The 22 GeV Luminosity Frontier: Theory Perspective

Jianwei Qiu
Theory Center

Presented To:
Jefferson Lab at 22 GeV Workshop

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

QCD: its emergent phenomena and its dual representations

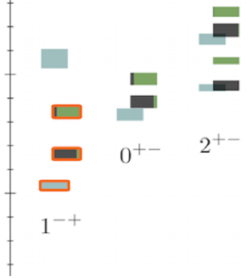
QCD: a theory of quarks & gluons

$$\mathcal{L}_{QCD}(\psi, A) = \sum_f \overline{\psi}_i^f \left[(i\partial_\mu \delta_{ij} - g A_{\mu,a} (t_a)_{ij}) \gamma^\mu - m_f \delta_{ij} \right] \psi_j^f - \frac{1}{4} \left[\partial_\mu A_{\nu,a} - \partial_\nu A_{\mu,a} - g C_{abc} A_{\mu,b} A_{\nu,c} \right]^2$$

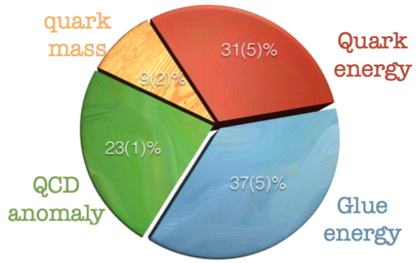
But, we saw none of them in isolation

QCD: its emergent phenomena and its dual representations

Exotics Meson



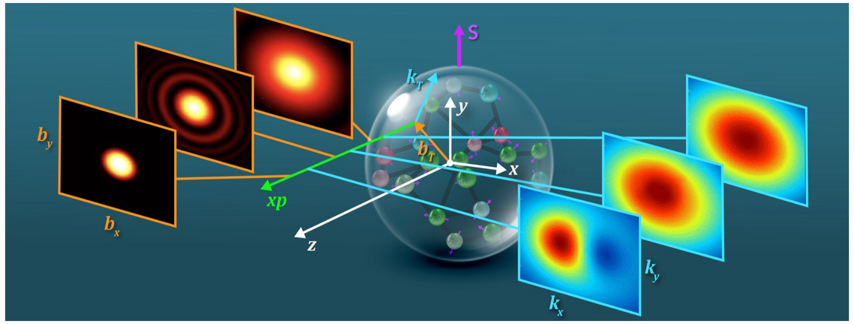
Hadron Mass



Emergent phenomena:

- Hadrons – spectroscopy
- Hadron properties – mass, spin, …
- Hadron structure – quark/gluon's
  confined motion,
  spatial distributions,
  quantum correlations, …

Hadron structure



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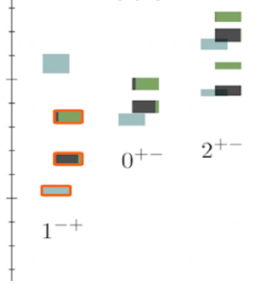

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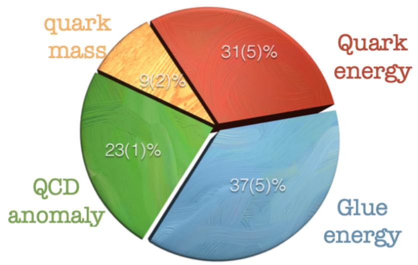

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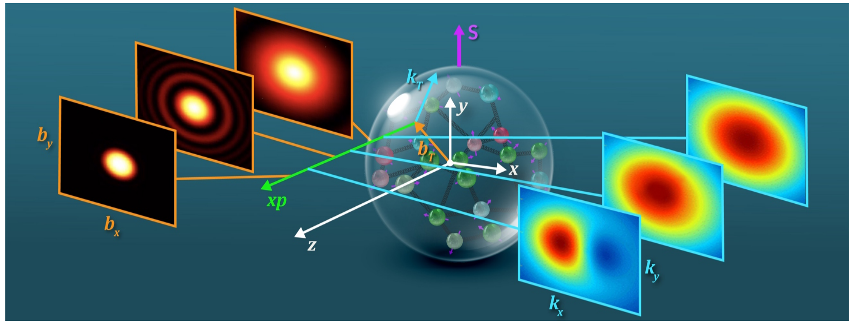

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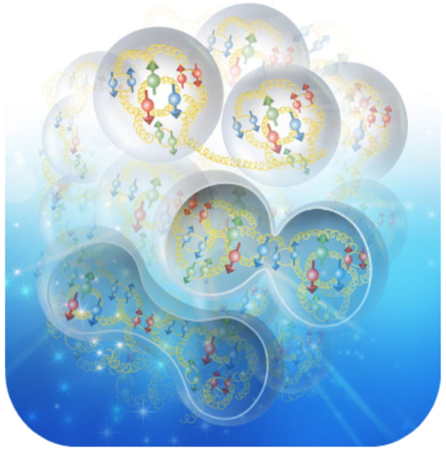
Nuclear structure



Dual representations – probing scale:

- fundamental quarks, gluons & their interactions
- hadrons & their effective interactions

nuclear structure

in terms of nucleons, mesons, …
in terms of fundamental quarks, gluons
in terms of constituent quarks, …

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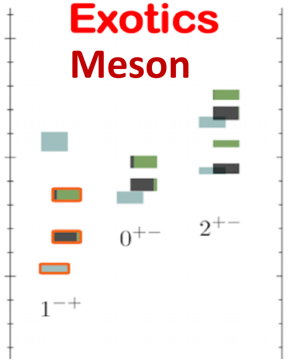

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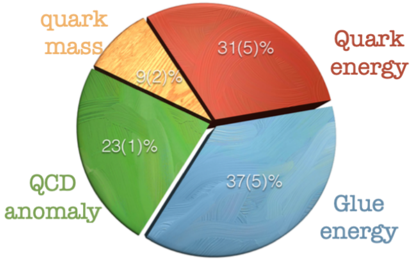

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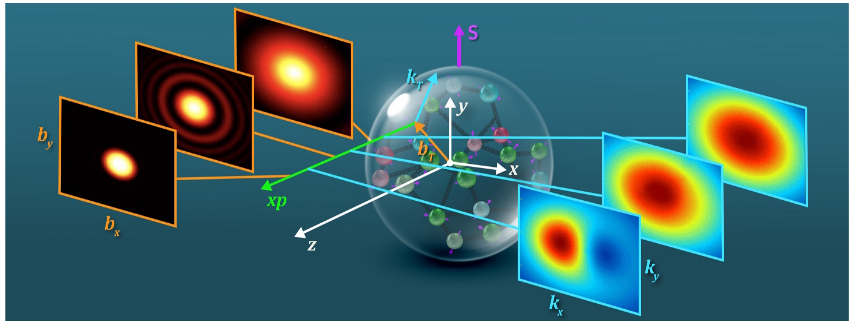

Calculation & Prediction for the emergent phenomena

LQCD,
EFTs,
Models, …

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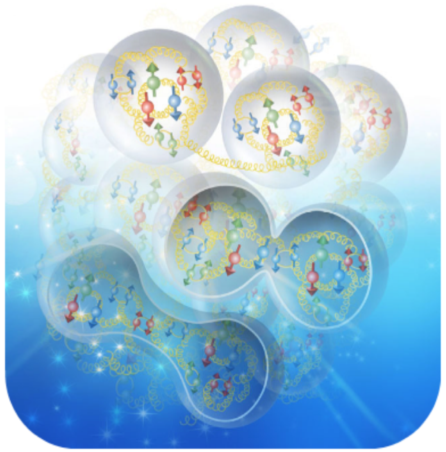
Extraction & "Understanding" of the emergent phenomena

PQCD factorization
from Expt'l data,
from LQCD data, …

Challenge to understand the extracted phenomena?

Nuclear structure



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How such rich phenomena are emerged from quarks, gluons & QCD dynamics?

See talk by Rolf

CEBAF: a facility for exploring emergent phenomena in QCD

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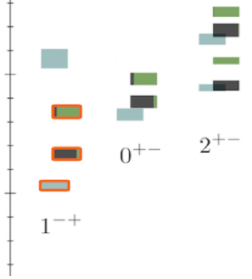

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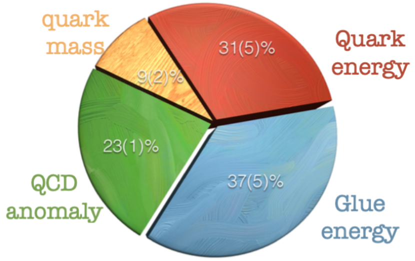

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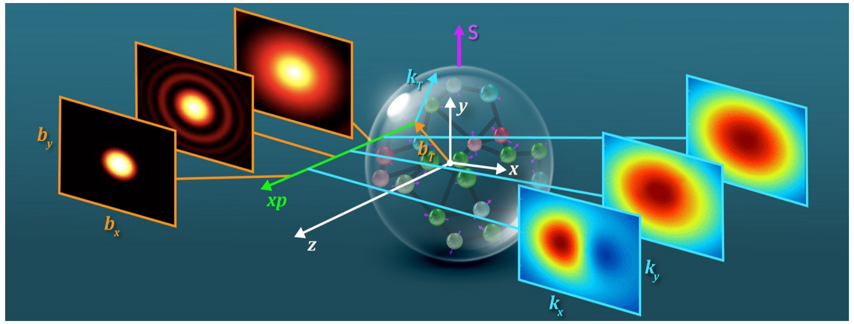

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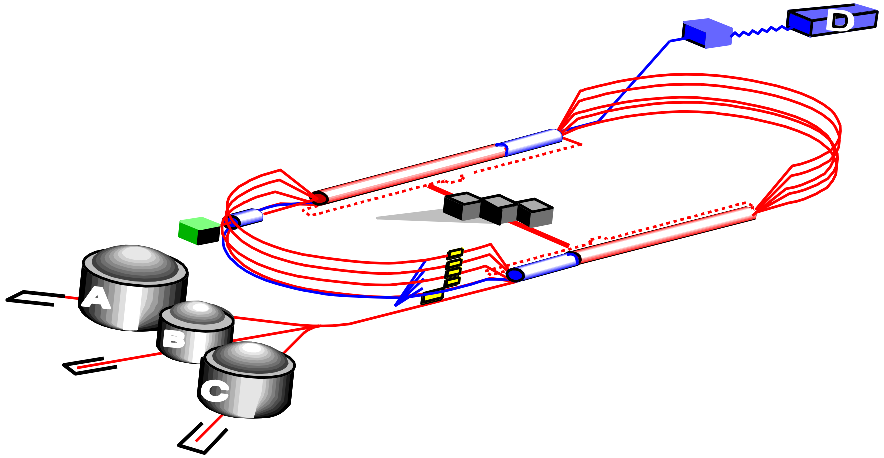

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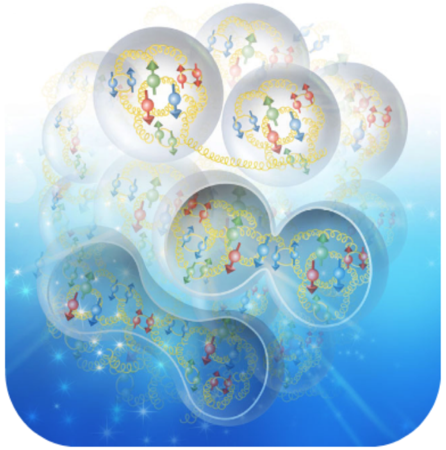

