Correlations in Partonic and Hadronic Interactions - 2020 (CPHI-2020)

3-7 February, 2020
CERN, Geneva
Switzerland

QCD factorization and hadron production near threshold

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February 6, 2020

Jefferson Lab

TMD Collaboration

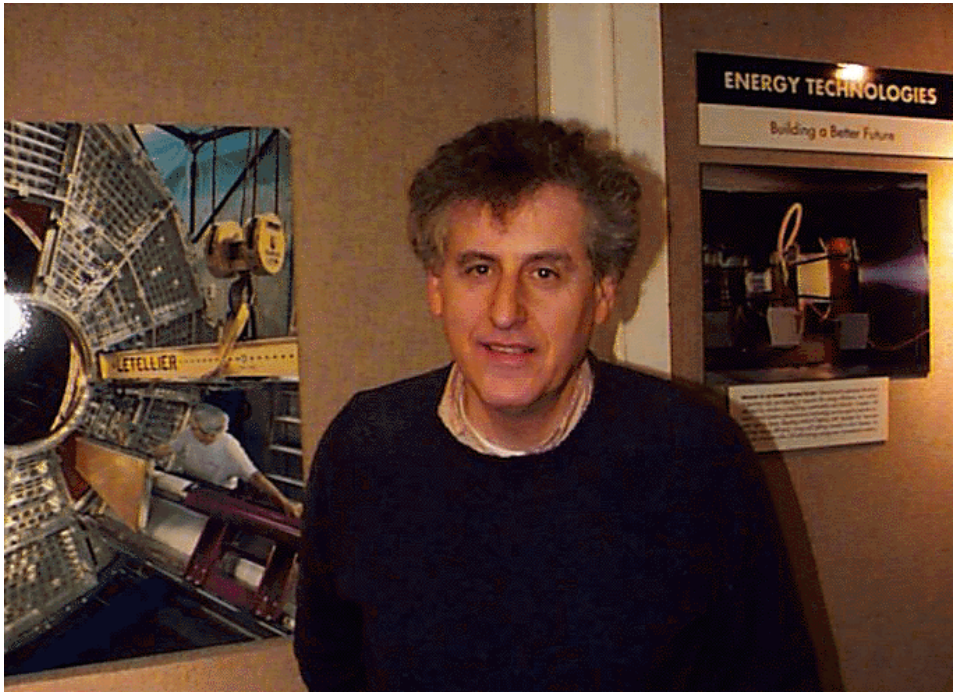
U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

“Shocking Reality”

Stan is 80!

Really? I do not believe it!



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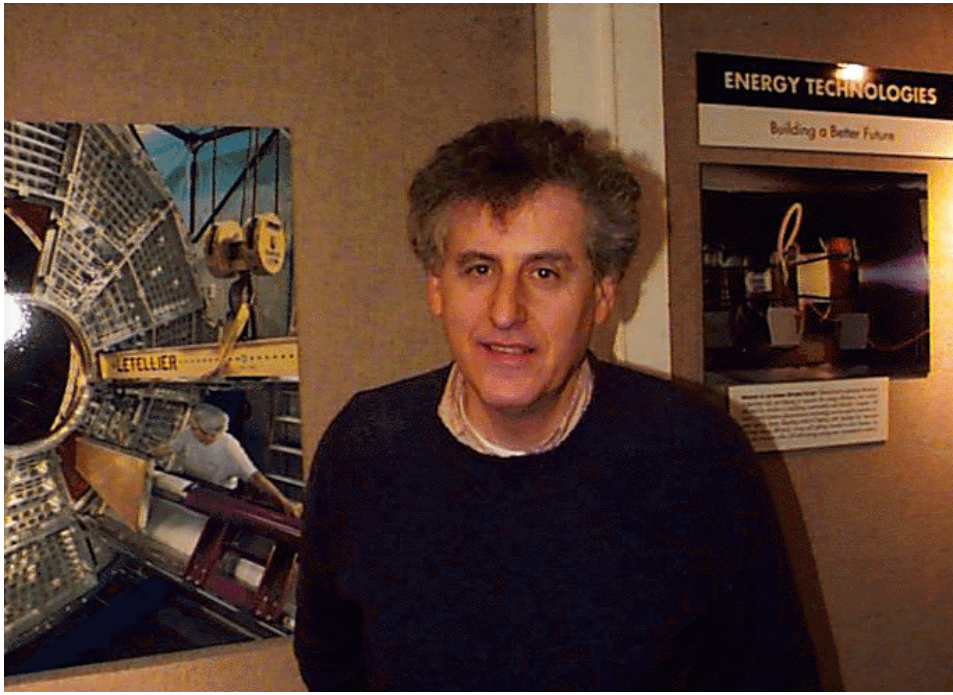

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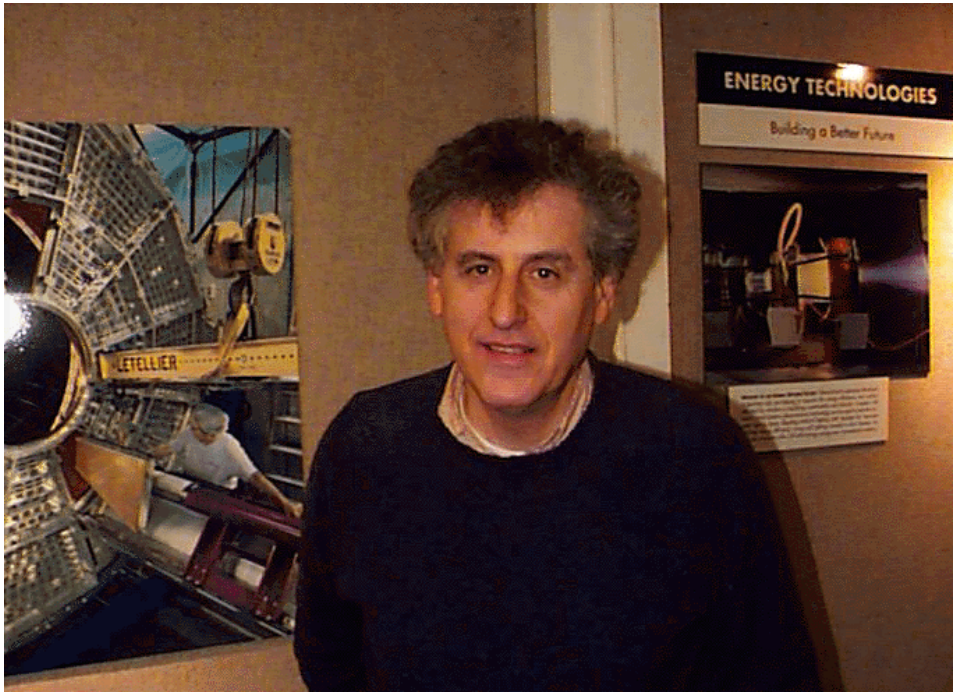

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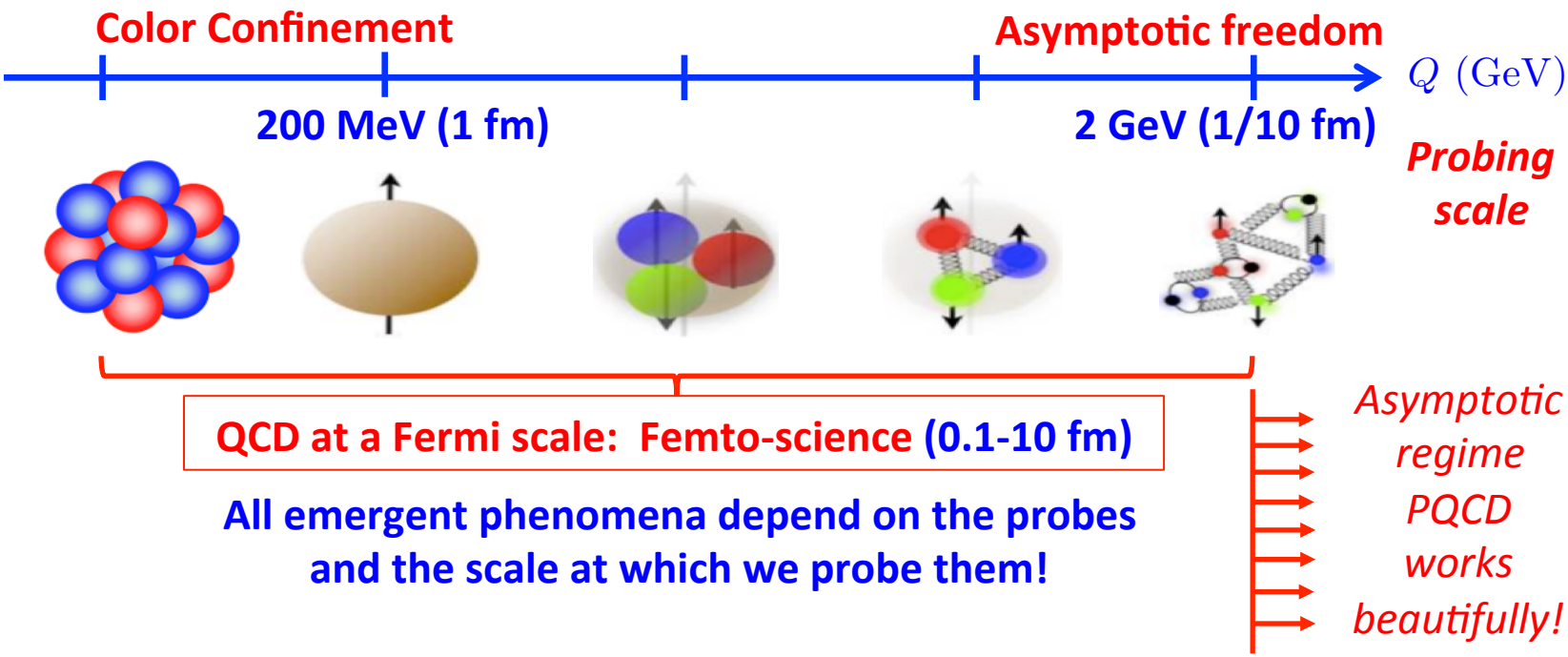
LET’S CELEBRATE!

