One Point Charge Correlator

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2605.15280 + work with Wanchen and Dingyu

Outline

- Hadron probe/Fragmentation
- Observables（Detectors）
  - Energy flow/Correlators
  - OPCC and Transverse Charge Distribution
- Phenomenology
- Conclusion

Hadron probe/Fragmentation

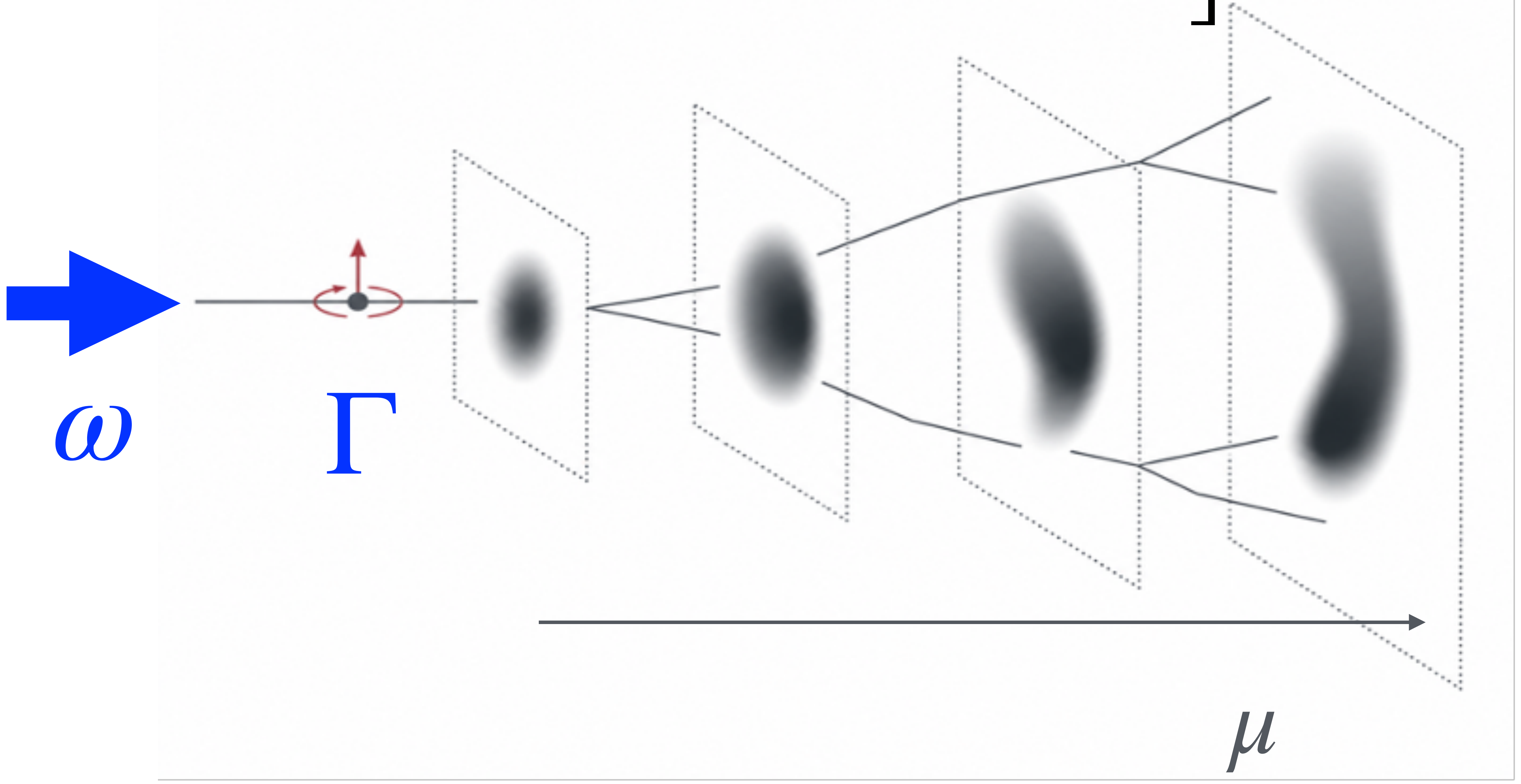
- A portal to hadronization
- An important probe
- Fragmentation functions (FFs)

e.g.,

$$d_{h/i}(z,\vec{p}_T) = \int \frac{d\xi d^2\vec{x}_T}{2z(2\pi)^3} e^{i\omega\xi}\,\mathrm{Tr}\left[\frac{\Gamma}{2}\langle 0|\psi(\xi,x_T)\sum\!\!\!\!\!\!\int_{X'}|h(z\omega,\vec{p}_T)X',\mathrm{out}\rangle\langle h(z\omega,\vec{p}_T)X',\mathrm{out}|\bar{\psi}(0)|0\rangle\right]$$

hadron distribution of fragmentation

$$|0\rangle \to |hX'\rangle$$



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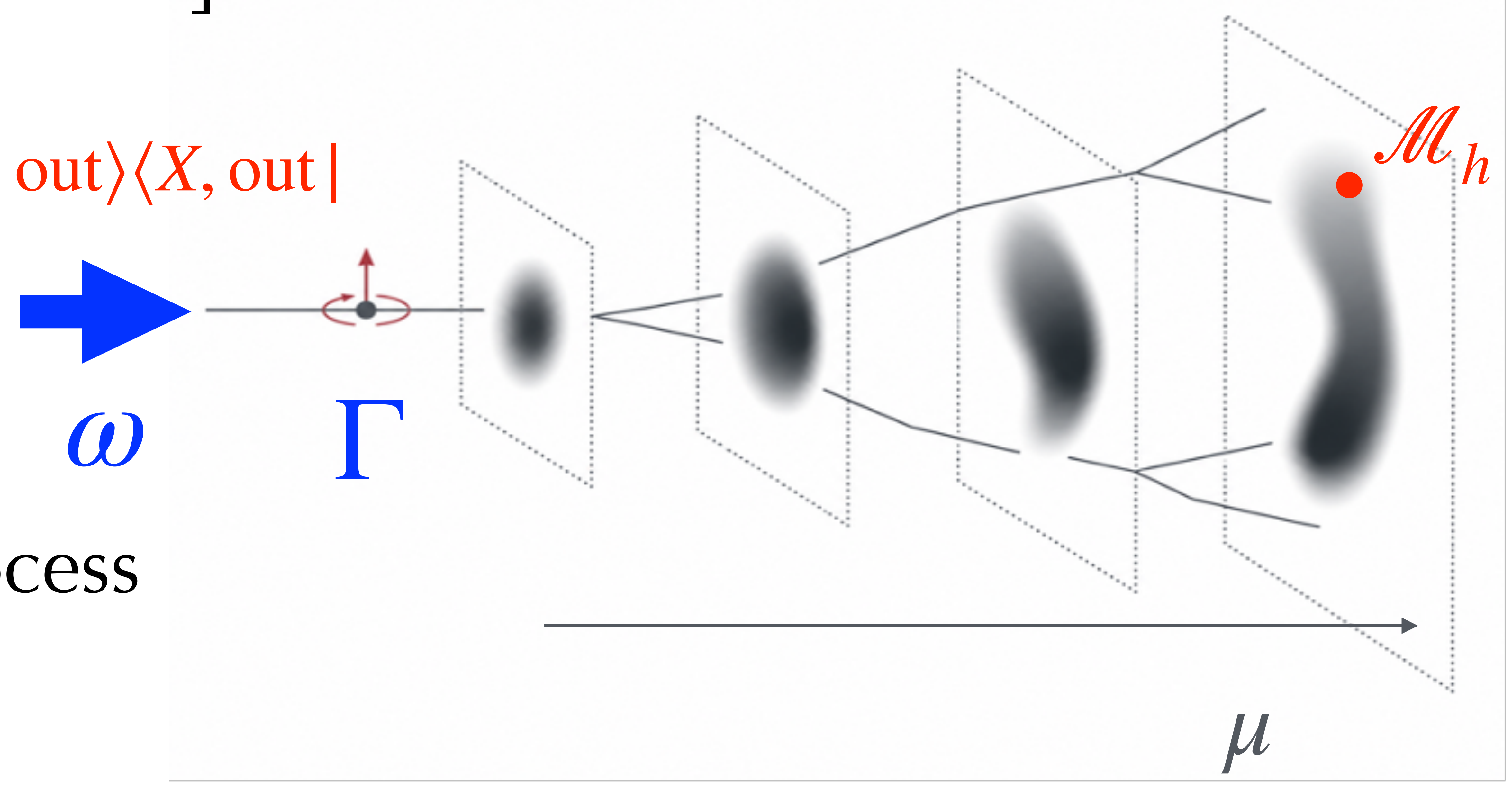
$$d_{h/i}(z, \vec{p}_T) = \int d\xi d^2\vec{x}_T e^{i\omega\xi}\,\mathrm{Tr}\left[\frac{\Gamma}{2}\langle 0|\psi(\xi, x_T)\,\mathcal{M}_h\,\bar{\psi}(0)\,|0\rangle\right]$$

$$\mathcal{M}_h(z, \vec{p}_T) = \sum\!\!\!\!\!\!\!\int_X \sum_{a\in X} \delta_{ah}\delta(z - \frac{E_a}{\omega})\delta^2(\vec{p}_T - \vec{p}_{a,T})\,|X, \mathrm{out}\rangle\langle X, \mathrm{out}|$$



Measure a hadron in a fragmentation process

Hadron probe/Fragmentation

- A portal to hadronization
- An important probe
- Fragmentation functions (FFs)

Fragmentation process

Detector that probes fragmentation

e.g.,

$$d_{h/i}(z,\vec{p}_T) = \int d\xi d^2\vec{x}_T e^{i\omega\xi}\,\mathrm{Tr}\left[\frac{\Gamma}{2}\langle 0|\psi(\xi,x_T)\,\mathscr{M}_h\,\bar{\psi}(0)\,|0\rangle\right]$$

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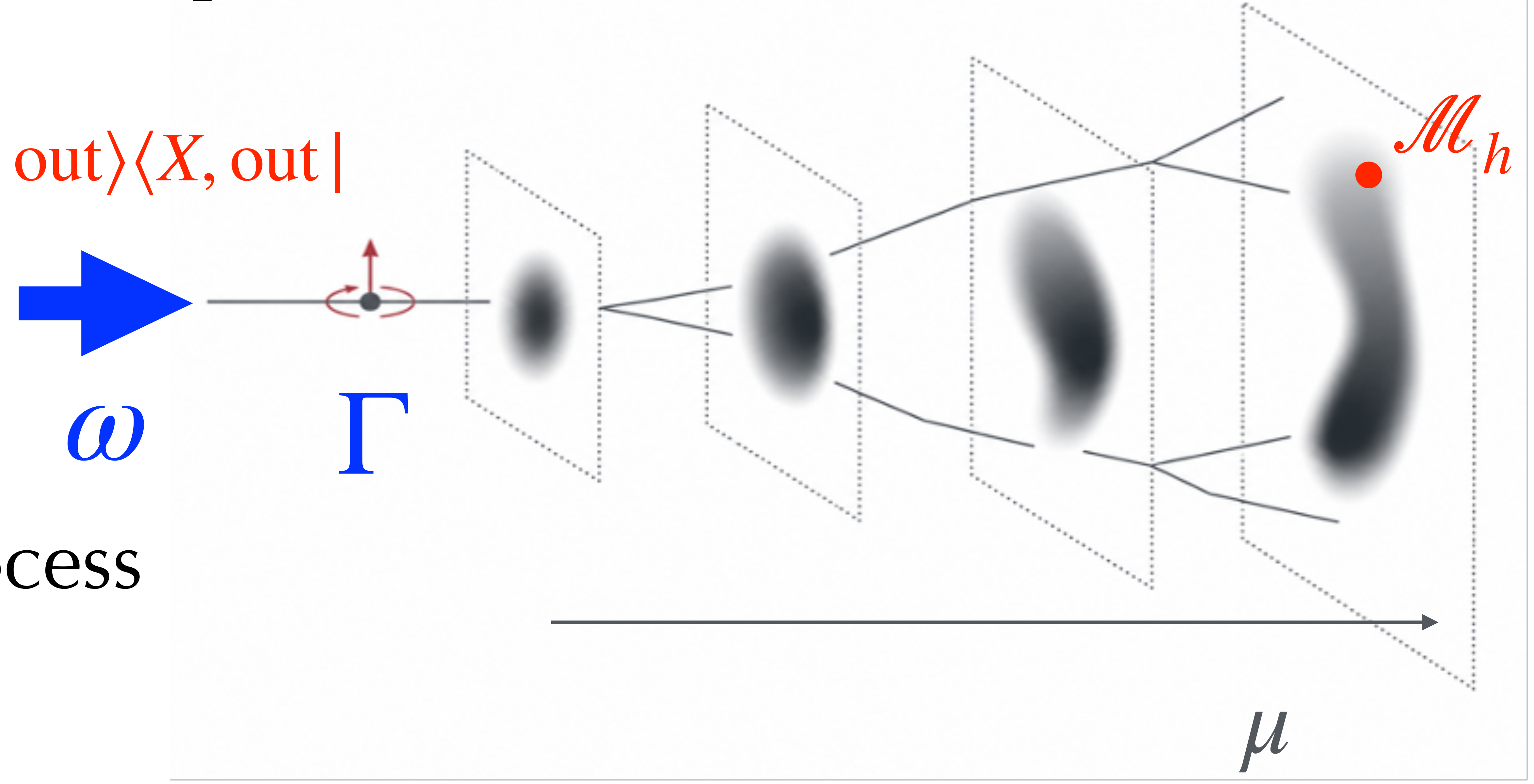

Measure a hadron in a fragmentation process to probe fragmentation

Hadron probe/Fragmentation

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Fragmentation process

Detector that probes fragmentation

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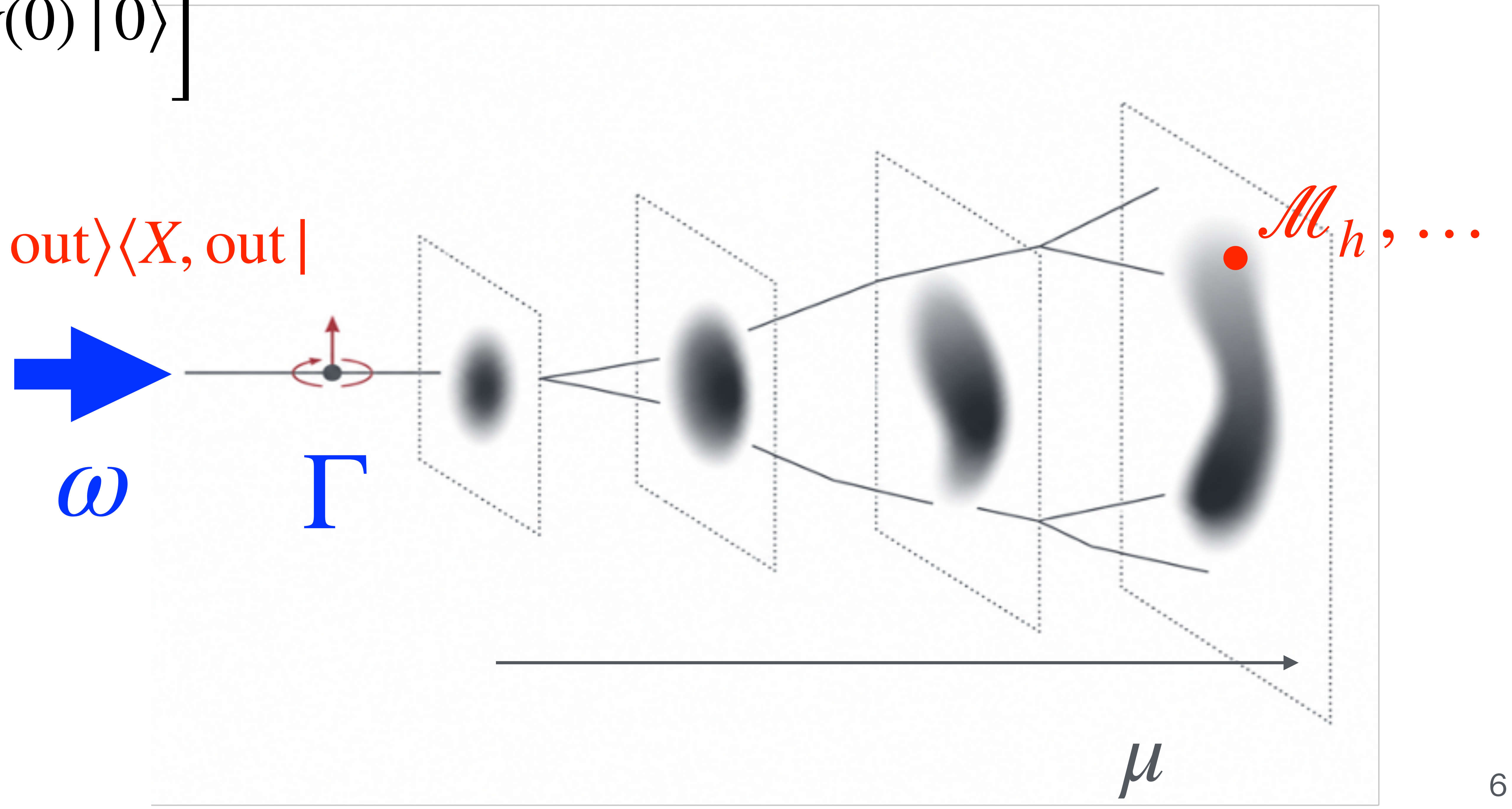
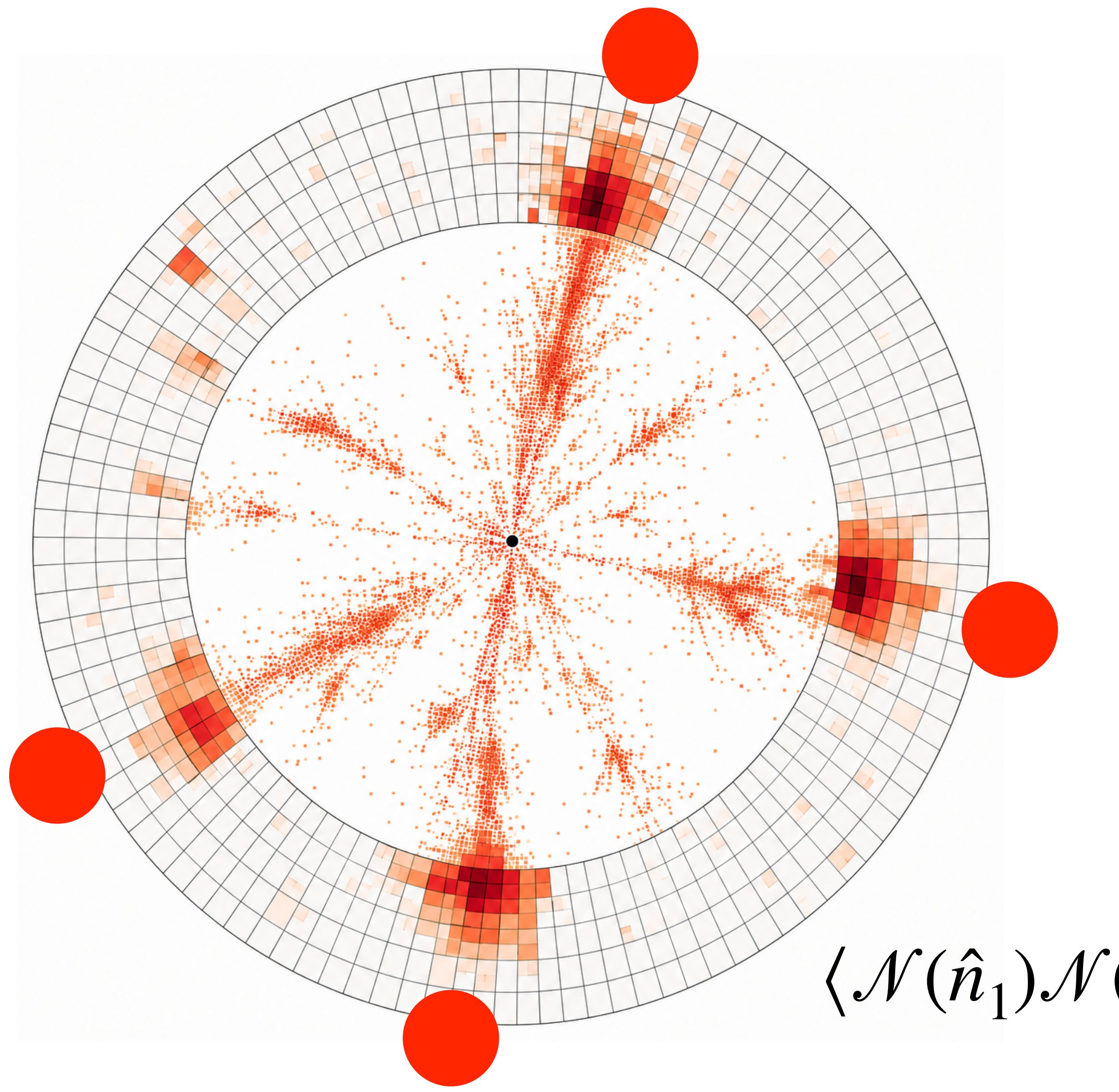