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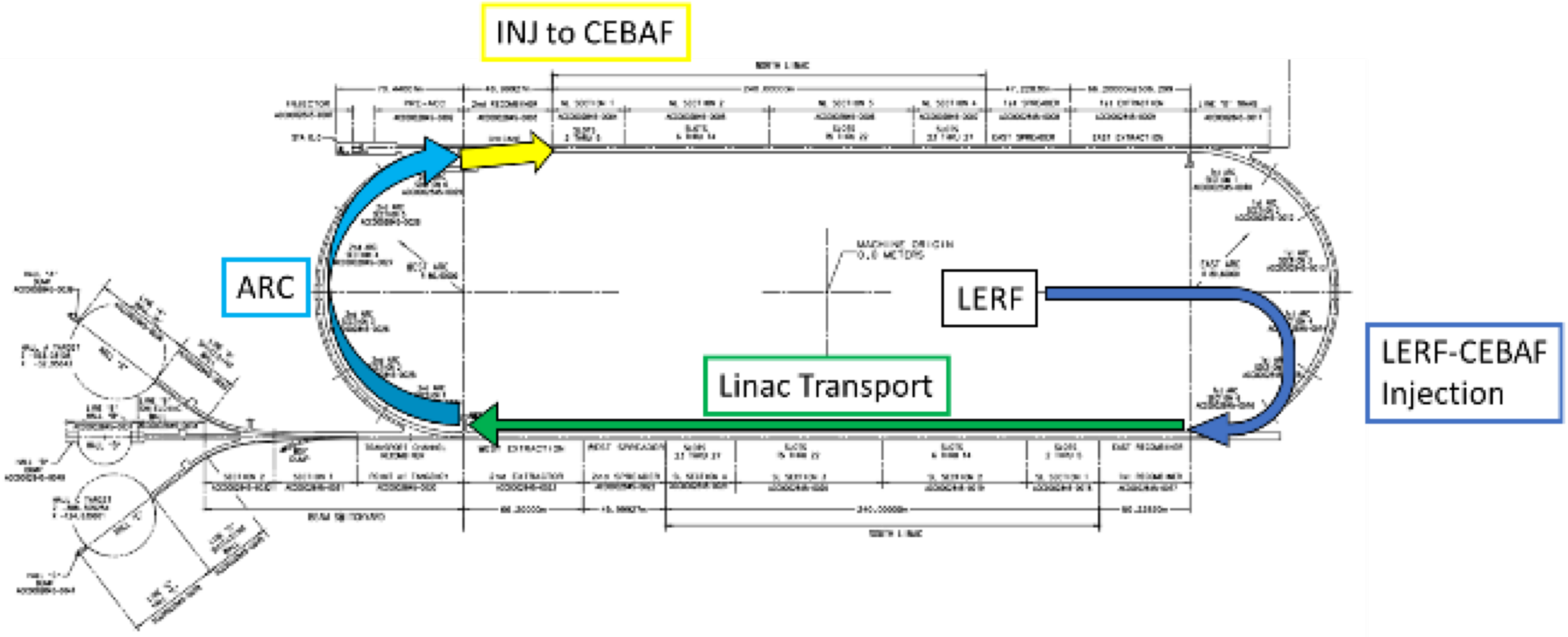
New Opportunity

See talk by Alex Bogacz

Adding FFA racetracks into the existing CEBAF tunnel to reach the top energy of about 22 GeV



- **What are NEW science opportunities for CEBAF and nuclear physics community, even with the EIC?**
- **How can we catch and fully realize such opportunities, if there are, in a cost-effective way?**

Discover new Charmonium states (X, Z_c) at a lepton-hadron facility

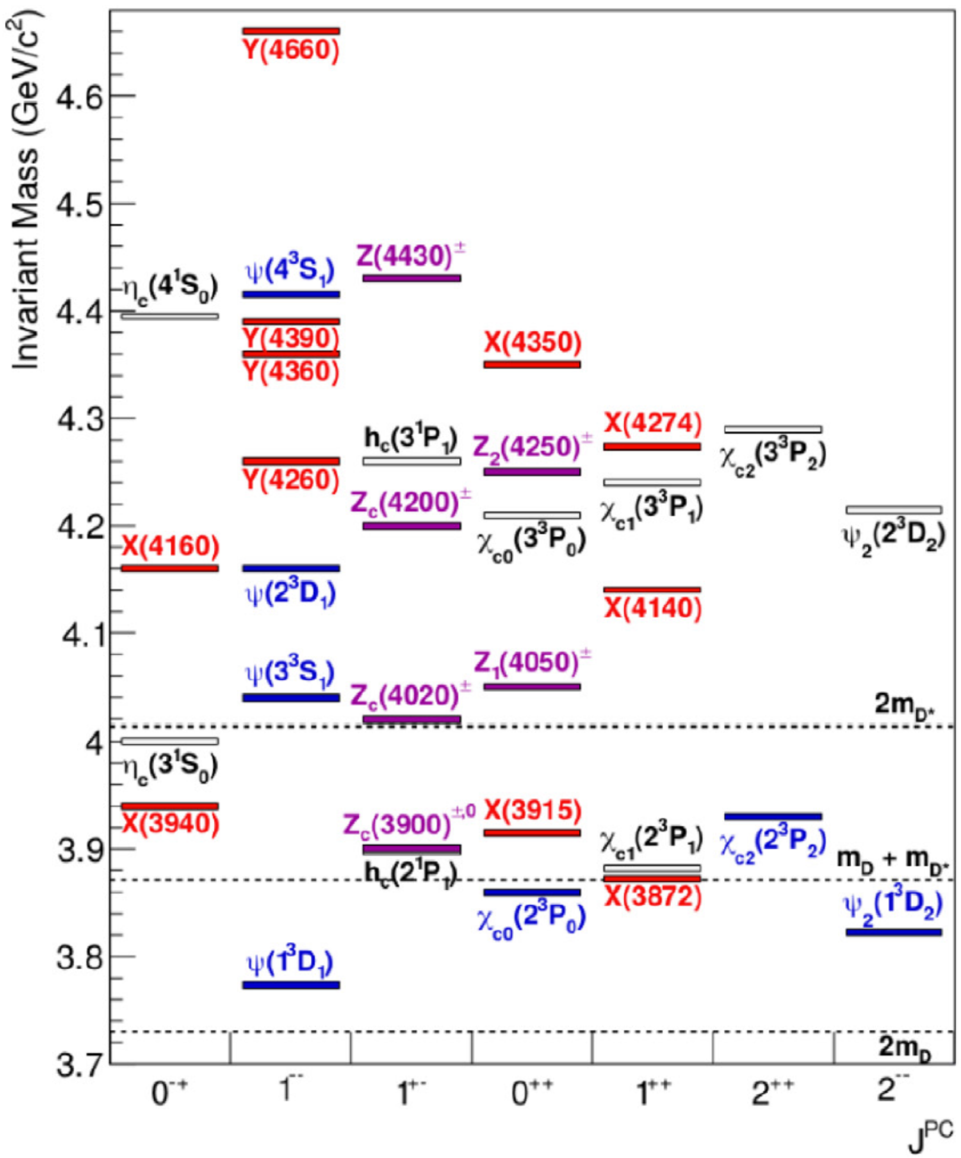
- **XYZ states:**

  Charmonium-like (bottomonium-like) exotic mesons

- **Belle II + BESIII + LHCb:**

  Many more XYZ states will be discovered and confirmed before the CEBAF upgrade and EIC turns on

  But, none of these will be produced in photon/lepton-hadron collisions



See talks in sessions 2 &3

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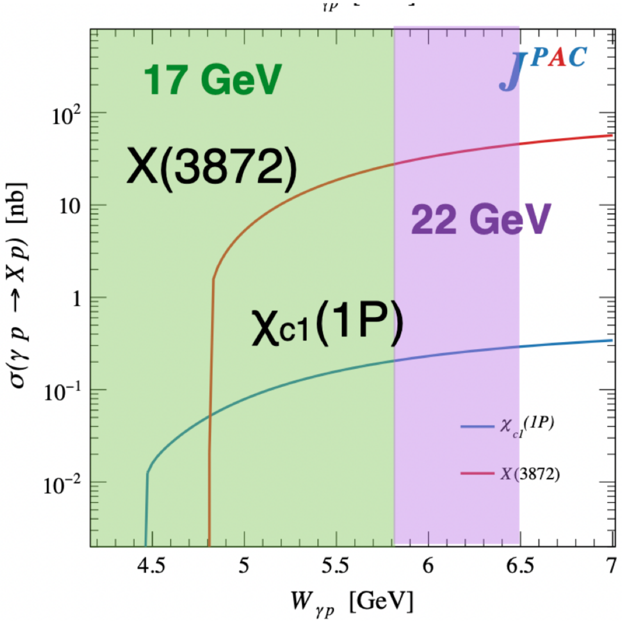
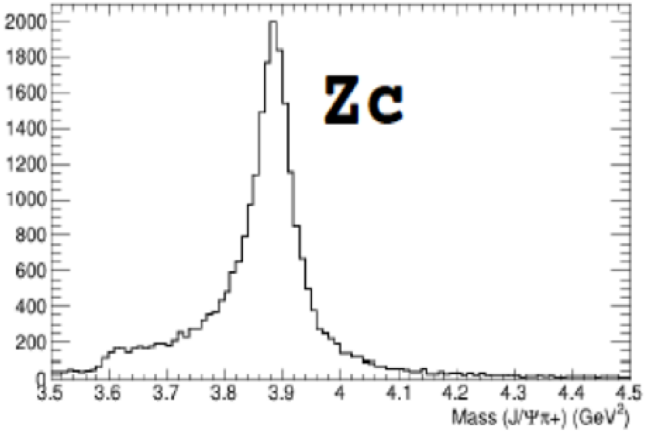
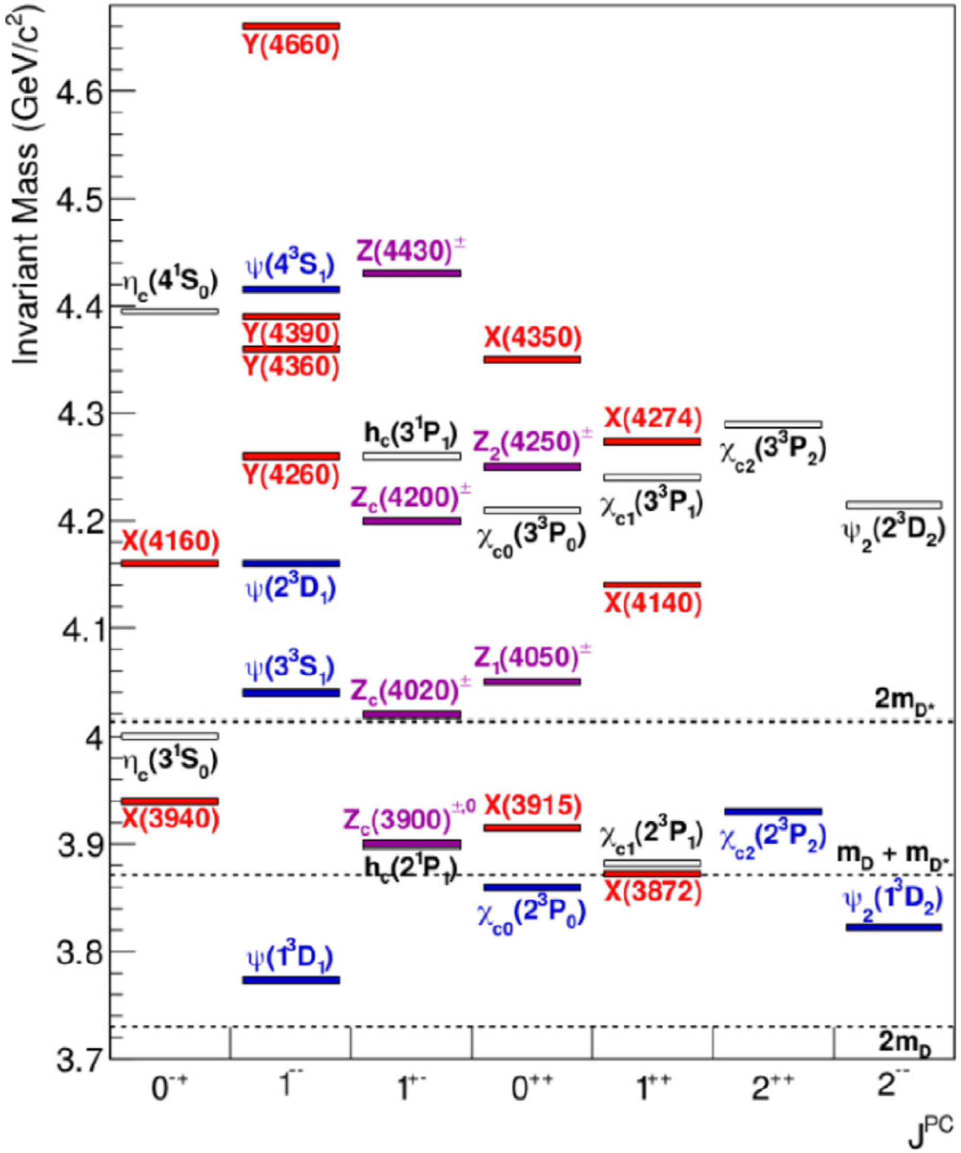
- **CEBAF with energy upgrade** – discovery potential:





Full reconstruction of Z_c production with CLAS12 simulations



See talks in sessions 2 &3

Emergence of a heavy quarkonium & XYZ states

- **J/psi was discovered in 1974:**

  Still not sure how a J/psi was emerged from high energy collisions, …

- **NRQCD for hadronization:**

$$d\sigma_{A+B\to H+X} = \sum_n d\sigma_{A+B\to Q\bar{Q}(n)+X}\langle \mathcal{O}^H(n)\rangle$$