QCD and the Structure of Nucleons and Nuclei

❑ QCD – Color Confinement:

- ✧ Do not see any quarks and gluons in isolation
- ✧ The structure of nucleons and nuclei – emergent properties of QCD



All emergent phenomena depend on the probes and the scale at which we probe them!

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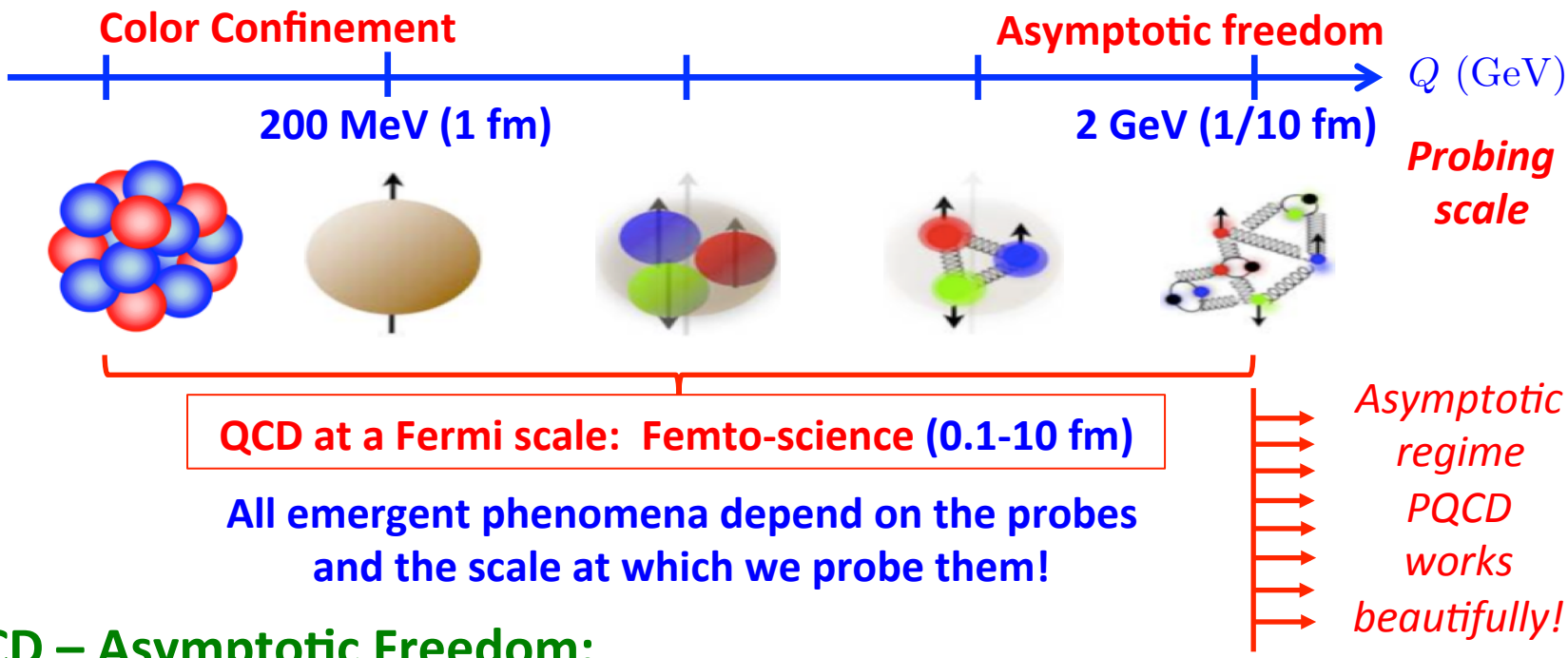

All emergent phenomena depend on the probes and the scale at which we probe them!

❑ QCD – Asymptotic Freedom:

- ✧ QCD Factorization – Controllable Approximation
- ✧ Explore the structure of nucleons and nuclei by using "controllable", "sharp" and "local" probes, …

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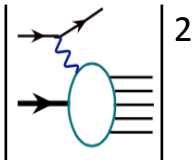
“See” the Structure of Nucleons and Nuclei

- Cross section with identified hadron is NOT perturbatively calculable!

$$\sigma_{\mathrm{DIS}}(x, Q^2) =$$



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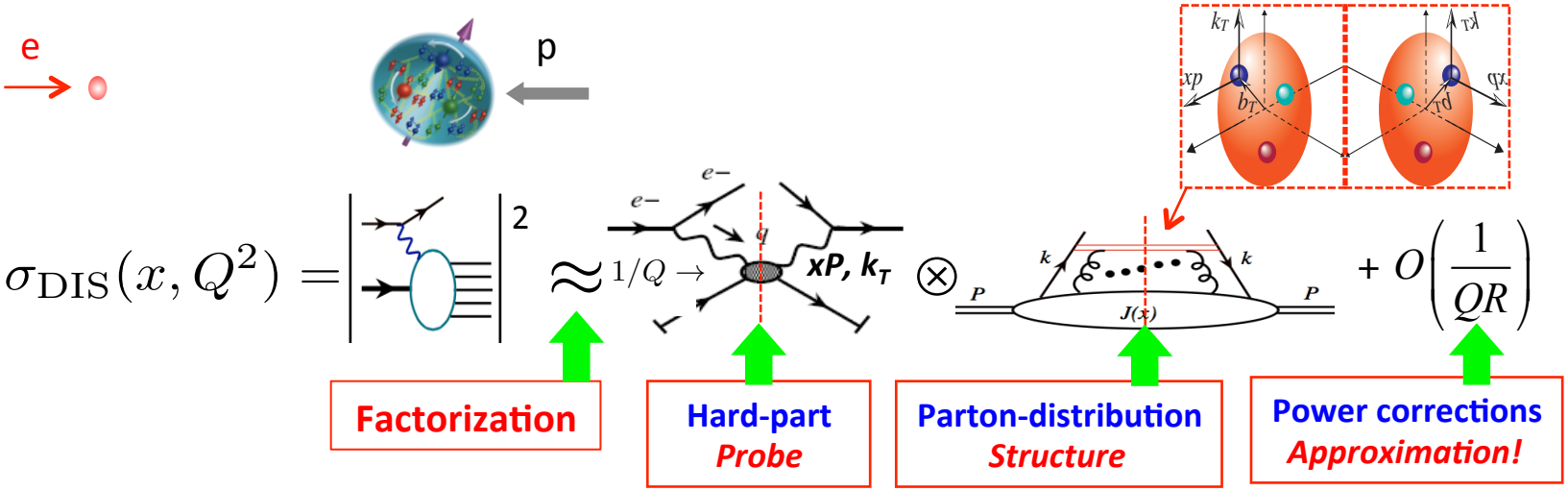

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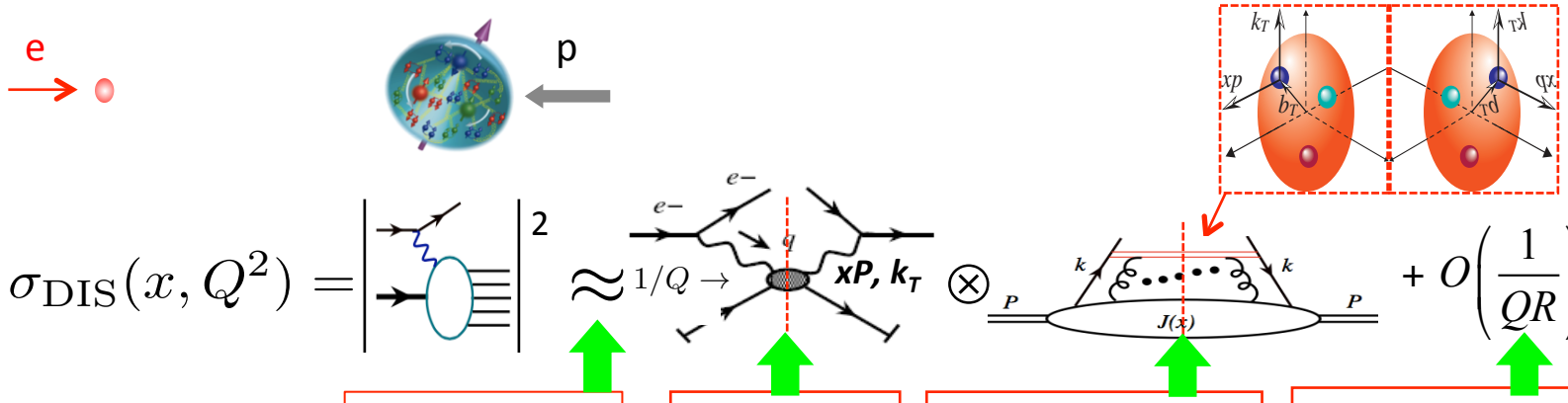

Factorization

Hard-part *Probe*

Parton-distribution *Structure*

Power corrections *Approximation!*

Structure: in terms of quantum probability distributions, correlations – matrix elements