- Hadron detectors (FFs) are not unique for fragmentation
- **We can have other detectors,** theoretical/experimentally more friendly

Detectors: Multiplicities

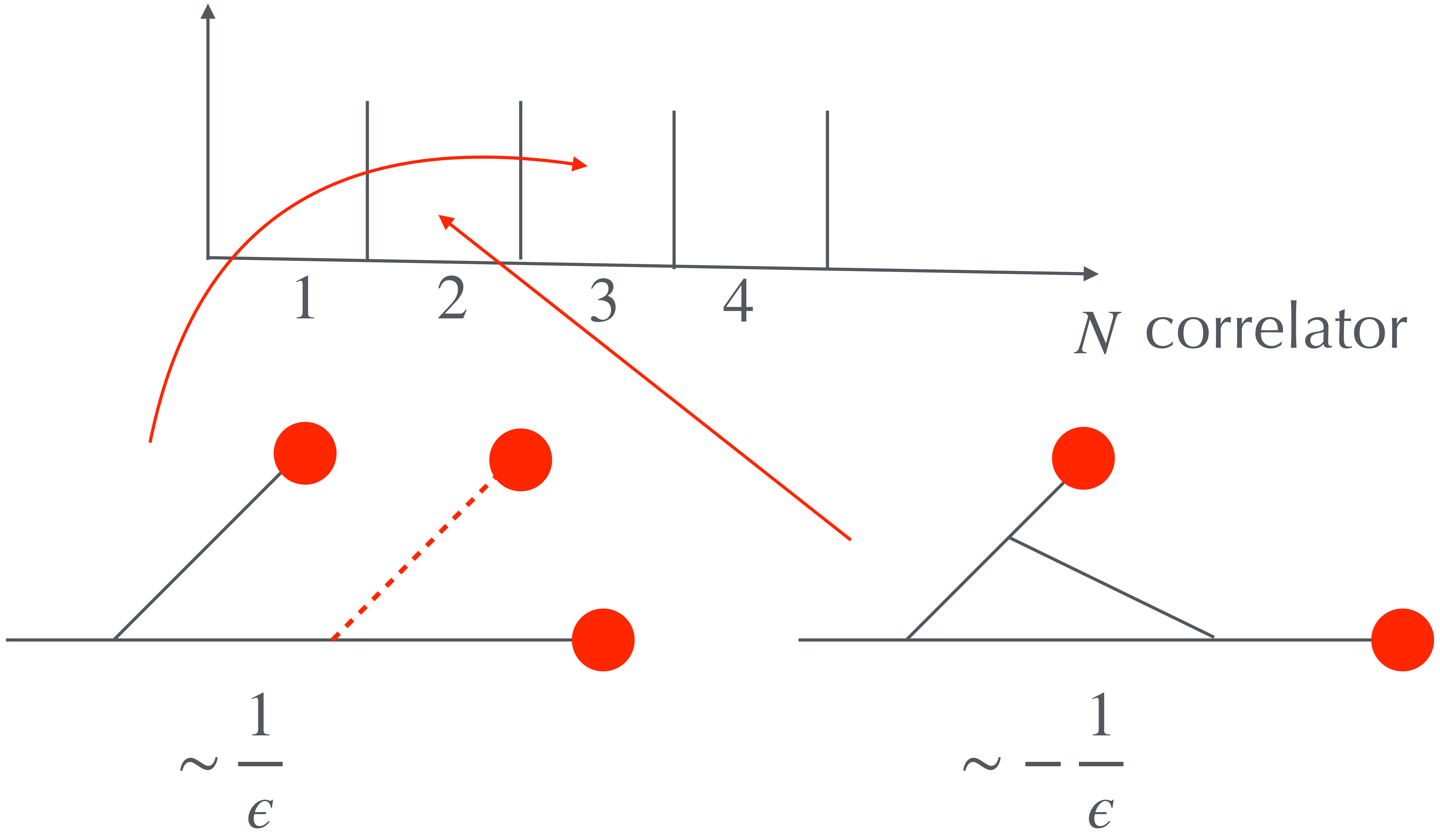
Multiplicity detector



$\langle \mathcal{N}(\hat{n}_1)\mathcal{N}(\hat{n}_2)\mathcal{N}(\hat{n}_3)\mathcal{N}(\hat{n}_4)\rangle$

$$\lim_{E_3 \to 0} N_1 + N_2 + N_3 = N_1 + N_2 + N_3$$

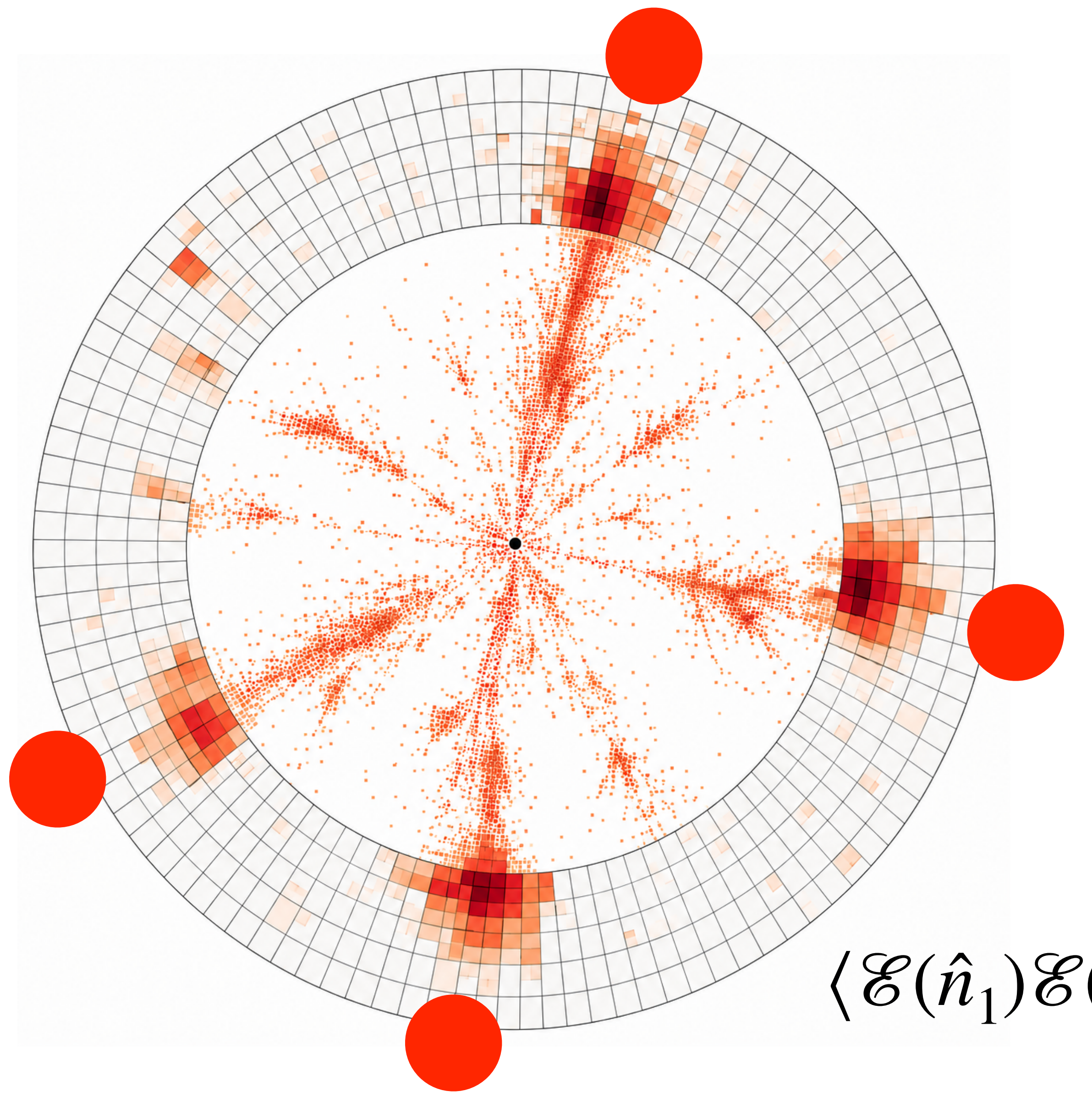
- Experimentally friendly
- IRC unsafe, How to calculate?



Poles fall into different bins
do not cancel

Detectors: Energy flow/Energy Correlator

Energy flow detector/energy correlators



$\langle \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\mathcal{E}(\hat{n}_3)\mathcal{E}(\hat{n}_4)\rangle$

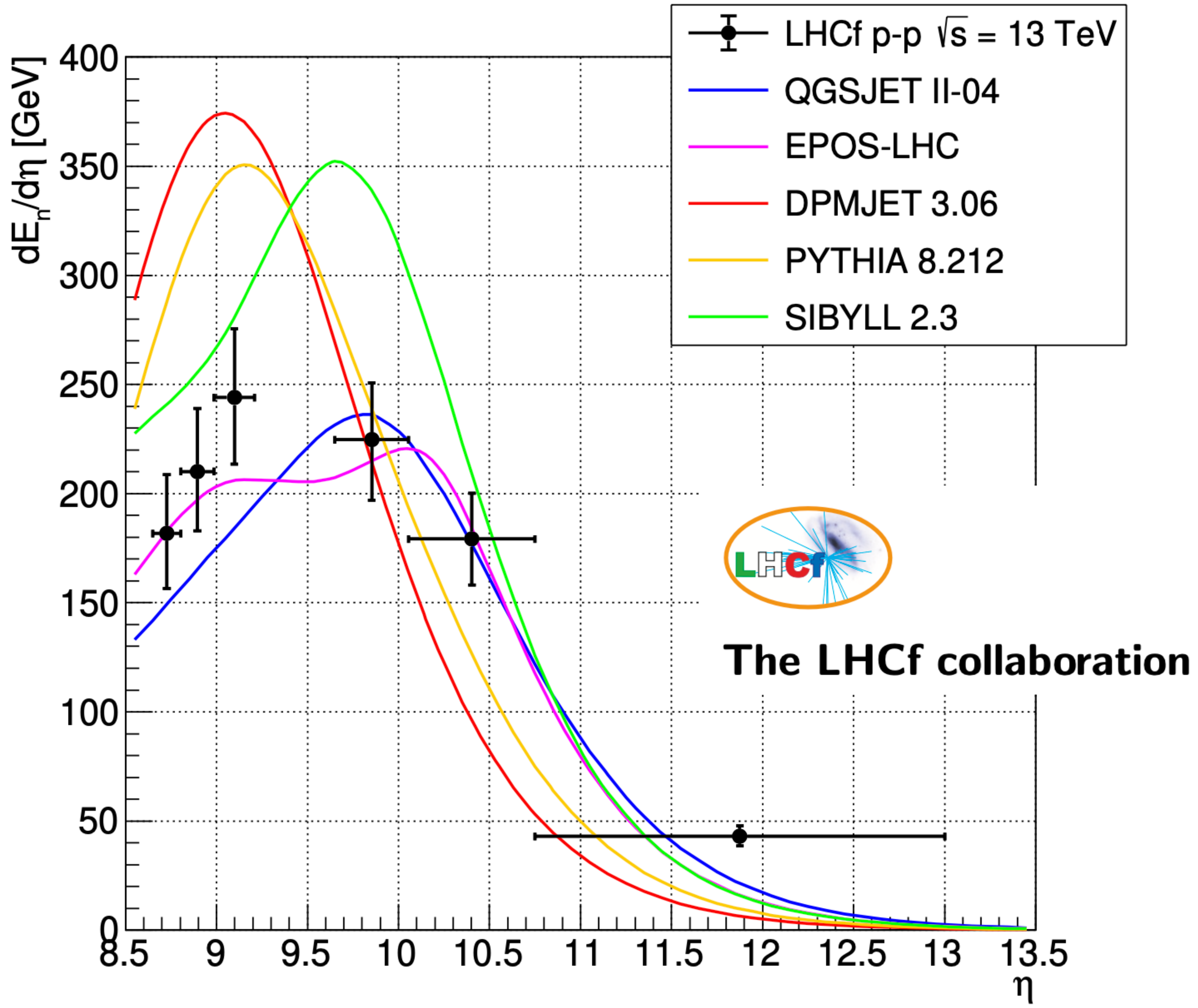
$$\lim_{E_3 \to 0} E_1 + E_2 + E_3 = E_1 + E_2$$

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

- Measure energy and angle, more inclusive than hadron detector
- Calorimeter information + PID?
- Infra-red safe ⇒ pQCD calculable

Detectors: Energy flow/Energy Correlator

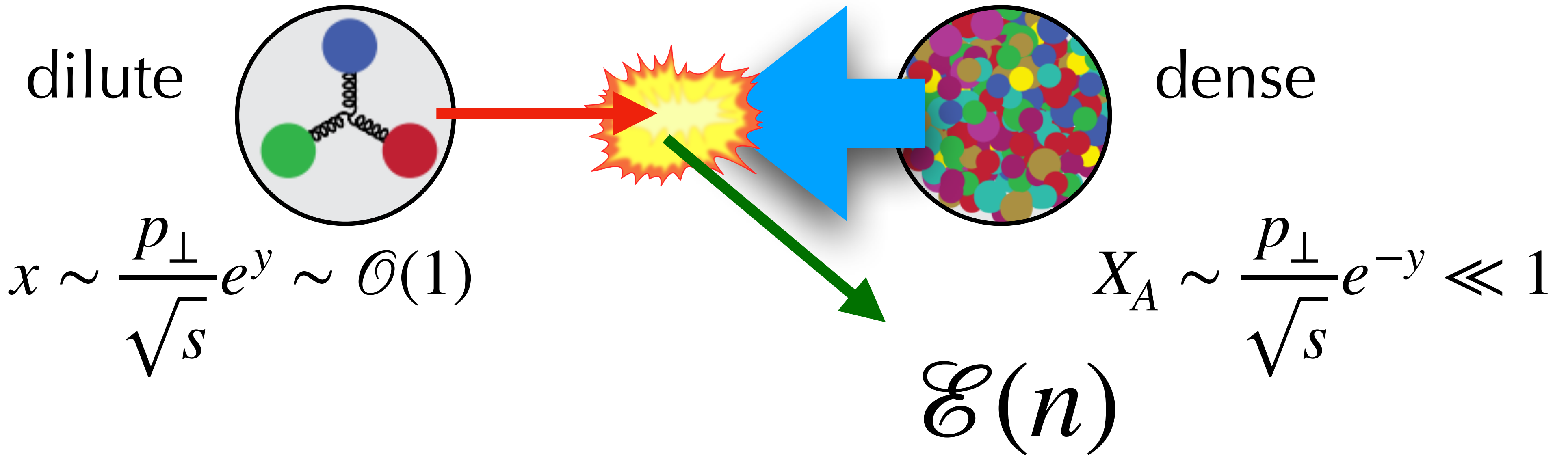
Energy flow detector/energy correlators

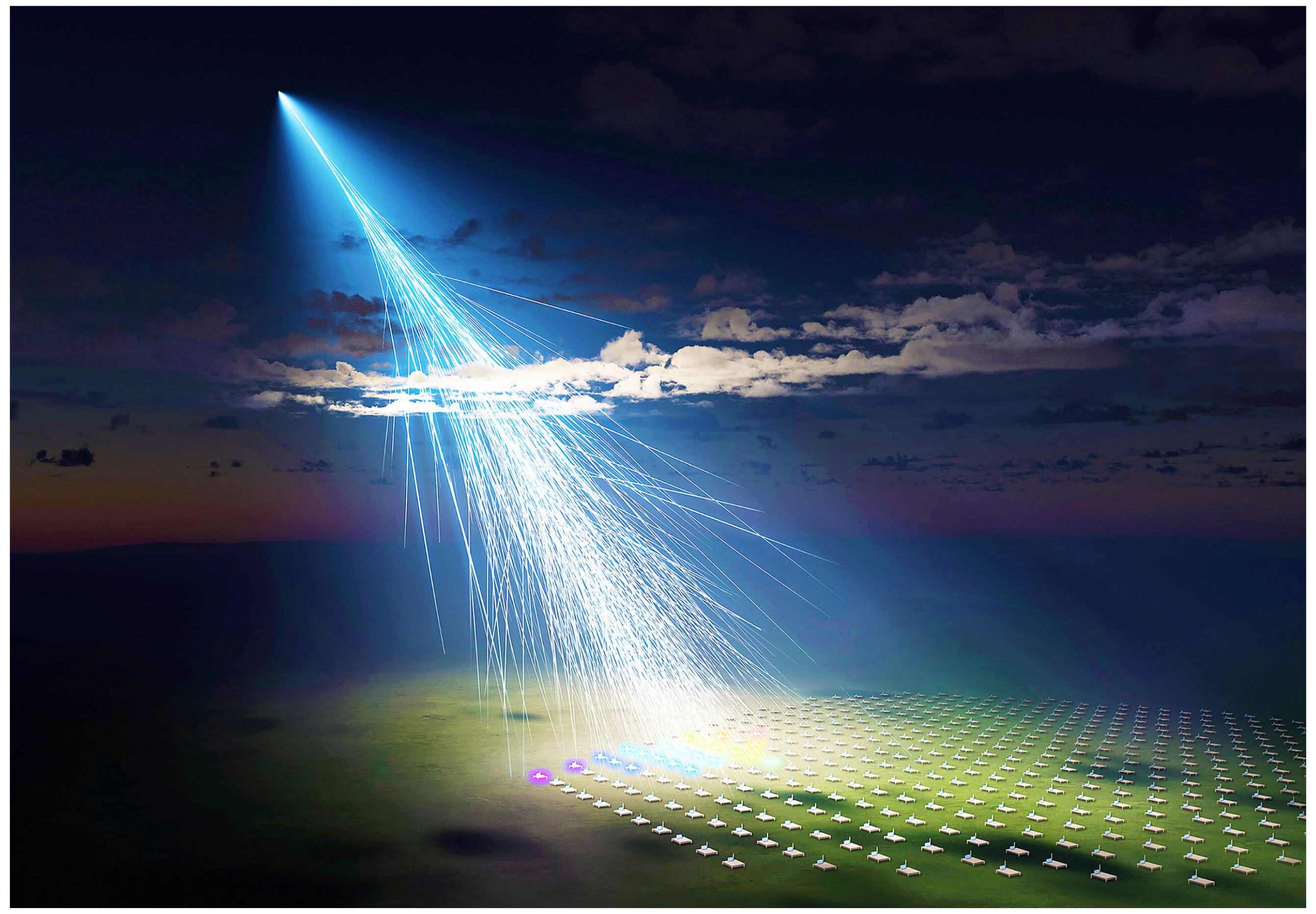


$$\frac{\mathrm{d}E_{\mathrm{n}}}{\mathrm{d}\eta} = \frac{1}{\Delta\eta}\frac{1}{\sigma_{\mathrm{inel}}}\sum_i \frac{\mathrm{d}\sigma_{\mathrm{n}}}{\mathrm{d}E}\bigg|_i E_i \mathrm{d}E_i$$

$\mathscr{E}(n)$ in the forward region

	Region A	Region B	Region C	Region D	Region E	Region F
η	10.75–∞	10.06–10.75	9.65–10.06	8.99–9.21	8.80–8.99	8.65–8.80
θ [μrad]	0–42	42–85	85–128	198–249	249–298	298–347
ϕ [°]	90–270	135–215	150–200	45–70	45–70	45–70



