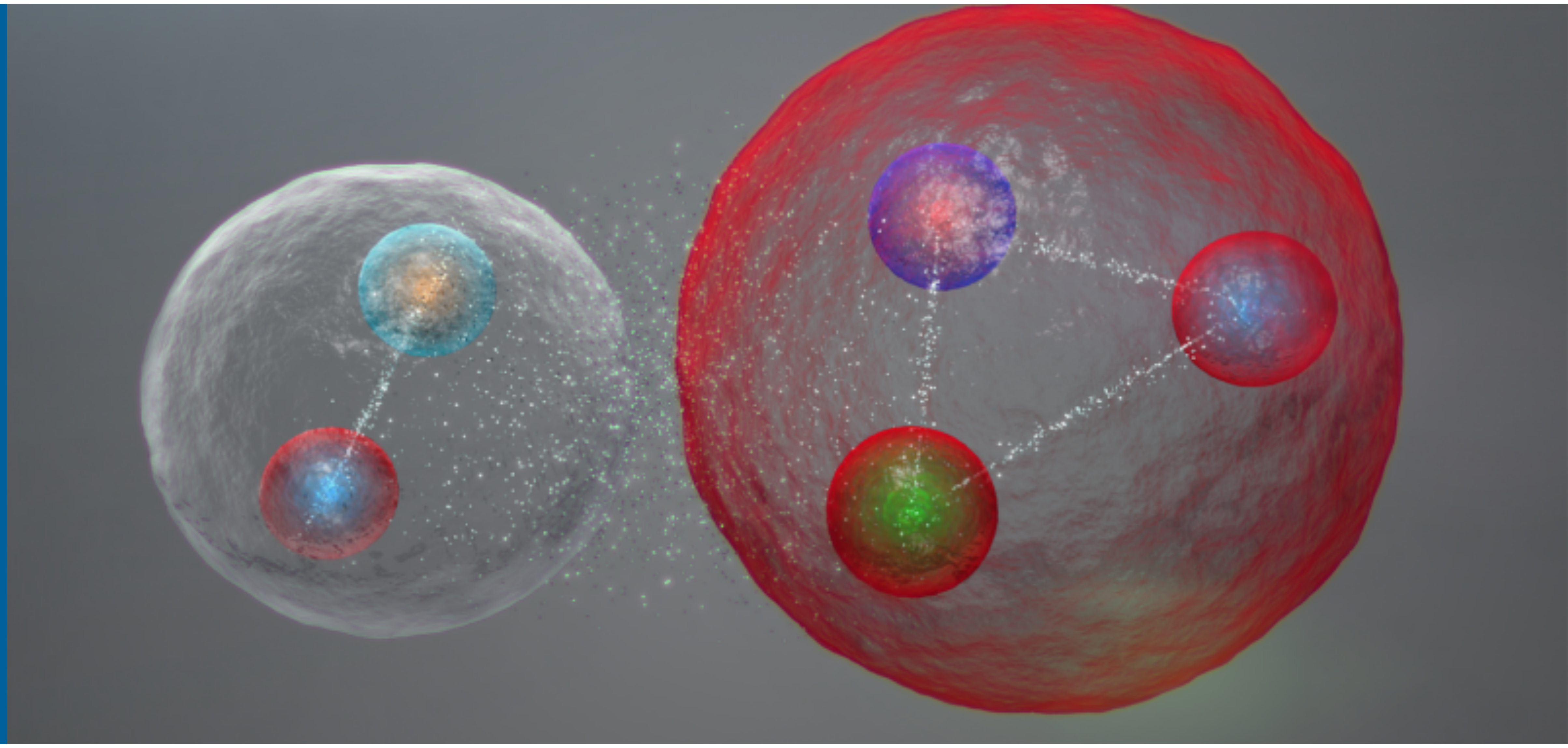
PHYSICS WITH QUARKONIUM PRODUCTION NEAR THRESHOLD AT JEFFERSON LAB AND EIC

Argonne NATIONAL LABORATORY

THE DYNAMIC ORIGIN OF THE PROTON MASS



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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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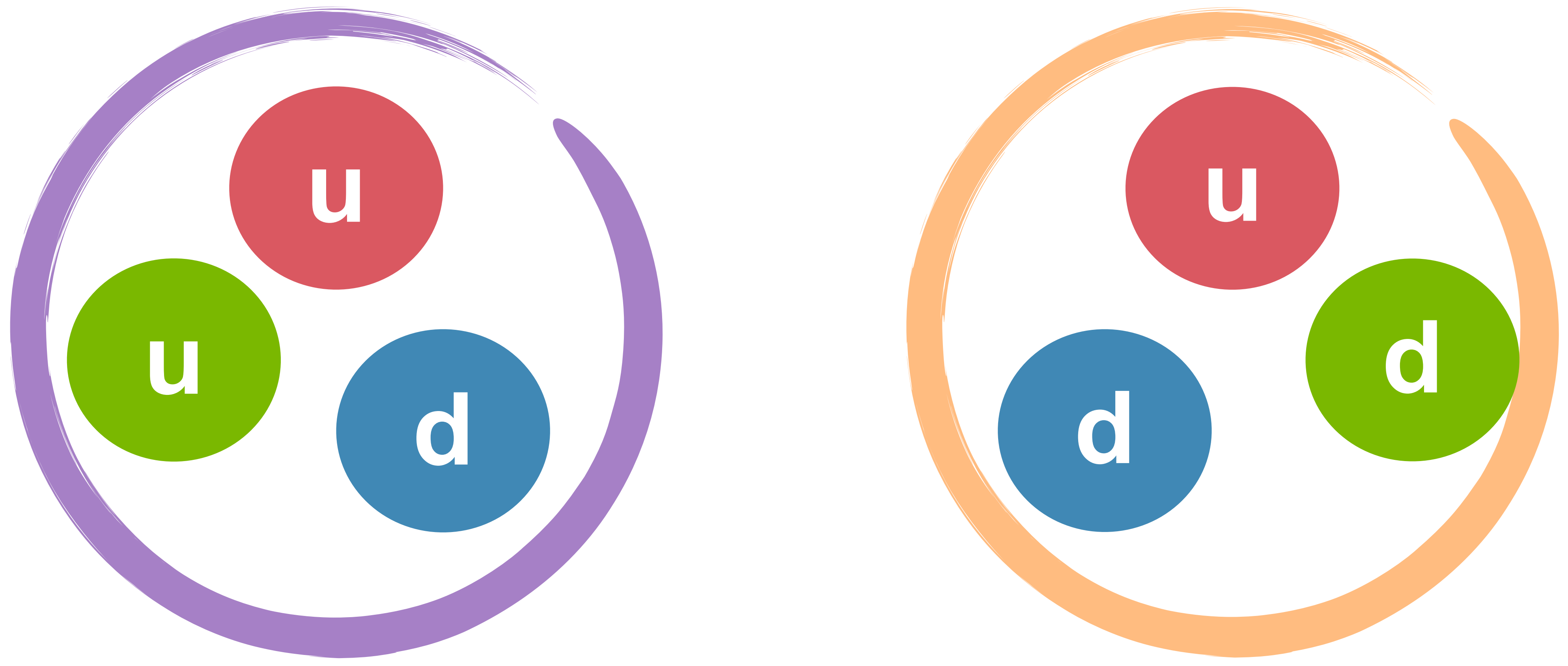
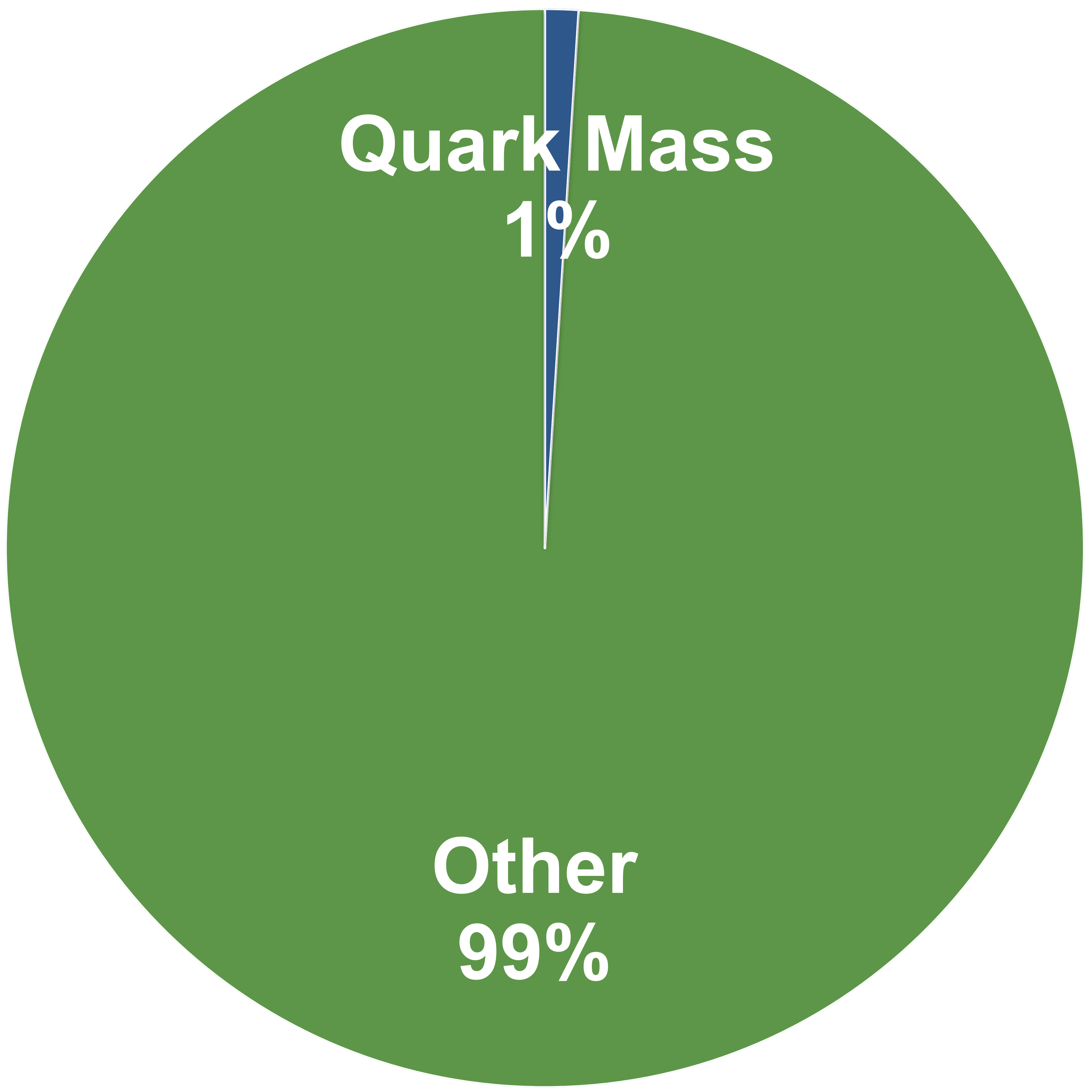
Jets for 3D imaging
November 24, 2020

THE NUCLEON IN QCD

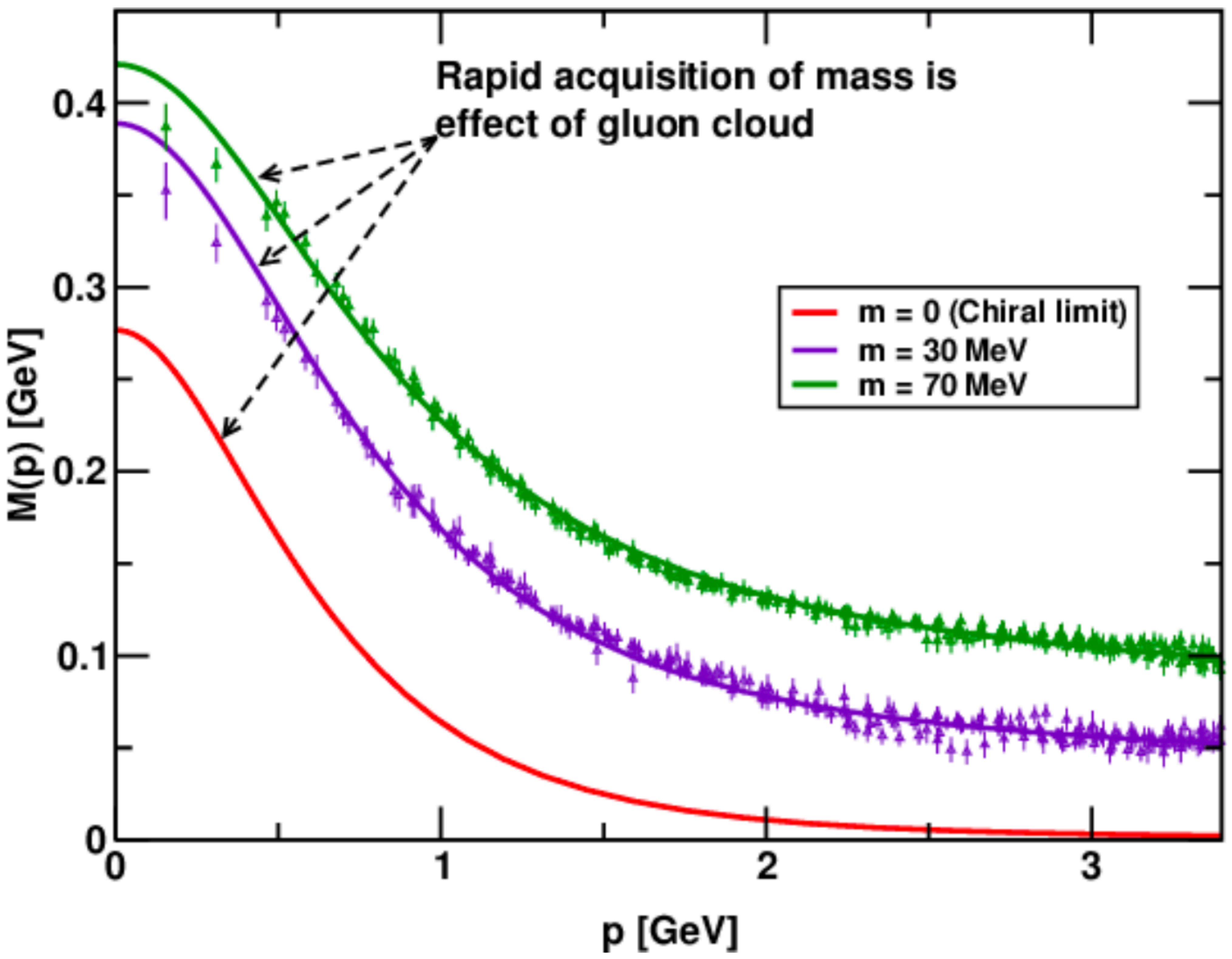
99% of the mass of the visible universe





- Fundamental building blocks of matter
- Only stable states of QCD Lagrangian
- Higgs mechanism responsible for the mass of elementary particles only.
- 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 QCD:
  - 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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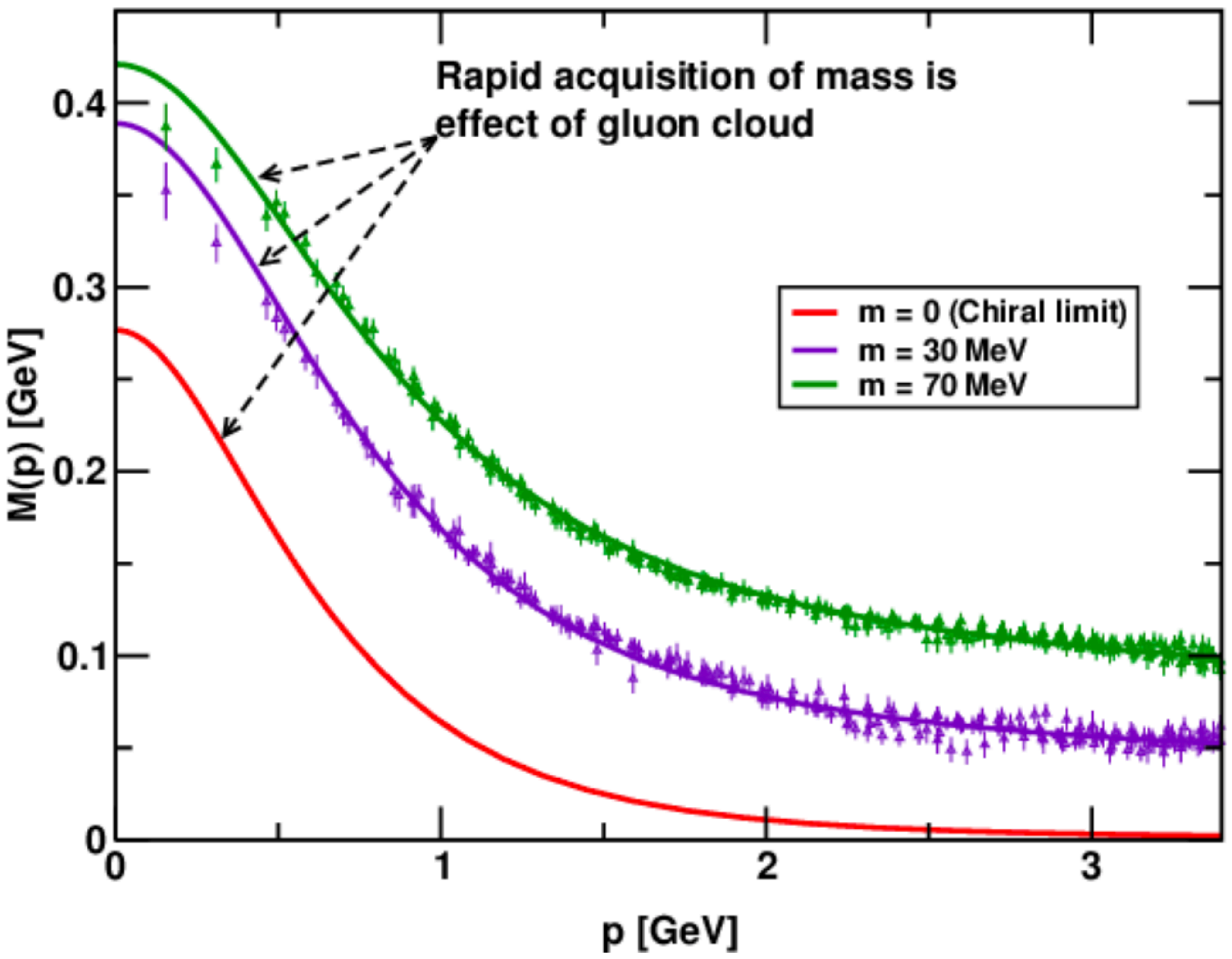

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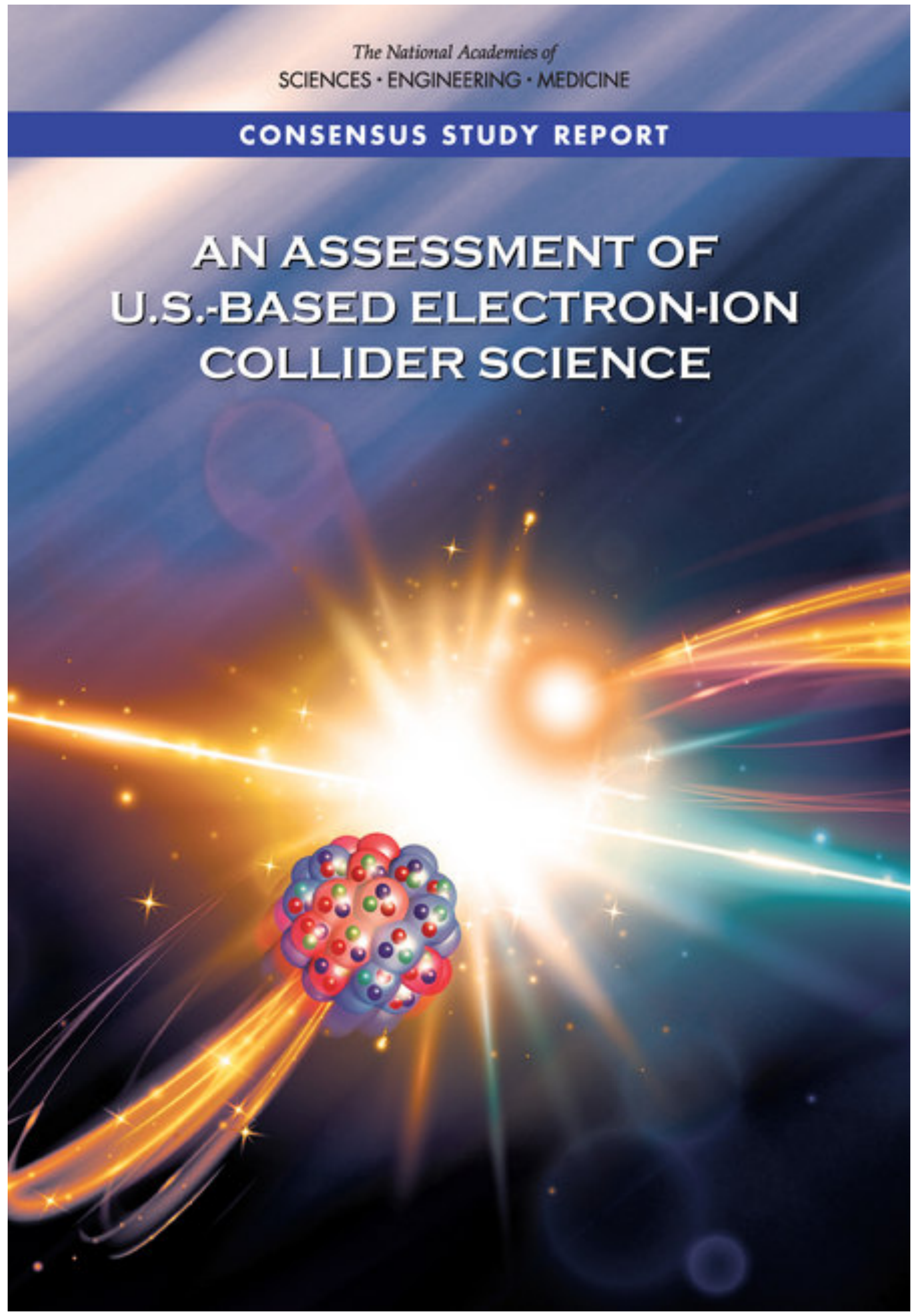
  - Even in the chiral limit: **mass from nothing!**

