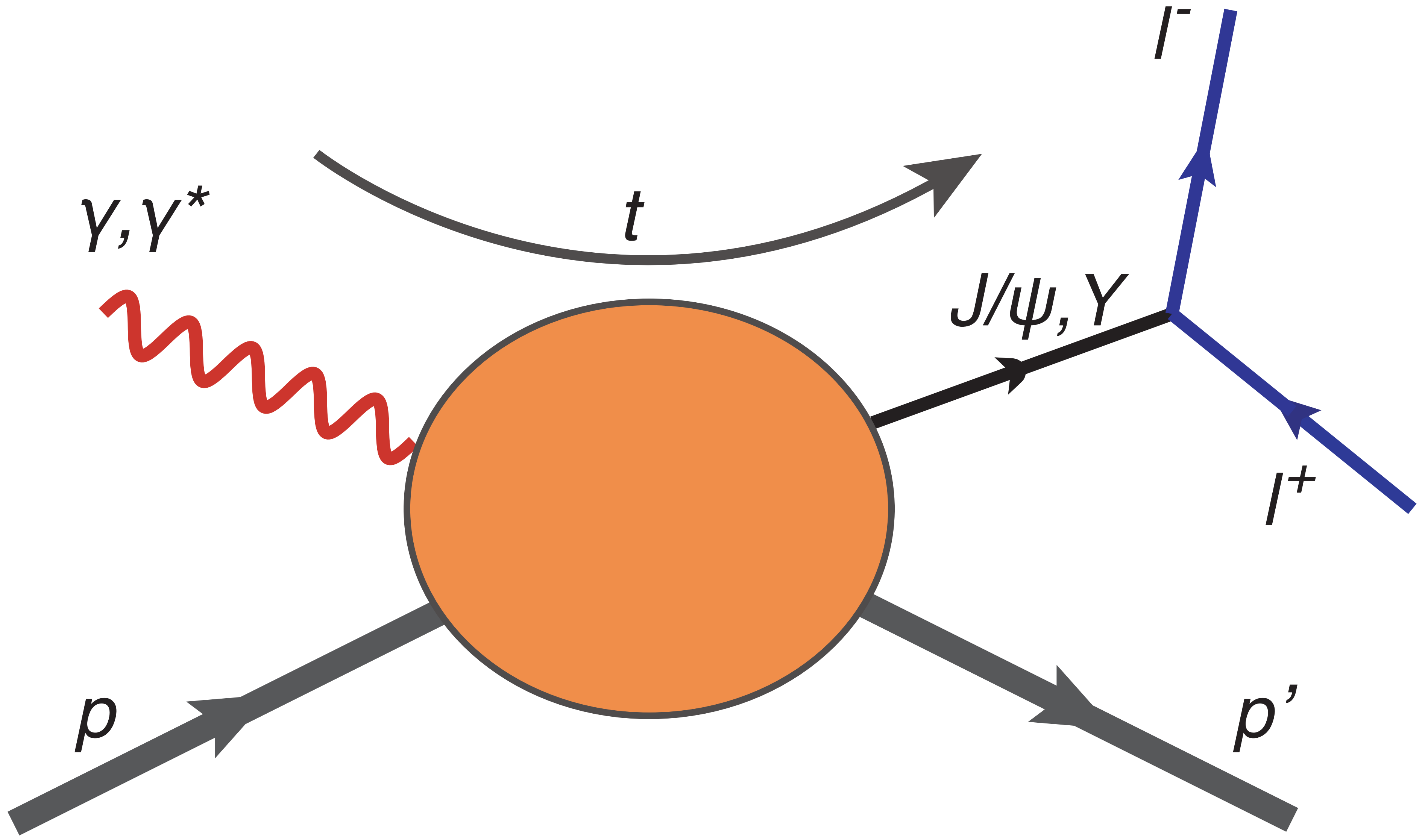
PROBING THE GLUONIC STRUCTURE OF THE NUCLEON AND NUCLEUS

QUARKONIUM PRODUCTION: FROM JLAB TO EIC



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U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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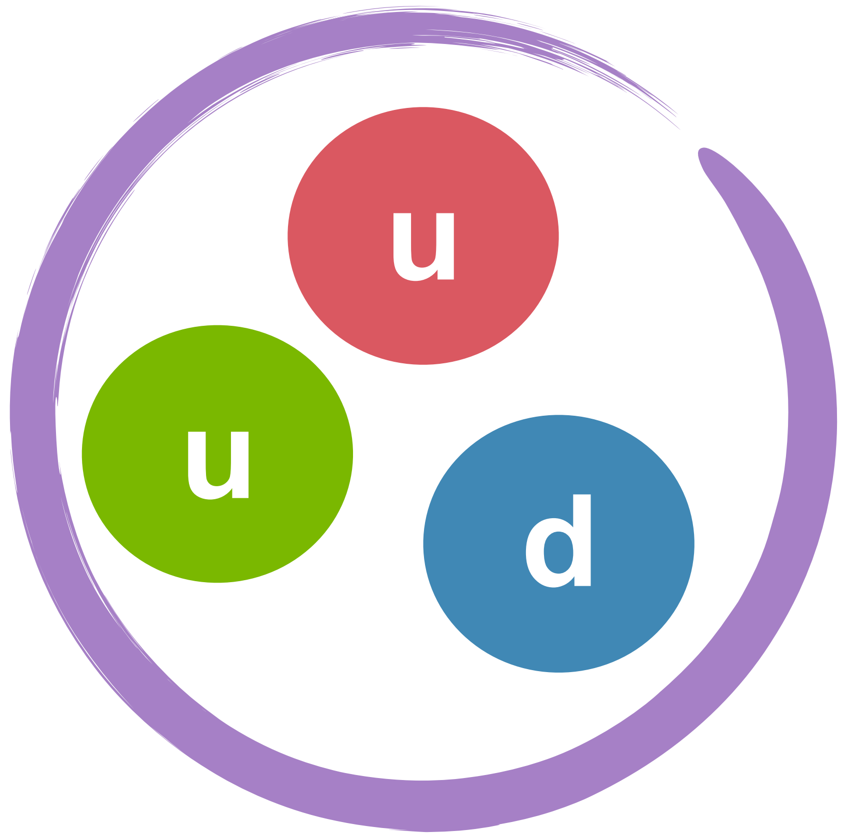
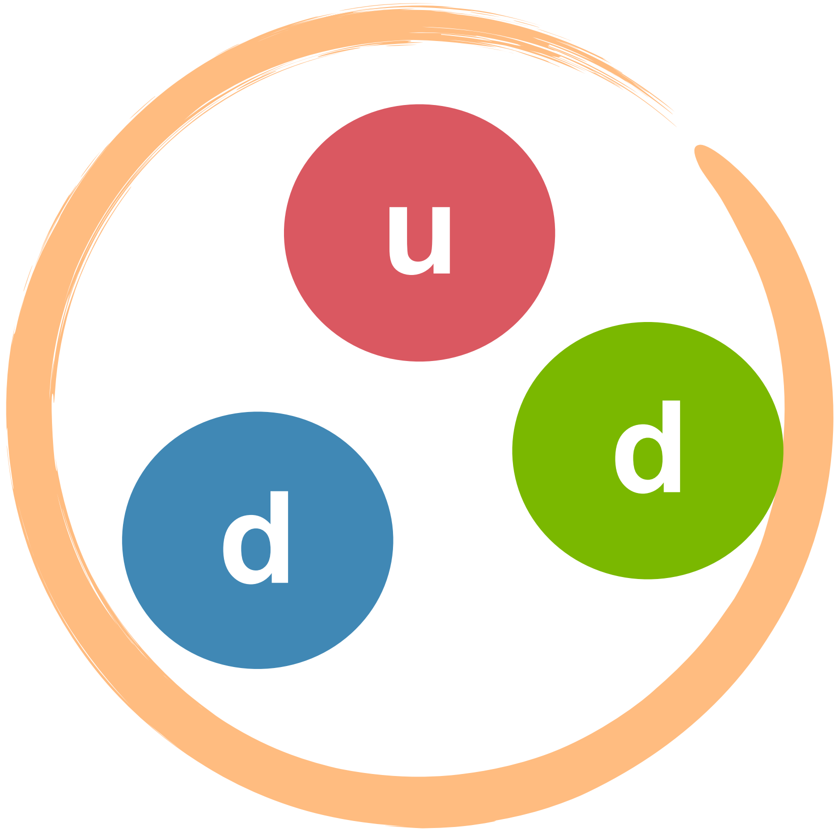
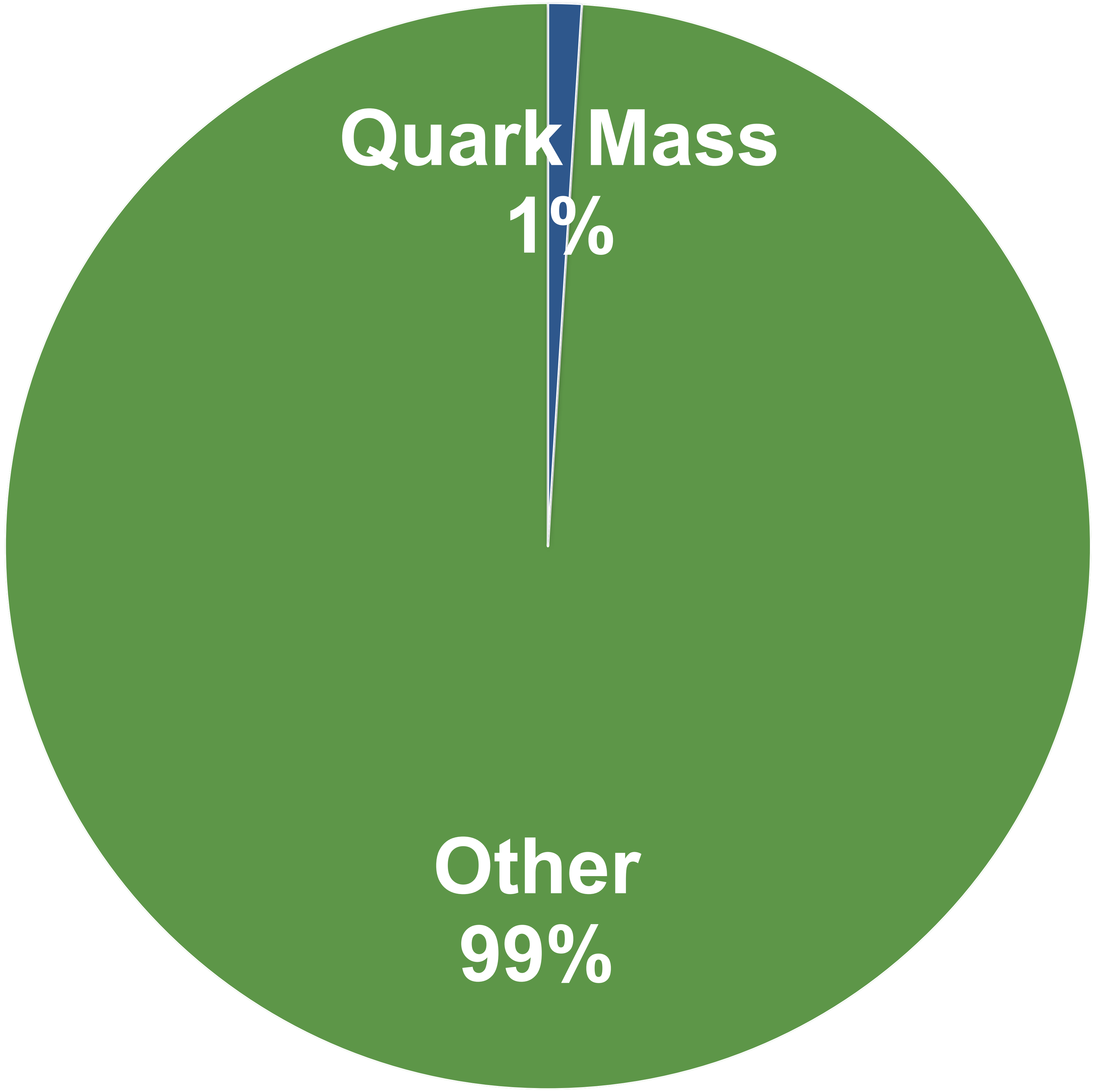
Exploring QCD with light nuclei at EIC Workshop, SBU, January 2020

THE NUCLEON IN QCD

99% of the mass of the visible universe

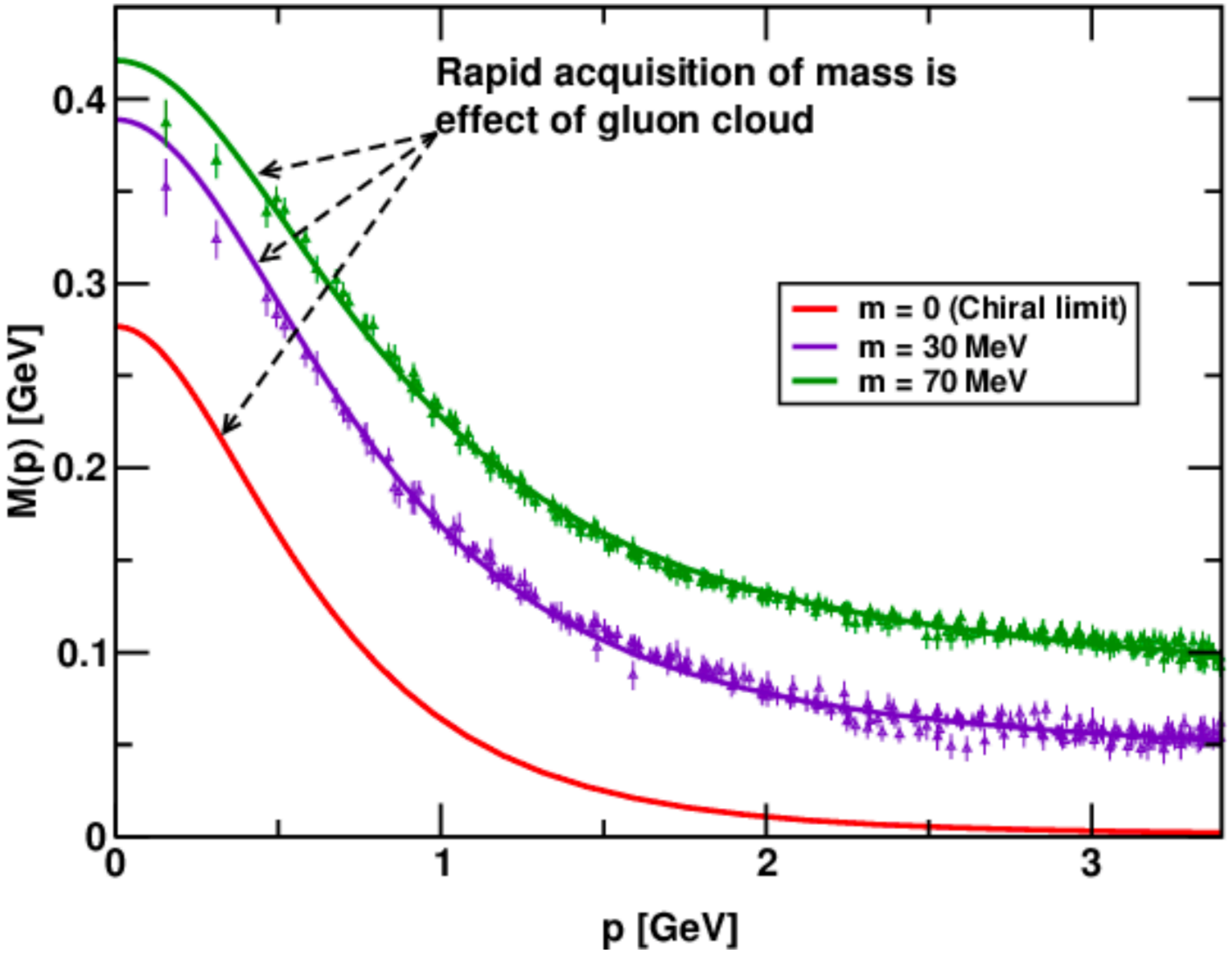






- Fundamental building blocks of matter
- Bound states of QCD Lagrangian
- Three **valence quarks** needed to define quantum numbers **contribute only ~1% of its mass**

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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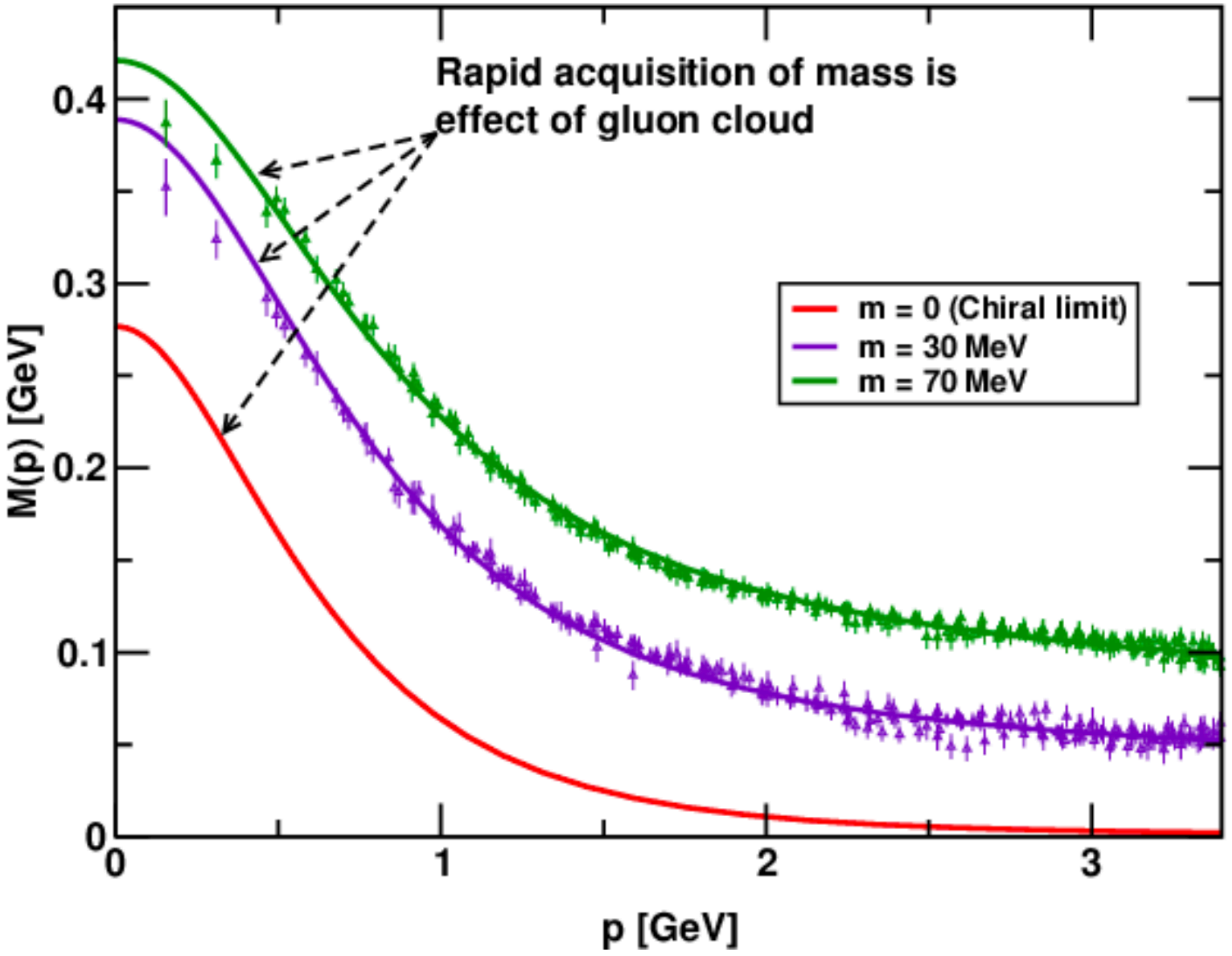

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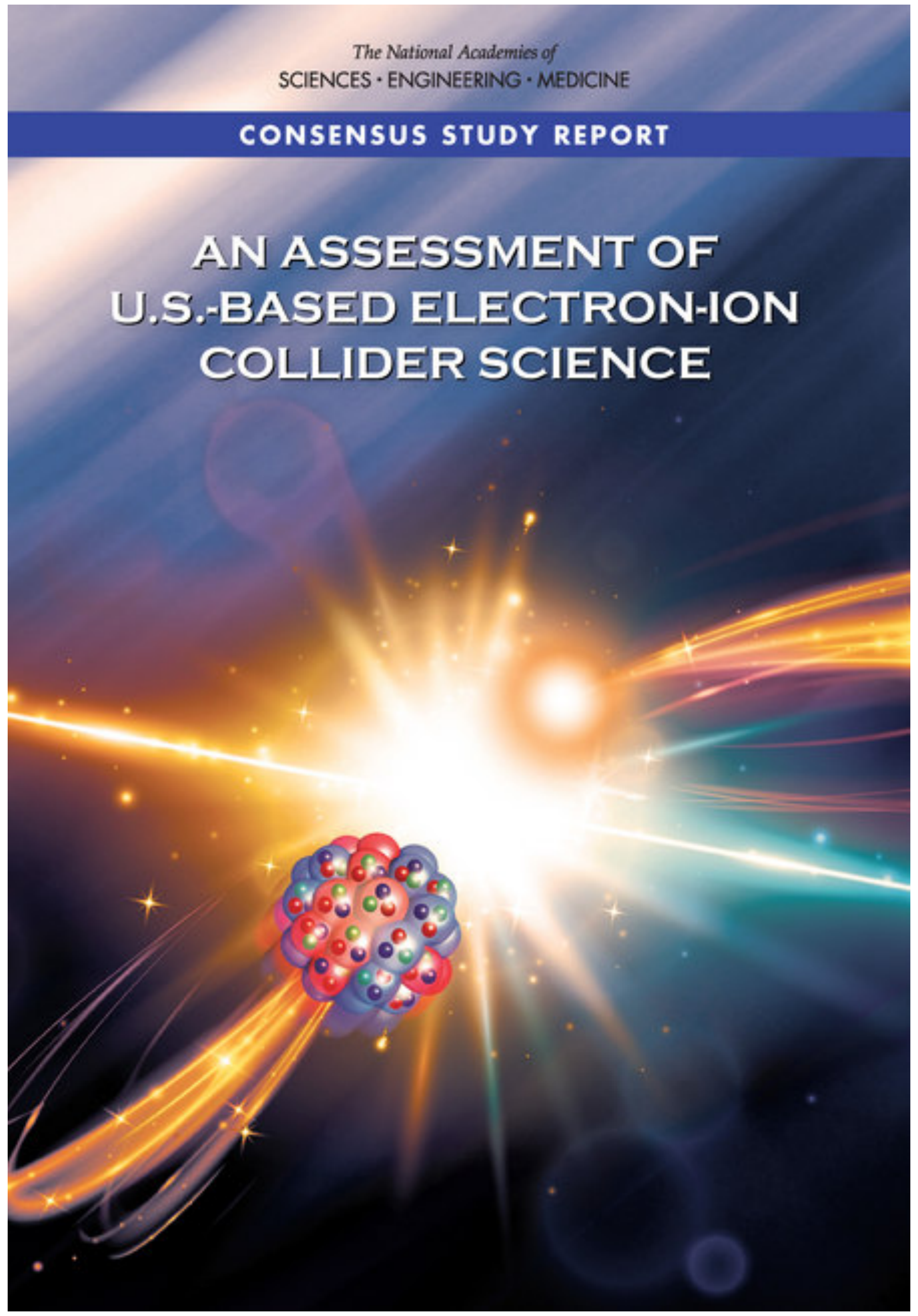
    mass from nothing!

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

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

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

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

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Trace Anomaly **Light Quark Mass**

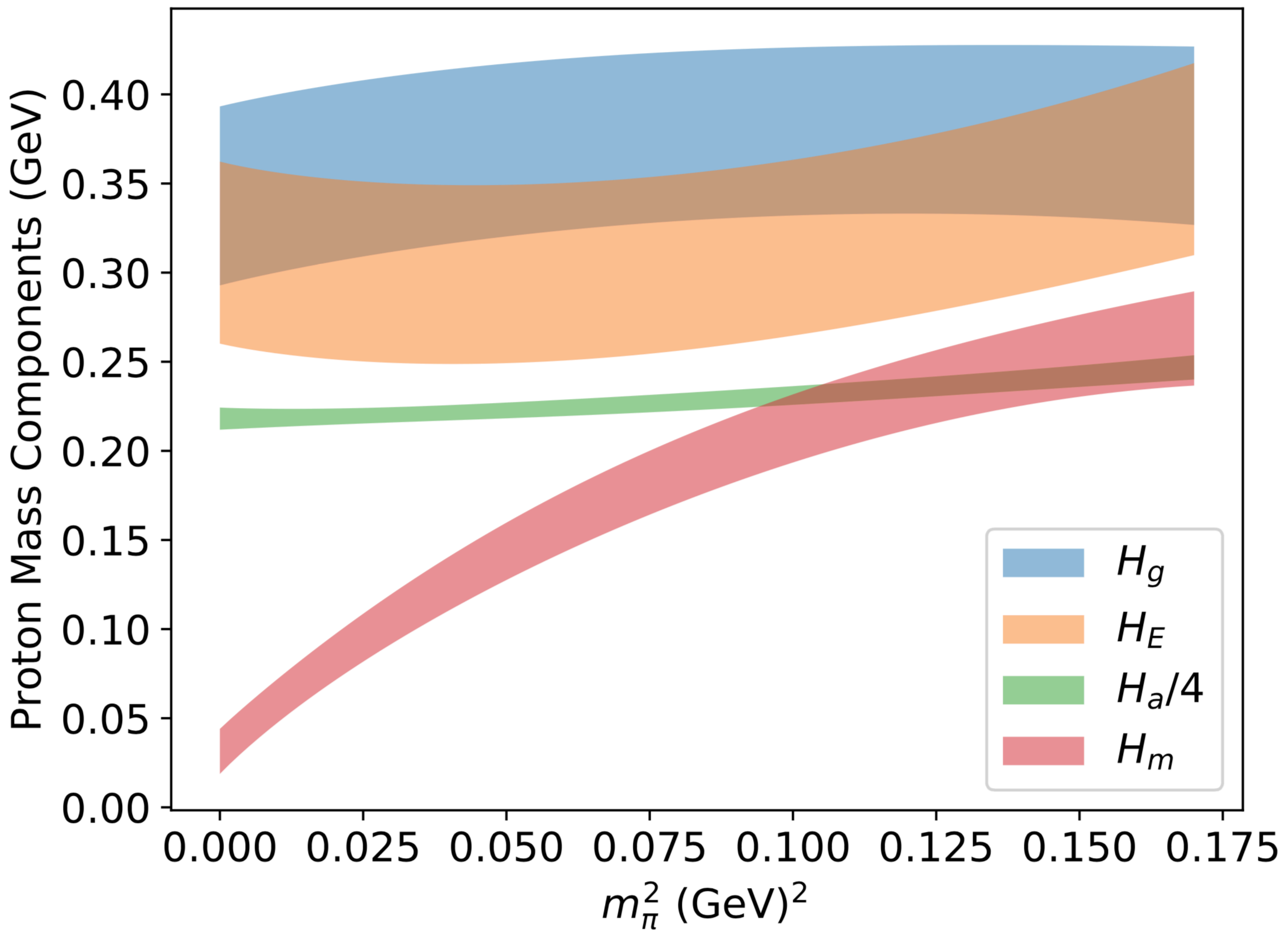
Trace anomaly dominant
"Proton mass result of the vacuum polarization induced by the presence of the proton."

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

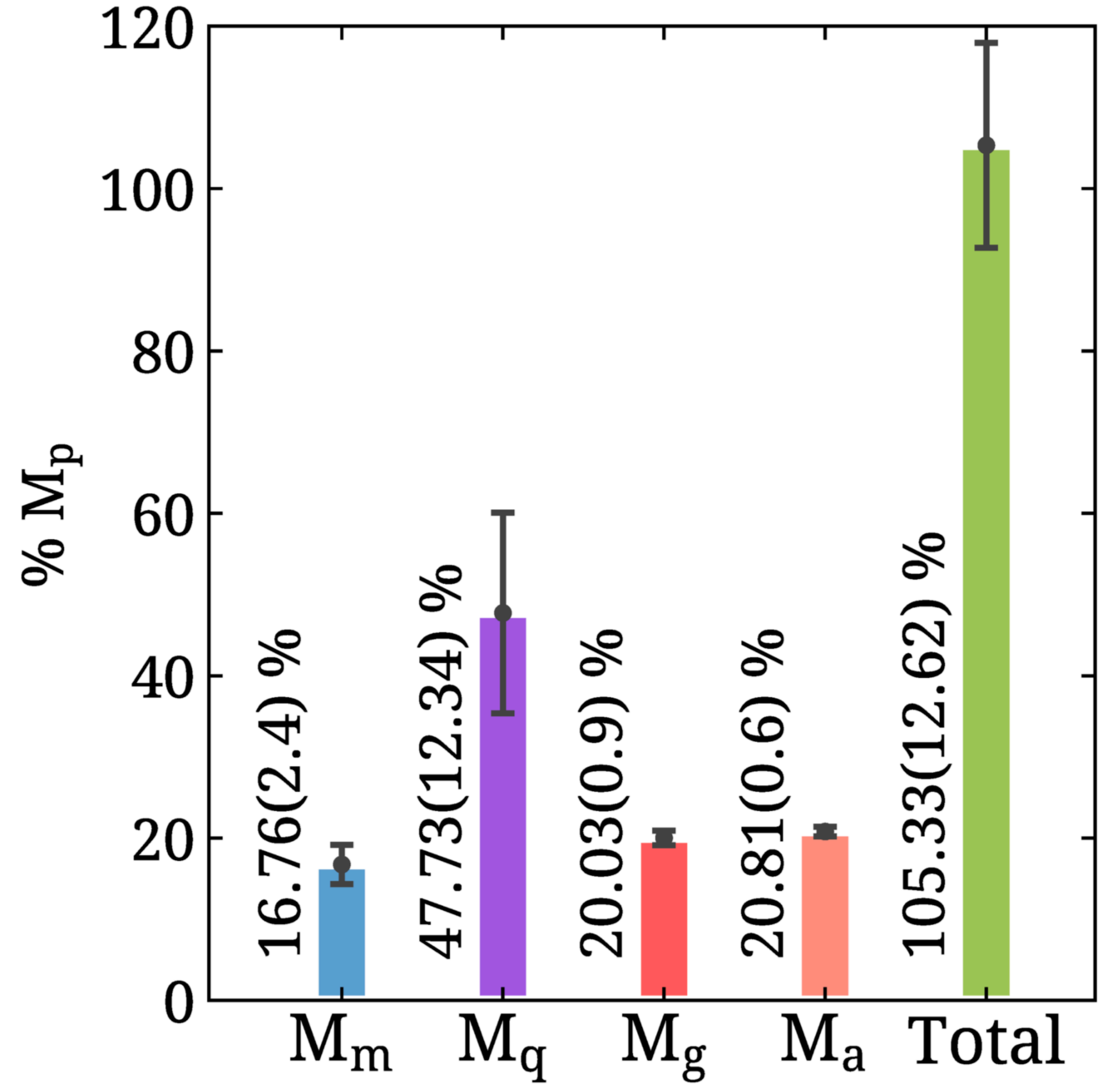
Trace anomaly intimately related to DCSB and the emergence of scale

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)
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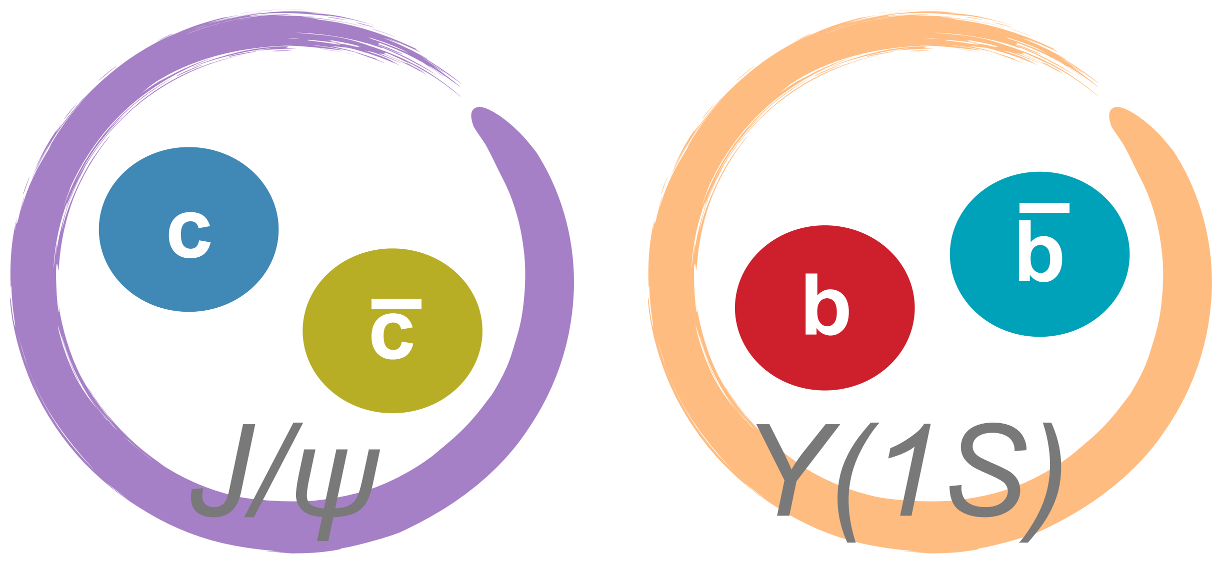
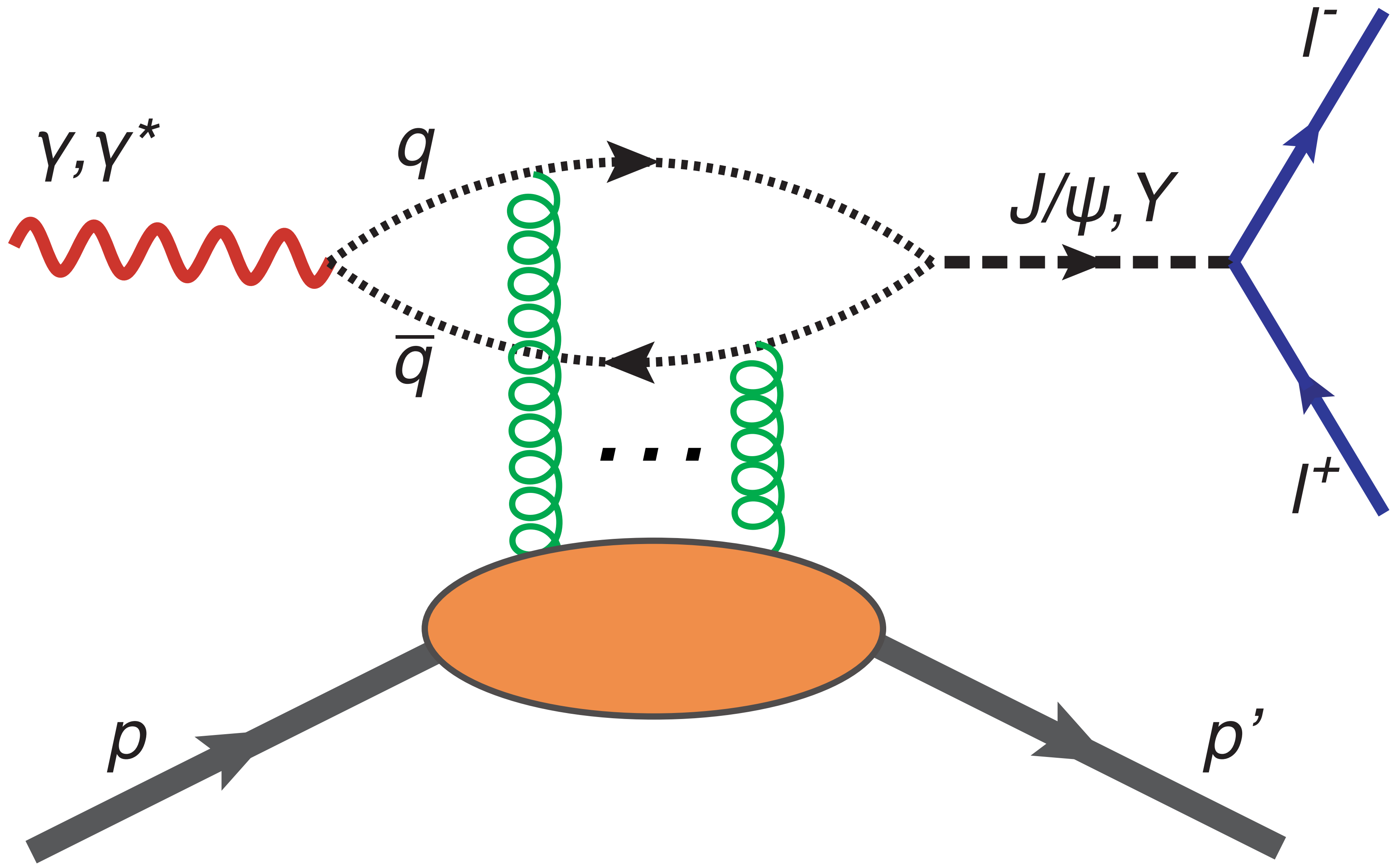
Trace anomaly only constrained through sum-rules

CAN WE MEASURE THE TRACE ANOMALY?

…Quarkonium production near threshold!





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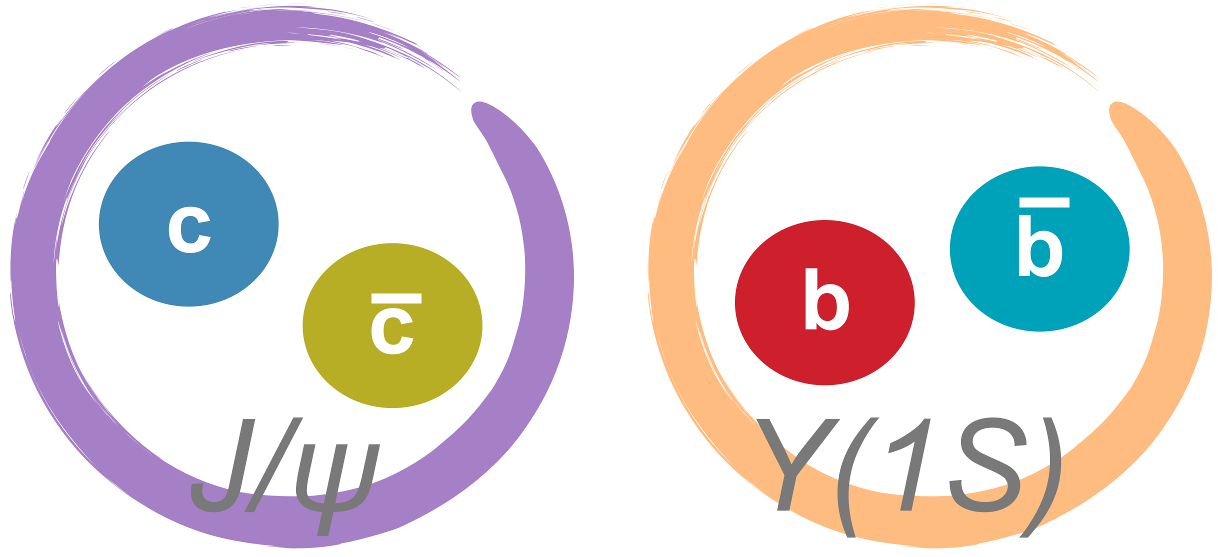
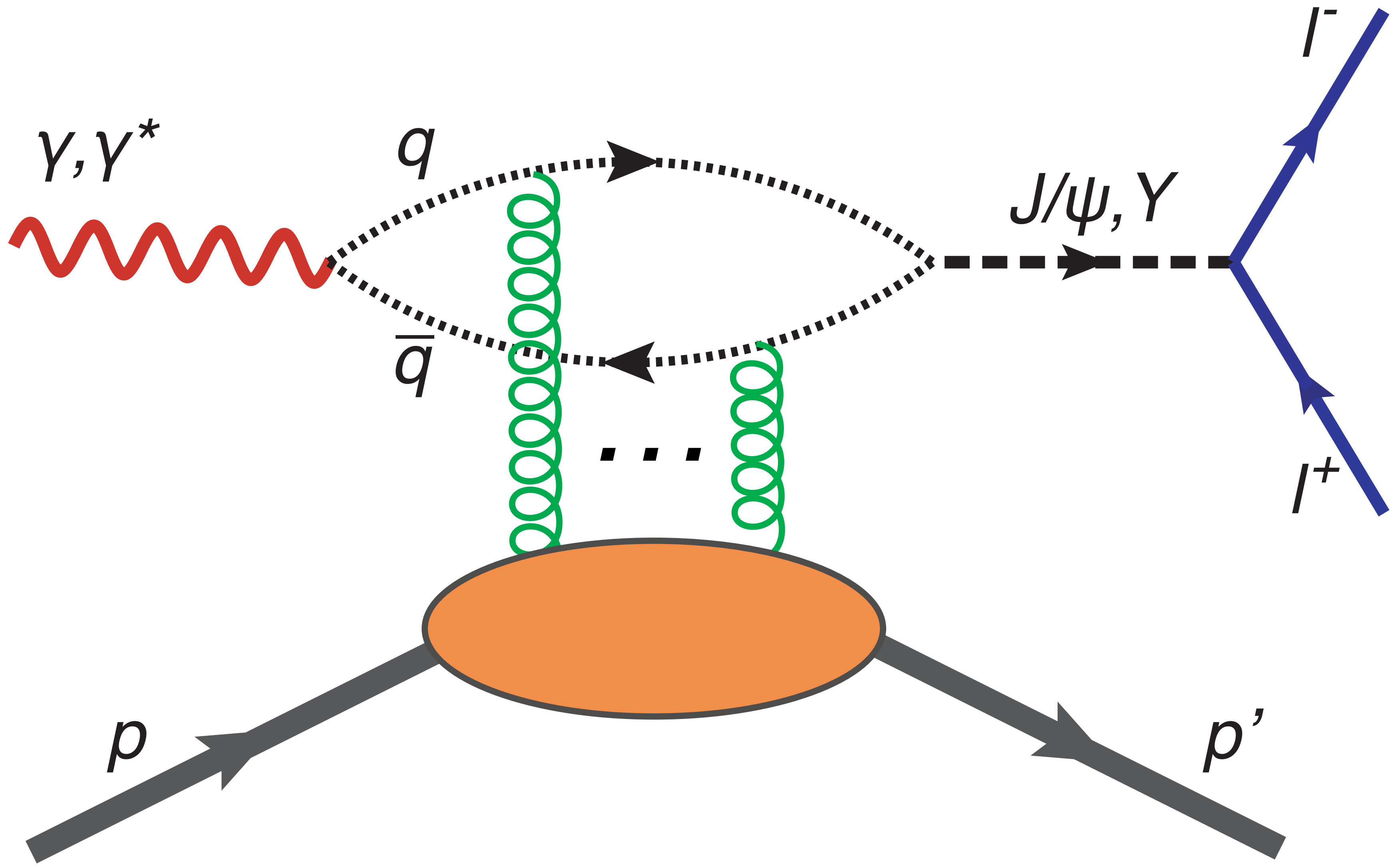


- *J/ψ* and *Y(1S)* only couple to gluons, not light quarks



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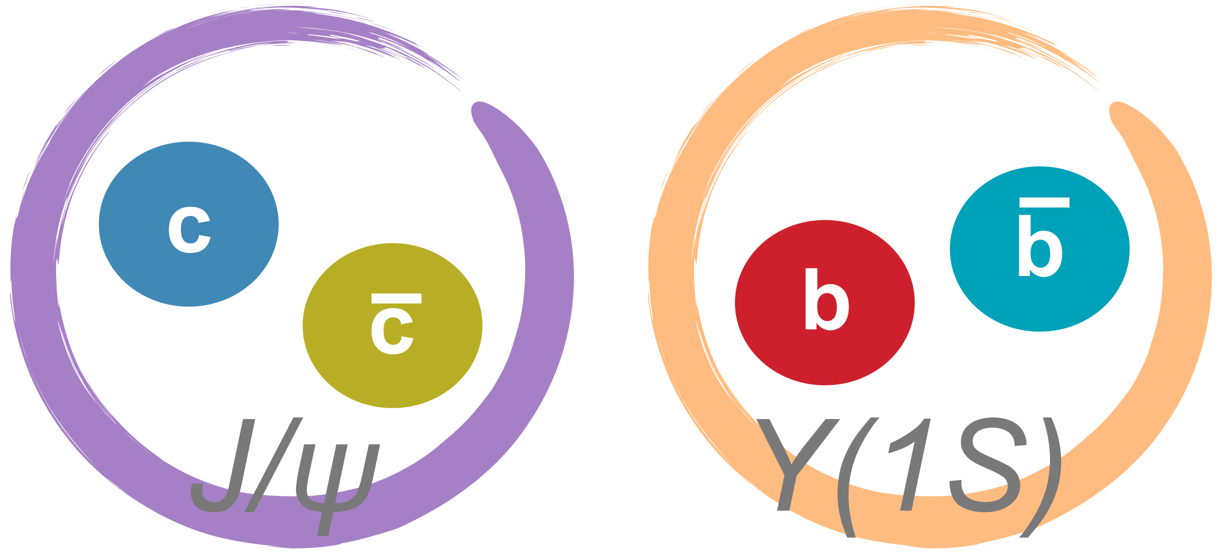
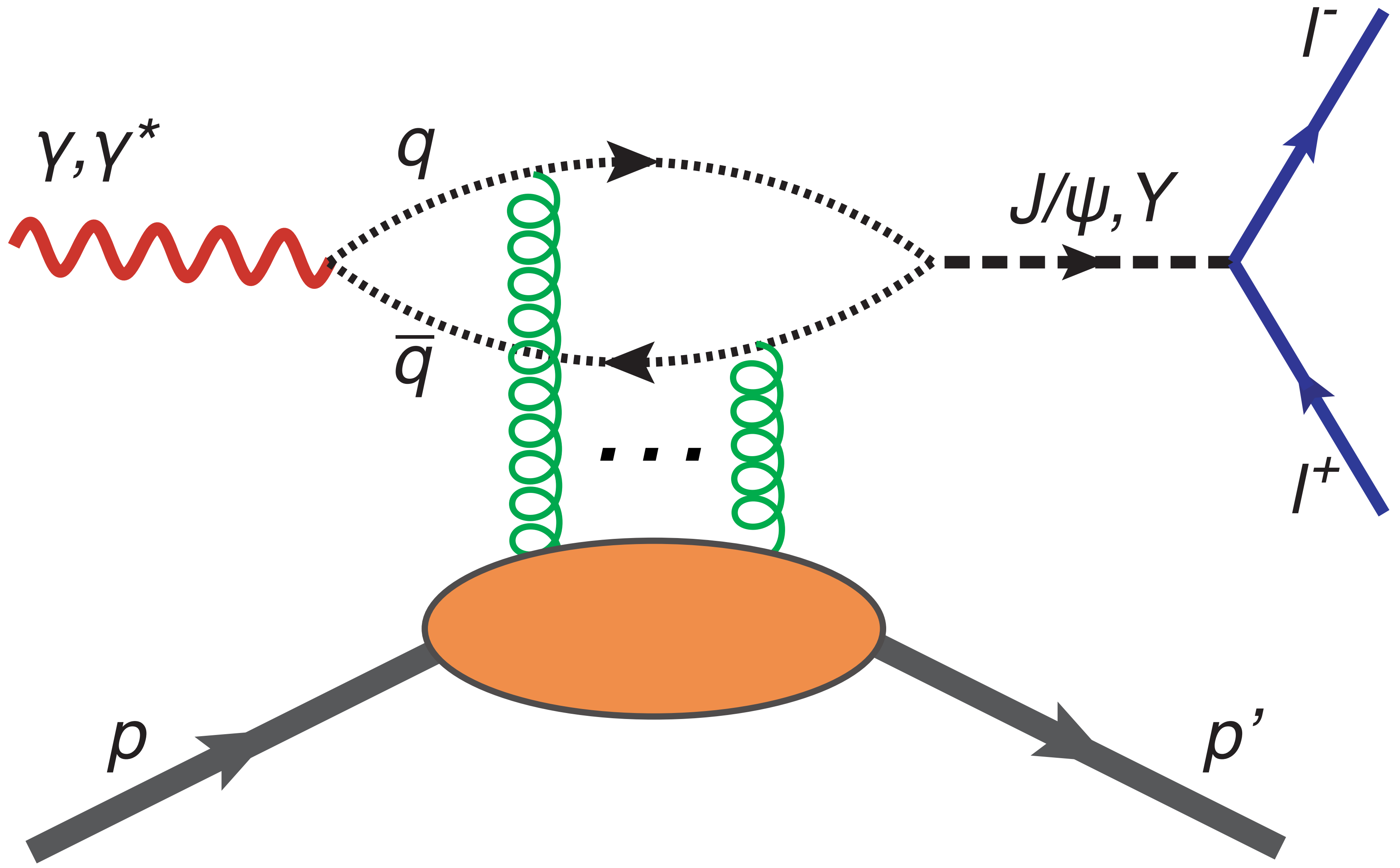


- *J/ψ* and *Υ(1S)* only couple to gluons, not light quarks
- Sensitive to gluonic structure of the proton



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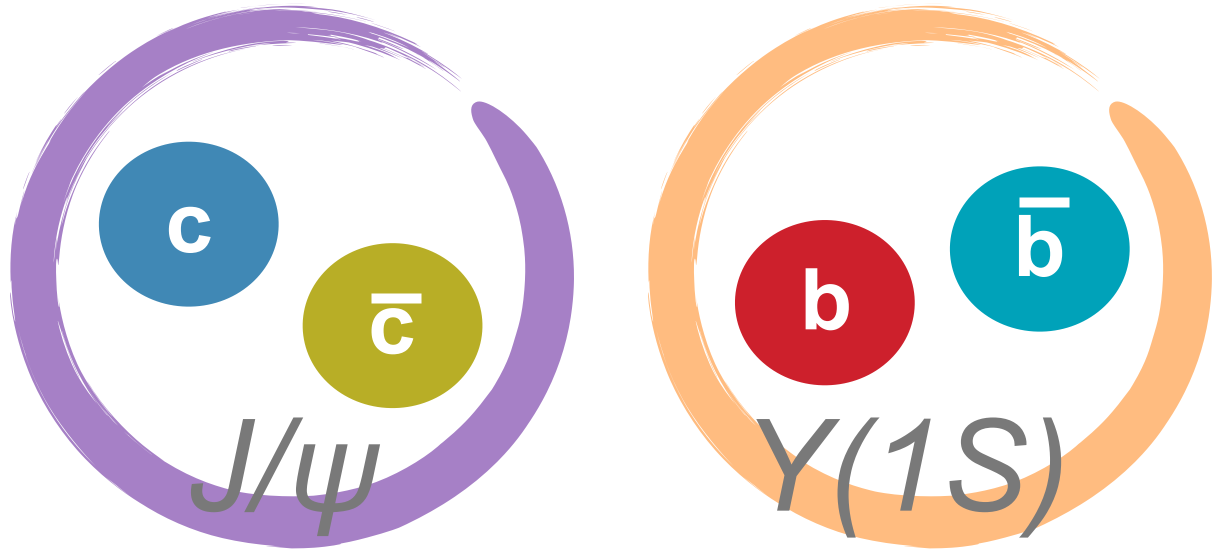
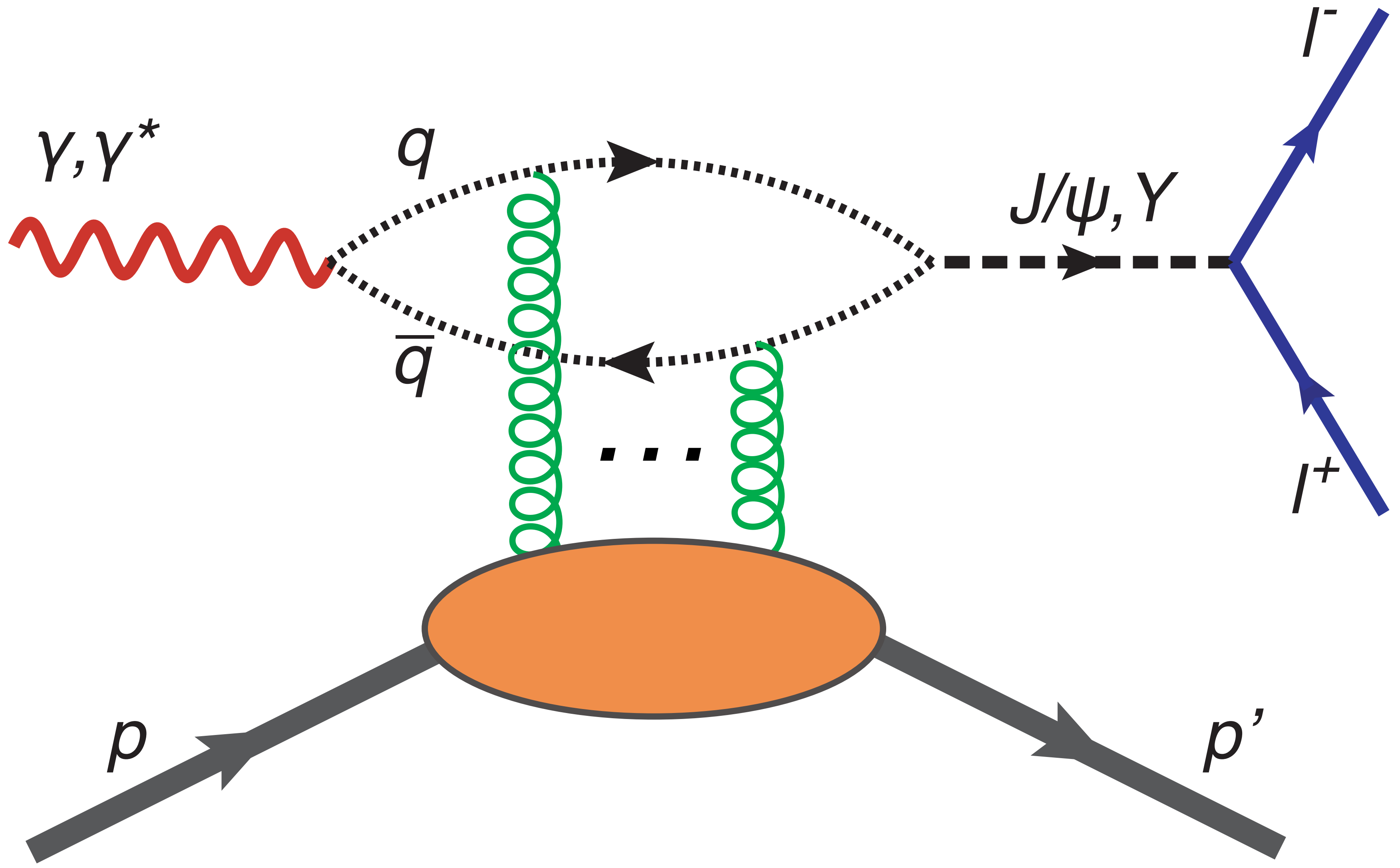


- J/ψ and $\Upsilon(1S)$ only couple to gluons, not light quarks
- Sensitive to gluonic structure of the proton
- Trace-anomaly operator twist-four:
  - Highly suppressed in high-energy scattering
  - QCD Factorization not yet established



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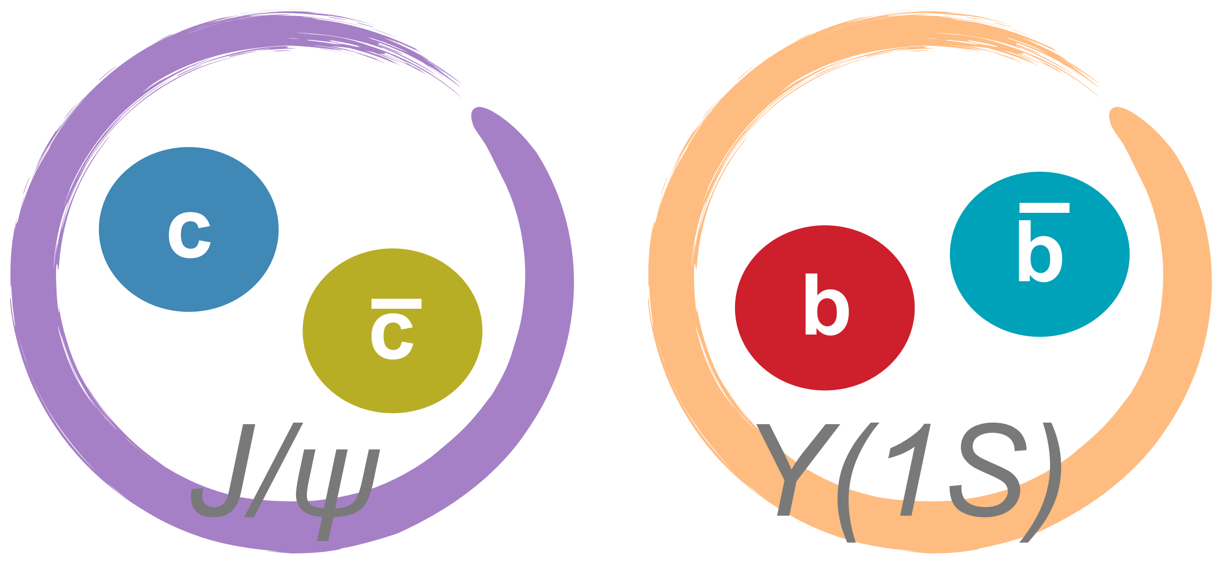
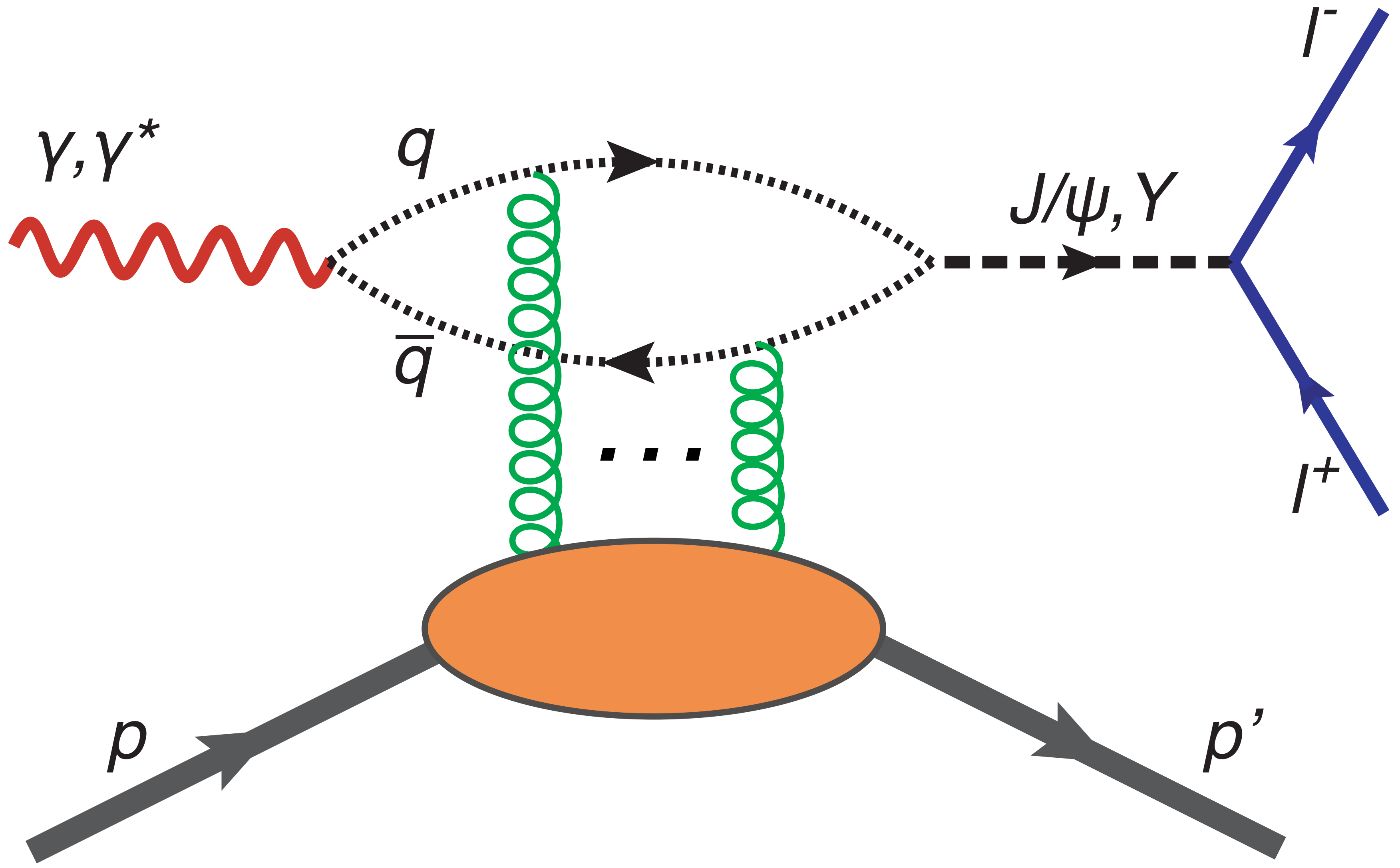
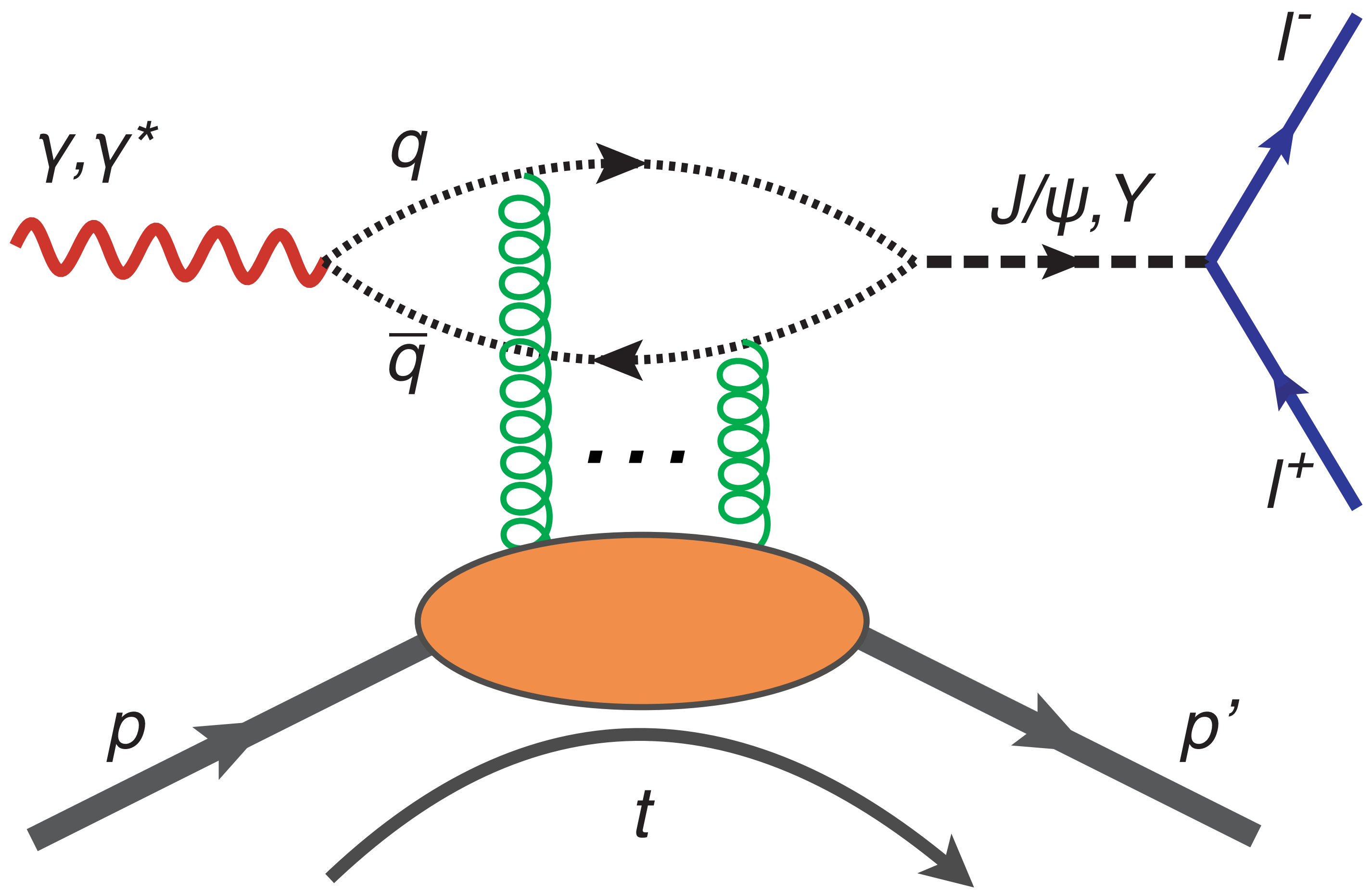


- *J/ψ* and *Y(1S)* only couple to gluons, not light quarks
- Sensitive to gluonic structure of the proton
- Trace-anomaly operator twist-four:
  - Highly suppressed in high-energy scattering
  - QCD Factorization not yet established
- Solution found in **low energy scattering** (production near threshold)



