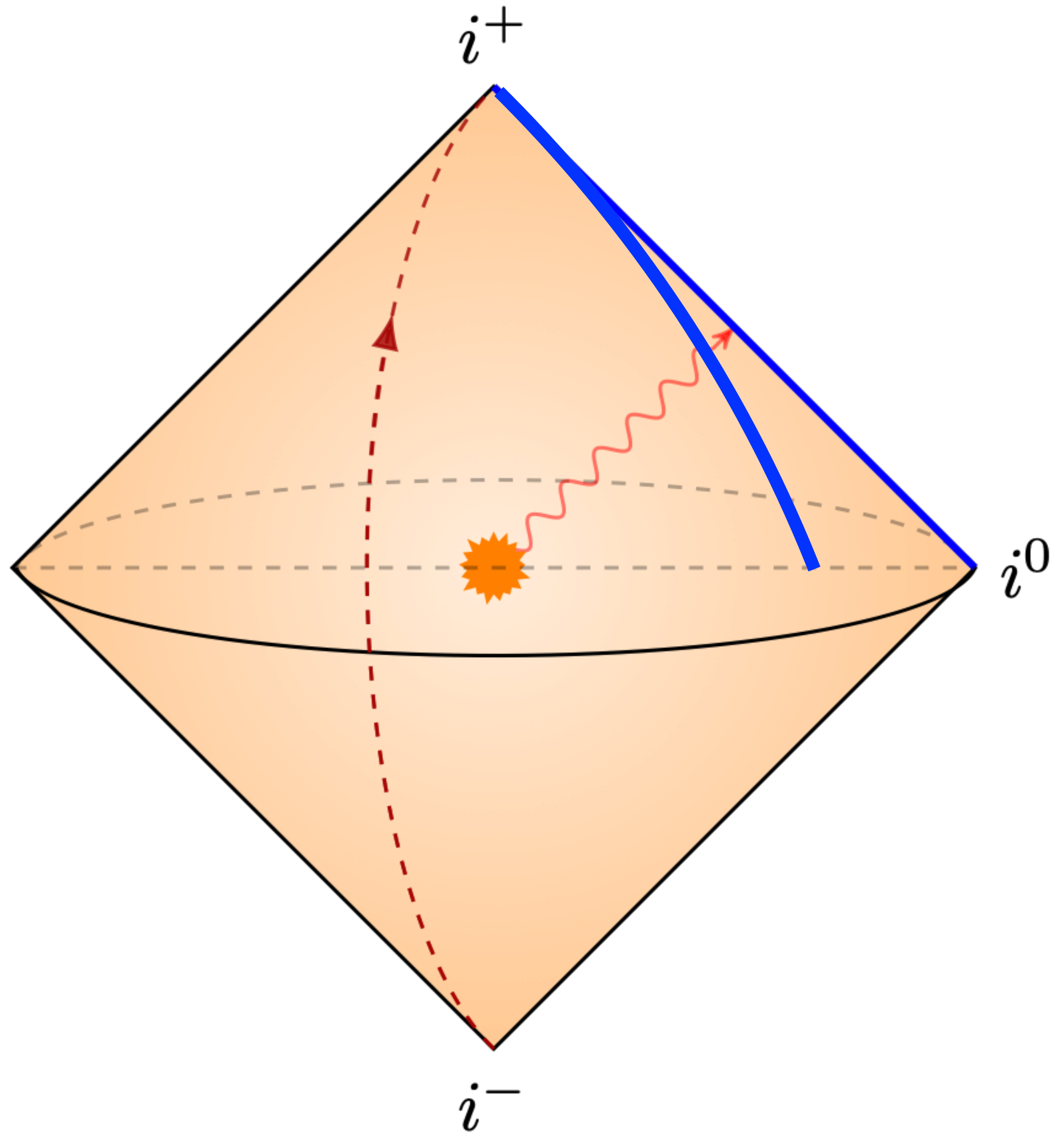
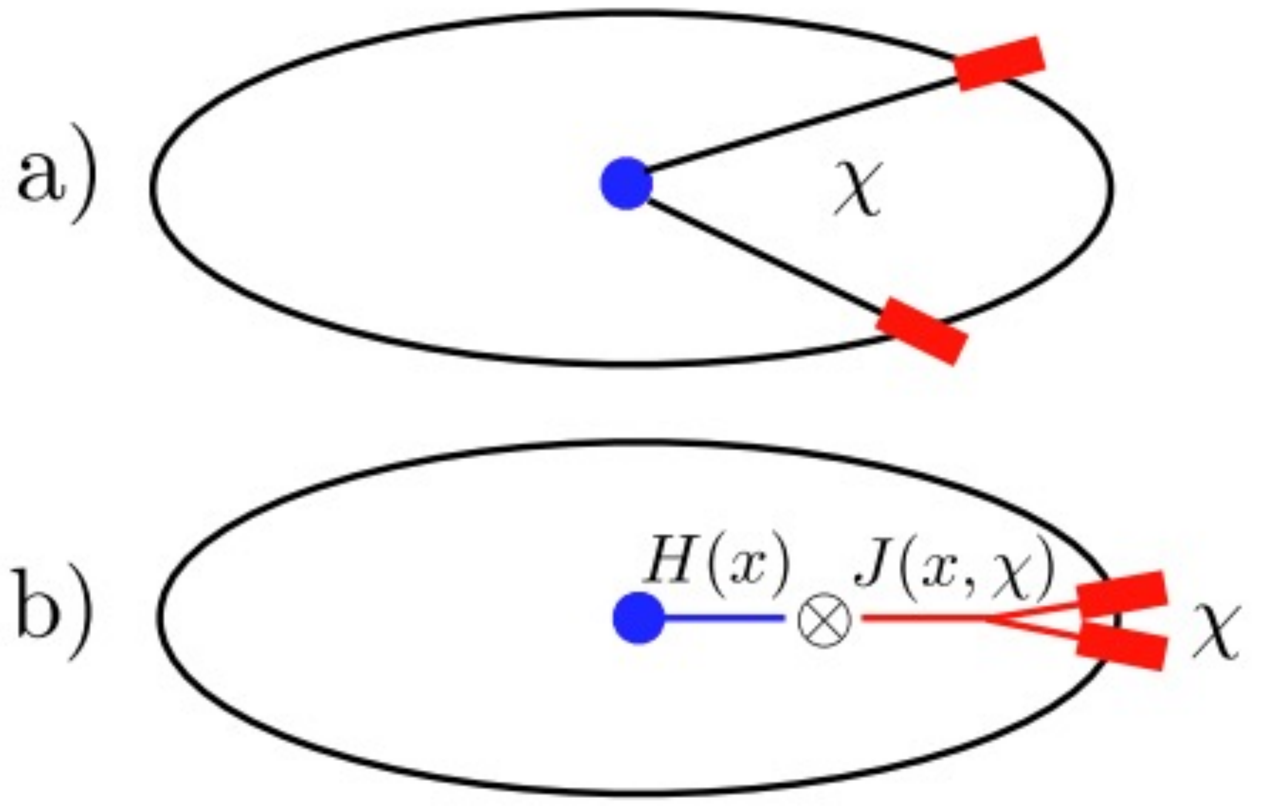
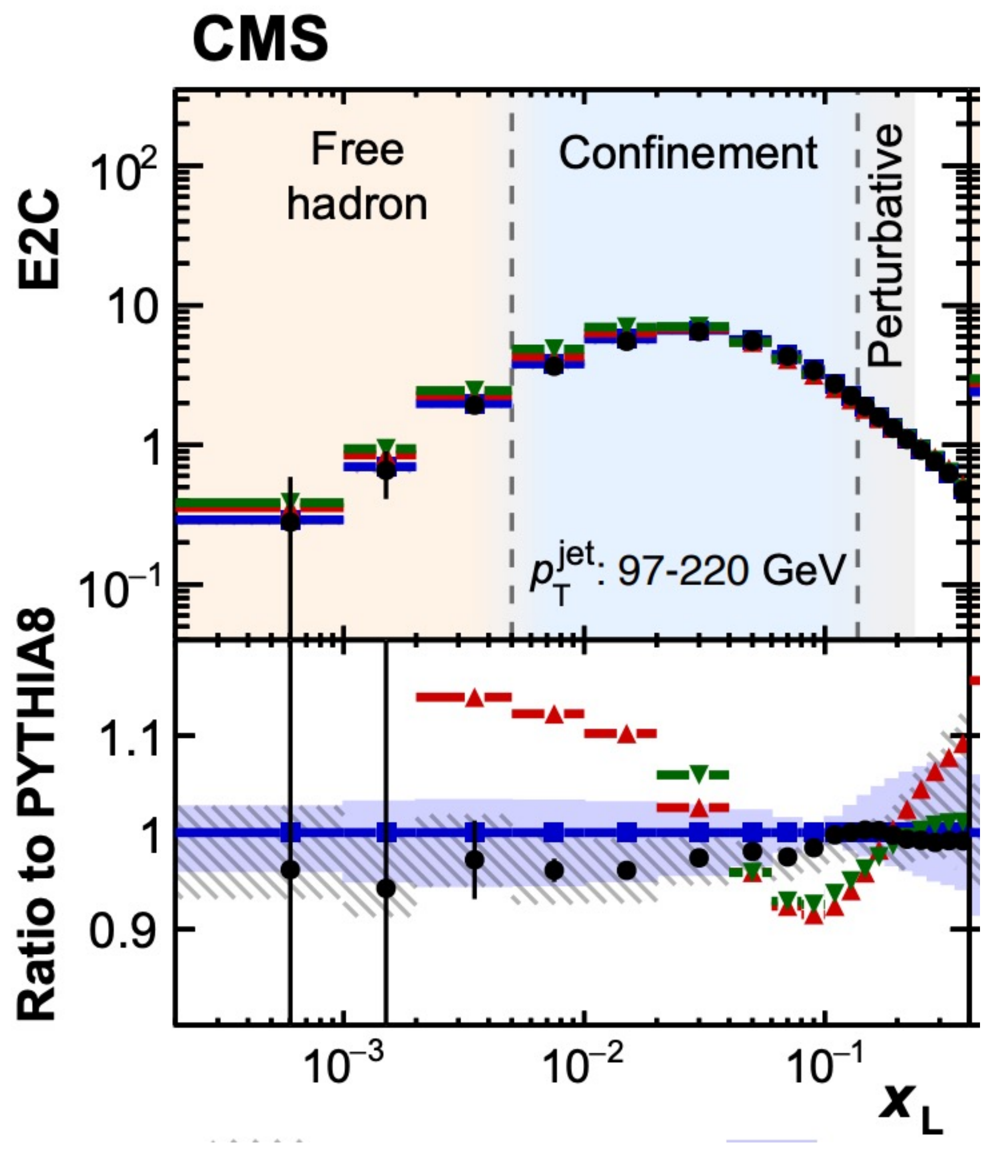
Progress on Energy Correlators:
Theory, Phenomenology, and Experiments





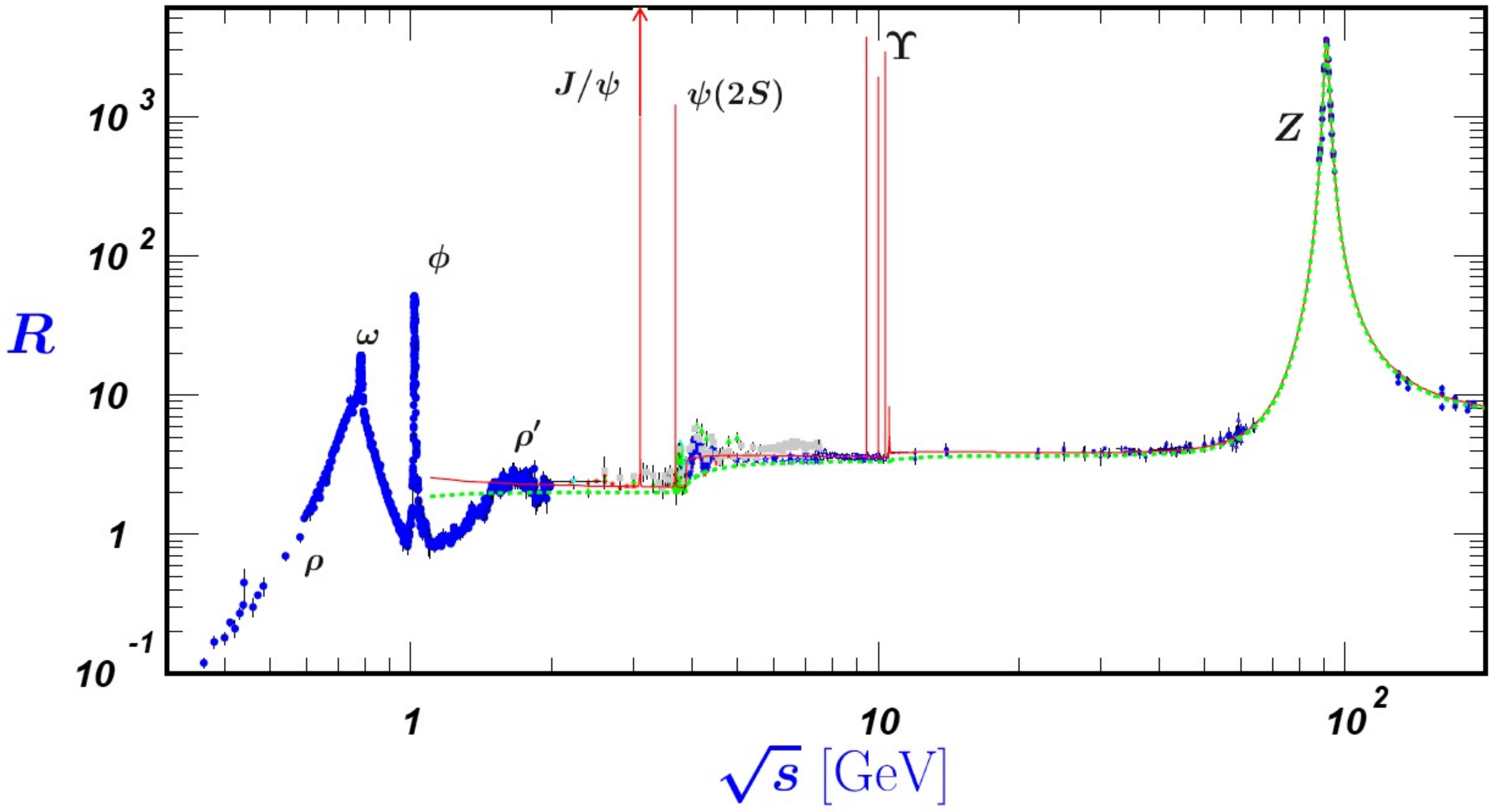


朱华星
北京大学

第三届强子与重味物理理论与实验联合研讨会
2024年4月6日

The R-ratio in e+e- annihilation

$$R = \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



$$\sigma(e^+e^- \to X) = \int d^4x\, e^{iqx} \langle\Omega|J^\mu(x)J^\dagger_\mu(0)|\Omega\rangle$$

One of the most important observables in particle physics!

Cleanest definition in terms of operators. Allows first principle calculation in Lattice QCD

Fully inclusive <=> contains less information

Energy Correlators (EECs)

Basham, Brown, Ellis, Love, 1977-1978

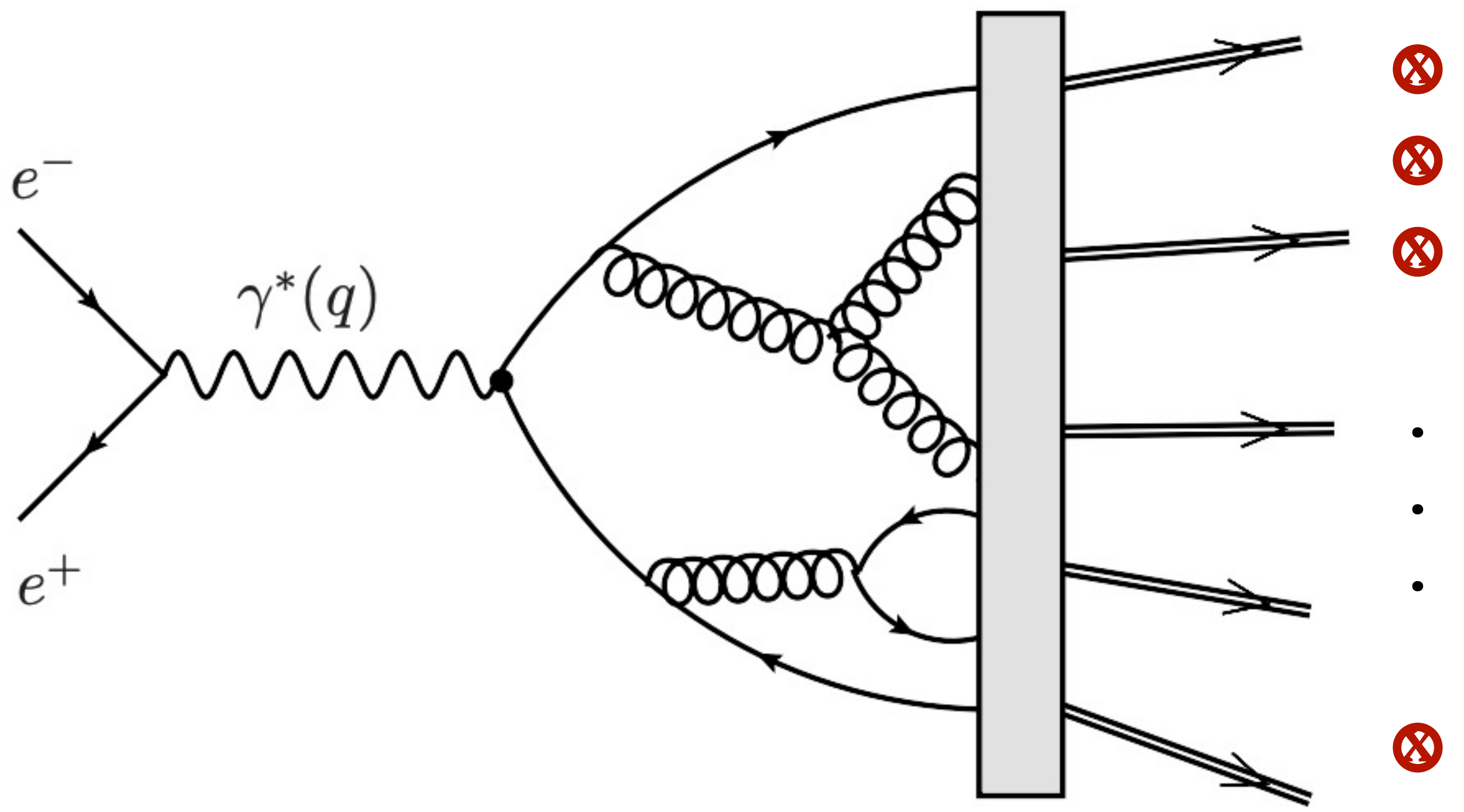
k-point Energy Correlator: Measurement of k-point angular correlation, weighted by product of energy of k particles, inclusive in all-particle combination

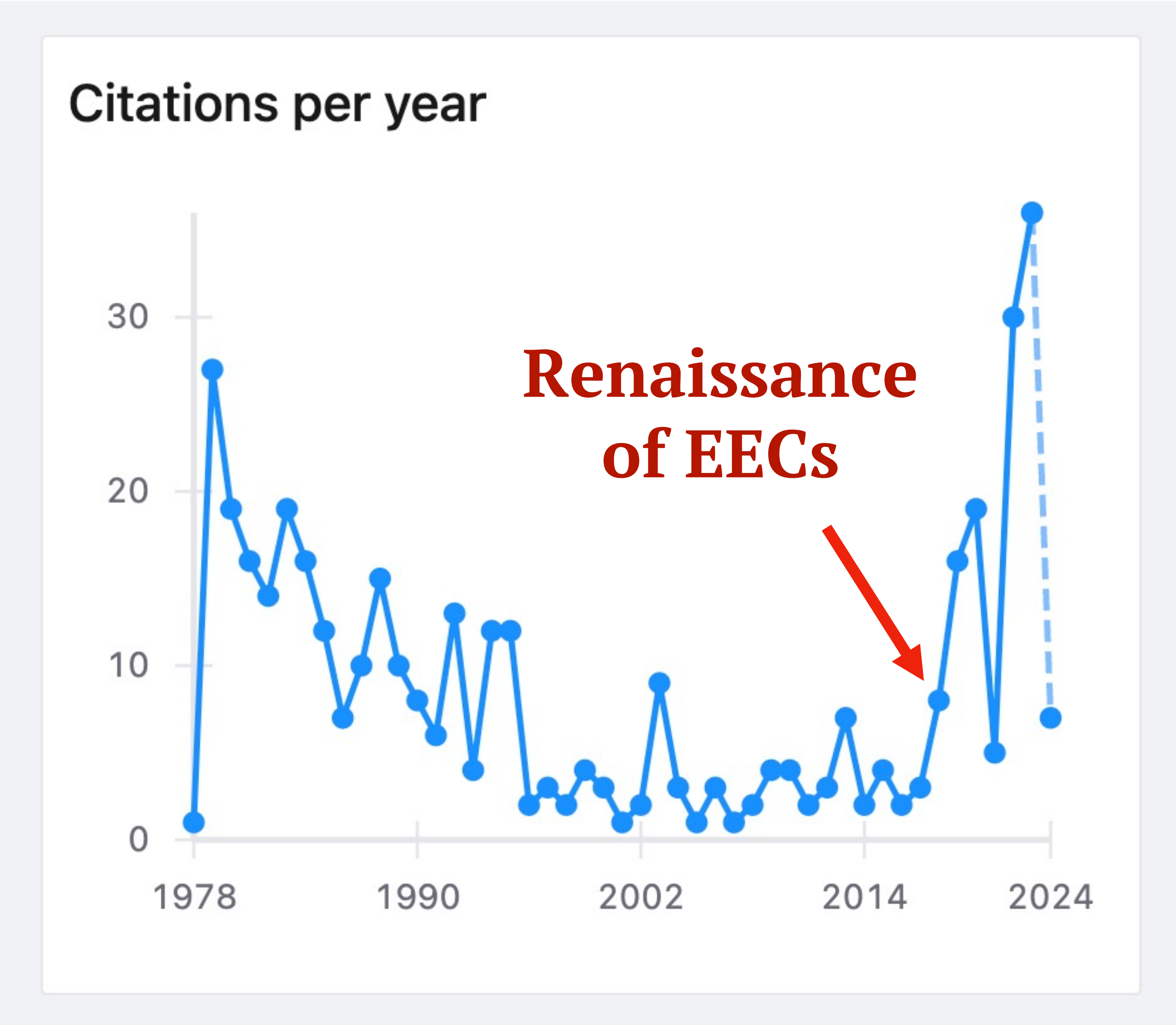
$$\Sigma(\{n\}) = \int d^4x\, e^{iqx} \langle \Omega | J^\mu(x) \mathcal{E}(n_1) \cdots \mathcal{E}(n_k) J_\mu^\dagger(0) | \Omega \rangle$$

