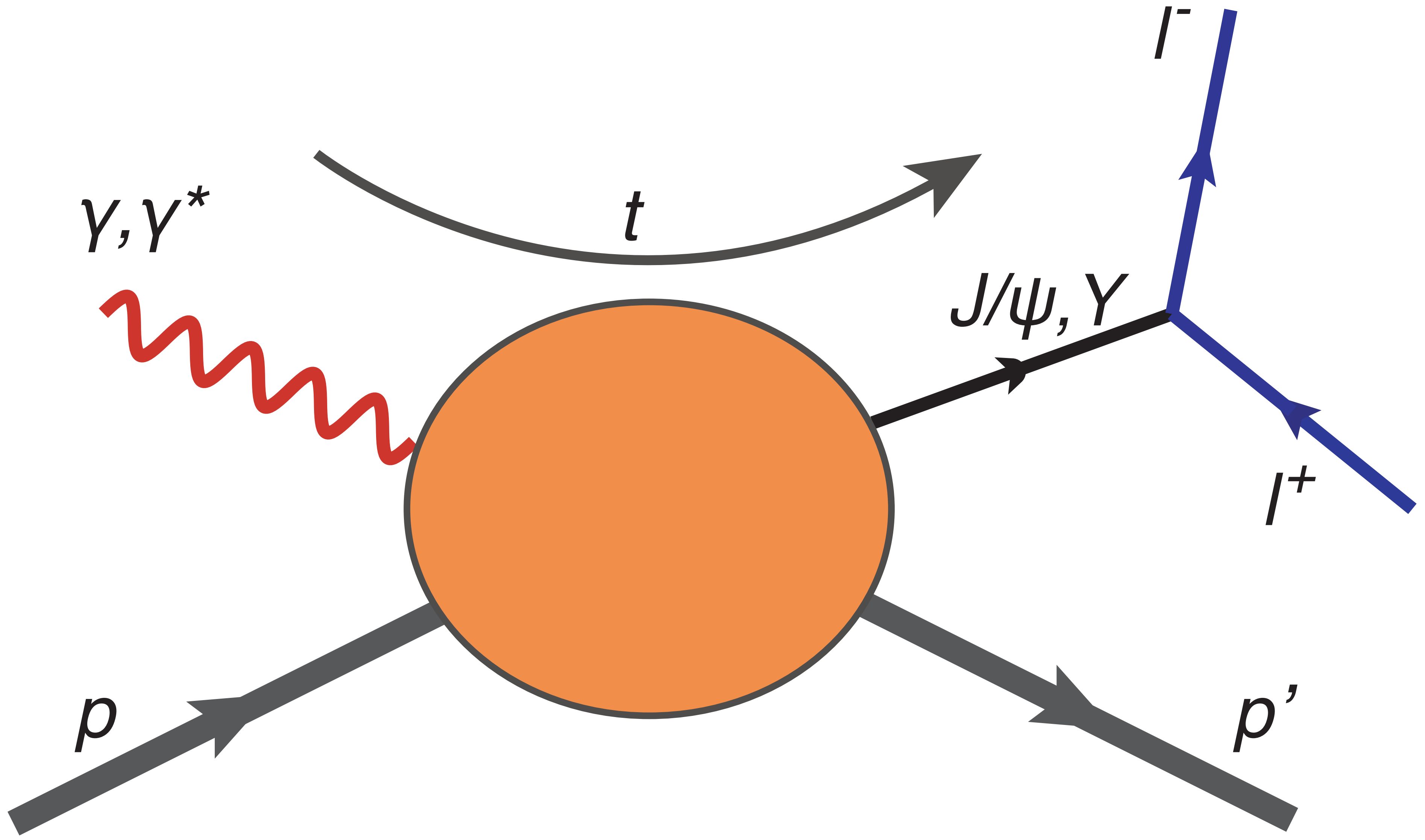
PROBING THE GLUONIC STRUCTURE OF THE NUCLEON AND THE DYNAMIC ORIGIN OF ITS MASS

Argonne NATIONAL LABORATORY

QUARKONIUM PRODUCTION: FROM JLAB TO EIC



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U.S. DEPARTMENT OF ENERGY
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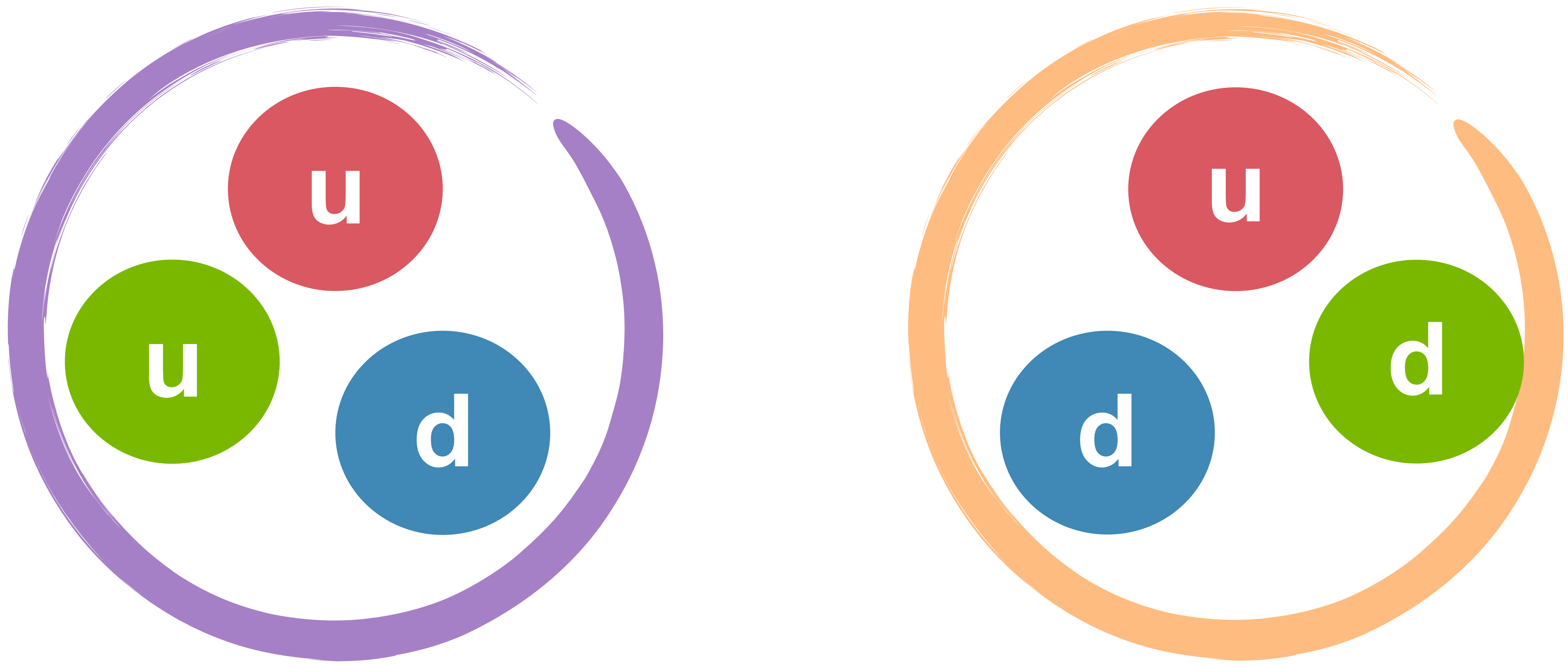
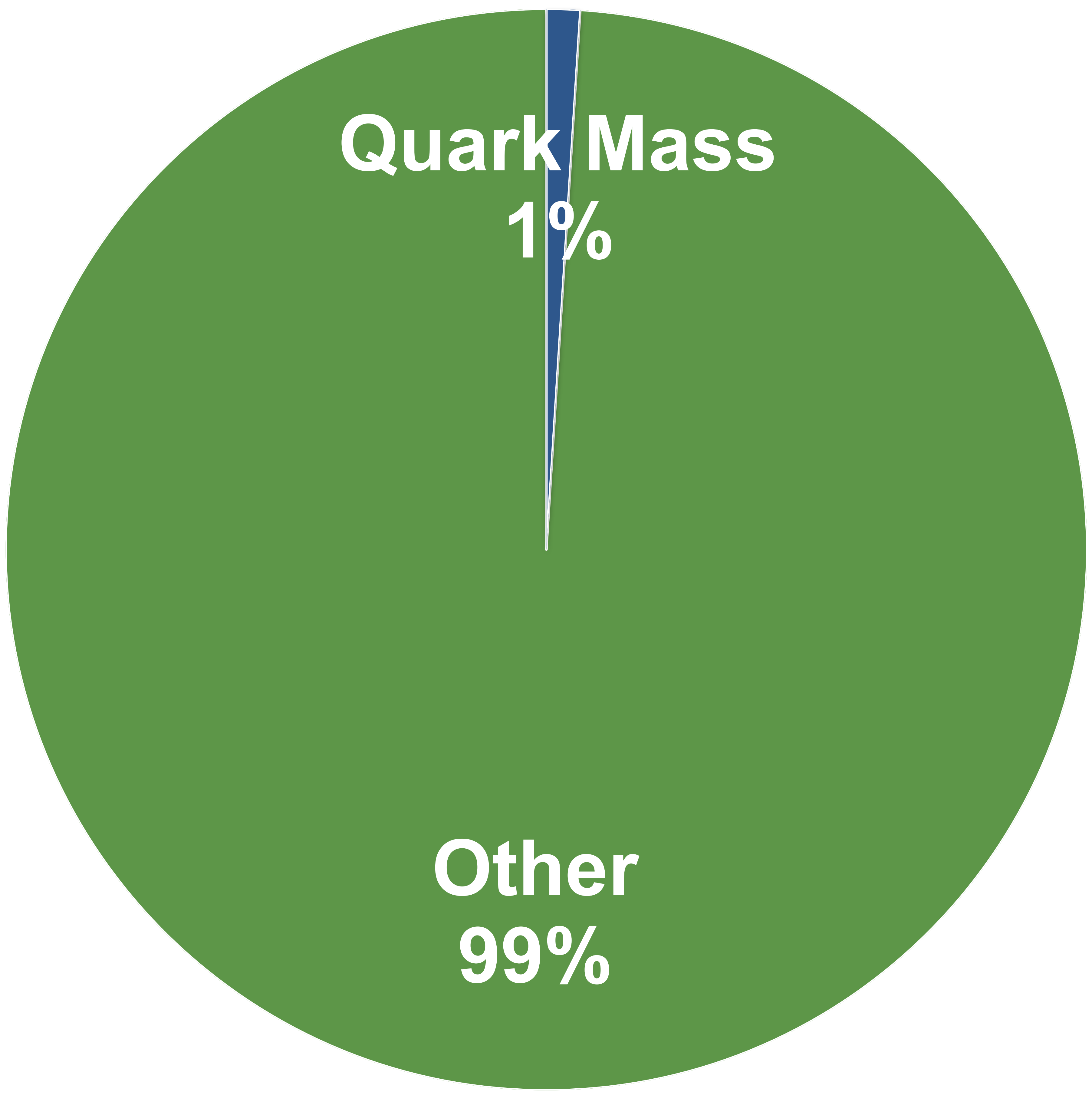
11th Workshop on Hadron Physics in China and Opportunities Worldwide

THE NUCLEON IN QCD

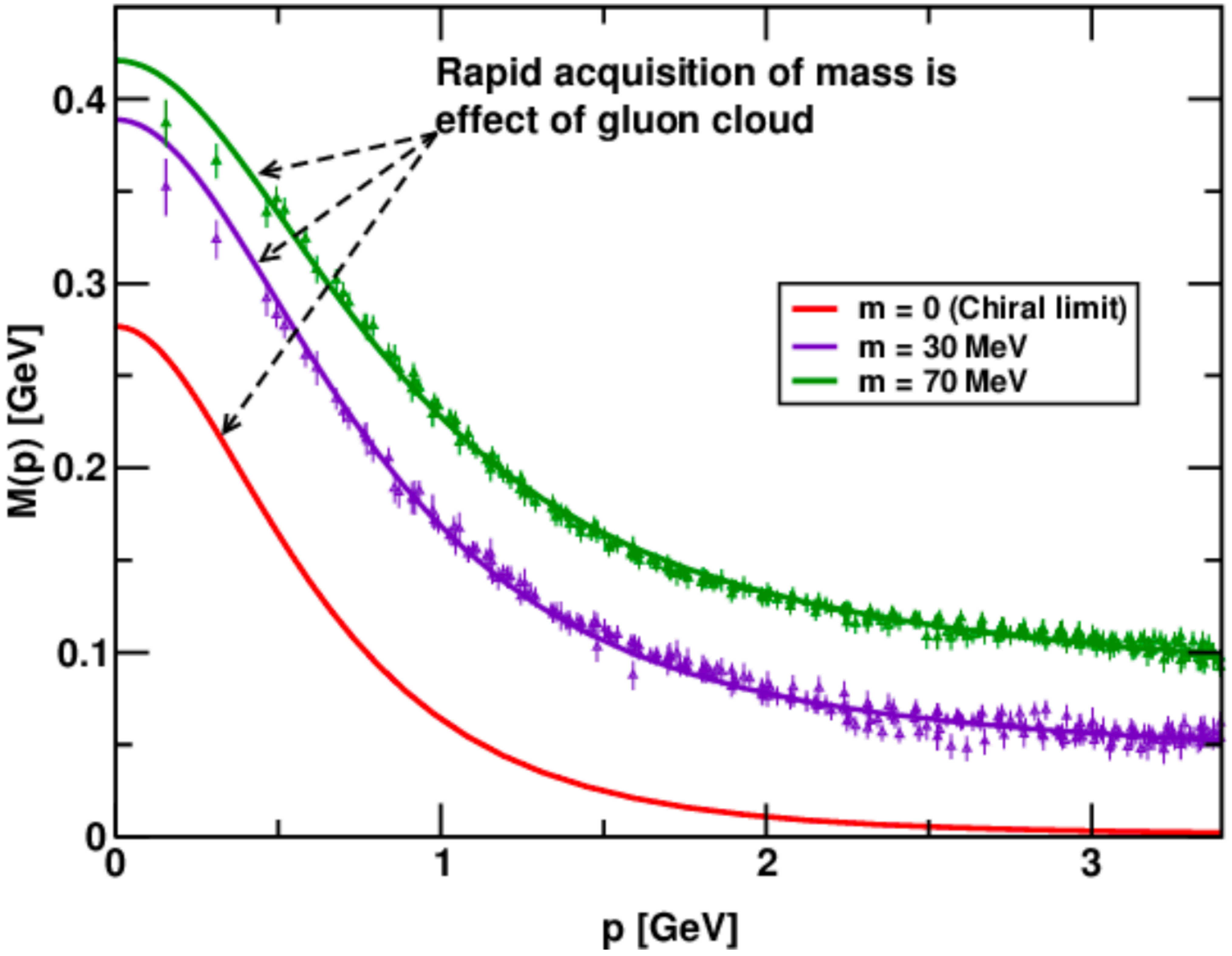
99% of the mass of the visible universe



- 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

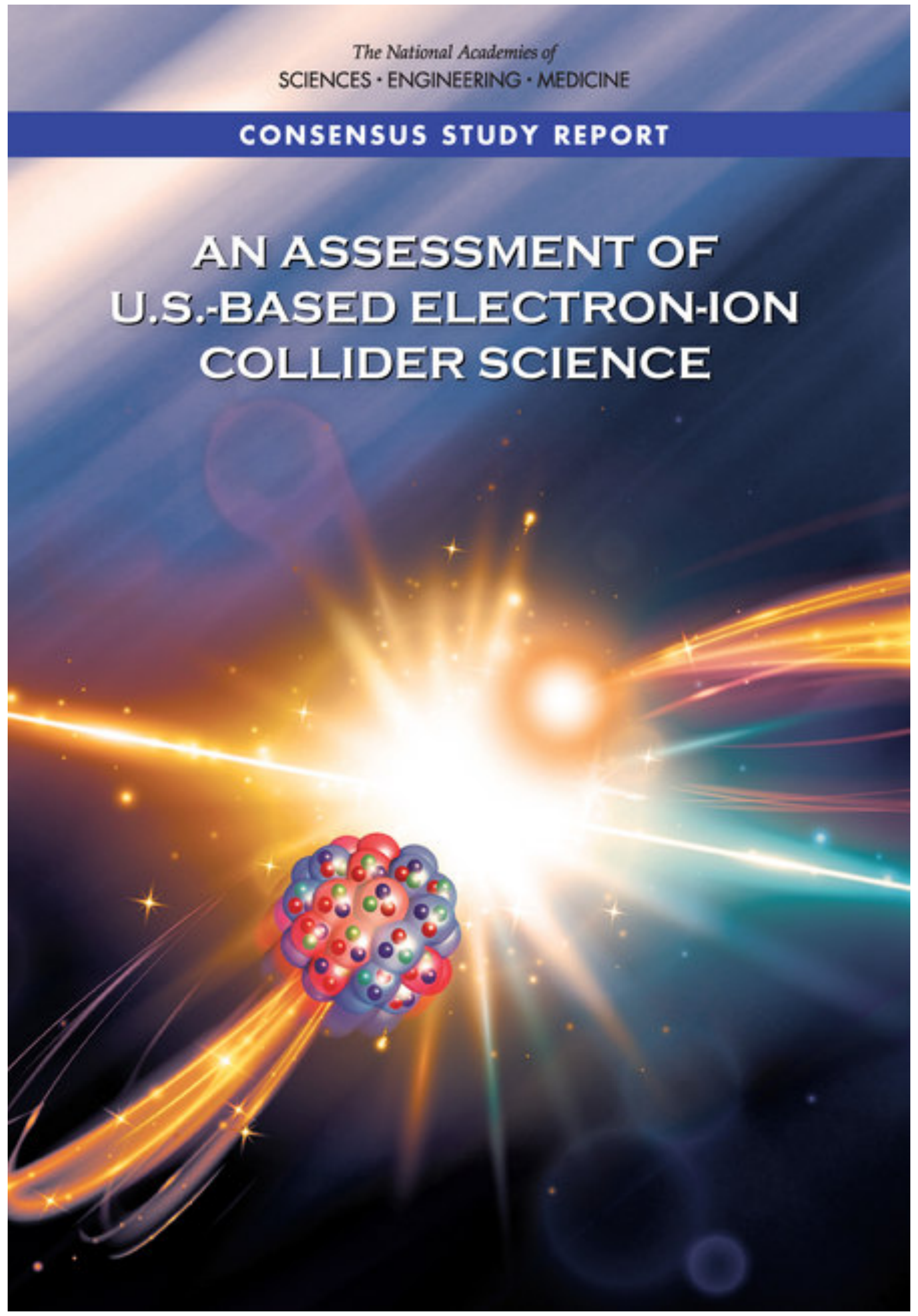


M. S. Bhagwat et al., Phys. Rev. C 68, 015203 (2003)
I. C. Cloet et al., Prog. Part. Nucl. Phys. 77, 1-69 (2014)

- 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!**

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

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

- At low momentum transfer, heavy quarks decouple: only two components remain

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

Trace Anomaly Light Quark Mass

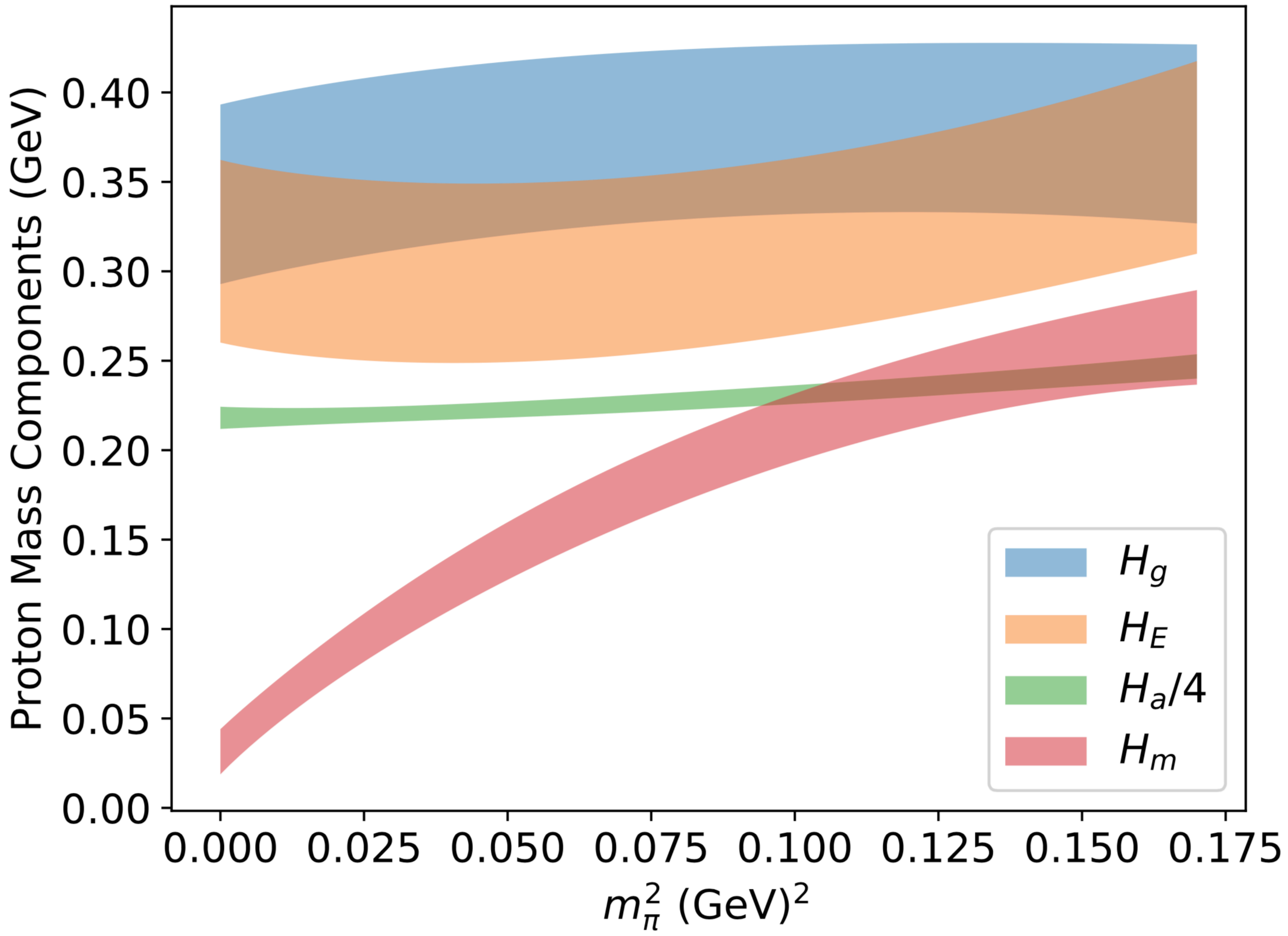
Trace anomaly dominant
"Proton mass result of the vacuum polarization induced by the presence of the proton."

Not so for pion
Unlike protons, trace anomaly must vanish for pions in the chiral limit!

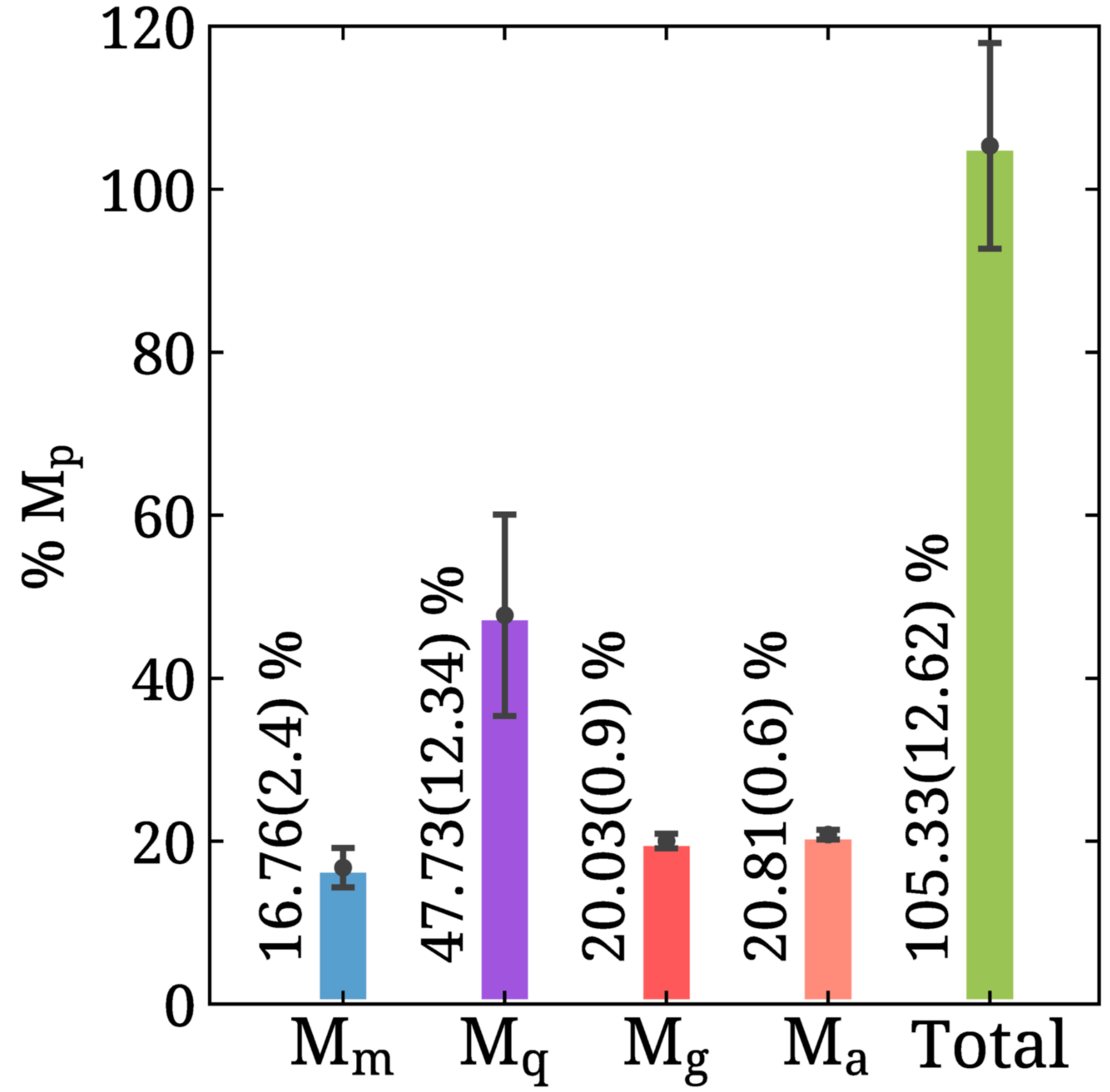
Trace anomaly intimately related to DCSB and the emergence of scale

PROTON MASS ON THE LATTICE

No direct calculation of trace anomaly to date.



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



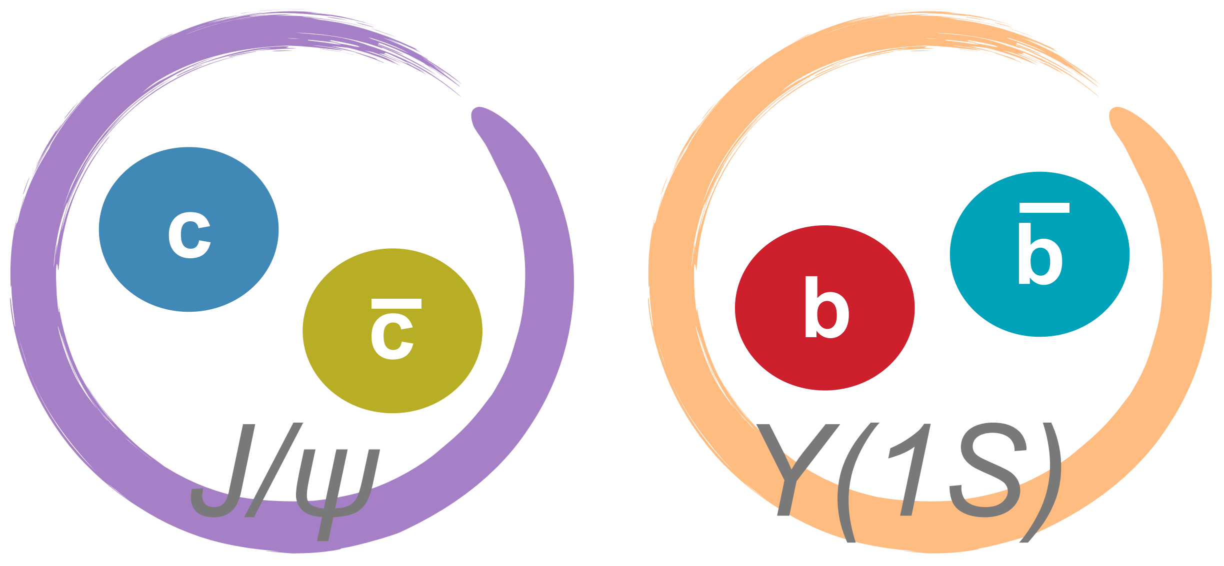
C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

Trace anomaly only constrained through sum-rules

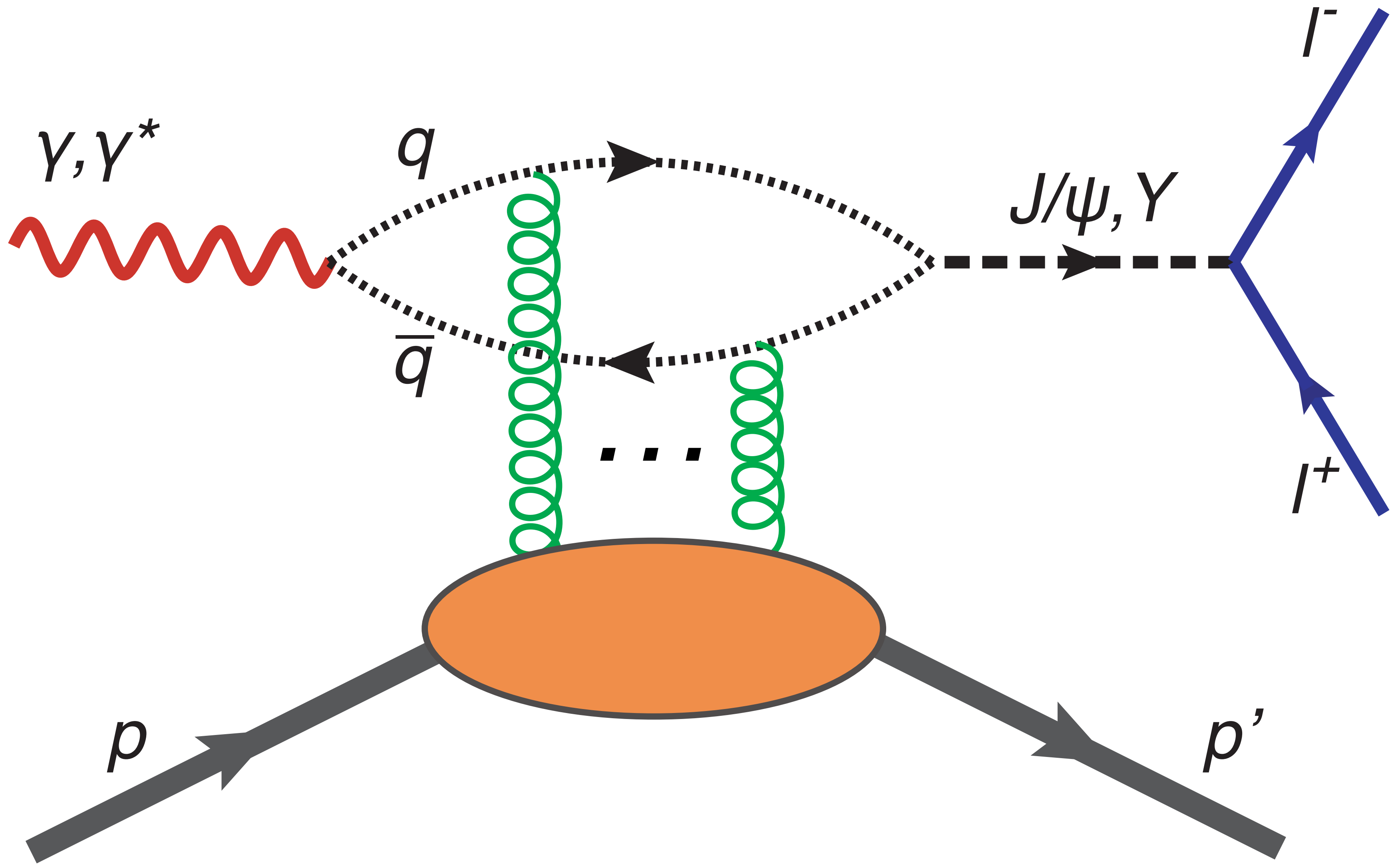
M. Luke *et al.*, PLB 288 355-359 (1992)
D. Kharzeev, Proc.Int.Sch.Phys.Fermi 130 105-131 (1996)

CAN WE MEASURE THE TRACE ANOMALY?

…Quarkonium production near threshold!