QUARKONIUM PHOTO-PRODUCTION

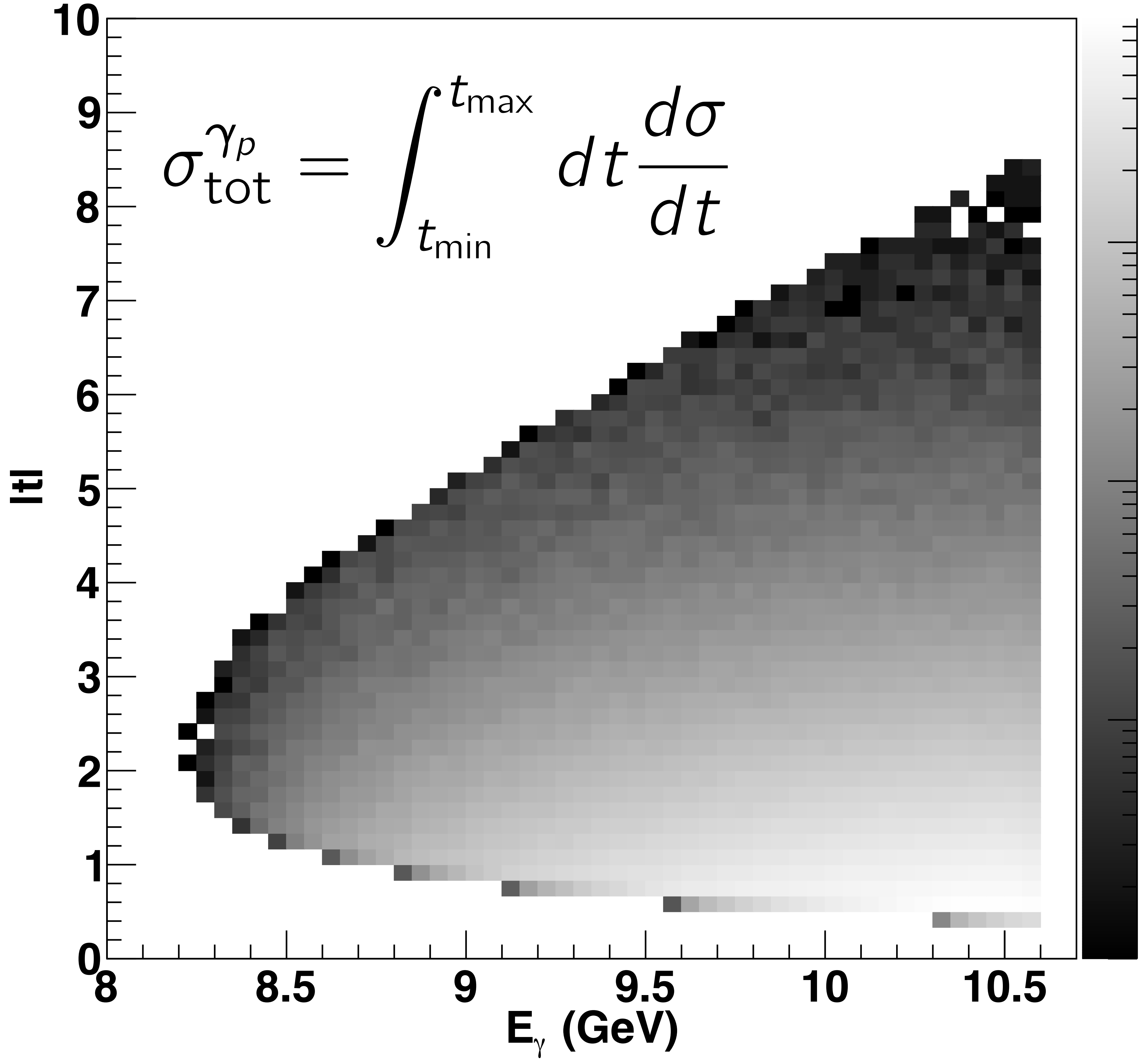
The basics



Υ(1S) threshold:

$W \approx 10.4\text{GeV}$

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



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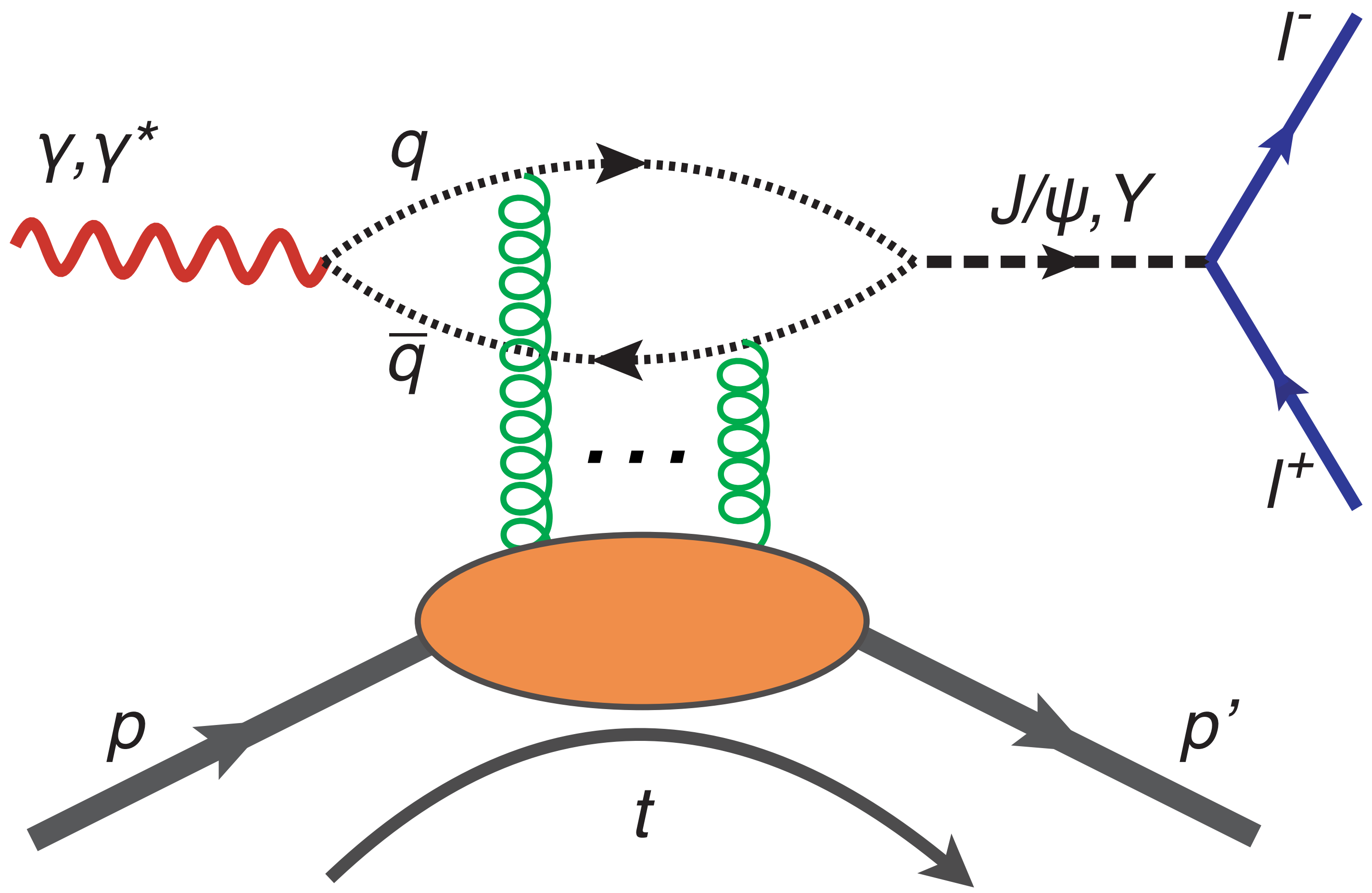

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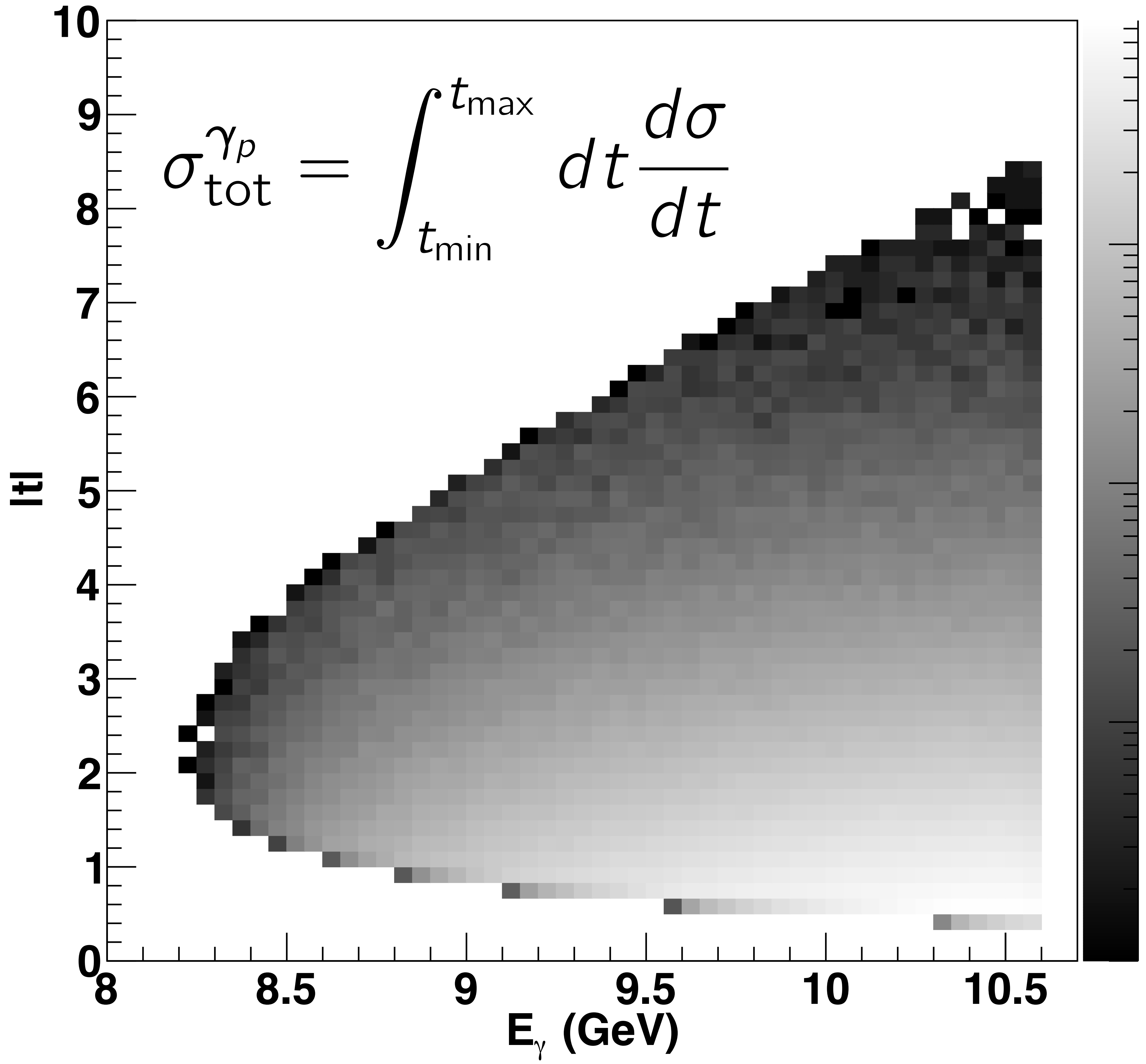
- Phase space limits defined by quarkonium direction



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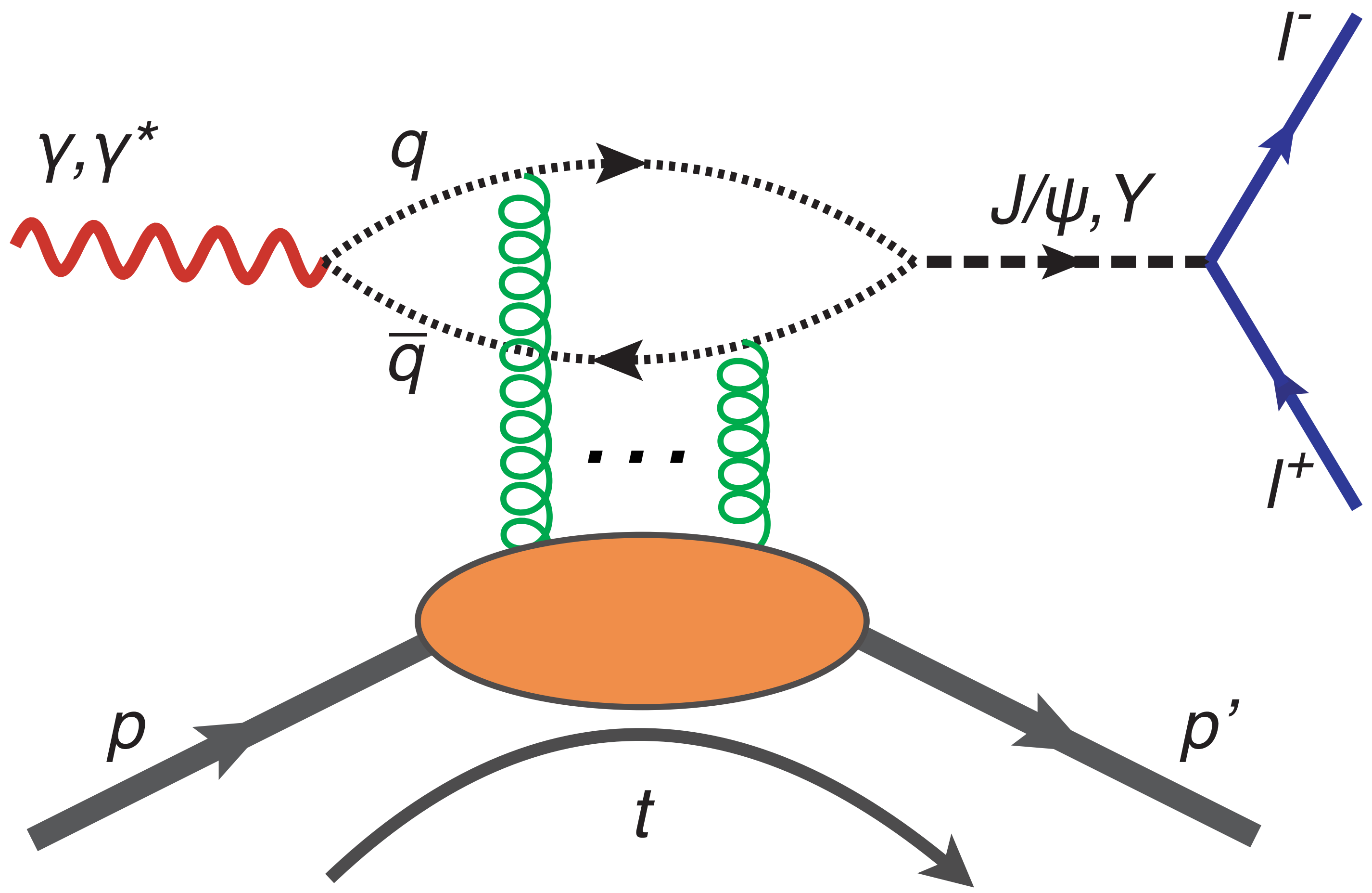

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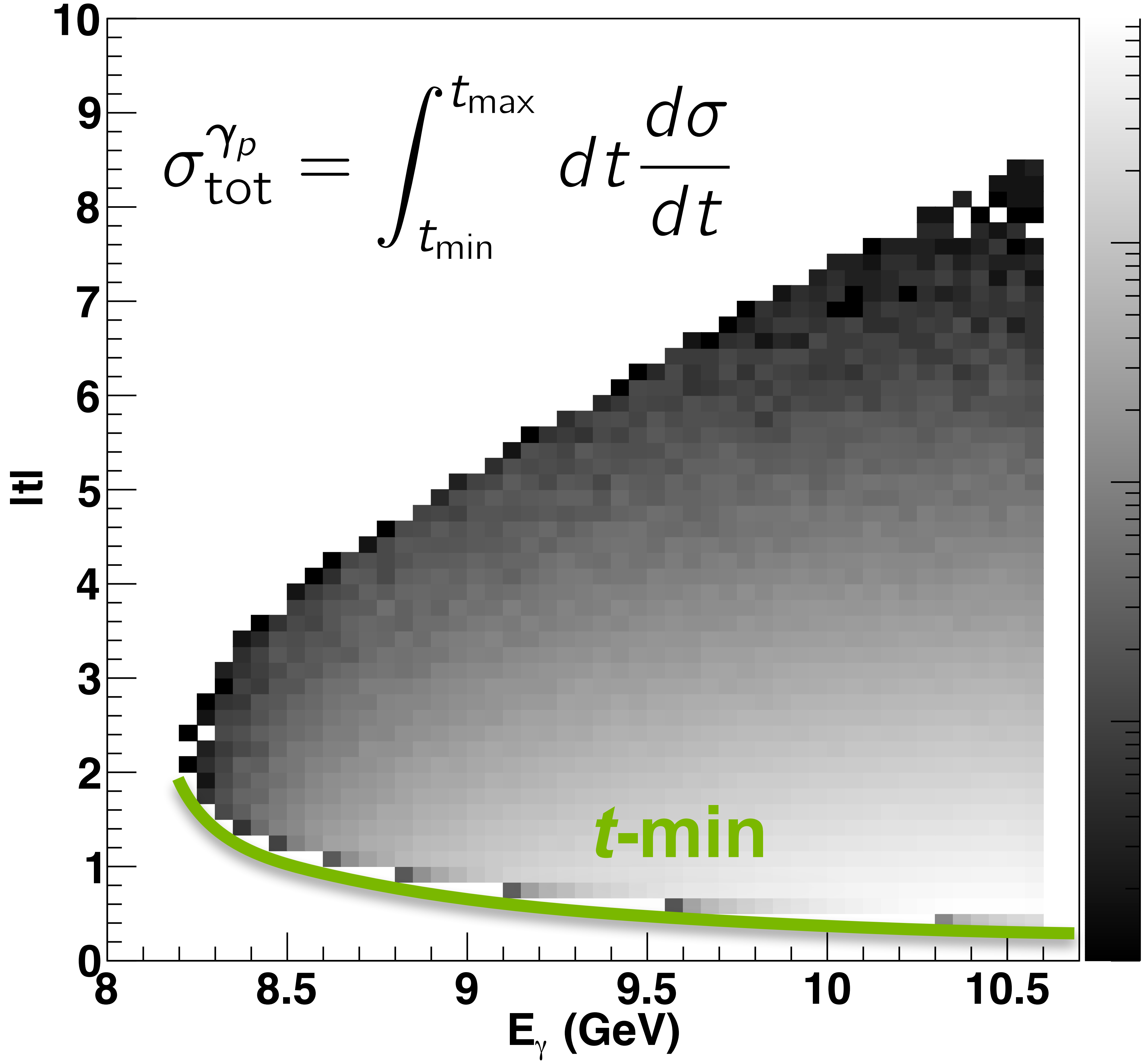

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  - Forward (with photon): $t = t_{min}$

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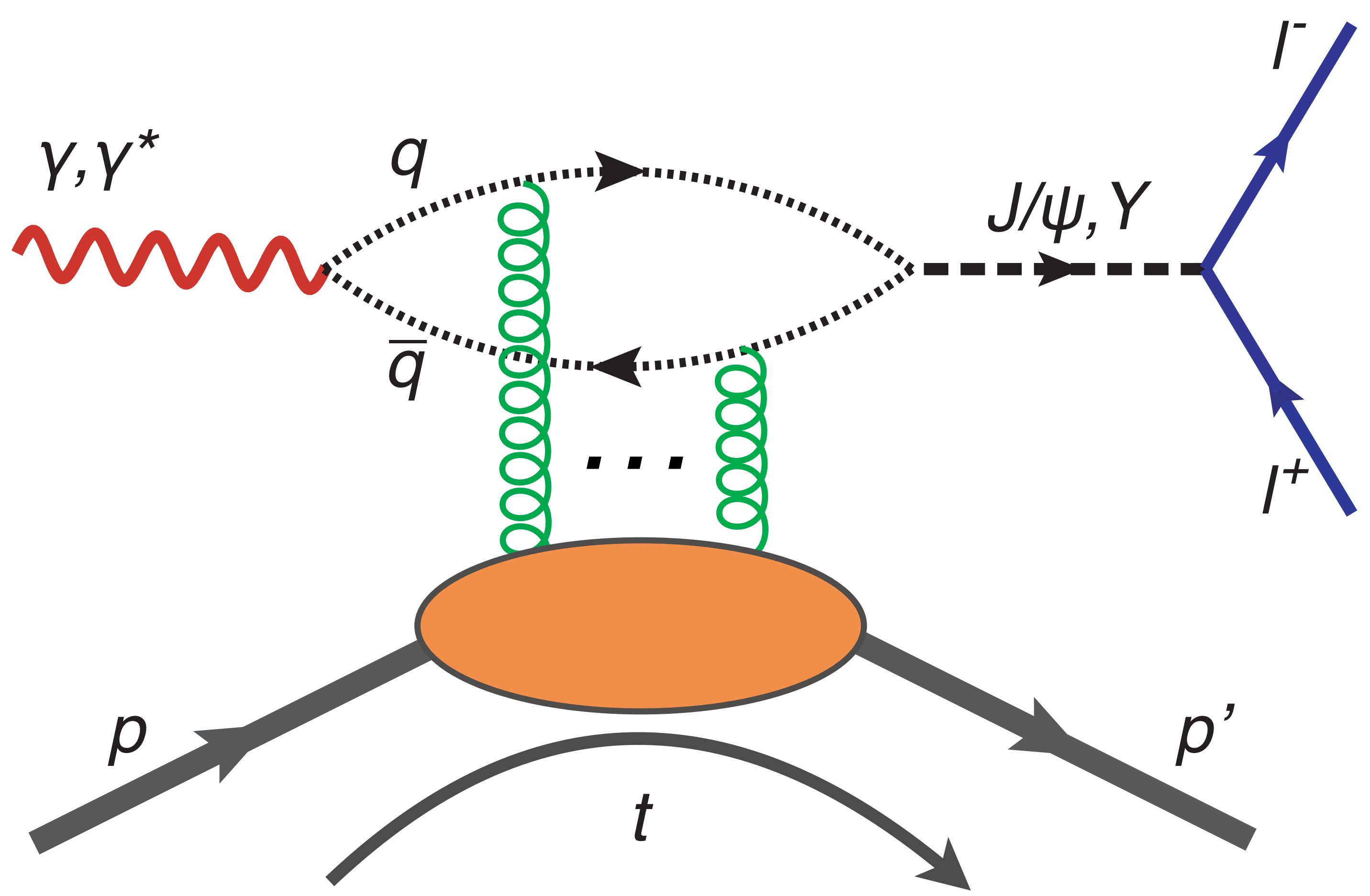

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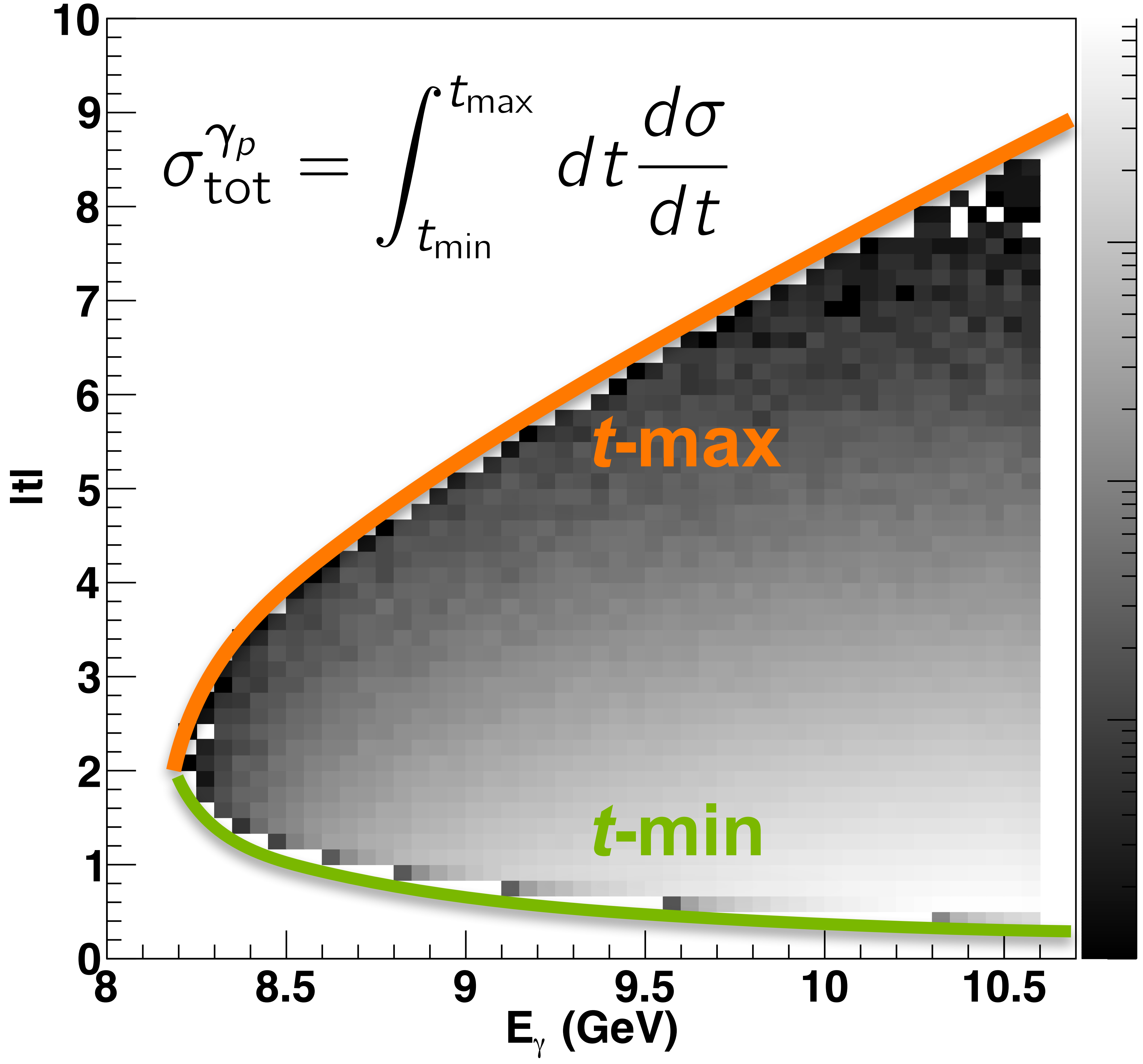

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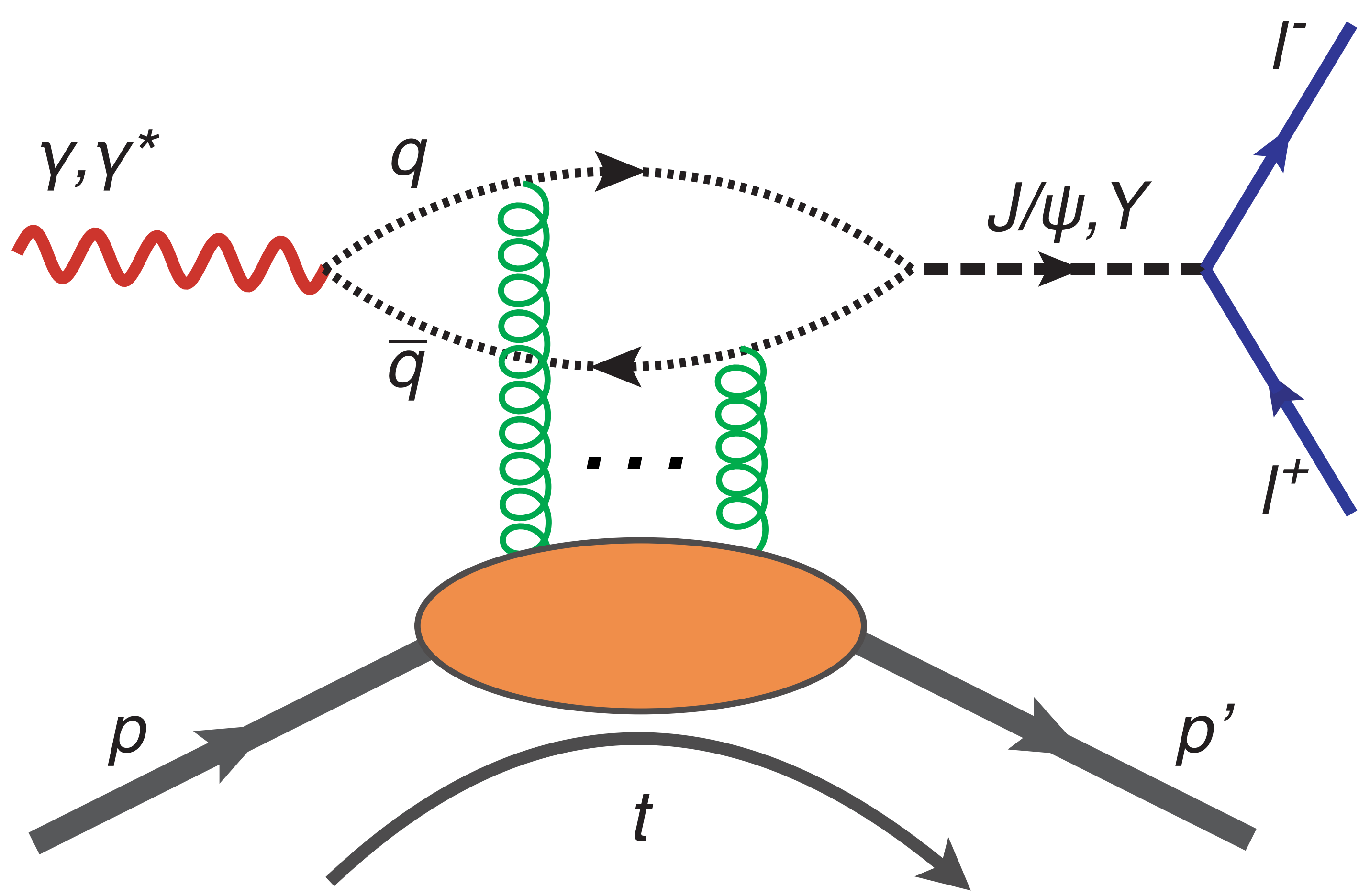

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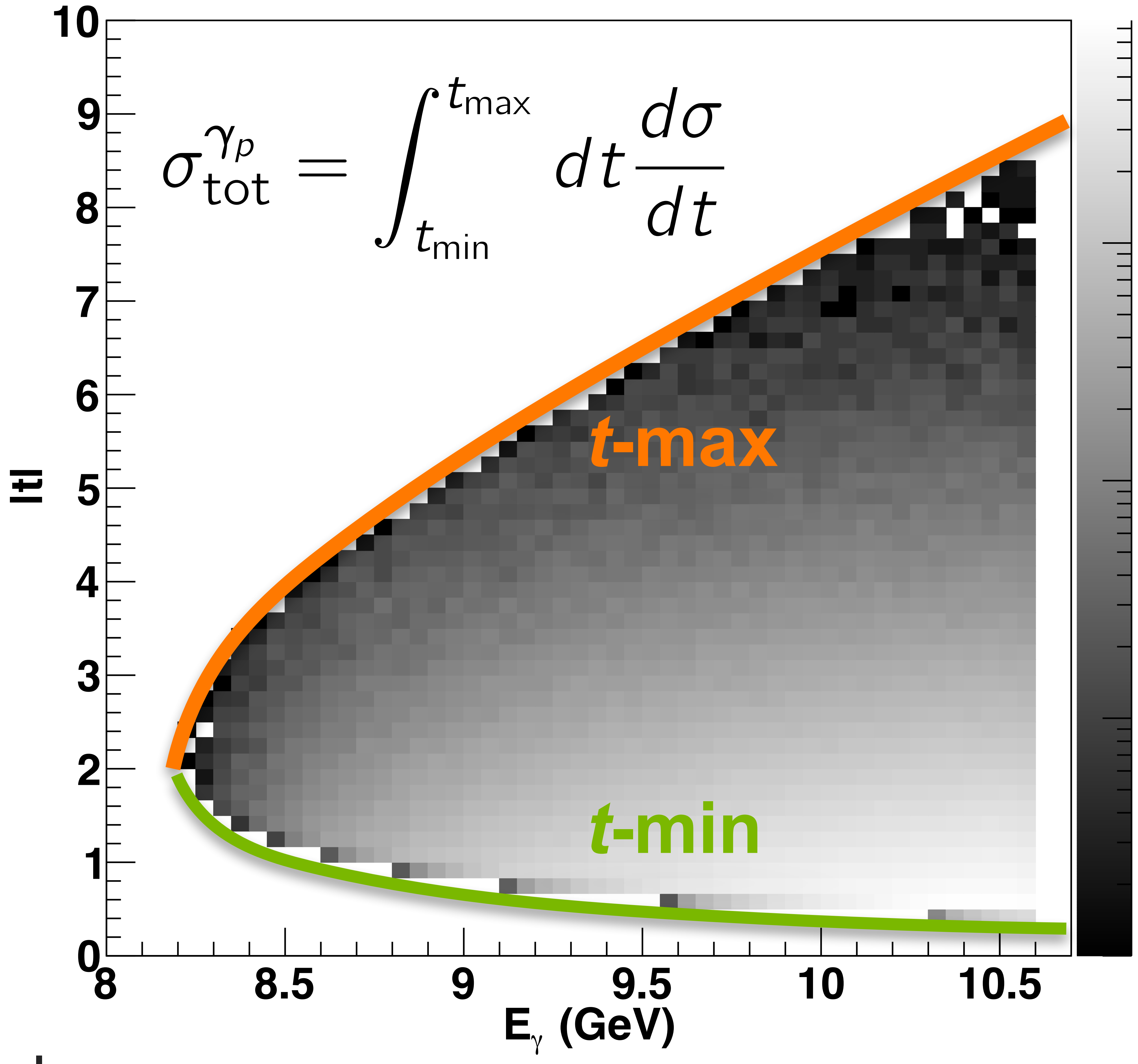

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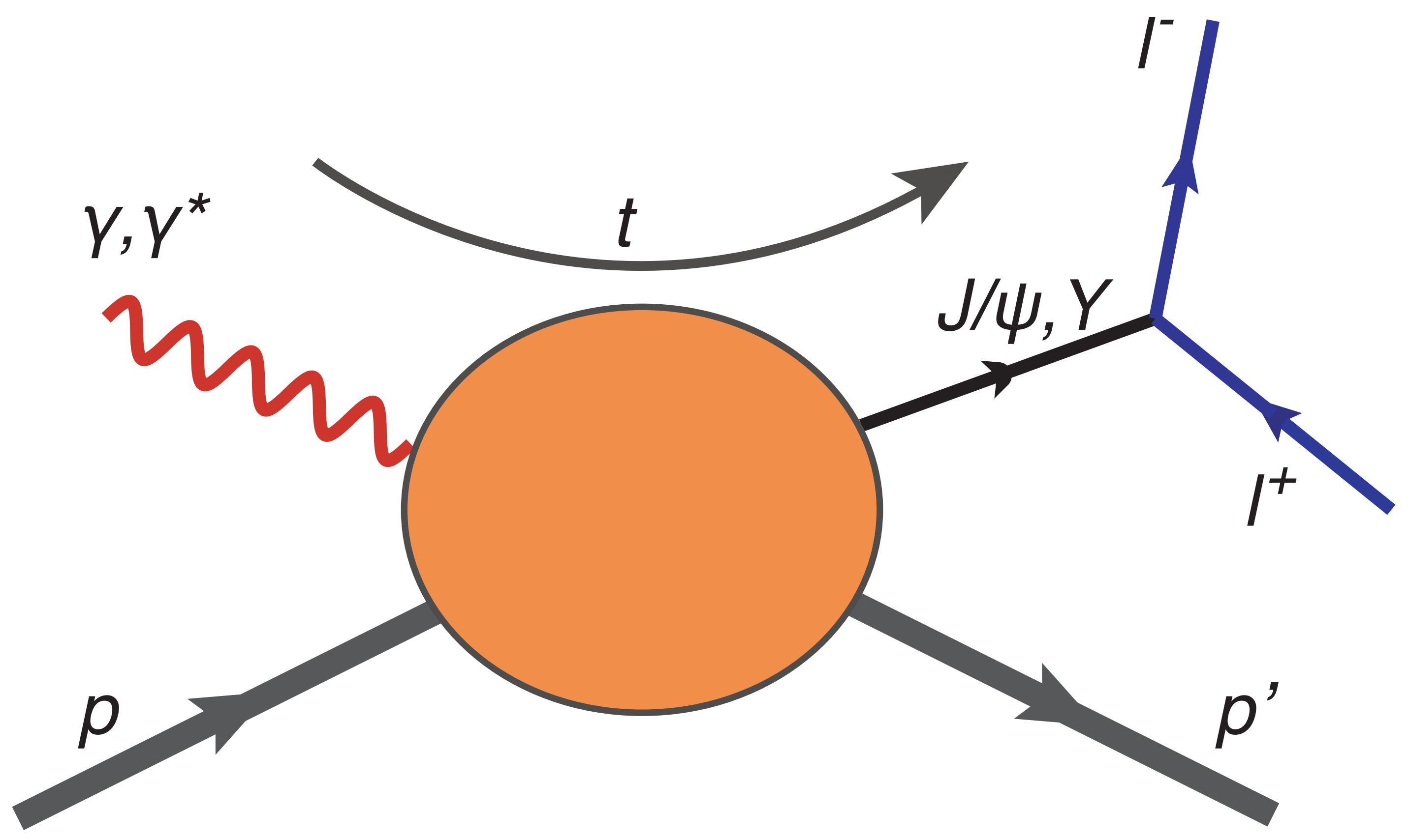
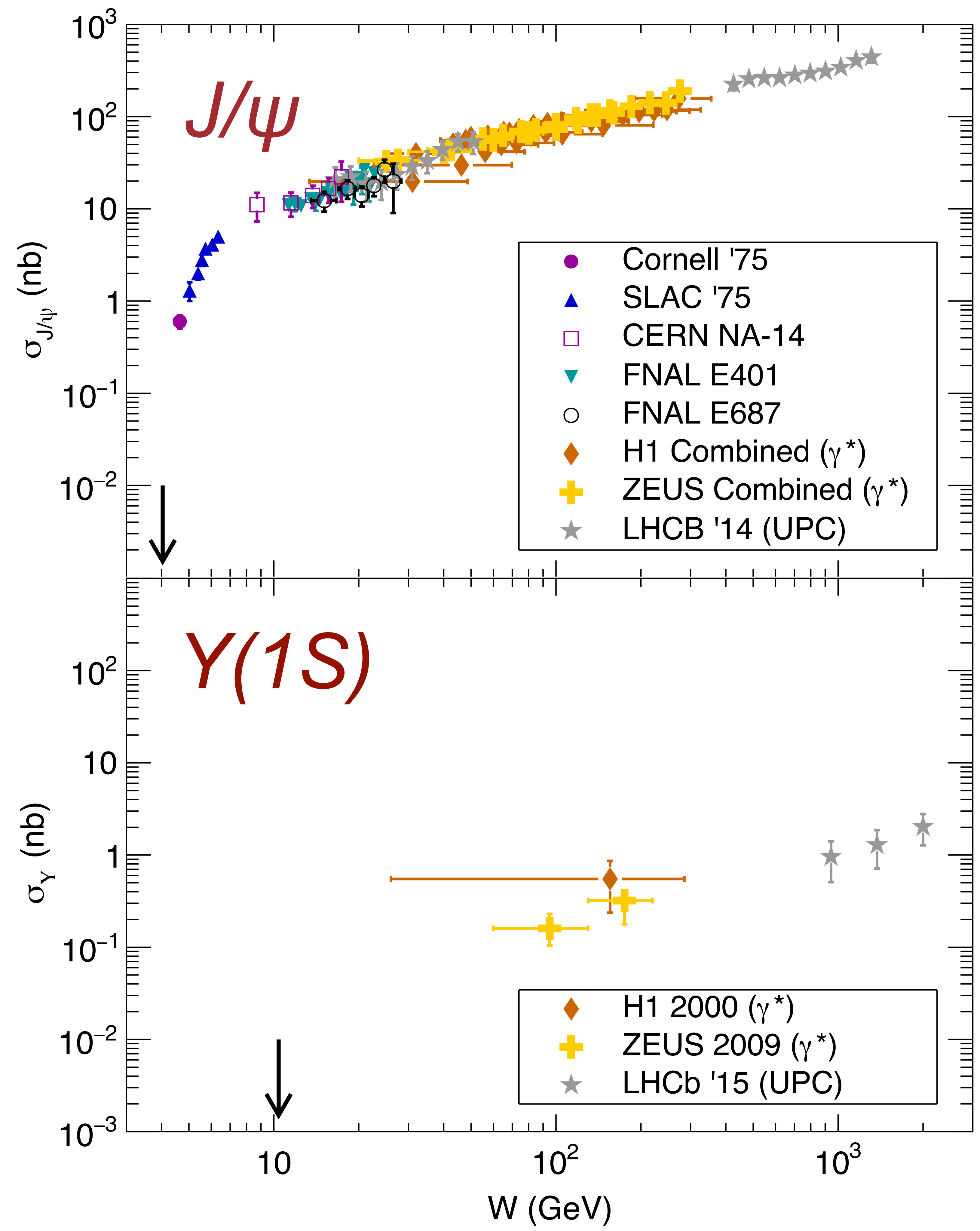
- Forward direction preferred: t-dependence ~exponential

QUARKONIUM PHOTO-PRODUCTION

What do we know?



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



- *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

What do we know?

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
- Test **SRC universality** with a gluonic probe

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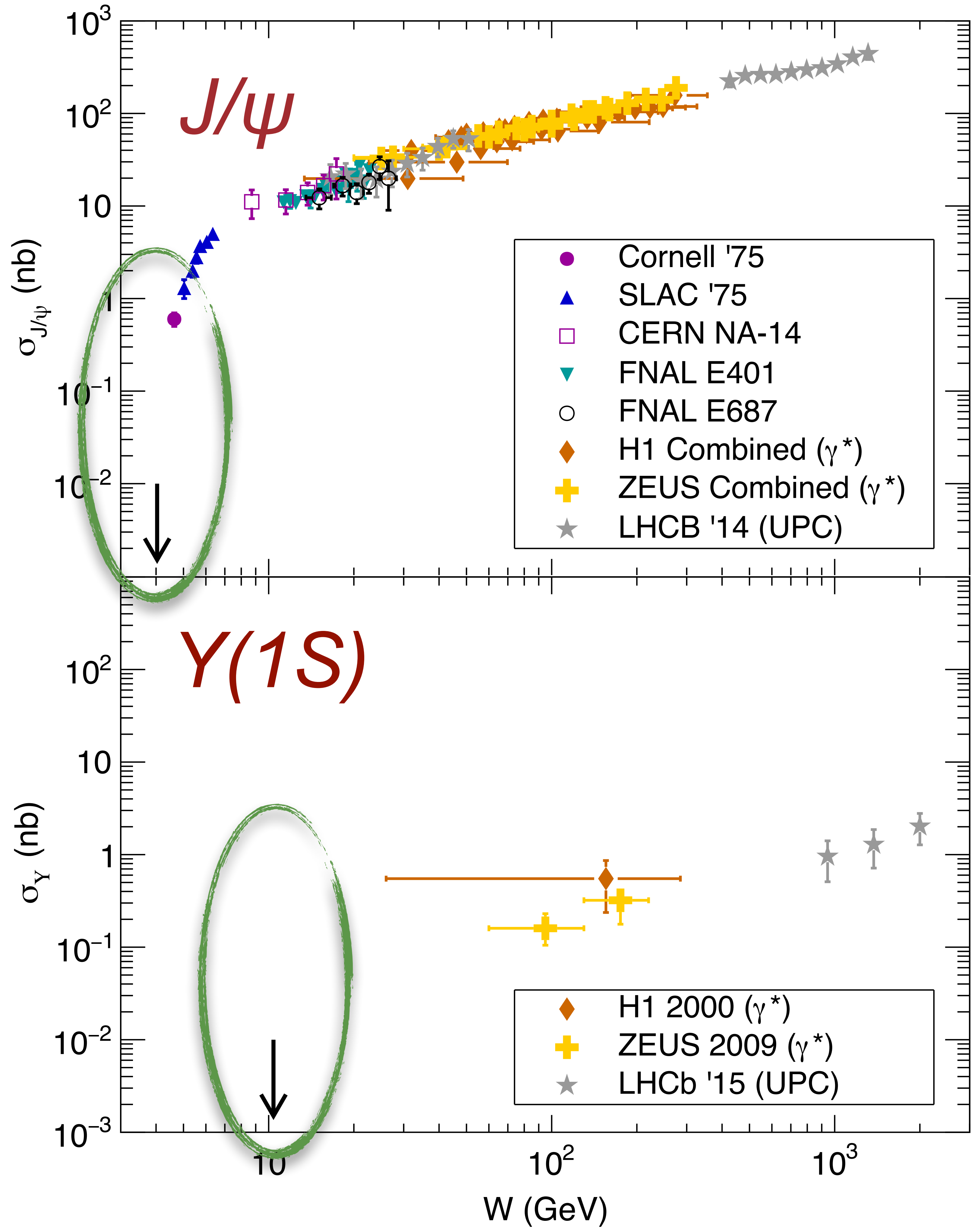
J/ψ at JLab
Y(1s) at EIC



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Electro-Production at high energies:

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

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J/ψ at JLab
Y(1s) at EIC

J/ψ and
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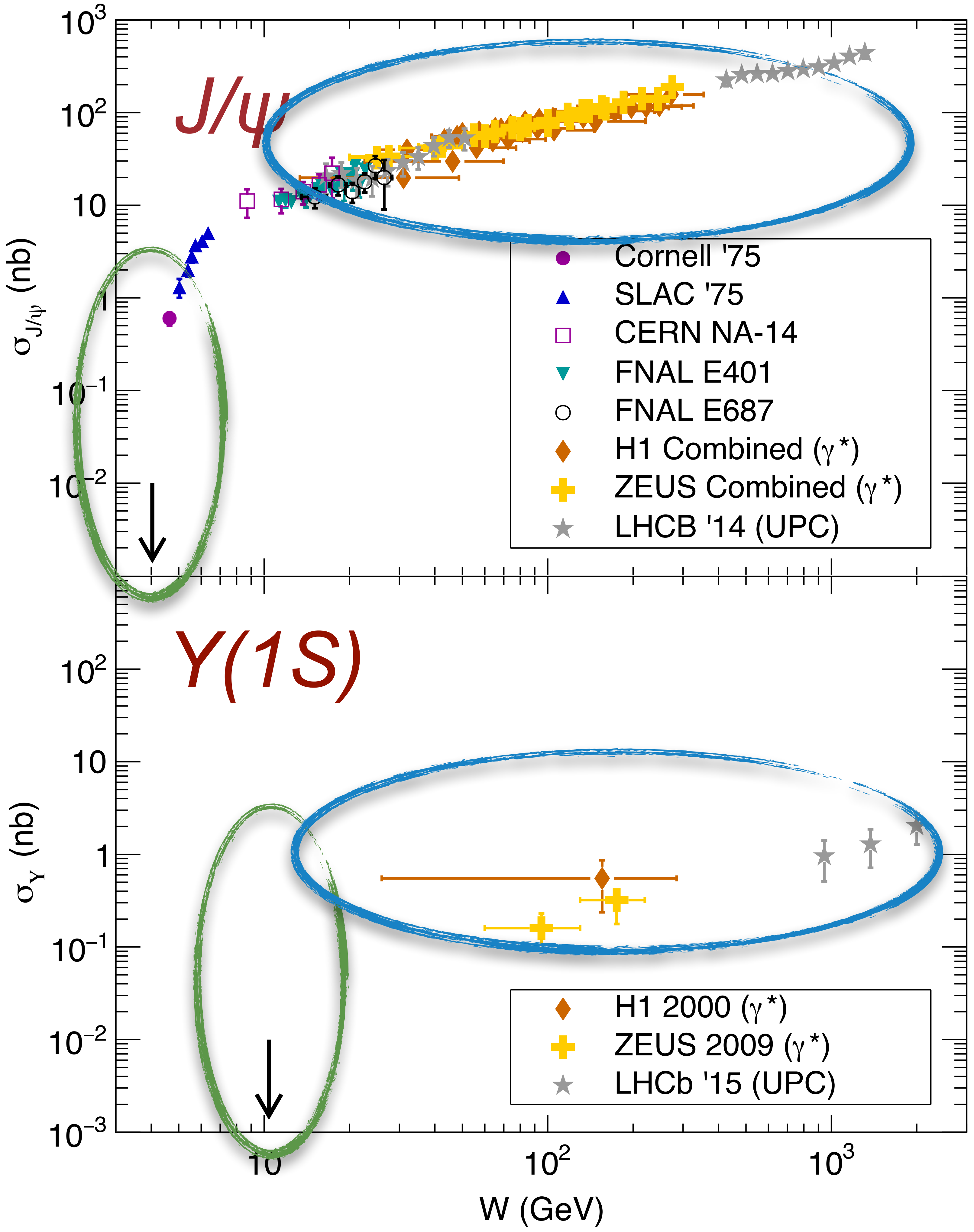
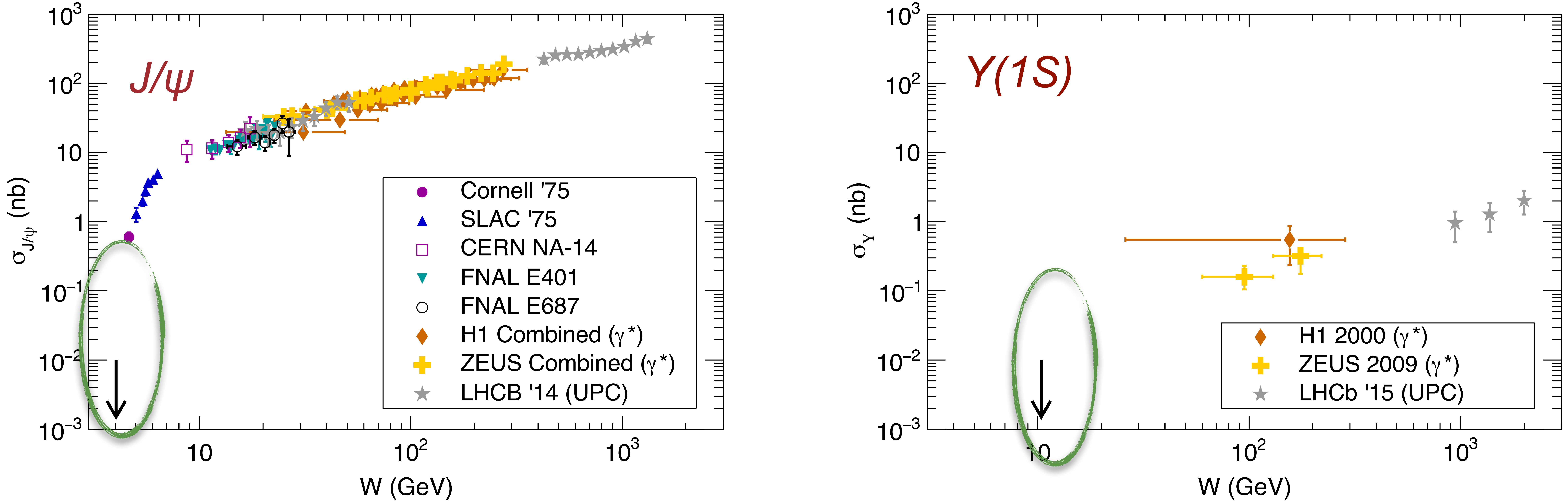


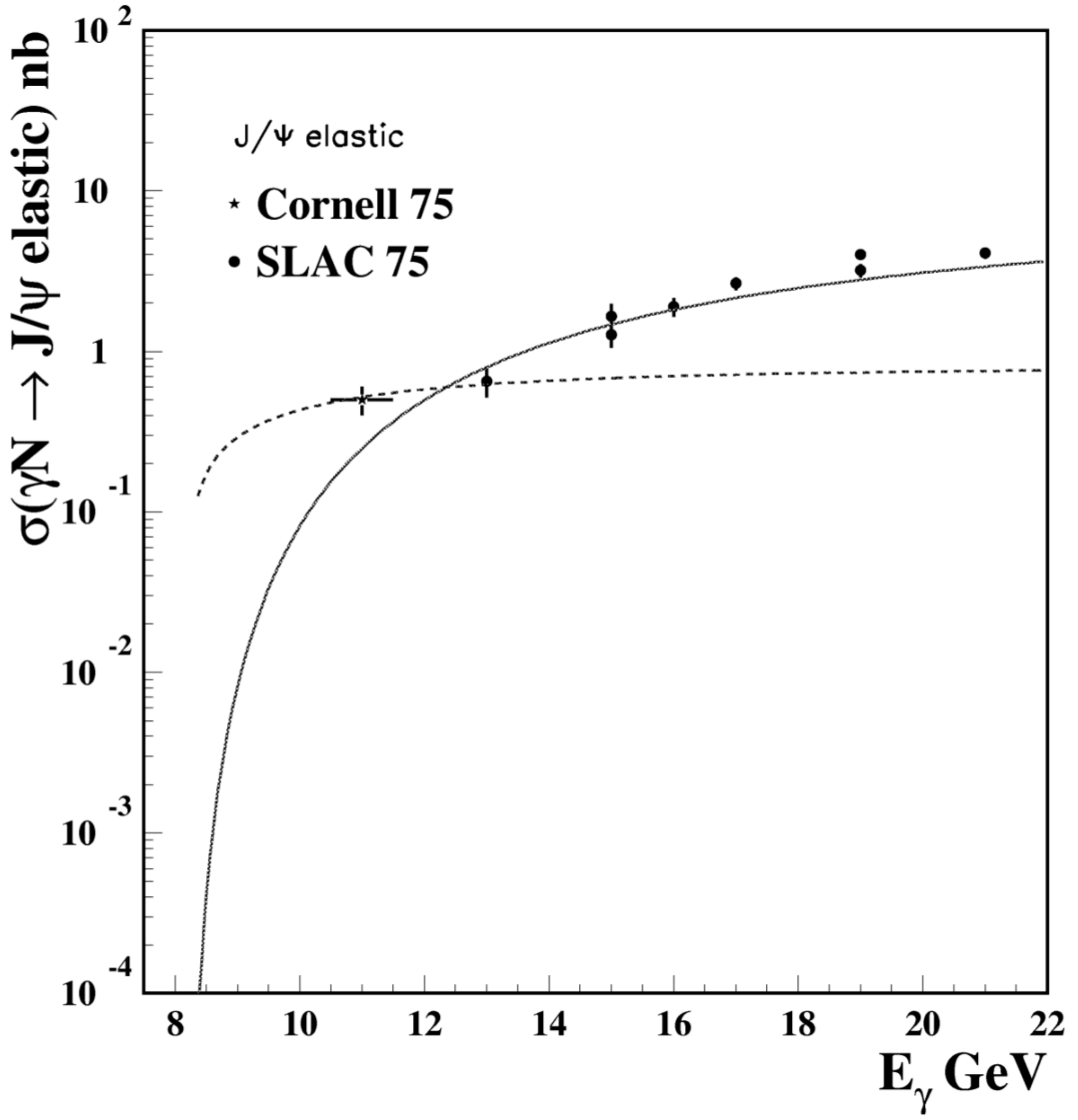


QUARKONIUM PRODUCTION NEAR THRESHOLD

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

PRODUCTION MECHANISM NEAR THRESHOLD?

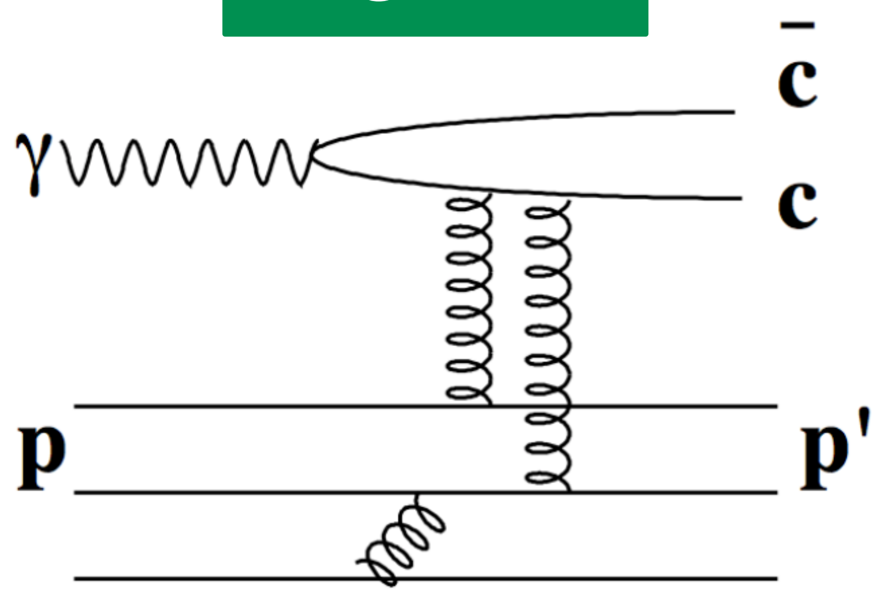
N-gluon exchange hard scattering



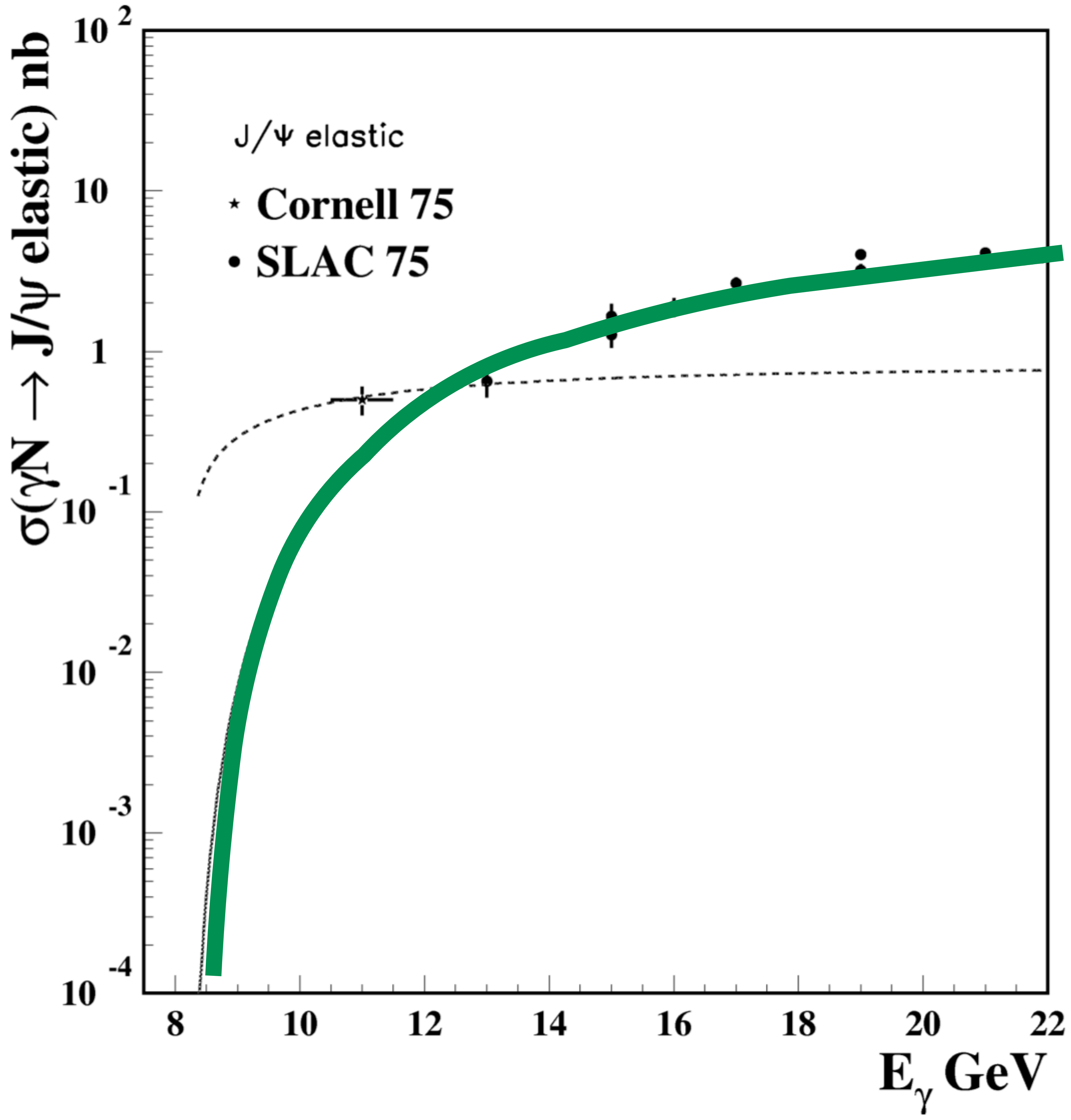
PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

2-gluon



- 2-gluon exchange works well at higher energies



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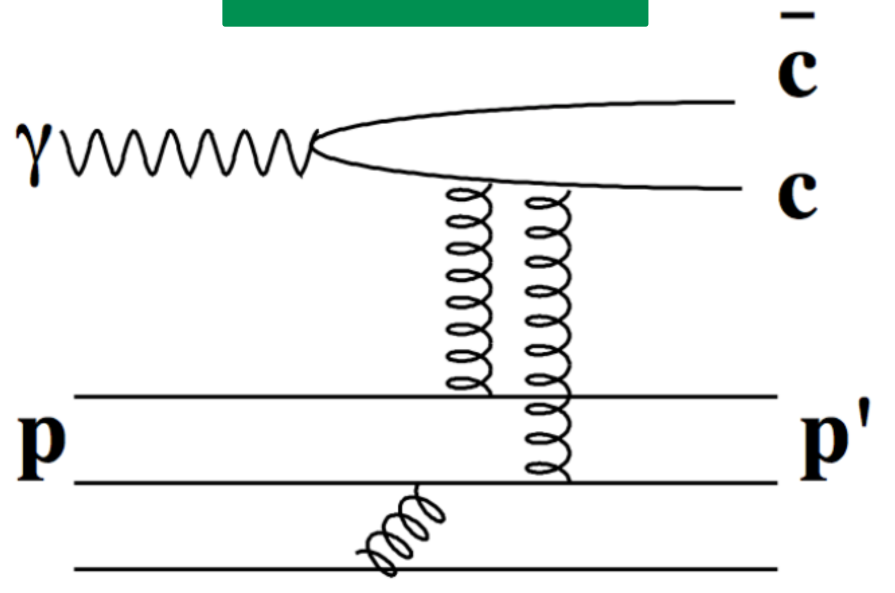
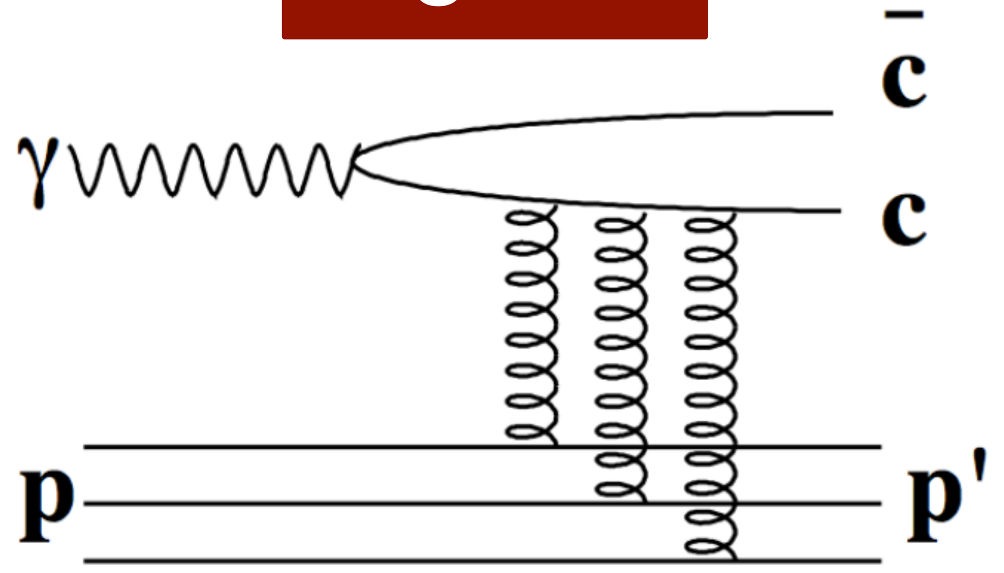
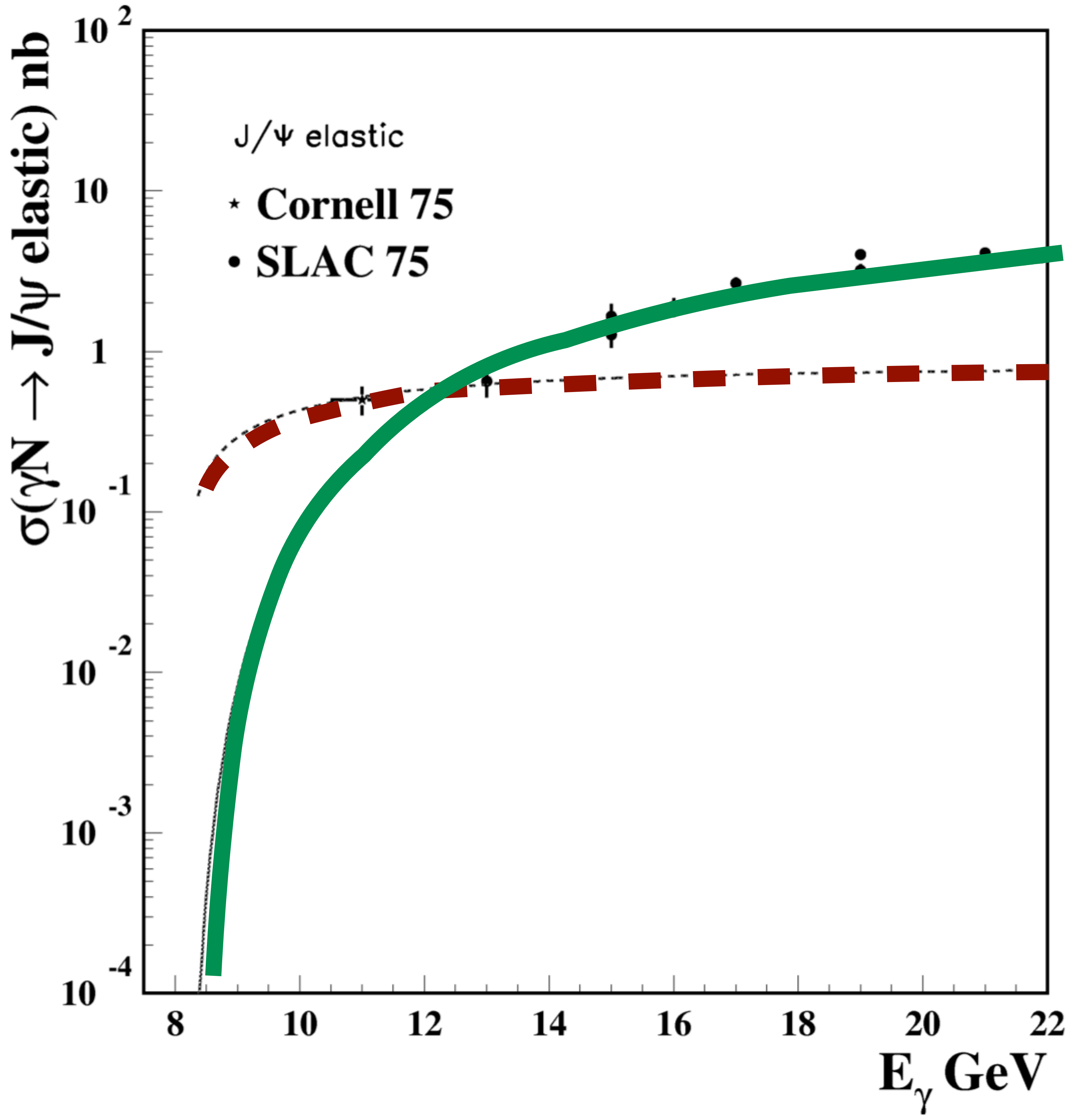


