QCD Dynamics in electron-nucleus collisions

Holly Szumila-Vance
Hall A/C Staff Scientist

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Jefferson Lab

Jefferson Lab

Course Overview

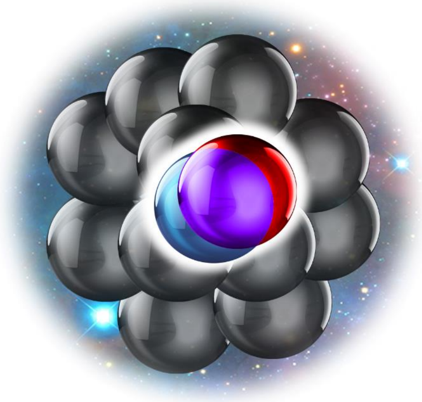
- Nuclear systems and the electron scattering probe
  - Elastic scattering
  - Quasielastic scattering
  - Deep inelastic scattering

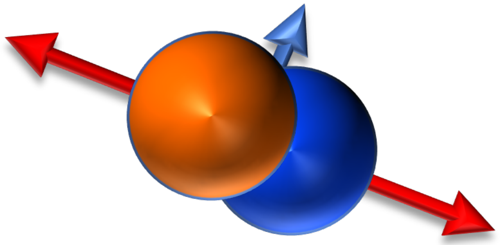
- Hadrons in the nucleus
  - Short and long range dynamics
  - EMC effect
  - Hadronization and color transparency

- Insights from J/ψ

Review from our last lecture

- Different avenues to better bridge the gap between the observances in the real world and QCD dynamics

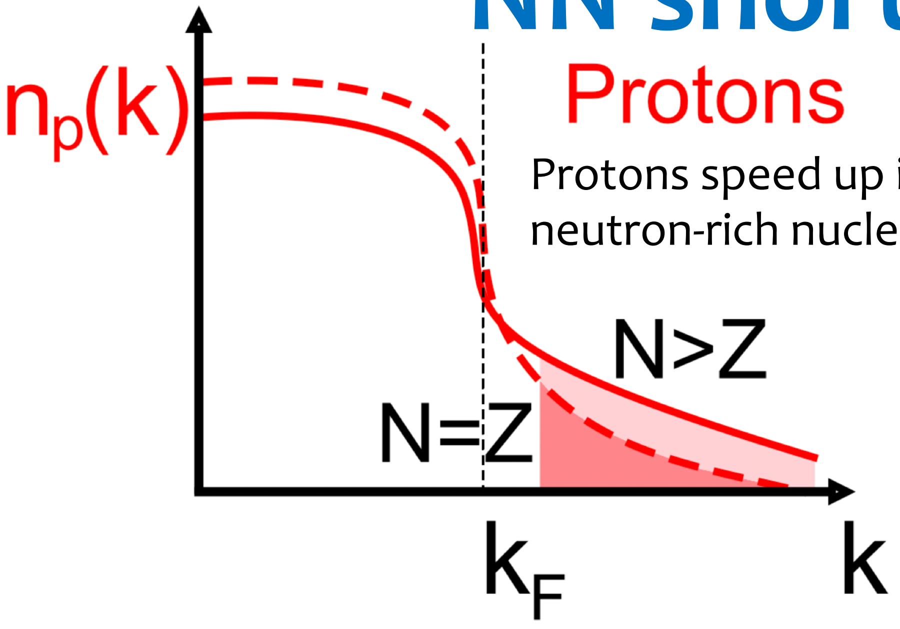




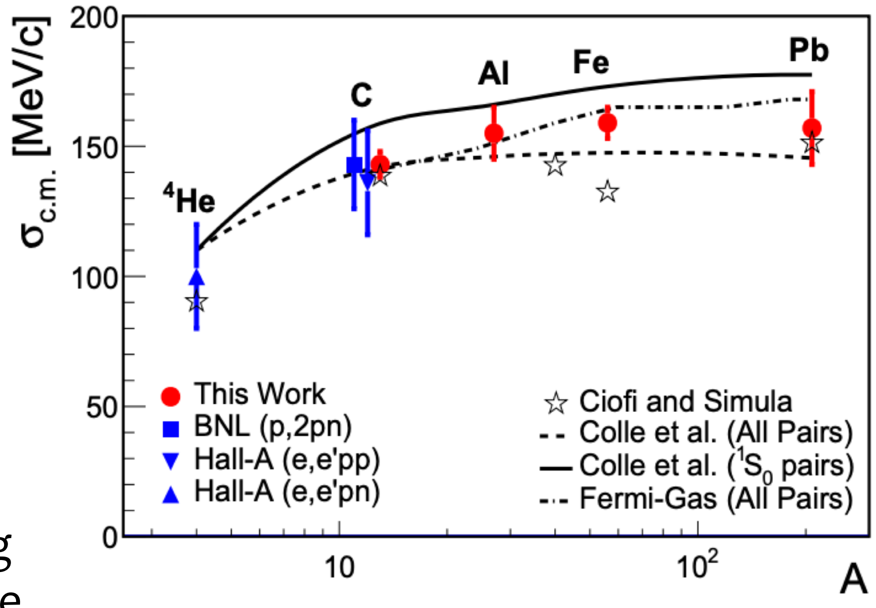
SRCs provide a unique insight in QCD dynamics in the nucleus:

- Related to local density (as is the EMC Effect)
- Universal to all nuclei
- High momentum tail
- Tensor dominated (pn vs pp or nn)
- Further studies in this area using spectator tagging will give us better clues on the relation to the EMC Effect

