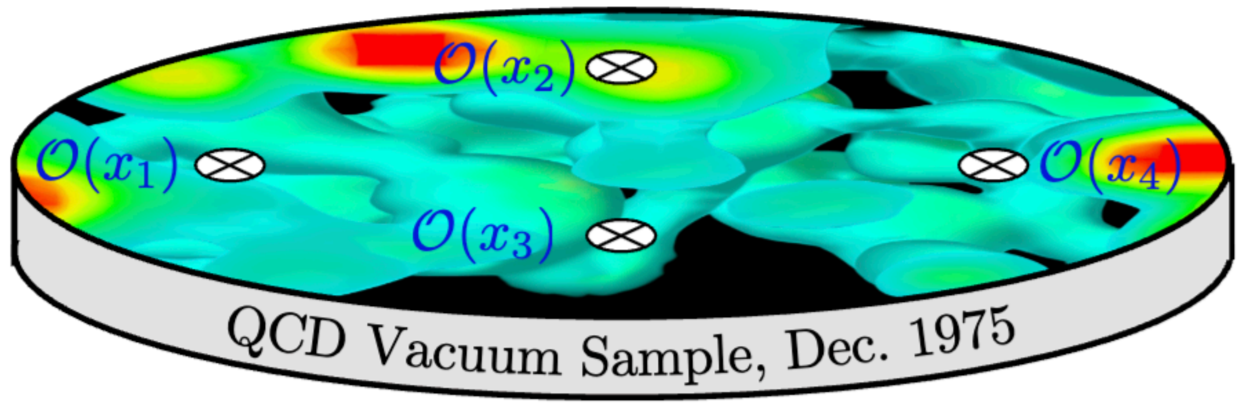
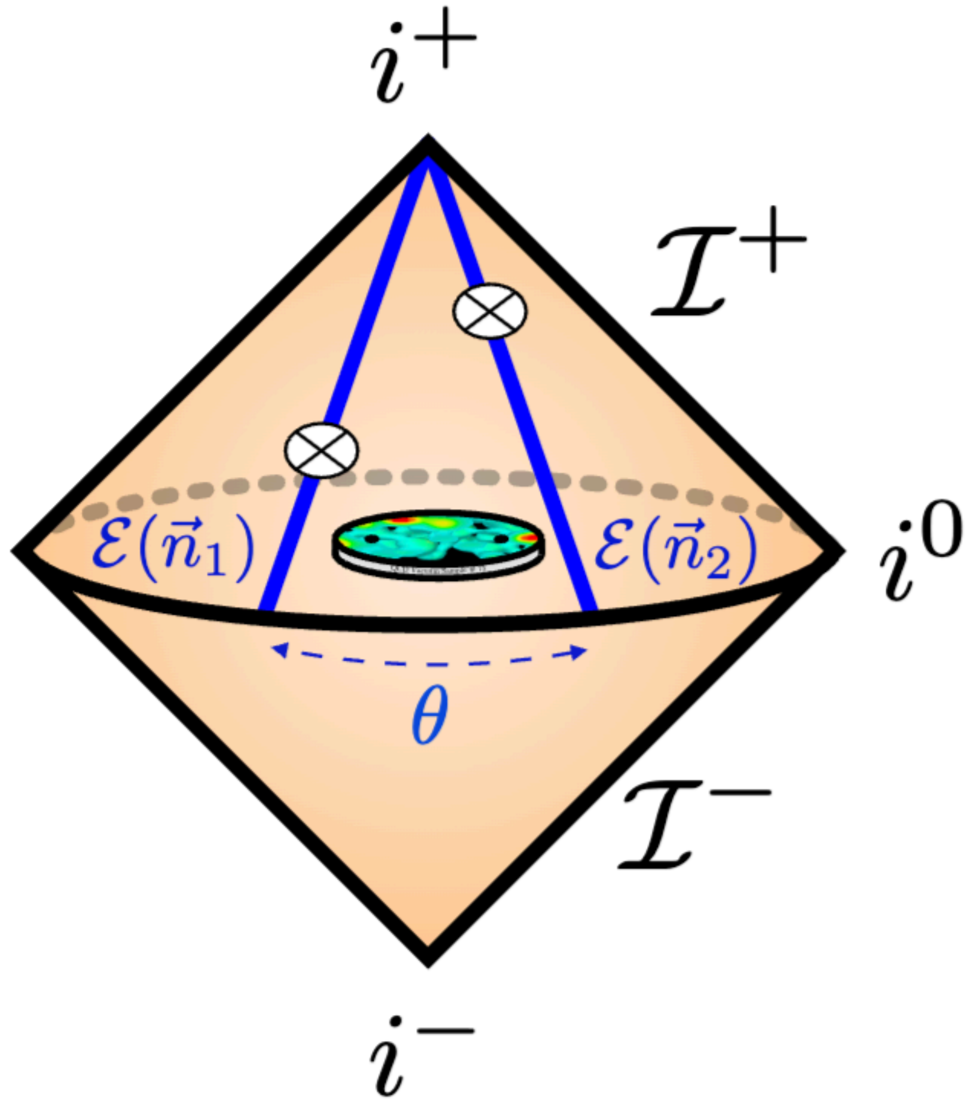
Energy Correlators:

from Colliders to the Celestial Sphere and Back

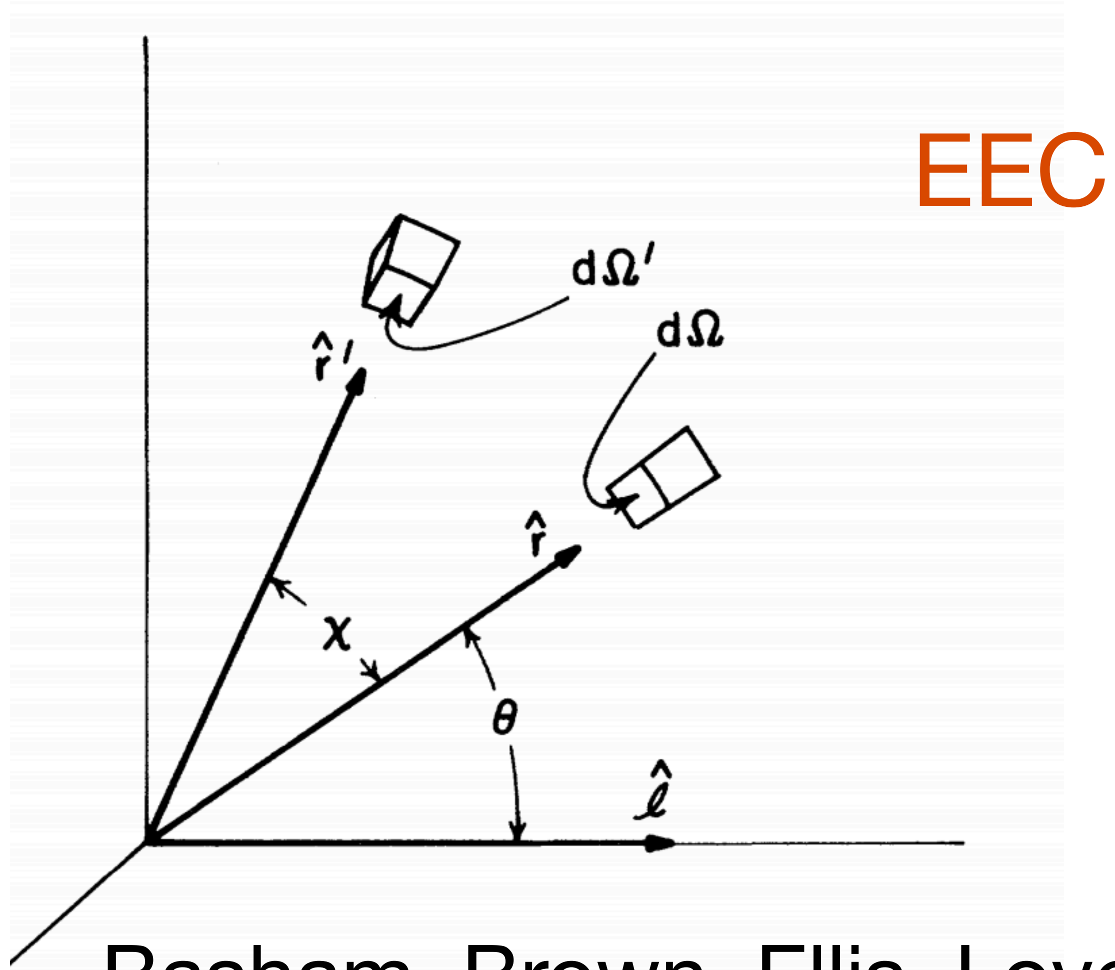




朱华星
北京大学

07-02-2026
BES实验物理研讨会

Some history



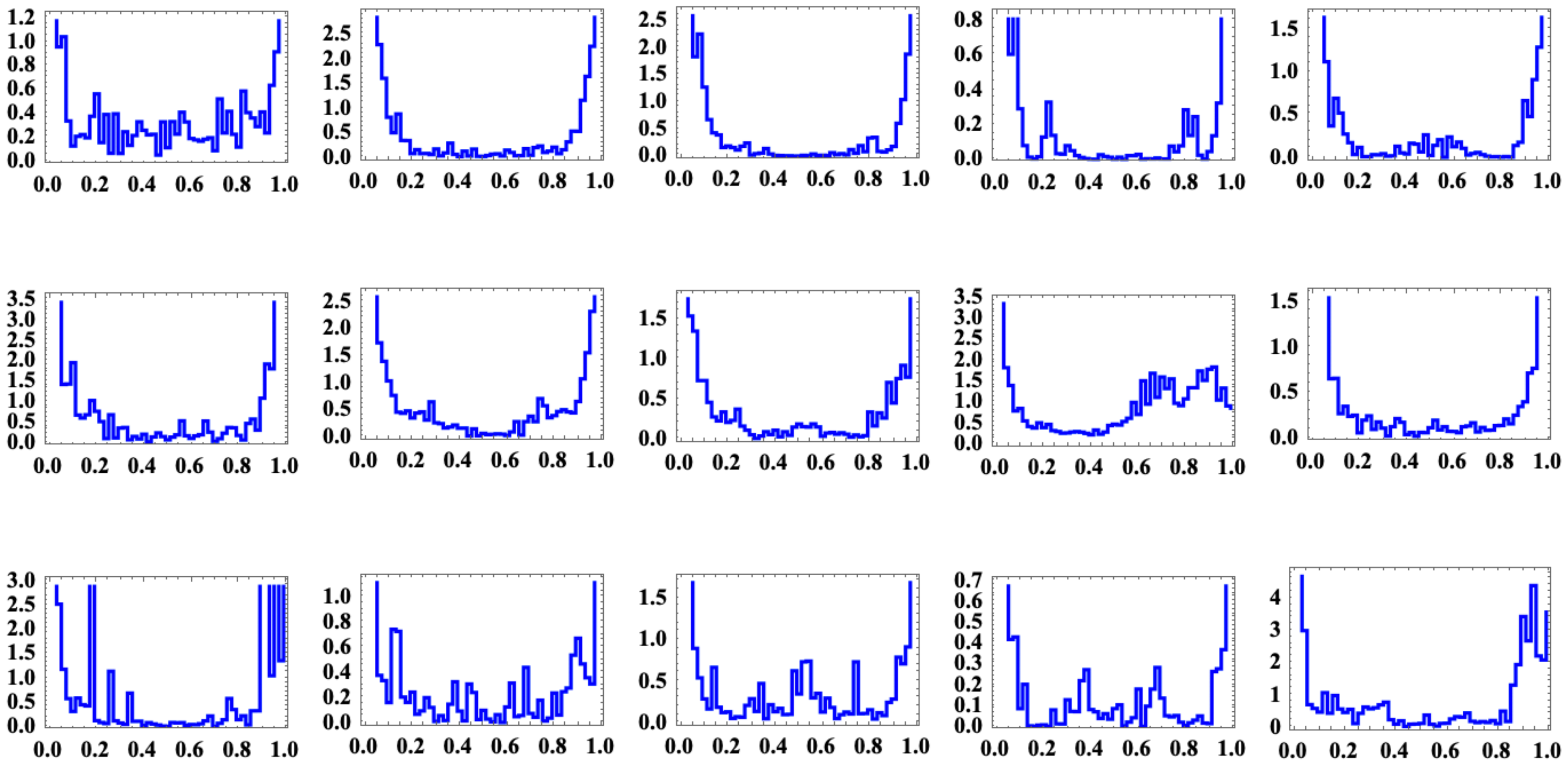
Basham, Brown, Ellis, Love, 1978

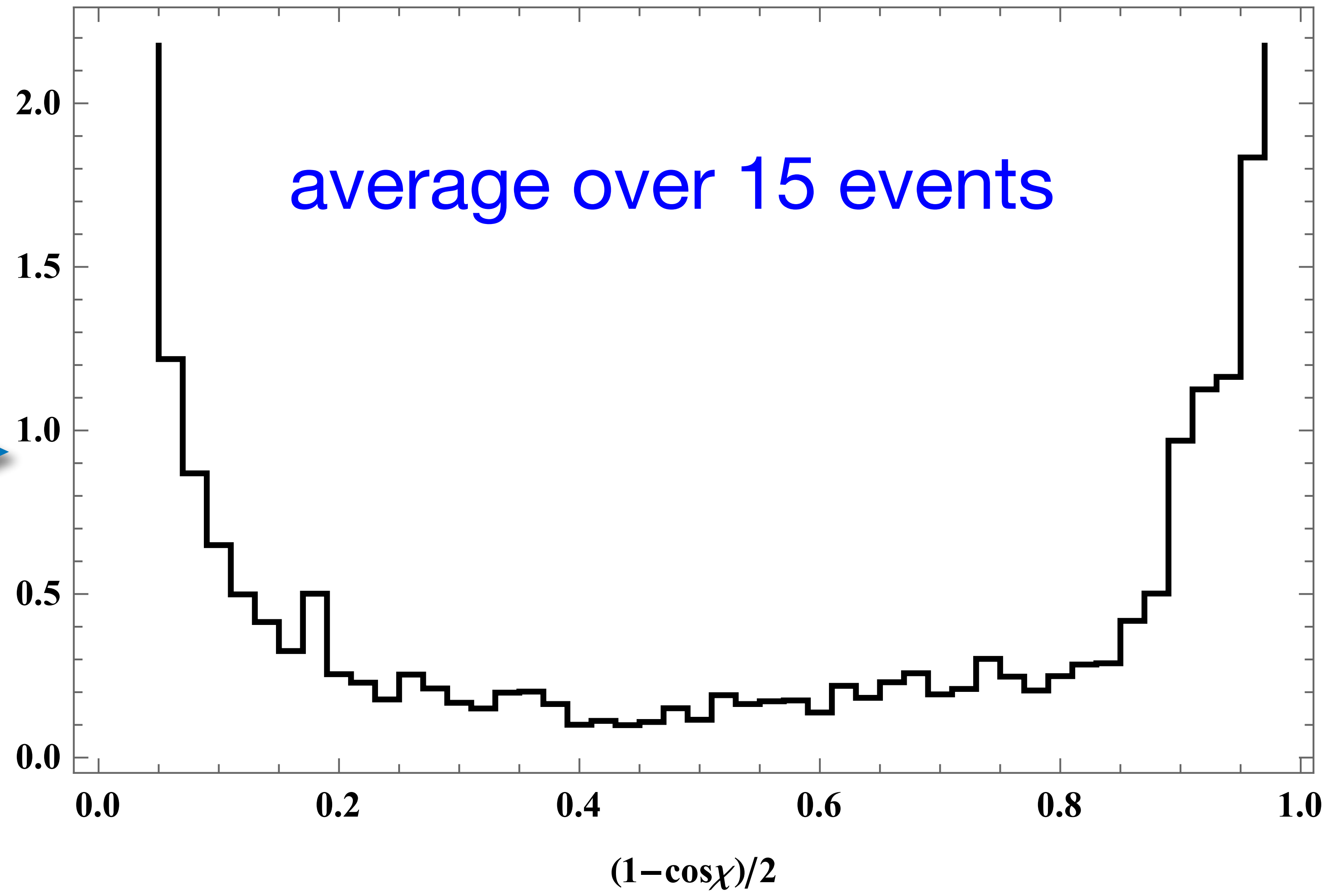
EEC: Correlation of energy deposition between two detector at an angle χ

Weighted cross section

$$\mathrm{EEC}(\chi) = \frac{1}{N}\sum_{\text{events}}^{N} \sum_{i,j}^{N_{\text{particles}}} \frac{E_i E_j}{E_{\text{tot}}^2} \left(\frac{1}{\Delta\chi} \int_{\chi-\Delta\frac{\chi}{2}}^{\chi+\Delta\frac{\chi}{2}} \delta(\chi' - \chi_{ij}) d\chi' \right)$$

Measurement on a single event gives a function





Jet Structure in e^+e^- Annihilation with Massless Hadrons*

George Sterman

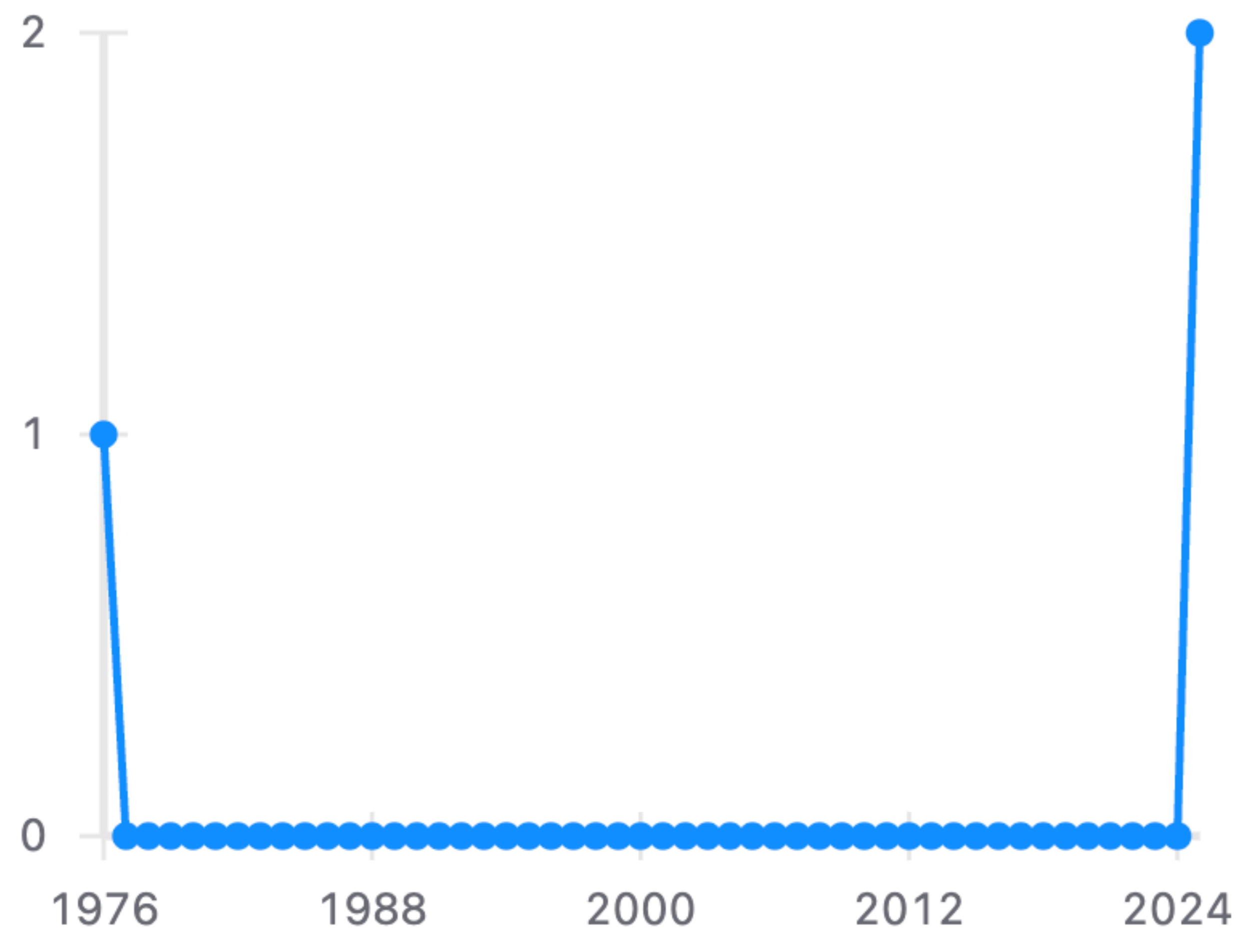
Department of Physics
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

Energy Correlations in Electron-Positron Annihilation: Testing Quantum Chromodynamics