3-gluon



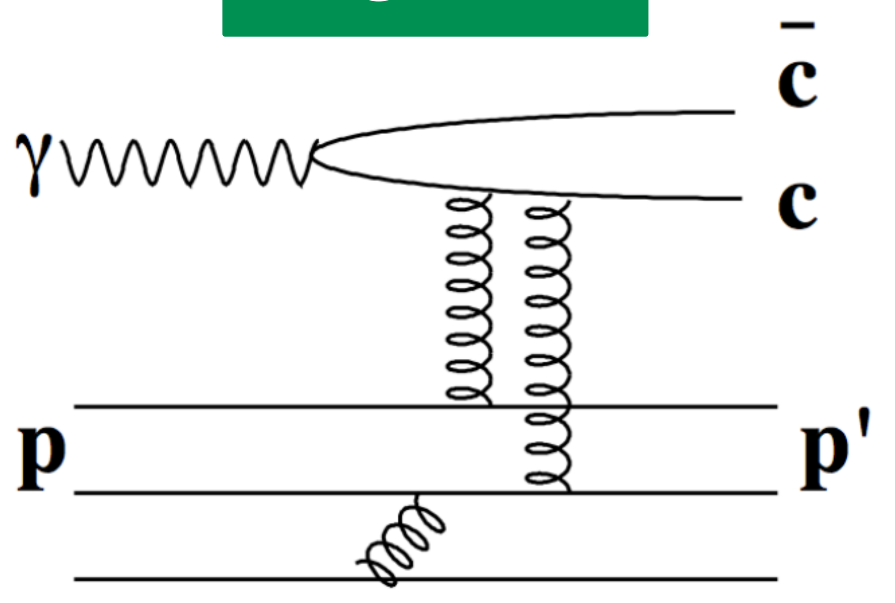
- 2-gluon exchange works well at higher energies
- Higher order gluon exchange expected to play role near threshold
  - Larger 3-gluon exchange contribution related to binding



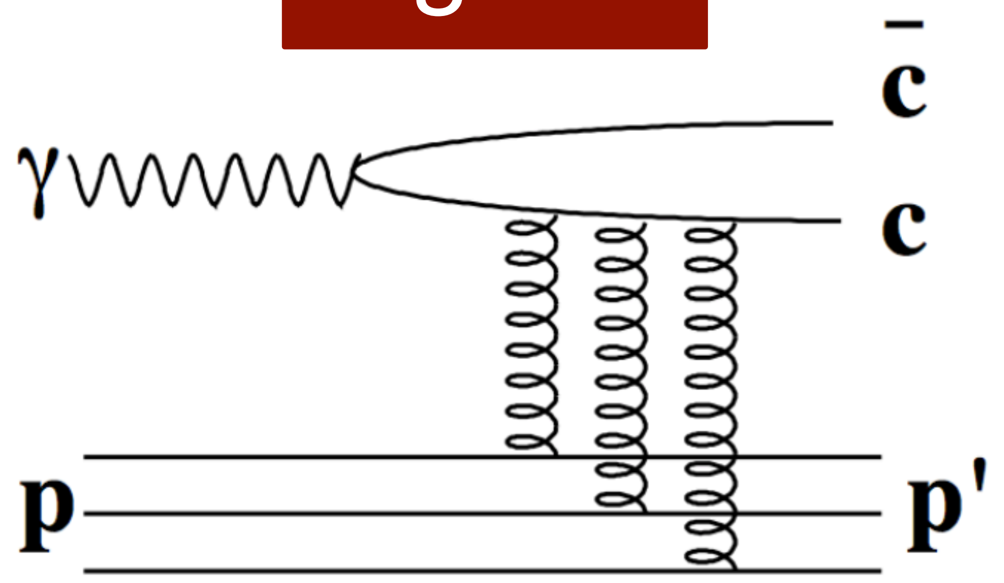
PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

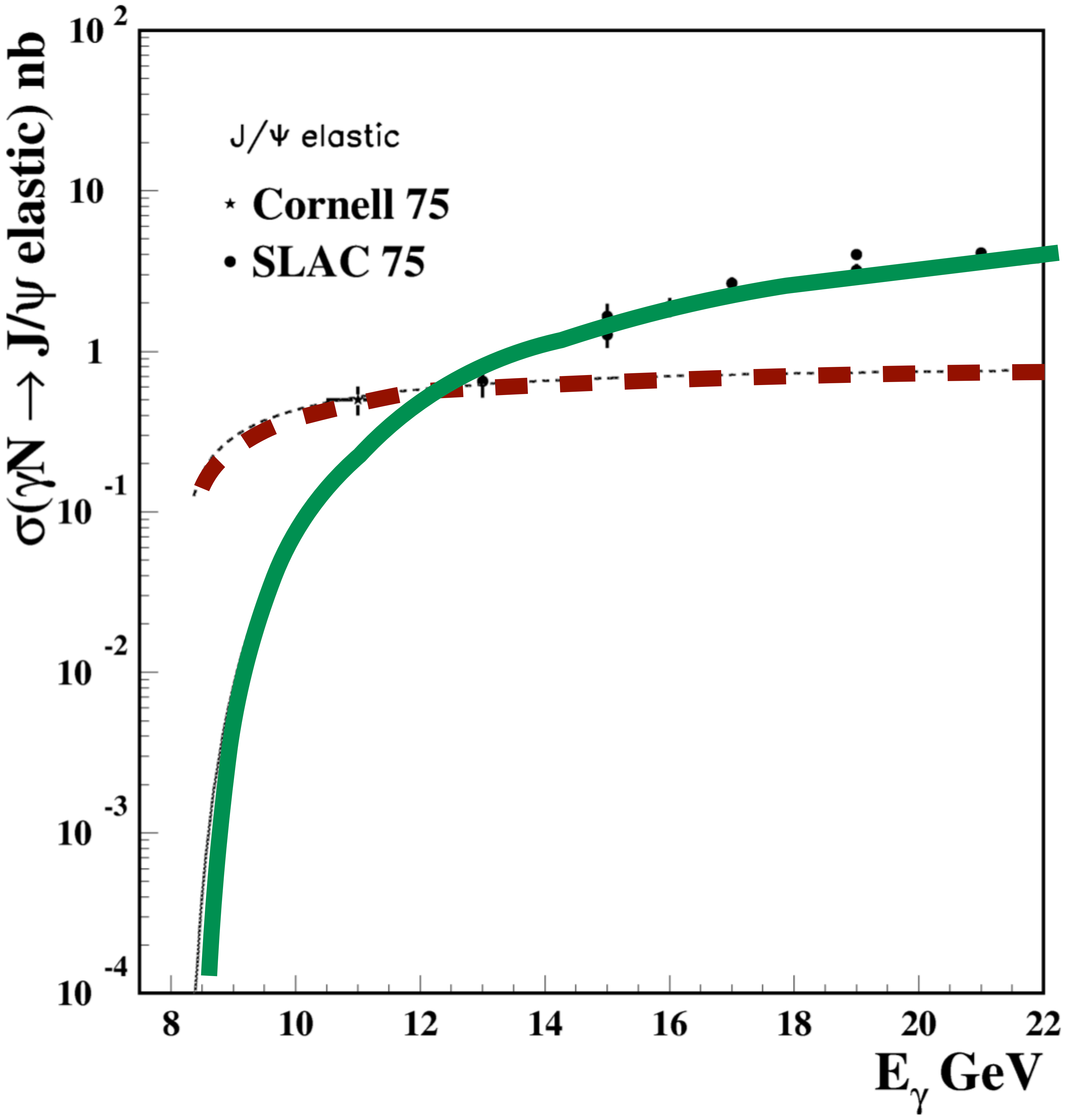
2-gluon



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)



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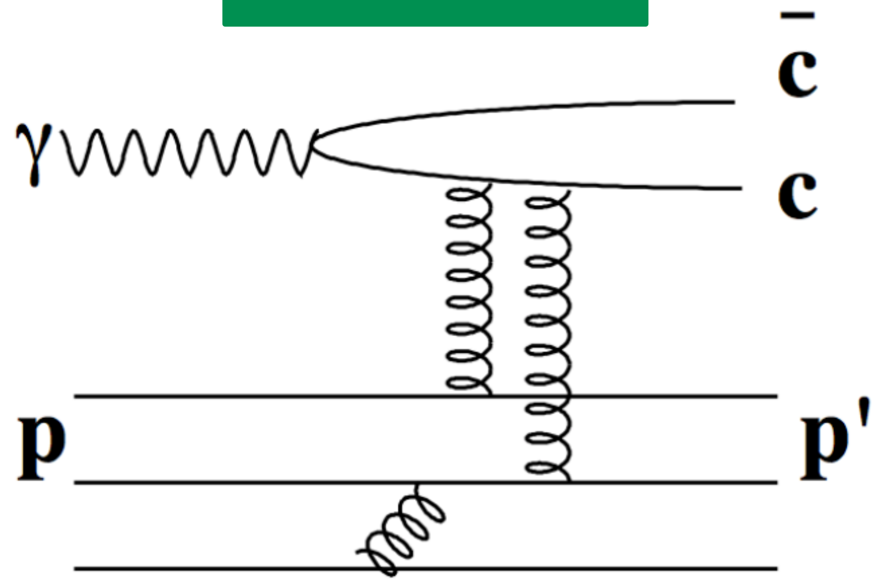
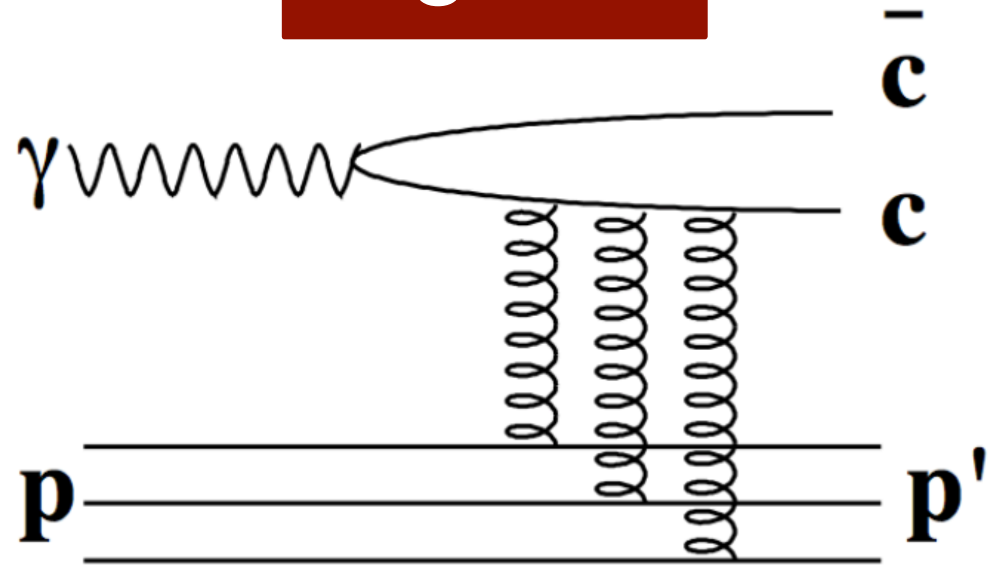
N-gluon exchange hard scattering

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)
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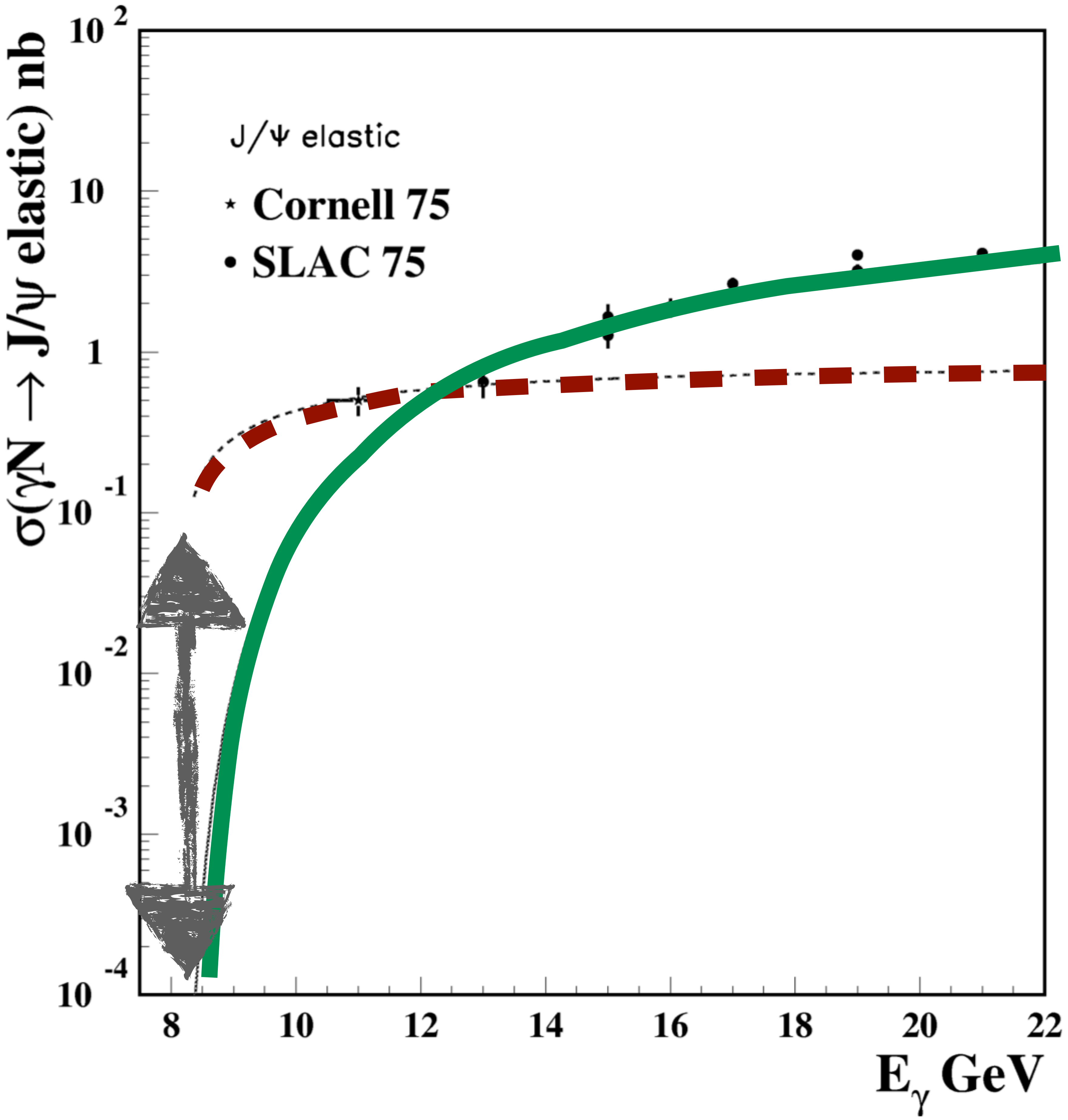

S.J. Brodsky, *et al.*, PLB 498, 23-28 (2001)

PRODUCTION MECHANISM NEAR THRESHOLD?

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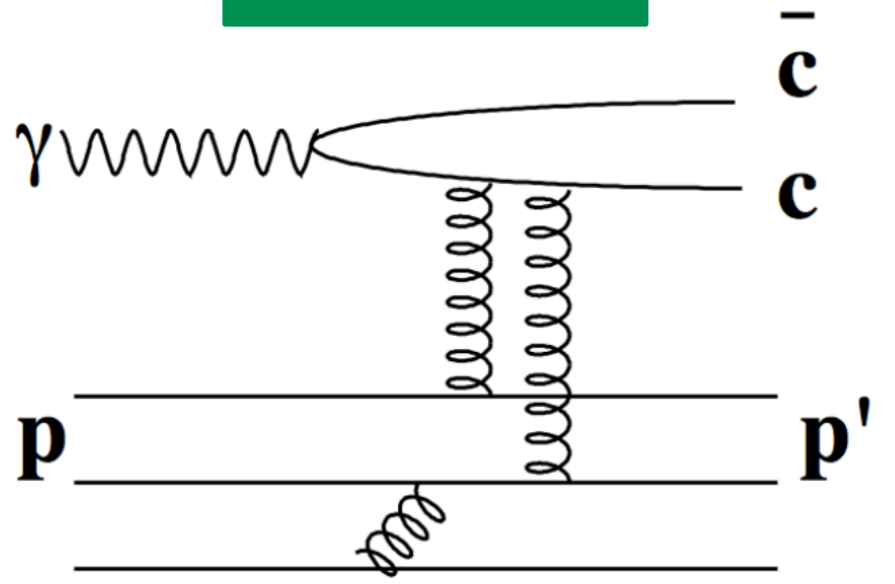

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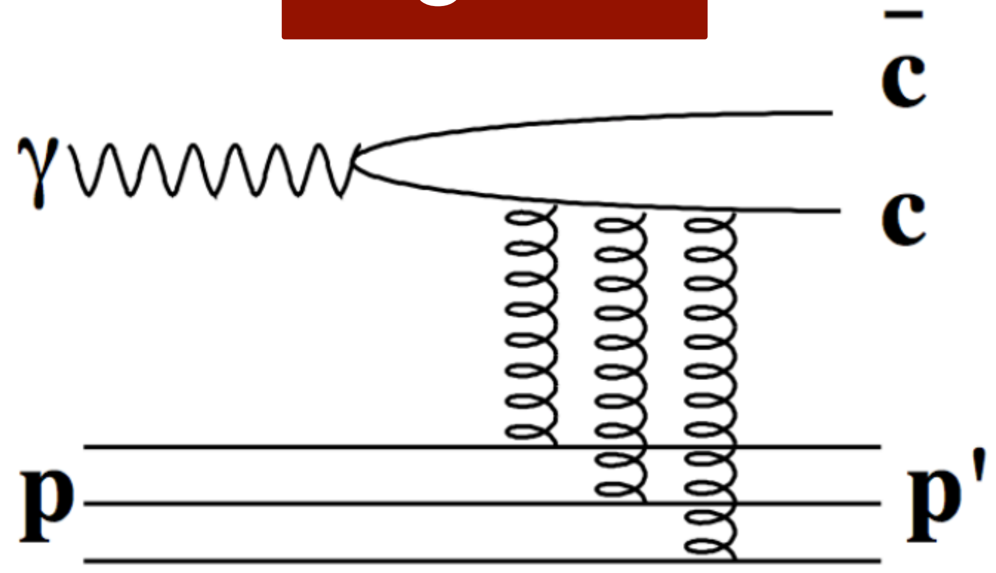

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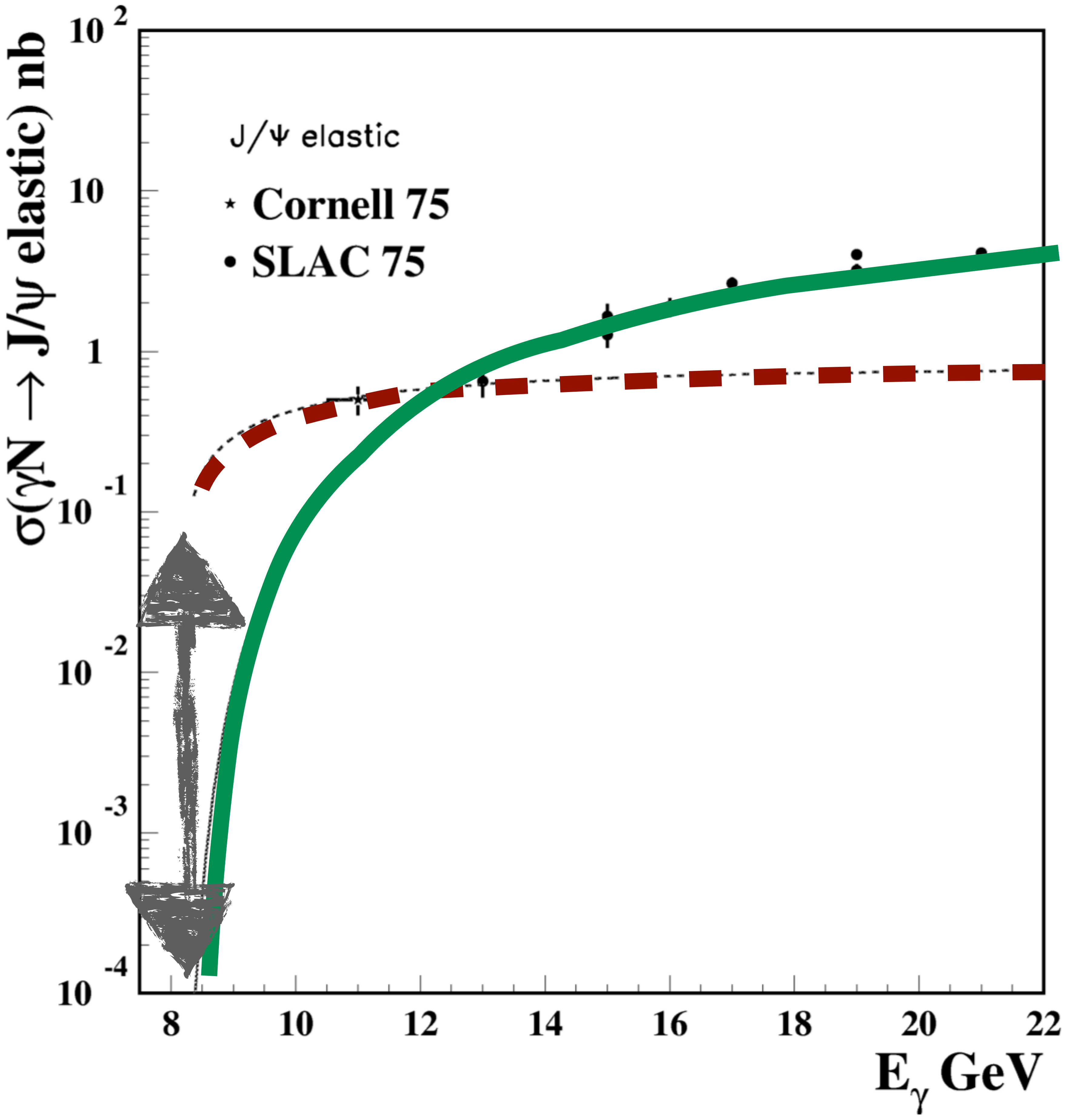
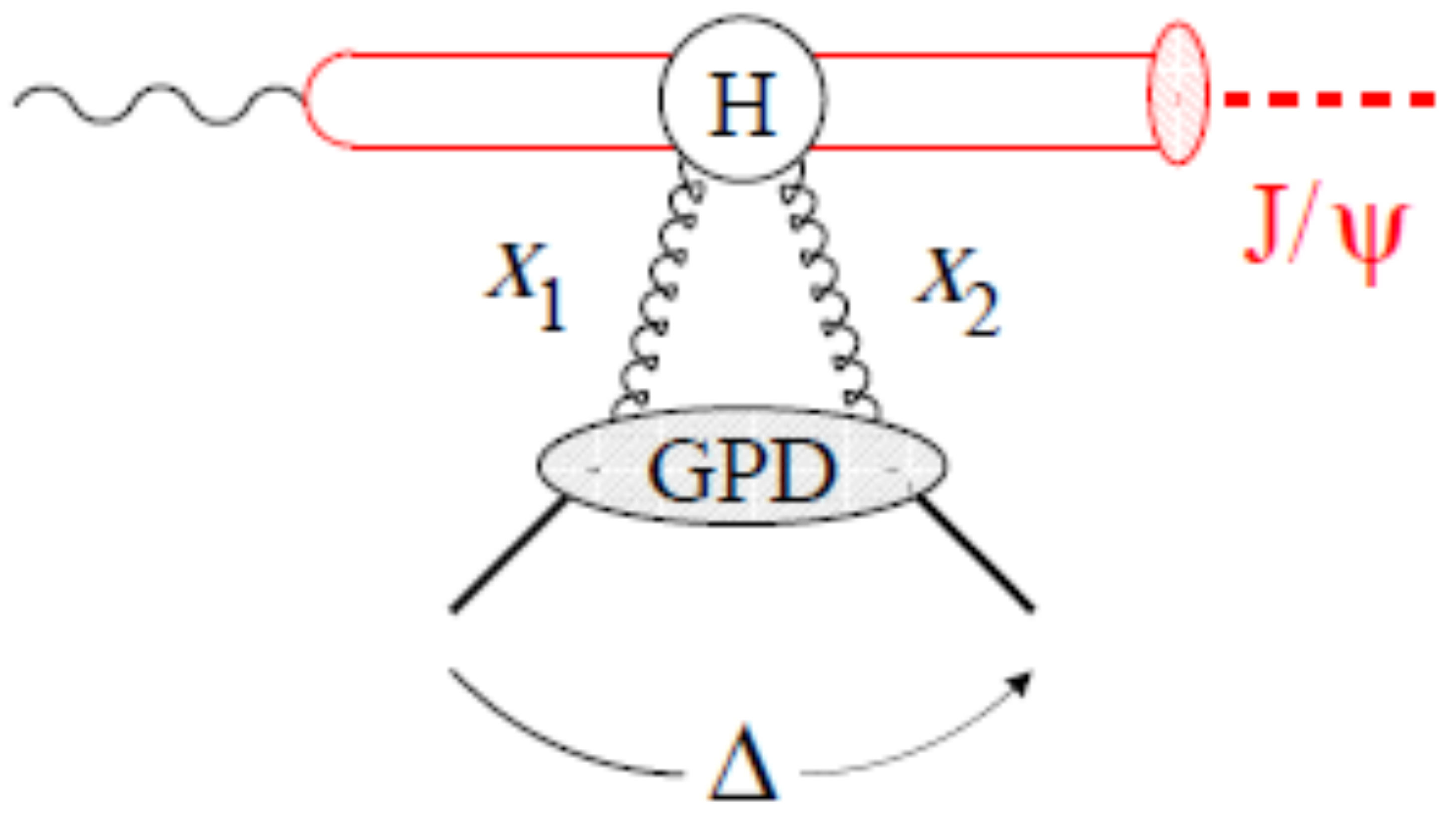
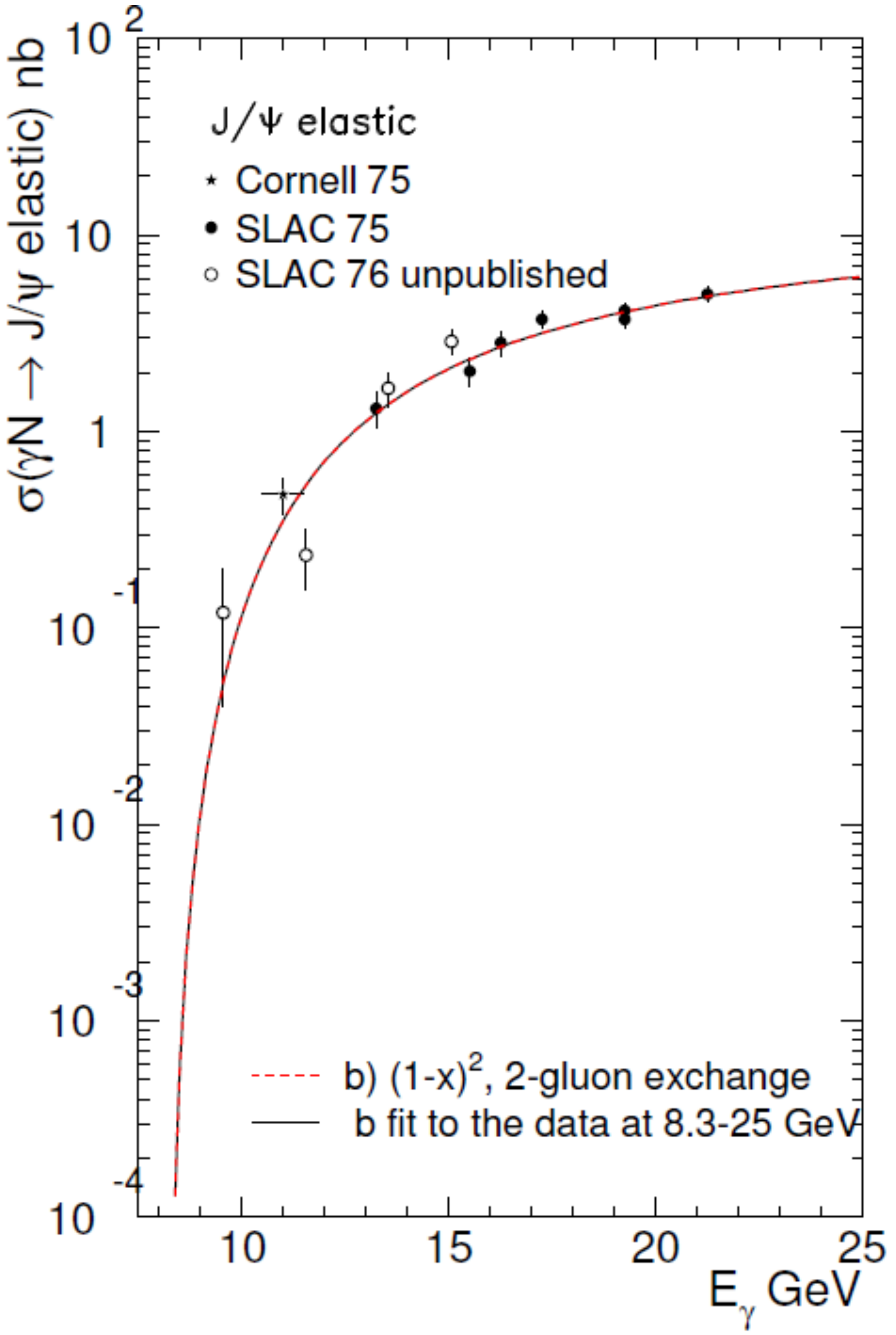


PRODUCTION MECHANISM NEAR THRESHOLD?

Partonic soft mechanism





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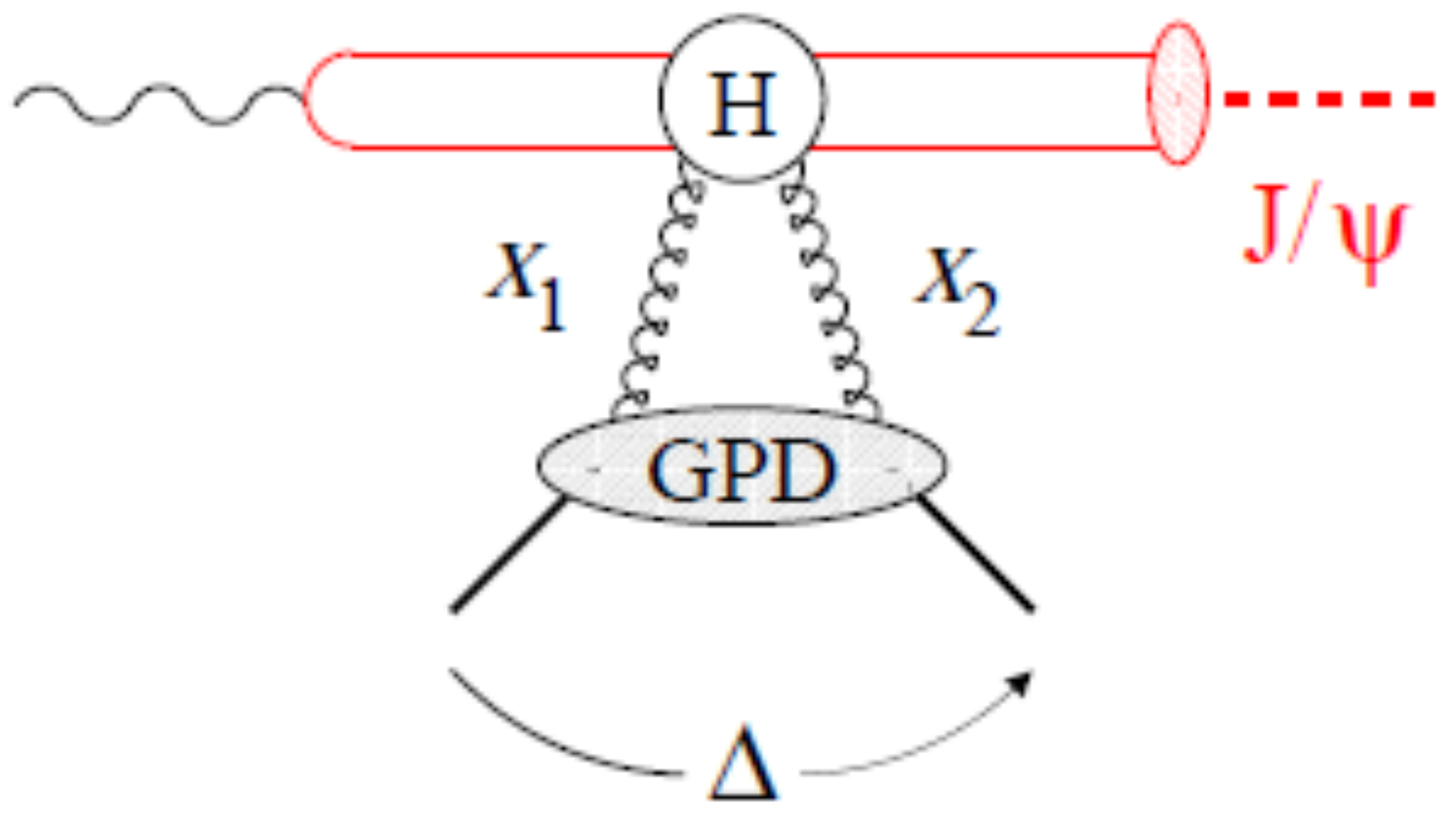

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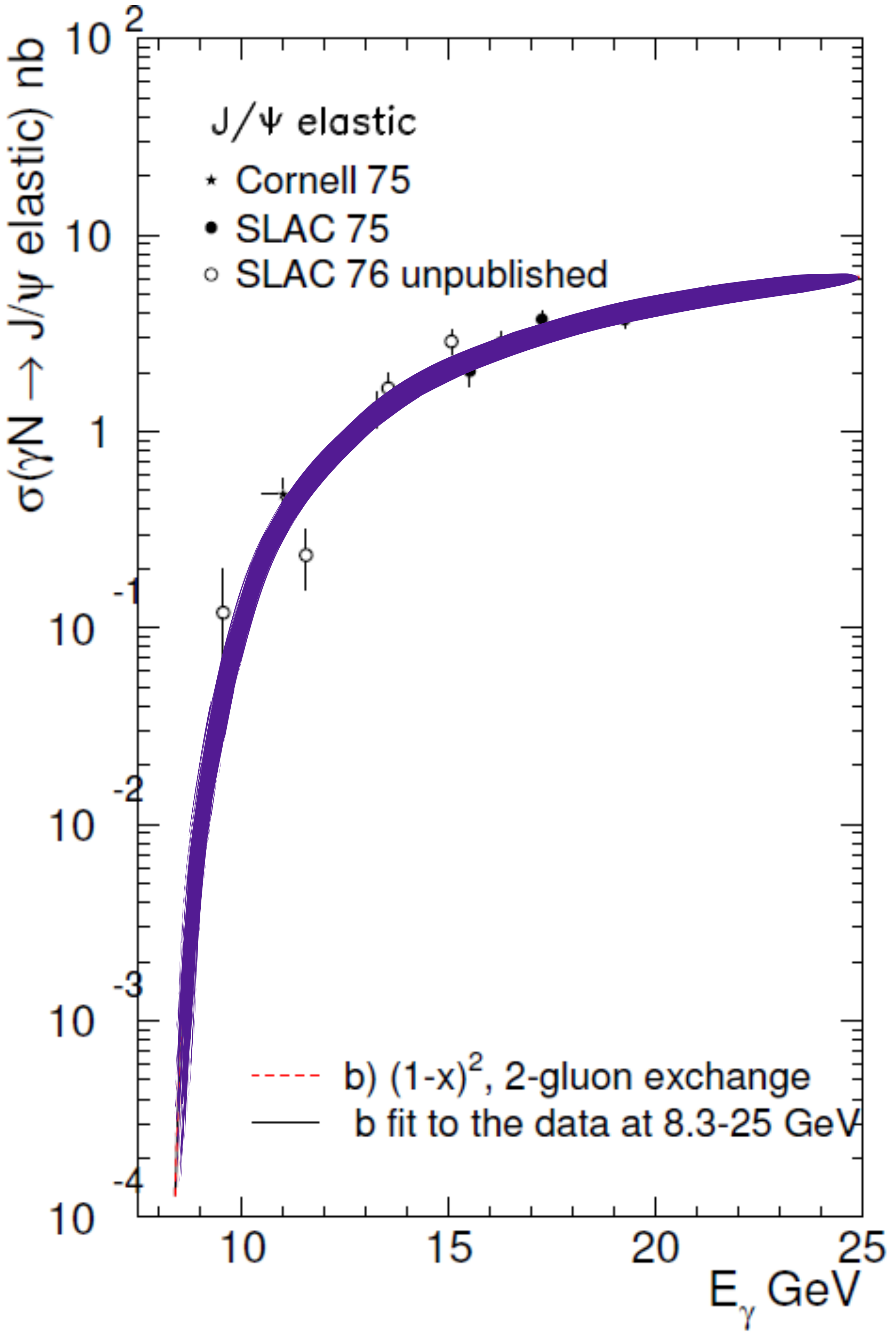

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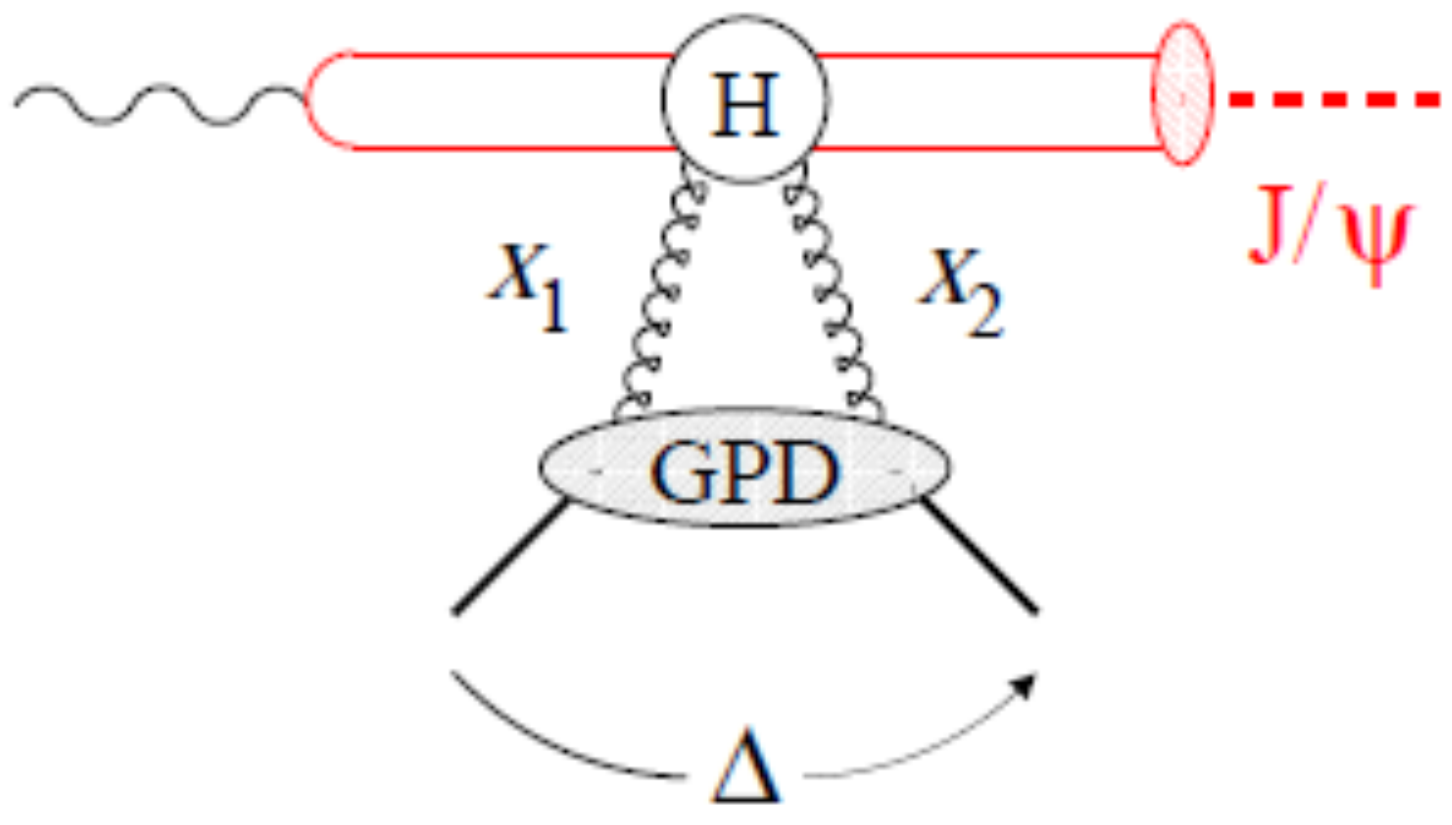

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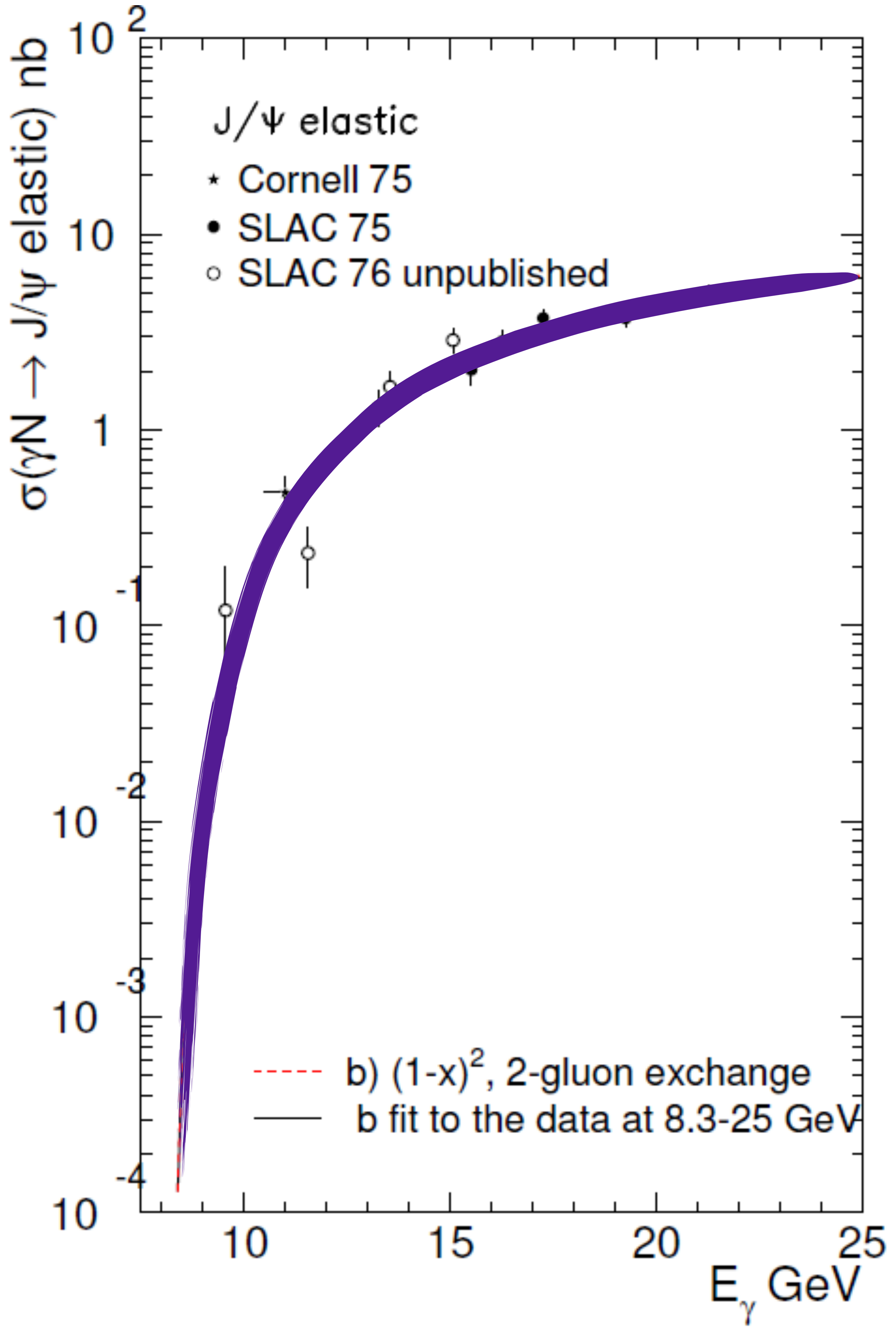

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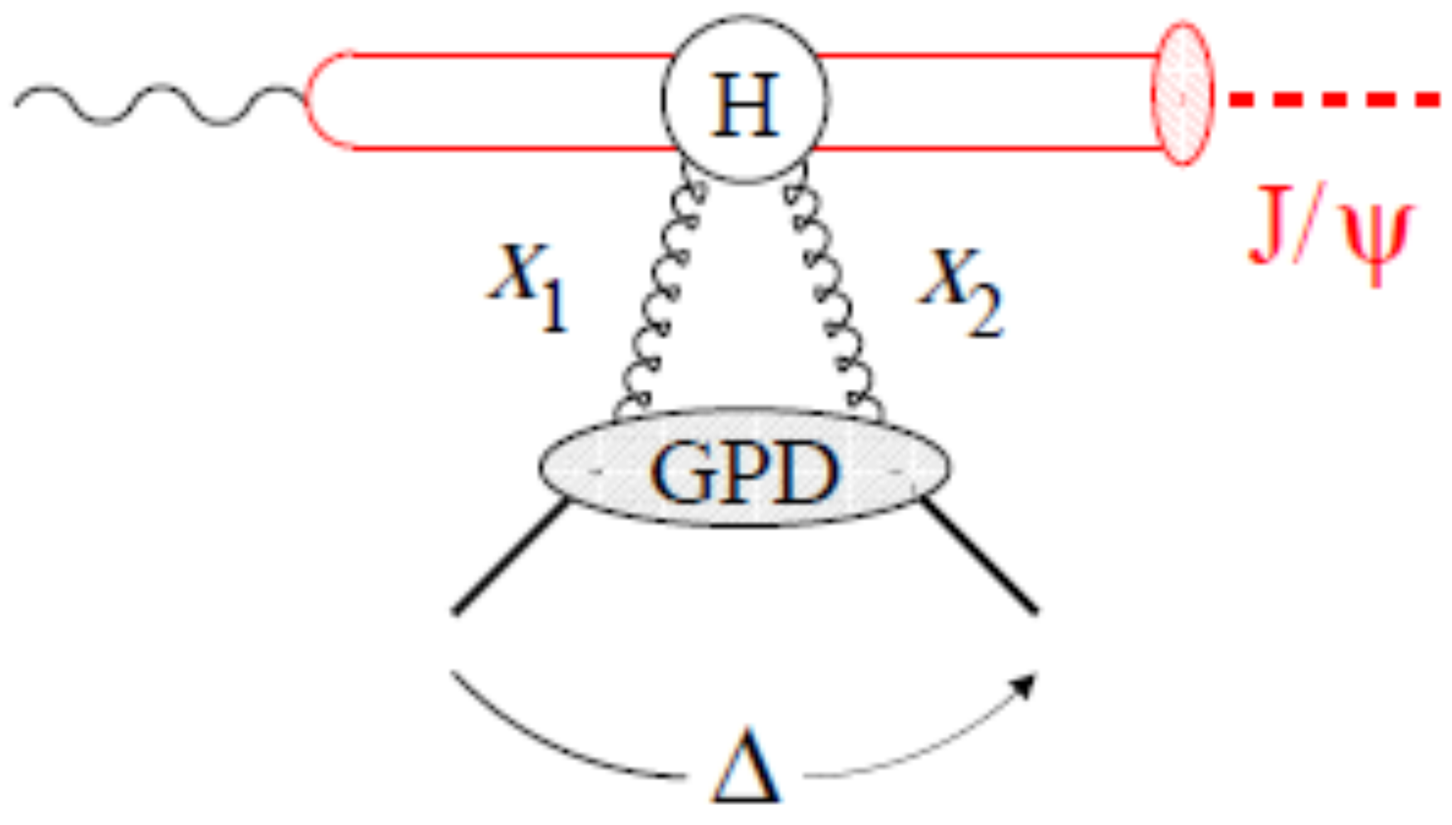

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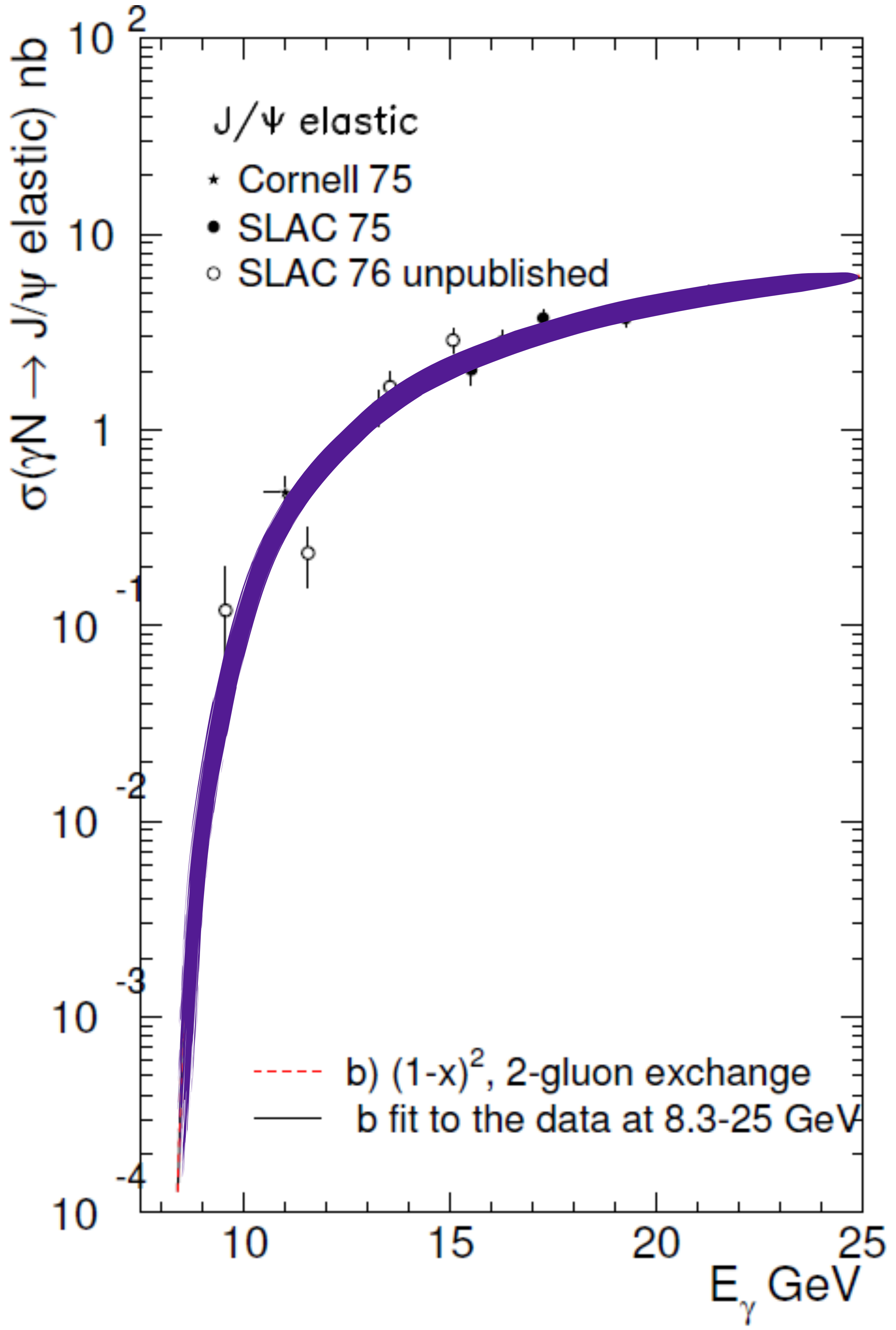

D. Kharzeev *et al.*, PLB 289 595-599 (1996), EPJ-C 9 459-462 (1999)
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)

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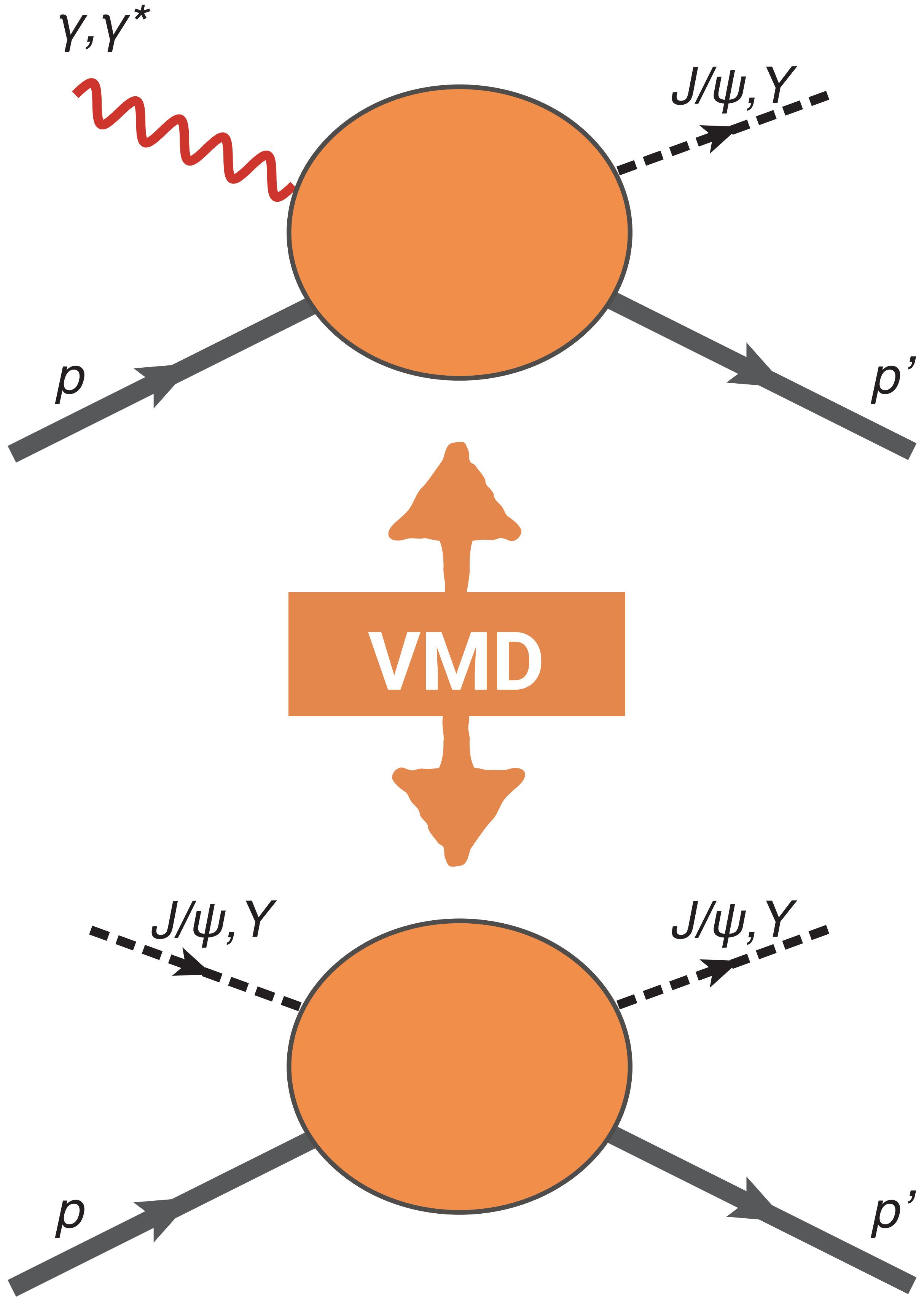

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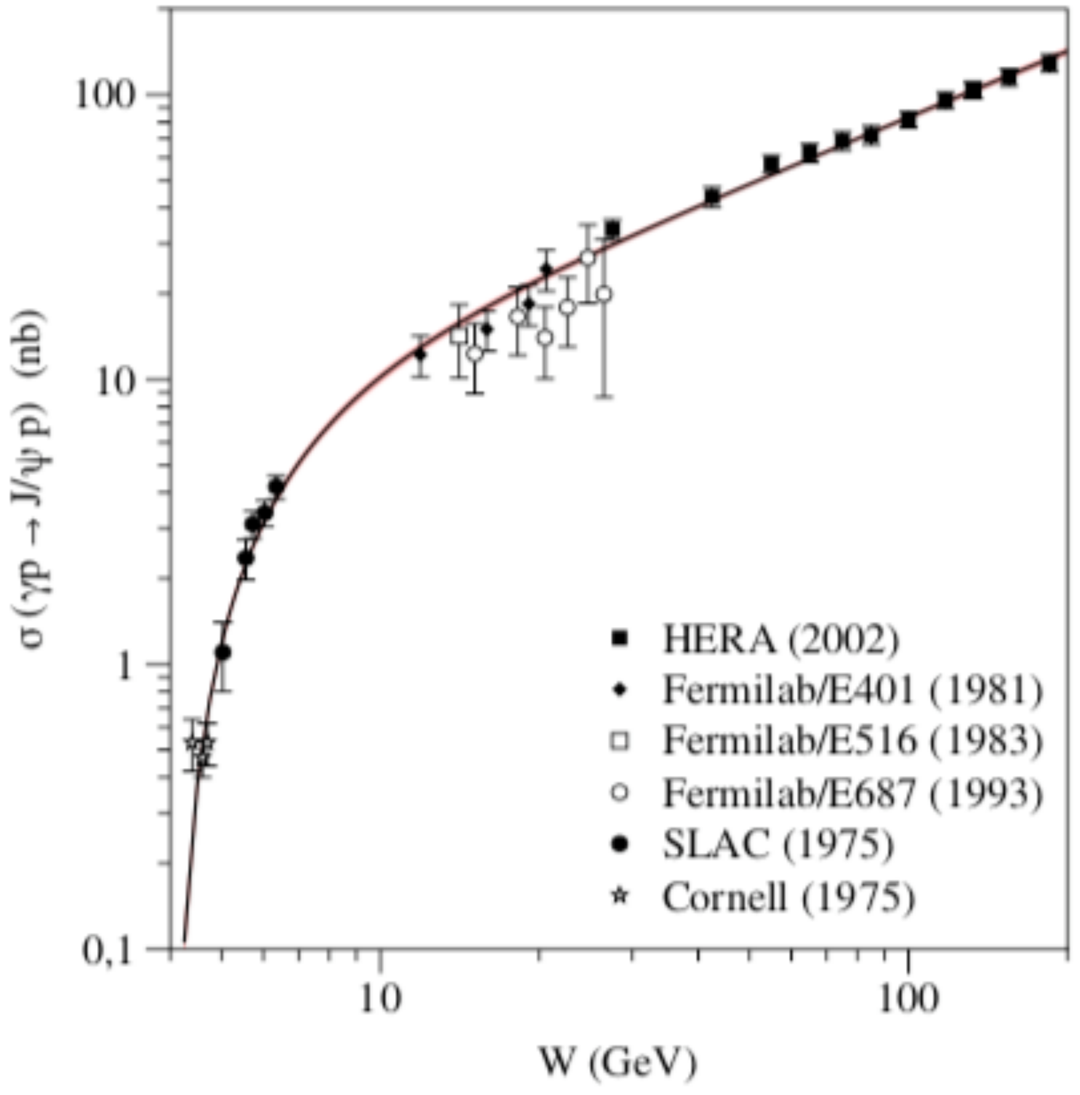

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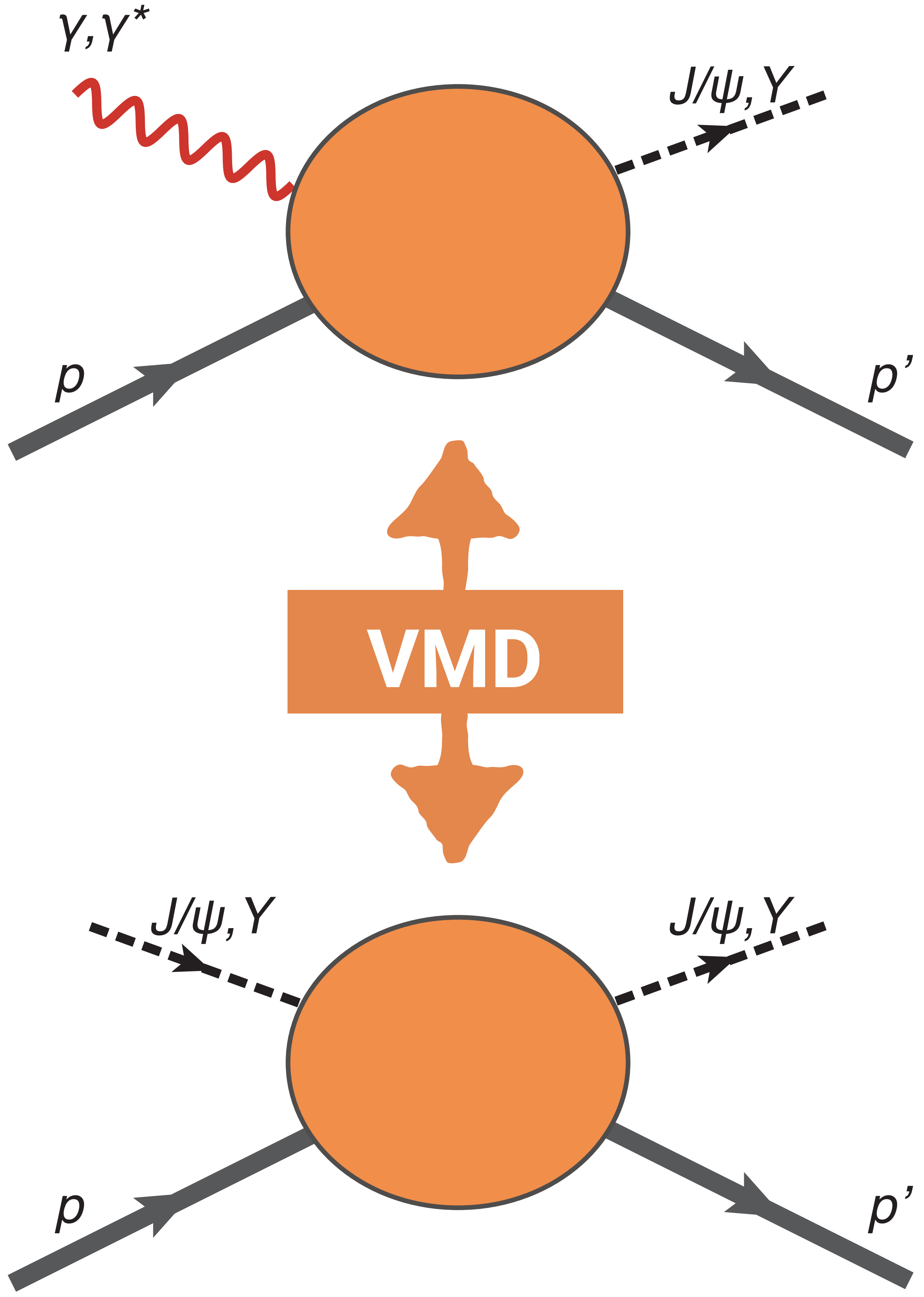

