Light and heavy quark spectroscopy at EIC

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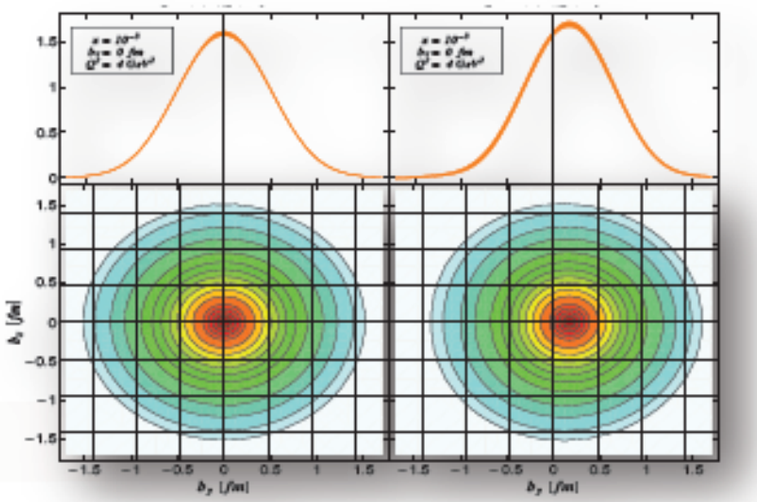
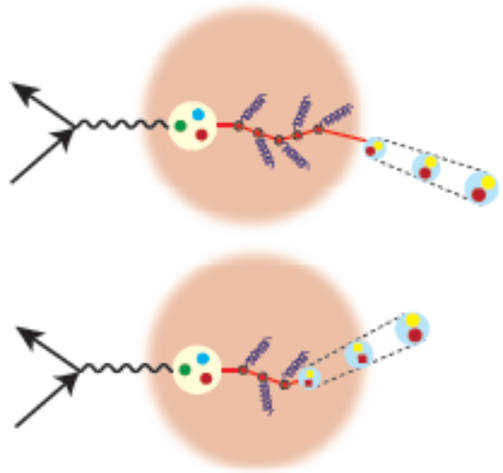
The EIC physics (so far ...)

Accardi et al., Eur. Phys. J. A (2016) 52: 268 **arXiv: 1212.1701.v3**

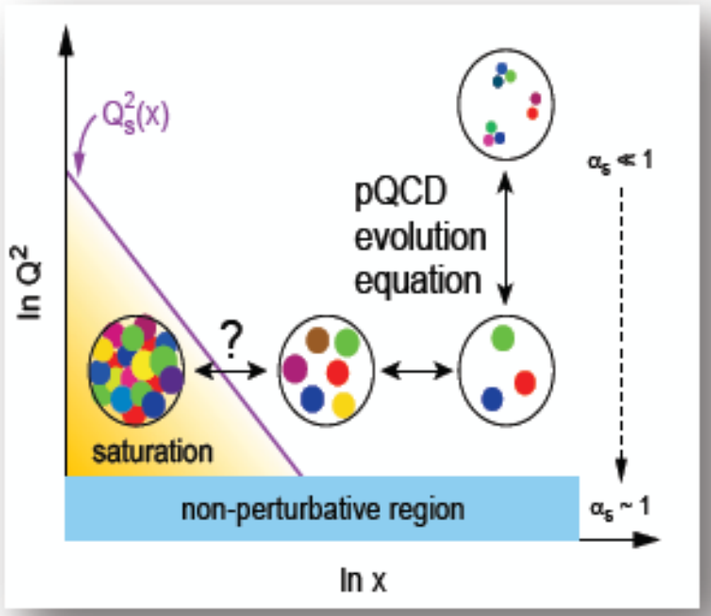
3D Imaging of Nucleon Structure



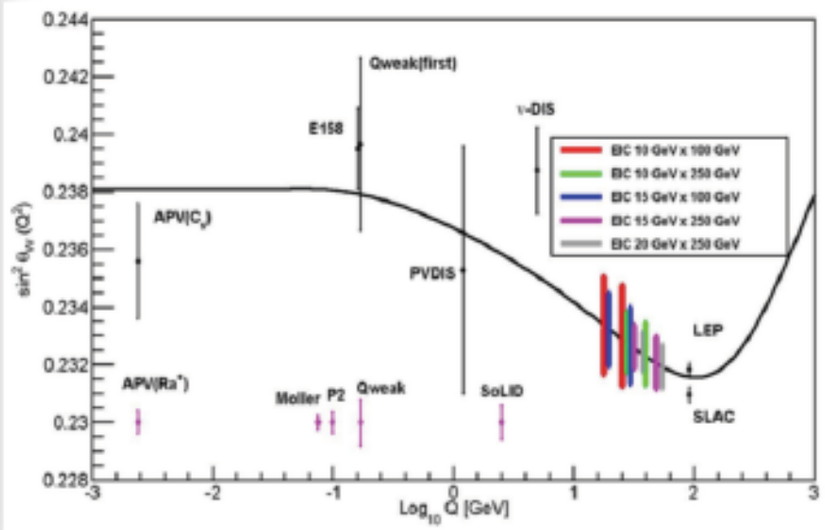
Hadronization in cold QCD matter



Gluon Saturation



EW Physics



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)**

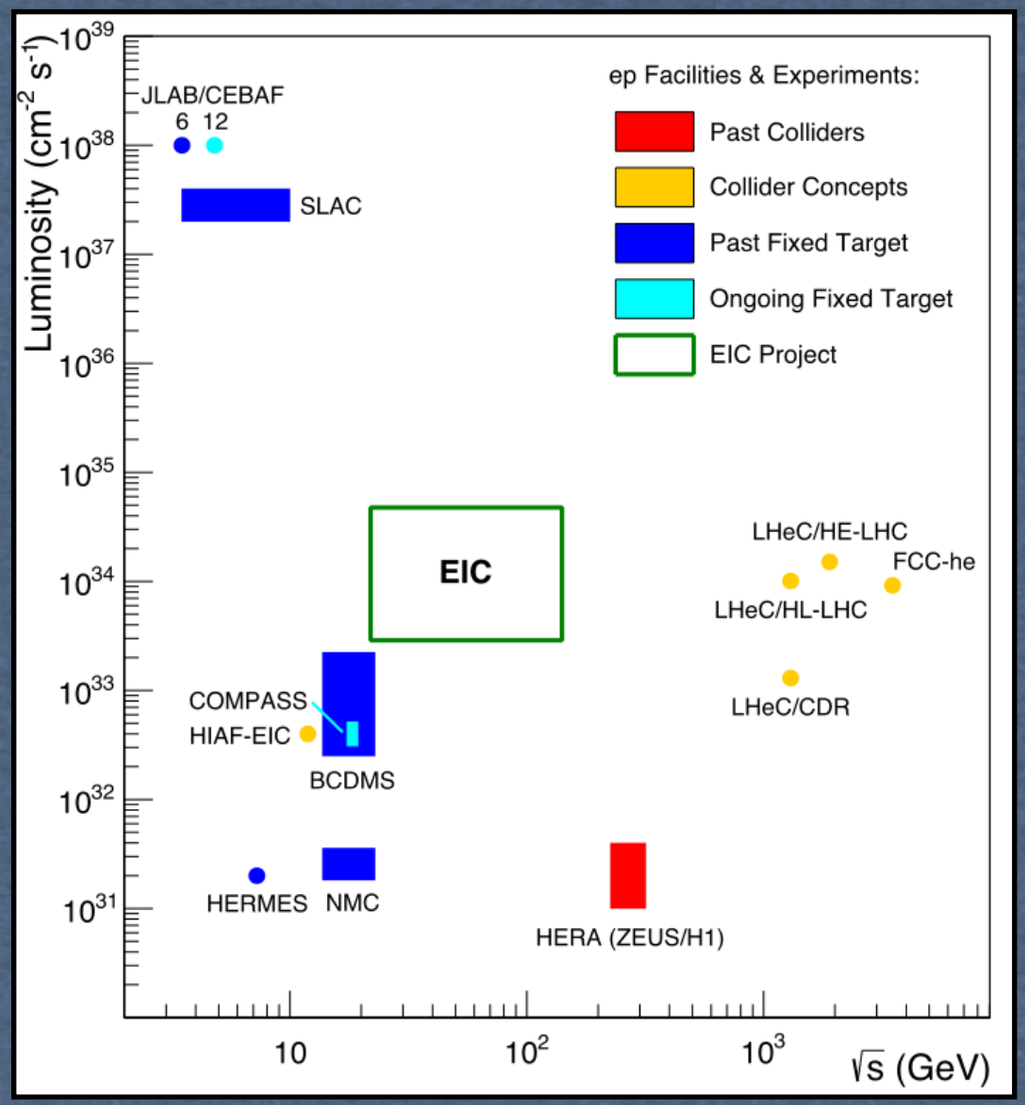
– To study gluon density at saturation scale and to search for coherent effects like the color glass condensate and test universality

- **Centre of mass variability with minimal loss of luminosity**

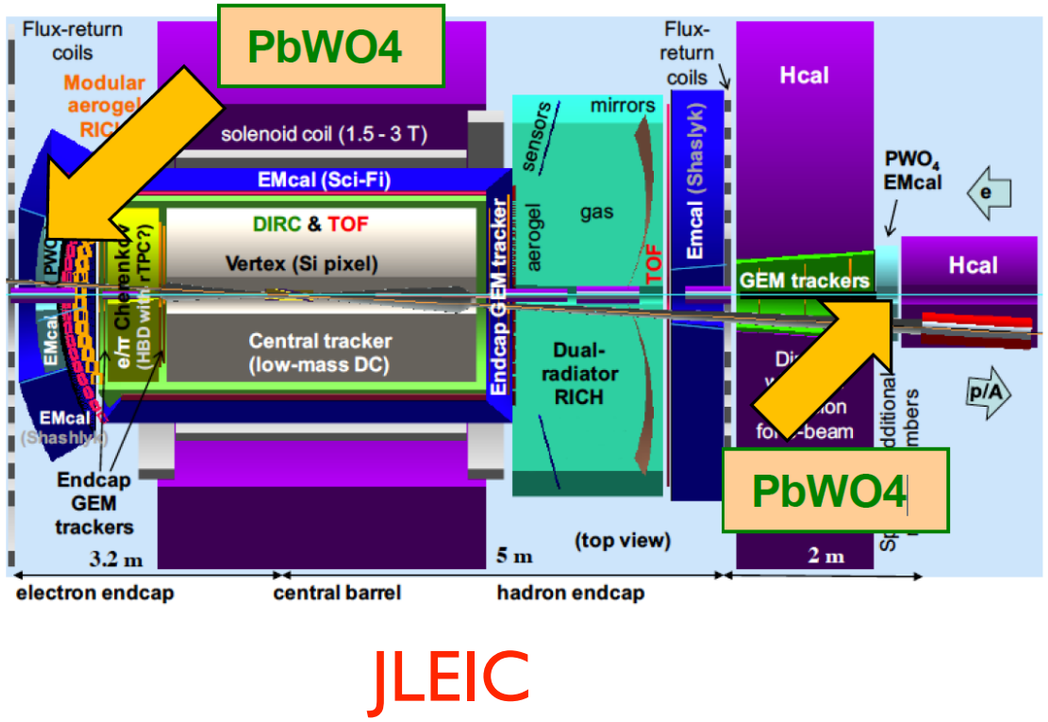
– Critical to study onset of interesting QCD phenomena

- Detector & IR designs mindful of "Lessons learned from HERA"

– No bends in e-beam, maximal forward acceptance….

