J/ψ at Threshold at JLab (Hall A, B)

Jian-ping Chen, Jefferson Lab,

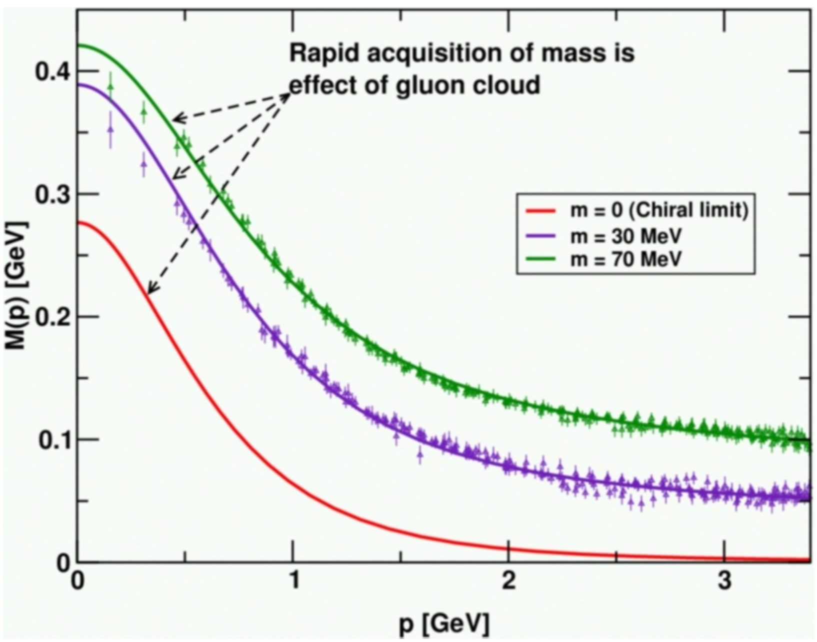
ECT* Workshop on Proton Mass, April 3-7, 2017

- Introduction
- Jefferson Lab 12 GeV Energy Upgrade
- J/ψ Threshold Production with SoLID
- J/ψ Threshold Production with CLAS12
- Summary

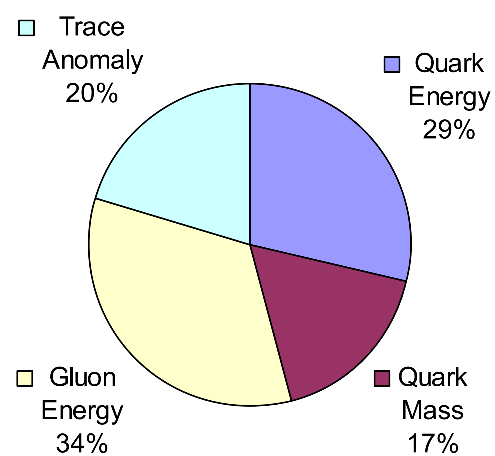
Thank Zein-Eddine Meziani and Stepan Stepanyan for helping with slides

Introduction: Proton Mass

Mass Generation



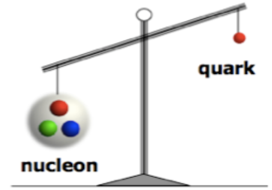
Mass Decomposition



Nucleon Structure: A Universe Inside

- Nucleon: proton =(uud) , neutron=(udd) + *sea quarks* + *gluons*
- Nucleon: ***99% of the visible mass in universe***

➢ **Proton mass "puzzle":**



m_q ~ 10 MeV

m_N ~ 1000 MeV

Quarks carry $\sim 1\%$? of proton's mass

How does glue dynamics generate the energy for nucleon mass?

➢ **Proton spin "puzzle":**

Quarks carry $\sim 30\%$ of proton's spin

How does quark and gluon dynamics generate the rest of the proton spin?

➢ **3D structure of nucleon**: **3D in momentum or (2D space +1 in momentum)**

Color Confinement — Asymptotic freedom → Q (GeV)

200 MeV (1 fm) — 2 GeV (1/10) — Probing momentum

How does the glue bind quarks and itself into a proton and nuclei?

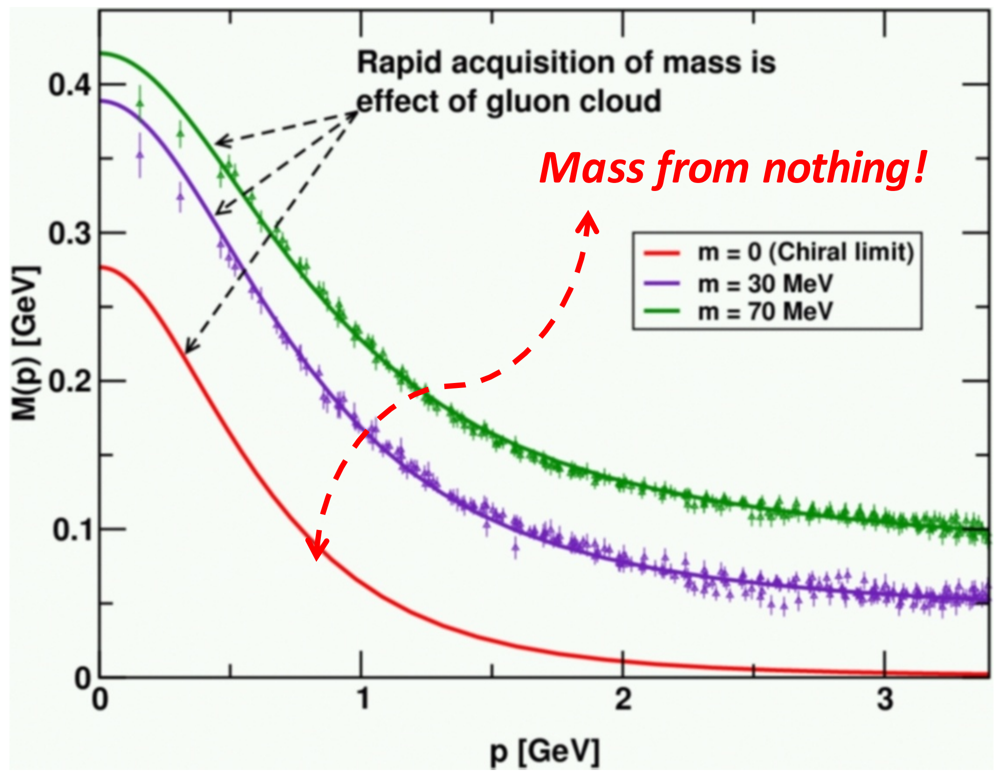
Can we scan the nucleon to reveal its 3D structure?

Theoretical Developments

- **Dynamical Chiral Symmetry Breaking <-> Confinement**
  - Responsible for ~99% of the nucleon mass
  - Higgs mechanism is (almost) irrelevant to light quarks
  - Understand proton mass (energy structure) can provide clue

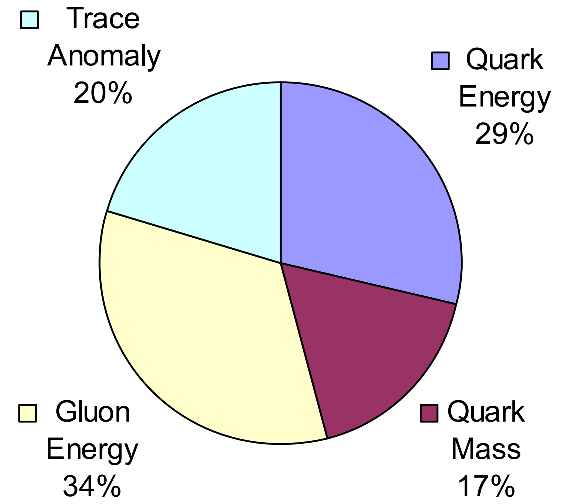
- **Recent development in theory**
  - Lattice QCD
  - Bound State QCD: Dyson-Schwinger
  - Ads/CFT: Holographic QCD
  - ……

- **Direct comparison becomes possible**
  - LQCD: Moments of PDFs
    Proton Mass Decomposition
  - Quasi-PDFs
    x-dependence of PDFs, TMDs, GPDs



Proton Mass: QCD energy

X. Ji, PRL741071(1995)



- One can calculate the proton mass through the expectation value of the QCD Hamiltonian,

$$H_{\rm QCD} = H_q + H_m + H_g + H_a \, .$$

$$H_q = \int d^3\vec{x}\; \bar{\psi}(-i\mathbf{D}\cdot\alpha)\psi,$$ ← *Quark energy*

$$H_m = \int d^3\vec{x}\; \bar{\psi}m\psi,$$ ← *Quark mass*

$$H_g = \int d^3\vec{x}\; \frac{1}{2}(\mathbf{E}^2+\mathbf{B}^2),$$ ← *Gluon energy*

$$H_a = \int d^3\vec{x}\; \frac{9\alpha_s}{16\pi}(\mathbf{E}^2-\mathbf{B}^2).$$ ← *Trace anomaly*

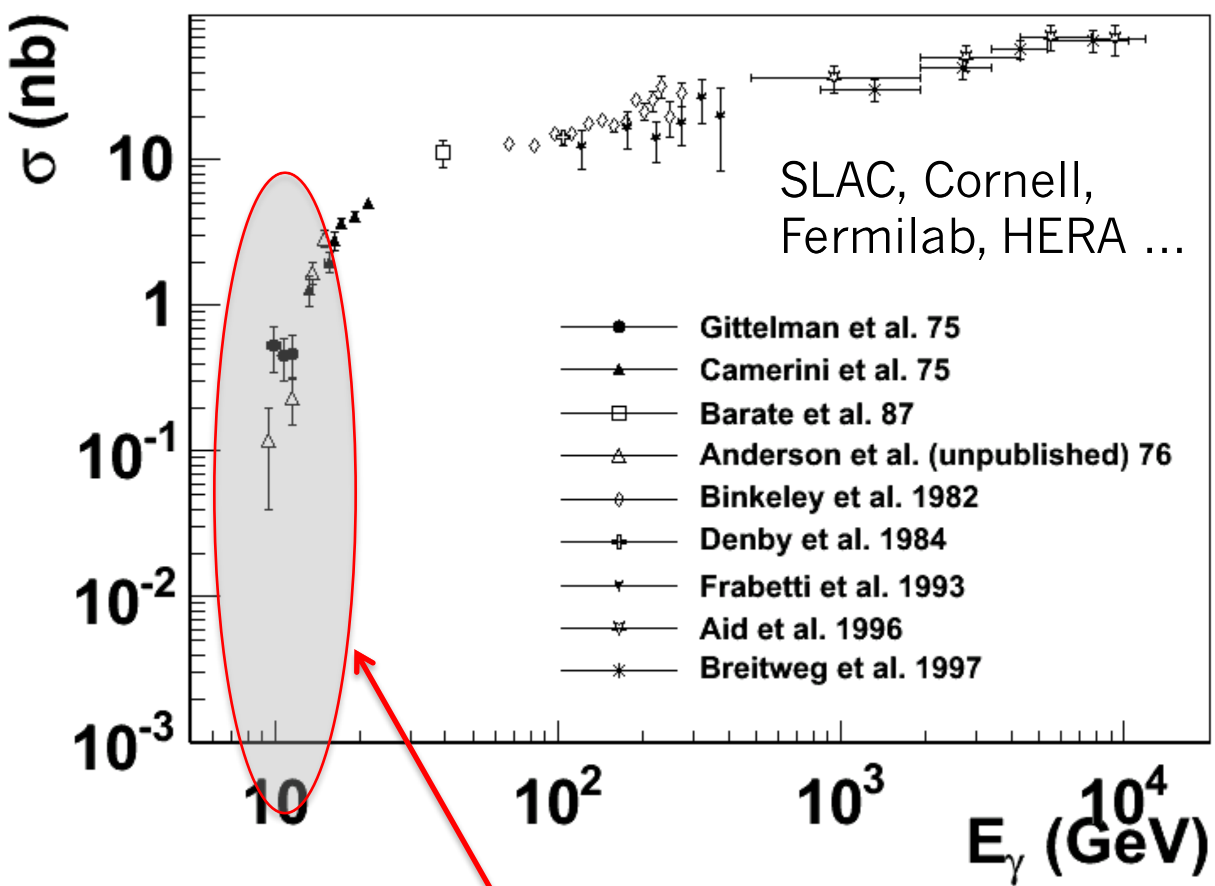
Relating to Measurements

- **Traceless part** at rest frame becomes ***quark kinetic energy and gluon energy***
  can be extracted from **parton distribution functions**
  scheme and scale dependent

- ***Quark mass***: u and d quark contribution obtain from **pi-nucleon sigma term**
  s quark from **Chiral Purturbation Theory for baryon octet**
  or LQCD, …

- ***Trace Anomaly***: **analogous to the cosmological constant (dark energy)!**
  J/ψ threshold production may provide access?