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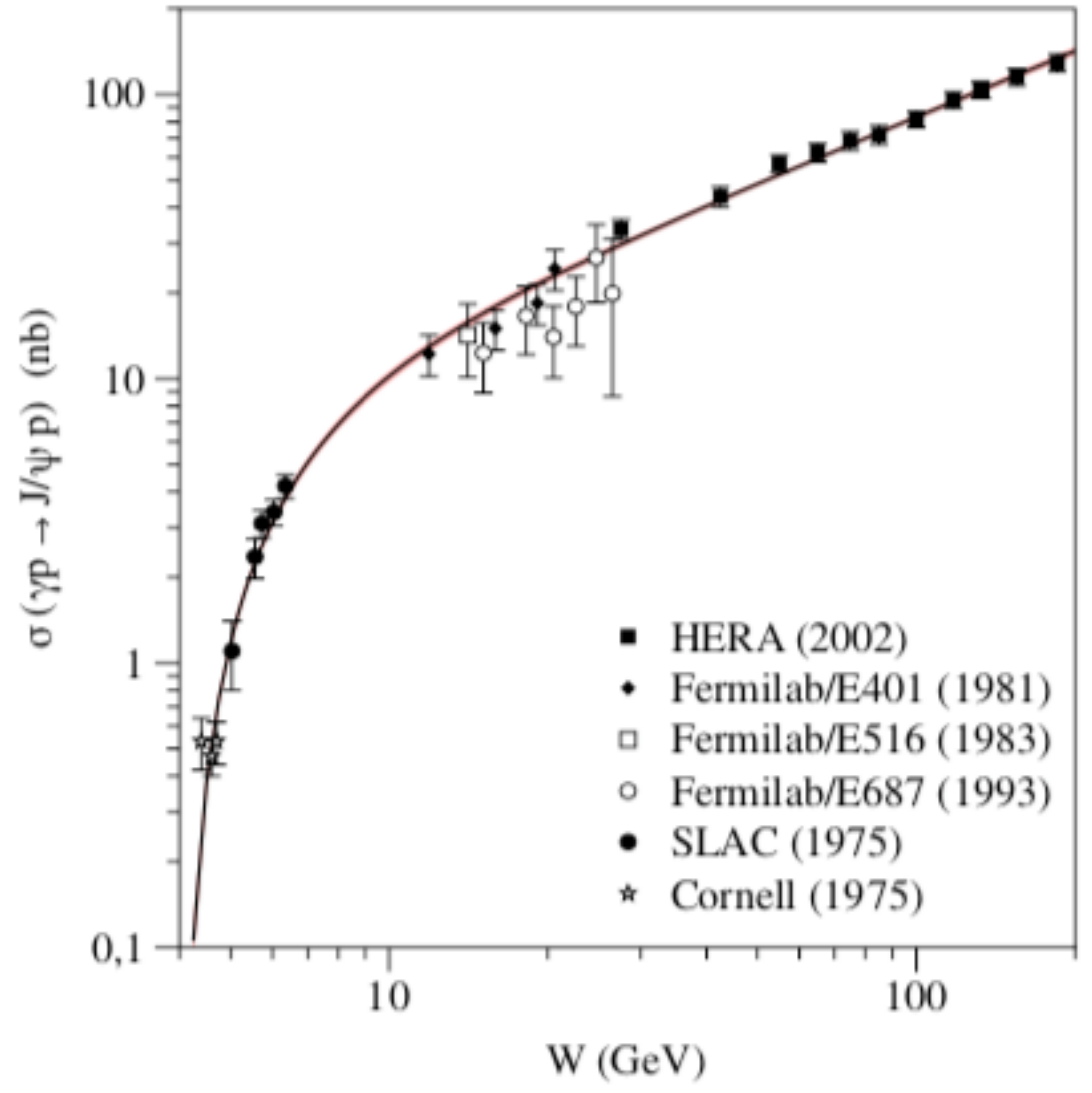

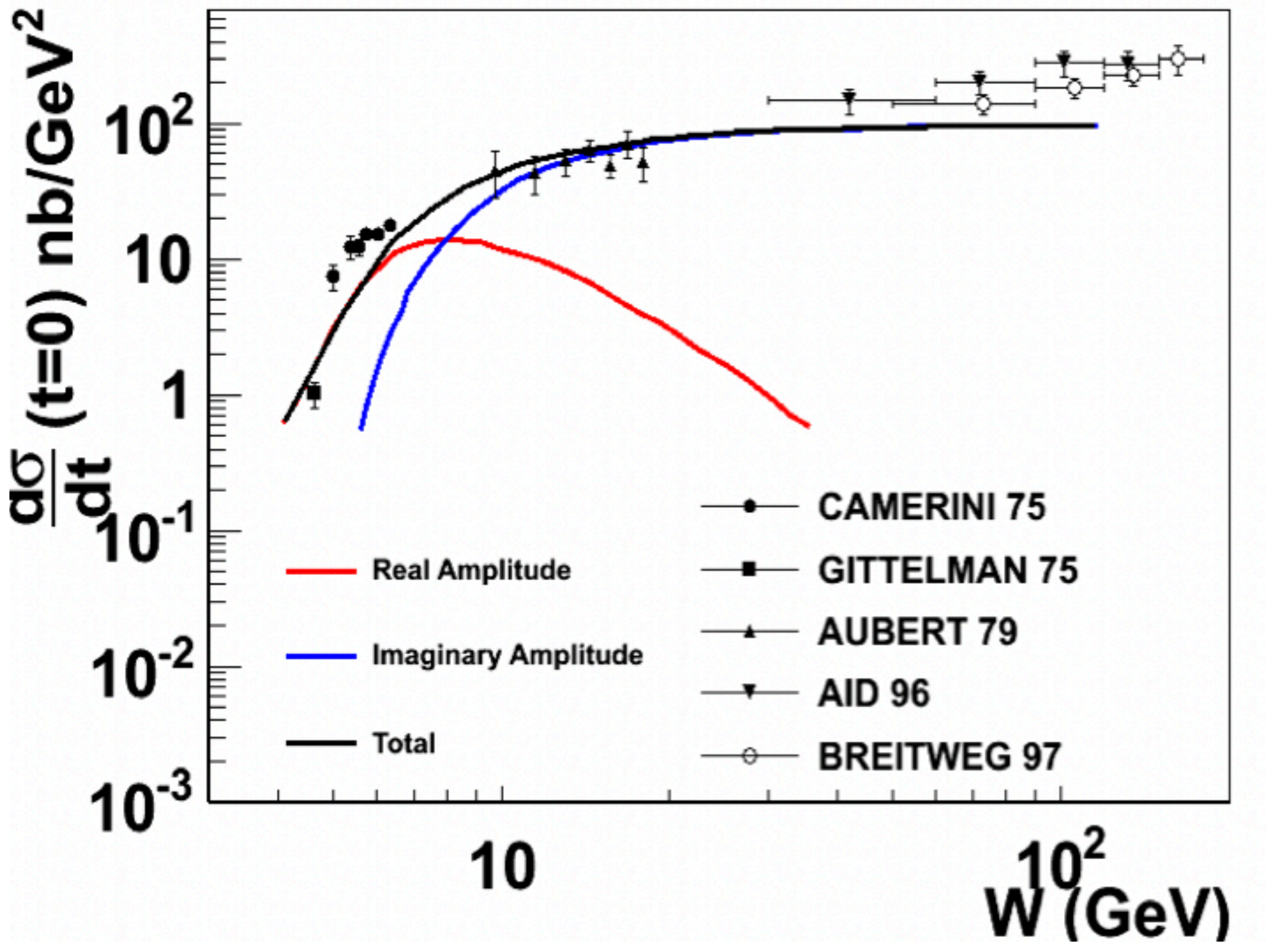

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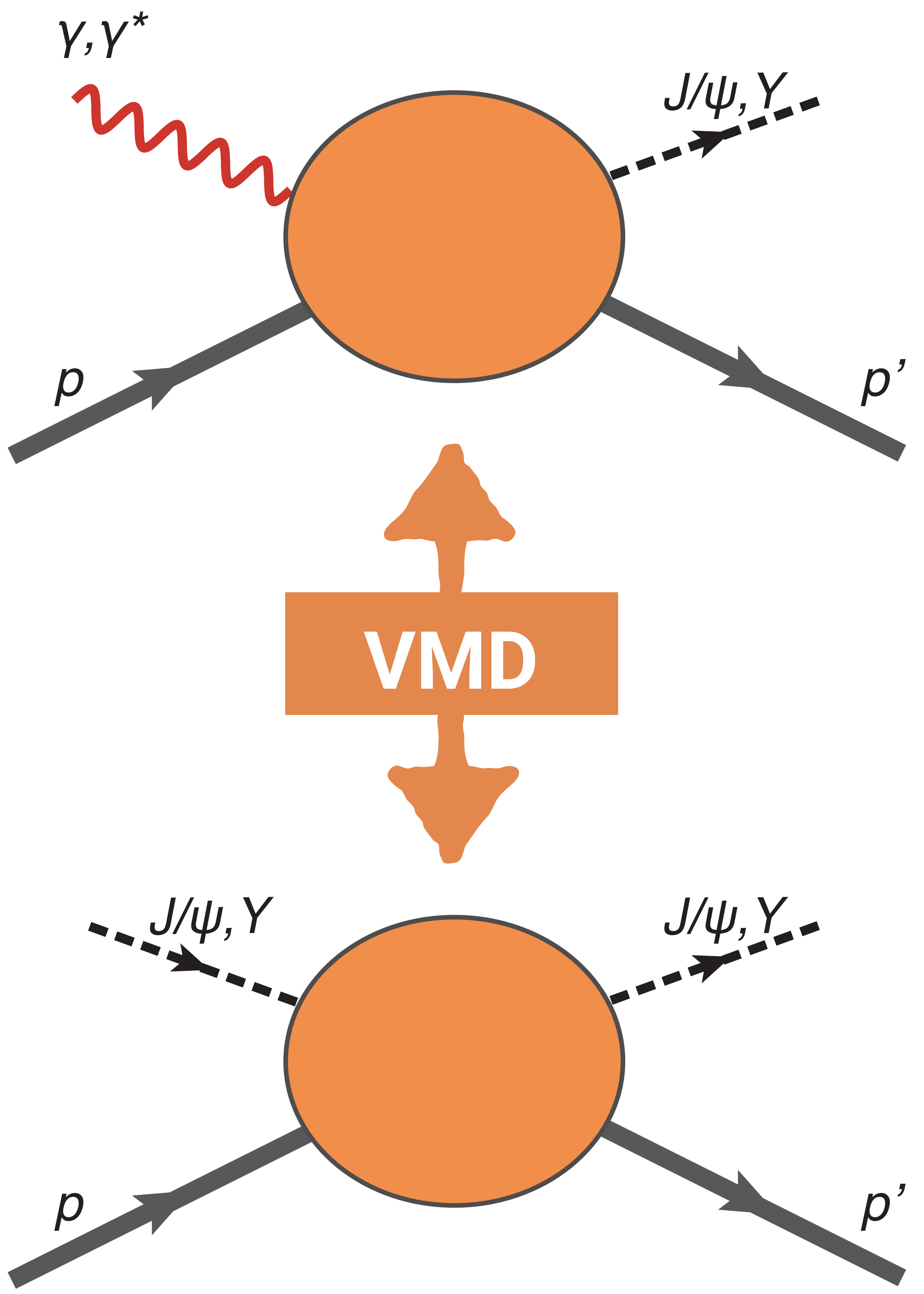

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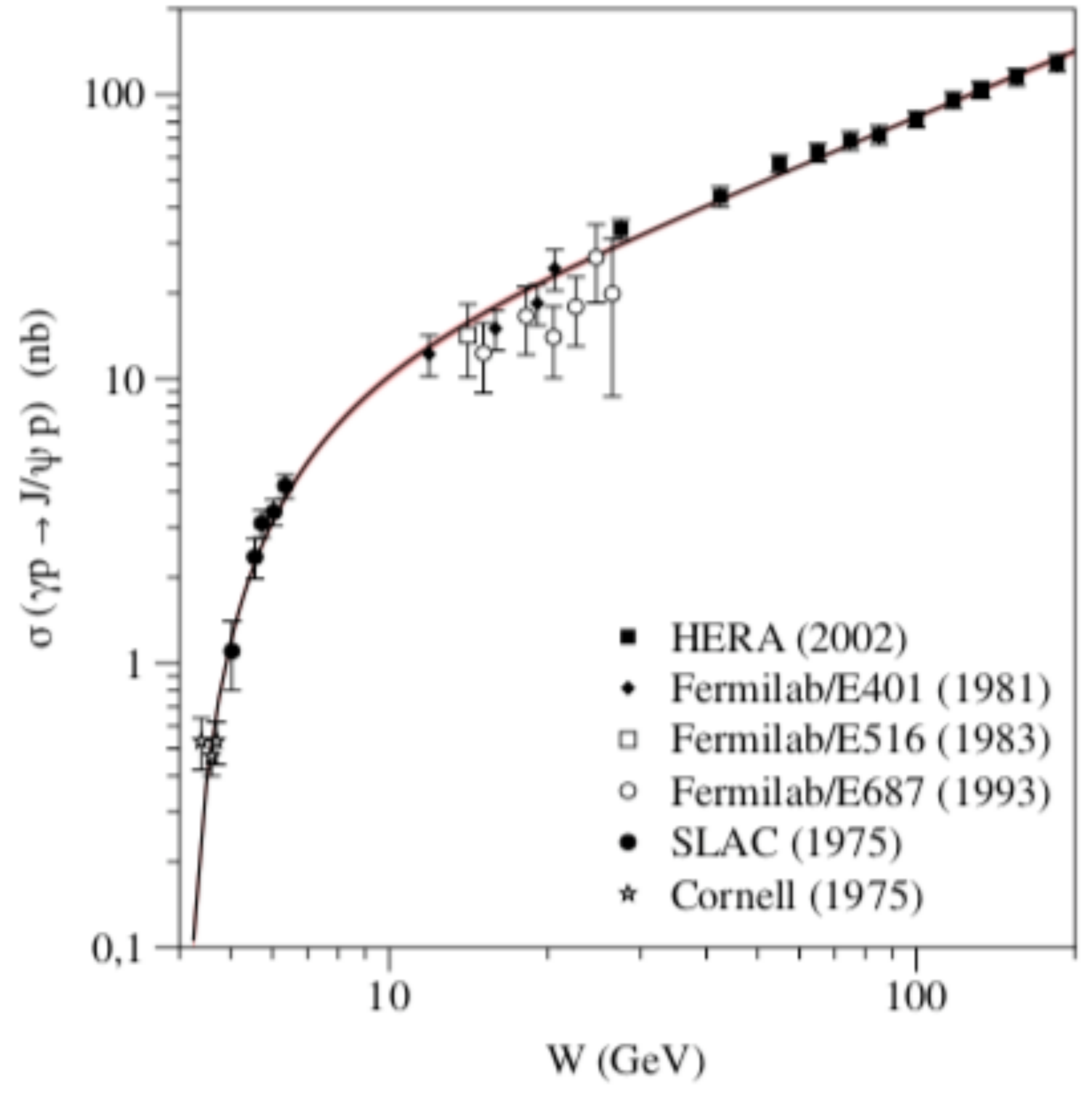
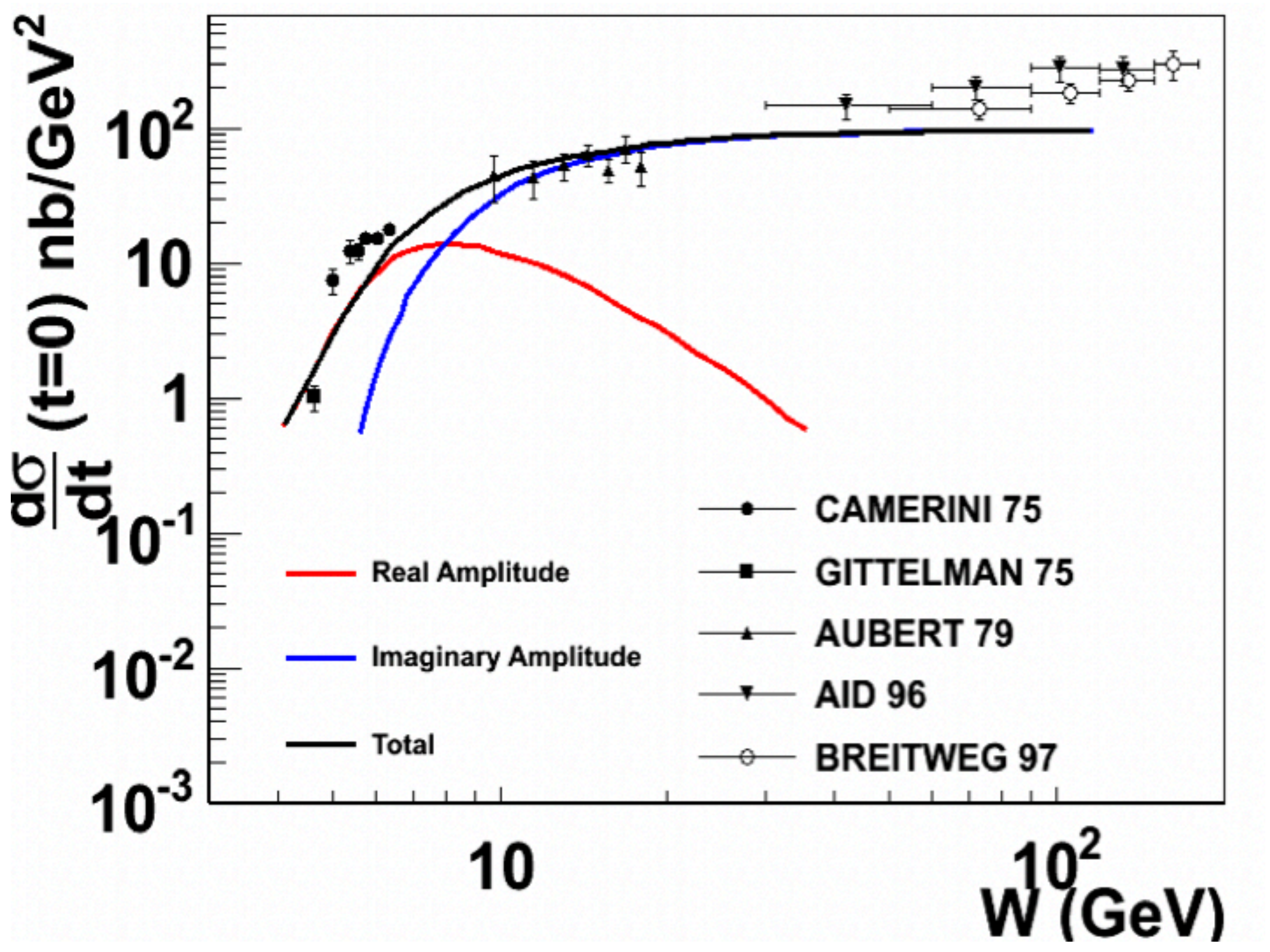
Experimental access to trace anomaly: *t*-dependence of quarkonium cross section *at* threshold





S. Joosten

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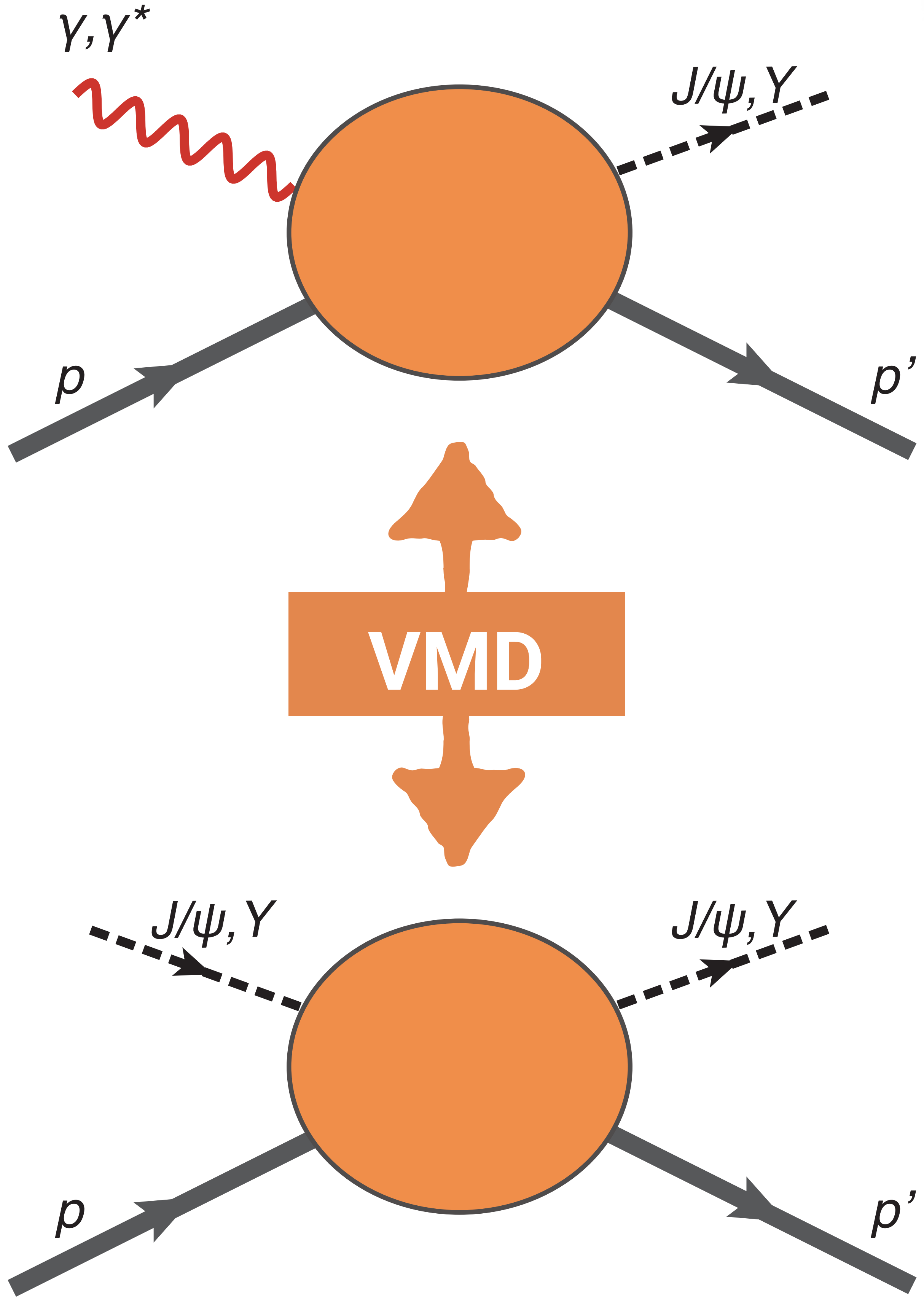

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WARNING LABEL: Keep in mind, no rigorous factorization theorem (yet)!

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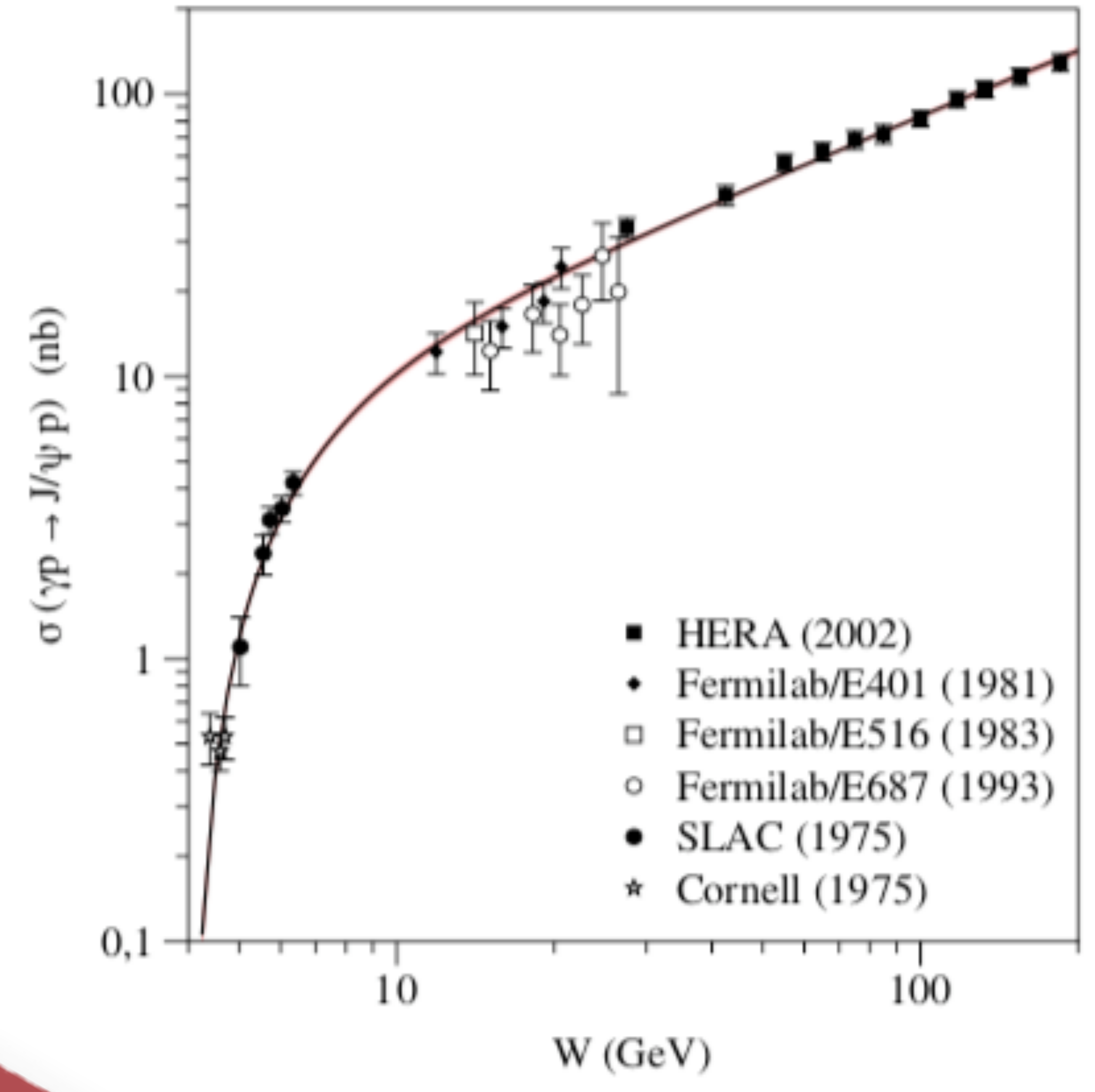

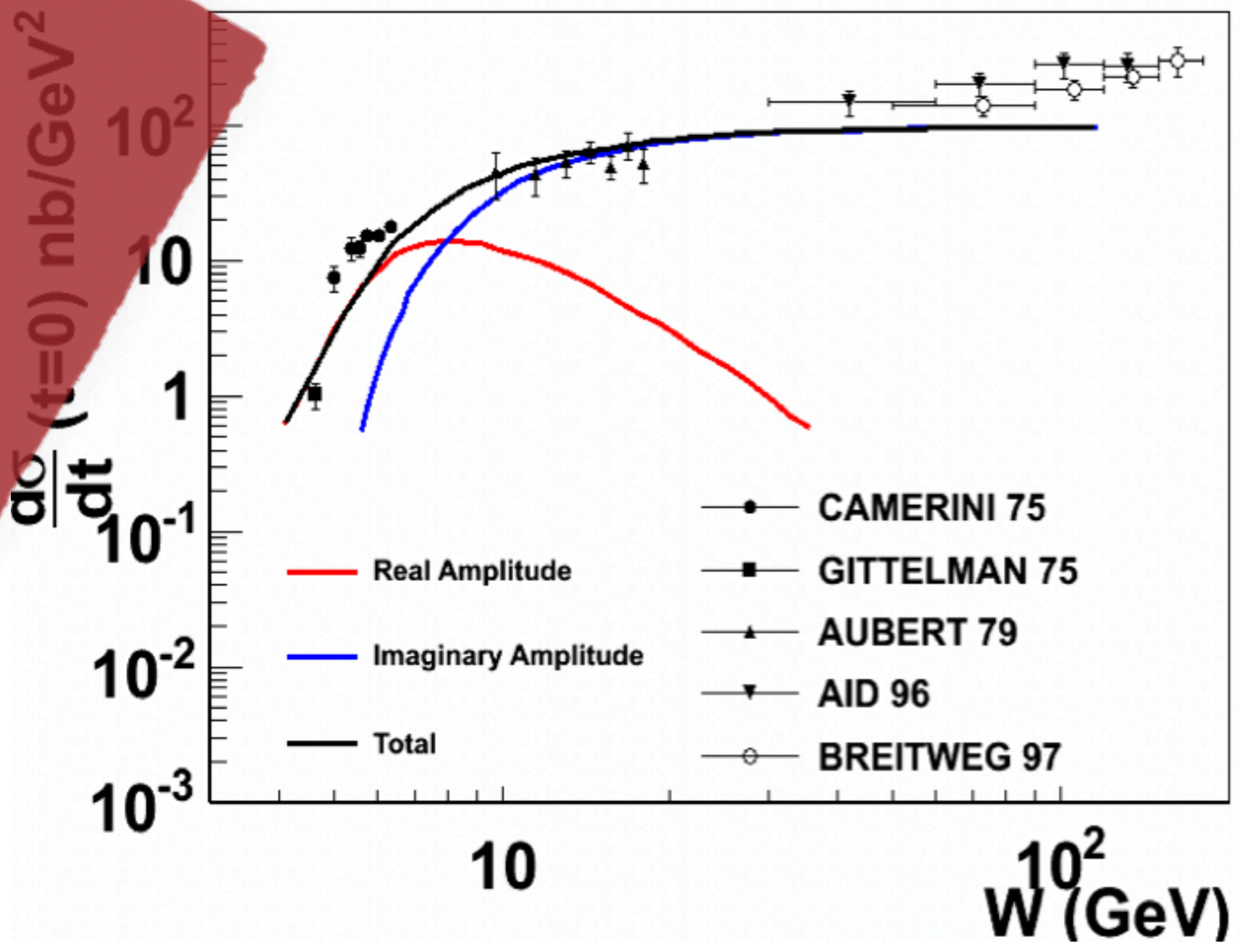

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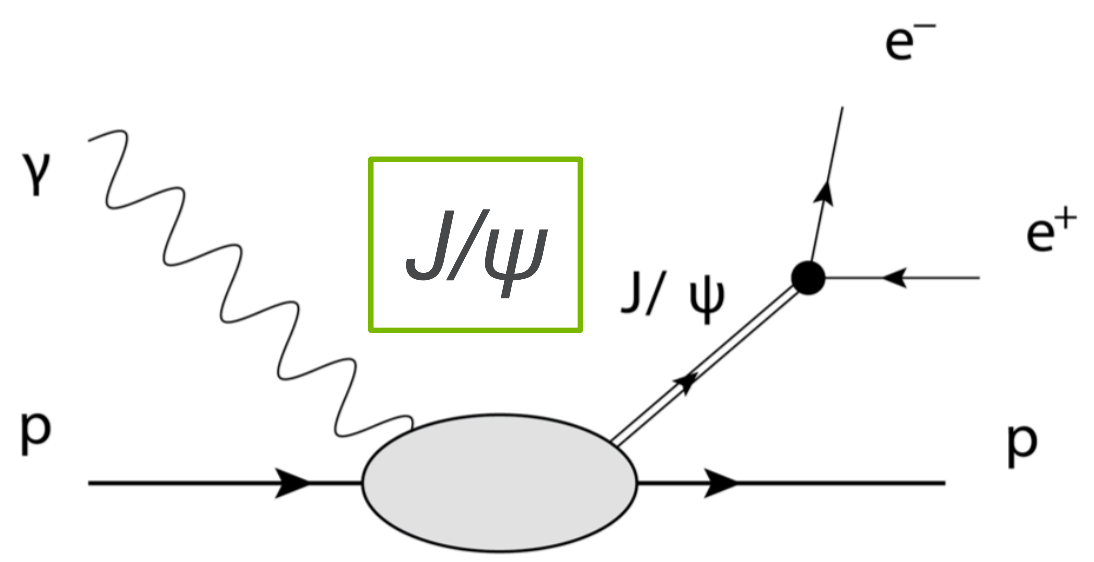

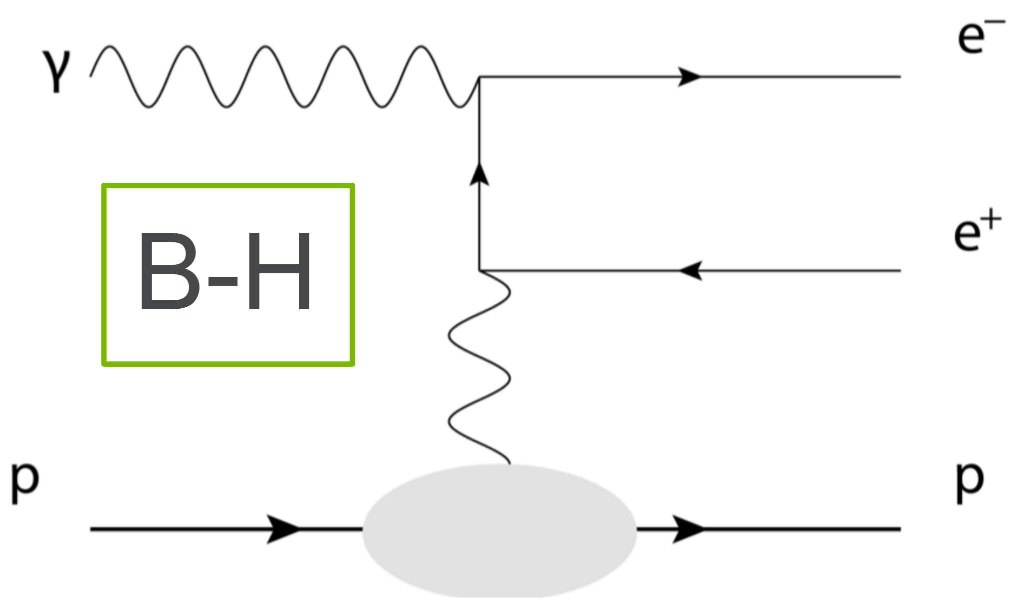

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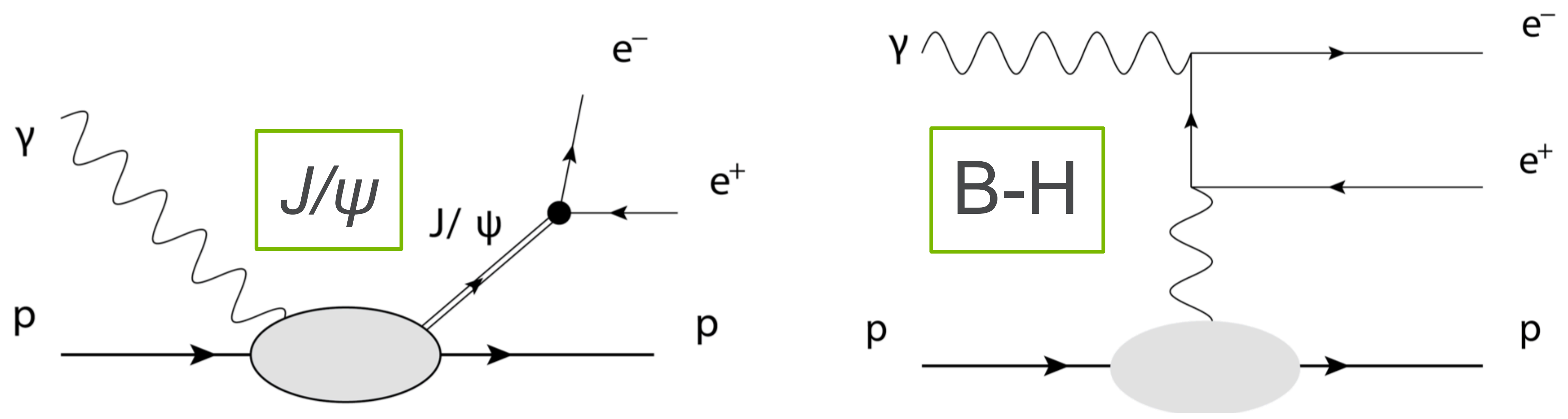

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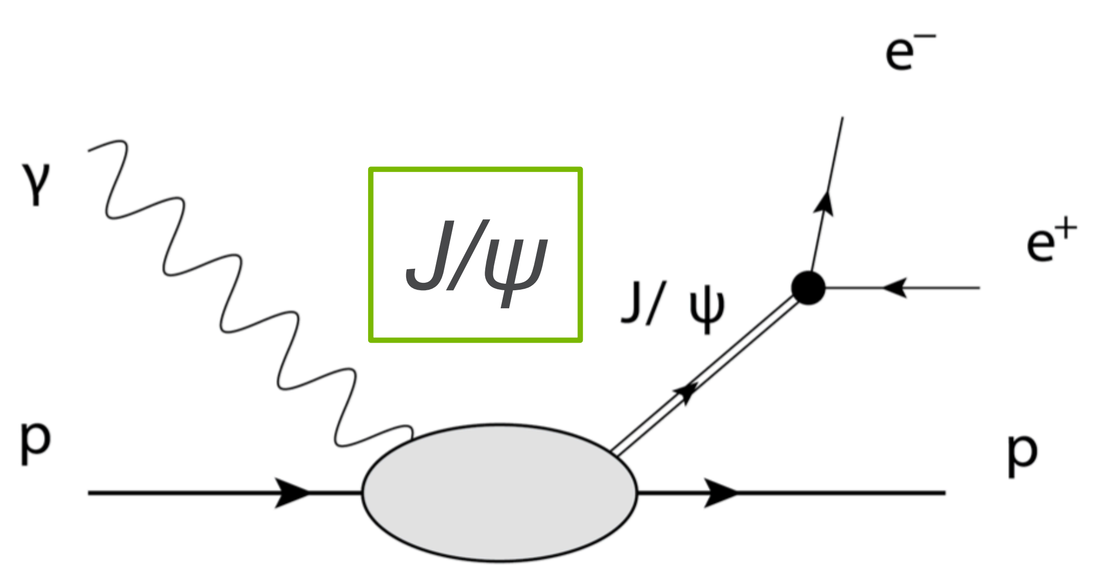
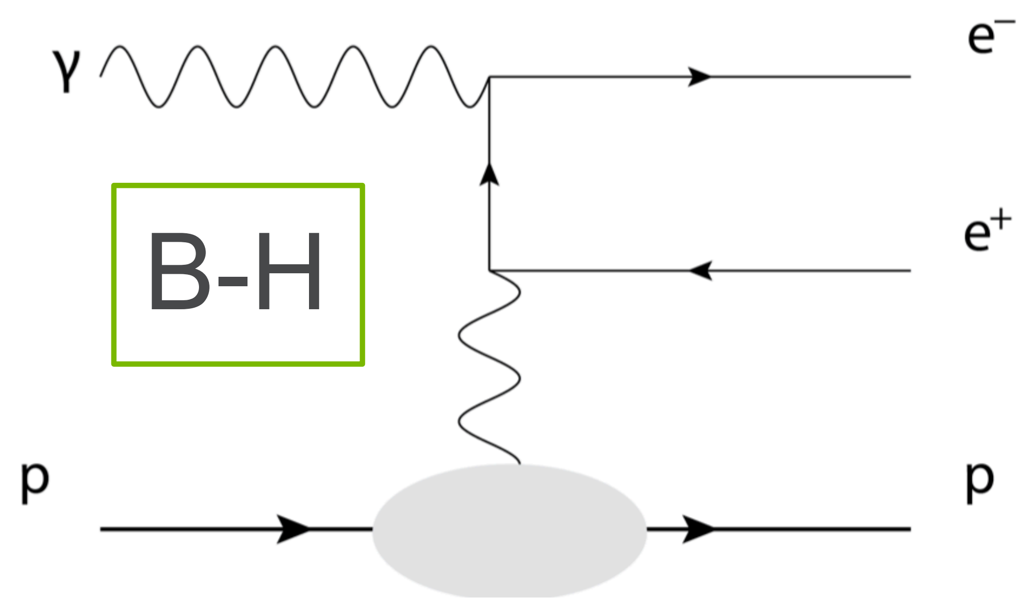
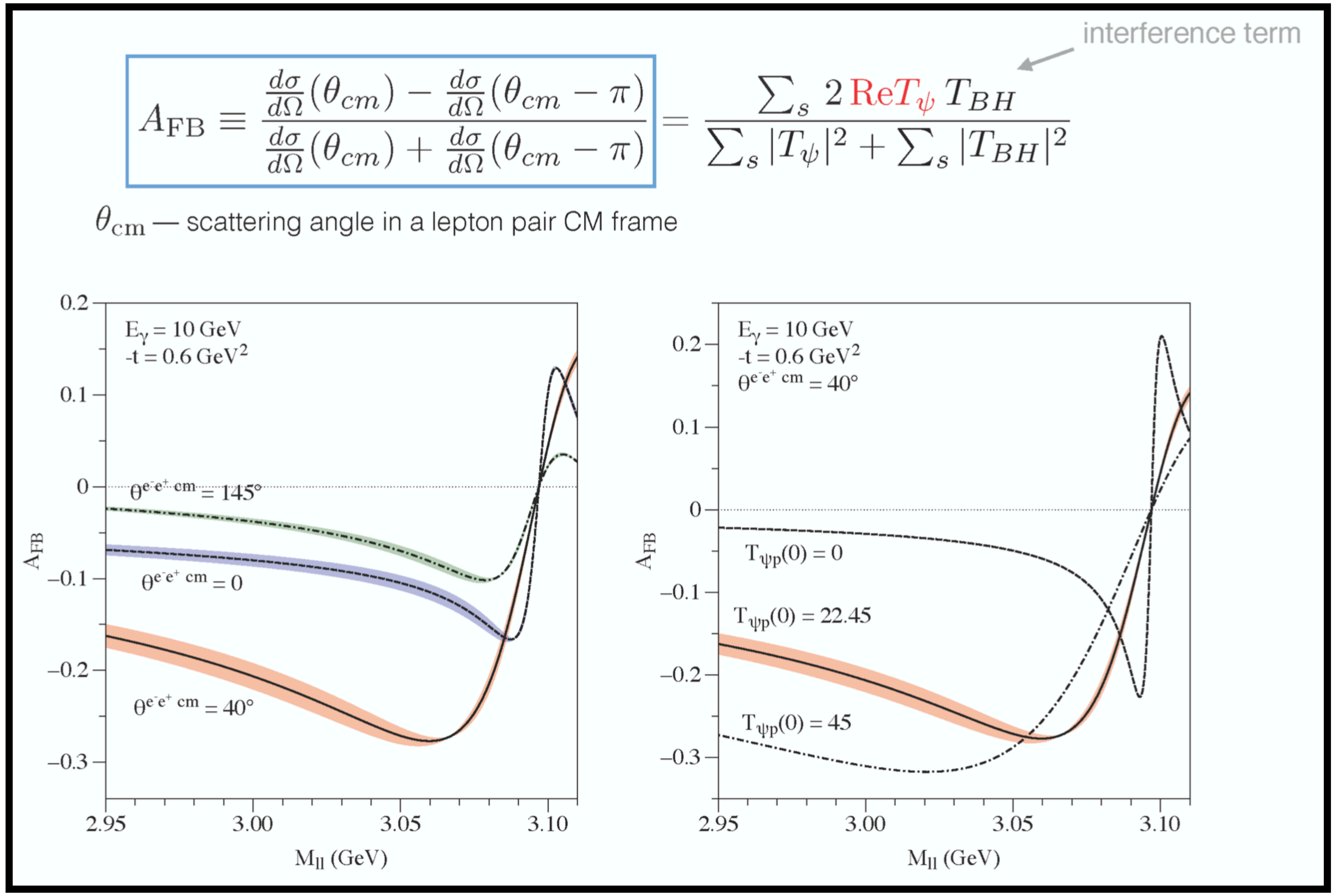




- Interference between elastic *J/ψ* production near threshold and Bethe-Heitler
- Forward-backward asymmetry near *J/ψ* invariant mass peak proportional to **Re(*T*$_{\psi p}$)**

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

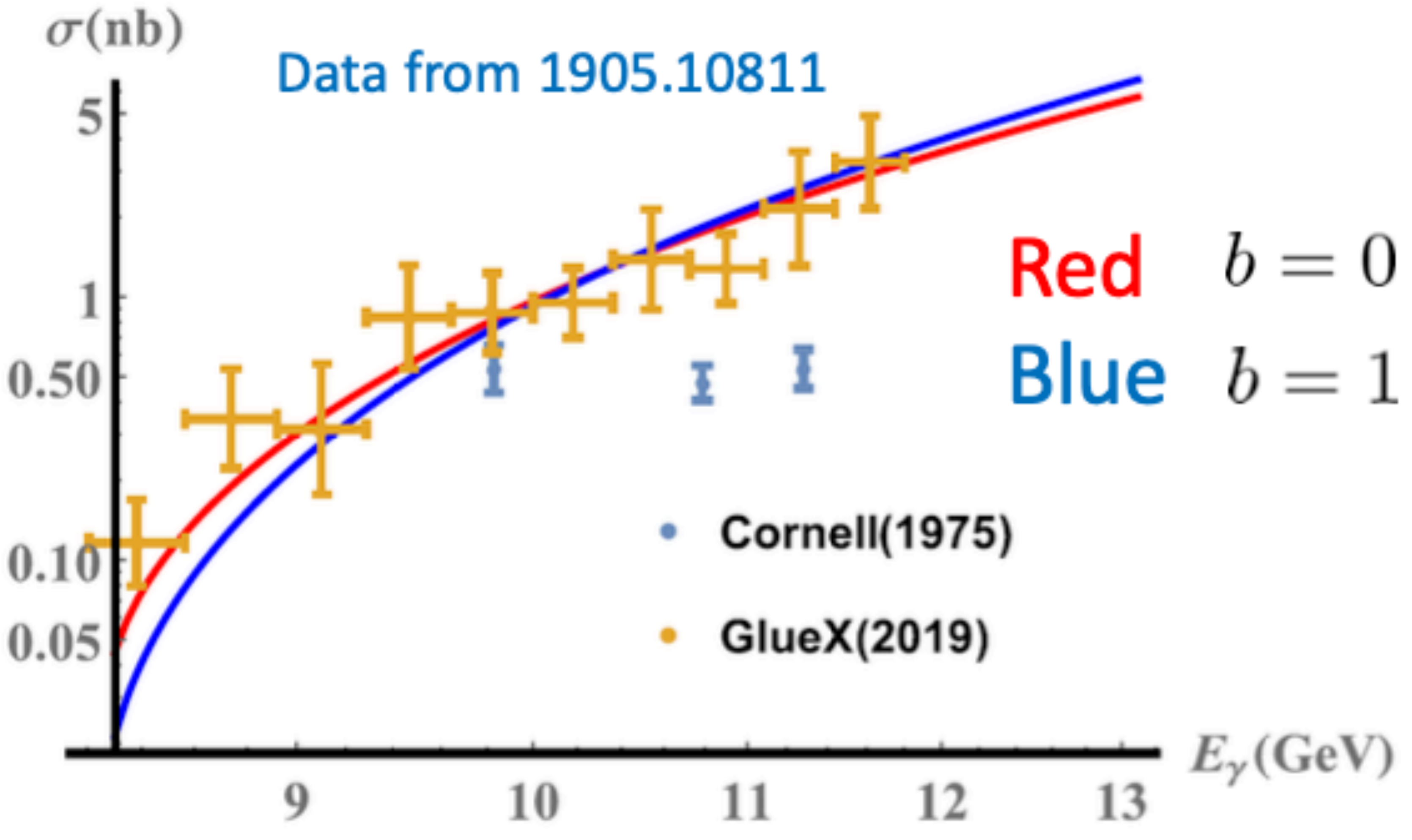


Slide from O. Gryniuk

Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)
Y. Hatta *et al.*, 1906.00894 (2019)

PRODUCTION MECHANISM NEAR THRESHOLD?

Holographic approach



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PRODUCTION MECHANISM NEAR THRESHOLD?

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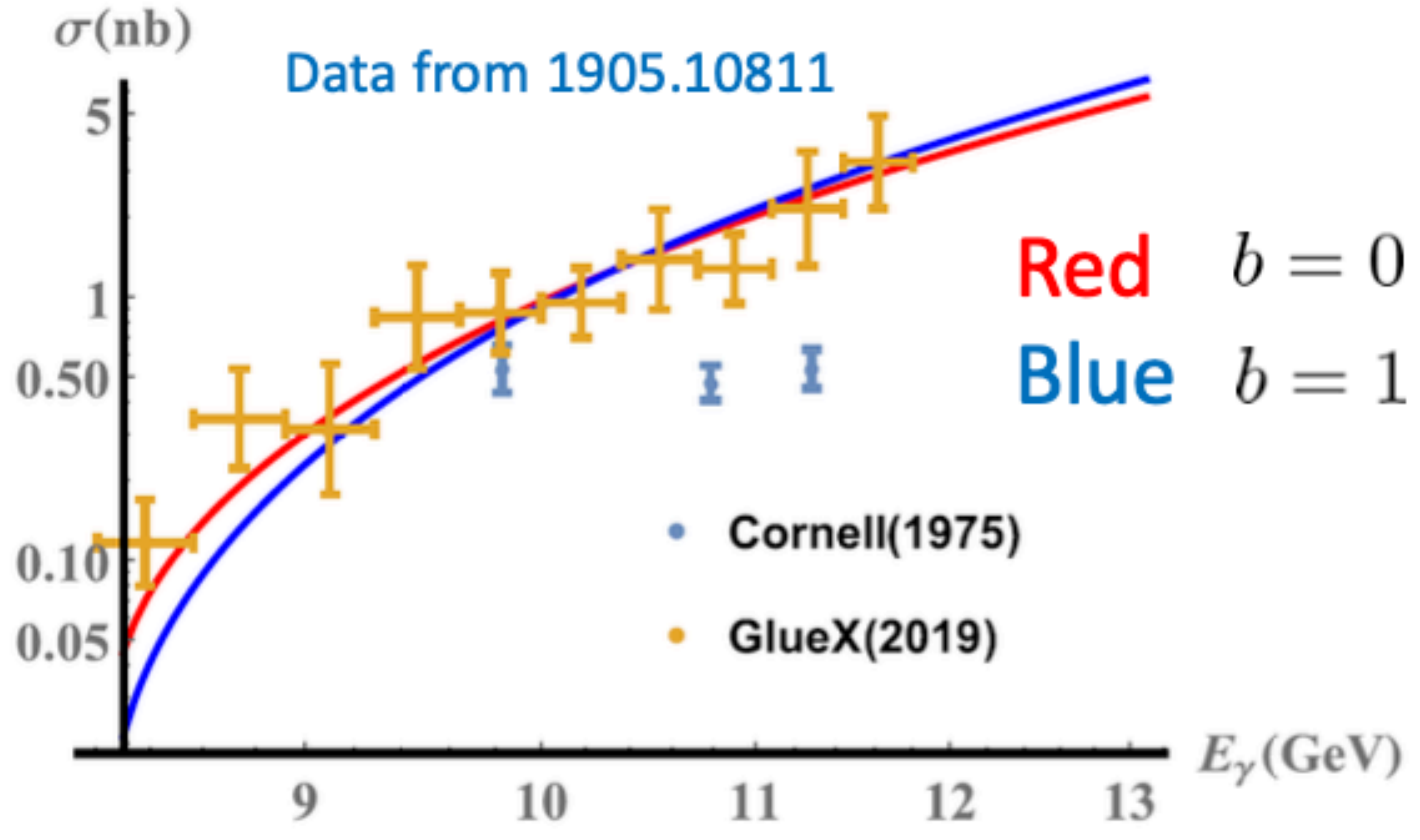

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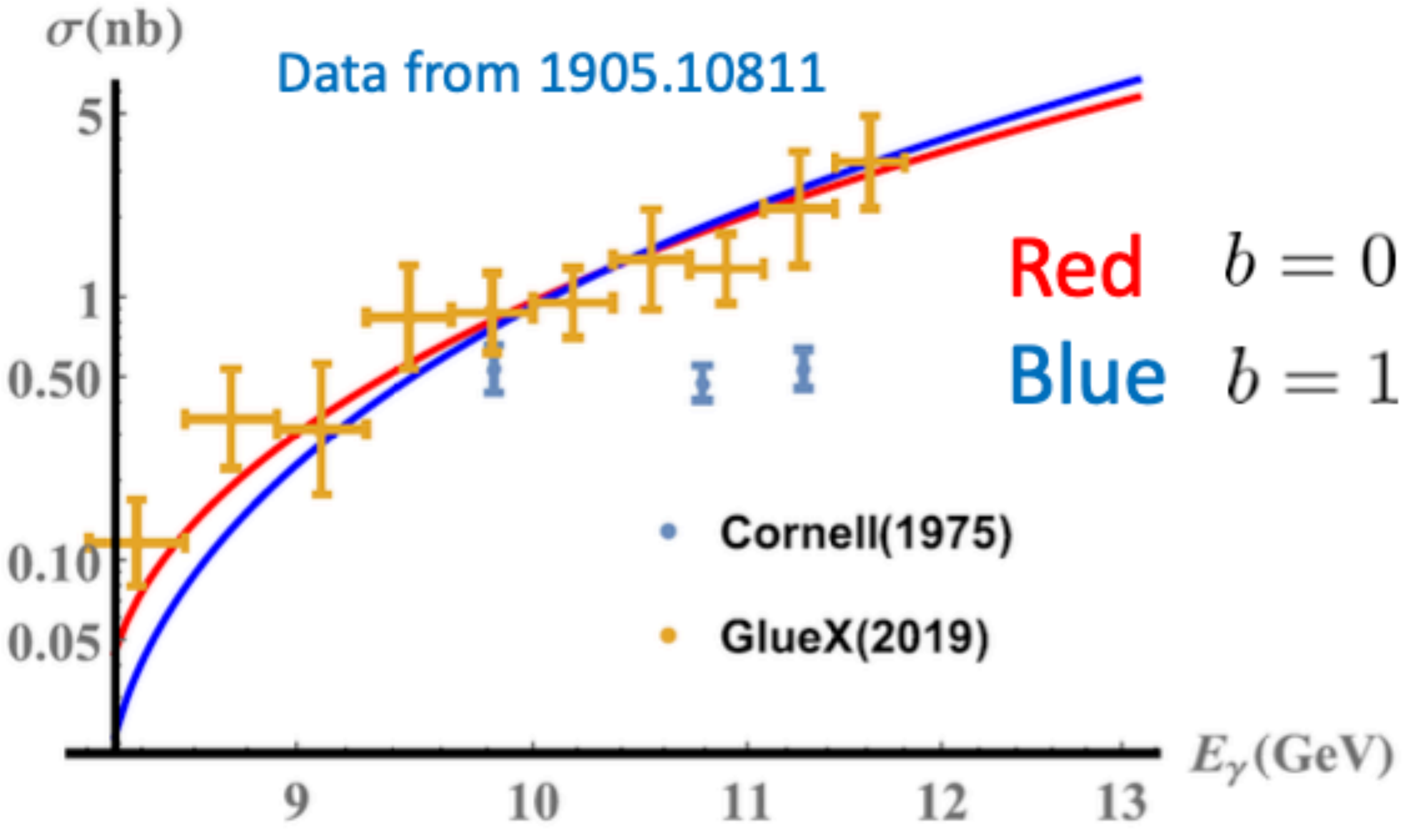

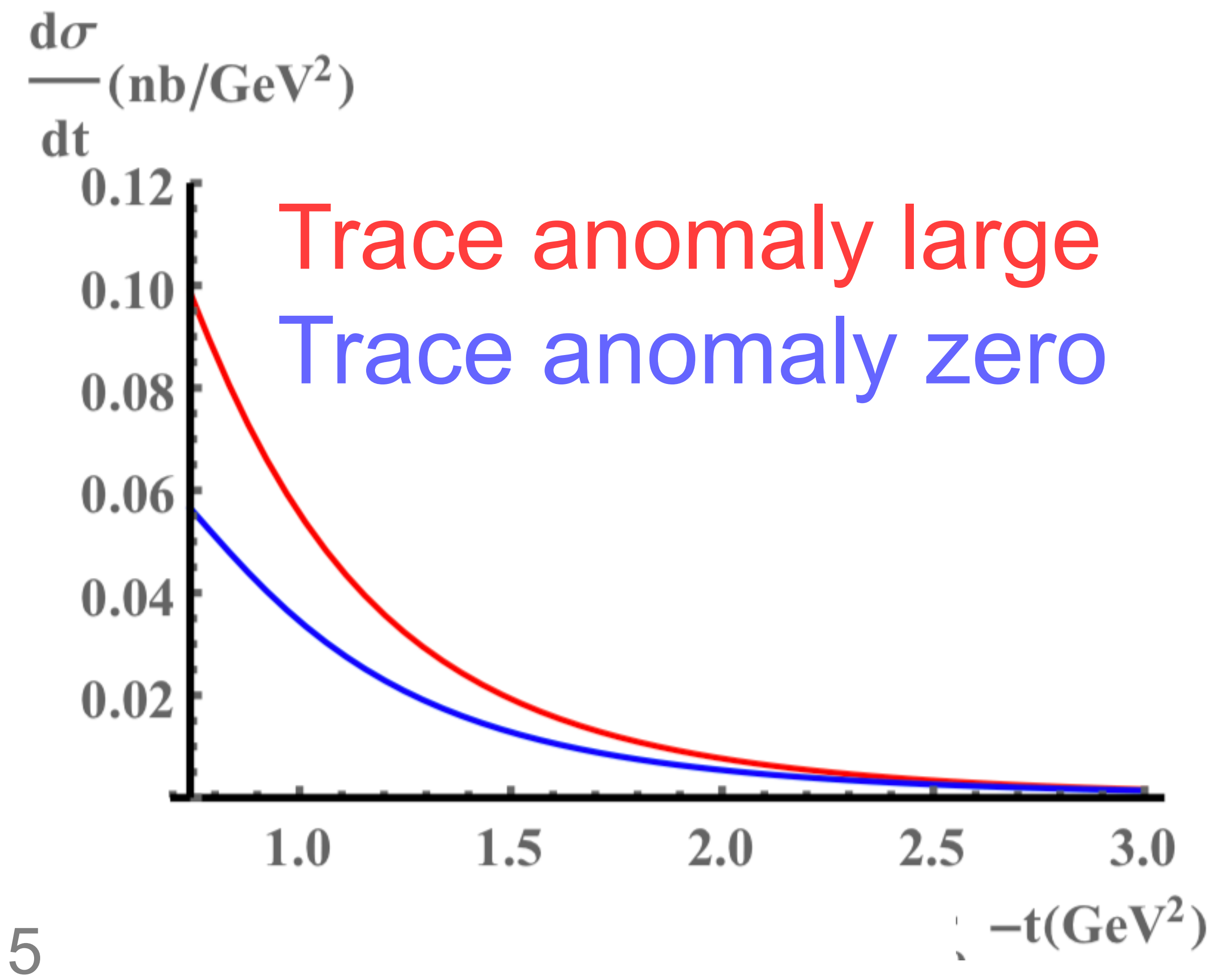

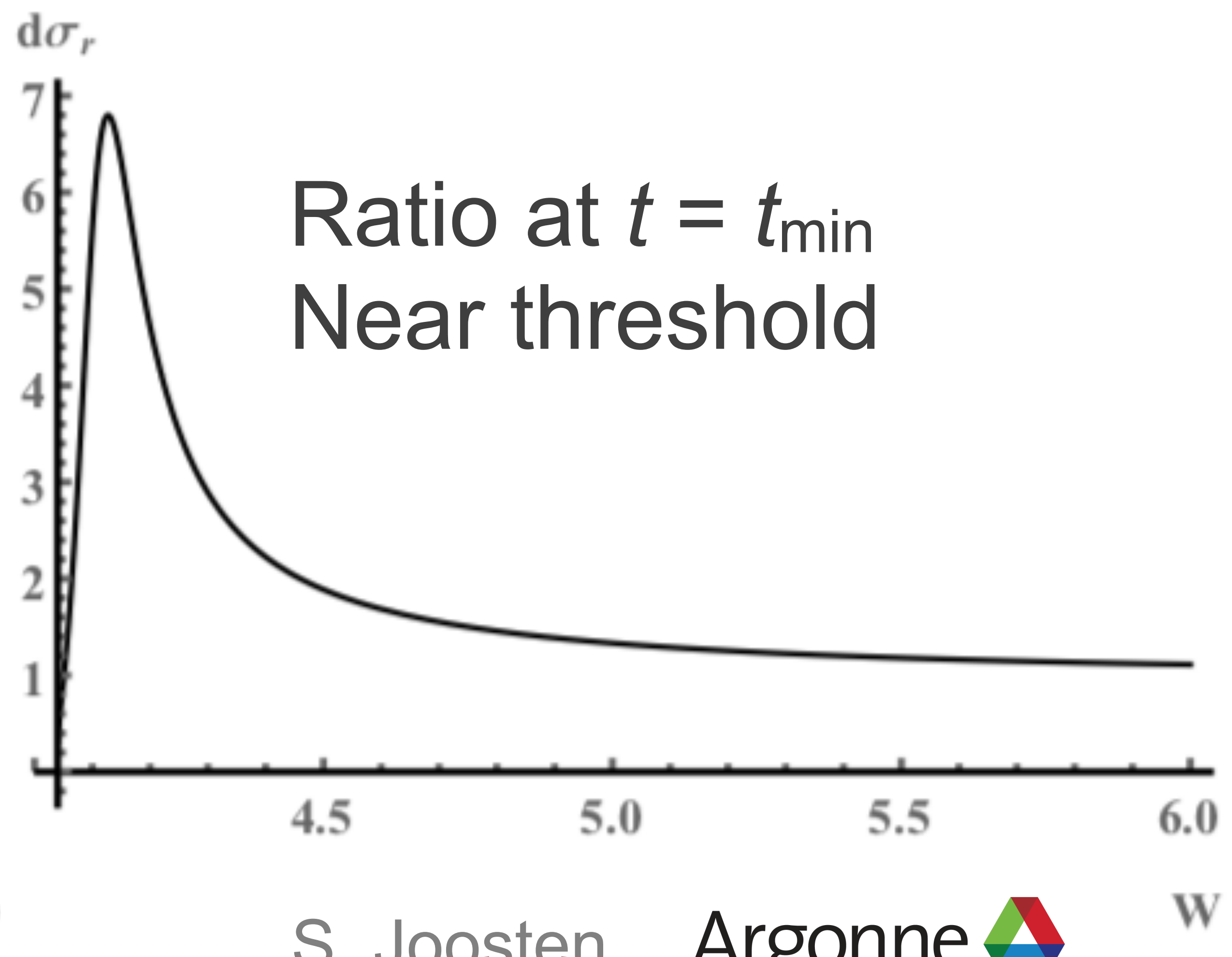

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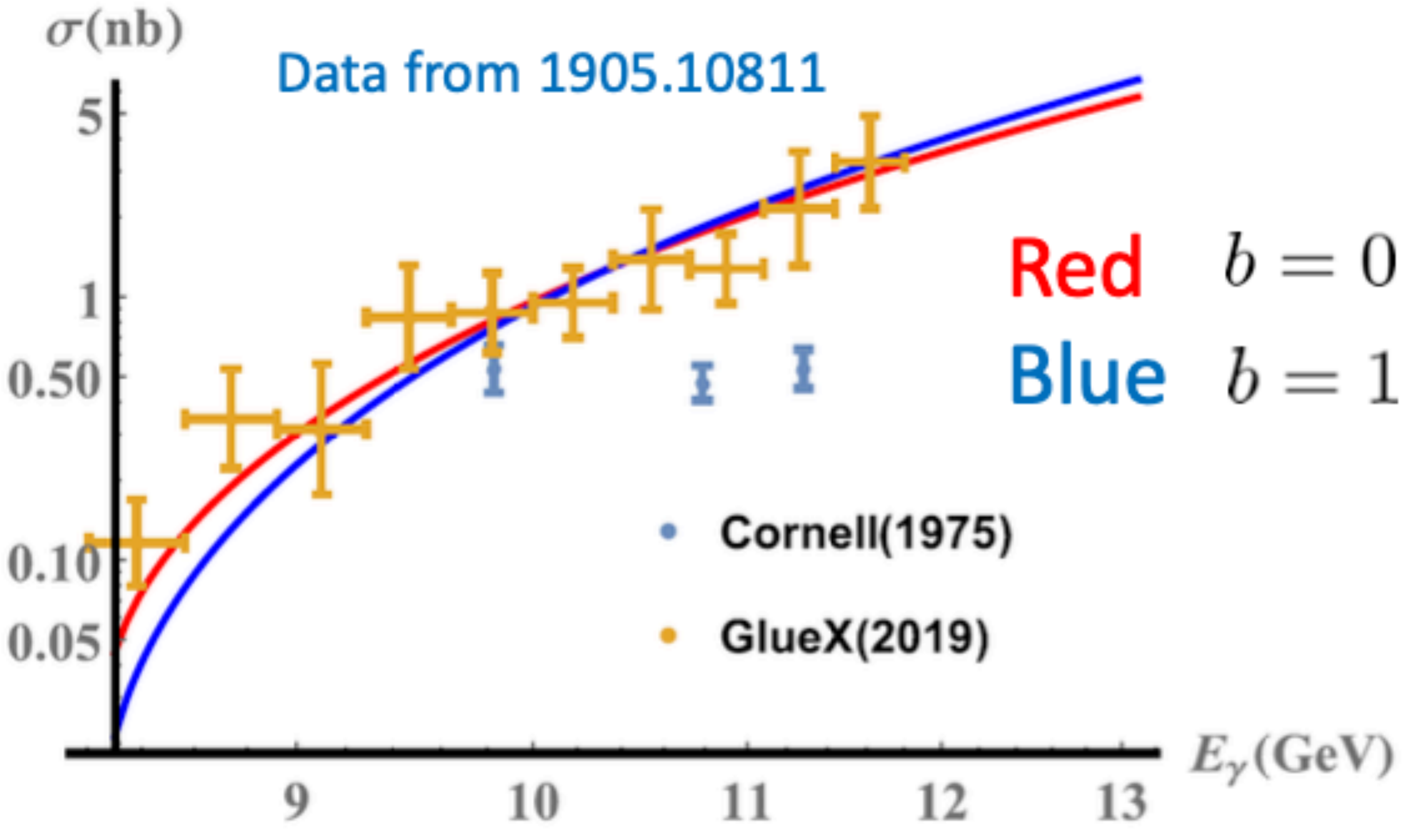
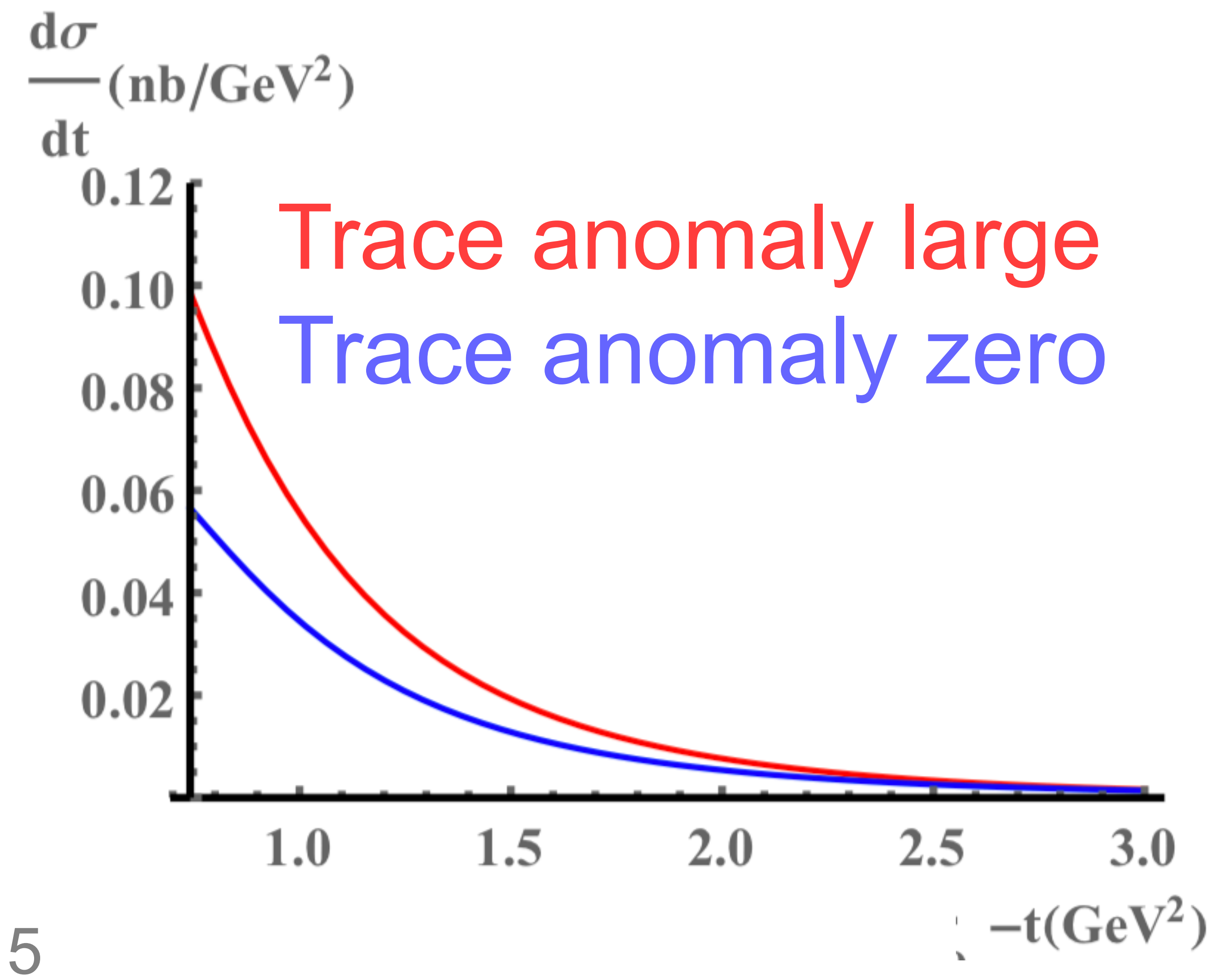
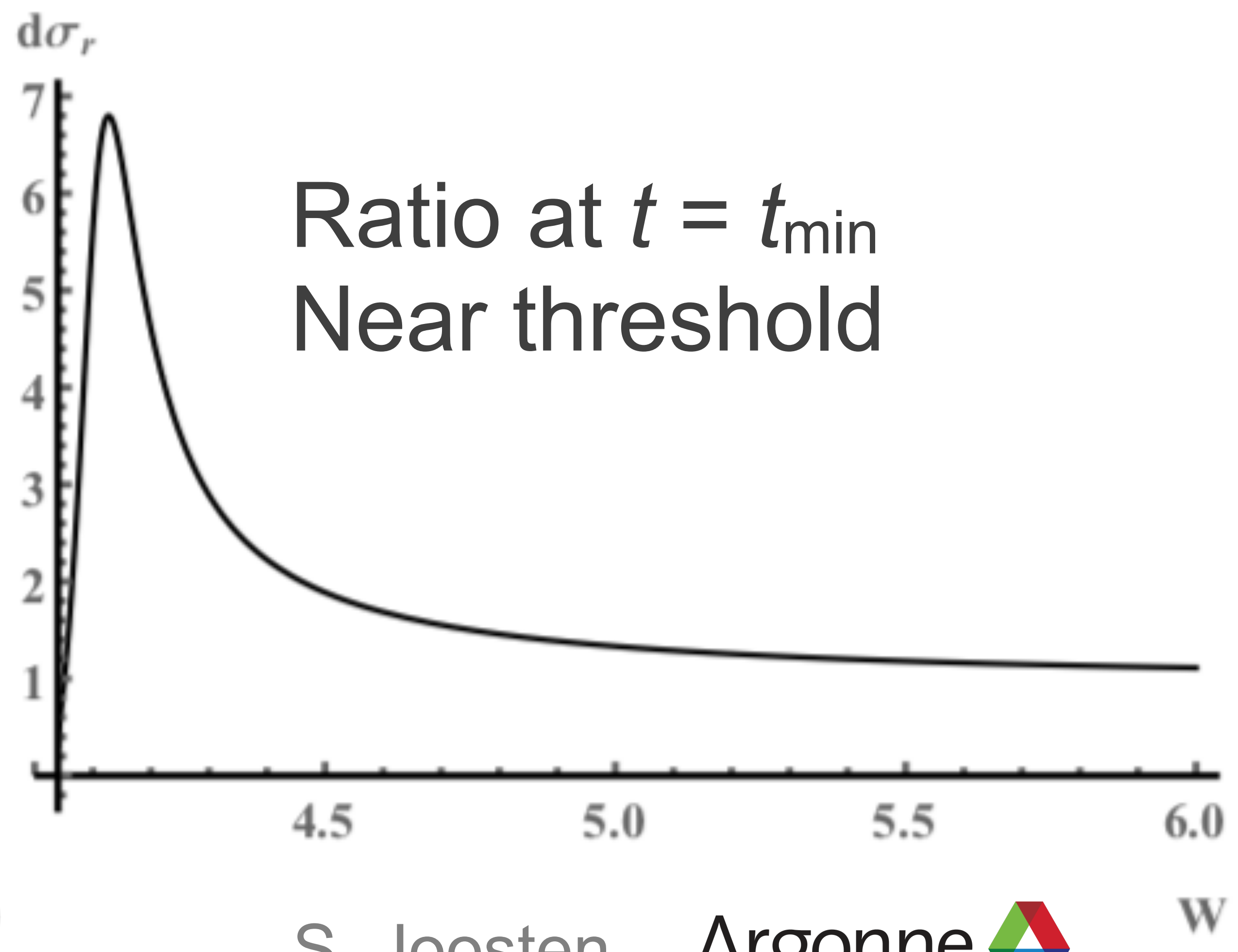


