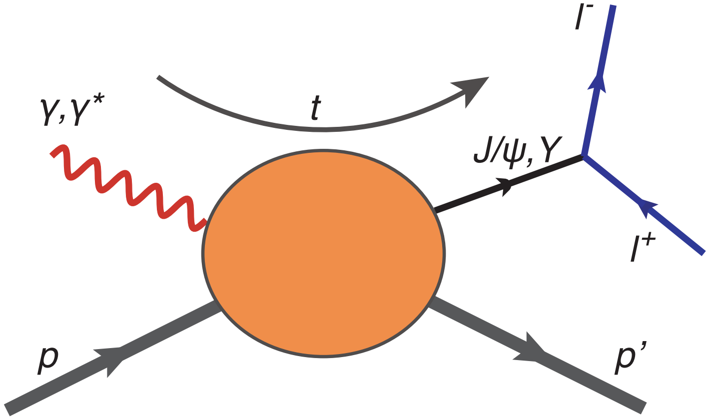
PROBING THE GLUONIC STRUCTURE OF THE NUCLEON AND THE DYNAMIC ORIGIN OF ITS MASS

Argonne NATIONAL LABORATORY

QUARKONIUM PRODUCTION: FROM JLAB TO EIC



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U.S. DEPARTMENT OF ENERGY
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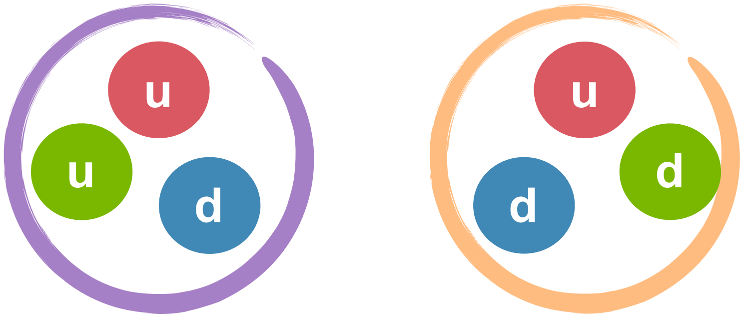
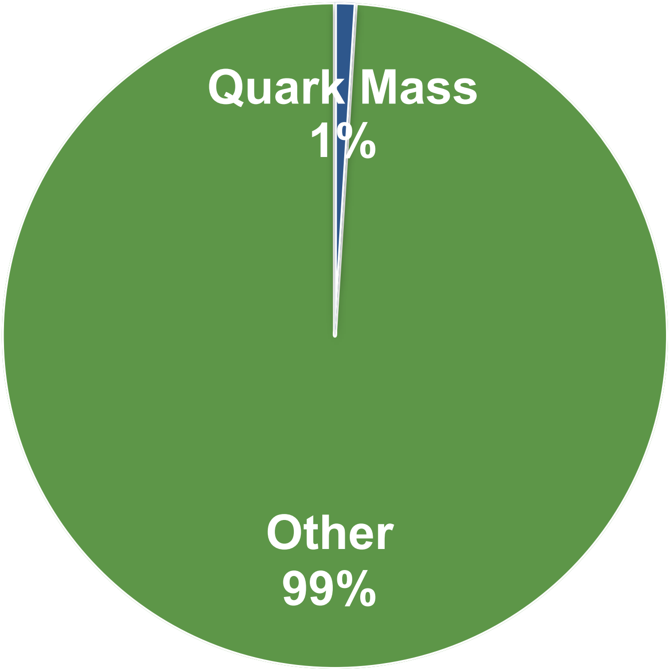
QCD Evolution 2019
Argonne National Laboratory

THE NUCLEON IN QCD

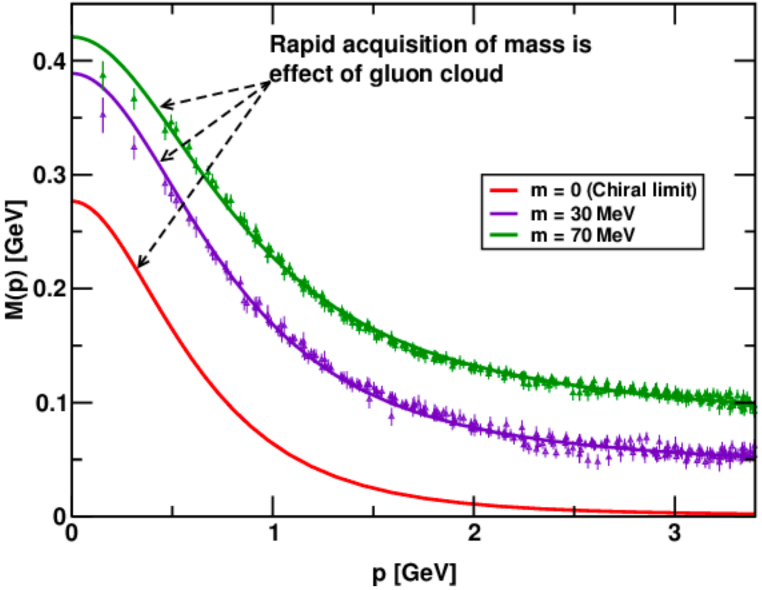
99% of the mass of the visible universe



- Fundamental building blocks of matter
- Bound states of QCD Lagrangian
- Three **valence quarks** needed to define quantum numbers **contribute only ~1% of its mass**



NUCLEON MASS IS AN EMERGENT PHENOMENON



M. S. Bhagwat et al., Phys. Rev. C 68, 015203 (2003)
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- From DSE and Lattice:
  - Low momentum gluons attach to the current quarks (DCSB)
  - Gluon field accumulates ~300MeV/constituent quark
  - Even in the chiral limit: **mass from nothing!**

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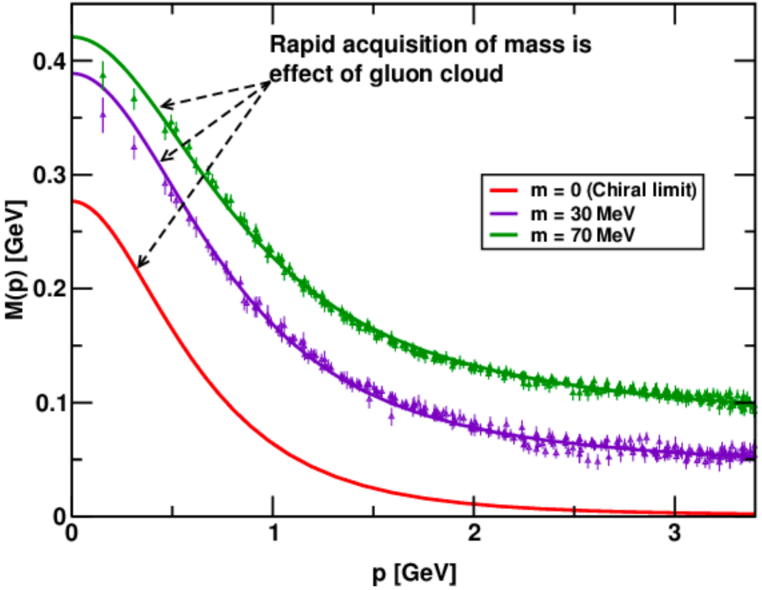

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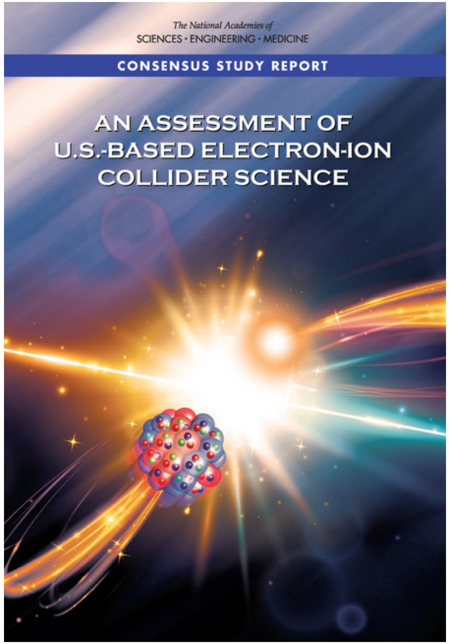
The Higgs mechanism is largely irrelevant in “normal” matter!

NAS CHARGE FOR EIC



- An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:
  - **How does the mass of the nucleon arise?**
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons

PROTON MASS: TRACE DECOMPOSITION

Why is the proton mass non-vanishing?

- Nucleon mass related to trace of energy-momentum tensor at zero momentum transfer

$$\langle P|T^{\mu}_{\mu}|P\rangle = 2P^{\mu}P_{\mu} = 2M_p^2$$

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$$T^{\mu}_{\mu} = \underbrace{\frac{\tilde{\beta}(g)}{2g}G^2}_{\text{Trace Anomaly}} + \underbrace{\sum_{q=u,d,s} m_q(1+\gamma_m)\bar{\psi}_q\psi_q}_{\text{Light Quark Mass}}$$

Trace Anomaly Light Quark Mass

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"Proton mass result of the vacuum polarization induced by the presence of the proton."

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Trace anomaly intimately related to DCSB and the emergence of scale

PROTON MASS: REST-FRAME DECOMPOSITION

Disentangling the proton mass in its rest frame

- Proton mass is the matrix element of the QCD Hamiltonian in the proton rest frame

$$H_{\text{QCD}} = \int d^3x T^{00}(0, \vec{x})$$
$$= H_q + H_m + H_g + H_a$$

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At leading order:

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right)M$$
$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)}bM$$
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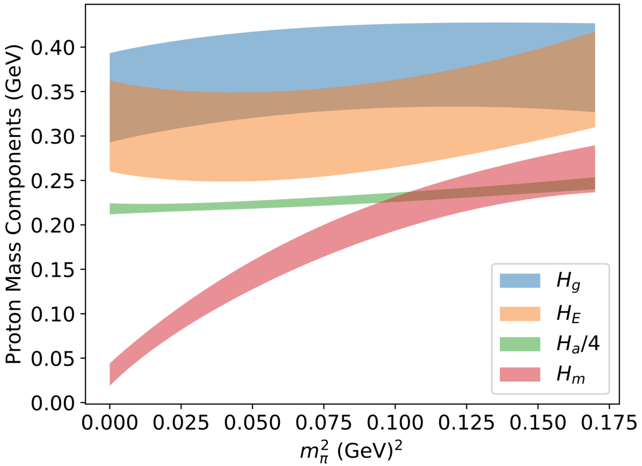
a(μ) related to PDFs, well constrained

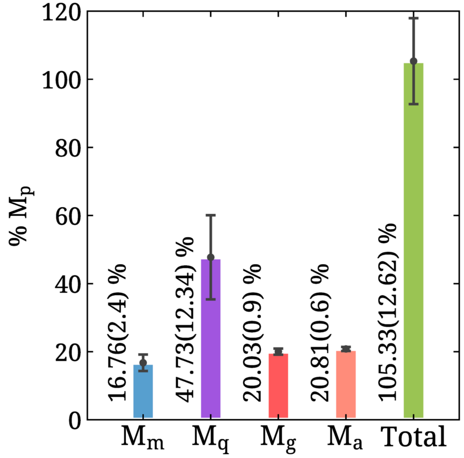
b(μ) related trace anomaly, unconstrained

PROTON MASS ON THE LATTICE

No direct calculation of trace anomaly to date.



Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)



C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
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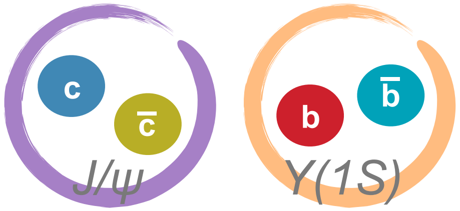
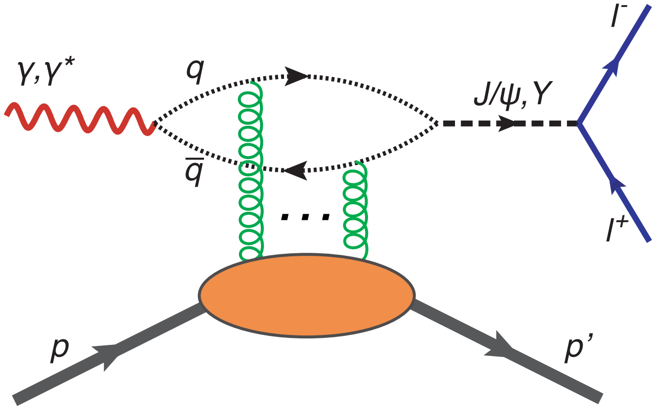
Trace anomaly only constrained through sum-rules

CAN WE MEASURE THE TRACE ANOMALY?

…Quarkonium production near threshold!





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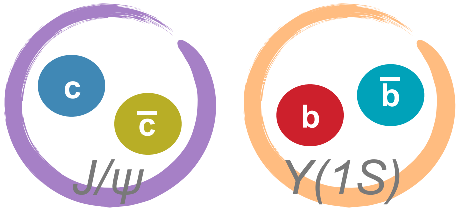

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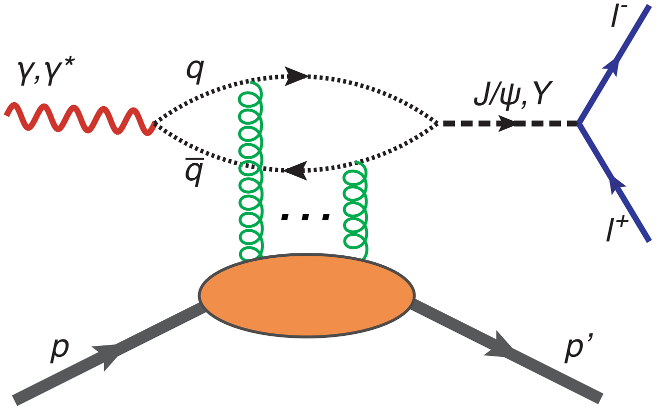

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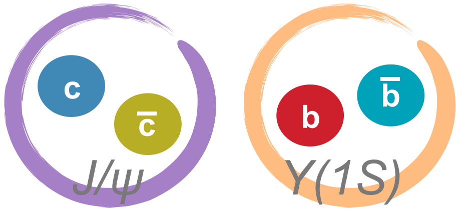

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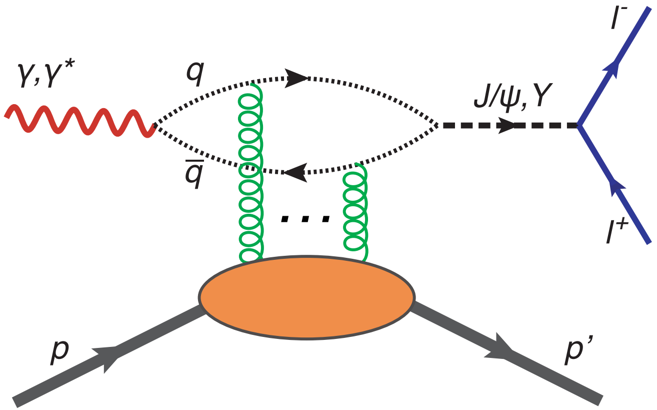

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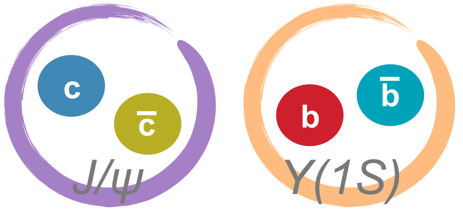

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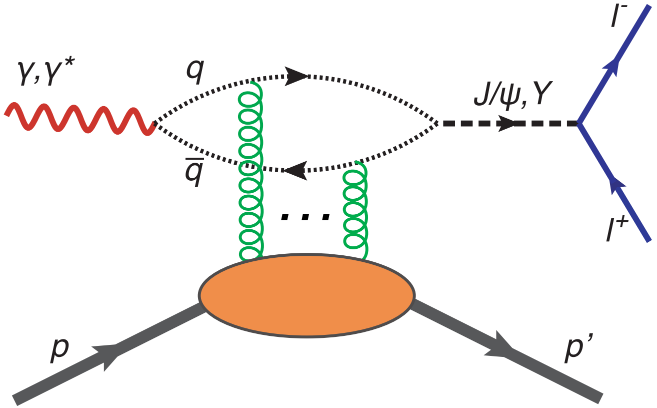
- Trace-anomaly operator twist-four:
  - Highly suppressed in high-energy scattering
  - QCD Factorization not yet established



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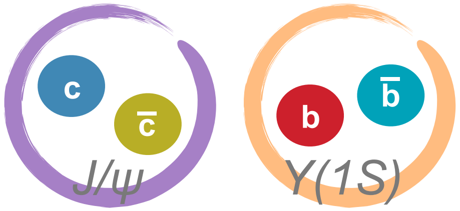

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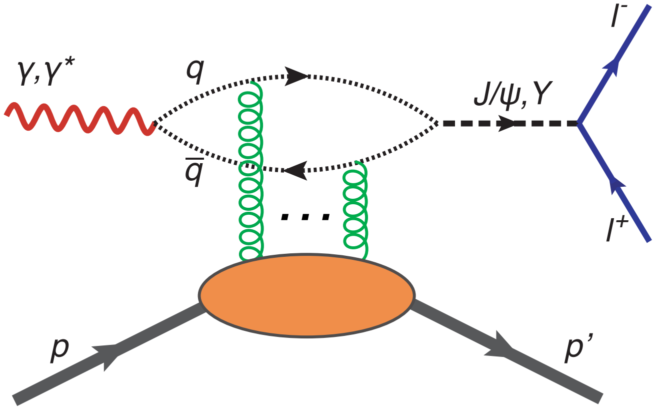
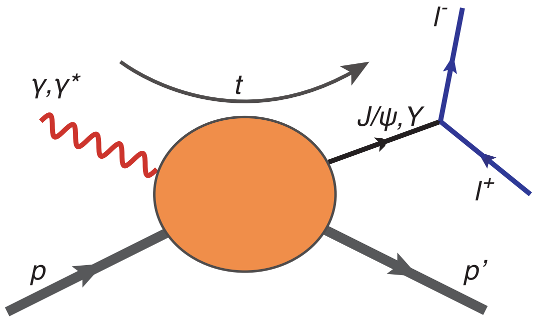
- Solution found in **low energy scattering** (production near threshold)