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

D. Kharzeev, Proc.Int.Sch.Phys.Fermi 130 (1996) 105-131

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

Trace Anomaly **Light Quark Mass**

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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 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

$$H_{\rm QCD} = \int d^3x T^{00}(0, \vec{x})$$

$$= \underbrace{H_q} + \underbrace{H_m} + \underbrace{H_g} + \underbrace{H_a}$$

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At leading order:

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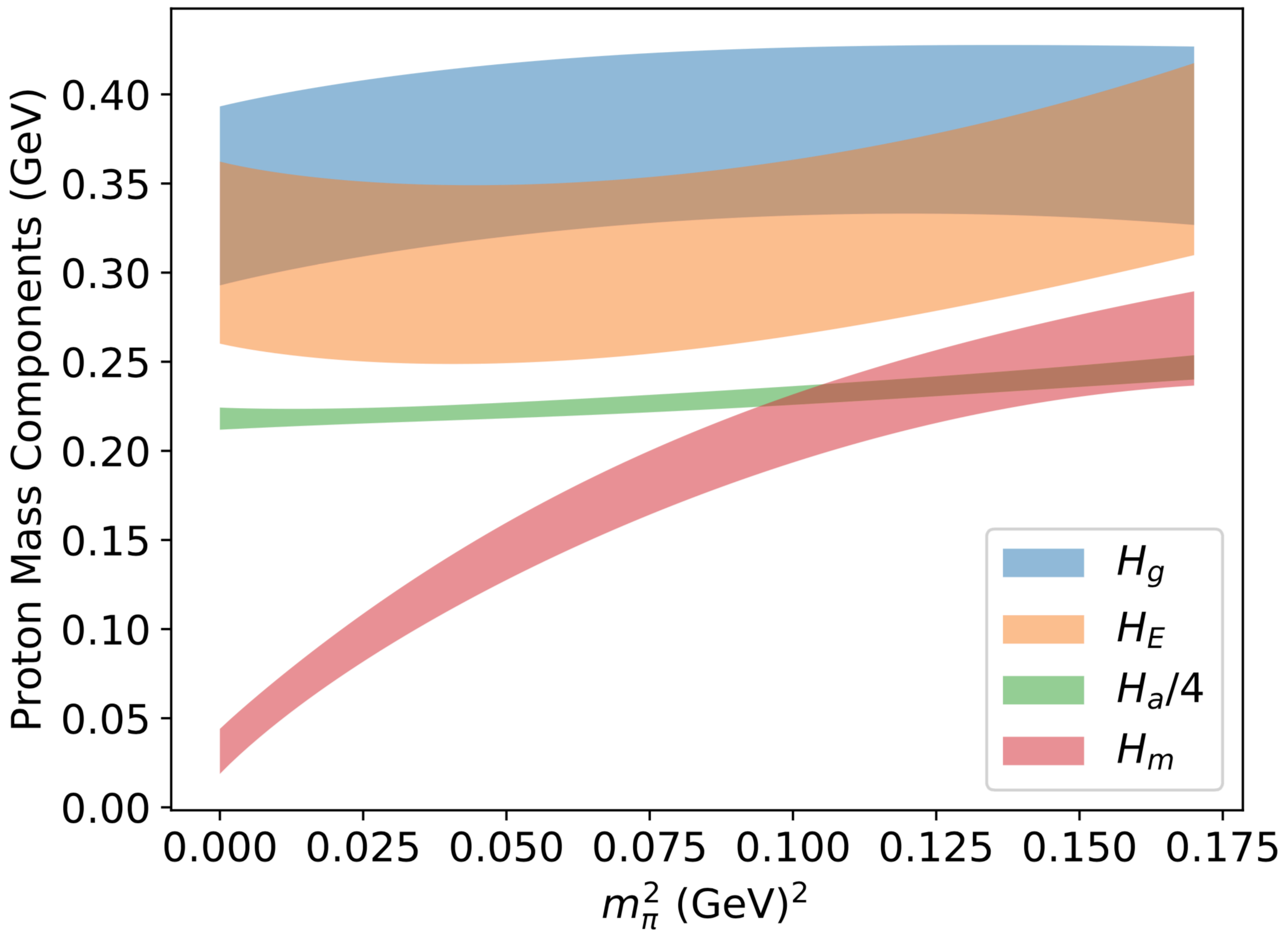
a(μ) related to PDFs, well constrained

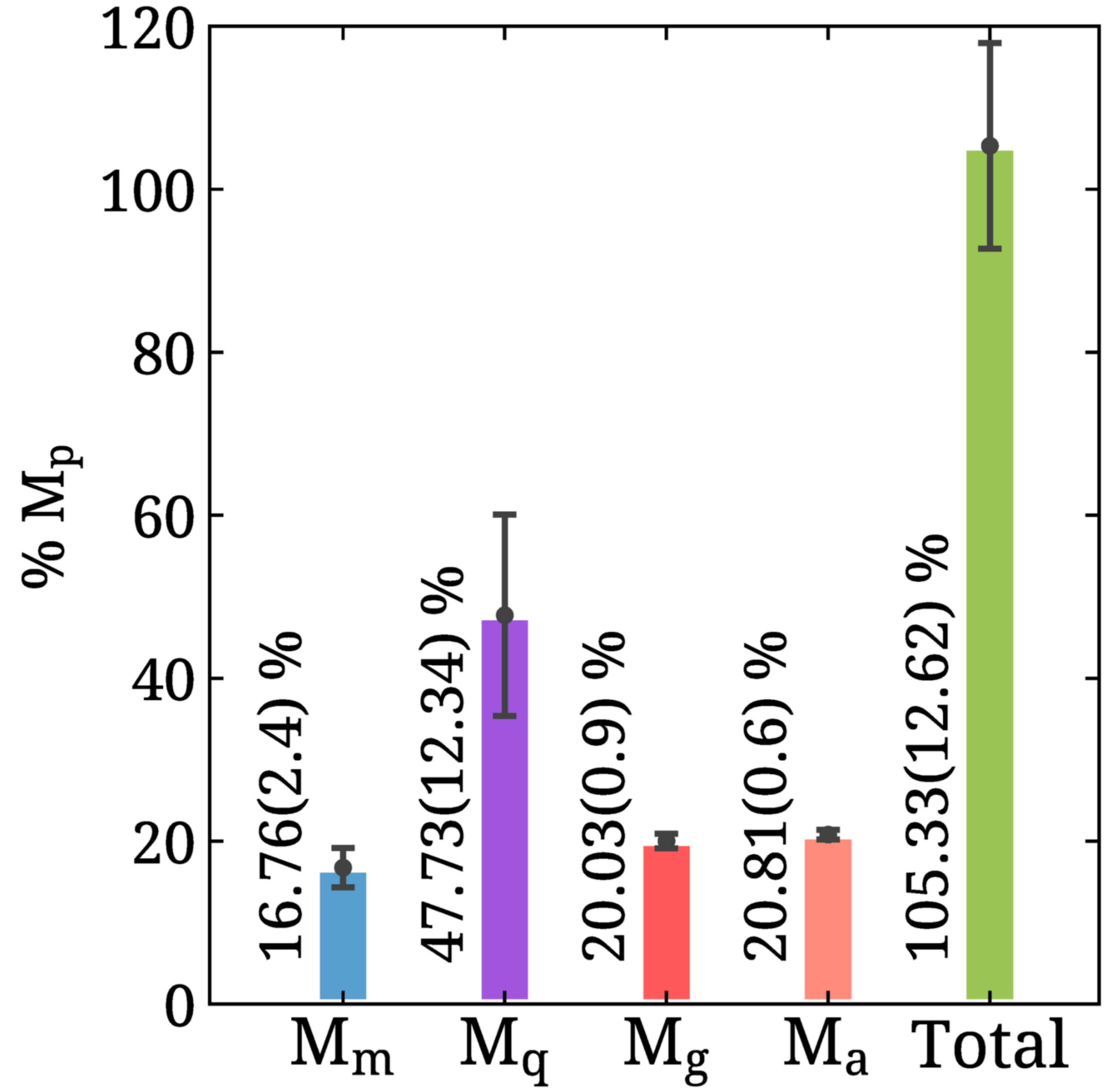
b(μ) related trace anomaly, unconstrained

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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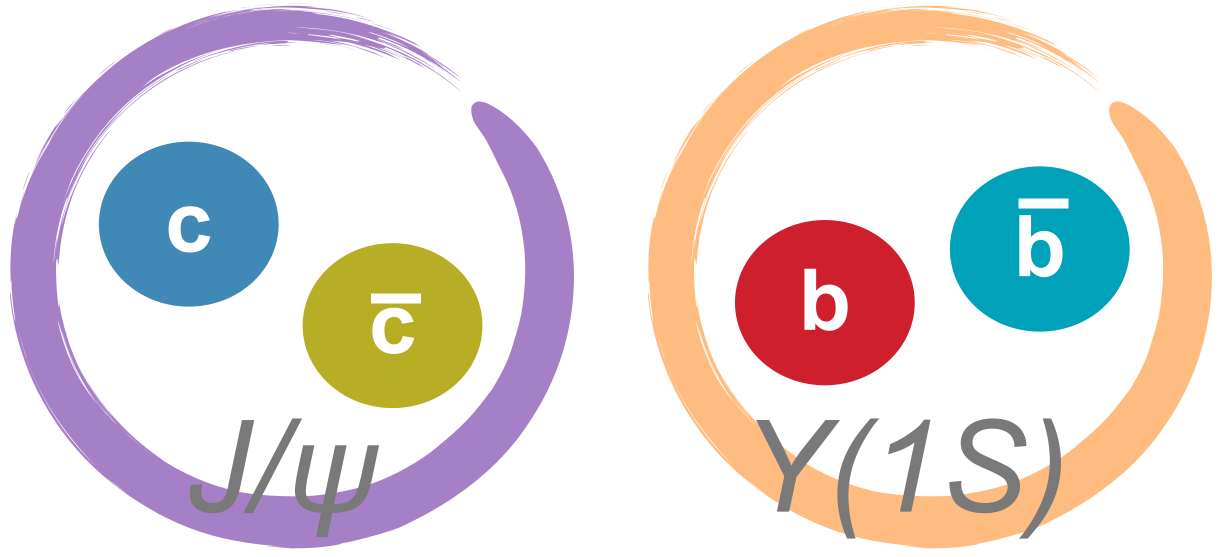
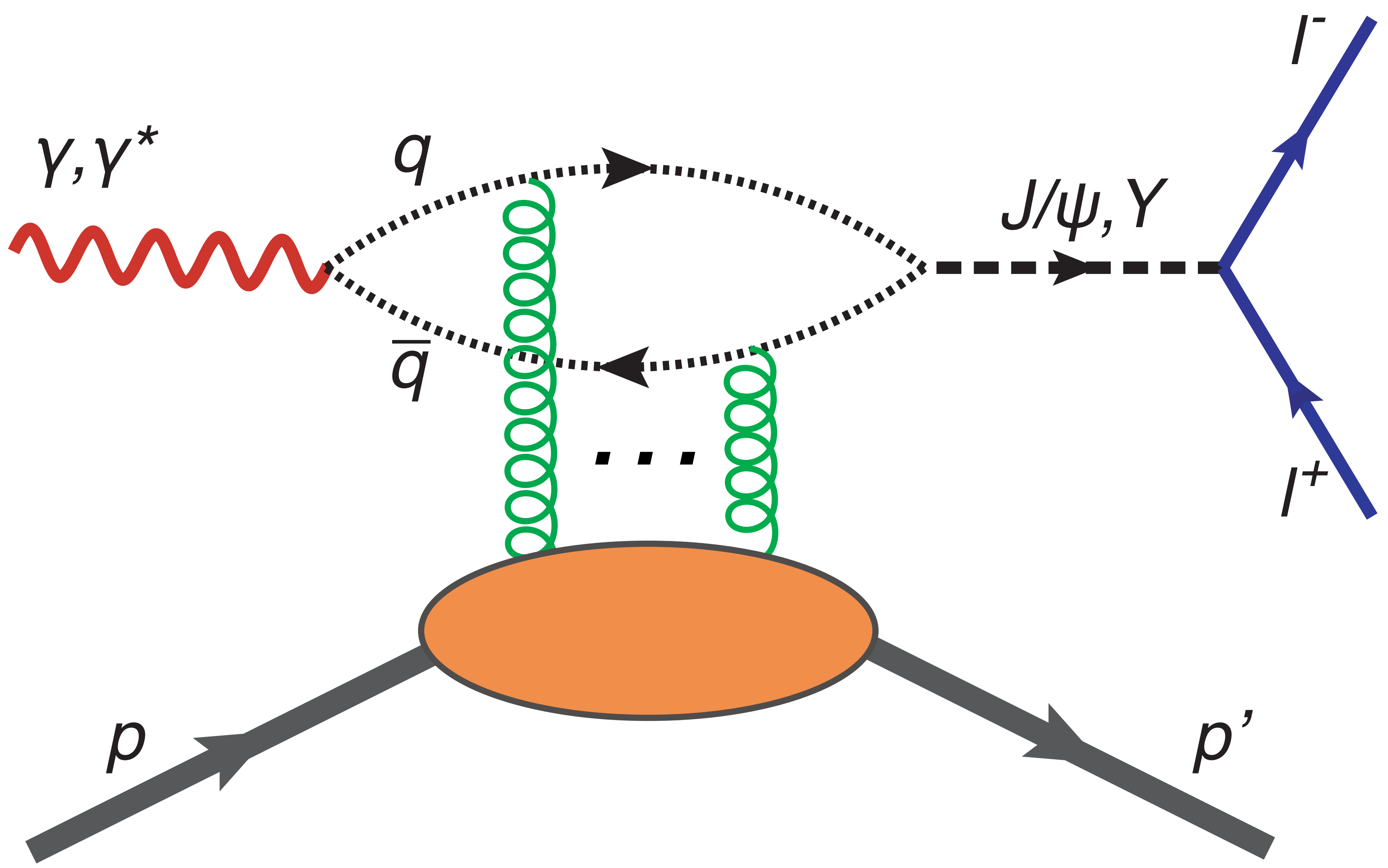
Trace anomaly only constrained through sum-rules

CAN WE MEASURE THE TRACE ANOMALY?

…Quarkonium production near threshold!





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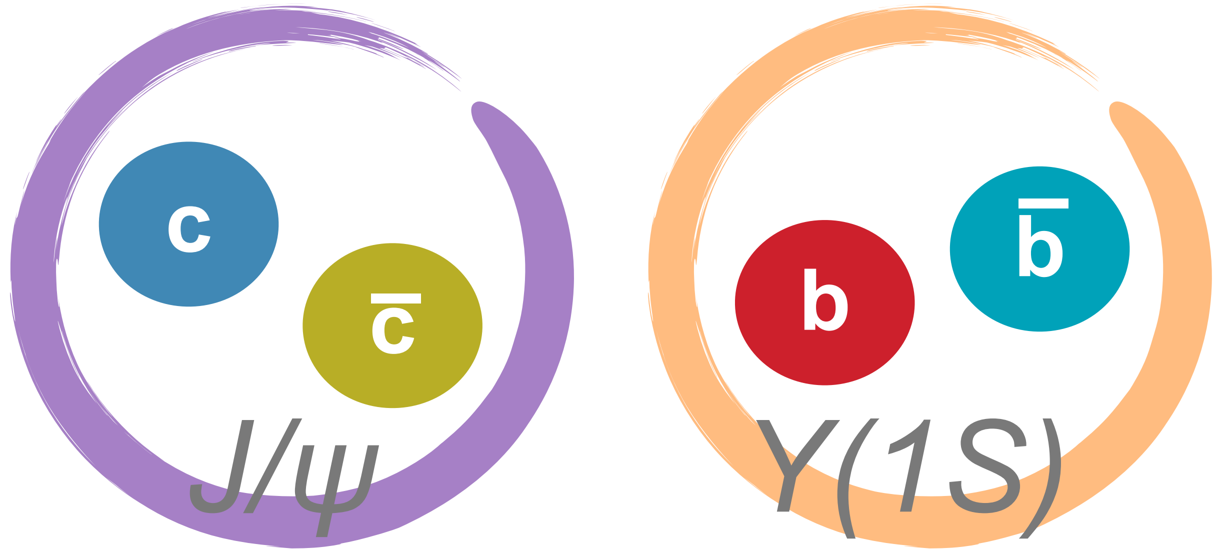

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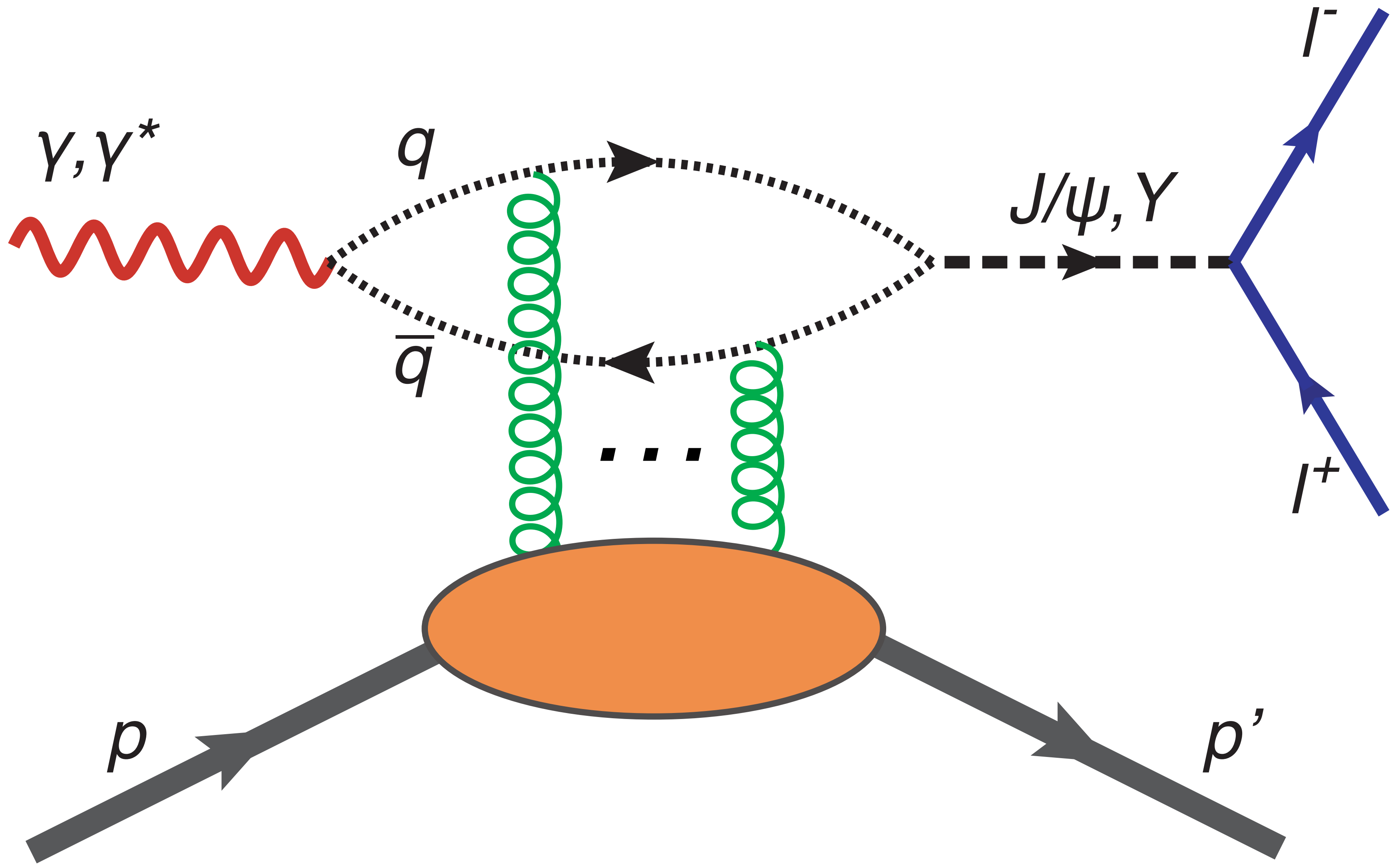

