Quarkonia As Tools 2020

12-18 January, 2020
Centre Paul Langevin
Aussois, France

Brainstorming on EIC "Inclusive" quarkonium production vs the HERA legacy

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Theory Center, Jefferson Lab

January 13, 2020

Jefferson Lab

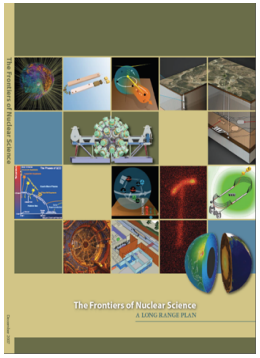
TMD Collaboration

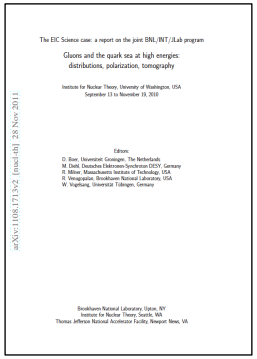
U.S. DEPARTMENT OF ENERGY | Office of Science

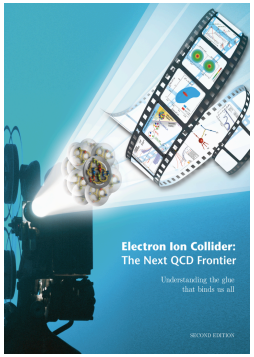
JSA

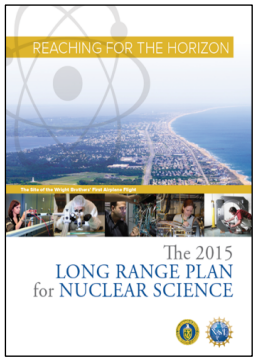
U.S. - based Electron-Ion Collider

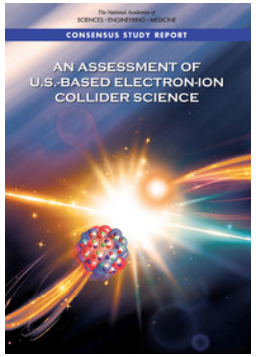
- **A long journey, a joint effort of the full community:**

… 









…

"… answer science questions that are compelling, fundamental, and timely, and help maintain U.S. scientific leadership in nuclear physics."

… three profound questions:

How does the mass of the nucleon arise?

How does the spin of the nucleon arise?

What are the emergent properties of dense systems of gluons?

- **On January 9, 2020:**

The U.S. DOE announced the selection of BNL as the site for the Electron-Ion Collider

→ *A new era to explore the emergent phenomena of QCD!*

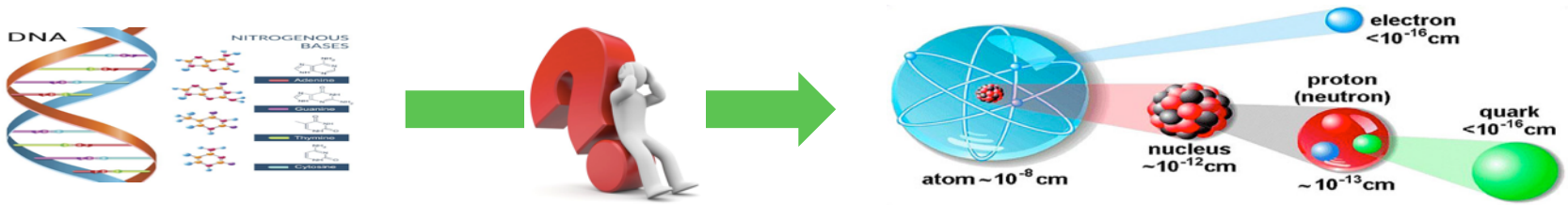
Frontiers of QCD and strong interaction

- **Understanding where did we come from?** Global Time: →

QCD at high temperature, high densities, phase transition, …

Facilities - Relativistic heavy ion collisions: SPS, RHIC, the LHC, …

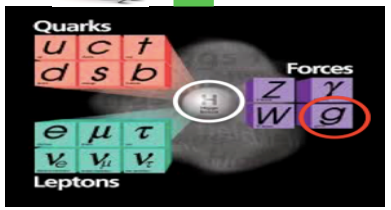
- **Understanding the visible world around us at 3°K – what are we made of?**



What is the internal structure and dynamics of hadrons?

How did hadrons are emerged from the quarks and gluons?

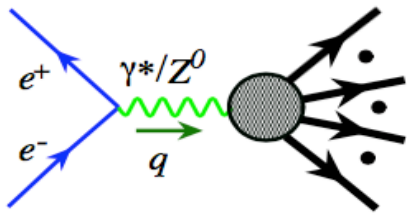
How does the glue bind us all?



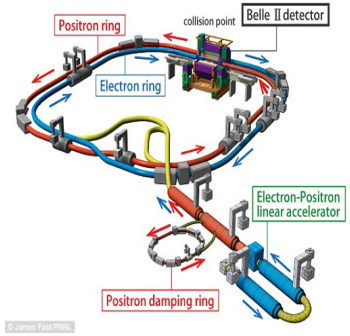
Need a lepton-hadron facility to address all these questions,
—— the emergent phenomena of QCD, with the precision and the uniqueness, …

Why do we need lepton-hadron facilities?

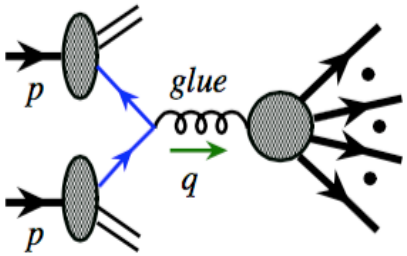
- **Hadrons are produced from the energy in e+e- collisions:**



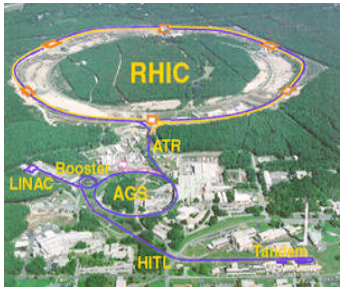
- *No hadron to start with*
- *Emergence of hadrons*



- **Hadrons are produced in hadron-hadron collisions:**

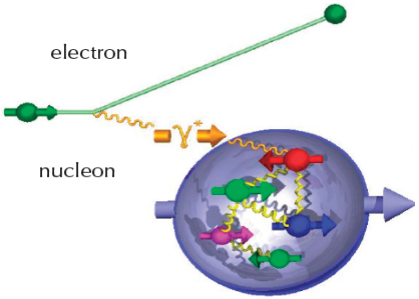


- *Partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam(s)*



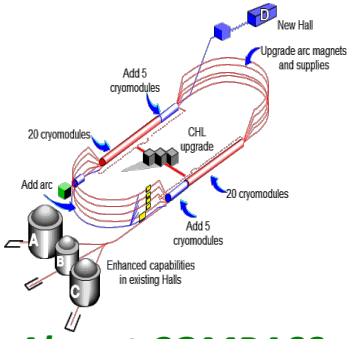
Also at the LHC

- **Hadrons are produced in lepton-hadron collisions:**



One facility covers all!