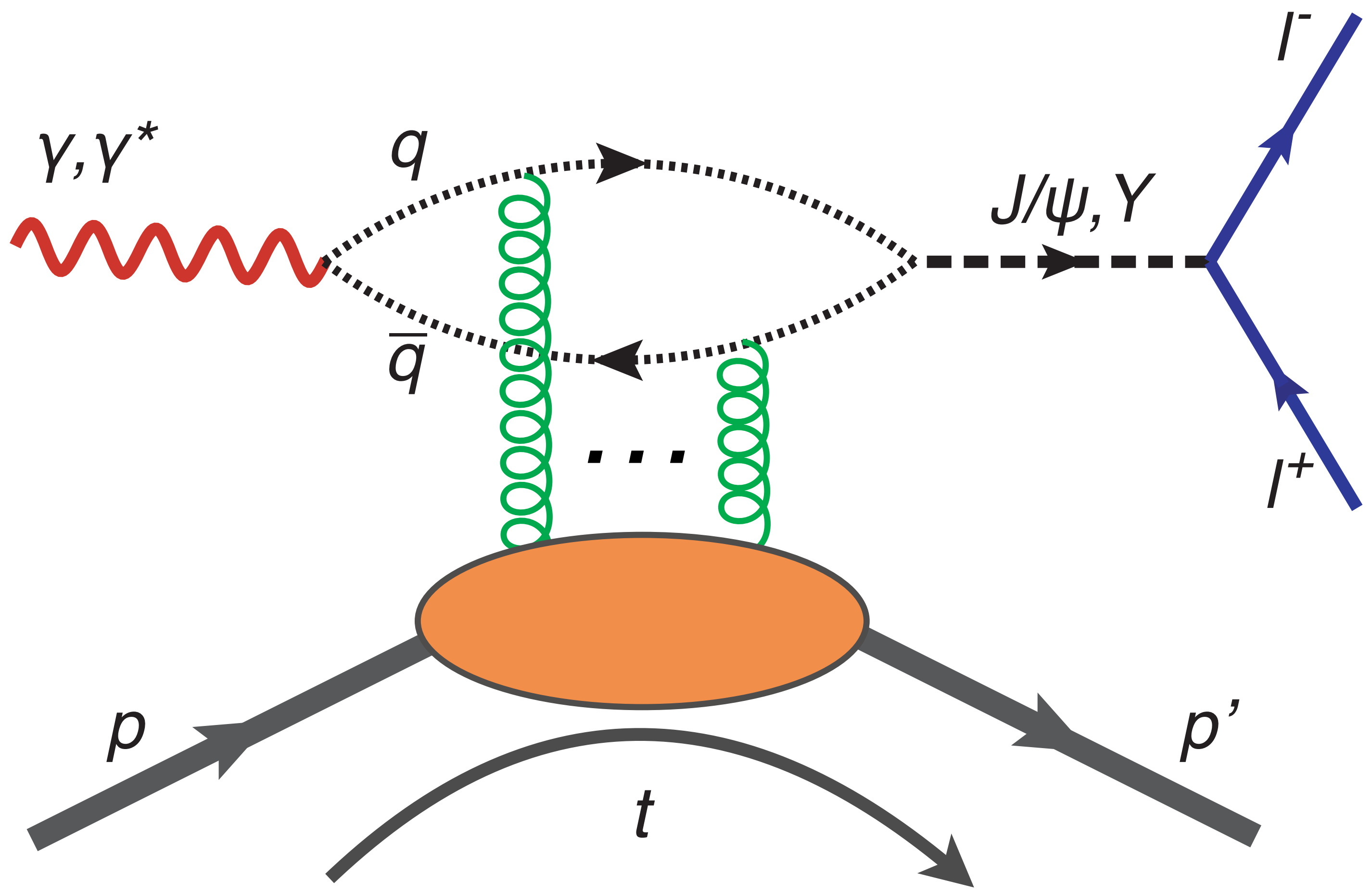


- *J/ψ* and *Y(1S)* only couple to gluons, not light quarks
- Sensitive to gluonic structure of the proton
- Trace-anomaly operator twist-four:
  - Highly suppressed in high-energy scattering
  - QCD Factorization not yet established
- Solution found in **low energy scattering** (production near threshold)



QUARKONIUM PHOTO-PRODUCTION

The basics



J/ψ threshold:

$W \approx 4.04\text{GeV}$

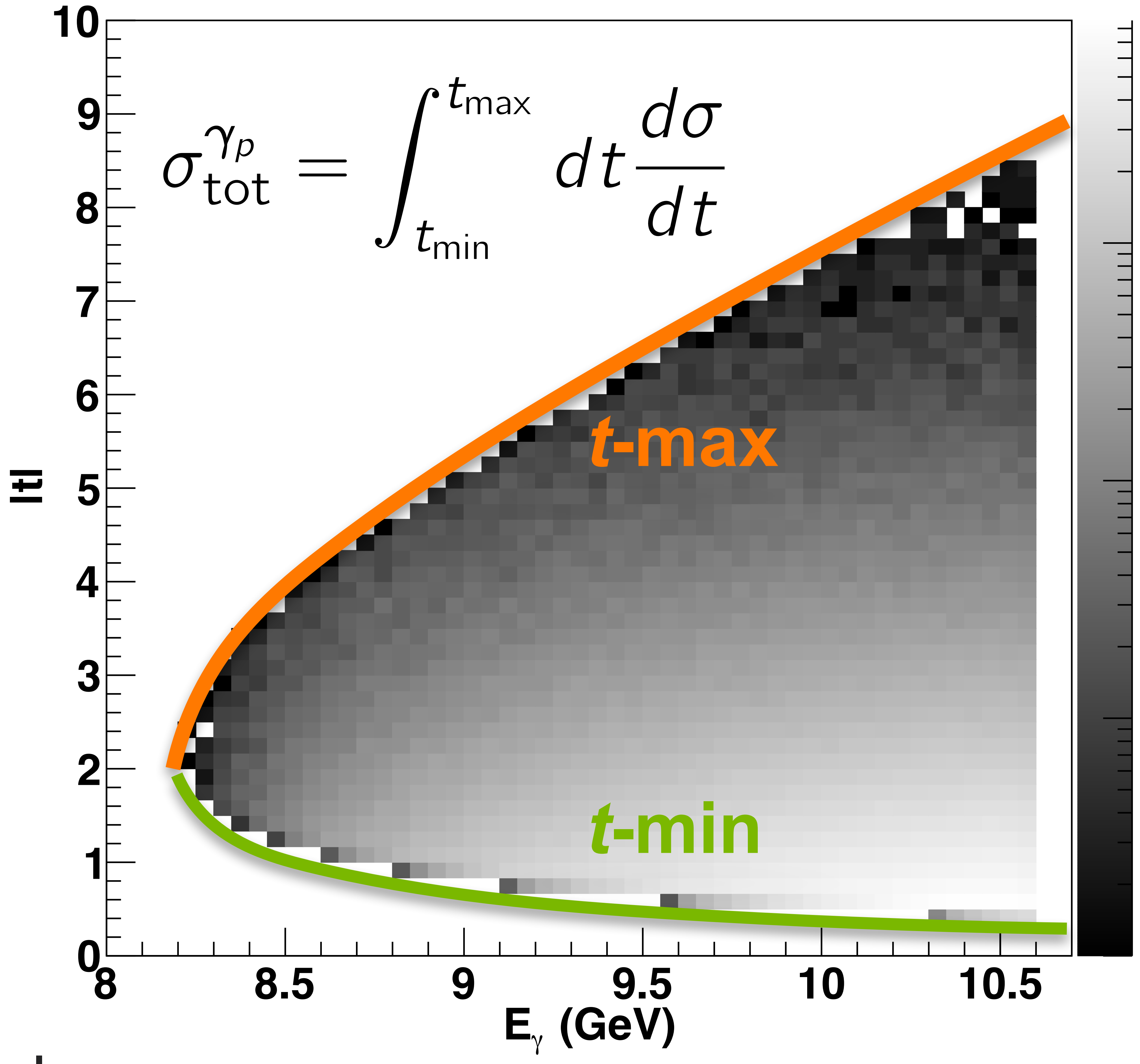
$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

$t \approx -1.5\text{GeV}^2$

Υ(1S) threshold:

$W \approx 10.4\text{GeV}$

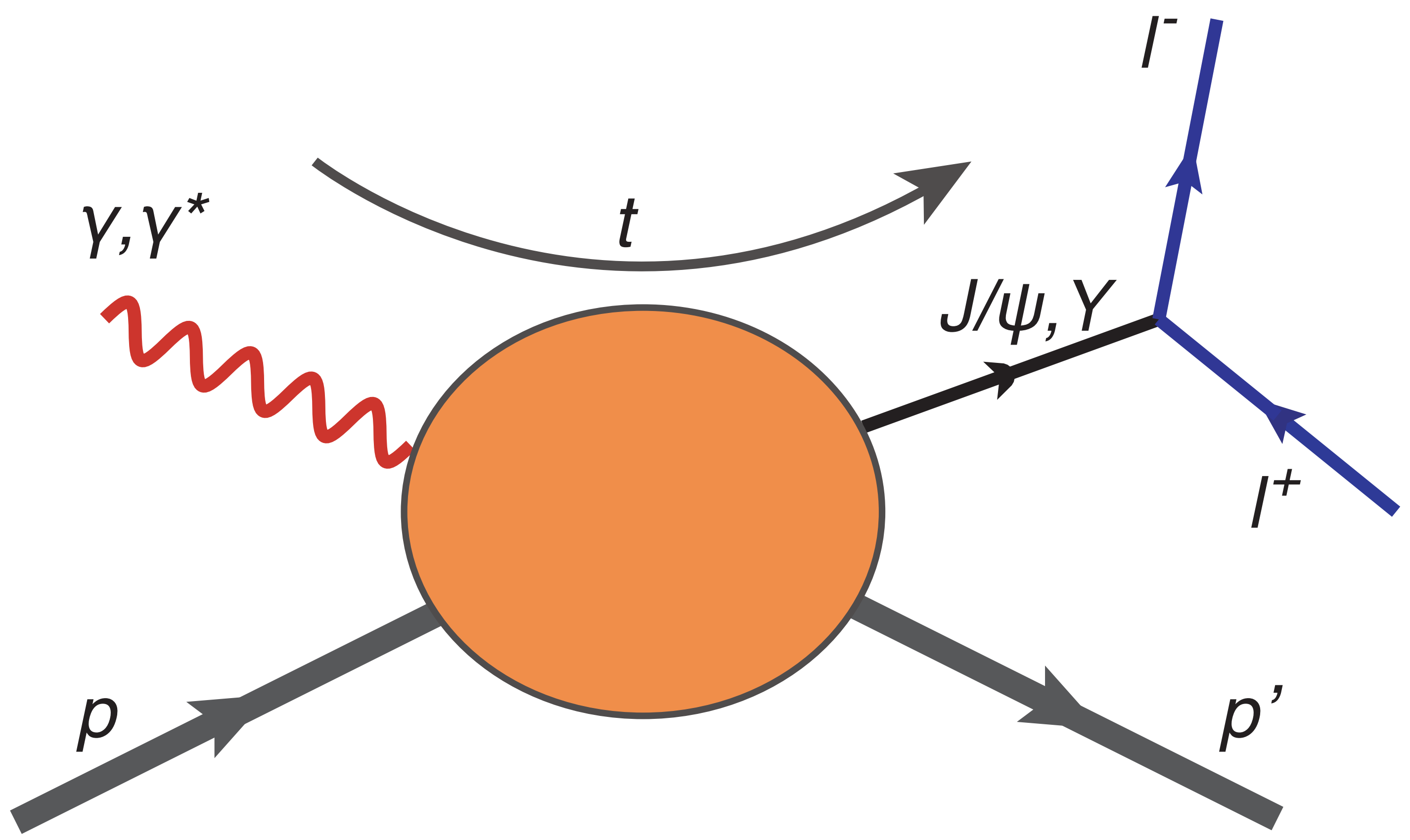
$t \approx -8.1\text{GeV}^2$



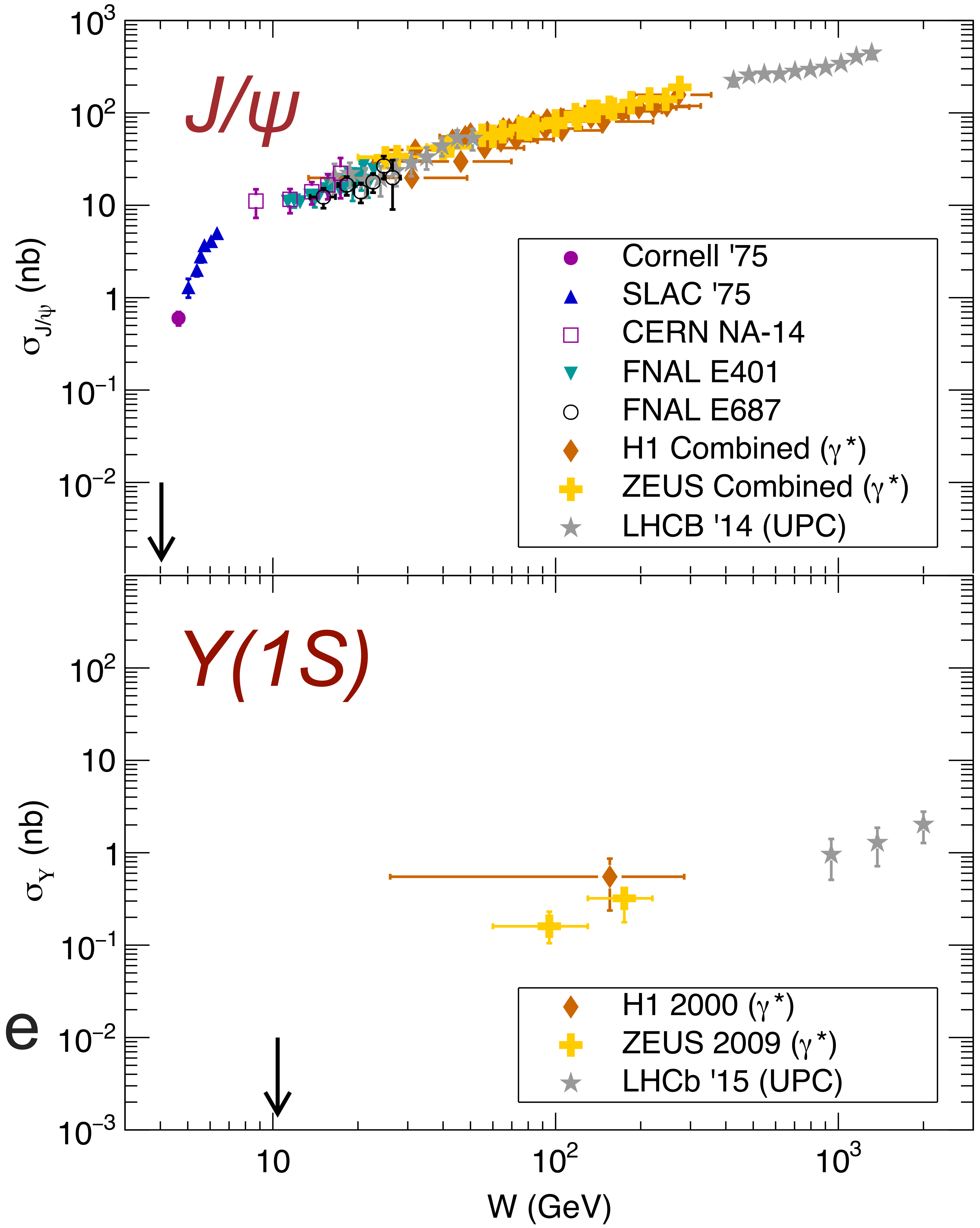
- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{min}$
  - Backward (with proton): $t = t_{max}$
- Forward direction preferred: *t*-dependence ~exponential

QUARKONIUM PHOTO-PRODUCTION

What do we know?



- *J/ψ* well constrained for high energies
- *Υ(1S)*: not much available
- No electro-production data available
- **Almost no data near threshold**



Near Threshold:

- **Origin of proton mass,** trace anomaly of the QCD EMT
- **Gluonic Van der Waals force**, possible quarkonium-nucleon/ nucleus bound states
- **Mechanism** for quarkonium production itself

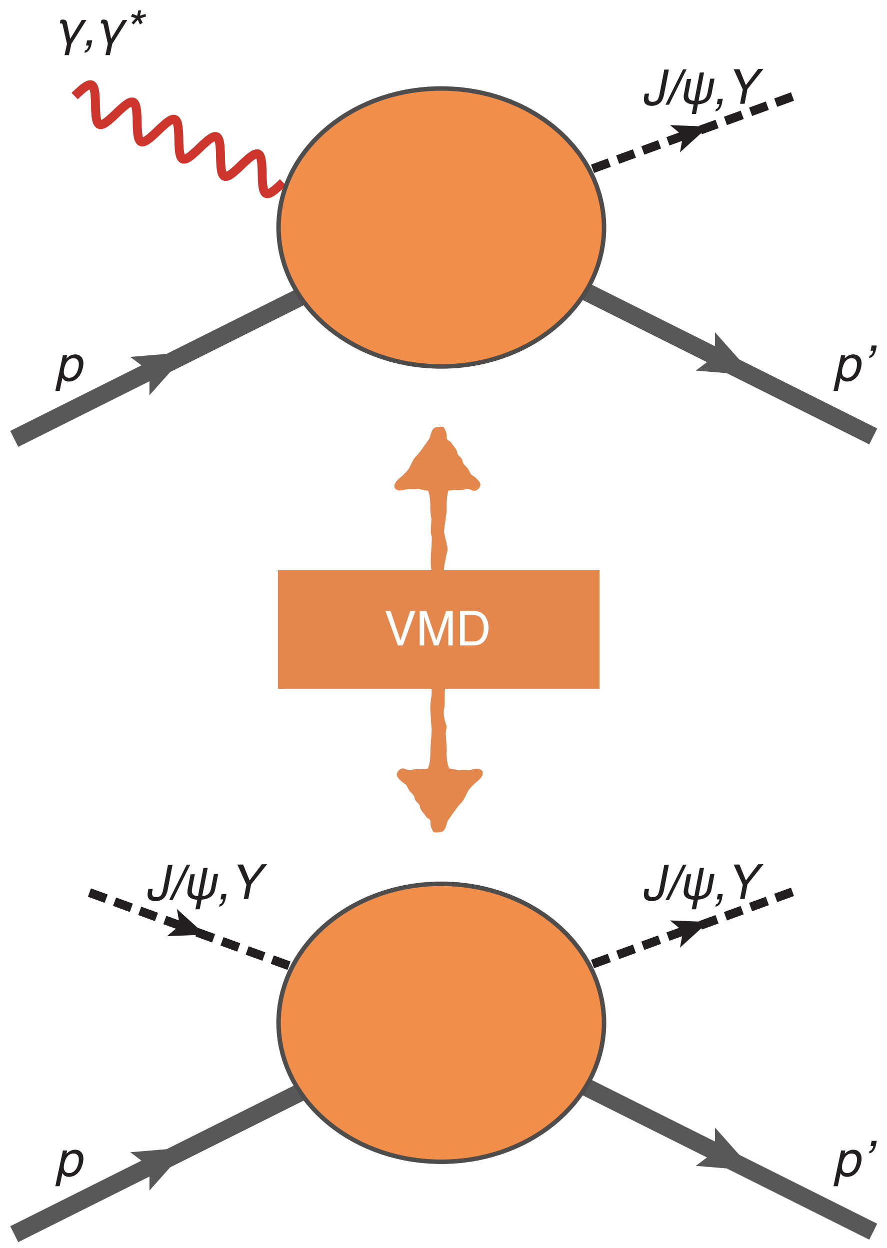
J/ψ at JLab
Υ(1s) at EIC

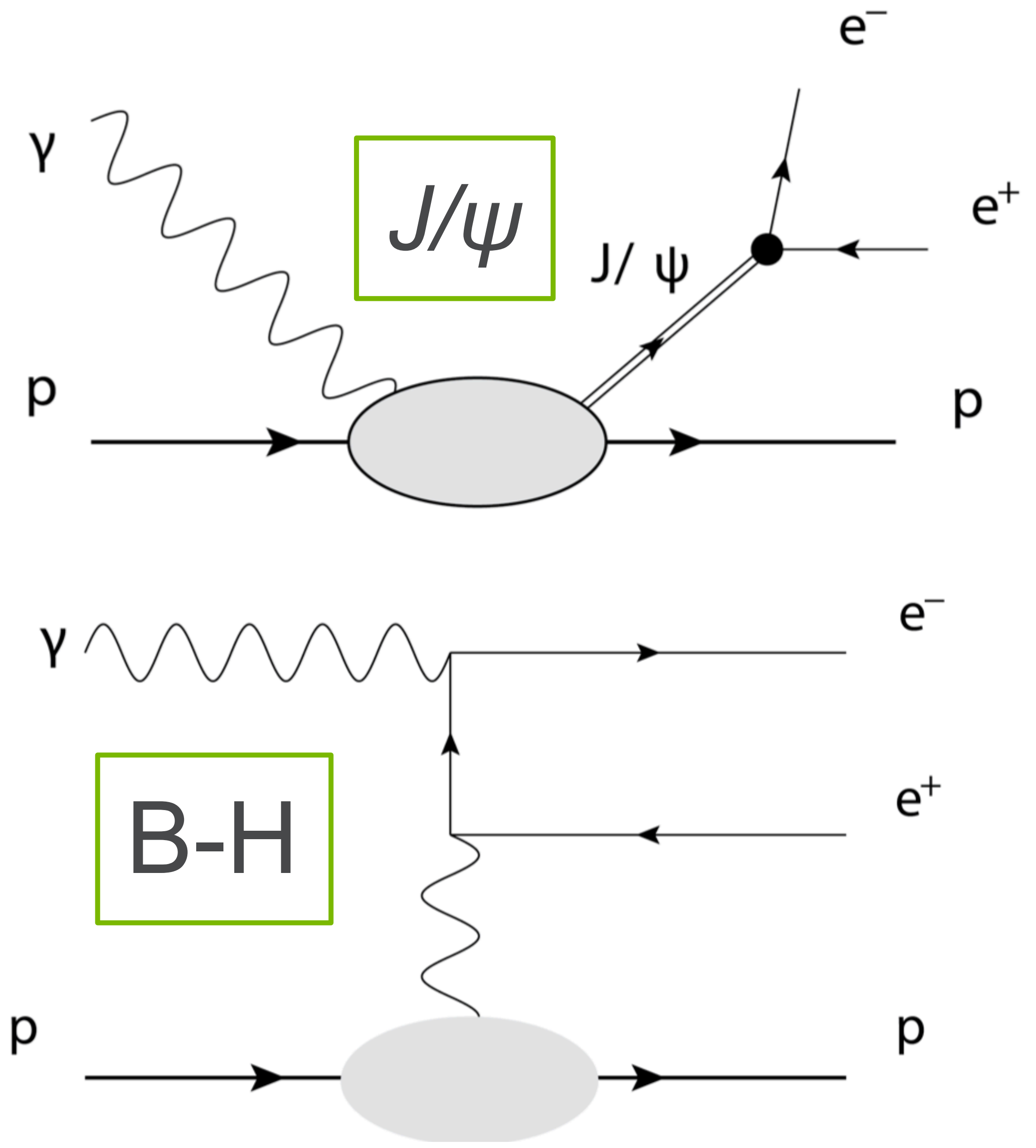
Three possible avenues for…

MEASURING THE TRACE ANOMALY

1. Cross section at threshold
Assuming VMD, measure t-dependence at threshold. Note: factorization not yet rigorously proven

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



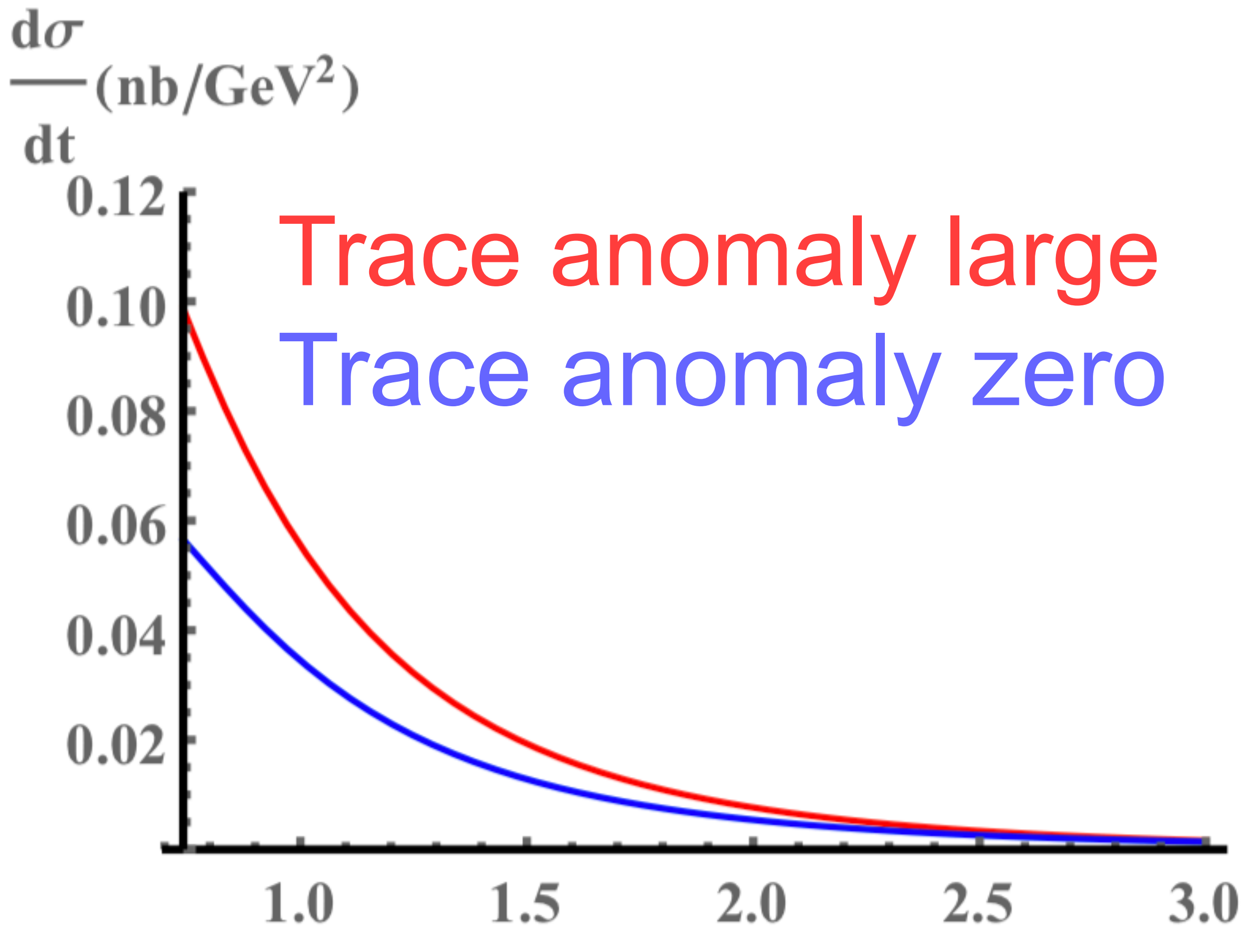


2. Interference with Bethe-Heitler
Interference between for *J/ψ* production and Bethe-Heitler near (but not at) threshold. Needs very high statistics. Possible at SoLID.

Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

3. Holographic approach:
Non-perturbative approach using AdS/CFT gauge-string duality. New development. Predicts sensitivity for *J/ψ* production near threshold.

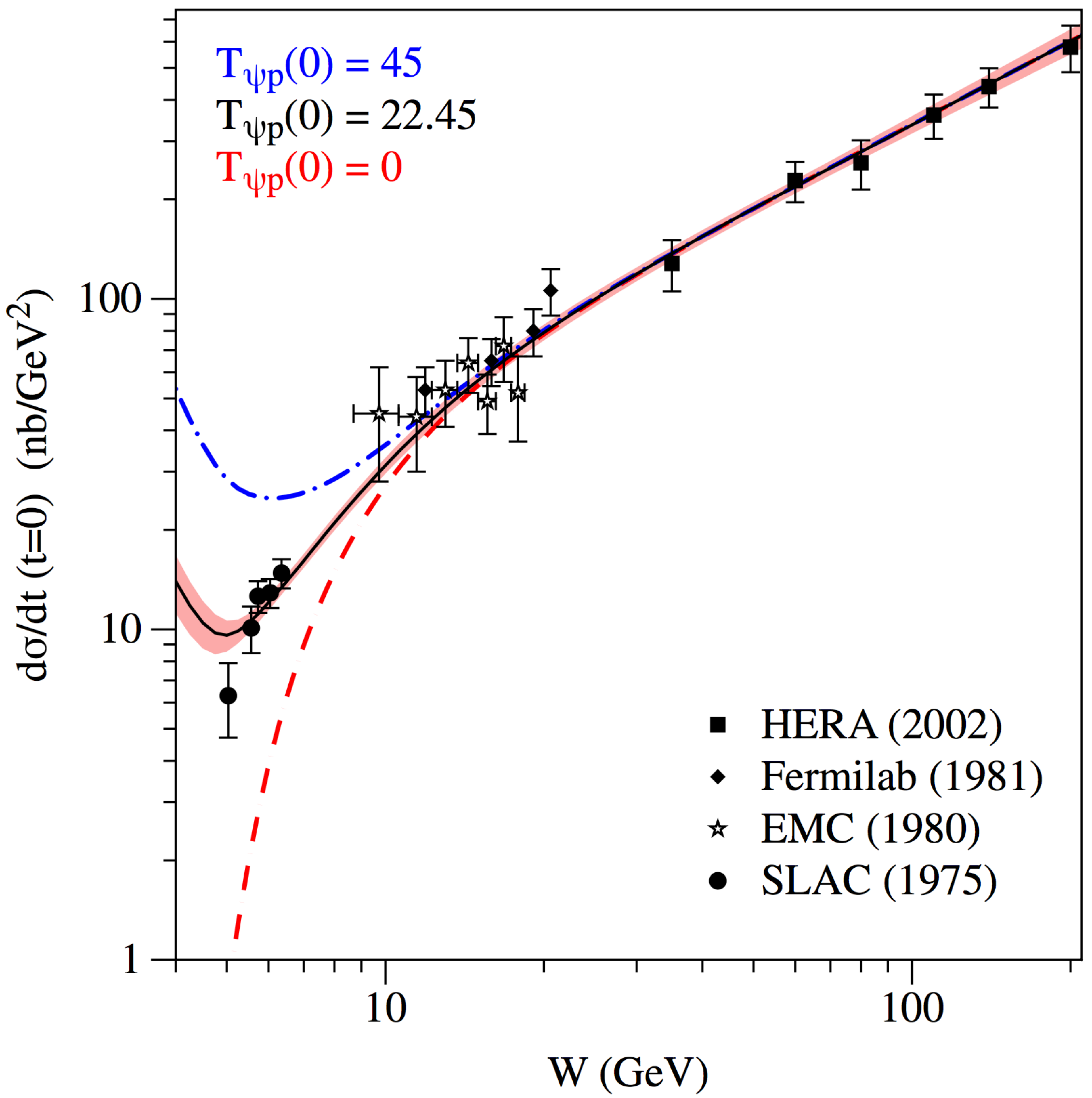
Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)



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

The nature of the gluonic Van der Waals force

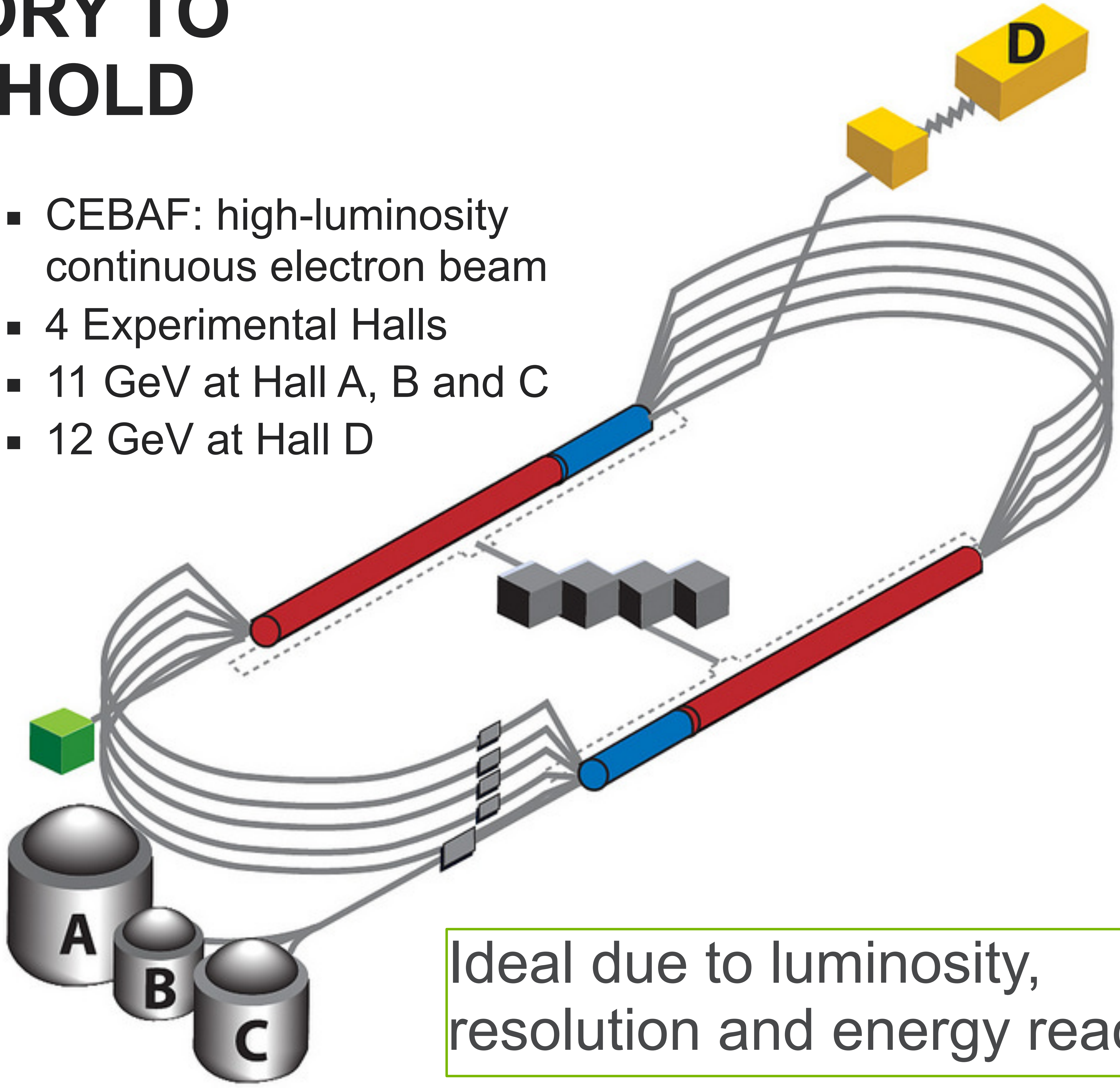
- Force between color neutral *J/ψ* and nucleon purely gluonic
- Binding energy $B_{\psi p}$ can be derived from s-wave scattering length $a_{\psi p}$ at threshold
  - $T_{\psi p} = 8\pi(M + M_\psi)a_{\psi p}$
  - Experimental access through *J/ψ* photo-production at threshold
  - Note: *link with trace anomaly*!
- Current estimates between 0.05-0.30fm (3-20MeV)
- Lattice QCD (at large pion mass): $B_{\psi p}$ < 40 MeV



