Theoretical Progress on Energy Correlators

Hua Xing Zhu
Peking University

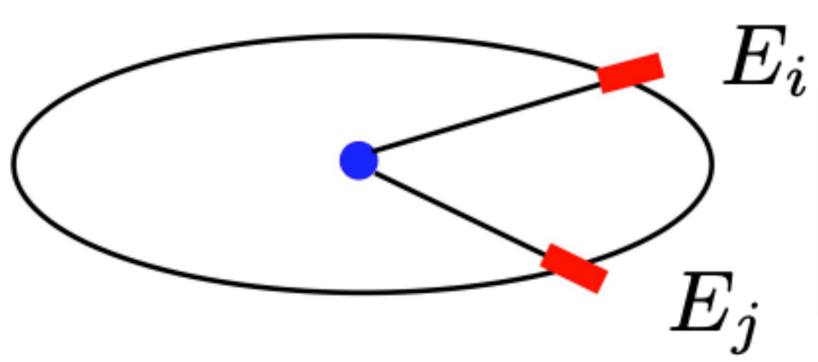
CEPC Workshop 2023
October 24, 2023, Nanjing

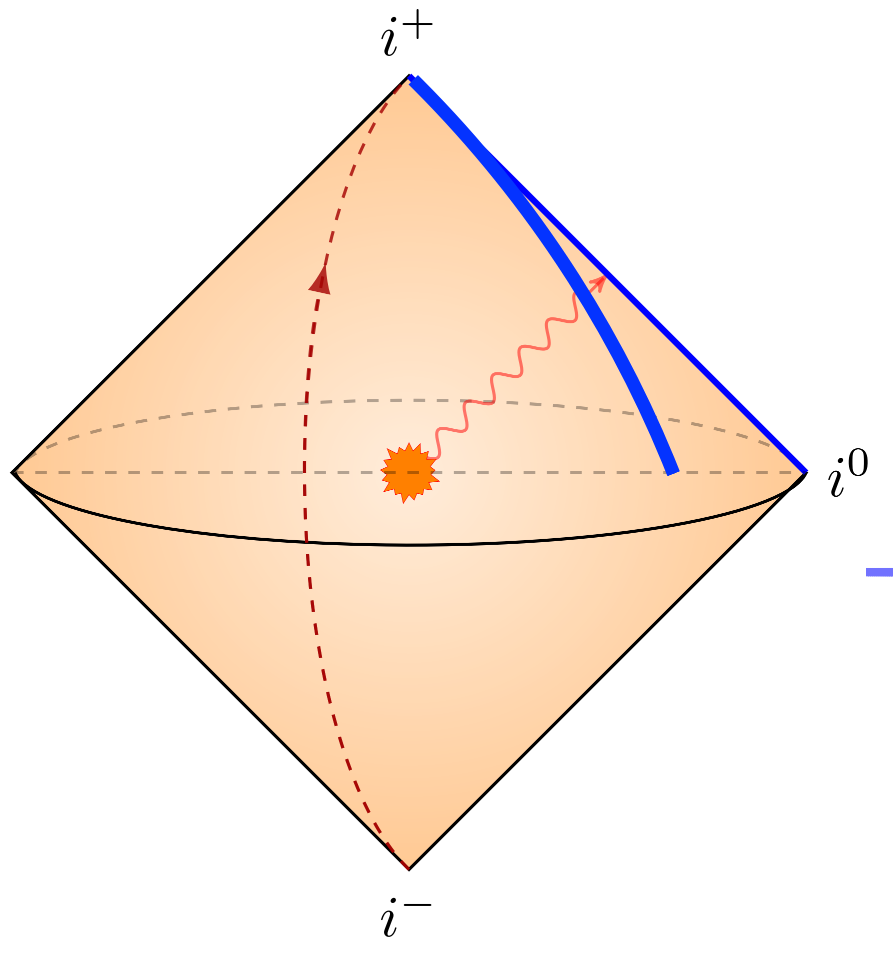
Theorists’ Paradise
Experimentalists’ Wonderland
N
1 mil
1 km
150 135 120 105 90 75 60 45 30 15 0 15 30 45 60 75 90 105 120 135 150

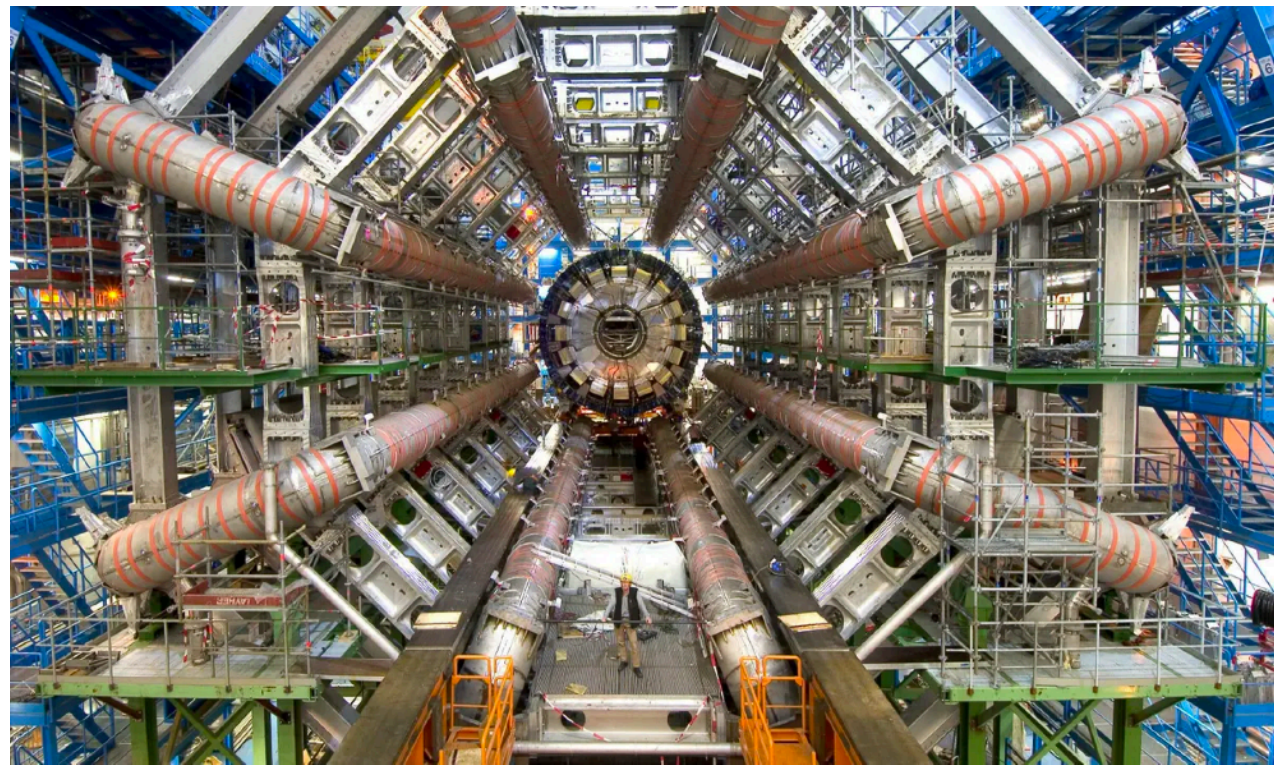

Theorists' Paradise
Energy Correlators
Experimentalists' Wonderland
(a)
(b)
χ
$H(x)$
$J(x,\chi)$
E3C/EEC
E4C/EEC
E5C/EEC
E6C/EEC
CMS 2011 Open Data
ENC/EEC Ratio
R_L
N
1 mile
1 km

Reformulating QCD measurements using energy correlators

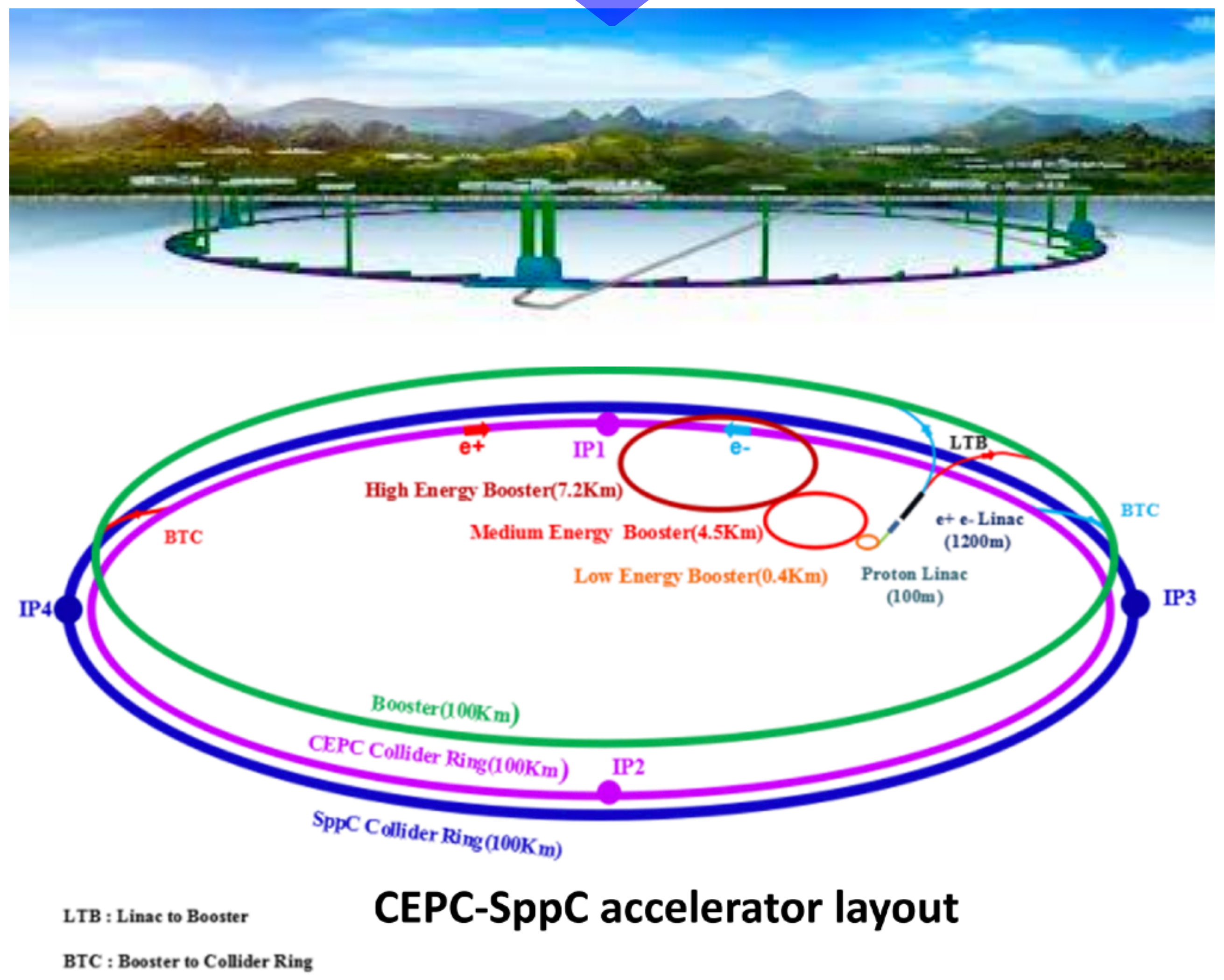
Energy-weighted multiple particle correlation function





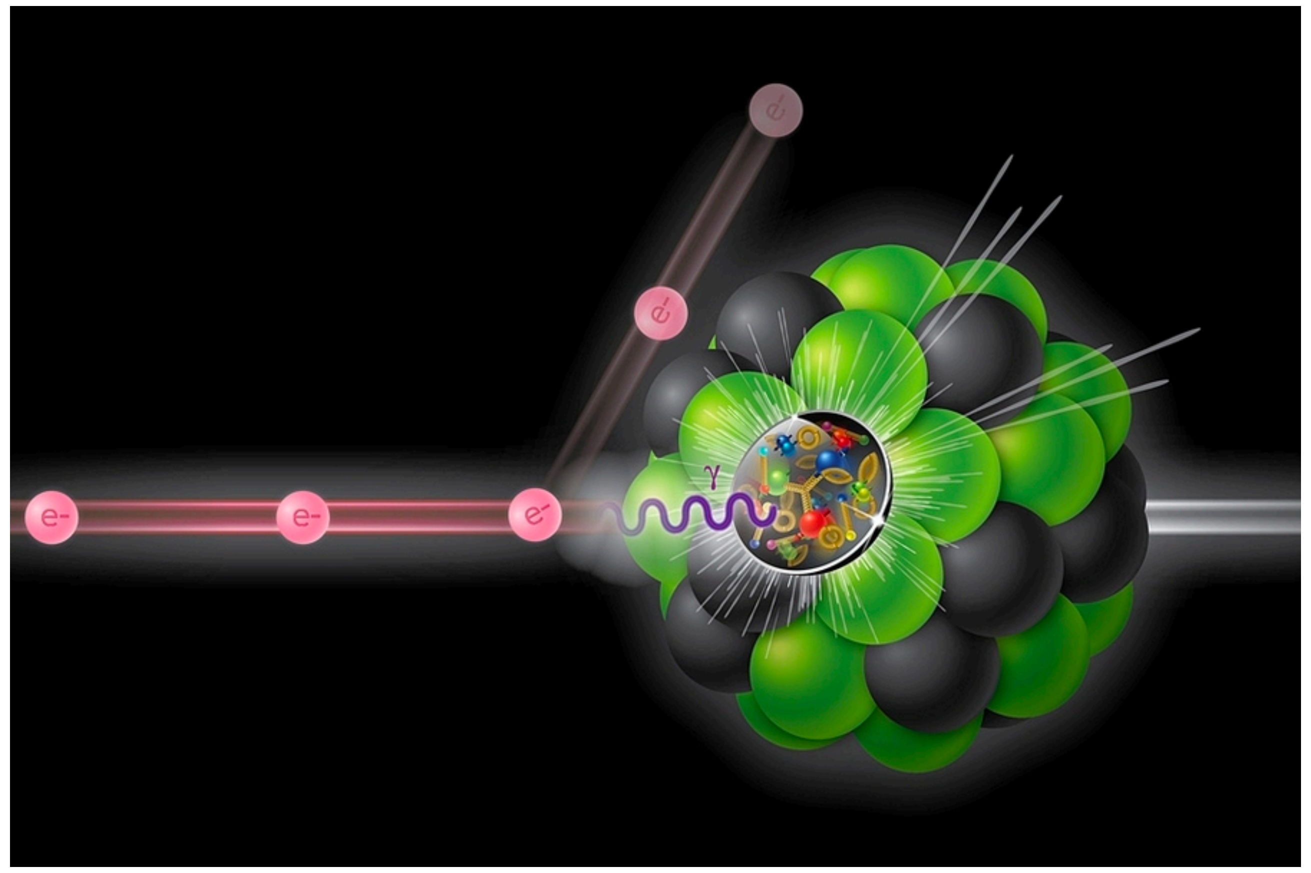


Proton-Proton Scattering



CEPC-SppC accelerator layout

Electron-Positron Scattering



Electron-Proton (Ion) Scattering

Energy flow operator

The energy flow operator measures the energy deposition on a detector at direction $\vec{n}$

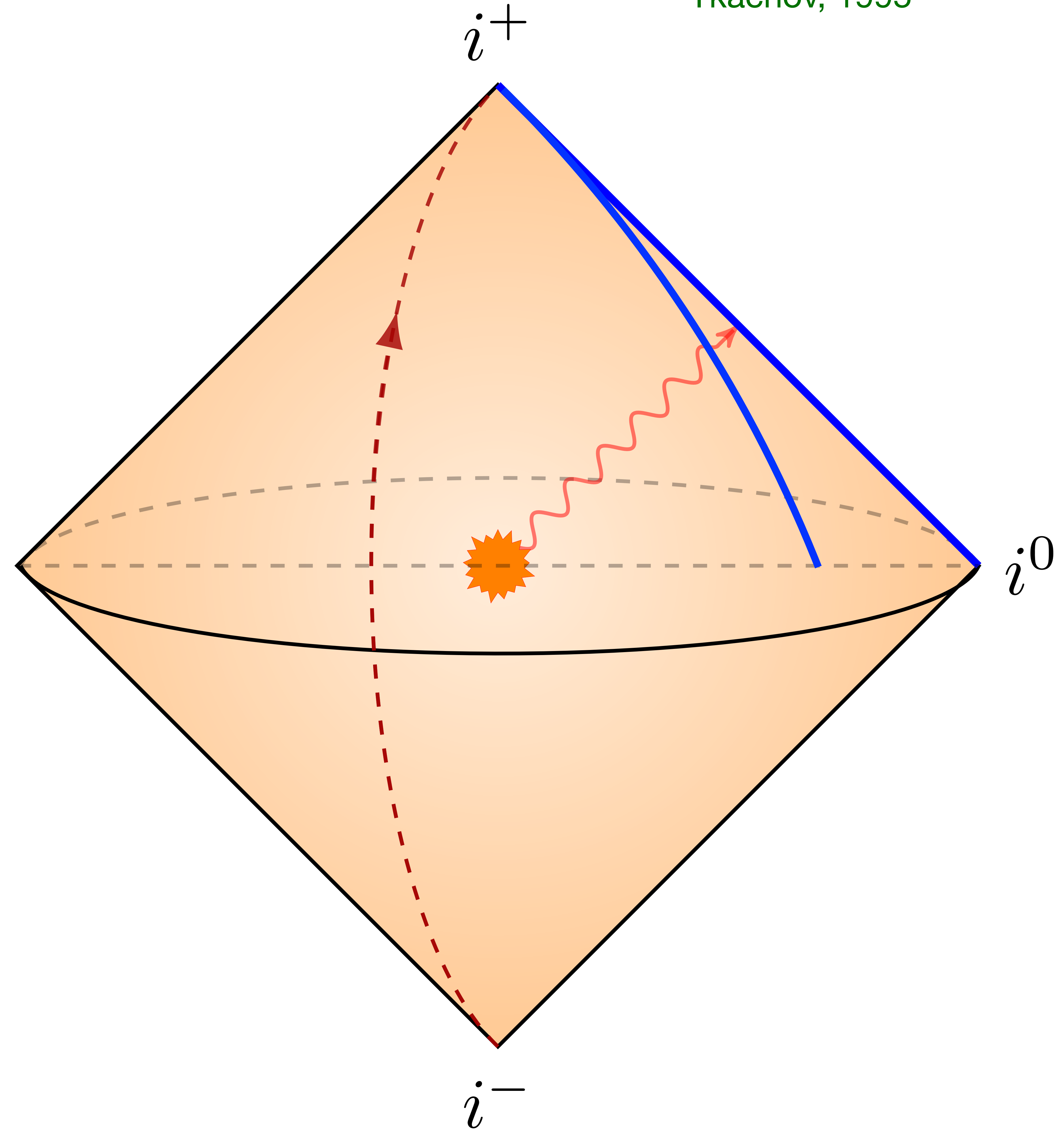
Tkachov, 1995

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

$$\mathcal{E}(\vec{n})|p\rangle = p^0 \delta^{(2)}(\hat{p} - \hat{n})|p\rangle$$

$$\mathcal{E}(\vec{n}) = \int_{-\infty}^{\infty} d(n\cdot x) \lim_{\bar{n}\cdot x\to\infty} (\bar{n}\cdot x)^2 \bar{n}^\mu \bar{n}^\nu T_{\mu\nu}(x)$$

The energy flow operator (ANEC) also found important application in black hole physics and quantum information!



