

8th Workshop of the APS Topical Group on Hadronic Physics

GHP 2019

APRIL 10-12, 2019 • DENVER, CO

THE GHP WORKSHOP PROVIDES GREAT OPPORTUNITIES FOR NUCLEAR AND PARTICLE PHYSICISTS TO MEET AND DISCUSS THEIR COMMON INTERESTS IN HADRONIC INTERACTIONS.

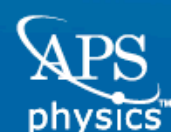
TOPICS INCLUDE:

- Light- and heavy-quark mesons & baryons
- Exotic hadrons
- Transverse and longitudinal structure of hadrons
- Hadron tomography and hadronization
- Neutrino-hadron interactions
- QCD effects in nuclei
- Physics of the quark-gluon plasma
- Physics of gluon saturation
- EFT approaches in hadron physics
- Lattice QCD and other non-perturbative approaches
- Future facilities



PROGRAM COMMITTEE:

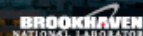
- Abhay Deshpande (Stony Brook University)
- Tanja Horn (Catholic Univ of America)
- Garth Huber (University of Regina) (co-chair)
- Spencer Klein (Lawrence Berkeley National Lab)
- Swagato Mukherjee (Brookhaven National Lab)
- Paul Reimer (Argonne National Lab)
- David Richards (Jefferson Lab) (chair)
- Susan Schadmand (Forschungszentrum Juelich)
- Anne Sickles (University of Illinois at Urbana-Champaign)
- Ramona Vogt (Lawrence Livermore National Lab and UC Davis)



The workshop immediately precedes the APS April Meeting 2019 and will take place at the same venue.

contact: ghpworkshops@gmail.com

www.aps.org/units/ghp/meetings/meeting.cfm?name=GHP19



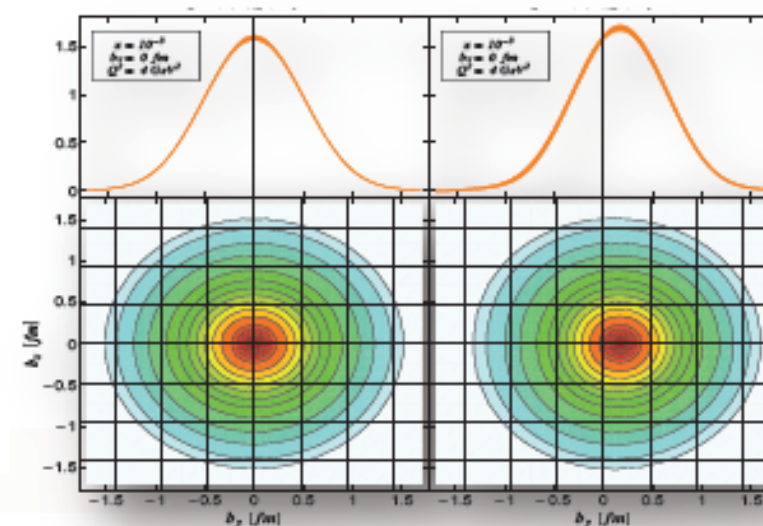
Light and heavy quark spectroscopy at EIC

M.Battaglieri
INFN -GE
Italy

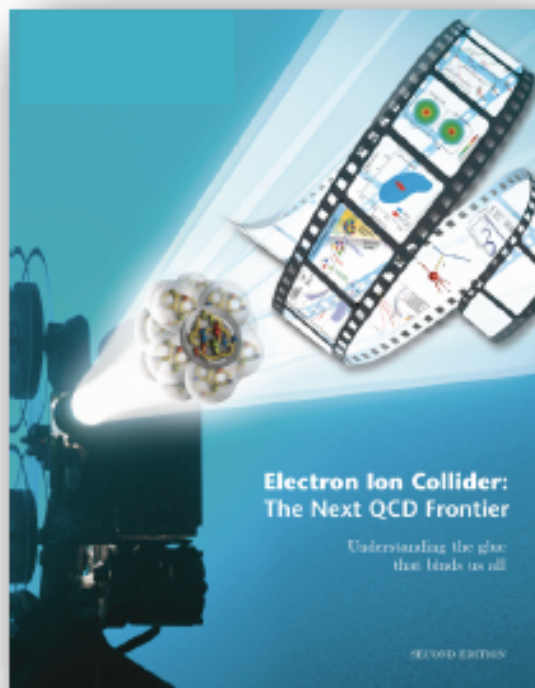
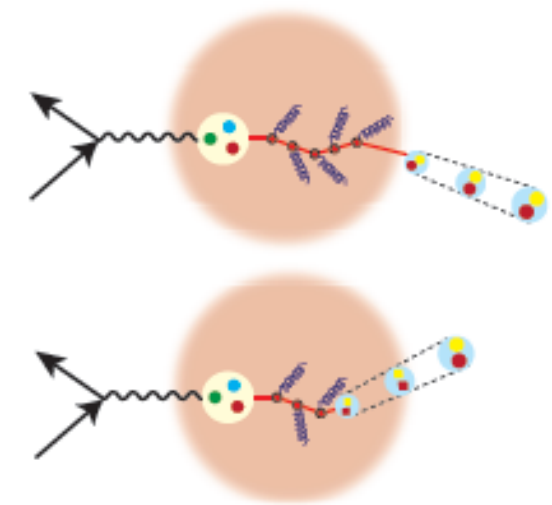
The EIC physics (so far ...)

