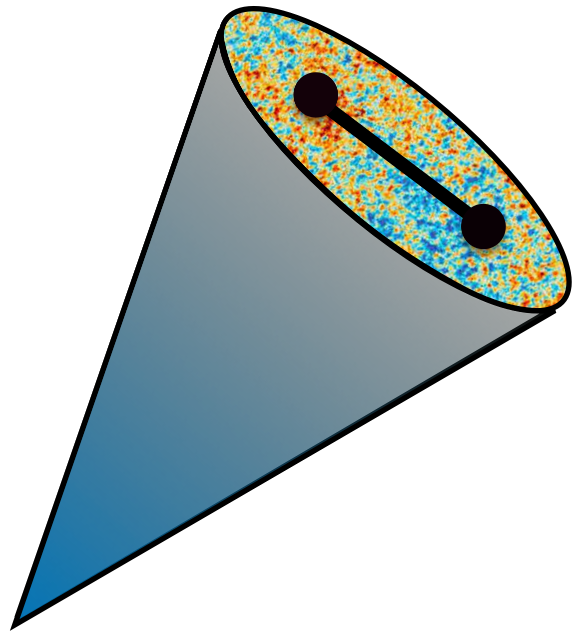
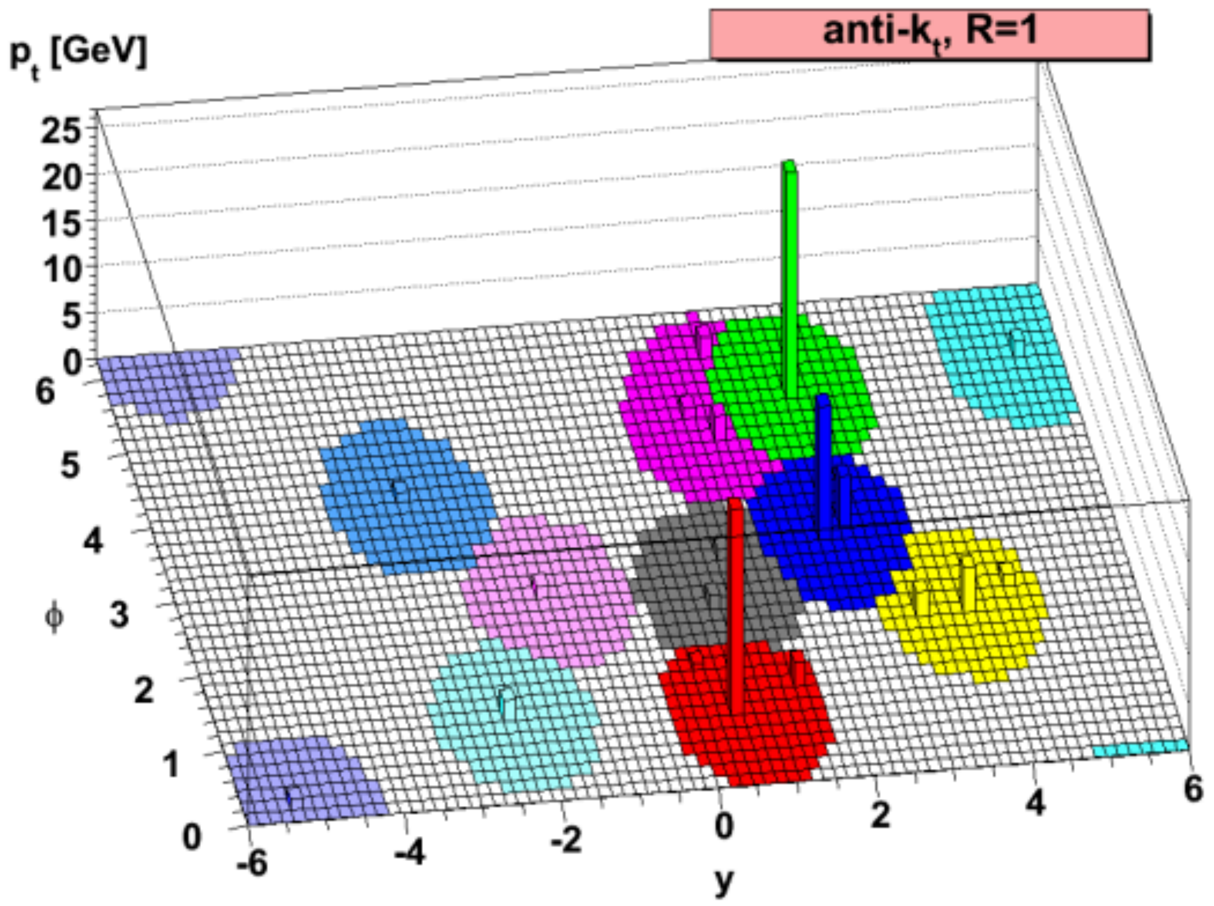
Reimagining Jet Substructure with Energy Correlators

Kyle Lee
CTP, MIT

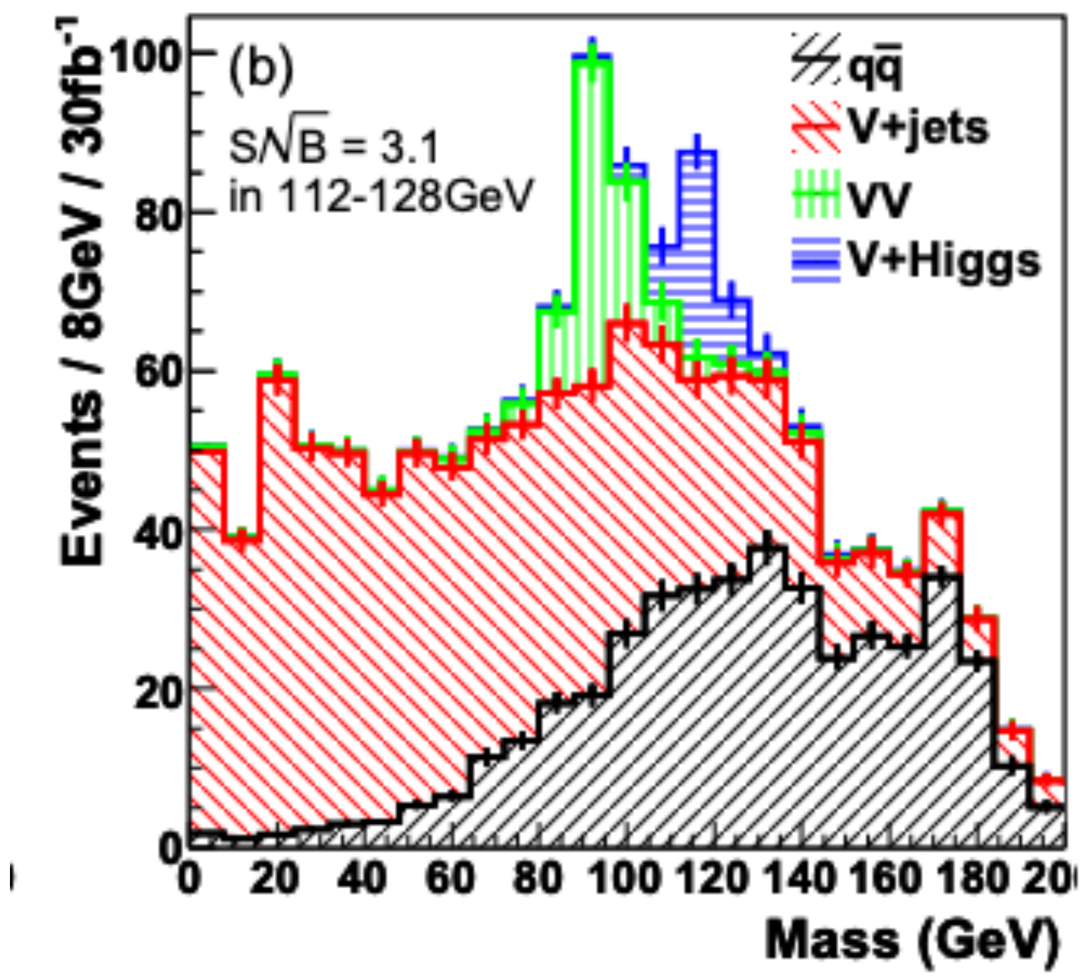
QCD@LHC 2023

JET SUBSTRUCTURE STUDY

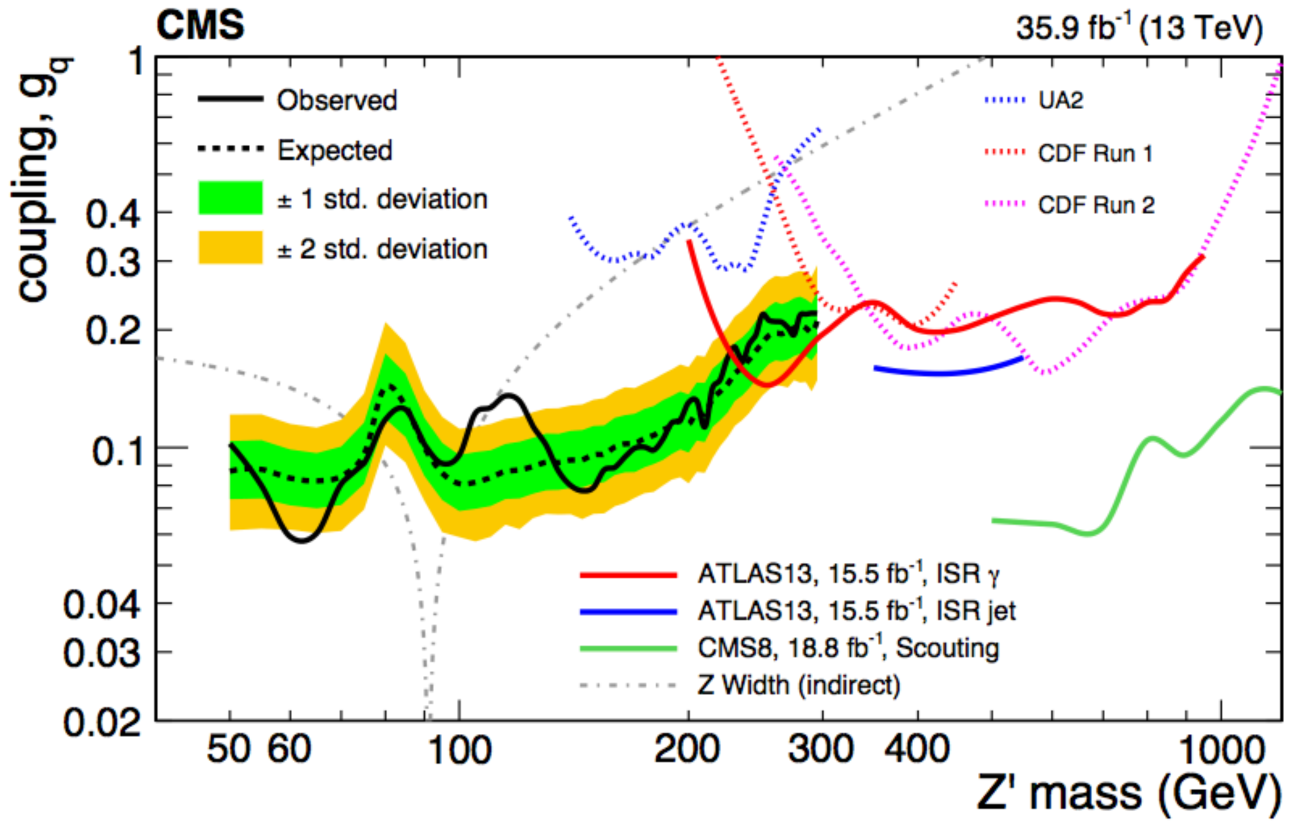




Cacciari, Salam, Soyez `08



Butterworth, Davison, Rubin, Salam `08

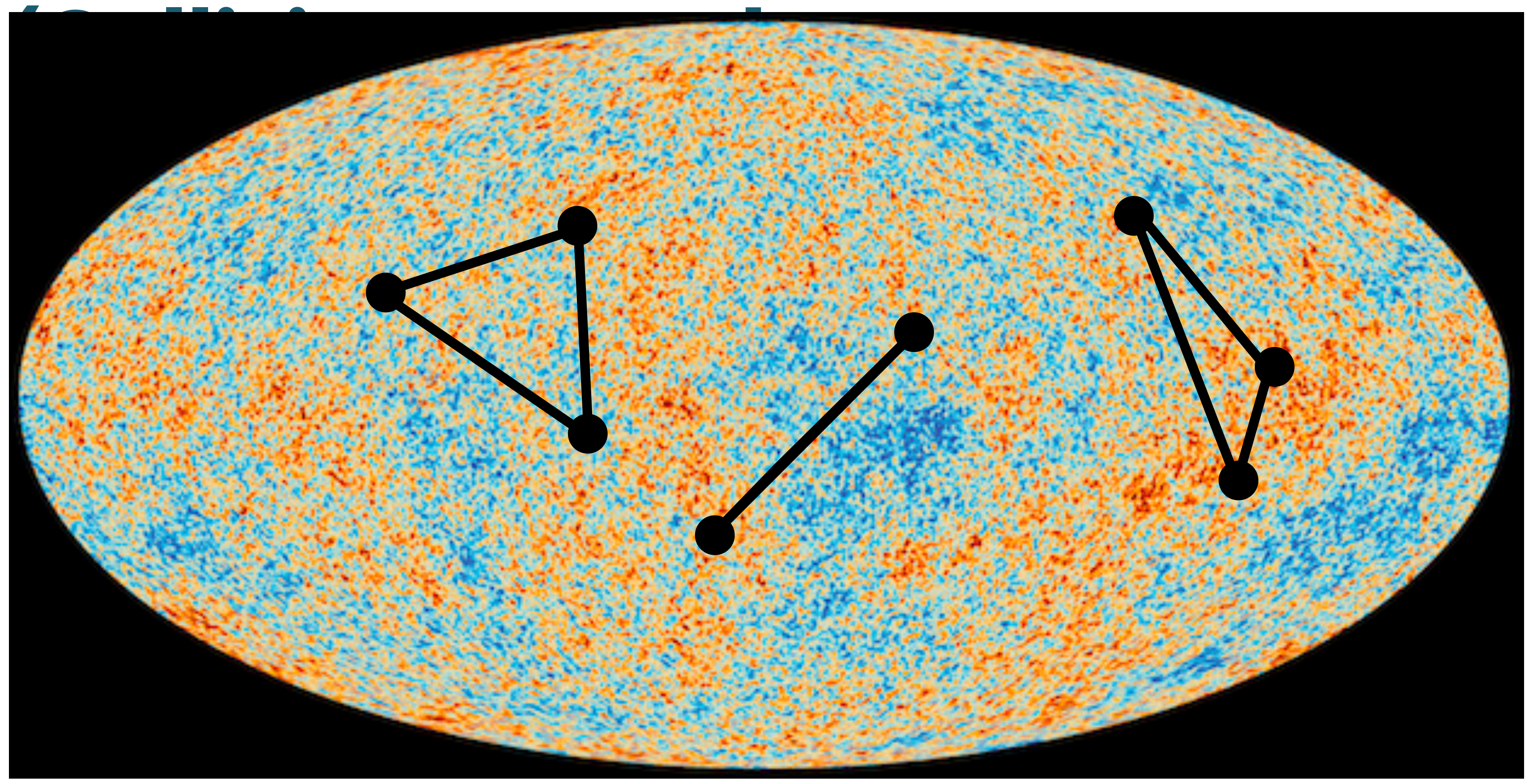


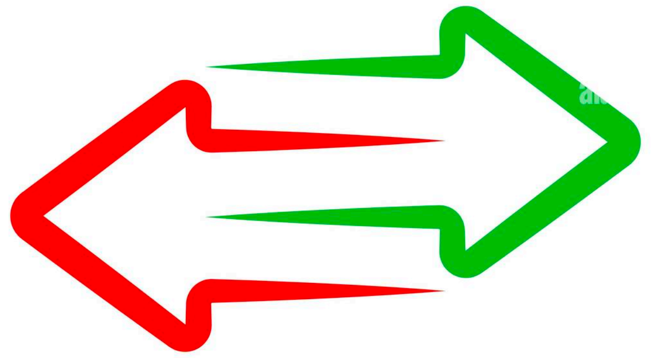
CMS Collaboration `17

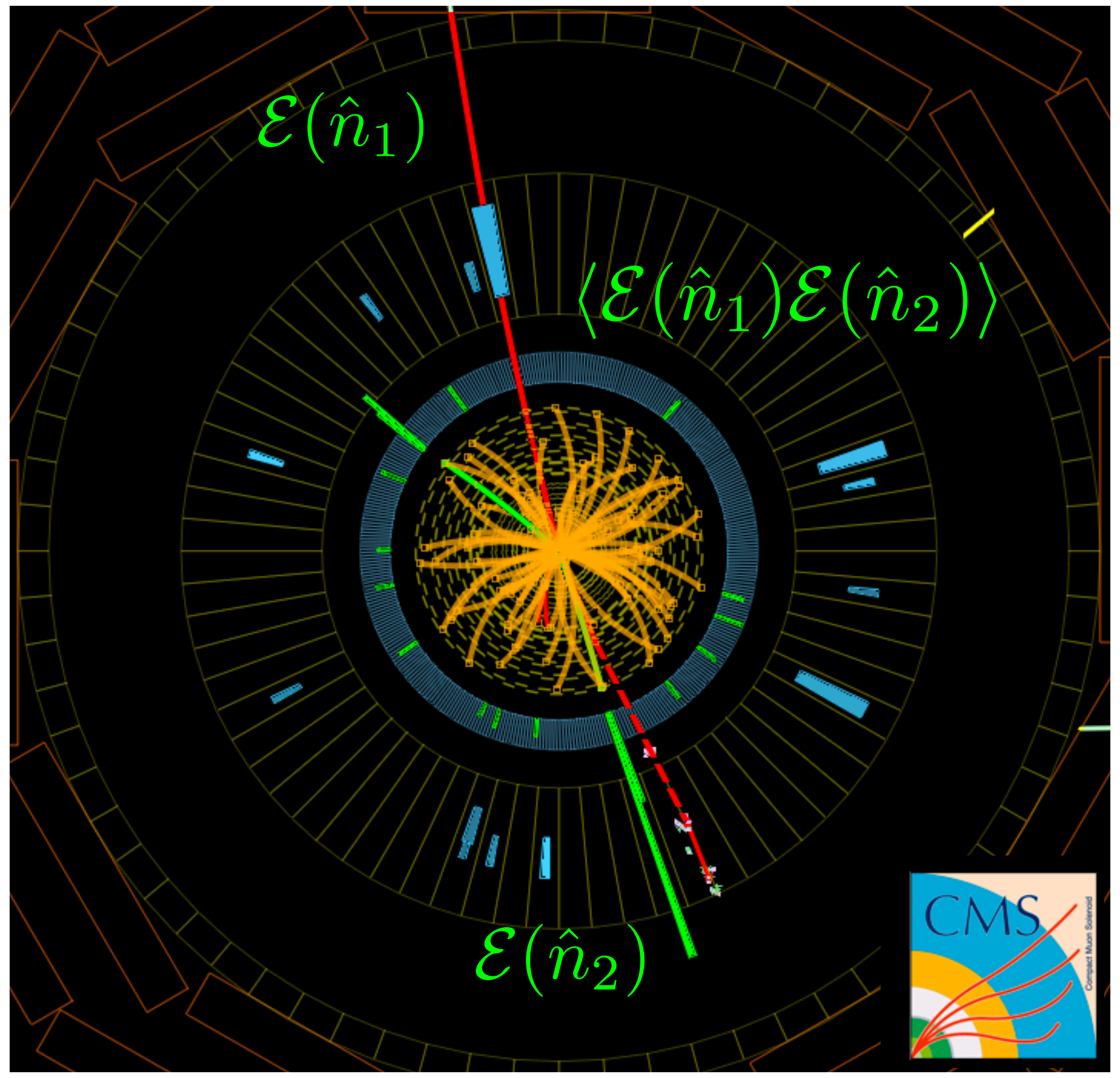
- **Since its first introduction in 2008 by Butterworth, Davison, Rubin and Salam to reconstruct Higgs along with development of $\text{anti-}k_T$ by Cacciari, Soyez, and Salam, jet substructure study has been central to collider program at the LHC and fueled much theoretic developments**

JET SUBSTRUCTURE AS CORRELATION FUNCTIONS

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



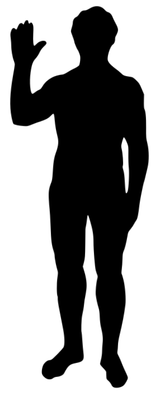


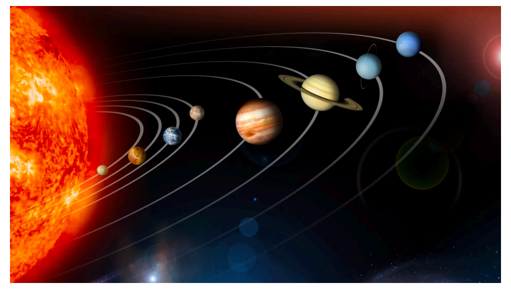


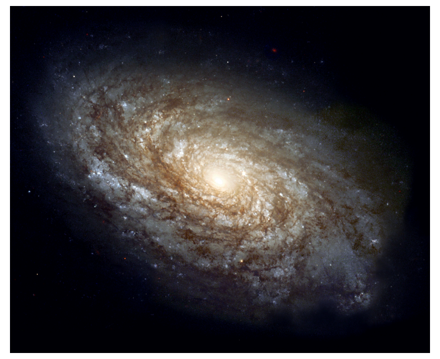
- Much like cosmology, we observe **asymptotic energy flux** at the detectors that are placed at **cosmic scale away** from where the events originated.

(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

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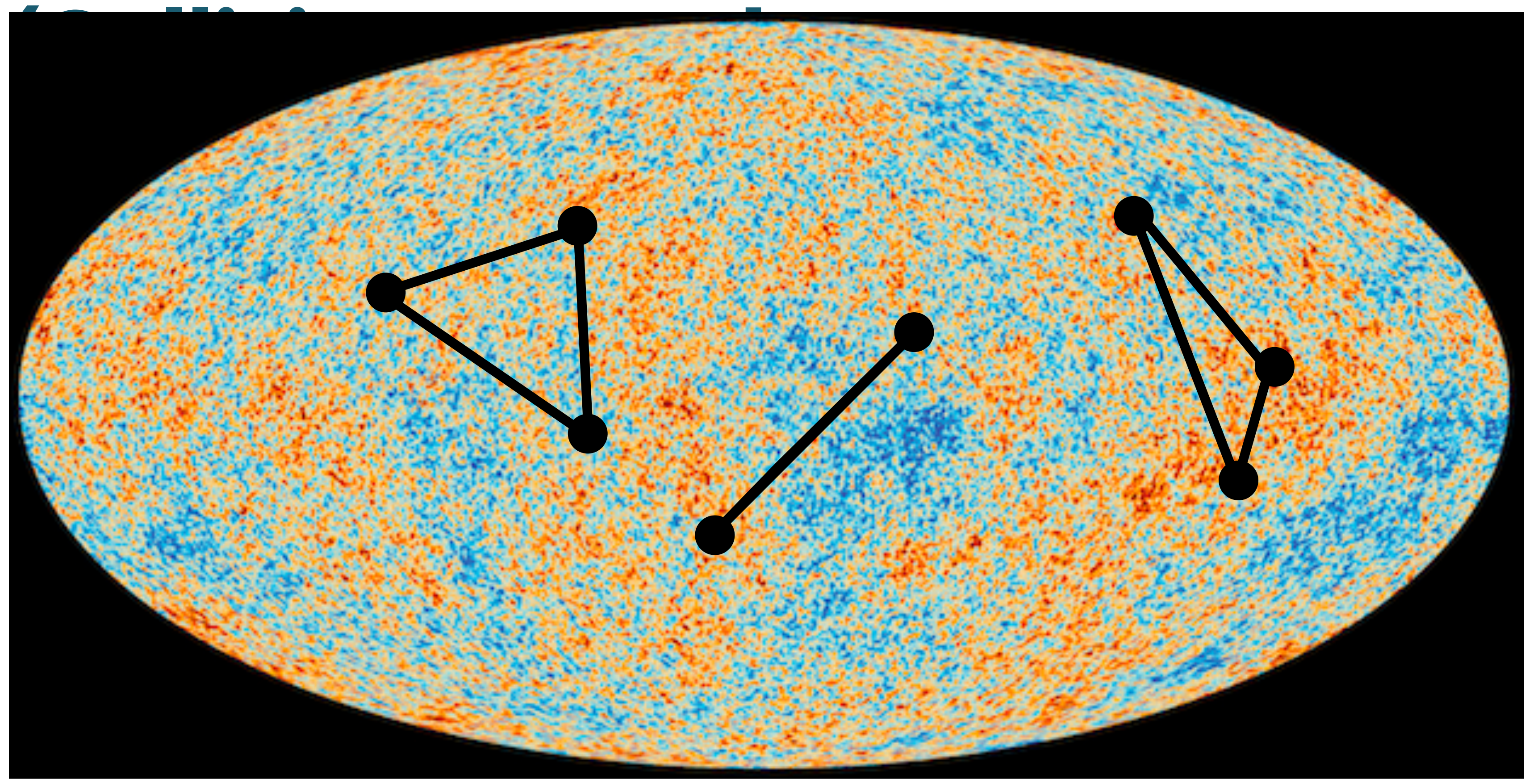
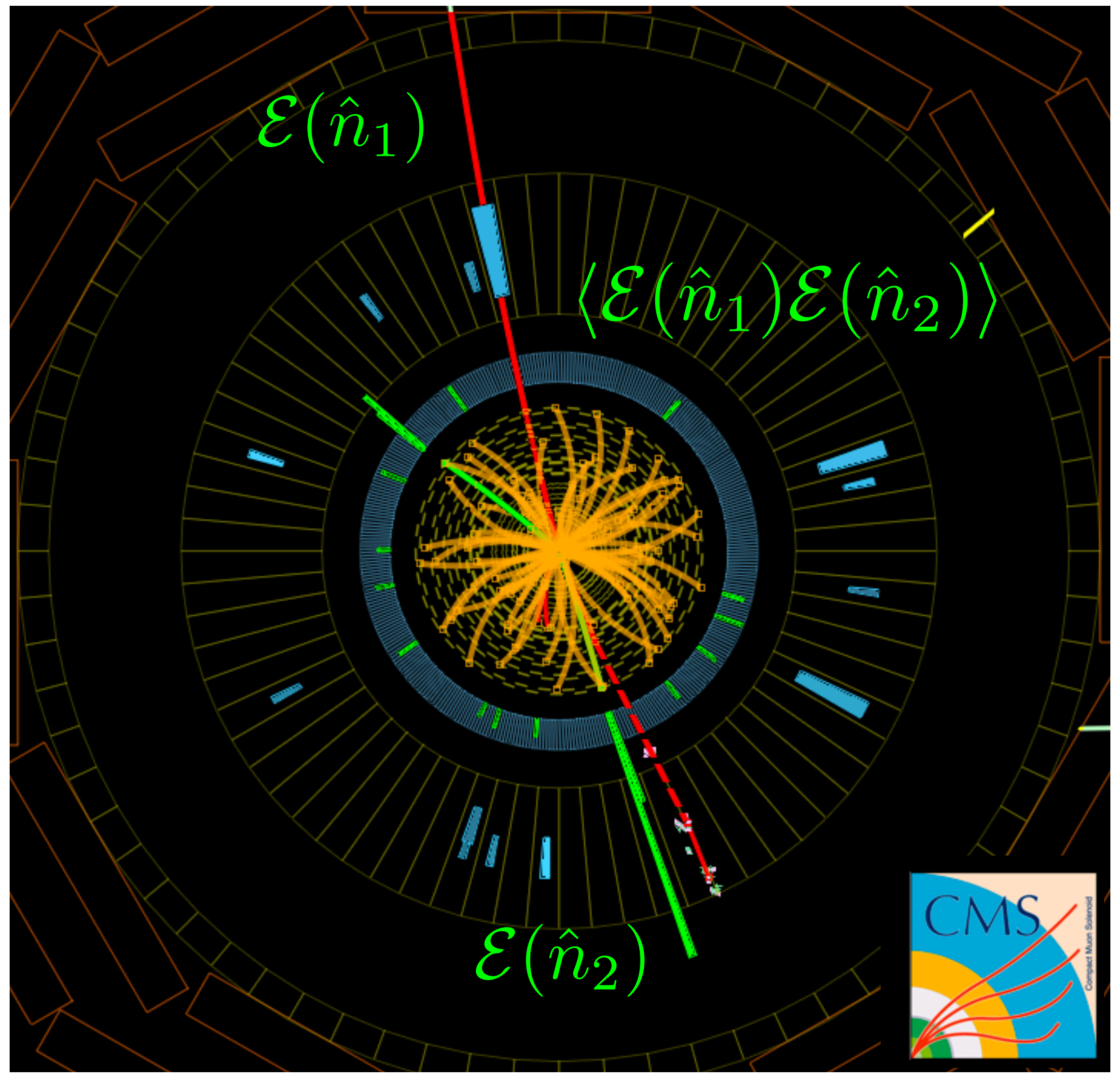
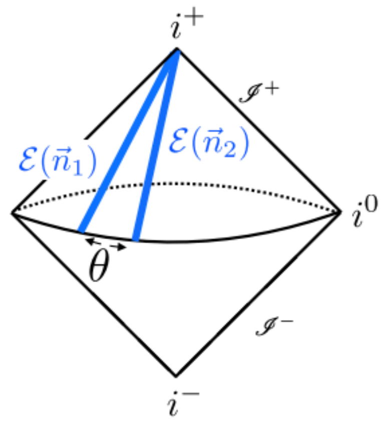




- Much like cosmology, we observe asymptotic energy flux at the detectors that are placed at cosmic scale away from where the events originated.