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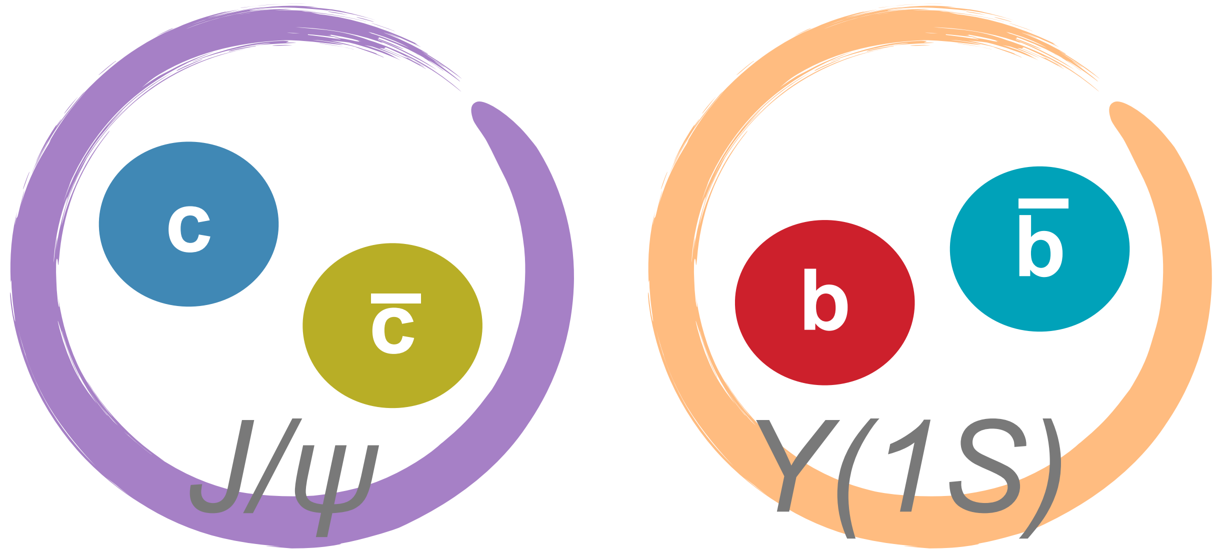

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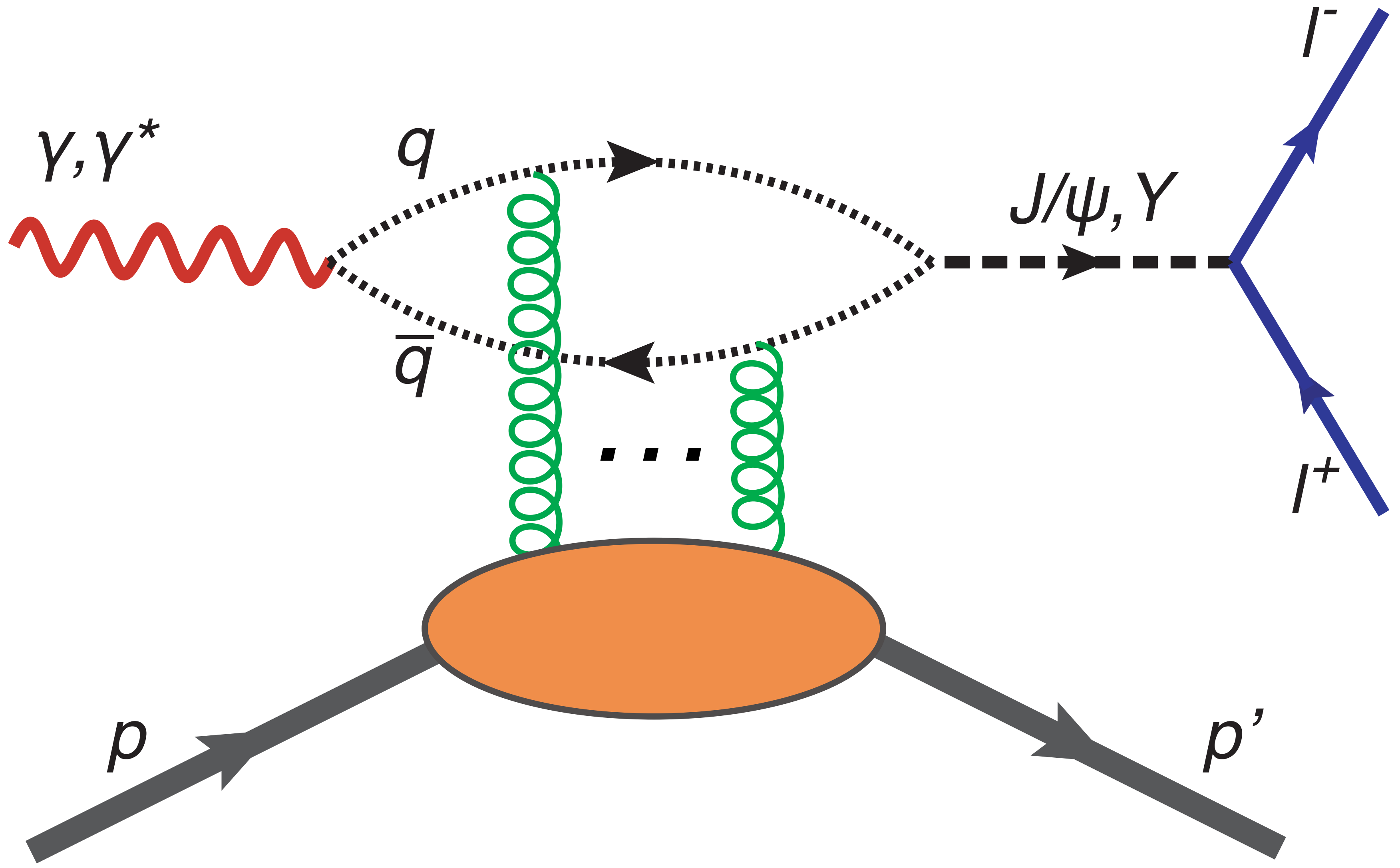

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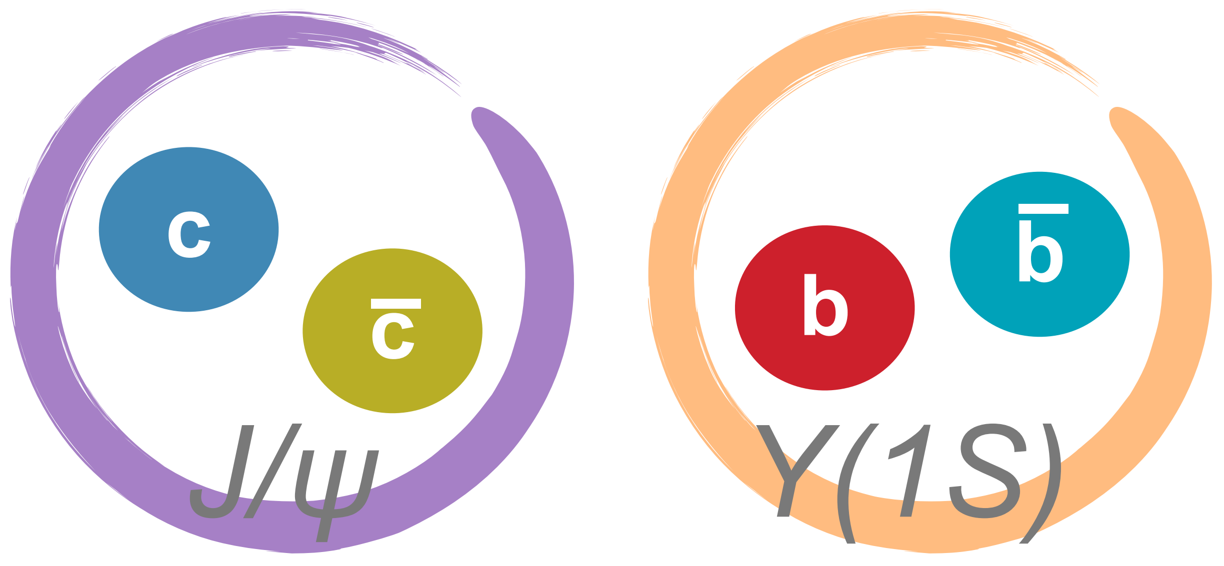

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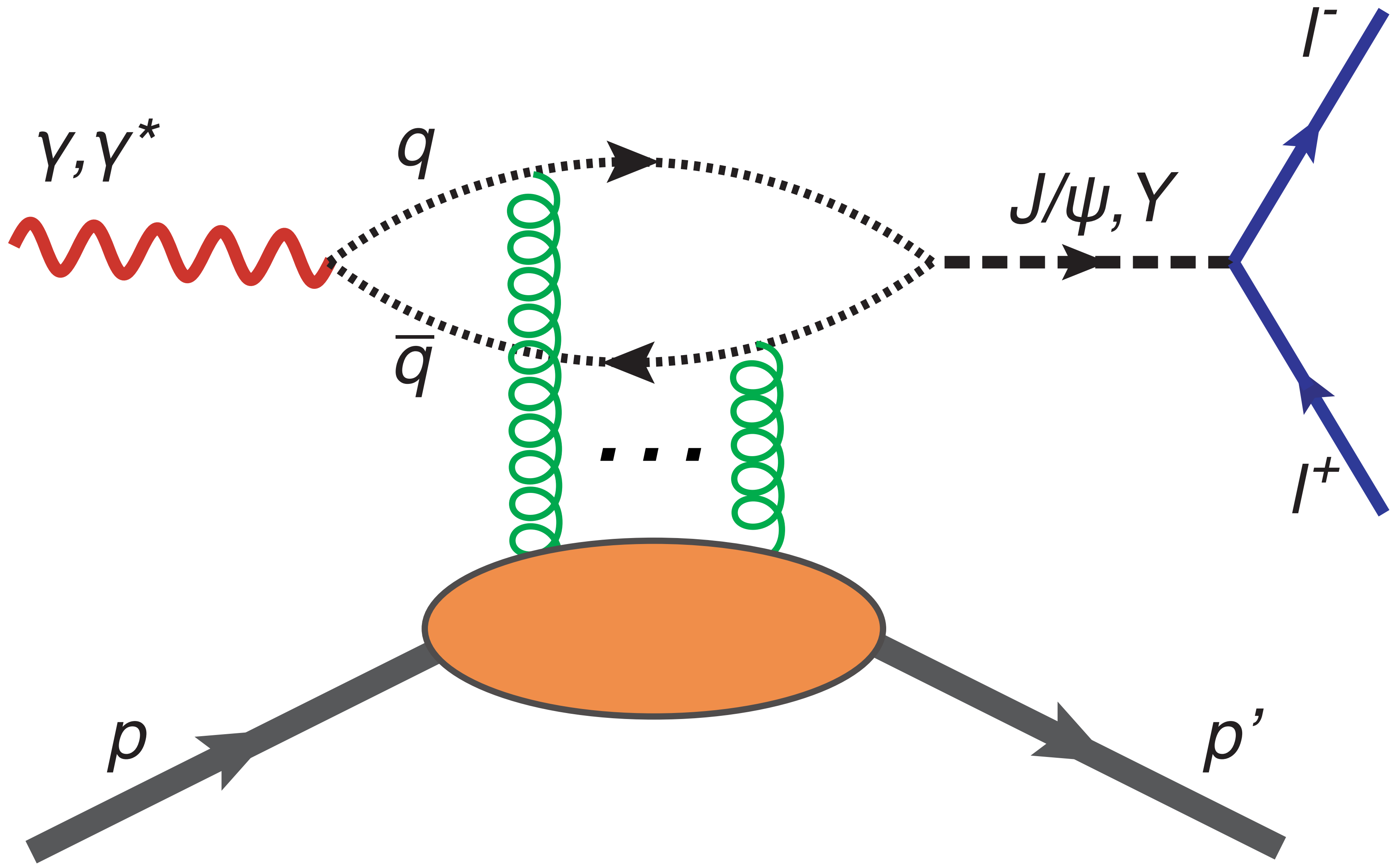

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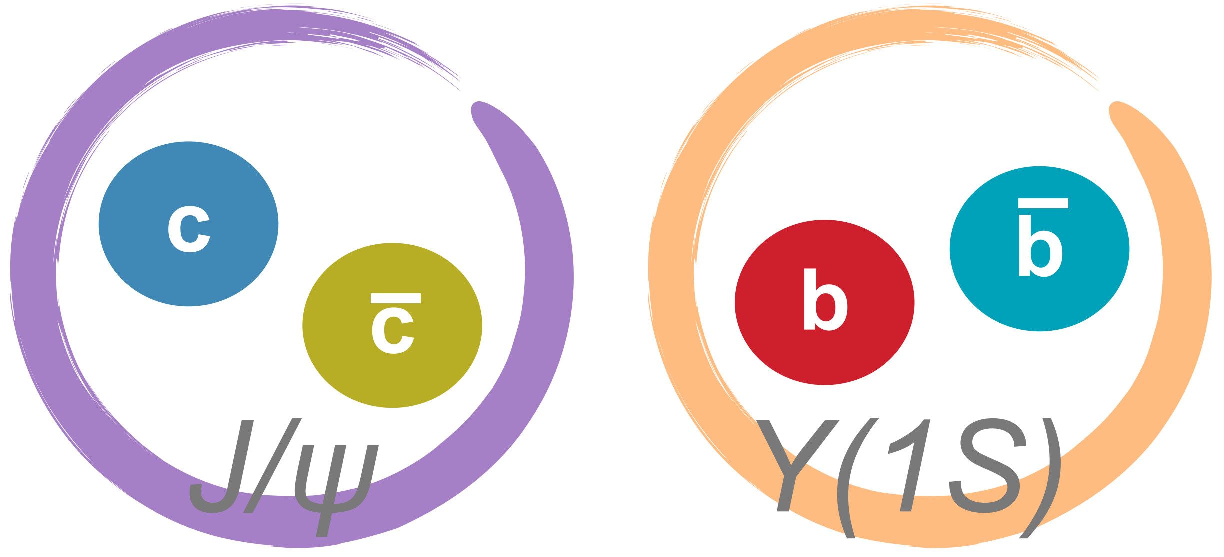

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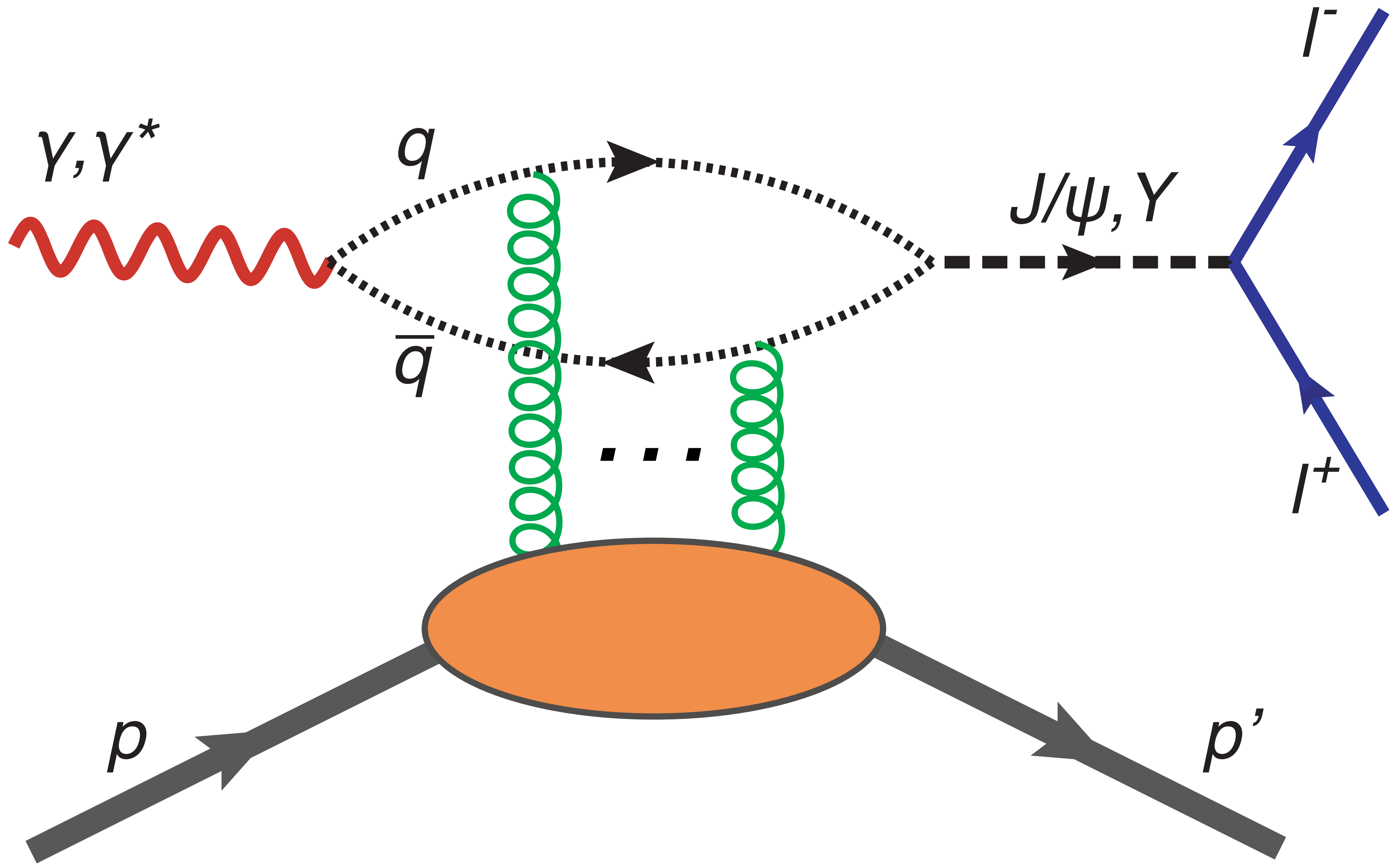

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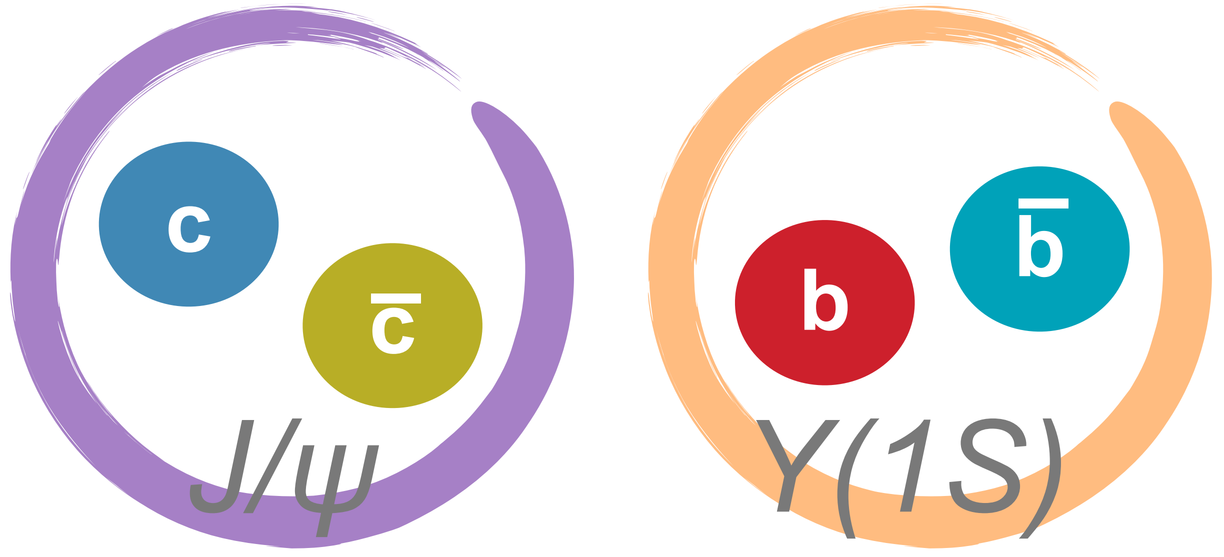