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

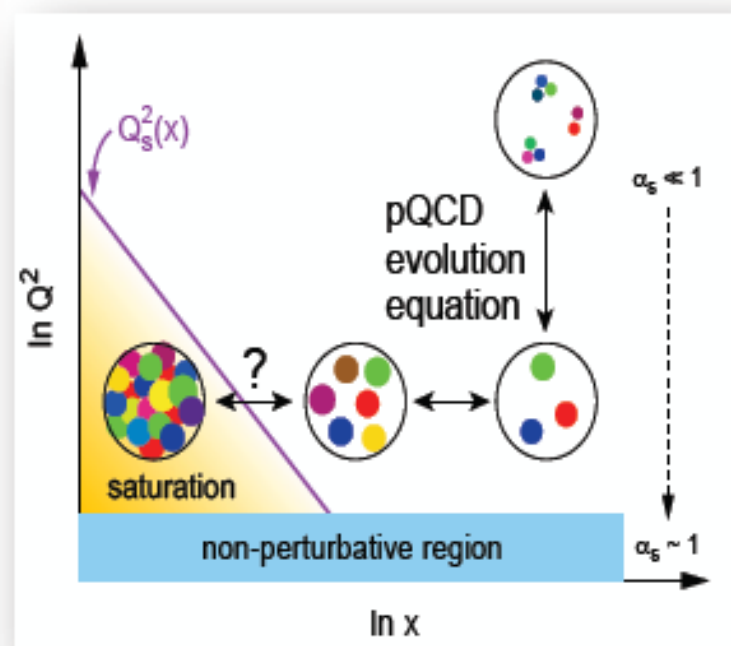
3D Imaging of Nucleon Structure



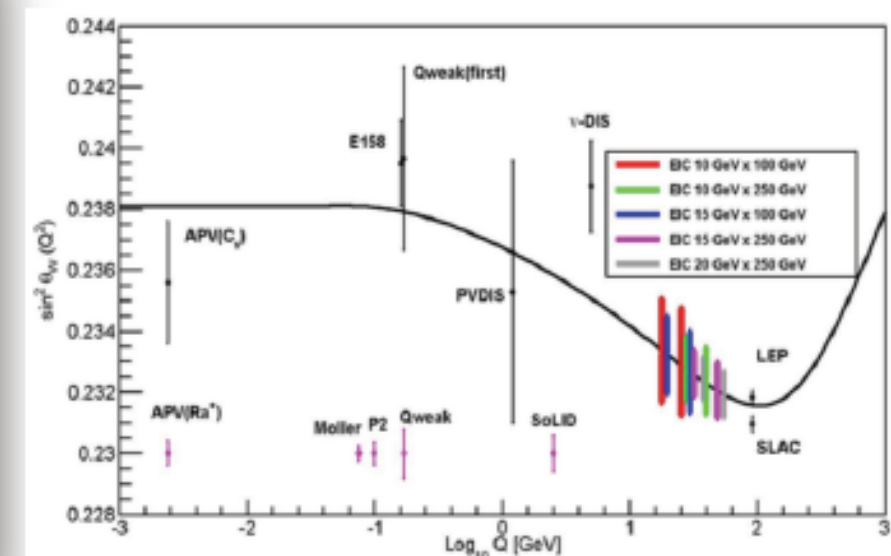
Hadronization in cold QCD matter



Gluon Saturation

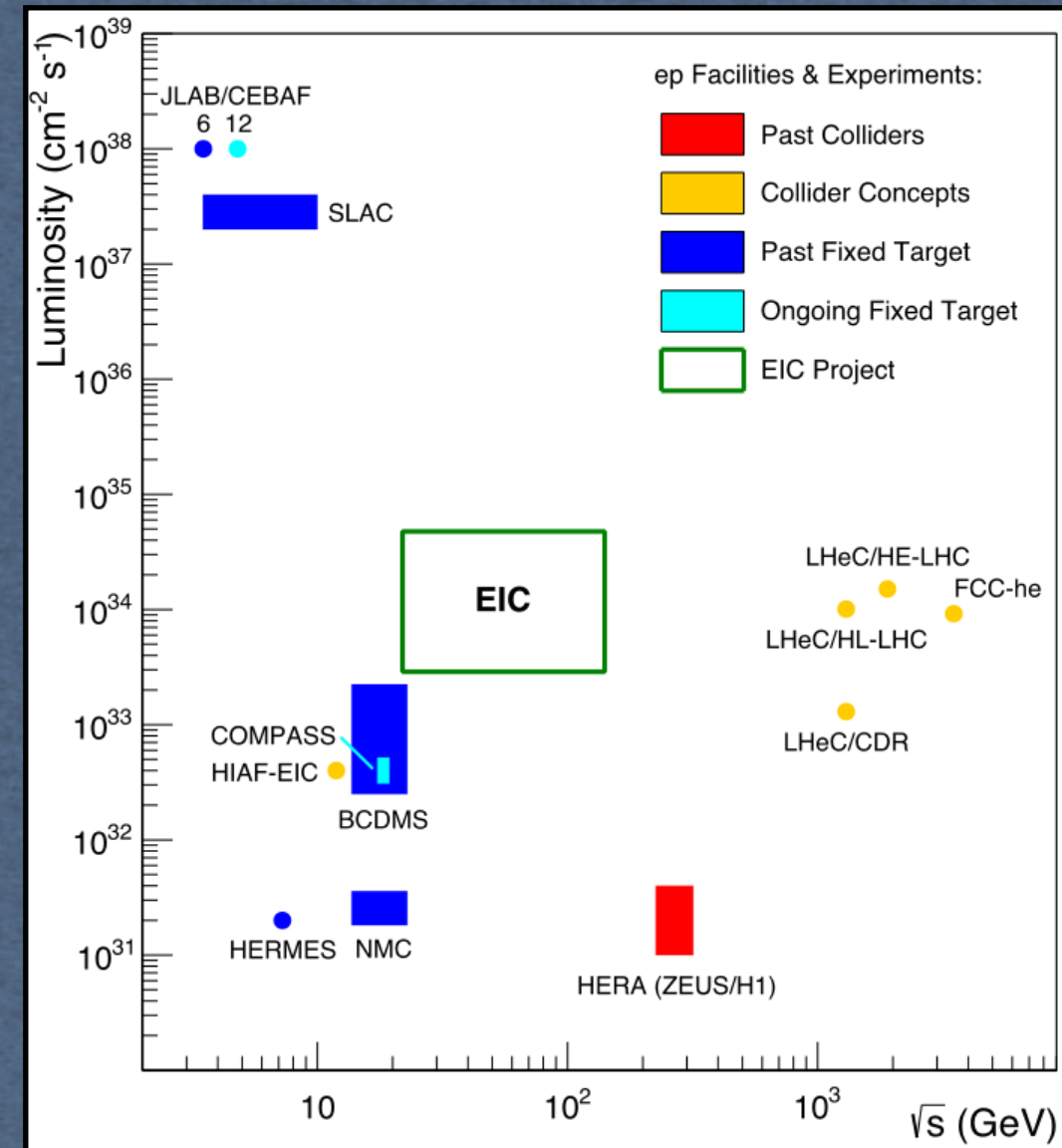


EW Physics

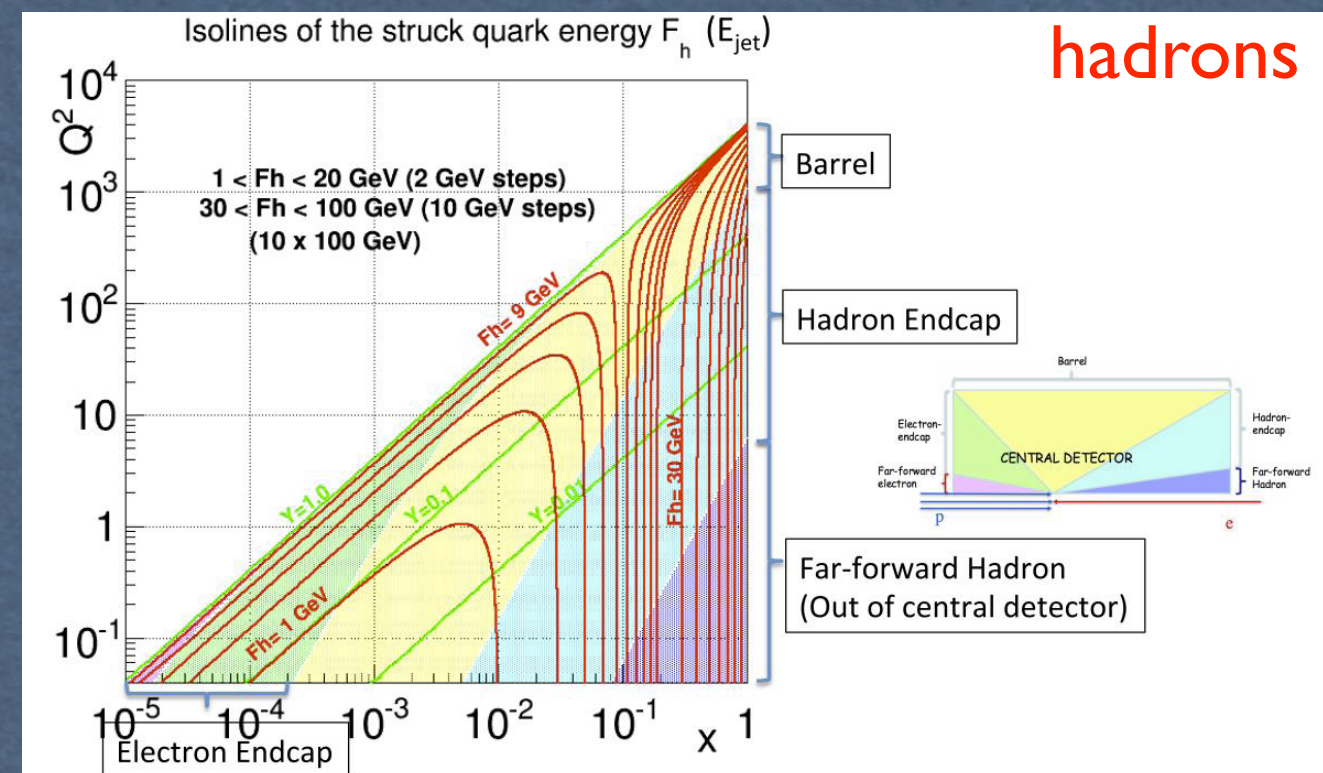
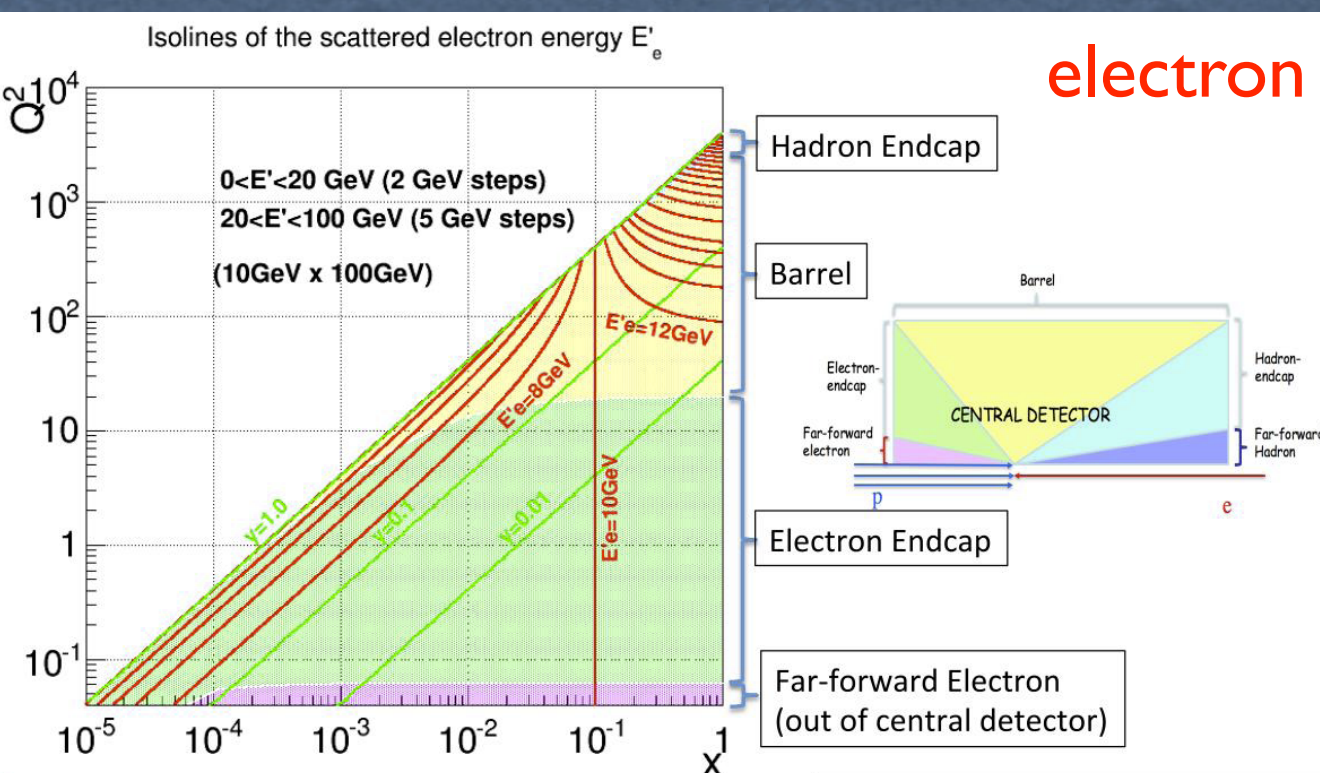
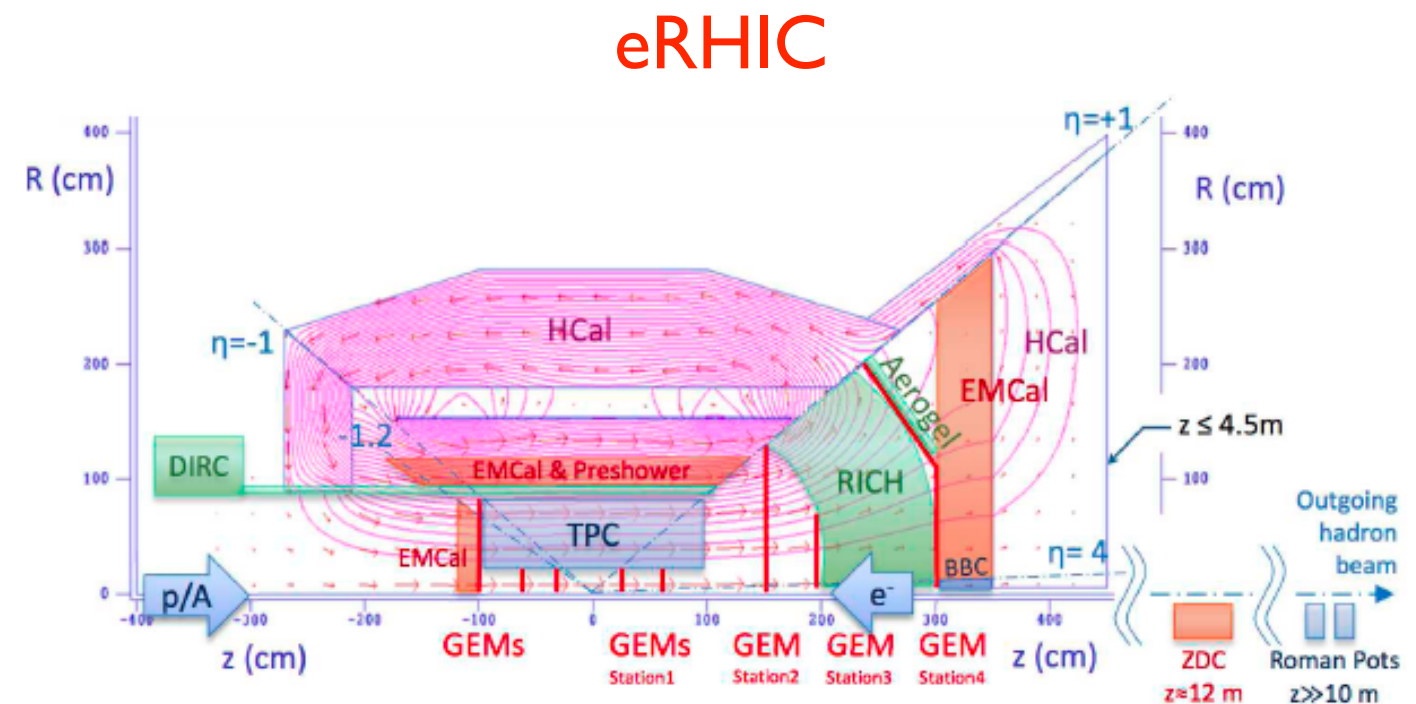
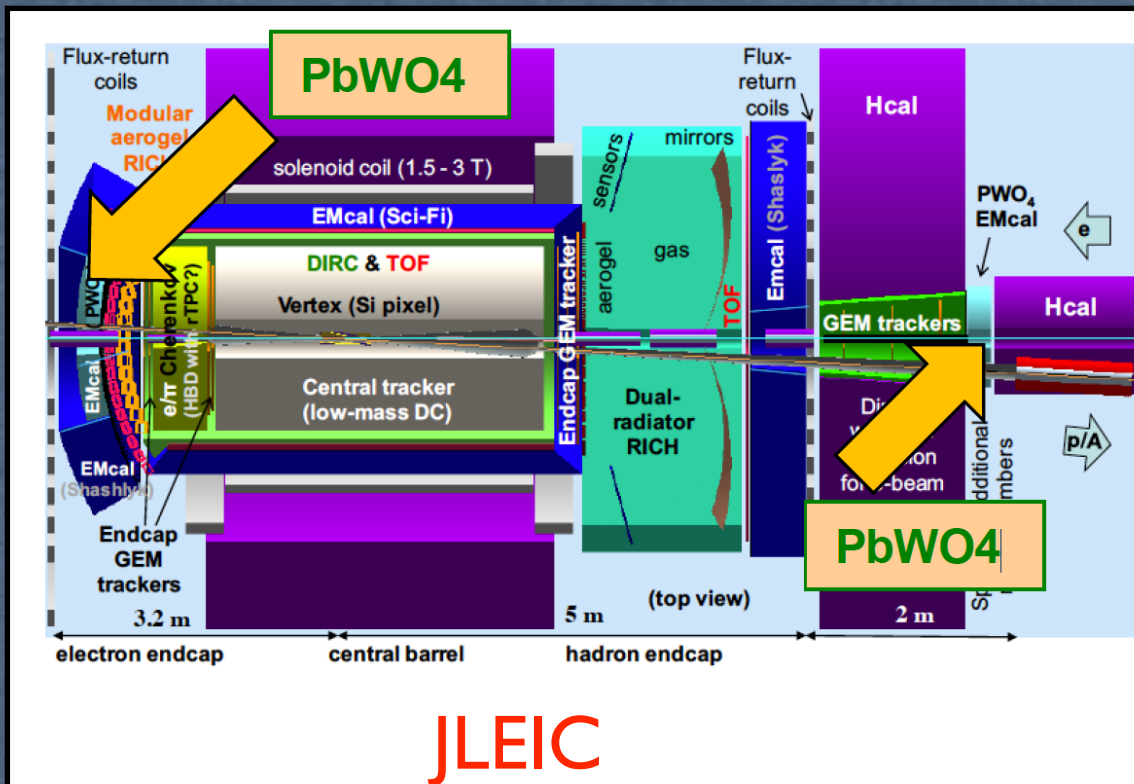


EIC and the other facilities

- **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 ($p \rightarrow U$)**
 - 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



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) Heavy flavours (open and hidden) to probe nuclear medium
- III) Diffractive physics

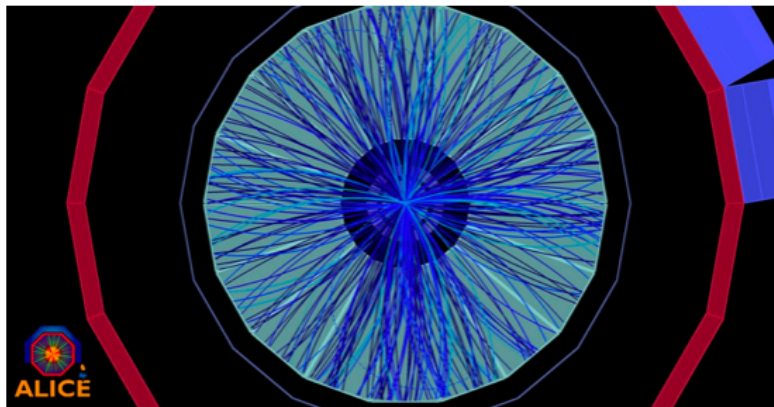


Opportunities



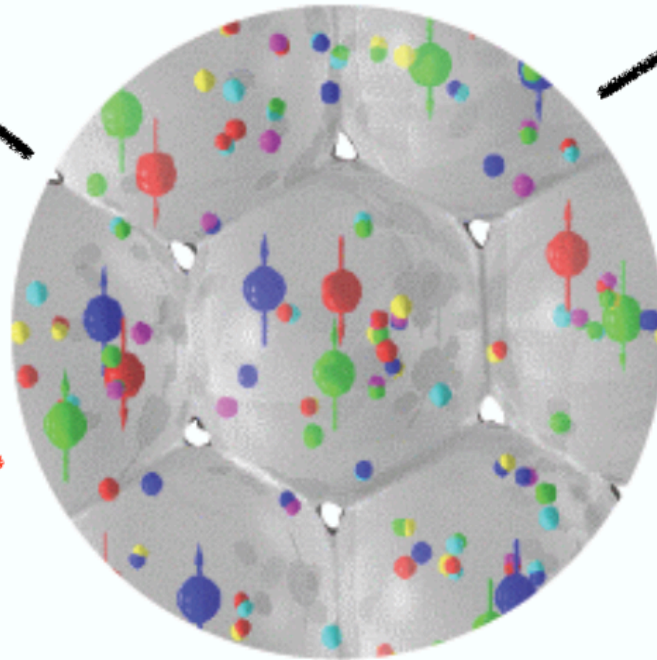
Requirements

Hadron spectroscopy at EIC

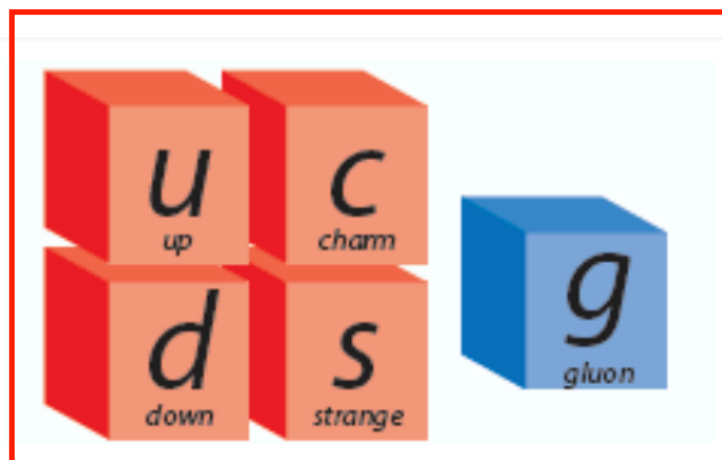
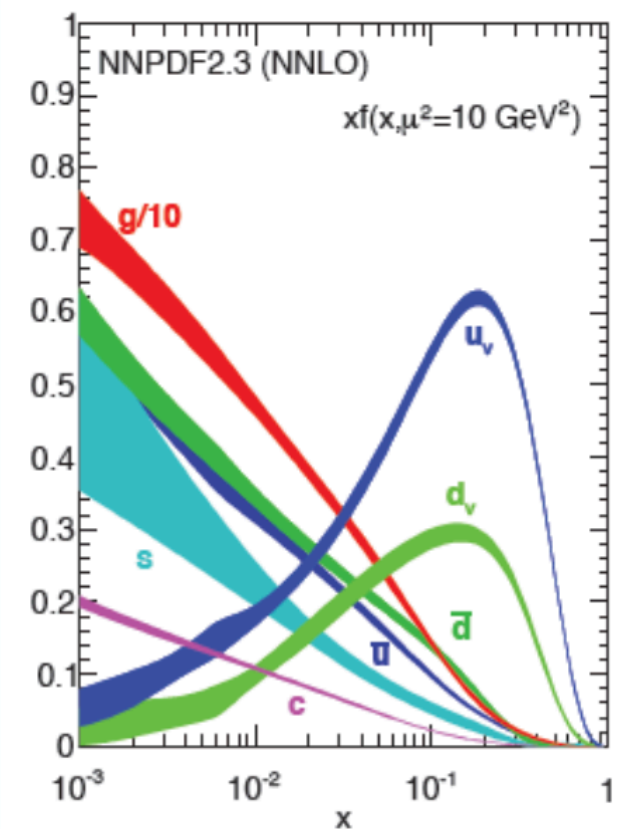


melt it!

Nuclear matter

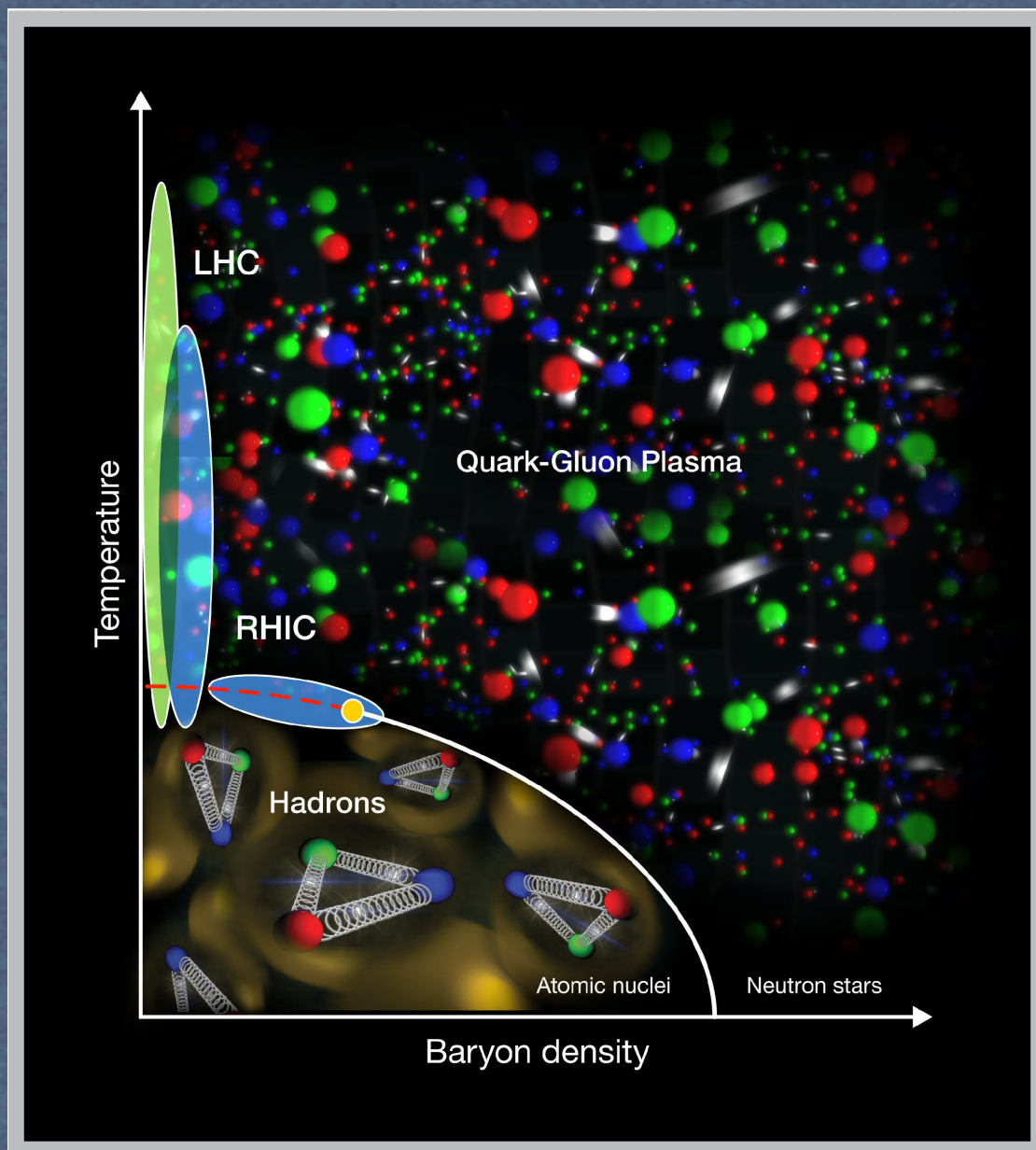


use a microscope
(nucleon structure)



produce and study known and new states:
Hadron Spectroscopy

Hadron spectroscopy at EIC

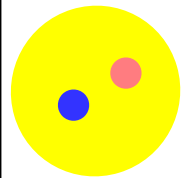


- ★ Meson and baryon spectroscopy as a tool to study QCD phases
- ★ Color confinement
- ★ manifestation of gluonic degrees of freedom
- ★ non-perturbative dressing effects
- ★ gluon-gluon interaction
- ★ confinement
- ★ light- q vs heavy- q

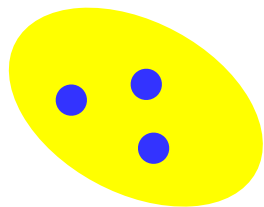
Significant world-wide effort: COMPASS, JLab BES-III, LHCb, ALICE, BELLE