General lightray operator

Hofman, Maldacena 08; Kologlu, Kravchuk, Simmons-Duffin, Zhiboedov, 19

$$\mathbb{O}_{J-1,\Delta-1}(\vec{n}) = \int_{-\infty}^{\infty} d(n\cdot x) \lim_{\bar{n}\cdot x\to\infty} (\bar{n}\cdot x)^{\Delta-J} \bar{n}_{\mu_1}\cdots\bar{n}_{\mu_J} O_{\Delta,J}^{\mu_1\cdots\mu_J}(x)$$

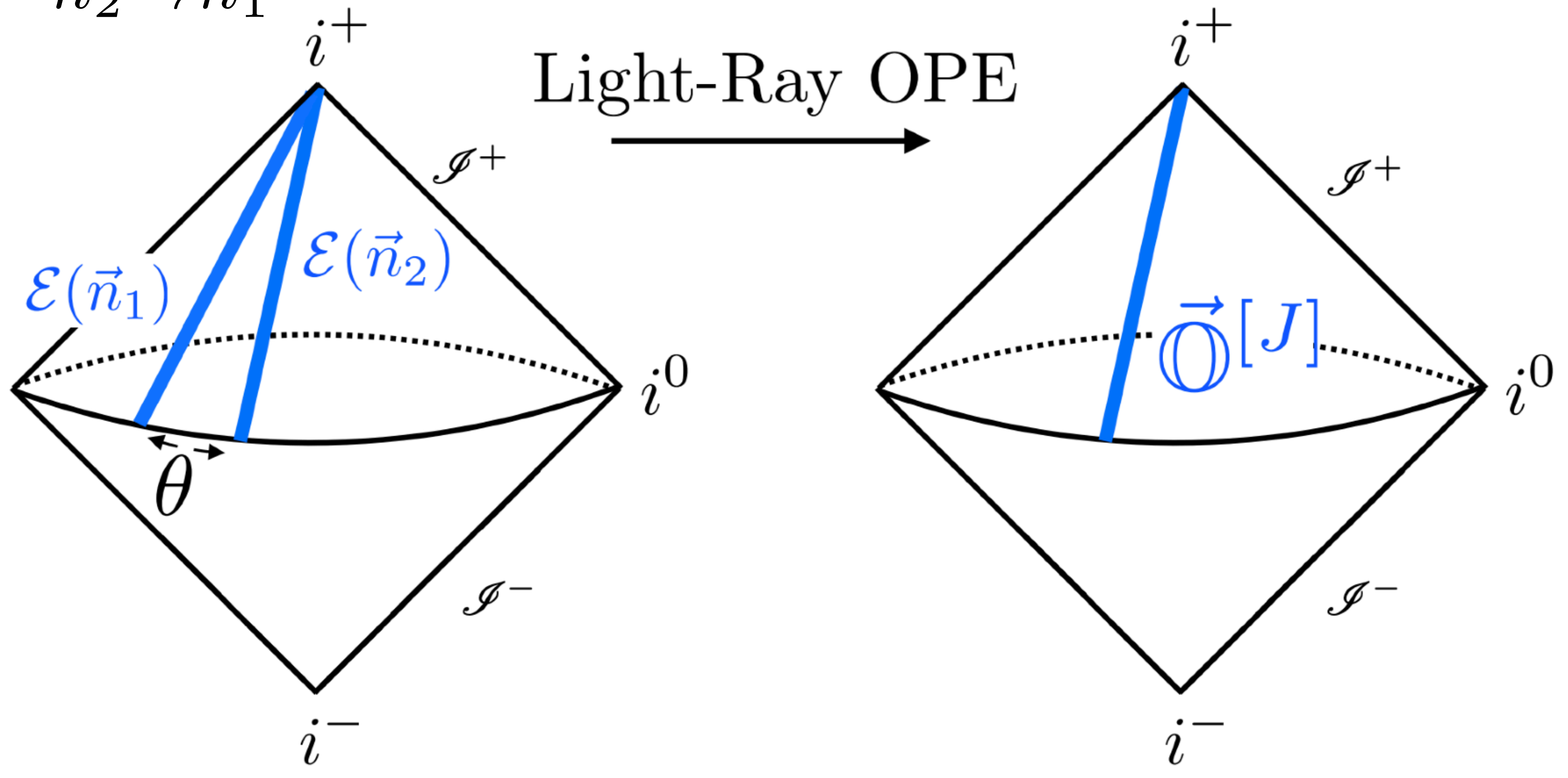
lightray operator living on the celestial sphere

local twist operator of dimension Δ and spin J

determined by celestial dimension

determined by bulk dimension

$$\lim_{\hat{n}_2\to\hat{n}_1} \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) = \sum c_i \theta^{\tau_i-4}\mathbb{O}_i(\hat{n}_1)$$



At twist 2 the relevant unpolarized operators are

$$\mathcal{O}_q^{[J]} = \frac{1}{2^J}\bar{\psi}\gamma^+(iD^+)^{J-1}\psi$$

$$\mathcal{O}_g^{[J]} = -\frac{1}{2^J}F_a^{\mu+}(iD^+)^{J-2}F_a^{\mu+}$$

$$\mathcal{O}_{\tilde{g},\lambda}^{[J]} = -\frac{1}{2^J}F_a^{\mu+}(iD^+)^{J-2}F_a^{\nu+}\epsilon_{\lambda,\mu}\epsilon_{\lambda,\nu}$$

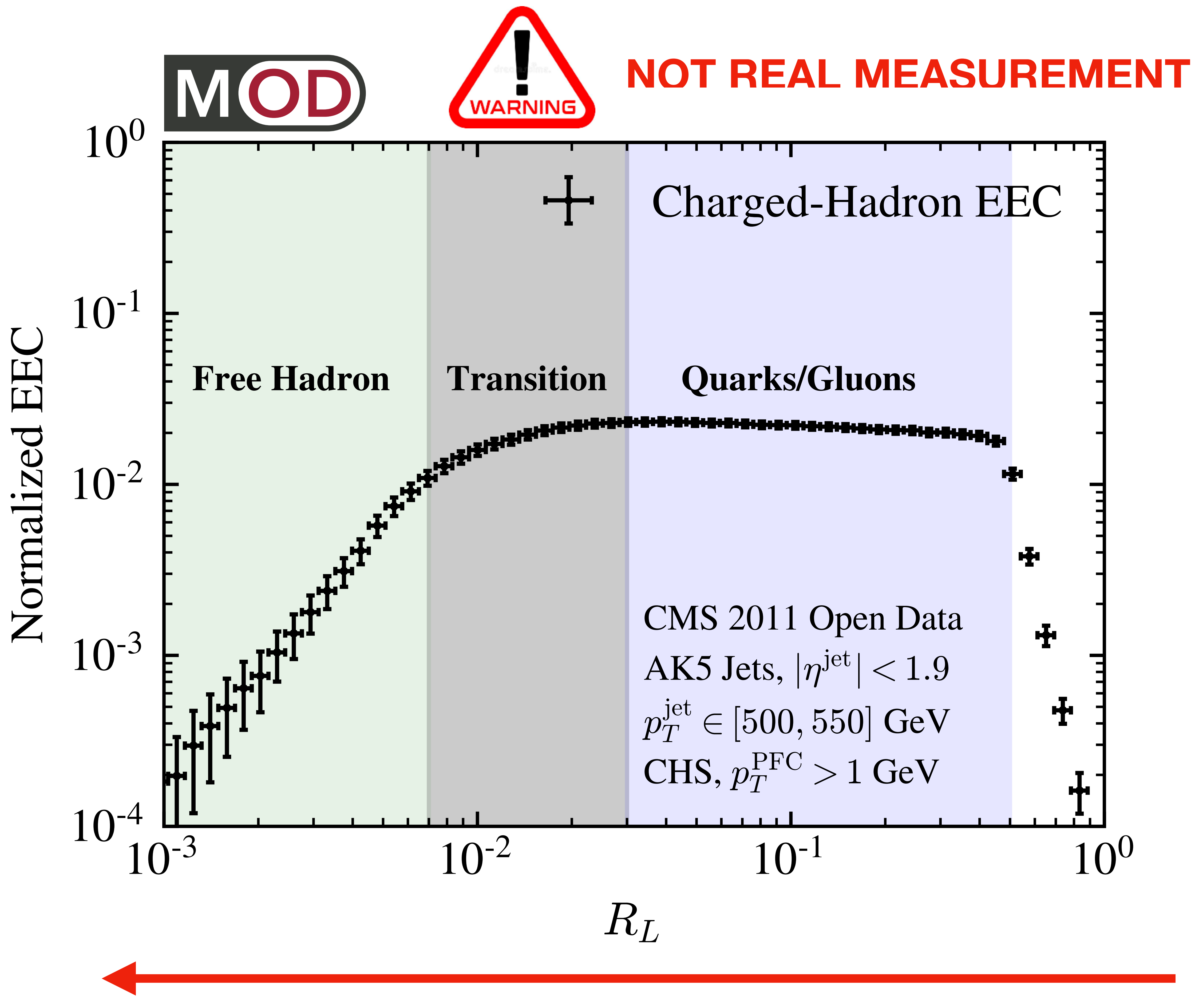
helicity ±

CFT picture receives controllable logarithmic corrections in QCD

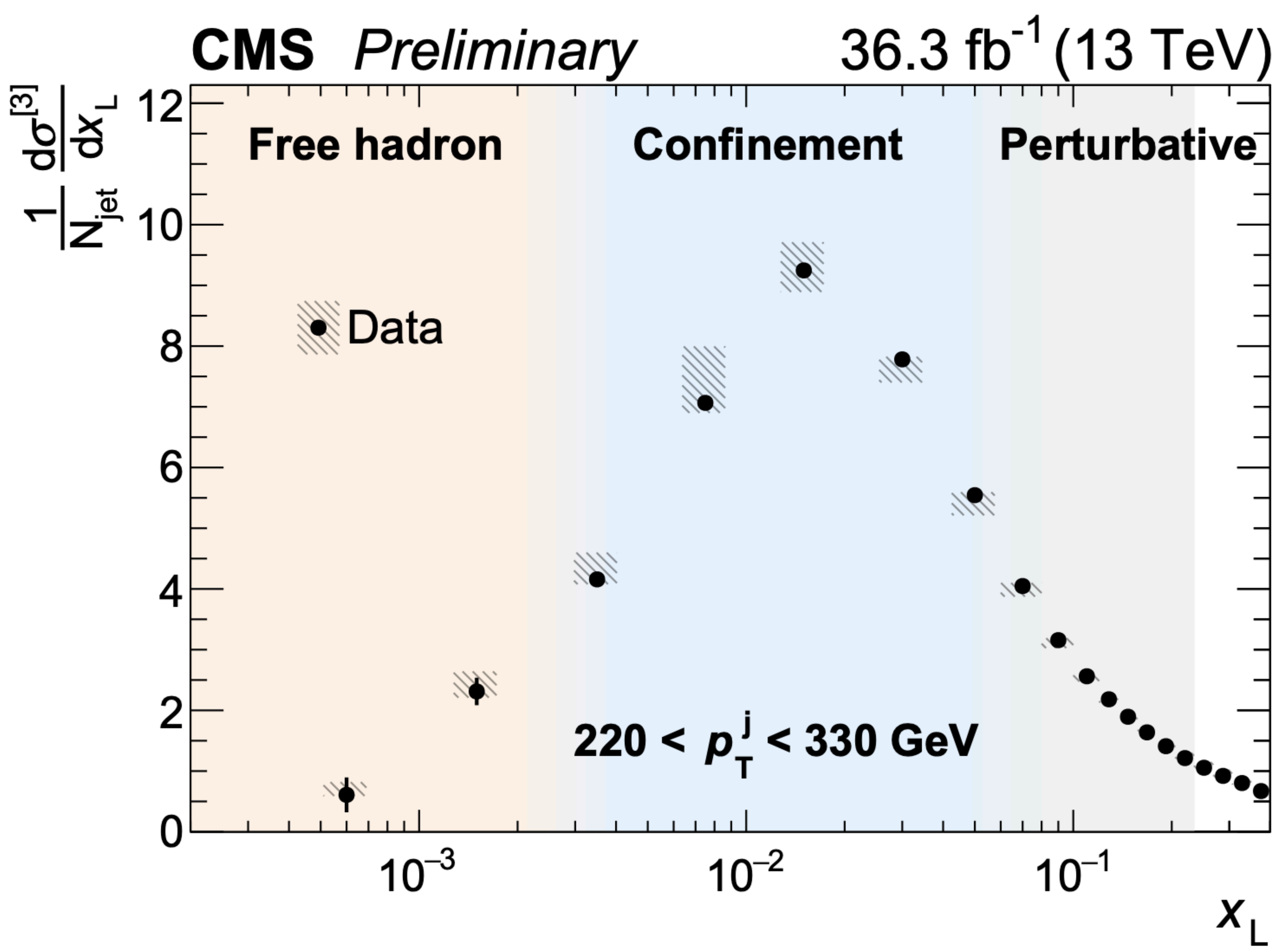
Dixon, Moult, HXZ, 2019

Visualizing quark/gluon hadronization (real-time confinement)