Energy Flow Operators (Light Ray Operators)

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

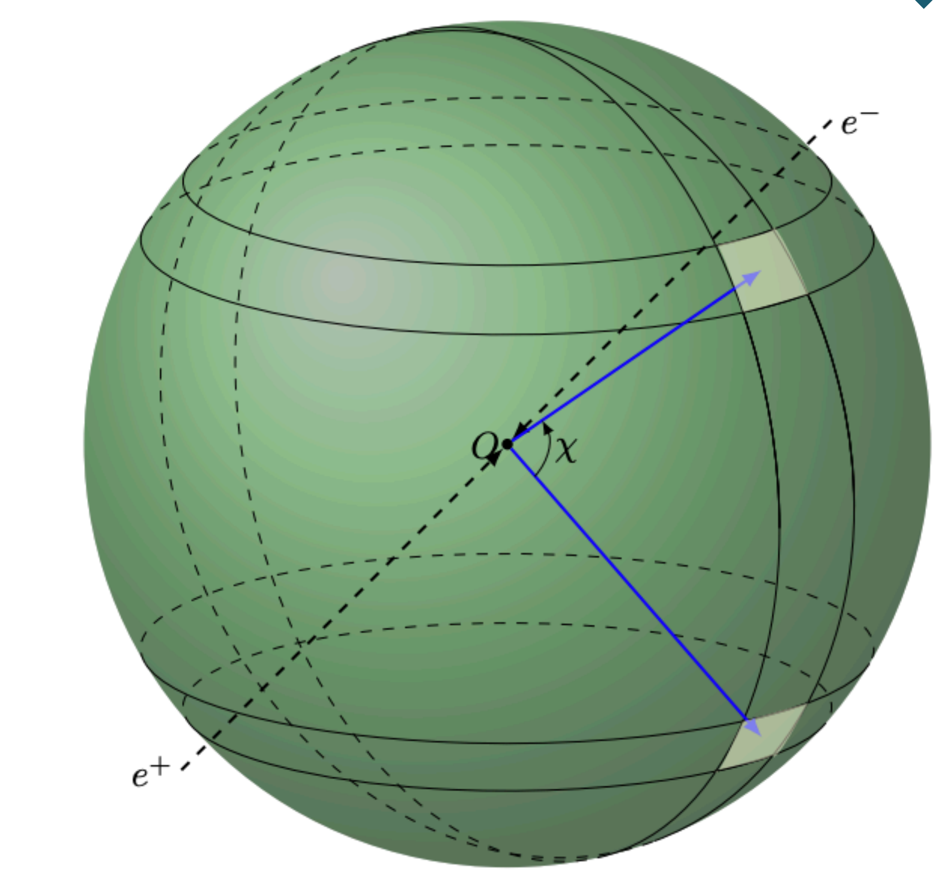


$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$

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

JET SUBSTRUCTURE AS CORRELATION FUNCTIONS

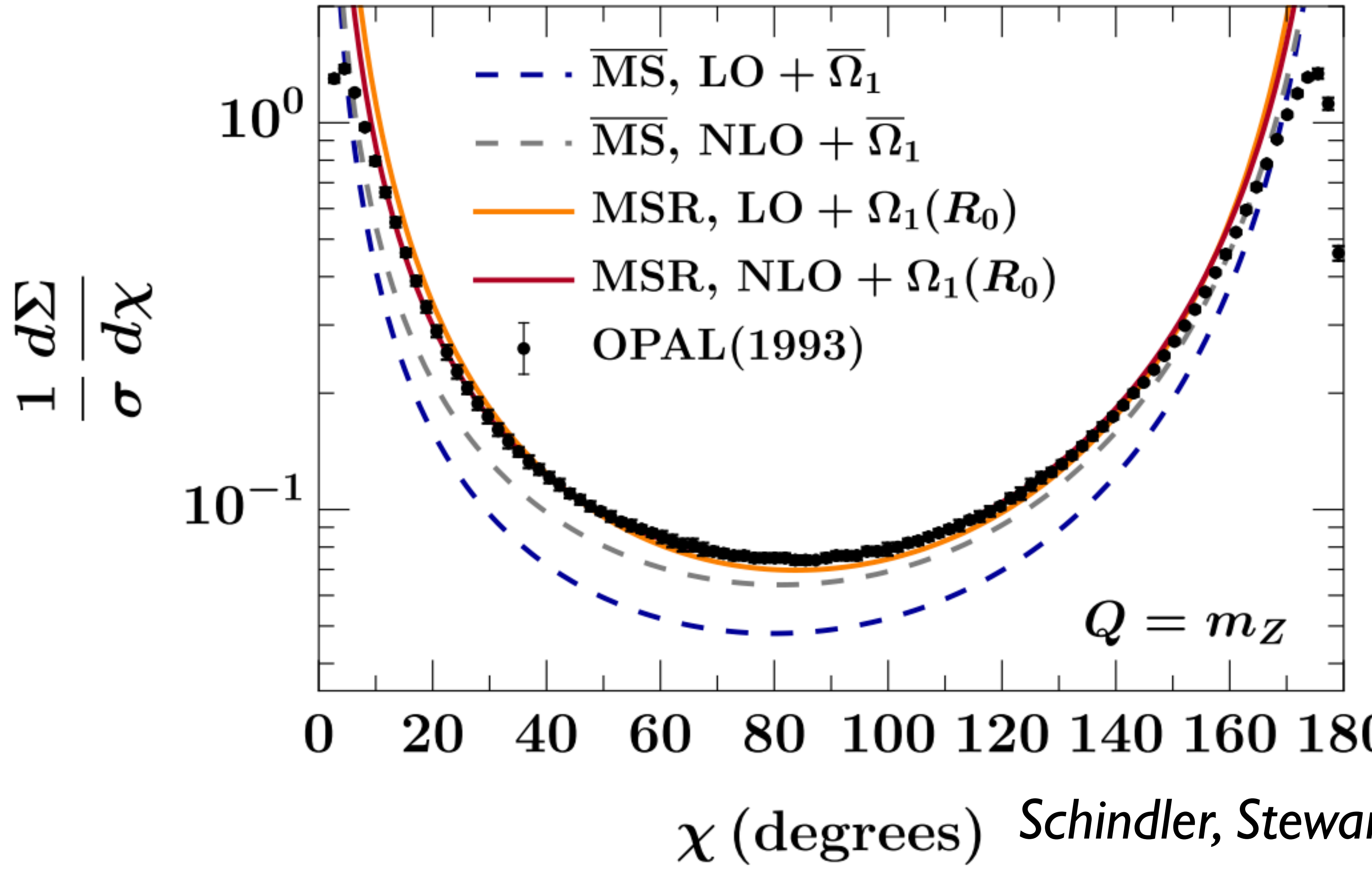
- **Indeed, energy-energy correlators are one of the very first studied event shape (or correlations) observables in QCD** *Basham, Brown, Ellis, Love, `78-79*



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

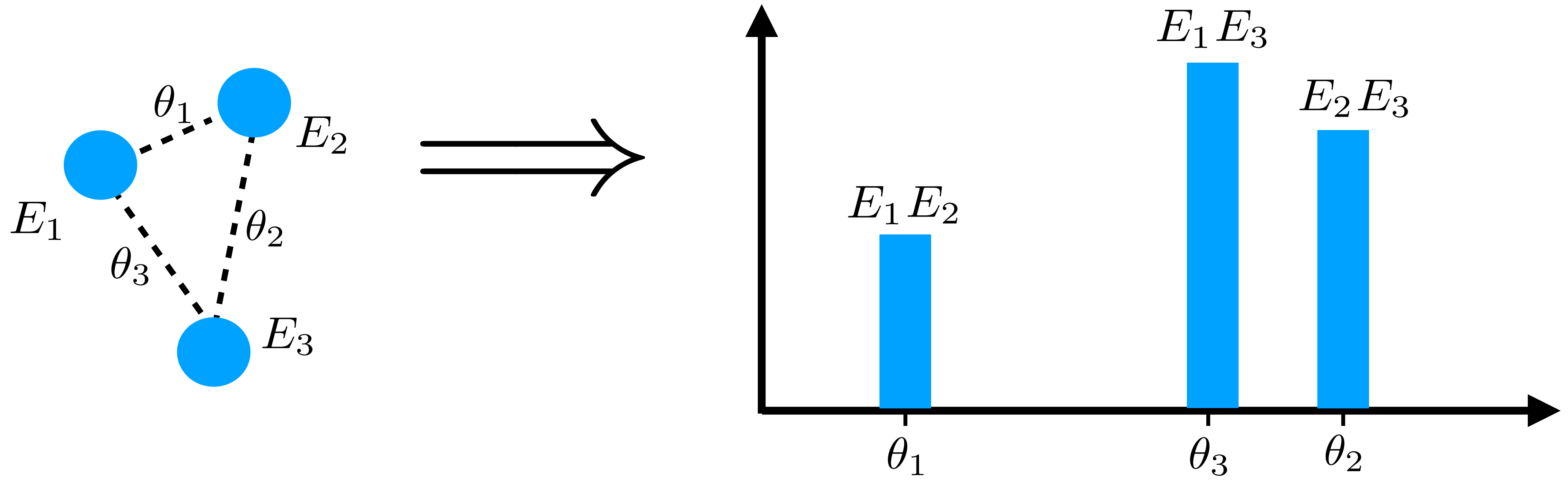
Many precise calculations!

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

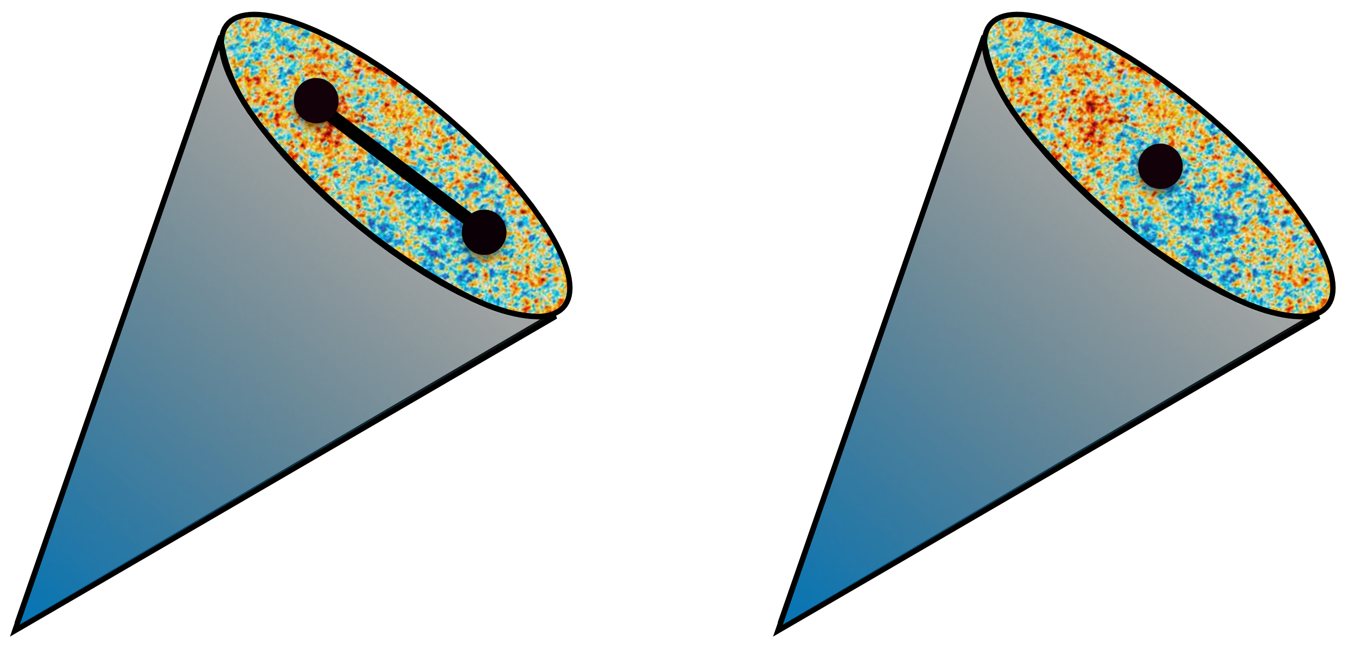
Impressive agreements from recent calculation, without any fits!



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

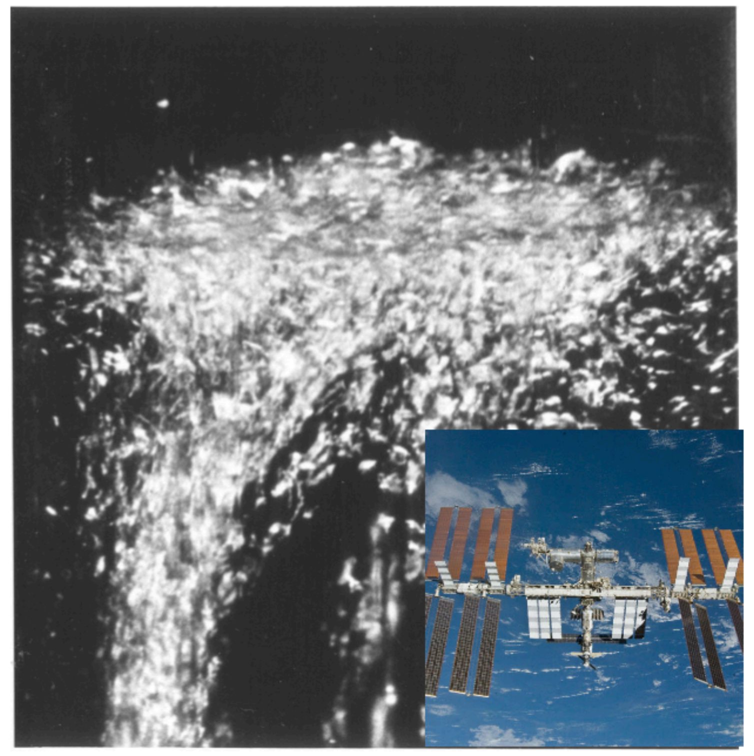
Weighted cross-section, or, ensemble averaged observable

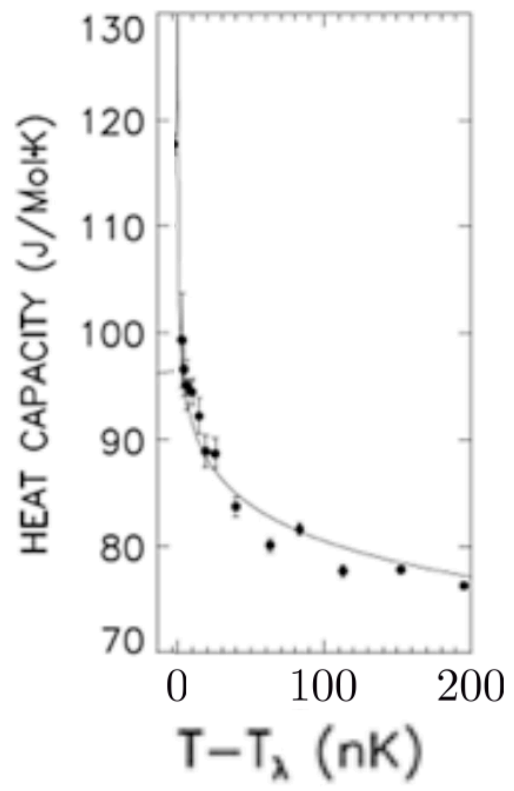
JET SUBSTRUCTURE AS CORRELATION FUNCTIONS



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

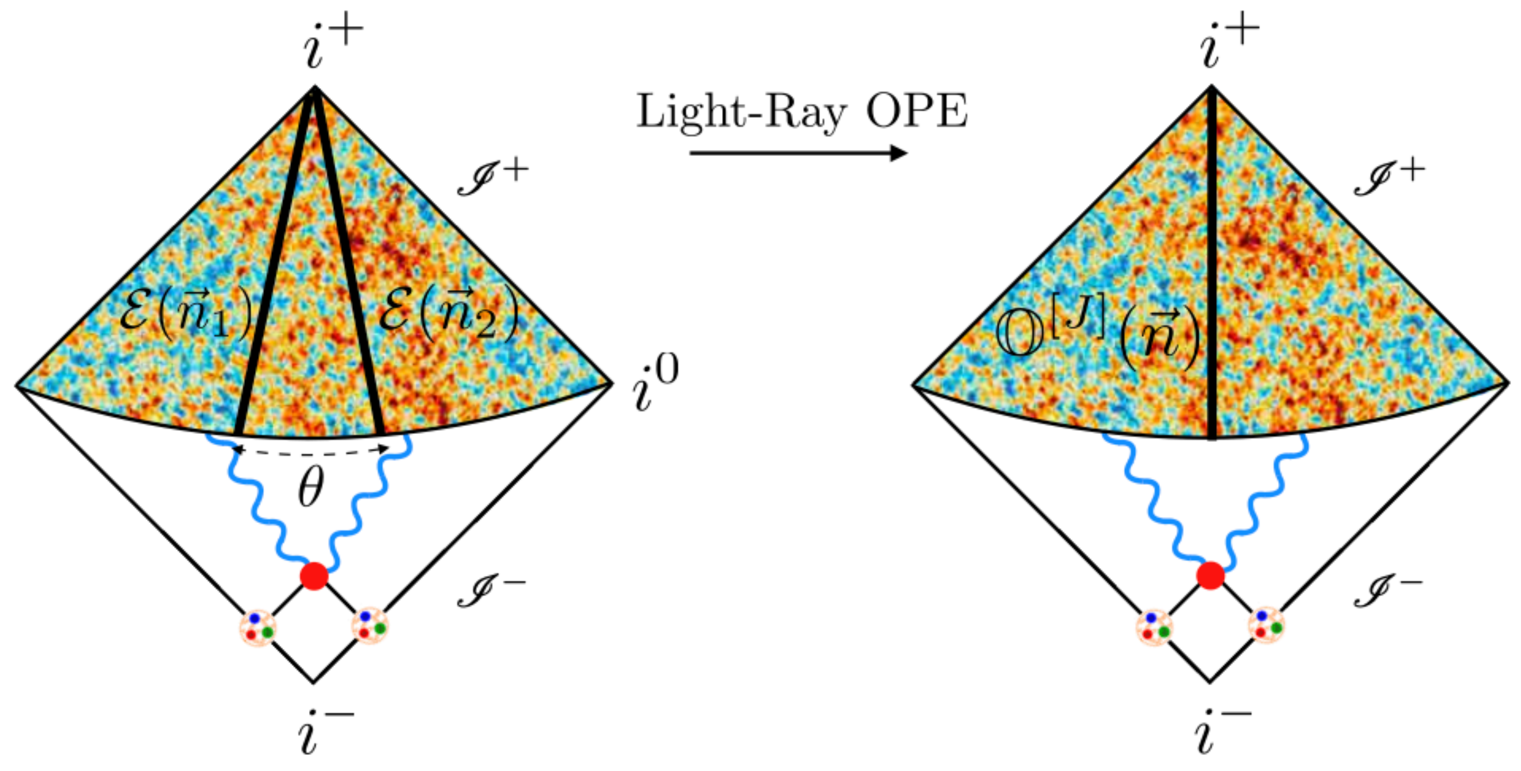
- **Field theory often predicts universal scaling as operators approach each other**





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

$\Longleftrightarrow$



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

Hofman, Maldacena, \`08

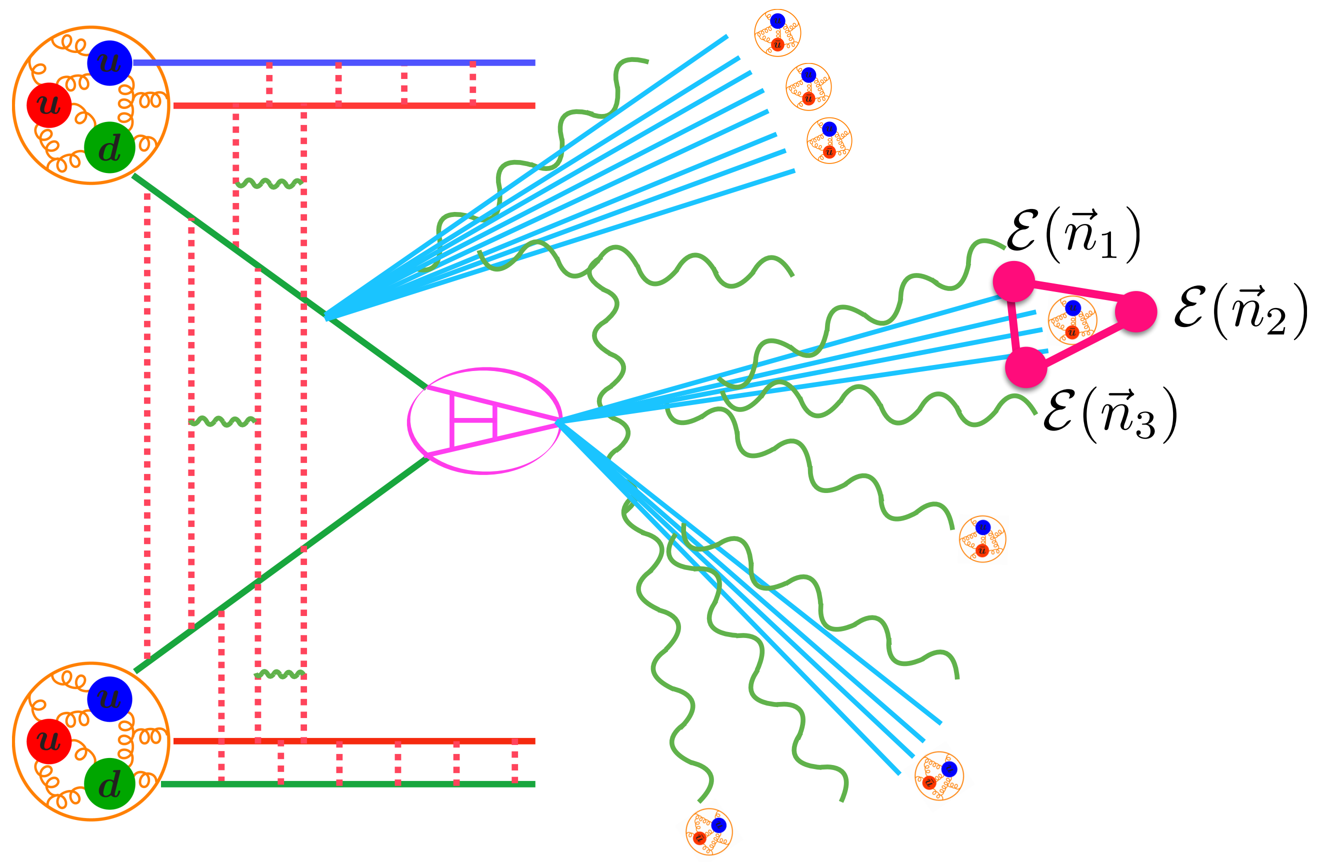
Much interests from the formal theory:

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 OPERATORS BE OBSERVED IN JETS AT THE LHC???

CONFORMAL COLLIDERS MEET THE LHC

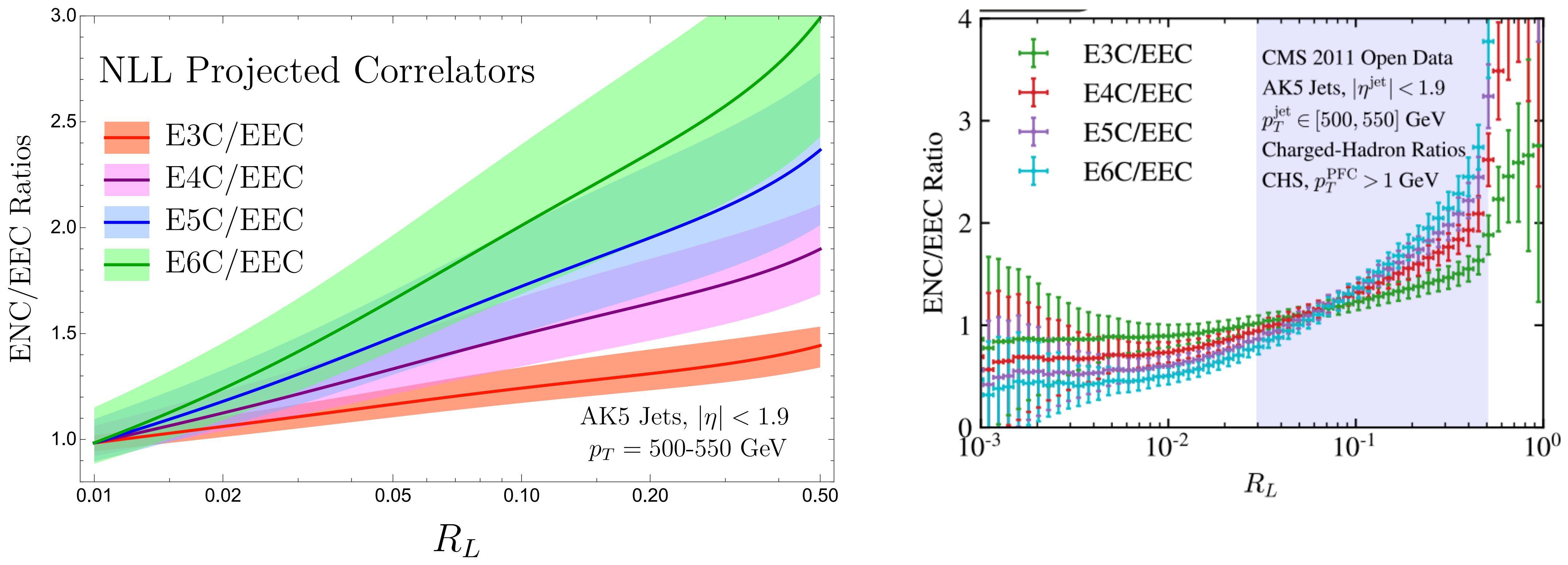
2019/2020



Rethinking Jets with Energy Correlators

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

2022



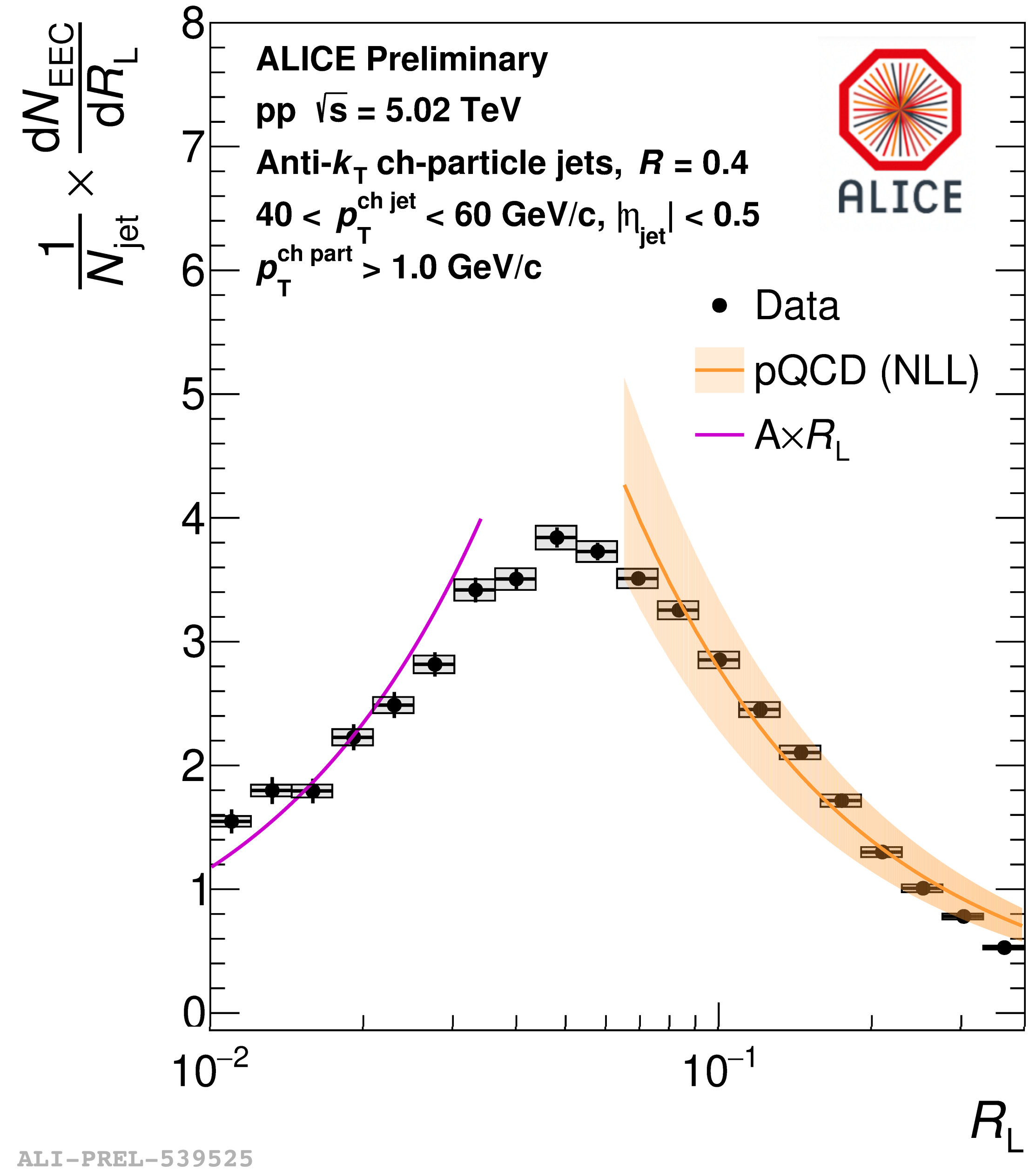
Open data analyses and QCD Factorization

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

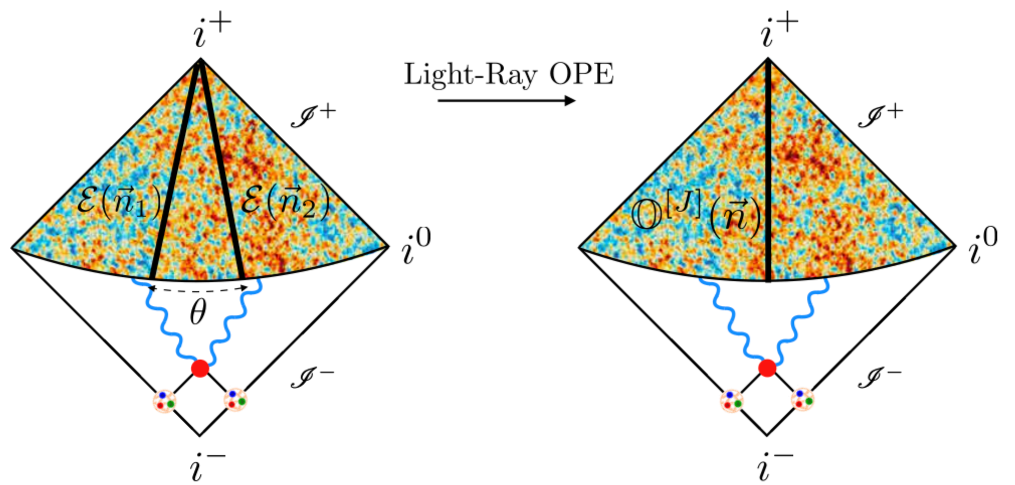
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\,\mathbb{O}_i(\hat{n}_1)$$

2023

ALICE `23



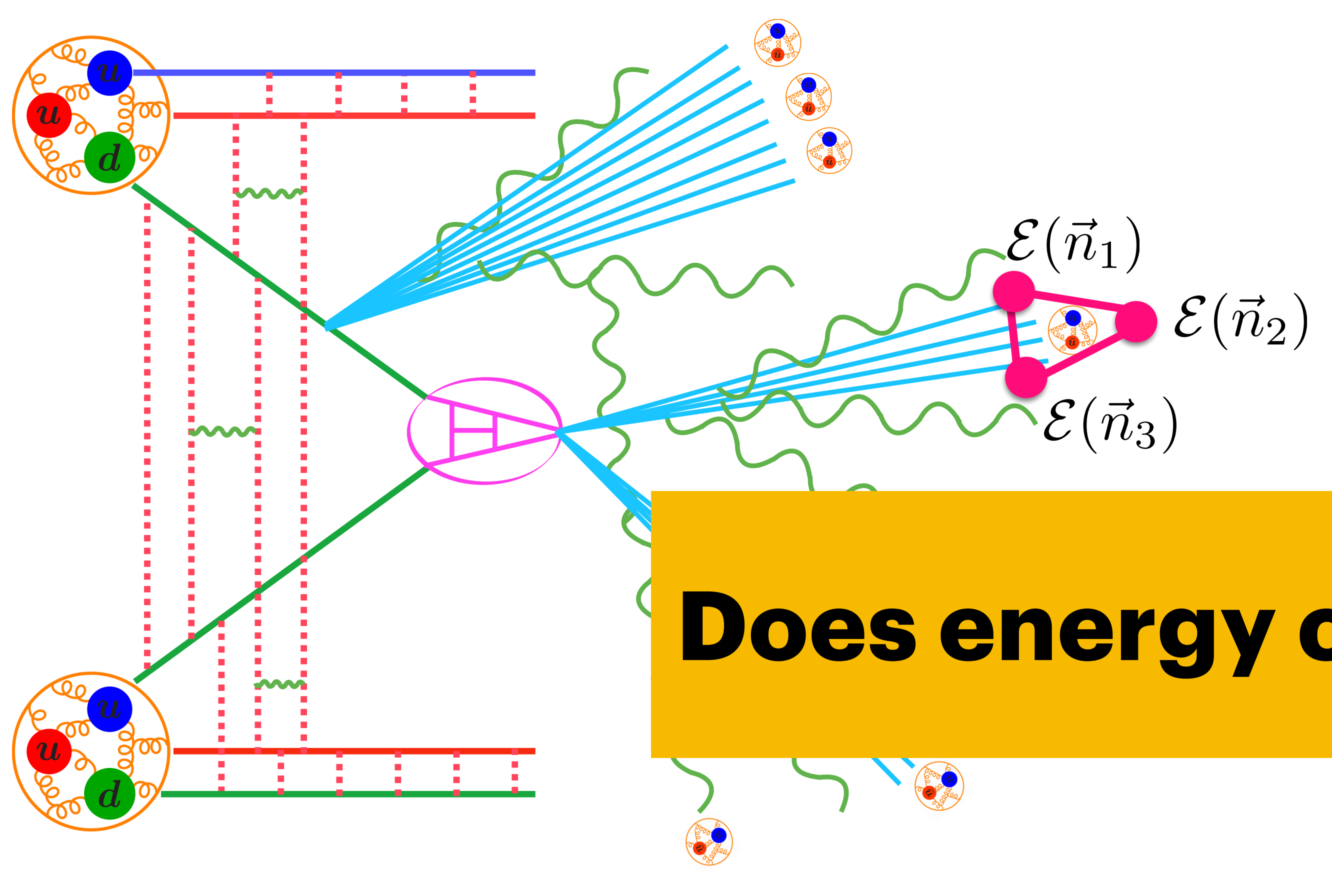
Real Data analyses at the LHC



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

CONFORMAL COLLIDERS MEET THE LHC

2019/2020



Rethinking Jets with Energy Correlators

Chen, Moult, Zhang, Zhu `20
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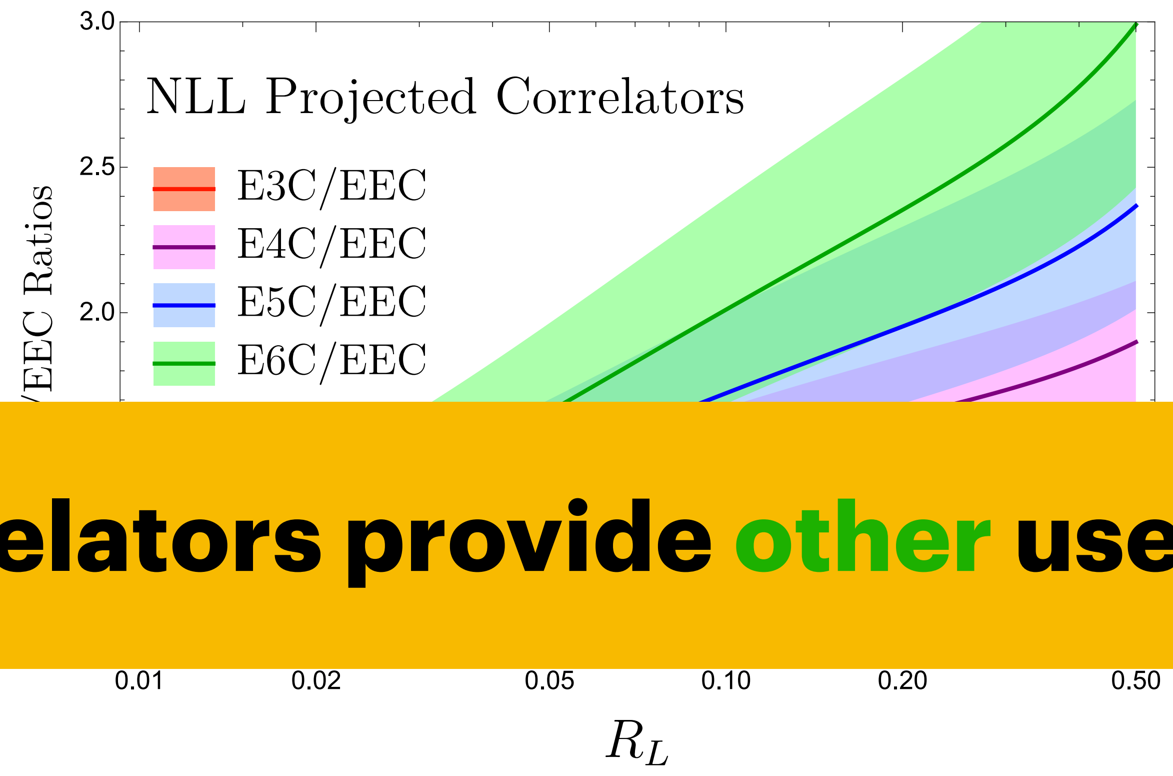
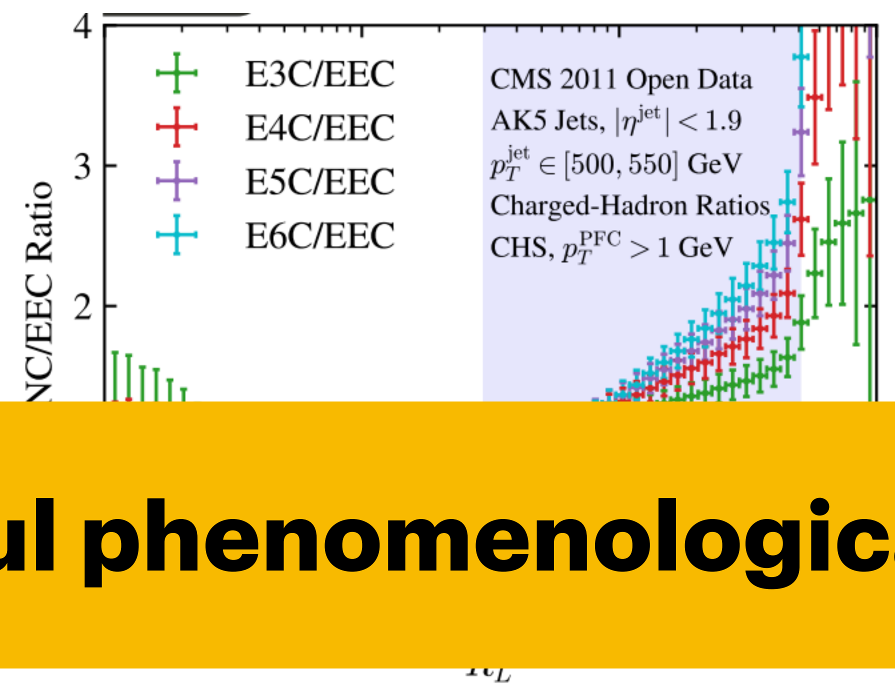
2022





Does energy correlators provide other useful phenomenological applications?