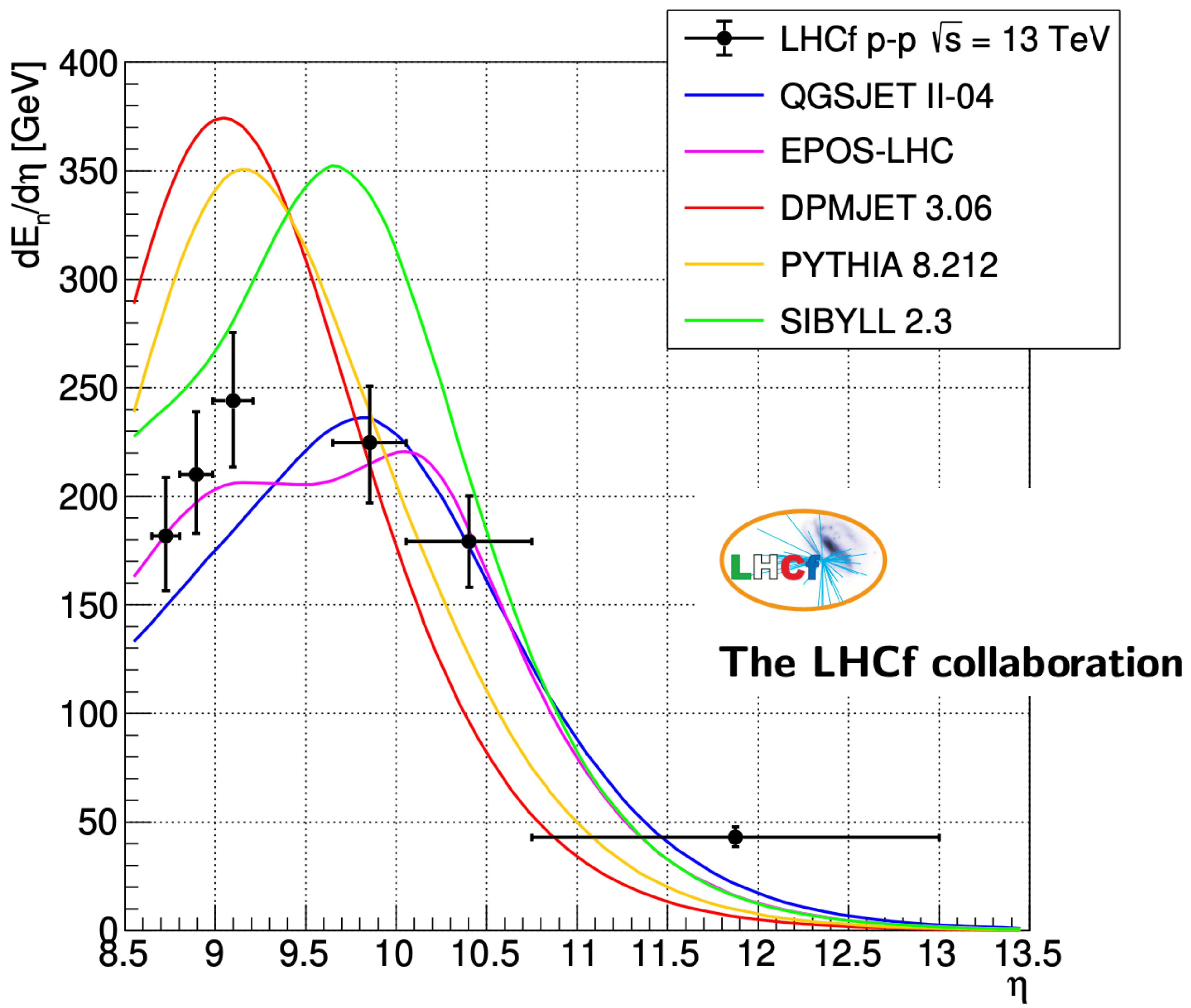


Closely related to the cosmic ray showers

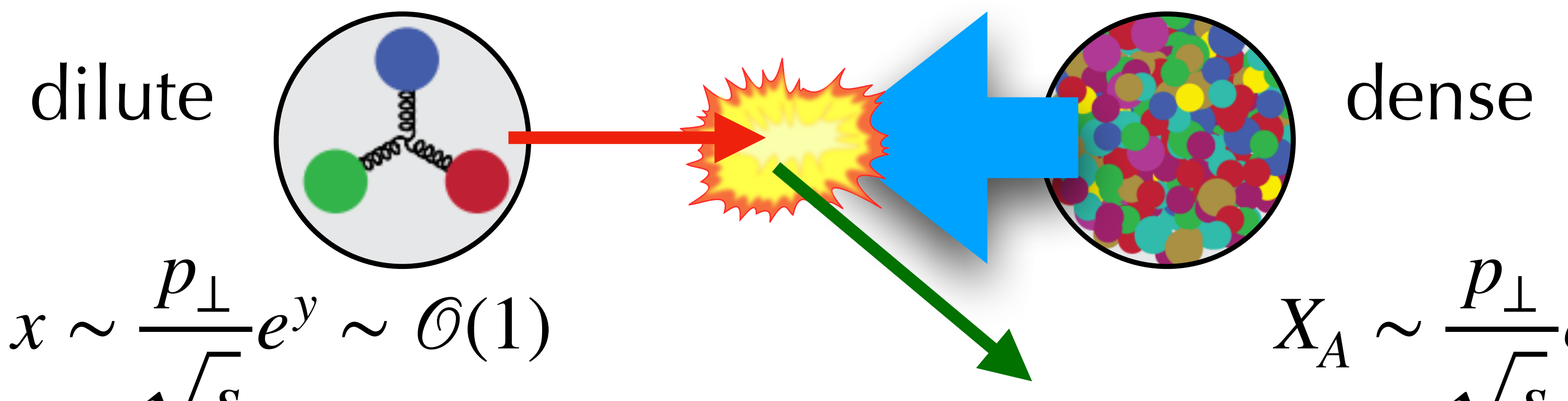
NOT well-understood

Detectors: Energy flow/Energy Correlator

Energy flow detector/energy correlators



$$\frac{\mathrm{d}E_\mathrm{n}}{\mathrm{d}\eta} = \frac{1}{\Delta\eta}\frac{1}{\sigma_\mathrm{inel}}\sum_i \frac{\mathrm{d}\sigma_\mathrm{n}}{\mathrm{d}E}\Big|_i E_i \mathrm{d}E_i$$



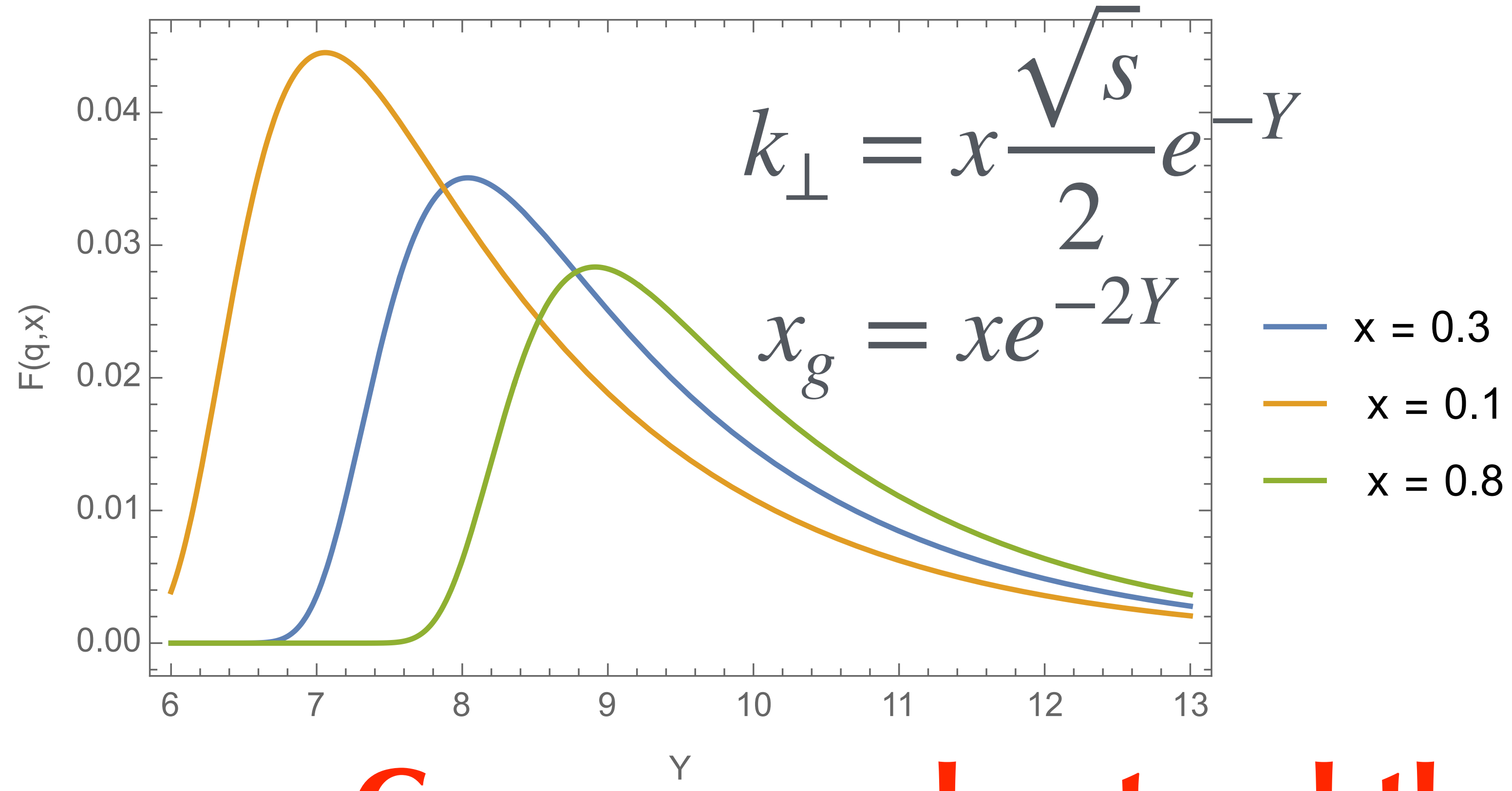
$x \sim \frac{p_\perp}{\sqrt{s}} e^{y} \sim \mathcal{O}(1)$

$\mathcal{E}(n)$

$X_A \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$

$$\frac{dE_n}{d\eta} \sim (2\pi)\big[\langle P|\mathcal{E}(\eta)|P\rangle\big] \times \mathcal{F}_A^{(2)}(k_\perp, \xi_g)$$

~ probe the CGC dipole distribution

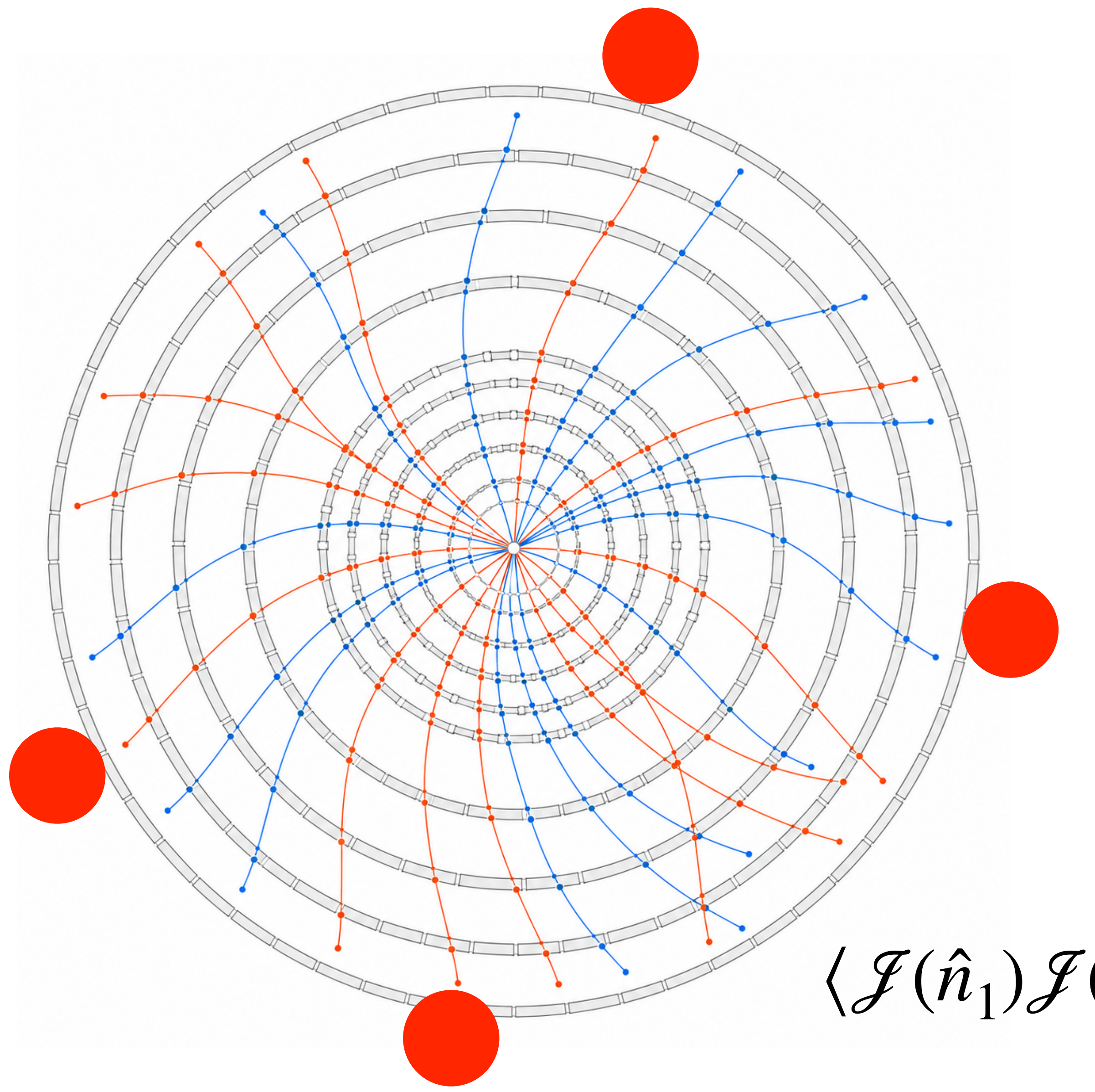


Peak and shape depend on the shape of the Energy Correlator/PDF at small μ_F

Can we understand the data by CGC?

Detectors: Track

Charge flow detector/charge correlators??

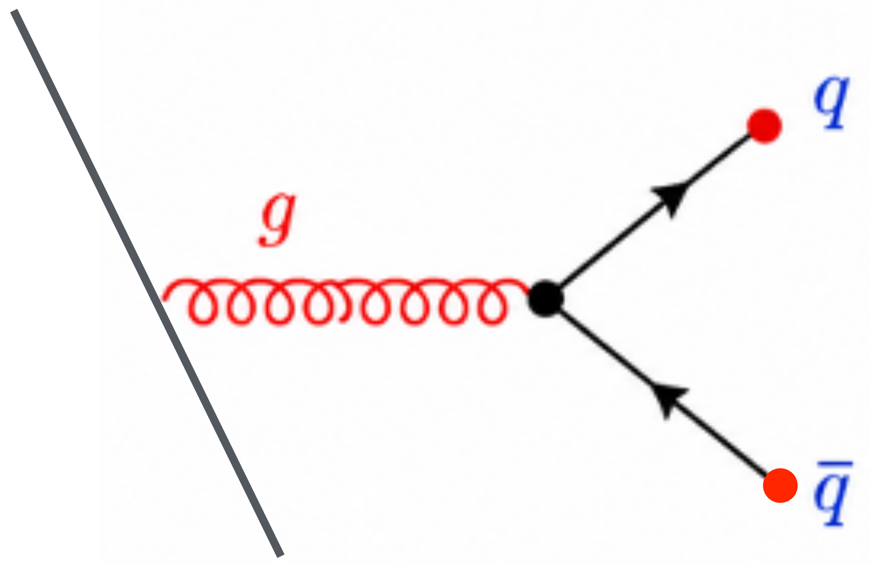


$\langle \mathcal{J}(\hat{n}_1)\mathcal{J}(\hat{n}_2)\mathcal{J}(\hat{n}_3)\mathcal{J}(\hat{n}_4)\rangle$

$$\mathcal{Q}(\hat{n}) = \lim_{r\to\infty} r^2 \int dt\, \hat{n}_i\, \mathcal{J}^{0i}(t, r\hat{n})$$

- Measure charge sign and angle, more inclusive than hadron detector
- Track information
- Infra-red safe??

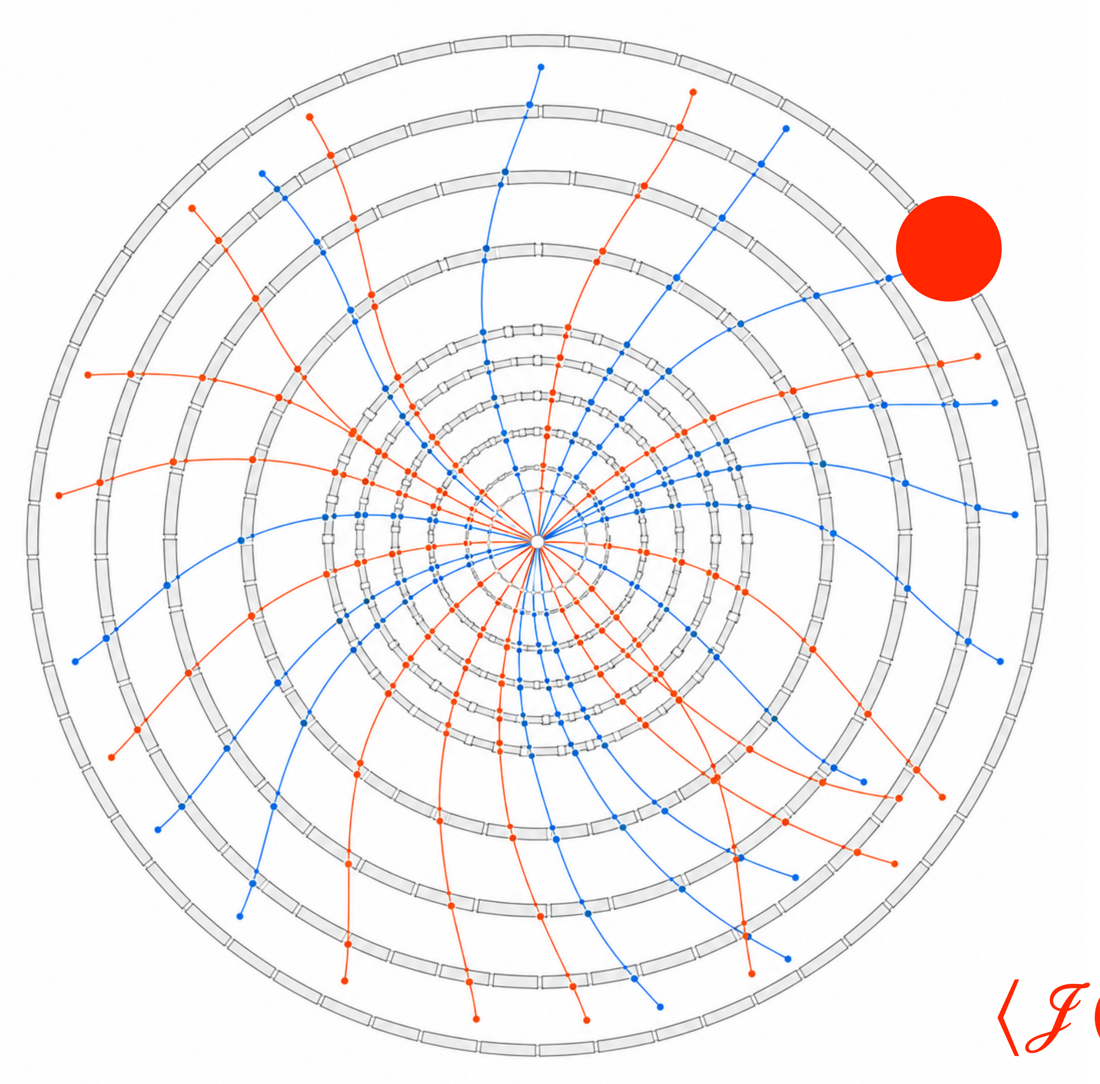
$$\lim_{E_3\to 0} Q_1 + Q_2 + Q_3 = Q_1 + Q_2 + Q_3$$



$\sim \dfrac{\alpha_s^2}{\epsilon} \times Q\bar{Q}$ event-by-event

One Point Charge Correlator

Charge flow detector/One Point Charge Correlator



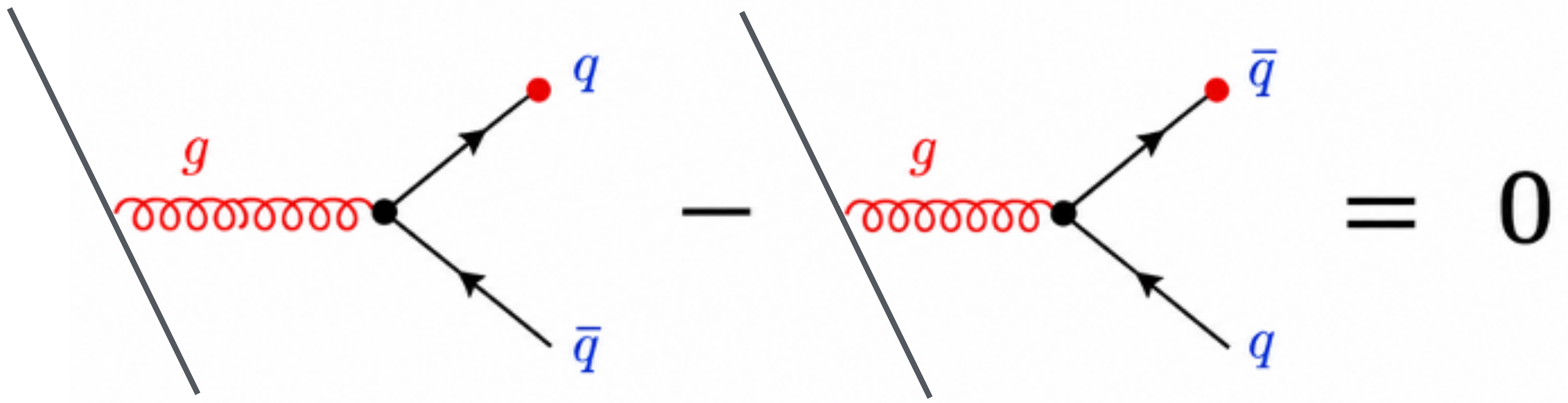
$\langle \mathcal{J}(\hat{n}) \rangle$

$$\mathcal{Q}(\hat{n}) = \lim_{r\to\infty} r^2 \int dt\, \hat{n}_i \mathcal{J}^{0i}(t, r\hat{n})$$

- Measure charge sign and angle, more inclusive than hadron detector
- Track information
- Infra-red safe for OPCC !

