QCD Energy Correlator at Colliders

Xiaohui Liu
Beijing Normal University

Nov 17, 2024 @ QingDao
CLHCP2024

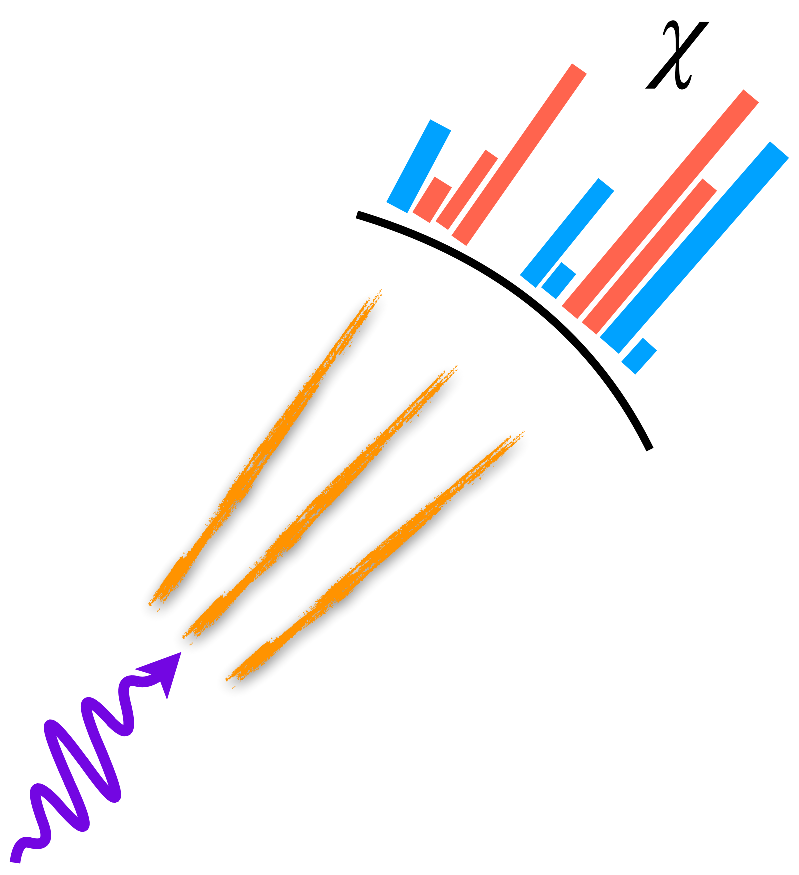
北京師範大學
BEIJING NORMAL UNIVERSITY

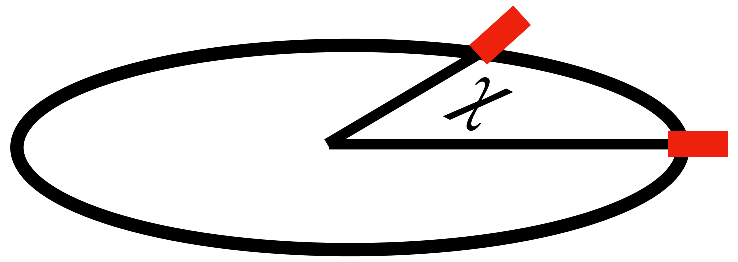
Outline

- Review of the Energy Correlators
- Collider Phenomenology
  - Features
  - α_s extraction
  - Top mass measurement
  - Heavy quark hadronization
- Conclusions

Energy Correlators

Energy-Energy-Correlator (EEC)

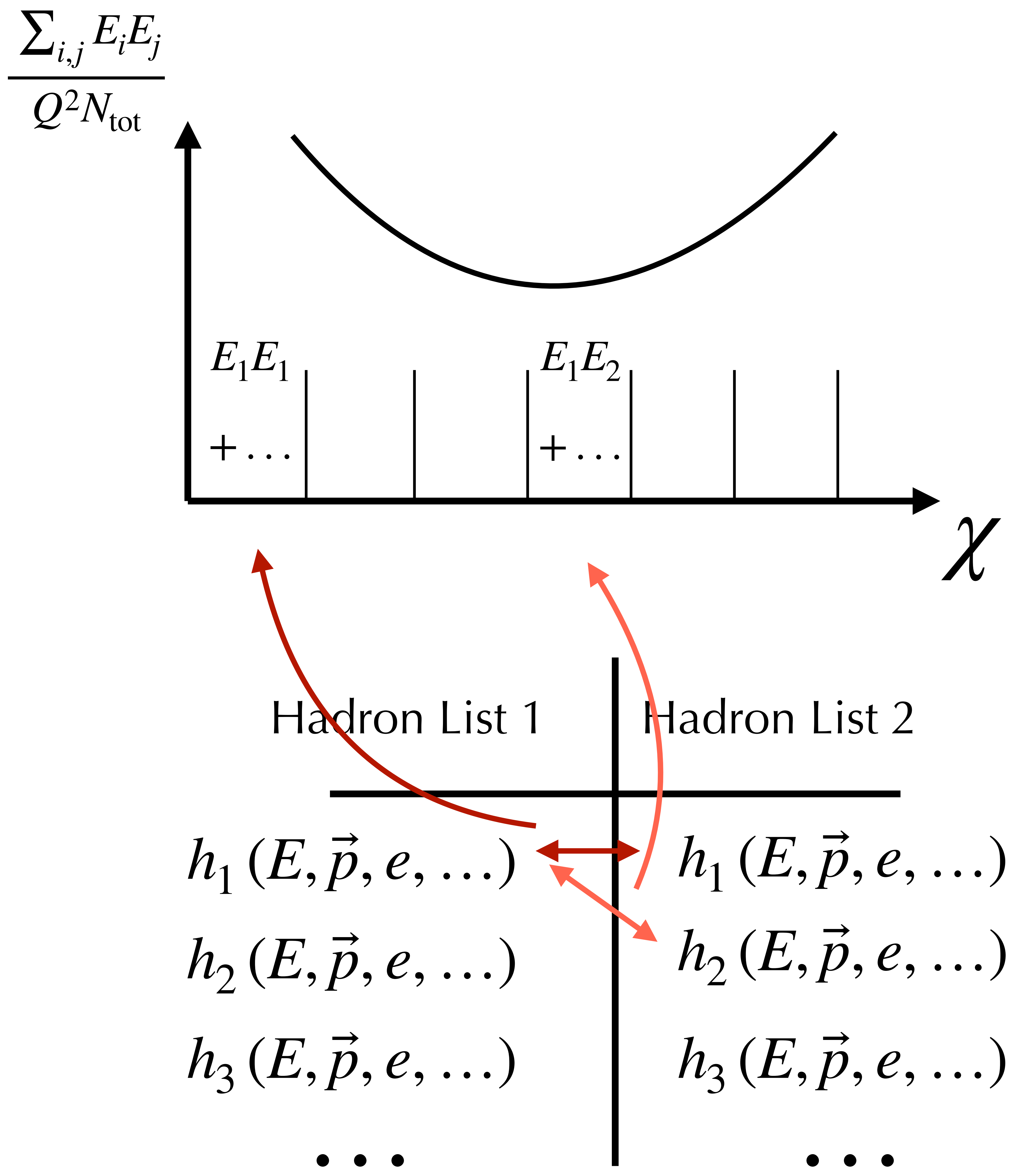




$$\text{EEC} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

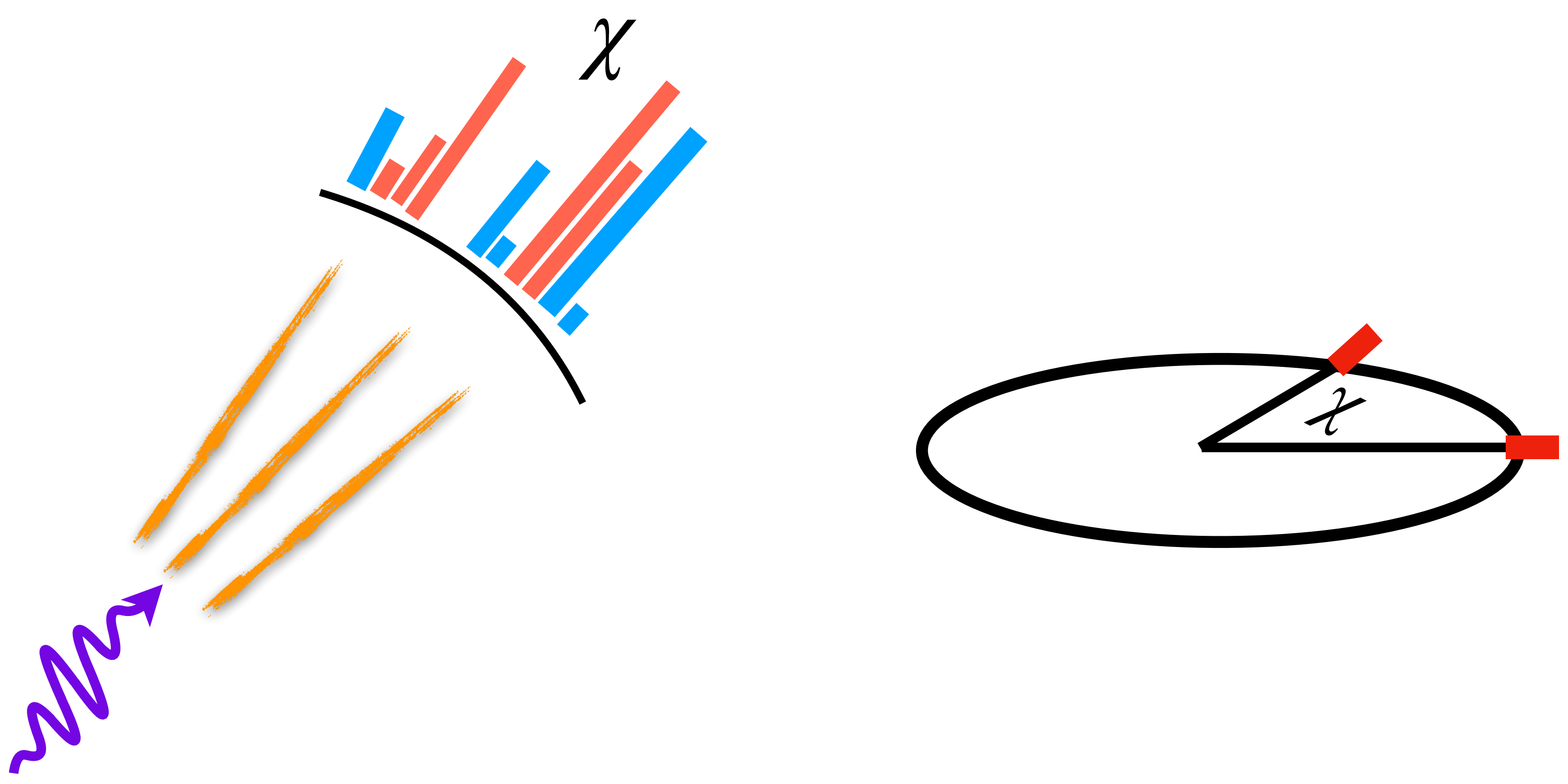
Sterman, 1975

Bashman, et al. 1978



Energy Correlators

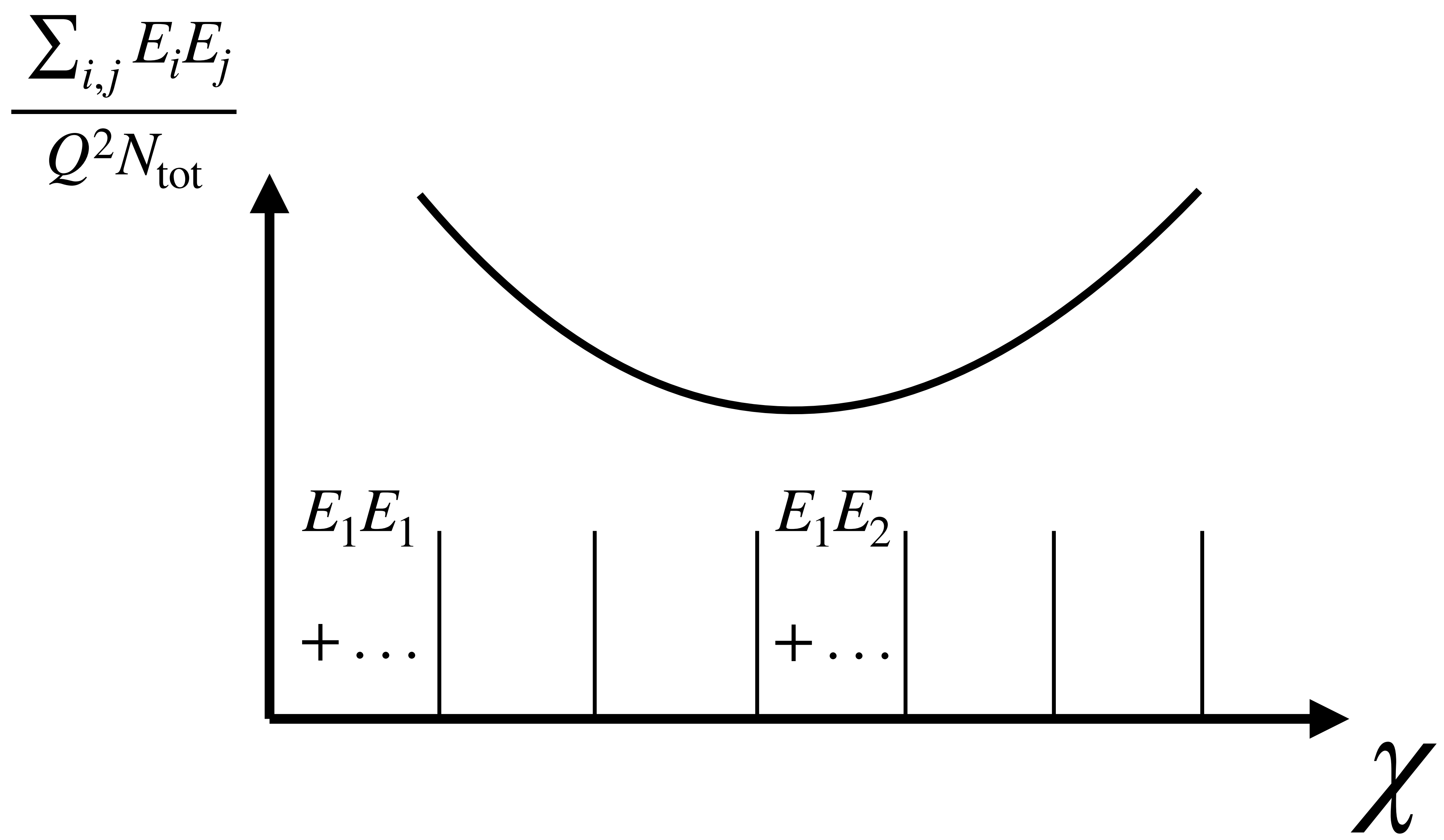
Energy-Energy-Correlator (EEC)