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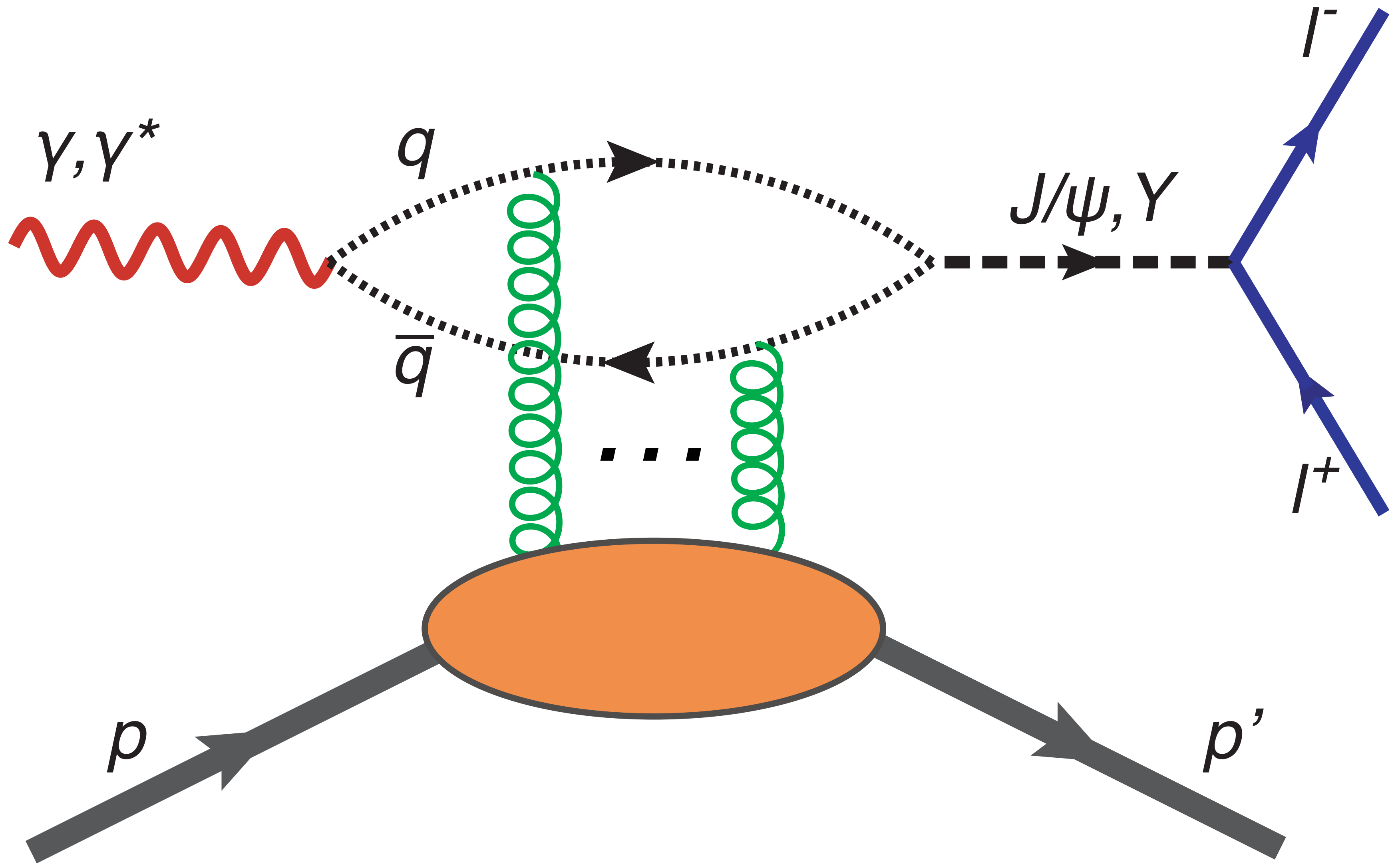
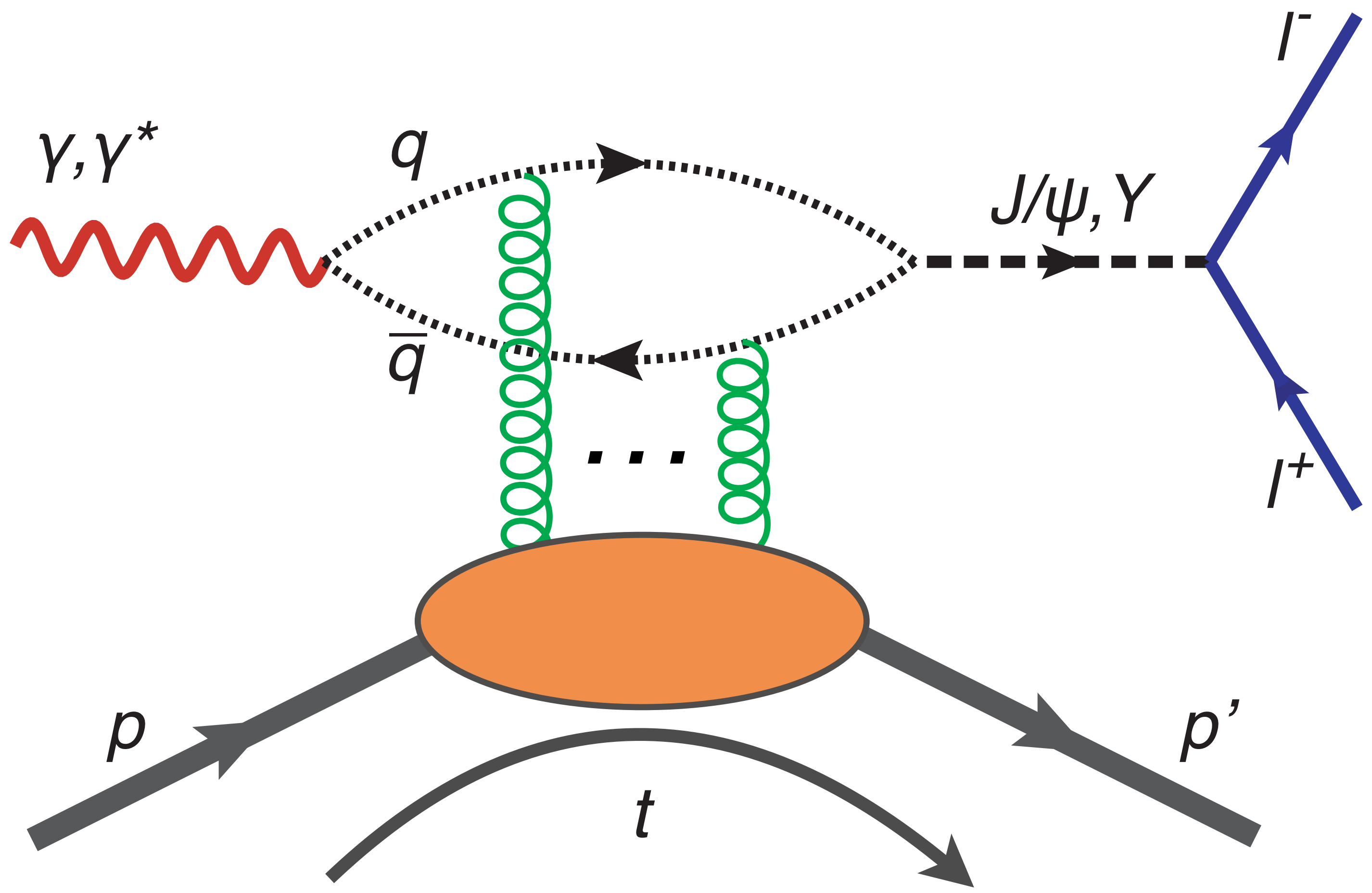


QUARKONIUM PHOTO-PRODUCTION

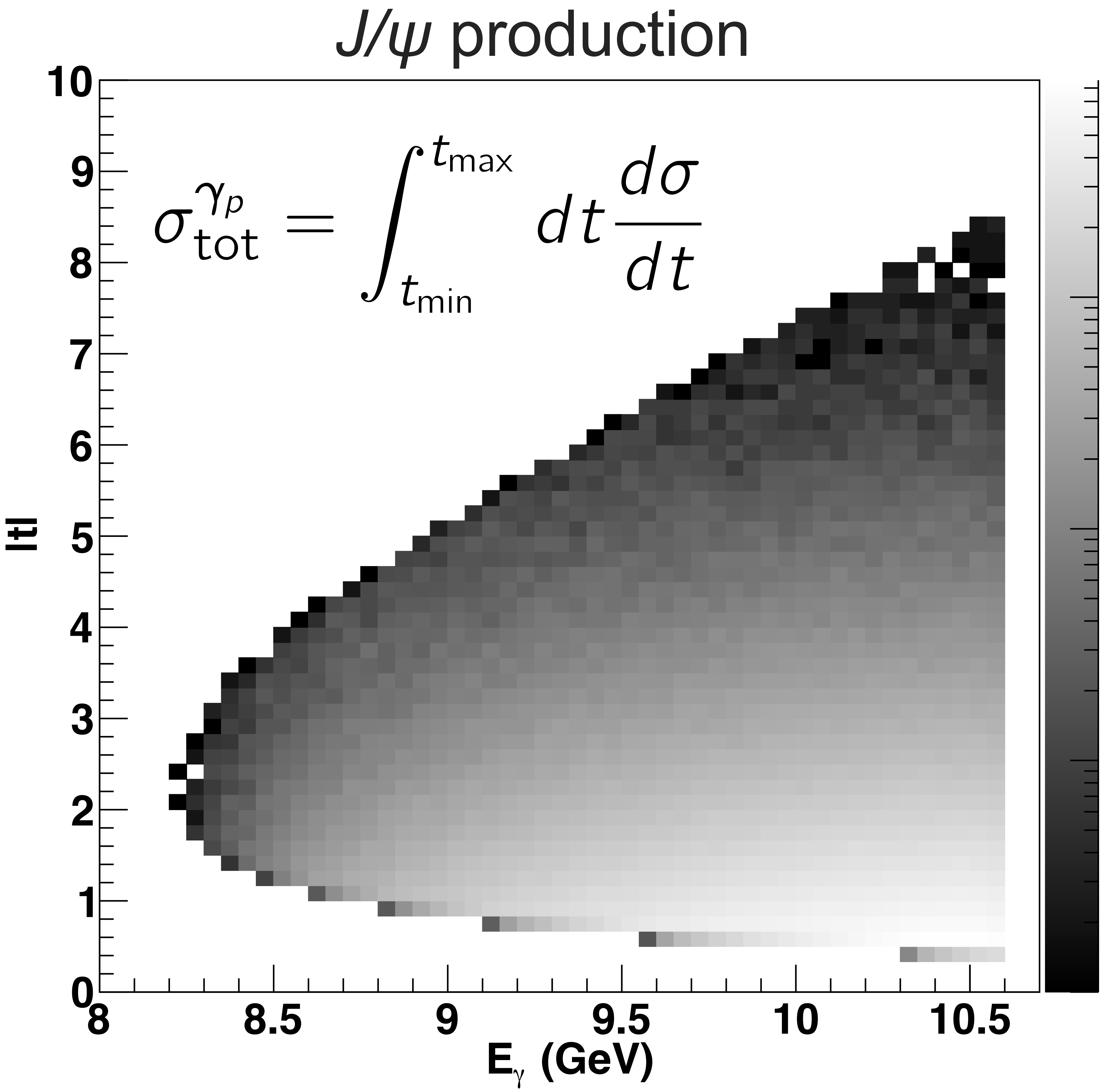
The basics



Υ(1S) threshold:

$W \approx 10.4\text{GeV}$

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



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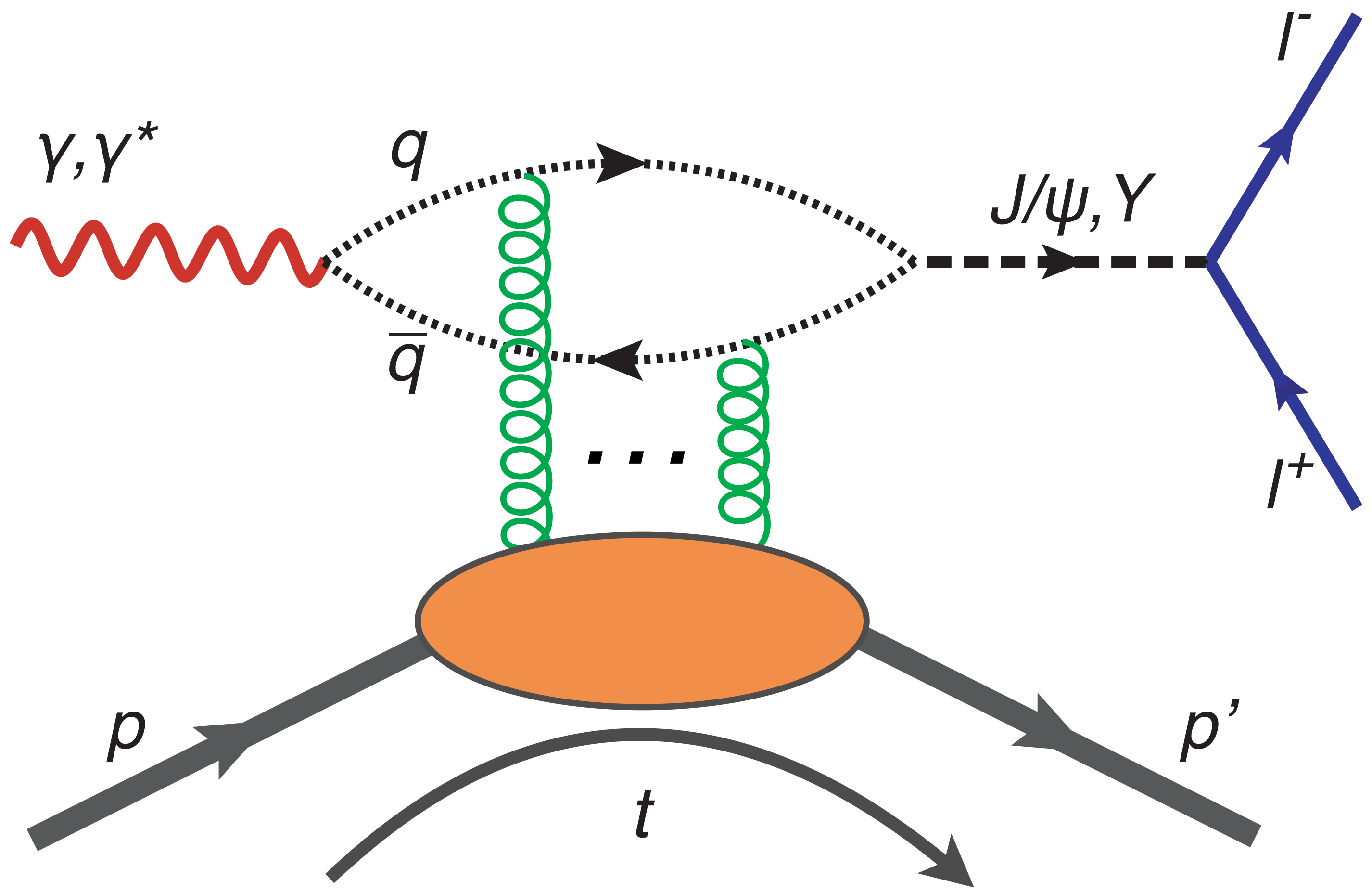

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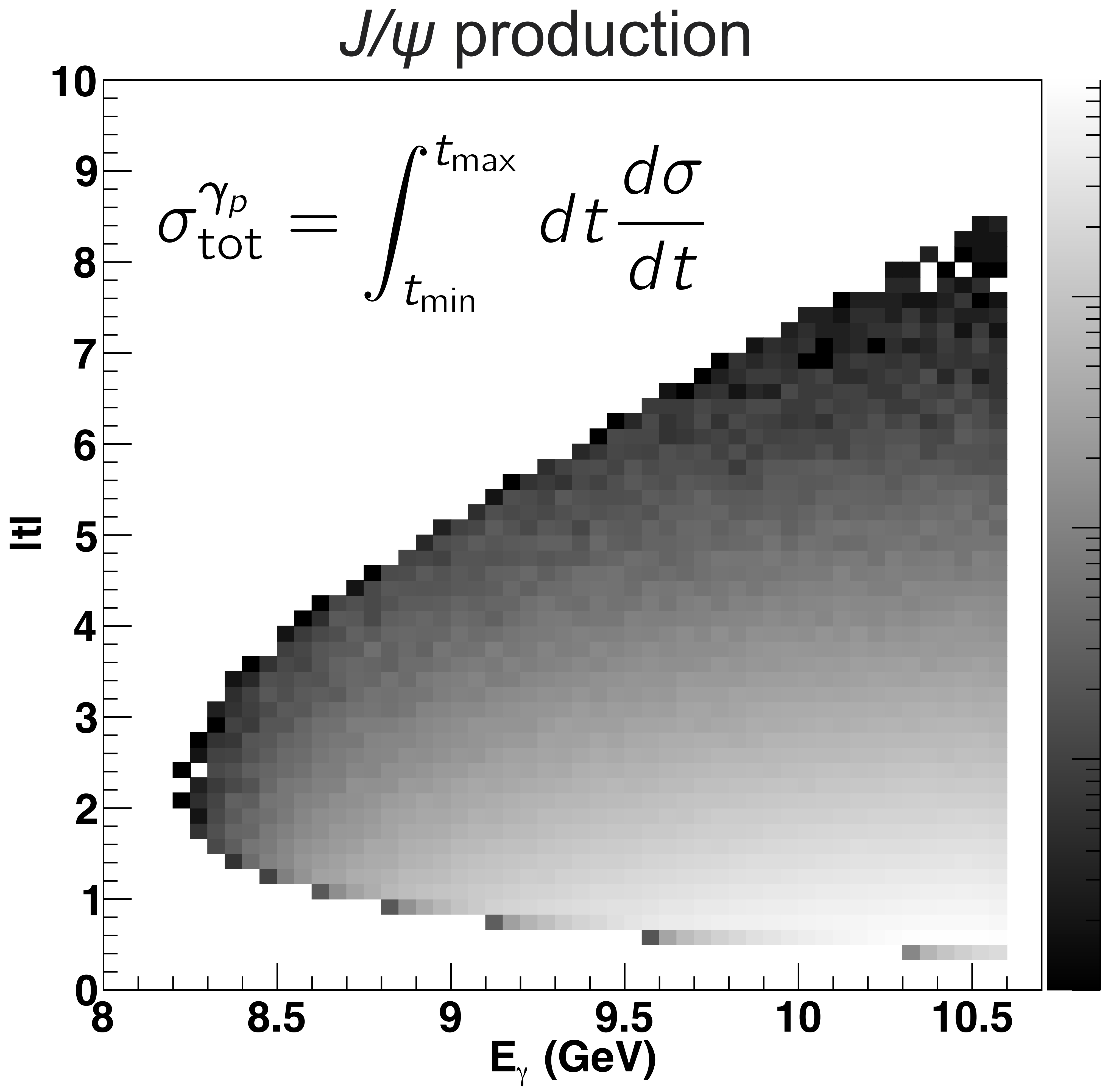

