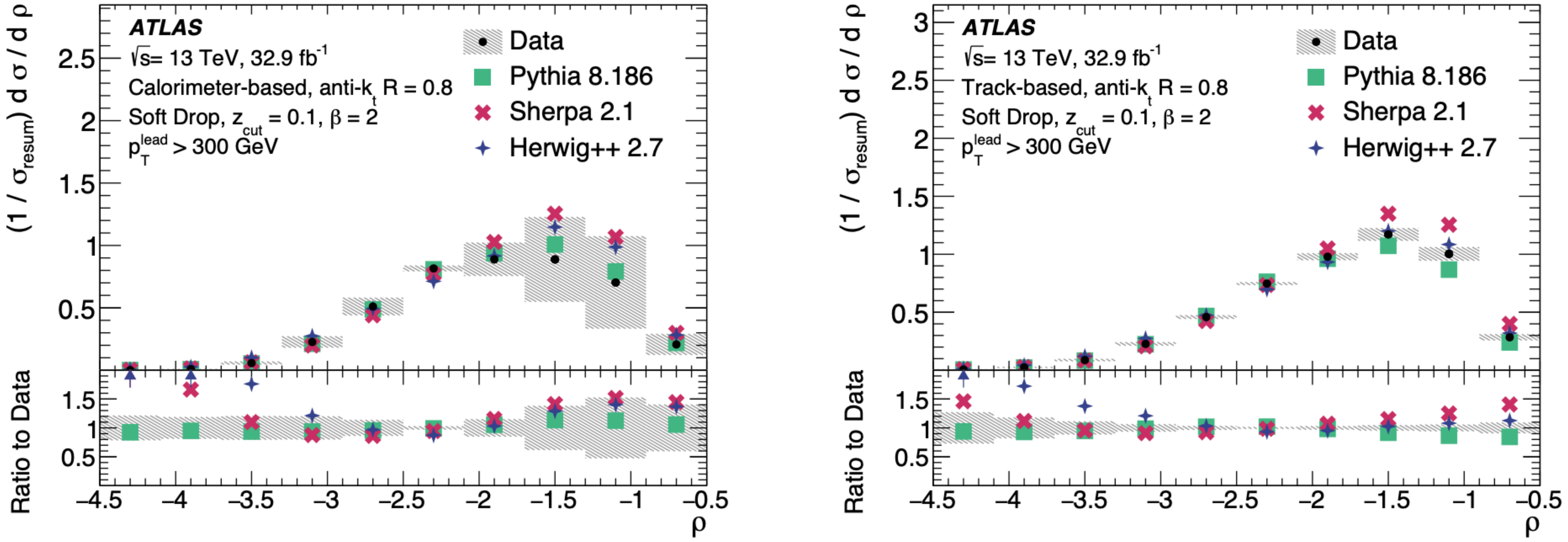
UNLOCK QCD DYNAMICS

PRECISION MEASUREMENTS



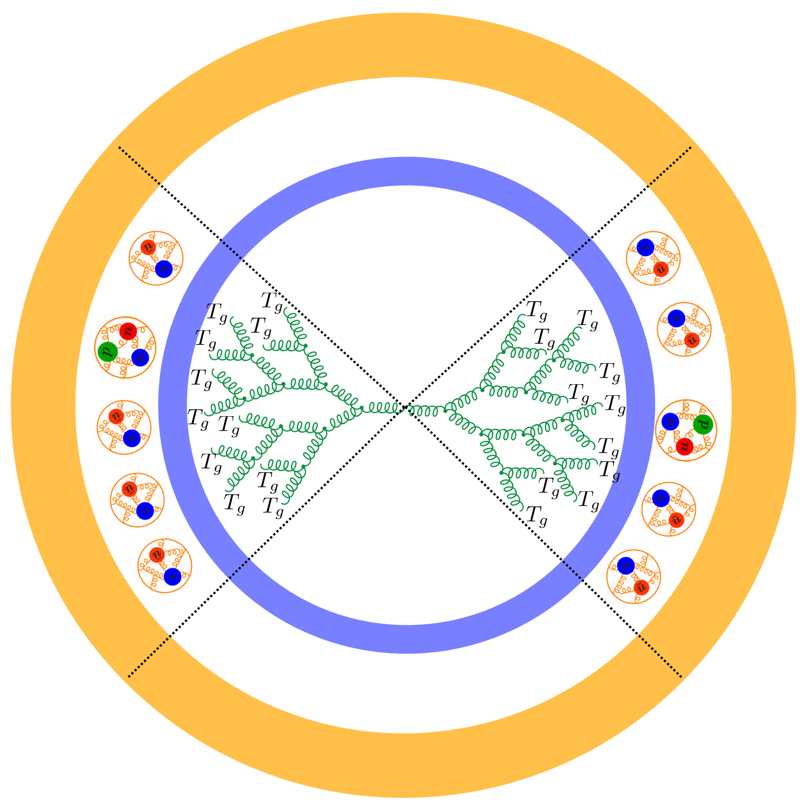
MEASURING ON TRACKS

- In order to unlock QCD dynamics and more, precision measurements are important!
- Experimentally, measurements on tracks are advantageous because much more precise measurements are possible

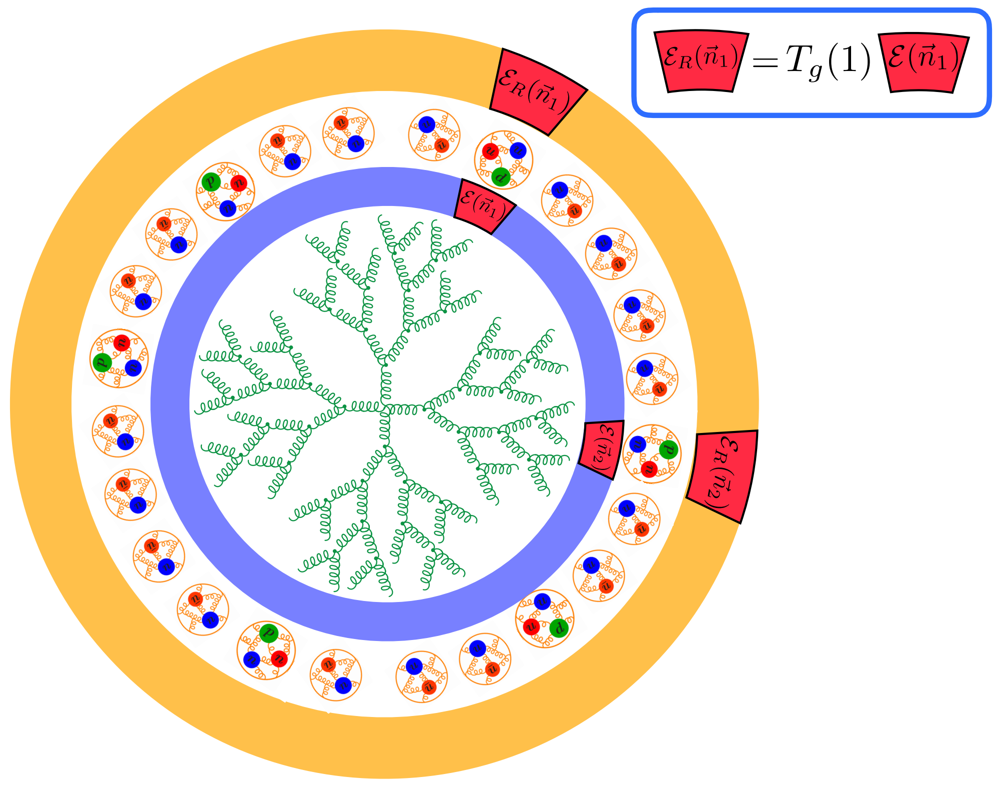


[ATLAS (2019)]

Jet shape



Energy correlators



space of the state vs space of the detectors

$\Longrightarrow$ NP functions

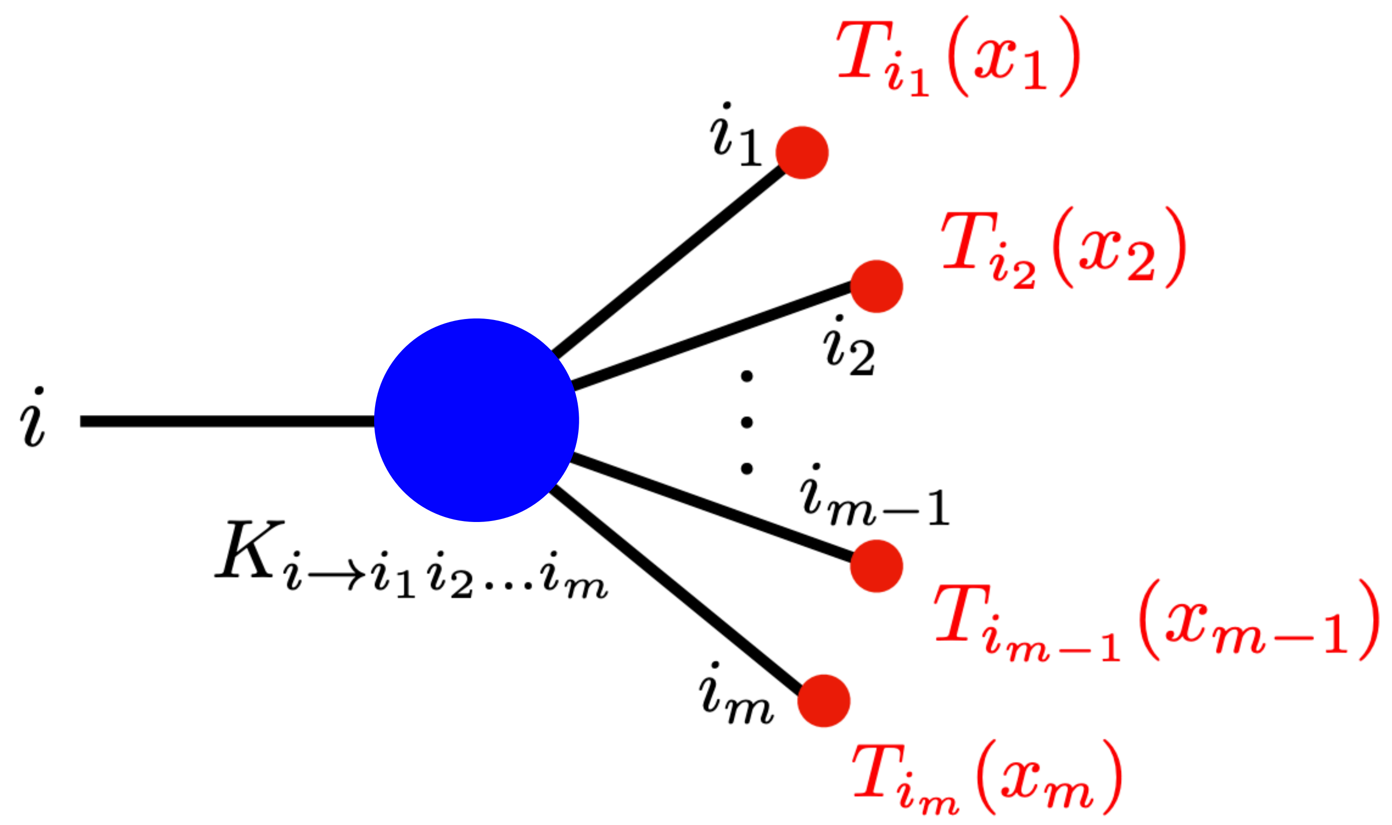
$\Longrightarrow$ *NP numbers*

- Recent advancements in energy correlators fueled much theoretical developments to carry out high precision calculation of jet substructure on tracks!

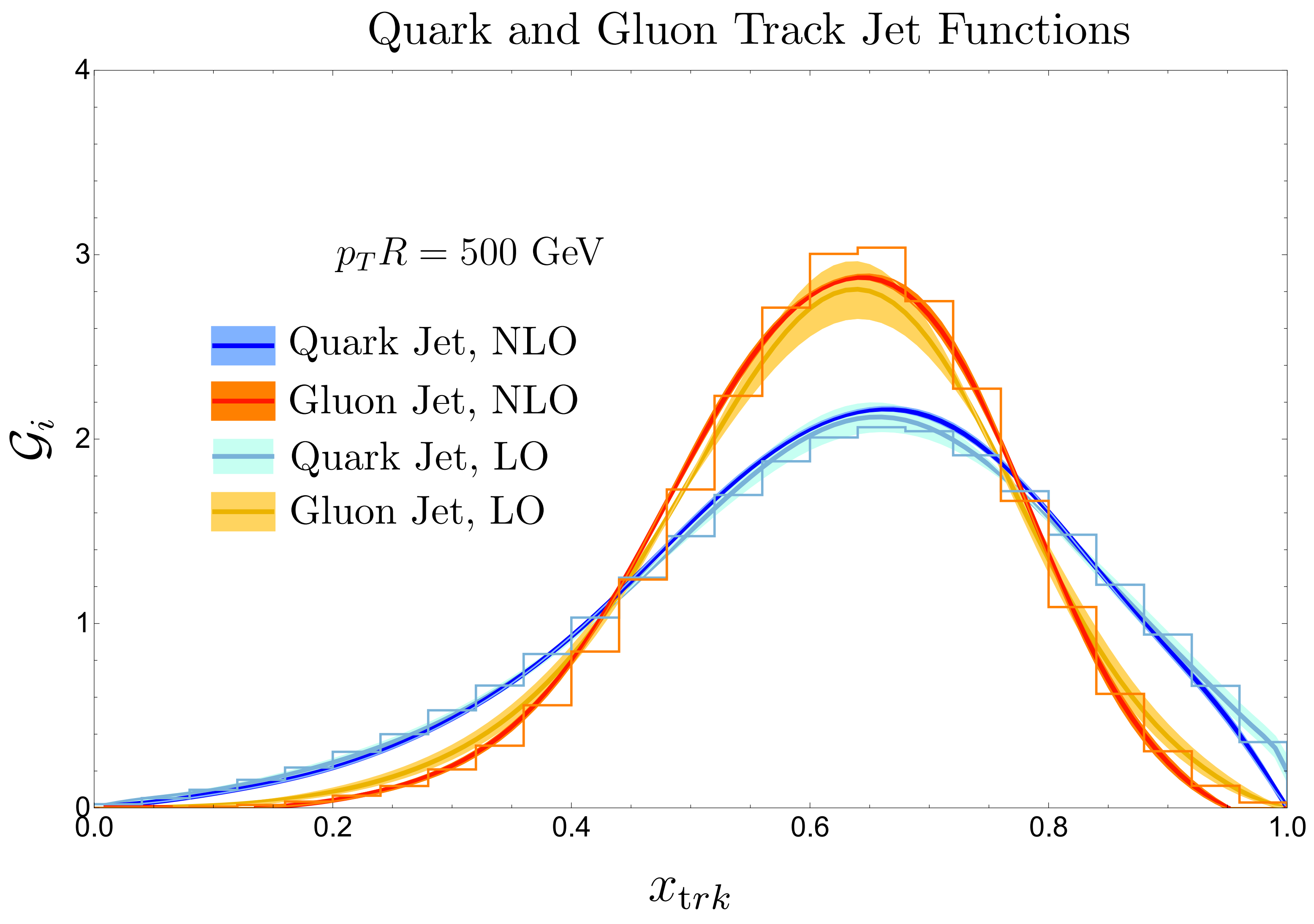
TRACK FUNCTION FORMALISM

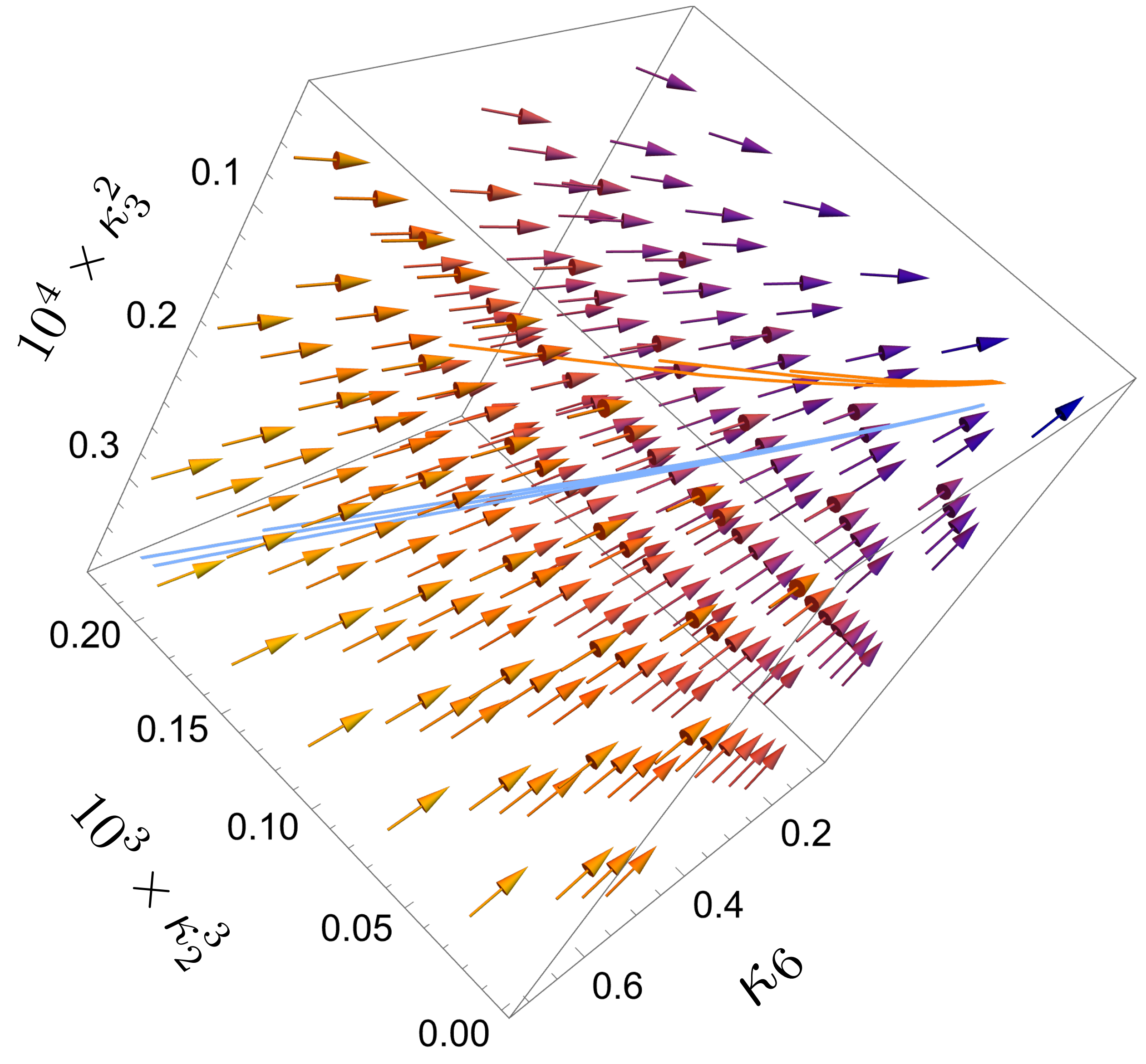
- **First formalism to study observables on tracks developed over a decade ago, and developments have rapidly advanced in recent years.**

Chang, Procura, Thaler, Waalewijn `13
Li, Moult, Waalewijn, Zhu et al `21, 22
KL, Moult, Ringer, Waalewijn `23
KL, Moult `23