- *Colliding hadron can be broken or stay intact!*
- *Imaging partonic structure*
- *Emergence of hadrons*
- *Heavy ion target or beam*



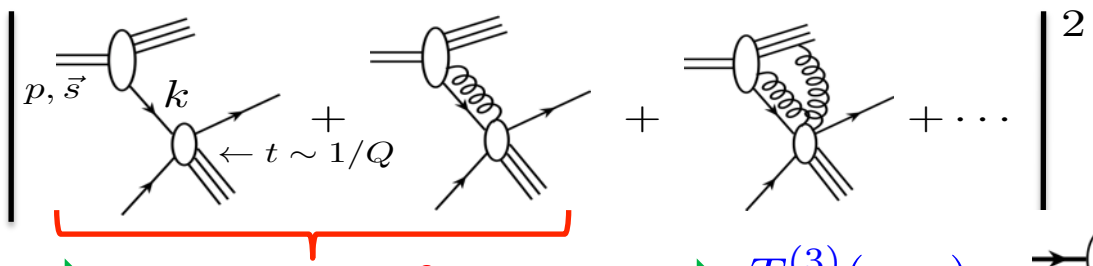
Also at COMPASS & future EIC

US EIC – can do what HERA could not do

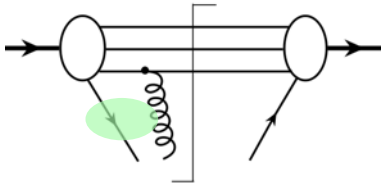
- **Quantum imaging:**
  - ✧ **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

- **Quantum interference & entanglement:**
  - ✧ **US-EIC: Highly polarized beams – *Origin of hadron property: Spin, …***
    Direct access to chromo-quantum interference!

$\sigma(Q, \vec{s}) \propto$



$\sigma(s) - \sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x, x) \propto$

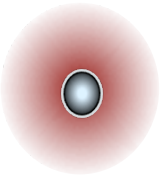


- **Nonlinear quantum dynamics:**
  - ✧ **US-EIC: Light-to-heavy nuclear beams – *Origin of nuclear force, …***
    Catch the transition from chromo-quantum fluctuation
    to chromo-condensate of gluons, …
    Emergence of hadrons (femtometer size detector!),
    – "a new controllable knob" – Atomic weight of nuclei

QCD – Unprecedented intellectual challenge

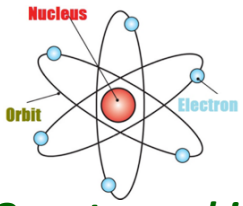
- **No modern detector has seen any quark or gluon in isolation:**
  - **Gluons are dark, but, carry color:**

    NO separation between color charges!
    Color is fully entangled!



$B^+(u\bar{b})$

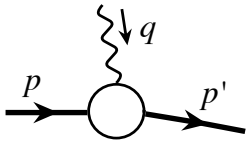
Brown-Muck



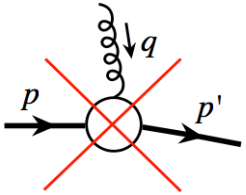
Quantum orbits

  - **No "color" radius of proton:**

    NO elastic "color" form factor!



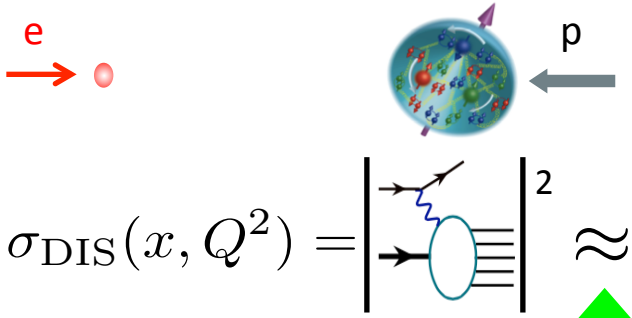
Proton radius



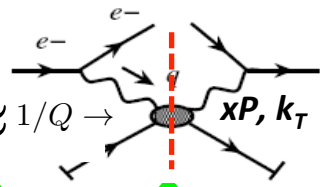
  - **The *challenge*:**

    How to test a theory, its dynamics, without seeing the players?

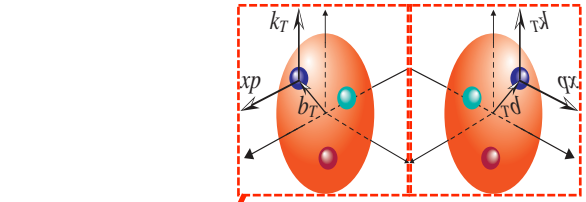
- **Any cross section with identified hadron(s) is NOT perturbatively calculable!**

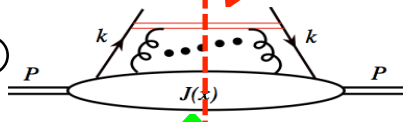


$$\sigma_{\rm DIS}(x,Q^2) = \Bigg|\quad\Bigg|^2 \approx$$



$$\otimes$$





$$+\,O\left(\frac{1}{QR}\right)$$

The way out:

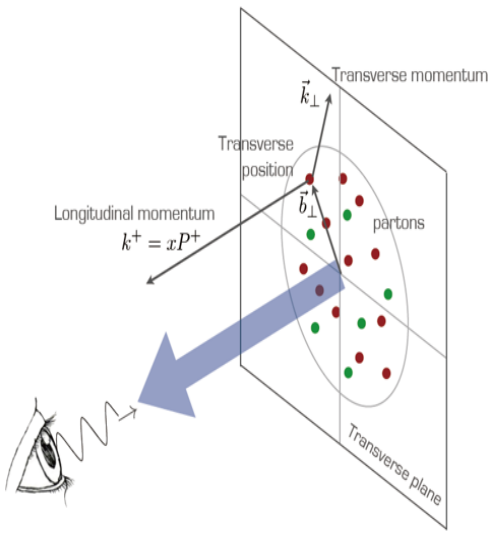
Factorization	Hard-part *Probe*	Parton-distribution *Structure*	Power corrections *Approximation!*

Heavy quarkonia are good and controllable probes

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

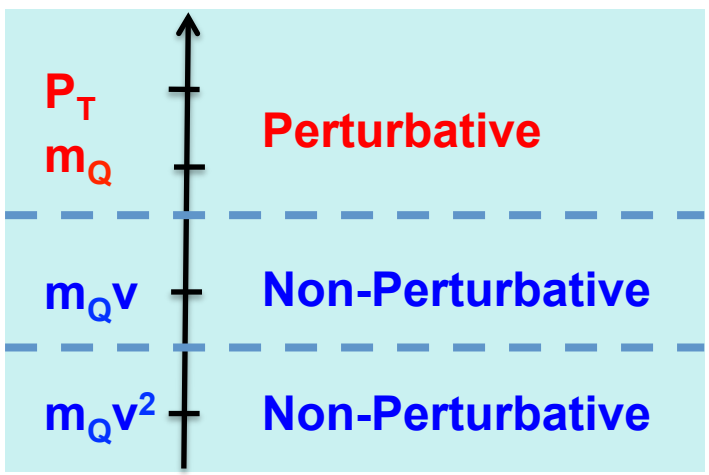
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

  - ✧ **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!**

- **Production of heavy quarkonia – naturally well-separated multiple scales:**



Localized color charges (heavy mass)