Energy operator

Hadron level observable

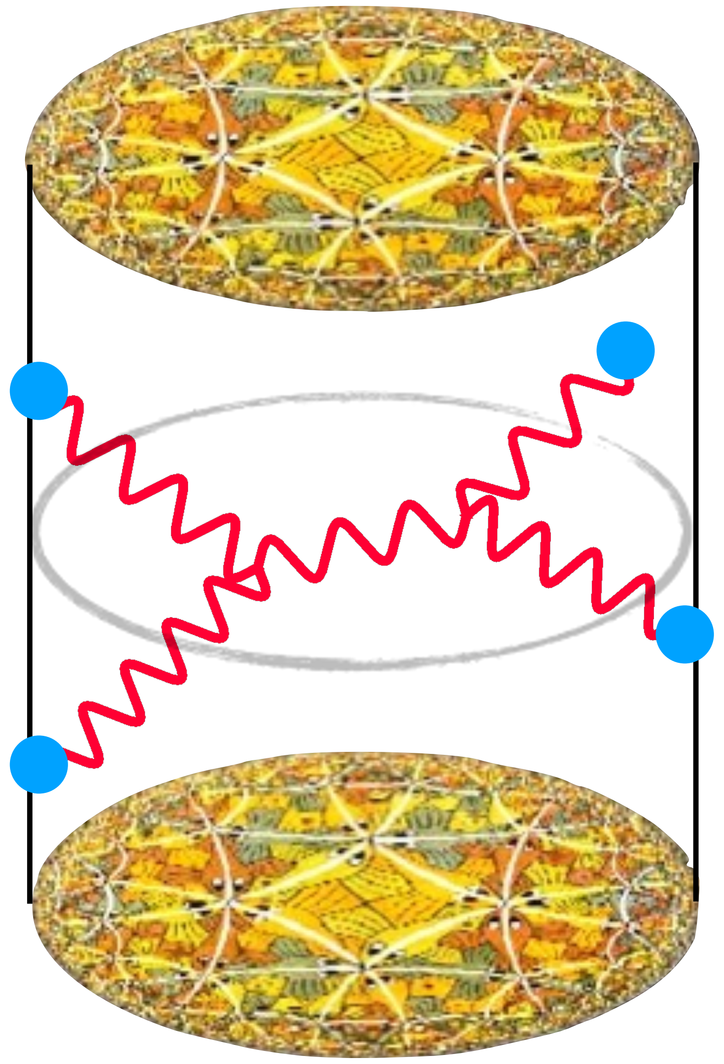
Sufficiently inclusive to allows perturbation calculations using quarks and gluons



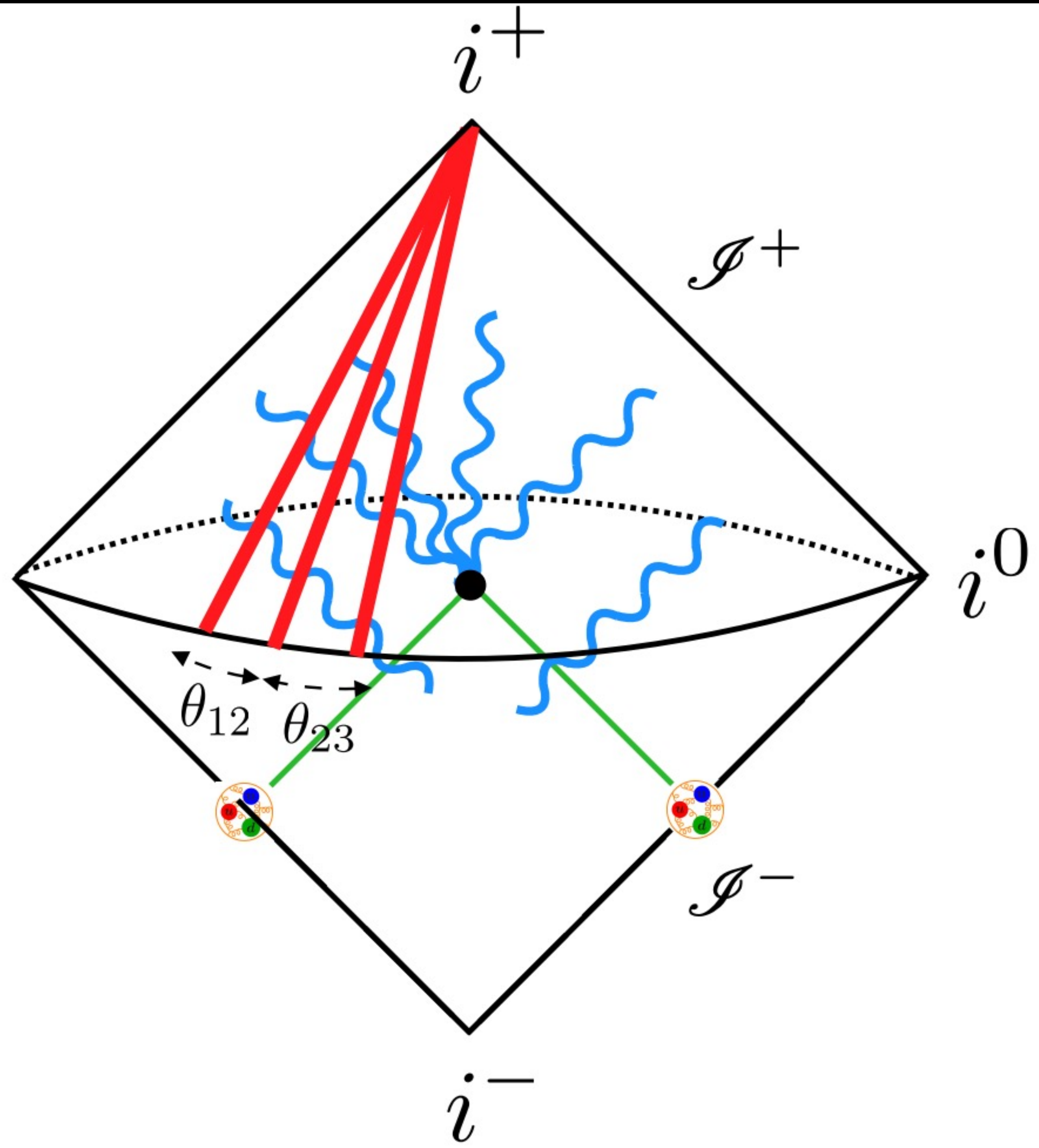


The trilogy

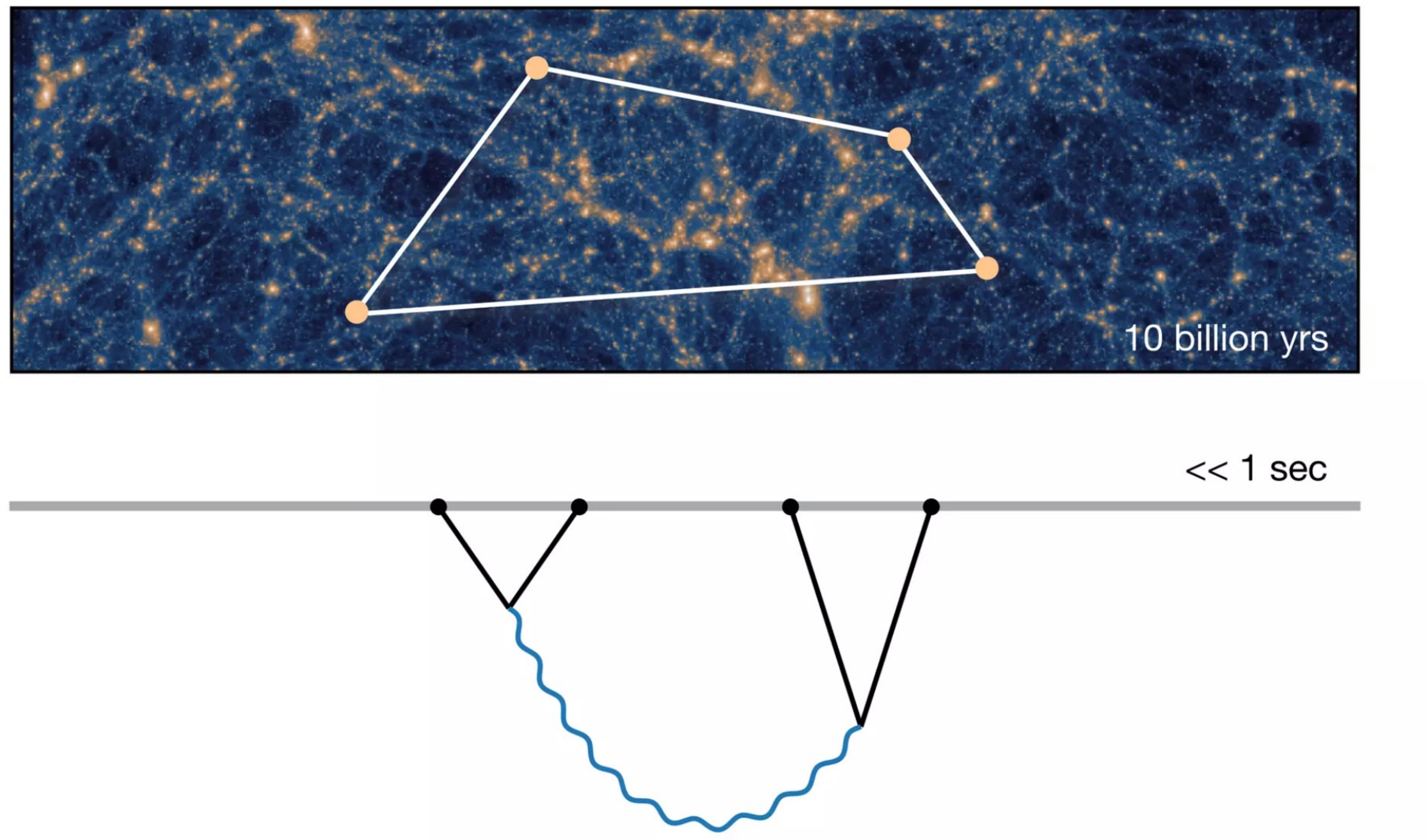
Formal and QCD theory ⇄ **Particle and nuclear phenomenology** ⇄ **Experiments across colliders**



AdS correlator



Collider correlator



Cosmological correlator

Community activities

A burst of dedicated workshops in the past and coming years:

- CCNU, Wuhan: One-day workshop on energy-energy correlator in high-energy collisions, 2023
- Mainz Institute of Theoretical Physics: Energy Correlators at the Collider Frontier, 2024
- Simmons Center for Geometry and Physics: Energy Operators in Particle Physics, Quantum Field Theory and Gravity, 2024
- Kavli Institute of Theoretical Physics: Frontiers of Quark-Gluon Matter, 2025

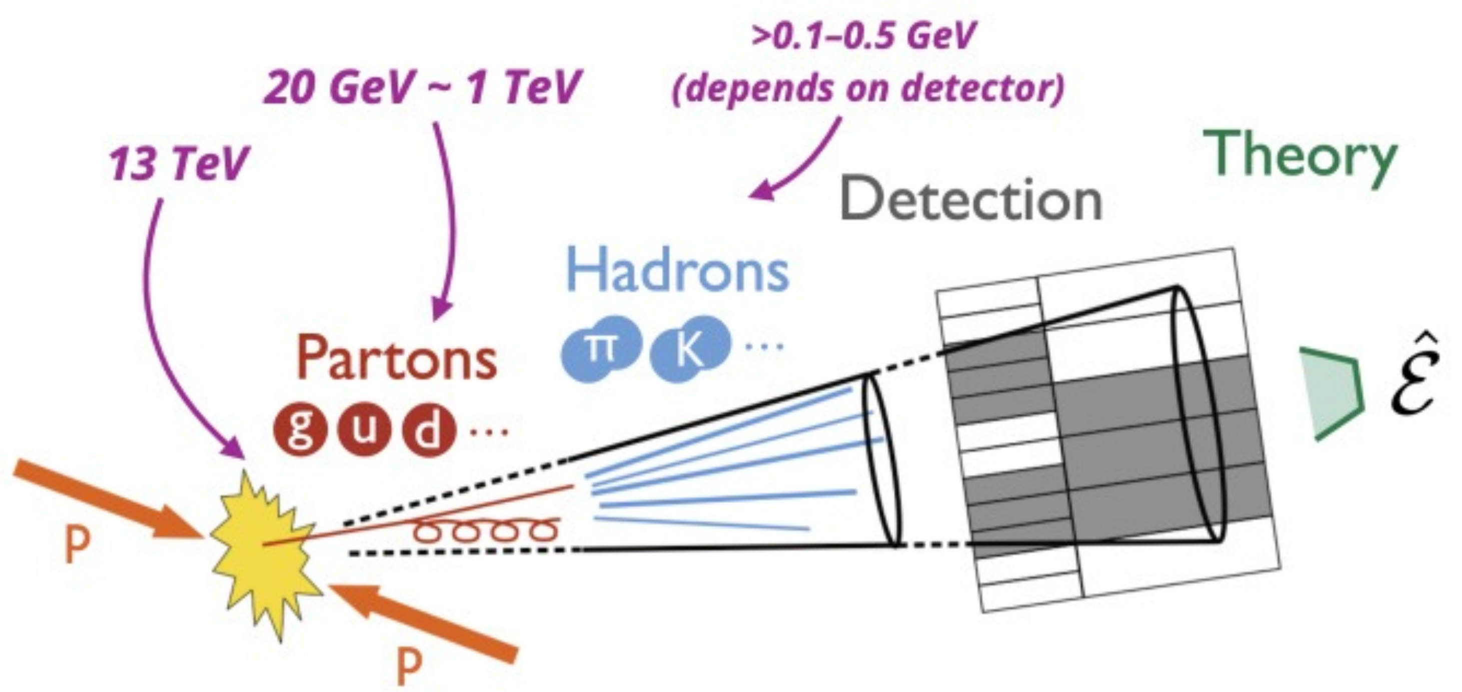
Snowmass Theory Frontier Report

- An explosion of theoretical activity in collider phenomenology has led to many new collider observables including many forms of jet substructure and the emerging field of multi-point correlators, employing widespread innovations in computational theory to leverage machine learning and artificial intelligence.

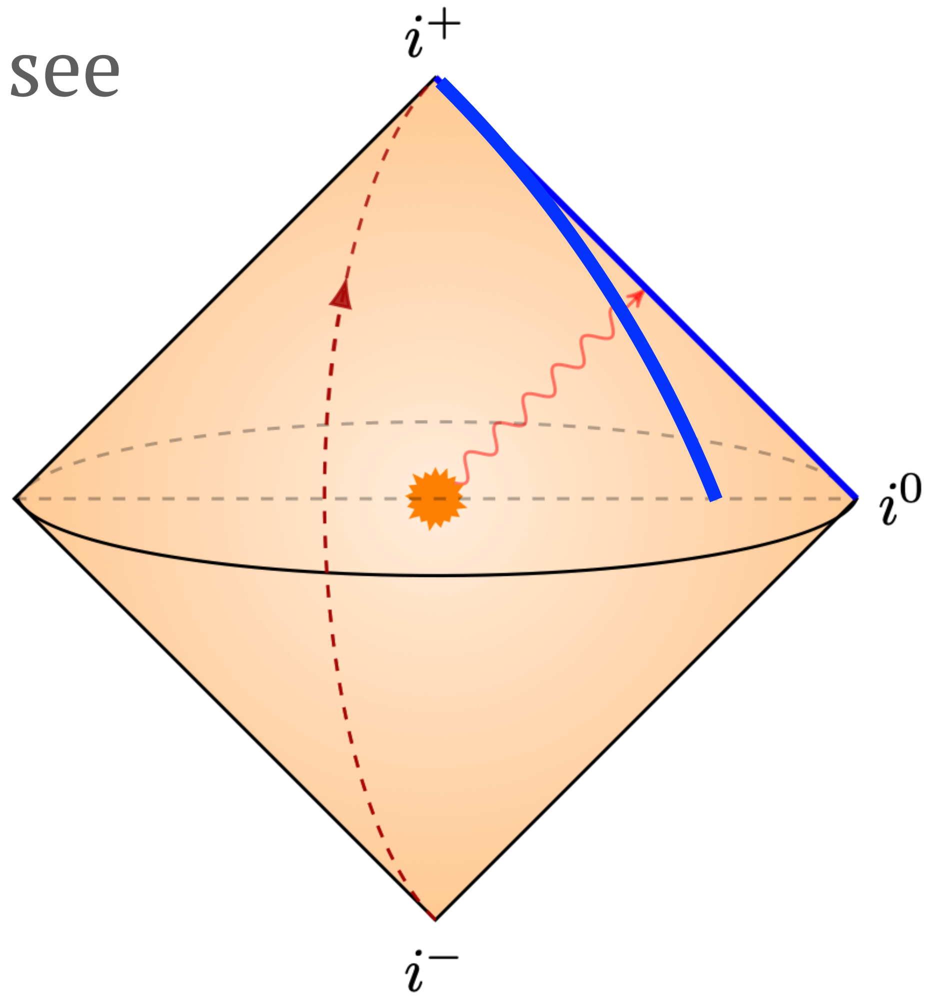
2211.05772

The Energy Operator

What experimentalist see



What theorist see



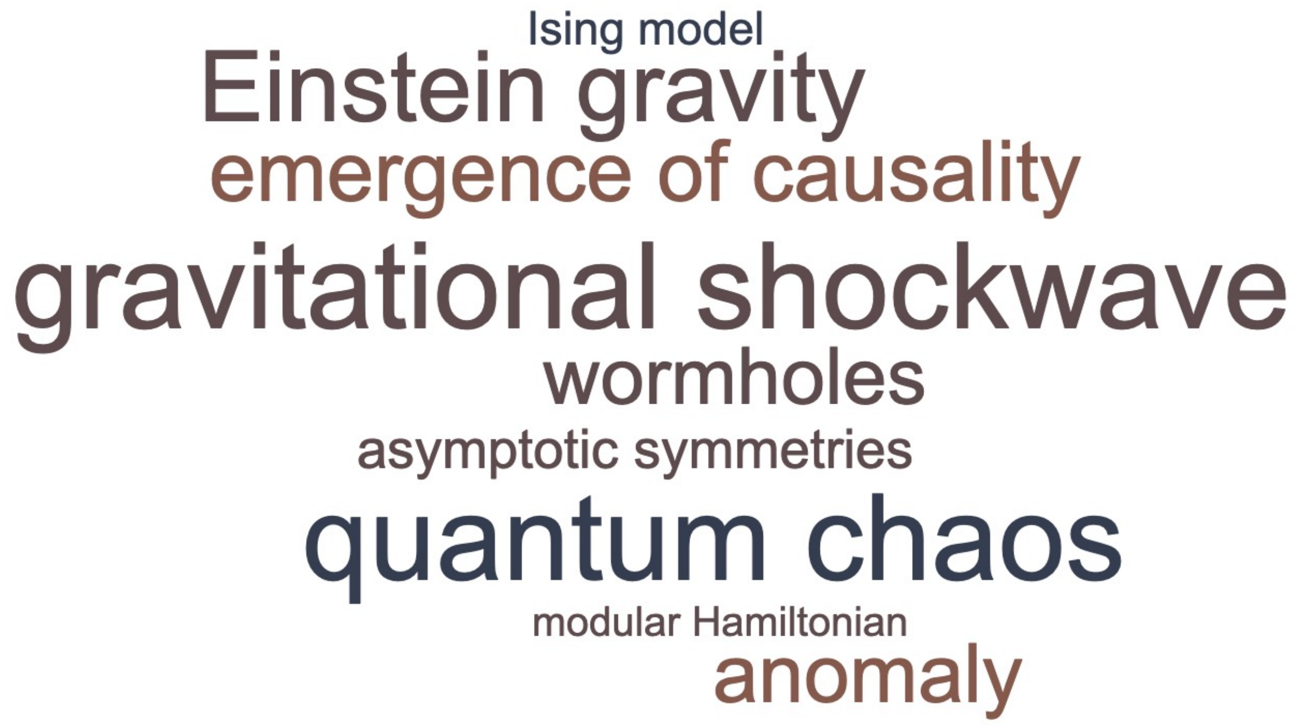
$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\, \vec{n}_i T^{0i}(t, r\vec{n})$$

- A local version appears in the construction of wormhole and time travel (Morris, Thorne, 1988)
- In collider context: (Sveshnikov, Tkachov, 1995)

$$\langle\Psi|T_{\mu\nu}|\Psi\rangle \geq 0 \quad ✗$$

$$\langle\Psi|\mathcal{E}(n)|\Psi\rangle \geq 0 \quad ✓$$

- Besides central in collider physics, appears in various other context:



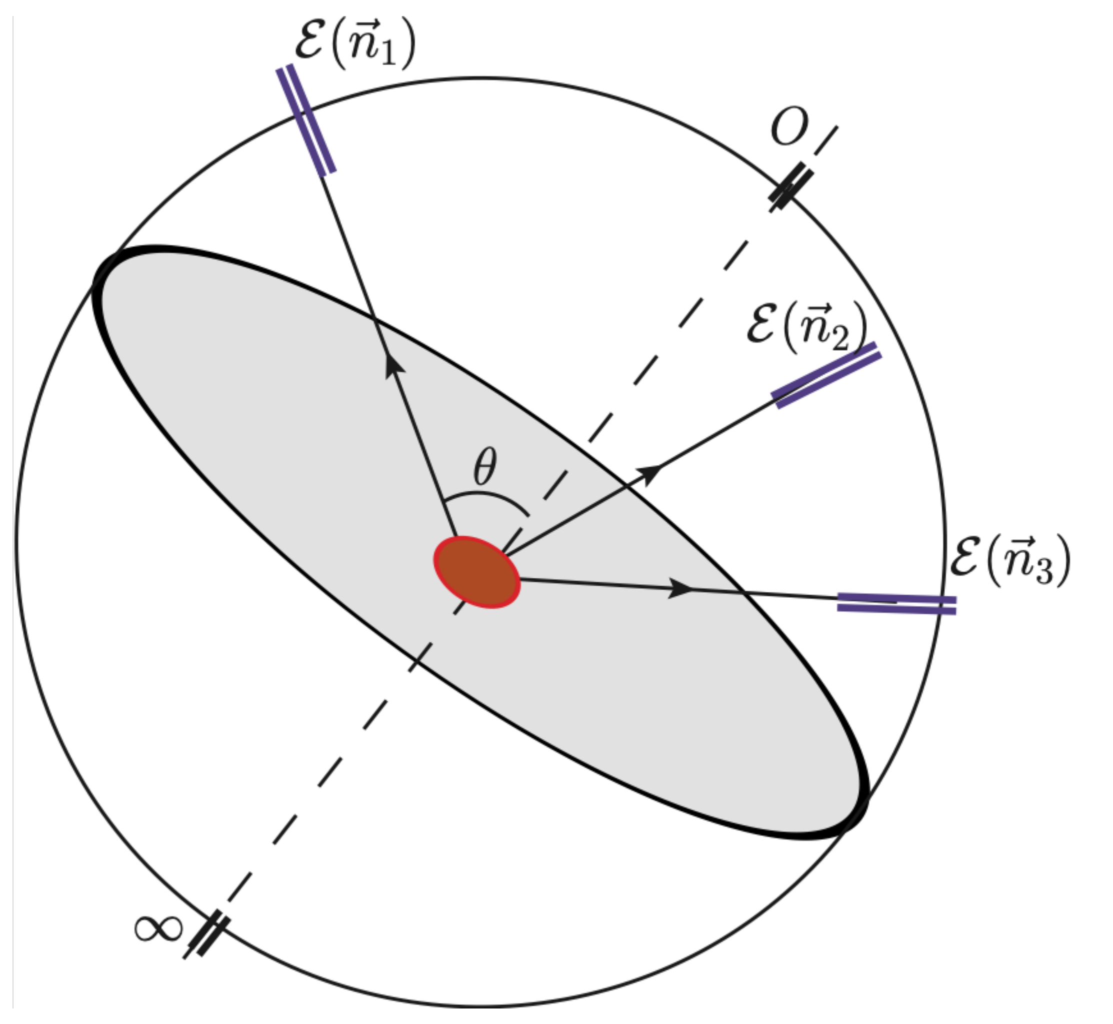
Analytic Simplicity

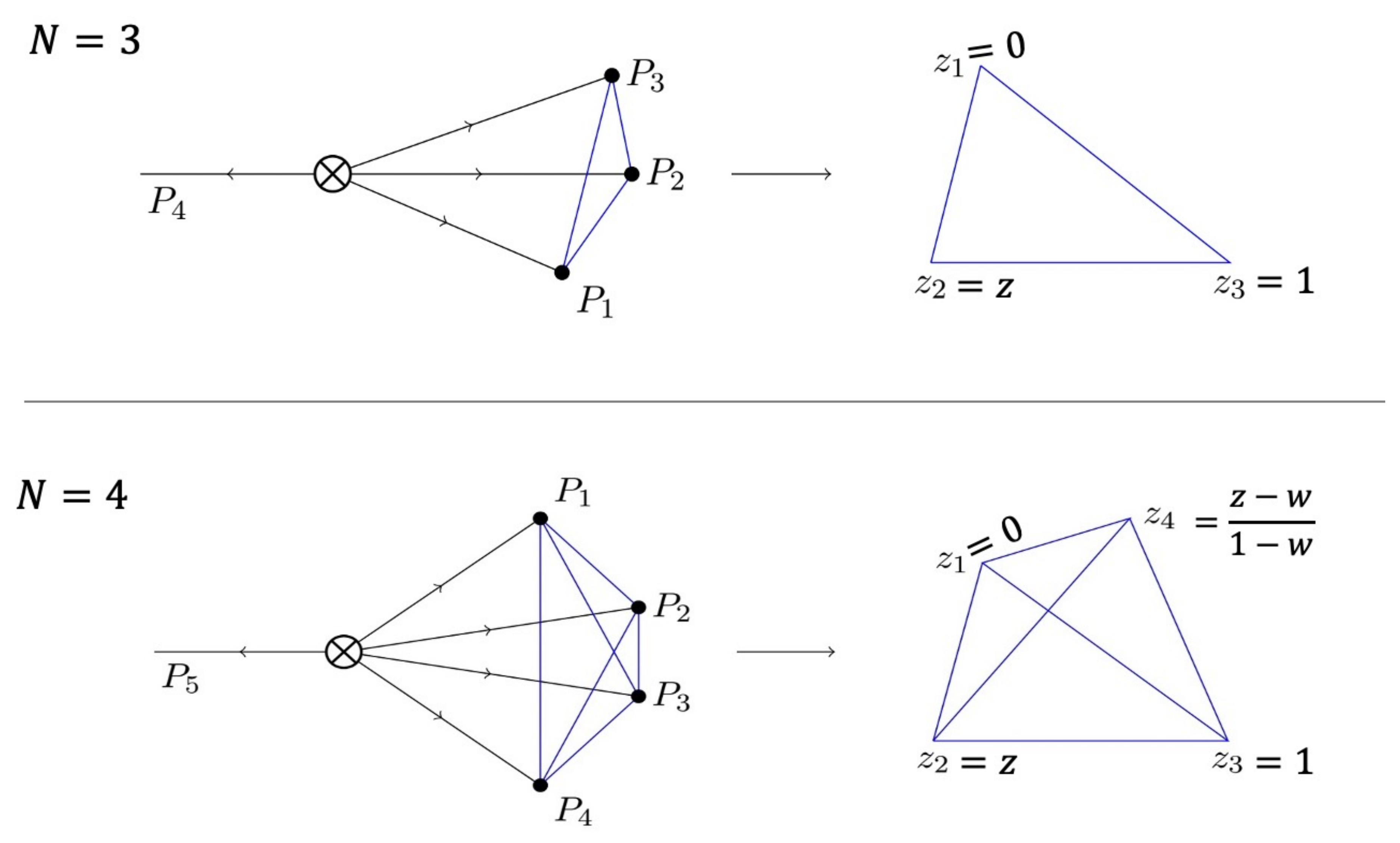
EEC is the only event shape observable analytically computed beyond leading order!

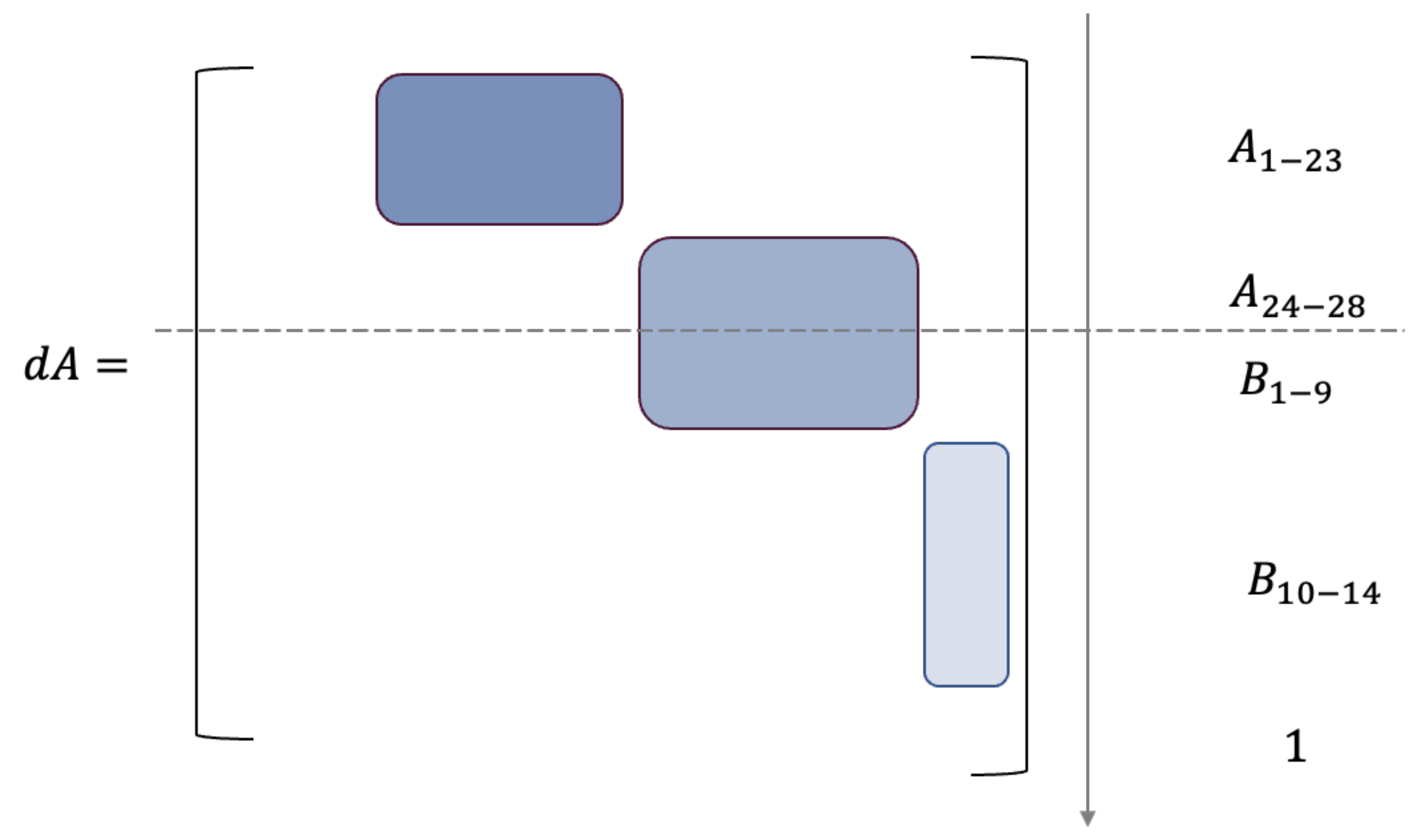
QCD at NLO (Dixon, M.X. Luo, Shtabovenko, T.Z. Yang, HXZ, 2018)
N=4 SYM at NNLO (Henn, Sokatchev, K. Yan, Zhiboedov, 2019)

Going beyond two point: Analytic bootstrap?

Chicherin, Moult, Sokatchev, K. Yan, T.Z. Yang,X.Y. Zhang, Y.Y. Zhu, et al.





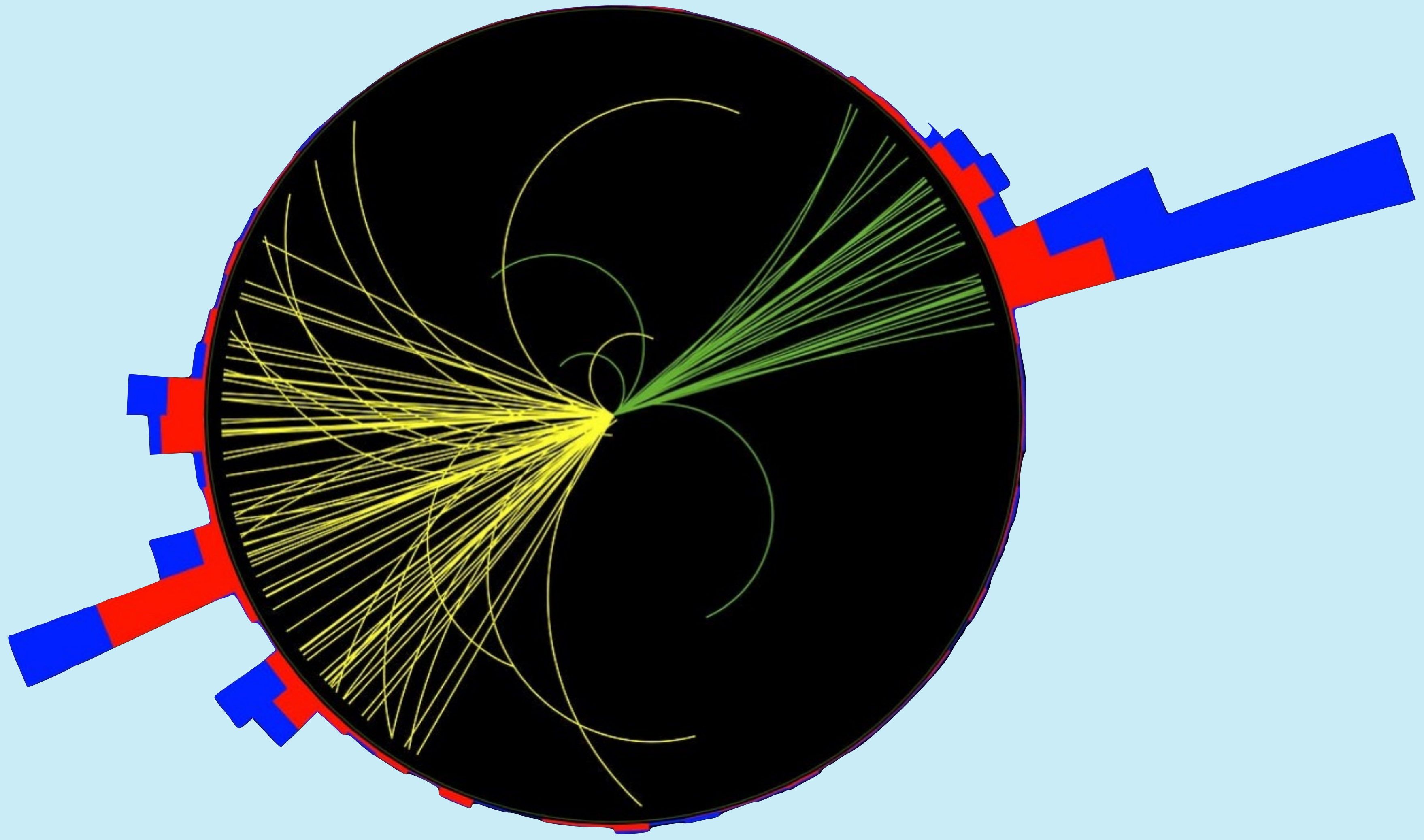


An iterative structure in N (number of point)?

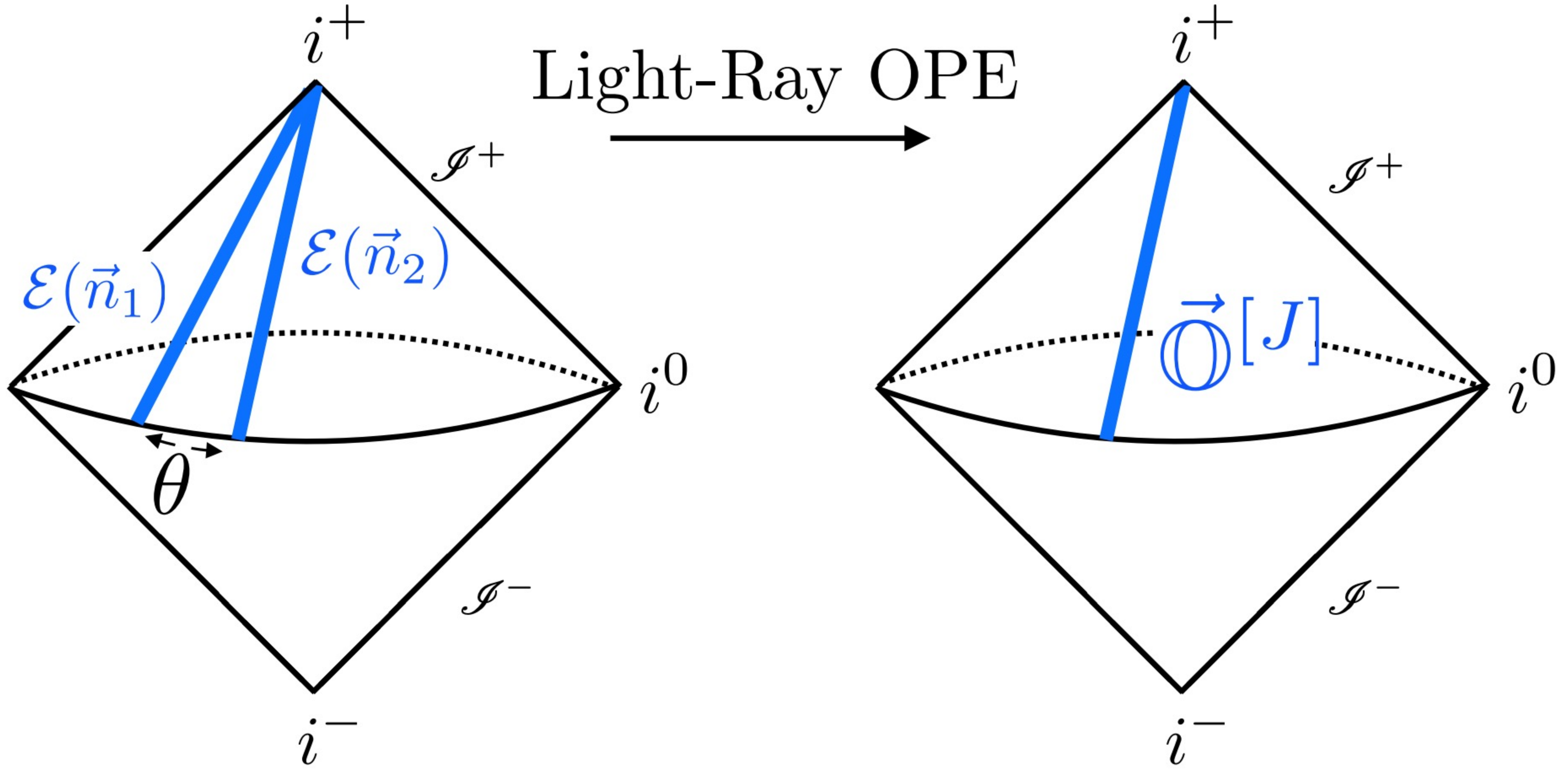
Conformal collider and lightray OPE

Hofman, Maldacena, 2008; Kologlu, Kravchuk, Simmons-Duffin, Zhiboedov, 2019

$$\lim_{n_2 \to n_1} \langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle_\Psi = ?$$



Enhancement of small-angle energy correlation is evident from experiment



$$\mathcal{E}(n_1)\mathcal{E}(n_2) = \frac{1}{\theta^{2-\gamma(3)}}\mathbb{O}(3) + \text{higher twist}$$

small-angle enhancement

anomalous dimension of twist-2 operator

Scaling law in jet?


But they didn't study the small angles. And I asked him whether they had a good reason for not studying the small angles and they said well we didn't know the resummation formula...
Polchinski: There is a lot of QCD data, can you see this (scaling behavior) there?
https://online.kitp.ucsb.edu/online/strings09/maldacena/rm/qt.html
47:13 / 1:42:43

Resummation formula in QCD

Dixon, Moult, HXZ, 2019; H. Chen, Moult, X.Y. Zhang, HXZ, 2020; H. Chen, 2023

Evolution for EEC, valid to all orders

$$\frac{d}{d\ln\mu^2} J_N(\theta,\mu) = \int_0^1 dx\, x^N J_N(\theta x^2, \mu) P_T(x,\mu)$$

conventional DGLAP evolution for parton fragmentation

$$\frac{d}{d\ln\mu^2} D_N(\mu) = D_N(\mu) \int_0^1 dx\, x^N P_T(x,\mu)$$

correlation of observable and convolution variables obstruct complete factorization

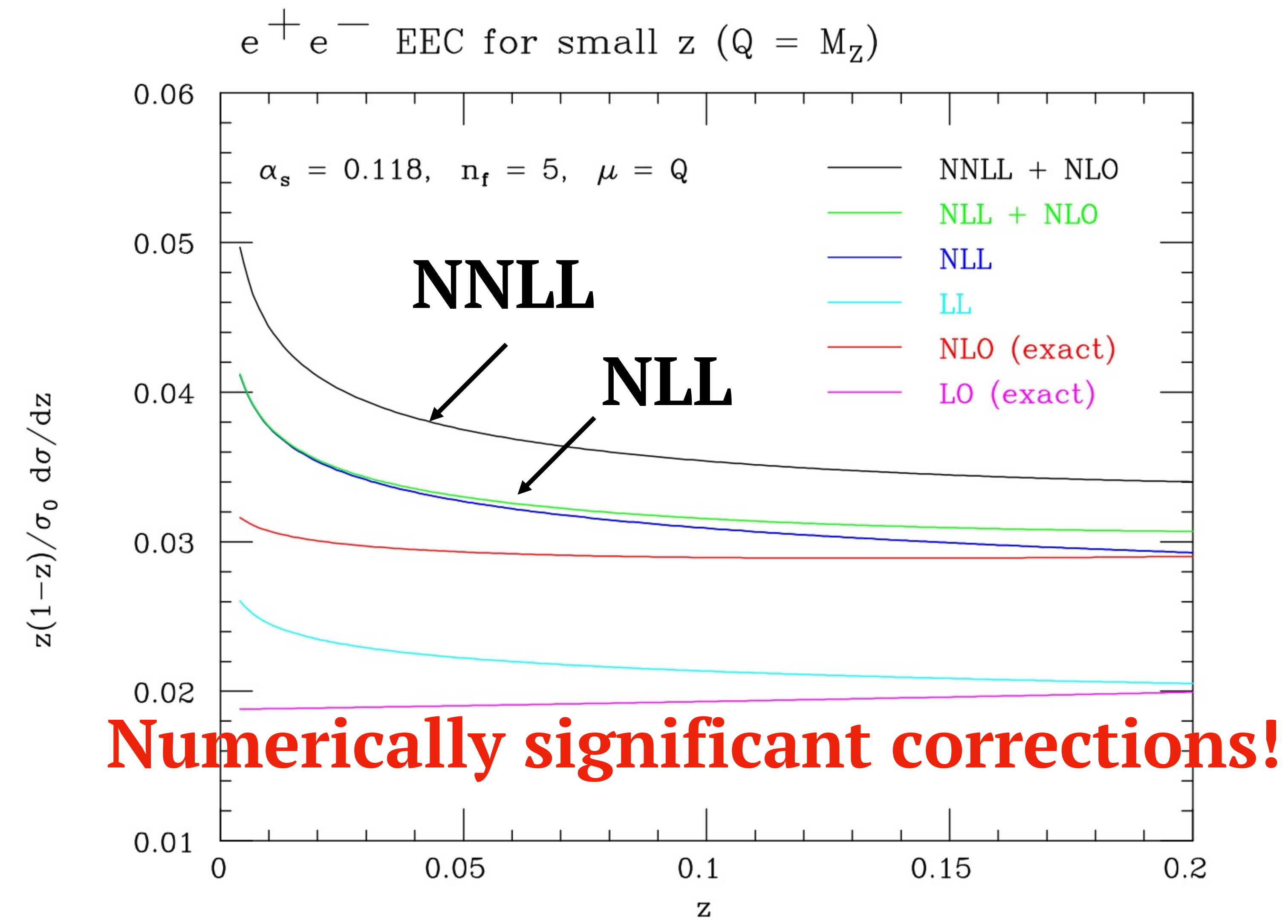
reciprocity relation:

Basso, Korchemsky, 2006
H. Chen, T.Z. Yang, Y.J. Zhu, HXZ, 2021

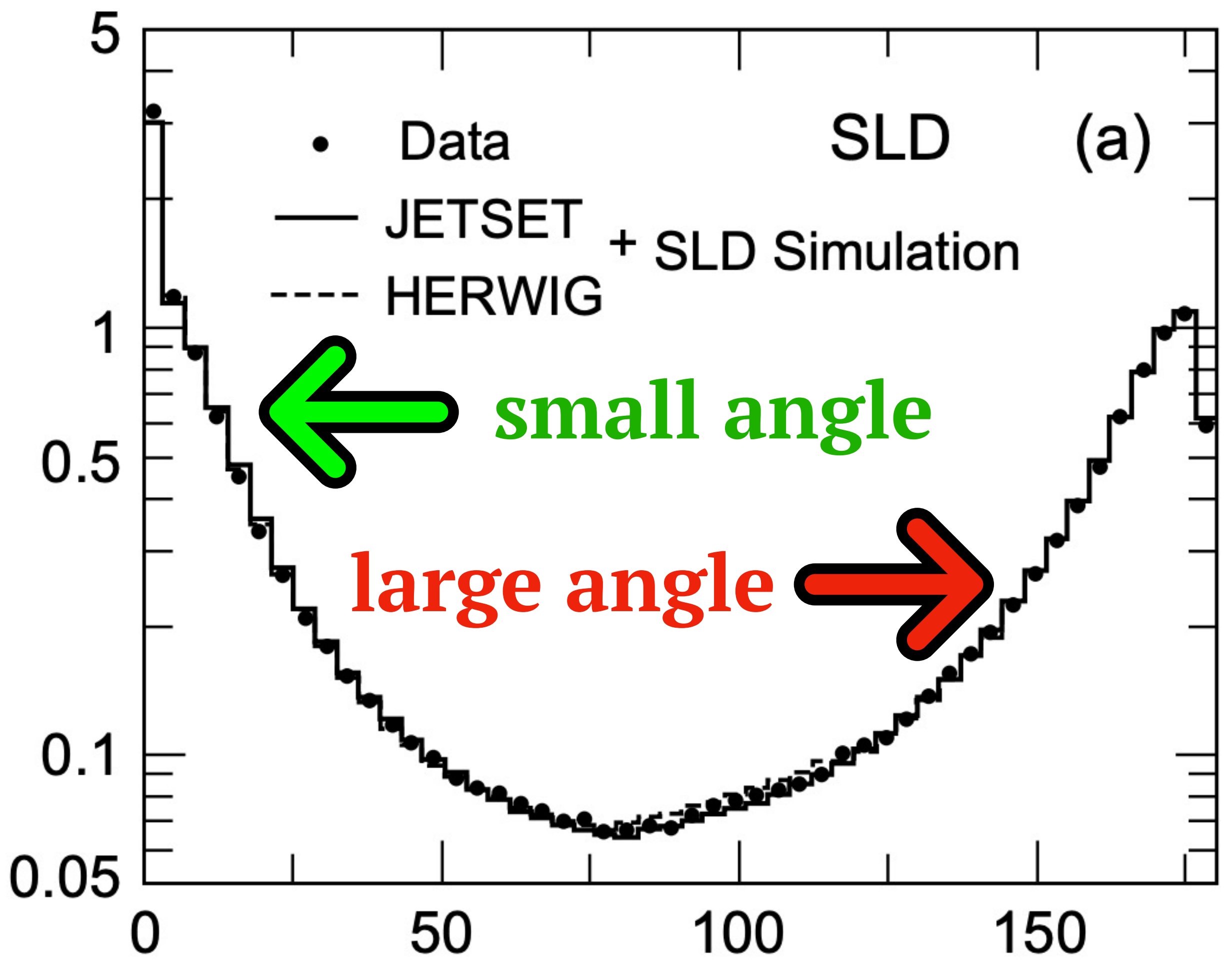
$$\gamma_S(N) = \gamma_T(N + 2\gamma_S(N))$$

moment of space-like DGLAP kernel

moment of time-like DGLAP kernel

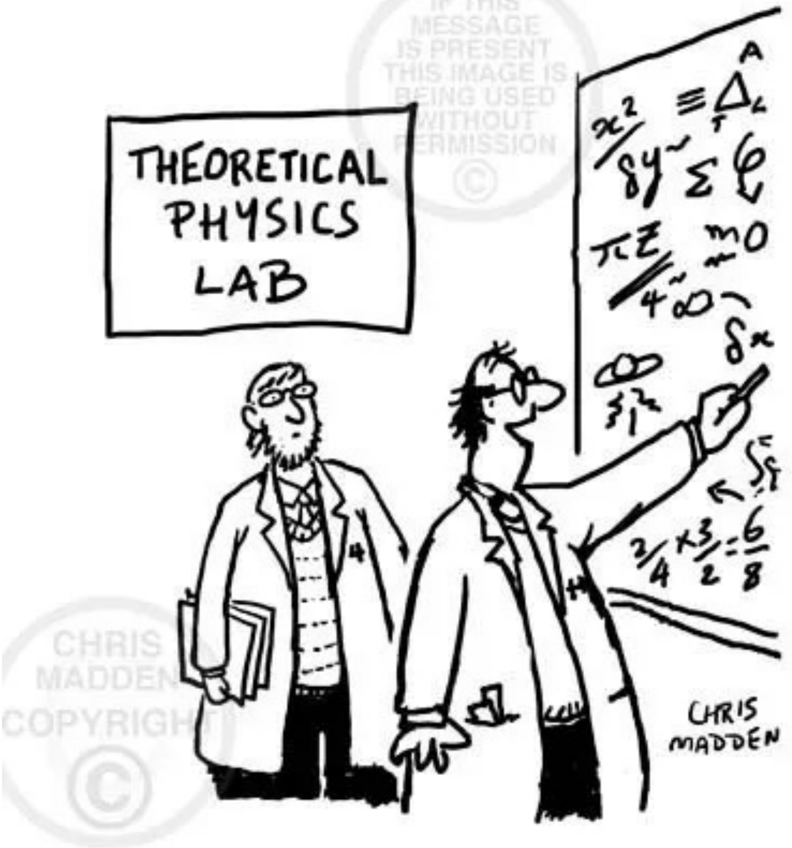


Theory re-inspire experiments

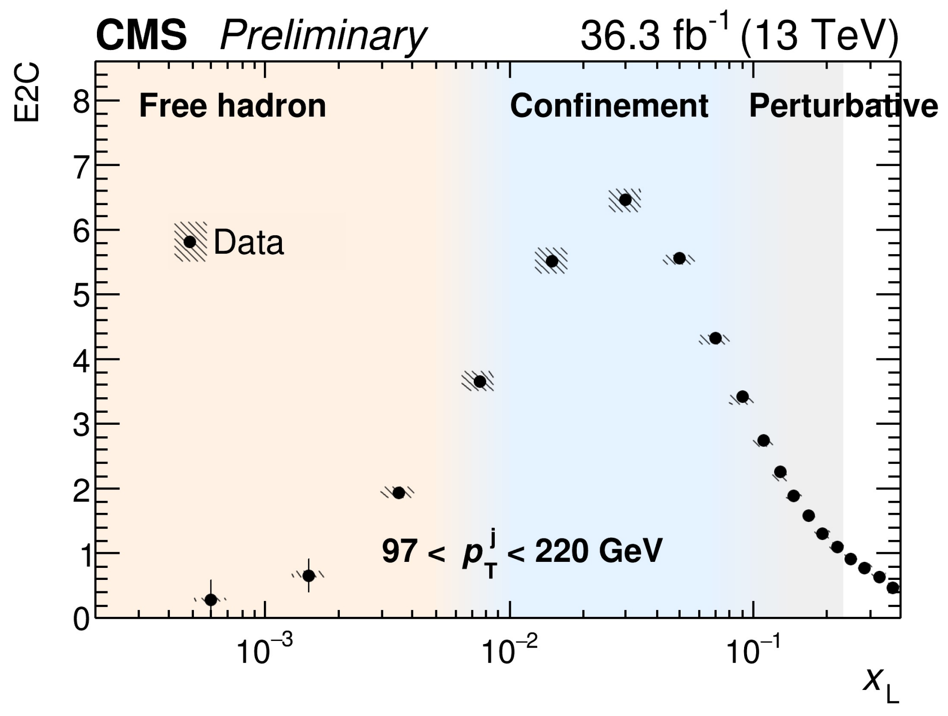


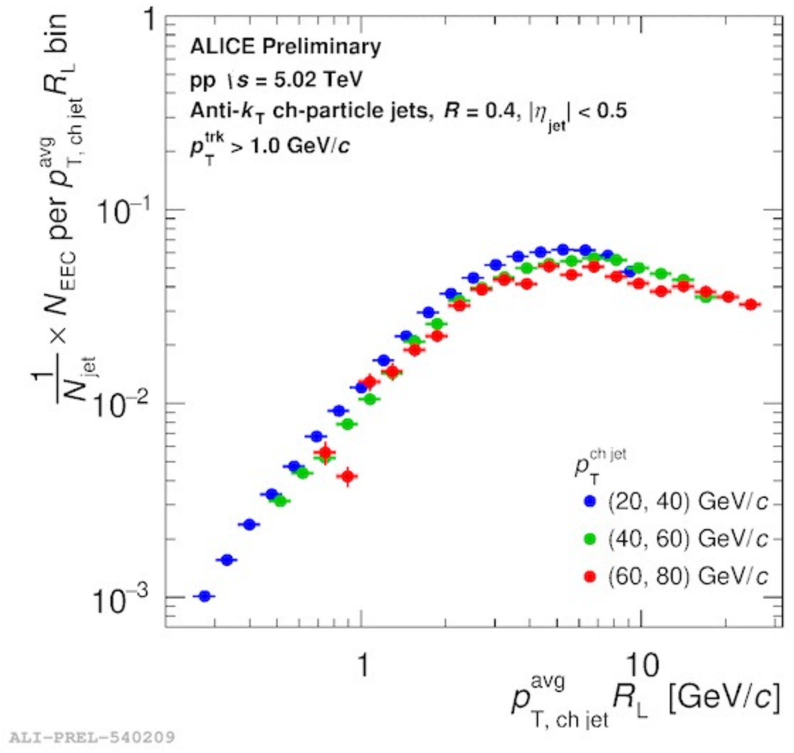
1994

theorists kick in



"Soon I will be able to answer one of the fundamental questions about the structure of the universe: *just how long is a piece of string?*"



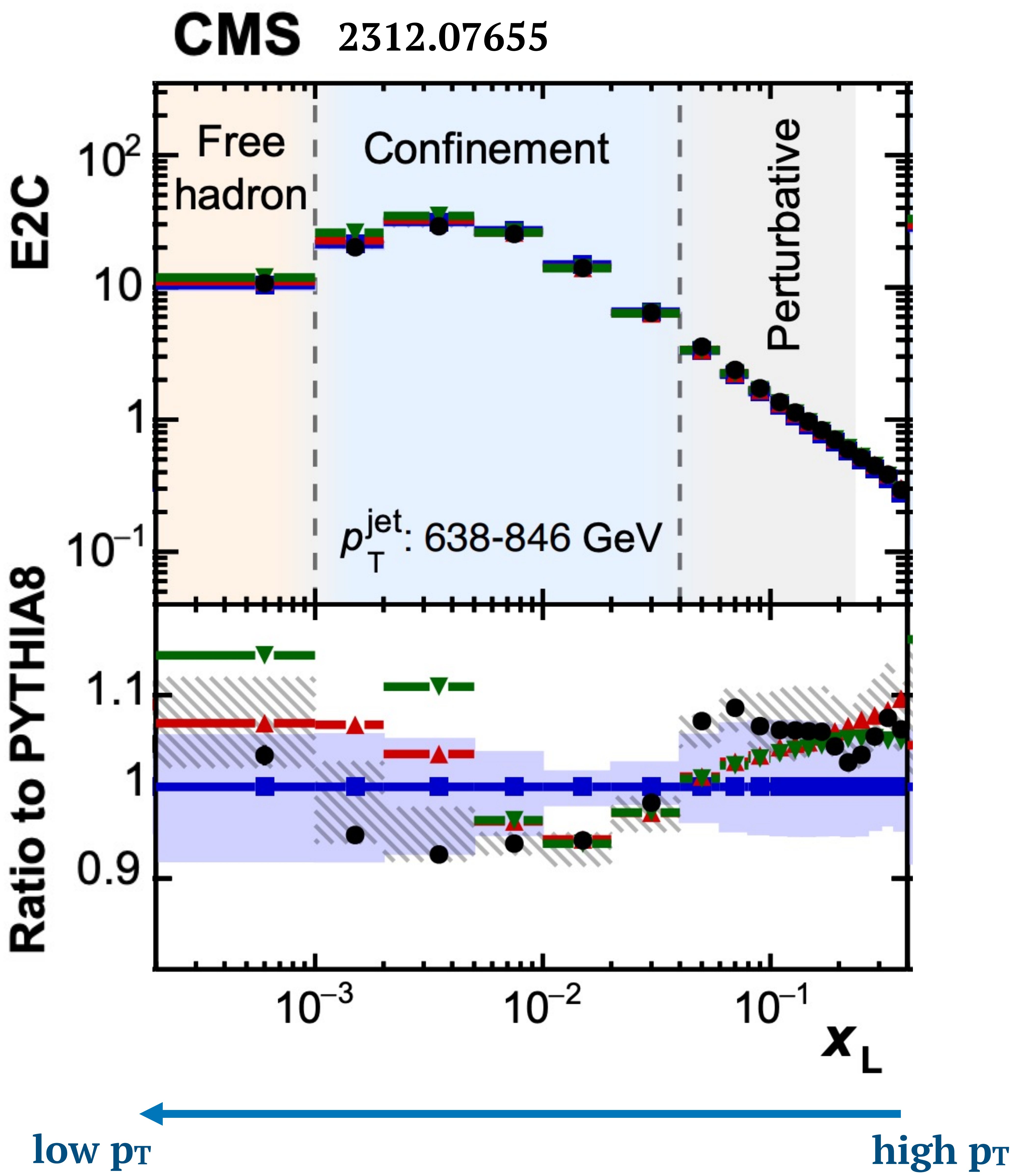


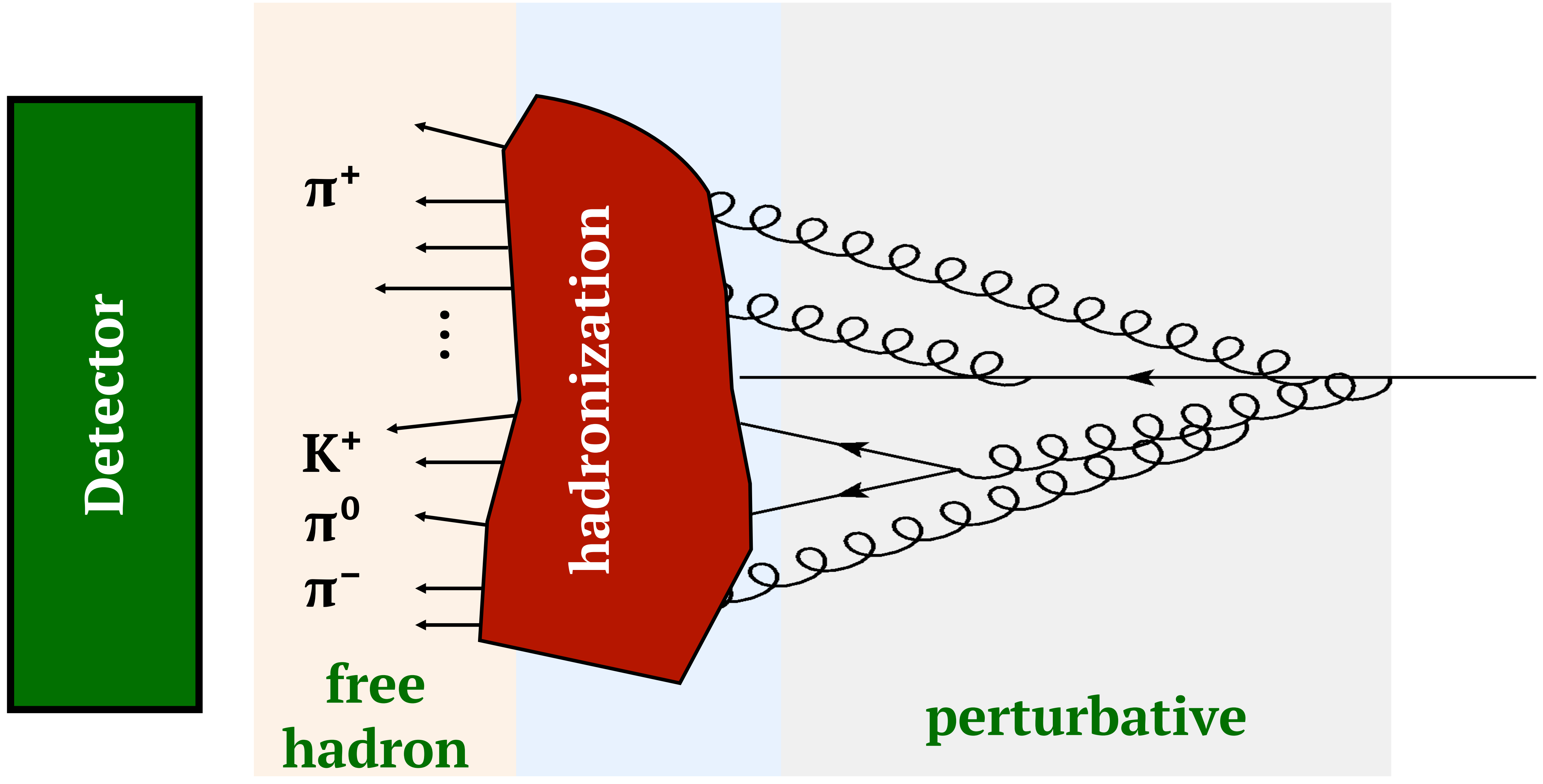
A re-analysis of LEP data is underway by a MIT group using tracks

"Jets elucidate how partons evolve into hadrons"

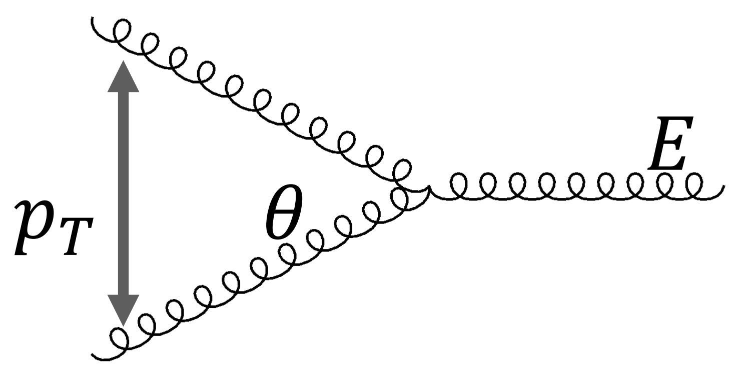
https://cms.cern/news/jets-elucidate-how-partons-evolve-hadrons

see also Komiske, Moult, Thaler, HXZ, 2022



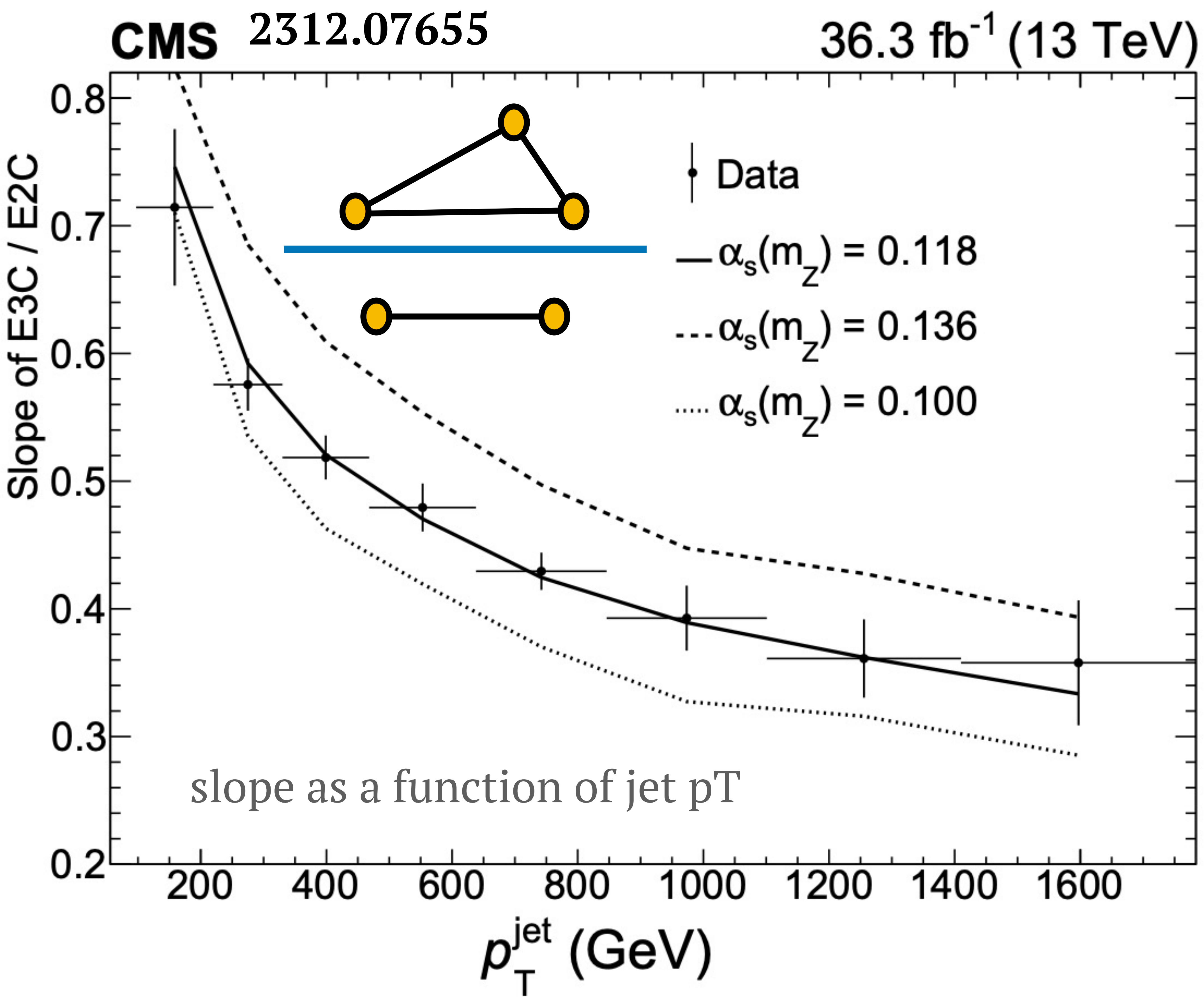


Observation of two scaling region in jet fragmentation for the first time!