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

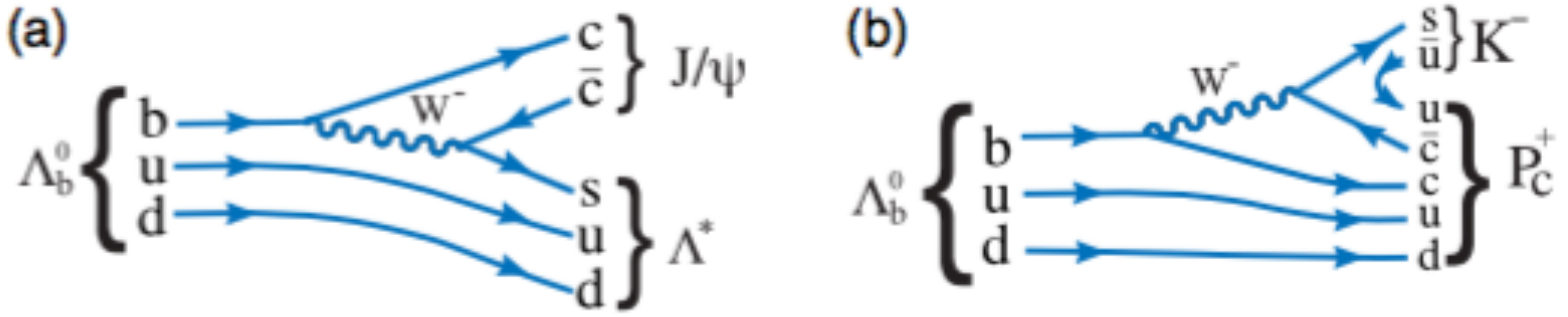


Ideal due to luminosity, resolution and energy reach

DISCOVERY OF THE LHCB CHARMED PENTAQUARK

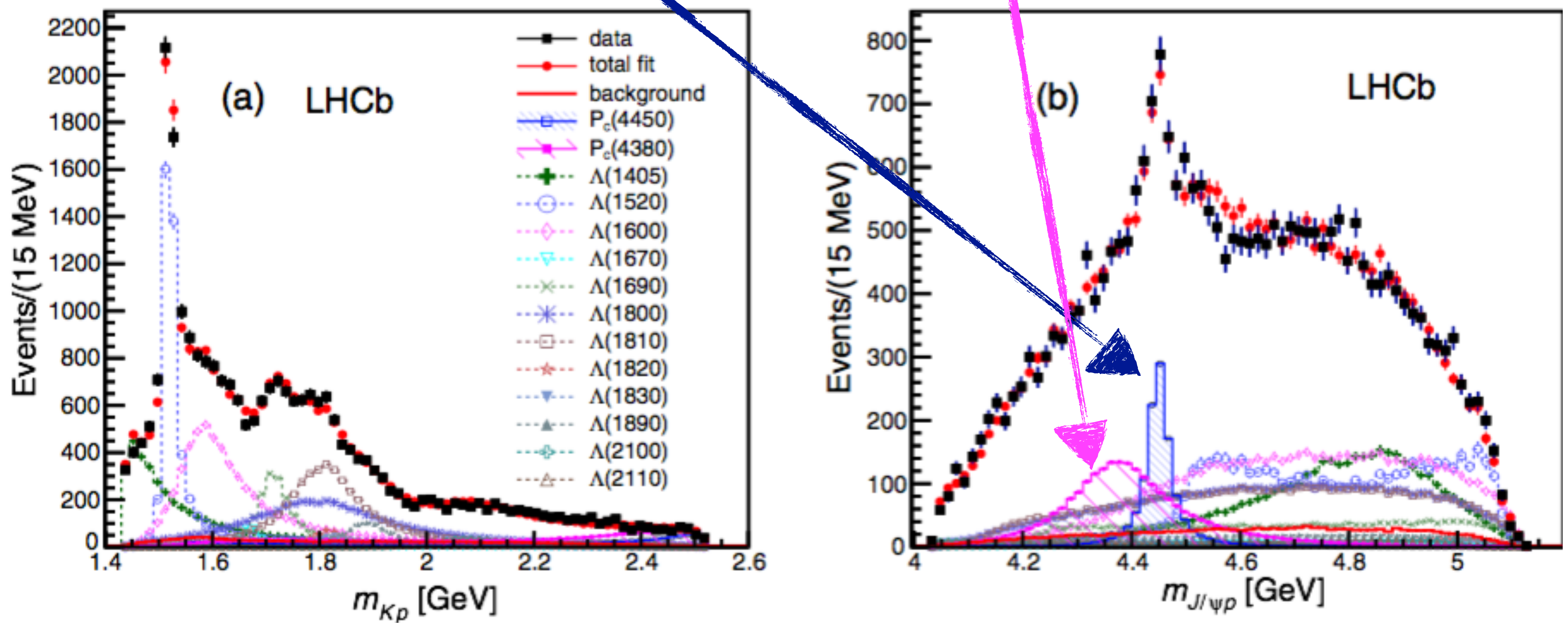
$$\Lambda_b \to \Lambda^* J/\Psi \to (K^- p) J/\Psi$$

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



narrow: P_c(4450) (12 σ)

wide: P_c(4390) (9σ)



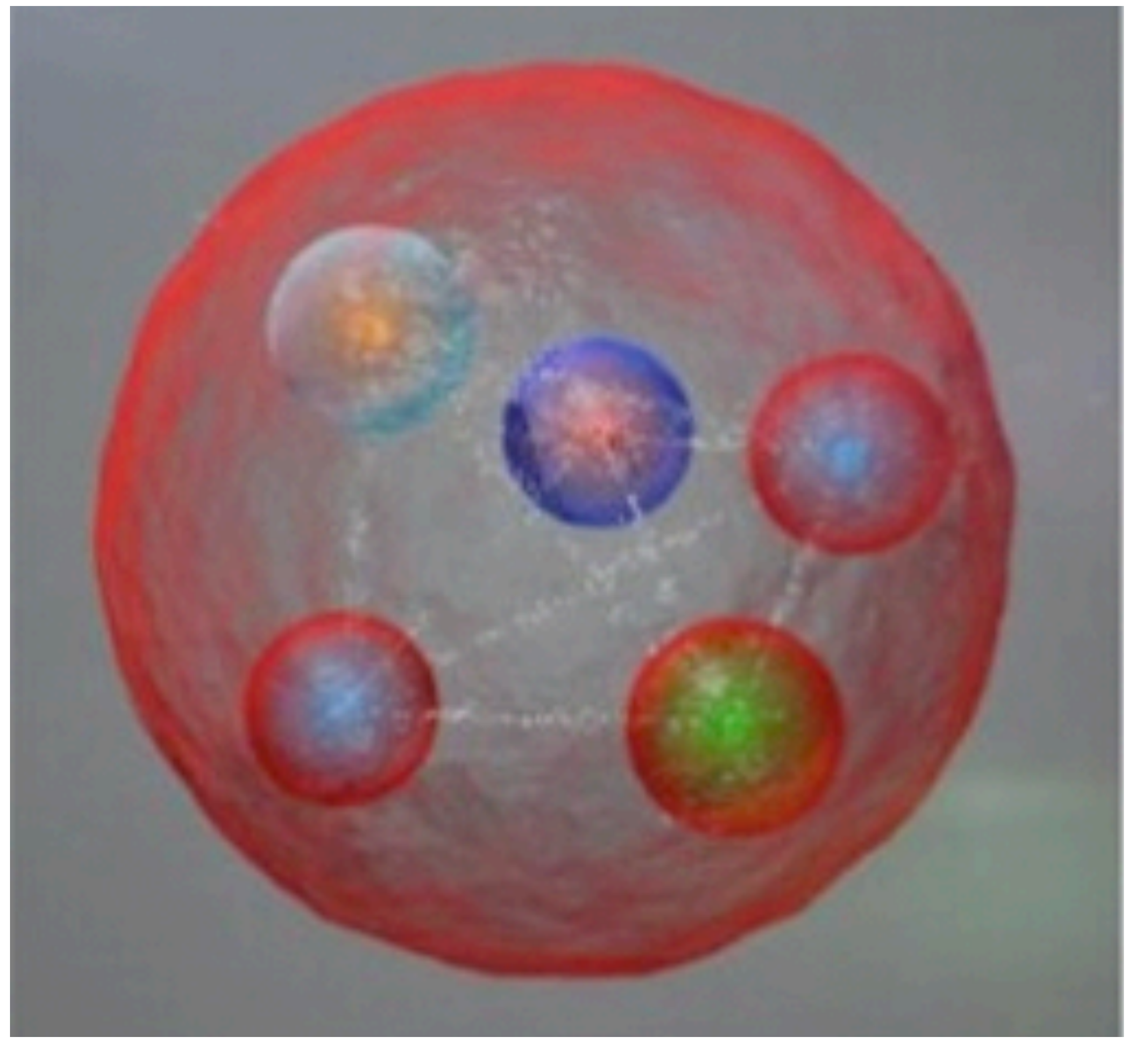
- LHCb collaboration findings: **two P_c states needed**:
- Spin/parity not fully constrained:
  - 5/2+ and 3/2- (most likely)
  - 5/2- and 3/2+
  - 3/2- and 5/2+

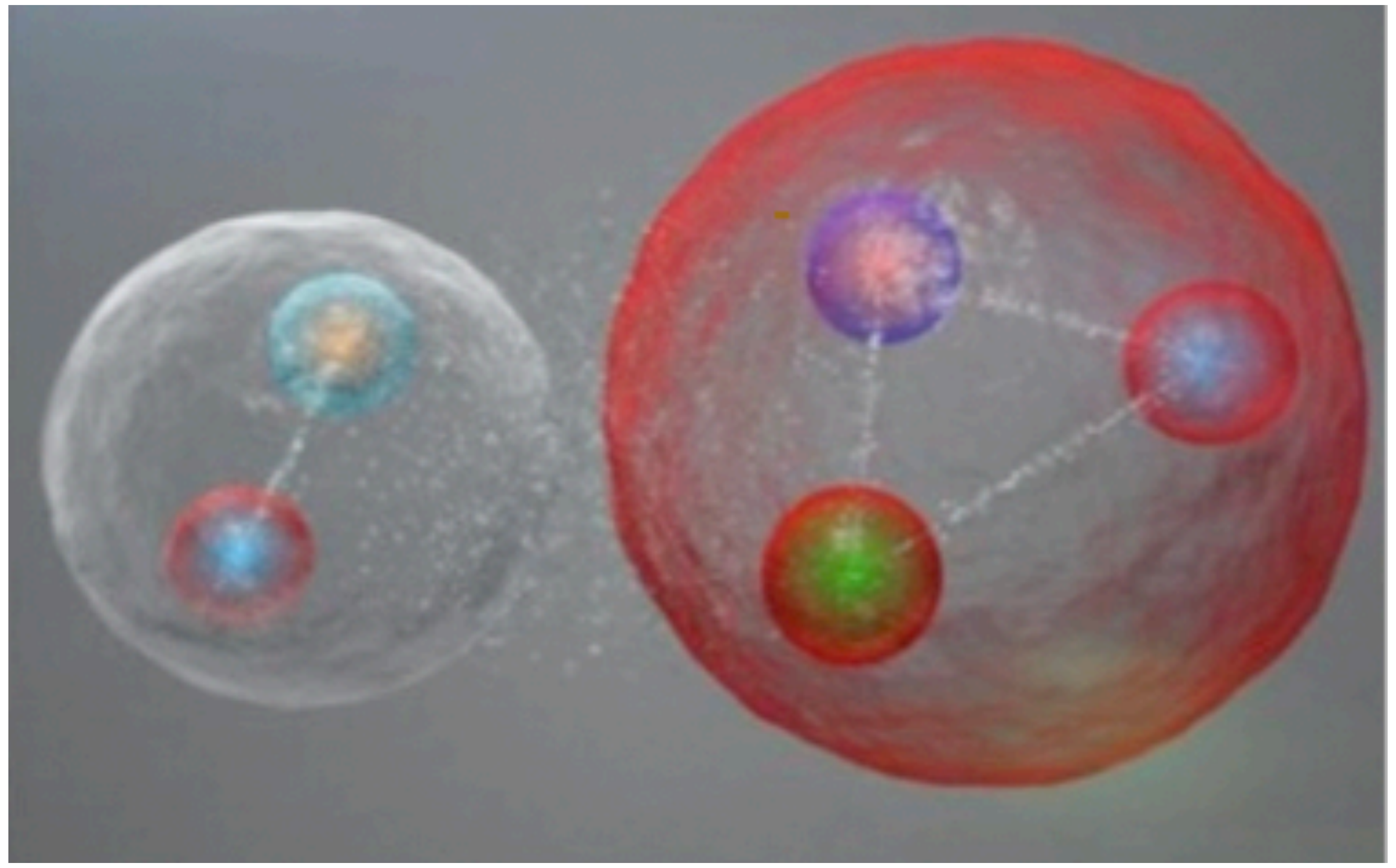
IS THIS A REAL PARTICLE?

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**

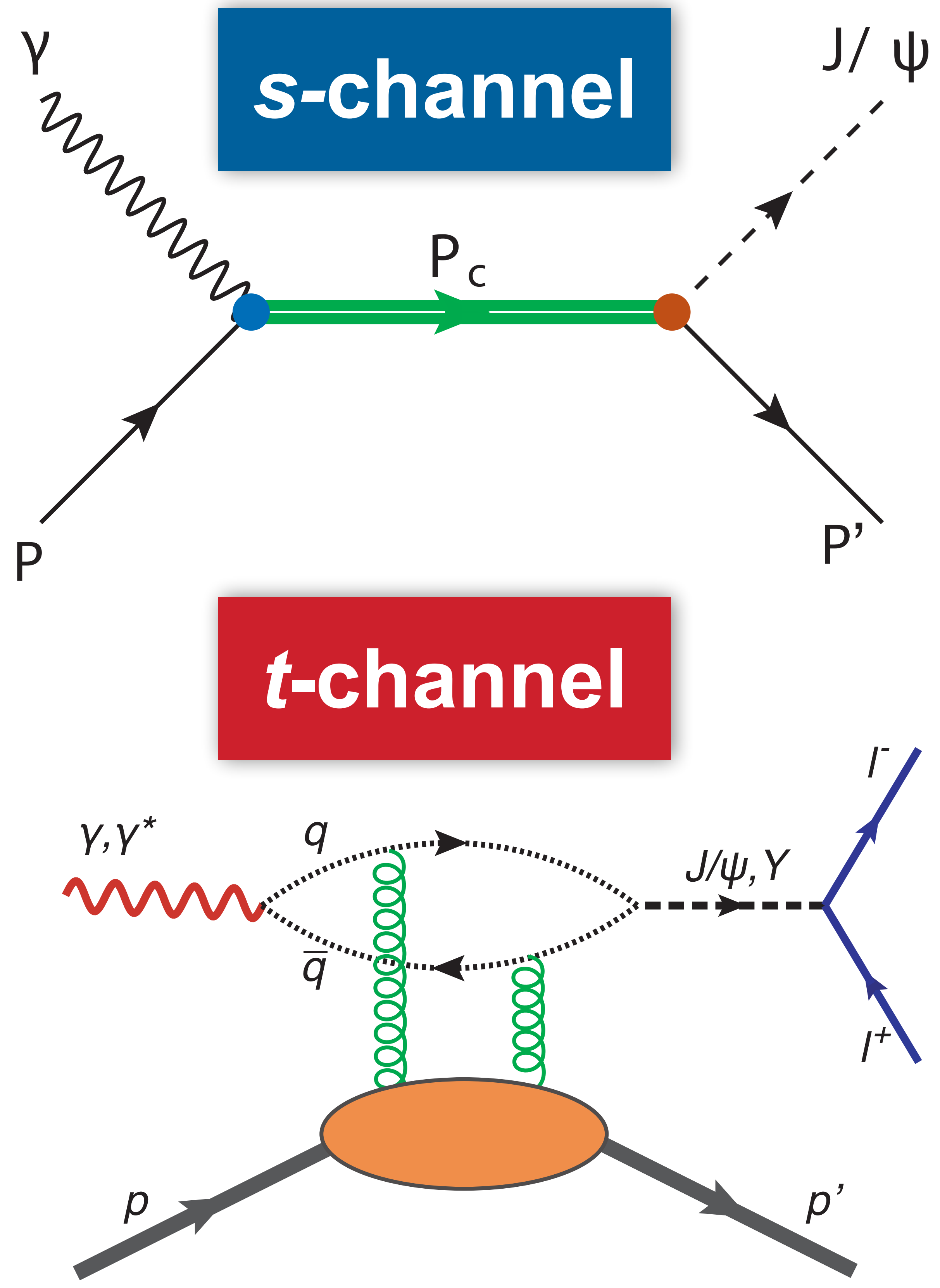
Jefferson Lab the perfect place to search for P_c





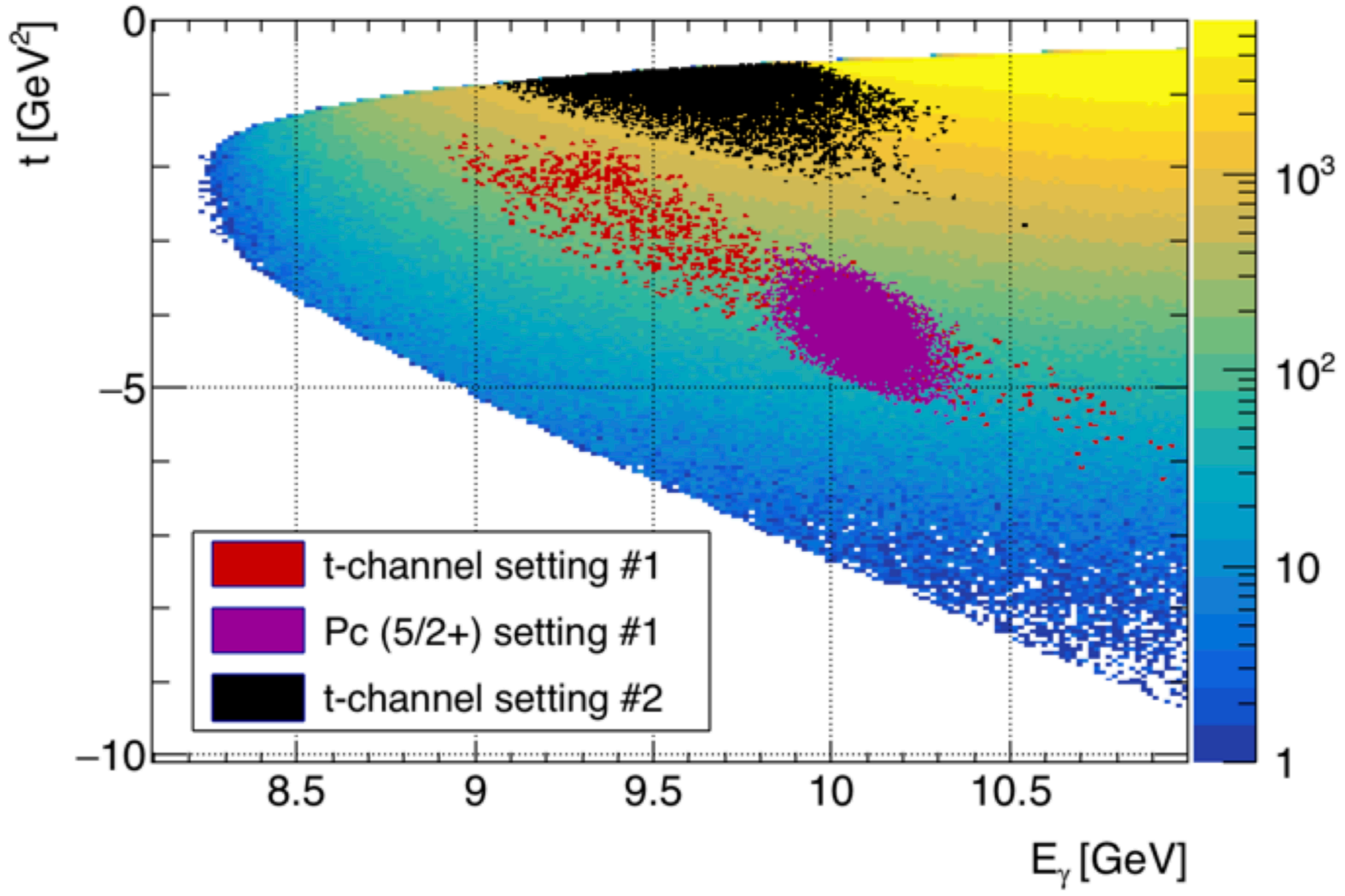
RESONANT *J/Ψ* PRODUCTION THROUGH *P*C DECAY

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***

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

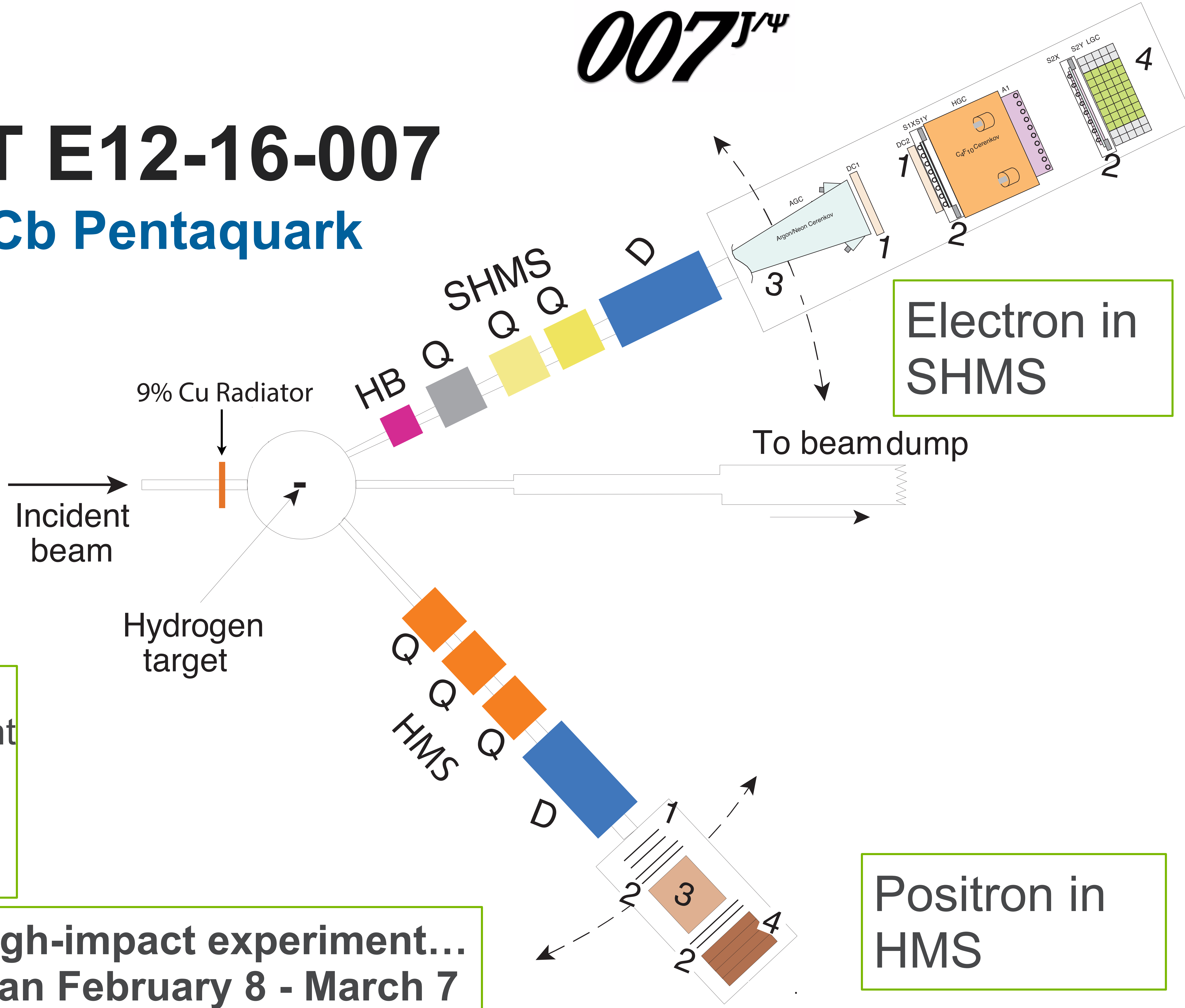
JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

- High intensity real photon beam (9% copper radiator)
- 10cm liquid hydrogen target
- Detect *J/ψ* decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained

"Symmetric" configurations for *t*-channel cross section measurement

"Asymmetric" configurations to measure high-t region for the s-channel measurement



Electron in SHMS

Positron in HMS

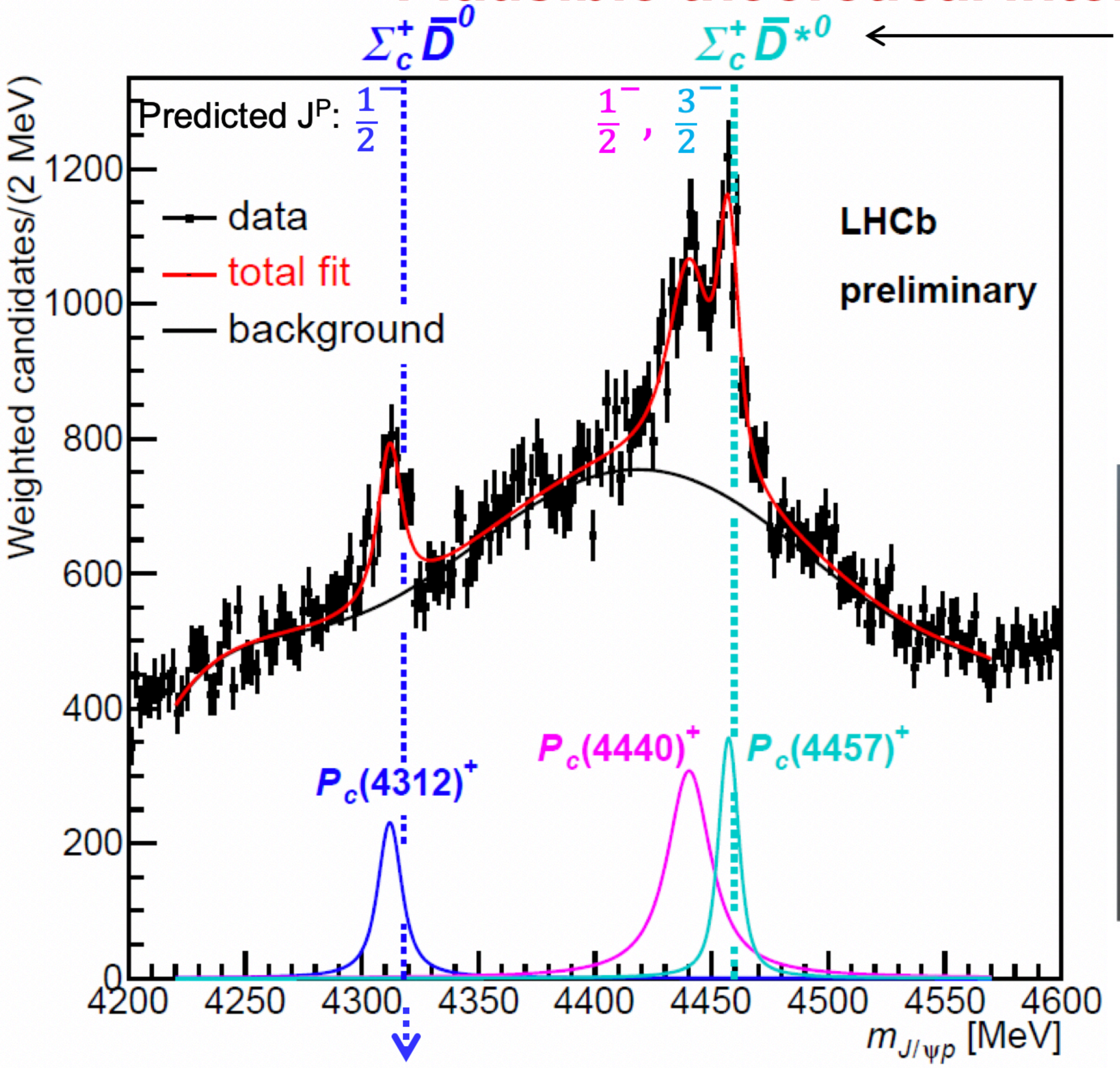
High-impact experiment…
Ran February 8 - March 7

The plot thickens…

NEW LHC-B RESULTS WITH 10X STATISTICS

Moriond QCD, Tomasz Skwarnicki, Mar 26, 2019 14

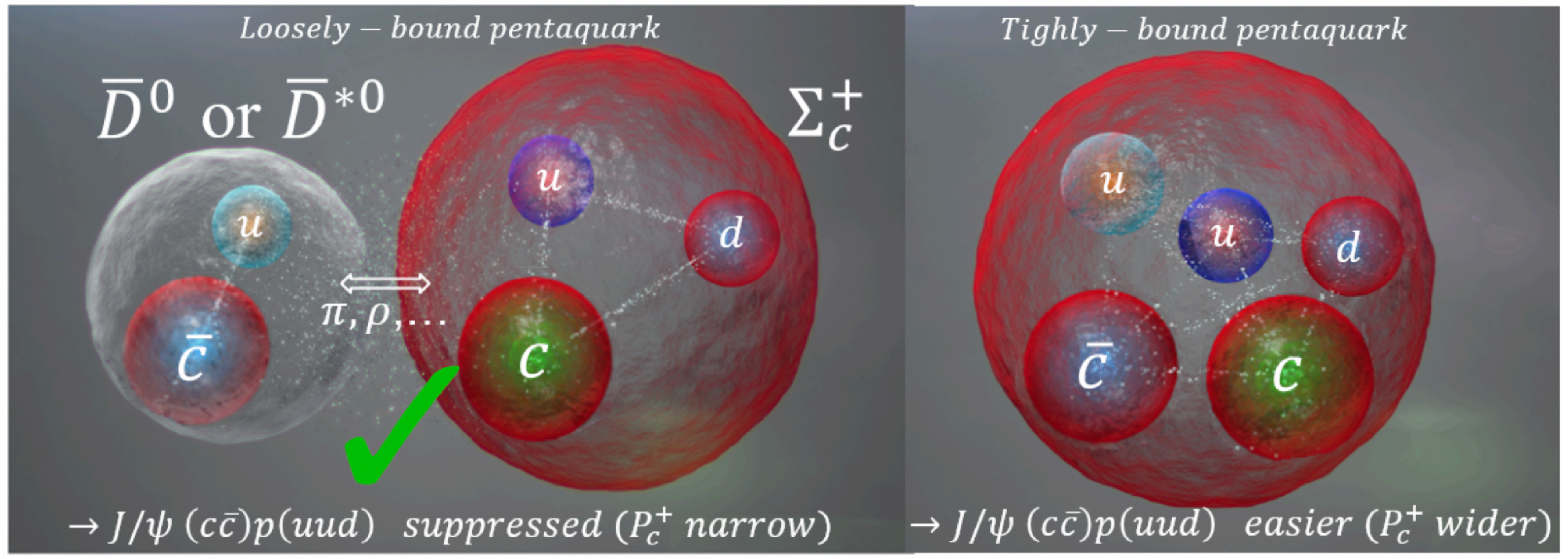
Plausible theoretical interpretation



The **only** thresholds below which molecular bound states are expected in this mass range

LHCb-PAPER-2019-014 in preparation

The near-threshold masses and the narrow widths of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ favor "molecular" pentaquarks with meson-baryon substructure!