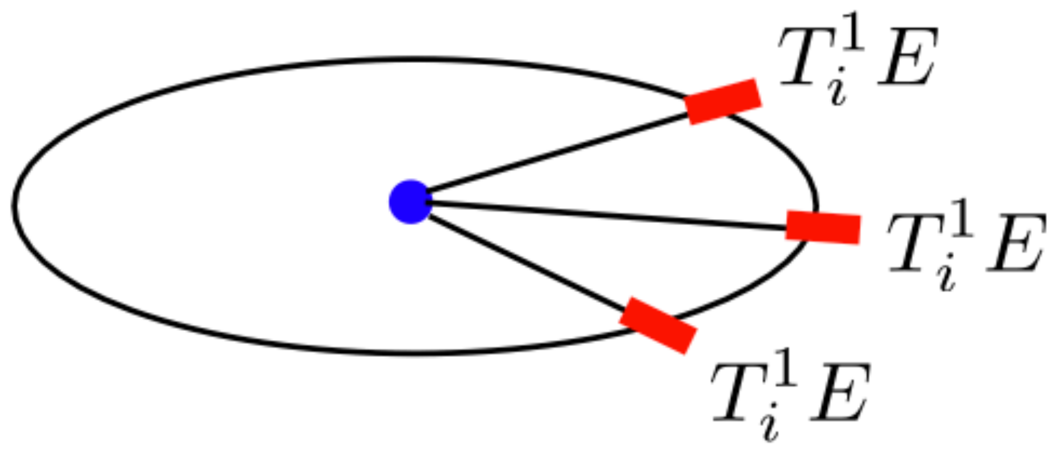
$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2} T_a(x) = \sum_N \sum_{\{a_f\}} \left[\prod_{i=1}^N \int_0^1 \mathrm{d}z_i\right] \delta\left(1 - \sum_{i=1}^N z_i\right) K_{a\to\{a_f\}}(\{z_f\}) \times \left[\prod_{i=1}^N \int_0^1 \mathrm{d}x_i T_{a_i}(x_i)\right] \delta\left(x - \sum_{i=1}^N z_i x_i\right),$$





ENERGY CORRELATORS ON TRACK

- **From this "detector" as a fundamental operator perspective, track function formalism provides the essential matching between partonic and hadronic detectors.**



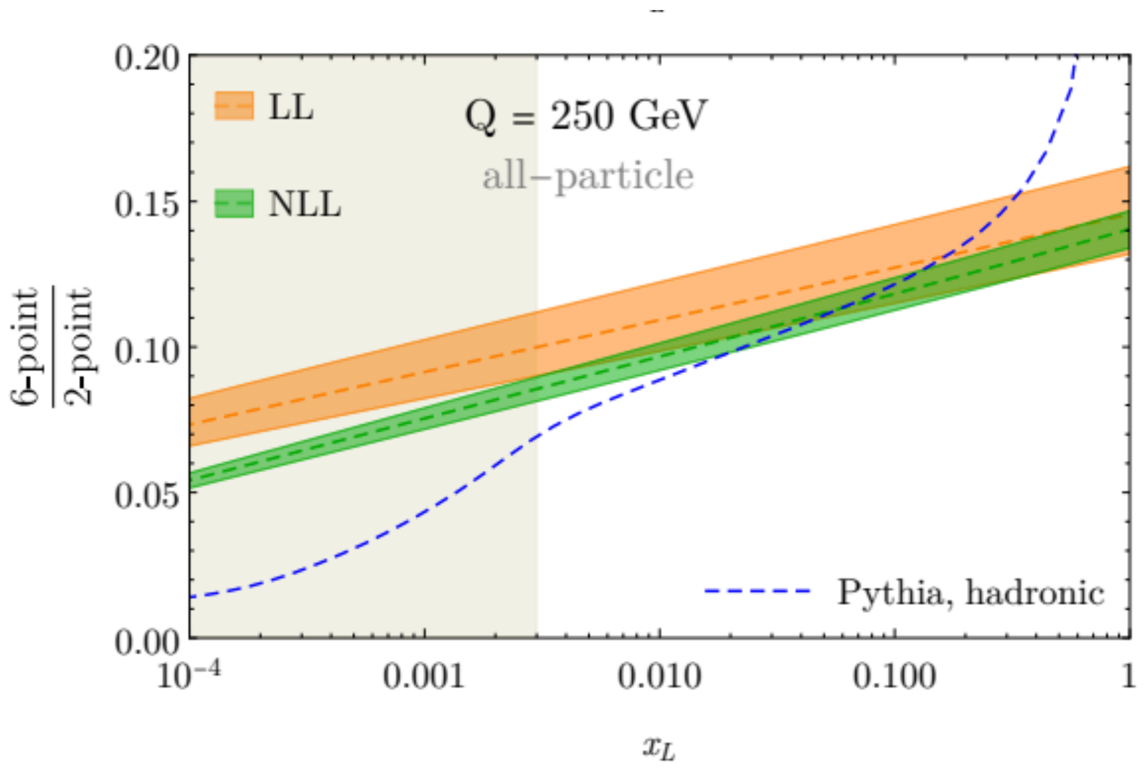
parton track

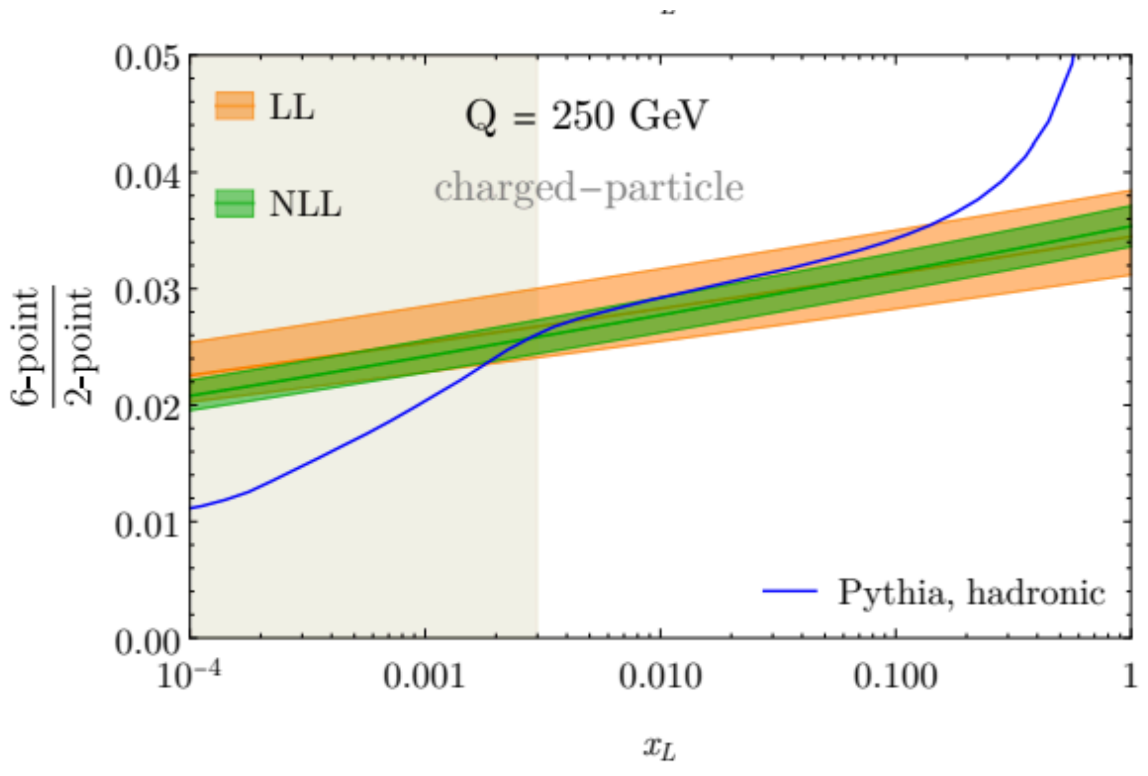
$$E_i^n \to \int dx_i T_i(x_i)\, x_i^n E_i^n = T_i(n) E_i^n$$

$$\langle \mathcal{E}_R(\vec{n}_1)\,\mathcal{E}_R(\vec{n}_2)\cdots\mathcal{E}_R(\vec{n}_k)\rangle = \sum_{i_1,i_2,\cdots i_k} T_{i_1}(1)\cdots T_{i_k}(1)\,\langle \mathcal{E}_{i_1}(\vec{n}_1)\,\mathcal{E}_{i_2}(\vec{n}_2)\cdots\mathcal{E}_{i_k}(\vec{n}_k)\rangle$$

+ contact terms. Requires up to k-th moment

- **Aside from the fact that this is technically much simpler, it only involves NP *numbers*, not functions.**





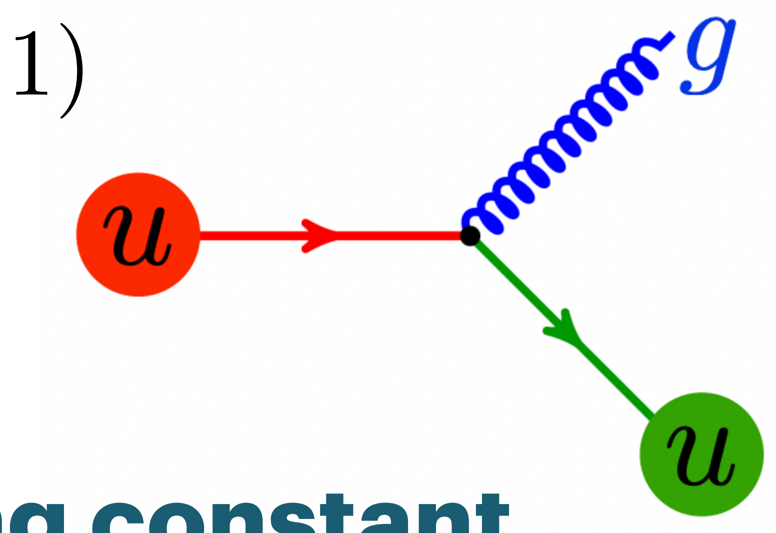
Up to 6 point EEC computed on tracks at NLL!

Jaarsma, Li, Moult, Waalewijn, Zhu `23

$$\langle \mathcal{E}(n_1)\,\mathcal{E}(n_2)\cdots\mathcal{E}(n_k)\rangle \to \langle \mathcal{E}_R(n_1)\,\mathcal{E}_R(n_2)\cdots\mathcal{E}_R(n_k)\rangle$$

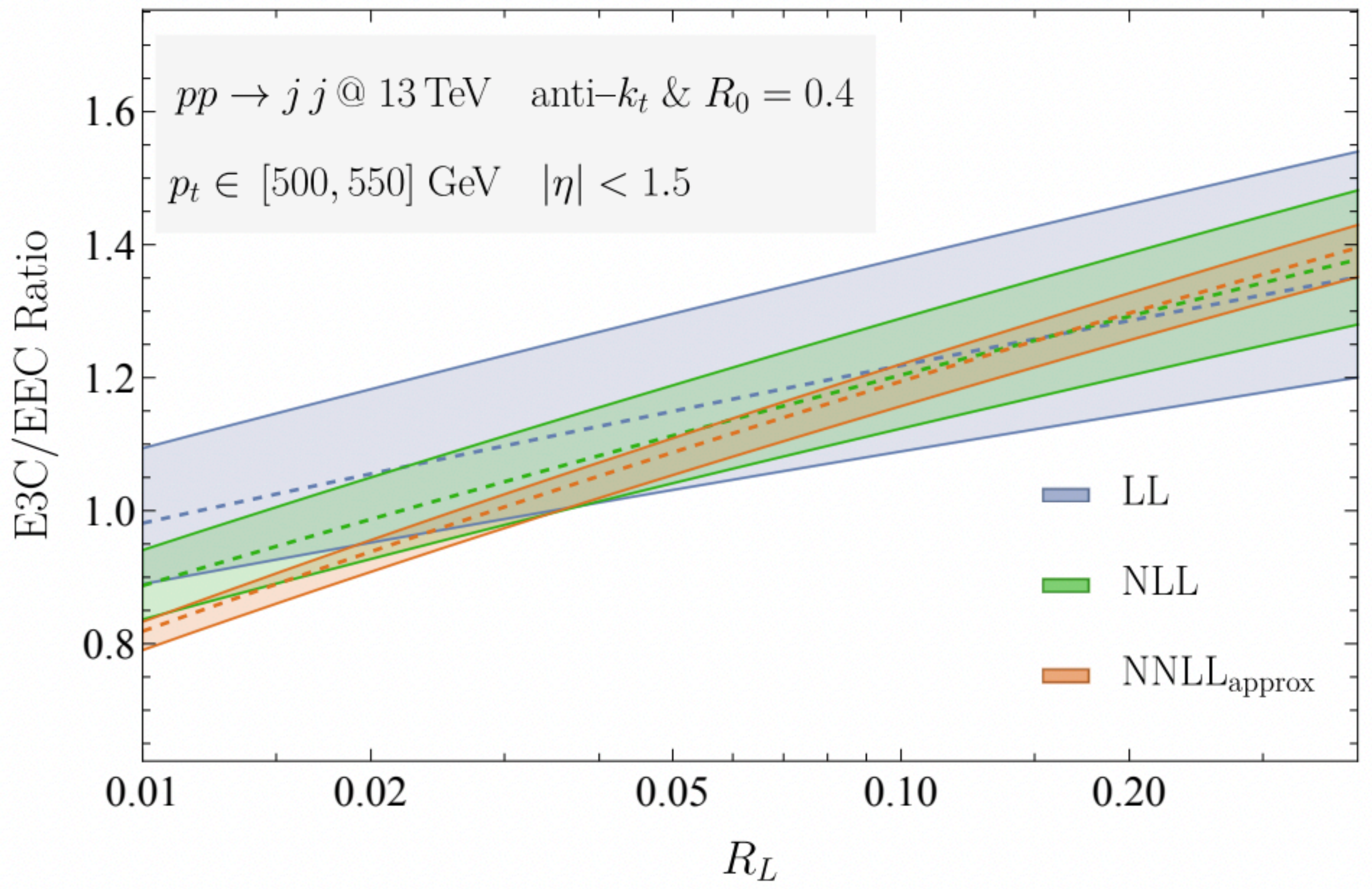
STRONG COUPLING DETERMINATION

- **How strong is the Strong Force?** In comparison, EM coupling: $\alpha_e = 0.0072973525693(11)$

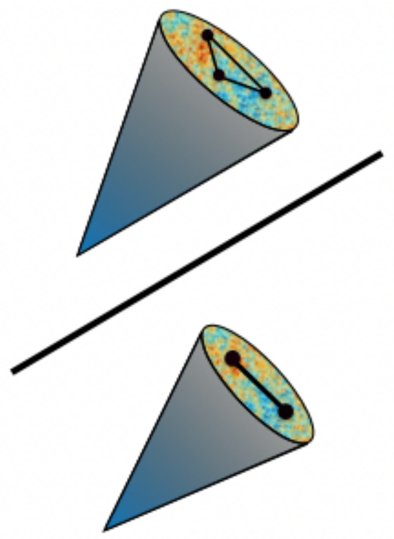


Quarks are never free and thus it is very hard to measure their coupling!

- **Ratio of projected energy correlators is directly sensitive to the strong coupling constant.**



Chen, Gao, Li, Xu, Zhang, Zhu`23

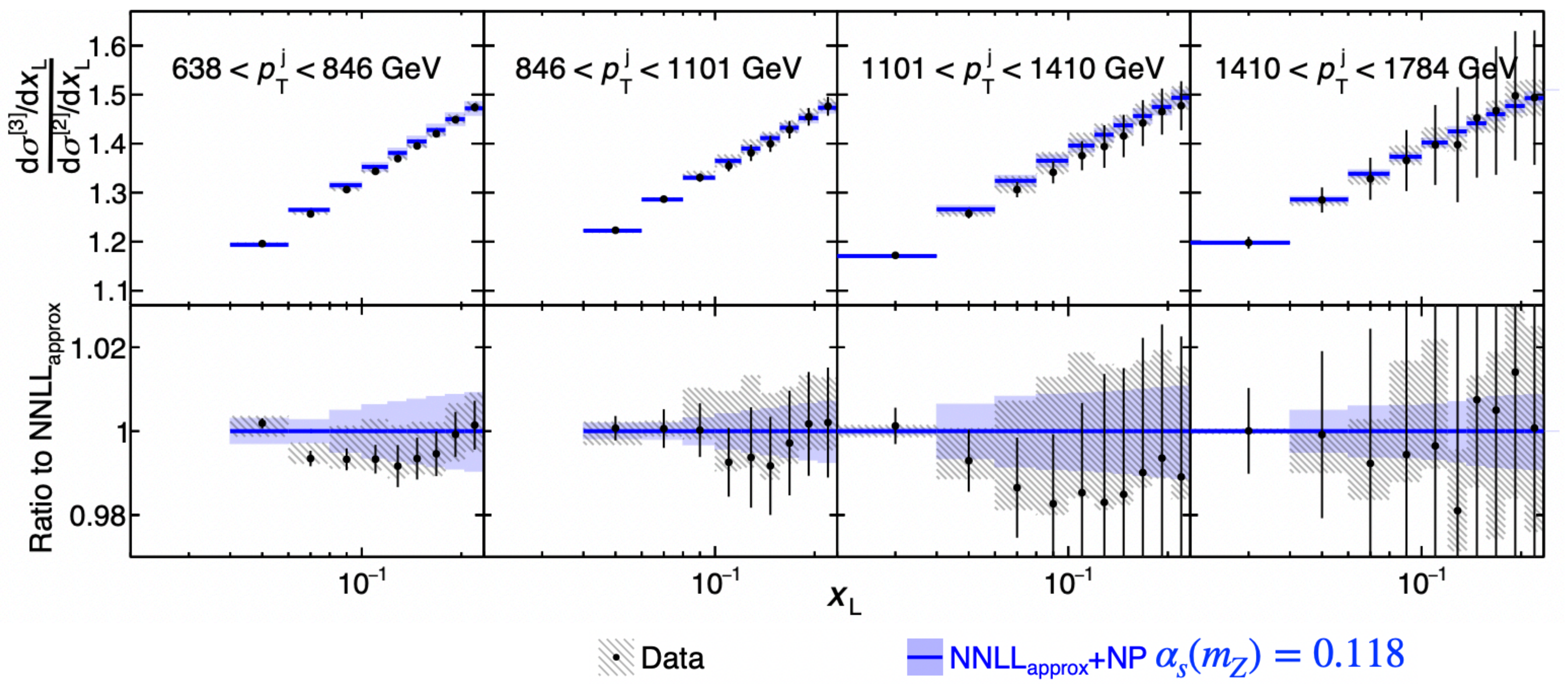


$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[J]} \rangle}{\langle \mathbb{O}^{[3]} \rangle}$$