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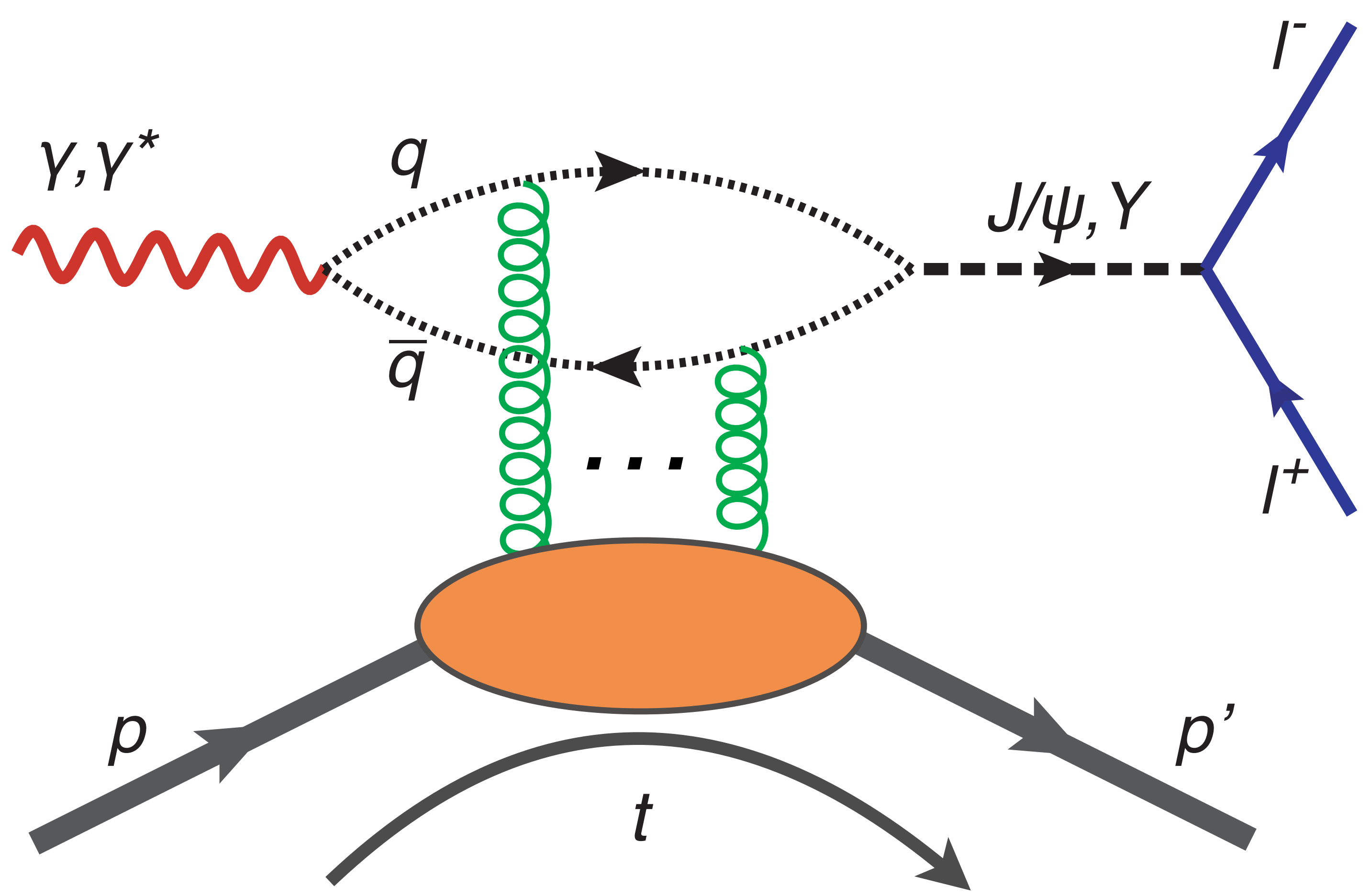

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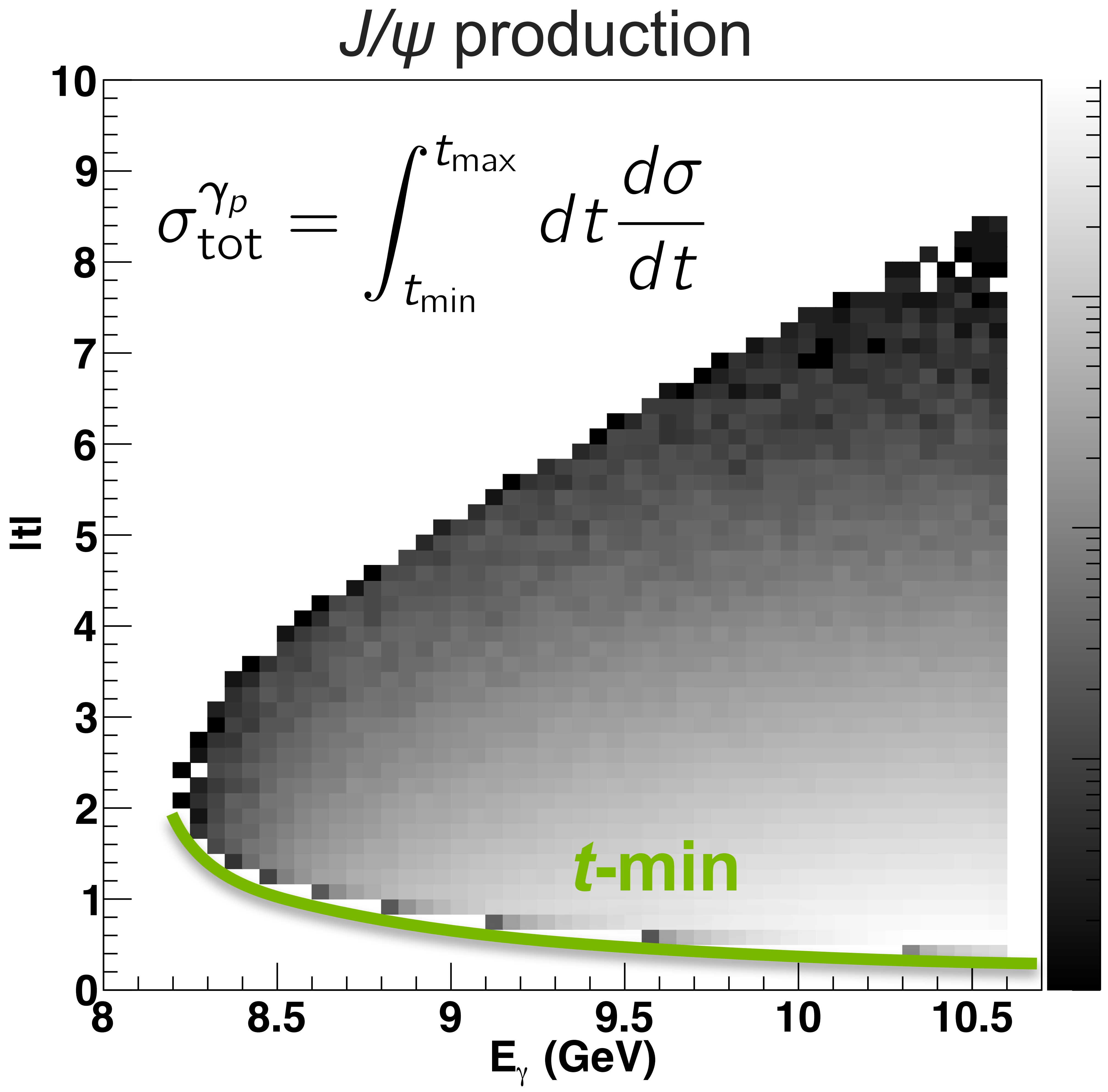

S. Joosten

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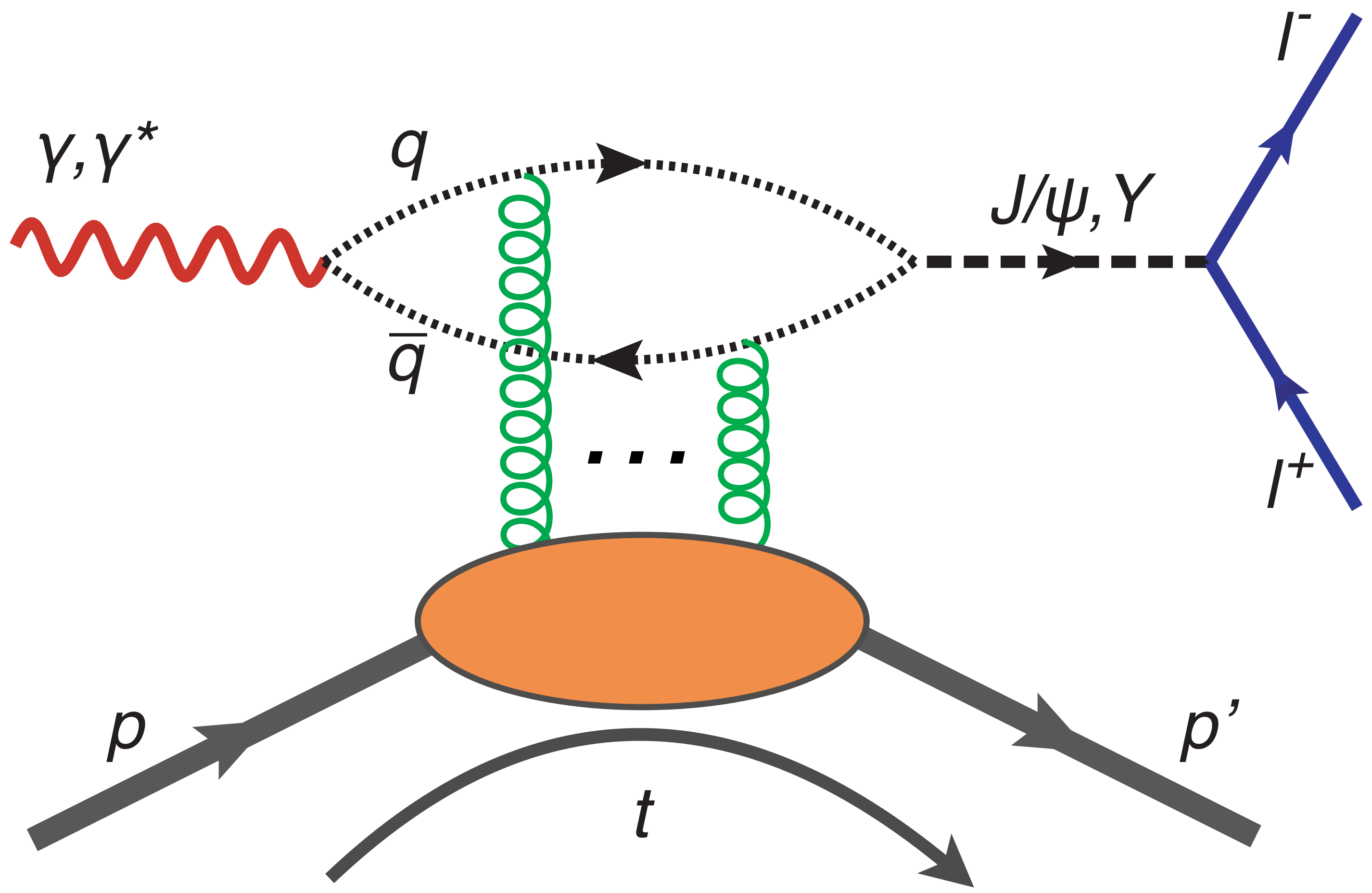

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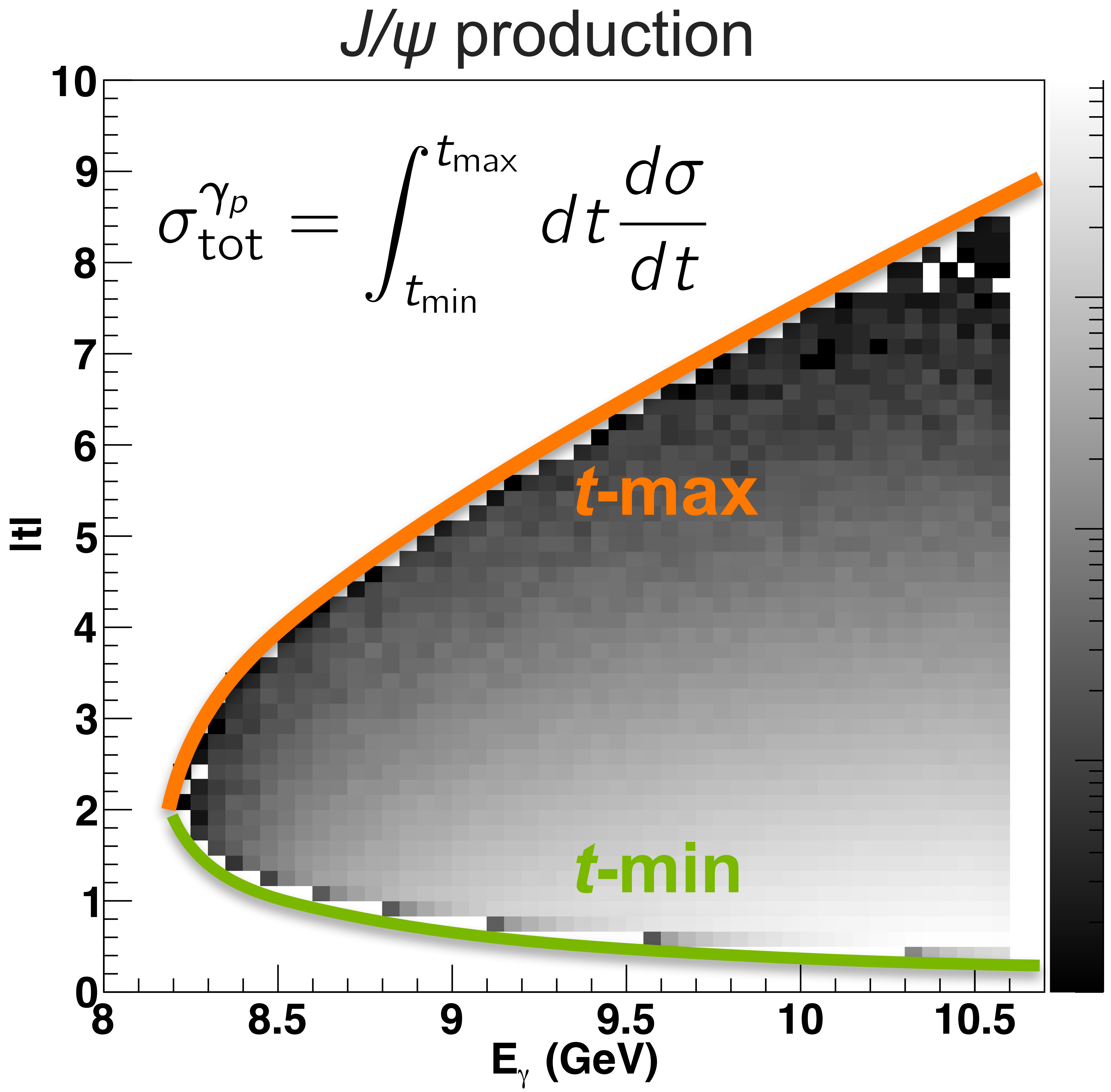

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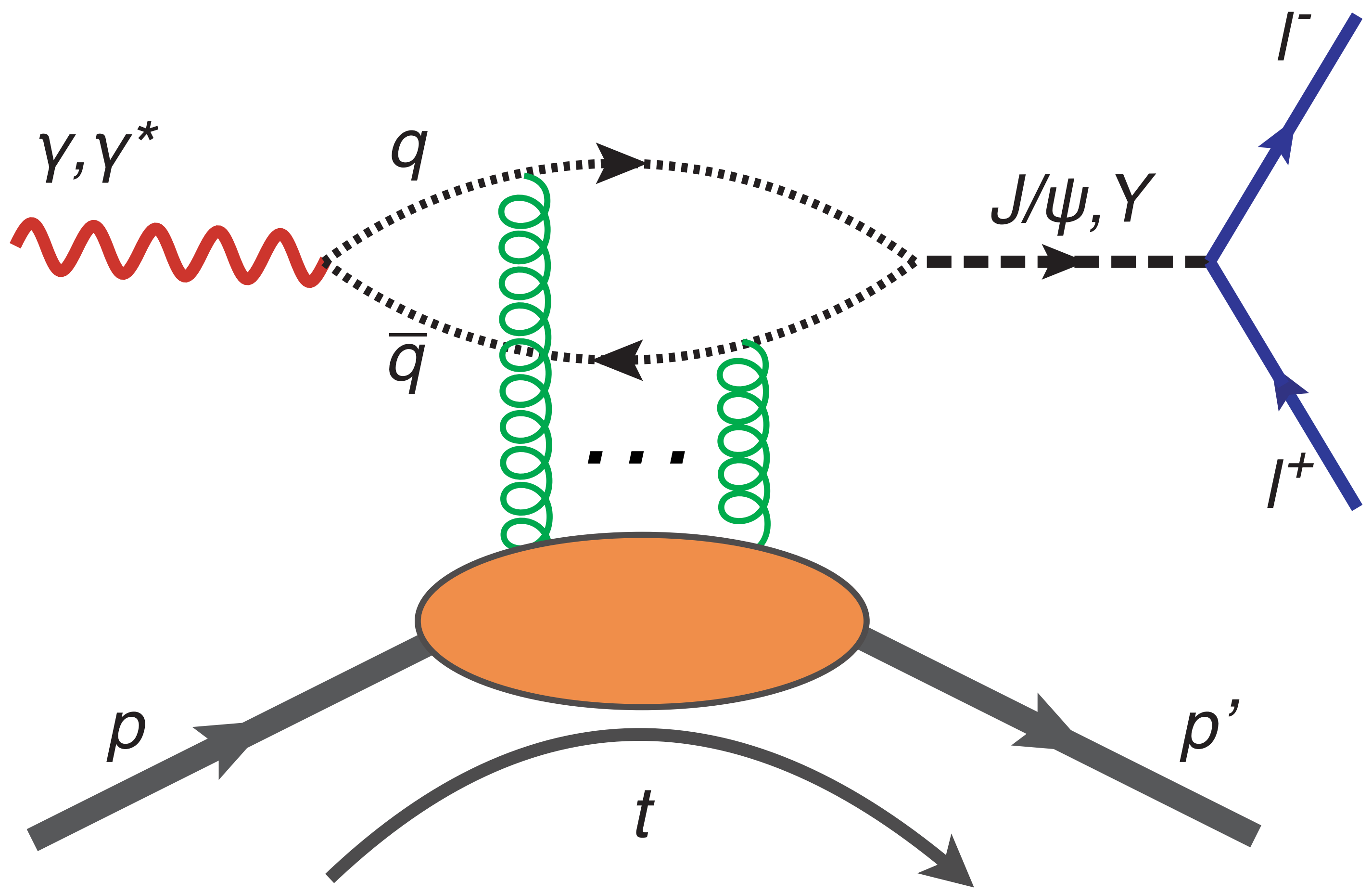

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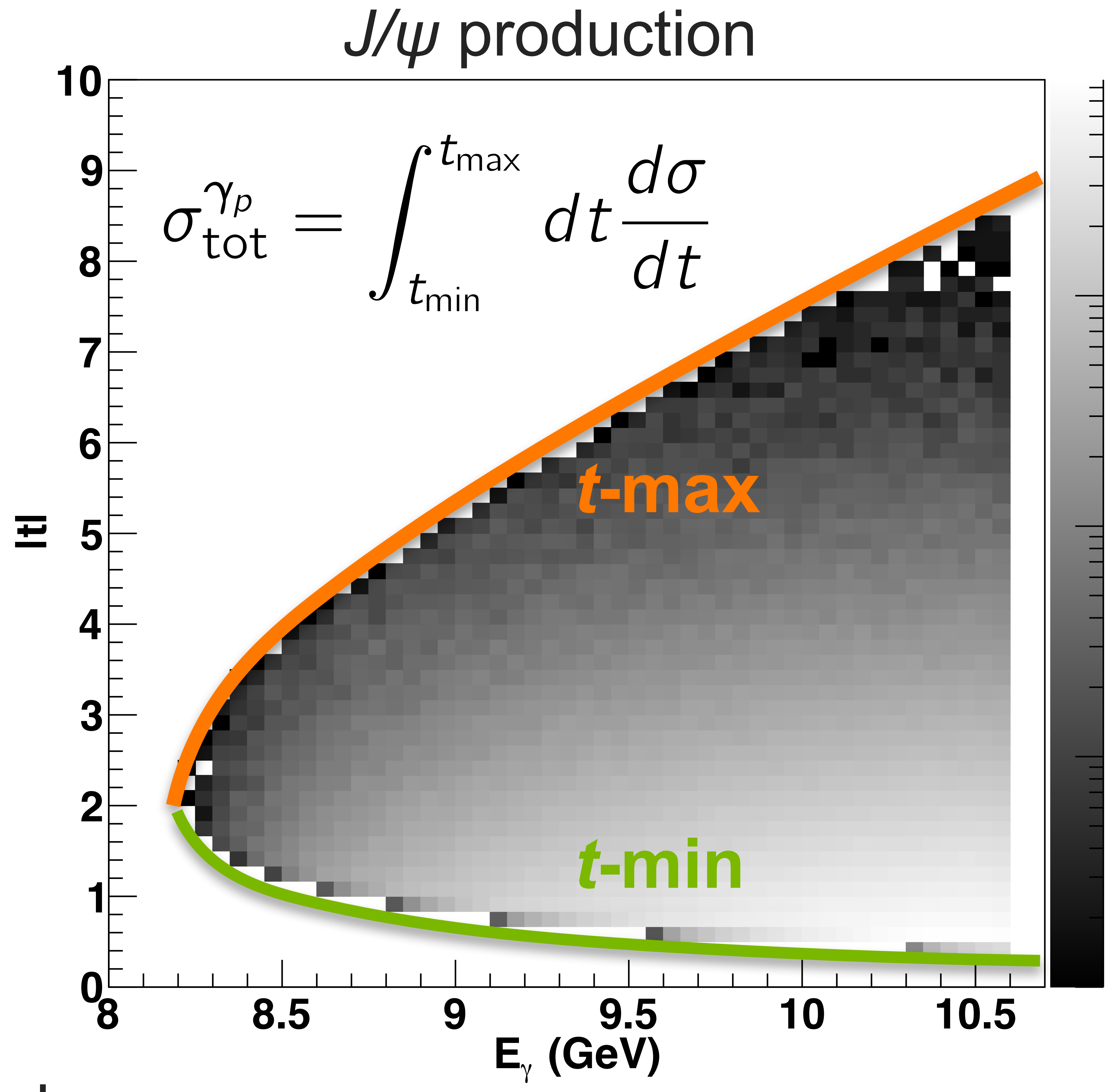