Hard — Production of $Q\bar{Q}$ **[pQCD]**

Soft — Relative Momentum **[NRQCD]**

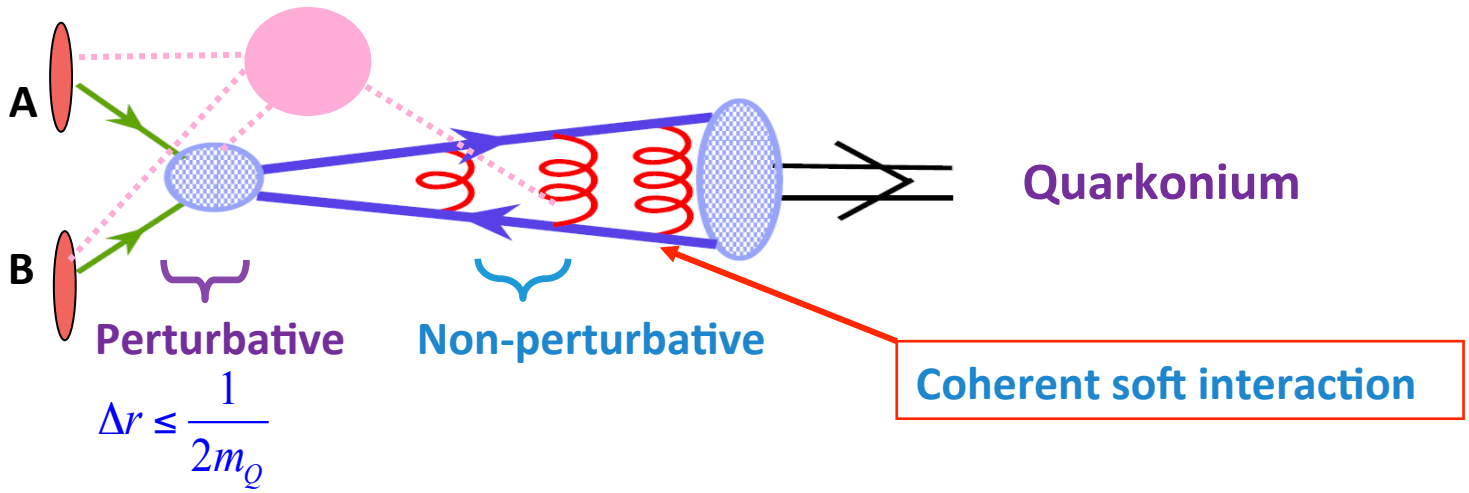
$\Lambda_{\rm QCD}$

Ultrasoft — Binding Energy **[pNRQCD]**

Factorization Difficulty: Emergence of a quarkonium from a heavy quark pair?

Basic production mechanism and factorization

- **Factorization is likely to be valid for producing the pairs:**
  - ✧ **Momentum exchange is much larger than 1/fm**
  - ✧ **Spectators from colliding beams are "frozen" during the hard collision**



- **Naïve factorization: on-shell pair + hadronization**

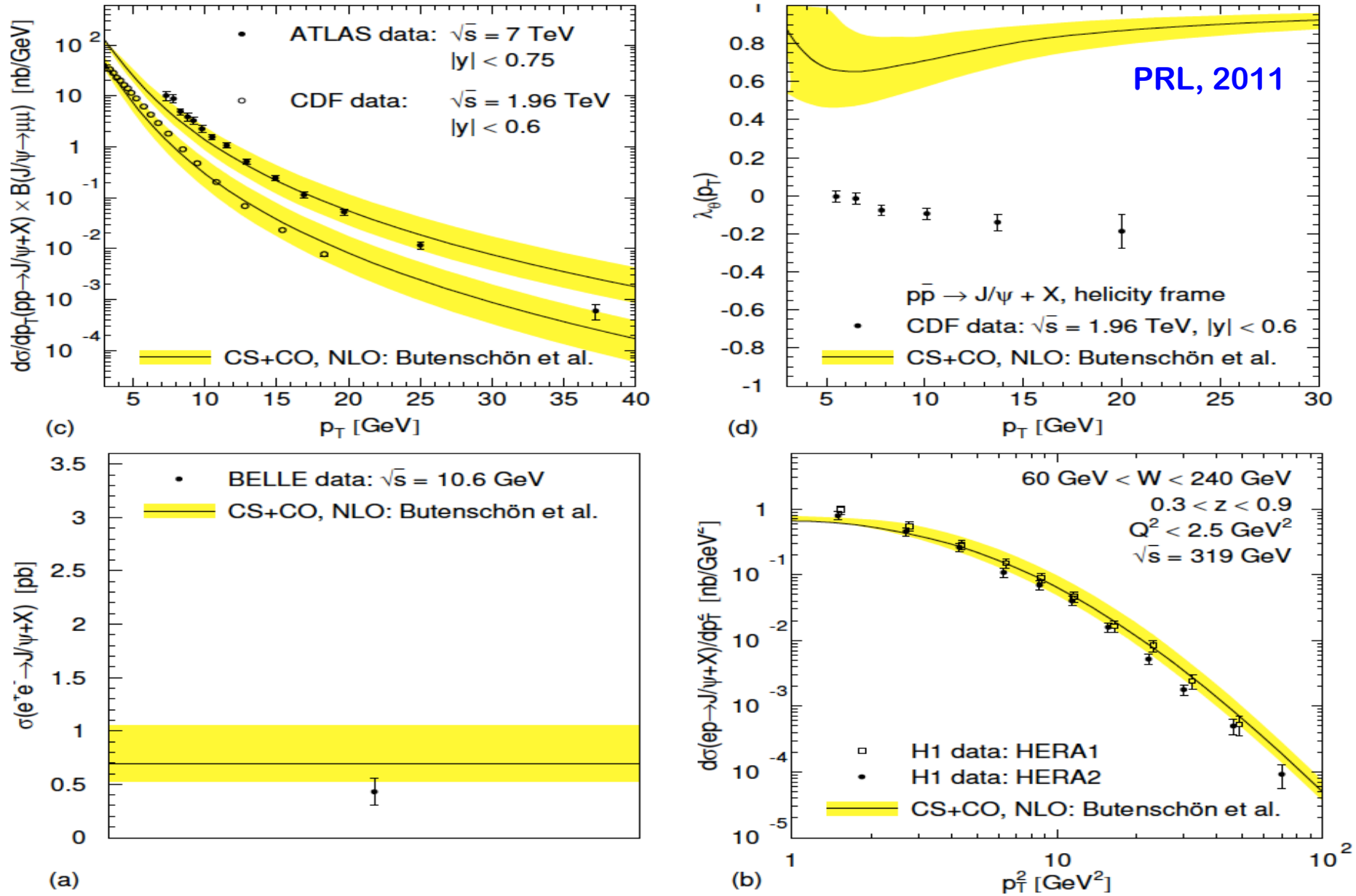
$$\sigma_{AB\to J/\psi} = \sum_{[Q\bar{Q}(n)]} \int d\Gamma_{[Q\bar{Q}]}\, \hat{\sigma}_{AB\to[Q\bar{Q}(n)]}(p_Q, p_{\bar{Q}}) F_{[Q\bar{Q}(n)]\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$$

Trouble from expansion to matrix elements of local operators!