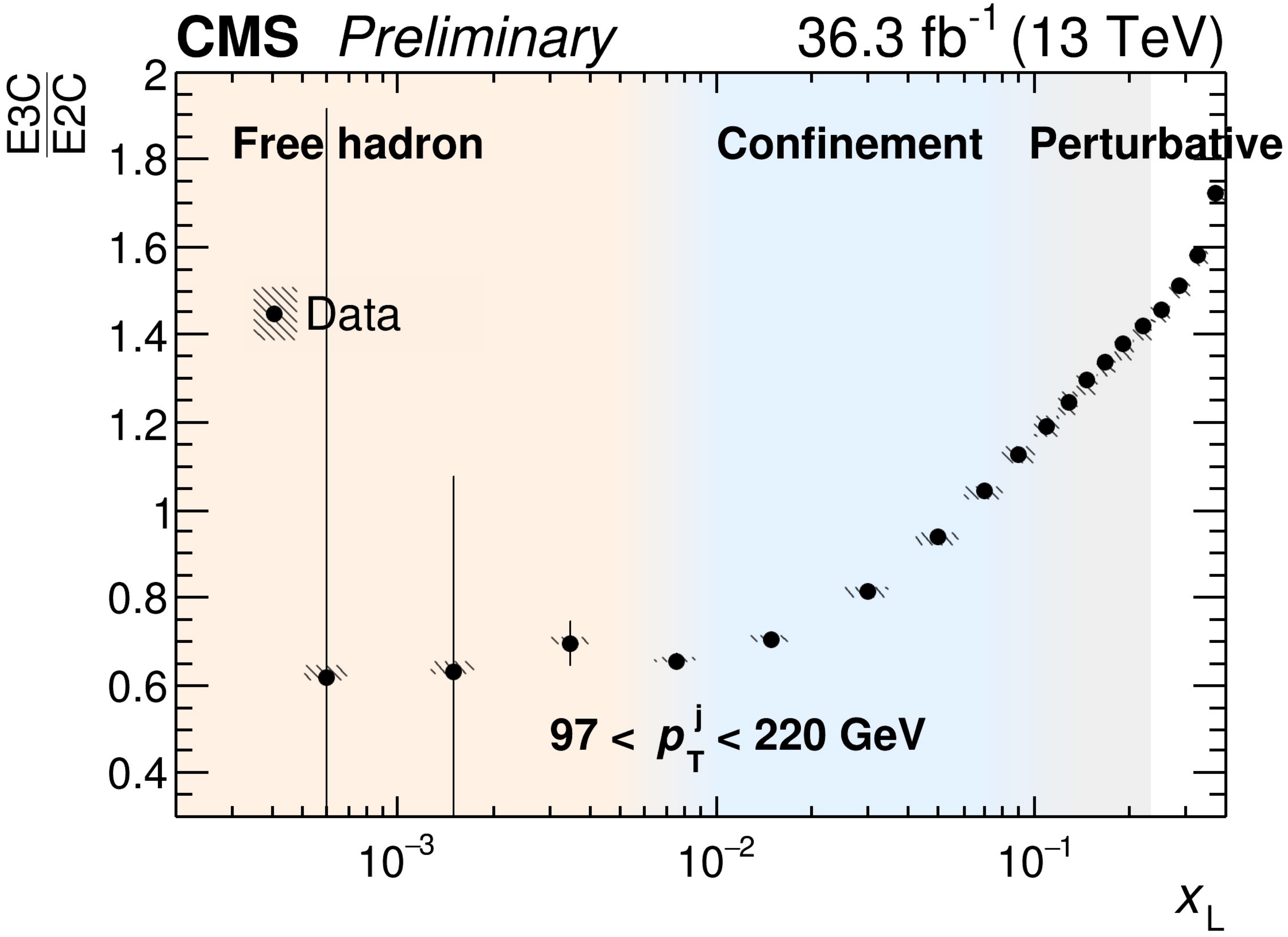


$$\theta \simeq \frac{p_T}{\langle E \rangle}$$

Asymptotic freedom in your face



Ratio between 3 point and 2 point energy correlator



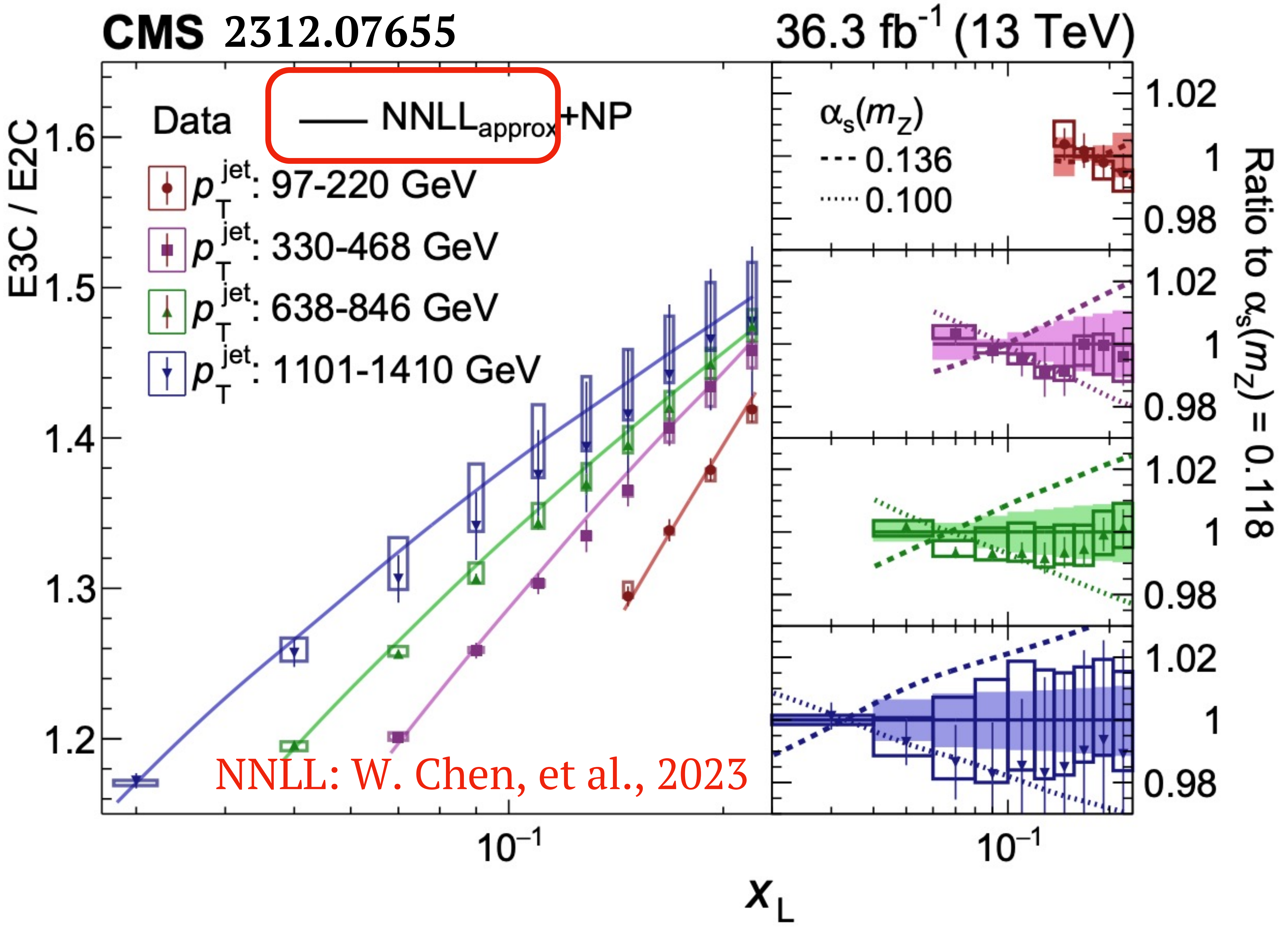
$$slope = \alpha_s(p_T\langle\theta\rangle) + \mathcal{O}(\alpha_s^2)$$

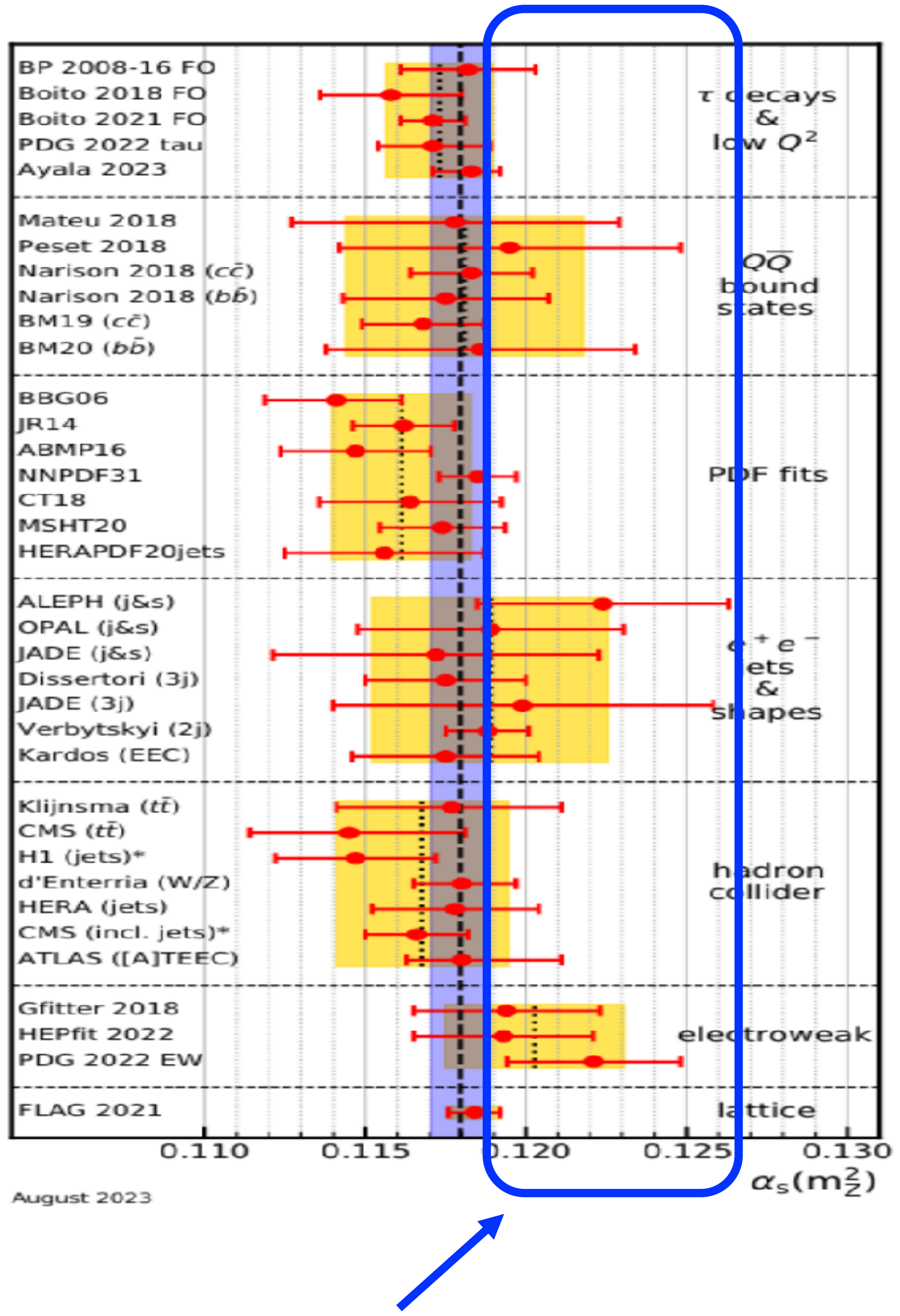
Reduction of slope at higher energy => asymptotic freedom!

Strong coupling from energy correlators

> jet-mass distribution. We find that quark jets and gluon jets have similar sensitivity to α_s, and emphasize that experimentally distinguishing quark and gluon jets is not required for an α_s measurement. We conclude that measuring α_s to the 10% level is feasible now, and with improvements in theory a 5% level measurement is possible. Getting down to the 1% level to be competitive with other state-of-the-art measurements will be challenging.

Hannesdottir, Pathak, Schwartz, Stewart, 2022



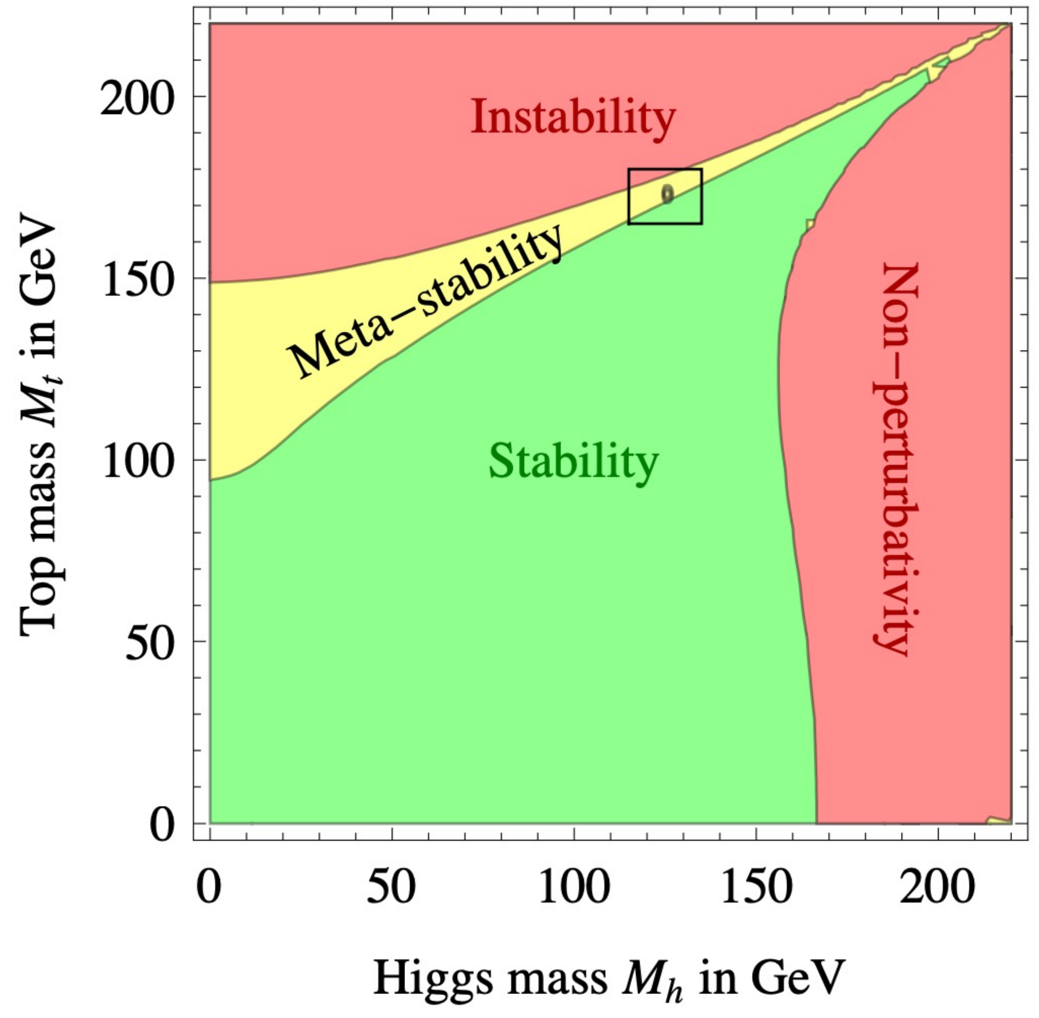


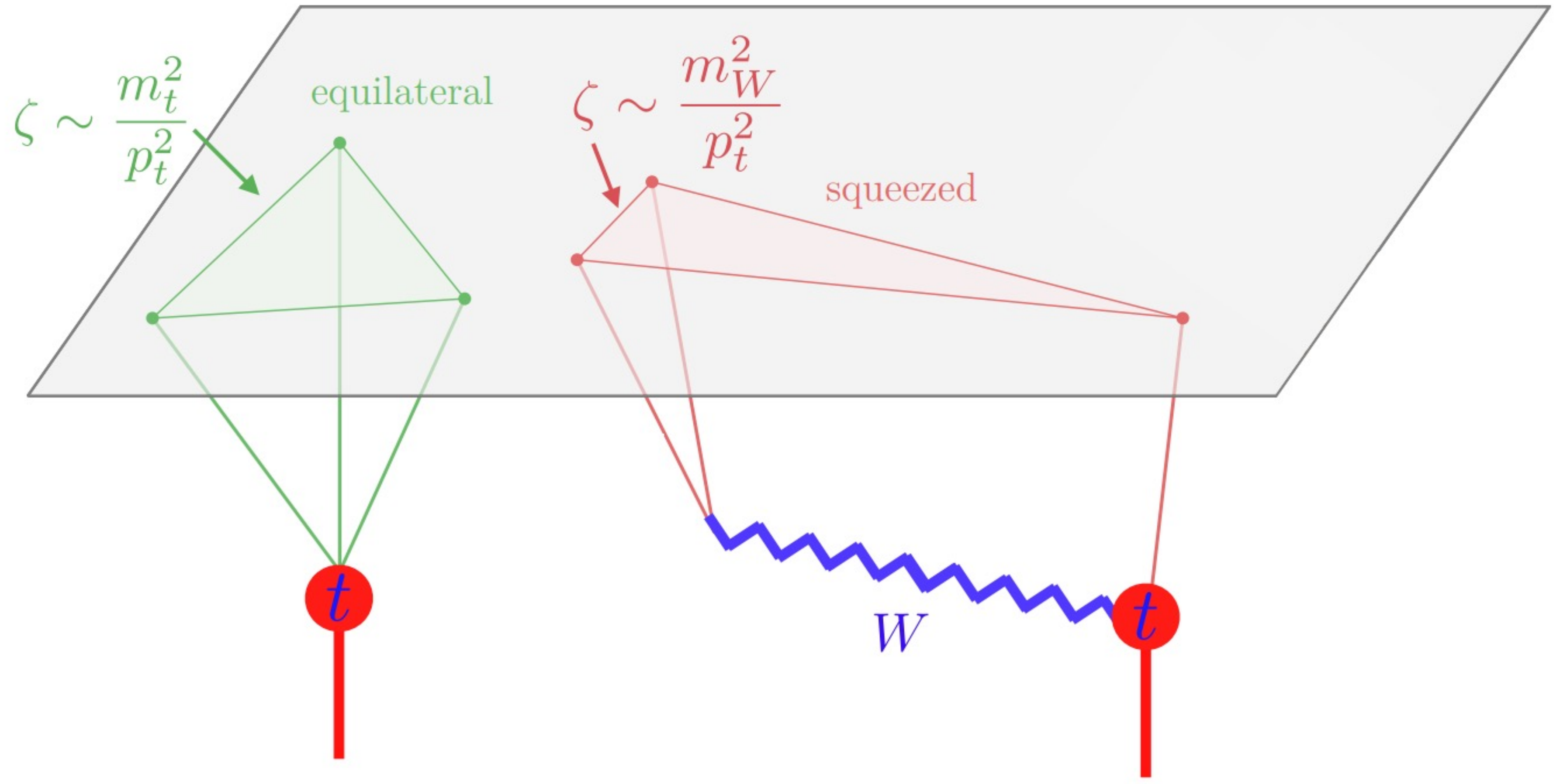
$$\alpha_s(m_Z) = 0.1229^{+0.0014}_{-0.0012}\,(\text{stat})^{+0.0030}_{-0.0033}\,(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$$

Matt Schwartz 9:42 PM
Congratulations on the αs measurement. 4% uncertainty seems shockingly small... was there much discussion after the talk?

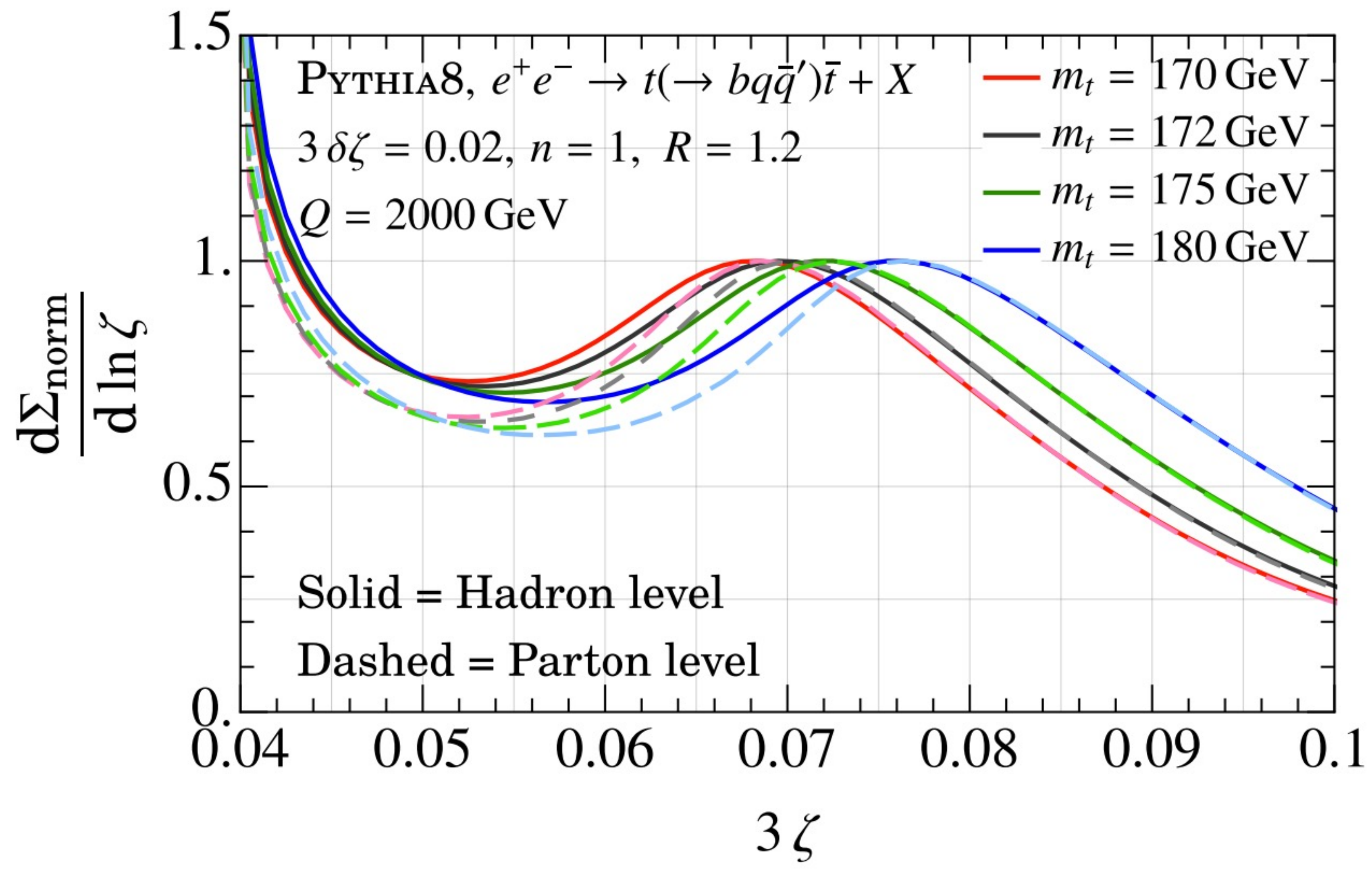
Energy correlators for top physics

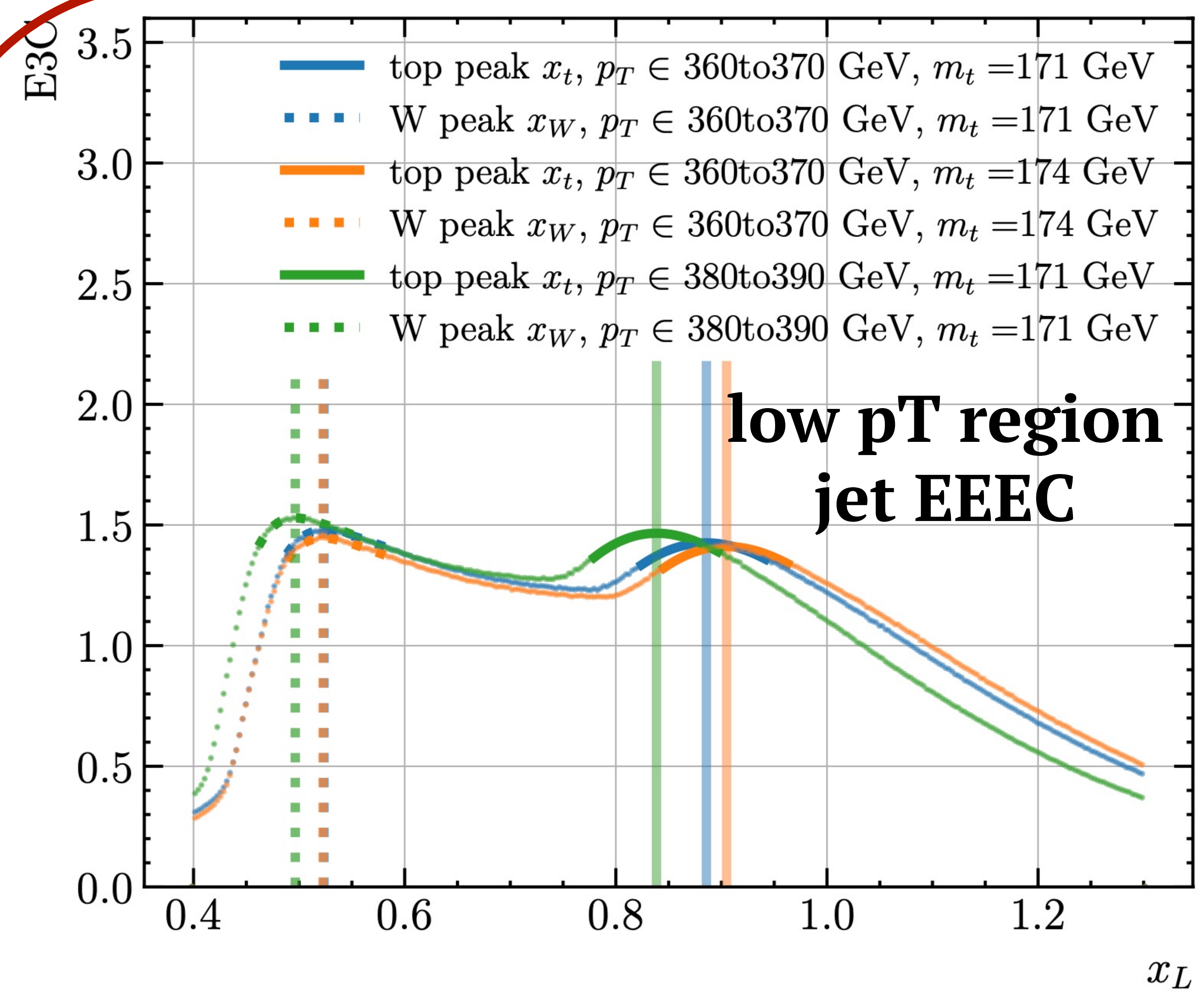
top quark mass is closely related to stability of the SM vacuum