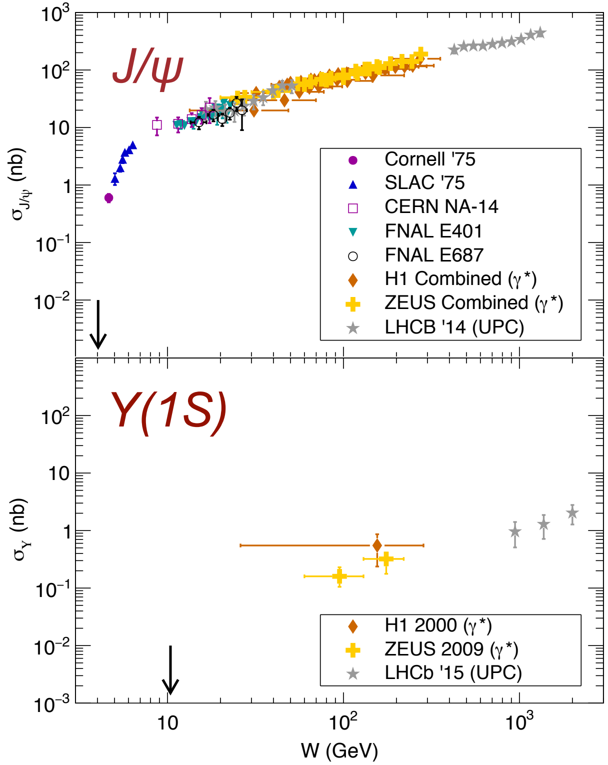


QUARKONIUM PHOTO-PRODUCTION

What do we know?



$$\sigma_{\mathrm{tot}}^{\gamma p} = \int_{t_{\min}}^{t_{\max}} dt \frac{d\sigma}{dt}$$



- *J/ψ* well constrained for high energies
- *Y(1S)*: not much available
- **Almost no data near threshold**
- Momentum transfer t very large near threshold

QUARKONIUM PHOTO-PRODUCTION

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Near Threshold:

- **Origin of proton mass,** trace anomaly of the QCD EMT
- **Gluonic Van der Waals force**, possible quarkonium-nucleon/nucleus bound states
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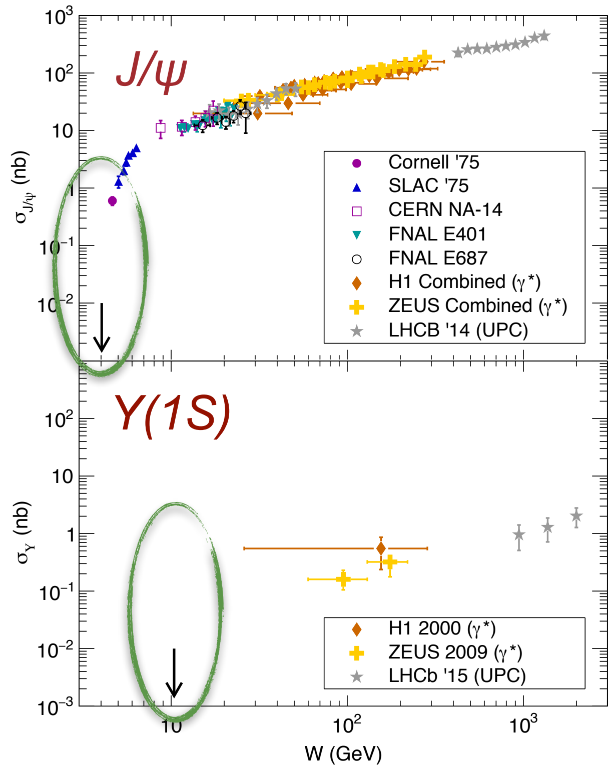
J/ψ at JLab
Y(1s) at EIC



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Electro-Production at high energies:

- **Access Gluon GPD:** Full 3D tomography of the gluonic structure of the nucleon
- L-T Separation and Q^2 dependence of *R* for quarkonium production

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J/ψ at JLab
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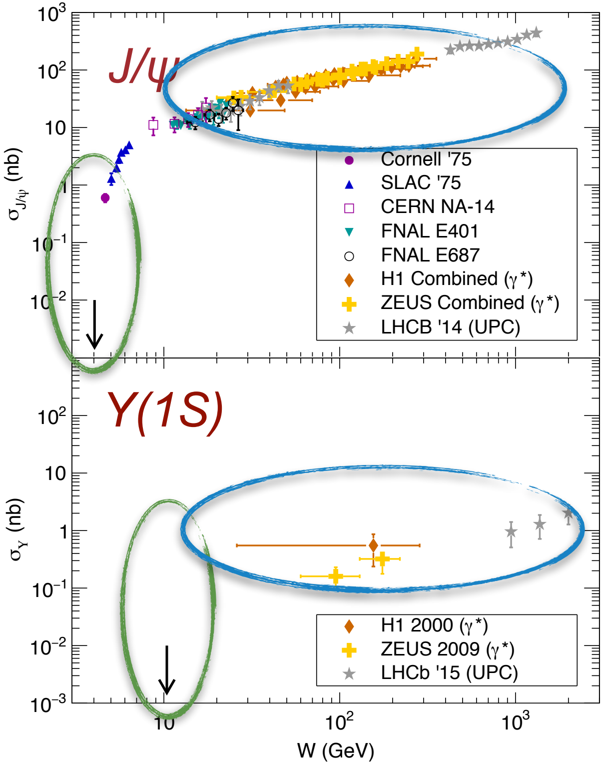
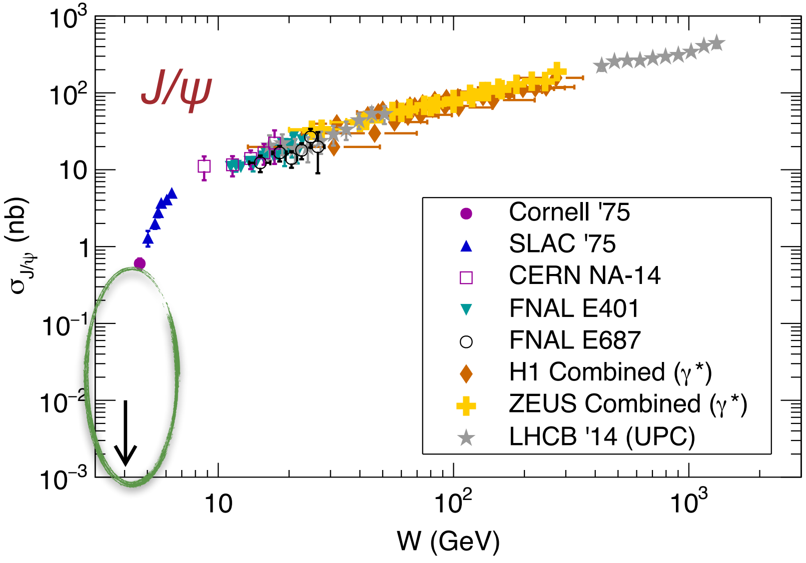
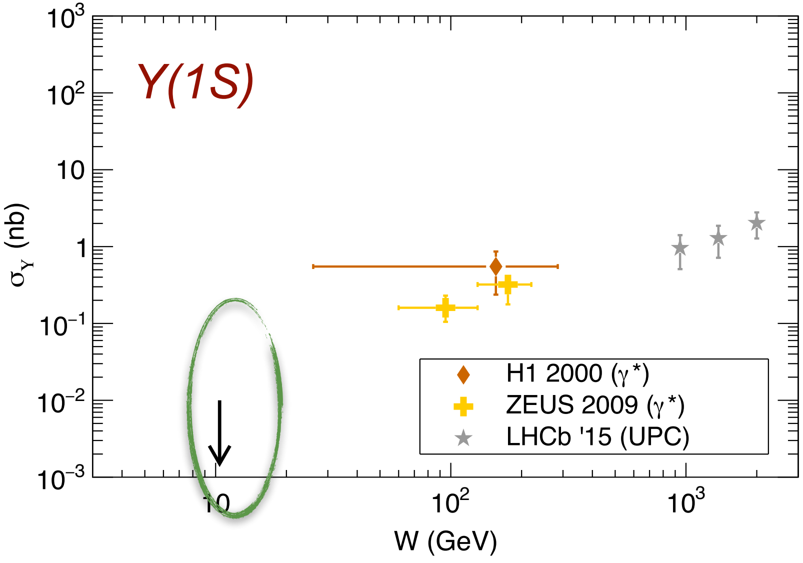






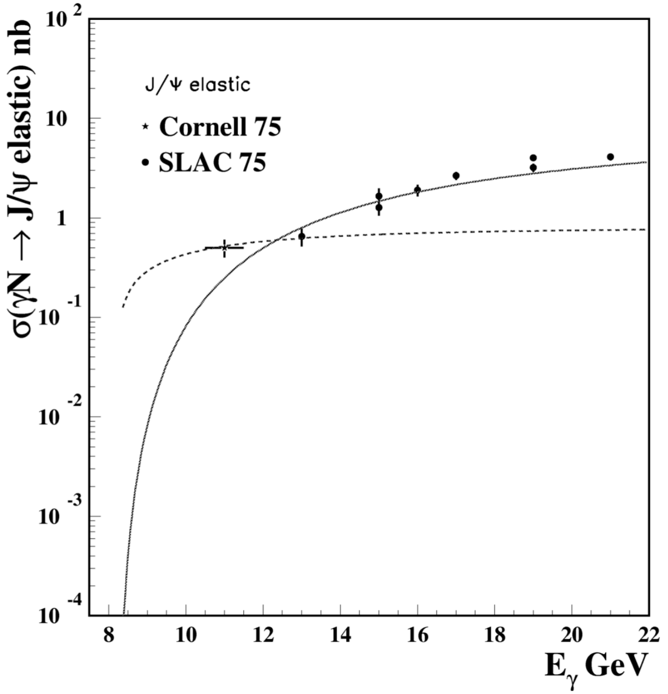
QUARKONIUM PRODUCTION NEAR THRESHOLD

- Experimental program at Jefferson Lab and EIC to study then origin of mass, binding and the hidden-charm pentaquark

S.J. Brodsky, *et al.*, PLB 498, 23-28 (2001)

PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering



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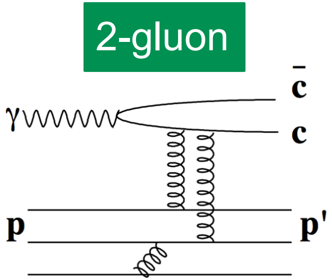
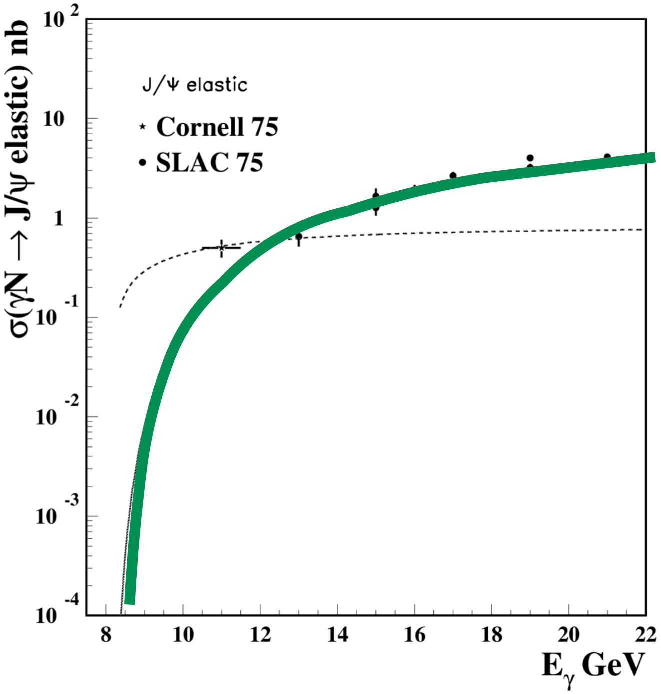


- 2-gluon exchange works well at higher energies



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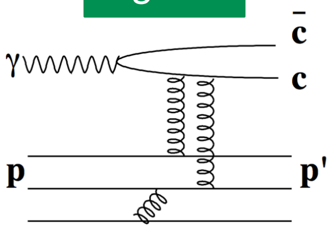

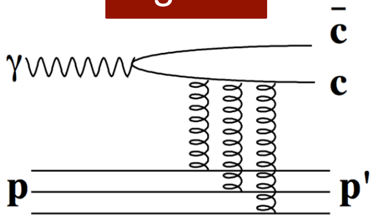

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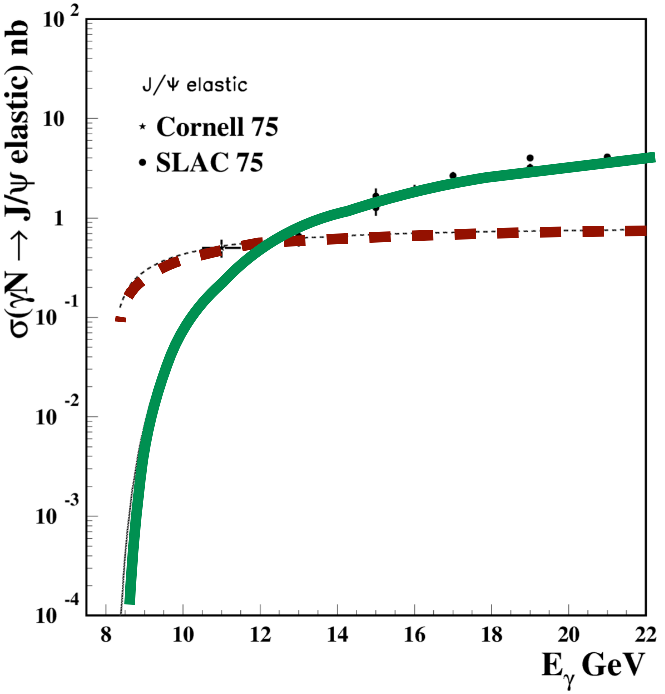
- Higher order gluon exchange expected to play role near threshold
  - Larger 3-gluon exchange contribution related to binding



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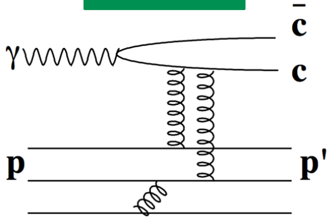
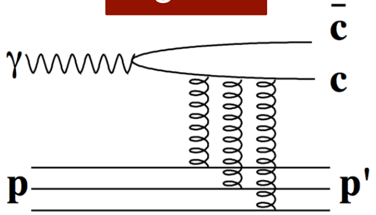


3-gluon



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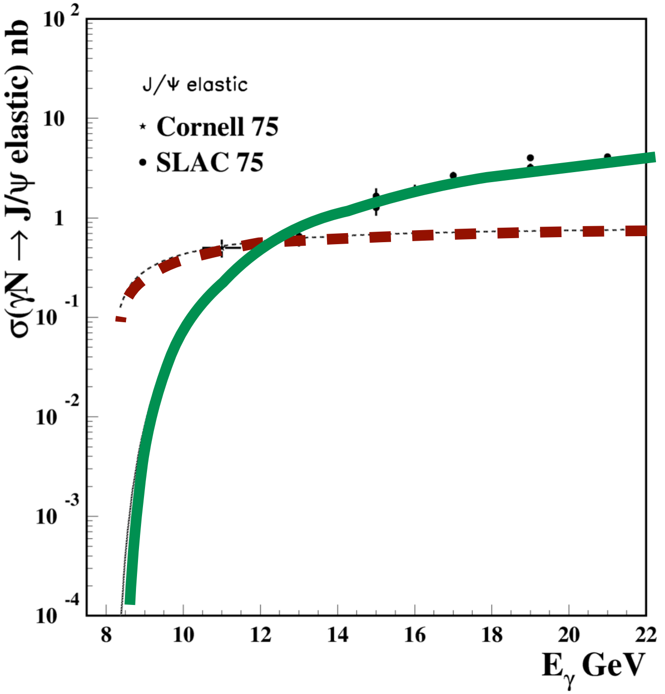

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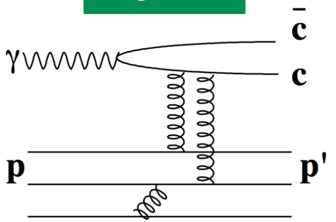

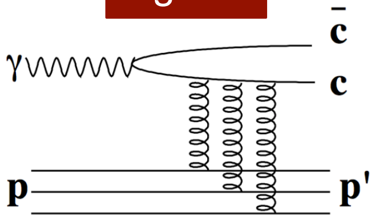

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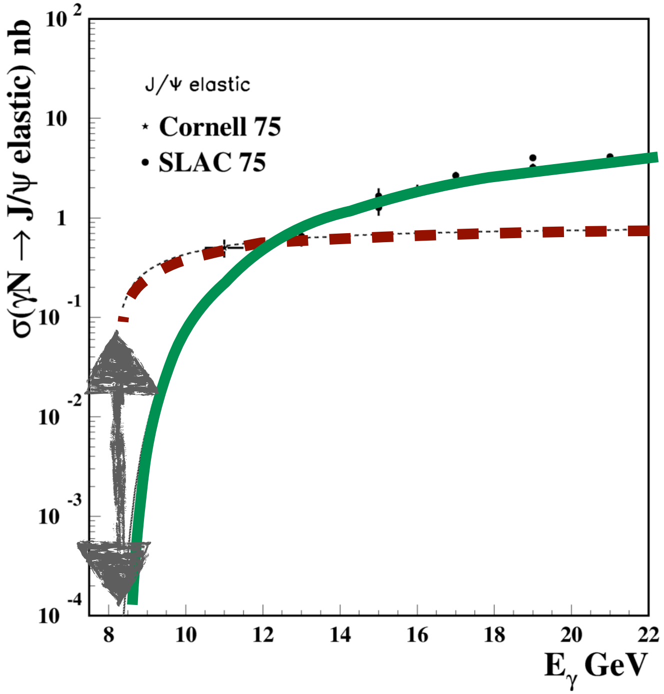

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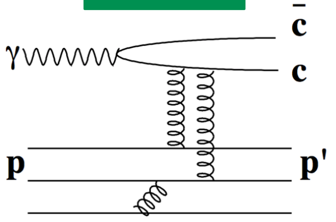

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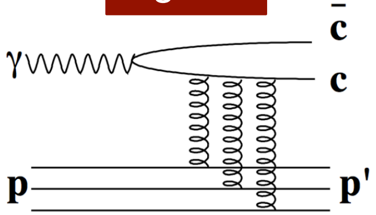

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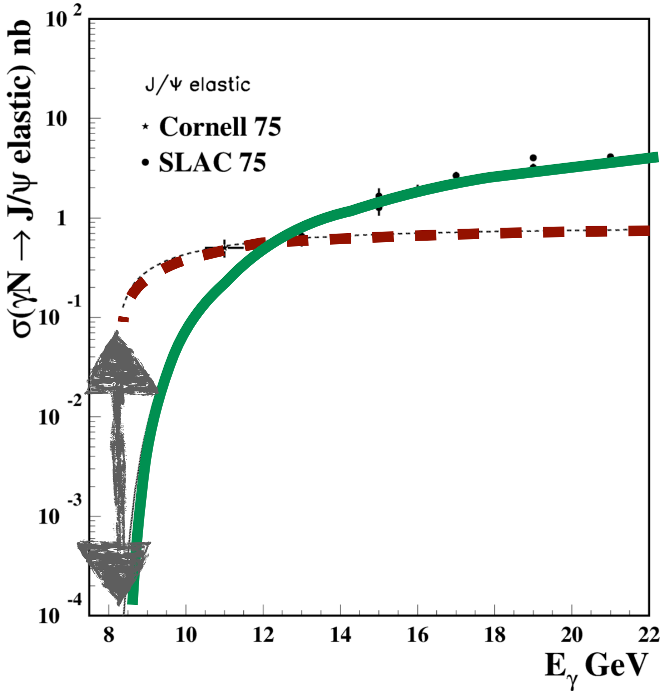
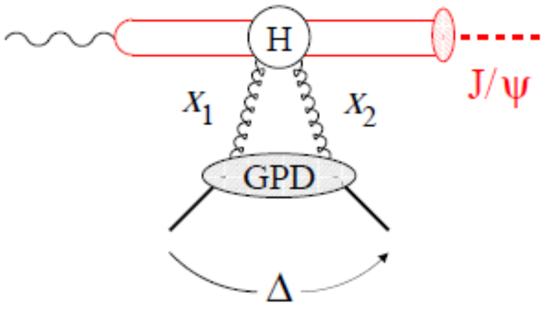
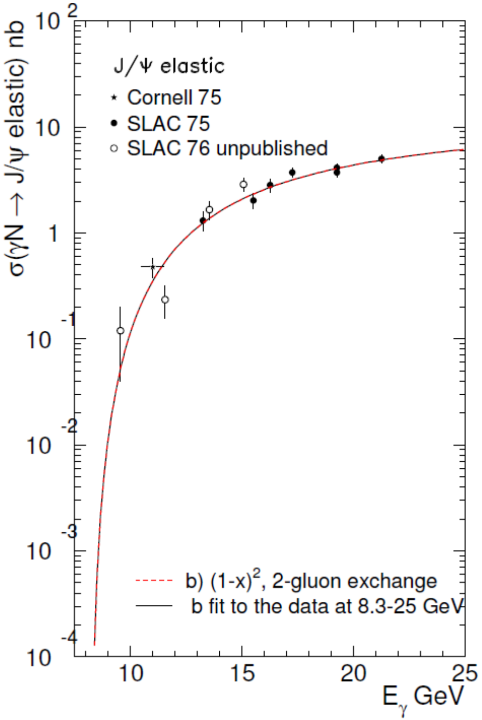
- **No link with trace anomaly**



PRODUCTION MECHANISM NEAR THRESHOLD?