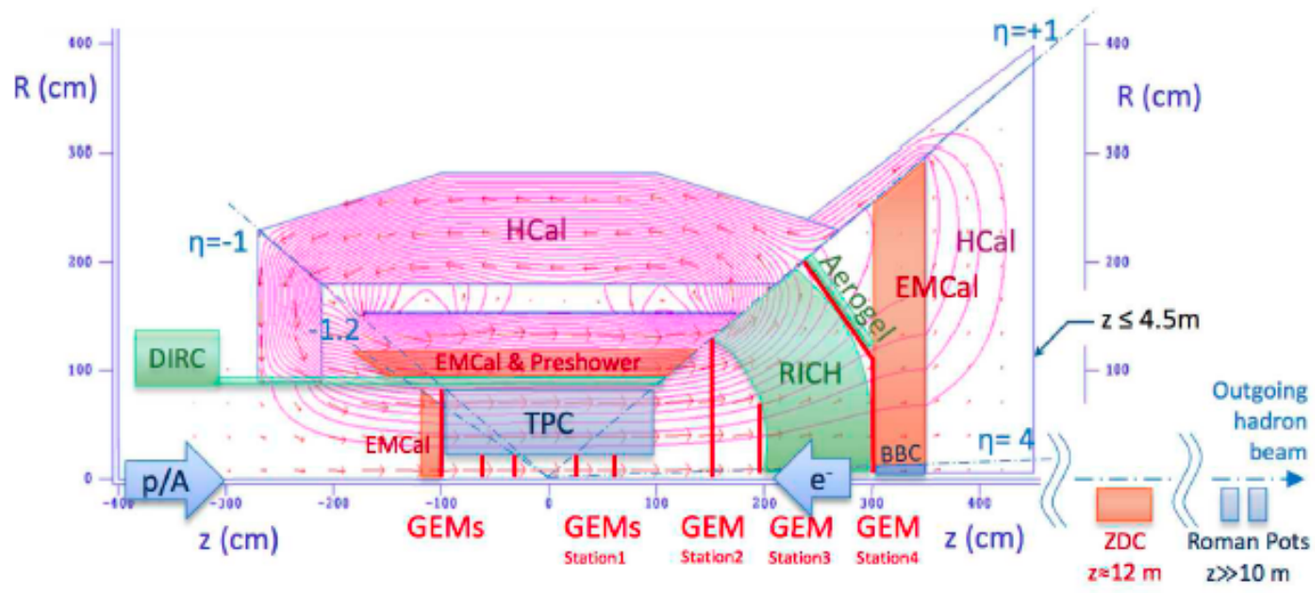


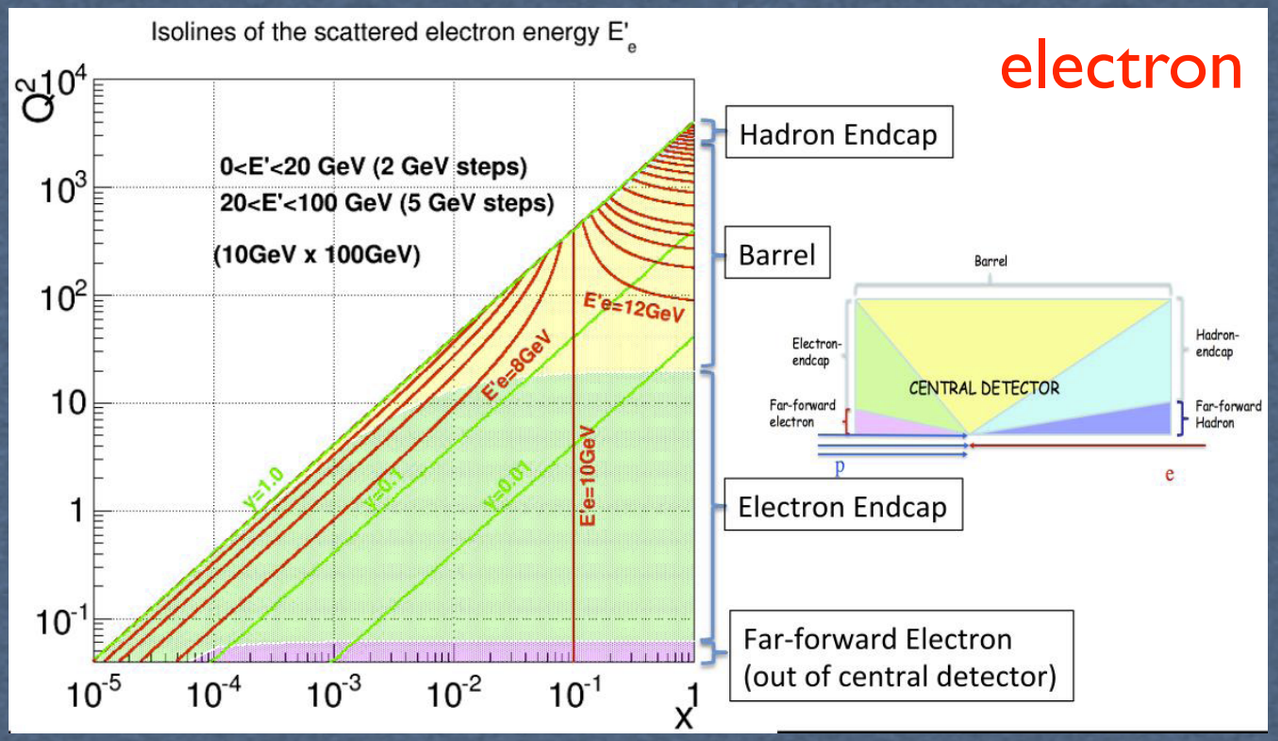
EIC detectors



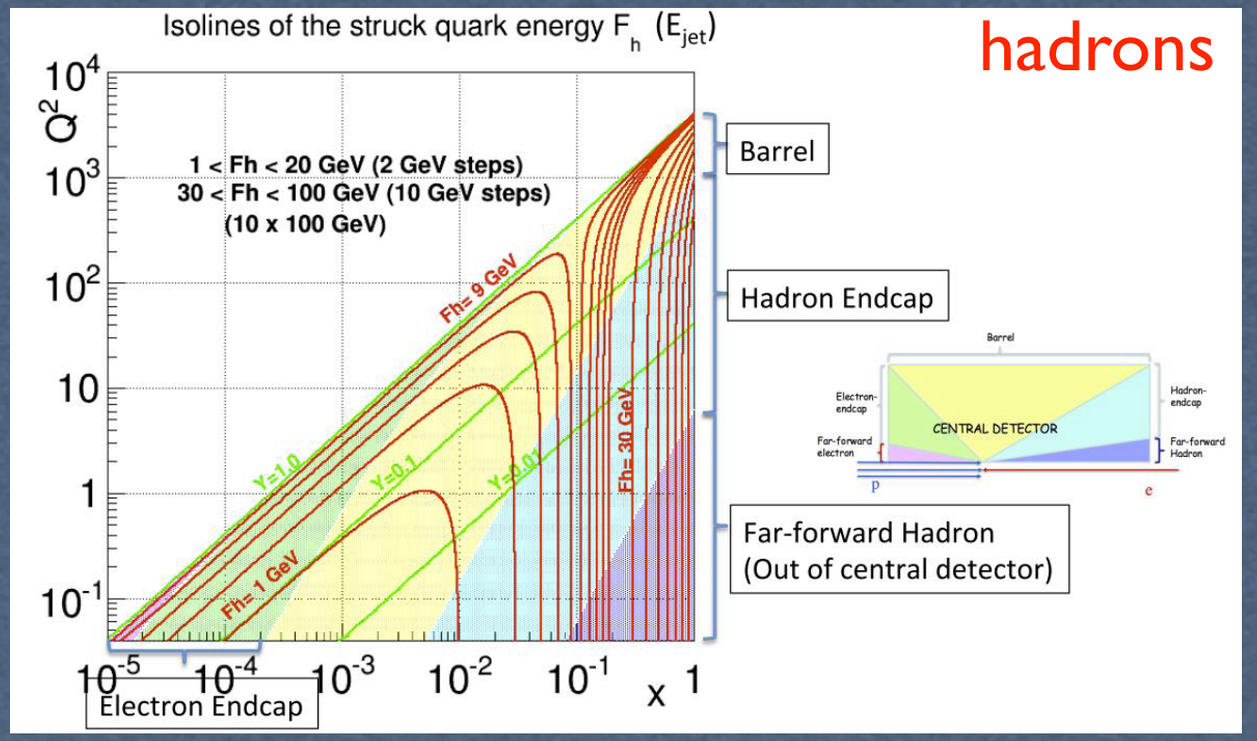
JLEIC

eRHIC





electron



hadrons

Hadron spectroscopy at EIC

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

EIC is the perfect place to study hadron spectroscopy addressing the remain ing 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

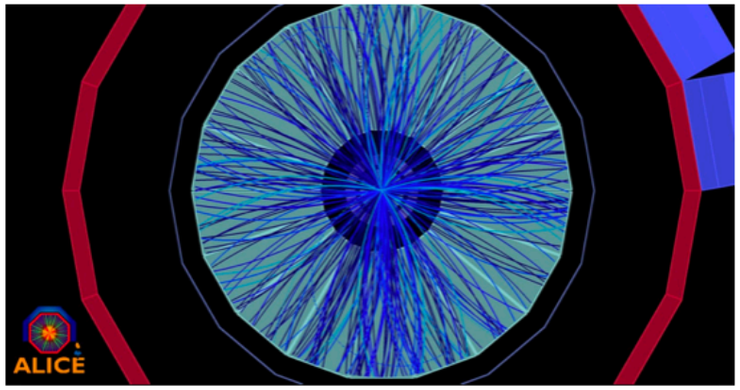
II) Heavy flavours (open and hidden) to prove nuclear medium

III) Diffractive physics

Opportunities

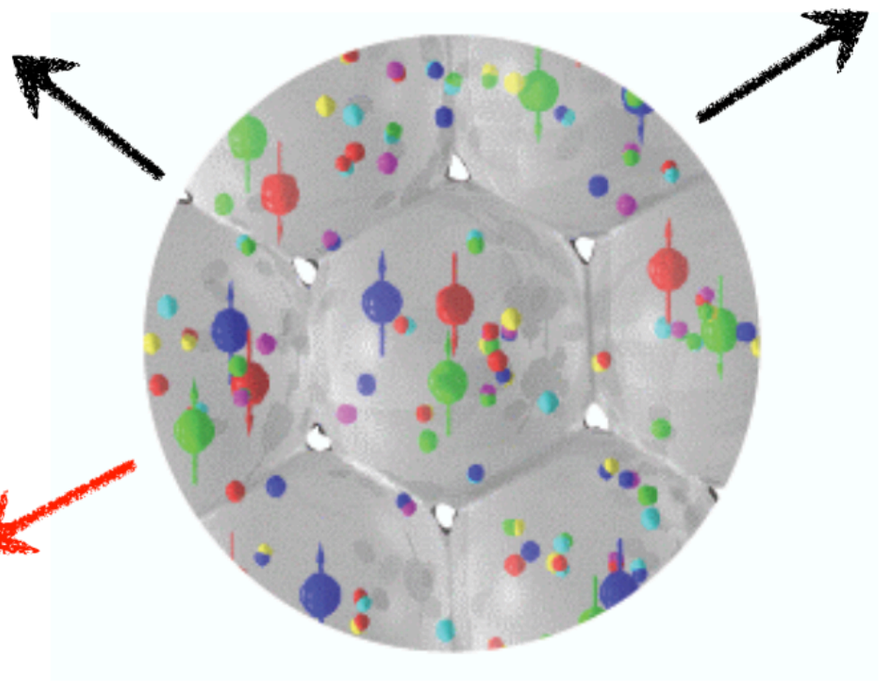
Requirements

Hadron spectroscopy at EIC

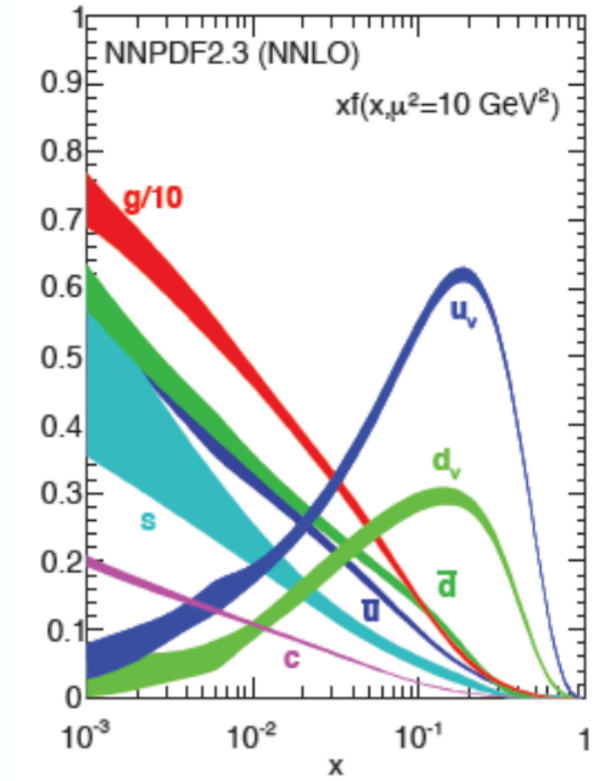


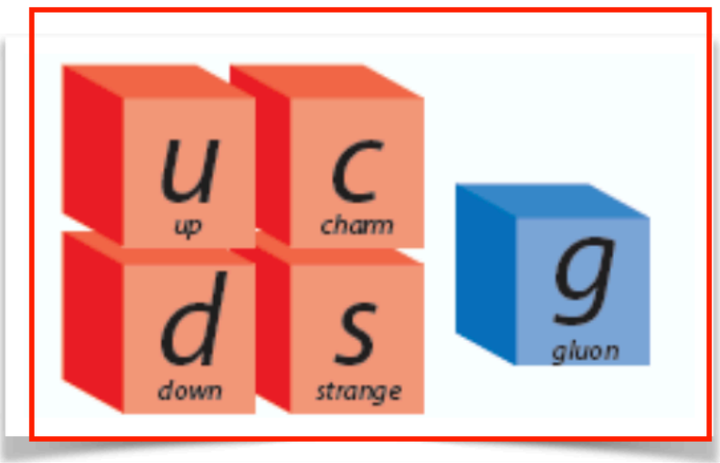
melt it!

Nuclear matter



use a microscope
(nucleon structure)

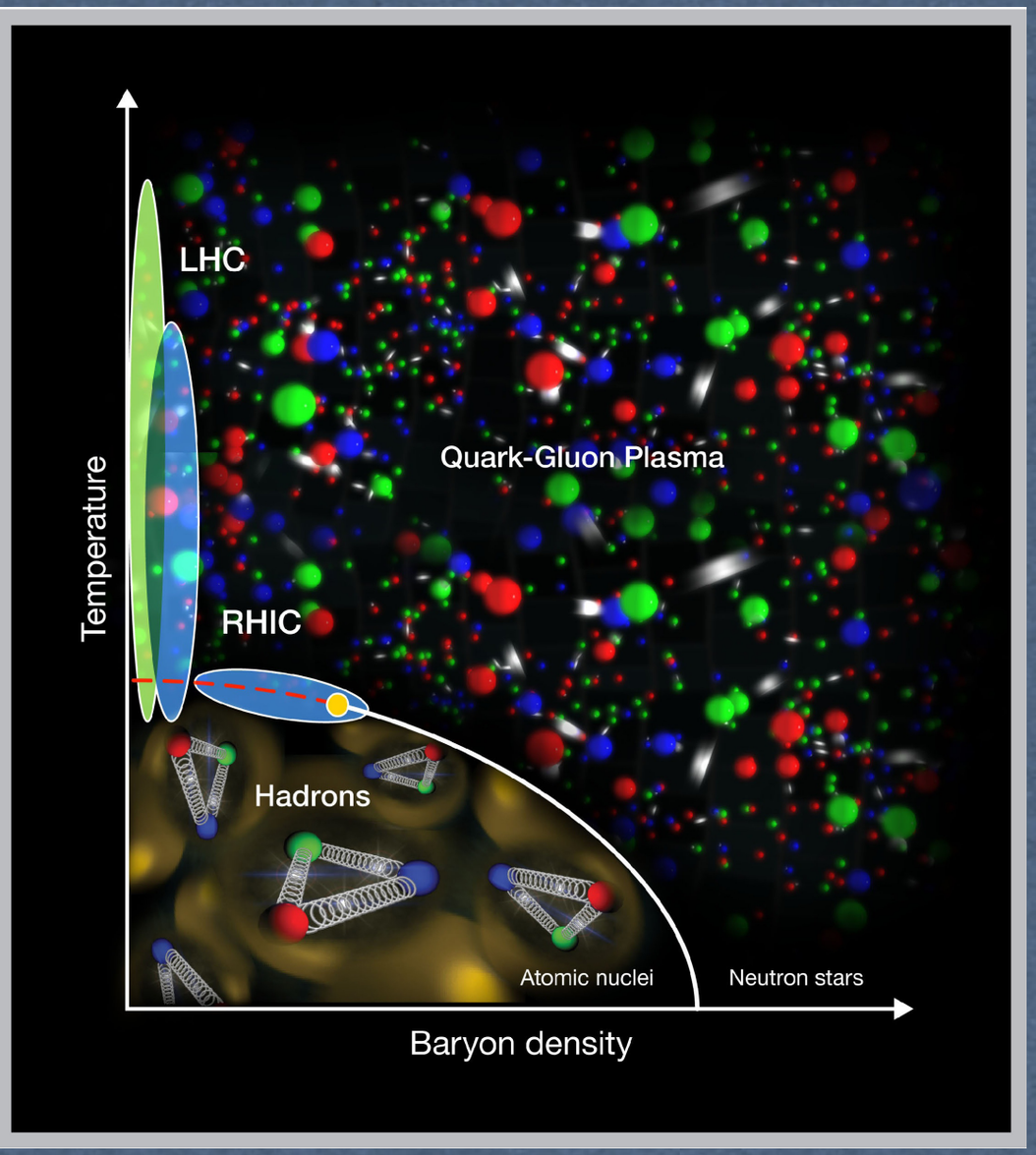




produce and study known and new states:

Hadron Spectroscopy

Hadron spectroscopy at EIC



★ Meson and baryon spectroscopy as a tool to study QCD phases

★ Color confinement

★ manifestation of gluonic degrees of freedom

★ non-perturbative dressing effects

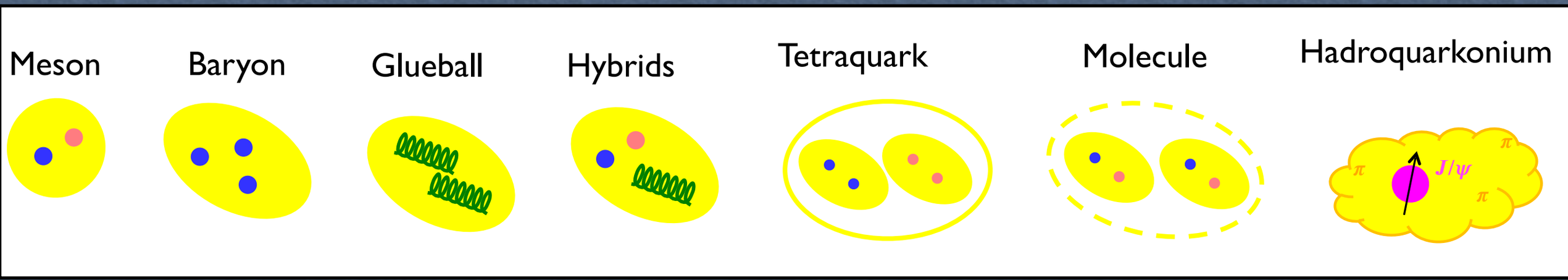
★ gluon-gluon interaction

★ confinement

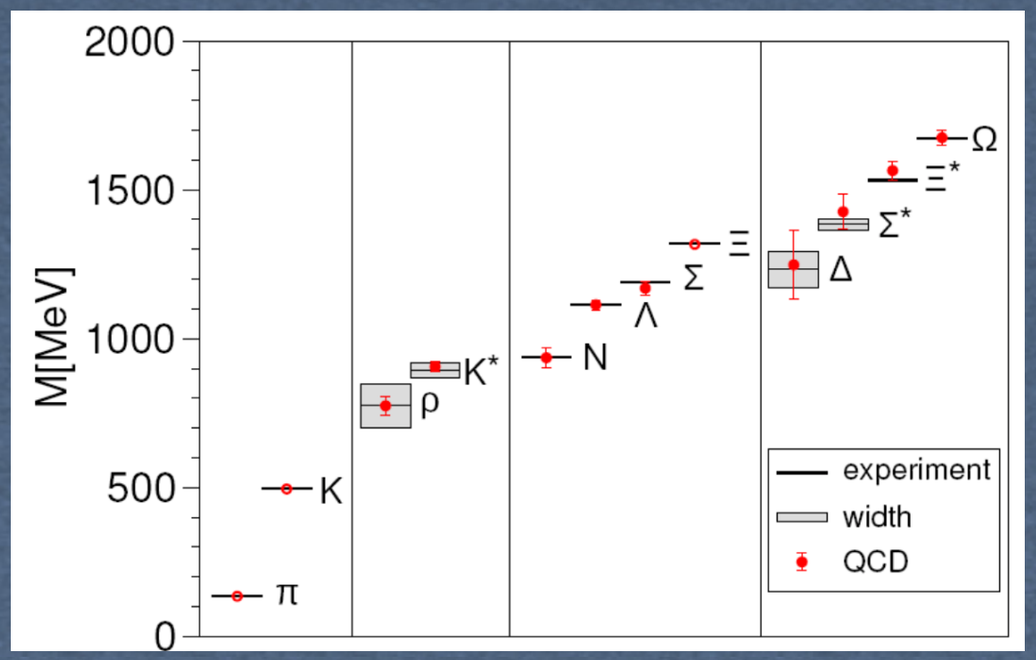
★ light-q vs heavy-q

Significant word-wide effort: COMPASS, JLab BES-III,LHCb, ALICE, BELLE

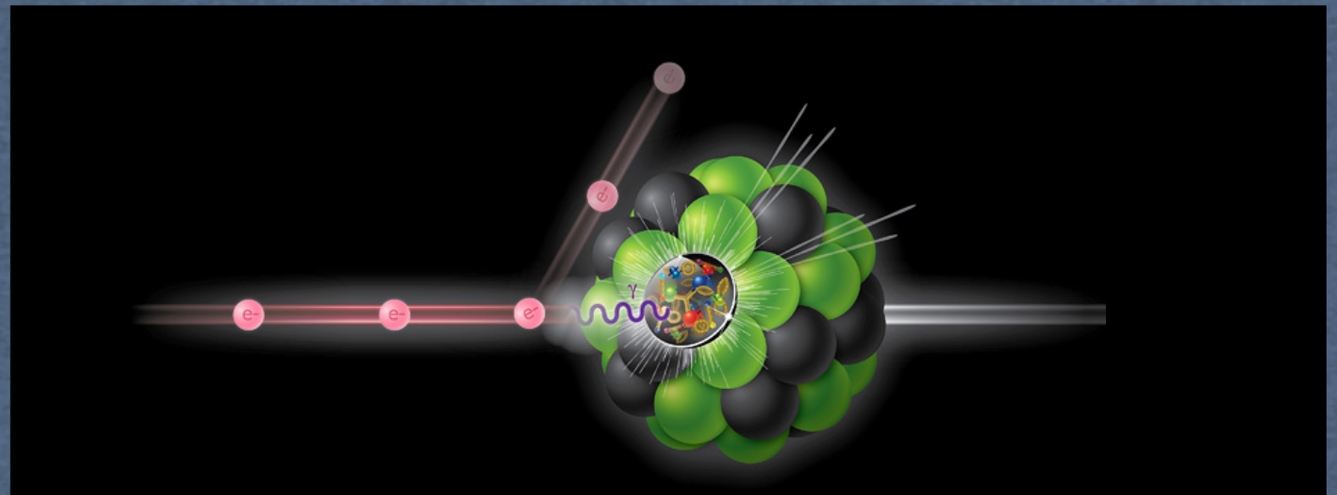
Hadron spectroscopy at EIC



Science (2008)



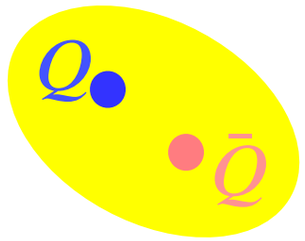
Observed mesons and baryons well described by 1st principles QCD



«The Electron Ion Collider will act as an enormous microscope» to study quarks inside hadrons

We want to use it to study «enormous» hadrons!

The charmonium orthodoxy

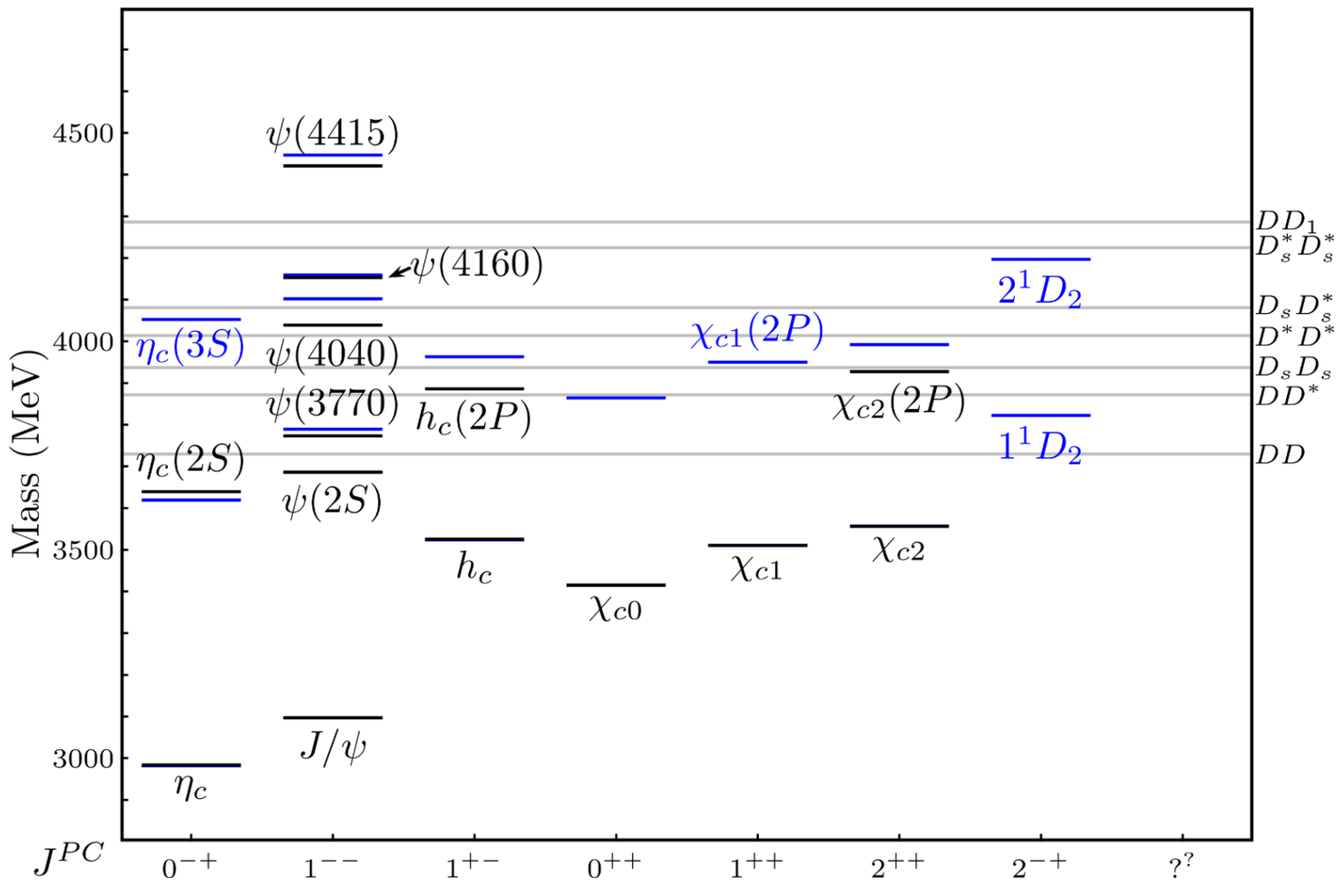


Potential models
(when)

$$V(r) = -\frac{C_F \alpha_s}{r} + \sigma r$$

Effective theories
(HQET, NRQCD, pNRQCD...)

Integrate out heavy DOF
↓
(spectrum), decay
& production rates

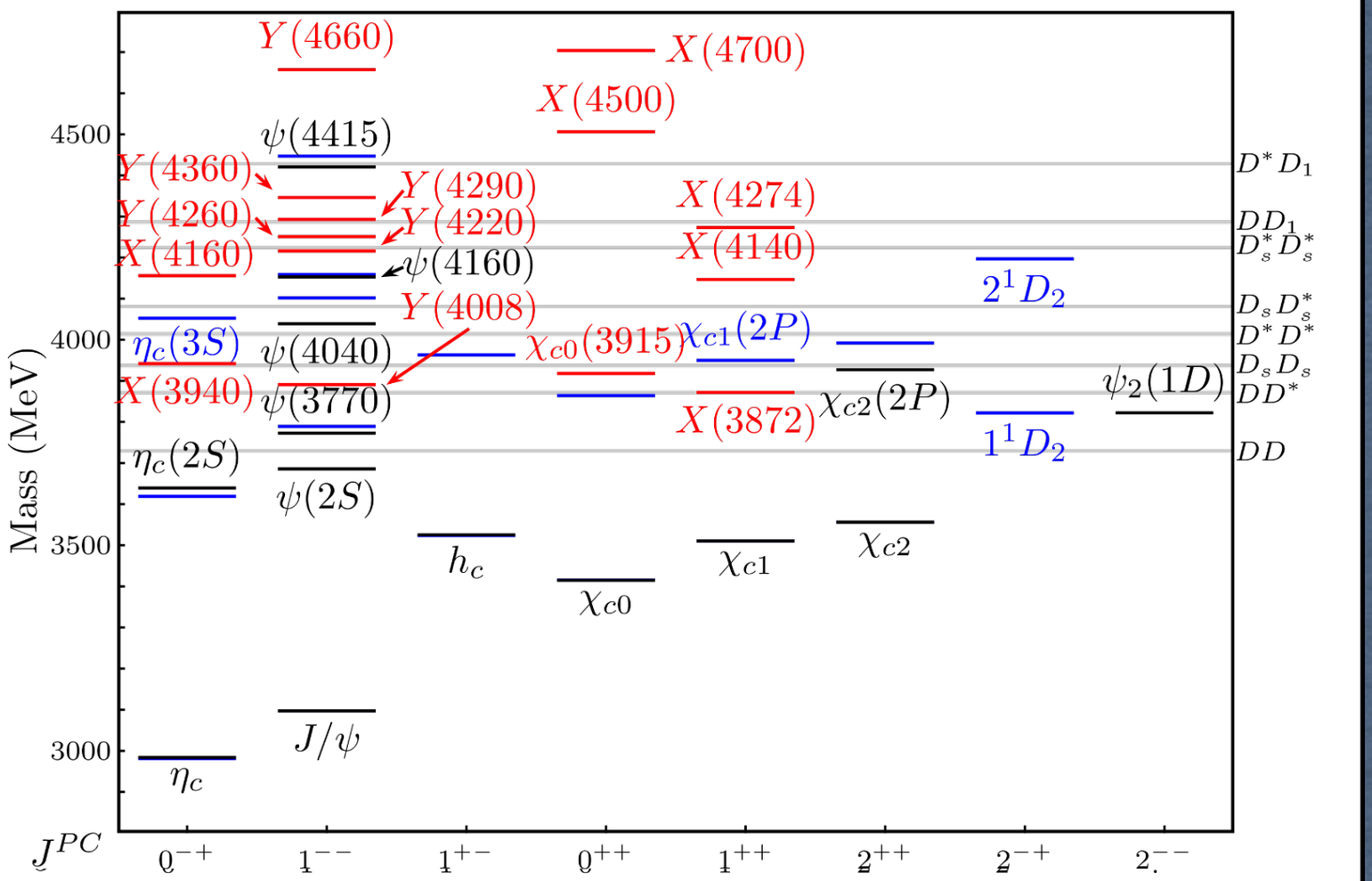


XYZ exotics

A host of new and unexpected resonances have appeared

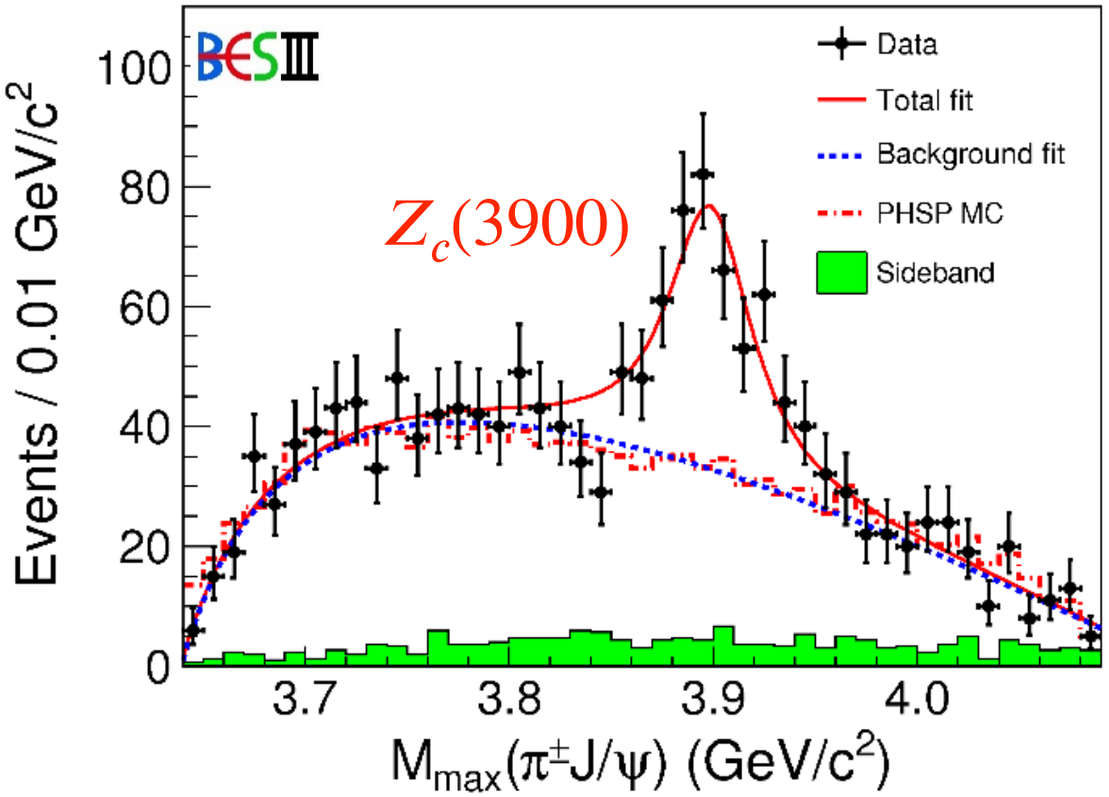
Preferred decay: charmonium + light

Difficult to reconcile with charmonium-like interpretation

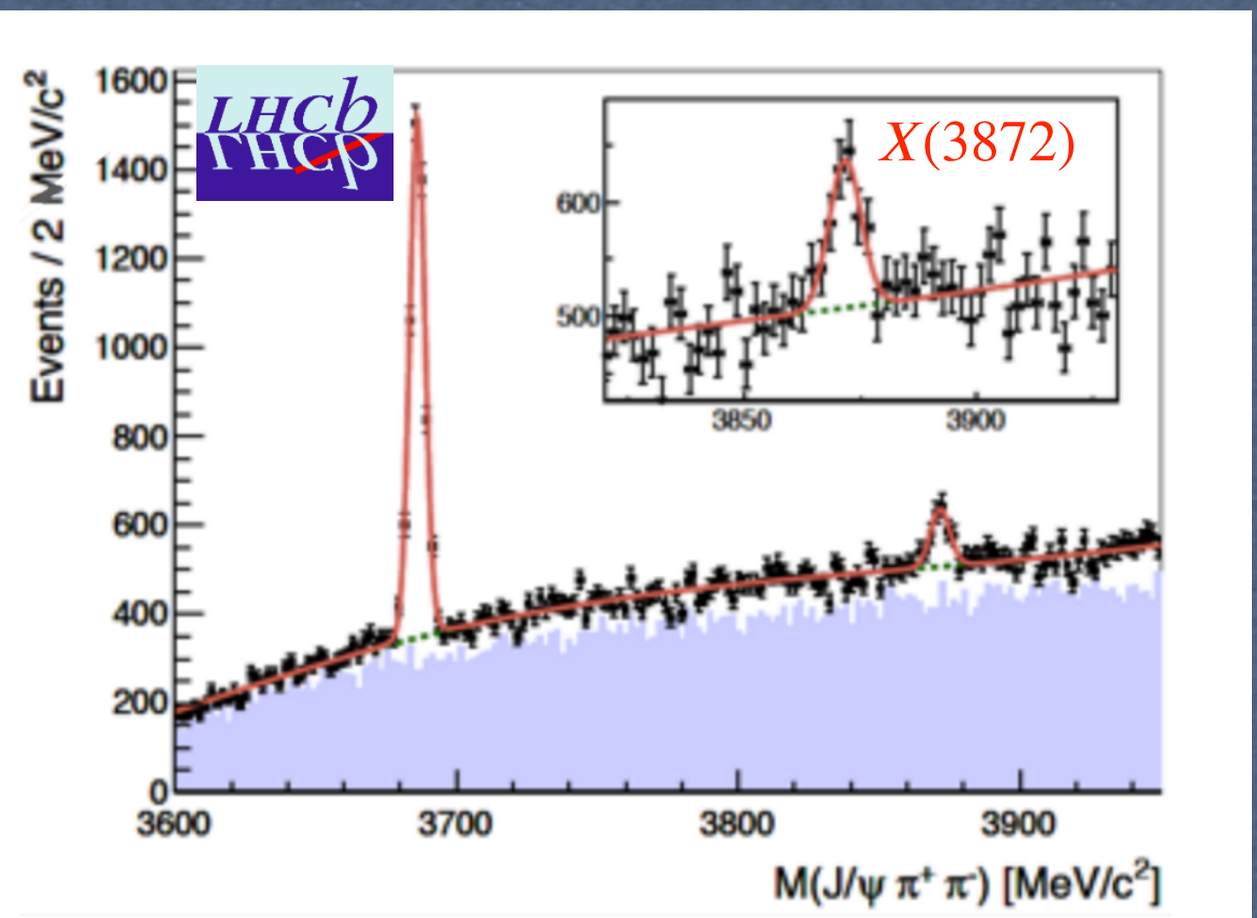


The *good old* times suddenly ended disclosing a realm populated by new and unknown states (multi-quarks? glue-rich? …)

