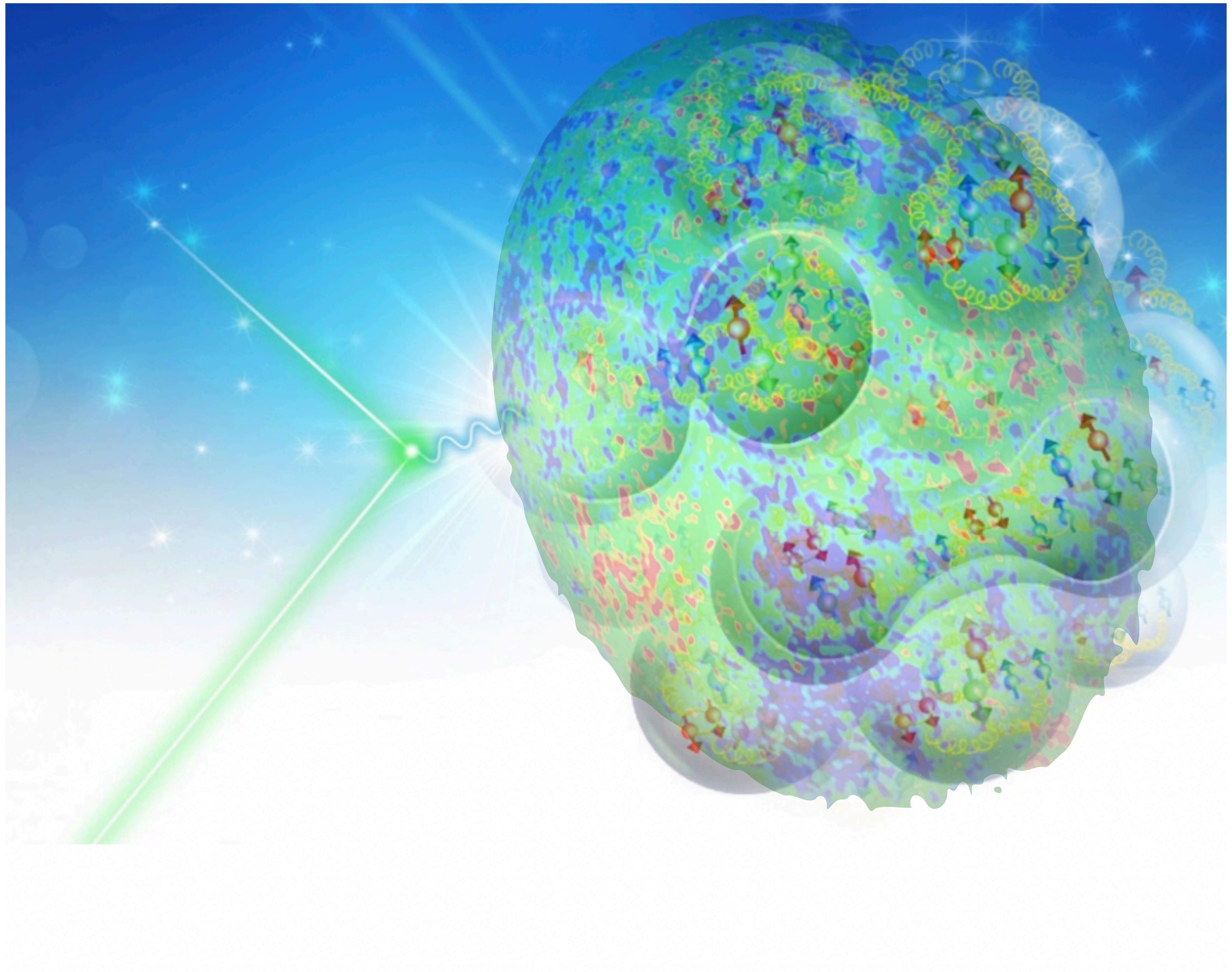


The Proton Energy-Energy Correlator

XL and Zhu, 2209.02080

Xiaohui Liu

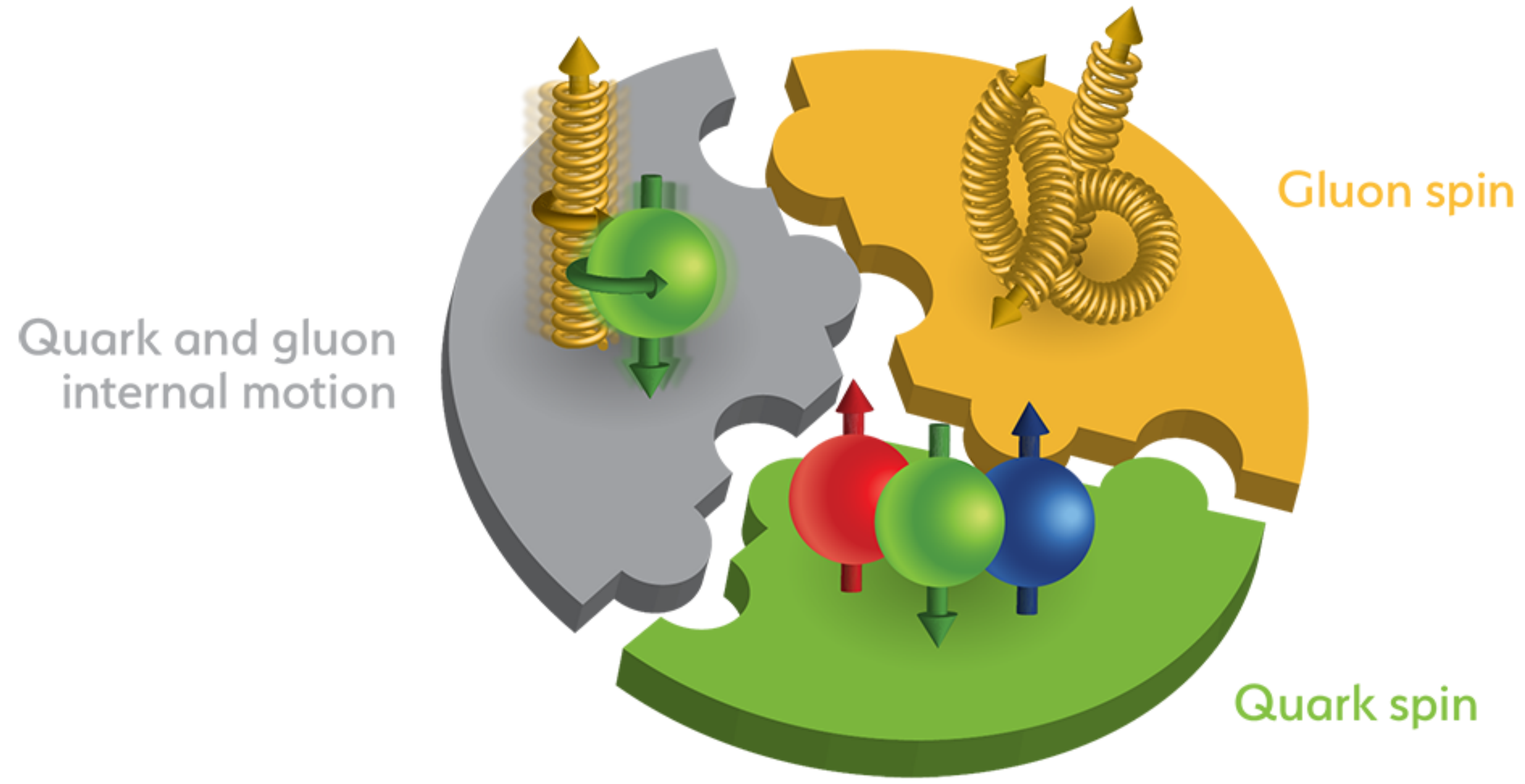
@ REF 2022

BEIJING NORMAL UNIVERSITY

Outline

- Current TMD probes
- Proton Energy Energy Correlator
  - Measurement and Theory
  - Numerical results
- Conclusion

Proton Structure

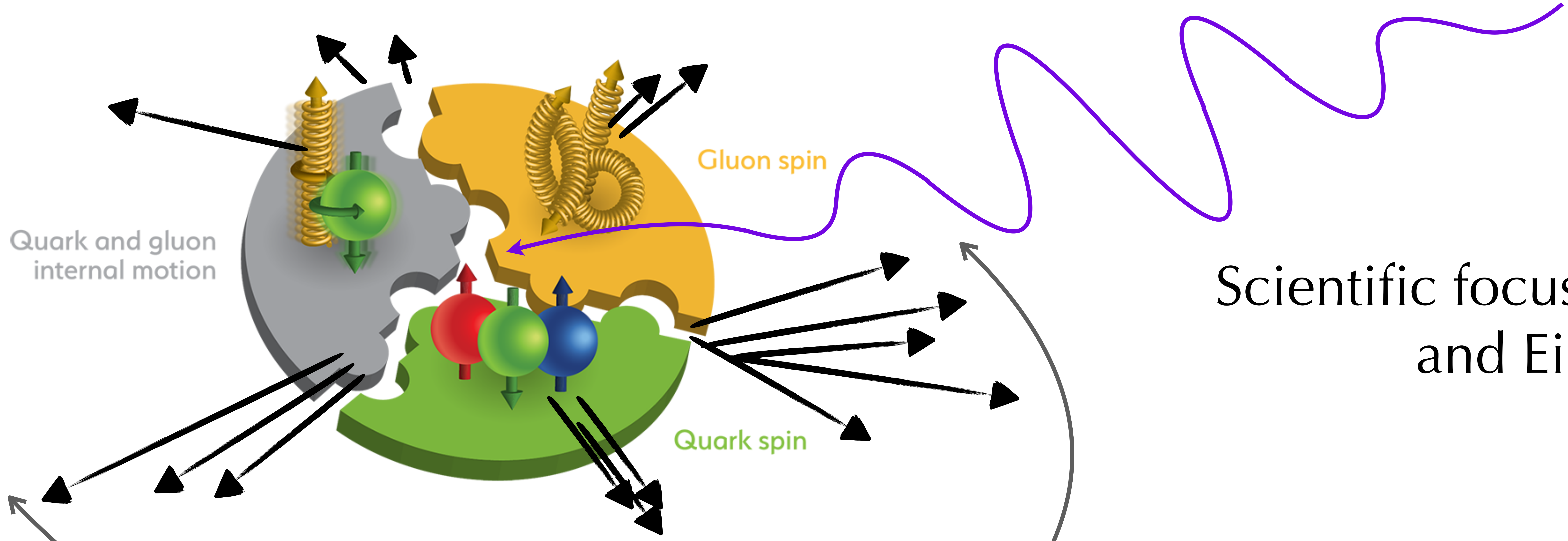


- A lot yet to answer
  - Spin components
    - 1/2 = 30% + ? + ?
  - Mass decomposition
    - proton mass ~ 1GeV, quark mass ~ keV
  - …

Transverse Momentum Dependent Parton Distribution Function (TMD PDFs)

$$f_{q/p}(x, \vec{k}_T) = \int_{-\infty}^{\infty} dy^- d^2\vec{y}_T e^{ixp^+y^-} e^{i\vec{k}_T\cdot\vec{y}_T} \langle p | \bar{\psi}(0) \frac{\gamma^+}{2} \mathscr{W}(\vec{y}_T, y^-) \psi(\vec{y}_T, y^-) | p \rangle$$

Proton Structure



Scientific focus of the EIC and EicC

$$\sigma \sim f_{q/p}(x, \vec{k}_T)$$

Current TMD probes

SIDIS $$\sigma = \hat{\sigma}(x, z)\, D(z, \vec{q}_T) \otimes f_{q/p}(x, \vec{k}_T)$$

Pro: well understood

Con: 2 non-pert objects convolution

Jet based $$\sigma = \hat{\sigma}(x, z)\, J_{wta}(q_T) \otimes f_{q/p}(x, \vec{k}_T)$$