Partonic soft mechanism





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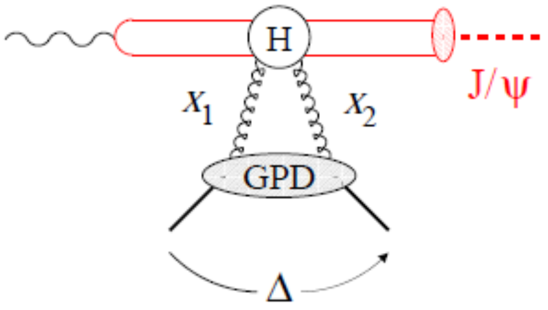
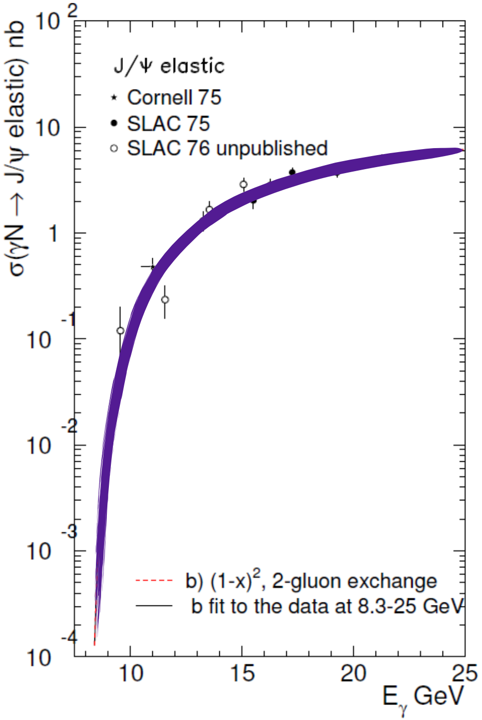


- Reasonable description of near-threshold data (on-par with 2-gluon)



PRODUCTION MECHANISM NEAR THRESHOLD?

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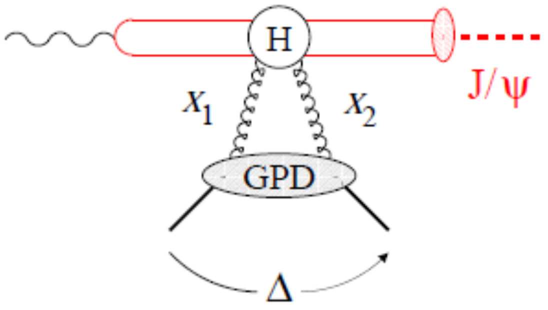
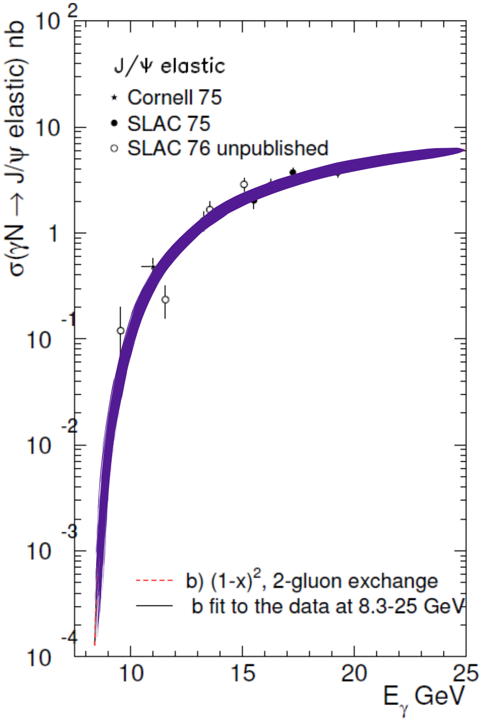


- Reasonable description of near-threshold data (on-par with 2-gluon)
- Power law *t*-dependence from 2-gluon form-factor



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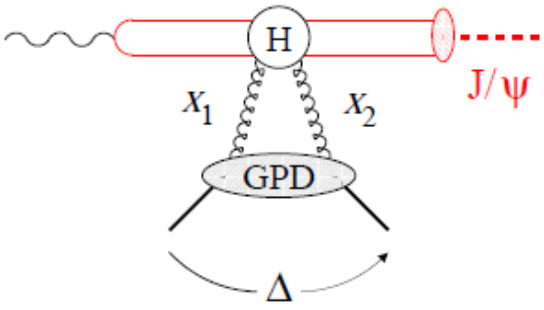

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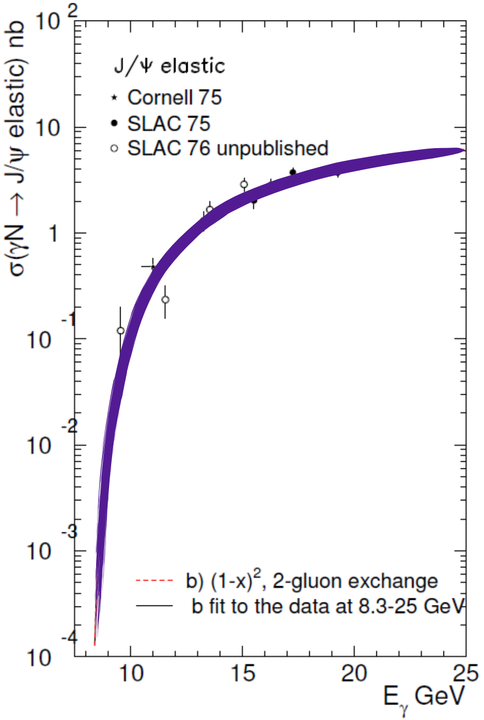
- **No link with trace anomaly**



D. Kharzeev *et al.*, PLB 289 595-599 (1996), EPJ-C 9 459-462 (1999)
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PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)

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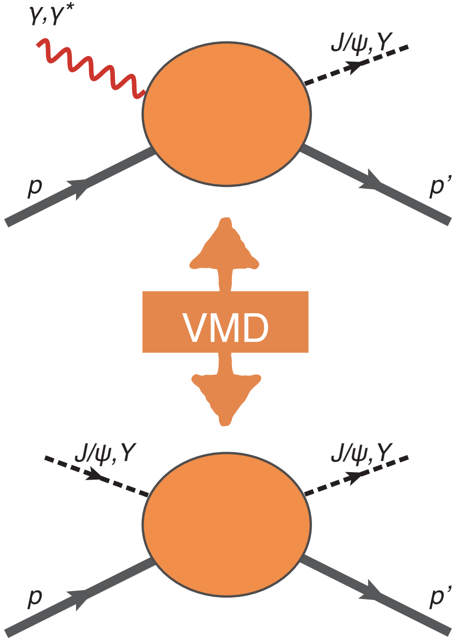
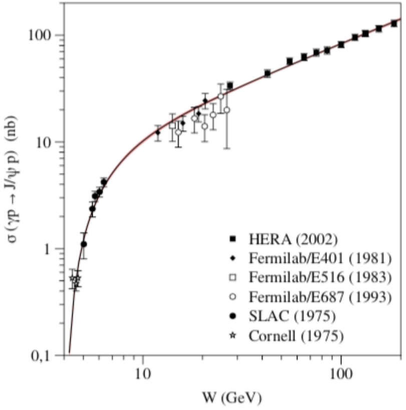


- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $T_{\psi p}$



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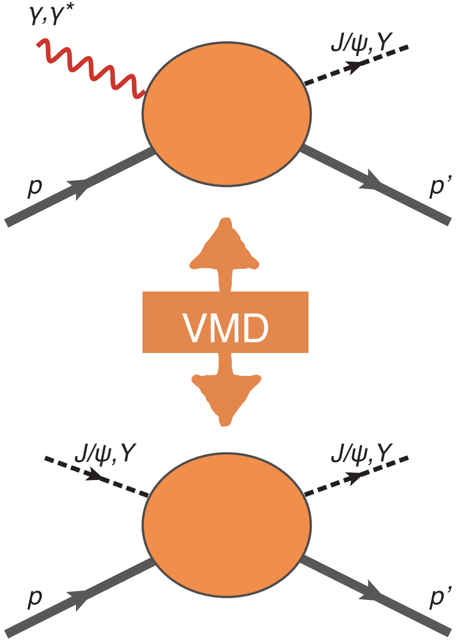

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  1. Obtain **Im($T_{\psi p}$)** from high energy data (extrapolated to t = 0)
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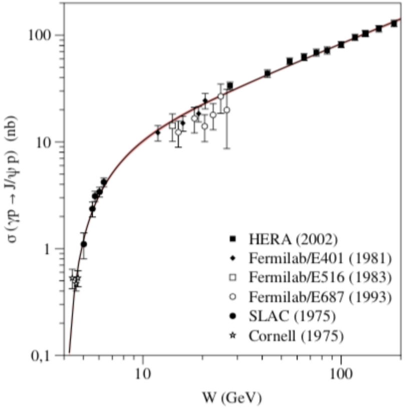

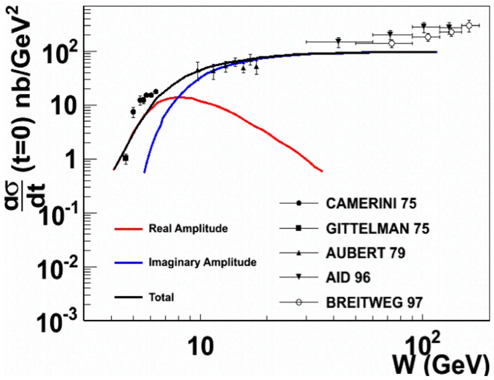

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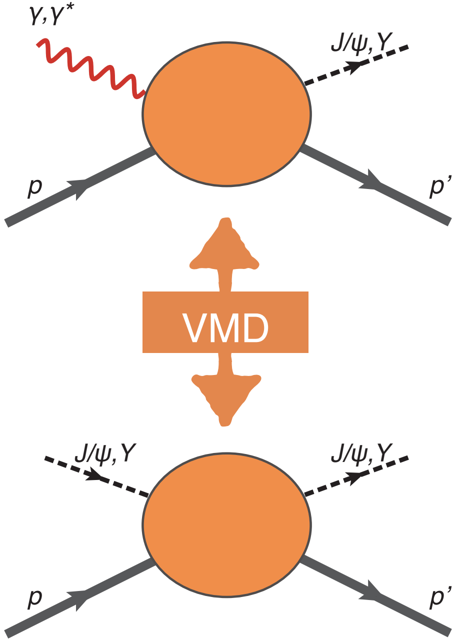

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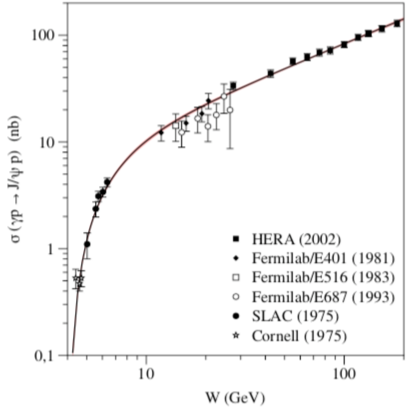
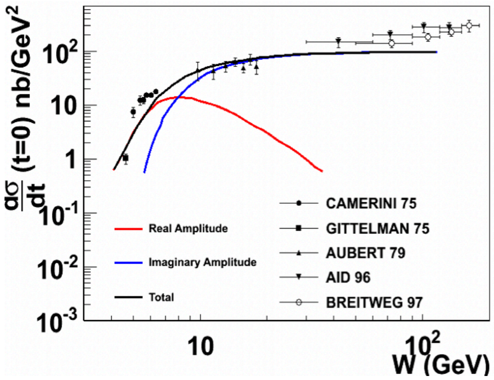
Experimental access to trace anomaly: t-dependence of quarkonium cross section *at* threshold





S. Joosten

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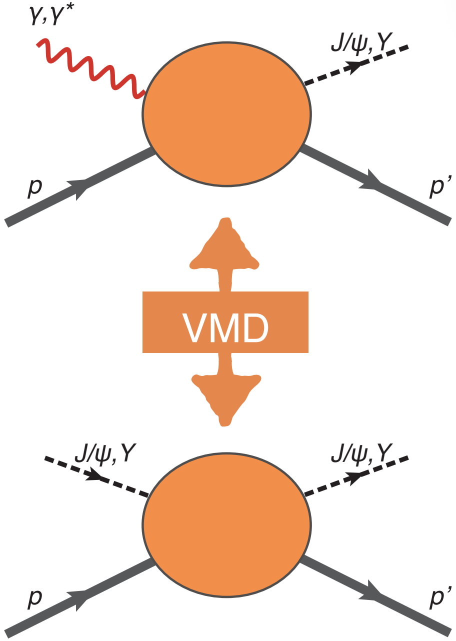

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WARNING LABEL:
Keep in mind, no rigorous factorization theorem (yet)!

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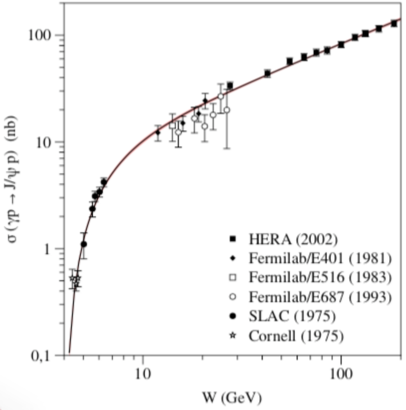

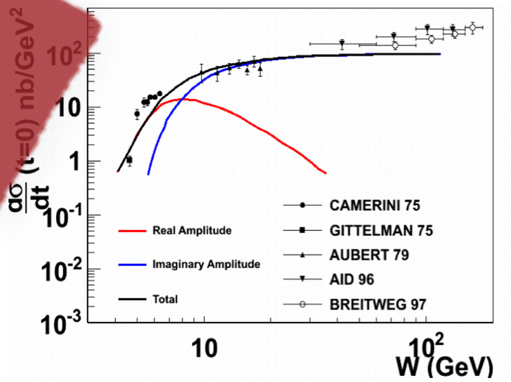

Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

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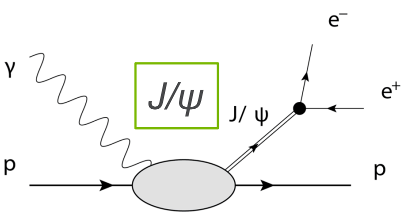

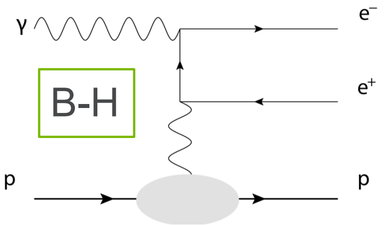

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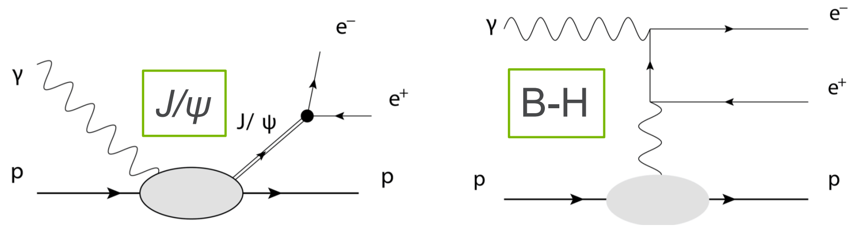

- Interference between elastic *J/ψ* production near threshold and Bethe-Heitler

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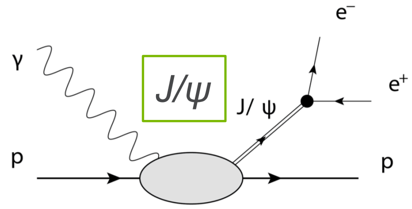