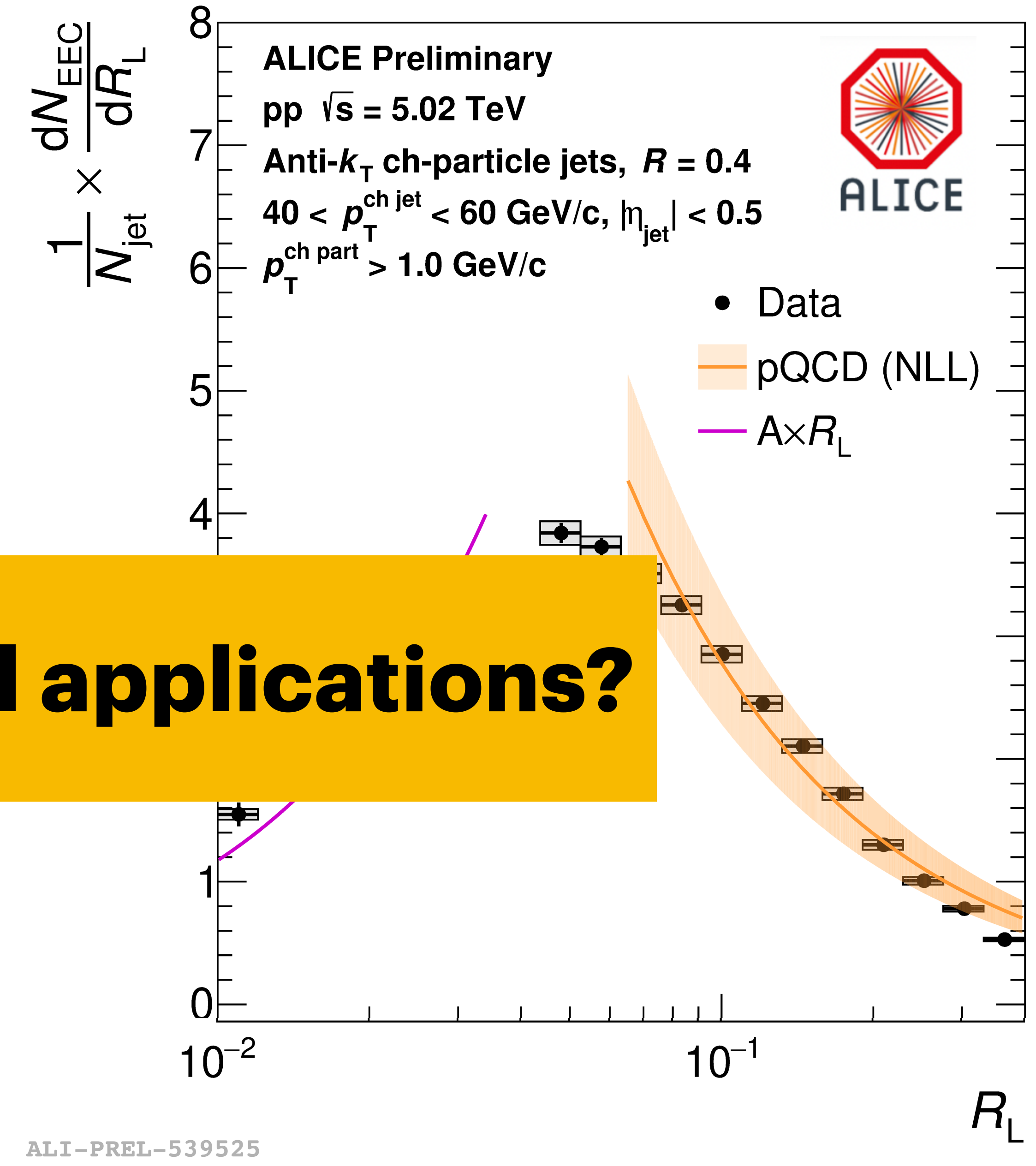
Open data analyses and QCD Factorization

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

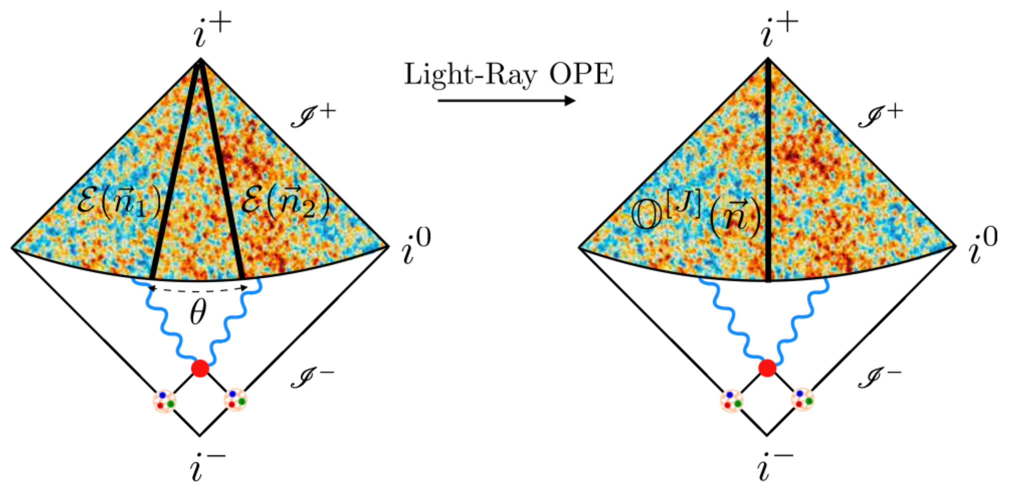
$$\mathcal{E}(\hat{n}_1)\,\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\,\mathbb{O}_i(\hat{n}_1)$$

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!

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

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100 MeV - 500 GeV
Heart
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
Rethinking jet substructure using energy correlators provide powerful framework for phenomenological applications!

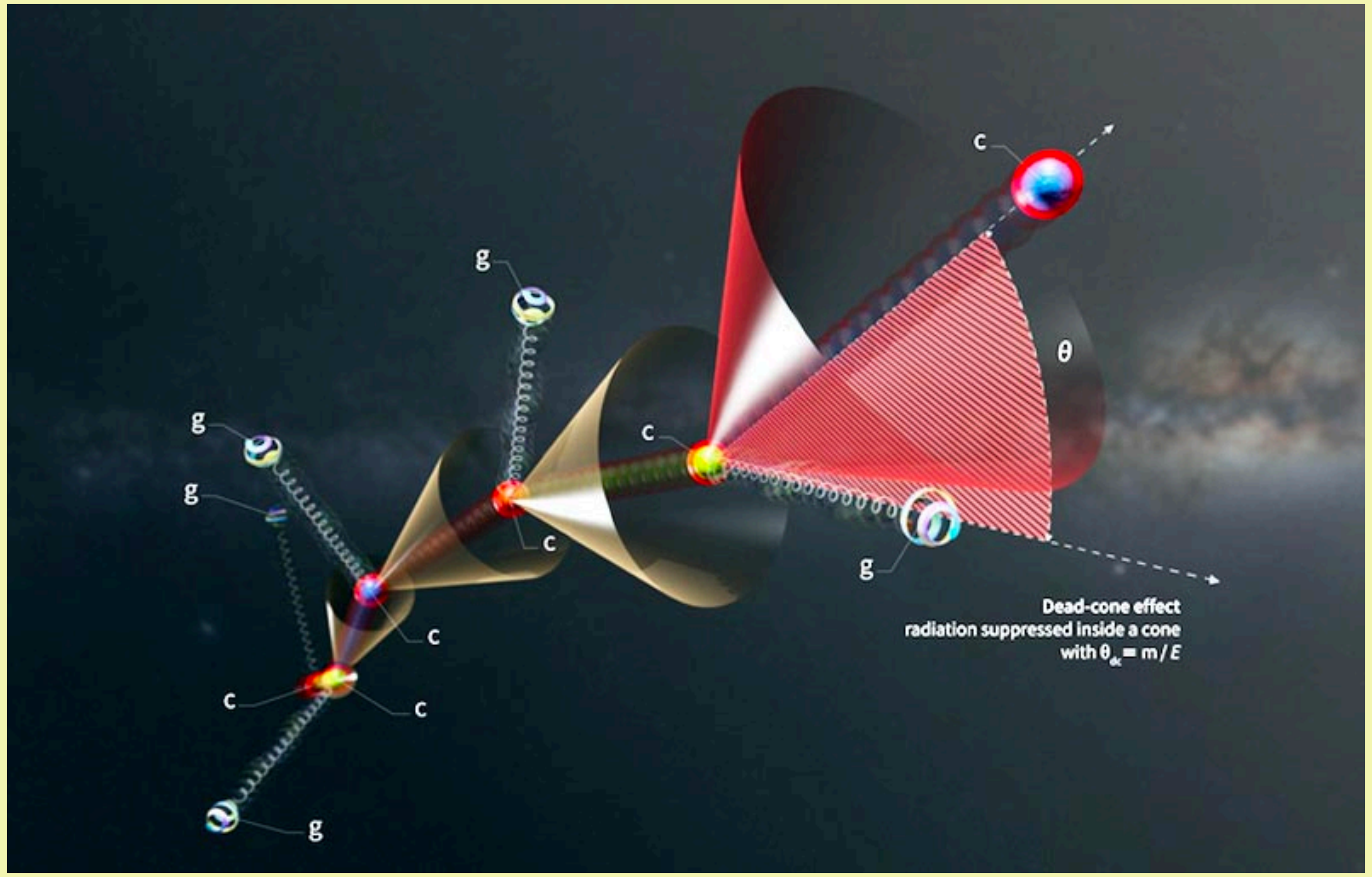
Heavy flavor physics
(Beauty and charm)

1 - 5 GeV

GOAL

HOW DO WE UNDERSTAND HEAVY FLAVOR PHYSICS?

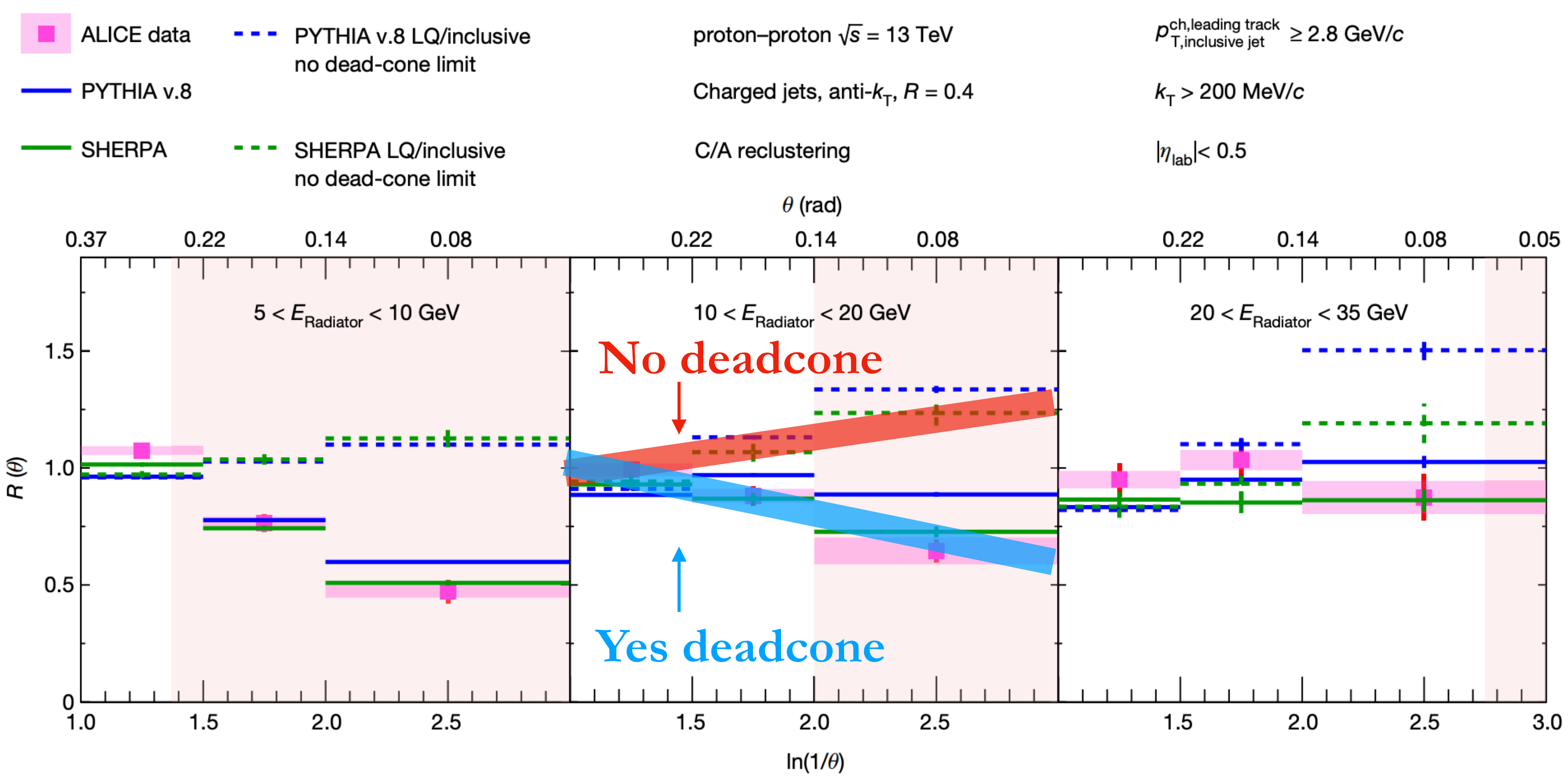
IMPROVING OUR UNDERSTANDING OF MASS EFFECTS

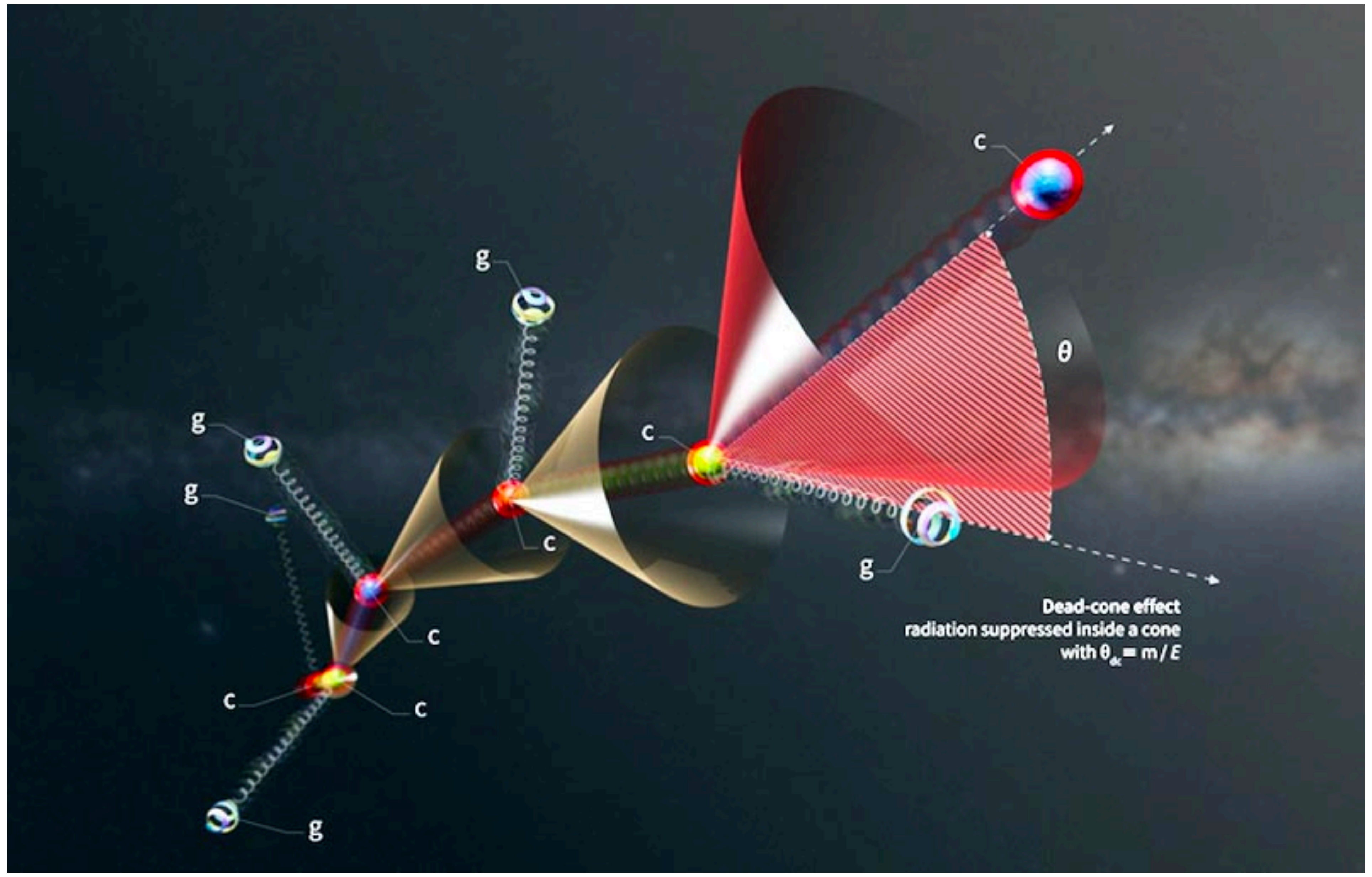


VERY FIRST DIRECT DETECTION OF DEADCONE

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

nature





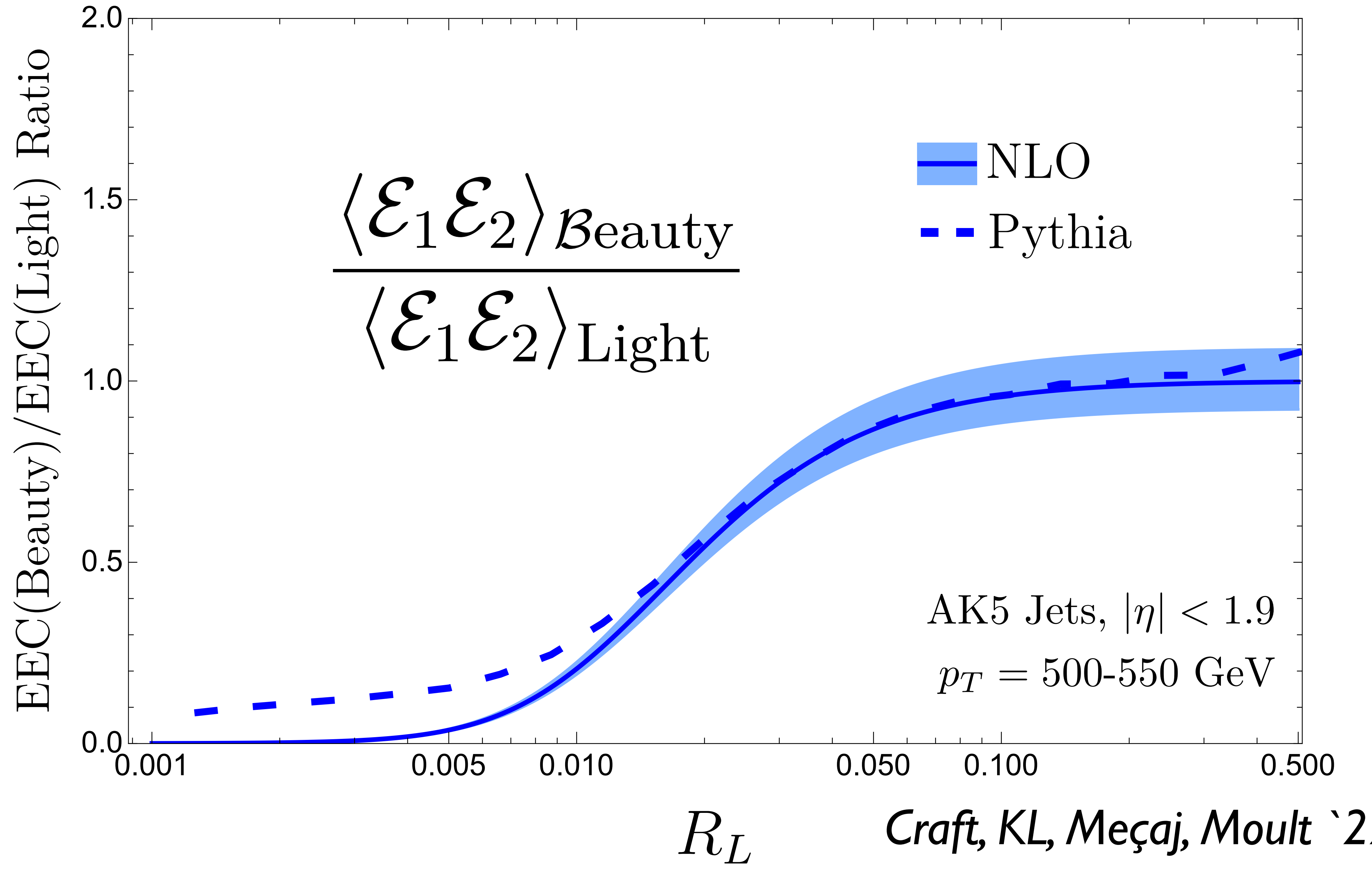
[ALICE 2022]

BEAUTIFUL AND CHARMING ENERGY CORRELATORS

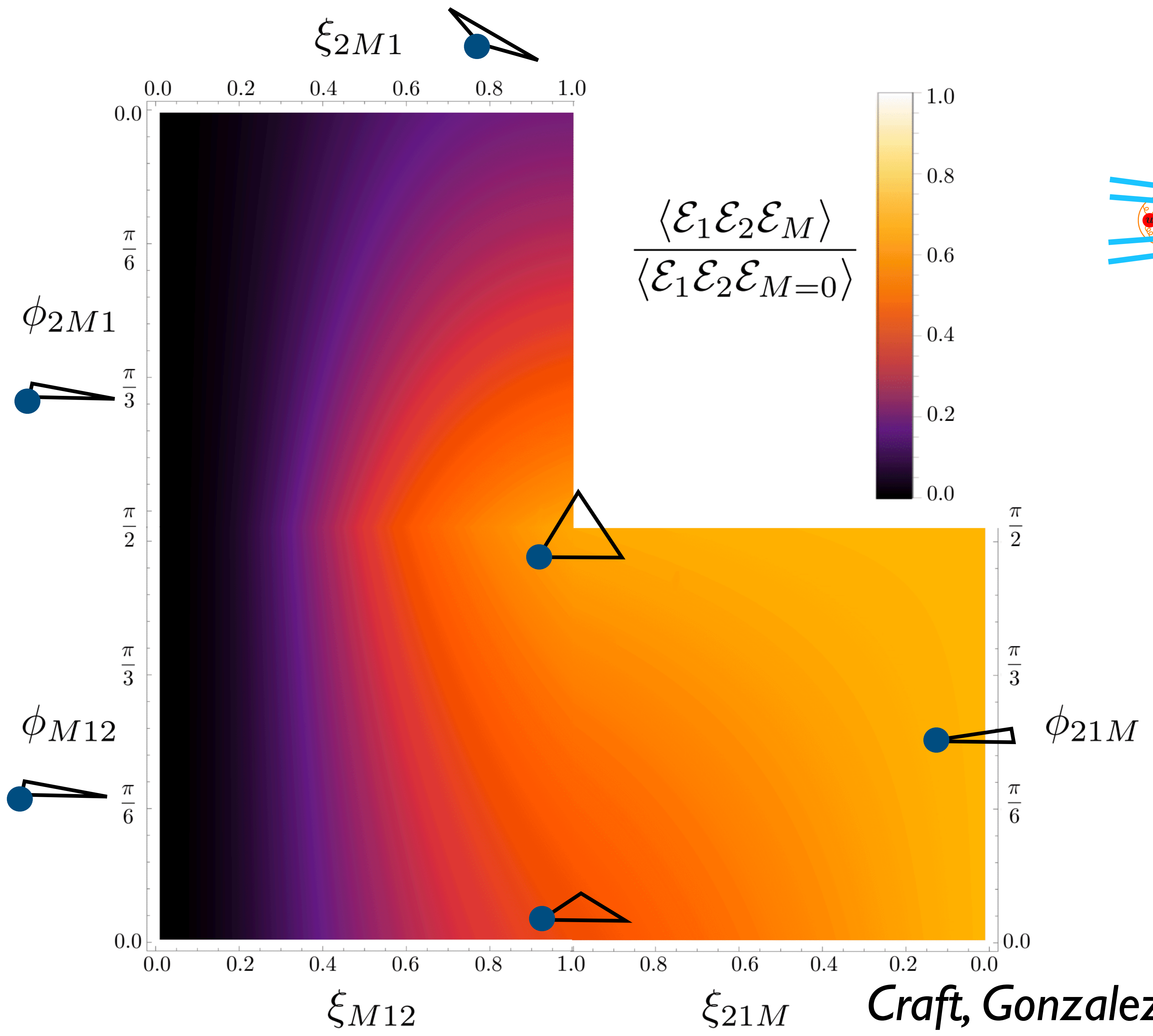
- **One can statistically measure the gluon suppression (dead cone) within the heavy jets as compared to the light jets by taking the ratio of energy correlators.**

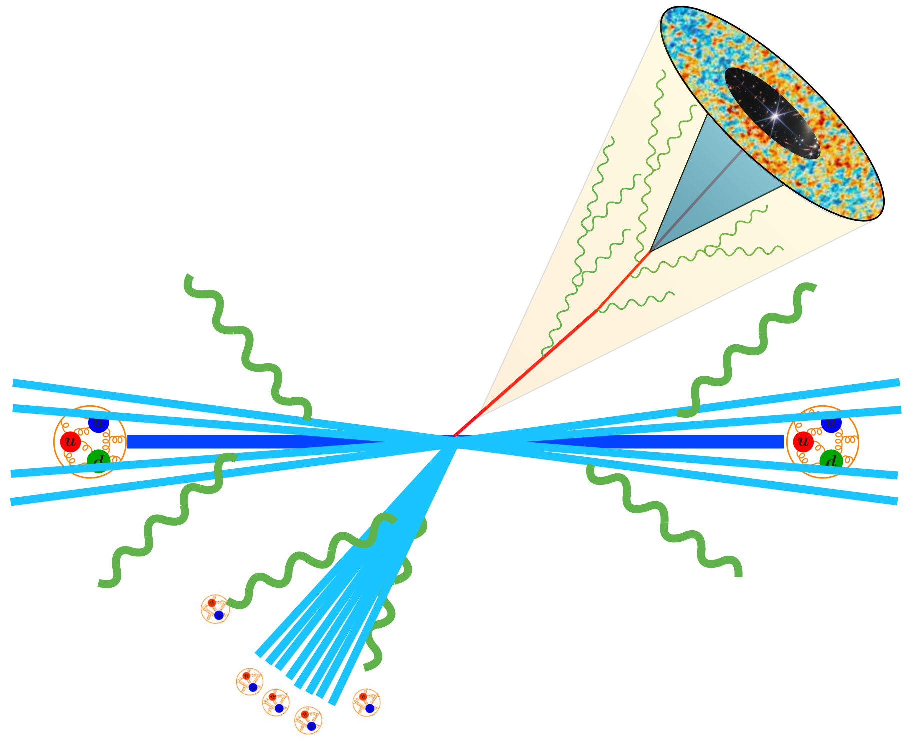
scale knob

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



Craft, KL, Meçaj, Moult `22





Craft, Gonzalez, KL, Meçaj, Moult `23

- **Higher-point structure provides nontrivial shape information**

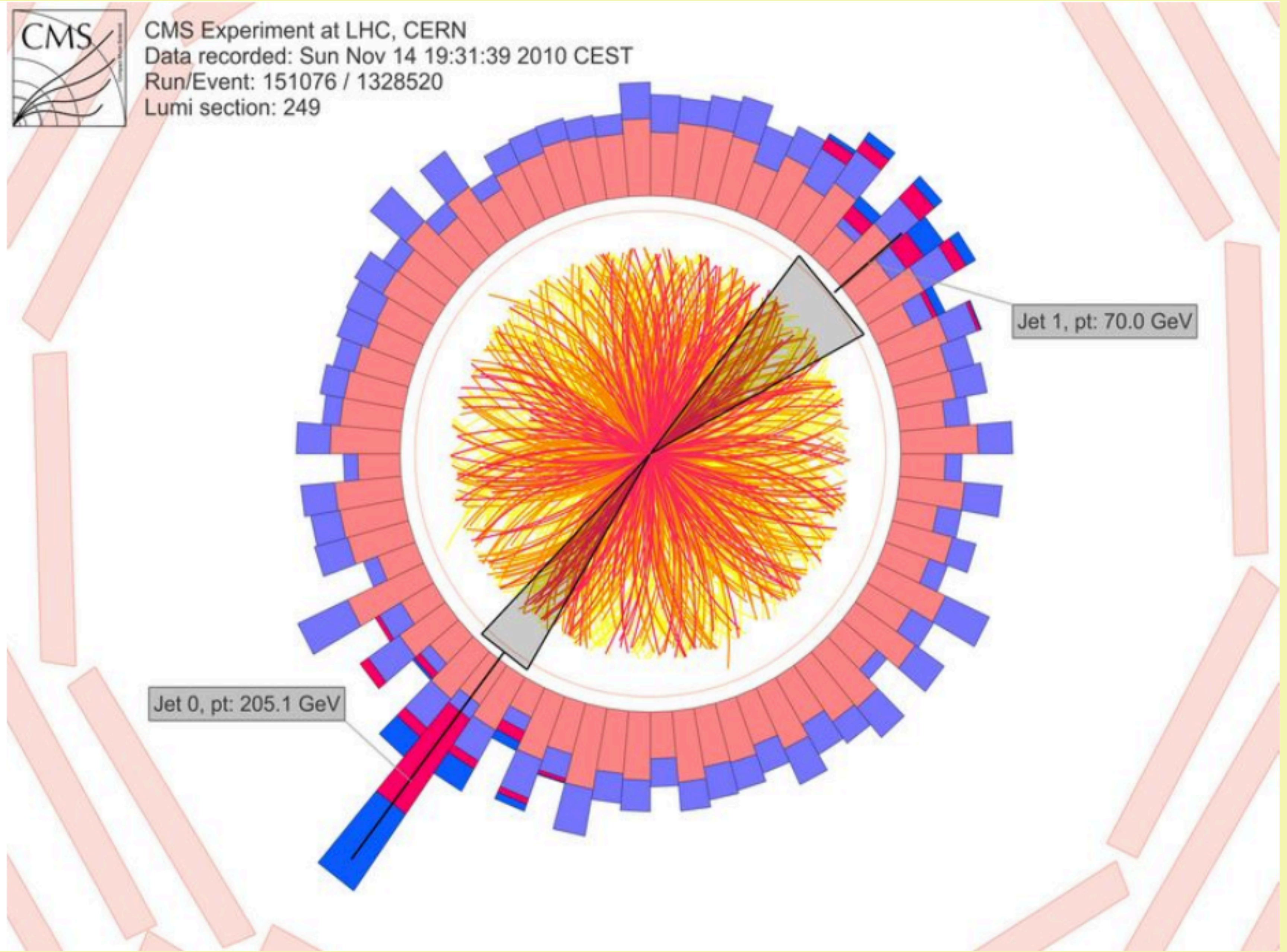
Heavy-ion physics

100 MeV - 500 GeV

GOAL

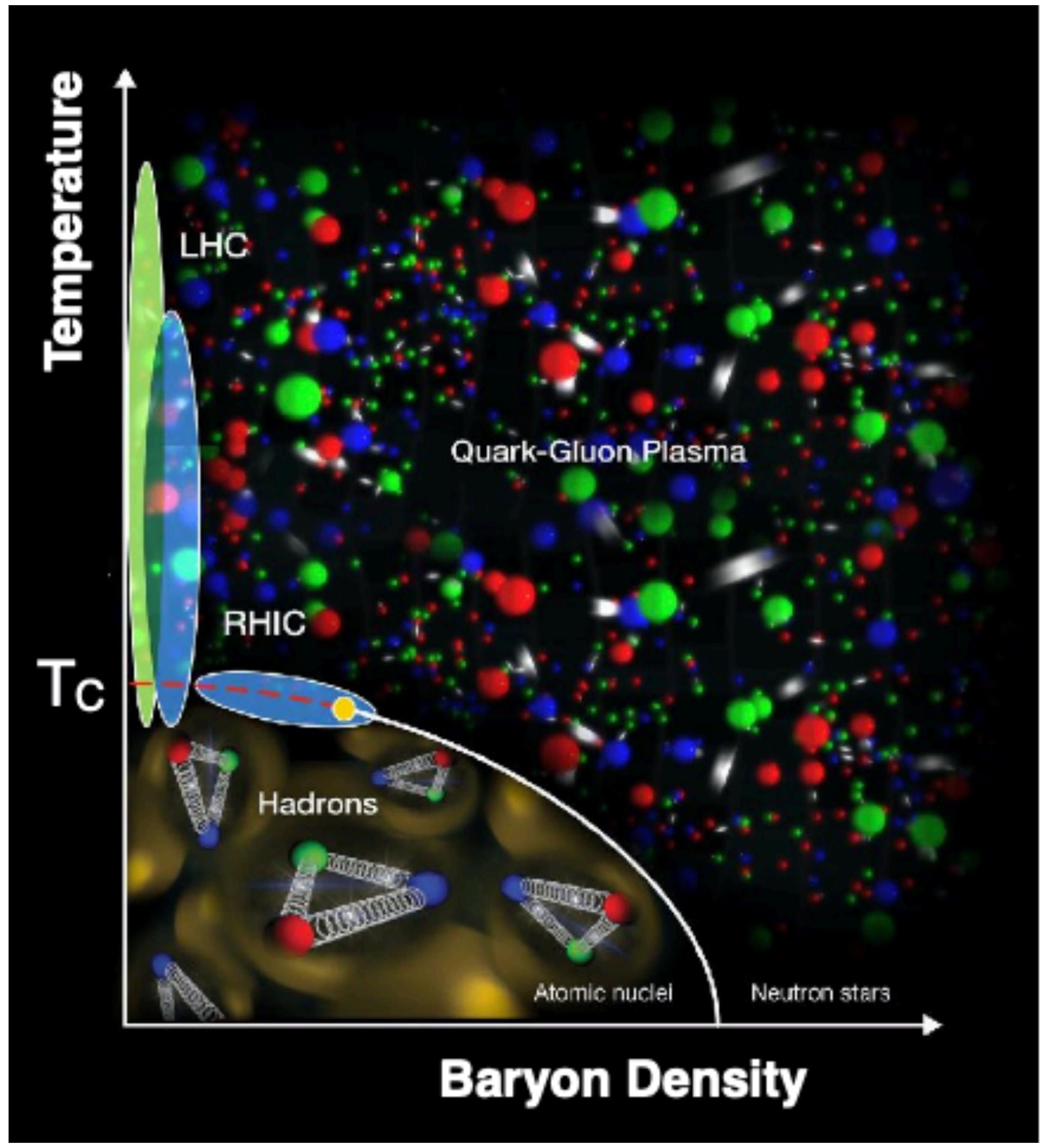
WHAT IS THE CONDITION OF OUR EARLY UNIVERSE?