Hadron spectroscopy at EIC

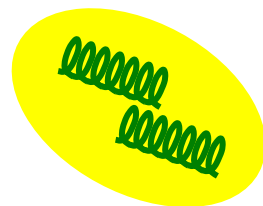
Meson



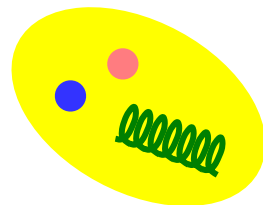
Baryon



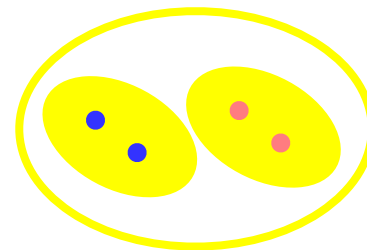
Glueball



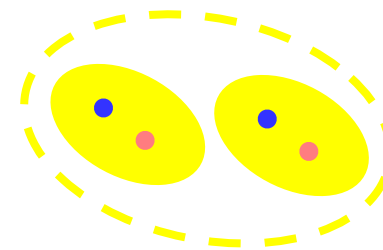
Hybrids



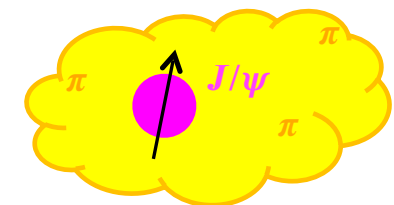
Tetraquark



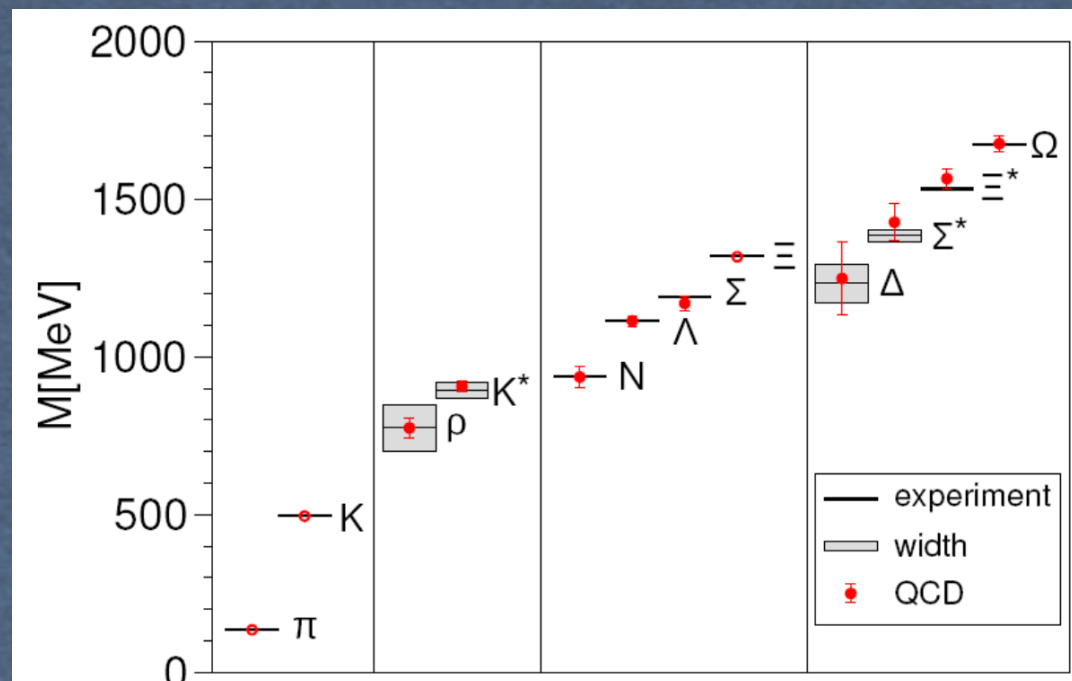
Molecule



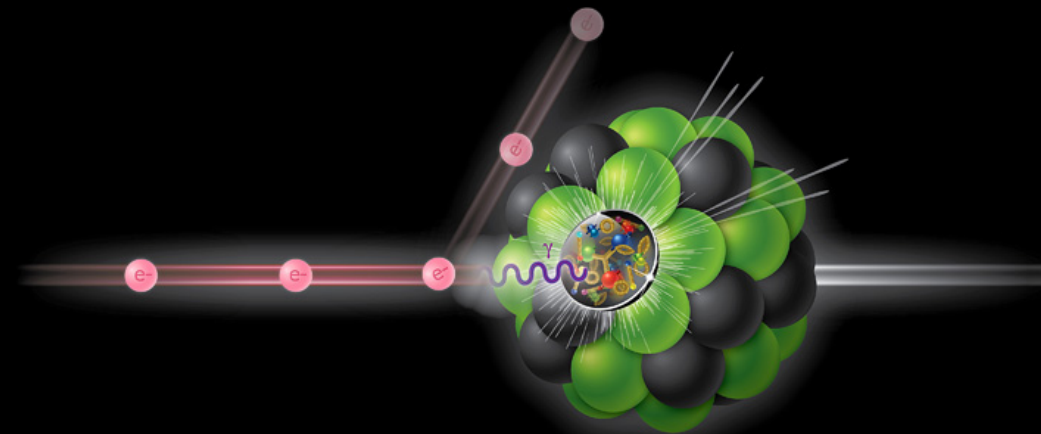
Hadroquarkonium



Science (2008)



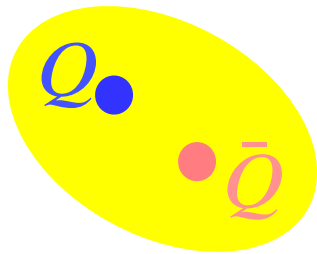
Observed mesons and baryons well described by 1st principles QCD



«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



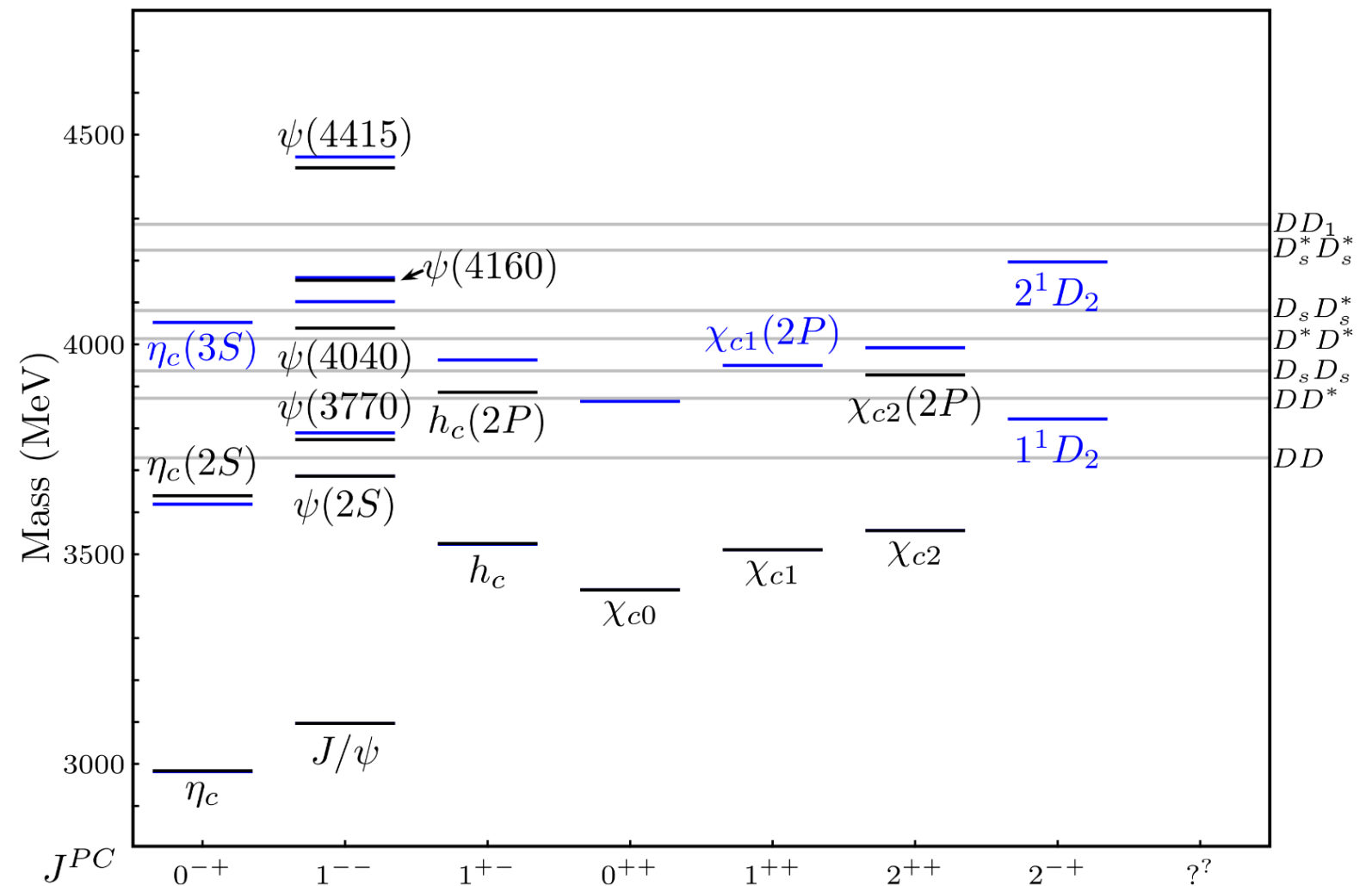
Potential models
(when)