(Also true for b2b QCC, see 2508.00977)

$$\lim_{E_3\to 0} Q_1 + Q_2 + Q_3 = Q_1 + Q_2 + Q_3$$



When averaging over events

Due to C symmetry of soft QCD

+ C-odd of OPCC

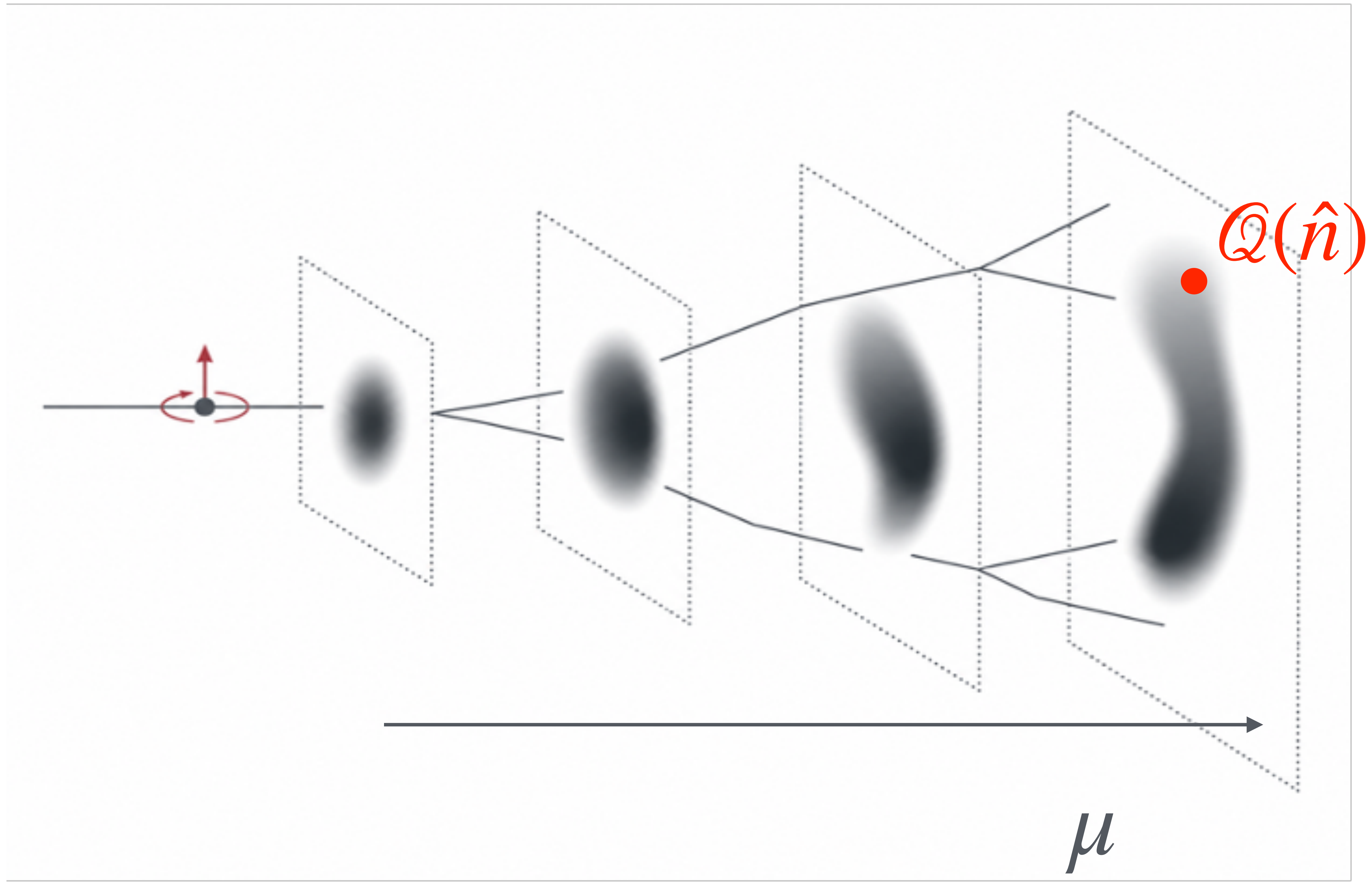
OPCC and transverse charge distribution

- A new portal to hadronization
- **Transverse charge distribution** Li et al.

$$\mathcal{J}_{\omega,\Gamma}(\vec{n}_T) = \int d\xi d^2\vec{x}_T e^{i\omega\xi}\,\mathrm{Tr}\left[\frac{\Gamma}{2}\langle 0\,|\,\psi(\xi,x_T)\,\mathcal{Q}(\hat{n})\,\bar{\psi}(0)\,|\,0\rangle\right] \qquad \mathcal{Q}(\hat{n}) = \lim_{r\to\infty} r^2 \int dt\,\hat{n}_i\,\mathcal{J}^{0i}(t,r\hat{n})$$

$$\hat{n} = (\vec{n}_T, \cos\theta) = (\sin(\theta)(\cos\phi, \sin\phi), \cos\theta) \approx (\vec{n}_T, 1)$$

Measures how charge is (re)-distributed
by hadronization

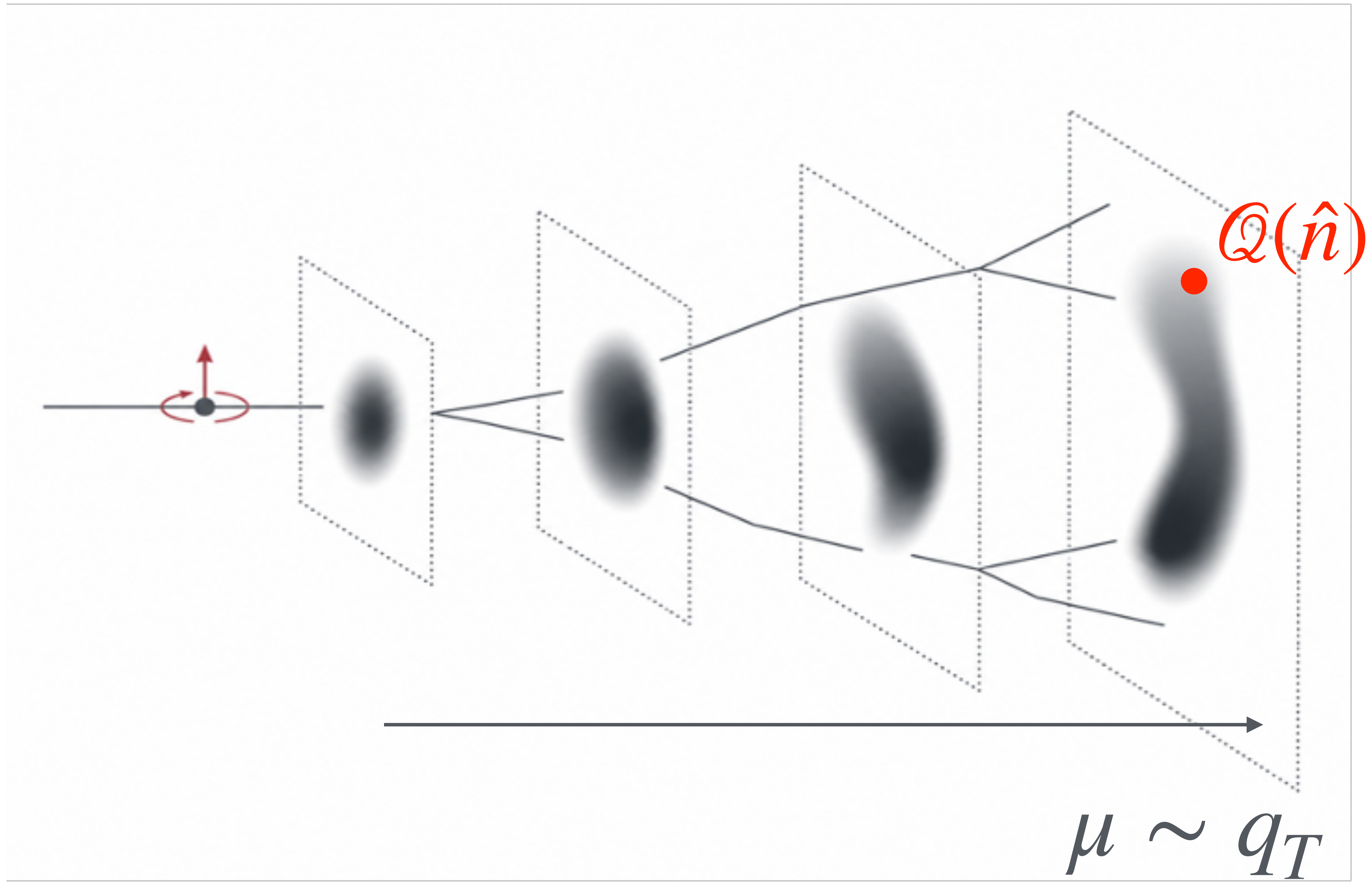


OPCC and transverse charge distribution

Properties (collinear limit)

$$\mathcal{J}_{\omega,\Gamma}(\vec{n}_T) = \int d\xi d^2\vec{x}_T e^{i\omega\xi}\,\mathrm{Tr}\left[\frac{\Gamma}{2}\langle 0|\,\psi(\xi,x_T)\,\mathcal{Q}(\hat{n})\,\bar{\psi}(0)\,|0\rangle\right]$$

- $\Gamma = \gamma^+$ unpol, $\Gamma = i\sigma^{\rho+}\gamma_5$ transversely pol. quark fragmentation
- $\mathcal{J}_{\omega,\Gamma}(\vec{n}_T) = \mathcal{J}_{\omega,\Gamma}(\omega\vec{n}_T) = \mathcal{J}_{\omega,\Gamma}(\vec{q}_T)$ due to boost invariance $\omega \to \omega e^Y,\ \vec{n}_T \to \vec{n}_T e^{-Y}$



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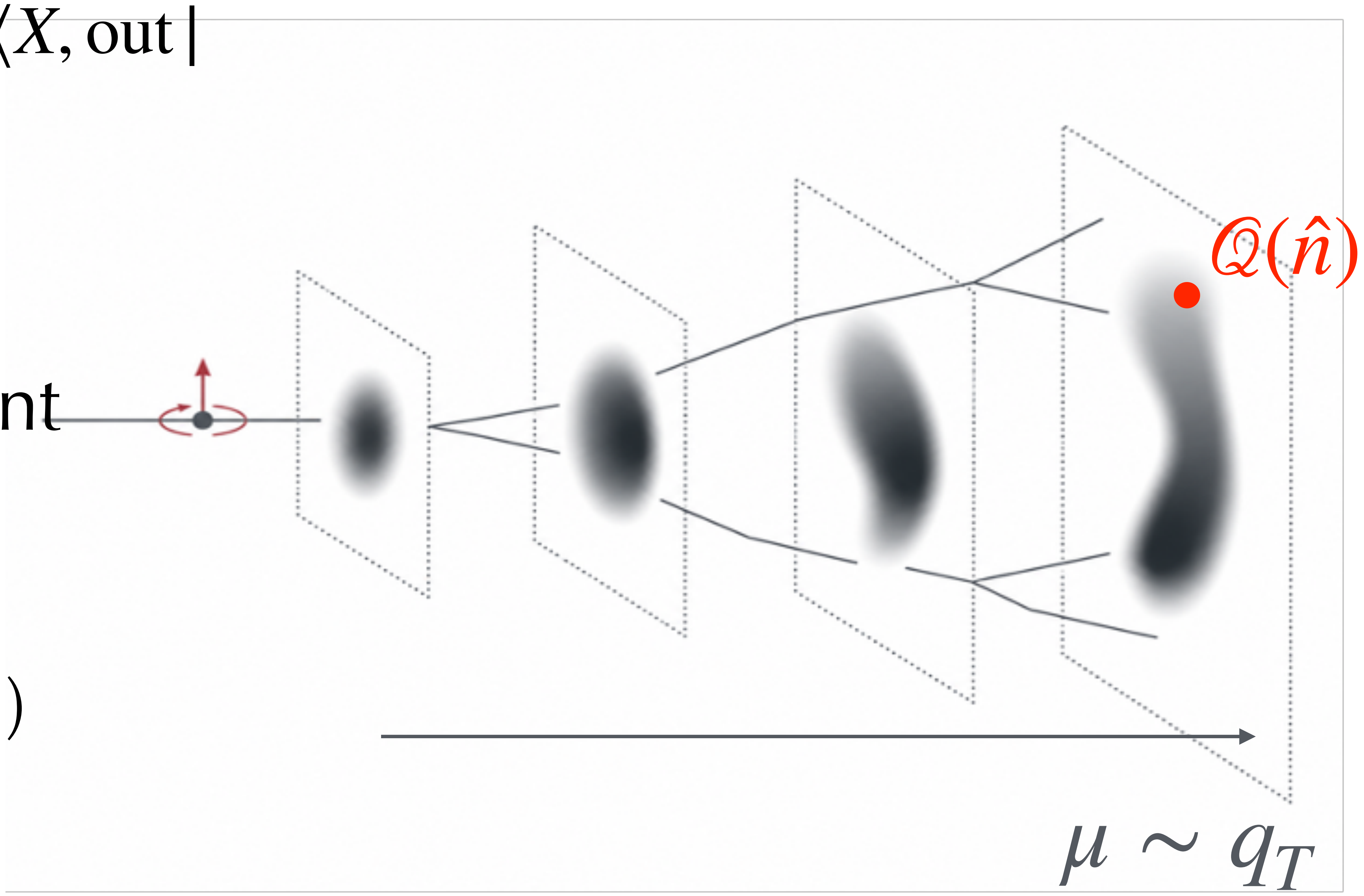
- Connection to the TMD FF

$$\mathcal{Q}(\hat{n}) \propto \sum\!\!\!\!\!\!\int_X \sum_{a\in X} Q_a \delta(\vec{q}_T - \vec{p}_{aT}/z_a)\,|X,\mathrm{out}\rangle\langle X,\mathrm{out}\,| \quad\Rightarrow\quad \mathcal{J}_{\omega\Gamma}(\vec{q}_T) = \int dz z^2 \sum_h Q_h\, d_{h/i,\Gamma}(z, z\vec{q}_T)$$

$$\mathcal{M}_h(z,p_T) = \sum\!\!\!\!\!\!\int_X \sum_{a\in X} \delta_{ah}\delta(z - \frac{p_a^+}{2\omega})\delta^2(p_T - q_{T,a})\,|X,\mathrm{out}\rangle\langle X,\mathrm{out}\,|$$

- The connection is not a must-be, $\mathcal{Q}$ is an observable independent of TMD FF (different measurement, no energy …)
- Allows for recycling known results in TMD physics (factorization, ope, calculations …)



OPCC and transverse charge distribution

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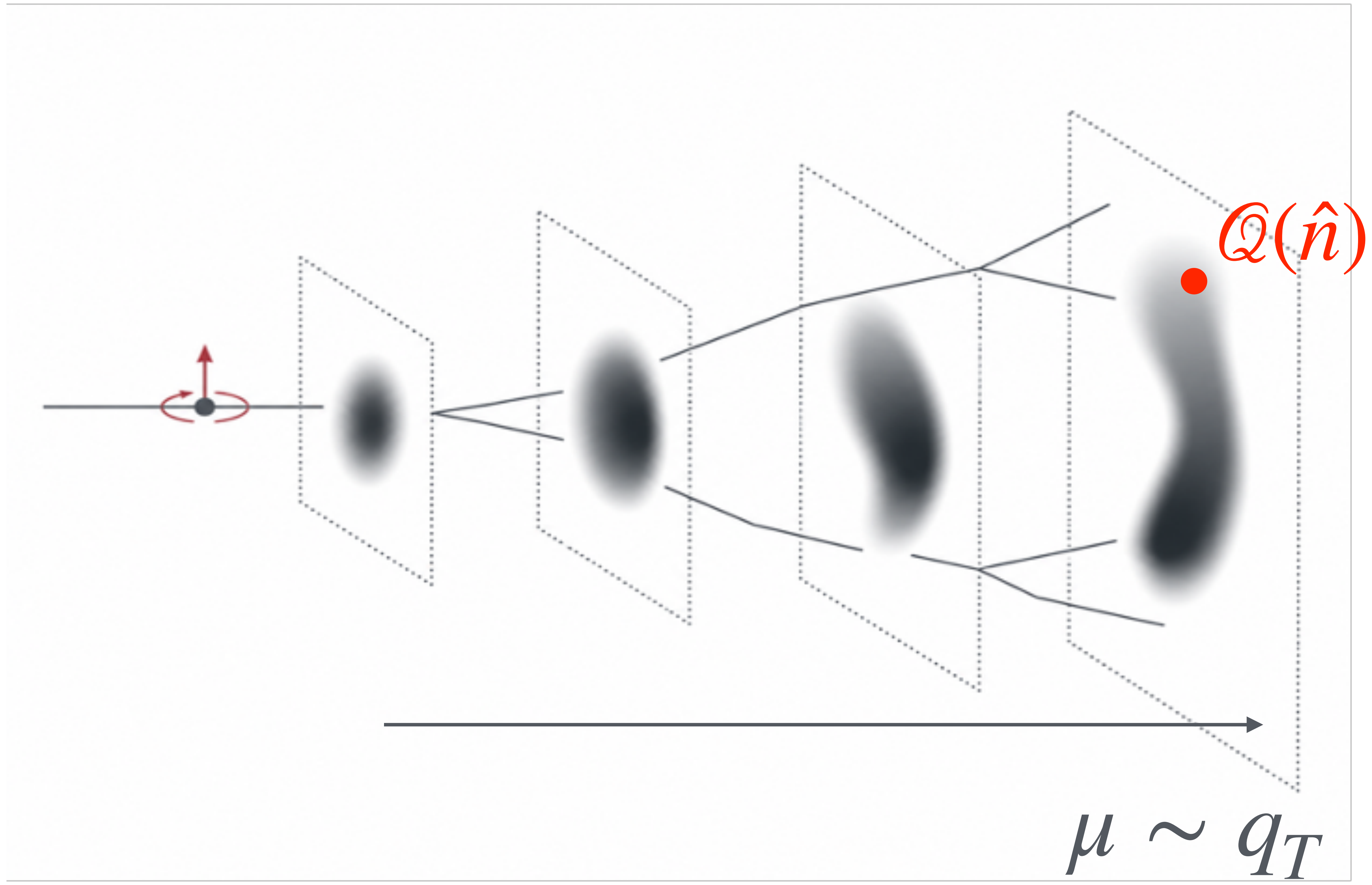
Properties (collinear limit)