Experimental status $\gamma(\gamma^*) + N \rightarrow N + J/\Psi$

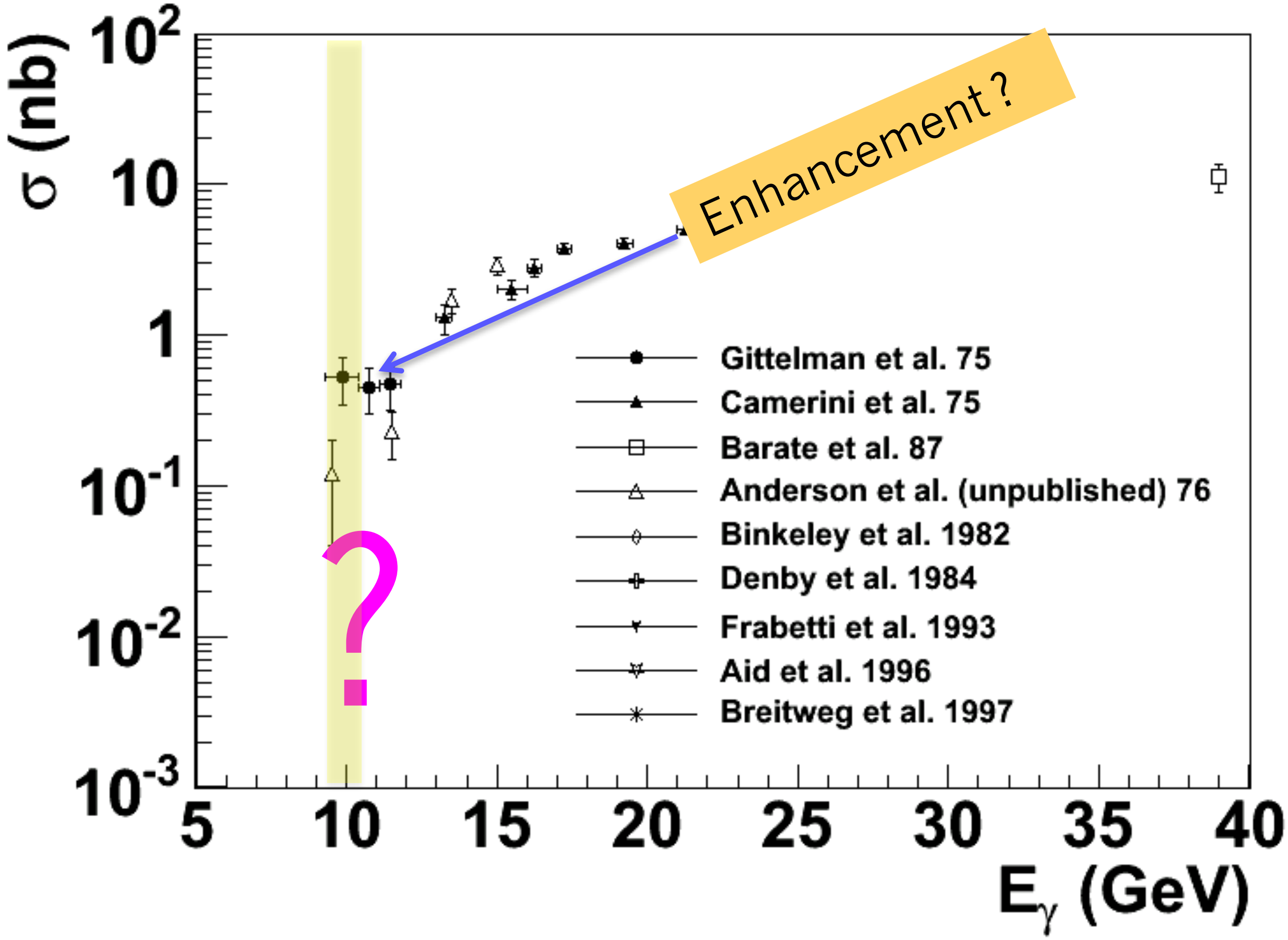


More data exist with inelastic scattering on nuclei, such as A-dependence.

Not included are the most recent results from HERA H1/ZEUS at large momentum transfers and diffractive production with electroproduction as well as the LHC results

The physics focus is this threshold region

Near Threshold $\gamma + N \longrightarrow N + J/\Psi$



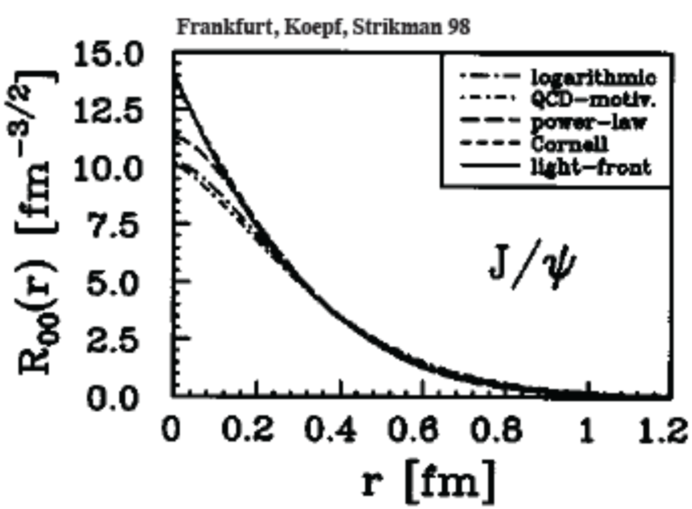
Intense experimental effort (SLAC, Cornell ...) shortly after the discovery of J/ψ

But near threshold not much since **~40 years till now**

J/ψ as probe of the strong color fields in the nucleon!

$$J/\psi(1S): I^G\left(J^{PC}\right) = 0^-\left(1^{--}\right) \qquad M_{J/\psi} \approx 3.097 GeV$$

- **J/ψ is a charm-anti-charm system**
  - Little common valence quark between J/ψ and nucleon
  - Quark exchange interactions are strongly suppressed
- **Charm quark is heavy** $\gg \Lambda_{QCD}$
  - Typical size of J/ψ is 0.2-0.3 fm



Interaction between J/ψ-N

- New scale provided by charm quark mass and size of the J/ψ
  - OPE, Phenomenology, Lattice QCD …
- High Energy region: Pomeron picture …
- Medium/Low Energy: 2-gluon exchange
- Very low energy: QCD color Van der Waals force
  - Prediction of J/ψ-Nuclei bound state
    - Brodsky et al. ….
- Experimentally no free J/ψs are available
  - Challenging to produce close to threshold!
  - **Photo/electro-production of J/ψ at JLab is an opportunity**

Reaction Mechanism ?

Models-I: Hard scattering mechanism

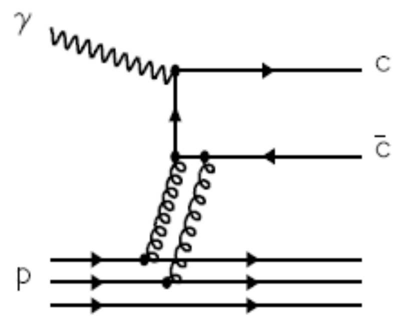
2-gluon exchange

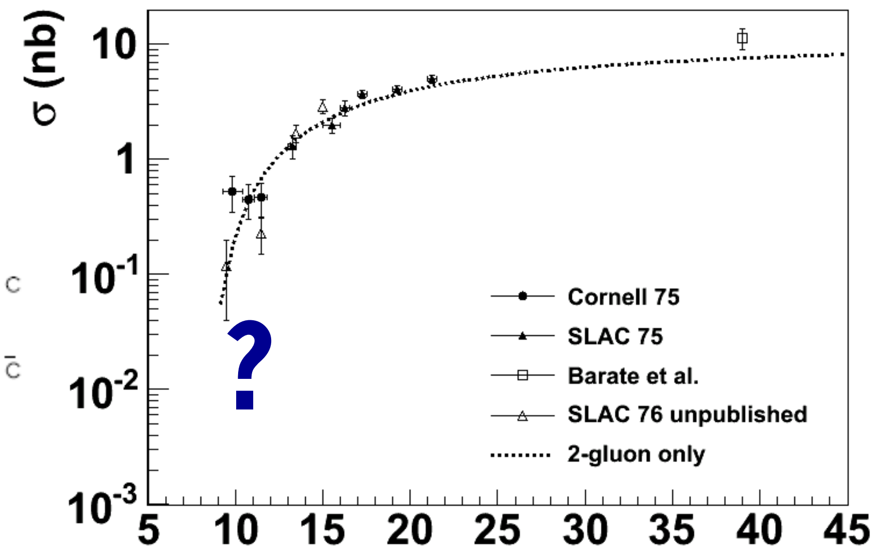
(Brodsky, Chudakov, Hoyer, Laget PLB 498, 23 (2001))

$$2-g:(1-x)^2 F(t)$$

$$F(t) \propto \exp(1.13t)$$

$$x = \frac{2M_p M_{J/\psi} + M_{J/\psi}^2}{2E_\gamma M_p}$$



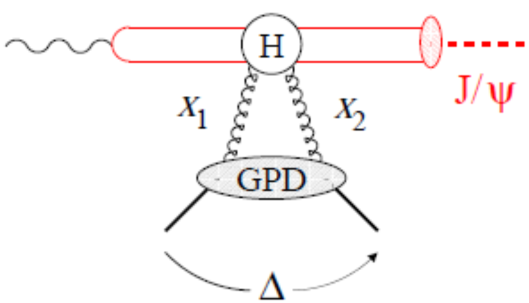


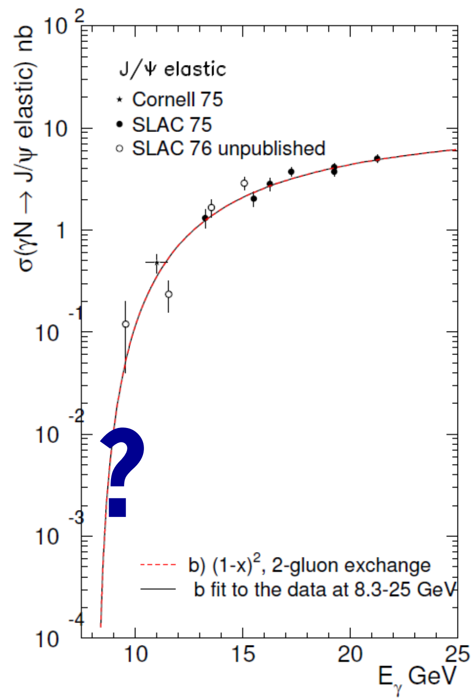
Models -II: Partonic soft mechanism

(Frankfurt and Strikman, PRD 66, 031502 [2002])