https://cds.cern.ch/record/2866560, 2023
See Prof. Meng Xiao's talk

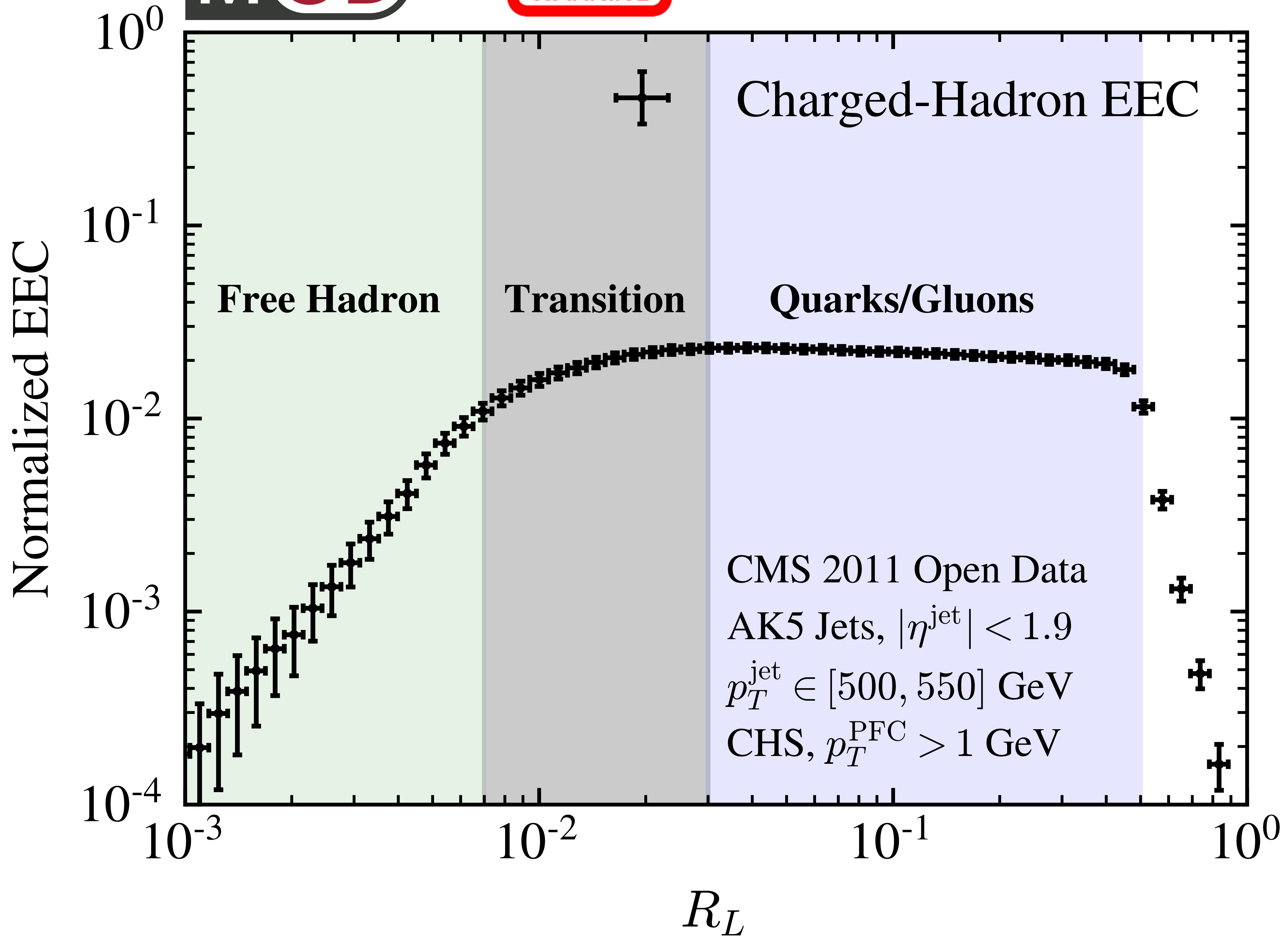


Komiske, Moult, Thaler, HXZ, 2022



Understanding the picture

NOT REAL MEASUREMENT



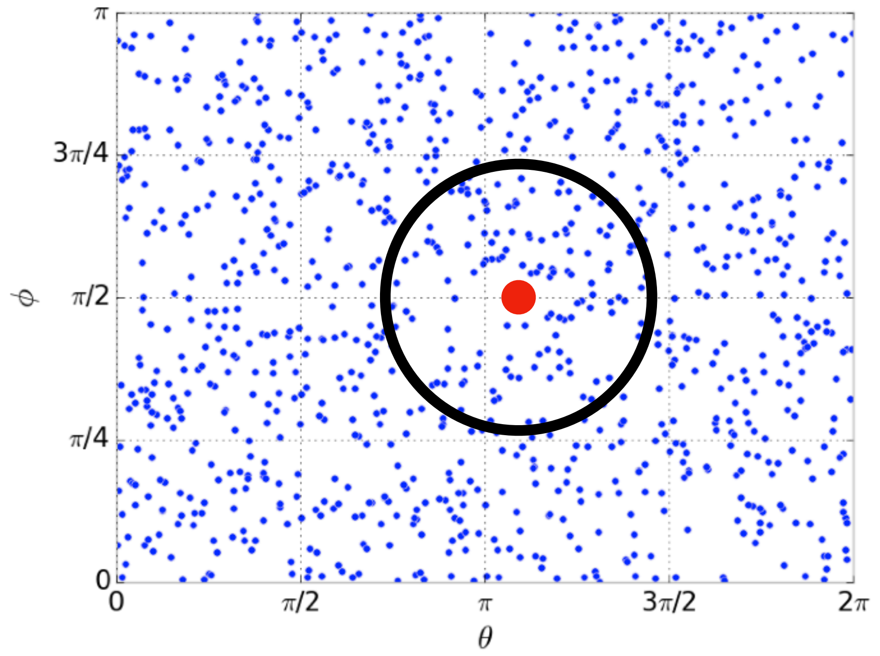
Komiske, Moult, Thaler, HXZ, 2022

Large R_L (perturbative region)

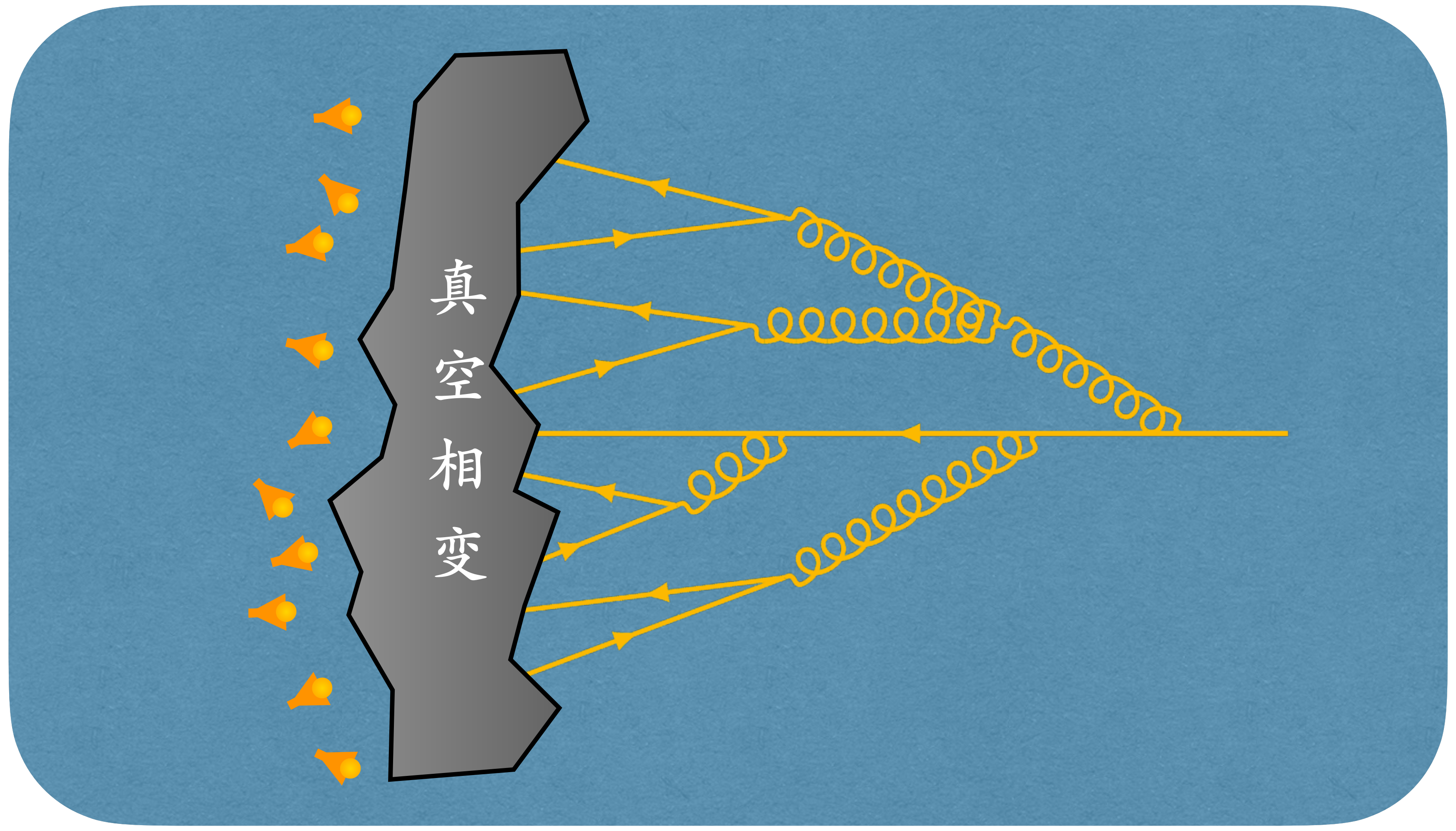
scaling law

$$\lim_{\hat{n}_2 \to \hat{n}_1} \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) = \sum c_i \theta^{\tau_i - 4} \mathbb{O}_i(\hat{n}_1)$$ + running coupling

very small R_L (free hadrons)



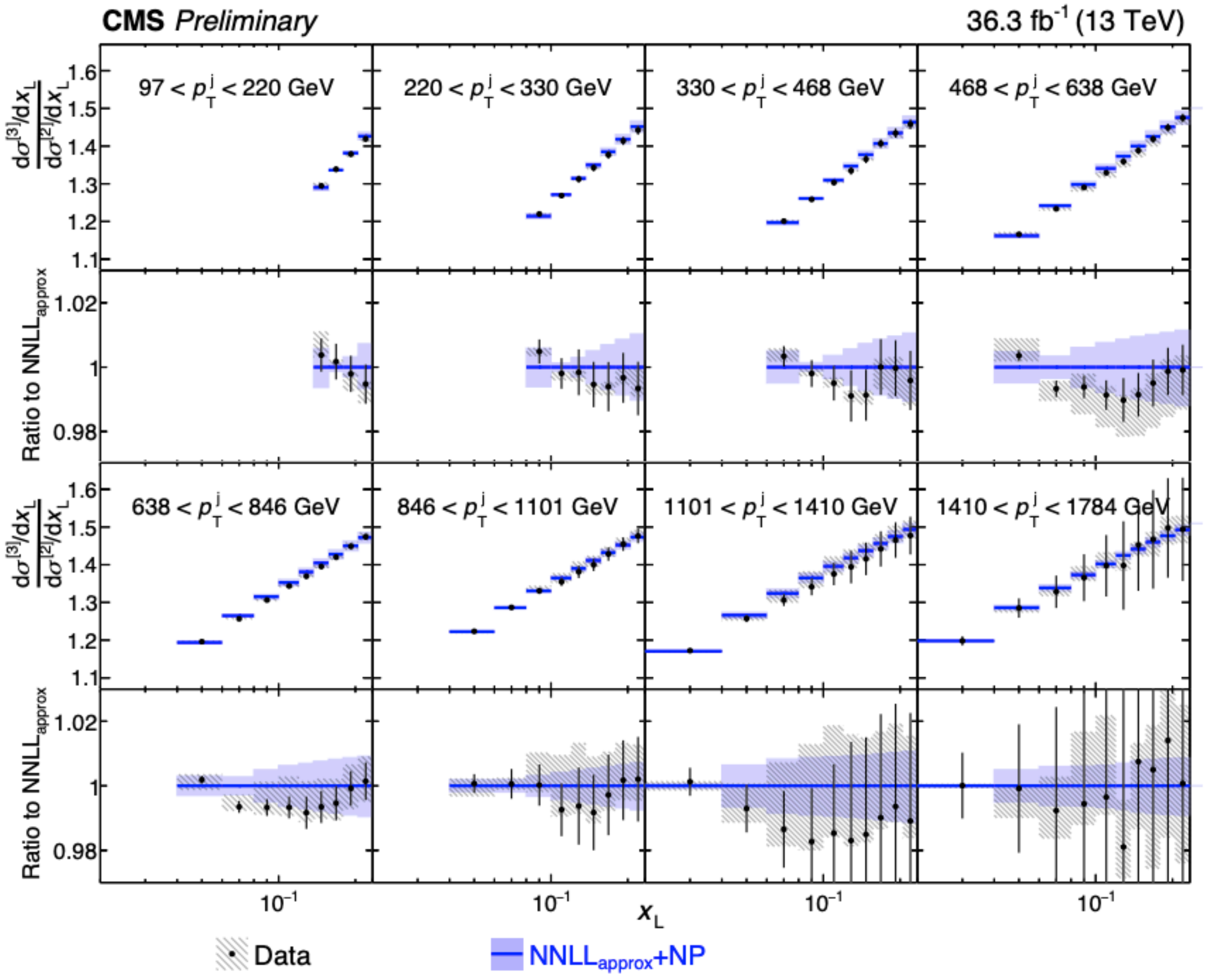
Starting from any given point, the number of points correlated with it grow linearly with radius R



Strong coupling from projected EECs

https://cds.cern.ch/record/2866560, 2023

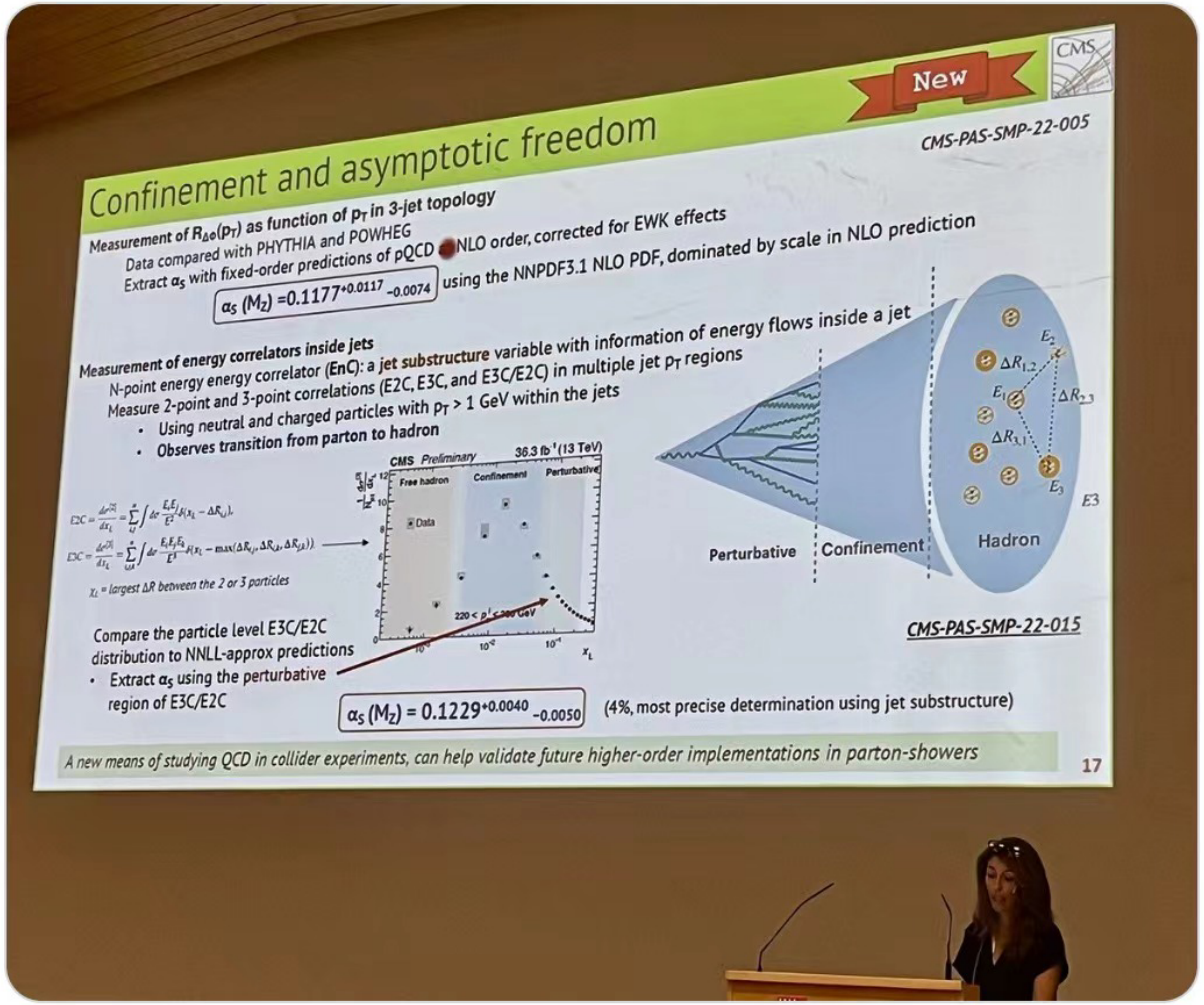
See Prof. Meng Xiao's talk



Theory predictions: W. Chen, J. Gao, Y.B. Li, Z. Xu, X.Y. Zhang, HXZ, 2023

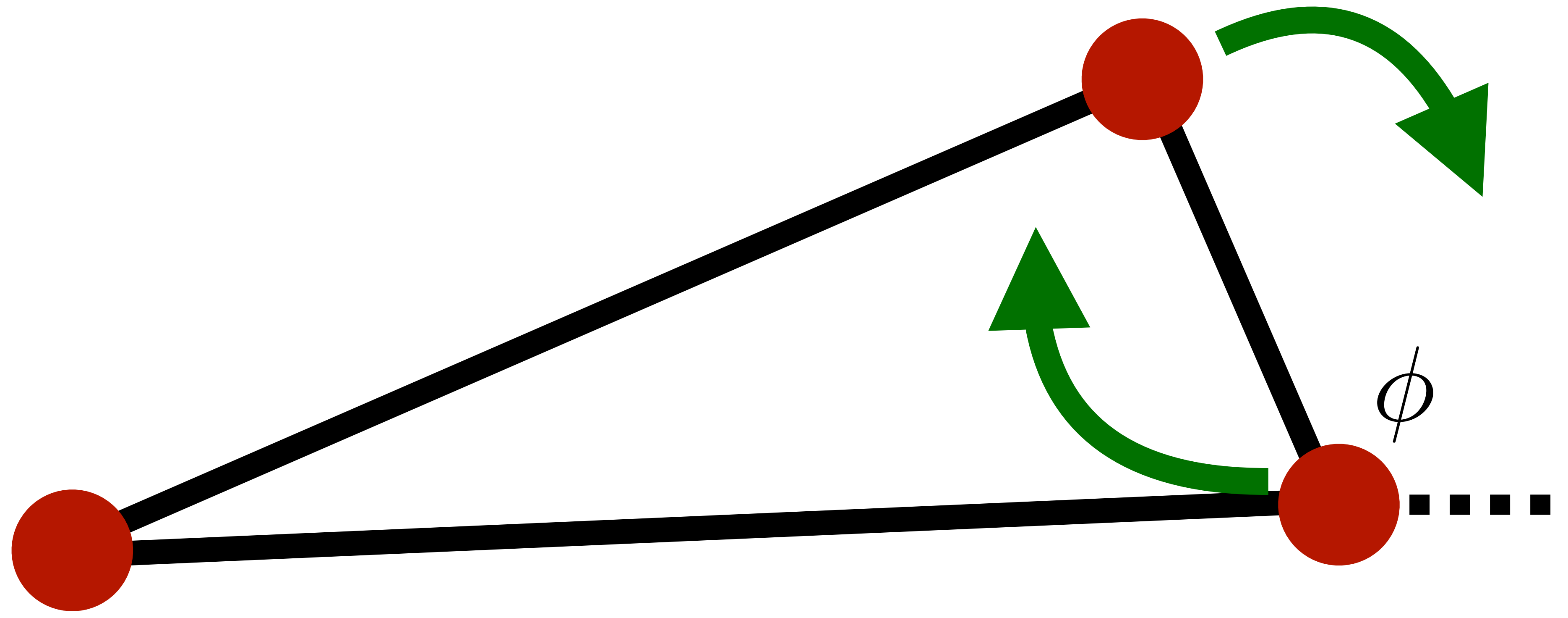
CERN Courier @CERNCourier · Aug 22

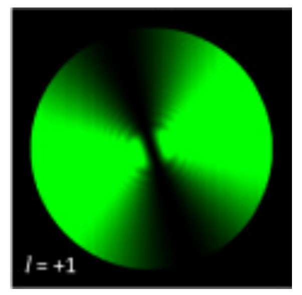
Florencia Canelli showed an overview of brand-new results from the @CMSExperiment, such as an updated value of the strong coupling constant

