New proposal:

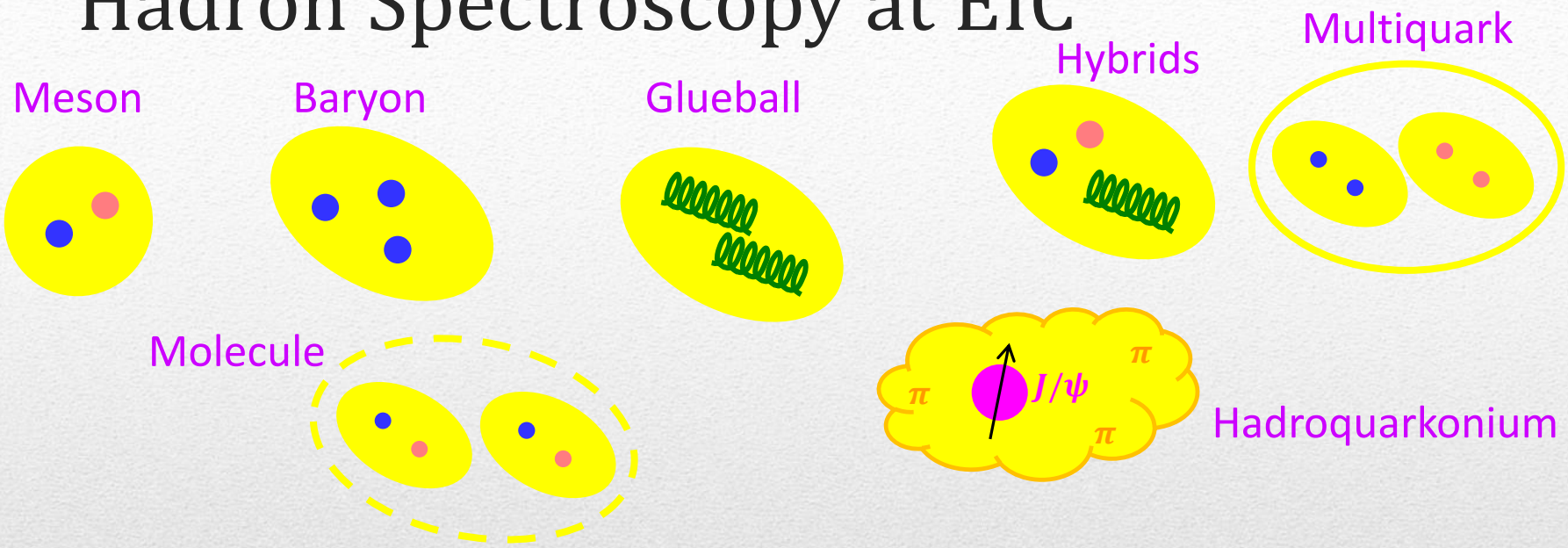
Light and heavy quark spectroscopy at EIC

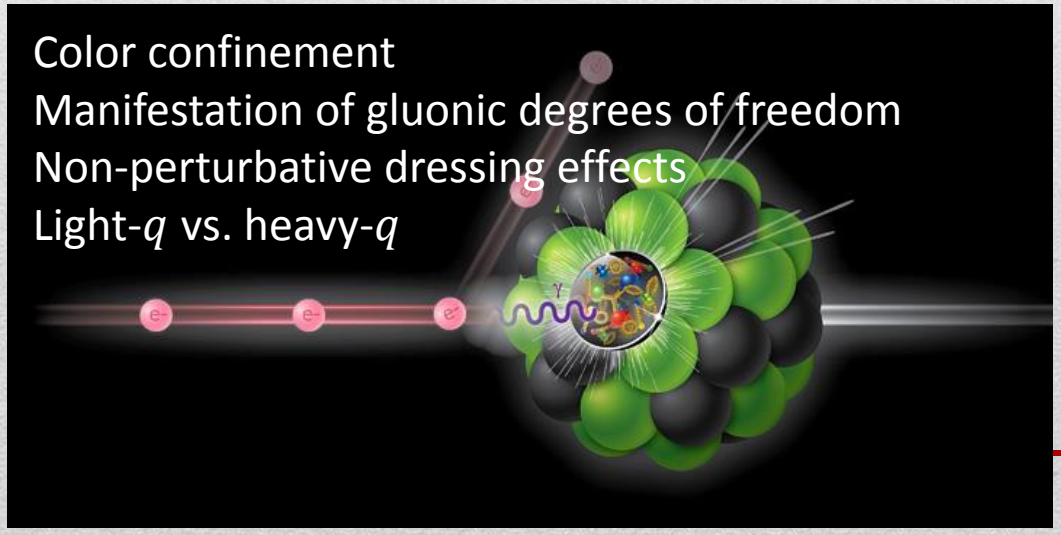
I - Theory

Alessandro Pilloni & Marco Battaglieri

Paris, July 26th, 2019

Hadron Spectroscopy at EIC





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

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

Building the EIC spectroscopy community

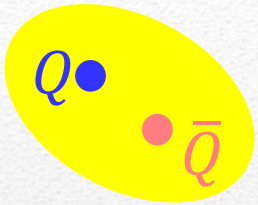
Goals

- 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...)

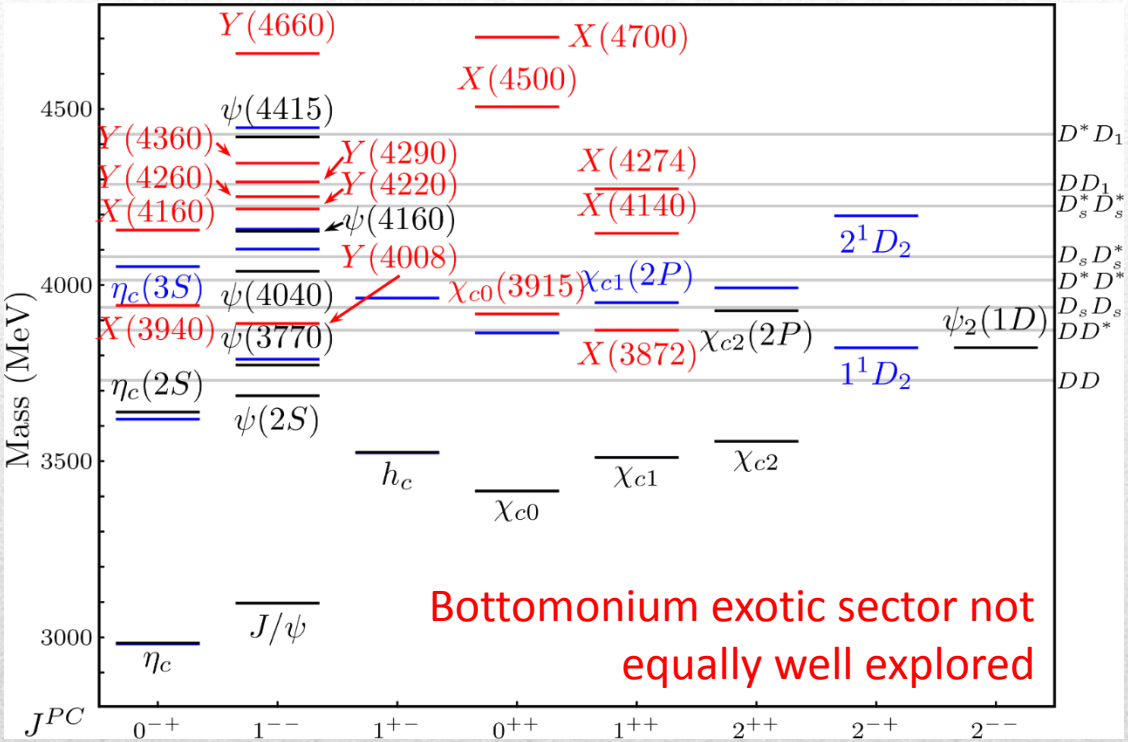
approximate heavy quark spin symmetry (HQSS)

Integrate out heavy DOF

↓

spectrum, decay & production rates

Esposito, AP, Polosa, Phys.Rept. 668



Bottomonium exotic sector not equally well explored

A host of unexpected resonances have appeared

Hardly reconciled with usual charmonium interpretation

New states to be confirmed/1

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

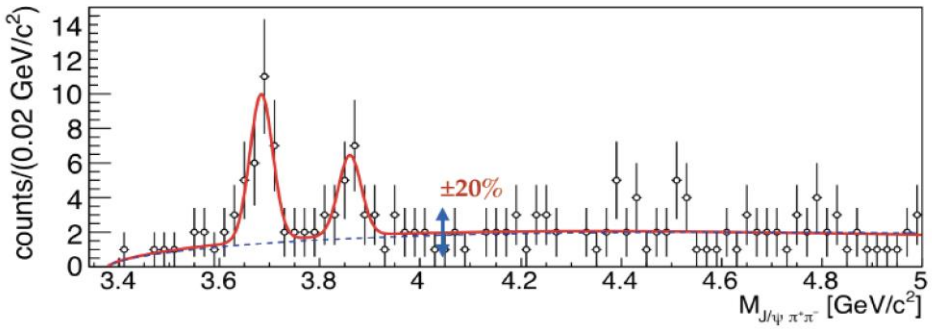
A. Guskov

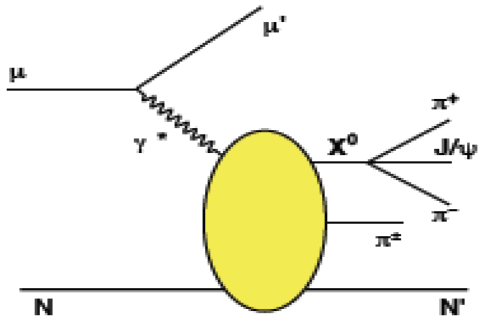
$m_{\tilde{X}(3872)} = (3860.0 \pm 10.4)\ MeV/c^2$

$\Gamma_{\tilde{X}(3872)} < 51\ MeV/c^2\ (CL=90\%)$

Significance (including systematics) is 4.1σ

$C=-1$ (?)