2-gluon Form Factor

$$F.F. \propto (1 - t/1.0\ \mathrm{GeV}^2)^{-4}$$





Reaction Mechanism

Models (I): Hard scattering
(Brodsky, Chudakov, Hoyer, Laget 2001)

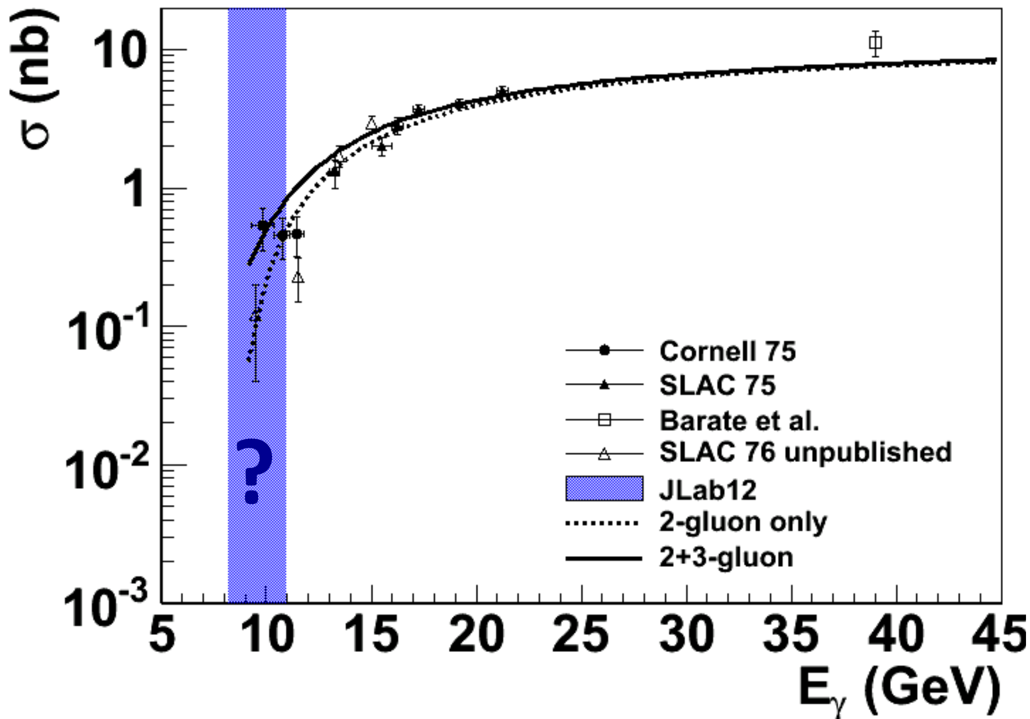
Add in 3-gluon scattering

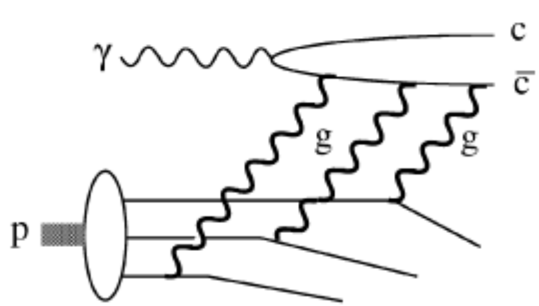
$$2-g:(1-x)^2 F(t)$$

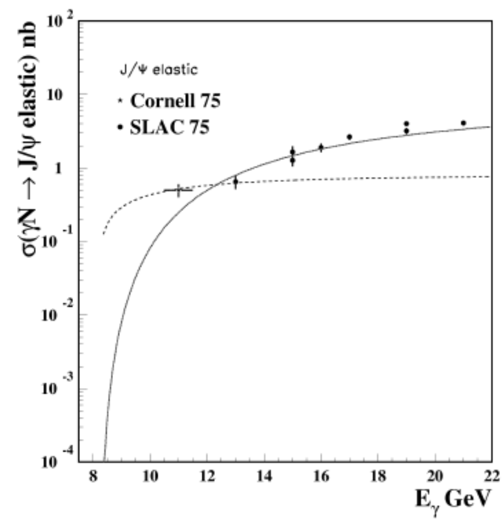
$$3-g:(1-x)^0 F(t)$$

$$F(t) \propto \exp(1.13t)$$

$$x = \frac{2M_p M_{J/\psi} + M_{J/\psi}^2}{2E_\gamma M_p}$$







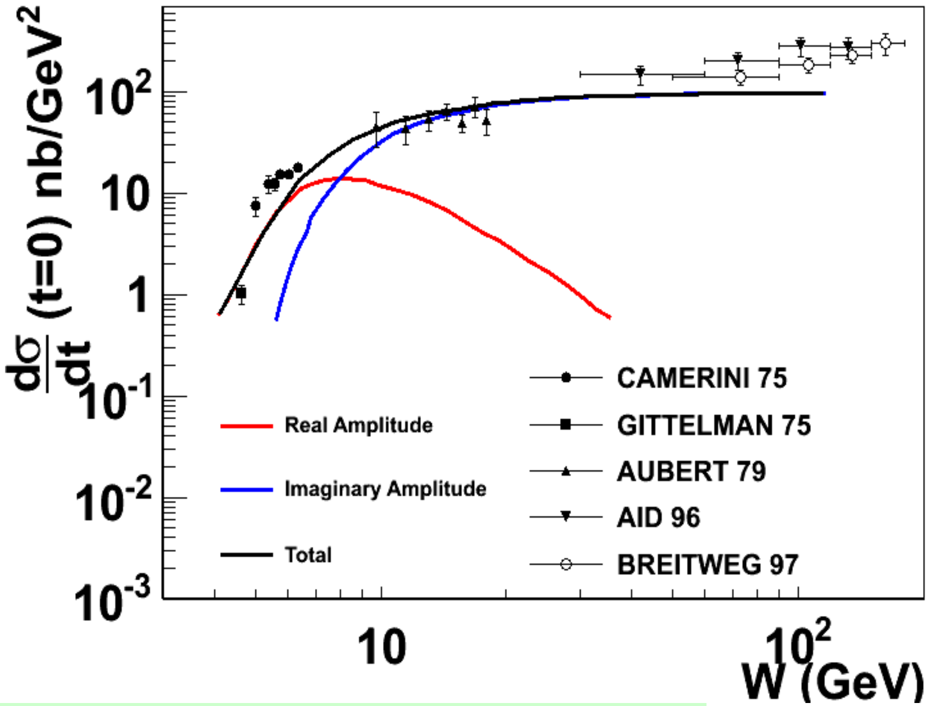
Another view: Reaction mechanism with FSI?

D. Kharzeev. Quarkonium interactions in QCD, 1995 nucl-th/9601029
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999

$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0)=\frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)=\frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$

- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly**
  - Dominate the near threshold region



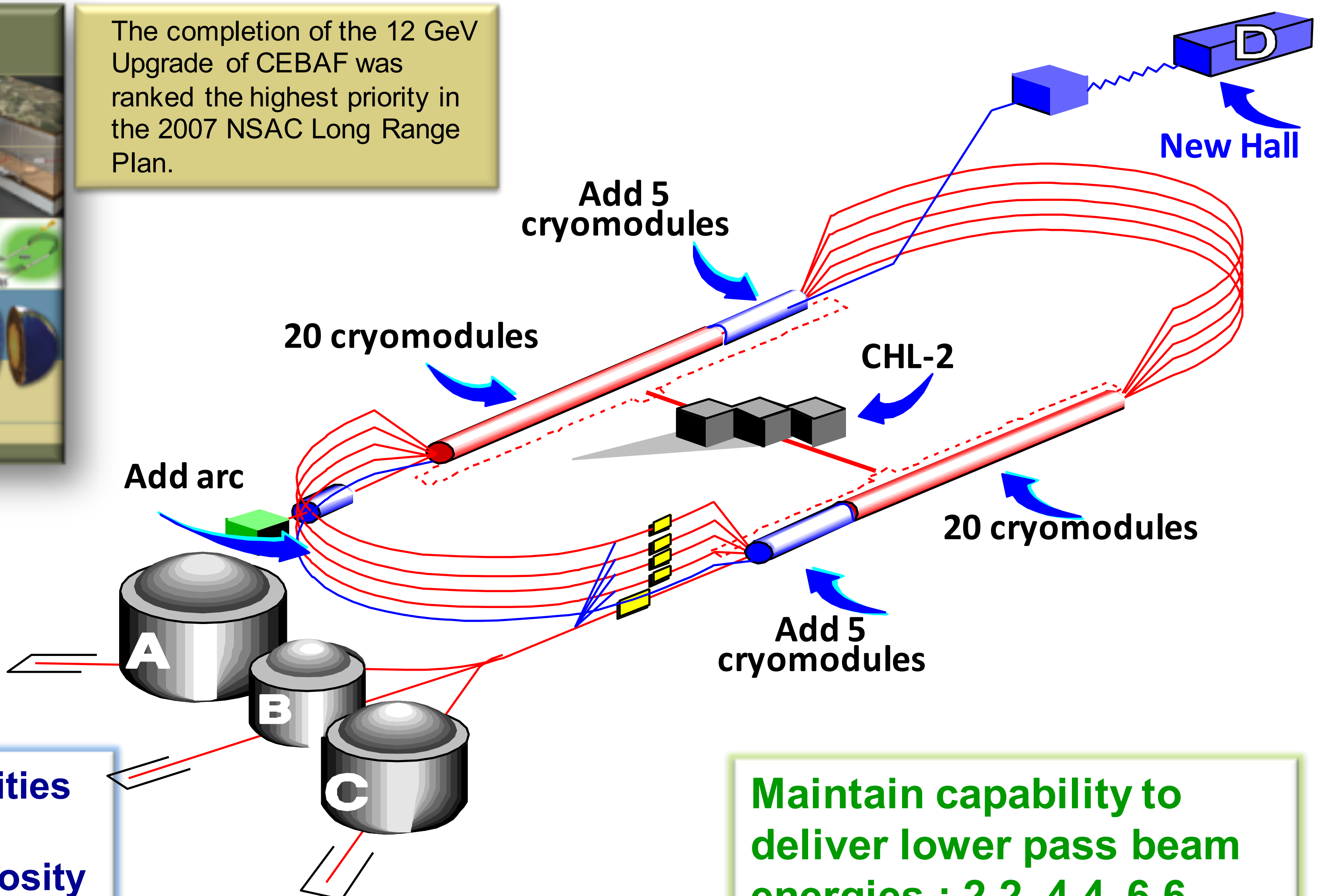
A measurement near threshold could shed light on the conformal anomaly

JLab 12 GeV Upgrade

12 GeV Physics Program

12 GeV Upgrade

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

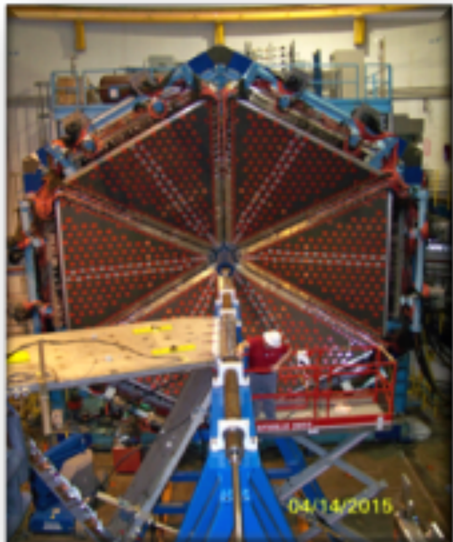


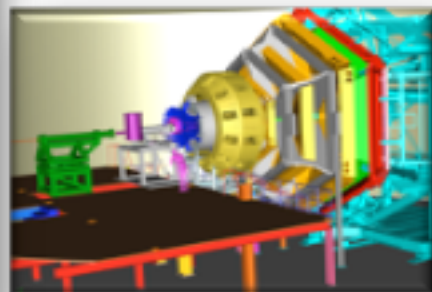
- **Enhanced capabilities in existing Halls**
- **Increase of Luminosity** **10^{35} - ~10^{39} cm^{-2}s^{-1}**

Maintain capability to deliver lower pass beam energies : 2.2, 4.4, 6.6,….