- Fourier transformation

$$\mathcal{J}_{\omega,\Gamma}(\vec{b}_T) \equiv \int d^2\vec{q}_T\, e^{i\vec{q}_T\cdot\vec{b}_T}\mathcal{J}_{\omega,\Gamma}(\vec{q}_T)$$



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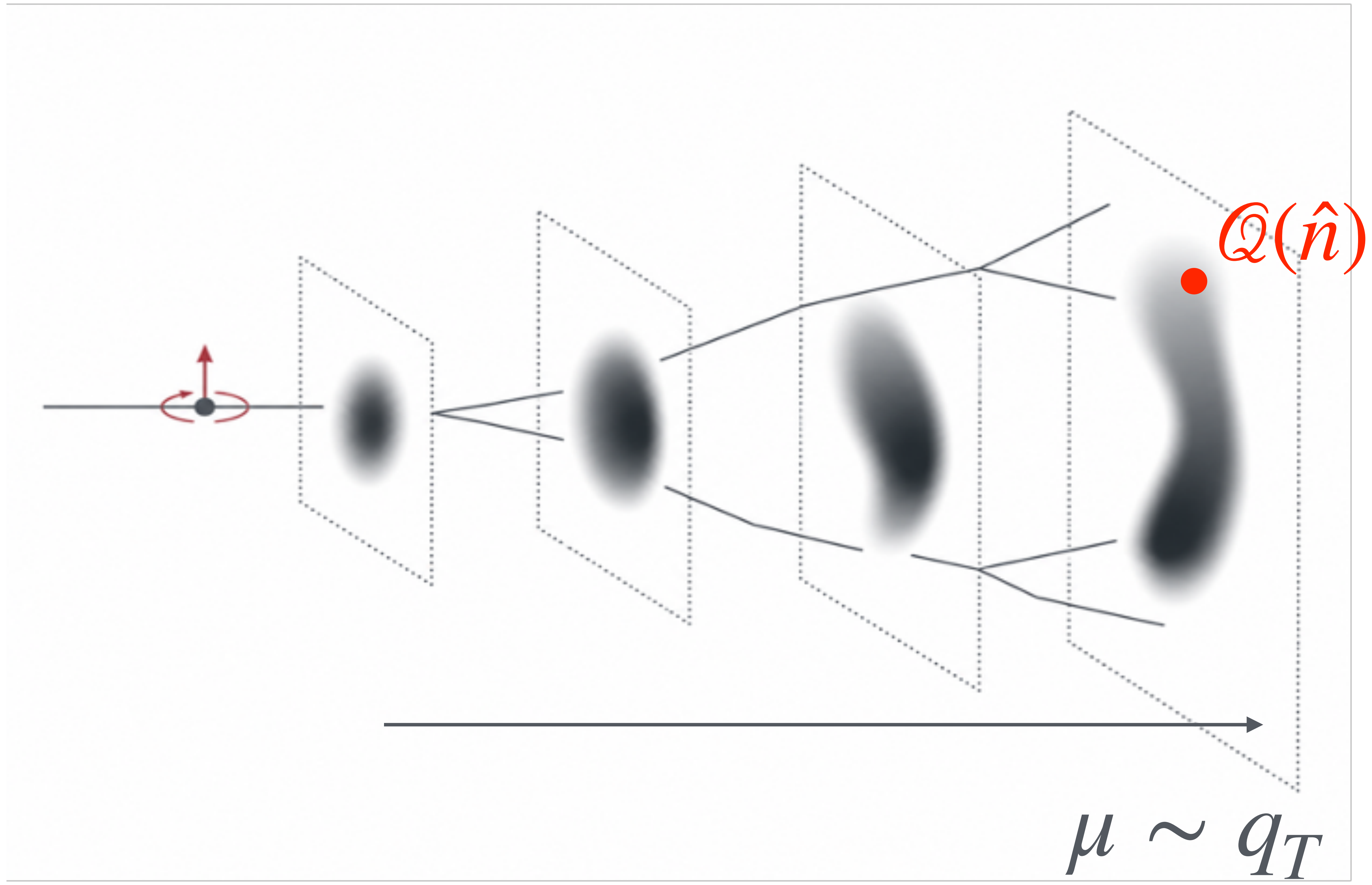
- OPE for $b_T\Lambda_{\mathrm{QCD}} \to 0$
  - Using Connection to TMD FF
  - Light-ray OPE/Matching
  - expanding $\mathcal{Q}$



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- Fourier transformation

$$\mathcal{J}_{\omega,\Gamma}(\vec{b}_T) \equiv \int d^2\vec{q}_T\, e^{i\vec{q}_T\cdot\vec{b}_T}\mathcal{J}_{\omega,\Gamma}(\vec{q}_T)$$

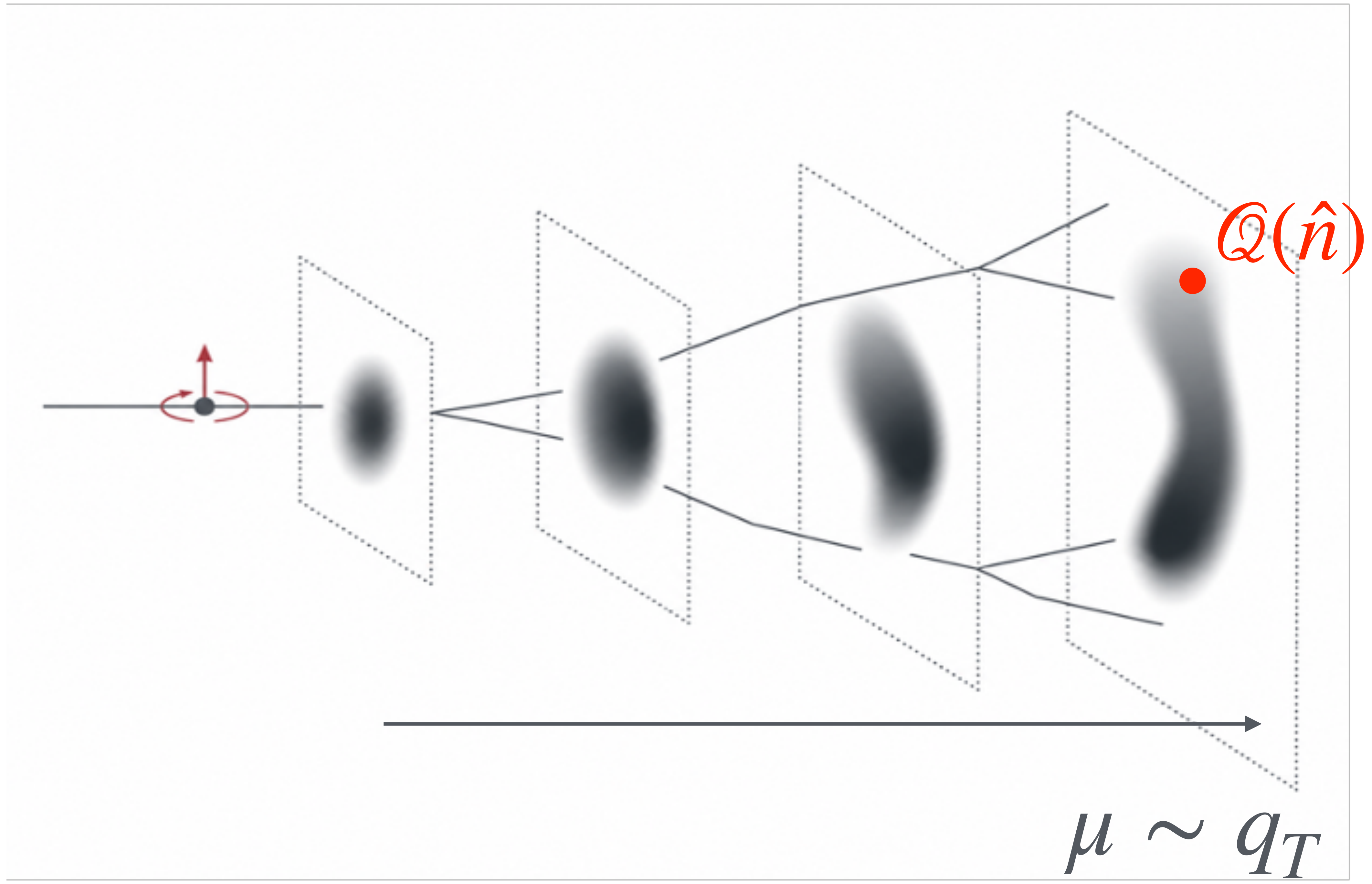
acts only on the detector in the parton frame,

migrates to the bulk field in the hadron frame ($\hat{n}$)

OPE for $b_T\Lambda_{\mathrm{QCD}} \to 0$:

$$\int d^2\vec{q}_T\, e^{i\vec{b}_T\cdot\vec{q}_T}\,\mathcal{Q}(\vec{q}_T) \;\; = \int d^2\vec{q}_T\,(1 + i\vec{b}_T\cdot\vec{q}_T + \ldots)\,\mathcal{Q}(\vec{q}_T)$$

$$= \hat{Q}_{\mathrm{tot}} + i\vec{b}\cdot\int d^2\vec{q}_T\,\vec{q}_T\,\hat{\mathcal{Q}}(\vec{q}_T) + \ldots$$



OPCC and transverse charge distribution

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- OPE for $b_T\Lambda_{\mathrm{QCD}} \to 0$

$$\int d^2\vec{q}_T\, e^{i\vec{b}_T\cdot\vec{q}_T}\,\mathcal{Q}(\vec{q}_T) = \int d^2\vec{q}_T\,(1 + i\vec{b}_T\cdot\vec{q}_T + \ldots)\,\mathcal{Q}(\vec{q}_T)$$

OPE of $\mathcal{J}_{\omega,\Gamma} \sim$ multiple expansion of the fragmentation charge distribution

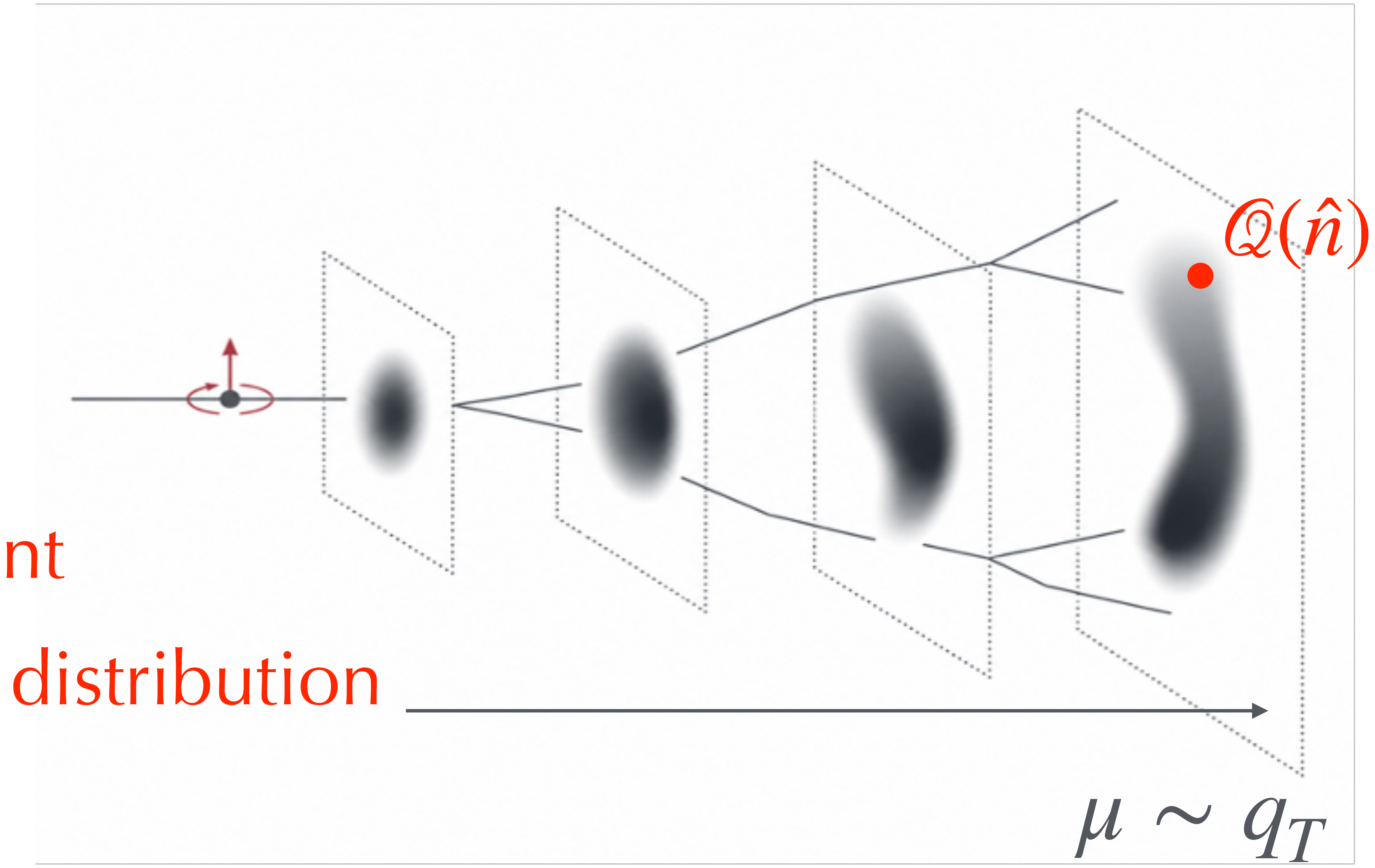
$$= \hat{Q}_{\mathrm{tot}} + i\vec{b}\cdot\int d^2\vec{q}_T\,\vec{q}_T\,\hat{\mathcal{Q}}(\vec{q}_T) + \ldots$$

Measures the total charge of fragmentation

$$[\hat{Q}_{\mathrm{tot}}, \bar{\psi}] = Q_q\bar{\psi}$$

Measures the dipole moment

sideways distortion of the net-charge distribution



OPCC and transverse charge distribution

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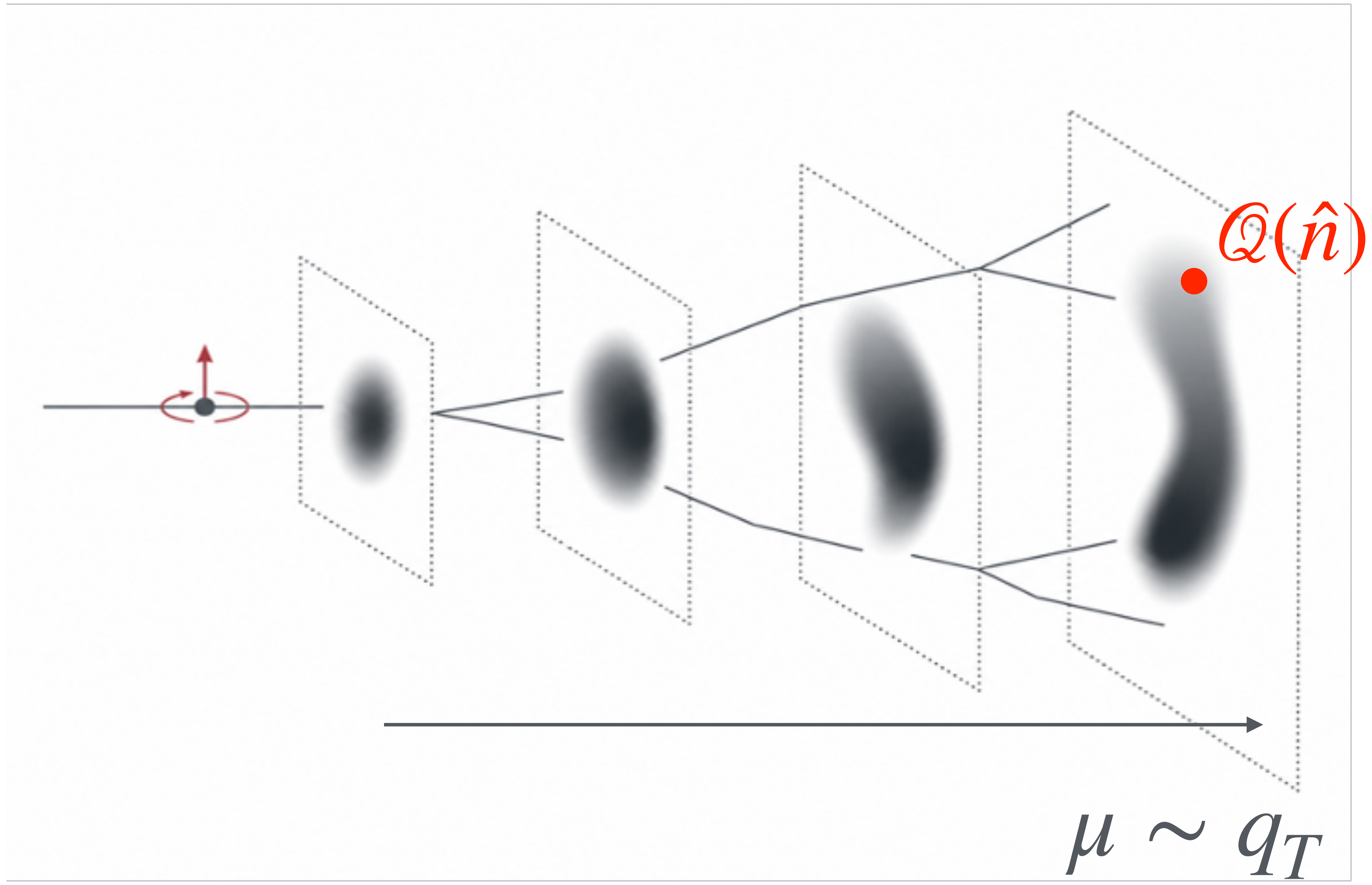
Properties (collinear limit)

- OPE for $b_T\Lambda_{\mathrm{QCD}} \to 0$

$$\hat{Q}_{\mathrm{tot}}: \quad \mathscr{J}_{\gamma^+}(\vec{b}_T) \sim \sum_j \tilde{C}^D_{j/i}(b_T;\mu,\zeta)\, Q_j \sim \sum_{j>0} \left(\tilde{C}^D_{j/i}(b_T;\mu,\zeta) - \tilde{C}^D_{\bar{j}/i}(b_T;\mu,\zeta)\right) Q_j$$

Can be understood perturbatively (N3LO)