NN short range correlated pairs

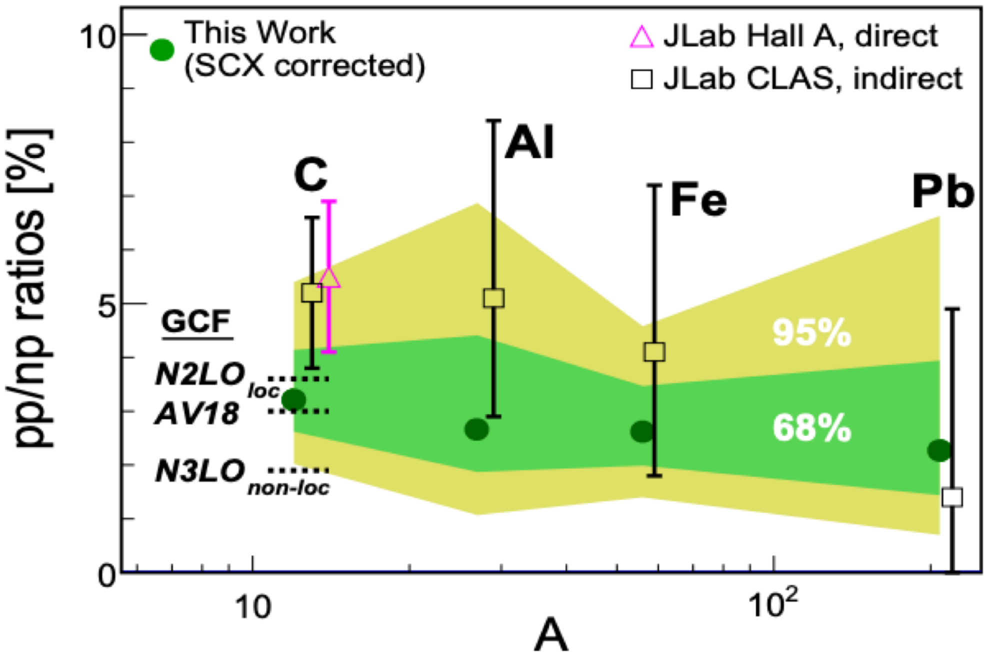


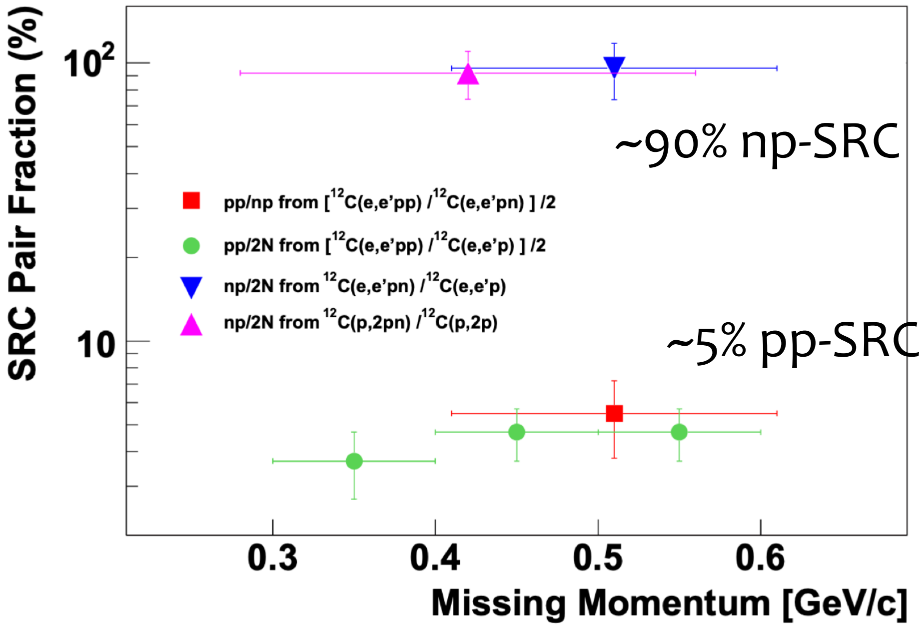
Protons speed up in neutron-rich nuclei



c.m. consistent with 2N

np-pairing dominance





~90% np-SRC

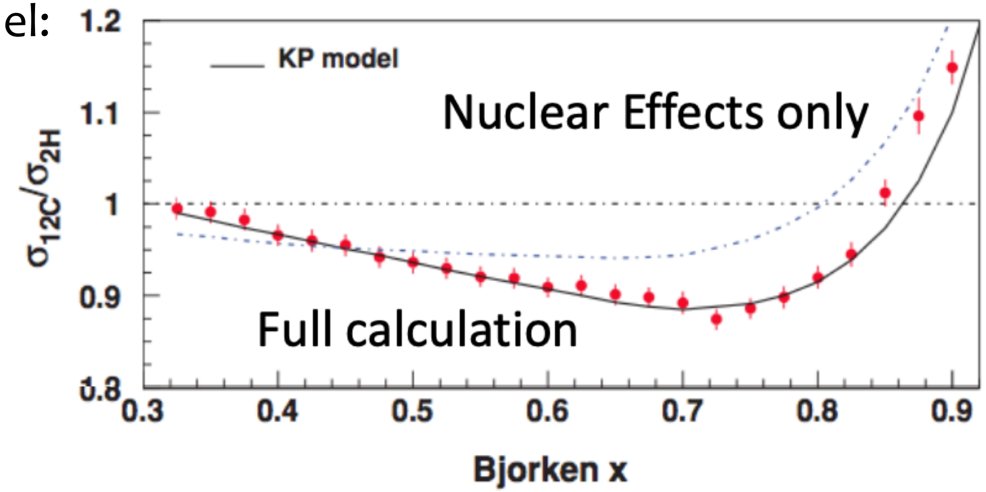
~5% pp-SRC

EMC Effect

Are all the nucleons each modified a little bit by the mean field?

EMC Effect cannot be fully accounted for in one model:

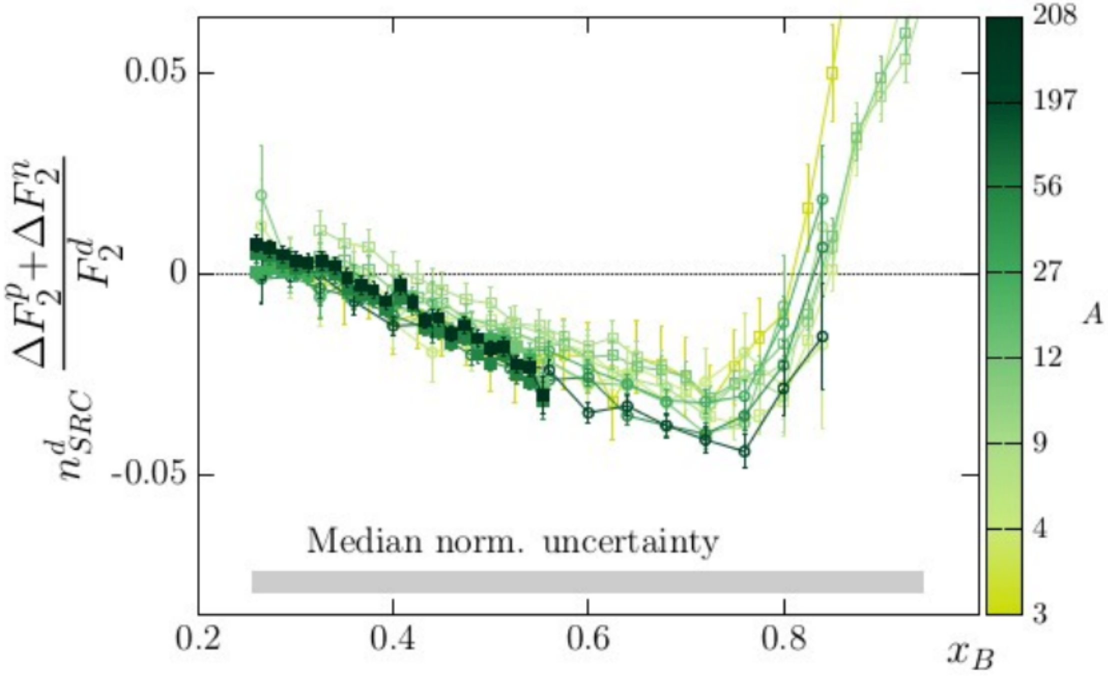
Are the few high-momentum nucleons each modified a lot by the short range interaction?

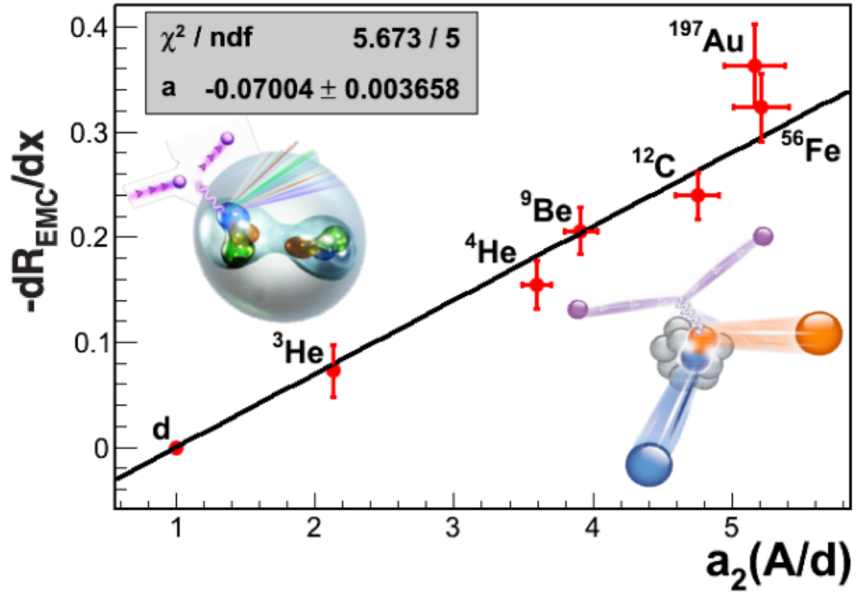


Strongly linked to local density, and correlates with SRCs:

$$n_d^{SRC}\frac{\Delta F_2^p+\Delta F_2^n}{F_2^d}=\frac{\frac{F_2^A}{F_2^d}-(Z-N)\frac{F_2^p}{F_2^d}-N}{\frac{A}{2}a_2-N}$$

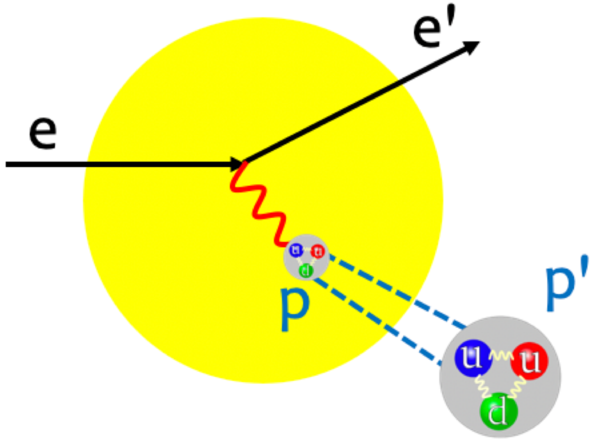
Universal??? Nucleus-Dependent





Review from our last lecture

- Different avenues to better bridge the gap between the observances in the real world and QCD dynamics

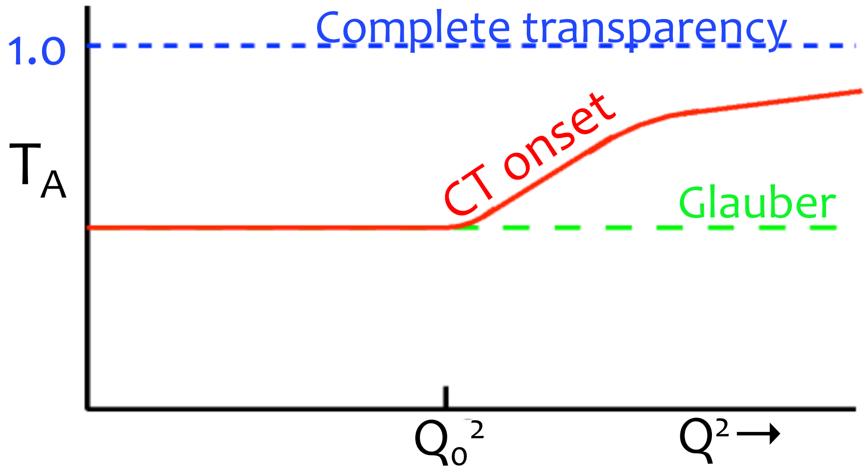


Onset of Color Transparency is important:

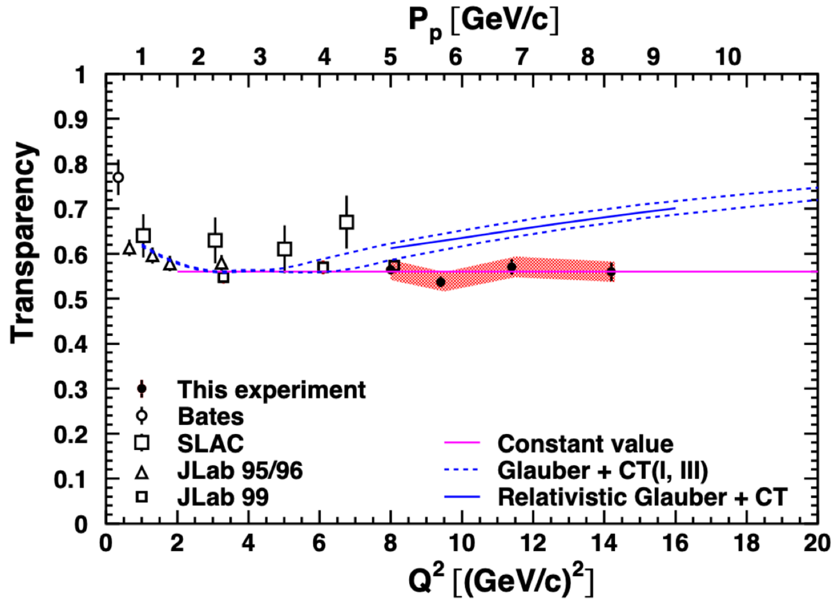
- Direct link from quark-gluon d.o.f. to the nucleonic picture
- Tells us where factorization theorems are relevant (essential for GPDs)
- Assumed in high energy reactions
- Onset but not the plateau is generally observed for mesons and will be explored further in the 12 GeV program
- Onset in protons is not yet established

Color transparency

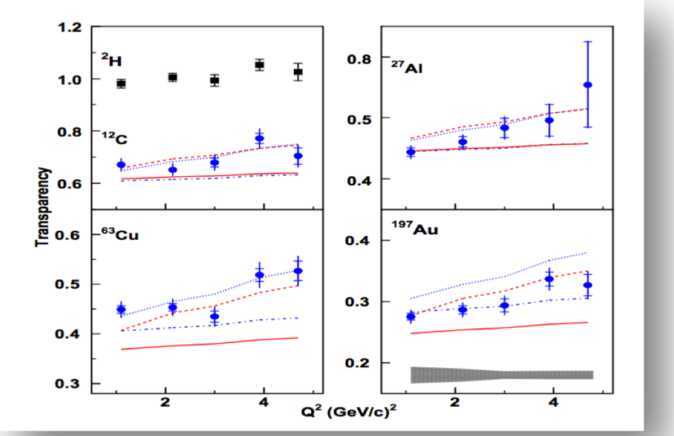
Predicted by QCD:
Observation of transition from q-g d.o.f.



Not seen in protons:

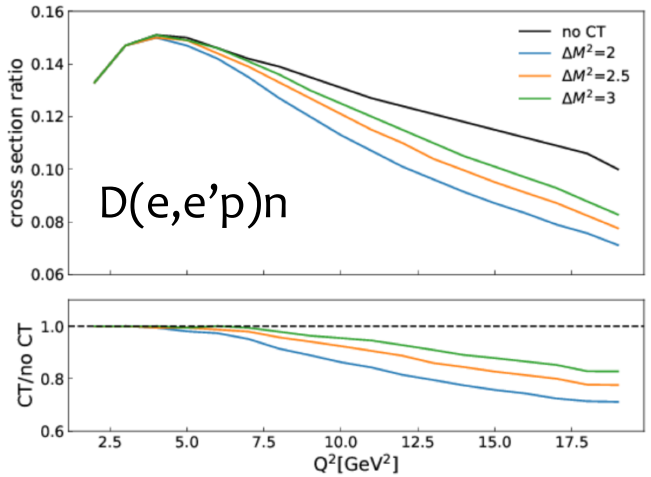


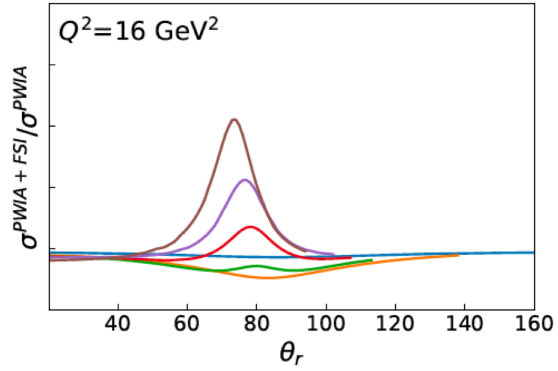
Hints from mesons:



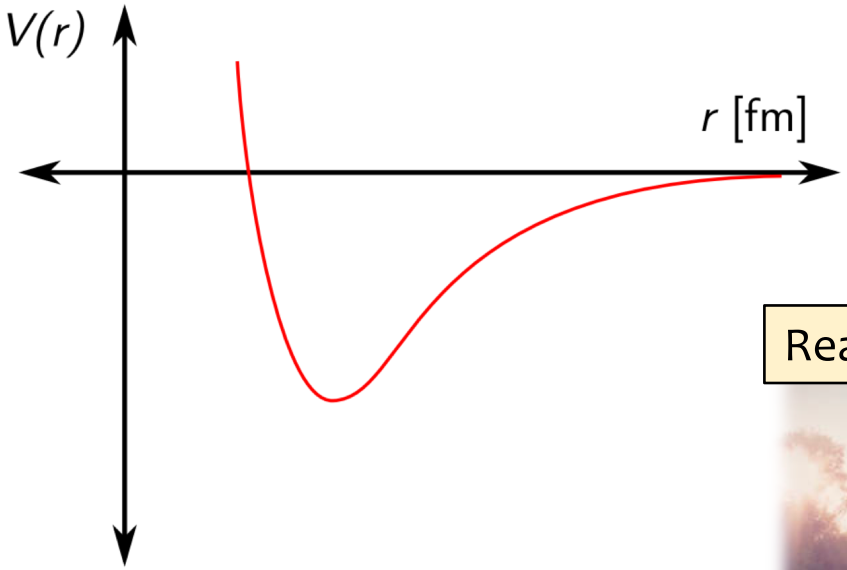
B.Clasie *et al.* PRL 99:242502 (2007)

Maybe need to re-think kinematics:

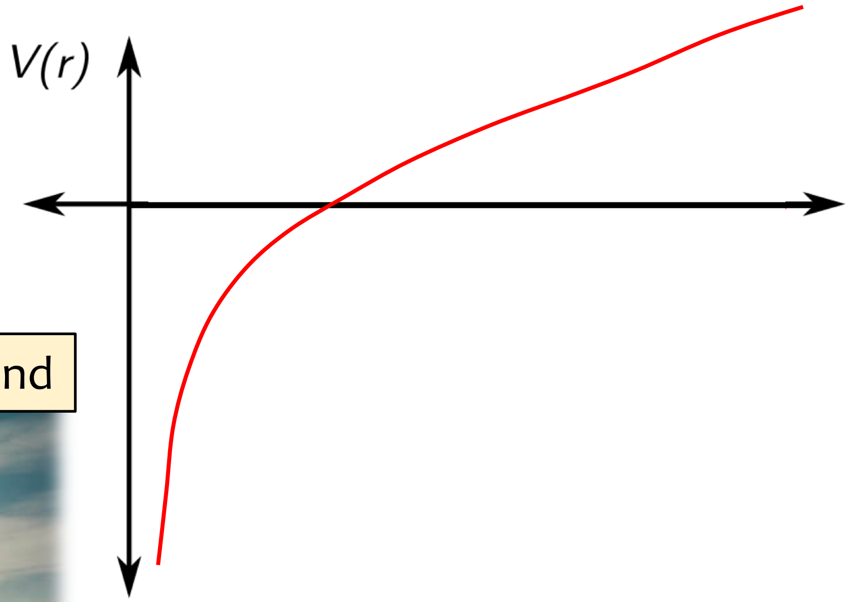




Today, we will examine another route in exploring the connection between QCD Land and the Real World