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

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

Integrate out heavy DOF

↓
(spectrum), decay
& production rates

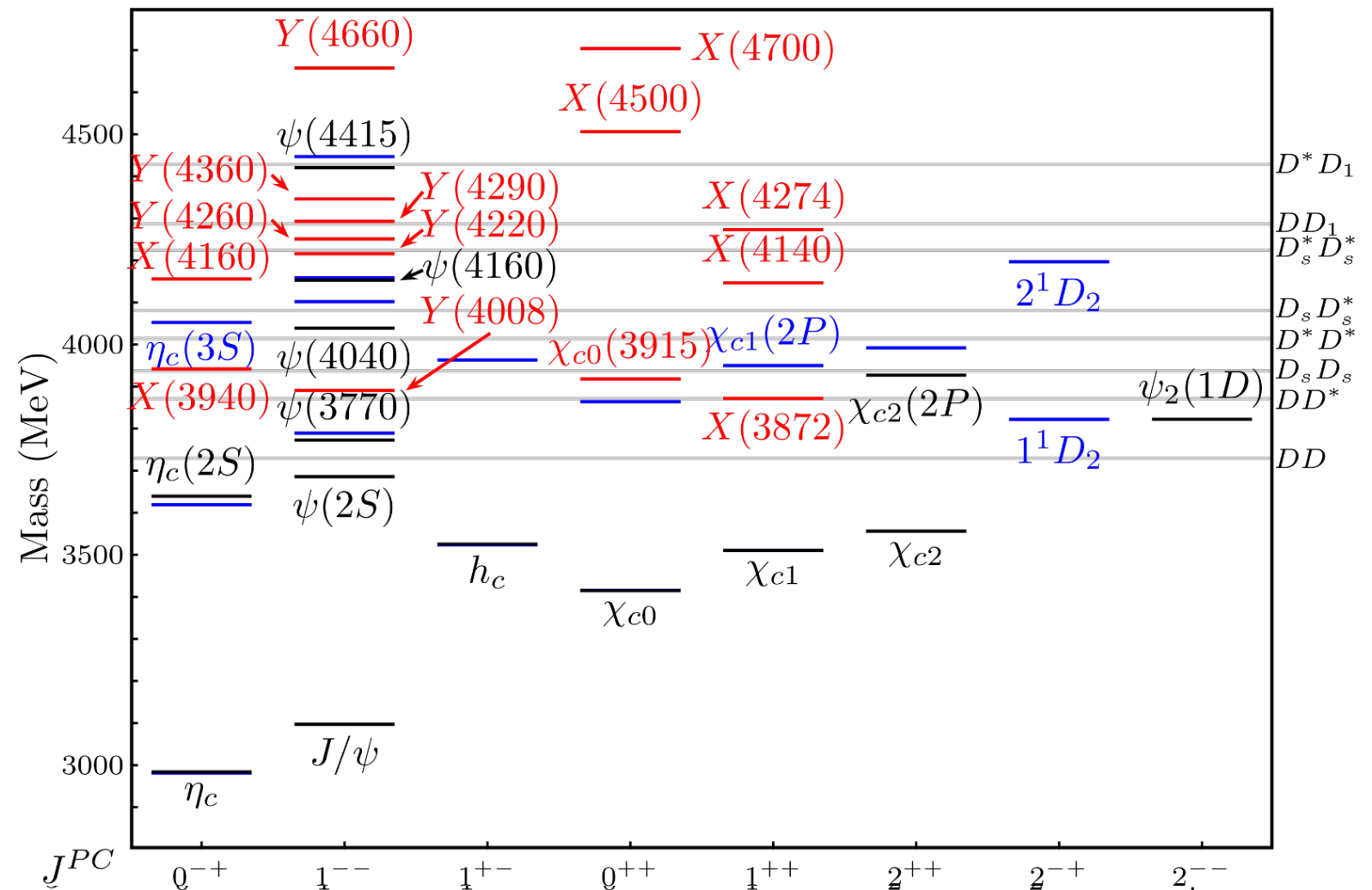


XYZ exotics

A host of new and unexpected resonances have appeared

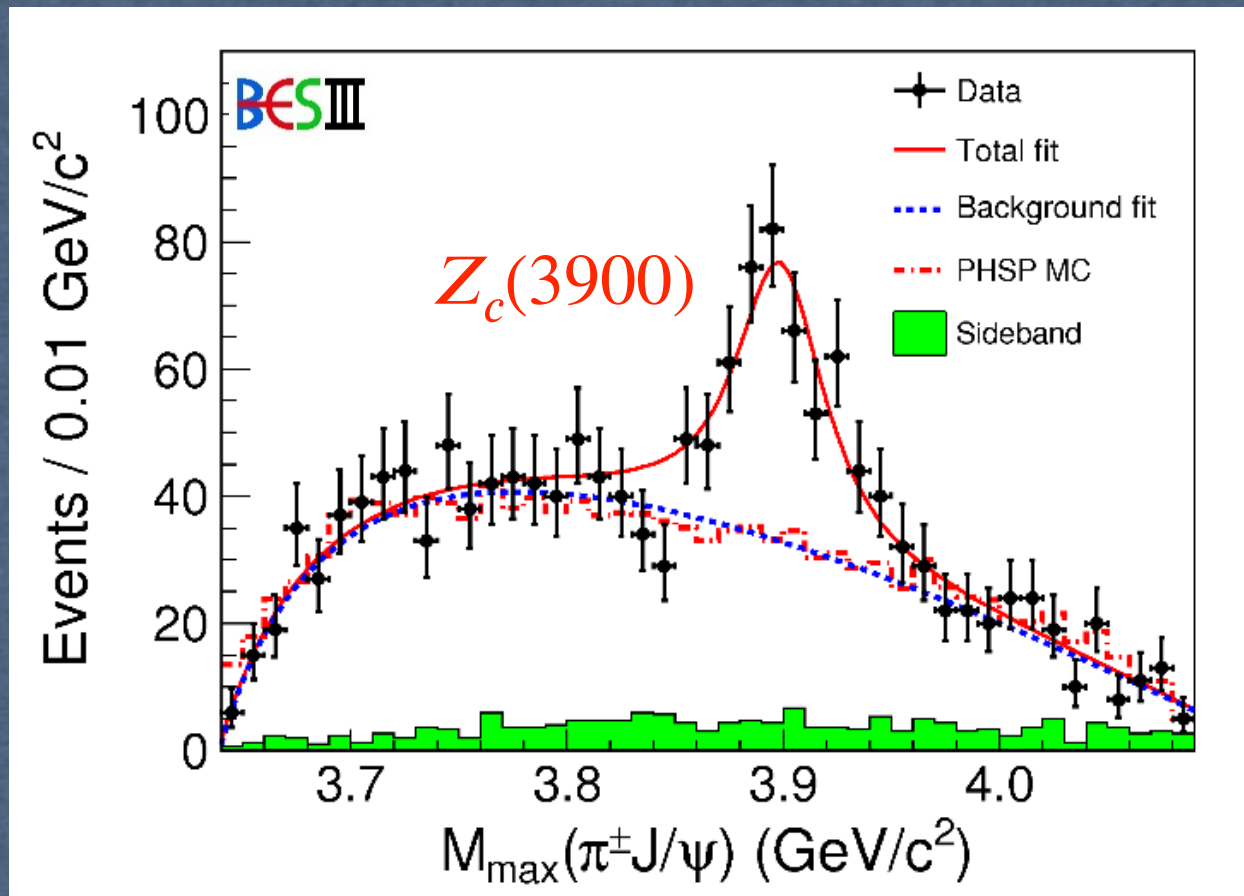
Preferred decay: charmonium + light

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

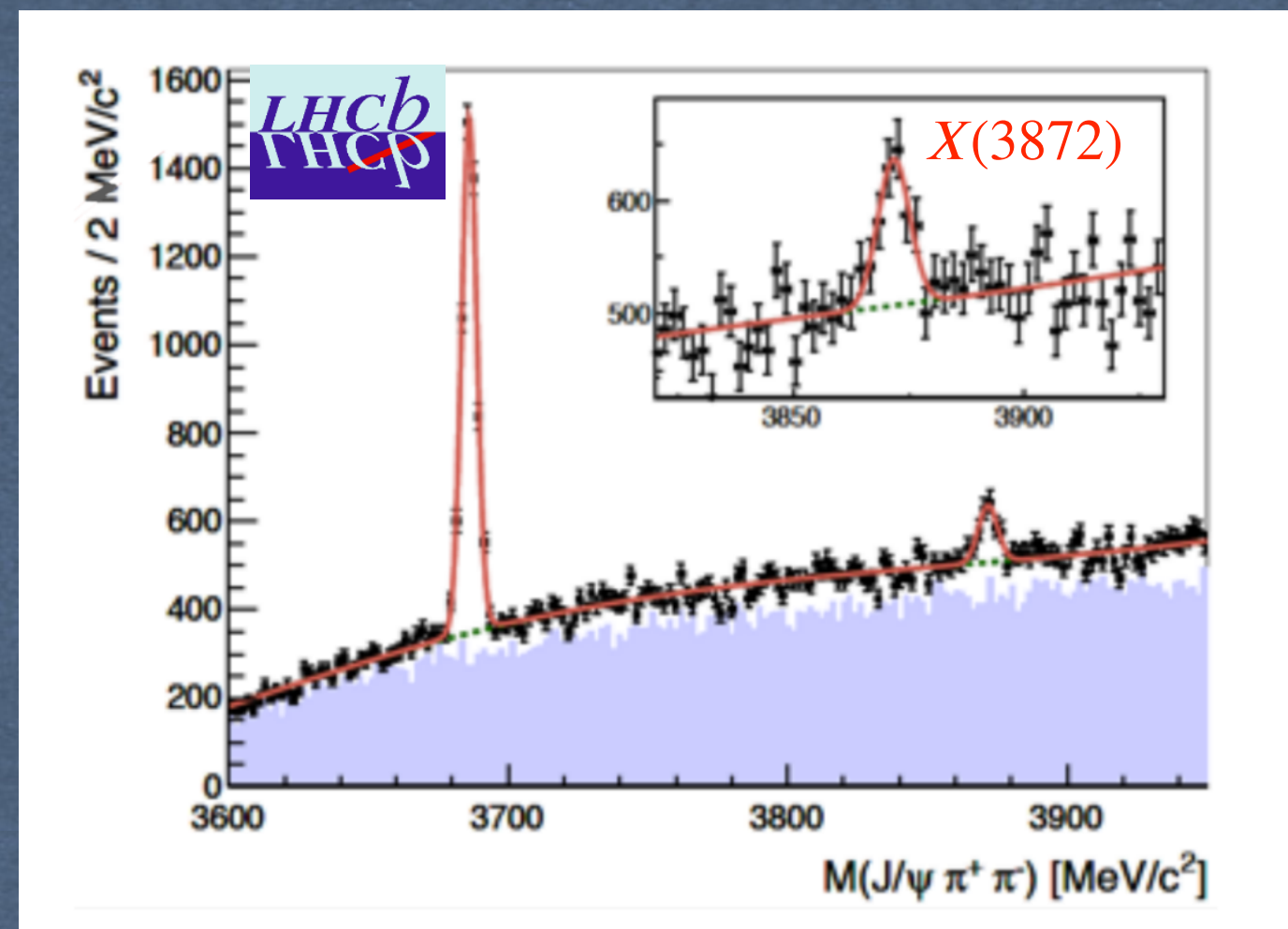


- Many new states in the charmonium sector
- Convincing evidence of new exotic hadronic states
- Probably, more to come
- Bottomonium almost unexplored

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

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

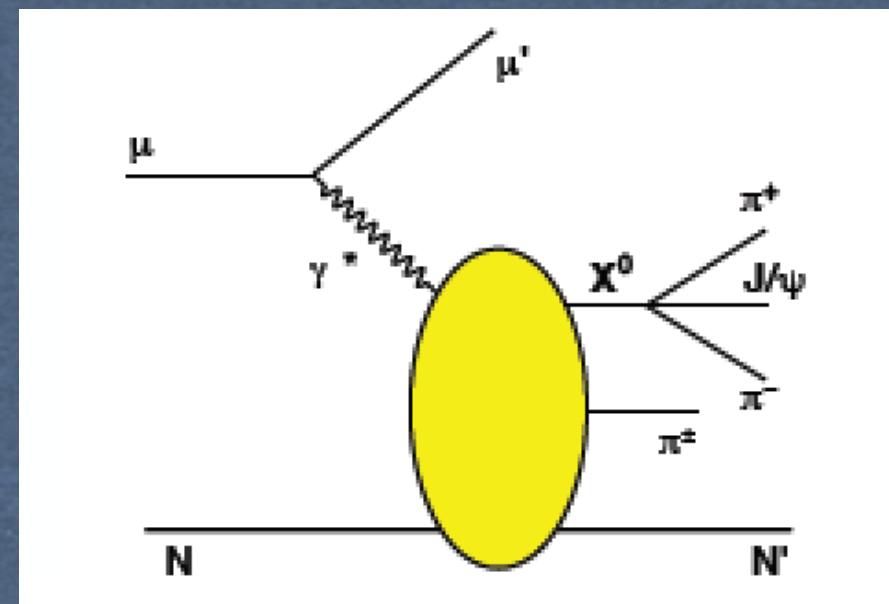
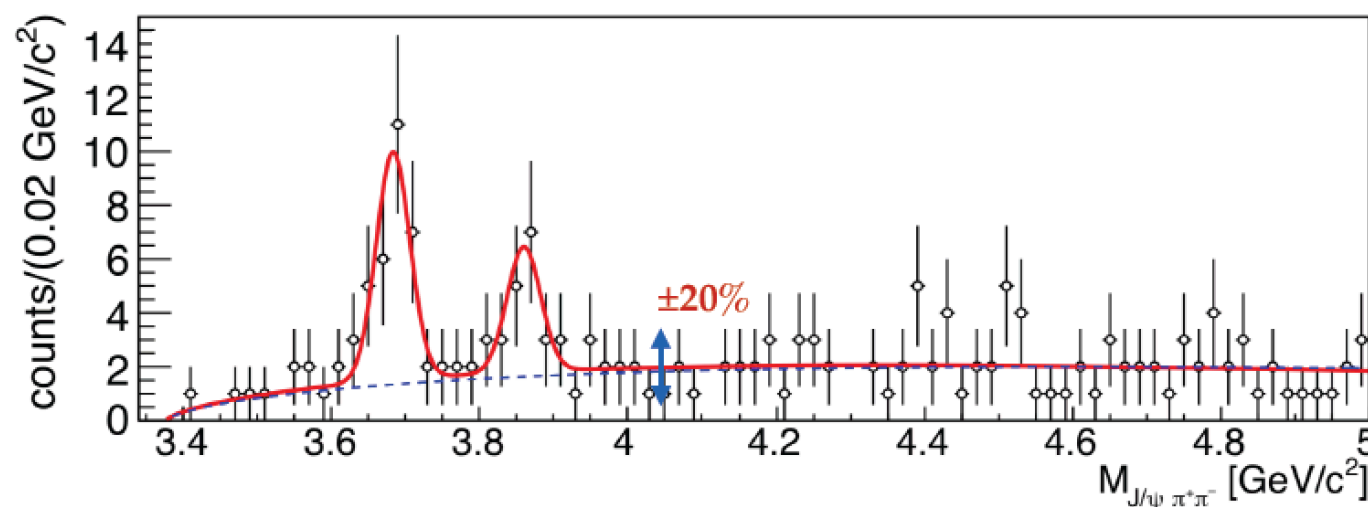
$\tilde{X}(3872)$ as a new state

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

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

Significance (including systematics) is 4.1σ

$$C = -1 \text{ (?)}$$



At COMPASS conditions:

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

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

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

~10 events per day

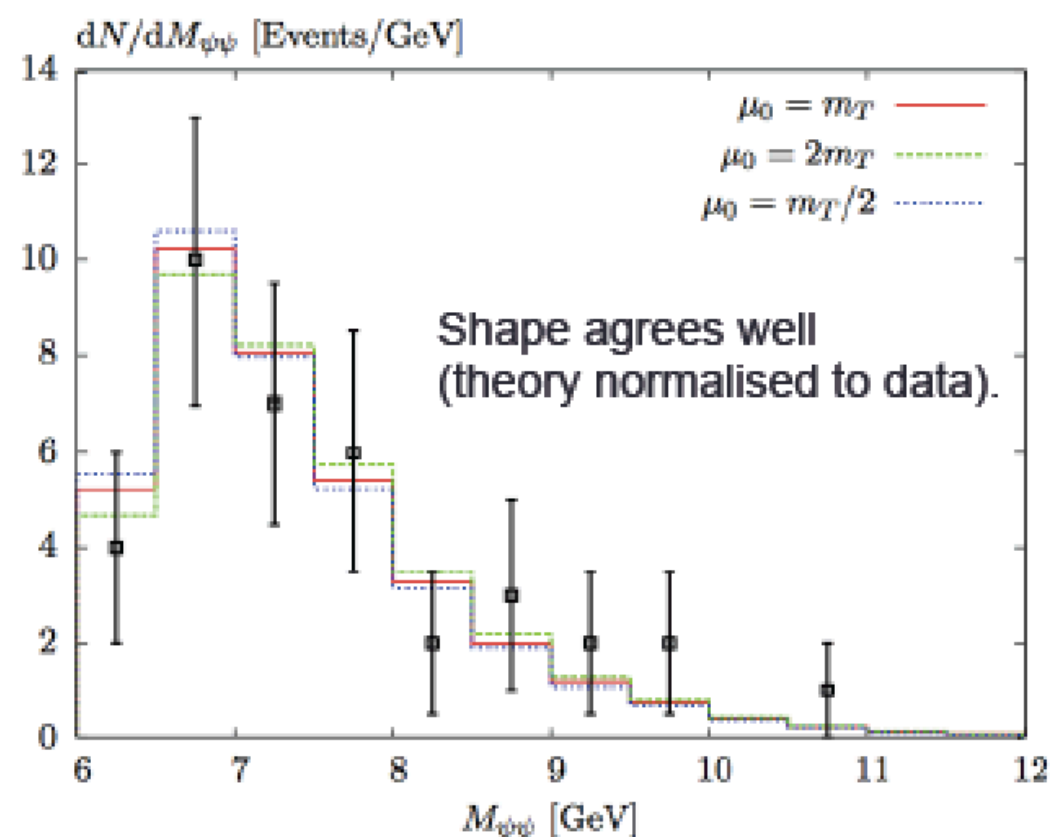
A.Guskov (JINR)



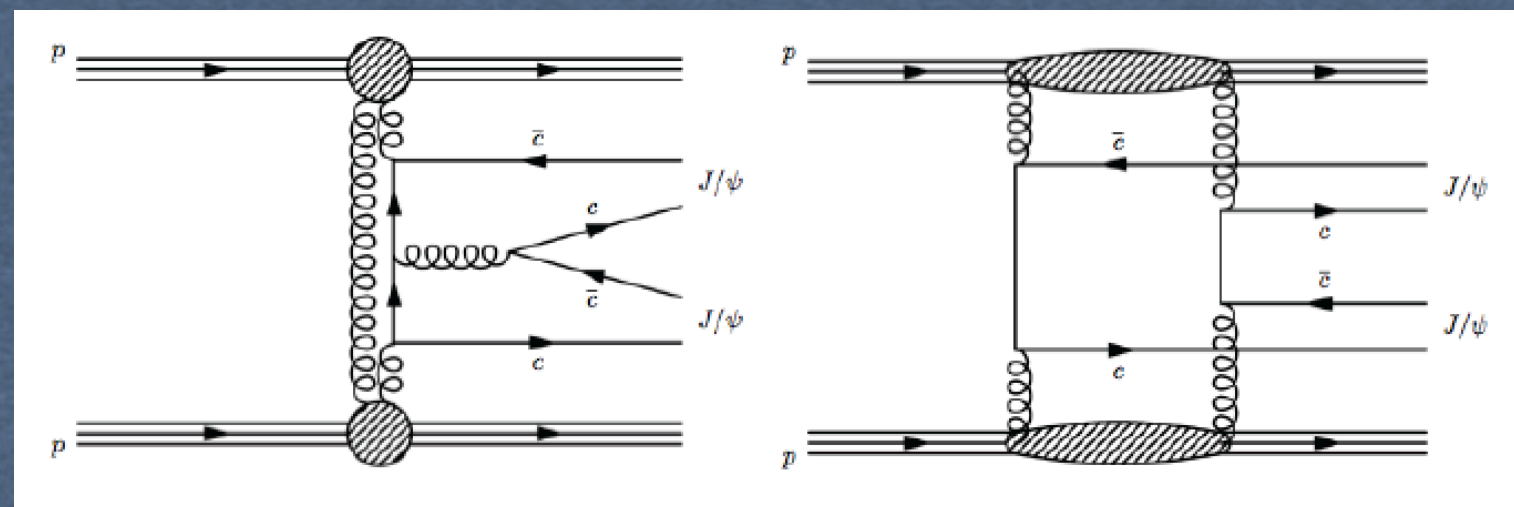
- * Tetraquarks
- * (light) hybrids
- * Glueballs
- * Odderon

Double J/ψ production

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



Exotica at LHCb



EIC may produce such states through gamma-gamma collisions

LHC
High Energy
Medium/High Luminosity
High Backgrounds

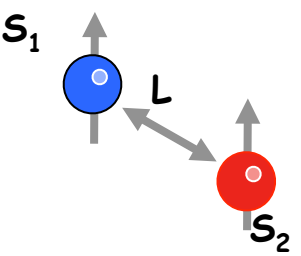


EIC
Low Energy
High Luminosity
Low Backgrounds
(detector design)

The light quark meson spectrum

Constituent Quark Model

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

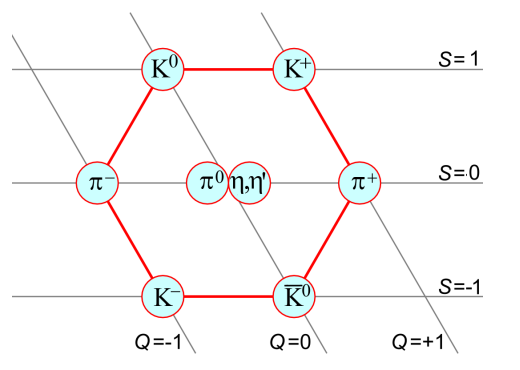


$S = S_1 + S_2$ $J = L + S$
 $P = (-1)^{L+1}$ $C = (-1)^{L+S}$

Not all the J^{PC} combinations are allowed:
 0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} 3^{+-} 3^{-+} 3^{--} ...

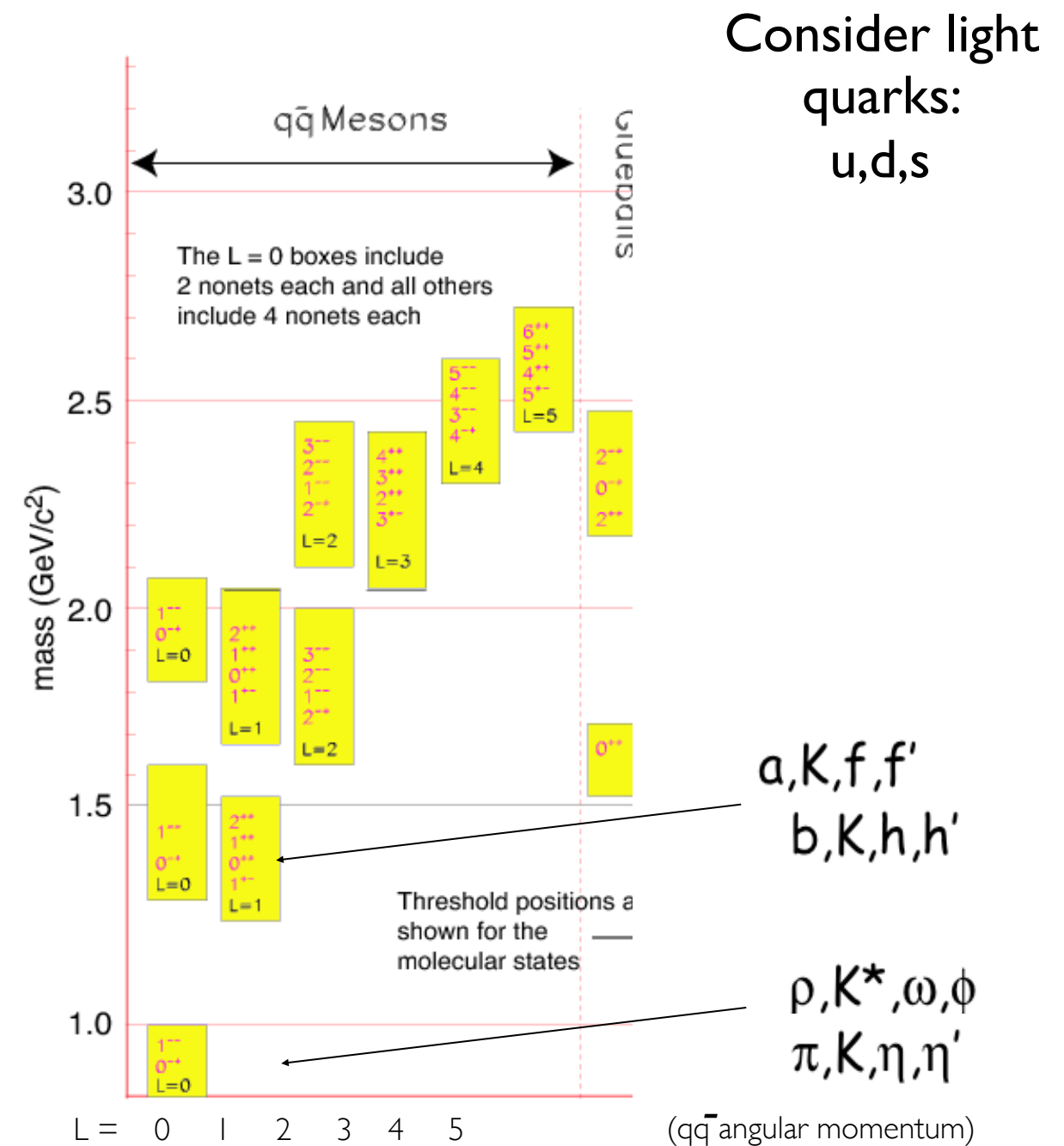
- SU(3) flavor symmetry
 → nonet ($8 \oplus 1$) of degenerate states

$J^{PC} = 0^{-+} \Rightarrow (\pi, K, \eta, \eta')$
 $1^{--} \Rightarrow (\rho, K^*, \omega, \Phi)$
 $1^{+-} \Rightarrow (b_1, K_1, h_1, h_1')$
 ...