Good for a probe



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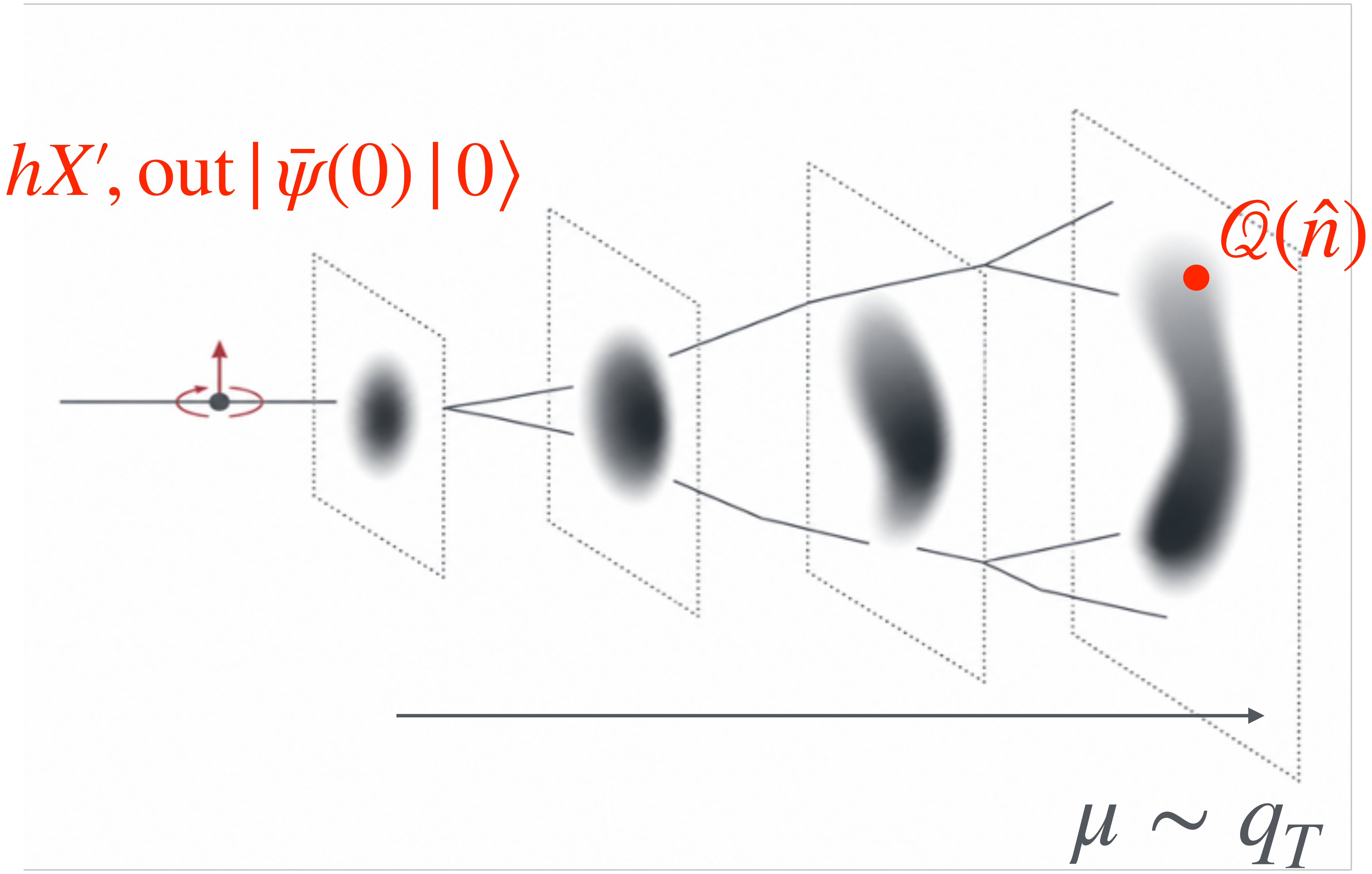
$$\mathcal{Q}(\hat{n}) \propto \sum\!\!\!\!\!\!\int_X \sum_{a\in X} Q_a\delta(\vec{q}_T - \vec{p}_{aT}/z_a)\,|X,\mathrm{out}\rangle\langle X,\mathrm{out}|$$

$ib_T \cdot \hat{\vec{D}}_T$:

$$\mathcal{J}_{\sigma^{\rho+}\gamma_5}(\vec{b}_T) = iC^H_{j/i}(b_T;\mu,\zeta)\; b_T^\alpha\; \mathcal{D}^{\rho\perp}_{\alpha,j}$$

$$\sum_h Q_h \int d\Phi_h \frac{p_{hT,\alpha}}{z_h} \ldots \frac{i\sigma^\rho\gamma_5}{2}\langle 0|\psi(\xi,\vec{x}_T)\sum\!\!\!\!\!\!\int_{X'} |hX',\mathrm{out}\rangle\langle hX',\mathrm{out}|\bar{\psi}(0)|0\rangle$$



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Properties (collinear limit)

- OPE for $b_T\Lambda_{\mathrm{QCD}} \to 0$

$$\mathcal{Q}(\hat{n}) \propto \sum\!\!\!\!\!\!\int_X \sum_{a\in X} Q_a \delta(\vec{q}_T - \vec{p}_{aT}/z_a)\,|X, \mathrm{out}\rangle\langle X, \mathrm{out}|$$

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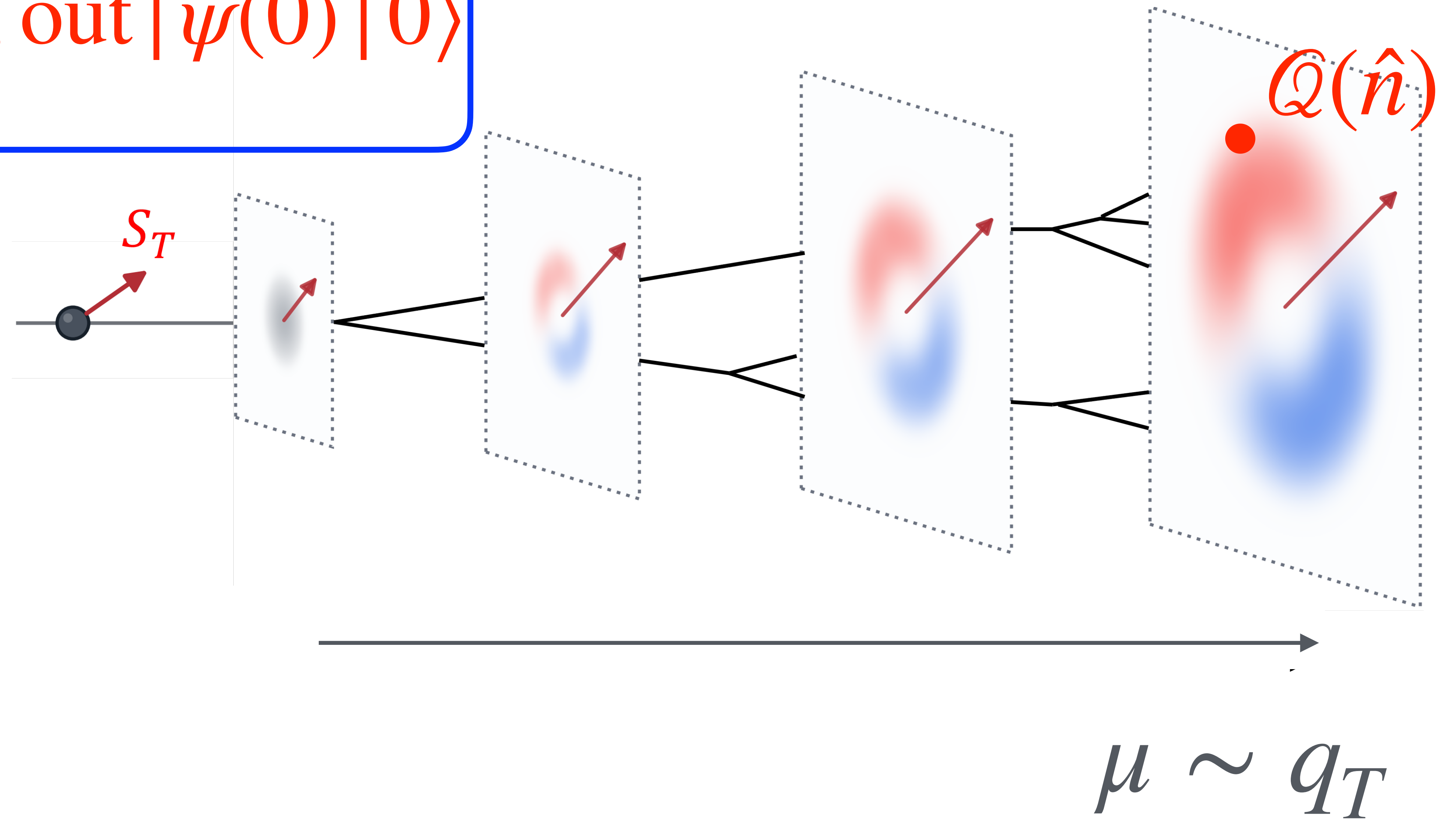
$$\sum_h Q_h \int d\Phi_h \frac{p_{hT,\alpha}}{z_h}\boxed{\ldots\frac{i\sigma^\rho\gamma_5}{2}\langle 0|\psi(\xi,\vec{x}_T)\sum\!\!\!\!\!\!\int_{X'}|hX', \mathrm{out}\rangle\langle hX', \mathrm{out}|\bar{\psi}(0)|0\rangle}$$

1st moment of

Collins Function

Collins effect ~ dipole moment

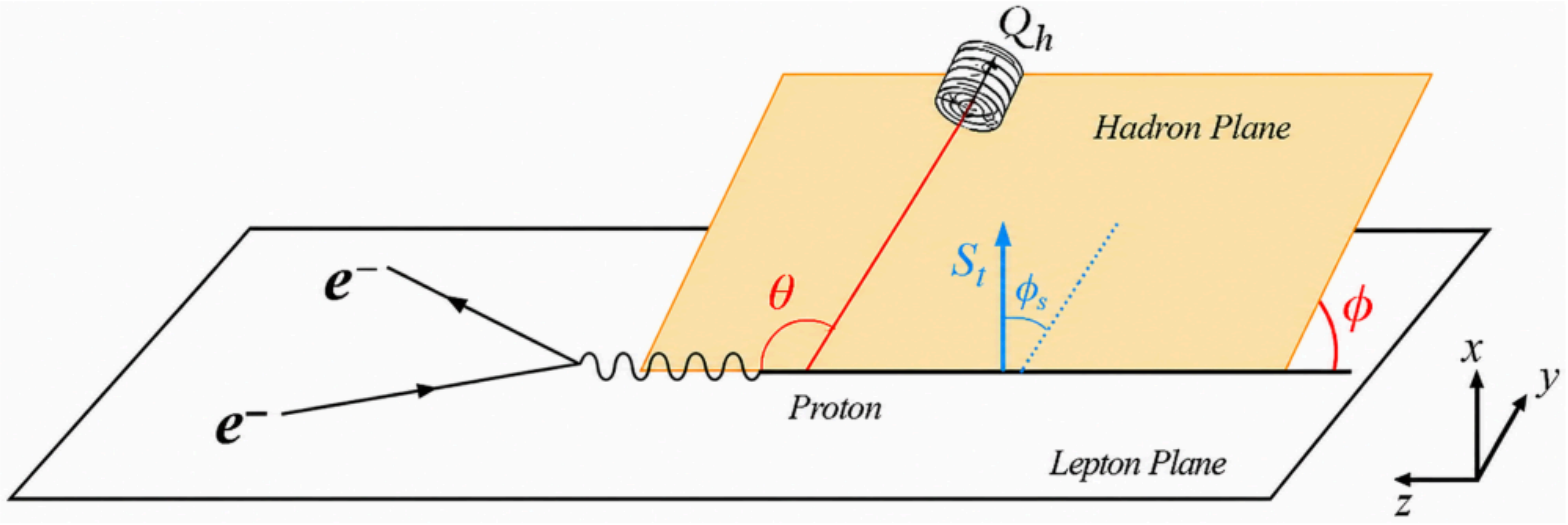


Phenomenology

- measurement w/ track + angular information only, but probe similar physics as the TMDFF

$$\Sigma_Q(\vec{n}, x_B, Q^2) = \sum_h \int d\sigma_{ep^\uparrow \to eh+X}\, Q_h\, \delta(\vec{n} - \vec{n}_h)$$

$$= F_{UU} + |S_t| \sin(\phi - \phi_S)\, F_{UT} + \dots .$$



$\theta \to \pi$ 2605.15280

Phenomenology

- measurement w/ track + angular information only, but probe similar physics as the TMDFF

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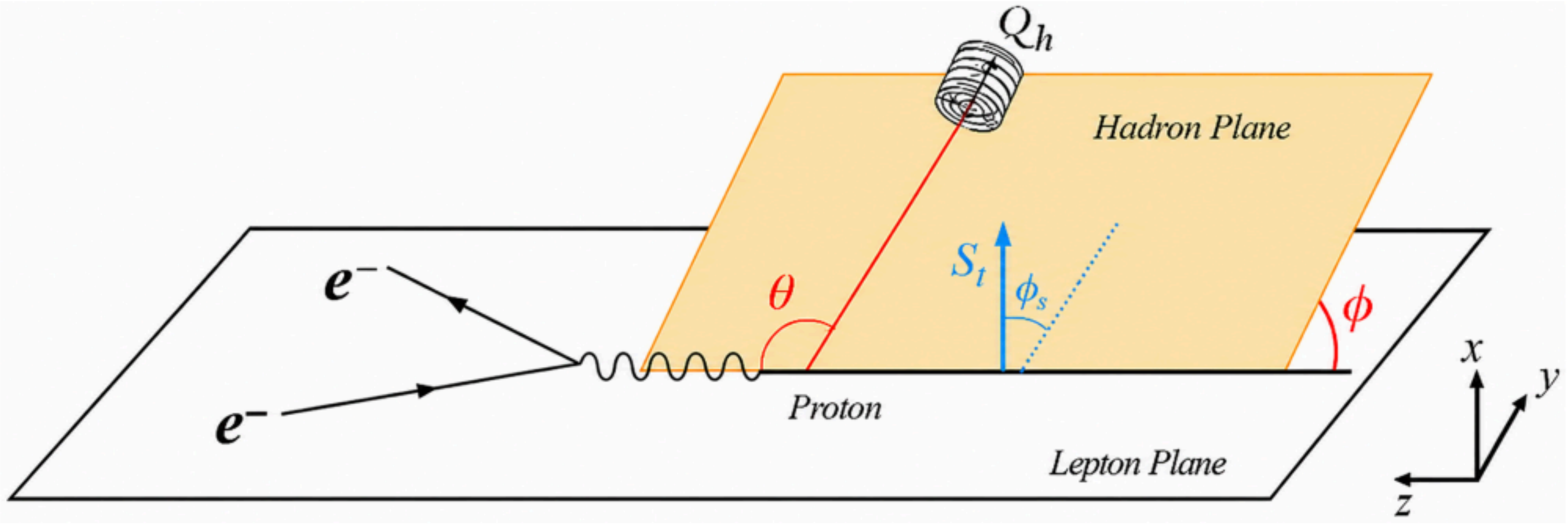

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- Factorization

$$F_{UU} = \sigma_0 H(Q^2, \mu) \frac{\bar{\theta} Q^2}{4} \int_0^\infty \frac{b\, db}{2\pi} J_0\left(b \frac{Q\bar{\theta}}{2}\right) \times \sum_f e_f^2 J_{f,\mathcal{Q}}(b, \mu, \nu) f_1^f(x_B, b, \mu, \nu) S(b, \mu, \nu)$$

$$F_{UT} = \sigma_0 H(Q^2, \mu) \frac{\bar{\theta} Q^2}{4} \int_0^\infty \frac{b^2\, db}{4\pi} J_1\left(b \frac{Q\bar{\theta}}{2}\right) \times \sum_f e_f^2 J_{f,\mathcal{Q}}(b, \mu, \nu) f_{1T}^{\perp,f}(x_B, b, \mu, \nu) S(b, \mu, \nu)$$

Overall vanishing contribution to the charge from soft radiation due to its charge conjugation symmetry

Exactly the TMD-like factorization with TMD FF replaced by the Transverse Charge Distribution

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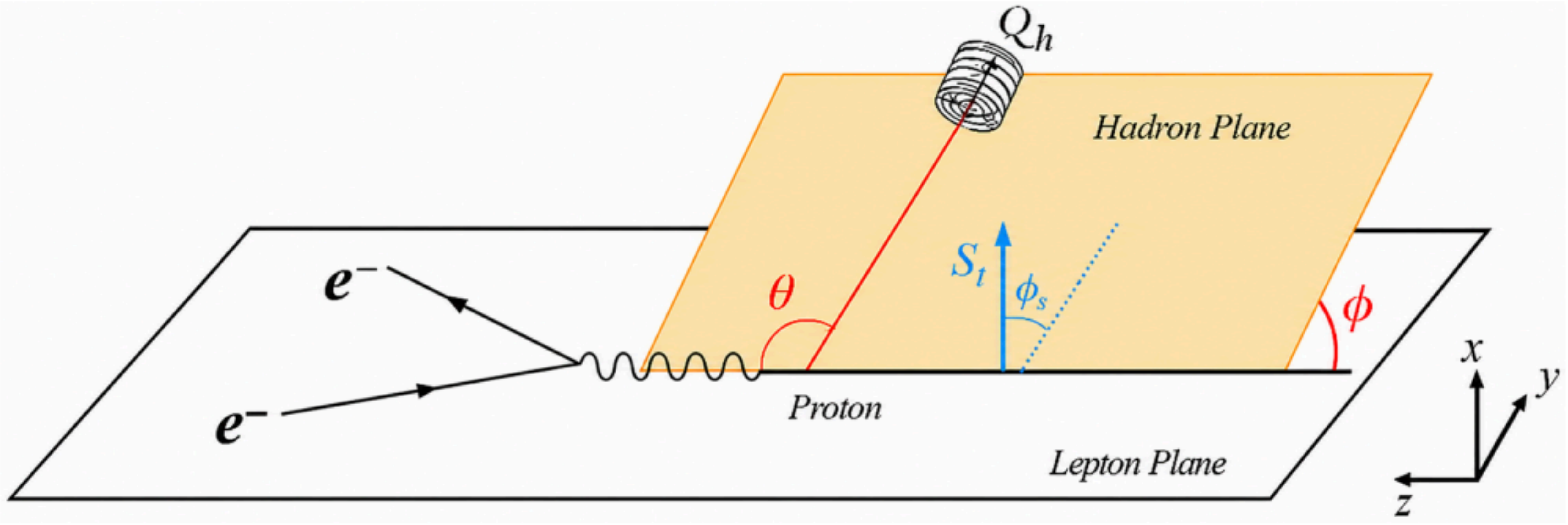

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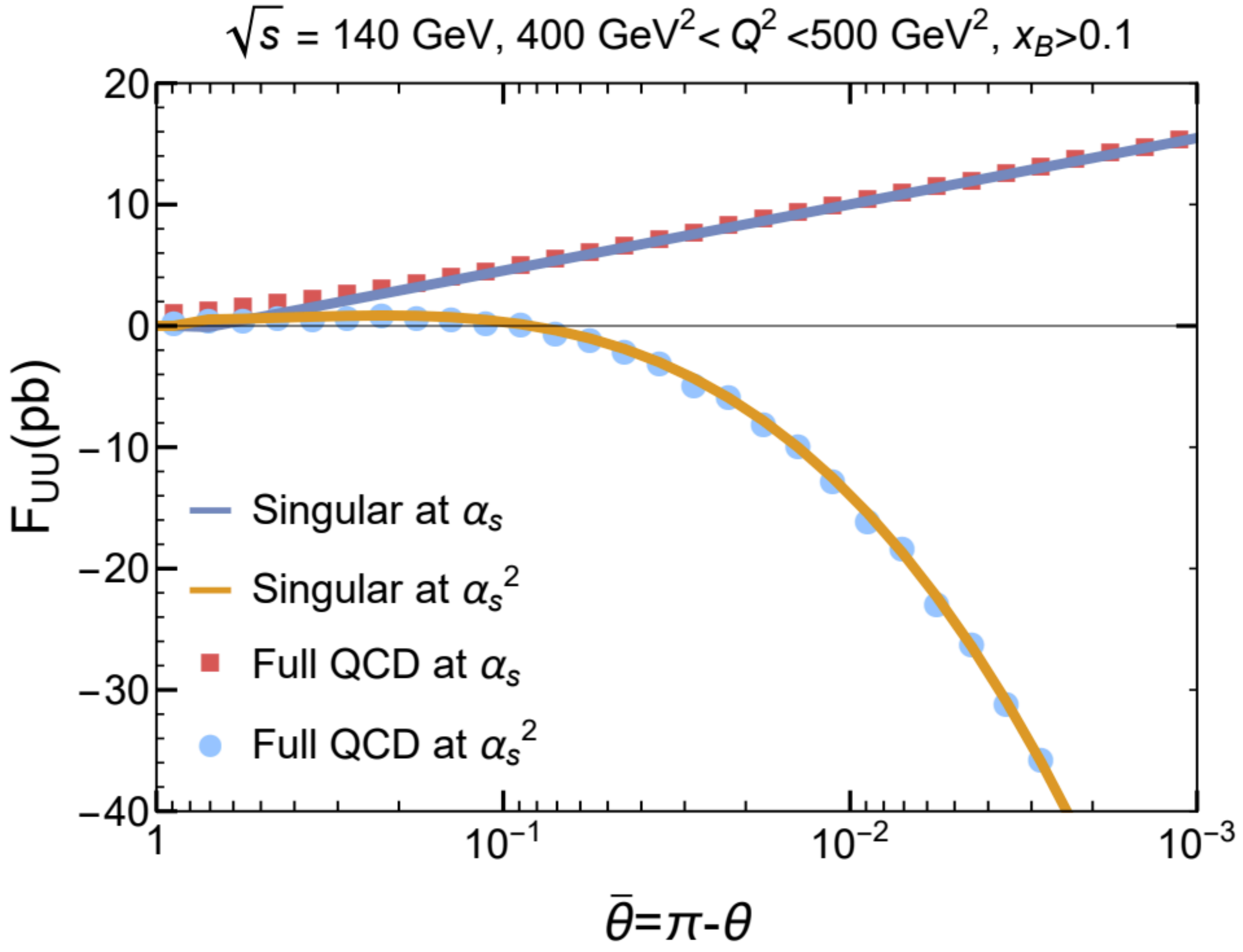