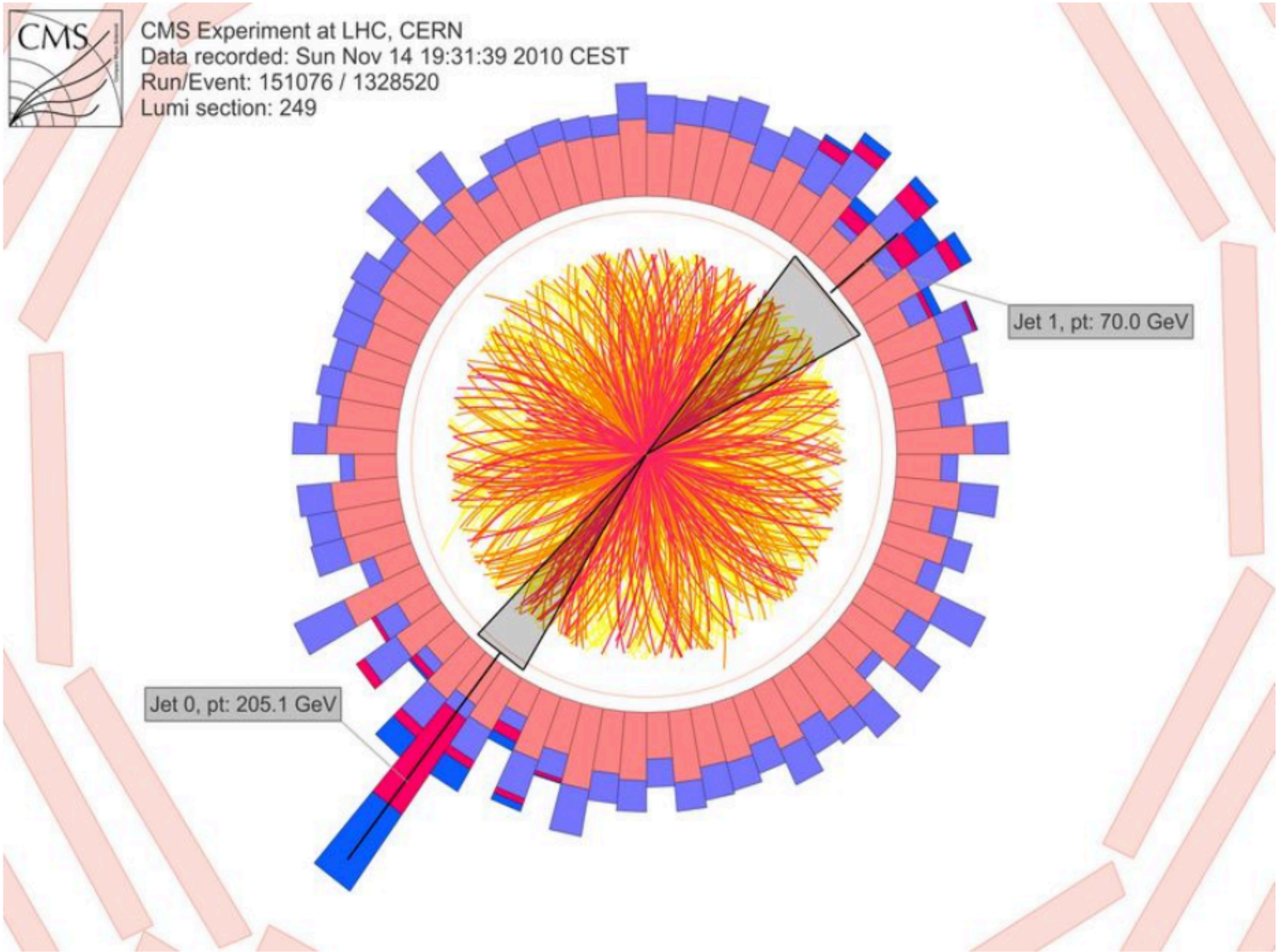
IMPROVING OUR UNDERSTANDING OF MEDIUM PROPERTIES



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.**

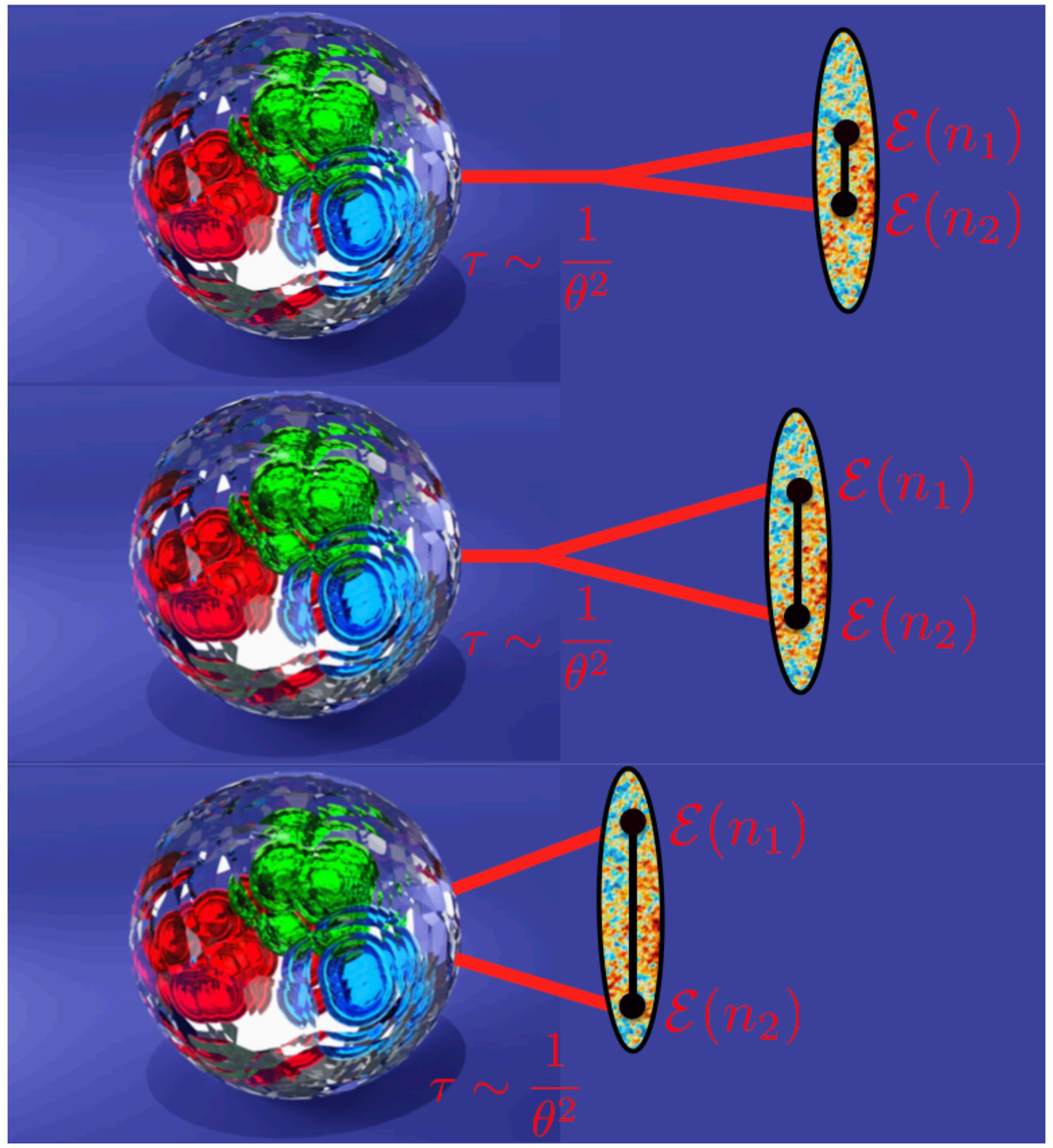


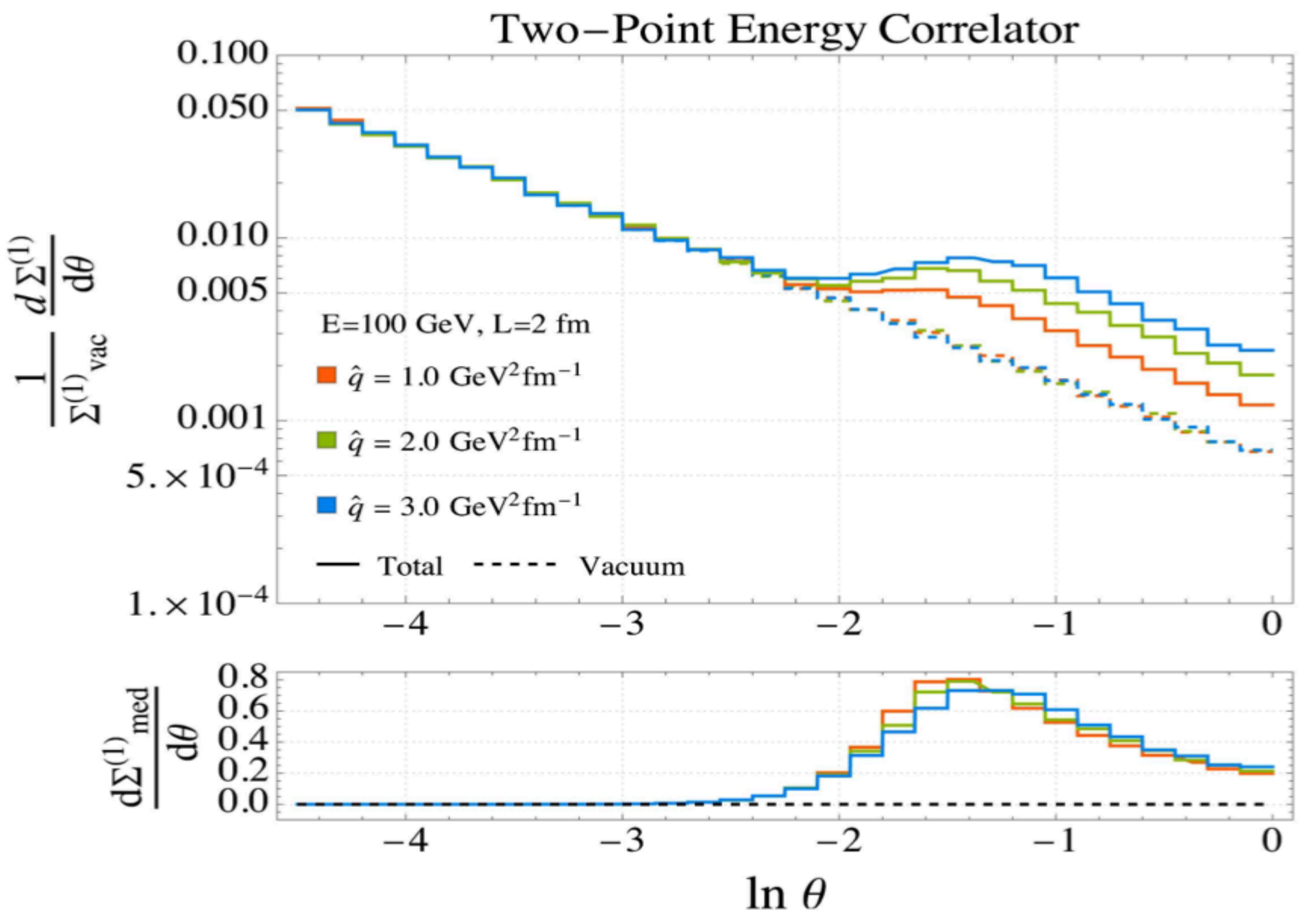


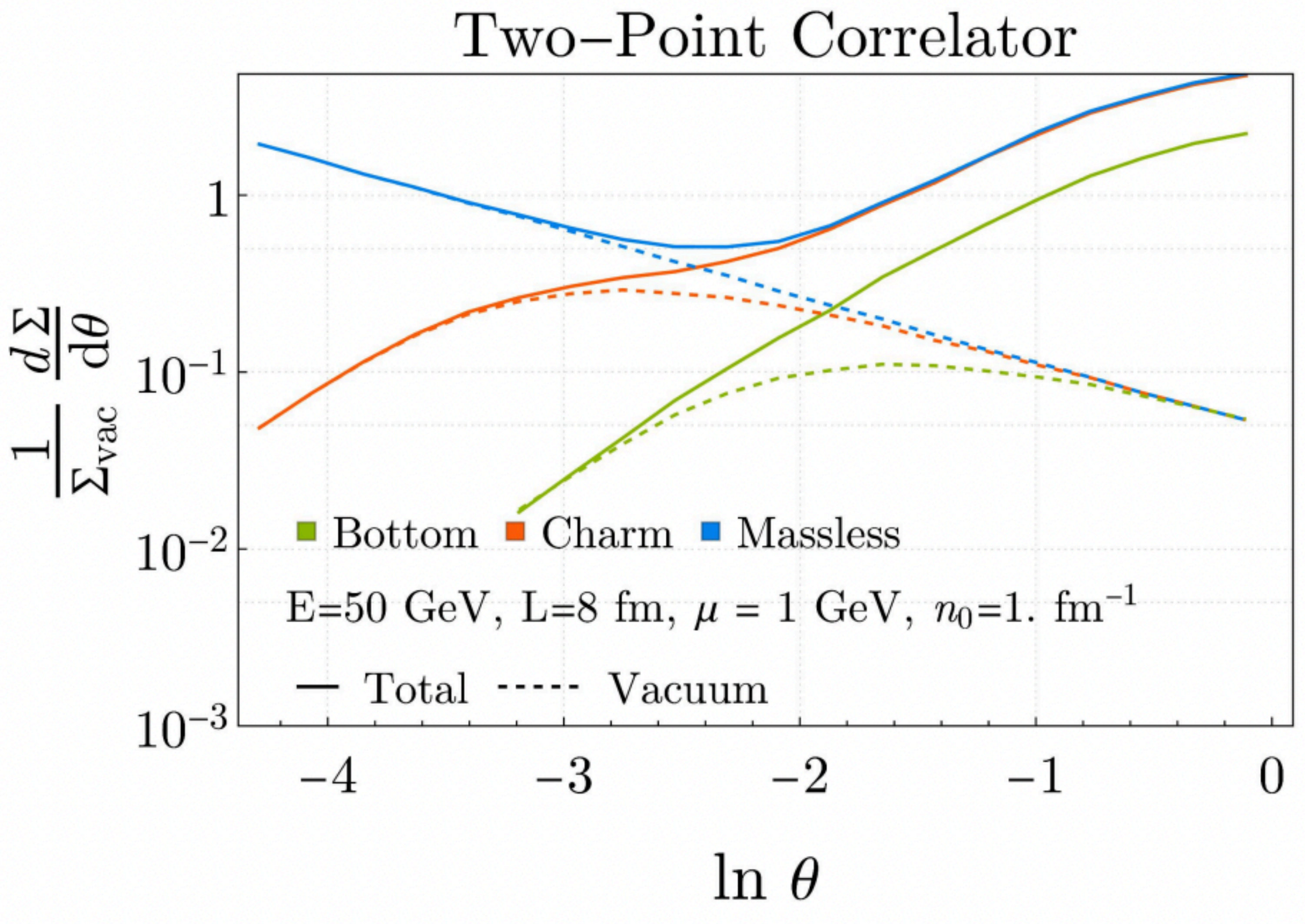
RESOLVING THE QGP USING ENERGY CORRELATORS

- 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 $\mu \sim p_T \theta_{ij}$

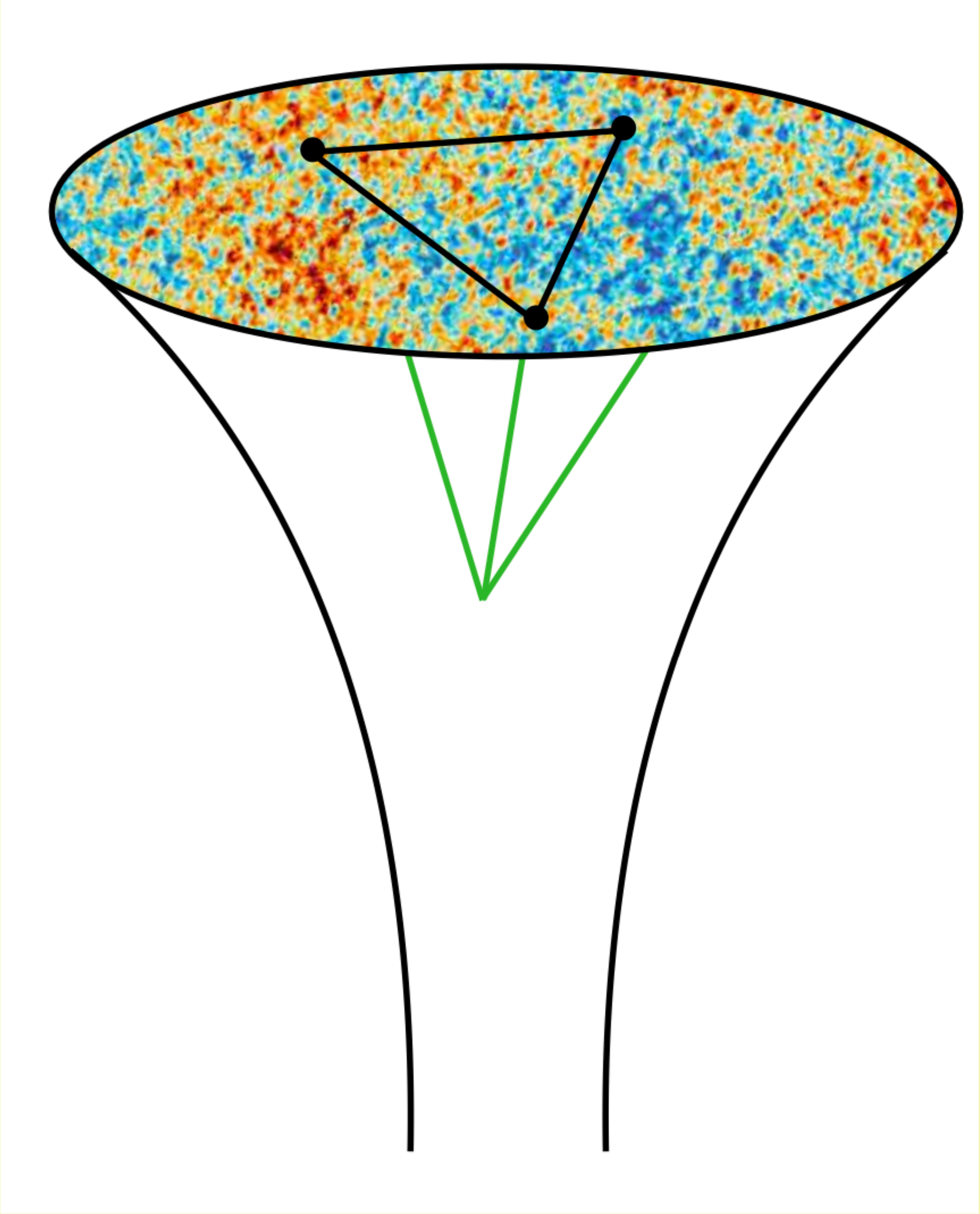






Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult `22
Andres, Dominguez, Holguin, Marquet, Moult `23
Barata, Mehtar-Tani `23

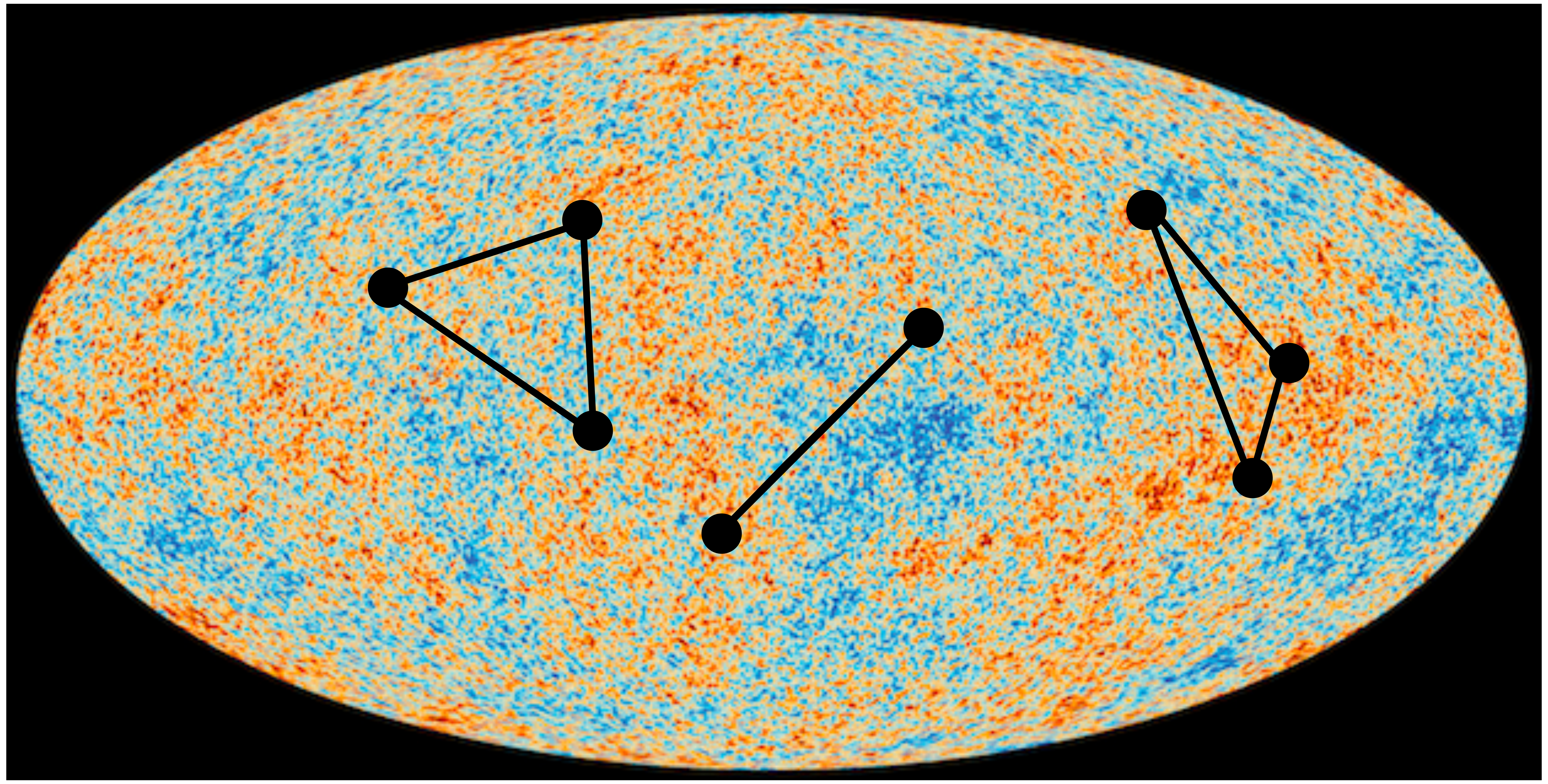
NON-GAUSSIANITIES /HIGHER POINTS IN PARTICLE COLLIDER

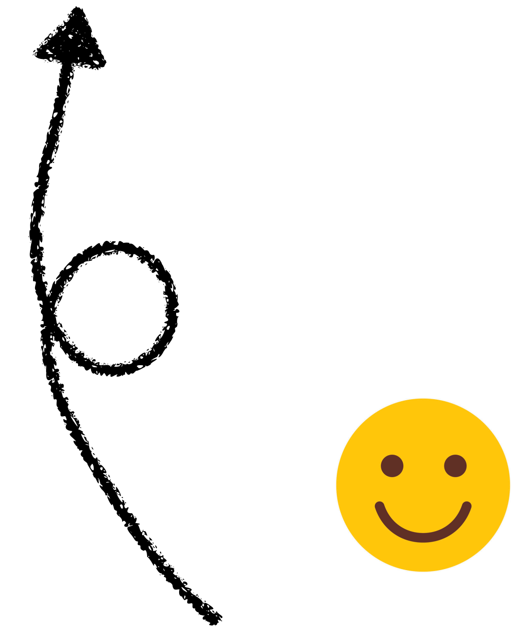


PROBING HIGHER POINT STRUCTURE

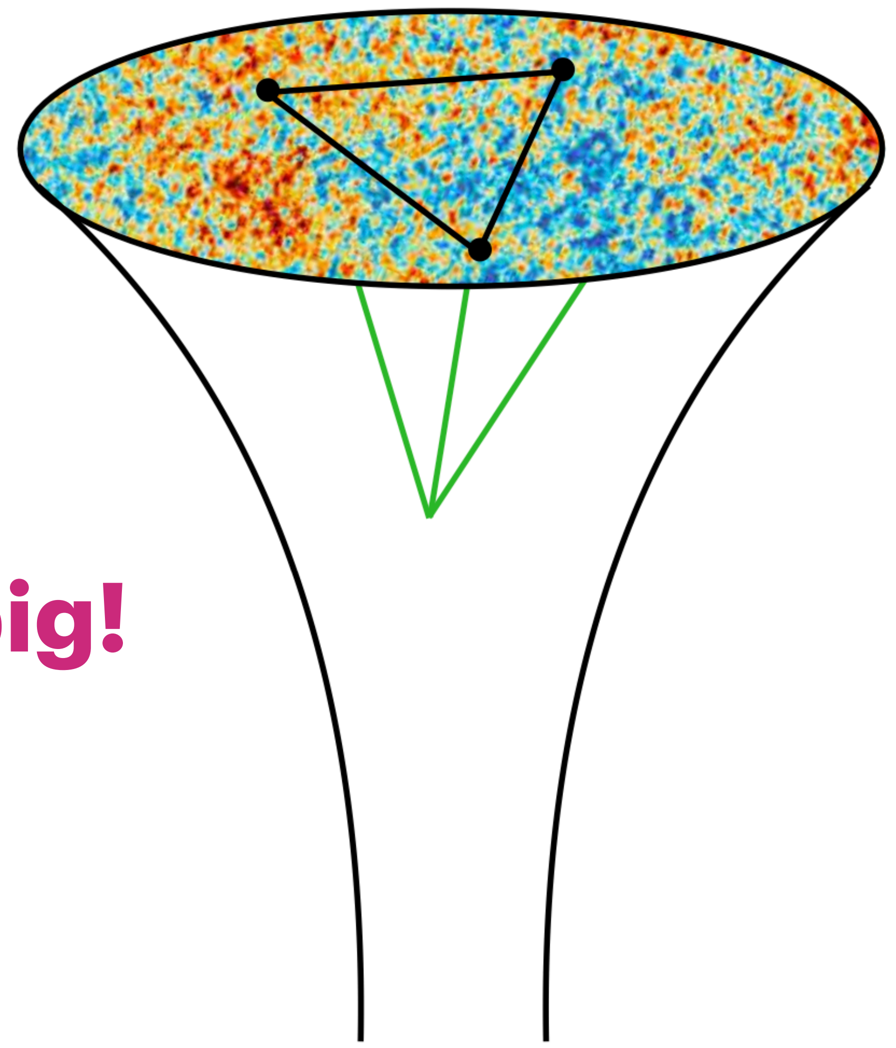
- **Higher-point correlators probe more detailed aspects of interactions.**
- **Hunting for non-gaussianities to distinguish the models of inflation.**
  Extremely interesting physics detail hiding under the 1 part in 100000 non-gaussianity in CMB!

Maldacena \`02, Komatsu \`10
Cabass, Pajer, Stefanyszyn, Supel \`21,...