- Great success in describing the lower mass states

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

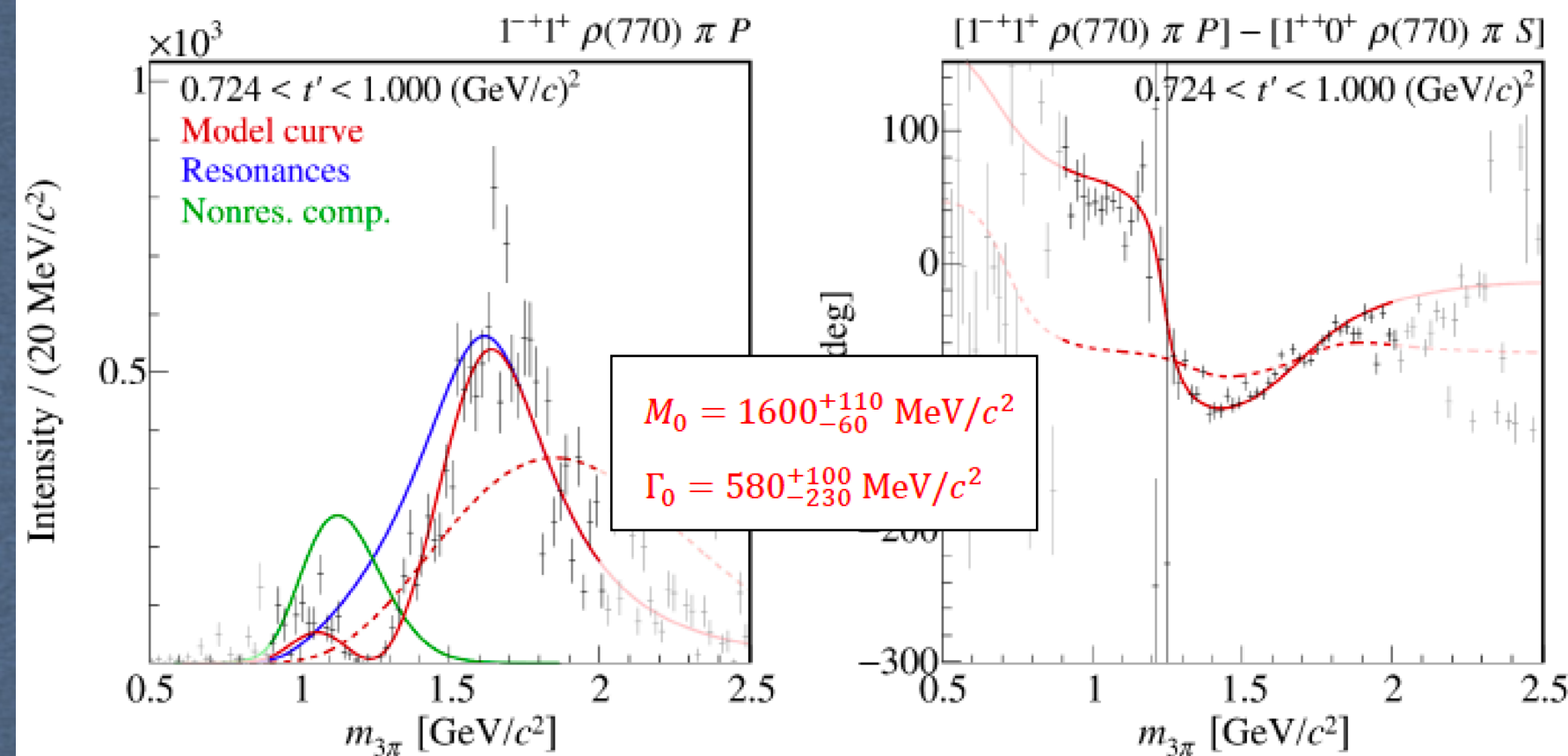
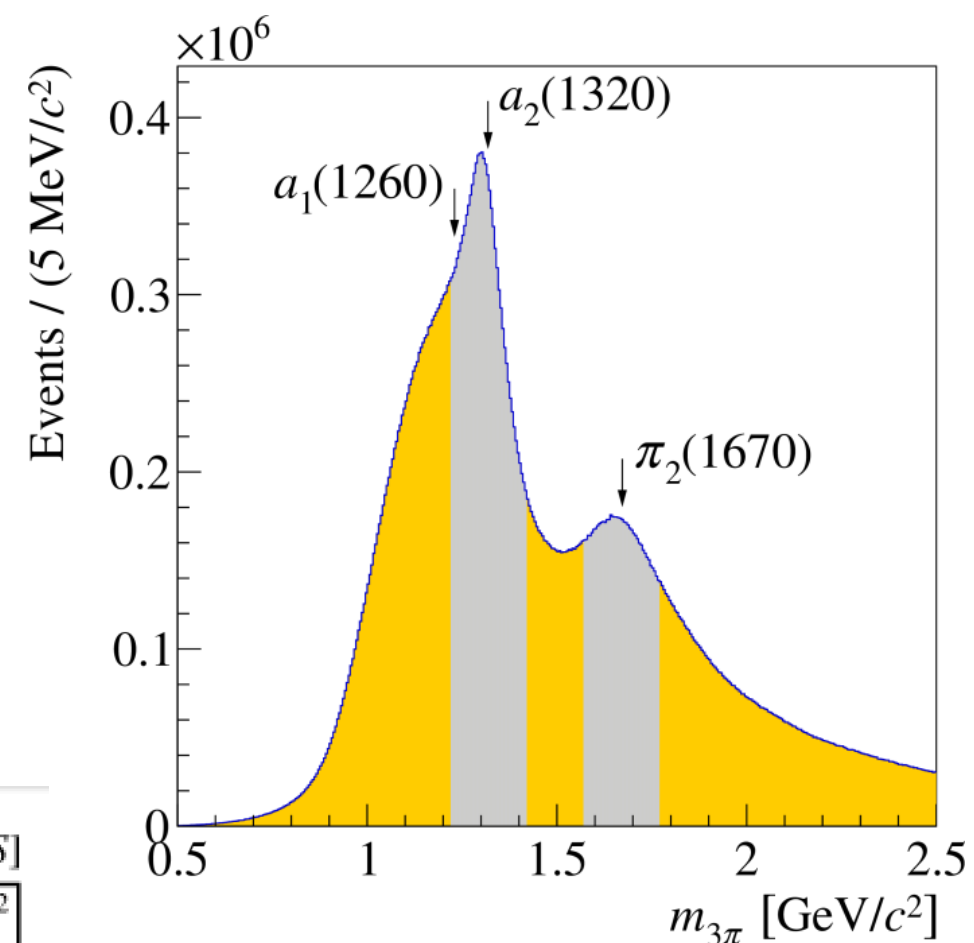




Hybrids at COMPASS

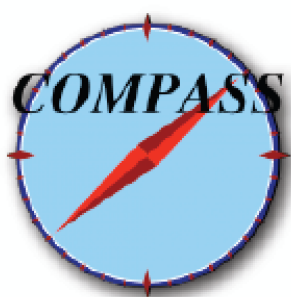
3 π final state

- * Possible evidence of exotic meson $\pi_1(1600)$ in $\pi^- p \rightarrow p \pi^- \pi^- \pi^+$ (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)



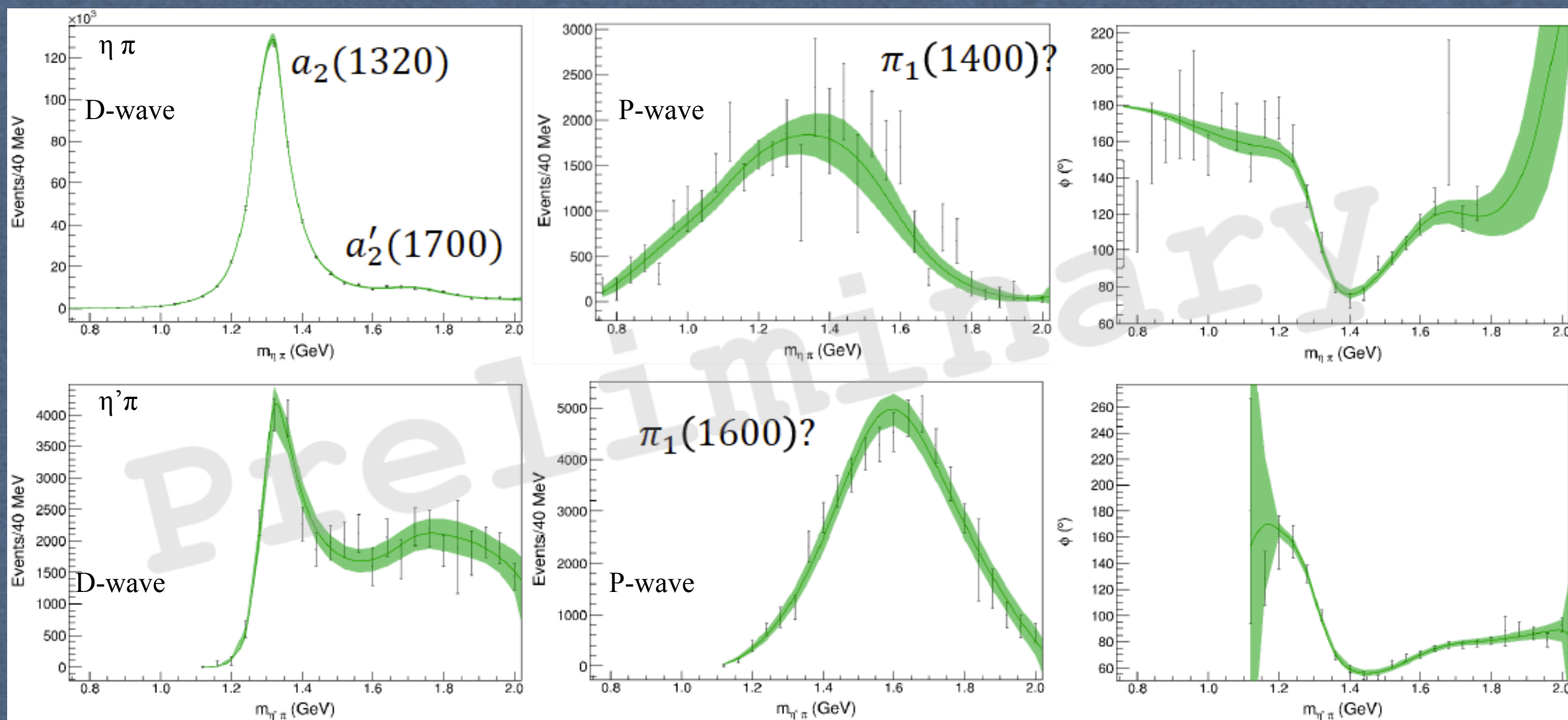
Hybrids at COMPASS

$\eta\pi$ final state

* $\pi^-p \rightarrow \rho\eta\pi^-$ and $\pi^-p \rightarrow \rho\eta'\pi^-$ at 19.1 GeV

* $\pi_1(1400)$ exotic state (1^-+ wave)

B.Ketzer (UBonn)





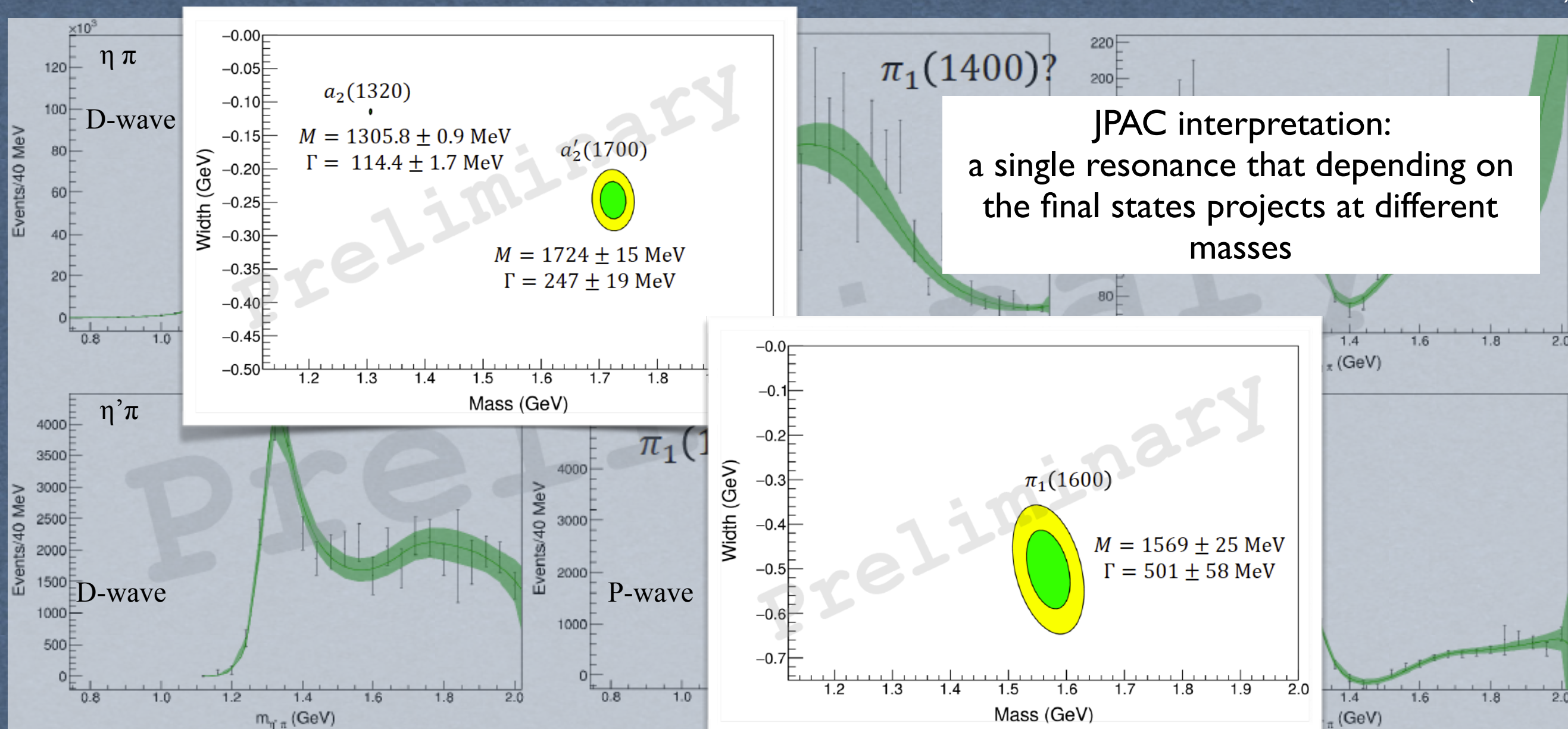
Hybrids at COMPASS

$\eta\pi$ final state

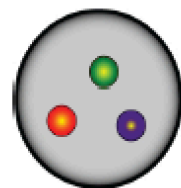
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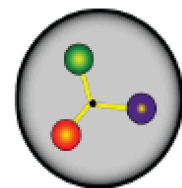
B.Ketzer (UBonn)