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  - Forward (with photon): $t = t_{\min}$
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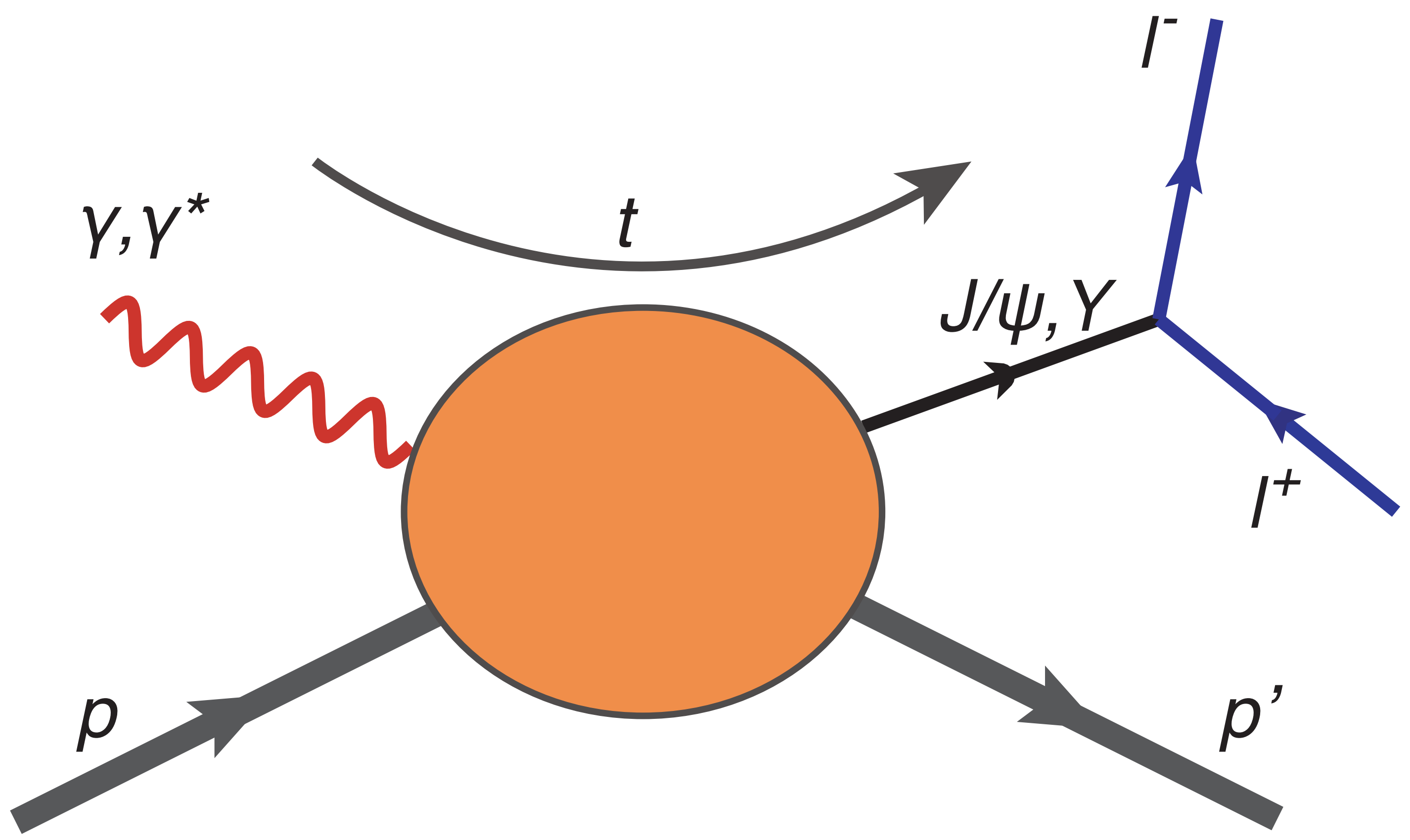
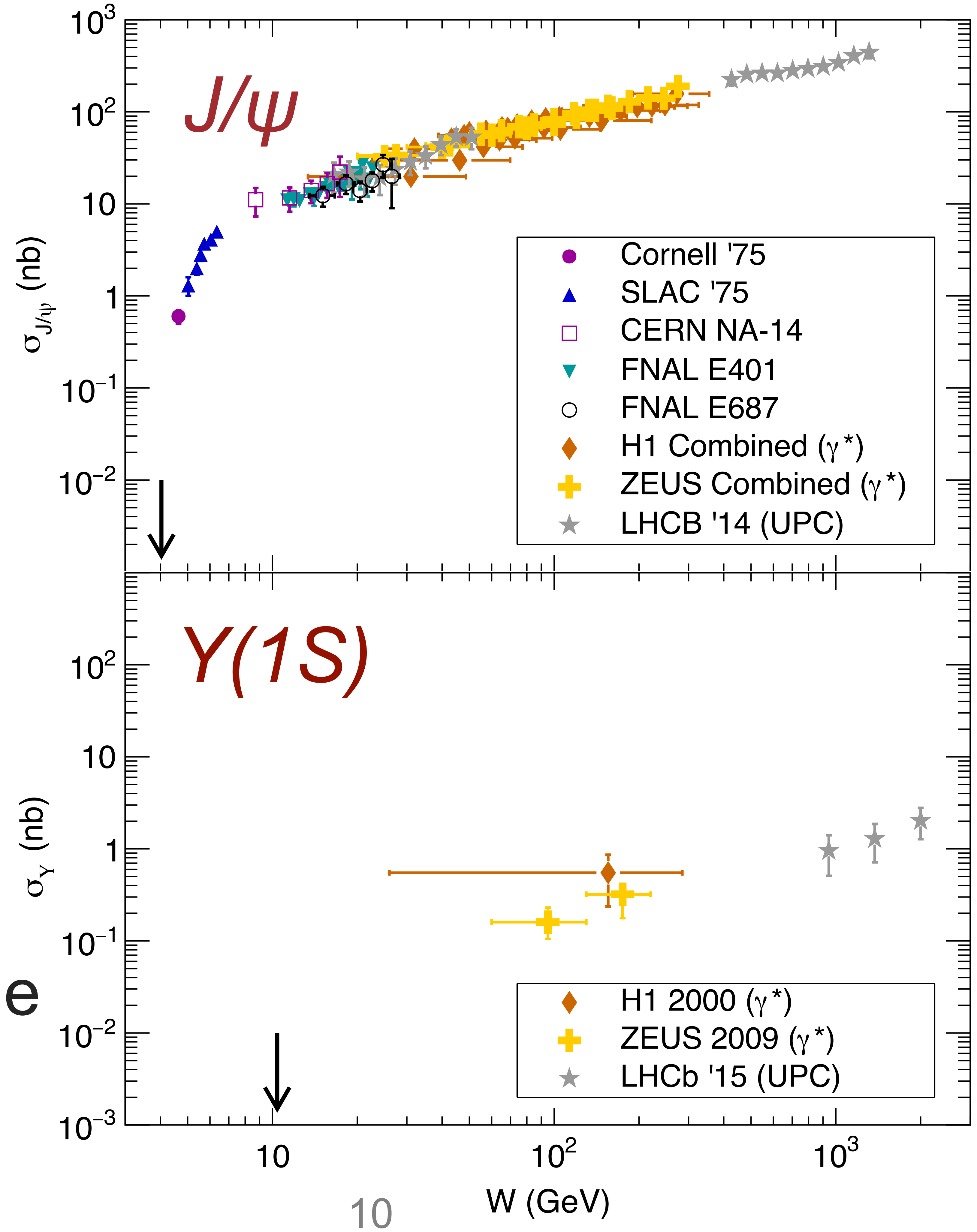
- Forward direction preferred: *t*-dependence ~exponential

QUARKONIUM PHOTO-PRODUCTION

What did we know before JLab?





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- **Almost no data near threshold**

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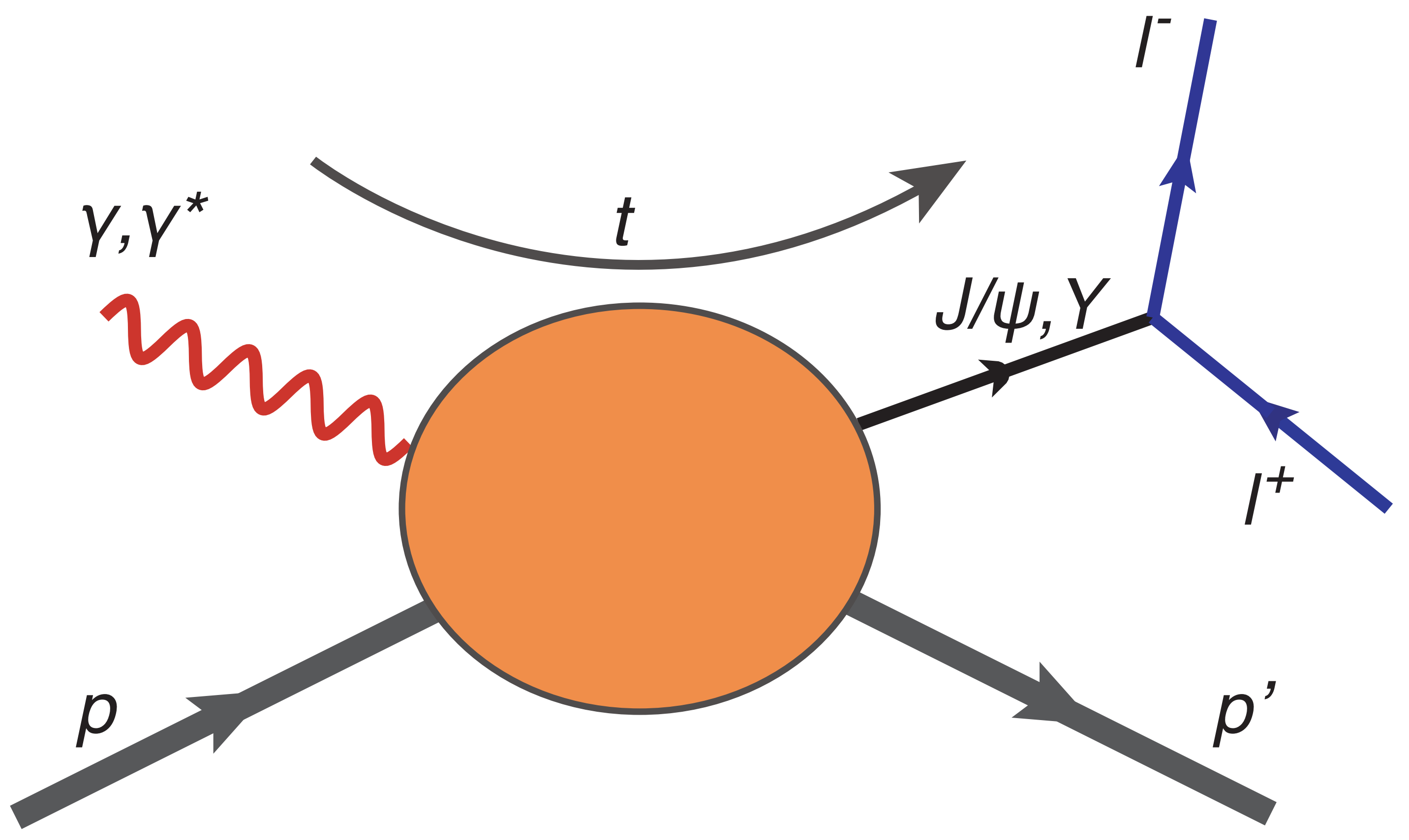

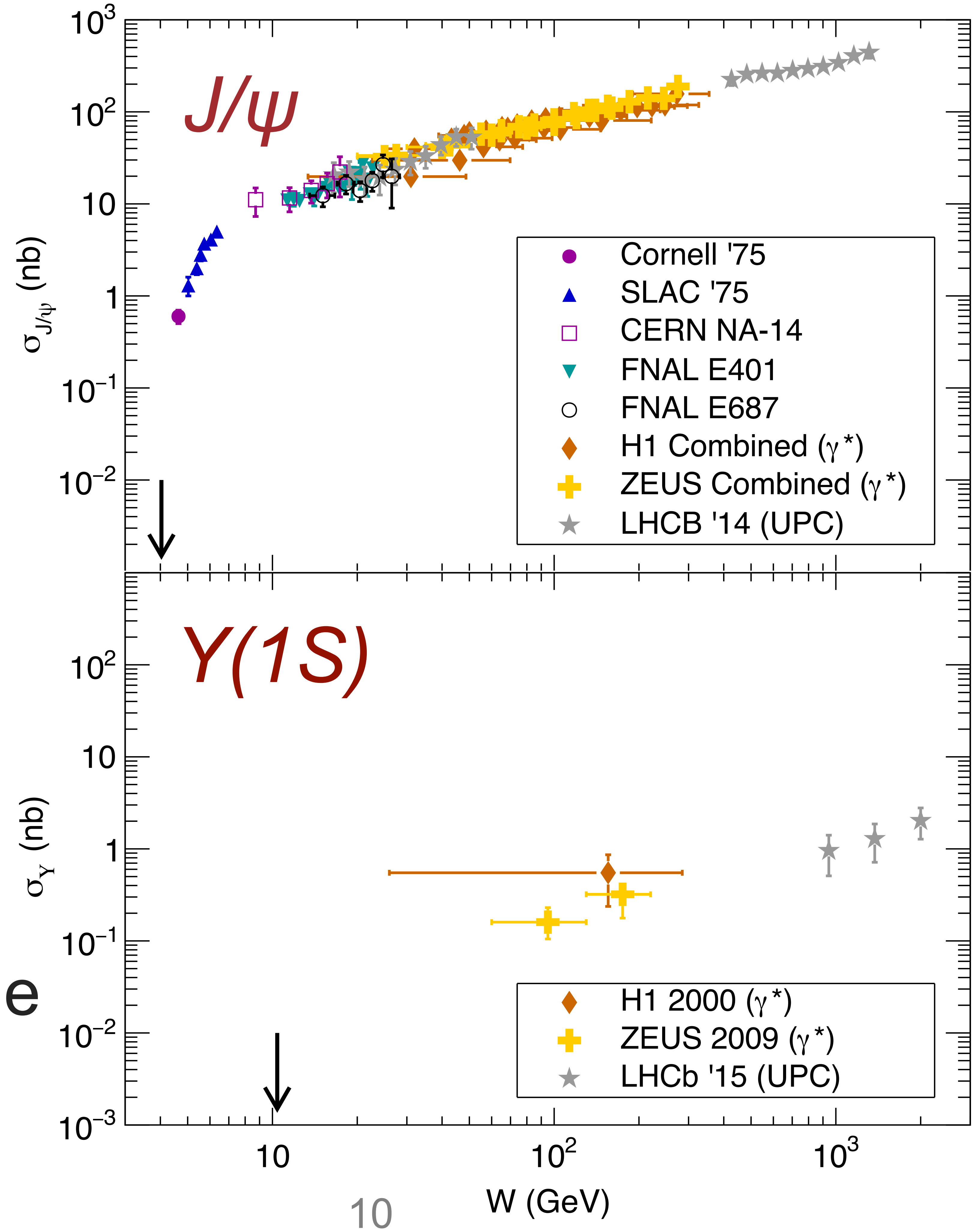

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Near Threshold:

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

J/ψ at JLab
Υ(1s) at EIC

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

HOW TO MEASURE THE TRACE ANOMALY

Vector meson dominance (dispersive framework)

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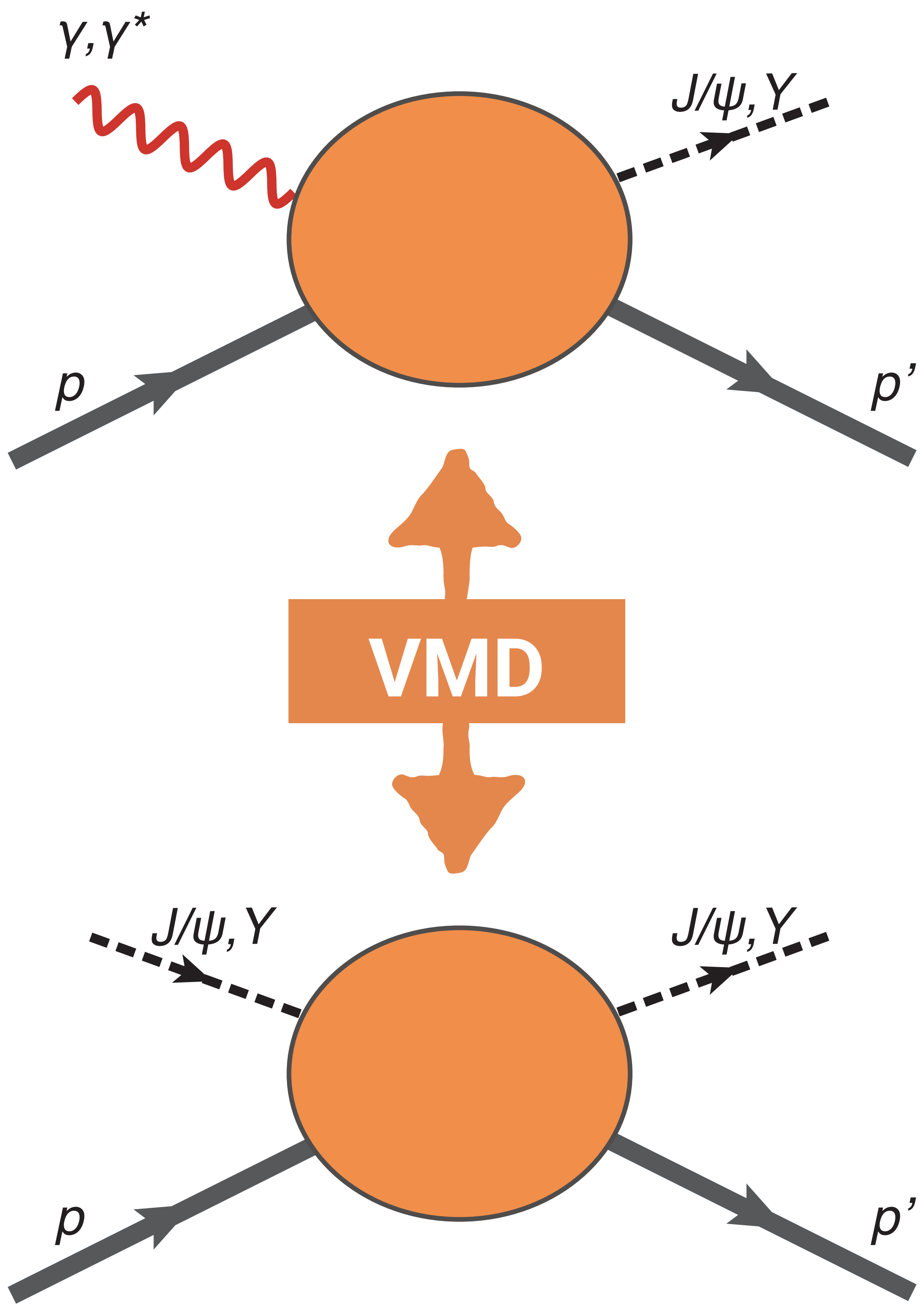