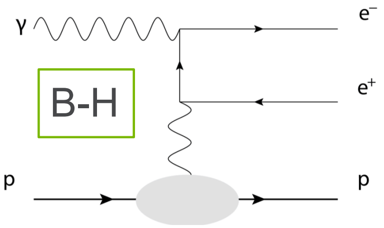

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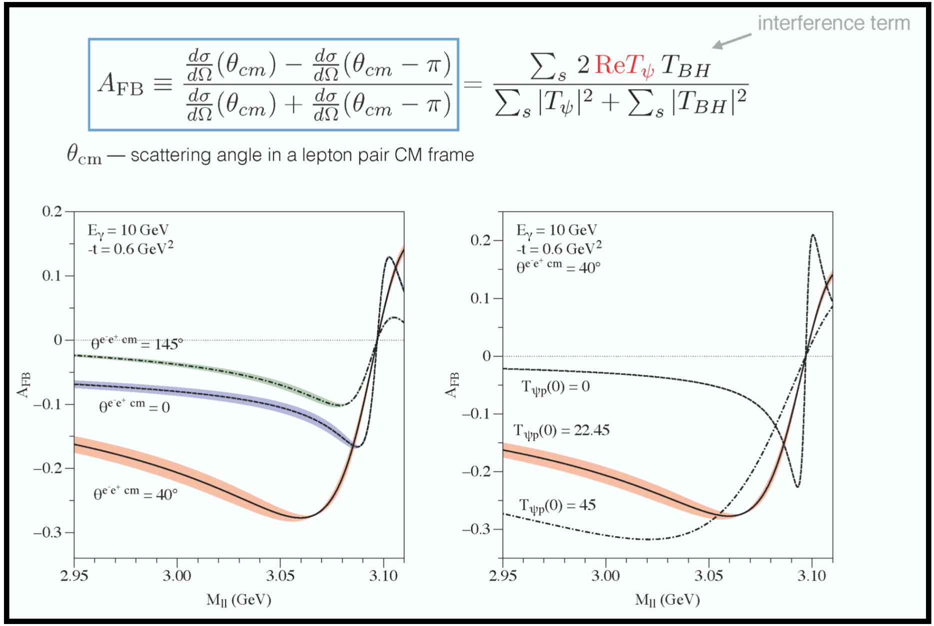

Slide from O. Gryniuk

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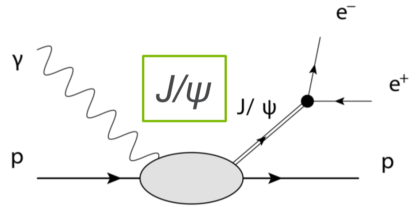

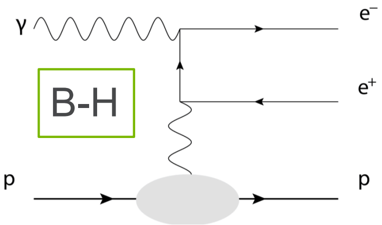

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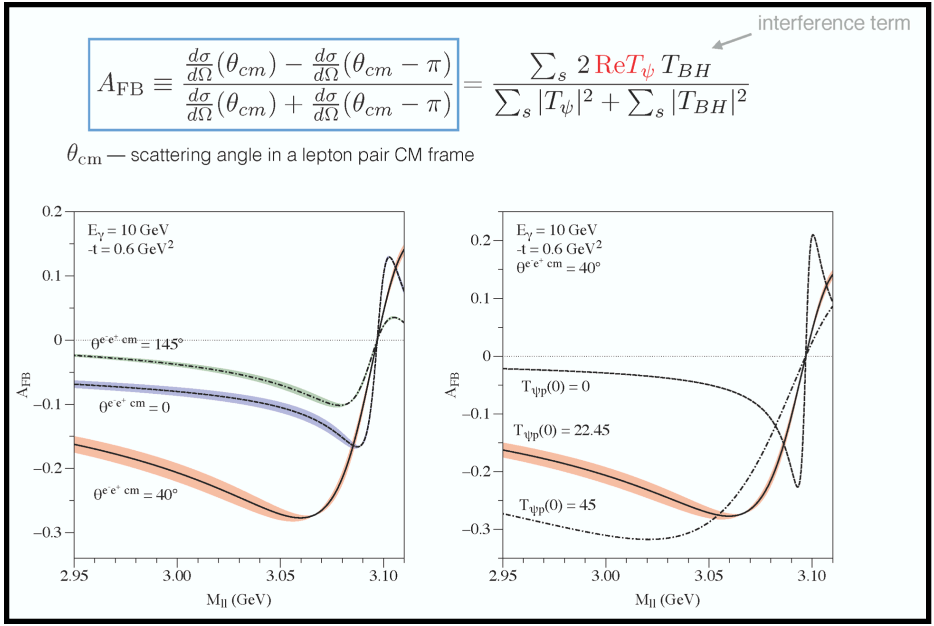
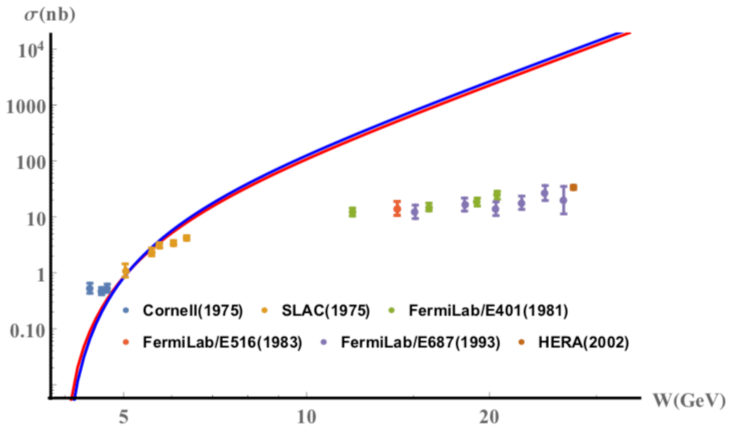
Independent channel to constrain **Re($T_{\psi p}$)** and trace anomaly



Slide from O. Gryniuk

PRODUCTION MECHANISM NEAR THRESHOLD?

Holographic approach



PRODUCTION MECHANISM NEAR THRESHOLD?

Holographic approach

- Perturbative approach difficult
  (no factorization for twist-4 trace anomaly operator)
- Use non-perturbative method instead through AdS/CFT
  (gauge-string duality: dilaton dual to $F^{\mu\nu}F_{\mu\nu}$)
- **Disaster at high energies** (scattering amplitude real but should be imaginary)
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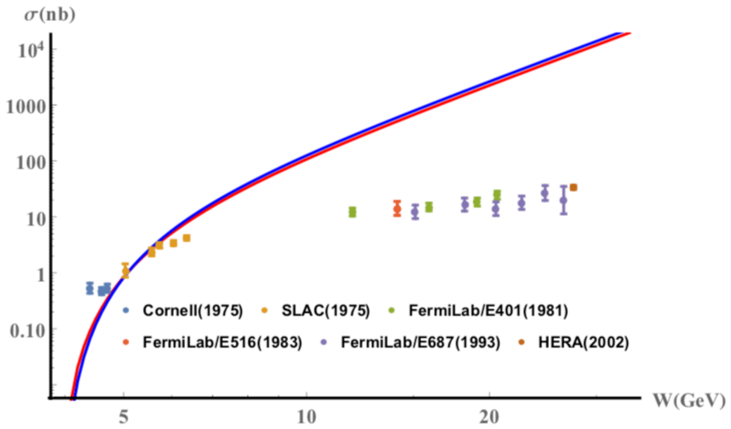

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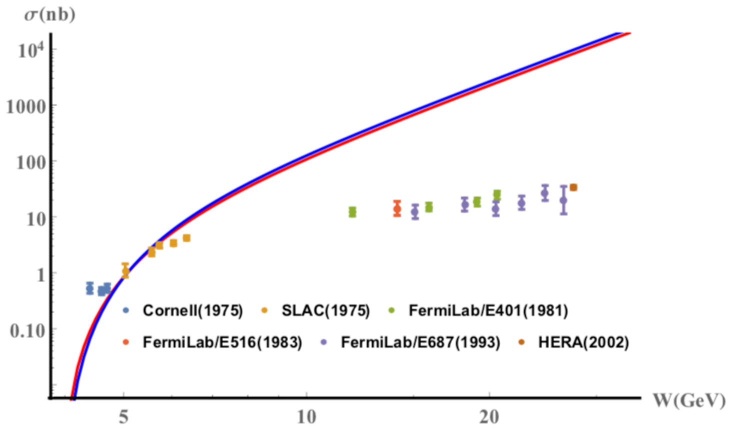

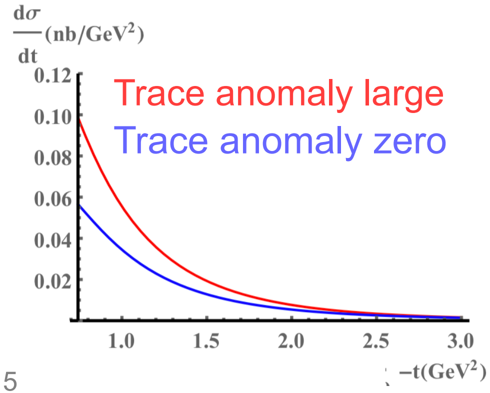

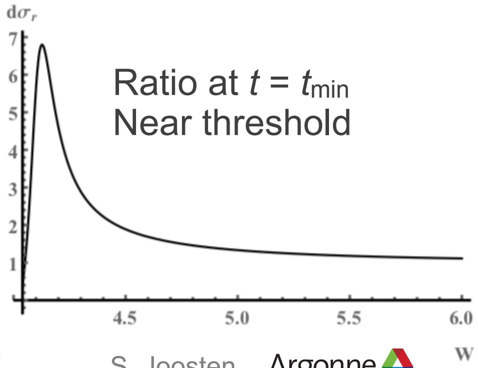

Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)

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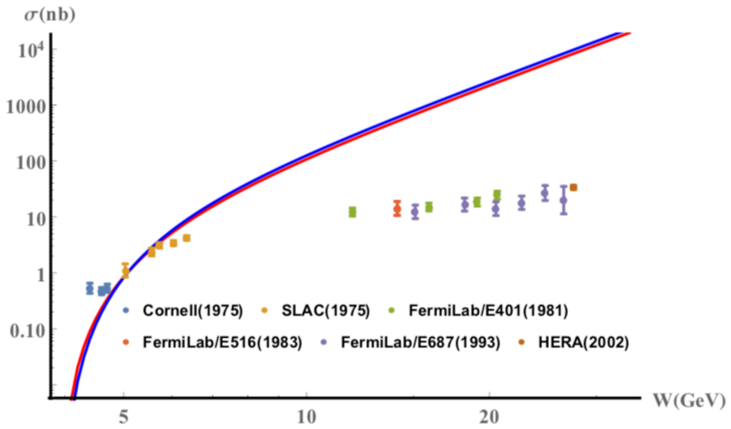
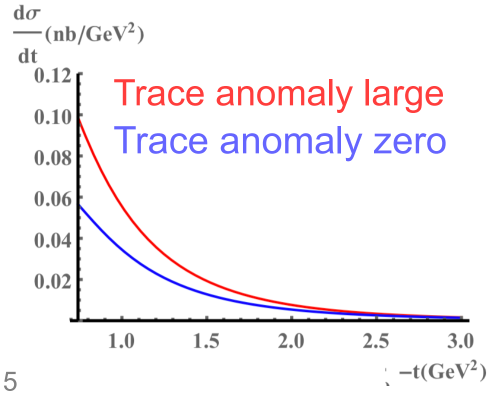
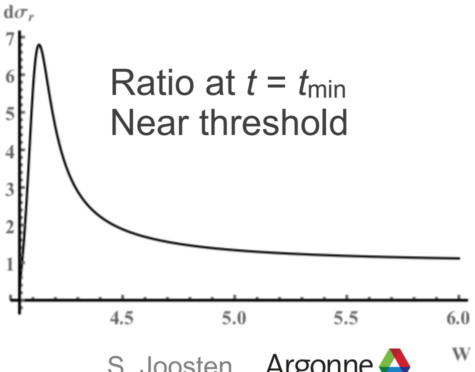
- New development, numerical predictions cary large model uncertainties







Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)
S. R. Beane *et al.*, PRD 91, 114503 (2015)

BINDING ENERGY OF THE *J/Ψ* - NUCLEON POTENTIAL

The nature of the gluonic Van der Waals force

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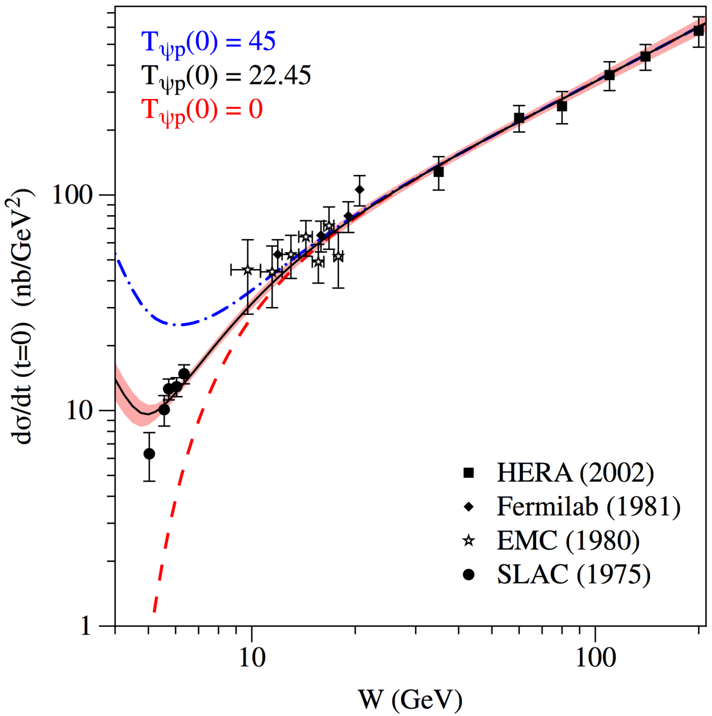

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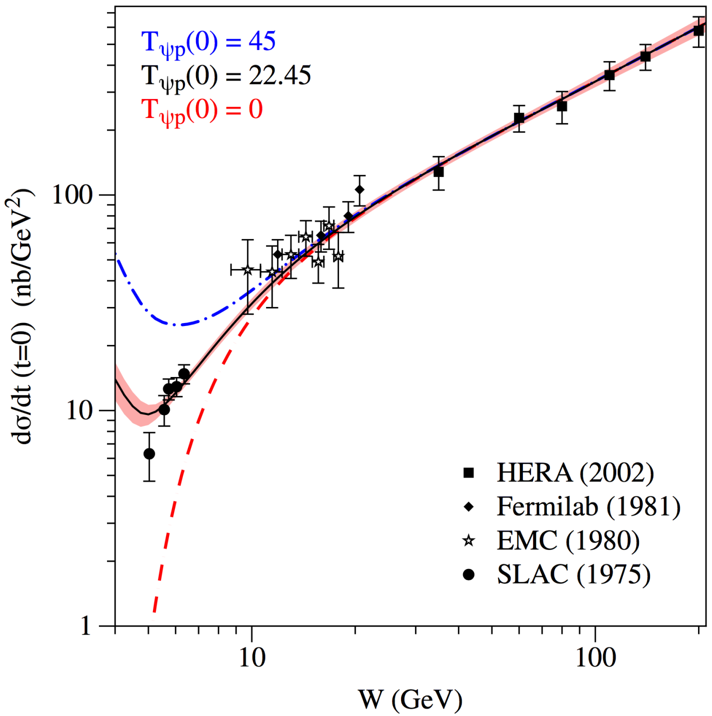

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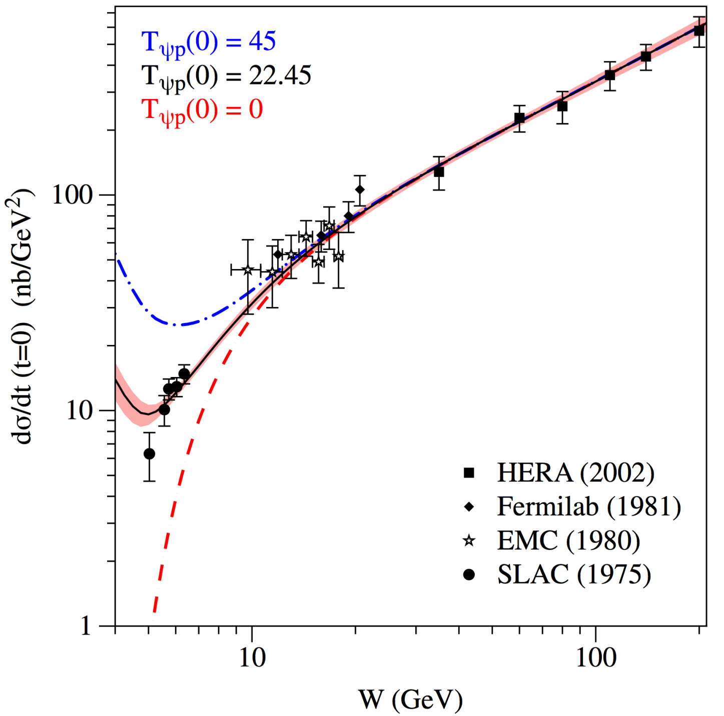