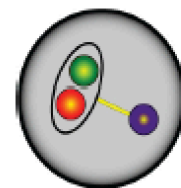
Hybrid baryons at CLAS12



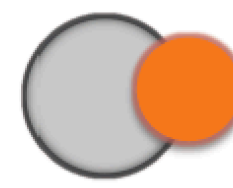
CQM



CQM+flux tubes



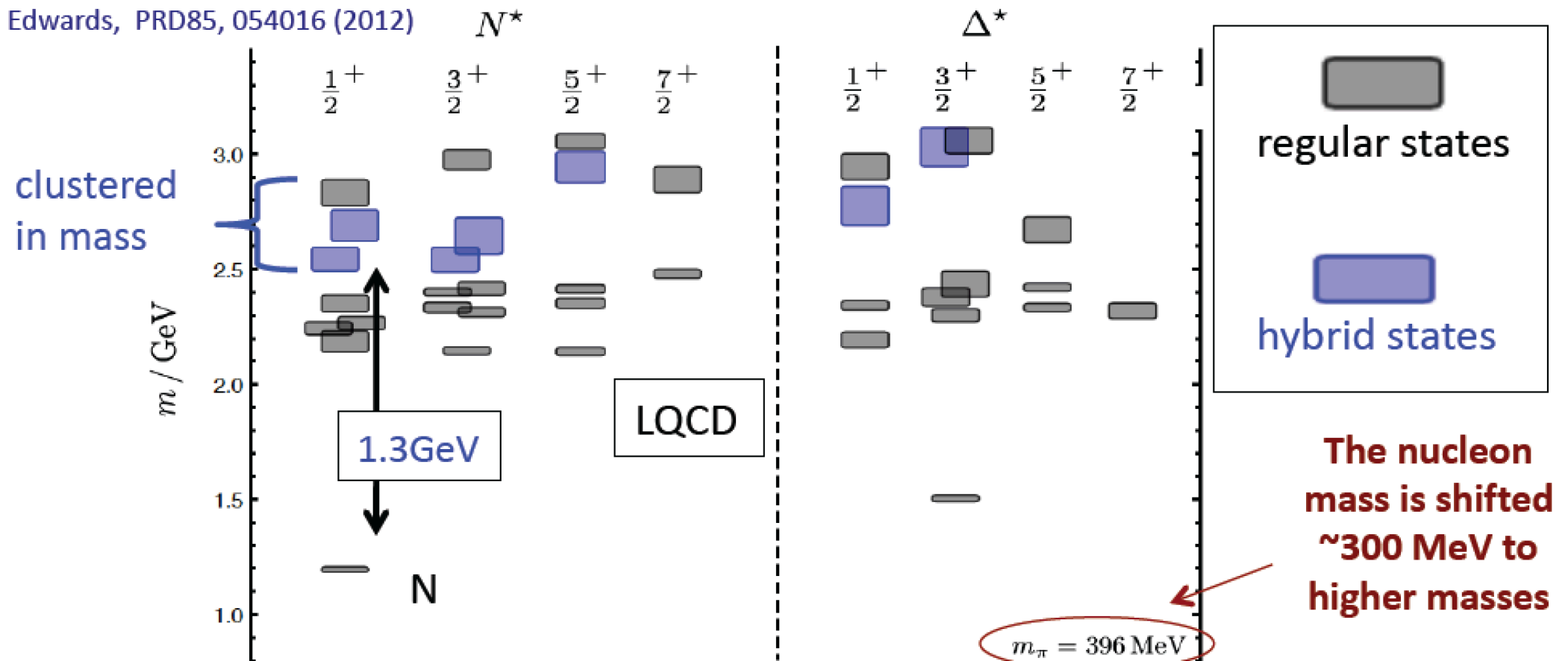
Quark-diquark clustering



Baryon-meson system

Hybrid Baryons in LQCD

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



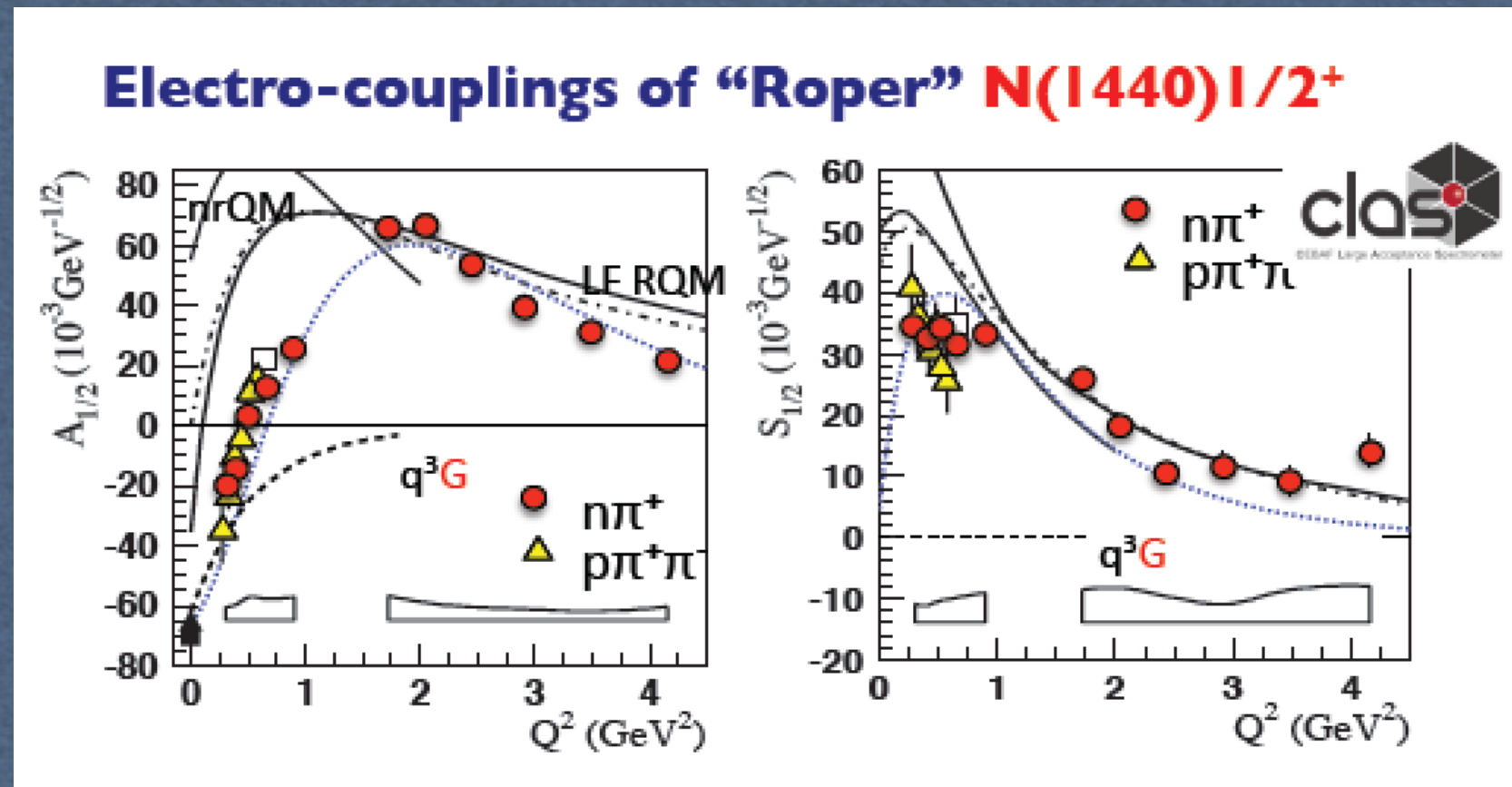
Hybrid states have same J^P values as qqq baryons. How to identify them?

- 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 (Q^2)



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

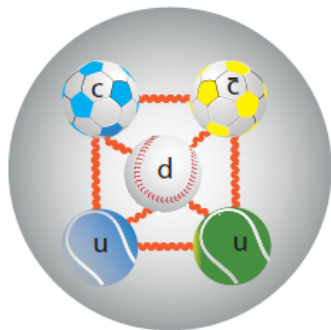
A suppressed longitudinal amplitude $S_{1/2}(Q^2)$ in comparison with transverse electro-excitation amplitude $Q_3 G$

- $N\pi$ and $N\pi\pi$ 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

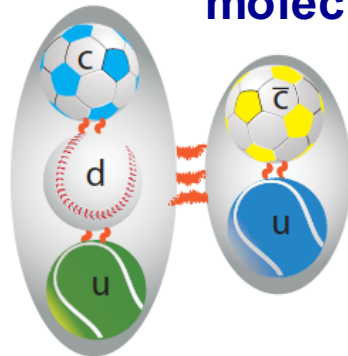
A.D'Angelo (URome-TV)

Pentaquark

5-quark
bound state

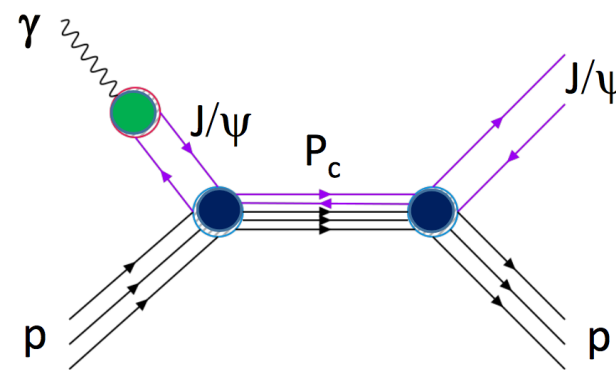
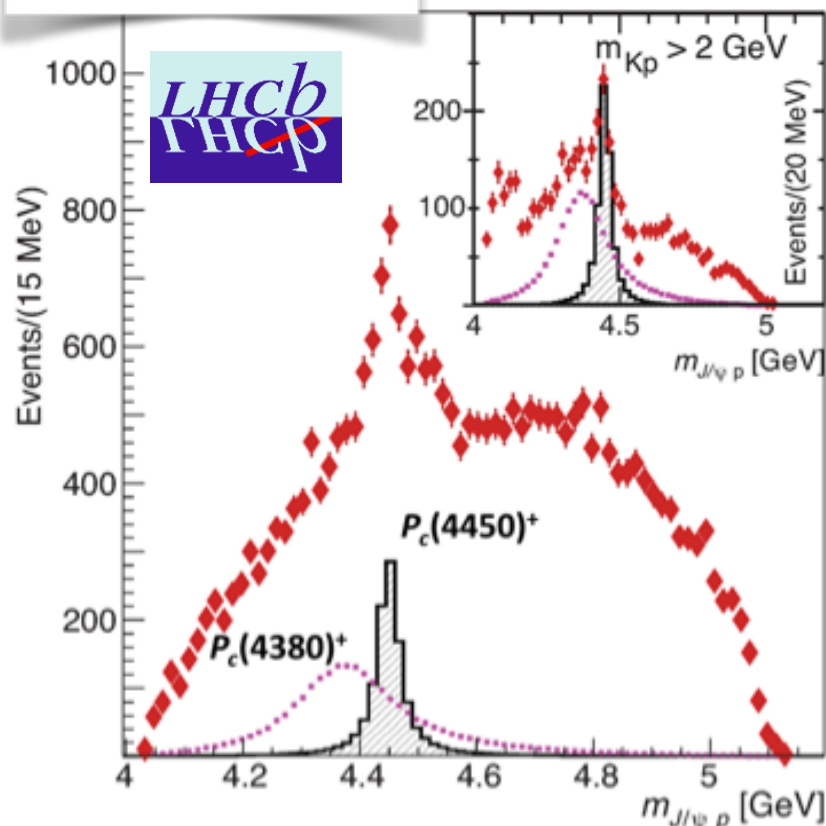


Hadronic
molecule

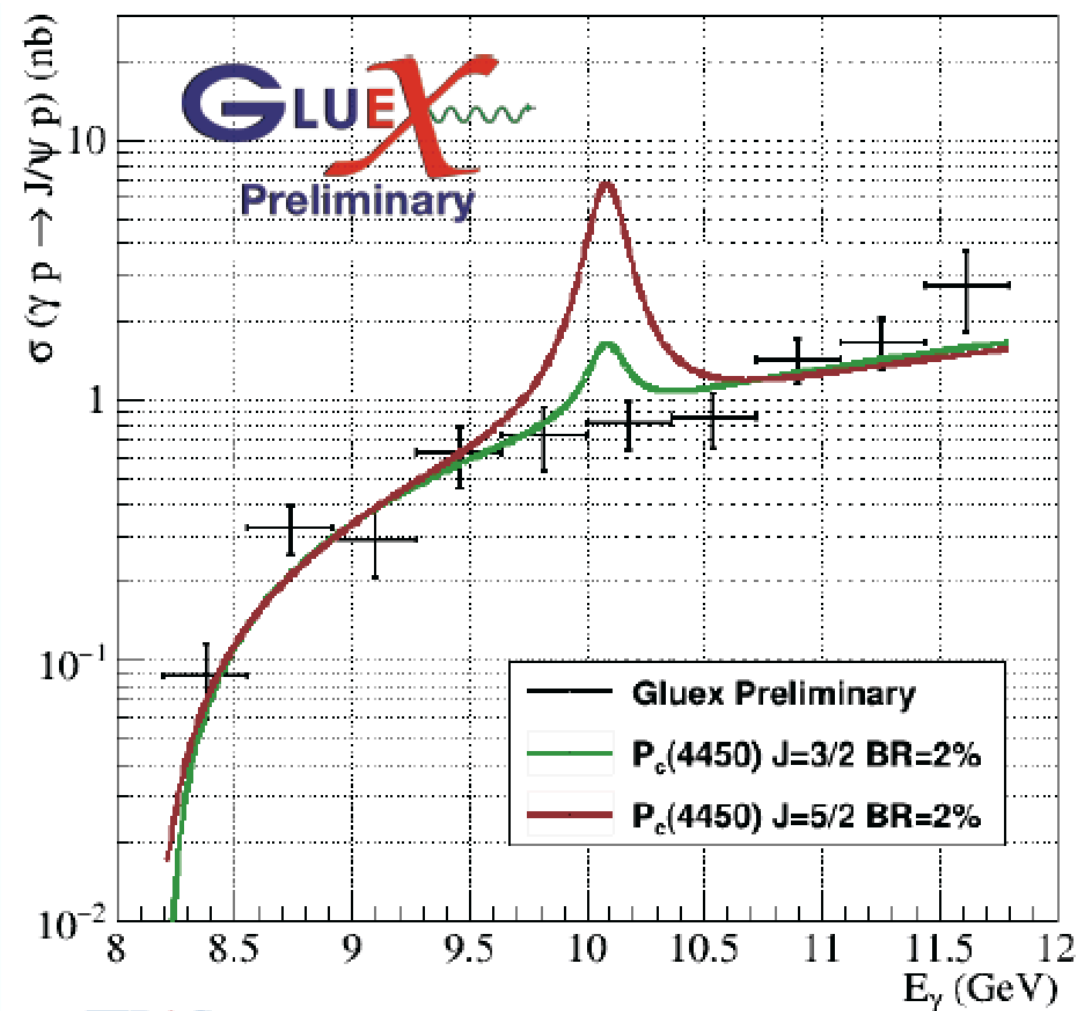
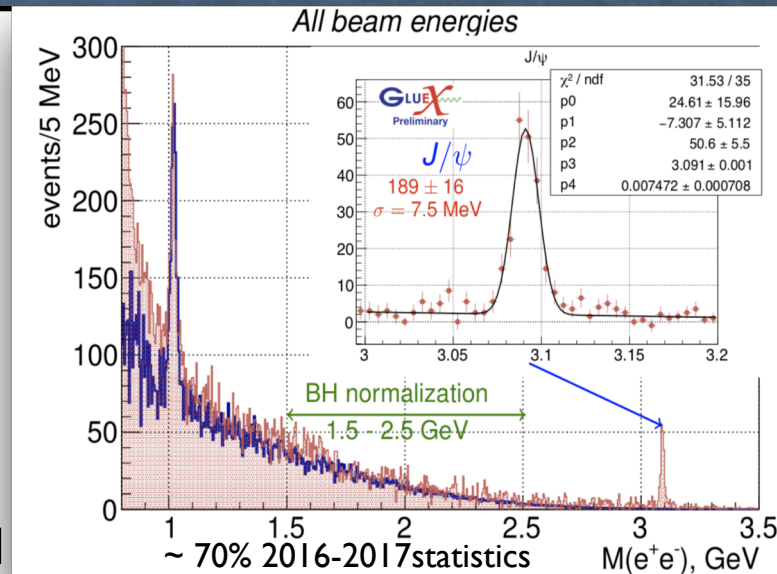


or cusp, triangle singularity, etc...