XYZ exotics



- Many new states in the charmonium sector
- Convincing evidence of new exotic hadronic states
- Probably, more to come
- Bottomonium almost unexplored

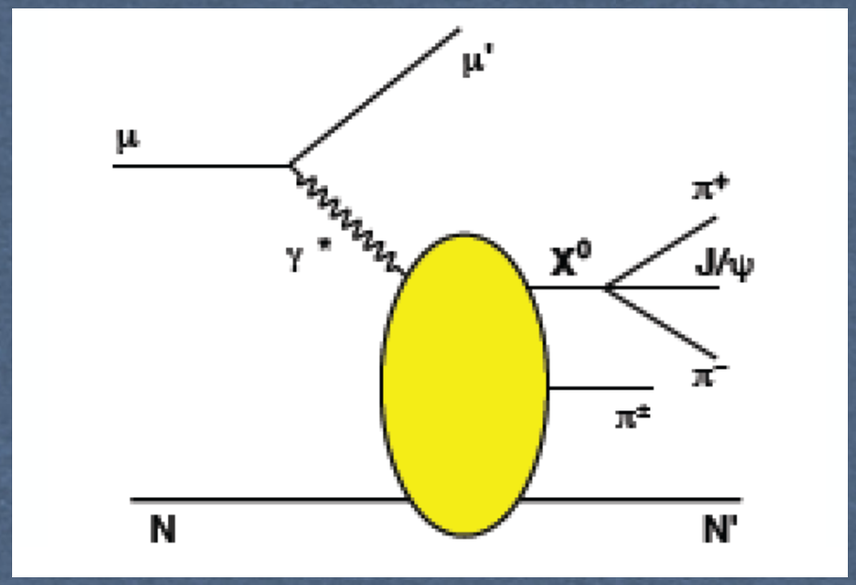


A rich phenomenology that requires to be understood and thoroughly studied in a high statistics, high precision experiment covering a wide kinematic range

Electron Ion Collider

Exotic charmonia at COMPASS

$\mu N \rightarrow \mu' (J/\Psi\, \pi^+\pi^-)\, \pi^\pm N^*$



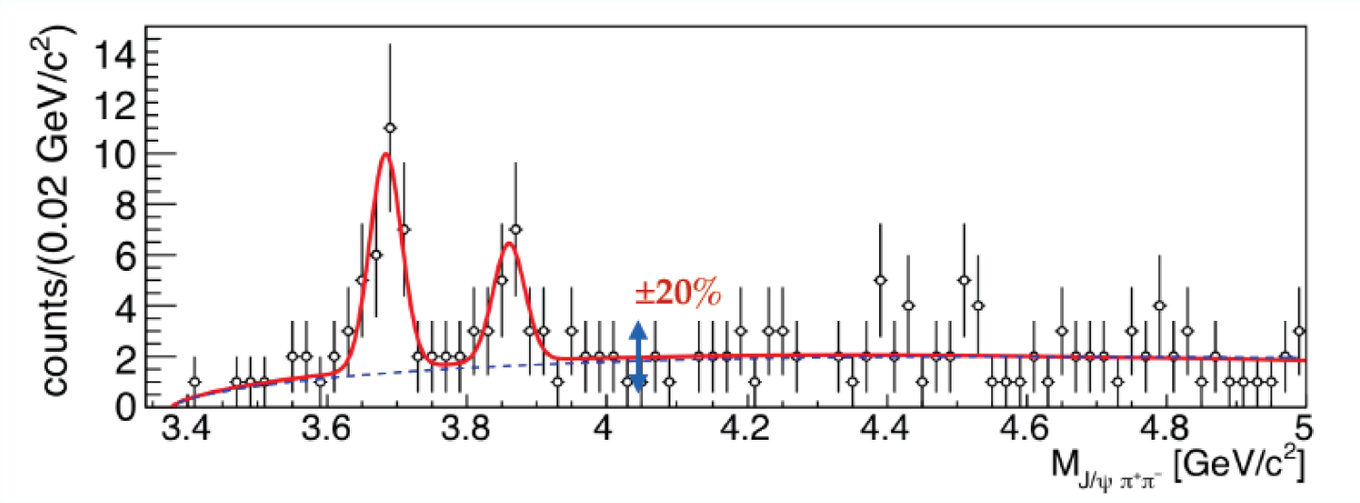
$\tilde{X}(3872)$ as a new state

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

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

Significance (including systematics) is 4.1σ

C=−1 (?)



At COMPASS conditions:

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

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

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

~10 events per day

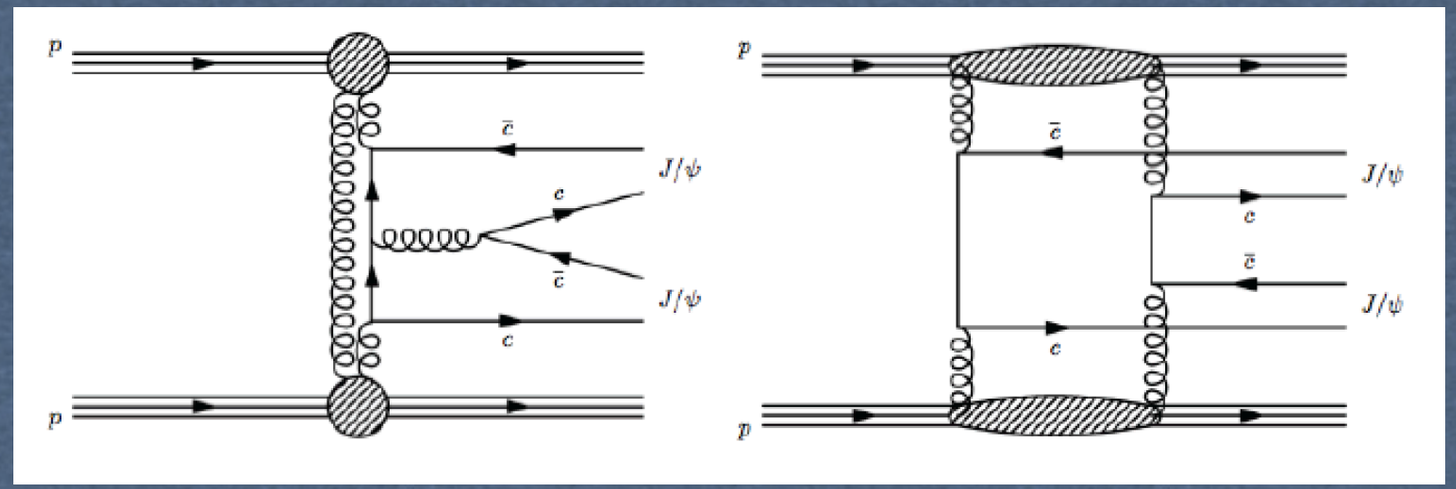
A.Guskov (JINR)

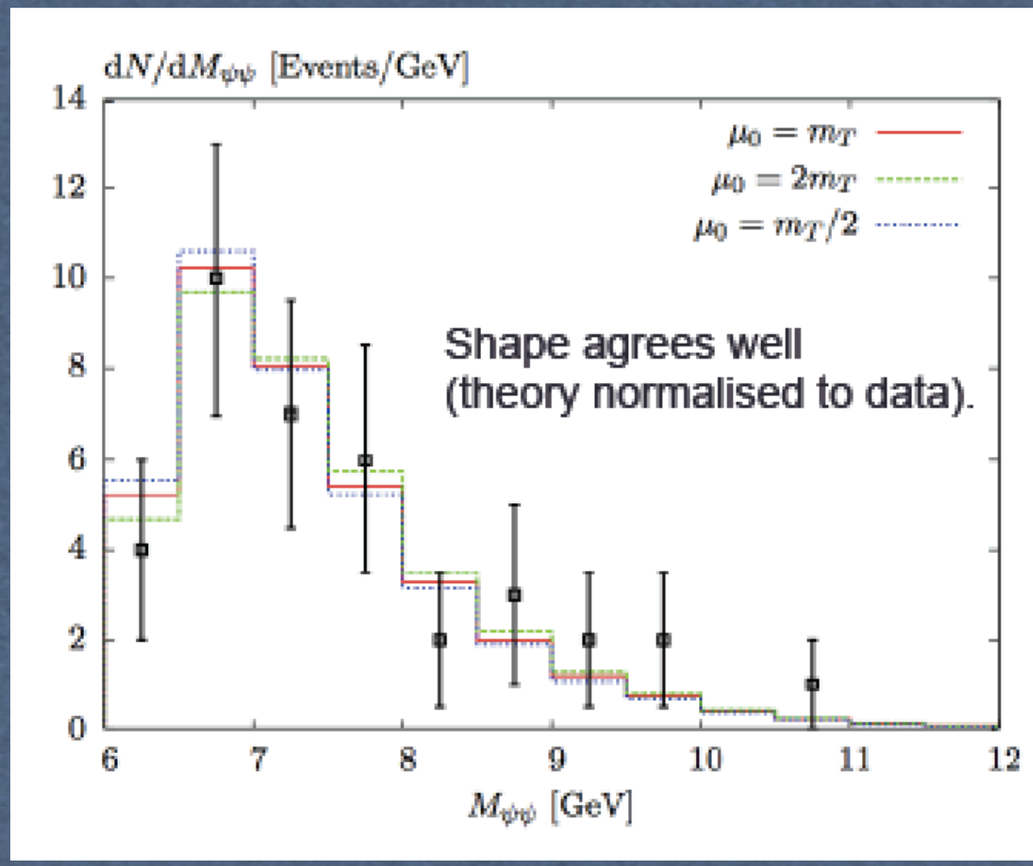
Exotica at LHCb

- ✳ Tetraquarks
- ✳ (light) hybrids
- ✳ Glueballs
- ✳ Odderon

Double J/Ψ production

- Double pomeron exchange
- Sensitivity to high mass states (tetraq)





EIC may produce such states trough gamma-gamma collisions

LHC
High Energy
Medium/High Luminosity
High Backgrounds

→

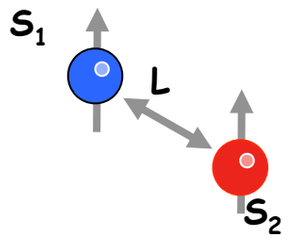
EIC
Low Energy
High Luminosity
Low Backgrounds
(detector design)

R.McNulty (UCD)

The light quark meson spectrum

Constituent Quark Model

- Quark-antiquark pairs with total spin S=0,1 and orbital angular momentum L



$S=S_1+S_2$ $\quad J= L+S$

$P = (-1)^{L+1}$ $\quad C= (-1)^{L+S}$

Not all the J^{PC} combinations are allowed:

0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} 3^{+-} 3^{-+} 3^{--} …

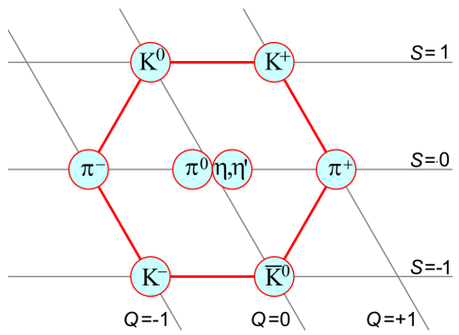
- SU(3) flavor symmetry
  → nonet (8⊕1) of degenerate states

$J^{PC}= 0^{-+}$ ⇒ (π,K,η,η')

1^{--} ⇒ (ρ,K*,ω,Φ)

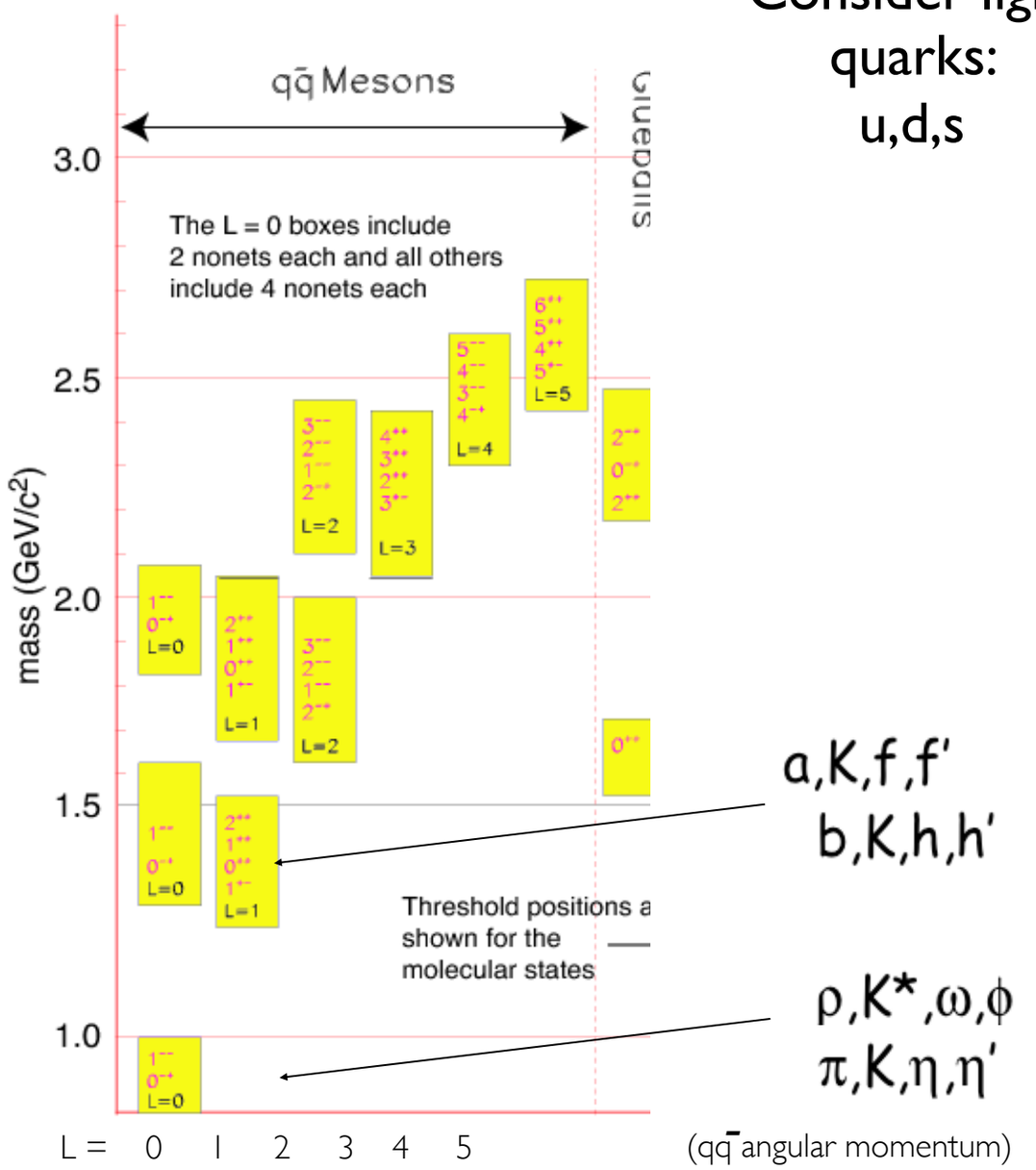
1^{+-} ⇒ (b_1,K_1,h_1,h_1')