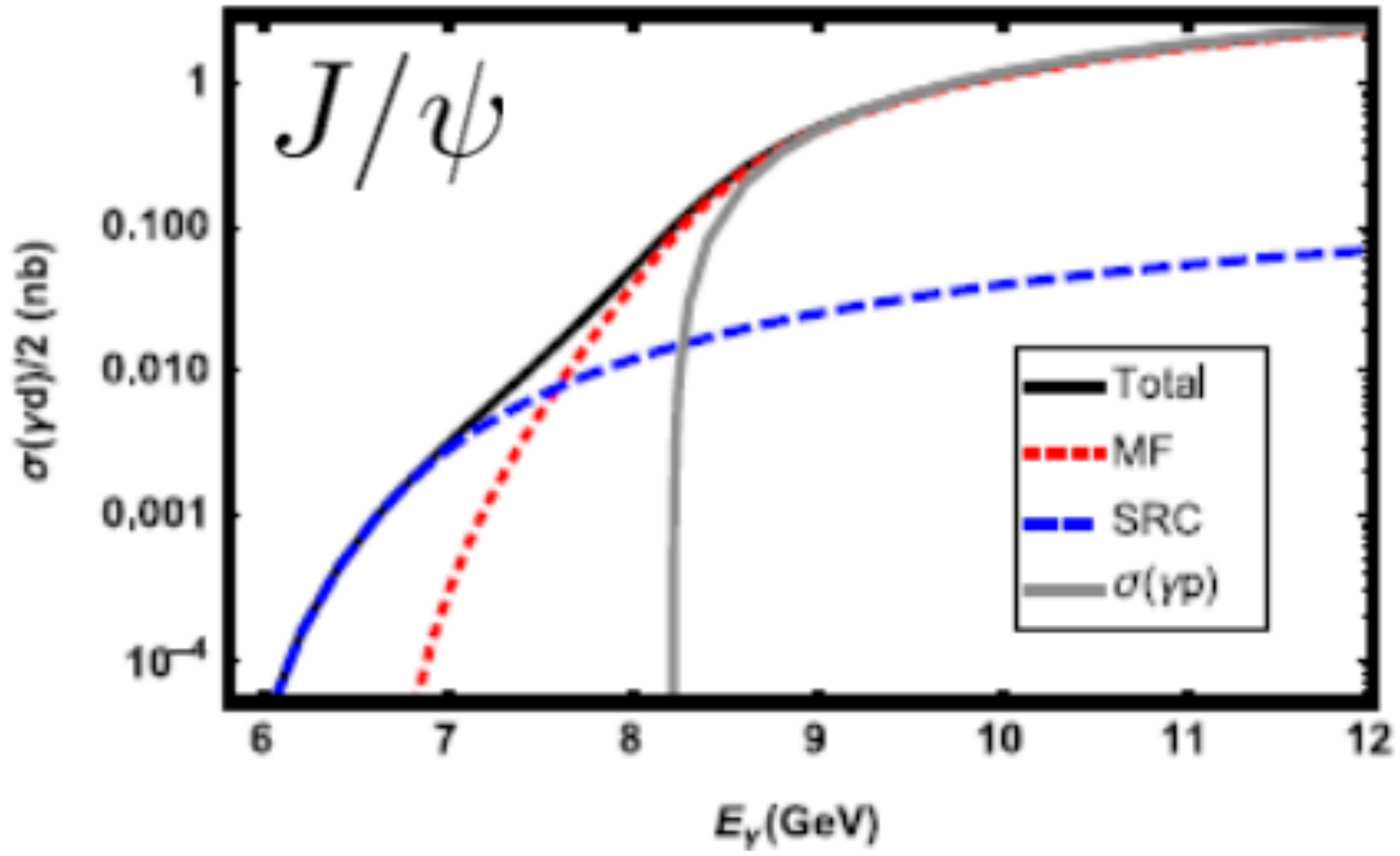


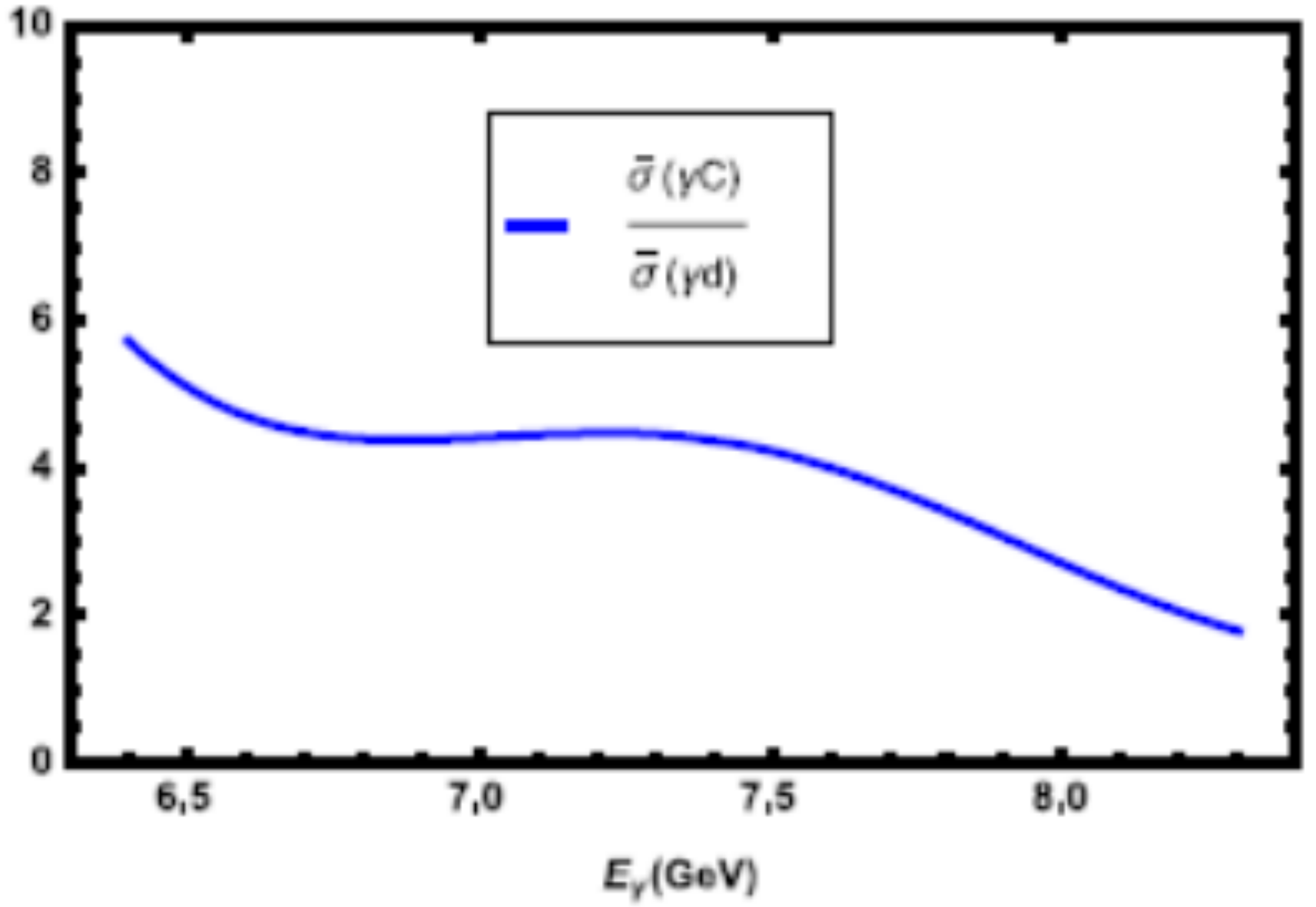


Hatta, Strickman, Xu, Yuan, 1911.11706 (2019)
Xu, Yuan, PLB801 (2020) 135187

INDEPENDENT PROBE FOR SRC UNIVERSALITY

Through incoherent sub-threshold quarkonium production





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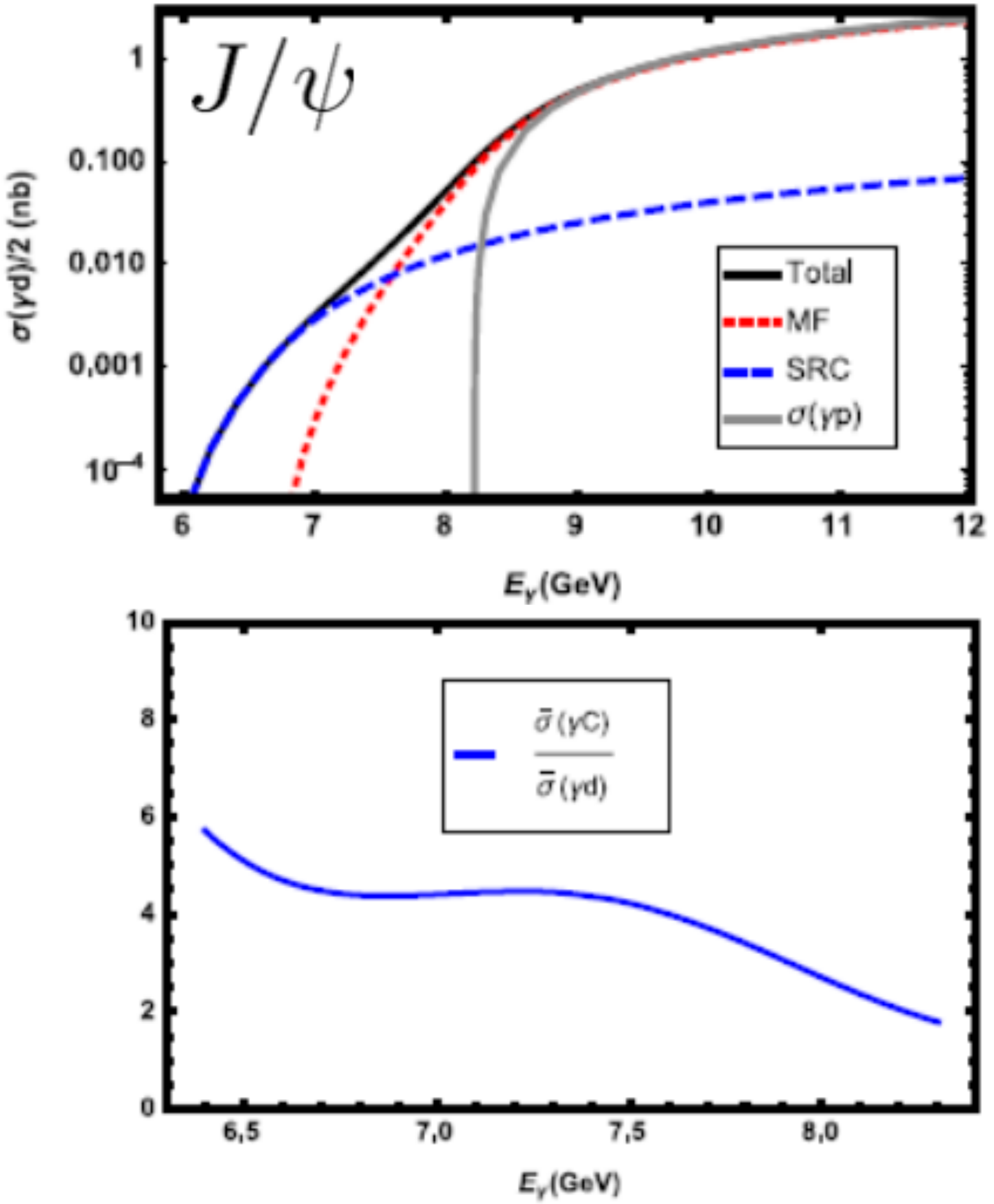

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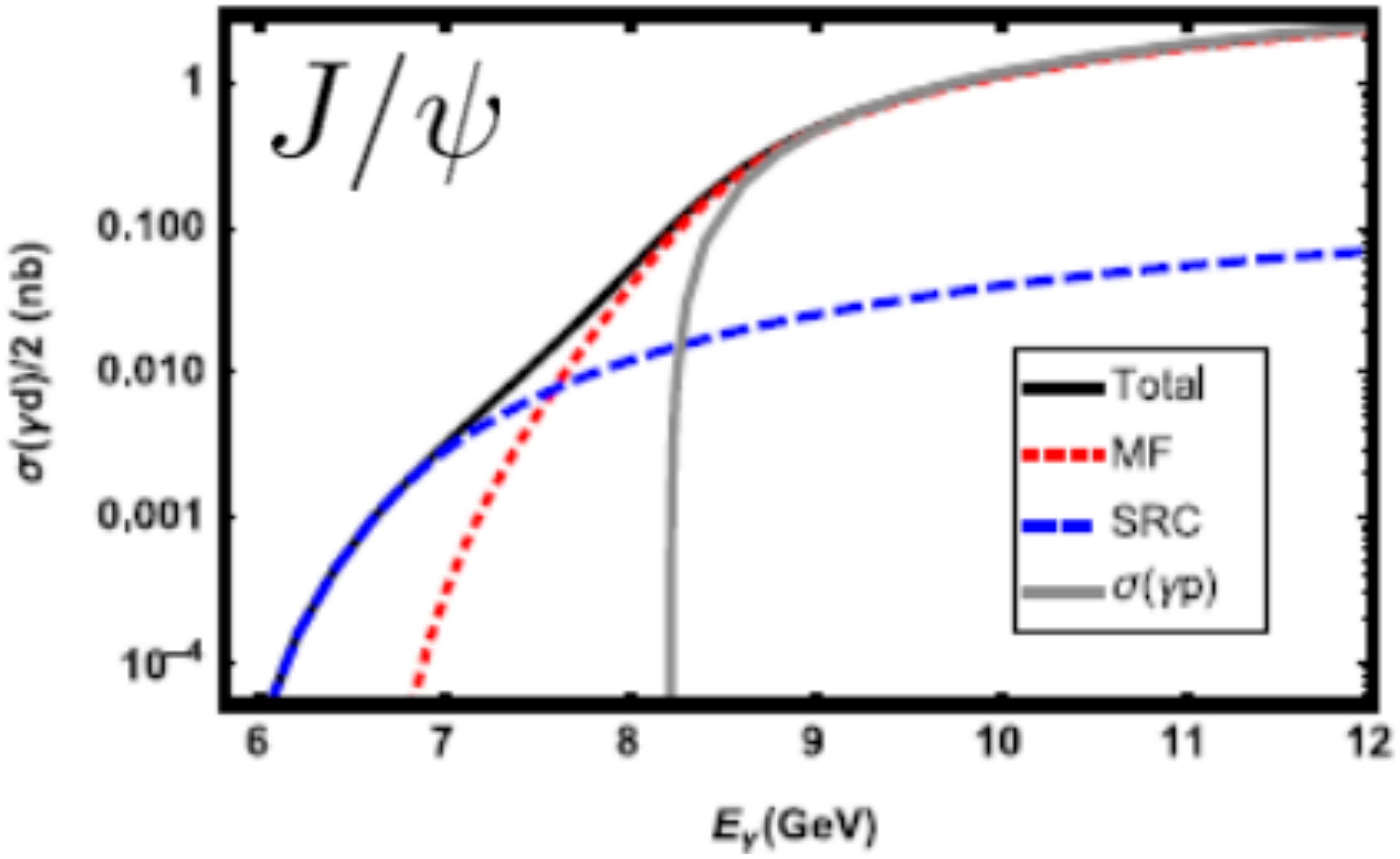

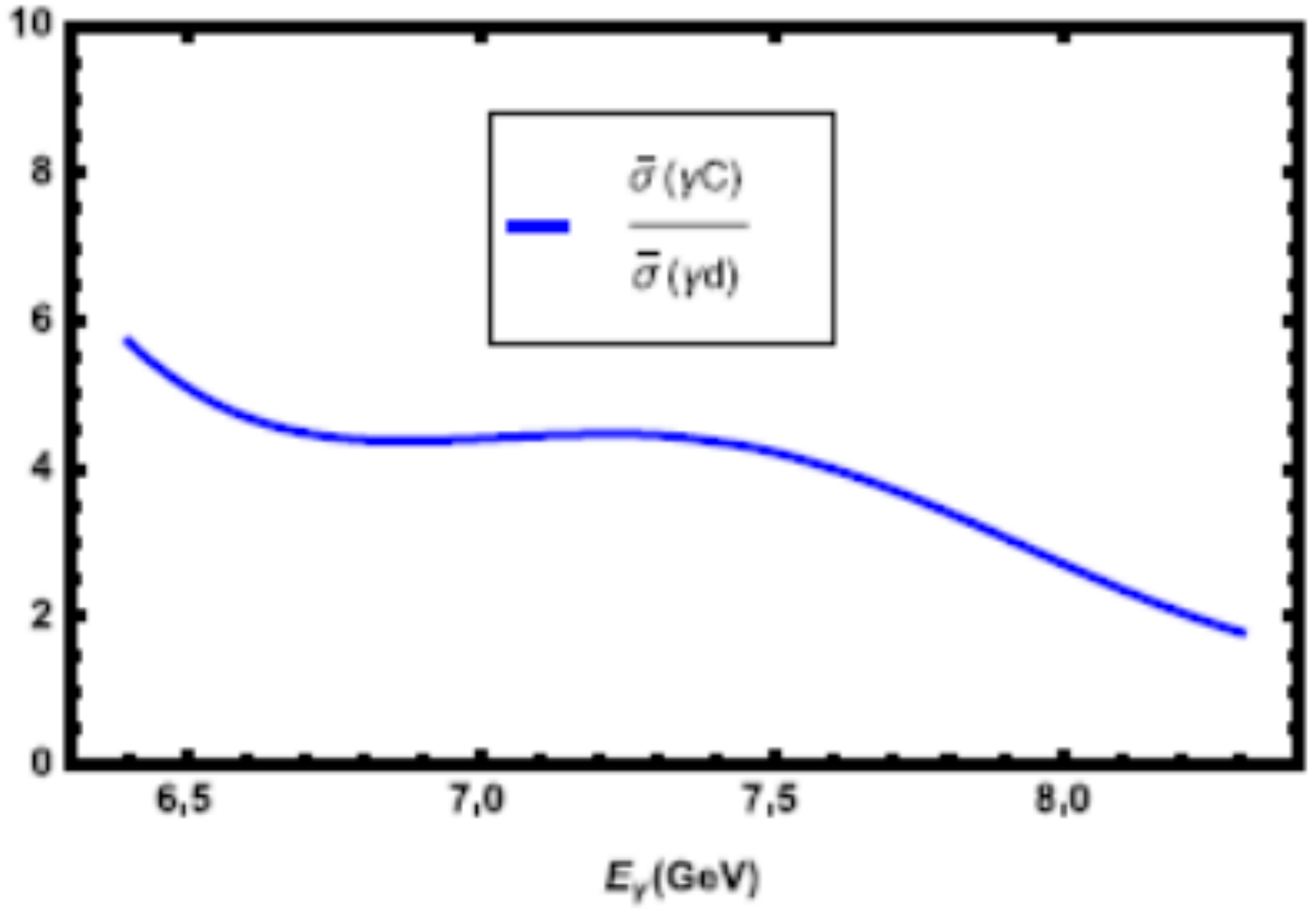

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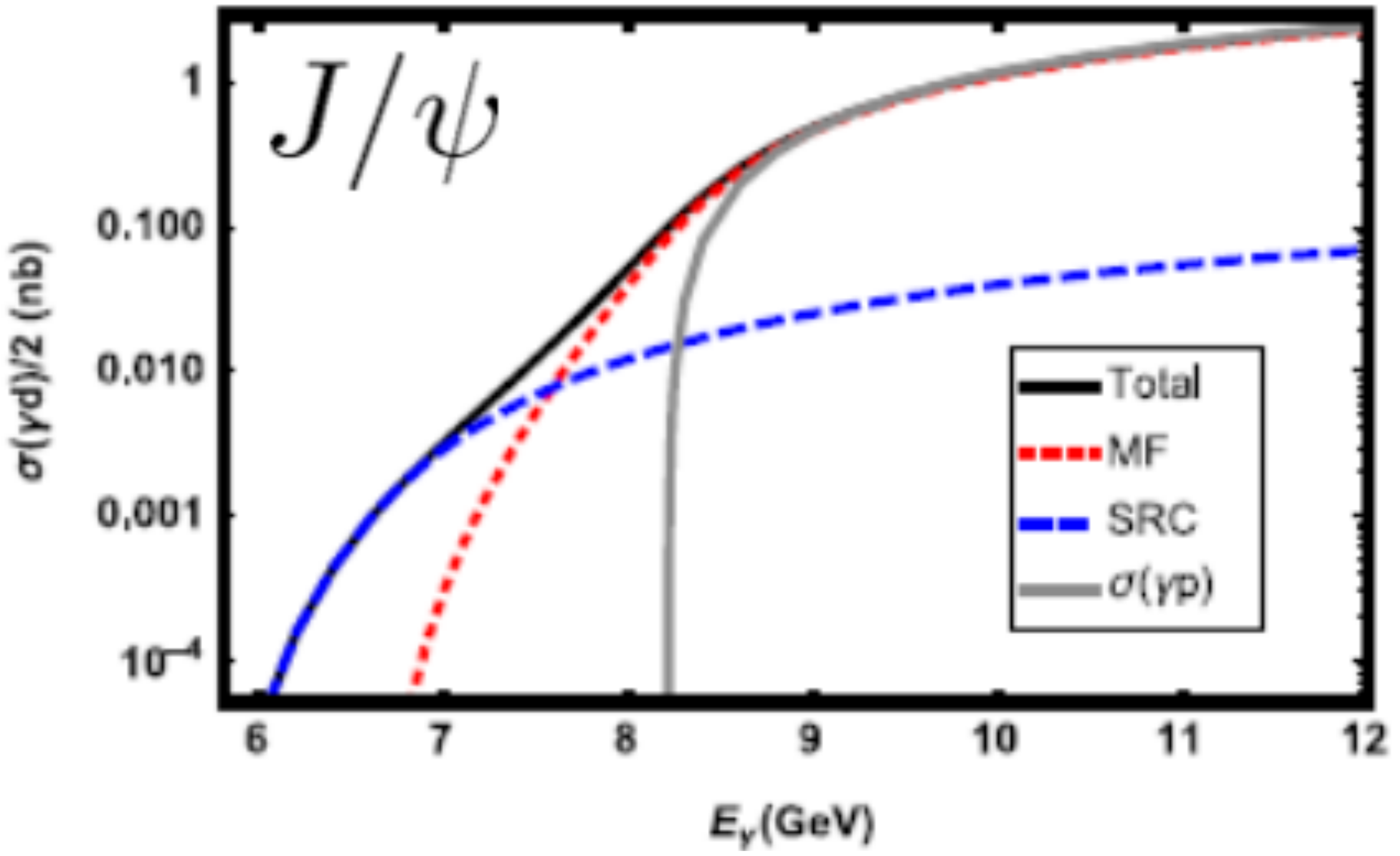
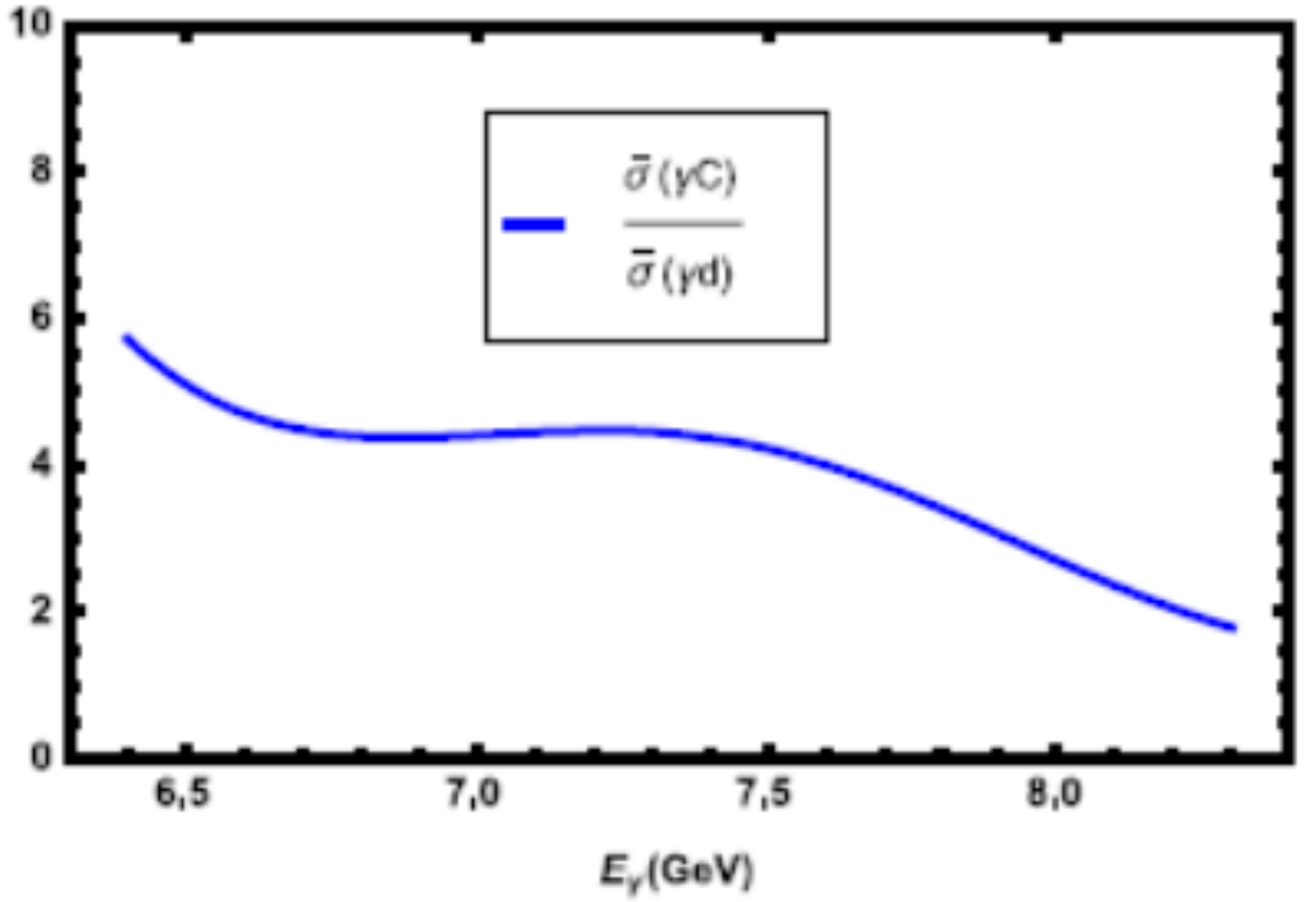
- Can be tested in JLab through *J/ψ* and EIC through *Υ* production.
- Subtreshold measurement requires very high luminosity.





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S. R. Beane *et al.*, PRD 91, 114503 (2015)

BINDING ENERGY OF THE J/Ψ - NUCLEUS POTENTIAL

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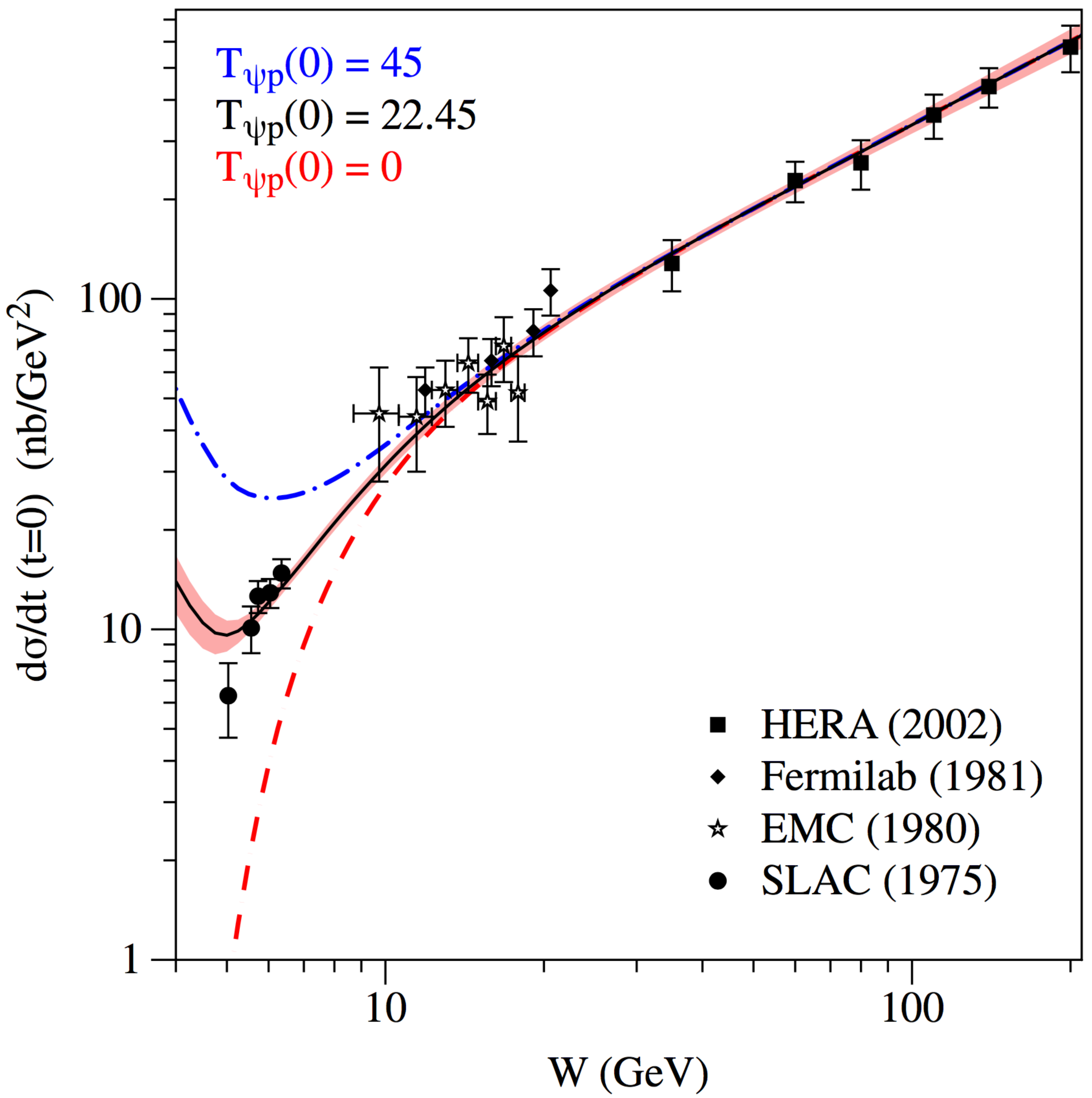
  - Note: *link with trace anomaly*!



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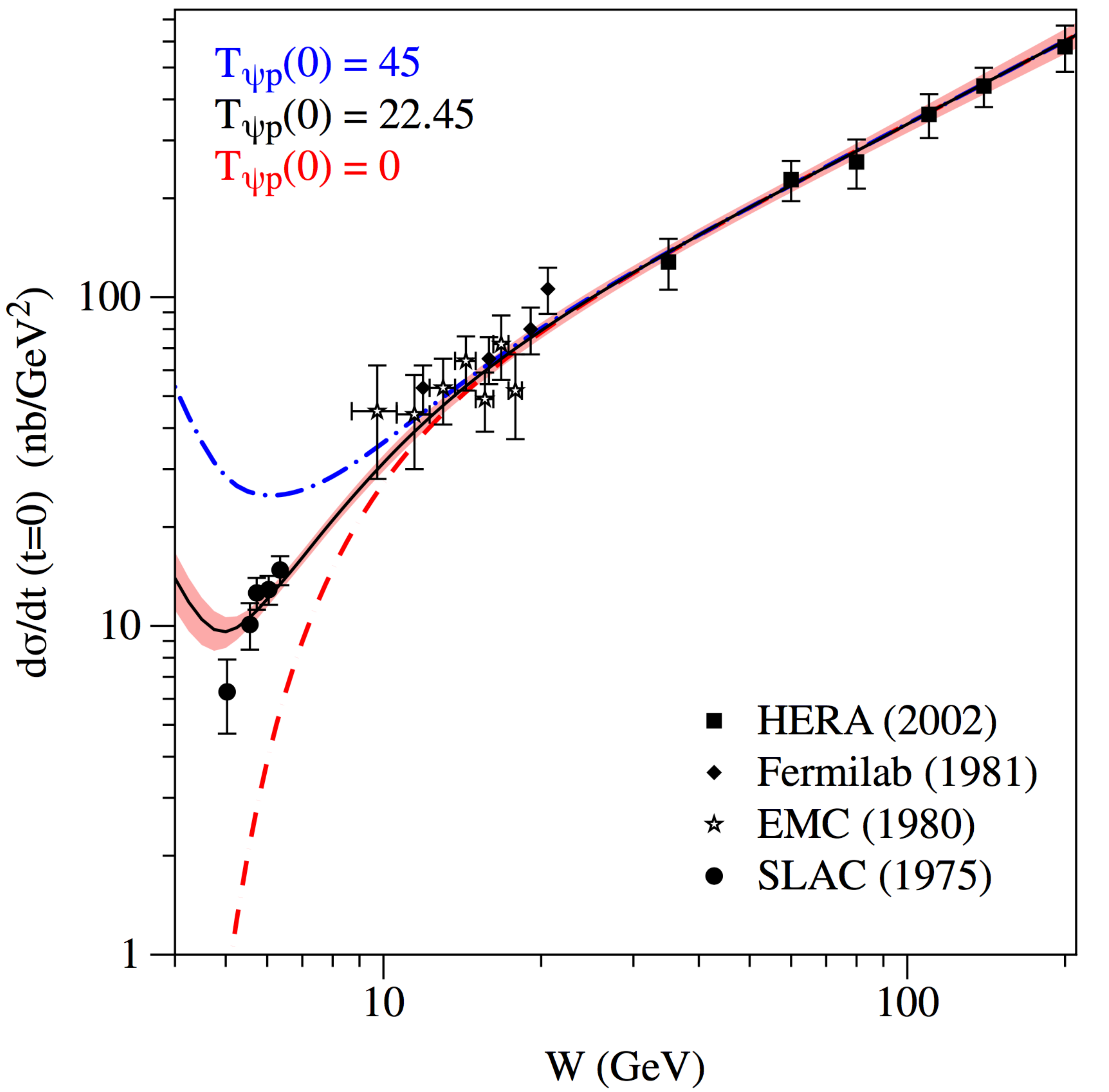
  - Note: *link with trace anomaly*!
- Current estimates between 0.05-0.30fm (3-20MeV)
- Lattice QCD (at large pion mass): $B_{\psi p}$ < 40 MeV

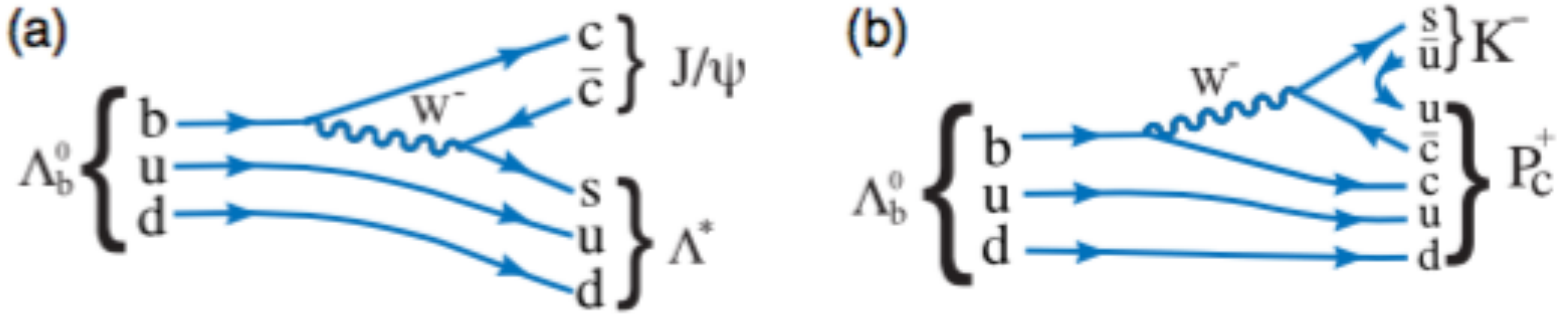
Need high-precision photo-production data near threshold



DISCOVERY OF THE LHCB CHARMED PENTAQUARK

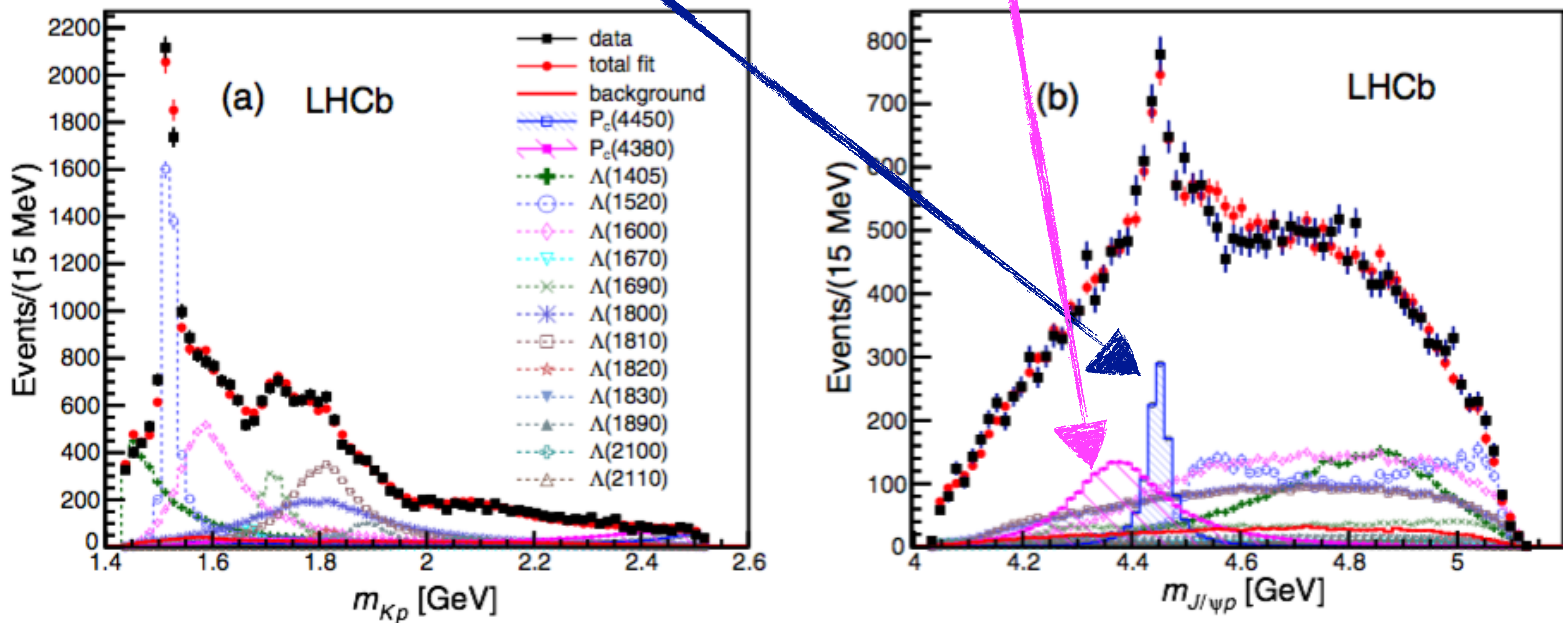
$$\Lambda_b \rightarrow \Lambda^* J/\Psi \rightarrow (K^- p) J/\Psi$$

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



narrow: P_c(4450) (12 σ)

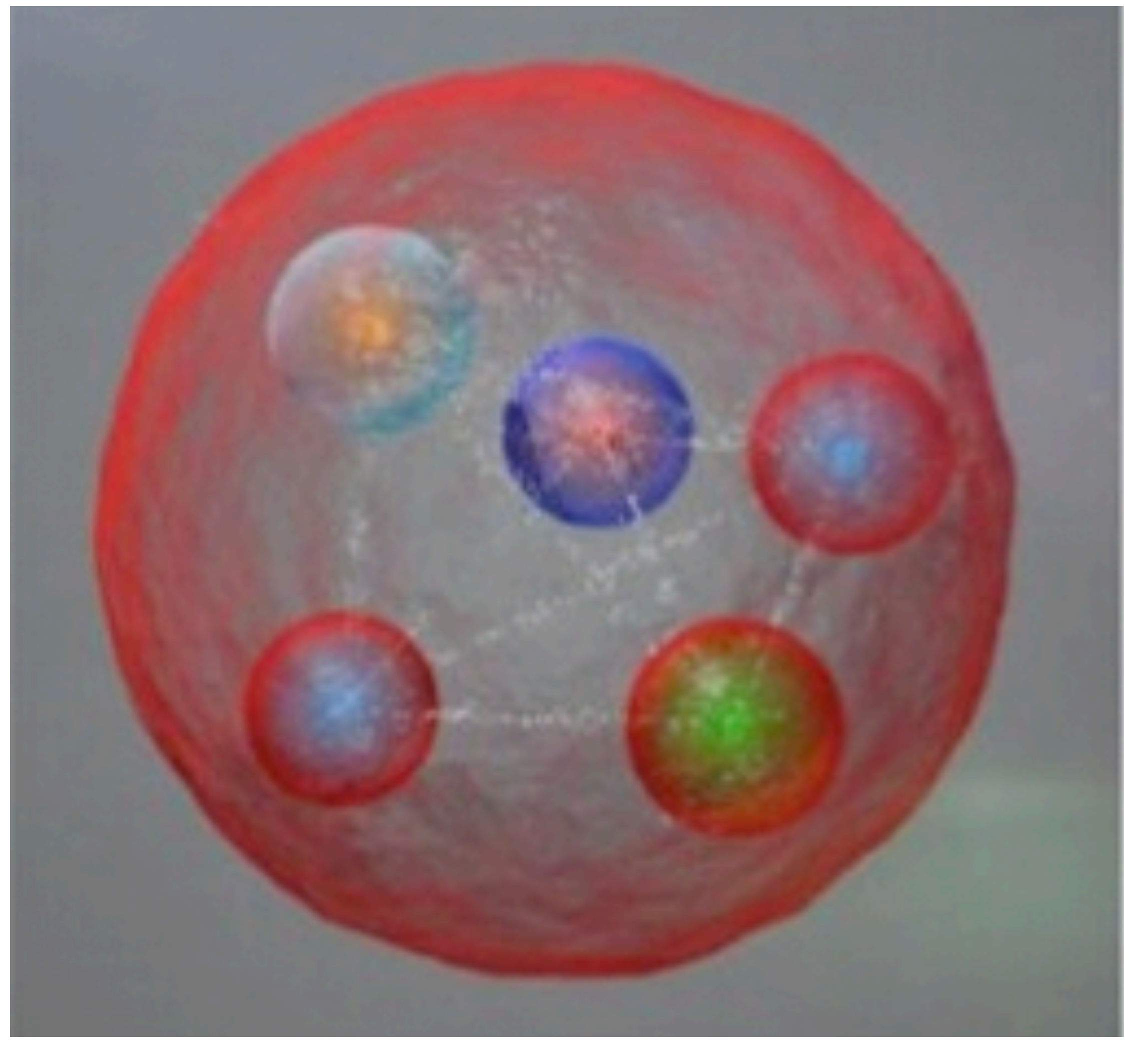
wide: P_c(4390) (9σ)

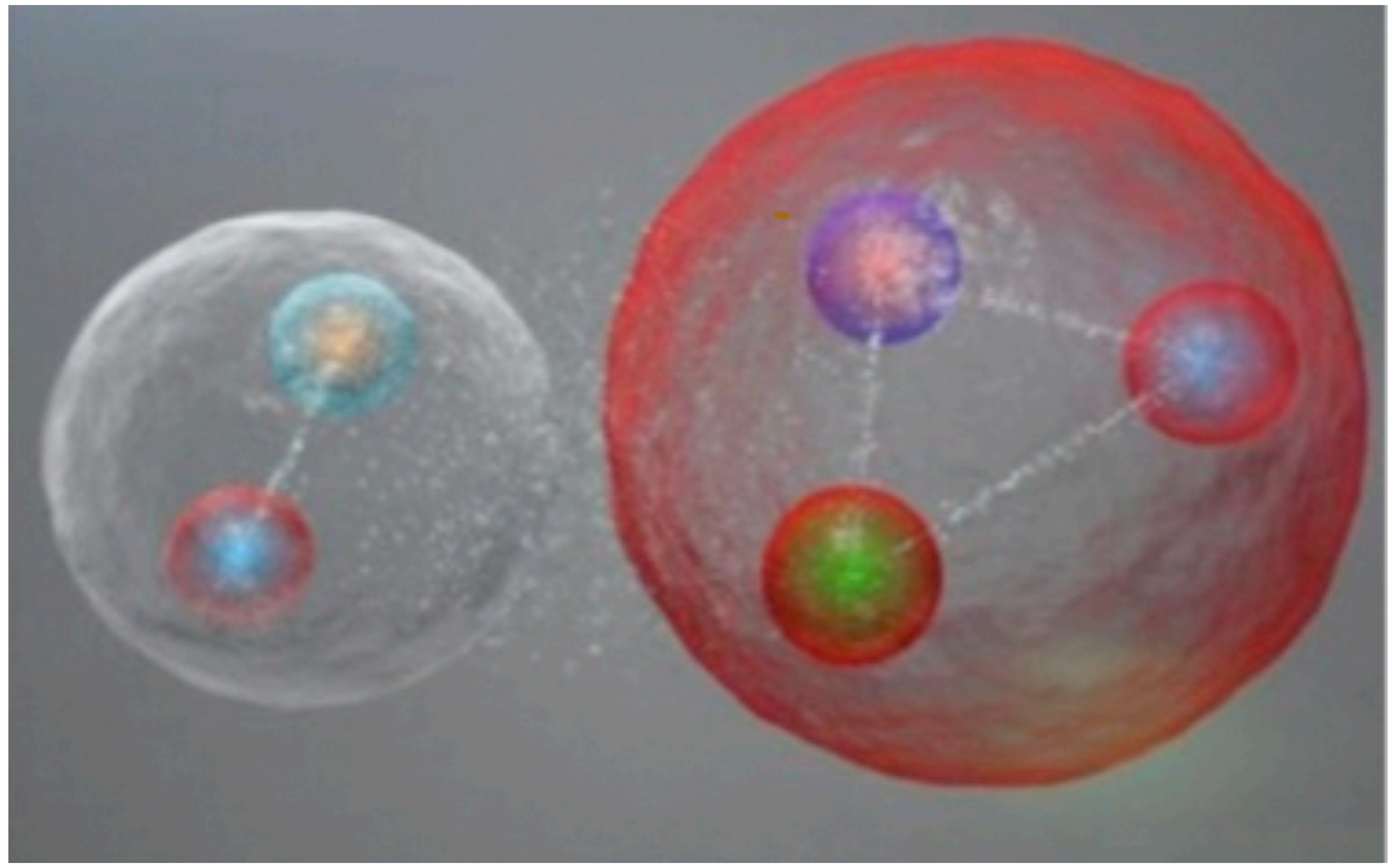


- LHCb collaboration findings: **two P_c states needed**:
- Spin/parity not fully constrained:
  - 5/2+ and 3/2- (most likely)
  - 5/2- and 3/2+
  - 3/2- and 5/2+

IS THIS A REAL PARTICLE?

We can confirm this at JLab!





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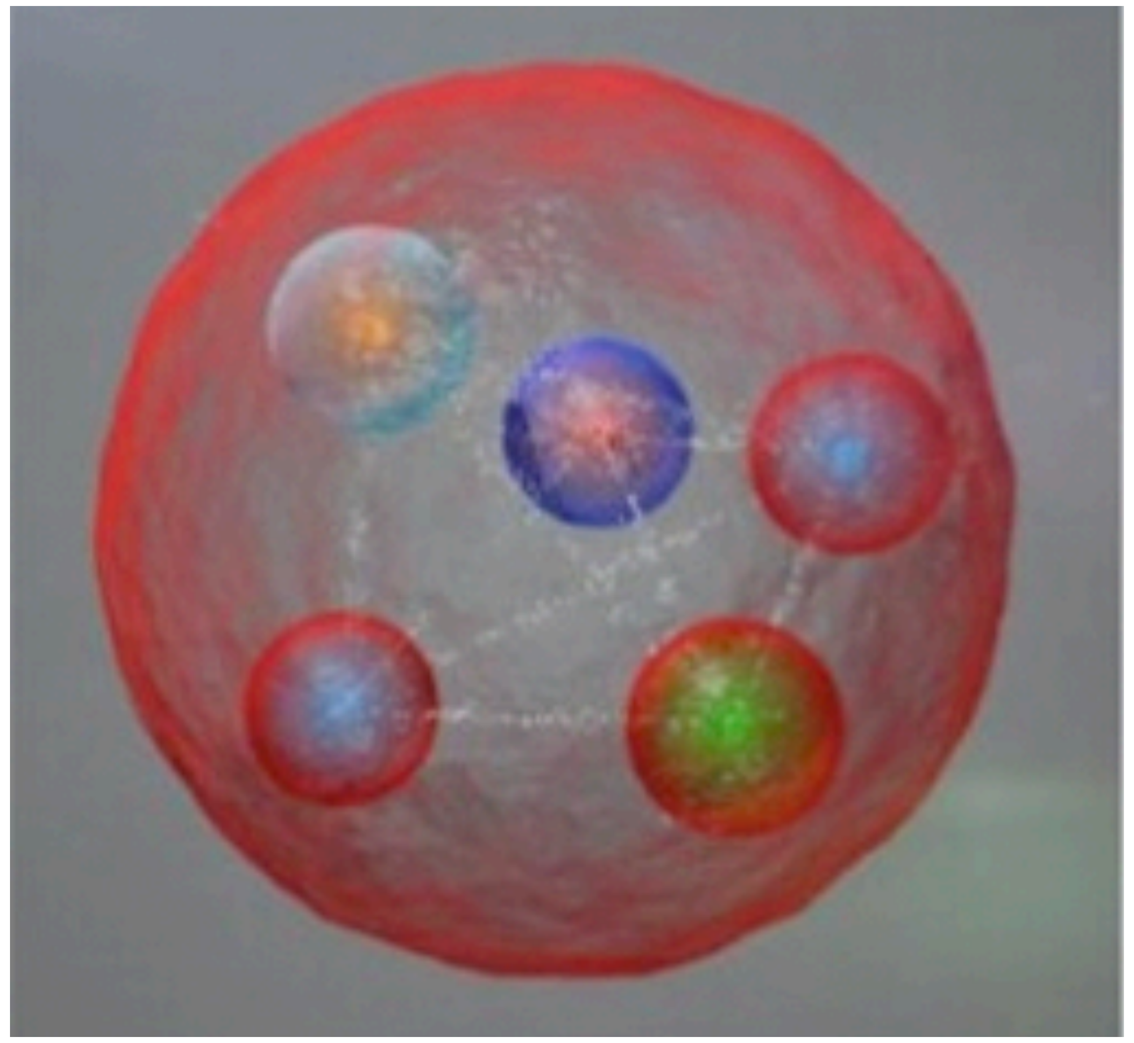
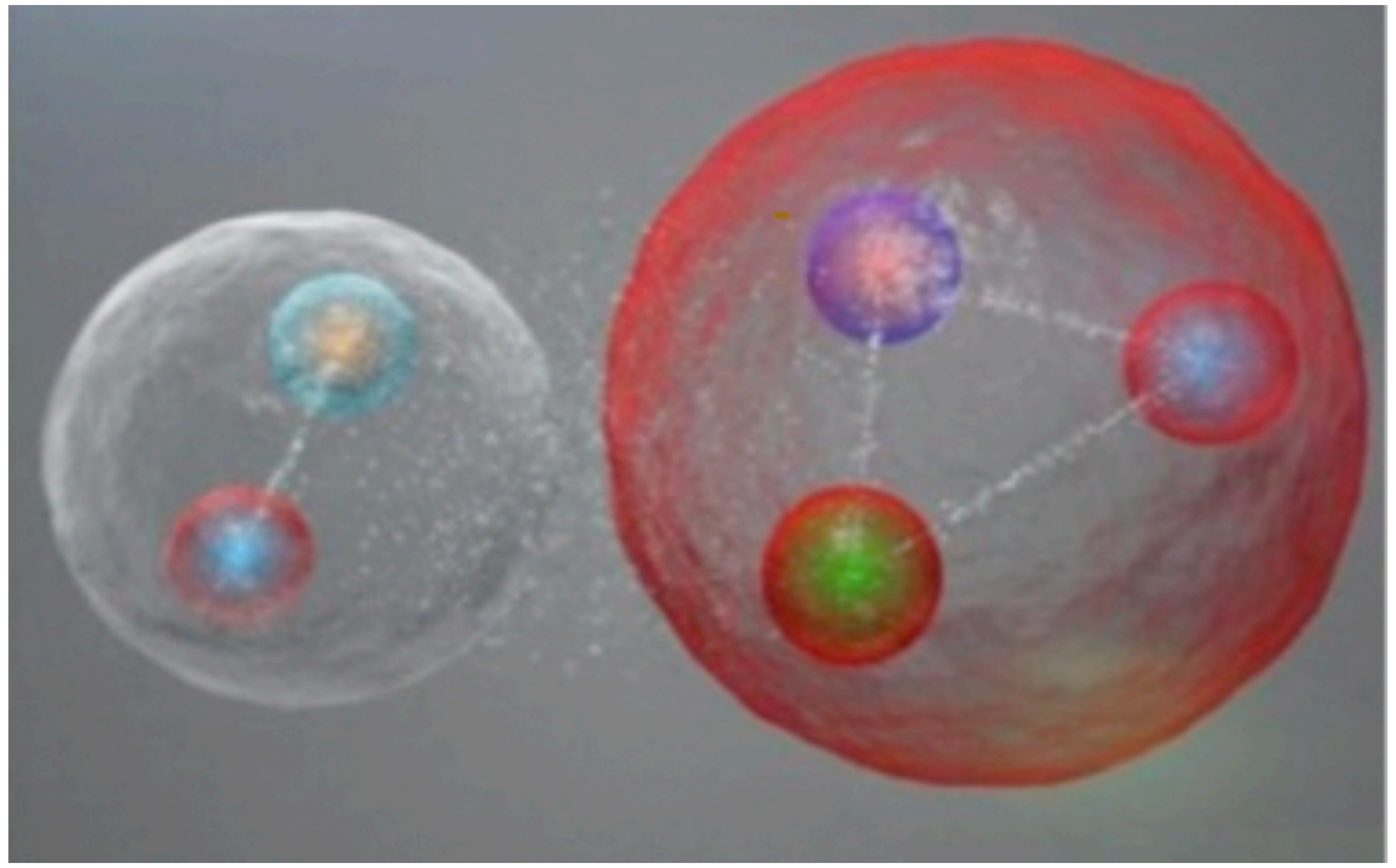
2. **Alternative:** Kinematic enhancement through anomalous triangle singularity (ATS)





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

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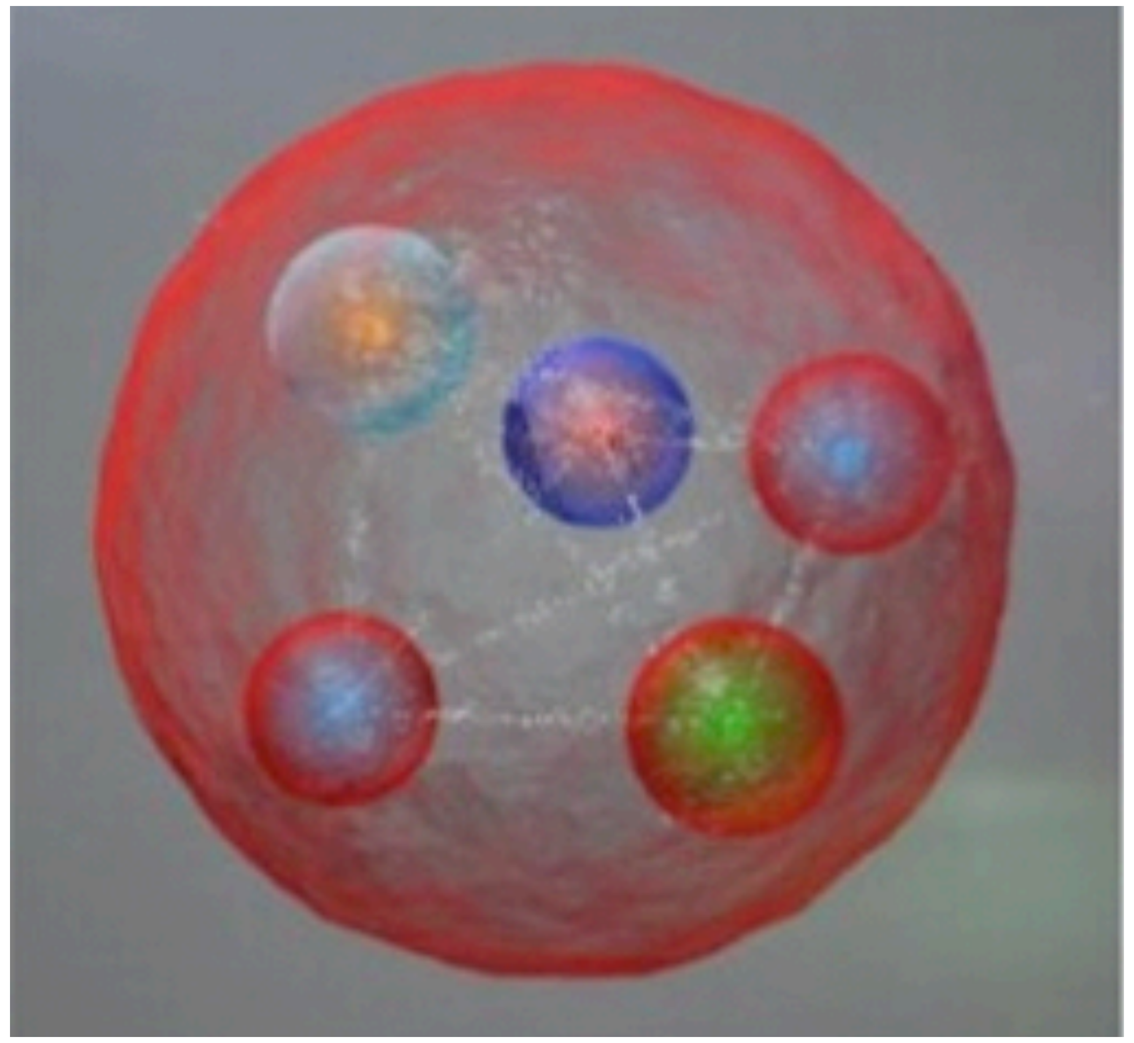