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

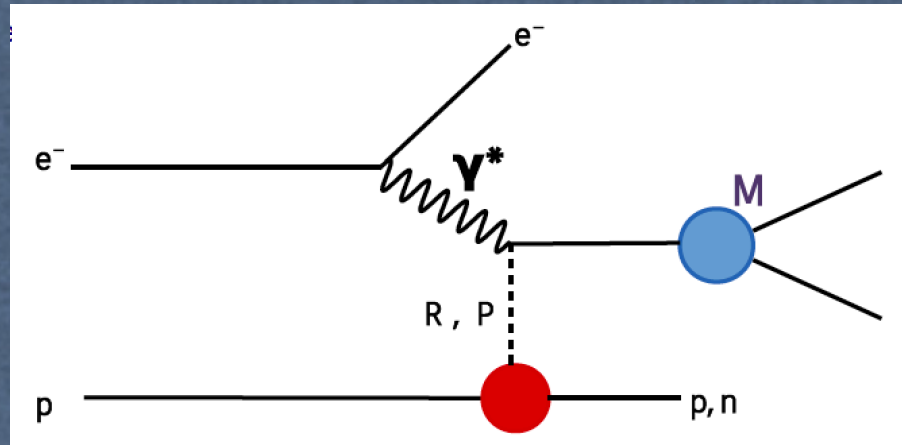


- J/ψ photoproduction at threshold
- Observation of charm at GLUEX
- Projections with CLAS12 shows a significant sensitivity

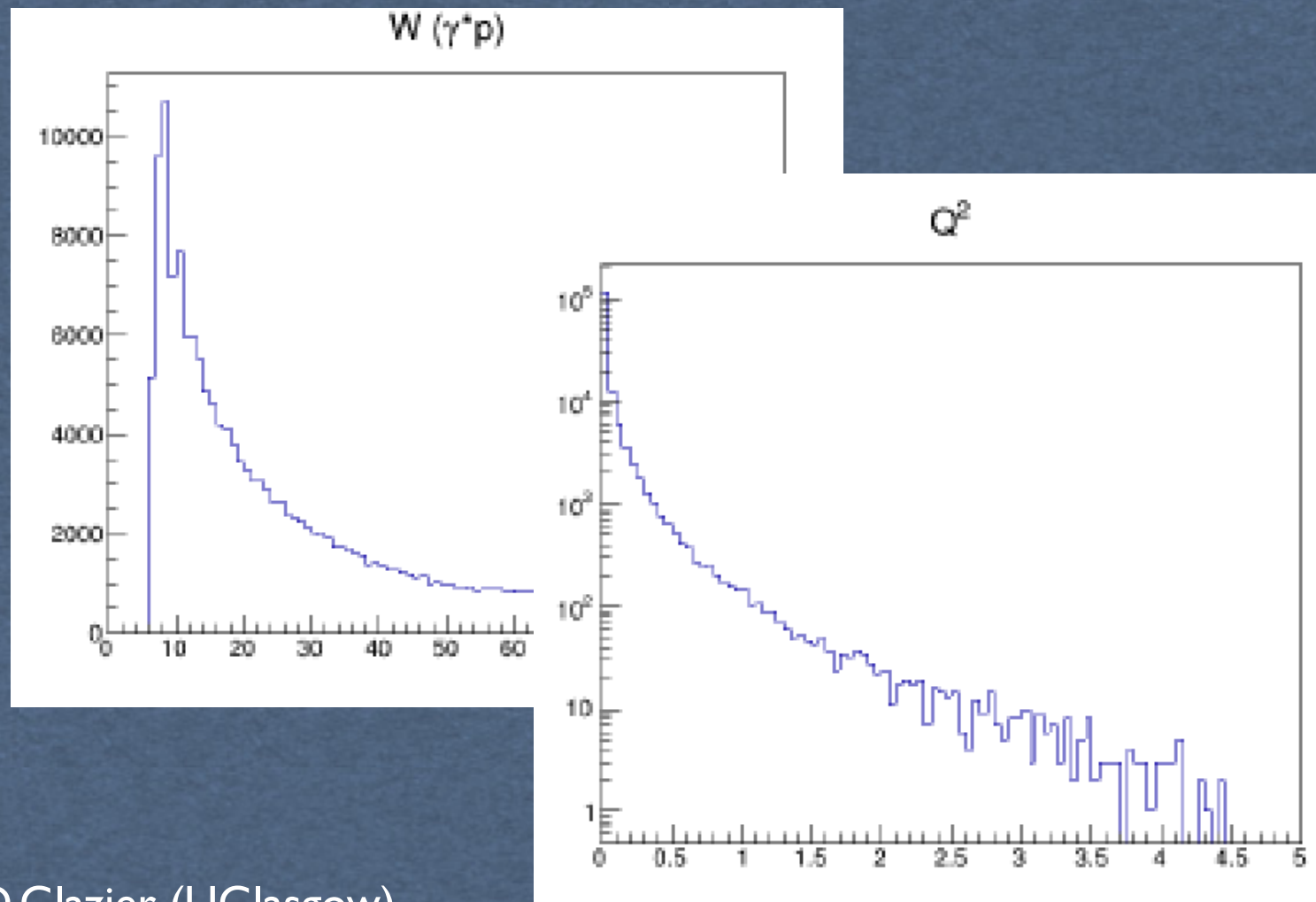


S.Dobbs (FSU)

EIC kinematics and yield estimates



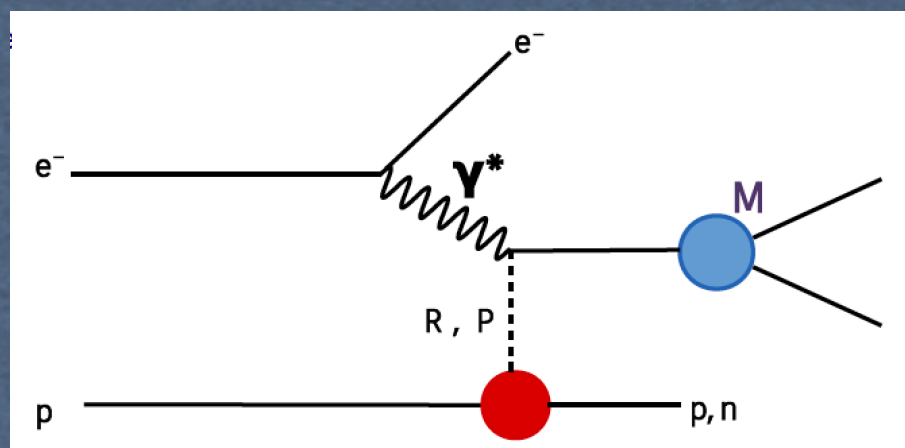
- EIC meson production kinematics studied in a simple diffractive ansatz (t-slope)
- Virtual photon flux + dipole form factor
- 10 GeV electron + 100 GeV proton
- Final state compatible with current detectors design: $M \rightarrow e^+e^-$



e'/p' kinematics

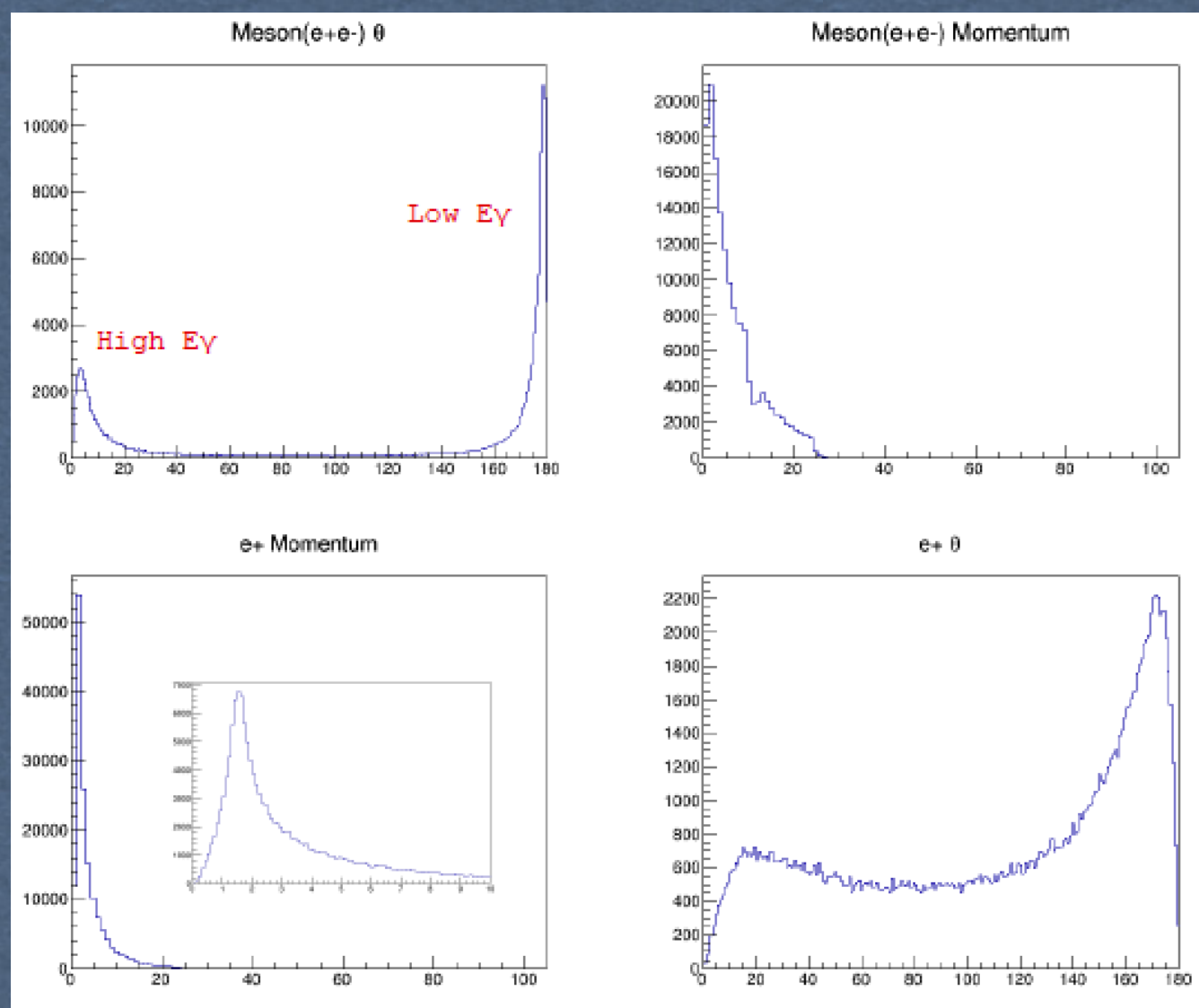
- Scattered electron: $E_{e'} \sim 10$ GeV within $\Delta\Theta \sim 2^\circ$ forward cone around the beam line
- Scattered proton: high p (~ 90 -100 GeV) $\Delta\Theta \ll 1^\circ$ cone in the opposite direction

EIC kinematics and yield estimates

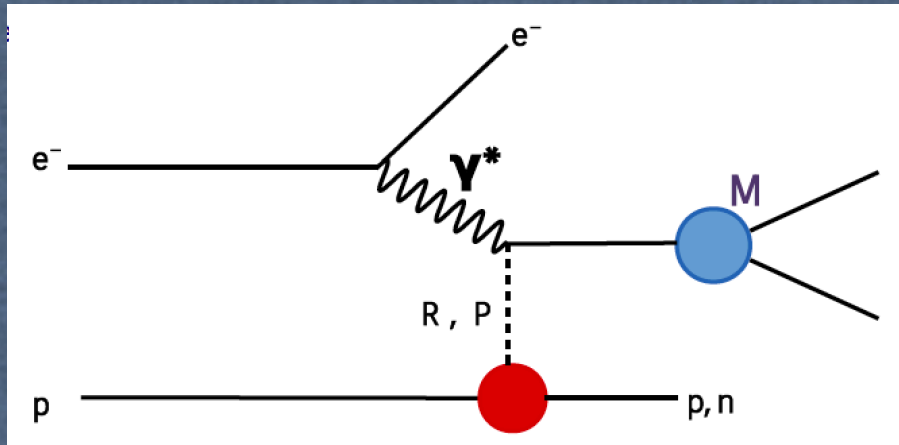


- EIC meson production kinematics studied in a simple diffractive ansatz (t-slope)
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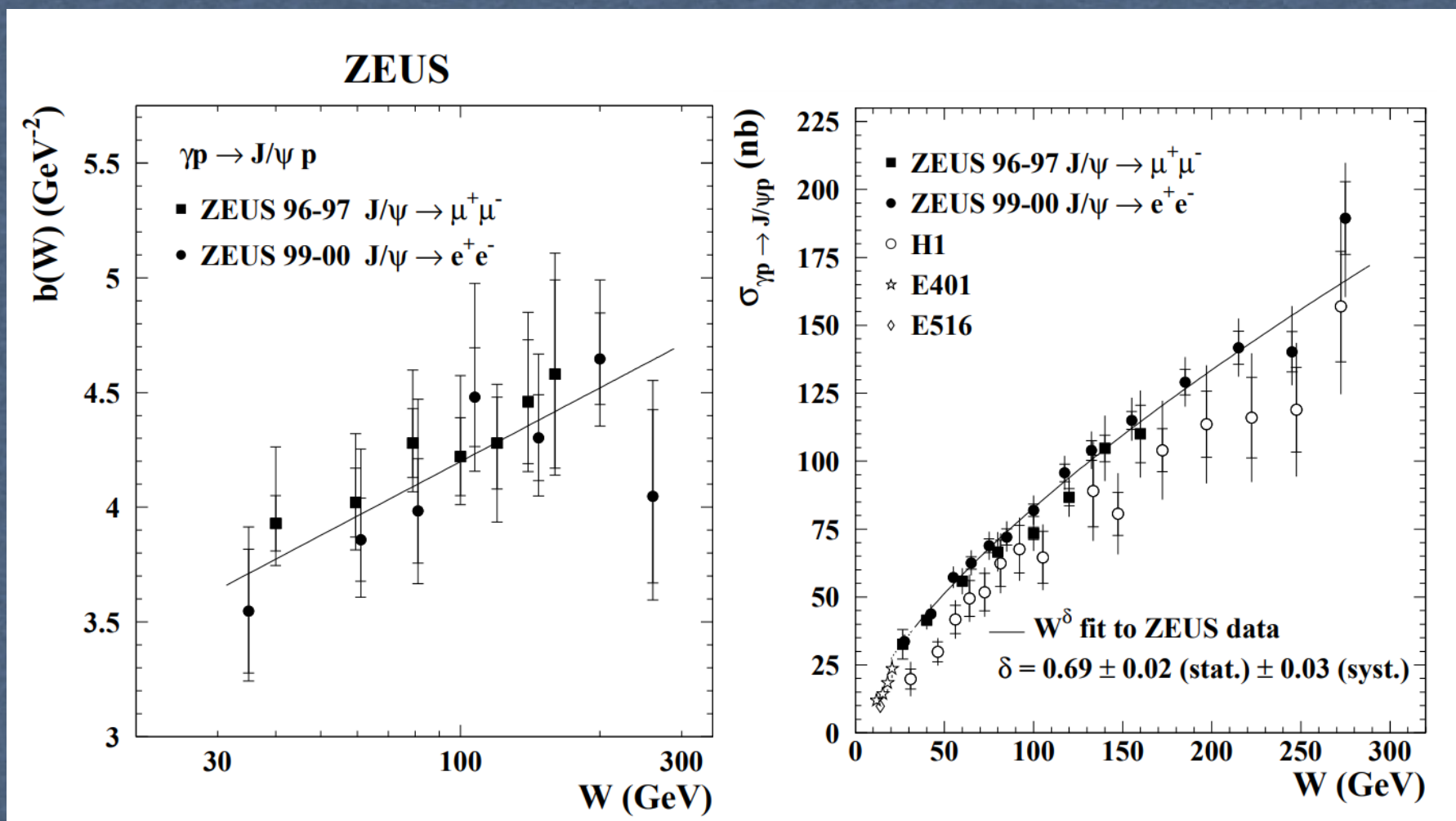
$M \rightarrow e^+e^-$
kinematics



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/Ψ rate = 0.8Hz
(~70k events/day)**

D.Glazier (UGlasgow)

EIC kinematics and yield estimates

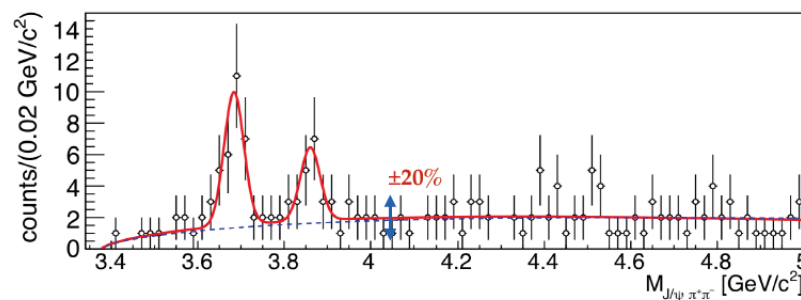
$$e N \rightarrow e' (J/\Psi \pi^+ \pi^-) \pi^\pm N^*$$

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

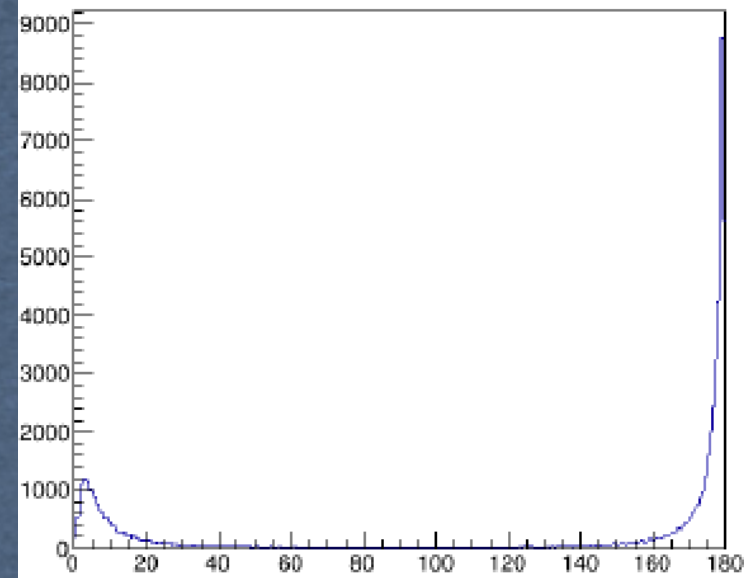
$$m_{\tilde{X}(3872)} = (3860.0 \pm 10.4) \text{ MeV}/c^2$$

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

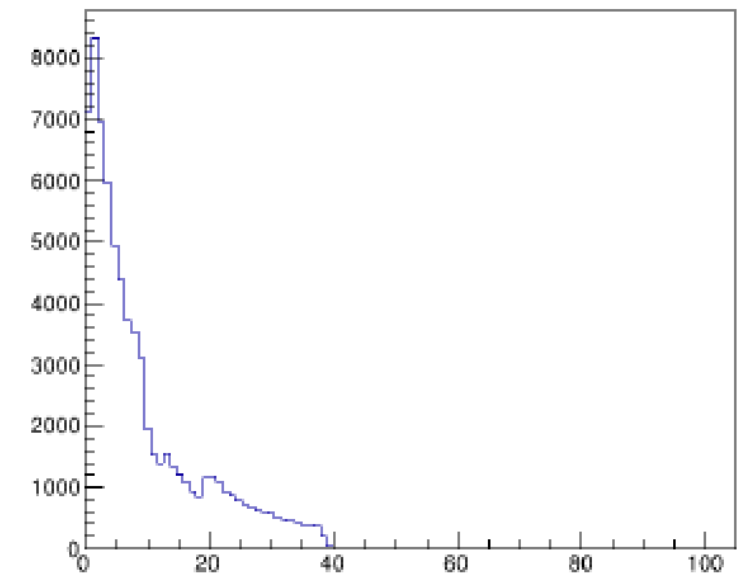
Significance (including systematics) is 4.1σ
 $C = -1$ (?)