12 GeV Scientific Capabilities

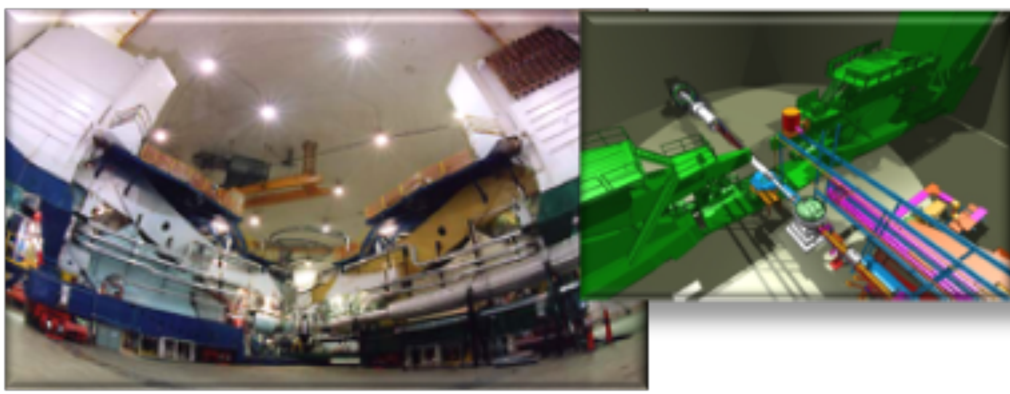
Hall B – understanding **nucleon structure** via **generalized parton distributions,…**





Hall D – exploring origin of **confinement** by studying **exotic mesons**

Hall A – form factors, **future new experiments (e.g., SoLID and MOLLER)**



Hall C – precision determination of **valence quark** properties in nucleons/nuclei

Status of JLab 12 GeV Upgrade

- **Hall A completed three experiments:**

  DVCS-I, GMp and Ar(e, e'p)

- **Hall B complete Prad experiment, partly complete HPS**

  achieved KPP (Key Performance Parameter), upgrade mostly complete

  only remaining equipment is the solenoid

- **Hall C achieved KPP, upgrade complete**
- **Hall D took initial data, have first publication (Eugene Chudakov's talk)**

JLab 12 GeV Upgrade Project pretty much complete

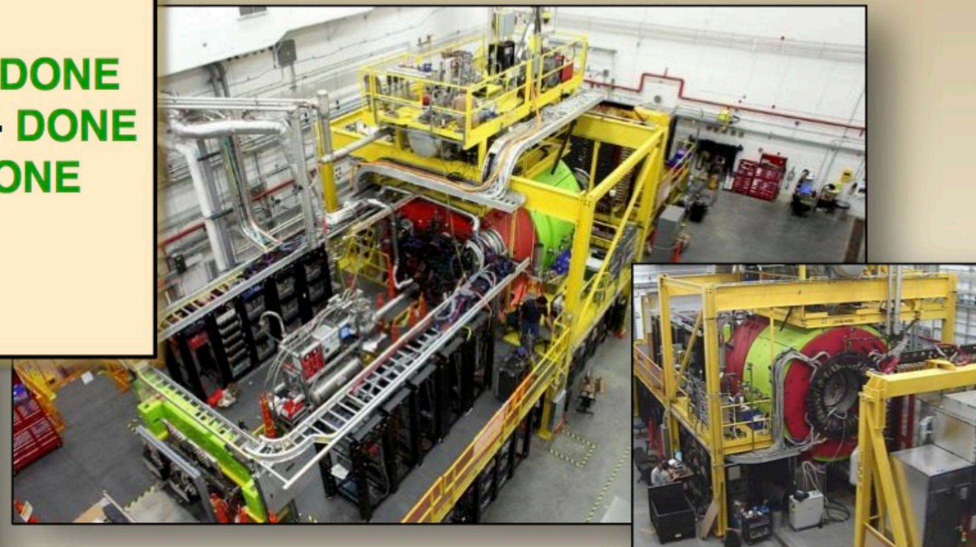
A. Lung

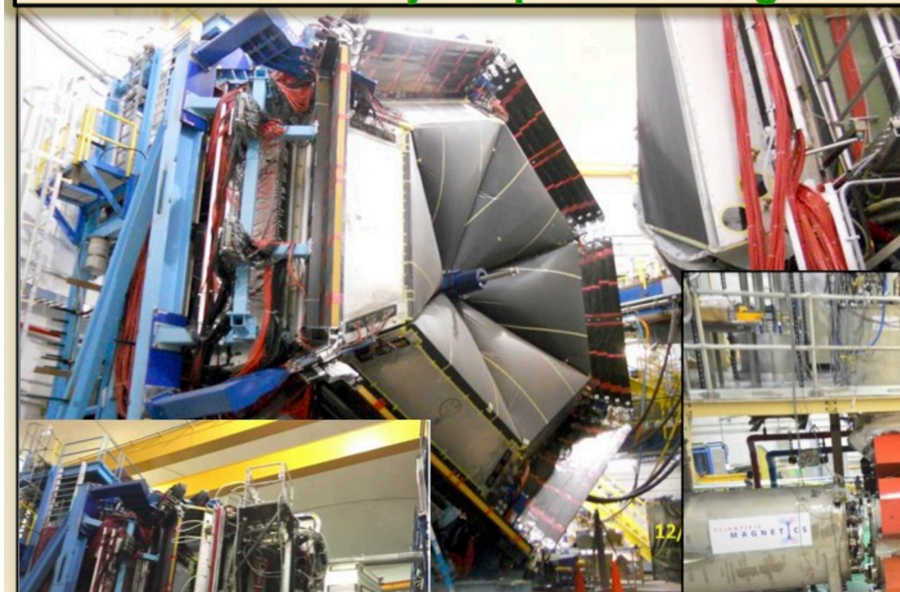
12 GeV Upgrade Project

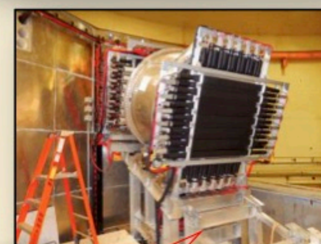
TPC = $338M
ETC < $2M

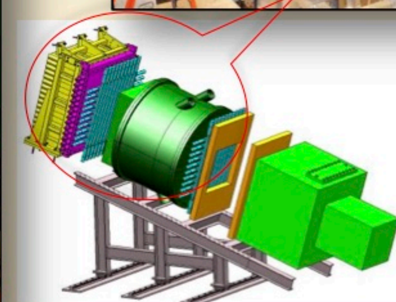
Project Scope (~99.7% complete):

- Doubling the accelerator beam energy - DONE
- New experimental Hall D and beam line - DONE
- Civil construction including utilities - DONE
- Upgrade to Experimental Hall C - DONE
- Upgrade to Experimental Hall B - 99%
  - Solenoid only scope remaining









Planned J/ψ threshold production study at JLab

SoLID Program

Why SoLID

- JLab 6 GeV: precision measurements

  high luminosity (10^{39}) but small acceptance (HRS/HMS: < 10 msr)

  or large acceptance but low luminosity (CLAS6: 10^{34})

- JLab 12 GeV crosses J/ψ production threshold and opens up a window of opportunities (DIS, SIDIS, Deep Exclusive Processes) to study valence quark (3-d) structure of the nucleon and other high impact physics (PVDIS, …)
- High precision in multi-dimension or rare processes requires very high statistics → large acceptance and high luminosity
- CLAS12: luminosity upgrade (one order of magnitude) to 10^{35}
- To fully exploit the potential of 12 GeV, taking advantage of the latest technical (detectors, DAQ, simulations, …) development

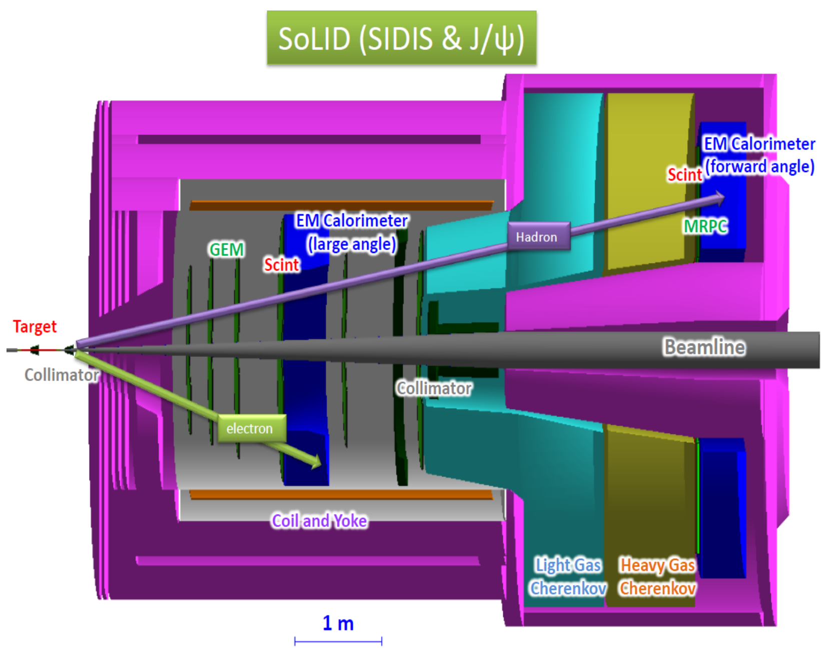
→ SoLID: large acceptance detector can handle 10^{37} luminosity (no baffles)