At COMPASS conditions:

$\sigma_{\mu N} \approx \sigma_{\gamma N} / 300$

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

$$e^- N \to e^- \widetilde{X}(3872)\pi^{\pm} N' \to$$
$$\to e^- J/\psi \pi^+\pi^-\pi^{\pm} N' \to e^-\mu^+\mu^-\pi^+\pi^-\pi^{\pm} N'$$

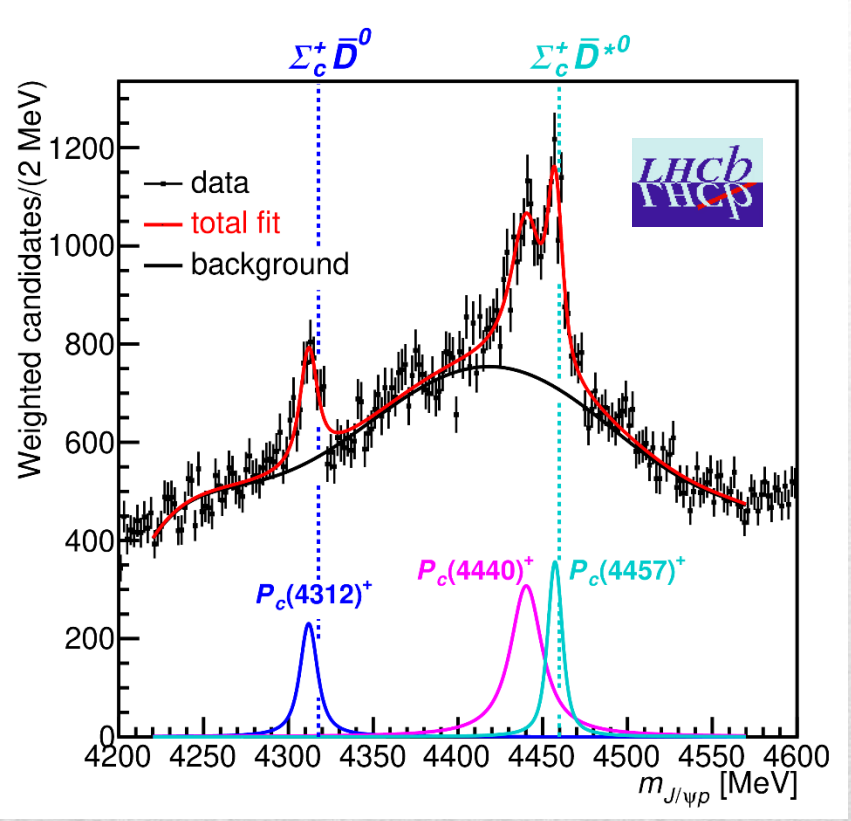
~10 events per day

Inclusive prompt cross section

$$\mathrm{Br}[X \to J/\psi\pi^+\pi^-]\sigma(X(3872), Q^2 > 1\ \mathrm{GeV}) \approx 2.6\ \mathrm{pb} \qquad \sqrt{s} = 100\ \mathrm{GeV}$$

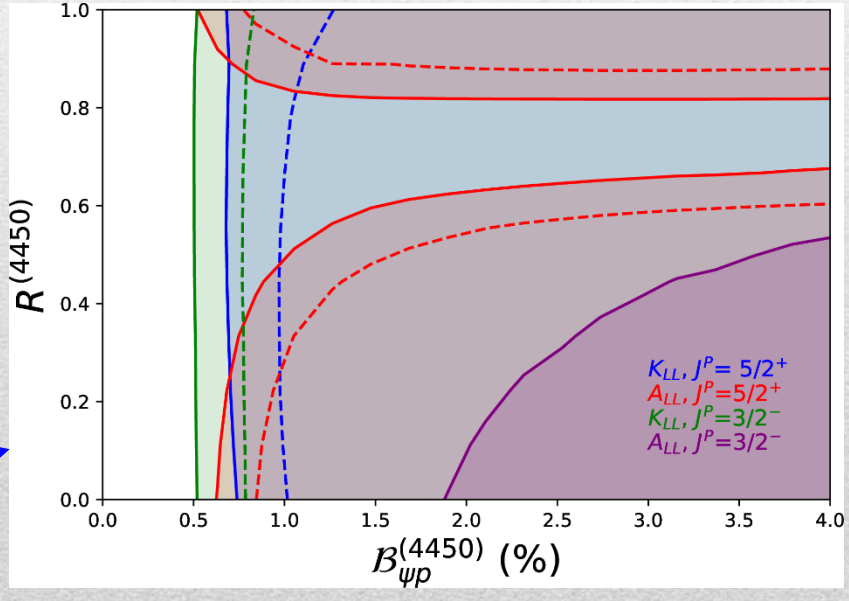
Luminosity: $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ **0.026 Br*X(3872) per second** X. Yao

New states to be confirmed/2



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

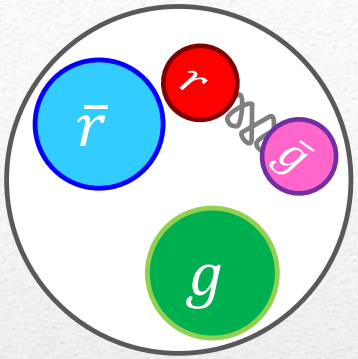
A confimation of the pentaquarks in photo- and electroproduction will shed light on their nature



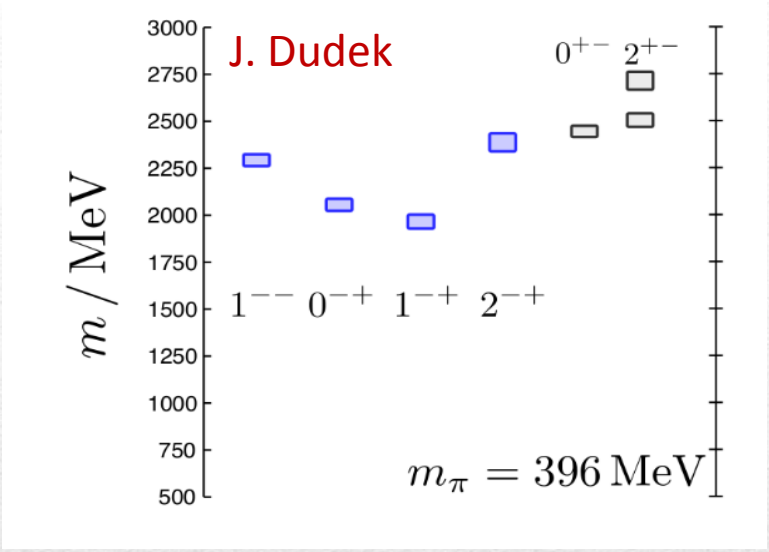
Sensitivity of Polarization observables to 5q parameters at SBS
Easily extended for the EIC

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

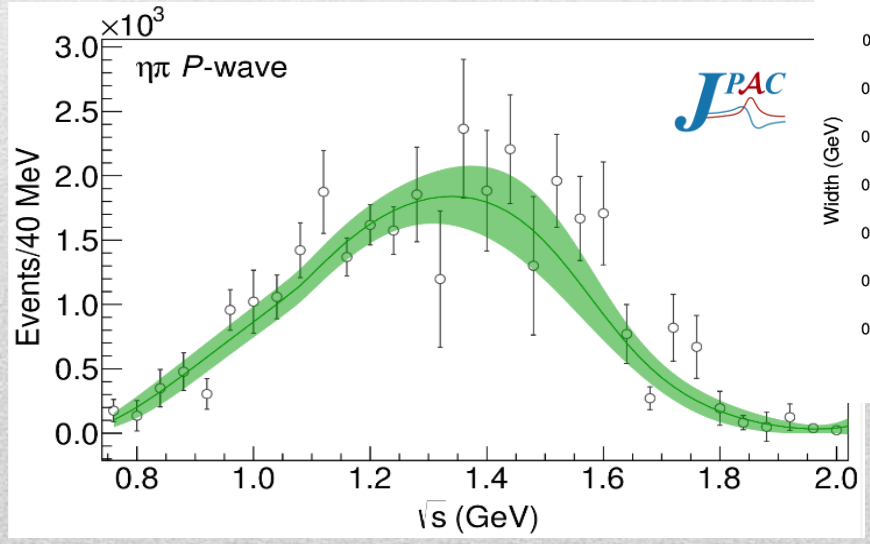
Hybrid hunting

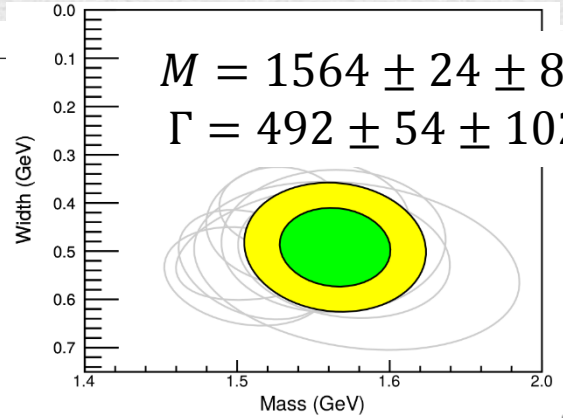


Searches at COMPASS (pion beam) and GlueX (photon beam),
EIC = same + quarkonium hybrids