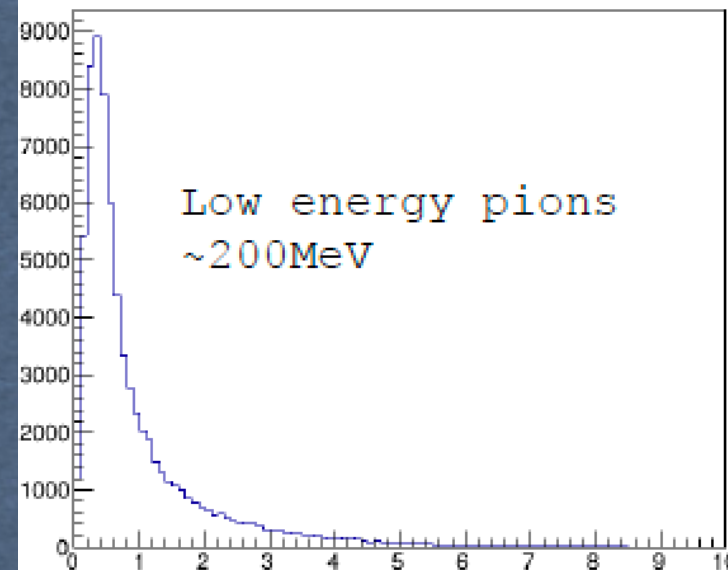
Meson($J/\psi \pi^+ \pi^-$) θ



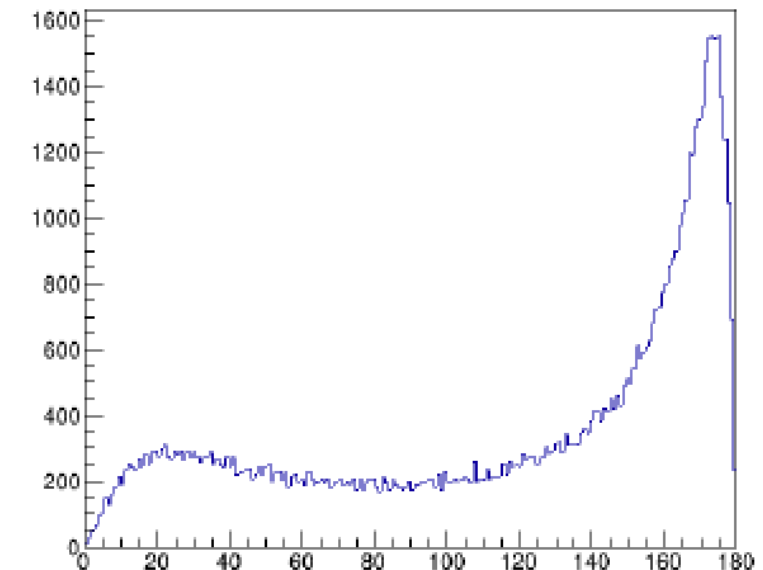
Meson($J/\psi \pi^+ \pi^-$) Momentum



π^+ Momentum



π^+ θ



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

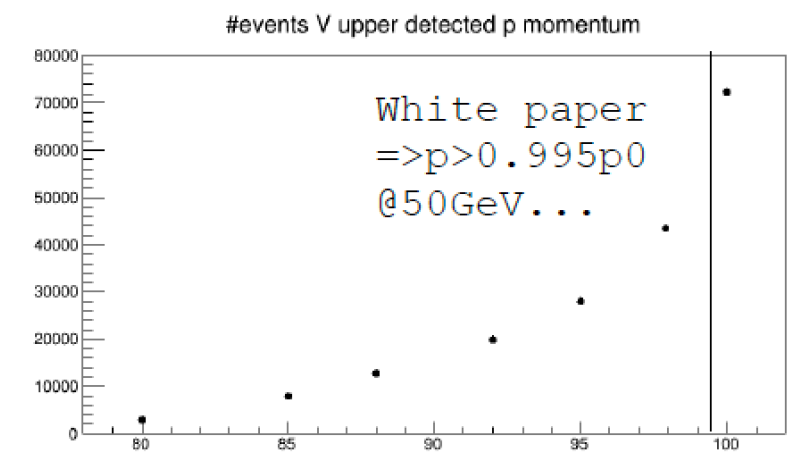
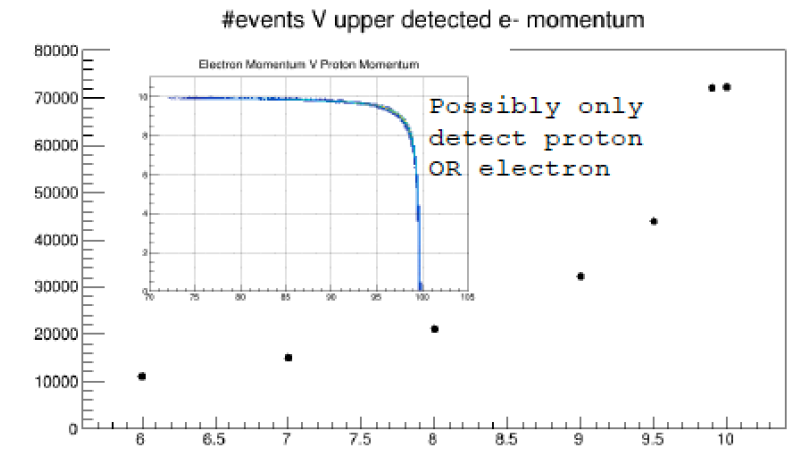
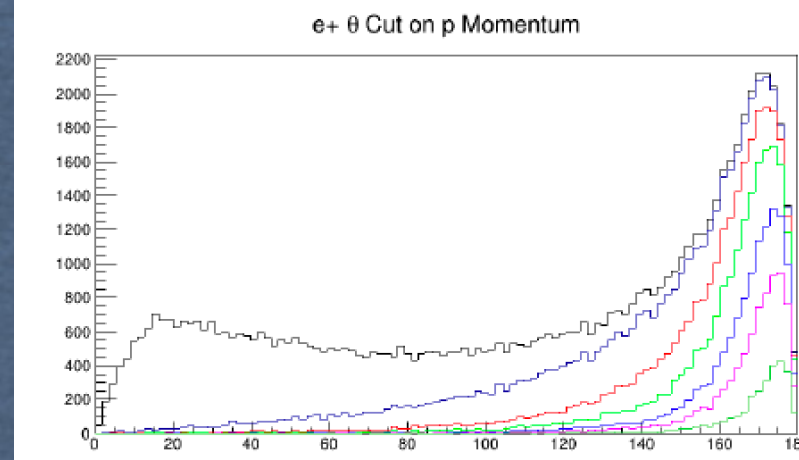
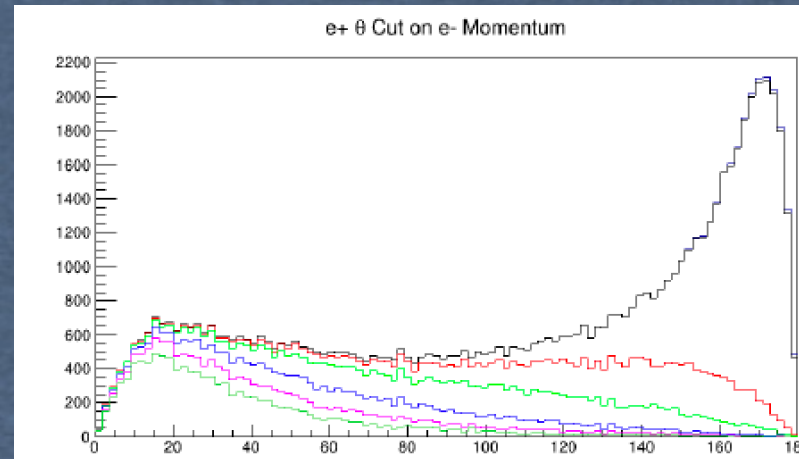
Impact on EIC detectors

Requirements

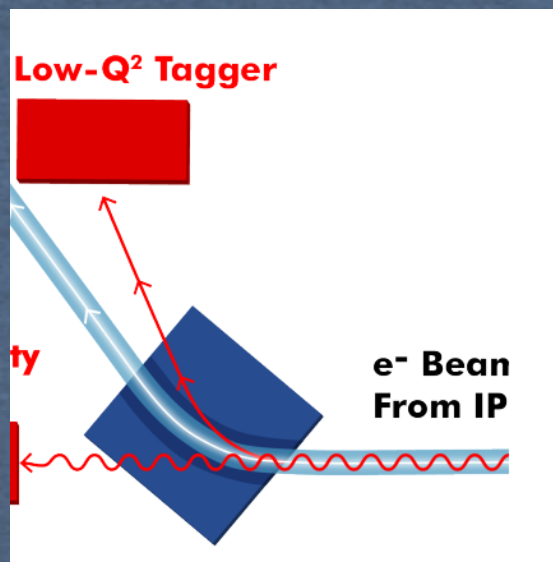
- Scattered electron and proton detection at 0 degrees!
- Far-forward detectors
- Tag scattered particle
- Determine momentum

Results

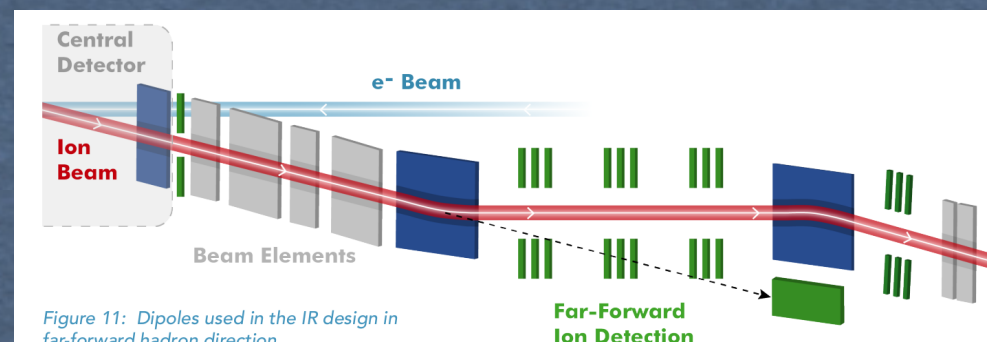
- Exclusive measurements for excellent bg rejection
- With good resolution ($<0.1\%$) MissingMass technique would help



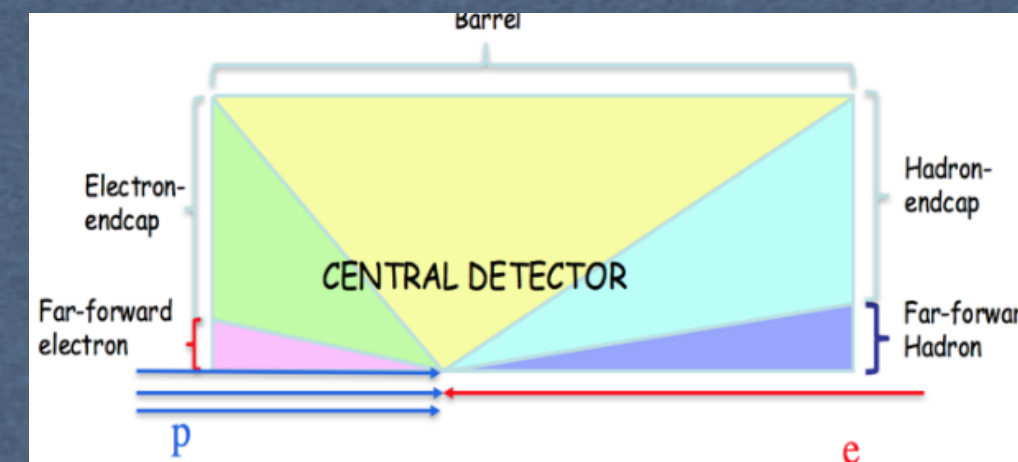
Far-forward electrons



Far-forward ion or Roman Pots?



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



EUROPEAN CENTRE FOR THEORETICAL
STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

TRENTO, ITALY

Institutional Member of the European Expert Committee NUPECC



Castello di Trento ("Trin"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

The Spectroscopy Program at EIC and Future Accelerators

Trento, December 19-21, 2018

Main Topics

- Multiquark Spectroscopy
- Gluonic States
- Diffractive production
- Interaction of Heavy Flavor with media

Conveners

Feng-Kun Guo (CAS-ITP), Ryan Mitchell (Indiana Univ.), Nora Brambilla (TUM), Umberto Tamponi (INFN Torino), Wolfgang Schäfer (INP Krakow), Ronan McNulty (UCD), Christian Weiss (JLab), Giuseppe Bruno (Università di Bari & INFN)

Organizers

M. Battaglieri (INFN Genova), A. Pilloni (JLab & ECT*), A. Szczepaniak (Indiana Univ. & JLab)

Director of the ECT*: Professor Jochen Wambach (ECT*)

The ECT* is sponsored by the "Fondazione Bruno Kessler" in collaboration with the "Assessorato alla Cultura" (Provincia Autonoma di Trento), funding agencies of EU Member and Associated States and has the support of the Department of Physics of the University of Trento.

For local organization please contact: Susan Driessen - ECT* Secretariat - Villa Tambosi - Strada delle Tabarelle 286 - 38123 Villazzano (Trento) - Italy
Tel.: (+39-0461) 314722 Fax: (+39-0461) 314750, E-mail: driessen@ectstar.eu or visit <http://www.ectstar.eu>

EICUG

Electron-Ion Collider User Group Meeting

2019

JULY 22-26
PARIS
École Nationale Supérieure de Chimie

The world's most powerful microscope for studying the "glue" that binds the building blocks of visible matter

International Advisory Committee

Daniël BOER: Groningen
Silvia DALLA TORRE: INFN/Trieste
Abhay DESHPANDE: BNL/Stony Brook
Rolf ENT: JLAB
Yuji GOTO: RIKEN
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Franck SABATIÉ: CEA-Saclay
Andrei SERV: JLAB
Ernst SICHTERMANN: LBNL
Bernd SURROW: Temple
Thomas ULLRICH: BNL
Ferdinand WILLEKE: BNL
Rikutarō YOSHIDA: JLAB

3D STRUCTURE OF PROTON AND NUCLEI

GLUON SATURATION AND THE COLOR GLASS CONDENSATE

SOLVING THE MYSTERY OF THE PROTON SPIN

QUARK AND GLUON CONFINEMENT

Local Organizing Committee

Francesco BOSSU: CEA-Saclay
Valérie FROIS: CNRS/IN2P3, Secretary
Carlos MUÑOZ CAMACHO: CNRS/IN2P3
Franck SABATIÉ: CEA-Saclay

<https://indico.in2p3.fr/event/EICUG2019>

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Building the EIC Hadron Spectroscopy community

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Build the future HS program at EIC joining the effort!



Main Topics

- Multiquark Spectroscopy
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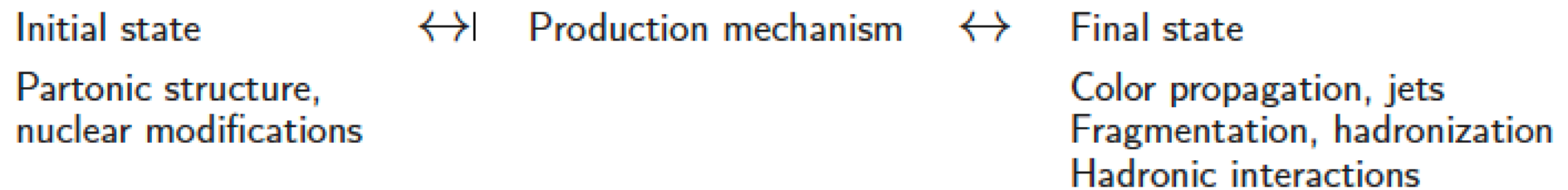
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Back up

Heavy Flavours in media

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

Schematic



A) HF as probe of initial-state gluons

- [EIC: Nuclear PDFs from inclusive DIS eA] $\leftrightarrow$ global analysis/PDFs
- EIC: Nuclear gluon densities from open HF production in eA
- EIC: Nuclear gluons from coherent HQium prodn: Transverse distns, shadowing $\leftrightarrow$ exclusive procs/GPDs

B) Propagation and hadronization of HF in cold matter

- EIC: Single-inclusive D/B/b,c production in ep+eA $\leftrightarrow$ light-quark fragmentation
- EIC: HF jets in ep+eA, including substructure, correlations $\leftrightarrow$ 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 $\leftrightarrow$ elastic scattering of a $q\bar{q}$ -dipole
- Large DDIS is the hallmark of a strongly absorptive target $\leftrightarrow$ “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