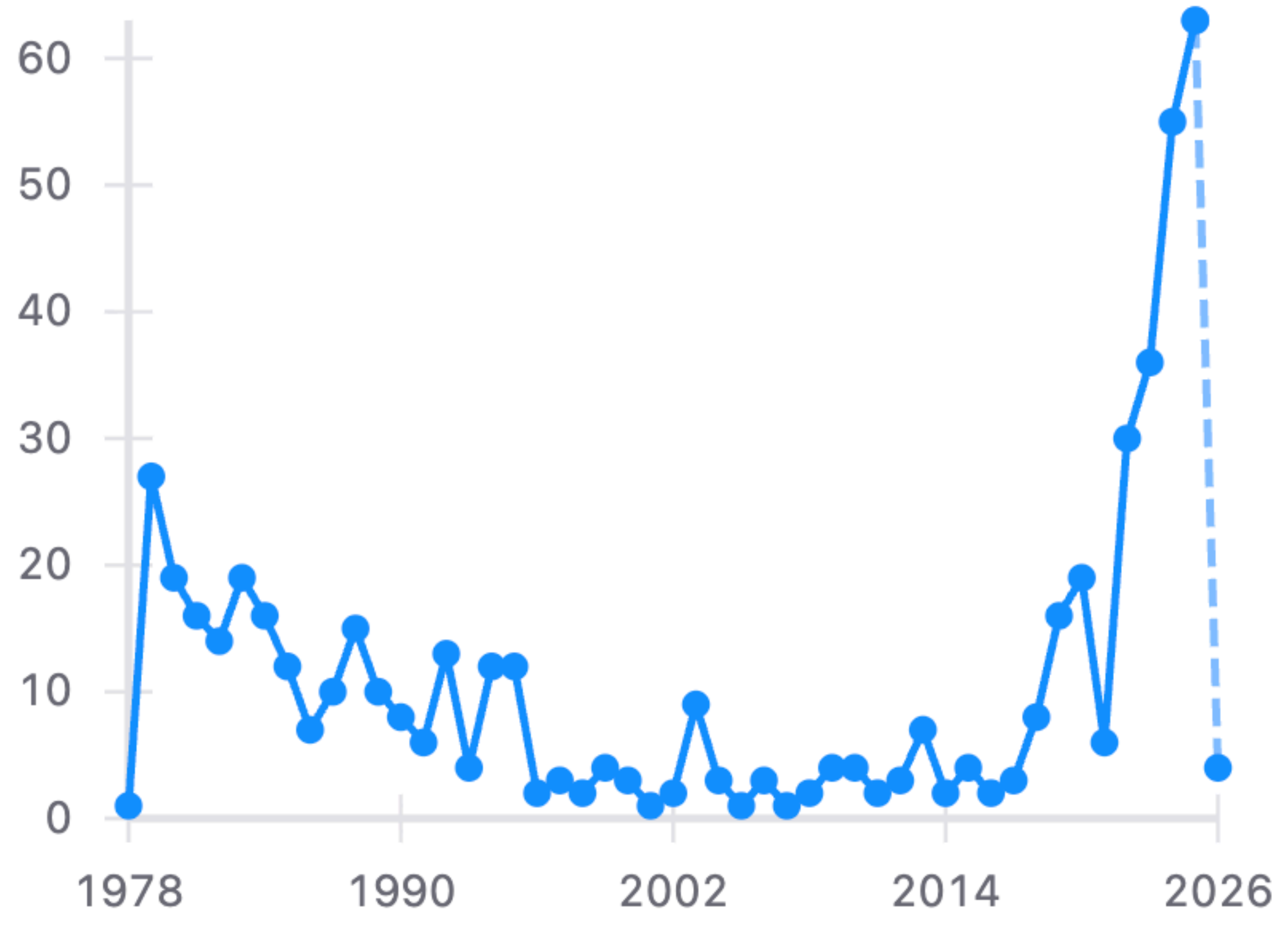
C. Louis Basham, Lowell S. Brown, Stephen D. Ellis, and Sherwin T. Love
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 21 August 1978)

An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process $e^+e^- \to$ hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order $1/W^2$) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

Citations per year



Citations per year



The innate human quest for deeper theoretical insight

The era of precision physics at the LHC

Remarkable agility in experimental realization

The innate human quest for deeper theoretical insight

The era of precision physics at the LHC

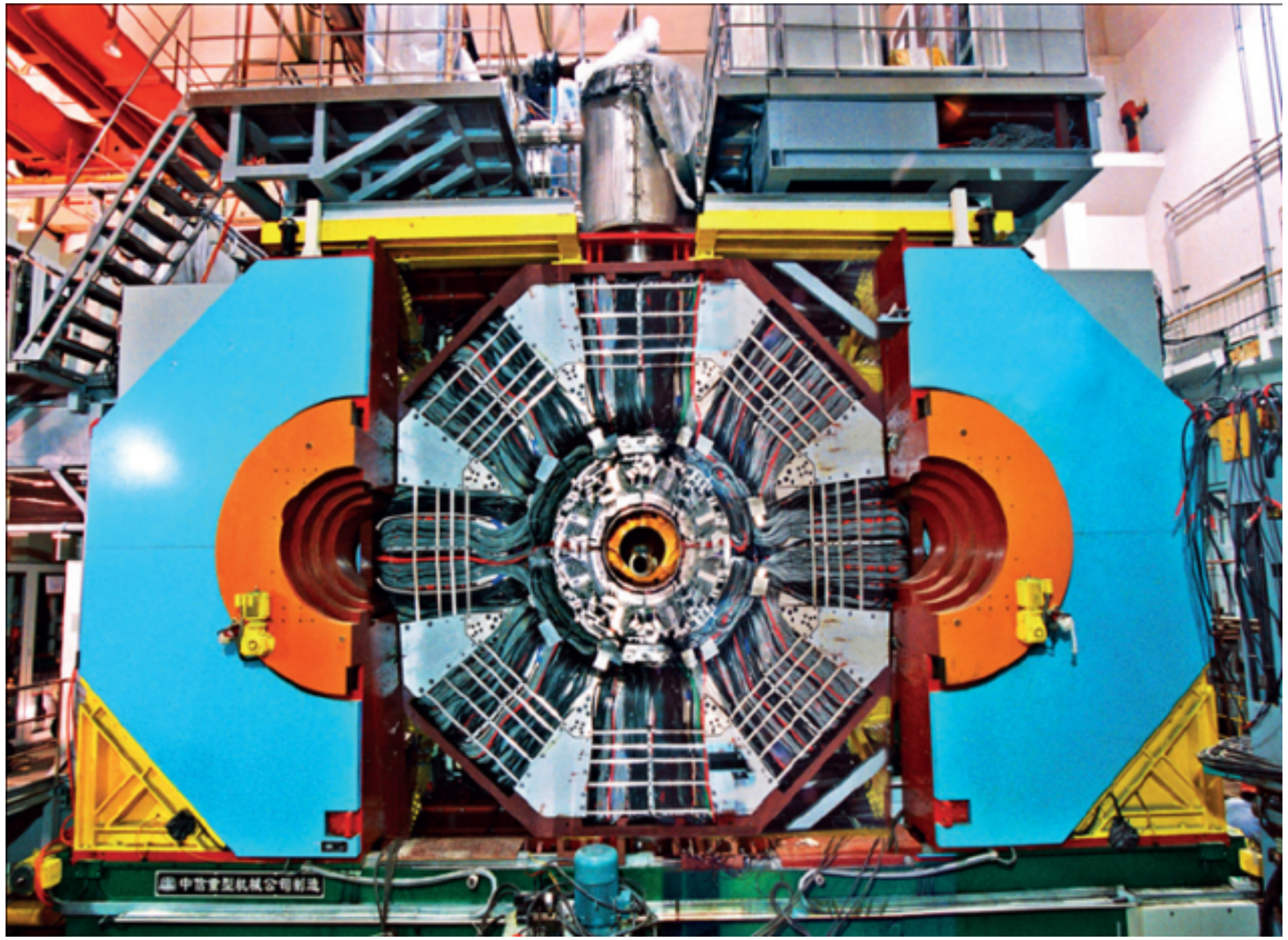
Remarkable agility in experimental realization

Nothing is as powerful as an idea whose time has come.

Victor Hugo

The journey began with a fundamental quest to understand detector

The journey began with a fundamental quest to understand detector **operators**



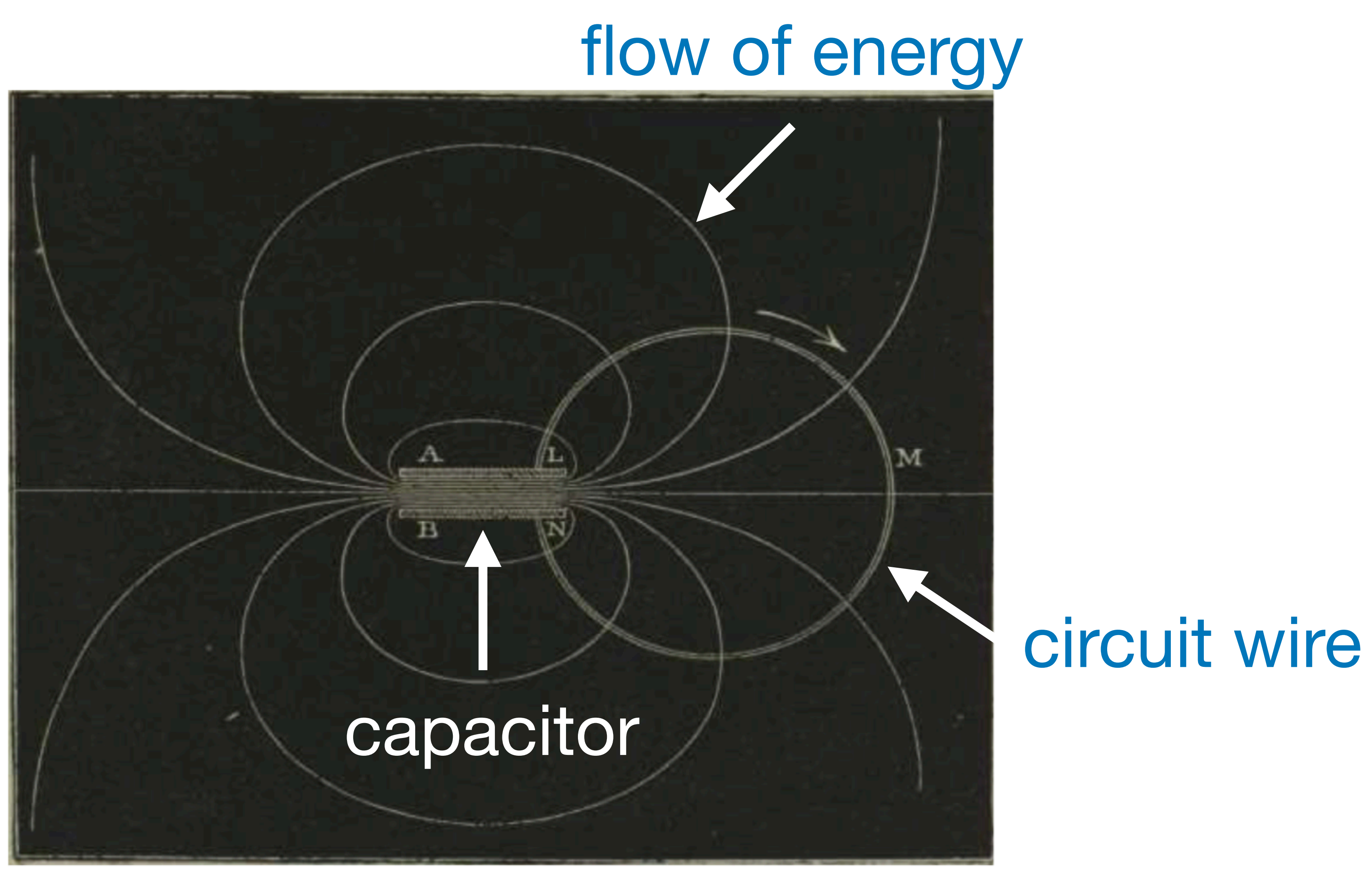
BES-III spectrometer

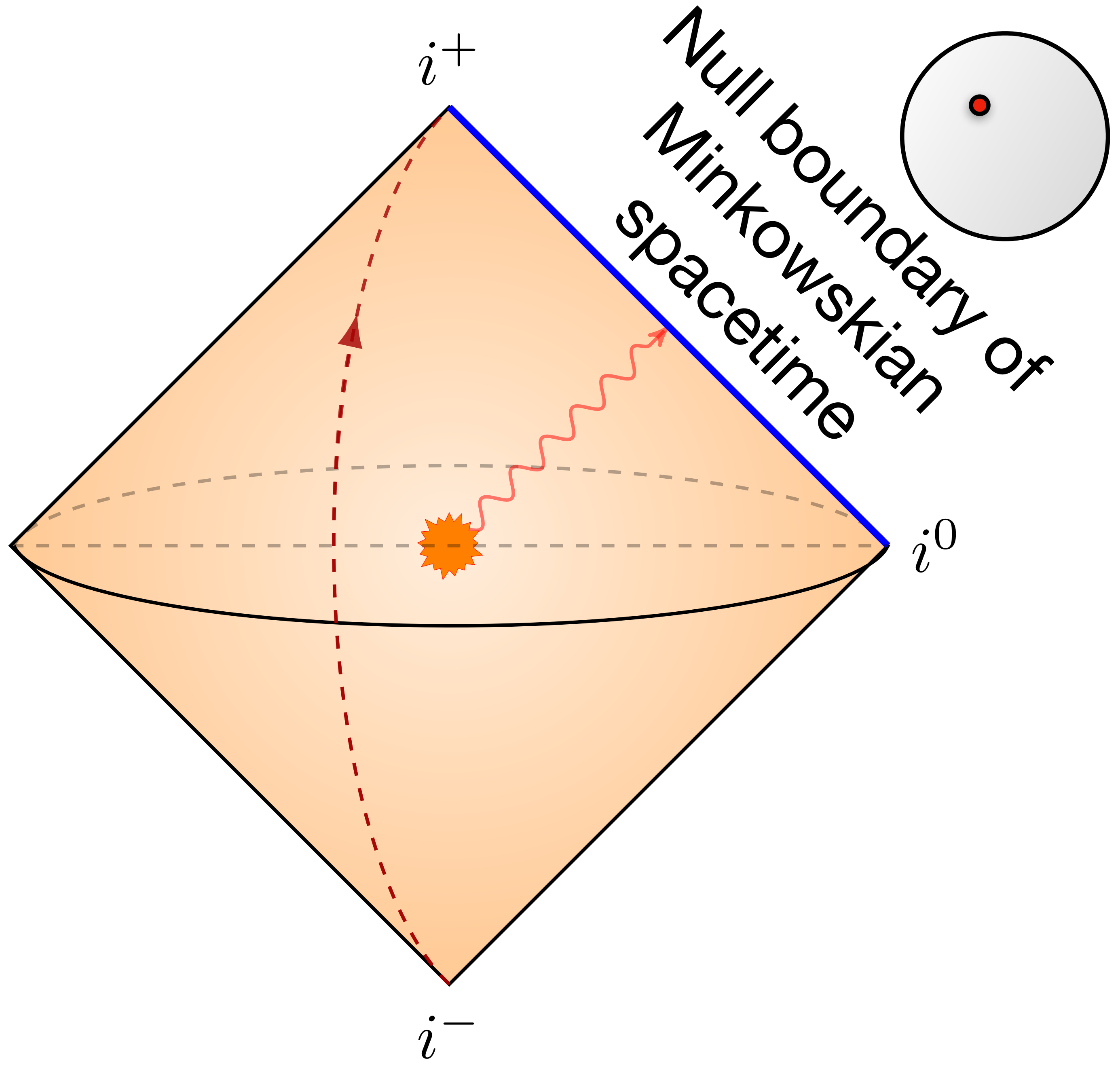
“Jets and quantum field theory”

Sveshnikov, Tkachov, 1996

“a systematic description of jet-related features of hadronic final state in high energy physics can be achieved in a QFT-compatible manner within the so-called formalism of **C-algebra**”

C is for calorimetric





$$T_{0i} = S_i = \frac{1}{\mu_0}(\boldsymbol{E} \times \boldsymbol{B})_i$$

energy opreator

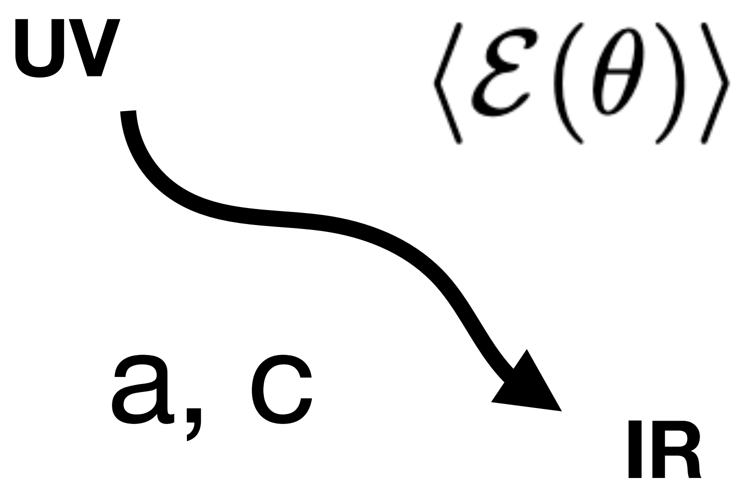
$$\mathcal{E}(\boldsymbol{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt\, n_i T_{0i}(t,r)$$

The birth of conformal collider physics

Hofman, Maldacena, 2008

$$\langle\psi|\mathcal{E}(n)|\psi\rangle \geq 0$$

Trivial in QCD,
not so in CFT and Gravity



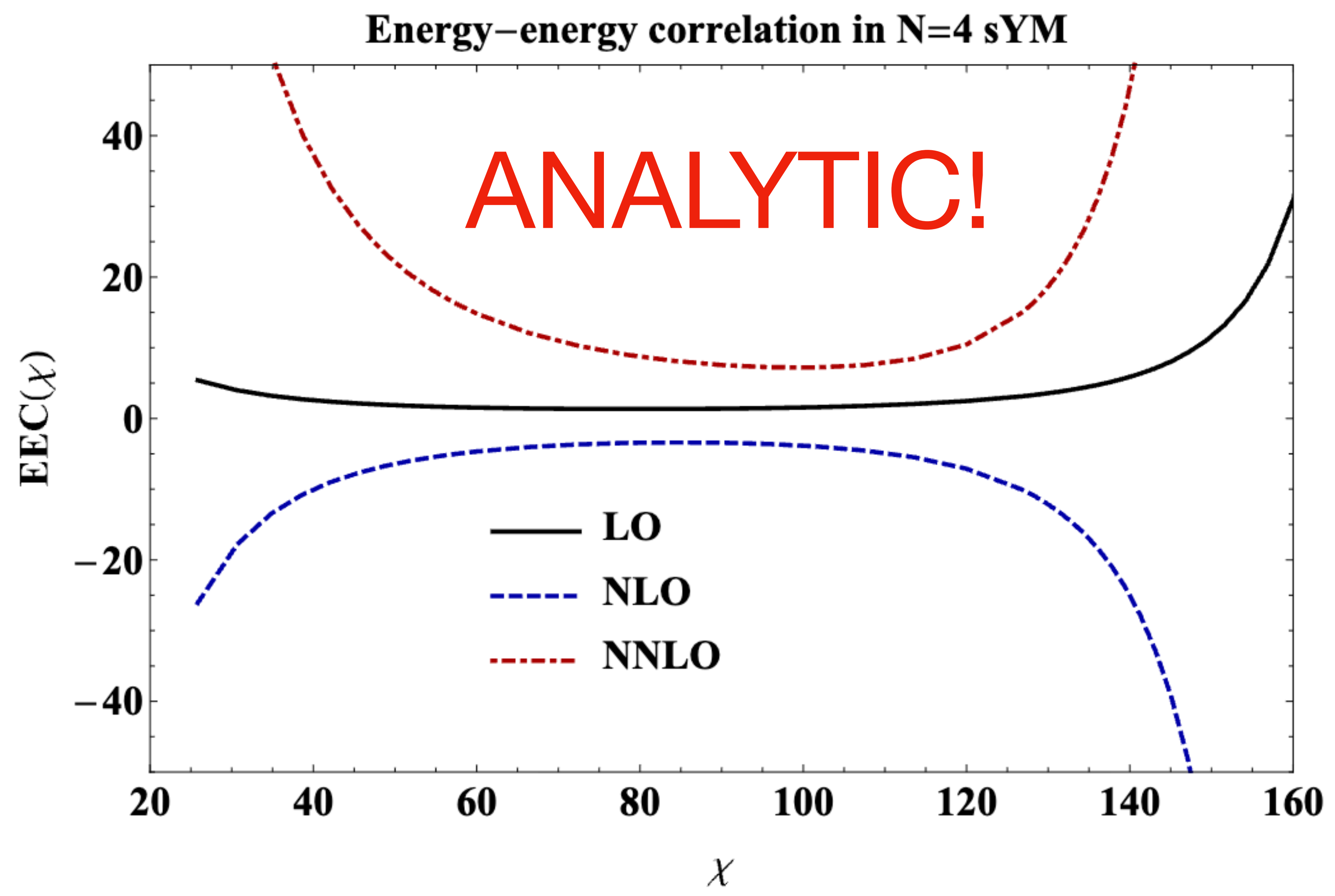
$$\langle\mathcal{E}(\theta)\rangle = 1 + 3\frac{c-a}{c}\left(\cos^2\theta - \frac{1}{3}\right)$$

Conformal collider bound $\frac{3c}{2} \geq a \geq 0$

Belitsky, Hohenegger, Korchemsky, Sokatchev, Zhiboedov, 2013

$$\text{EEC} = \langle\psi|\mathcal{E}(n_1)\mathcal{E}(n_2)|\psi\rangle$$
$$= \int \langle\Omega|JTTJ|\Omega\rangle$$