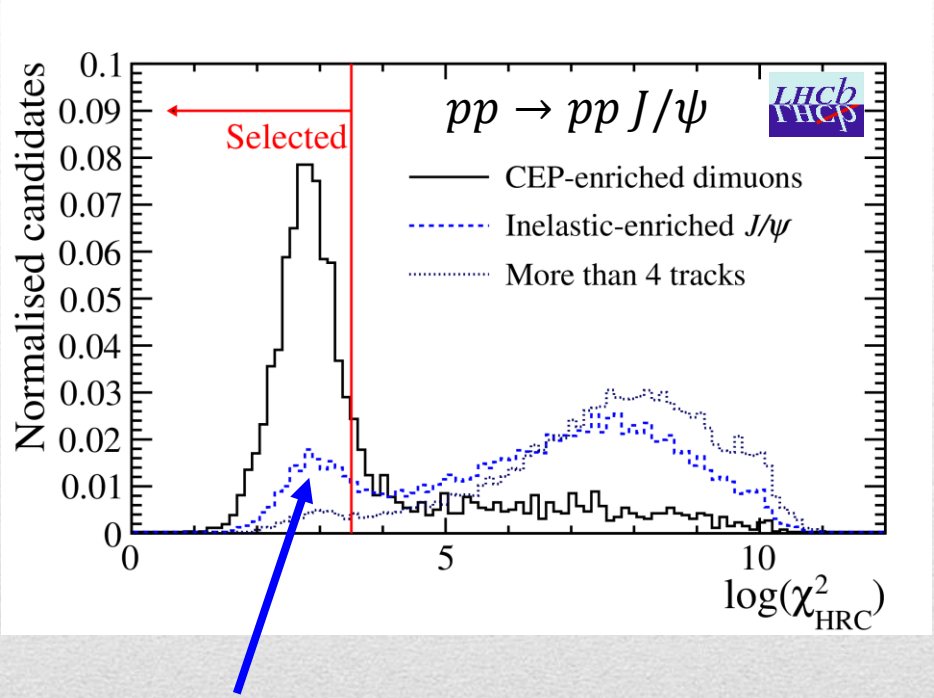
A. Rodas, AP *et al.* (JPAC), PRL122, 042002



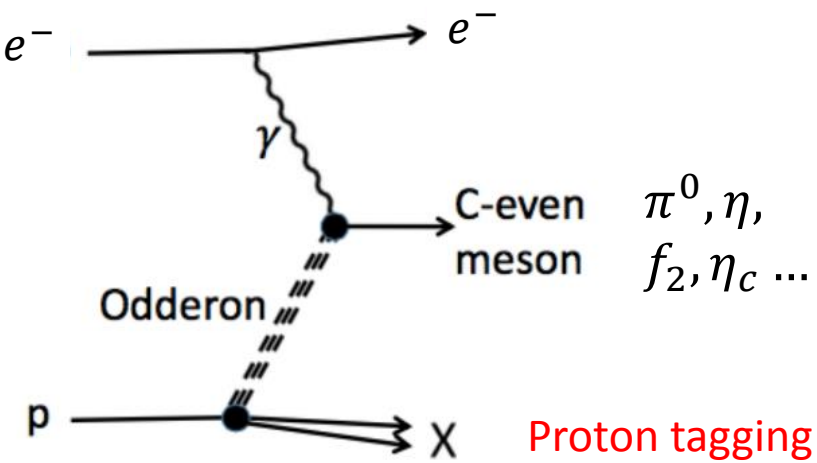


$M = 1564 \pm 24 \pm 86$ MeV
$\Gamma = 492 \pm 54 \pm 102$ MeV

Diffractive production: the odderon



R. McNulty



Events from proton dissociation or Odderon exchange?

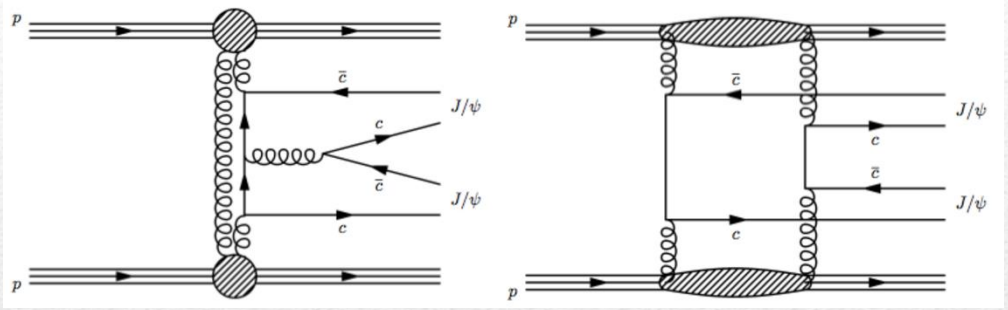
EIC message: Perfect use-case. Comparison of ep and eA in high luminosity environment should find these if they exist

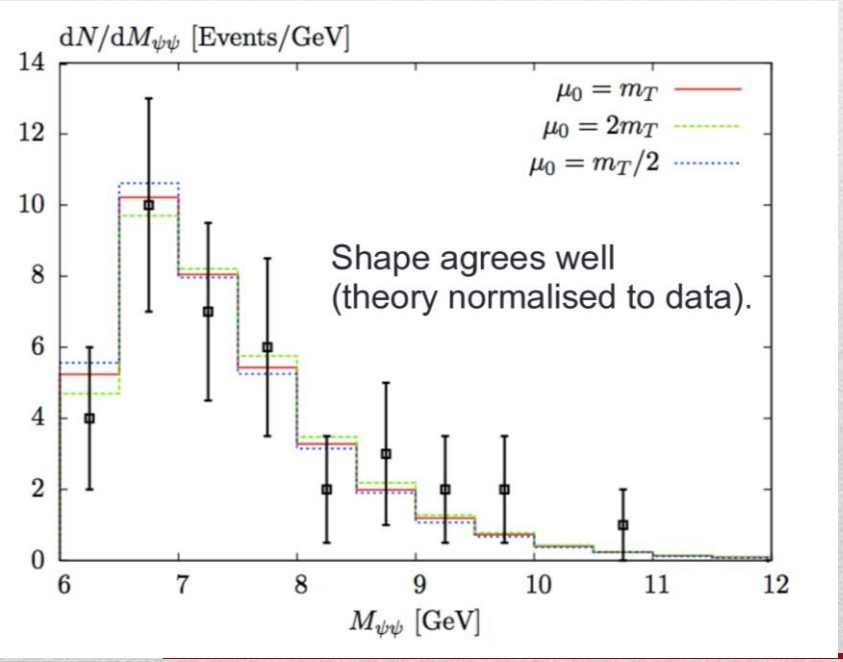
Diffractive production: double J/ψ (Υ)

R. McNulty

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

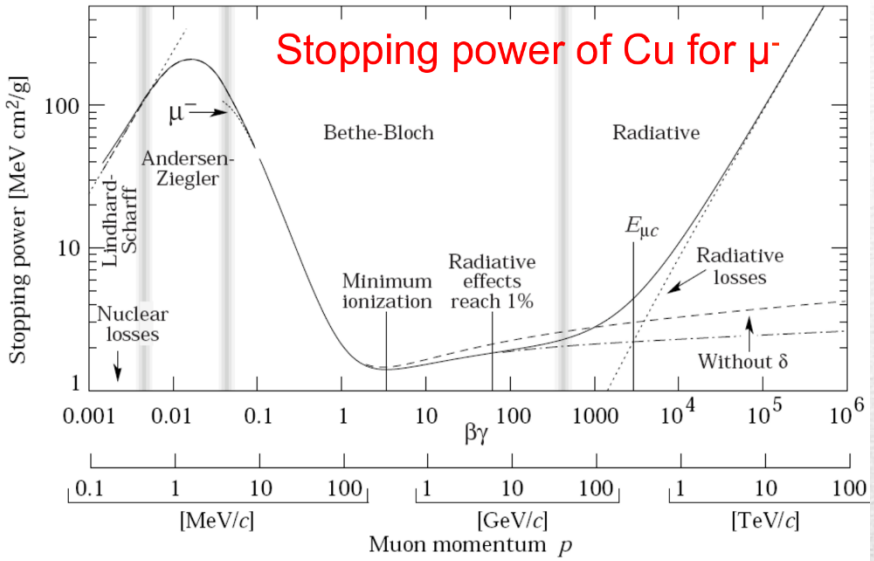
LHC
High Energy
Medium/High Luminosity
High Backgrounds

→

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 ν, 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(min) ~ 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



PDG (2008)

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

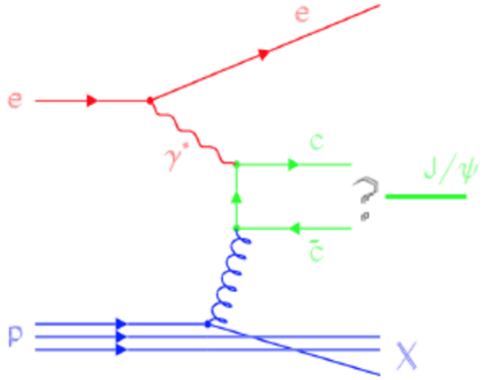
I. Vitev

Opportunities with quarkonia at EIC

- Historically J/ψ used to determine gluon densities at HERA. Suitable for studies of shadowing and gluon saturation physics at the 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)

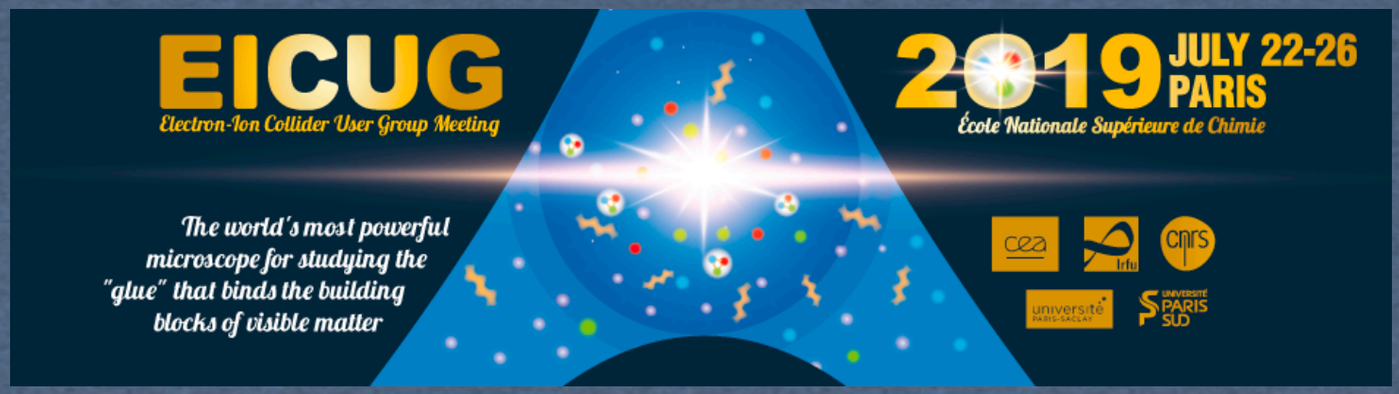


- Using J/ψ to study the saturation limit and determine the proximity to black body limit in DIS