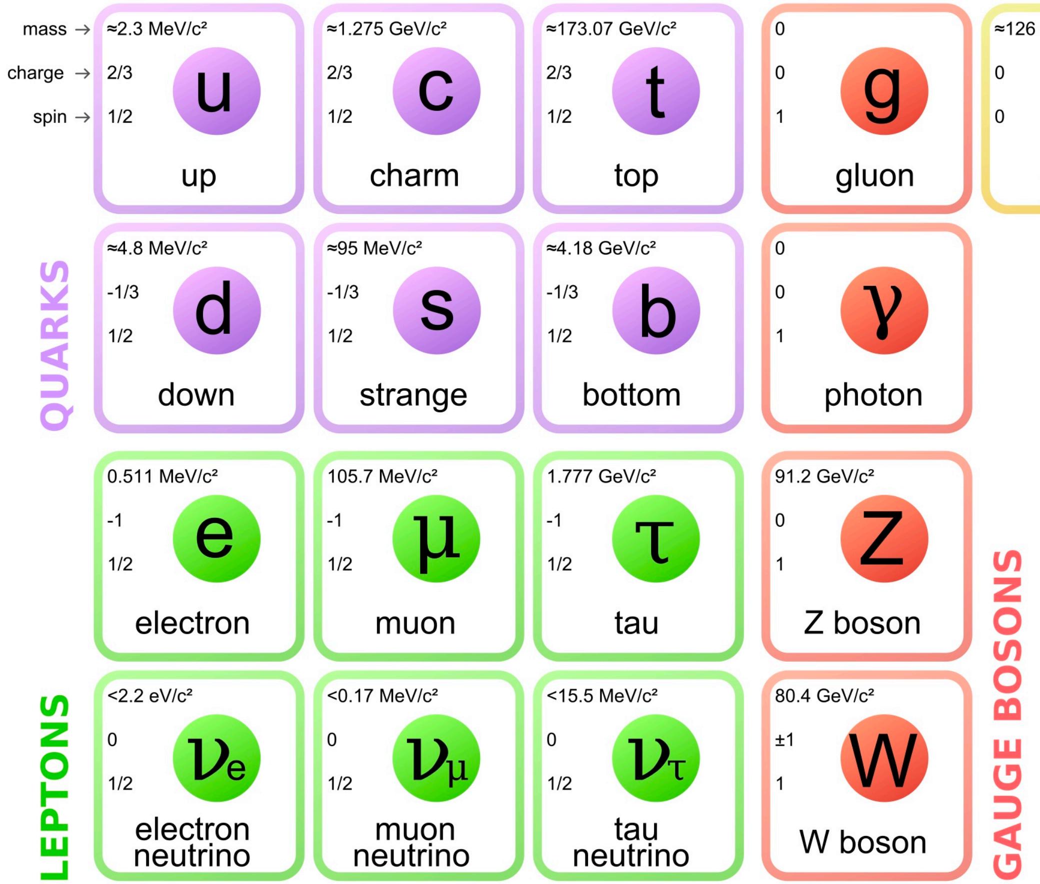
nucleons & mesons



quarks & gluons

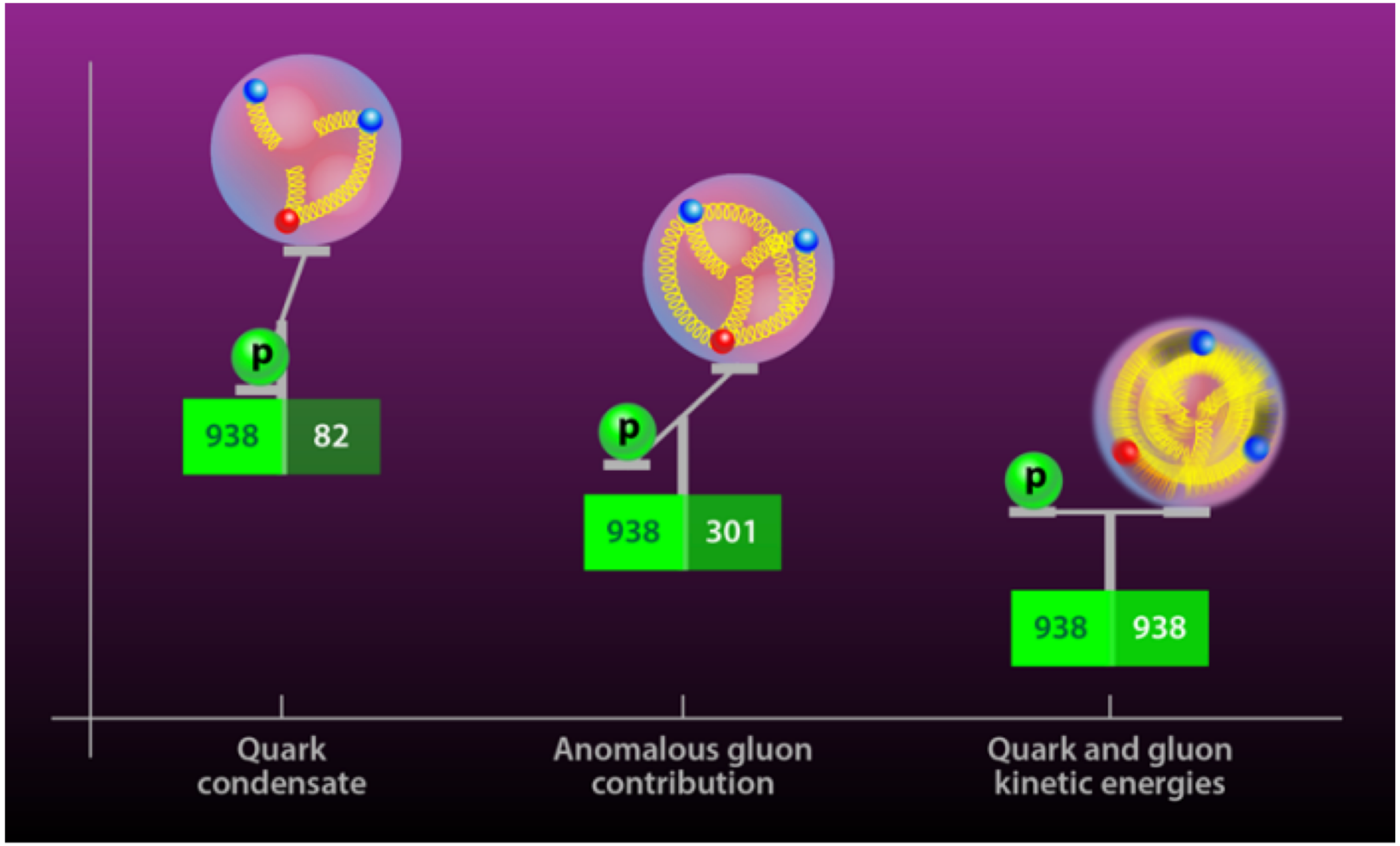
Where does the proton get its mass?

Mass emerges out of the complex structure of the proton



Mass of the proton > 100x the sum of the constituent quark masses!

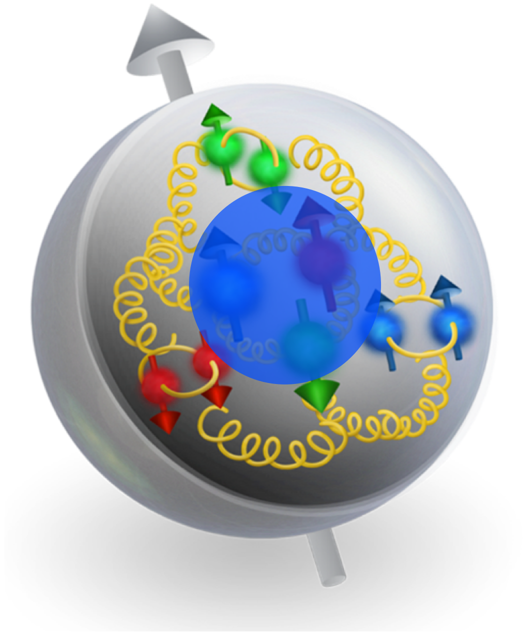
90% from the dynamics of quarks and gluons

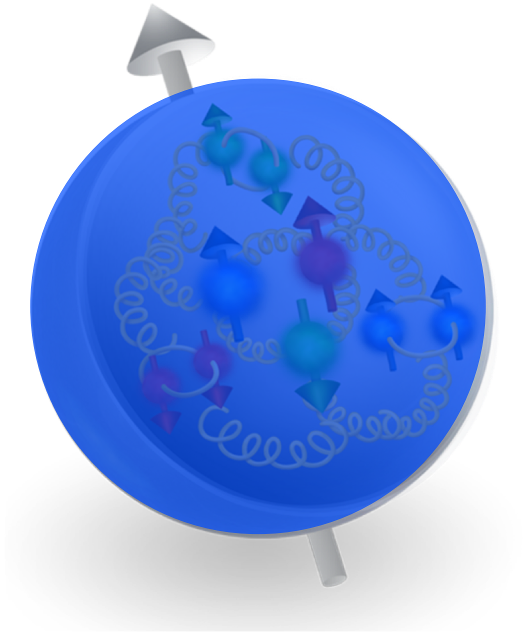


A. Walker-Loud, https://physics.aps.org/articles/pdf/10.1103/Physics.11.118
Y.-B. Yang et al, Phys. Rev. Lett. 121, 212001 (2018).

How does the mass radius compare to the charge radius?

Where is the energy inside the proton?