Existence of $\Sigma_c^+ \bar{D}^0$ molecule would imply importance of ρ-exchange

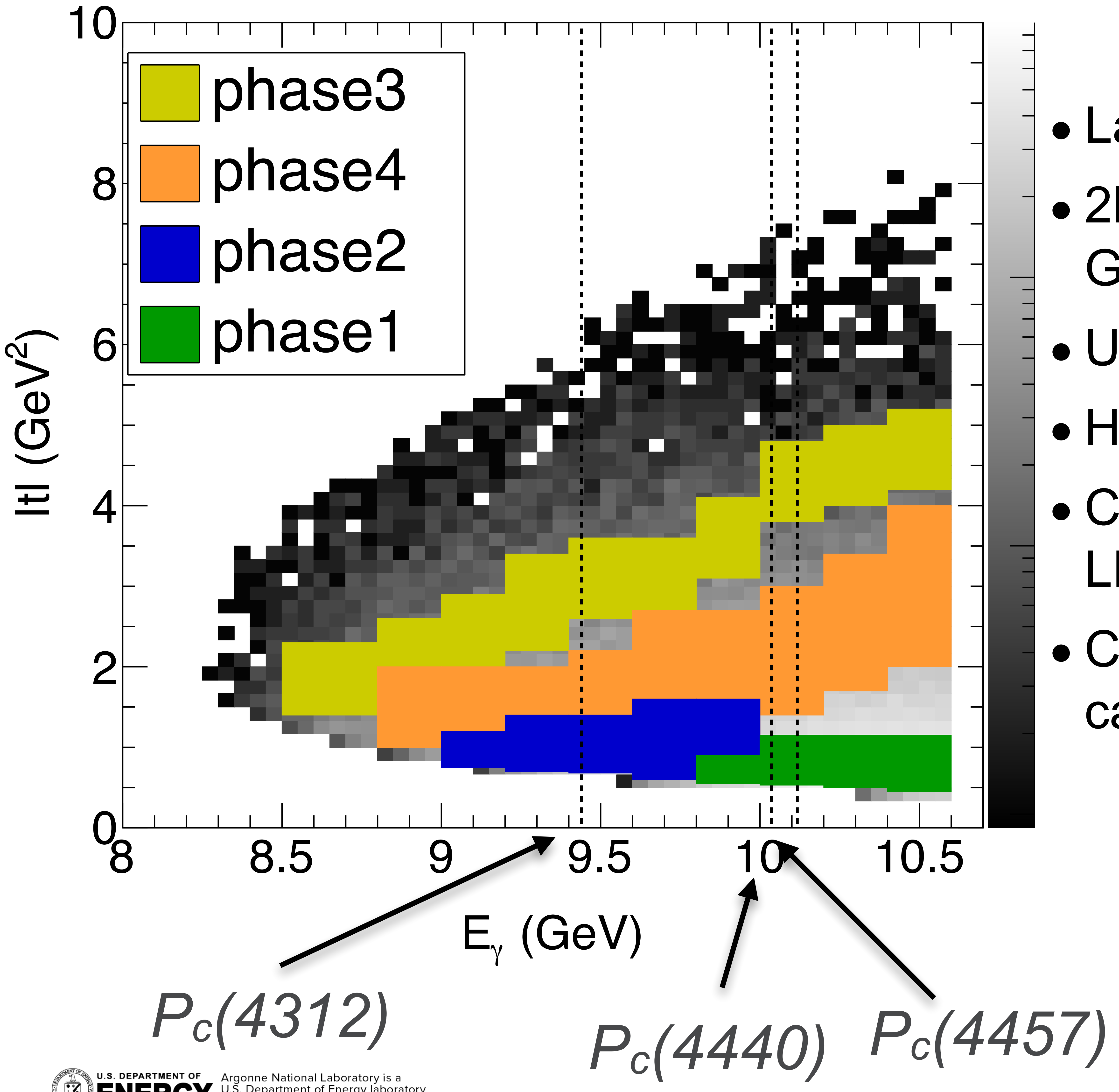
However, we need to measure J^Ps to confirm molecular hypothesis, find isospin partners, …

Can diquark substructure separated by a potential barrier [Maiani, Polosa, Riquer, PL,B778, 247 (2018)] produce width suppression?
Are masses near thresholds just by coincidence?
This hypothesis is not ruled out

$P_c(4312)^+$, $P_c(4440)^+$ not near triangle diagram thresholds, $P_c(4457)^+$ is (see backup slides).

FEATURES OF THIS MEASUREMENT

007$^{J/\psi}$

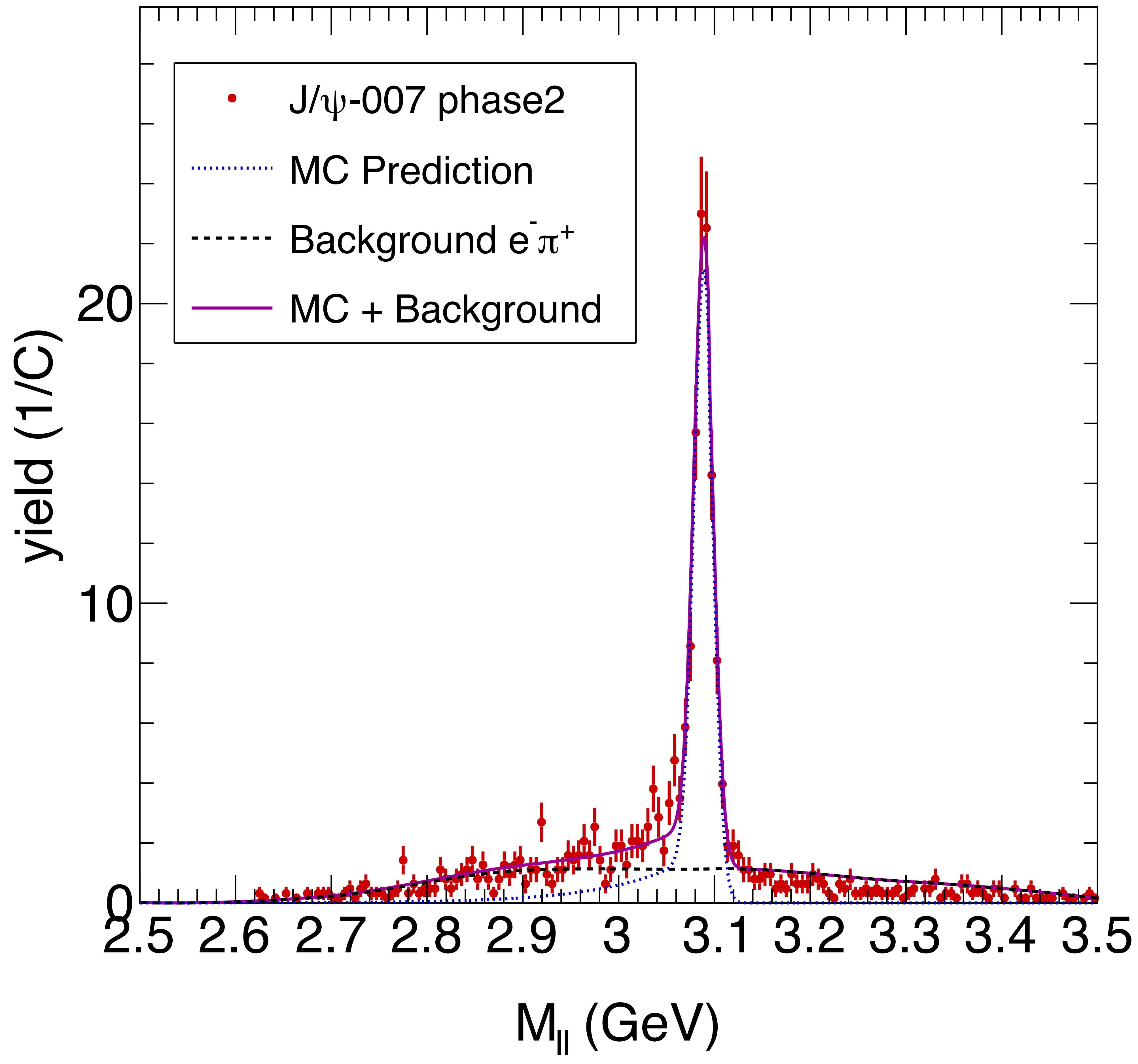


- Largest dataset of J/ψ produced with a real photon beam.
- 2D photo-production cross section between 8.5-10.6 GeV
- Used 4 settings to cover entire phase space
- High-t "enriched" sample, only possible at Hall C!
- Combine data from all settings for maximal sensitivity to LHCb pentaquark
- Covers energy range the three new LHCb pentaquark candidates

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

SIGNAL SHAPE WELL UNDERSTOOD

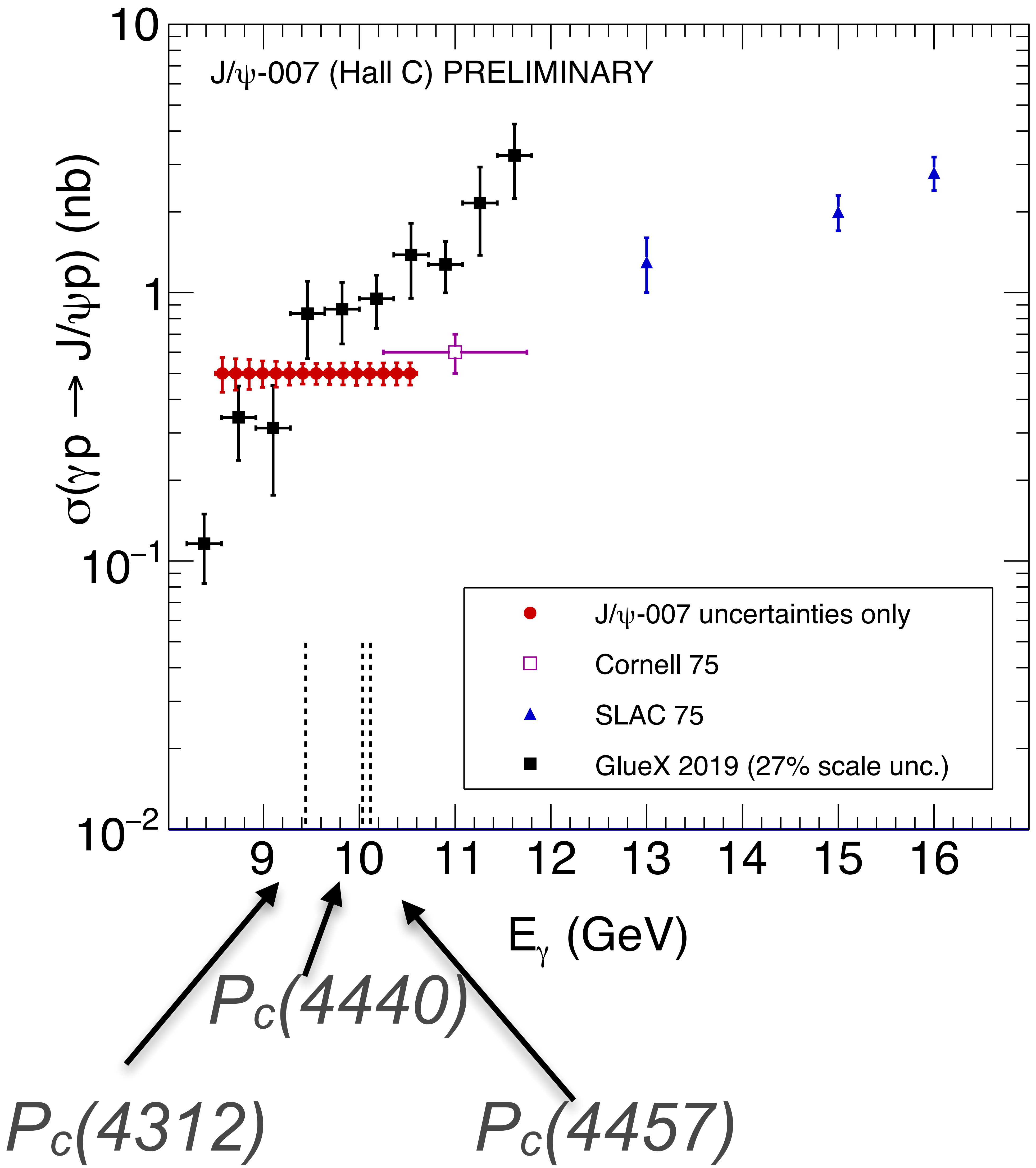
$007^{J/\psi}$



- MC has model of radiator, realistic target, detector and RC (using PHOTOS)
- Measured signal well described by MC for all settings.
- Background dominated by pion electro-production
- Bethe-Heitler contamination very small due to large spectrometer angles
- Took data with open trigger: **background shape from real data!**

ABSOLUTE CROSS SECTION

007$^{J/\psi}$



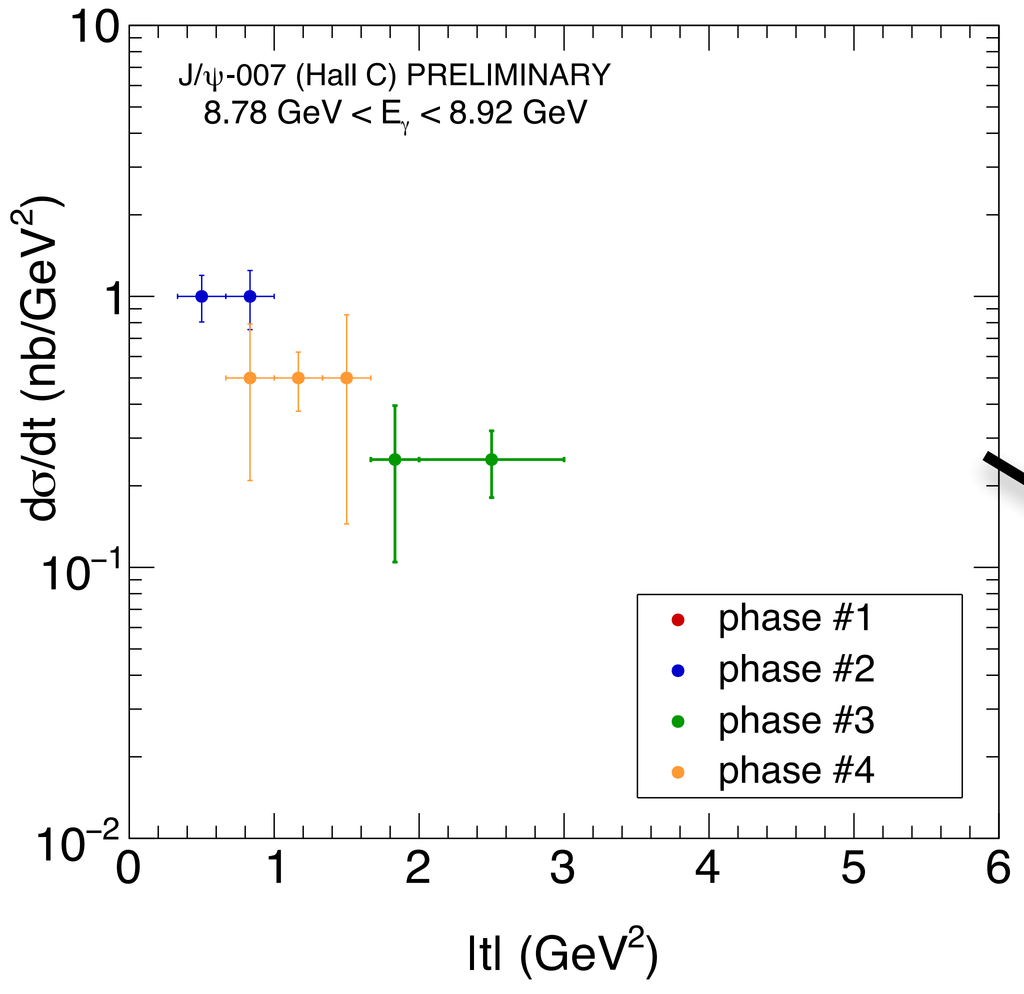
- **Only showing (preliminary) uncertainties!**
- High-precision measurement of the *t*-dependent cross section between 8.5-10.6 GeV
- Precise (~5%) absolute cross section possible due to calibration measurements of elastic and inelastic cross sections
- Will shed light on apparent discrepancy between GlueX and SLAC/Cornell data

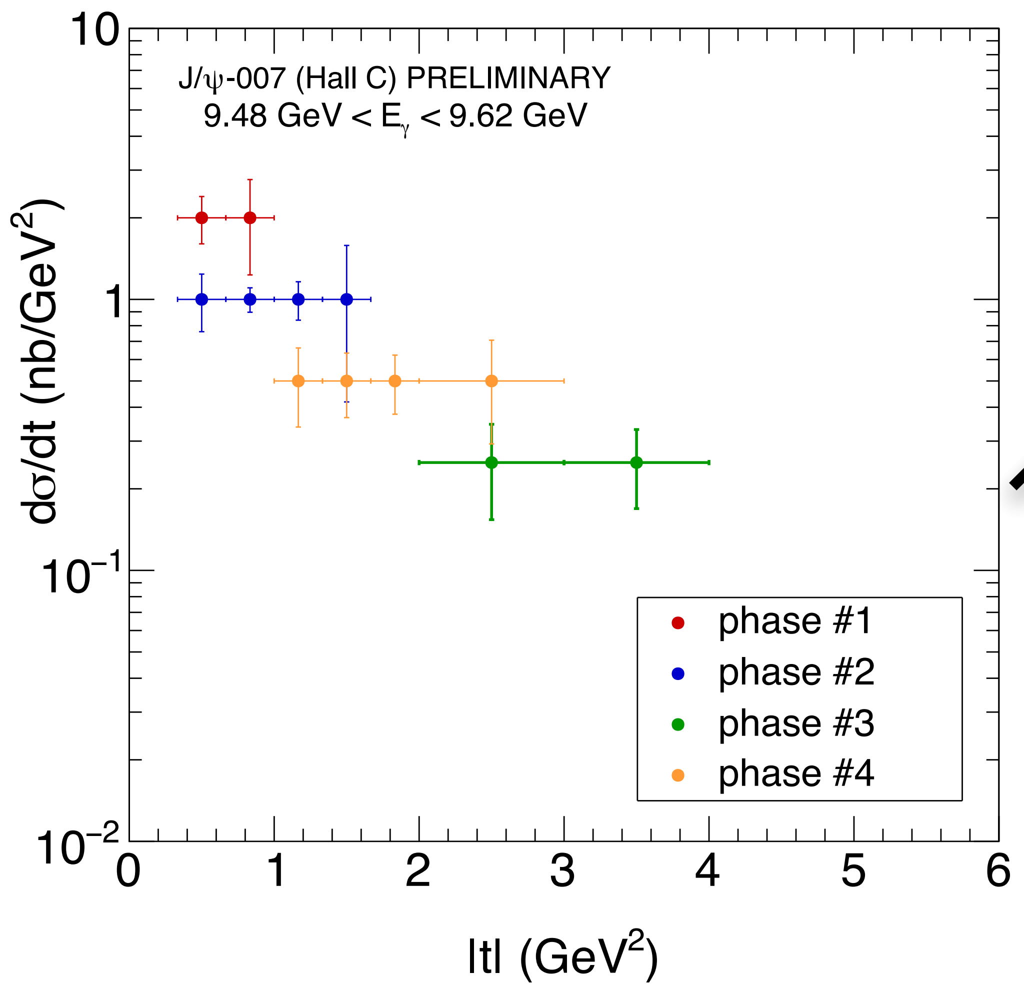
Absolute cross section ~5% precision

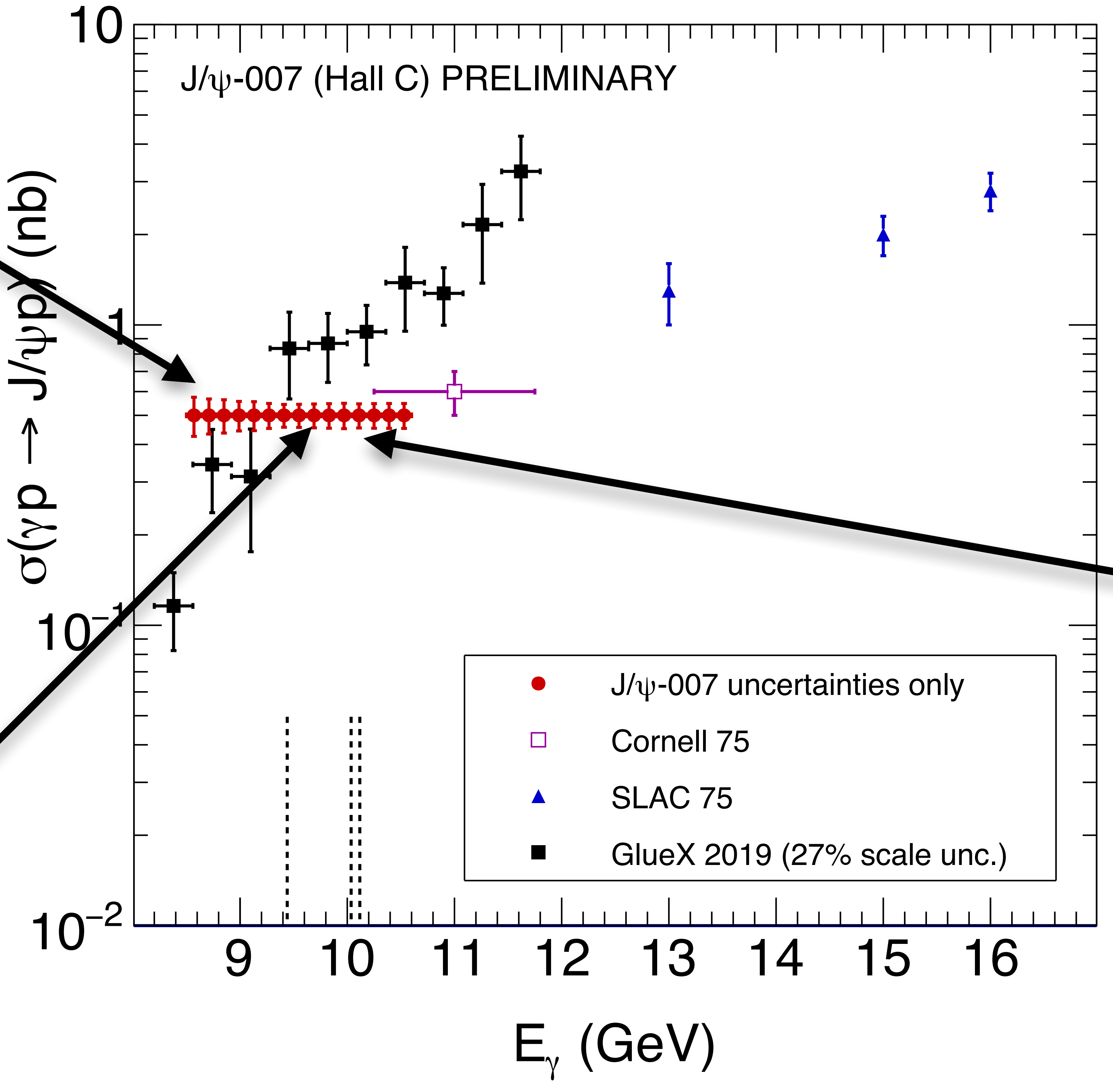
A FULL 2D MEASUREMENT

007$^{J/\psi}$

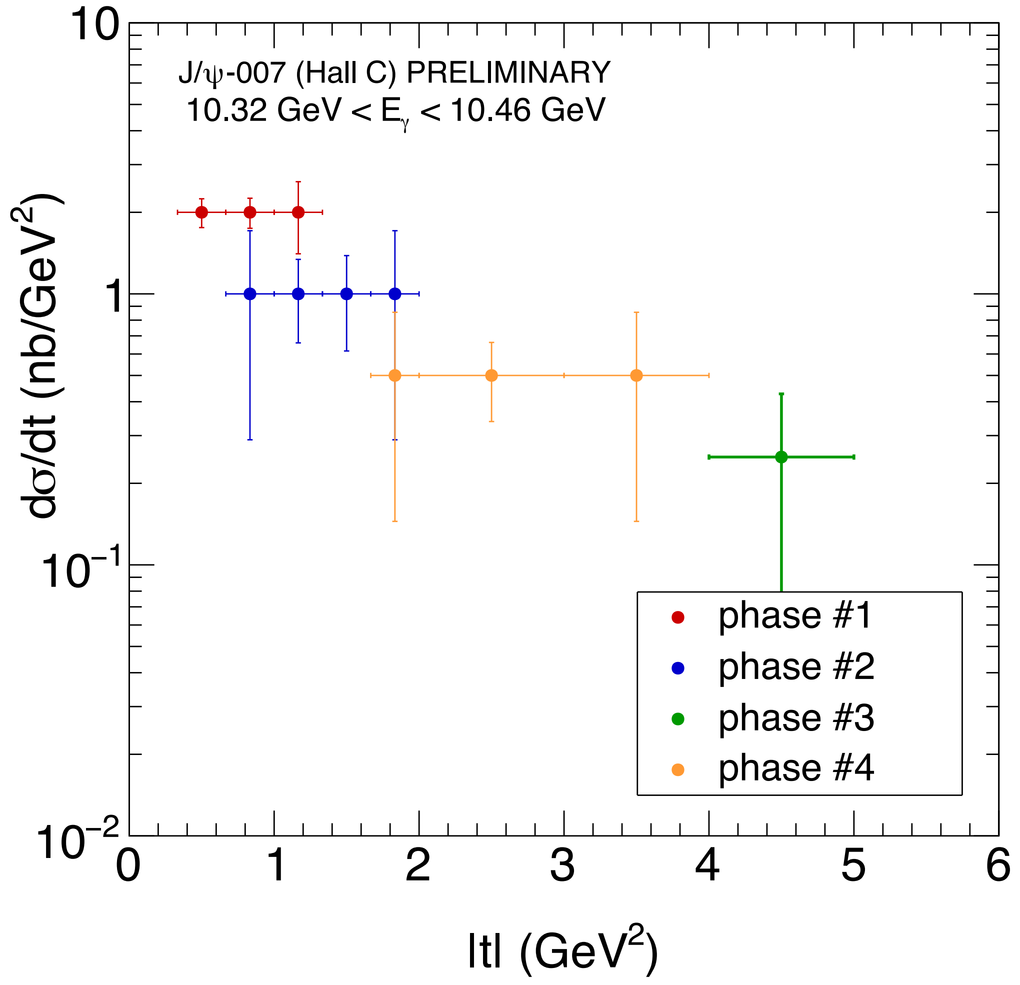
$$J/\psi \rightarrow e^+e^-$$







- **Only showing uncertainties!** *(y-position for each setting arbitrary for improved visibility)*



First 2D measurement near threshold: access Color van der Waals force and trace anomaly