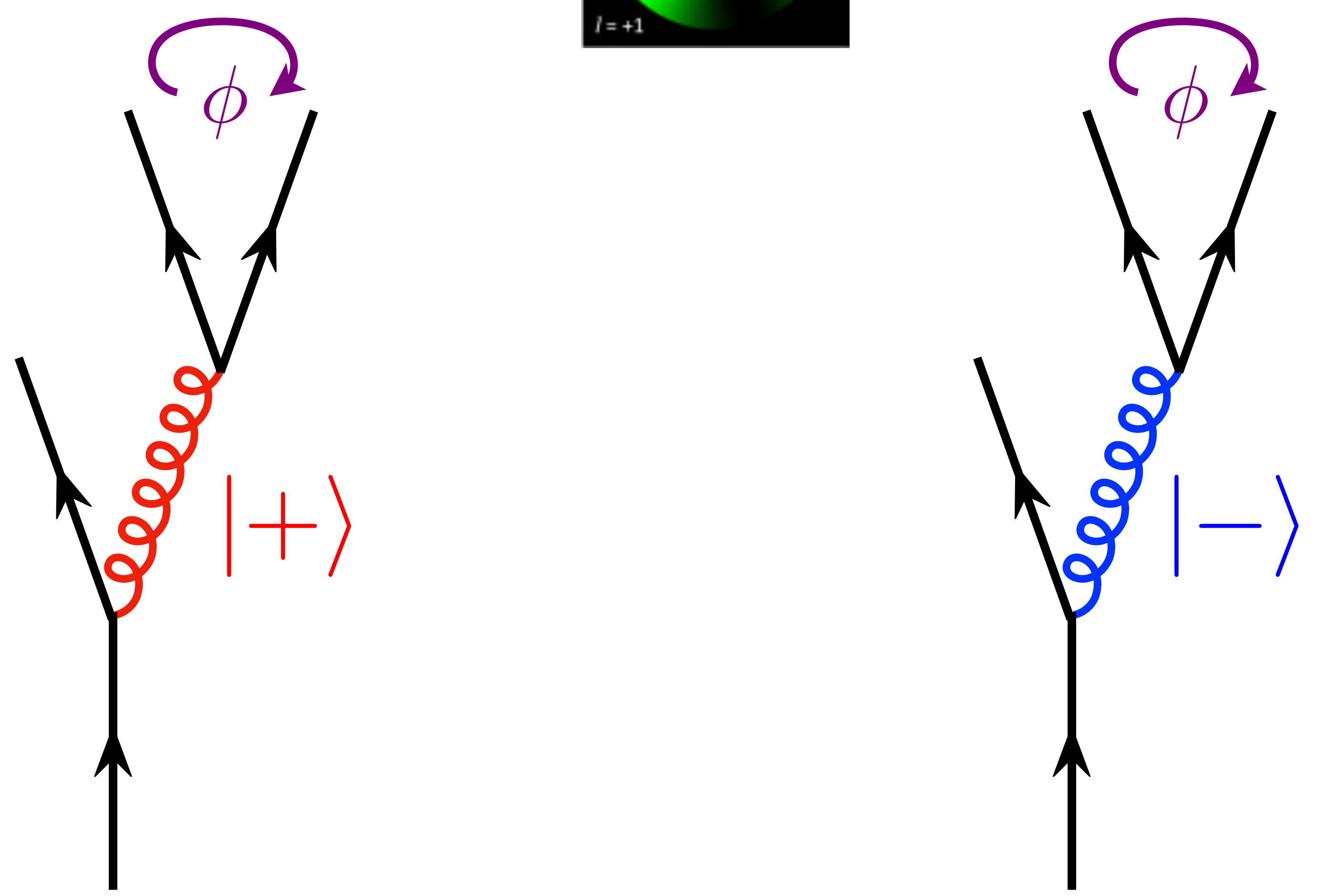


13 45 3,499

Spin interference from energy correlators







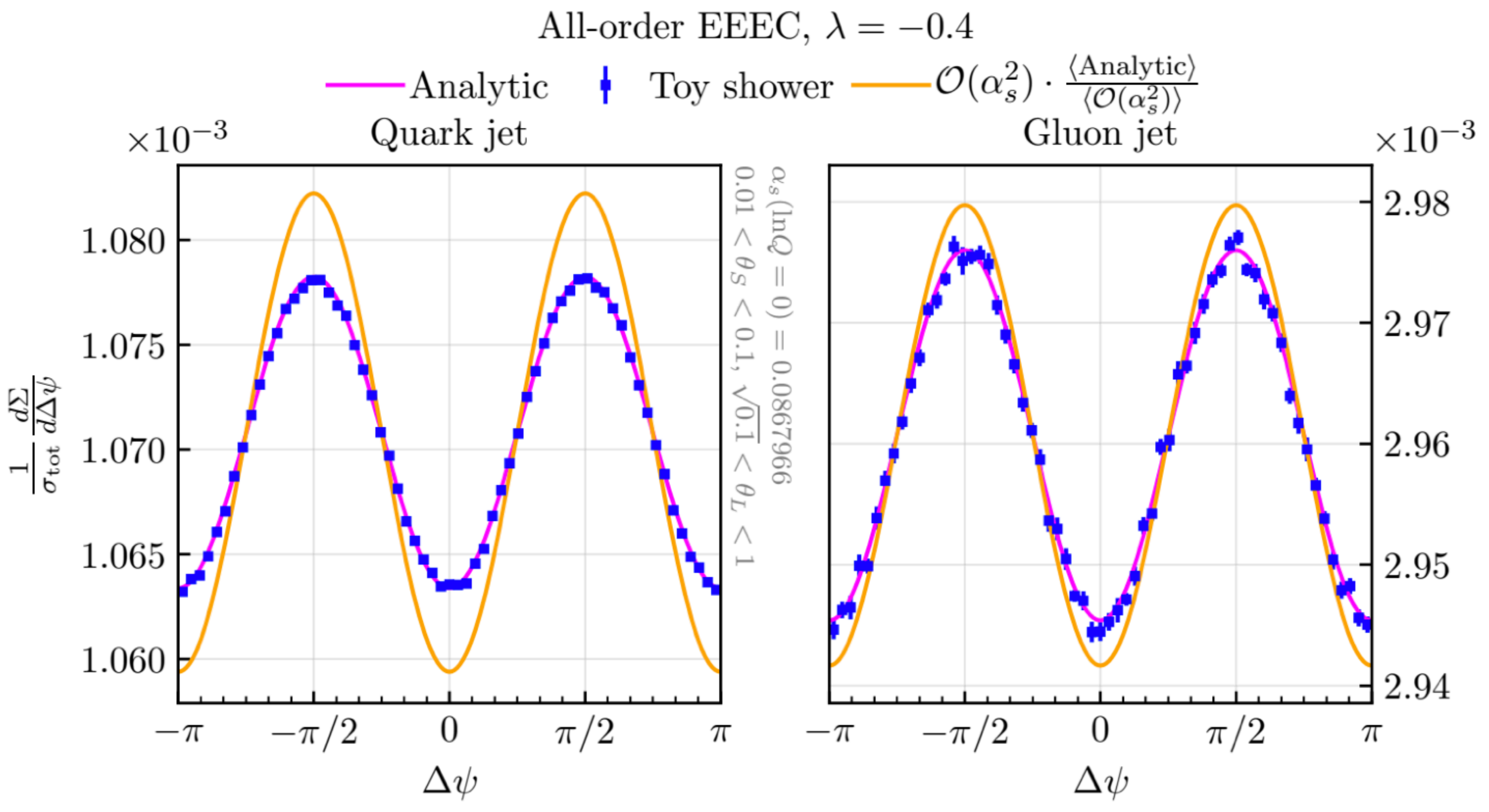
H. Chen, Moult, HXZ, 2021

One-loop perturbation theory calculation:

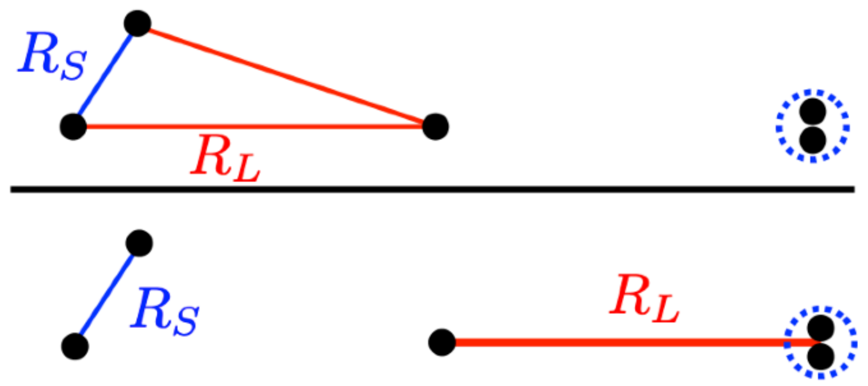
$$\mathrm{Sq}_q^{(0)}(\phi) = C_F n_f T_F \left(\frac{39 - 20\cos(2\phi)}{225}\right) + C_F C_A \left(\frac{273 + 10\cos(2\phi)}{225}\right) + C_F^2 \frac{16}{5}$$

$$\mathrm{Sq}_g^{(0)}(\phi) = C_A n_f T_F \left(\frac{126 - 20\cos(2\phi)}{225}\right) + C_A^2 \left(\frac{882 + 10\cos(2\phi)}{225}\right) + C_F n_f T_F \frac{3}{5}$$