Open the door for exploiting the
remarkable data for 4-pt function of CFT

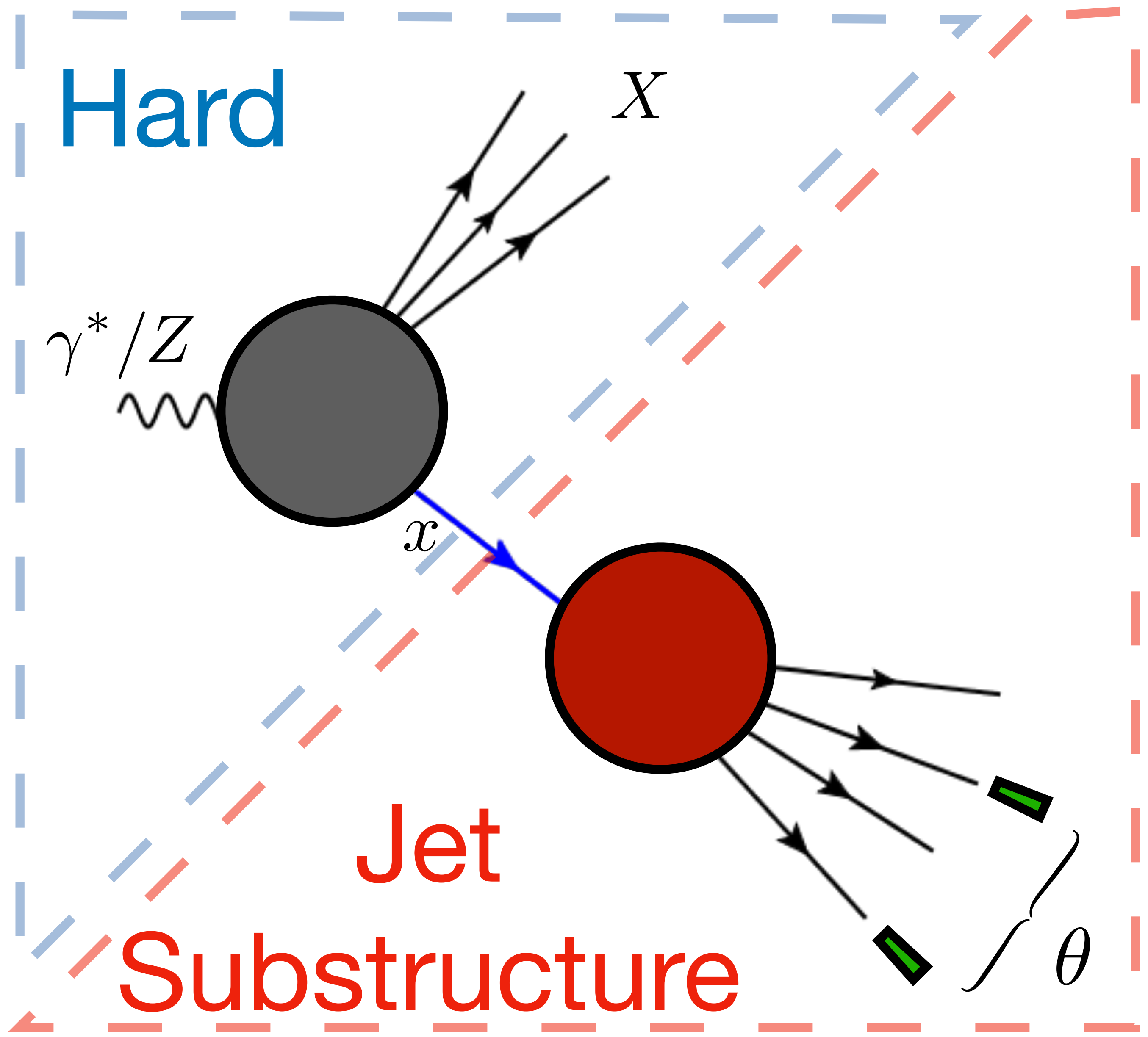


Henn, Sokatchev, Yan, Zhiboedov, 2019

Dual view on energy flow measurement

particle language

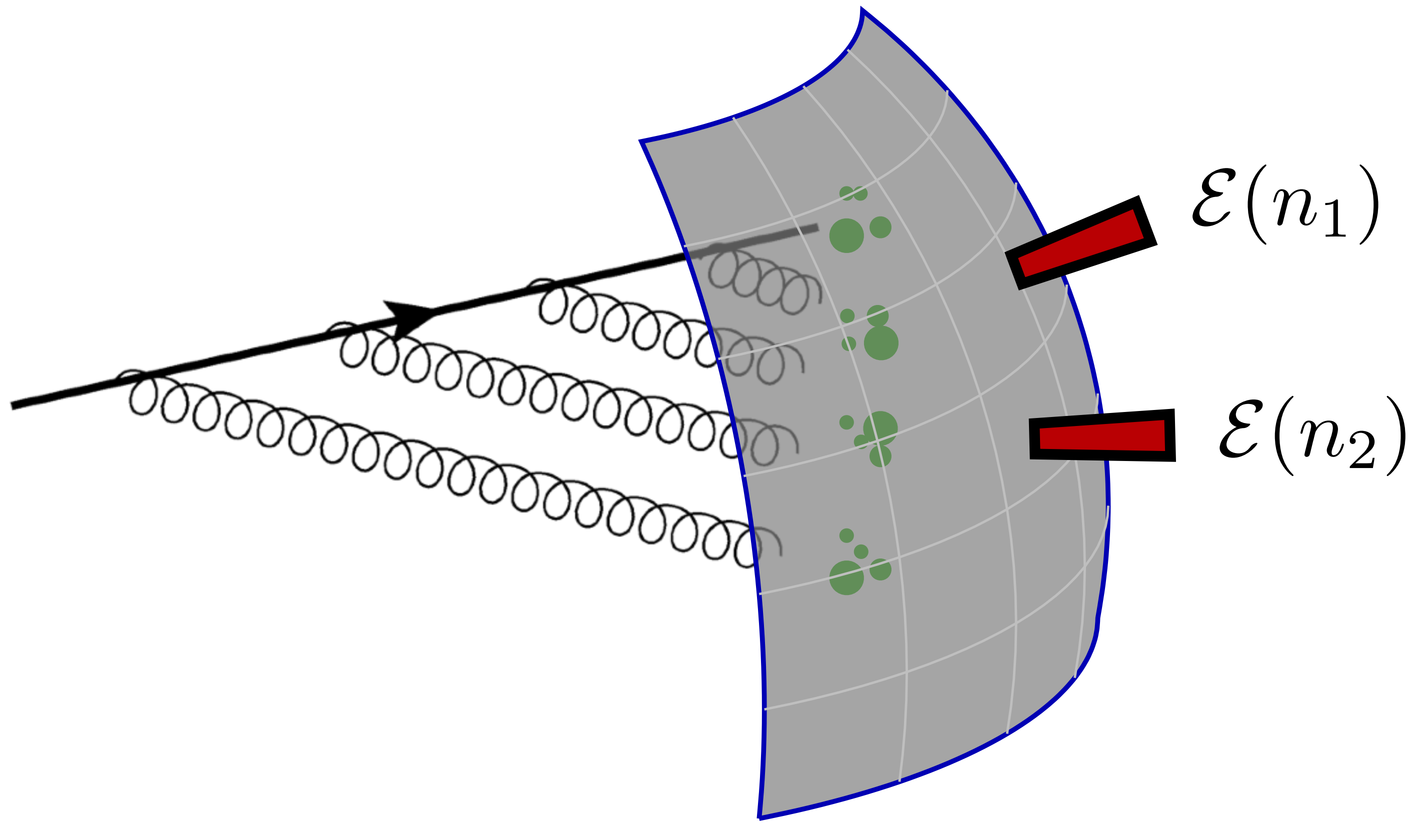
Factorization, resummation



LL -> NNLL

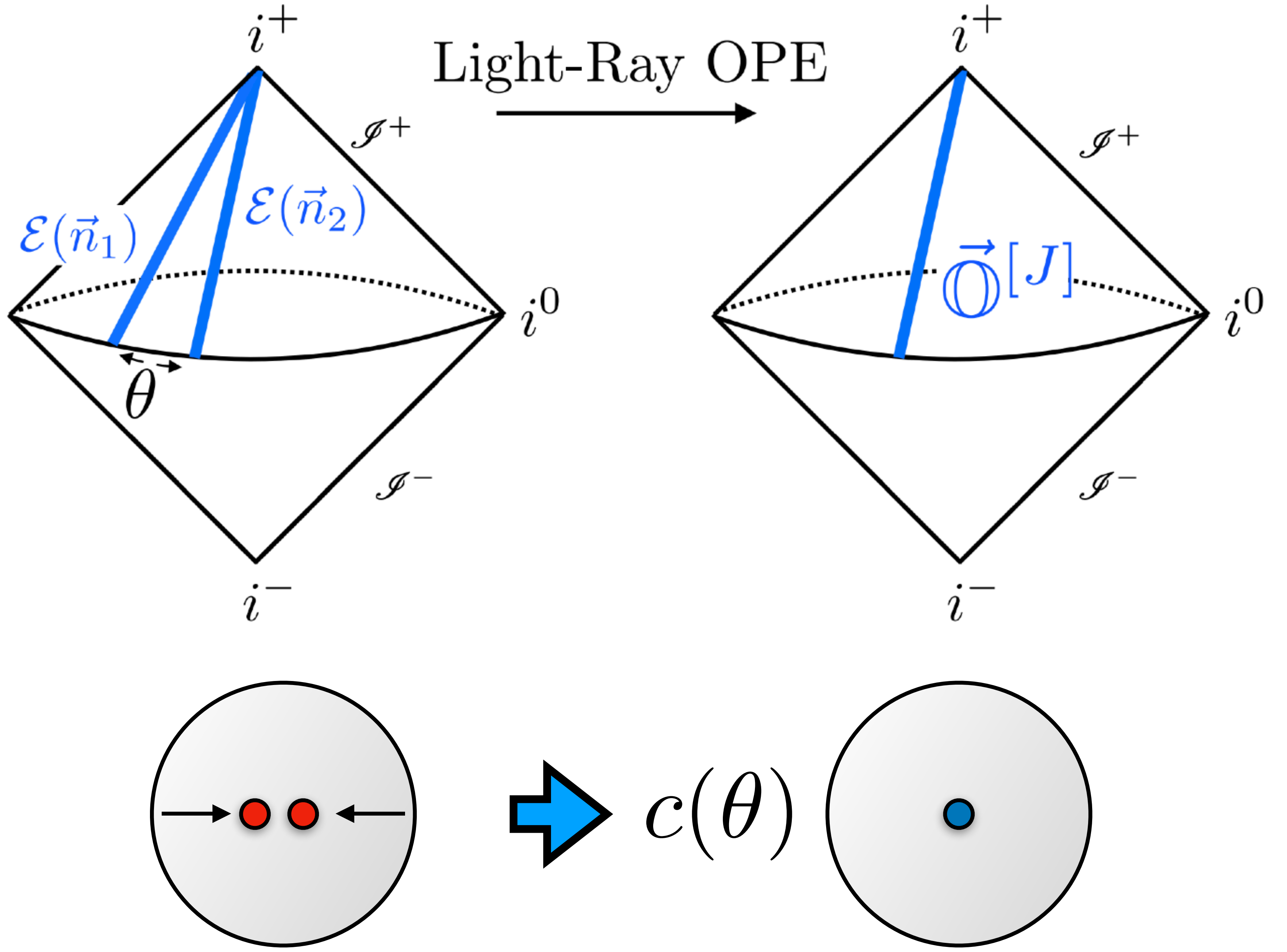
Dixon, Moult, HXZ, 2019
Chen, Moult, Zhang, HXZ, 2020

Dual view of energy correlators



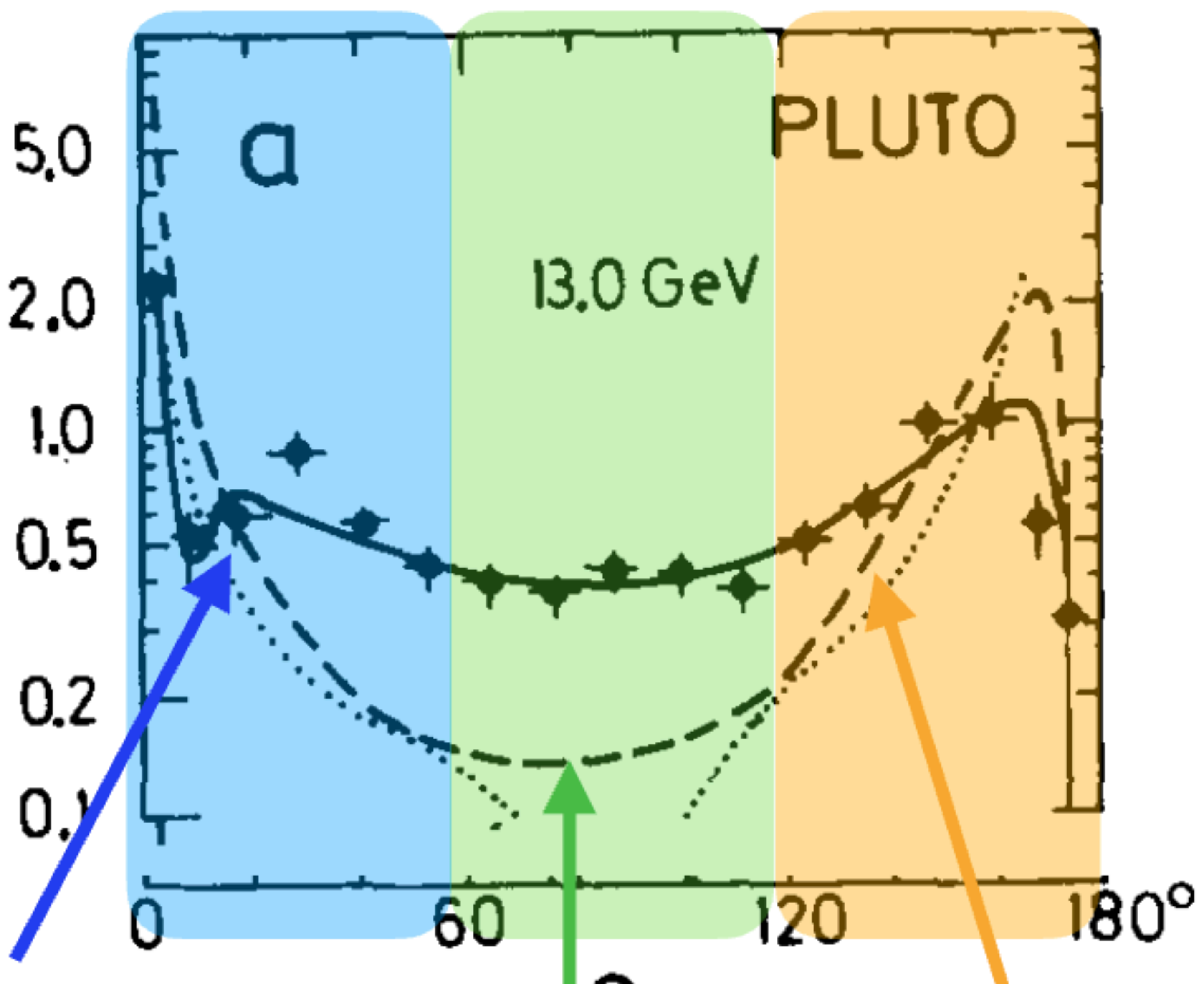
operator language

Light-ray OPE, Symmetry



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

The quest for precision



Collinear:

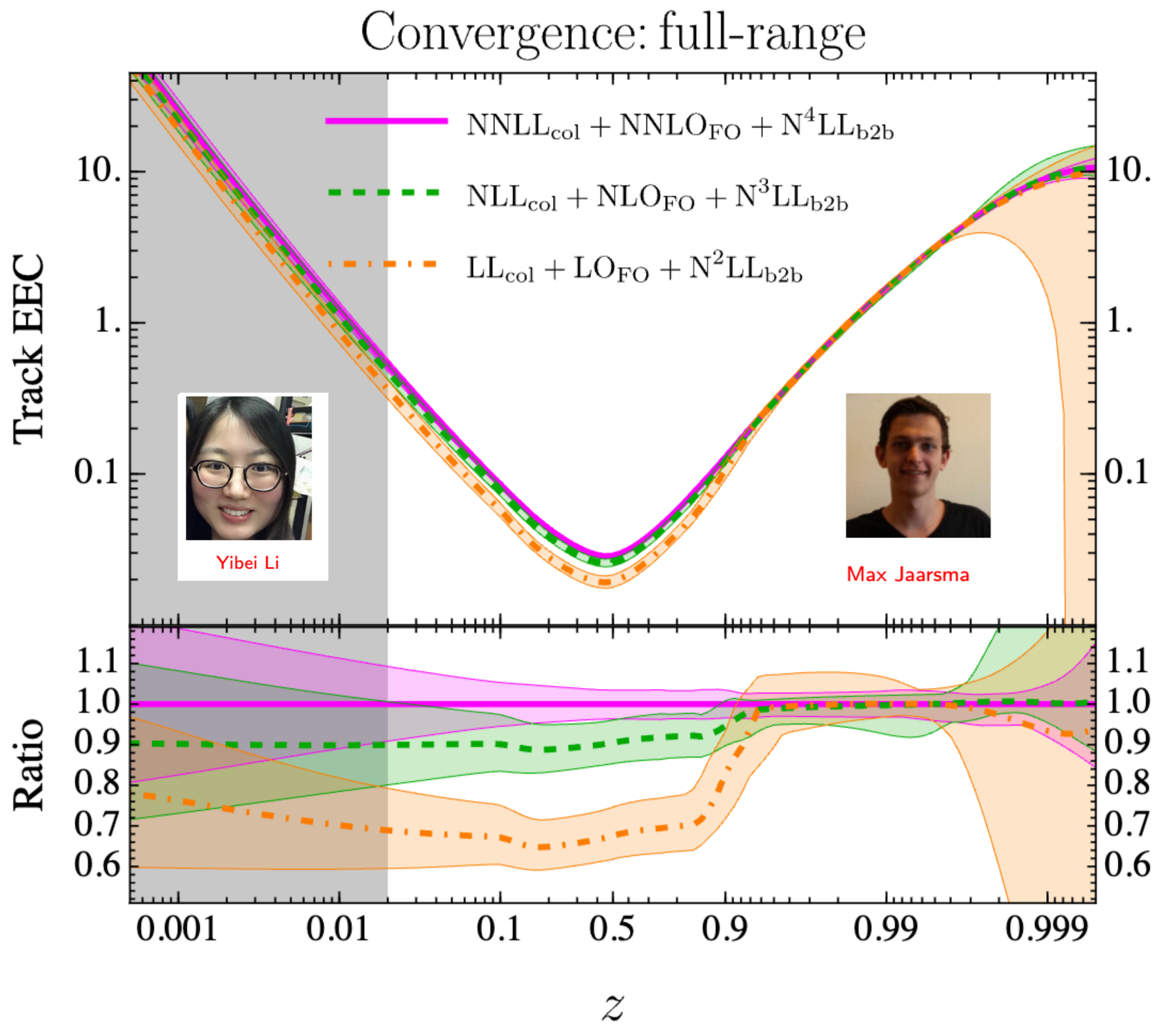
Konishi, Ukawa, Veneziano

Central:

Basham, Brown, Ellis, Love

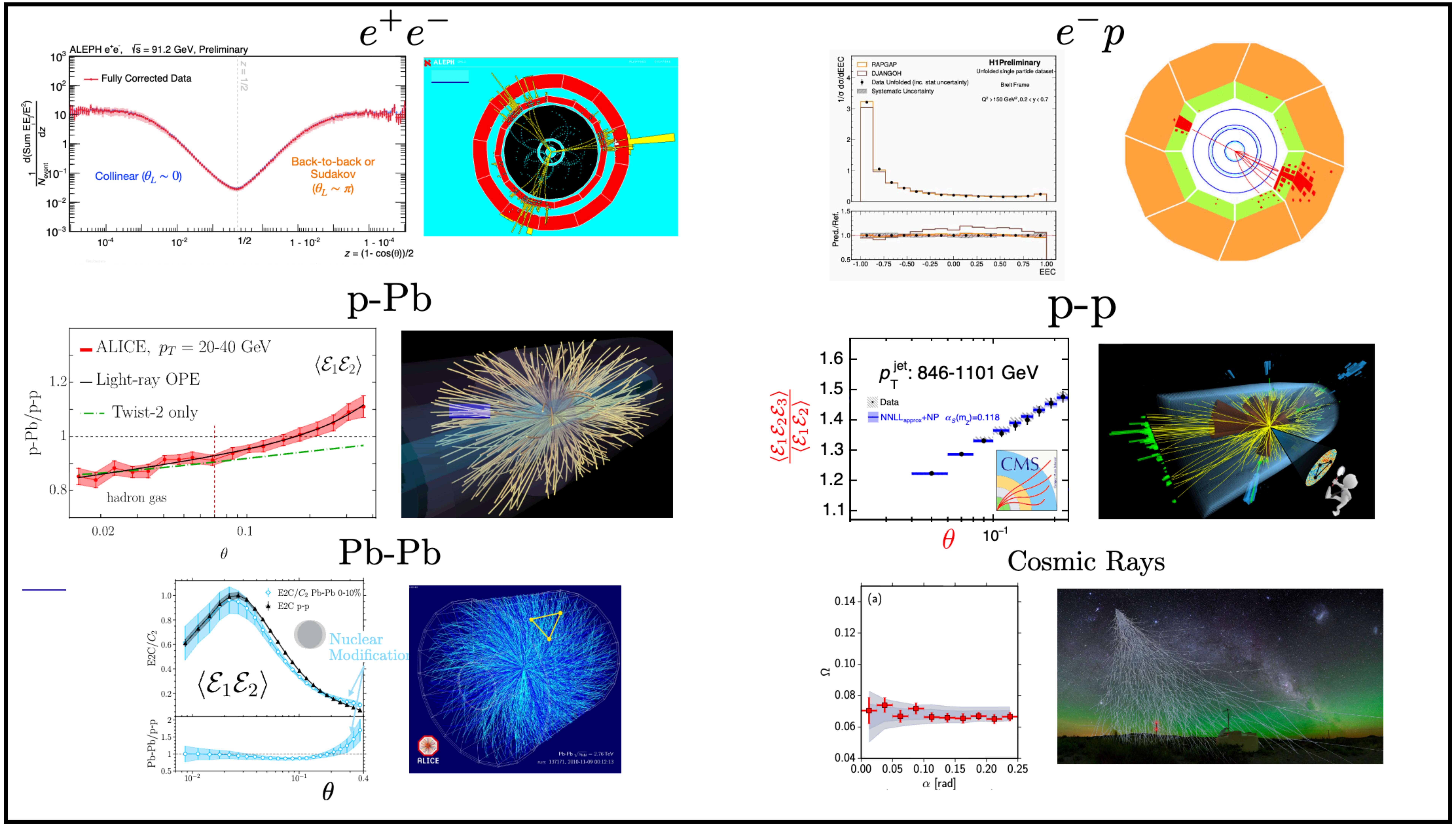
b2b:

Parisi, Petronzio



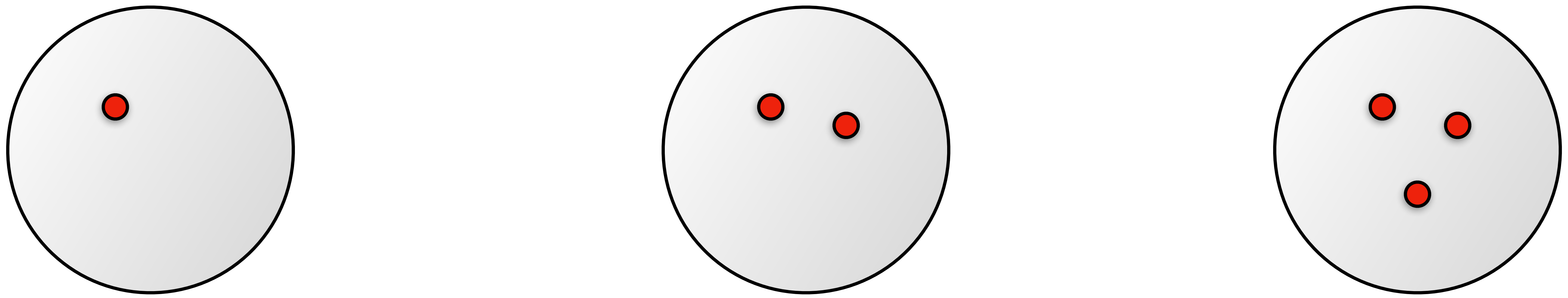
Jaarsma, Li, Moult, Watlewijn, HXZ, 2025