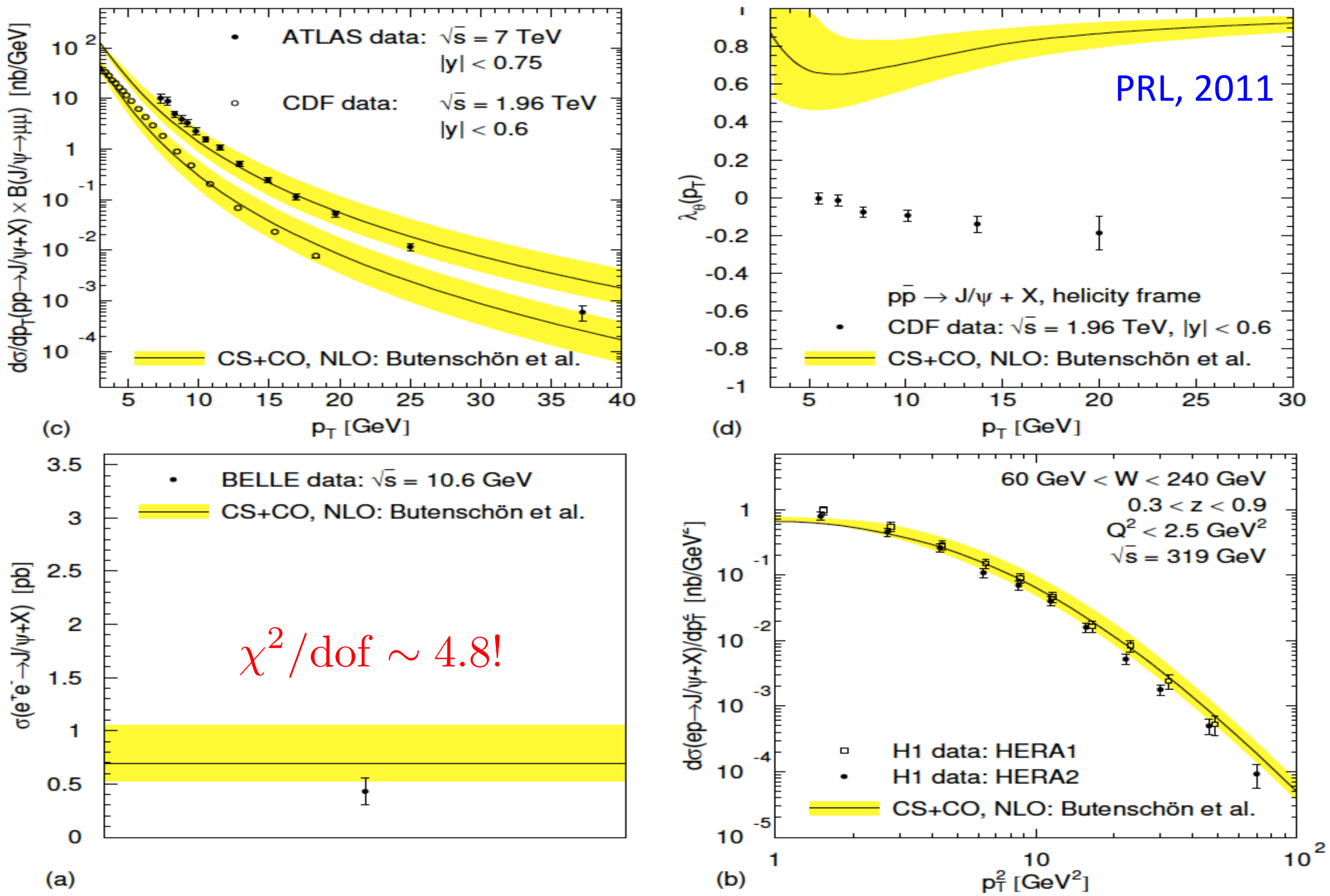
  - 4 leading channels in v:

$$^3S_1^{[1]},\ ^1S_0^{[8]},\ ^3S_1^{[8]},\ ^3P_J^{[8]}$$

	$\langle\mathcal{O}(^3S_1^{[1]})\rangle$ GeV^3	$\langle\mathcal{O}(^1S_0^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3S_1^{[8]})\rangle$ 10^{-2} GeV^3	$\langle\mathcal{O}(^3P_0^{[8]})\rangle$ 10^{-2} GeV^5
Set I (Butenschoen *et al.*)	1.32	3.04	0.16	−0.91
Set II (Chao *et al.*)	1.16	8.9	0.30	1.26
Set III (Gong *et al.*)	1.16	9.7	−0.46	−2.14
Set IV (Bodwin *et al.*)	-	9.9	1.1	1.1

LDMEs should be universal, however:

- Numbers are not the same,
- Not even the sign!

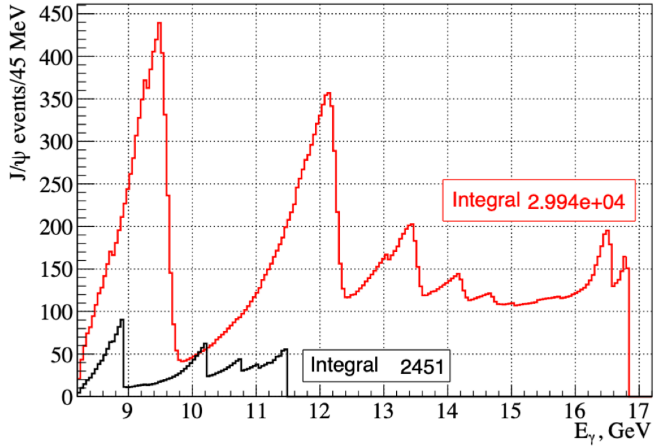


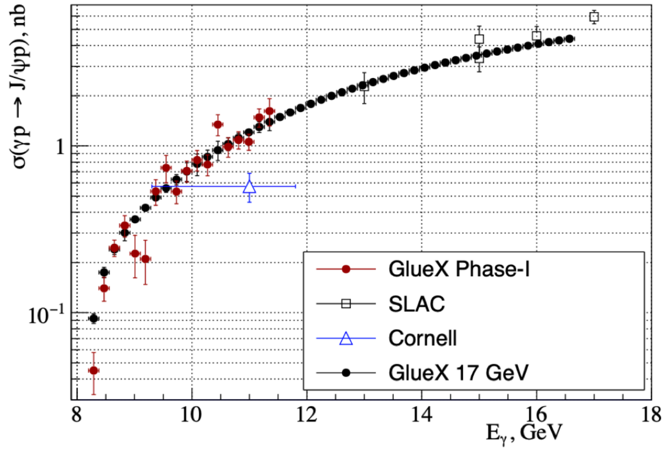
- **Having XYZ produced in photon/lepton-hadron environment is necessary for exploring their emergence:**

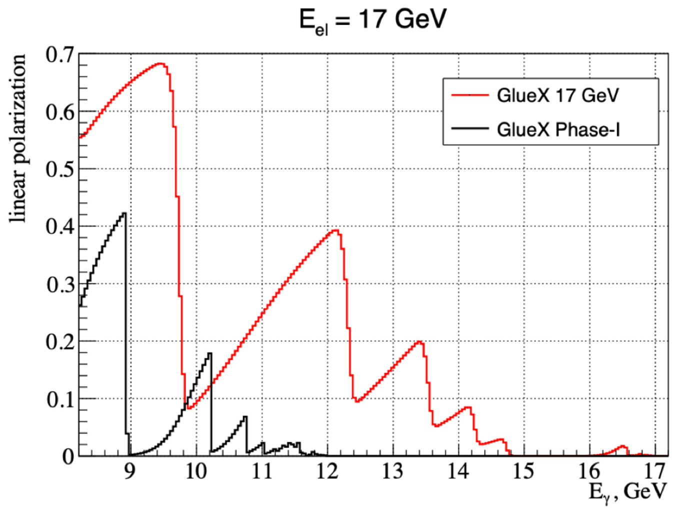
  Coupling photons to exotics, polarization transfer, …

CEBAF with HE is a new facility for charmonium production

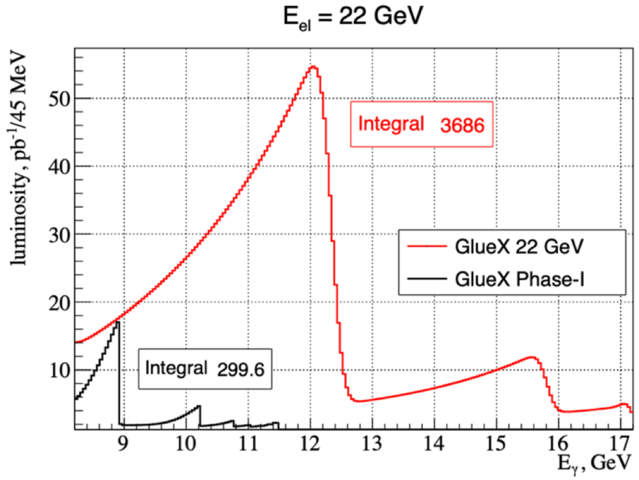
- **HE: High photon flux and polarization at Hall D:**