H. Chen, M.X. Luo, Moult, T.Z. Yang, X.Y. Zhang, HXZ, 2019

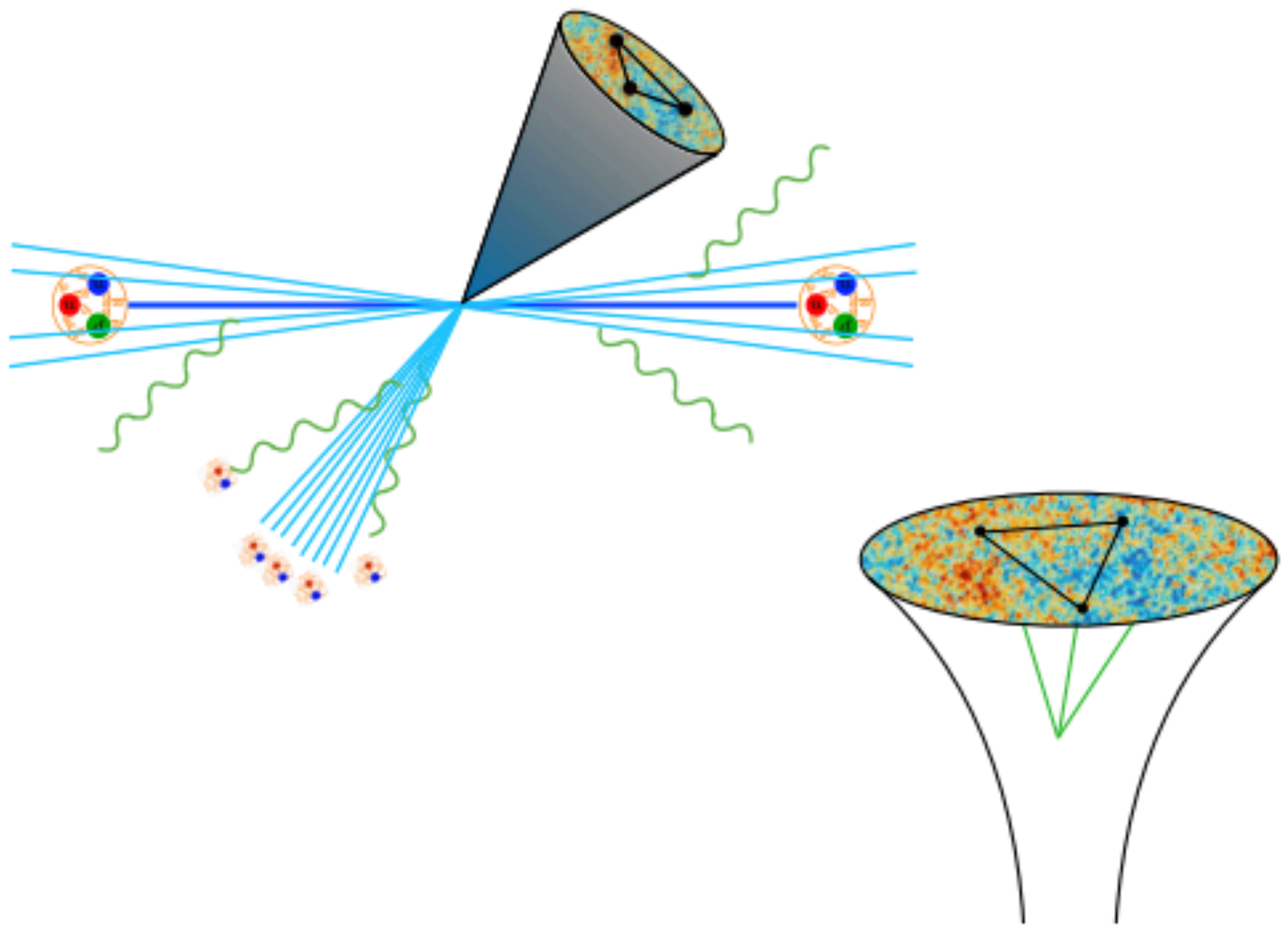


Karlberg, Salam, Scyboz, Verheyen, 2022

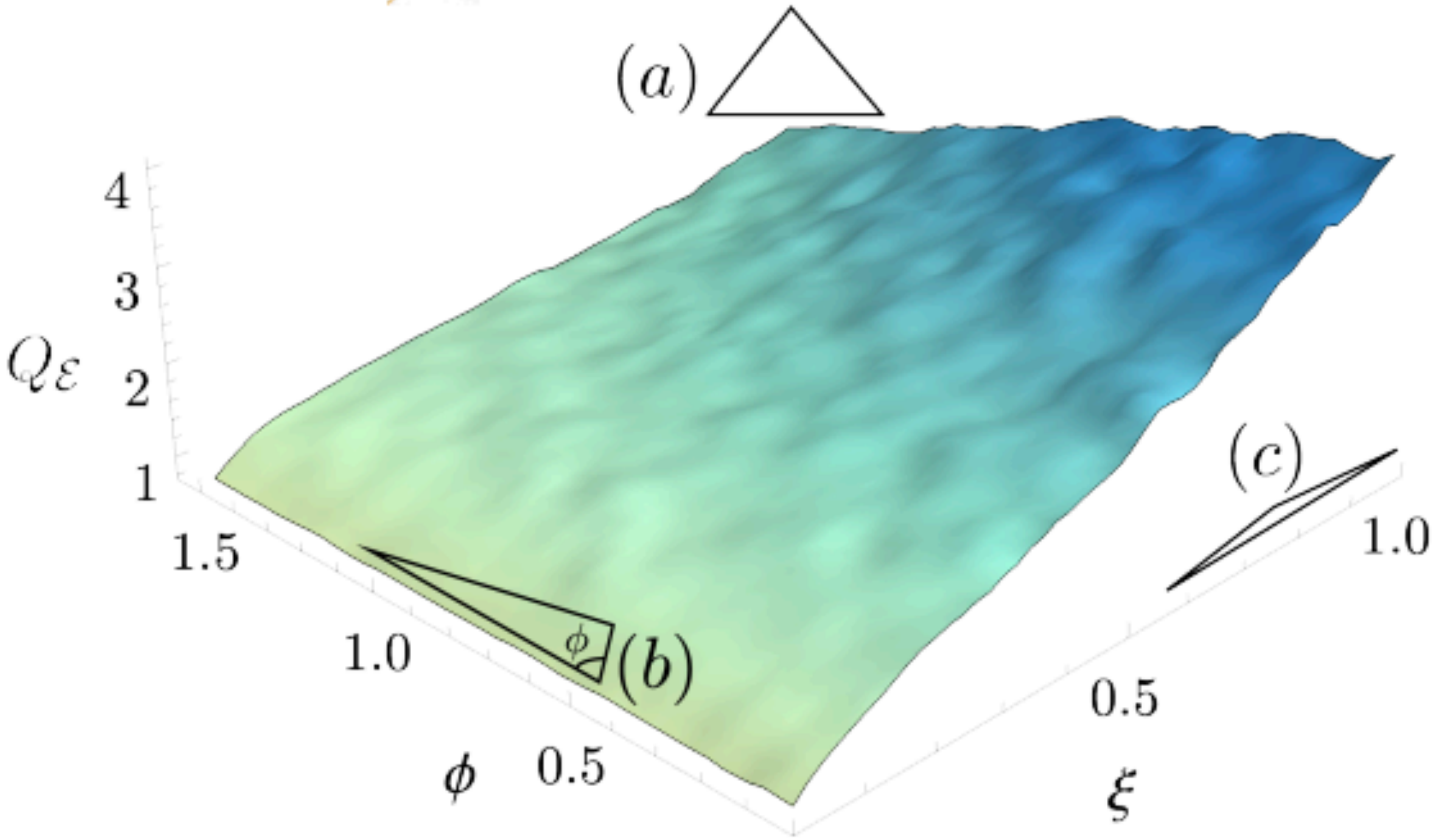


Non-Gaussianity at the LHC

H. Chen, Moult, Thaler, HXZ, 2022



$R_L \in (0.3,\ 0.4)$



← UV to IR →

← Theory to Experiment →

Technique from collider physics and QCD

Interpreted through lens of cosmology

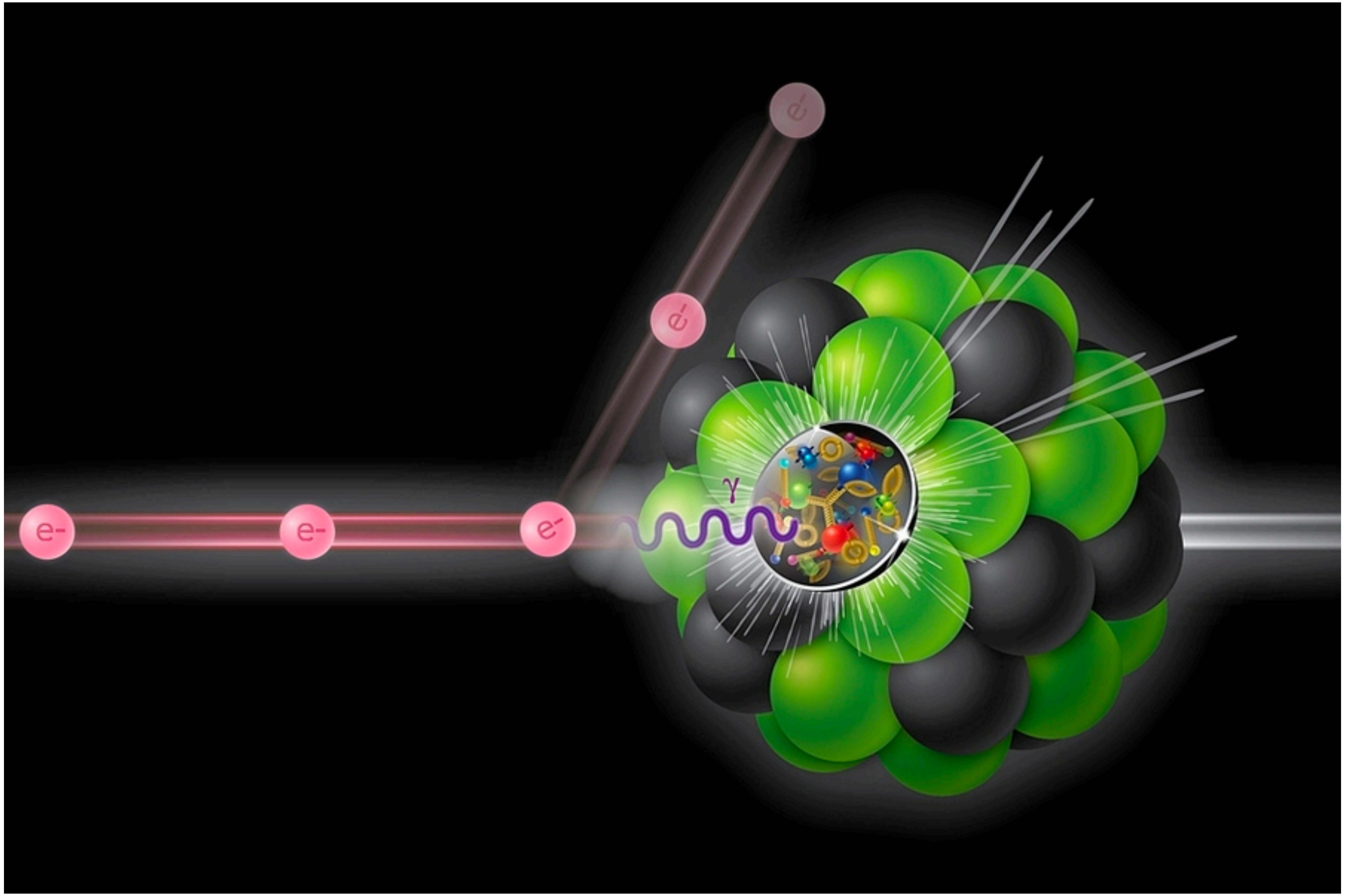
Computed through lens of conformal field theory

Analyzed with public collider data

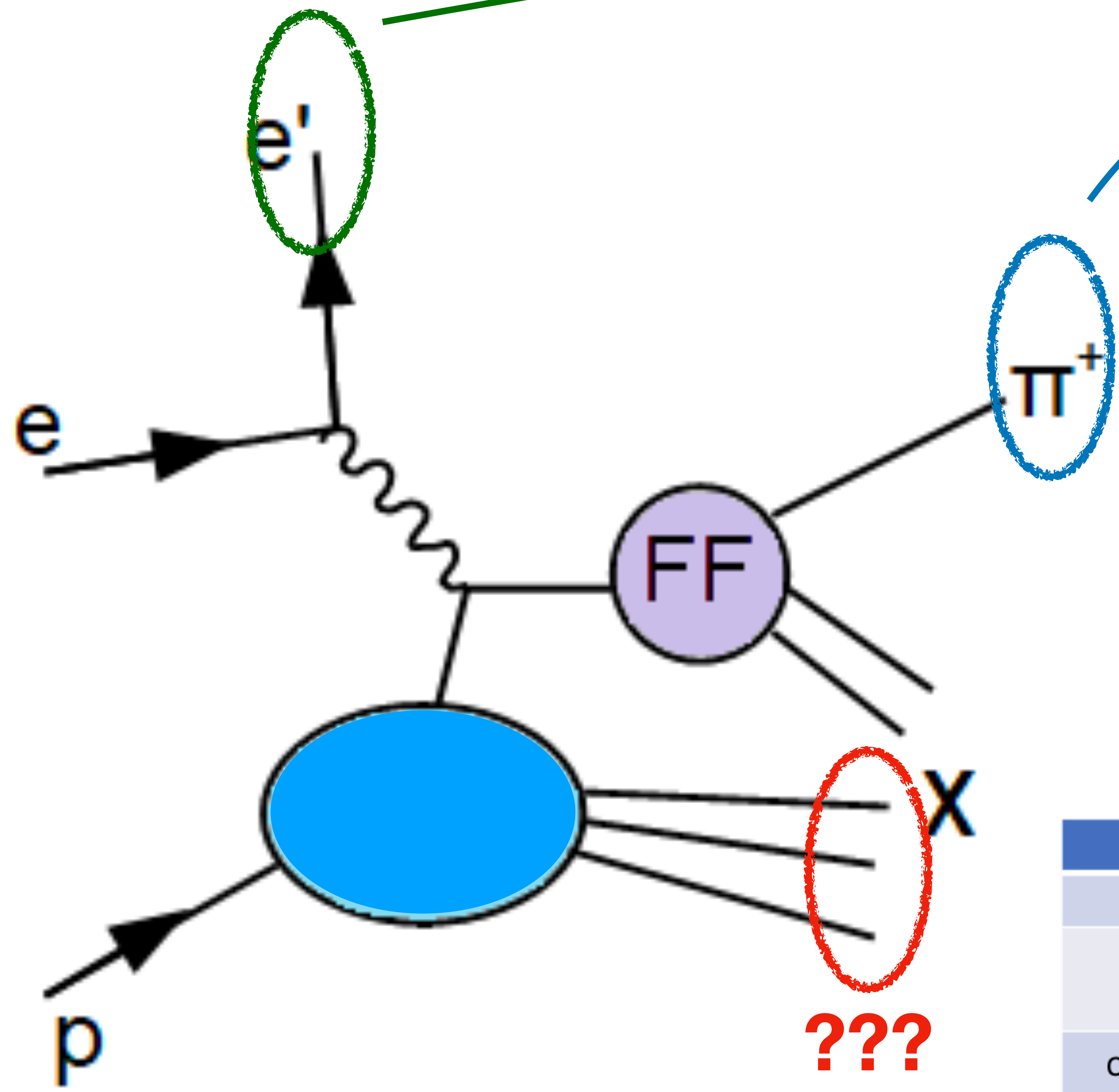
← Phenomenological to Formal →

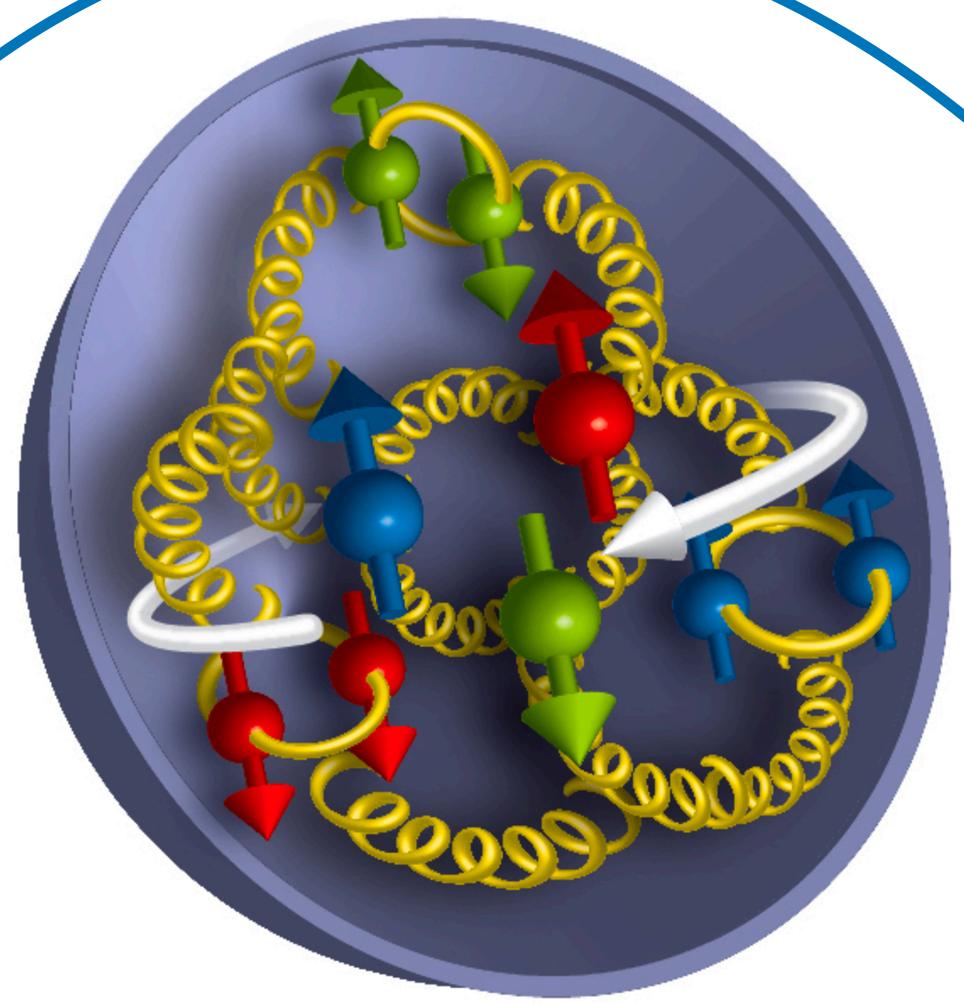
Slide adapted from J. Thaler, Snowmass, July, 2022

Energy correlators for jets at the EIC/EICC



ep and nucleon structure



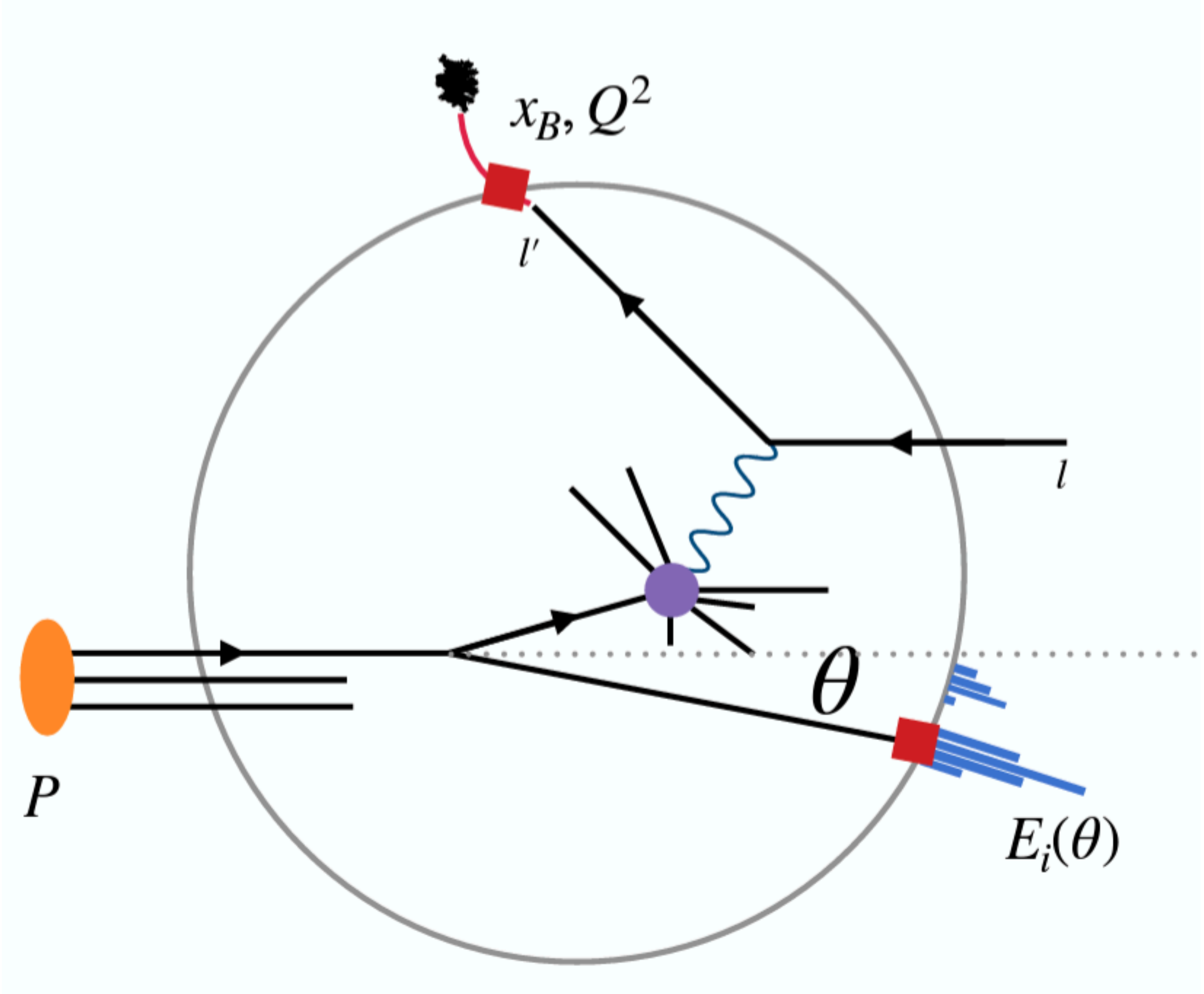


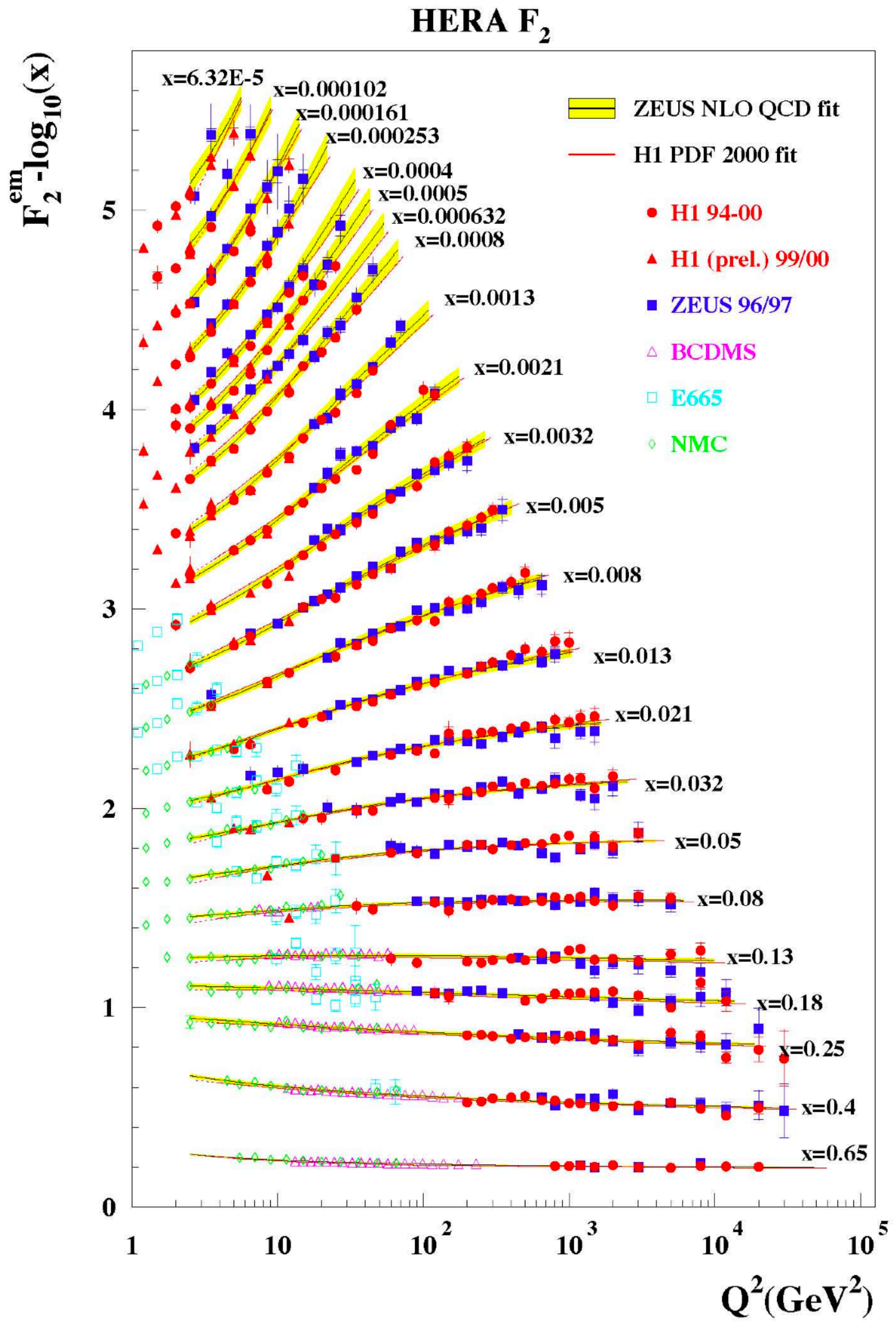
Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	0.0* $< \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (OMD)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
B0 Sensors (4 layers, evenly spaced)	$5.5 < \theta < 20.0$ mrad ($4.6 < \eta < 5.9$)