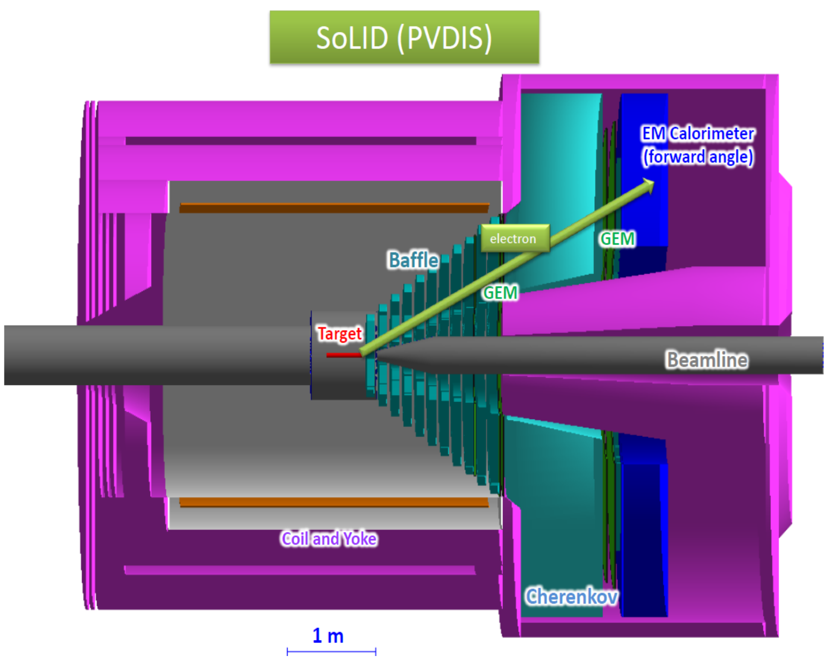
10^{39} with baffles

Overview of SoLID

Solenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**
  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** (10^{37}-10^{39})
  Take advantage of latest development in detectors , data acquisitions and simulations
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region and threshold J/ψ
- **5 highly rated experiments approved**
  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 3 run group experiments)
- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)





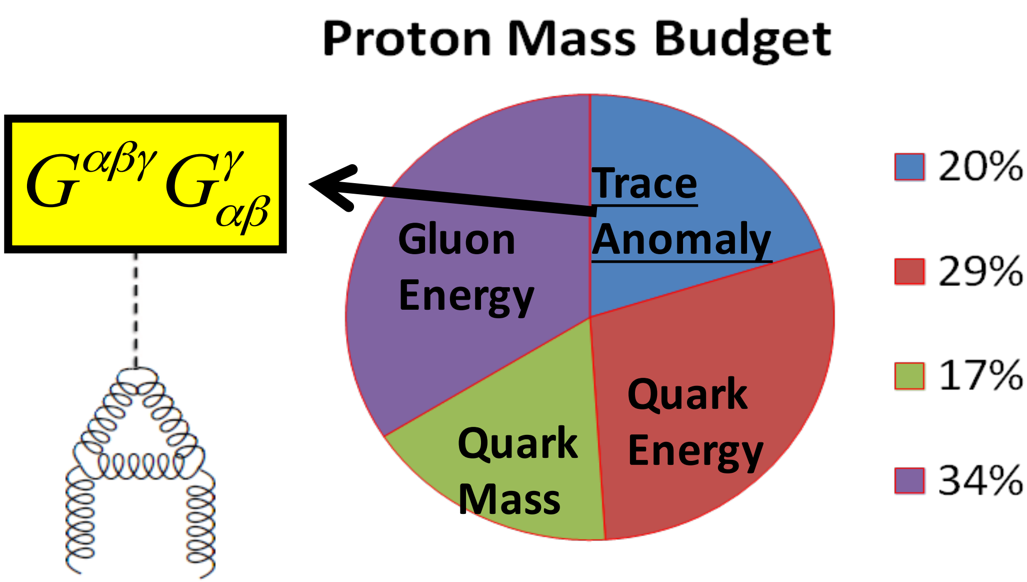
SoLID-J/ψ: Study Non-Perturbative Gluons

J/ψ: ideal probe of non-perturbative gluon

The high luminosity & large acceptance capability of SoLID enables a unique "precision" measurement near threshold

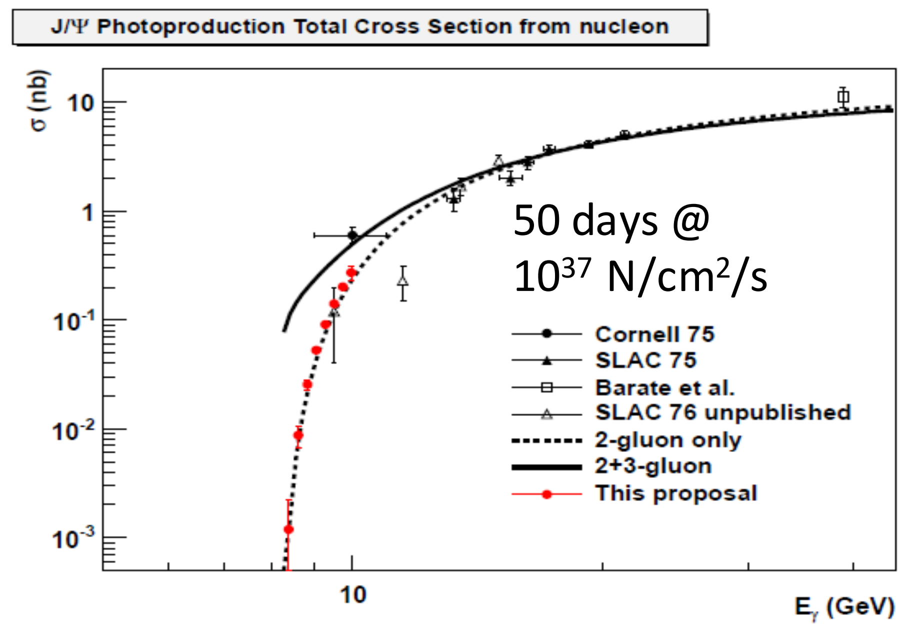
- **Shed light on the low energy J/ψ-nucleon interaction (color Van der Waals force)**
- **Shed light on the 'conformal anomaly' an important piece in the proton mass budget:**

Models relate J/ψ enhancement to trace anomaly



X. Ji PRL 74 1071 (1995)

$$\gamma^* + N \rightarrow N + J/\psi$$



SoLID-J/ψ Program

- **Measure the *t* dependence and energy dependence of *J/ψ* cross sections near threshold**
  - Probe the nucleon strong fields in a non-perturbative region
  - Search for a possible enhancement of the cross section close to threshold
  - Shed some light on the conformal/trace anomaly

Establish a baseline for *J/ψ* production in the JLab energy range!

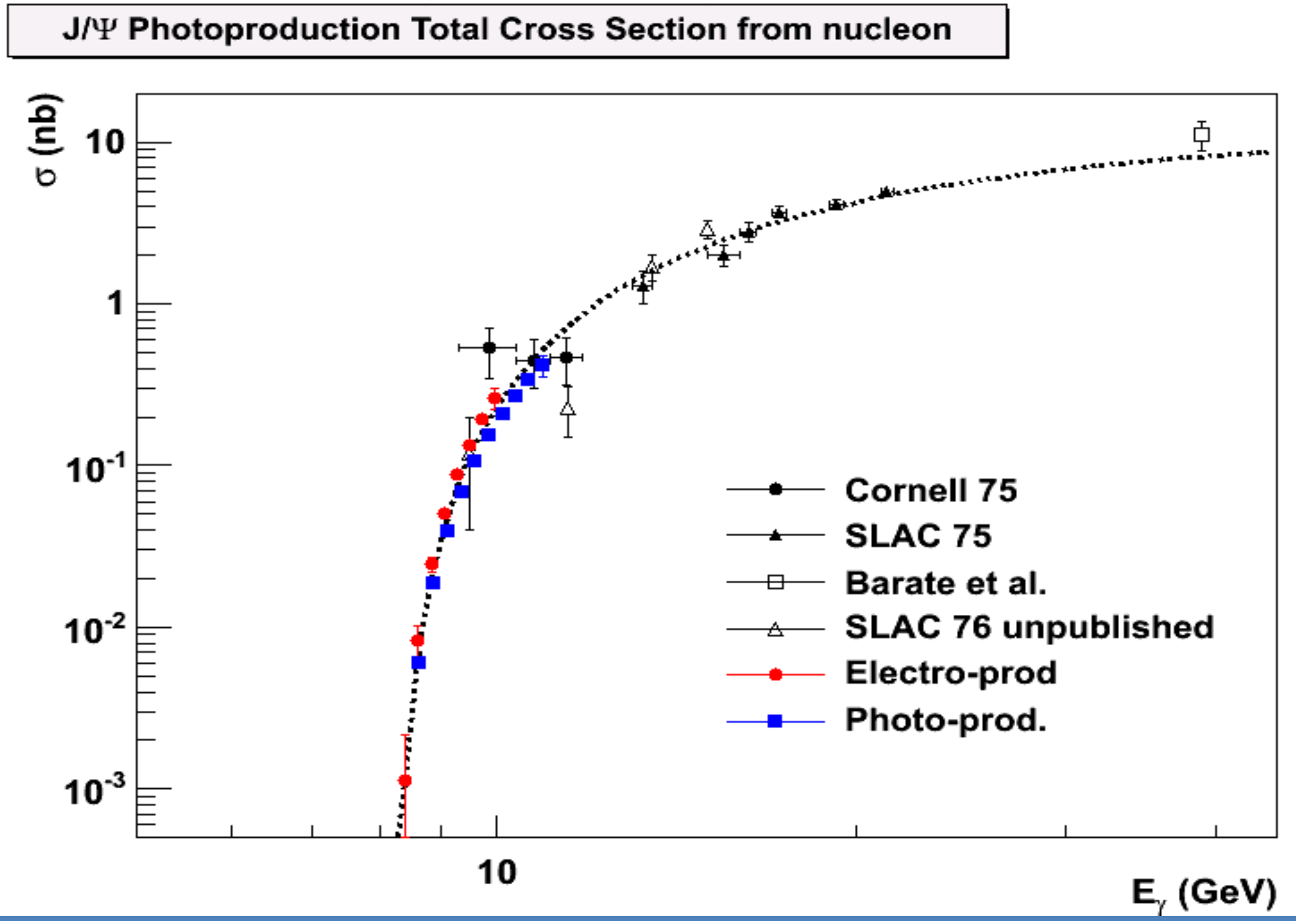
- **Bonuses:**
  - Photoproduction data
  - Decay angular distribution of J/ψ
  - Interference with Bethe-Heitler term (real vs. imaginary)
- **Future Plans:**
  - Search for J/ψ-Nuclei bound states
  - J/ψ medium modification

Experimental Overview

- 50 days of 3 $\mu\mathrm{A}$ beam on a 15 cm long LH_2 target at $1 \times 10^{37} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 10 more days include calibration/background run
- SoLID design overall compatible with SIDIS with some changes
  - +10 cm of the radius of the first three GEM planes
  - Move large angle detector upstream by 12 cm
  - Opening angle at 26 degrees achieved by adding a 20 cm iron ring behind the front yoke
- Main Trigger: Triple coincidence of $e^-e^-e^+$
  - Additional trigger double coincidence (e^+e^-)

$$e^- + p \longrightarrow e^- + p + J/\Psi(e^- + e^+)$$

Projection of Total Cross Section



Lumi 1.2*10^{37}/cm^2/s
11GeV 3uA e- on 15cm LH2
50 Days

Highest statistics at JLab

Study the threshold behavior of cross section with high precision
could shed light on the conformal anomaly