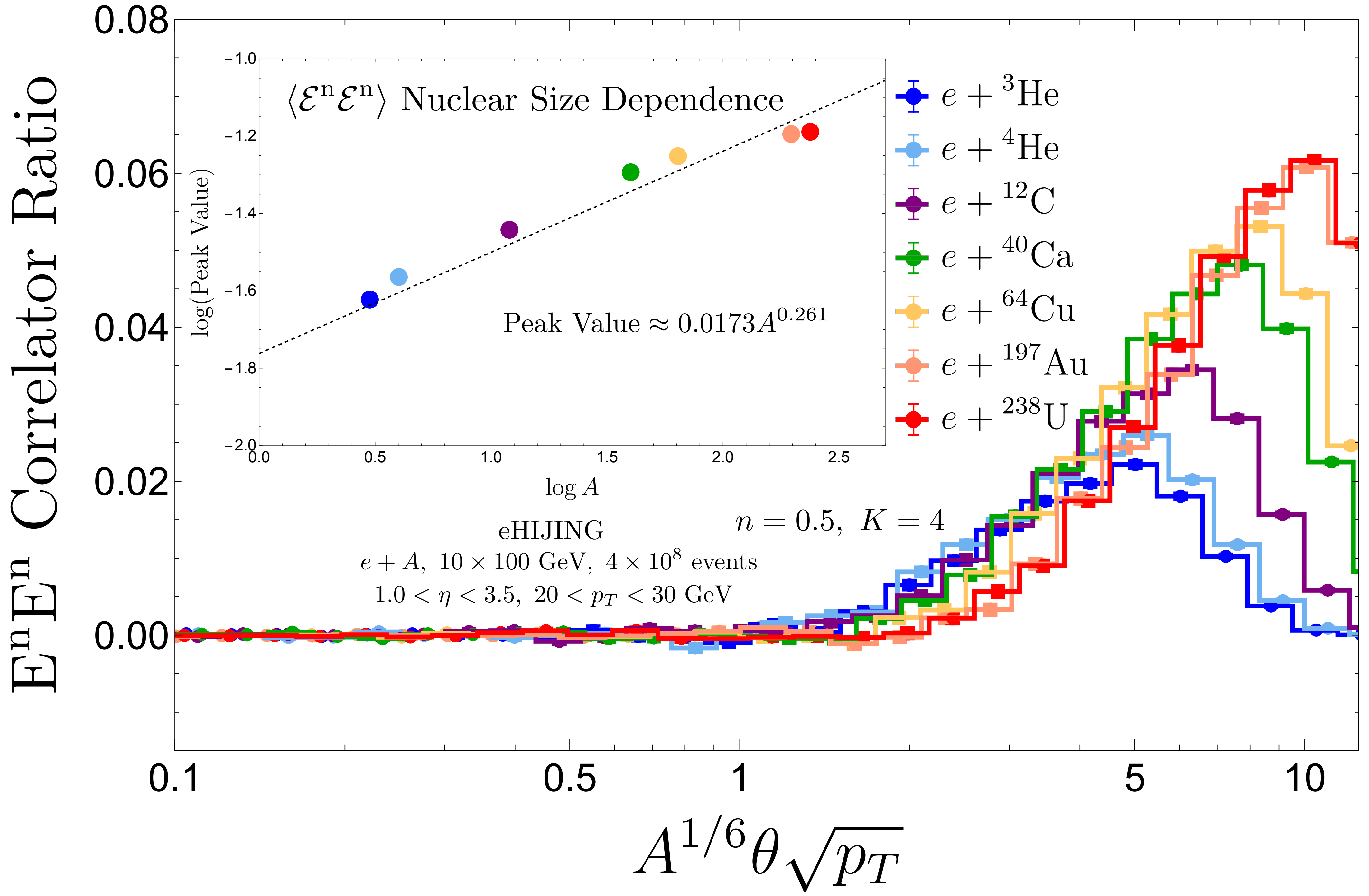


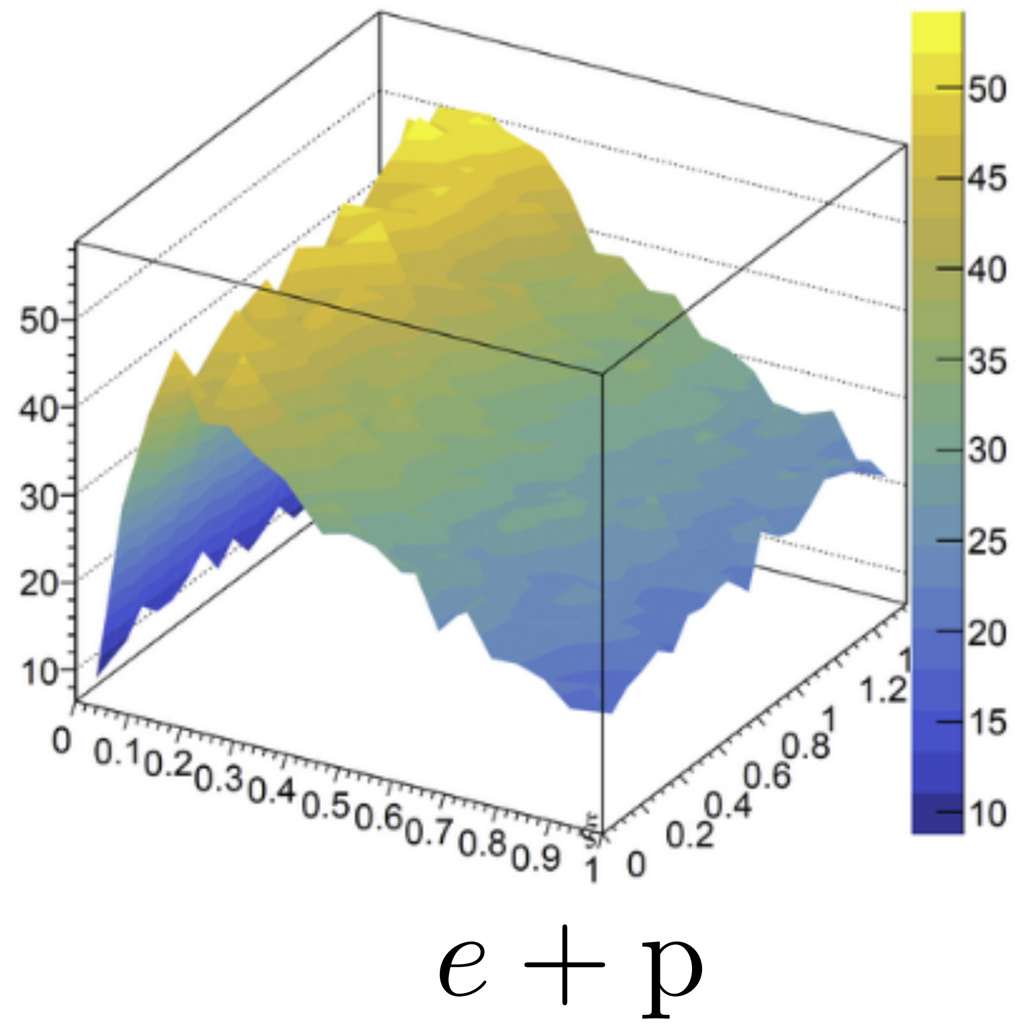
We must also dream big!

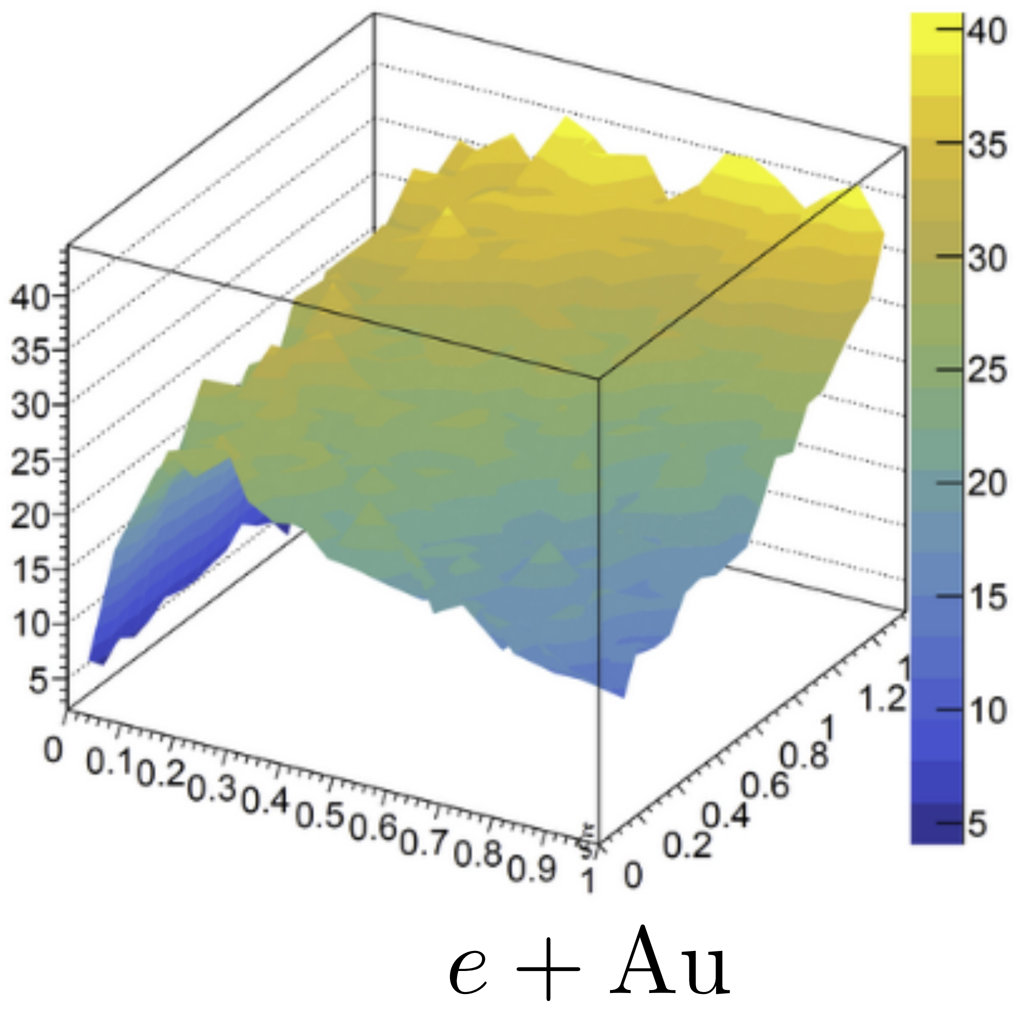


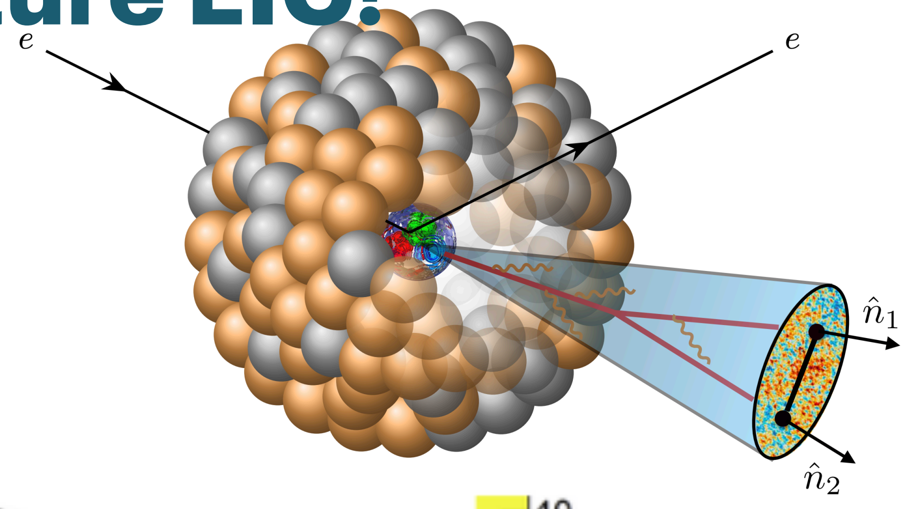
COLD NUCLEAR EFFECTS AND JET SUBSTRUCTURE

- **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

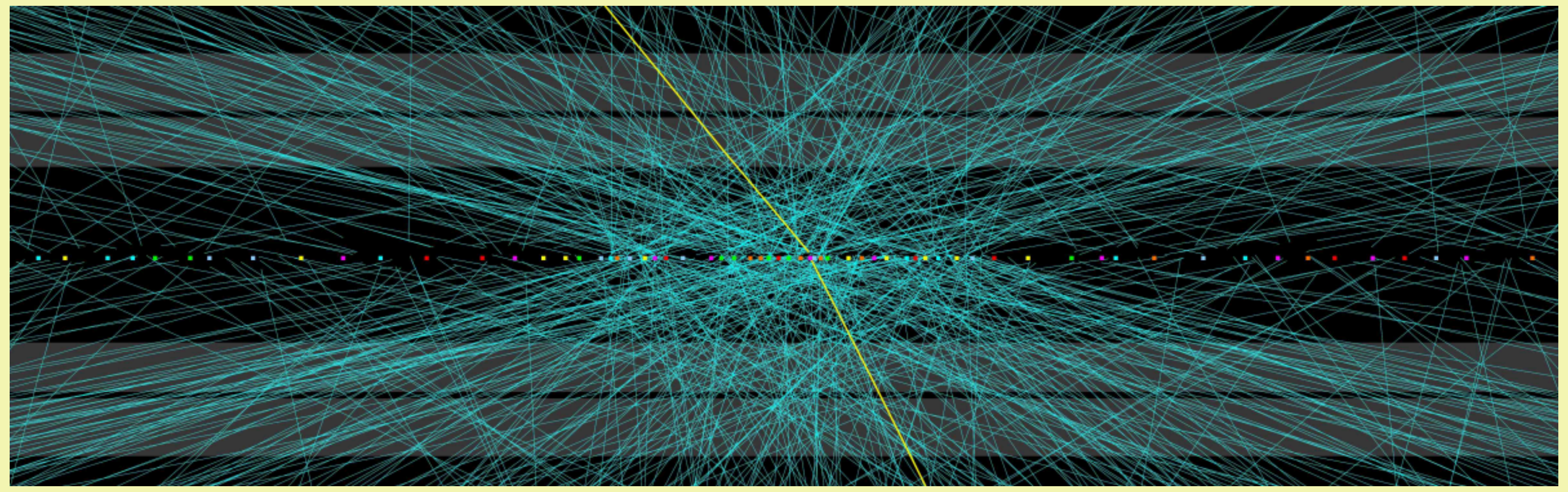
Standard-model physics (QCD and electroweak)

100 MeV - 4 TeV

GOAL

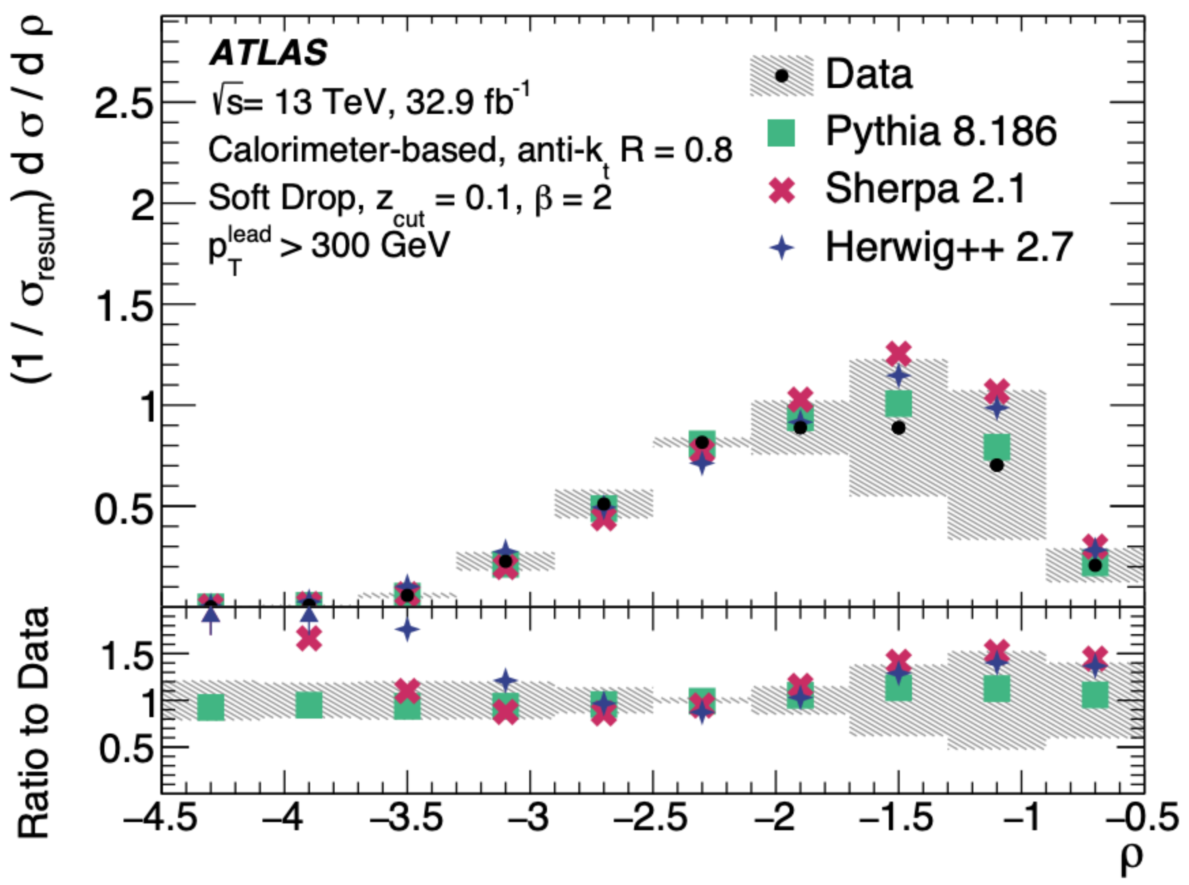
UNLOCK QCD DYNAMICS

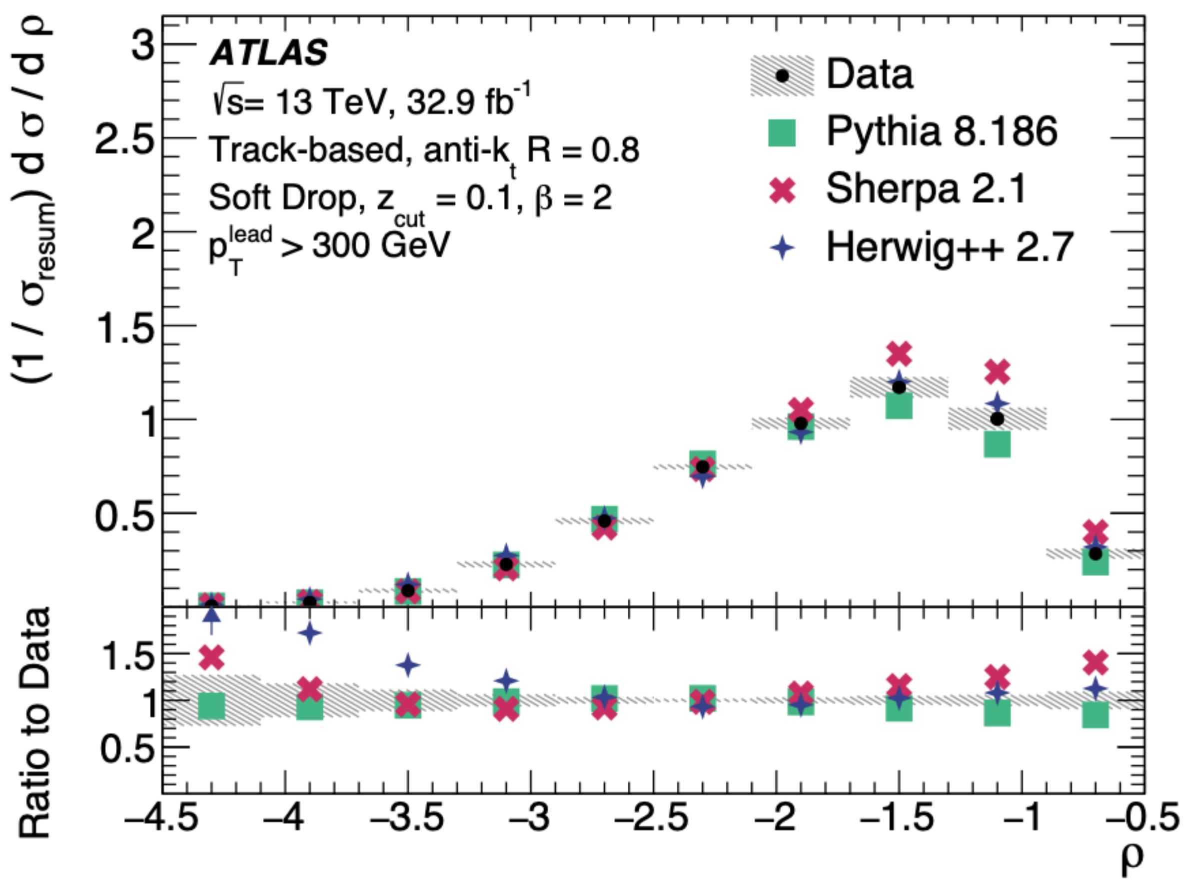
PRECISION MEASUREMENTS



MEASURING ON TRACKS

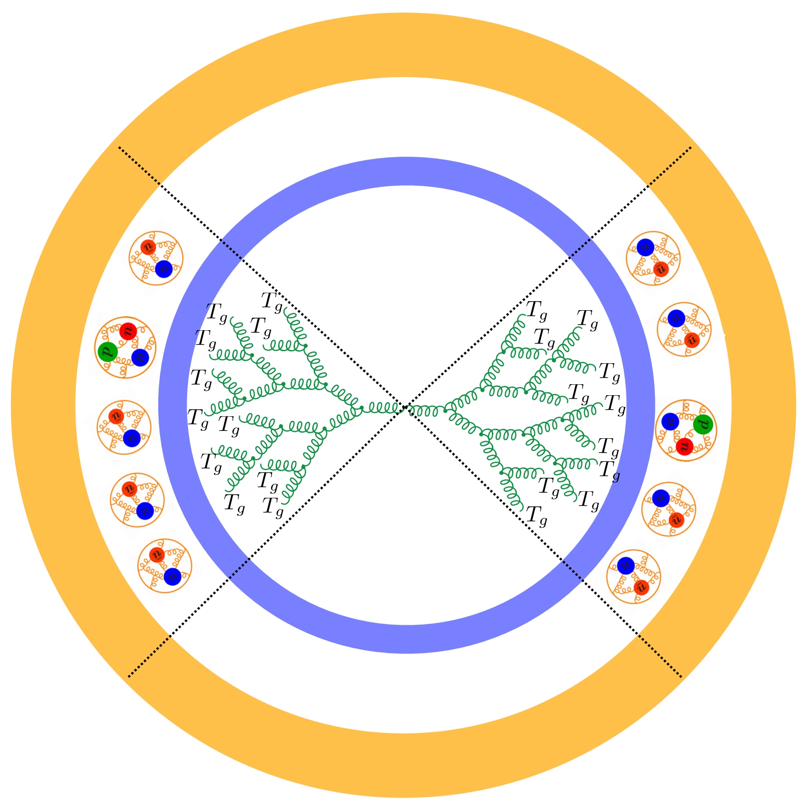
- In order to unlock QCD dynamics and more, precision measurements are important!
- Experimentally, measurements on tracks are advantageous because much more precise measurements are possible



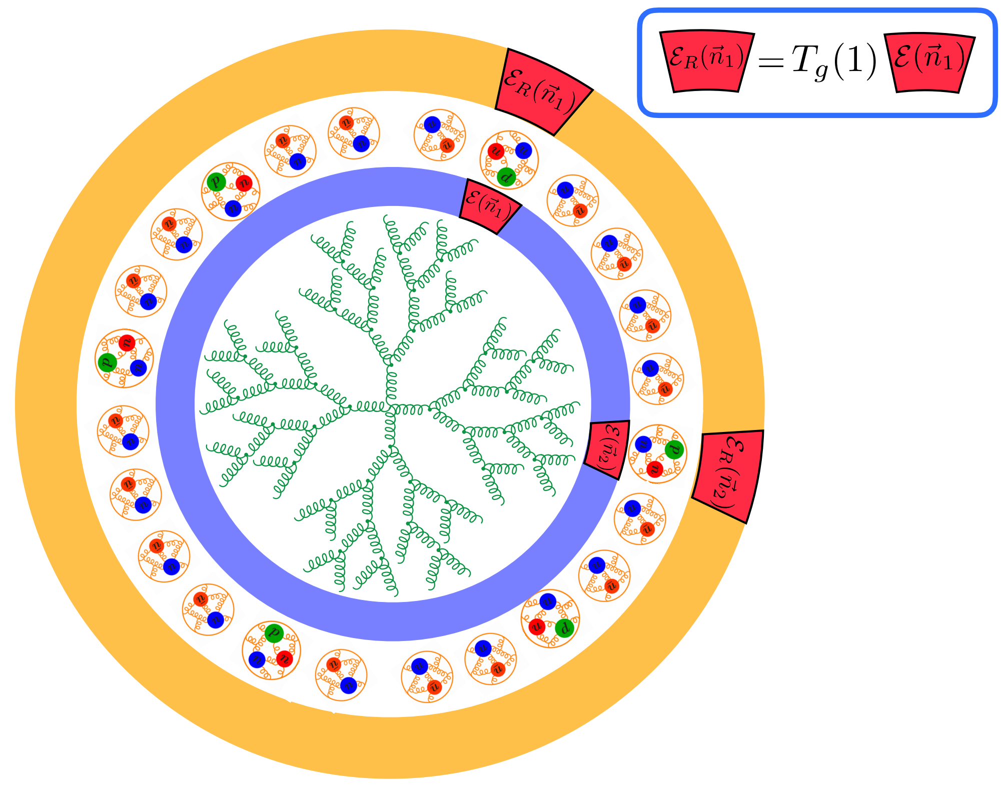


[ATLAS (2019)]

Jet shape



Energy correlators



space of the state vs **space of the detectors**

$\Longrightarrow$ **NP functions** $\Longrightarrow$ ***NP numbers***

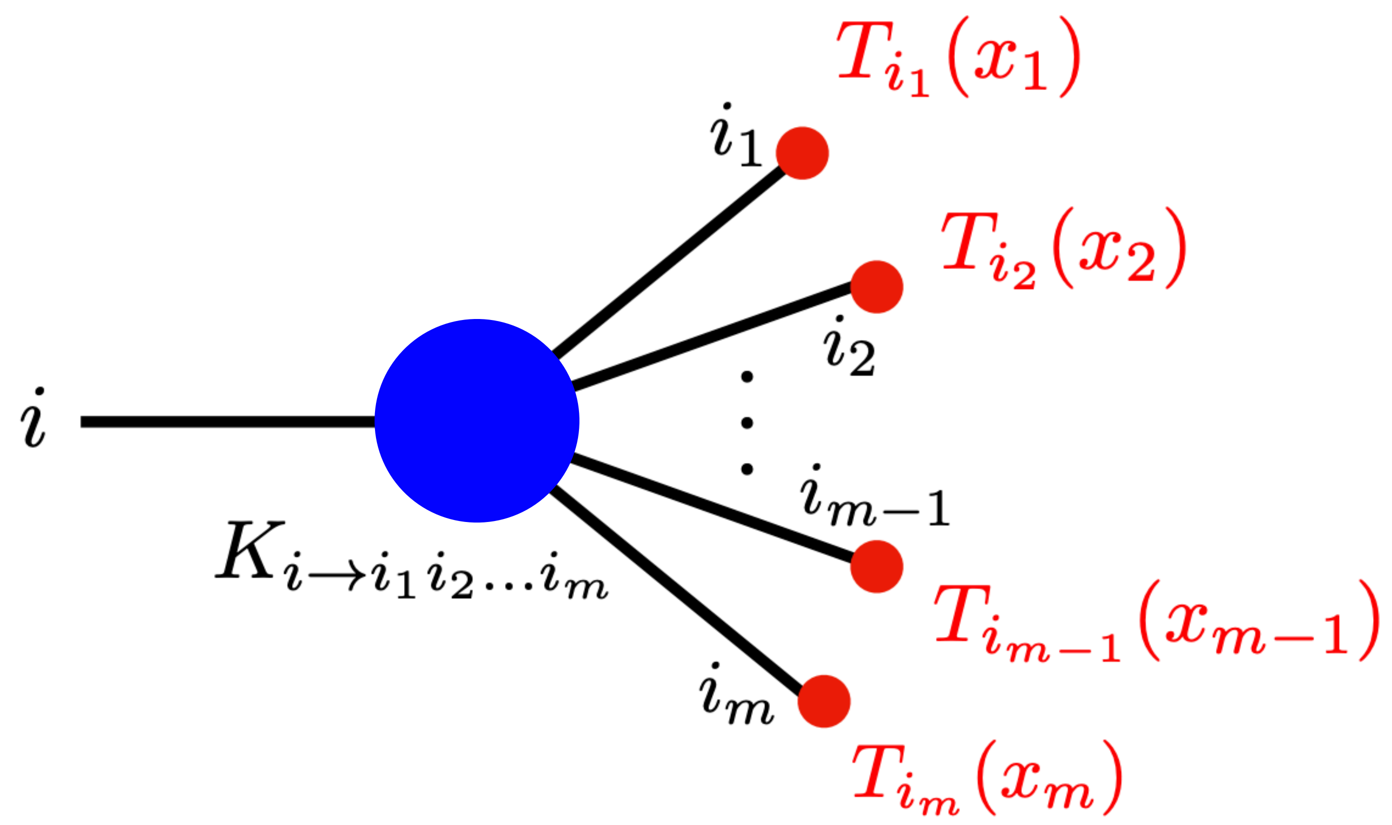
- Recent advancements in energy correlators fueled much theoretical developments to carry out high precision calculation of jet substructure on tracks!

TRACK FUNCTION FORMALISM

Refer to Wouter's talk for more detail!

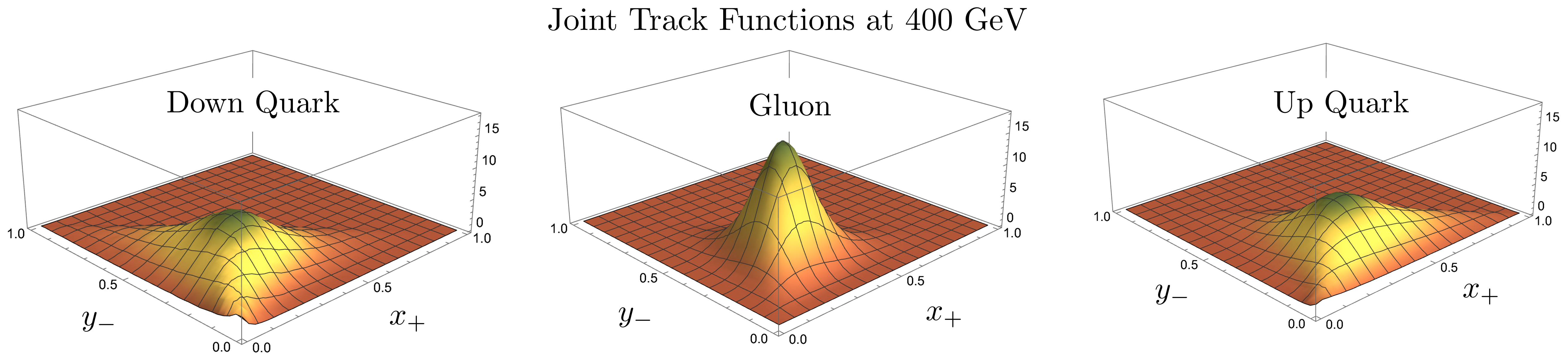
- **First formalism to study observables on tracks developed over a decade ago, and developments have rapidly advanced in recent years.**

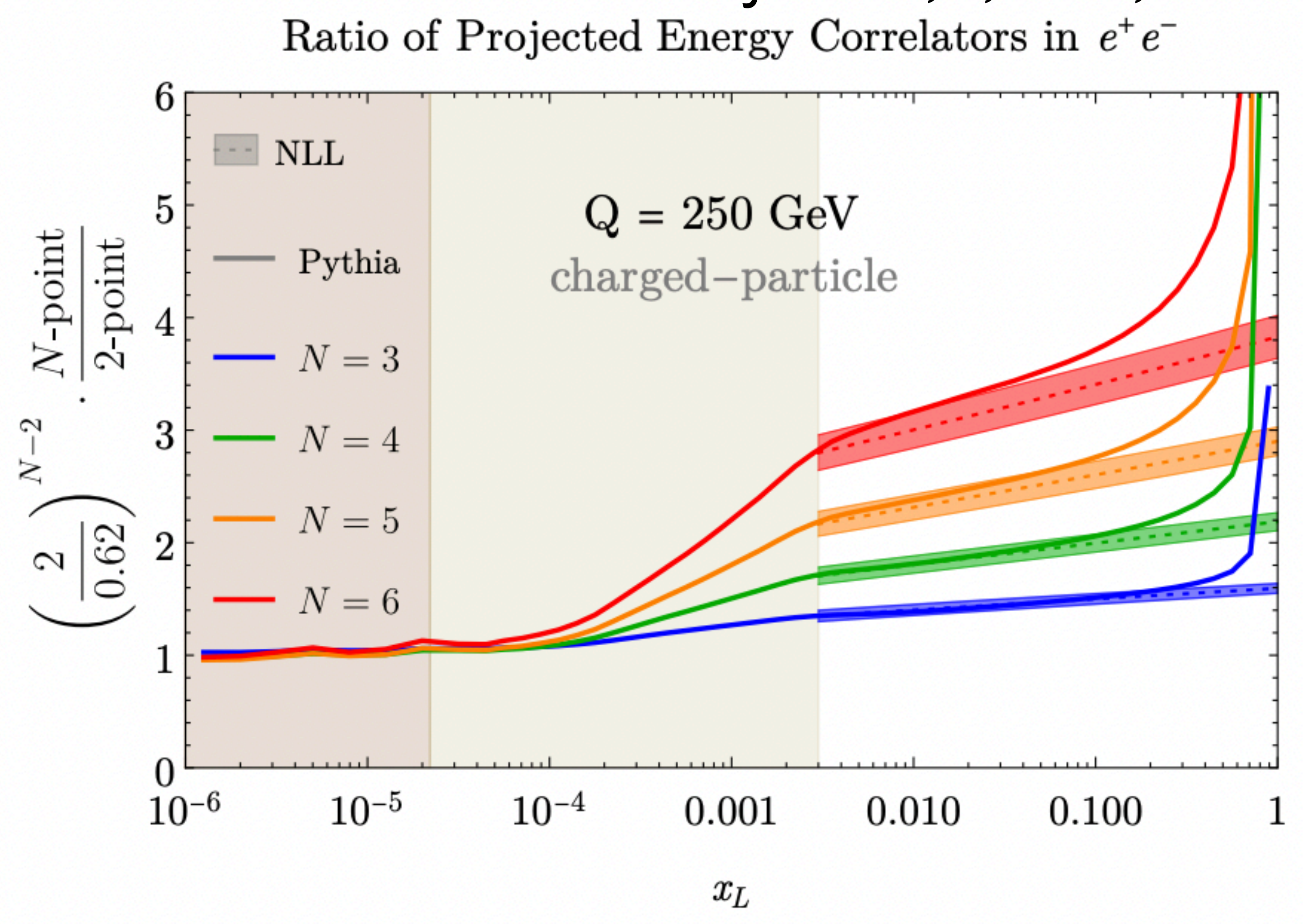
Chang, Procura, Thaler, Waalewijn `13
Li, Moult, Waalewijn, Zhu et al `21, 22
KL, Moult, Ringer, Waalewijn `23
KL, Moult `23