$$\text{EEC} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

Sterman, 1975

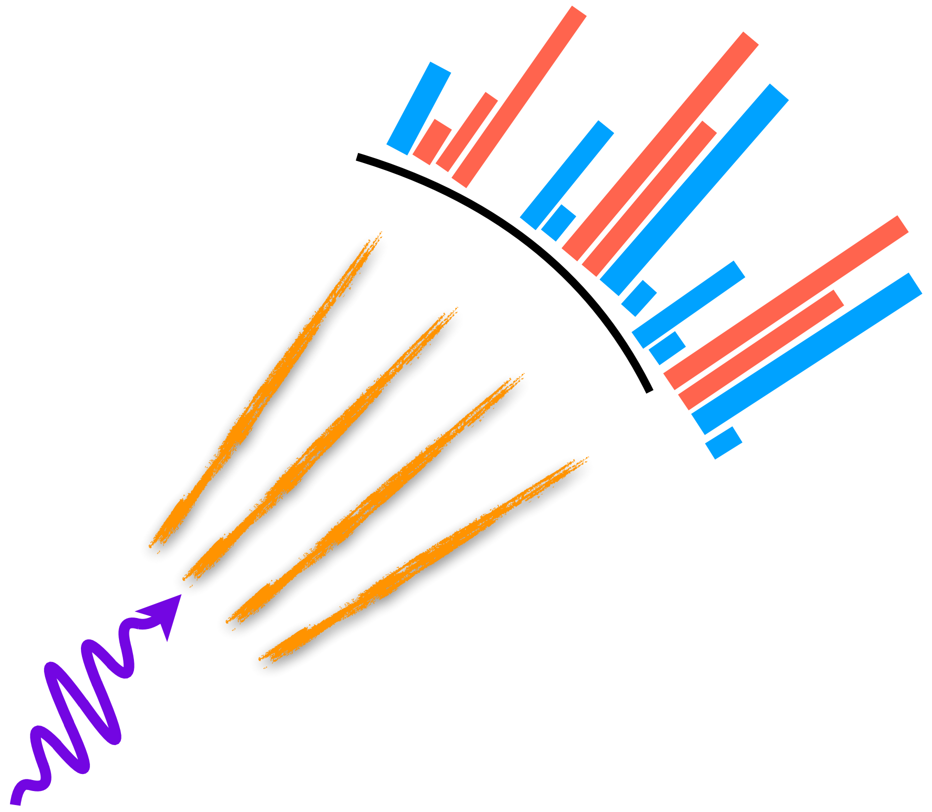
Bashman, et al. 1978

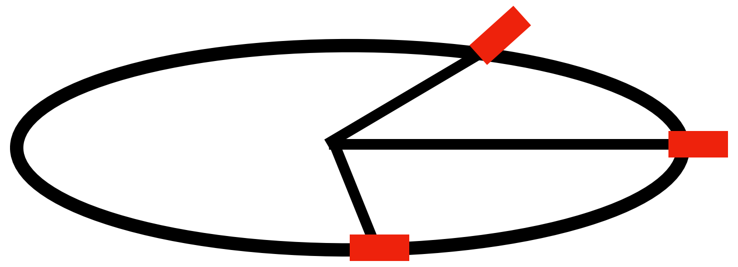


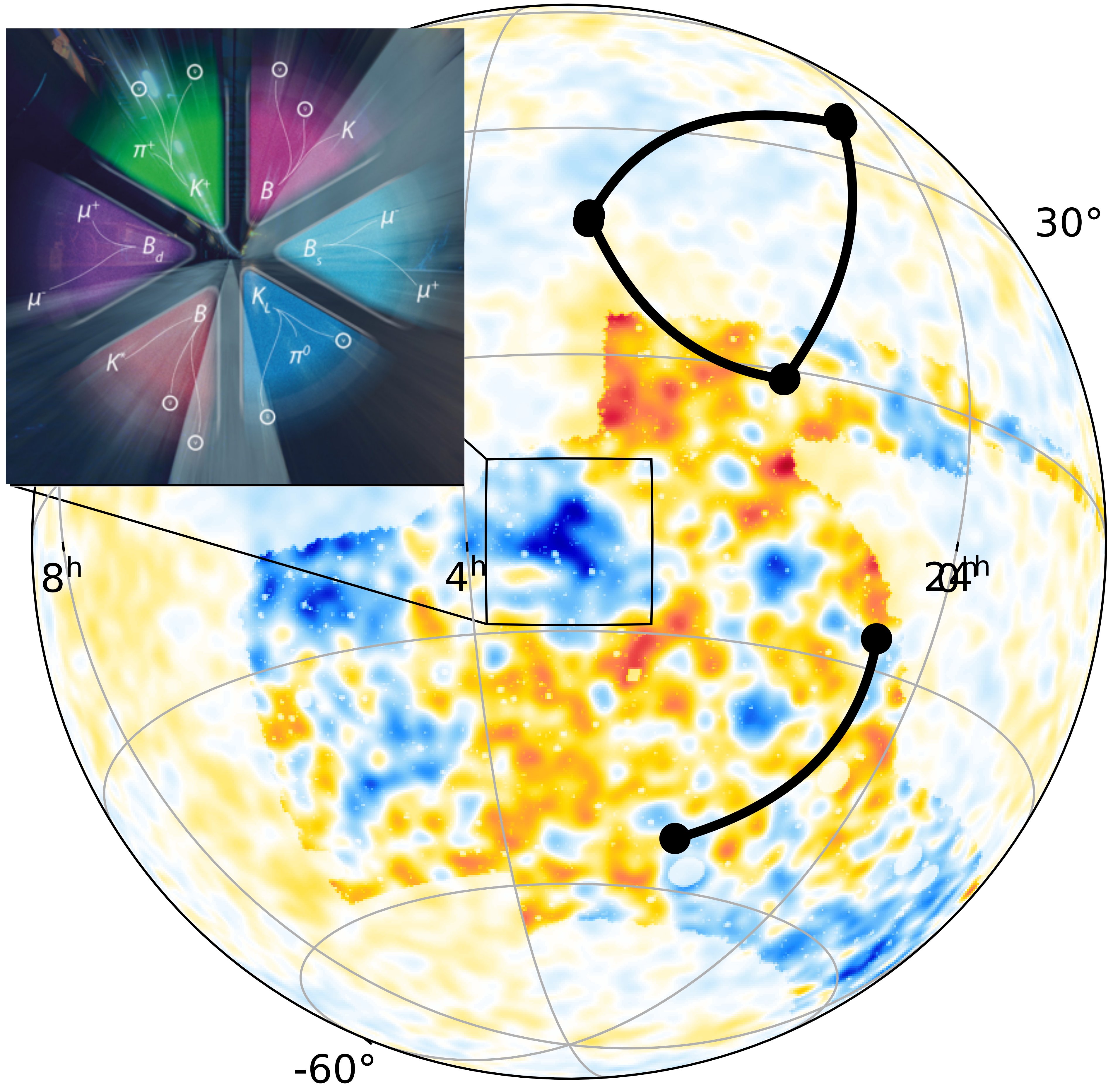
- Easy to implement and nature, **"Jet w/o jet"**
- Energy weight suppresses the soft contamination
- Infrared-collinear safe, perturbatively understandable
- Can be measured within jet, can use tracks to improve angular resolution Li et al., PRL 22

Energy Correlators

Energy-Correlators (ENC)







$$\mathrm{ENC} = \frac{1}{\sigma}\int d\sigma \sum \frac{E_1 E_2 \ldots E_N}{Q^N} \mathscr{M}(\{\theta_{ij}\})$$

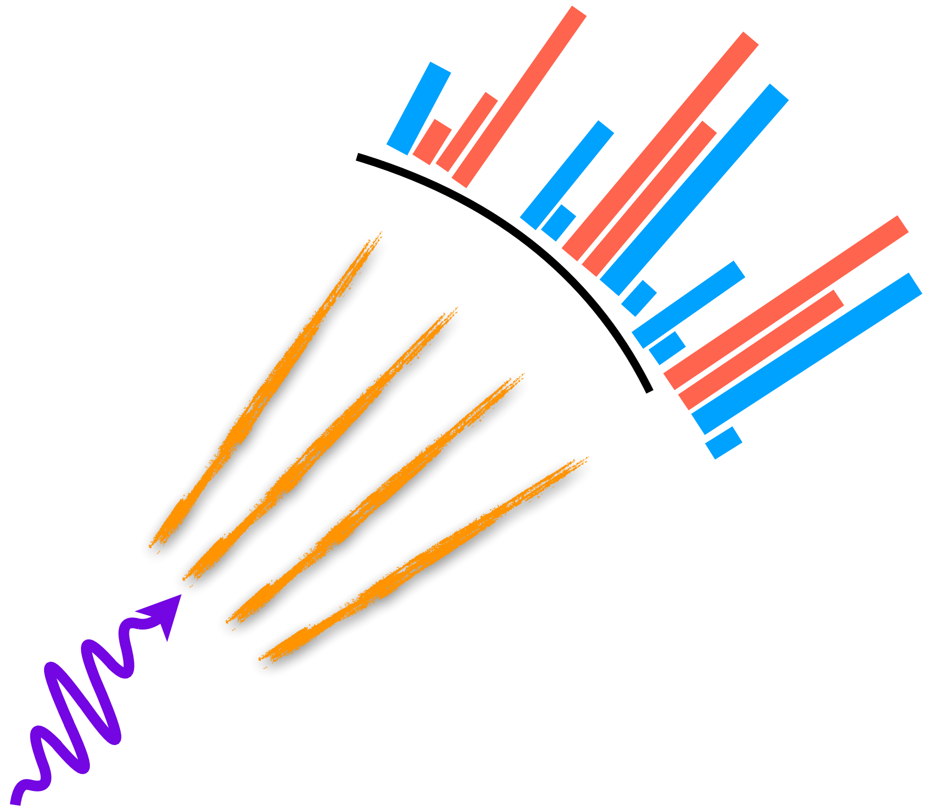
- Can be generalized to multiple pt correlation, **a Collider CMB**
  - Long/short wave physics $\Longleftrightarrow$ smaller/larger angular separations

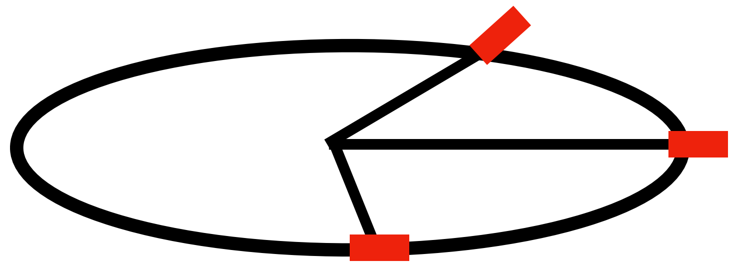
Energy Correlators

Energy-Correlators (ENC)

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

detector represented by the light-ray operator



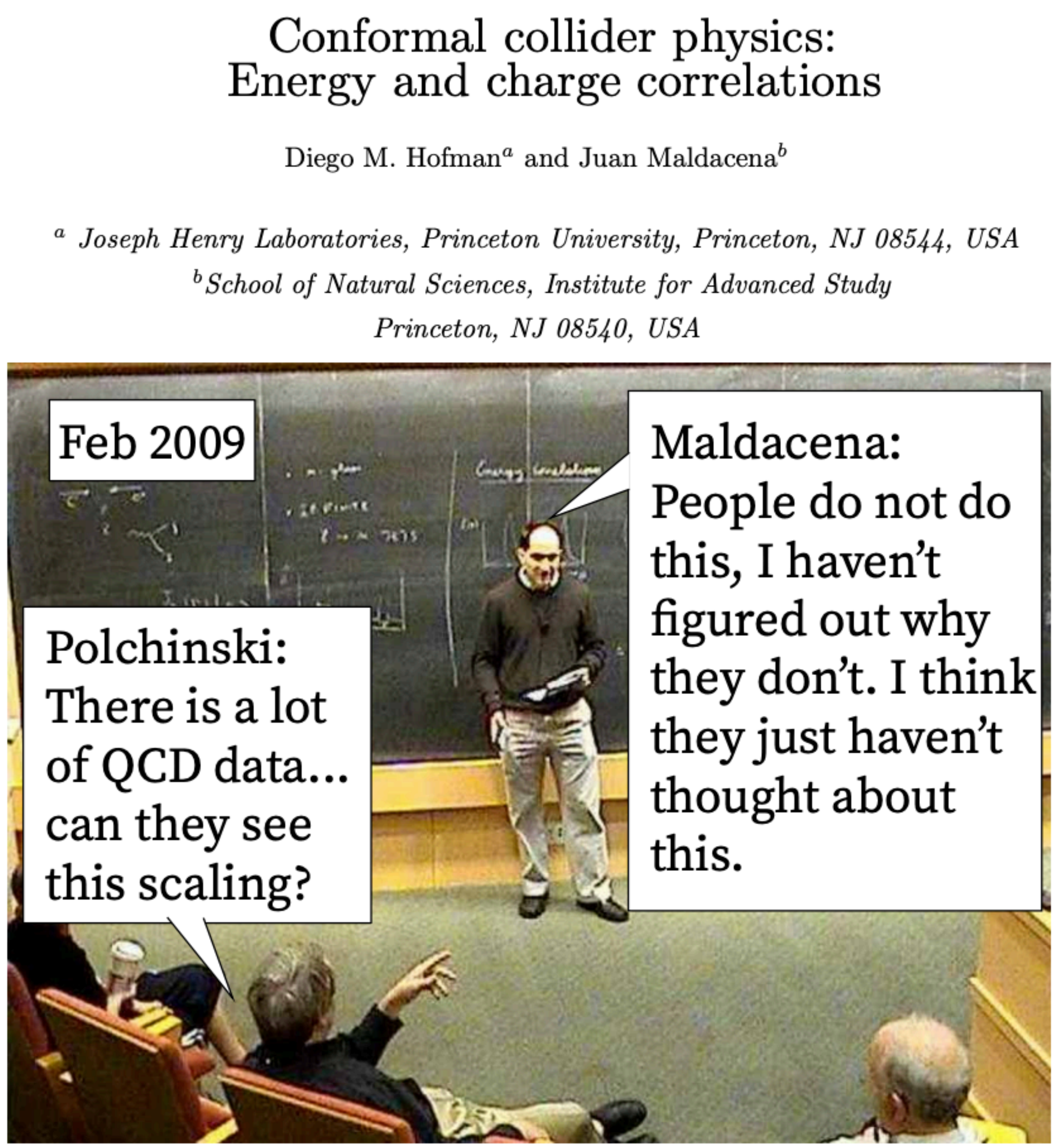


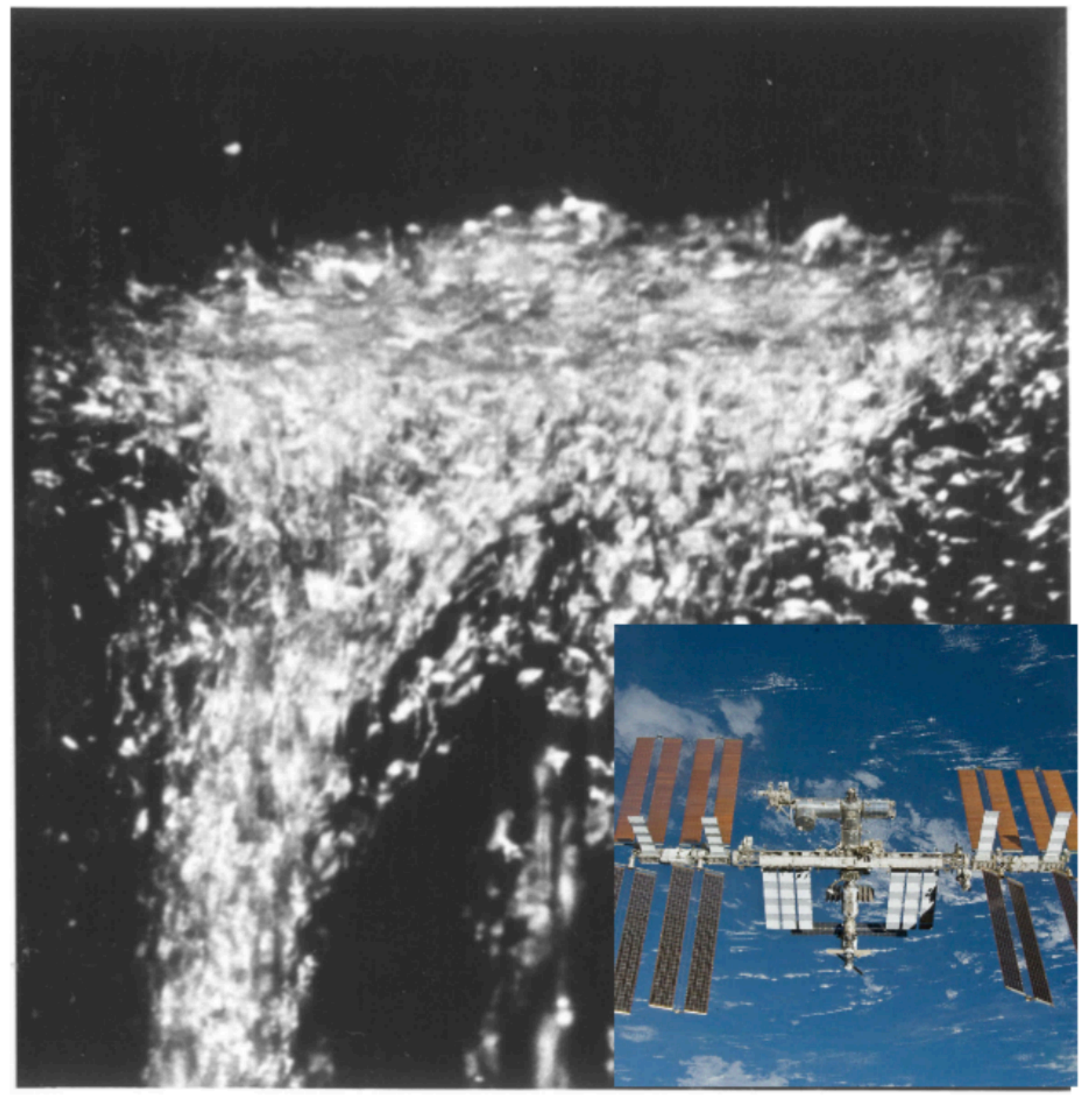
$$\text{ENC} = \frac{1}{\sigma}\int d\sigma \sum \frac{E_1 E_2 \ldots E_N}{Q^N} \mathscr{M}(\{\theta_{ij}\})$$

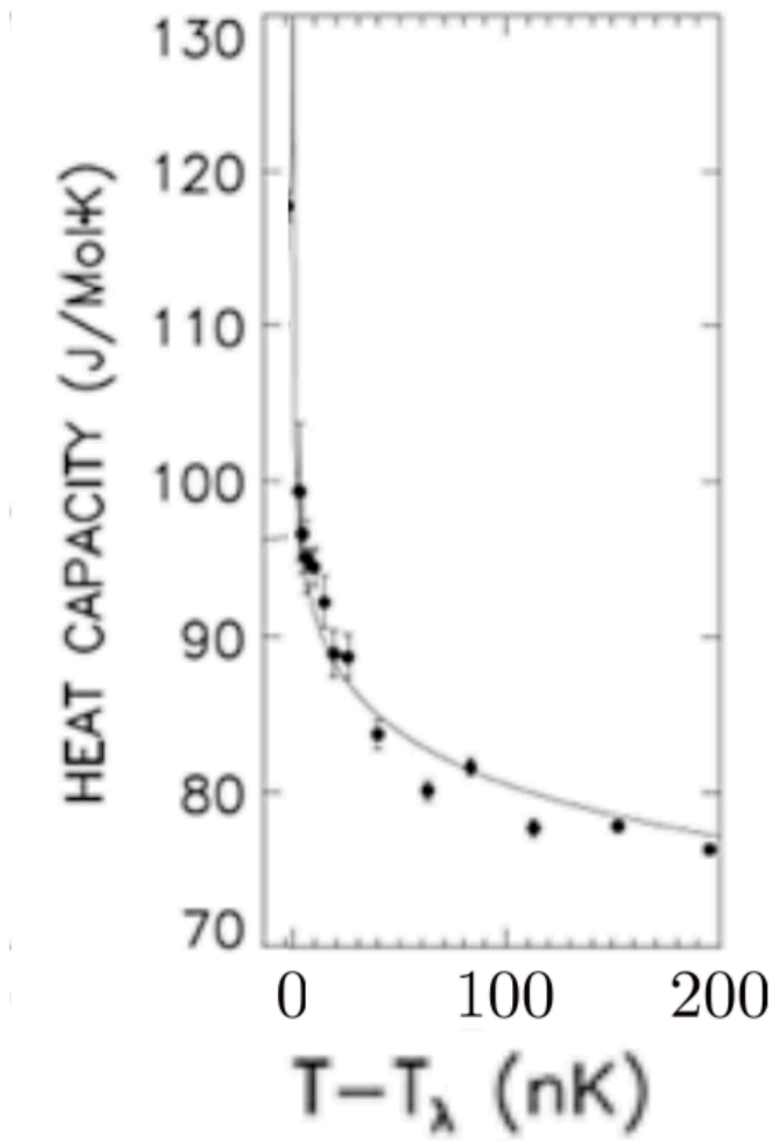
$$\propto \frac{1}{Q^N}\langle \mathcal{E}(n_1)\ldots\mathcal{E}(n_N)\rangle_J$$