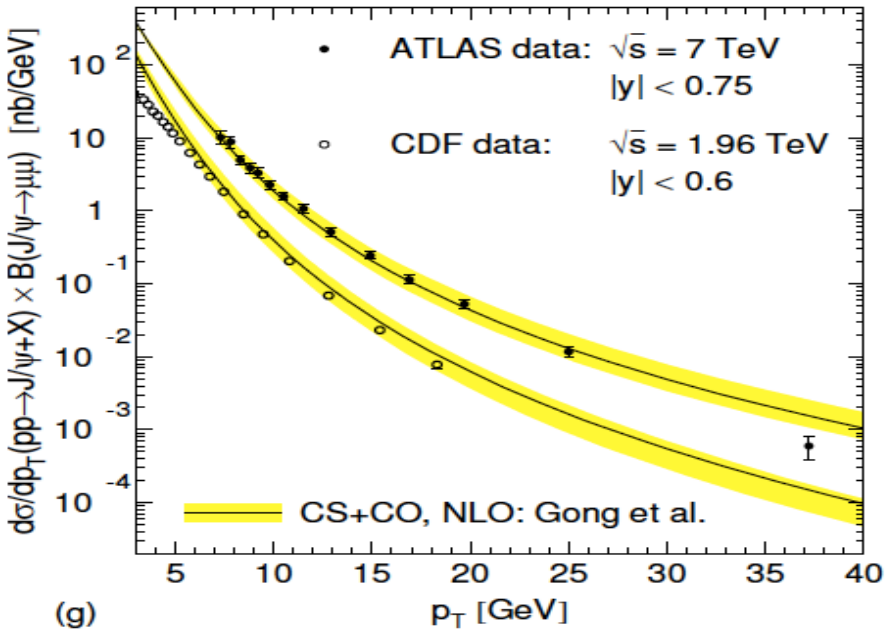
Models & Debates:

⇔ **Different assumptions/treatments on** $F_{[Q\bar{Q}(n)]\to J/\psi}(p_Q, p_{\bar{Q}}, P_{J/\psi})$ **how the heavy quark pair transforms into a quarkonium?**

Challenges: NLO theory fits – Butenschoen et al.



Challenges: NLO theory fits – Gong et al.



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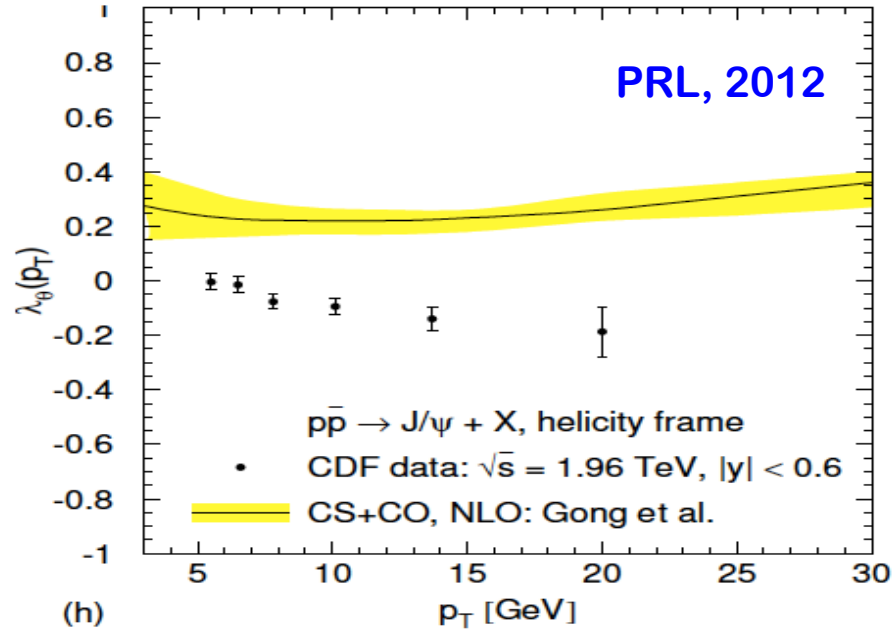

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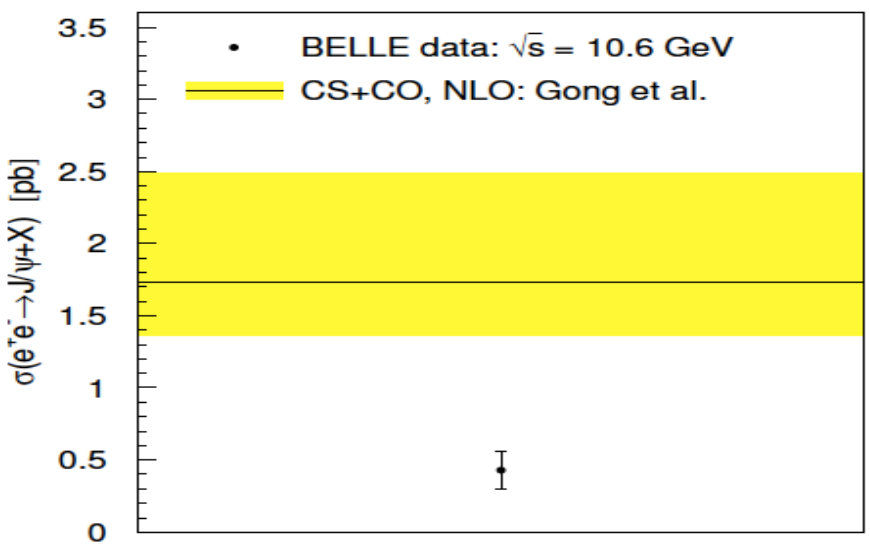