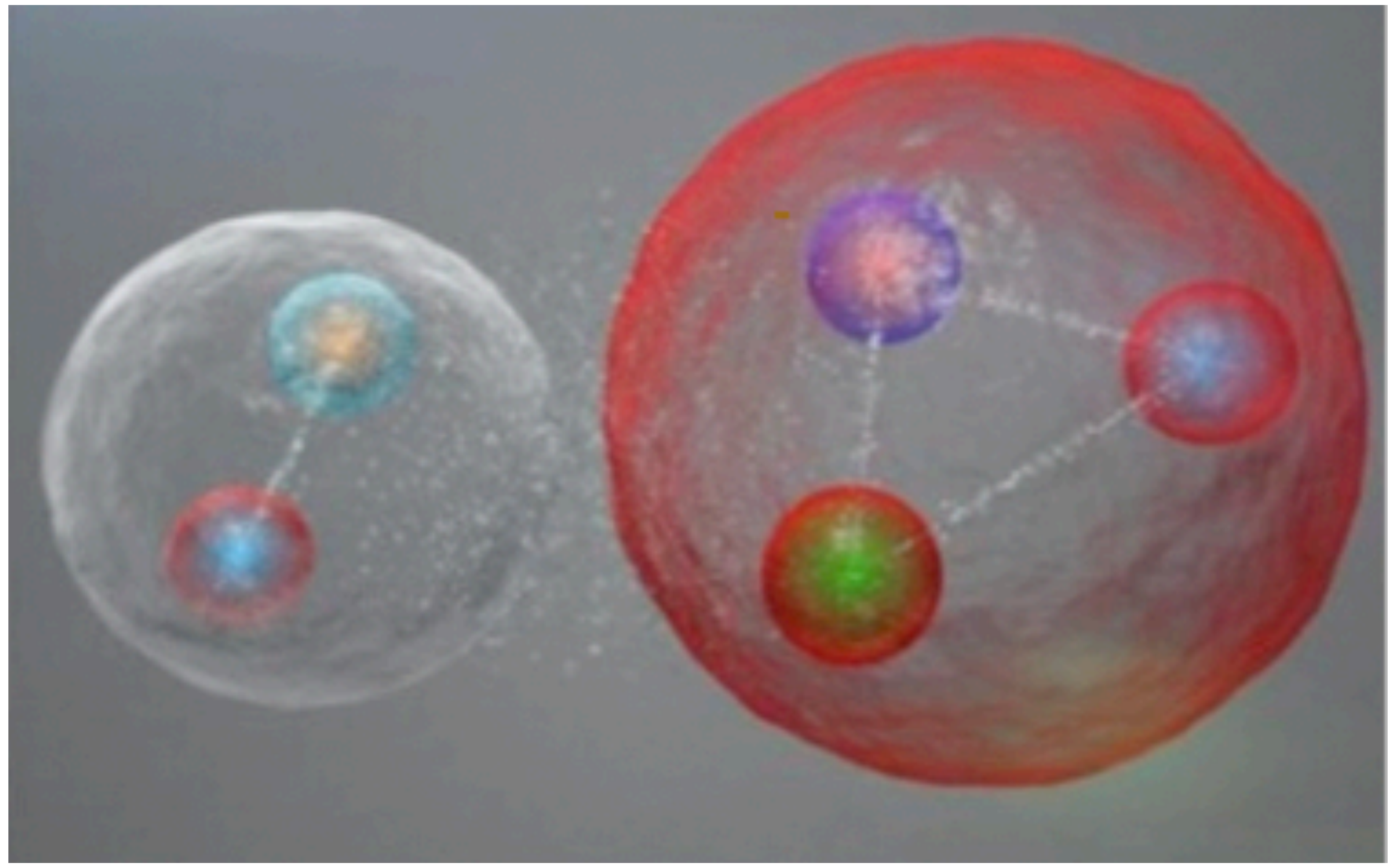

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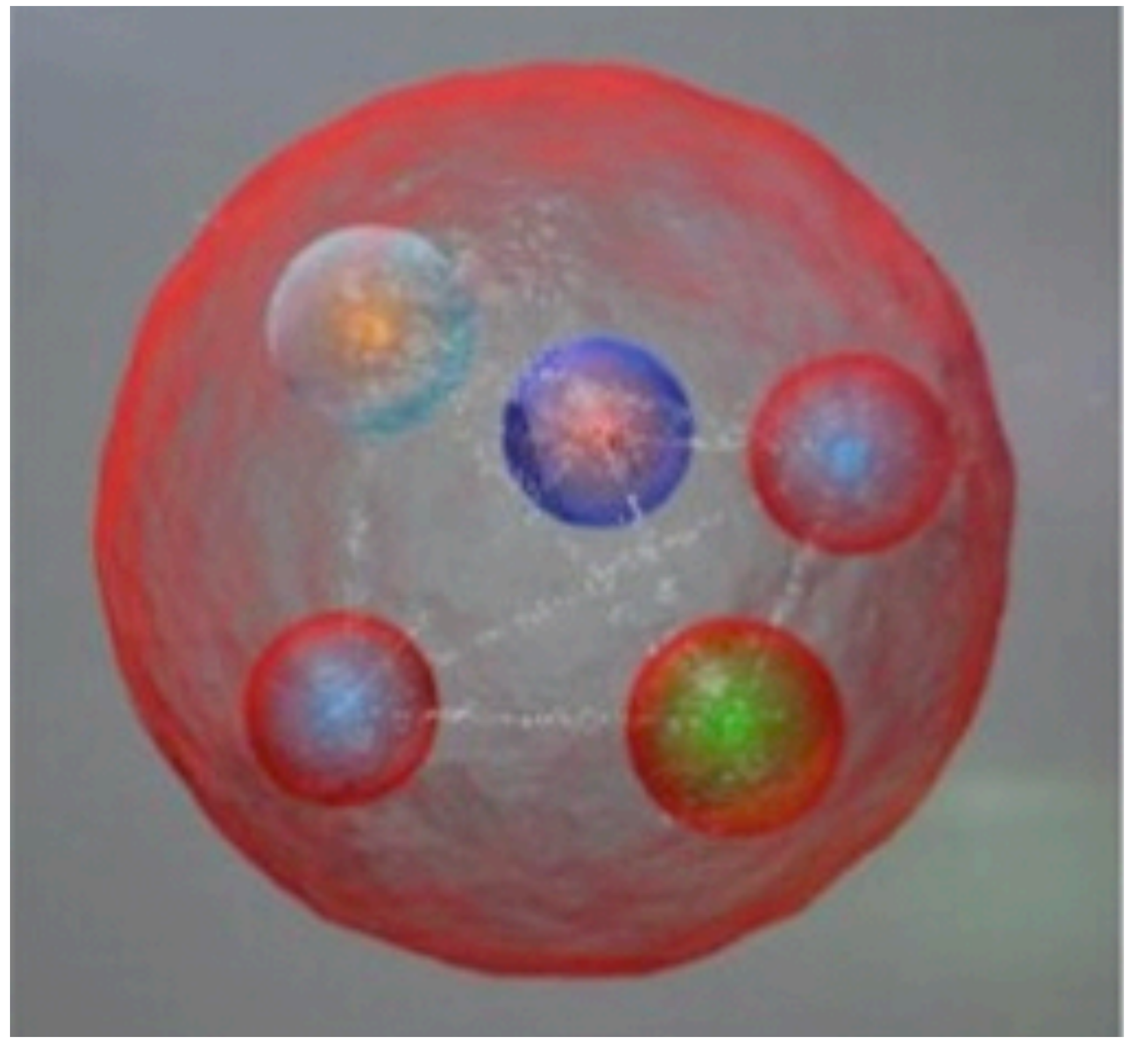

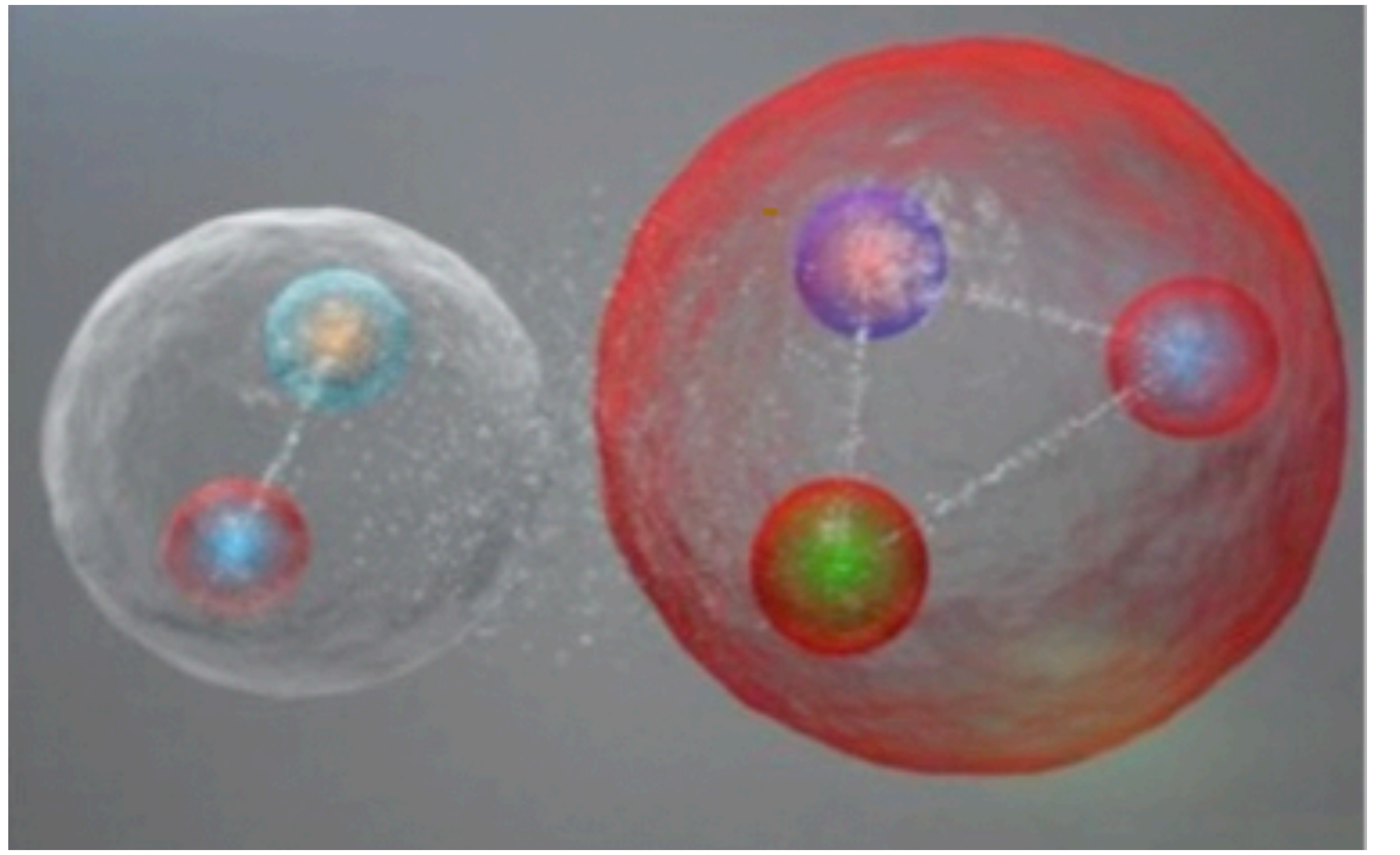

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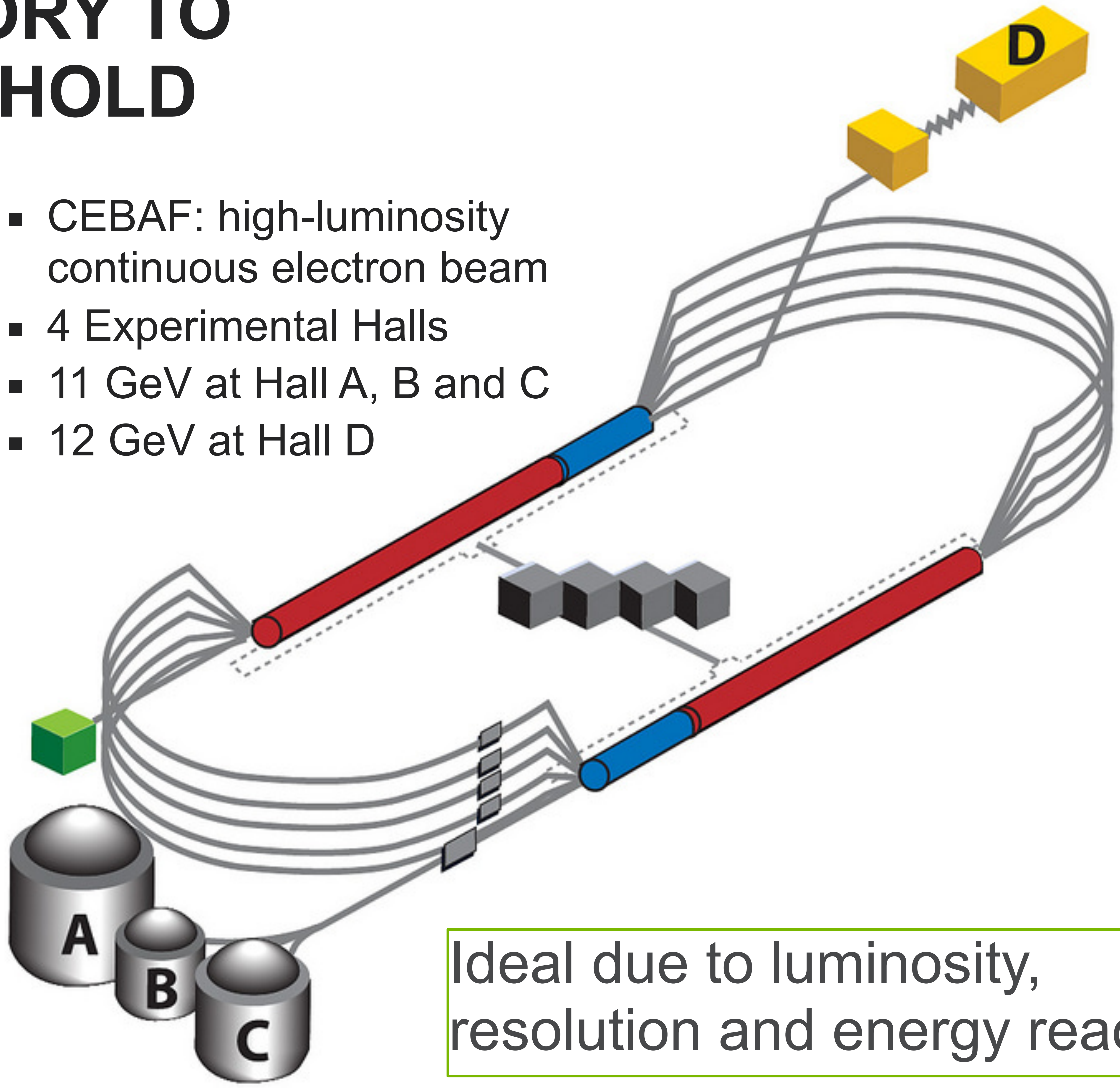
- Photo-production ideal tool to distinguish:
  1. **Truly new states:** P_c also created in photo-production
  2. **Alternative:** ATS not possible in photo-production
- P_c(4450) translates to **narrow peak around E_γ = 10.1 GeV**

Jefferson Lab the perfect place to search for P_c

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



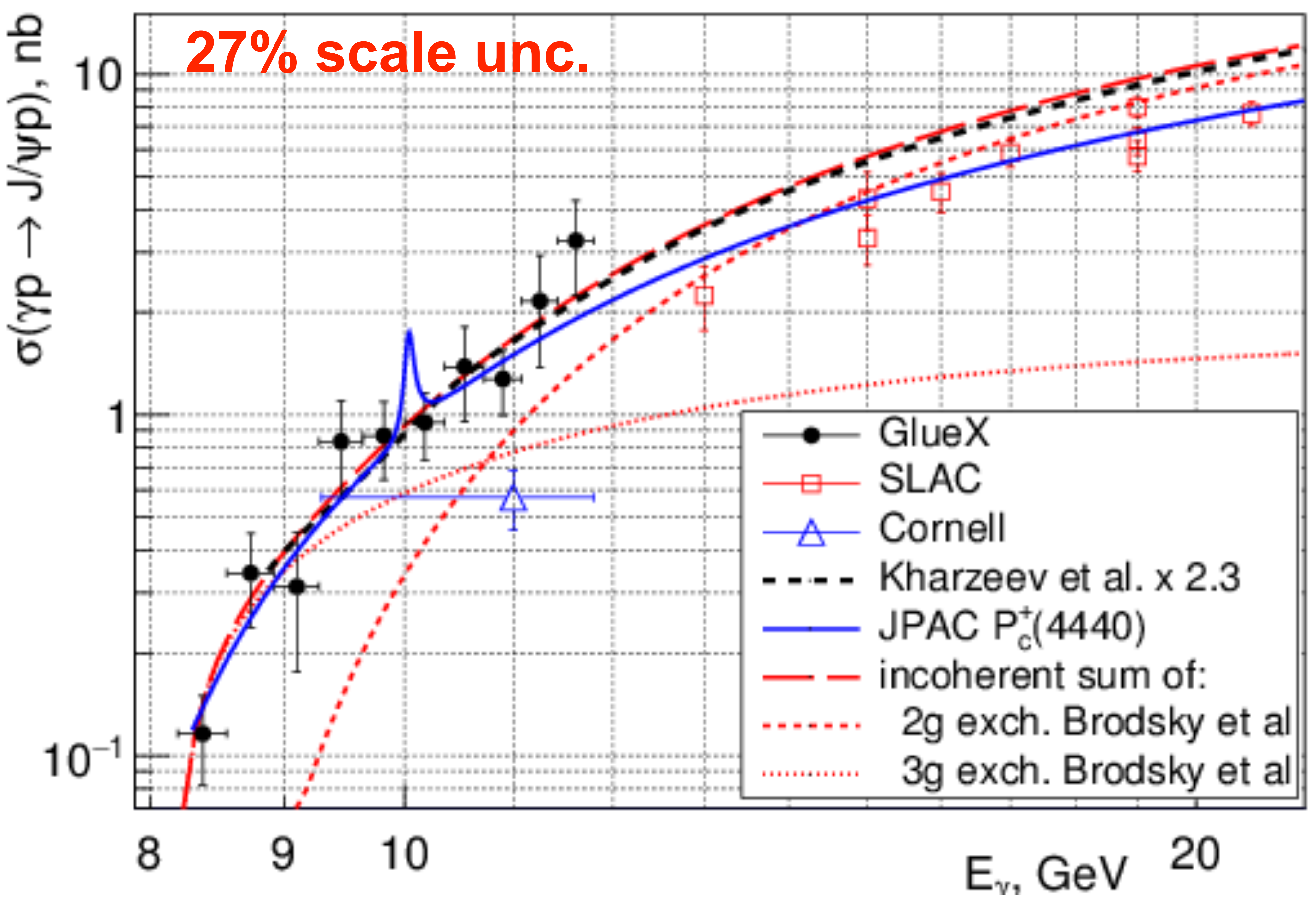
Ideal due to luminosity, resolution and energy reach

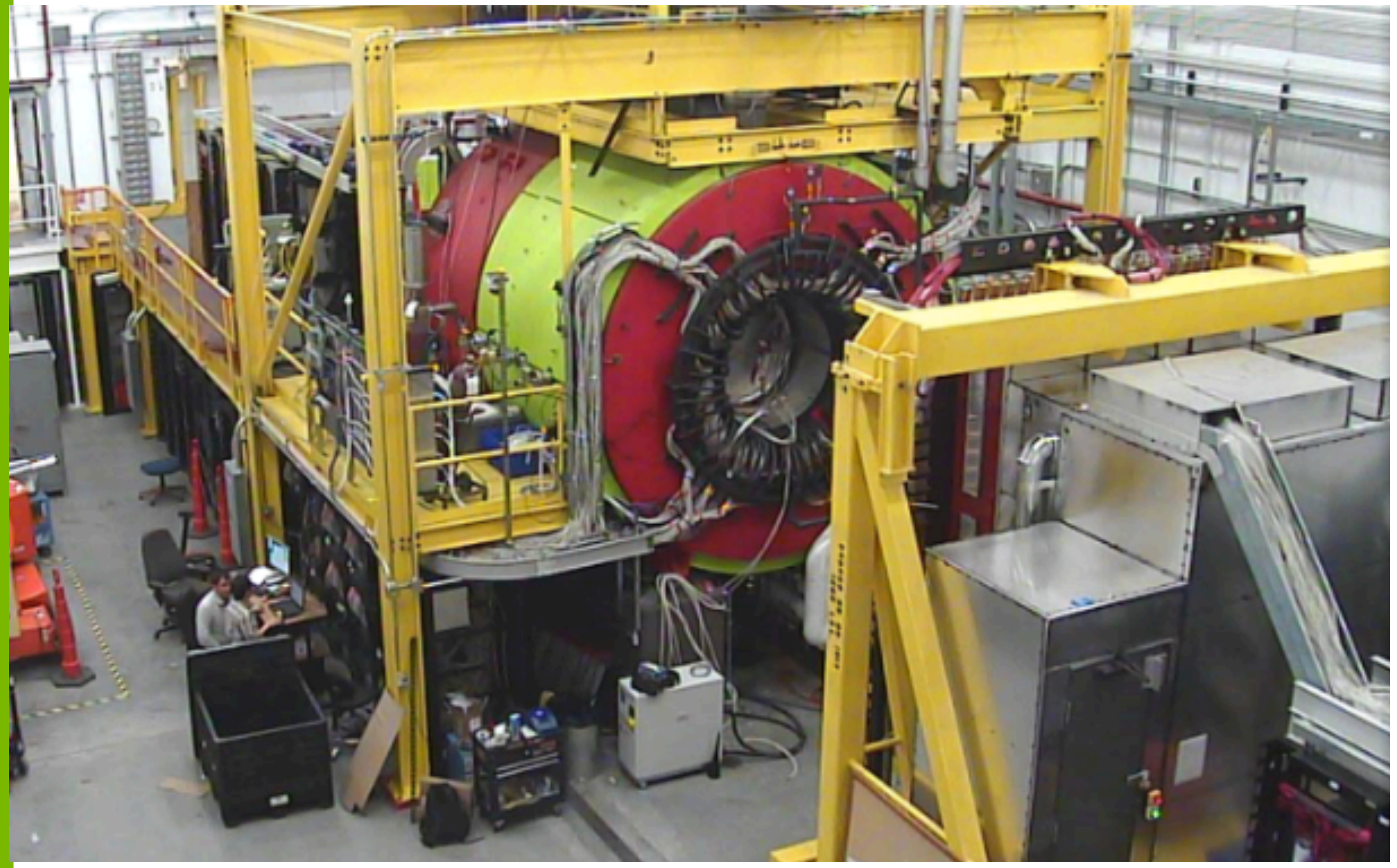
GlueX Collaboration (Ali, *et al*), PRL 123 (2019) no.7 072001

J/Ψ IN HALL D/GLUEX

First *J/ψ* measurement at Jefferson Lab

- Published data from GlueX: first *J/ψ* at JLab!
- Substantially higher than old world data (even with scale uncertainty)





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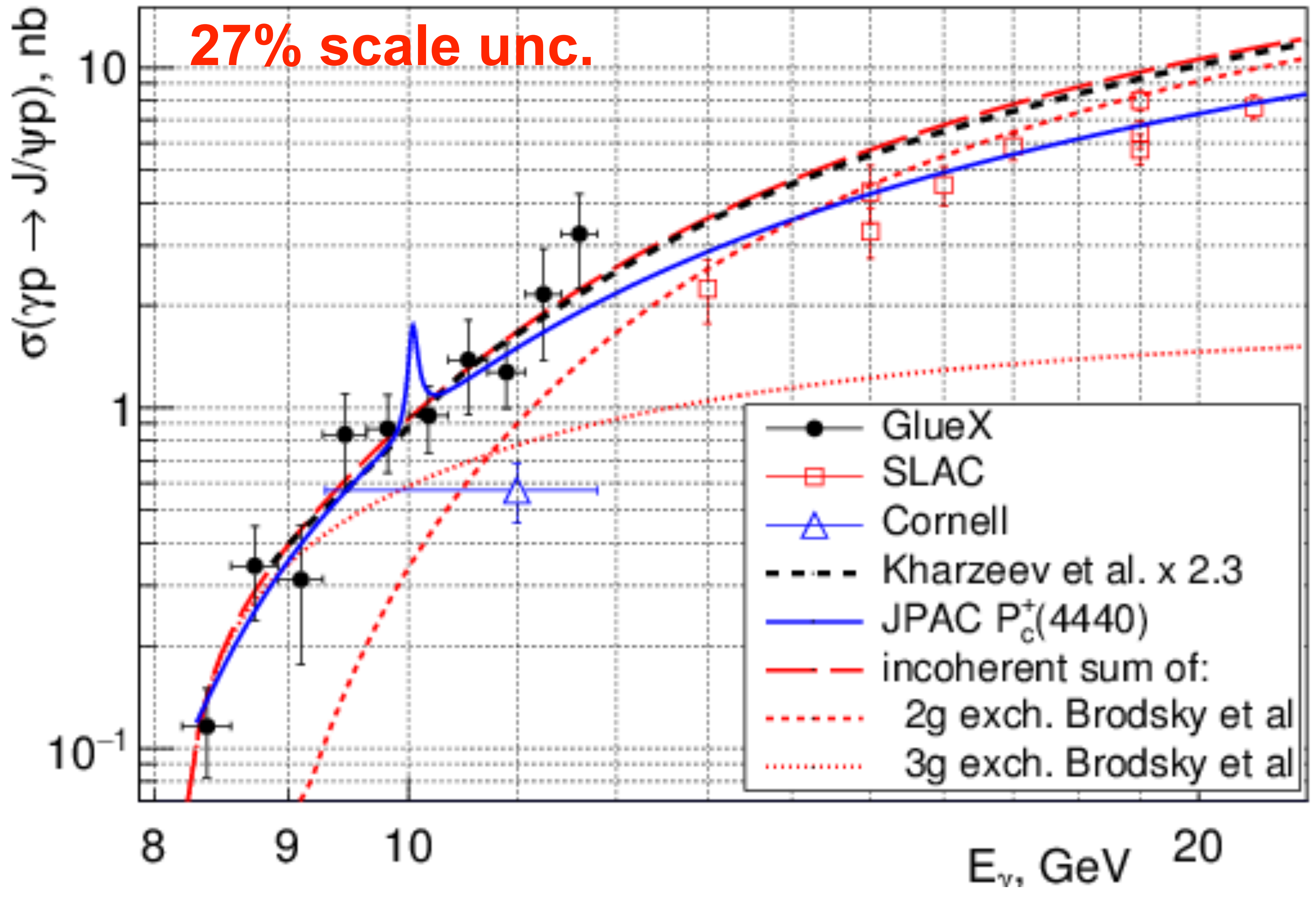
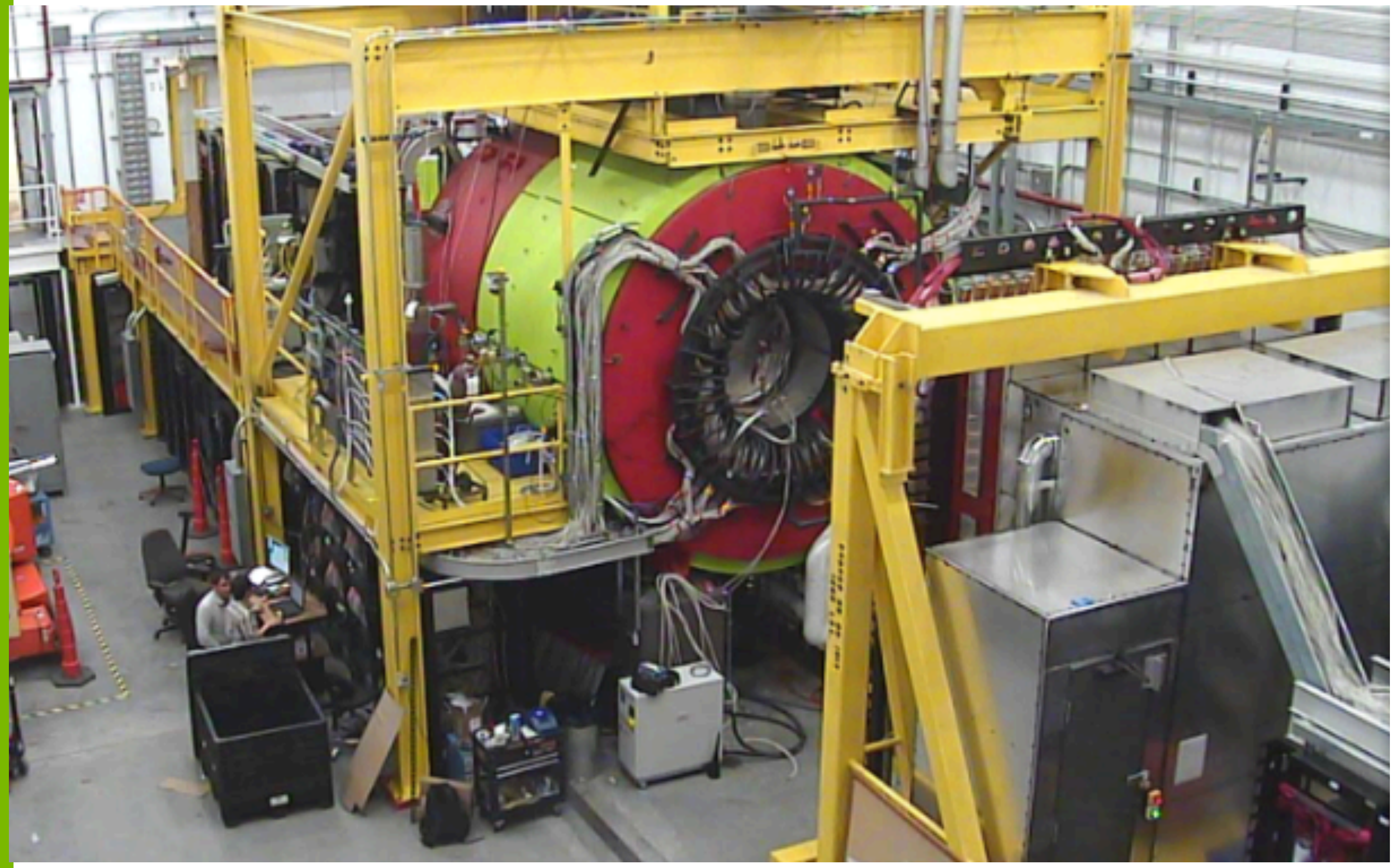
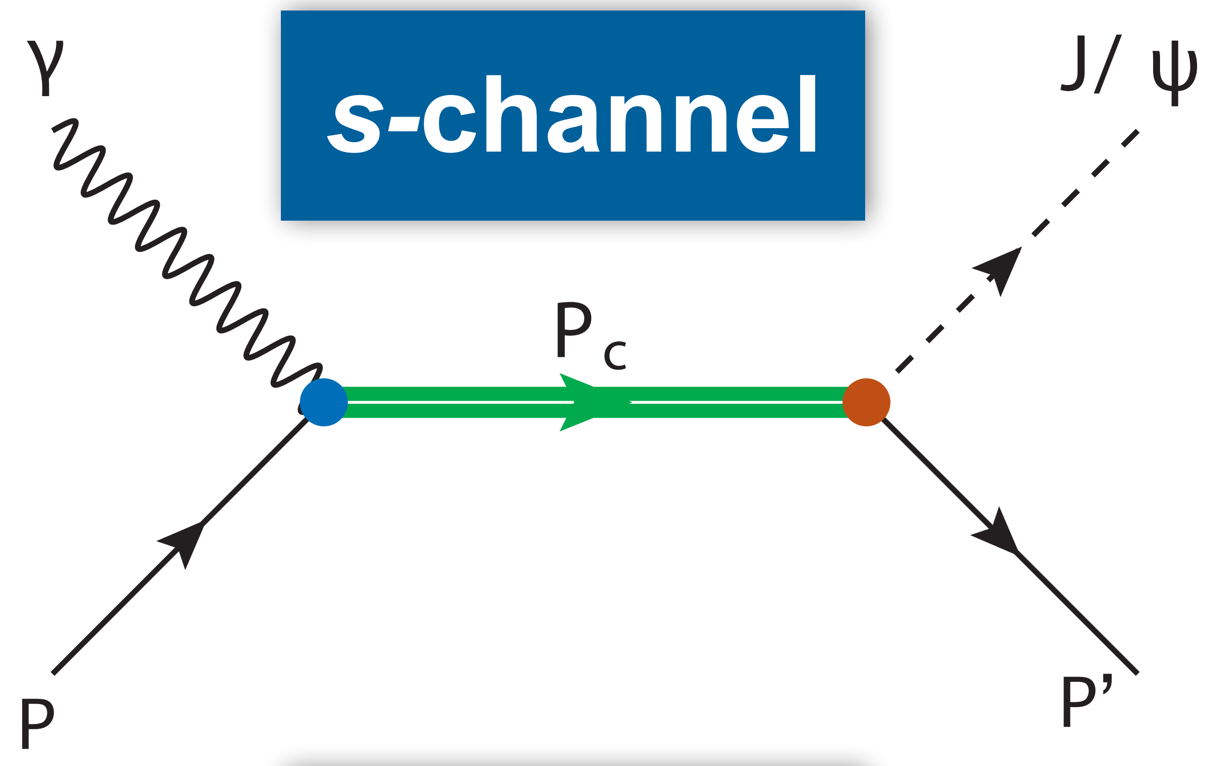


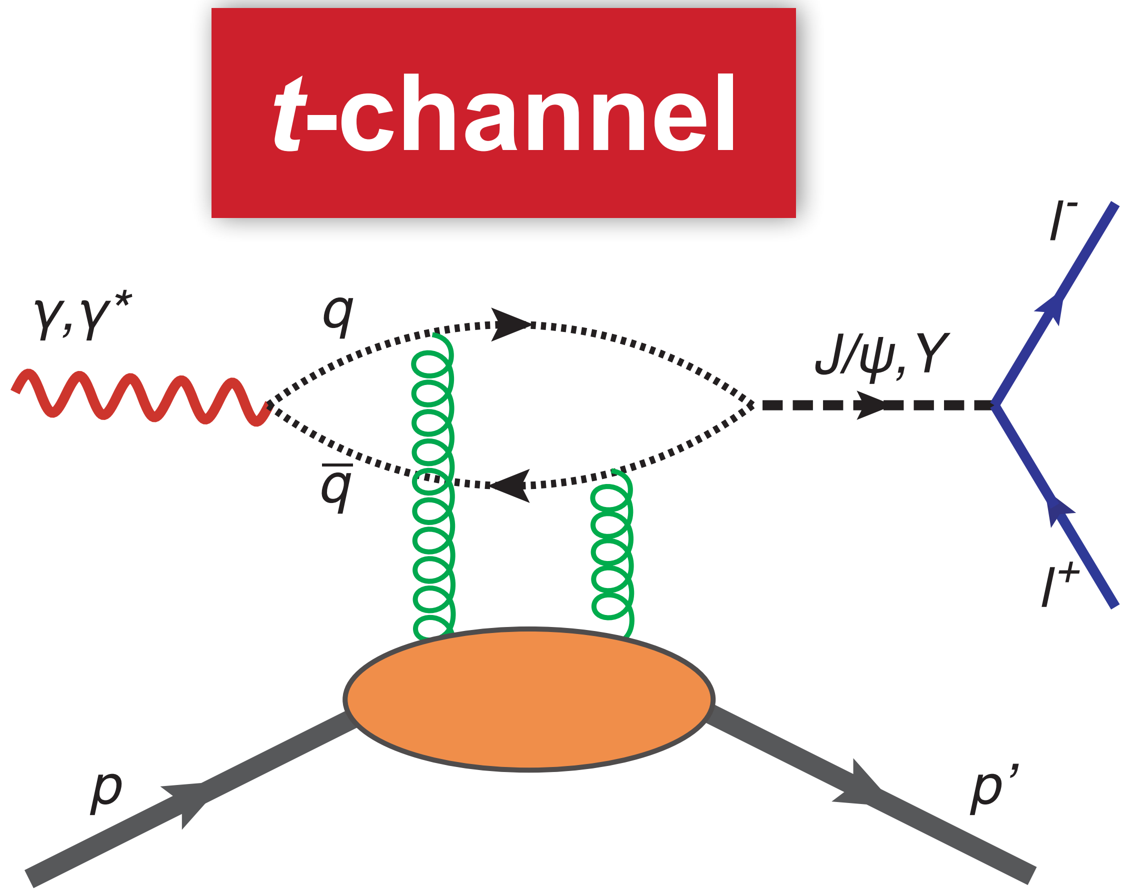


- No large pentaquark signal observed
- However, relatively low-luminosity experiment not very sensitive to high-t.
- Complimentary to Hall C (*J/ψ-007)* results

RESONANT J/Ψ PRODUCTION THROUGH P_C DECAY

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





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

- *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)

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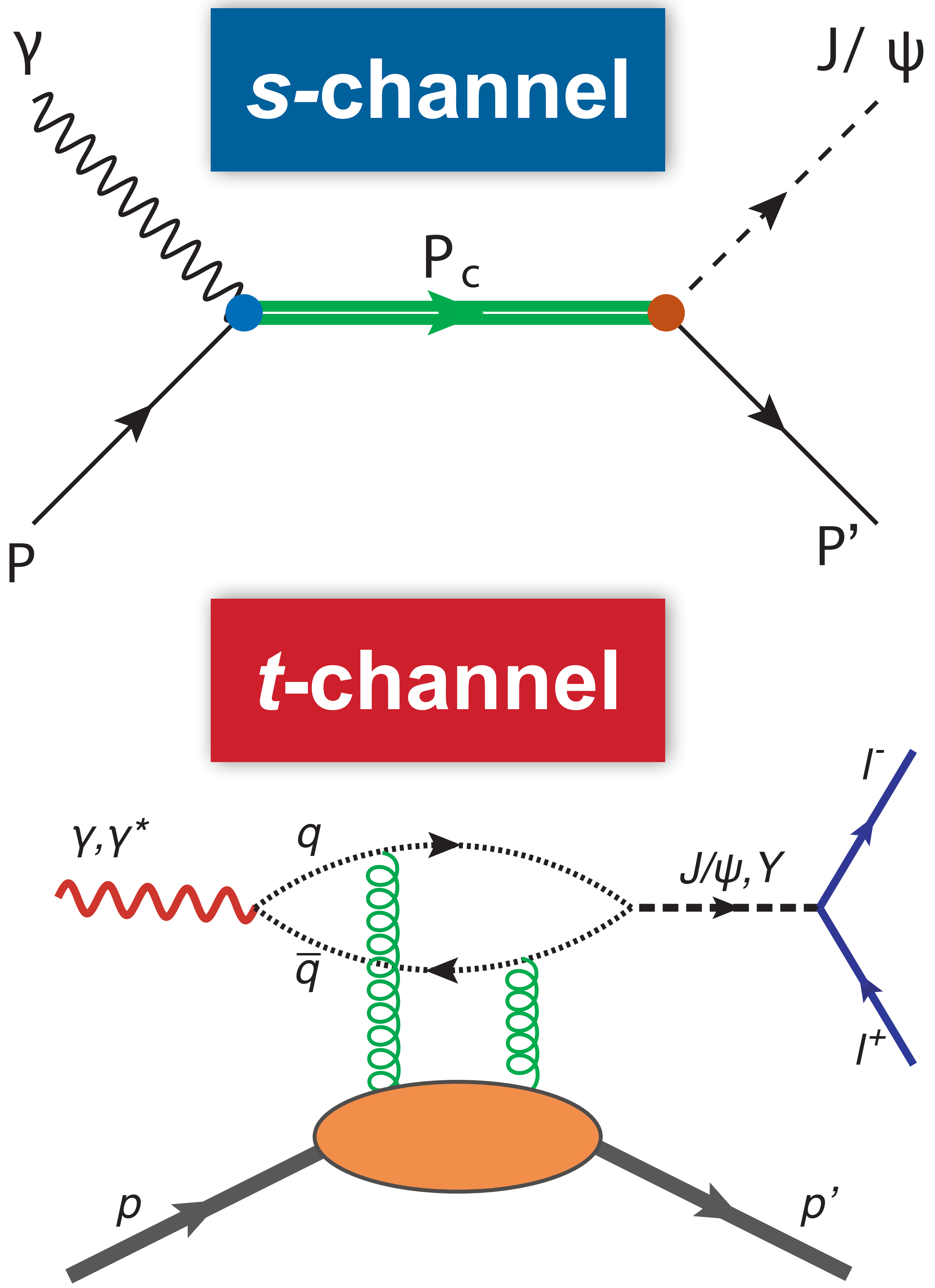

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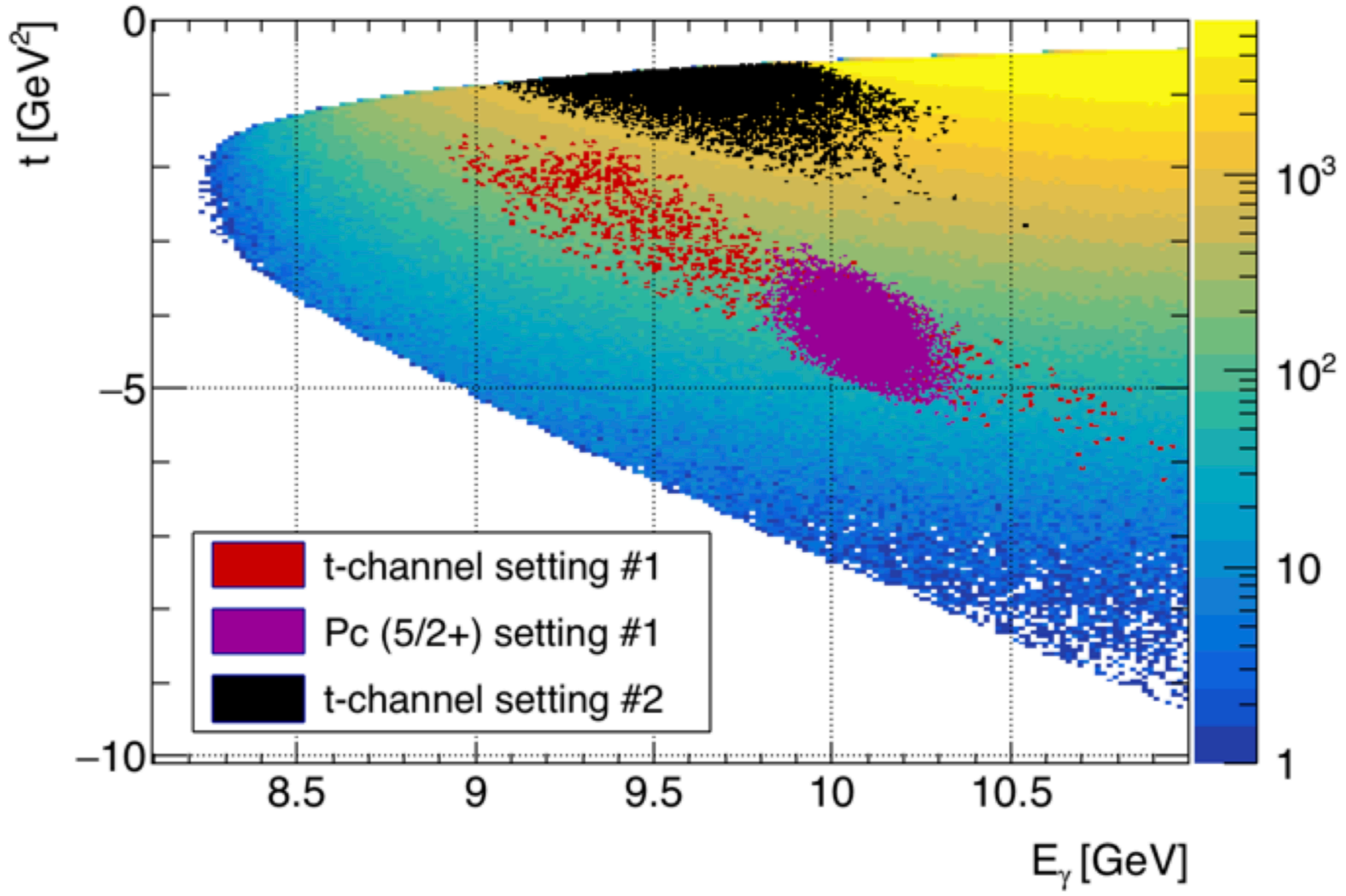

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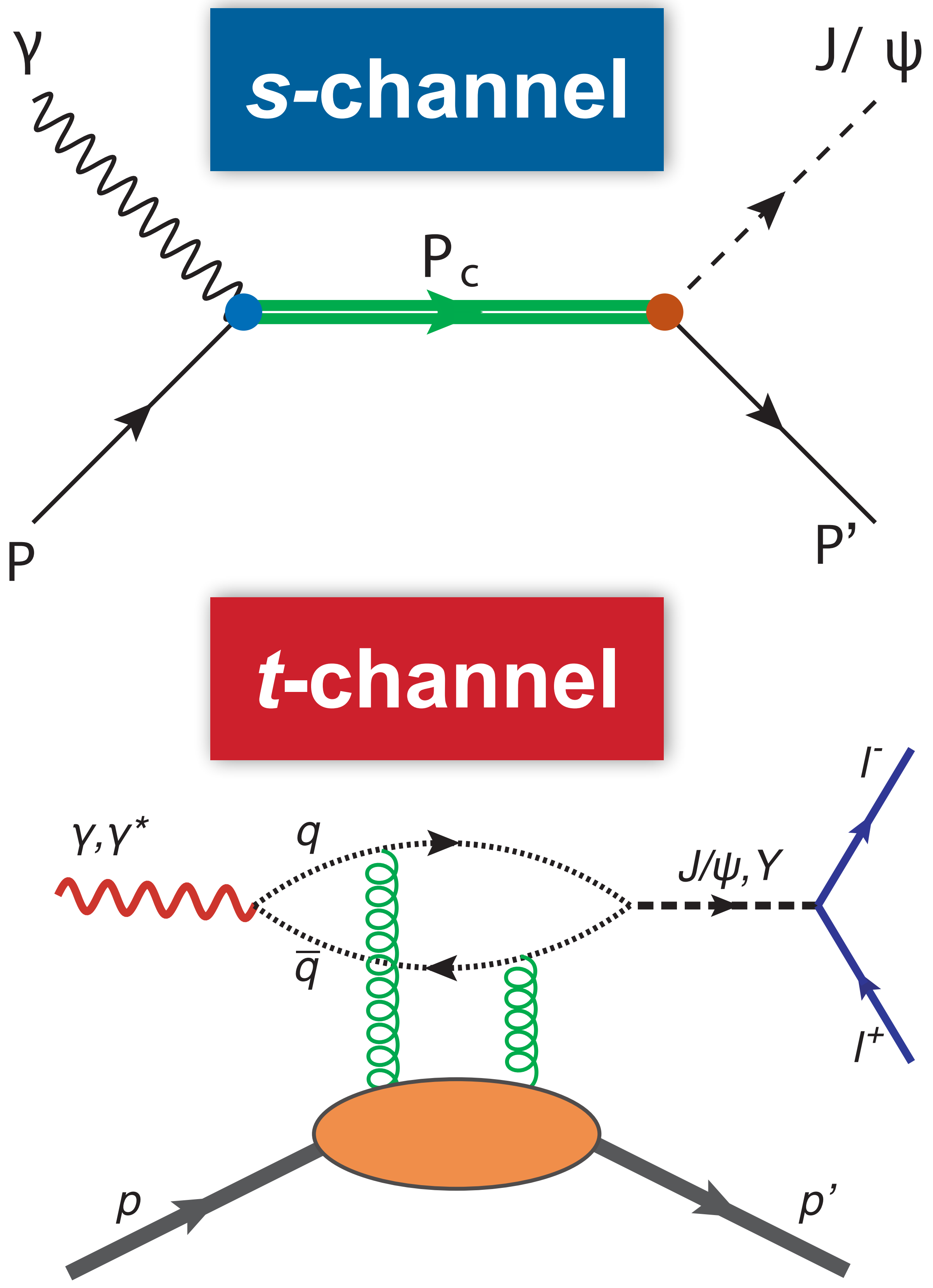

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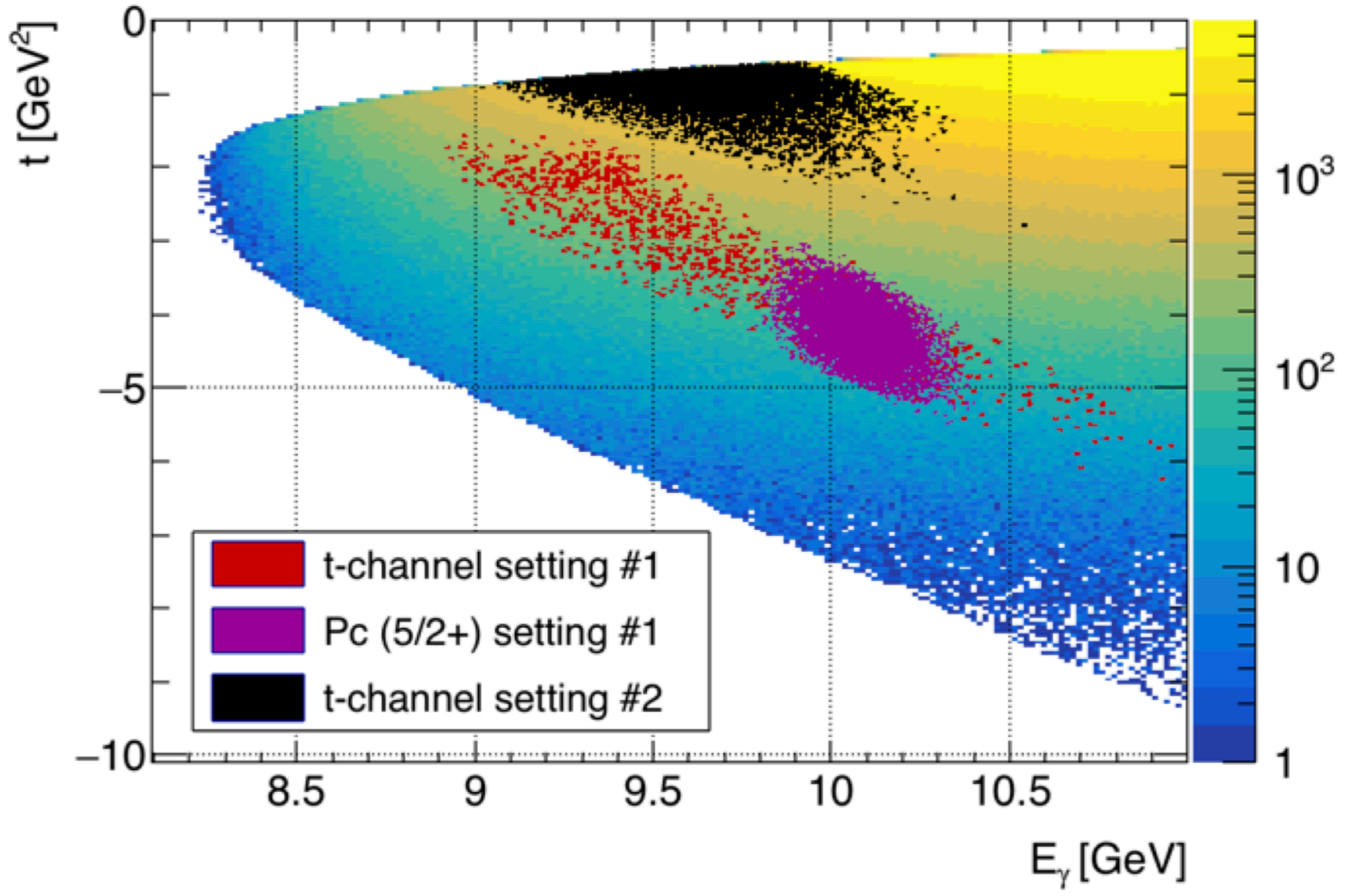


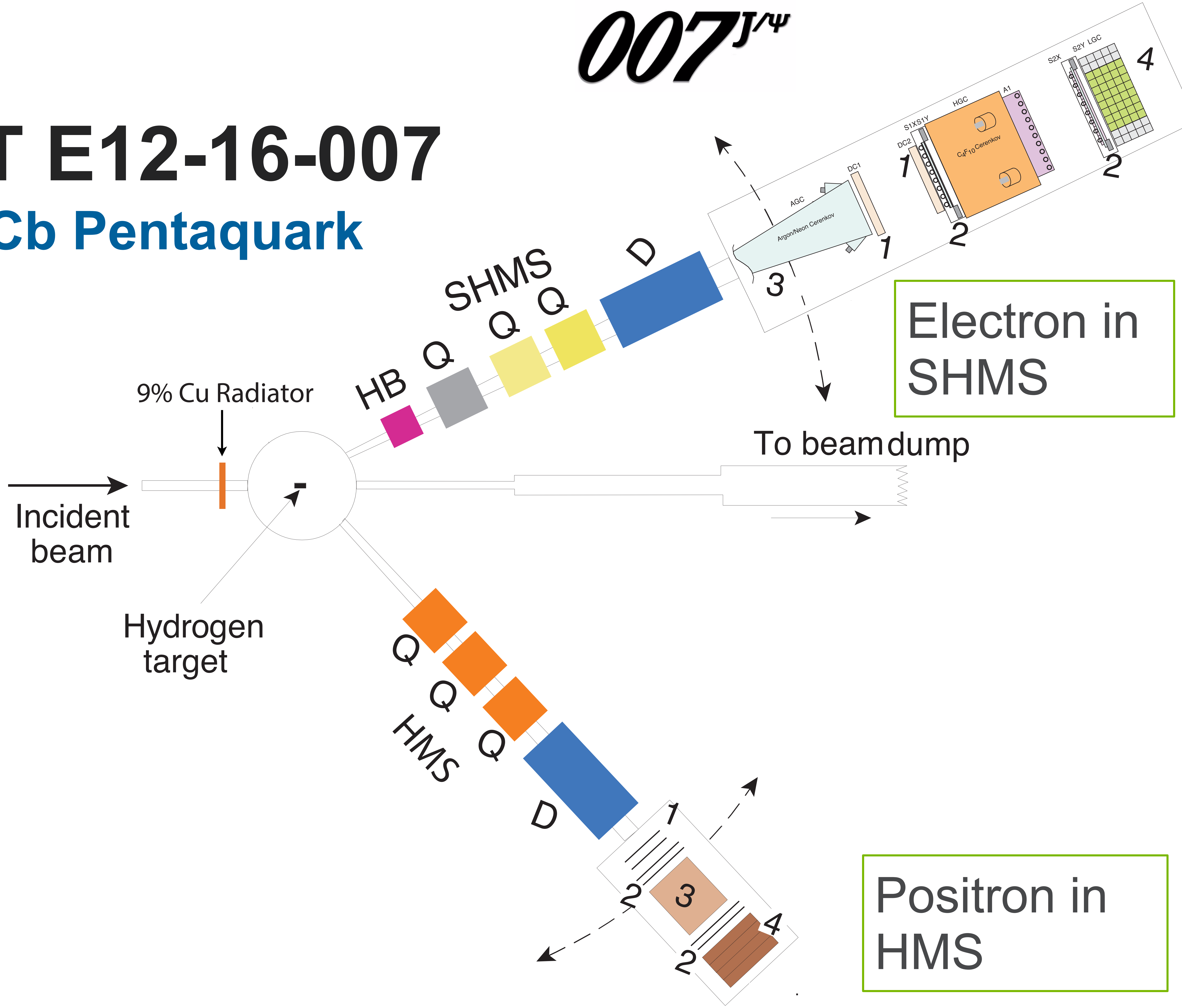
Best signal-to-background for resonant *J/ψ* production **at high *t***

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



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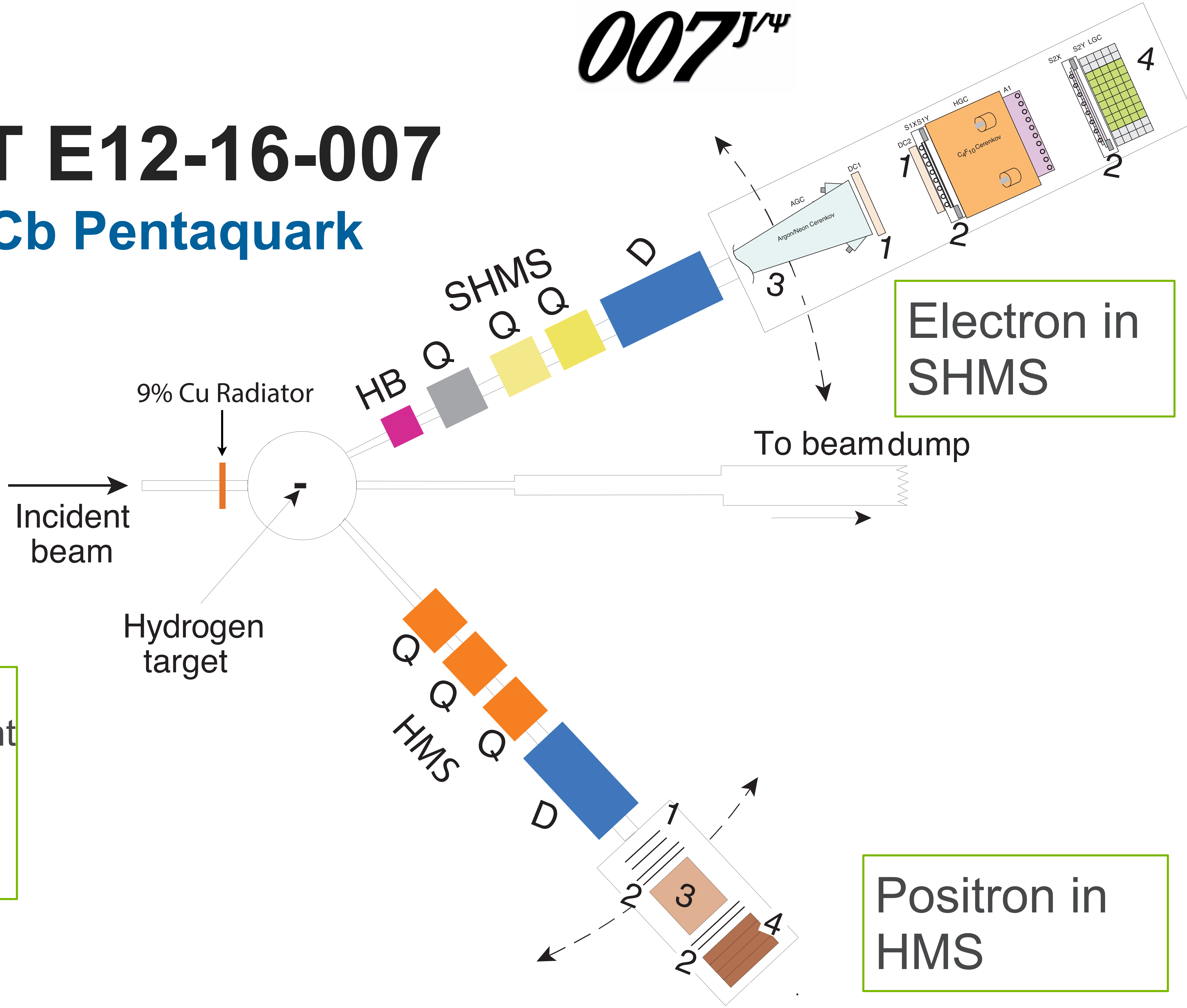
"Symmetric" configurations for *t*-channel cross section measurement

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



Electron in SHMS

Positron in HMS

Z.-E. Meziani, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
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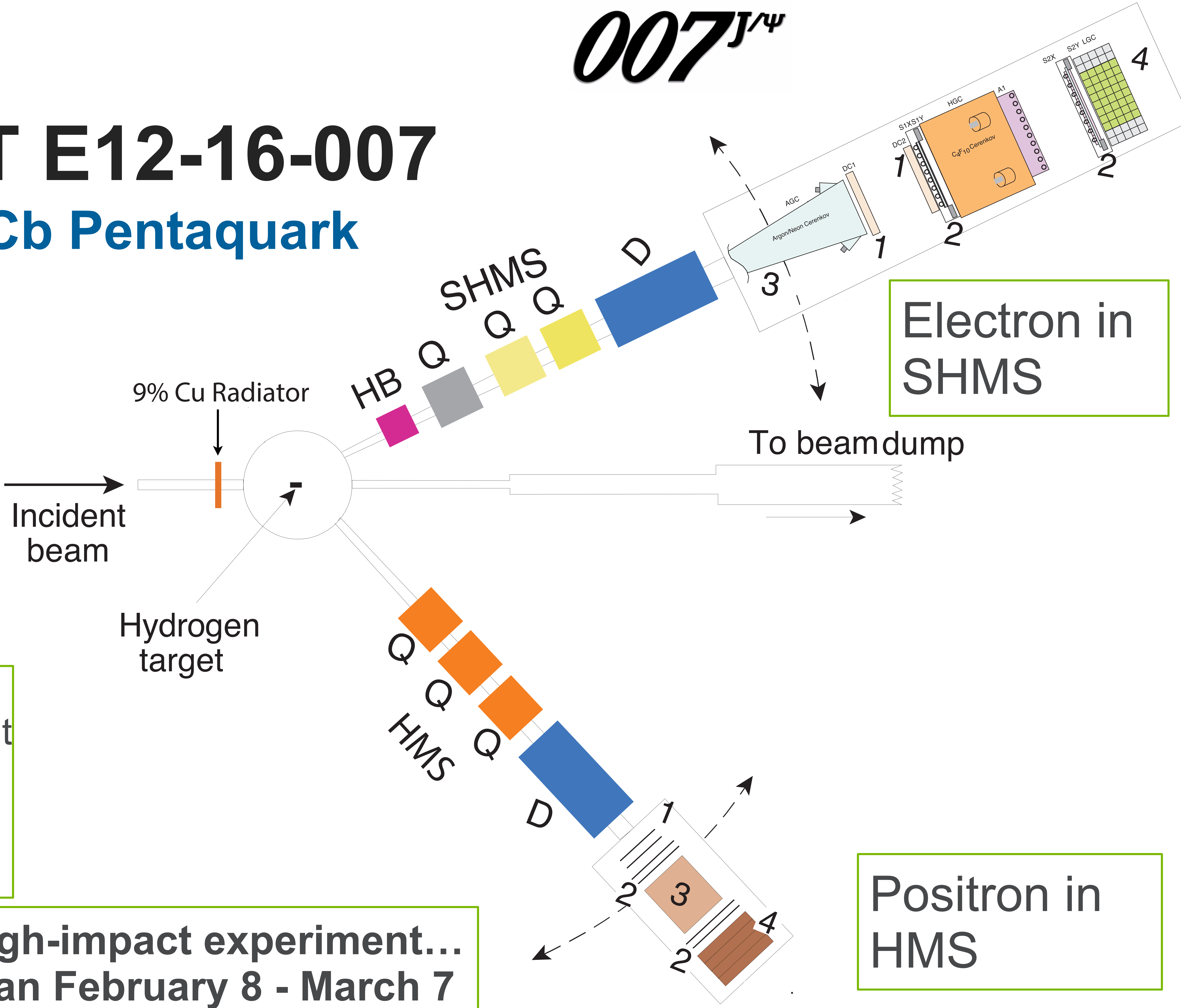


Electron in SHMS

Positron in HMS

High-impact experiment…
Ran February 8 - March 7

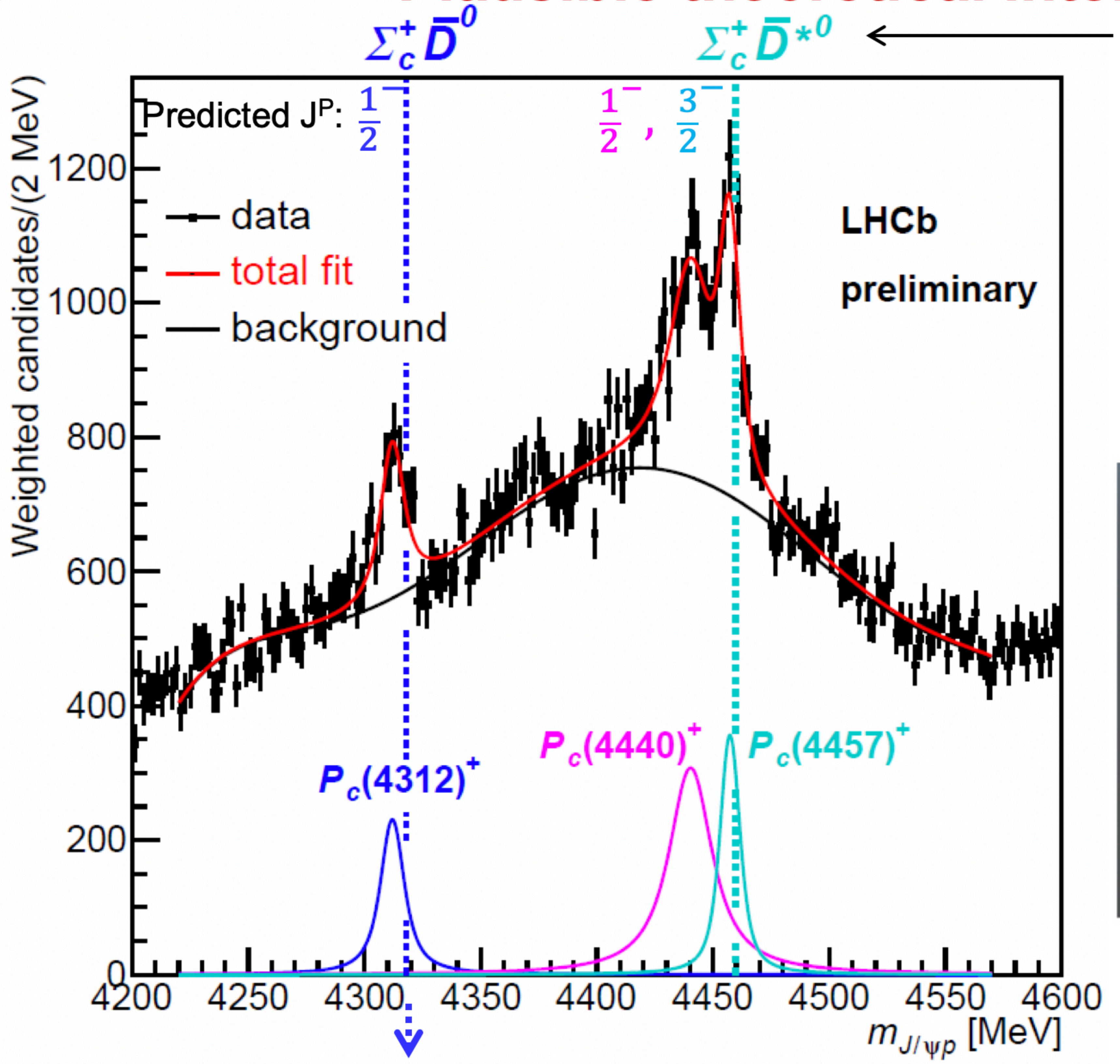
R. Aaij *et al.* (LHCb), Phys.Rev.Lett. 122 (2019) no.22, 222001