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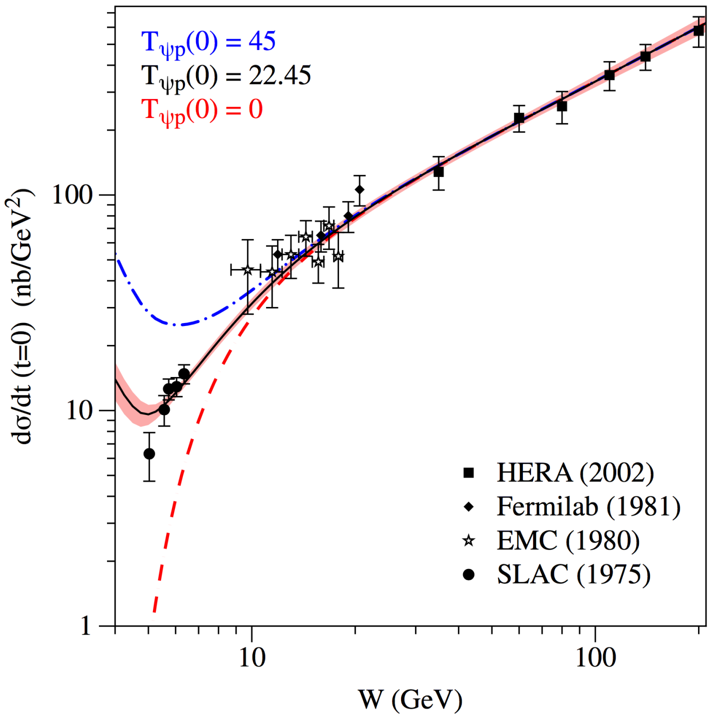
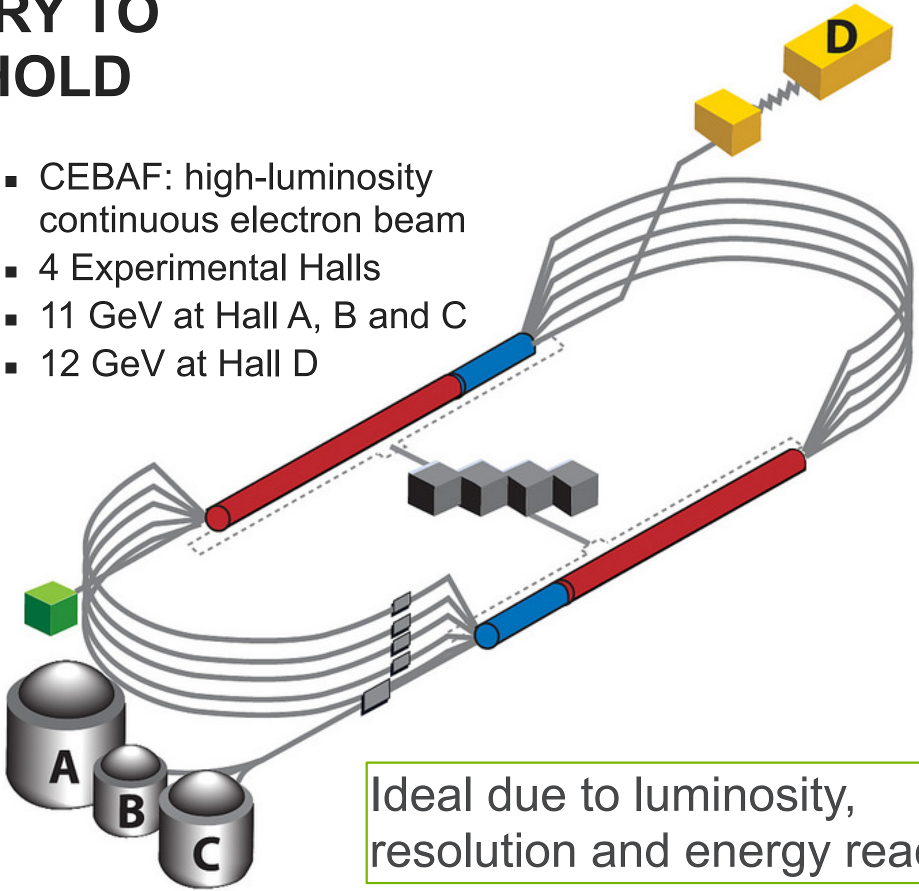
Need high-precision photo-production data near threshold



JLAB: THE IDEAL LABORATORY TO MEASURE *J/Ψ* NEAR THRESHOLD

- CEBAF: high-luminosity continuous electron beam
- 4 Experimental Halls
- 11 GeV at Hall A, B and C
- 12 GeV at Hall D



Ideal due to luminosity, resolution and energy reach

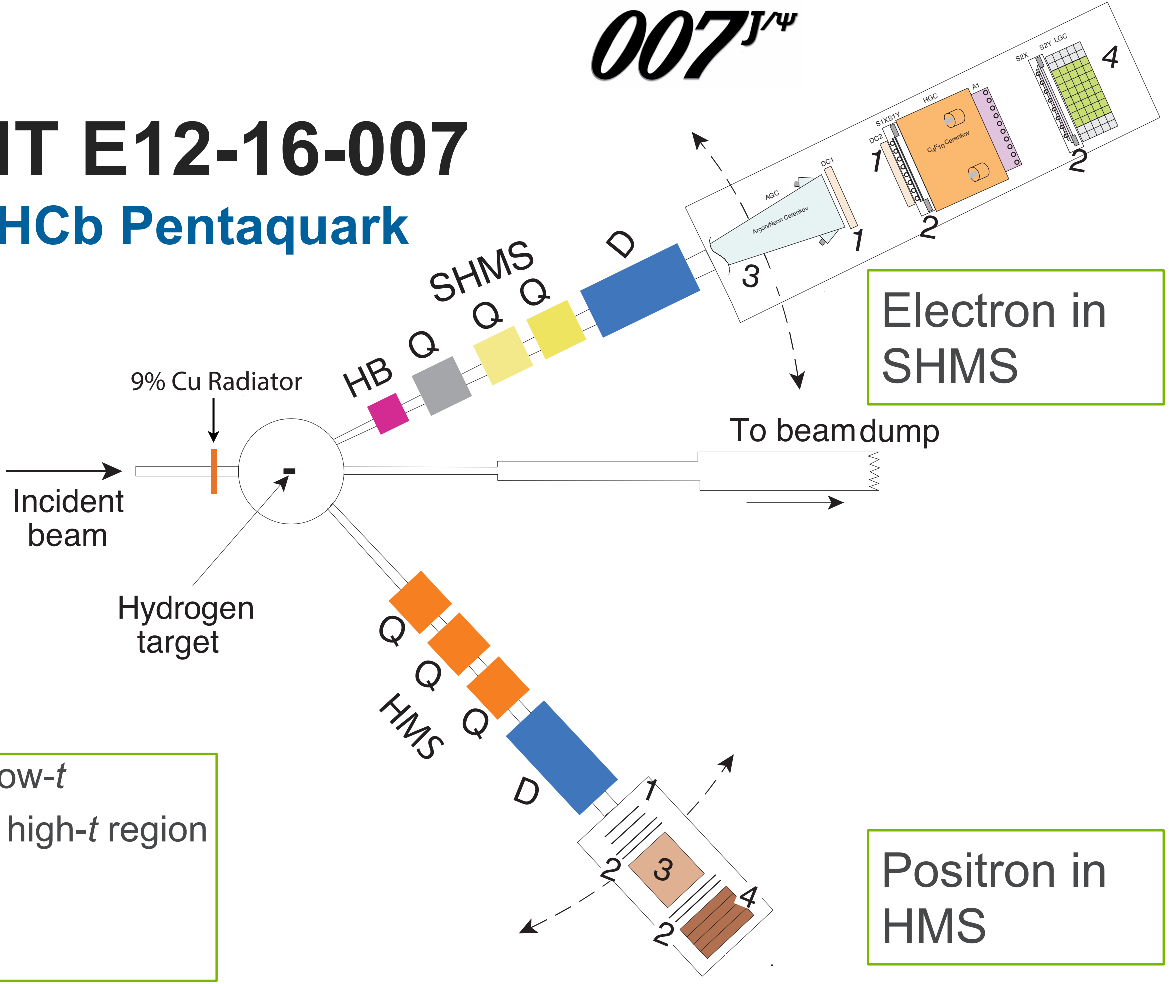
Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

$007^{J/\psi}$

JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

- 70μA electron beam at 10.6 GeV for 11 days
- 9% copper radiator
- 10cm liquid hydrogen target (total 10% RL)
- Detect *J/ψ* decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained

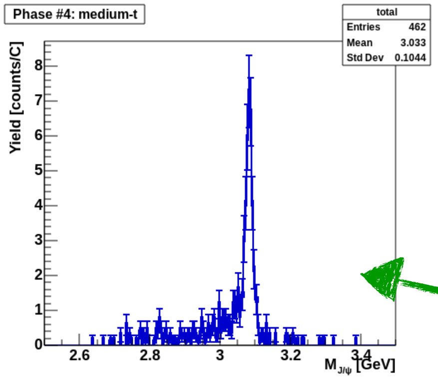


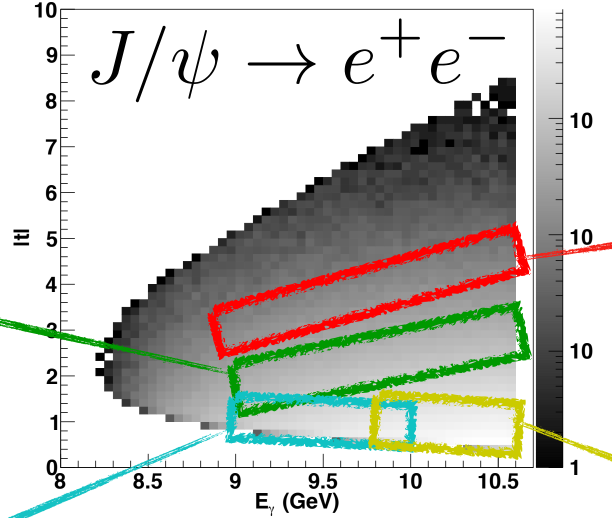
Electron in SHMS

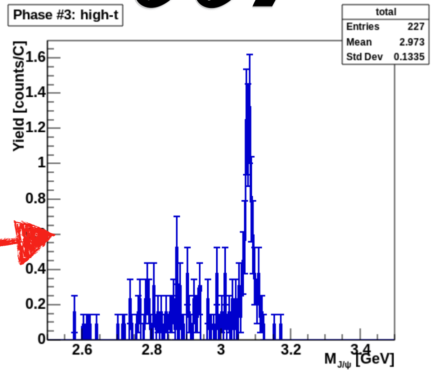
Positron in HMS

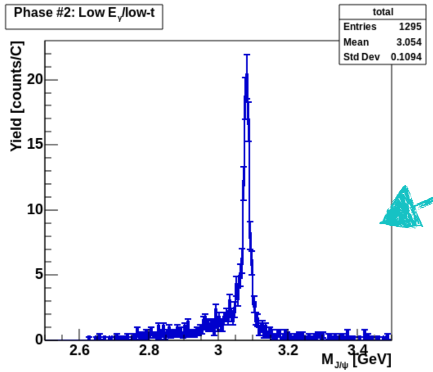
"Symmetric" configurations to measure low-*t*
"Asymmetric" configurations to measure high-*t* region
High impact experiment…
Ran February 8 - March 7, 2019!

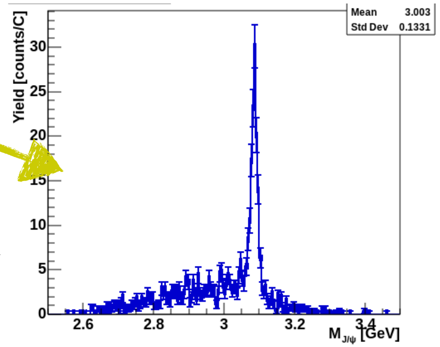
ONLINE RESULTS: INVARIANT MASS









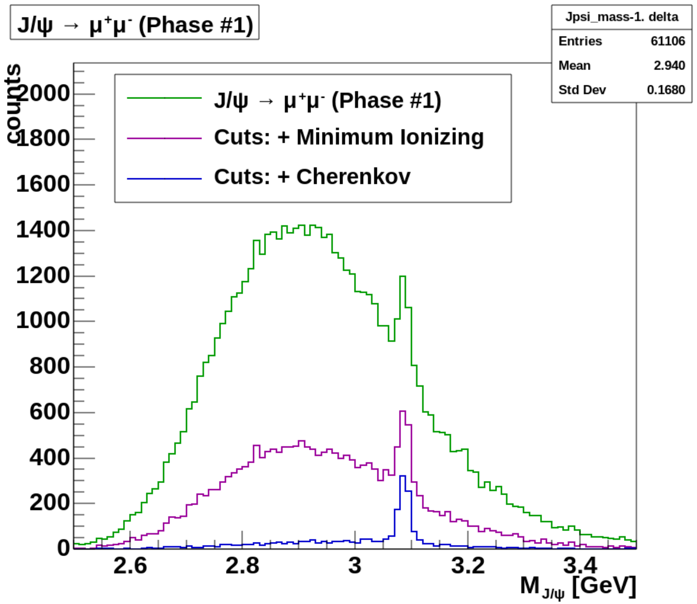


- High-precision measurement of the *t*-dependent cross section between 9-10.6 GeV
- Aim to publish results on pentaquark production before JLab user's meeting
- Largest dataset of *J/ψ* produced with a real photon beam.

ONLINE RESULTS: MUON CHANNEL

Potential to double statistics!

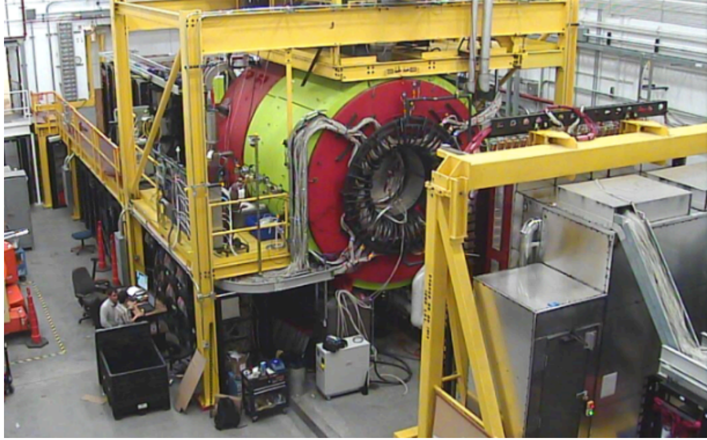
$$J/\psi \to \mu^+\mu^-$$

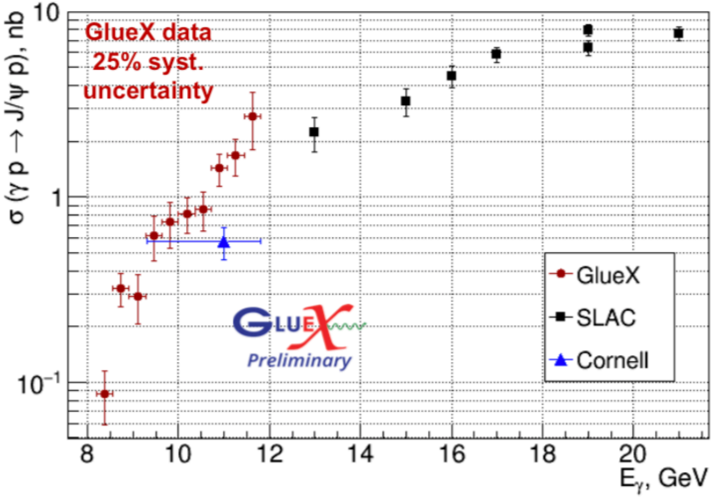


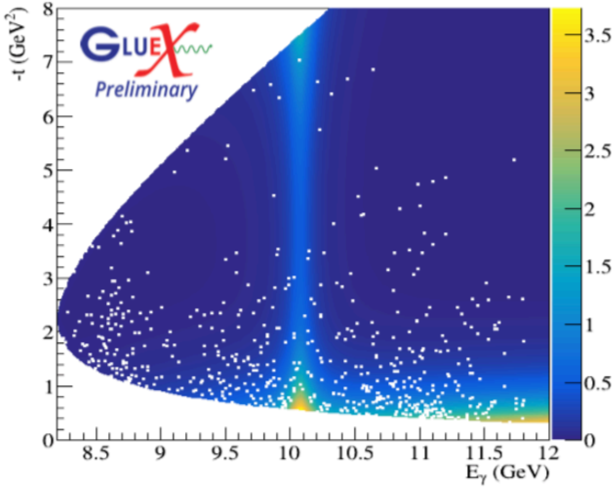
J/Ψ IN HALL D/GLUEX

OTHER *J/ψ* measurements at Jefferson Lab

- Preliminary data from GlueX: first *J/ψ* at JLab!
- Dominated by systematic uncertainty
- Possible issues with background
- Complimentary to Hall C (*J/ψ-007)* results



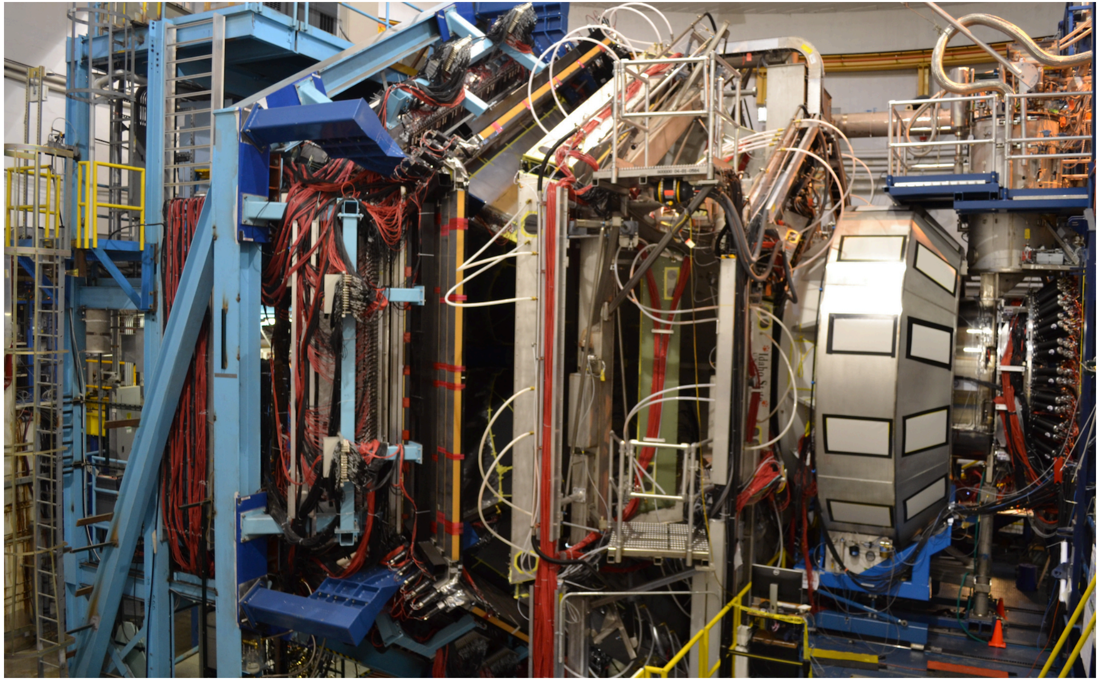




~20% background events

J/Ψ IN HALL B/CLAS 12

OTHER J/ψ measurements at Jefferson Lab



- Expected daily yield: 45J/ψ for 130 days
- First data taken in 2018 during run-group A
- Expect first results in ~1year

See K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141 and references therein

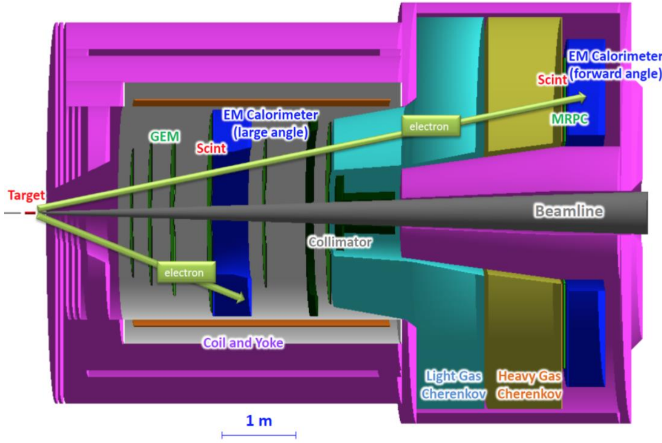
ATHENNA Collaboration

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

J/Ψ EXPERIMENT E12-12-006 AT SOLID

The ultimate experiment to study *J/ψ* at threshold.

