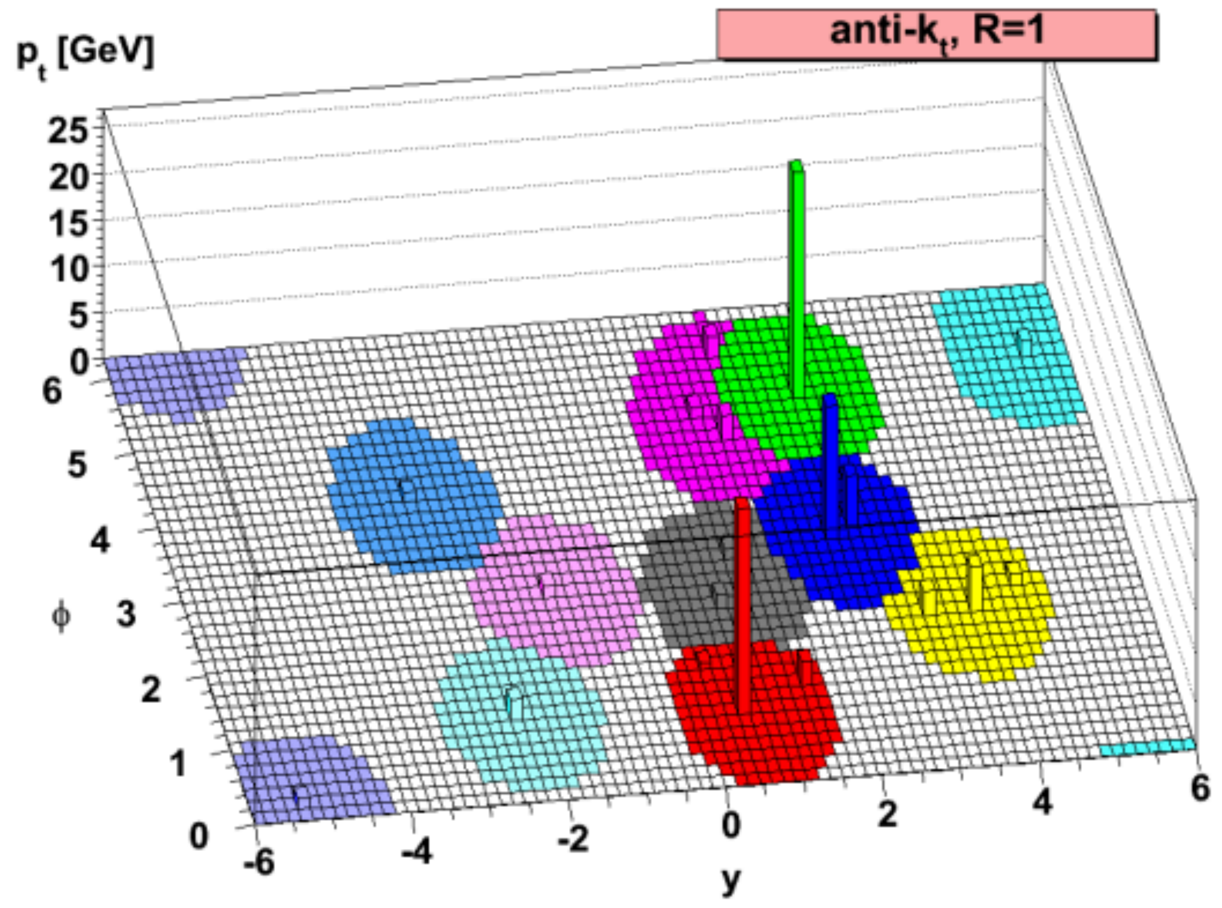
Theory Overview

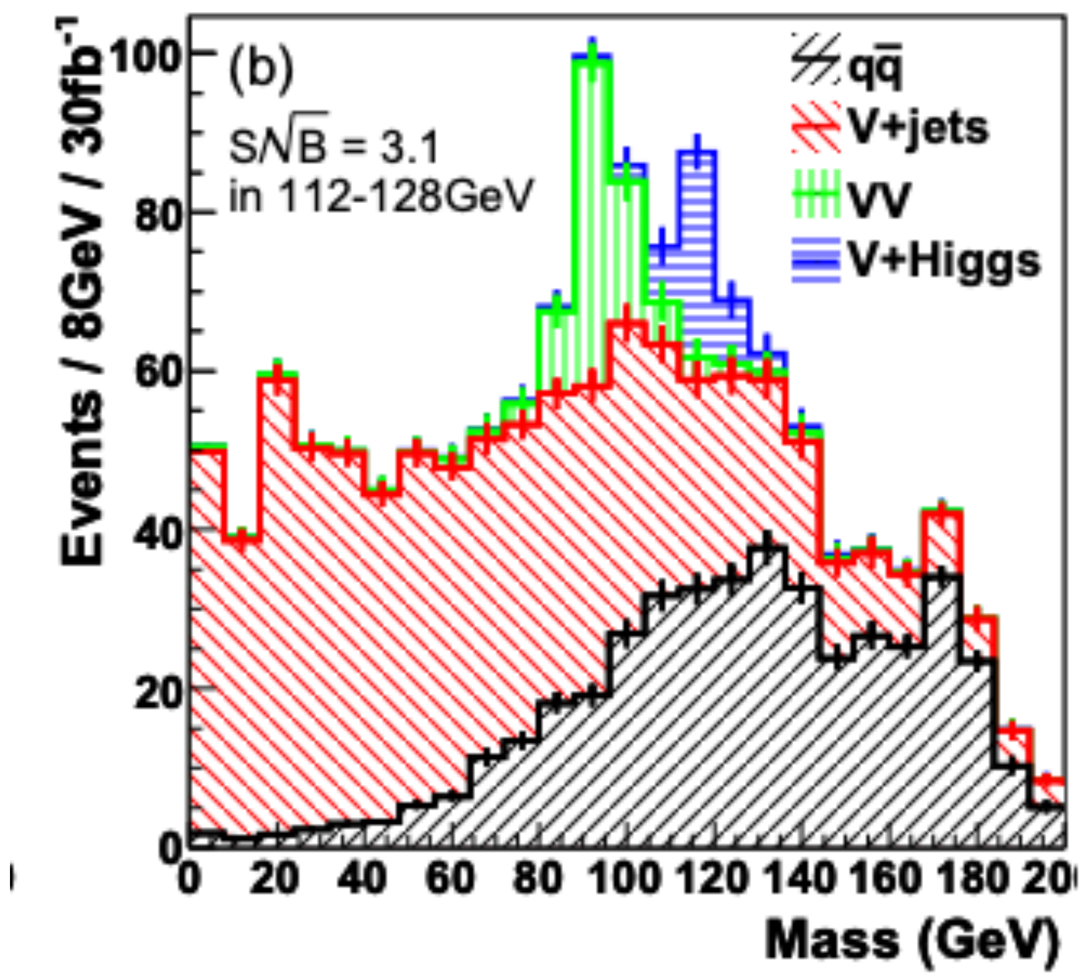
Kyle Lee
CTP, MIT

BOOST 2023

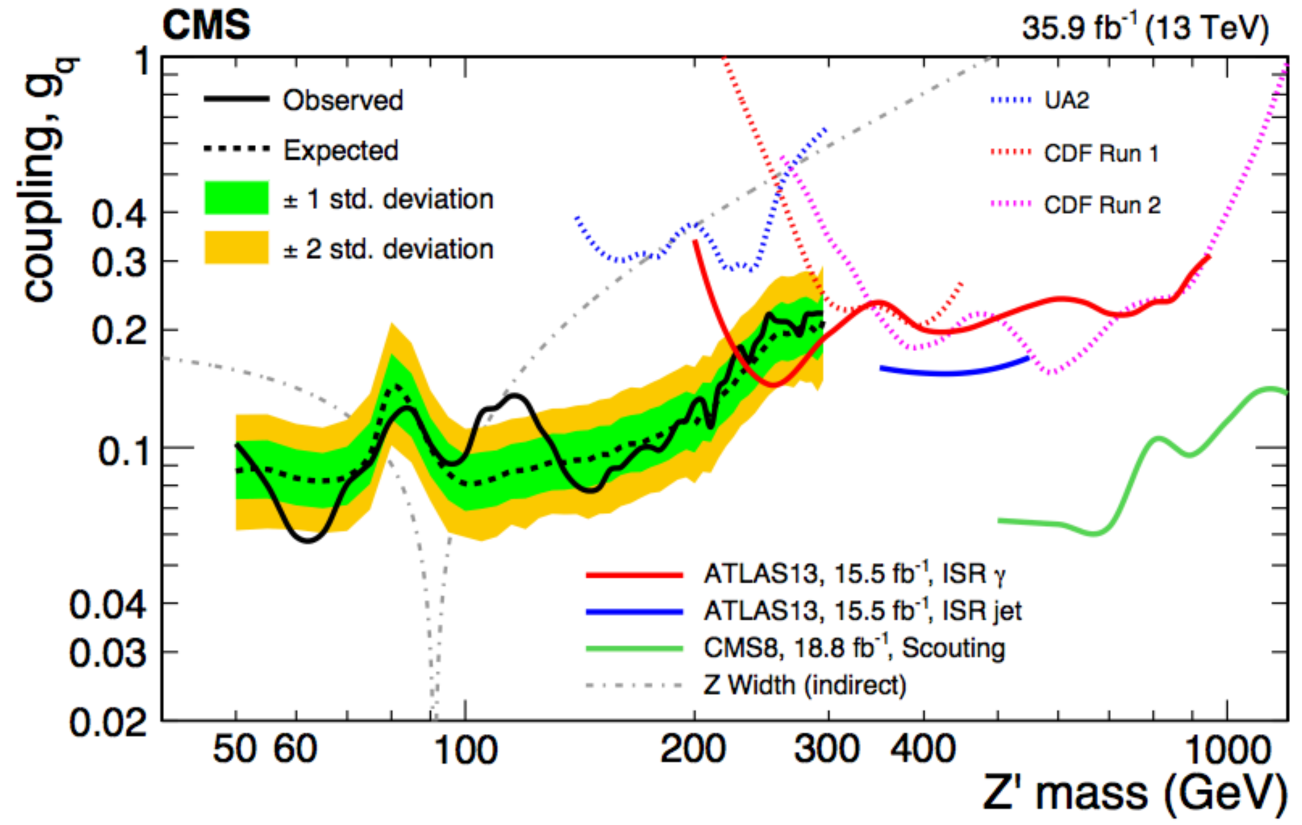
JET SUBSTRUCTURE STUDY



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**

BRIEF HISTORY OF JET SUBSTRUCTURE THEORY DEVELOPMENTS

(Many are still developing or advancing areas of research. Here, I only indicate the year when they roughly began)

(Too many people / developments / papers to credit in a single page!)

1970s

Event shapes and cone jet

- **Thrust, Sphericity, EECs**
- **First cone-algorithm jets**

1990s

Reclustering algorithms

- **kT jet clustering**
- **CA jet clustering**

2008-2010

First jet substructure and anti-kT

- **Beginning of Jet substructure**
- **anti-kT jet clustering**
- **Pruning, trimming**

2010-2015

Grooming and multi-prong observables

- **N-(sub)jettiness**
- **Xcone jet algorithms**
- **Soft Drop Jet grooming, …**

2016-2019

New observables and ML

- **Sudakov safe observables**
- **Groomed multi-prong jets**
- **Lund Jet Plane**
- **Machine Learning for Jets**

2020s

- **Energy Correlators for Jets**

more to come!

Many decades of theoretical developments gave us analytical tools to study jets and its structure!

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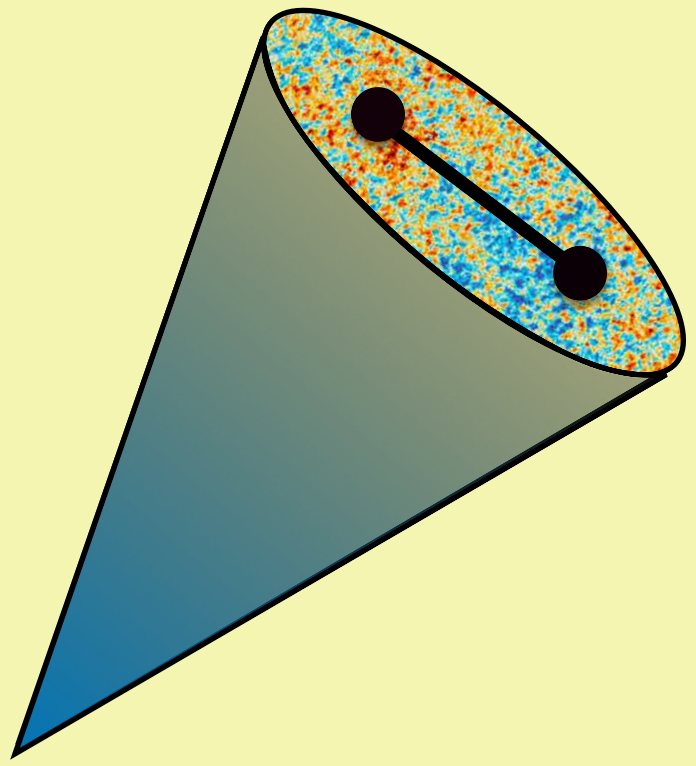
Many decades of theoretical developments gave us analytical tools to study jets and its structure!

- **Important new development in jet substructure theory in recent years is an idea to reframe jet substructure study in terms of correlation functions of energy flow operators**

Chen, Moult, Zhang, Zhu `20

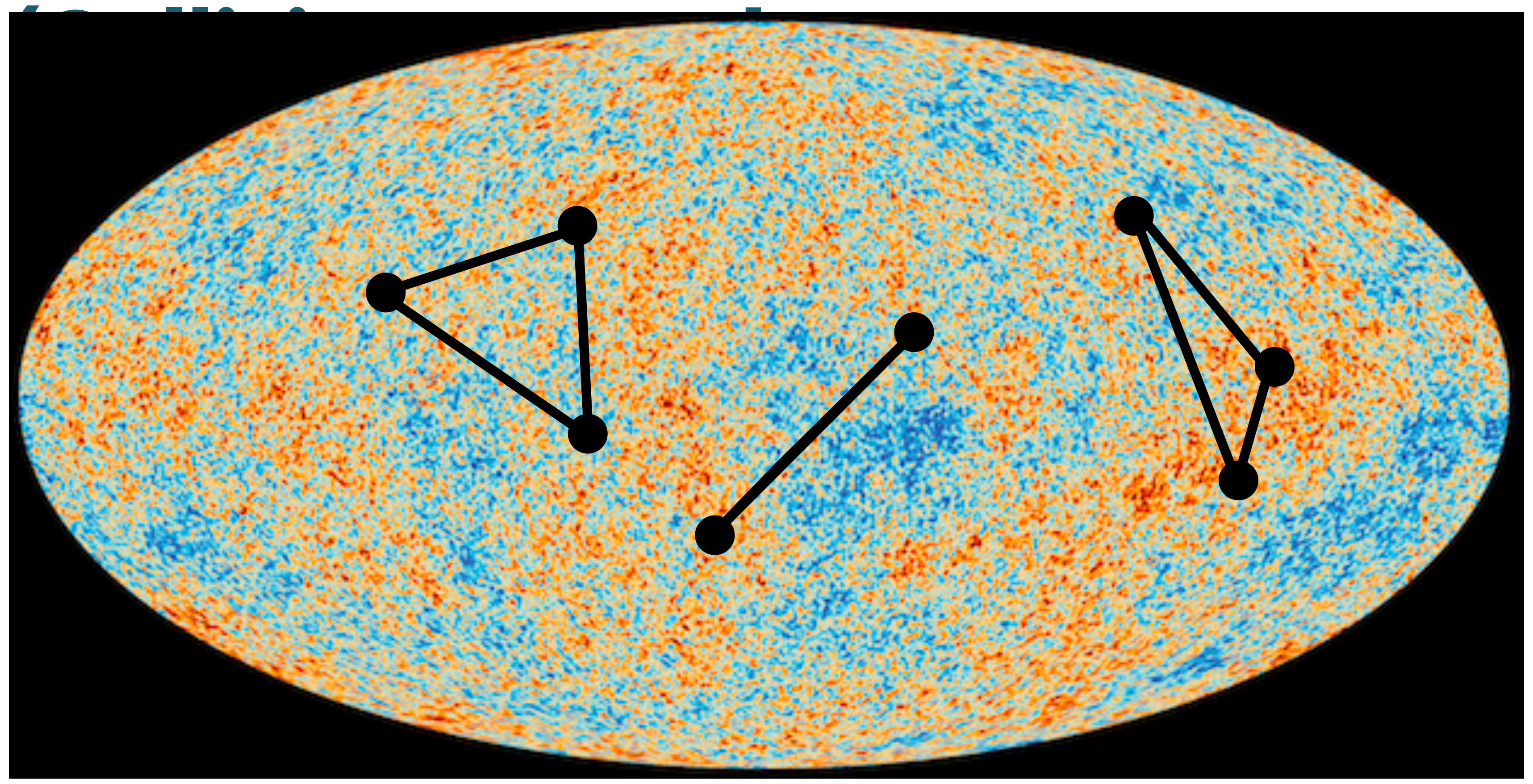
Many theory talks this year at BOOST 2023

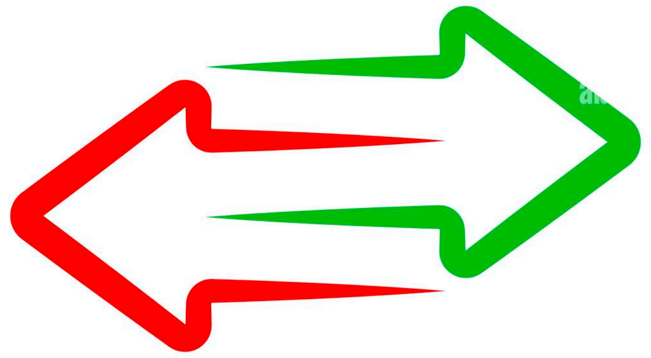
RETHINKING JET SUBSTRUCTURE AS ENERGY CORRELATORS

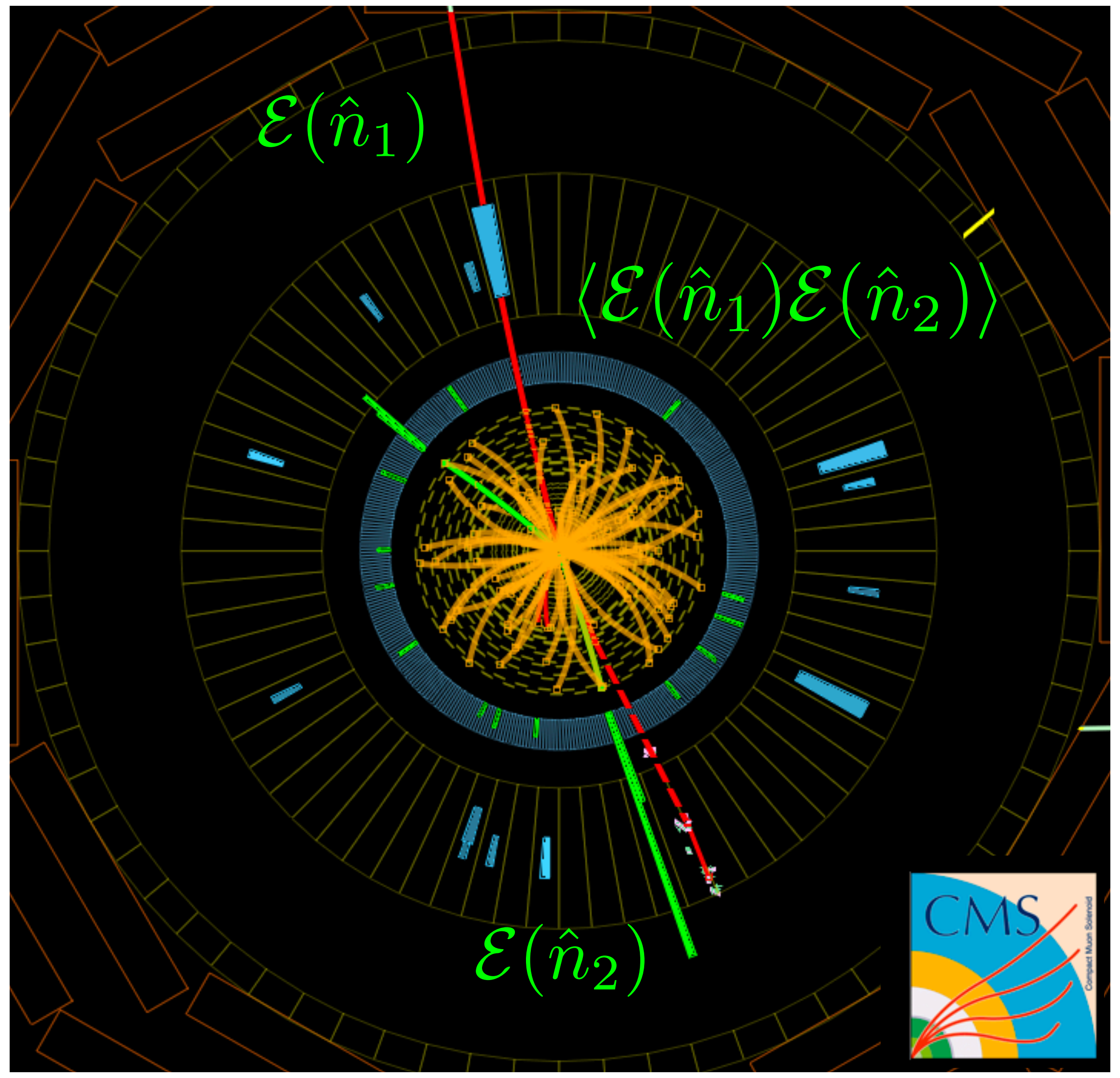


JET SUBSTRUCTURE AS CORRELATION FUNCTIONS

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



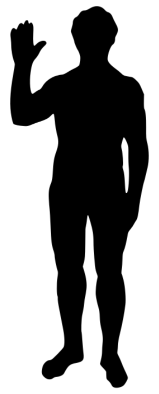




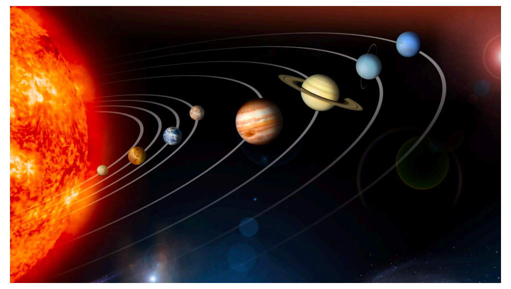
- Much like cosmology, we observe **asymptotic energy flux** at the detectors that are placed at **cosmic scale away** from where the events originated.

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

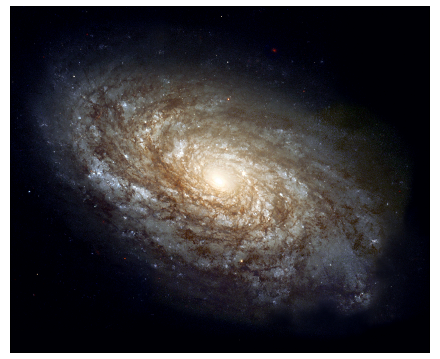
10^{21} **orders in distance!**



$\mathcal{O}(1)$ meters



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



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

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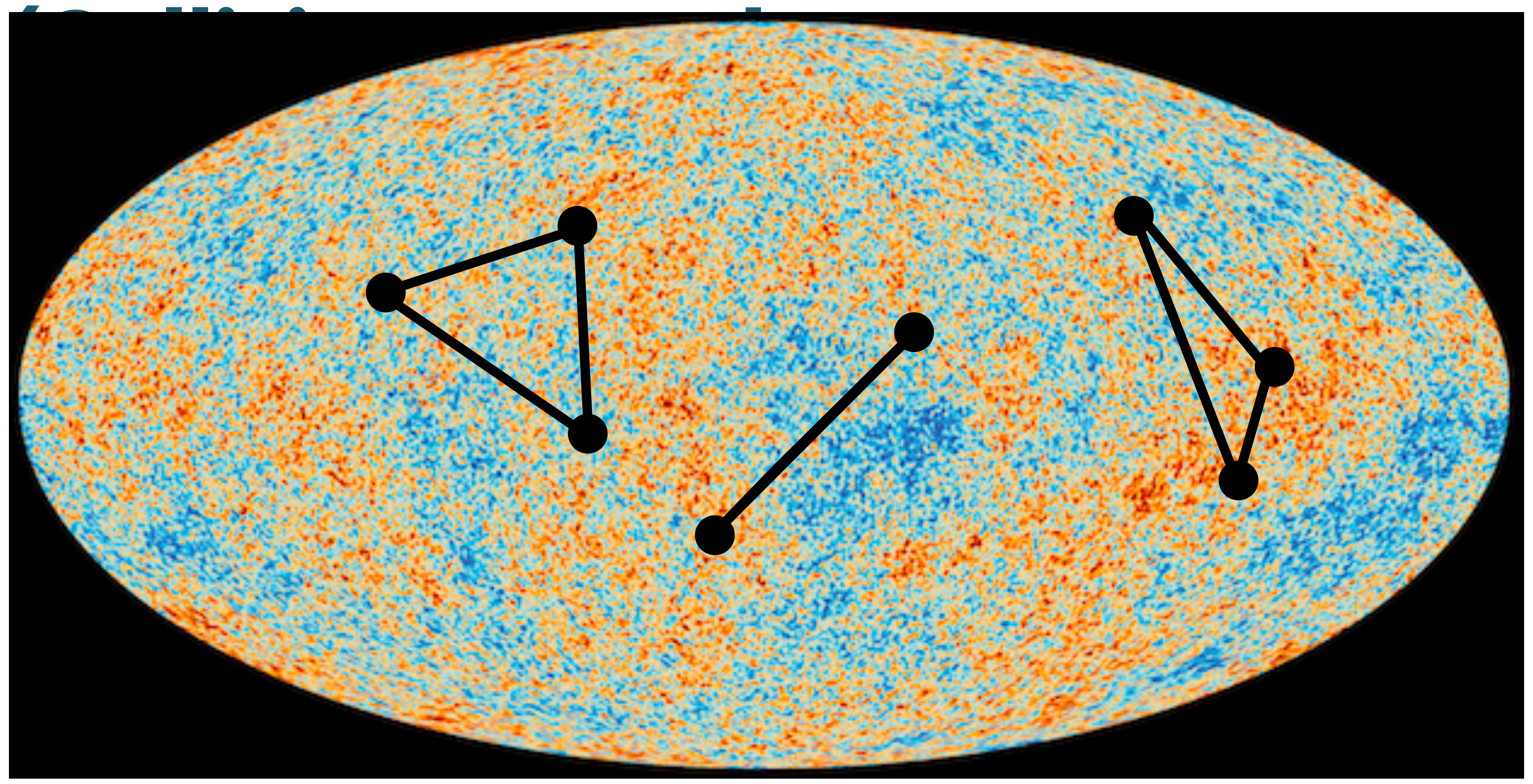
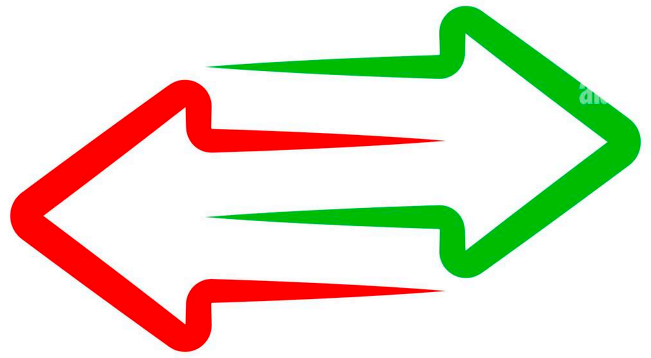
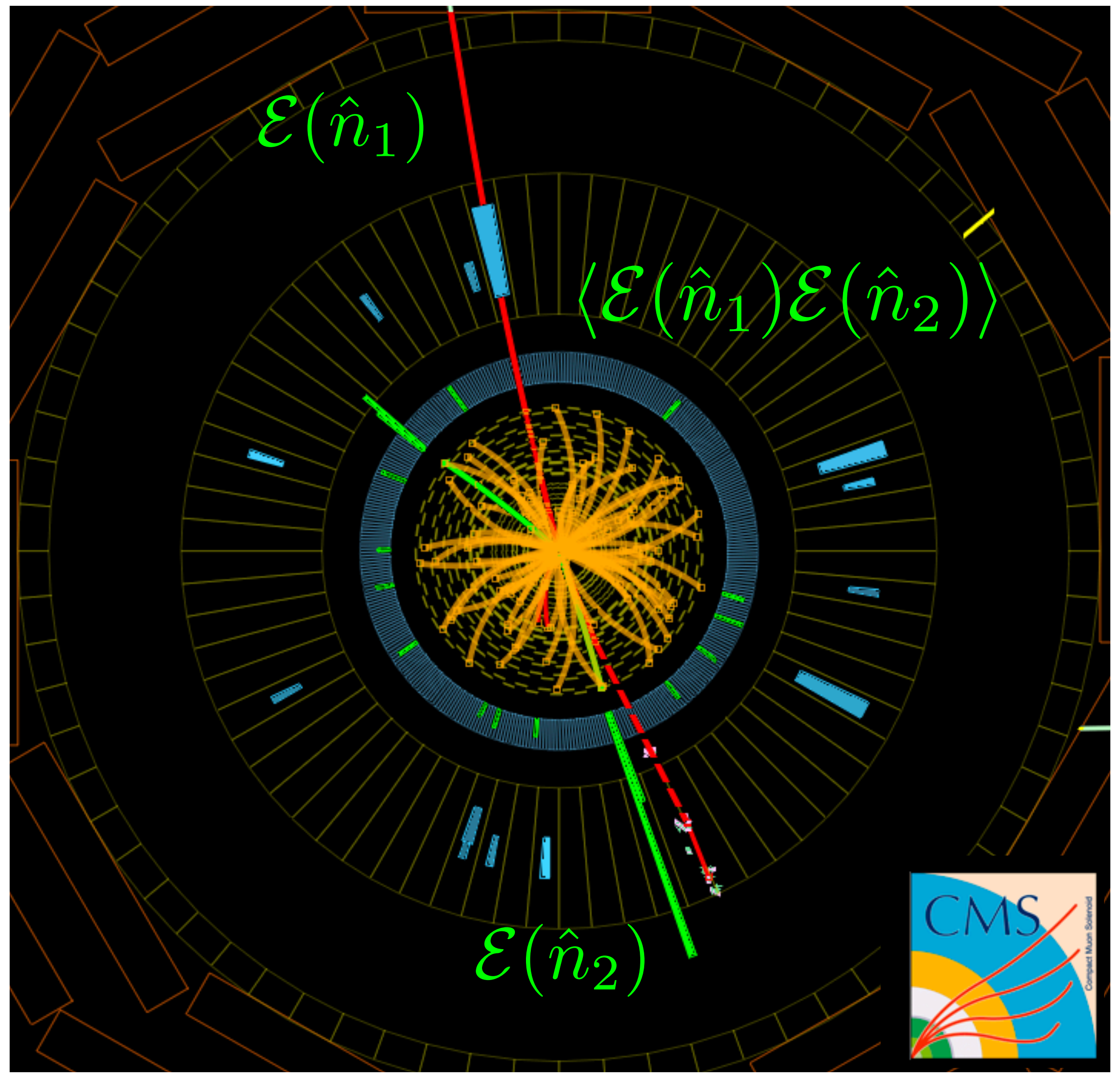




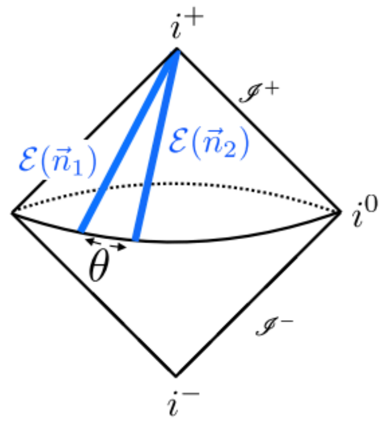


- Much like cosmology, we observe **asymptotic energy flux** at the detectors that are placed at **cosmic scale away** from where the events originated.

Energy Flow Operators (Light Ray Operators)

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

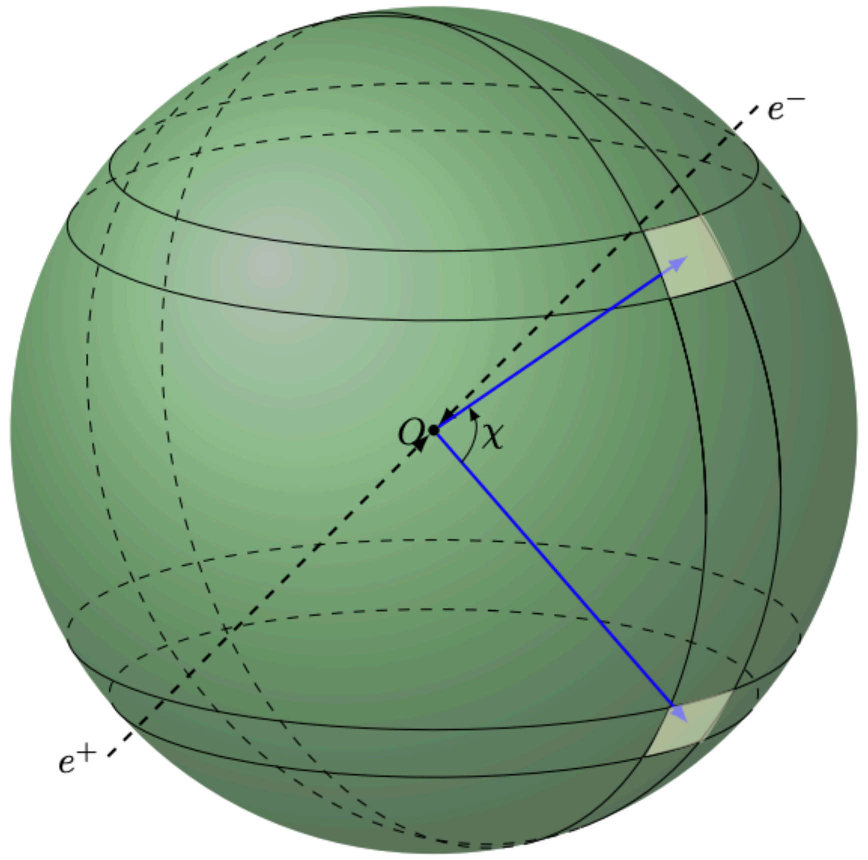
$$\mathcal{E}(\hat{n})|X\rangle = \sum_a E_a \delta^{(2)}\left(\Omega_{\vec{p}_a} - \Omega_{\hat{n}}\right)|X\rangle$$



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

JET SUBSTRUCTURE AS CORRELATION FUNCTIONS

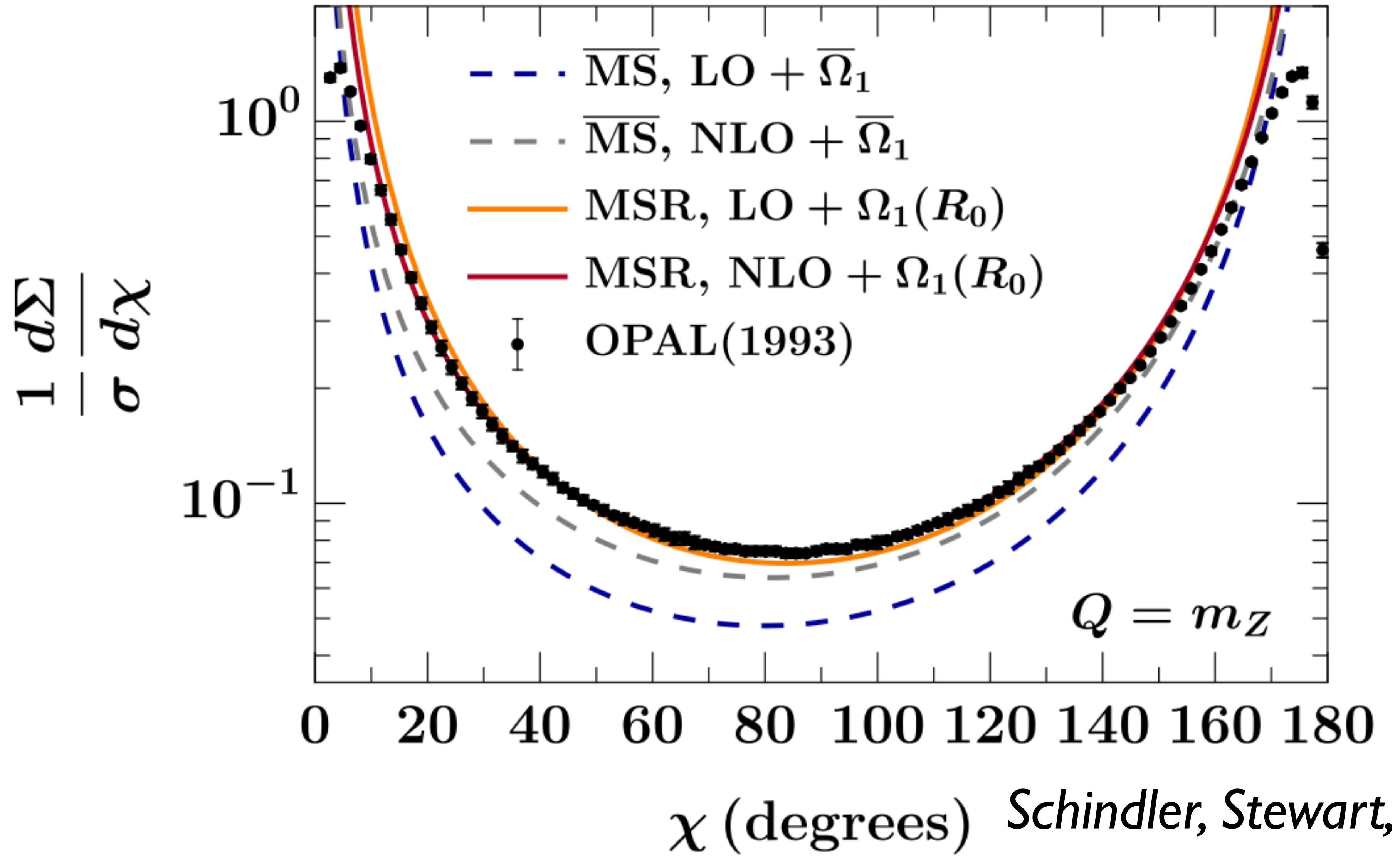
- **Indeed, energy-energy correlators are one of the very first studied event shape (or correlations) observables in QCD** *Basham, Brown, Ellis, Love, `78-79*



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

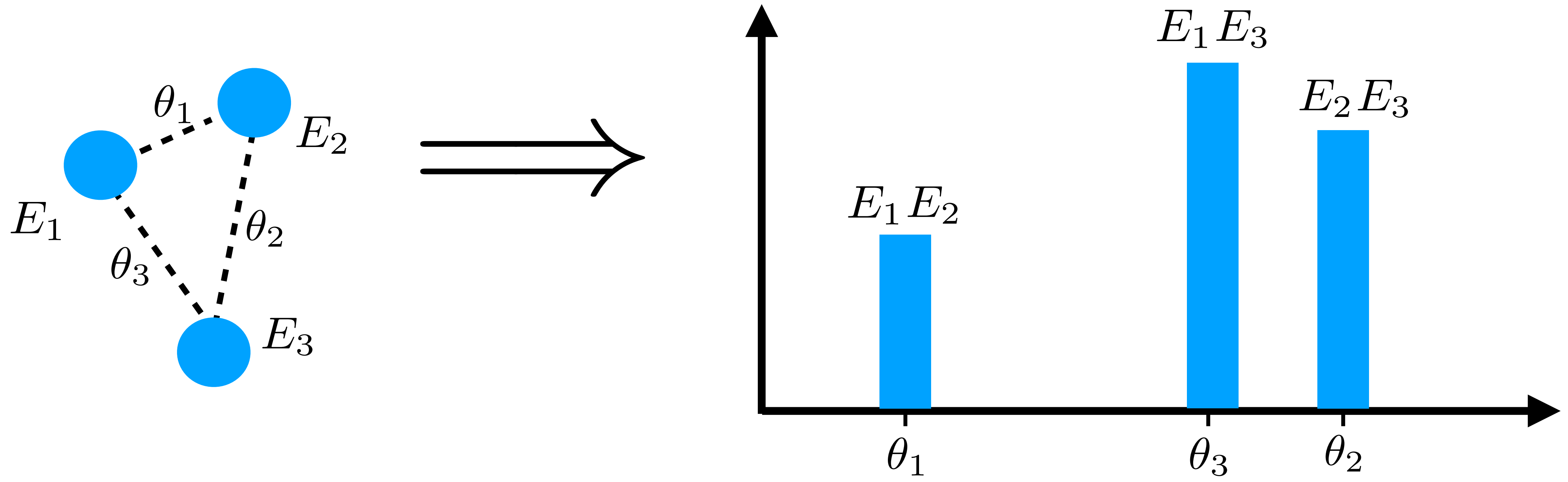
Many precise calculations!