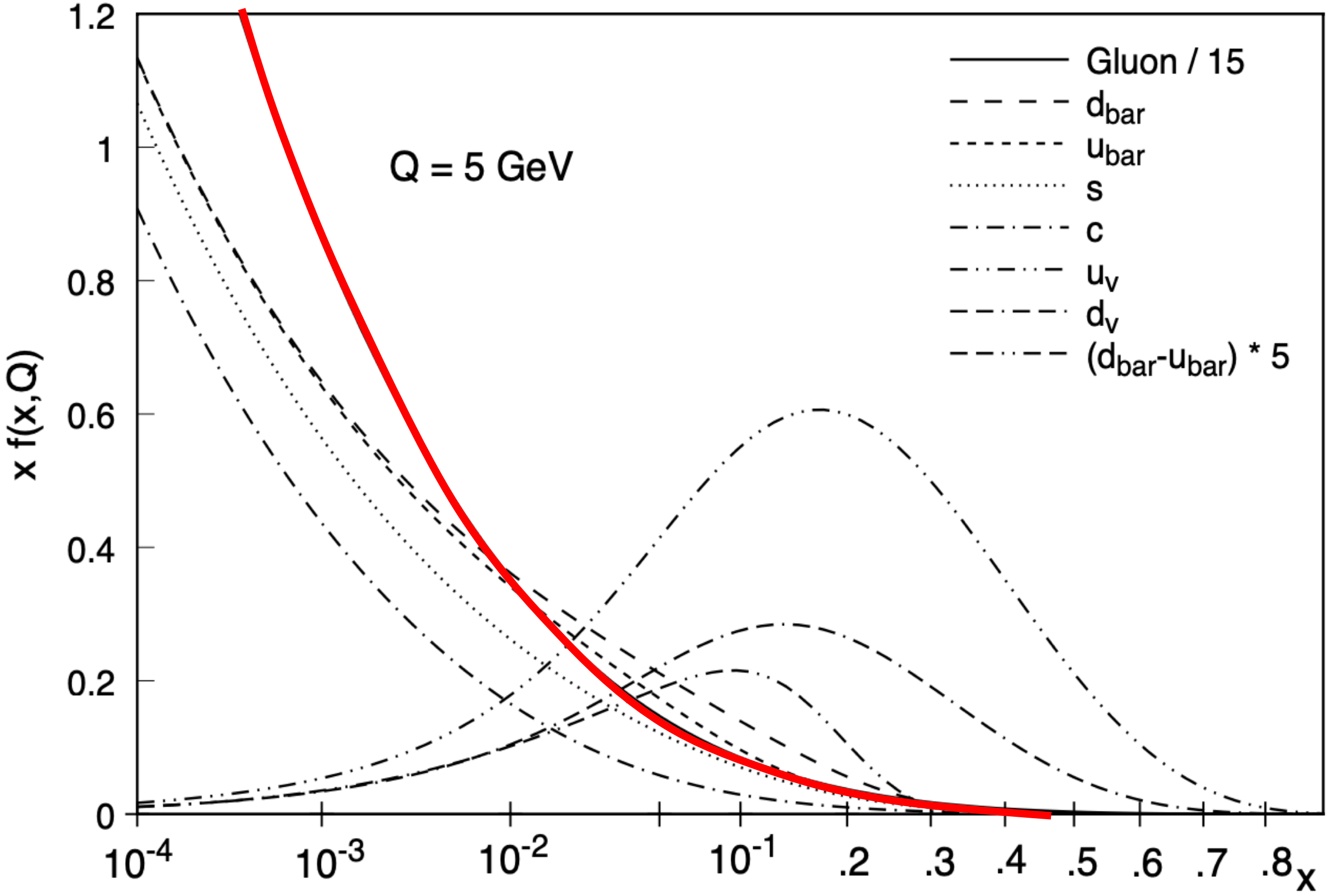


Dense, energetic core?

Same as the charge radius?

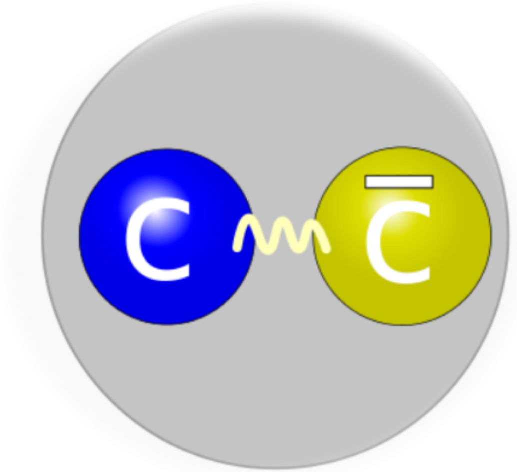
Halo beyond the charge radius?

Recall the enormous gluonic contribution!



How do we learn about the gluonic part?

Hints from quarkonium: J/ψ



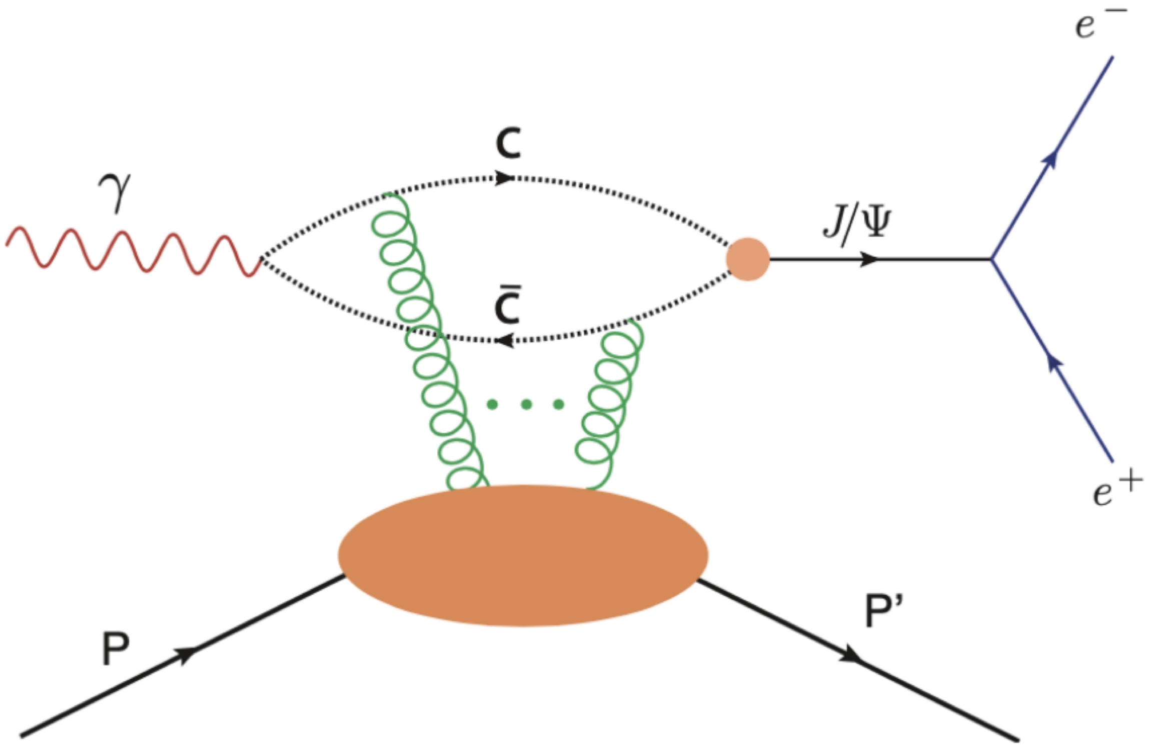
Discovered separately (simultaneously) by groups at SLAC and BNL

J/ ψ only couple to gluons, not light quarks

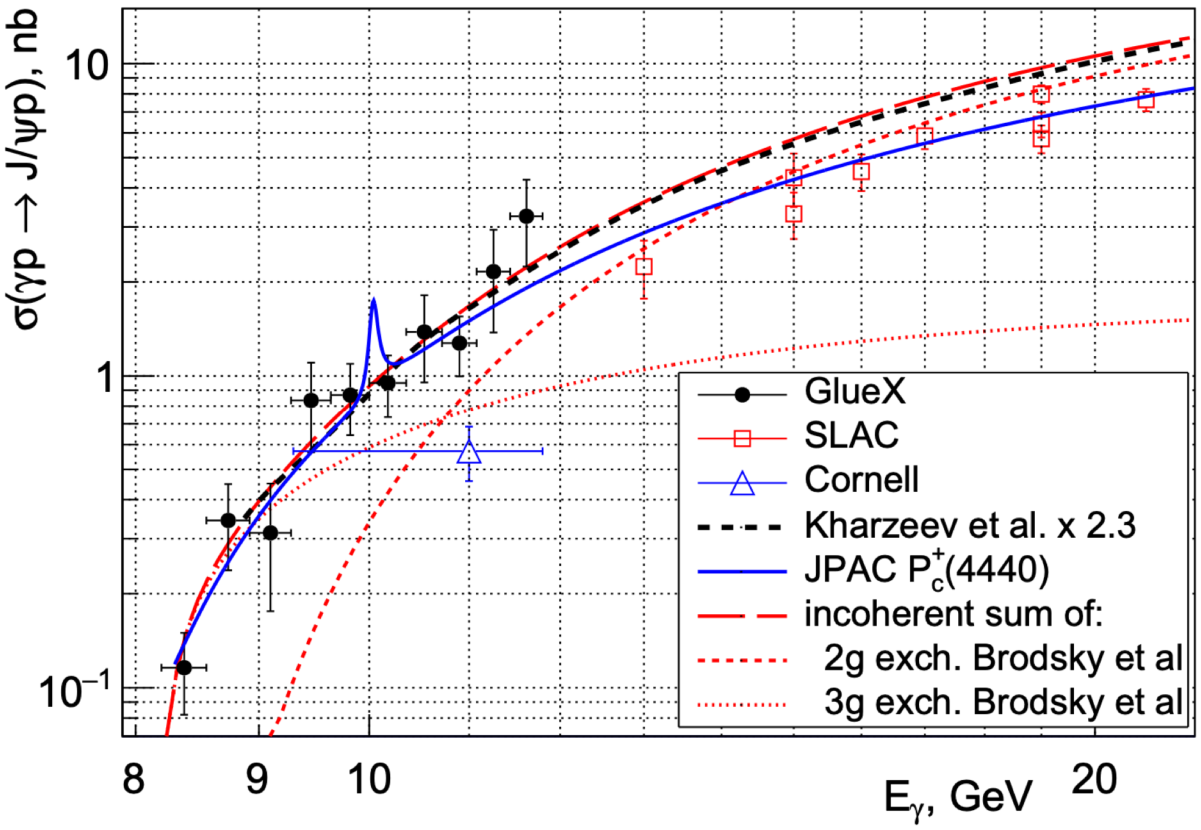
Near threshold cross section provides direct insight to gluons