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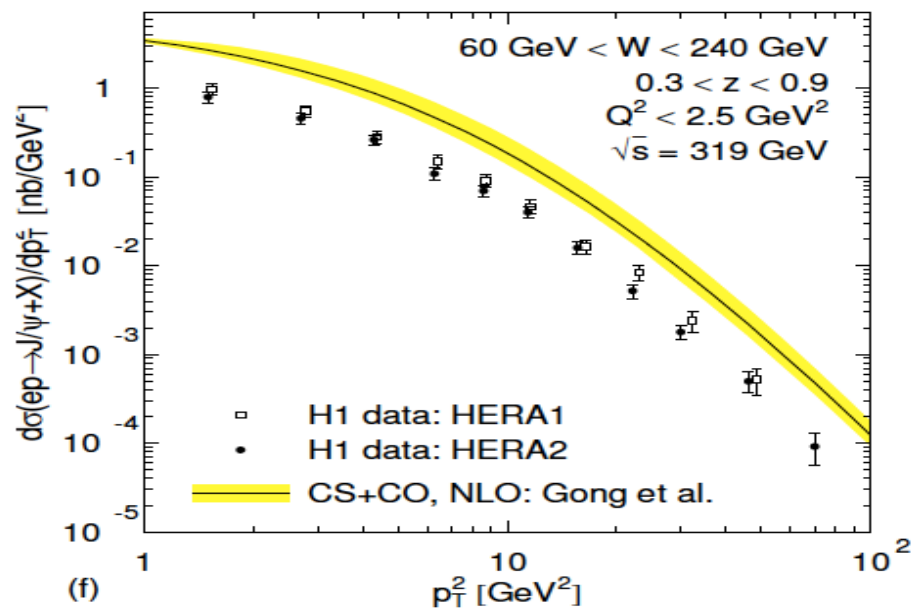
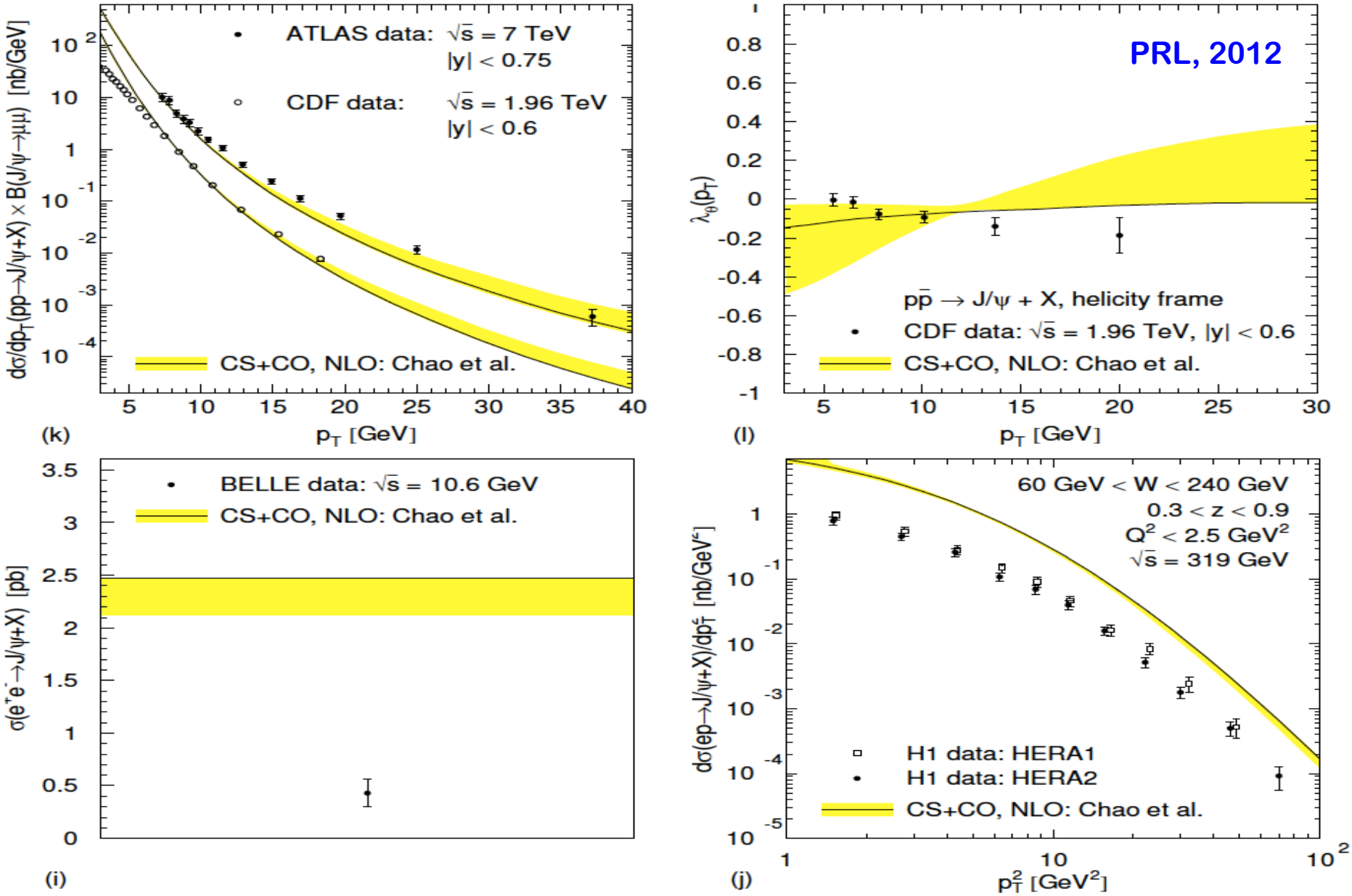


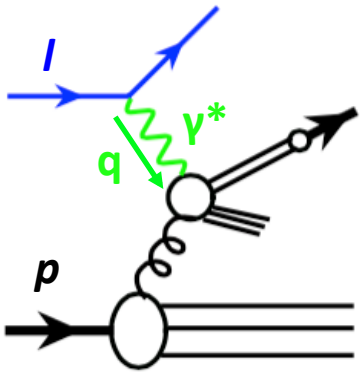
(f)

Challenges: NLO theory fits – Chao et al.



Heavy quarkonium production at HERA – the legacy

❑ Inclusive production:



H=J/ψ,ψ',Υ,...

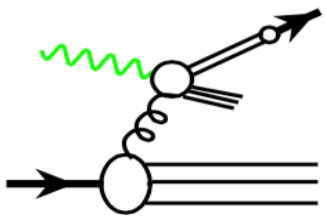
Photon-hadron frame:

Gluon TMD!

P_T depends choice of frame!

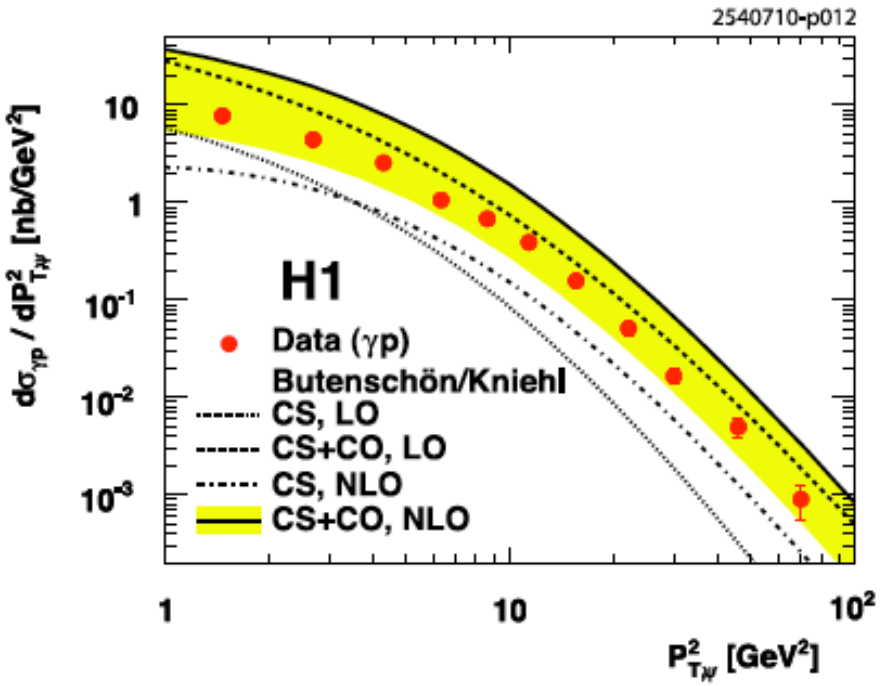
Elasticity: $z = \frac{p_H \cdot p}{q \cdot p} \implies \frac{E_H}{E_q}$