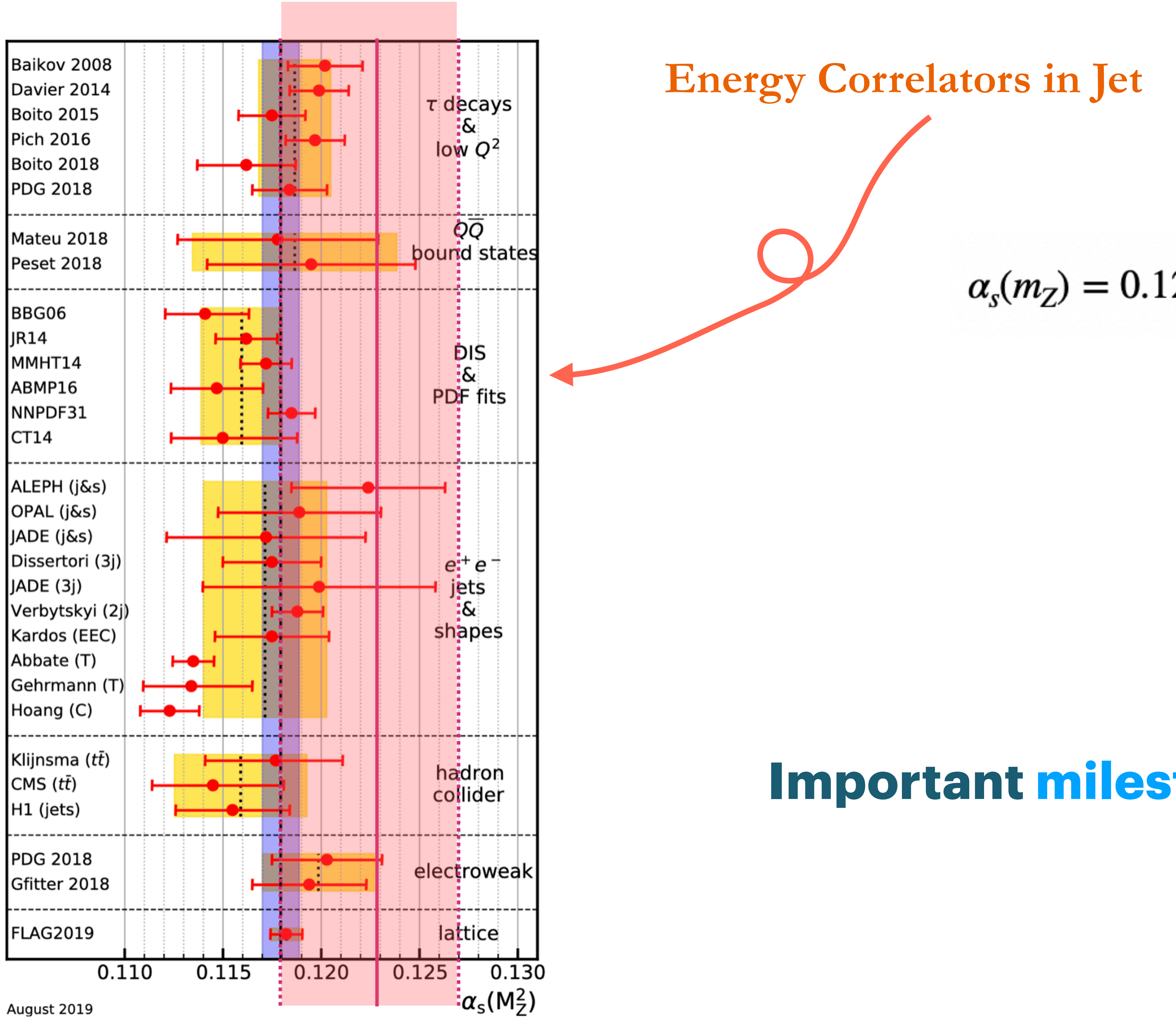
$$\frac{d}{d\ln\mu^2} \vec{\mathbb{O}}^{[J]}(\hat{n}_1) = \hat{\gamma}(J) \vec{\mathbb{O}}^{[J]}(\hat{n}_1)$$

$$\hat{\gamma}(J) \propto \alpha_s$$

CMS Collaboration `23



STRONG COUPLING DETERMINATION



CMS Collaboration `23

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} = 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

major source

Covariance matrix

QCD scale of NNLL$_{\text{approx}}$

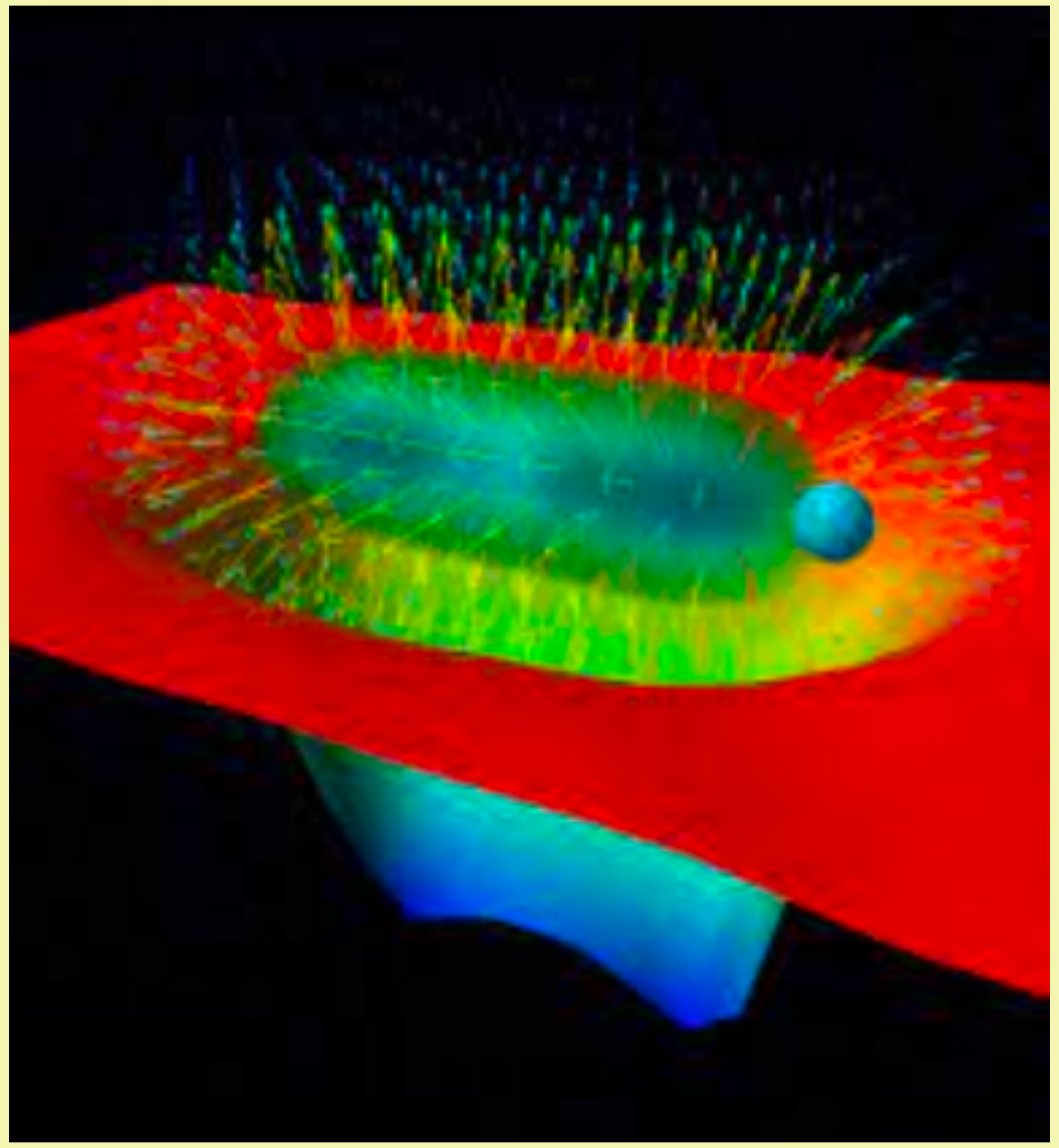
Neutral hadron energy scale

Uncertainty ~ 4%, most precise from jet-substructure measurement to date

Important milestone for jet substructure precision study!

- **CMS collaboration carried out most precise determination of the strong coupling constant for jet substructure!**

UNDERSTAND HADRONIZATION



QUARK GLUON SCALING AND HADRONIZATION

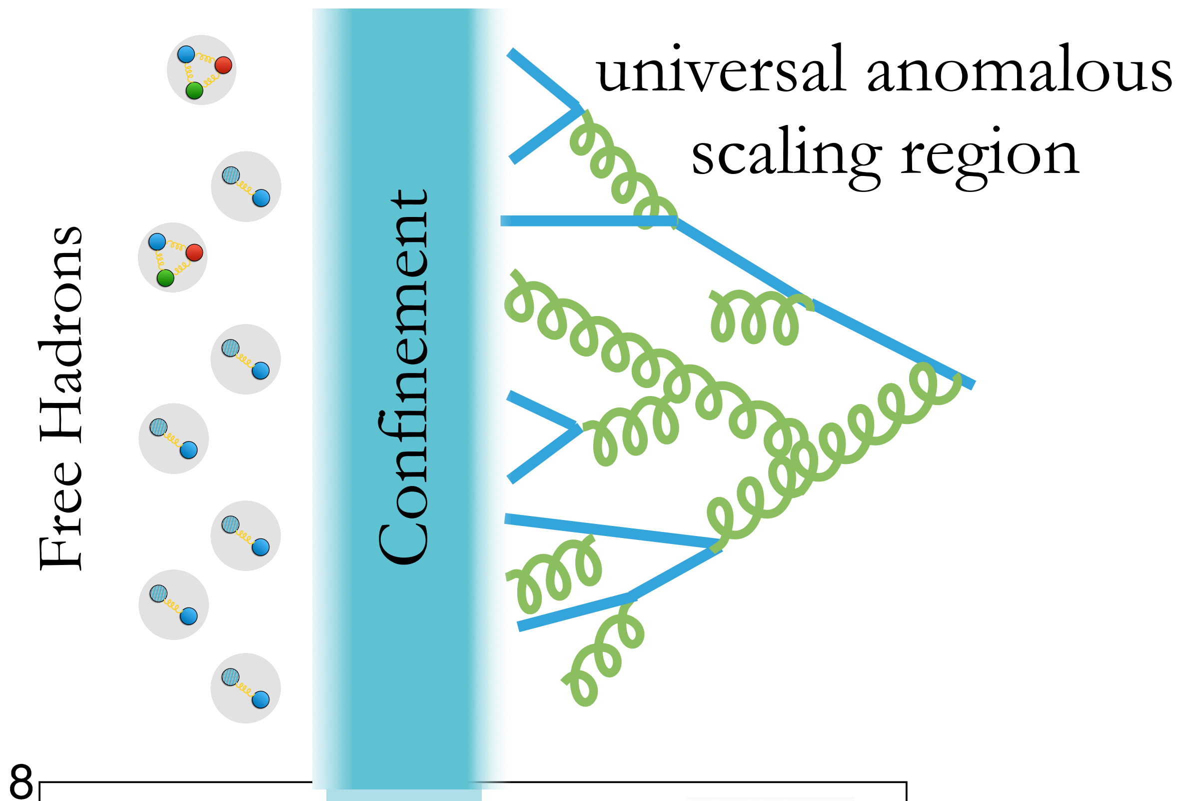
- **Energy correlators allow the hadronization process to be directly imaged inside high energy jets: transition from interacting quarks and gluons and free hadrons is clearly visible!**

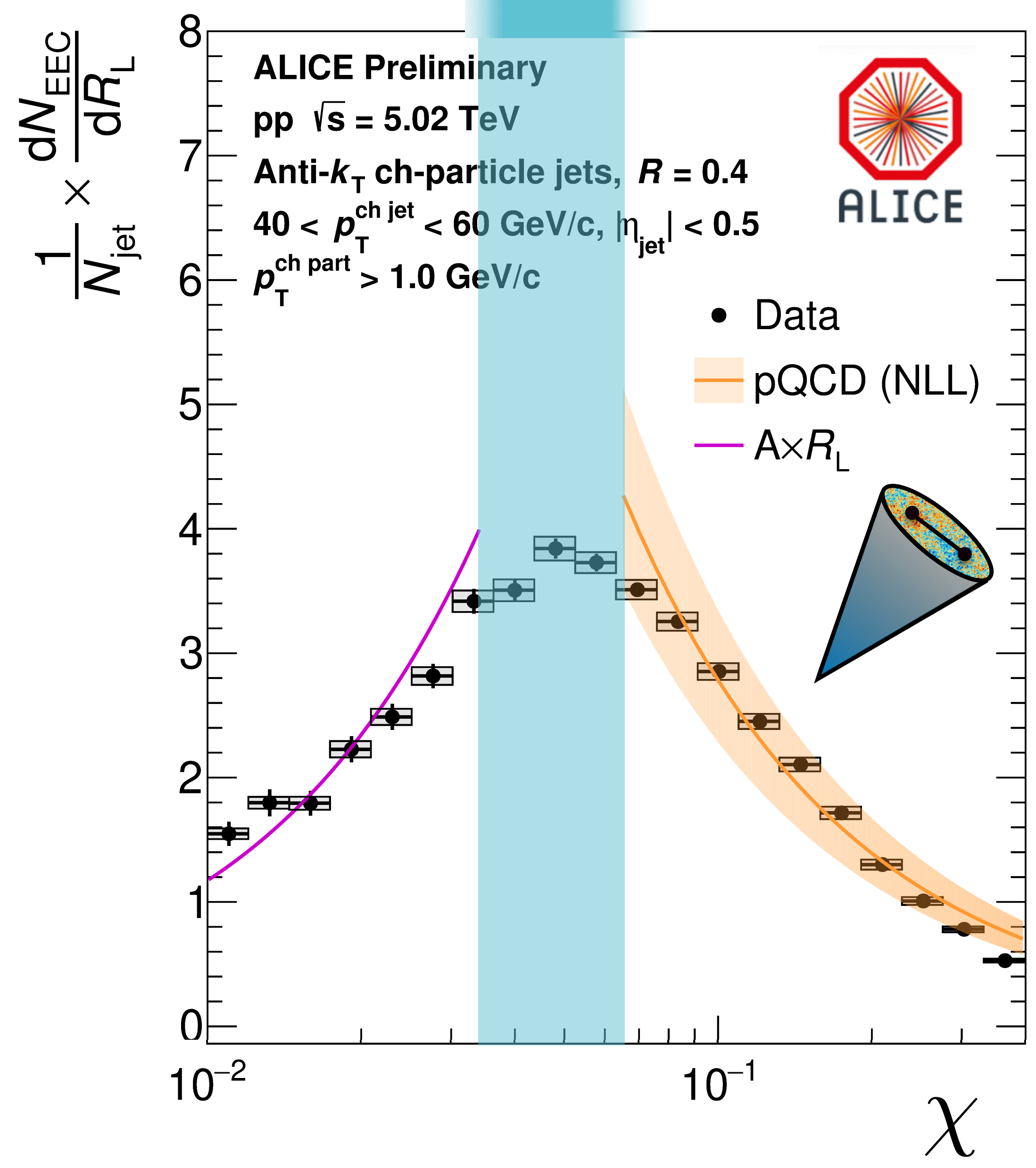
Free hadrons

$$\frac{d\sigma}{d\theta^2} = \text{const}$$

$$\frac{d\sigma}{d\theta} = \text{const} \times 2\theta$$

EEC gives angular scale $\mu \sim p_T \theta_{ij}$





Interacting quarks and gluons

$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

Hofman, Maldacena, `08

KL, Meçaj, Moult `22
Komiske, Moult, Thaler, Zhu `22

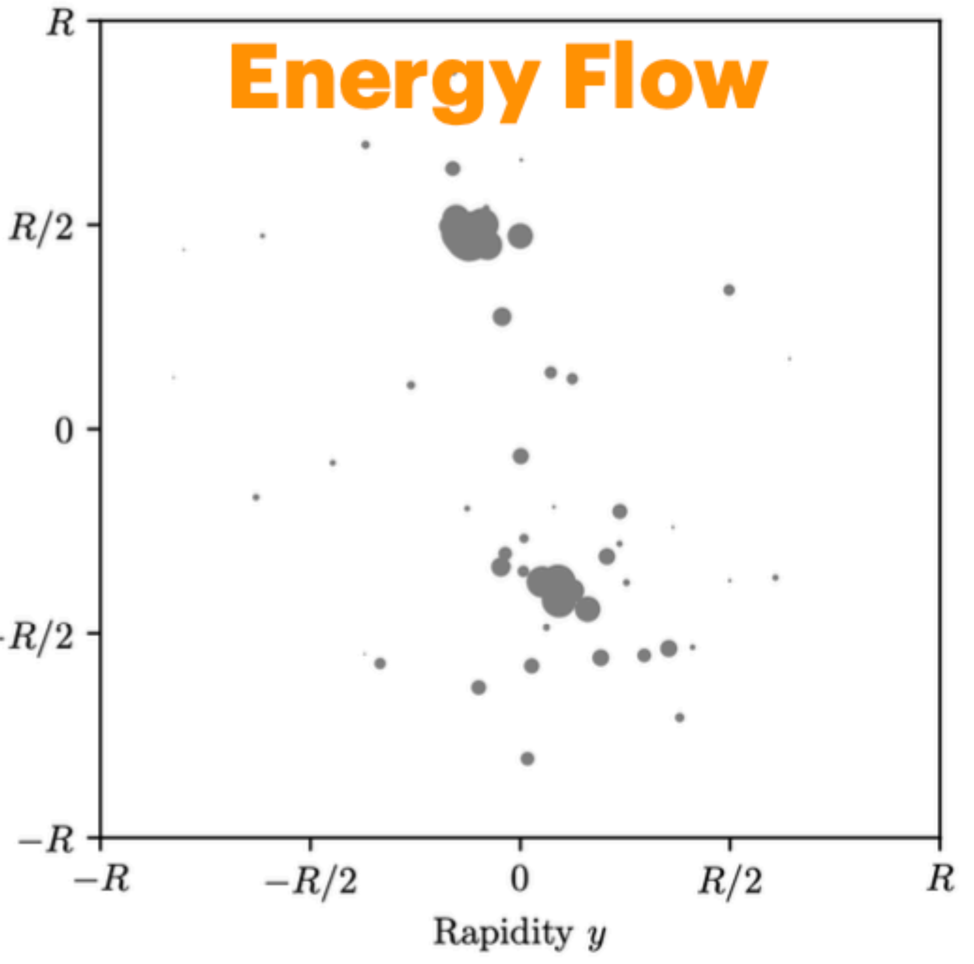
WHAT IS A DETECTOR?

- **Collider detector can give us more than just an energy flow. What constitutes a field-theoretically well-defined detector?**

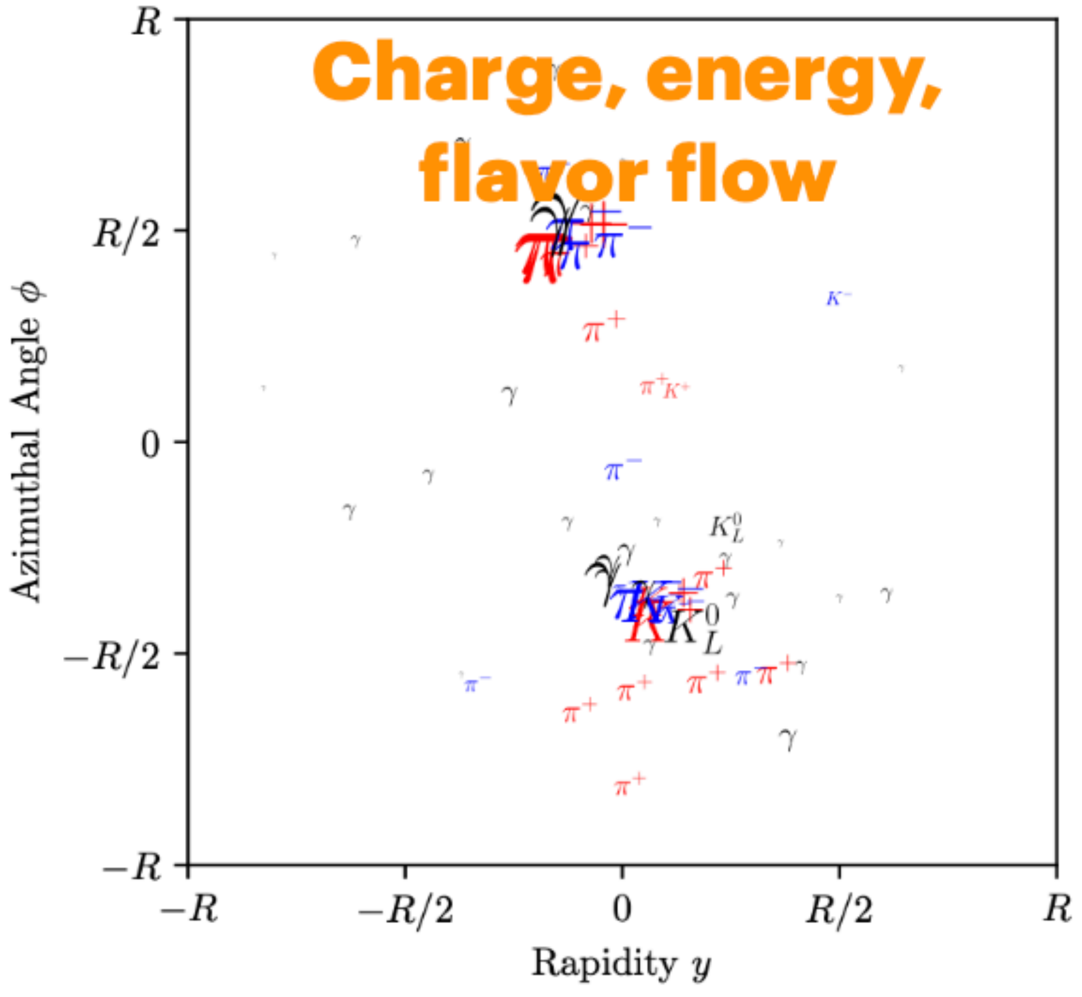
  Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin`22