Branching ratios to leptons

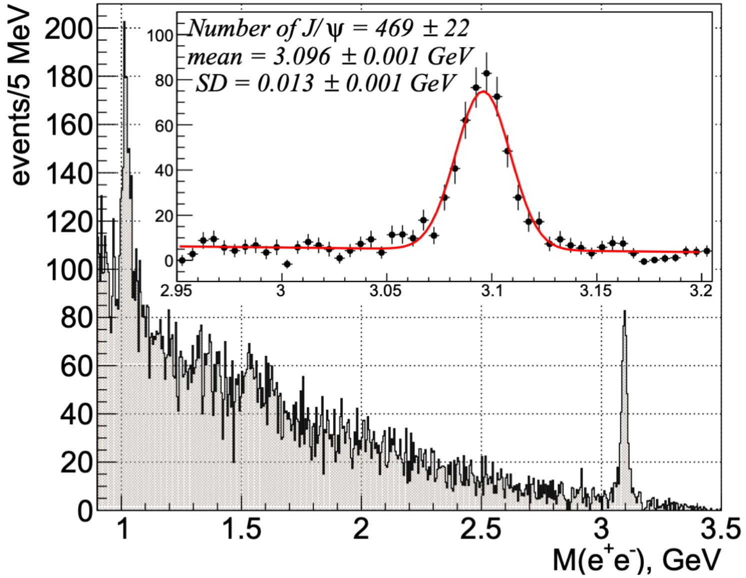
$J/\psi(1S) \rightarrow e^- e^+ / \mu^- \mu^+$ 6.0%

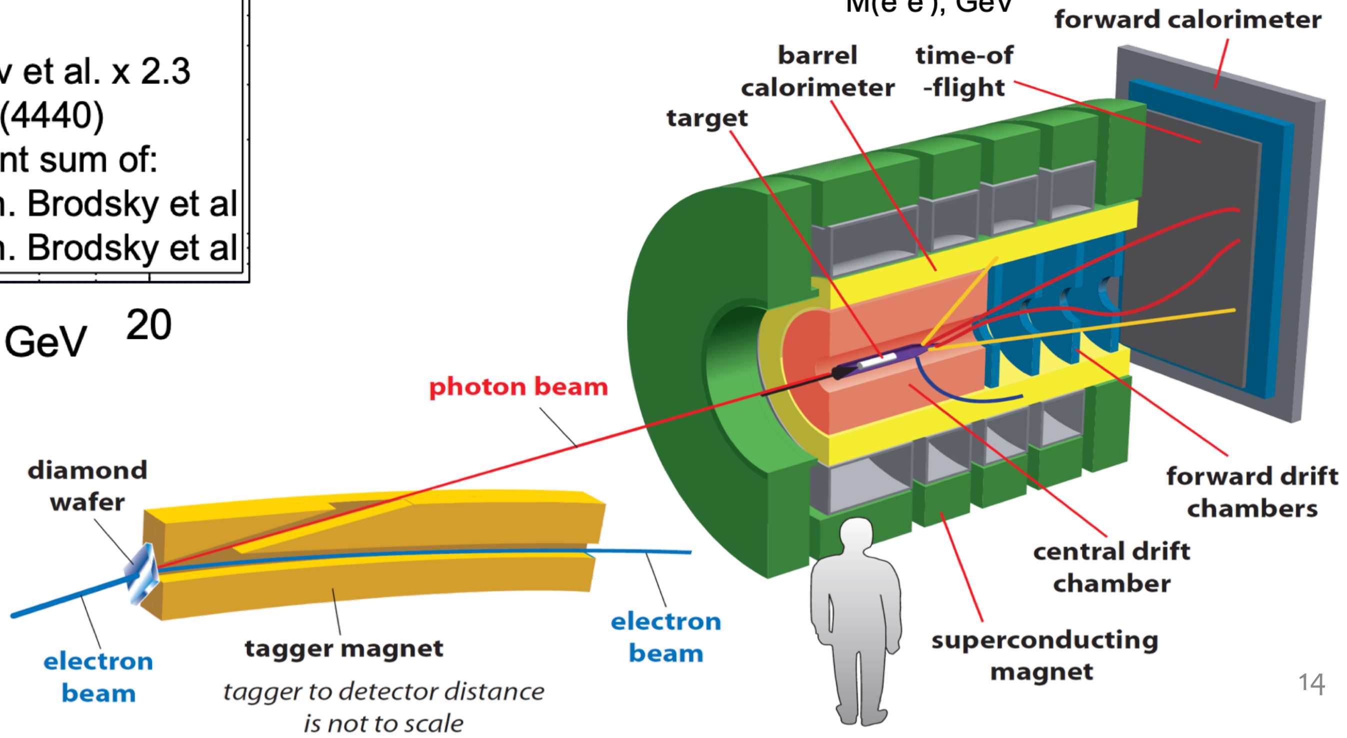


Hall D at JLab measures the J/ψ



A. Ali et al, Phys. Rev. Lett. **123**, 072001 (2019)





Gravitational Form Factors (GFF)

QCD Energy-Momentum Tensor (EMT):

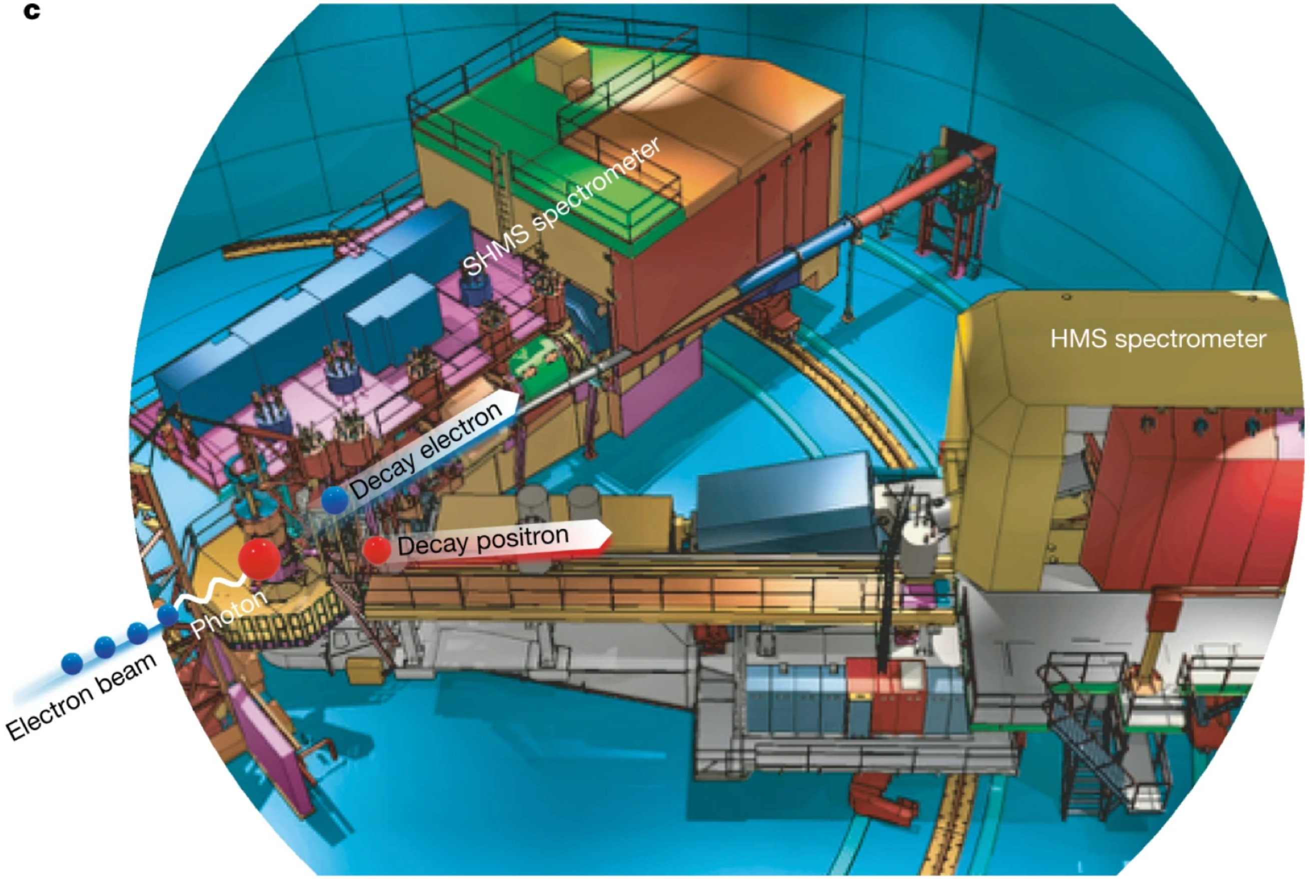
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N \rangle = \bar{u}(N') \left(A_{g,q}(t) \gamma^{\{\mu} P^{\nu\}} + B_{g,q}(t) \frac{i P^{\{\mu} \sigma^{\nu\}} \rho \Delta_\rho}{2M} + C_{g,q}(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{M} + \bar{C}_{g,q}(t) M g^{\mu\nu} \right) u(N)$$