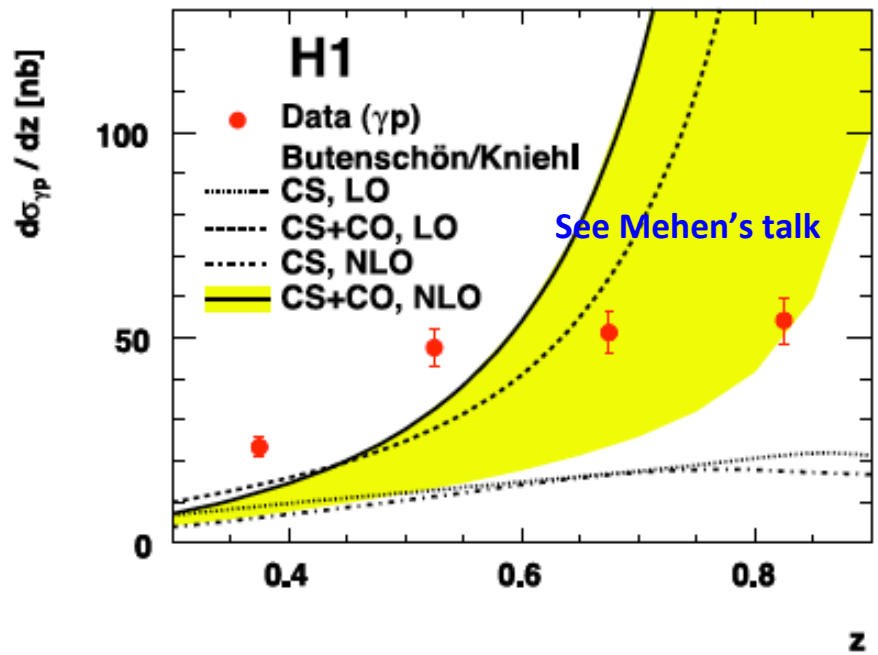
Photoproduction: $z \lesssim 0.3$ Small Q^2



$20 < W_{\gamma p} < 320 GeV$

Collinear factorization





Heavy quarkonium production at HERA – the legacy

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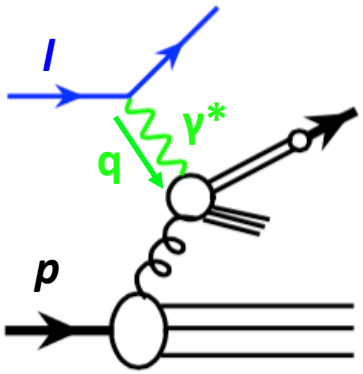

H=J/ψ,ψ',Y,…

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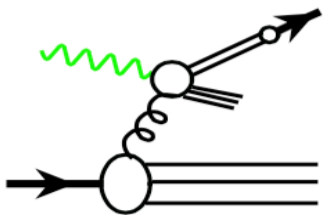
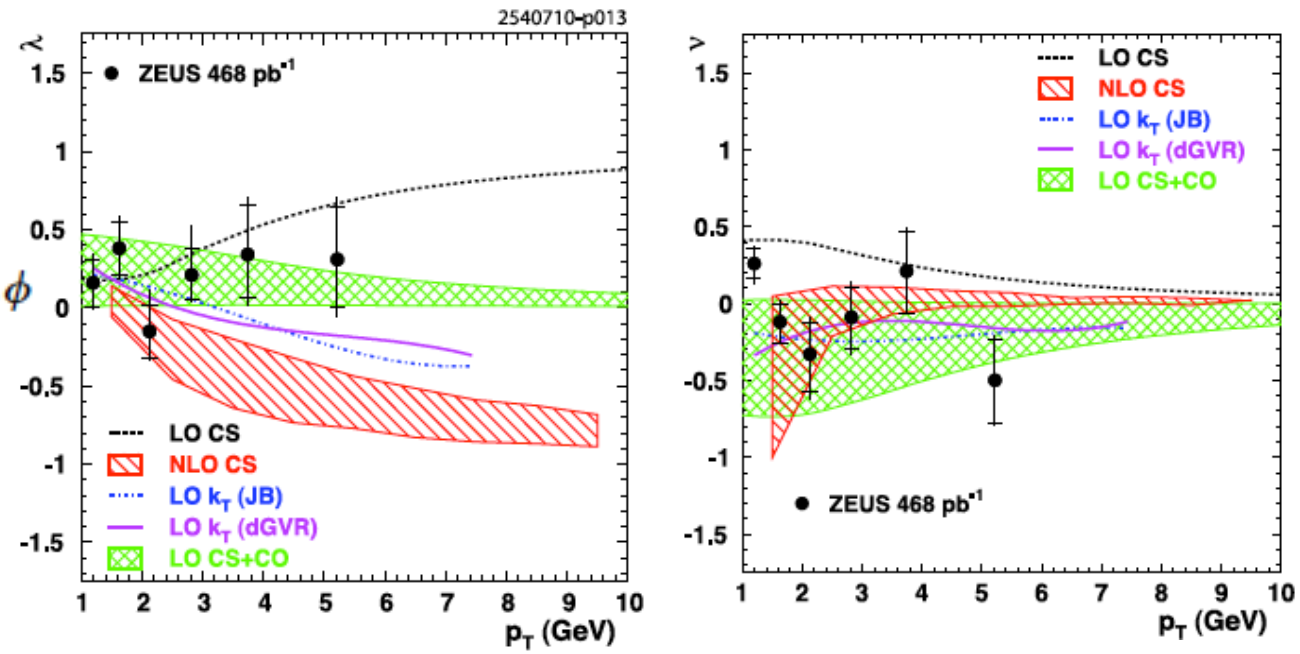


$20 < W_{\gamma p} < 320 GeV$

Collinear factorization

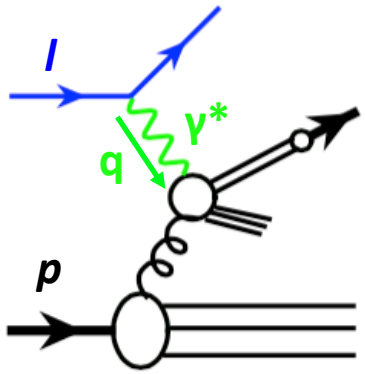
❑ Polarization:

$$\frac{d\Gamma(J/\psi \to l^+l^-)}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



Heavy quarkonium production at EIC

- **Inclusive production:**

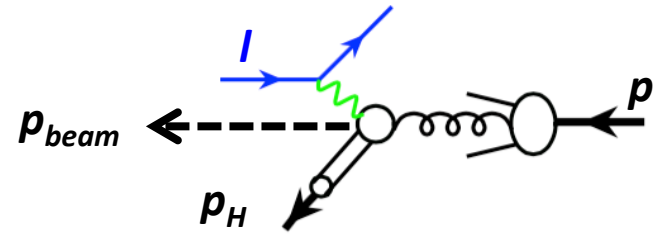


H=J/ψ,ψ',Υ,…

Photon-hadron frame:

Gluon TMD!