"See" the Structure of Nucleons and Nuclei

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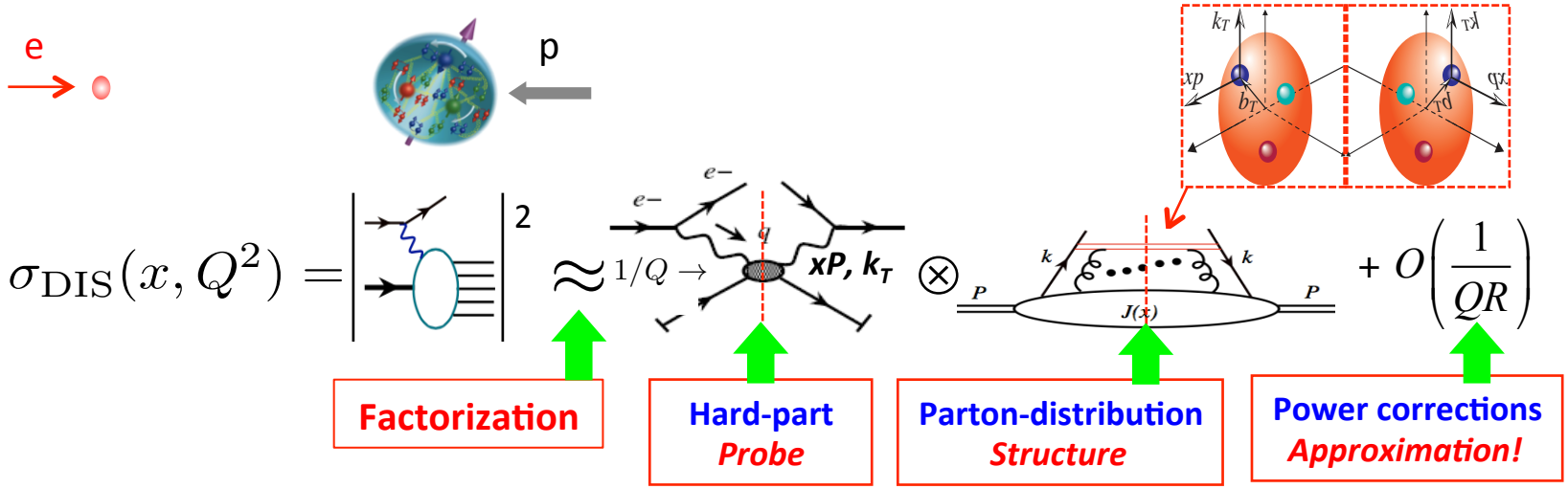
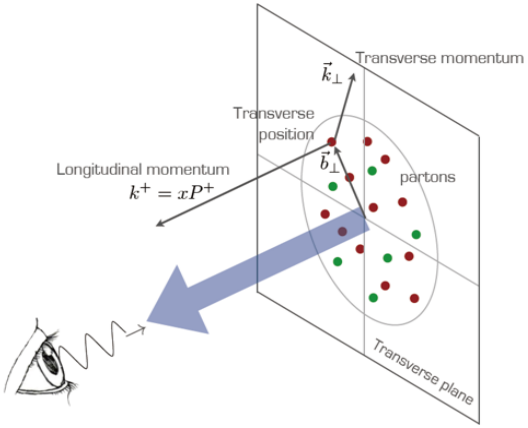


Structure: in terms of quantum probability distributions, correlations – matrix elements

- **Need to identify observables with two-momentum scales:**

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

- ✧ **Hard scale:** localizes the probe
  particle nature of quarks/gluons
- ✧ **"Soft" scale:** could be more sensitive to the
  hadron structure ~ 1/fm
- ✧ **Hit the hadron "very hard" without breaking it, clean information on the structure!**



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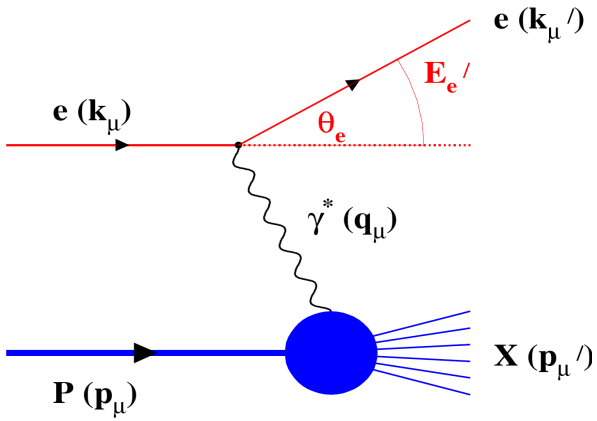
Lepton-Hadron Deep Inelastic Scattering



Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\,x\,y$

- **Many complementary probes at one facility:**

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment – Single hard scale!)

Semi-Inclusive events: e+p/A → e'+h(p,K,p,jet)+X

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

Exclusive events: e+p/A → e'+ p'/A'+ h(p,K,p,jet)

Detect every things including scattered proton/nucleus (or its fragments)

(Initial hadron is NOT broken – tomography!

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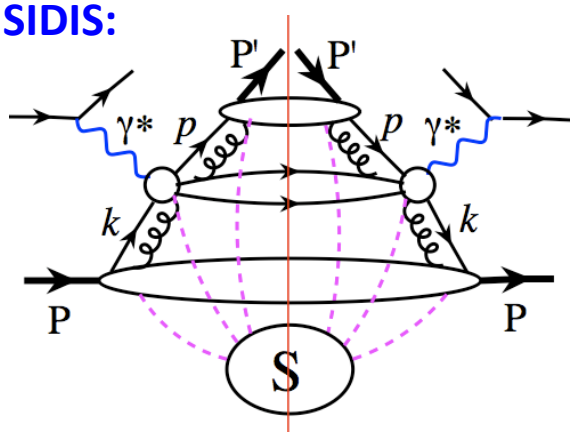
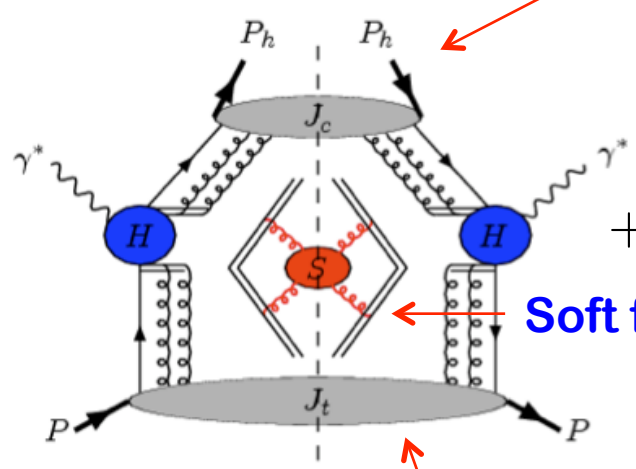
Lepton-Hadron Deep Inelastic Scattering

- QCD is fully color entangled – Factorization:

SIDIS:





$$+\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2},\frac{\langle p^2\rangle}{Q^2}\right)$$

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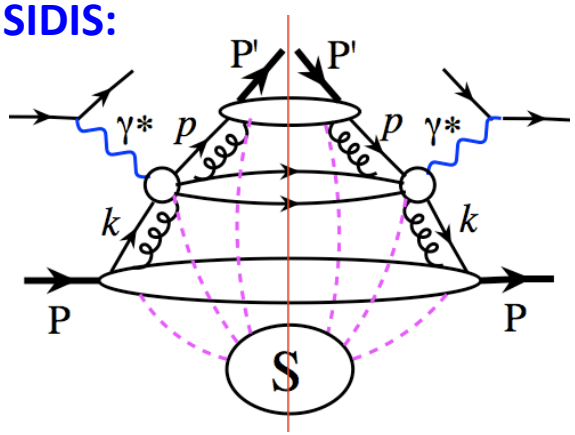

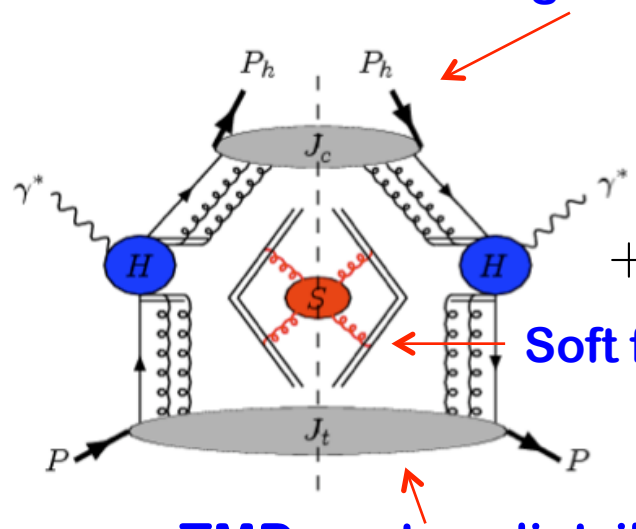

$$+\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2},\frac{\langle p^2\rangle}{Q^2}\right)$$

- **Low P_{hT} – TMD factorization:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h)=\hat{H}(Q)\otimes\Phi_f(x,k_\perp)\otimes\mathcal{D}_{f\to h}(z,p_\perp)\otimes\mathcal{S}(k_{s\perp})+\mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

- **High P_{hT} – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h)=\hat{H}(Q,P_{h\perp},\alpha_s)\otimes\phi_f\otimes D_{f\to h}+\mathcal{O}\left(\frac{1}{P_{h\perp}},\frac{1}{Q}\right)$$

- **P_{hT} Integrated - Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q,x_B,z_h)=\tilde{H}(Q,\alpha_s)\otimes\phi_f\otimes D_{f\to h}+\mathcal{O}\left(\frac{1}{Q}\right)$$