Pro: Theoretically cleaner

Flexibility

Con:clustering, low energy machine? Spin structures? convolution

Current TMD probes

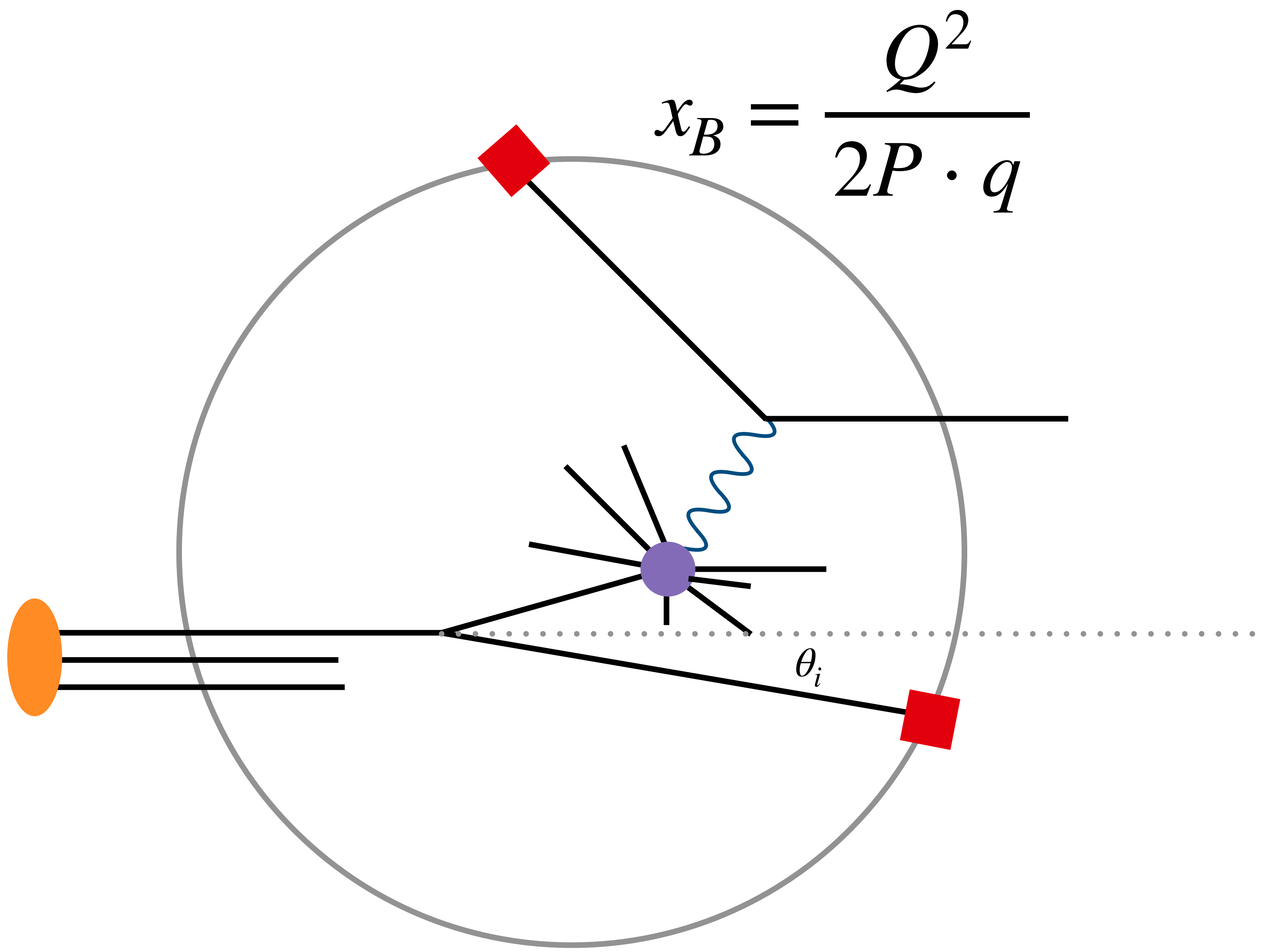
SIDIS

Jet based

Final state correlations

Indirect probe of the nucleon microscopic structures through TMDs

Proton Energy Energy Correlator



$$\frac{d\Sigma(\theta, N)}{d\theta} = \sum_i \int x_B^{N-1} \frac{E_i}{P} \frac{d\sigma(x_B, p_i)}{\sigma_{tot}} \delta(\theta - \theta_i)$$

- Full inclusive measurement, no clustering, weighted by x_B^{N-1} and E_i
- $N > 1$
- i will include the beam remnants when θ is small enough. Break the proton, and re-collect at a certain θ.

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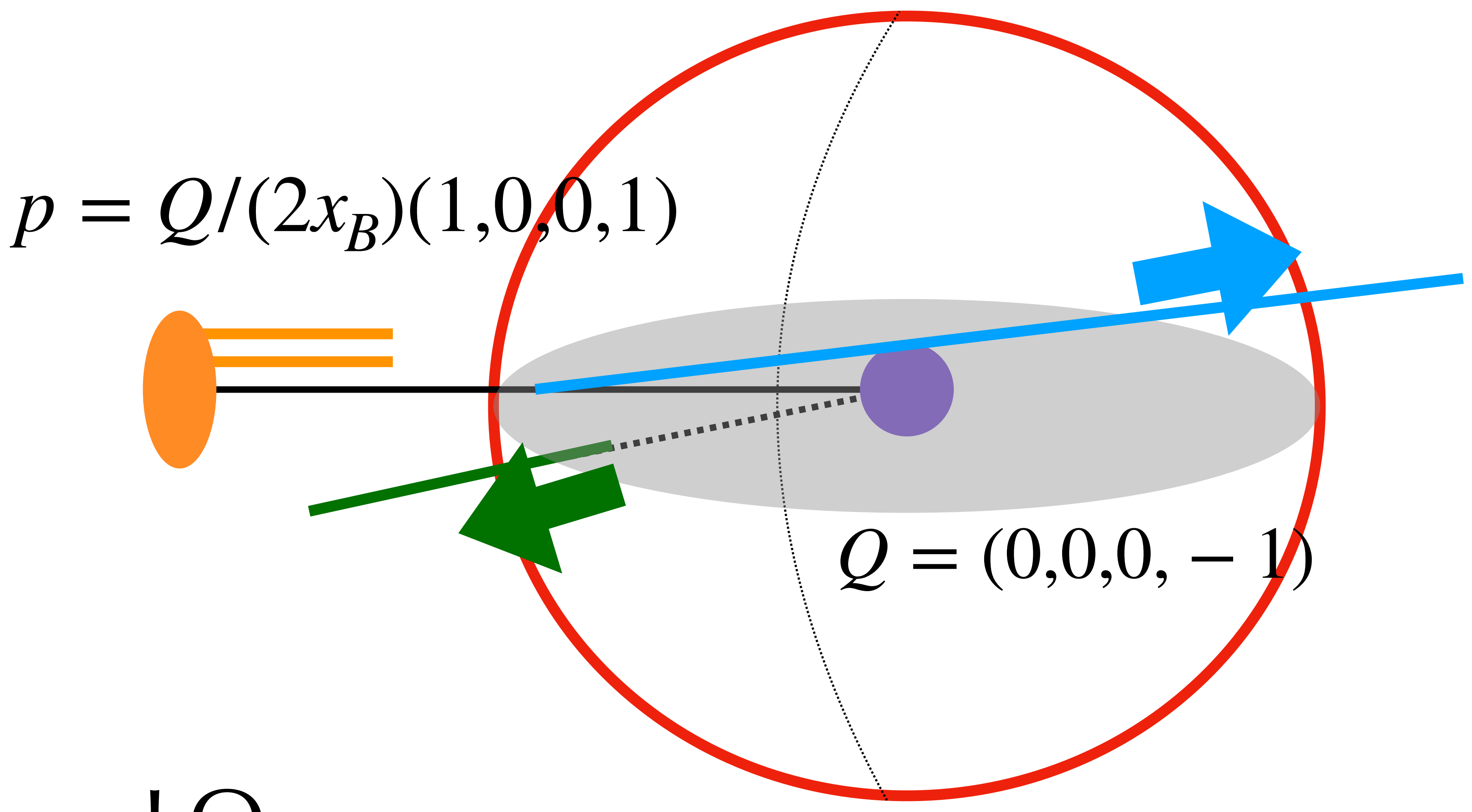
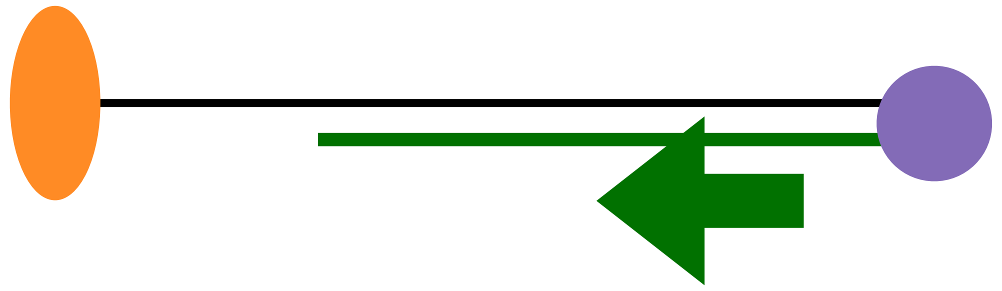
Proton Energy Energy Correlator

Breit frame



LO



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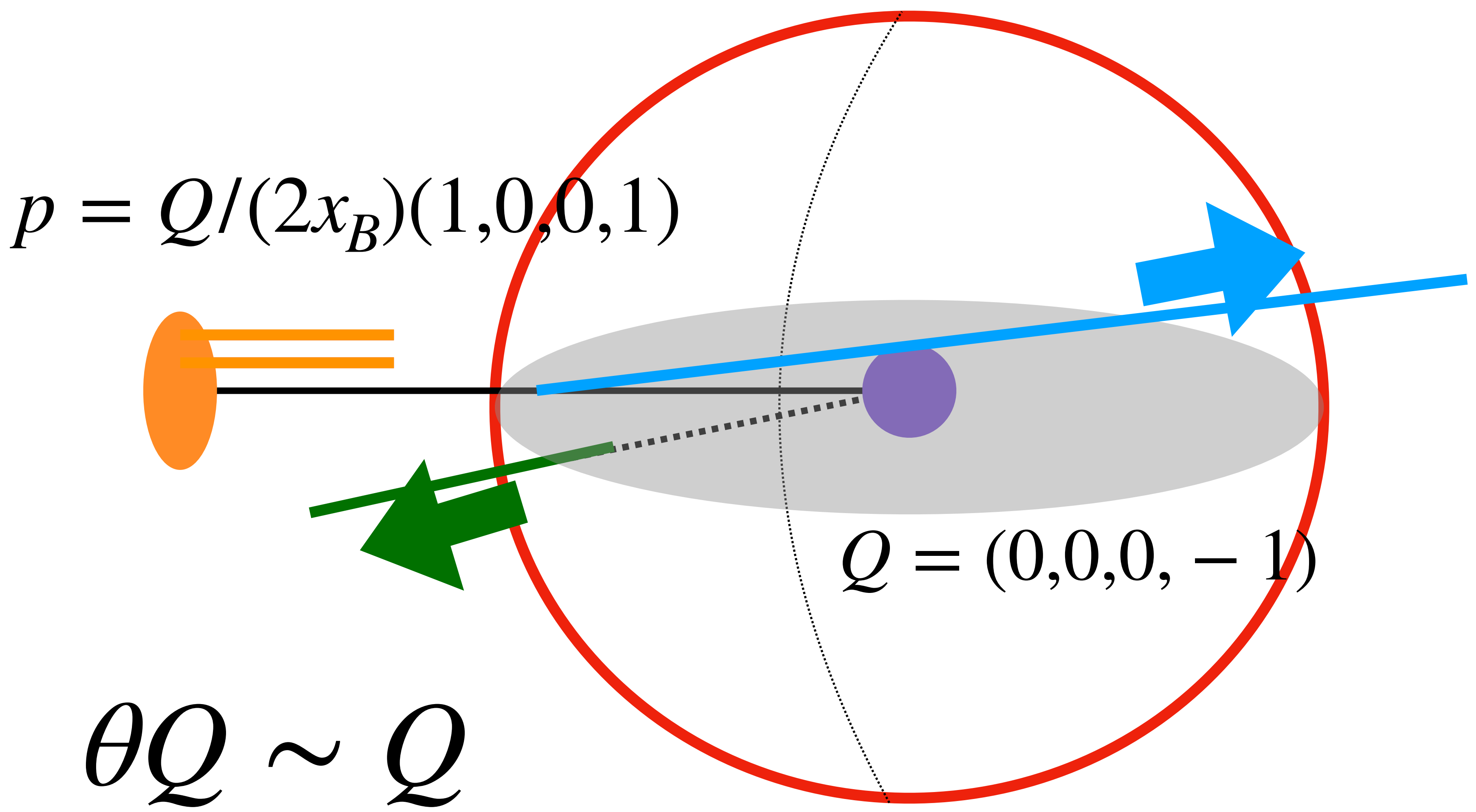

$$\theta Q \sim Q$$

$$\frac{d\Sigma(\theta, N)}{d\theta} = \sum_i \int x_B^{N-1} \frac{E_i}{P} \frac{d\sigma(x_B, p_i)}{\sigma_{tot}} \delta(\theta - \theta_i)$$