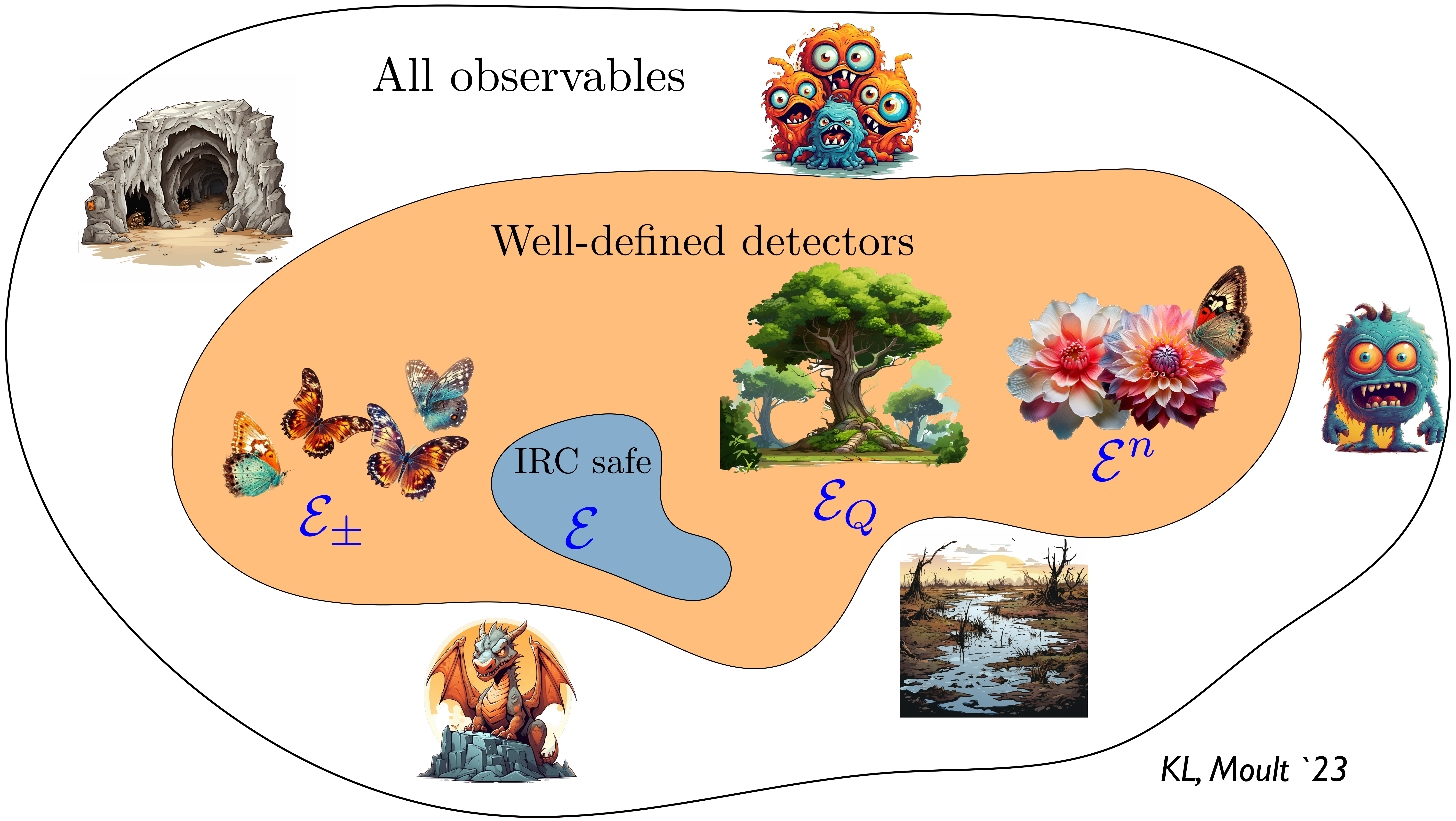
- **Well-defined detectors provide sharp link with underlying field theory through observables!**

The energy flow is unpixelized and ignores charge/flavor information



Full event is a set of particles having momentum and charge/flavor





KL, Moult `23

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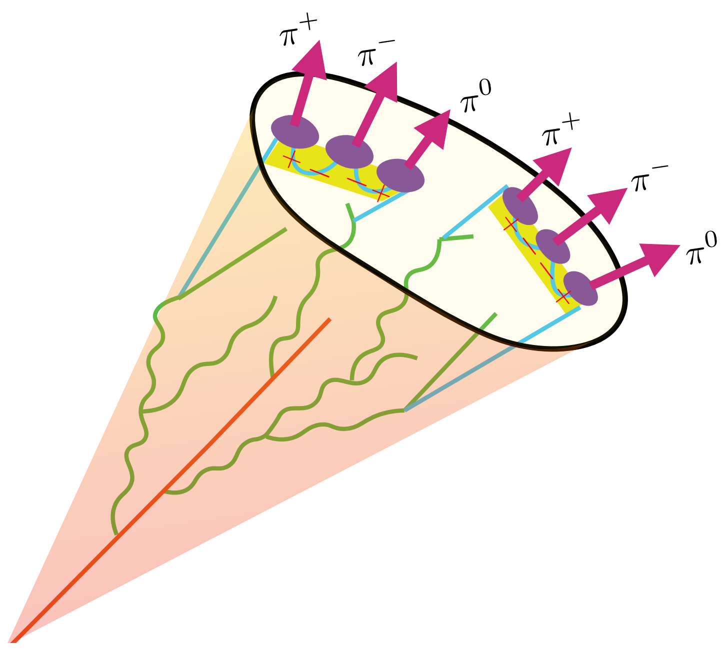
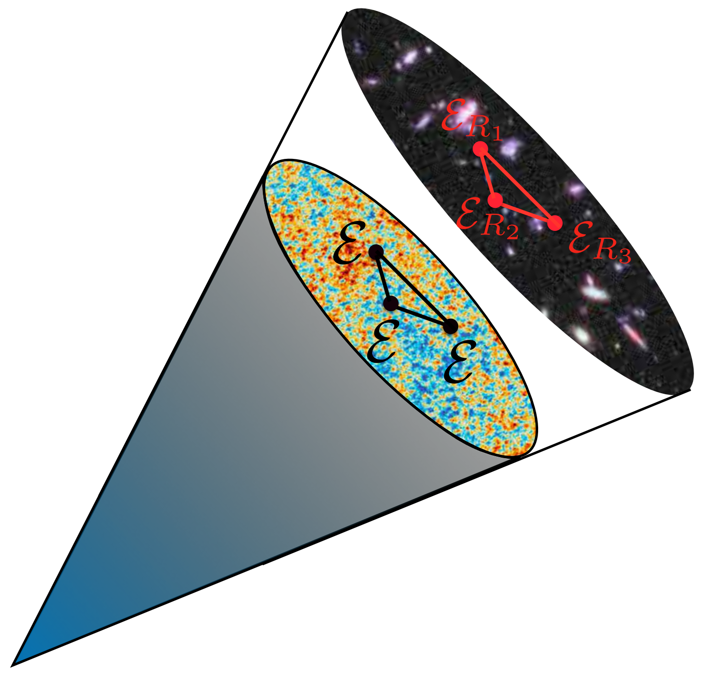
Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin`22

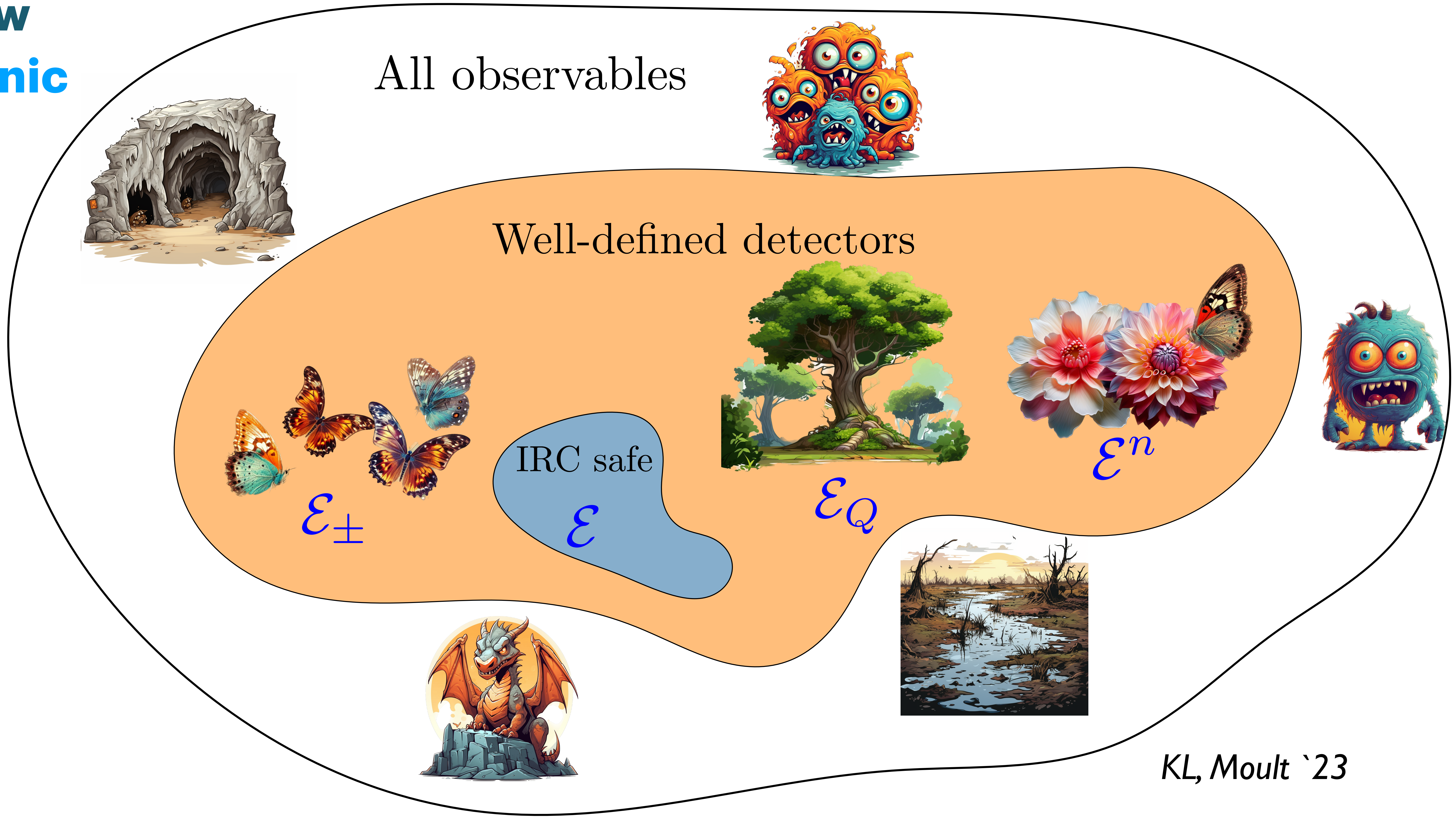
- **Well-defined detectors provide sharp link with underlying field theory through observables!**

- **Interesting measurements of energy flow can be made on a restricted set of hadronic states, R, for example, charged hadrons (tracks).**

$$\mathcal{E}_R = \sum_{i\in R} \mathcal{E}_i$$



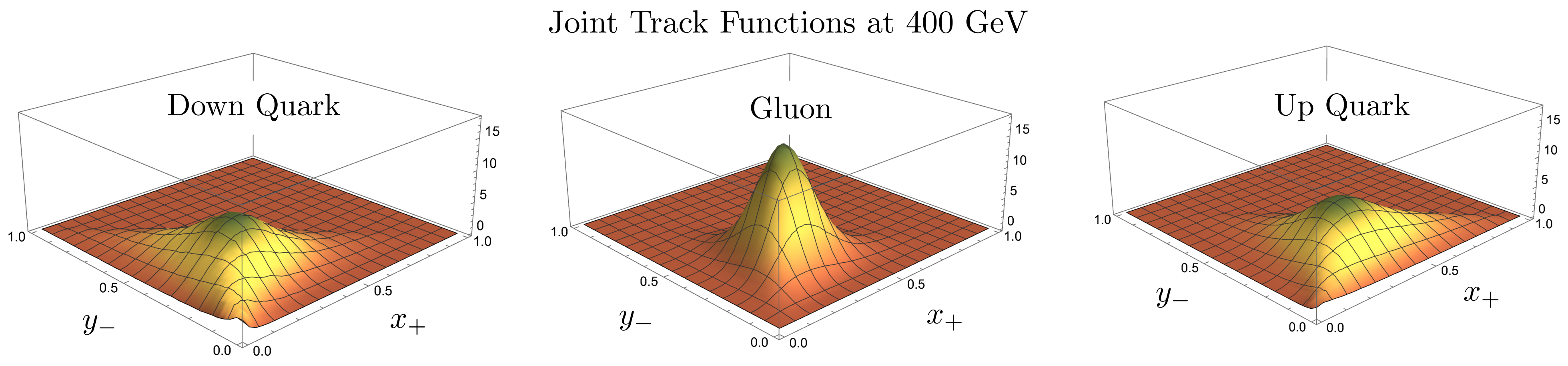




KL, Moult `23

GENERALIZING ENERGY FLOW CORRELATIONS

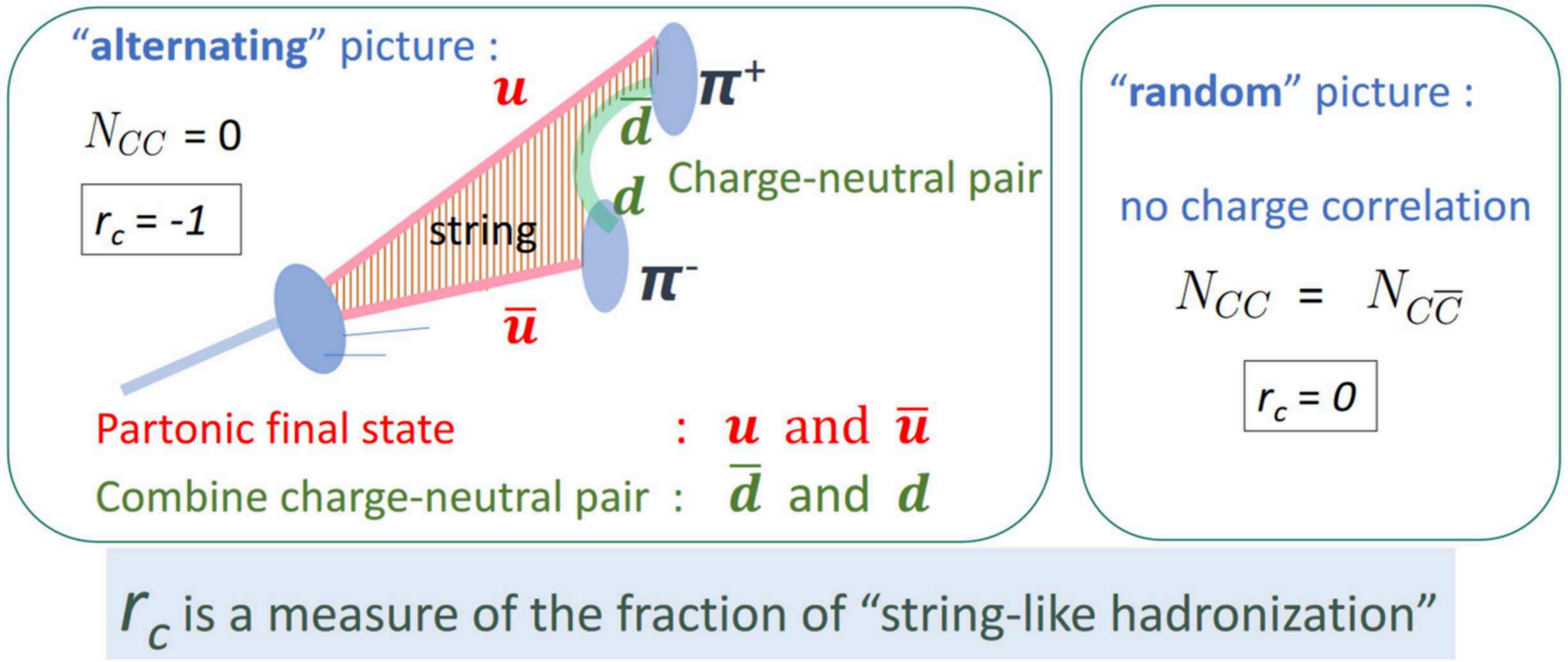
- **Writing down more general detectors allow us to consider more general correlation functions from**

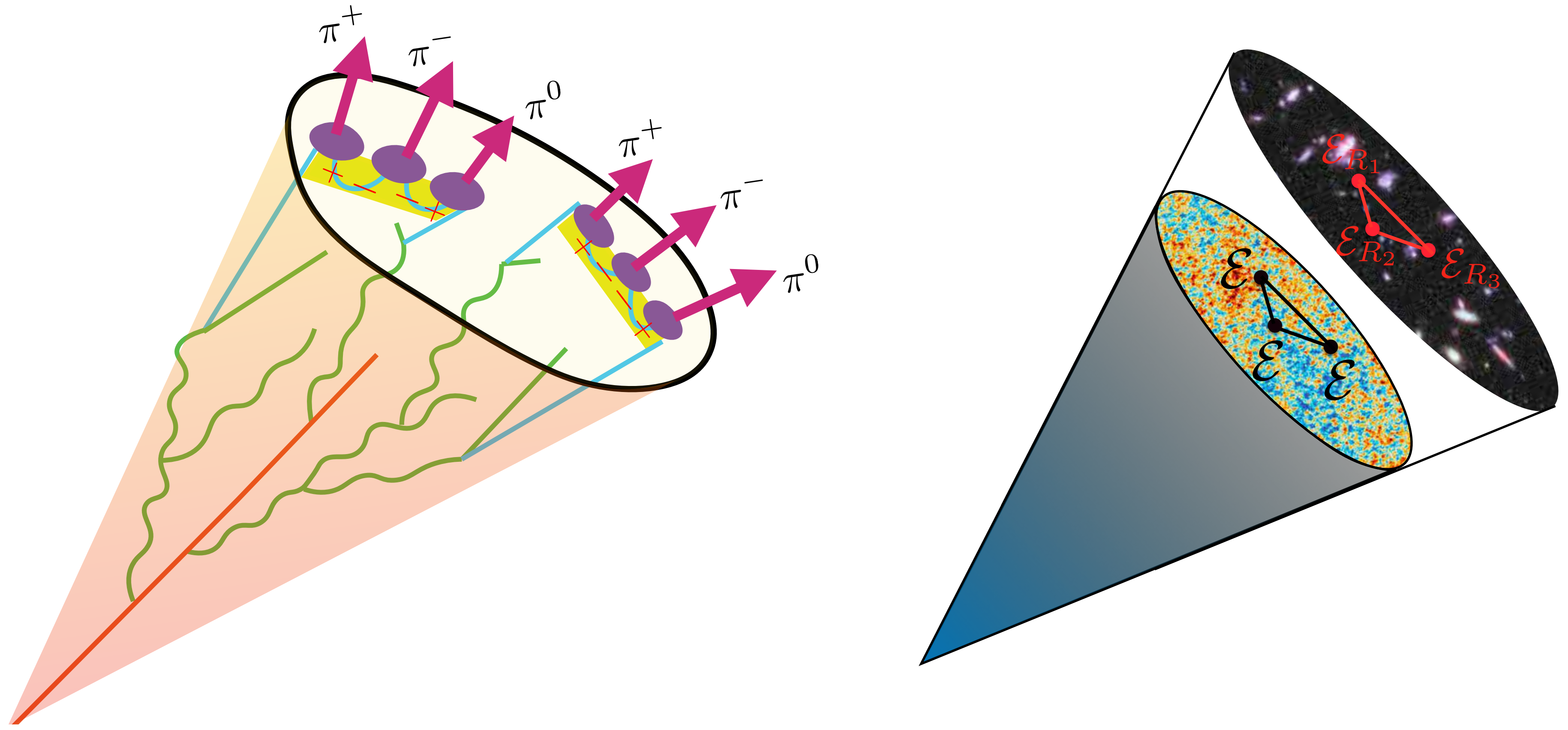


$$\langle \mathcal{E}(n_1)\,\mathcal{E}(n_2)\cdots\mathcal{E}(n_k)\rangle \to \langle \mathcal{E}_{R_1}(n_1)\,\mathcal{E}_{R_2}(n_2)\cdots\mathcal{E}_{R_k}(n_k)\rangle$$