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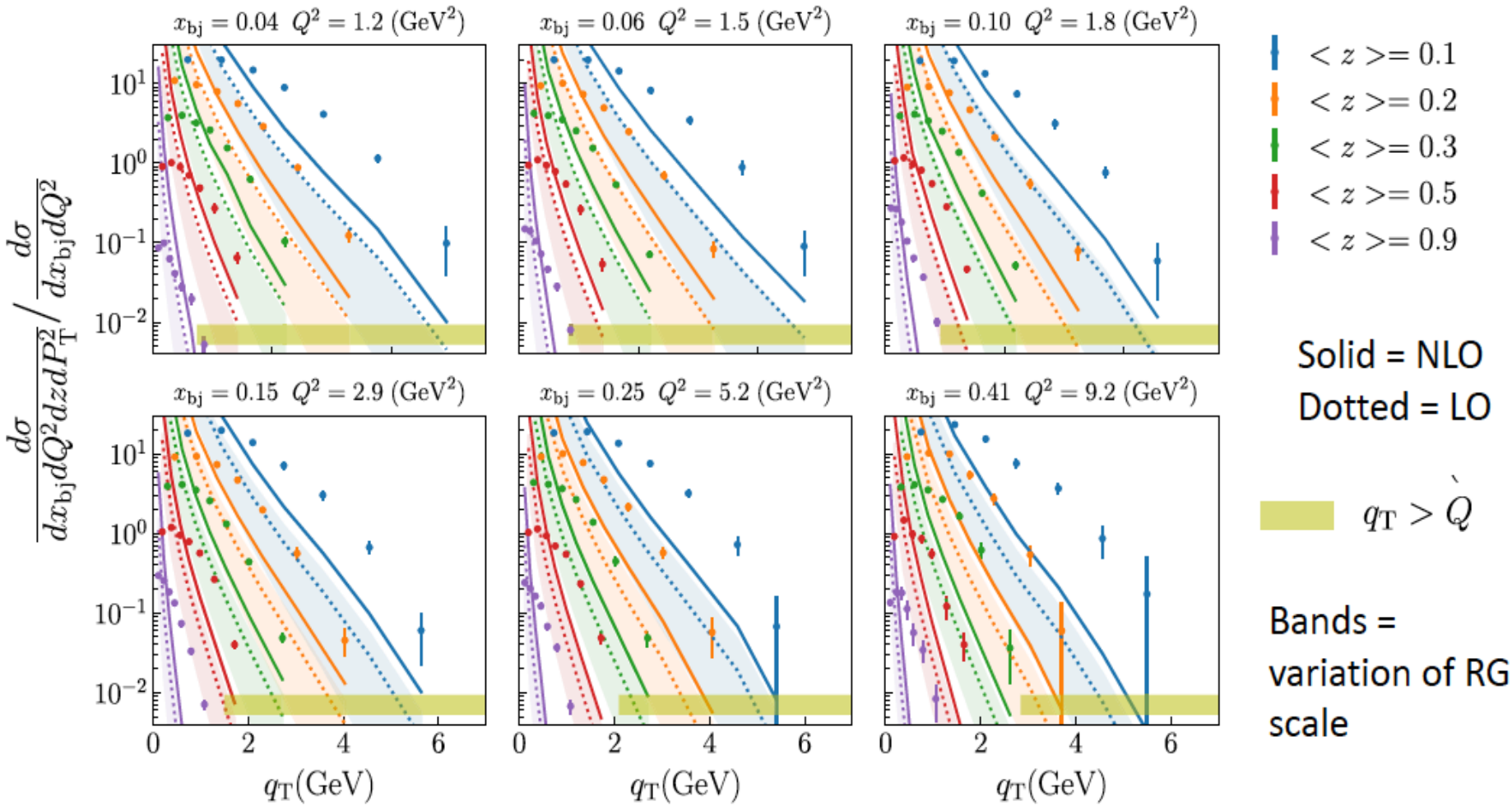
Surprise from COMPASS

- **SIDIS production of charge hadron:**

Also see Ted Rogers' talk



Data: M. Aghasyan et al. (COMPASS Collaboration), Phys. Rev. D97 (2018) 032006

Theory: B. Wang et al. Phys. Rev. D99 (2019) 094029

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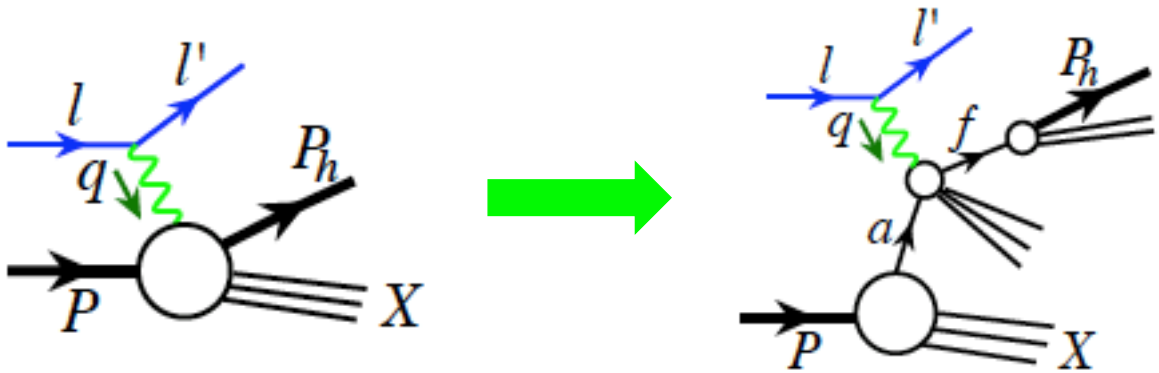
Theoretical Calculations



$$x_B = \frac{Q^2}{2P \cdot q}, \quad z_h = \frac{P \cdot P_h}{P \cdot q}$$

- **QCD factorization is an approximation – leading power:**

$$\frac{d\sigma_{l+P\to l'+P_h+X}}{d^3\mathbf{l}'/(2E')\, d^3\mathbf{P}_h/(2E_h)} \approx \sum_{i,j} \int_{x_B}^{1} \frac{dx}{x} \int_{z_h}^{1} \frac{dz}{z^2}\, \phi_{i/P}(x)\, D_{j\to h}(z)\, \frac{d\hat{\sigma}_{l+i\to l'+j+X}}{d^3\mathbf{l}'/(2E')\, d^3\mathbf{p}/(2E_p)}$$

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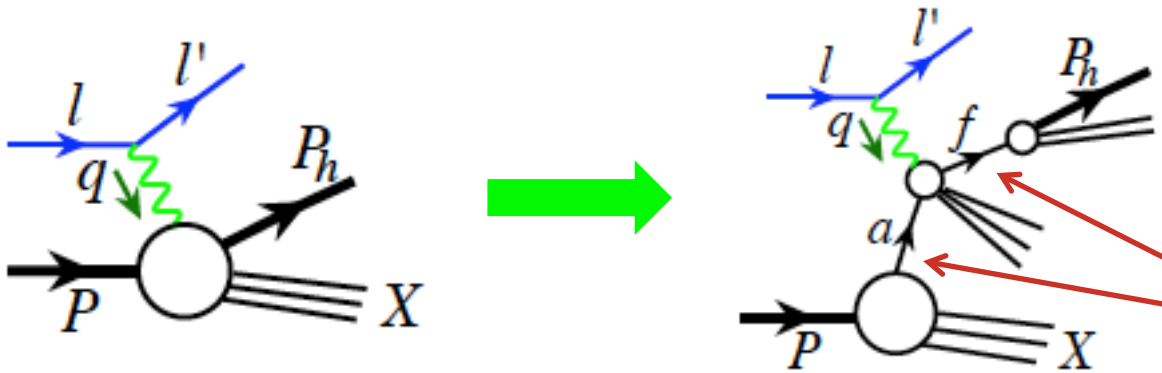

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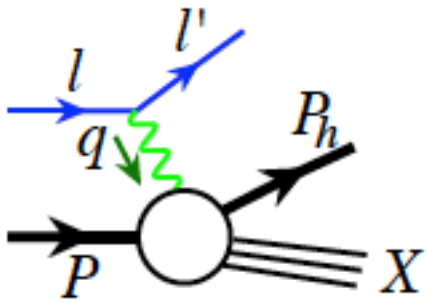
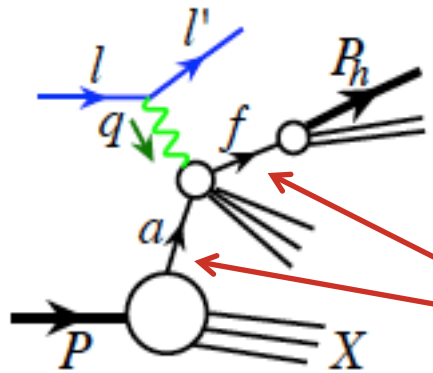
- Where does the color go?

Theoretical Calculations





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Colored !

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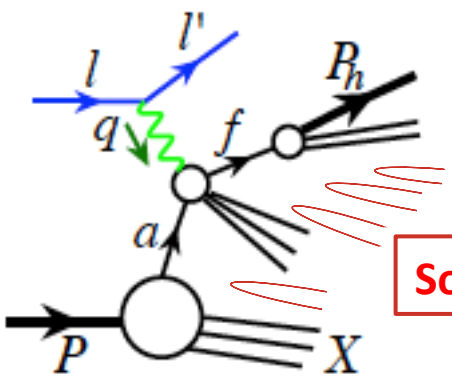

Soft pions

Color neutralization needs:

- ✧ Large enough phase space to shower
- ✧ Sufficiently high multiplicity
- ✧ AND: $E_{\text{pions}} \ll E_h$ for factorization

Near threshold – low multiplicity?