- Collinear factorization if θ is not too close to π, calculable perturbatively

$$d\hat{\sigma}(x_B, p_i) = \int d\hat{\sigma}_j(z, p_i, \xi) f_{j/P}(\xi, Q) \delta(\xi z - x_B)$$

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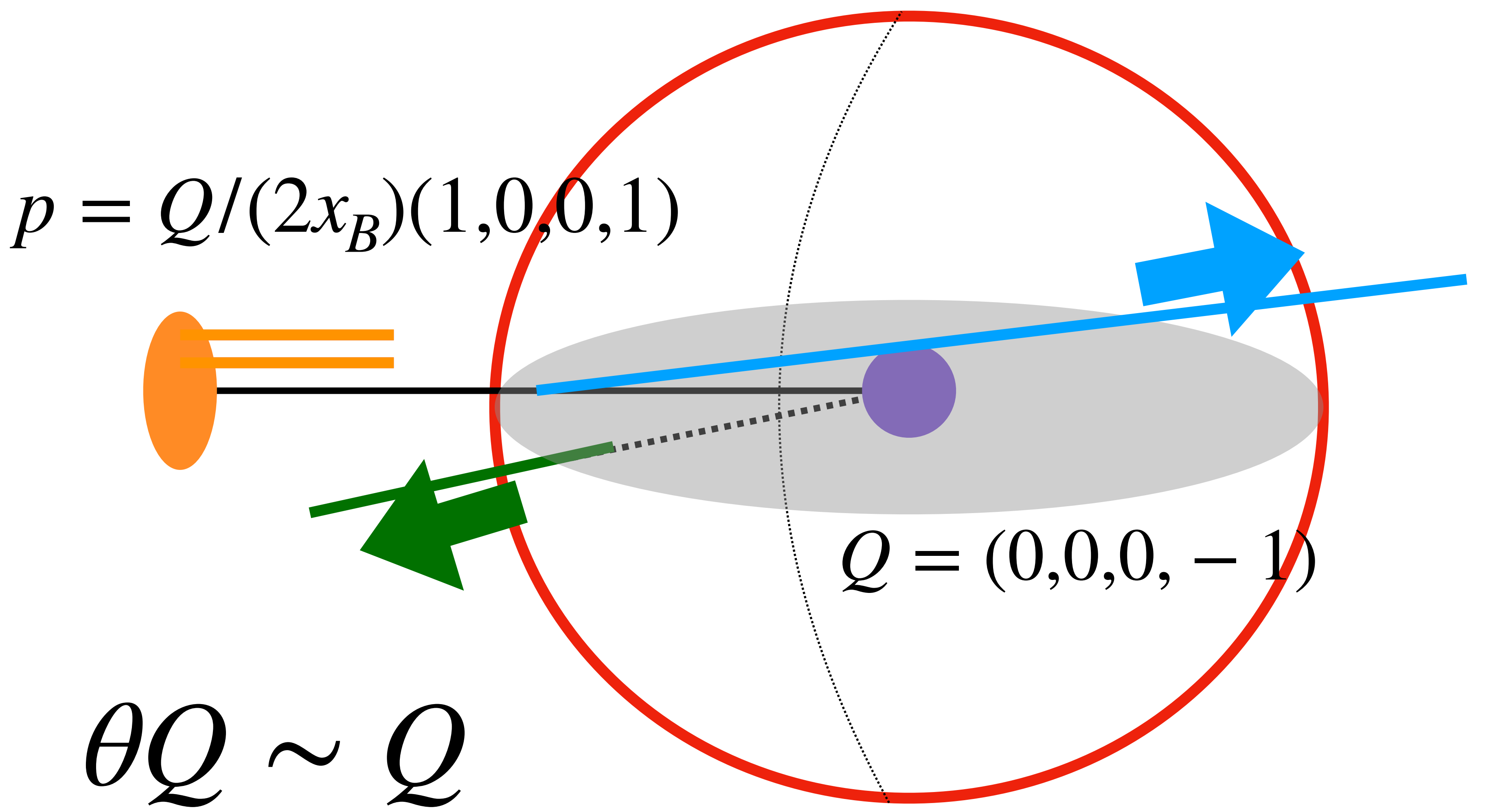
Proton Energy Energy Correlator

Breit frame



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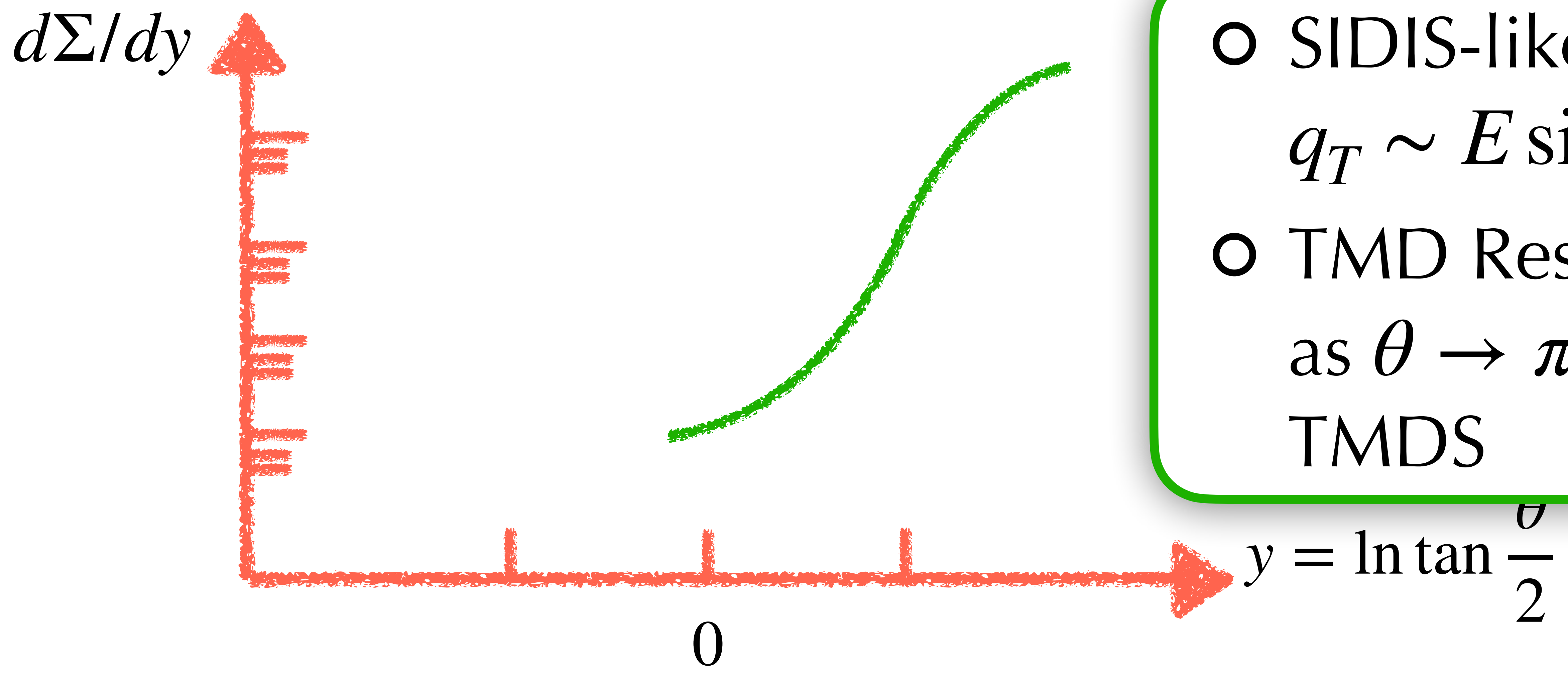

- SIDIS-like distribution, $q_T \sim E\sin\theta$
- TMD Resummatoin required as $\theta \to \pi$, able to probe TMDS