- 3μA electron beam at 11 GeV for 50 days
- 15 cm liquid hydrogen target
- **Ultra-high luminosity: 43.2 ab^{-1}**
- General purpose large acceptance spectrometer
- Symmetric acceptance for electrons and positrons
- Channels:
  - Electro-production
  - Quasi-real production
  - Photo-production through bremsstrahlung in target cell



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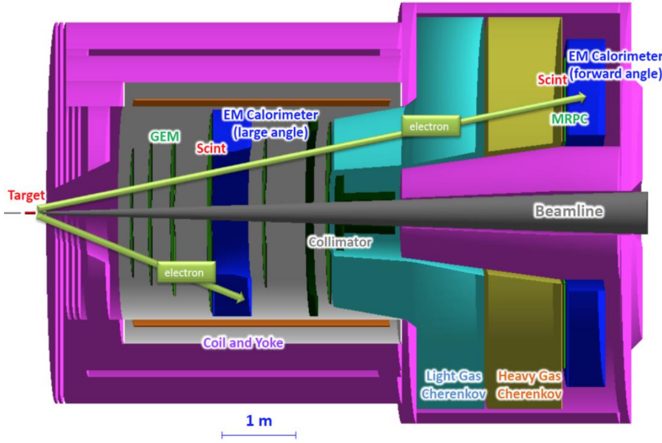

- Electro-production
  - Measure scattered electron and decay leptons
  - t-channel J/ψ rate: ~90/day
  - Clean signal (less background)
  - Closer to threshold

- Photo-production
  - Measure decay leptons and recoil proton
  - t-channel J/ψ rate: >1600 per day
  - Ultra-high rate

See K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141 and references therein

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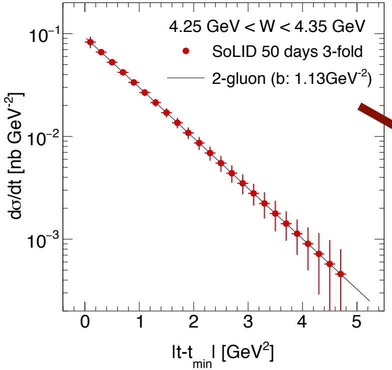
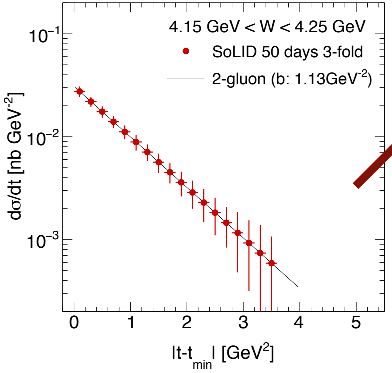
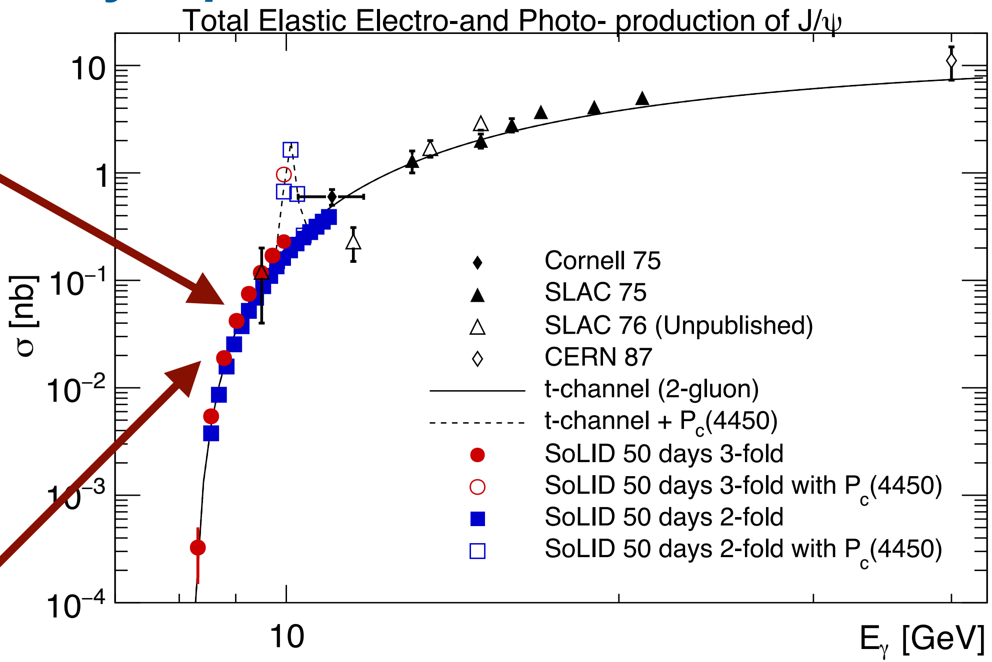






Sensitivity below 10^{-3} nb!

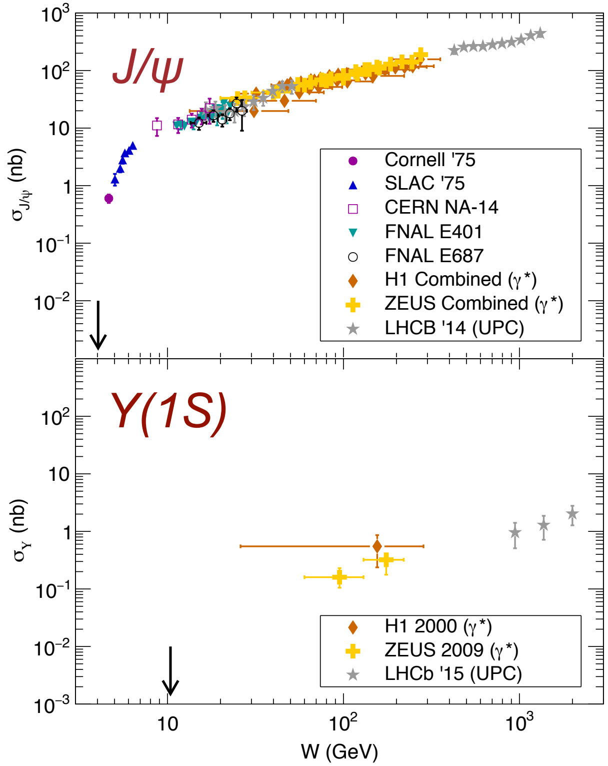
J/Ψ EXPERIMENTS IN JLAB IN A NUTSHELL

Exciting times for *J/ψ* near threshold!

	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	~400	~2100 (4200 with muons)	45/day	1627/day
J/ψ Rate (electro-prod.)				86/day
Experiment		E12-16-007	E12-12-001	E12-12-006
PAC days		9+2	130	50
When?	Finished	Finished	Ongoing	~10 years?

Y(1S): THE OPTIMAL GLUONIC PROBE

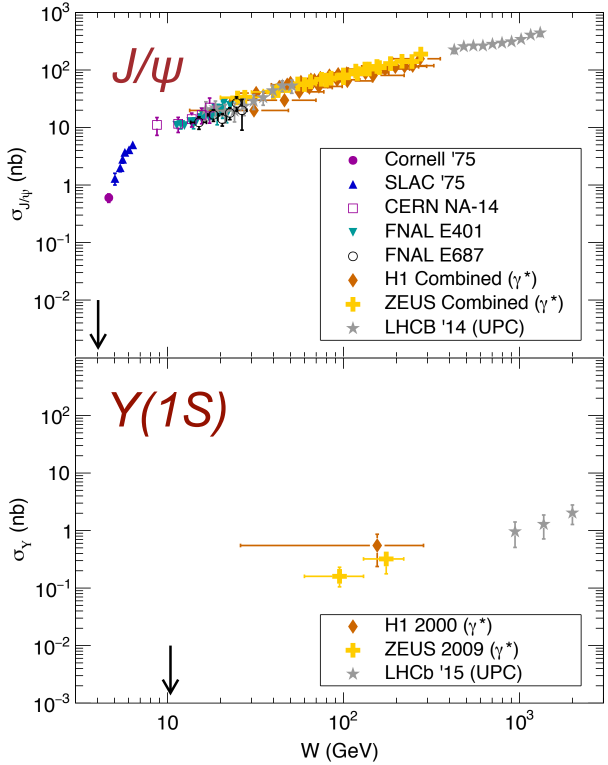
…but a challenging measurement



Y(1S): THE OPTIMAL GLUONIC PROBE

…but a challenging measurement

- *Y(1S)* is a heavier (smaller) probe than *J/ψ*
  - *Y(1S)* production near threshold crucial to **universality**



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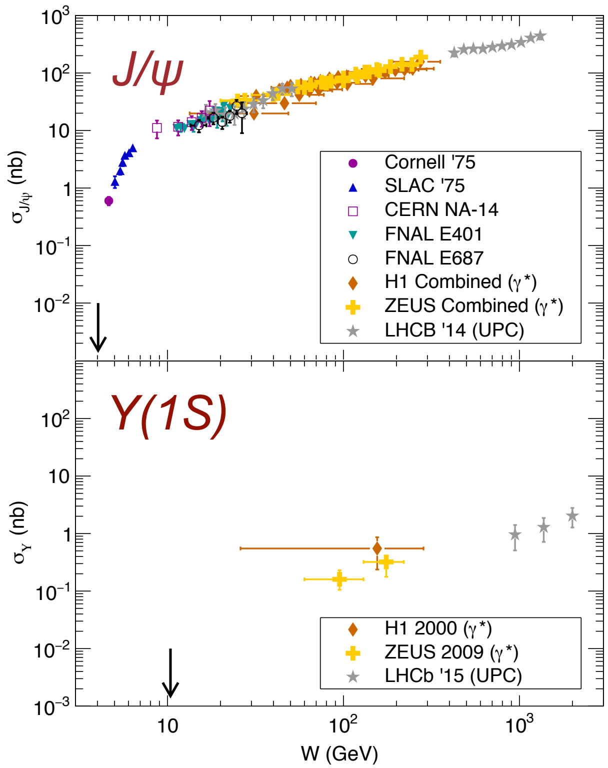

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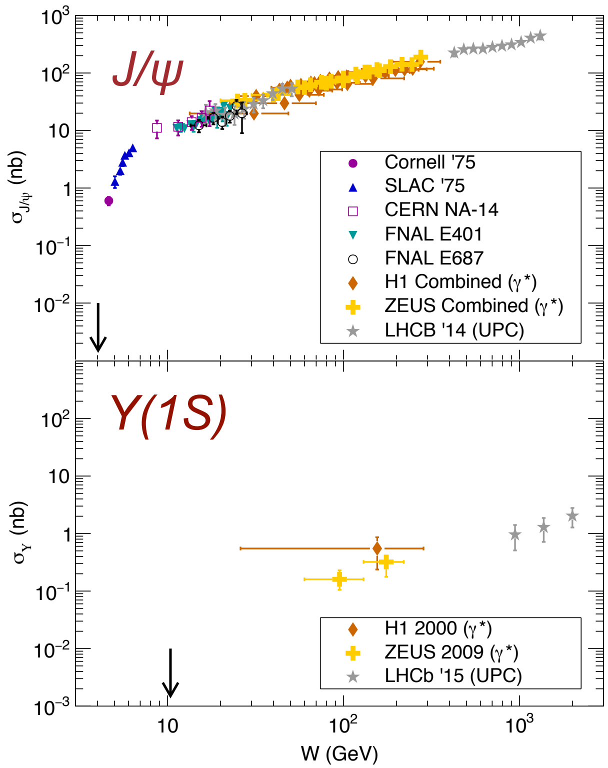
- *Y(1S)* is a heavier (smaller) probe than *J/ψ*
  - *Y(1S)* production near threshold crucial to **universality**
- Cross section very small (2 orders of magnitude smaller than *J/ψ)*
- Measurement can (only) be done at EIC

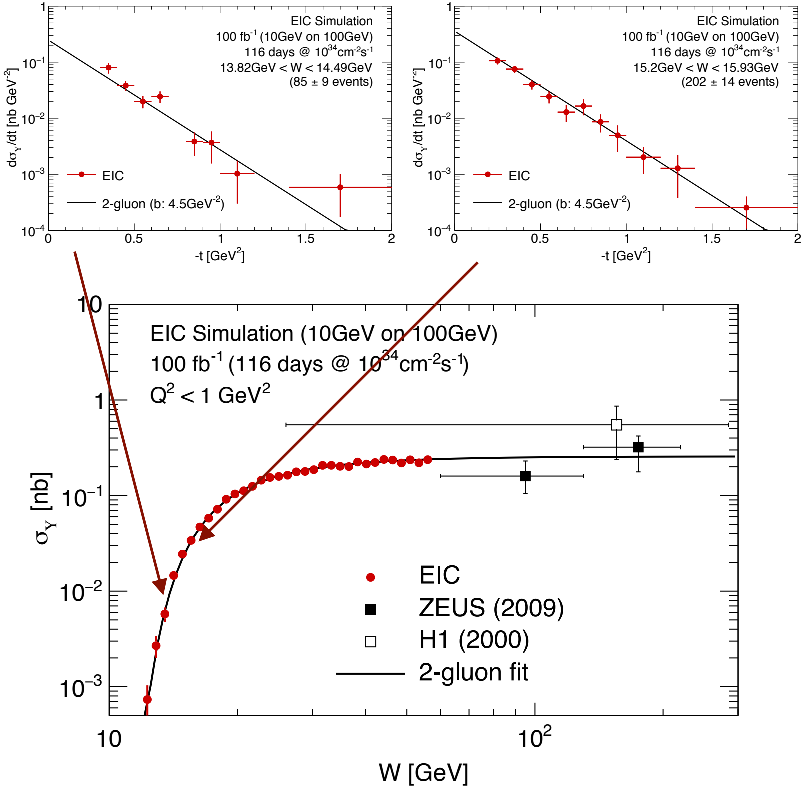


S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)

Y(1S) PHOTO-PRODUCTION AT EIC

…Threshold measurement possible!

- **Quasi-real production** at an EIC
- Both electron and muon channel
- **Fully exclusive** reaction
- Can go **to near-threshold region**



Υ(1S) PHOTO-PRODUCTION AT EIC

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- **Fully exclusive** reaction
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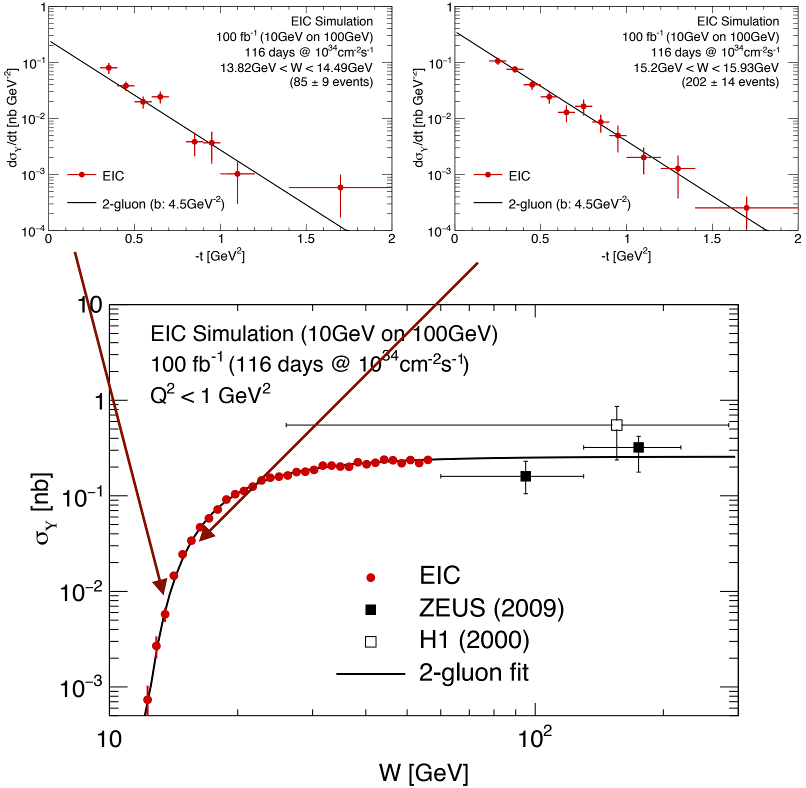
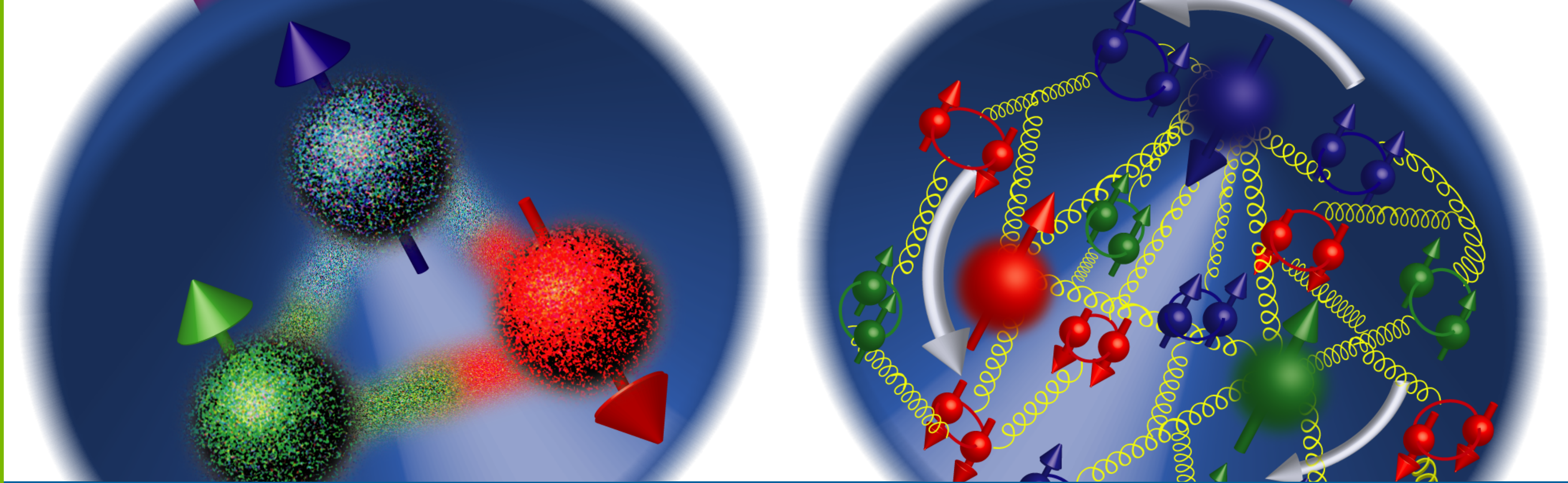


- ***Υ(1s)*** production possible at threshold!
  - Provides measure for **universality,** complimentary to threshold *J/ψ* program at JLab12
  - Are there a “beautiful” pentaquarks?
- Sensitivity down to ~10^{-3} nb!