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

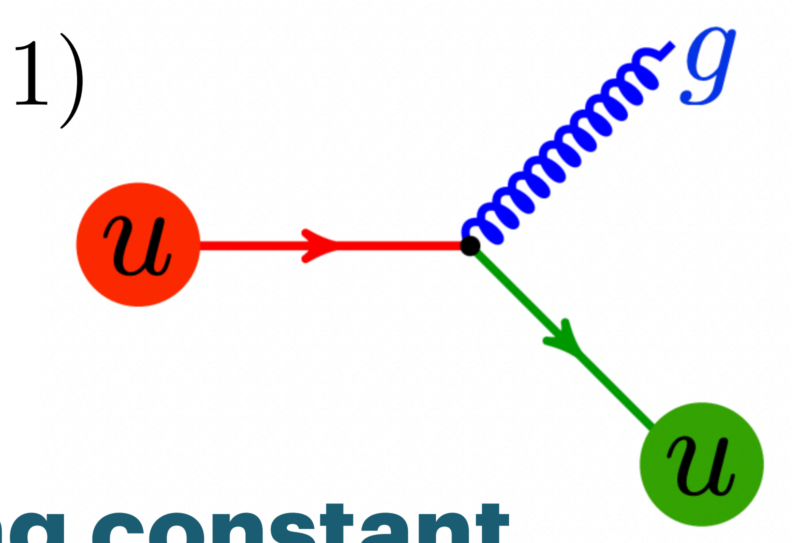
Jaarsma, Li, Moult, Waalewijn, Zhu `23





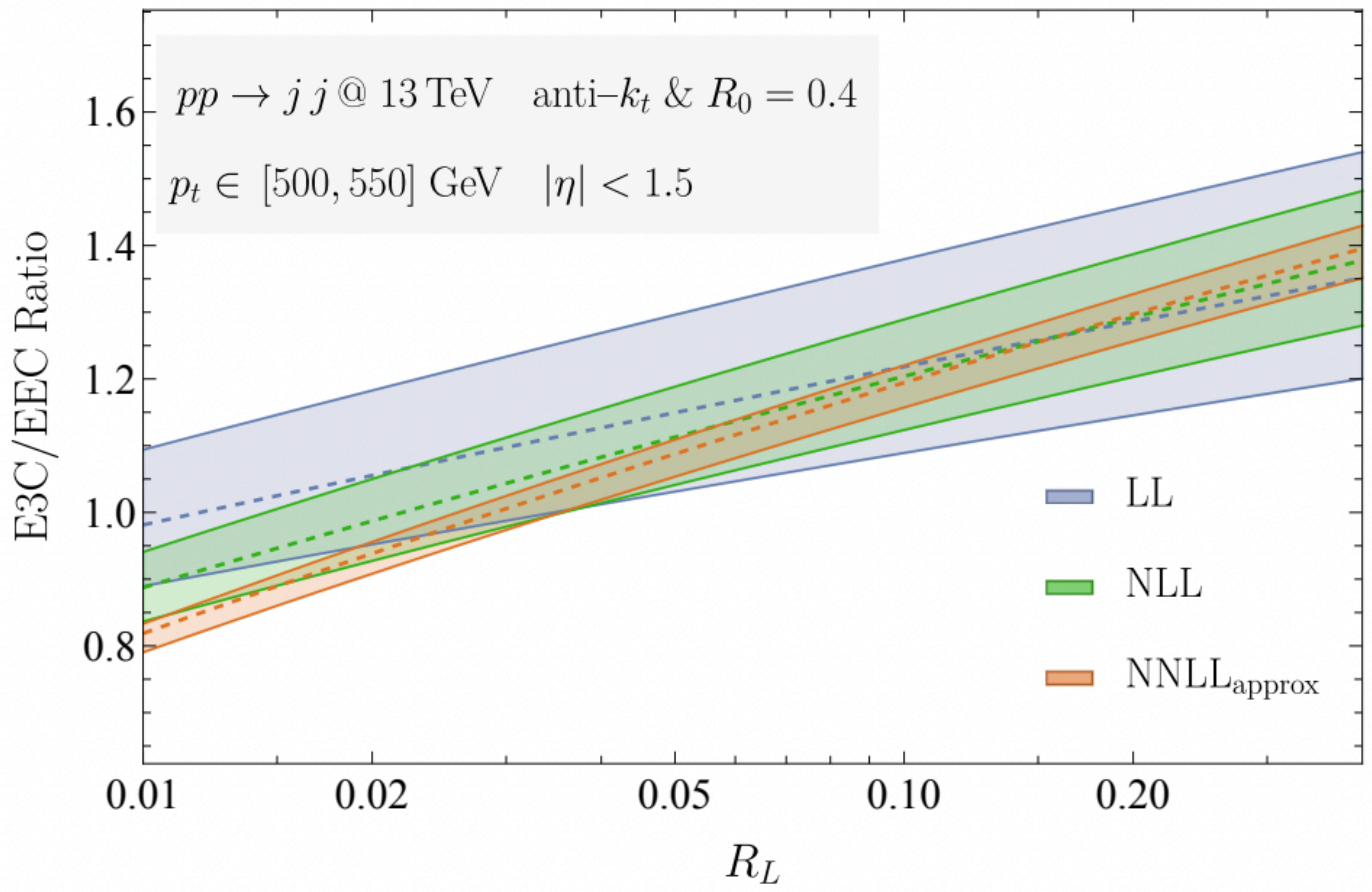
STRONG COUPLING DETERMINATION

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

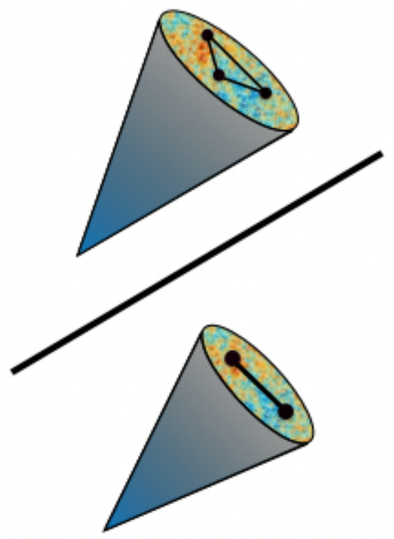


Quarks are never free and thus it is very hard to measure their coupling!

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

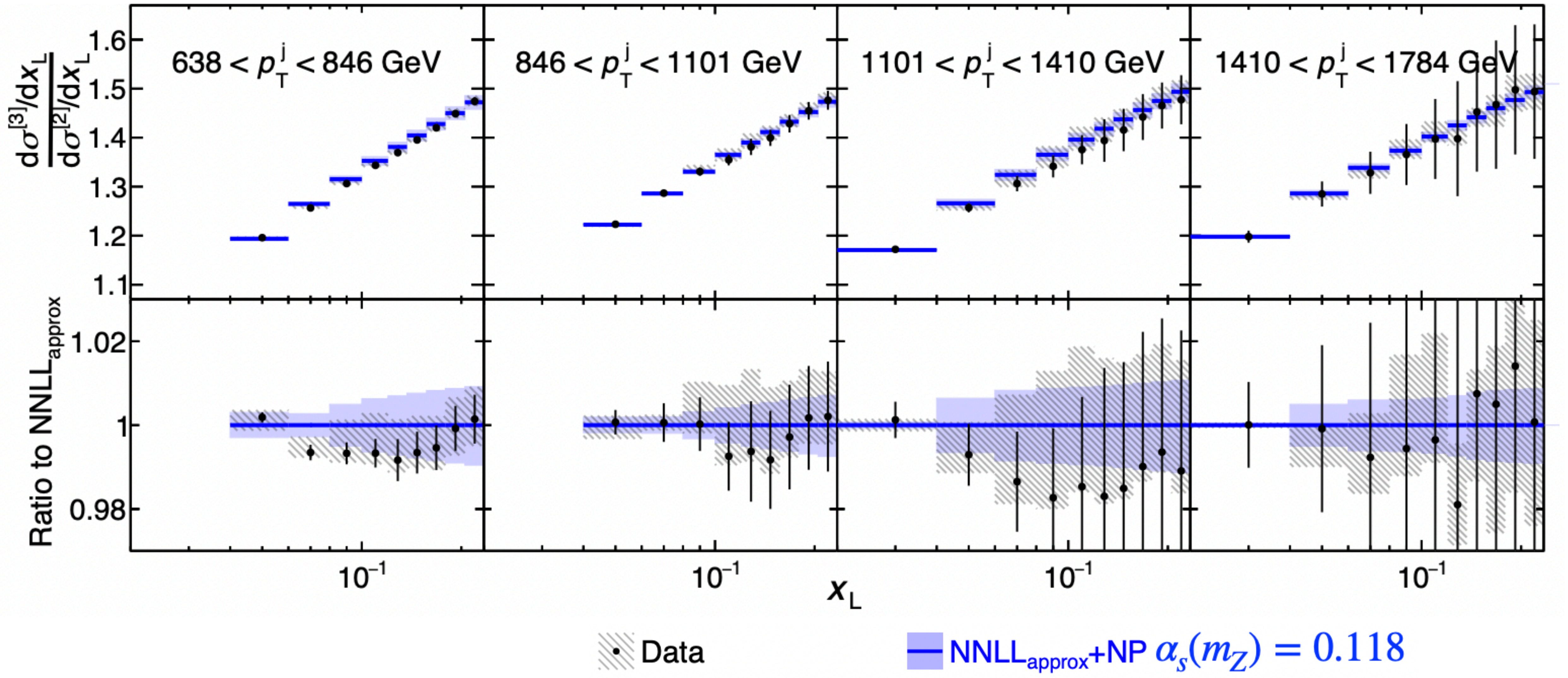


Chen, Gao, Li, Xu, Zhang, Zhu`23



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

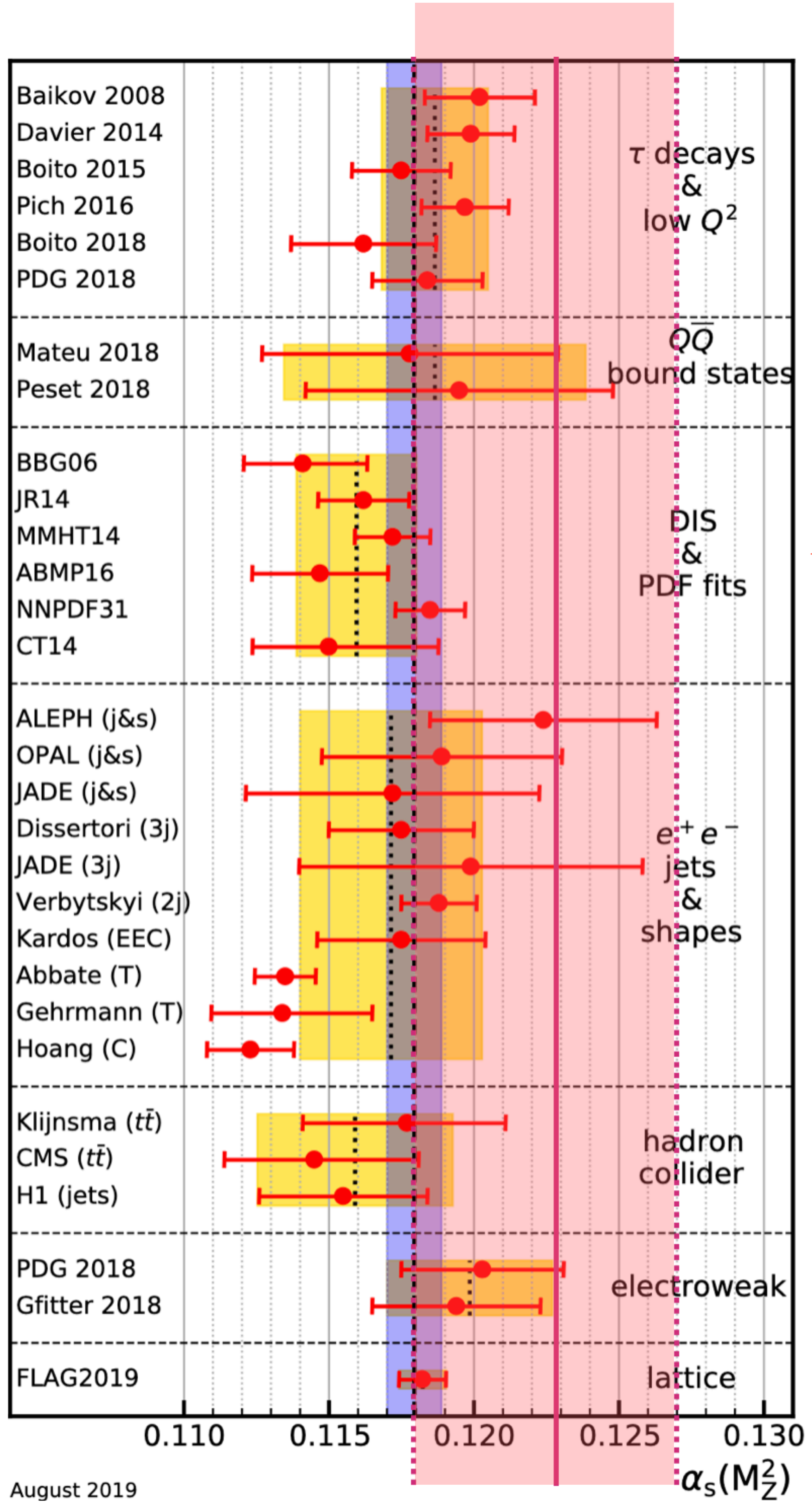
CMS Collaboration `23



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

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

STRONG COUPLING DETERMINATION



Energy Correlators in Jet

CMS Collaboration `23

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

Covariance matrix

major source

QCD scale of NNLLapprox

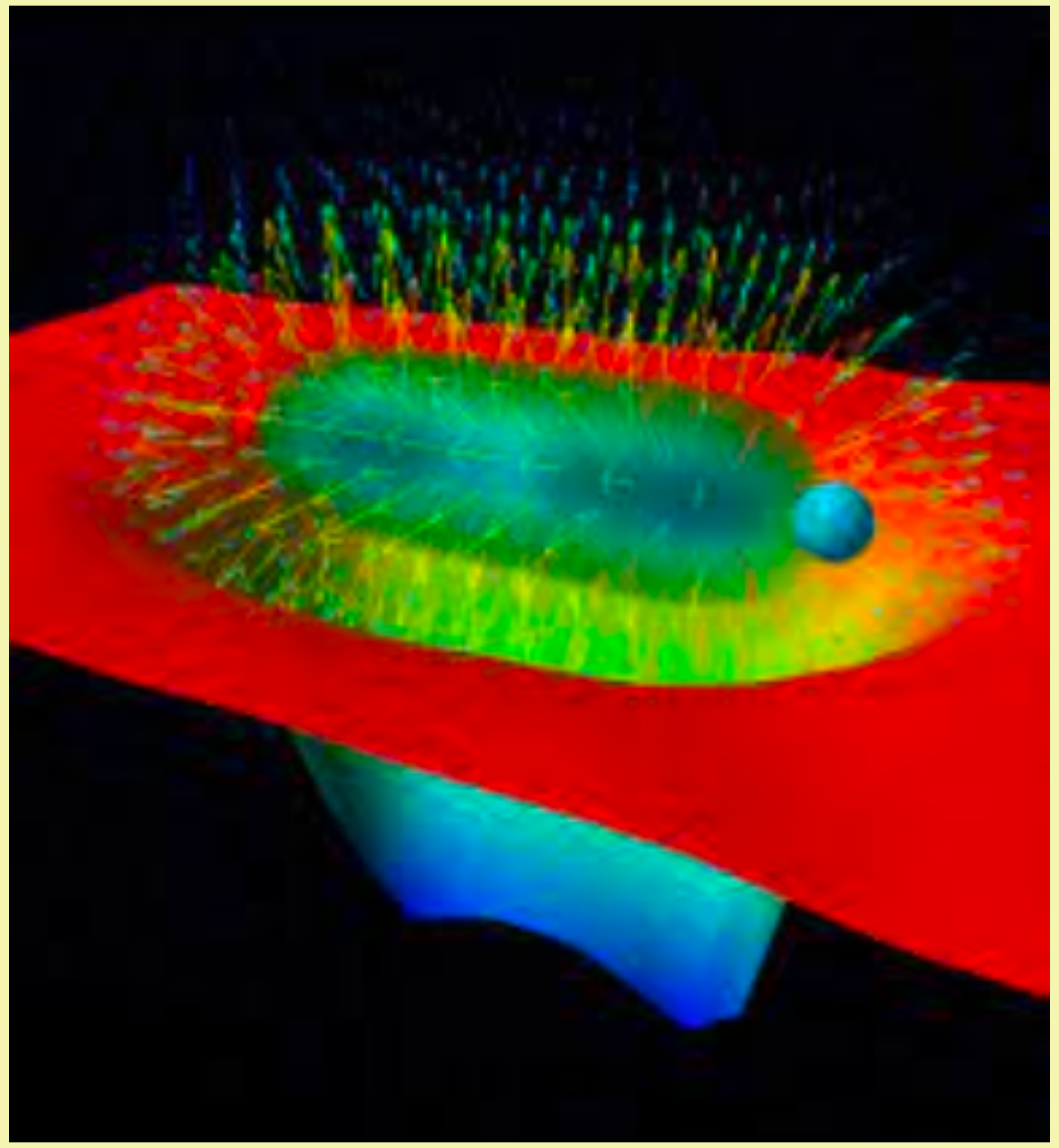
Neutral hadron energy scale

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



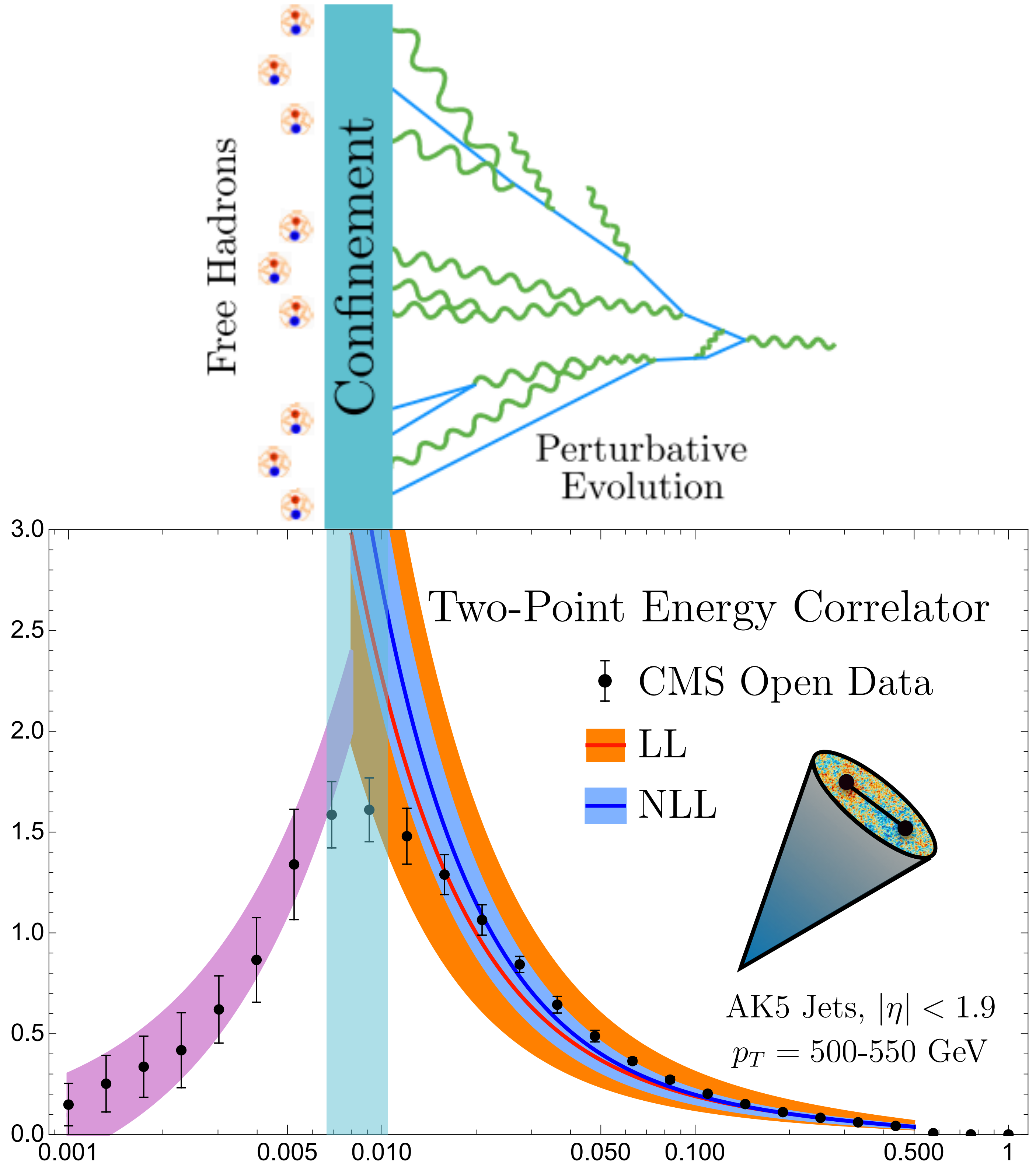
QUARK GLUON SCALING AND HADRONIZATION

- **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

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

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



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

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

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

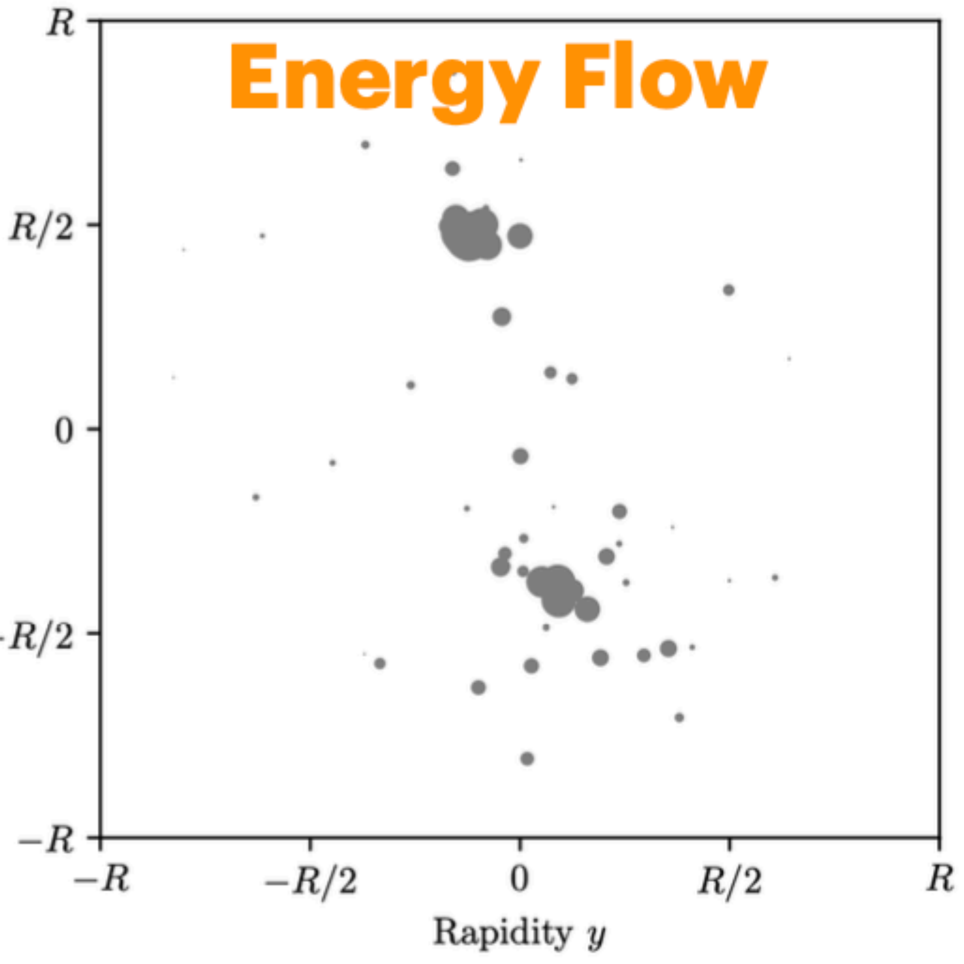
WHAT IS A DETECTOR?

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

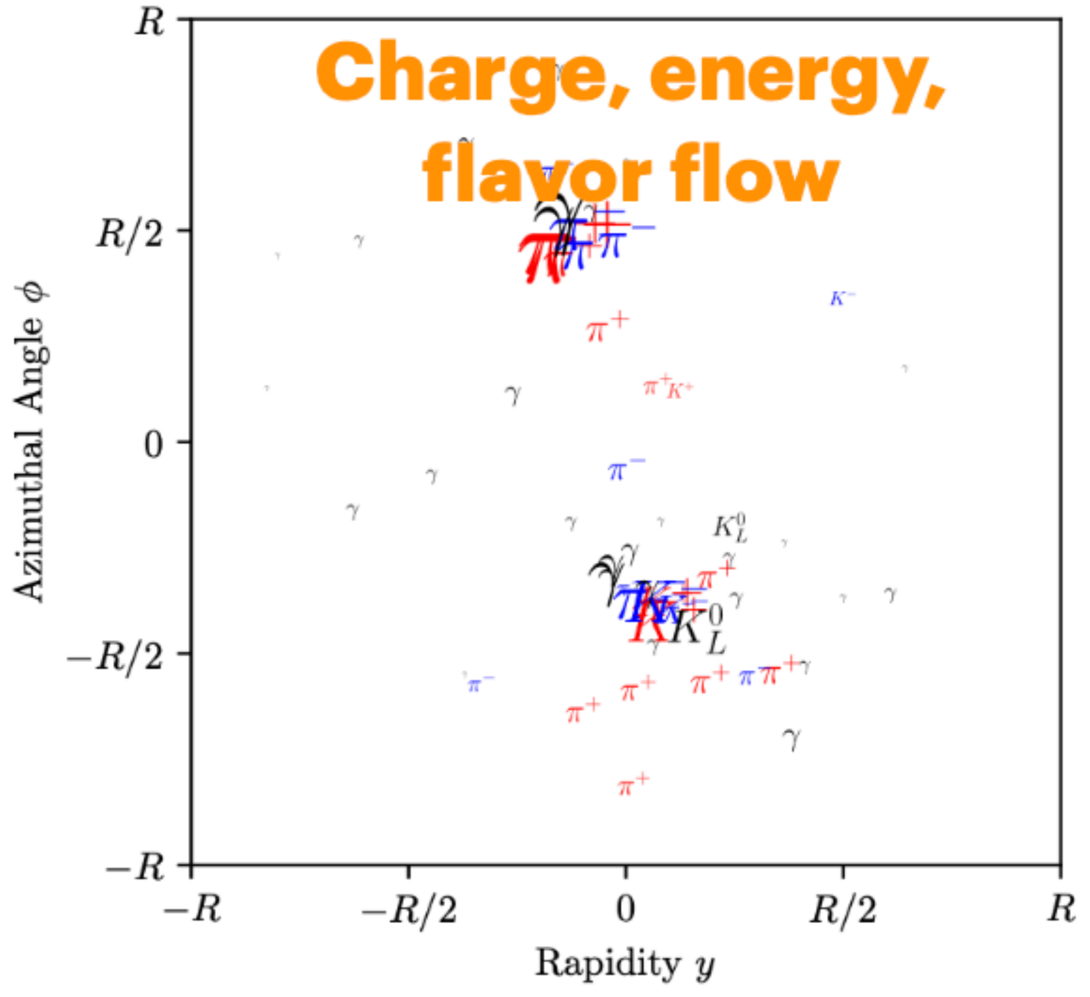
  Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin`22

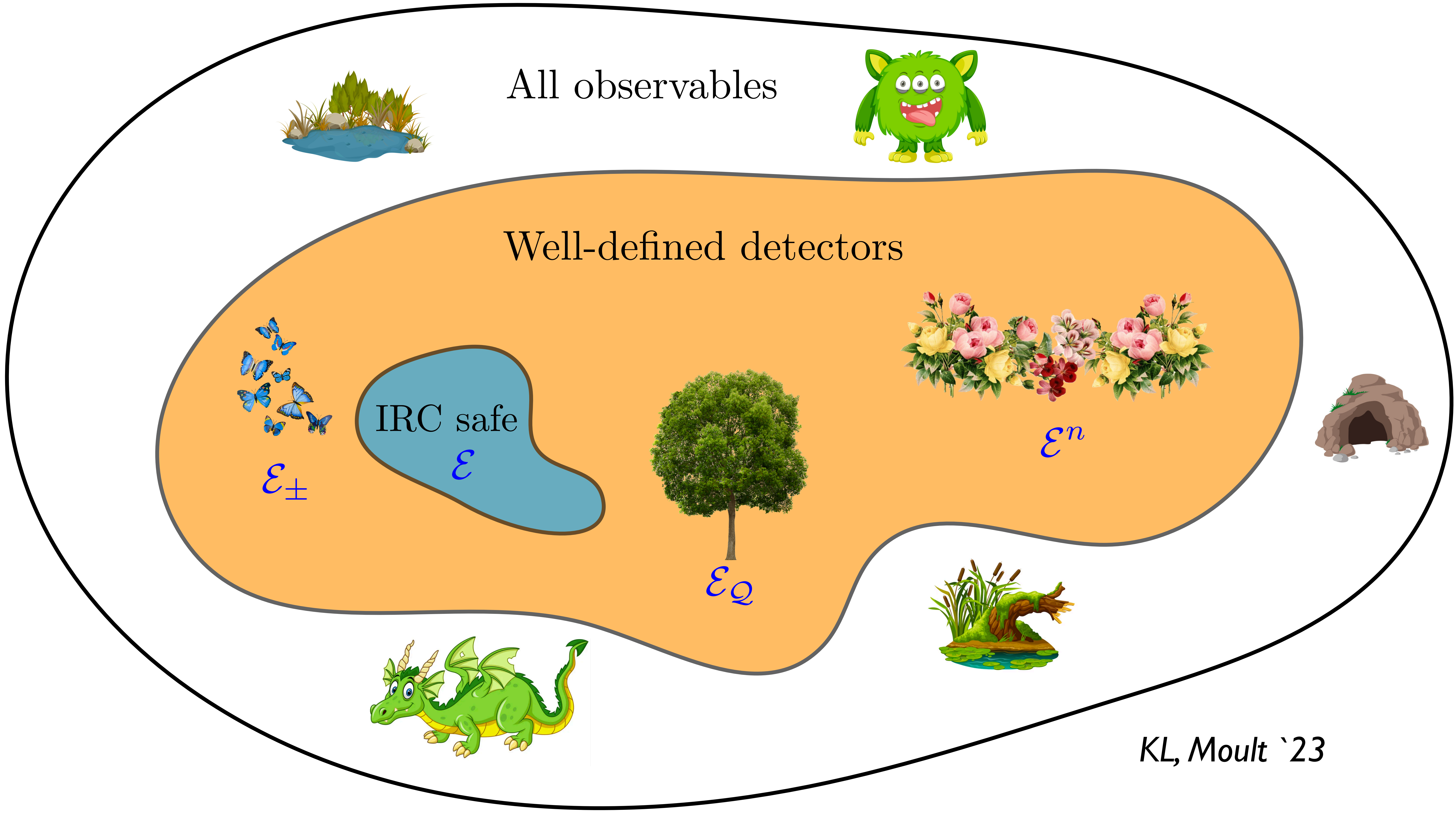
- **Well-defined detectors provide sharp link with underlying field theory through observables!**