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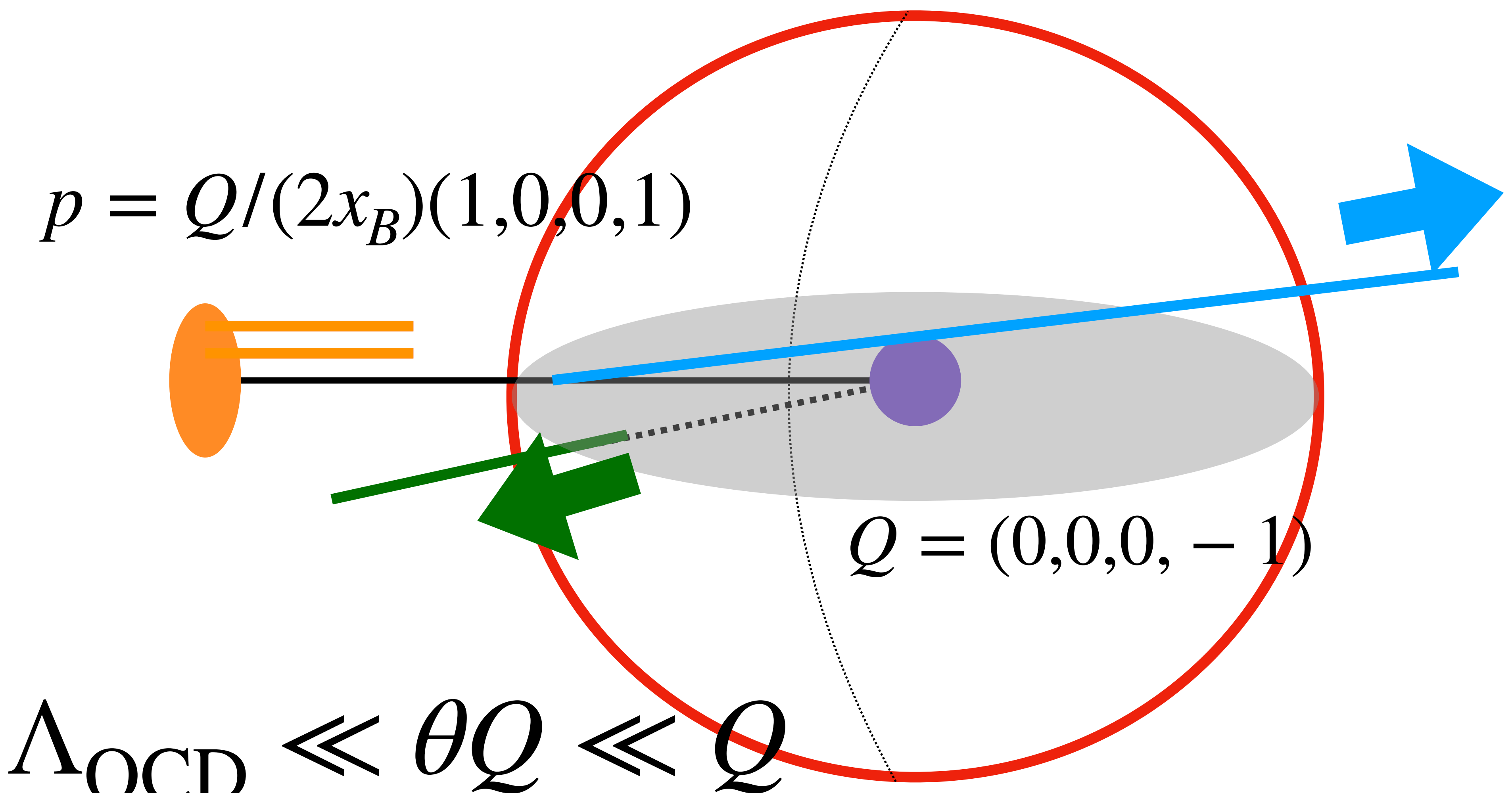
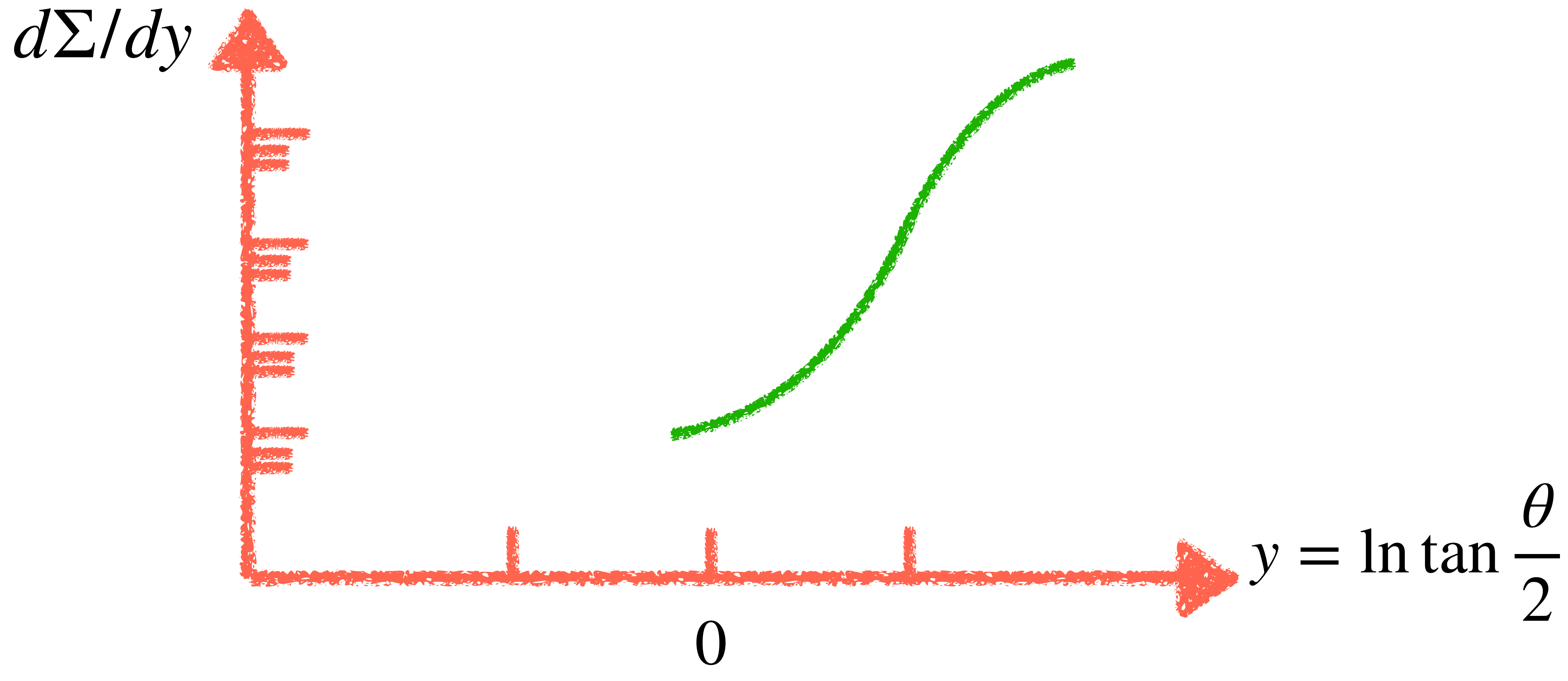
Proton Energy Energy Correlator

Breit frame



$\Lambda_{\text{QCD}} \ll \theta Q \ll Q$



$$\frac{d\Sigma(\theta, N)}{d\theta} = \sum_i \int x_B^{N-1} \frac{E_i}{P} \frac{d\sigma(x_B, p_i)}{\sigma_{tot}} \delta(\theta - \theta_i)$$

- Perturbative collinear ISR enters the detector; contributions from the radiations due to the hard interaction are power suppressed, beam remnants are mainly untouched

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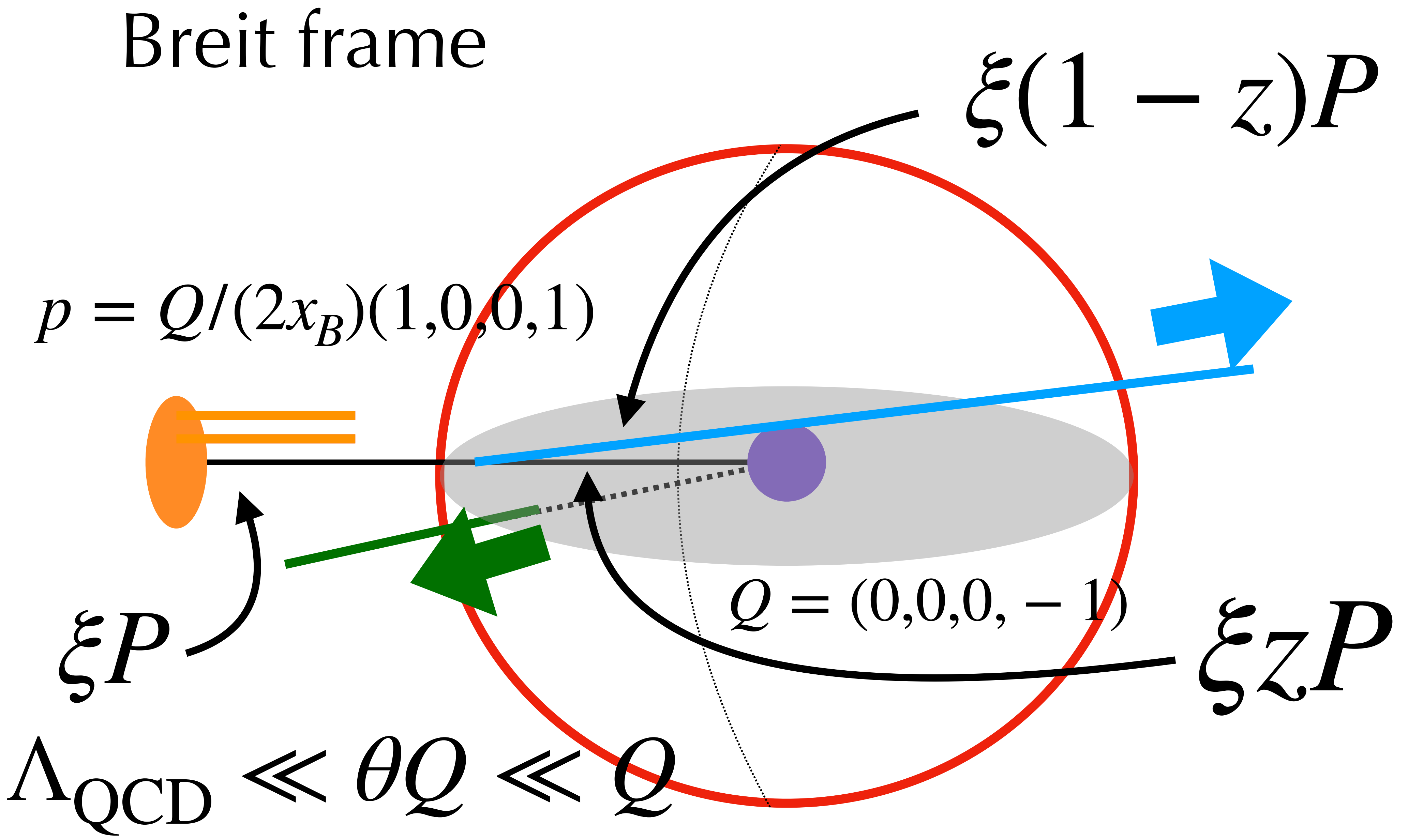
Proton Energy Energy Correlator



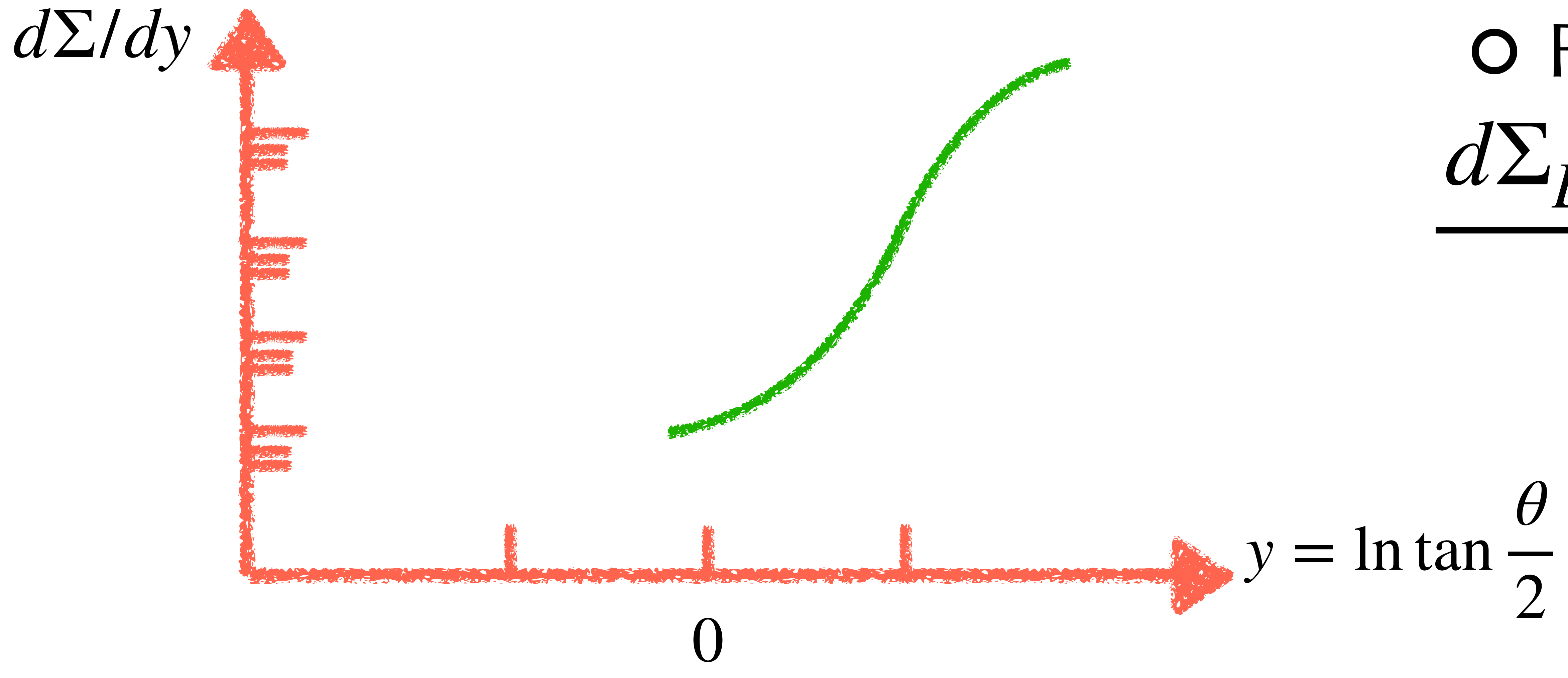
$$\frac{d\Sigma(\theta, N)}{d\theta} = \sum_i \int x_B^{N-1} \frac{E_i}{P} \frac{d\sigma(x_B, p_i)}{\sigma_{tot}} \delta(\theta - \theta_i)$$