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

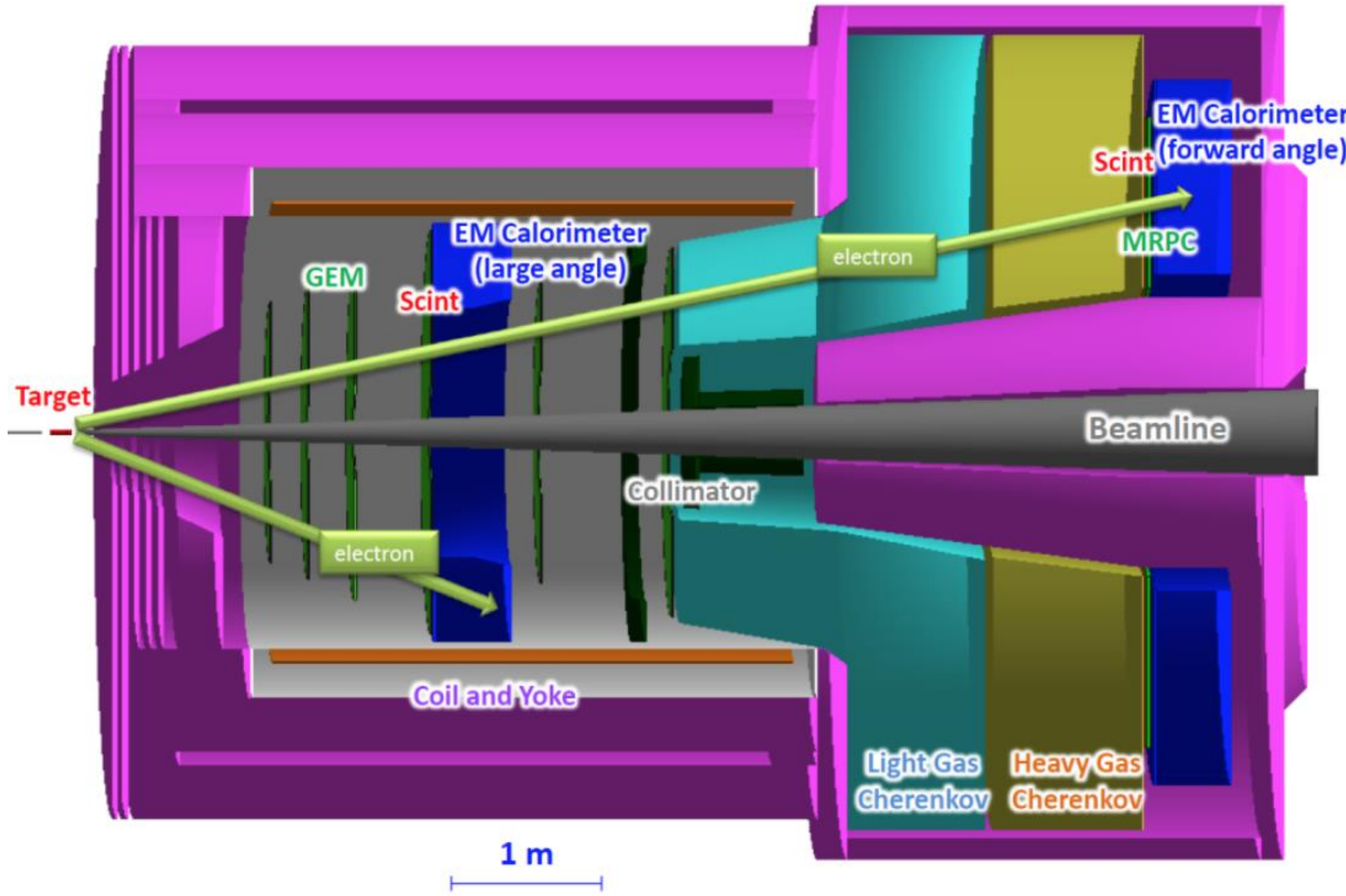
ATHENNA Collaboration

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

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



- 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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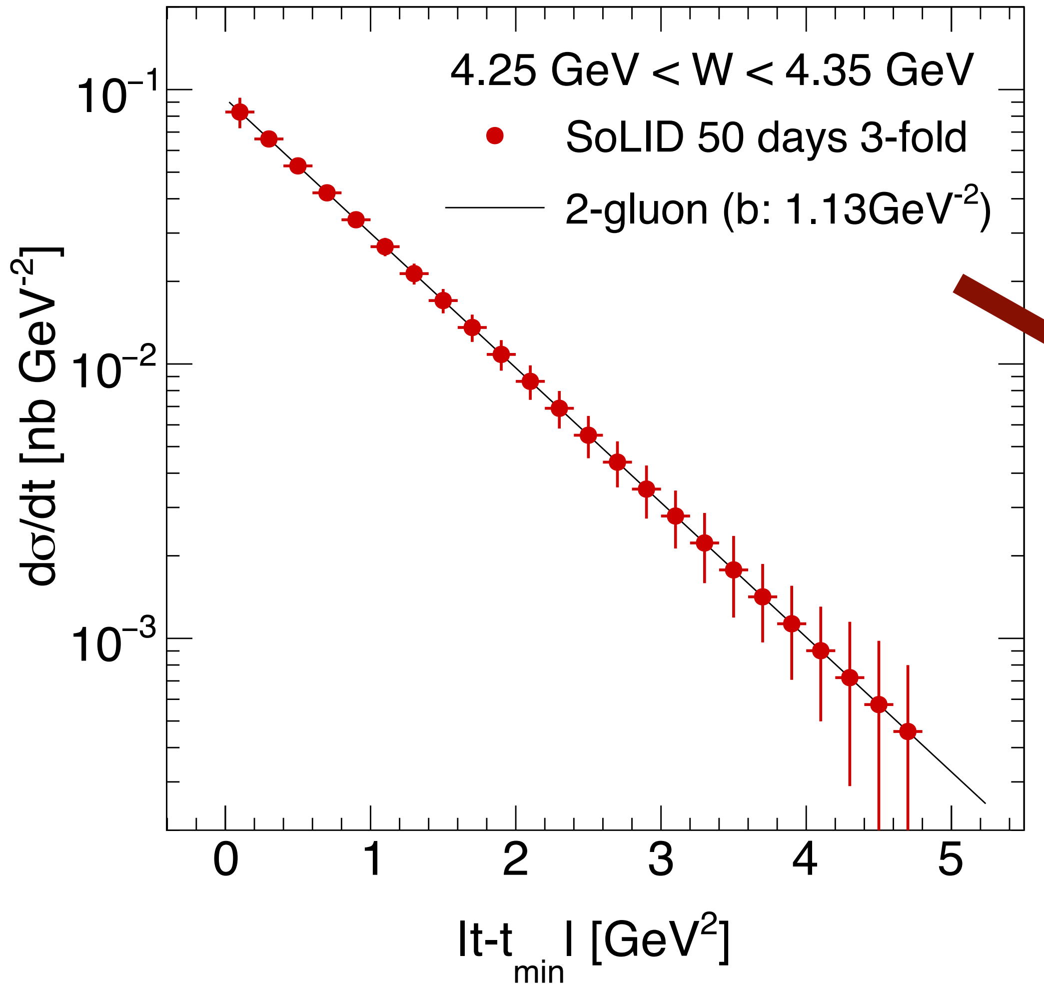
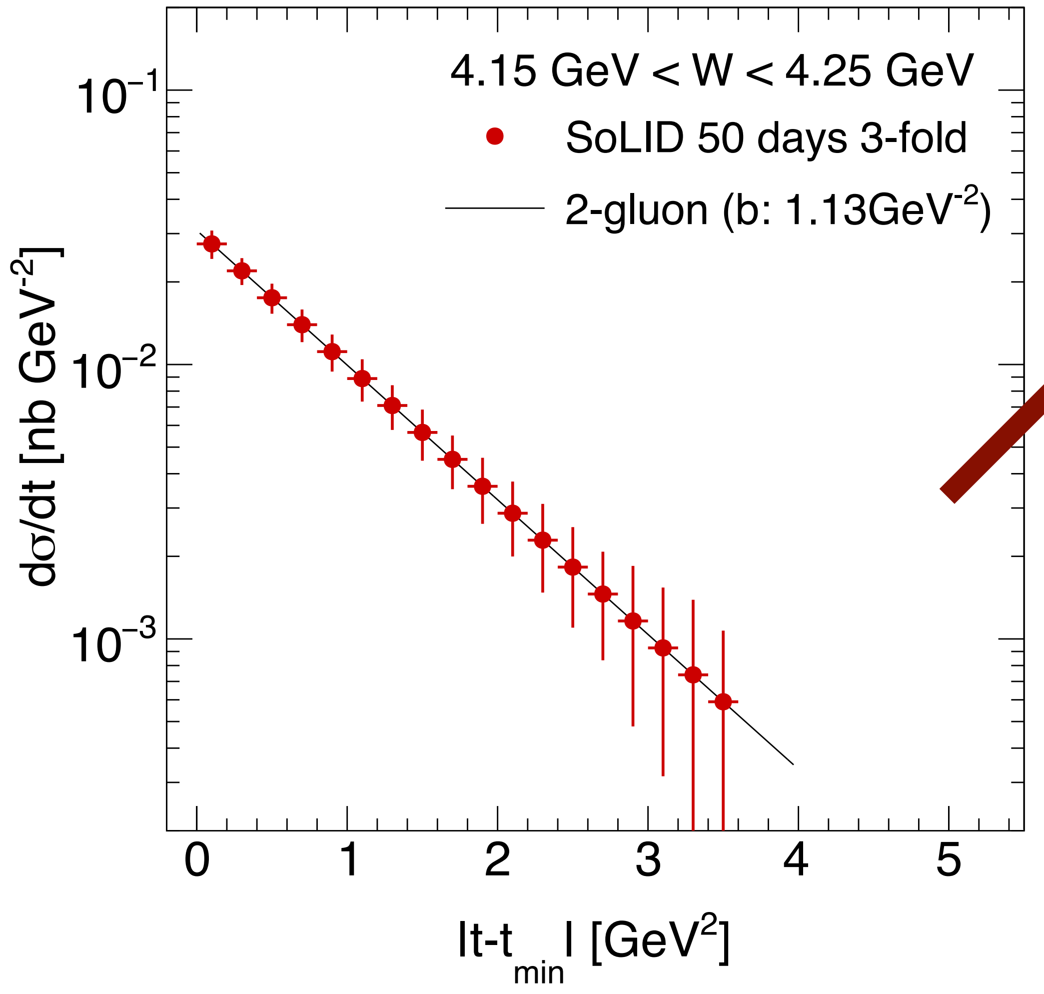
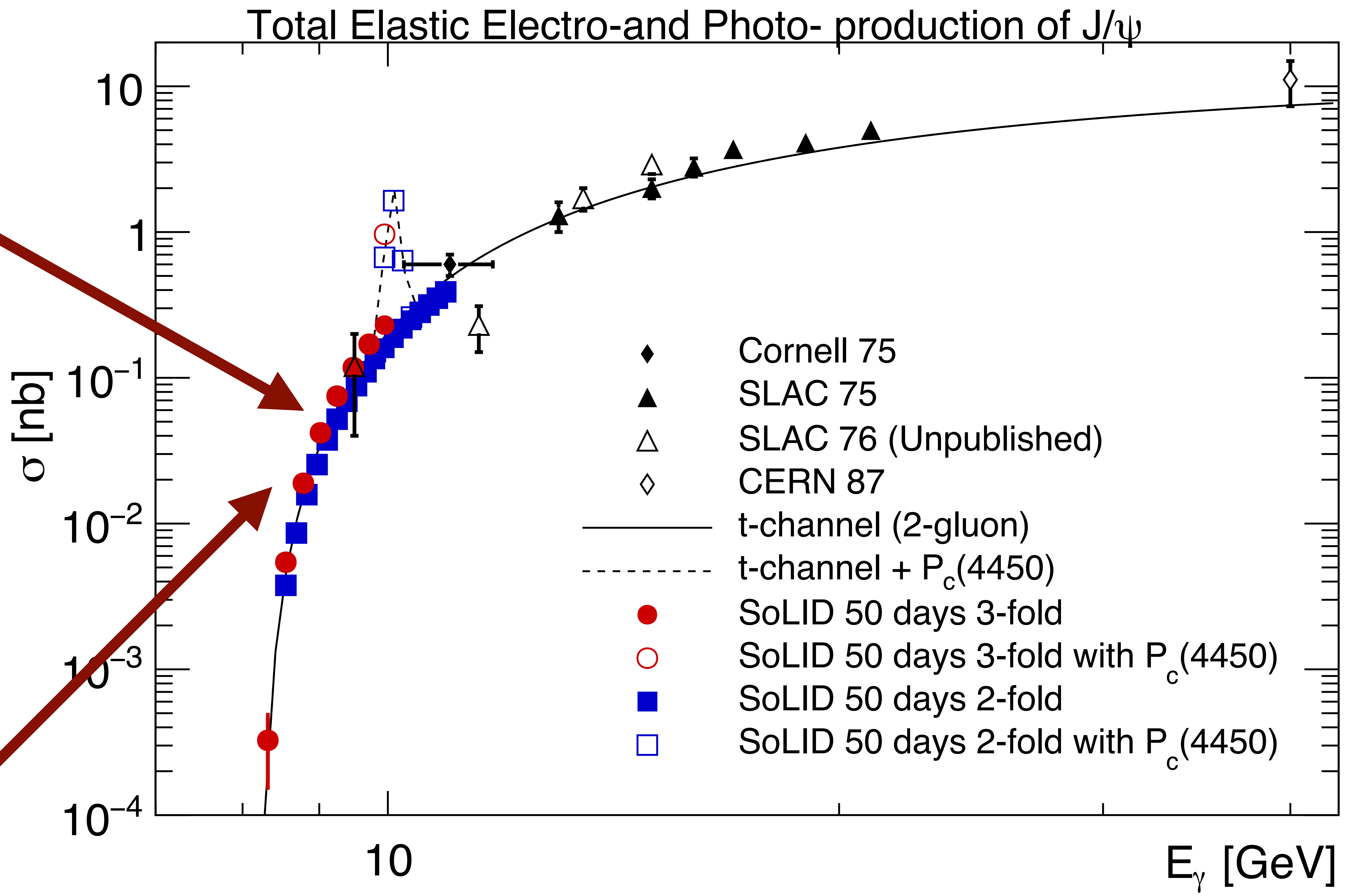






Sensitivity below 10^{-3} nb!

J/Ψ EXPERIMENTS IN JLAB IN A NUTSHELL

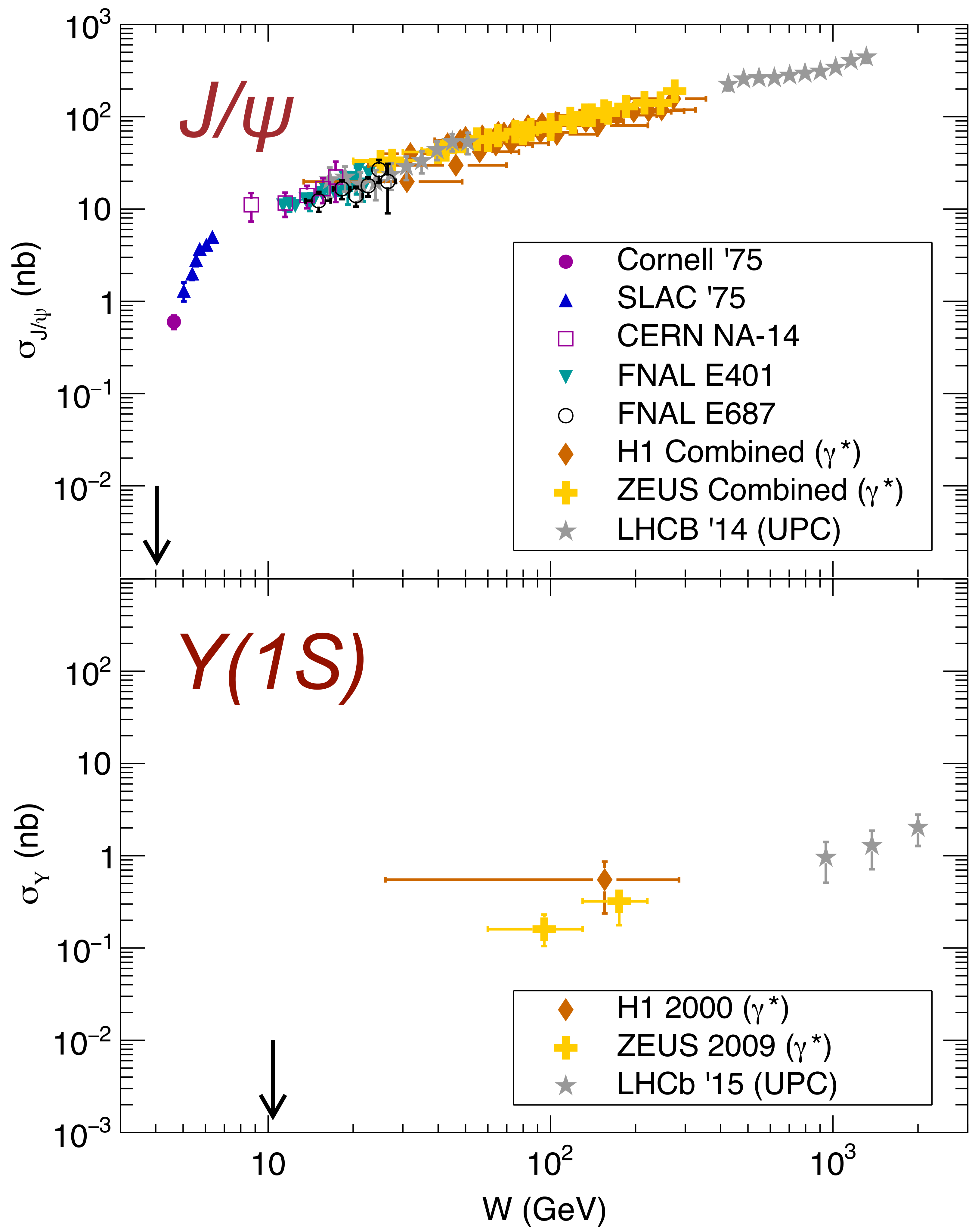
Exciting times for J/ψ near threshold!

	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?

Υ(1S): THE OPTIMAL GLUONIC PROBE

…but a challenging measurement

- *Υ(1S)* is a heavier (smaller) probe than *J/ψ*
  - *Υ(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

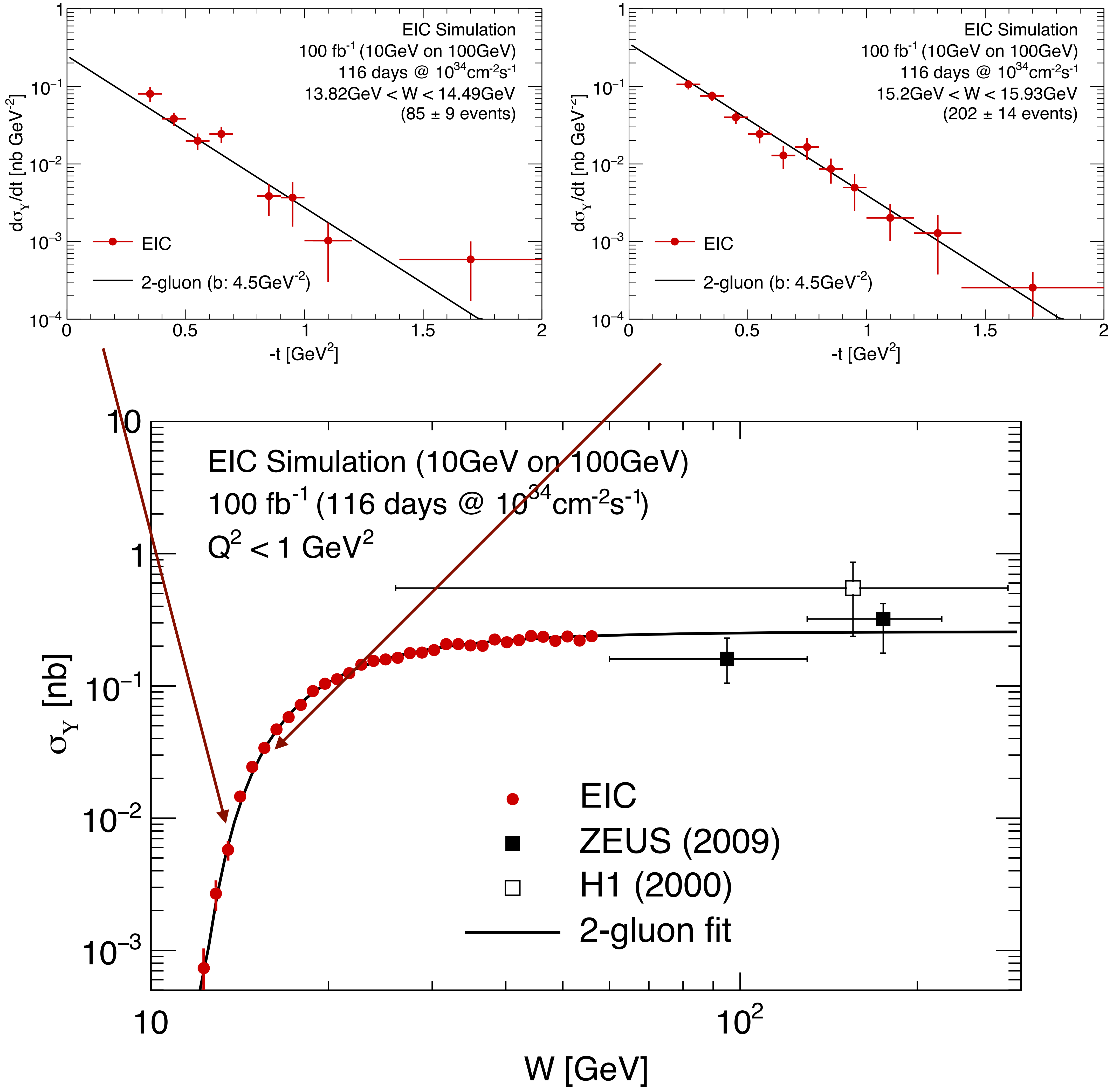


S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)

Y(1S) PHOTO-PRODUCTION AT EIC

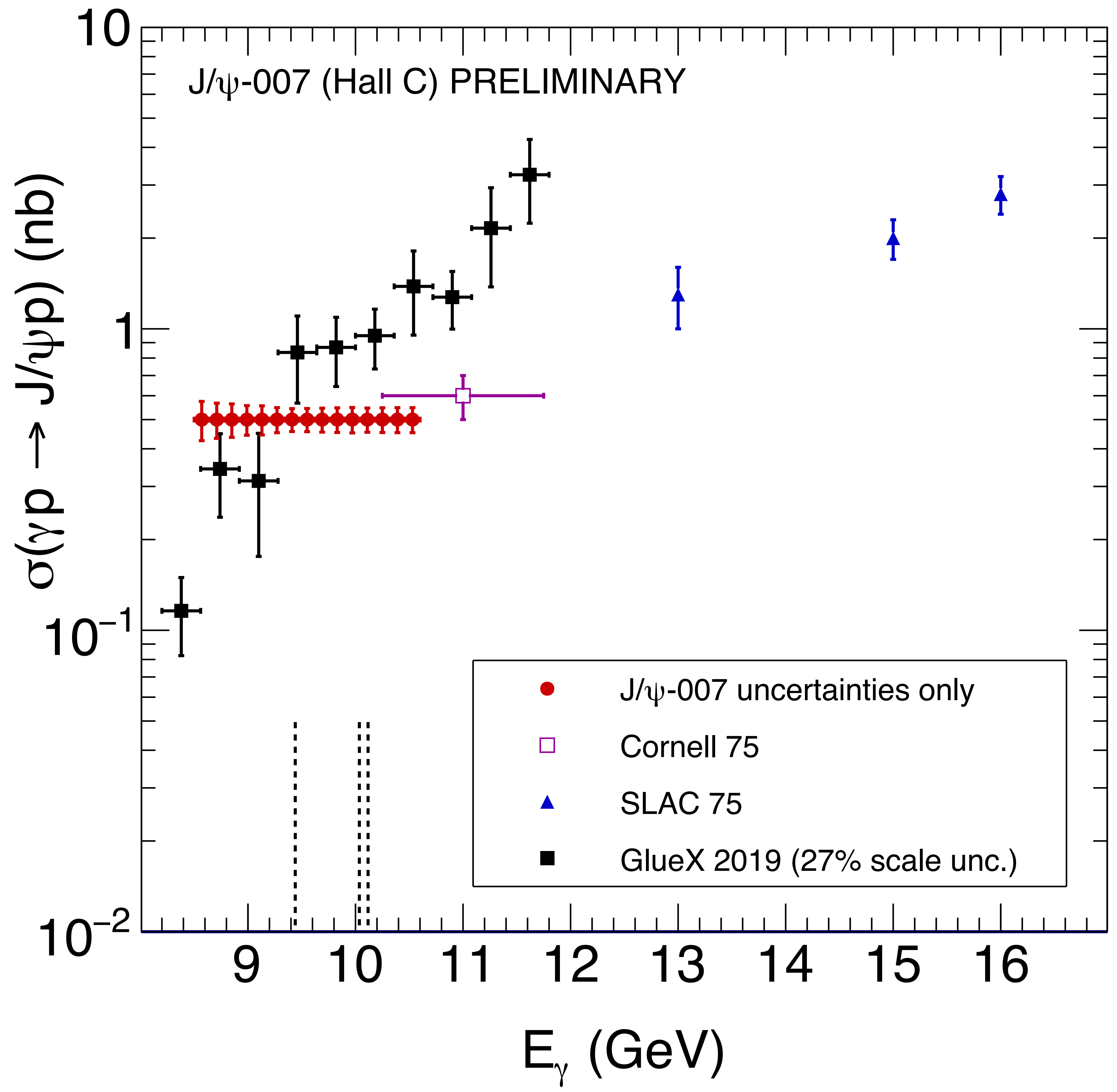
…Threshold measurement possible!

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



- ***Y(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!

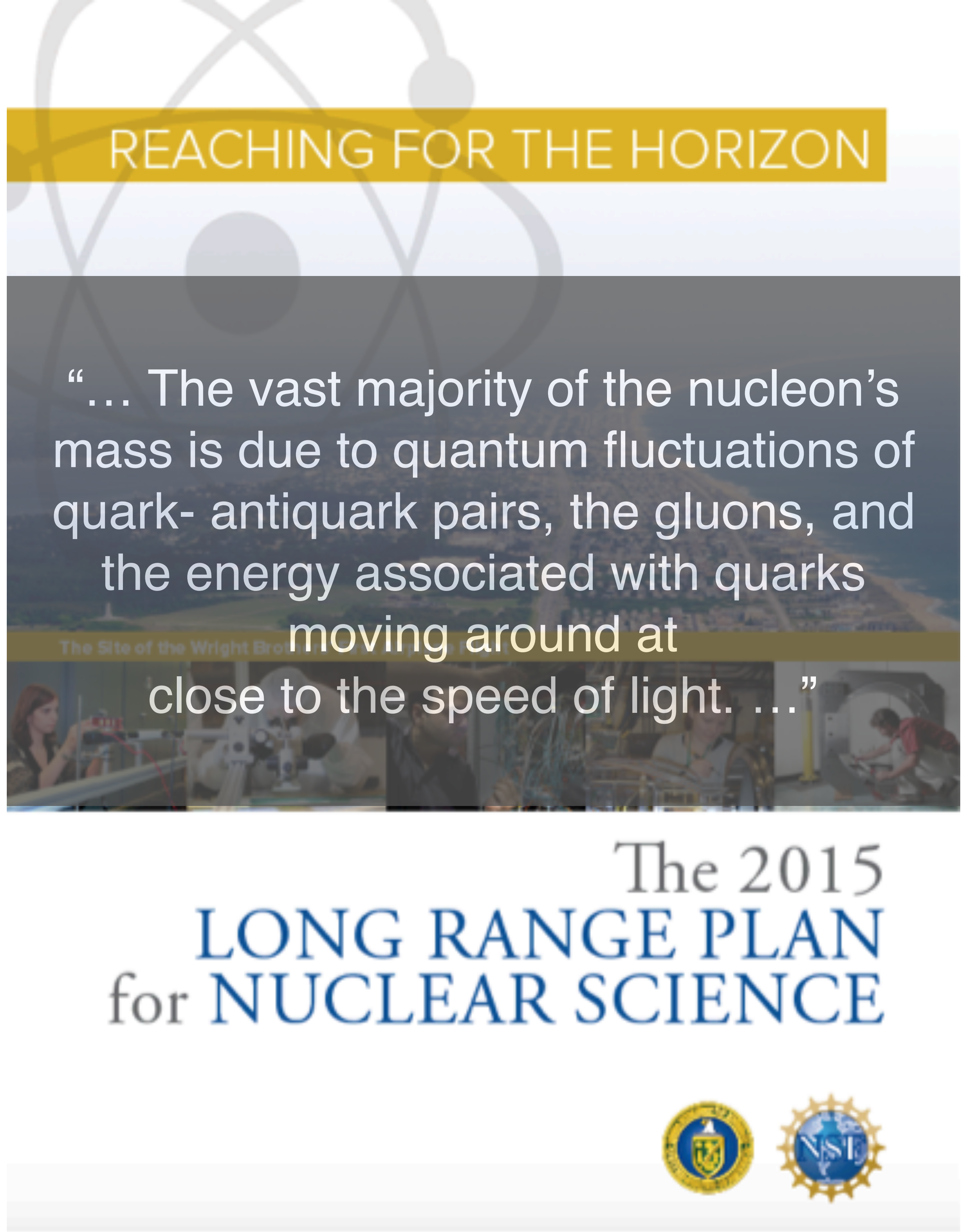
CONCLUSION

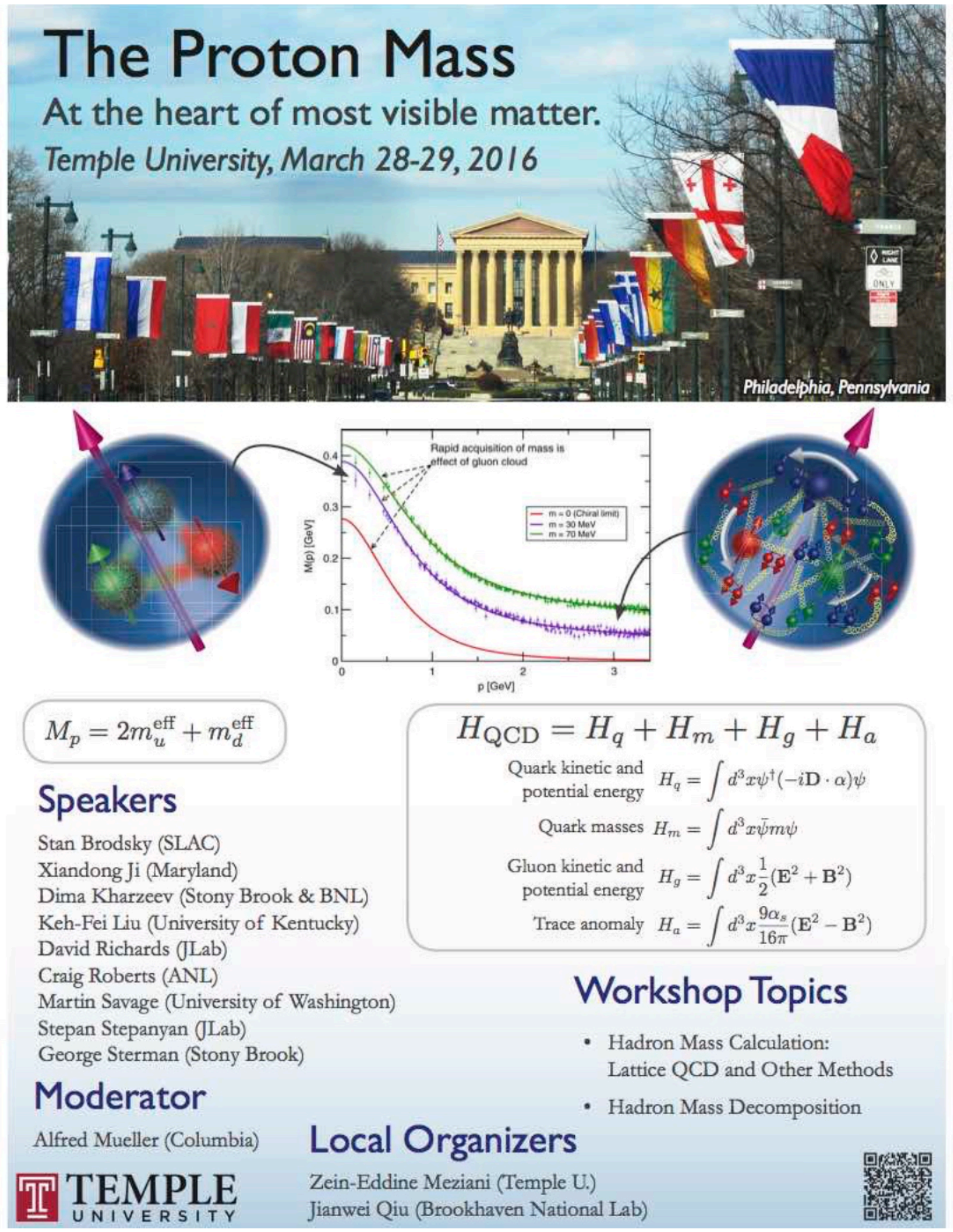


- **Quarkonium** production an important tool to study the **gluonic fields** in the nucleon
- **Threshold production** of quarkonium can shed light on the **trace anomaly,** quarkonium-nucleon **binding,** the LHCb **pentaquark** and the origin of the **proton mass**
- Possible to study “charming” (and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

BACKUP

THE PROTON MASS… A HOT TOPIC!





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

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

At leading order:

$$M_q = \frac{3}{4}\left(a - \frac{b}{1+\gamma_m}\right)M$$
$$M_m = \frac{4+\gamma_m}{4(1+\gamma_m)}bM$$
$$M_g = \frac{3}{4}(1-a)M$$
$$M_a = \frac{1}{4}(1-b)M$$

a(μ) related to PDFs, well constrained

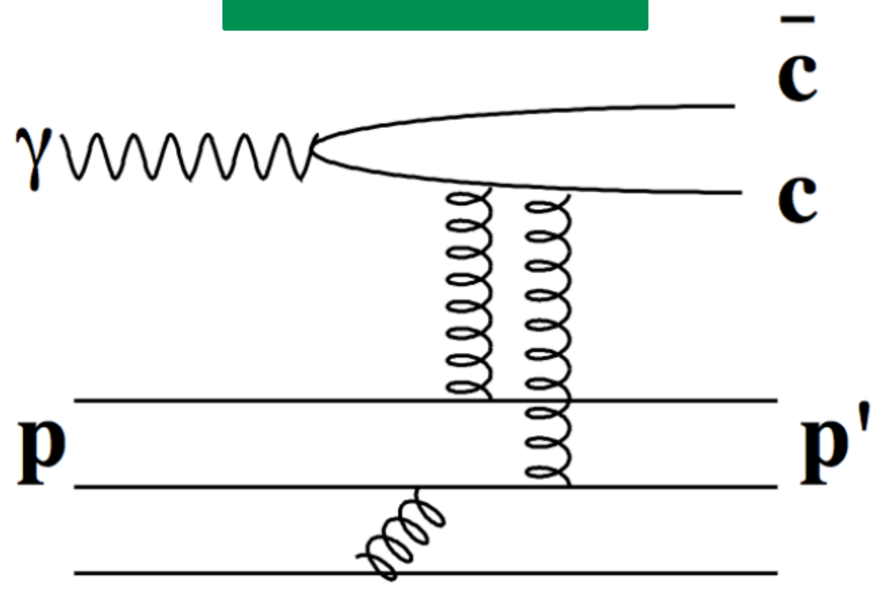
b(μ) related trace anomaly, unconstrained

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

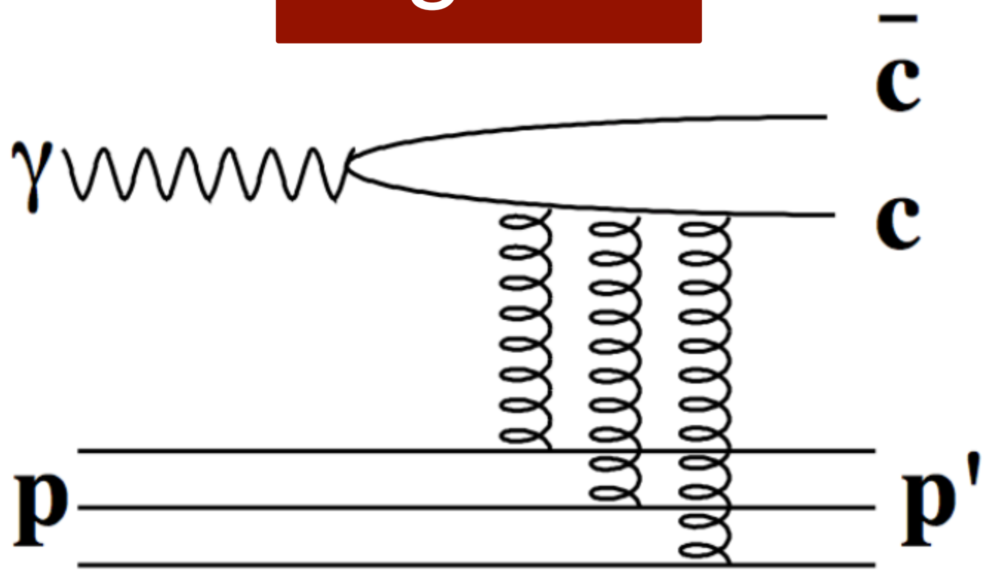
PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