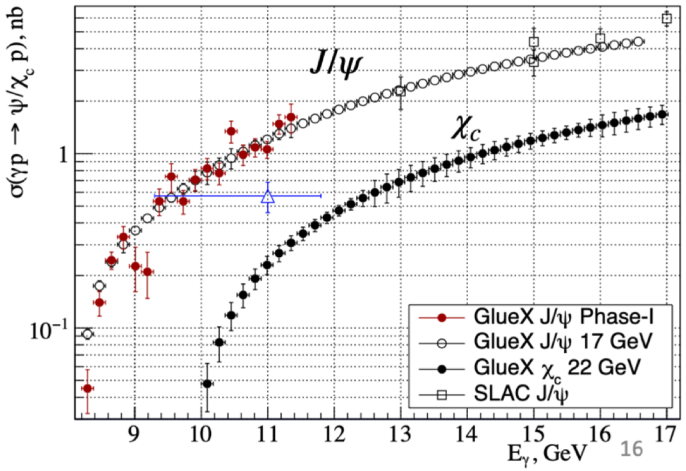


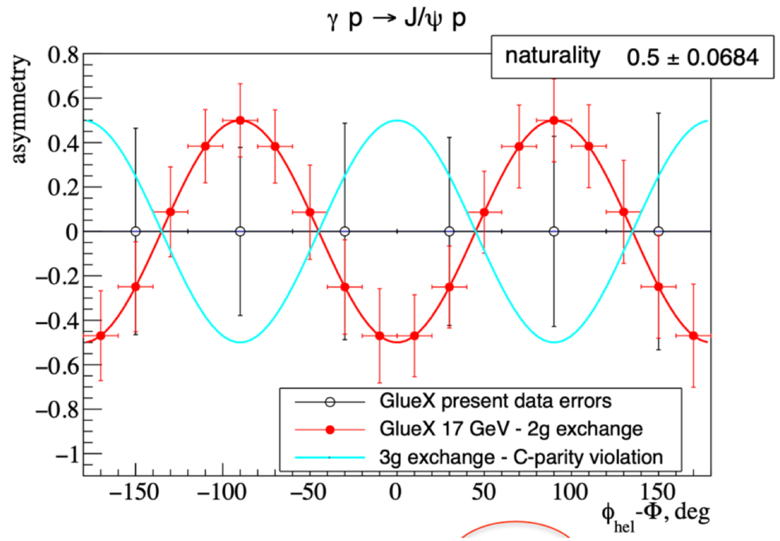




- **HE @ 22 GeV:**



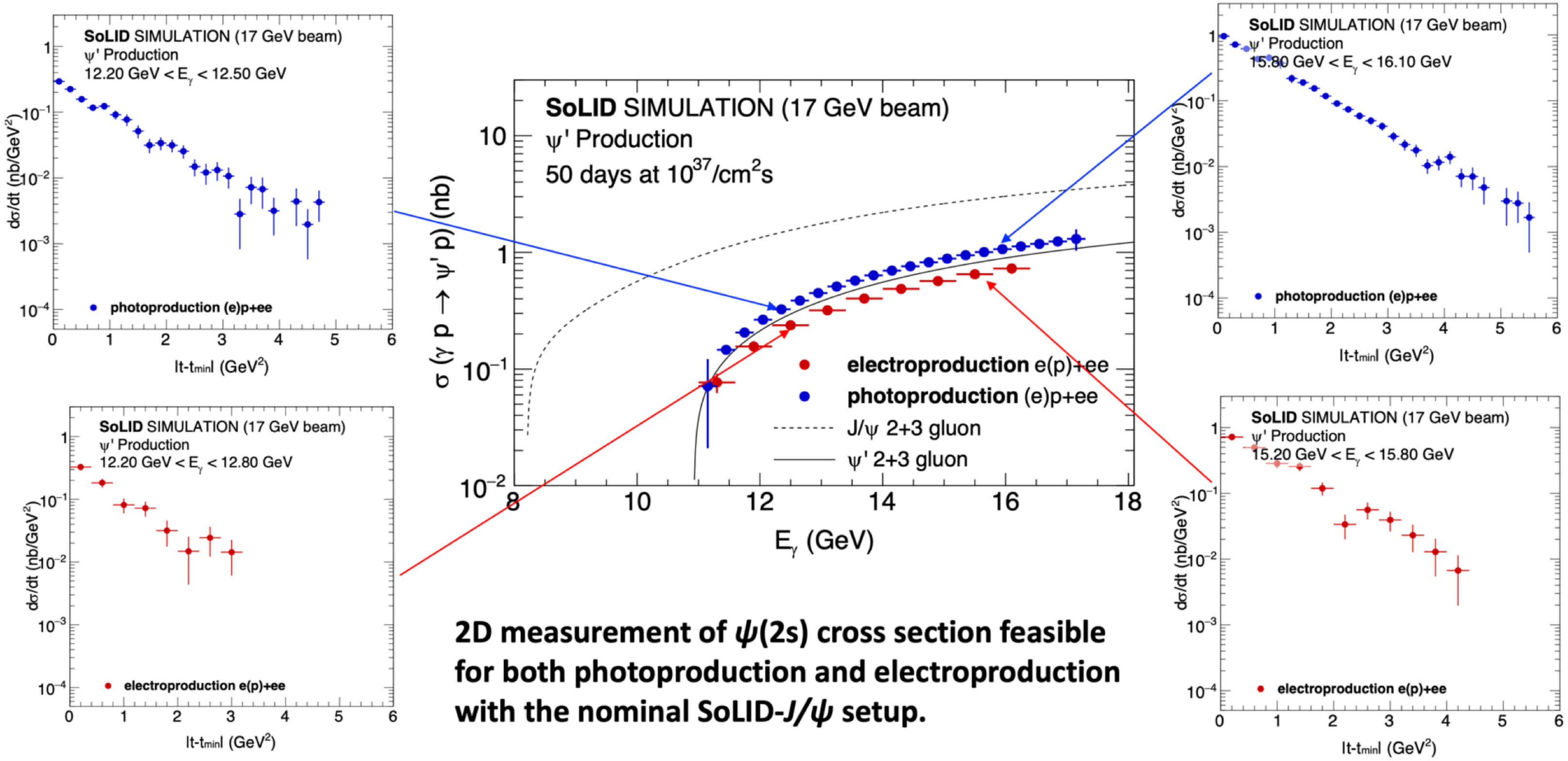




See talks in session 3

New facility for charmonium production – away from the threshold

- **HE: Precision charmonium production beyond the threshold:**



2D measurement of $\psi(2s)$ cross section feasible for both photoproduction and electroproduction with the nominal SoLID-J/ψ setup.

- Trace anomaly
- Gravitational form factors
- Proton mass radius
- Proton radius of quark, or gluon density,
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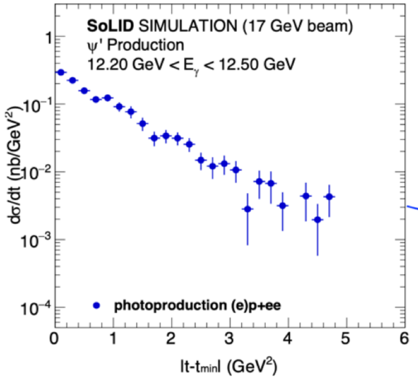

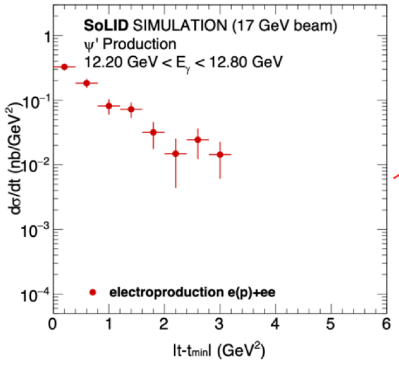

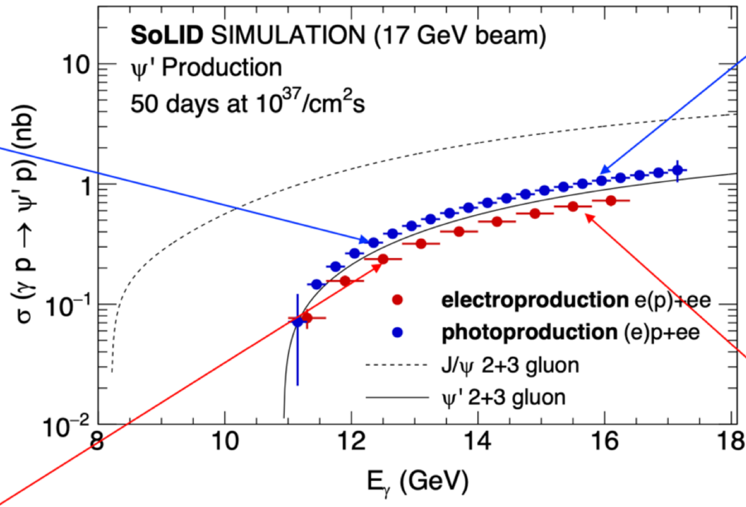

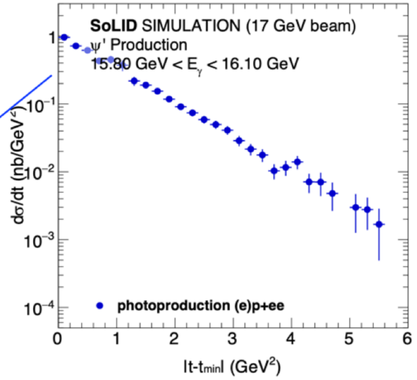

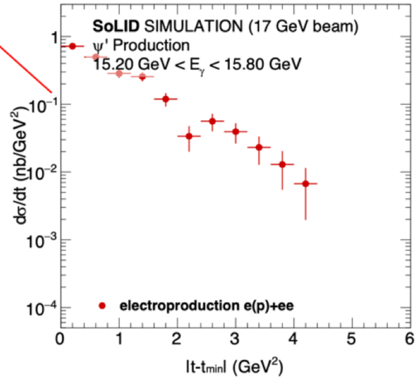

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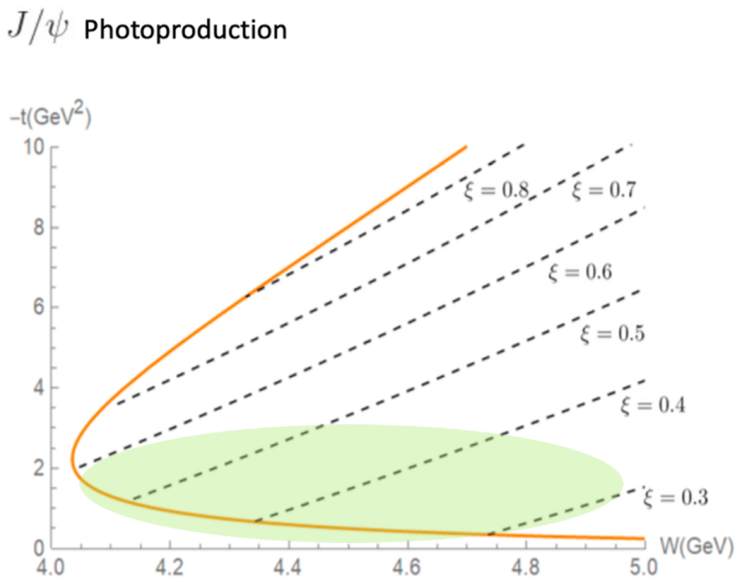
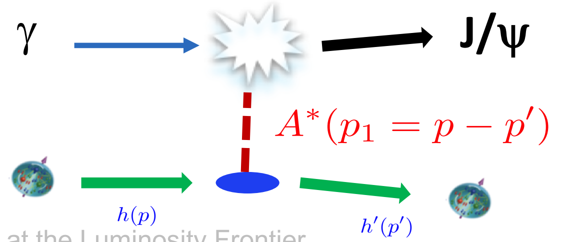


- **Better separation of hadron property from production J/ψ:**



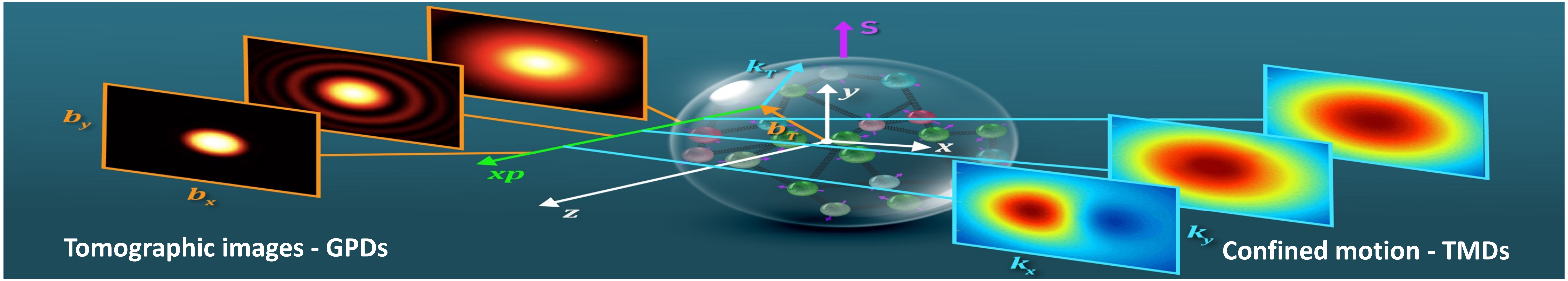
$A^*(p_1 = p - p')$ A virtual state of multi-"partons" or "mesons"

- Large ξ and small -t
- Need the phase space – the energy upgrade!

See talks in session 3

3D Imaging in Momentum Space

NO quarks and gluons can be seen in isolation!

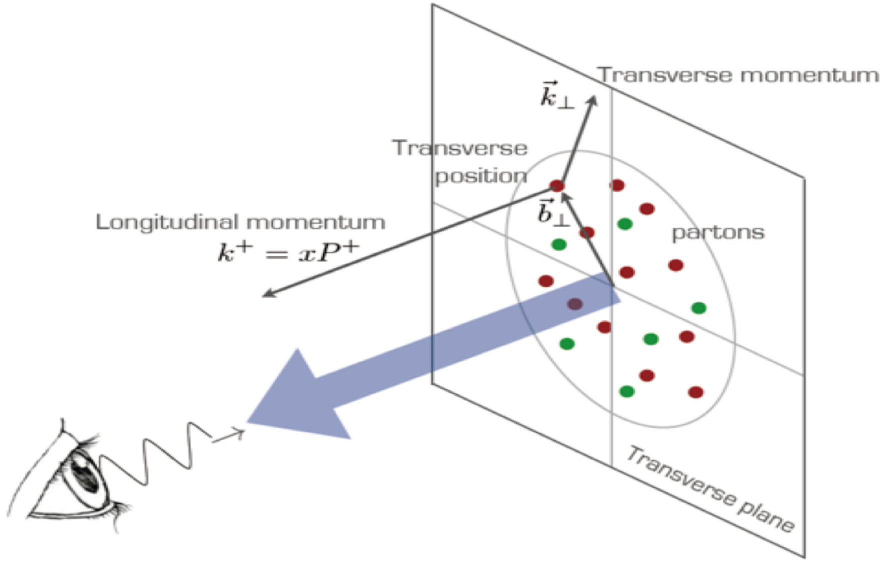


- **Need new observables with two distinctive: scales:**

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

  - **Hard scale: Q_1 to localize the probe to see the particle nature of quarks/gluons**