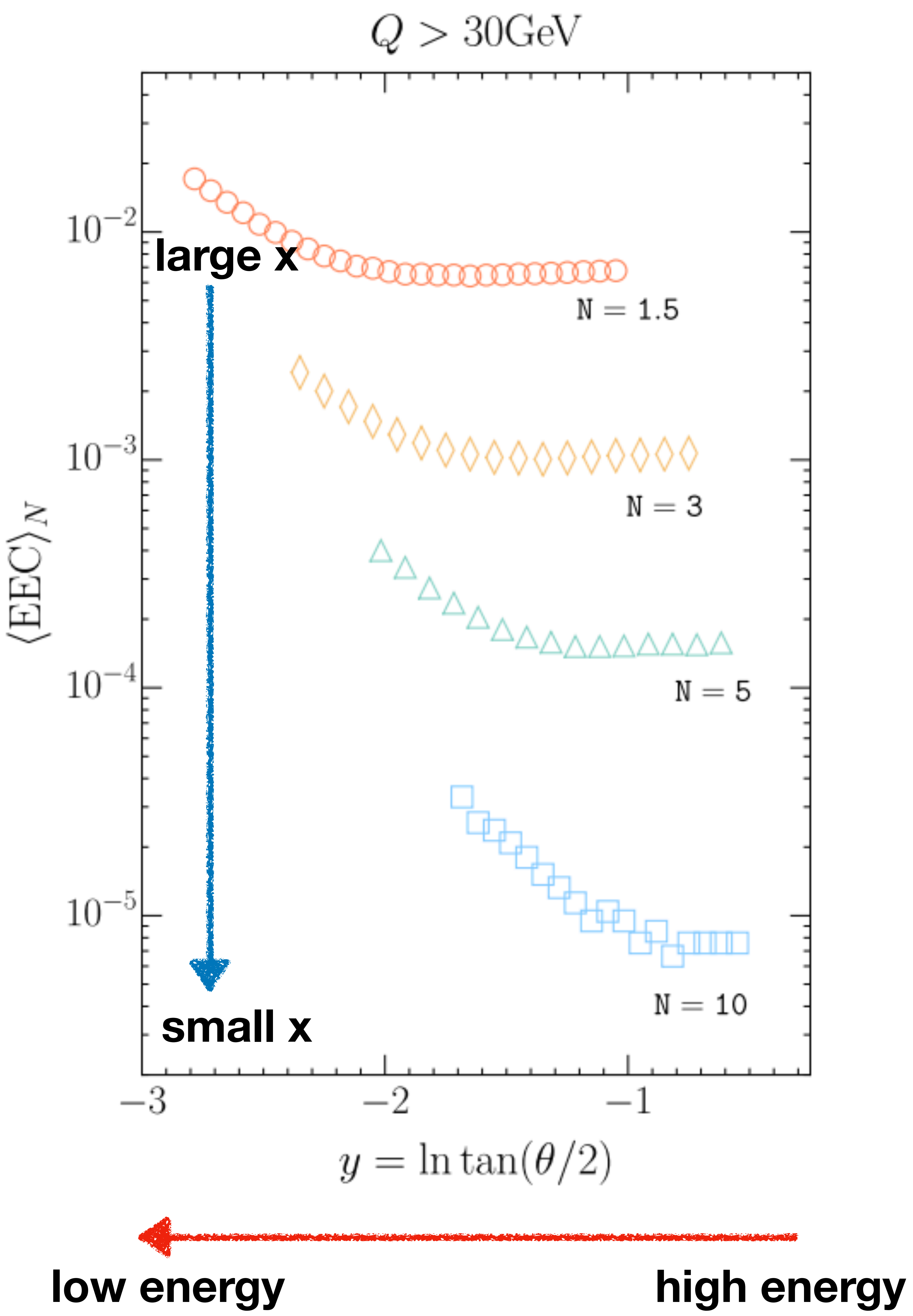
- Structure function measurement: PDFs(x)
- SIDIS:
  - TMD
  - spin
- How can we utilize the forward information and what does it probes?

The Nucleon Energy Correlator

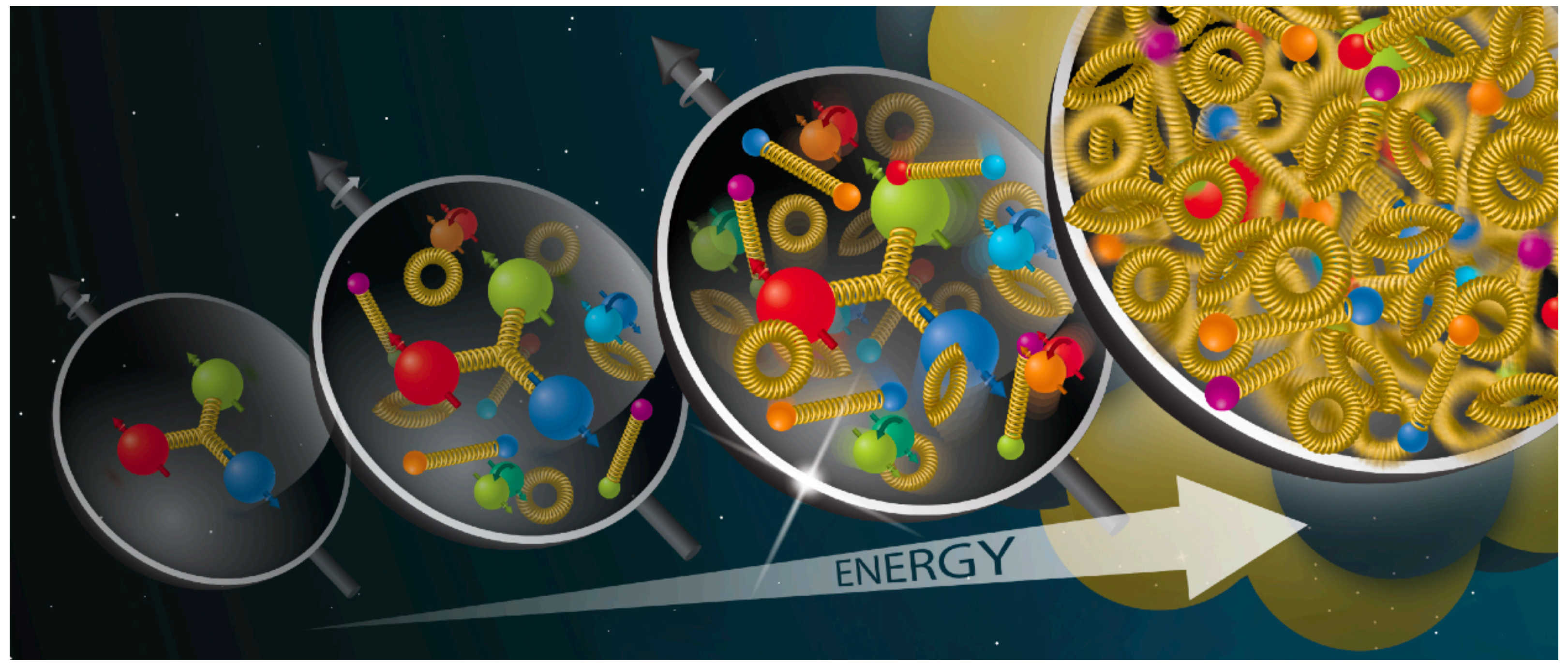
X.H. Liu, HXZ, 2022
H.T. Cao, Liu, HXZ, 2023