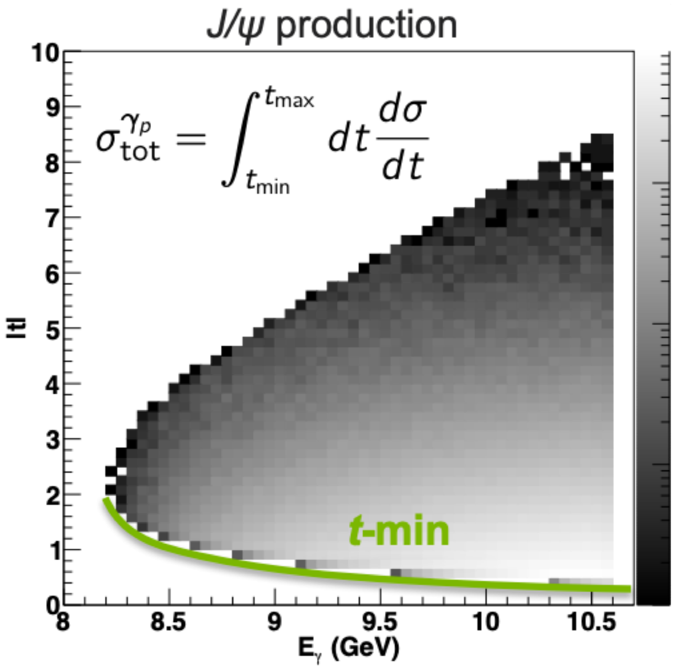
- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = 1/2 \left(A_{g,q}(t) + B_{g,q}(t) \right)$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

Read recent article from Hall C experiment in pairs, and discuss:
B. Duran et al, *Nature* volume 615, pages813–816 (2023)
https://www.nature.com/articles/s41586-023-05730-4

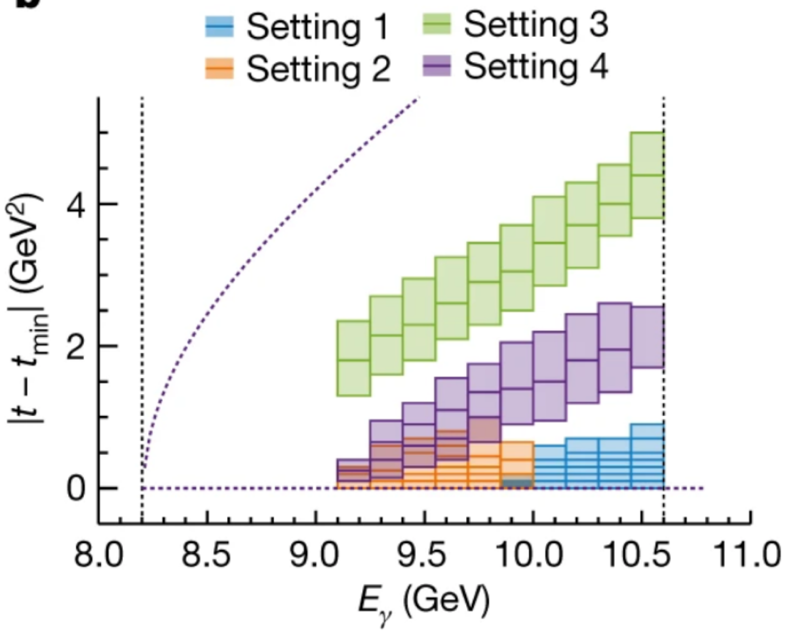
Some guiding questions:
1. How was the experiment set up?
2. What was it trying to measure?
3. What did we learn from this data?
4. Why does this matter?

c

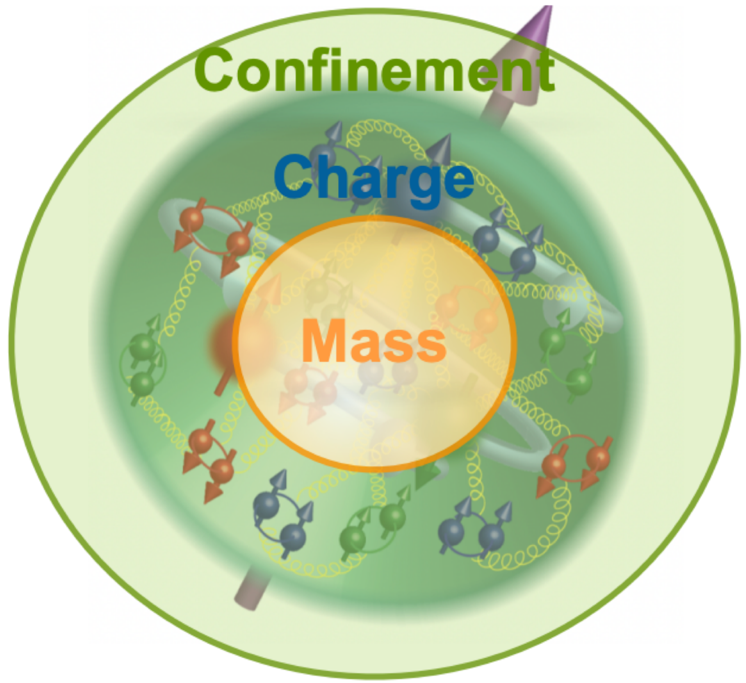

SHMS spectrometer
HMS spectrometer
Decay electron
Decay positron
Photon
Electron beam


J/ψ production
$\sigma^{\gamma_p}_{tot} = \int_{t_{min}}^{t_{max}} dt \frac{d\sigma}{dt}$
|t|
E_γ (GeV)
t-min
0 1 2 3 4 5 6 7 8 9 10
8 8.5 9 9.5 10 10.5

b

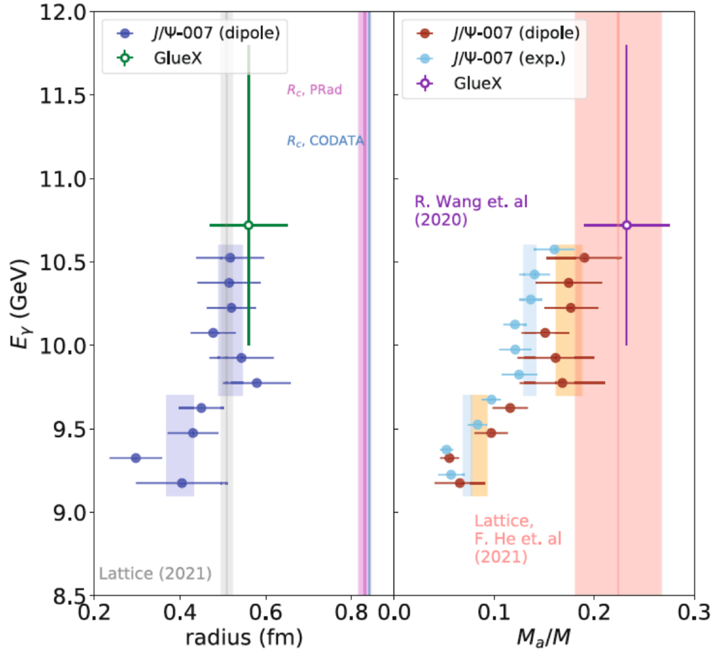

Setting 1
Setting 2
Setting 3
Setting 4
$|t - t_{min}|$ (GeV^2)
E_γ (GeV)
0 2 4
8.0 8.5 9.0 9.5 10.0 10.5 11.0