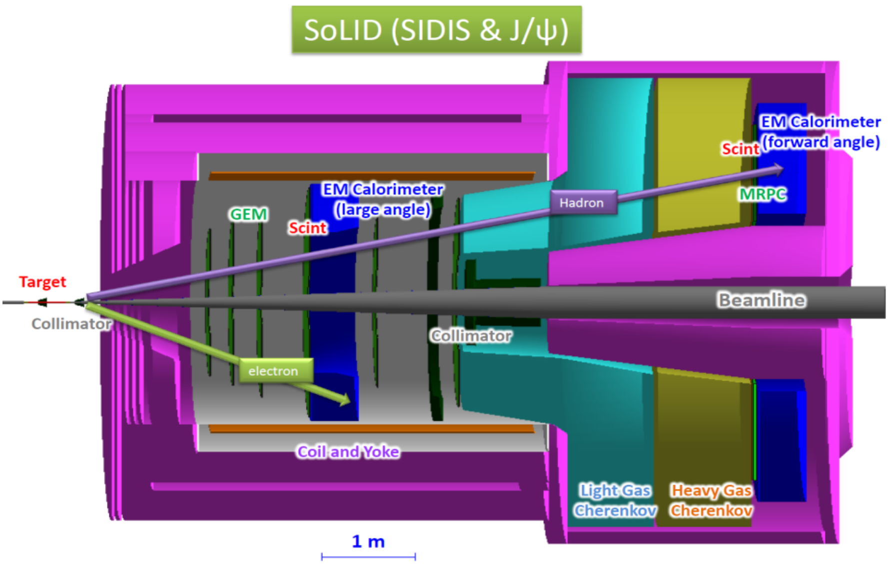
SoLID Programs and Status

SIDIS-Spin: TMDs and Transversity/Tensor Charge

PVDIS: Precision Test of Standard Model

Timeline and Plan

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

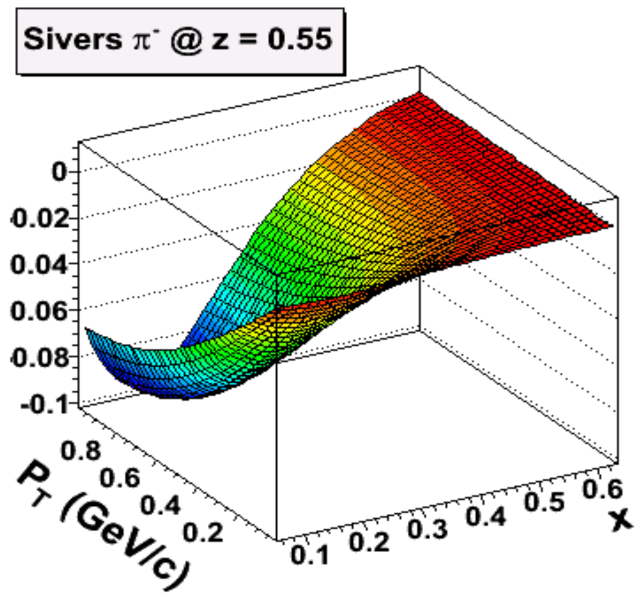


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

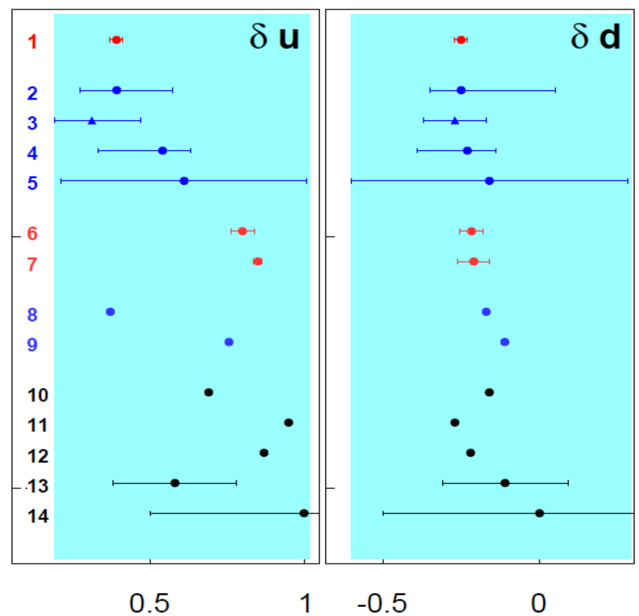
E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, **rating A**

Two run group experiments DiHadron and Ay

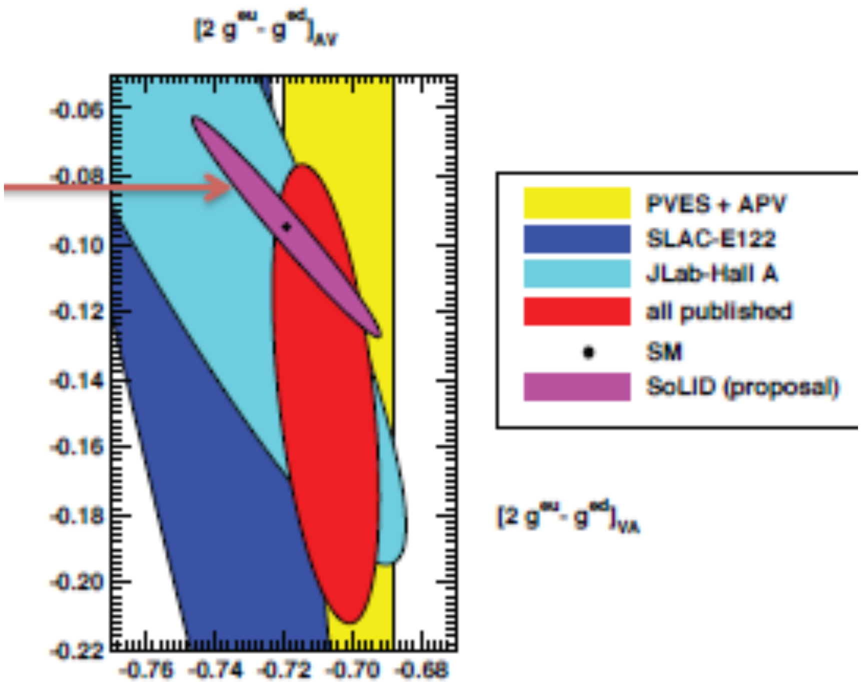


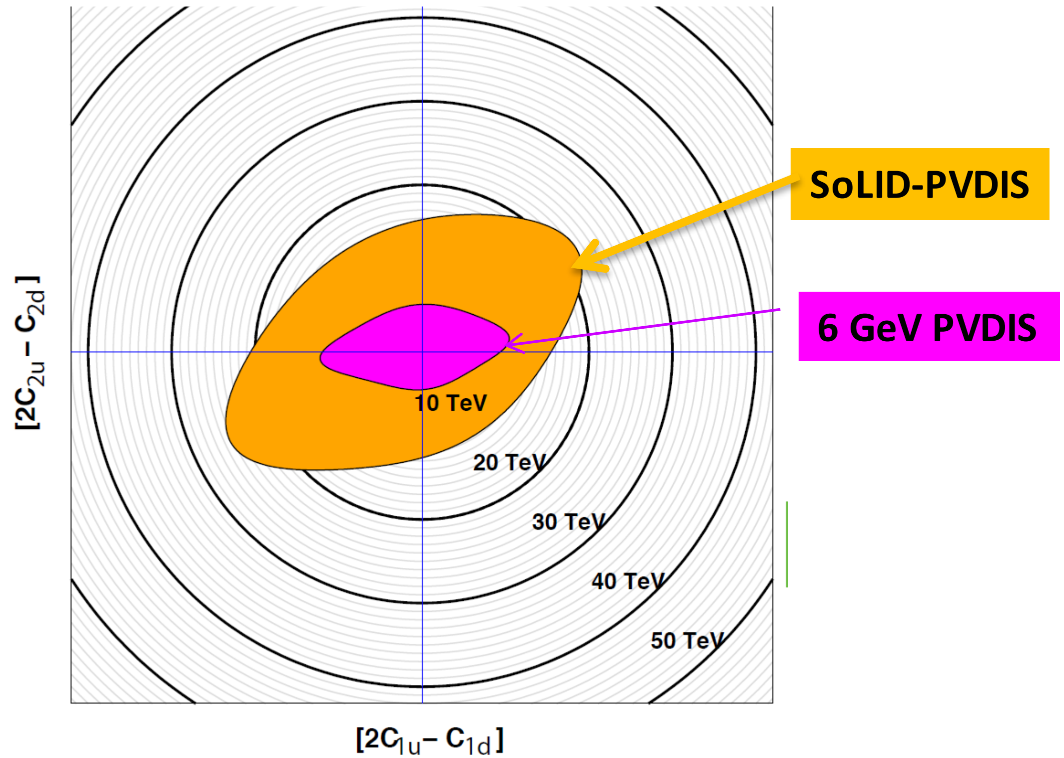
Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

Tensor Charges



Parity Violation with SoLID





PVDIS asymmetry has two terms:

1) C_{2q} weak couplings, test of Standard Model

2) Unique precision information on **quark structure of nucleon**

Mass reach in a composite model, SoLID-PVDIS ~ 20 TeV, sensitivity match LHC reach with complementary Chiral and flavor combinations

6 GeV Results: D. Wang et al., Nature 506, no. 7486, 67 (2014)

SoLID Timeline, Status

- 2010-now: Five highly rated SoLID experiments approved by PAC + 3 run group
- 2013: CLEO-II magnet formally requested and agreed, site visits and planning

--2010-now: Progress

  - Spectrometer magnet study, modifications
  - Detailed simulations
  - Detector/DAQ design and pre-R&D
  - Strong International collaboration (Chinese, Canadian, …)

✓ 7/2014: pre-CDR submitted

✓ 2/2015: Director's Review, successful

✓ 2014-2015: Long Range Plan, SoLID strongly endorsed

✓ 2015: discussion with DOE on pre-R&D

✓ 2016: CLEO-II magnet transported JLab

✓ 2017: Responses to Director's Review Recommendations

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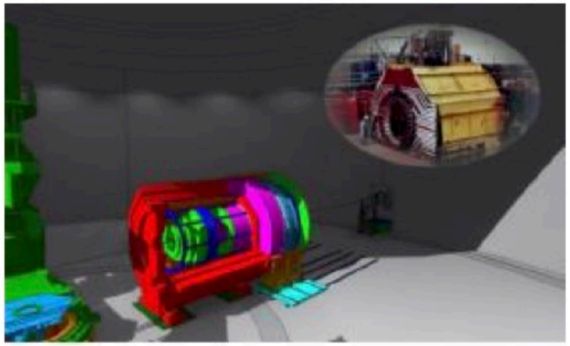
Plan:

- 2017: Update pCDR (MIE) → DOE Science Review
- CD processes/ PED/R&D (2017 – 2019)
- Construction starts FY 2020

Jefferson Lab Mission: SoLID

A. Lung

Proposed QCD & Fundamental Symmetries MIE



Unique Capability:

✓High luminosity (10^{37-39})

✓ Large acceptance detector with full ϕ coverage

- Unprecedented precision in 3D momentum space imaging of the nucleon.
- A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.
- Allowing access to threshold of J/ψ production, allowing access to the QCD conformal anomaly with unmatched precision.