…



- Great success in describing the lower mass states

Consider light quarks: u,d,s



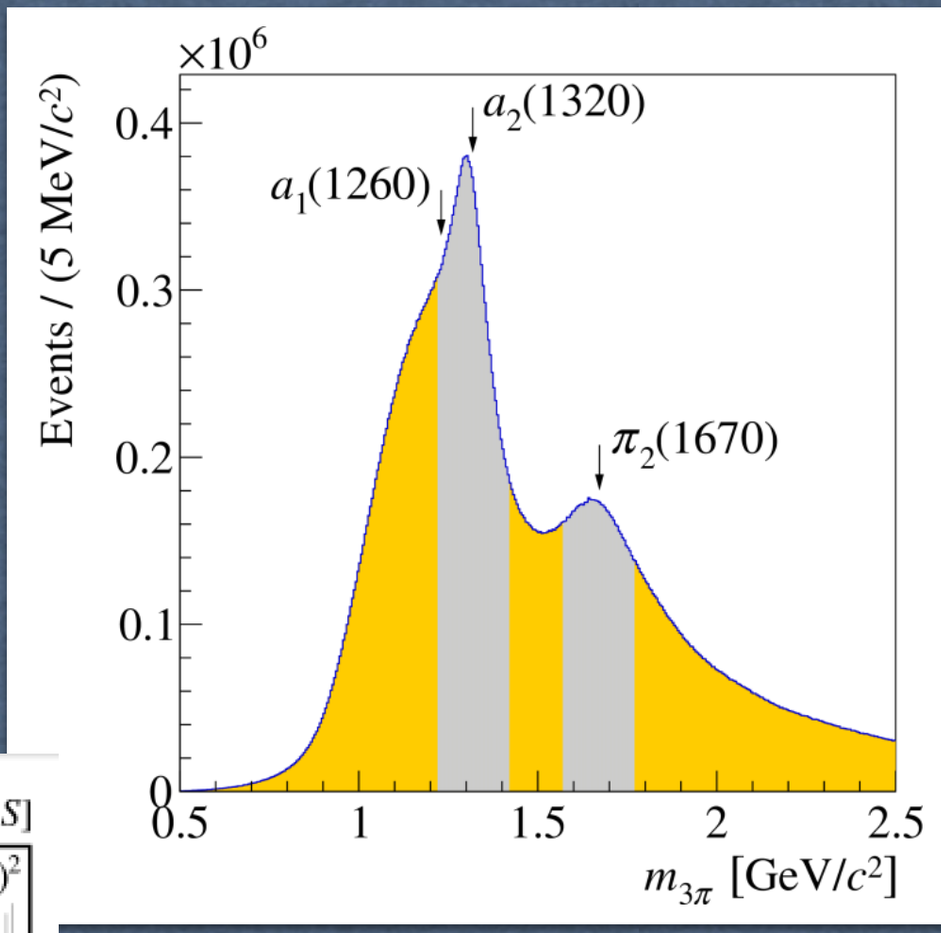
- A number of predicted states is not experimentally observed and assignments are uncertain

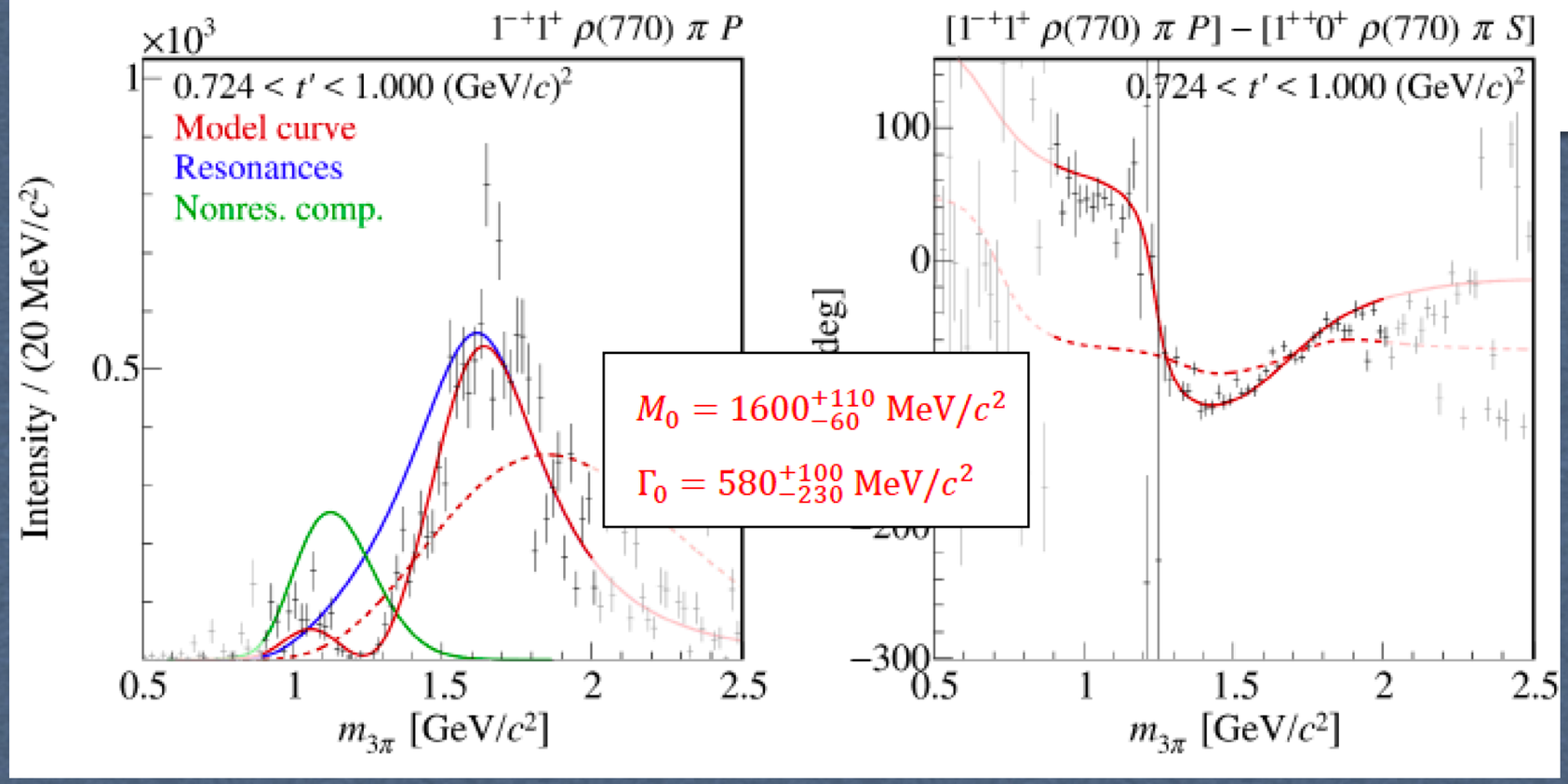
Hybrids at COMPASS

3π final state

✳ Possible evidence of exotic meson $\pi_1(1600)$ in $\pi^- p \to p\,\pi^-\pi^-\pi^+$ (E852-Brookhaven)

✳ Simple final state with low bg





Bad description of data without resonance component $\pi 1(1600)$ needed to describe data

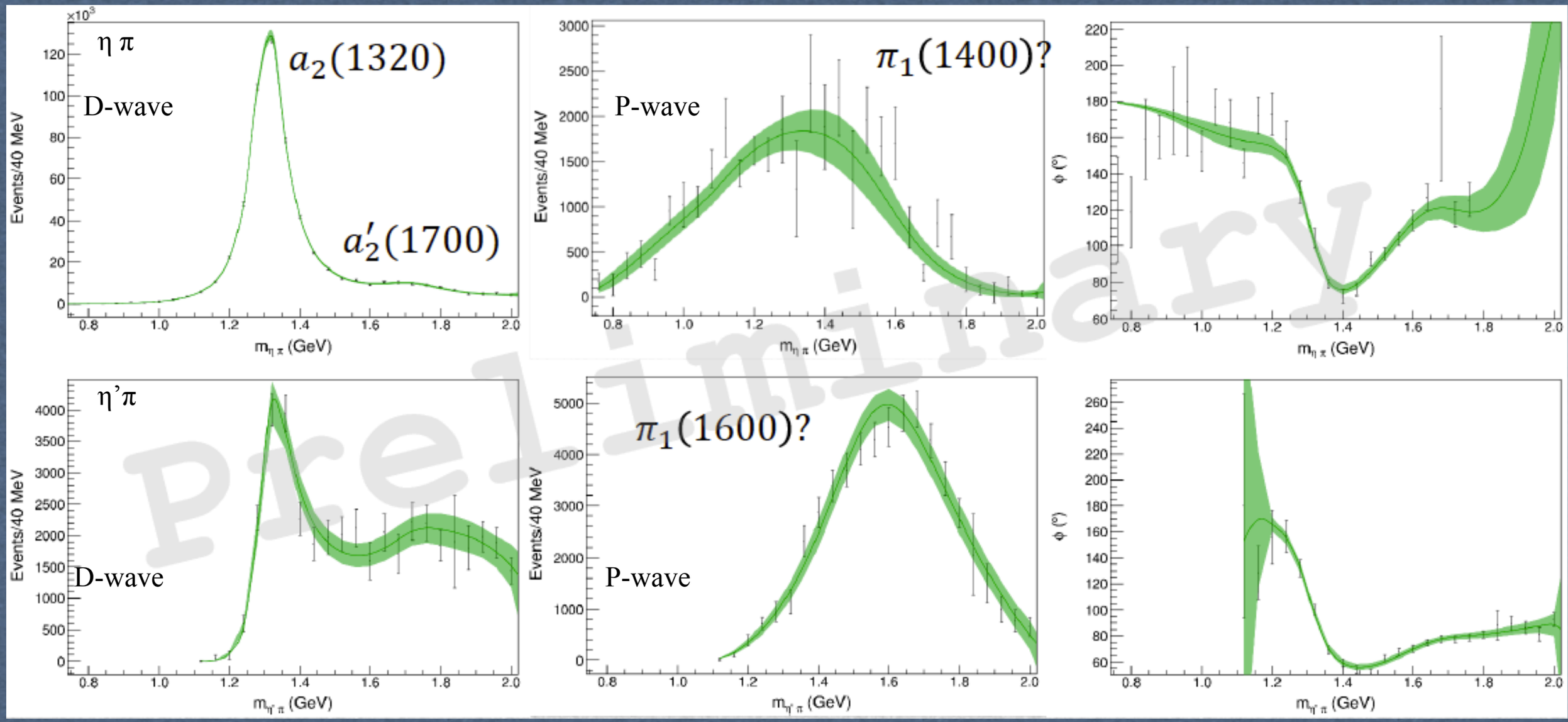
B.Ketzer (UBonn)

Hybrids at COMPASS

ηπ final state

- ✳ $\pi^- p \to p\eta\pi^-$ and $\pi^- p \to p\eta'\pi^-$ at 191 GeV
- ✳ $\pi_1(1400)$ exotic state (1^{-+} wave)

B.Ketzer (UBonn)



Hybrids at COMPASS

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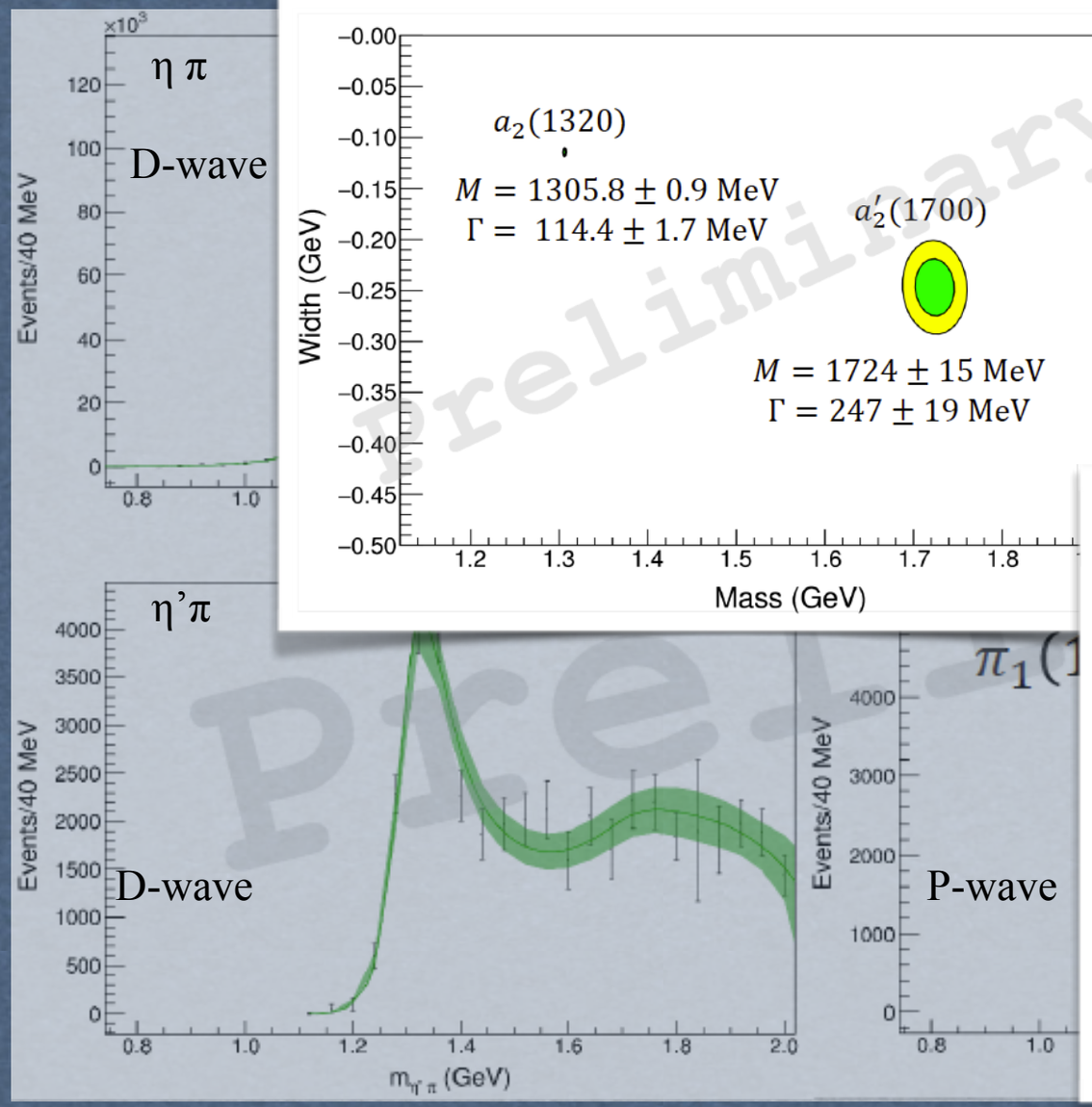
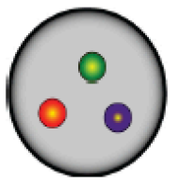
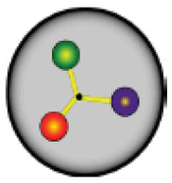
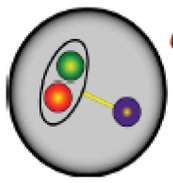


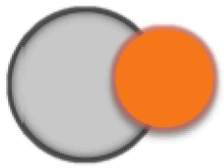
JPAC interpretation:
a single resonance that depending on the final states projects at different masses

Hybrid baryons at CLAS12


CQM

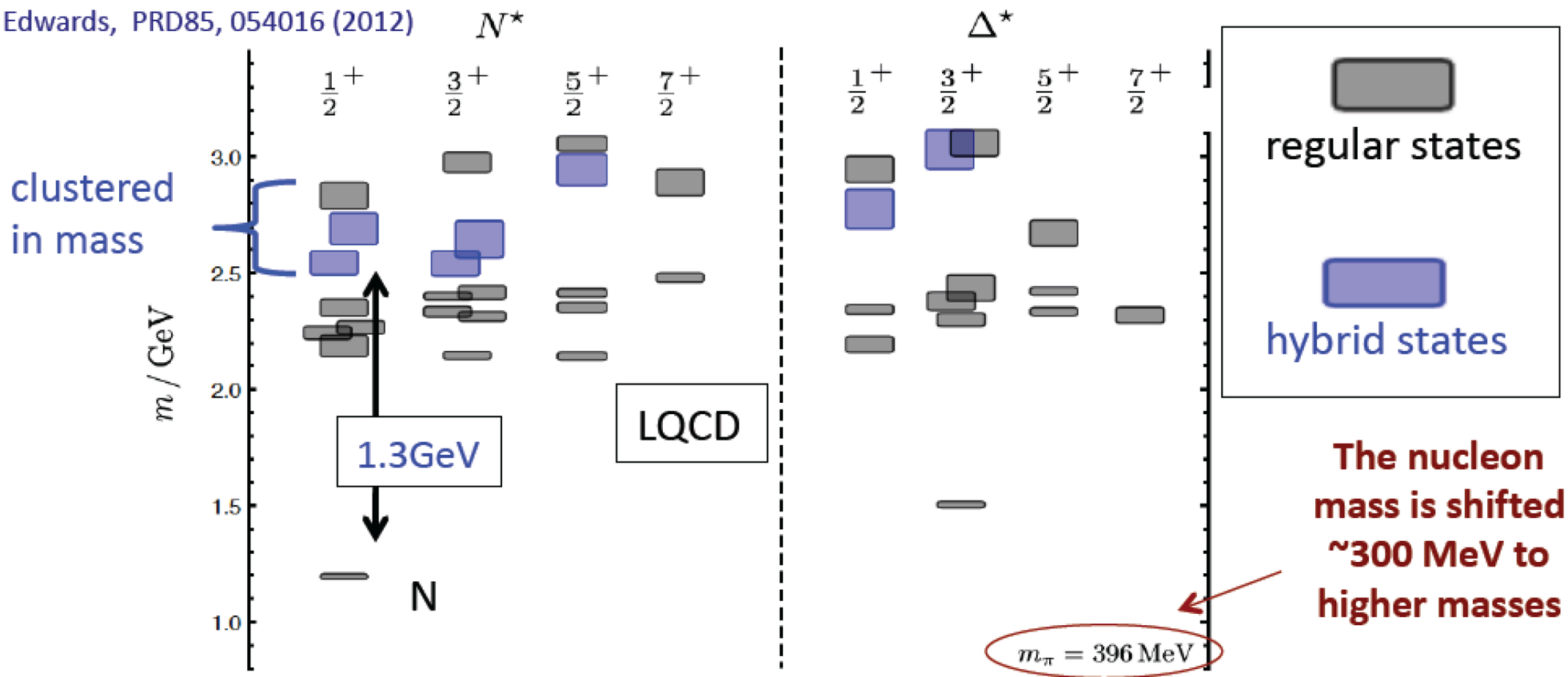

CQM+flux tubes


Quark–diquark clustering


Baryon-meson system

Hybrid Baryons in LQCD

J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012)



Hybrid states have same J^P values as qqq baryons. How to identify them?