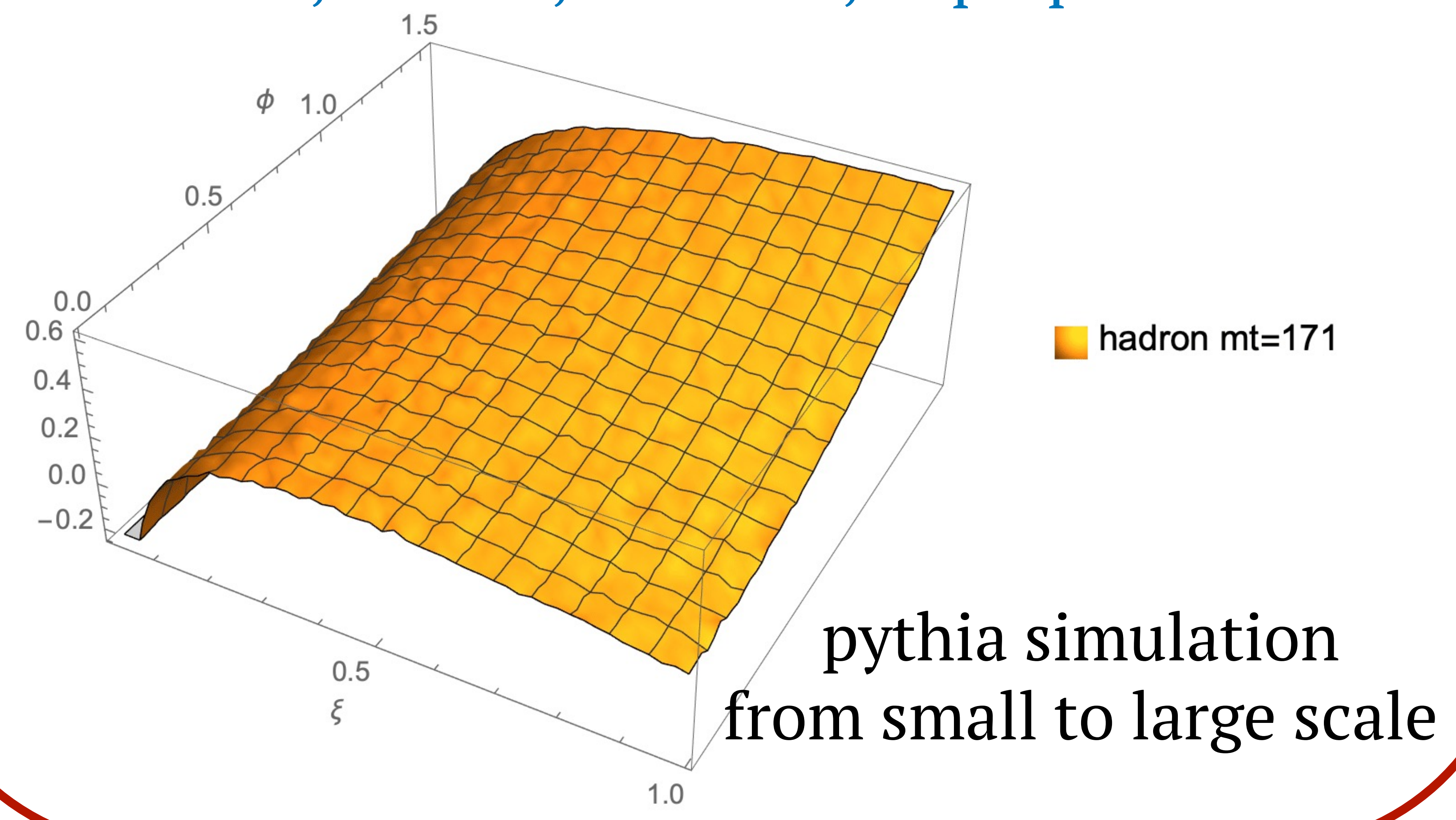
Holguin, Moult, Pathak, Procura, 2022





lgRL = [−2.08, −2.00);

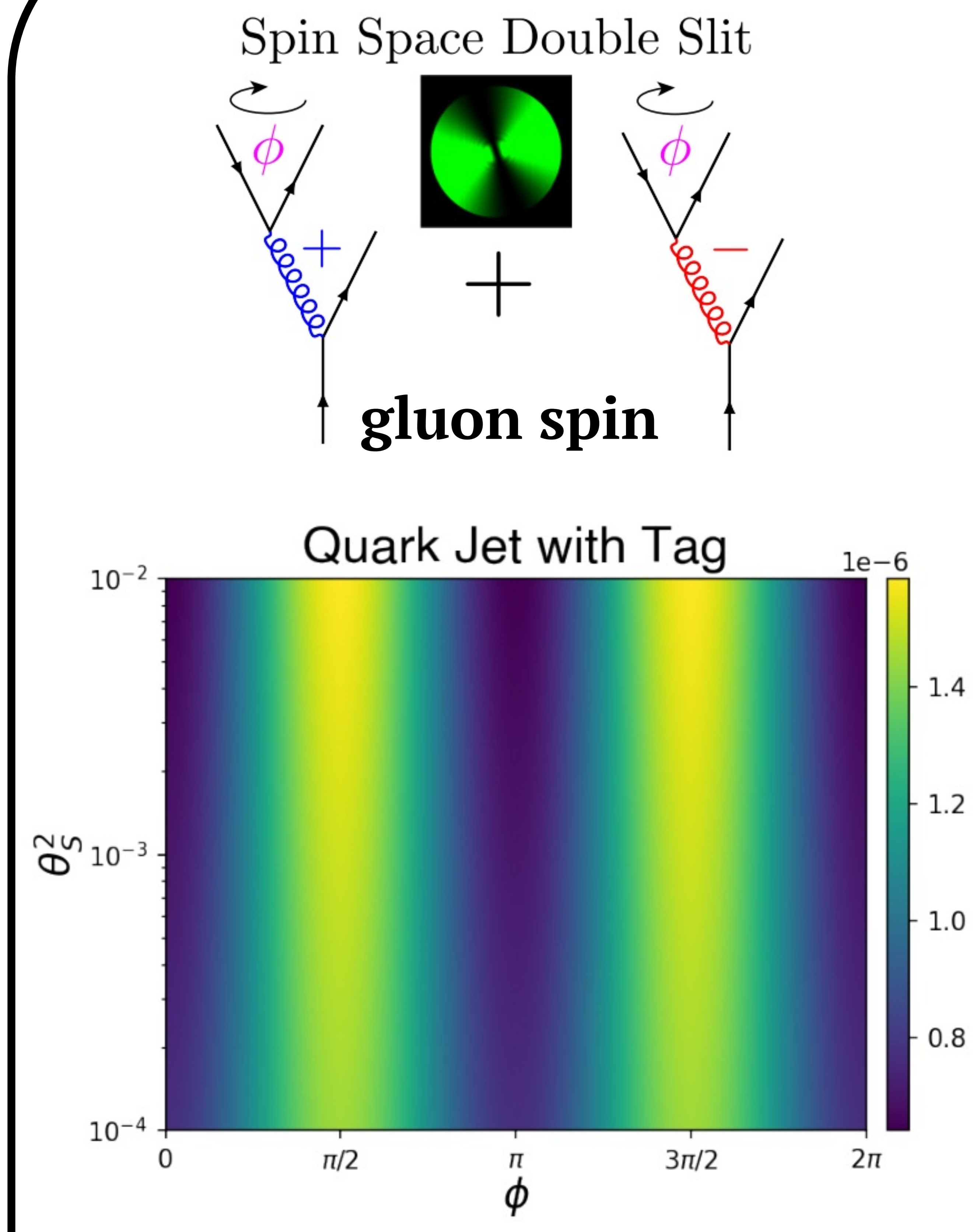
M. Xiao, Y.L. Ye, X.Y. Zhu, in preparation



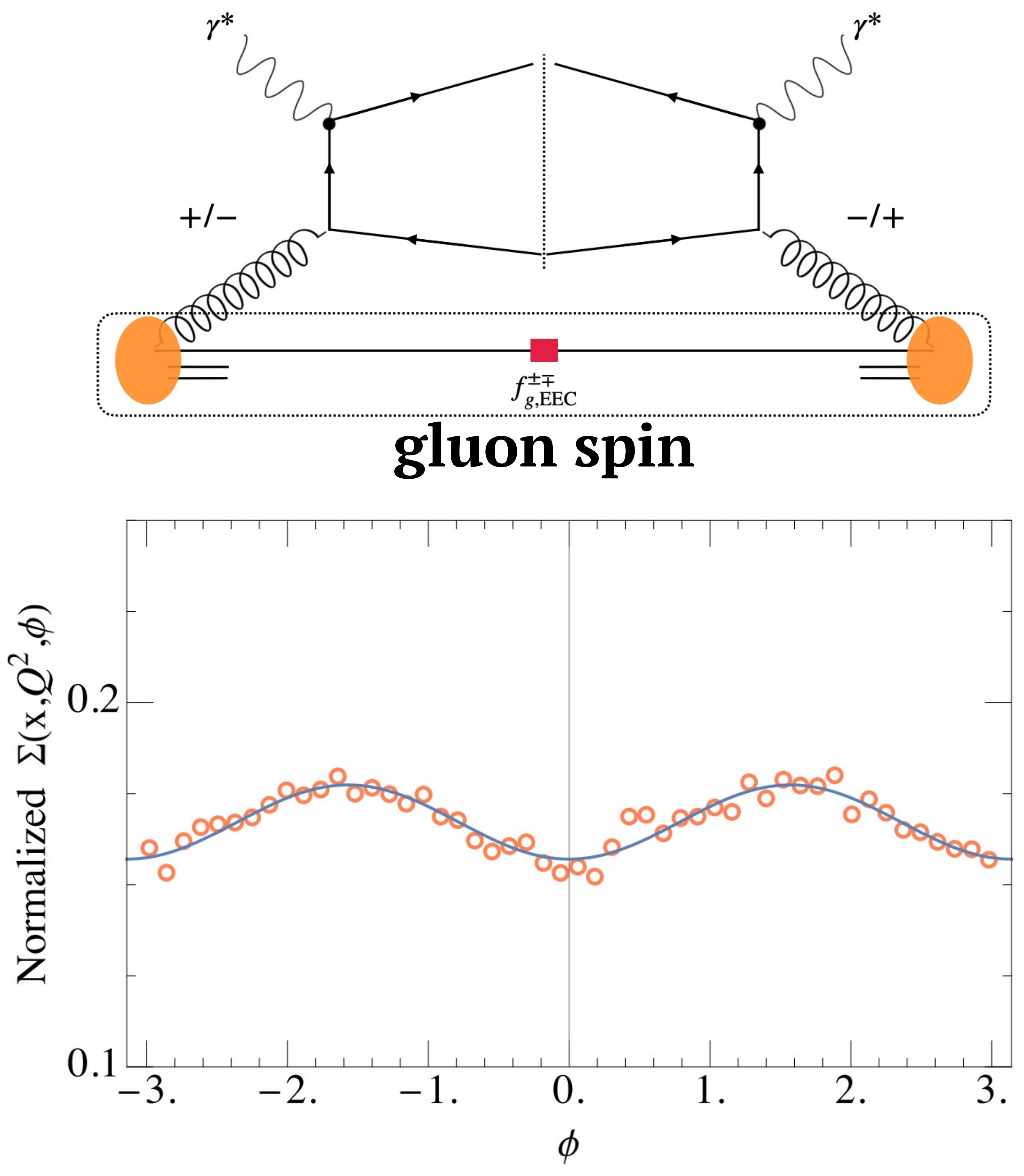
Energy correlators for spin physics

Spin correlation is mostly conveniently measured using Energy Correlators

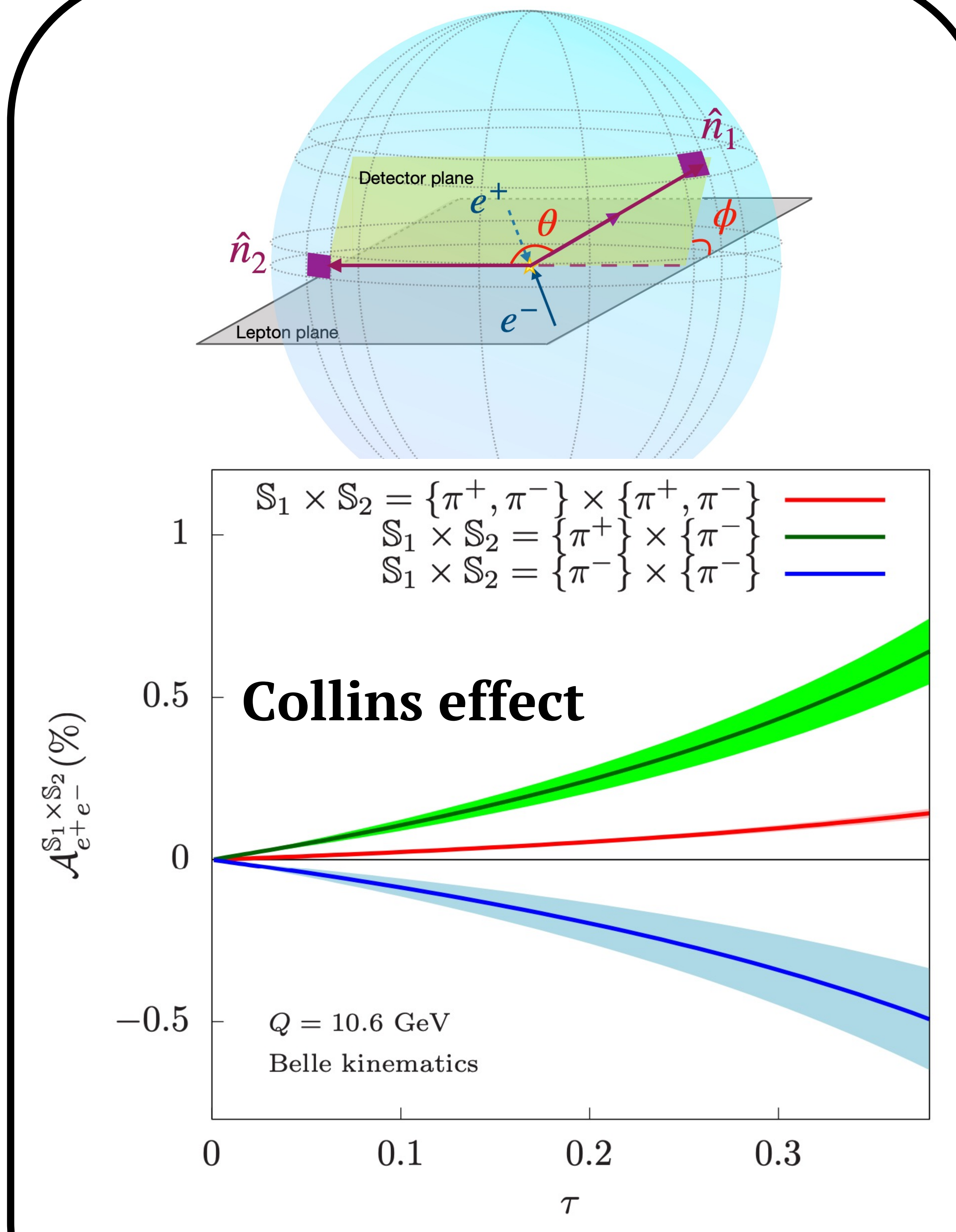
perturbative calculable + No ambiguity in definition of angle