  - **"Soft" scale: Q_2 could be more sensitive to the hadron structure ~ 1/fm**



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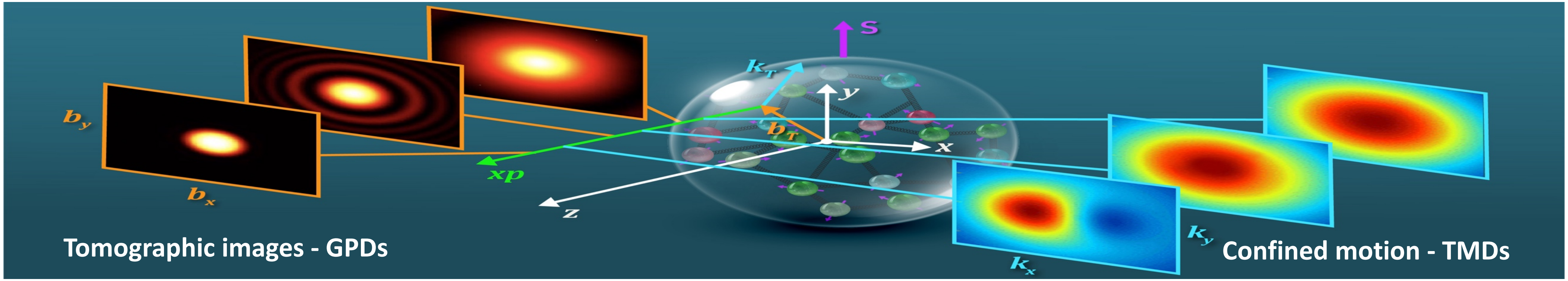
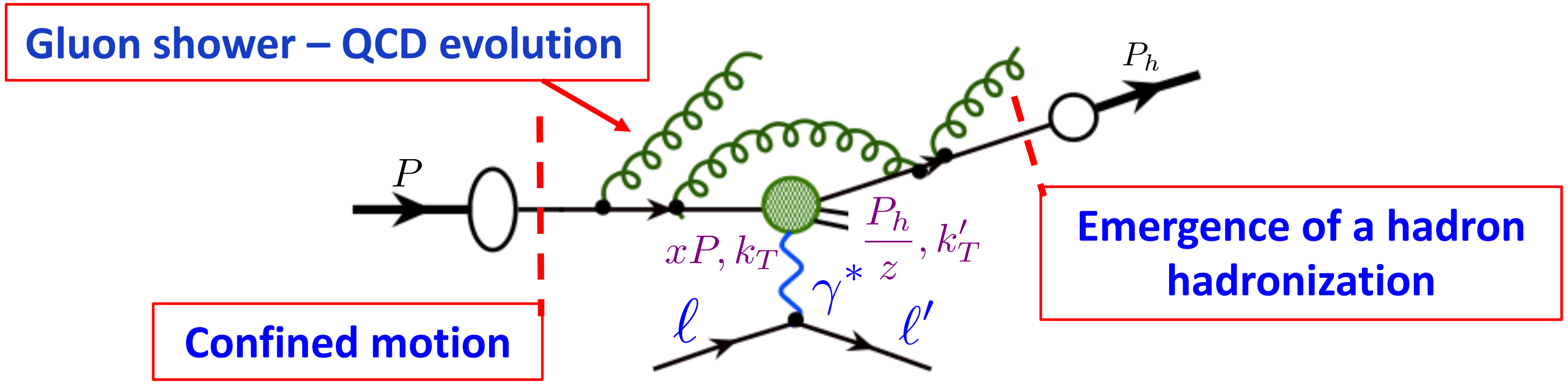


If the proton is broken, e.g., in SIDIS, …



Transverse momentum broadening:

$$\Delta k_T^2 \propto \Lambda_{\rm QCD}^2 \times \alpha_s(C_F, C_A) \times \log(Q^2/\Lambda_{\rm QCD}^2) \times \log(s/Q^2)$$

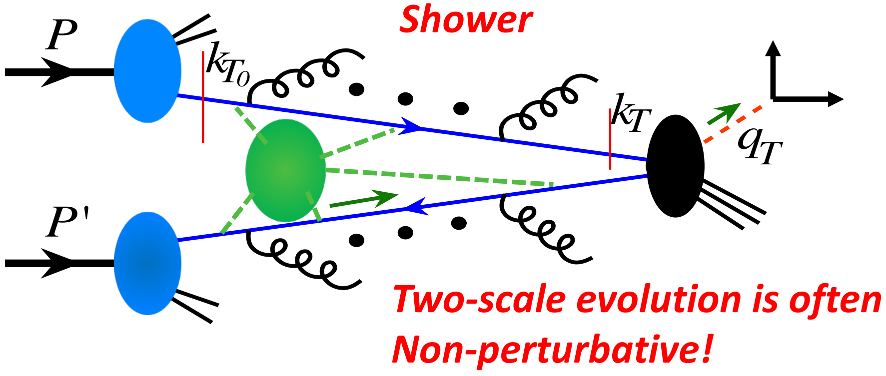
$$\alpha_s(C_F, C_A) \times \log(Q^2/\Lambda_{\rm QCD}^2) \times \log(s/Q^2) \gtrsim 1$$

- *Measured k_T is NOT the same as k_T of the intrinsic confined motion!*
- *Structure information vs. collision effects*

Structure information is diluted by the collision induced shower!

Challenge for extracting the "True" Hadron Structure – example

- **Challenge to separate "true" hadron structure from "collision effects":**



- Drell-Yan type (W/Z, H^0): Q >> q_T (two scales)
- Parton *shower* develops when hadron broken
- *Parton k_T probed at the hard collision is NOT the same as the intrinsic "confined motion" in a hadron*
- The difference is encoded in QCD evolution
- Two-scale evolution *is different* from DGLAP!

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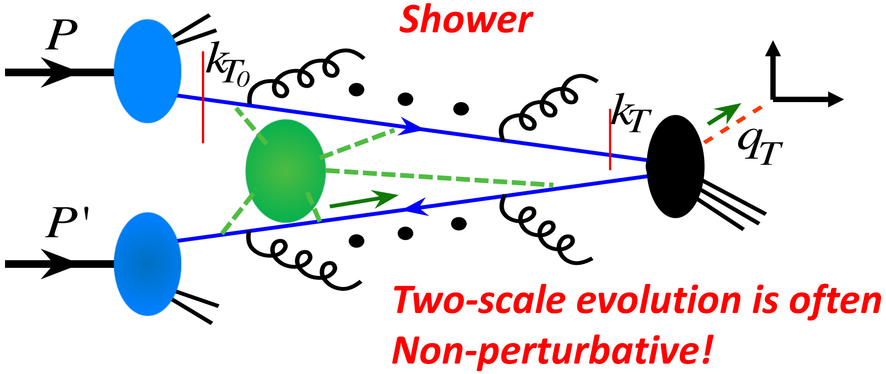

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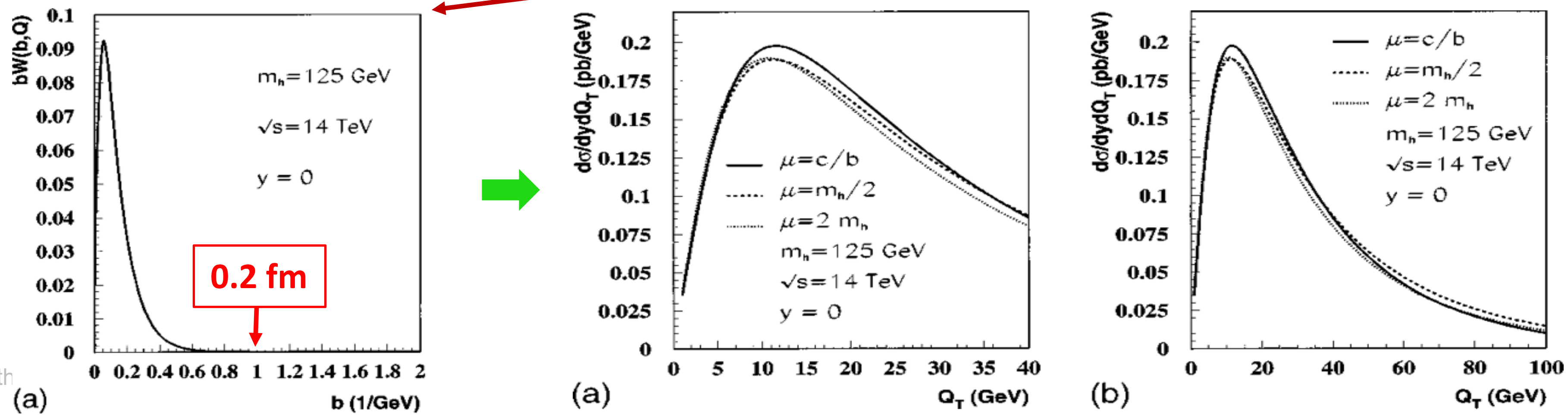
  - The difference is encoded in QCD evolution
  - Two-scale evolution *is different* from DGLAP!

- **Structure information could be easily washed out in high energy collisions:**

e.g., Higgs production at the LHC:

$$f(x_b, k_T, \mu, \zeta_b) \quad \text{F.T.}$$

$$\frac{d\sigma(Q,q_T)}{dy\,dq_T} = \int_0^\infty \frac{db_T}{2\pi} b_T J_0(q_T b_T) H(Q,\mu) f(x_a, b_T, \mu, \zeta_a) f(x_b, b_T, \mu, \zeta_b) + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

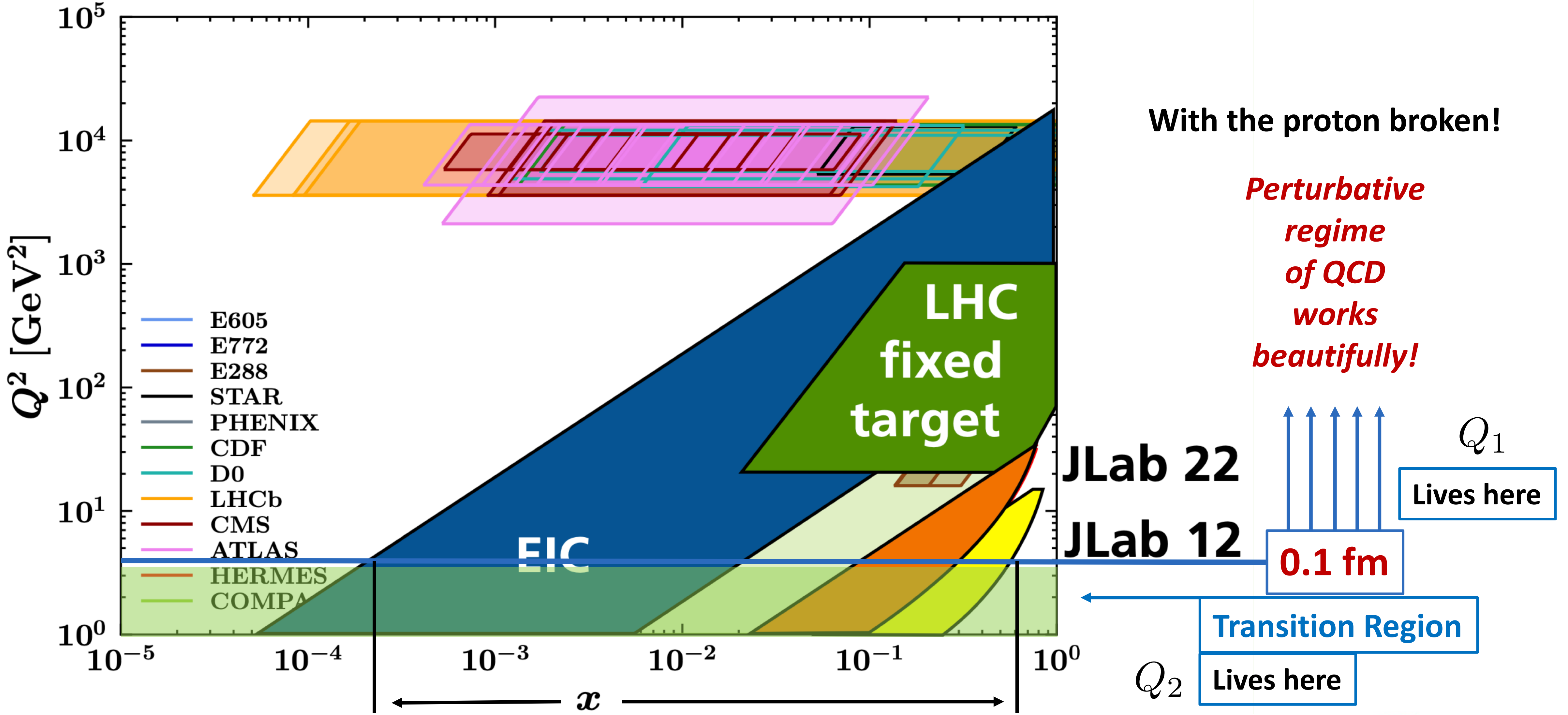


Berger, Qiu PRD67 (2003) 034026

Not sensitive to the structure other than PDFs!