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

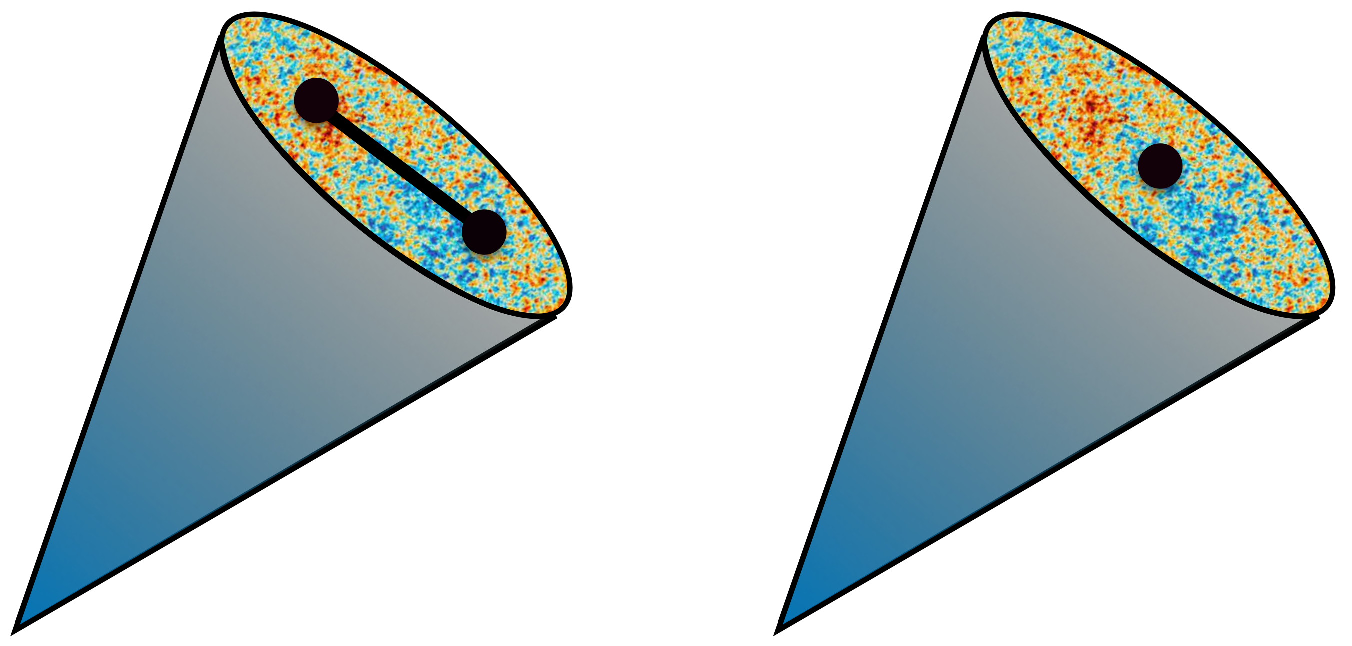
Impressive agreements from recent calculation, without any fits!



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

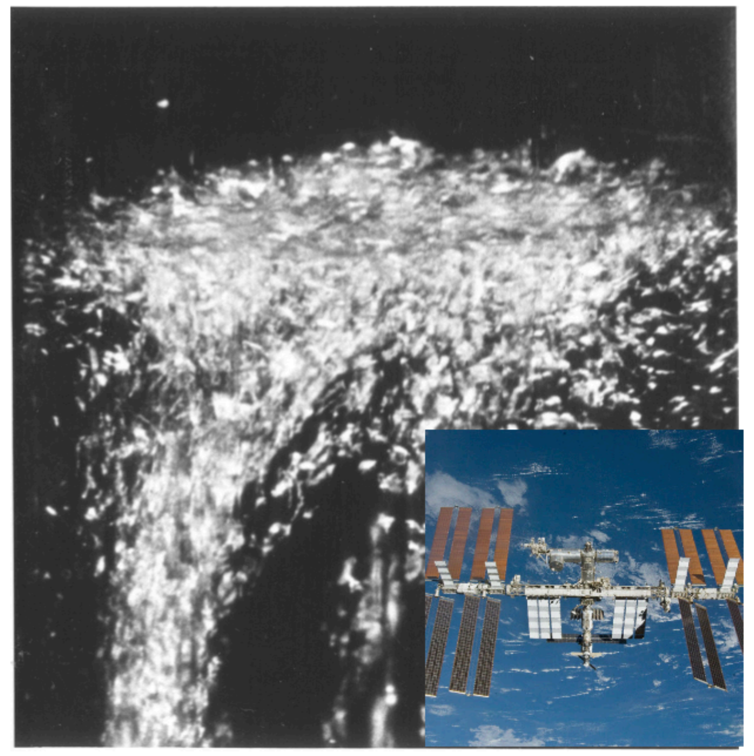
Weighted cross-section, or, ensemble averaged observable

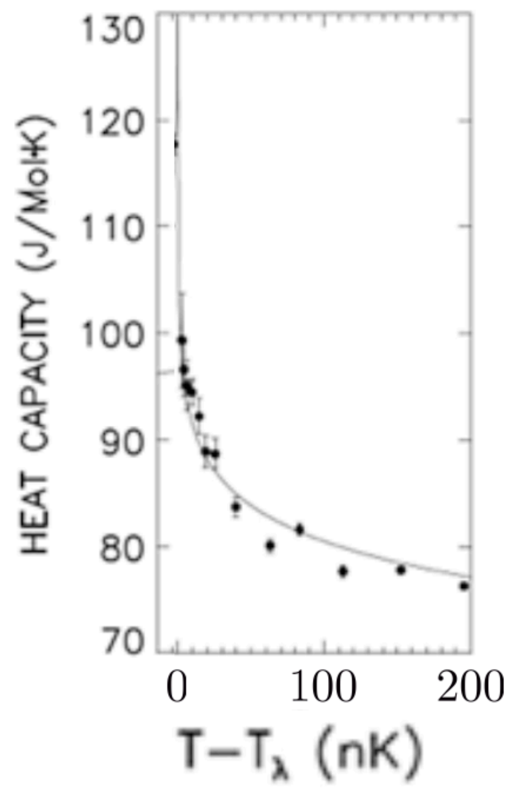
JET SUBSTRUCTURE AS CORRELATION FUNCTIONS



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

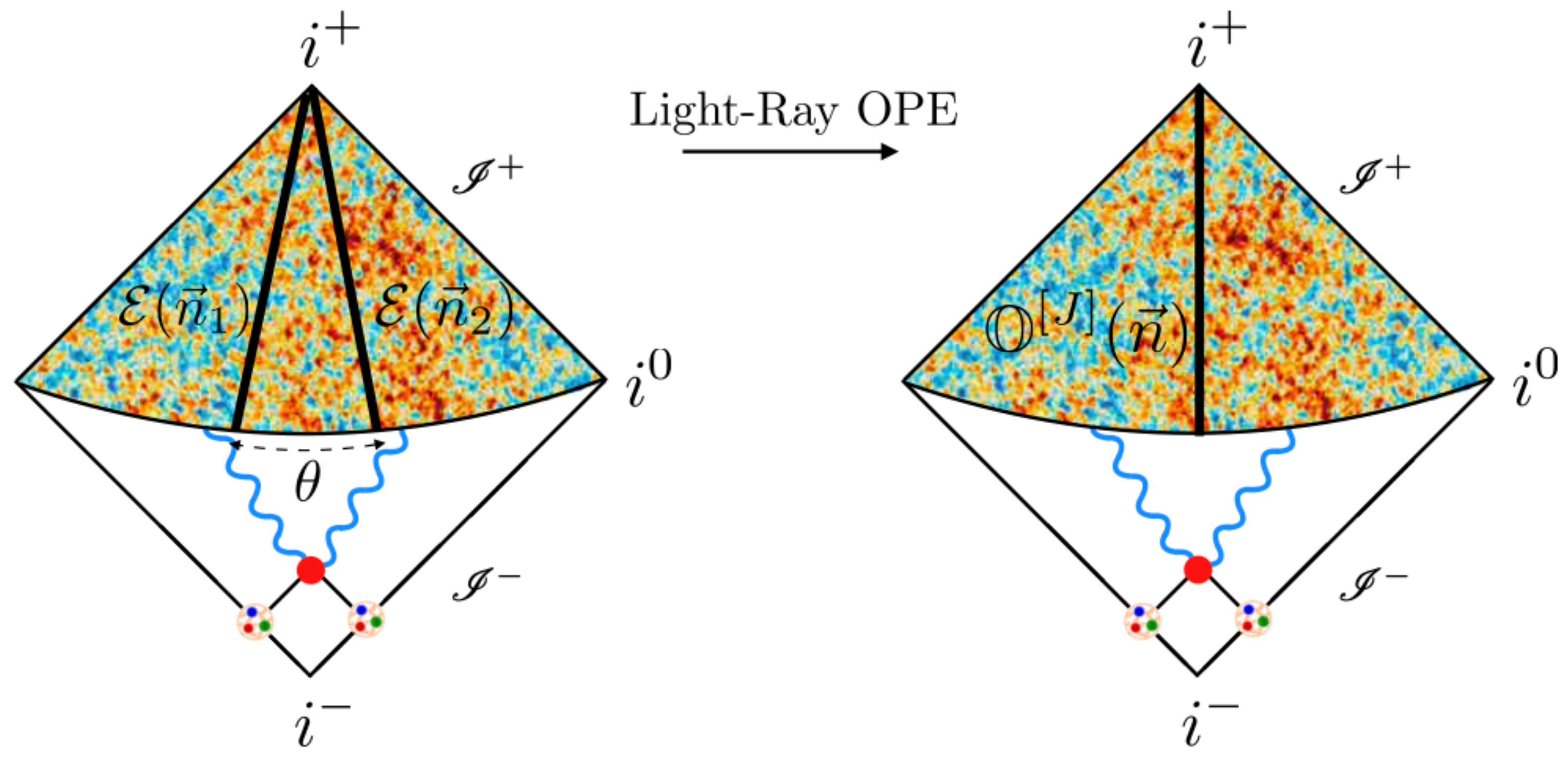
- **Field theory often predicts universal scaling as operators approach each other**





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

$\Longleftrightarrow$



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

Hofman, Maldacena, `08

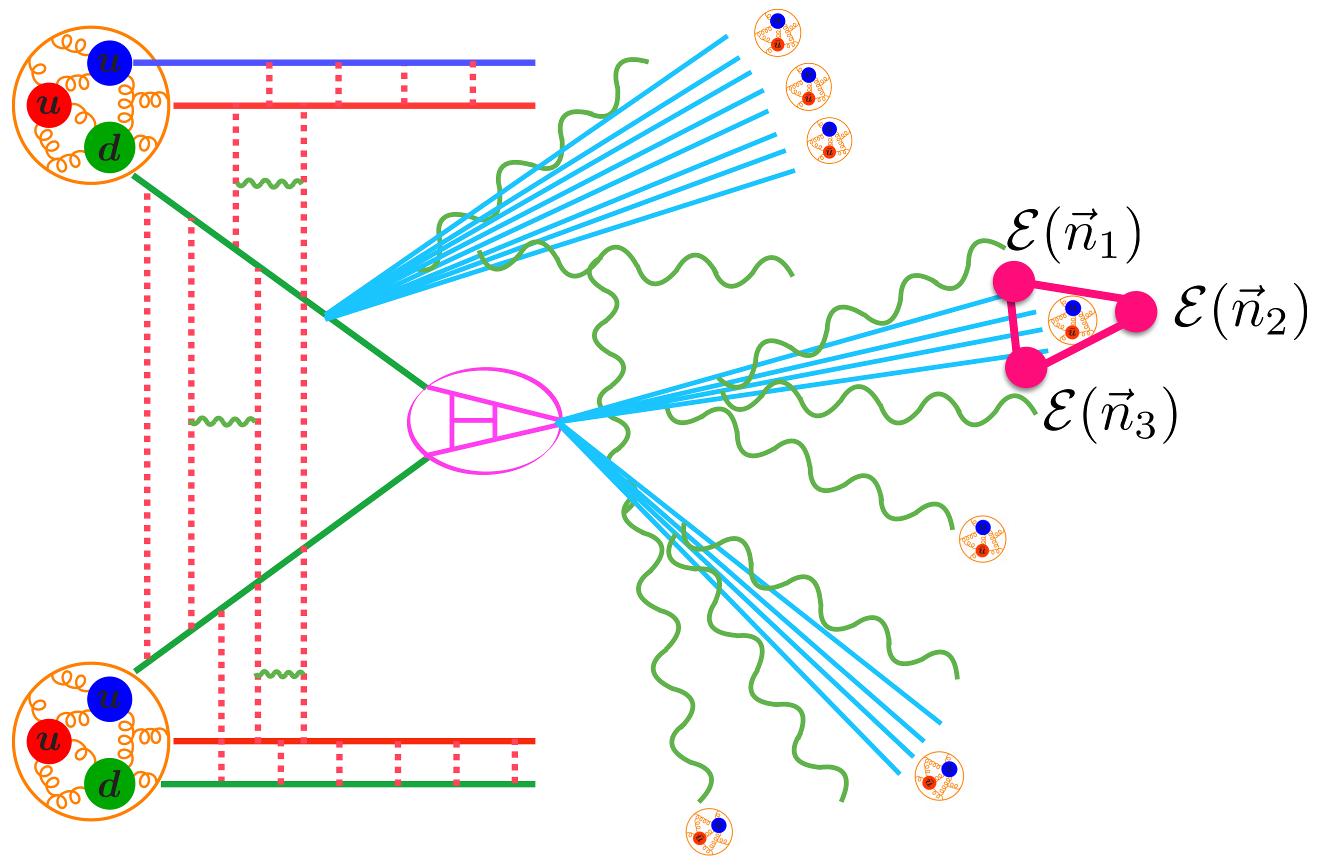
Much interests from the formal theory:

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

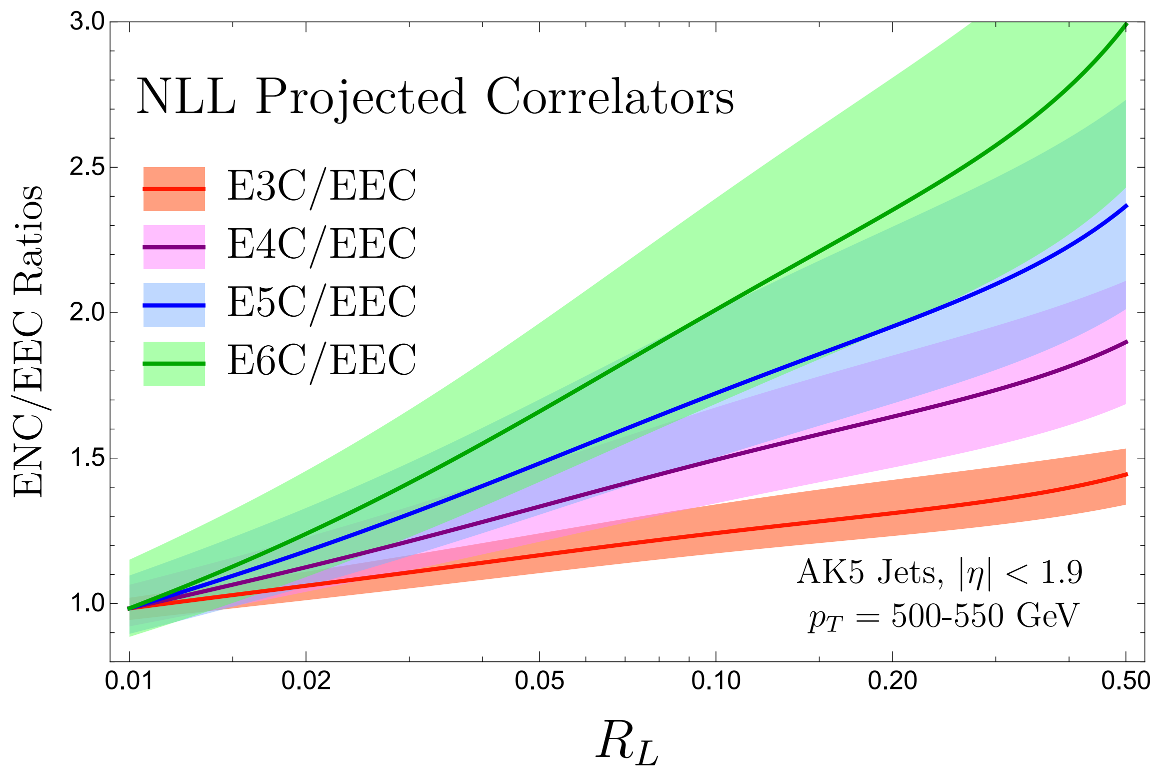
2019/2020

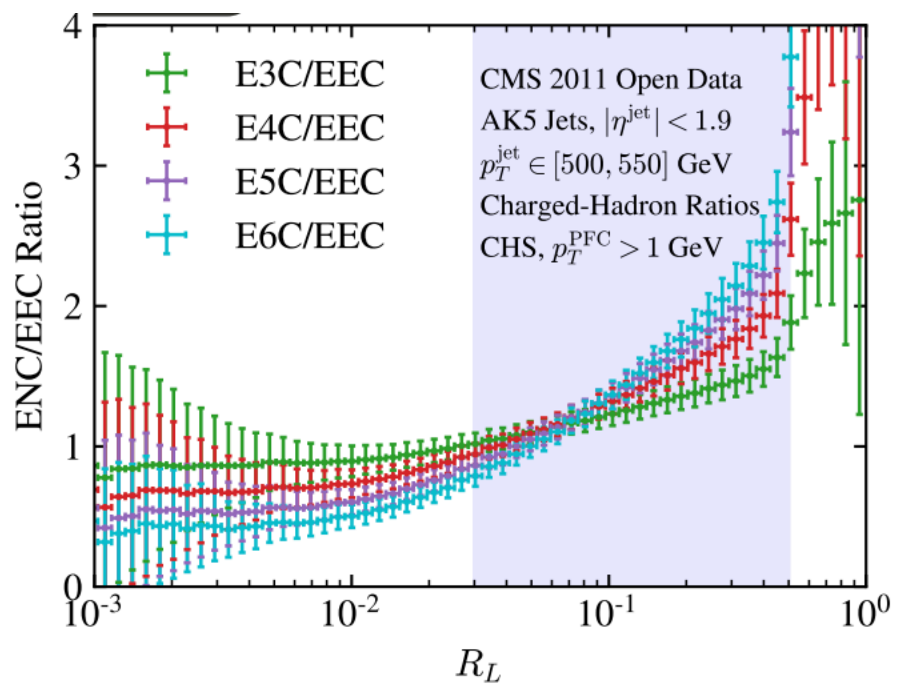


Rethinking Jets with Energy Correlators

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

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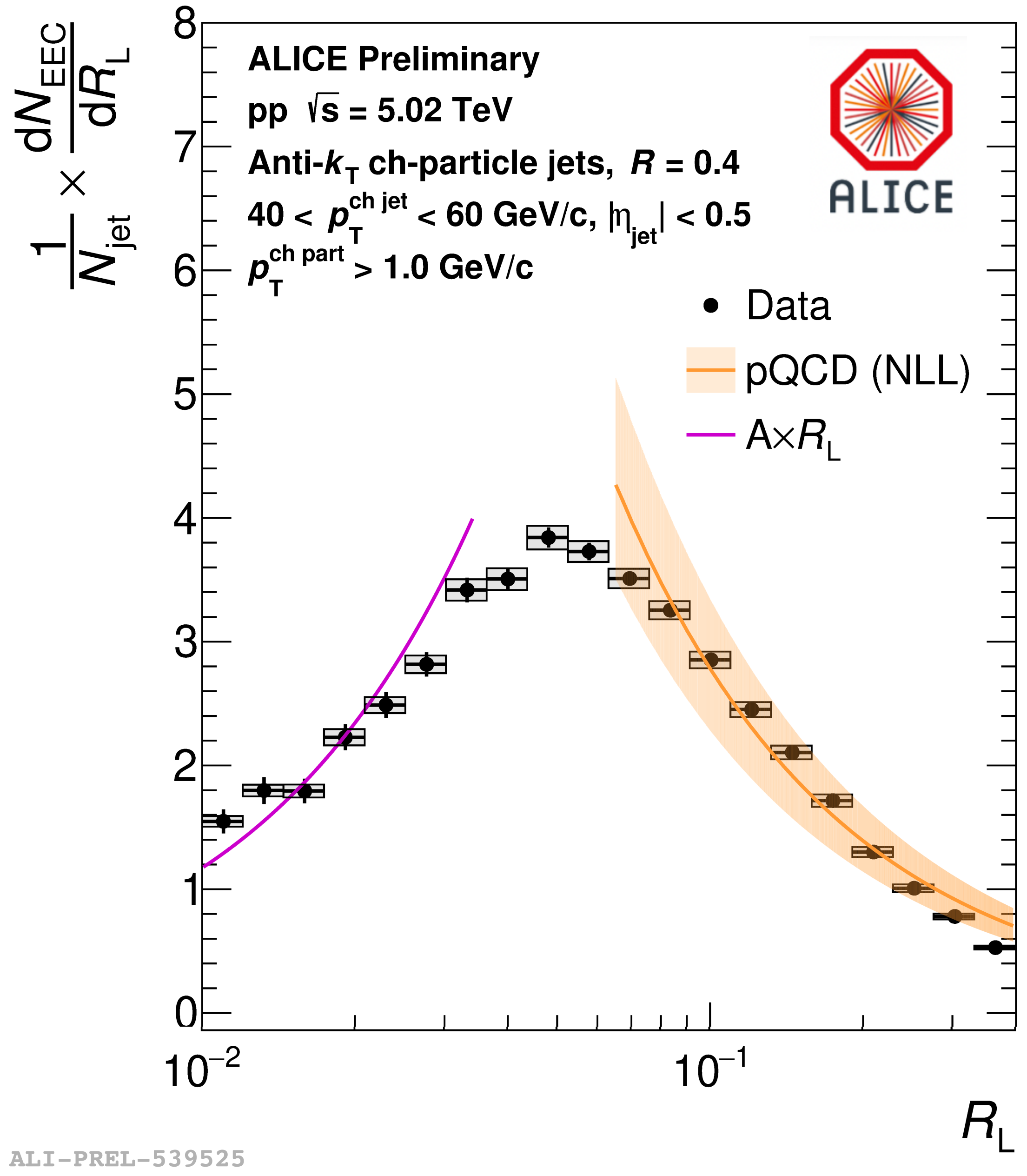
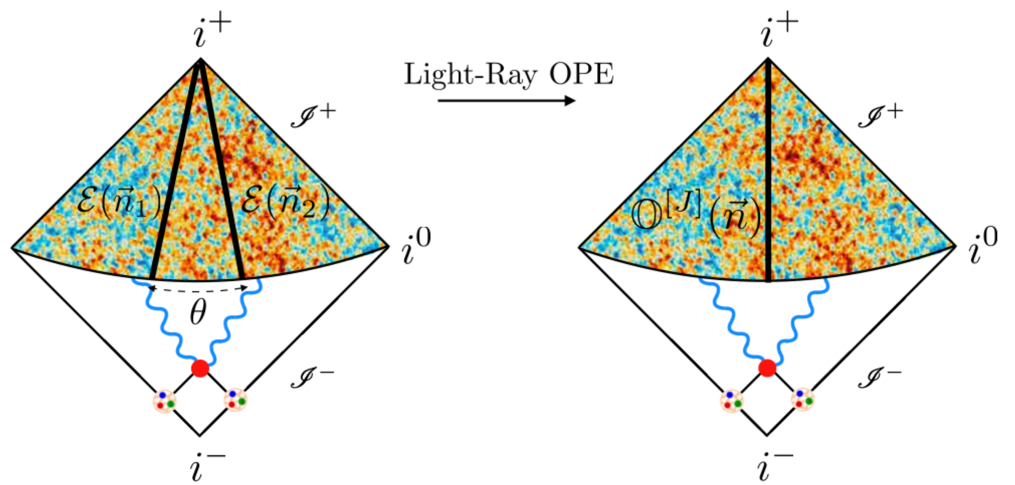
2023

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!

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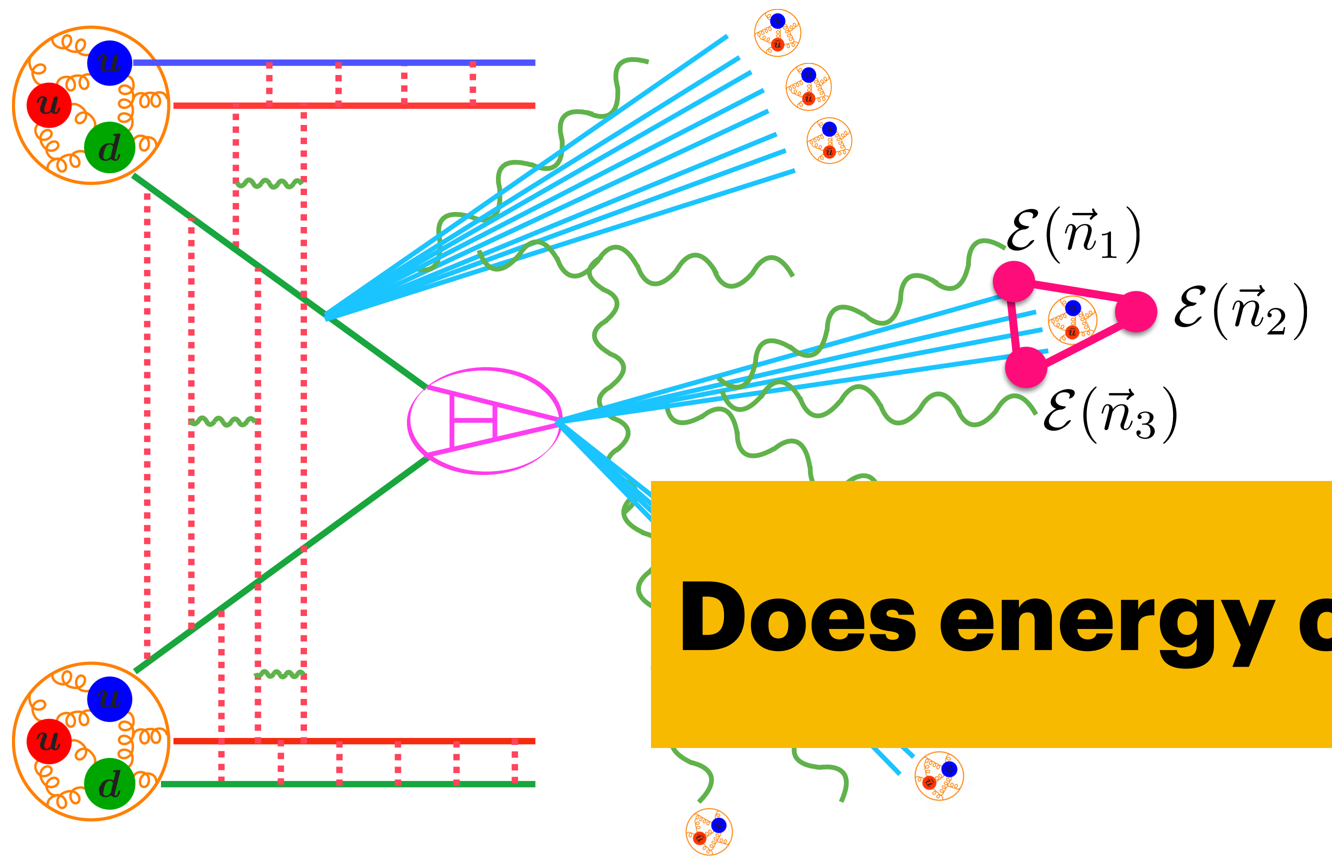

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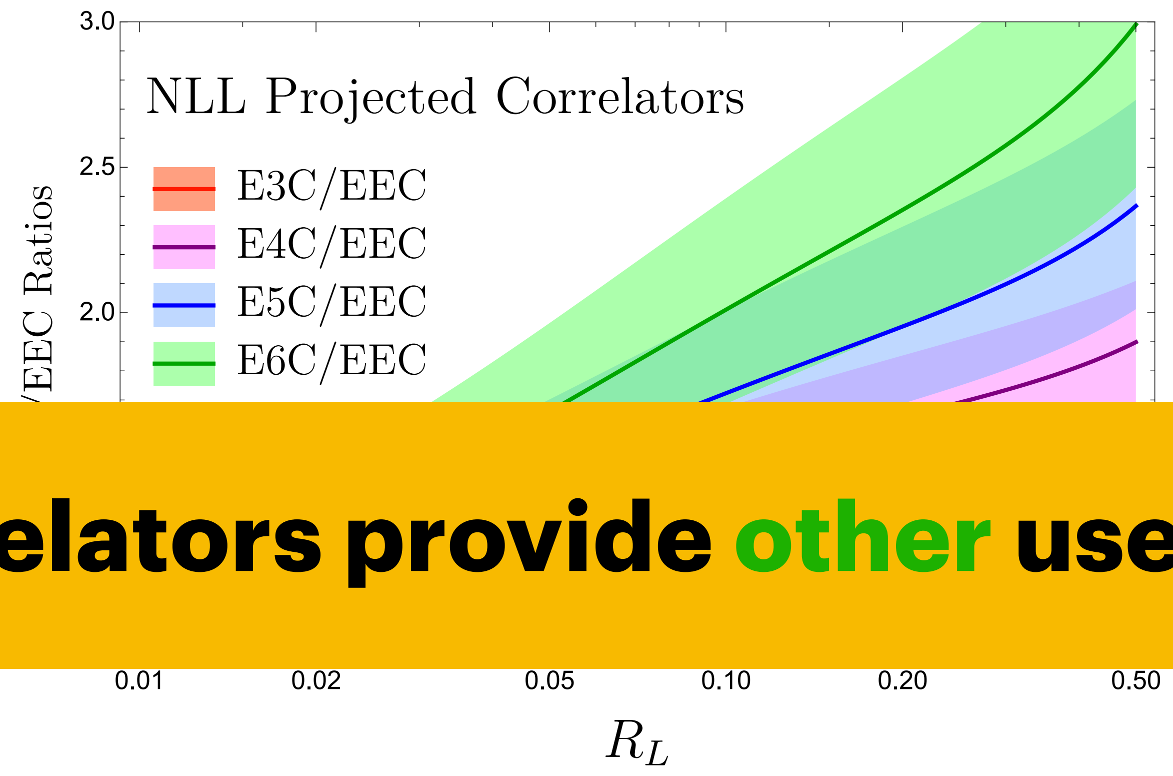
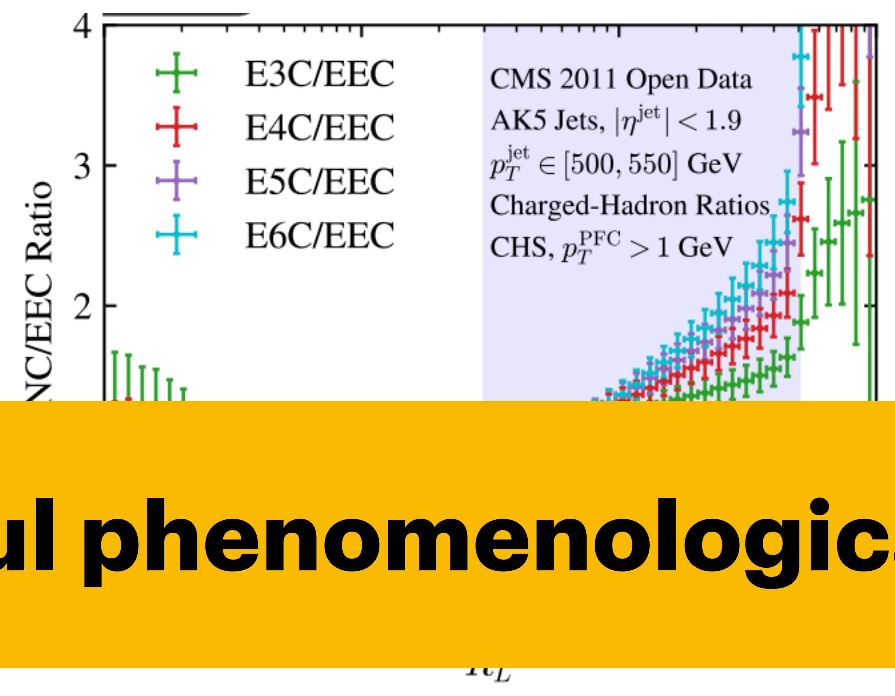
2022





Does energy correlators provide other useful phenomenological applications?

Open data analyses and QCD Factorization

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

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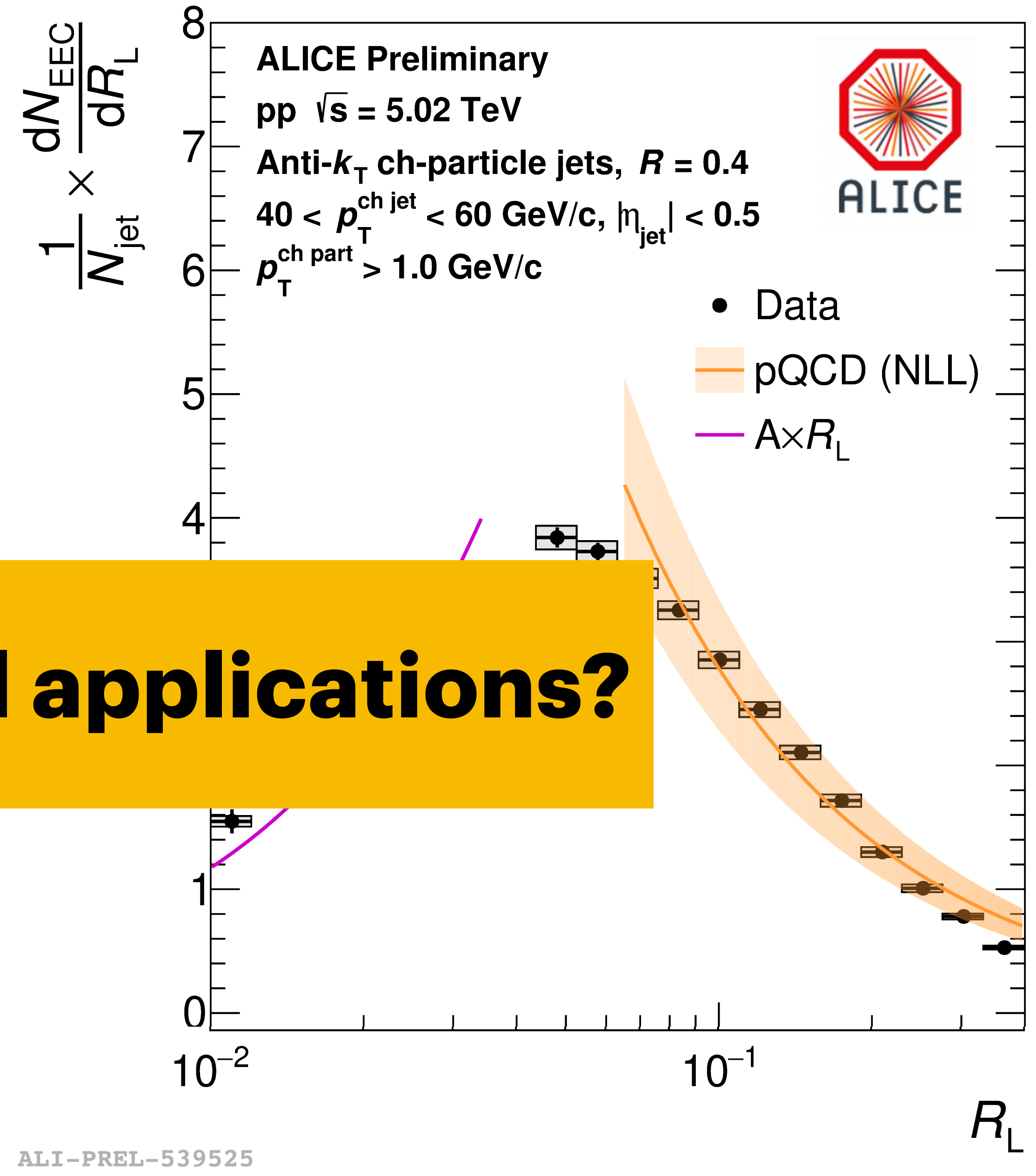
2023

ALICE `23



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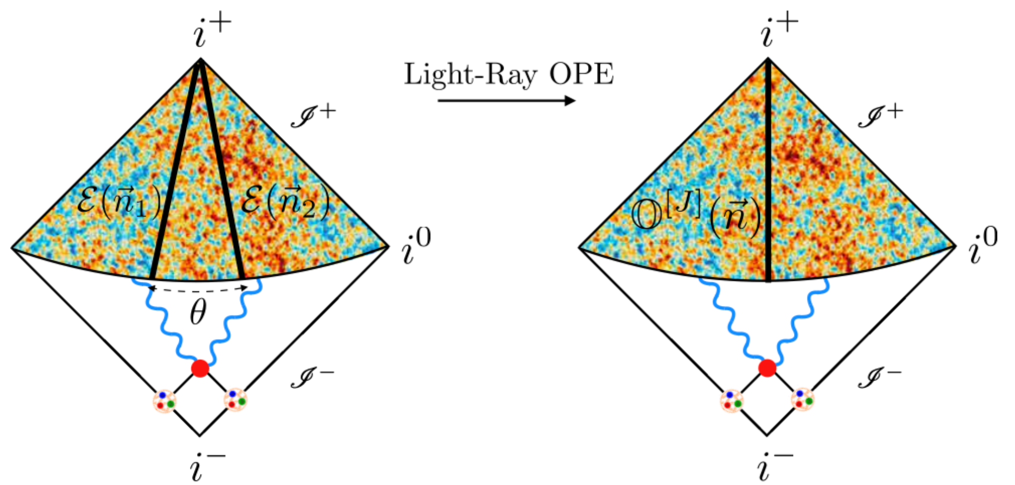
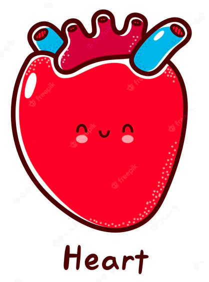


Observation of the universal of QCD predicted at the operator levels from the light-ray operator product expansion!


