New proposal:
Light and heavy quark spectroscopy at EIC
I - Theory

Alessandro Pilloni & Marco Battaglieri

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Hadron Spectroscopy at EIC

«The Electron Ion Collider will act like an enormous microscope»

We want to use it to study «human-size» hadrons!

Color confinement
Manifestation of gluonic degrees of freedom
Non-perturbative dressing effects
Light-\(q\) vs. heavy-\(q\)
Building the EIC spectroscopy community

Goals

- Demonstrate a strong physics case for a hadron spectroscopy program at EIC (to be part of the next EIC physics book)
- Study the impact on EIC design (machine and detectors)

Working groups

- Multiquark & Gluonic states conveners: F.K. Guo, R. Mitchell
- Diffractive production conveners: W. Schafer, R. McNulty
- Heavy flavor in media conveners: C. Weiss, G. Bruno
Quarkonium orthodoxy & exotic

\[ V(r) = -\frac{C_F \alpha_s}{r} + \sigma r \]
(Cornell potential)

Effective theories
(HQET, NRQCD, pNRQCD...) approximate heavy quark spin symmetry (HQSS)
Integrate out heavy DOF ↓
spectrum, decay & production rates

Esposito, AP, Polosa, Phys.Rept. 668

A host of unexpected resonances have appeared
Hardly reconciled with usual charmonium interpretation

Bottomonium exotic sector not equally well explored

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New states to be confirmed/1

\( \bar{X}(3872) \) as a new state

A. Guskov

\[
\begin{align*}
\bar{X}(3872) &= (3860.0 \pm 10.4) \text{ MeV}/c^2 \\
\Gamma_{\bar{X}(3872)} &< 51 \text{ MeV}/c^2 \text{ (CL=90\%)} \\
\text{Significance (including systematics) is } 4.1\sigma \\
C &= -1 \text{ (?)}
\end{align*}
\]

\[
\text{At COMPASS conditions: } \sigma_{\mu N} \approx \sigma_{\gamma N} / 300
\]

EIC \quad L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}

e^- N \to e^- \bar{X}(3872)\pi^\pm N' \to \\
e^- J/\psi \pi^+ \pi^- \pi^\pm N' \to e^- \mu^+ \mu^- \pi^+ \pi^- \pi^\pm N' \sim 10 \text{ events per day}

Inclusive prompt cross section

\[
\text{Br}[X \to J/\psi \pi^+ \pi^-] \sigma(X(3872), Q^2 > 1 \text{ GeV}) \approx 2.6 \text{ pb}
\]

\[
\sqrt{s} = 100 \text{ GeV}
\]

Luminosity: \(10^{34} \text{ cm}^{-2} \text{ s}^{-1}\)

0.026 Br\*X(3872) per second

X. Yao

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New states to be confirmed/2

Hiller Blin, AP, et al. (JPAC), PRD94, 034002

A confirmation of the pentaquarks in photo- and electroproduction will shed light on their nature

Sensitivity of Polarization observables to $5q$ parameters at SBS
Easily extended for the EIC

D. Winney, C. Fanelli, AP et al. (JPAC), 1907.09393
Hybrid hunting

Searches at COMPASS (pion beam) and GlueX (photon beam), EIC = same + quarkonium hybrids

A. Rodas, AP et al. (JPAC), PRL122, 042002

\[ M = 1564 \pm 24 \pm 86 \text{ MeV} \]
\[ \Gamma = 492 \pm 54 \pm 102 \text{ MeV} \]
Diffractive production: the odderon

Events from proton dissociation or Odderon exchange?

EIC message: Perfect use-case. Comparison of $ep$ and $eA$ in high luminosity environment should find these if they exist

R. McNulty

$\pi^0, \eta, f_2, \eta_c ...$

Proton tagging

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Diffractive production: double $J/\psi$ ($\Upsilon$)

At LHC dominated by double pomeron exchange

Sensitivity to high mass states, as tetraquarks or hybrids with $0^{\pm+}$

EIC may produce such states through $\gamma\gamma$ collisions

LHC
High Energy
Medium/High Luminosity
High Backgrounds

EIC
Low Energy
High Luminosity
Low Backgrounds (detector design)
Opportunities with open heavy flavor at EIC

- Theory of nuclear modification as a function of momentum transfer $v$, virtuality $Q$ - constrained kinematics & $B$- and $D$-mesons (mass) to vary formation times
- Stopping power of matter for charged particles is a fundamental probe of its properties. In QED $X_0(\text{min}) \sim \text{mm}$, in nuclei 10 orders of magnitude smaller! Transport properties of CNM
- Determination of the production mechanisms for open heavy flavor in SIDIS. Global analysis
- A whole class of new observables to be added – jets and jet substructure

Test unique predictions of QCD
Determine the cross sections for heavy jet suppression
Pinpoint the heavy quark mass effect in parton showers

I. Vitev
Opportunities with quarkonia at EIC

- Historically $J/\psi$ used to determine gluon densities at HERA. Suitable for studies of shadowing and gluon saturation physics at the EIC.