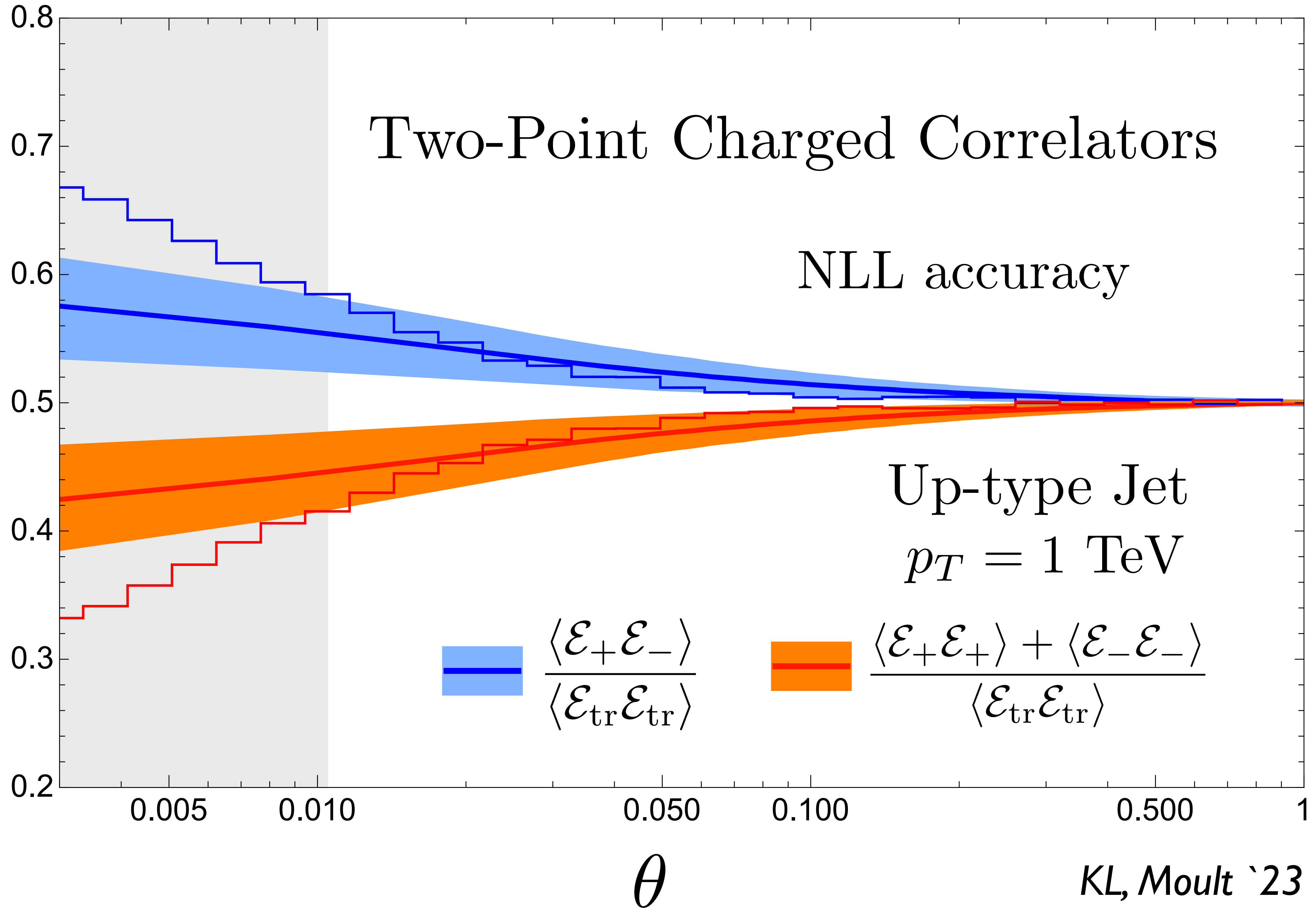
- **In general, restricting to a set of hadronic states to some particular quantum number R introduces sensitivity to the IR scale. As a concrete example, one can ask "is there more unlike-signed correlations compared with the like-signed correlations?"**

i.e. $\langle \mathcal{E}_+\mathcal{E}_-\rangle$ or $\langle \mathcal{E}_+\mathcal{E}_+\rangle + \langle \mathcal{E}_-\mathcal{E}_-\rangle$

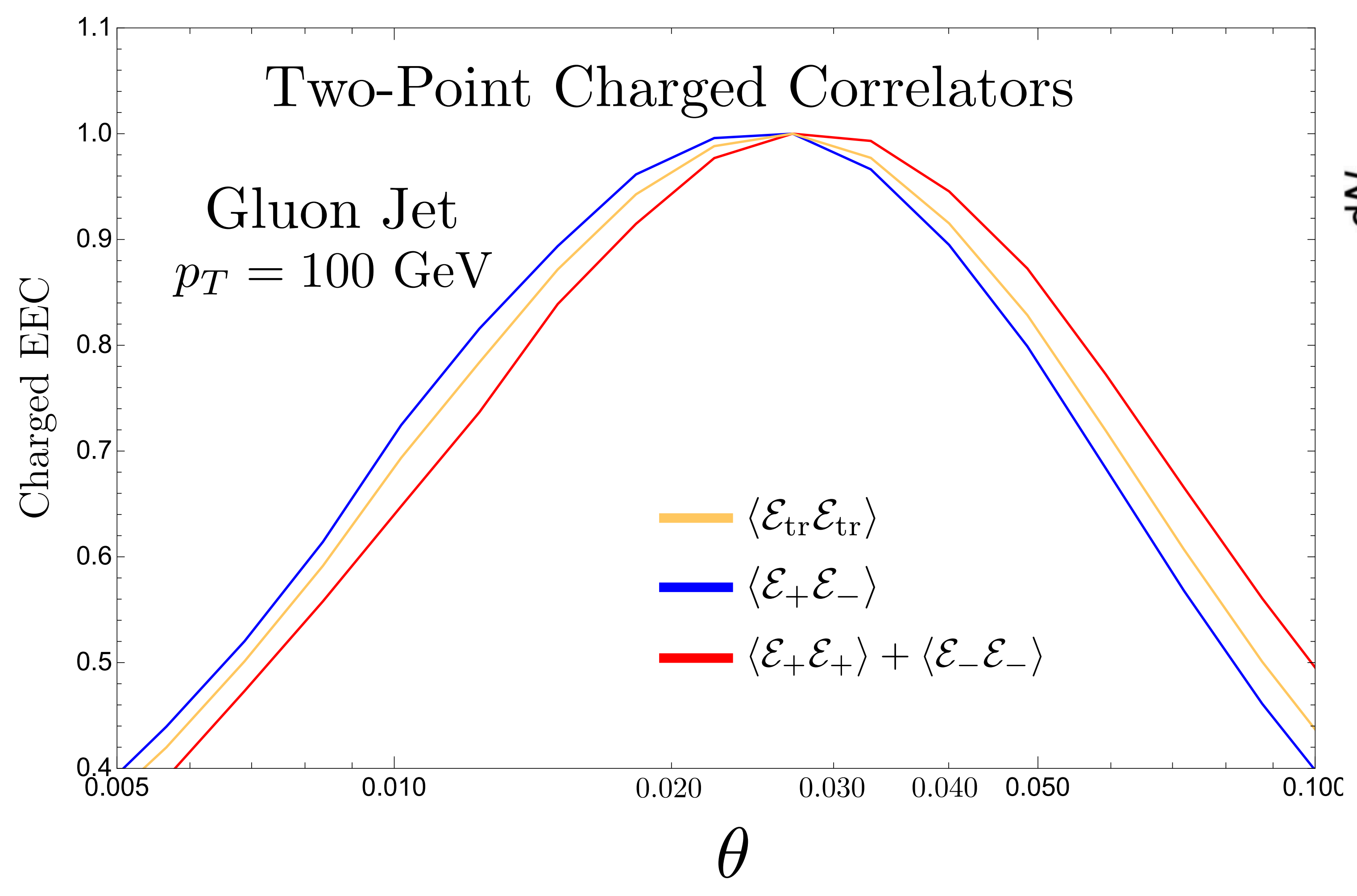


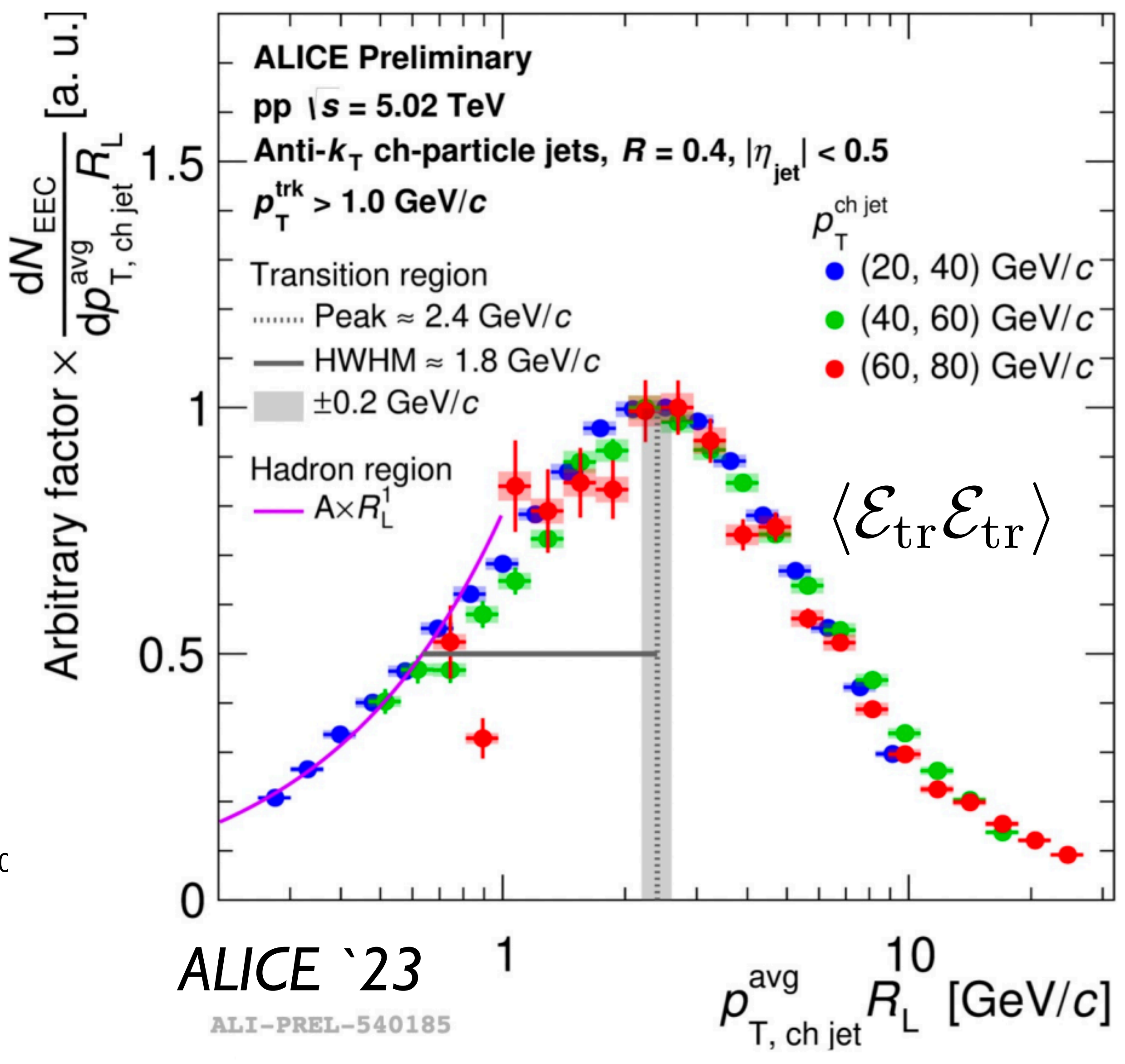


TWO-POINT CHARGED CORRELATORS



- Charged correlators have **modified scaling** in the perturbative region and unlike signed correlators are **correlated more** as the angle becomes smaller!



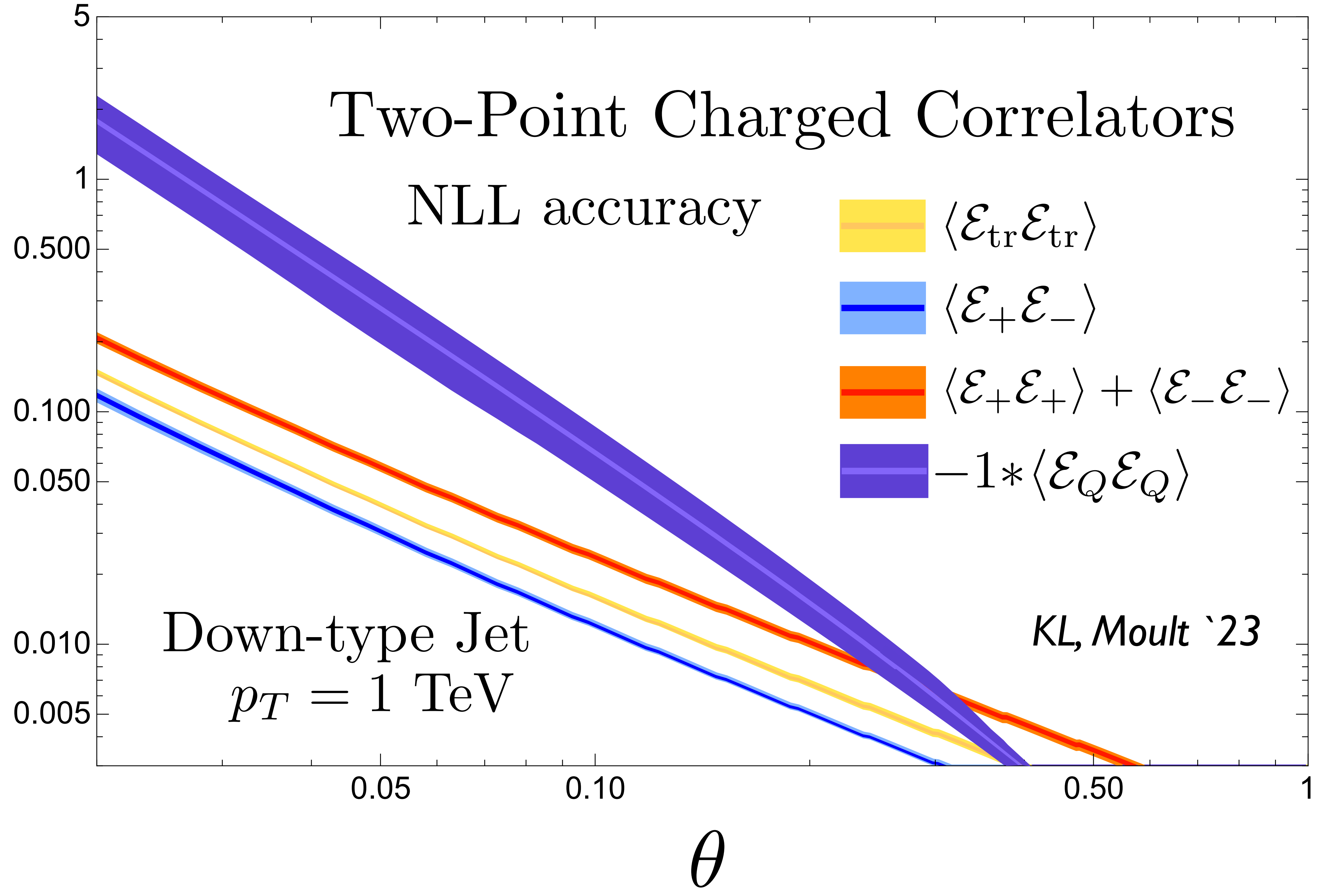


- We also observe that unlike signed correlators have **narrower transition** and the peak is also **shifted**!

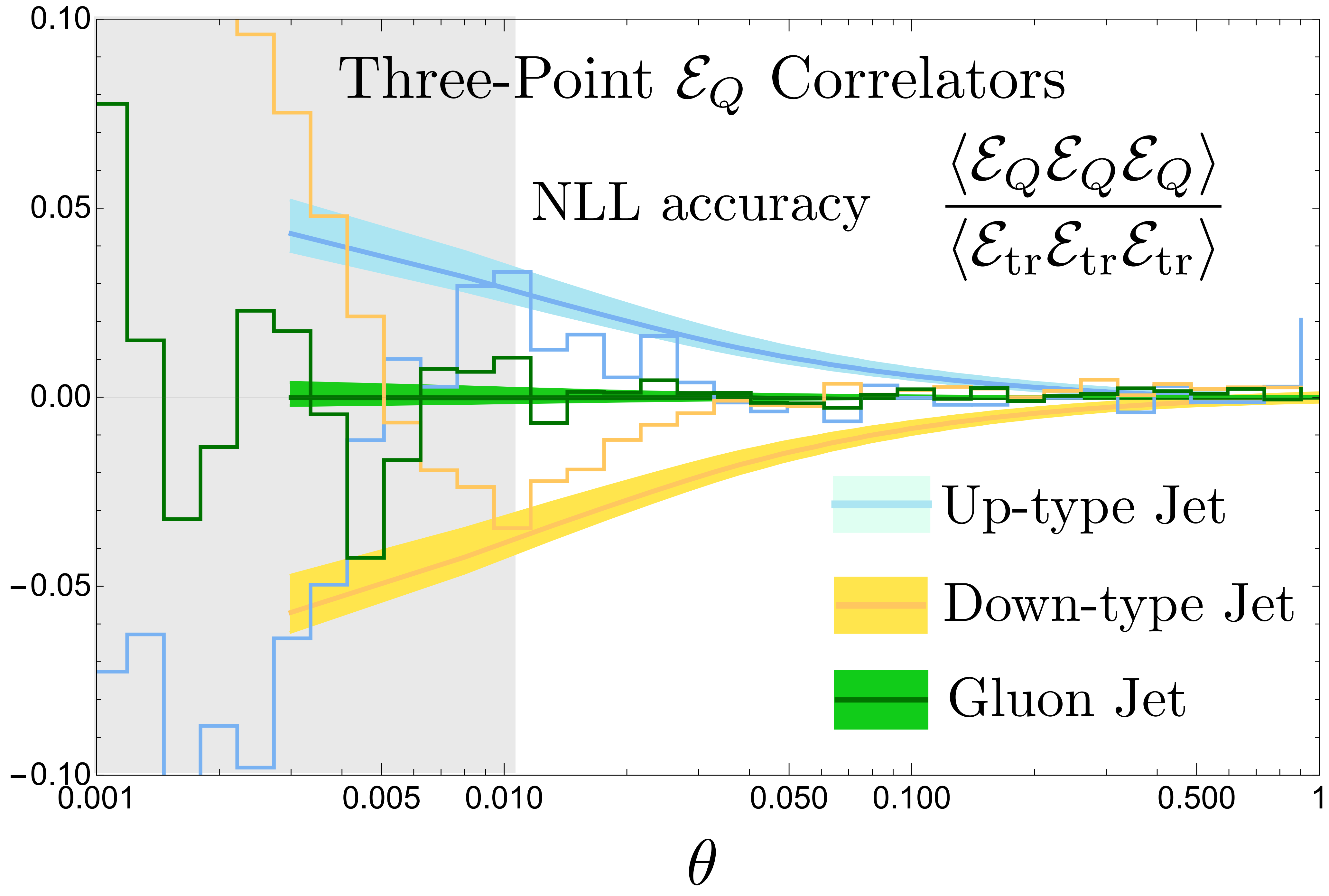
C-ODD DETECTOR

- **We can define also operator odd under charge conjugation.**

$$\mathcal{E}_Q\left(\vec{n}_1\right)|k\rangle = E_k Q_k \delta\left(\hat{n}_1 - \hat{k}\right)|k\rangle$$



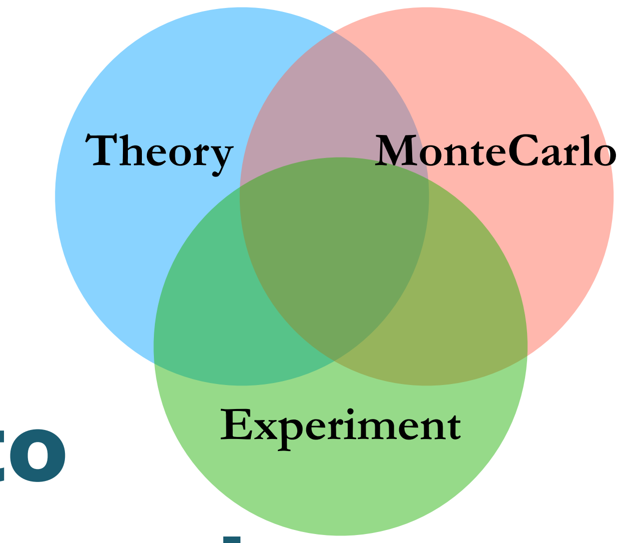
- **There is a large cancellation between like-sign and unlike-sign correlations, modifying the scaling by an integer amount.**