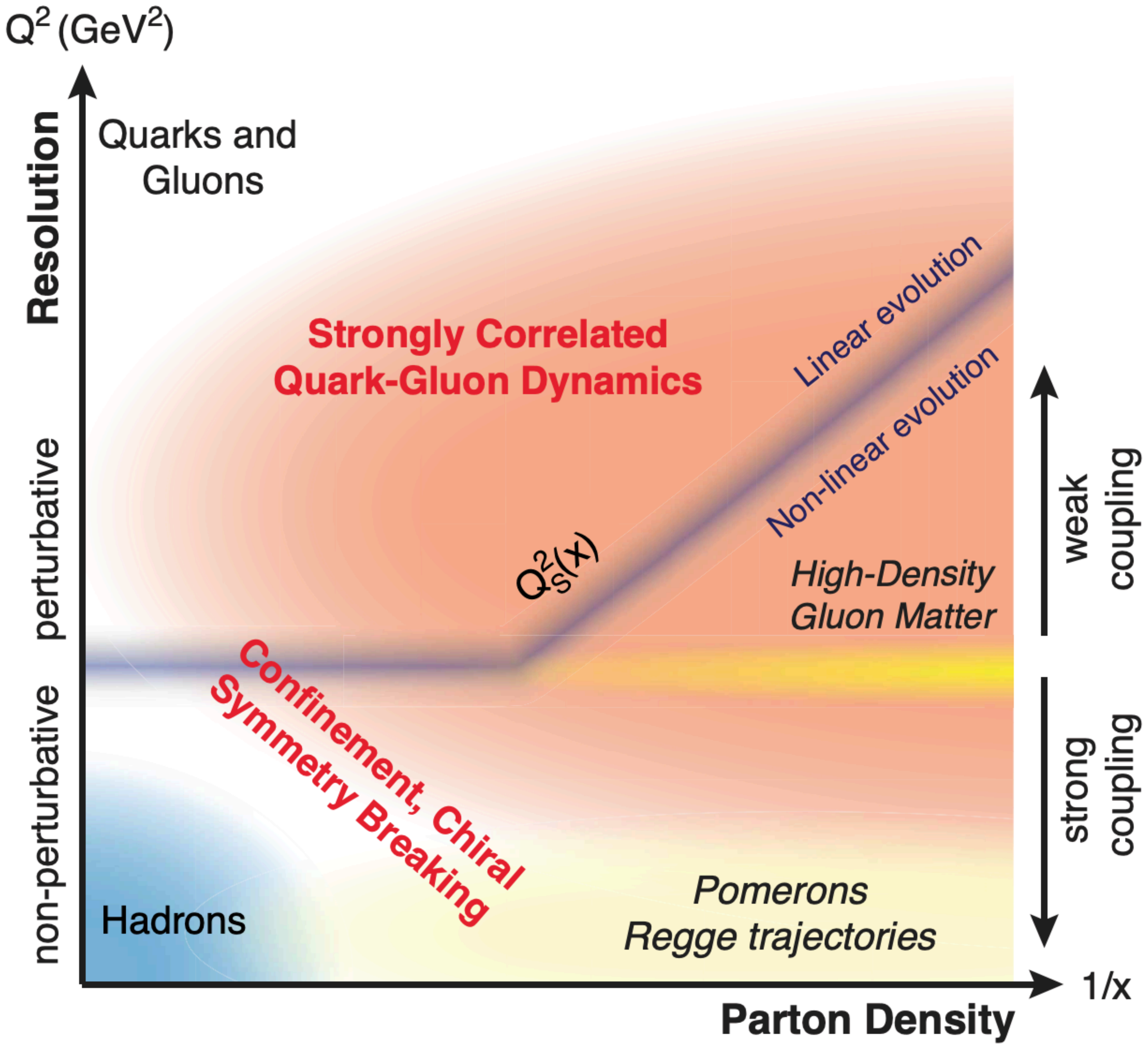




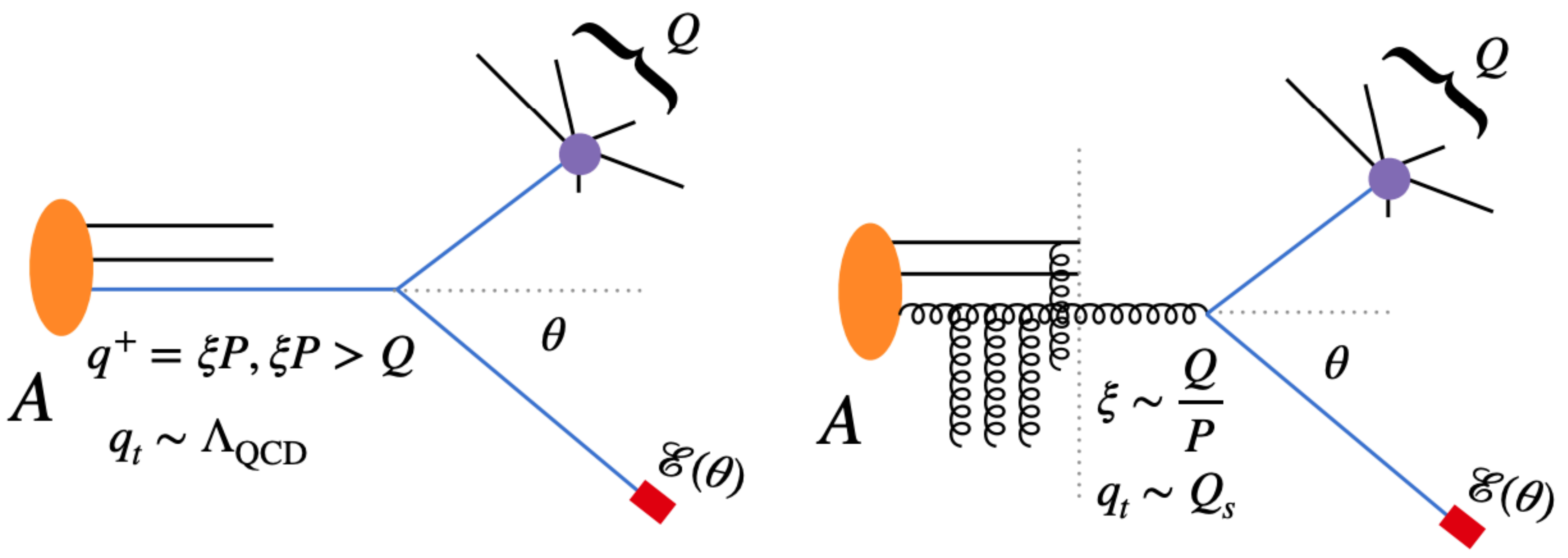


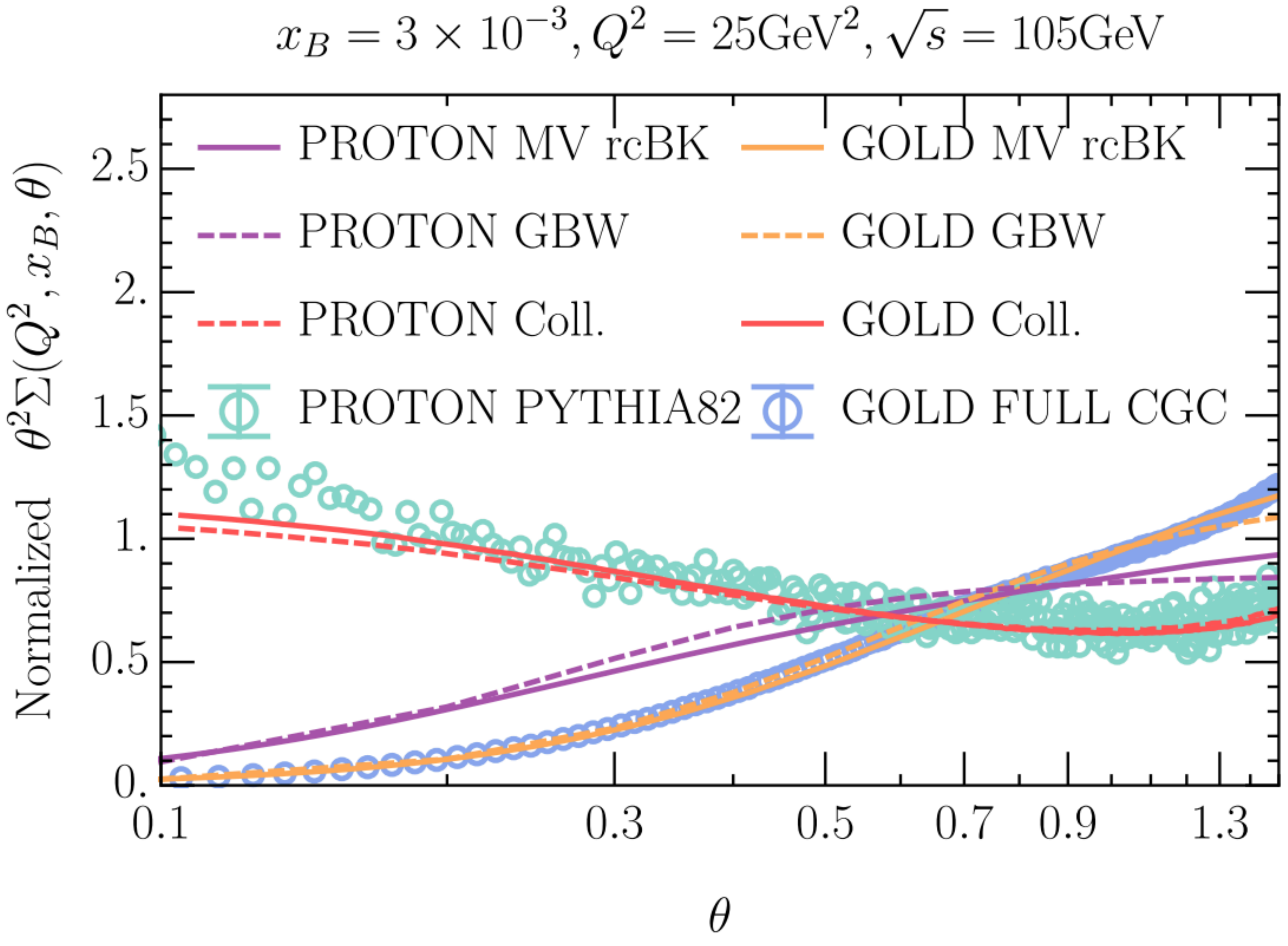
Probing gluon saturation



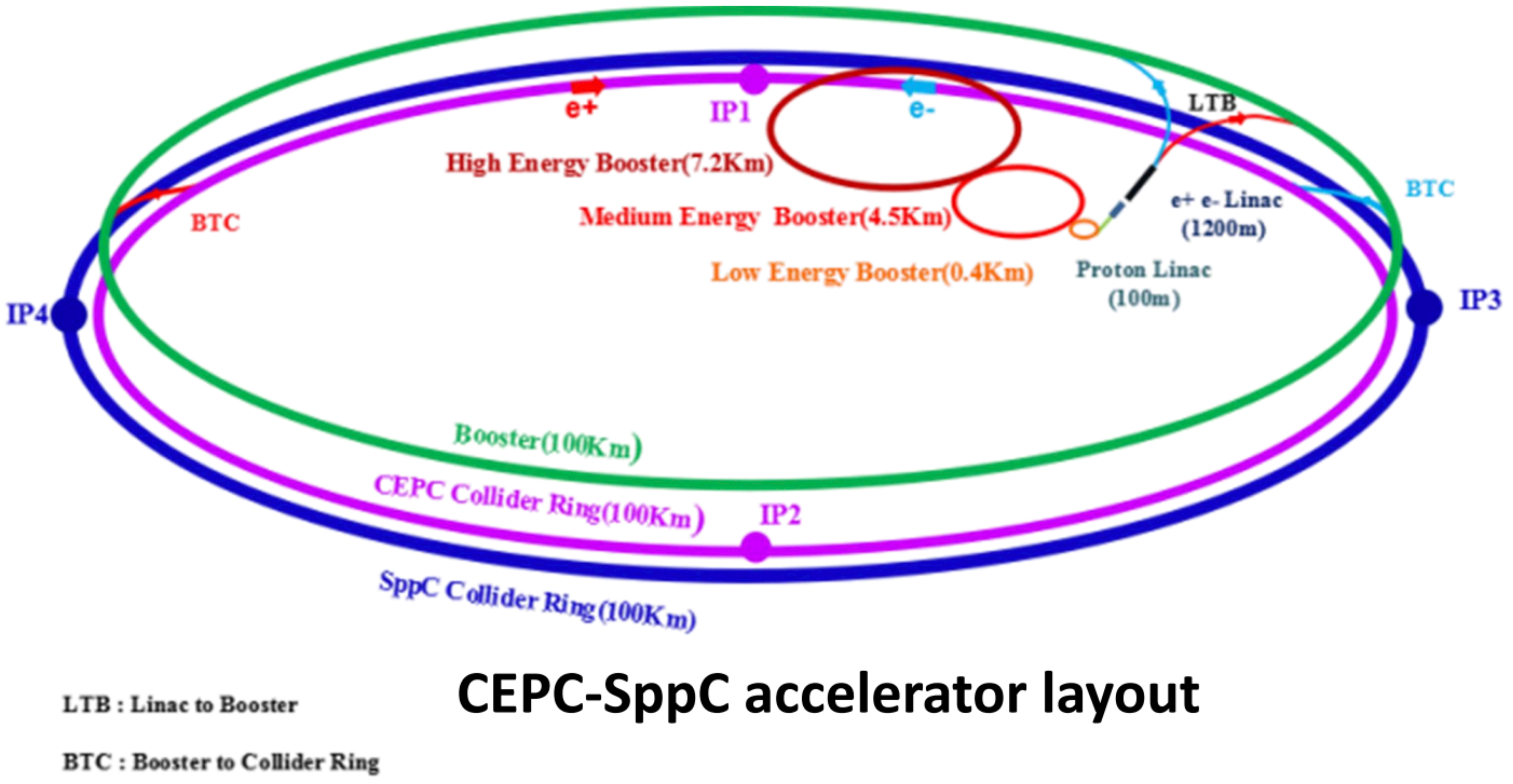


H.Y. Liu, X.H. Liu, J.C. Pan, F. Yuan, HXZ, 2023





Track energy correlators at the CEPC/FCC-ee



CEPC-SppC accelerator layout

Understanding hadronization with high precision data

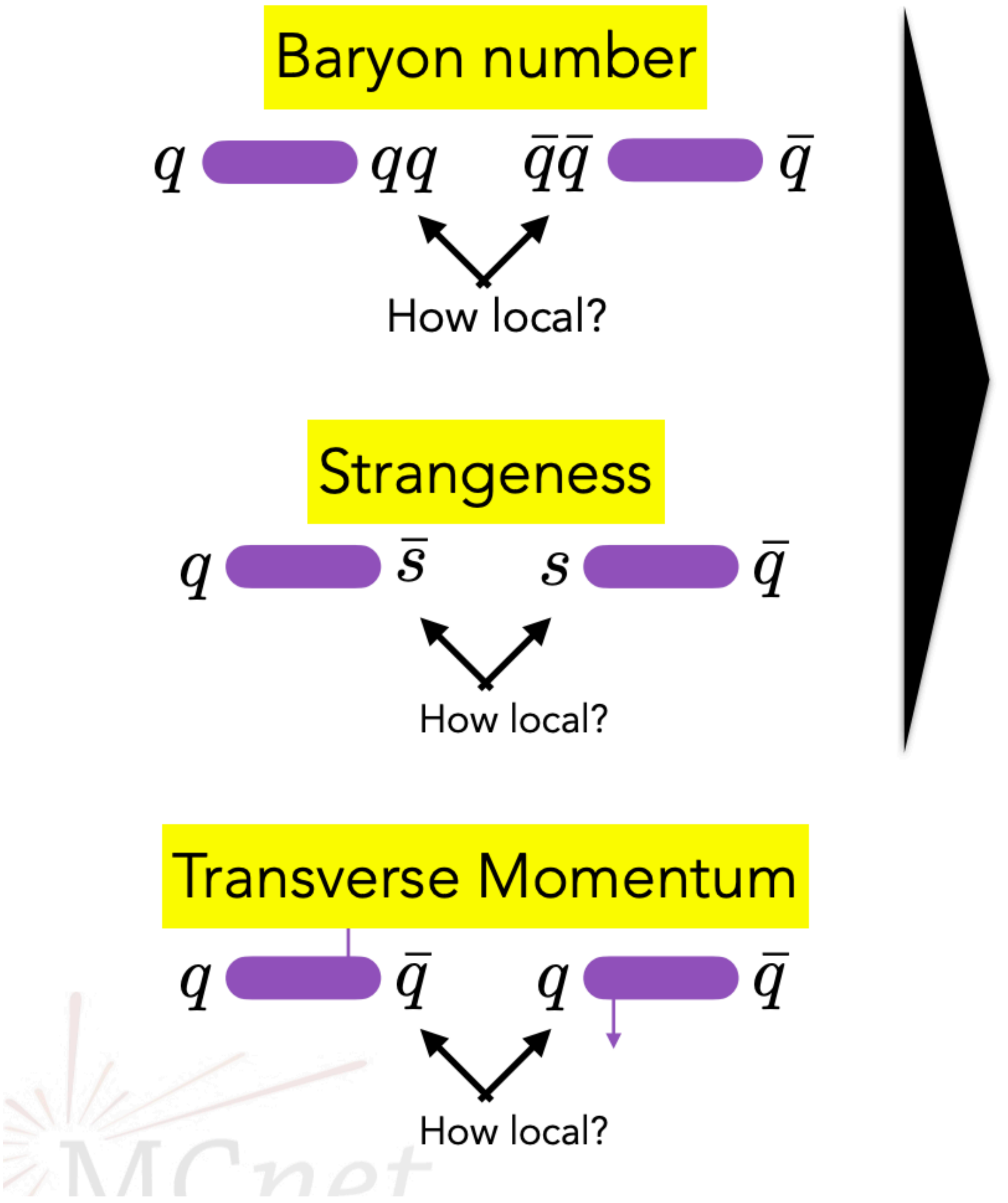
谢去病

山东大学

Hadronization

- 高能碰撞必先产生各种夸克。
- 夸克如何强子化成各种各样的强子？
- 强子化过程不仅出现于任何高能反应，而且是与夸克禁闭、QCD真空结构等一系列重大理论问题直接相关的非微扰QCD过程。 ————其研究是当代物理中一个基本又艰巨课题

QCD conserves baryon number, strangeness, and momentum



➜ Particle Correlations

E.g., **how far** from a baryon (or a strange particle) do you have to go before you find an anti-baryon (anti-strange)?

Must be able to tell **which hadrons are which** (strangeness, baryon number, spin) ➤ PID

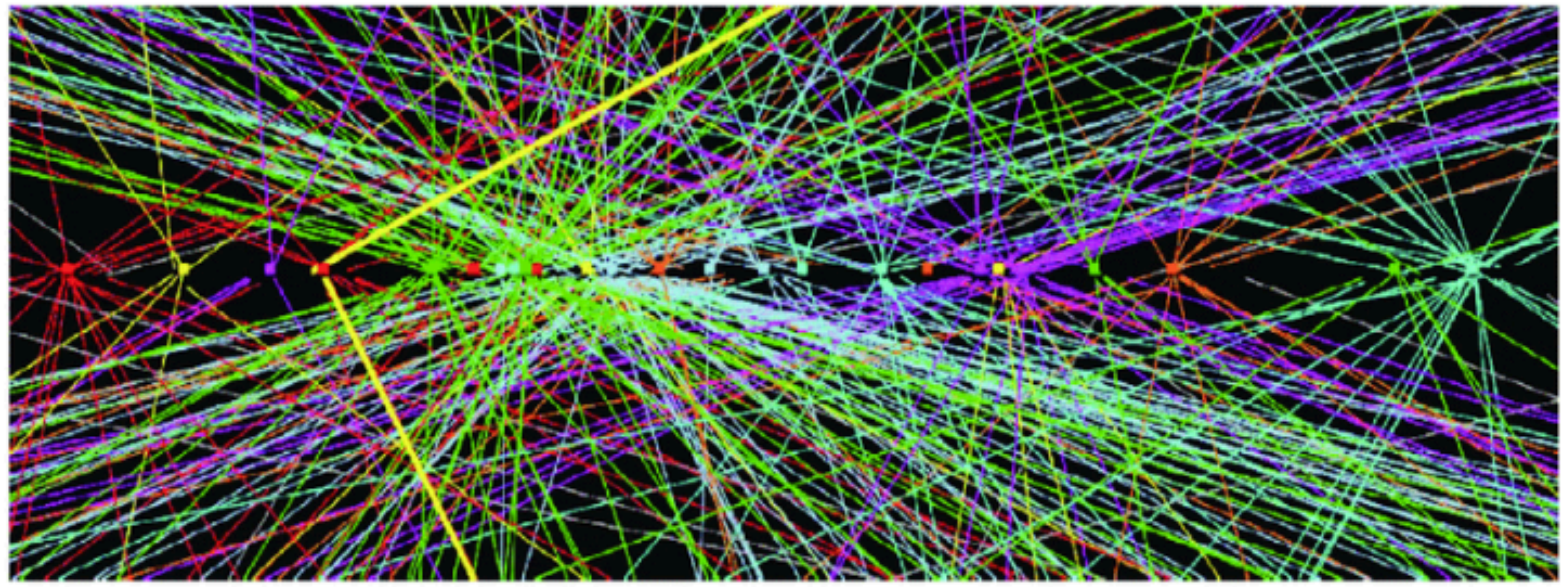
Relative **momentum kicks** of order Λ_{QCD} ~ 100 MeV must be well resolved

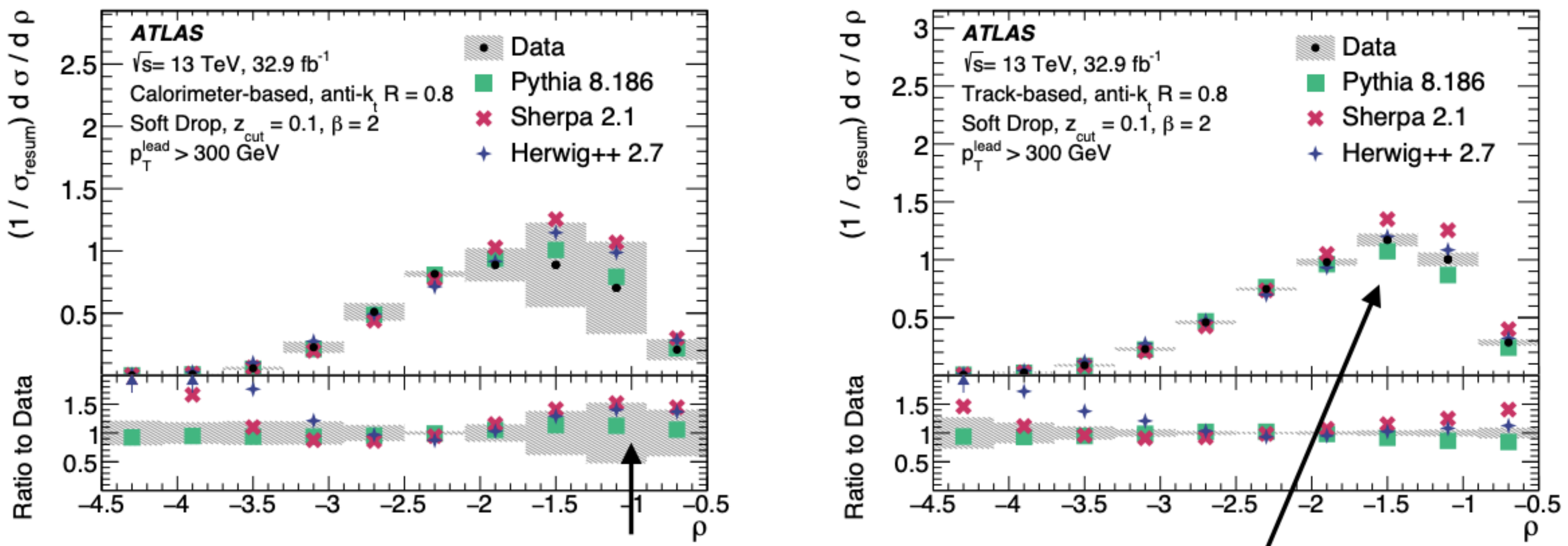
credit: Peter Skands

As an example, evolution of charge quantum number can be probed by track EEC with precision

Track EEC

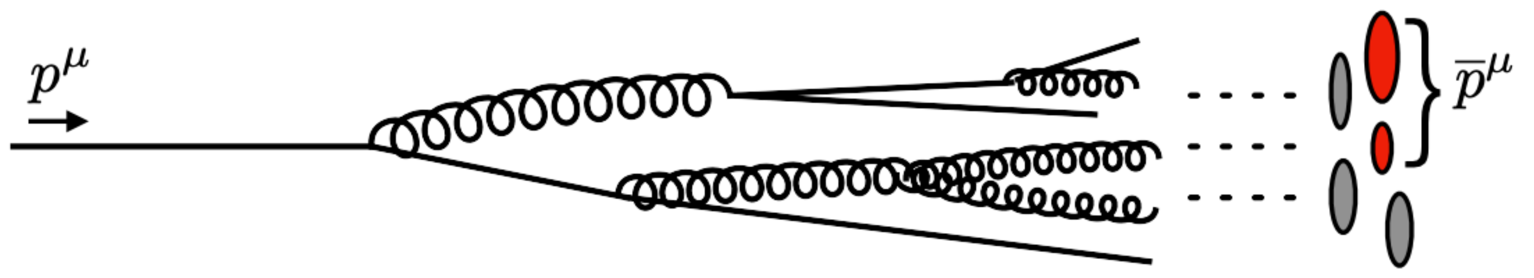
problem of pile up at the LHC





Pile up

Difference of parton showers larger than exp. uncertainty



Chang, Procura, Thaler, Waalewijn, 201

- Ordinary EEC

$$\frac{d\sigma}{d\cos\chi} = \sum_{i,j}\int d\sigma\,\frac{E_iE_j}{Q^2}\,\delta(\cos\chi - \cos\theta_{ij})$$