H. Chen, Moult, HXZ, 2020



X.L. Li, X.H. Liu, F. Yuan, HXZ, 2023

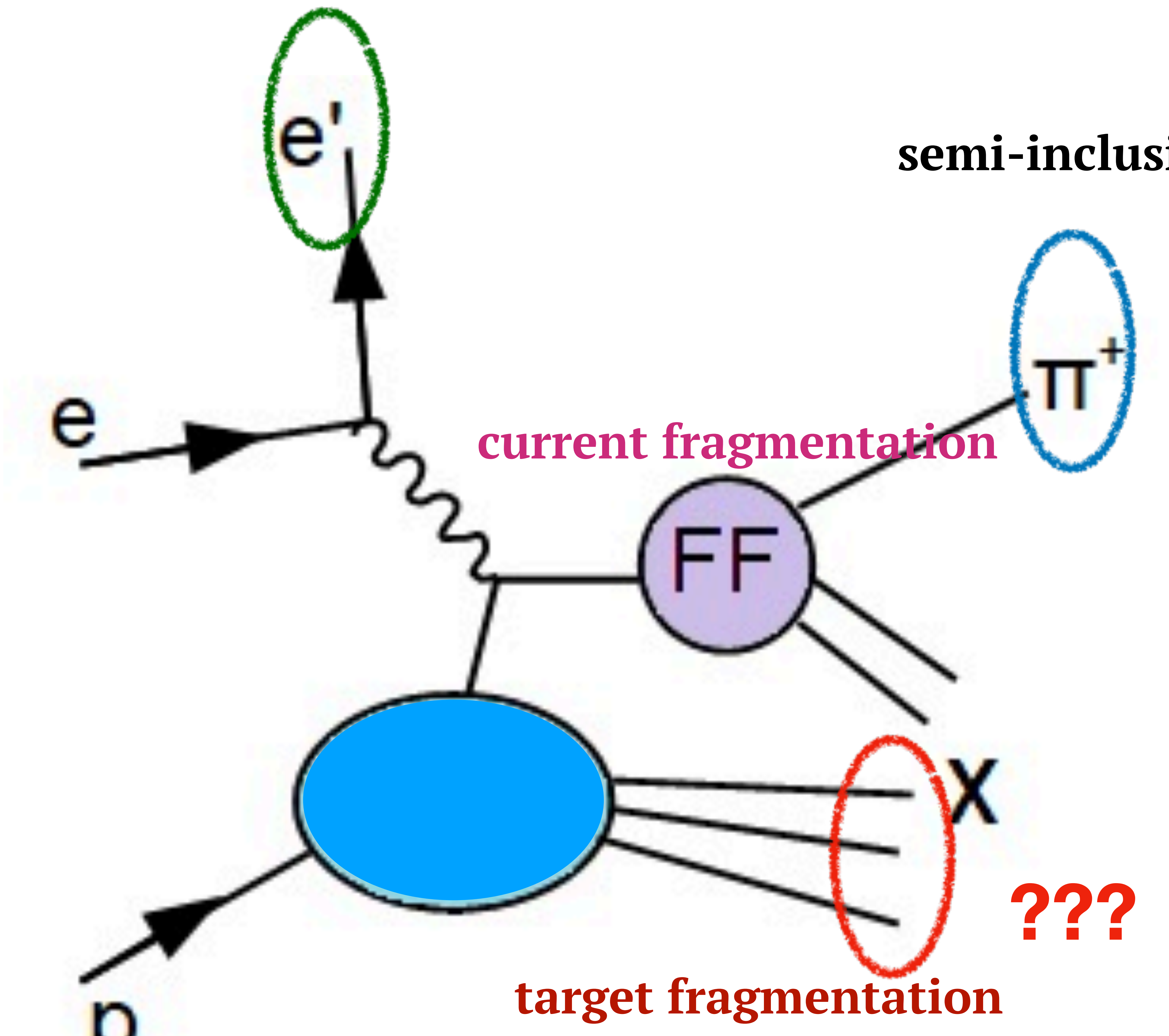


Z.B. Kang, K. Lee, D.Y. Shao, F.Y. Zhao, 2023

The nucleon EEC: new angle to hadron structure

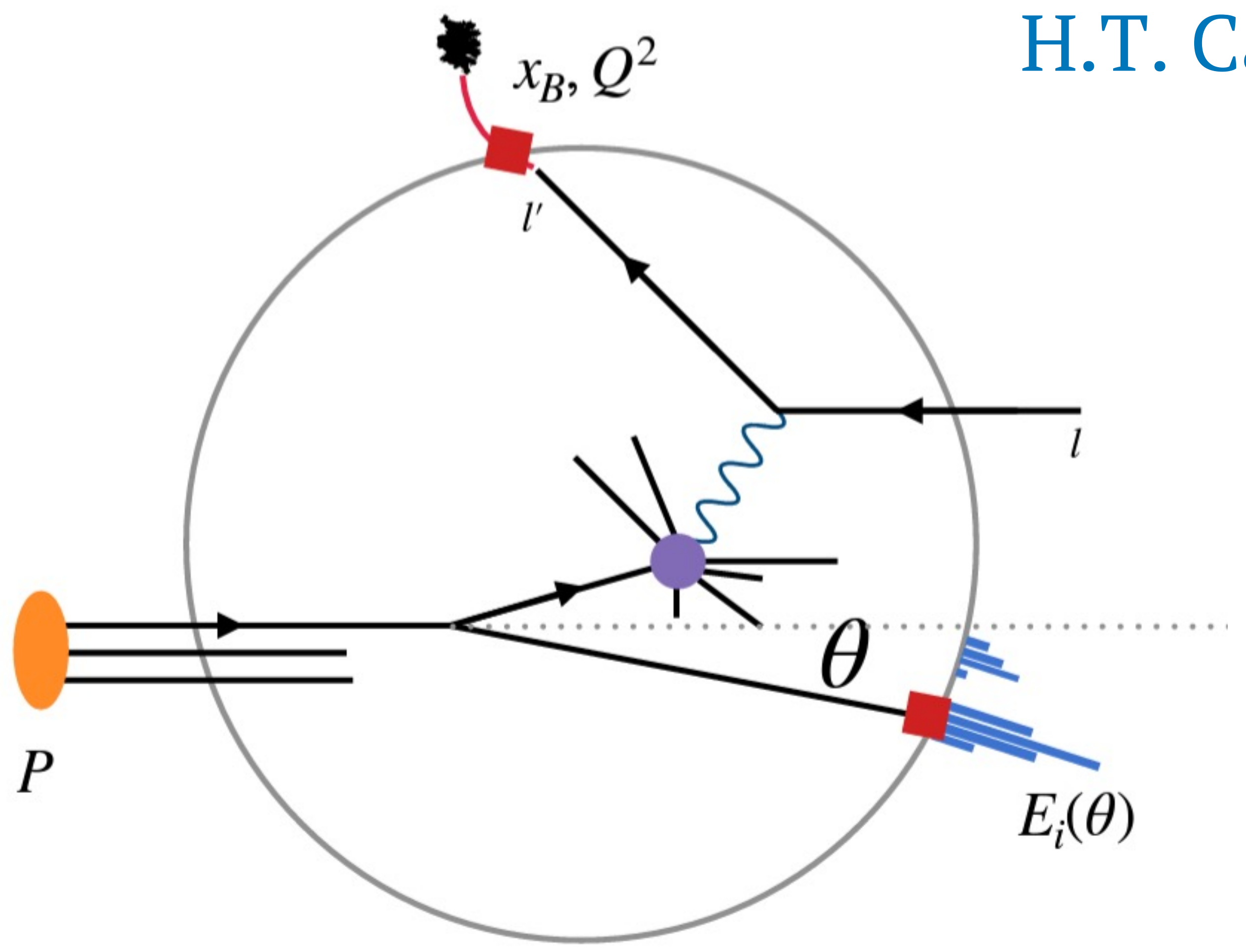
inclusive DIS

semi-inclusive DIS

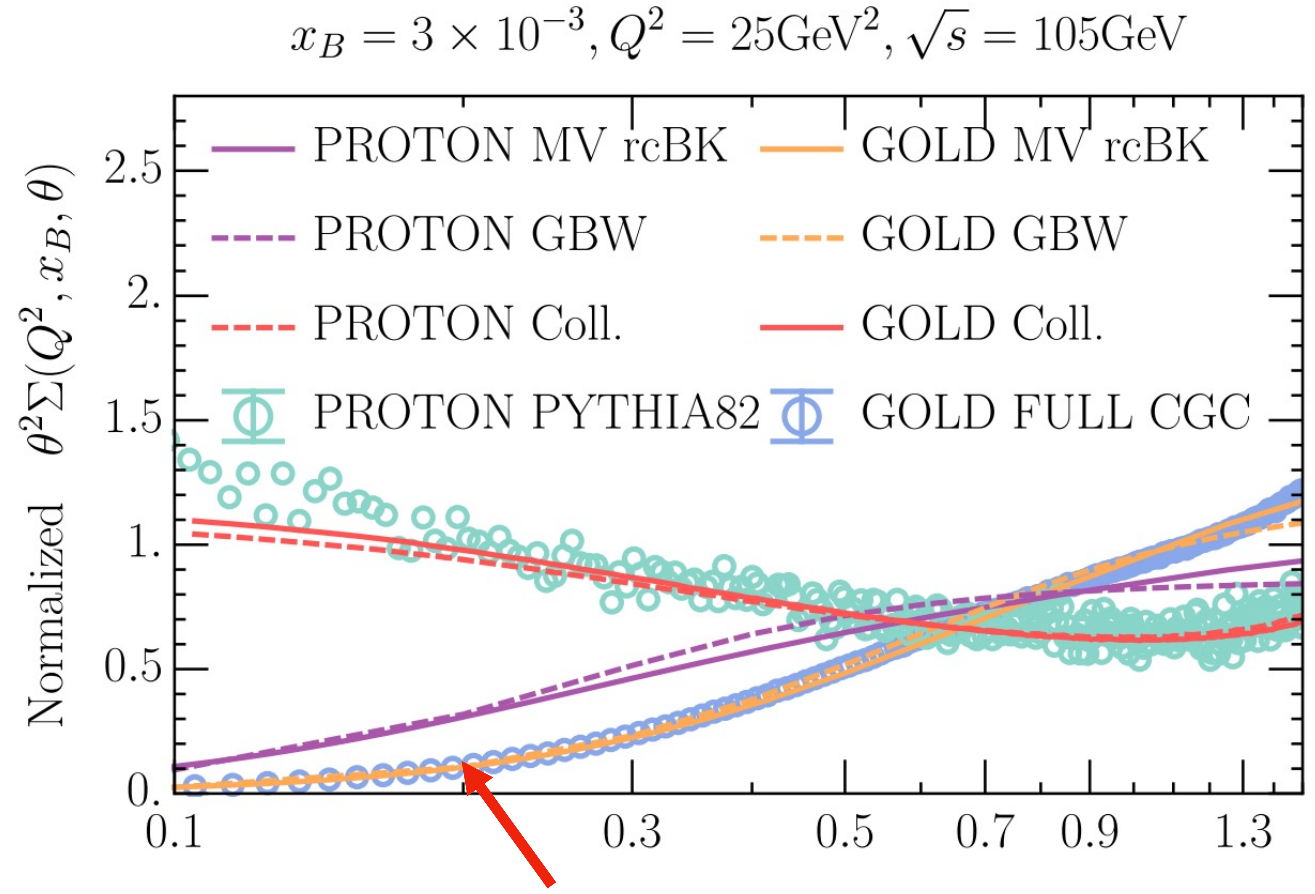


Trentadue, Veneziano, 1994

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



nEEC probing the angular (transverse) structure of nucleon



suppression of nEEC due to gluon saturation

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

SYNOPSIS

A Different Angle on the Color Glass Condensate

June 12, 2023 • *Physics* 16, s89

APS Synopsis

New Method Could Explore Gluon Saturation at the Future Electron-Ion Collider

DOE Science Highlight

Theorists propose nucleon energy-energy correlator as a probe to the gluon saturation phenomena at the future electron-ion collider.

inclusive -> current frag. -> target frag.

increasing in detecting techniques

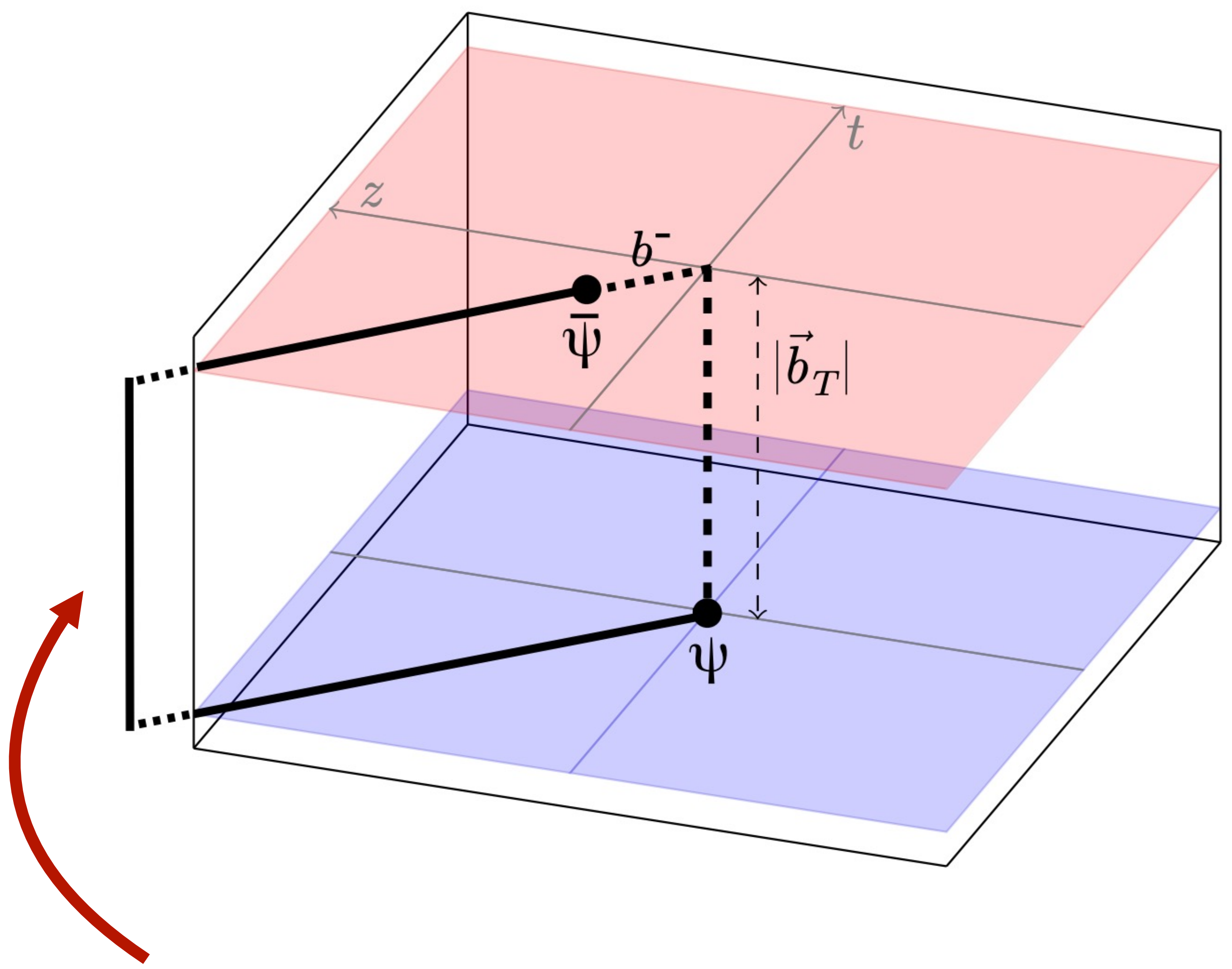
Connecting nEEC to TMD PDFs

Nucleon Energy Correlator

$$\int dy^- \, e^{-ixy^- P^+} \langle P, s | \bar{\psi}(y^-) \mathcal{E}(\Omega) \frac{\Gamma}{2} \psi(0) | P, s \rangle$$

(quark) TMD PDF

$$\int dy^- \, e^{-ixy^- P^+} \langle P, s | \bar{\psi}(y^-, y_\perp) \frac{\Gamma}{2} \psi(0) | P, s \rangle$$



The transverse gauge link leads to interesting physics

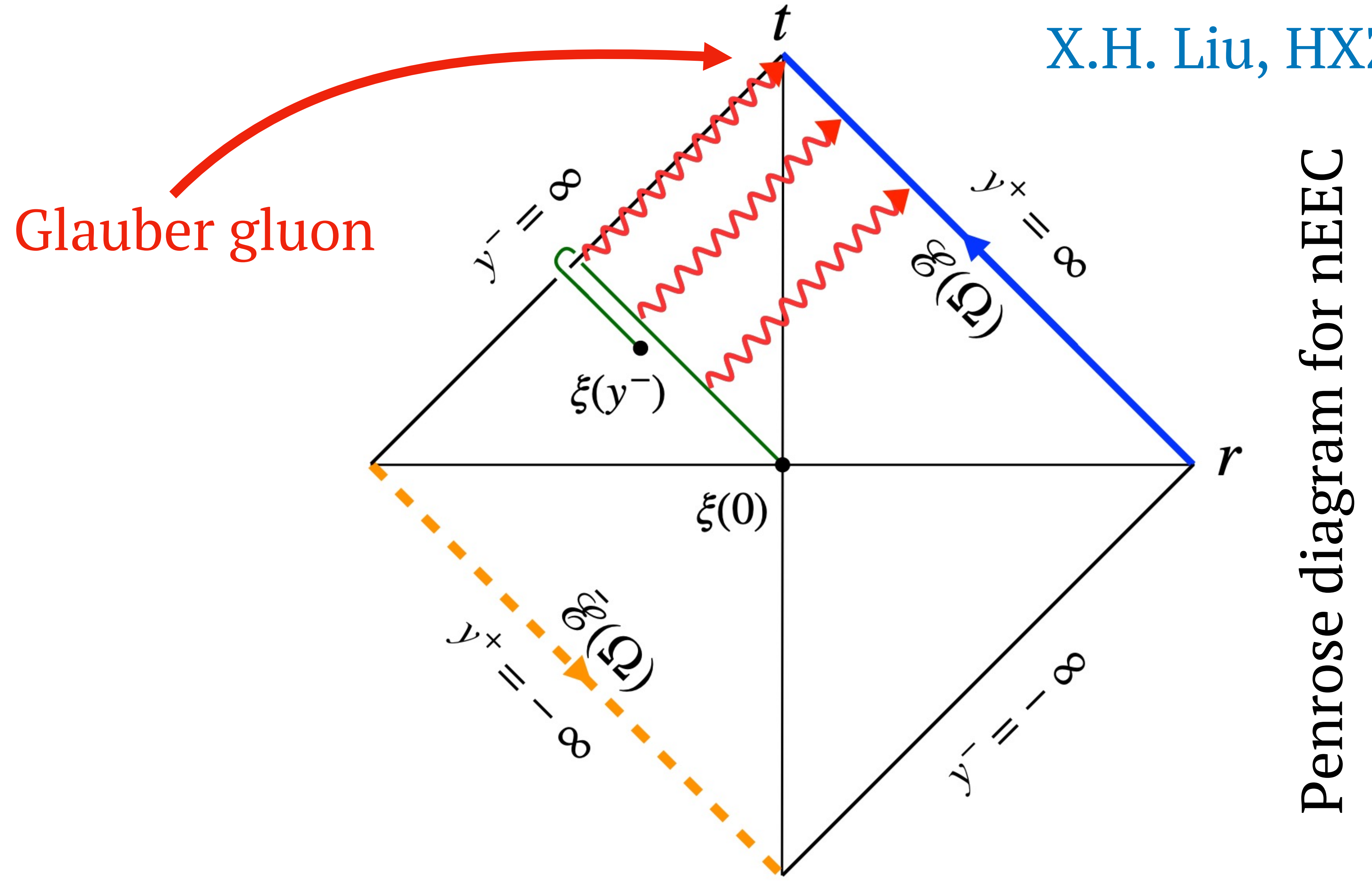
the Sivers effect $\vec{s} \times \vec{y}_\perp$

Connecting nEEC to TMD PDFs

Nucleon Energy Correlator

$$\int dy^- \, e^{-ixy^- P^+} \langle P, s | \bar{\psi}(y^-) \mathcal{E}(\Omega) \frac{\Gamma}{2} \psi(0) | P, s \rangle$$

X.H. Liu, HXZ, 2024



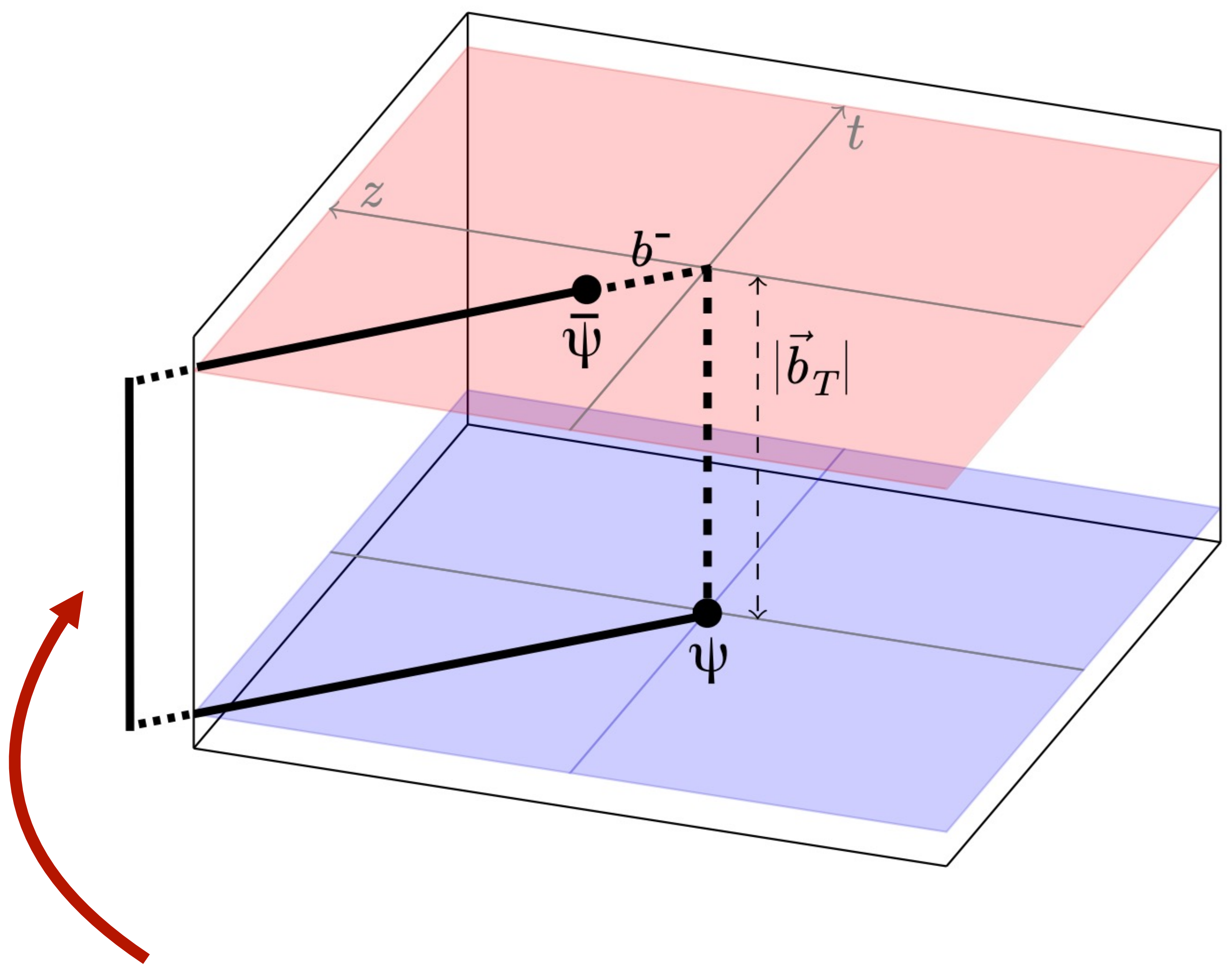
Allows signal transmitted to $y^- = y^+ = \infty$

In momentum space => $k = (k^+, k^-, k_\perp) \sim Q(\lambda^2, \lambda^2, \lambda)$

the Sivers effect $\vec{s} \times \vec{\Omega}$

(quark) TMD PDF

$$\int dy^- \, e^{-ixy^- P^+} \langle P, s | \bar{\psi}(y^-, y_\perp) \frac{\Gamma}{2} \psi(0) | P, s \rangle$$



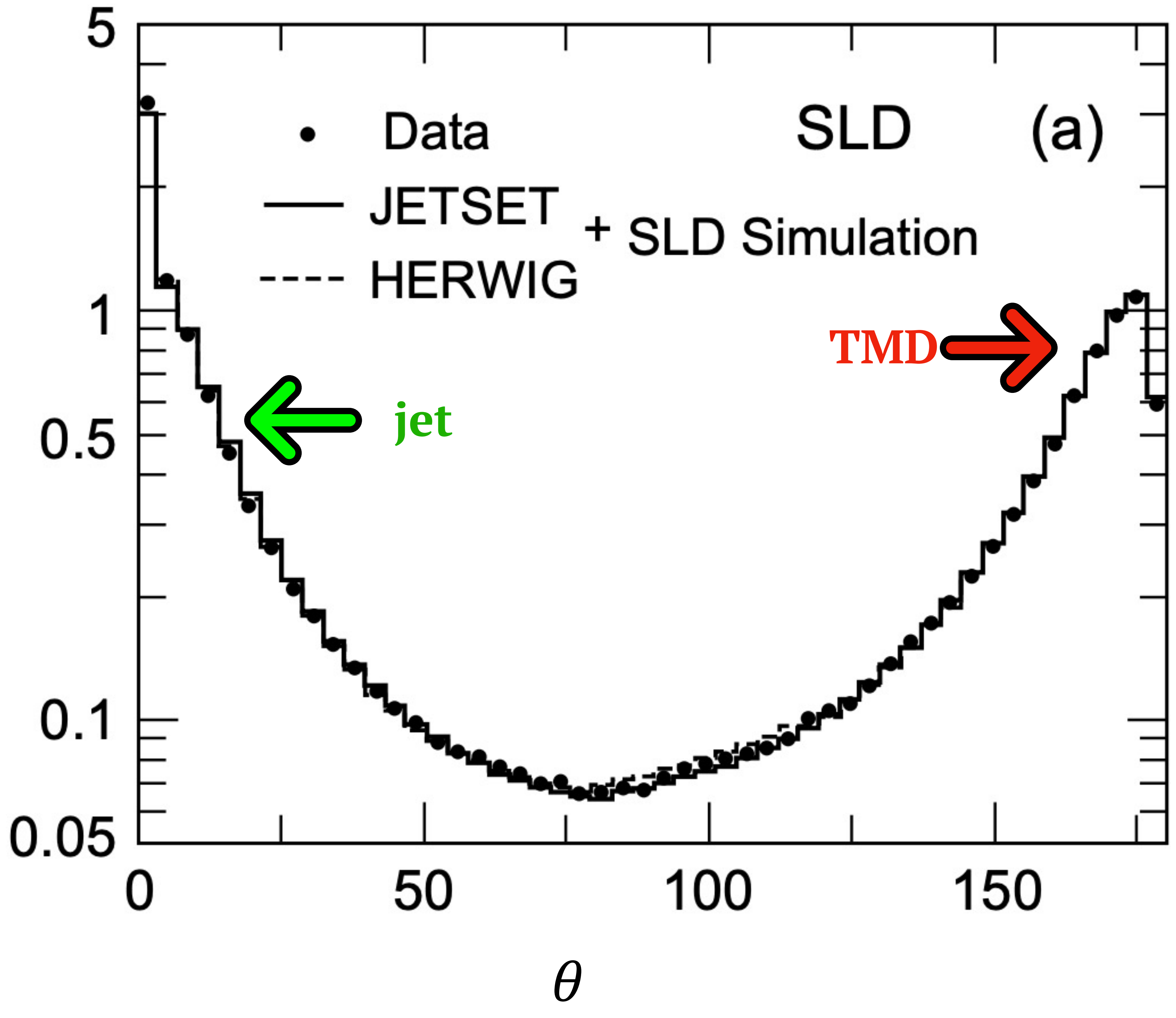
The transverse gauge link leads to interesting physics