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

Brief outline

- Jet substructure is at the  of collider program!

- I will discuss exciting recent progresses in different areas of collider program from jet substructure theory
- I will highlight some new developments of thinking about jet substructure in terms of correlation of energy flow operators

Standard-model physics (QCD and ele...
New physics searches
Top-quark phys...
...physics ...harm)
Higgs ph...
...physics
170 GeV - O(Te...
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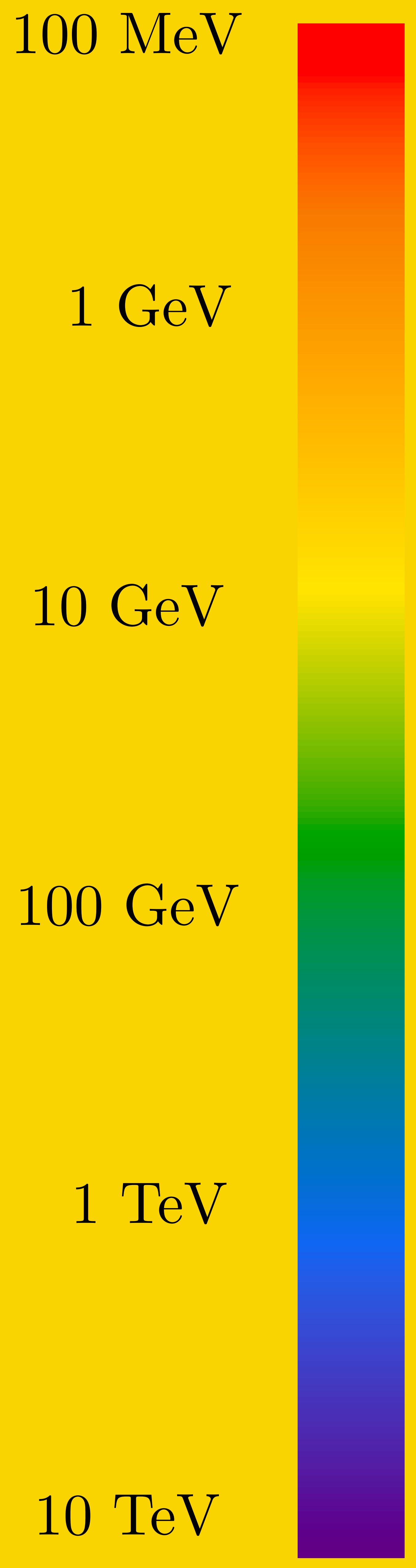
100 MeV - 500 GeV



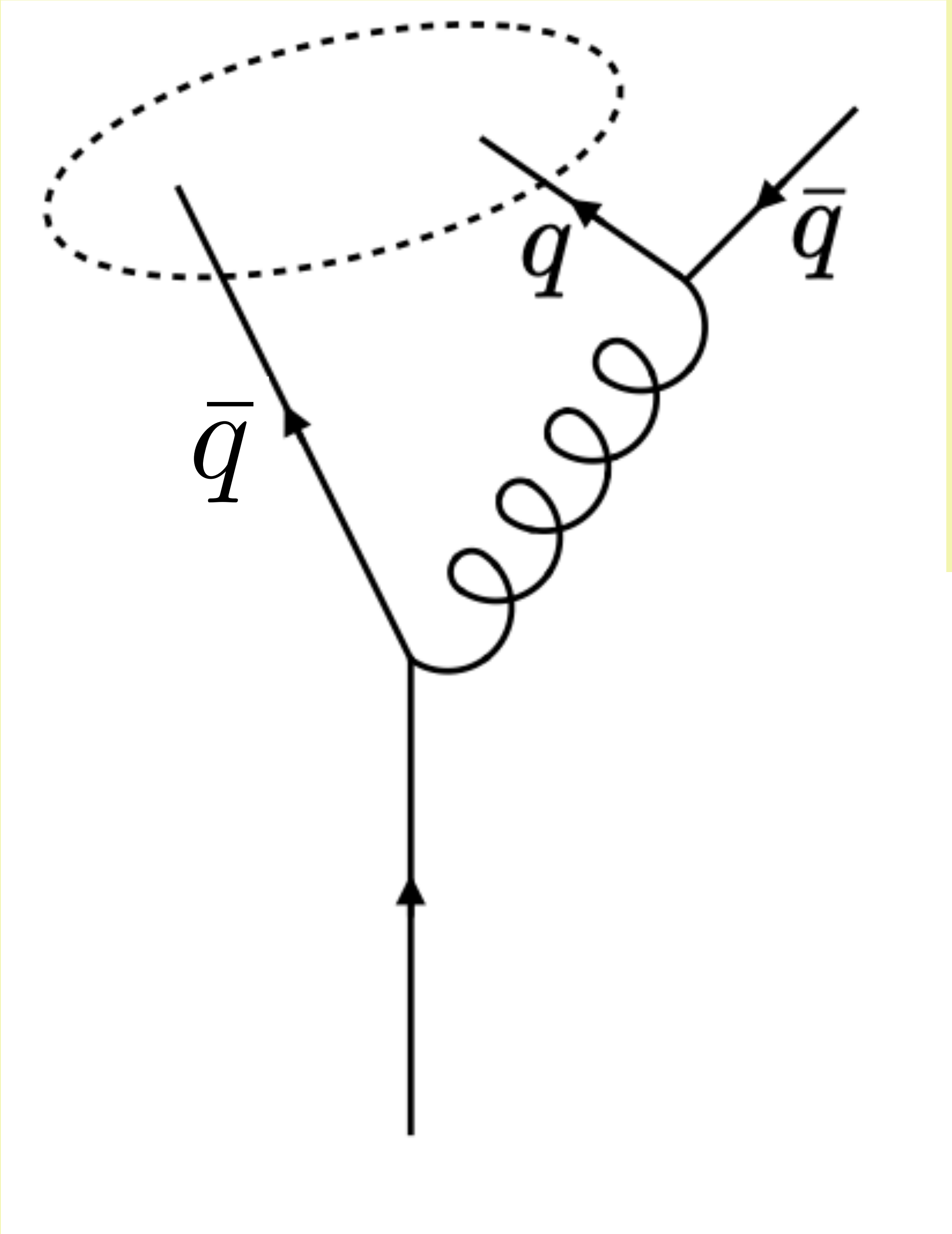
Heavy flavor physics
(Beauty and charm)

1 - 5 GeV

GOAL

HOW DO WE UNDERSTAND HEAVY FLAVOR PHYSICS?

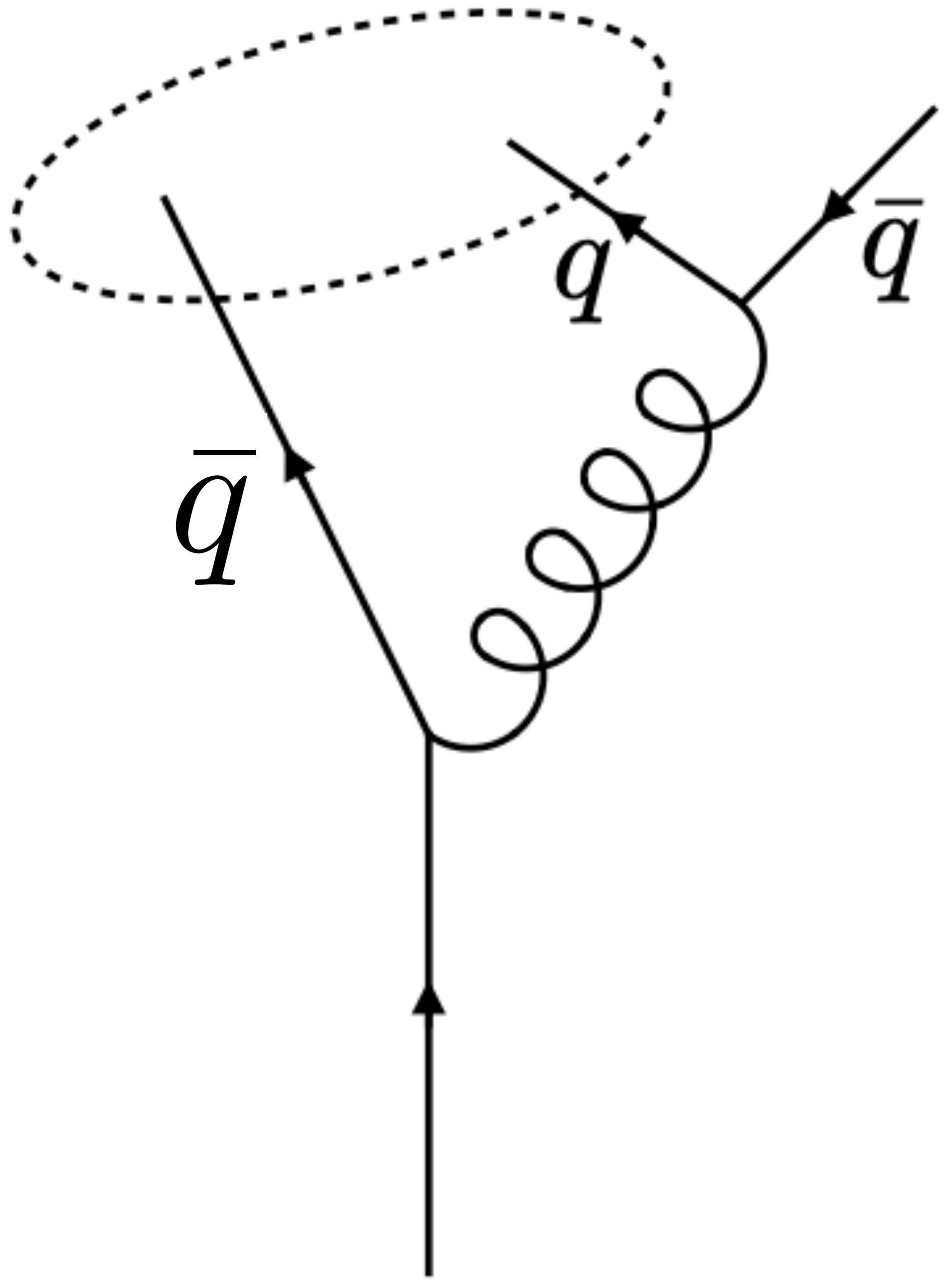
DEFINING JET FLAVOUR



DEFINING JET FLAVOUR

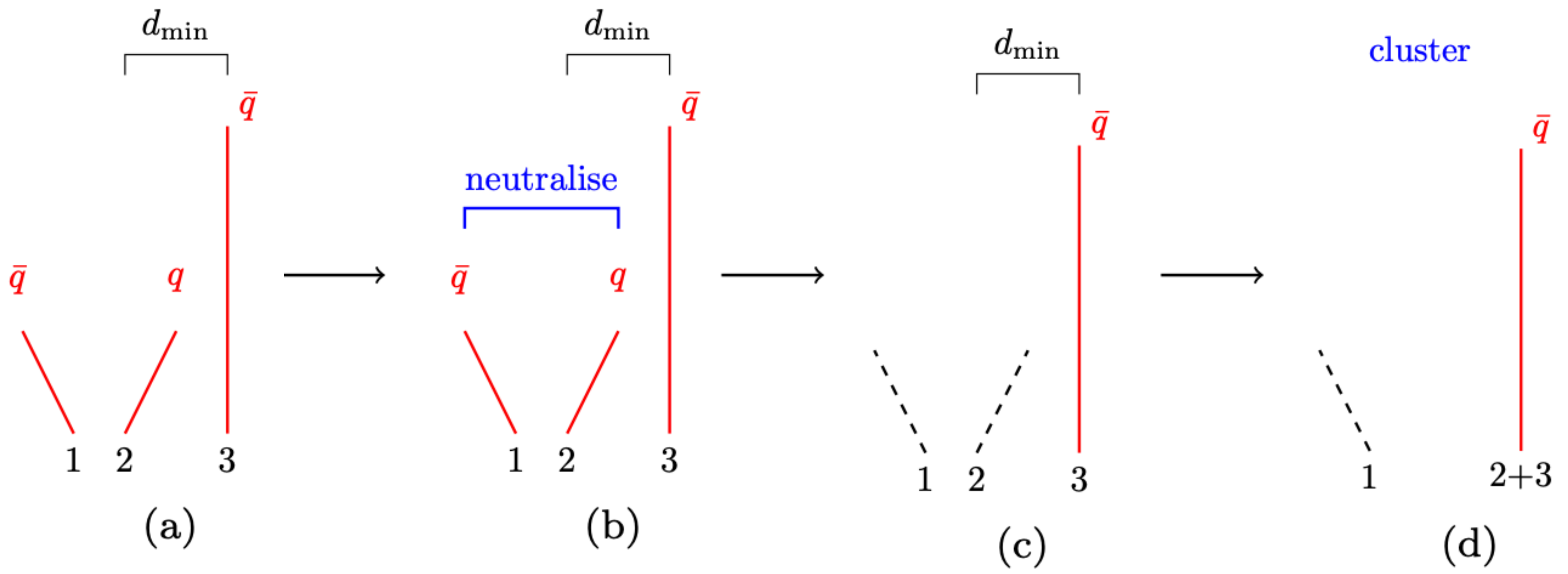
- **Defining the flavour of jet simply by counting have subtleties beyond NLO configuration**
- **In last two years, there has been many new proposals to define IRC safe flavoured jets**
  - flavor anti-k_T **method**
    Czakon, Mitov, Poncelet `22
  - **Interleaved Flavour Neutralization (IFN) method**
    Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler `23
  - **Based on Soft Drop grooming techniques**
    Caletti, Larkoski, Marzani, Reichelt `22
  - **Using the alignment of flavored particles along the WTA axis**
    Caletti, Larkoski, Marzani, Reichelt `22
  - **Successive iterations of** flavor-k_T **and** anti-k_T
    Caletti, Fedkevych, Marzani, Reichelt `21
  - **Using jet angularities and Lund jet plane as discriminants**
    Fedkevych, Khosa, Marzani, Sforza `22

  and more…



Banfi, Salam, Zanderighi `06

DEFINING JET FLAVOUR



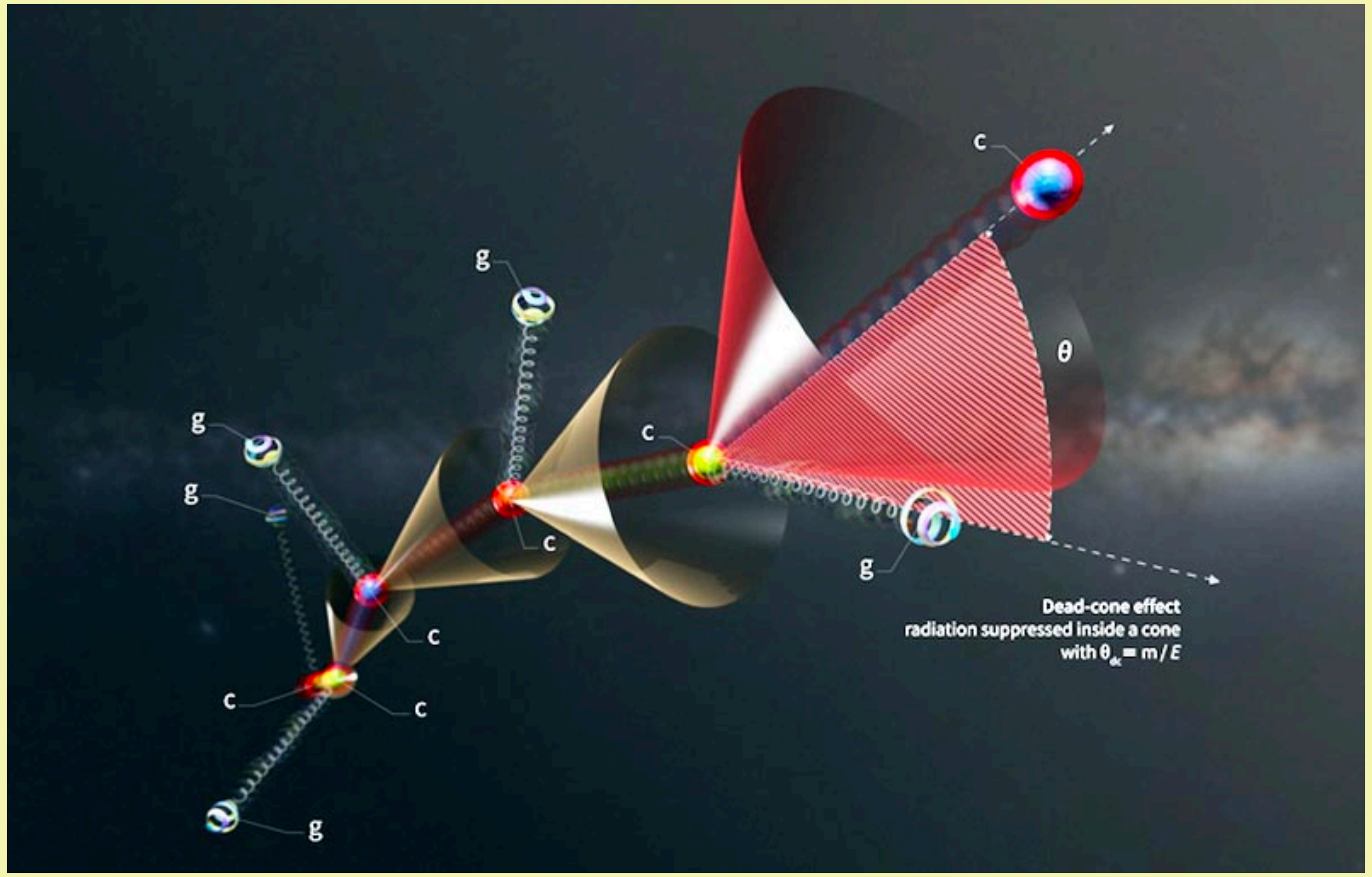
order relative to Born		anti-k_t	flav-k_t ($\alpha = 2$)	CMP	GHS$_{\alpha,\beta}$ (2, 2)	anti-k_t+IFN$_\alpha$	C/A+IFN$_\alpha$
α_s	FHC	✓	✓	✓	✓	✓	✓
	IHC	✓	✓	✓	✓	✓	✓
α_s^2	FDS	× II B	✓	✓	✓	✓	✓
	IDS	× II B	✓	✓	✓	✓	✓
	FHC×IHC	✓	✓	✓	✓	✓	✓
	IHC^2	✓	✓	× C 2	✓	✓	✓
	FHC^2	✓	✓	✓	× C 4	✓	✓
α_s^3	IHC×IDS		∼ C 1	× C 3	∼ C 1	✓	✓
	rest					✓	✓
α_s^4	IDS×FDS				× C 5	✓	✓
	rest					✓	✓
α_s^5						✓	✓
α_s^6						✓	✓

Illustration of Interleaved Flavour Neutralization (IFN) method

Caola, Grabarczyk, Hutt, Salam, Scyboz, Thaler `23

IRC safety test to $\mathcal{O}(\alpha_s^6)$!

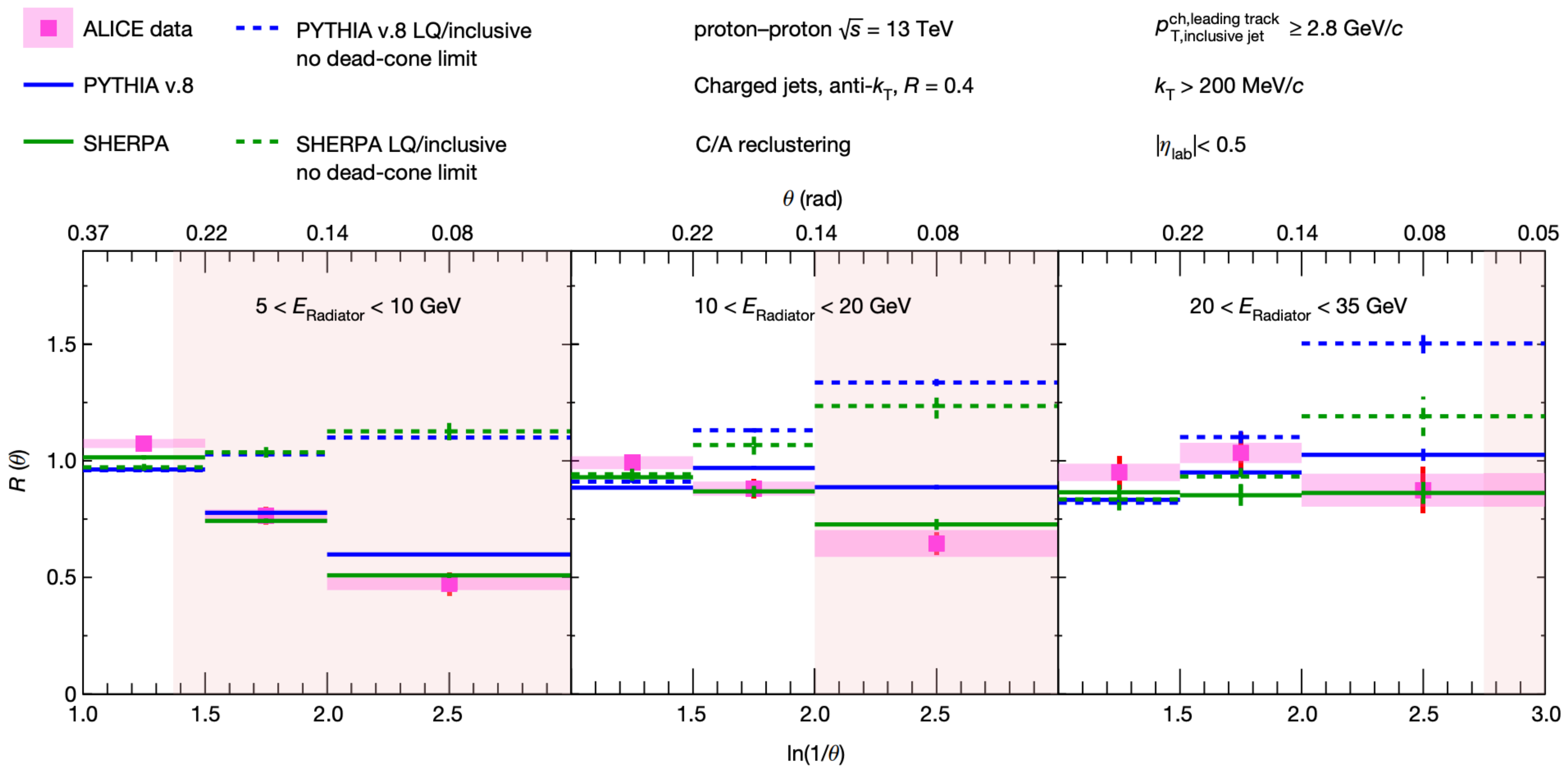
IMPROVING OUR UNDERSTANDING OF MASS EFFECTS

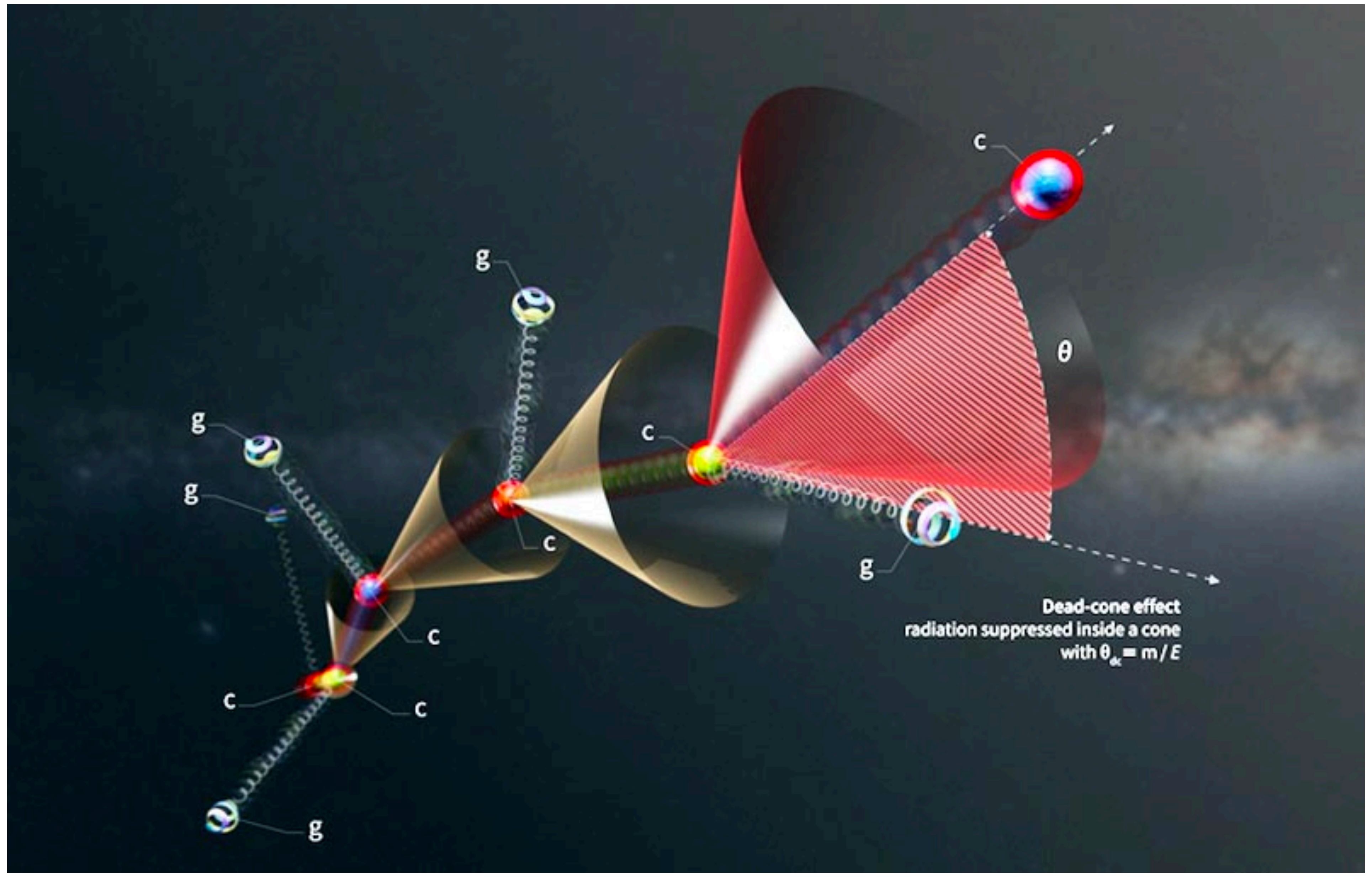


VERY FIRST DIRECT DETECTION OF DEADCONE

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

nature





[ALICE 2022]

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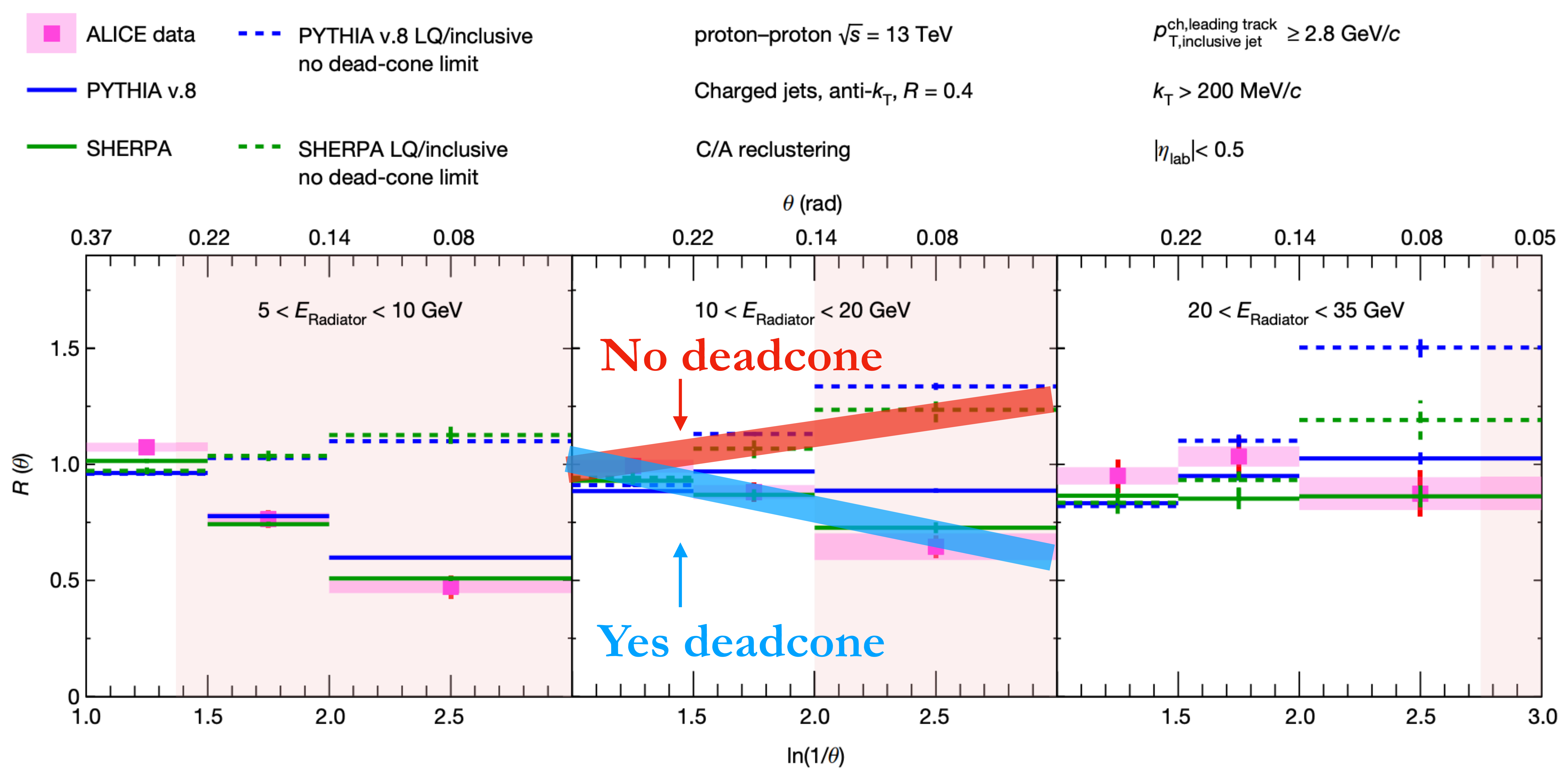
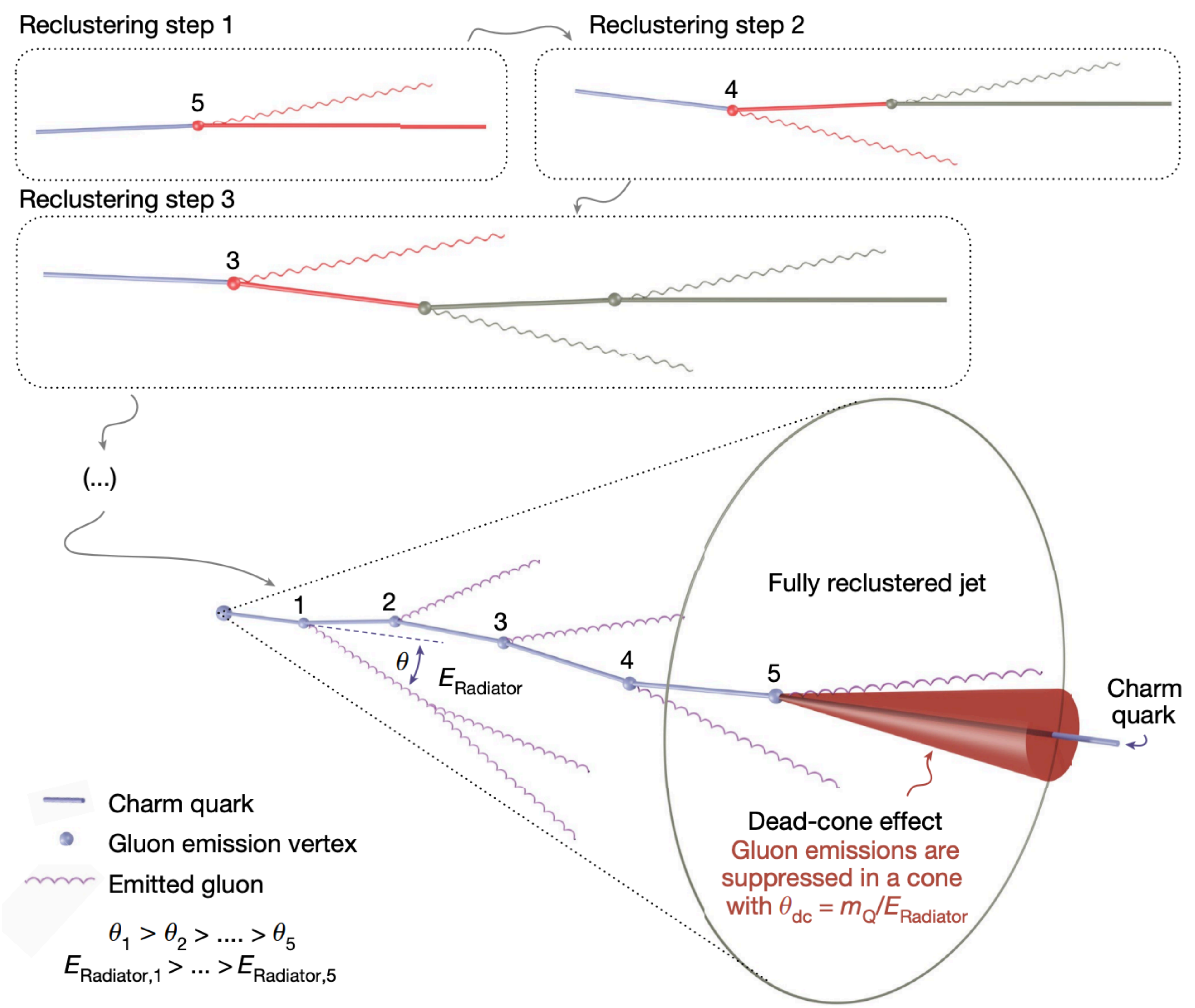


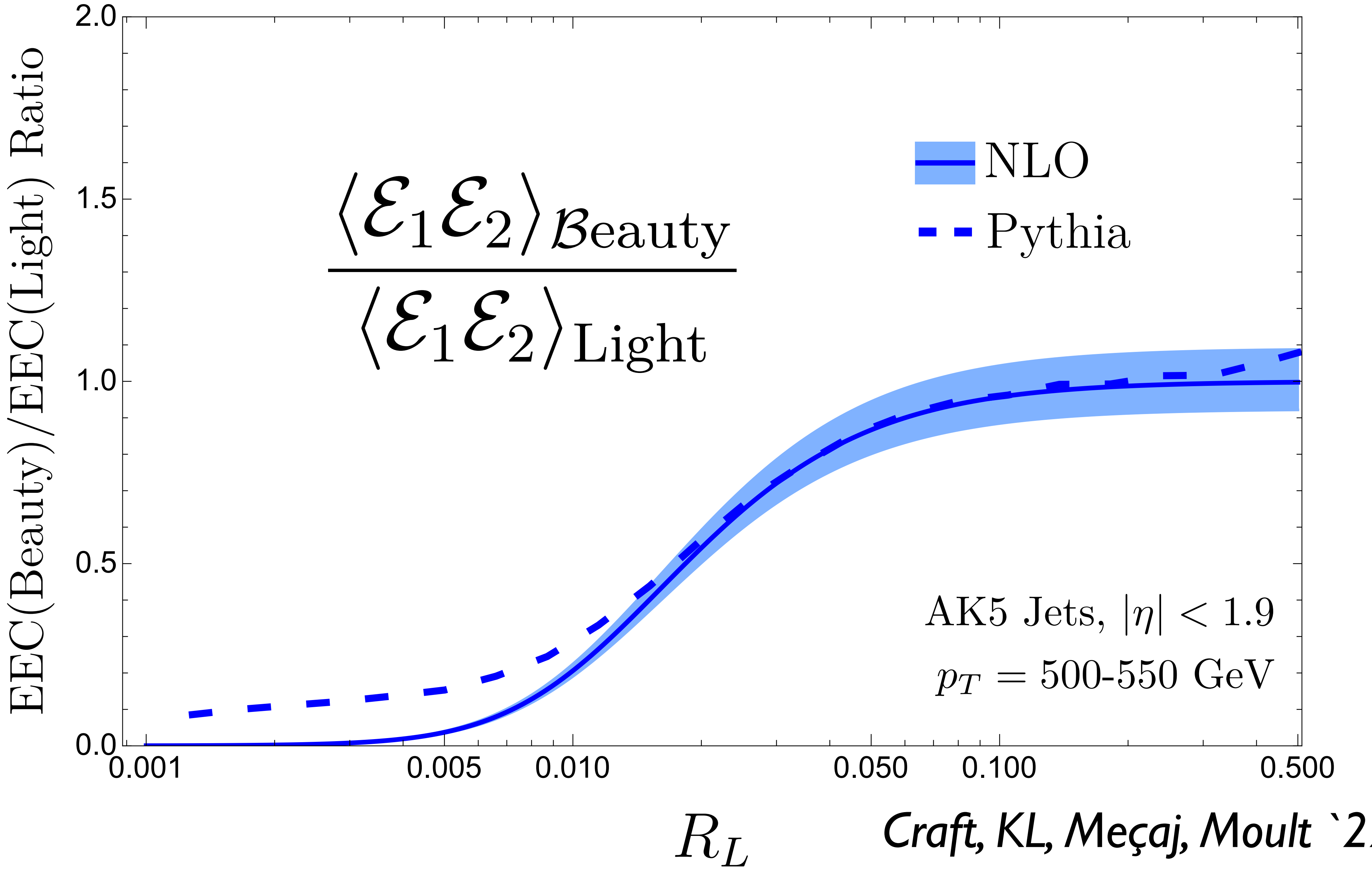


Tune into Oleh and Evan's talk!