Challenge for extracting the "True" Hadron Structure

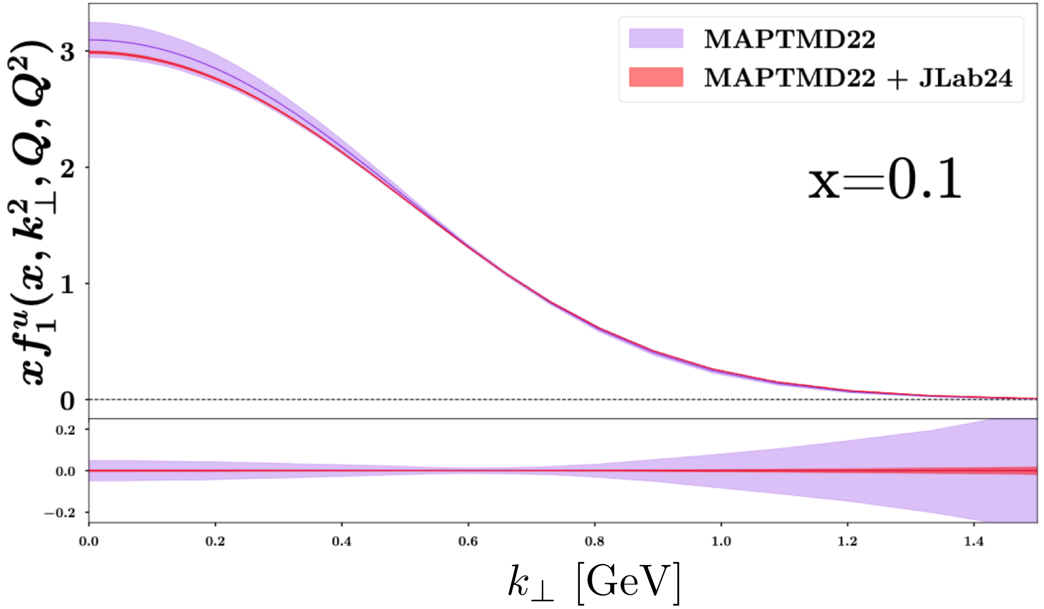
- Extracting hadron structure needs data with **sufficiently large Q^2, but, not too large S**

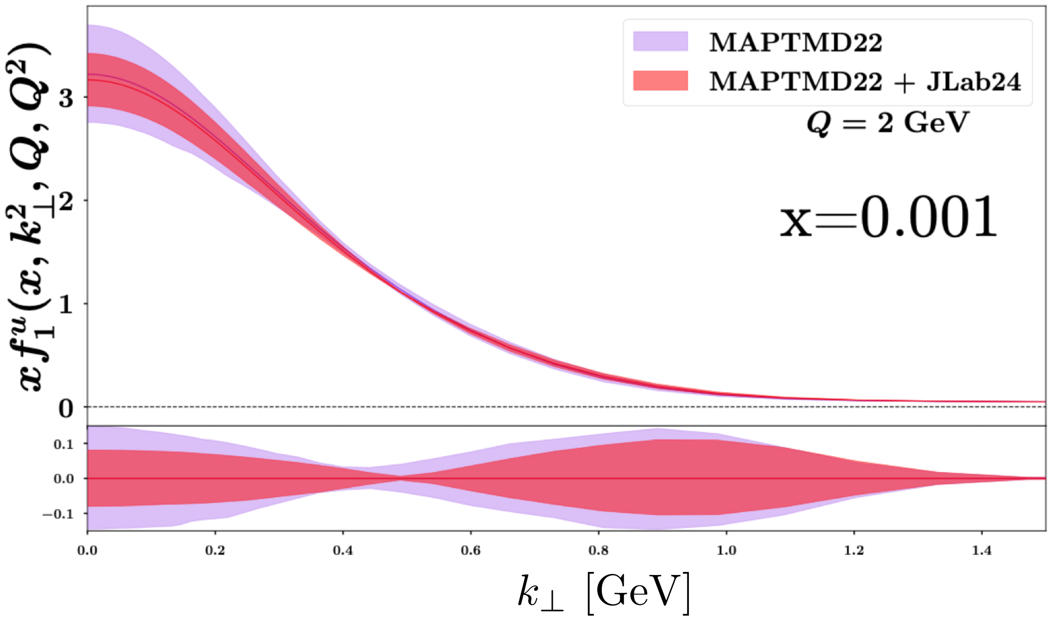


3D Imaging in Momentum Space – Impact

- **Spin-averaged TMD - up quark:**

Matteo Cerutti, ECT* workshop, 9/28/2022





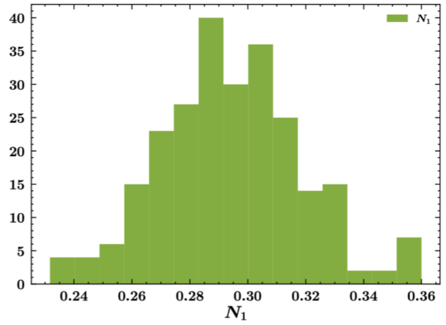
Simulated JLab data: $Q^2 > 1.4\ \text{GeV}^2;\quad 0.2 < z < 0.7;\quad P_{hT} < \min[\min[0.2Q, 0.5zQ] + 0.3\ \text{GeV}, zQ]\qquad \pi^+$

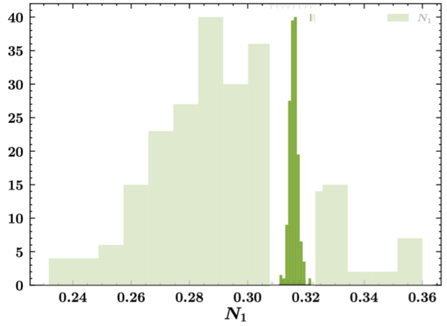
- **Impact on TMD parameter:**

$$f_{1\text{NP}}(x, b_T^2) \propto \text{F.T. of } \left(e^{-\frac{k_T^2}{g1}} + \lambda^2 k_T^2 e^{-\frac{k_T^2}{g1B}} + \lambda_2^2 e^{-\frac{k_T^2}{g1C}}\right)$$

Width:

$$g_1(x) = N_1 \frac{(1-x)^\alpha\ x^\sigma}{(1-\hat{x})^\alpha\ \hat{x}^\sigma}$$





See talks in sessions 4-10

3D Imaging in Position Space

M. Burkdart, PRD 2000

- **Impact parameter dependent parton density distribution:**

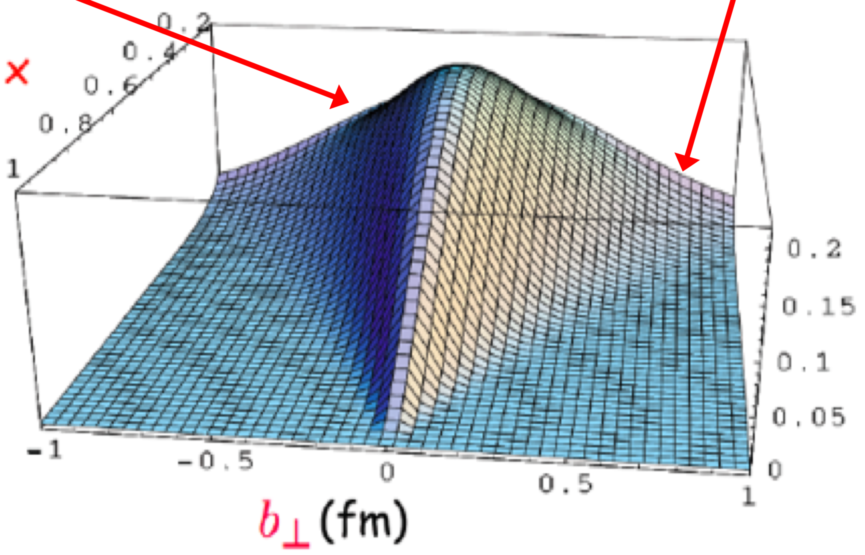
$$q(x, b_\perp, Q) = \int d^2\Delta_\perp e^{-i\Delta_\perp \cdot b_\perp} H_q(x, \xi = 0, t = -\Delta_\perp^2, Q)$$

Quark density in $\mathrm{d}x\,\mathrm{d}^2 \boldsymbol{b}_T$

How fast does glue density fall?

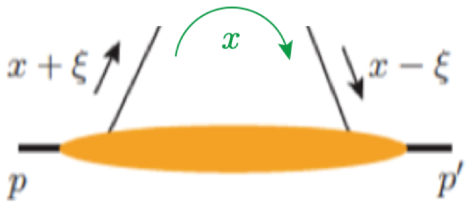
3D image

How far does glue density spread?

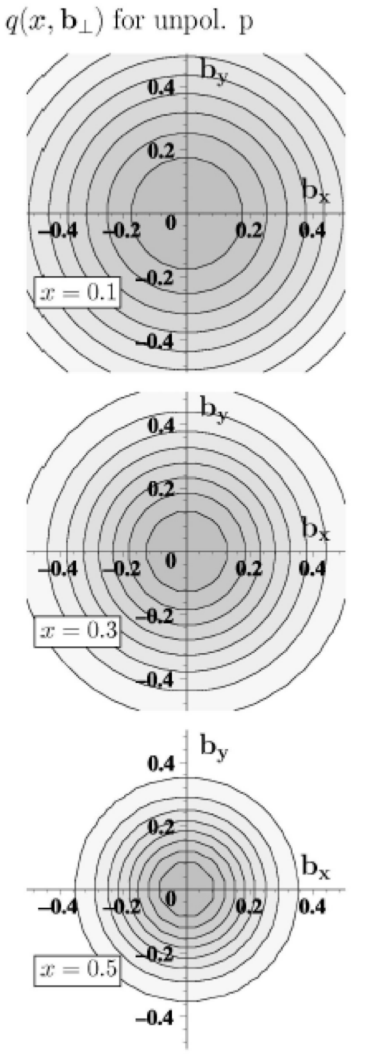


Proton radii of quark and gluon spatial density distribution, $r_q(x)$ & $r_g(x)$

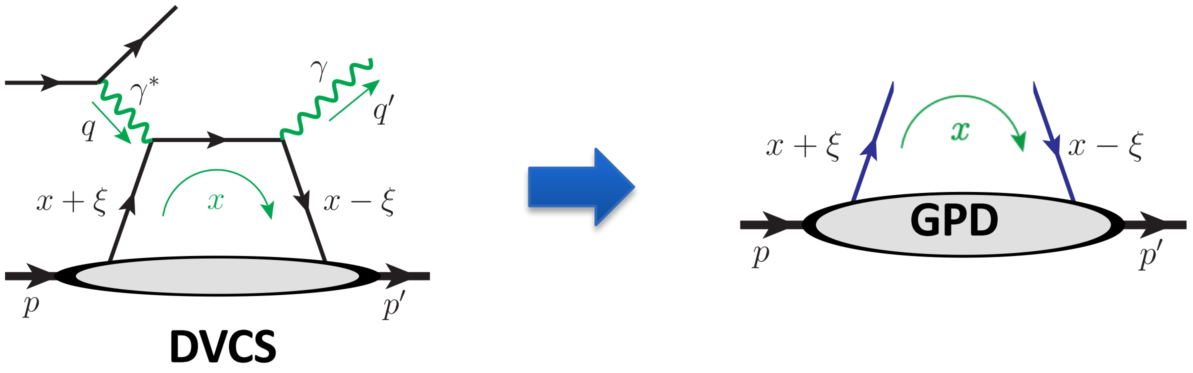
Unpolarized proton



- **Should $r_q(x)$ > $r_g(x)$, or vice versa?**
- **Could $r_g(x)$ saturates as $x \to 0$**
- **How do they compare with known radius (EM charge radius, mass radius, …)?**
- **Tomographic images in slides of different x value!**



DVCS & DVMP are not very sensitive to x-dependence of GPDs



- **Amplitude nature: exclusive processes**

$$\mathcal{M} \sim \int_{-1}^{1} \mathrm{d}x F(x,\xi,t)\cdot C(x,\xi;Q/\mu)$$

$x \sim$ **loop momentum**

- **At LO, DVCS hard coefficient factorizes**

$$C(x,\xi;Q/\mu) = C_Q(Q/\mu)\cdot C_x(x,\xi) \propto \frac{1}{x-\xi+i\varepsilon}\cdots$$

$$\Rightarrow\quad i\mathcal{M} \propto \int_{-1}^{1} \mathrm{d}x \frac{F(x,\xi,t)}{x-\xi+i\varepsilon} \equiv \text{“}F_0(\xi,t)\text{”}$$

x-dependence is only constrained by a “moment”

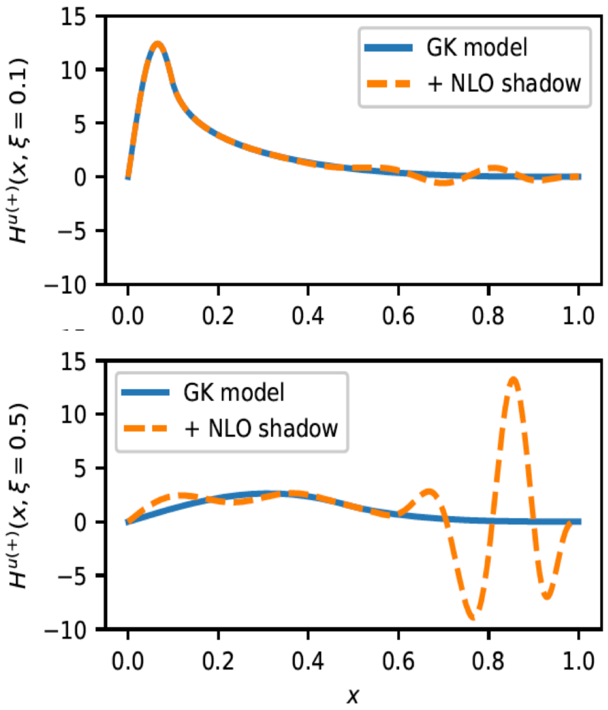
- **Shadow GPDs:** $F_s(x,\xi,t)$

$$\int_{-1}^{1} dx \frac{F_s(x,\xi,t)}{x-\xi+i\varepsilon} = 0$$

$\Rightarrow$ GPDs with any shadow GPDs:

$$F(x,\xi,t) + F_s(x,\xi,t)$$

Can fit the same DVCS data at LO



Blue and dashed Fit the same CFFs !