The plot thickens…

NEW LHC-B RESULTS WITH 10X STATISTICS

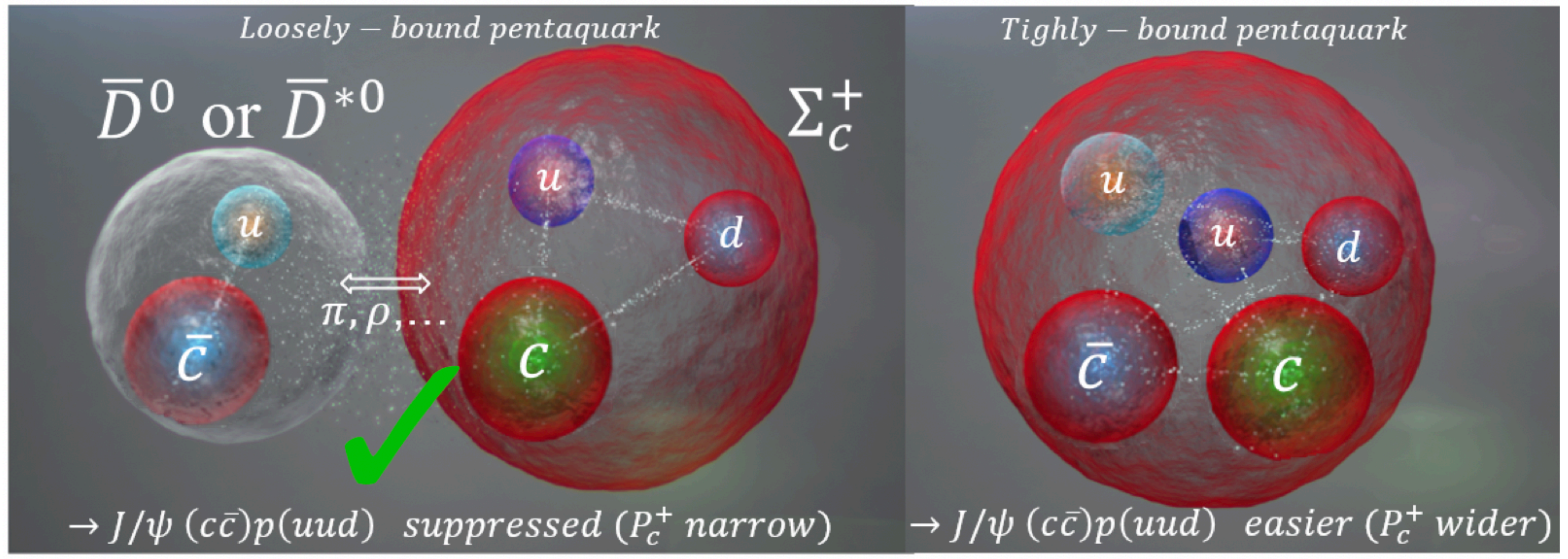
Plausible theoretical interpretation

LHCb-PAPER-2019-014 in preparation



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

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

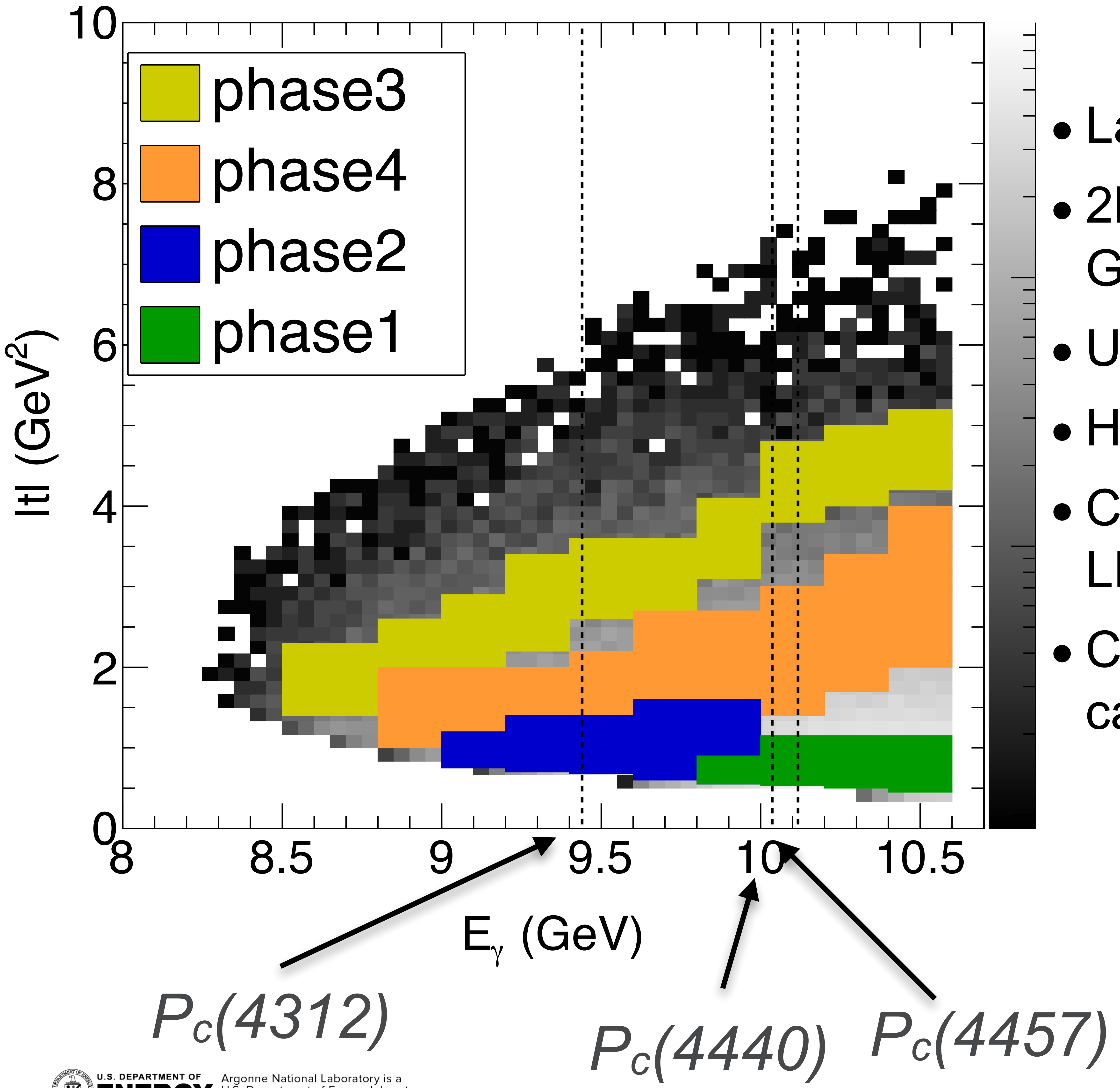
However, we need to measure J^Ps to confirm molecular hypothesis, find isospin partners, …

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$^{J/\psi}$

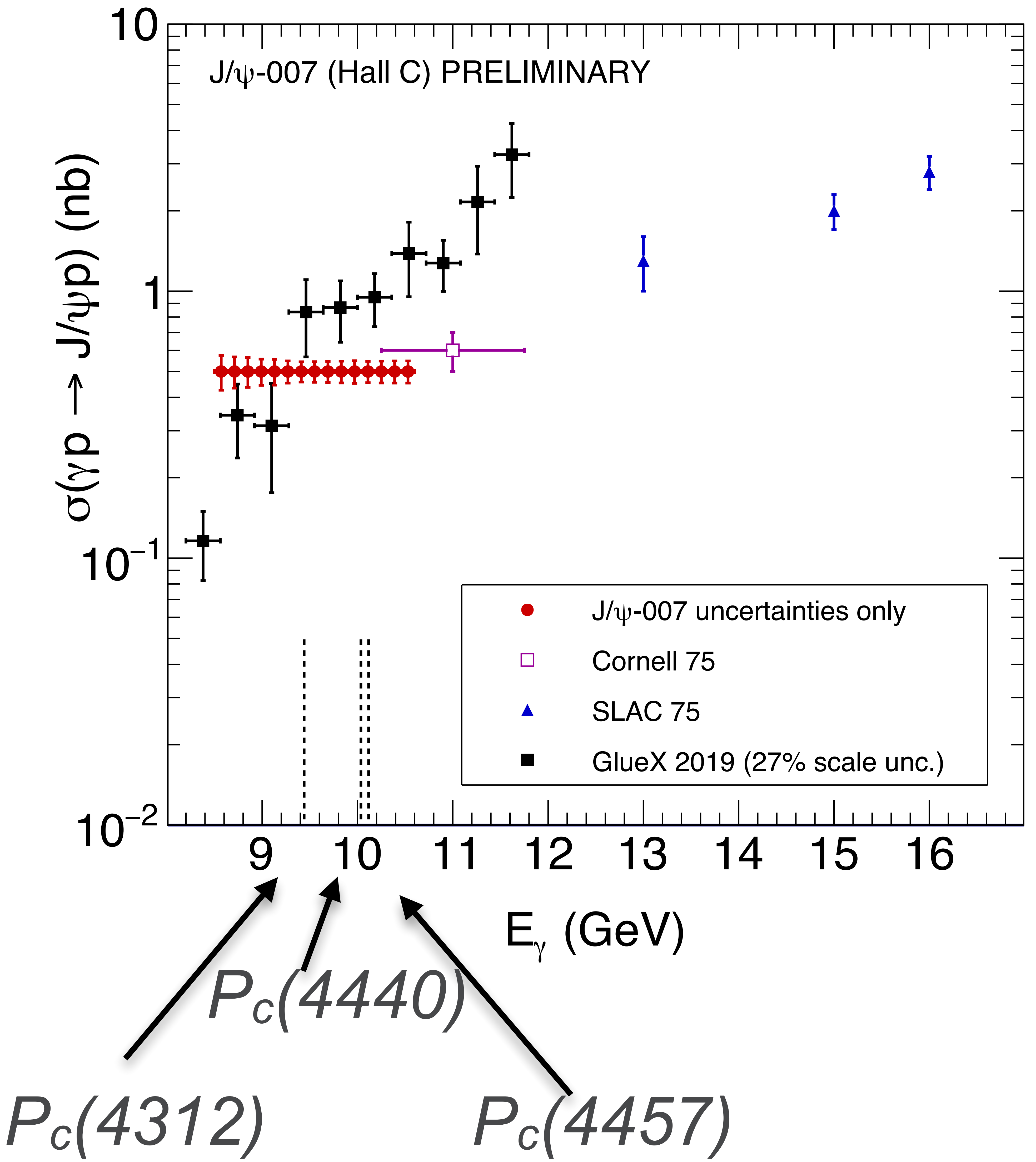


- Largest dataset of J/ψ produced with a real photon beam.
- 2D photo-production cross section between 8.5-10.6 GeV
- Used 4 settings to cover entire phase space
- High-t "enriched" sample, only possible at Hall C!
- Combine data from all settings for maximal sensitivity to LHCb pentaquark
- Covers energy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

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

ABSOLUTE CROSS SECTION

007J/ψ



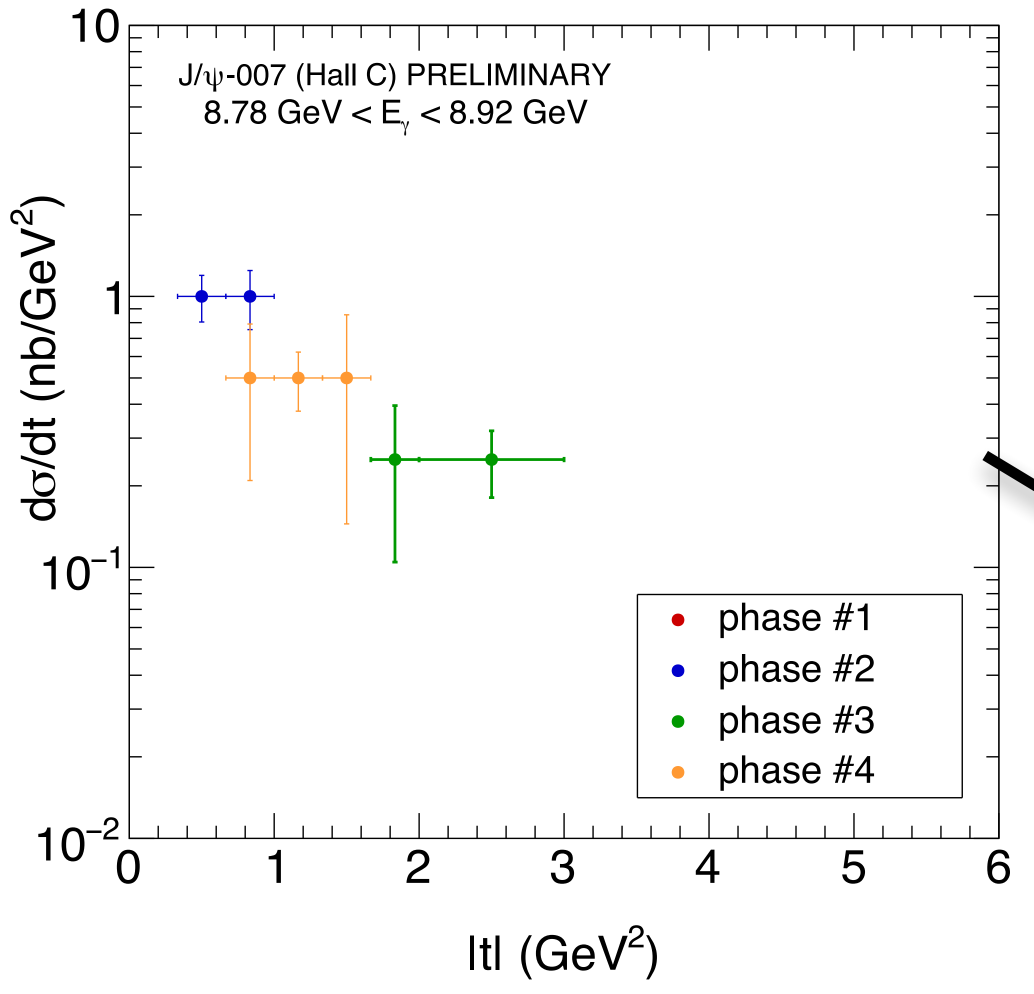
- **Only showing (preliminary) uncertainties!**
- High-precision measurement of the *t*-dependent cross section between 8.5-10.6 GeV
- Precise (~5%) absolute cross section possible due to calibration measurements of elastic and inelastic cross sections
- Will shed light on apparent discrepancy between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

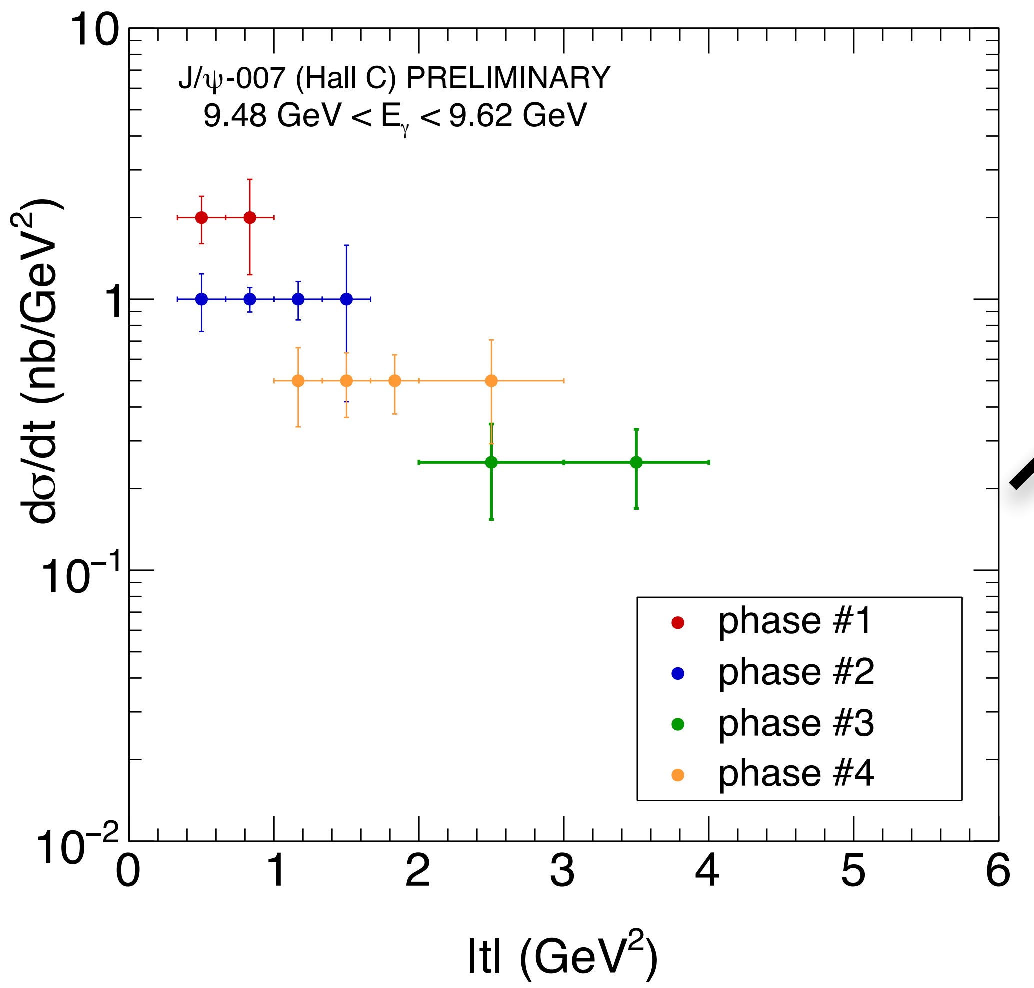
Absolute cross section ~5% precision

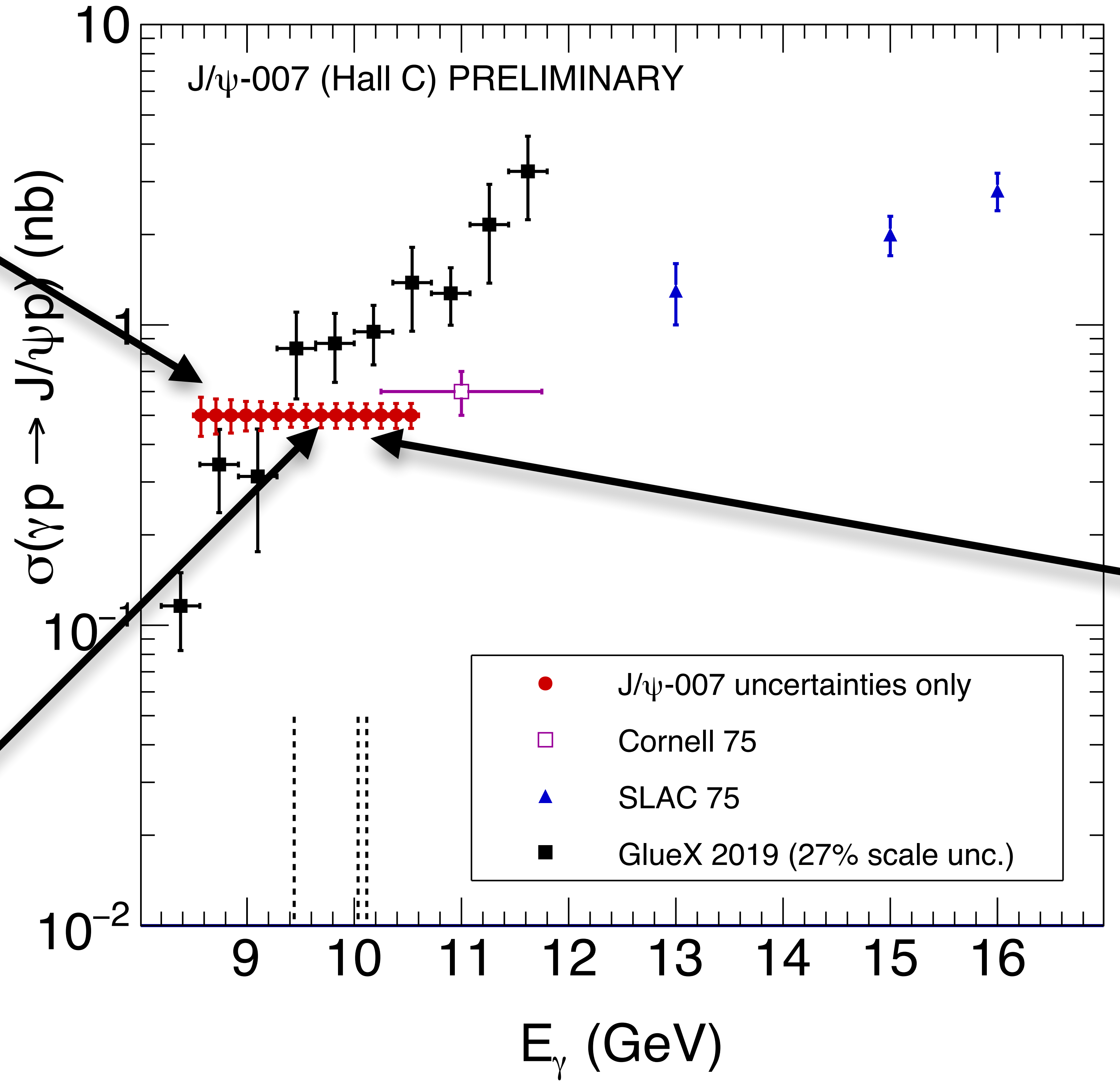
A FULL 2D MEASUREMENT

$007^{J/\psi}$

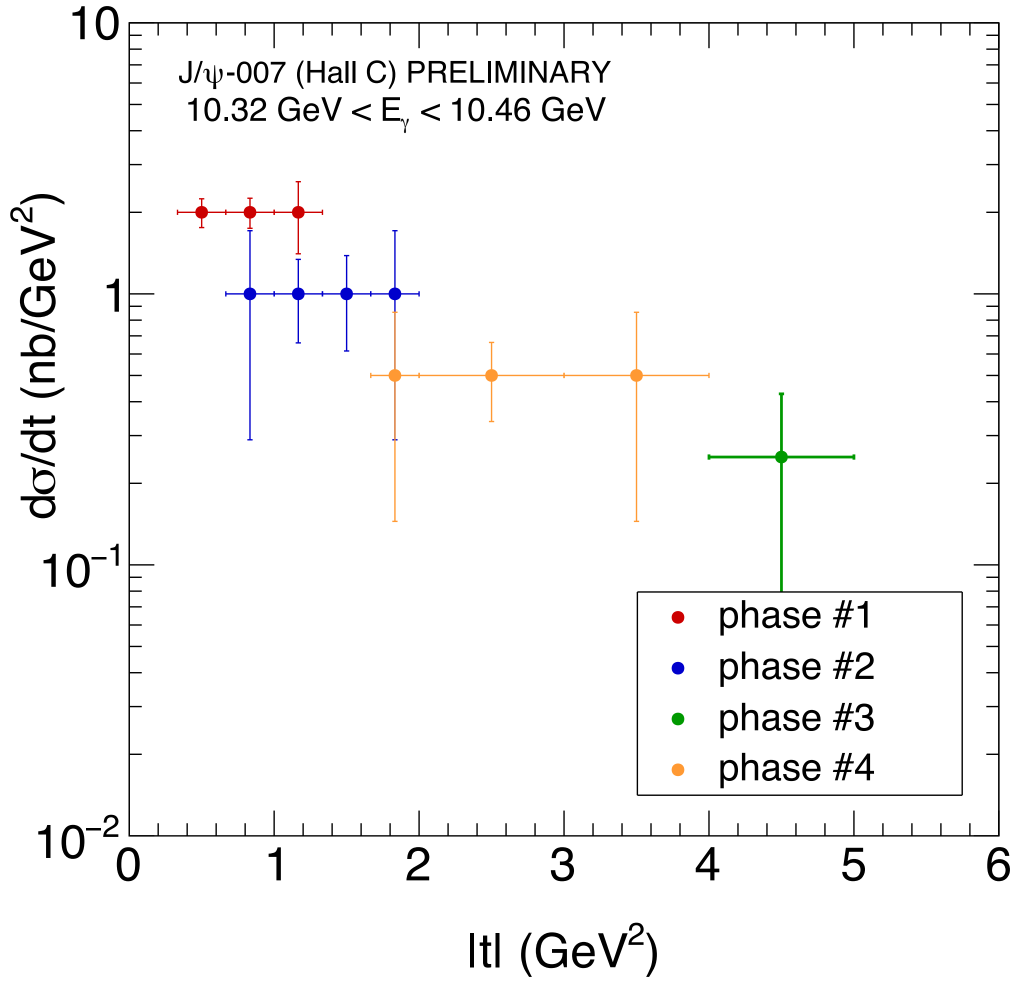
$$J/\psi \to e^+ e^-$$







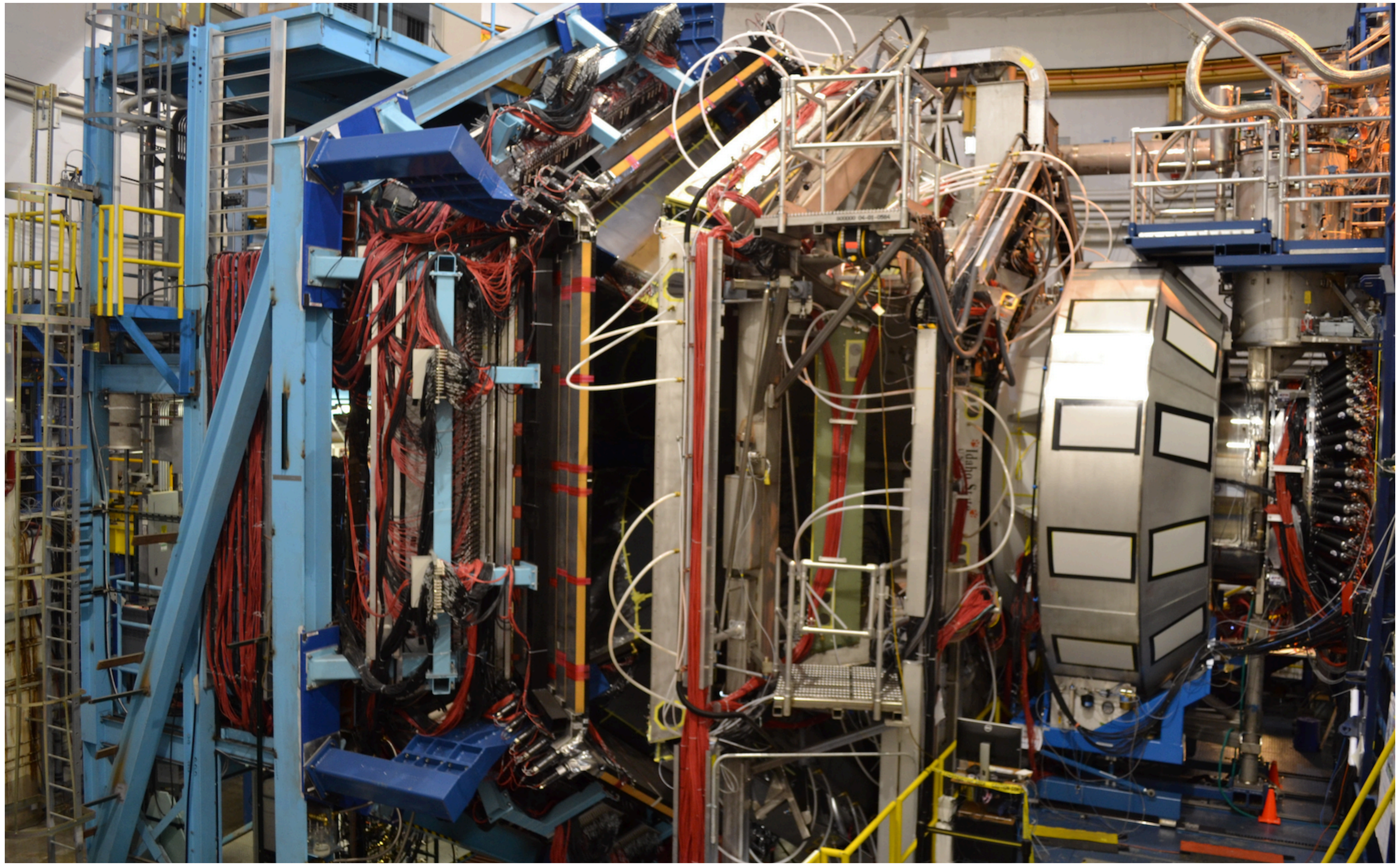
- **Only showing uncertainties!**
  (y-position for each setting arbitrary for improved visibility)



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

J/Ψ IN HALL B/CLAS 12

OTHER *J/ψ* measurements at Jefferson Lab



- Expected daily yield: 45 *J/ψ* for 130 days
- First data taken on proton and deuteron in 2018 and 2019
- Expect first results in ~1year (this year?)

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

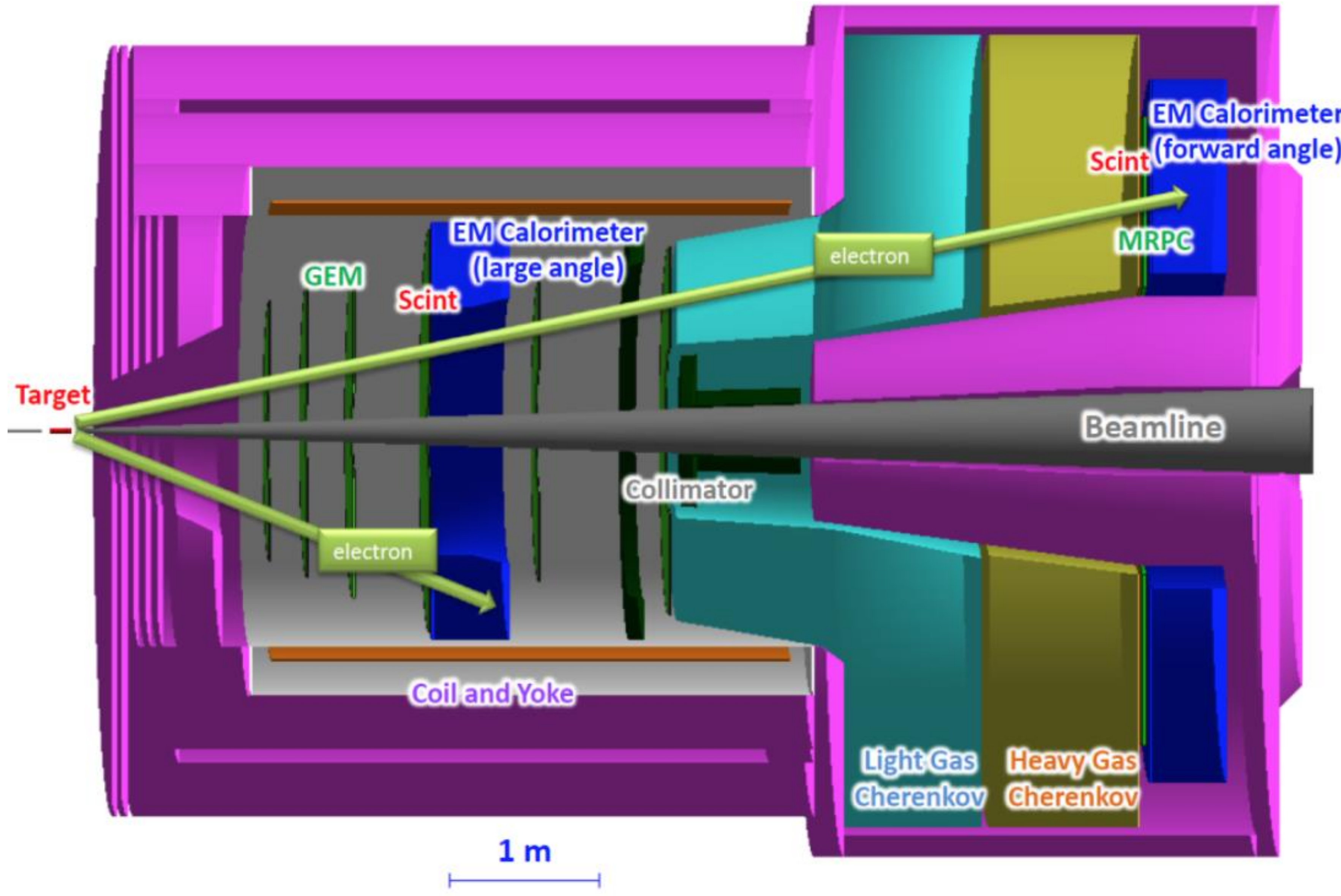
ATHENNA Collaboration

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

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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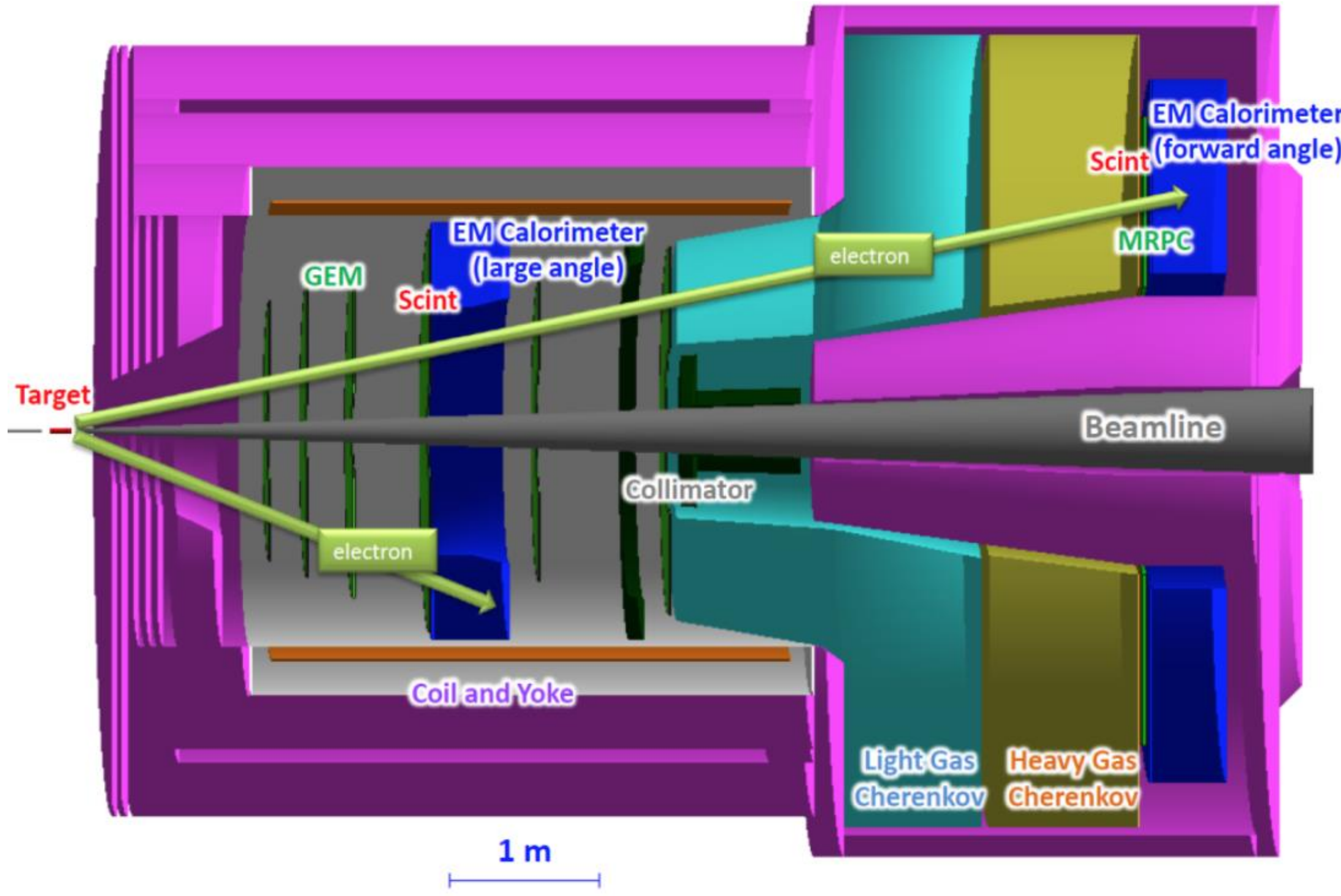


- Electro-production
  - Measure scattered electron and decay leptons
  - t-channel J/ψ rate: ~90/day
  - Clean signal (less background)
  - Closer to threshold

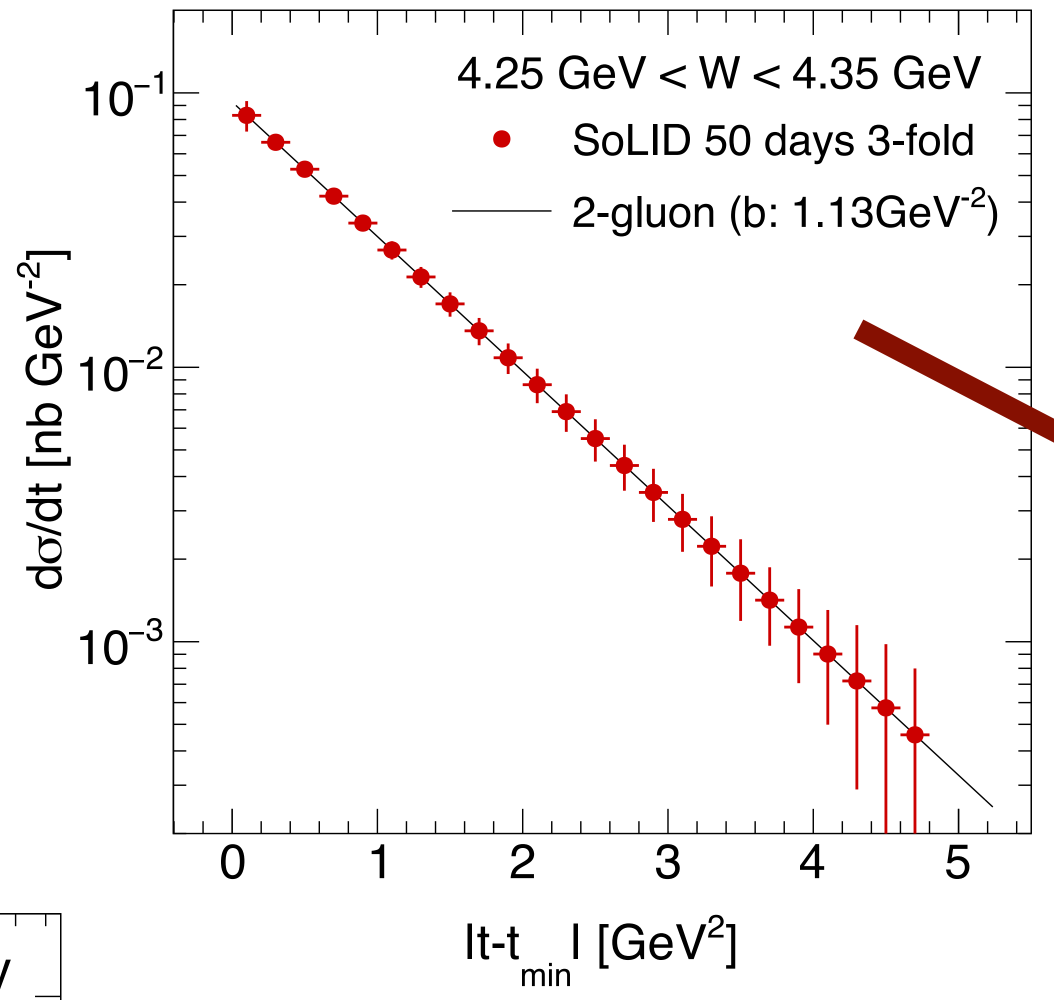
- Photo-production
  - Measure decay leptons and recoil proton
  - t-channel J/ψ rate: >1600 per day
  - Ultra-high rate

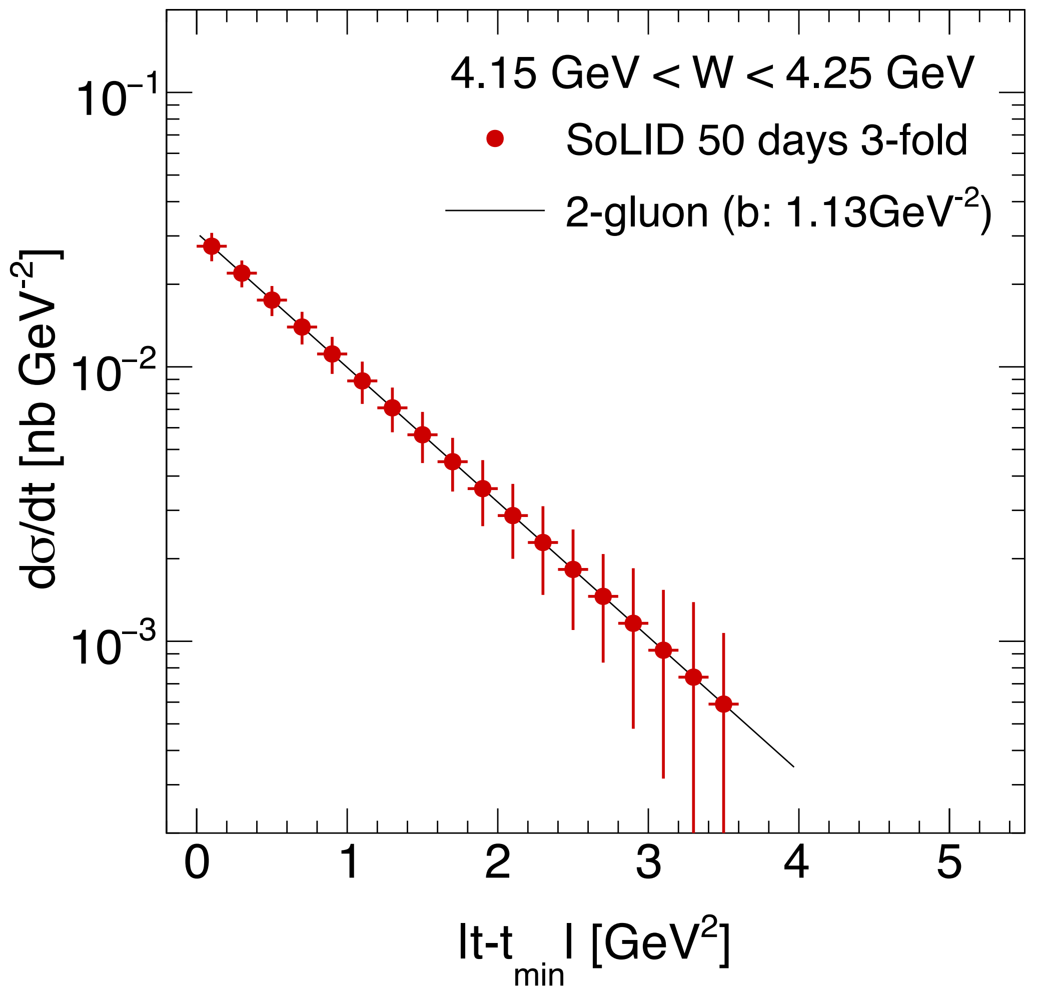
ATHENNA Collaboration

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

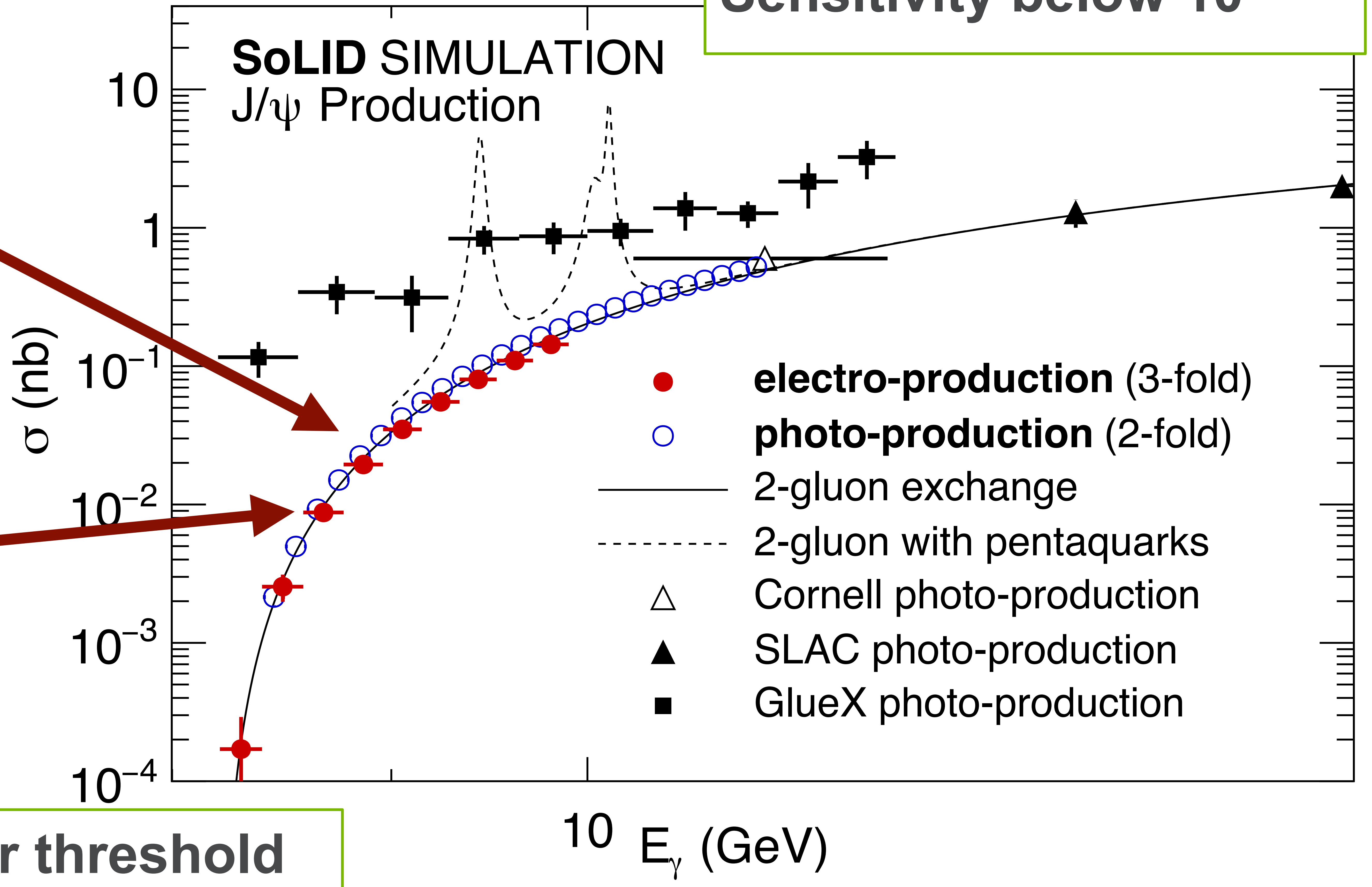
J/Ψ EXPERIMENT E12-12-006 AT SOLID

First true electro-production of *J/ψ*!





Sensitivity below 10^{-3}

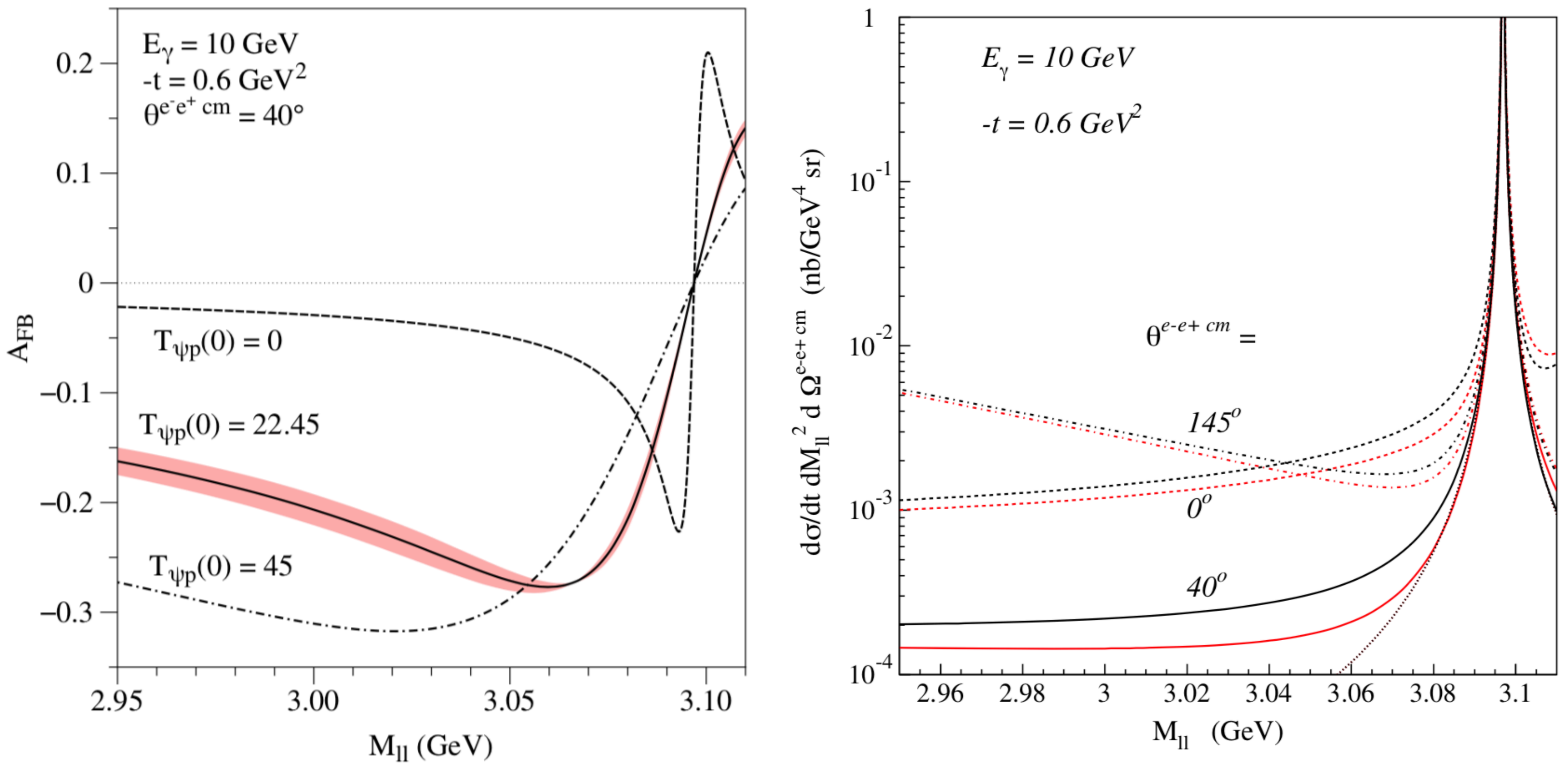


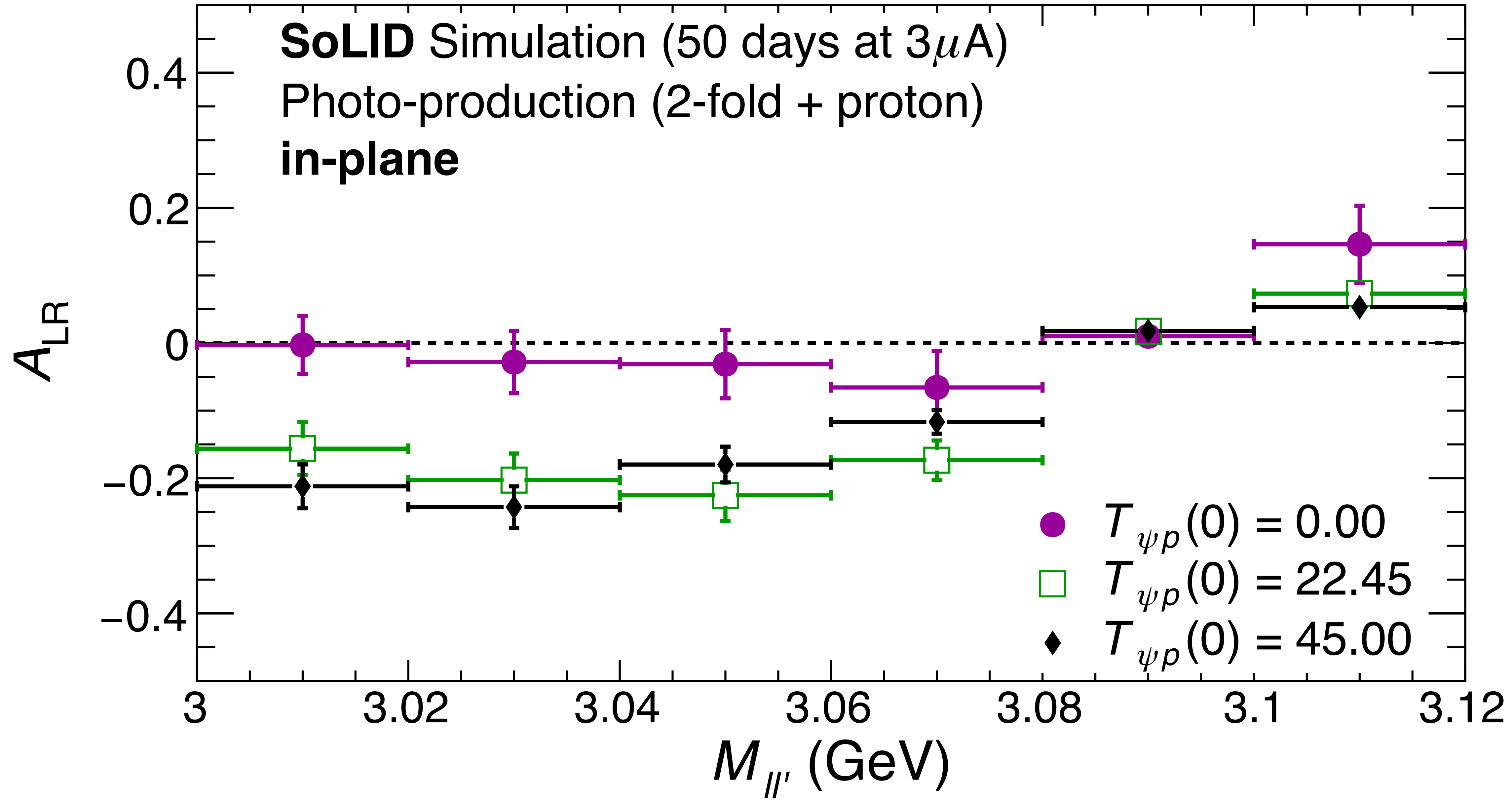
Lever-arm in Q^2 near threshold could help with factorization.

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

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

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

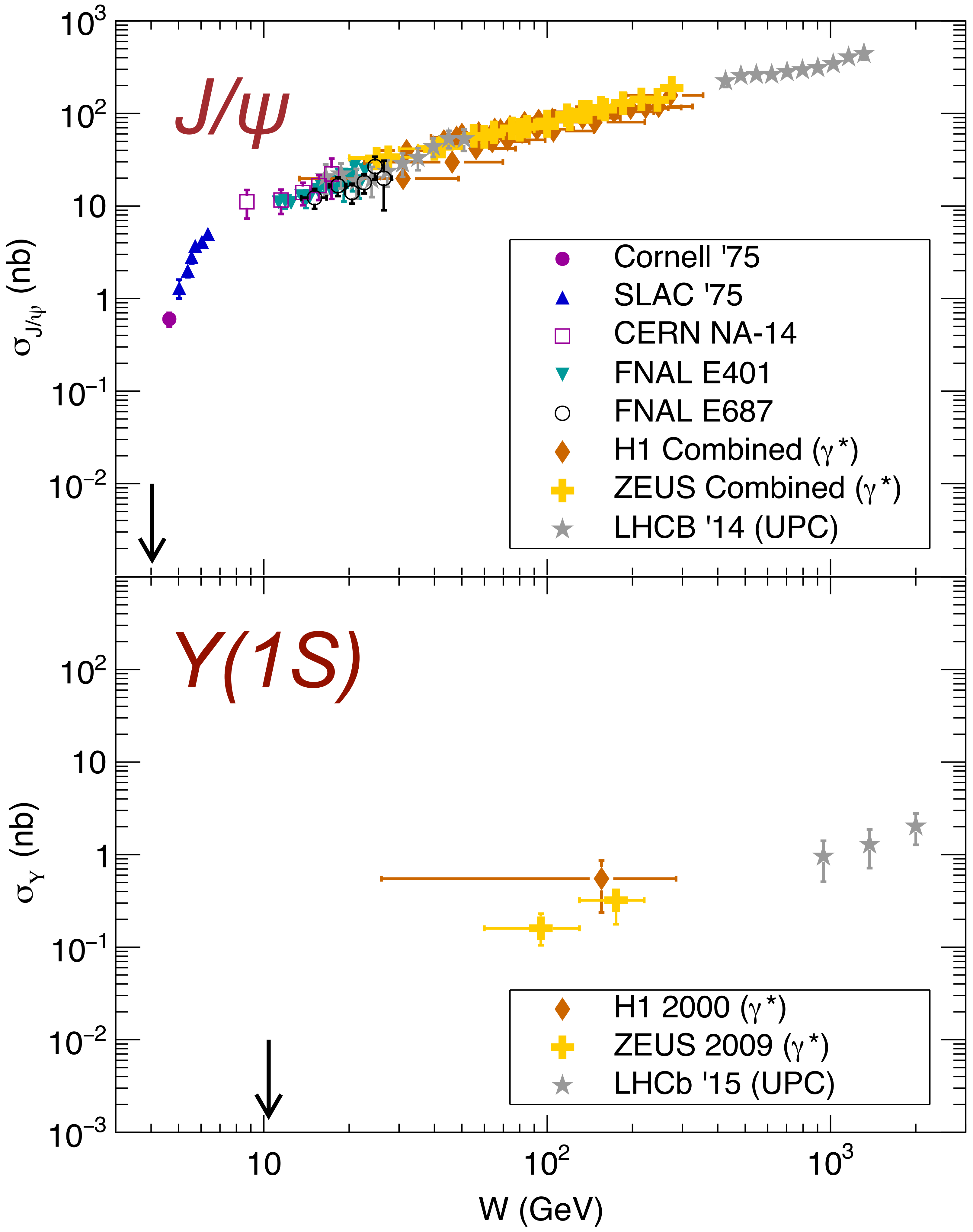
J/Ψ EXPERIMENTS IN JLAB IN A NUTSHELL

Exciting times for *J/ψ* near threshold… maybe room for

	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

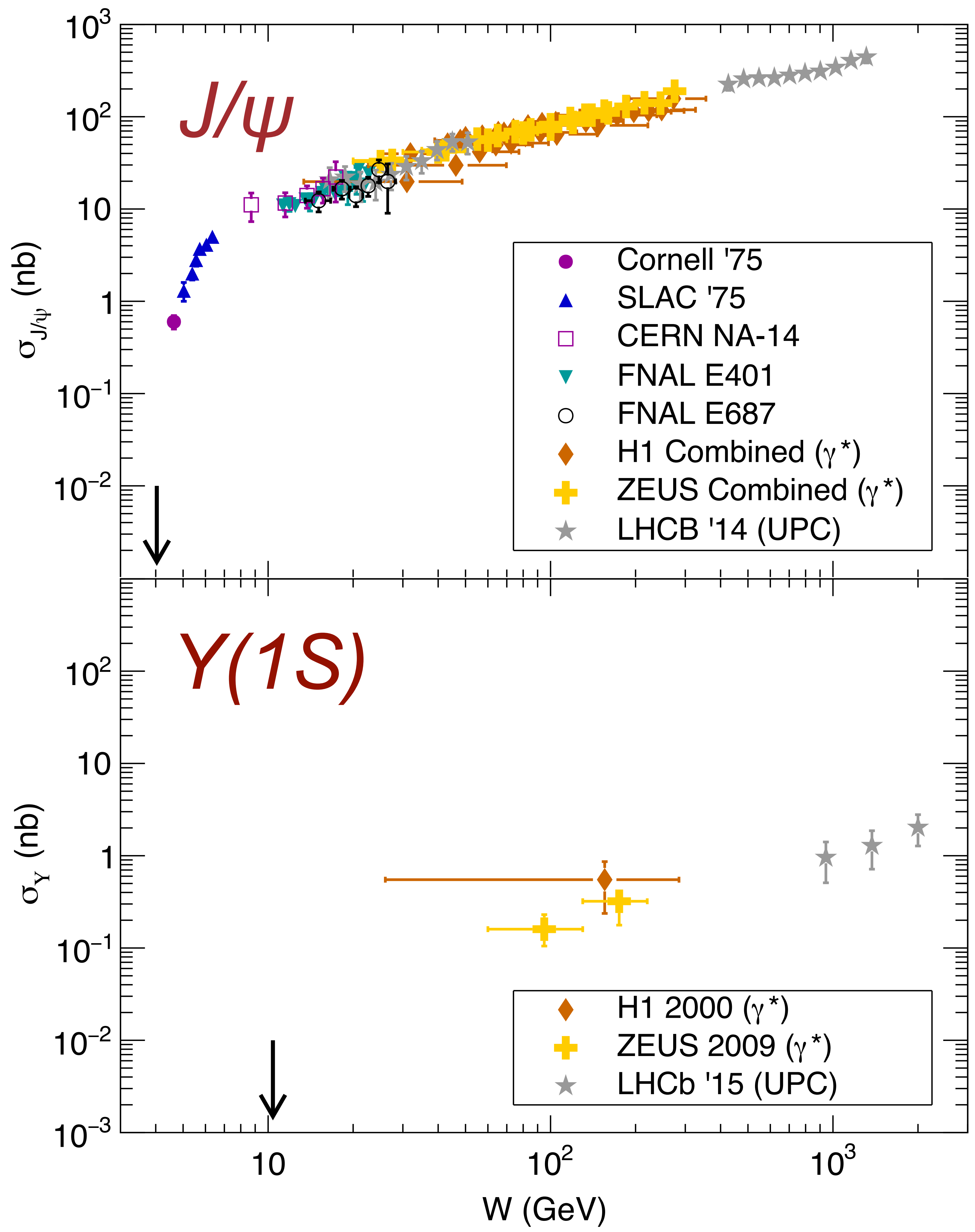
…but a challenging measurement



Υ(1S): THE OPTIMAL GLUONIC PROBE

…but a challenging measurement

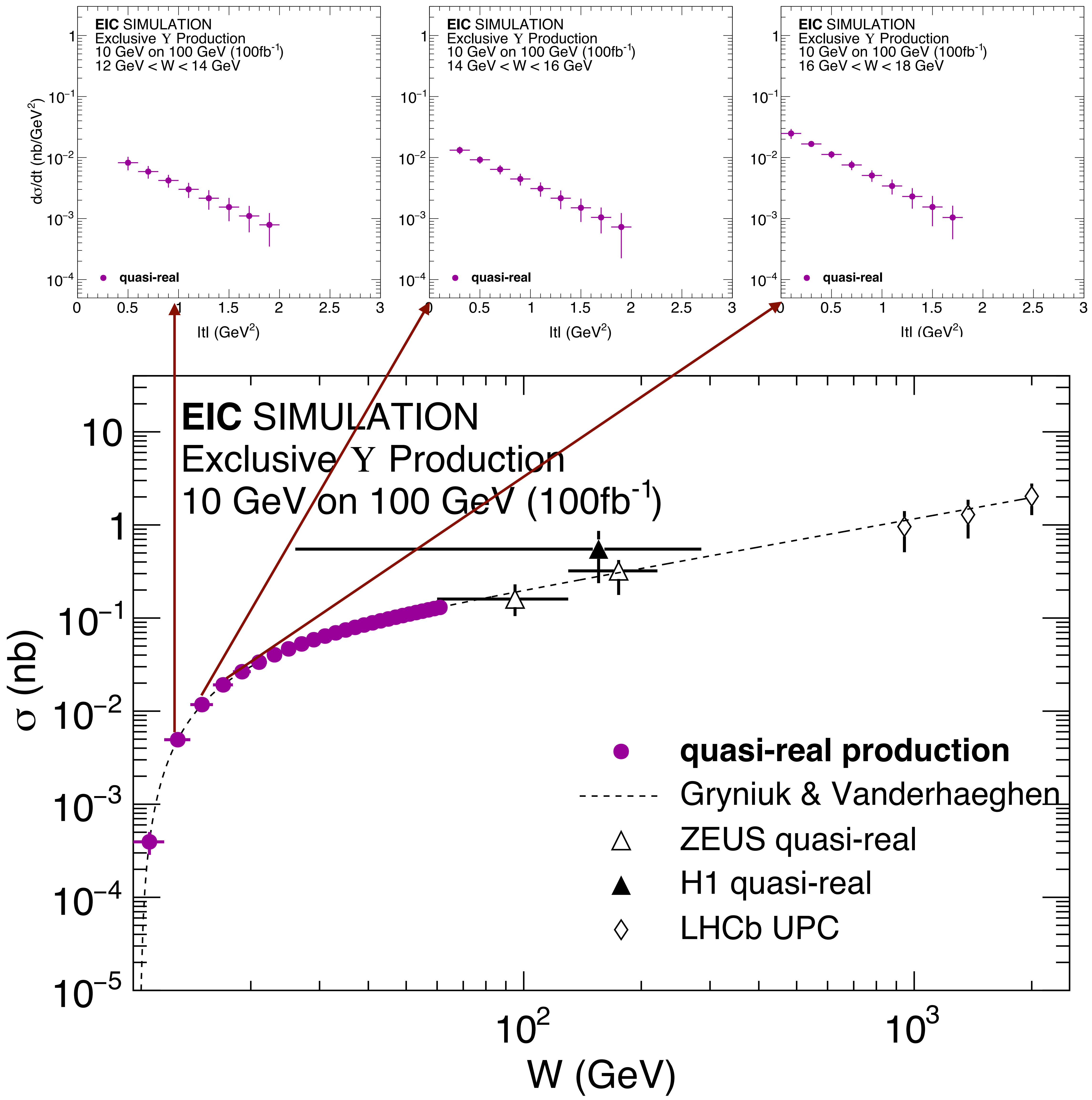
- *Υ(1S)* is a heavier (smaller) probe than *J/ψ*
  - *Υ(1S)* production near threshold crucial to **universality**
- Cross section very small (2 orders of magnitude smaller than *J/ψ)*
- Measurement can (only) be done at EIC



Υ(1S) PHOTO-PRODUCTION AT EIC

…Threshold measurement possible!