T. Rogers (2003)

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

I. Vitev



New proposal: light and heavy quark spectroscopy at EIC II Experimental

M.Battaglieri - A.Pilloni
INFN -GE
Italy

EIC and the other facilities

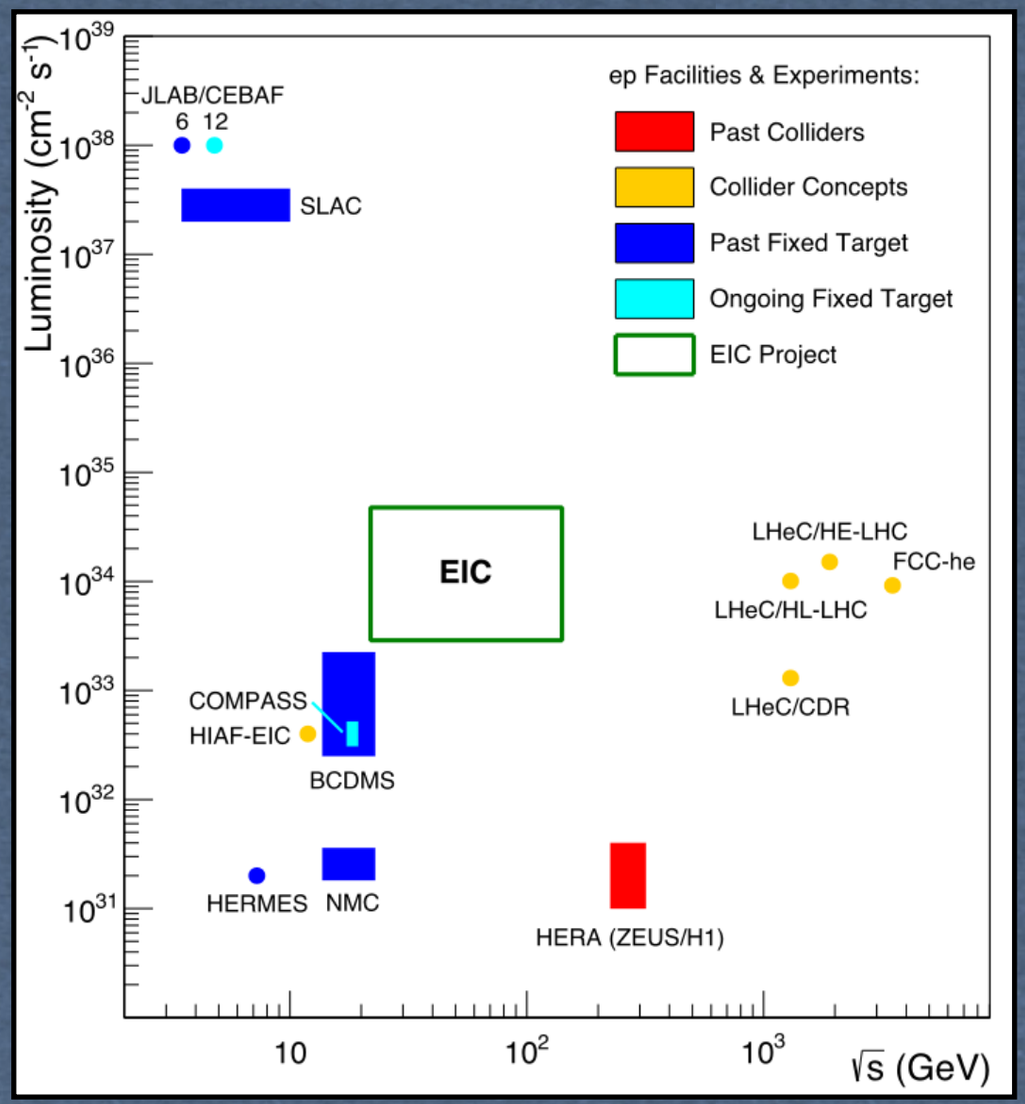
- **Luminosity 100-1000 times that of HERA**
  – Enable 3D tomography of gluons and sea quarks in protons

- **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

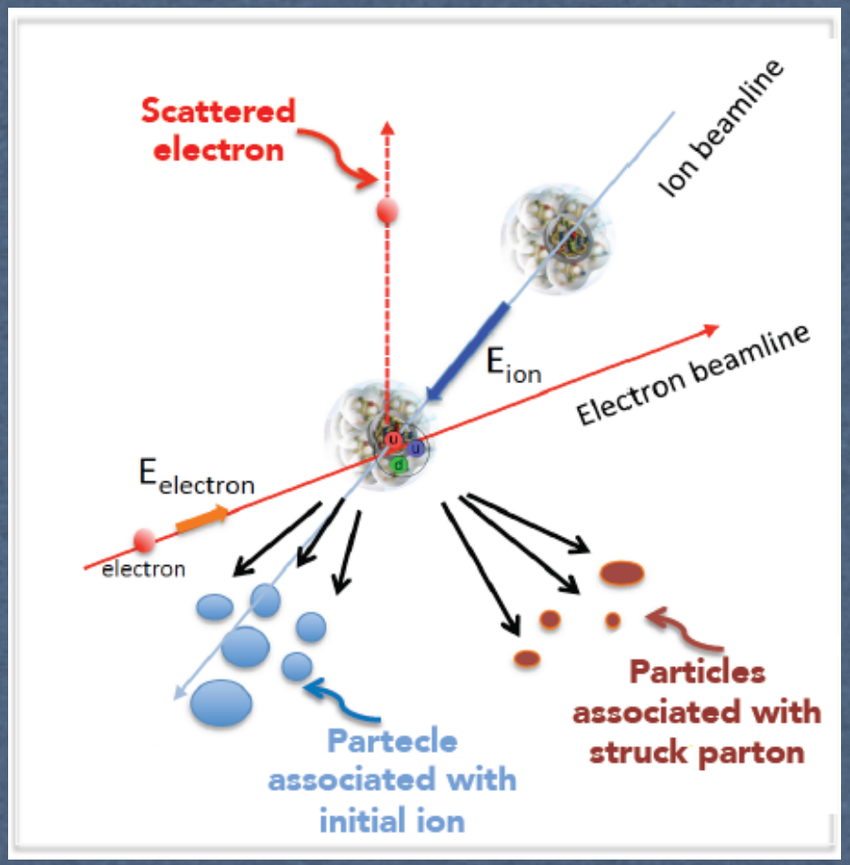
- **Nuclear beams of all A (p→U)**
  – To study gluon density at saturation scale and to search for coherent effects like the color glass condensate and test universality

- **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….



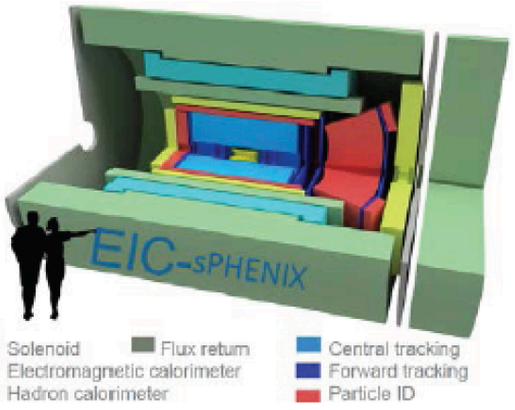
EIC detectors



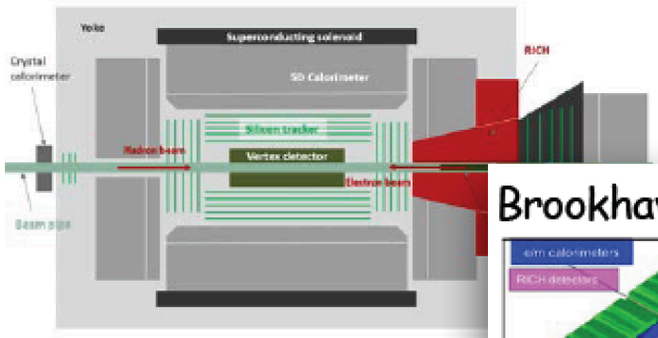
- ✳ Resolve partons in nucleons
  - ⇨ high beam energies and luminosities
  - ⇨ Q2 up to ~1000 GeV^2
- ✳ Resolve (k_t, b_t) of the order a few hundred MeV in the proton
  - ⇨ High Granularity, wide dynamic range
- ✳ Detect all types of remnants to seek for correlations:
  - ⇨ scattered electron
  - ⇨ particles associated with initial ion
  - ⇨ particles associated with struck parton