From celestial sphere back to reality



Slide from Ian Moult, QCD@LHC 2025

Imaging of emerging and intrinsic scales



One-point energy flux

Kravchuk, Simmons-Duffin, 2018
Chen, Moult, HXZ, 2021
Caron-Huot, Kologlu, Kravchuk, Meltzer, Simmons-Duffin, 2022

light transform

$\nu = -1 - J_L$

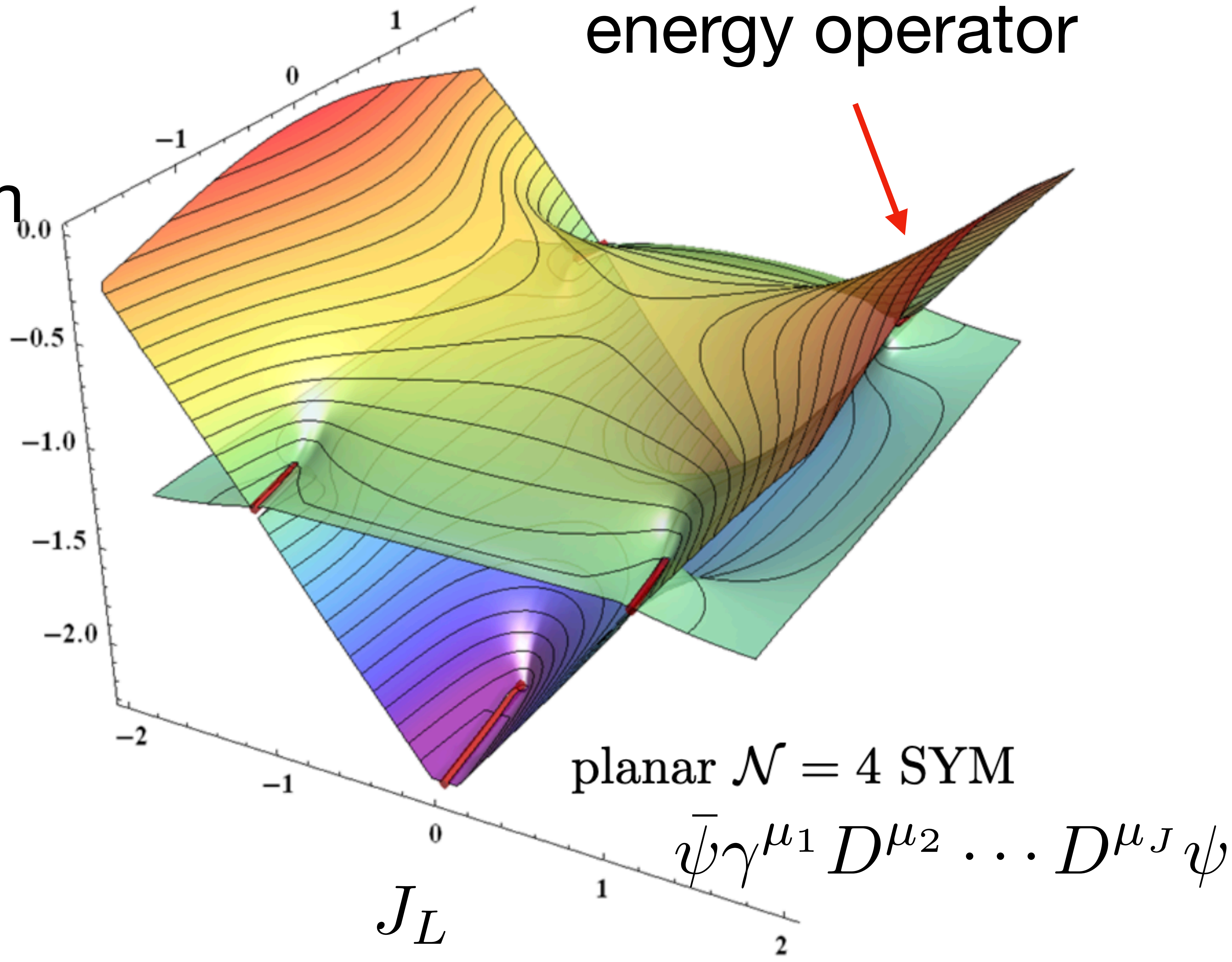
$$\mathbb{O}^H_{J_L}(z) = \sum_h \int \frac{d^3\vec{p}}{(2\pi)^3 2E} \delta^{(2)}(\hat{p} - \hat{z})\, E^{\nu-1} a_h^\dagger(p) a_h(p)$$

sum over all particles

measurement function

$$f(\nu, Q) = \frac{1}{\sigma_{\text{tot}}} \sum_X \int d\sigma_{e^+e^- \to X} \boxed{\sum_{h \in X} \left(\frac{E_a}{Q}\right)^{\nu-1}} = \frac{4\pi}{\sigma_{\text{tot}}} \frac{\langle \mathbb{O}^H_{J_L}(z) \rangle_Q}{Q^{\nu-1}}$$

c.o.m. energy



The horizontal position determines measurement, the vertical position determines Q scaling

Art from Quantum Spectral Curve

Gromov, Levkovich-Maslyuk, Sizov, 2015

From multiplicity to DGLAP trajectory

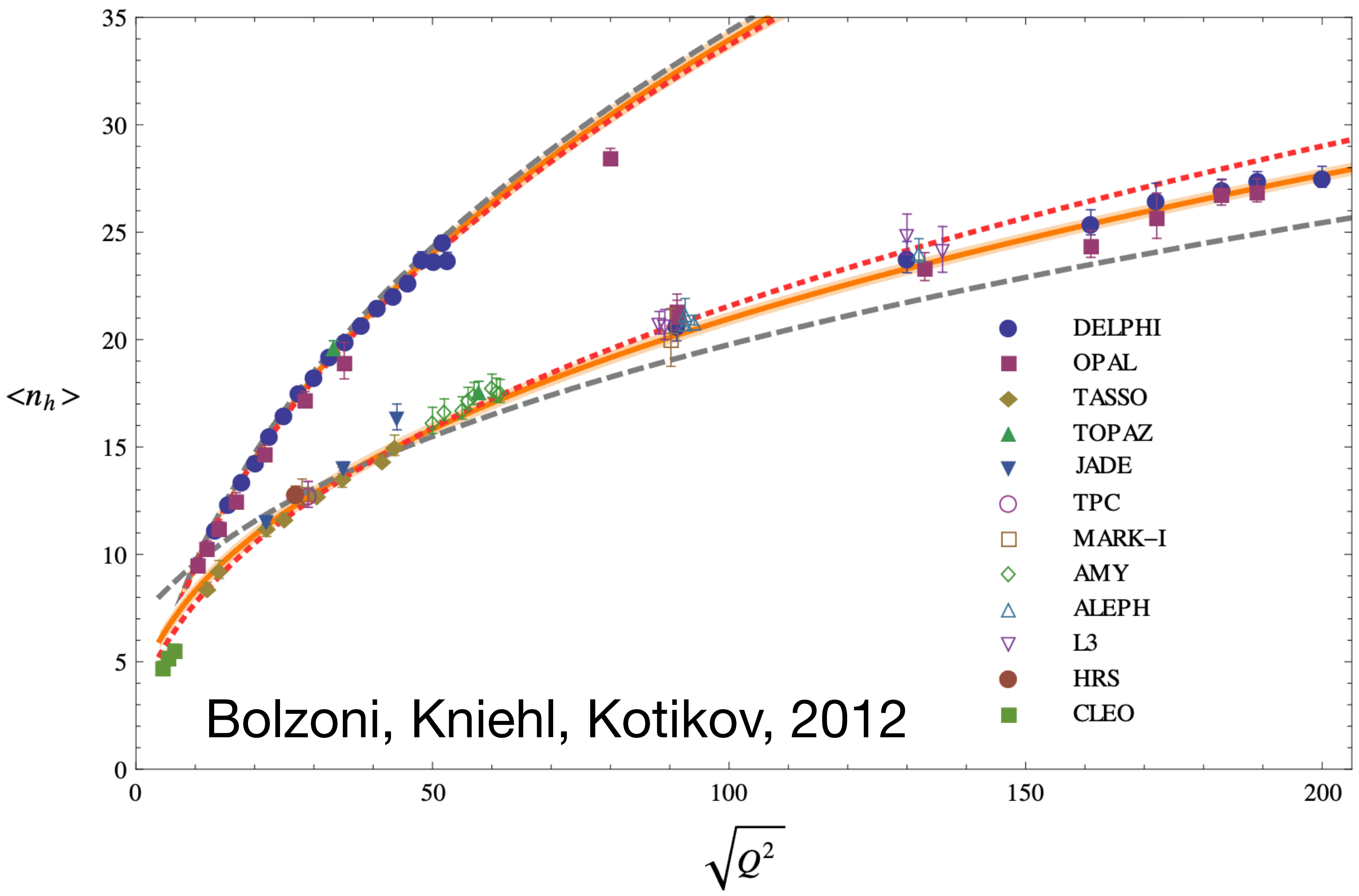
$$\mathbb{O}^{H}_{J_L}(z) = \sum_{h} \int \frac{d^3\vec{p}}{(2\pi)^3 2E} \delta^{(2)}(\hat{p}-\hat{z})\, E^{\nu-1} a_h^\dagger(p) a_h(p)$$