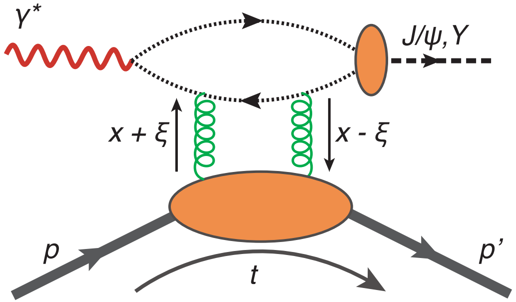


QUARKONIUM PRODUCTION AT HIGH ENERGIES

- Full 3D tomography of the gluonic structure of the nucleon

DEEPLY-VIRTUAL QUARKONIUM PRODUCTION

Accessing the gluon GPD



Hard scale: $Q^2 + M_V^2$

Modified Bjorken-x: $x_V = \frac{Q^2 + M_V^2}{2p \cdot q}$

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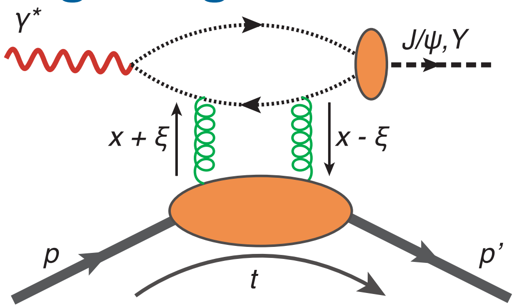

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average unpolarized gluon GPD related to t-dependent cross section (LO)

$$|\langle \mathcal{H}_g \rangle|(t) \propto \sqrt{\frac{d\sigma}{dt}(t) / \frac{d\sigma}{dt}(t=0)}$$

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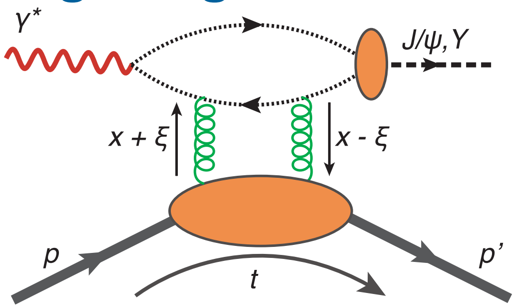

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Fourier transform:
transverse gluonic profile

$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

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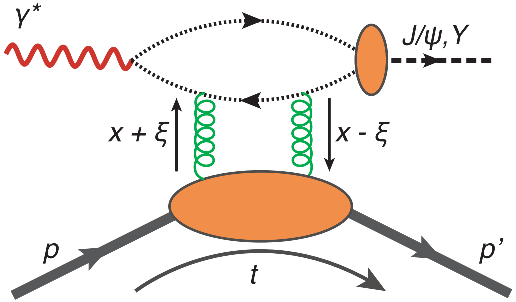

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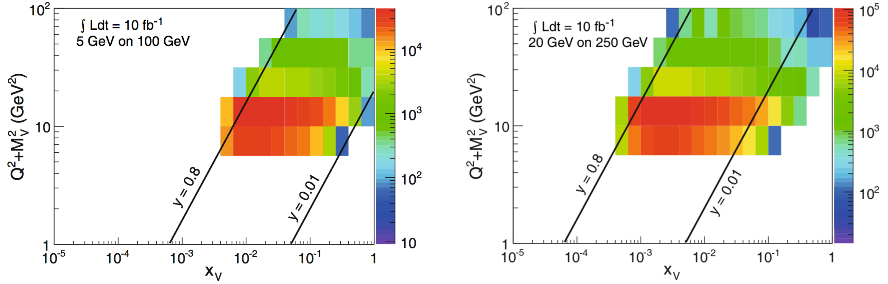
- Remarks:
  - **Simplest** possible GPD extraction
  - Intrinsic systematic uncertainty due to **extrapolation** outside of measured *t*-range
  - **NLO effects** could be significant
    - Corrections expected to be smaller for *Υ(1s)* than for *J/ψ*

GLUON TOMOGRAPHY WITH *J/Ψ*



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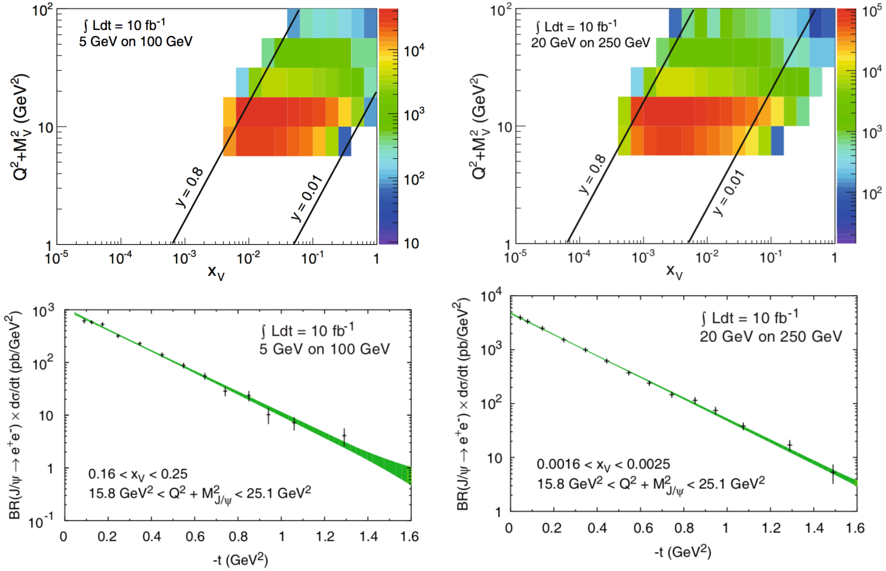
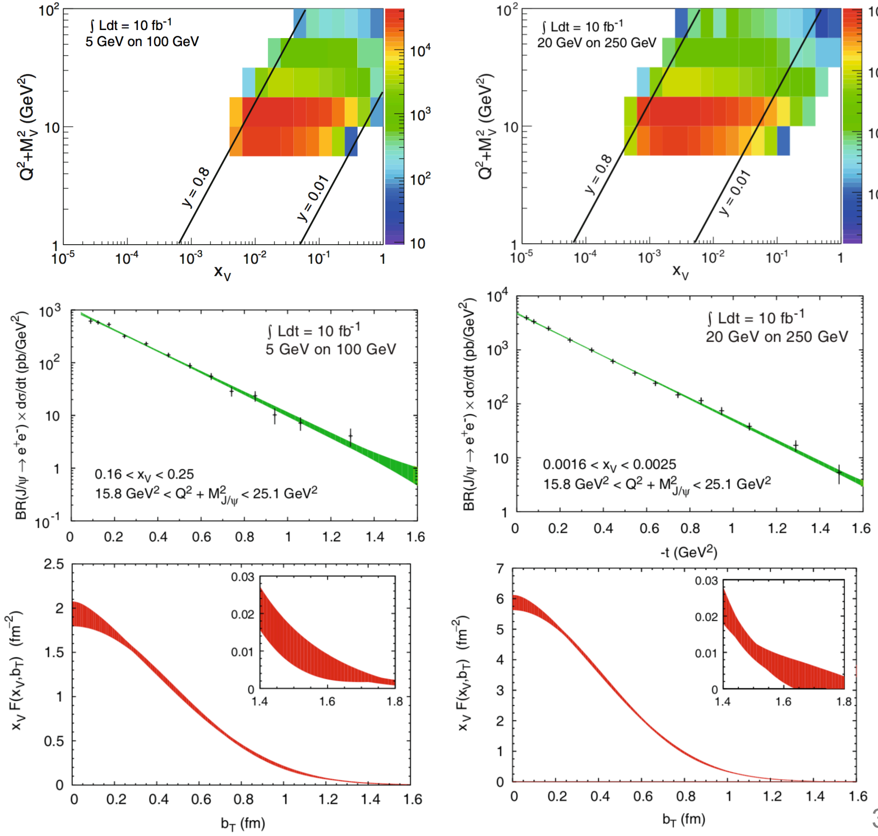


***t*-spectra**

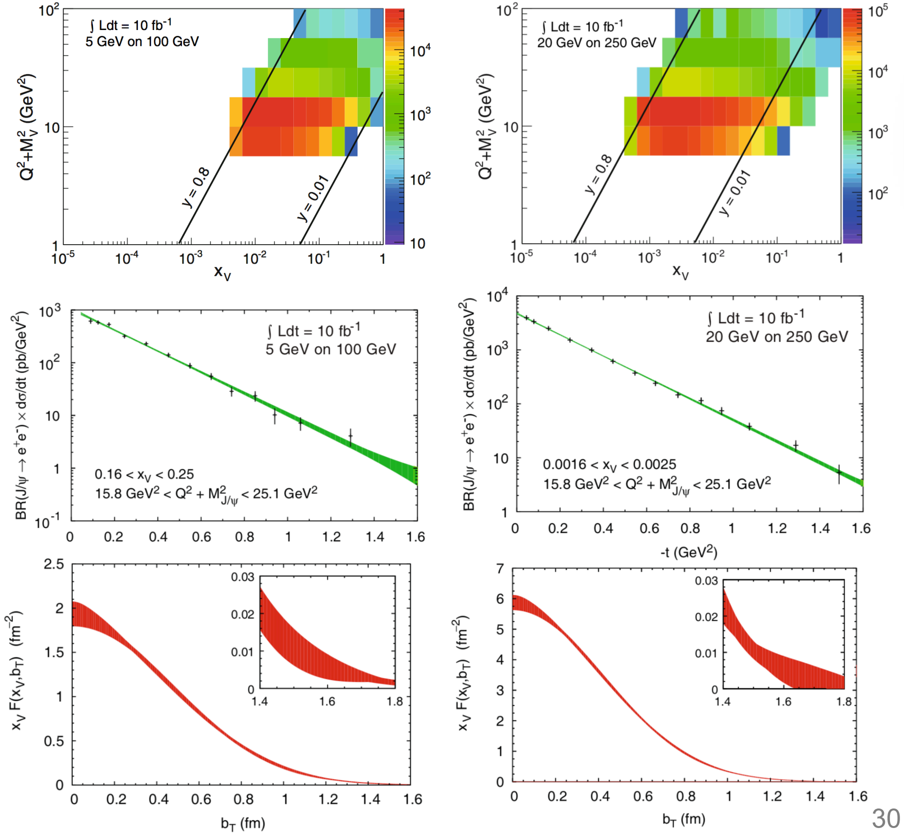
GLUON TOMOGRAPHY WITH *J/Ψ*



***t*-spectra**

Normalized average gluon density

GLUON TOMOGRAPHY WITH *J/Ψ*



Only possible at an EIC:
from the valence region deep into the sea!

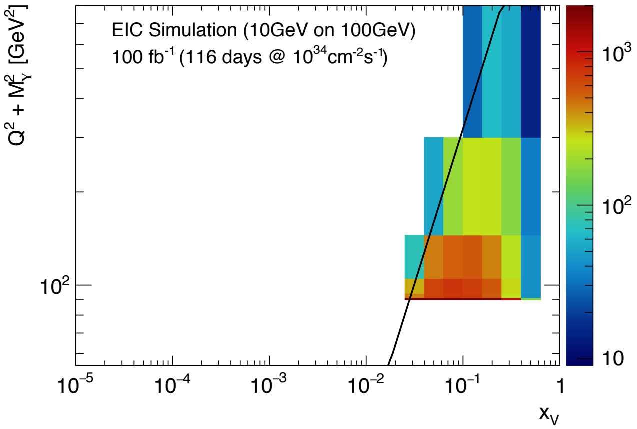
***t*-spectra**

Normalized average gluon density

S. Joosten
Argonne NATIONAL LABORATORY

S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)
S. Joosten, arXiv:1803.08615 (2018)

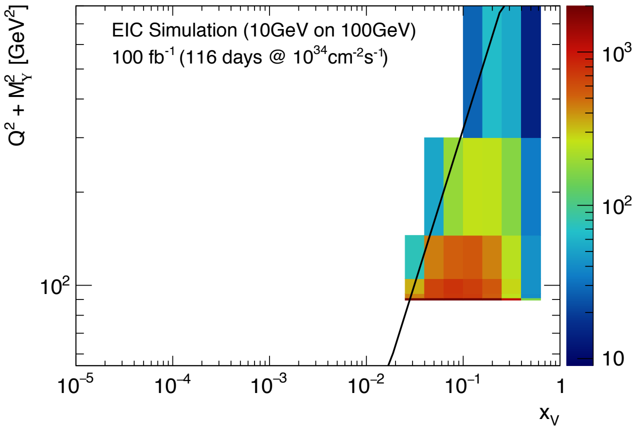
GLUON TOMOGRAPHY WITH *Υ(1S)*



- Requires ~100fb^{-1}
- Electron and muon channels
- Complimentary to J/ψ, important handle on universality

S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)
S. Joosten, arXiv:1803.08615 (2018)

GLUON TOMOGRAPHY WITH *Υ(1S)*



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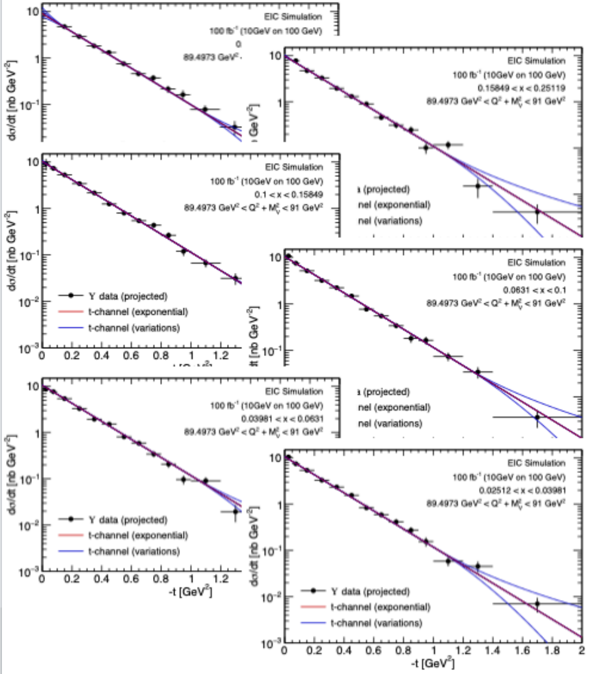

t-spectrum

S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)
S. Joosten, arXiv:1803.08615 (2018)

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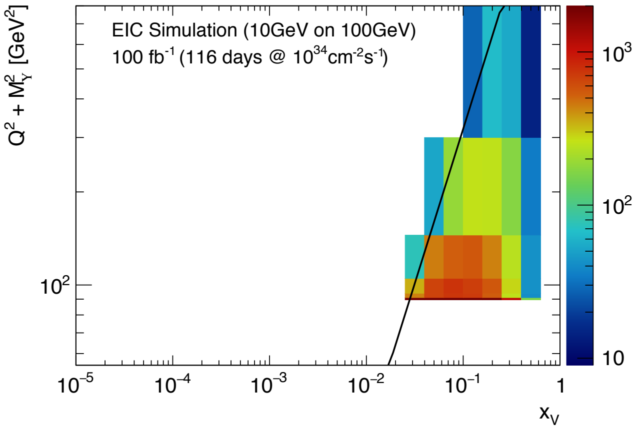

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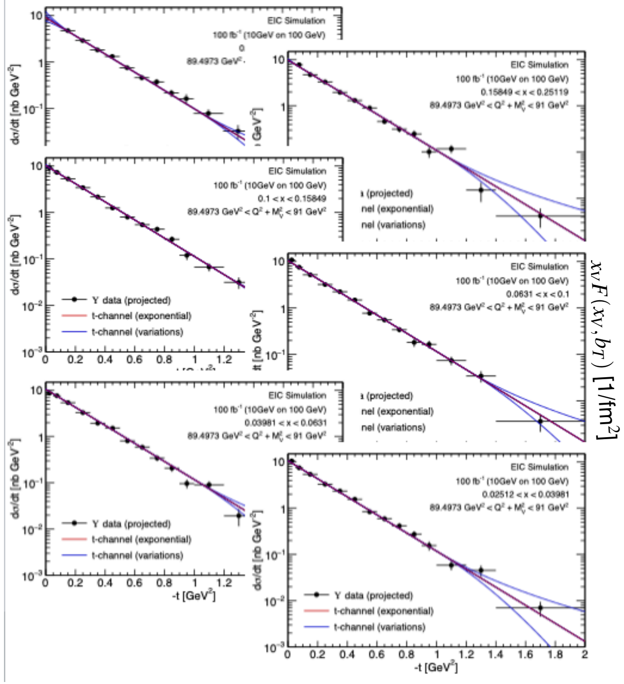
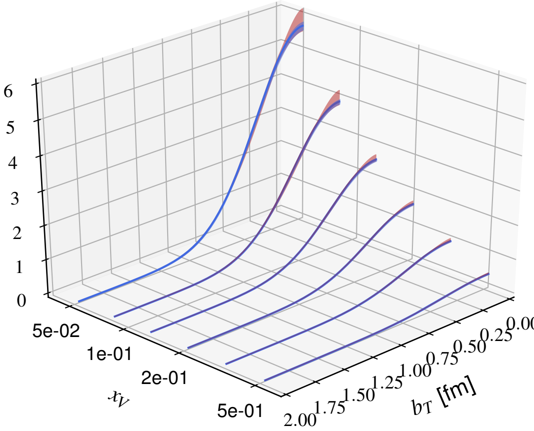
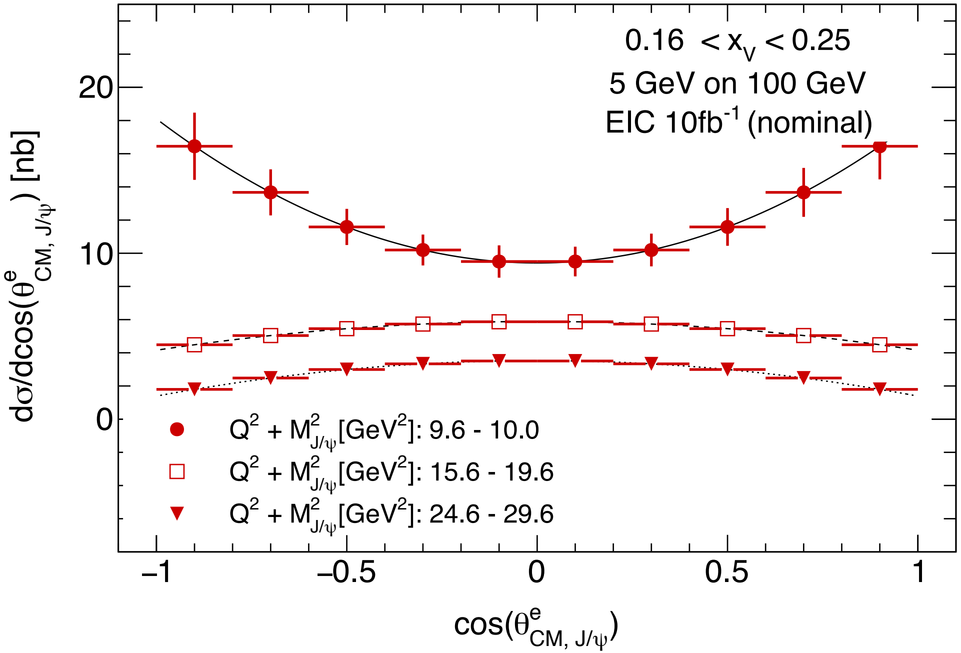




t-spectrum → Average gluon density

L-T SEPARATION AND Q² DEPENDENCE OF R

Using S-channel helicity conservation



$$R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

$$\mathcal{W}(\cos\theta_{\rm CM}) = \frac{3}{8}\left(1 + r^{04}_{00} + (1 - 3r^{04}_{00})\cos^2\theta_{\rm CM}\right)$$