Test of the factorization

Good agreement between full QCD and results from the factorization

$\Rightarrow$

Singular behavior captured by the factorization

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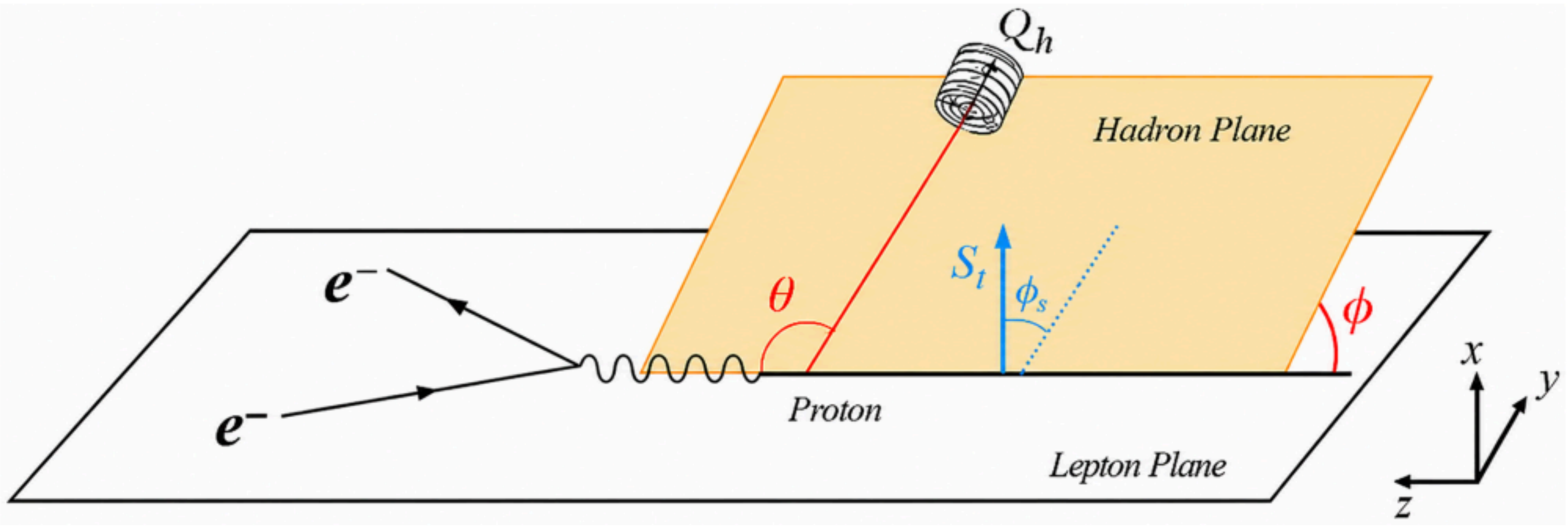

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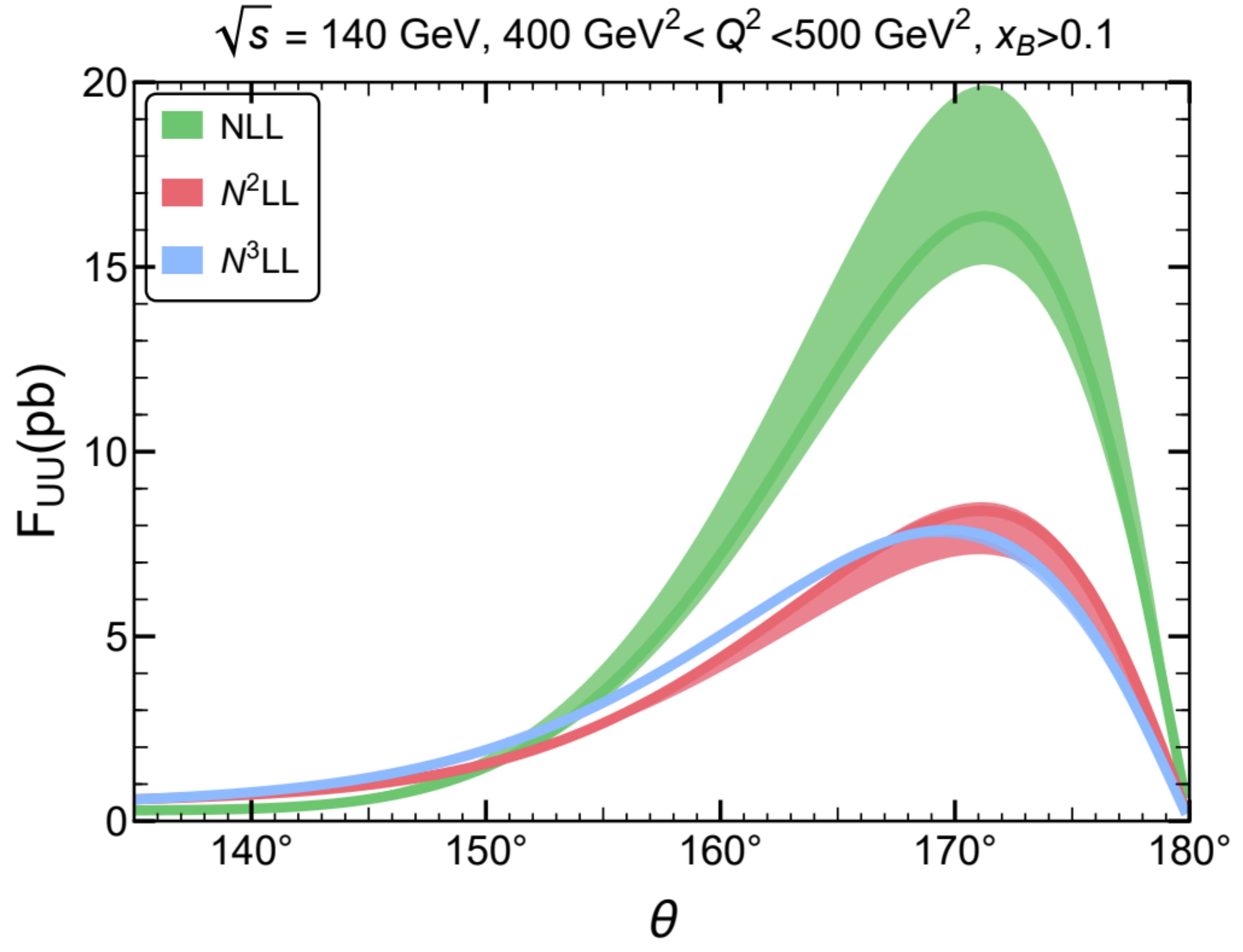

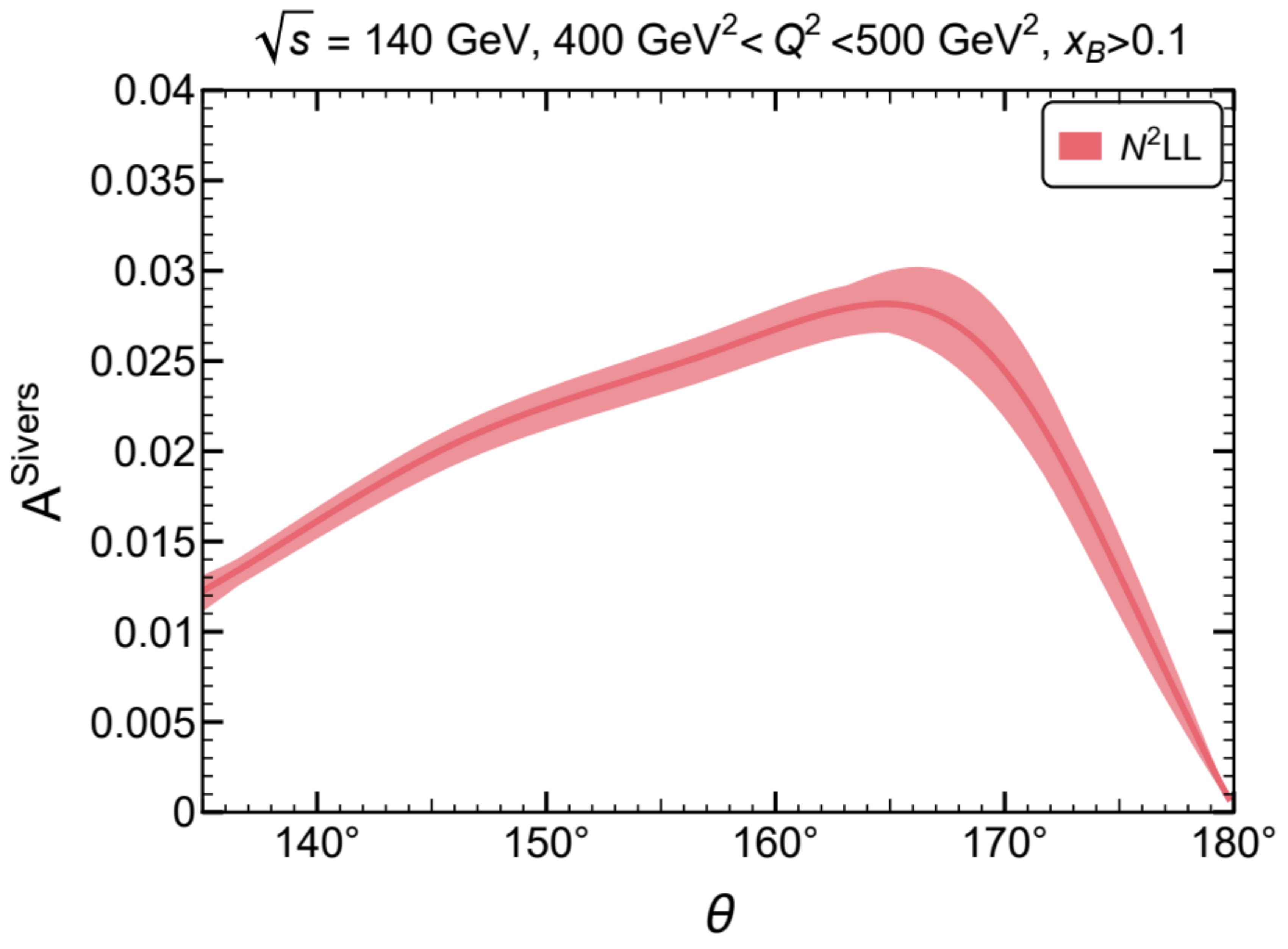

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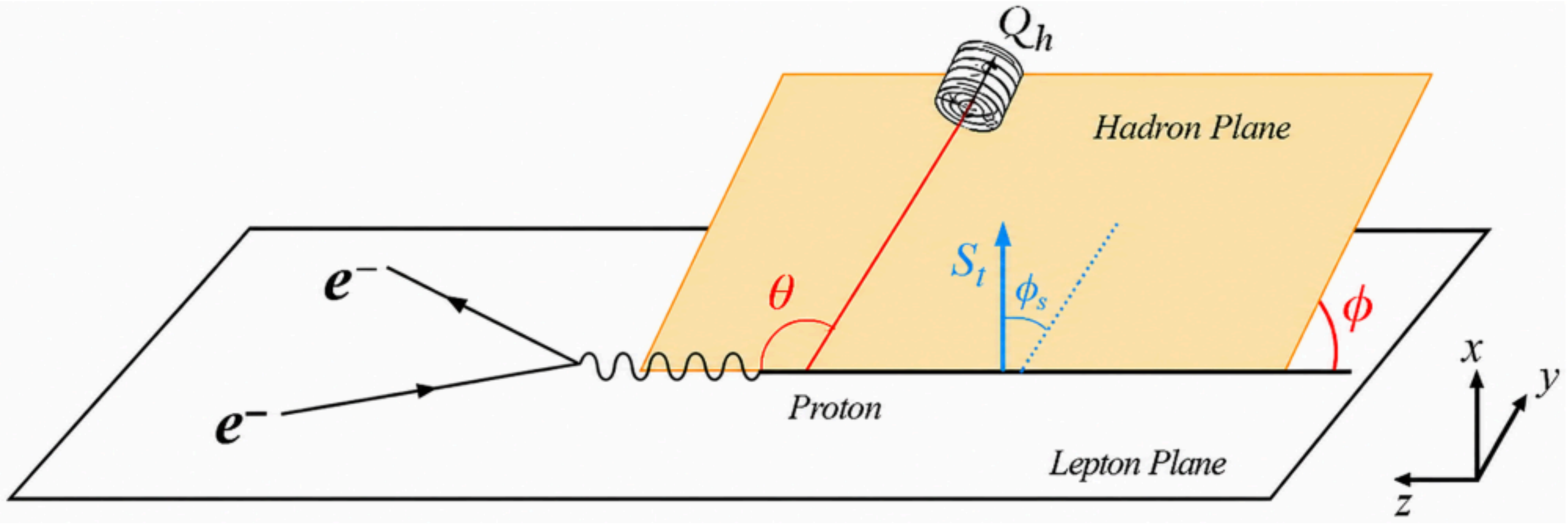

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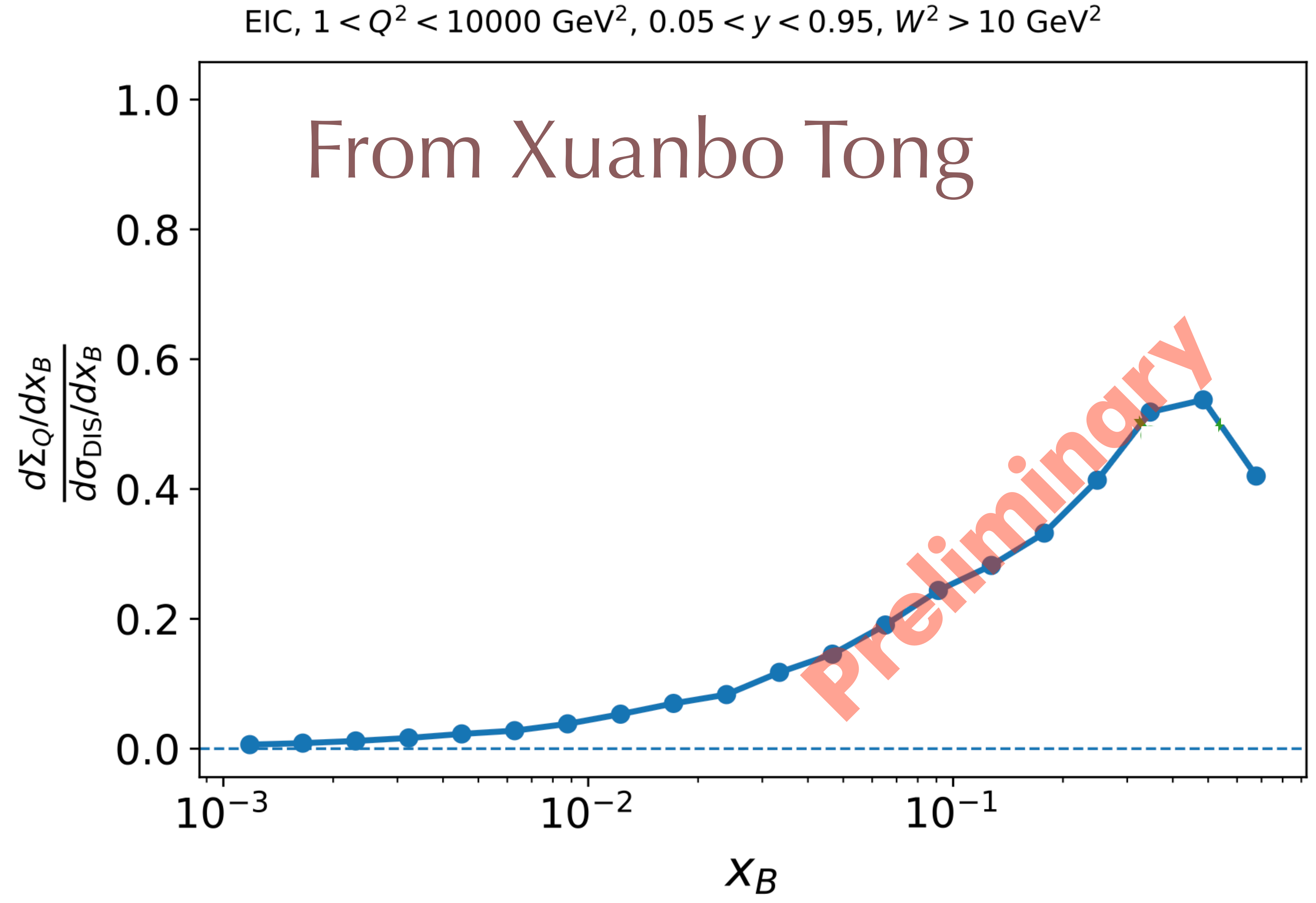

- $x \to 0$, gluon PDF dominant, $F_{UU} \to 0$
- Increasing sensitivity to charge-odd signals, e.g., spin-dependent odderon induced by quarks (see jianzhou's talk)

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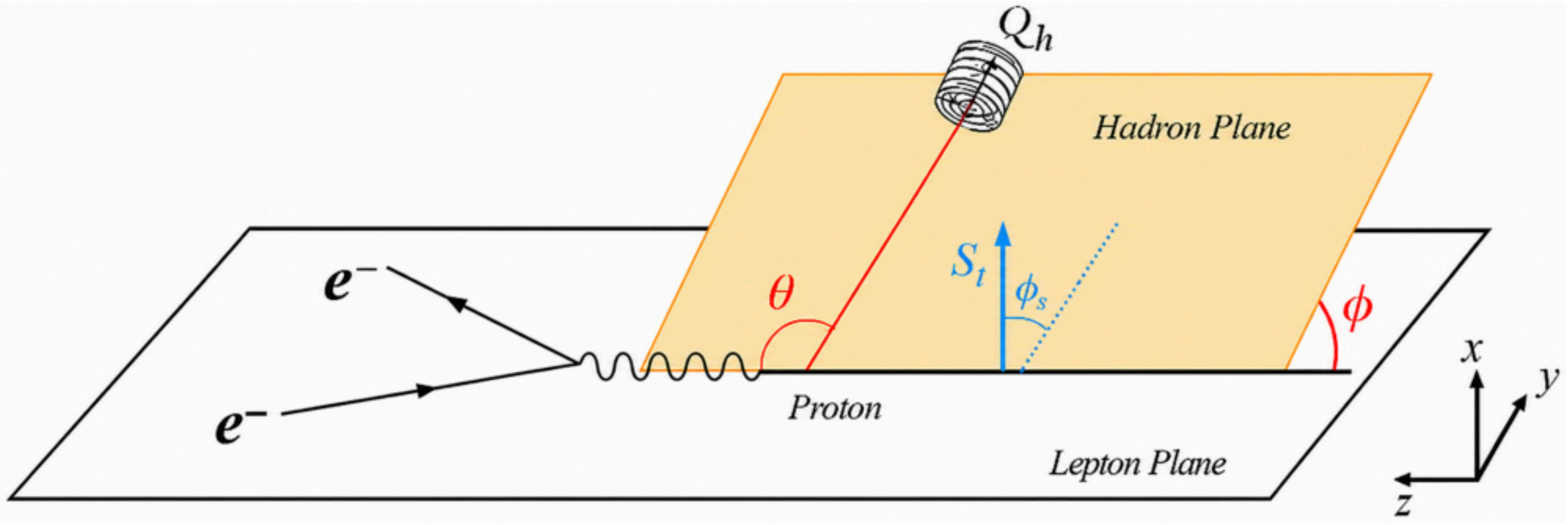