- Perturbative collinear ISR enters the detector; contributions from the radiations due to the hard interaction are power suppressed, beam remnants are mainly untouched

- Factorized form

$$\frac{d\Sigma_{LO}(\theta, N)}{d\theta} = \int (\xi z)^{N-1} \xi(1-z) \frac{d\hat{\sigma}_{DIS}}{\sigma_{tot}} \frac{2}{\theta} P(z) f(\xi)$$

$$= \frac{2}{\theta} \frac{d\hat{\sigma}_{DIS}}{\sigma_{tot}} (P(N) - P(N+1)) f(N+1)$$



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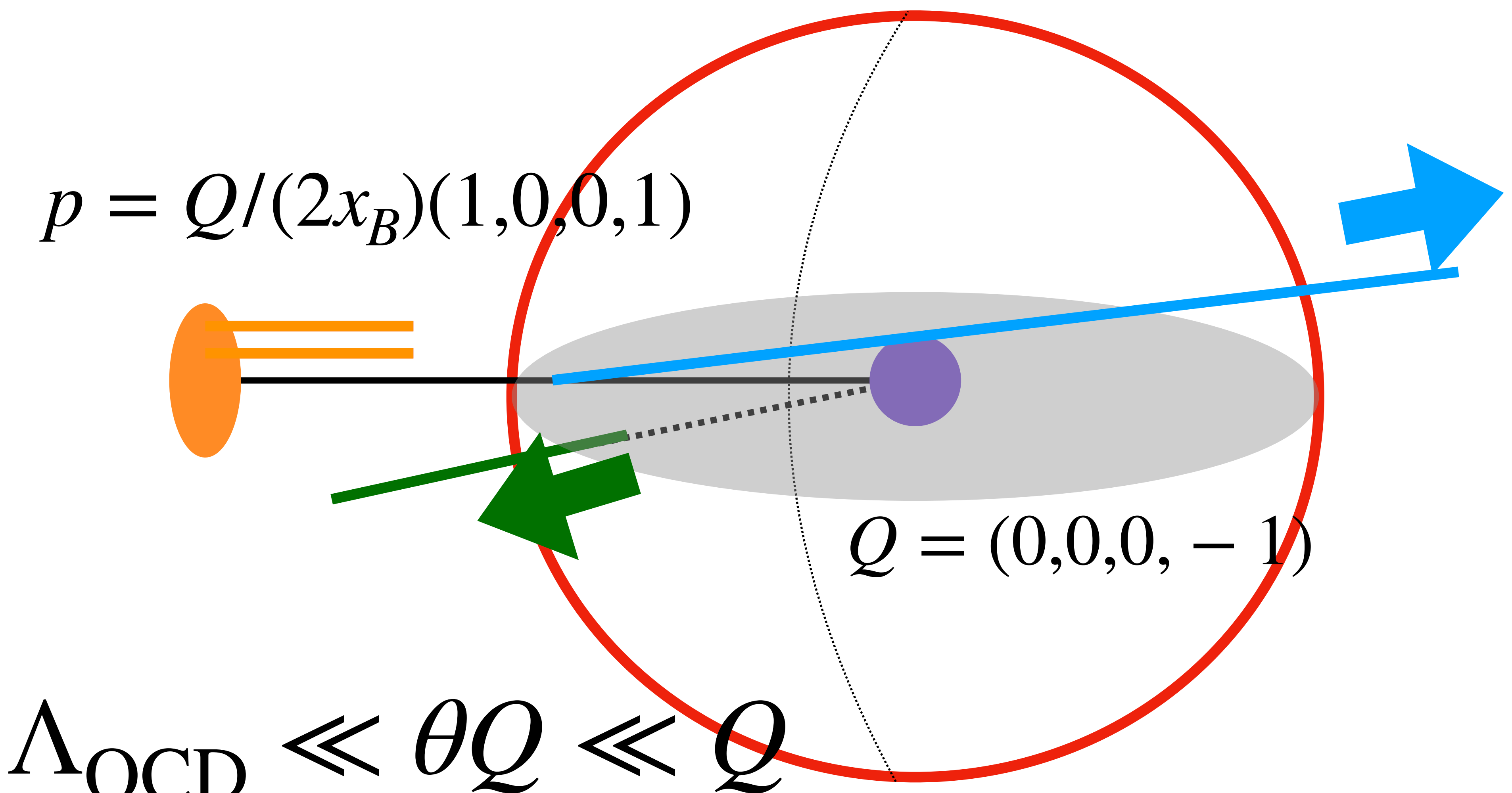
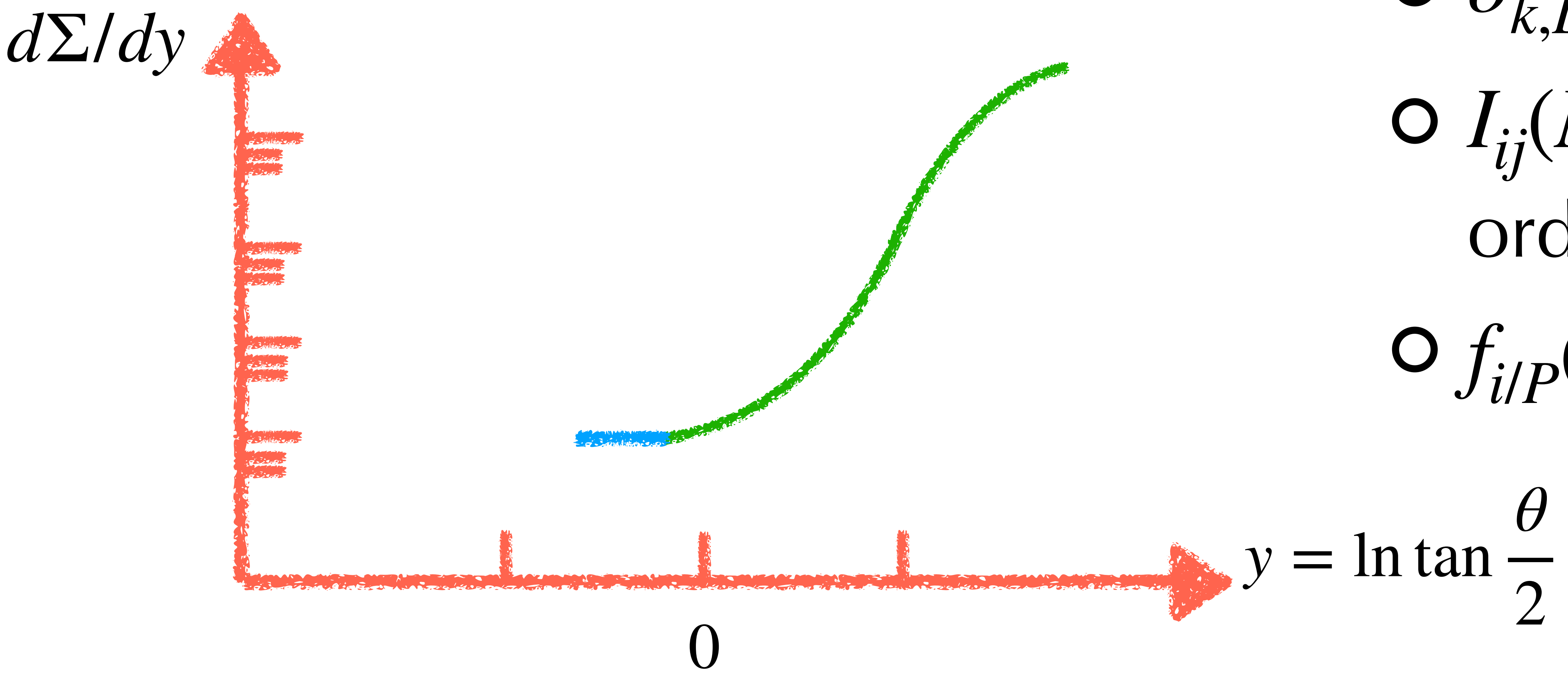


$\Lambda_{\rm QCD} \ll \theta Q \ll Q$



$$\theta\frac{d\Sigma(\theta,N)}{d\theta} = \frac{\hat{\sigma}_{i,DIS}(N,Q^2)}{\sigma_{tot}} \times \left(I_{ij}(N,N+1) + \text{Running coupling effects, scaling law mixing} \right) f_{j/P}(N+1)$$

$$\sim_{LL} \theta\frac{d}{d\theta}\left(e^{-\frac{2P(N)}{\beta_0}L} e^{\frac{2P(N+1)}{\beta_0}L}\right)_{ij}, L = \ln\frac{\alpha_s(Q\theta)}{\alpha_s(Q)}$$

- $\hat{\sigma}_{k,DIS}(N,\mu)$: moment of partonic DIS x-sec.
- $I_{ij}(N)$: contains moments of the splitting functions to all orders
- $f_{i/P}(N)$: moment of collinear PDF

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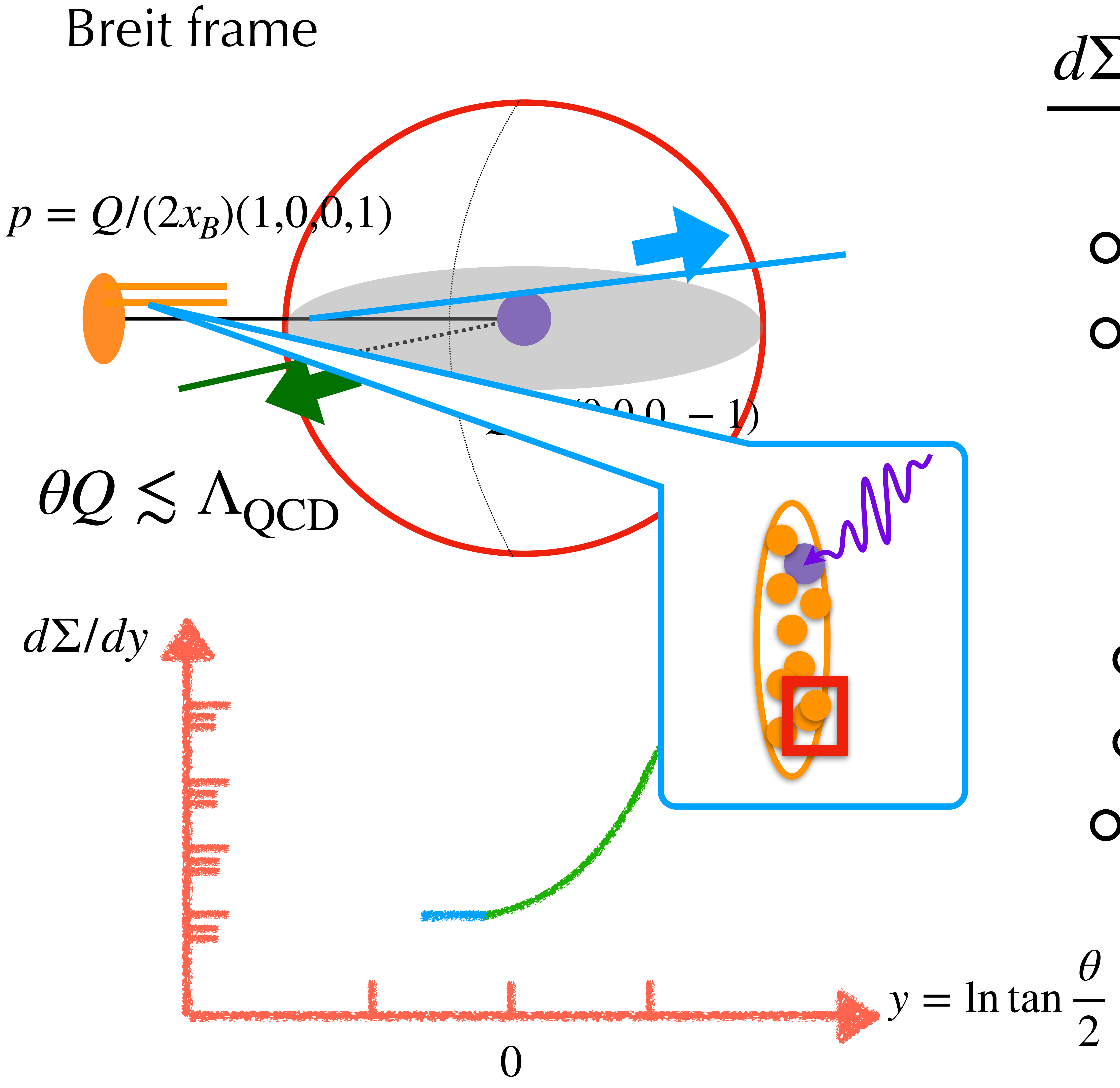
Proton Energy Energy Correlator



$$\frac{d\Sigma(\theta, N)}{d\theta} = \sum_{k=q,g} f_{k,\mathrm{EEC}}(N,\theta,\mu)\frac{\hat\sigma_{k,DIS}(N,\mu)}{\sigma_0}$$