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

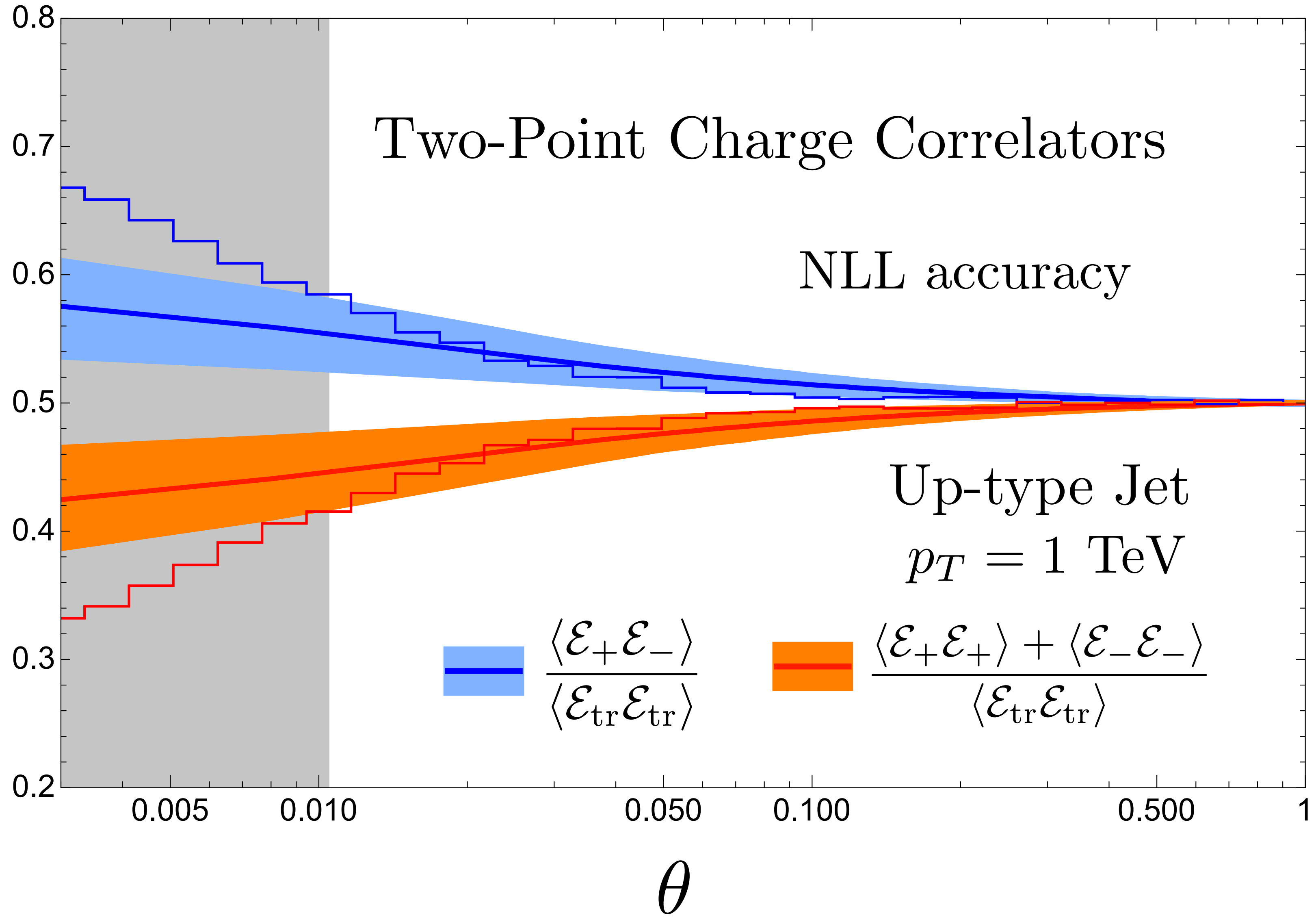
GENERALIZING ENERGY FLOW CORRELATIONS

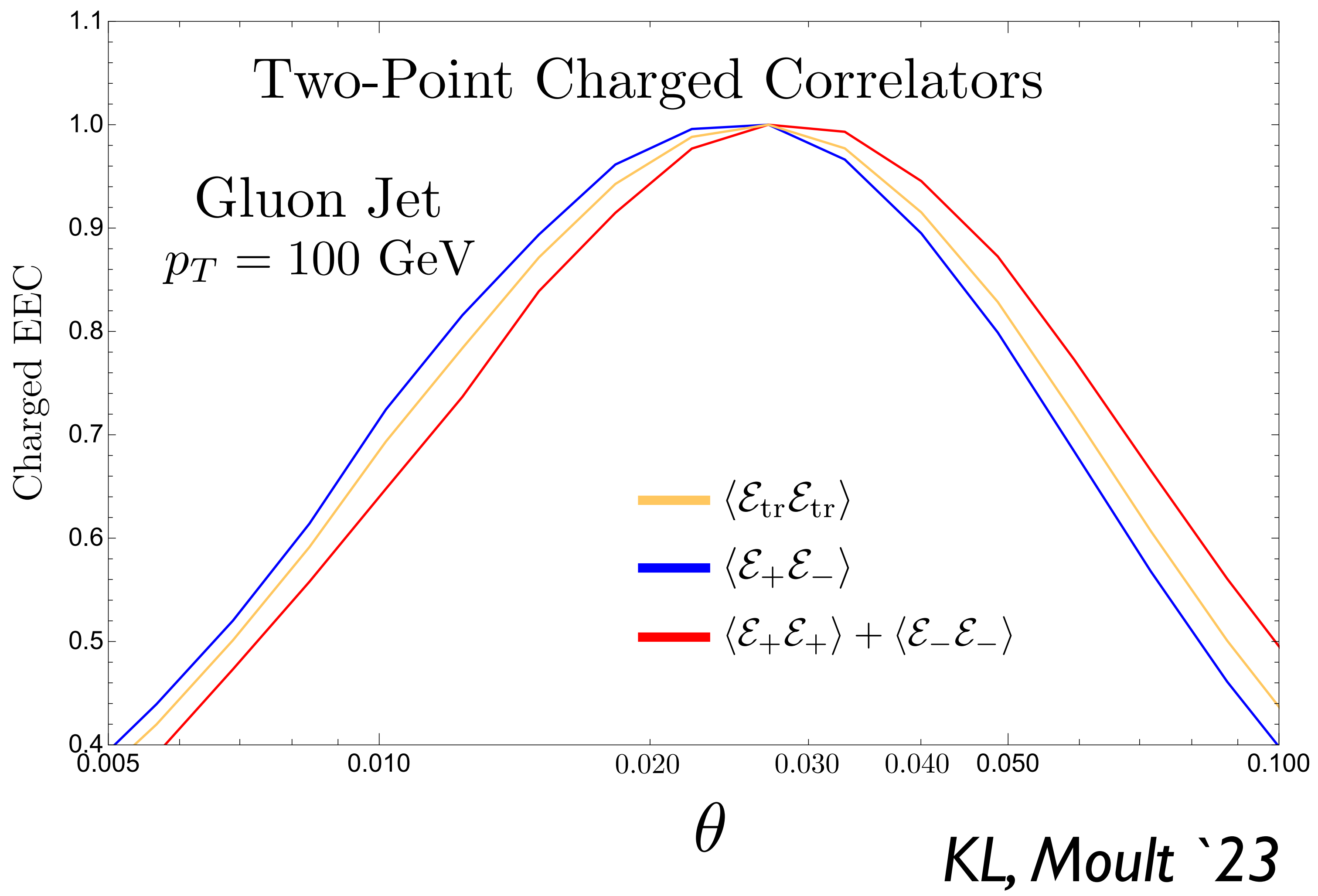
- **Writing down more general detectors allow us to consider more general correlation functions from**

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

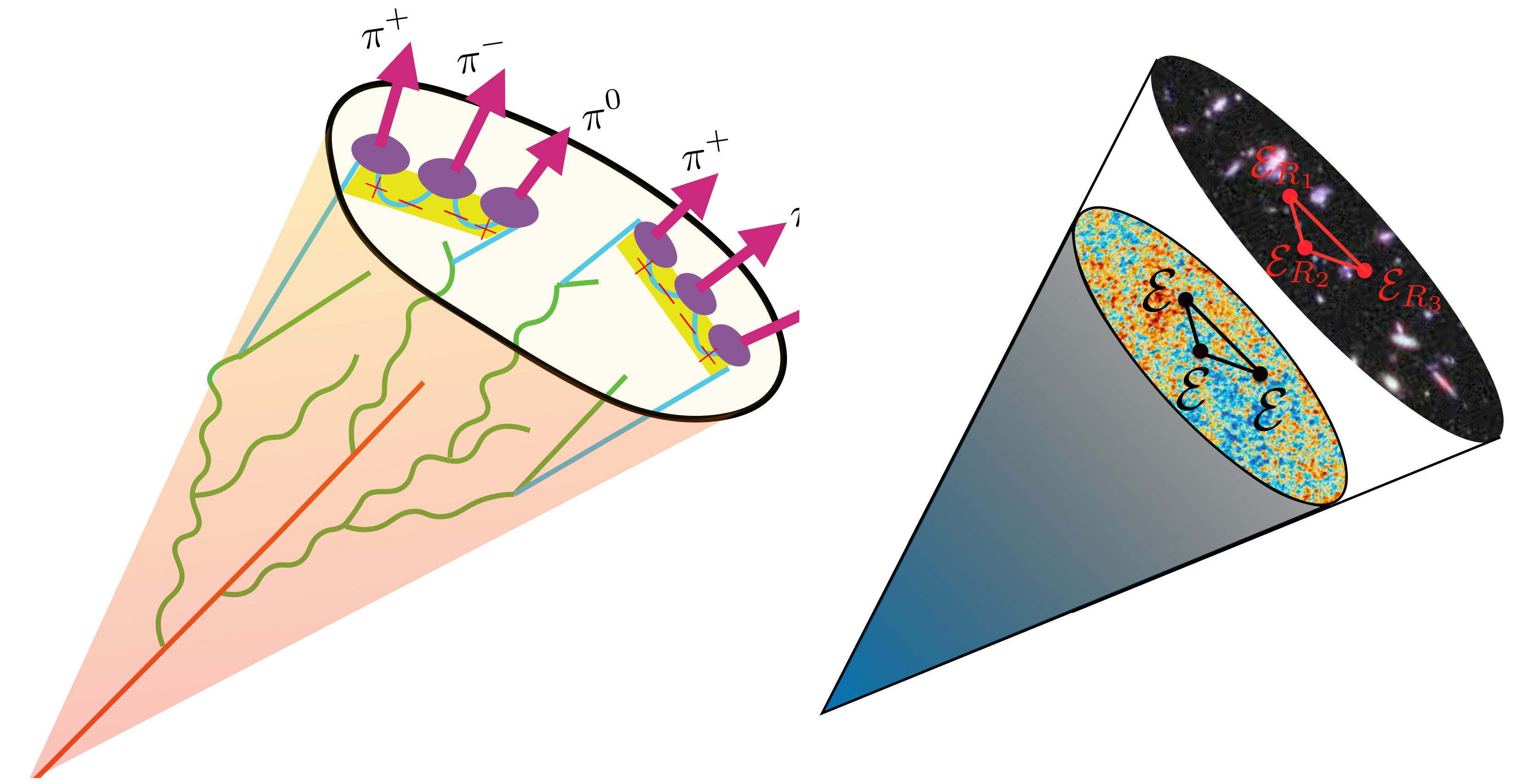
- **In general, restricting to a set of hadronic states to some particular quantum number R introduces sensitivity to the IR scale. As a concrete example, one can ask "is there more unlike-signed correlations compared with the like-signed correlations?"**

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



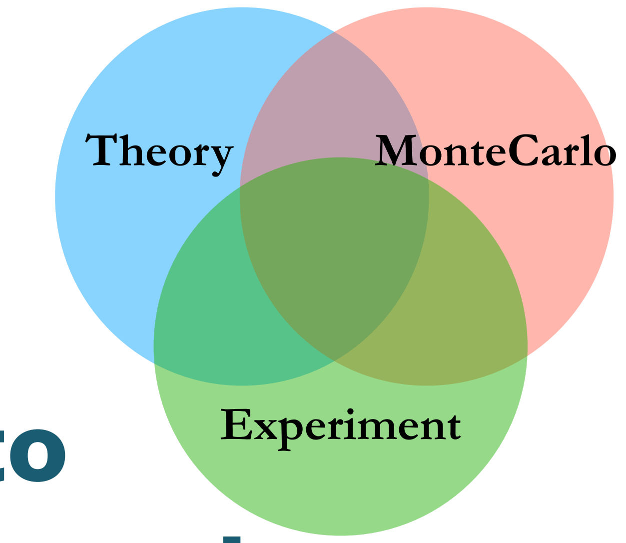


KL, Moult `23

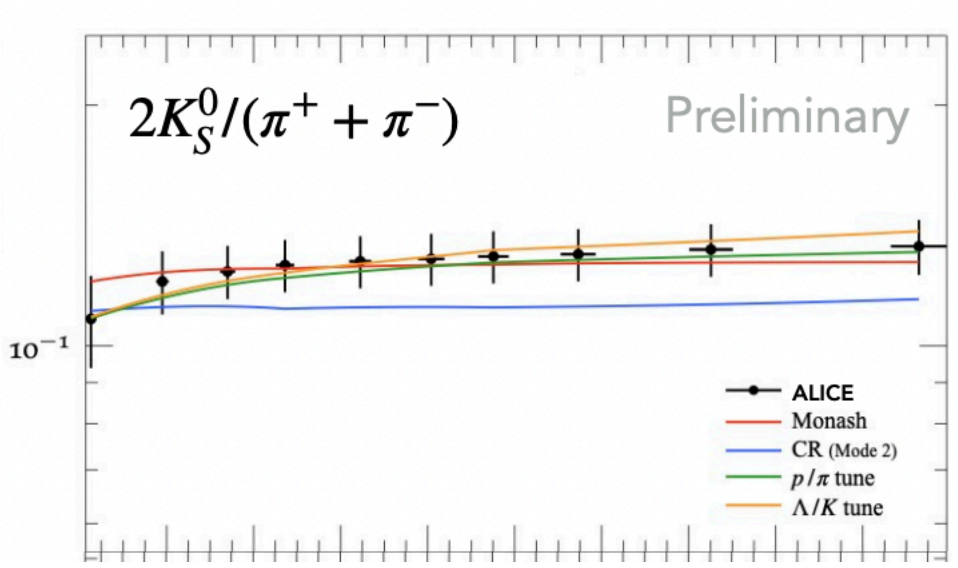


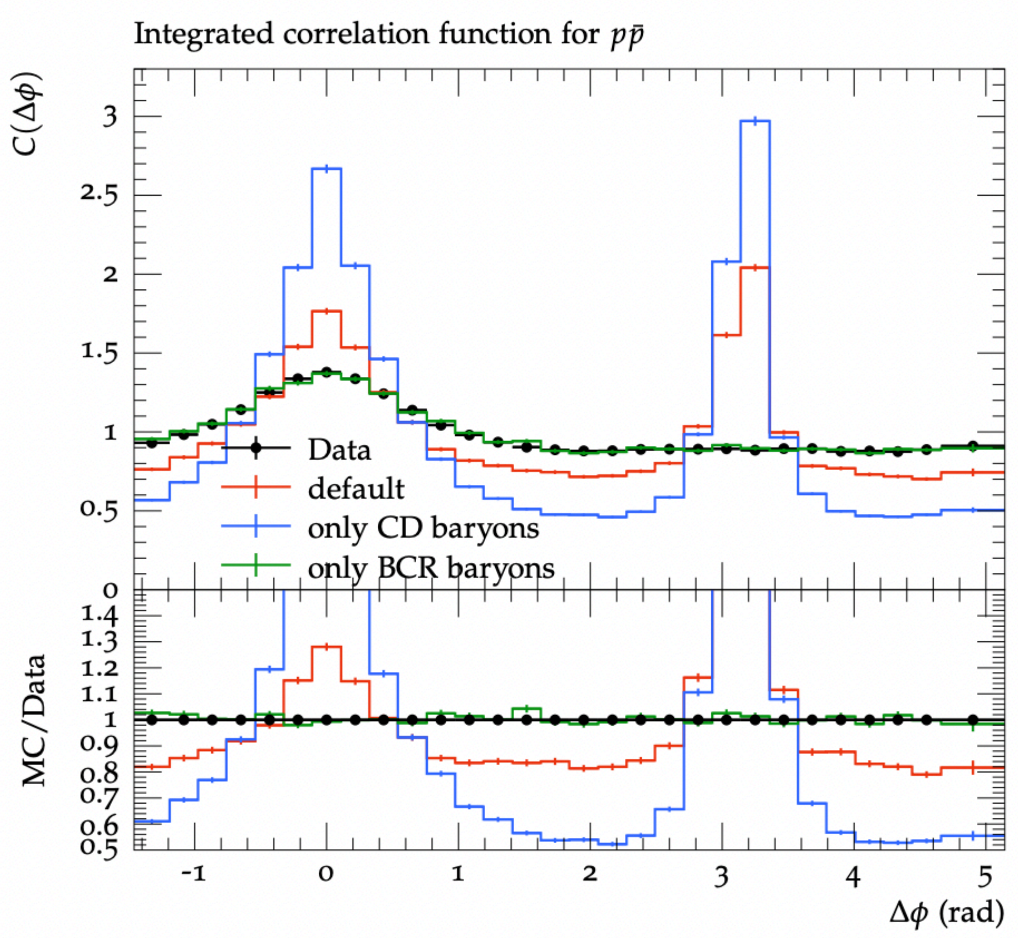
ASIDE: INTERPLAY WITH PARTON SHOWERS DEVELOPMENT

- 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.



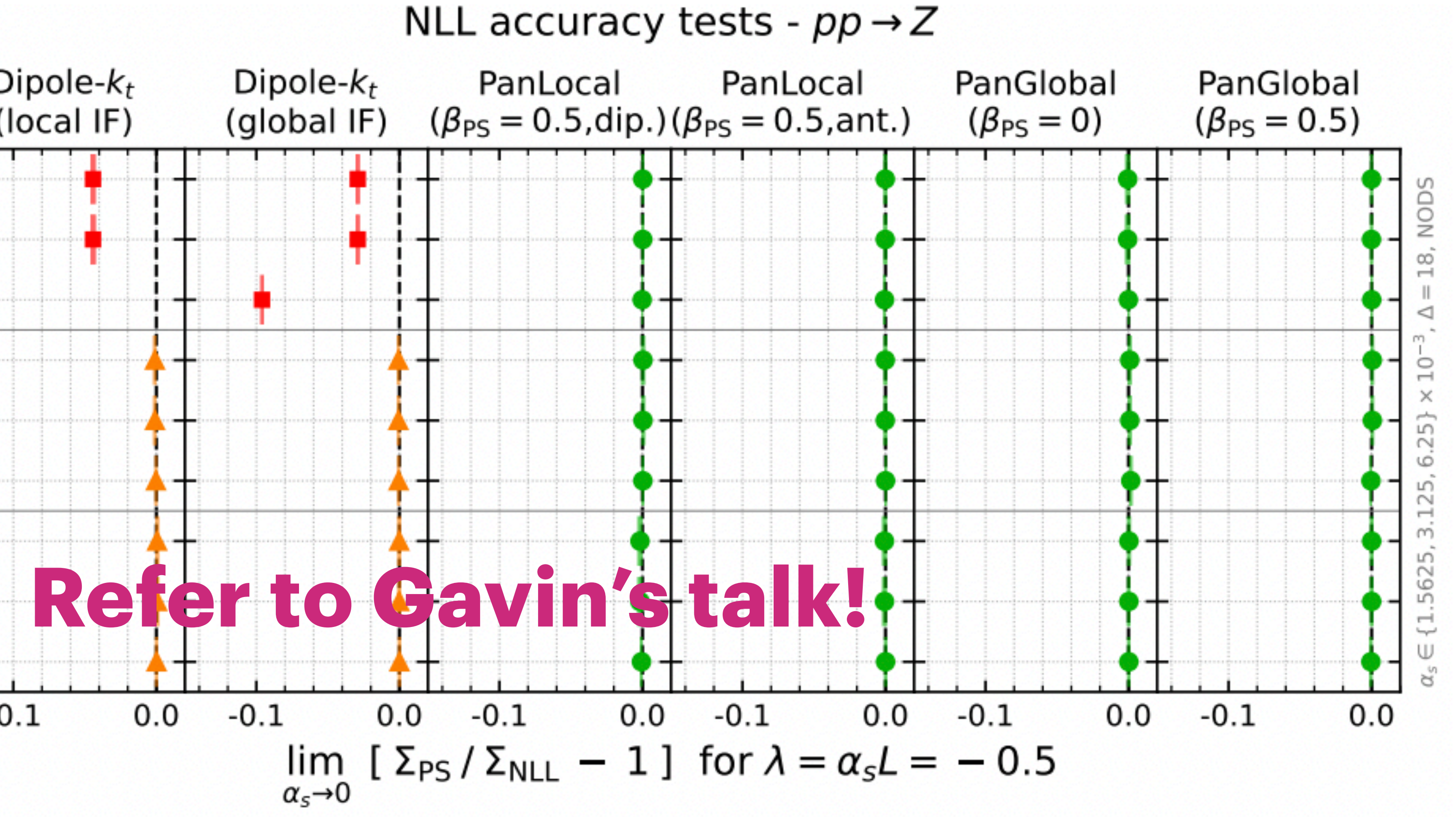
Hadronization models





Refer to Peter and Stefan's talk!

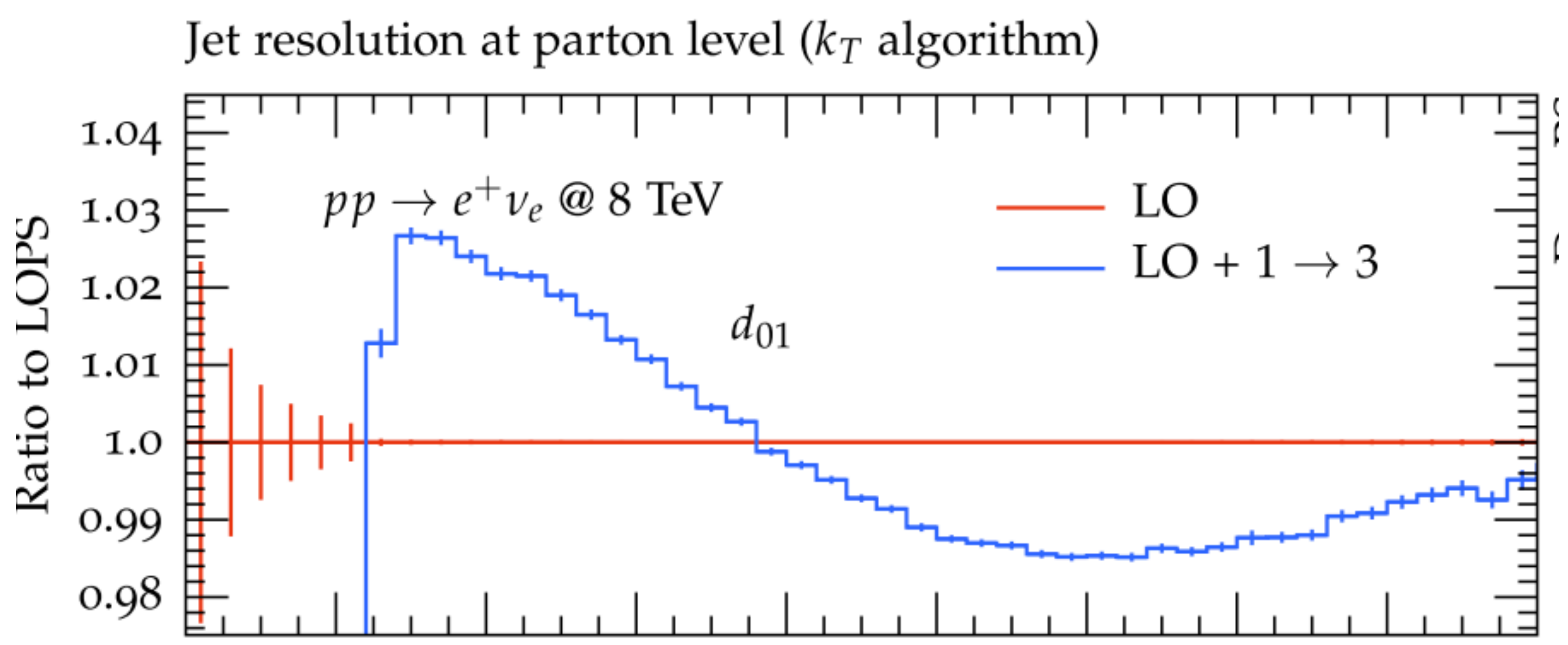
NLL improvements



Refer to Gavin's talk!

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

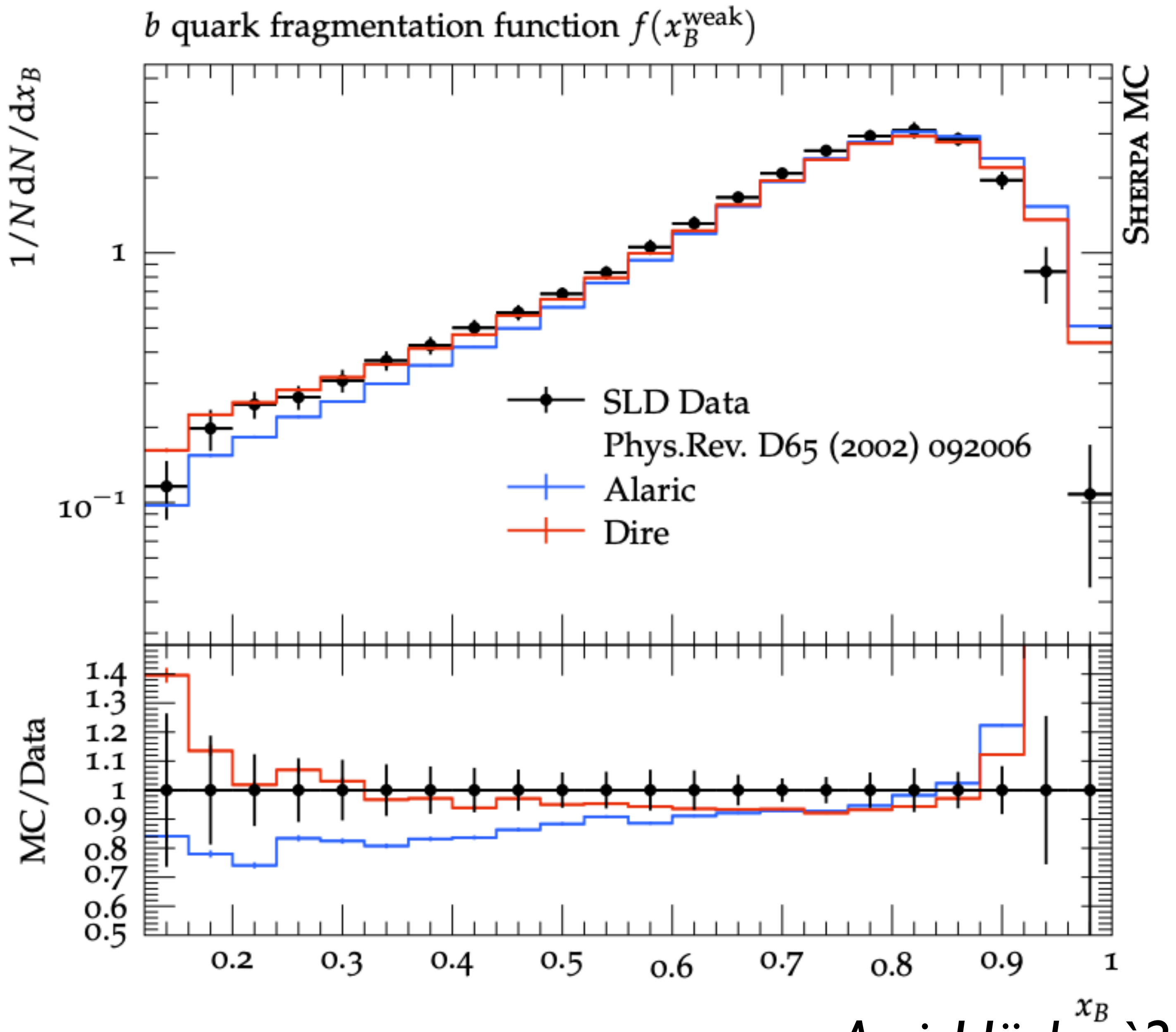
Triple collinear splitting



Höche, Prestel `17

See also Emanuele and James's talk!

Massive splitting

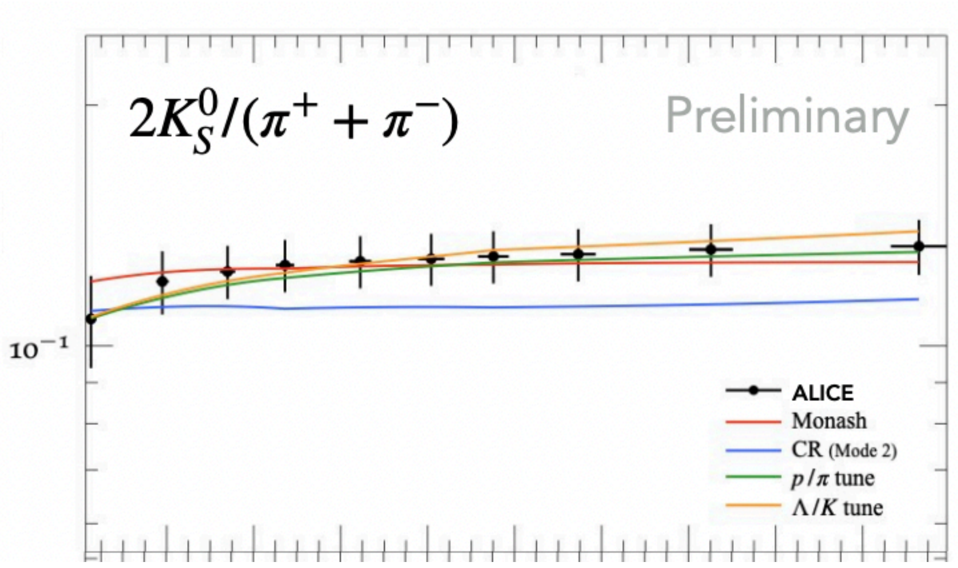


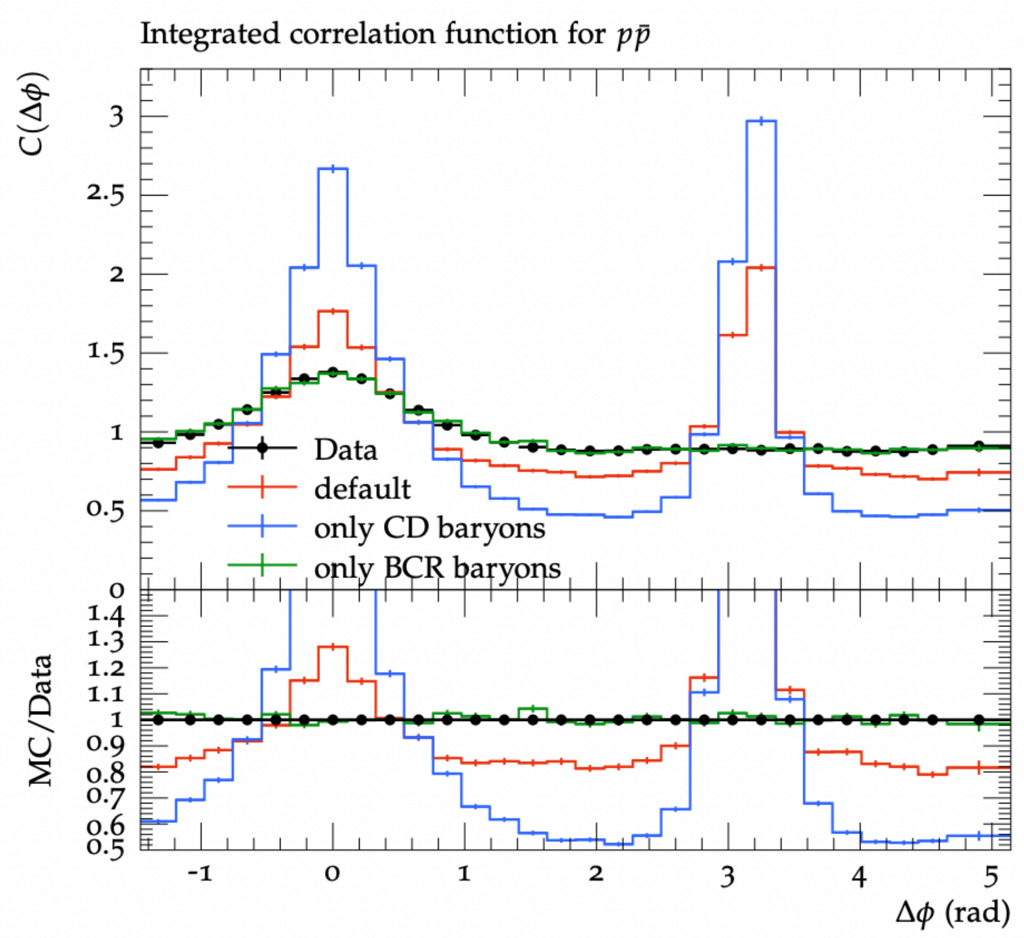
Assi, Höche `23

Refer to Enrico and Daniel's talk!