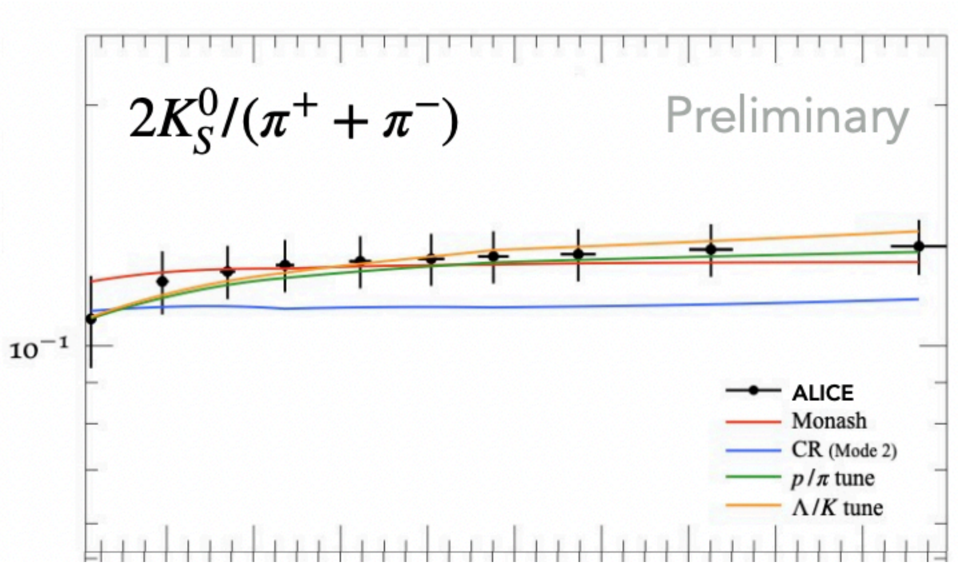
- **Due to C-odd nature, we observe that 3-pt correlators of EQ gives zero for gluon, while approximately opposite results between up and down-type due to approximate isospin symmetry. Furthermore, we observe nontrivial abrupt changes in structure in the transition region**

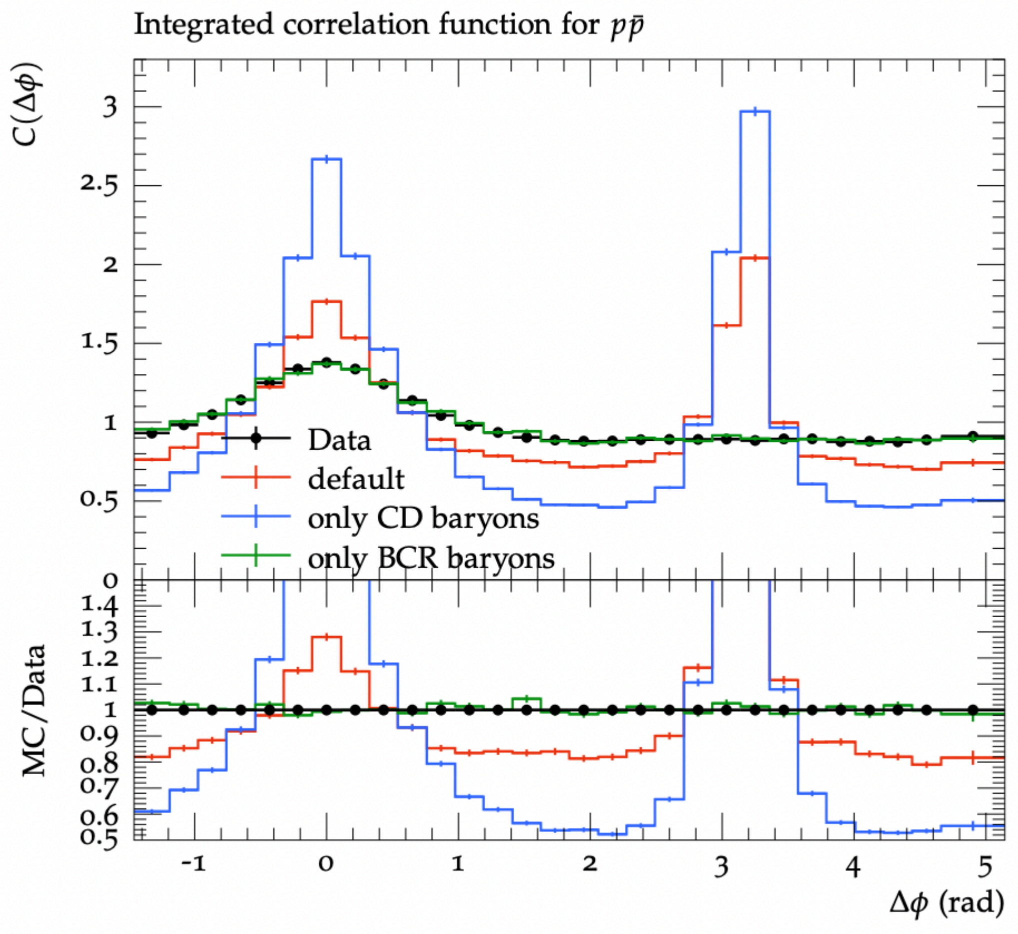
ASIDE: INTERPLAY WITH PARTON SHOWERS DEVELOPMENT

- **Almost every analysis of high-energy collider data relies on simulations with MC generators.**
- **Much progress is being made on all fronts of parton shower developments!**
- **Jet substructure observables can be used to provide sensitivity to different perturbative and non-perturbative effects.**



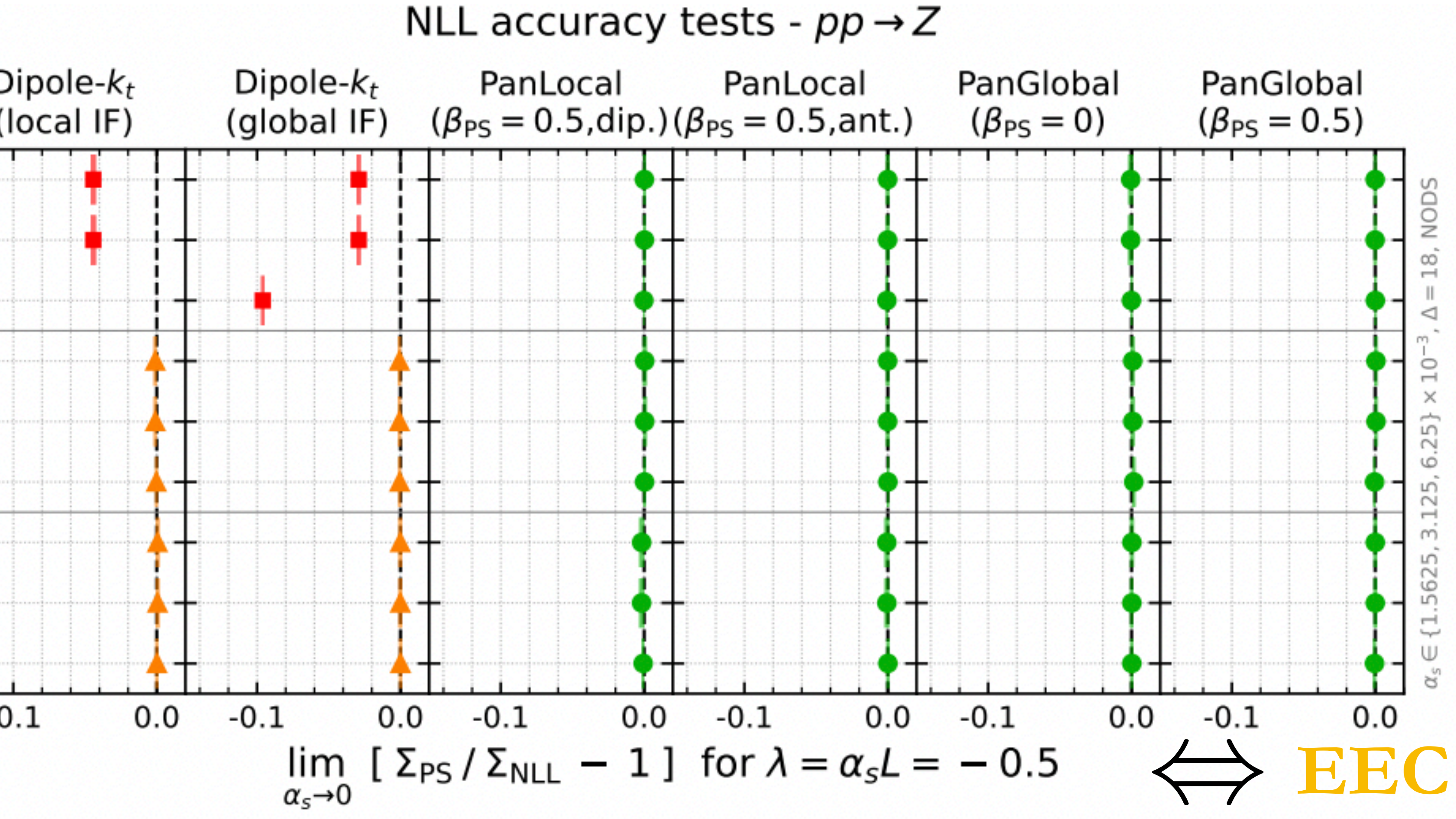
Hadronization models





⇔ Charged EECs

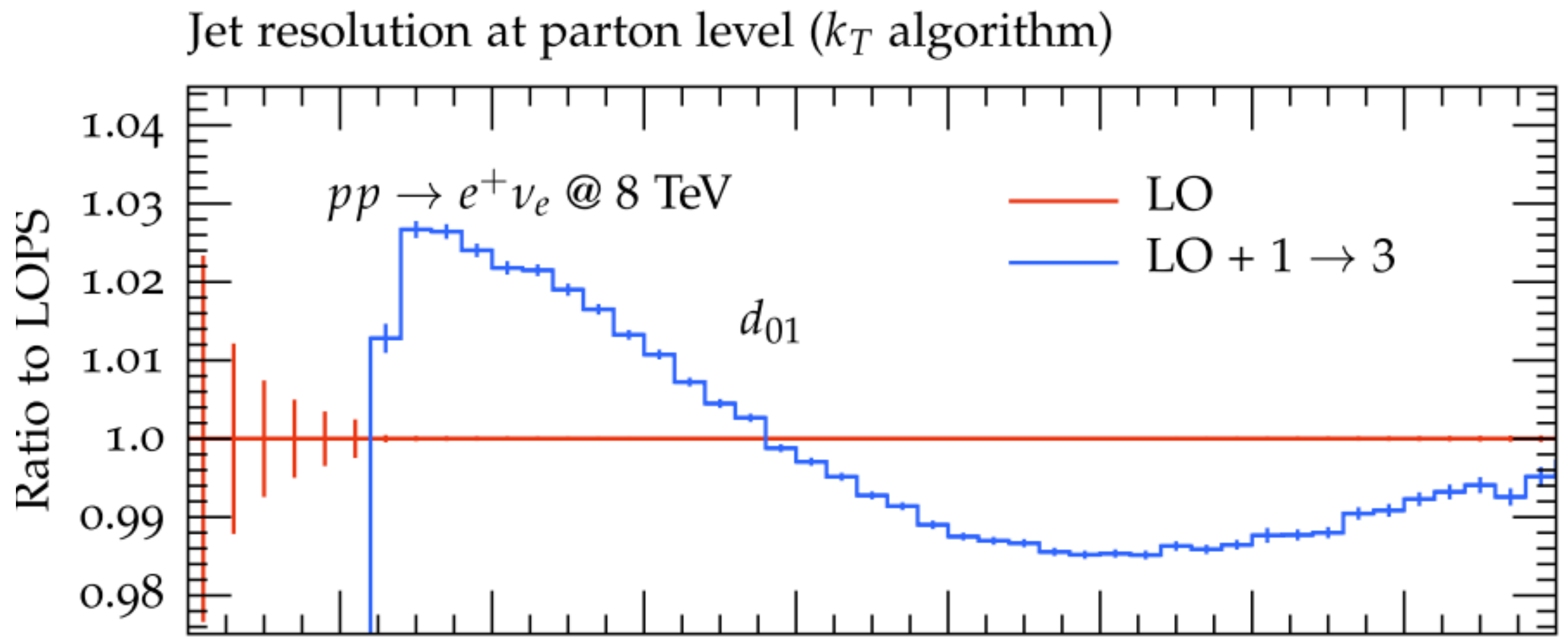
NLL improvements



⇔ EEC anomalous scaling

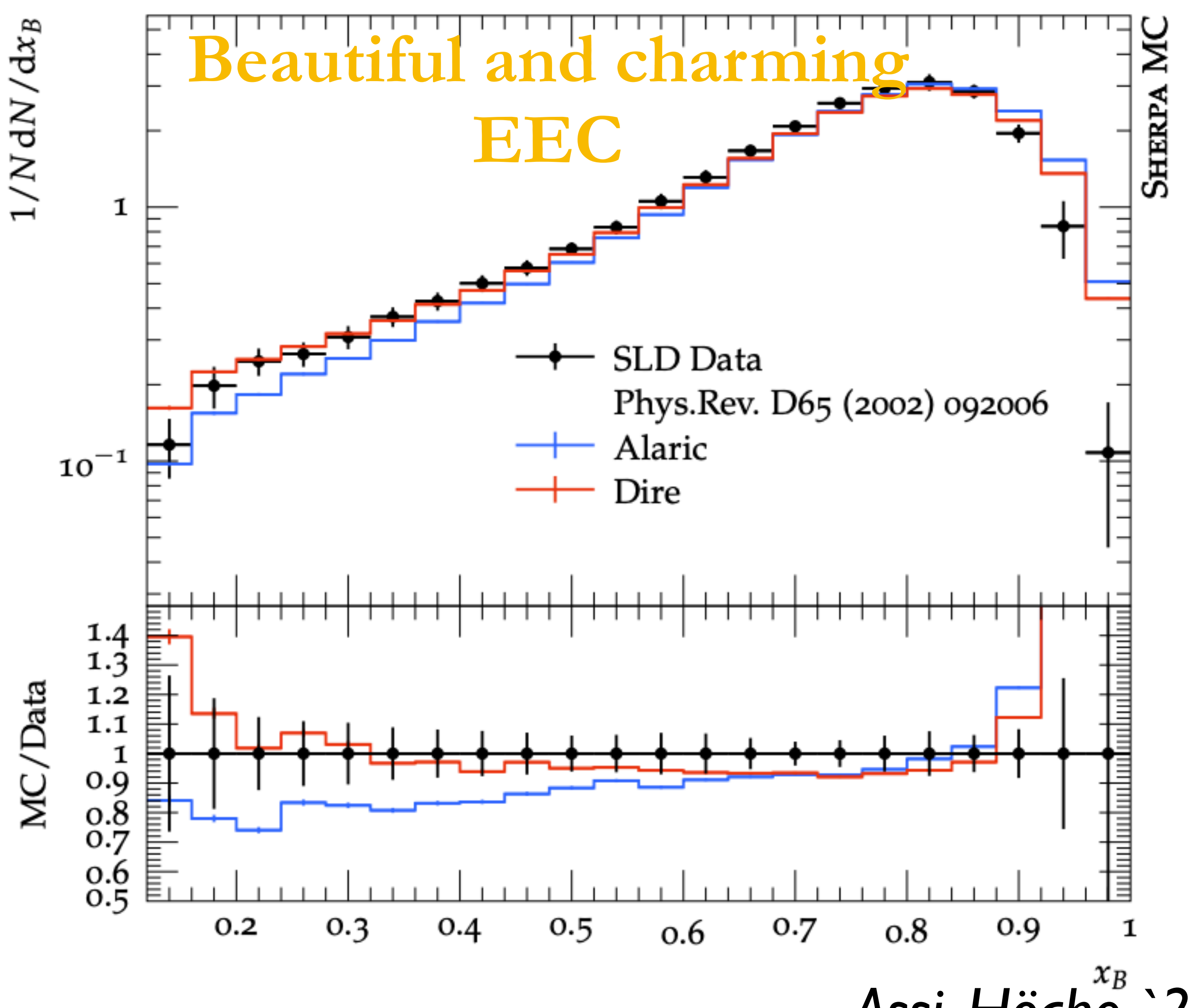
van Beekveld, Ravasio, Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen `23

Triple collinear splitting ⇔ 3-point EEC



Höche, Prestel `17

Massive splitting ⇔



Assi, Höche `23

GOAL

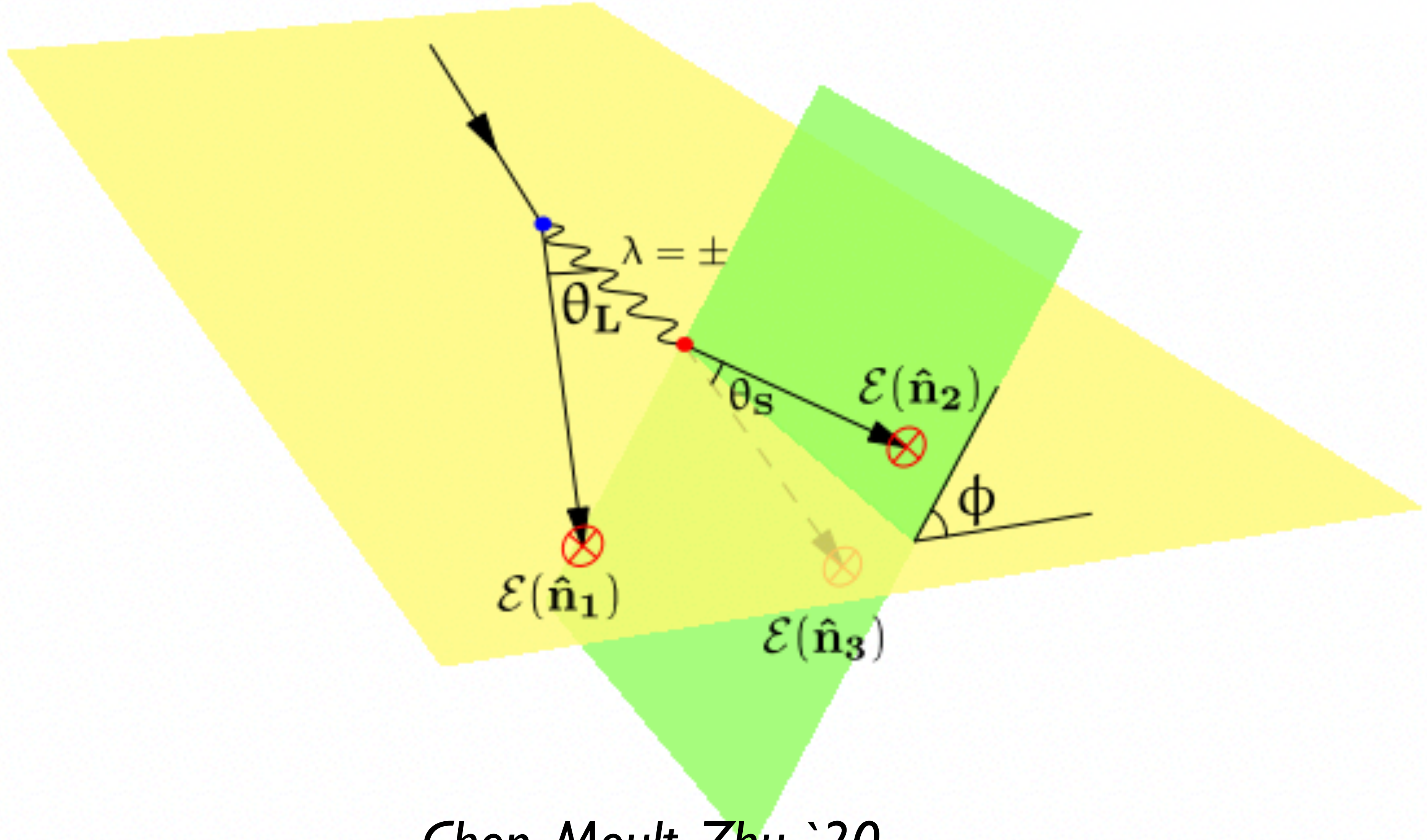
SPIN PHYSICS WITH JET SUBSTRUCTURE

SPINNING GLUON IN ENERGY CORRELATORS

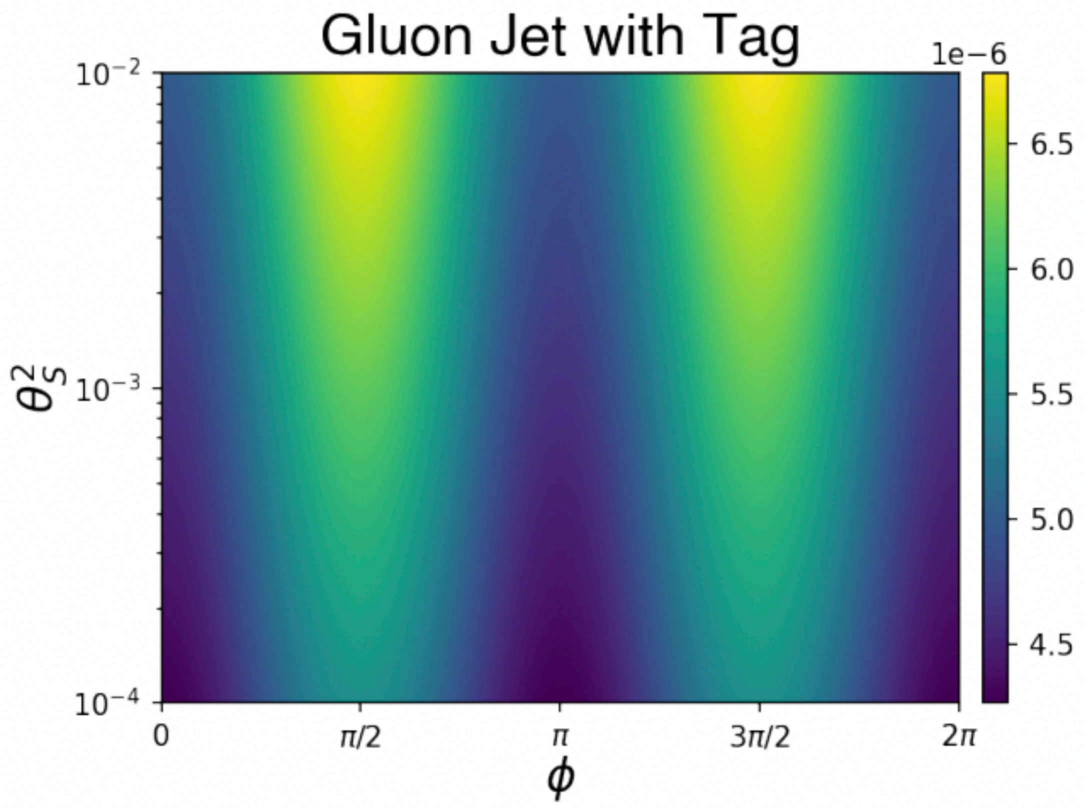
- **Higher point correlators give arise to $\cos(2\phi)$ asymmetry in the squeezed limit of a pair of detector.**
- **This azimuthal asymmetry describes the interference between gluon helicity states**