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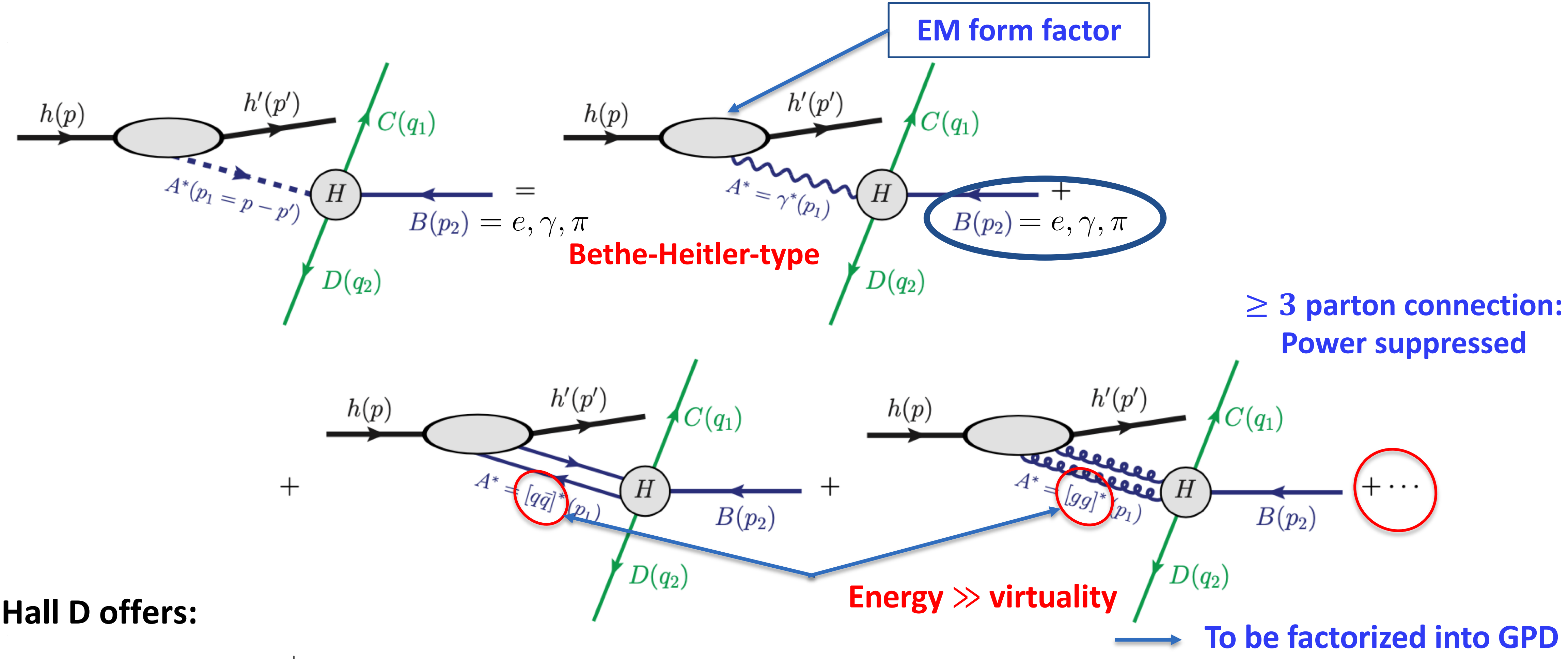
See talks in sessions 11-12

CEBAF with HE offers new opportunities for x-dependence of GPDs

- **Single-Diffractive Hard Exclusive Processes (SDHEP) can be sensitive to x-dependence of GPDs**



- **Hall D offers:**

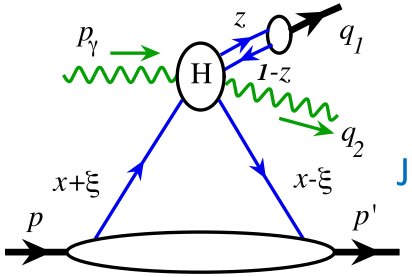
$$\gamma(p_\gamma) + h(p) \to \pi^\pm(q_1) + \gamma(q_2) + h'(p')$$

Plus similar processes!

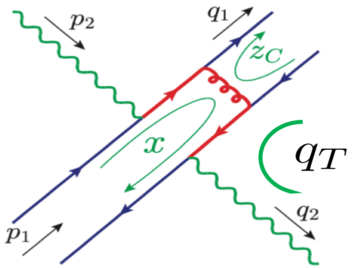
CEBAF with HE offers new opportunities for x-dependence of GPDs

- **Processes:** $\gamma(p_\gamma) + h(p) \to \pi^{\pm}(q_1) + \gamma(q_2) + h'(p')$
  - **Hard scale is not given by a point like virtual photon**
  - **The qT (or angle) is sensitive to x-dependence of GPDs**

QCD Factorization: $|q_{1T}| = |q_{2T}| \gg \sqrt{|t|} = \sqrt{|(p-p')^2|}$



JLab, EIC



- **Phenomenology:**

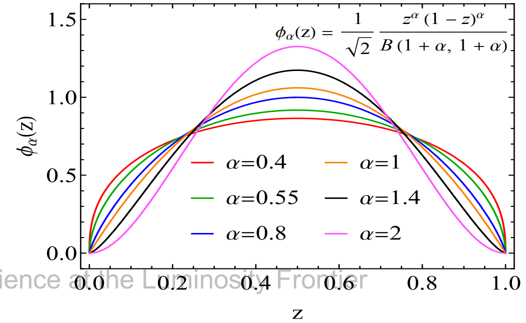
$$\frac{d\sigma}{d|t|\,d\xi\,d\cos\theta_\pi\,d\phi_\pi} = \frac{|\mathcal{A}|^2}{32\,s\,(2\pi)^4\,(1+\xi)^2}$$

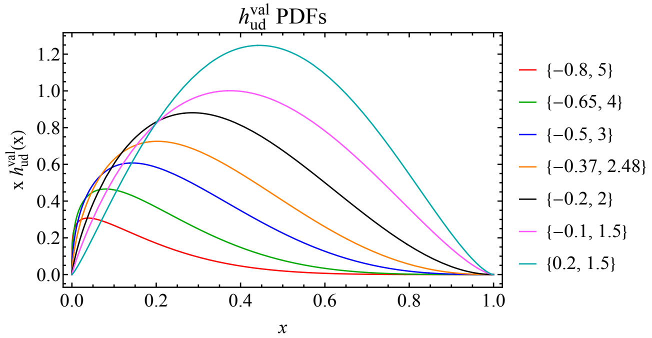
$$\frac{1}{2}\overline{|\mathcal{A}|^2} = \left(\frac{2\pi\alpha_s}{s}f_\pi\right)^2 \left(\frac{C_F}{N_c}\right)^2 \left(\frac{1+\xi}{\xi}\right)^2 (1-\xi^2) \times \left[|O_{++}^{[\tilde{H}]}|^2 + |O_{+-}^{[\tilde{H}]}|^2 + |\tilde{O}_{++}^{[H]}|^2 + |\tilde{O}_{+-}^{[H]}|^2\right]$$

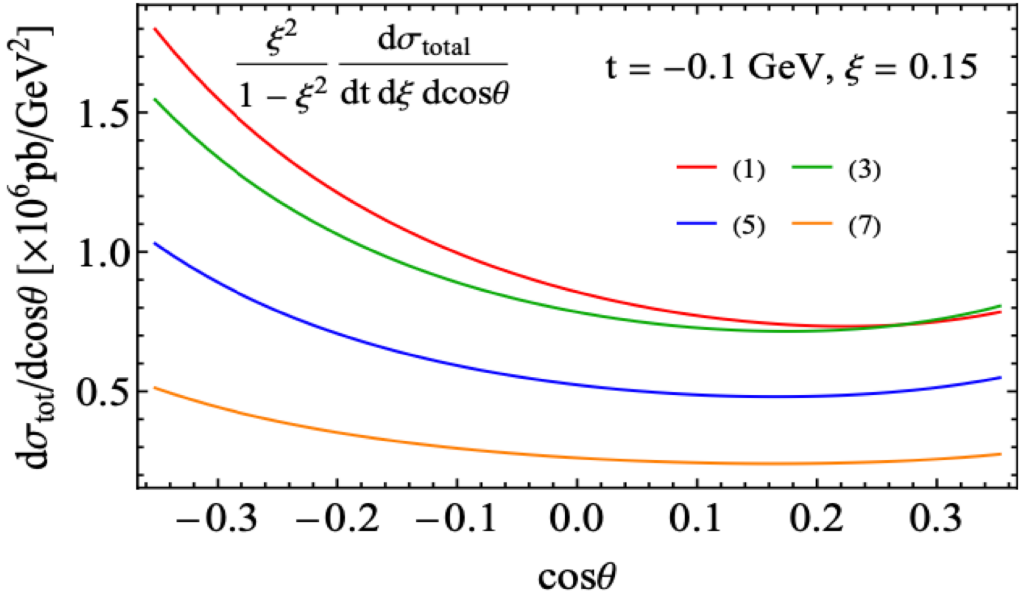
With factorized helicity amplitude:

$$O_{\lambda\lambda'}^{[\tilde{H}]} = \sum_q \int_{x_L}^{x_R} dx \int_0^1 dz\, \tilde{H}^q(x,\xi,t)\,\phi_\pi^q(z)\,O_{\lambda\lambda'}^q(x,z)$$

With flexible Pion DA + Simplified GK model for GPDs:

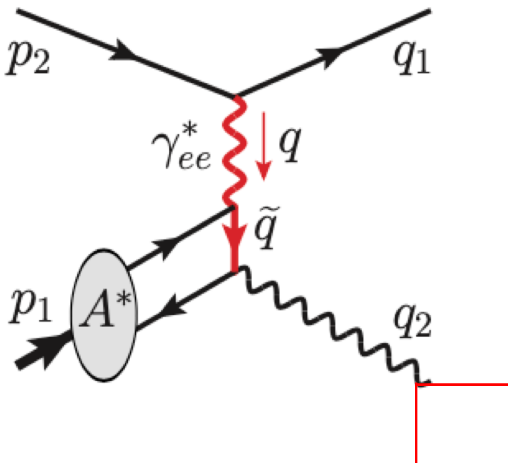






CEBAF with HE offers new opportunities for x-dependence of GPDs

- **DDVCS is sensitive to the x-dependence of GPDs – Needs luminosity & energy!**



Transverse momentum flow from the final-state lepton and the virtual photon is sensitive to the virtuality of the dilepton

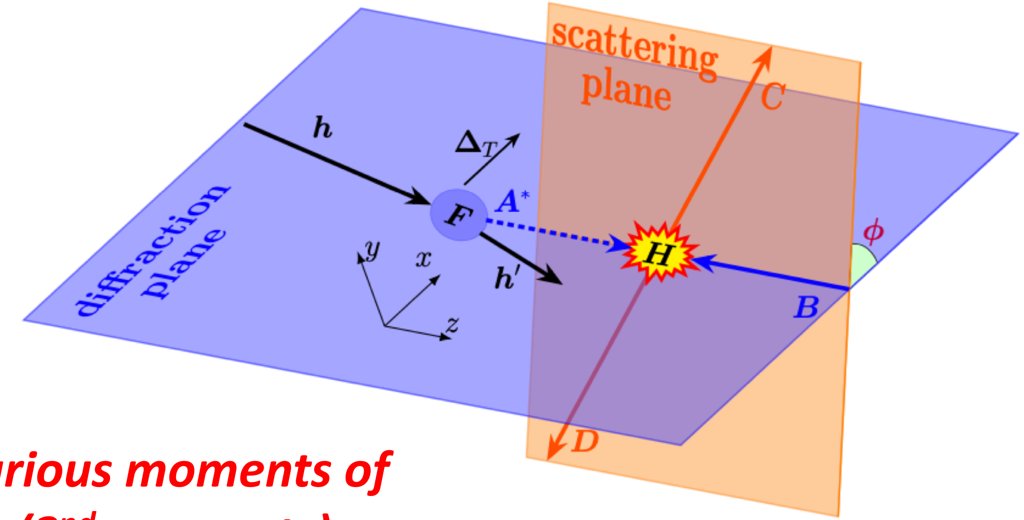
$$q_2^2 = (2\xi P + q)^2 = (2\xi)2P \cdot q - Q^2 + \mathcal{O}(|t|)$$

$$\tilde{q}^2 = ((x+\xi)P + q)^2 = \frac{Q^2 + q_2^2}{2\xi}\left[x - \xi\left(\frac{1 - q_2^2/Q^2}{1 + q_2^2/Q^2}\right)\right] \to x - \xi \quad \text{as} \quad q_2^2 \to 0 \quad \textbf{DVCS}$$

Direct sensitive to external variable, q_2^2, directly sensitive to q_T

- **More opportunities:**
  - Diffractive plane
  - Exclusive hard scattering plane
  - Angular modulation between the two planes