Mass radius < charge radius

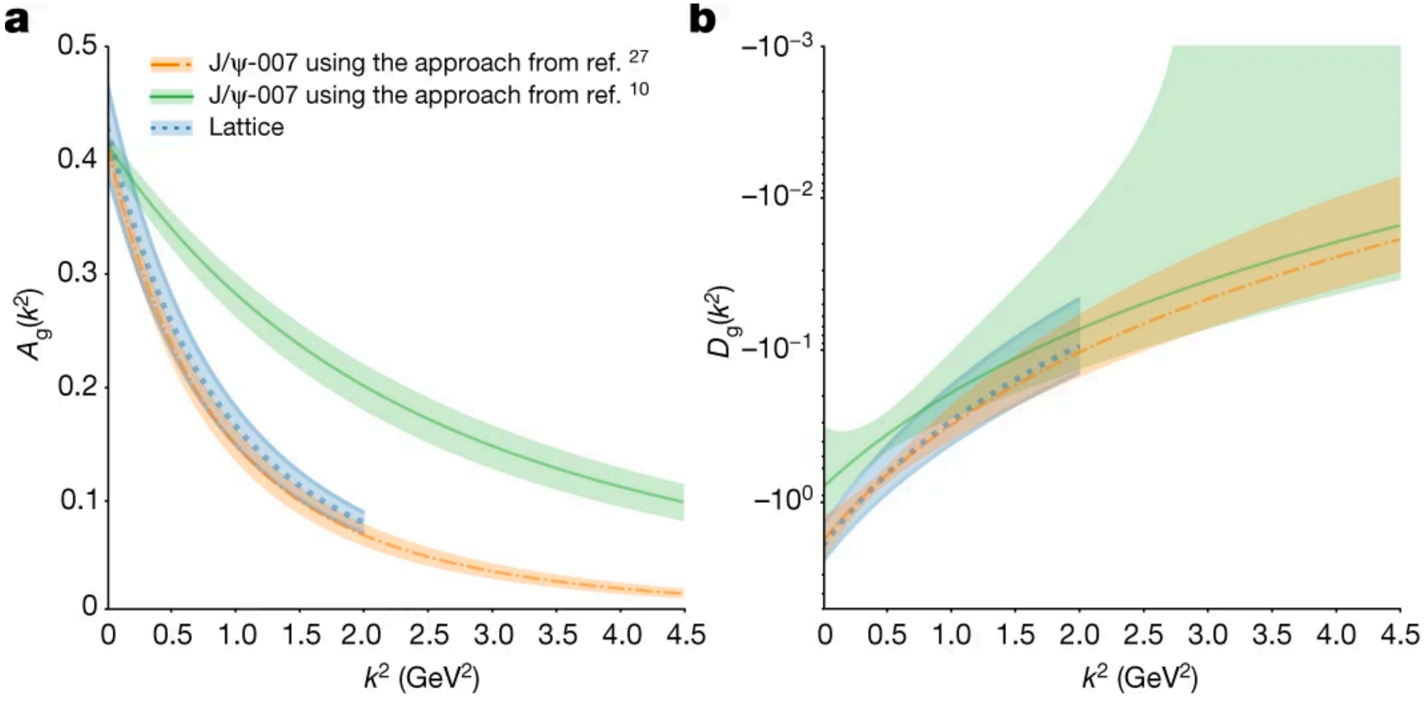


Inner core, dominated by tensor gluonic fields

Confining scalar gluon density (> charge radius)



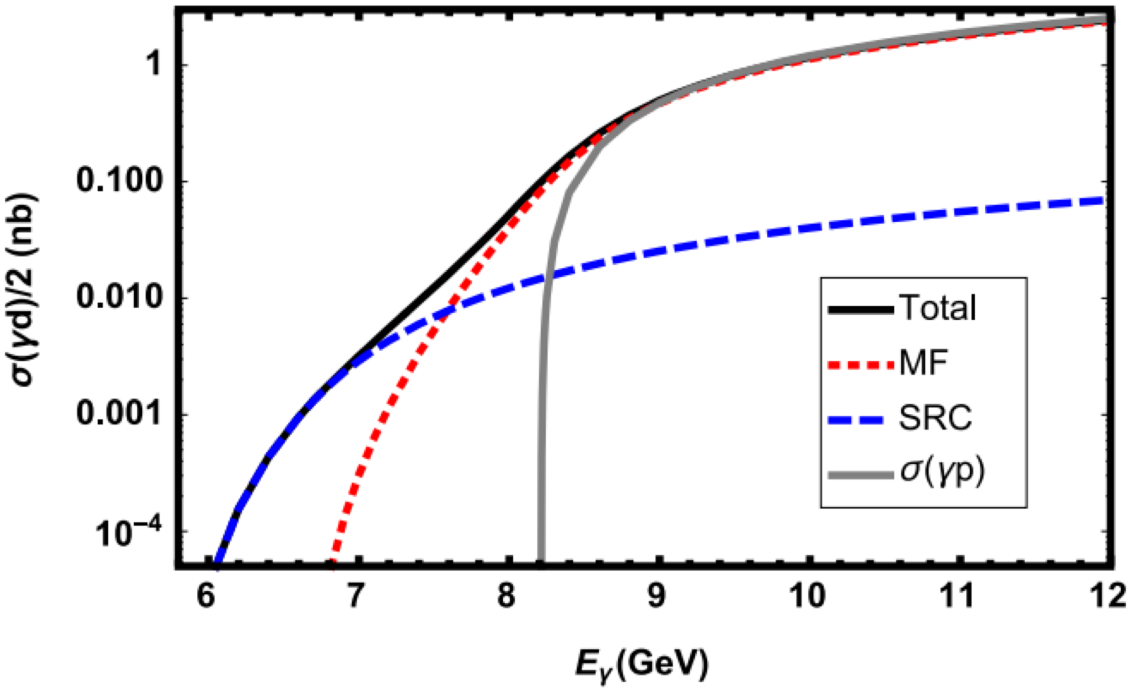
Extended Data Fig. 2 | Mass radius and trace anomaly. Left panel: The extracted radius as a function of the photon energy according to ref.[9] together with the GlueX result. Both our and the GlueX extractions used a dipole fit of the form factor. The charge radius from CODATA and the latest electron scattering[6] (labeled PRad) are plotted as lines with error bands. The lattice result[12] is plotted as a grey line with grey error band. Right panel: The extracted M_a/M according to Ji's mass decomposition[40] following[32] along with a recent direct lattice calculation of the same quantity[41].



Lots of possibilities with J/ψ

Is there a gluonic analogue to the EMC Effect? Near threshold could tell us …

Can we study SRCs? Theory says yes! Could be a gluonic probe of SRCs

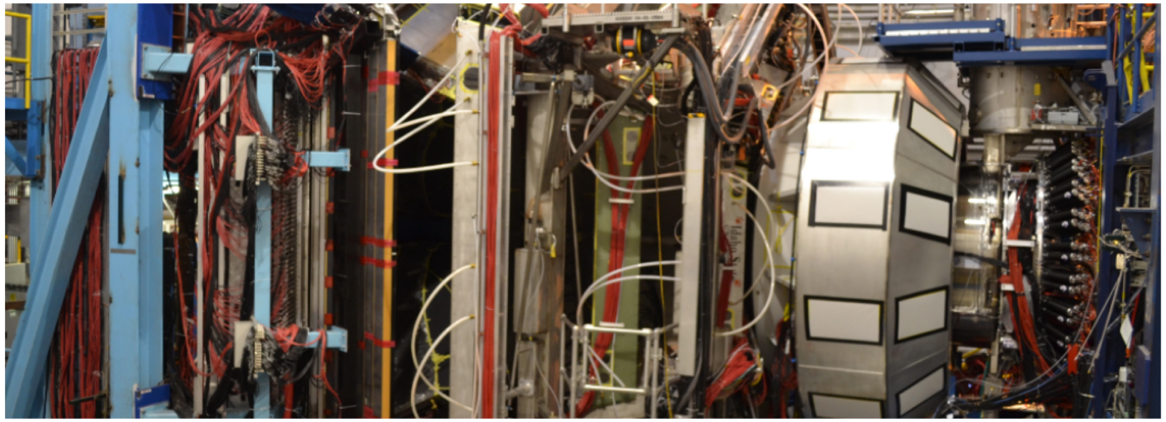


Test of SRC Universality:
i.e. SRCs are responsible for the EMC Effect across all different nuclei in the same manner?

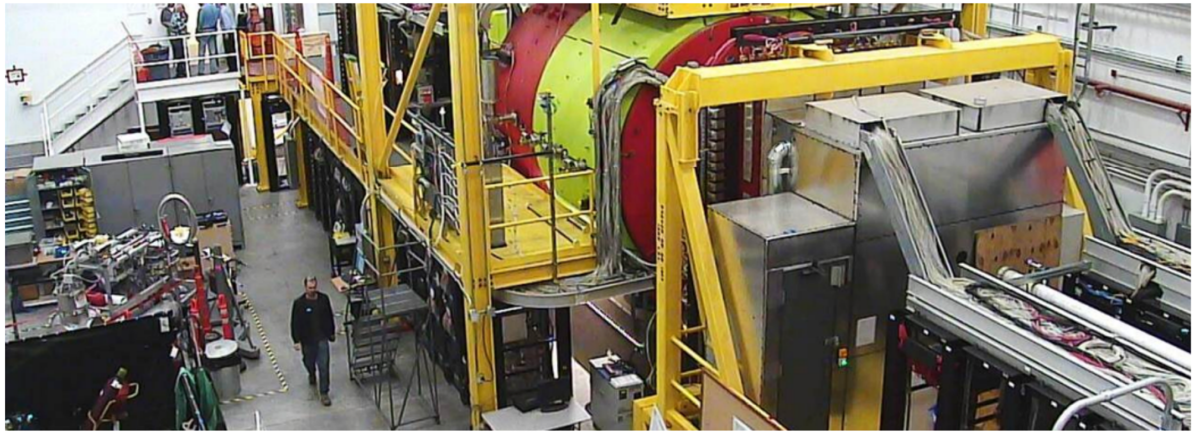
Y. Hatta et al, Physics Letters B, vol. 803, p. 135321, (2020).

J/ψ has a rich program at JLab and an exciting future!

Hall B CLAS12 detector in RG-A and RG-B



Hall D: first results at Jlab, future with sub-threshold?



Future large acceptance spectrometer in Hall A to measure both electro- and photoproduction, in both inclusive and exclusive channels