  - Variety of presumed production mechanisms:
    - Diffractive/elastic
    - Gluon-gluon-fusion, photon-gluon-fusion
    - Gluon fragmentation
    - "Resolved photon"-gluon/quark-fusion
    - + decays

  A. Mayer (2002)

- Using $J/\psi$ to study the saturation limit and determine the proximity to black body limit in DIS


- It could be interesting to add a program that focuses on the ground and excited charmonium and bottomonium states and their dissociation in nuclear matter to the EIC program.

  I. Vitev
New proposal: light and heavy quark spectroscopy at EIC

M. Battaglieri - A. Pilloni
INFN - GE
Italy
EIC and the other facilities

- **Luminosity 100-1000 times that of HERA**
  - Enable 3D tomography of gluons and sea quarks in protons

- **Polarized protons and light nuclear beams**
  - Critical to all spin physics related studies, including precise knowledge of gluon’s spin & angular momentum contributions from partons to the nucleon’s spin

- **Nuclear beams of all A (p→U)**
  - To study gluon density at saturation scale and to search for coherent effects like the color glass condensate and test universality

- **Centre of mass variability with minimal loss of luminosity**
  - Critical to study onset of interesting QCD phenomena

- Detector & IR designs mindful of “Lessons learned from HERA”
  - No bends in e-beam, maximal forward acceptance....
EIC detectors

- Large acceptance
- Frwrd/Bckw angles
- Precise vertexing
- HRes Tracking
- Excellent PID

Resolve partons in nucleons
- high beam energies and luminosities
- Q2 up to ~1000 GeV^2

Resolve \((k_t, b_t)\) of the order a few hundred MeV in the proton
- High Granularity, wide dynamic range

Detect all types of remnants to seek for correlations:
- scattered electron
- particles associated with initial ion
- particles associated with struck parton

sPHENIX → EIC

Argonne concept: TOPSiDE

Brookhaven concept: BEAST

Jefferson lab concept: JLEIC
**Hadron spectroscopy at EIC**

- Beams (intensity, polarization)
- Detectors
- Kinematic coverage

EIC is the perfect place to study hadron spectroscopy addressing the remaining open questions in hadron physics.

We want to do better optimising the EIC design for the next HS generation.

### Build the physics case

1. Light and heavy quarks (+ gluons) spectroscopy studying exotic configurations
2. Diffractive physics
3. Heavy flavours (open and hidden) to prove nuclear medium

### Opportunities

### Requirements
EIC kinematics and yield estimates

- EIC meson production kinematics studied in a simple diffractive ansatz (t-slope)
- Virtual photon flux + dipole form factor
- 10 GeV electron + 100 GeV proton
- Final state compatible with current detectors design: $M \rightarrow e^+e^-$

**e'/p' kinematics**

- Scattered electron: $E_e' \sim 10$ GeV within $\Delta \Theta \sim 2^\circ$ forward cone around the beam line
- Scattered proton: high $p$ ($\sim 90-100$ GeV) $\Delta \Theta \ll 1^\circ$ cone in the opposite direction
EIC kinematics and yield estimates

- EIC meson production kinematics studied in a simple diffractive ansatz (t-slope)
- Virtual photon flux + dipole form factor
- 10 GeV electron + 100 GeV proton
- Final state compatible with current detectors design: $M \rightarrow e^+ e^-$

$M \rightarrow e^+ e^-$ kinematics

$M \rightarrow \mu^+ \mu^-$ would simplify the detection dedicated detector

D.Glazier (UGlasgow)
EIC kinematics and yield estimates

- EIC meson production kinematics studied in a simple diffractive ansatz (t-slope)
- Virtual photon flux + dipole form factor
- 10 GeV electron + 100 GeV proton
- Final state compatible with current detectors design: $M \rightarrow e^+e^-$
- Use production cross section and slope ($\sigma_{J/\psi} \sim 20\text{nb}$ and $b \sim 4$) as measured in ZEUS

$J/\Psi$ rate = 0.8Hz (~70k events/day)
EIC kinematics and yield estimates

\[ eN \rightarrow e' (J/\Psi \pi^+\pi^-) \pi^\pm N^* \]

\( \tilde{X}(3872) \) as a new state

\[ m_{\tilde{X}(3872)} = (3860.0 \pm 10.4) \text{ MeV}/c^2 \]
\[ \Gamma_{\tilde{X}(3872)} < 51 \text{ MeV}/c^2 \text{ (CL=90\%)} \]

Significance (including systematics) is 4.1\( \sigma \)
\( C=-1 \) (?)