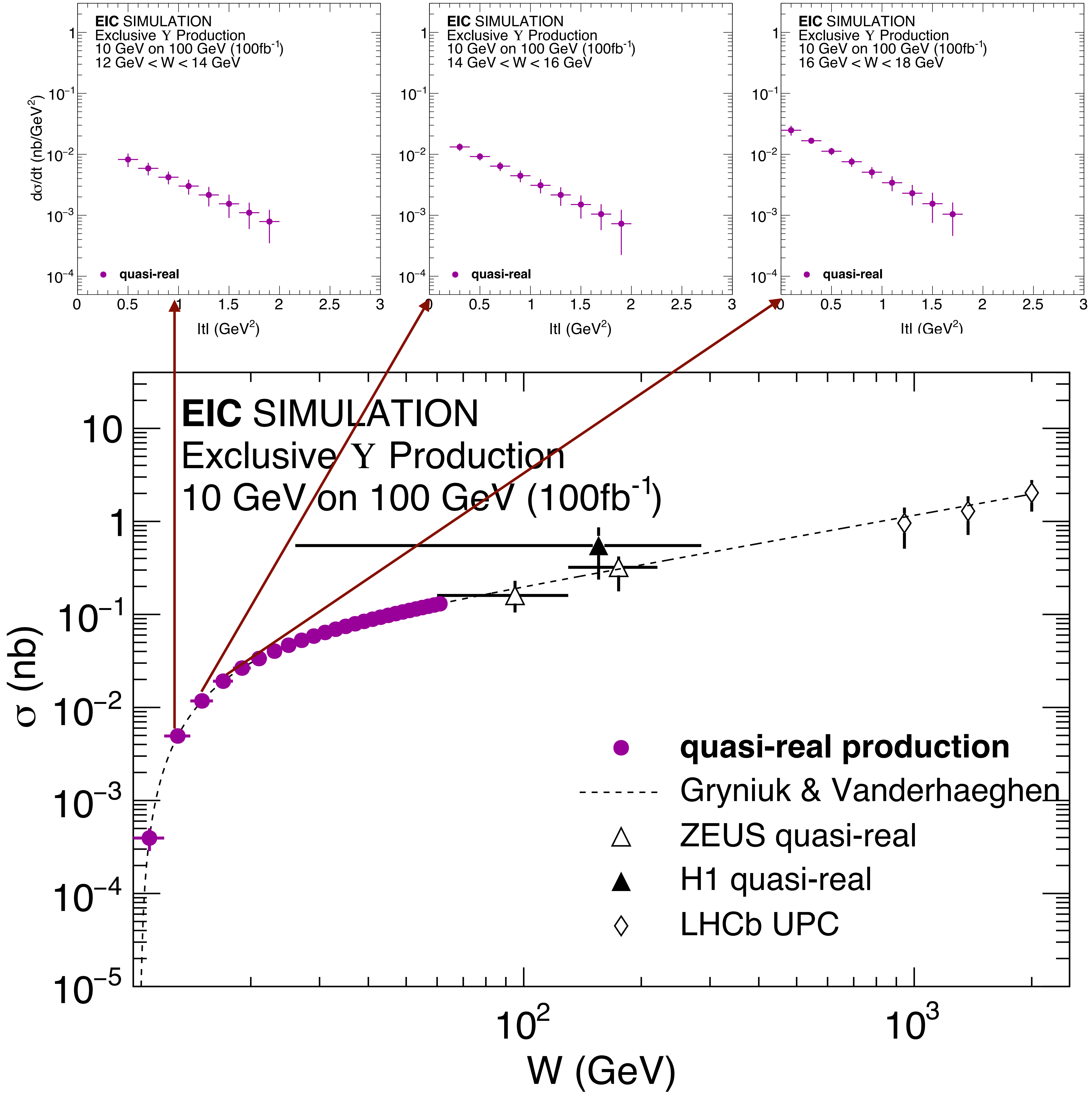
- **Quasi-real production** at an EIC
- Both electron and muon channel
- **Fully exclusive** reaction
- Can go **to near-threshold region**



Y(1S) 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**



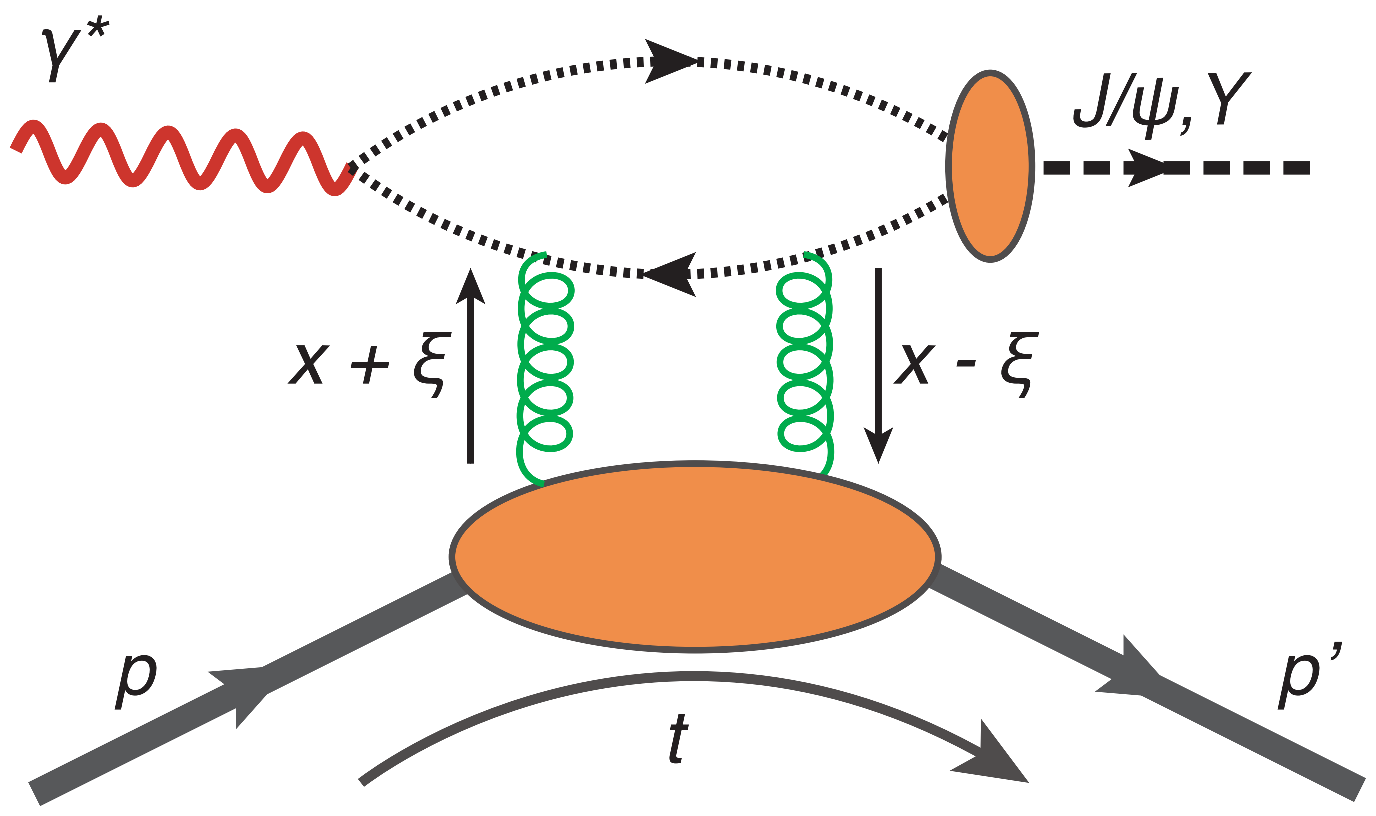
- ***Y(1s)*** production possible at threshold!
  - Provides measure for **universality,** complimentary to threshold *J/ψ* program at JLab12
  - Are there a "beautiful" pentaquarks?
- Sensitivity down to ~10^{-3} nb!

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*: $x_V = \dfrac{Q^2 + M_V^2}{2p \cdot q}$

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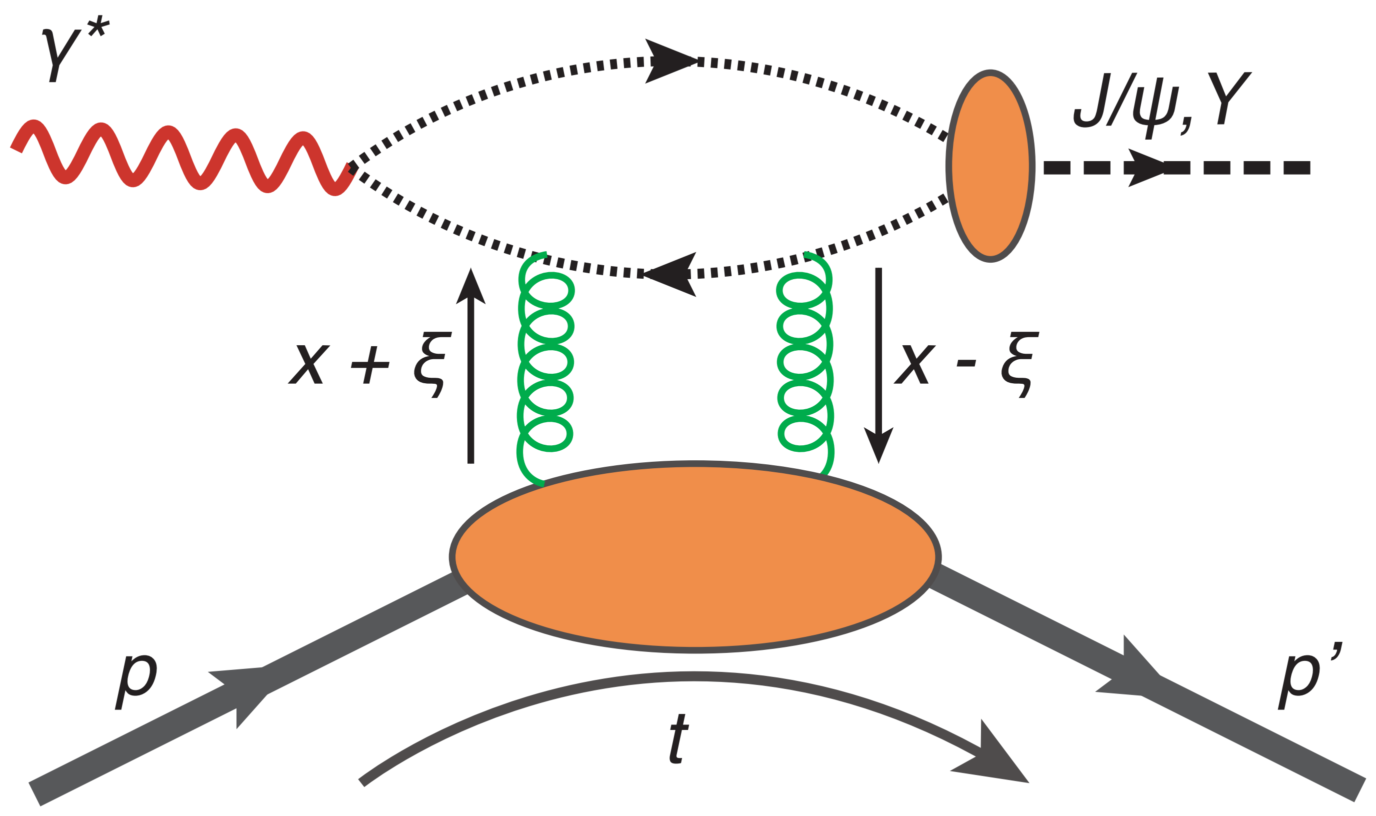

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average unpolarized gluon GPD related to *t*-dependent cross section (LO)

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

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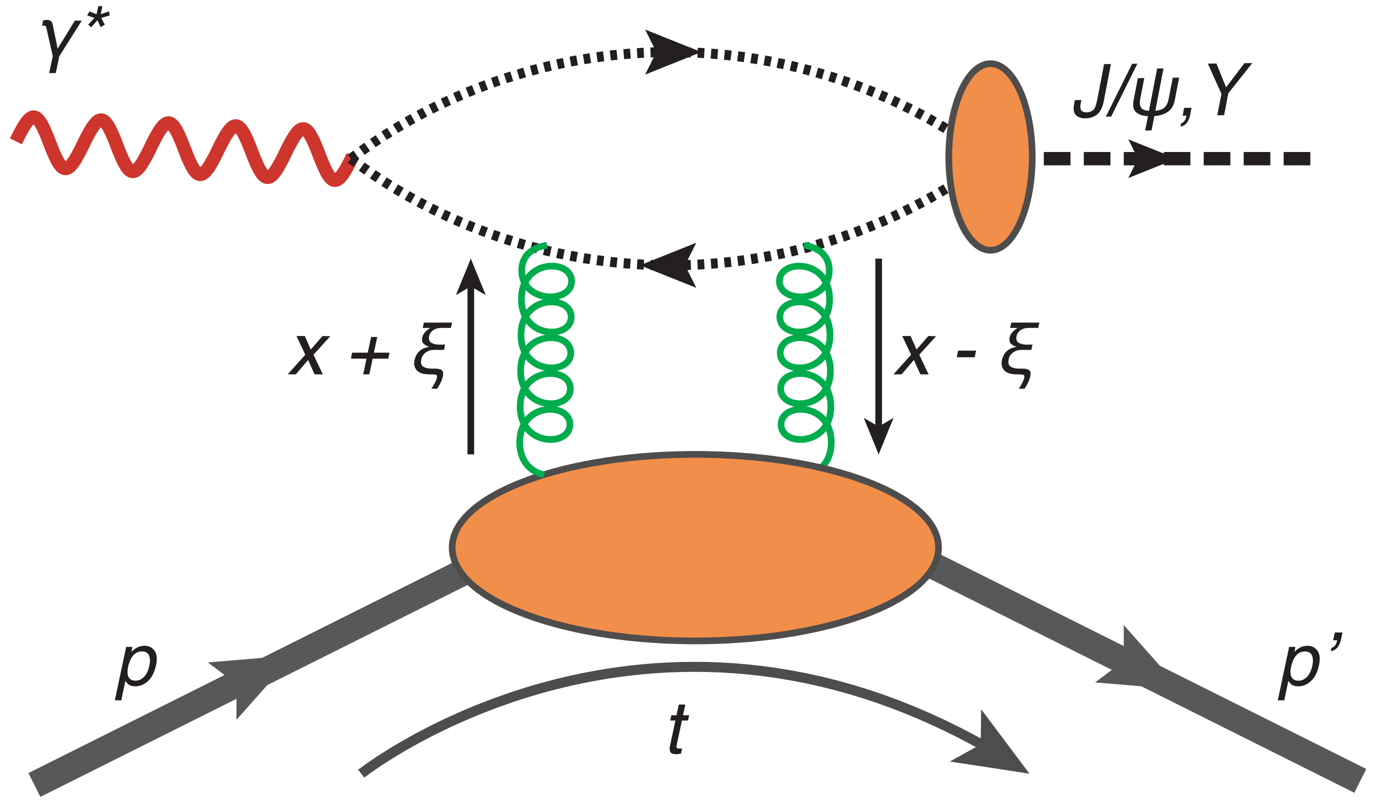

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transverse gluonic profile

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

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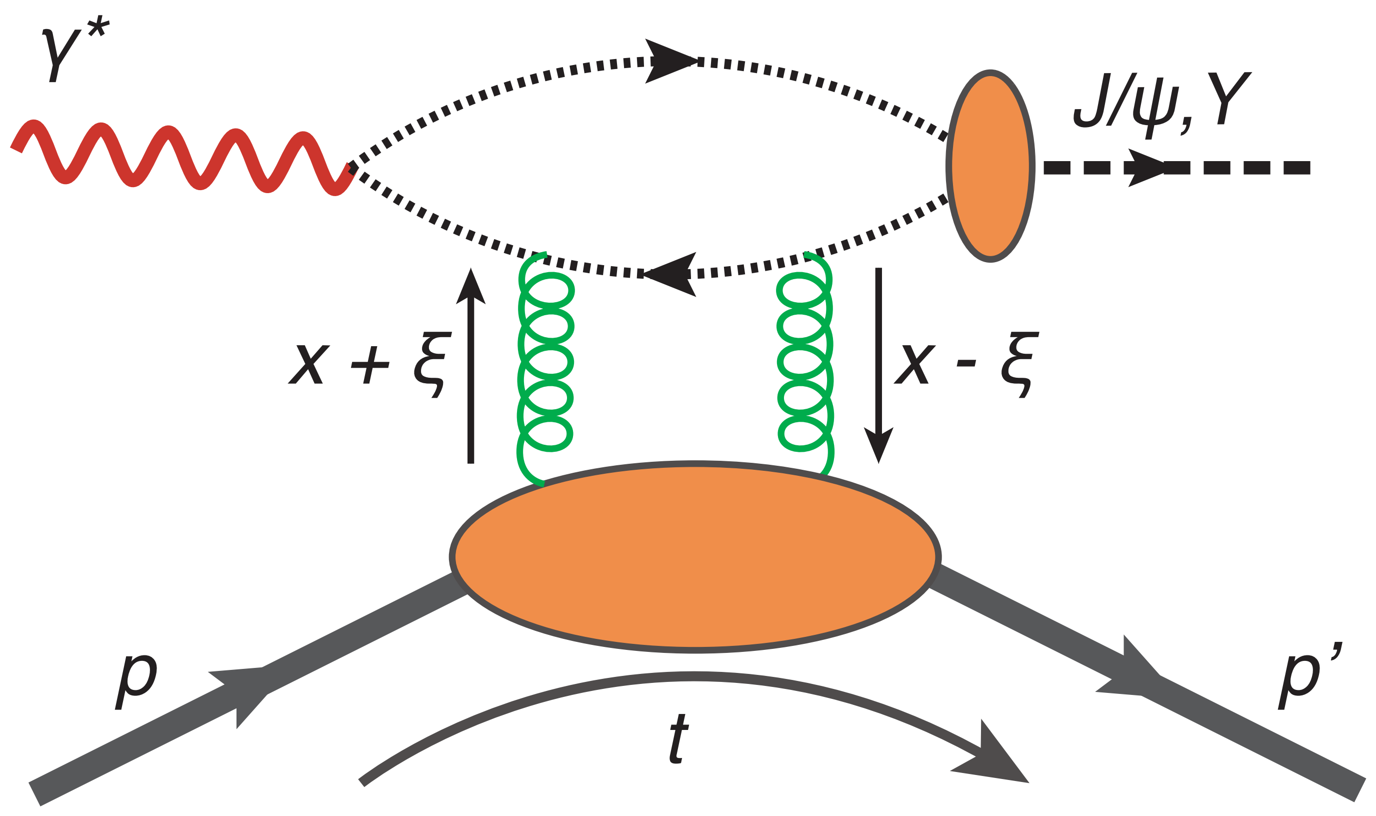

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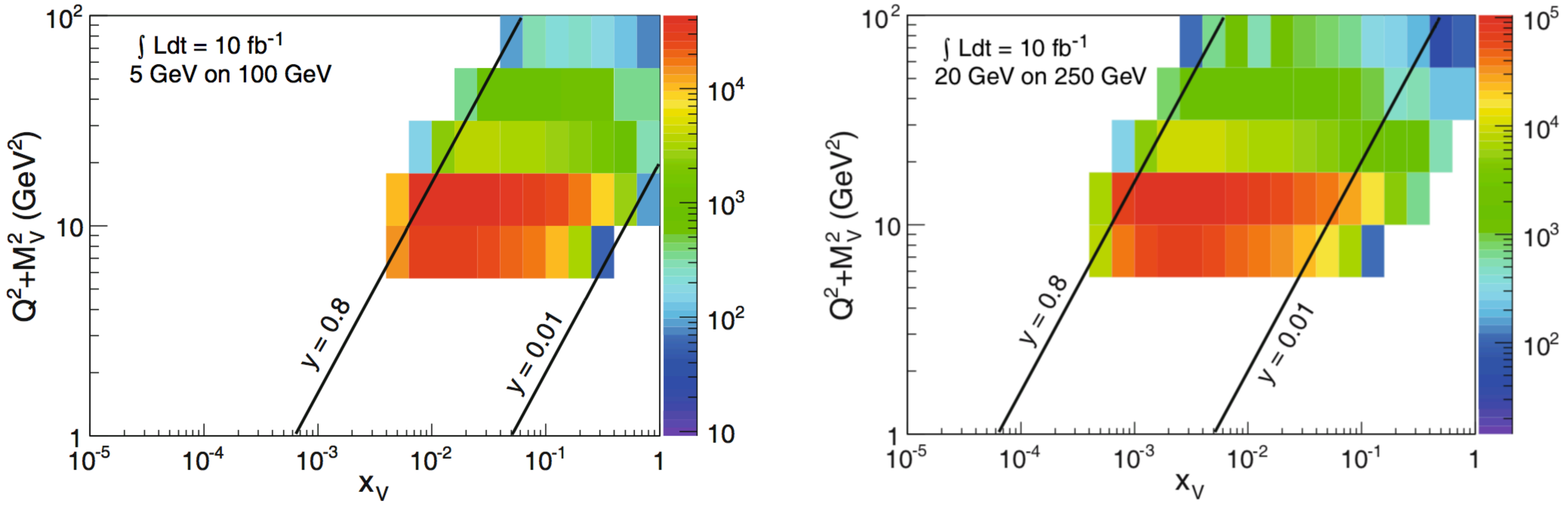
- Remarks:
  - **Simplest** possible GPD extraction
  - Intrinsic systematic uncertainty due to **extrapolation** outside of measured *t*-range
  - **NLO effects** could be significant
    - Corrections expected to be smaller for *Υ(1s)* than for *J/ψ*

GLUON TOMOGRAPHY WITH J/Ψ



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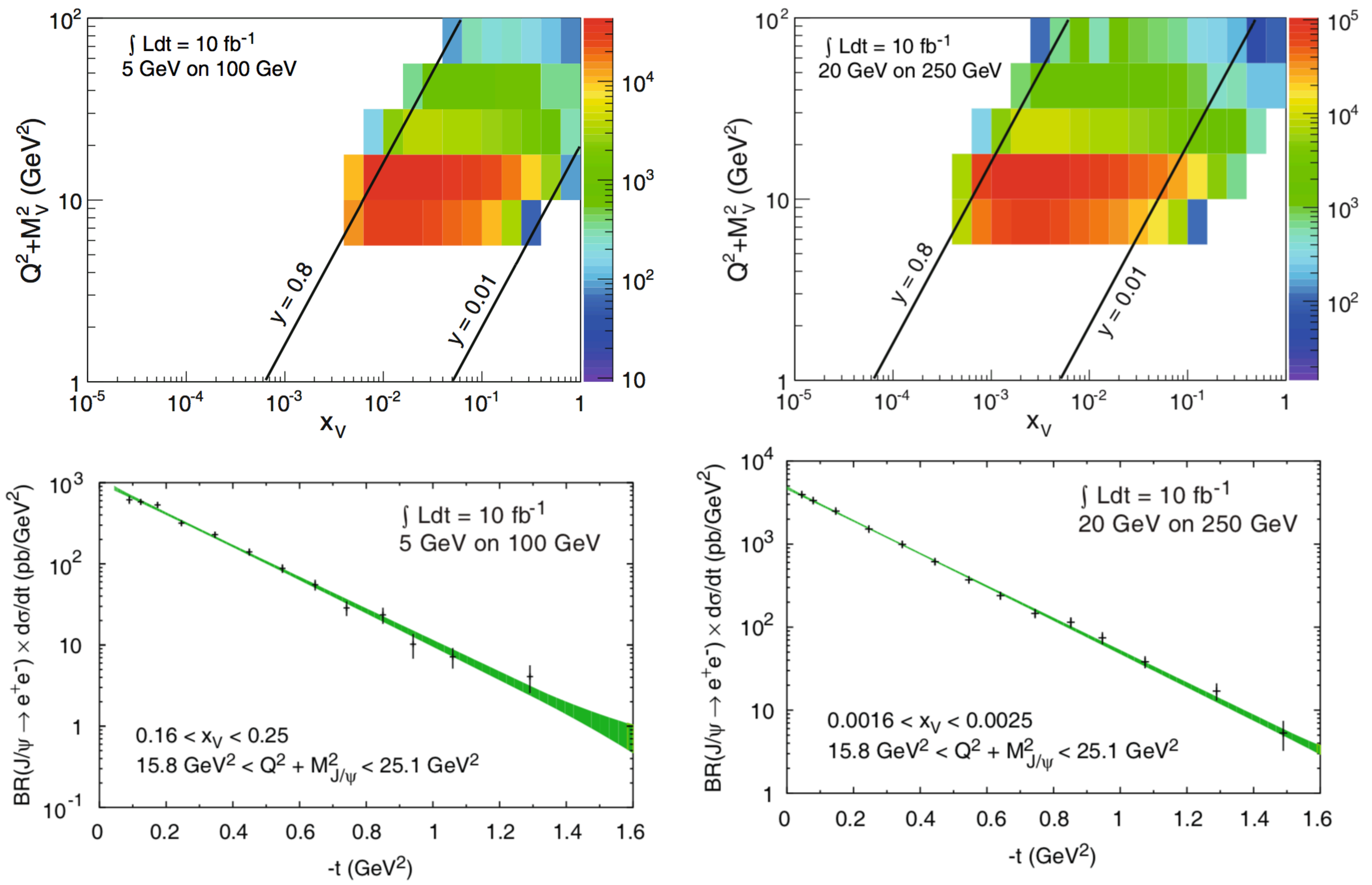

***t*-spectra**

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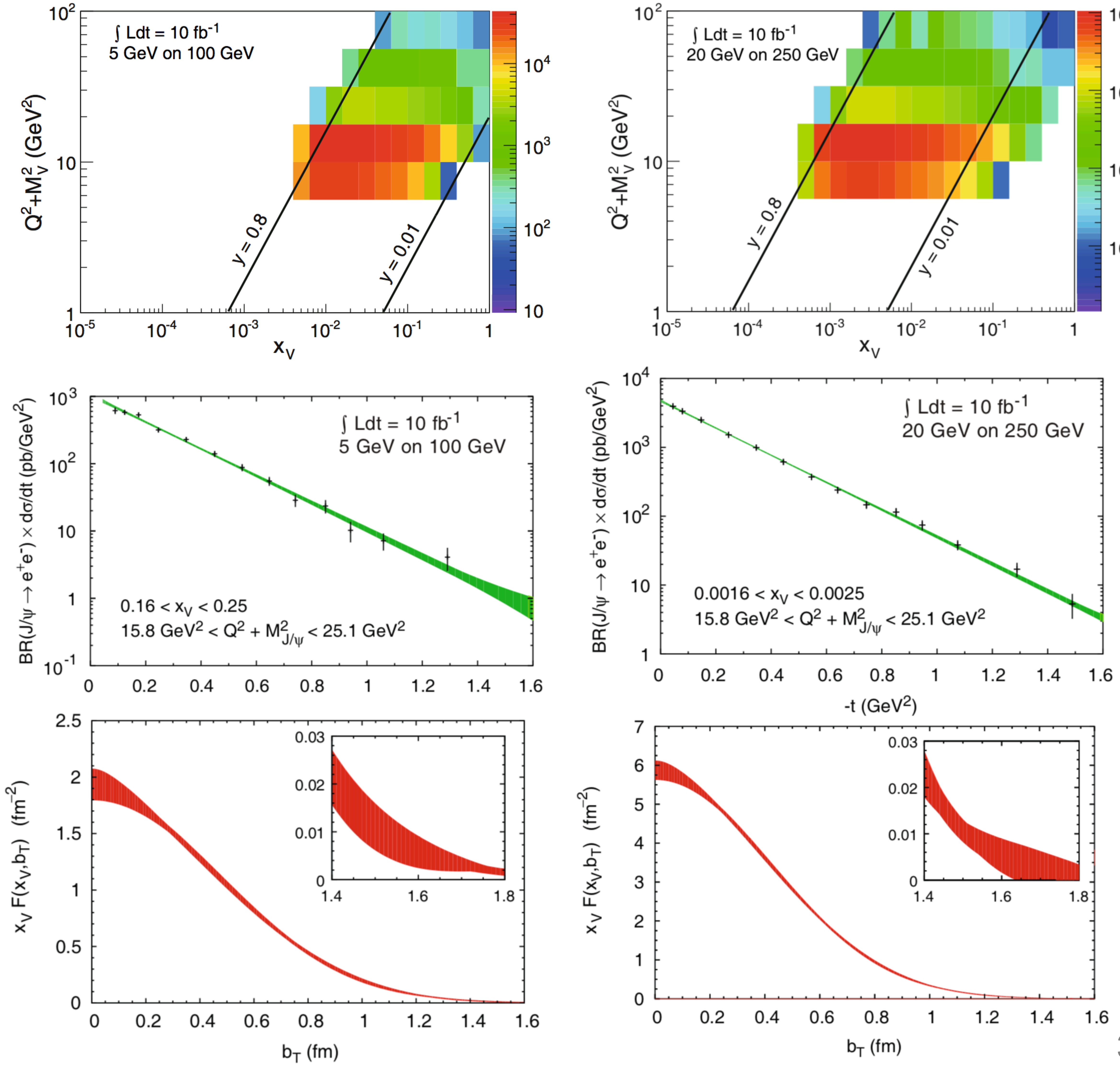
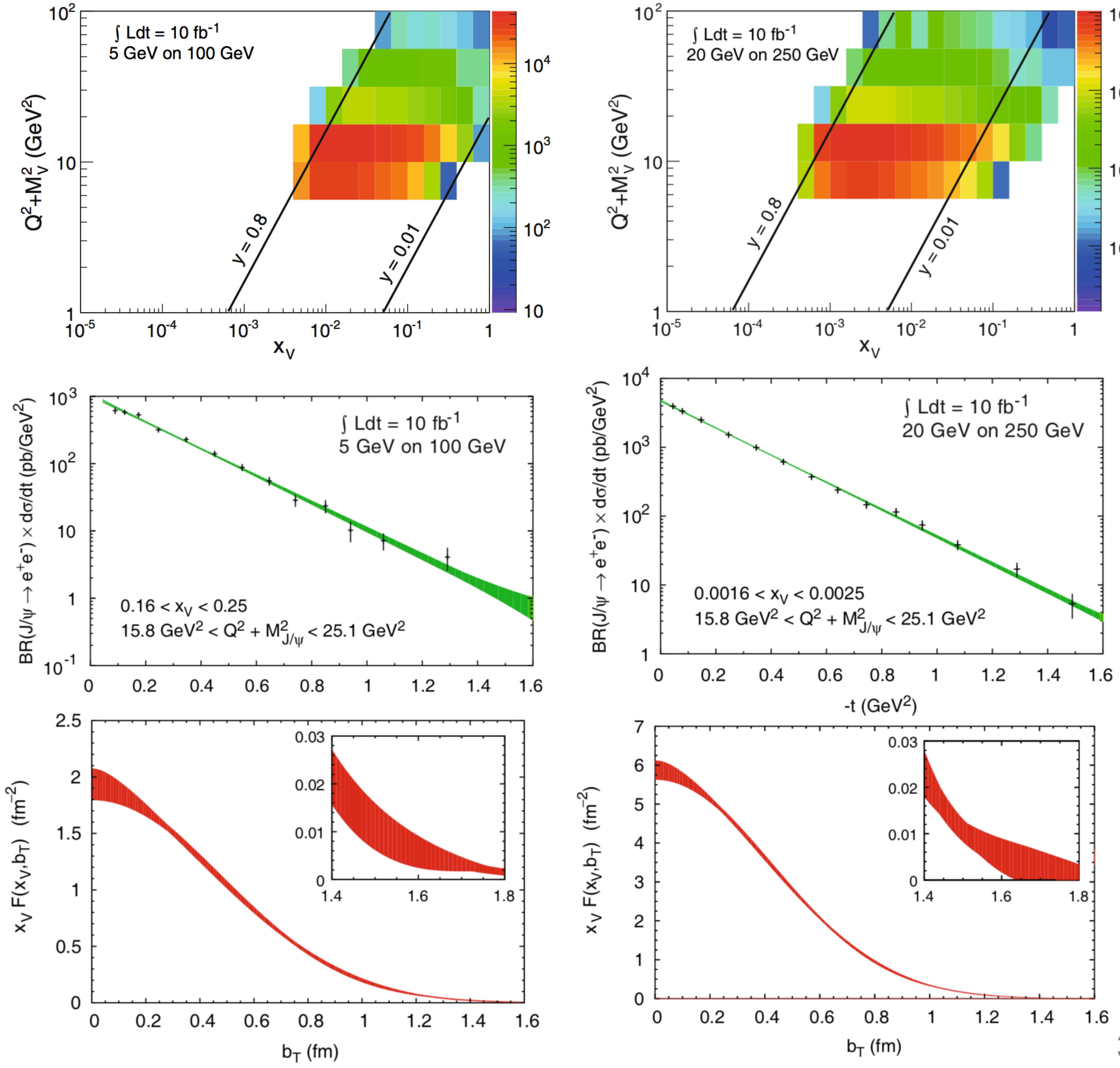


t-spectra

Normalized average gluon density

GLUON TOMOGRAPHY WITH *J/Ψ*



Only possible at an EIC:

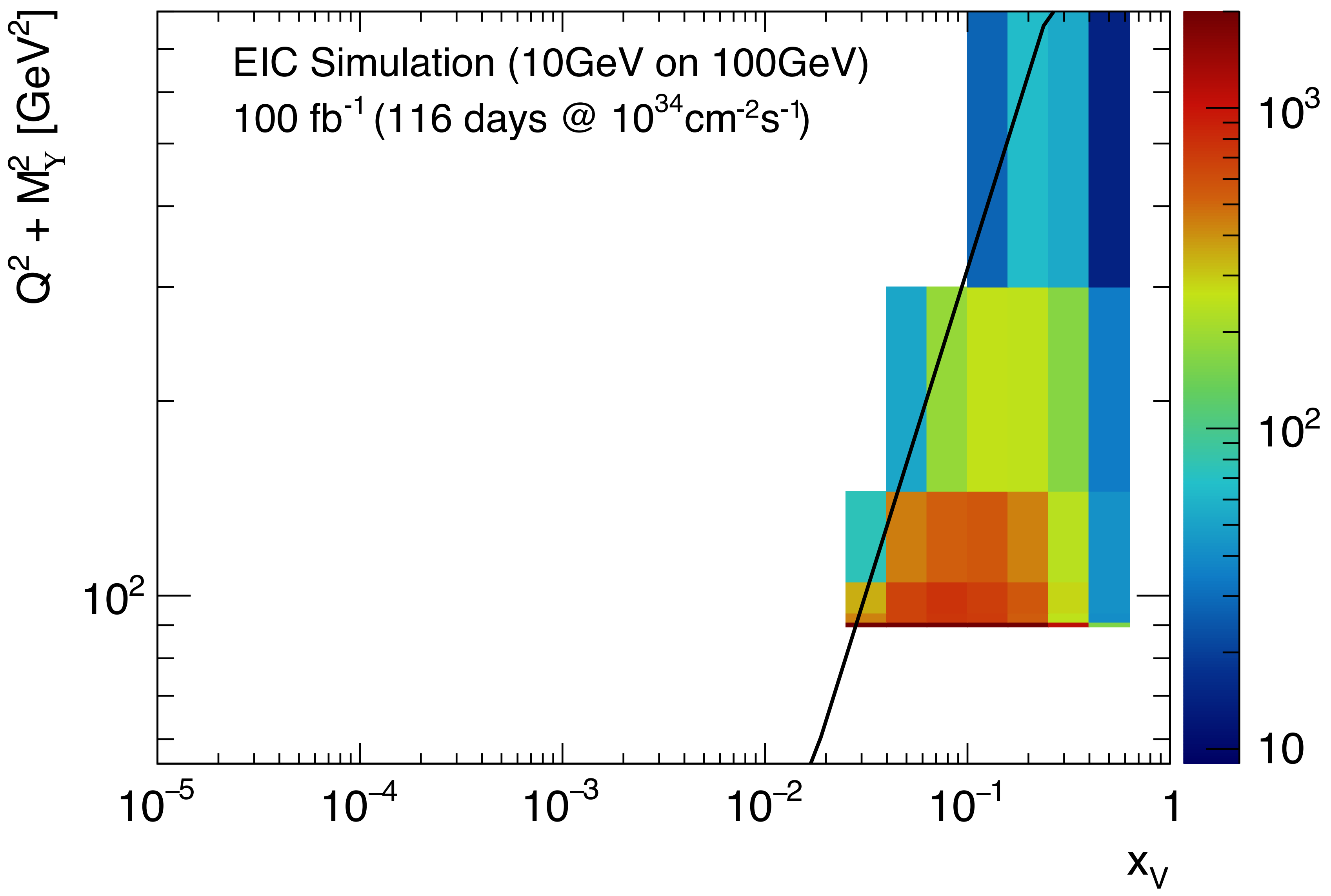
from the valence region deep into the sea!

***t*-spectra**

↓

Normalized average gluon density

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)

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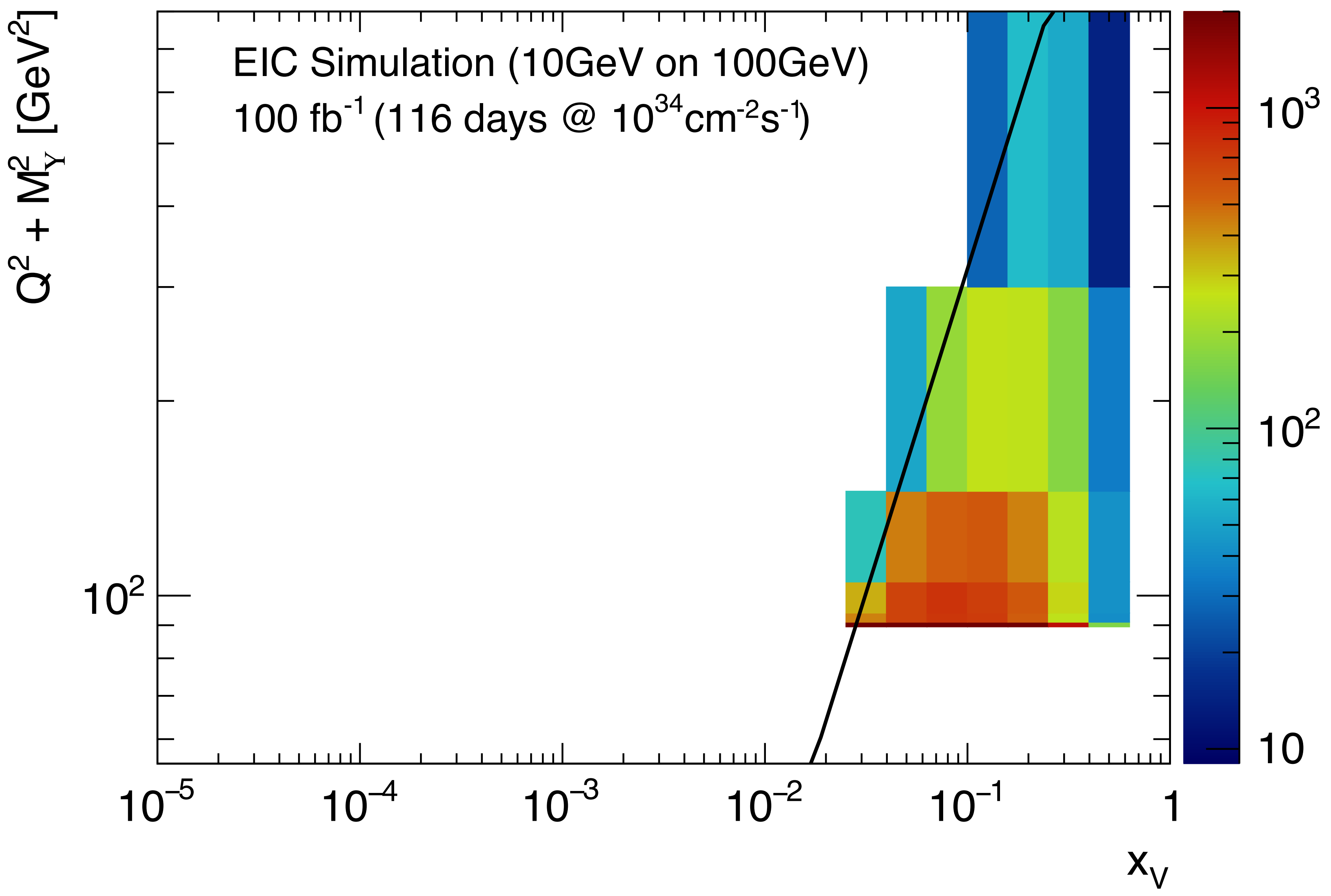

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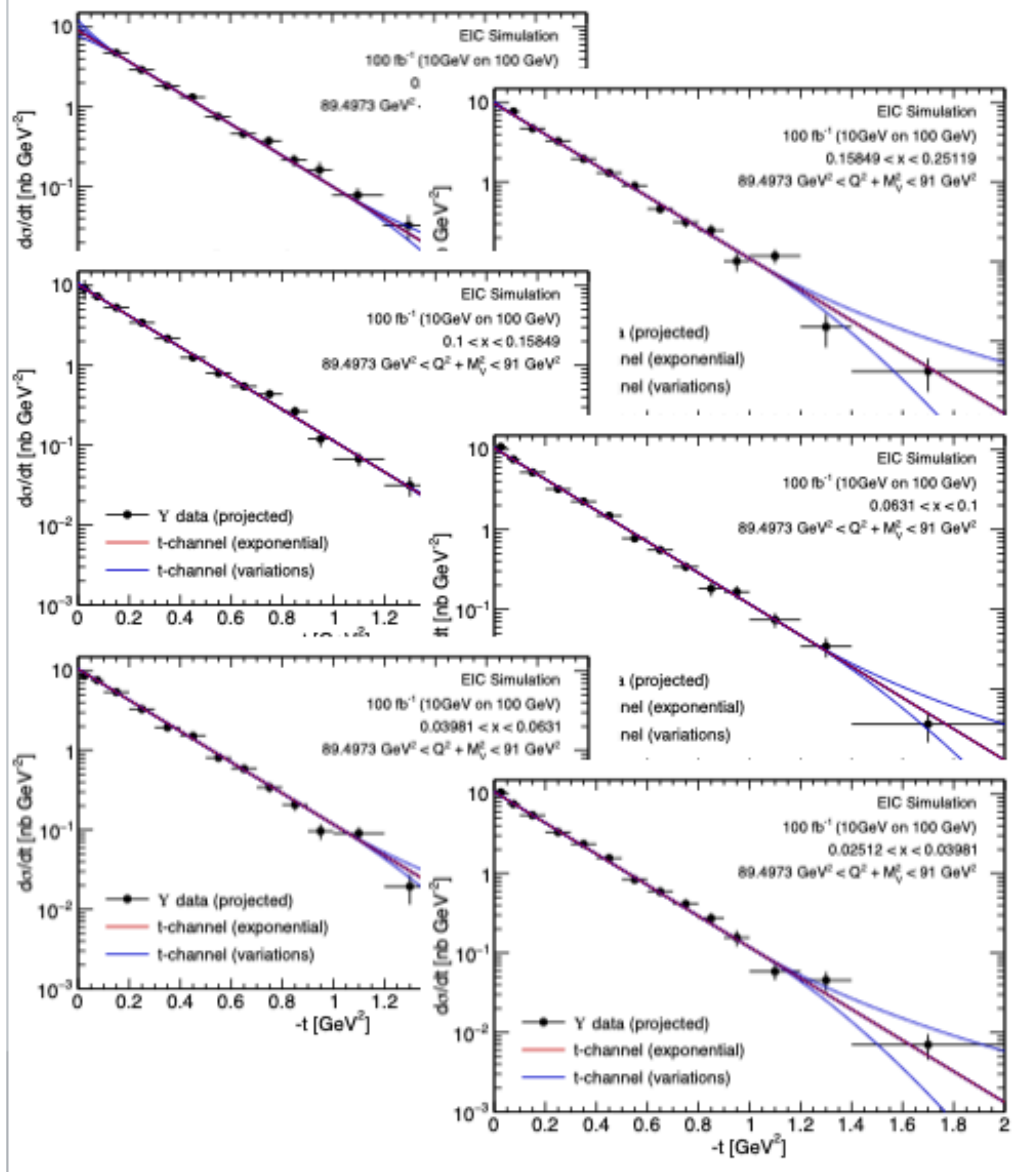

***t*-spectrum**

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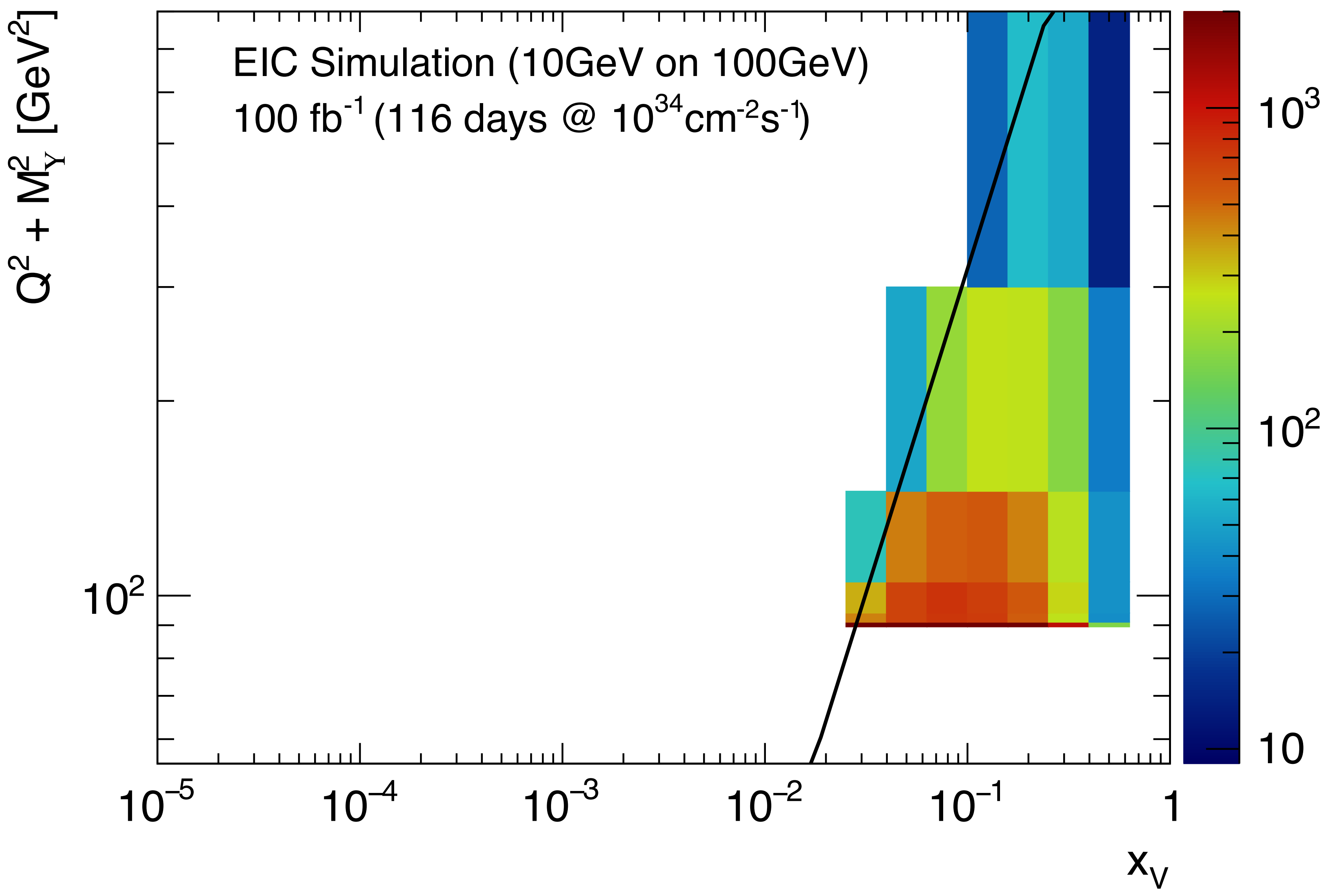

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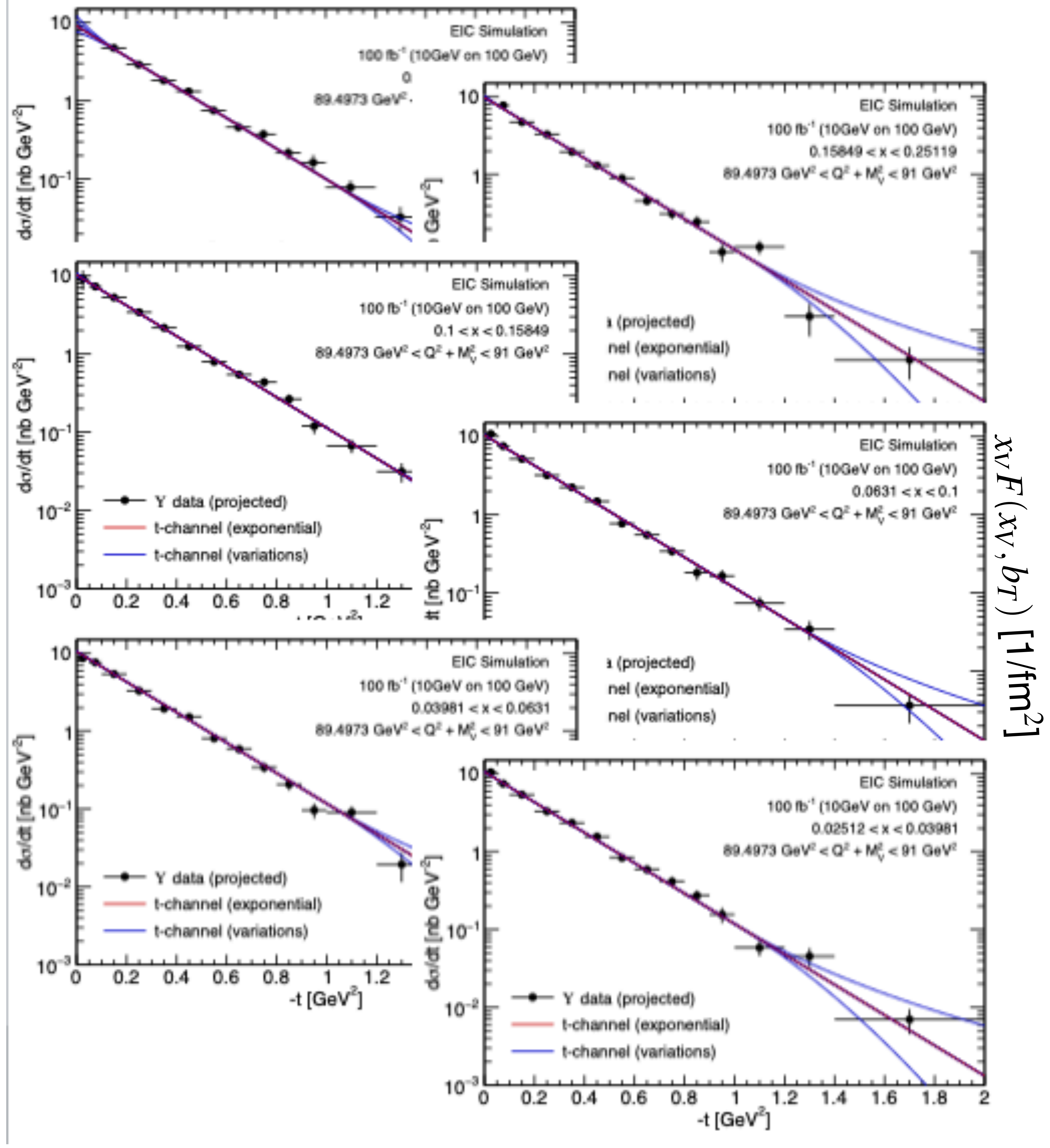

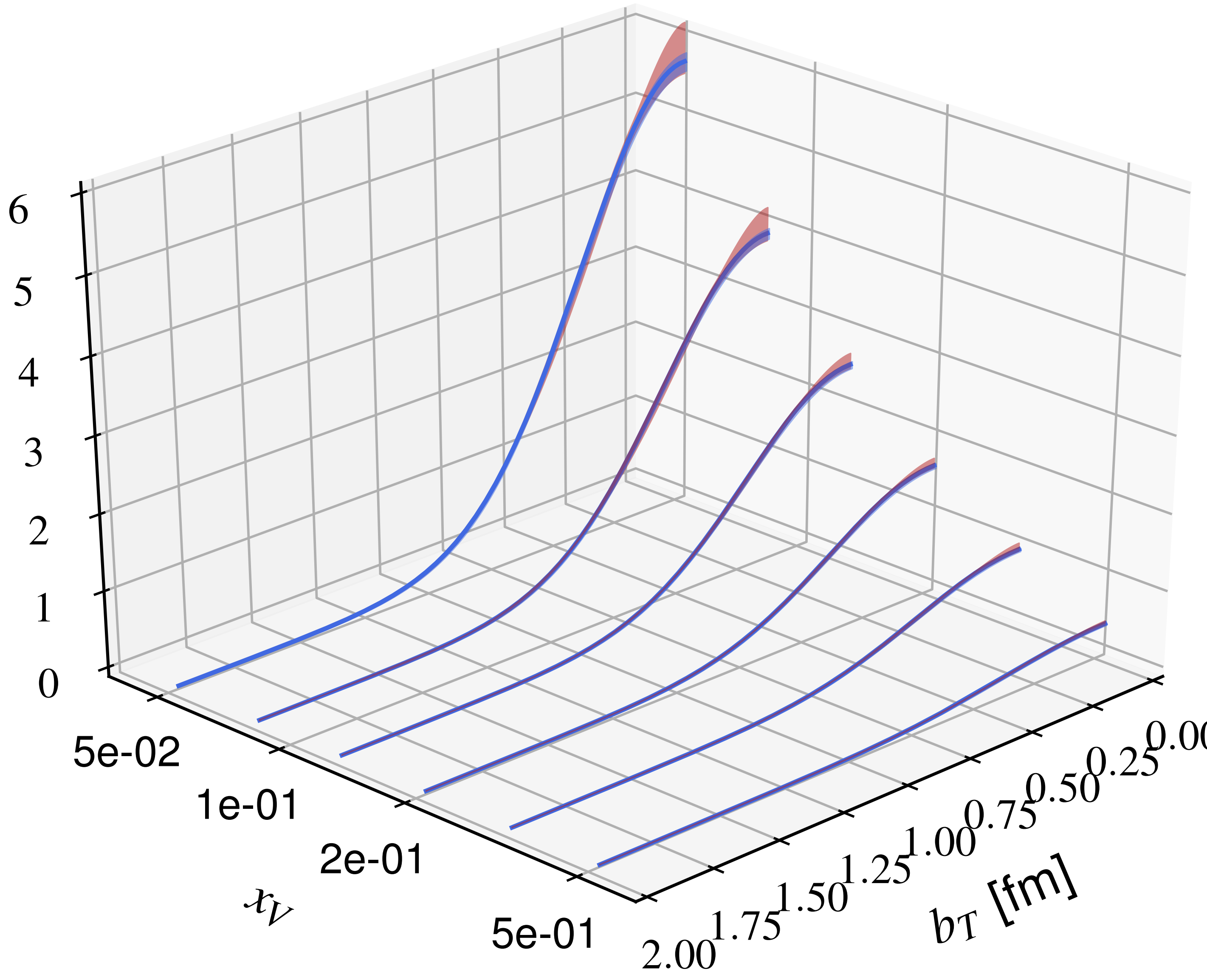

***t*-spectrum** → **Average gluon density**

THE GLUONIC STRUCTURE OF NUCLEI

At EIC and …JLab?

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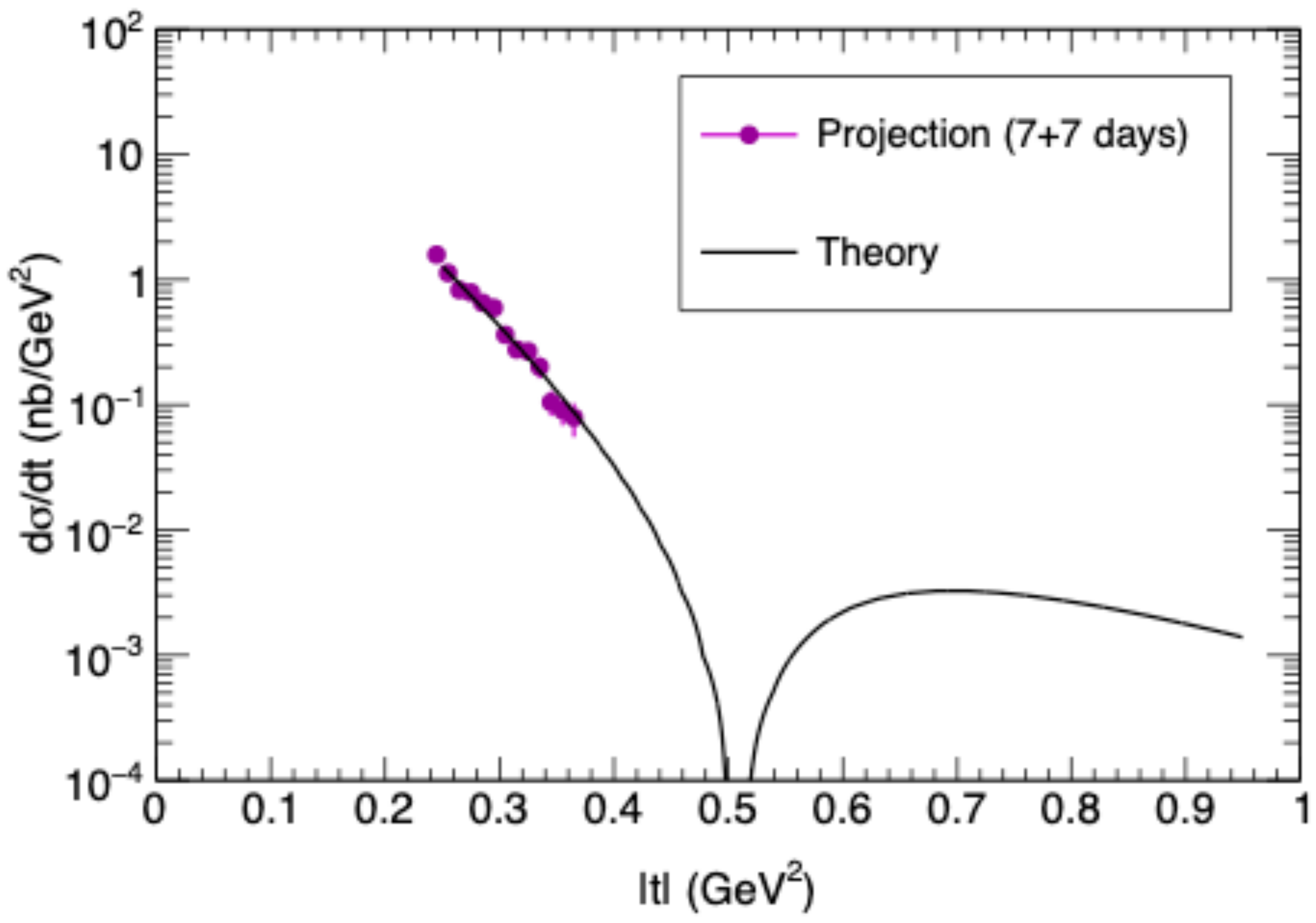

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- Might allow for “**imaging-style” quarkonium physics at JLab**
- New LOI for PAC47 to start constraining the gluonic form-factor of ^{4}He through direct photo-production in Hall C

JLab LOI12-19-007 (Hall C)

Armstrong, Cloet, Jones, Lee, SJ, Meziani, PAC47 LOI12-19-007

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**, **SRC universality**, and **proton mass**
- Possible to study "charming" (and "beautiful"?) pentaquarks
- At **high energies***:* possible to access **gluon GPDs**, and study the gluonic degrees of freedom of SRCs.
- Can **test universality by comparing *Υ* to *J/ψ***
- **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

X. Ji, PRL 74, 1071 (1995) & PRD 52, 271 (1995)

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

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

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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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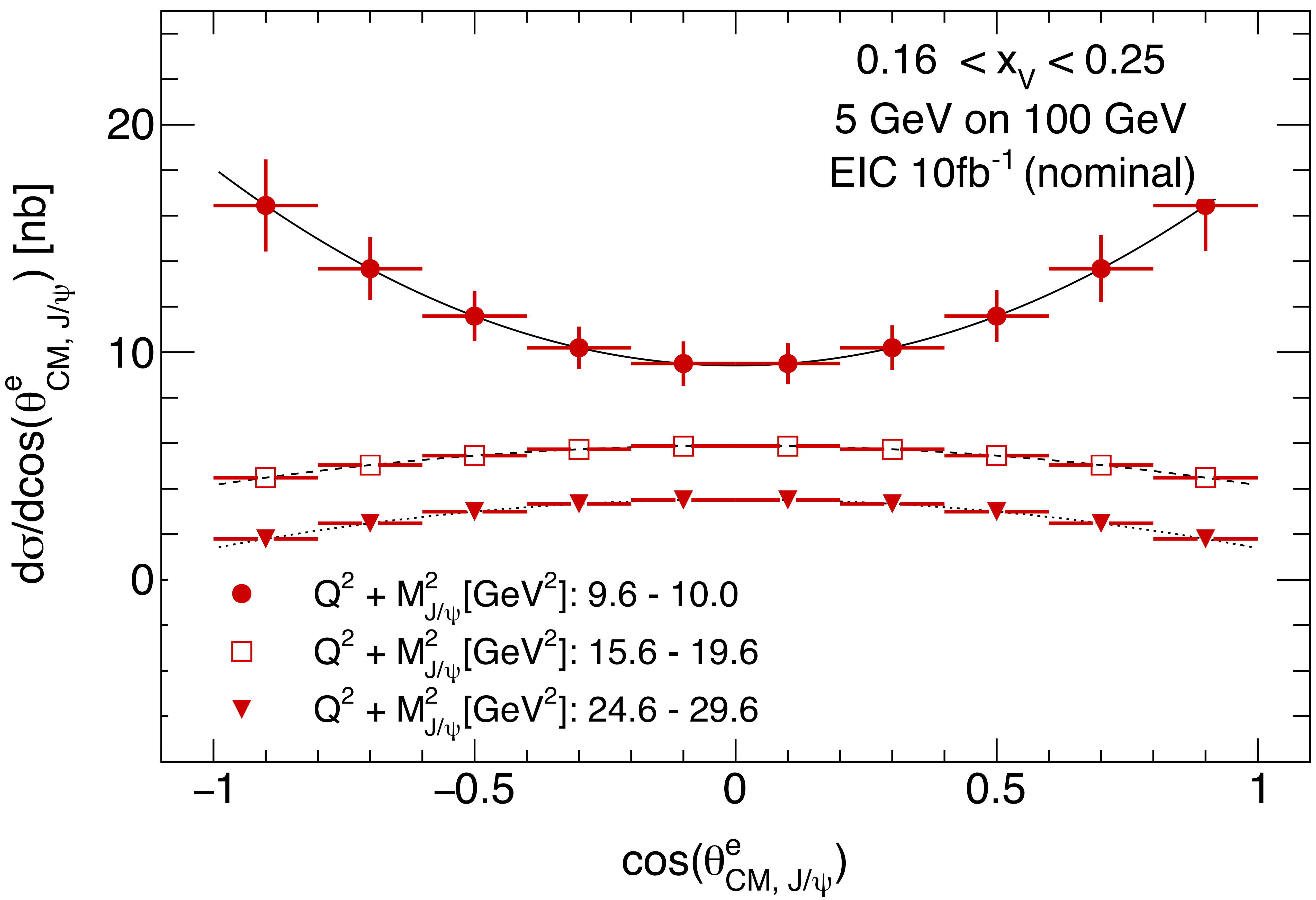
$$M_a = \frac{1}{4}(1-b)M$$

a(μ) related to PDFs, well constrained

b(μ) related trace anomaly, unconstrained

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*