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

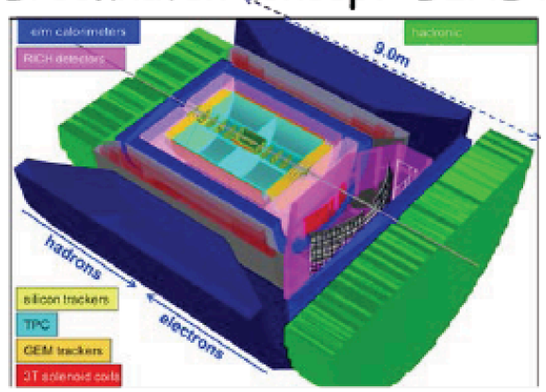
sPHENIX → EIC



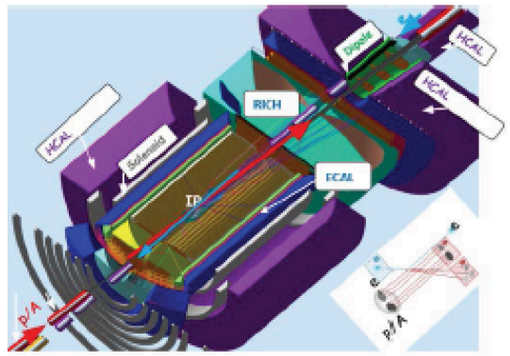
Argonne concept: TOPSiDE



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

I) Light and heavy quarks (+ gluons) spectroscopy studying exotic configurations

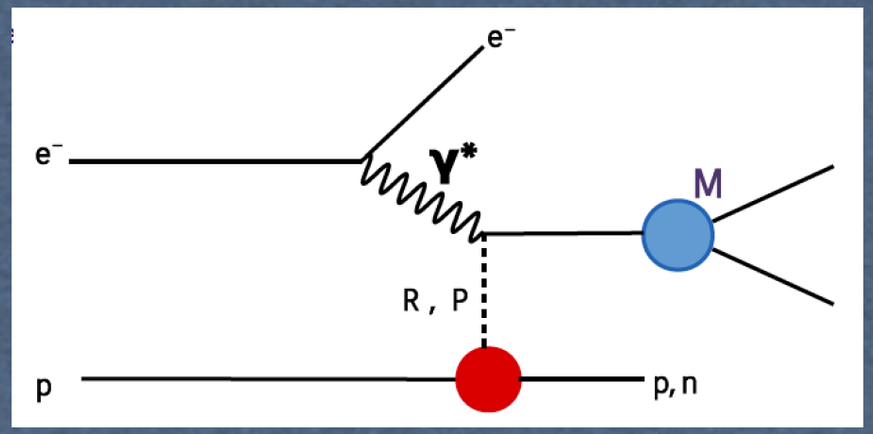
II) Diffractive physics

III) Heavy flavours (open and hidden) to prove nuclear medium

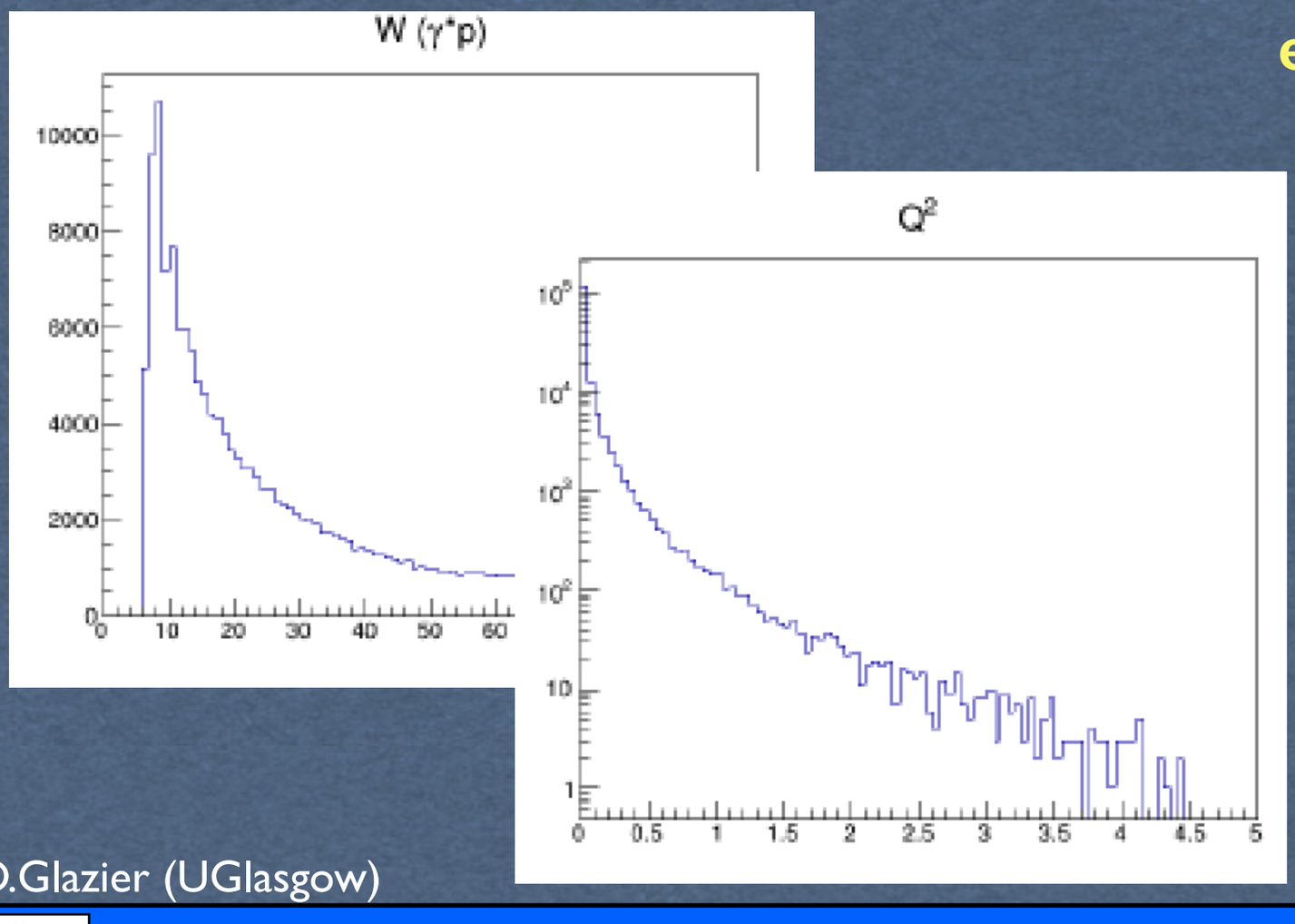
Opportunities

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→e+e-

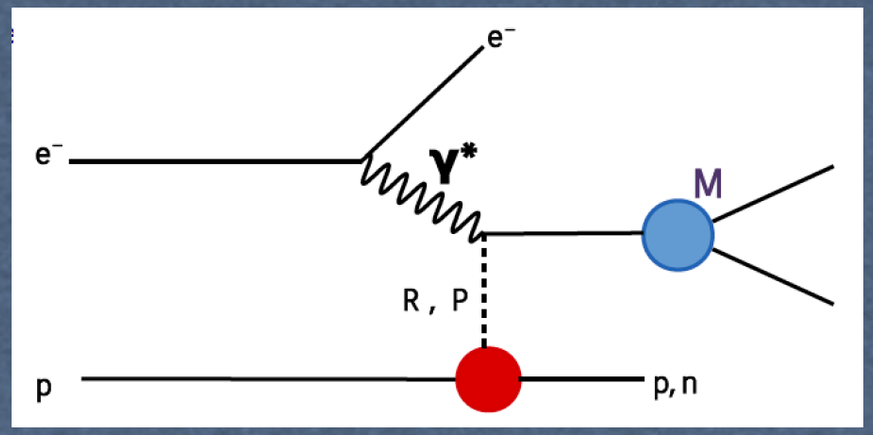


D.Glazier (UGlasgow)

e'/p' kinematics

- Scattered electron: $E_{e'}$ ~10 GeV within $\Delta\Theta \sim 2^\circ$ forward cone around the beam line
- Scattered proton: high p (~90-100 GeV) $\Delta\Theta << 1^\circ$ 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
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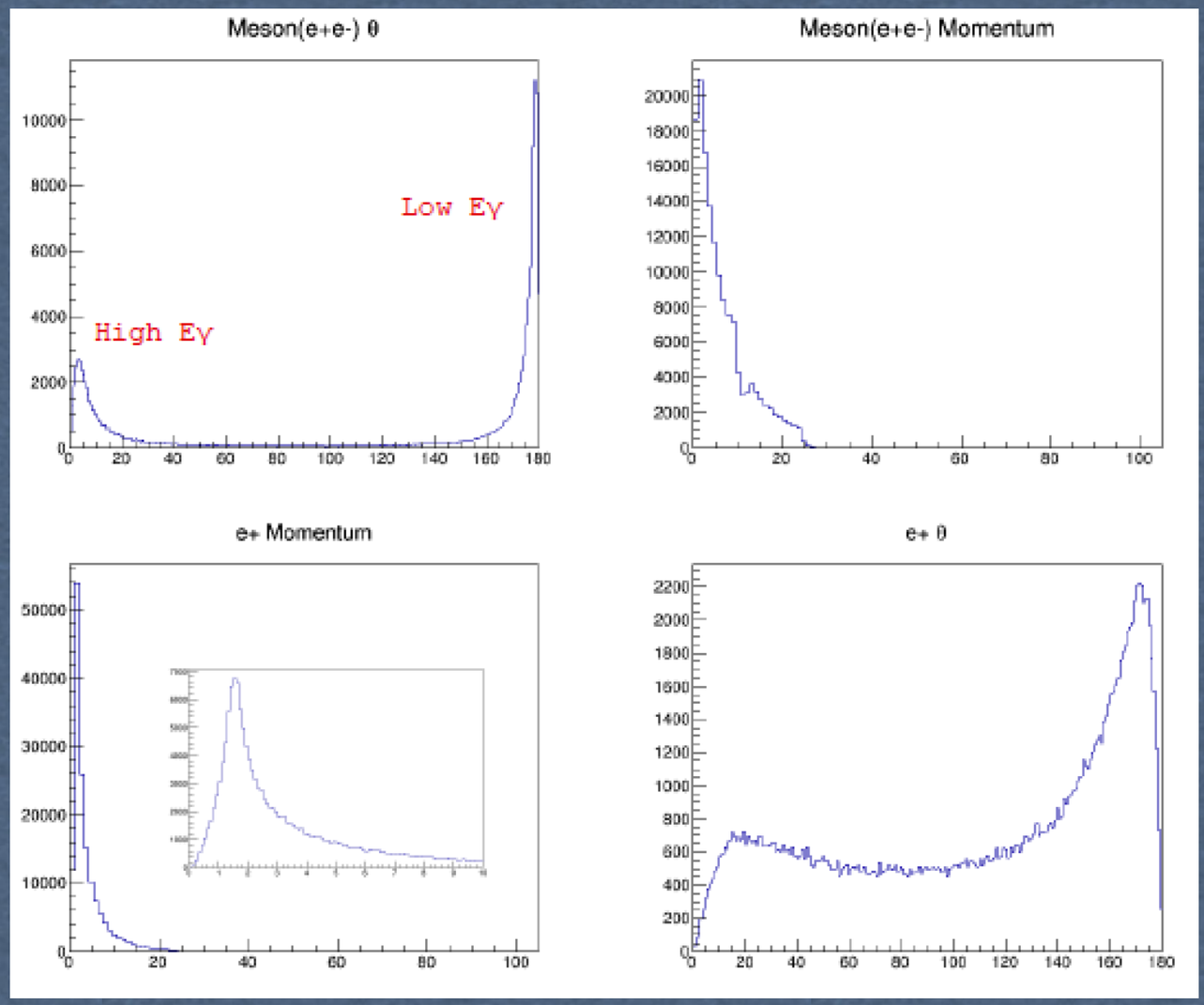
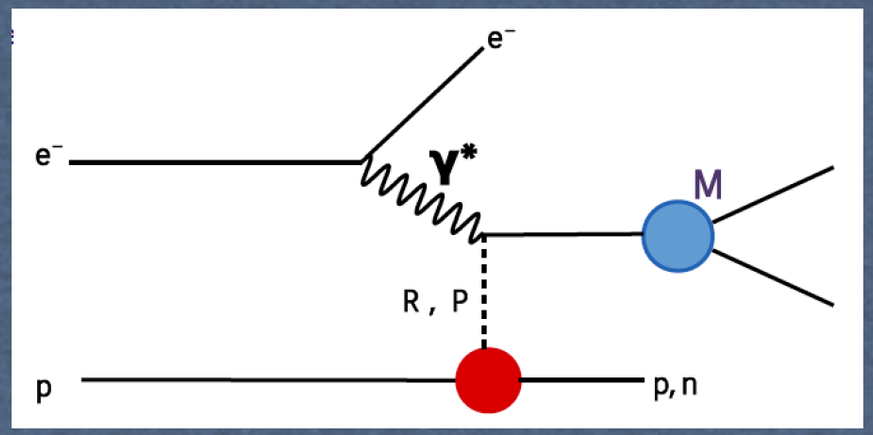
M→e+e- kinematics