Meson\((J/\psi \pi^+ \pi^-)\) \( \Theta \) vs \( M_{e'N} \) (GeV/c^2)

Meson\((J/\psi \pi^+ \pi^-)\) Momentum vs \( \Theta \)

\( \pi^+ \) Momentum vs \( \Theta \)

Low energy pions 
\( \sim 200 \text{ MeV} \)

\( \tilde{X}(3872) \) Yield \( \sim 100(s) \) events/day
**Impact on EIC detectors**

**Requirements**
- Scattered electron and proton detection at 0 degrees!
- Far-forward detectors
- Tag scattered particle
- Determine momentum

**Results**
- Exclusive measurements for excellent bg rejection
- With good resolution (<0.1%) Missing Mass technique would help

**Far-forward electrons**

**Final states detection**
Summary

★ Goals:
• Demonstrate a strong physics case for a hadron spectroscopy program at EIC (to be part of the next EIC physics book)
• Study the impact on EIC design (machine and detectors)

★ Working groups:
• I) Quarks & Gluons
• II) HF in media
• III) Diffraction

★ Kick-off meeting at ECT* Trento in Dec 2018
★ White-paper in preparation

Build the future HS program at EIC joining the effort!
BACKUP
Diffraction

- Diffractive DIS (DDIS): diffractive dissociation ↔ elastic scattering of a $q^-q$-dipole
- Large DDIS is the hallmark of a strongly absorptive target ↔ “saturation physics”
- Clean environment (only few particles in the final state)
- EIC ideal to measure exclusive channels

The physics case

- Production of light vector & higher spin mesons: radial & orbital excitations of (say) mesons show distinctive systematics of s-channel helicity violation.
- Color dipole approach + light-front wave-functions: can be formulated also at low $Q^2$
- Hard pQCD regime (large $Q^2$): chiral odd vs chiral even meson distribution amplitudes
- Diffractive photoproduction of tetraquarks/hybrids: unexplored (?) Larger transverse sizes: stronger nuclear absorption ! nuclei as another tool?
- Odd C-parity three gluon exchange: the Odderon.
- Photo/electroproduction of C-even mesons in diffractive kinematics
- Charge asymmetries in $+- -$-production
Heavy Flavours in media

A) HF as probe of initial-state gluons
   • [EIC: Nuclear PDFs from inclusive DIS eA] ↔ global analysis/PDFs
   • EIC: Nuclear gluon densities from open HF production in eA
   • EIC: Nuclear gluons from coherent HQium prodn: Transverse distns, shadowing ↔ exclusive procs/GPDs

B) Propagation and hadronization of HF in cold matter
   • EIC: Single-inclusive D/B/b,c production in ep+eA ↔ light-quark fragmentation
   • EIC: HF jets in ep+eA, including substructure, correlations ↔ light-quark jet physics
   • EIC: Exclusive HQium production in ep+eA, color transparency

C) Hadronic interactions of HF mesons and baryons
   • EIC: Nuclear transparency in heavy meson-baryon production
   • EIC: Exclusive HQium production in nuclei, final-state interactions
What for?

• High energy in the COM, possibility to study heavy flavors
  • Meson(-like) spectroscopy: $X_b, Z_b, (?)_b$
  • Baryon(-like) spectroscopy: $P_b, (?)_b$
  • Doubly heavy: $\Xi_{cc}, \Xi_{bc}; T_{bb}, T_{cc}$
  • Gluon-rich (small-x): heavy hybrids production?
• Diffractive production (photon-pomeron fusion, Primakoff)
• Interaction of heavy flavor with nuclear media
• .............

Need for cross section estimates
 (NRQCD? Regge models?)
XYZ states in photoproduction

\[
\mathcal{L}_{V\gamma} = -\frac{eM_V^2}{f_V} V_\mu A^\mu \\
\mathcal{L}_{Z_{\psi\pi}} = \frac{g Z_{\psi\pi}}{M_Z} \left( \partial^\mu \psi^\nu \partial_\mu \pi Z_\nu - \partial^\mu \psi^\nu \partial_\nu \pi Z_\mu \right) \\
\mathcal{L}_{\pi NN} = -\frac{8\pi NN}{2m_N} \bar{N} \gamma_5 \gamma_\mu (\widehat{\tau} \cdot \partial^\mu \pi) \gamma N
\]

Several proposals to study XYZ states in photoproduction

- \( \gamma p \rightarrow Z_c^+ (3900)n, Z_c^+ \rightarrow J/\psi \pi^+ \)  
  PRD 88 (2013) 114009

- \( \gamma p \rightarrow Z_c^+ (4430)n, Z_c^+ \rightarrow \psi' \pi^+ \)  

- \( \gamma p \rightarrow Z_c^+ (4200)n, Z_c^+ \rightarrow J/\psi \pi^+ \)  

- \( \gamma p \rightarrow Y (3940)p, Y (3940) \rightarrow J/\psi \omega \)  
  PRD 80 (2009) 114007

- Use an Effective Lagrangian approach with Vector Meson Dominance
Hybrid production

Suprisingly, no calculation for heavy hybrid production has been carried out so far.

The only example for B decays is Petrov et al. PRD58, 034013.

Room for improvement and inclusion of the large number of gluons at small x.
Doubly heavy

Lots of attention recently on tetraquark and baryons with two heavy quarks, driven by LHCb and lattice results

Quigg and Eicthen, PRL119, 202002
Esposito, AP et al. PRD88, 054029
Karliner and Rosner, PRD90, 094007
Karliner and Rosner, PRL119, 202001
Francis et al. PRL118, 142001

MC code available, GENXICC2.0, which implements the heavy diquark in Pythia NRQCD approach in $e^+e^-$ collisions in Chen et al. JHEP1412, 018