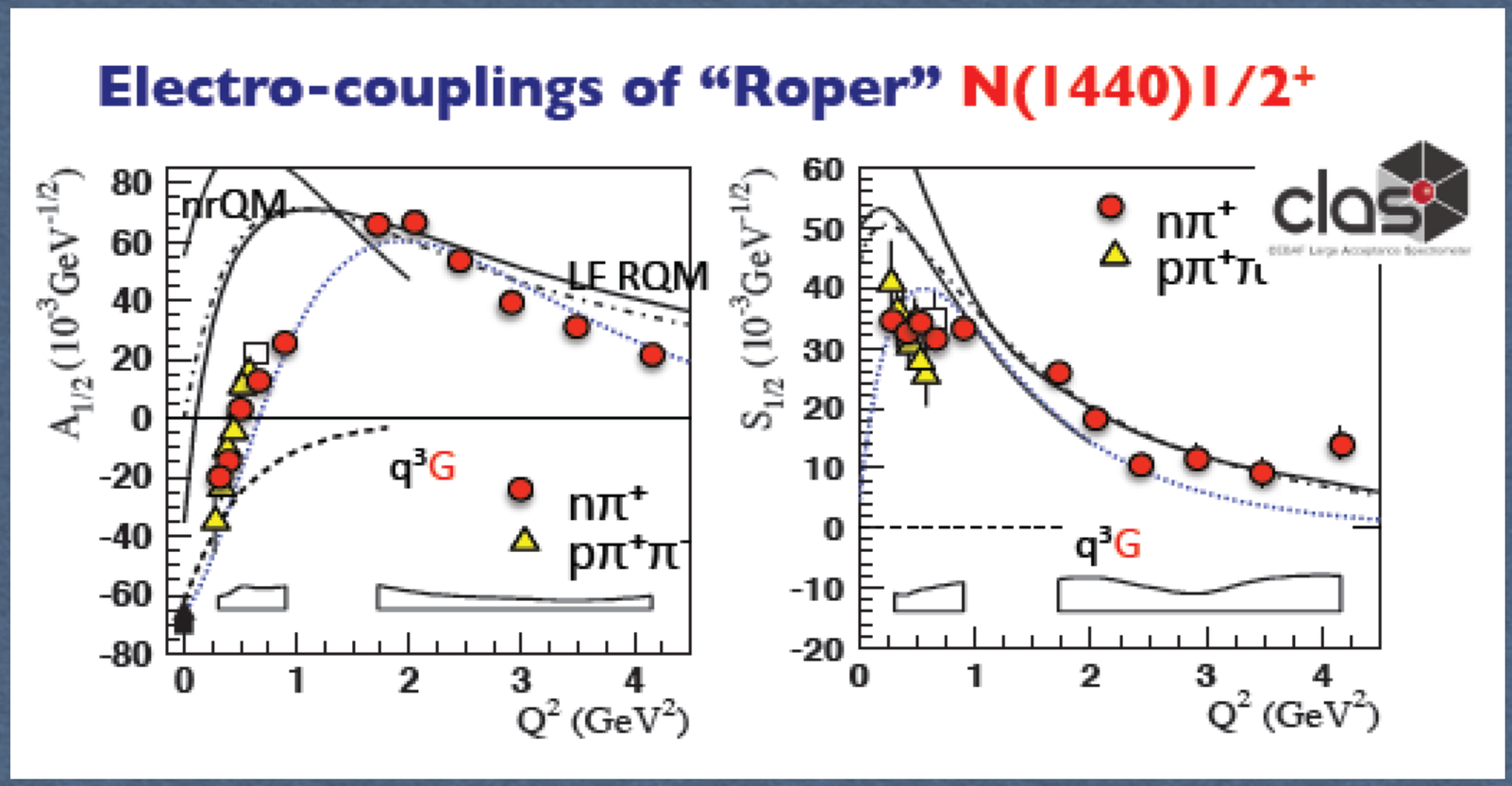
- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution. Can we do it?**

A.D'Angelo (URome-TV)

Hybrid baryons at CLAS12

Electro-production can be used to explore the hadron structure at different wavelengths (Q2)

A drop of the transverse helicity amplitudes $A_{1/2}(Q_2)$ faster than for ordinary three quark states, because of extra glue-component in valence structure



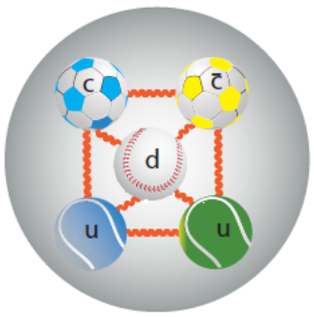
A suppressed longitudinal amplitude $S_{1/2}(Q_2)$ in comparison with transverse electro-excitation amplitude Q_3G Q_3G

- Nπ and Nππ give consistent results
- $A_{1/2}$ changes sign and has large magnitude at high Q^2
- QM fails to reproduce low Q^2 behavior, LFQM better at large Q^2
- Both $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ inconsistent with hybrid model prediction

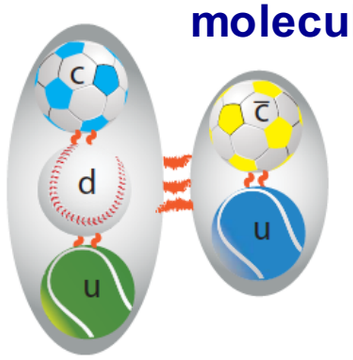
A.D'Angelo (URome-TV)

Pentaquark

5-quark bound state

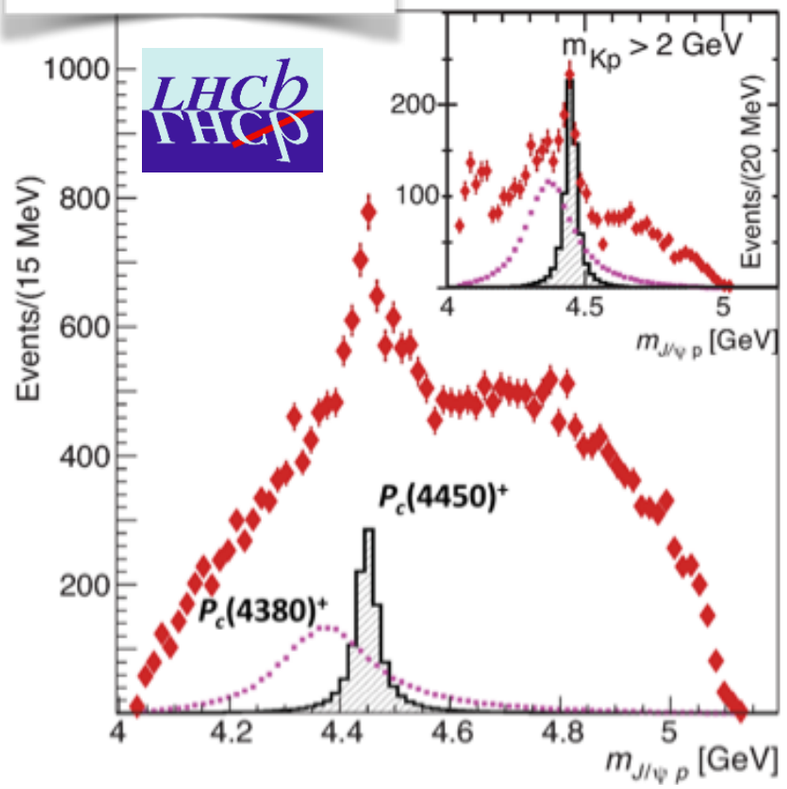


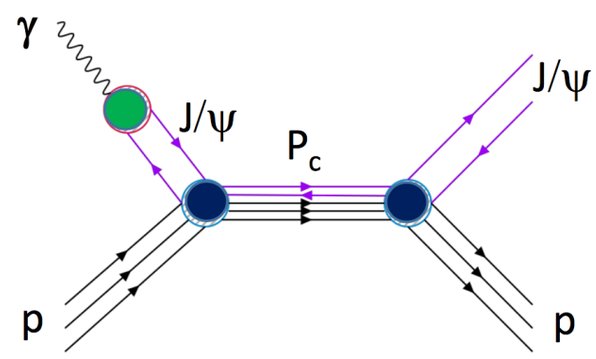
Hadronic molecule

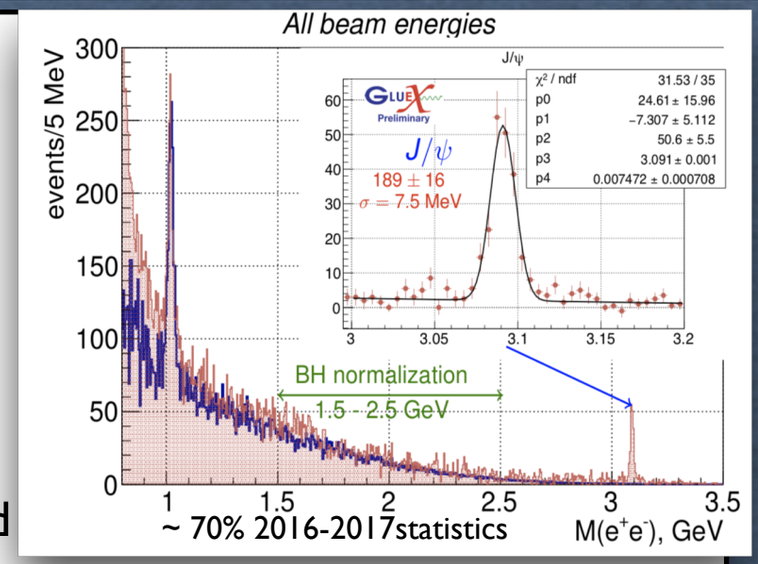


or cusp, triangle singularity, etc…

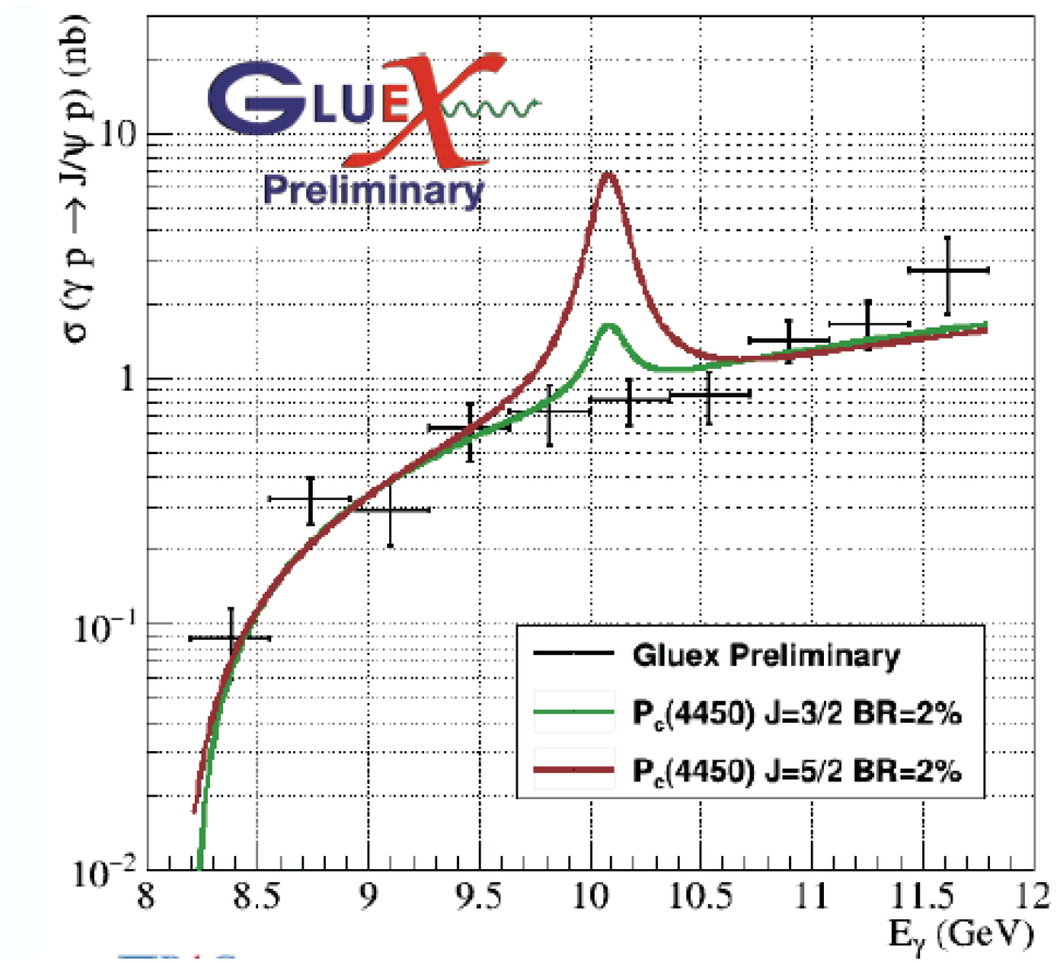
$\Lambda_b \to J/\psi p K^-$







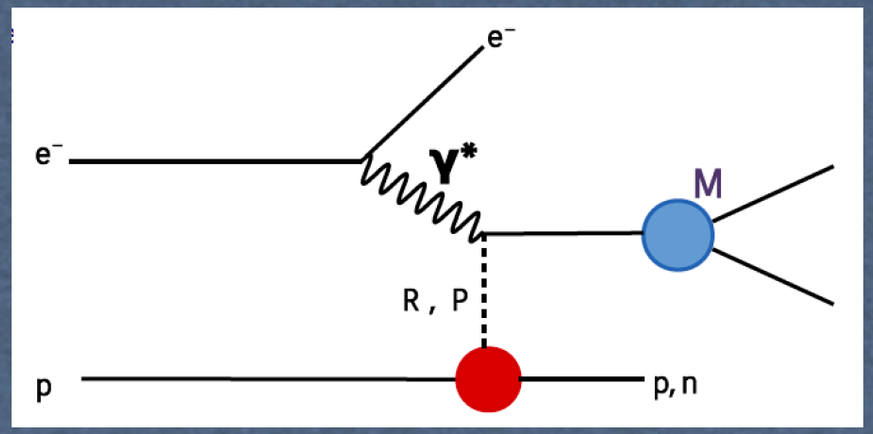
- J/ψ photoproduction at threshold
- Observation of charm at GLUEX
- Projections with CLAS12 shows a significant sensitivity