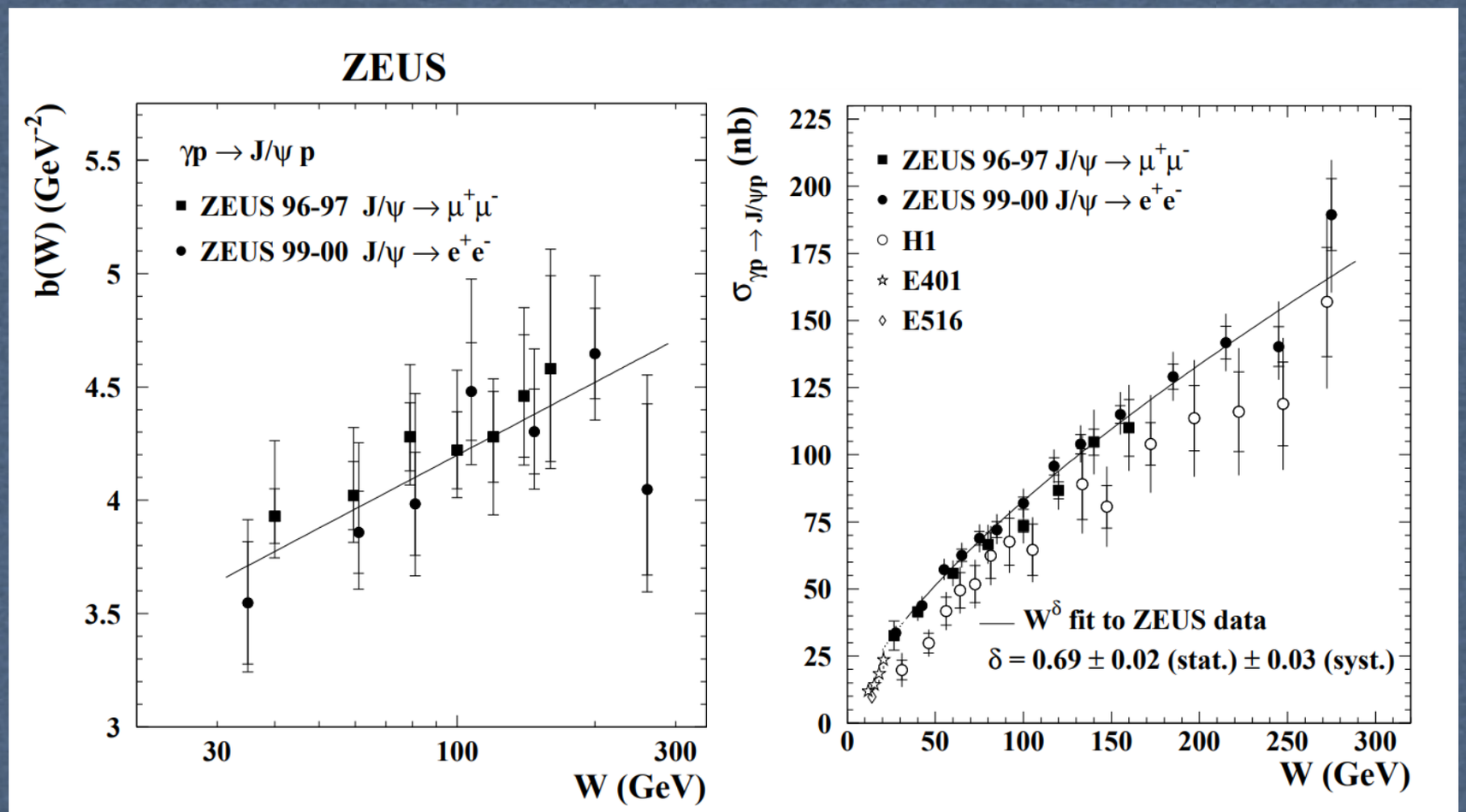
M→*μ*+μ- would simplify the detection dedicated detector

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→e+e-
- Use production cross section and slope ($\sigma_{J/\psi}$~20nb and b~4) as measured in ZEUS

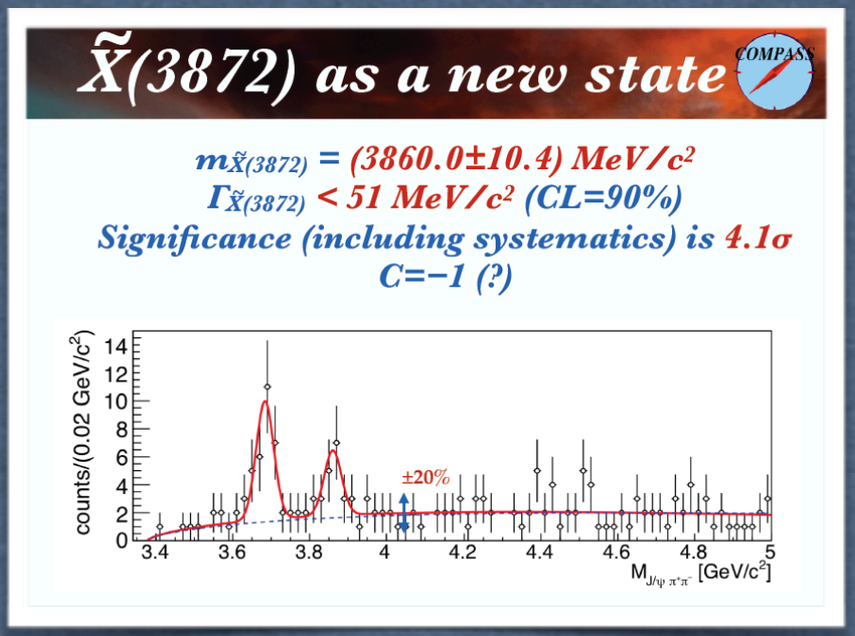


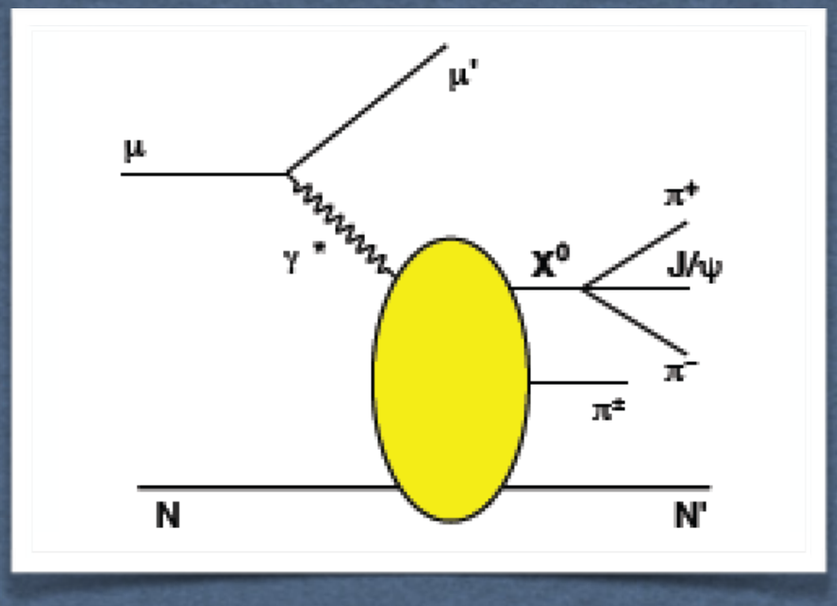
J/Ψ rate = 0.8Hz (~70k events/day)

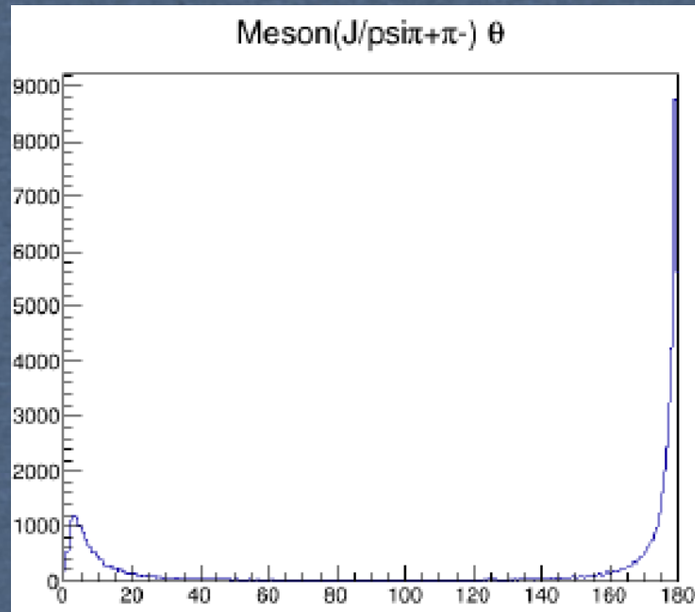
D.Glazier (UGlasgow)