- Beam remnants contribute
- $f_{k,\mathrm{EEC}}(N,\theta,\mu)$: Proton EEC, a new non-pert. object, initial-final correlation

$$f_{EEC}(\theta) = \sum_i \frac{1}{P^N}\langle P\,|\,\bar\psi(0)\,\bar{\mathscr{E}}^{N-1}\mathscr{E}(\theta)\,\psi(\vec{x}_T, x^-)\,|\,P\rangle$$

- Detect the angular distribution of the partons
- Evolves like the PDF, no sudakov suppression
- Product form instead of convolution, nothing else, no clustering, no fragmentation …

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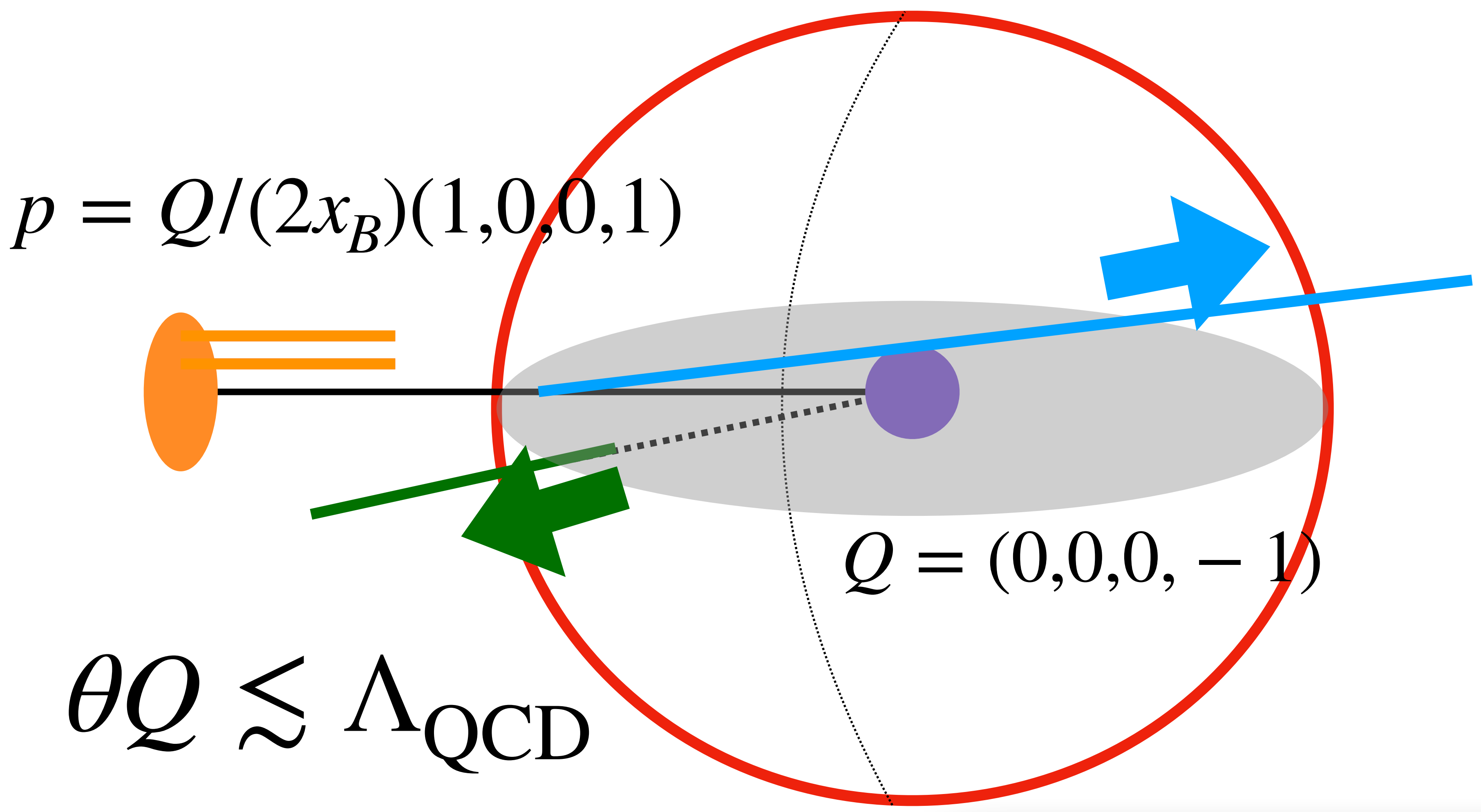
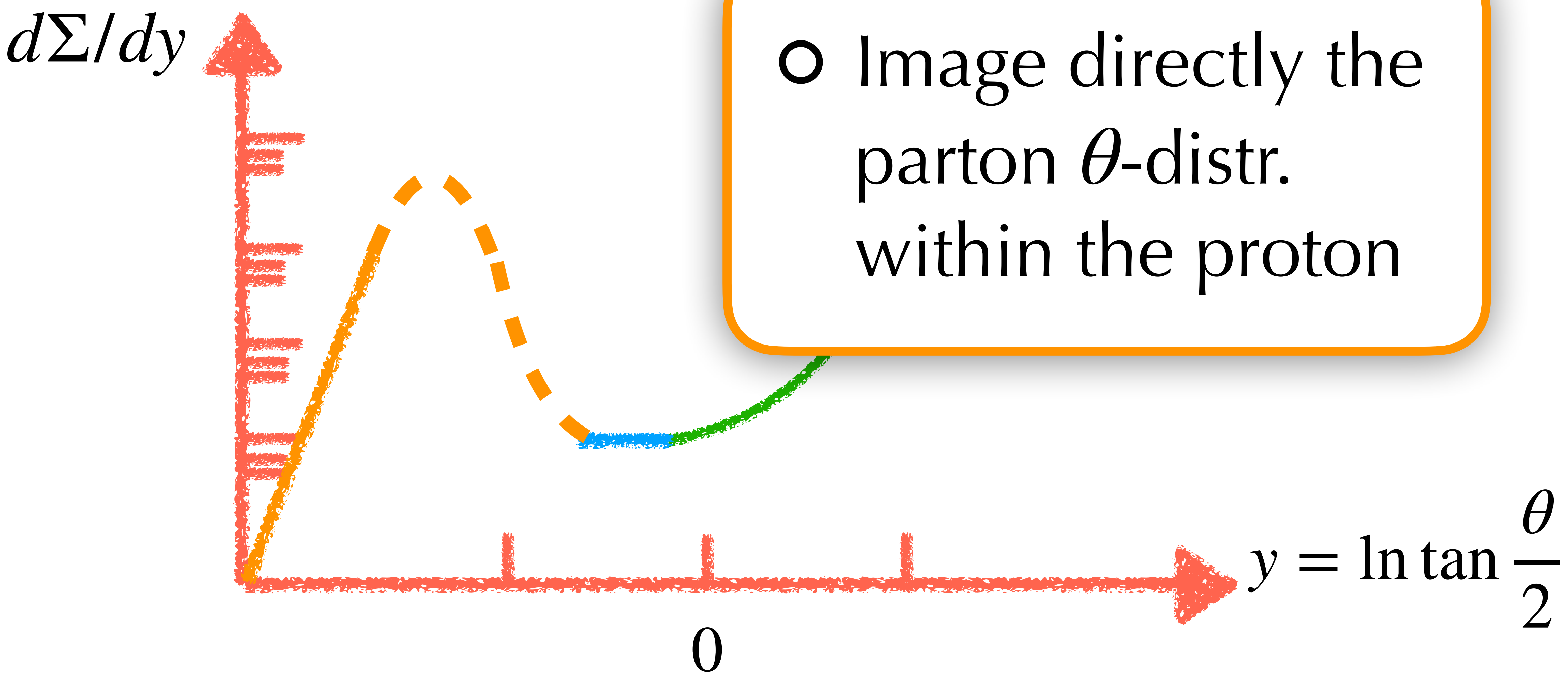
Proton Energy Energy Correlator

Breit frame



$\theta Q \lesssim \Lambda_{\rm QCD}$



- Image directly the parton θ-distr. within the proton

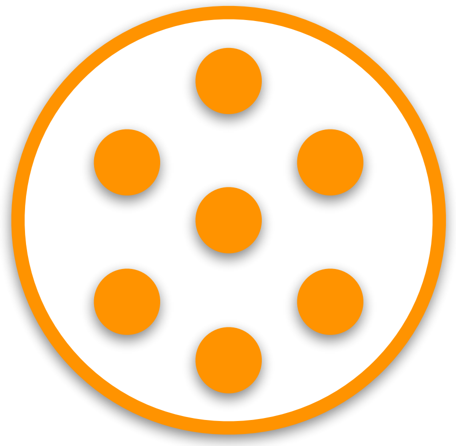
$$\frac{d\Sigma(\theta,N)}{d\theta} = \sum_{k=q,g} f_{k,\rm EEC}(N,\theta,\mu)\frac{\hat{\sigma}_{k,DIS}(N,\mu)}{\sigma_0}$$

- Beam remnants contribute
- $f_{k,\rm EEC}(N,\theta,\mu)$: Proton EEC, a new non-pert. object, initial-final correlation

$$f_{EEC}(\theta) = \sum_i \frac{1}{P^N}\langle P|\bar{\psi}(0)\,\bar{\mathscr{E}}^{N-1}\mathscr{E}(\theta)\,\psi(\vec{x}_T,x^-)|P\rangle$$