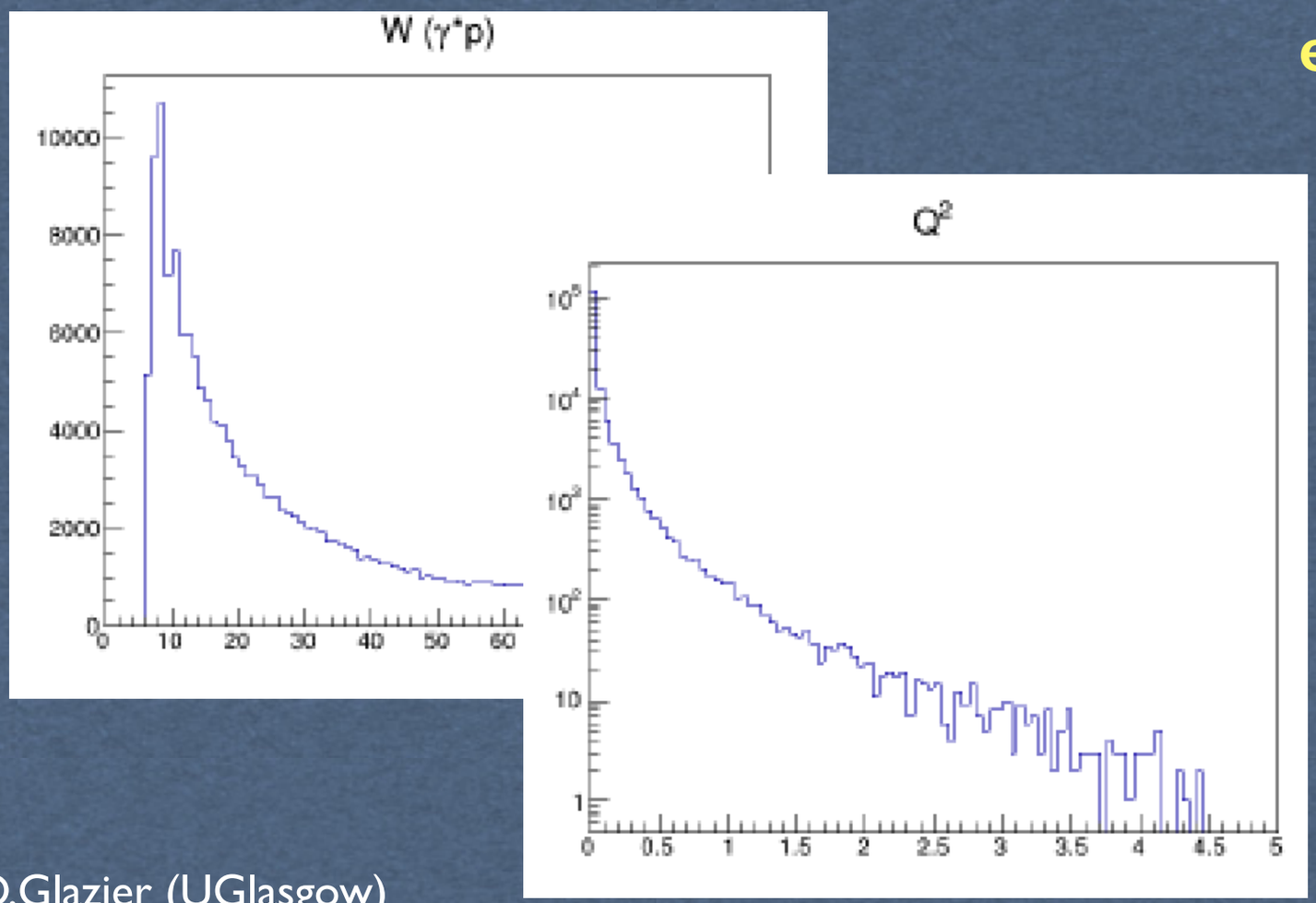
clas

S.Dobbs (FSU)

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-

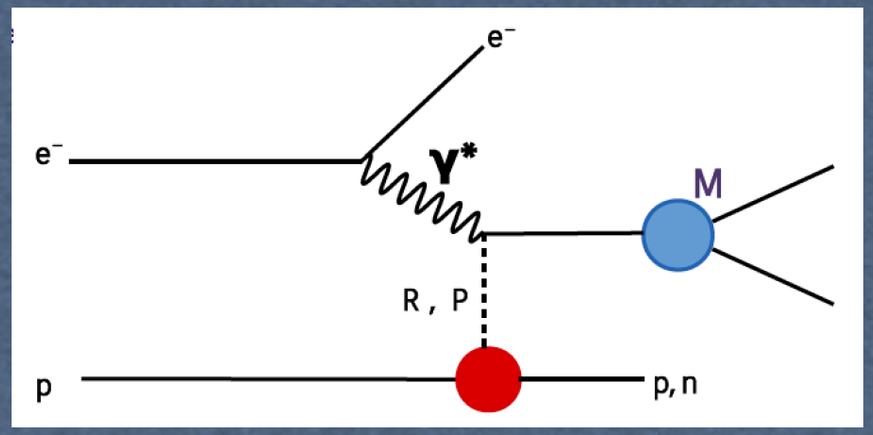


D.Glazier (UGlasgow)

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



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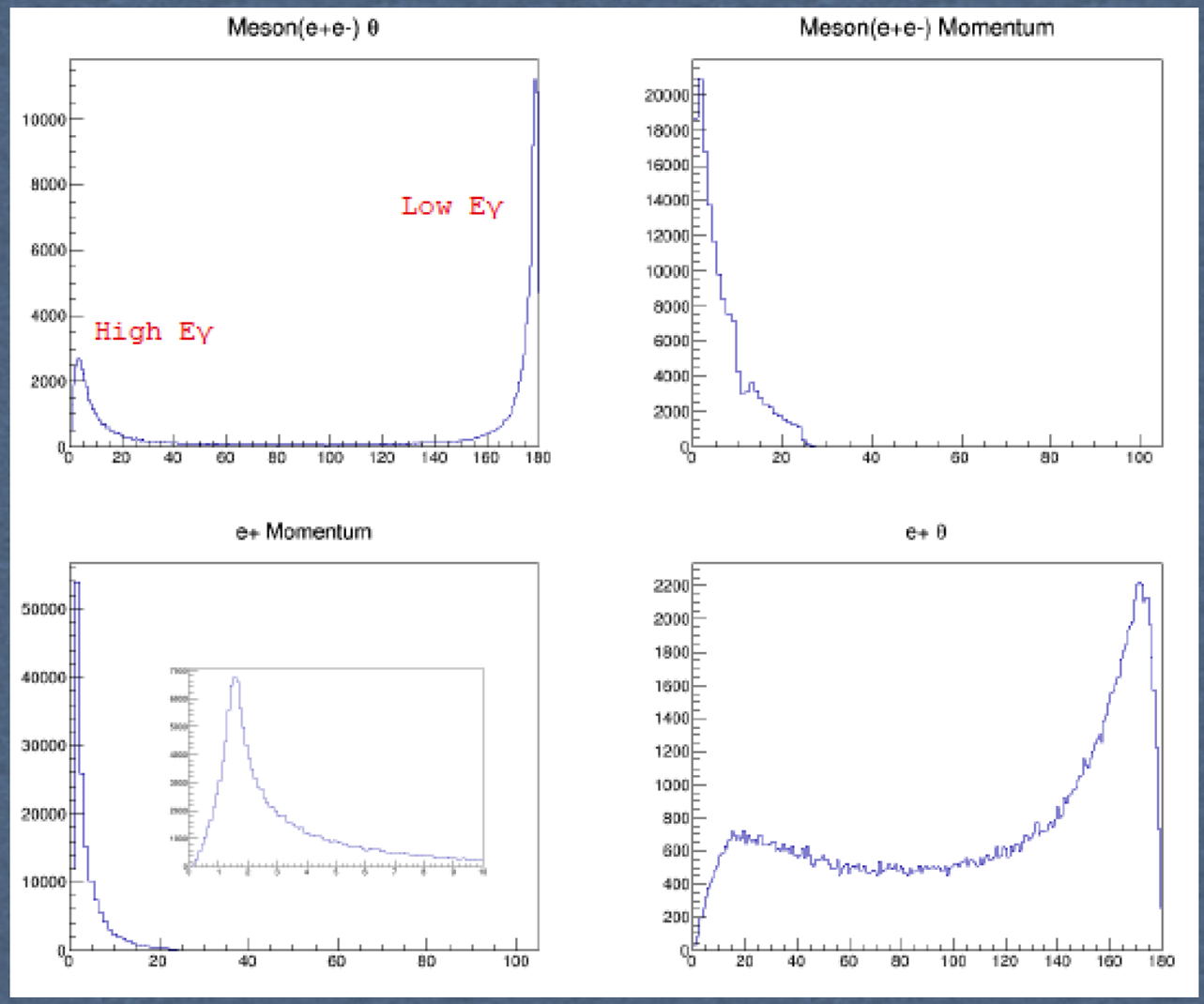
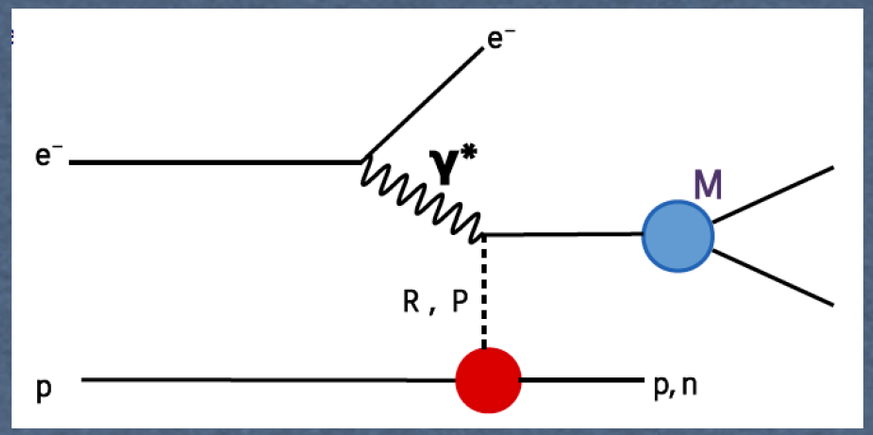
M→e+e- kinematics

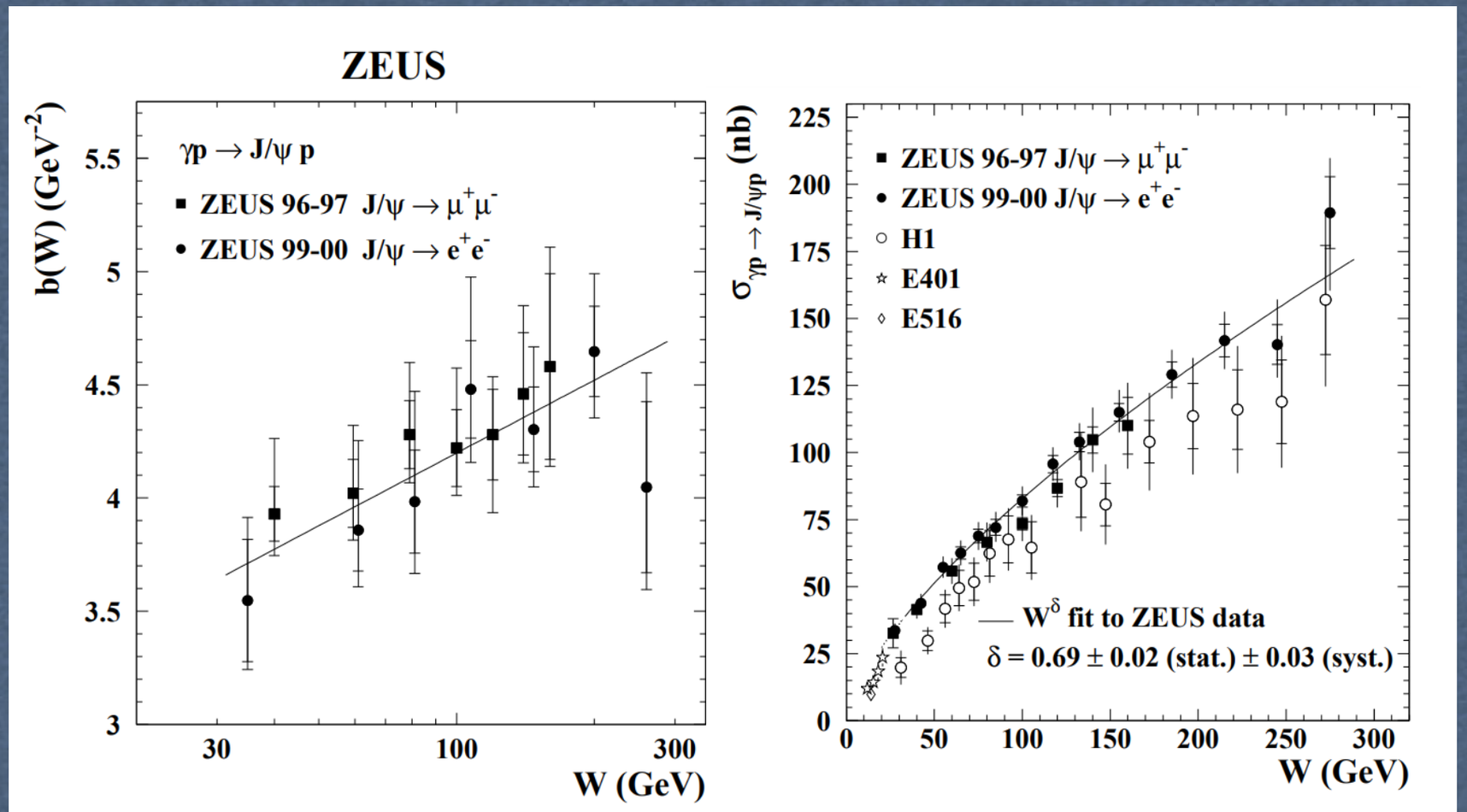


D.Glazier (UGlasgow)

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

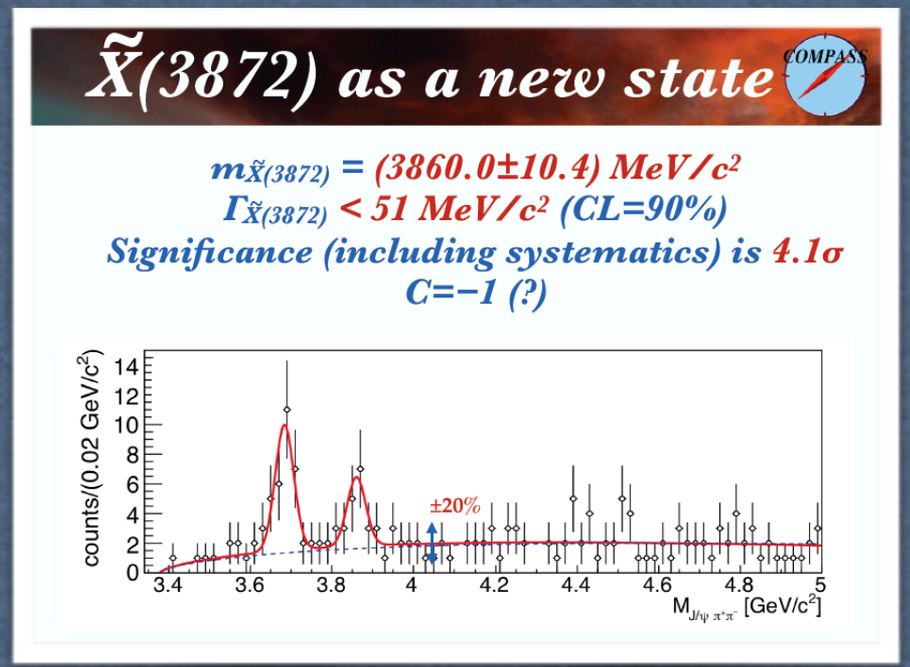


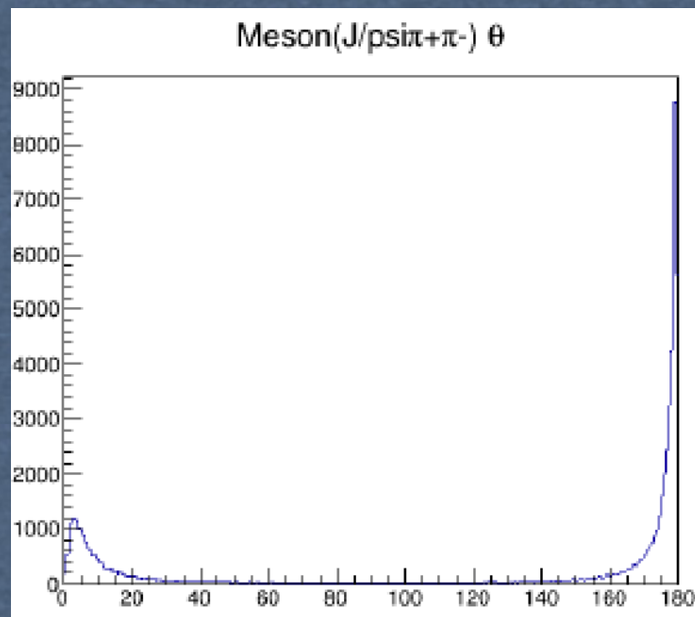
J/Ψ rate = 0.8Hz (~70k events/day)