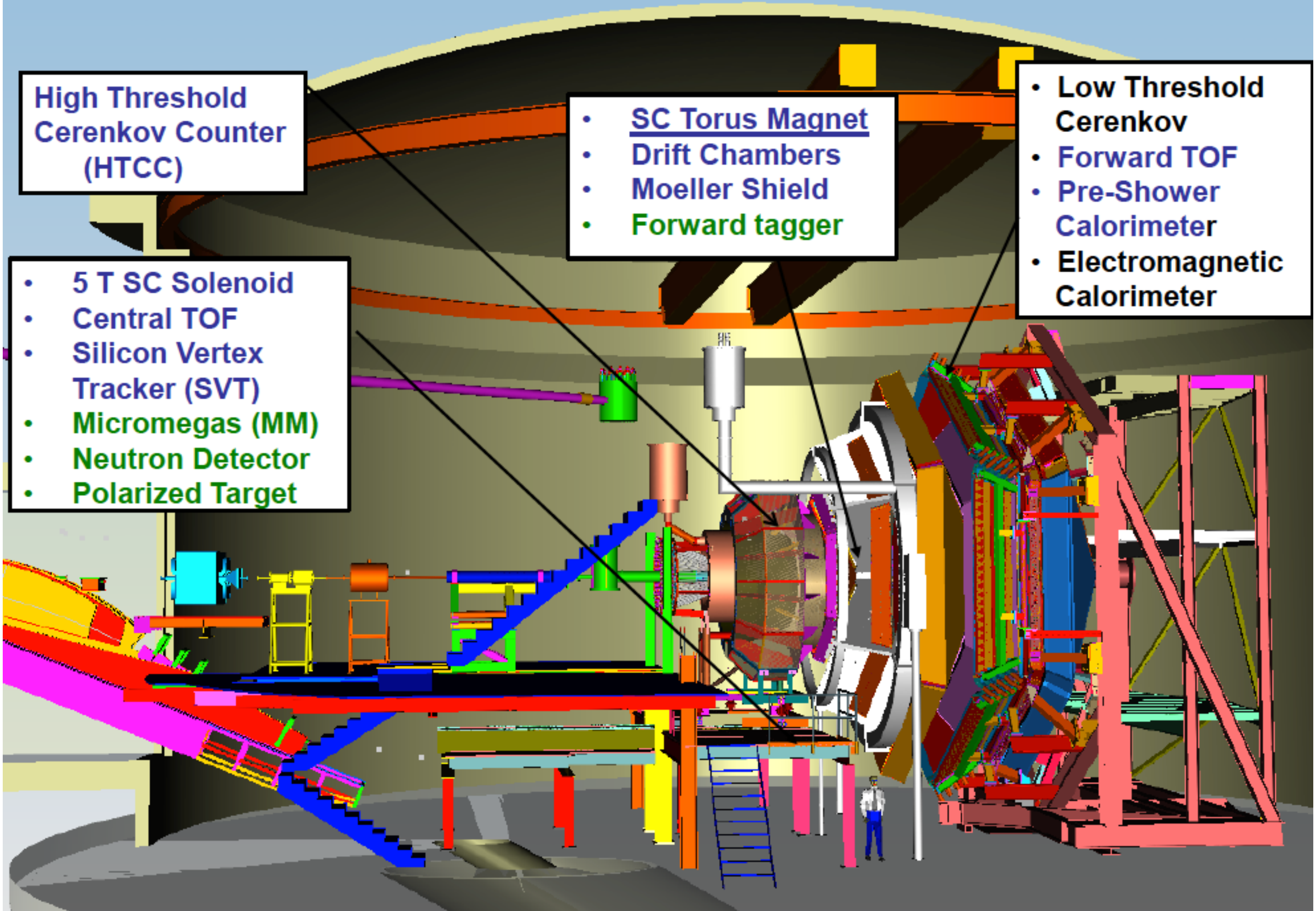
Item	Date
Director's Review	February 2015
SoLID User Meeting with DOE/NP	November 2015
Director's Review Recommendations affecting science reach; progress: simulations of core measurements, DAQ rate capability, detector/magnet integration	February 2016
CLEO-II Magnet Disassembly at CESR	Summer 2016
CLEO-II Magnet move to Jefferson Lab	Fall 2016
Follow-Up Director's Review (in progress)	Late 2016
Draft MIE Submission – goal	February 2017
DOE/NP-led Science Review – possible timing	Spring 2017
Annual Budget Briefing – include budget profile	February 2018
MIE Start	FY2020

- CLEO-II cryostat at JLab, steel follows this Spring
- Working with collaboration to follow up from Director's review and finalize draft MIE

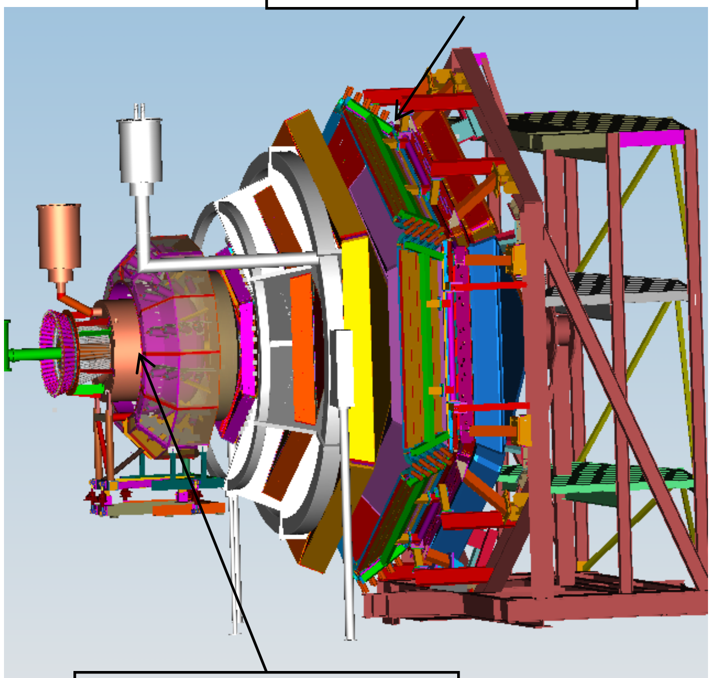
Planned J/ψ threshold production study at JLab

CLAS12 Program

CLAS12 in Hall B



CLAS12 in Hall-B

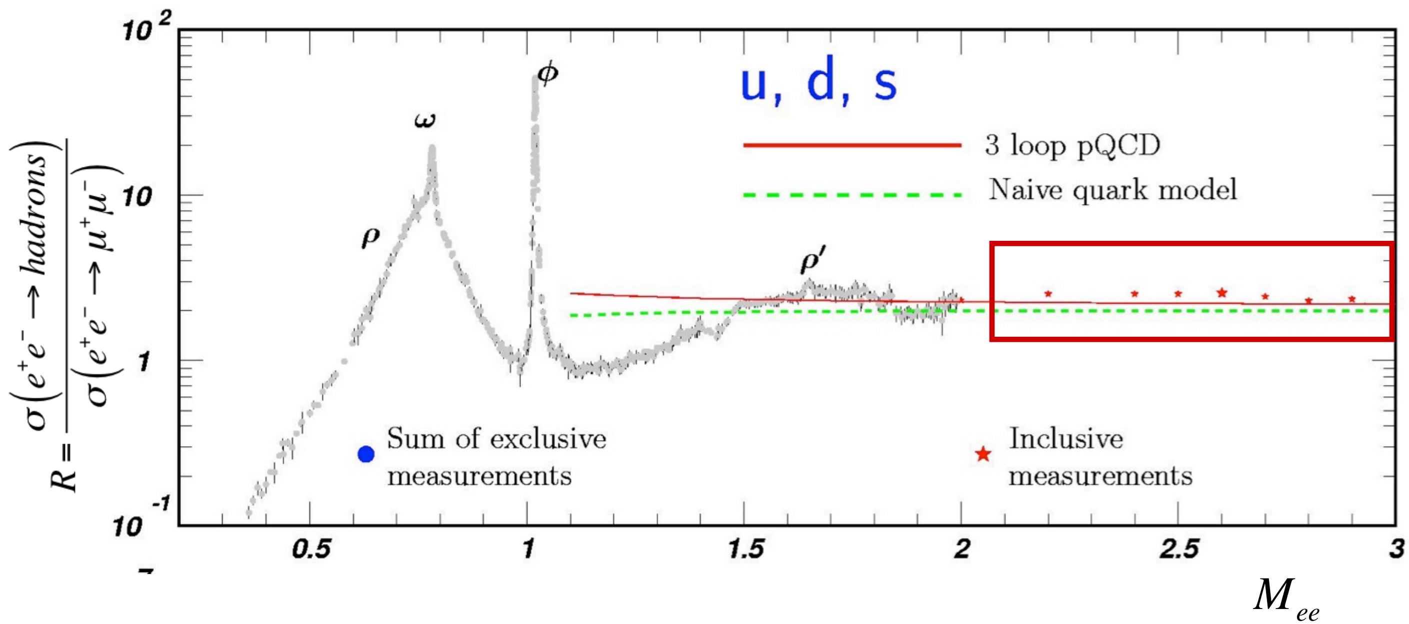


$$L = 10^{35} cm^{-2} s^{-1}$$

	FD	CD
Angular range		
Track	$5^0 - 40^0$	$35^0 - 125^0$
Photons	$2^0 - 40^0$	---
Resolution		
dp/p (%)	< 1 @ 5 GeV/c	< 5 @ 1.5 GeV/c
$d\theta$ (mr)	< 1	< 10 – 20
$\Delta\phi$ (mr)	< 3	< 5
Photon detection		
Energy (MeV)	>150	---
$\delta\theta$ (mr)	4 @ 1 GeV	---
Neutron detection	N_{eff}< 0.7	N_{eff}< 0.3
Particle ID		
e/π	Full range	---
π/p	< 5 GeV/c	< 1.25 GeV/c
π/K	< 2.6 GeV/c	< 0.65 GeV/c
K/p	< 4 GeV/c	< 1.0 GeV/c
$\pi(\eta)\rightarrow\gamma\gamma$	Full range	---

Lepton pair production with 12 GeV CEBAF

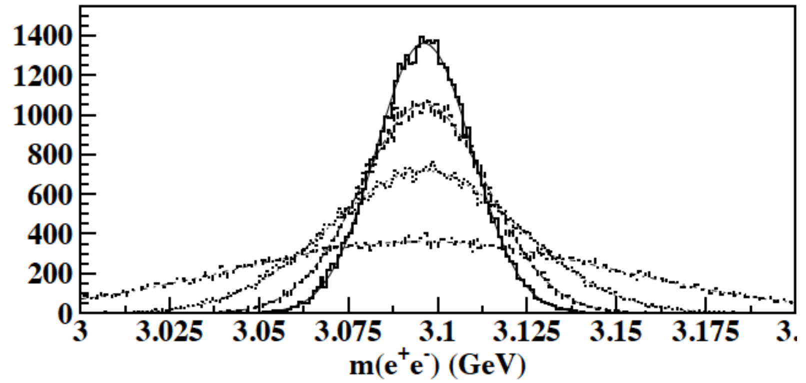
- Experiments to measure TCS and J/Ψ photo- and electroproduciton have been approved for CLAS12 in Hall-B and SoLID in Hall-A
- With 11 GeV electron beam $M_{ee} \leq 3.4 GeV$
- TCS will be studied in the range of outgoing photon virtualities, $M_{ee}^2 \equiv Q'^2$, from 4 GeV² to 9 GeV² (resonances free region)