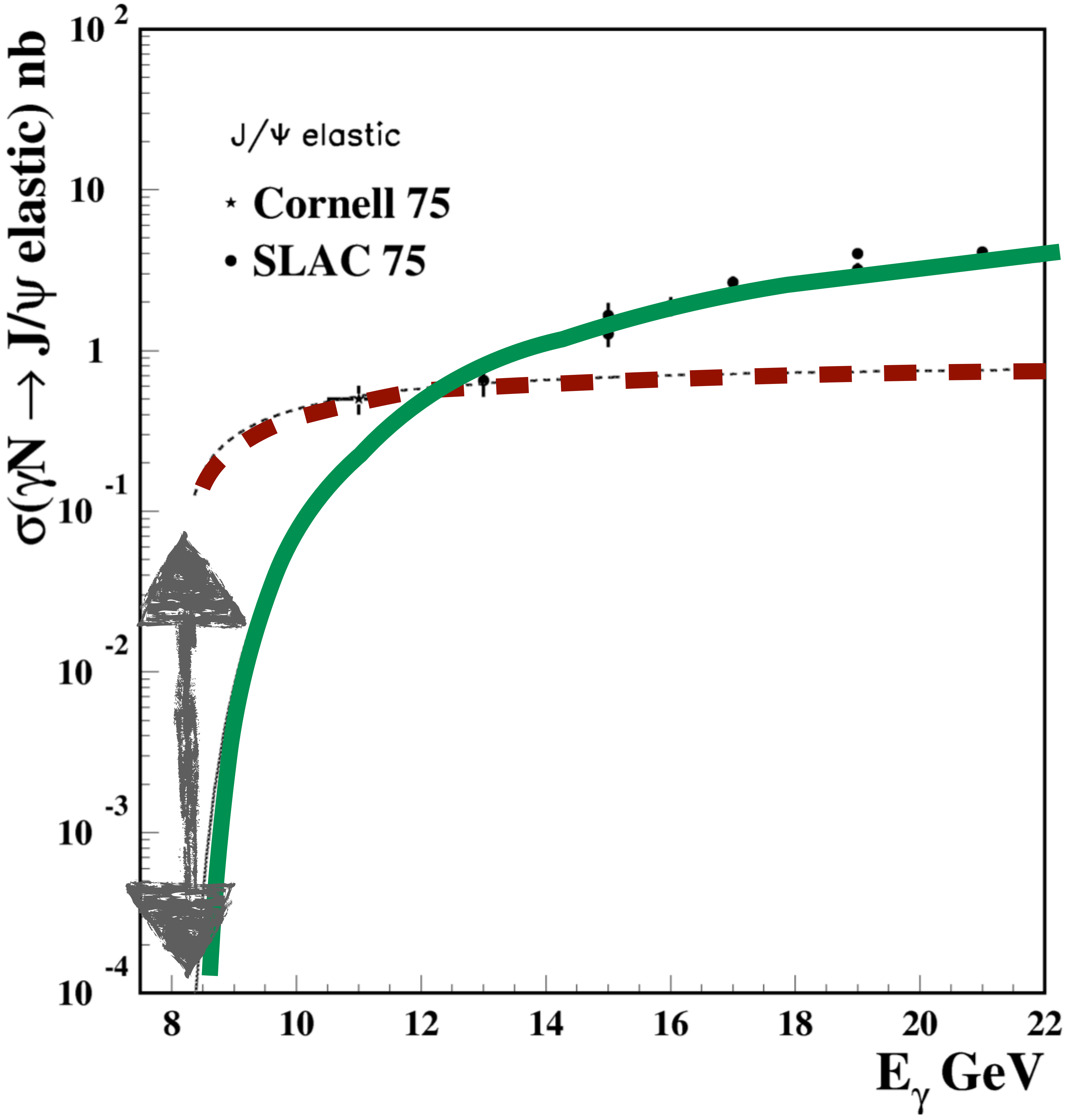
2-gluon



3-gluon



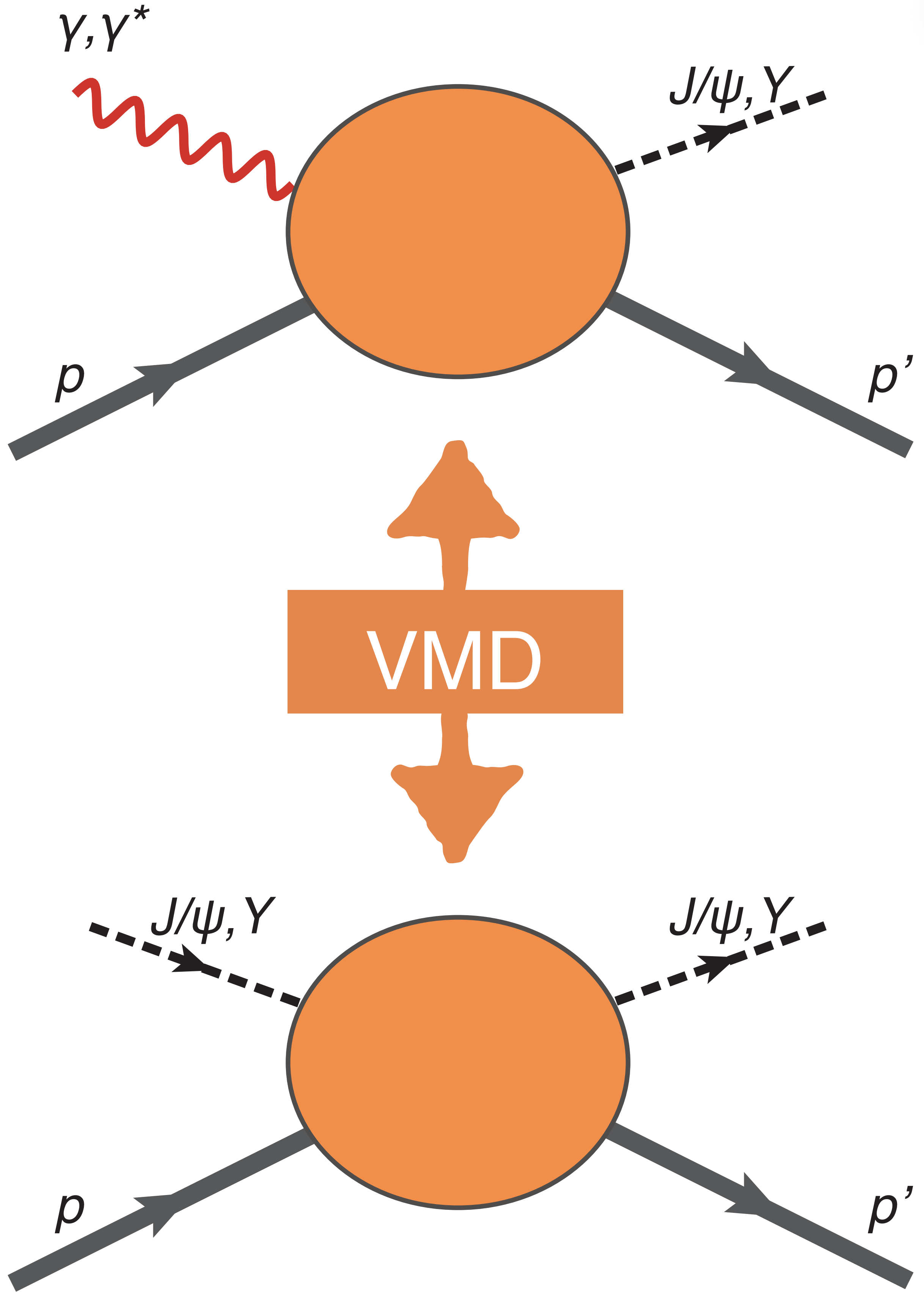
- 2-gluon exchange works well at higher energies
- Higher order gluon exchange expected to play role near threshold
  - Larger 3-gluon exchange contribution related to binding
- Exponential *t*-dependence (or dipole)
- Orders of magnitude difference between predictions: **threshold region still unknown**
- **No link with trace anomaly**



D. Kharzeev *et al.*, PLB 289 595-599 (1996), EPJ-C 9 459-462 (1999)
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)

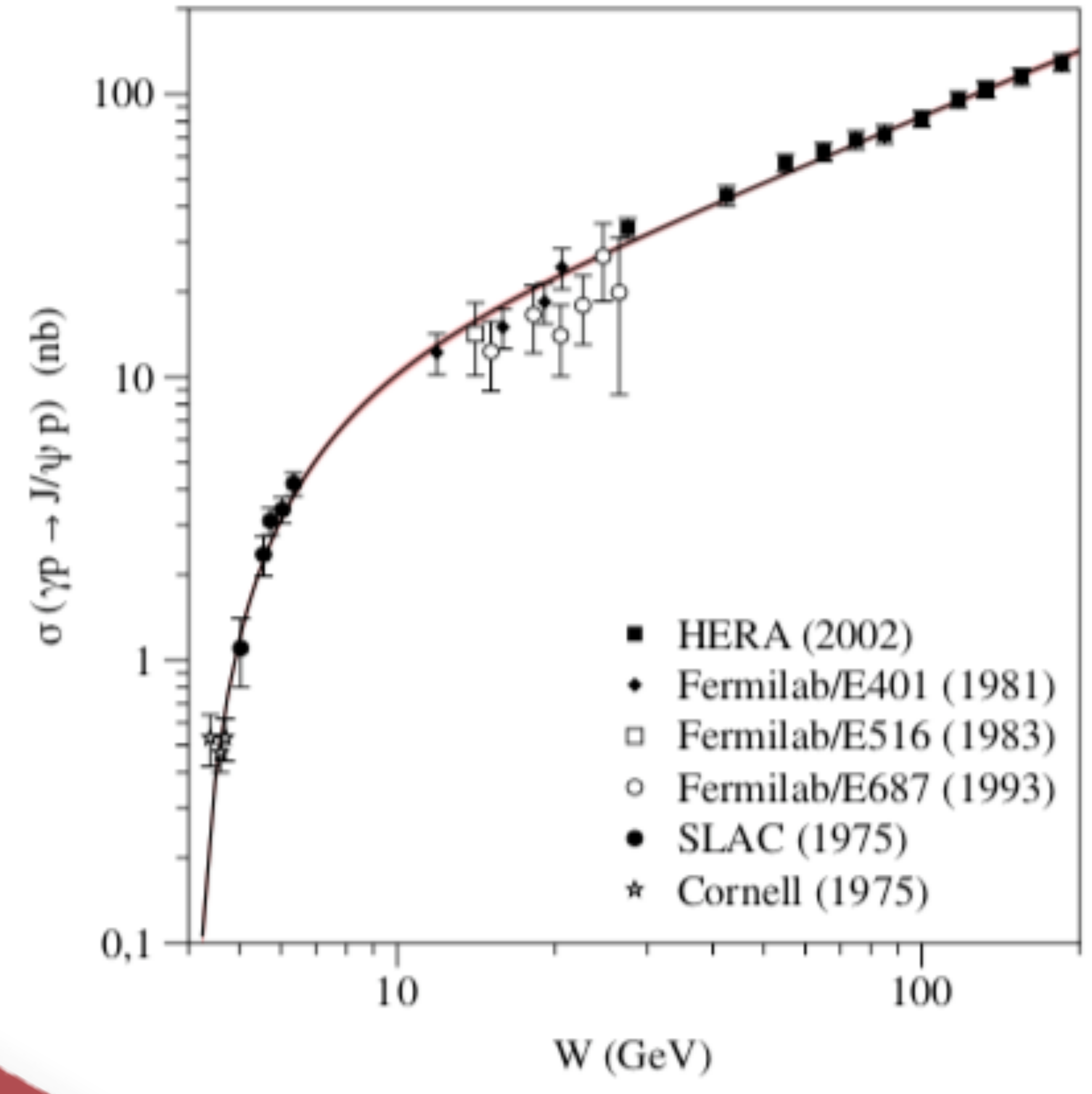


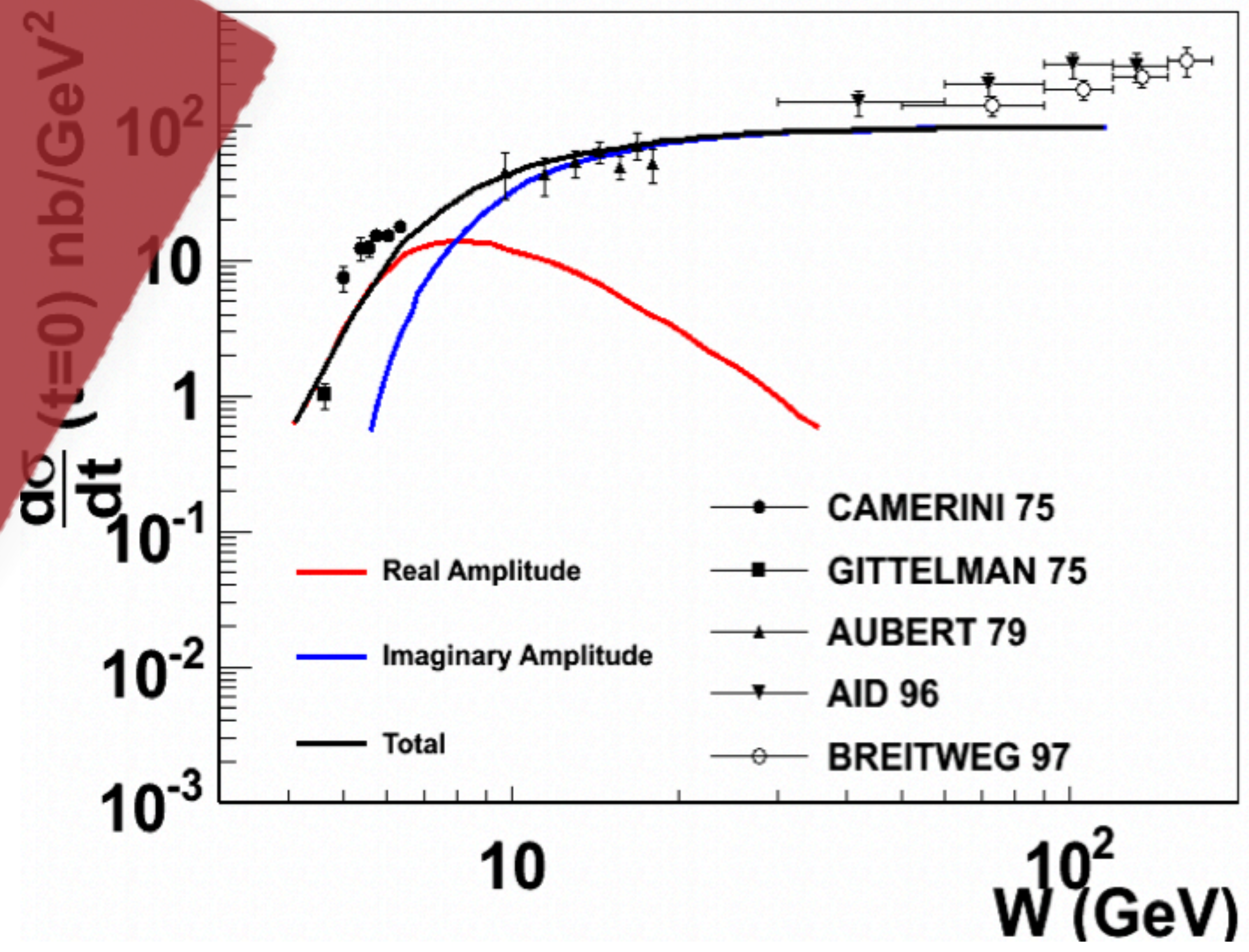
- VMD relates photoproduction cross section to quarkonium-nucleon scattering amplitude $T_{\psi p}$
- Approach well-defined at **high energies:**
  1. Obtain **Im($T_{\psi p}$)** from high-energy data (extrapolated to $t=0$)
  2. **Re($T_{\psi p}$)** dominates **near threshold:** constrain through dispersion relations

$$\mathcal{R}e T_{\psi p}(\nu) = T_{\psi p}(0) + \frac{2}{\pi}\nu^2 \int_{\nu_{\mathrm{el}}}^{\infty} d\nu' \frac{1}{\nu'} \frac{\mathcal{I}m T_{\psi p}(\nu')}{\nu'^2 - \nu^2}$$

- Trace anomaly proportional to **Re($T_{\psi p}$) at threshold** $\langle P|G^2|P\rangle \sim T_{\psi p}(\nu_{\mathrm{thresh}})$

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

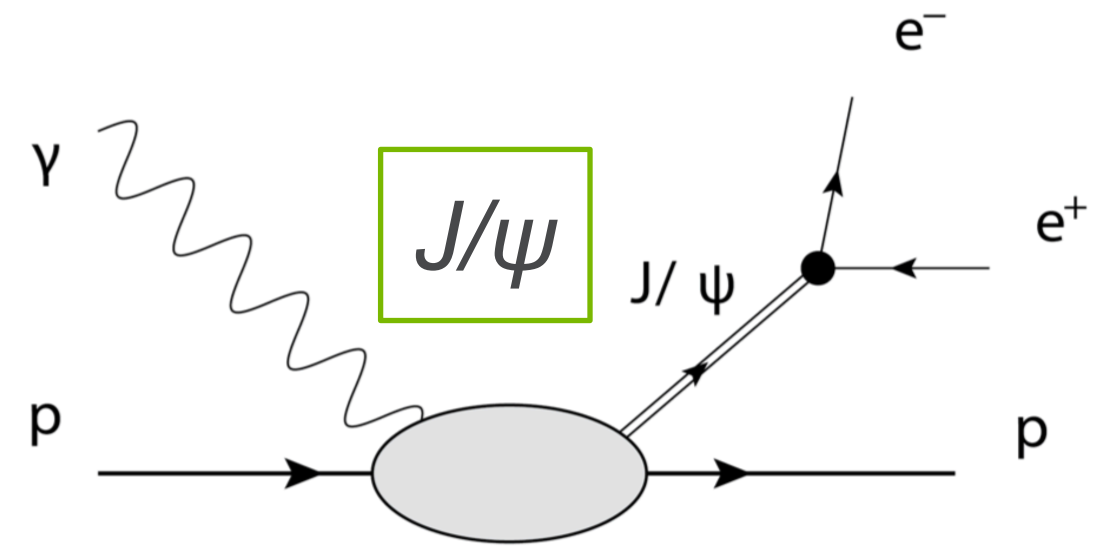


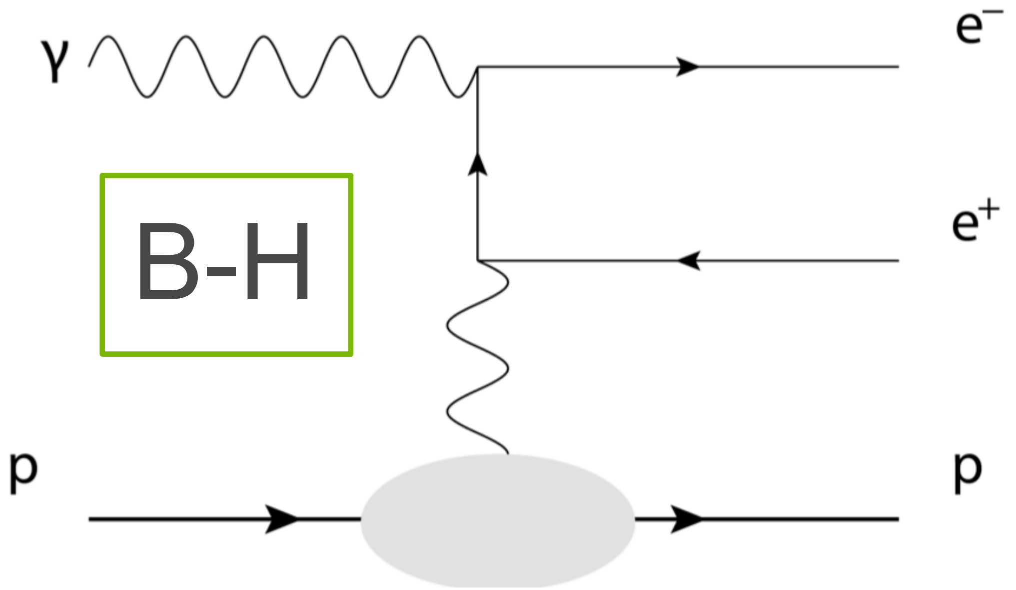


Experimental access to trace anomaly: *t*-dependence of quarkonium cross section *at* threshold

PRODUCTION MECHANISM NEAR THRESHOLD?

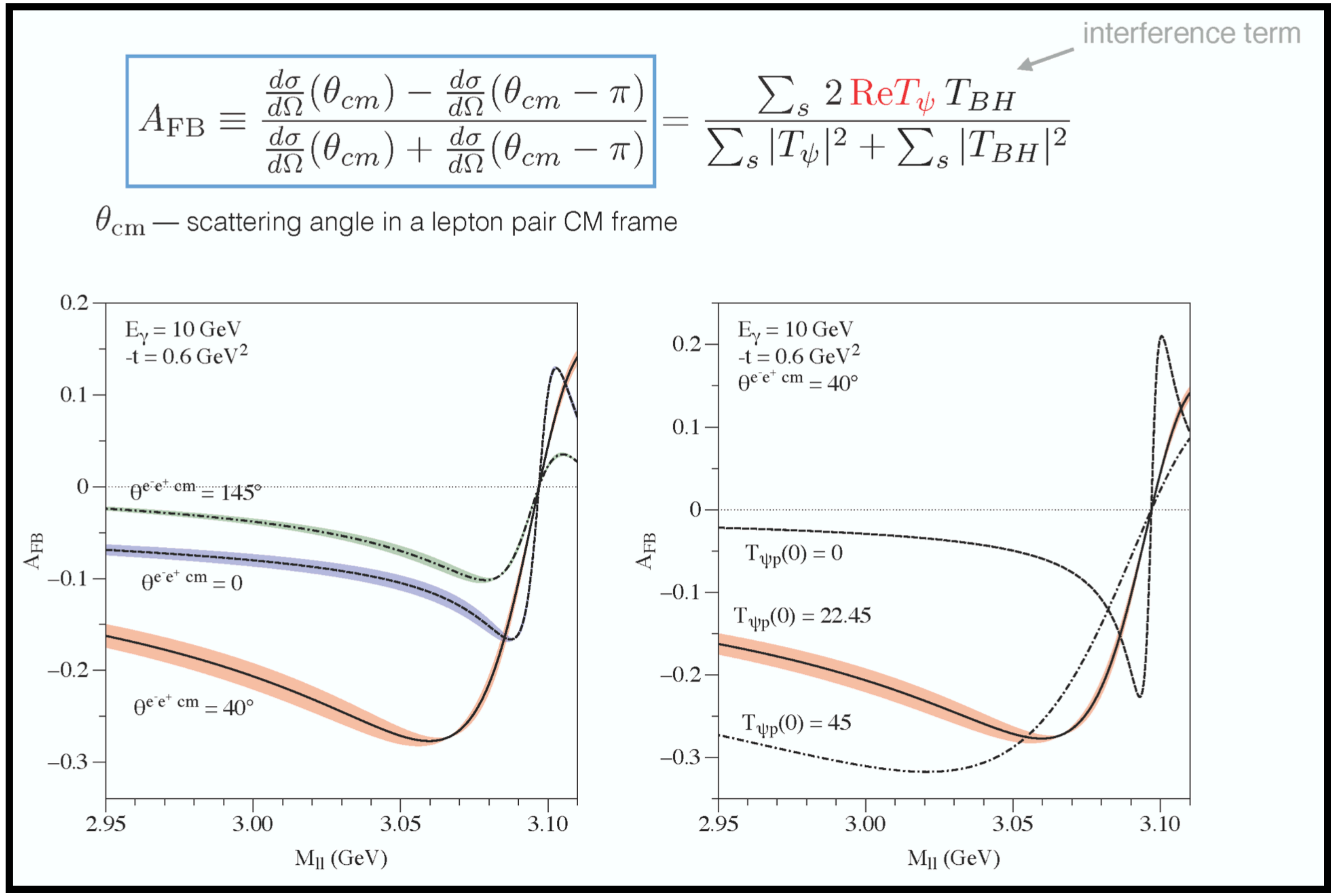
Vector meson dominance (dispersive framework)





- Interference between elastic *J/ψ* production near threshold and Bethe-Heitler
- Forward-backward asymmetry near *J/ψ* invariant mass peak proportional to **Re(*T*$_{\psi p}$)**

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

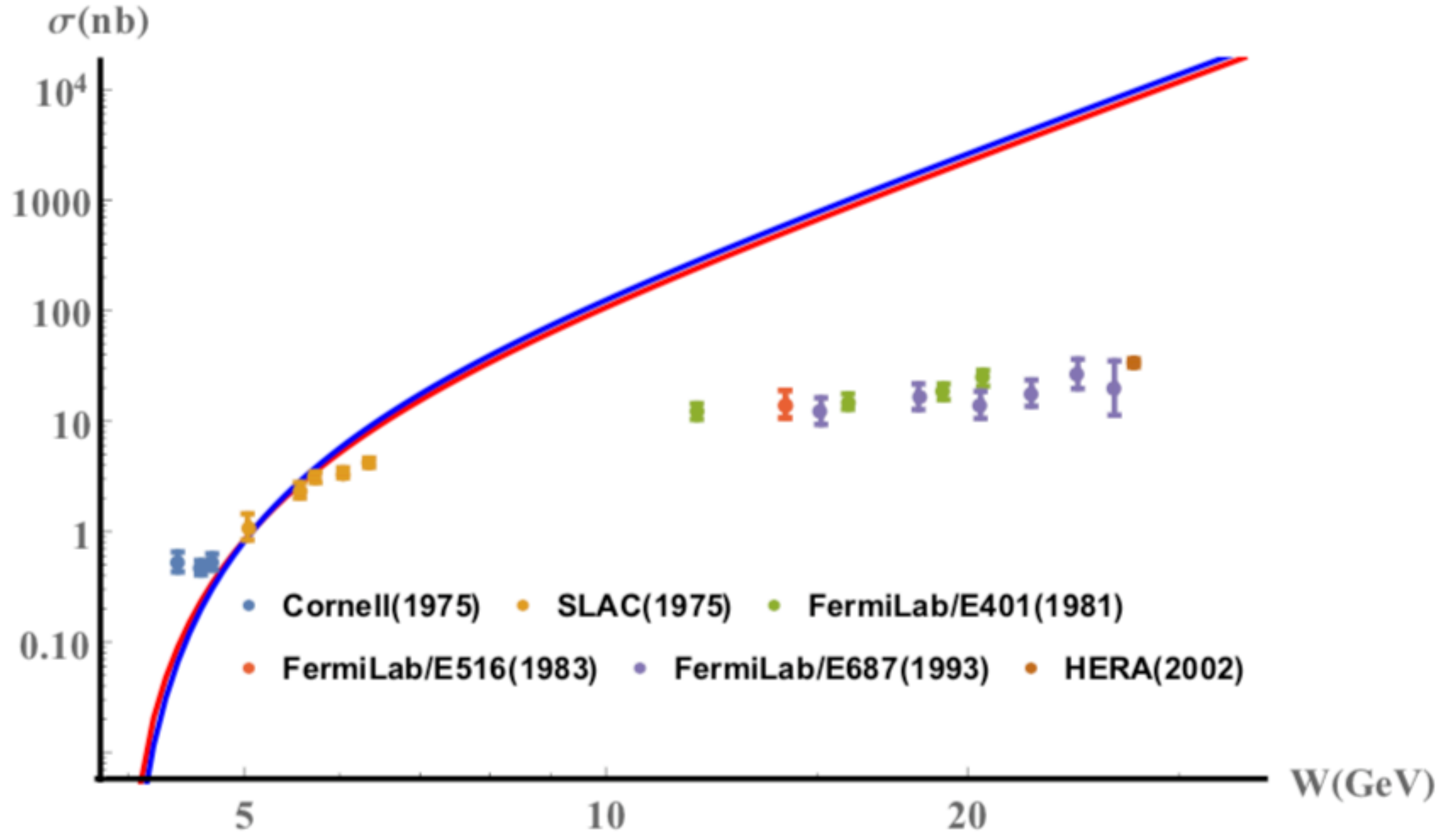


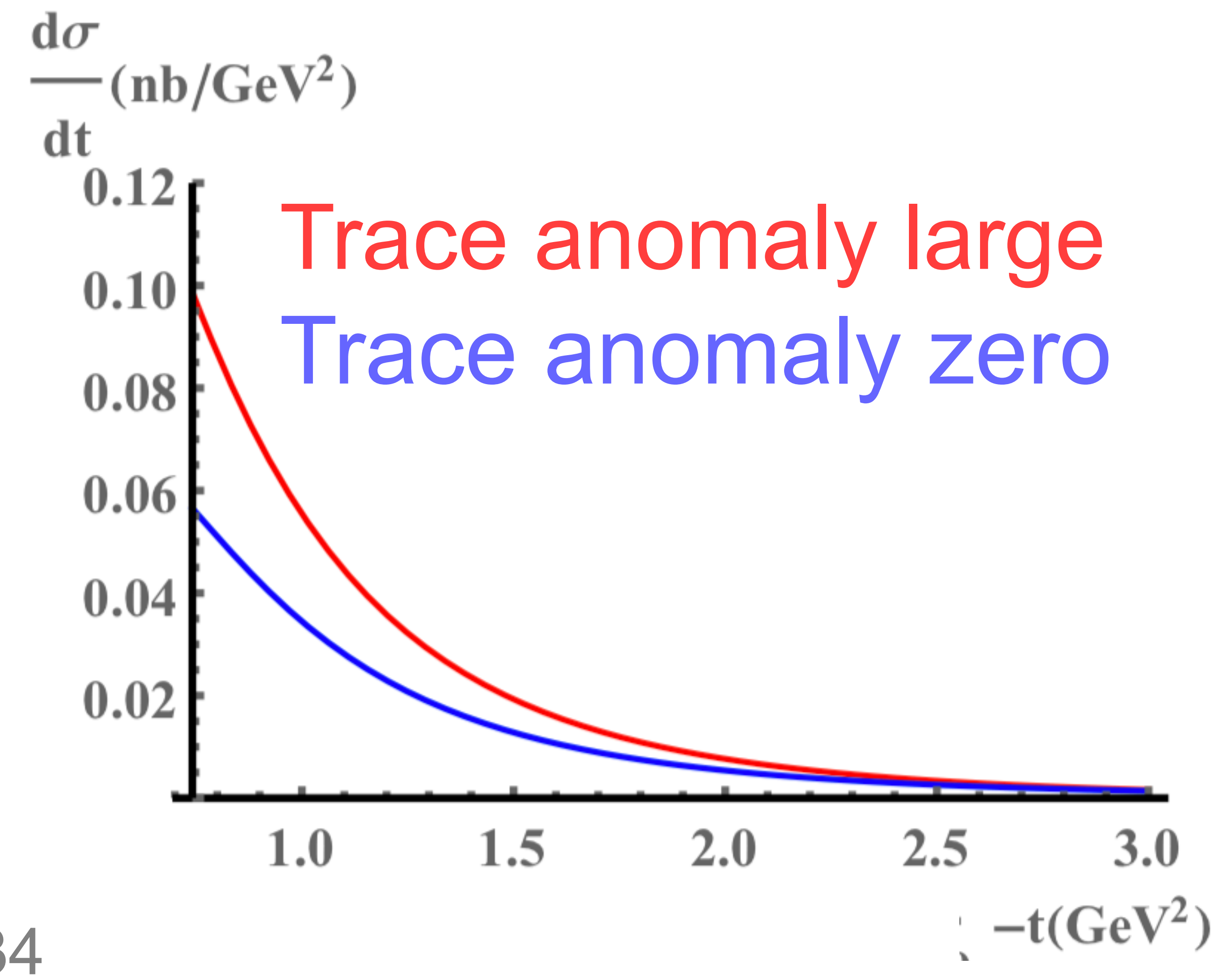
Slide from O. Gryniuk

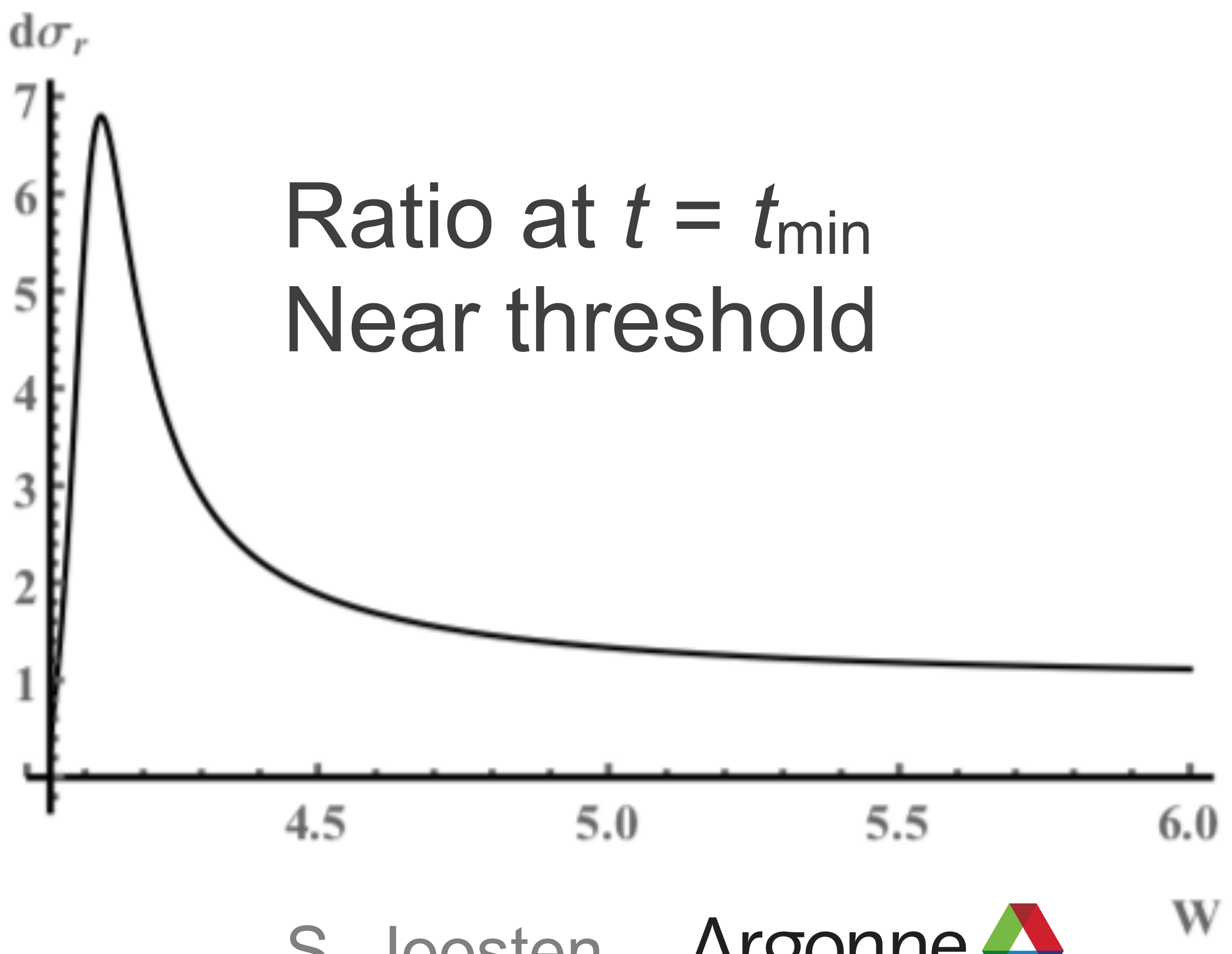
PRODUCTION MECHANISM NEAR THRESHOLD?