- Observable: angular dependence of decay leptons
- Possible to extract R in 3D or even 4D
- Precise measurement of the scale dependence of *R*

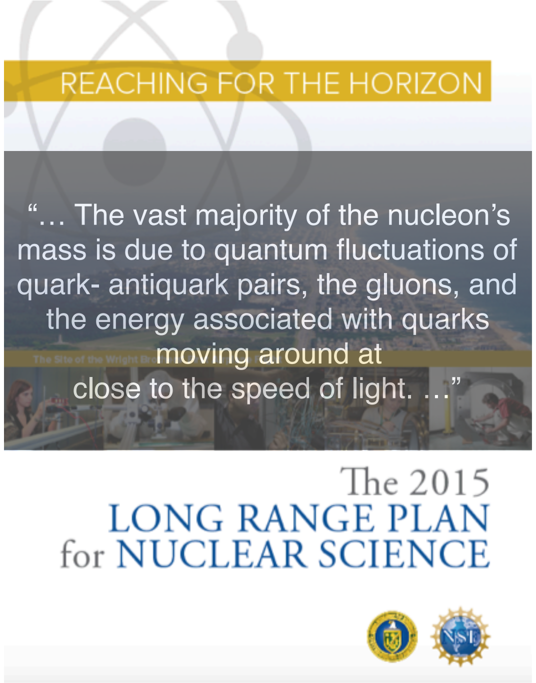
CONCLUSION

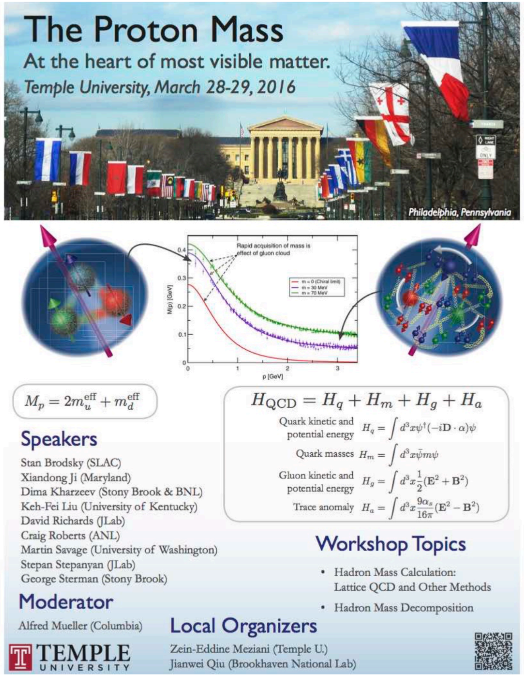
- **Quarkonium** production an important tool to study the **gluonic fields** in the nucleon
- **Threshold production** of quarkonium can shed light on the **trace anomaly,** quarkonium-nucleon **binding** and **proton mass**
- Possible to study "charming" (and "beautiful"?) pentaquarks
- At **high energies**: possible to access **gluon GPDs**
- Can **test universality by comparing** ***Υ*** **to** ***J/ψ*** results
- **JLab12 and the EIC** are (will be) perfectly positioned to **significantly contribute to these topics**

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

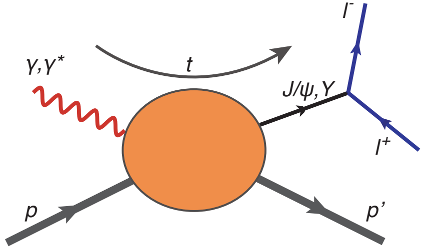
BACKUP

THE PROTON MASS… A HOT TOPIC!

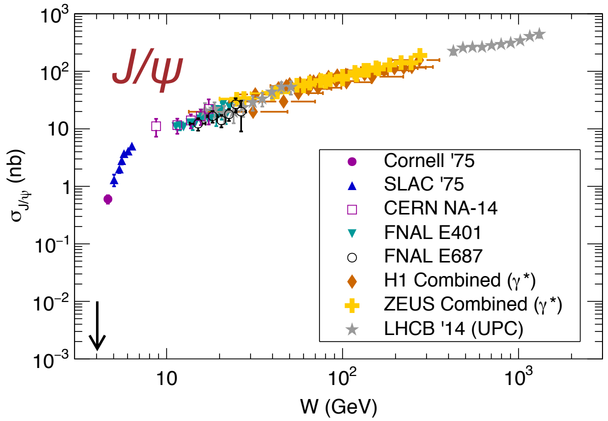


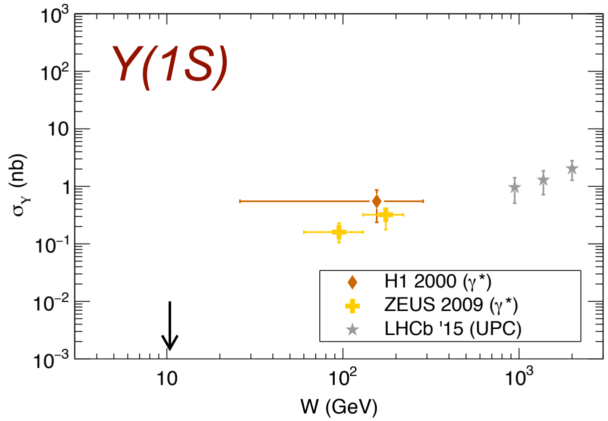


QUARKONIUM PHOTO-PRODUCTION: WHAT DO WE KNOW?



$$\sigma_{\rm tot}^{\gamma p} = \int_{t_{\rm min}}^{t_{\rm max}} dt \frac{d\sigma}{dt}$$





- **Direct photo-production**
  Cornell ’75
  SLAC ’75
  CERN NA-14
  FNAL E401, E687
- **Electro-production (quasi-real)**
  H1 and ZEUS
- **Ultra-peripheral collisions**
  LHCb ’14 (*pp*) and ALICE ’14 (*p*Pb)

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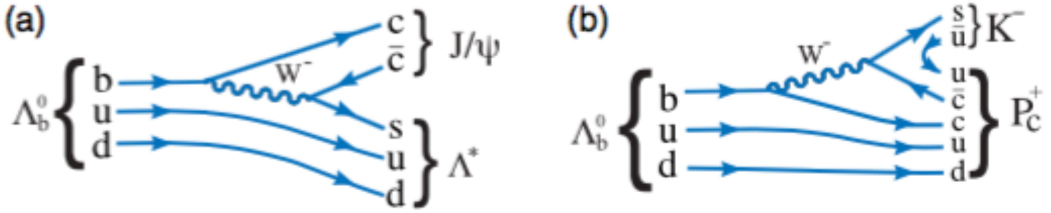
  H1 and ZEUS
- **Ultra-peripheral collisions**
  LHCb `15 (*pp*)

R. Aaij *et al.* (LHCb), PRL 115-7 (2015)

DISCOVERY OF THE LHCB CHARMED PENTAQUARK

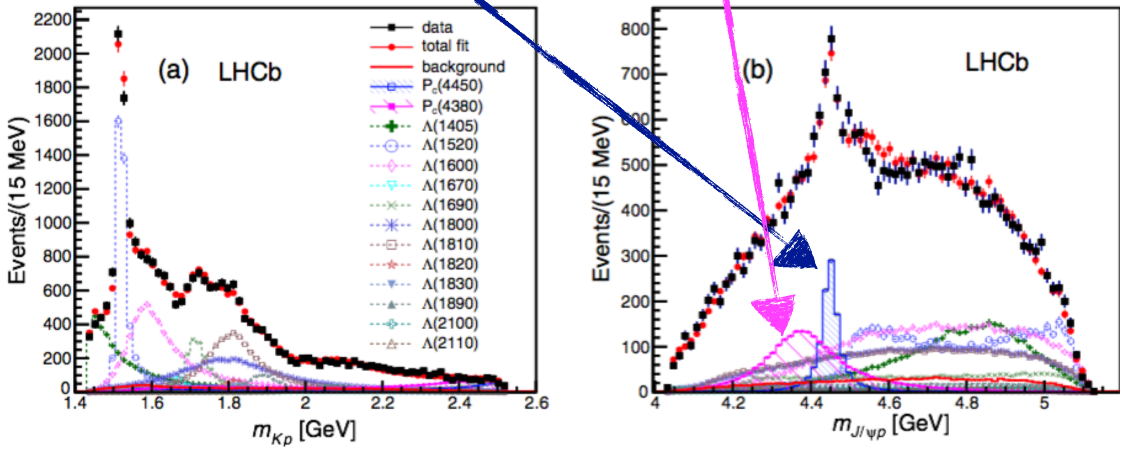
$$\Lambda_b \rightarrow \Lambda^* J/\Psi \rightarrow (K^- p) J/\Psi$$

$$\Lambda_b \rightarrow K^- P_c \rightarrow K^- (p J/\Psi)$$



narrow: P_c(4450) (12 σ)

wide: P_c(4390) (9σ)



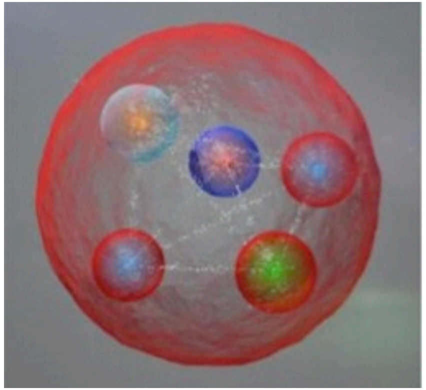
- LHCb collaboration findings: **two P_c states needed**:
- Spin/parity not fully constrained:
  - 5/2+ and 3/2- (most likely)
  - 5/2- and 3/2+
  - 3/2- and 5/2+

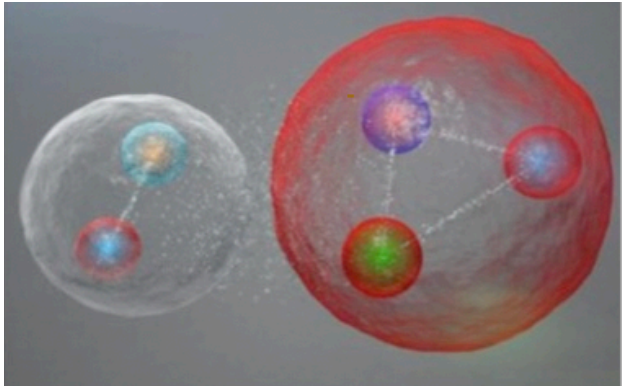
X-H Lui *et al.*, PLB 757, 231 (2016) and references therein
Q. Wang *et al.*, PRD 92-3 034022-7 (2015) and references therein

IS THIS A REAL PARTICLE?

We can confirm this at JLab!

- LHCb definitely saw something, but was it a pentaquark?
  1. **Truly new states:** P_c either true pentaquark or molecule
  2. **Alternative:** Kinematic enhancement through anomalous triangle singularity (ATS)
- Photo-production ideal tool to distinguish:
  1. **Truly new states:** P_c also created in photo-production
  2. **Alternative:** ATS not possible in photo-production
- P_c(4450) translates to **narrow peak around E_γ = 10.1 GeV**

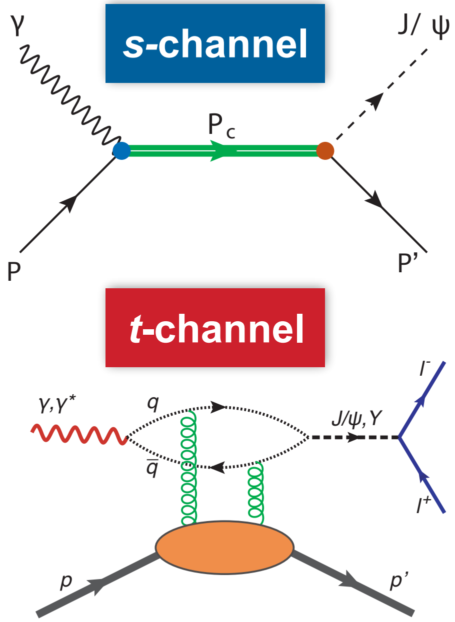




Jefferson Lab the perfect place to search for P_c

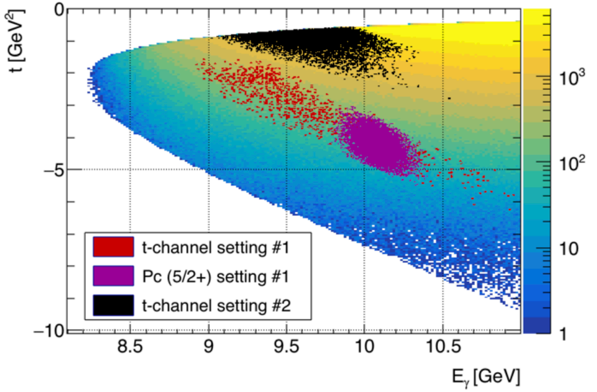
RESONANT *J/Ψ* PRODUCTION THROUGH P_C DECAY

Leverage the *t*-dependence to maximize signal over background



$$\frac{d\sigma}{dt}(\gamma p \rightarrow P_c \rightarrow J/\psi p)$$

- *J/ψ* angular distribution differs between *t*-channel and *s(u)*-channel:
  - *t*-channel production mostly forward (exponential-like *t*-dependence)
  - *s*-channel production more isotropic (flatter *t*-dependence)

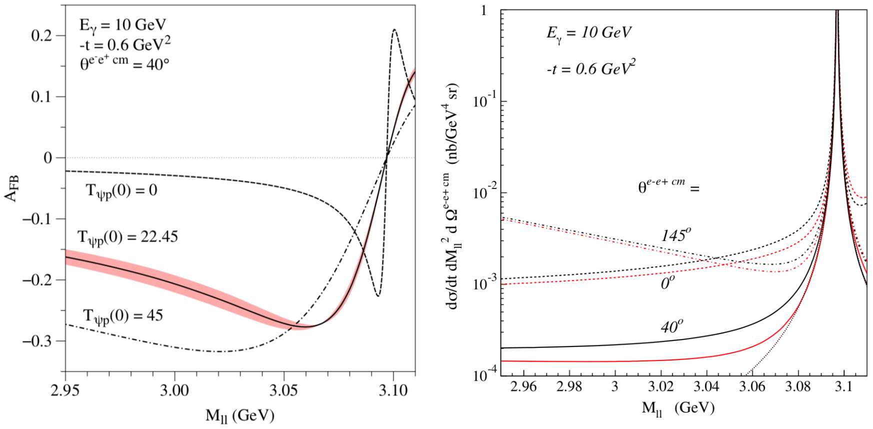


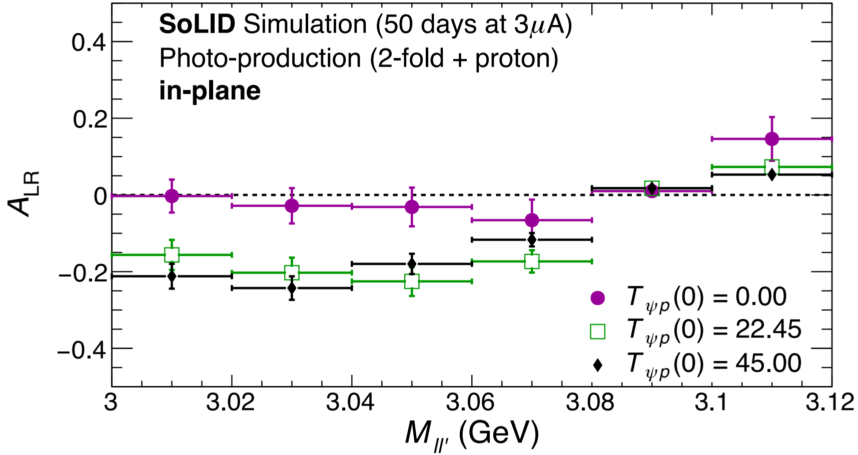
Best signal-to-background for resonant *J/ψ* production at high *t*

J/Ψ EXPERIMENT E12-12-006 AT SOLID

Measuring the interference with Bethe-Heitler

Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)





- Node at *J/ψ* peak: need to be outside of peak
- Cross section very low within typical experimental acceptance

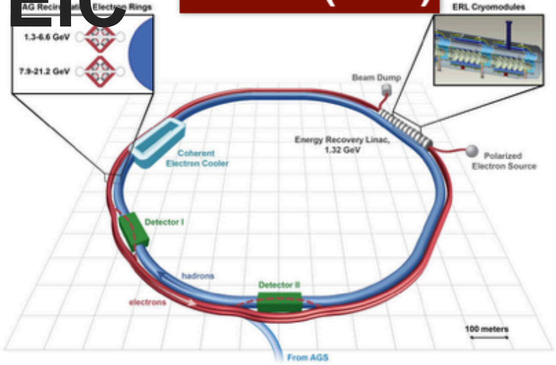
$$A_{FB} \equiv \frac{d\sigma(\theta^{e^-e^+\text{cm}}) - d\sigma(\theta^{e^-e^+\text{cm}} - 180°)}{d\sigma(\theta^{e^-e^+\text{cm}}) + d\sigma(\theta^{e^-e^+\text{cm}} - 180°)}$$

- Translates into left-right asymmetry that is experimentally better defined

Υ(1S) PHOTO-PRODUCTION AT EIC

- Nominal parameters relevant to quarkonium production:
  - (Consistent with accelerator/detector specs from white-paper for *J/ψ* production)
  - **10 GeV electrons on 100 GeV protons:** in range of both designs
  - **Luminosity: 100 fb^{-1}** (1 year @ 10^{34} cm^{-2}s^{-1})
  - **Acceptance**:
    - **Leptons**: pseudo-rapidity $|\eta| < 5$
    - **Recoil proton:** scattering angle $\theta > 2$ mrads
  - Resolution:
    - Angular < 0.5 mrad
    - Momentum < 1%

eRHIC (BNL)



JLEIC (JLab)