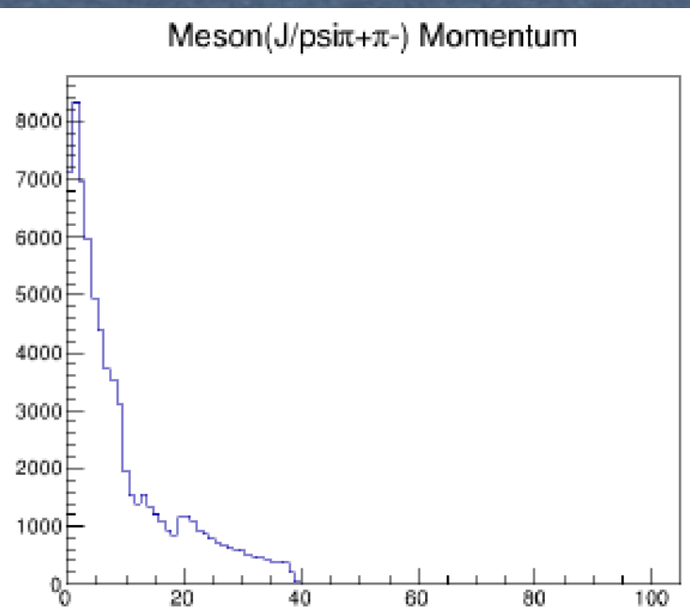
D.Glazier (UGlasgow)

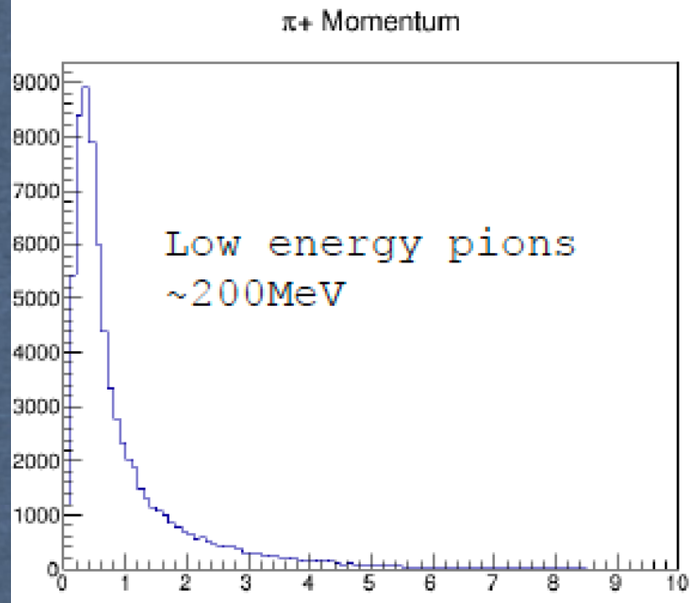
EIC kinematics and yield estimates

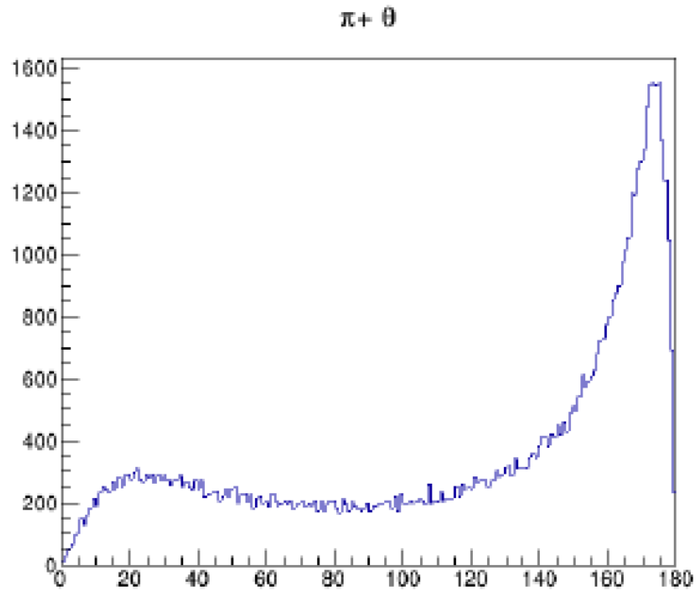
e N → e' (J/Ψ $\pi^+\pi^-$) $\pi^\pm$ N*











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

D.Glazier (UGlasgow)

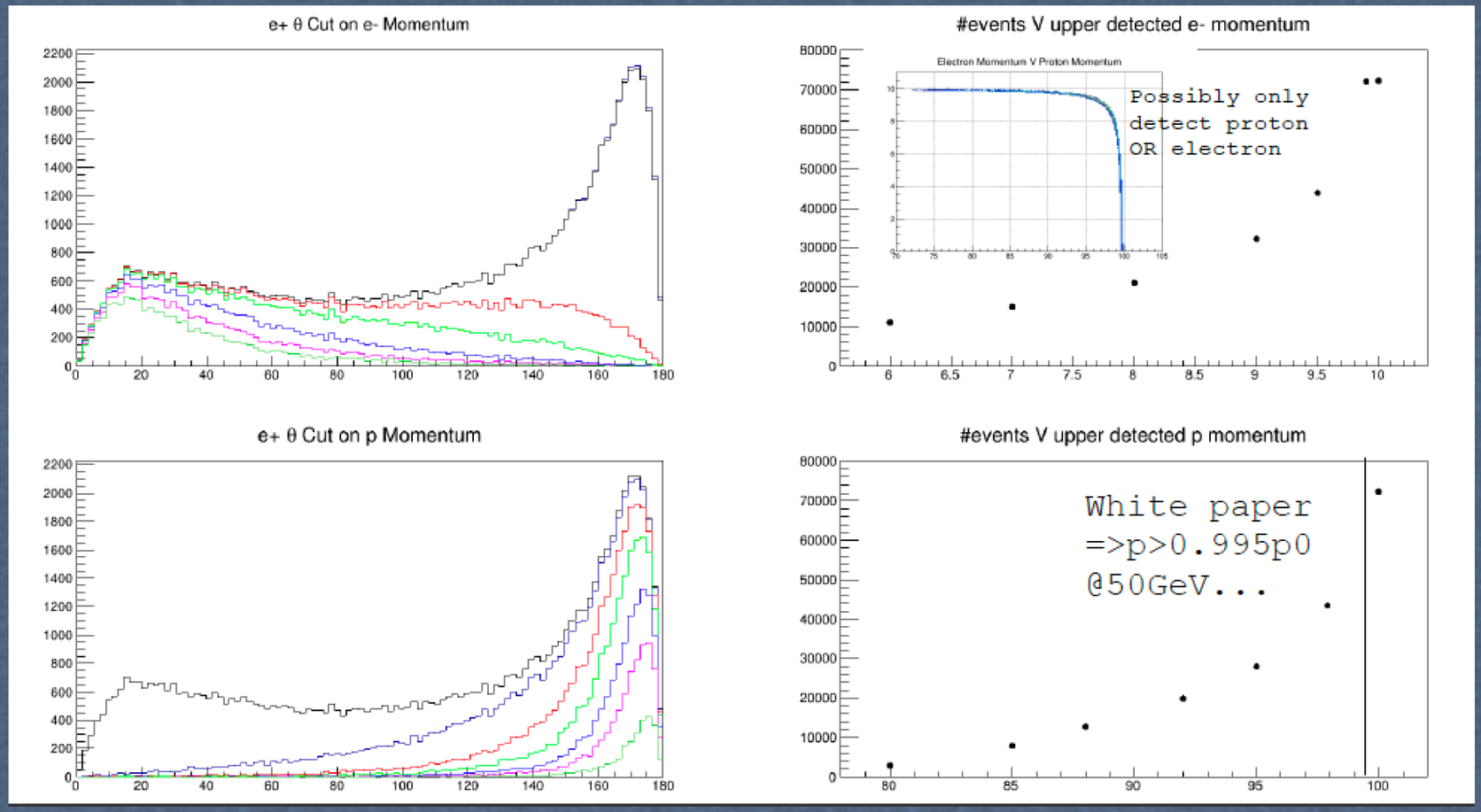
Impact on EIC detectors

Requirements

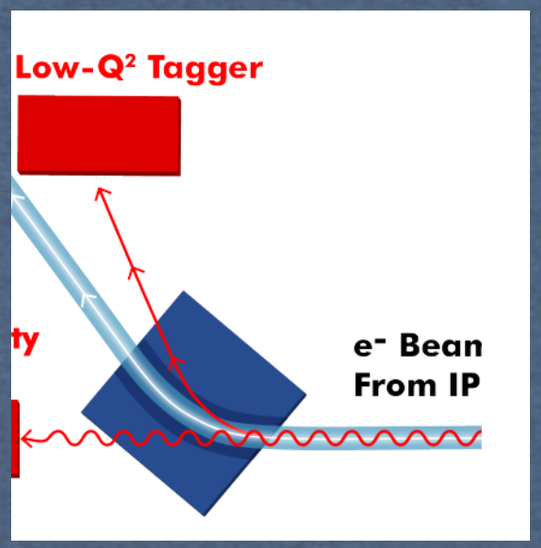
- Scattered electron and proton detection at 0 degrees!
- Far-forward detectors
- Tag scattered particle
- Determine momentum

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?

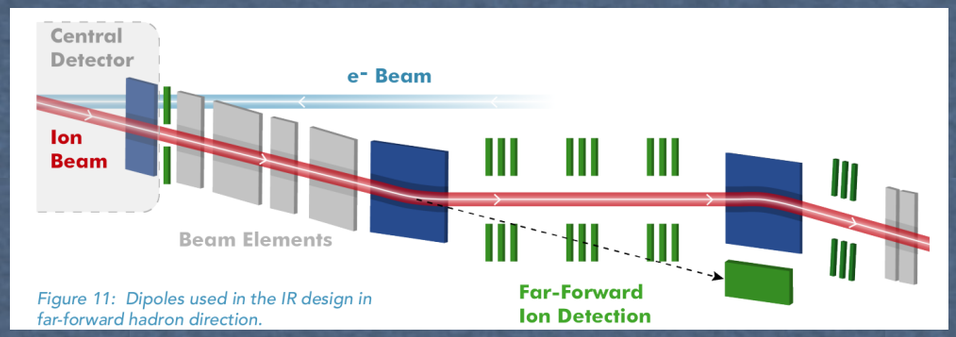
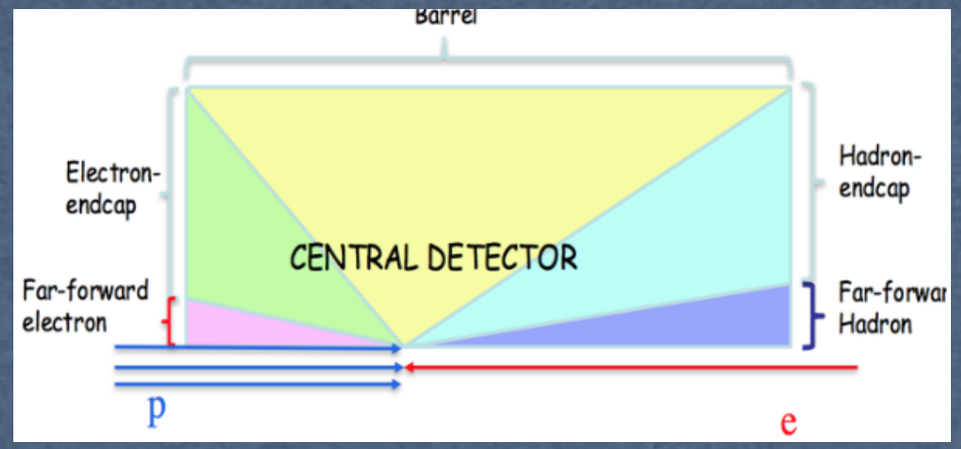
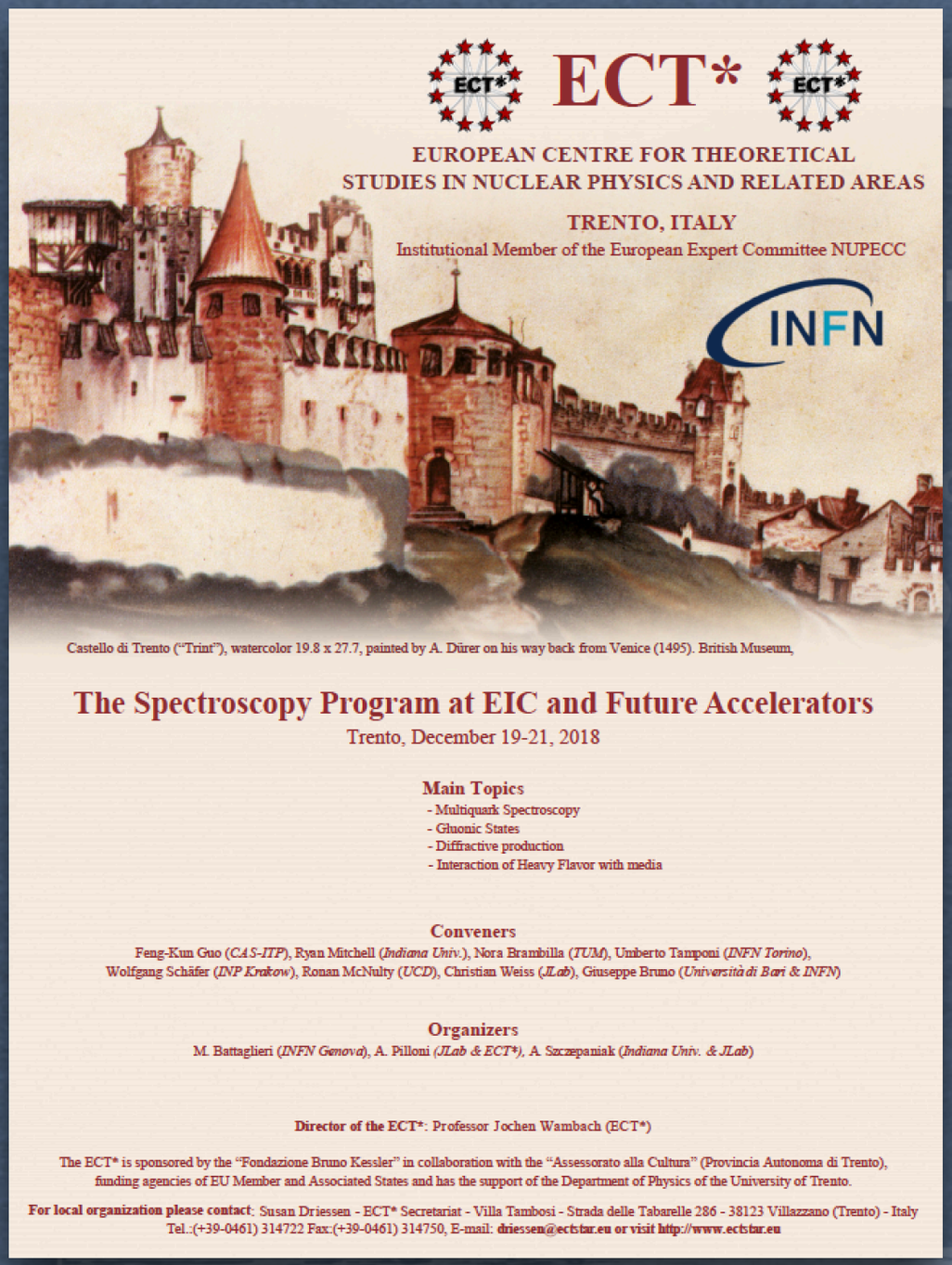


Figure 11: Dipoles used in the IR design in far-forward hadron direction.

Final states detection



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

★ Will meet again in Paris at EICUG2019

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)
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Build the future HS program at EIC joining the effort!

Back up

Heavy Flavours in media

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

Schematic

Initial state	$\leftrightarrow\vert$	Production mechanism	$\leftrightarrow$	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

Diffraction

- Diffractive DIS (DDIS): diffractive dissociation ↔ elastic scattering of a $q\bar{q}$-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