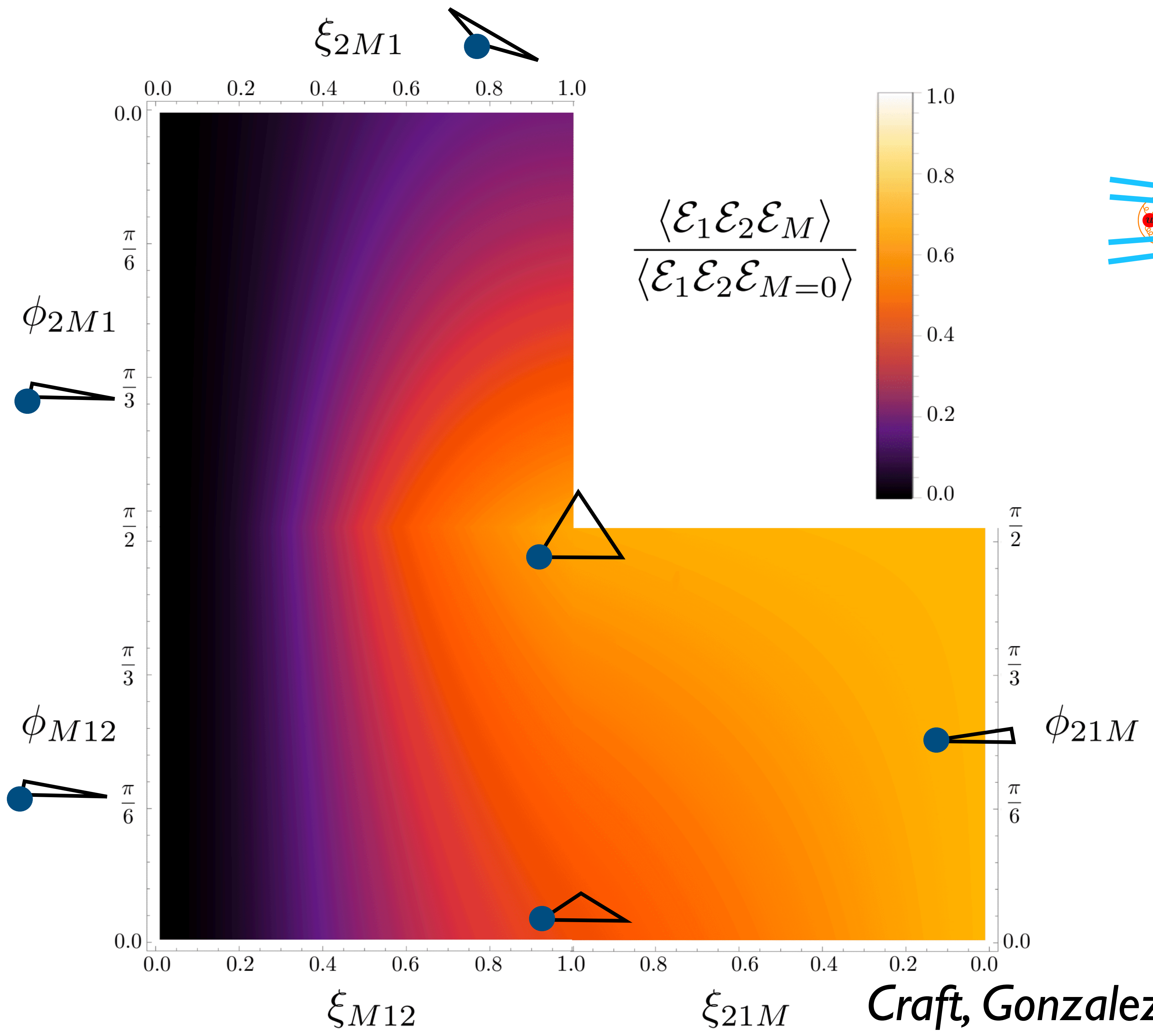
BEAUTIFUL AND CHARMING ENERGY CORRELATORS

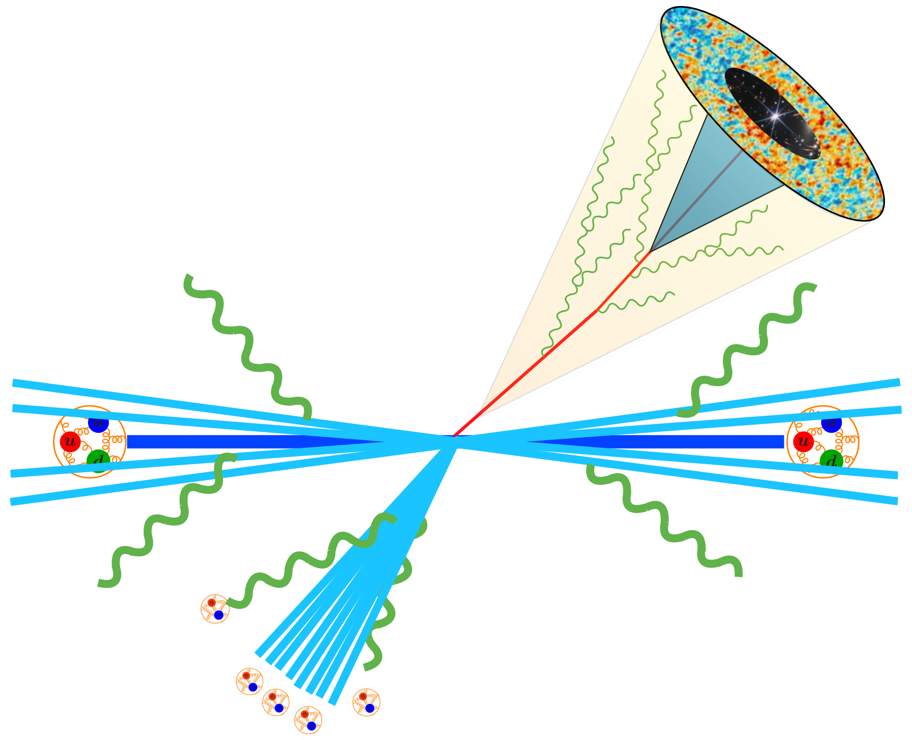
- **One can statistically measure the gluon suppression (dead cone) within the heavy jets as compared to the light jets by taking the ratio of energy correlators.**

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



Craft, KL, Meçaj, Moult `22



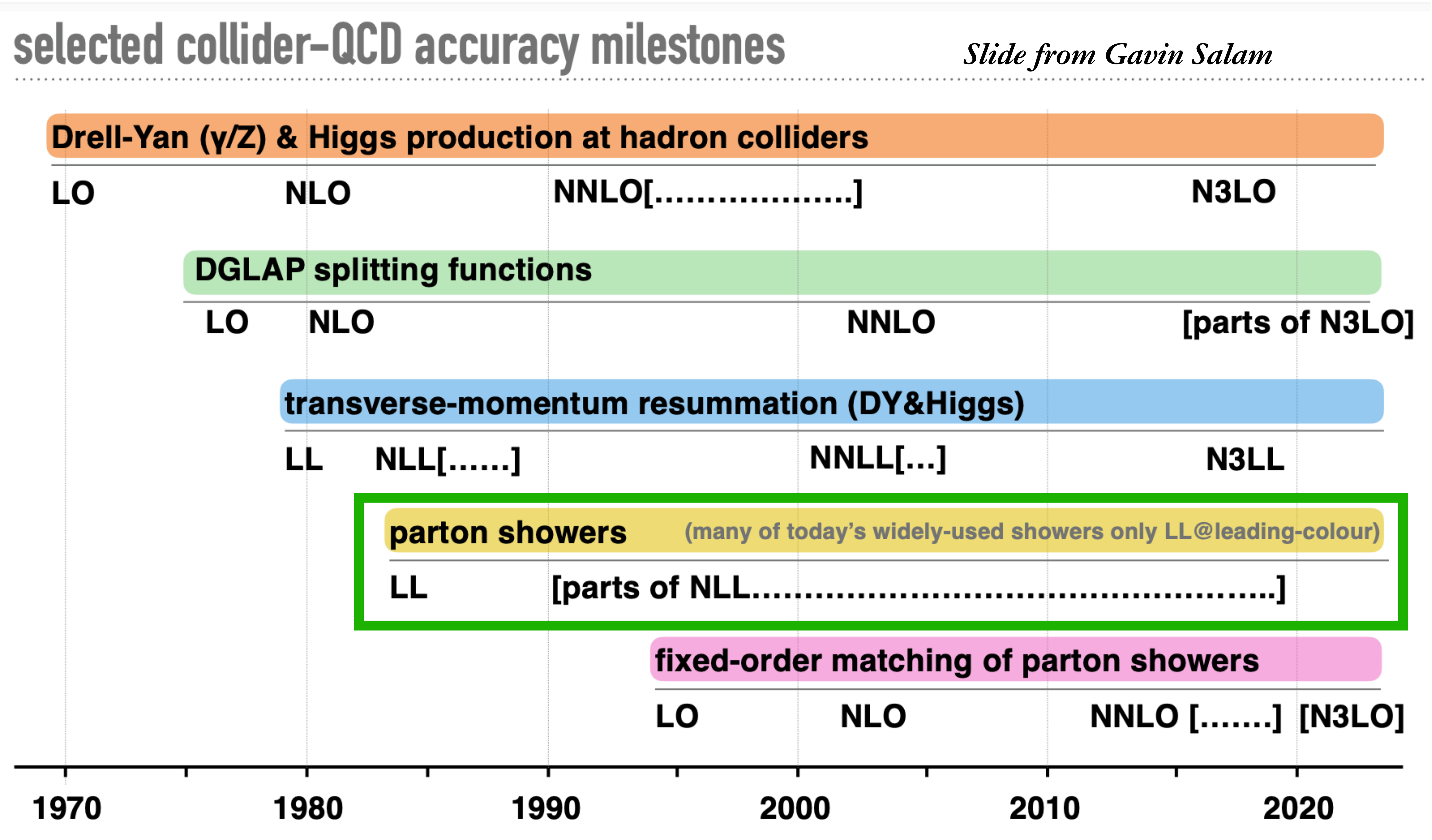


Craft, Gonzalez, KL, Meçaj, Moult `23

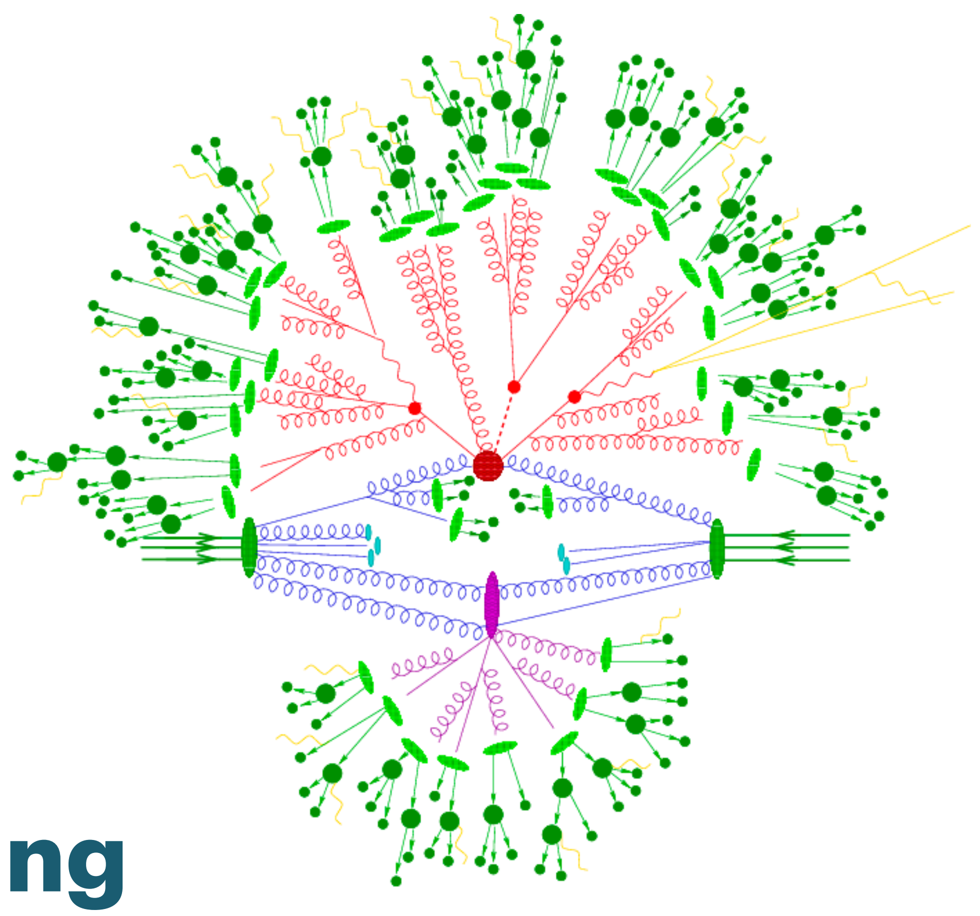
- **Higher-point structure provides nontrivial shape information**

Tune into Evan's talk!

IMPORTANT ASIDE: MONTE CARLO PARTON SHOWERS

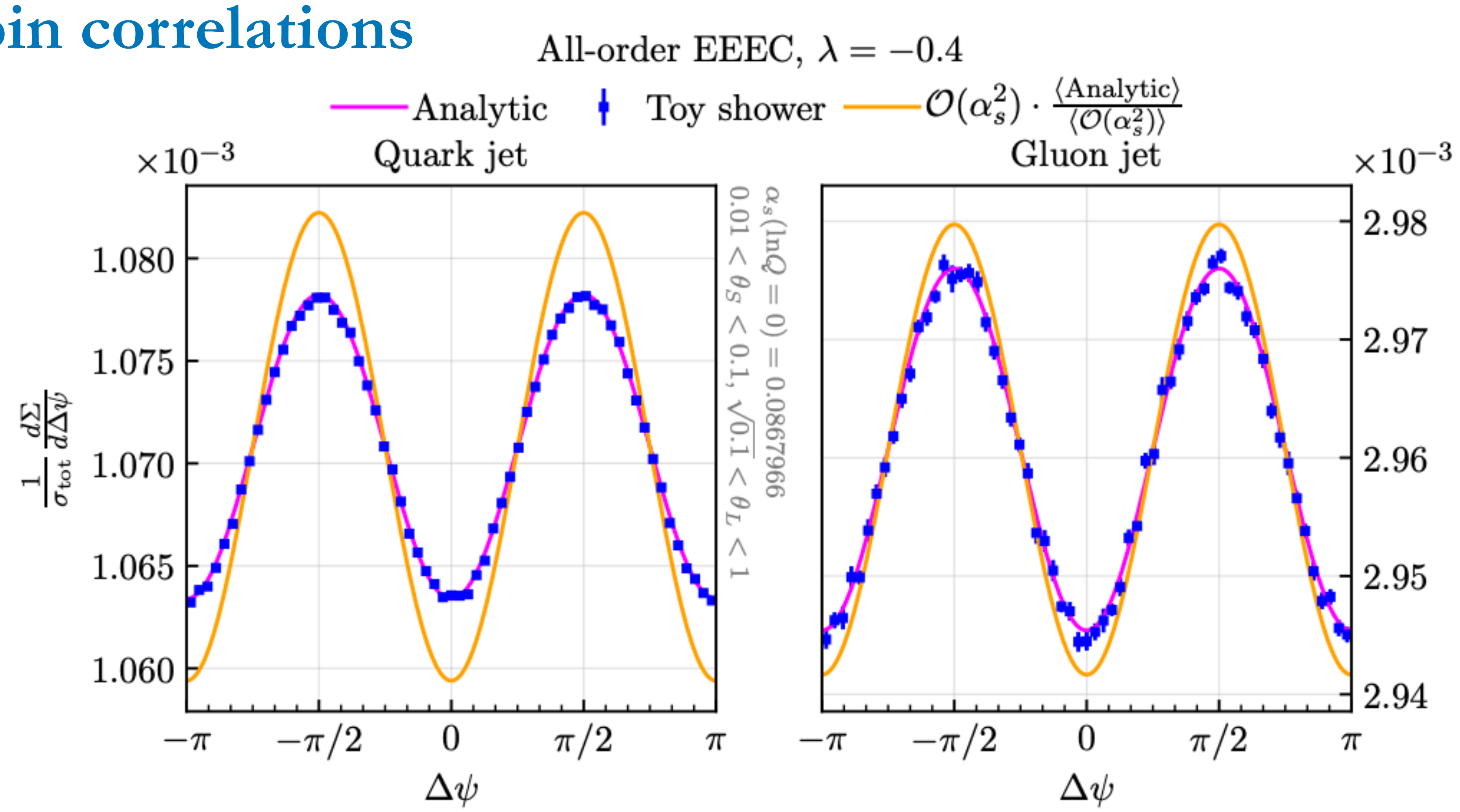


- **Almost every analysis of high-energy collider data relies on simulations with MC generators.**
- **Including mass effects just discussed, it is important to advance MC generators in order to include new perturbative ingredients in parton showers:**
  - **NLO DGLAP**
  - **Spin Correlations**
  - **Triple Collinear**
  - **Massive splitting**
  - **Finite N_c**
  - **Medium-induced splitting**



IMPORTANT ASIDE: MONTE CARLO PARTON SHOWERS

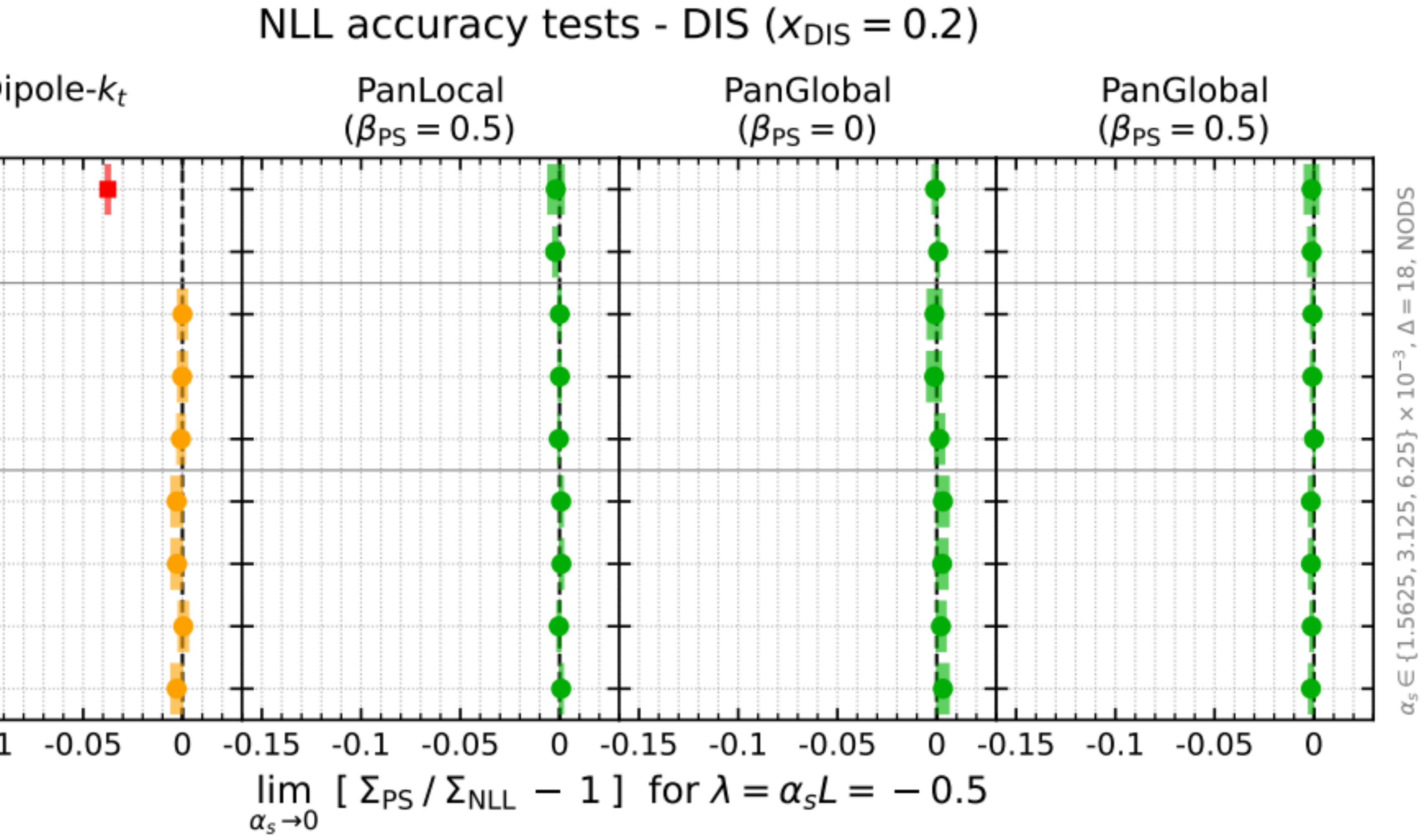
Spin correlations



Karlberg, Salam, Scyboz, Verheyen `21

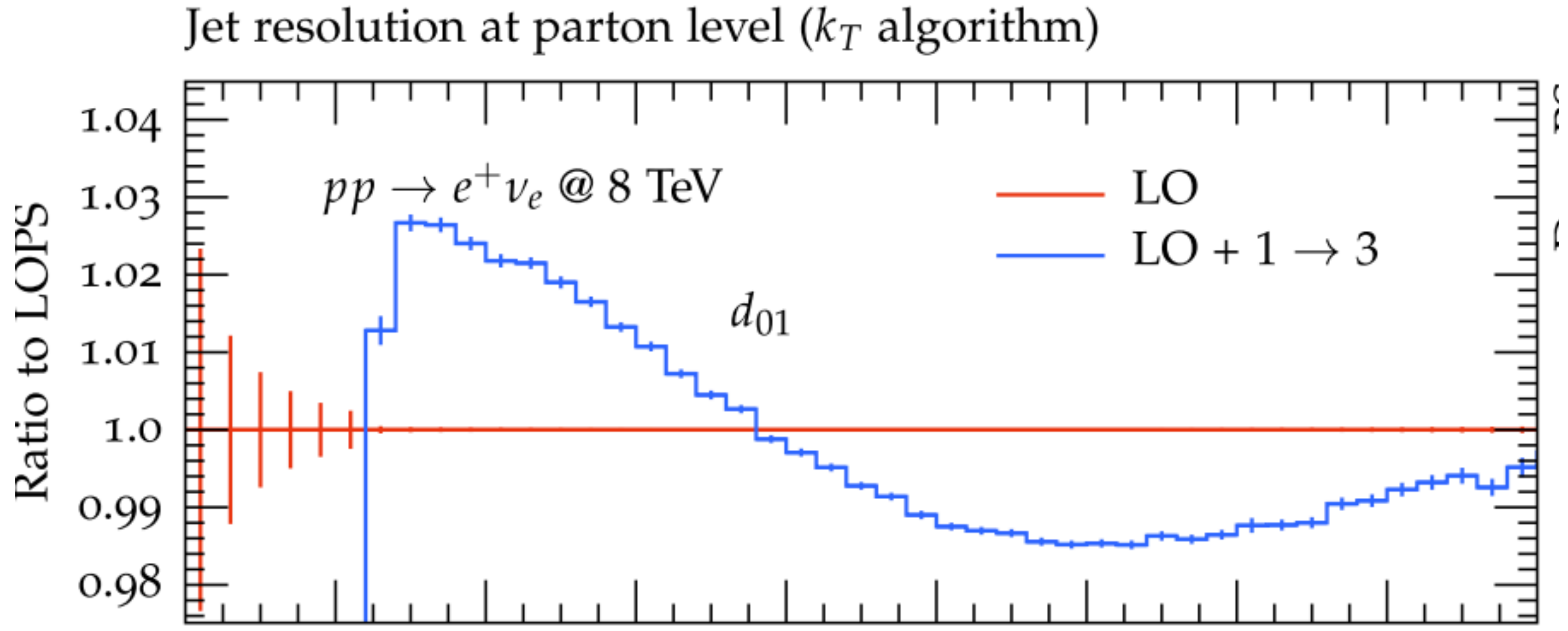
- **Much progress is being made on all fronts of parton shower developments!**
- **Jet substructure observables can be used to provide sensitivity to different perturbative and non-perturbative effects.**

NLL improvements



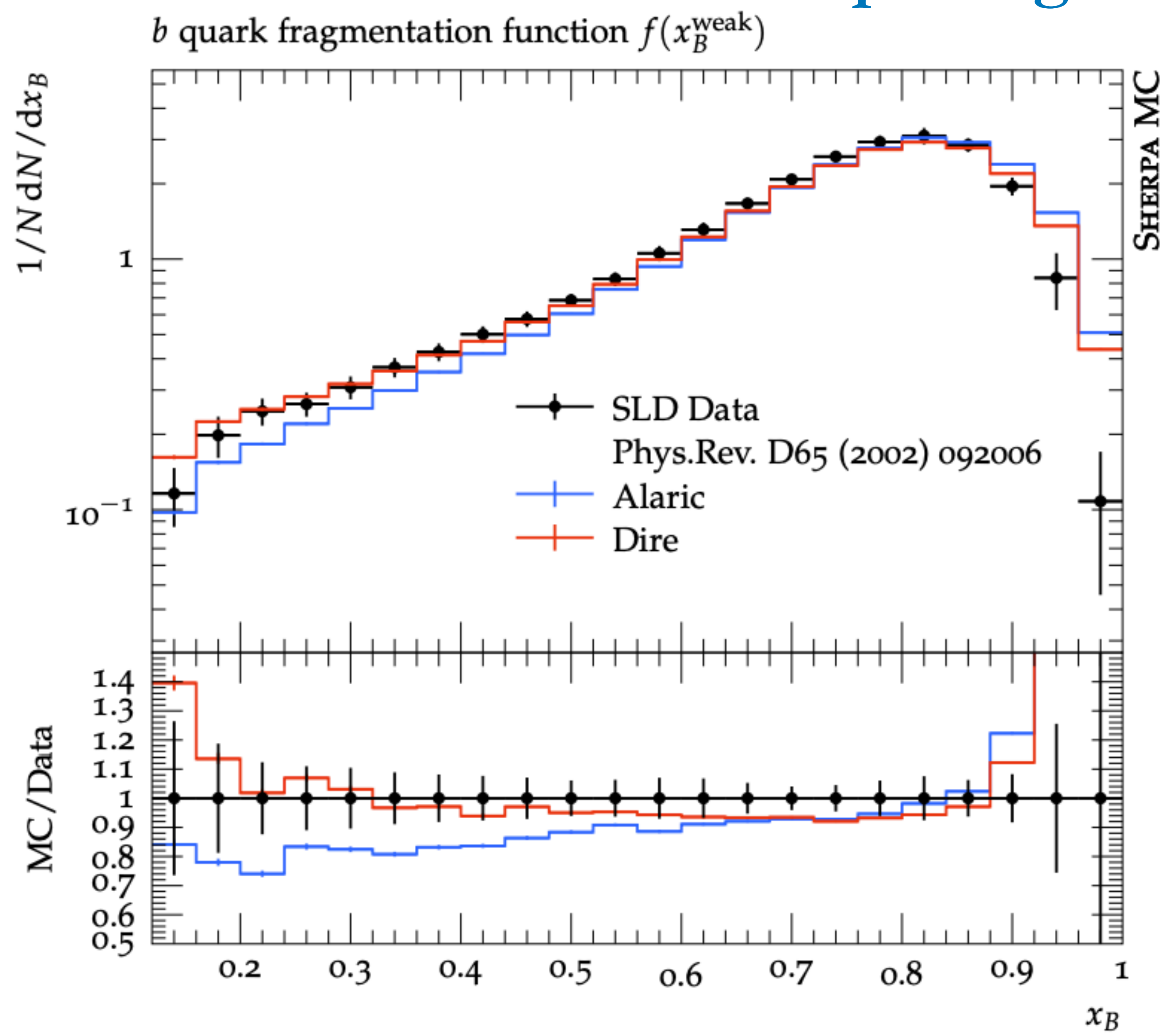
van Beekveld, Ravasio `23

Triple collinear splitting



Höche, Prestel `17

Massive splitting



Assi, Höche `23

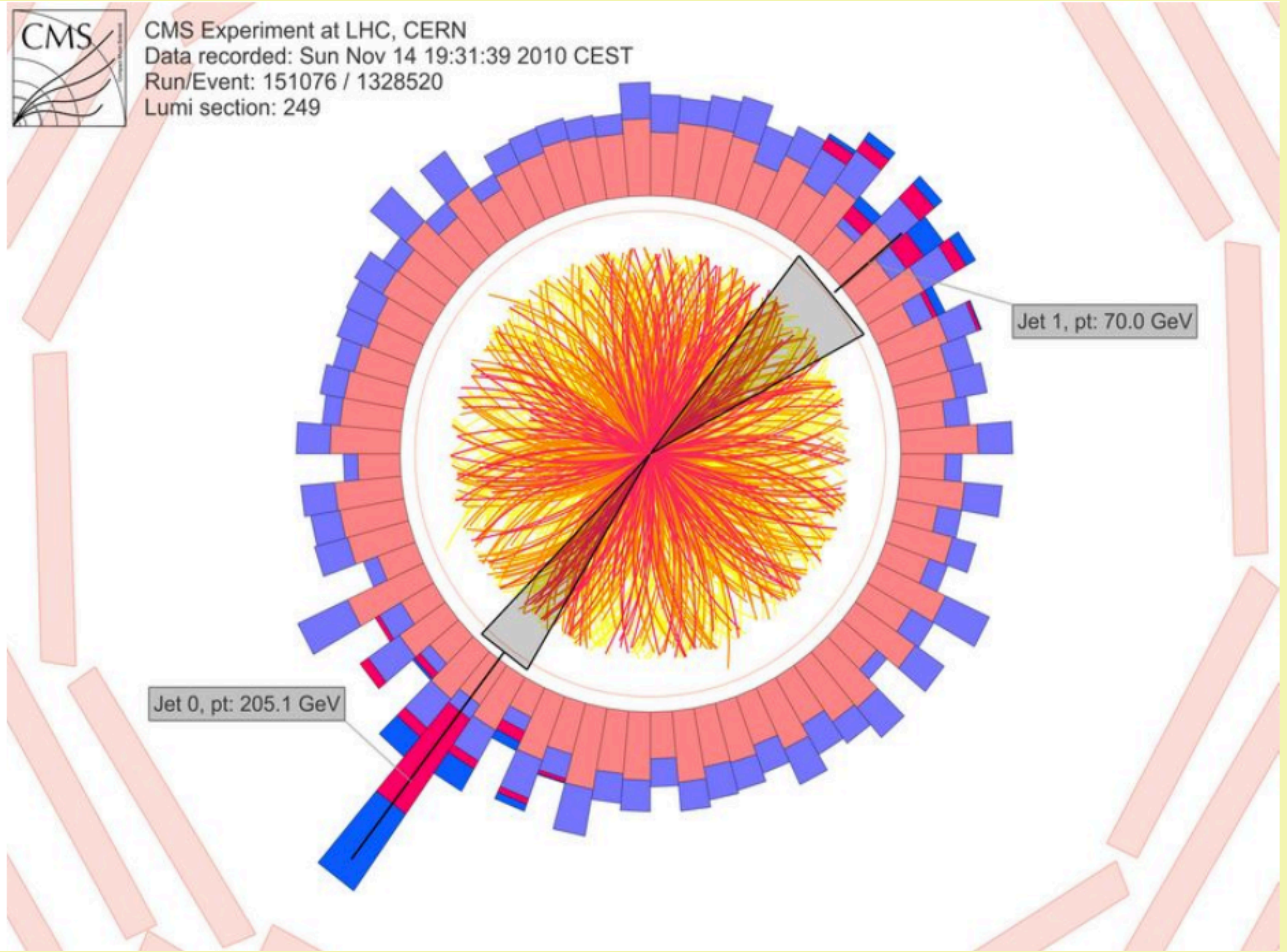
Heavy-ion physics

100 MeV - 500 GeV

GOAL

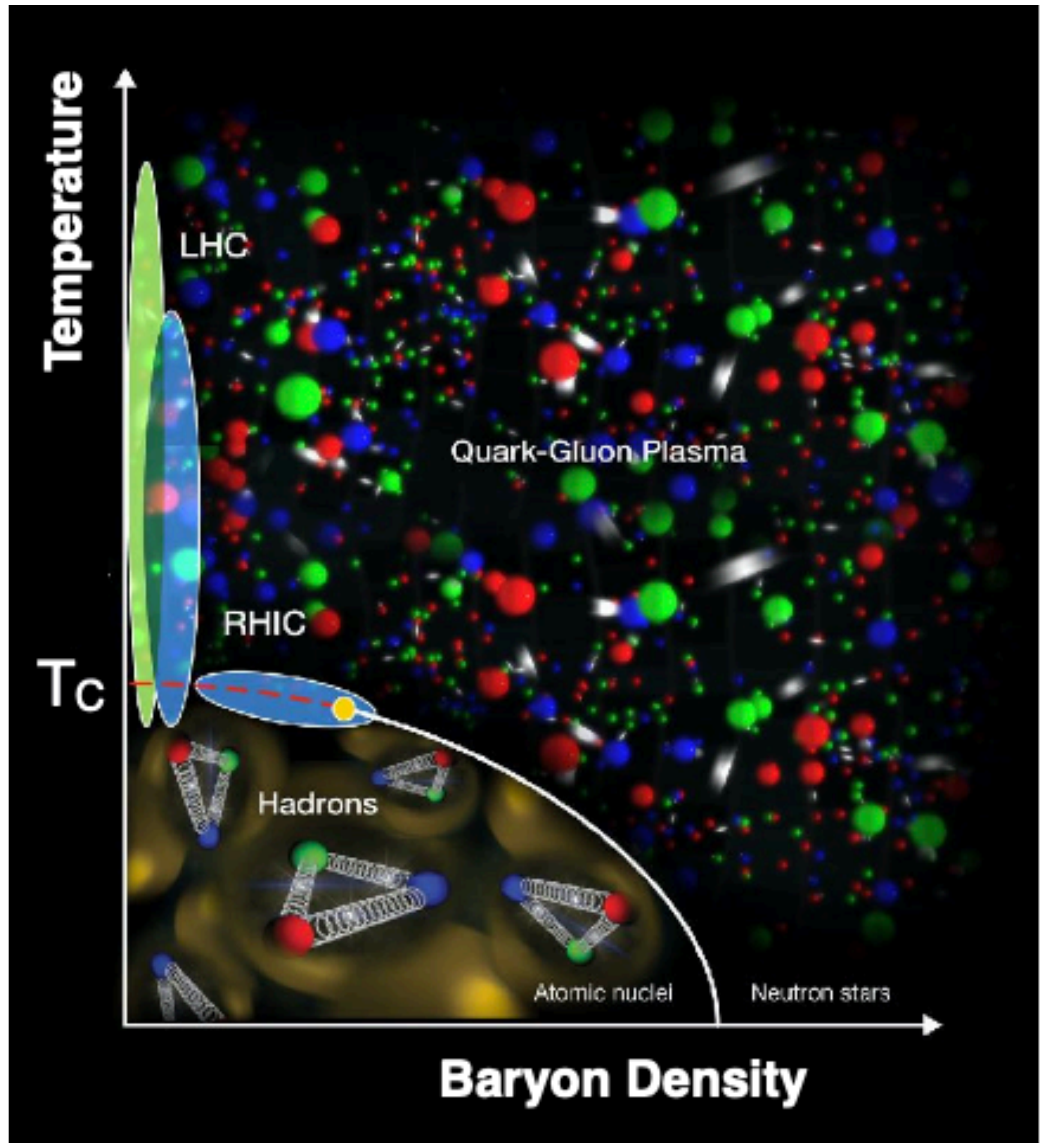
WHAT IS THE CONDITION OF OUR EARLY UNIVERSE?