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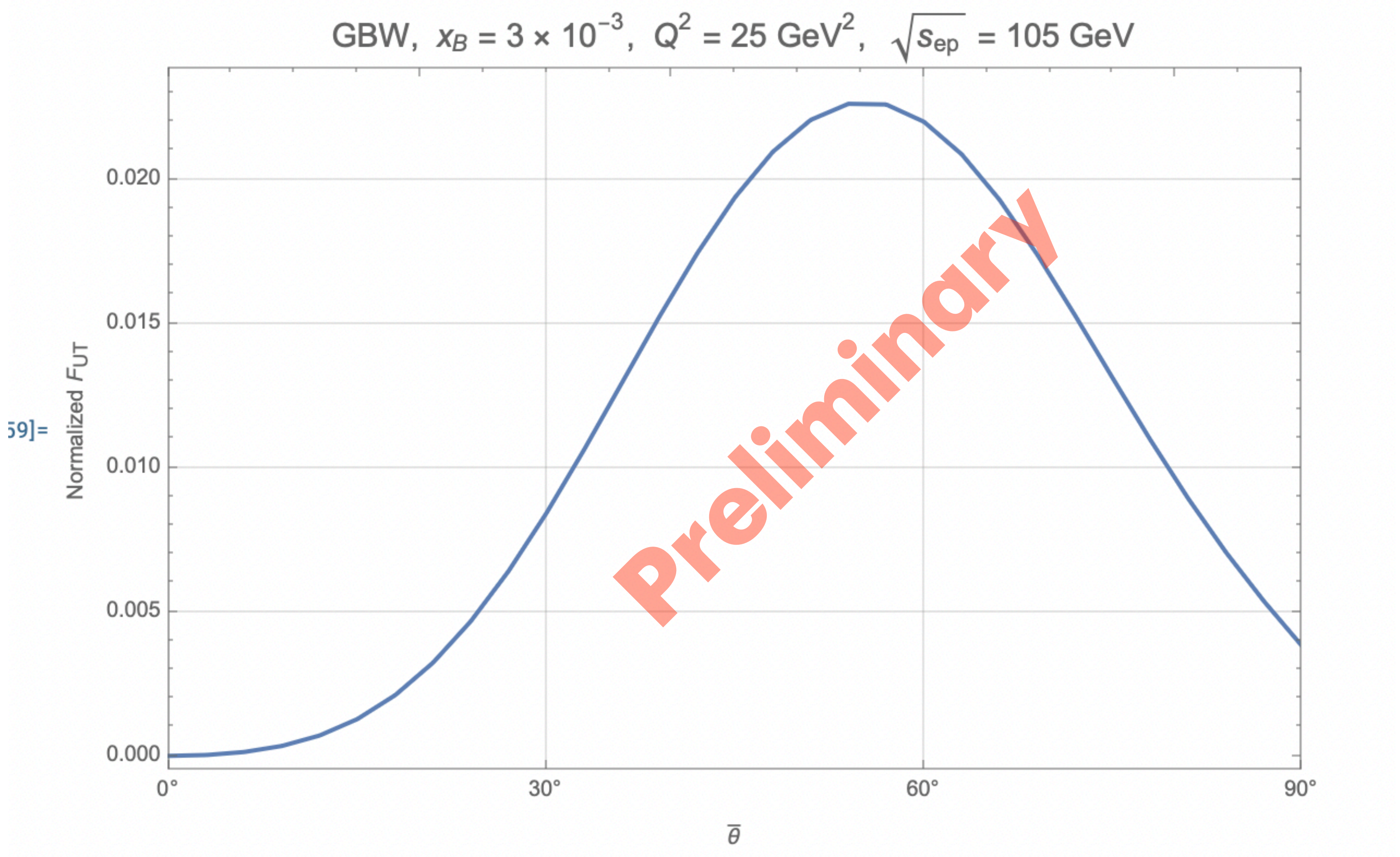

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Phenomenology

- Probing transversity

$$\frac{\mathrm{d}\Sigma_Q}{\mathrm{d}\theta_n\,\mathrm{d}\phi_n\,\mathrm{d}\eta\,\mathrm{d}p_T} = \sum_{h\in J}\int \mathrm{d}^2\Omega_h\, Q_h\, \delta(\theta_n-\theta_h) \times \delta(\phi_n-\phi_h)\frac{\mathrm{d}\sigma}{\mathrm{d}^2\Omega_h\,\mathrm{d}\eta\,\mathrm{d}p_T}$$

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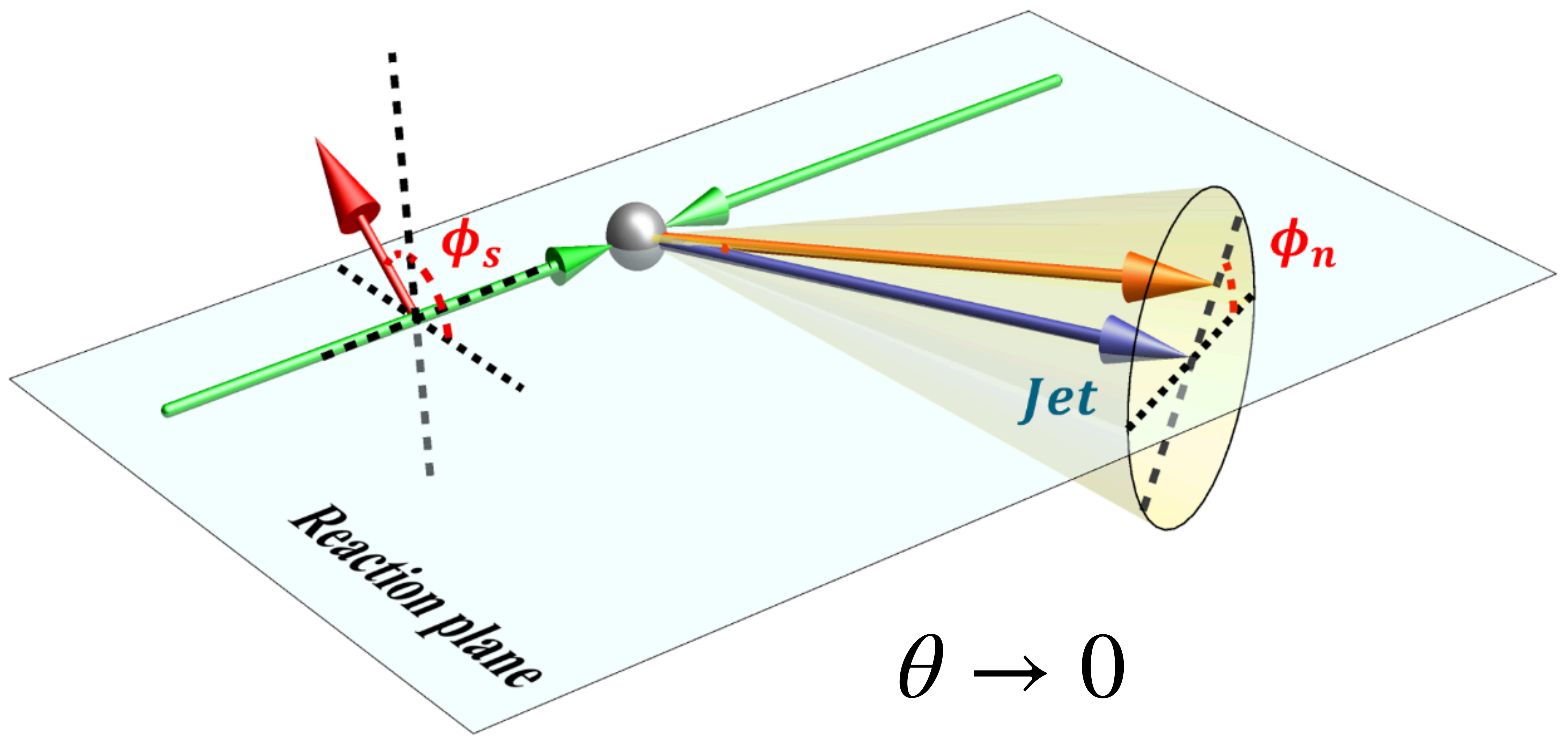

$\theta \to 0$

Li et al.

Phenomenology

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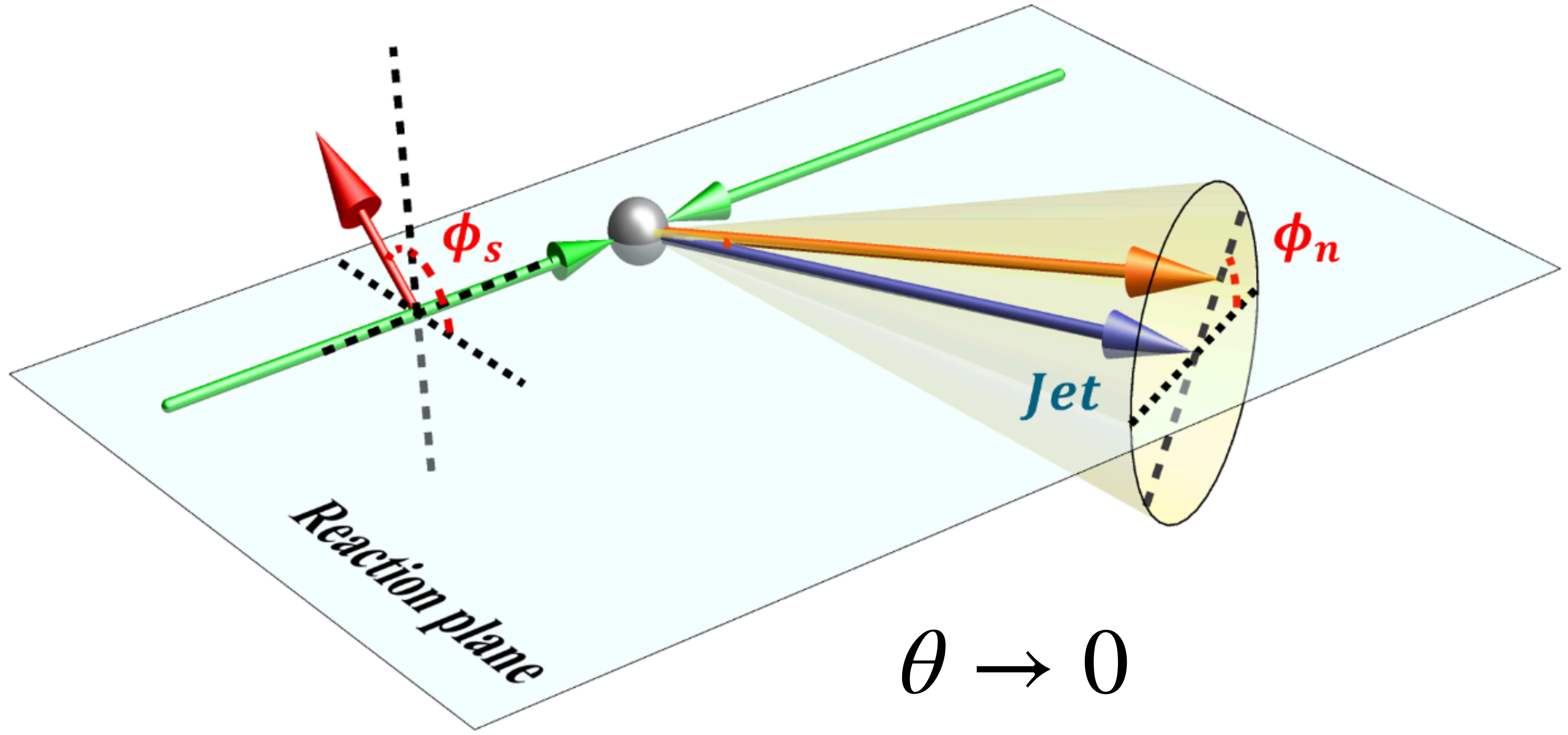

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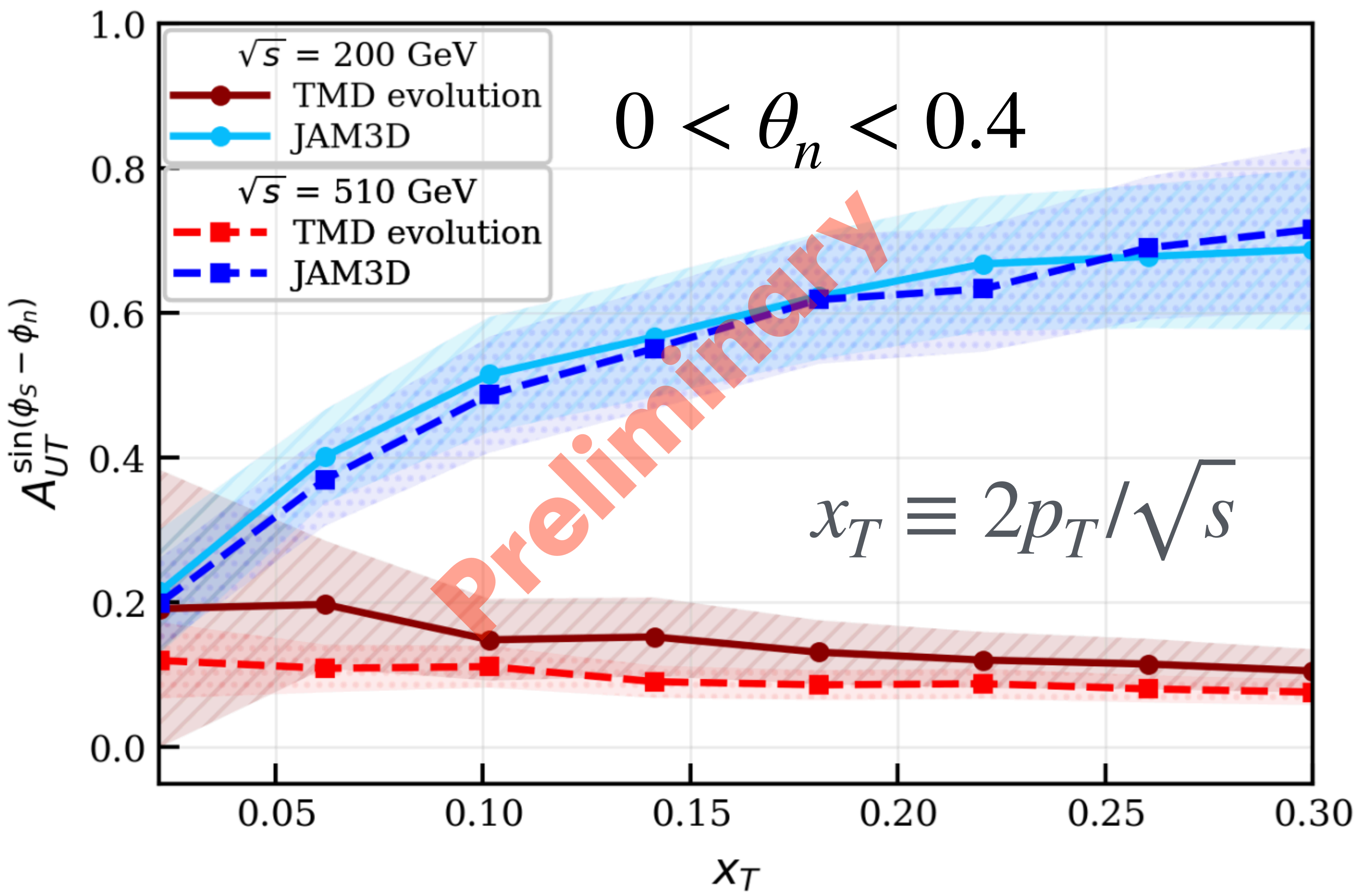
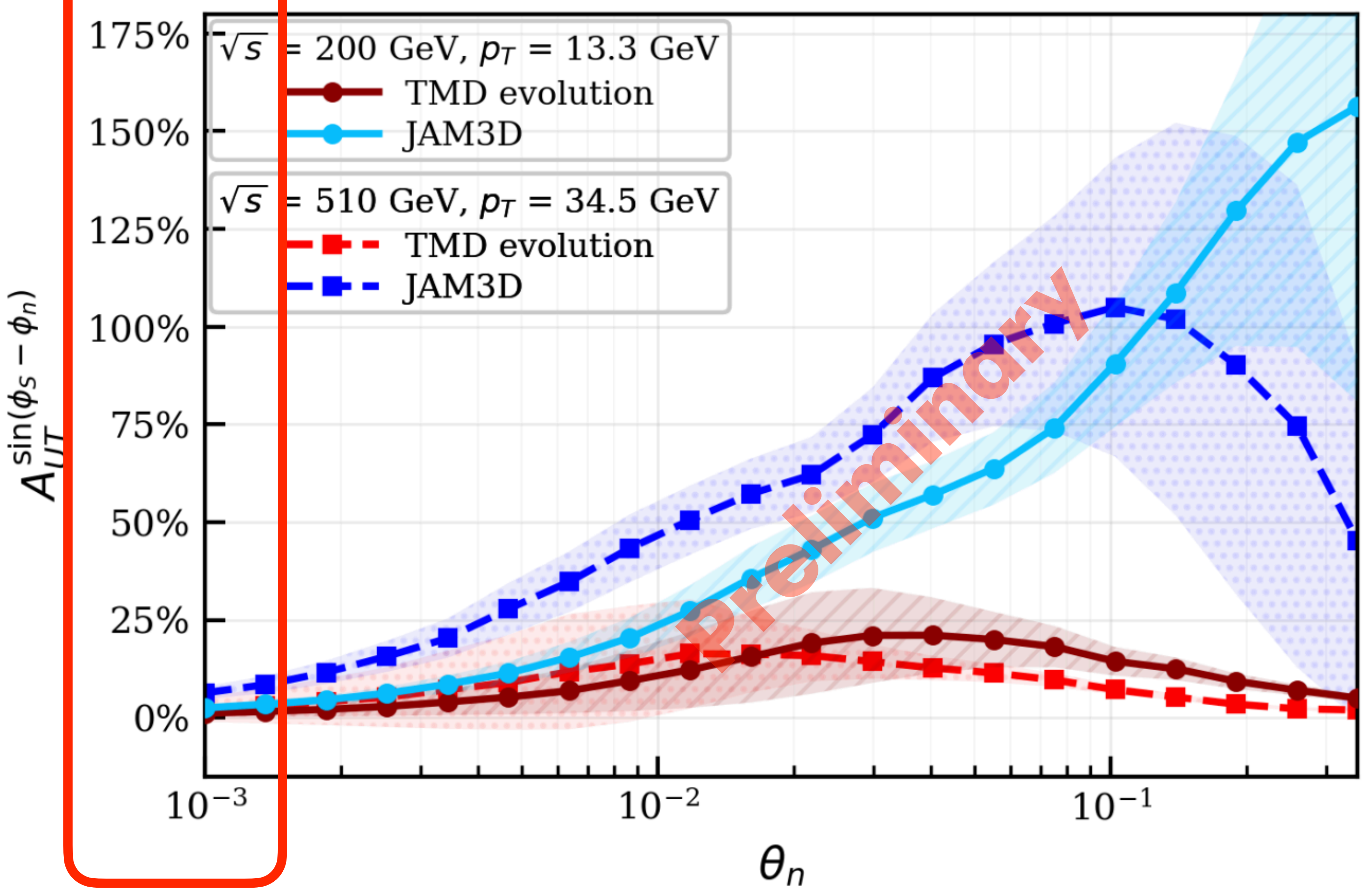
Li et al.





Conclusion

- One Point Correlator complements the hadronization studies
  - Theoretically clean, known with high precision
  - A probe requires only track and angular information
  - Improved sensitivity to C-odd signals
- Conclusion