Lepton-hadron Lab frame:



Collinear factorization:

$$(p_H - p_{beam})^2 - (m_H + m_{beam})^2 \gg \Lambda^2_{\rm QCD}$$

- **PQCD factorization for production:**

Kang, Ma, Qiu, Sterman, 2014

$$E_p \frac{d\sigma^{\rm PQCD}_{l+h\to H(p)+X}}{d^3p} \approx \sum_f E_c \frac{d\hat{\sigma}_{l+h\to f(p_c)+X}}{d^3p_c} \otimes D_{f\to H}(z;m_Q)$$
$$+ \sum_{[Q\bar{Q}(\kappa)]} E_c \frac{d\hat{\sigma}_{l+h\to [Q\bar{Q}(\kappa)](p_c)+X}}{d^3p_c} \otimes \mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}(z,u,v;m_Q)$$

Valid for $p_T >> m_Q$

Resummation of $\log(p_T/m_Q)$ – closed evolution accurate to $1/p_T^2$:

$$\frac{\partial}{\partial \ln \mu^2}\mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}(z,\xi,\zeta;\mu^2) = \Gamma_{[Q\bar{Q}(\kappa)]\to[Q\bar{Q}(\kappa')]} \otimes \mathcal{D}_{[Q\bar{Q}(\kappa')]\to H}(z,\xi,\zeta;\mu^2)$$
$$\frac{\partial}{\partial \ln \mu^2}D_{f\to H}(z,\mu^2) = \gamma_{f\to f'} \otimes D_{f'\to H}(z,\mu^2) + \frac{1}{\mu^2}\overline{\gamma}_{f\to[Q\bar{Q}(\kappa)]} \otimes \mathcal{D}_{[Q\bar{Q}(\kappa)]\to H}(z,\xi,\zeta;\mu^2)$$

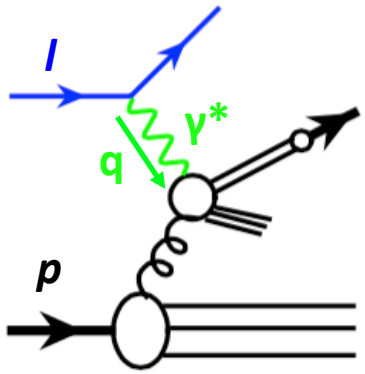
Impact on polarization

Input distributions at $\mu_0 \sim 2m_Q$(non-pert.):

"approximated" in NRQCD factorization?

Heavy quarkonium production at EIC

- **Inclusive production:**



H=J/ψ,ψ',Υ,…

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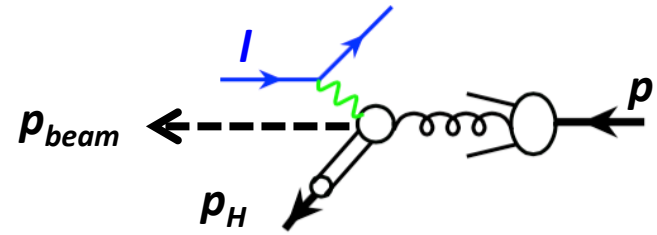
Gluon TMD!

Lepton-hadron Lab frame:



Collinear factorization:

$$(p_H - p_{beam})^2 - (m_H + m_{beam})^2 \gg \Lambda^2_{\rm QCD}$$

- **Matching for $p_T \rightarrow m_Q$:**

$$E_p \frac{d\sigma_{l+h\to H(p)+X}}{d^3p} \approx E_p \frac{d\sigma^{\rm PQCD}_{l+h\to H(p)+X}}{d^3p} - E_p \frac{d\sigma^{\rm PQCD-Asym}_{l+h\to H(p)+X}}{d^3p} + E_p \frac{d\sigma^{\rm NRQCD}_{l+h\to H(p)+X}}{d^3p}$$

Kang, Qiu, 2008
Lee, Qiu, Sterman, Watanabe, 2020

When $p_T >> m_Q$:

$$d\sigma_{l+h\to H(p)+X} \to d\sigma^{\rm PQCD}$$

No-logarithmic mass terms in $d\sigma^{\rm NRQCD}$ **vanish**

$d\sigma^{\rm PQCD-Asym}$ cancels $d\sigma^{\rm NRQCD}$

When $p_T \rightarrow m_Q$:

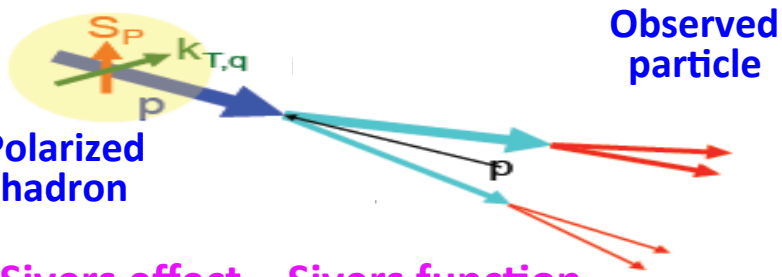
$$d\sigma_{l+h\to H(p)+X} \to d\sigma^{\rm NRQCD}$$

Power of log(p_T/m_Q) in $d\sigma^{\rm PQCD}$ **less important**

$d\sigma^{\rm PQCD-Asym}$ cancels $d\sigma^{\rm PQCD}$

Heavy quarkonium production at EIC – TMDs

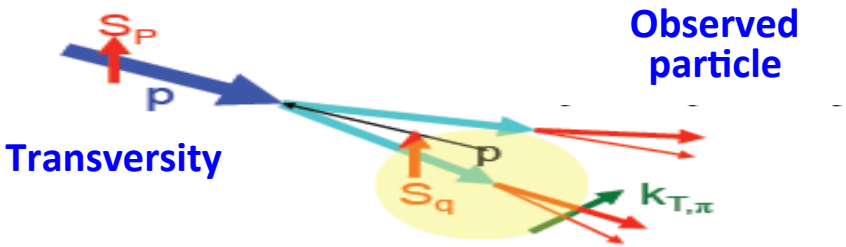
- **Quantum correlation between hadron spin and parton motion:**



✧ **Sivers effect – Sivers function**

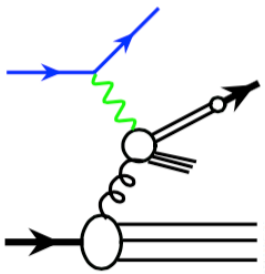
Hadron spin influences parton's transverse motion

- **Quantum correlation between parton's spin and its hadronization:**



✧ **Collins effect – Collins function**

Parton's transverse polarization influences its hadronization



Low p_T << Q in photon-hadron frame

TMDs

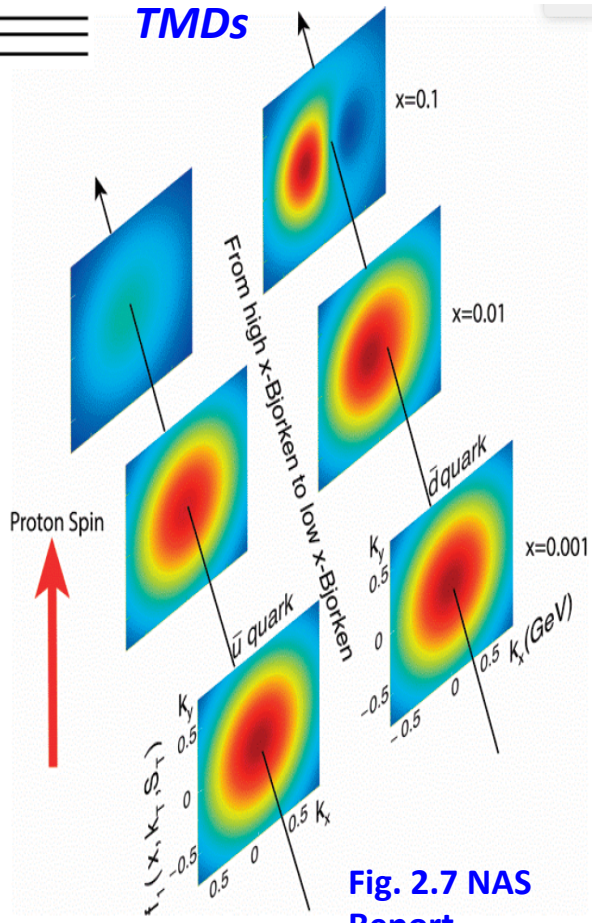
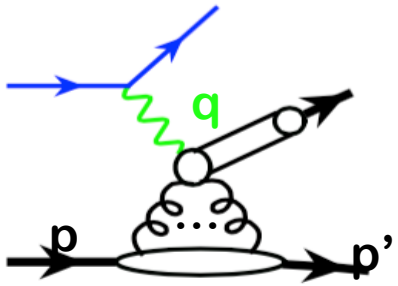