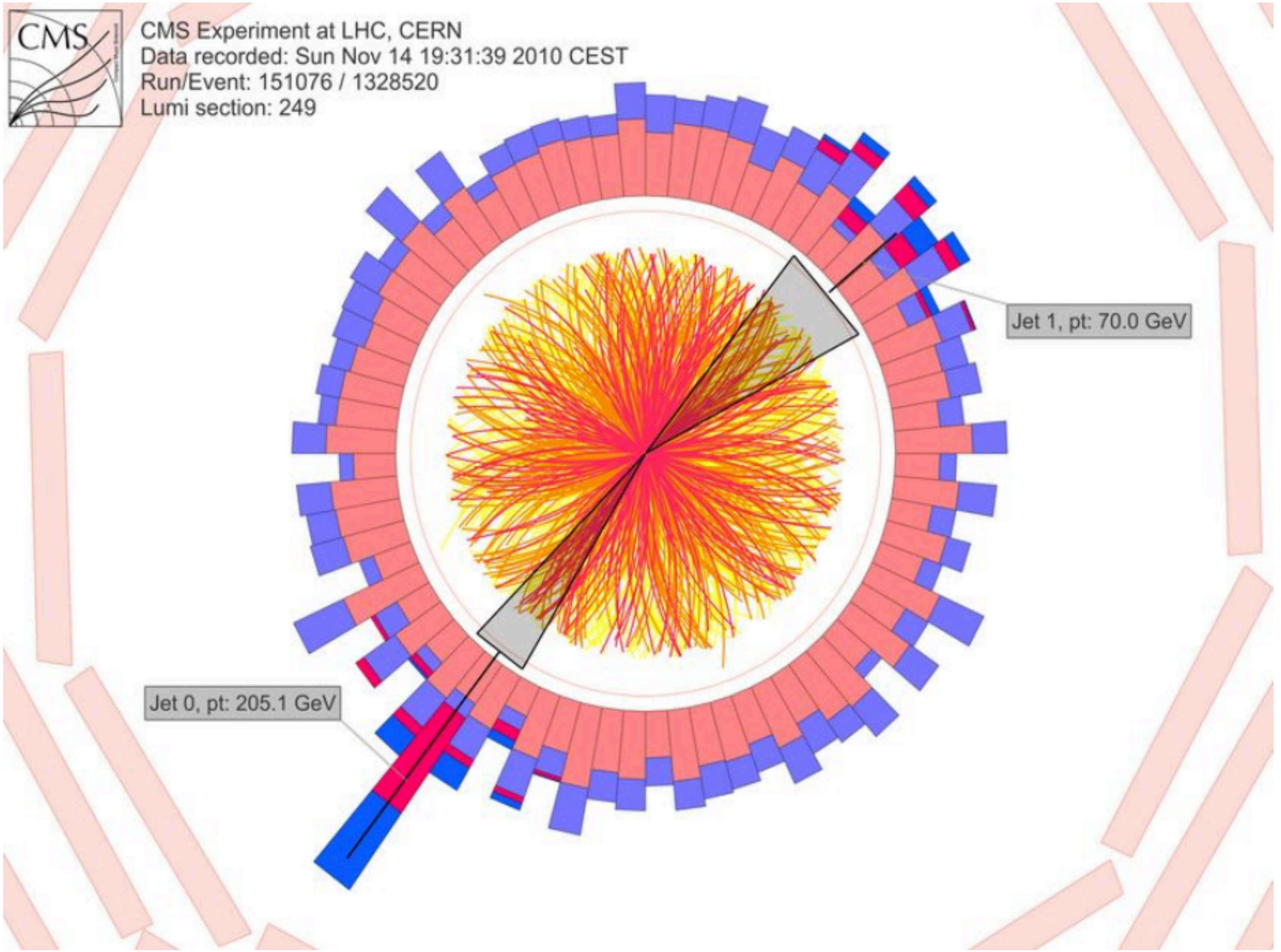
IMPROVING OUR UNDERSTANDING OF MEDIUM PROPERTIES



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.**

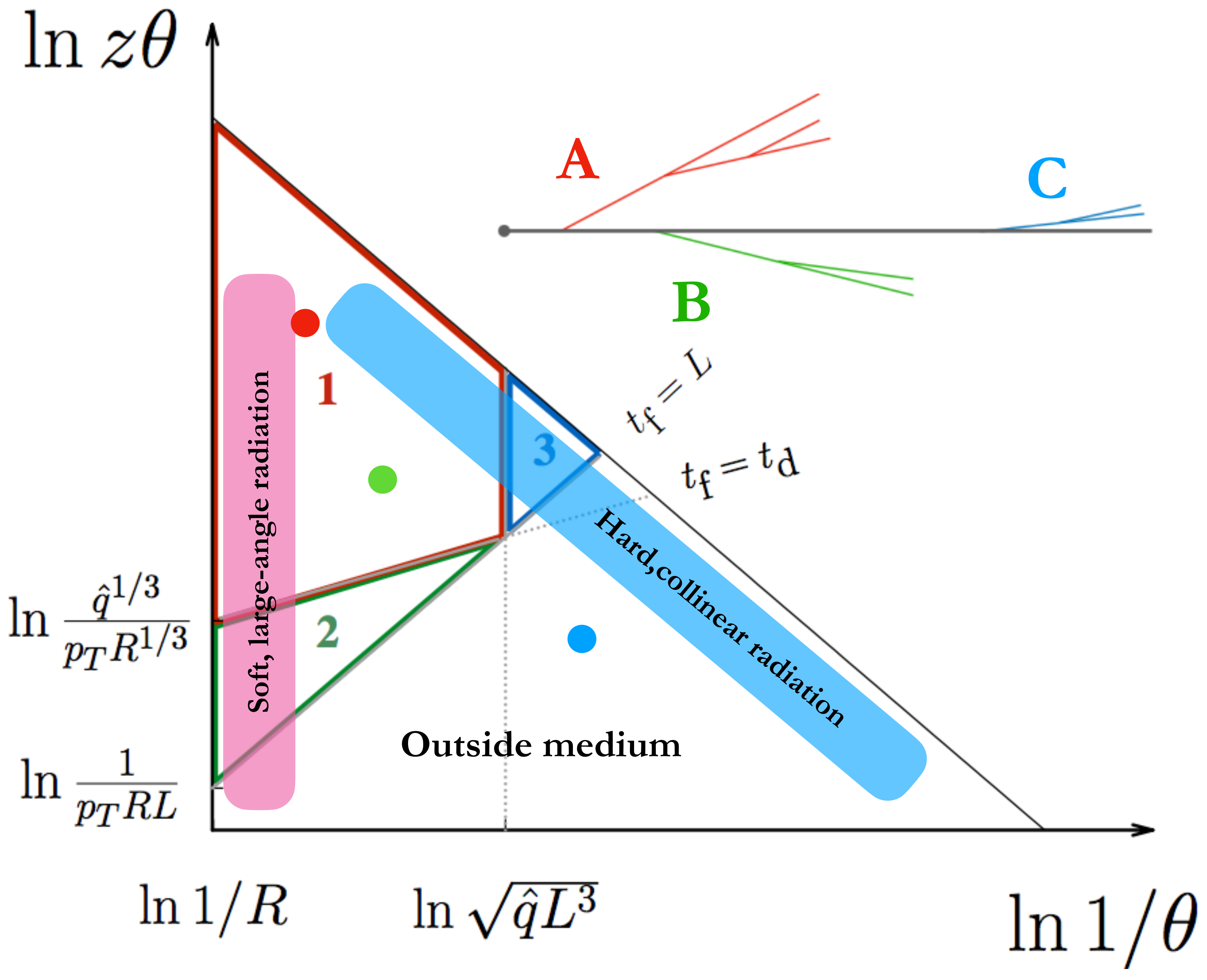




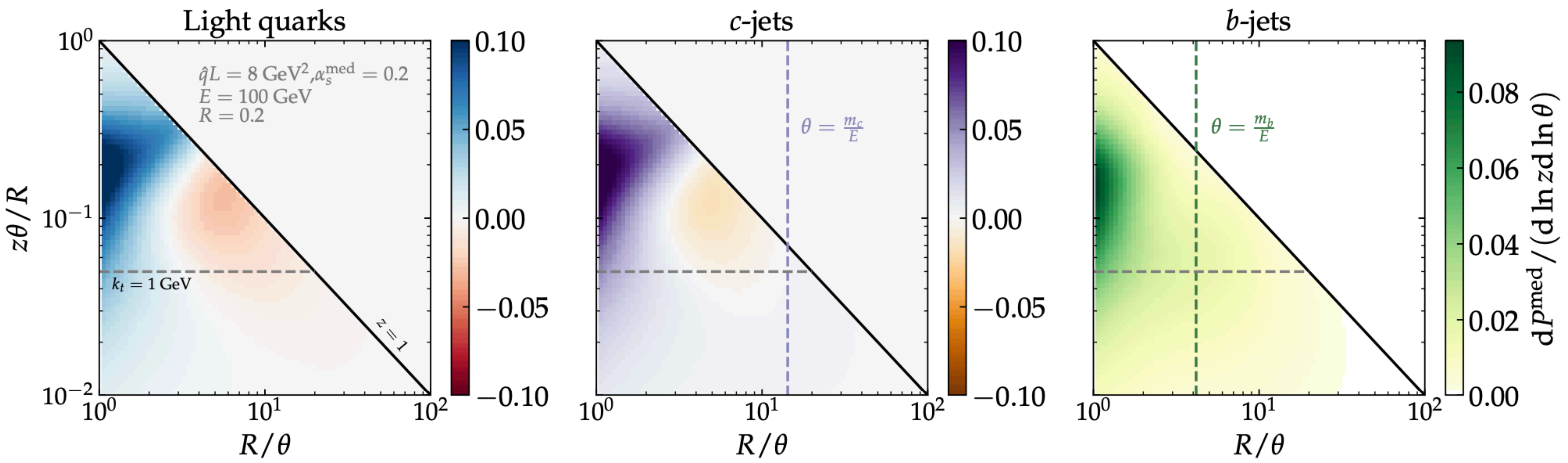
LUND JET PLANE

Andrews et al `18
Dreyer, Salam, Soyez `18
Lifson, Salam, Soyez `21
Khosa, Marzani `21

- **Lund jet plane follows splitting history to identify different kinematical regions, which helps you to identify collinear vs soft region, and in-medium vs out-of-medium regions.**
- **Recent analyses shows intricate interplay between dead-cone effects and medium induced radiations.**



Cunqueiro, Napoletano, Soto-Ontoso `22

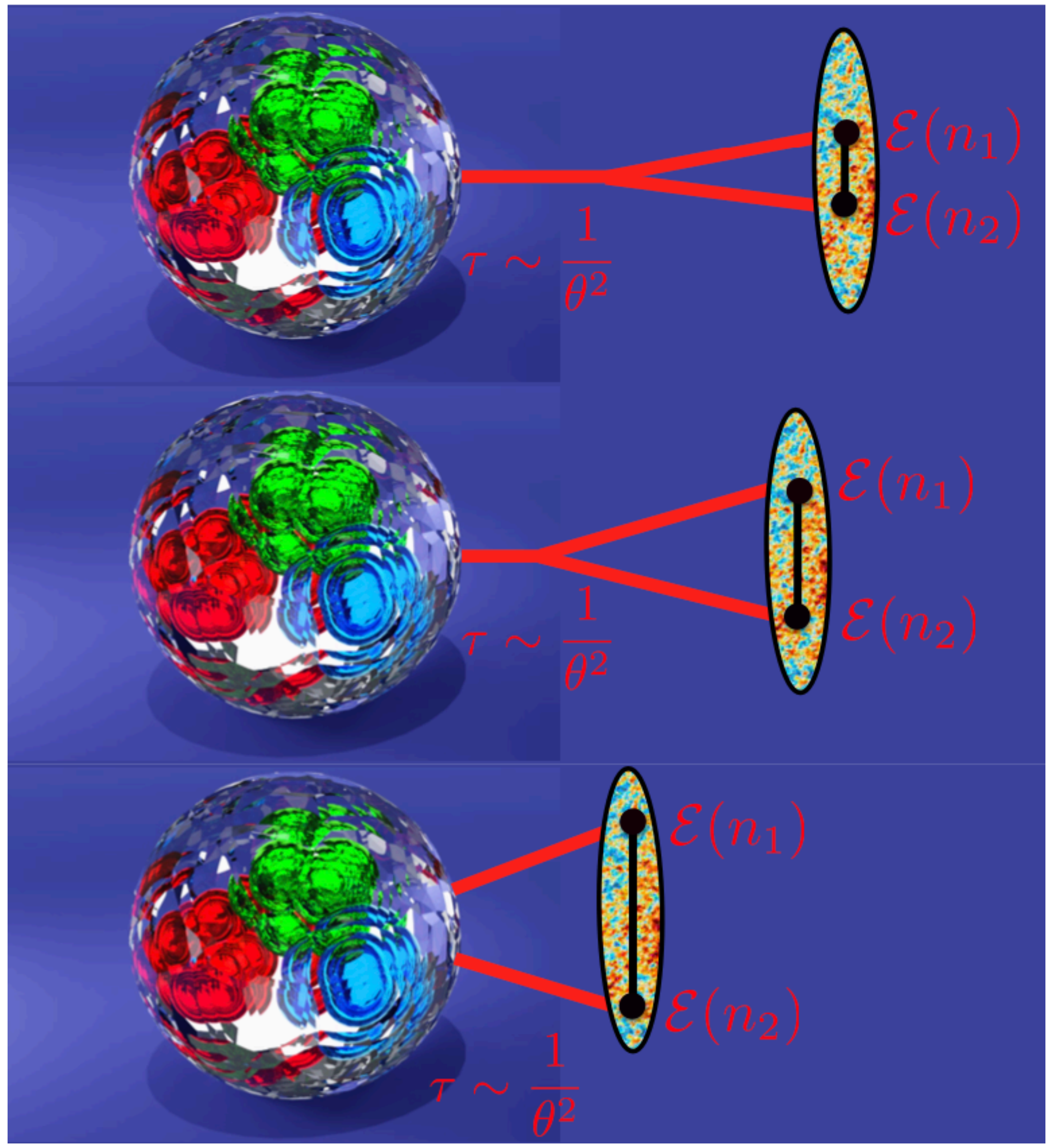


(zero means no modification)

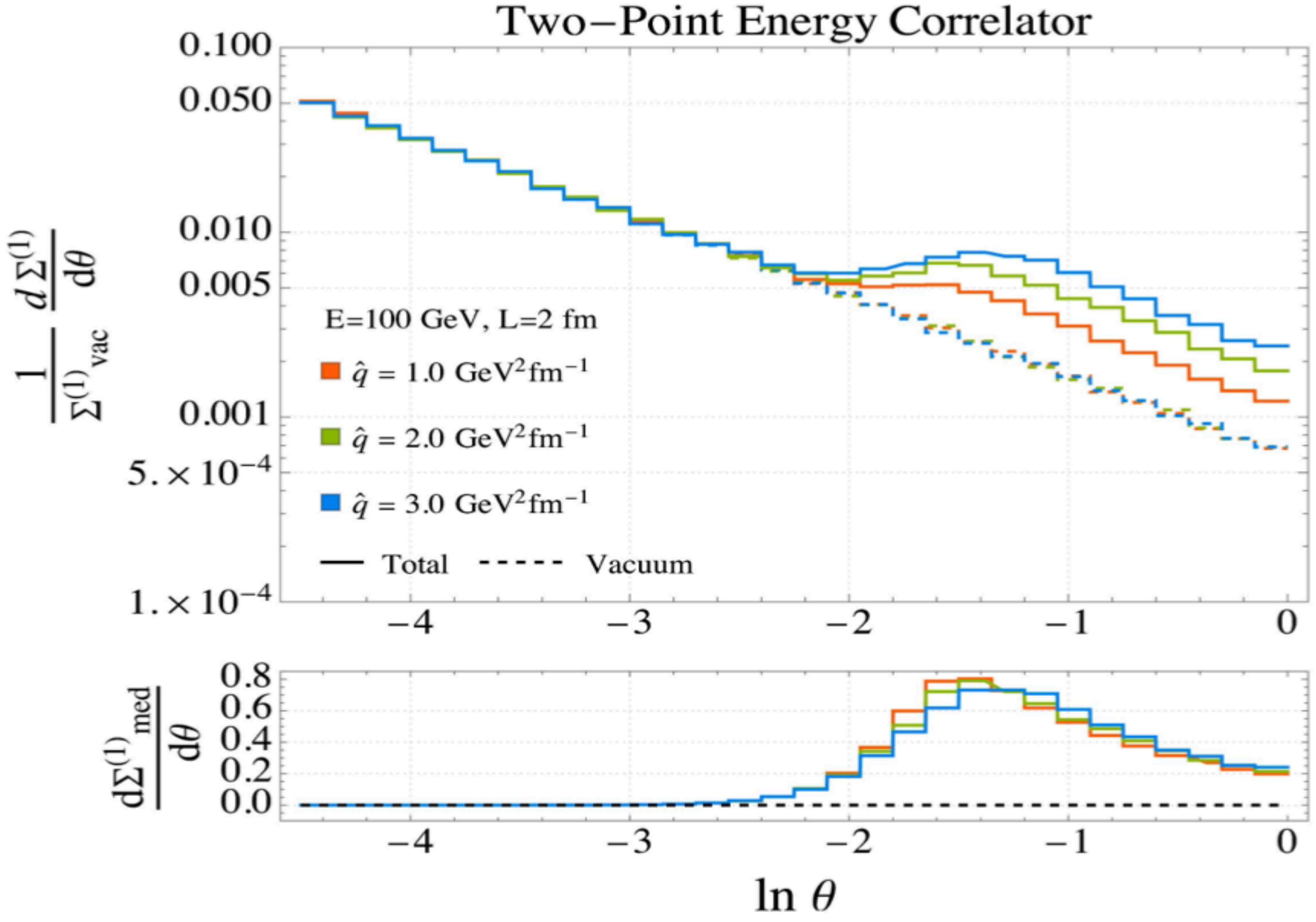
Refer to many talks on measurements on Lund Jet Plane!
See also Christiane's talk on application to Dark Sector!

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!**



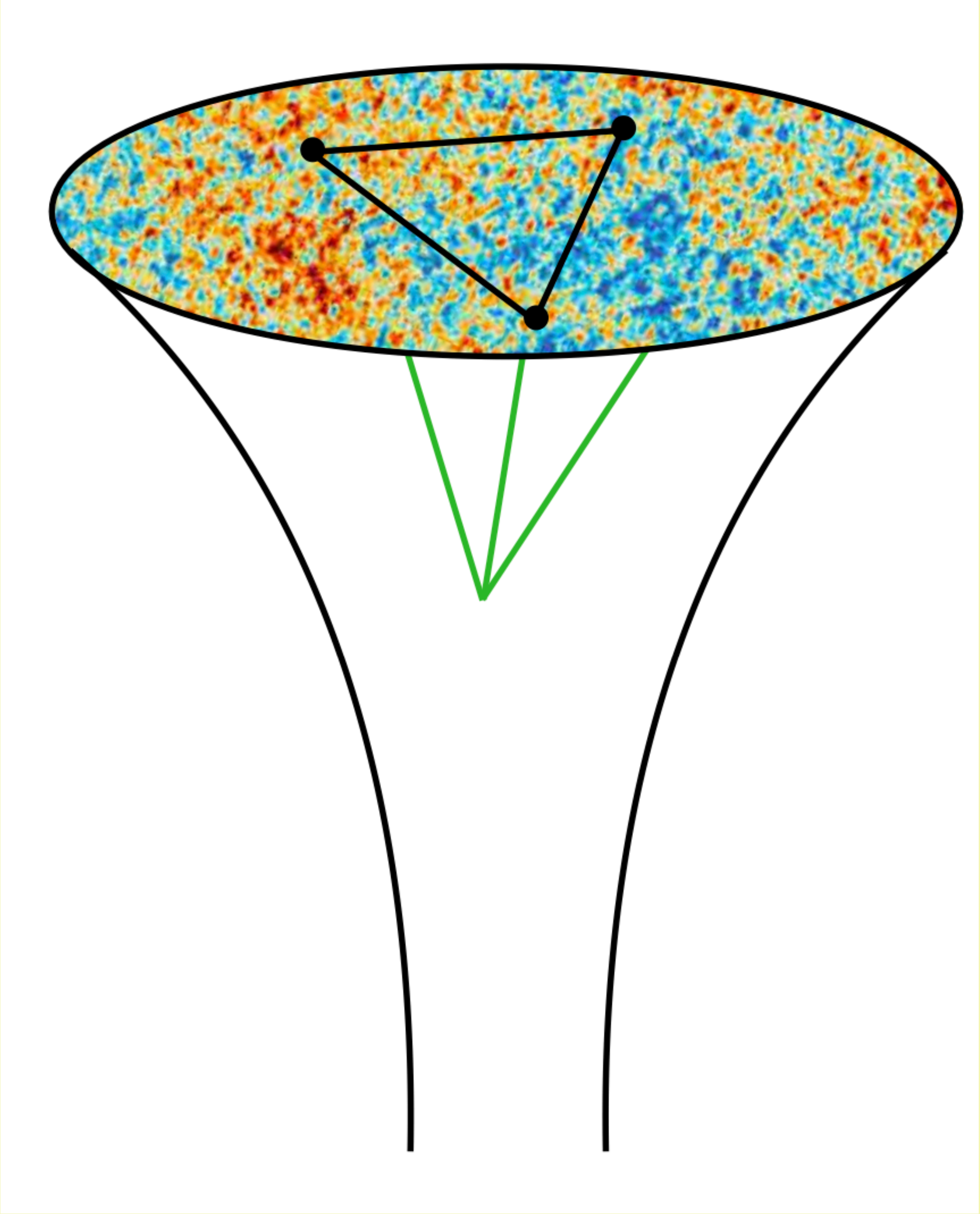
EEC gives angular scale $\mu \sim p_T\theta_{ij}$



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

Tune into Ian and Joao's talk also!

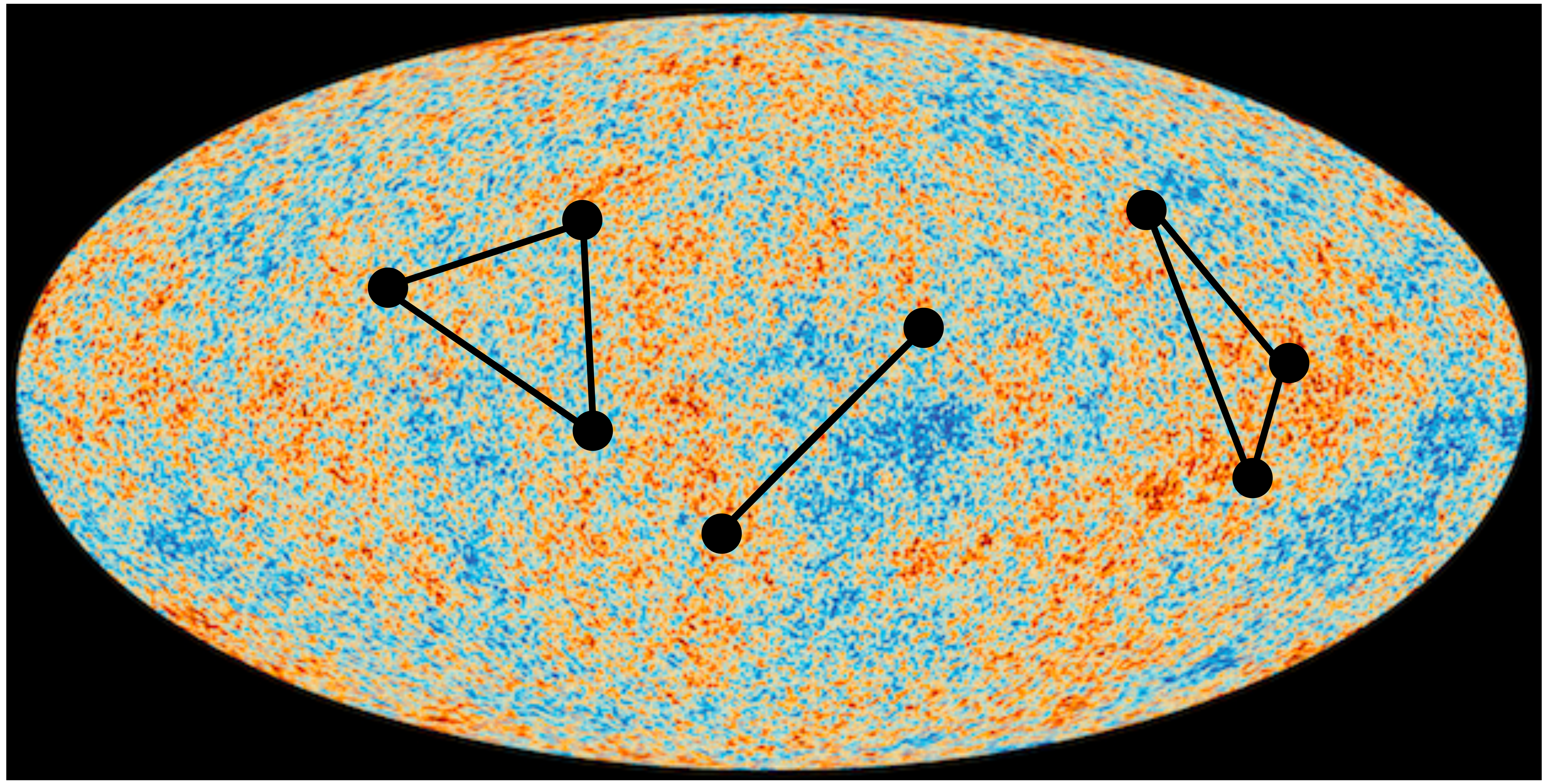
NON-GAUSSIANITIES /HIGHER POINTS IN PARTICLE COLLIDER

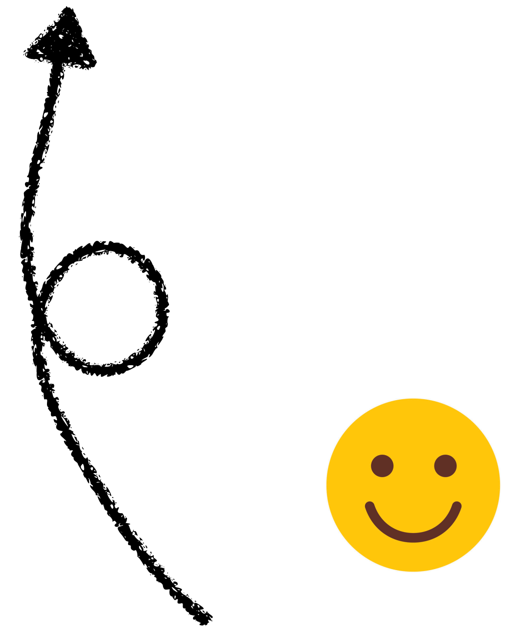


PROBING HIGHER POINT STRUCTURE

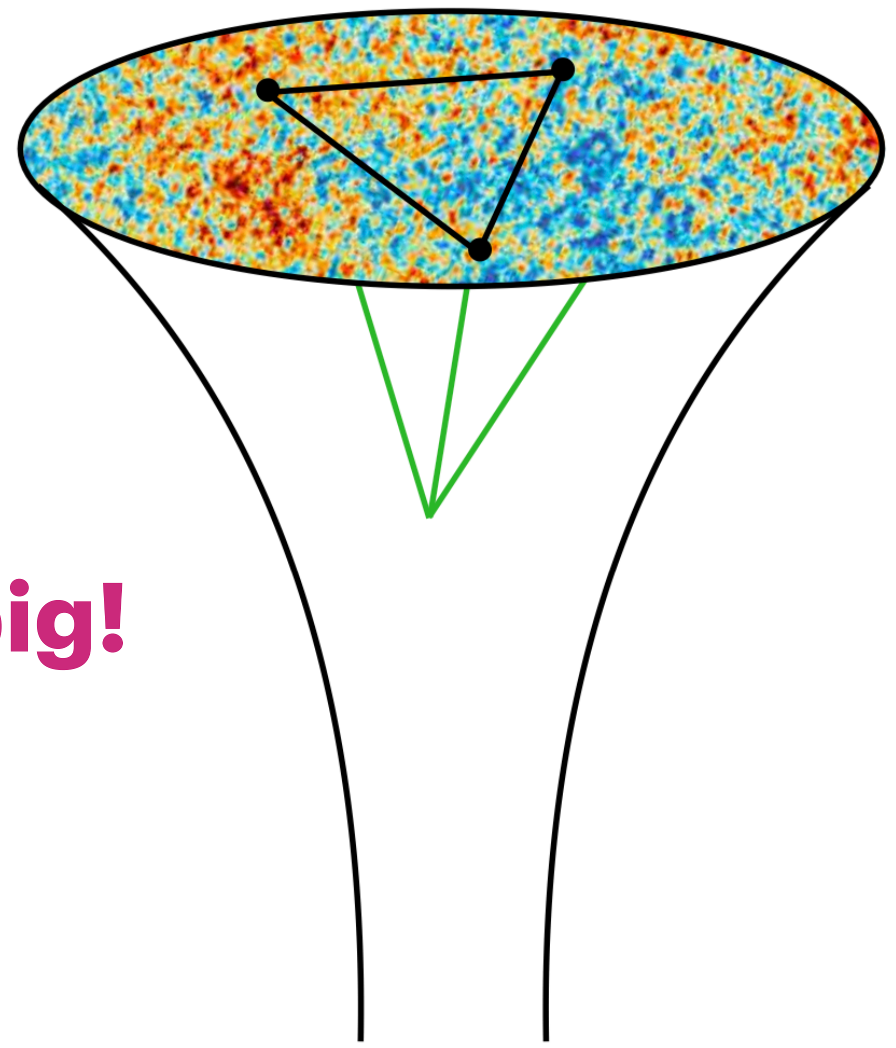
- Higher-point correlators probe **more detailed** aspects of interactions.
- **Hunting for non-gaussianities** to distinguish the models of inflation. *Maldacena `02, Komatsu `10 Cabass, Pajer, Stefanyszyn, Supel `21,…*

  Extremely interesting physics detail hiding under the **1 part in 100000** non-gaussianity in CMB!



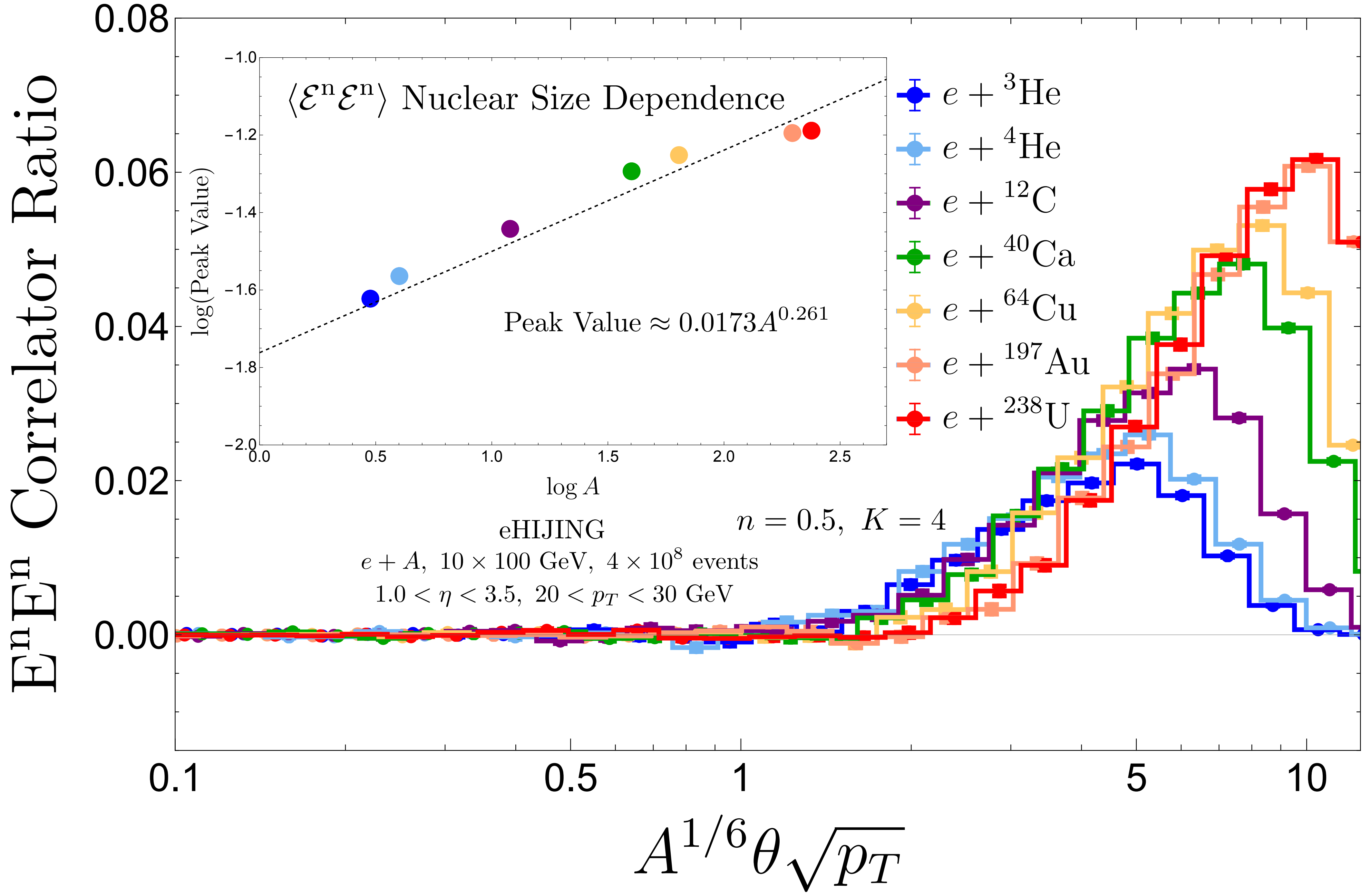


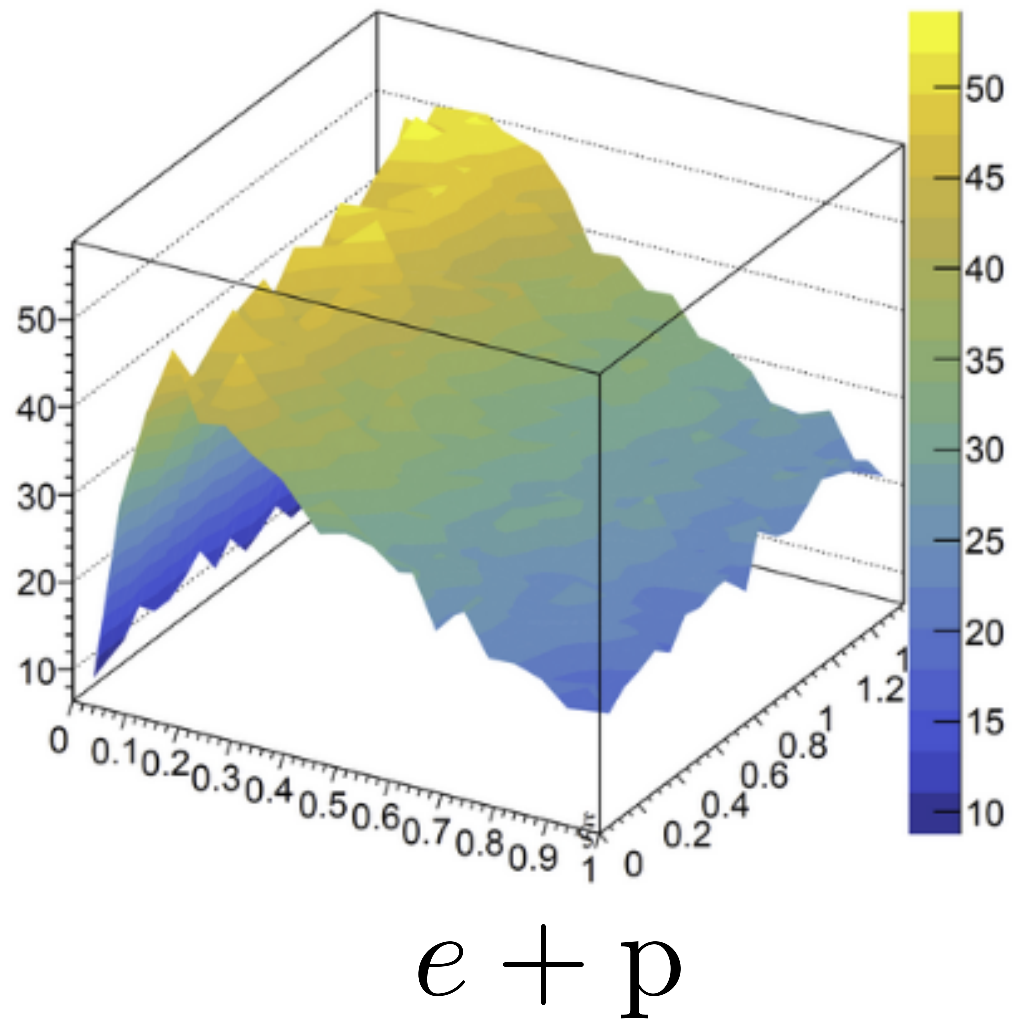
We must also dream big!