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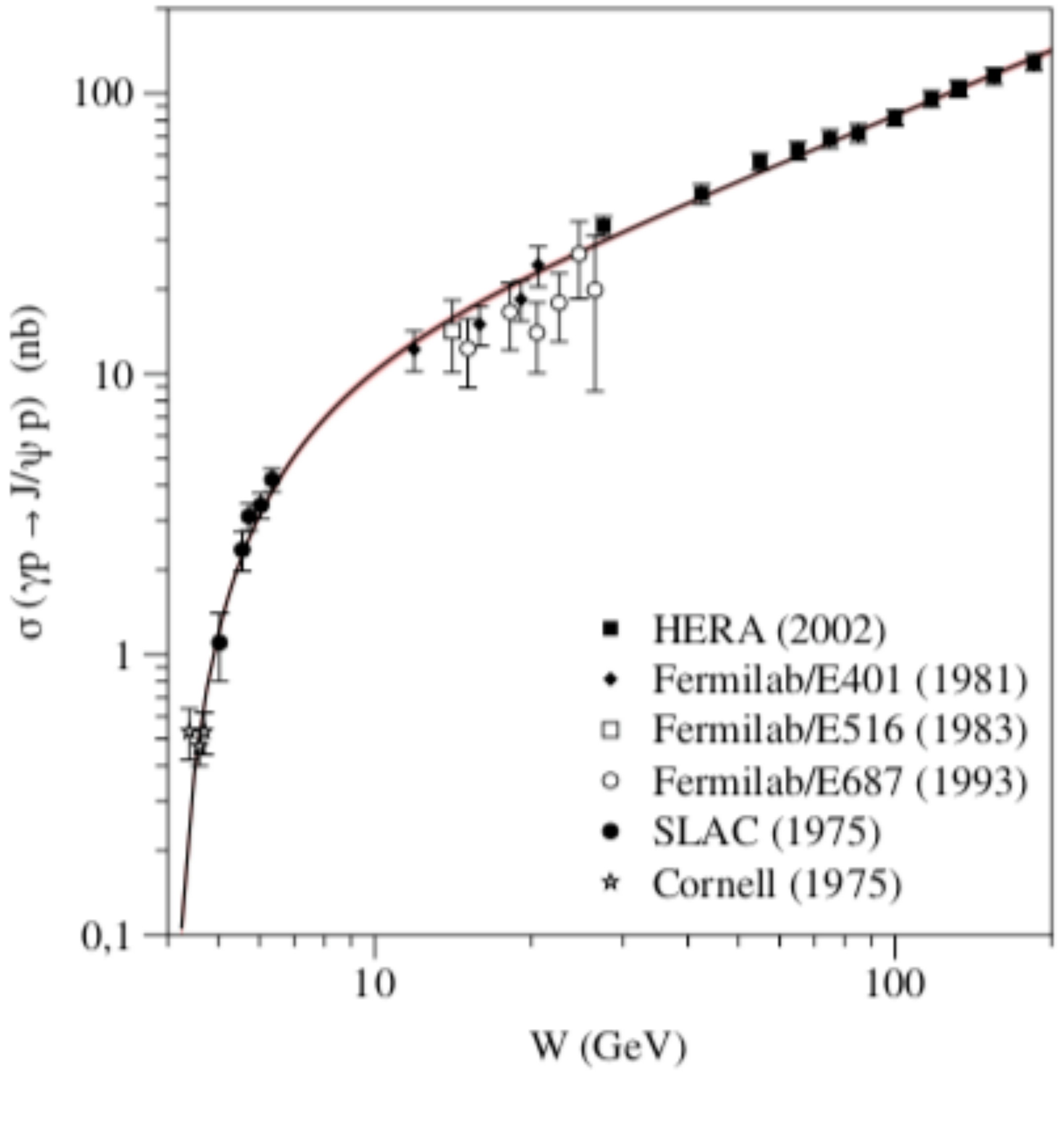

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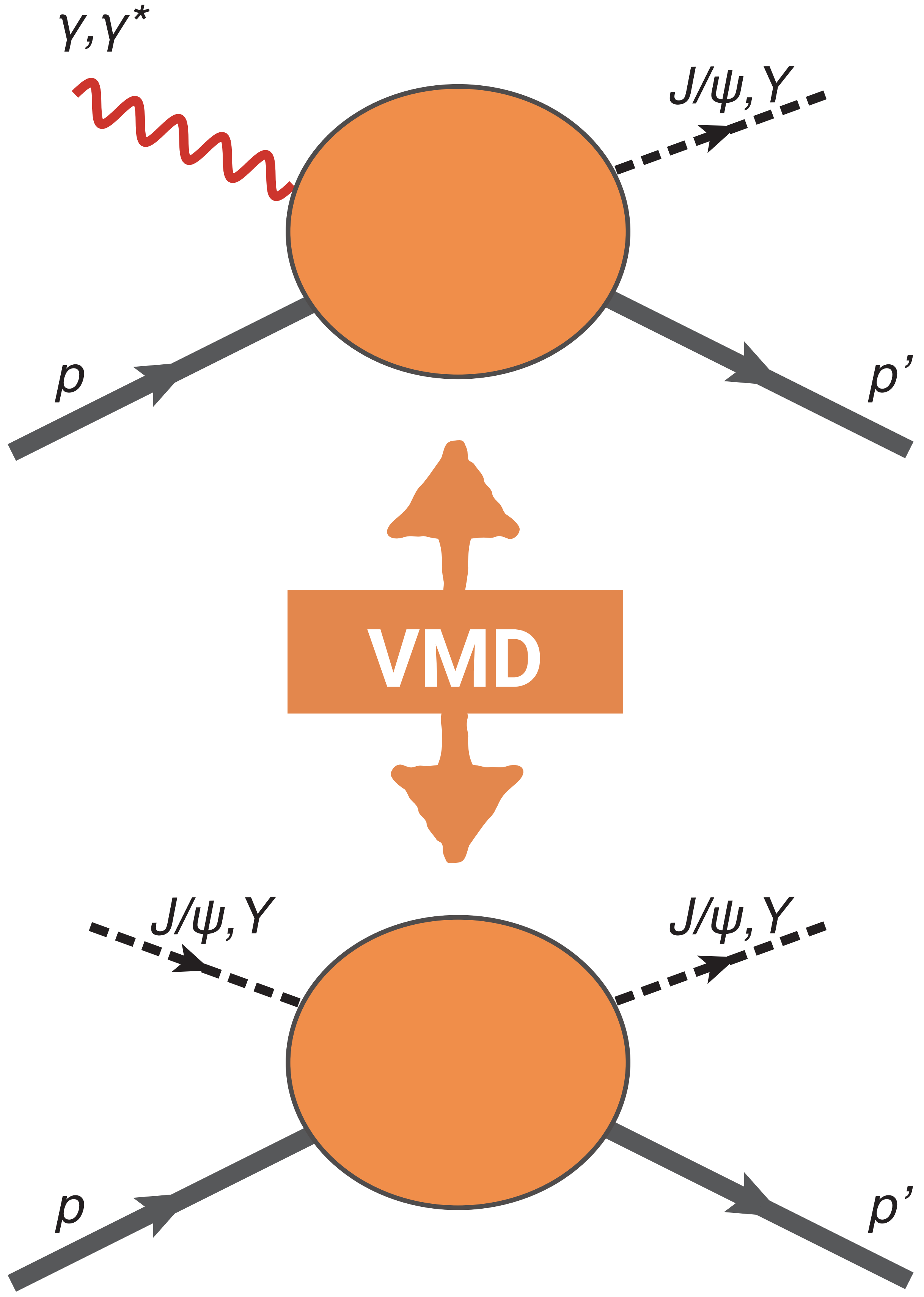
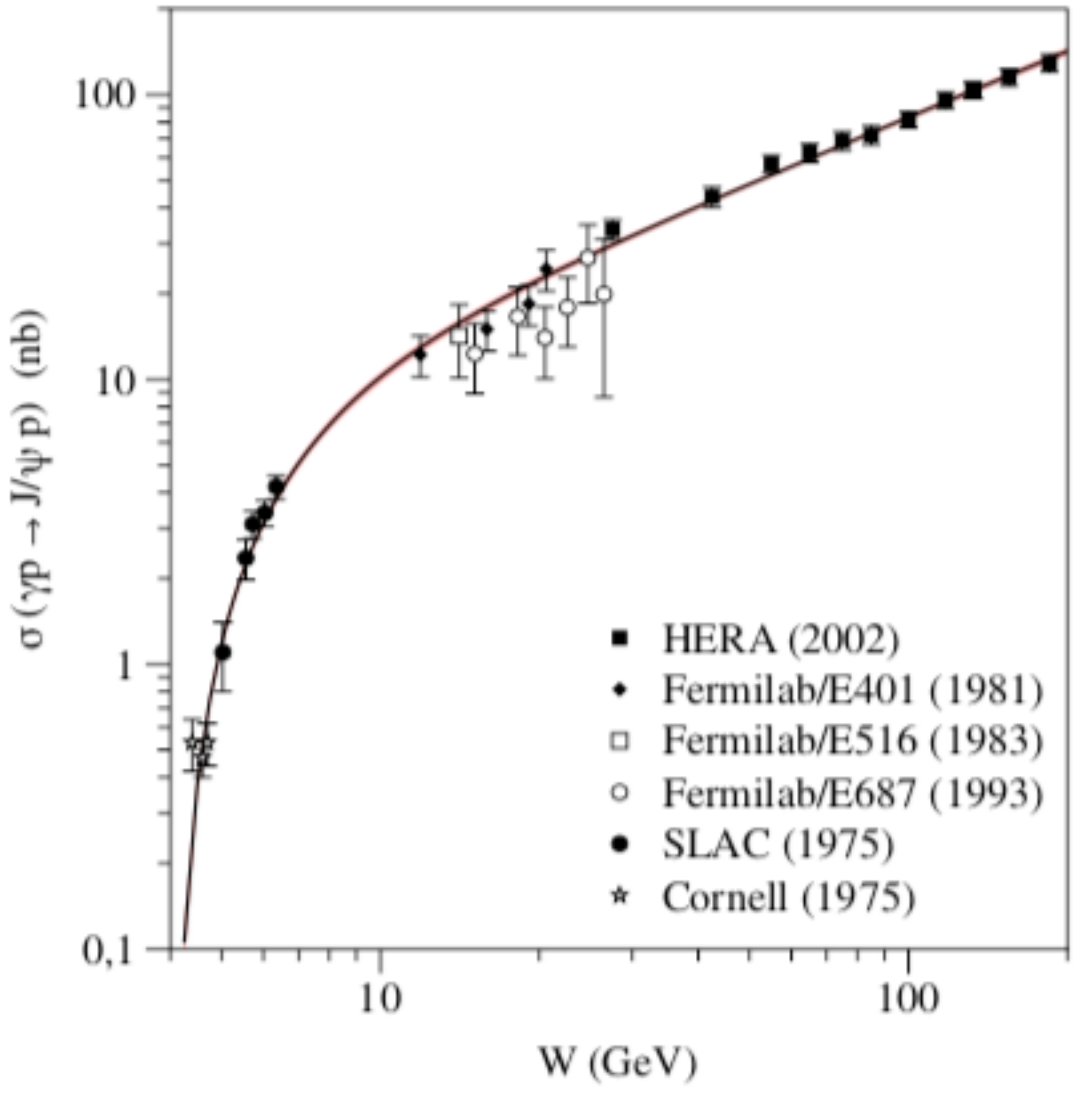
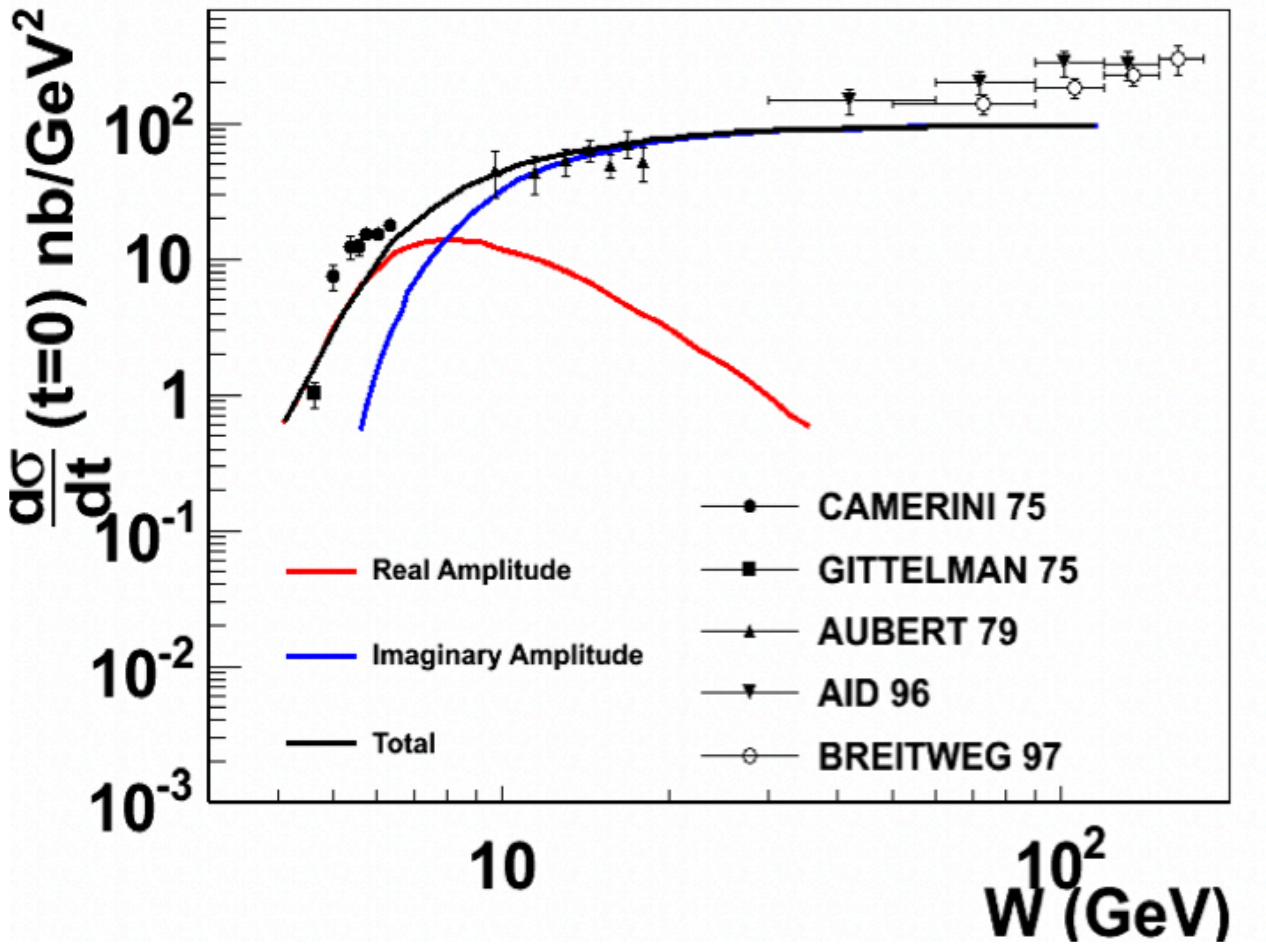


- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $T_{\psi p}$
- Approach well-defined at **high energies:**
  1. Obtain **Im($T_{\psi p}$)** from high energy data (extrapolated to t = 0)
  2. **Re($T_{\psi p}$)** dominates **near threshold**: constrain through dispersion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

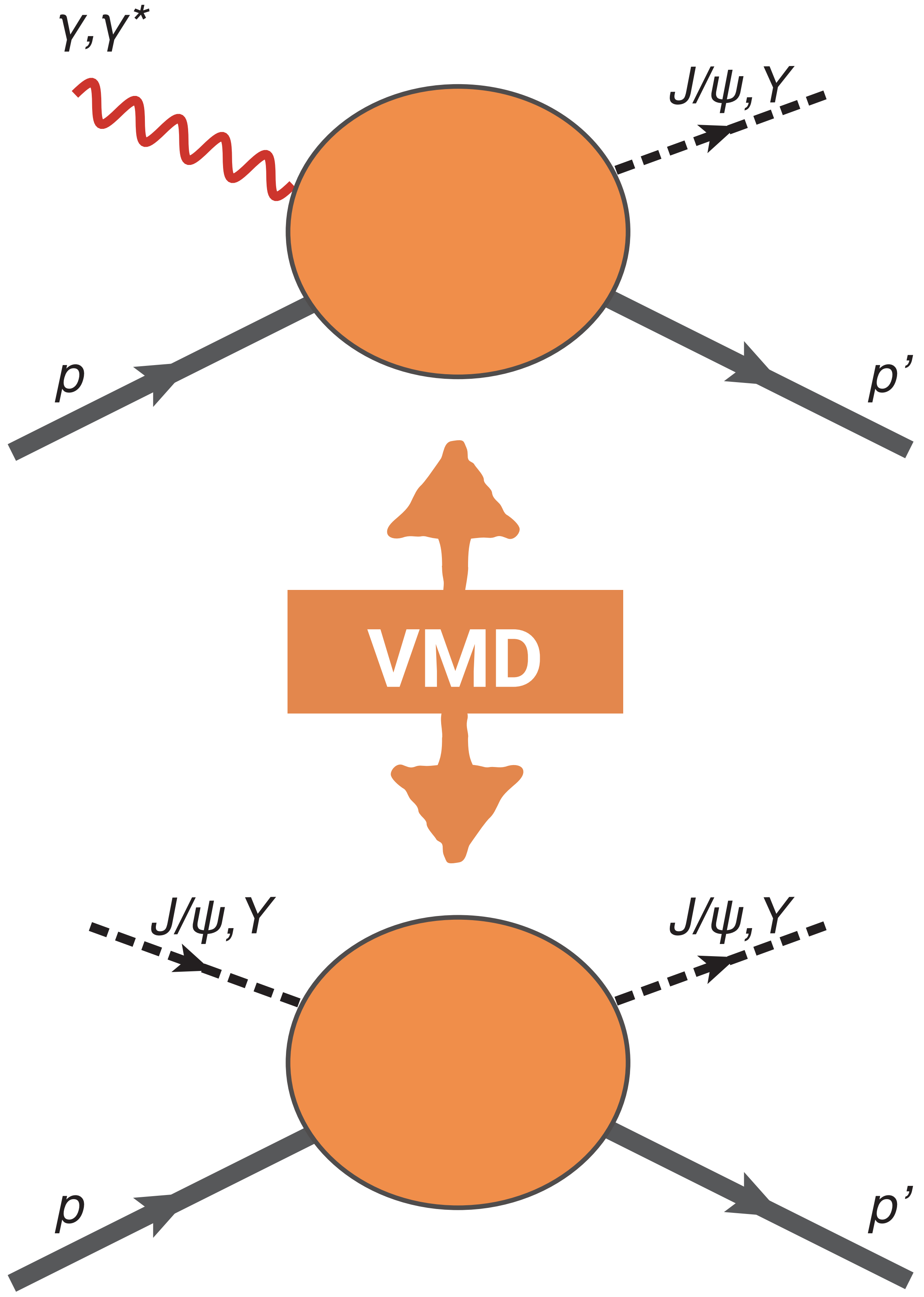
$$\mathcal{R}eT_{\psi p}(\nu) = T_{\psi p}(0) + \frac{2}{\pi}\nu^2 \int_{\nu_{\rm el}}^{\infty} d\nu' \frac{1}{\nu} \frac{\mathcal{I}mT_{\psi p}(\nu')}{\nu'^2 - \nu^2}$$





HOW TO MEASURE THE TRACE ANOMALY

Vector meson dominance (dispersive framework)