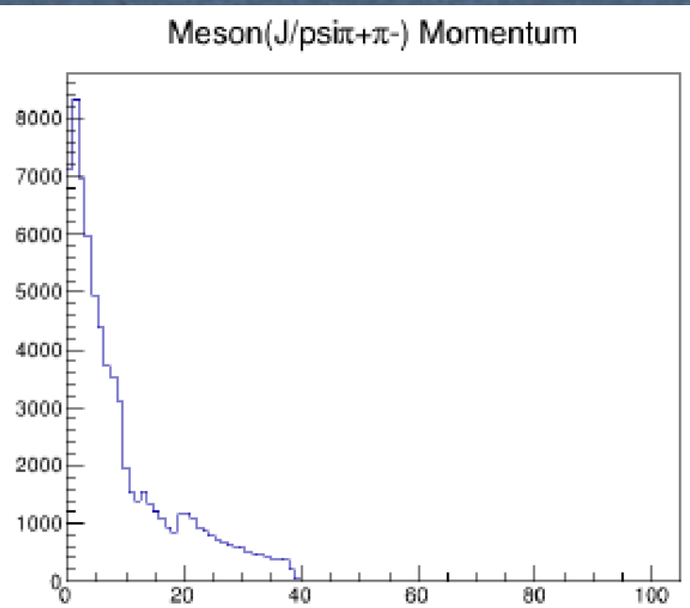
EIC kinematics and yield estimates

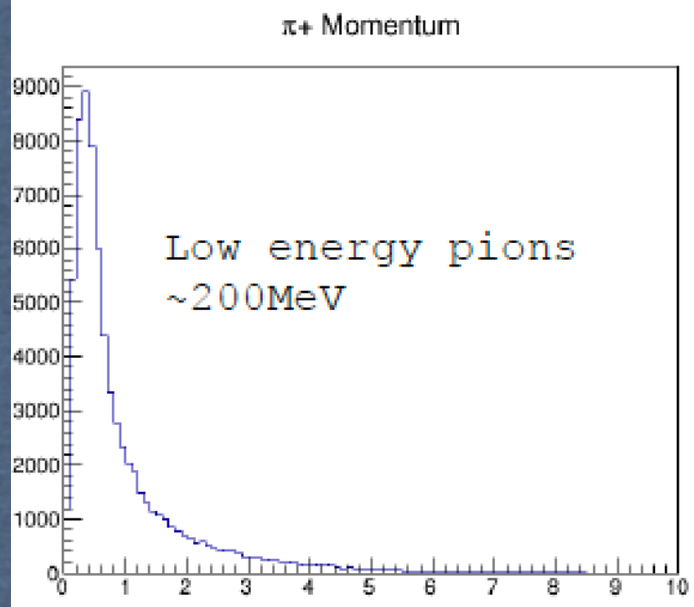
e N → e' (J/Ψ π⁺π⁻) π± N*

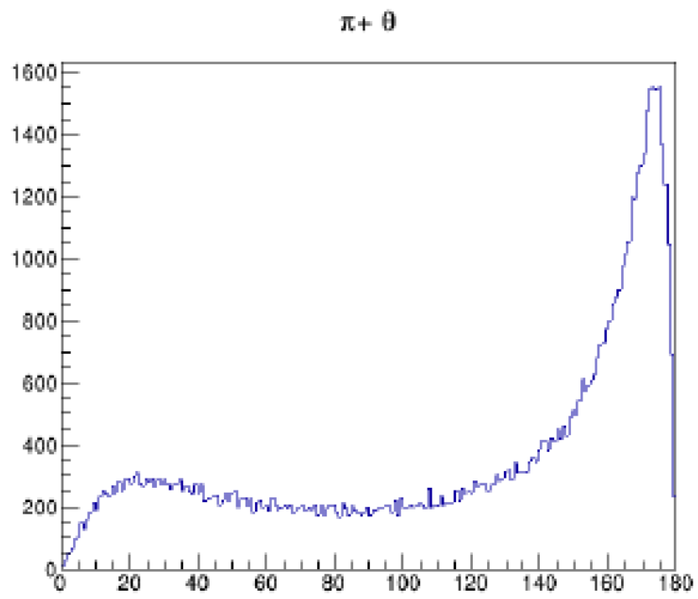












D.Glazier (UGlasgow)

X(3872) Yield ~ 100(s) events/day

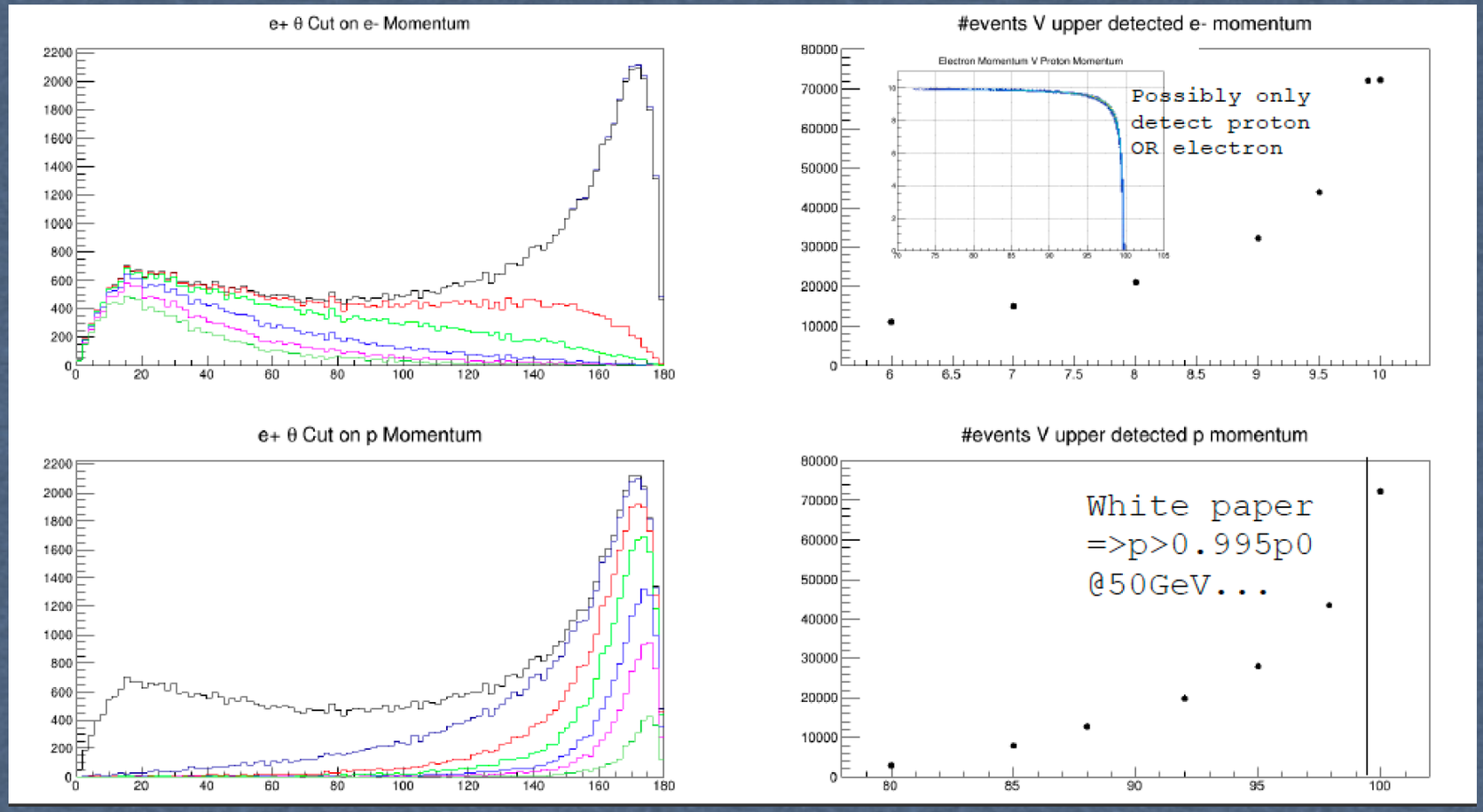
Impact on EIC detectors

Requirements

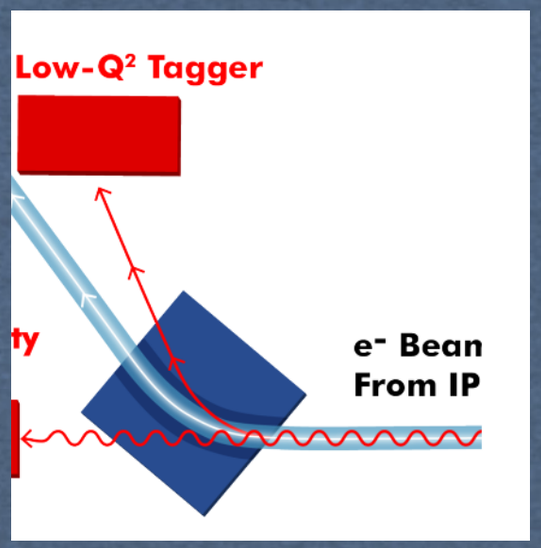
- Scattered electron and proton detection at 0 degrees!
- Far-forward detectors
- Tag scattered particle
- Determine momentum

Results

- Exclusive measurements for excellent bg rejection
- With good resolution (<0.1%) MissingMass technique would help



Far-forward electrons



Far-forward ion or Roman Pots?