Holographic approach

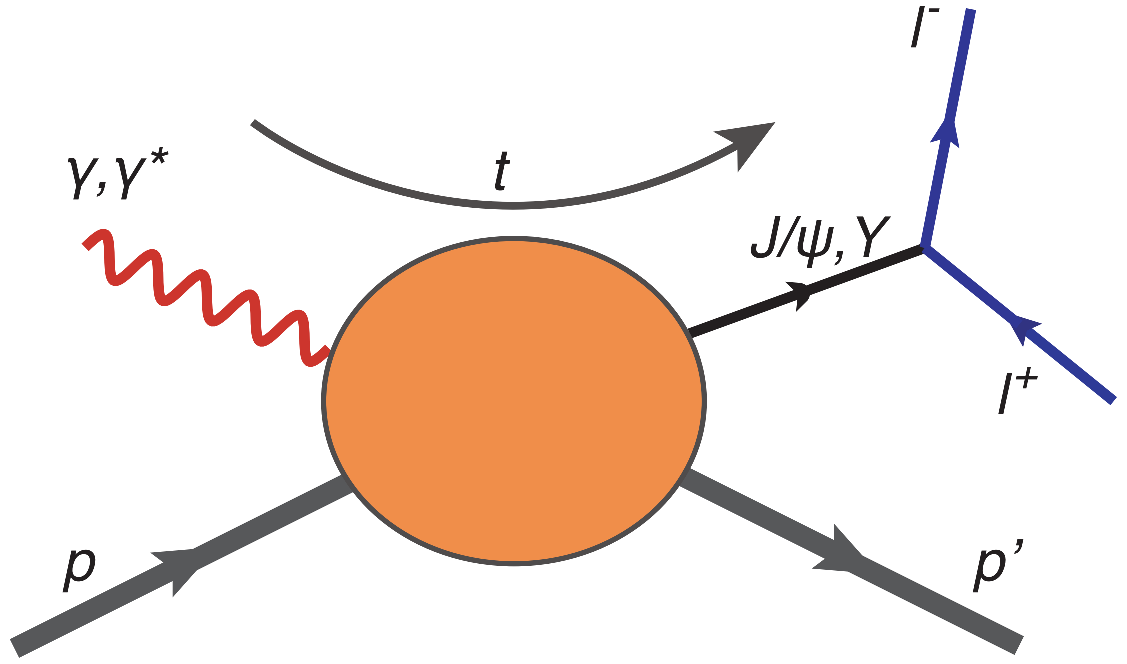
- Perturbative approach difficult
  (no factorization for twist-4 trace anomaly operator)
- Use non-perturbative method instead through AdS/CFT
  (gauge-string duality: dilaton dual to $F^{\mu\nu}F_{\mu\nu}$)
- **Disaster at high energies** (scattering amplitude real but should be imaginary)
- Some **hope at low energies**: QCD amplitudes should be real at low energies anyway
- Predicts largest sensitivity to trace anomaly near threshold at low *t*
- New development, numerical predictions cary large model uncertainties



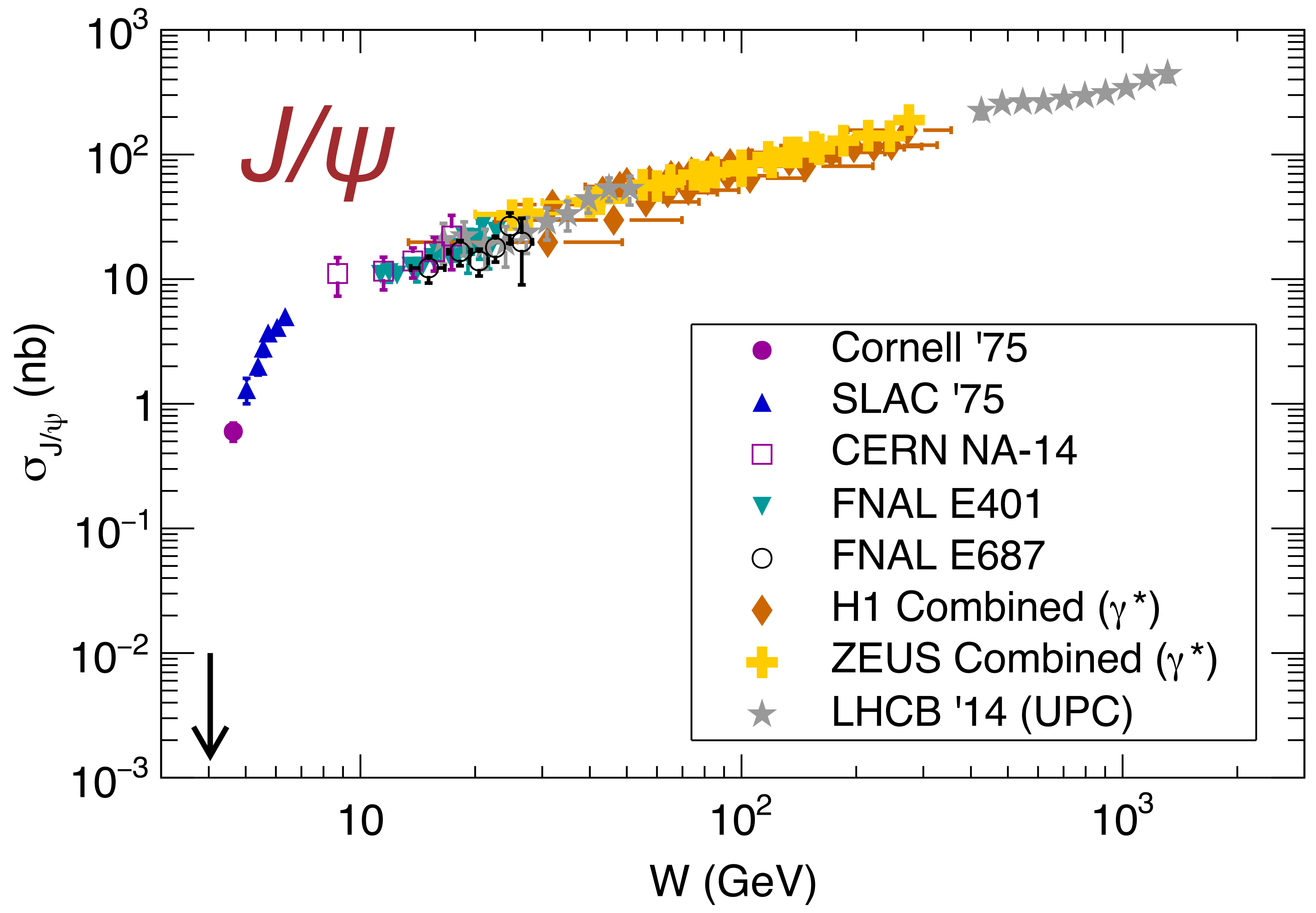




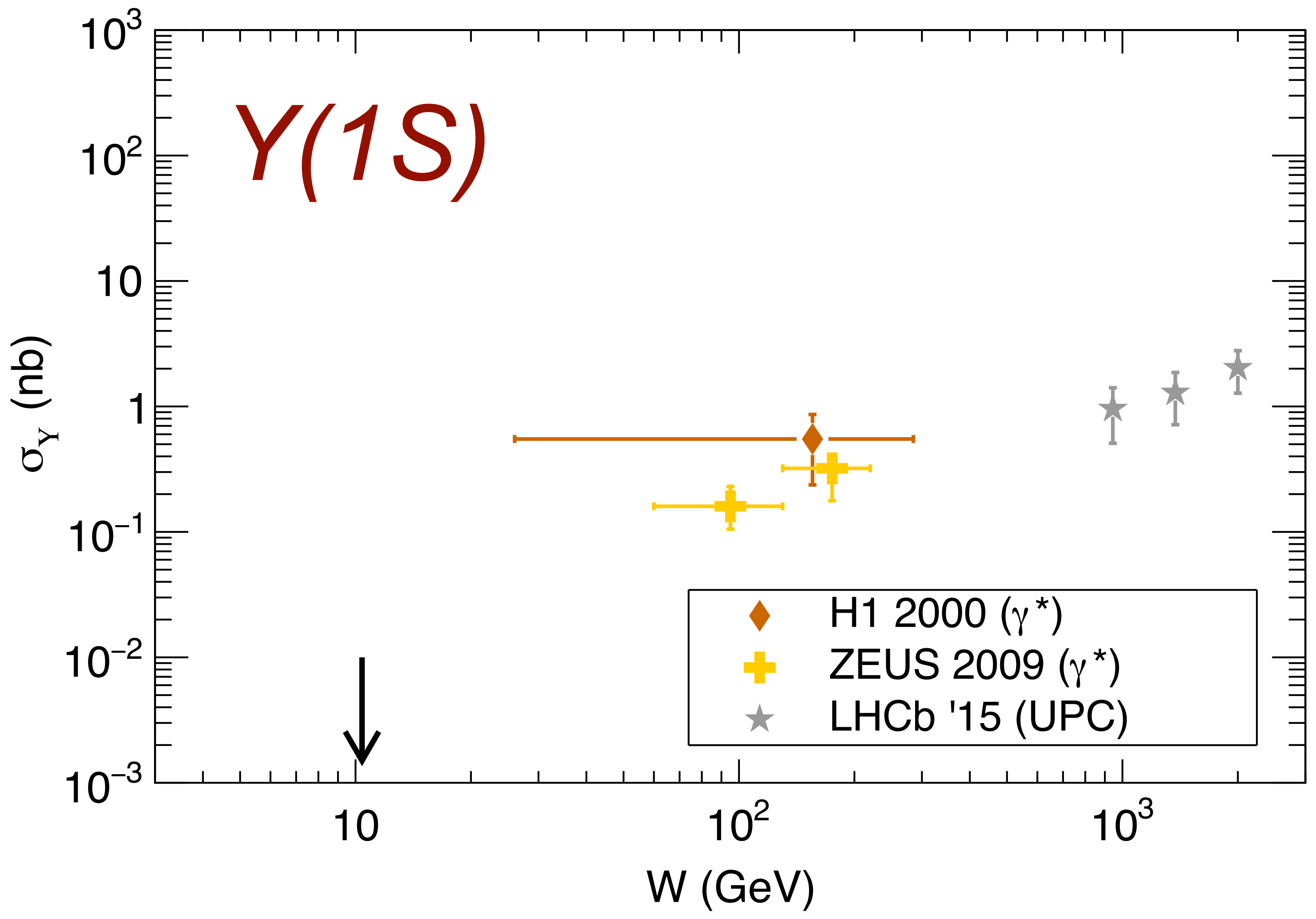
QUARKONIUM PHOTO-PRODUCTION: WHAT DO WE KNOW?



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



- **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)



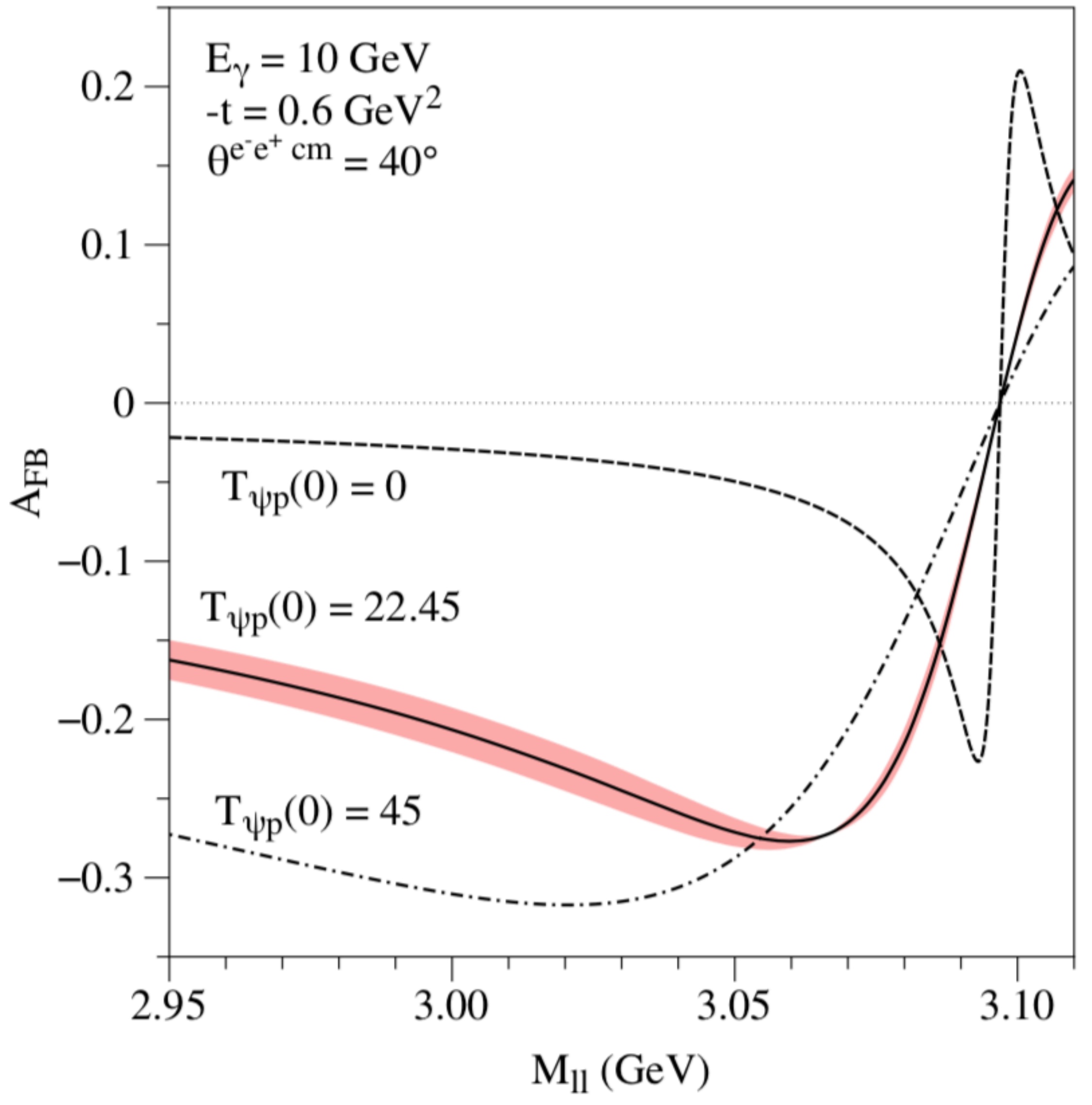
- **Electro-production (quasi-real)**
  H1 and ZEUS
- **Ultra-peripheral collisions**
  LHCb `15 (*pp*)

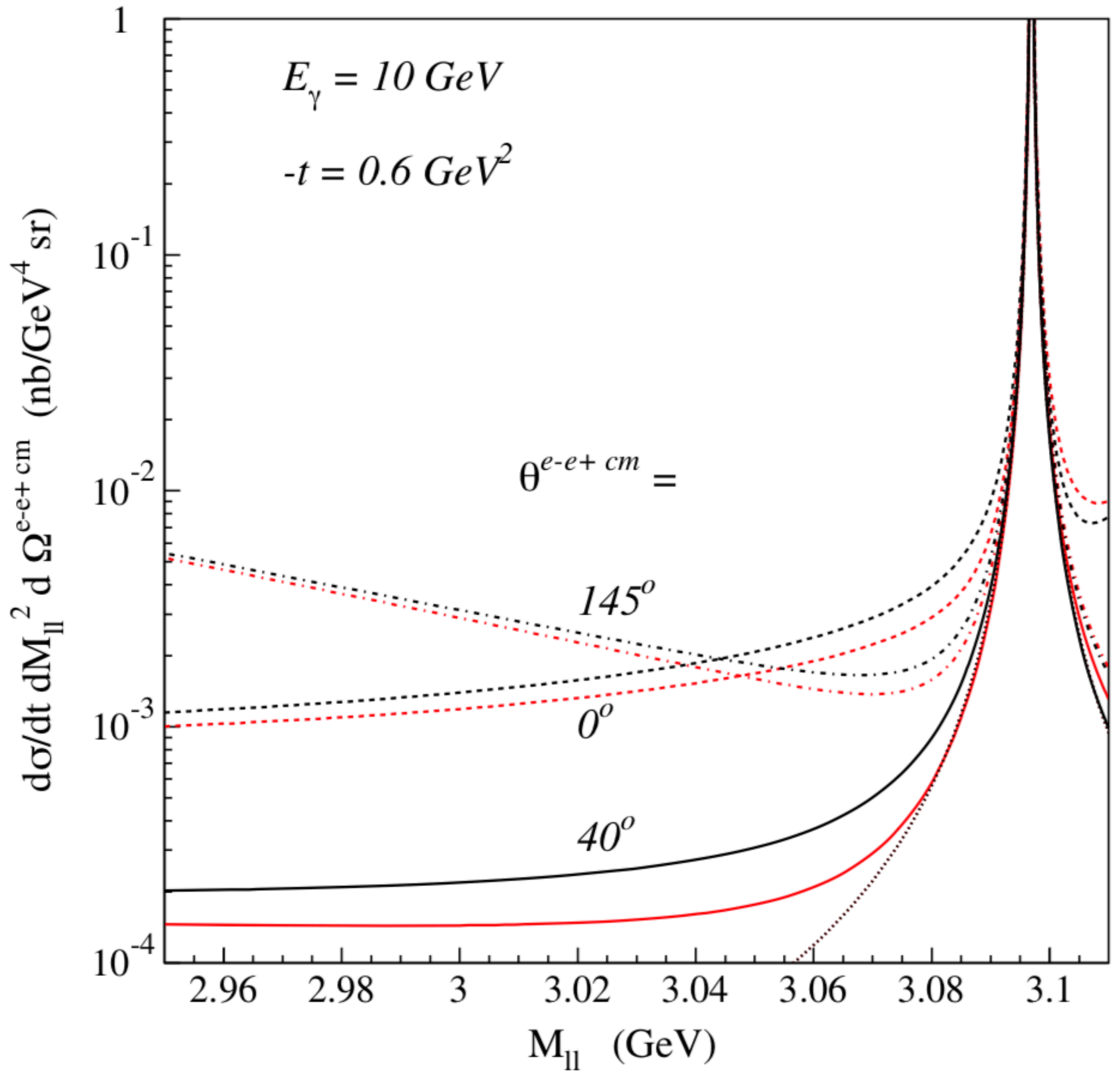
ATHENNA Collaboration

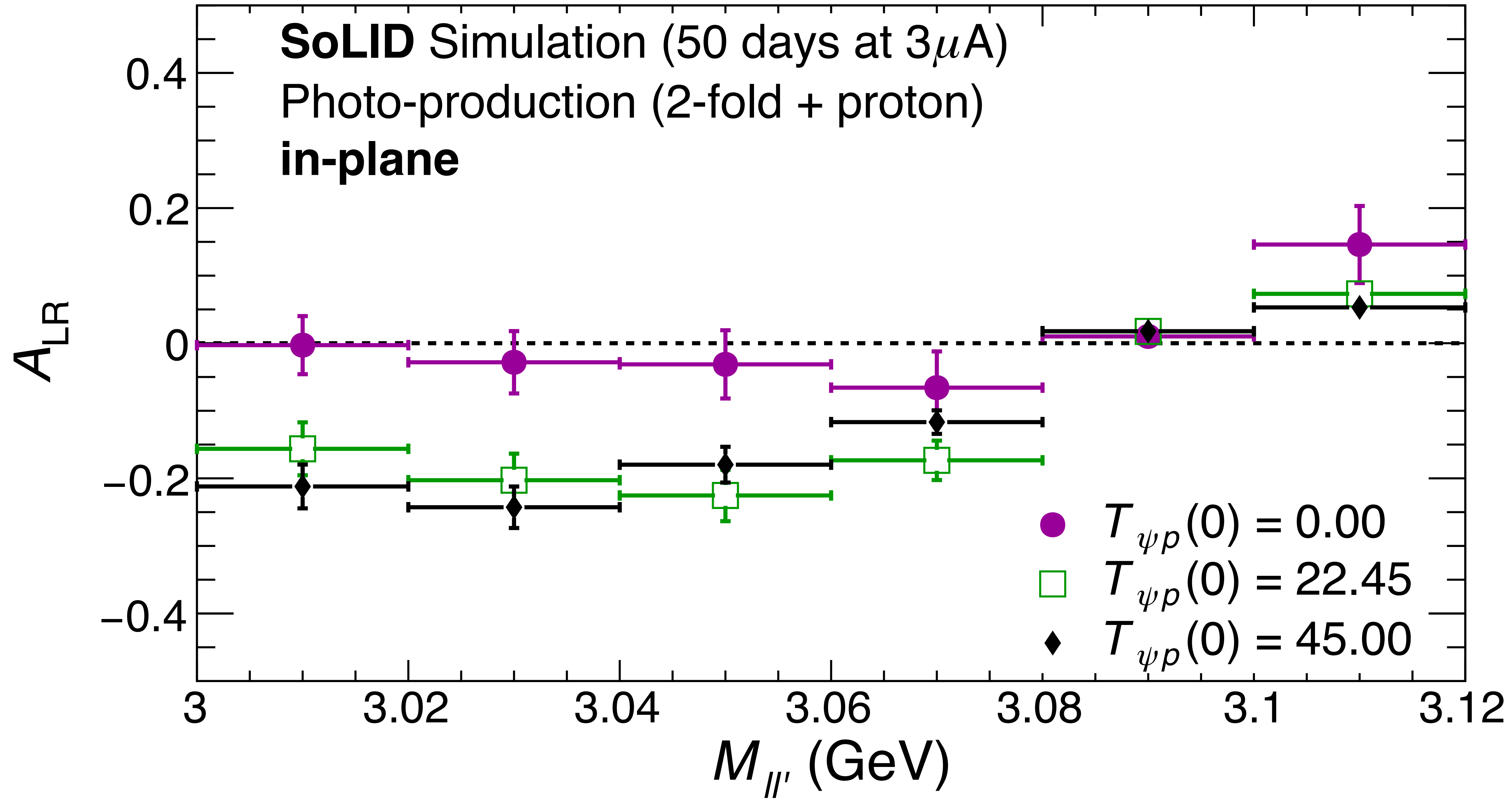
J/Ψ EXPERIMENT E12-12-006 AT SOLID

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

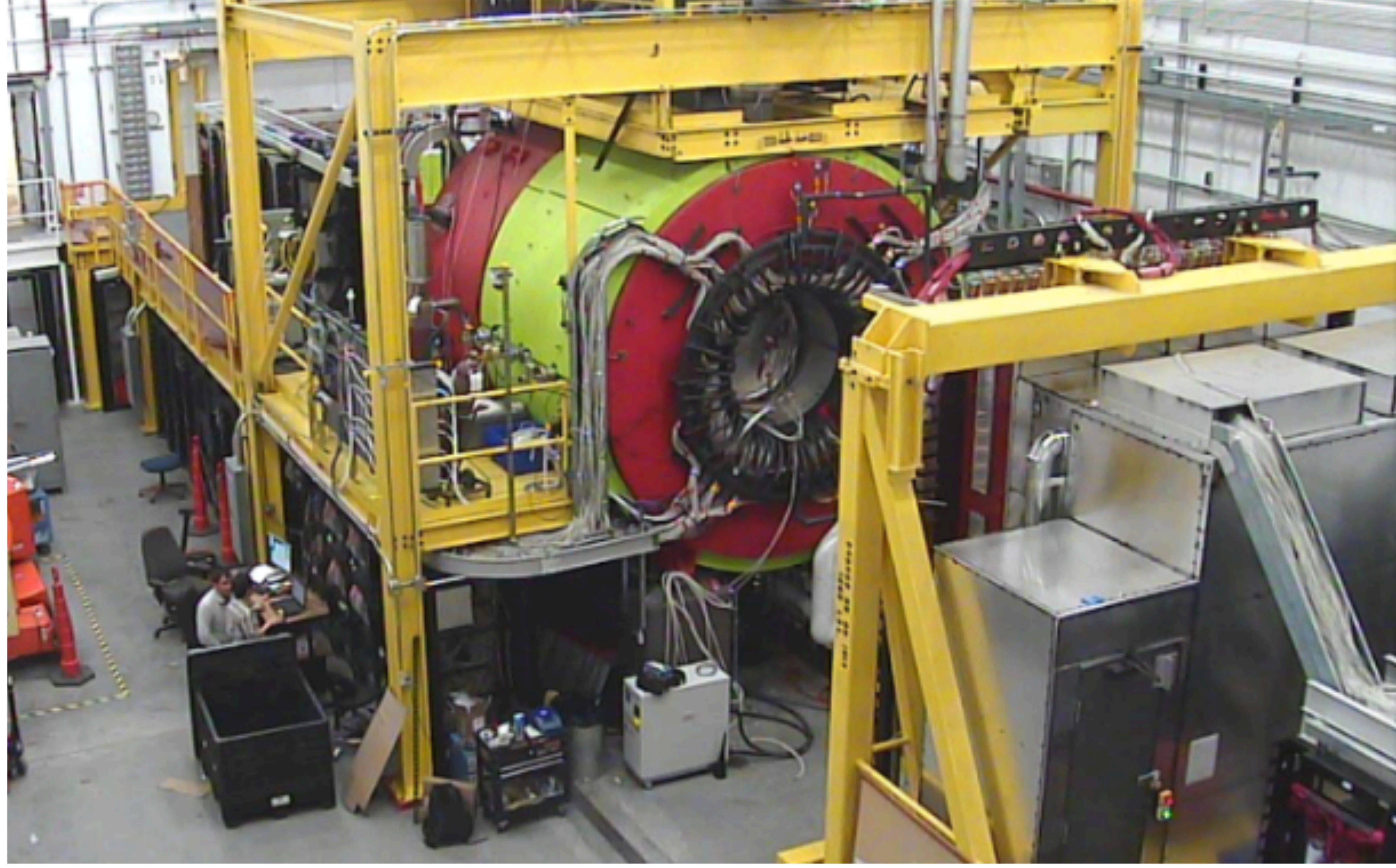
$$A_{FB} \equiv \frac{d\sigma(\theta^{e^-e^+\mathrm{cm}}) - d\sigma(\theta^{e^-e^+\mathrm{cm}} - 180°)}{d\sigma(\theta^{e^-e^+\mathrm{cm}}) + d\sigma(\theta^{e^-e^+\mathrm{cm}} - 180°)}$$

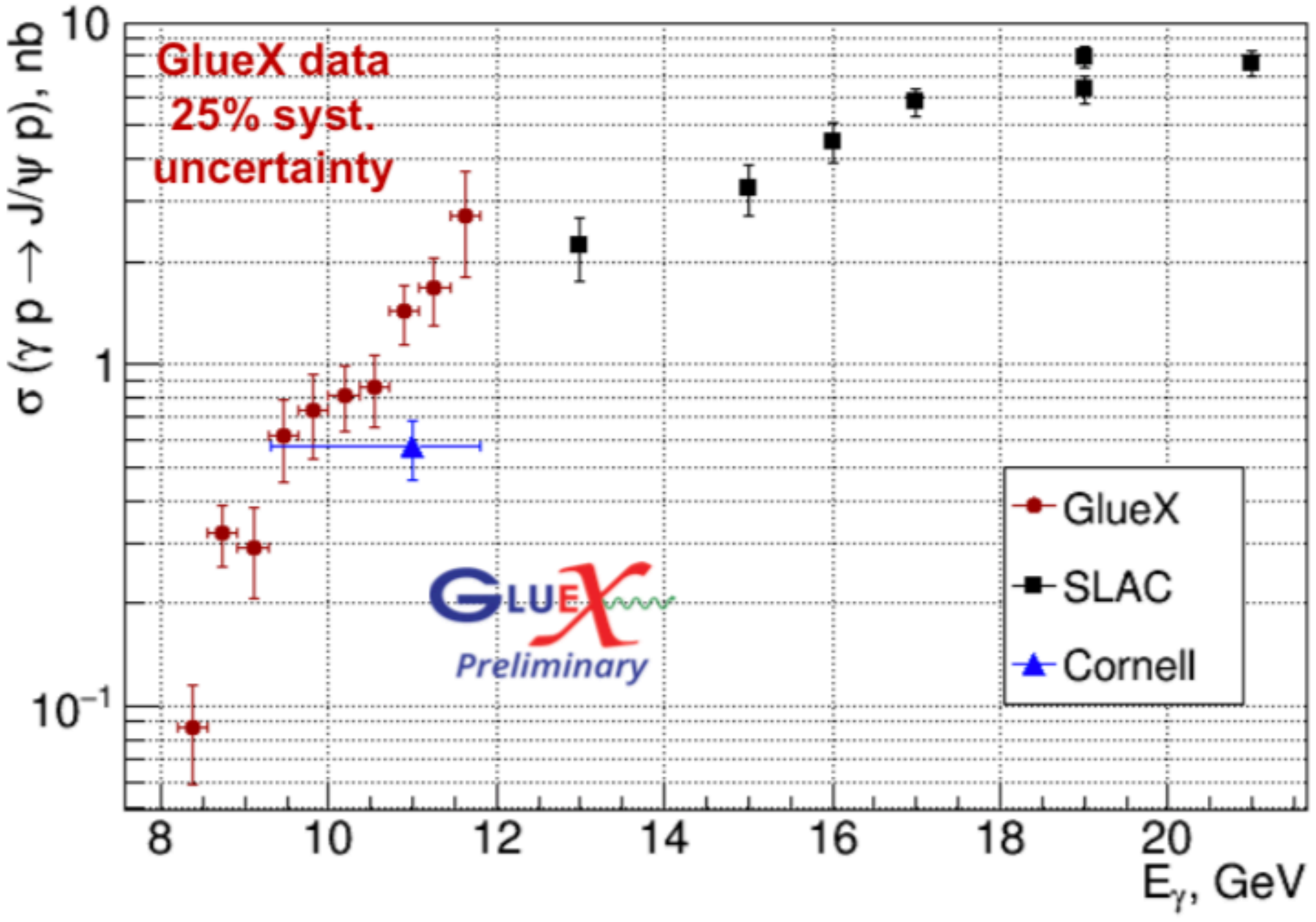
- Translates into left-right asymmetry that is experimentally better defined