- A Dual description
- Measuring a "fundamental" quantity in QFT

Collider Phenomenology







$$\mathscr{E}(n_1)\mathscr{E}(n_2) \sim \theta^{-1+\gamma}\mathscr{O}, \theta \ll 1, Q\theta \gg \Lambda_{QCD}$$

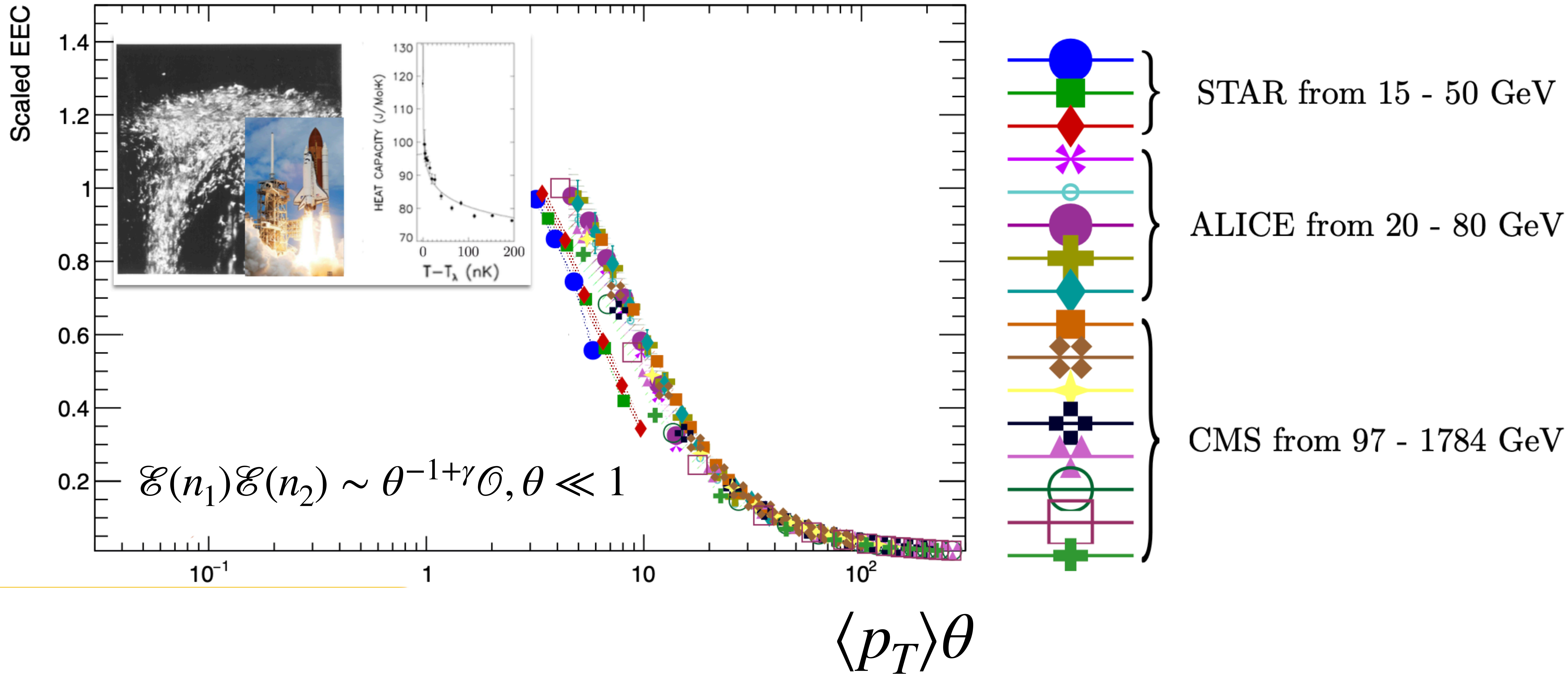
Universal Scaling rule by conformal theory

Hofman, Maldecena, 2008

Derived using factorization for QCD by Dixon, Moult, Zhu, 2019

Collider Phenomenology

When Conformal meets Collider



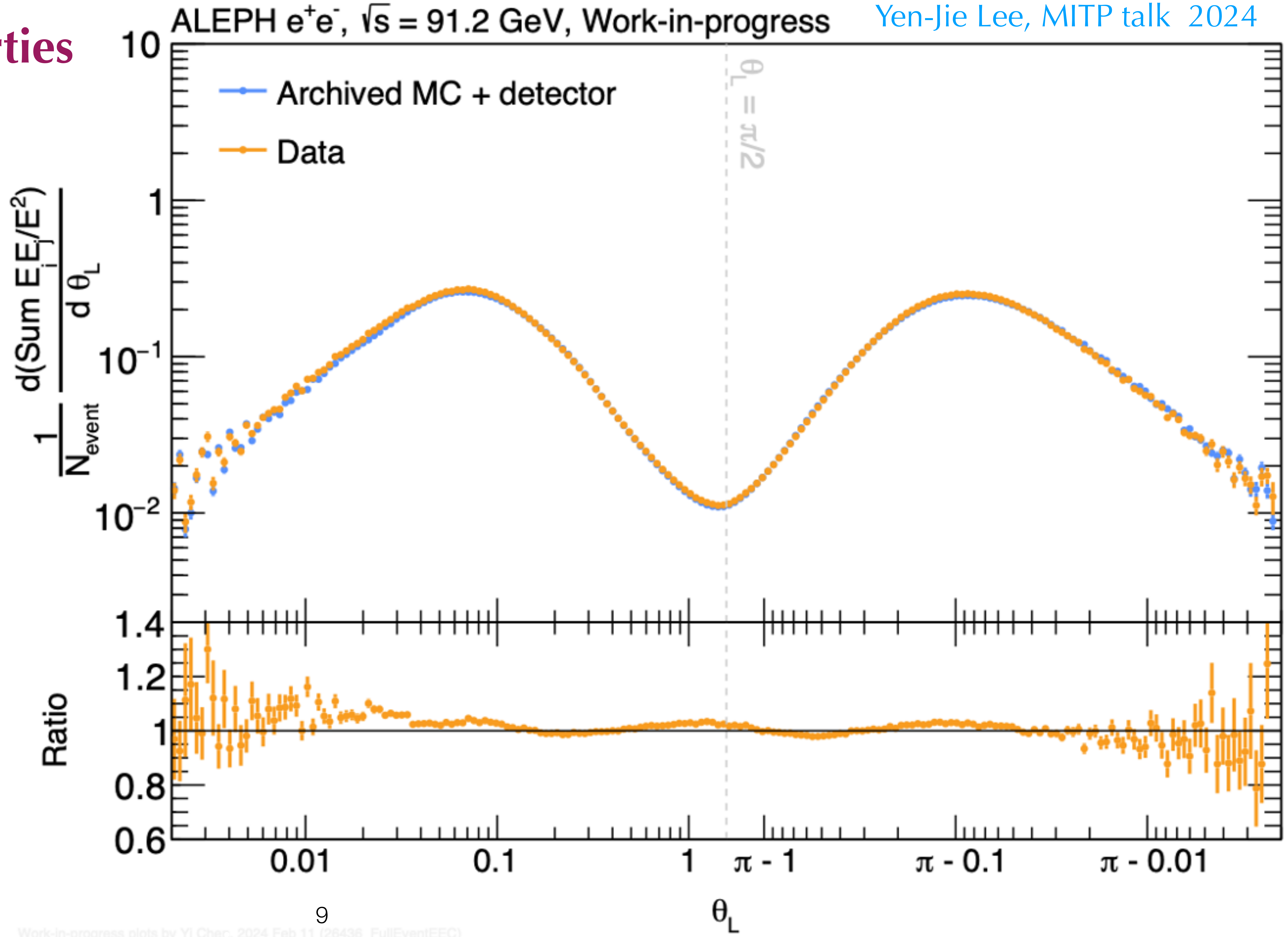
Confirmed by Collider experiments, across a large range of energies

Collider Phenomenology

Yen-Jie Lee, MITP talk 2024

The Full Spectrum and Properties

- Tracks for good angular resolution
- Different angles probe **different physics@$Q\theta$**

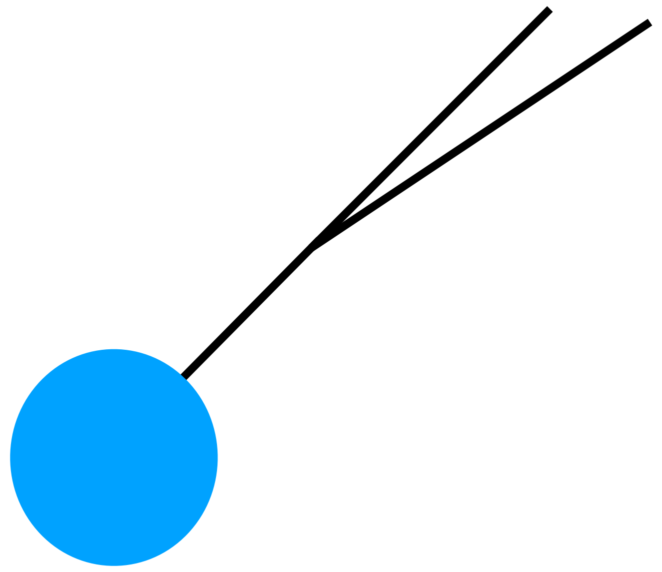


Collider Phenomenology

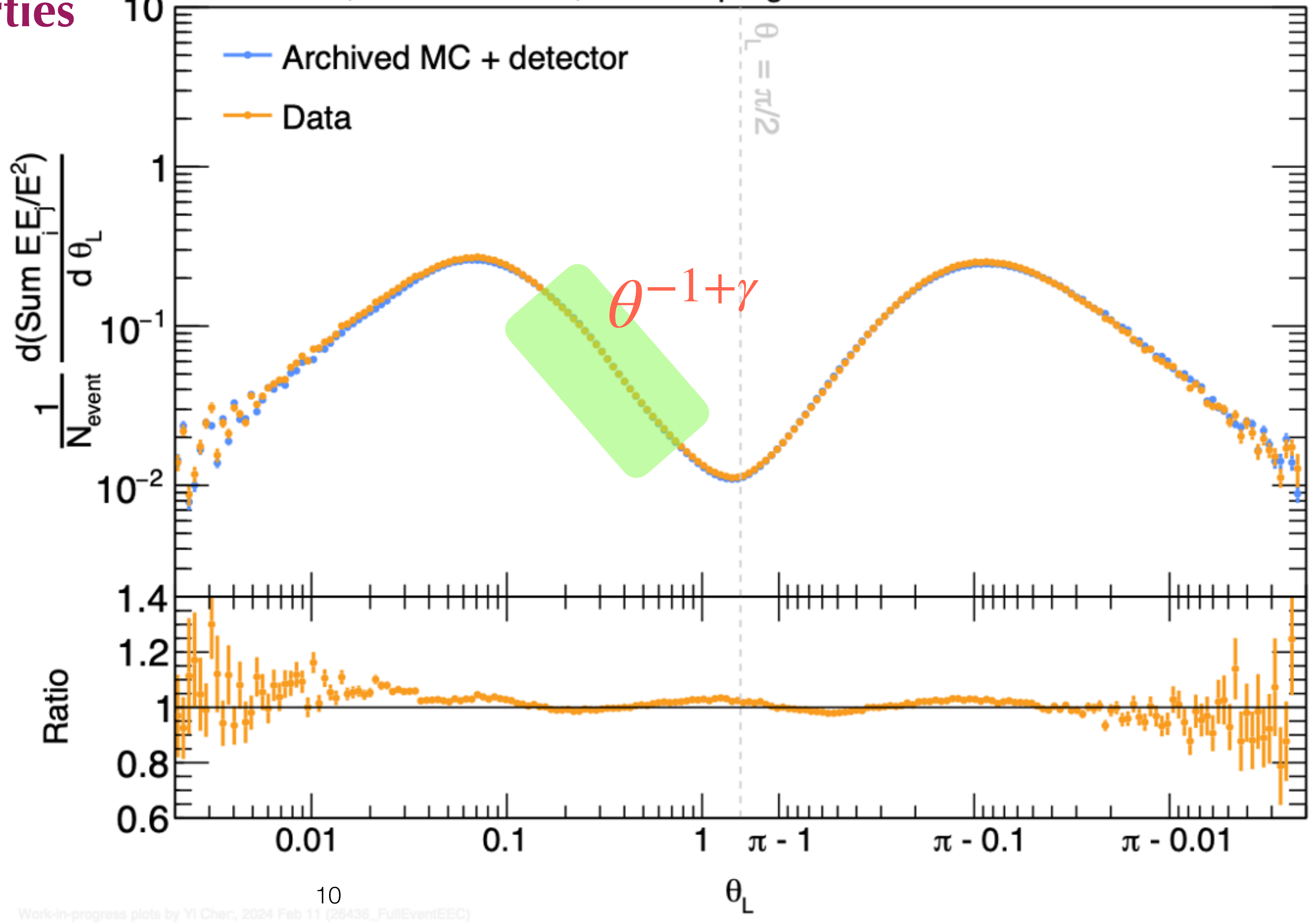
The Full Spectrum and Properties

- Can be understood by pQCD Dixon, et al., 2019

$$\gamma = \int_0^1 dx x^{3-1} P(x) dx$$



Yen-Jie Lee, MITP talk 2024



Collider Phenomenology

The Full Spectrum and Properties

- Can be understood by pQCD Dixon, et al., 2019

$$\gamma = \int_0^1 dx x^{3-1} P(x) dx$$

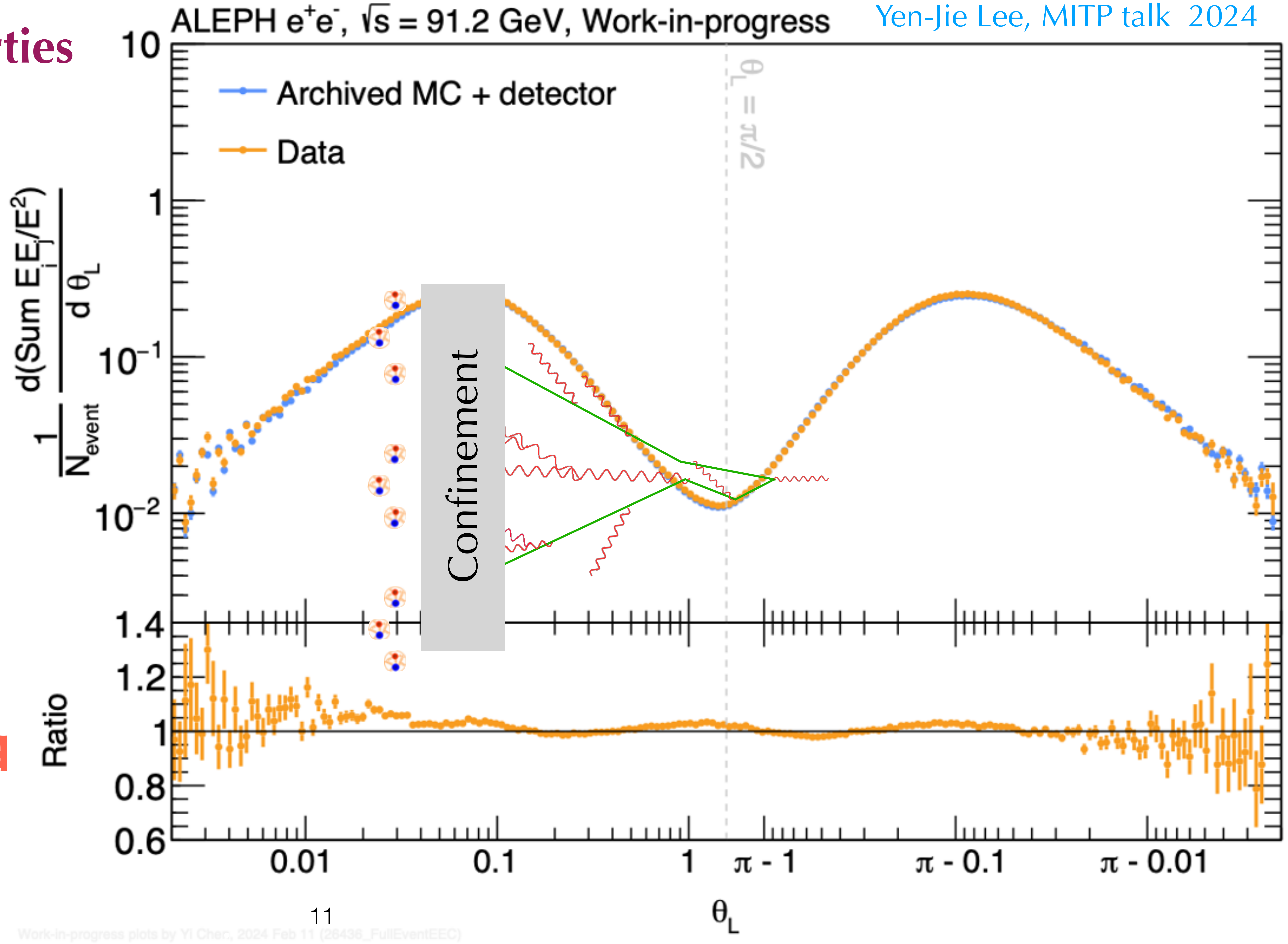
- Striking phase transition from parton to free hadron

$$d\cos\theta \sim \theta d\theta \Longrightarrow \Sigma \propto \theta d\sigma$$