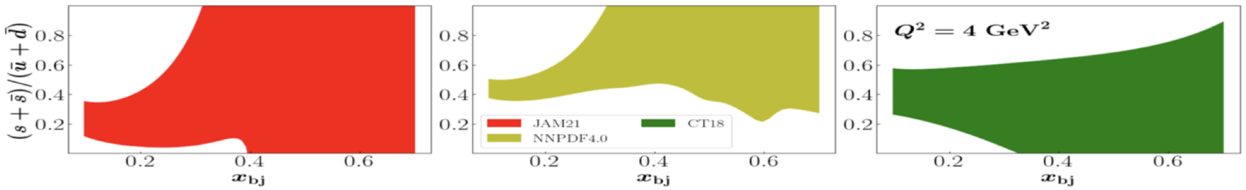
➡ ***Selection from different exchange state A* (or different GPDs)***

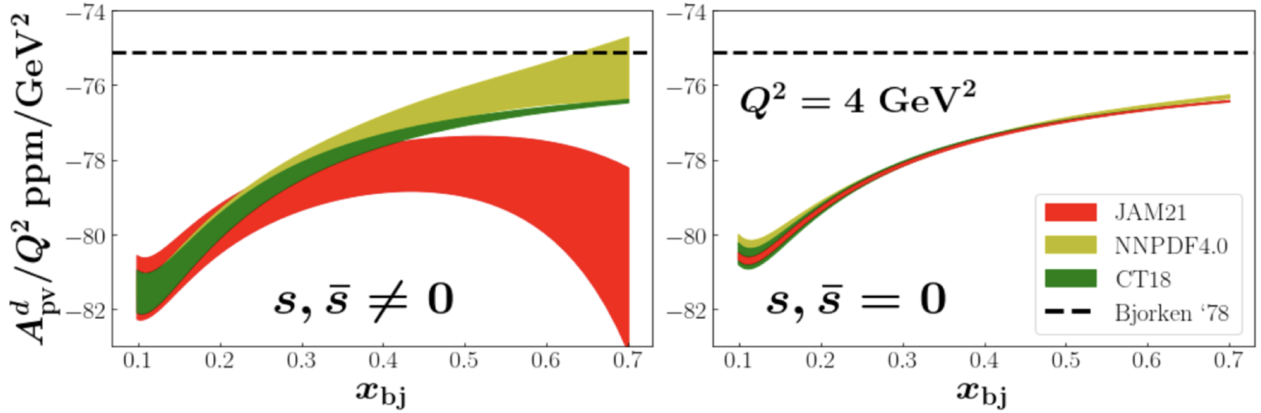


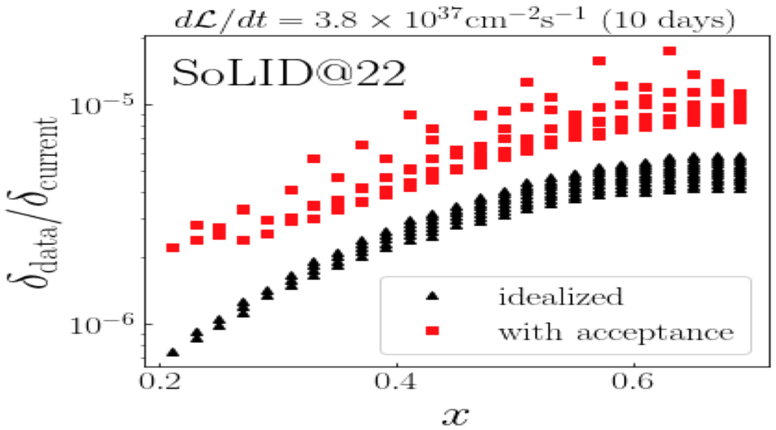
It is the x-dependence of GPDs that allows us to calculate various moments of GPDs – total angular momentum, gravitational form factors (2nd moments), …

PVDIS: Sea and strange quark distributions and more

- **Current uncertainty in strangeness:**

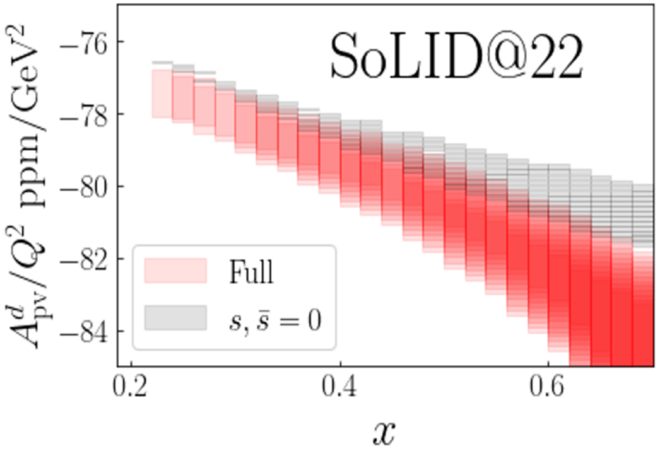


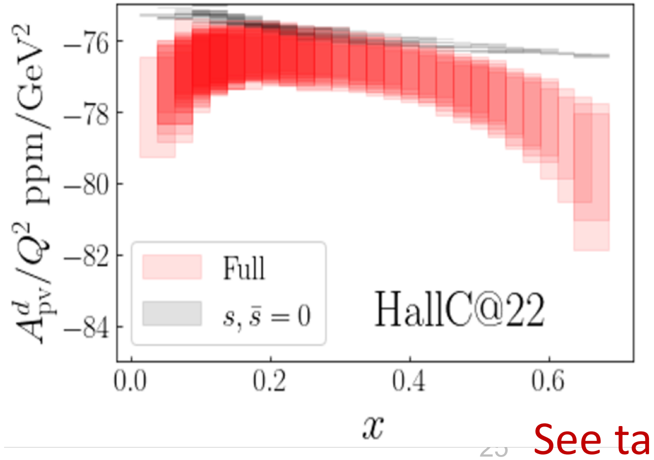


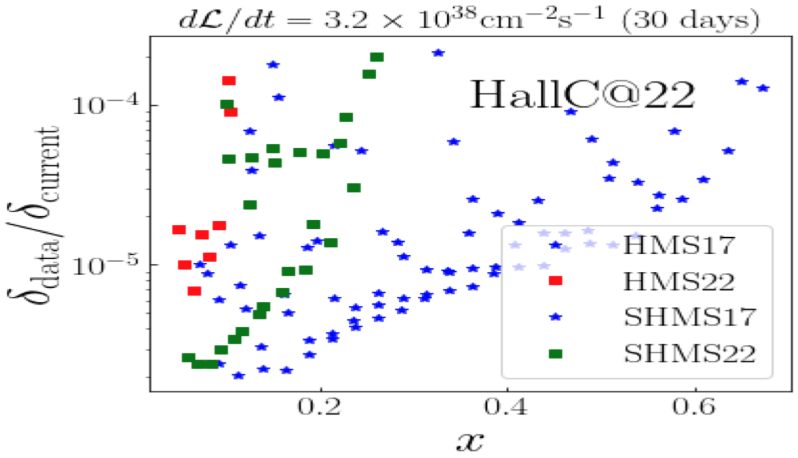


Precision extraction of $\sin^2\theta_W$

- **Impact on A_{PV} of PVDIS:**



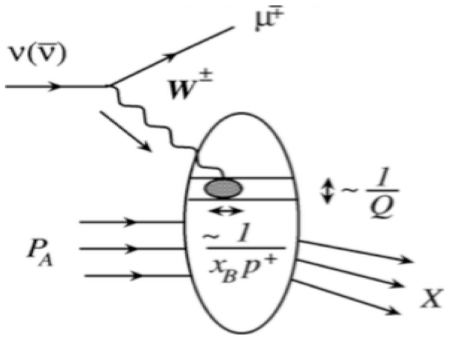




See talks in sessions 4-10

Anti-shadowing – opportunity to solve a multi-decade mystery

- **Hard probes are localized in space, but, might be larger Lorentz-contracted colliding hadron:**



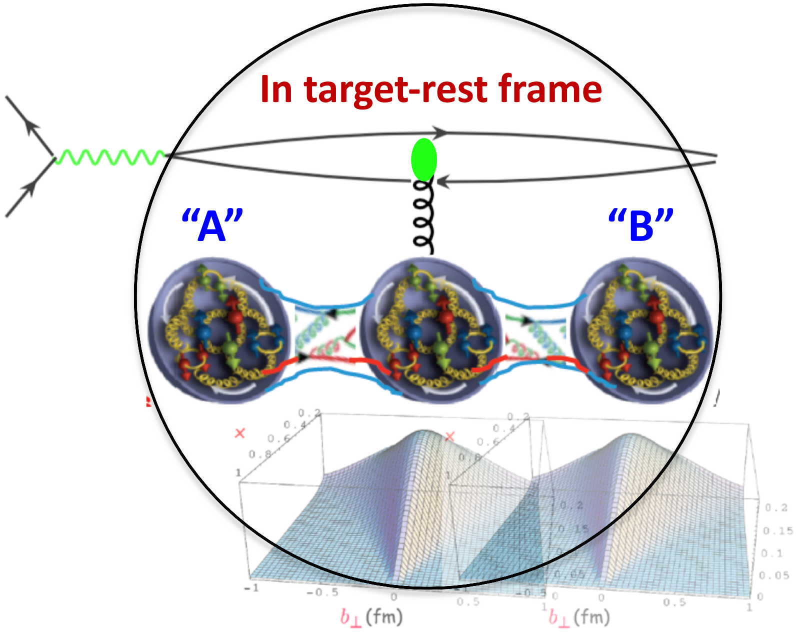
In c.m. frame

Longitudinal probing size

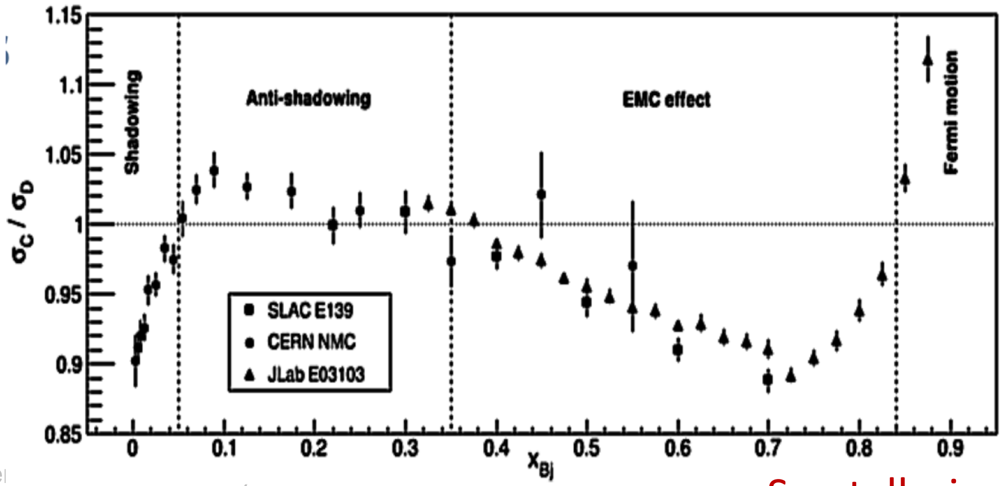
> Lorentz contracted nucleon

if $\frac{1}{xp} > 2R\frac{m}{p}$ or $x < 0.1$

A hard probe at small-x can interact with multiple nucleons (partons from multiple nucleons) at the same impact parameter ***coherently***



- **CEBAF with HE is ideal for exploring anti-shadowing regime:**



- **Hard probe with x in the anti-shadowing region is sensitive to the inter-nucleon distance in a nucleus**
- **Scattering off the pion cloud leading to too strong "anti-shadowing" – "old EMC effort"**
- **Coherent multiple scattering leading to "Shadowing"**

Need a lepton-hadron facility to pin down the kinematics!

Origin of anti-shadowing?

See talks in sessions 14-15

Summary and outlook

- CEBAF 20+ GeV upgrade is technically feasible – Opportunity
- A very strong science case for such an upgrade is emerging:
  - New charmonium states, so-called “XYZ states,” could be discovered/studied at JLab
    – Fundamental question on how hadrons are emerged?
  - Precision charmonium production near & beyond the threshold in lepton-hadron collisions
    – as a precision probe of fundamental hadron properties and its tomography
  - Open up a sweet region for determining the 3D structure – intrinsic confined motion
    – Critically important for understanding how partons are confined in a bound hadron
  - New opportunities for exploring 3D structure in position space – x-dependence of GPDs
    – Tomography + moments of GPDs (gravitational form factors, angular momentum, …)
  - Ideal facility to explore the anti-shadowing phenomenon
    – a chance to solve the multi-decade mystery + look into the origin of nuclear force, …
  - New and unique opportunities to search for physics beyond SM
    – Did not cover
- Capitalizing on past investment: We are obligated to explore new opportunity for CEBAF