$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\mathcal{E}(\hat{n}_3) = \frac{1}{(2\pi)^2}\frac{2}{\theta_S^2}\frac{2}{\theta_L^2}\vec{J}\left[\hat{C}_{\phi_S}(2) - \hat{C}_{\phi_S}(3)\right]\left[\frac{\alpha_s(\theta_L Q)}{\alpha_s(\theta_S Q)}\right]^{\frac{\hat{\gamma}^{(0)}(3)}{\beta_0}}$$

$$\left[\hat{C}_{\phi_L}(3) - \hat{C}_{\phi_L}(4)\right]\left[\frac{\alpha_s(Q)}{\alpha_s(\theta_L Q)}\right]^{\frac{\hat{\gamma}^{(0)}(4)}{\beta_0}}\vec{\mathbb{O}}^{[4]}(\hat{n}_1) + \cdots$$



Chen, Moult, Zhu `20

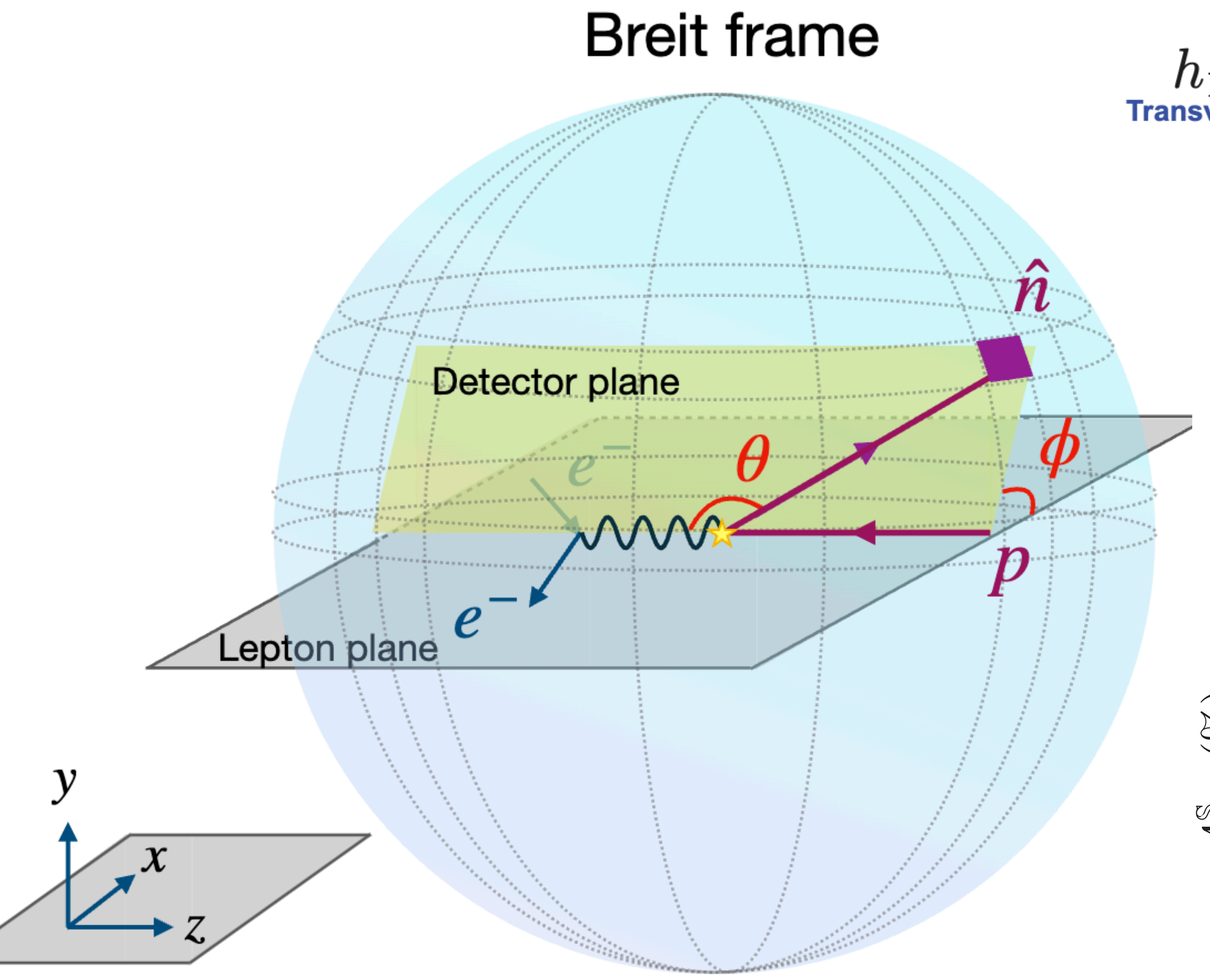


AZIMUTHAL ANGLE ASYMMETRY AT THE FUTURE EIC

- **Non-rotationally symmetric states allow different ways of considering azimuthal asymmetry of the energy flow, which imprints spin dynamics**

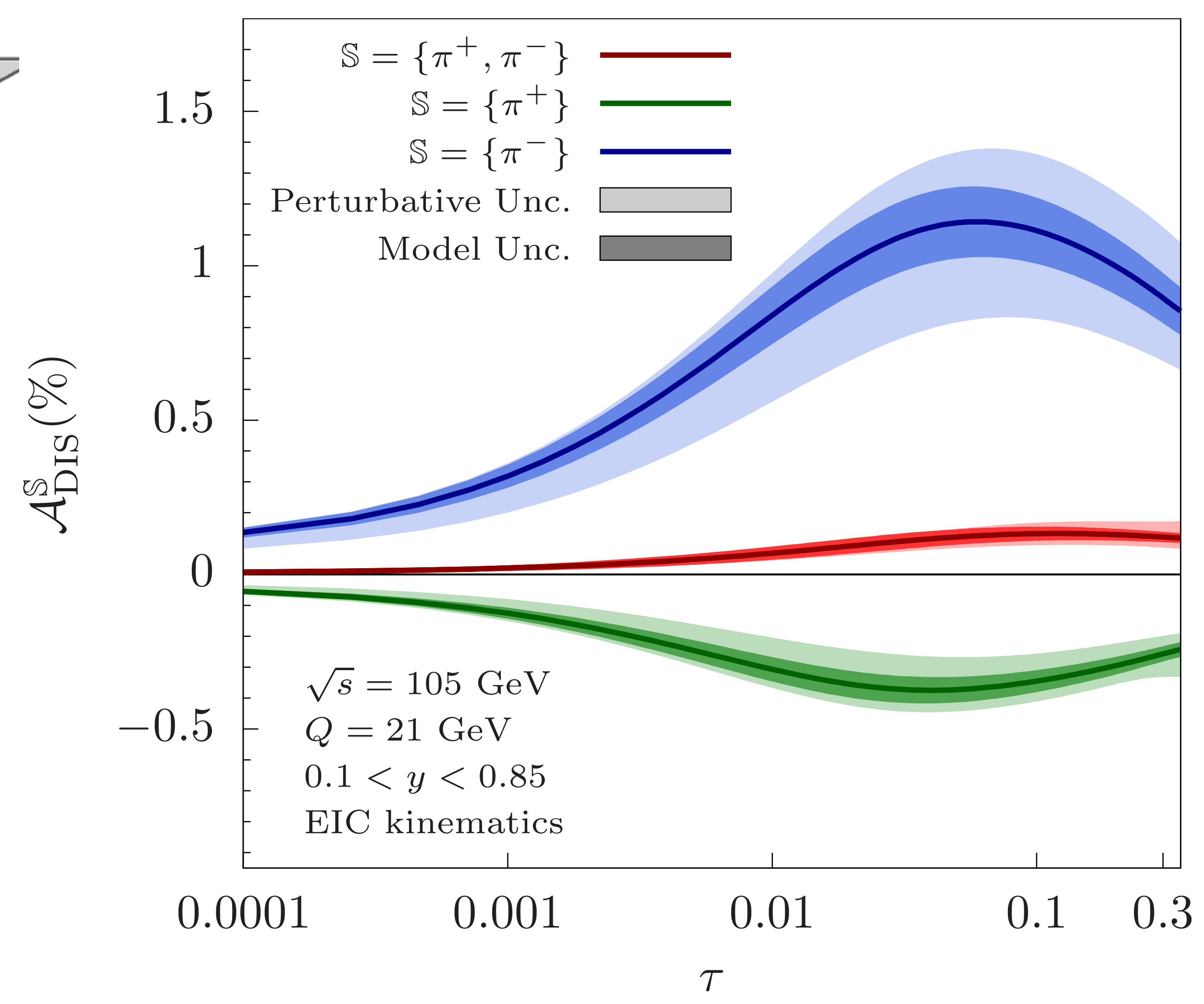
Collins-type EEC

$$\mathcal{A}^{\mathbb{S}}_{\mathrm{DIS}} = \frac{2(1-y)}{1+(1-y)^2}\frac{\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)}}{\mathcal{F}_{UU}}$$



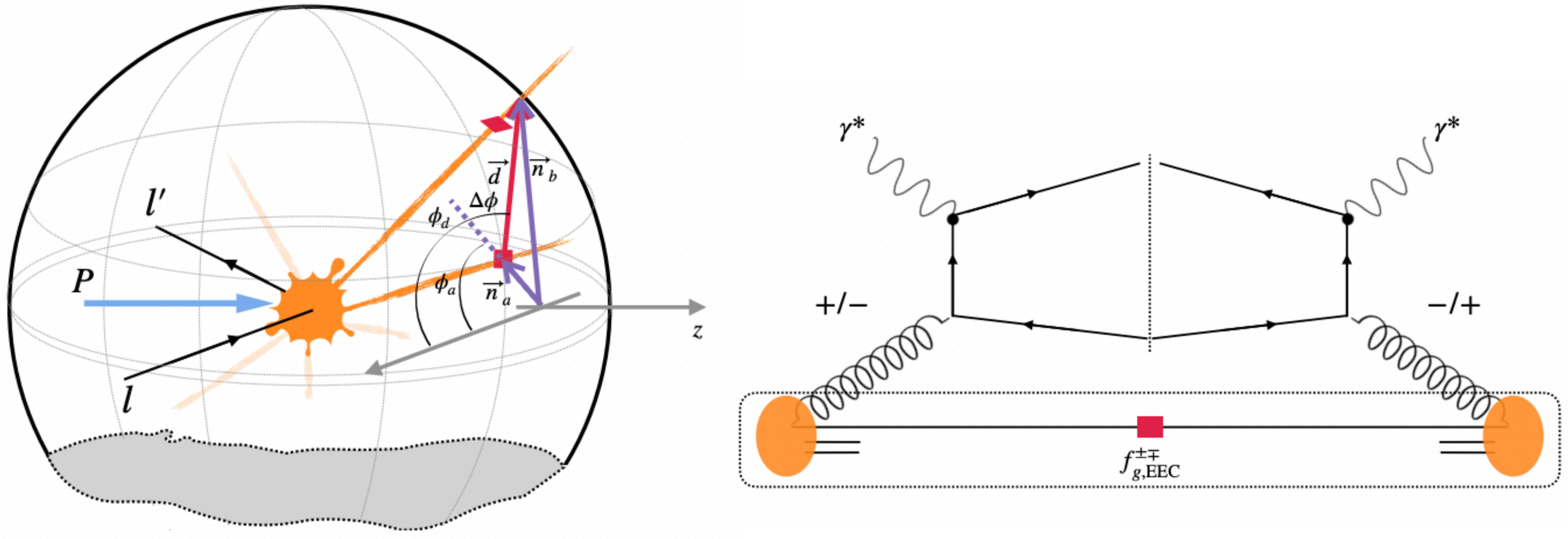
h_1 = (Transversity) $\mathcal{F}_{UT}^{\sin(\phi_{q_T}+\phi_s)} \sim h_1 \otimes J_q^{\perp}$

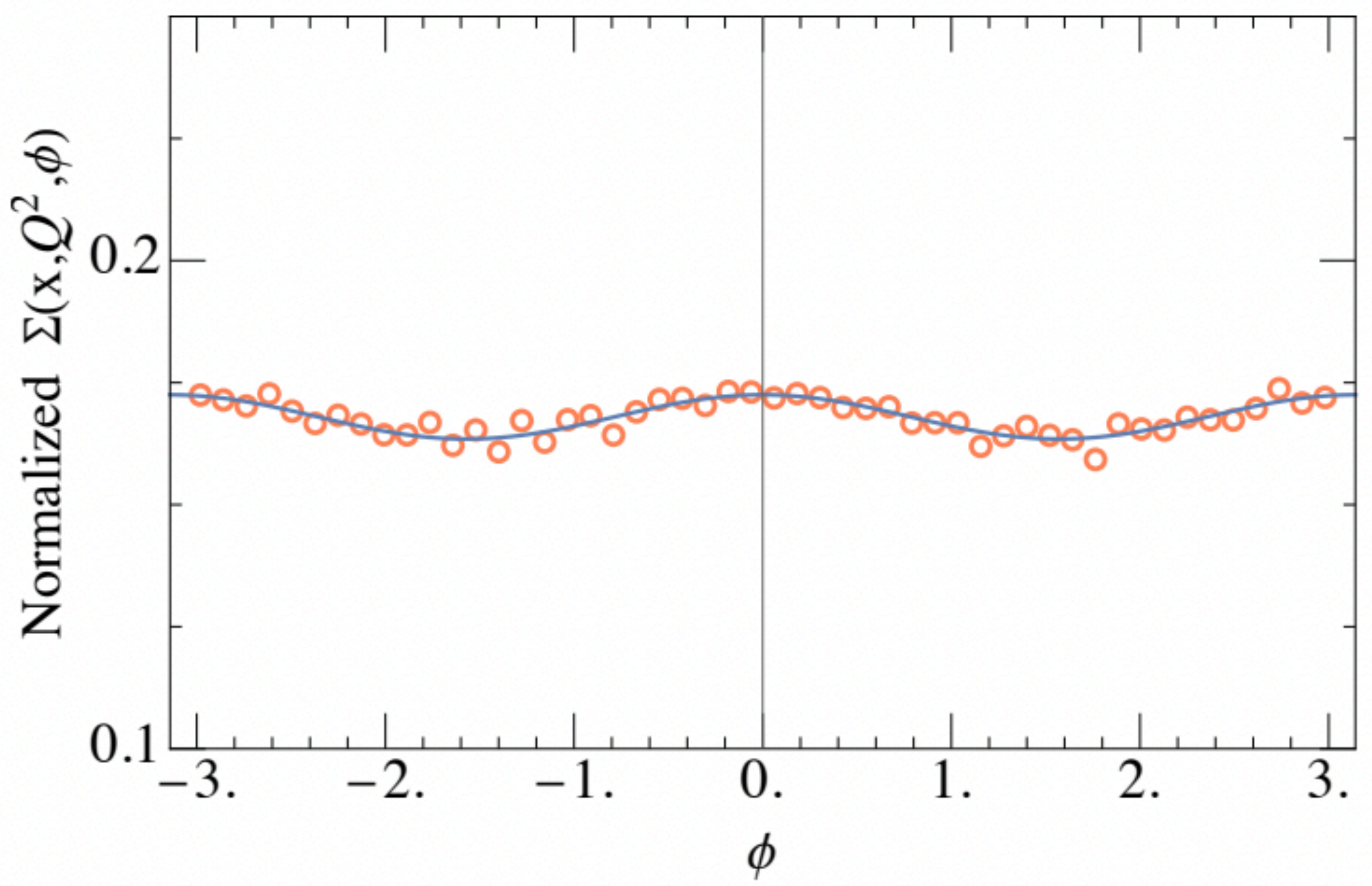
f_1 = (Unpolarized) $\mathcal{F}_{UU} \sim f_1 \otimes J_q$