- Detect the angular distribution of the partons

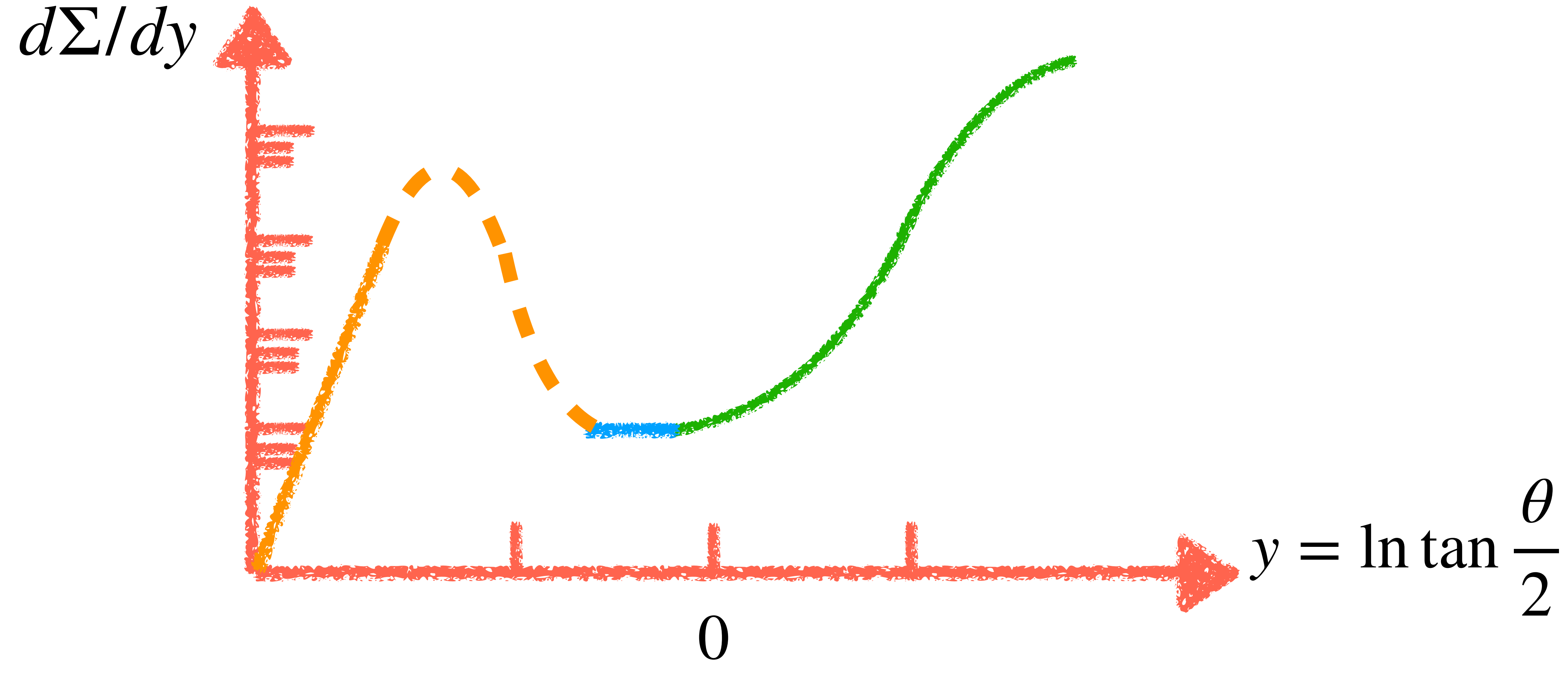
$\theta Q \ll \Lambda_{QCD}$ Uniformly distributed free hadron gas



$$\theta\frac{d\Sigma(\theta,N)}{d\theta} \propto \theta\frac{d}{d\theta}\frac{a}{\pi(\tilde{P}\theta)^2} \sim \frac{1}{\theta^2} \sim e^{2y}$$

Proton Energy Energy Correlator

Theoretically clean behavior



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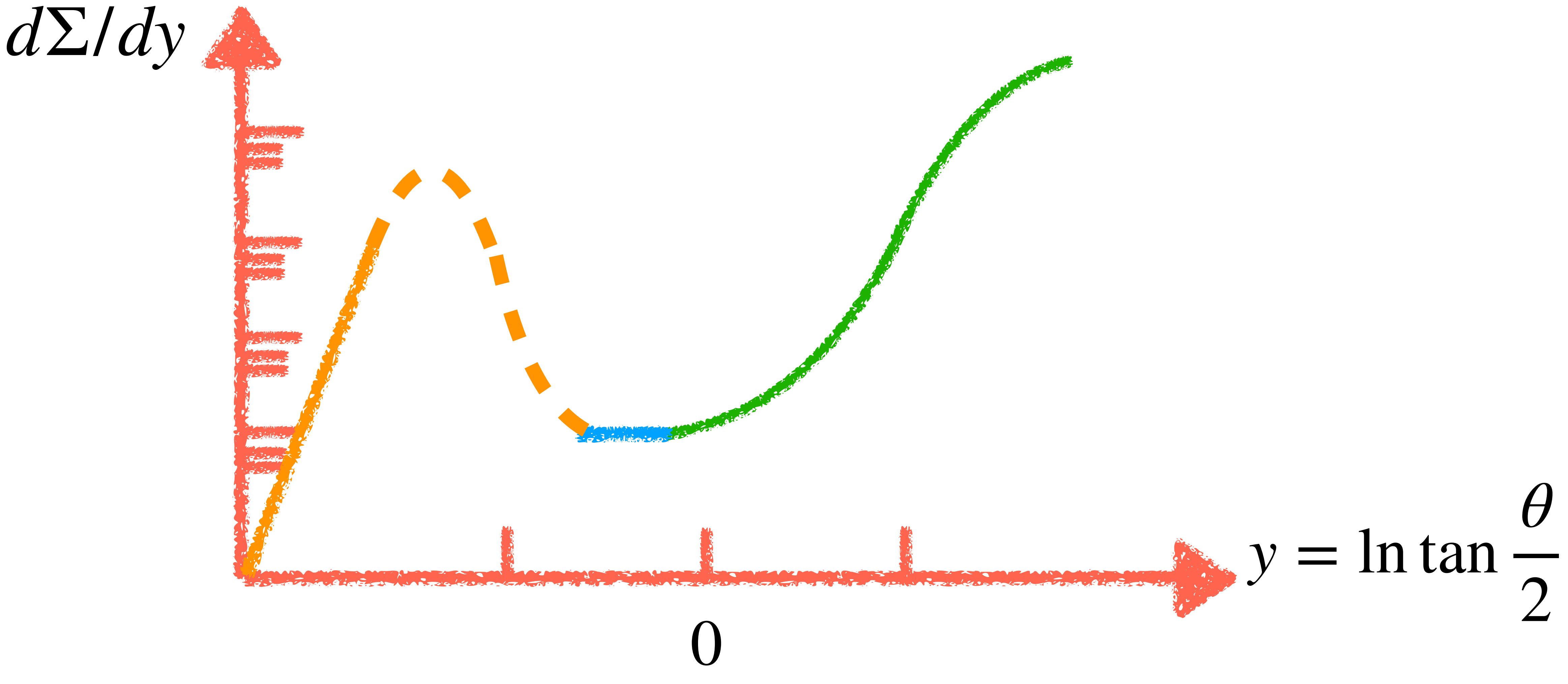

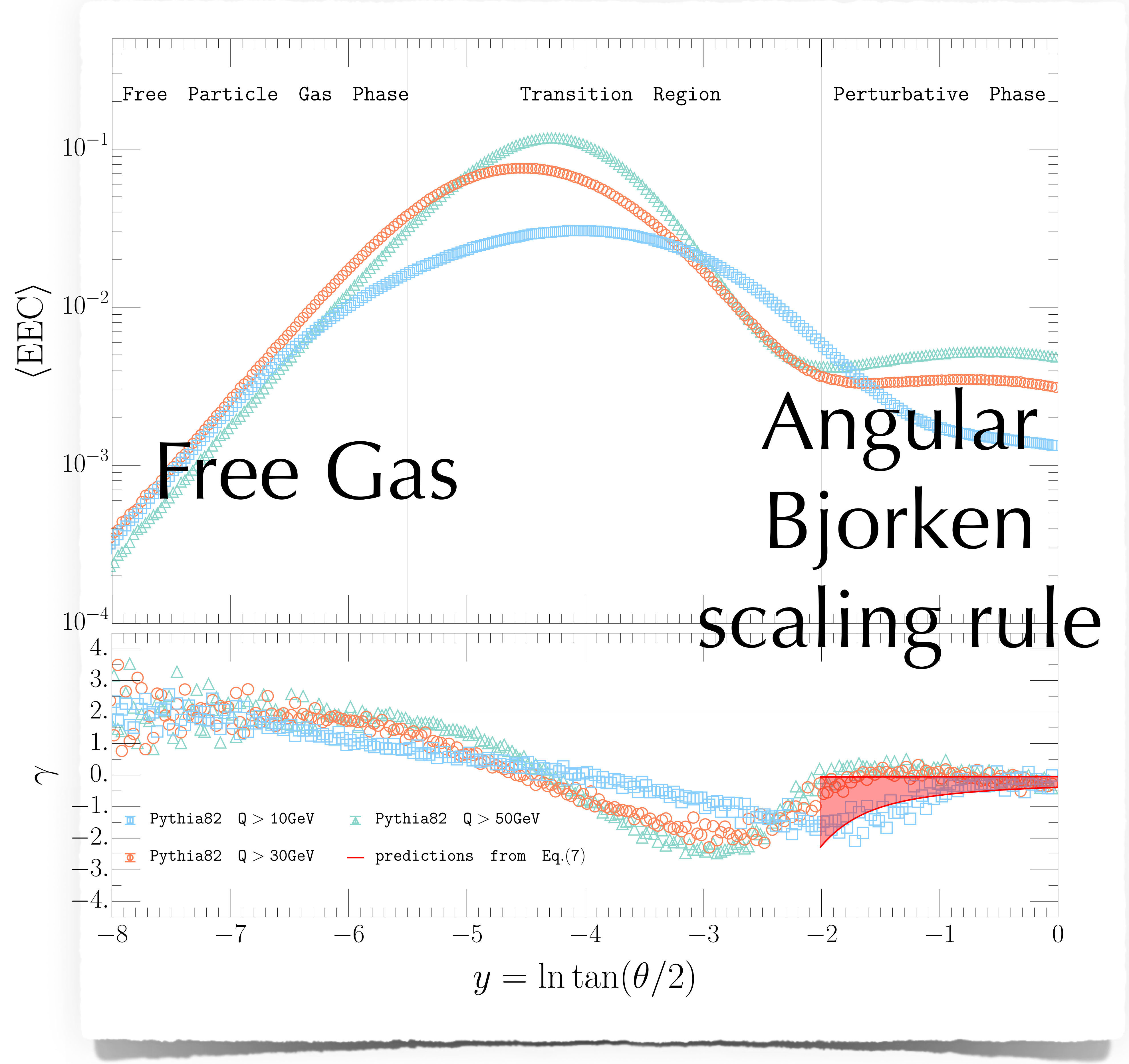

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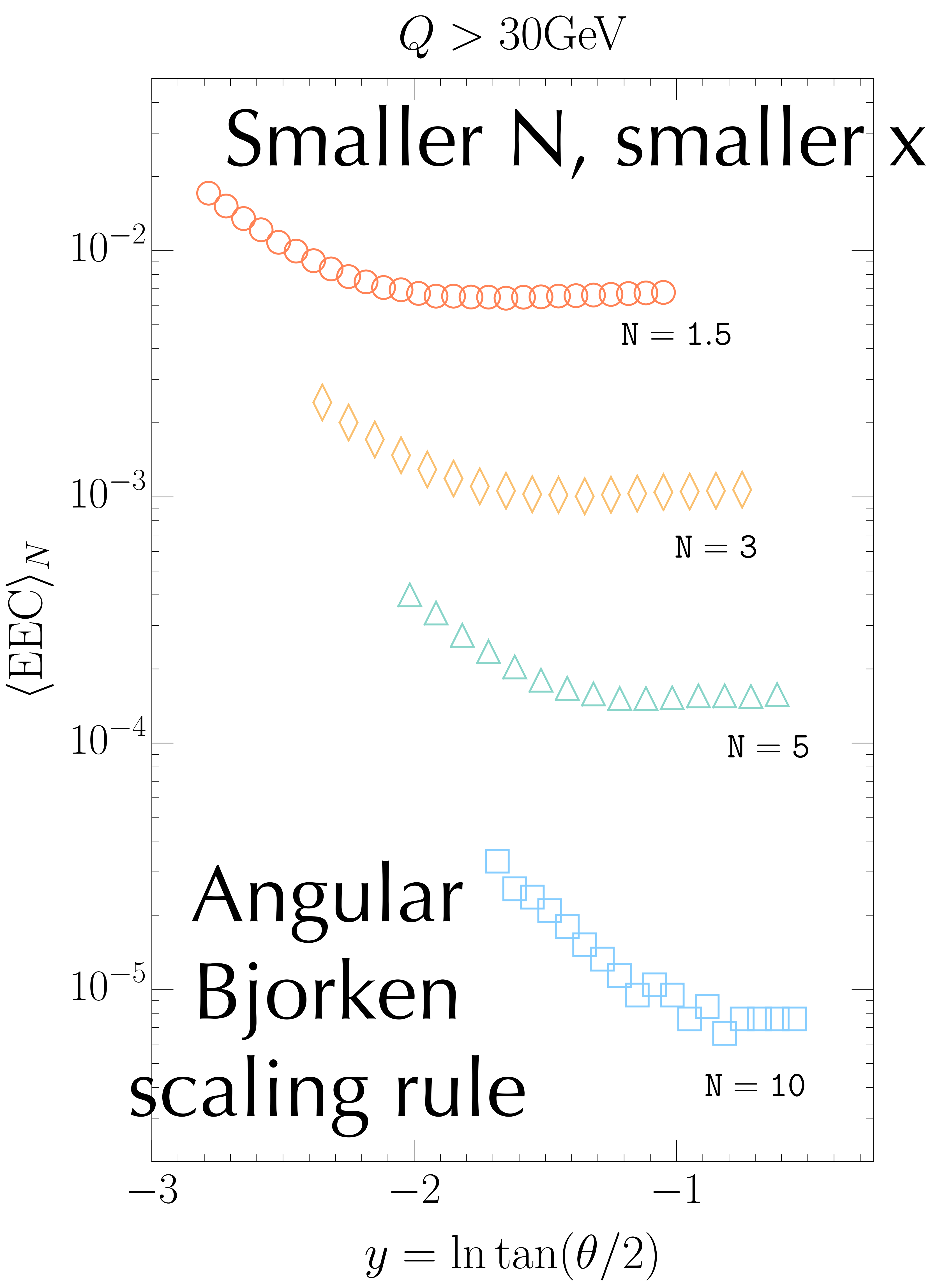