$\nu = -1 - J_L$

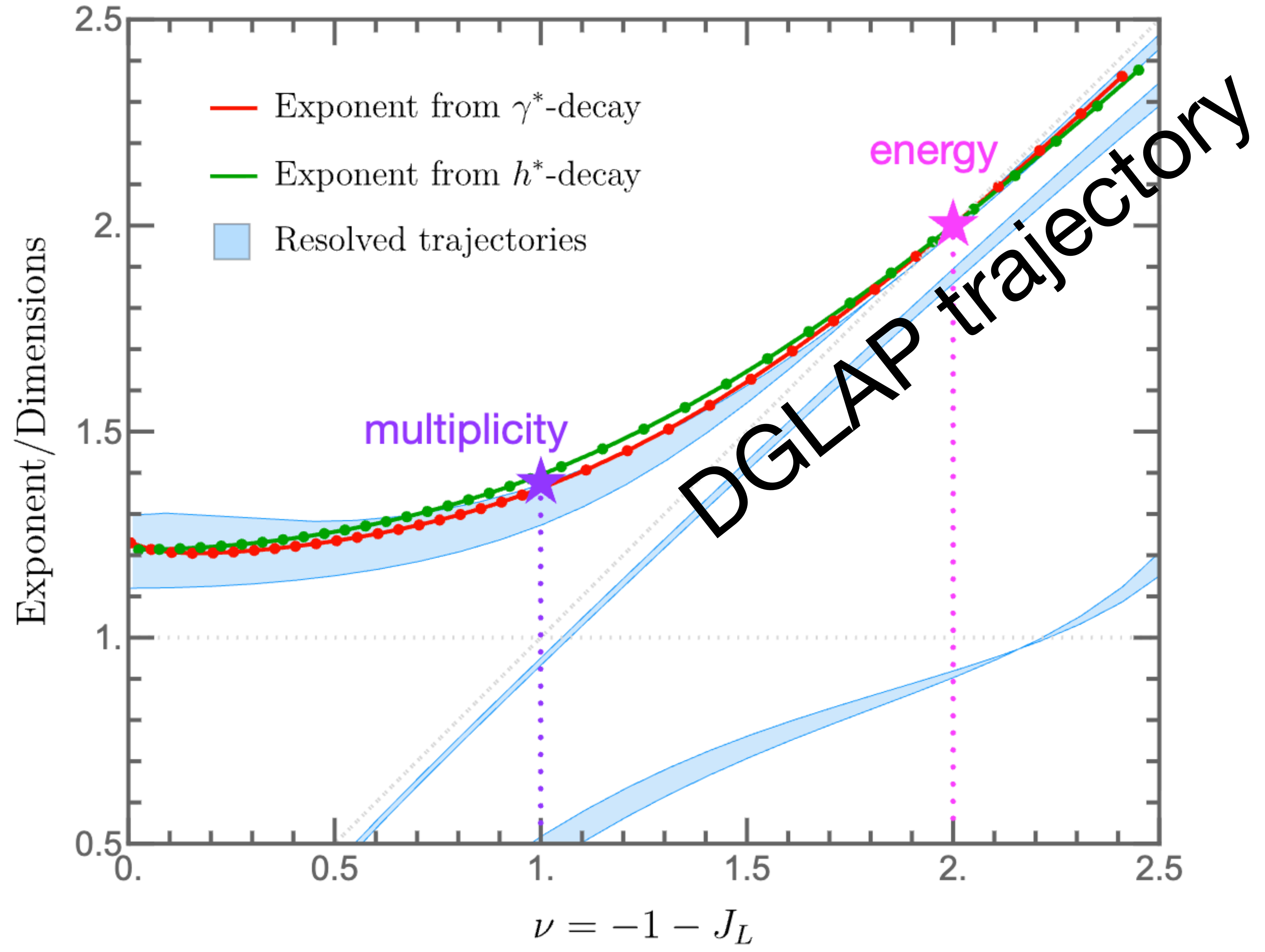
sum over all particles

J_L=-1, multiplicities

$$f(\nu, Q) \sim Q^{\Delta_L^{\max}-\nu+1}$$

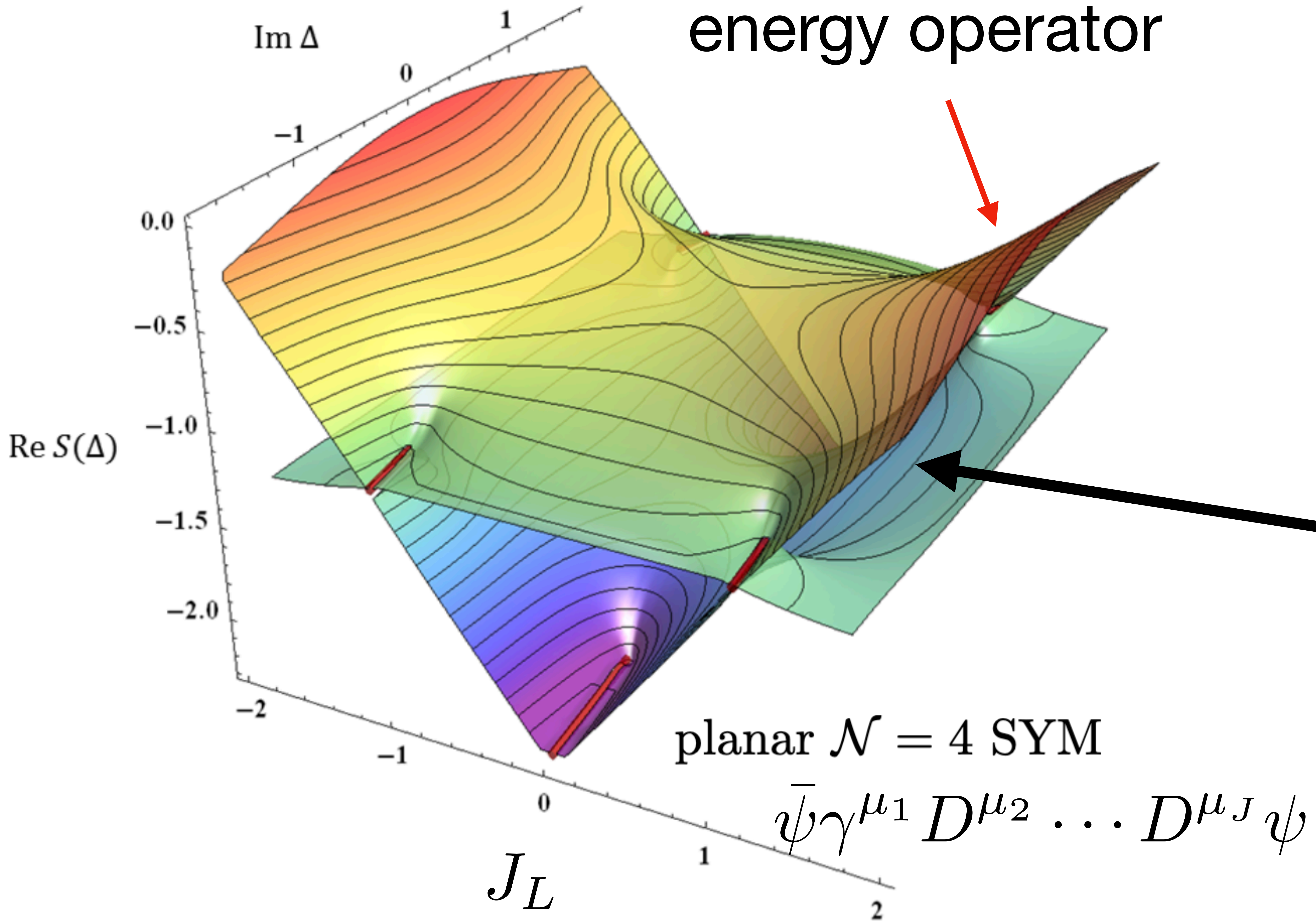


Bolzoni, Kniehl, Kotikov, 2012

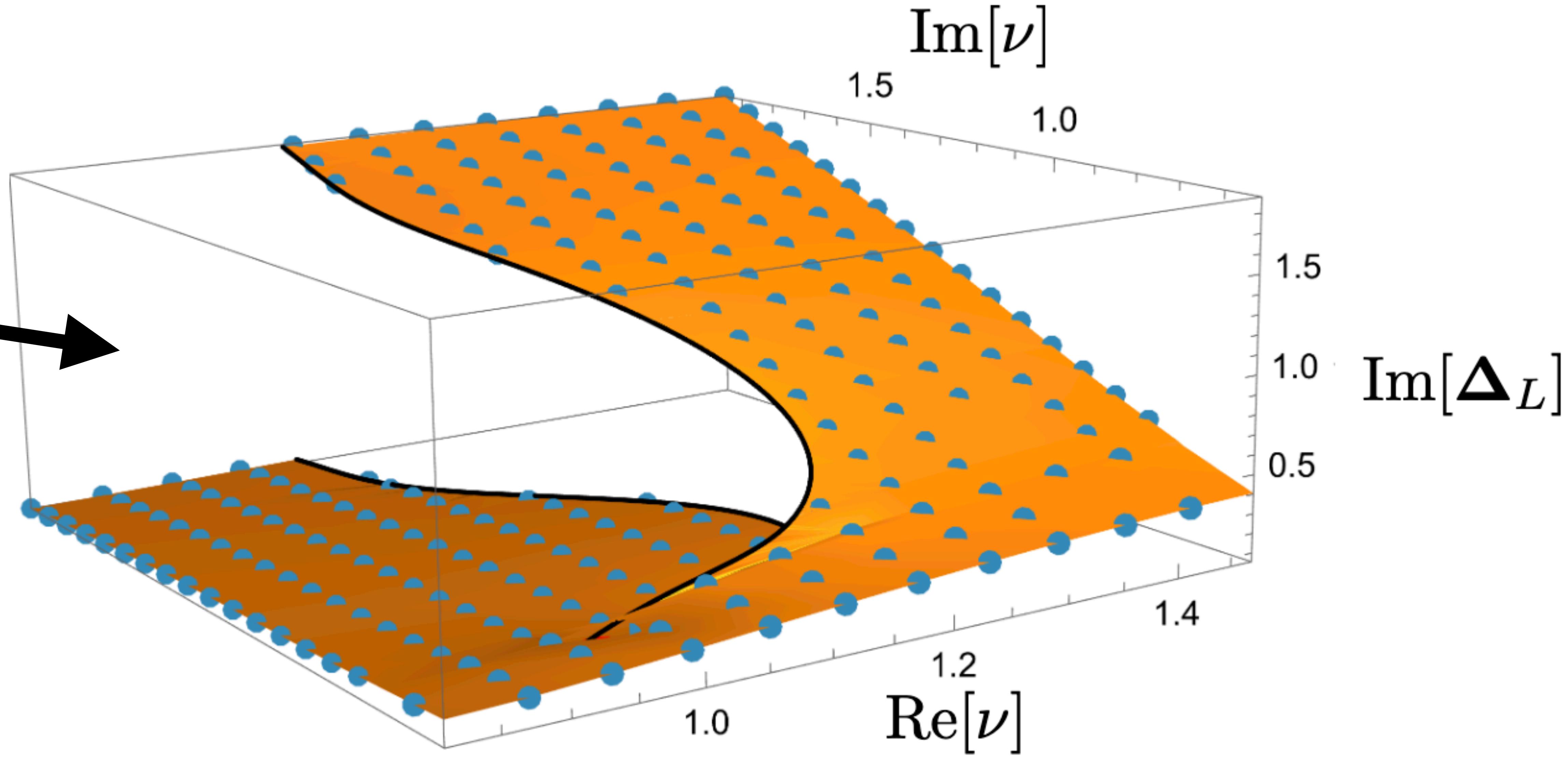


Chang, Chen, Simmons-Duffin, HXZ, 2025

From DGLAP to the full Riemann Surface



$$f(\nu, Q) \sim Q^{\mathbf{\Delta}_L^{\max} - \nu + 1}$$



Art from Quantum Spectral Curve

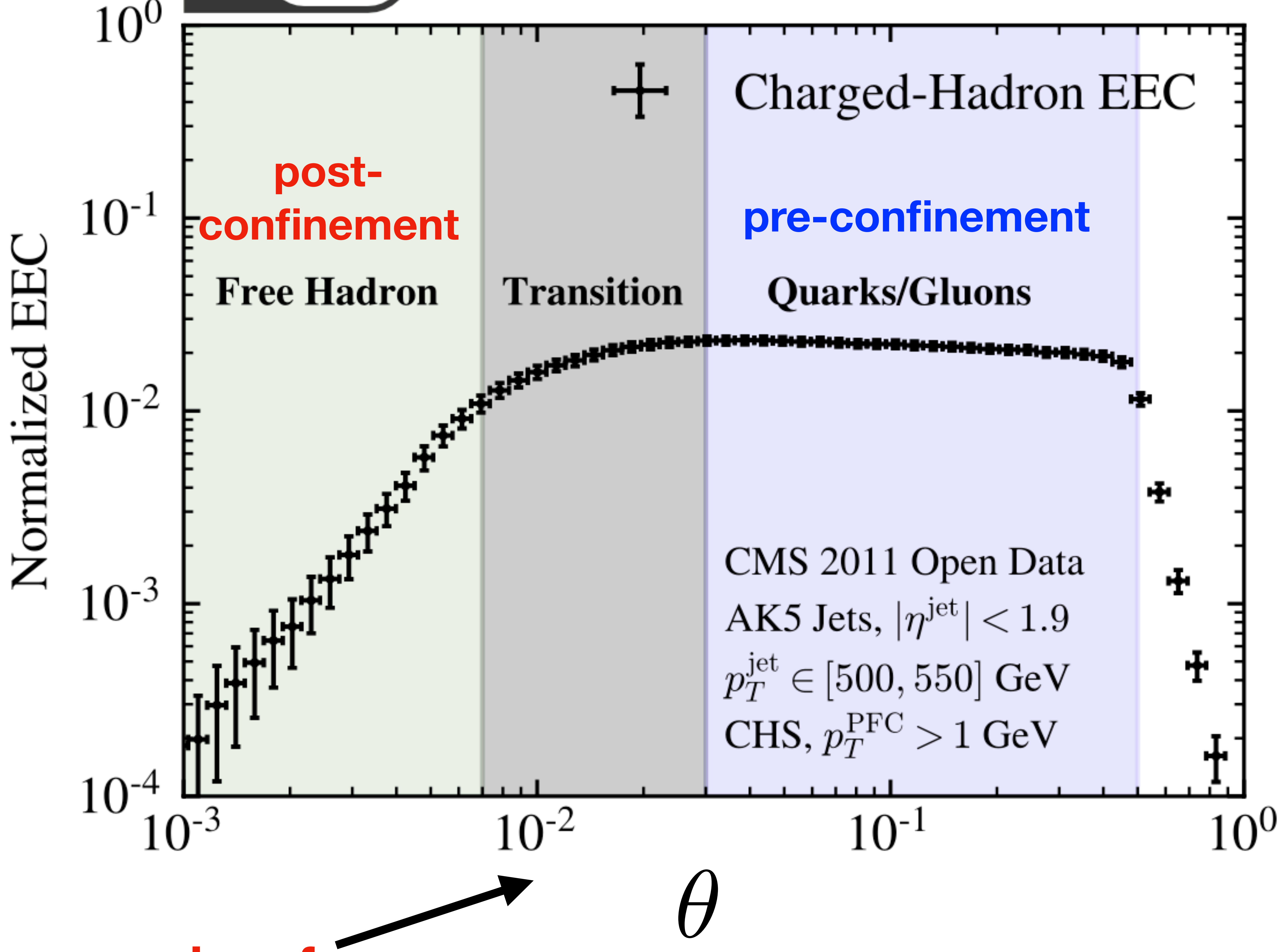
Gromov, Levkovich-Maslyuk, Sizov, 2015

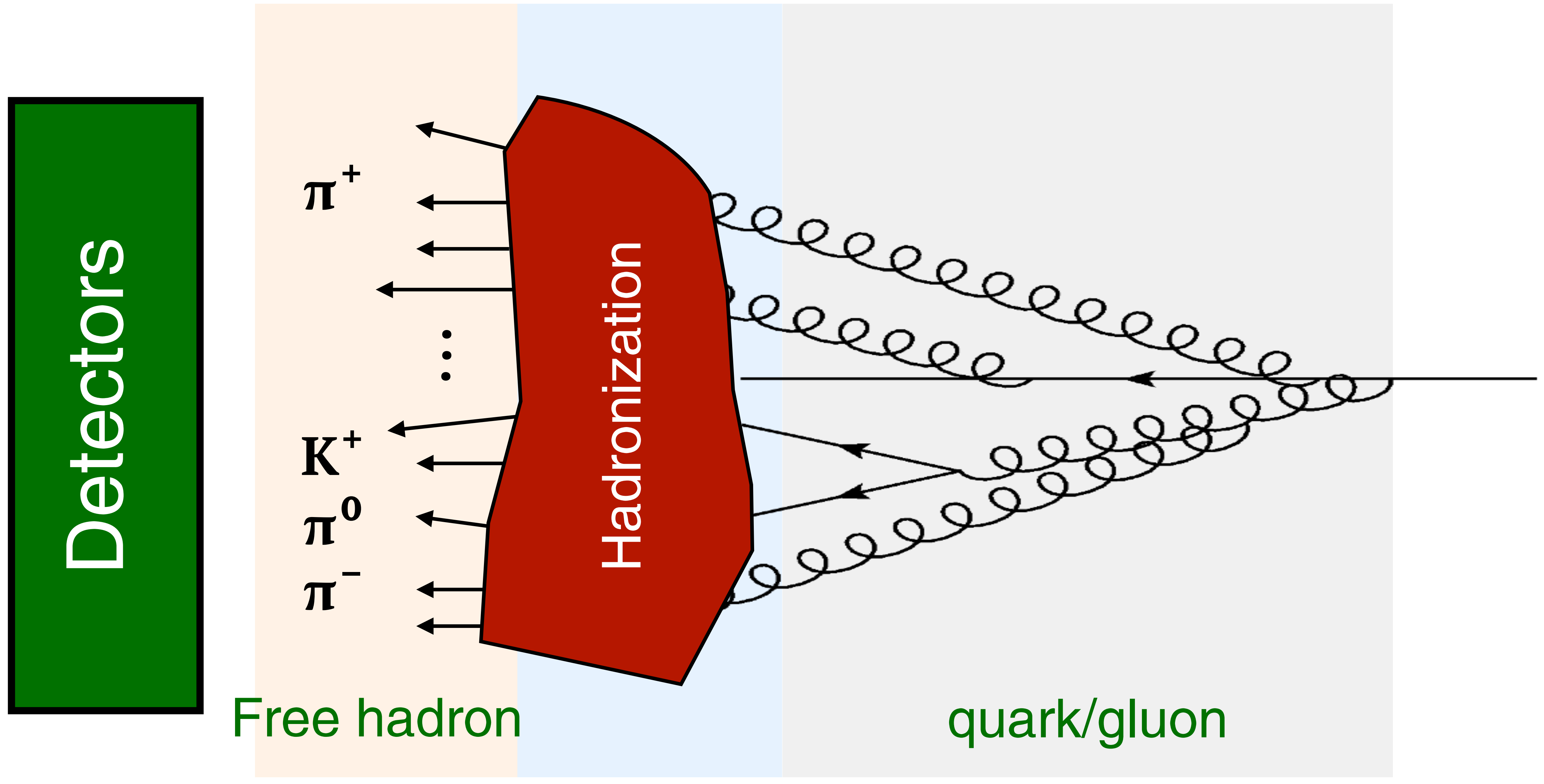
LHC simulation data

Chang, Chen, Simmons-Duffin, talk at 2026, Beijing

The scale of confinement from energy correlator

Komiske, Moult, Thaler, HXZ, 2022





low energy

late time

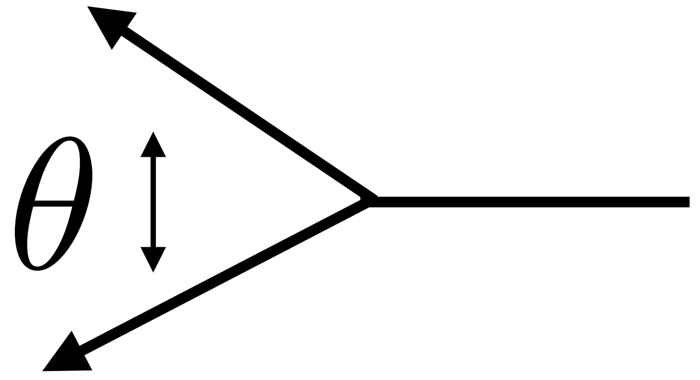
$$\Delta p_T \sim E_1 E_2 \theta$$

high energy

early time

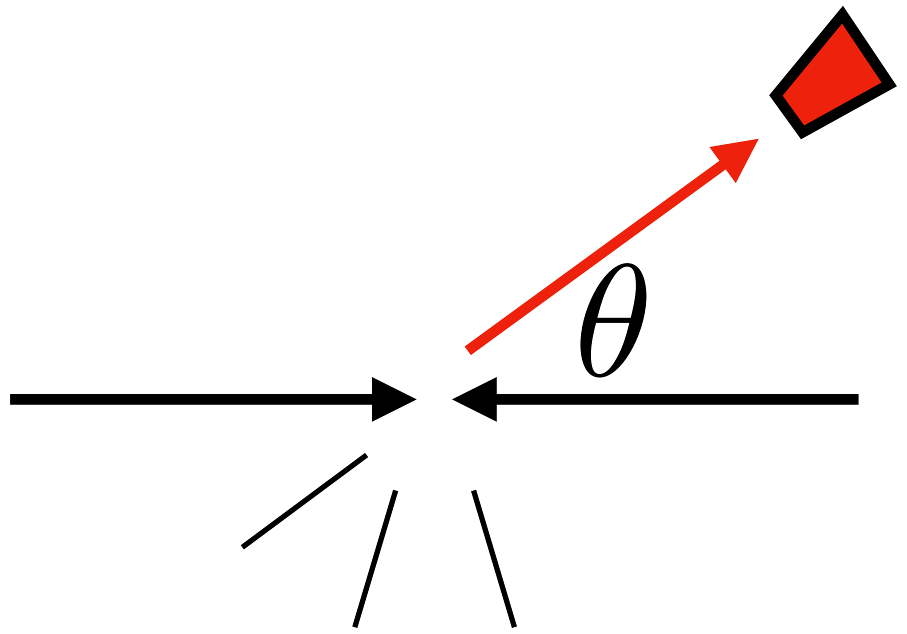
a probe of “confinement” scale

Angular resolution helps!

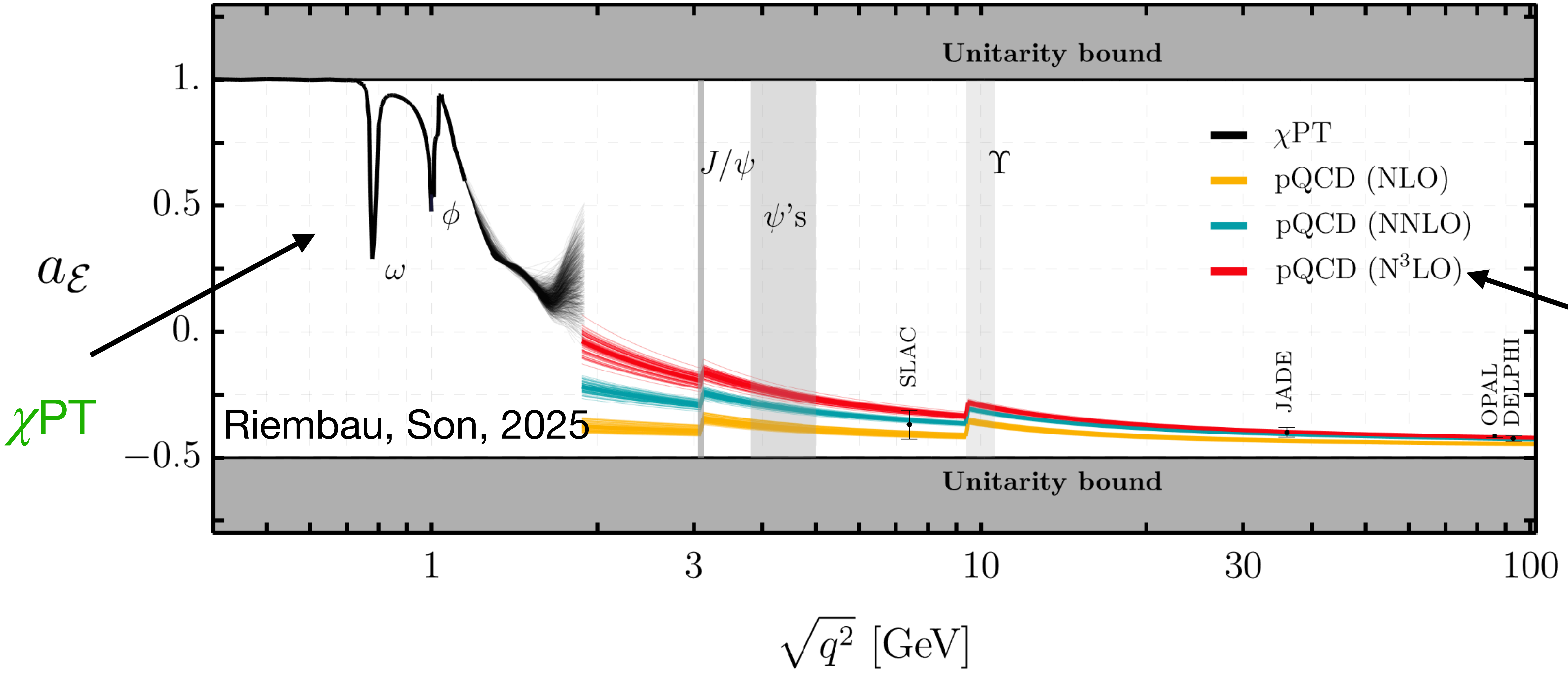


RG flow in QCD

Hofman, Maldacena, 2008



$$\langle \mathcal{E}_n \rangle = \frac{\langle \mathcal{E} \rangle}{4\pi}\left[1 + a_{\mathcal{E}}\left(\frac{3}{2}\sin^2\theta - 1\right)\right] \quad \begin{cases} \text{fermion} & a_{\mathcal{E}} = -\frac{1}{2} \\ \text{scalar} & a_{\mathcal{E}} = 1 \end{cases}$$

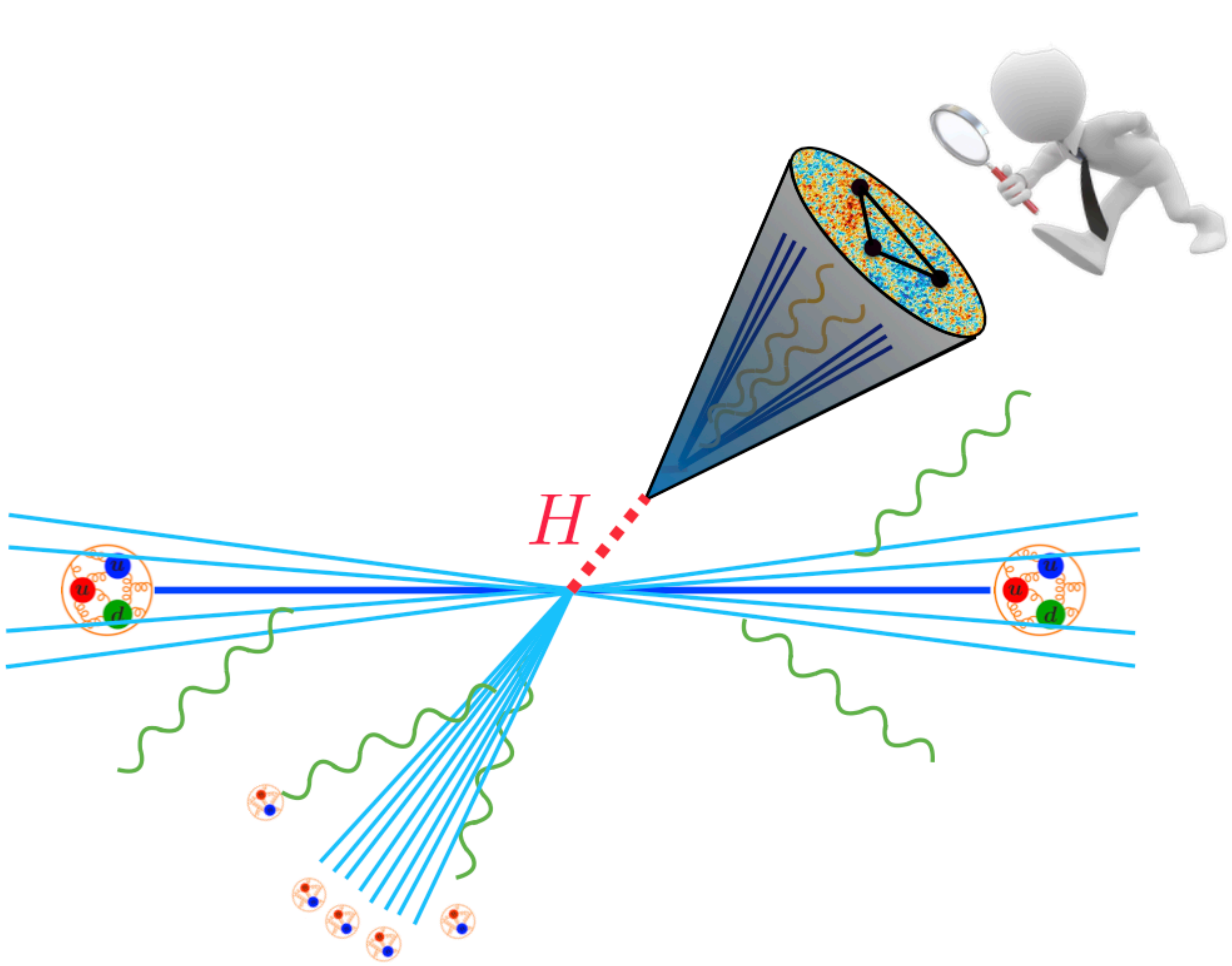


Monte Carlo of χPT

PHOKHARA

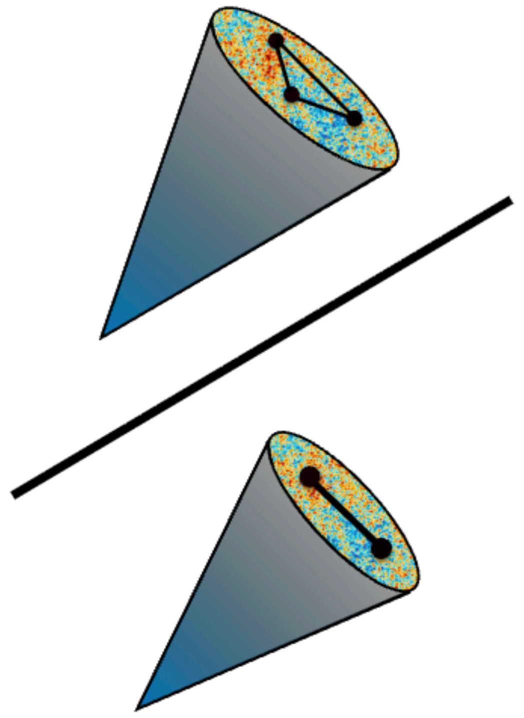
He, Xing, Yang, HXZ, 2025

Energy correlators shed new light on strong coupling measurement



Rethinking **jet substructure** in terms of energy correlators

Chen, Moult, Zhang, HXZ, 2020



remove complex non-perturbative corr. by ratio

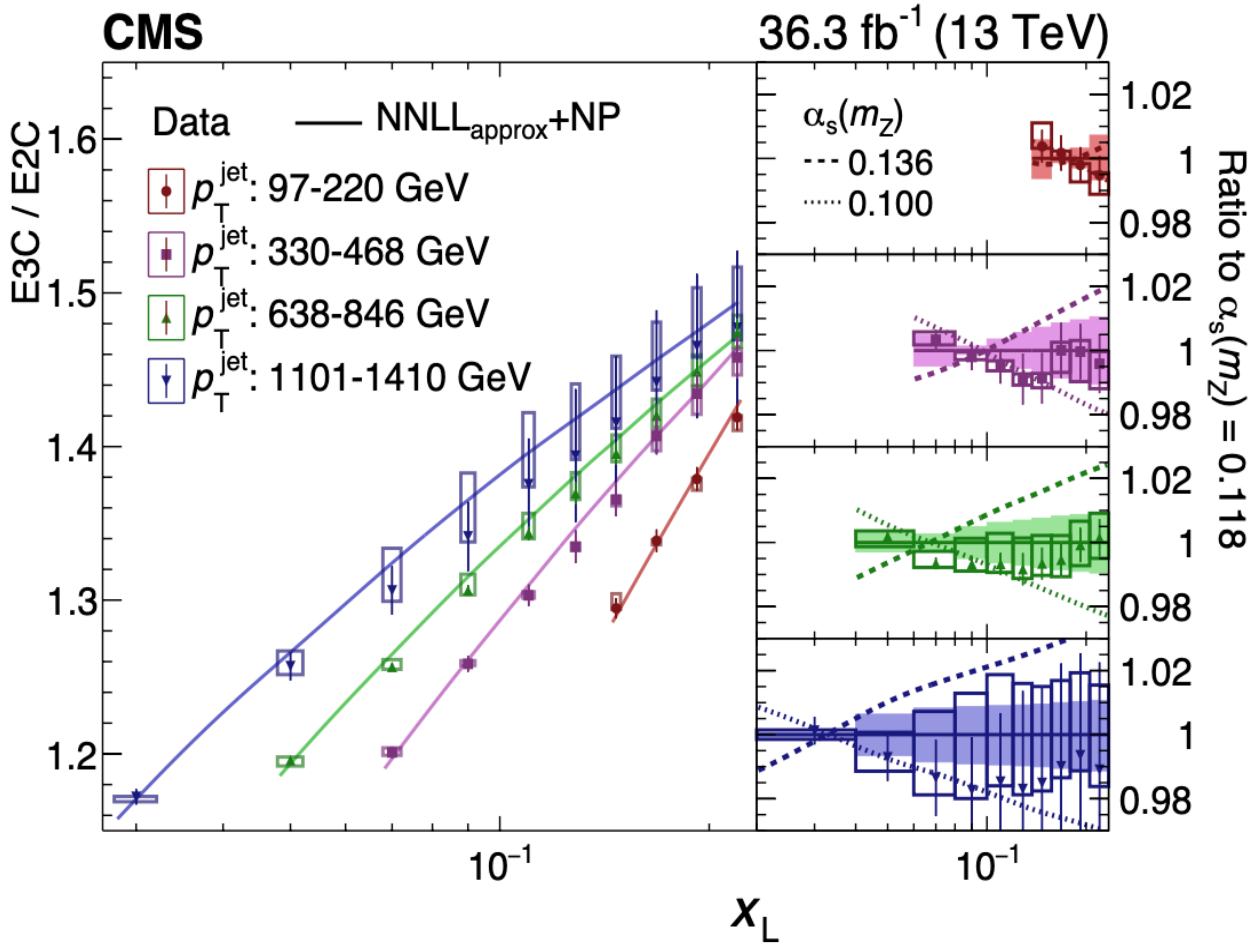
$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[J]} \rangle}{\langle \mathbb{O}^{[3]} \rangle} \sim \theta^{\gamma(J)-\gamma(3)}$$