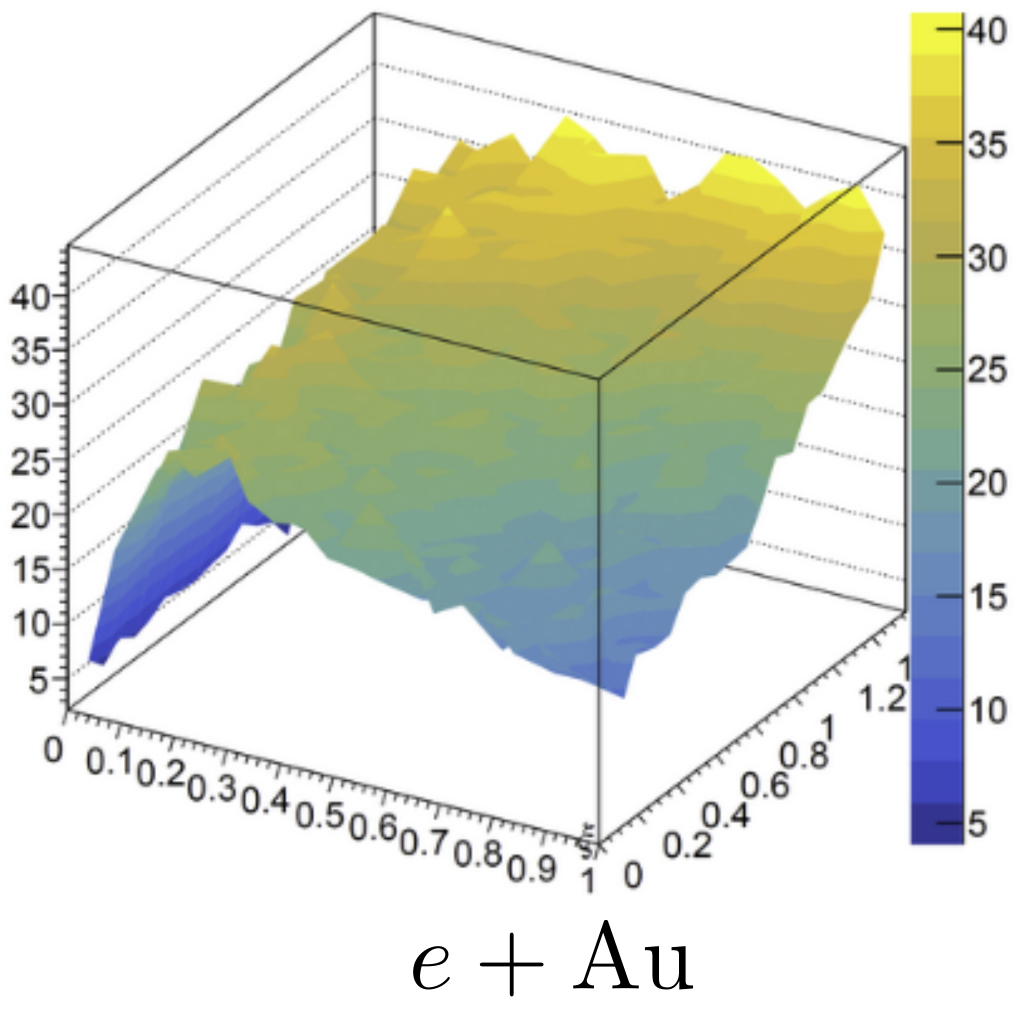


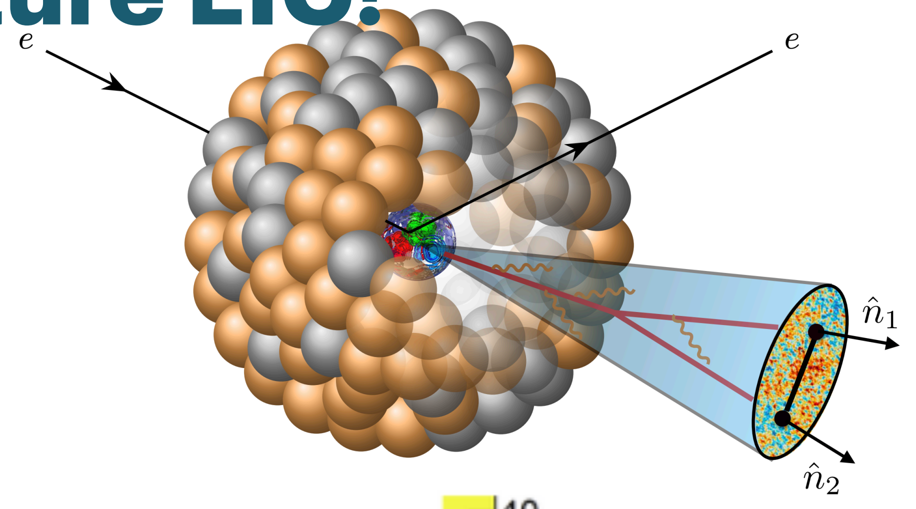
COLD NUCLEAR EFFECTS AND JET SUBSTRUCTURE

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









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

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

Tune into Kyle's talk for more detail!

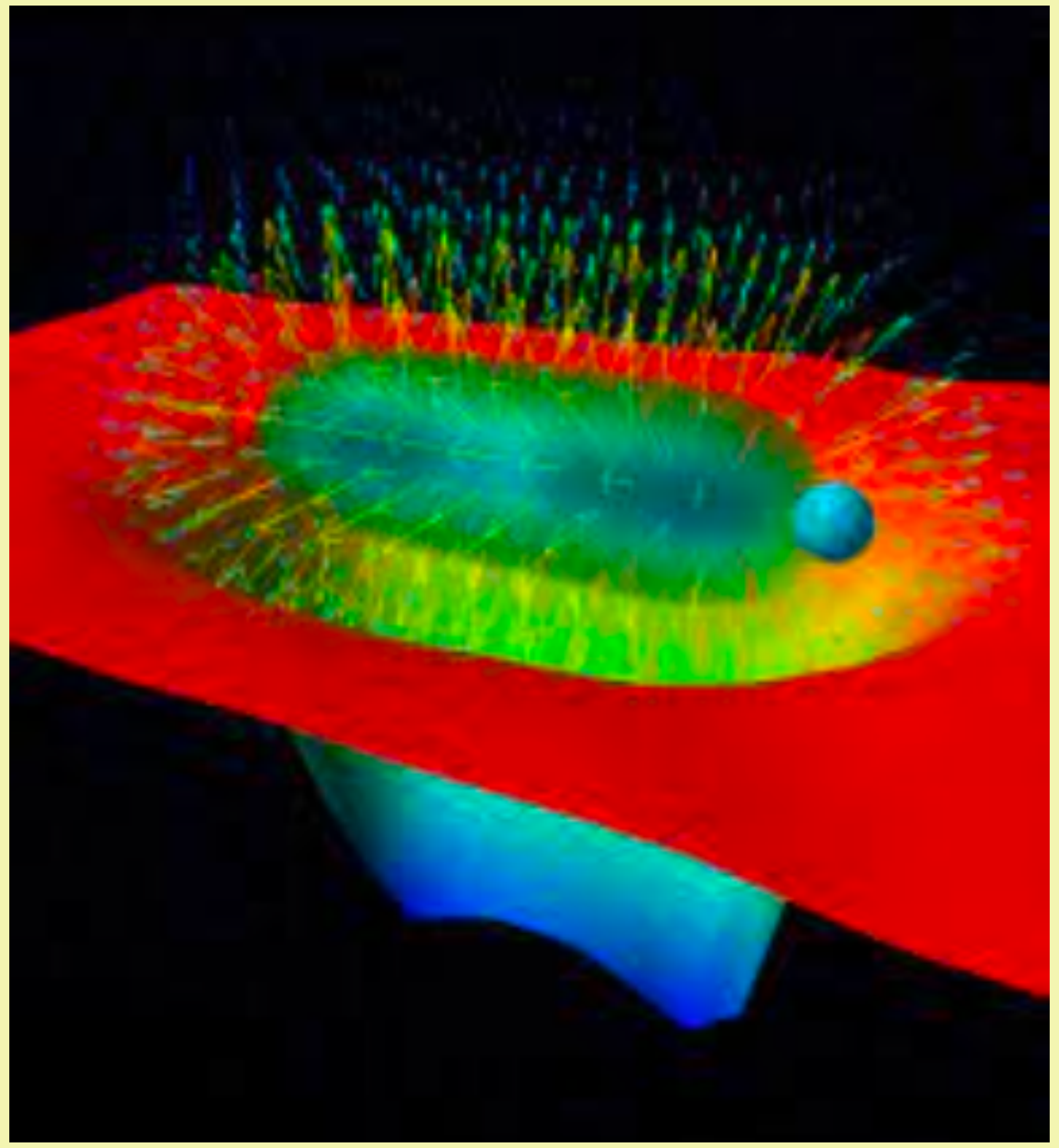
Standard-model physics (QCD and electroweak)

100 MeV - 4 TeV

GOAL

UNLOCK QCD DYNAMICS

UNDERSTAND HADRONIZATION



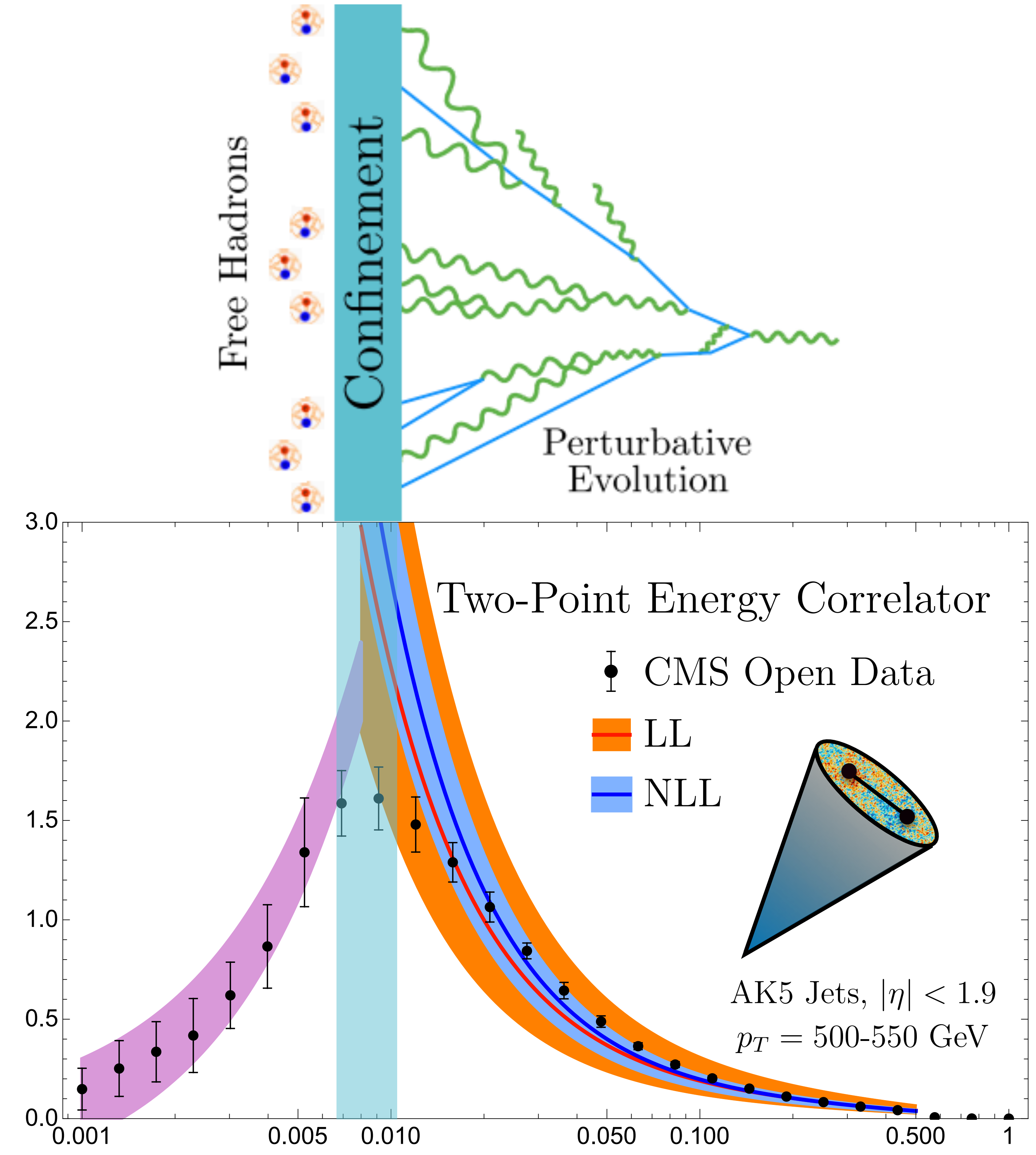
QUARK GLUON SCALING AND HADRONIZATION

- **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

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

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



Interacting quarks and gluons

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

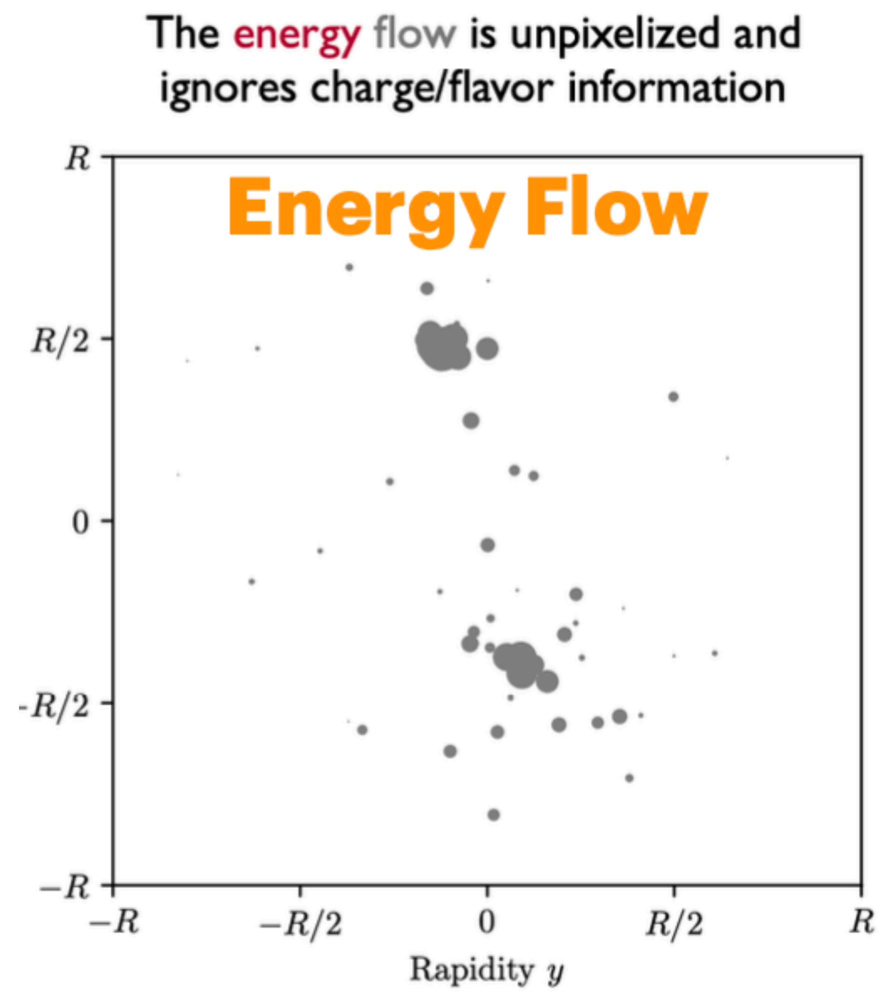
Hofman, Maldacena, `08

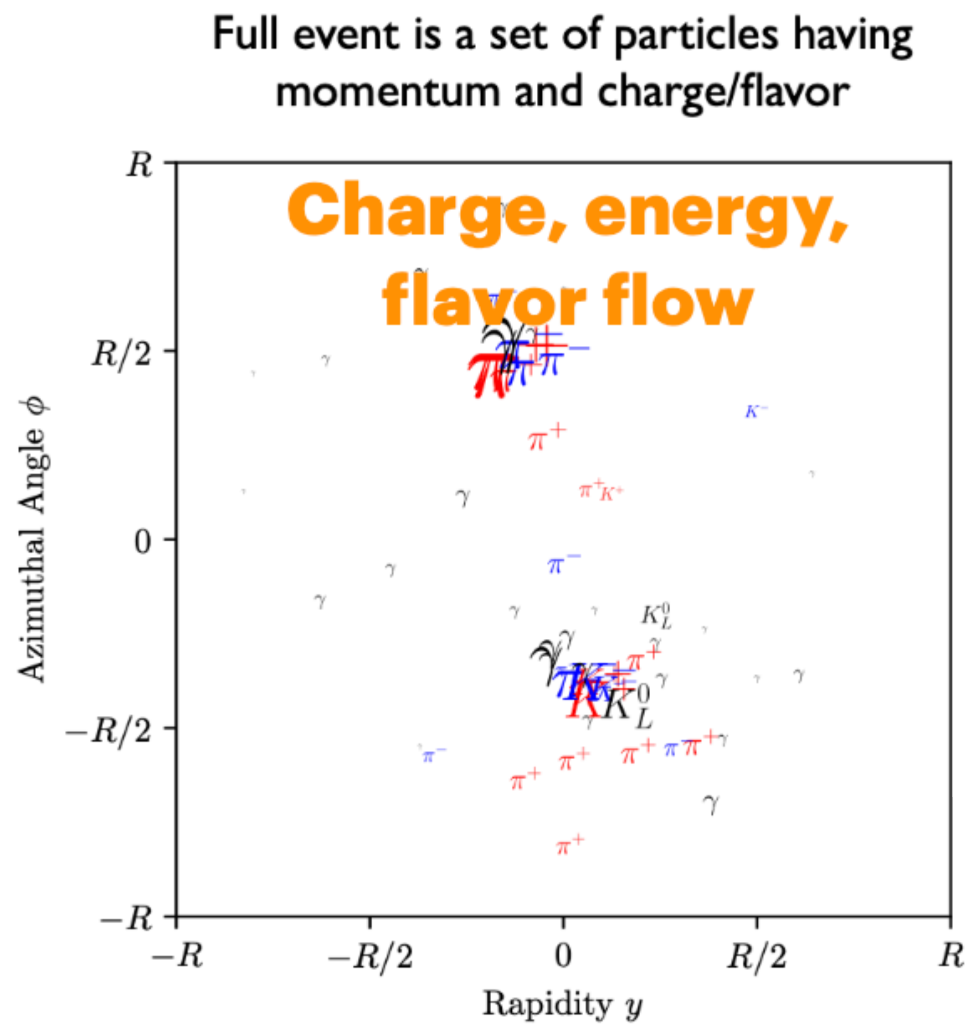
EEC gives angular scale $\mu \sim p_T \theta_{ij}$

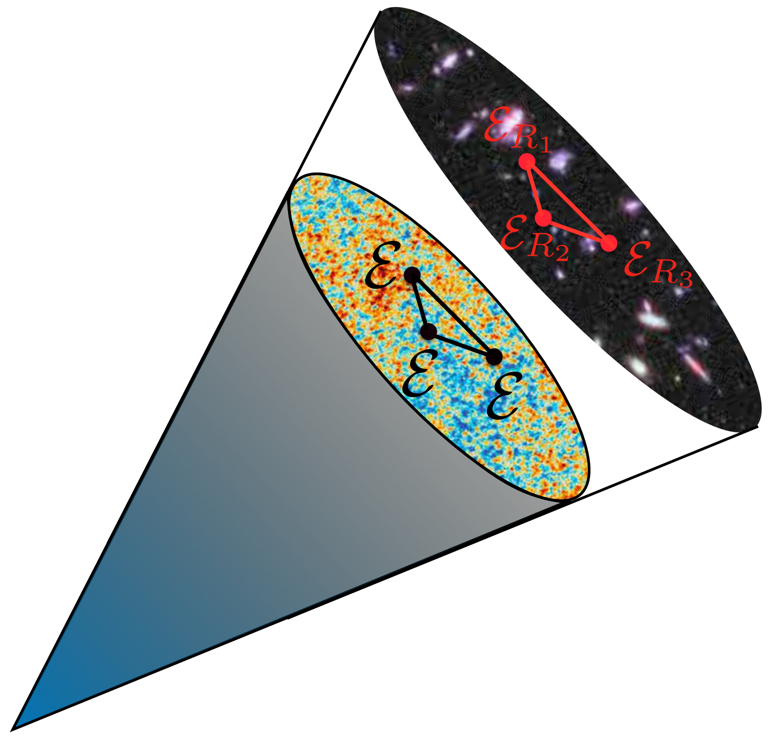
KL, Meçaj, Moult `22
Komiske, Moult, Thaler, Zhu `22

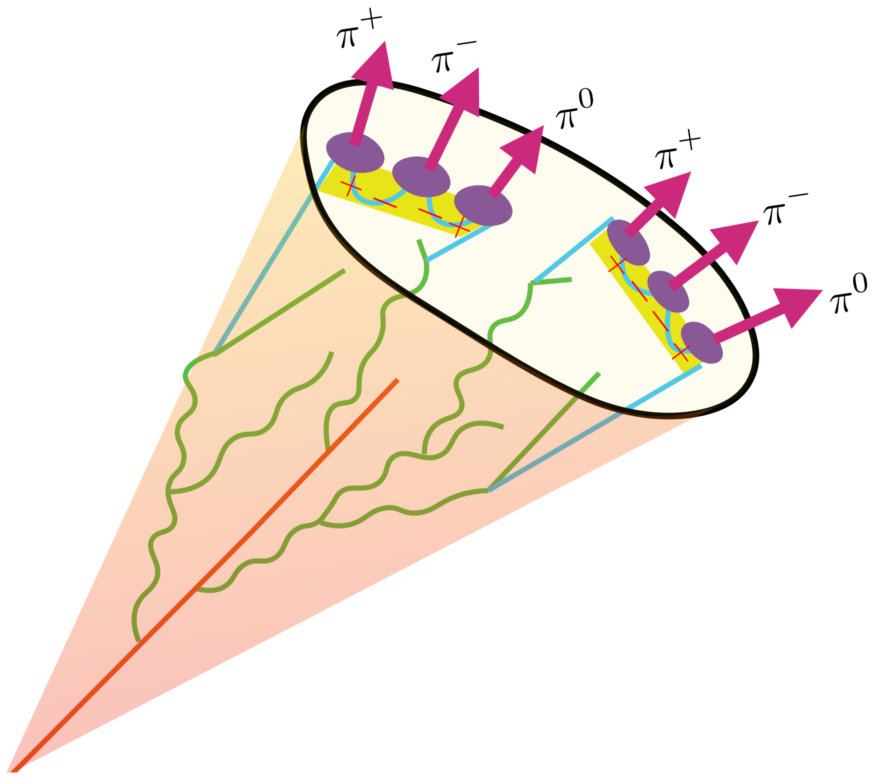
CHARGE FLUX AND HADRONIZATION

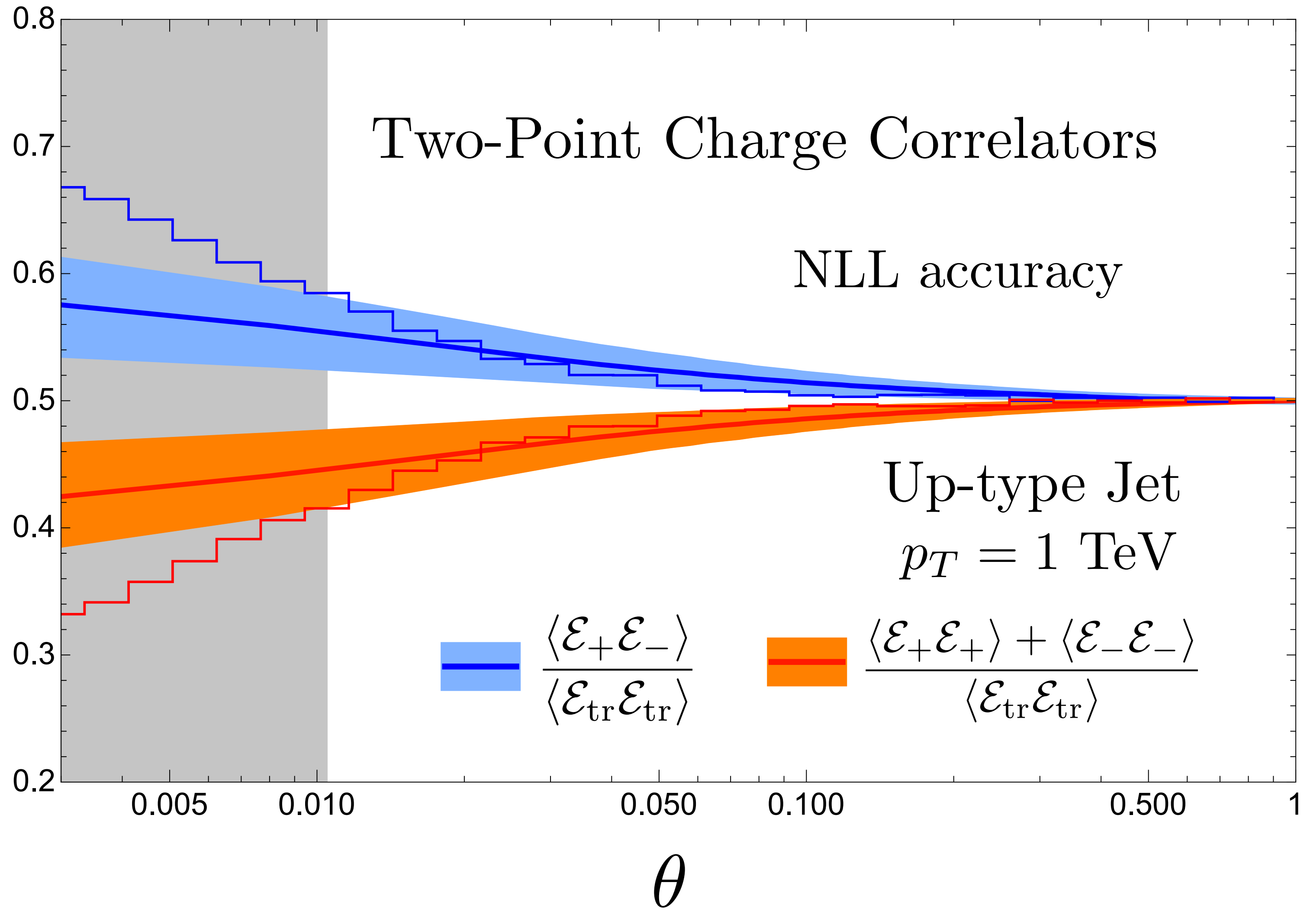
- **Theoretically, track measurement represents "minimal breaking" of perturbative calculations in a controlled way to introduce sensitivity to the nonperturbative effects.**









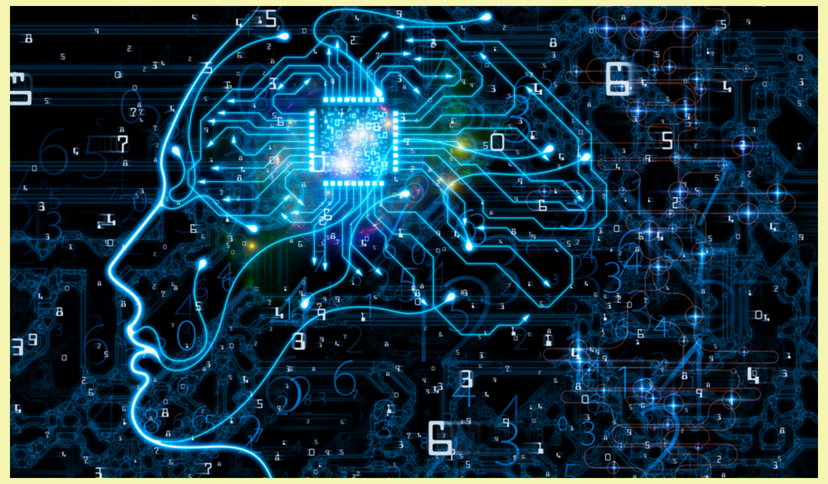


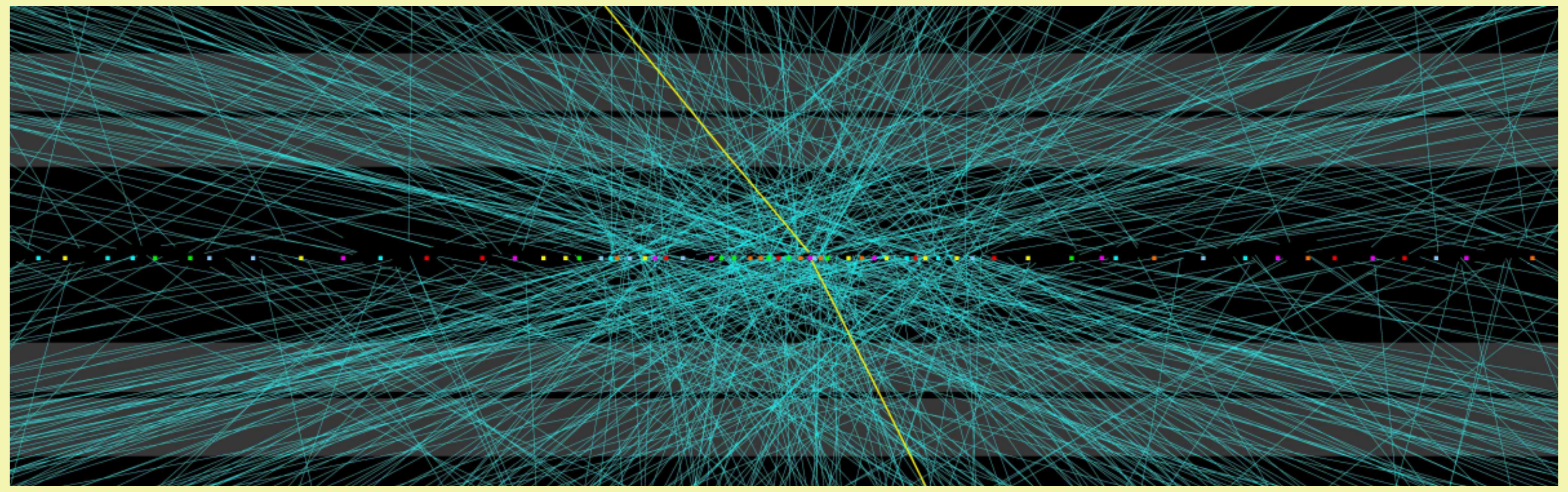
- **+ - and ++/- - correlations are expected to behave differently in hadronization processes.**

Tune into my talk for more detail!

PRECISION MEASUREMENTS

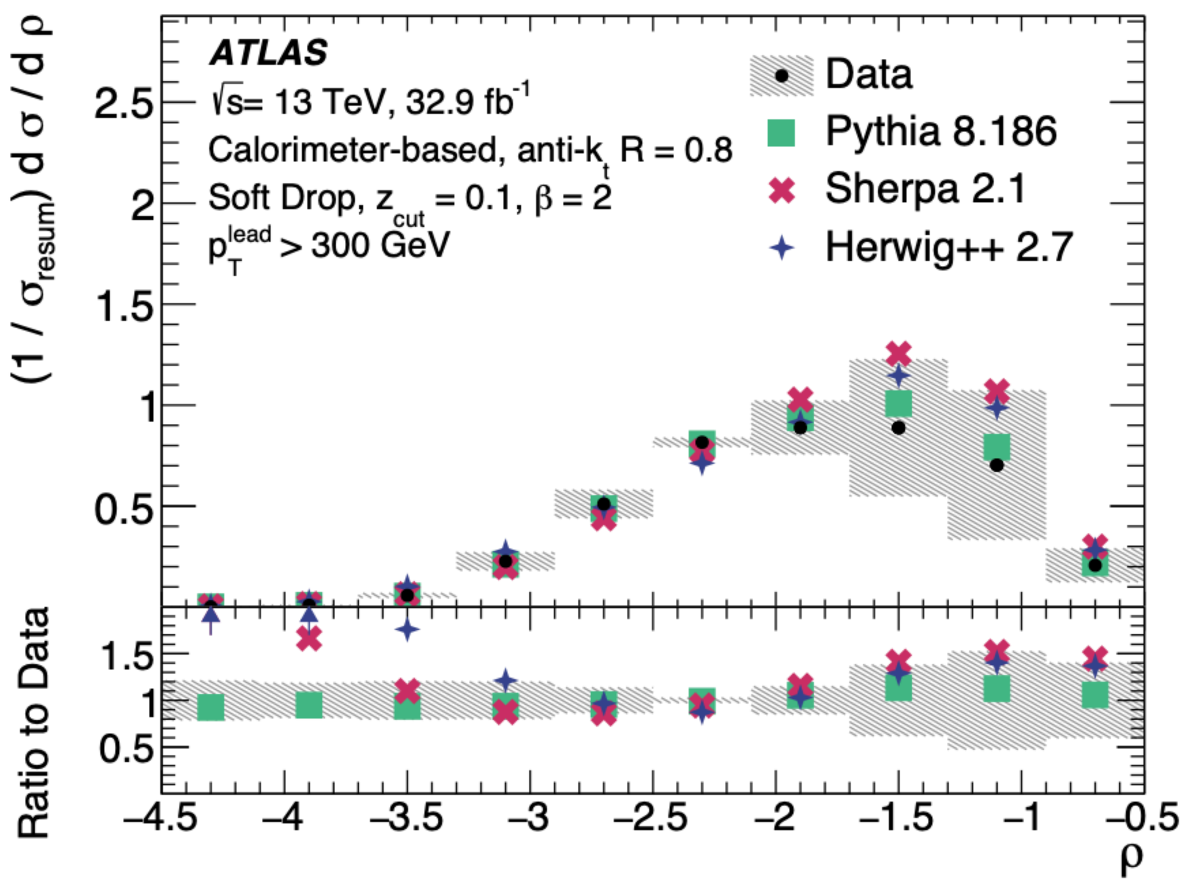
TRACKS AND ML

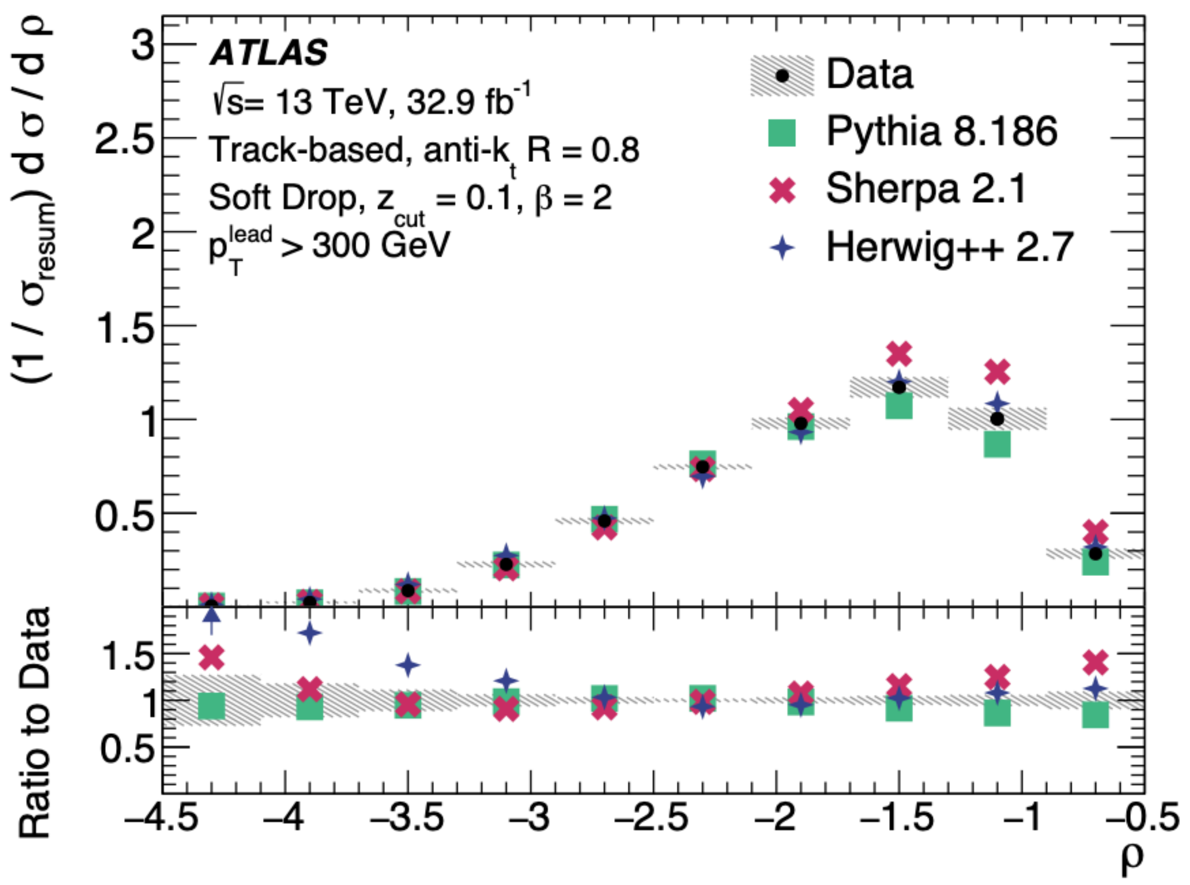




MEASURING ON TRACKS

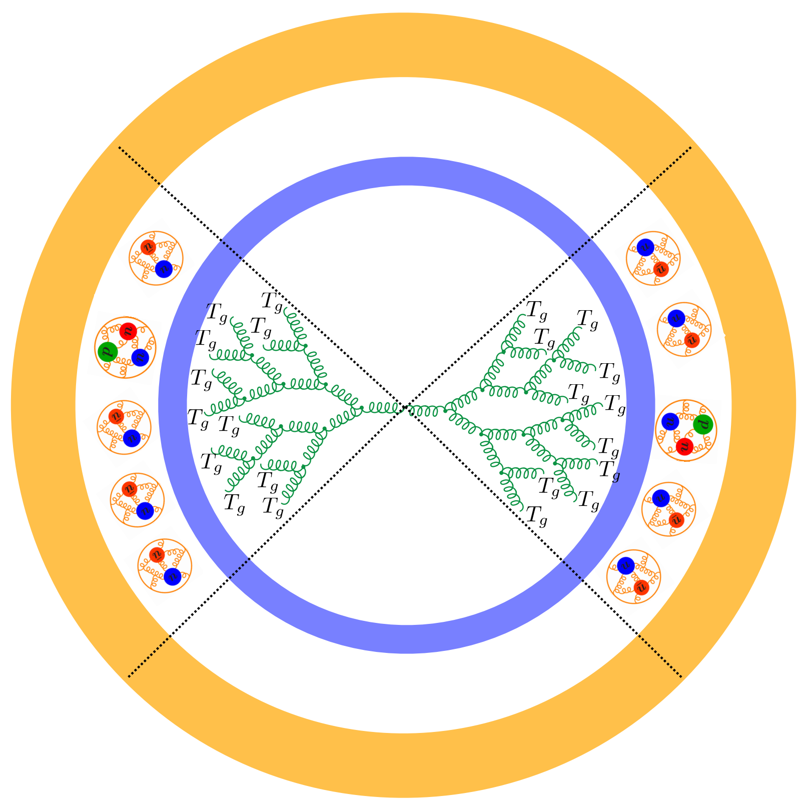
- In order to unlock QCD dynamics and more, precision measurements are important!
- **Experimentally**, measurements on tracks are advantageous because **much more precise** measurements are possible