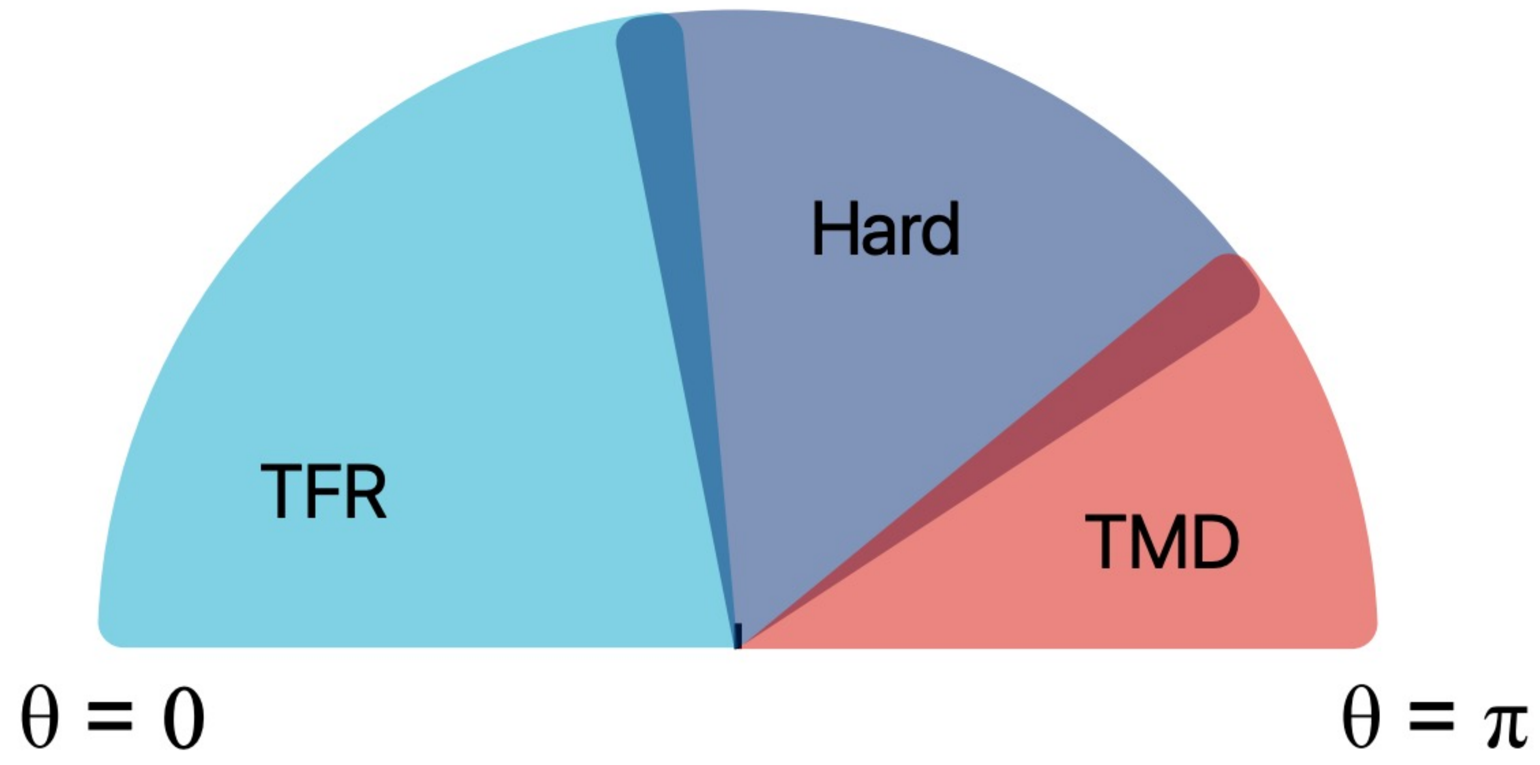
the Sivers effect $\vec{s} \times \vec{y}_\perp$

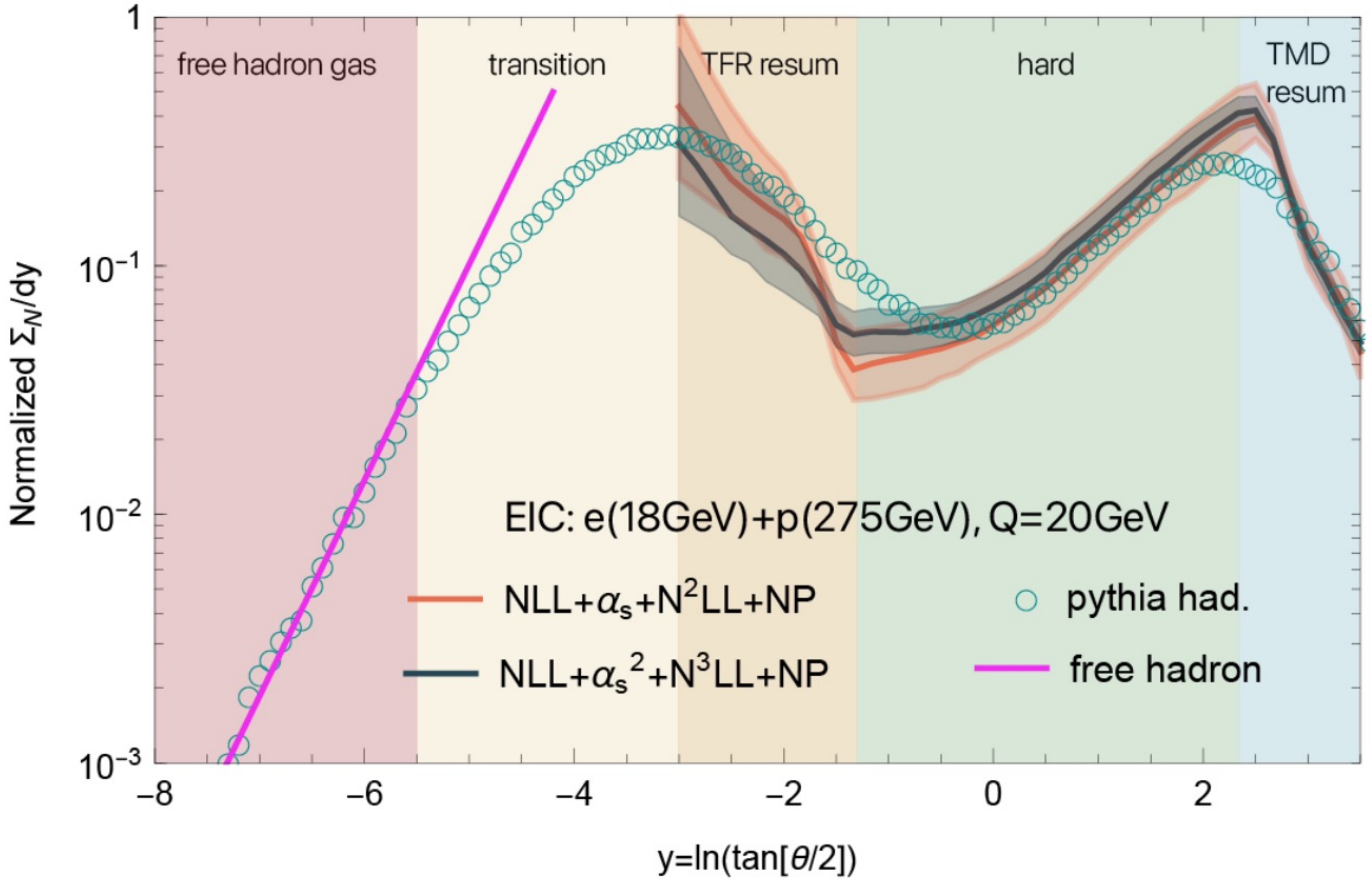
Covering the full 4π angle at EIC

H.T. Cao, H.T. Li, Z.H. Mi, 2023

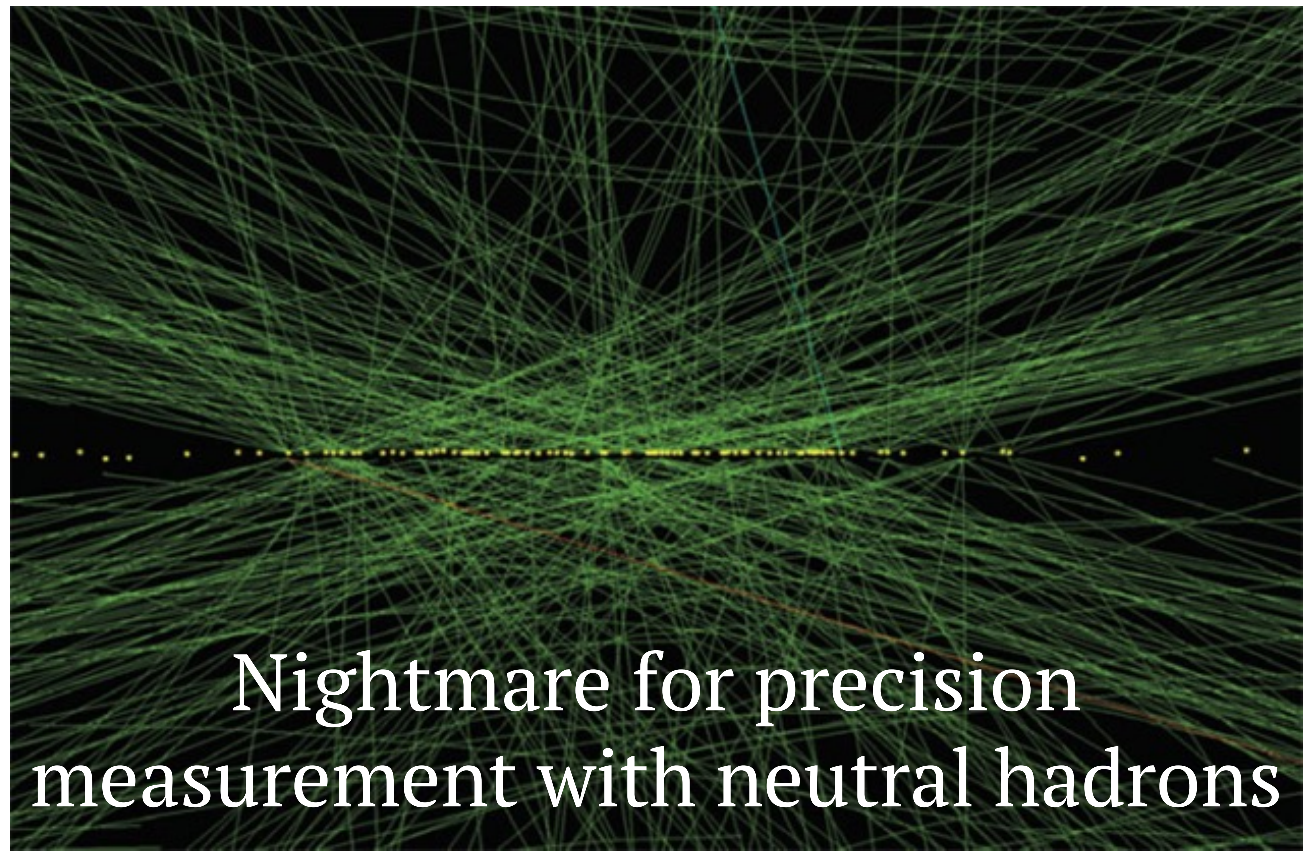
Full phase space coverage in e+e- exhibit rich dynamics.
Now the same can be done for DIS!





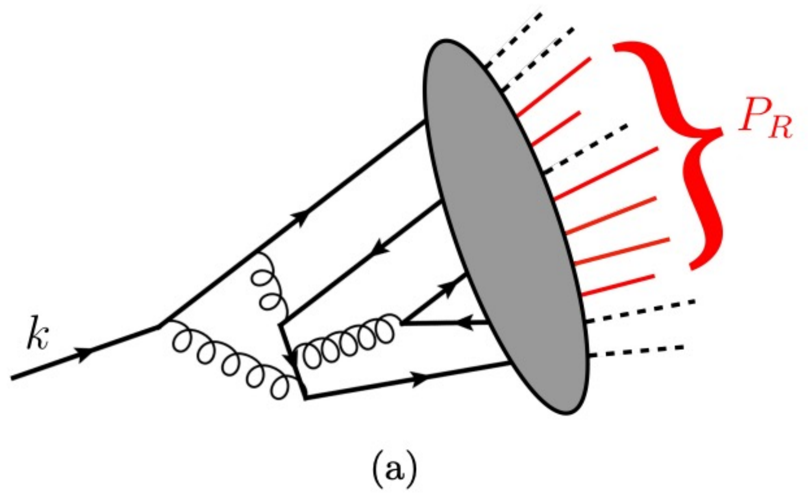


Theorizing the track measurement



solution:

Using tracks!

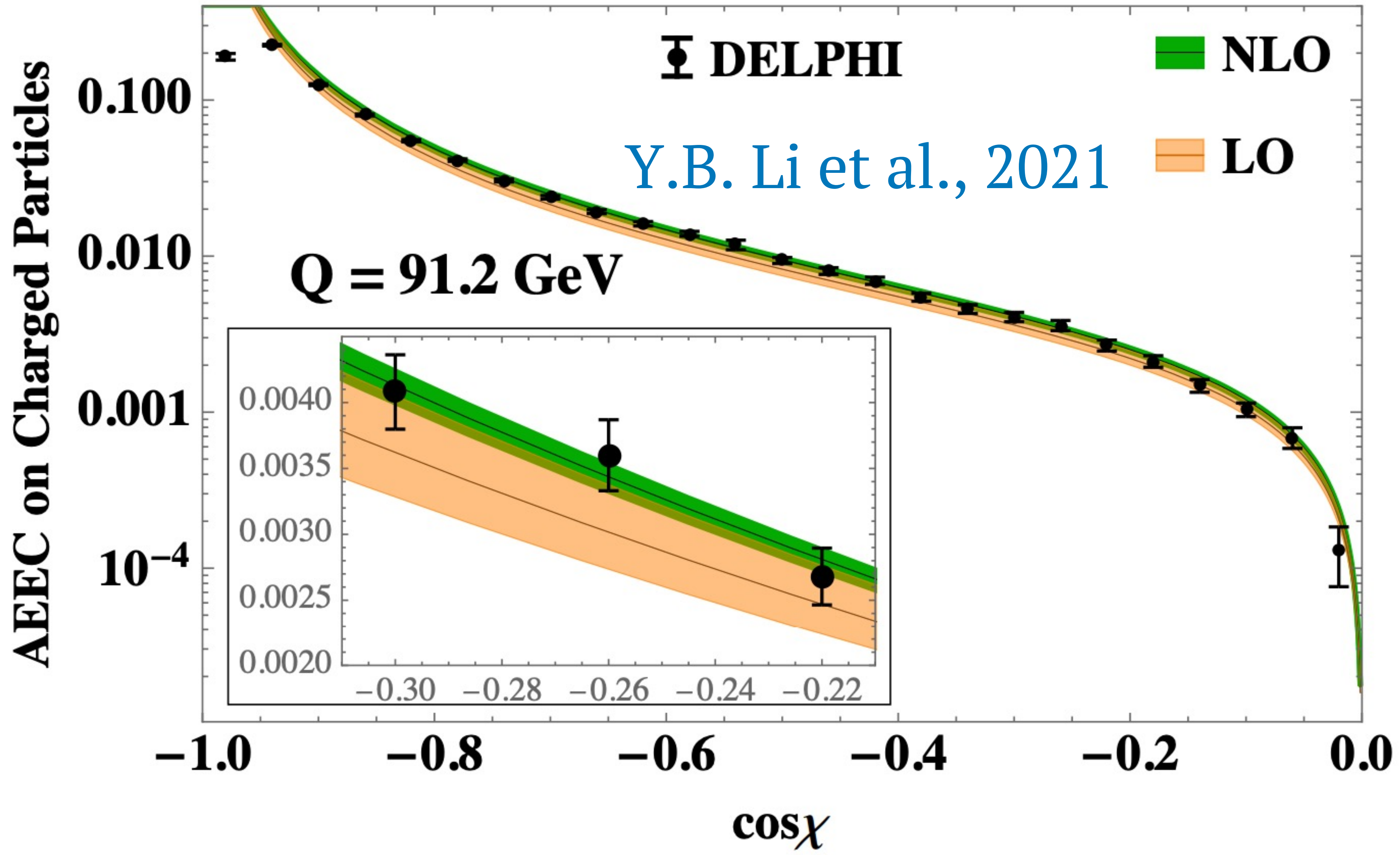


track function: probability for finding charged hadrons with total momentum fraction x

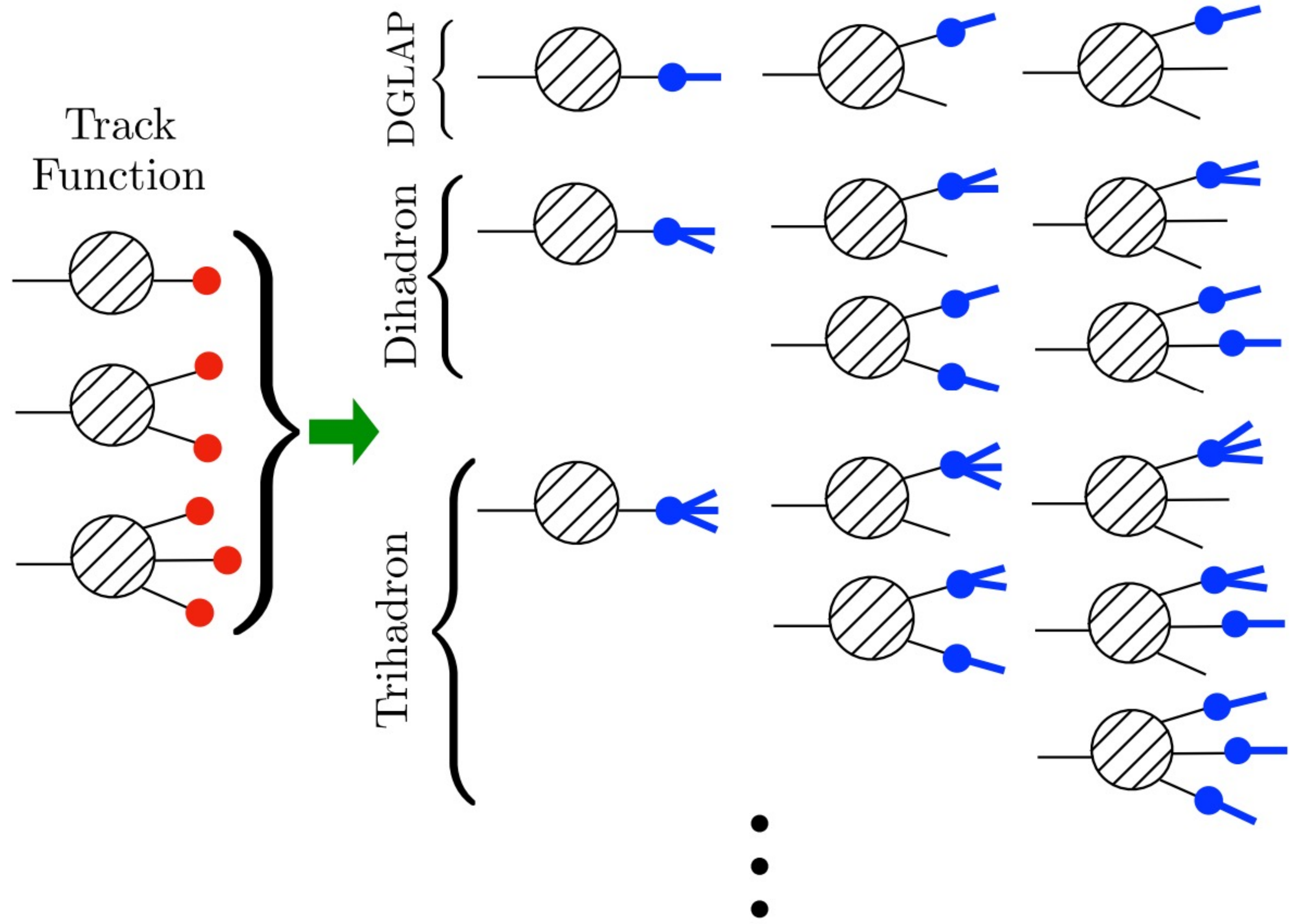
$$T_q(x) = \int \mathrm{d}y^+ \mathrm{d}^{d-2}y_\perp e^{ik^- y^+/2} \sum_X \delta\left(x - \frac{P_R^-}{k^-}\right) \frac{1}{2N_c} \mathrm{tr}\left[\frac{\gamma^-}{2} \langle 0|\psi(y^+,0,y_\perp)|X\rangle\langle X|\bar{\psi}(0)|0\rangle\right]$$

Chang, Procura, Thaler, Waalewijn, 2013

Asymmetric EEC on tracks



First NLO calculation with tracks!

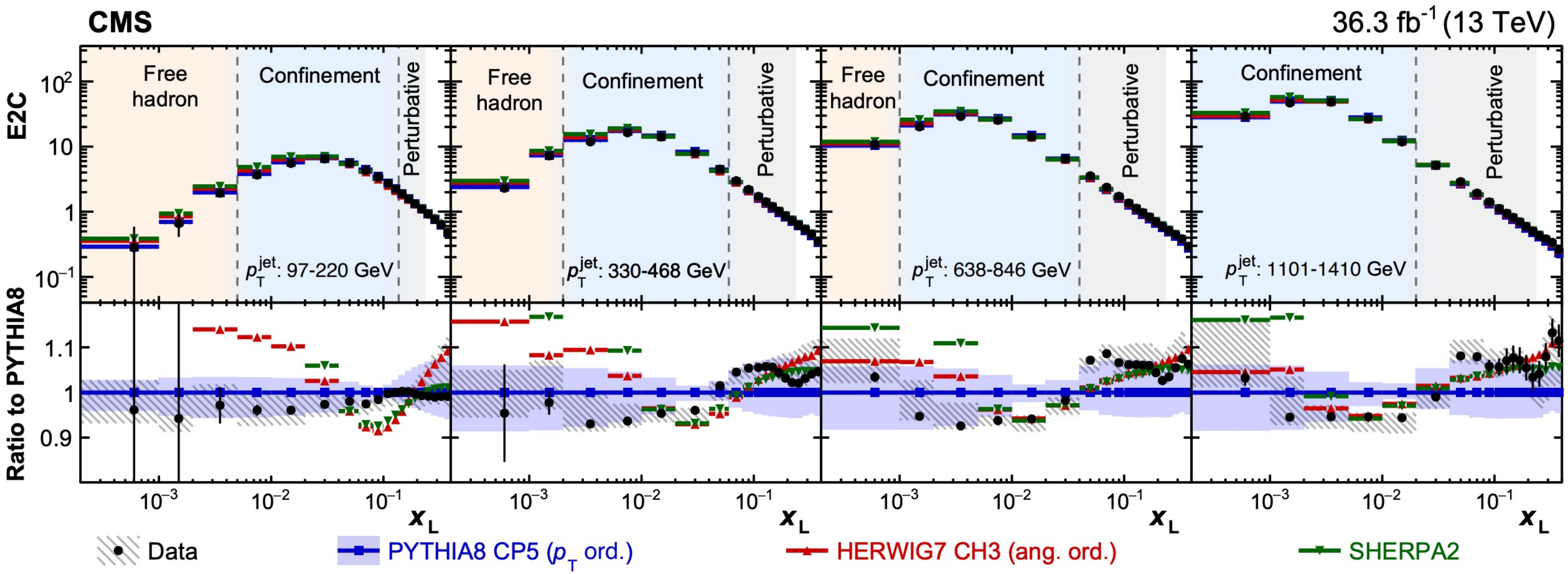


Full NLO evolution for track function

H. Chen et al., 2022

By-product: first NLO evolution kernel for dihadron fragmentation!

Energy correlators for future colliders



e+e- below 10 GeV: explore the transition from quarks to hadrons in unprecedented details

small angle → large angle

e+e- above 200 GeV: open up the perturbative window for numerous precision measurements

Conclusion

- Energy correlators bridge the gap between quark/gluon and hadron dynamics
- Significant progress in the past few years. It has been transformed from a theoretical concept to actual measurements in experiment
- Many interesting aspects not covered: its numerous roles in formal theory; heavy ion collisions; non-perturbative corrections, …
- Many exciting opportunities to be explored!

Thank you for your attention!