In the first order approximation, scaling in angle depends α_s

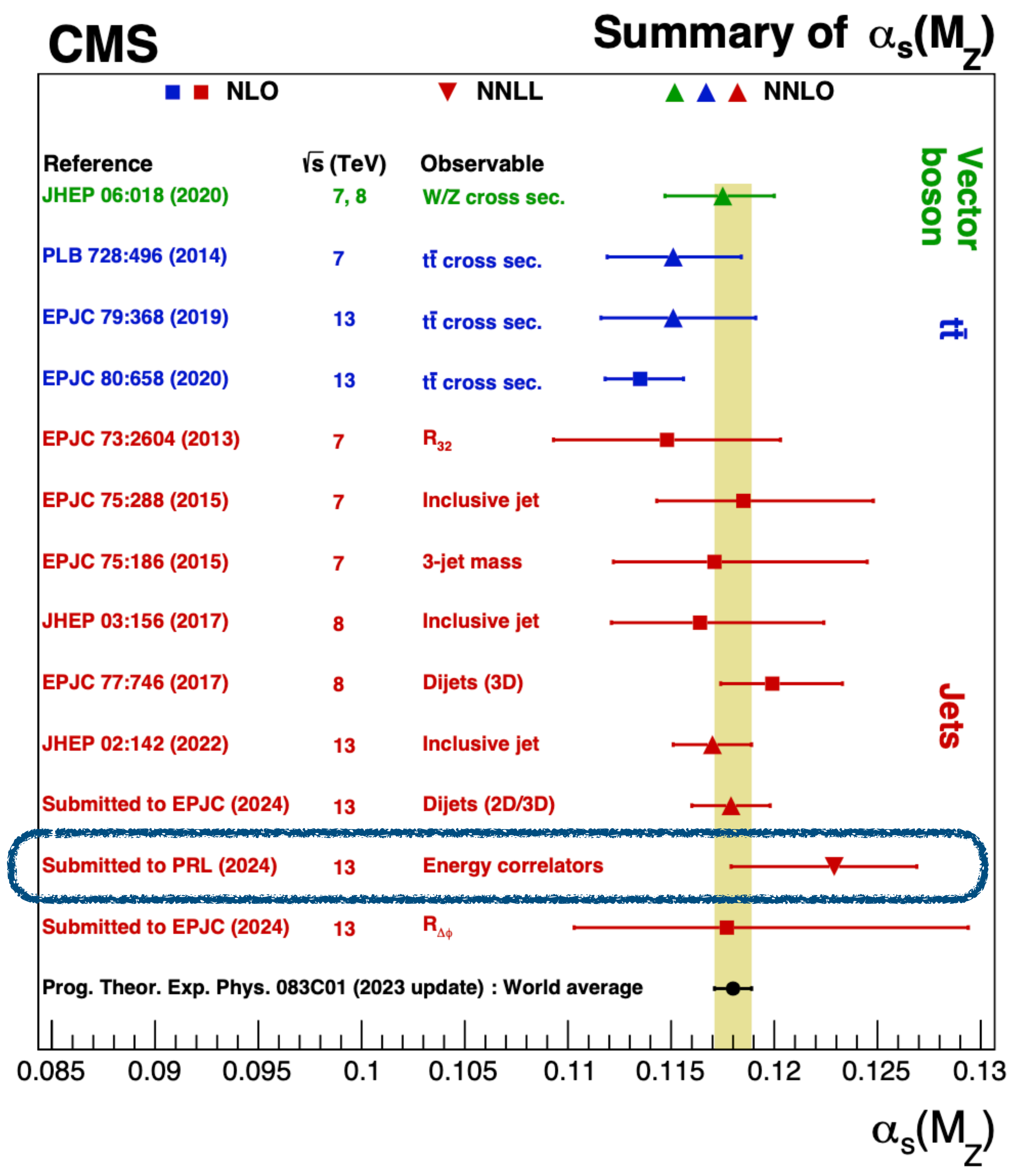
Heroic efforts to calculate $\gamma(J)$

Moch, Vermaseren, Vogt, 2004
Moch, Ruijl, Ueda, Vermaseren, Vogt, 2017
+ on going work

Strong coupling from energy correlators



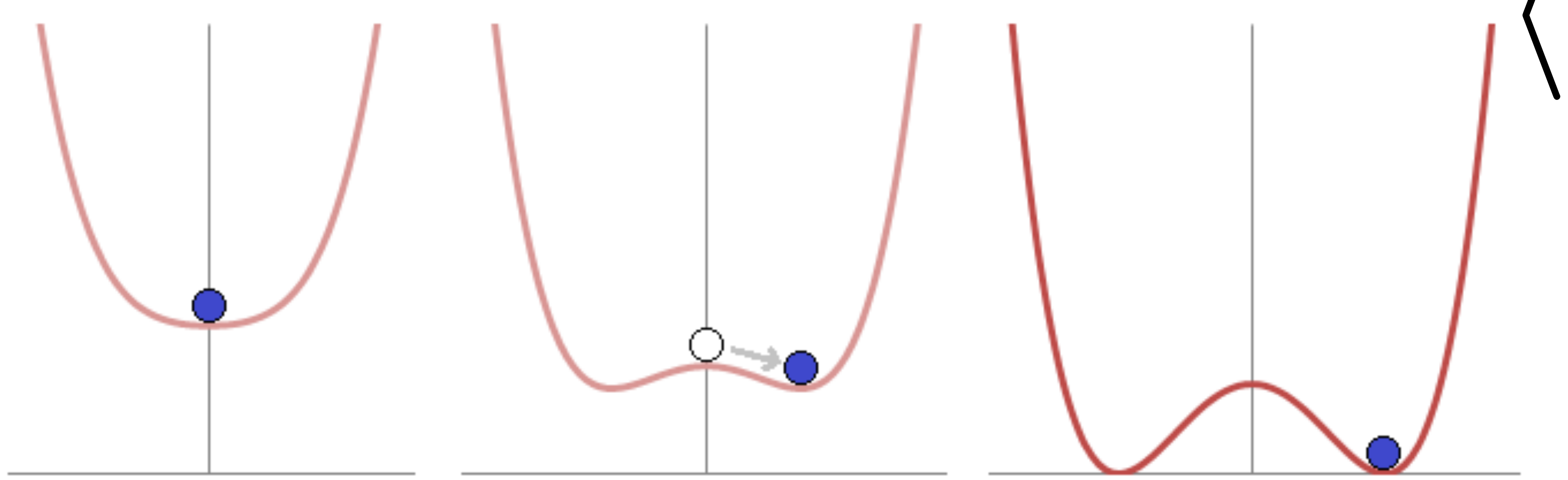
approx NNLL: Chen, Gao, Li, Xu, Zhang, HXZ, 2023



Many directions to improve:
Loops, non-perturbative, matching

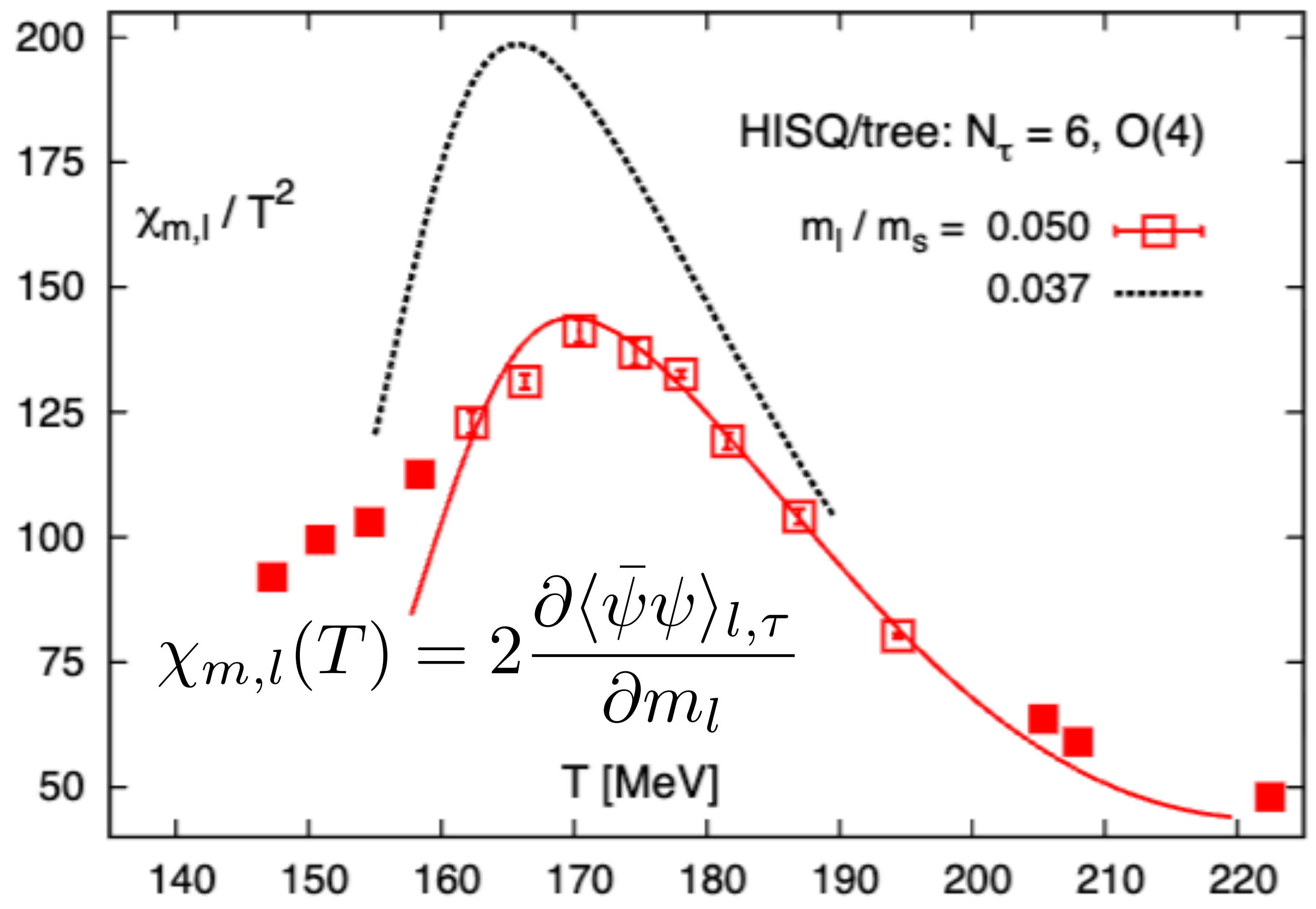
4%. Most precise alphas from jet substructure!

The scale of chiral symmetry breaking



$$\langle\bar{\psi}\psi\rangle$$

Bazavov et.al., 1111.1710



What is the scale of chiral symmetry breaking?
How is it different from confinement scale?
How can we probe it?

Is it possible to probe the scale of chiral symmetry breaking at zero temperature?

Fragmentation of Transversely Polarized Quarks Probed in Transverse Momentum Distributions

John Collins

Physics Department, Penn State University,
University Park, PA 16802, U.S.A.

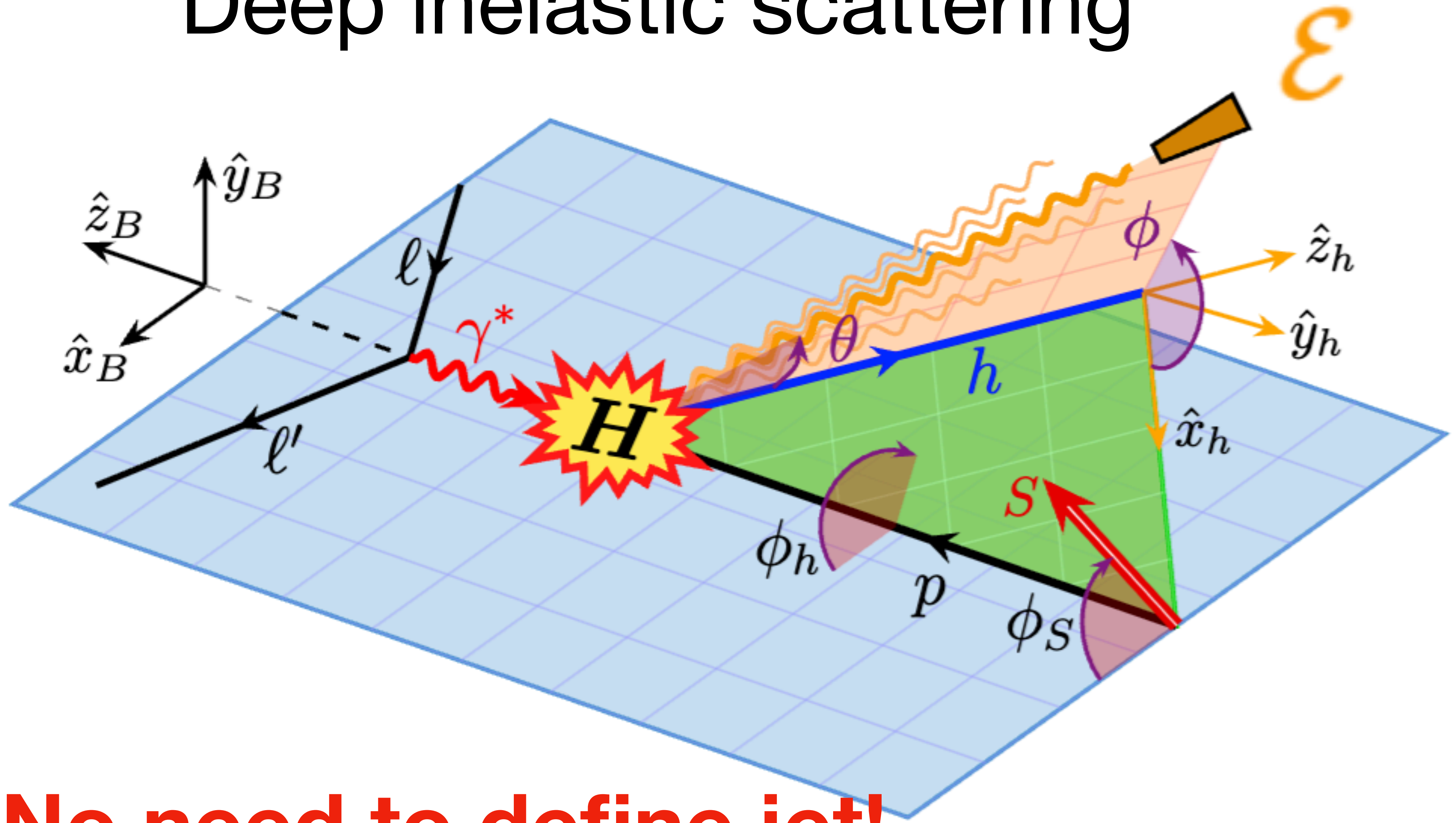
The new fragmentation function is sensitive to the coupling of the fragmentation process to (spontaneous) chiral symmetry breaking.

Collins, 1992

Fragmentation energy correlators

Deep inelastic scattering

Cao, Yu, Yuan, Zhang, HXZ, 2025



$$\overline{|\mathcal{M}_\mathcal{E}|^2} \simeq \sum_{a,b} \int \frac{d\xi_1}{\xi_1} \int \frac{d\xi_2}{\xi_2^2} \Big\{ \mathcal{D}_{1,h/b}(\xi_2, \Lambda_F, \mu) \Big[f_{a/p}(\xi_1,\mu)\, C_{ab}\left(\frac{x}{\xi_1}, \frac{z}{\xi_2}; \frac{\boldsymbol{p}_{hT}}{Q}, \frac{Q^2}{\mu^2}\right) + P_N g_{a/p}(\xi_1,\mu)\, \Delta C_{ab}\left(\frac{x}{\xi_1}, \frac{z}{\xi_2}; \frac{\boldsymbol{p}_{hT}}{Q}, \frac{Q^2}{\mu^2}\right)\Big]$$

$$+ \mathcal{H}^{\perp}_{1,h/b}(\xi_2, \Lambda_F, \mu)\, h_{a/p}(\xi_1,\mu) \sum_{i,j=1}^{2} \frac{(\hat{p}_h \times \boldsymbol{n}_T)^i}{|\boldsymbol{n}_T|} T^{ij}_{ab}\left(\frac{x}{\xi_1}, \frac{z}{\xi_2}; \frac{\boldsymbol{p}_{hT}}{Q}, \frac{Q^2}{\mu^2}\right) s^j_T \Big\}$$

$$+\mathcal{O}(\Lambda_F/Q, \Lambda_F/p_{hT}).$$

No need to define jet!

$$\mathcal{D}^{[\Gamma]}_{h/q,1}(z, \boldsymbol{n}; p_h) = \frac{z}{2N_c} \sum_X \int \frac{dy^-}{2\pi} e^{ip_h^+ y^-/z}\, \mathrm{Tr}[\,\Gamma \langle 0| W(\infty, y^-; w)\, \psi(y^-)\, \mathcal{E}(\boldsymbol{n}) \mid h, X;\ \mathrm{out}\,\rangle \times \langle h, X;\ \mathrm{out}\, |\bar{\psi}(0) W^\dagger(\infty, 0; w)|0\rangle],$$

$$\mathcal{D}^{[\gamma^+\gamma^i\gamma_5/2]}_{h/q,1}(z, \boldsymbol{n}; p_h) = \frac{(\hat{z} \times \boldsymbol{n}_T)^i}{|\boldsymbol{n}_T|} \mathcal{H}^{\perp}_{1,h/q}(z, \theta; p_h)$$

s_T: quark transverse spin
T^{ij}: spin transfer matrix
h: transversity
H: FEC Collins function

Pure collinear factorization formula
No Sudakov logs!

Decomposition of polarization functions

Cao, Yu, Yuan, Zhang, HXZ, 2025

$$\left[\frac{y^2}{z(1-\varepsilon)}\frac{\alpha_e^2}{(8\pi^2Q^2)^2}\right]^{-1}\frac{d\Sigma}{dxdQ^2d\phi_S dz dp_{hT}^2 d\phi_h d\eta d\phi}$$
$$= \mathcal{C}_{F_{UU,T}}[f,\mathcal{D}] + \varepsilon\mathcal{C}_{F_{UU,L}}[f,\mathcal{D}]$$
$$+ s_T\left\{\left[-\mathcal{C}_{F_{UT,T}}\left[h,\mathcal{H}^\perp\right] - \varepsilon\mathcal{C}_{F_{UT,L}}\left[h,\mathcal{H}^\perp\right]\right]\sin\left(\phi-(\phi_S-\phi_h)\right)\right.$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\left[\mathcal{C}_{F_{UT}^{(1+)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-(\phi_S-2\phi_h)\right)+\mathcal{C}_{F_{UT}^{(1-)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-\phi_S\right)\right]$$
$$\left.+\varepsilon\left[\mathcal{C}_{F_{UT}^{(2+)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-(\phi_S-3\phi_h)\right)+\mathcal{C}_{F_{UT}^{(2-)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-(\phi_S+\phi_h)\right)\right]\right\}$$

	+	0	-
+	1	$\sqrt{\varepsilon(1+\varepsilon)}$	$-\varepsilon$
0	$\sqrt{\varepsilon(1+\varepsilon)}$	2ε	$-\sqrt{\varepsilon(1+\varepsilon)}$
-	$-\varepsilon$	$-\sqrt{\varepsilon(1+\varepsilon)}$	1

$\pm\phi_h$

+ longitudinal polarization, power corrections, etc

Modulation effects generated by non-perturbative coupling of transversity and Collins

Structure determines by symmetry

follow from Diehl, Sapeta, 2005

Decomposition of polarization functions

Cao, Yu, Yuan, Zhang, HXZ, 2025

$$\left[\frac{y^2}{z(1-\varepsilon)}\frac{\alpha_e^2}{(8\pi^2Q^2)^2}\right]^{-1}\frac{d\Sigma}{dx\,dQ^2\,d\phi_S\,dz\,dp_{hT}^2\,d\phi_h\,d\eta\,d\phi}$$
$$= \mathcal{C}_{F_{UU,T}}[f,\mathcal{D}] + \varepsilon\,\mathcal{C}_{F_{UU,L}}[f,\mathcal{D}]$$
$$+\, s_T\Big\{\left[-\mathcal{C}_{F_{UT,T}}\left[h,\mathcal{H}^{\perp}\right] - \varepsilon\,\mathcal{C}_{F_{UT,L}}\left[h,\mathcal{H}^{\perp}\right]\right]\boxed{\sin\left(\phi-(\phi_S-\phi_h)\right)}$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\left[\mathcal{C}_{F_{UT}^{(1+)}}\left[h,\mathcal{H}^{\perp}\right]\sin\left(\phi-(\phi_S-2\phi_h)\right)+\mathcal{C}_{F_{UT}^{(1-)}}\left[h,\mathcal{H}^{\perp}\right]\sin\left(\phi-\phi_S\right)\right]$$
$$+\varepsilon\left[\mathcal{C}_{F_{UT}^{(2+)}}\left[h,\mathcal{H}^{\perp}\right]\sin\left(\phi-(\phi_S-3\phi_h)\right)+\mathcal{C}_{F_{UT}^{(2-)}}\left[h,\mathcal{H}^{\perp}\right]\sin\left(\phi-(\phi_S+\phi_h)\right)\right]\Big\}$$