Kang, KL, Shao, Zhao `23

Nucleon EEC





Li, Liu, Yuan, Zhu `22

Top-quark physics

170 GeV - O(TeV)

Higgs physics

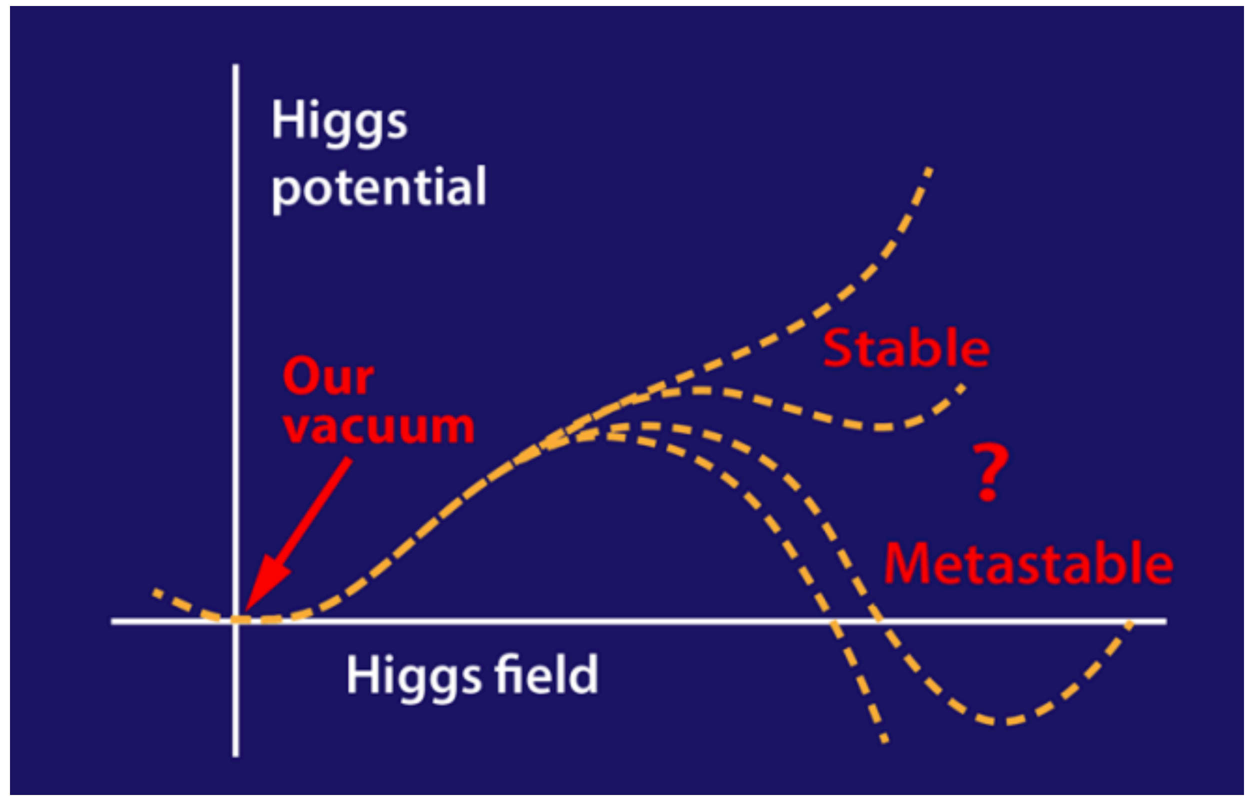
125 GeV - 500 GeV

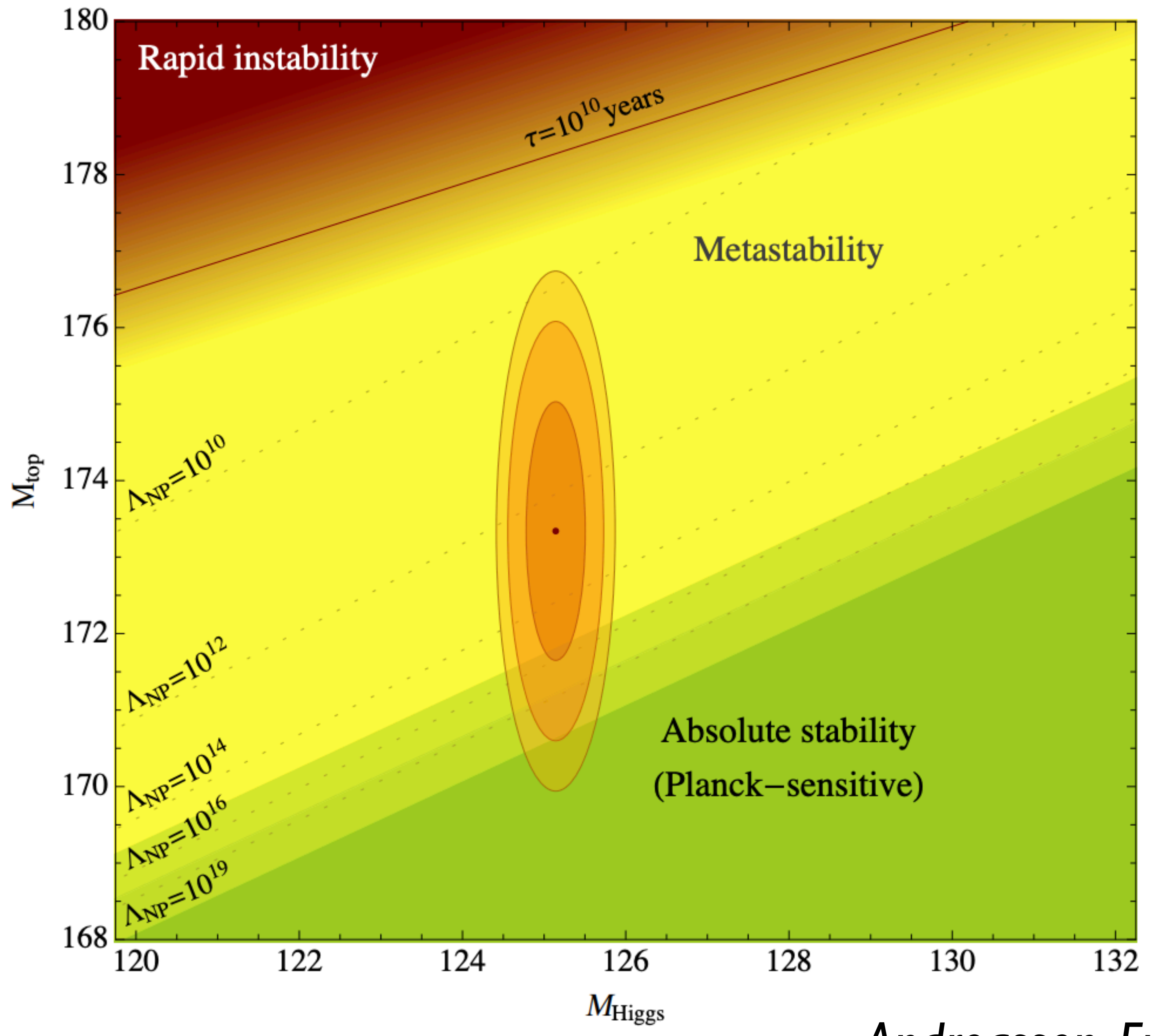
GOAL

WHAT IS THE FATE OF OUR UNIVERSE?

METASTABILITY OR STABILITY OF OUR UNIVERSE

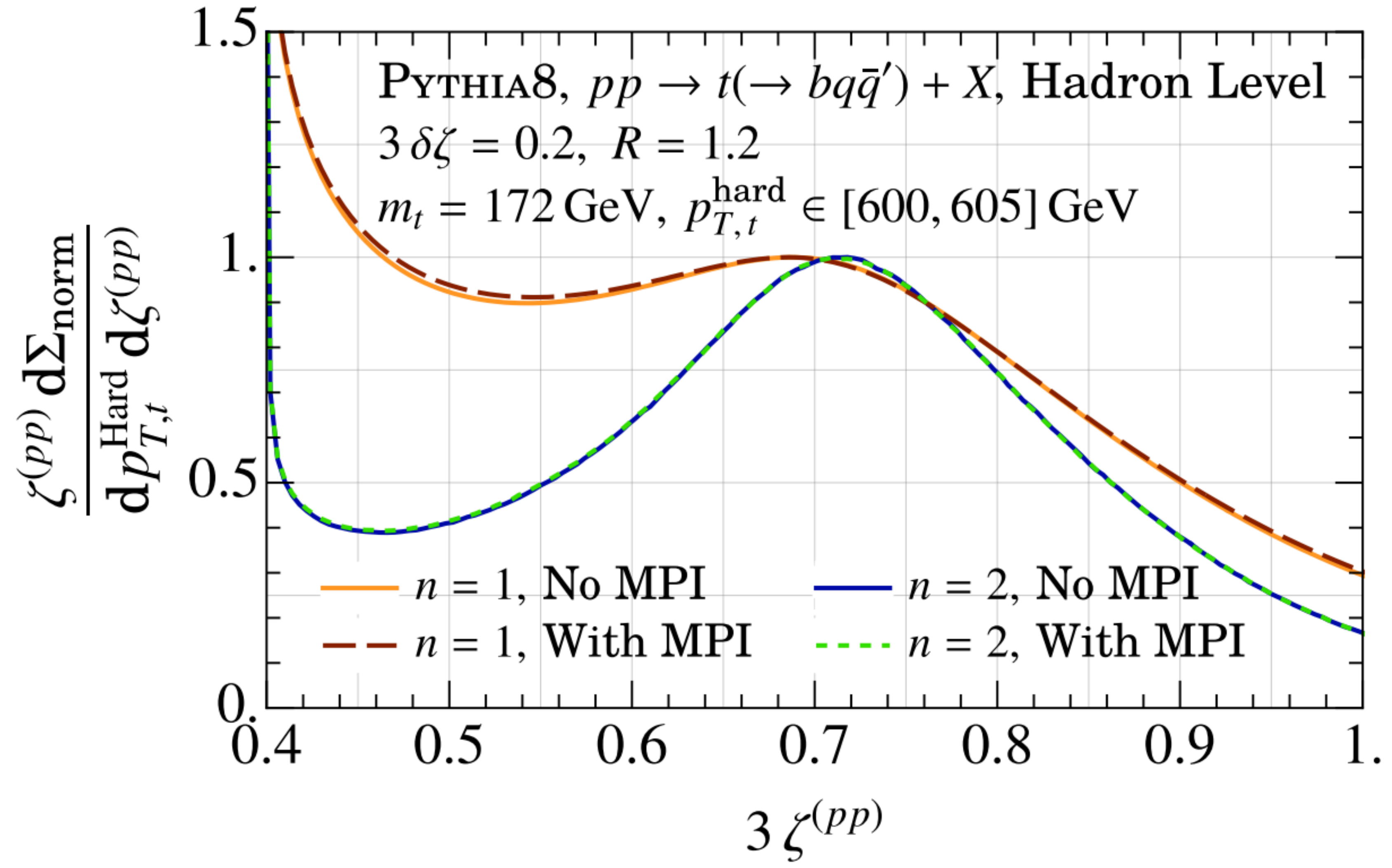
- **Will our universe undergo eternal inflation, or will it undergo some catastrophic big crunch? Can the jet substructure come to the rescue in answering this question?**

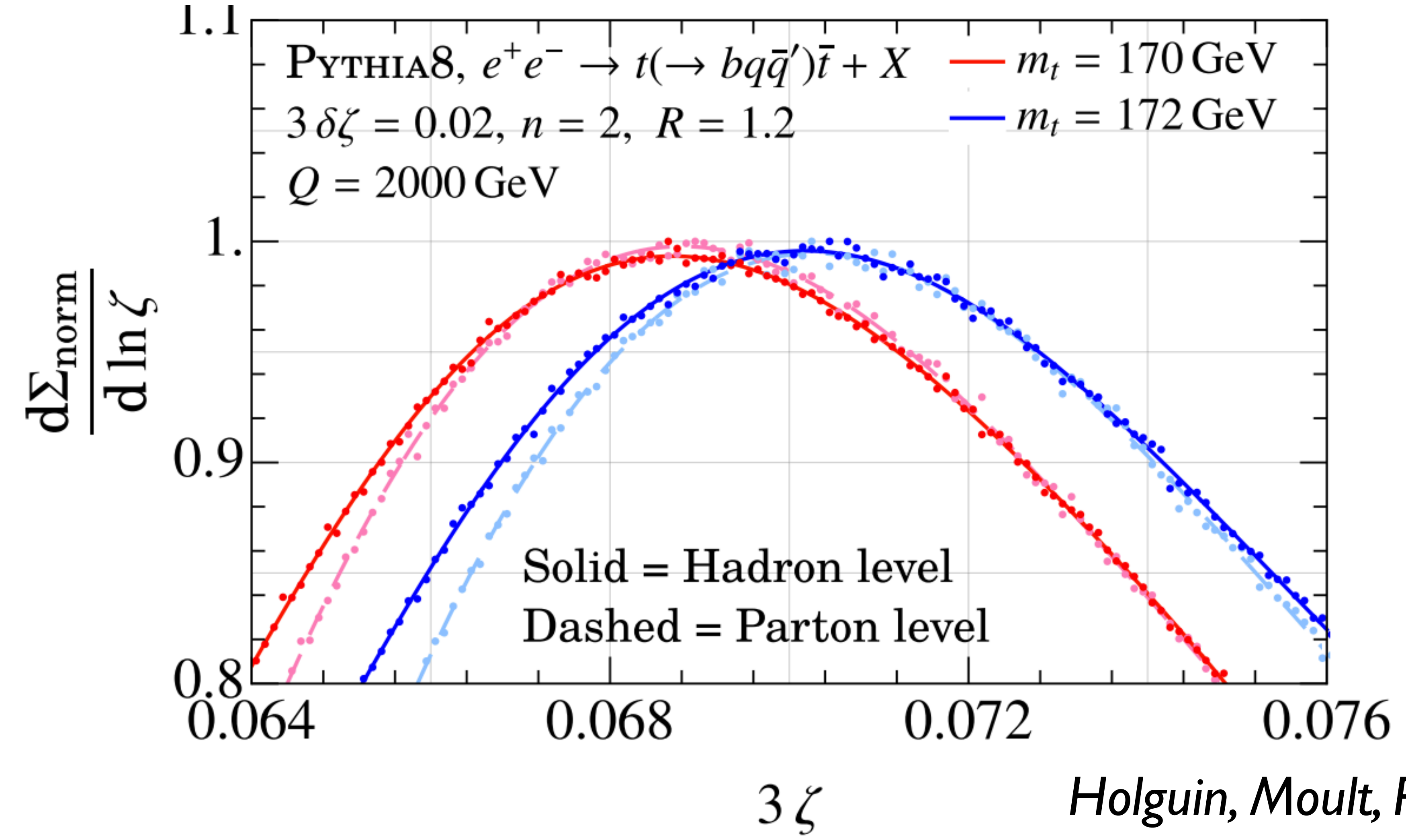




Andreassen, Frost, Schwartz `14

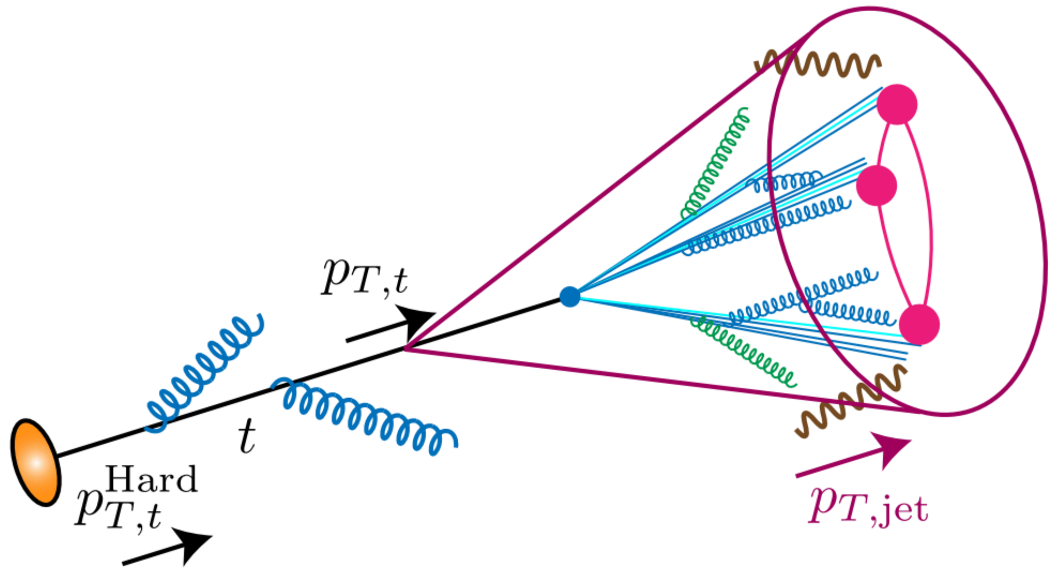
ENERGY ENERGY CORRELATORS ON TOP JET





Holguin, Moult, Pathak, Procura `22

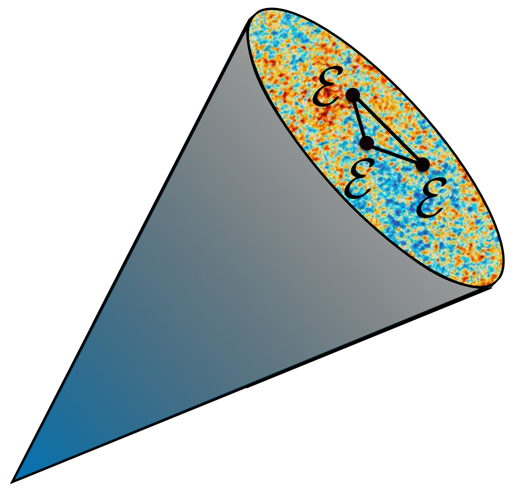
- **Large samples of highly boosted top quarks produced at the LHC!**
- **Recent development show that three-point energy correlators are sensitive to the top mass and show robustness to underlying events!**
- **Small hadronization effects, which enter additively**



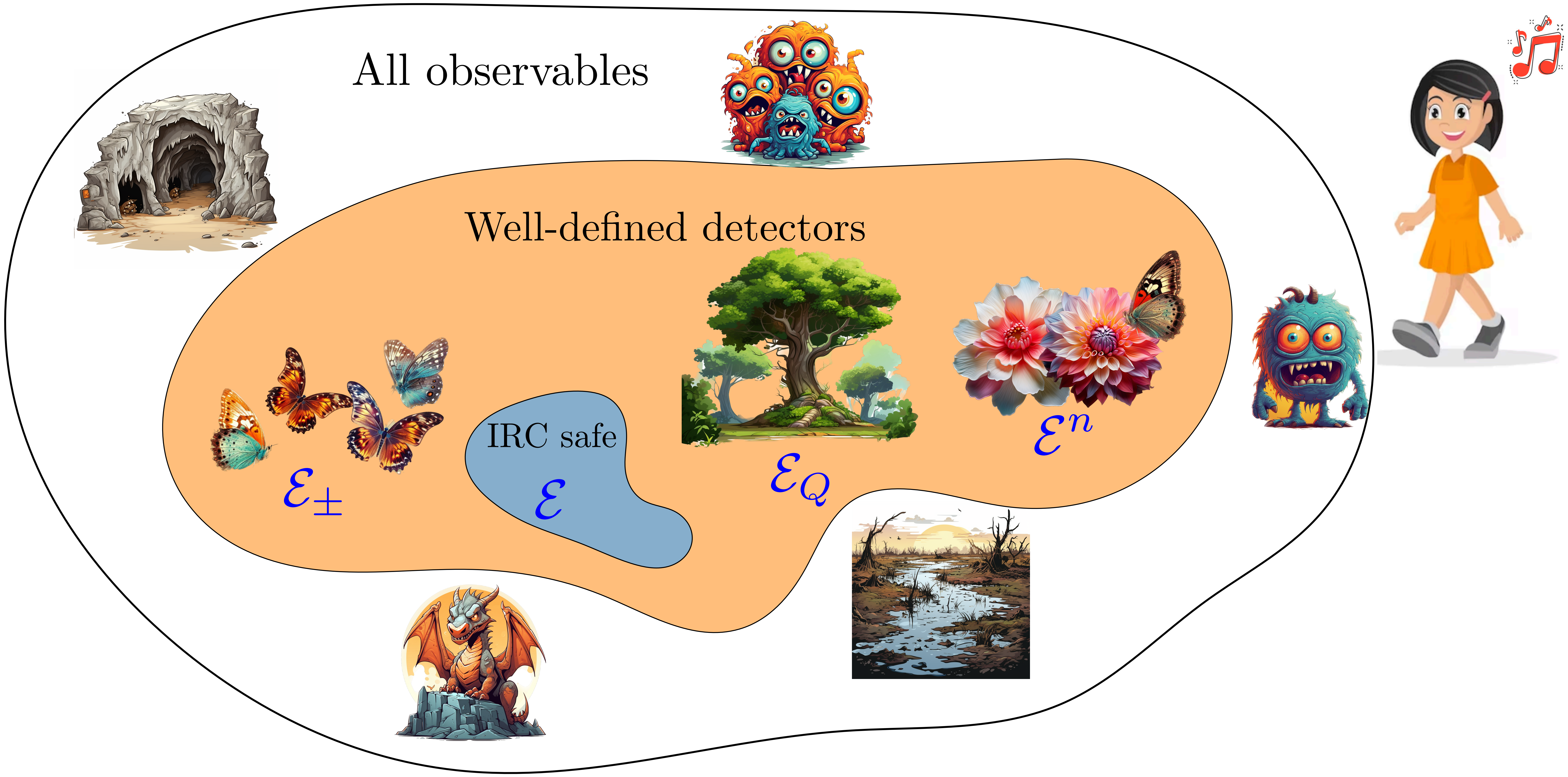
$$\zeta \approx 3m_t^2/p_{T,\text{jet}}^2$$

- **Precise understanding of the non-perturbative corrections to the hard scale is required**

SUMMARY



- Jet substructure is at the heart of the collider program and provides us the effective means to study many different aspects of high energy QCD and nuclear physics.
- Energy flux operator sharpens the connection between jet substructure study and underlying field theory
- Intrinsic scales of QCD can be identified using energy correlators: medium, heavy quark, cold nuclear matter, confinement region
- Different quantum numbers through confinement transition region can be tracked using energy correlators
- Spin dynamics can be probed using energy correlators at the future EIC



Let us explore the landscape of well-defined detectors and study its correlations!