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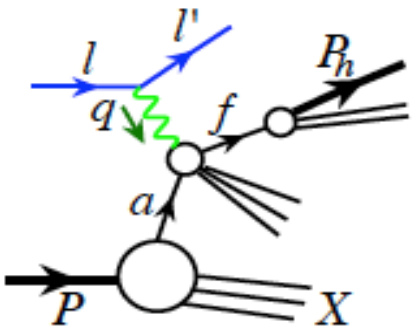
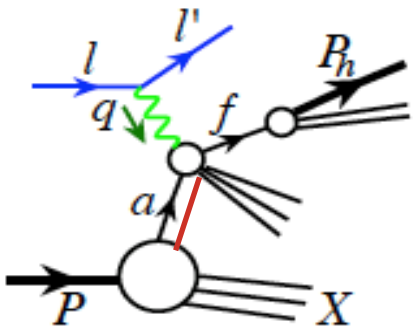
Much Enhanced Power "Corrections" – High p_T

arXiv:1907.06136
T. Liu & J.W. Qiu



$$\mathcal{O}\left(D_f(z)\right)$$

+



$$\mathcal{O}\left(\frac{1}{Q^2} \times D_f(z)\right)$$

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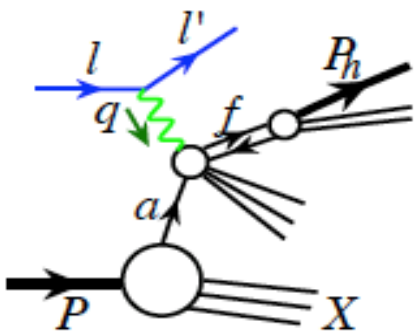

$$\mathcal{O}\left(\frac{1}{P_T^2} \times \mathcal{D}_{qq'}(z, \ldots)\right)$$

+ …

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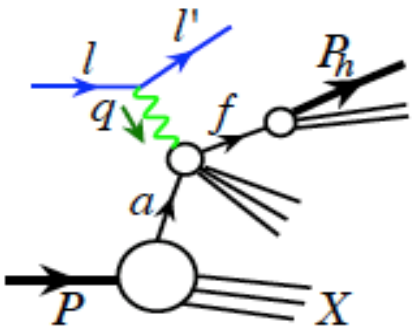

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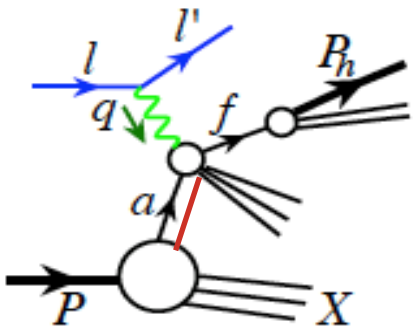

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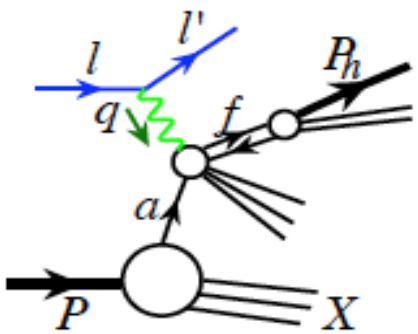

$\mathcal{O}\left(\frac{1}{P_T^2} \times \mathcal{D}_{qq'}(z, \ldots)\right)$

+ ...

- **Low multiplicity events – edge of phase space:**

Large P_T and large $z_h \sim z$

$$\frac{d\sigma_{l+P\to l'+P_h+X}}{d^3\mathbf{l}'/(2E')\, d^3\mathbf{P}_h/(2E_h)} \approx \sum_{i,j} \int_{x_B}^1 \frac{dx}{x} \int_{z_h}^1 \frac{dz}{z^2}\, \phi_{i/P}(x)\, D_{j\to h}(z)\, \frac{d\hat{\sigma}_{l+i\to l'+j+X}}{d^3\mathbf{l}'/(2E')\, d^3\mathbf{p}/(2E_p)}$$

✧ **Leading power:** $\sigma \propto D(z) \propto (1-z)^n \sim (1-z_h)^n$

COMPASS: $\langle z_h \rangle$ as large as 0.9

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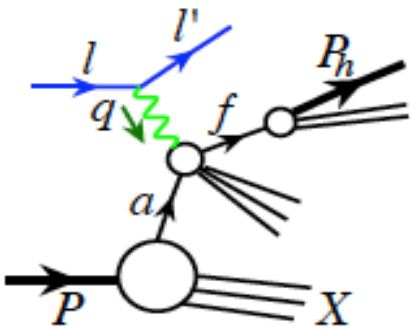

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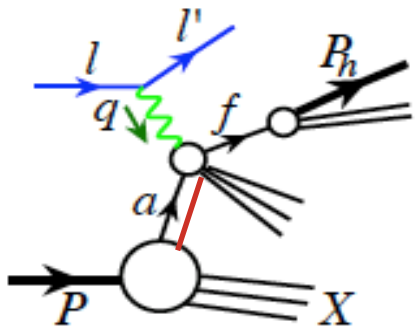

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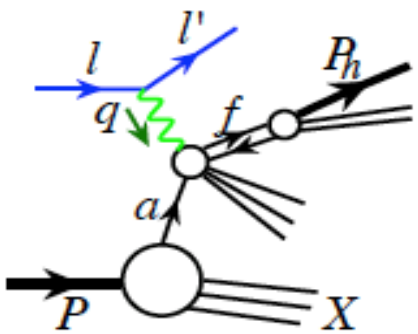

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- **NL power:** $\sigma \propto \frac{1}{P_T^2}\mathcal{D}(z, \ldots) \sim \frac{1}{P_T^2}\,\delta(1-z)$

COMPASS: <z_h> as large as 0.9

Hadronization – "pre-hadron state" – better chance to form hadron

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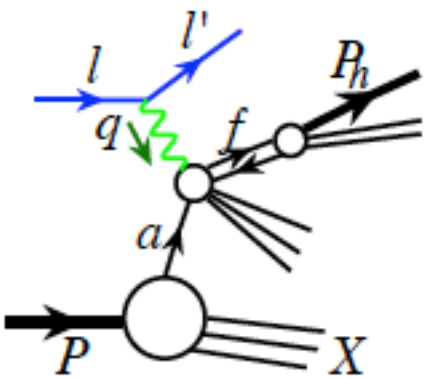
Calculation of the P_T-suppressed Power Correction

arXiv:1907.06136
T. Liu & J.W. Qiu

❑ QCD factorization:

$$\frac{d\sigma_{\gamma^*+A\to h+X}}{d^3\mathbf{P}_h/(2E_h)} \approx \sum_{a,f}\int_{x_B}^1 \frac{dx}{x}\int_{z_h}^1 \frac{dz}{z^2}\,\phi_{a/P}(x)\,D_{f\to h}(z)\frac{d\hat{\sigma}_{\gamma^*+a(l)\to f(p)+X}}{d^3\mathbf{p}/(2E_p)}$$

$$+\sum_{a,[ff'(\kappa)]}\int_{x_B}^1 \frac{dx}{x}\int_{z_h}^1 \frac{dz}{z^2}\int_0^1 d\xi d\zeta\,\phi_{a/P}(x)\,D_{[ff'(\kappa)]\to h}(z,\xi,\zeta)\frac{d\hat{\sigma}_{\gamma^*+a(l)\to[ff'(\kappa)](p,\xi,\zeta)+X}}{d^3\mathbf{p}/(2E_p)}$$



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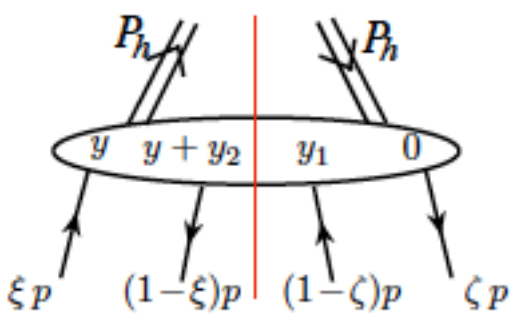
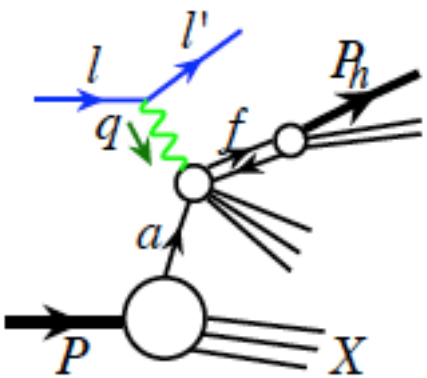
❑ Two-parton fragmentation functions:





$$D_{[qq'(\kappa)]\to h}(z,\xi,\zeta) = \sum_X \int \frac{P_h^+ dy^-}{2\pi}\int \frac{P_h^+ dy_1^-}{2\pi}\int \frac{P_h^+ dy_2^-}{2\pi}$$

$$\times\, e^{i(1-\zeta)\frac{P_h^+}{z}y_1^-}\, e^{-i\frac{P_h^+}{z}y^-}\, e^{-i(1-\xi)\frac{P_h^+}{z}y_2^-}$$

$$\times\, \mathcal{C}\,\mathcal{P}\,\langle 0|\bar{q}'(y_1^-)[\Phi_n(y_1^-)]^\dagger[\Phi_n(0)]q(0)|h(P_h)X\rangle$$

$$\times\, \langle h(P_h)X|\bar{q}(y^-)[\Phi_n(y^-)]^\dagger[\Phi_n(y^-+y_2^-)]q'(y^-+y_2^-)|0\rangle$$

Gauge link:

$$\Phi_n(y^-) = P\exp\left[-ig_s\int_{y^-}^{\infty} d\lambda\, n\cdot G^A(\lambda n)\,t^A\right]$$

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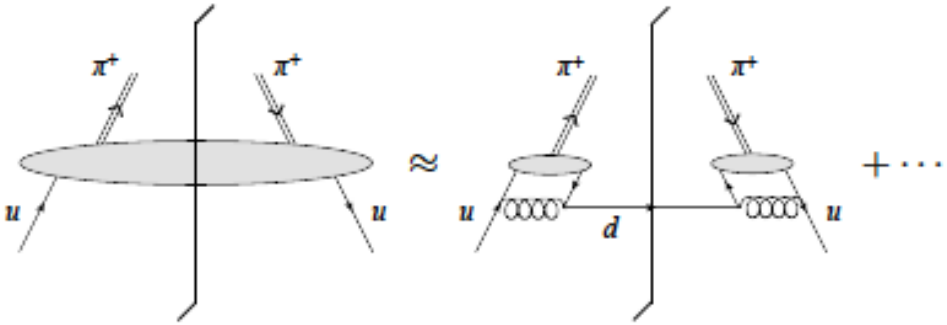
Fragmentation Functions - Hadronization

arXiv:1907.06136
T. Liu & J.W. Qiu

- **Leading power fragmentation function:**

$D_q(z)$:



$\propto (1-z)^n$

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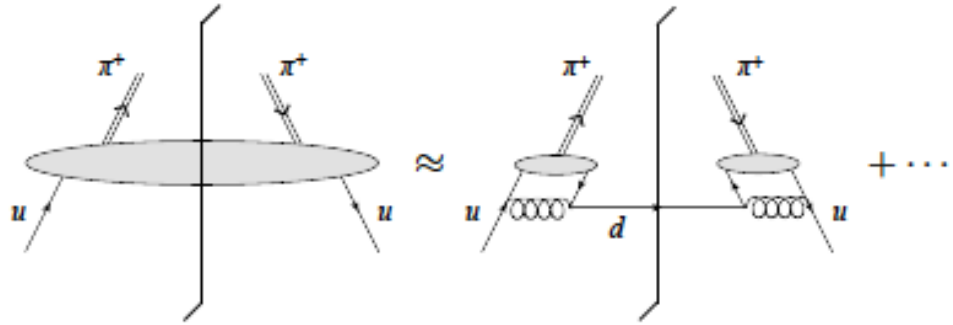
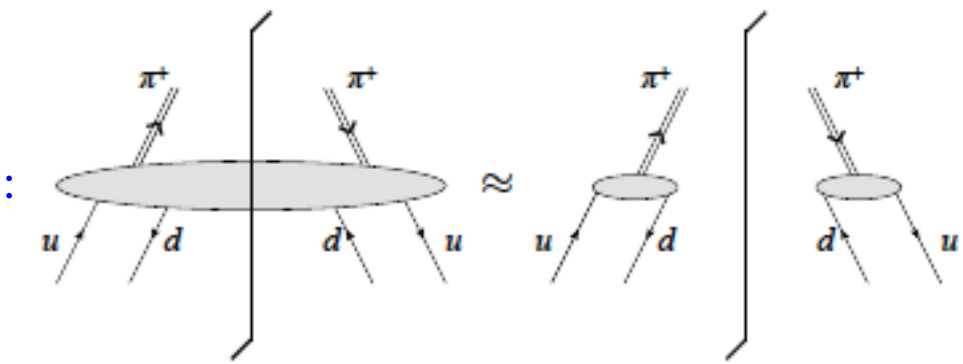


$\propto (1-z)^n$

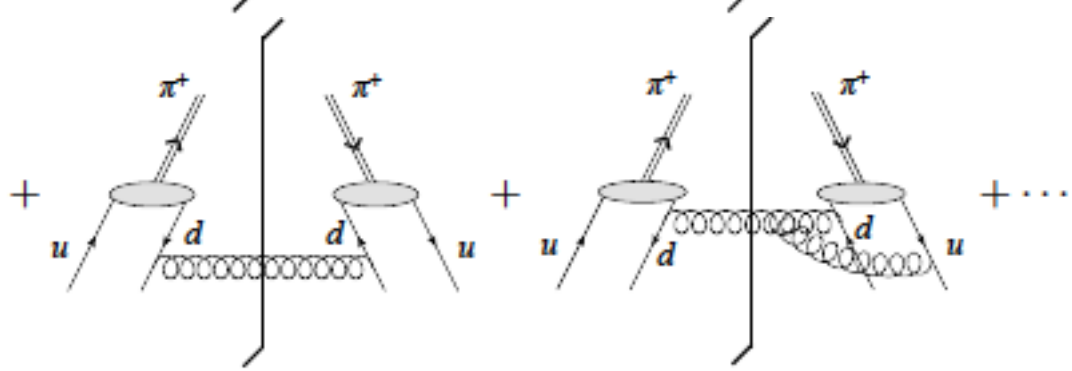
- **Next-to-Leading power fragmentation function:**

$\mathcal{D}_{u\bar{d}}(z,u,v)$:



$\longrightarrow \delta(1-z)$

"Exclusive"



$\longrightarrow (1-z)^m$

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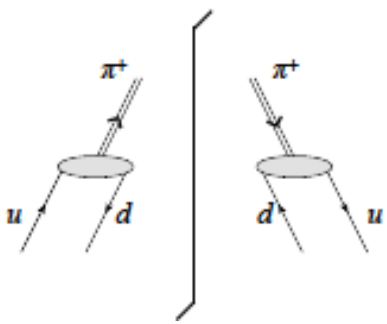
Two-parton Fragmentation Function – Approximation

arXiv:1907.06136
T. Liu & J.W. Qiu

❑ Lowest order two-parton fragmentation function:



(1a)

$$D_{[qq'(1a)]}(z,\xi,\zeta,\mu_0) \approx \int \frac{P_h^+ dy^-}{2\pi} \int \frac{P_h^+ dy_1^-}{2\pi} \int \frac{P_h^+ dy_2^-}{2\pi} e^{i(1-\zeta)\frac{P_h^+}{z}y_1^-} e^{-i\frac{P_h^+}{z}y^-} e^{-i(1-\xi)\frac{P_h^+}{z}y_2^-}$$

$$\times \frac{1}{4N_c P_h^+} \langle 0|\bar{q}'_{c',k}(y_1^-)(\gamma\cdot n\gamma_5)_{kl} U_{c'd'}(y_1^-,0) q_{d',l}(0)|h(P_h)\rangle$$

$$\times \frac{1}{4N_c P_h^+} \langle h(P_h)|\bar{q}_{a',i}(y^-)(\gamma\cdot n\gamma_5)_{ij} U_{a'b'}(y^-,y^-+y_2^-) q'_{b',j}(y^-+y_2^-)|0\rangle$$

$$= \frac{1}{16N_c^2} \int \frac{P_h^+ dy^-}{2\pi} \int \frac{P_h^+ dy_1^-}{2\pi} \int \frac{P_h^+ dy_2^-}{2\pi} e^{i(1-\zeta)\frac{P_h^+}{z}y_1^-} e^{-i\frac{P_h^+}{z}y^-} e^{-i(1-\xi)\frac{P_h^+}{z}y_2^-}$$

$$\times f_h^2 e^{iP_h^+ y^-} \int_0^1 d\zeta' e^{-i(1-\zeta')P_h^+ y_1^-} \phi_h(\zeta',\mu_0) \int_0^1 d\xi' e^{i(1-\xi')P_h^+ y_2^-} \phi_h(\xi',\mu_0)$$

$$= \frac{f_h^2}{16N_c^2} z\,\delta(1-z)\phi_h(\zeta,\mu_0)\phi_h(\xi,\mu_0).$$

Two-parton Fragmentation Function – Approximation

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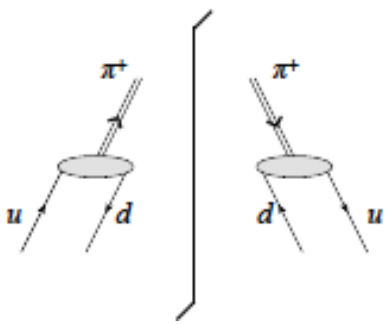

(1a)

$$D_{[qq'(1a)]}(z,\xi,\zeta,\mu_0) \approx \int \frac{P_h^+ dy^-}{2\pi} \int \frac{P_h^+ dy_1^-}{2\pi} \int \frac{P_h^+ dy_2^-}{2\pi} e^{i(1-\zeta)\frac{P_h^+}{z}y_1^-} e^{-i\frac{P_h^+}{z}y^-} e^{-i(1-\xi)\frac{P_h^+}{z}y_2^-}$$

$$\times \frac{1}{4N_c P_h^+} \langle 0|\bar{q}'_{c',k}(y_1^-)(\gamma\cdot n\gamma_5)_{kl} U_{c'd'}(y_1^-,0) q_{d',l}(0)|h(P_h)\rangle$$

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$$\times f_h^2 e^{iP_h^+ y^-} \int_0^1 d\zeta' e^{-i(1-\zeta')P_h^+ y_1^-} \phi_h(\zeta',\mu_0) \int_0^1 d\xi' e^{i(1-\xi')P_h^+ y_2^-} \phi_h(\xi',\mu_0)$$

$$= \frac{f_h^2}{16N_c^2} z\,\delta(1-z)\phi_h(\zeta,\mu_0)\phi_h(\xi,\mu_0).$$

❑ Pseudoscalar distribution amplitude: $\phi_h(x,\mu)$

$$\langle 0|\bar{q}_{a,i}(y^-+y_1^-)(\gamma\cdot n\gamma_5)_{ij} U_{ab}(y^-+y_1^-,y^-) q_{b,j}(y^-)|h(P_h)\rangle$$

$$= iP_h^+ f_h \int_0^1 dx\, e^{-ixP_h^+ y^- - i(1-x)P_h^+(y^-+y_1^-)} \phi_h(x,\mu)$$

$$= iP_h^+ f_h\, e^{-iP_h^+ y^-} \int_0^1 dx\, e^{-i(1-x)P_h^+ y_1^-} \phi_h(x,\mu),$$

$$U_{ab}(y_2^-,y_1^-) = [\Phi_n(y_2^-)]^\dagger_{ac}[\Phi_n(y_1^-)]_{cb}$$

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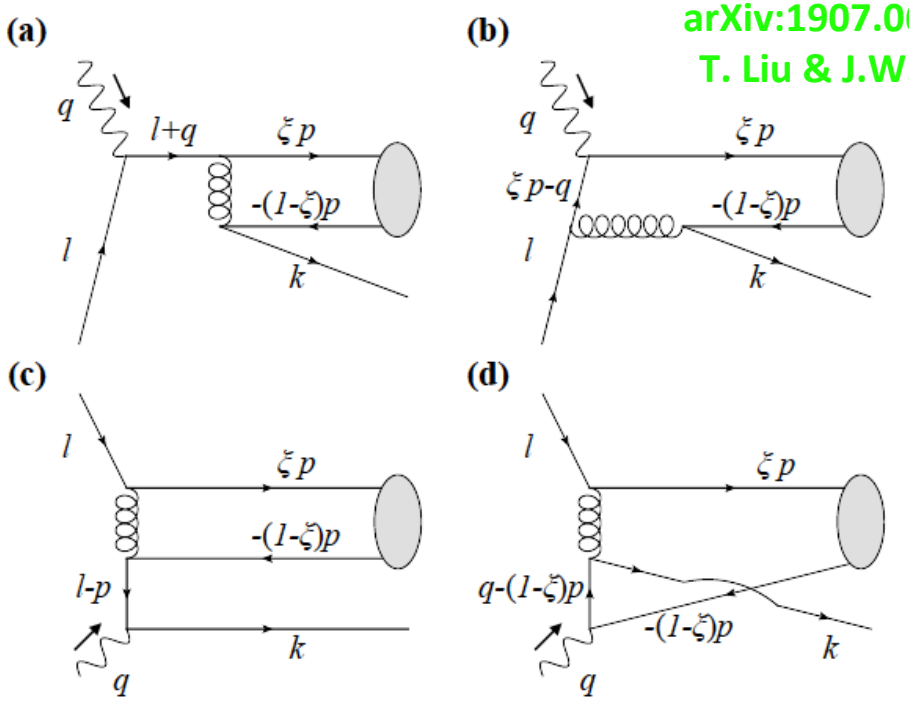
Partonic Hard Part at Next-to-Leading Power

arXiv:1907.06136
T. Liu & J.W. Qiu

❑ LO Feynman diagrams:

Two possible channels



Partonic Hard Part at Next-to-Leading Power

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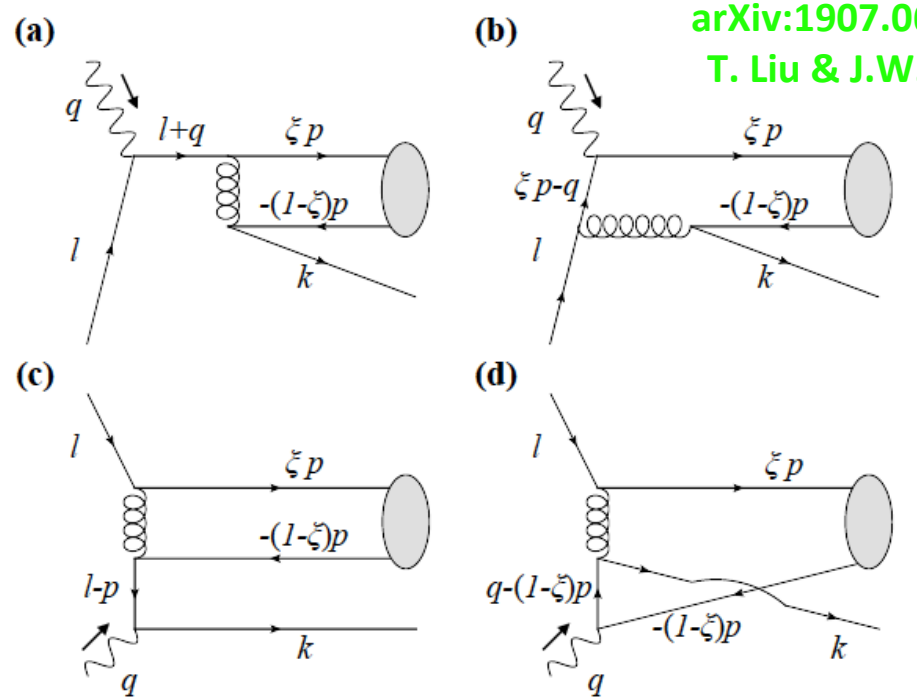
T. Liu & J.W. Qiu

- **LO Feynman diagrams:**

  Two possible channels

- **Hard parts:**

$$\frac{E_p d\hat{\sigma}_{\gamma^*+a(l)\to[ff'](p)+X}}{d^3\mathbf{p}} = \frac{|\overline{\mathcal{M}}_{\gamma^*+a(l)\to[ff'(\kappa)](p)+X}|^2}{2(\hat{s}+Q^2)} \times \frac{1}{2(2\pi)^2}\delta(\hat{s}+\hat{t}+\hat{u}+Q^2)$$



$$\hat{s} = (q+l)^2, \quad \hat{t} = (q-p)^2, \quad \hat{u} = (l-p)^2$$

Partonic Hard Part at Next-to-Leading Power

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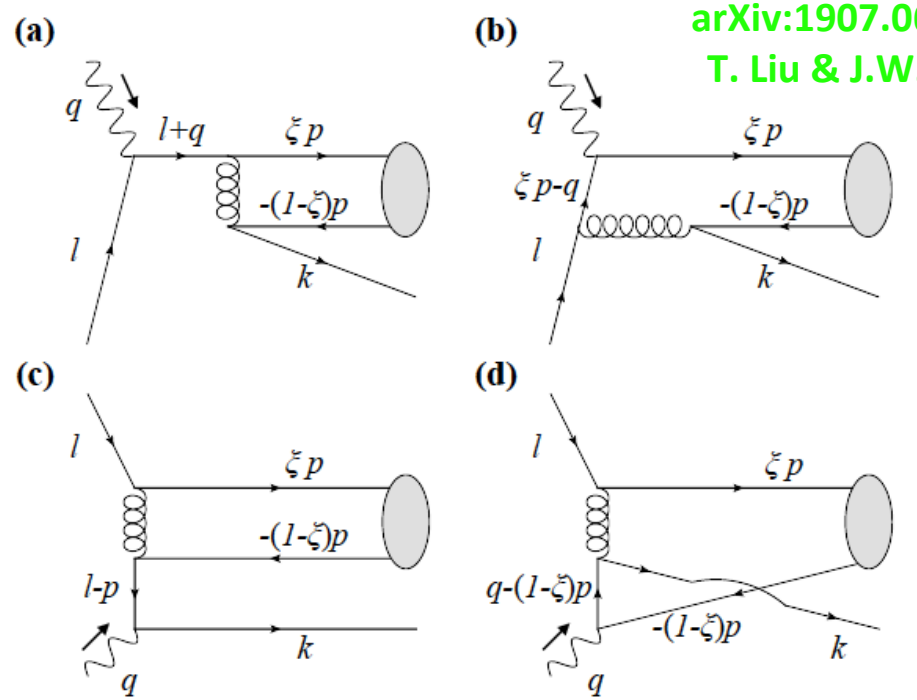

- **One example:**

$$\hat{s} = (q+l)^2, \quad \hat{t} = (q-p)^2, \quad \hat{u} = (l-p)^2$$

$$|\overline{\mathcal{M}}_T^{a^\dagger a + a^\dagger b + b^\dagger a + b^\dagger b}|^2 = 4CKe_q^2\left[-\frac{(\hat{t}+2\hat{u})A_{\bar{\xi}}A_{\bar{\zeta}} + \hat{u}^2(\hat{t}-\bar{\xi}A_{\bar{\zeta}}-\bar{\zeta}A_{\bar{\xi}})}{\bar{\xi}\bar{\zeta}\hat{s}^2A_{\bar{\xi}}A_{\bar{\zeta}}} + \frac{2\hat{u}^3(\hat{s}+\hat{t}+\hat{u})}{\hat{s}(\hat{t}+\hat{u})^2A_{\bar{\xi}}A_{\bar{\zeta}}}\right]$$

Transverse polarized photon

$$K = e^2g_s^4 = (4\pi)^3\alpha_{\rm em}\alpha_s^2$$

$$A_\eta = \hat{t} + \eta(\hat{s}+\hat{u}), \qquad \eta = \xi, \zeta, \bar{\xi}, \bar{\zeta}$$

$$B_\eta = \hat{s}\hat{t} - \hat{u}(\hat{t}+\eta\hat{u}), \qquad \bar{\xi} = 1-\xi,\ \bar{\zeta} = 1-\zeta$$

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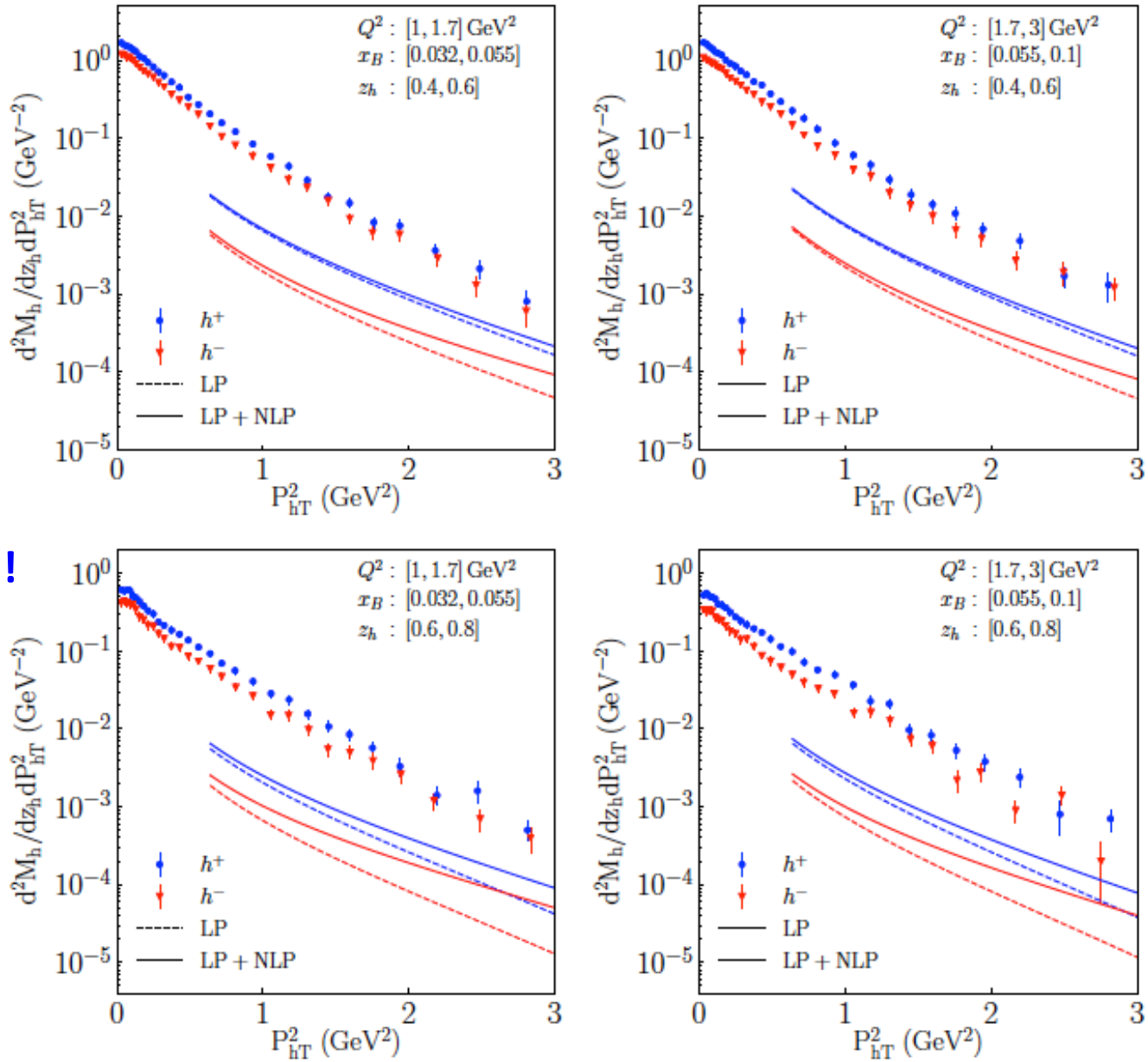
Numerical Estimate – Lower Limit

- **Differential multiplicity:**

$$\frac{d^2 M_h}{dz_h dP_T^2} = \frac{\frac{d^4\sigma^{\rm SIDIS}}{dx_B dQ^2 dz_h dP_T^2}}{\frac{d^2\sigma^{\rm DIS}}{dx_B dQ^2}}$$

Lower limit for the power correction!