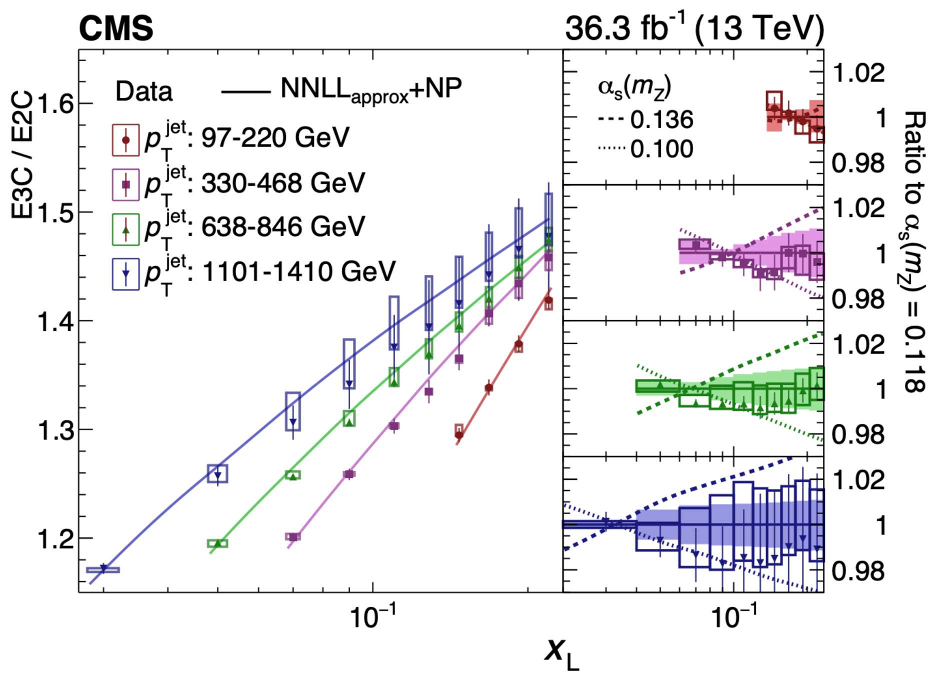
Hofman, Maldecena, 2008
Komiske, Moult, Thaler, Zhu, PRL 23

- **Intrinsic scale imprinted in the spectrum**

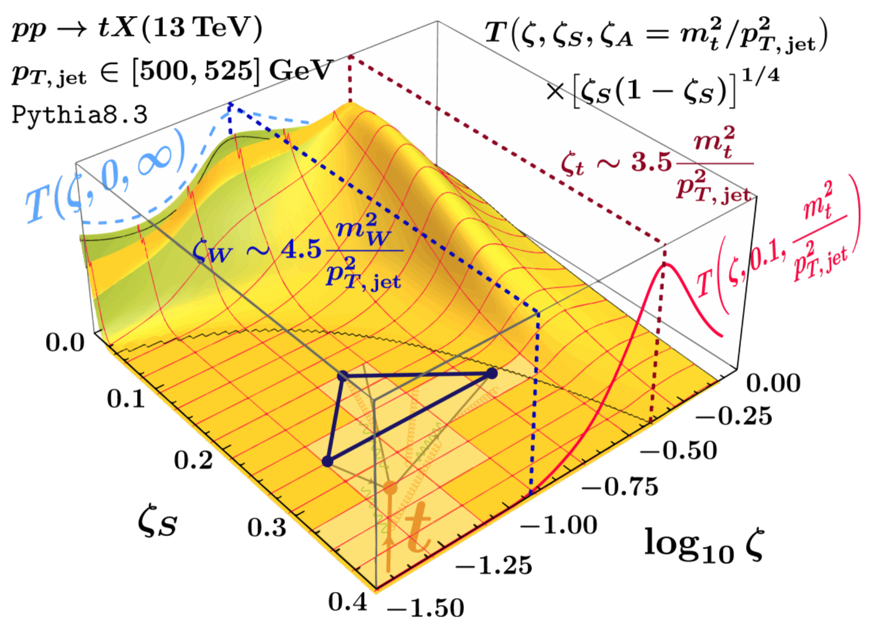
Yen-Jie Lee, MITP talk 2024



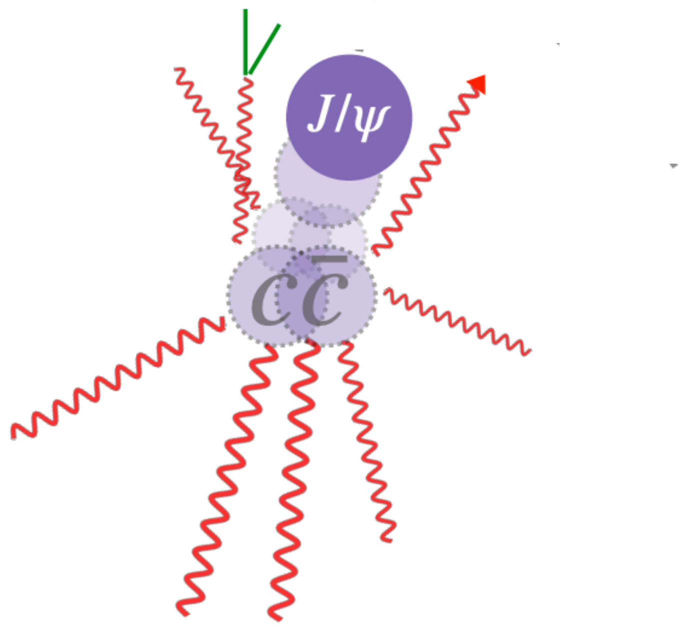
Collider Phenomenology



Scaling behavior $\Longrightarrow$ α_s extraction



Revealing scales $\Longrightarrow$ top mass determination



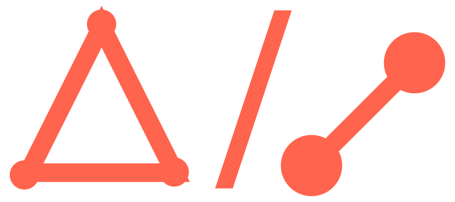
Extension $\Longrightarrow$ Heavy quark hadronization

See An-Ping Chen's talk

Collider Phenomenology: α_s extraction

Scaling behavior $\text{ENC} \propto \theta^{-1+\gamma(N+1)}$

$$\gamma(N+1) = \int_0^1 dx x^N P(x) dx$$ Chen et al., 2020



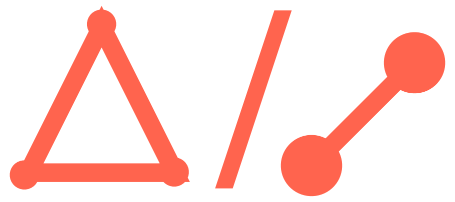
$$\propto \theta^{\gamma(4)-\gamma(3)} \sim \alpha_s(Q) \ln\theta + \dots$$

- The ratio probes directly the quantum effect
- Slope is directly related to α_s

Collider Phenomenology: α_s extraction

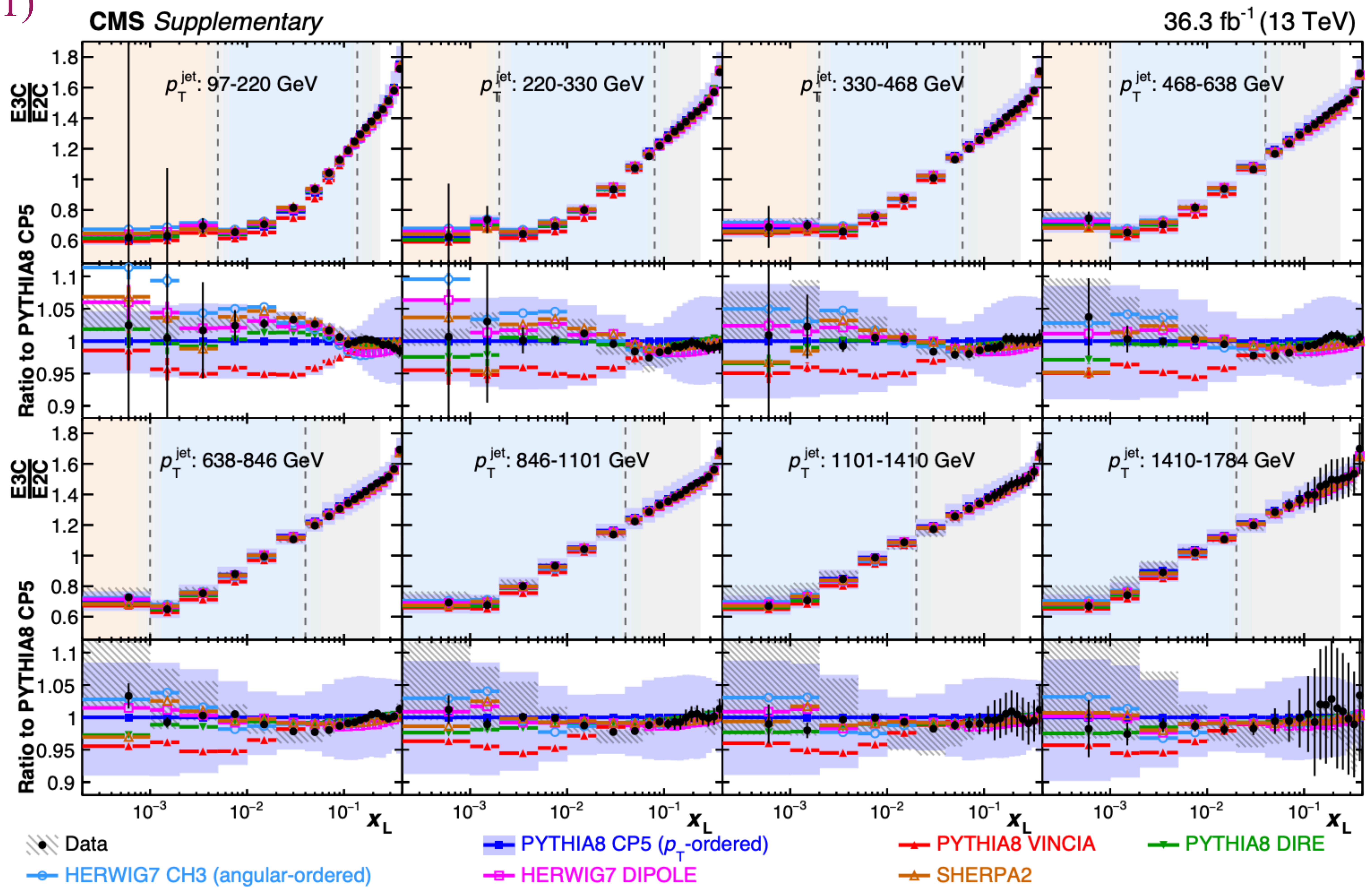
Scaling behavior $\mathrm{ENC} \propto \theta^{-1+\gamma(N+1)}$

$$\gamma(N+1) = \int_0^1 dx x^N P(x) dx$$ Chen et al., 2020



$$\propto \theta^{\gamma(4)-\gamma(3)} \sim \alpha_s(Q) \ln \theta + \ldots$$

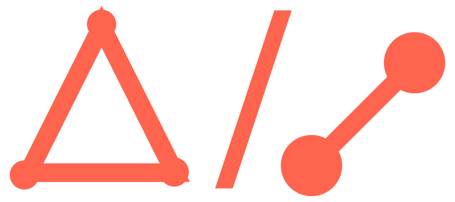
- The ratio probes directly the quantum effect
- Slope is directly related to α_s



Collider Phenomenology: α_s extraction

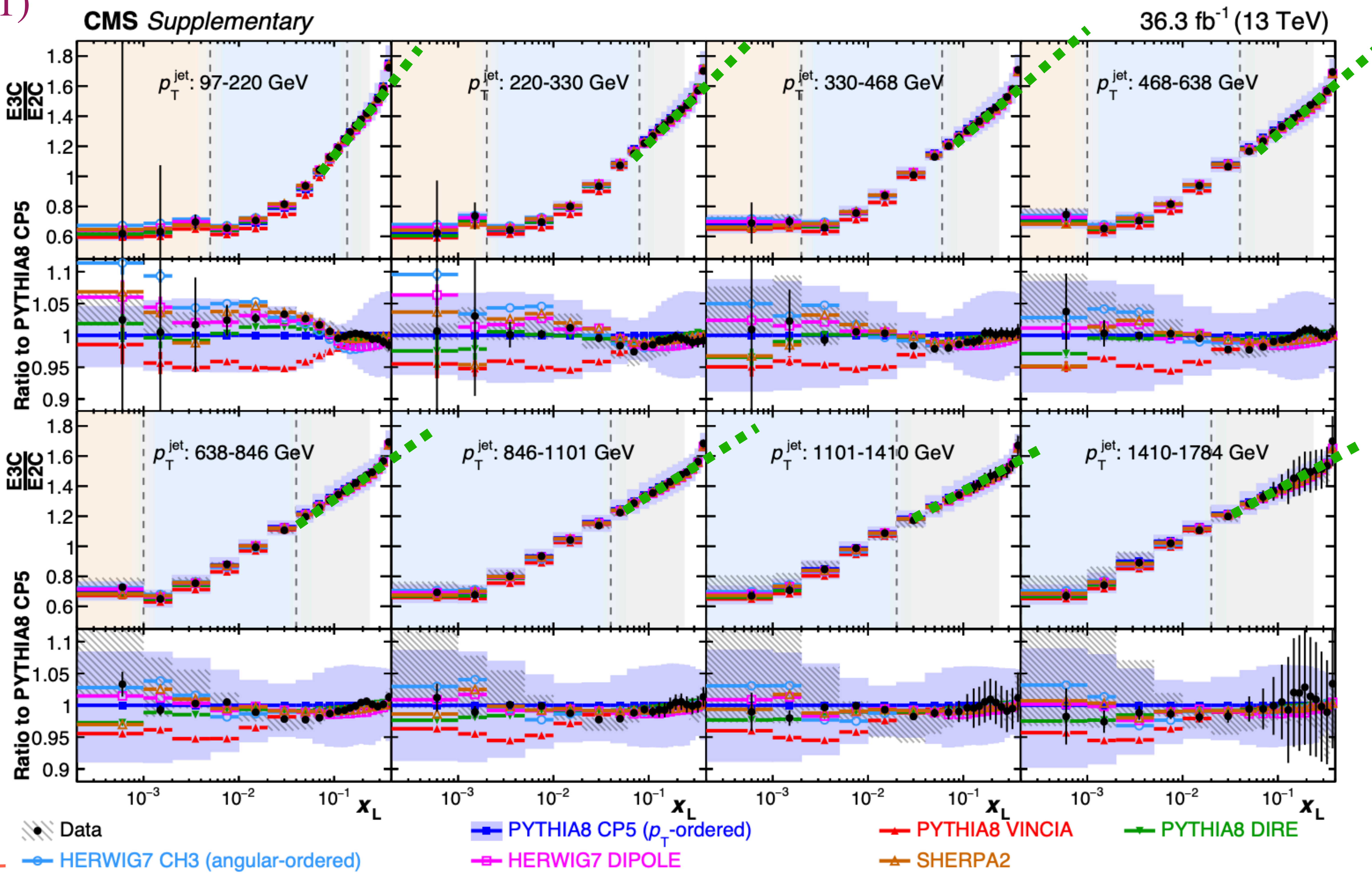
Scaling behavior ENC $\propto \theta^{-1+\gamma(N+1)}$

$$\gamma(N+1) = \int_0^1 dx x^N P(x) dx$$ Chen et al., 2020



$\propto \theta^{\gamma(4)-\gamma(3)} \sim \alpha_s(Q) \ln \theta + \ldots$

- The ratio probes directly the quantum effect
- Slope is directly related to α_s