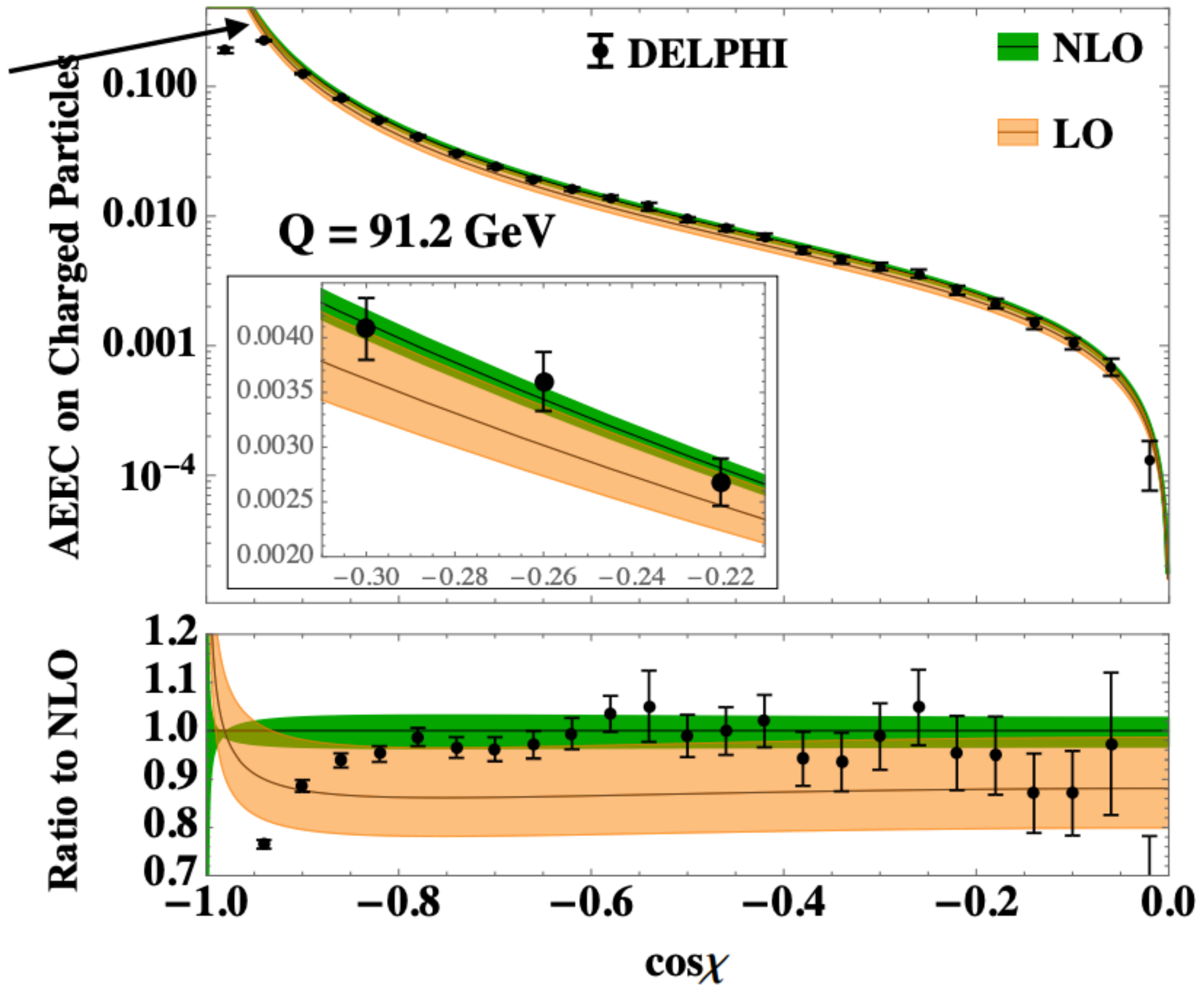
[Basham, Brown, Ellis, Love]

- Track EEC

$$E_i \to \int dx_i\, T_i(x_i)x_iE_i = T_i(1)E_i$$

H. Chen, Moult, X.Y. Zhang, HXZ, 2020

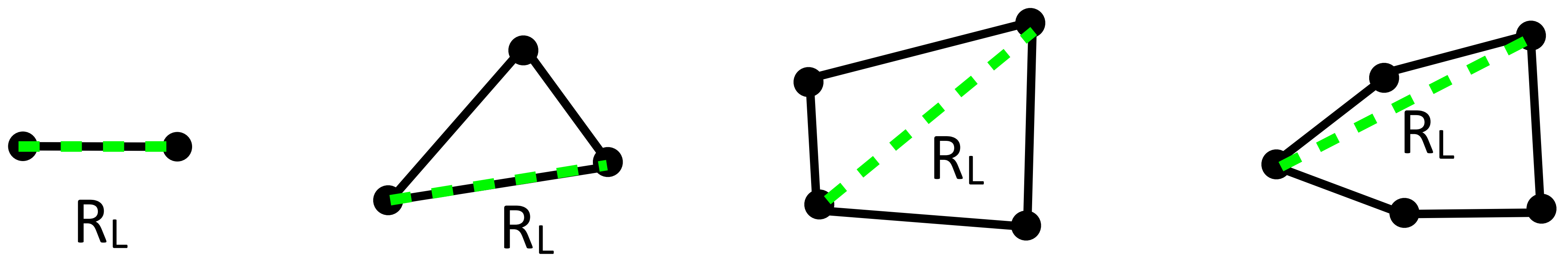
resummation needed



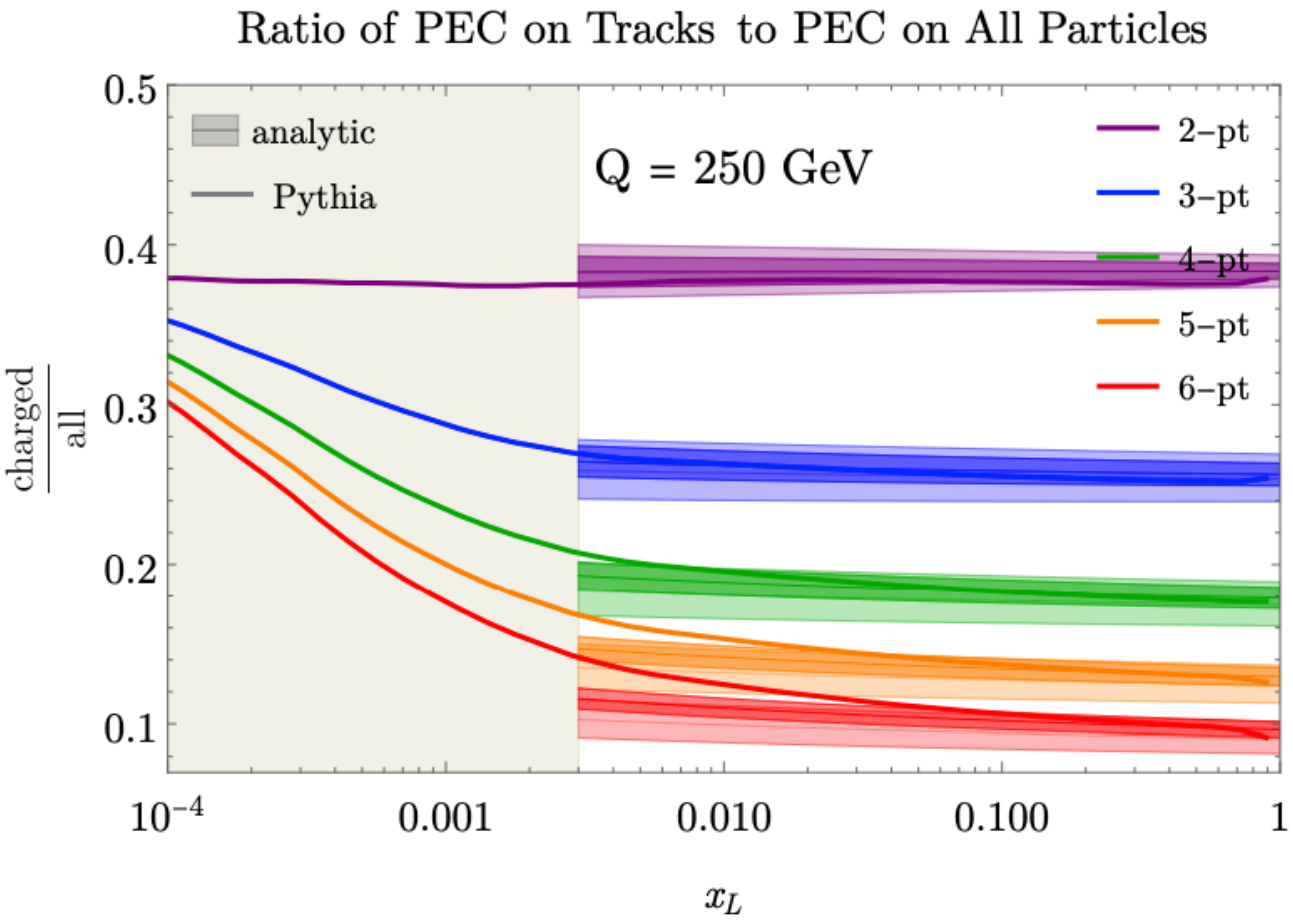
First ever NLO calculation for track-based observable!

Y.B. Li, Moult, van Velzen, Waalewijn, HXZ, 2021

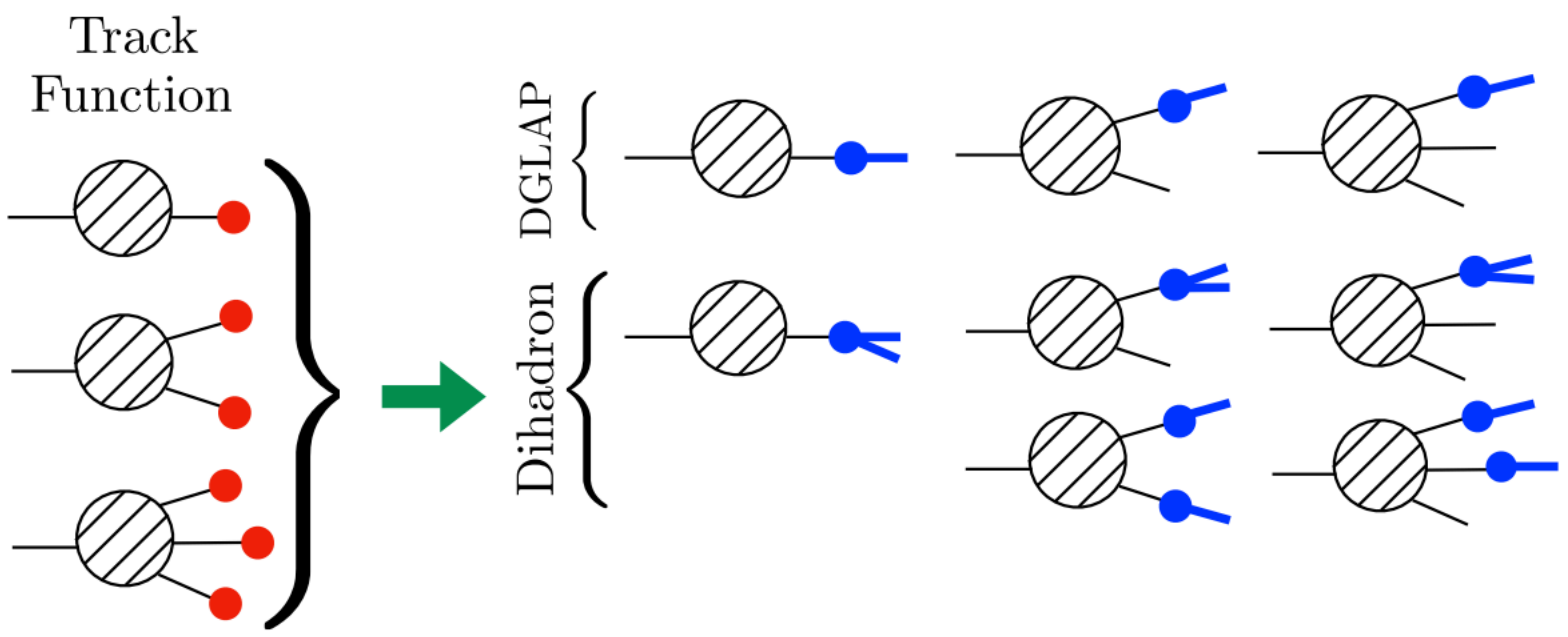
Projected energy correlators on track



H. Chen, Moult, X.Y. Zhang, HXZ, 2020



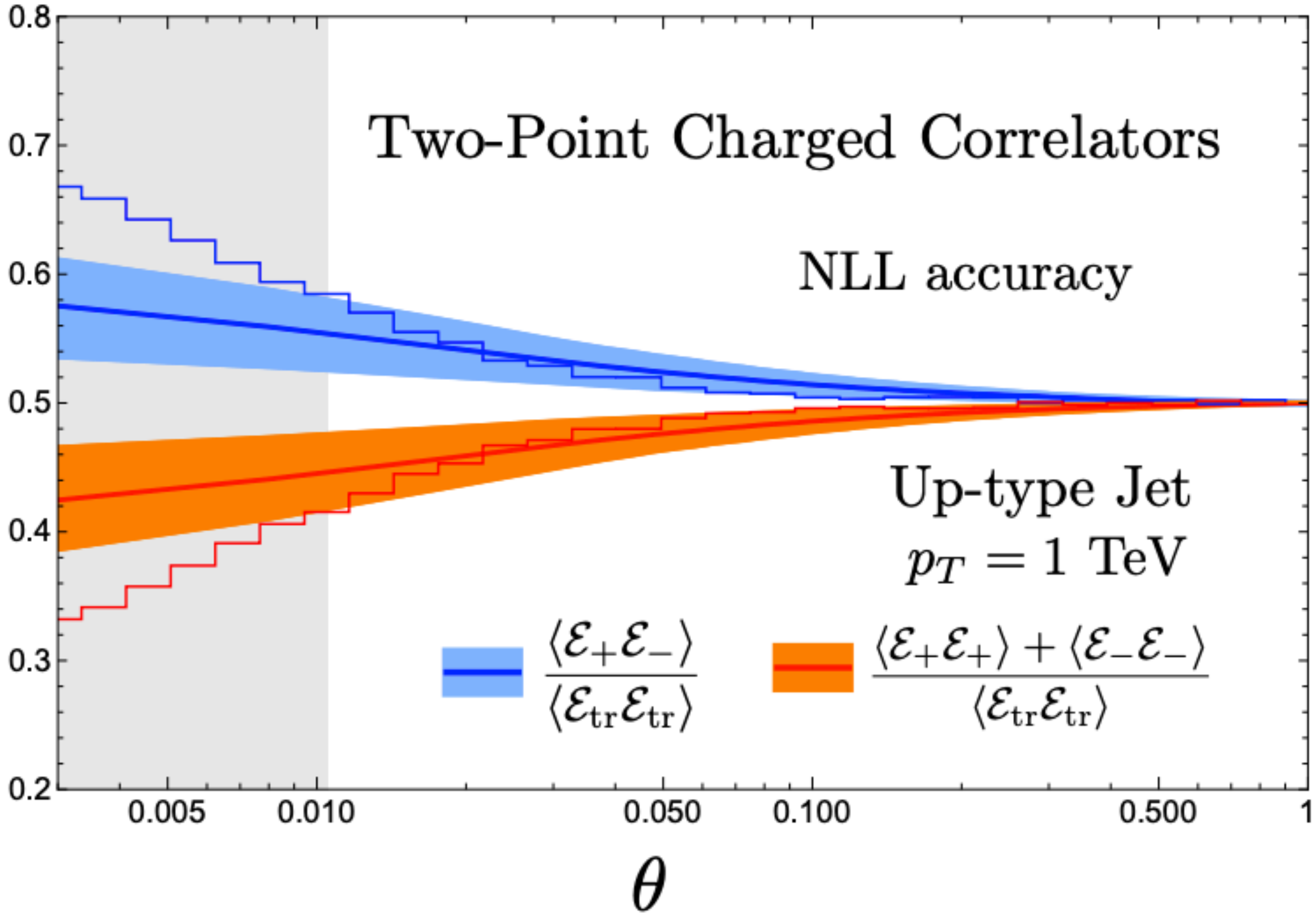
Y.B. Li, Jaarsma, Moult, Waalewijn, HXZ, 2023



H. Chen, Y.B. Li, Jaarsma, Moult, Waalewijn, HXZ, 2022

- Ratio of charged v.s. all-hadron calculable for projected EECs
- Non-vanishing slope visible starting from three points: signal of multiple-particle correlation in the fragmentation process

Positive and negative charge energy correlator



- Beyond track, sign of particle charge can also make a difference
- Enhanced small angle correlation between opposite charge particles

Lee, Moult, 2023

Summary

- Resurgence of interests in EEC and its generalization inspired by conformal collider physics
- Remarkably rich QCD dynamics can be probed by EECs
    - Scaling behavior in jet evolution and real time hadronization
    - Spinning gluon effects in jet substructure
    - Non-Gaussianity at the LHC
    - Scaling in DIS through nucleon EEC
    - Probing Gluon saturation
    - Global quantum number in parton fragmentation from EECs: track EEC