Only used leading term of two-parton fragmentation functions



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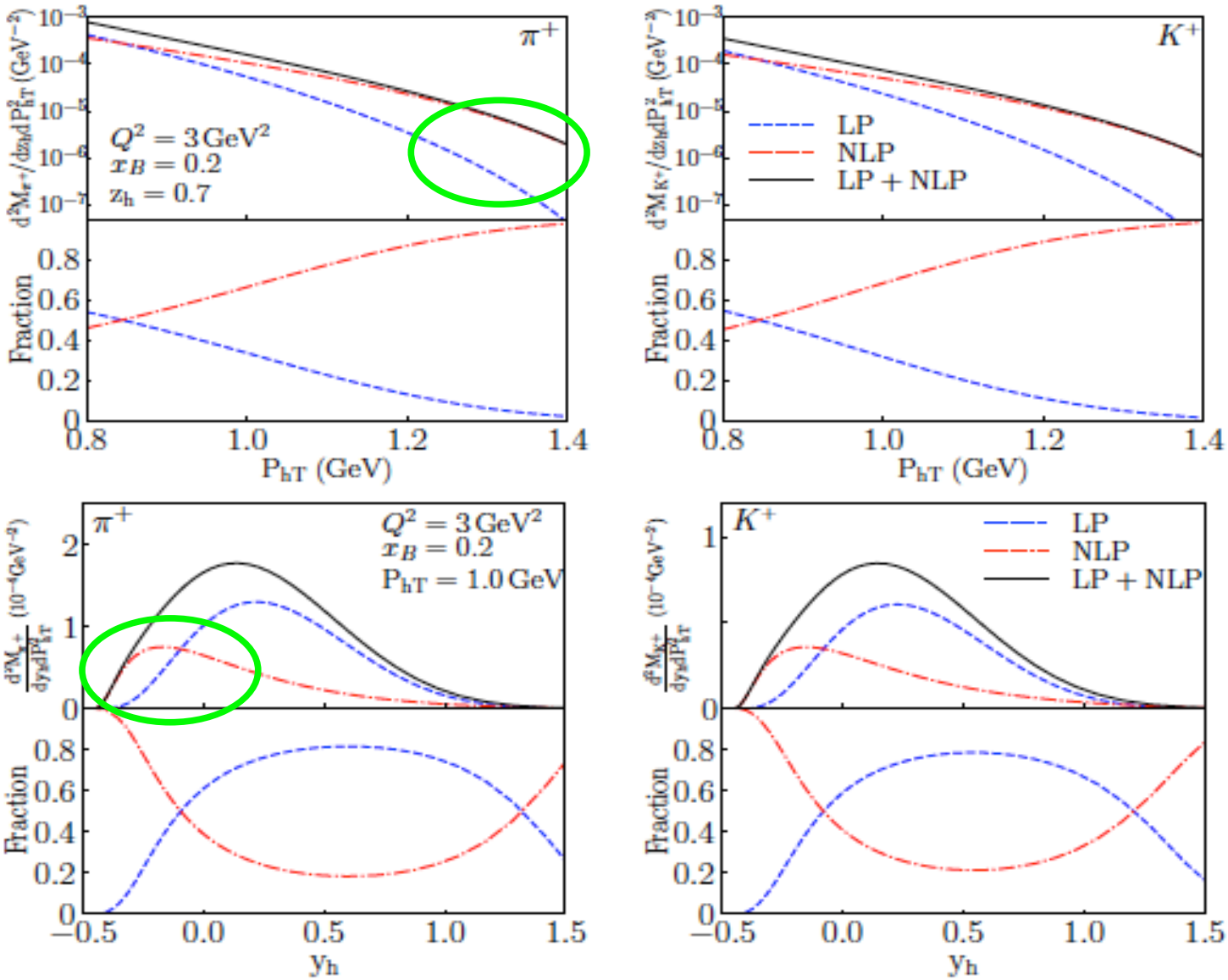
JLab Kinematics

- **Differential multiplicity:** $E_{\text{beam}} = 11\,\text{GeV}$, $Q^2 = 3\,\text{GeV}^2$, $x_B = 0.2$, and $z_h = 0.7$



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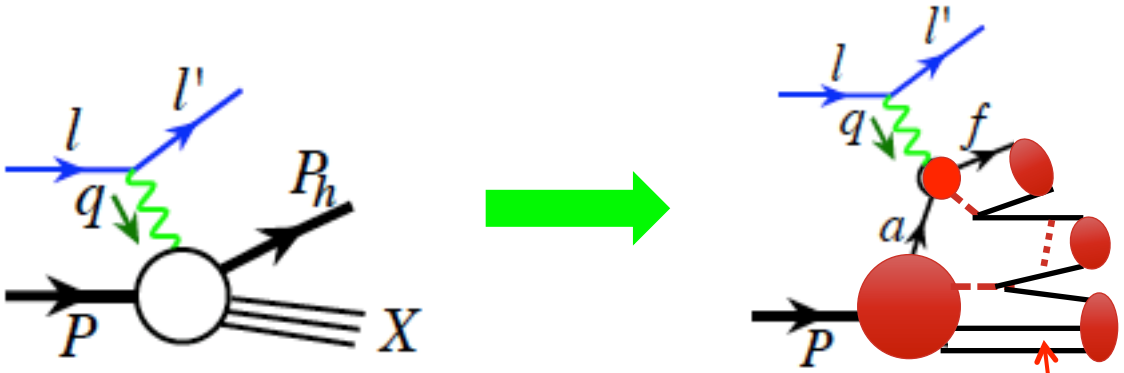
Near Threshold – Lower p_T

- Lower W^2 with sufficiently large Q^2 – less phase space to "shower":



Lower multiplicity!

Leading power TMD factorization should not work here!

Color singlet pre-hadron states

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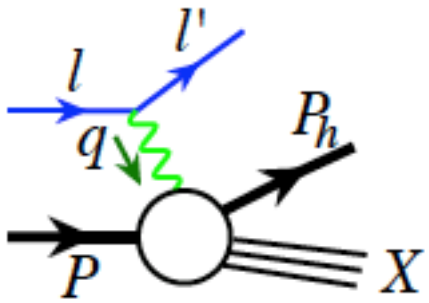
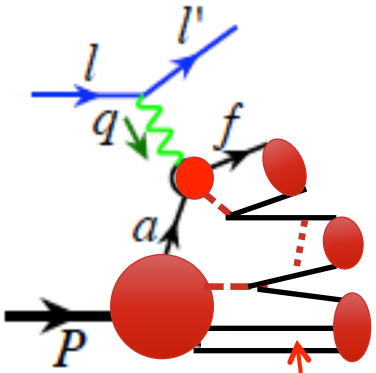




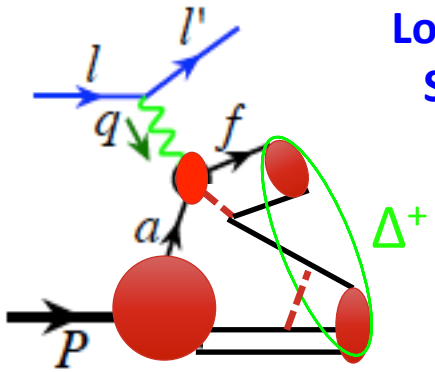
Lower multiplicity!

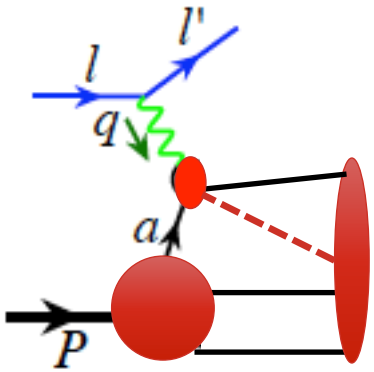
Leading power TMD factorization should not work here!

Color singlet pre-hadron states

- Threshold and resonance region:

Q^2 is still sufficiently large
Localized hard collision
Single active parton





Formation of pre-hadron states is not a hard process
$1/Q^2$ – inclusive high twist terms should be small – duality

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Summary

- **Lepton-hadron facility is an excellent one for QCD study:**
  - Many observables/probes at one facility
  - Probe the partonic structure by either breaking or not breaking the hadron
  - Study the hadronization with controllable probes
- **QCD is fully color entangled:**
  - QCD Factorization is an approximation with suppressed color entanglement
  - Power "corrections" are important near the threshold
- **"Power corrections" is much more important for hadronization:**
  - $1/P_T^2$-type correction to fragmentation is important near threshold
  - When lower W or PT, the $1/P_T^2$-type contribution to hadronization are much enhanced, or dominate
  - $1/Q^2$-type high-twist contribution to SIDIS is small if Q is large enough

Thank you!

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