ASIDE: INTERPLAY WITH PARTON SHOWERS DEVELOPMENT

Hadronization models





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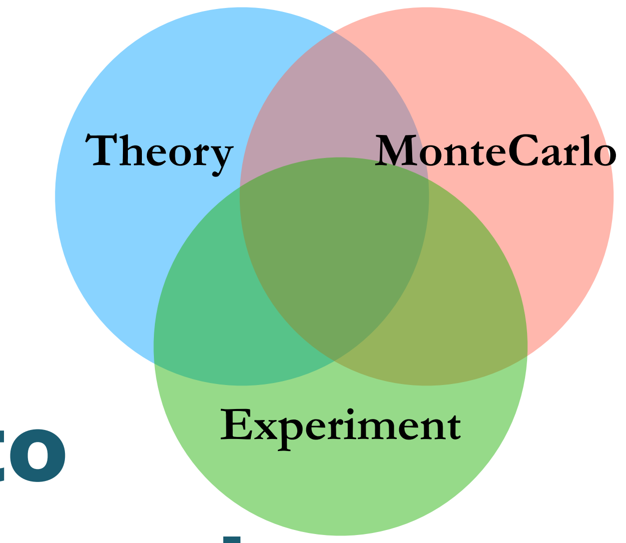
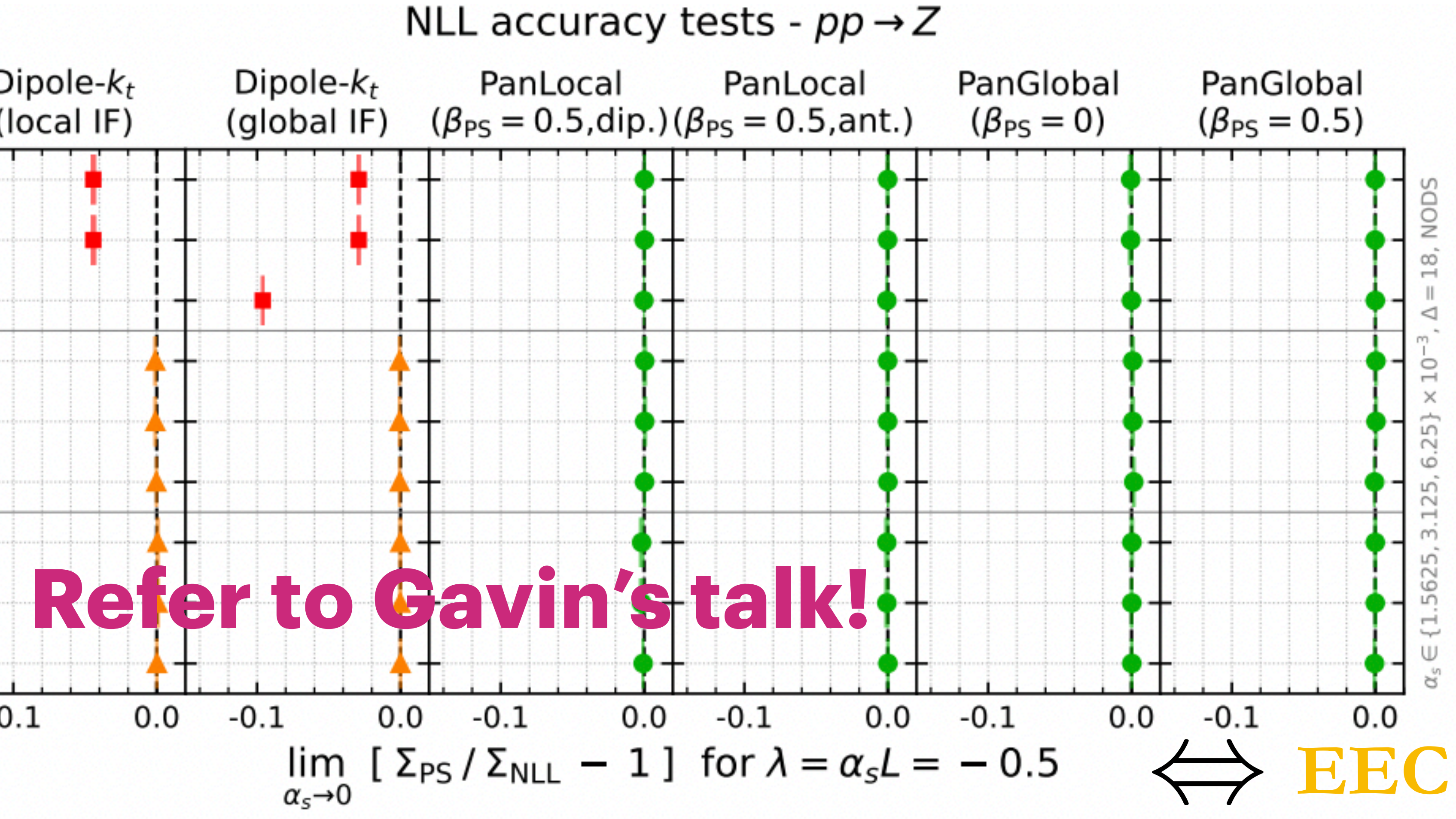
- **Jet substructure observables can be used to provide sensitivity to different perturbative and non-perturbative effects.**



Refer to Peter and Stefan's talk!

NLL improvements ⟺ Charged EECs

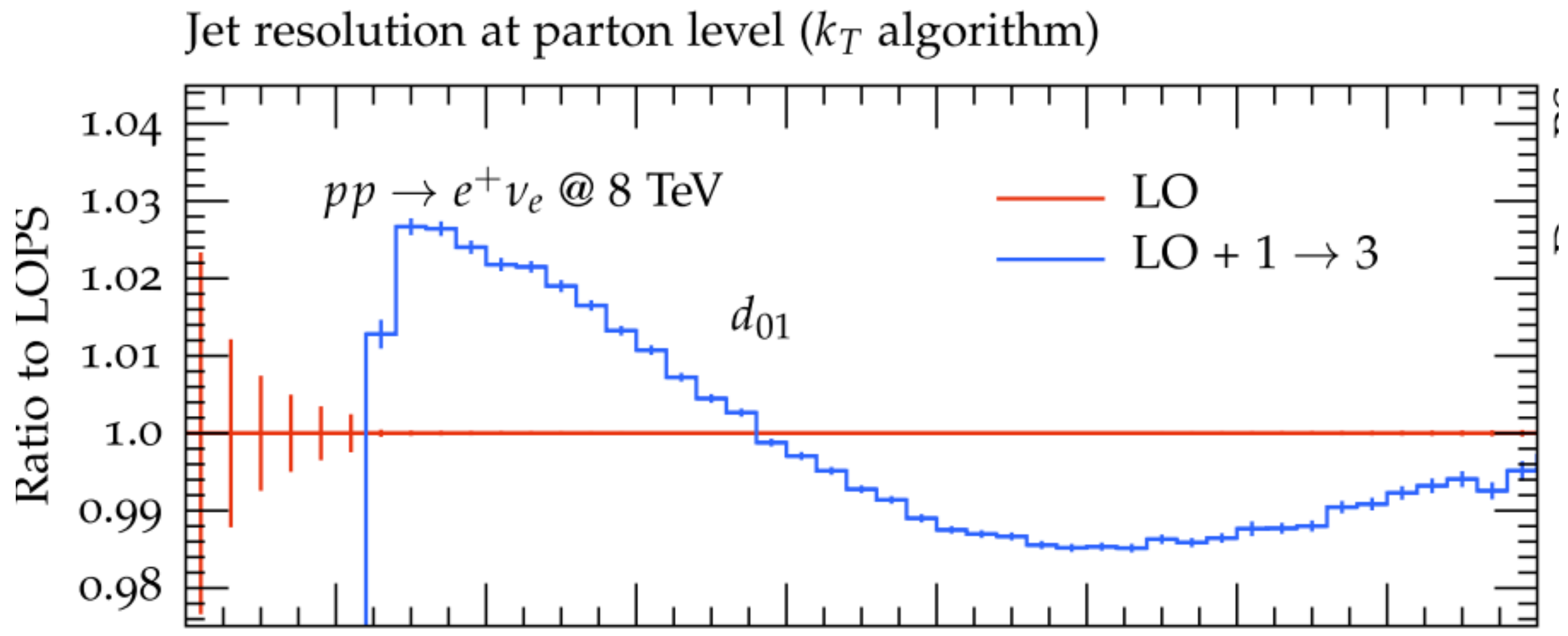


Refer to Gavin's talk!

⟺ EEC anomalous scaling

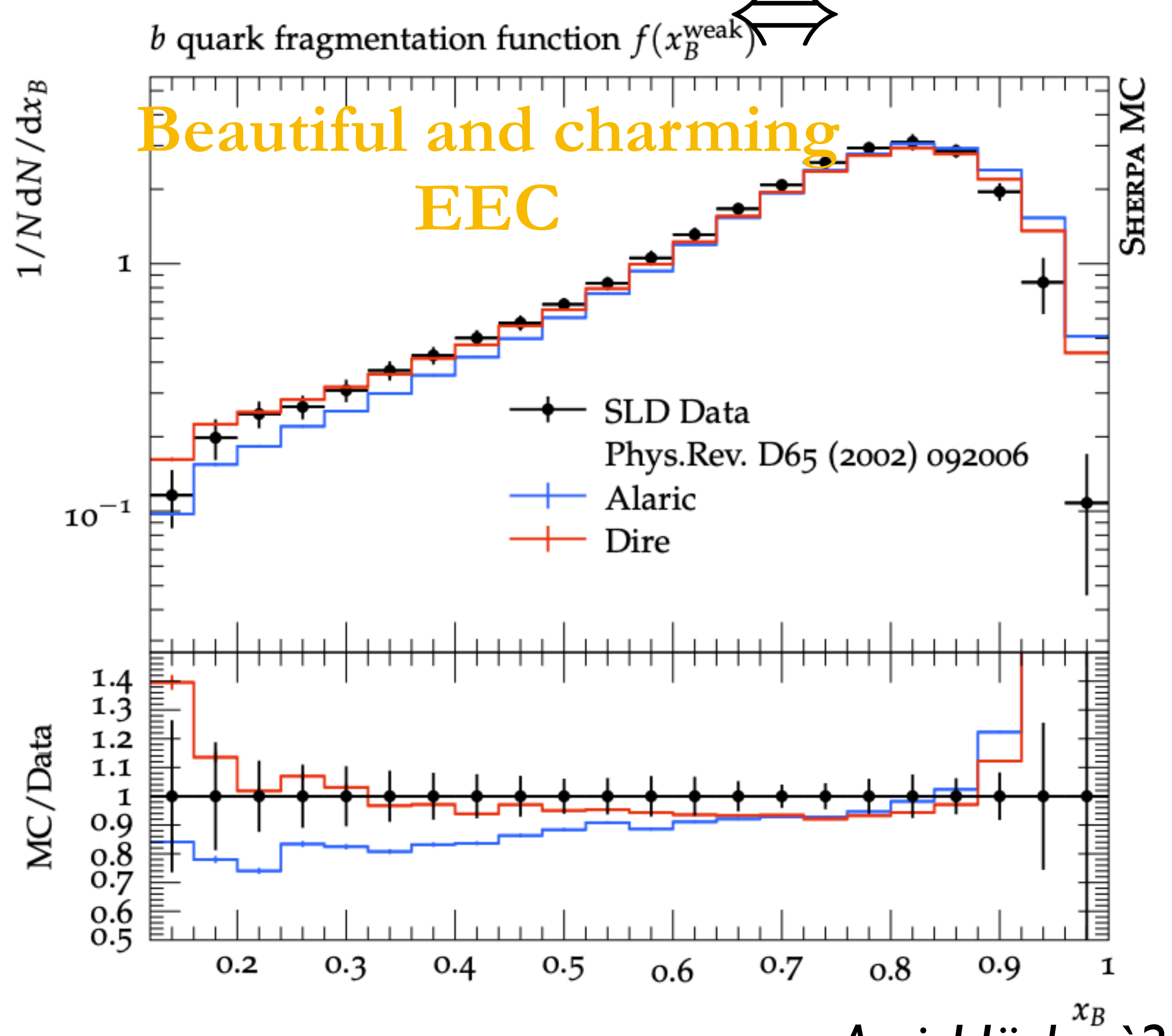
van Beekveld, Ravasio, Hamilton, Salam, Soto-Ontoso, Soyez, Verheyen `23

Triple collinear splitting ⟺ 3-point EEC



Höche, Prestel `17

Massive splitting ⟺ Beautiful and charming EEC



Assi, Höche `23

See also Emanuele and James's talk!

Refer to Enrico and Daniel's talk!

Top-quark physics

170 GeV - O(TeV)

Higgs physics

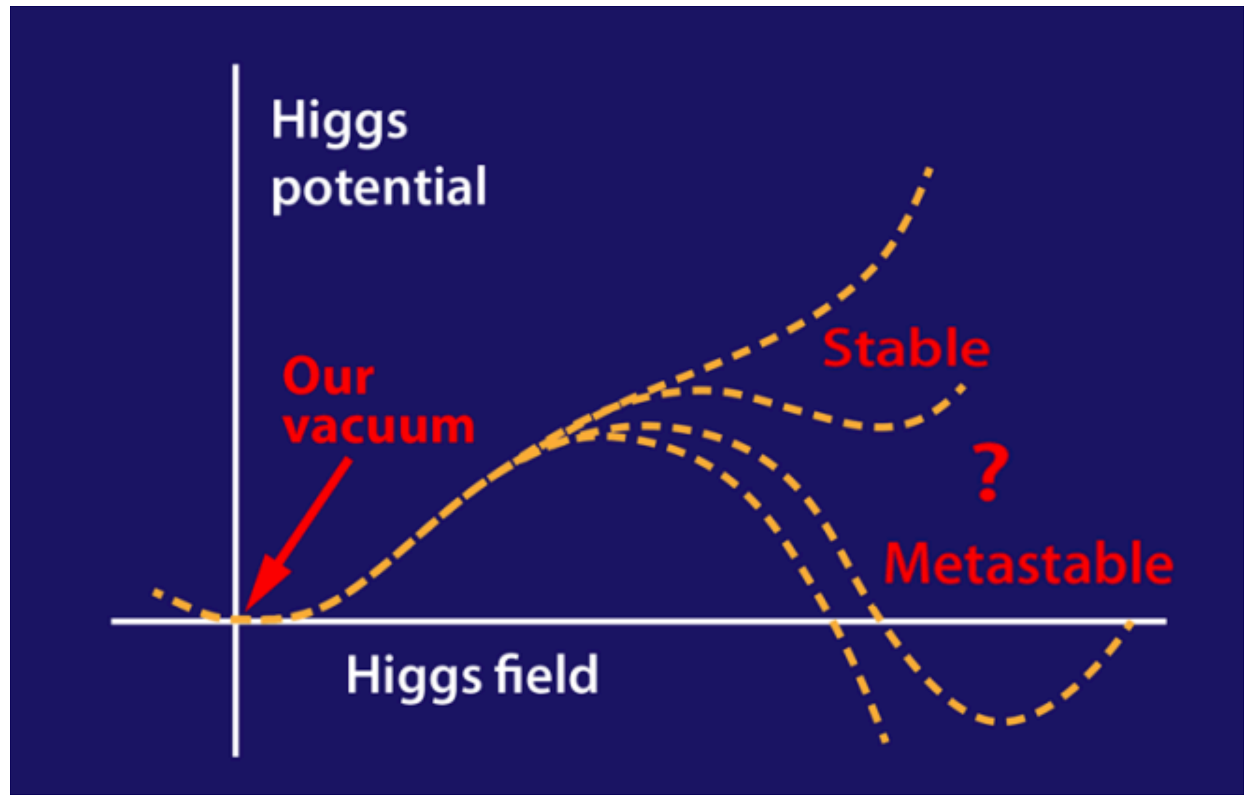
125 GeV - 500 GeV

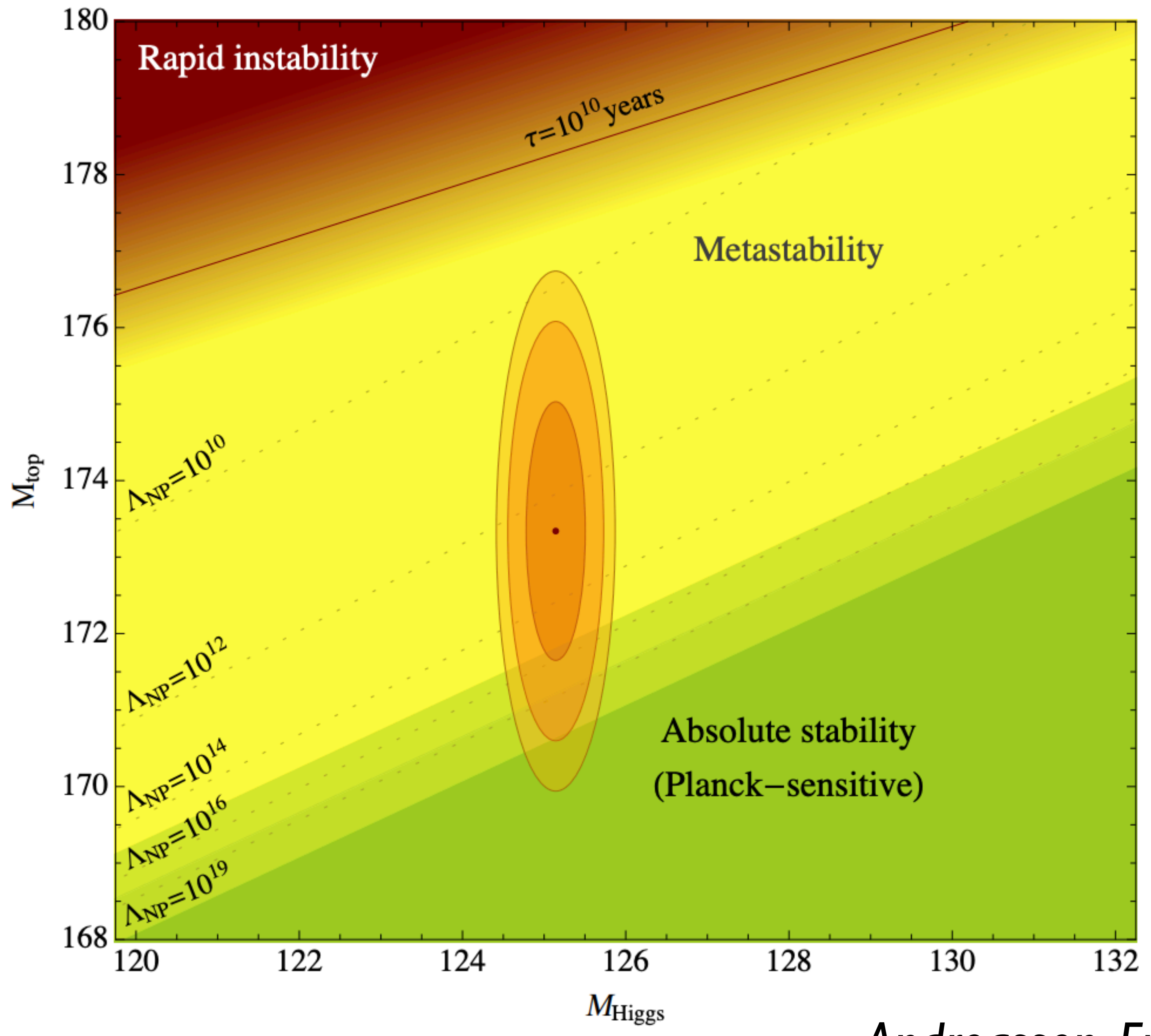
GOAL

WHAT IS THE FATE OF OUR UNIVERSE?

METASTABILITY OR STABILITY OF OUR UNIVERSE

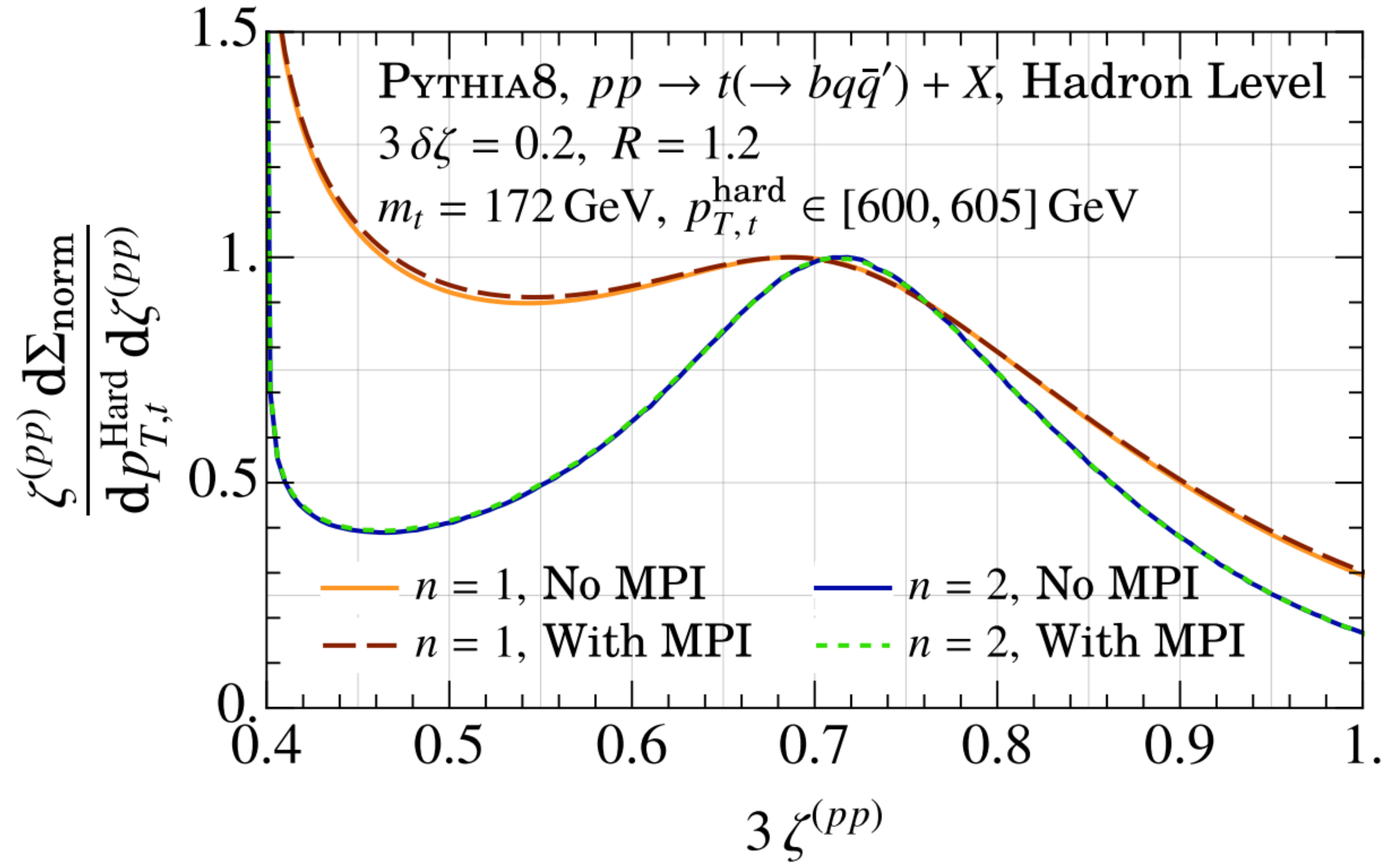
- **Will our universe undergo eternal inflation, or will it undergo some catastrophic big crunch? Can the jet substructure come to the rescue in answering this question?**

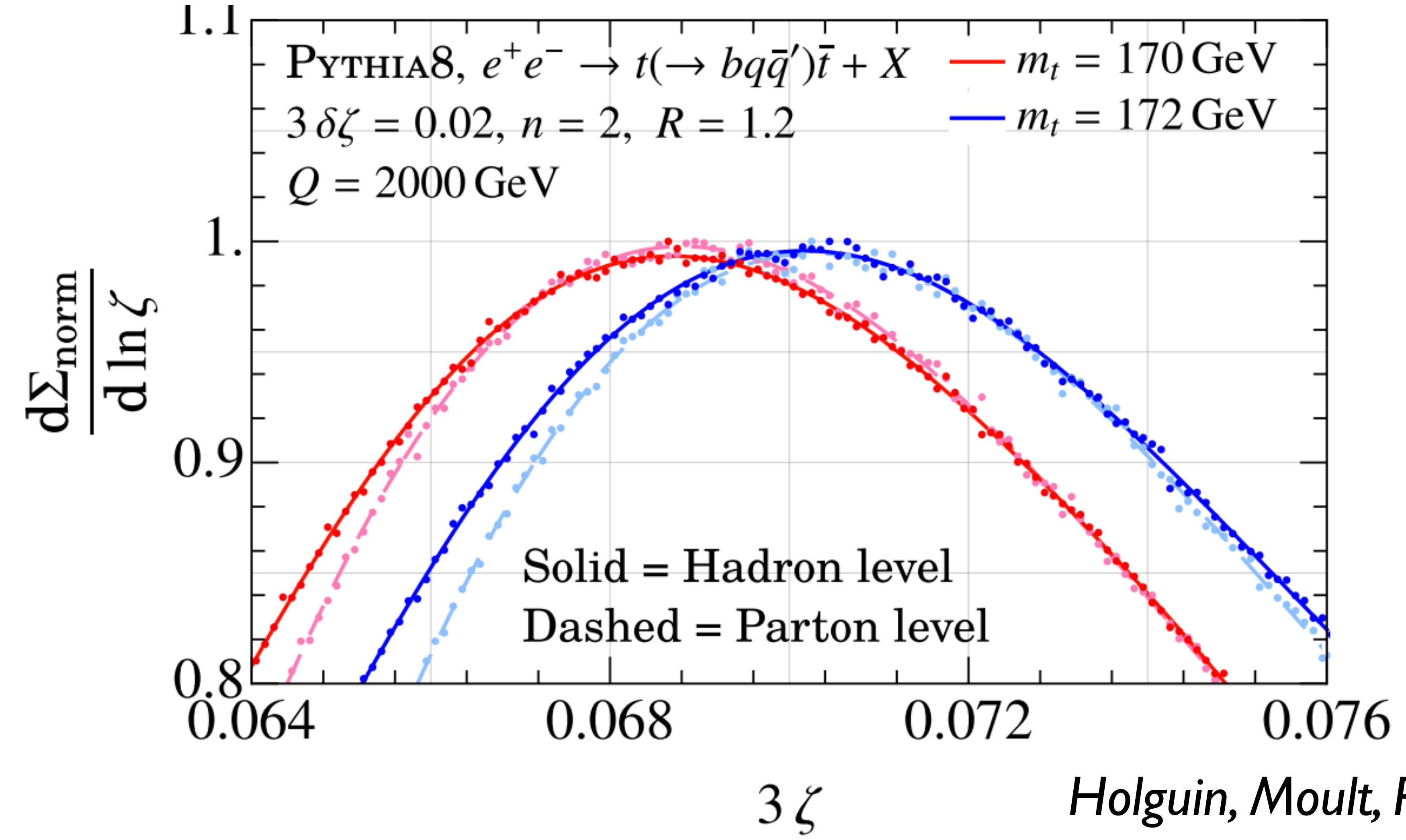




Andreassen, Frost, Schwartz `14

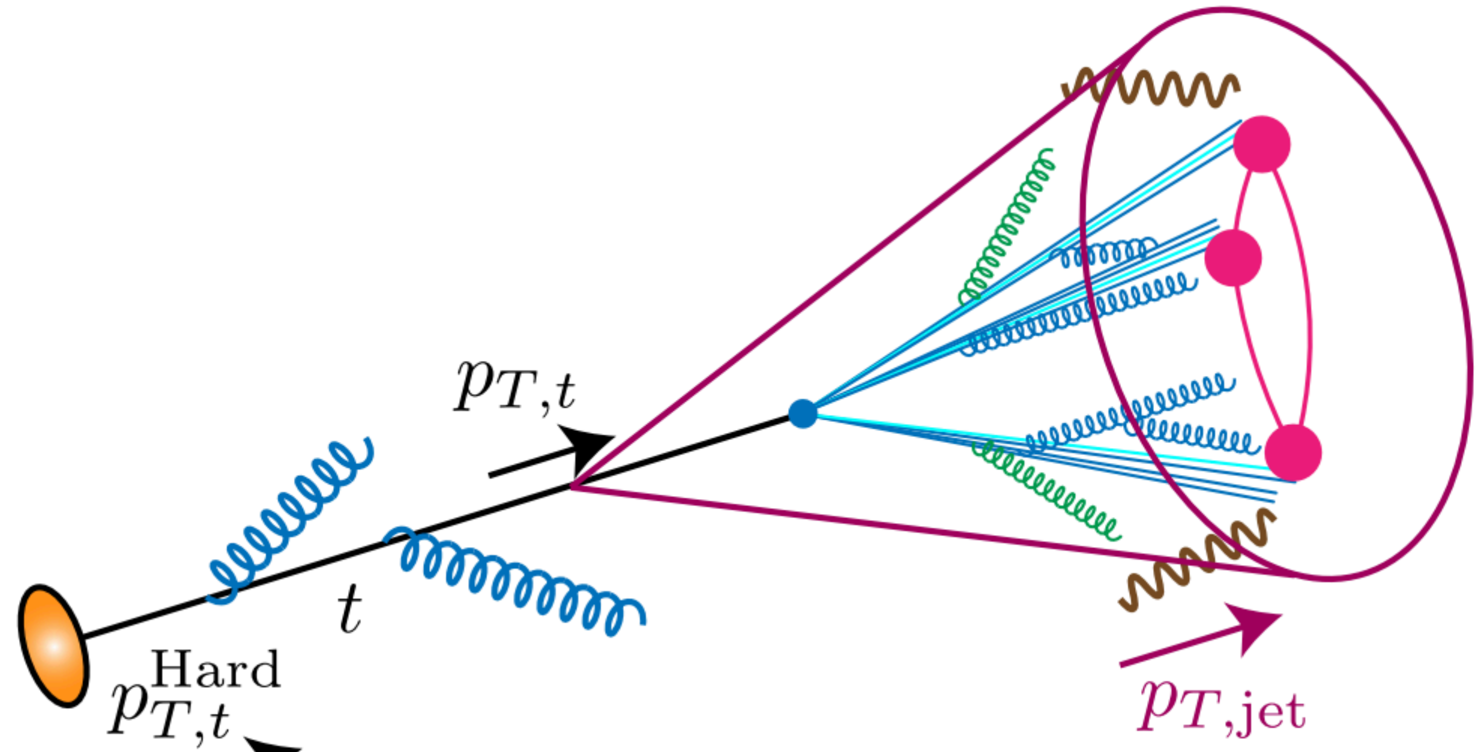
ENERGY ENERGY CORRELATORS ON TOP JET





Holguin, Moult, Pathak, Procura `22

- **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**
- **More analyses to come!**

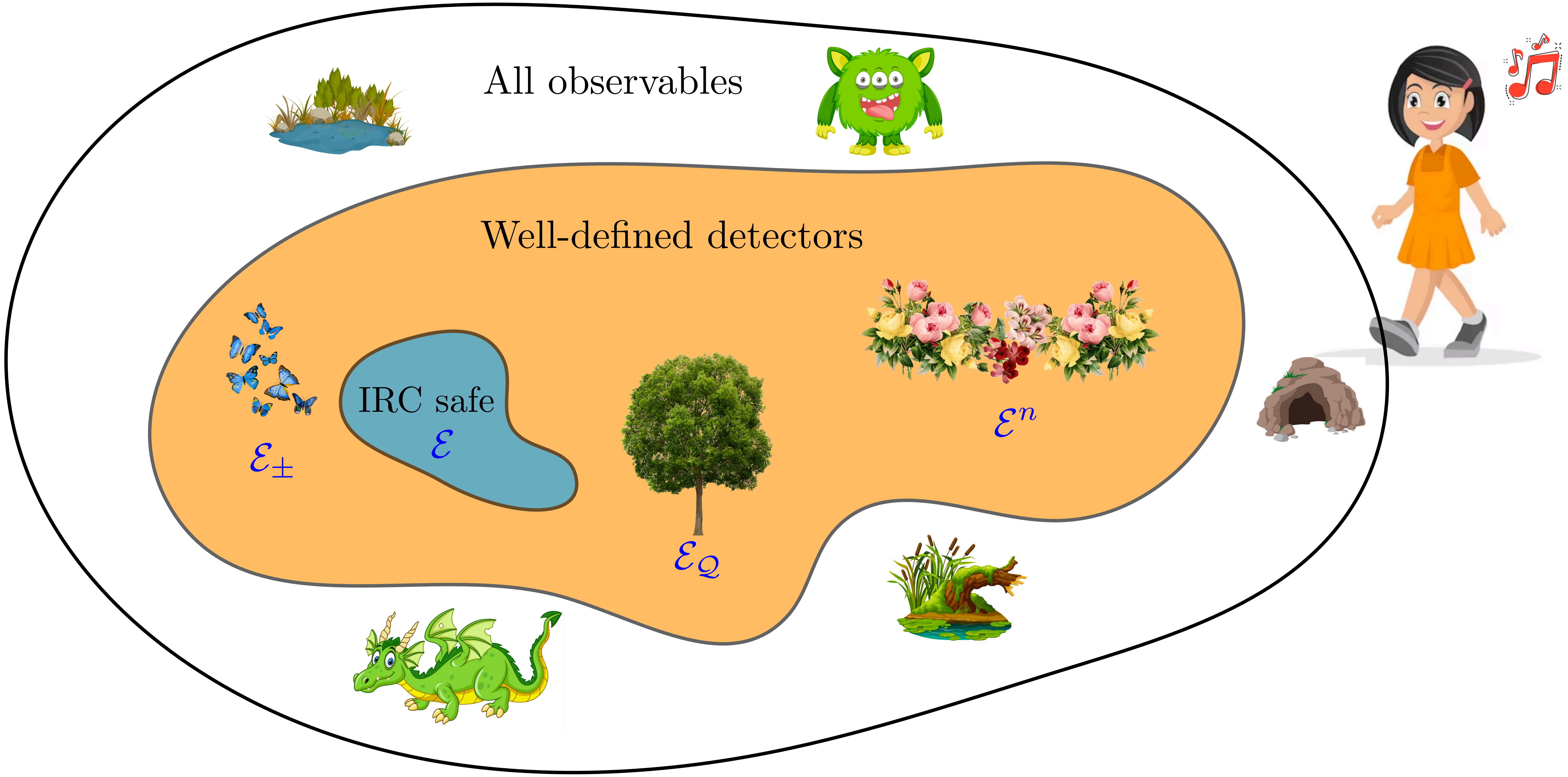


NICE PRECISION GOAL FOR JET SUBSTRUCTURE

- "[We are able to determine the stability of our universe] by performing high precision measurement of the Higgs mass (with uncertainty $\Delta m_H \sim 0.2$ GeV), the top mass ($\Delta m_t \sim 60$ MeV) and the strong coupling constant ($\Delta\alpha_s/\alpha_s \sim 10^{-3}$)"

Arkani-Hamed, Dubovsky, Senatore, Villadoro `08

We must dream big! The fate of our universe is at our hands!



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