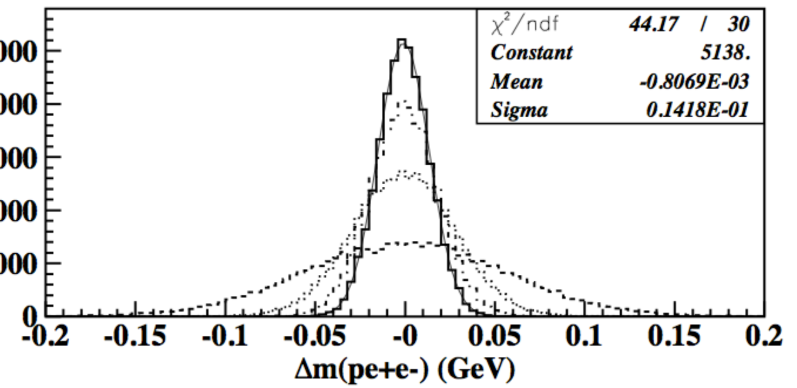


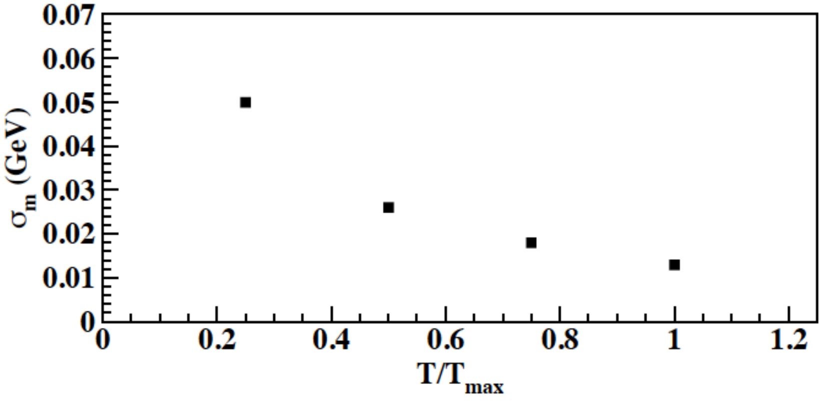
J/Ψ photo-production can be studied in energy range from threshold to 11 GeV

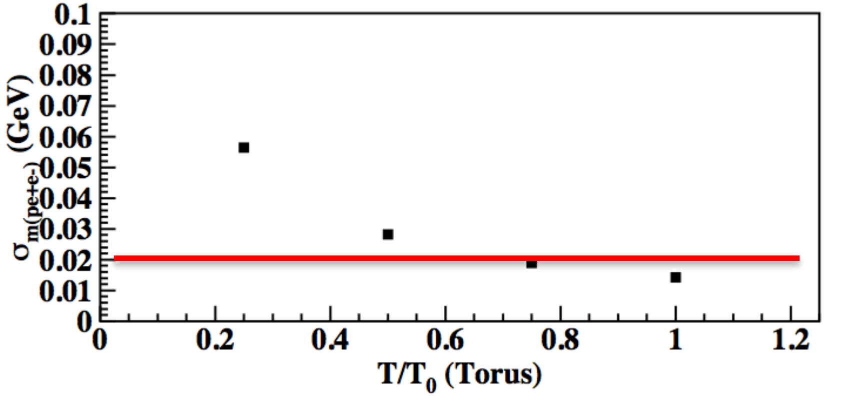
J/ψ quasi-real photoproduction with CLAS12

- The J/ψ is identified as a peak on top of smooth BH background in the invariant mass distribution of decay leptons, e^+e^-, detected in CLAS12 FD
- CLAS12 FD resolution for magnet (torus) field settings down to 75% will be adequate





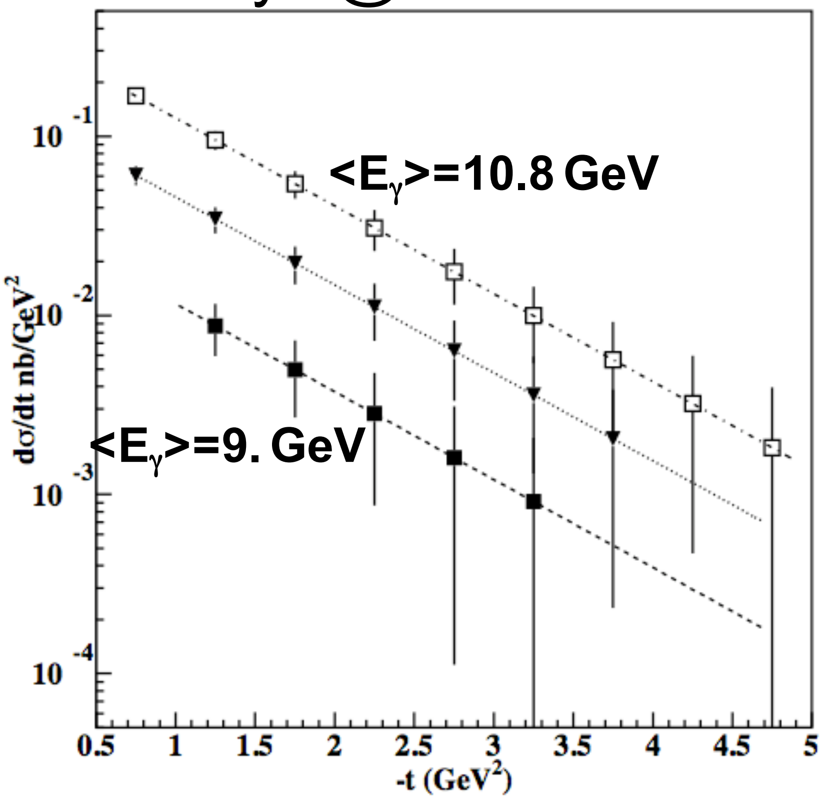


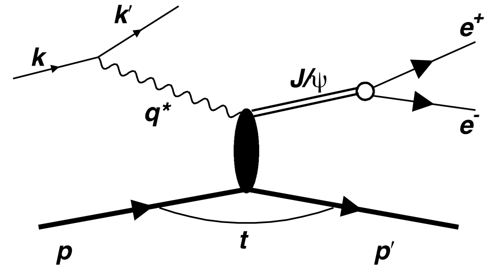


t-dependence: projected data

$$ep \to e^+ e^- pX$$

100 days @ 10^{35} cm^{-2} sec^{-1}





Estimates assume:

$$\frac{d\sigma}{dt} \propto e^{Bt}; \quad B = 1.2\,GeV^{-2}$$

and

$$\frac{d\sigma}{dt} \propto \frac{1}{Q^4}$$

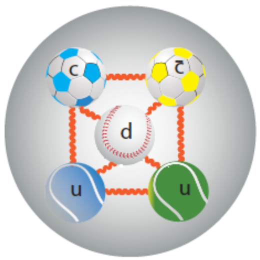
Integrated for $Q^2 < 0.01$ GeV^2

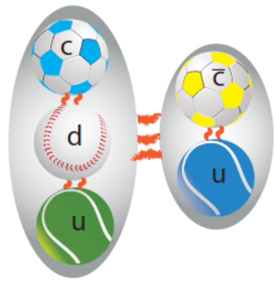
Search for hidden charmed pentaquarks and study of gluonic structure of the nucleon

What is the exact nature of charmed pentaquark states discovered by LHCb collaboration at CERN

$$P_c \Rightarrow J/\psi\, p$$

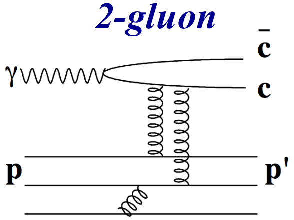
5-quark bound state *or* *Hadronic molecule*

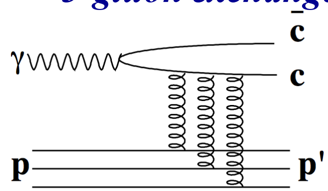


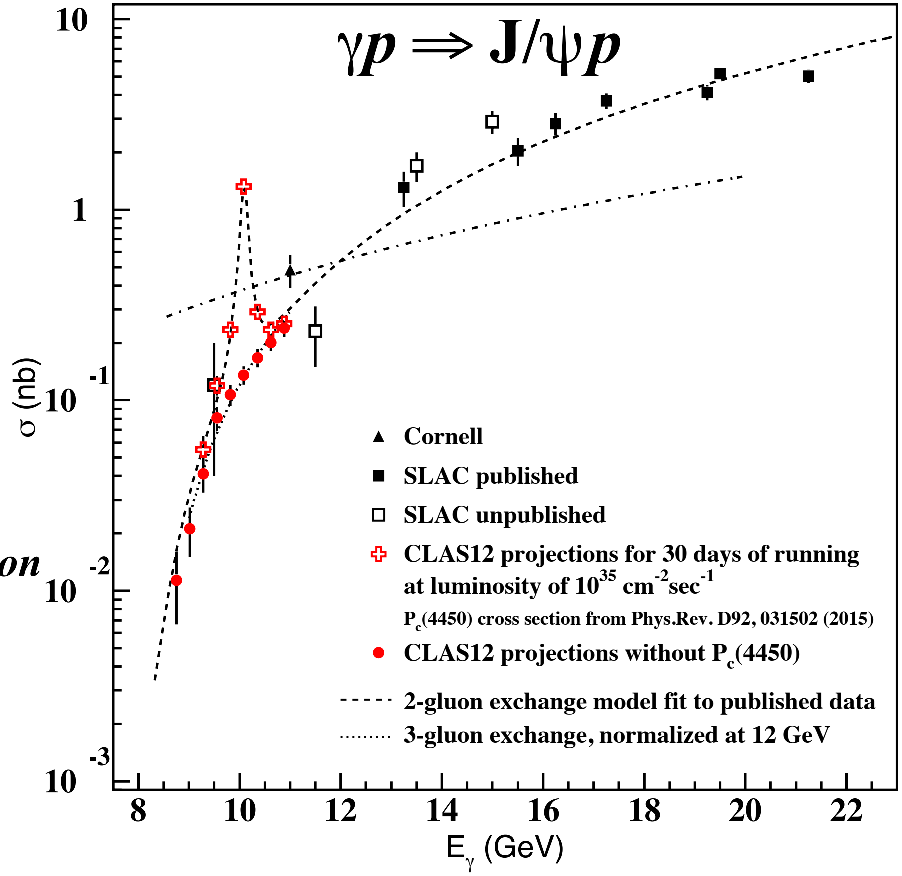


What is the mechanism of charmonium production at the threshold

2-gluon *or* *3-gluon exchange*







Experiment E12-12-001 measures J/ψ production on the proton near threshold – will verify existence of the charmed pentaquarks and will study the gluon field of the nucleon

Summary

J/ψ threshold production studies gluon dynamics, trace anomaly
→ may provide information on trace part of the proton mass

JLab 12 GeV energy upgrade crosses a threshold to allow J/ψ production measurements

Both SoLID and CLAS12 J/ψ program will measure with high precision J/ψ elertroproduction and photoproduction near threshold

- Probe the nucleon strong fields in a non-perturbative region
- Search for a possible enhancement of the cross section close to threshold
- Shed some light on the conformal/trace

The data sets can also be used to search and study LHCb hidden charm pentaquark states in the pJ/ψ decay mode, $P_c(4380)$ and $P_c(4450)$