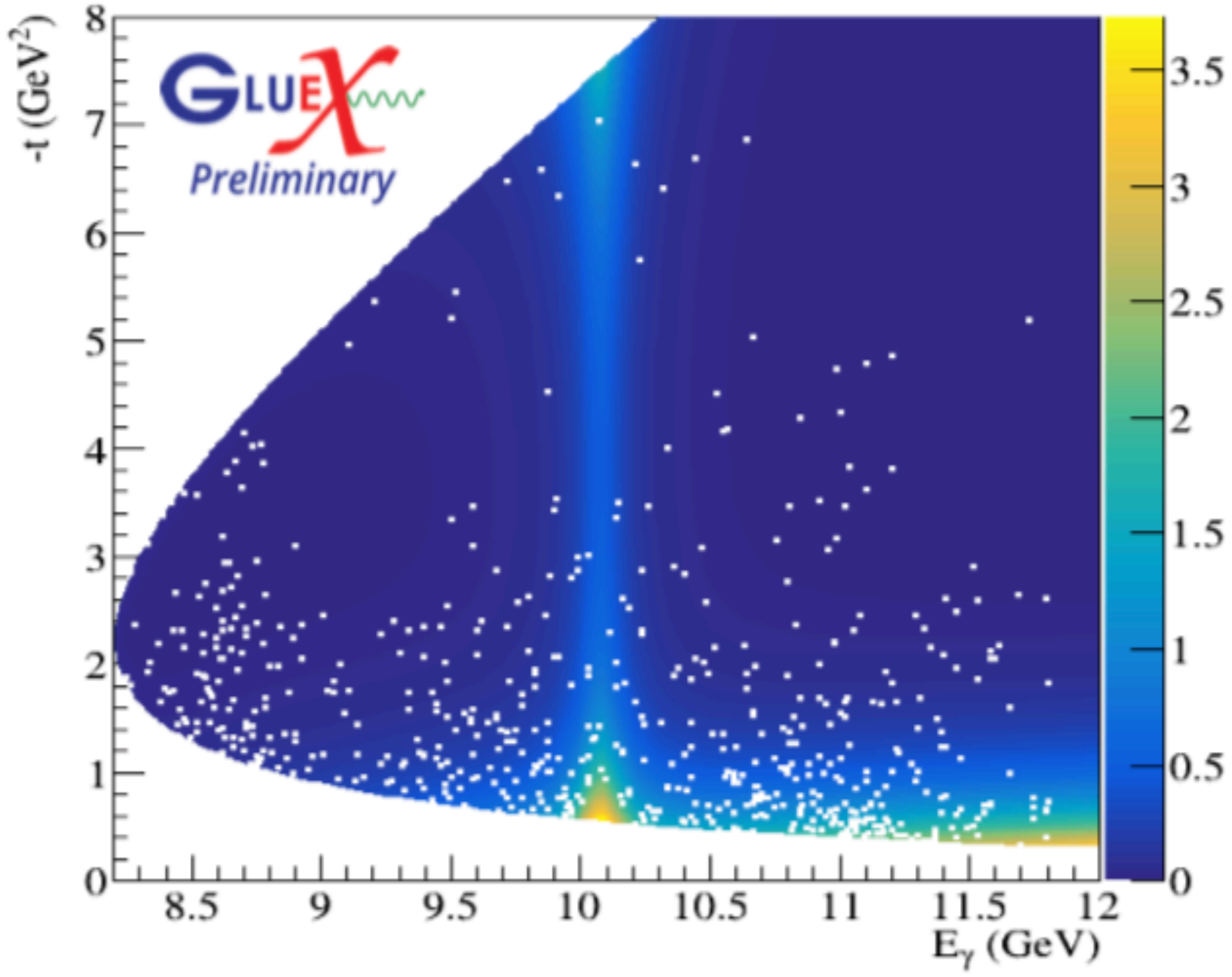
J/Ψ IN HALL D/GLUEX

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





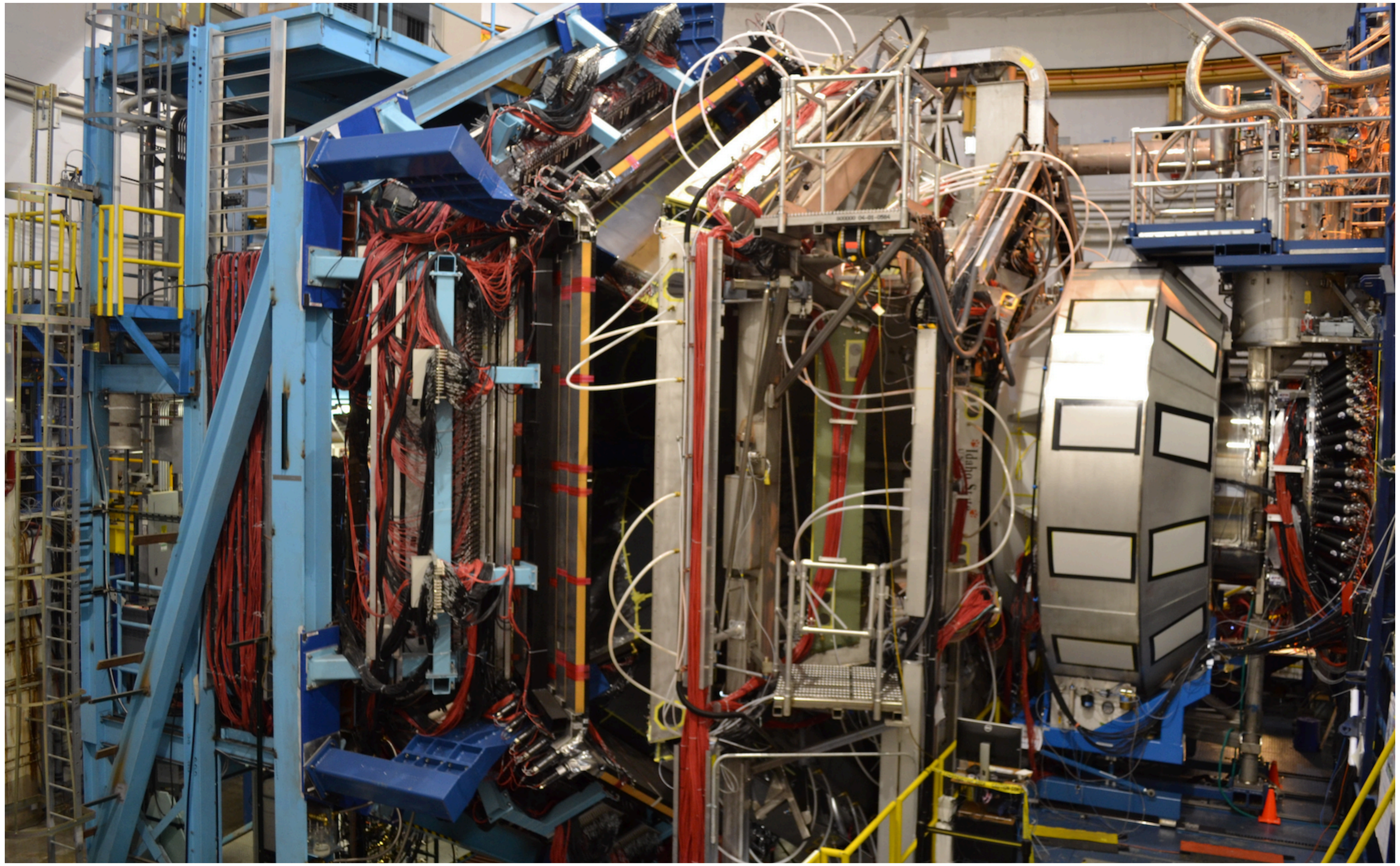


~20% background events

S. Joosten

J/Ψ IN HALL B/CLAS 12

OTHER J/ψ measurements at Jefferson Lab

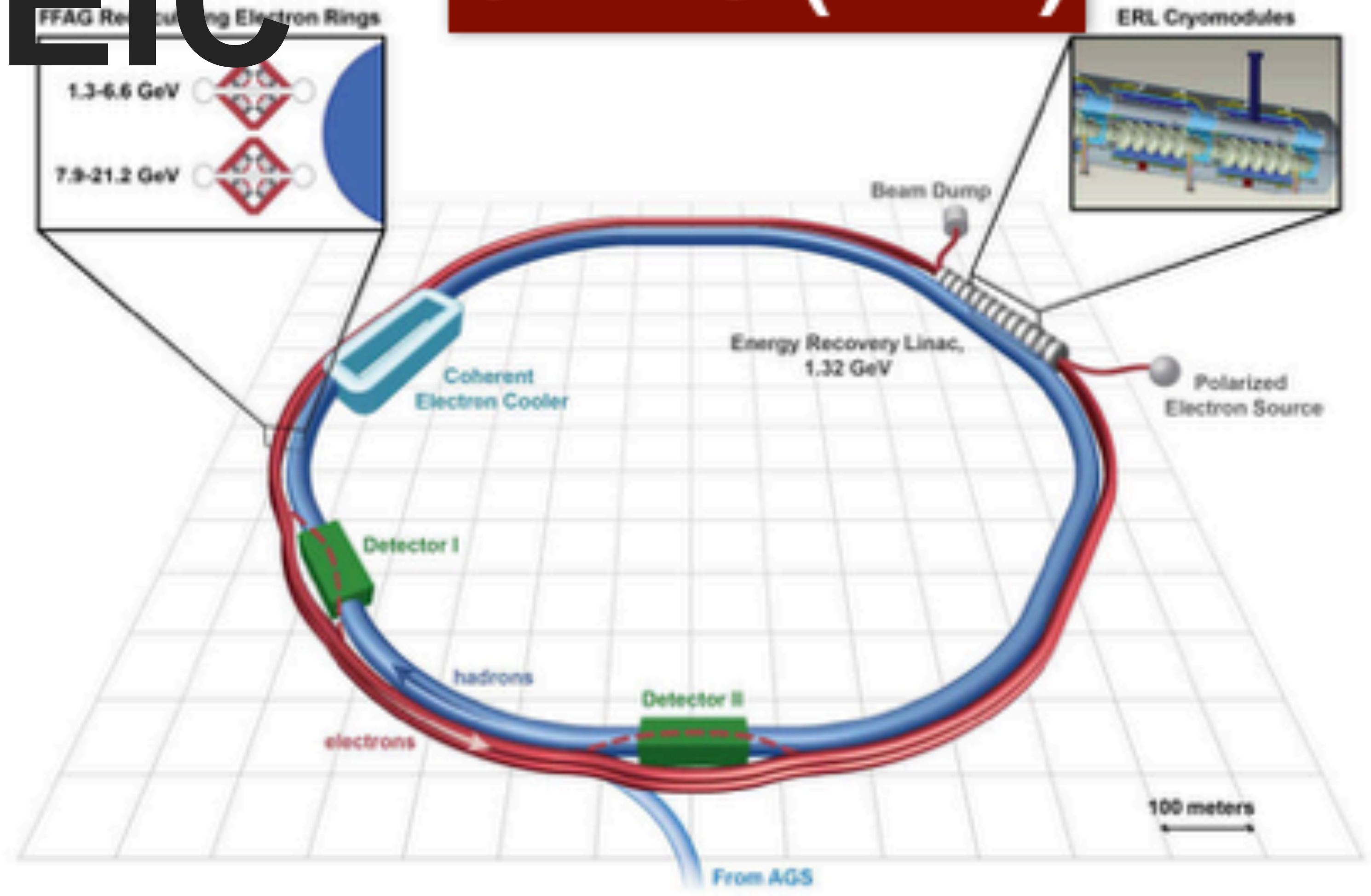


- Expected daily yield: 45J/ψ for 130 days
- First data taken in 2018 during run-group A
- Expect first results in ~1year

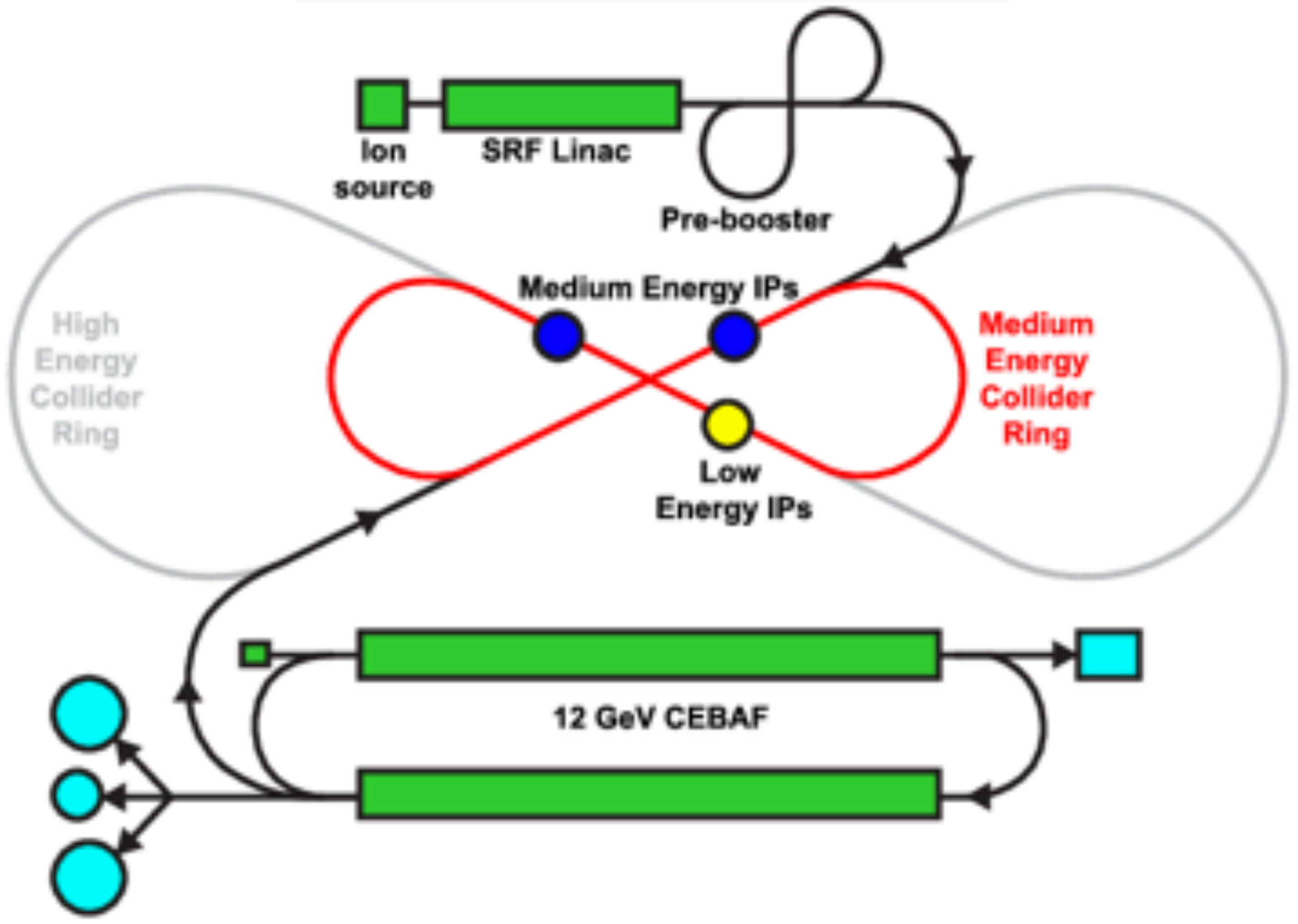
Y(1S) PHOTO-PRODUCTION AT EIC

- 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)

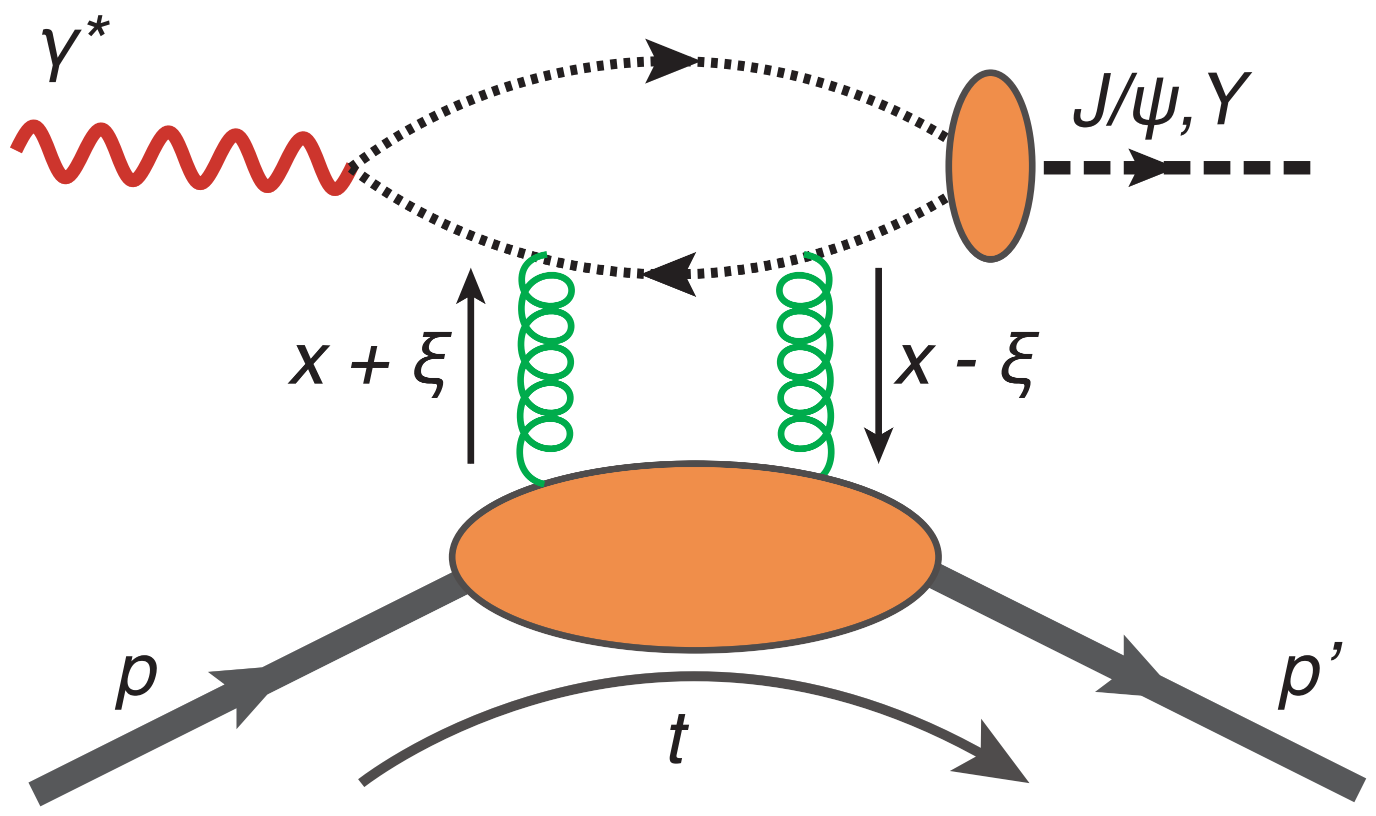


JLEIC (JLab)



DEEPLY-VIRTUAL QUARKONIUM PRODUCTION

Accessing the gluon GPD



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

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

Fourier transform:
transverse gluonic profile

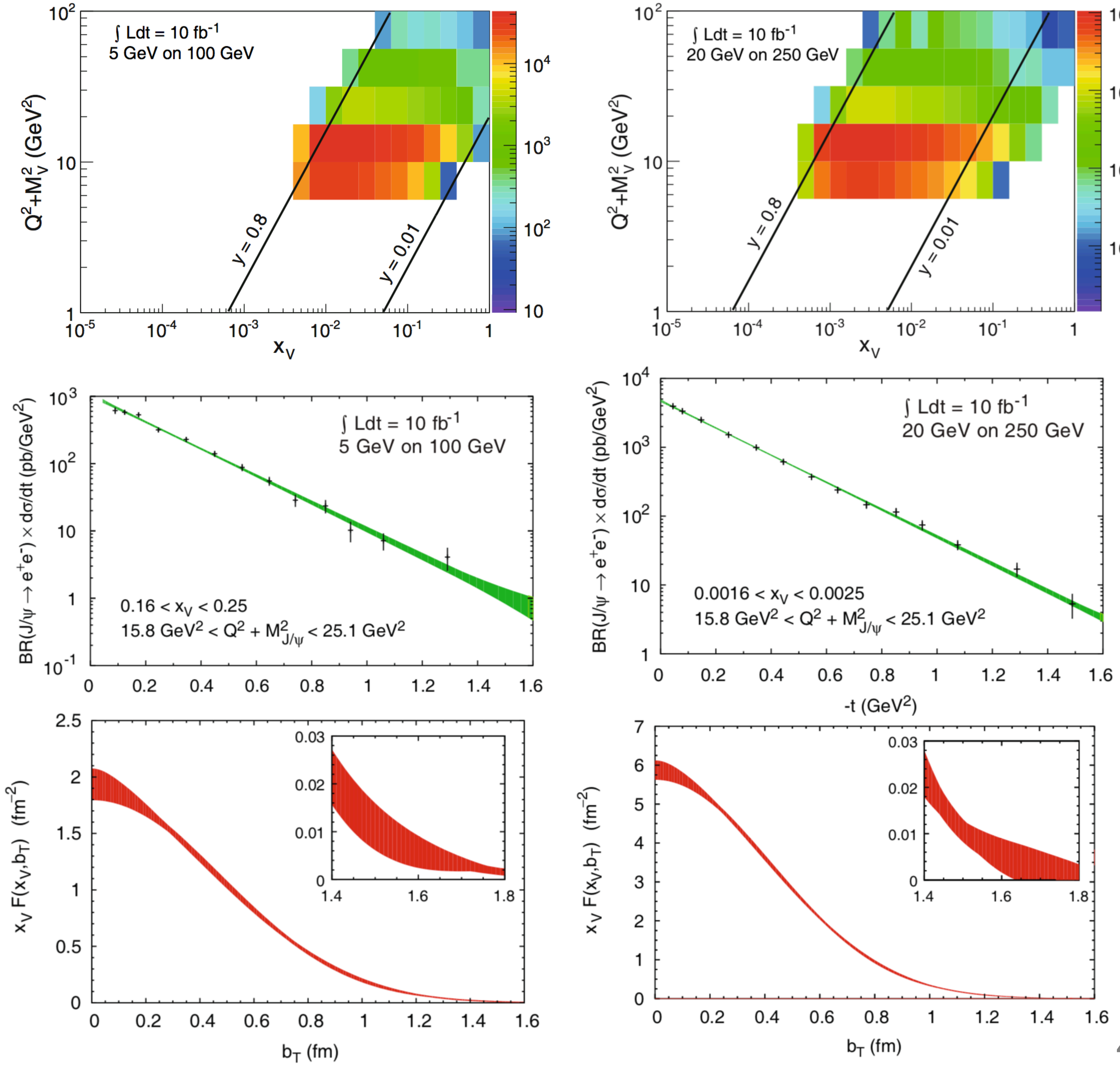
$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2 \vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

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

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

- 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*



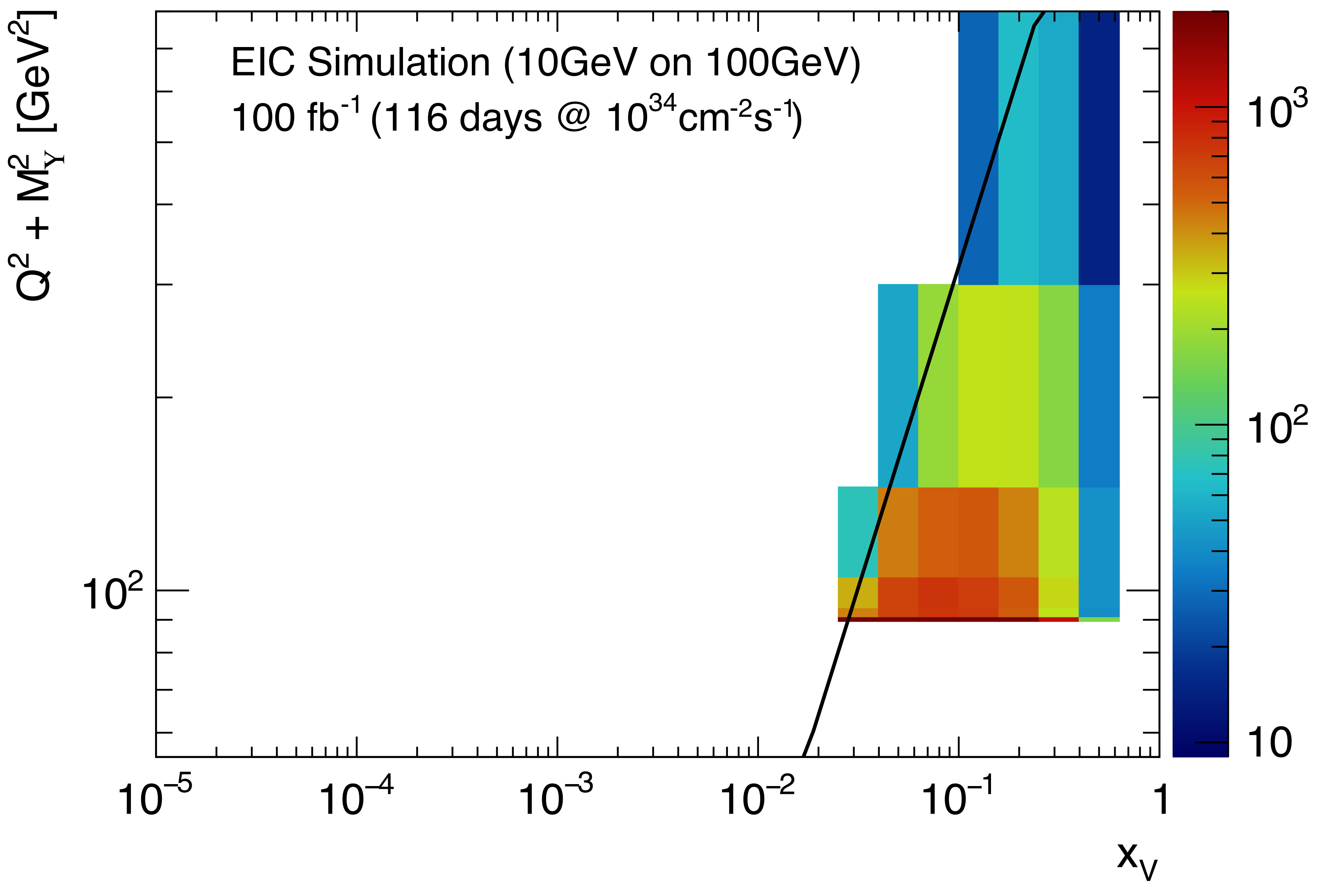
Only possible at an EIC:
from the valence region deep into the sea!

***t*-spectra**

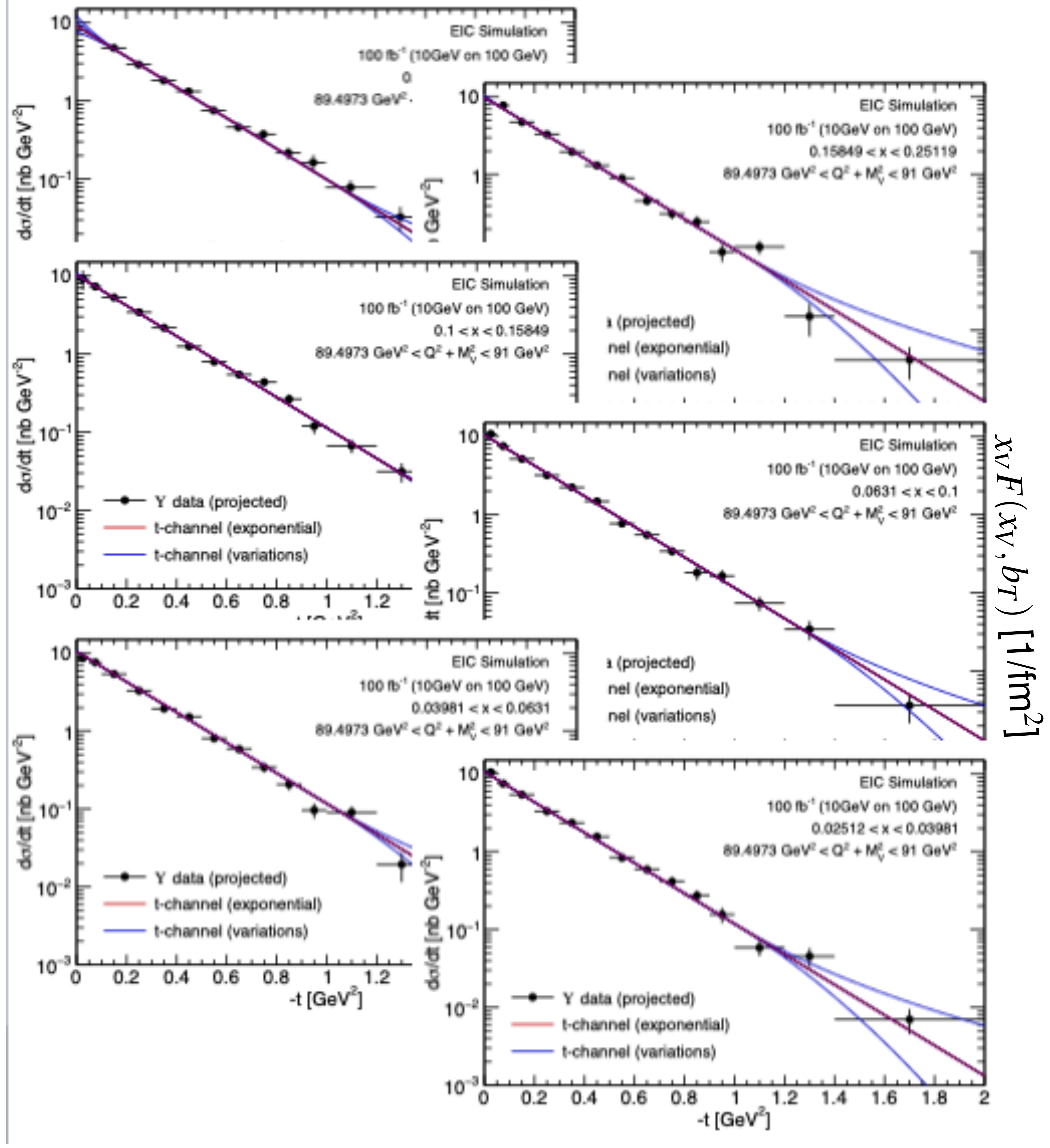
Normalized average gluon density

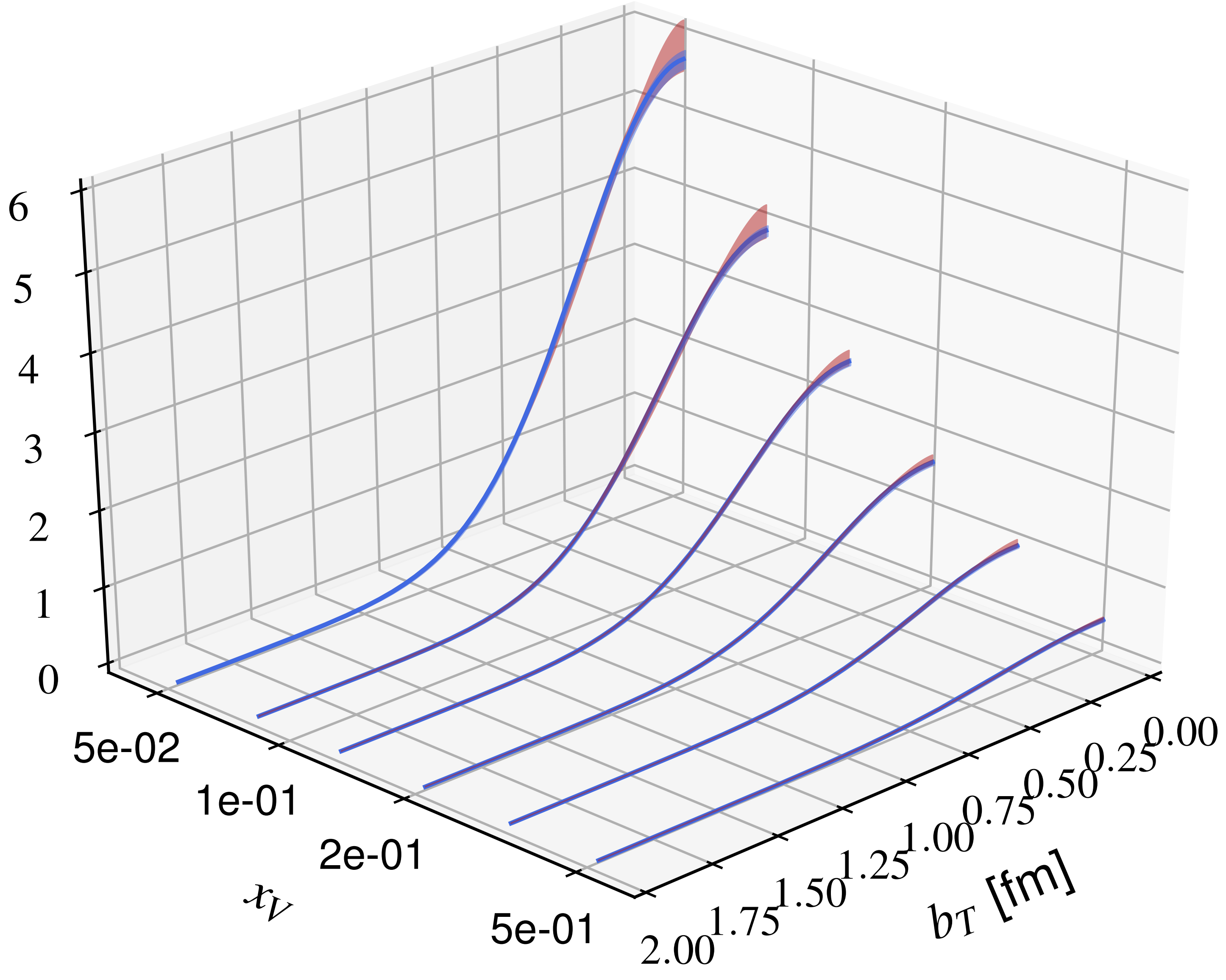
S. Joosten, Z.-E. Meziani, PoS QCDEV2017 017 (2018)
S. Joosten, arXiv:1803.08615 (2018)

GLUON TOMOGRAPHY WITH *Υ(1S)*



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

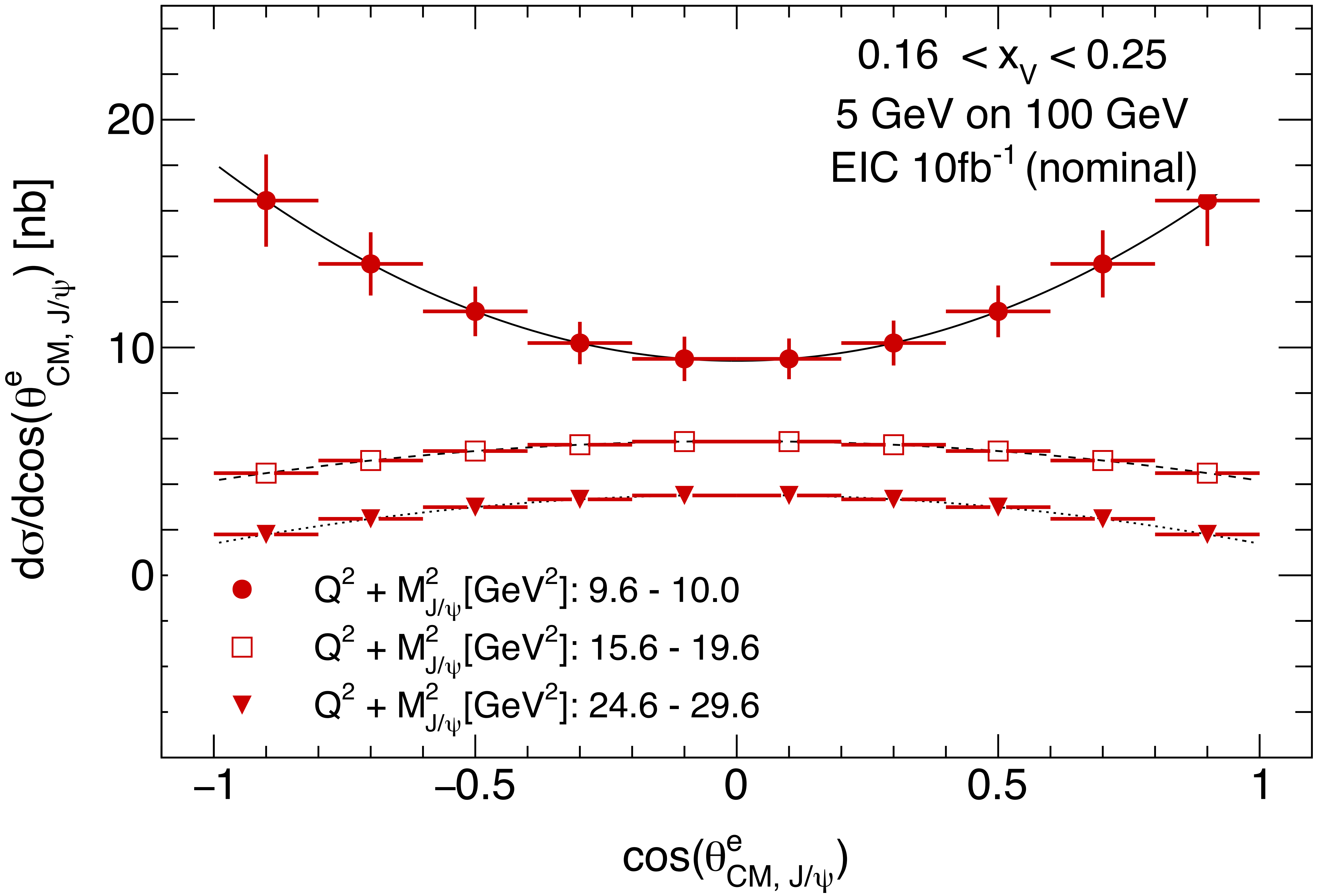




t-spectrum → Average gluon density

L-T SEPARATION AND Q^2 DEPENDENCE OF R

Using S-channel helicity conservation



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

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

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