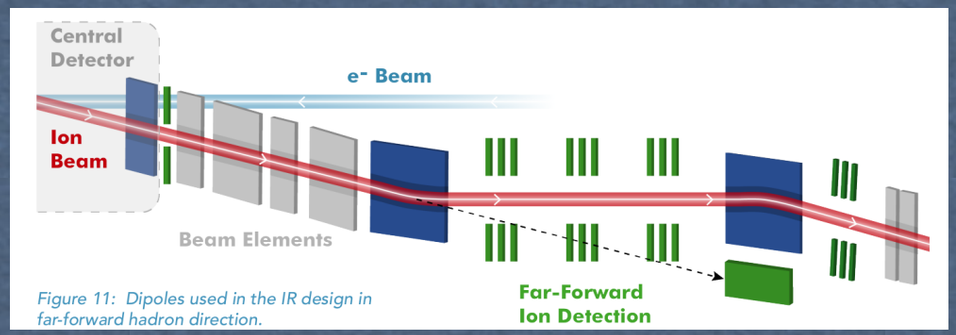
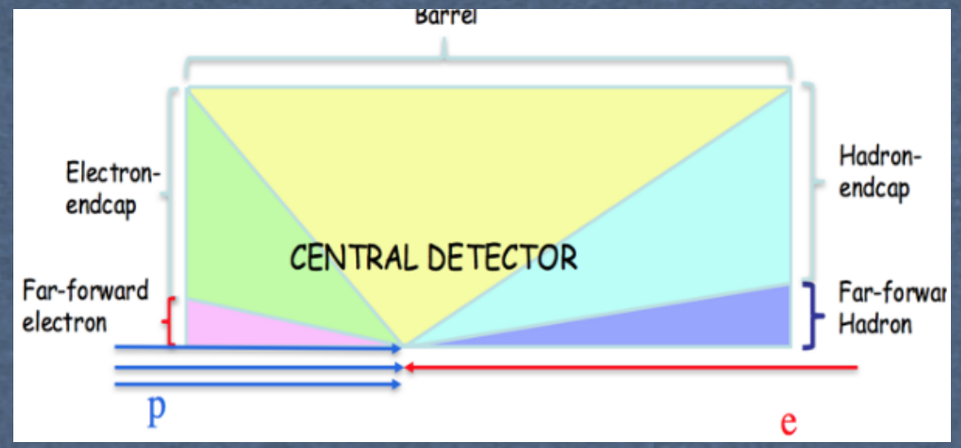


Figure 11: Dipoles used in the IR design in far-forward hadron direction.

Final states detection



Summary

Building the EIC Hadron 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:

- 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 $Q2$
- Hard pQCD regime (large $Q2$): 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

$$\text{HF}\left\{\begin{array}{l}\text{open } D, B, \Lambda_{c,b}, \ldots \\ \text{hidden } J/\psi, \eta_c, \Upsilon, \ldots\end{array}\right. \qquad \text{matter}\left\{\begin{array}{l}\text{cold} \\ \text{hot}\end{array}\right. \qquad \text{interaction}\left\{\begin{array}{l}\text{high-energy} \gg 1 \text{ GeV} \\ \text{low-energy} \lesssim 1 \text{ GeV}\end{array}\right.$$

Schematic

Initial state	↔	Production mechanism	↔	Final state
Partonic structure, nuclear modifications				Color propagation, jets Fragmentation, hadronization Hadronic interactions

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

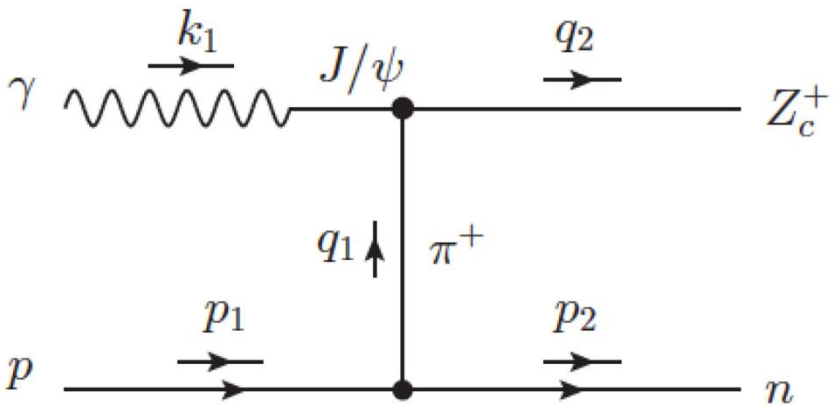
What for?

- 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: Ξ_{cc}, Ξ_{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

Justin Stevens, APS 2015



PRD 88 (2013) 114009

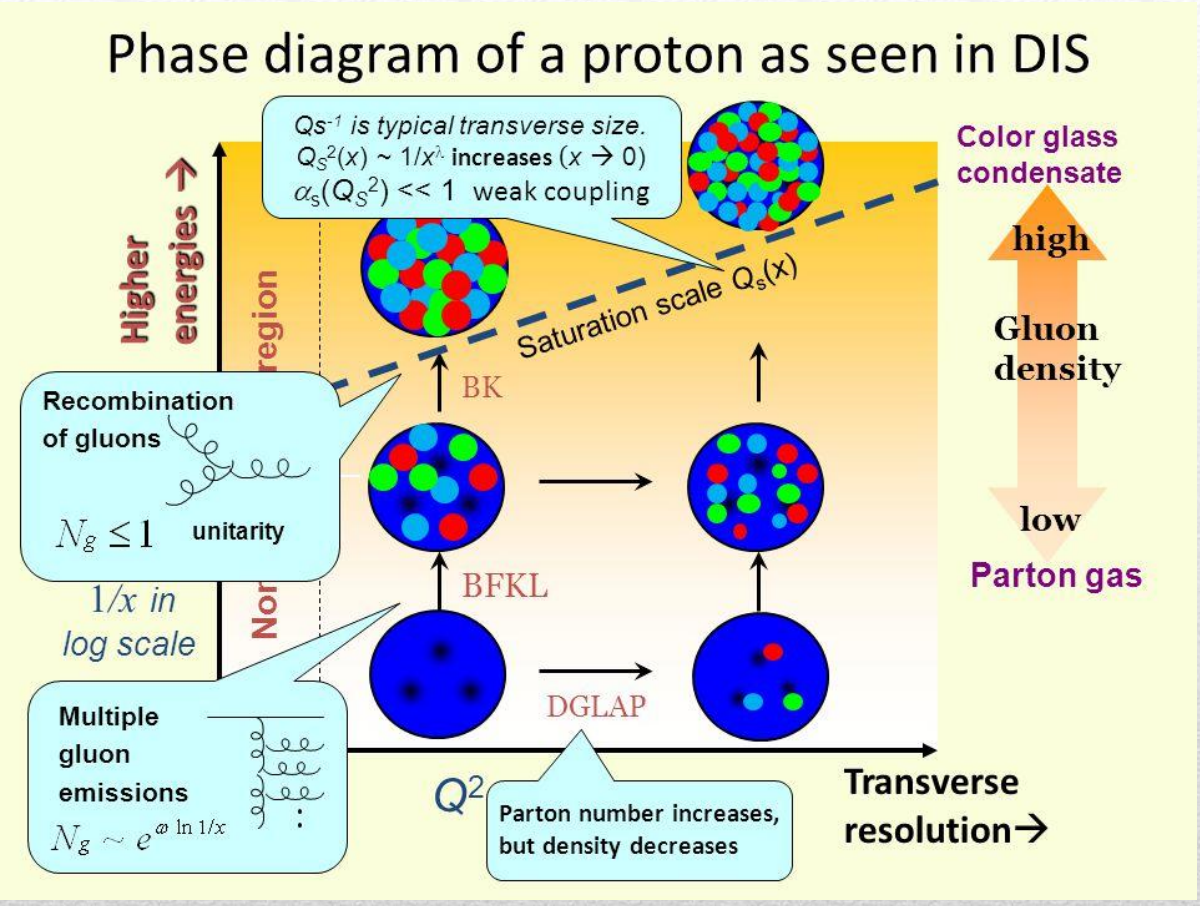
$$\mathcal{L}_{V\gamma} = -\frac{eM_V^2}{f_V} V_\mu A^\mu$$

$$\mathcal{L}_{Z\psi\pi} = \frac{g_{Z\psi\pi}}{M_Z}\left(\partial^\mu \psi^\nu \partial_\mu \pi Z_\nu - \partial^\mu \psi^\nu \partial_\nu \pi Z_\mu\right)$$

$$\mathcal{L}_{\pi NN} = -\frac{g_{\pi NN}}{2m_N} \bar{N}\gamma_5\gamma_\mu(\vec{\tau}\cdot\partial^\mu\vec{\pi})N$$

- Several proposals to study XYZ states in photoproduction
  - $\gamma p \to Z_c^+(3900)n, Z_c^+ \to J/\psi\pi^+$ PRD 88 (2013) 114009
  - $\gamma p \to Z_c^+(4430)n, Z_c^+ \to \psi'\pi^+$ PRD 77 (2008) 094005, PRC 83 (2011) 065203
  - $\gamma p \to Z_c^+(4200)n, Z_c^+ \to J/\psi\pi^+$ arXiv:1503:02125 (incl. Regge trajectories in model)
  - $\gamma p \to Y(3940)p, Y(3940) \to J/\psi\omega$ PRD 80 (2009) 114007
- Use an Effective Lagrangian approach with Vector Meson Dominance

Hybrid production

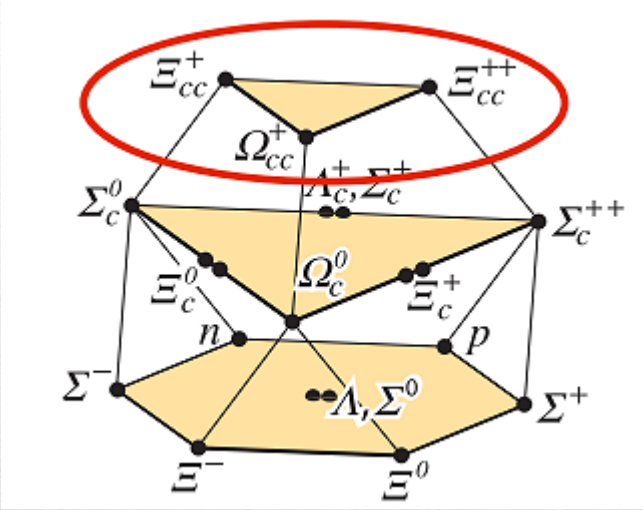


Suprisingly, no calculation for heavy hybrid production has been carried out so far

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