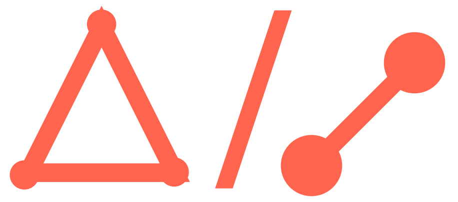


$p_T^{\text{jet}} \uparrow$, slope $\sim \alpha_s(p_T^{\text{jet}}) \downarrow$

Collider Phenomenology: α_s extraction

Scaling behavior ENC $\propto \theta^{-1+\gamma(N+1)}$

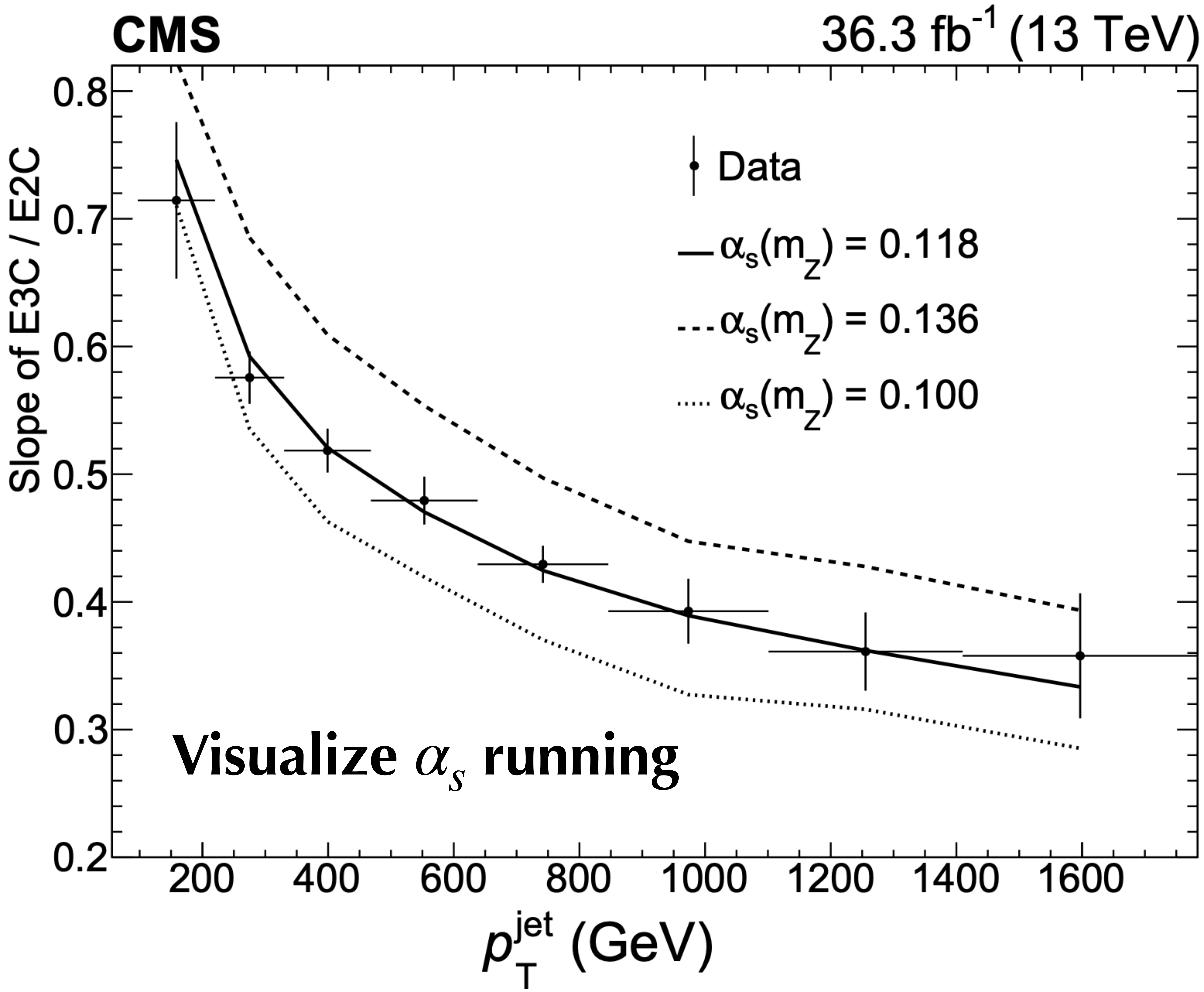
$$\gamma(N+1) = \int_0^1 dx x^N P(x) dx$$ Chen et al., 2020



$\propto \theta^{\gamma(4)-\gamma(3)} \sim \alpha_s(Q) \ln \theta + \dots$

- The ratio probes directly the quantum effect
- Slope is directly related to α_s

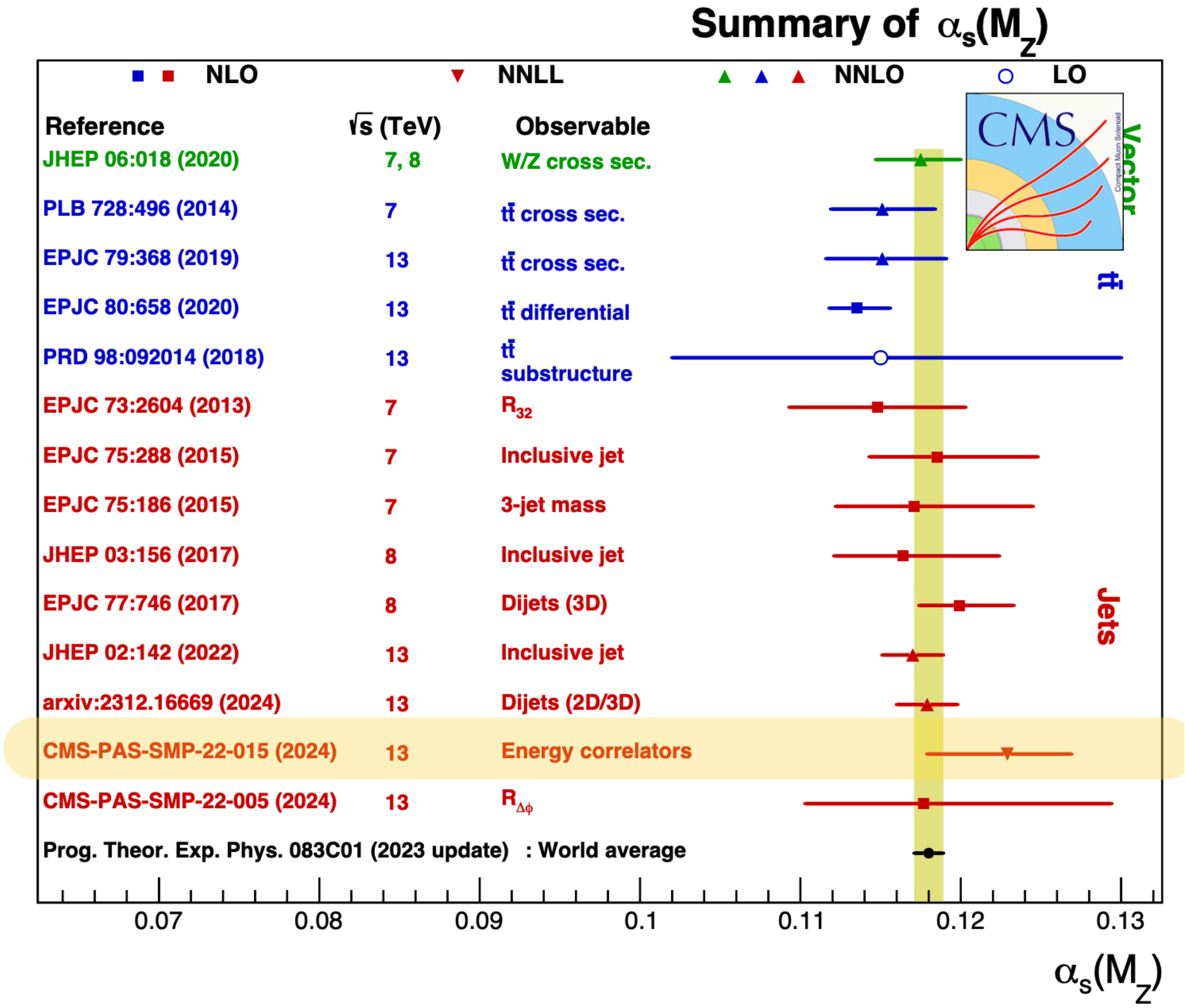
$p_T^{\text{jet}} \uparrow$, slope $\sim \alpha_s(p_T^{\text{jet}}) \downarrow$

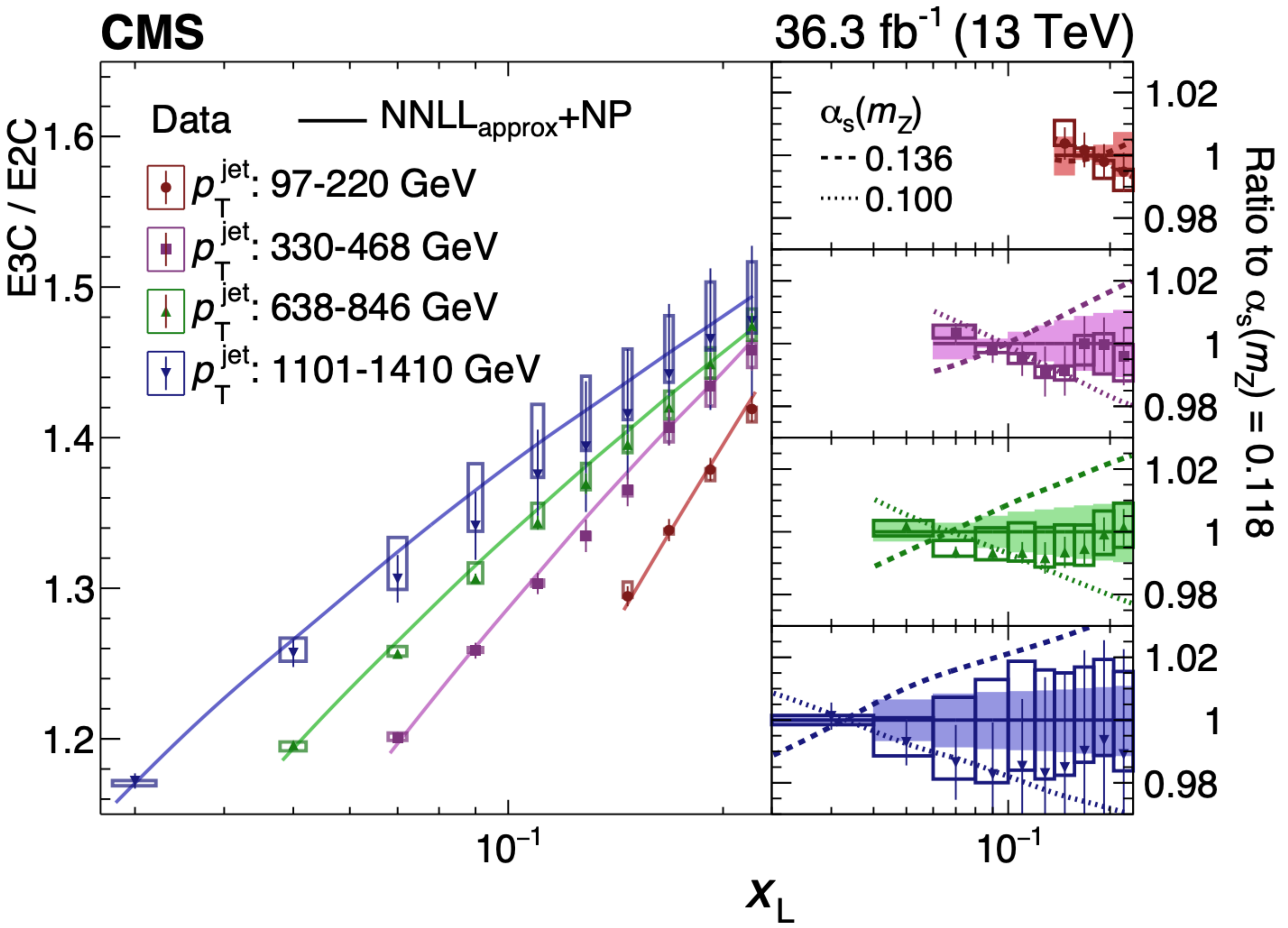


Collider Phenomenology: α_s extraction

NNLO from Chen et al. arXiv:2307.07510.

α_s extraction by the scaling behavior





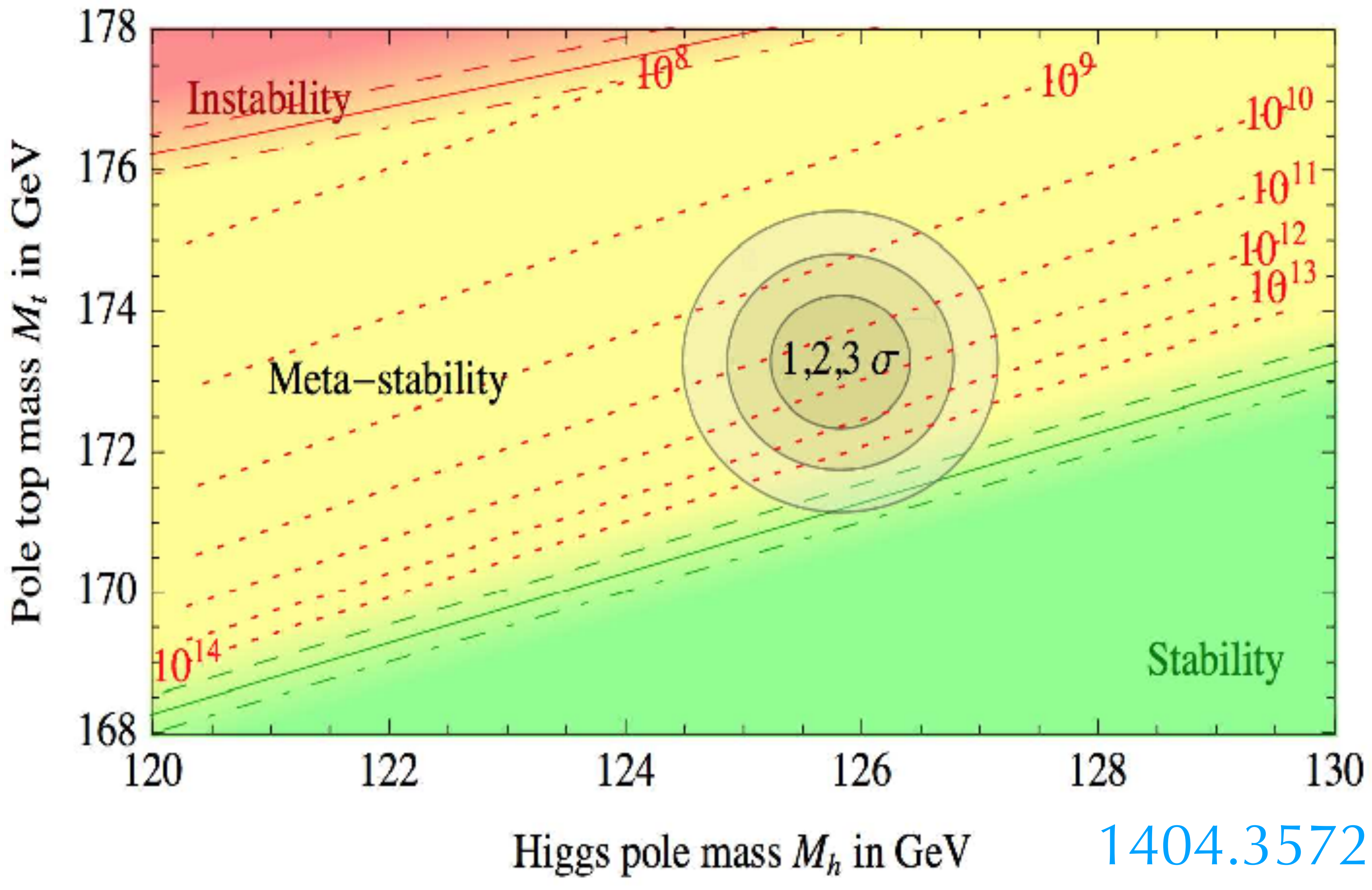
$$\alpha_s(m_Z) = 0.1229^{+0.0014(\text{stat.})+0.0030(\text{theo.})+0.0023(\text{exp.})}_{-0.0012(\text{stat.})-0.0033(\text{theo.})-0.0036(\text{exp.})}$$

- Scaling vs NNLL (no NNLO yet)
- 4% error, already the most precise α_s extraction using jet substructures (~10%)