+ longitudinal polarization, power corrections, etc

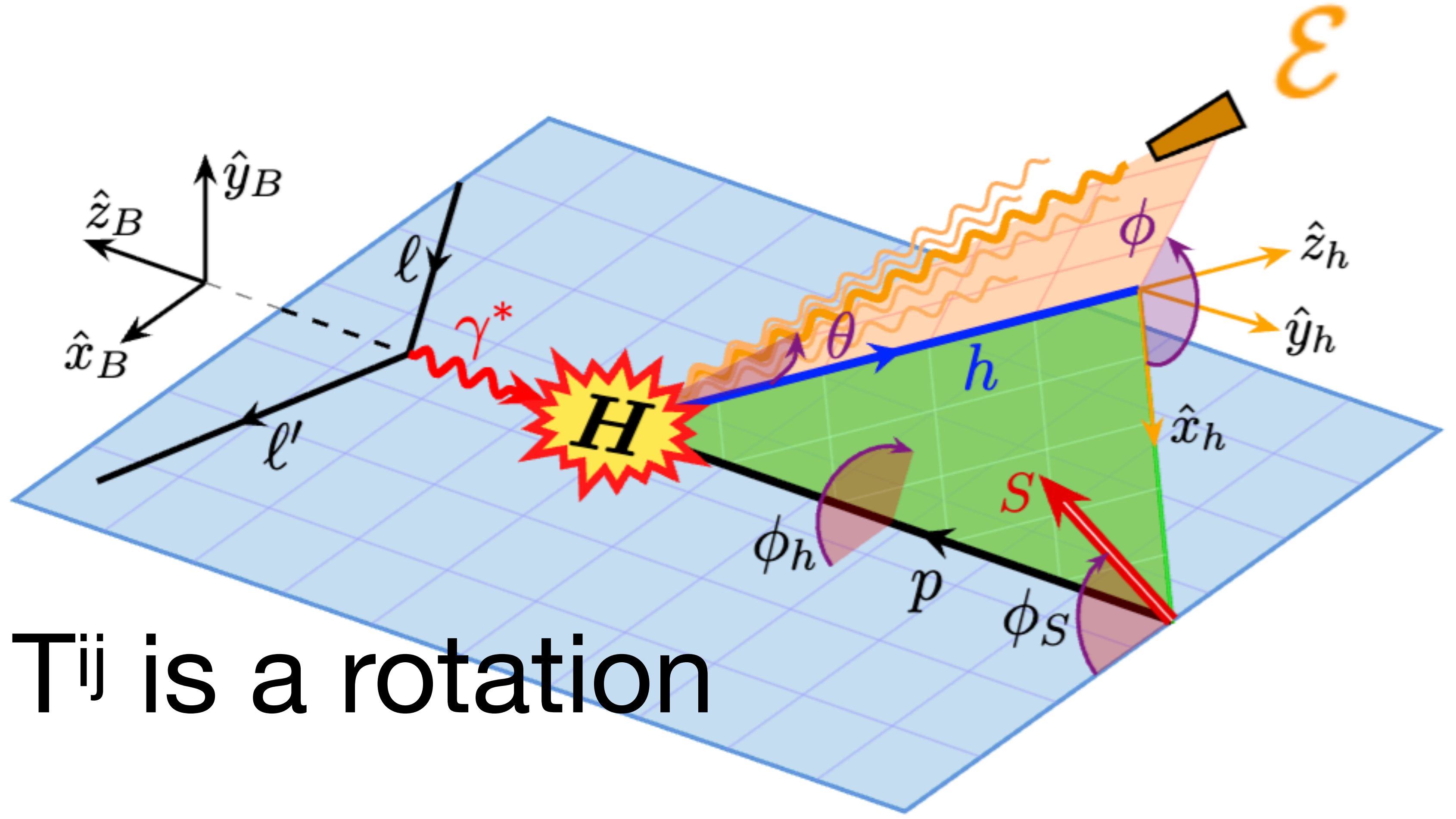
Modulation effects generated by non-perturbative coupling of transversity and Collins

Structure determines by symmetry

follow from Diehl, Sapeta, 2005

	+	0	-
+	1	$\sqrt{\varepsilon(1+\varepsilon)}$	$-\varepsilon$
0	$\sqrt{\varepsilon(1+\varepsilon)}$	2ε	$-\sqrt{\varepsilon(1+\varepsilon)}$
-	$-\varepsilon$	$-\sqrt{\varepsilon(1+\varepsilon)}$	1

$\pm\phi_h$



T^{ij} is a rotation

Decomposition of polarization functions

Cao, Yu, Yuan, Zhang, HXZ, 2025

$$\left[\frac{y^2}{z(1-\varepsilon)}\frac{\alpha_e^2}{(8\pi^2 Q^2)^2}\right]^{-1}\frac{d\Sigma}{dx\,dQ^2\,d\phi_S\,dz\,dp_{hT}^2\,d\phi_h\,d\eta\,d\phi}$$
$$=\mathcal{C}_{F_{UU,T}}[f,\mathcal{D}]+\varepsilon\,\mathcal{C}_{F_{UU,L}}[f,\mathcal{D}]$$
$$+\,s_T\left\{\left[-\mathcal{C}_{F_{UT,T}}\left[h,\mathcal{H}^\perp\right]-\varepsilon\,\mathcal{C}_{F_{UT,L}}\left[h,\mathcal{H}^\perp\right]\right]\boxed{\sin\left(\phi-(\phi_S-\phi_h)\right)}\right.$$
$$+\sqrt{2\varepsilon(1+\varepsilon)}\left[\mathcal{C}_{F_{UT}^{(1+)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-(\phi_S-2\phi_h)\right)+\mathcal{C}_{F_{UT}^{(1-)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-\phi_S\right)\right]$$
$$\left.+\,\varepsilon\left[\mathcal{C}_{F_{UT}^{(2+)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-(\phi_S-3\phi_h)\right)+\mathcal{C}_{F_{UT}^{(2-)}}\left[h,\mathcal{H}^\perp\right]\sin\left(\phi-(\phi_S+\phi_h)\right)\right]\right\}$$

+ longitudinal polarization, power corrections, etc

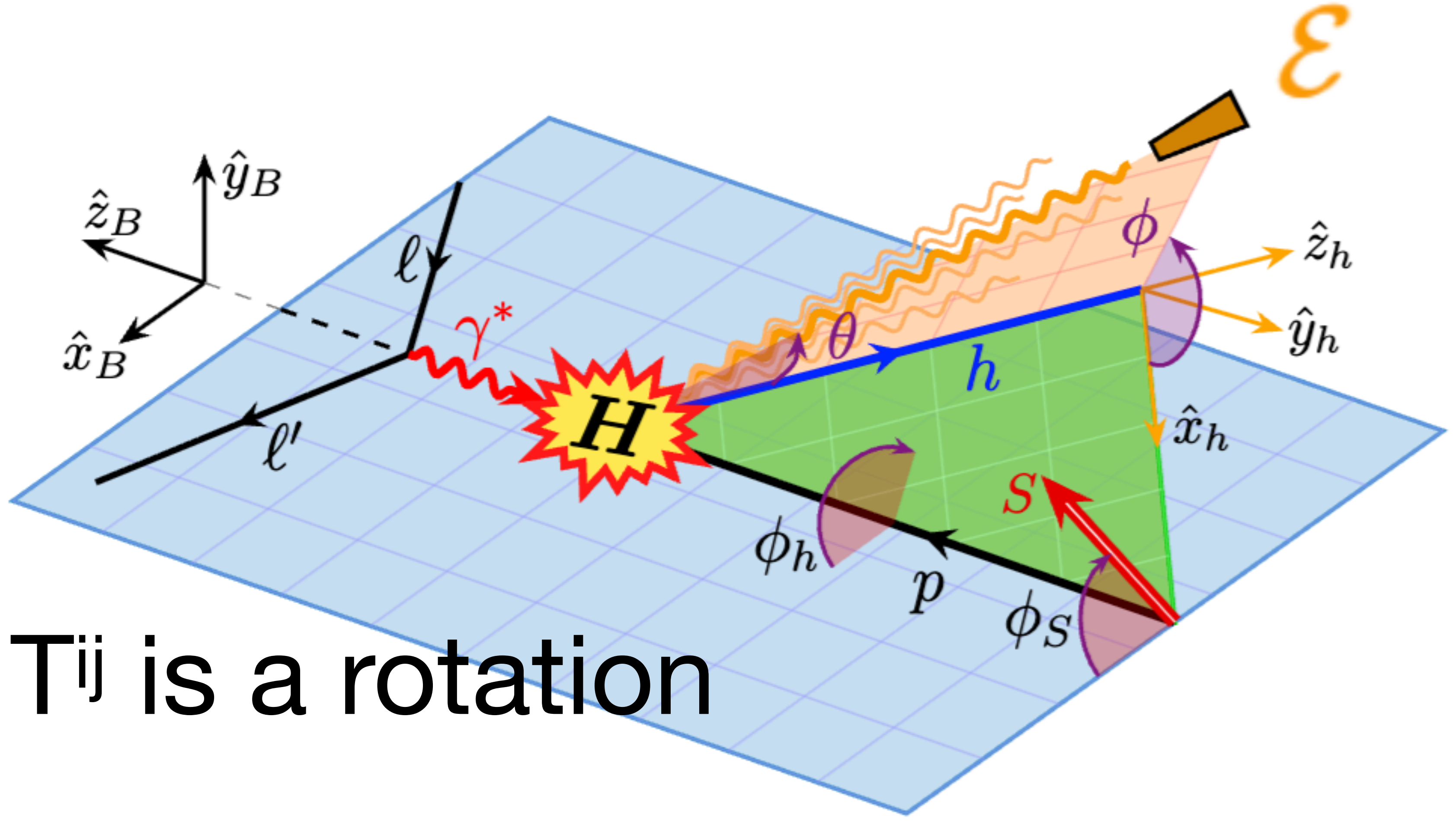
Modulation effects generated by non-perturbative coupling of transversity and Collins

Structure determines by symmetry

follow from Diehl, Sapeta, 2005

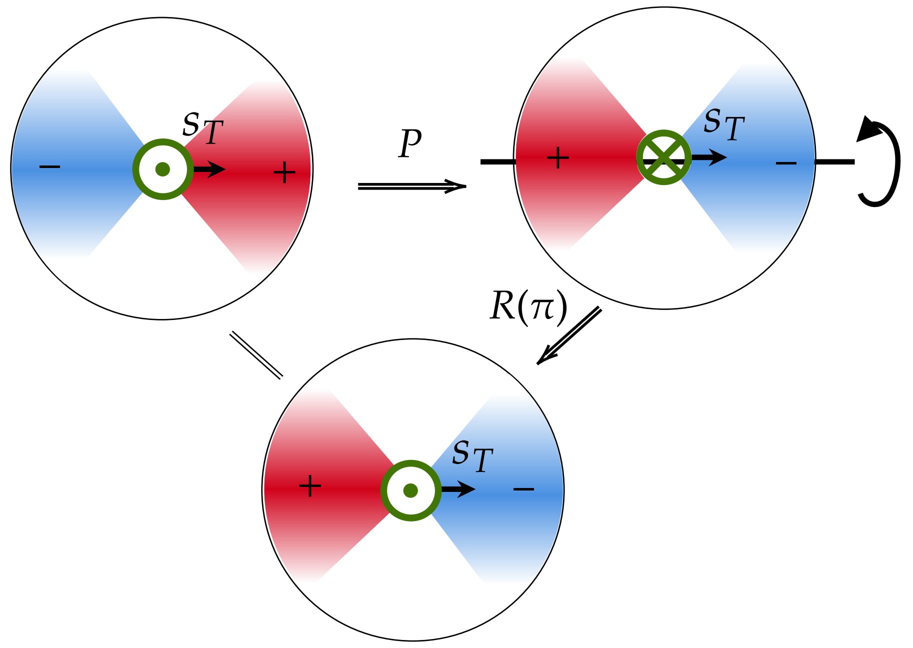
$$\begin{array}{c|ccc} & + & 0 & - \\ \hline + & 1 & \sqrt{\varepsilon(1+\varepsilon)} & -\varepsilon \\ 0 & \sqrt{\varepsilon(1+\varepsilon)} & 2\varepsilon & -\sqrt{\varepsilon(1+\varepsilon)} \\ - & -\varepsilon & -\sqrt{\varepsilon(1+\varepsilon)} & 1 \end{array}$$

$\pm\phi_h$



T^{ij} is a rotation

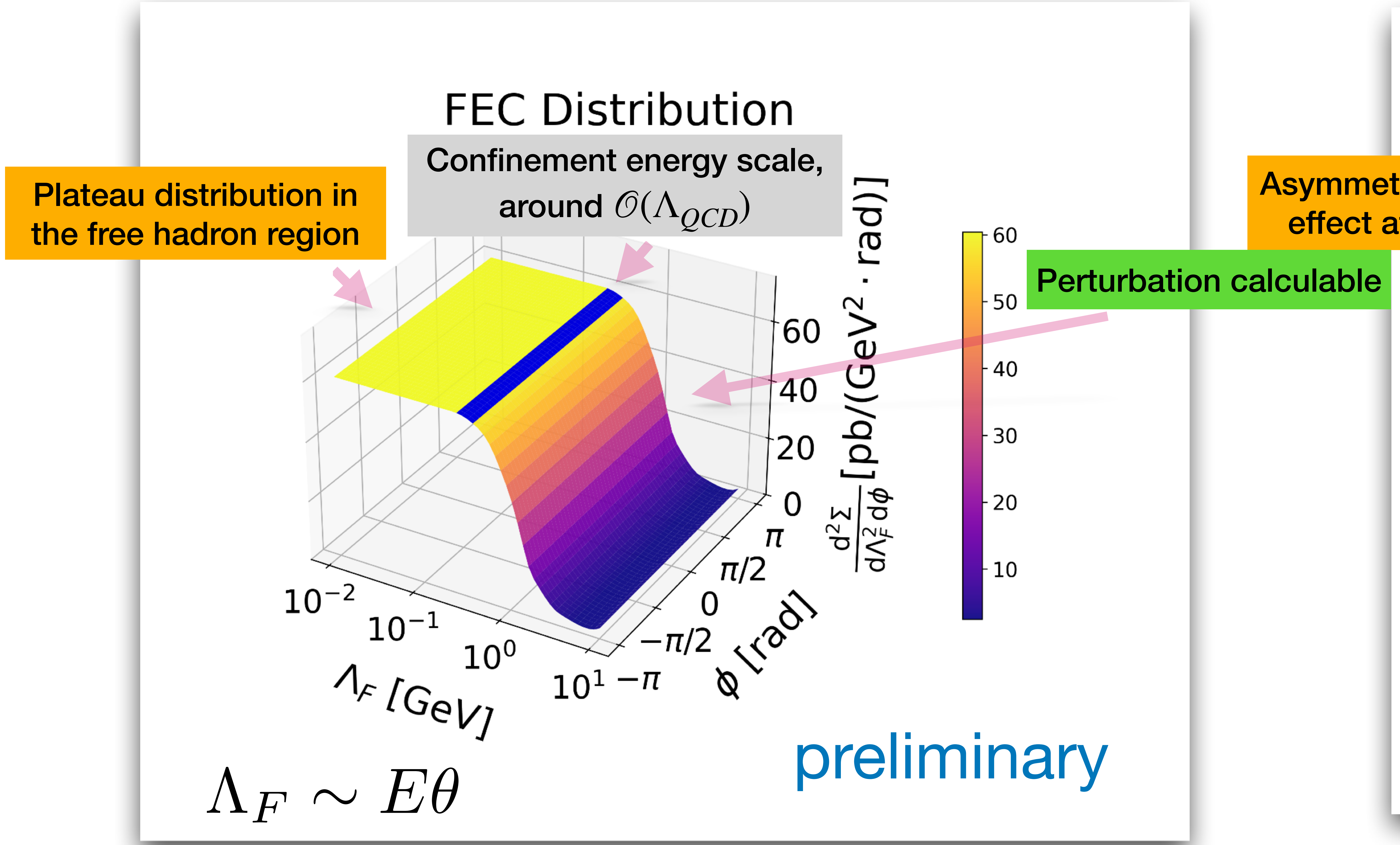
$\cos(\phi-\phi_s)$
violate parity



Imaging the chiral breaking scale ?

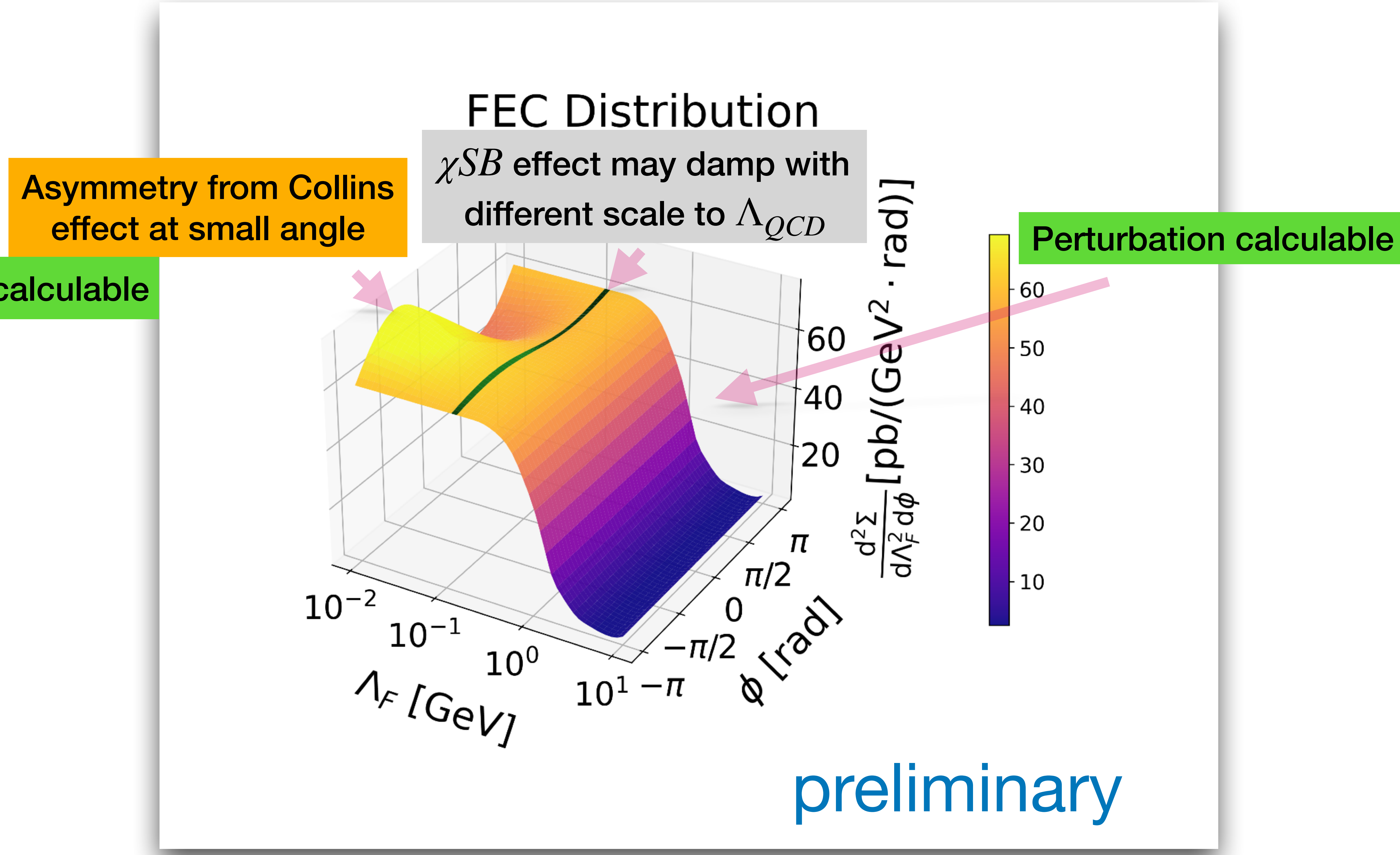
Cao, Liu, Yu, Yuan, Yuan, Zhang, HXZ, in progress

Unpolarized only



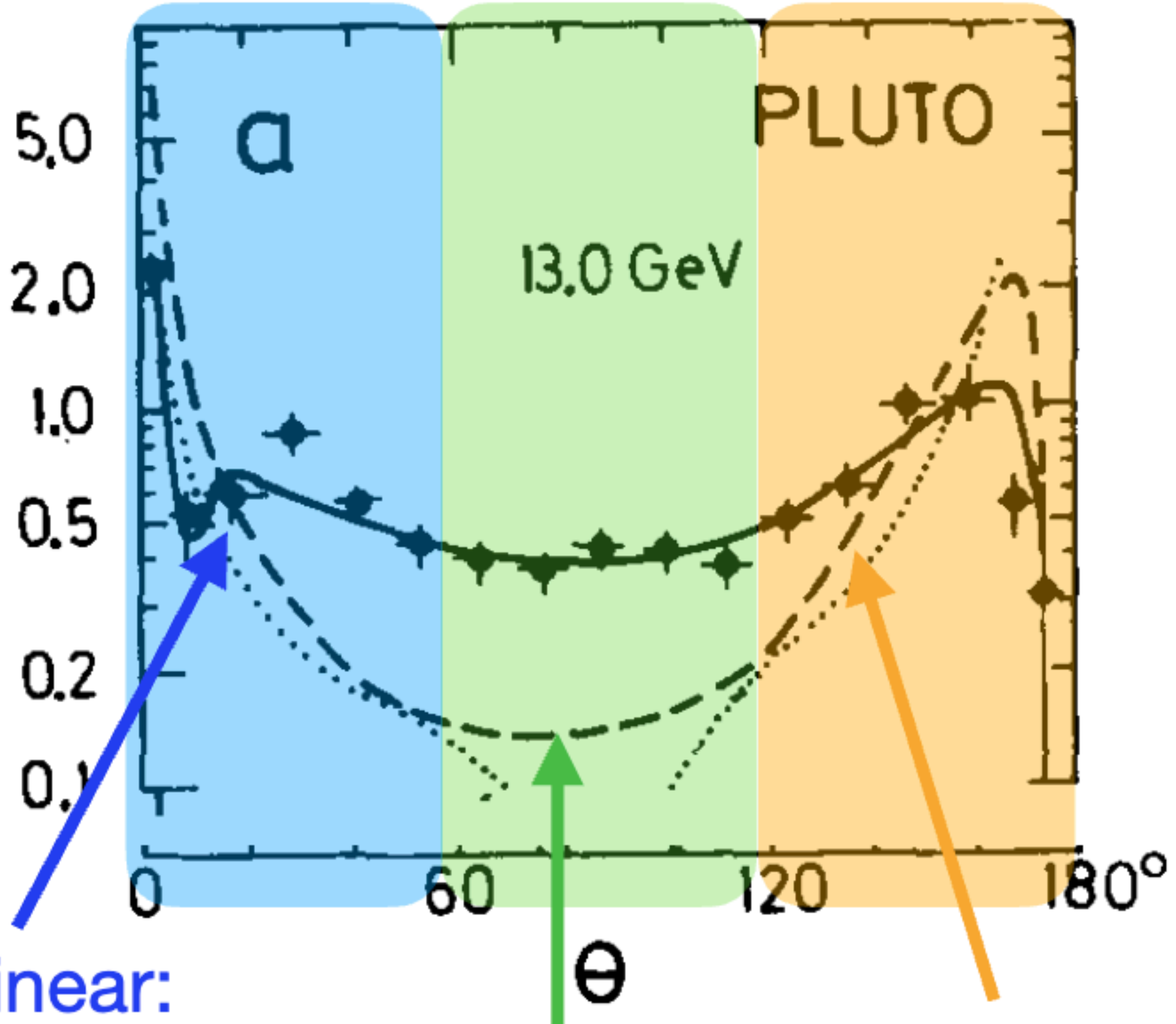
$\Lambda_F \sim E\theta$

With Collins effects



Interesting to compare the confinement scale and CSB scale

The quest for precision



Collinear:

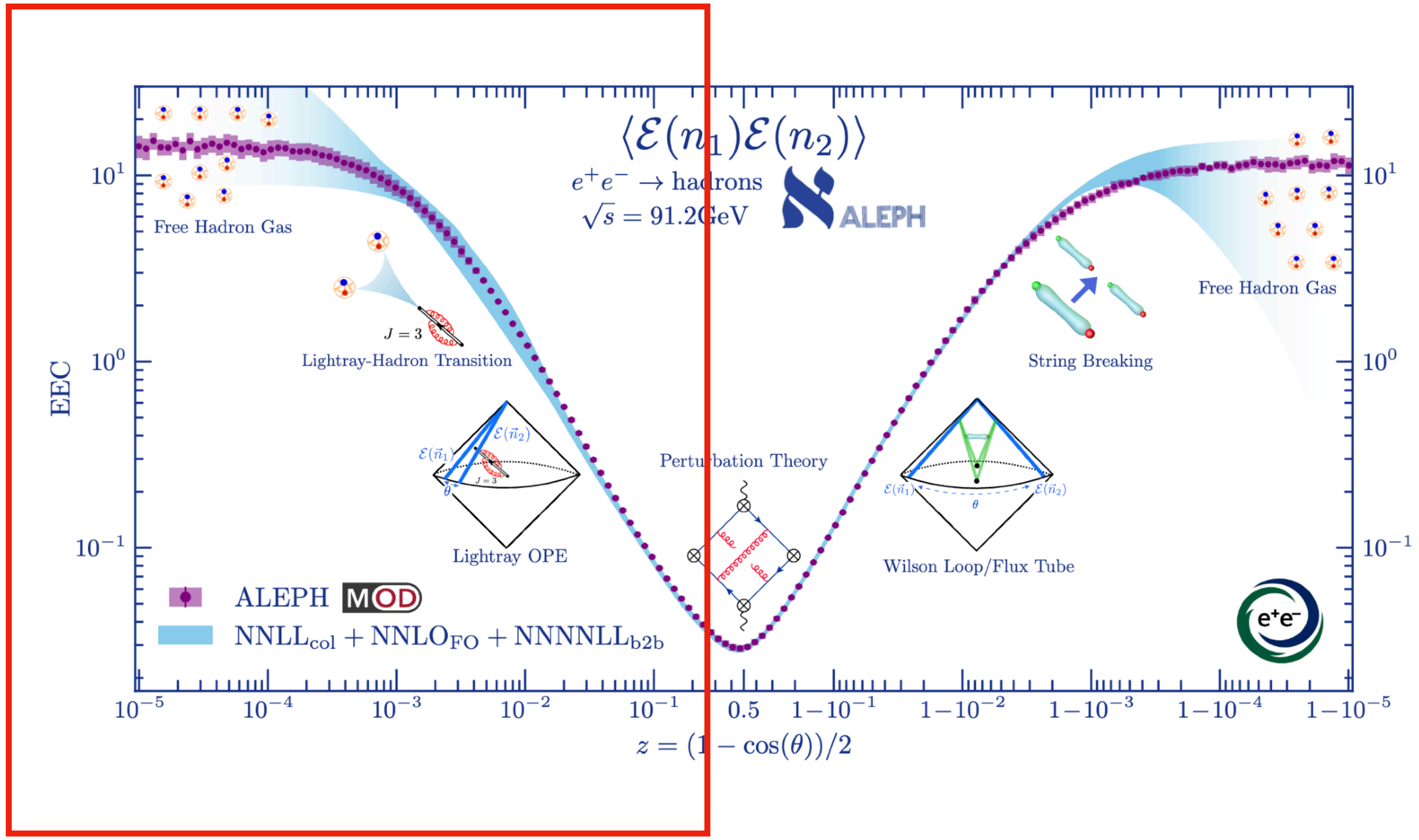
Konishi, Ukawa, Veneziano

Central:

Basham, Brown, Ellis, Love

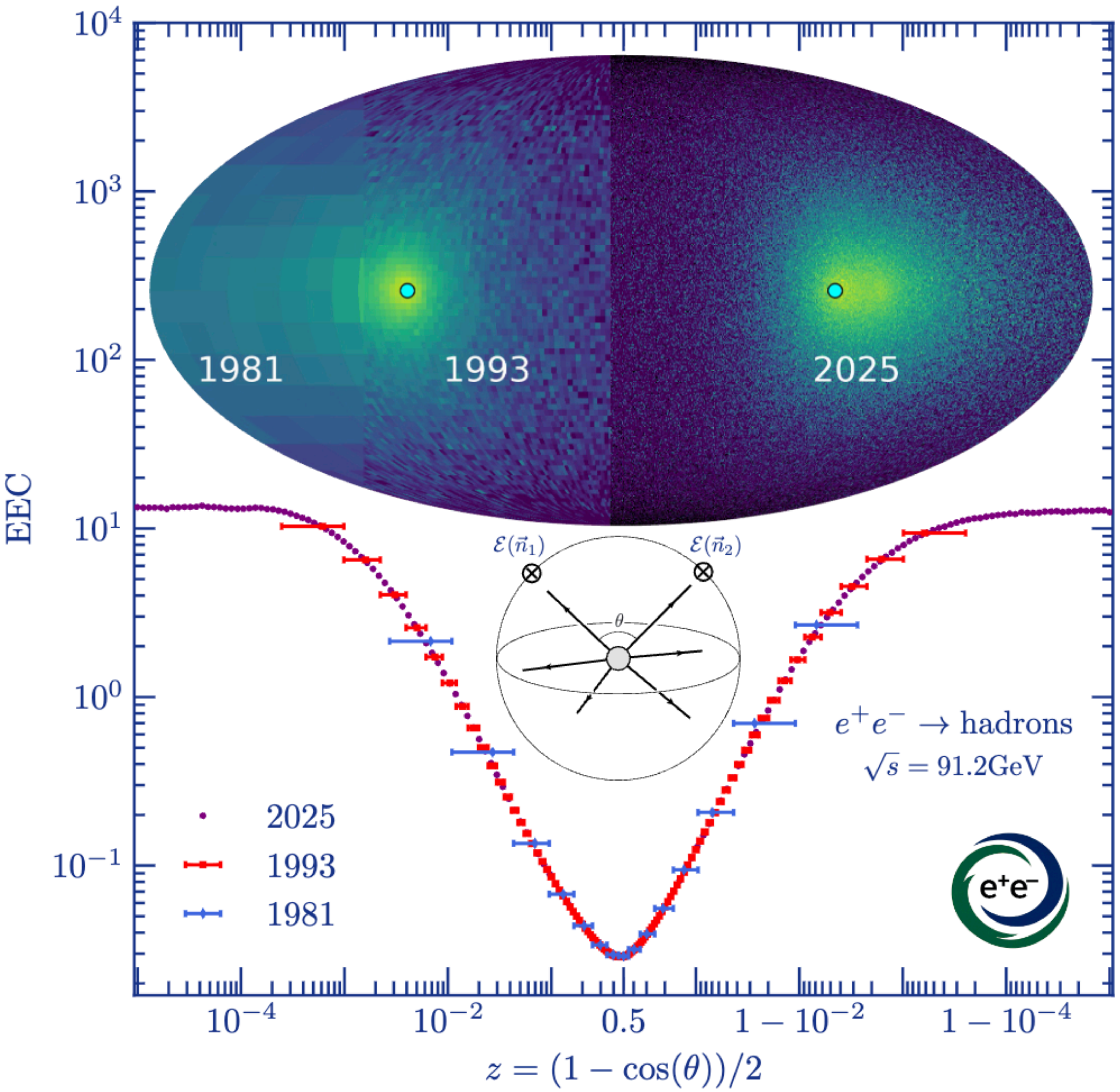
b2b:

Parisi, Petronzio

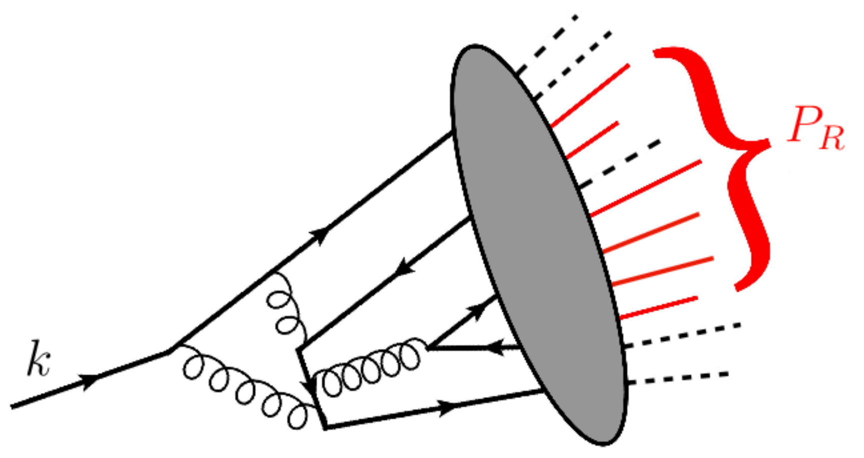


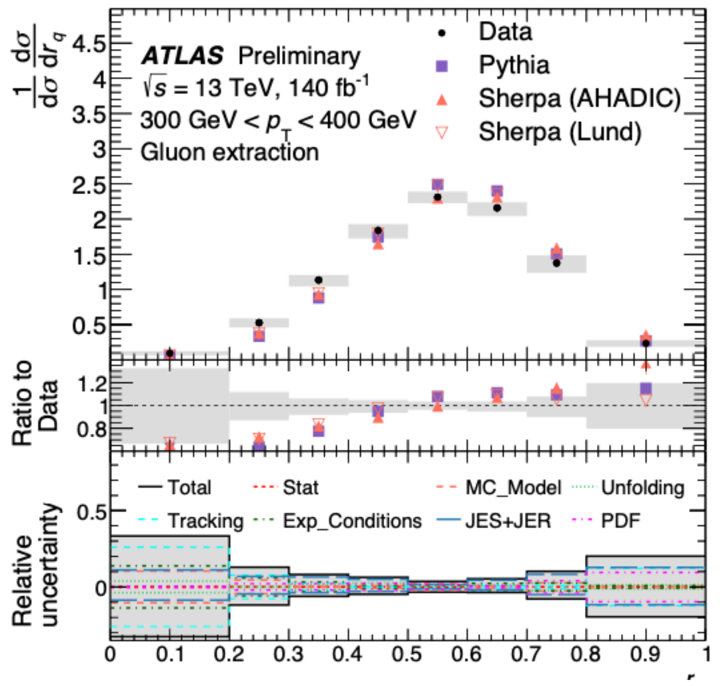
Electron-Positron Alliance Collaboration, 2511.00149

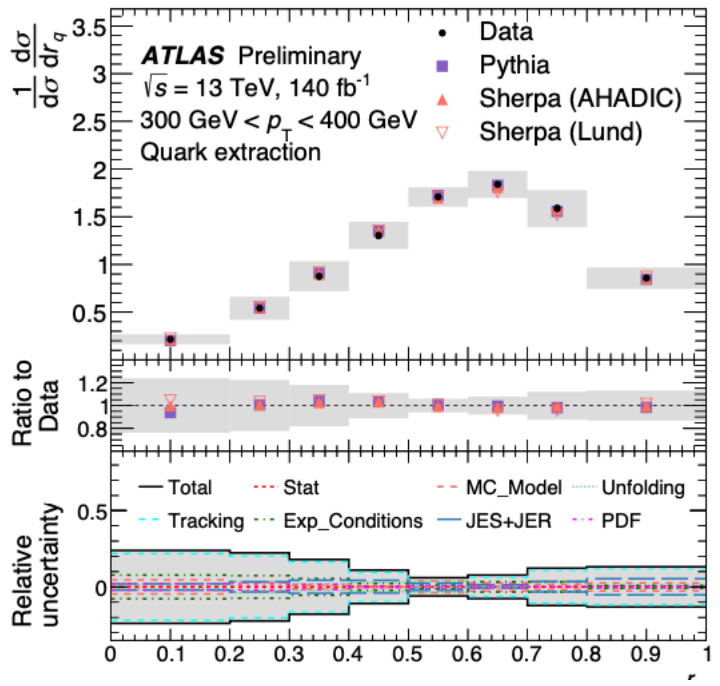
The Recycle Frontier



- Comparison of data from 1981, 1993, 2025
- Archived ALEPH data from 1994, reanalysis at 2025
- ALEPH tracking detector, reproduce published thrust data
- Track function for EEC

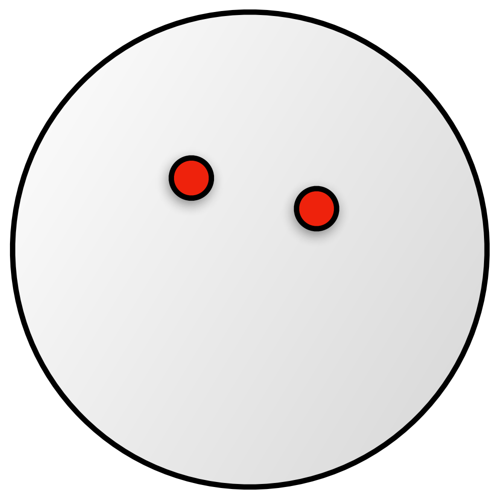




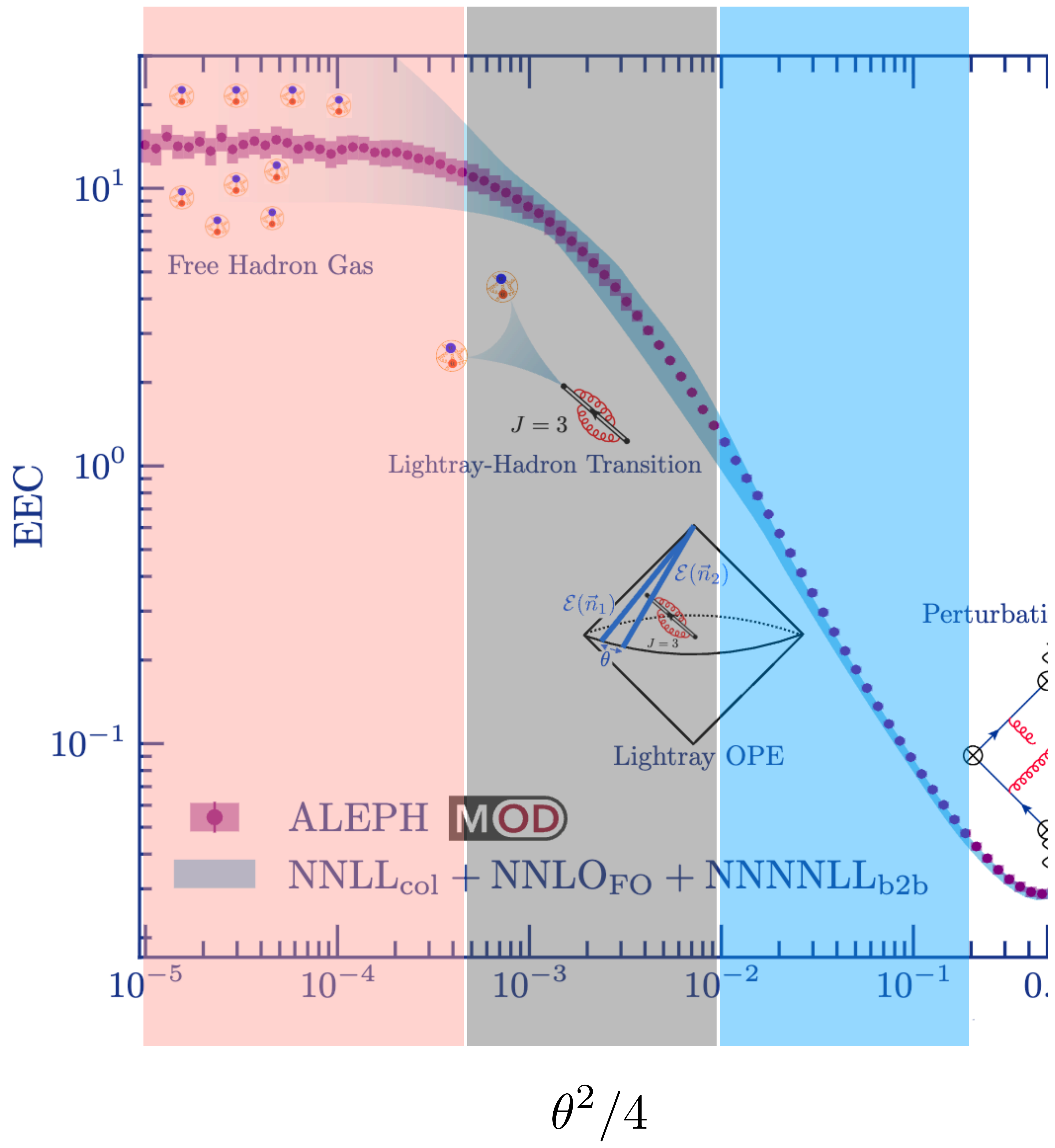


Chang, Procura, Thaler, Waalewijn, 2013

Chen, Moult, Zhang, HXZ, 2020



Various scaling in EEC



pre-confinement

$$\mathrm{EEC} = \frac{1}{\theta^2}(1+\log \mathrm{corr.}) + \frac{\Lambda_{\mathrm{QCD}}}{Q}\frac{1}{\theta^3}(1+\log \mathrm{corr.}) + \cdots$$

post-confinement

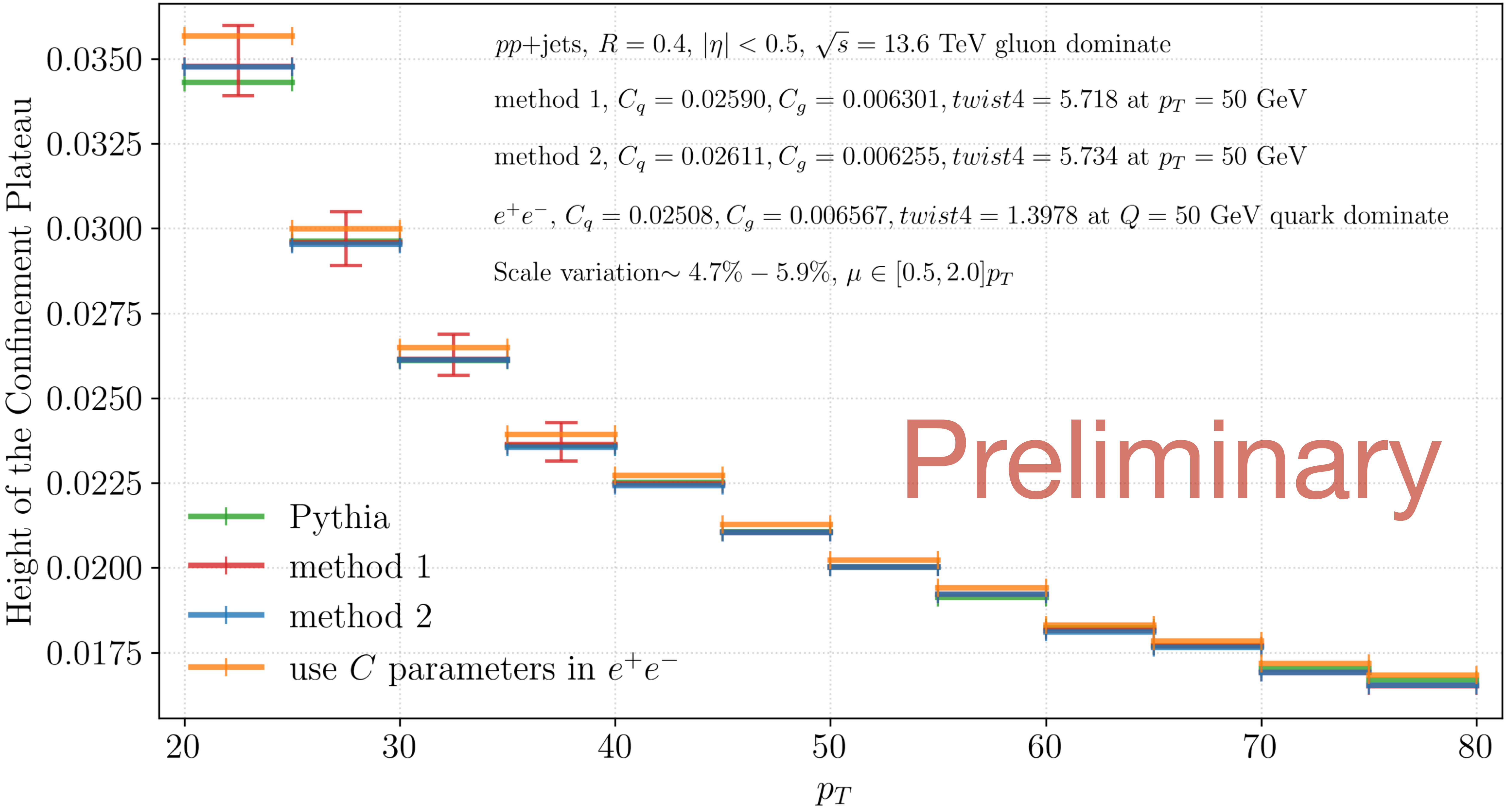
$$\mathrm{EEC} = \frac{Q^2}{\Lambda_{\mathrm{QCD}}^2}\theta^0(1+\log \mathrm{corr.}) + \cdots$$

Lee, Pathak, Stewart, Sun, 2024; Chen, Monni, Xu, HXZ, 2024; Liu, Vogelsang, Yuan, HXZ, 2024; Barata, Kang, Lopez, Penttala, 2024; Lee, Stewart, 2025; Chang, Chen, Liu, Simmons-Duffin, Yuan, HXZ, 2025; Guo, Yuan, Zhao, 2025; Kang, Metz, Pitonyak, Zhang, 2025

All published in PRL

Determine α_s from post-confinement plateau

Log running of the plateau height predicted by perturbation theory



Chen, Liu, Wang, Xing, Yang, HXZ, in progress

Take home message

1. Energy correlators are a rare example where formal theory, collider phenomenology, and experiments are finding common ground

2. Energy correlators provide an new way to image emergent and intrinsic scales

3. Energy correlators provide a common language to discuss diverse phenomena