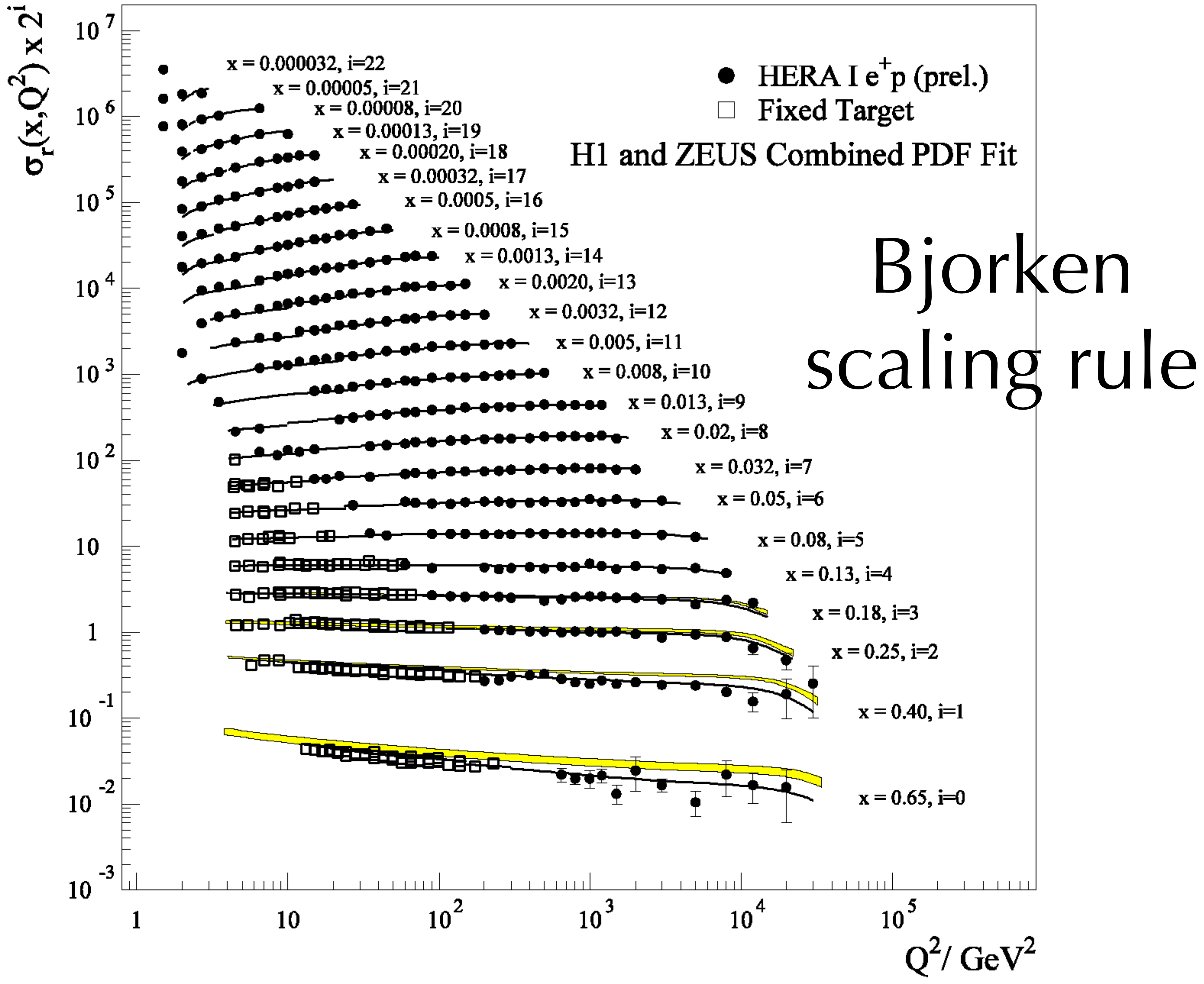

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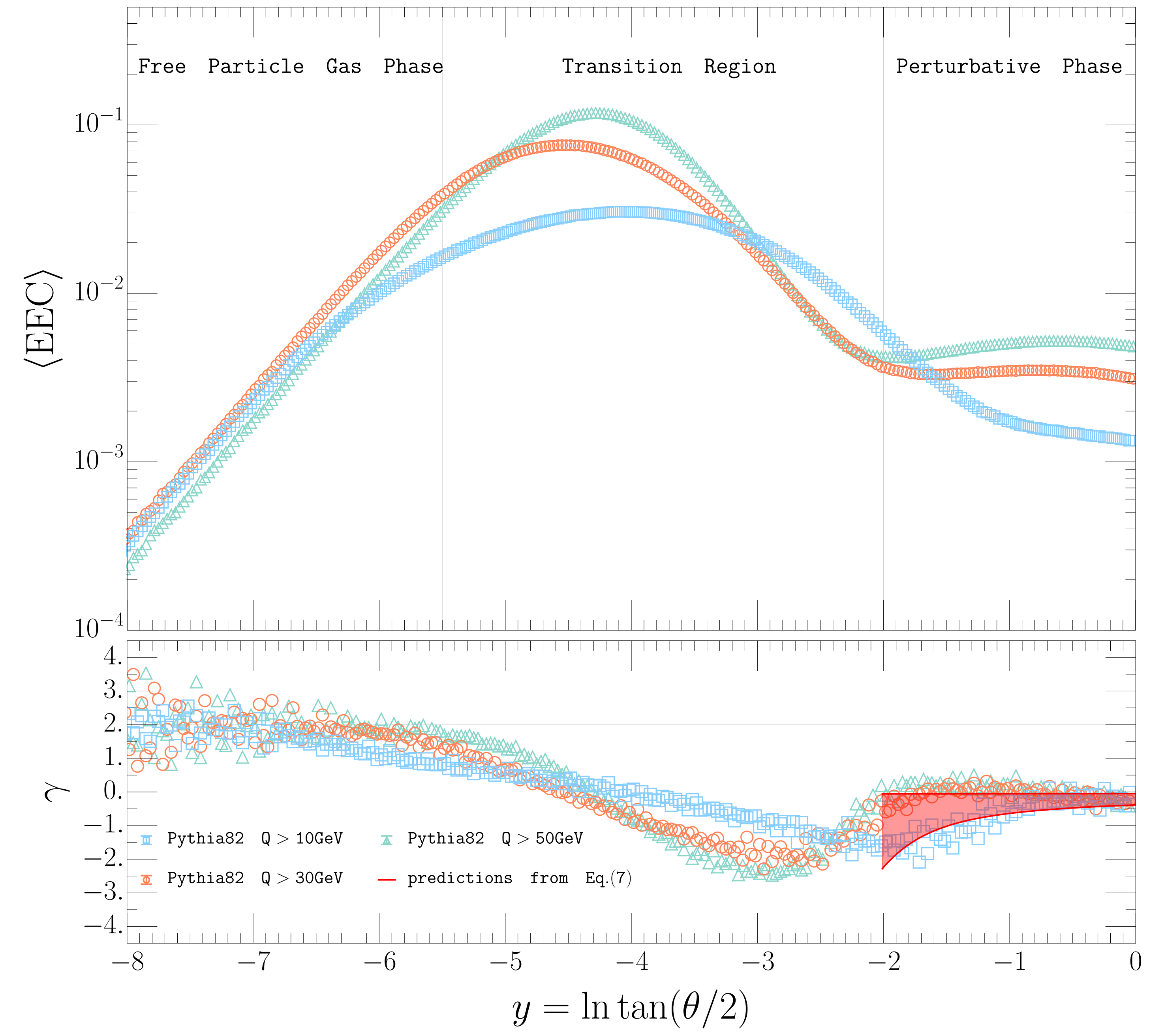
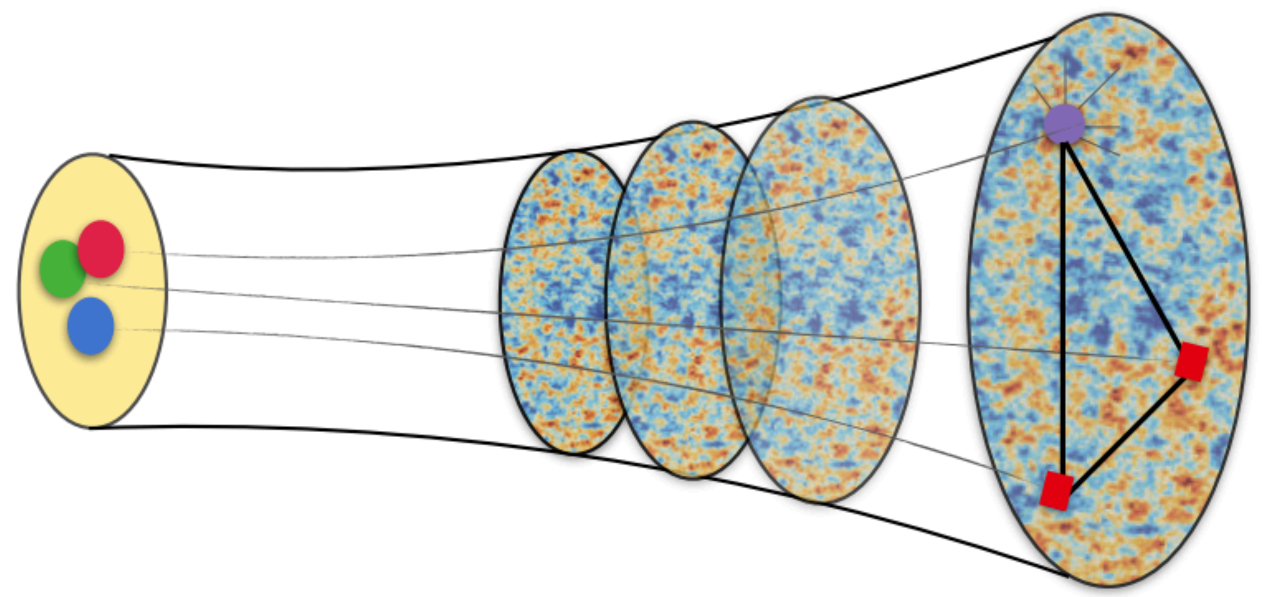
Conclusion

- Probe of the partonic angular structure
- Extremely clean, all ingredients known for at least NNLL
- Straightforward to generalize to spin by adding ϕ of the detector
- Small-x, medium effect modify the slope (slope fully determined by vacuum splitting kernel)
- Generalize to multiple correlators





Thanks