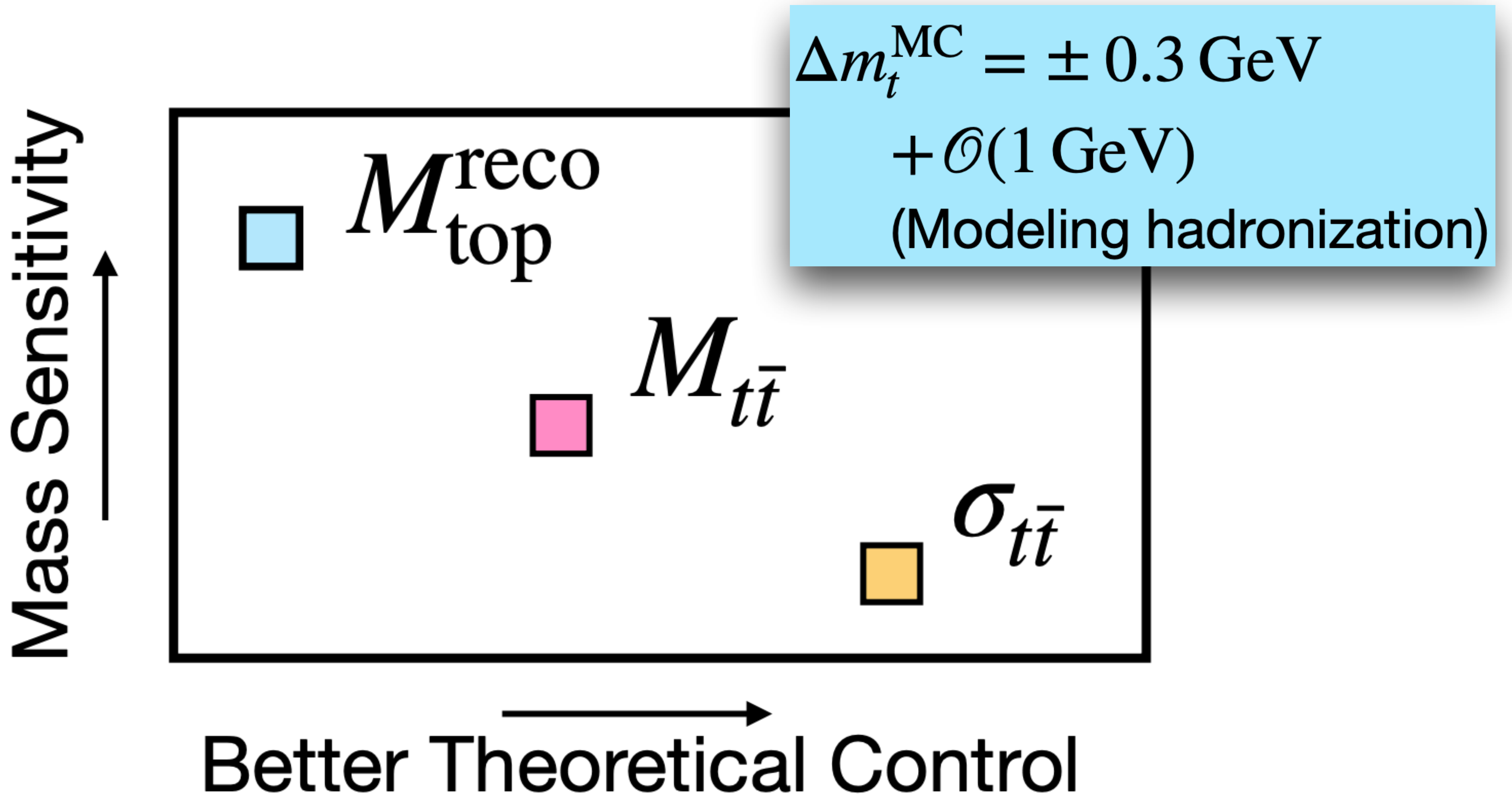
Collider Phenomenology: weighing tops

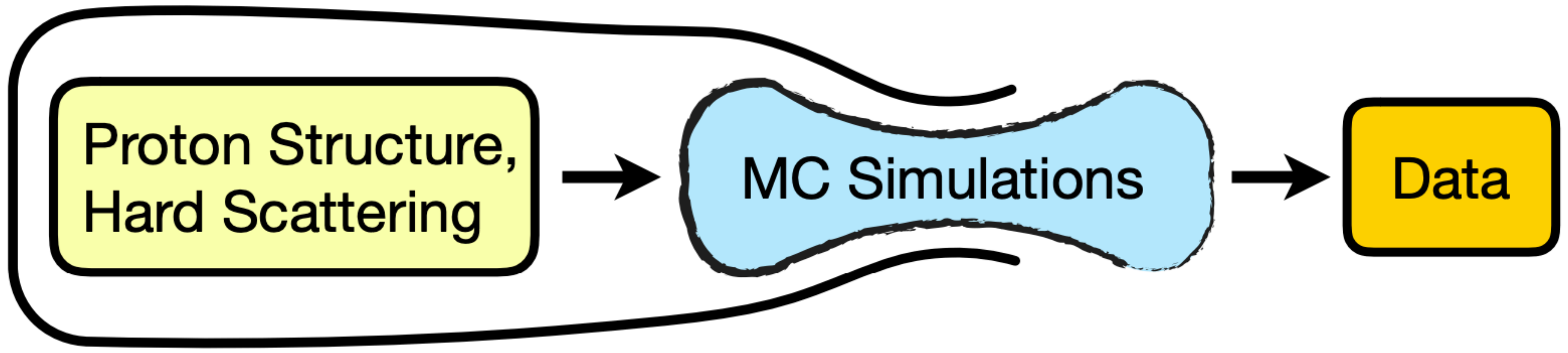
Top mass

- one of the most important SM parameters. e.g. electroweak vacuum stability, electroweak fits, etc
- The current approaches by MC simulations present a bottleneck that limits precision.
- Call for a field definition clean measurement



1404.3572

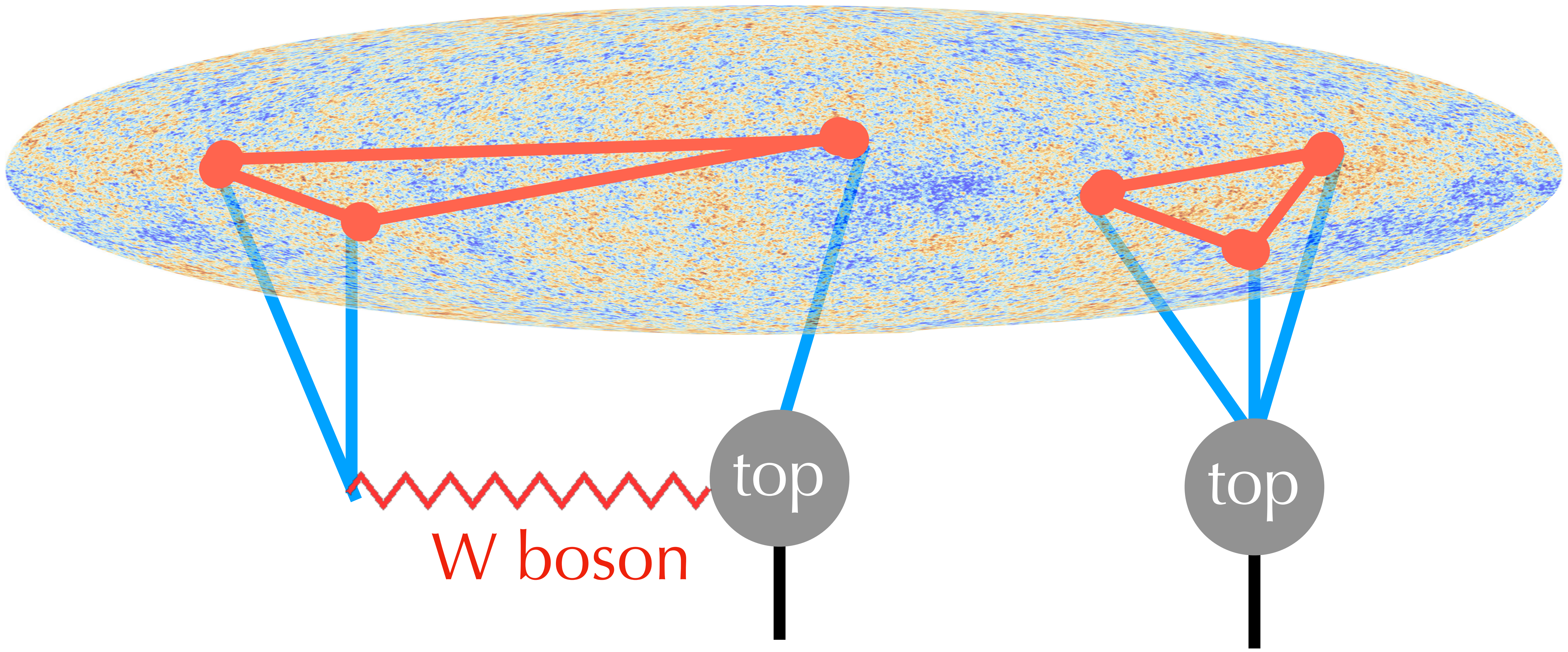




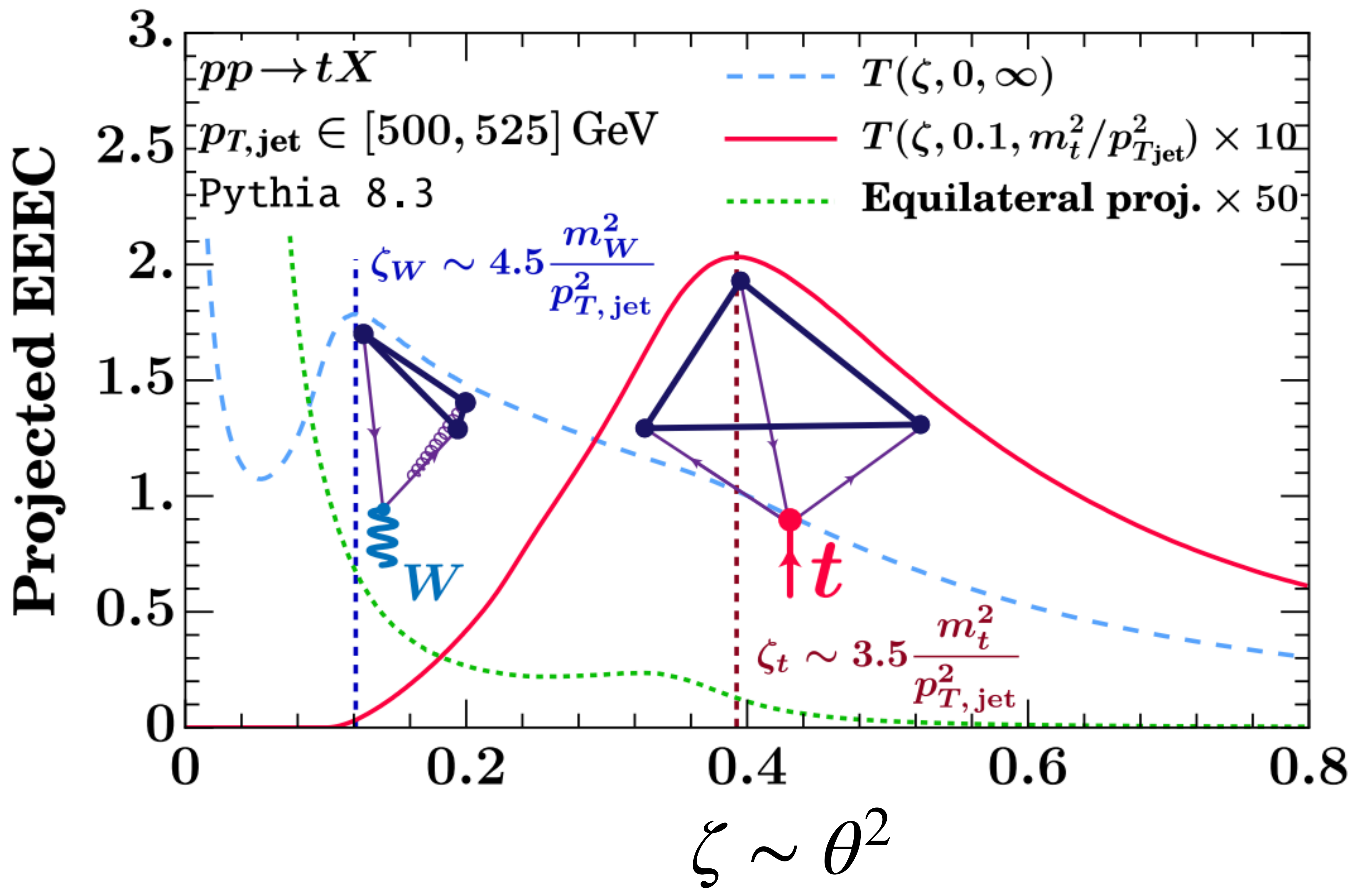
Collider Phenomenology: weighing tops

Top mass scale in the E3C spectrum

Holguin et al, 2023
Xiao et al,, 2024



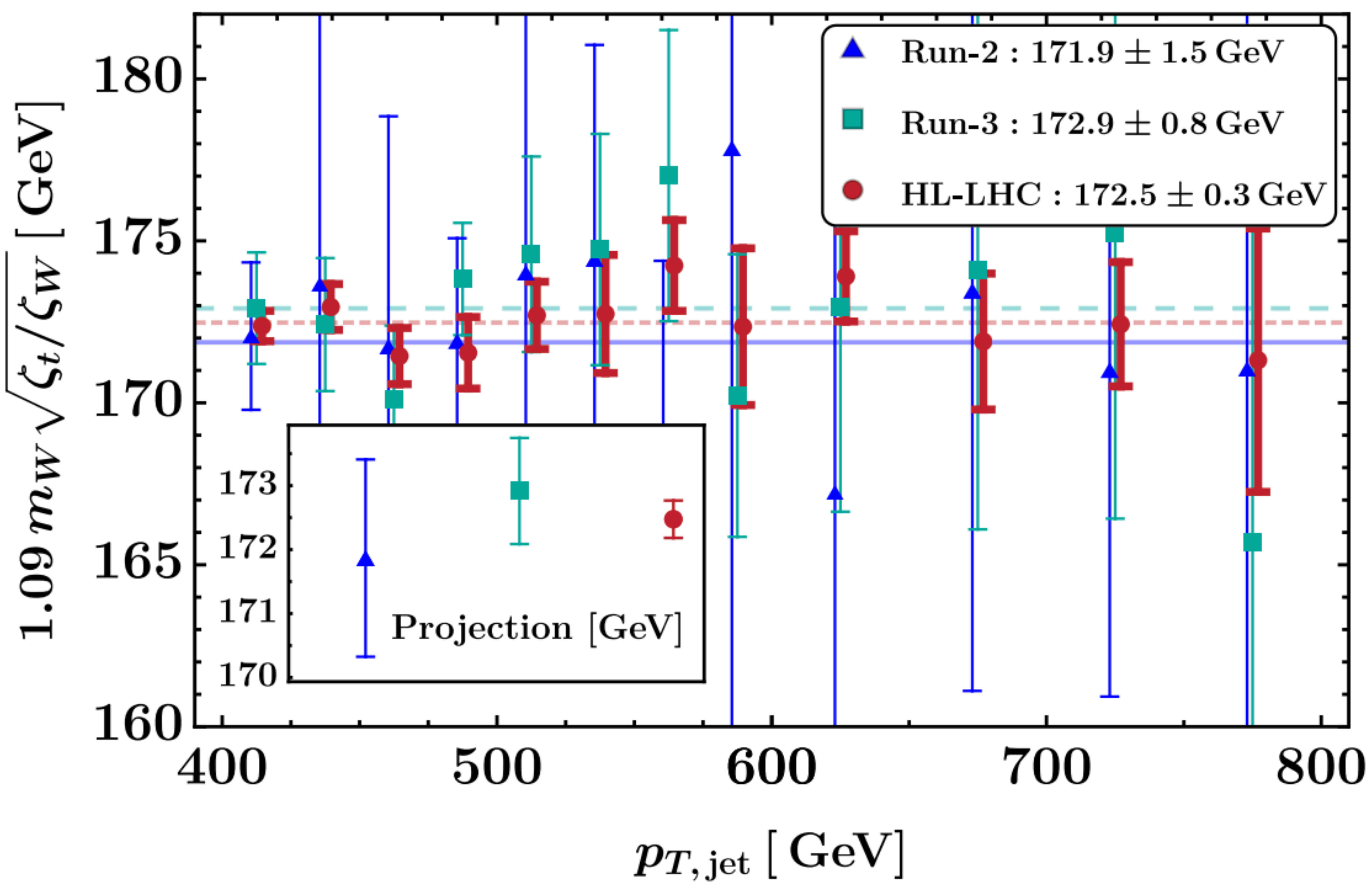
Squeeze limit, $\theta_W \sim \frac{m_W}{p_T}$ Equilateral, $\theta_t \sim \frac{m_t}{p_T}$



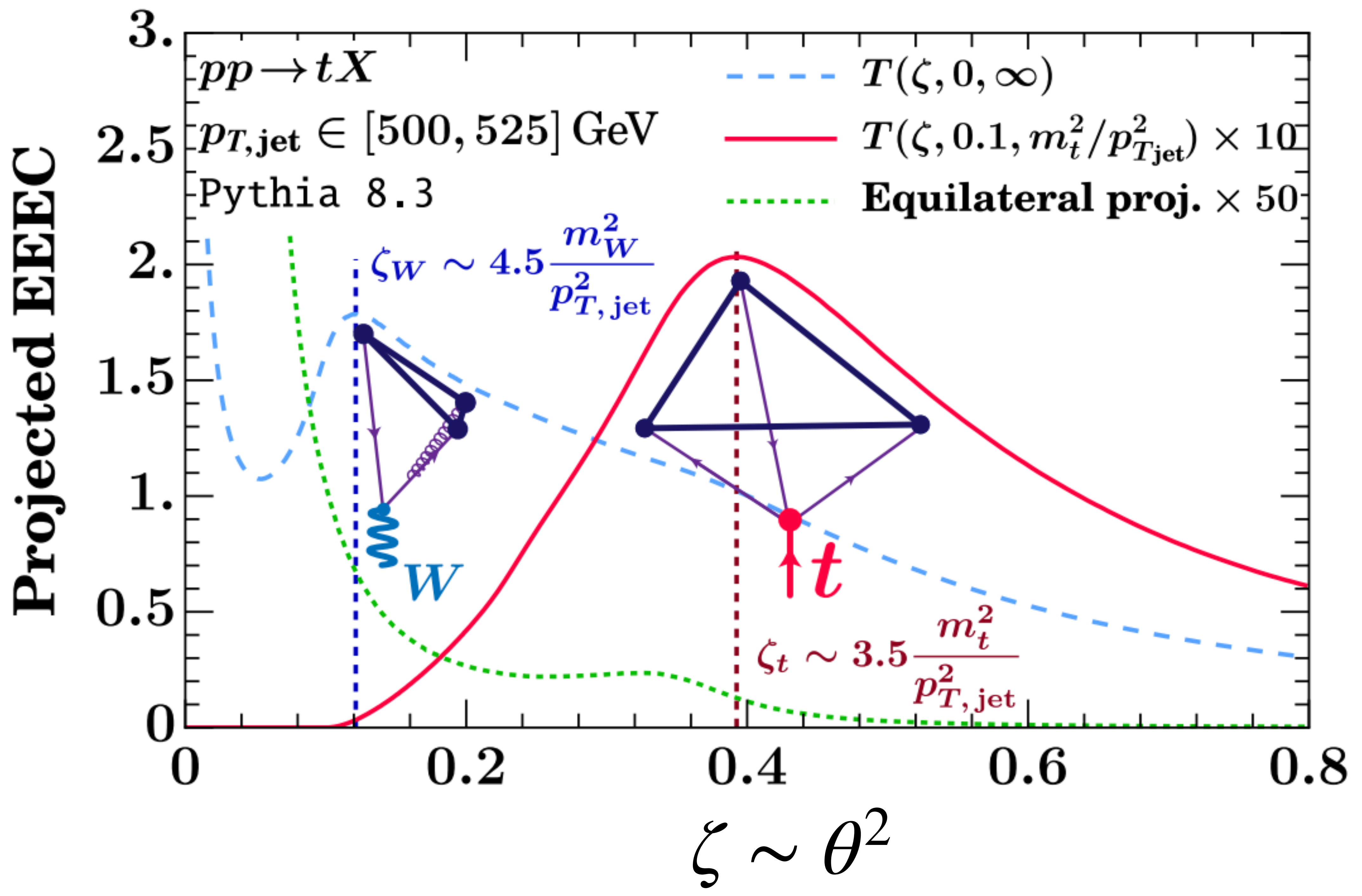
$$m_t \sim m_W \sqrt{\zeta_t / \zeta_W}$$