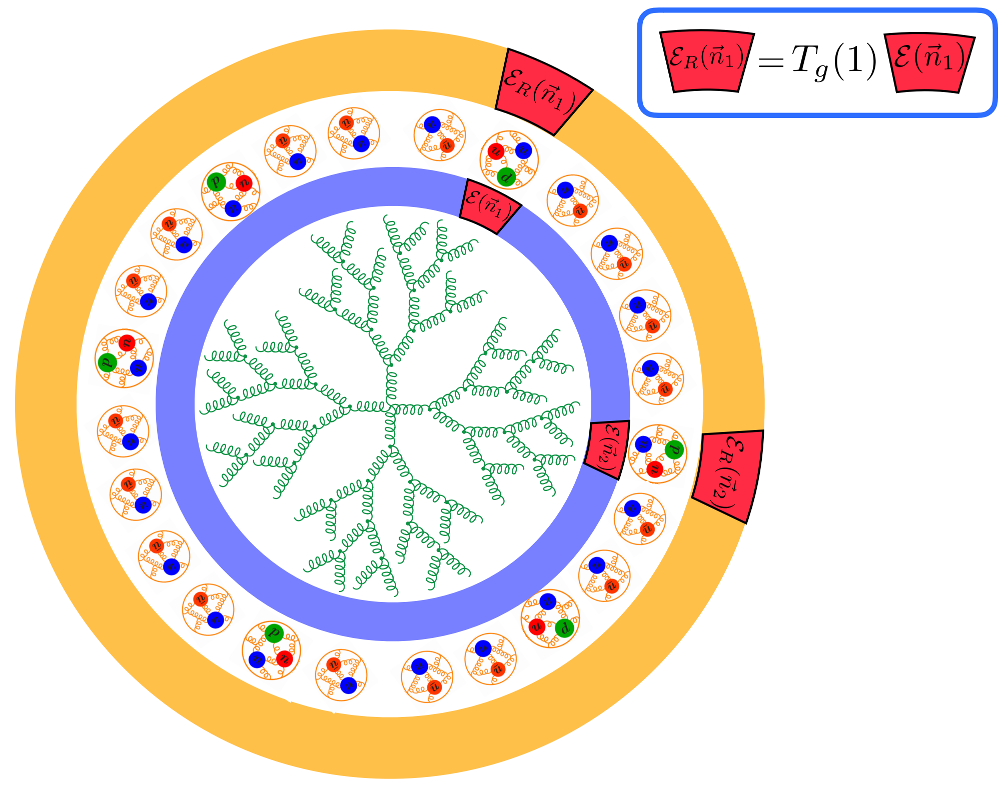


[ATLAS (2019)]

Jet shape



Energy correlators



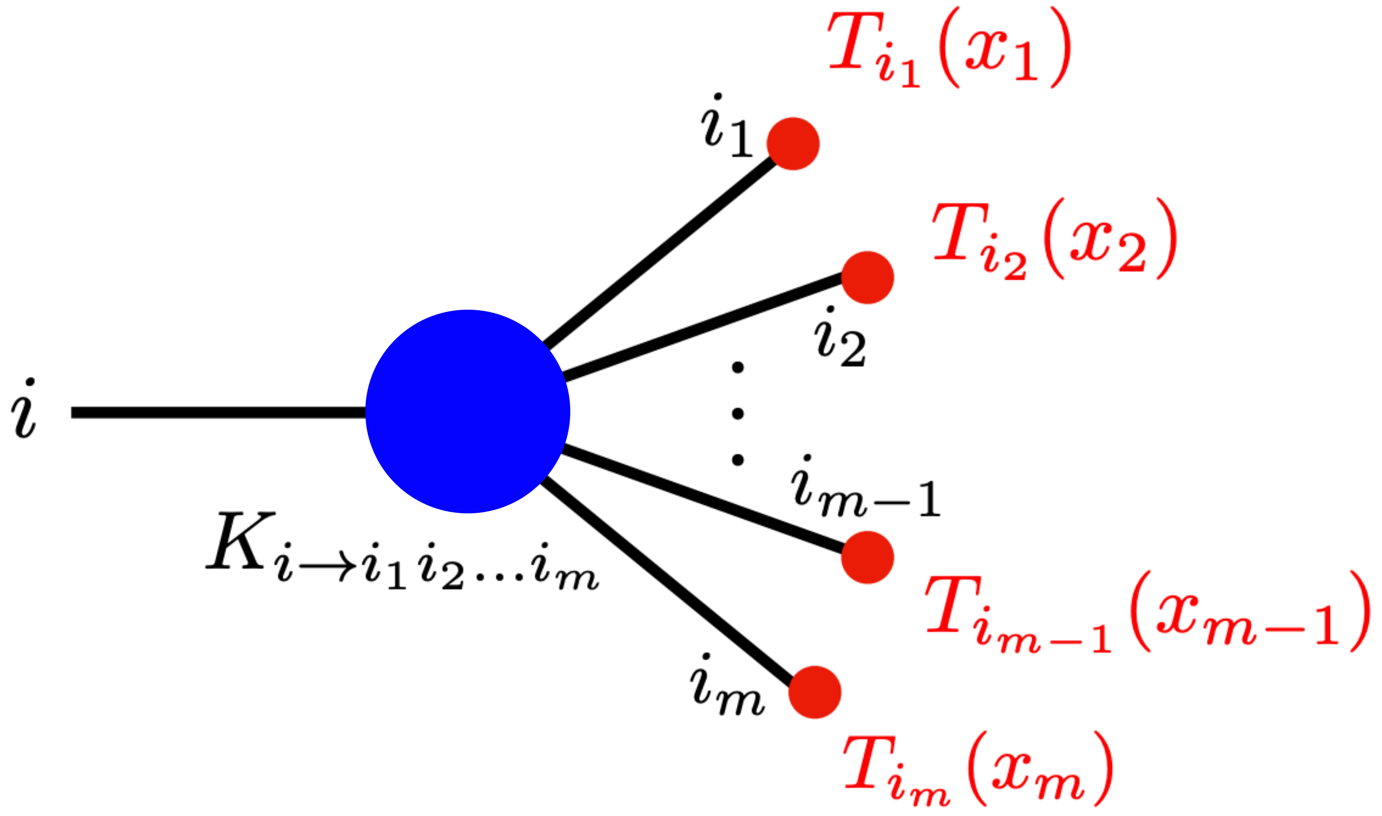
space of the state vs **space of the detectors**

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

TRACK FUNCTION FORMALISM

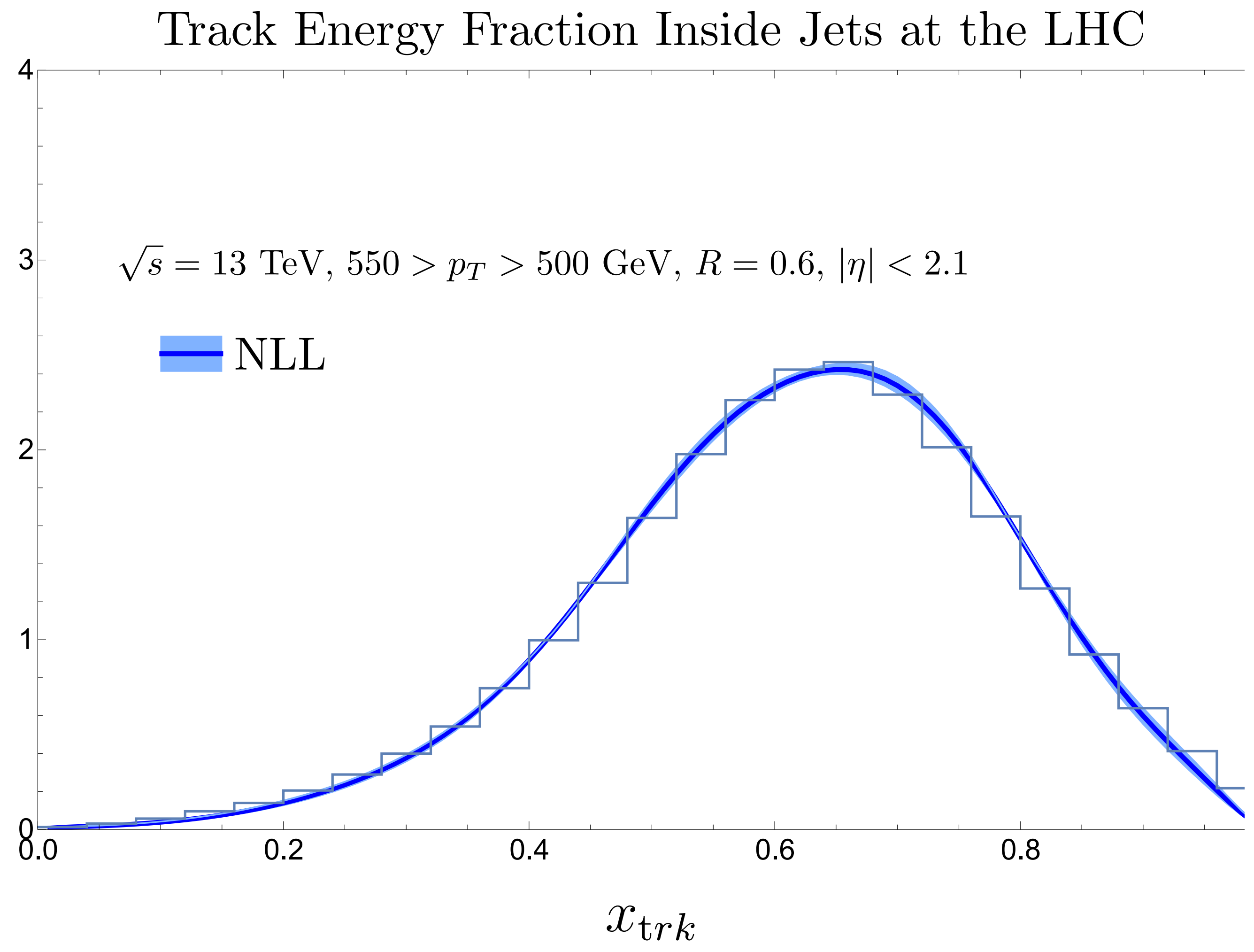
- **First formalism to study observables on tracks developed over a decade ago, and developments have rapidly advanced in recent years.**

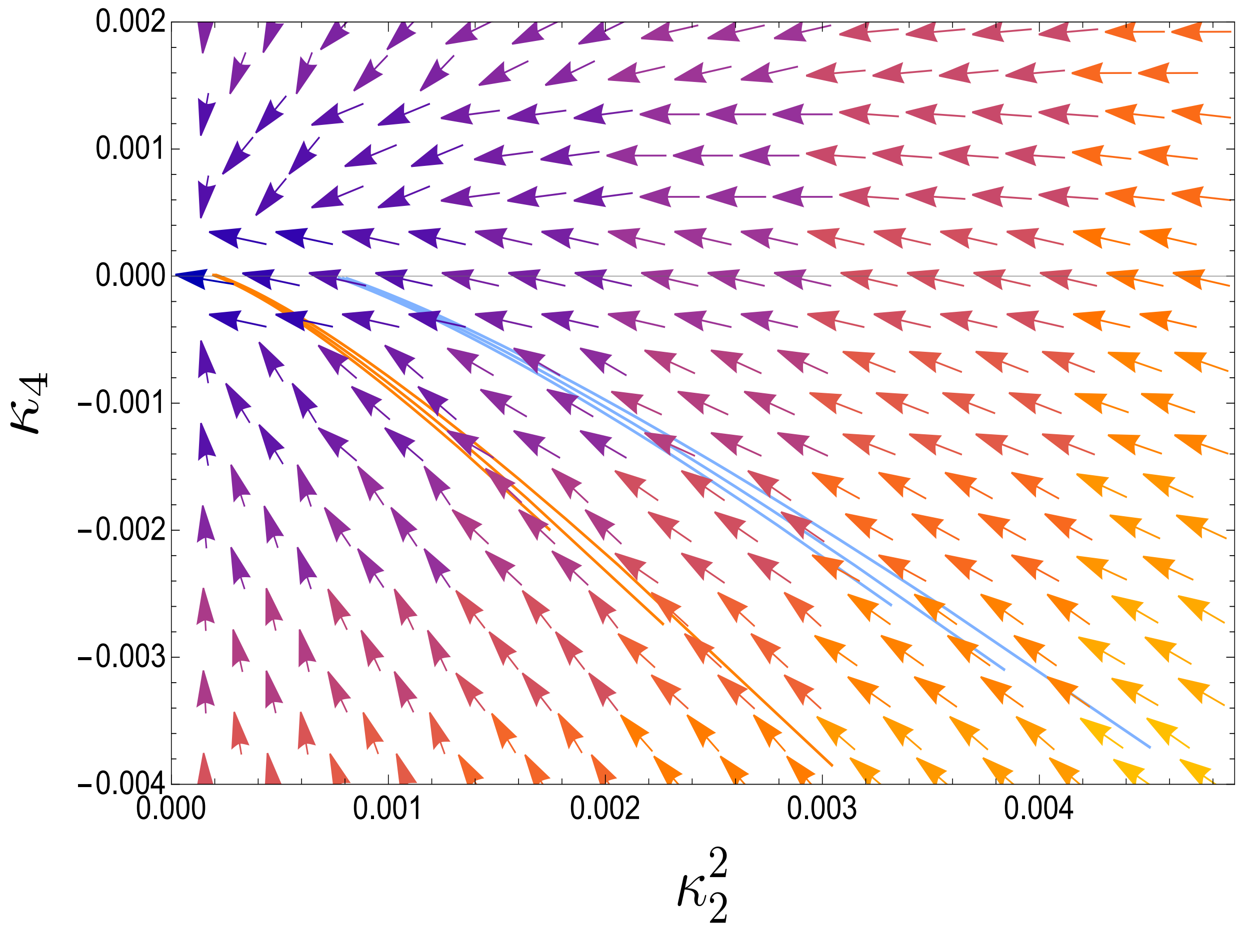
Chang, Procura, Thaler, Waalewijn `13
Li, Moult, Waalewijn, Zhu et al `21, 22



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

- **We are now able to study track inside the LHC jets, which allow their extractions once measured. One can observe very non-trivial Lorentzian mixing RG structure at the LHC.** *KL, Moult, Ringer, Waalewijn `23*

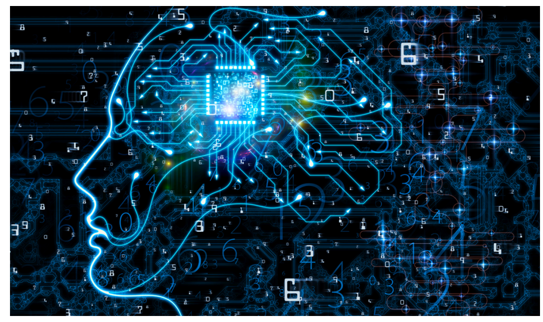




For discussion on jet charge, see Andrew's talk!

Kang, Larkoski, Yang `23

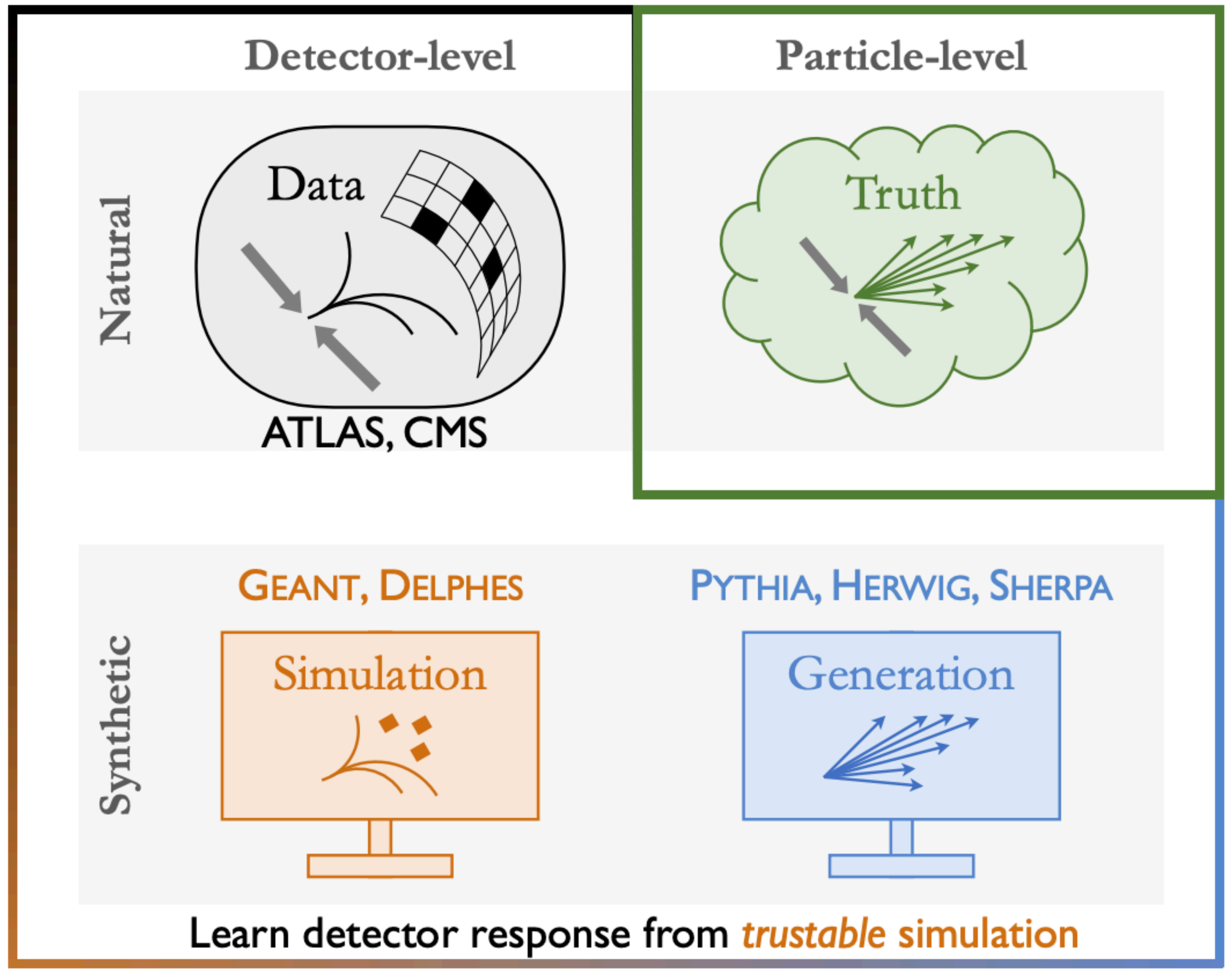
ML AND PRECISION MEASUREMENTS



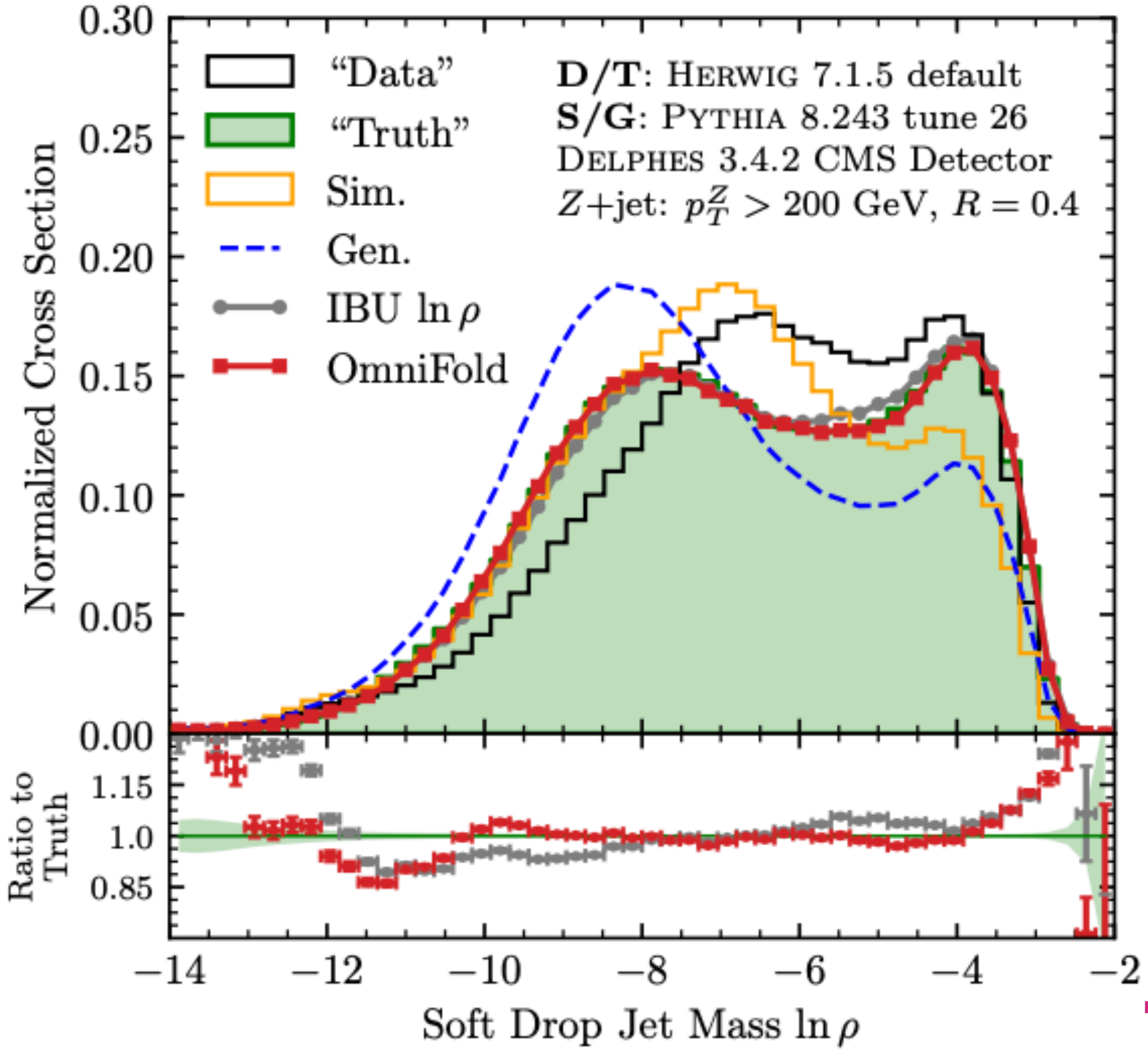
- **Machine learning is making seminal advances in all fronts of collider physics, including jet analyses.**
- **Omnifold gives us access to fully unbinned phase space by iterated reweighing methods in order to learn detector effects. Either equals or outperforms Iterative Bayesian Unfolding (IBU).**

Andreassen, Komiske, Metodiev, Nachman, Thaler `19

Andreassen, Nachman `19



Slide from Ben Nachman

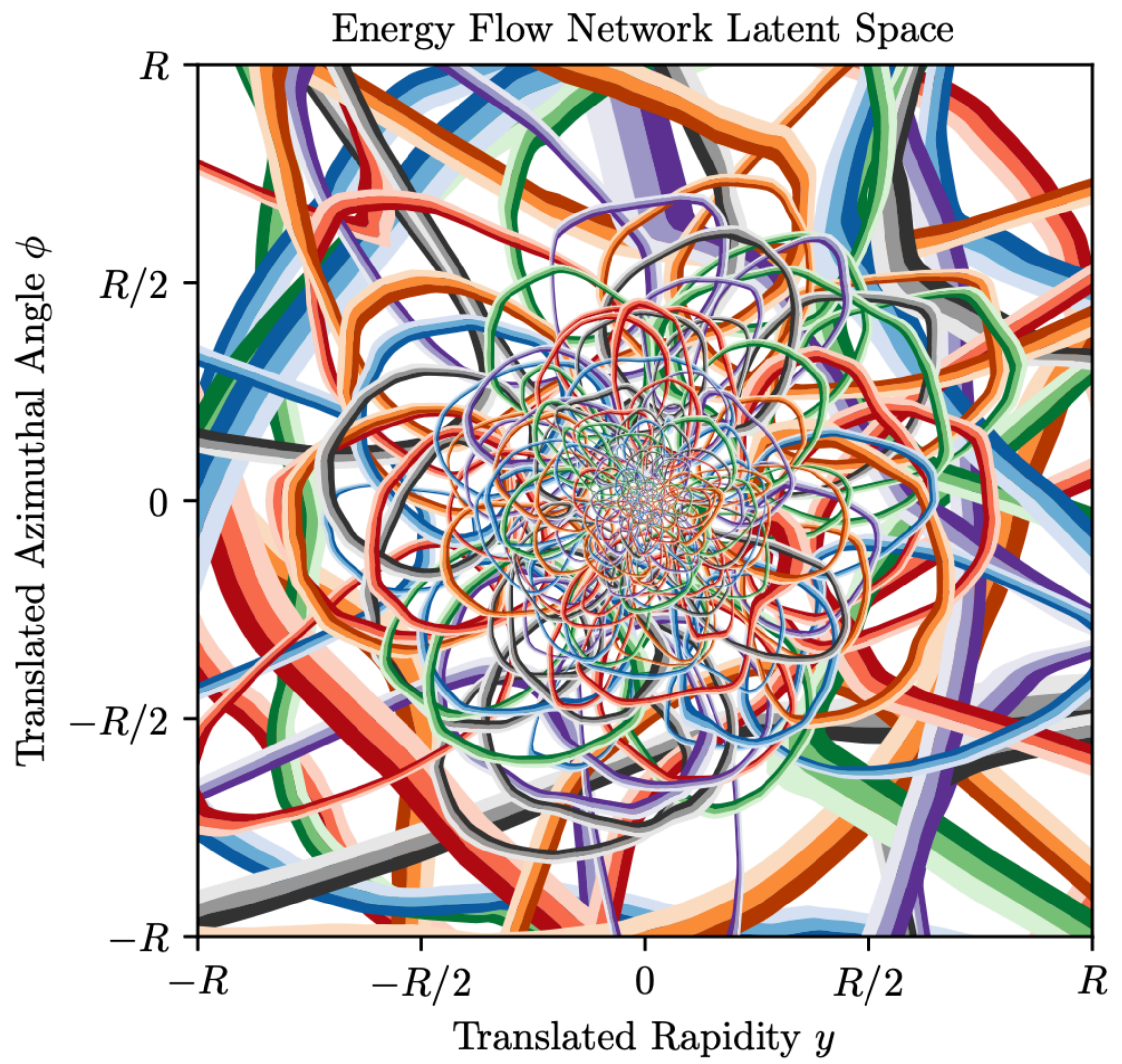


- **Combined with precise track measurements, ML methods give us state-of-the-art precision from experiments!**

Tune into Jingjing's talk for more detail!

IMPORTANT ASIDE: MACHINE LEARNING AND JET SUBSTRUCTURE

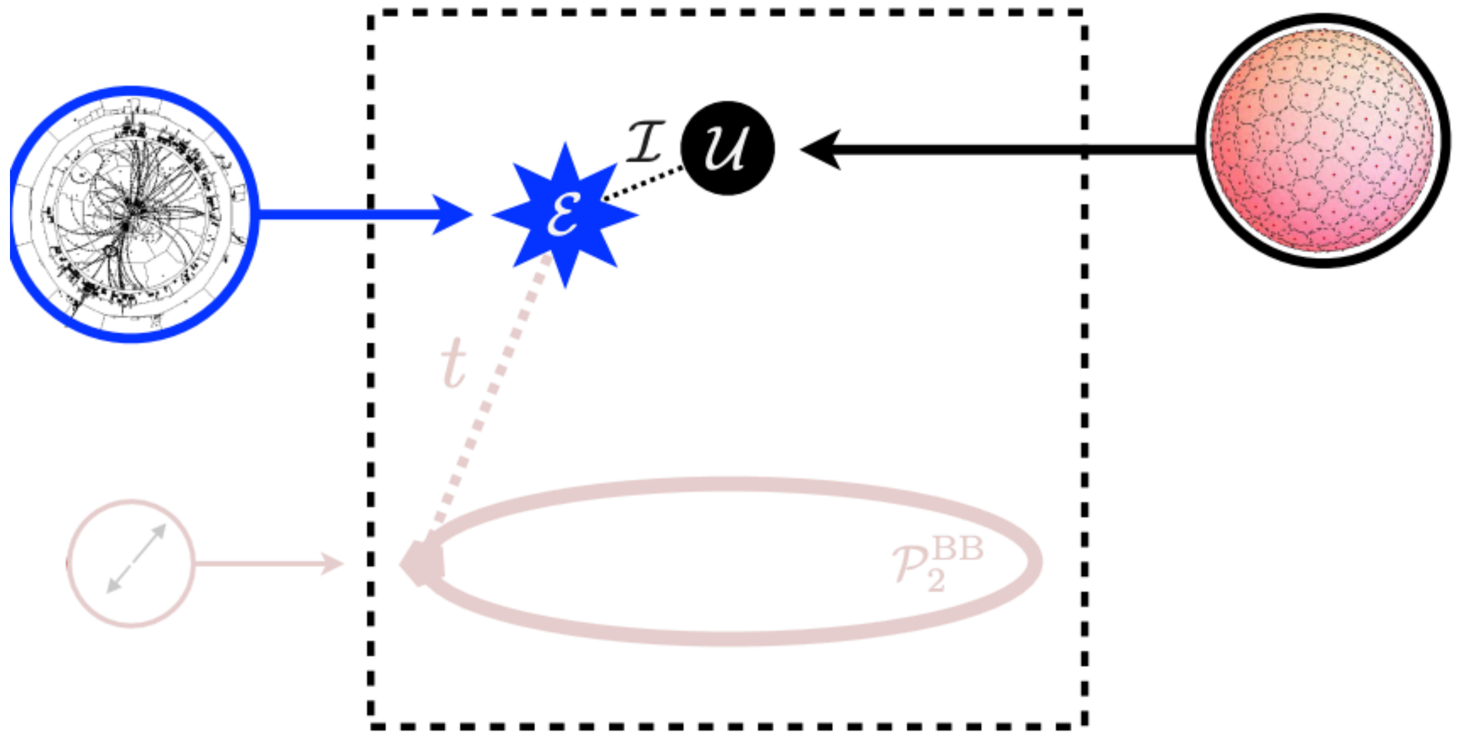
- **Machine learning provides a completely novel way to analyze and precisely measure collider data.**
- **It is very important to allow ideas to cross-pollinate between ML and analytical techniques!**



$$\mathcal{O}(\{p_1, \ldots, p_M\}) = F\left(\sum_{i=1}^{M} z_i \Phi(\hat{p}_i)\right)$$

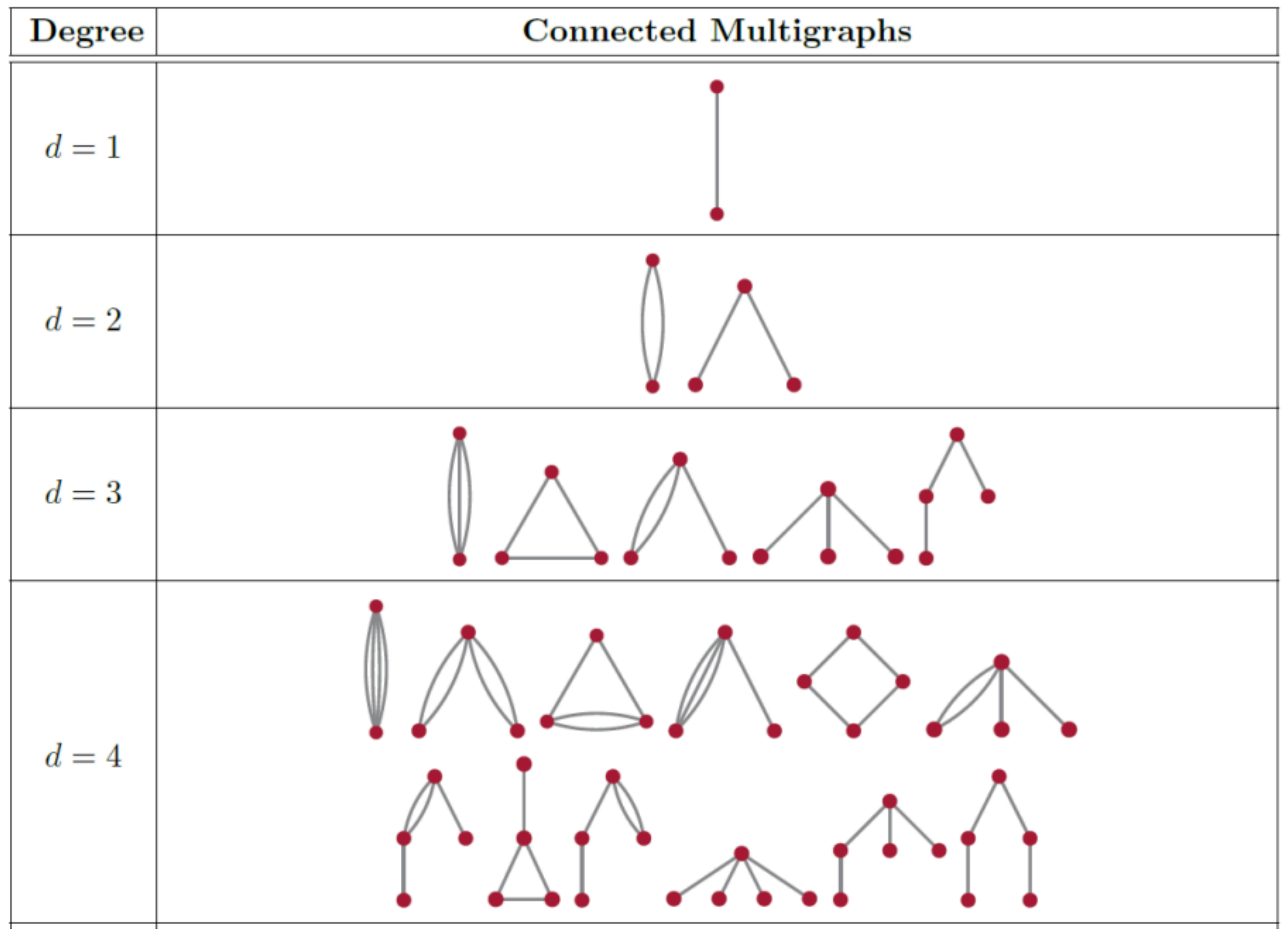
Komiske, Metodiev, Thaler `18
Ba, Dogra, Gambhir, Tasissa, Thaler `23

See Rikab's talk!



Komiske, Metodiev, Thaler `19
Cesarotti, Thaler `20
Cesarotti, Leblanc et al `23

See Cari's talk!



Komiske, Metodiev, Thaler `17
Cal, Thaler, Waalewijn `22

- **Precise understanding of what ML methods achieve require physics-aware tools like EFN, EFP, and EMDs, which gives us hope for interpreting from theory what Machine Learning gives us.**

See Arianna's talk!

Top-quark physics

170 GeV - O(TeV)

Higgs physics

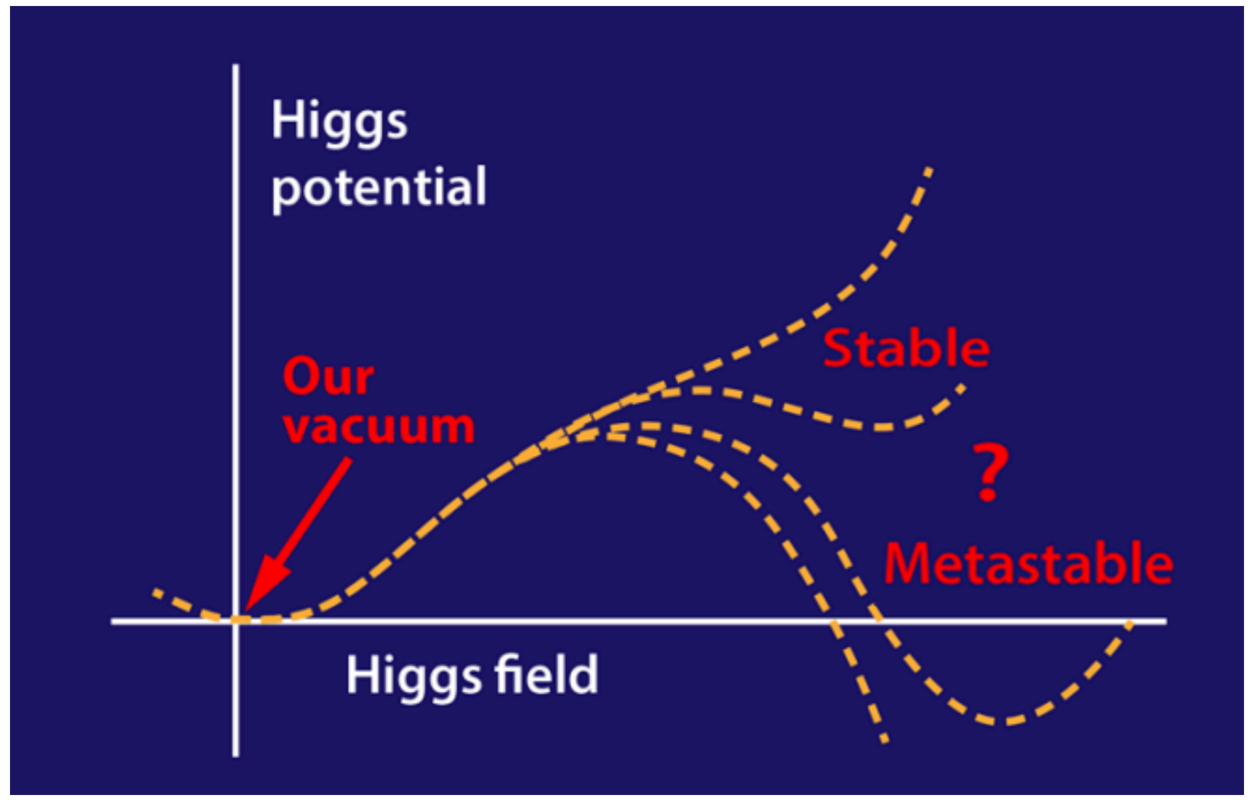
125 GeV - 500 GeV

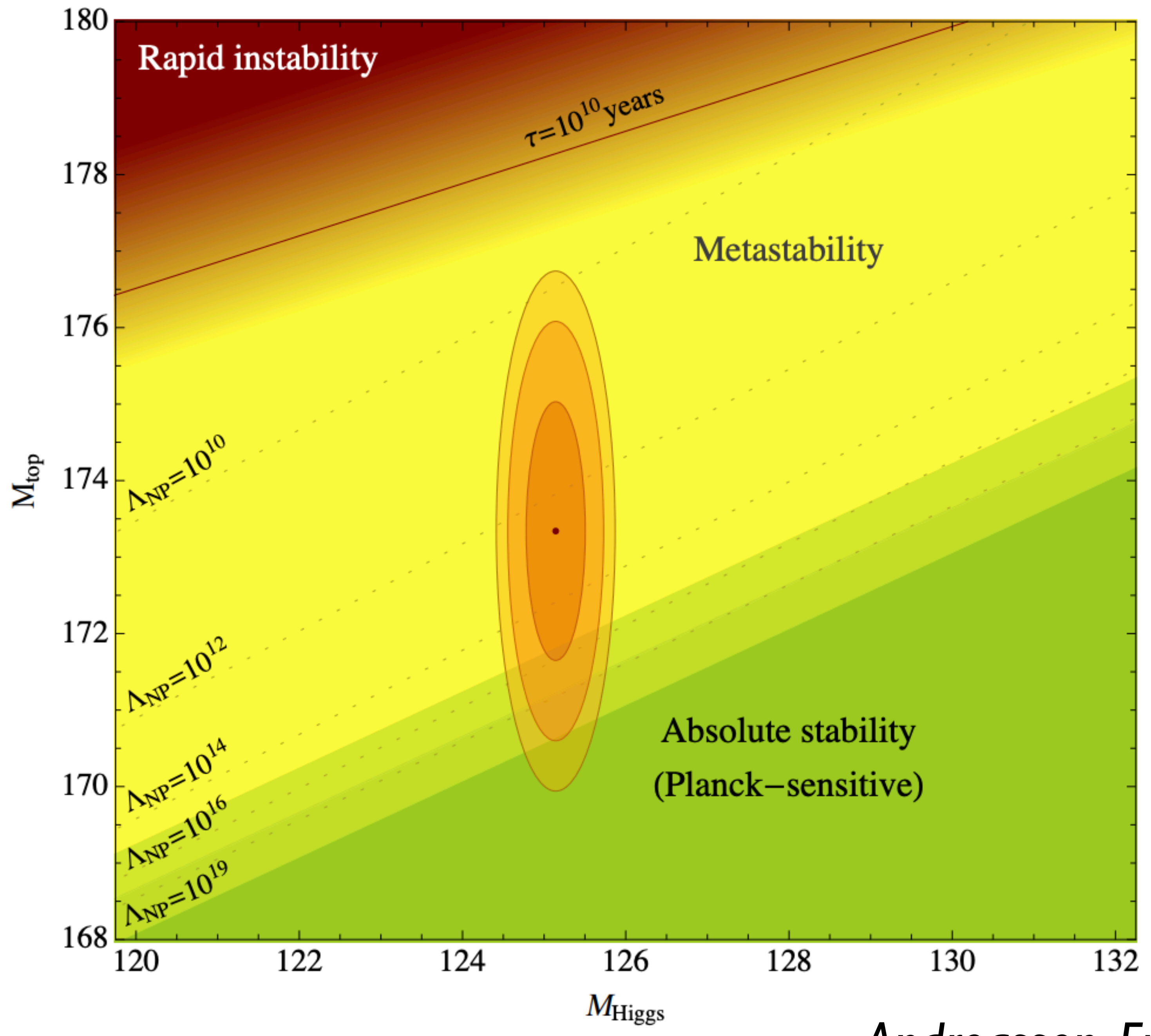
GOAL

WHAT IS THE FATE OF OUR UNIVERSE?