Fig. 2.7 NAS Report

Heavy quarkonium production at EIC

❑ Exclusive production – Near threshold:



Photoproduction:

- ✧ 2-to-2 kinematics is uniquely fixed
- ✧ No separation in scales between s, t, u
- ✧ No factorization between formation of quarkonium and nucleon

Lepton production:

- ✧ Virtual photon momentum is determined q = l – l'
- ✧ 2-to-2 kinematics with a virtual photon is uniquely fixed
- ✧ At the threshold, there is a separation of scales: $|t = (p-p')^2| \ll s \sim u$

$$\gamma^*(q) + h(p) \to \Upsilon + h(p') \quad \Rightarrow \quad |t/s| \propto m_h/m_\Upsilon \ll 1$$

- ✧ Exchange between nucleon and quarkonium dominated by 2-gluon channel
- ✧ Possible factorization between $\langle p|F^2|p'\rangle$ and the hard part to produce Υ
- ✧ Information on trace anomaly, relevant to the origin of hadron mass

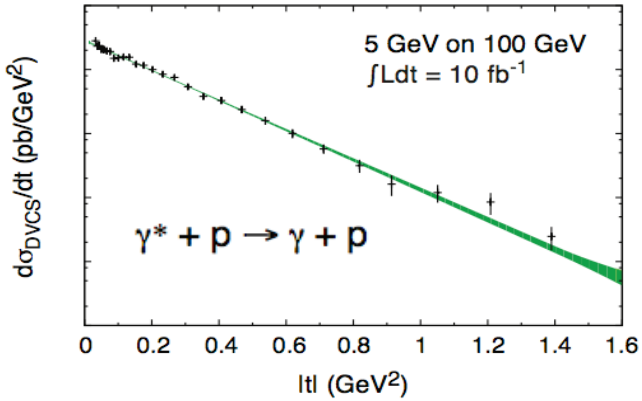
❑ Exclusive production away from threshold – Golden observable for EIC:

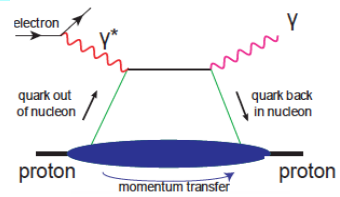
3D imaging of spatial distribution gluon density inside a hadron

HERA won't be able to do it because of the lack of events even with higher energy

Diffractive production of heavy quarkonia at EIC

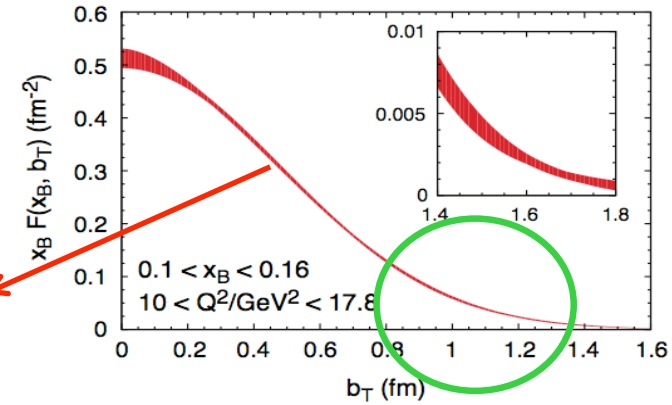
❑ DVCS at EIC:



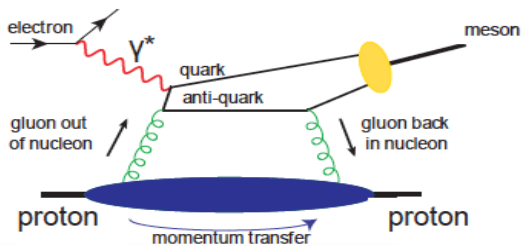


Factorization → **GPDs** → **F.T.** →

Proton radius of quarks (x)!

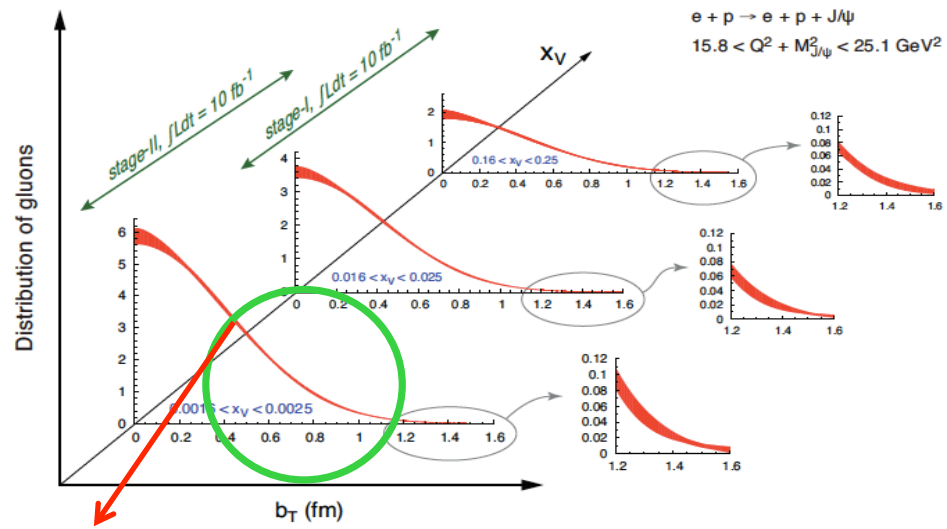


❑ "Seeing" the glue at EIC:



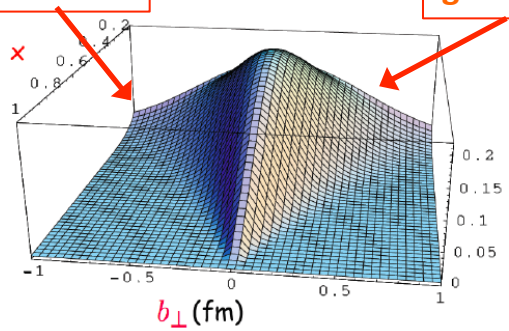
J/Ψ, Φ, …

F.T. **t-dep** →



How far does glue density spread?

How fast does glue density fall?



Proton radius of gluons (x)!

Only possible at EIC!
100-1000 times Luminosity!

Summary and outlook

- EIC is a ultimate QCD machine and a facility, capable of discovering and exploring the emergent phenomena of QCD, and the role of color and glue
- With its well-separated scales, production of heavy quarkonia is a good probe for the emergence of heavy quarkonia from heavy quark pairs, as well as an excellent tool to probe 3D spatial distributions of gluons
- With its much high luminosity, physics of heavy quarkonia at the EIC will be much richer than what have been explored at the HERA
- The production of heavy quarkonia is still one of the most fascinating subjects in strong interaction physics after the discovery of J/psi over 45-year ago!

Thanks!