Collider Phenomenology: weighing tops

Top mass scale in the E3C spectrum



$$m_t \sim m_W \sqrt{\zeta_t / \zeta_W}$$

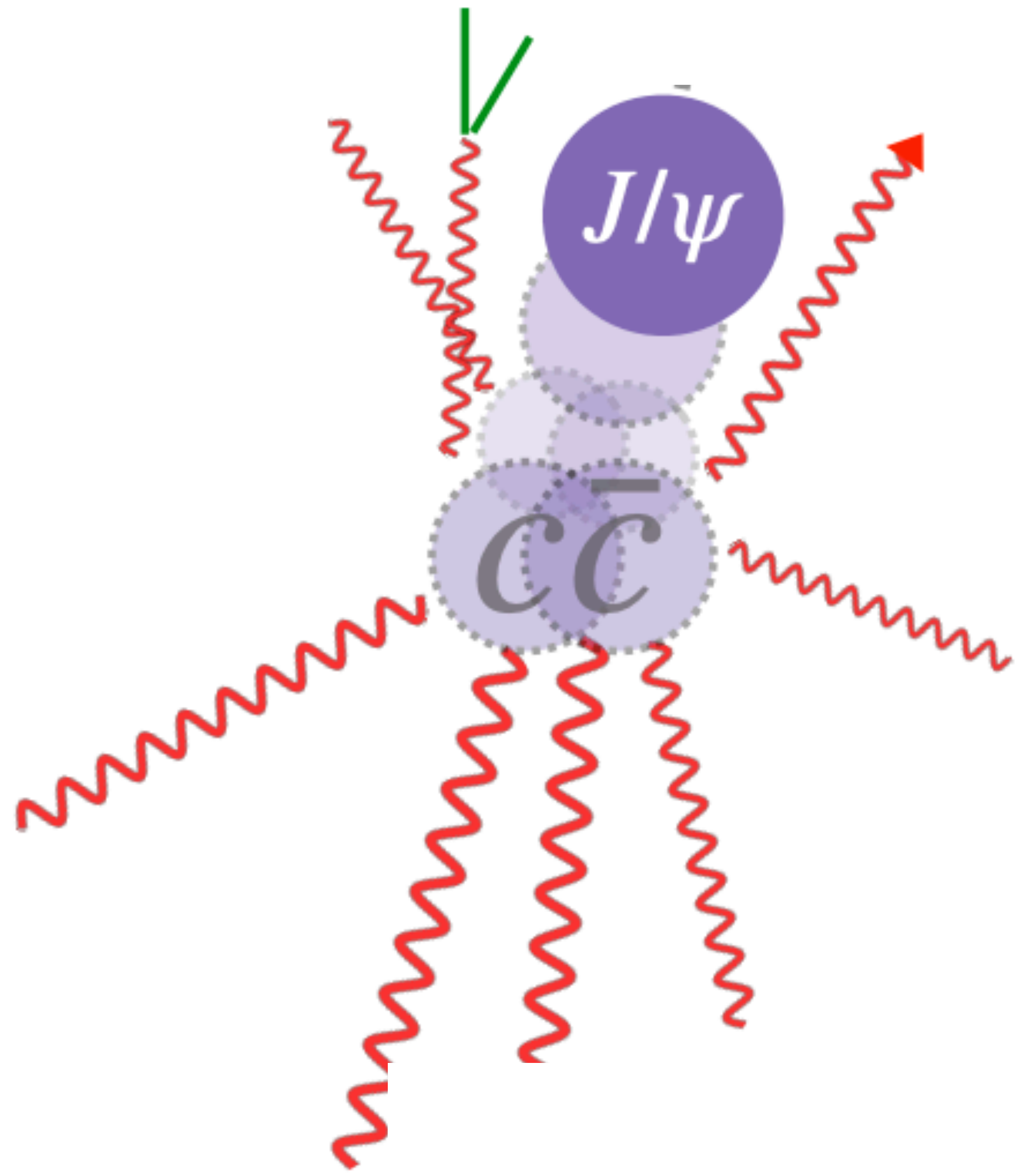


- Use W as a standard candle
- Can be calculated perturbatively
- Clean field definition, $\overline{\text{MS}}$ mass
- Call for precision calculation of E3C in top decay

Collider Phenomenology: heavy quark hadronization

Quarkonium Physics

- regarded as an excellent place to study non-pert phenomenon for a long time
- How $c\bar{c} \to J/\psi$?
  - NRQCD: encoded in $\langle \mathcal{O}_{\mathbf{1}} \rangle$, $\langle \mathcal{O}_{\mathbf{8}} \rangle$
  - remains largely unknown: amount of energy released? Energy Distribution?



Collider Phenomenology: heavy quark hadronization

Quarkonium Physics

Probing Quarkonium Production Mechanisms with Jet Substructure

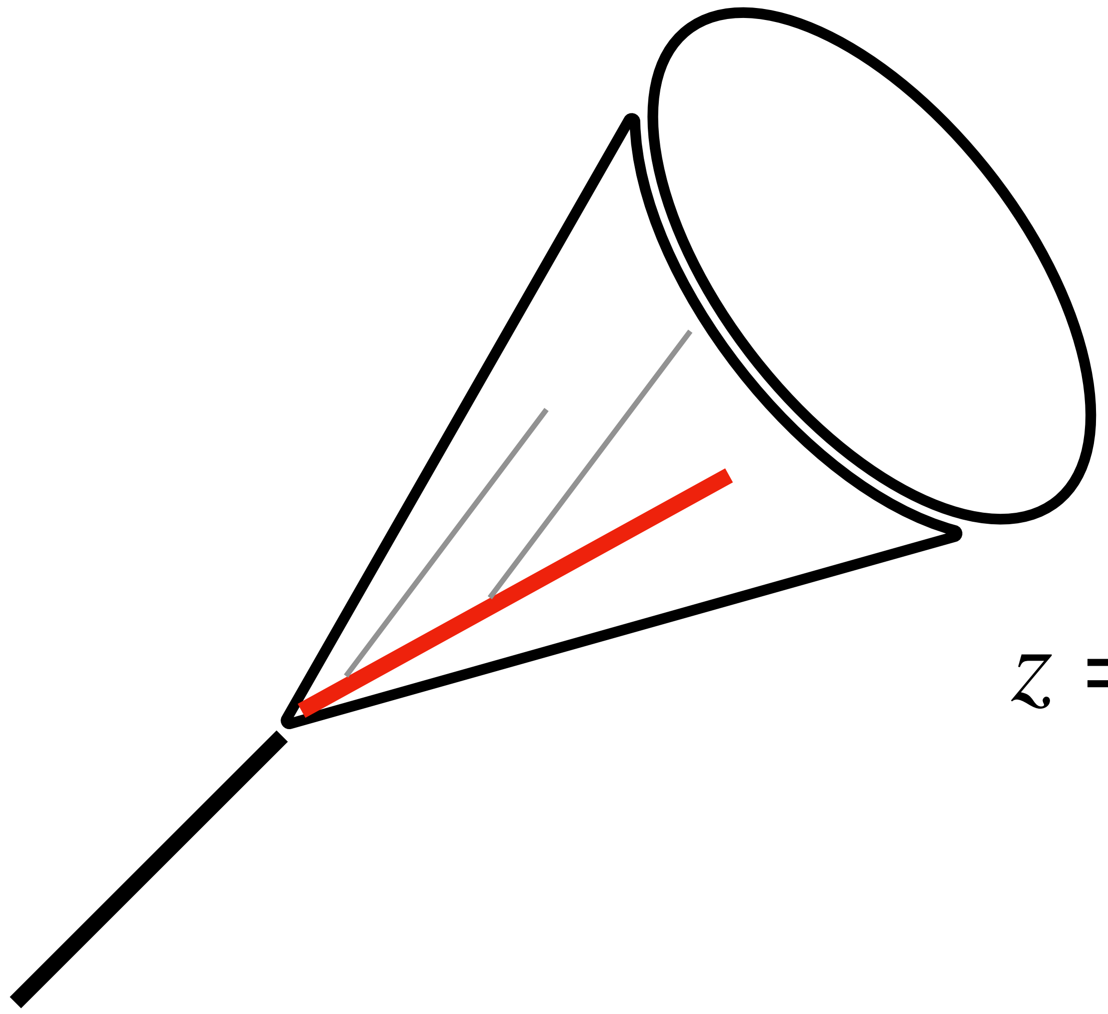
Matthew Baumgart[a,1] Adam K. Leibovich[b,2] Thomas Mehen[c,3] and Ira Z. Rothstein[d1]

[1] *Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213*

[2] *Pittsburgh Particle Physics Astrophysics and Cosmology Center (PITT PACC)*
Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260

[3] *Department of Physics, Duke University, Durham, NC 27708*

(Dated: June 27, 2018)



$z = E_{J/\psi}/E_J$

Unlike light hadron fragmentation, $D_{q\to J/\psi}(z)$ dominated by perturbative radiation

Collider Phenomenology: heavy quark hadronization

Quarkonium Energy Correlator Chen, XL, Ma, PRL 2024, See An-Ping Chen's talk

$$E_{J_{near}} \sim E_s \sim \mathcal{O}(M), E_{J_{away}} \sim \mathcal{O}\left(\frac{\hat{s}}{2M}\right)$$

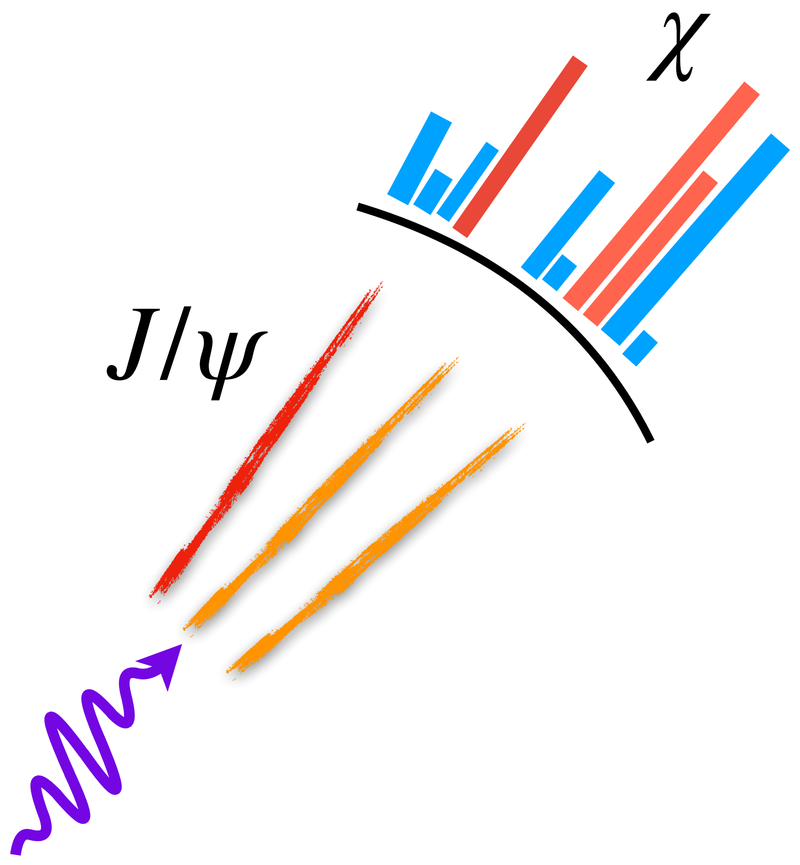
$$\Sigma_{\mathcal{Q}\mathrm{EC}}(\chi) \propto \frac{1}{\sigma_{J/\psi}} \int d\sigma_{J/\psi} \frac{E_i}{M} \delta(\chi - \chi_i)$$

~ average energy at the angle χ

- Perturbative radiations depleted in the neighbor of J/ψ, due to the boost and dead cone effects
- An ideal place to look for hadronization energy

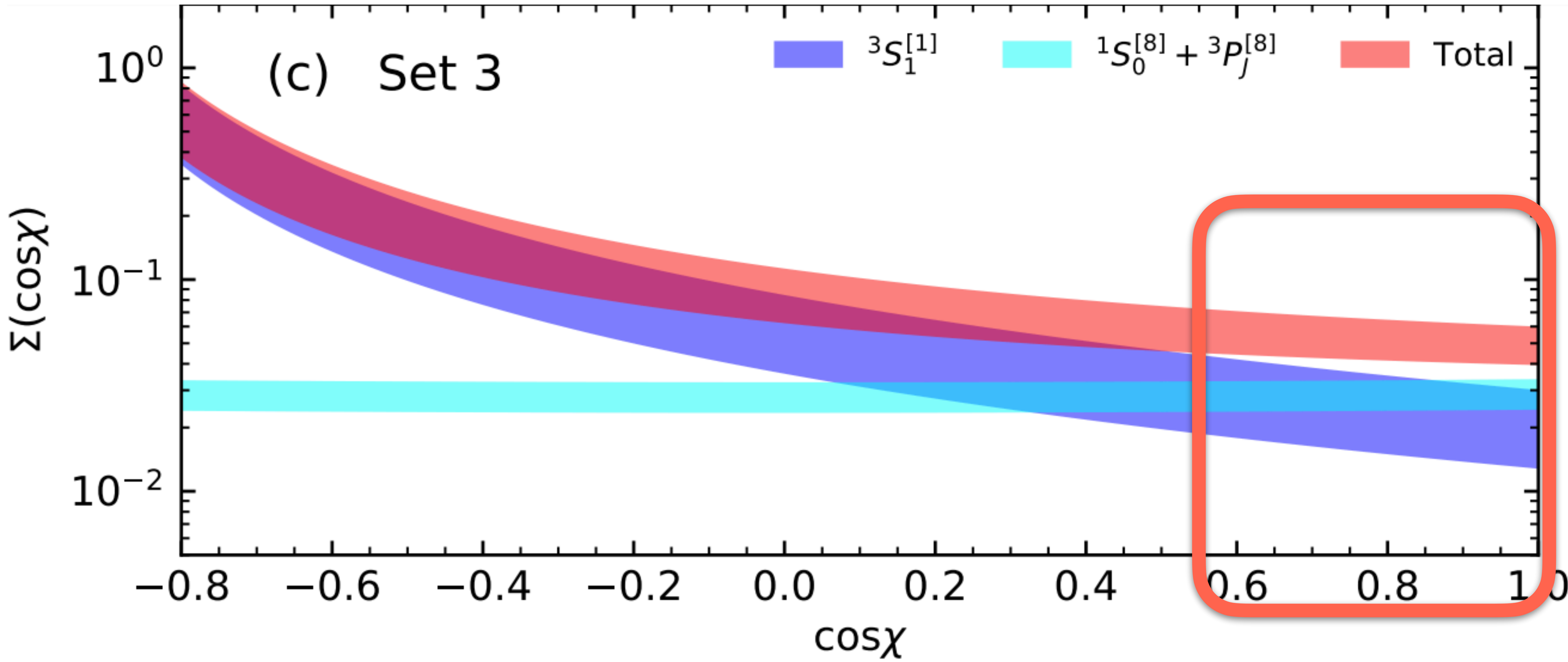
Collider Phenomenology: heavy quark hadronization

Quarkonium Energy Correlator Chen, XL, Ma, PRL 2024, See An-Ping Chen's talk



$$\Sigma_{\mathbb{Q}\mathrm{EC}}(\chi) \propto \frac{1}{\sigma_{J/\psi}} \int d\sigma_{J/\psi} \frac{E_i}{M} \delta(\chi - \chi_i)$$

~ average energy at the angle χ

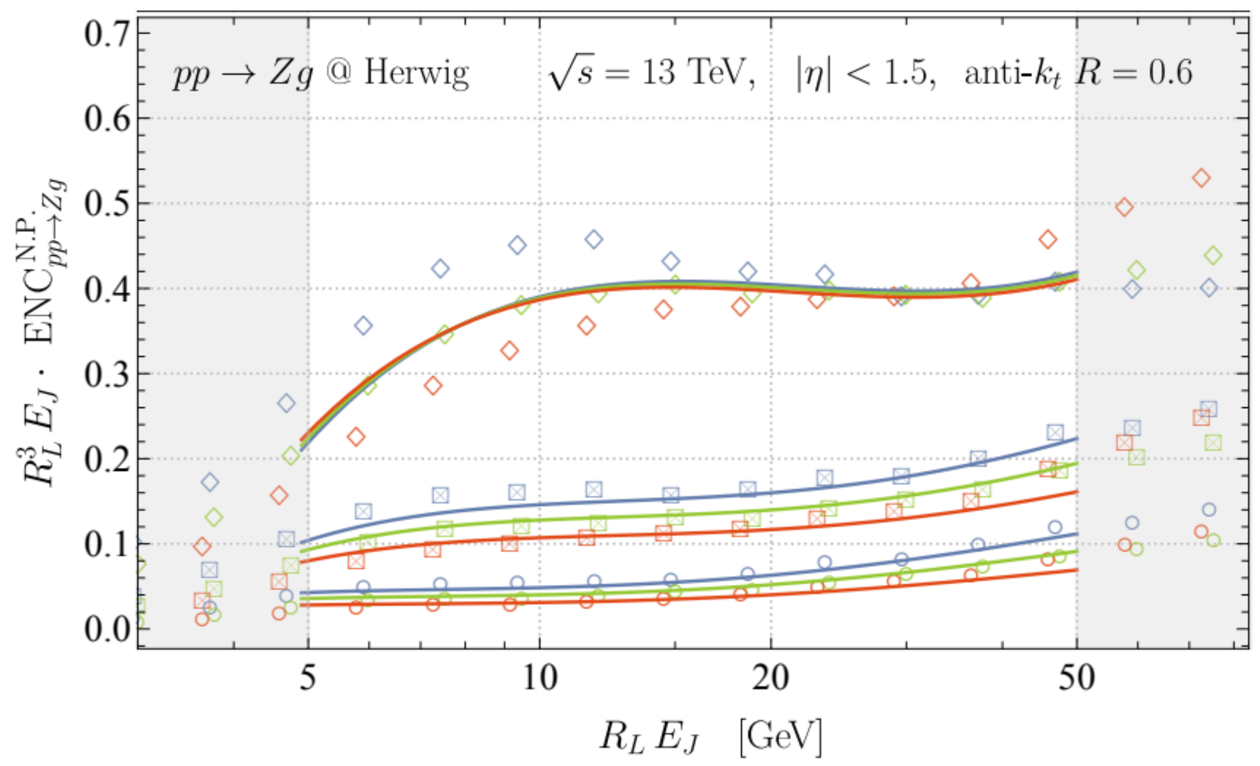


Sizable hadronization effect!!