METASTABILITY OR STABILITY OF OUR UNIVERSE

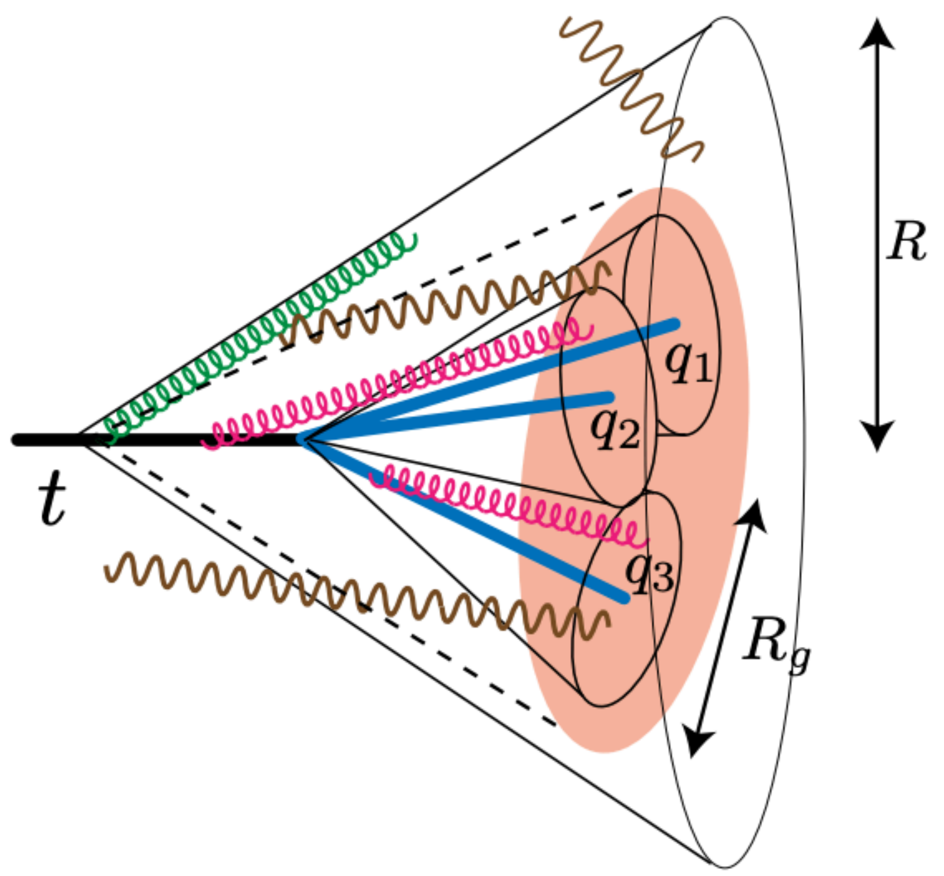
- **Will our universe undergo eternal inflation, or will it undergo some catastrophic big crunch? Can the jet substructure community come to the rescue in answering this question?**





Andreassen, Frost, Schwartz `14

GROOMED TOP JET MASS



Global soft: $\mu_{gs} \sim Q_{\rm cut}$,

Ultra-collinear: $\mu_{uc} \sim \Gamma_t$,

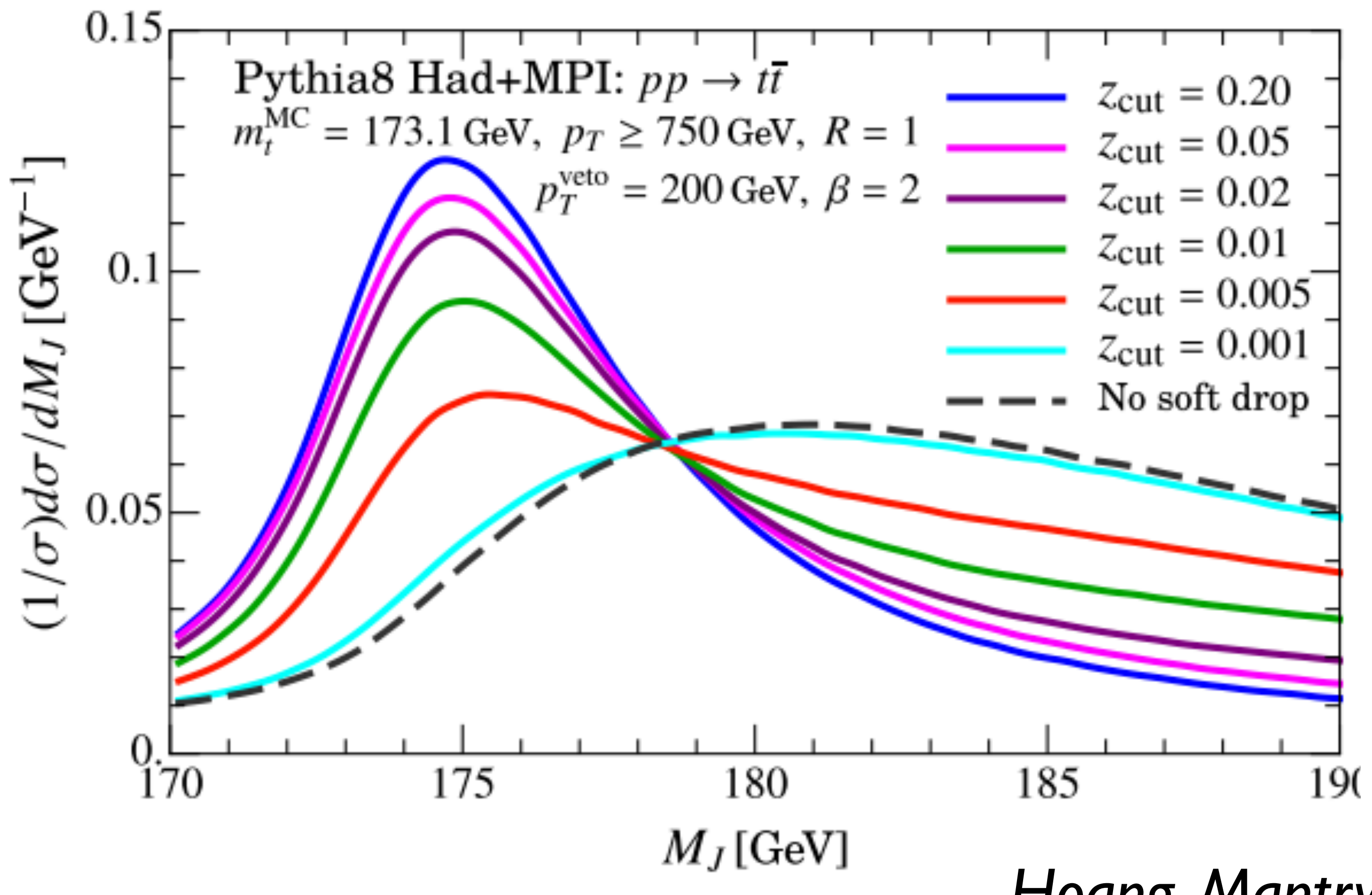
Decay products: $\mu_{\rm decay} \sim m_t$,

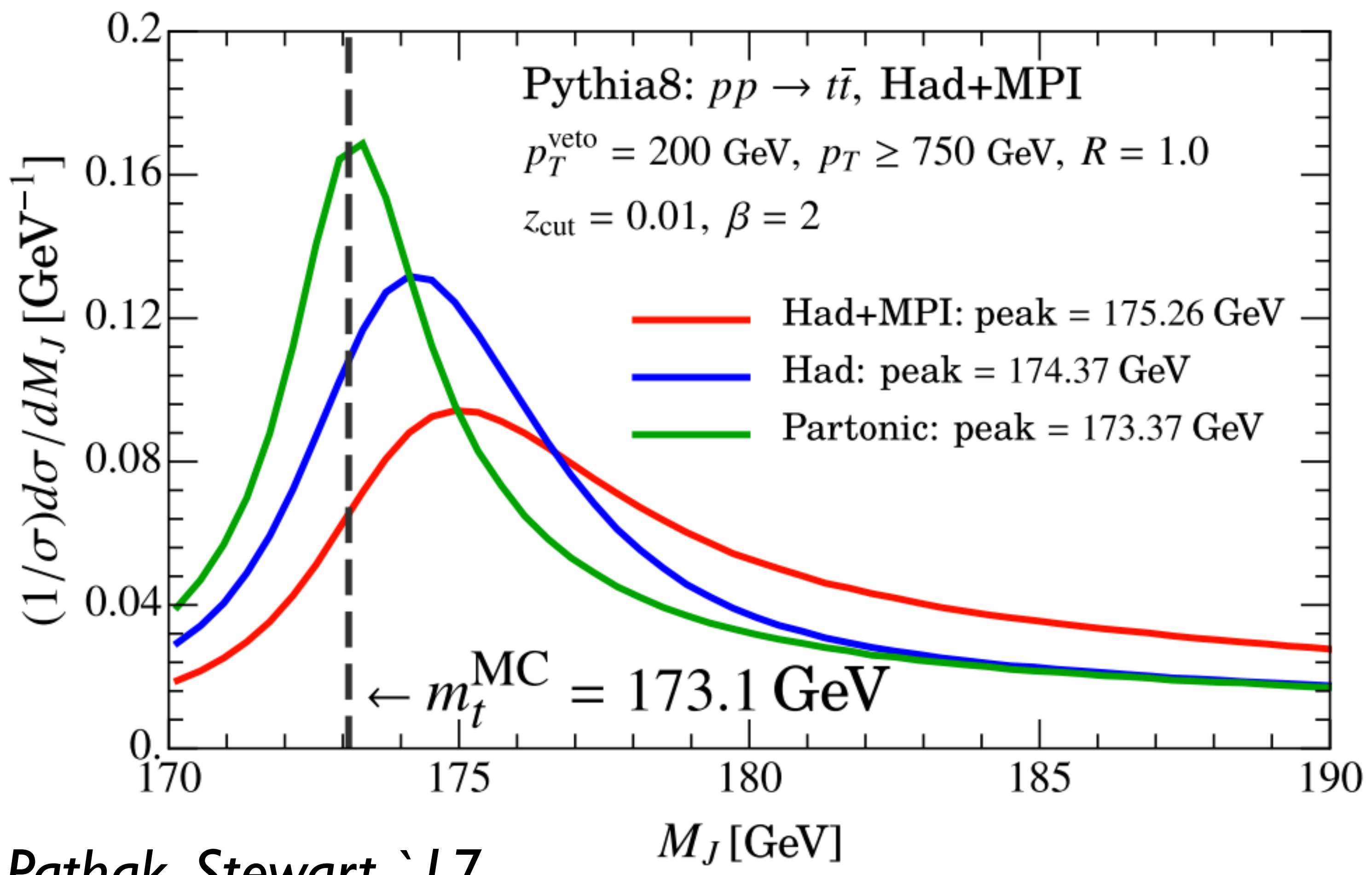
Collinear Soft: $\mu_{cs} \sim \frac{m_t \hat{s}_t}{Q r_g^{\max}(\hat{s}_t)}$,

Nonperturbative: $\mu_\Lambda \sim \Lambda_{\rm QCD}$,

- **Developments have been made to use groomed top jet to weigh top quark mass, which reduces sensitivity to the decay products and soft contaminations.**
- **SCET and bHQET effectively captures all the modes that are present in the groomed top jet!**
- **Still sensitive to residual hadronization and MPI effects. Field theory based analyses of the complicated groomed jet hadronization effects are developed and analyzed for LHC kinematics.**

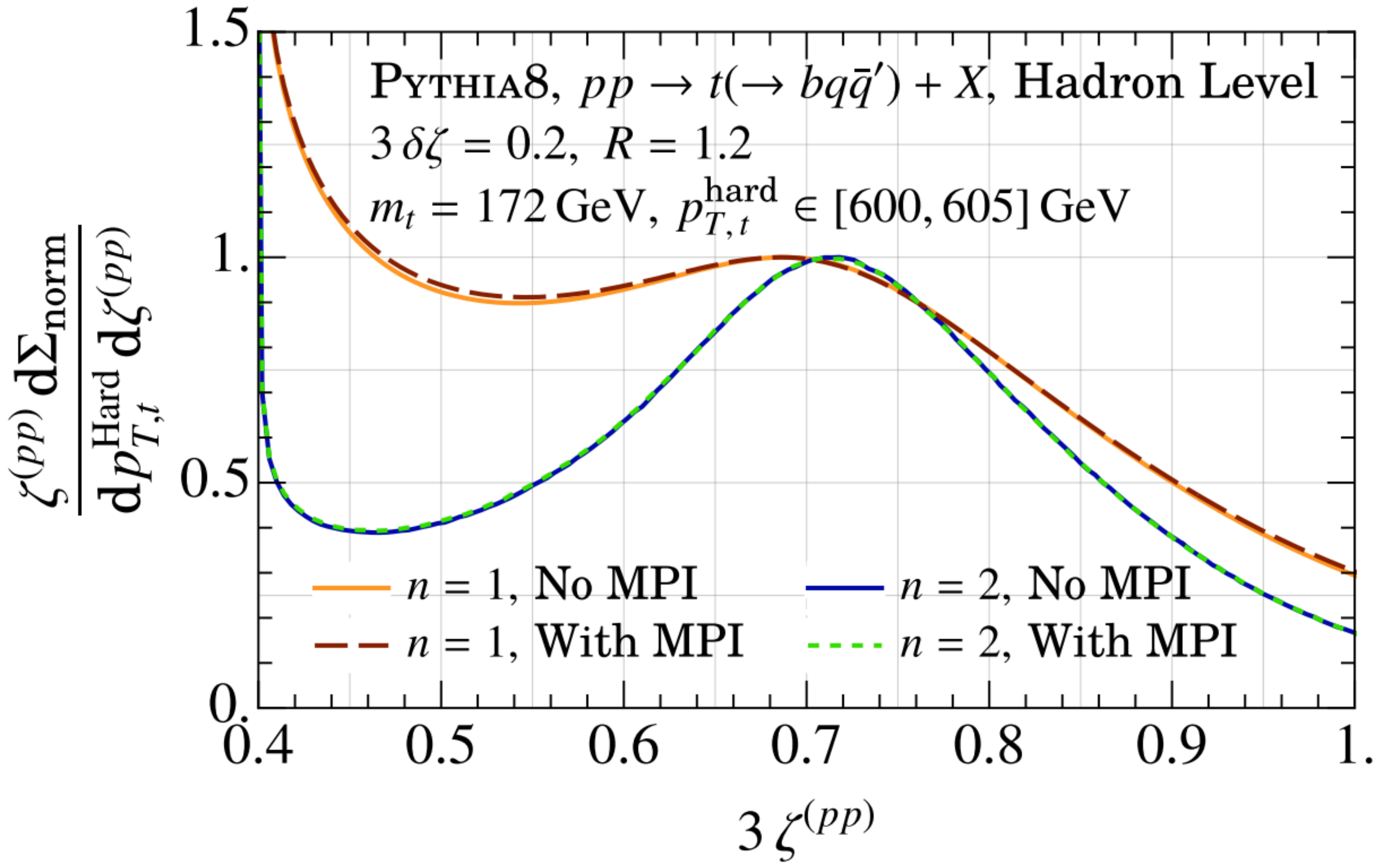
Hoang, Mantry, Pathak, Stewart `19
Pathak, Stewart, Vaidya, Zoppi `20
Ferdinand, KL, Pathak `23

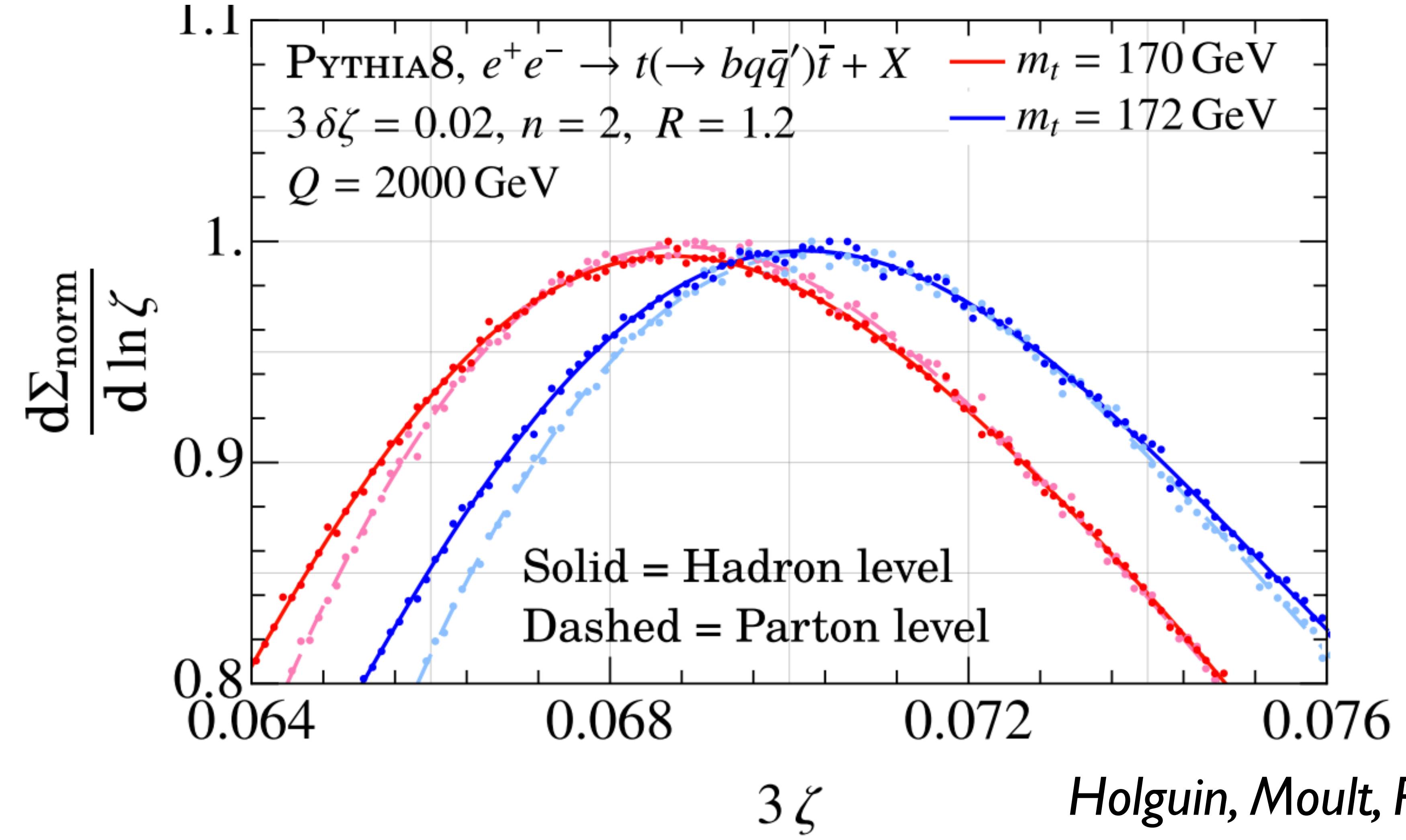




Hoang, Mantry, Pathak, Stewart `17

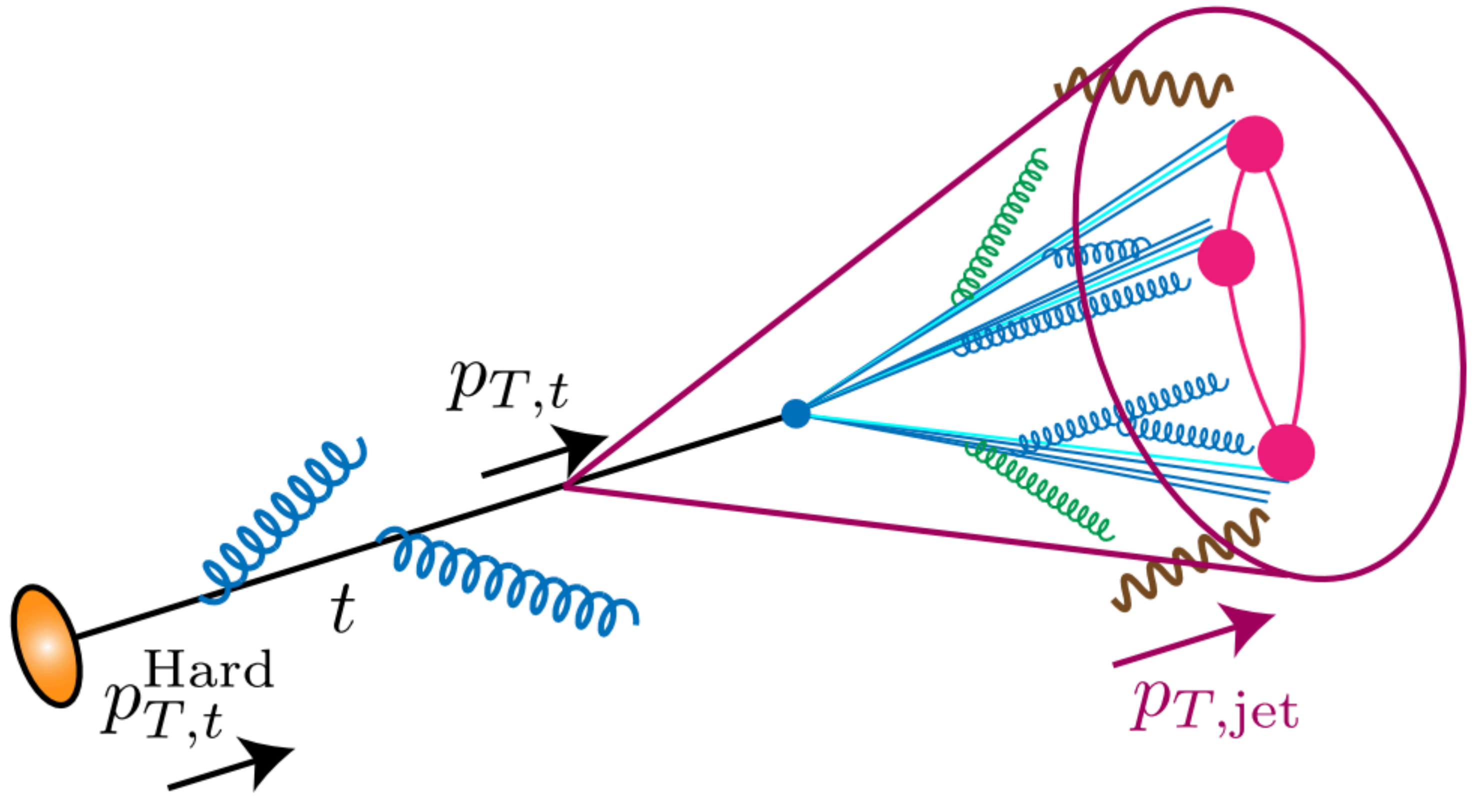
ENERGY ENERGY CORRELATORS ON TOP JET





Holguin, Moult, Pathak, Procura `22

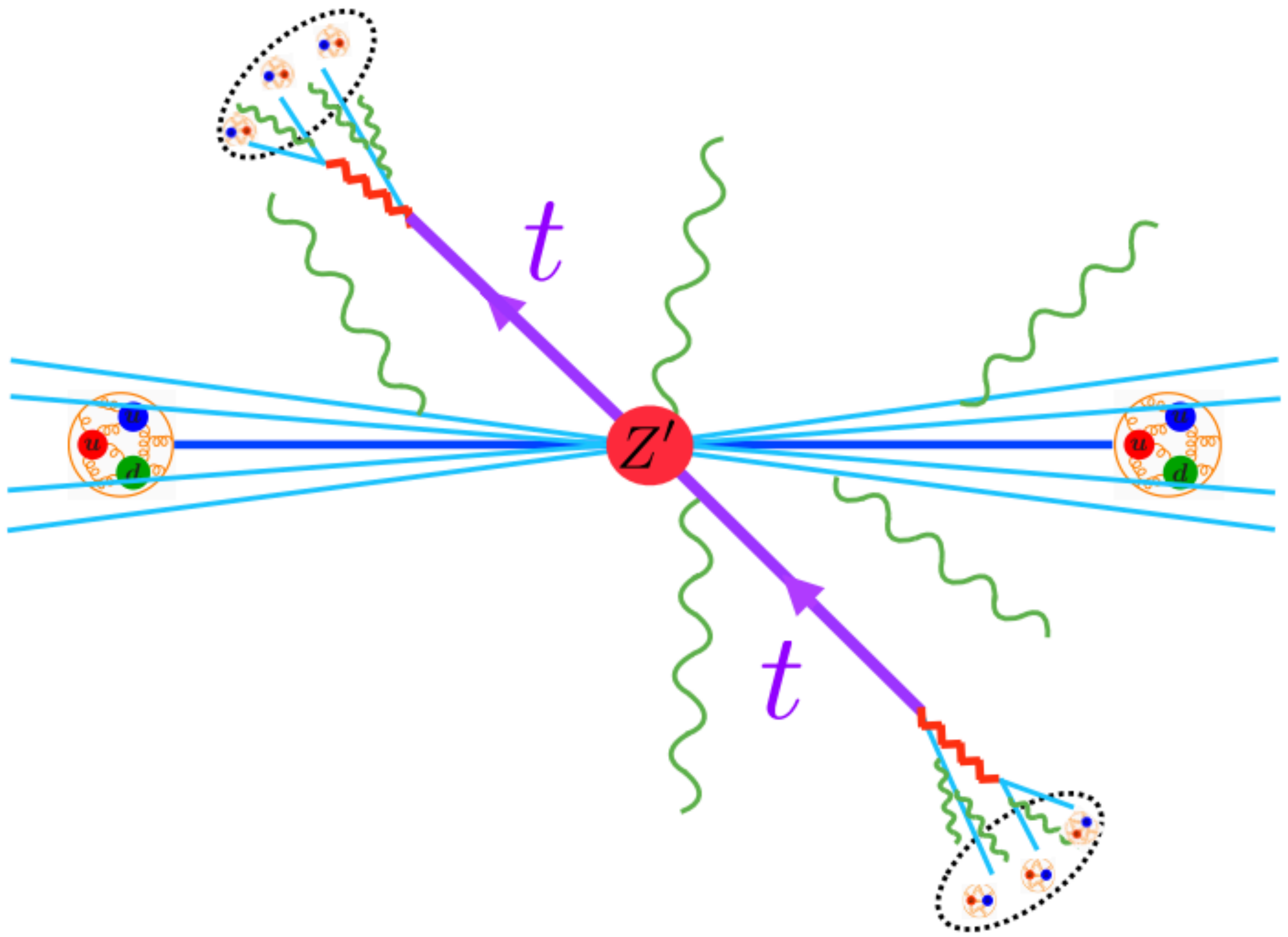
- **Recent development show that three-point energy correlators are sensitive to the top mass and show robustness to underlying events!**
- **Small hadronization effects, which enter additively**
- **More analyses to come!**



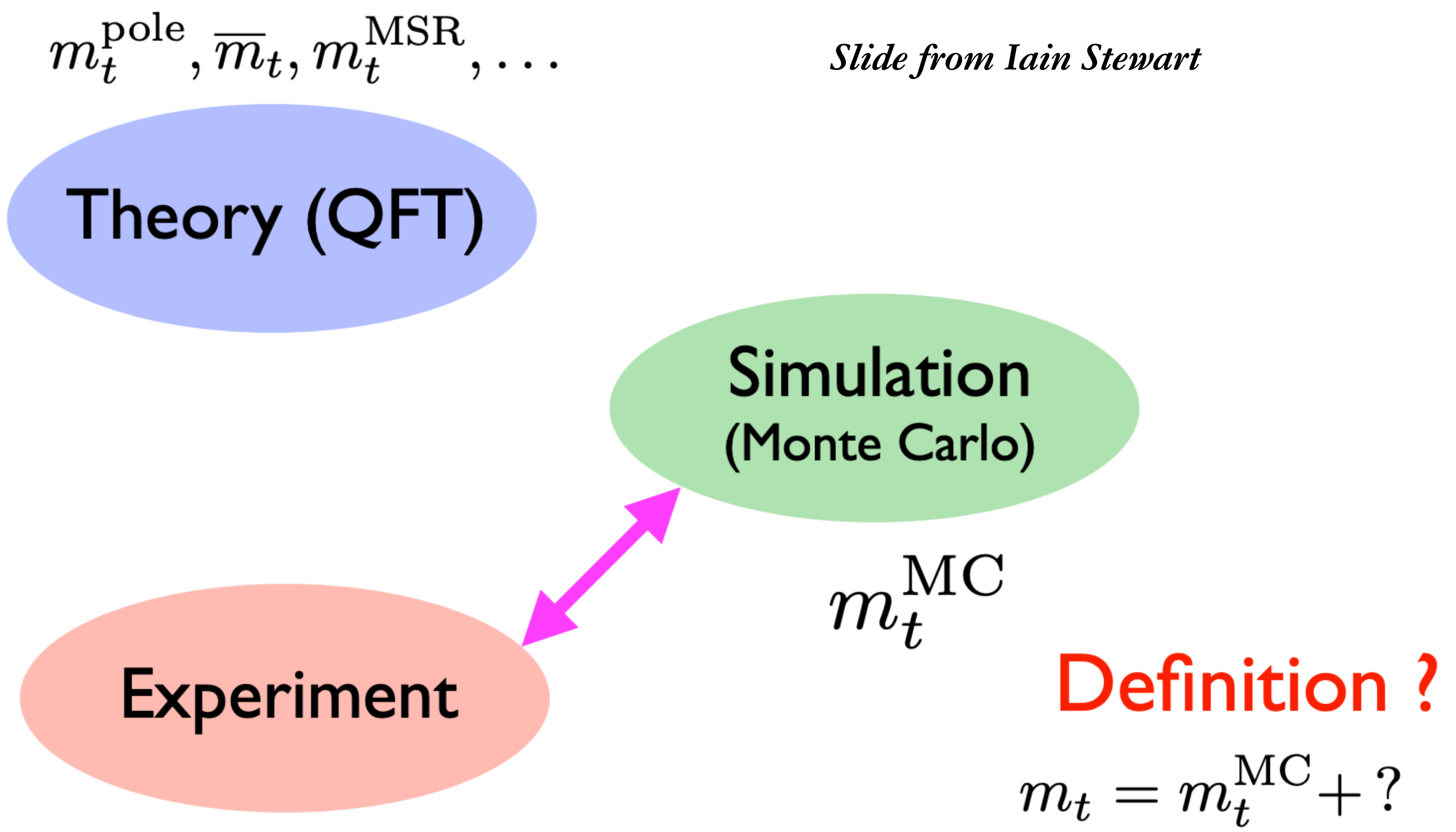
COMPLICATION OF MEASURING TOP MASS

- **Top mass is measured in experiments with help of MC simulations. The relation to its theory calculation requires careful treatments**

Hoang, Stewart `08
Hoang, Jain, Scimemi, Stewart `08
Tanabashi et al `18
Hoang, Pltzer, Samitz `18
Hoang `20
…

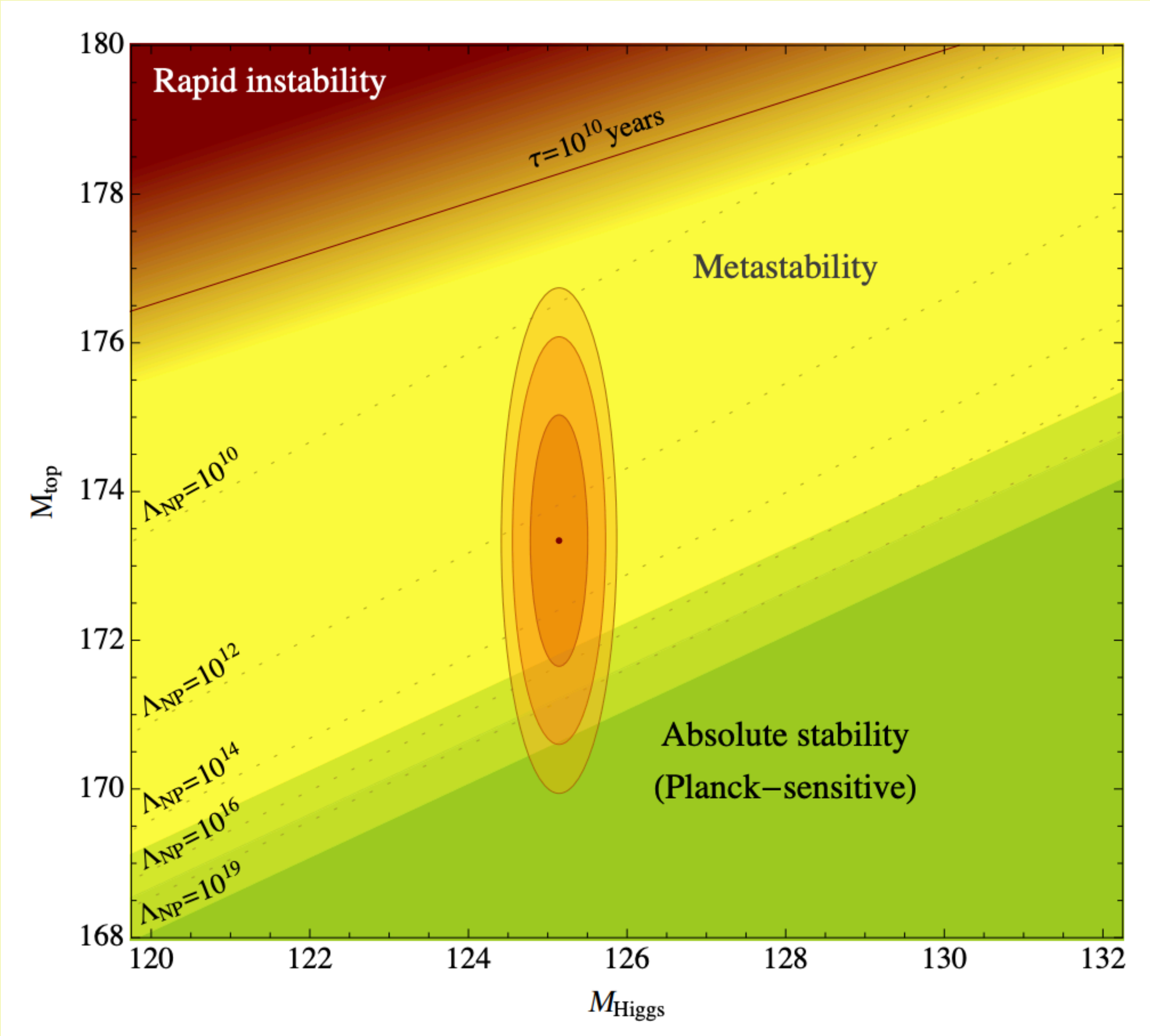


Slide from Iain Stewart



Tune into Naseem's talk for more detail!

PRECISION GOAL



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!


Theory of Jets
Cosmology
Parton Showers
Flavor Physics
High Energy Theory
Heavy Quark Effective Theory
Precision QCD
Heavy-Ion Collisions
Machine Learning
Soft-Collinear Effective Theory
QCD Factorization
Electroweak