"See" the hadronization energy distribution

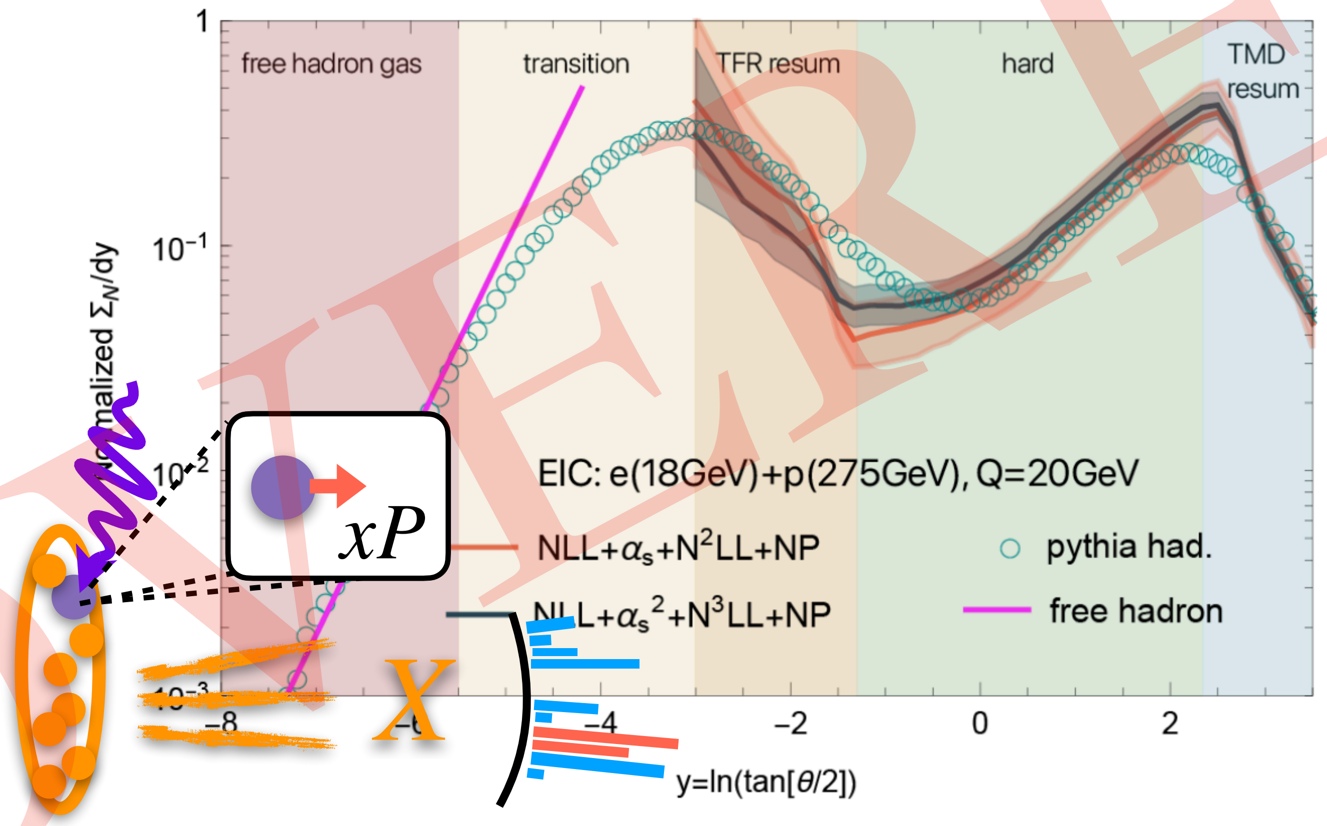
Conclusions

Chen, Monni, Xu, Zhu, PRL 2024 Lee, et al. , PRL 2024



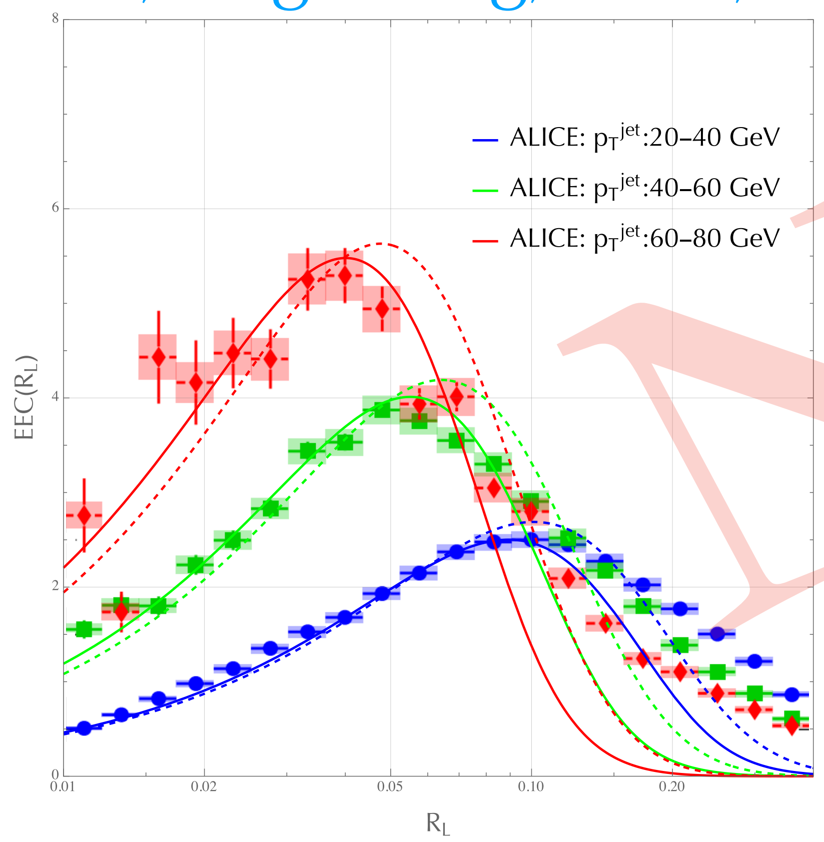
Hadronization in light quark ENC using QFT

XL, Zhu PRL 2023



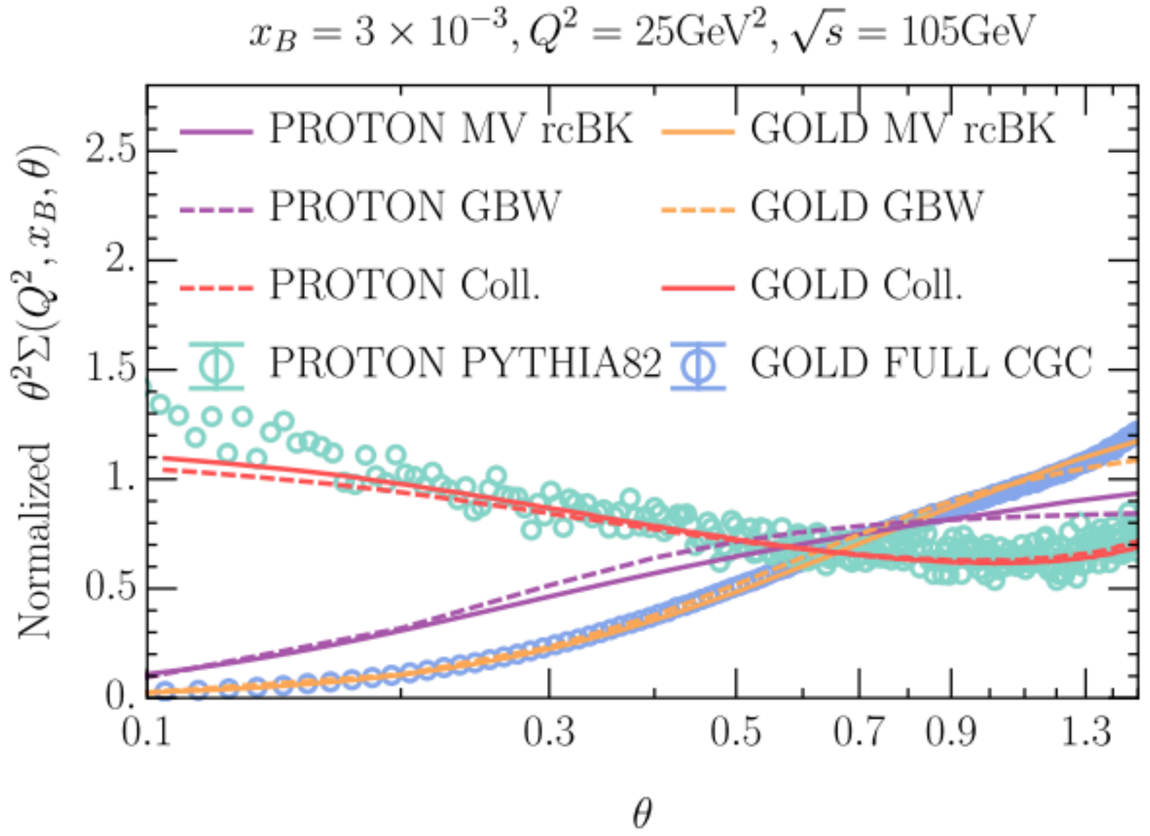
Energy correlator originated from the proton structure: **NEEC**

XL, Vogelsang, Yuan, Zhu, 2410.16371



Understanding the NP transition in Energy Correlator, and its possible relation to the TMD.

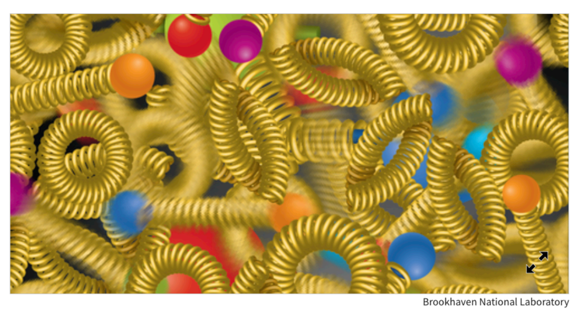
Liu, XL, Pan, Yuan, Zhu, PRL 2023



A Different Angle on the Color Glass Condensate

June 12, 2023 • *Physics* 16, s89

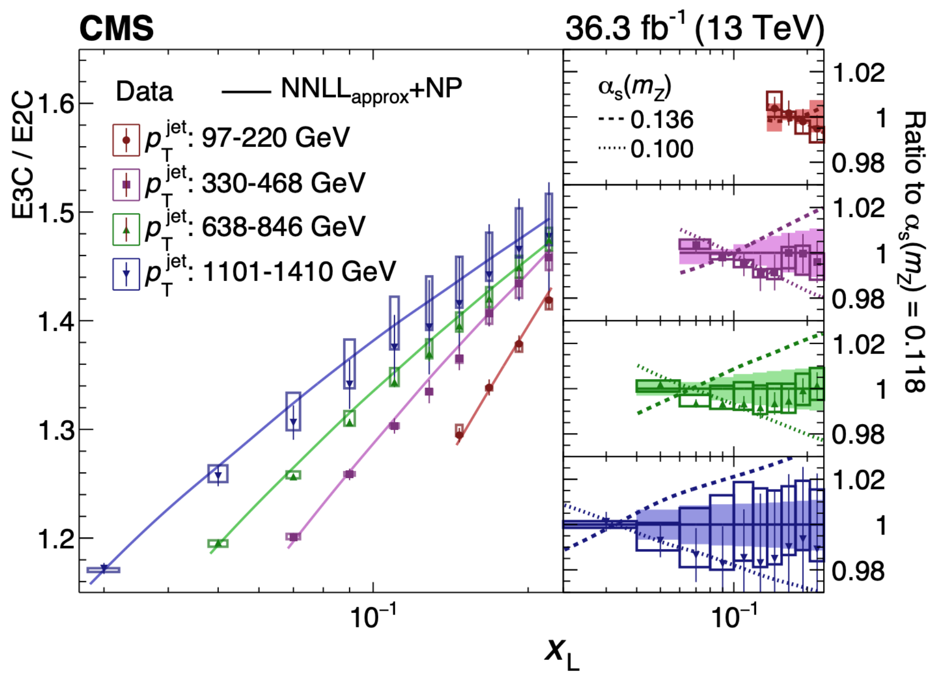
Predictions indicate that a new type of measurement at the future electron-ion collider could spot an elusive high-density regime of gluons called the color glass condensate.



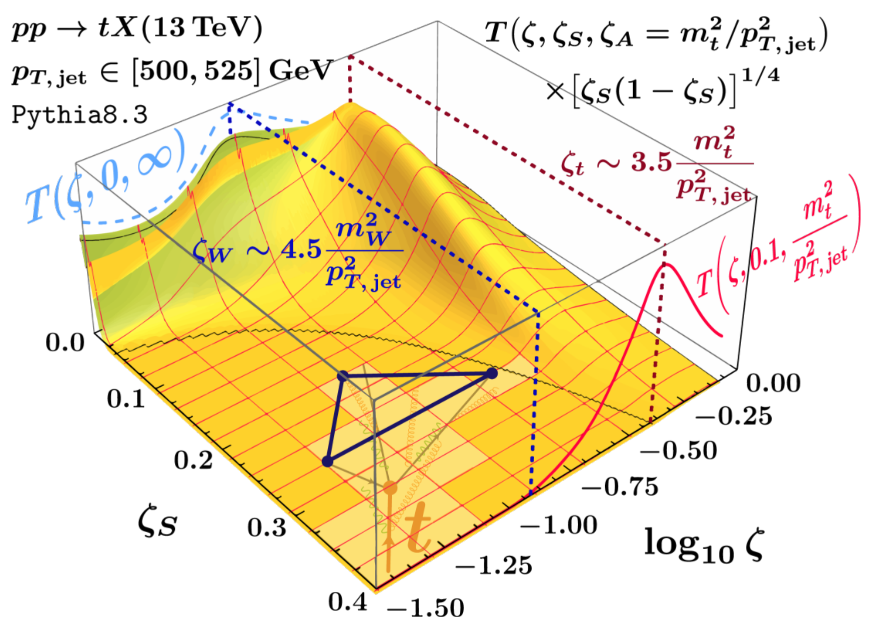
Physics

NEEC as a promising probe of the gluon saturation

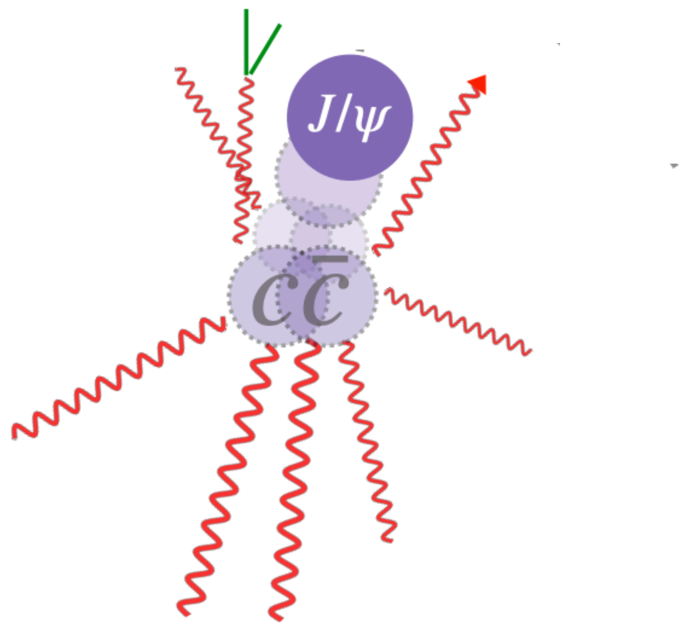
Conclusions



Scaling behavior $\Longrightarrow$ α_s extraction



Revealing scales $\Longrightarrow$ top mass determination



Extension $\Longrightarrow$ Heavy quark hadronization

Can motivate new pheno. applications/ observables for TeV and QCD/hadron physics

Thanks