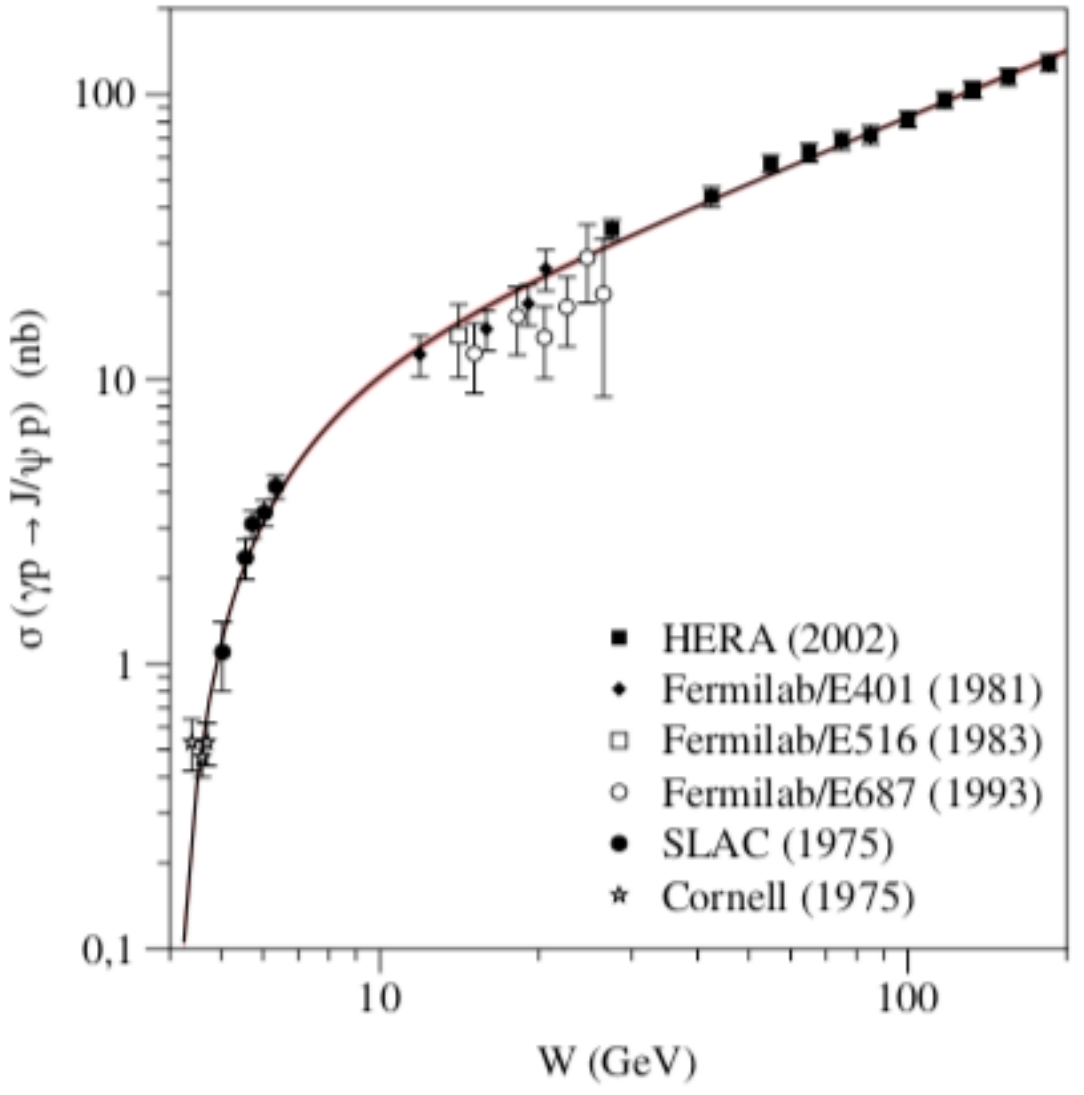


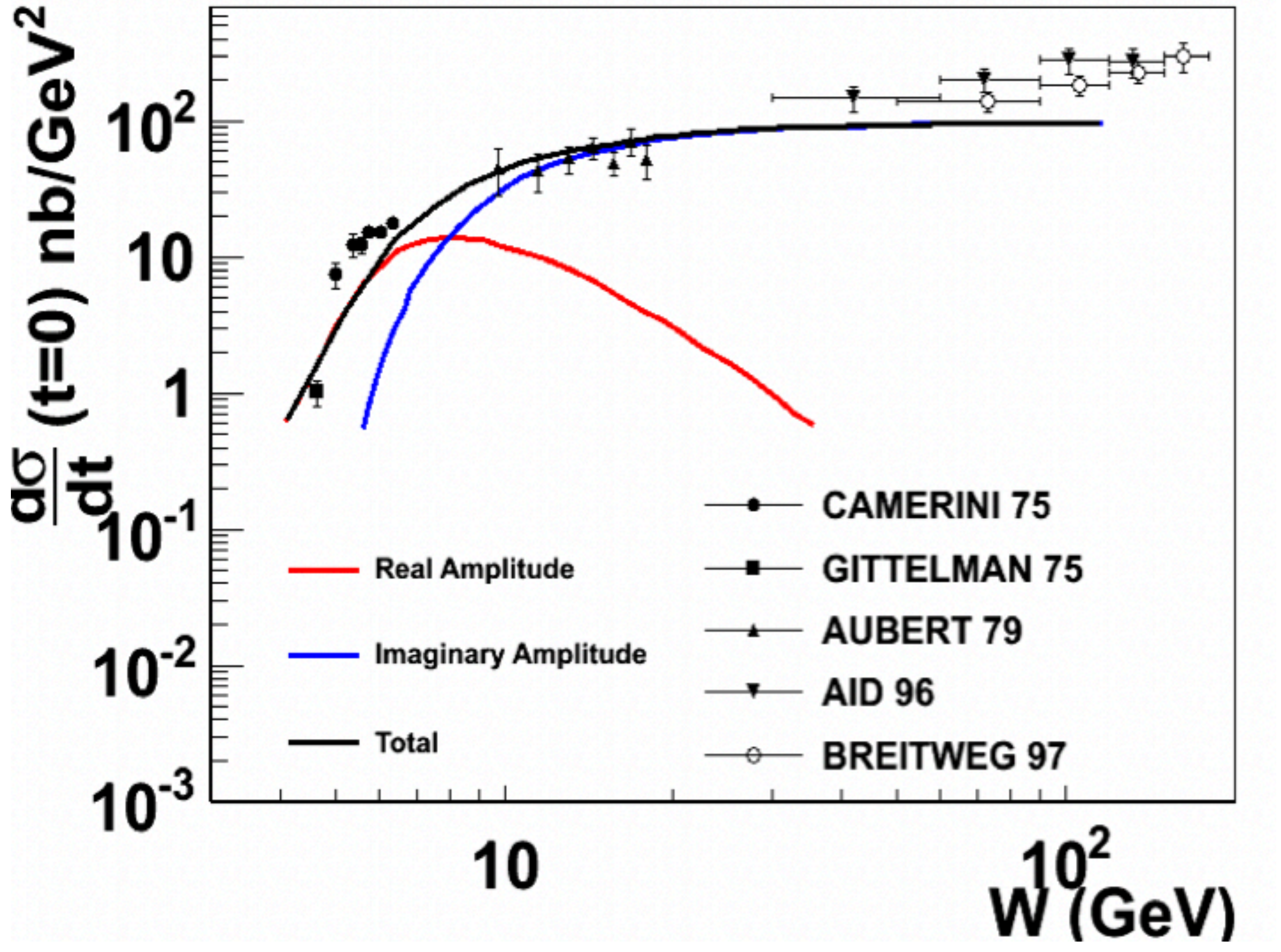
- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $T_{\psi p}$
- Approach well-defined at **high energies:**
  1. Obtain **Im($T_{\psi p}$)** from high energy data (extrapolated to t = 0)
  2. **Re($T_{\psi p}$)** dominates **near threshold**: constrain through dispersion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

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

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

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





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

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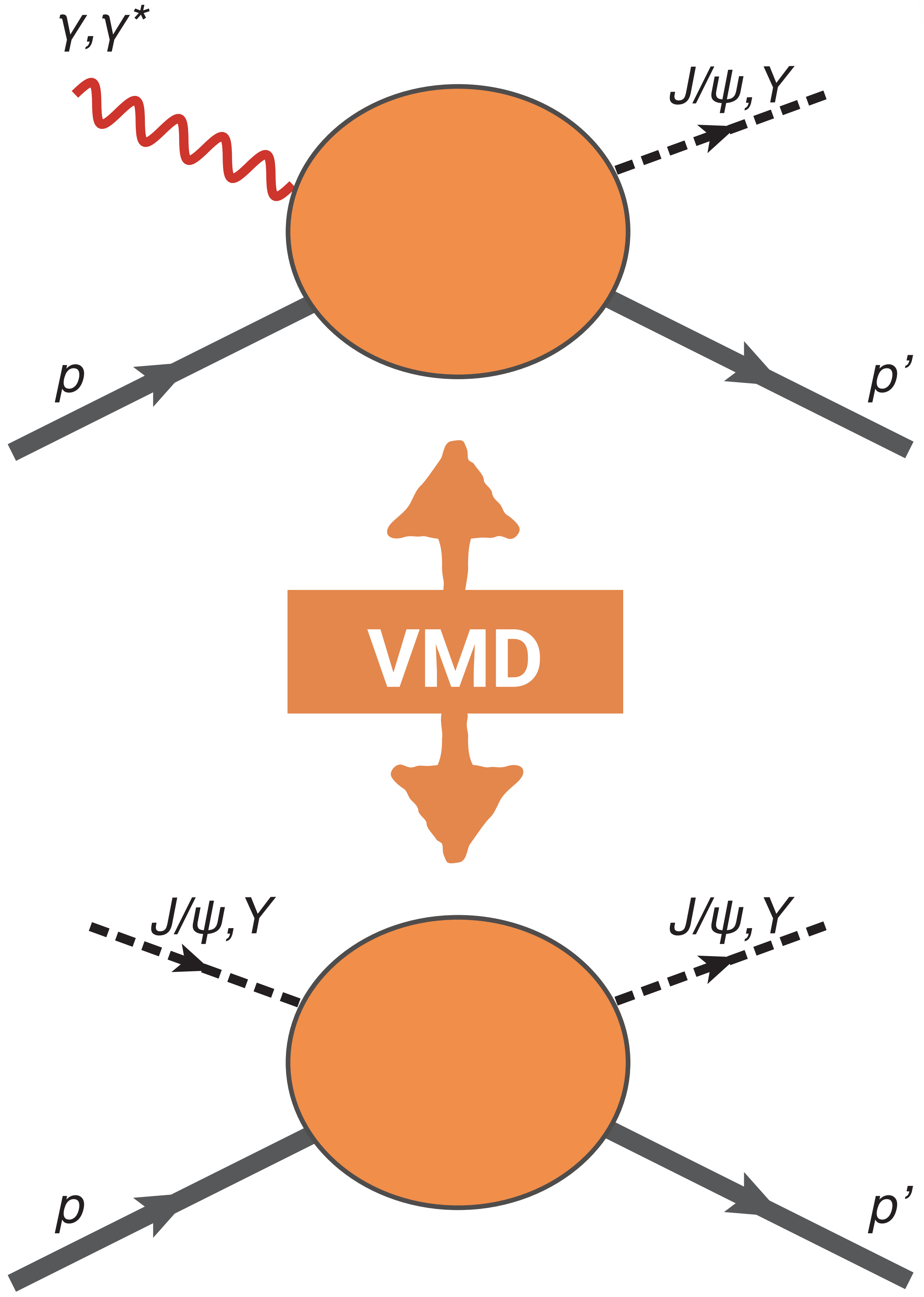

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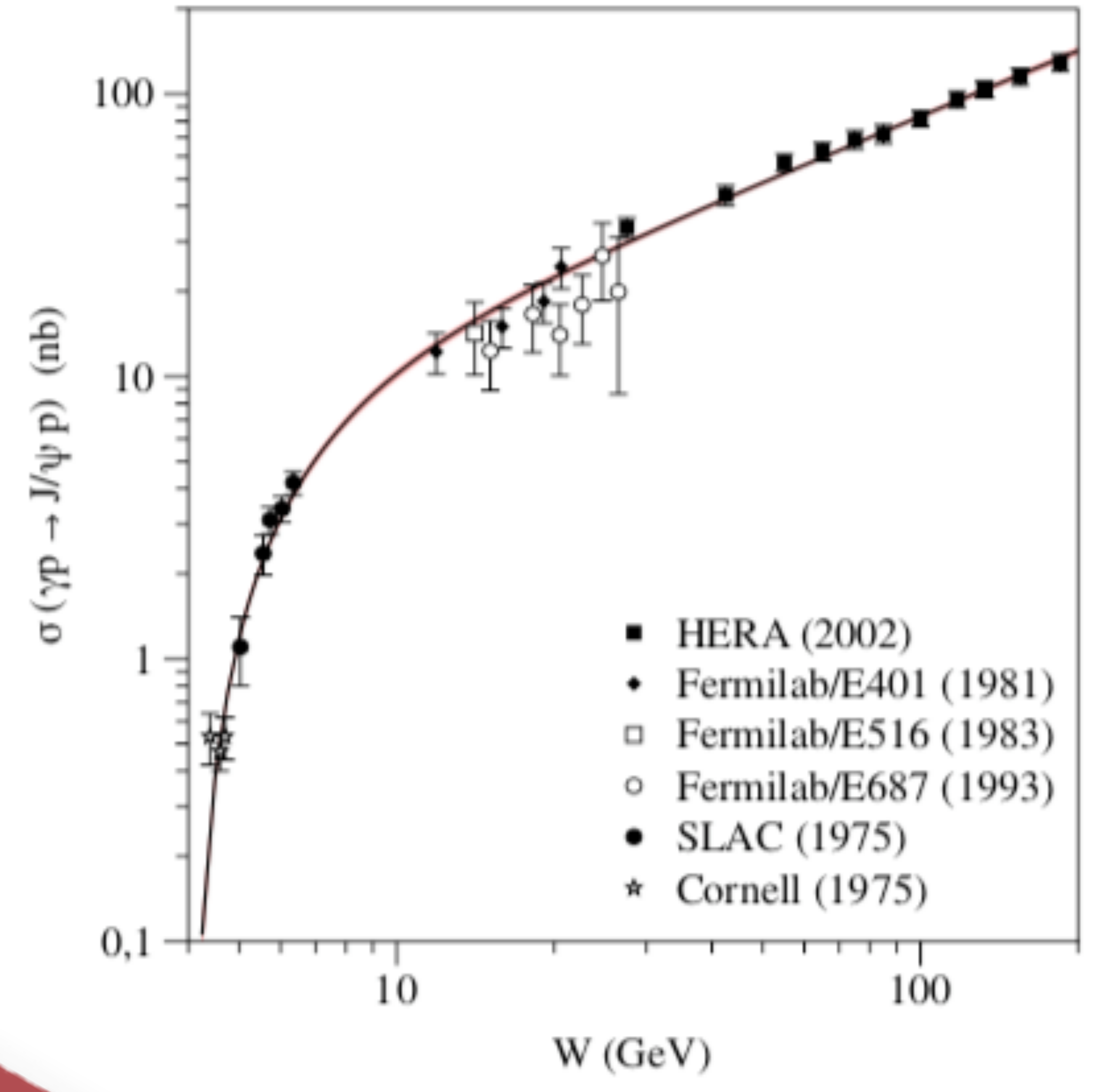
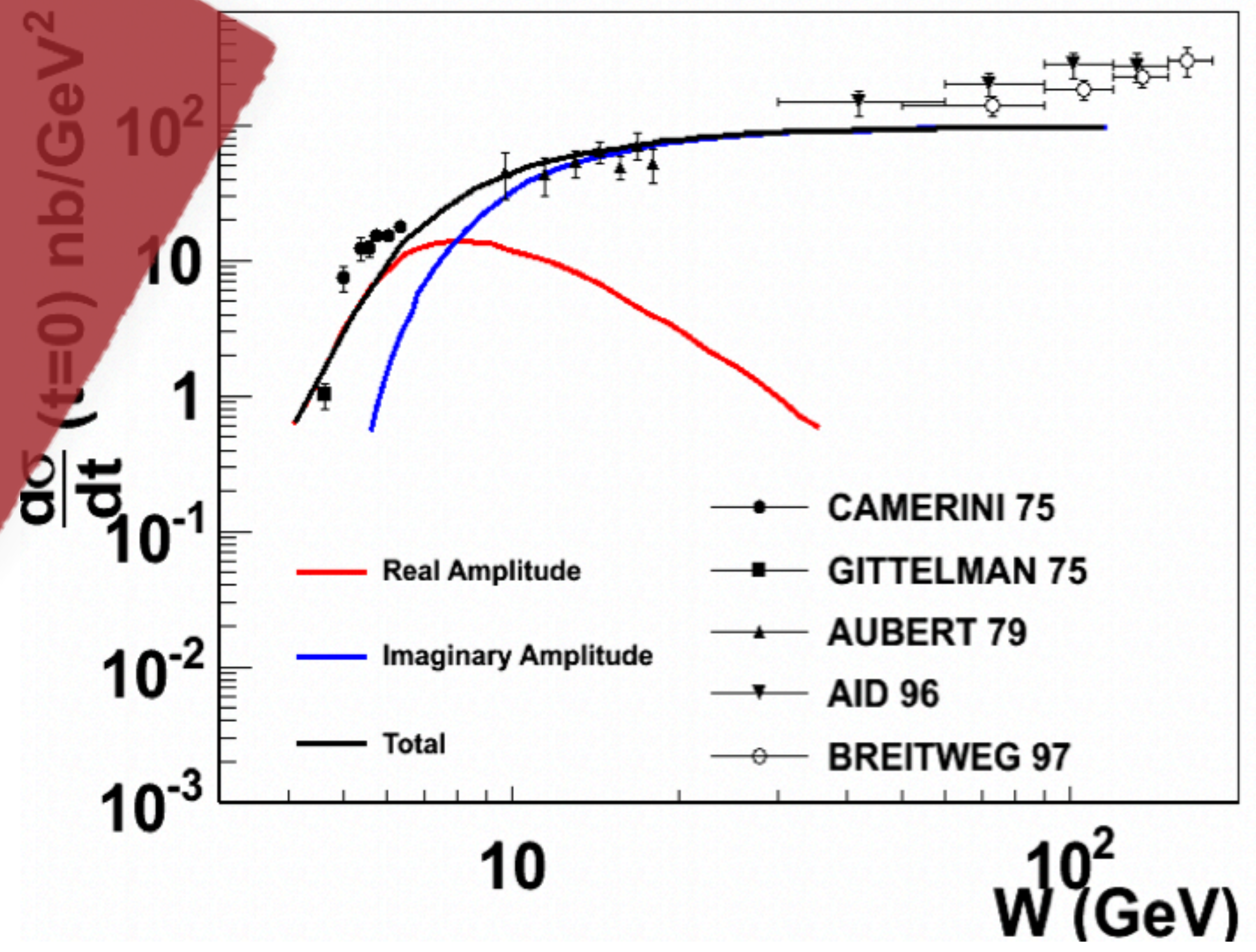
WARNING LABEL:
Keep in mind, no rigorous factorization theorem (yet)!



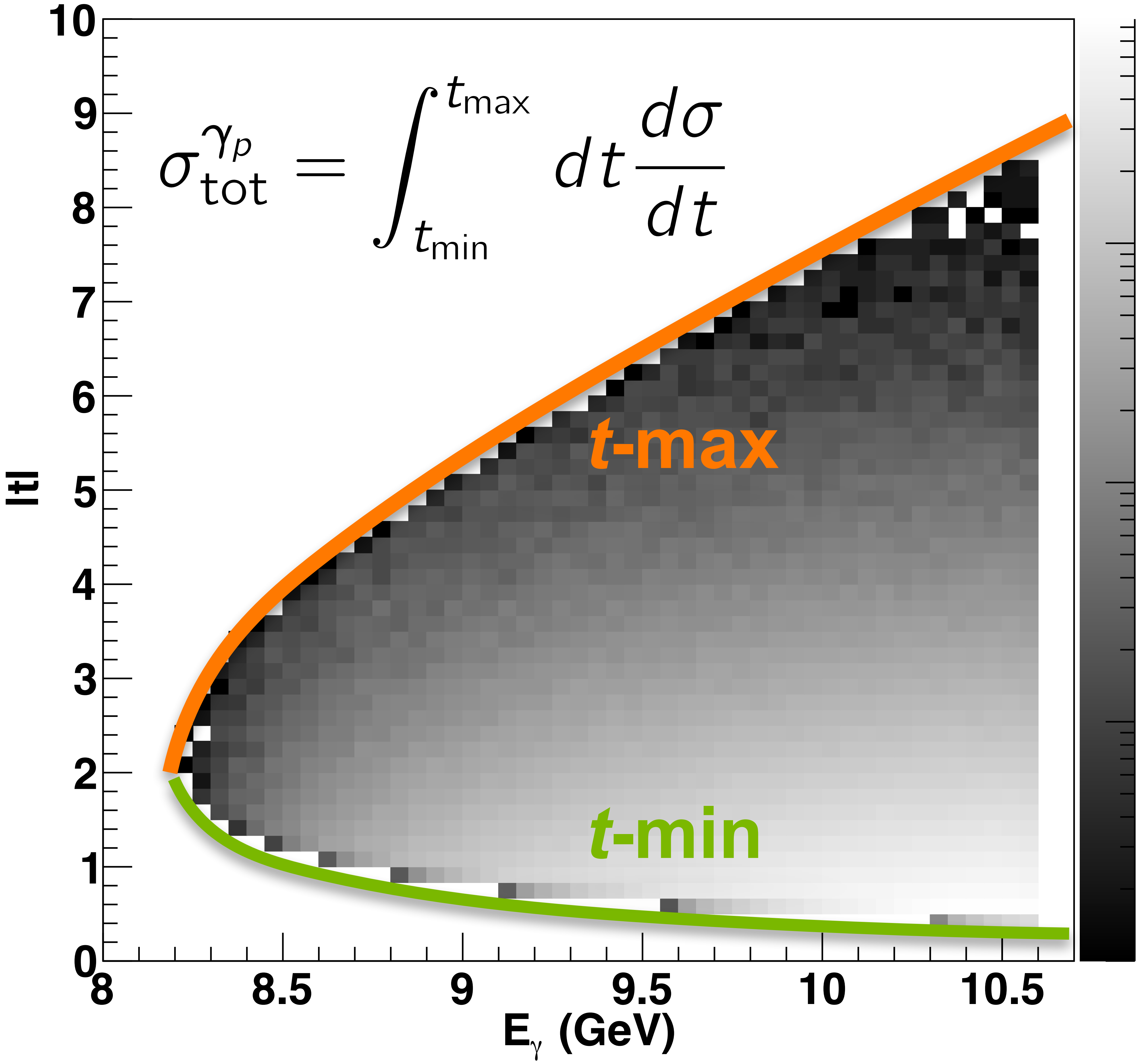


HOW TO MEASURE THE TRACE ANOMALY

Vector meson dominance (dispersive framework)

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

- Measure *t*-dependence near threshold
- Extrapolate to forward limit (t=0)
- **Requires extremely high statistics experiment to allow for optimal lever arm in *t***

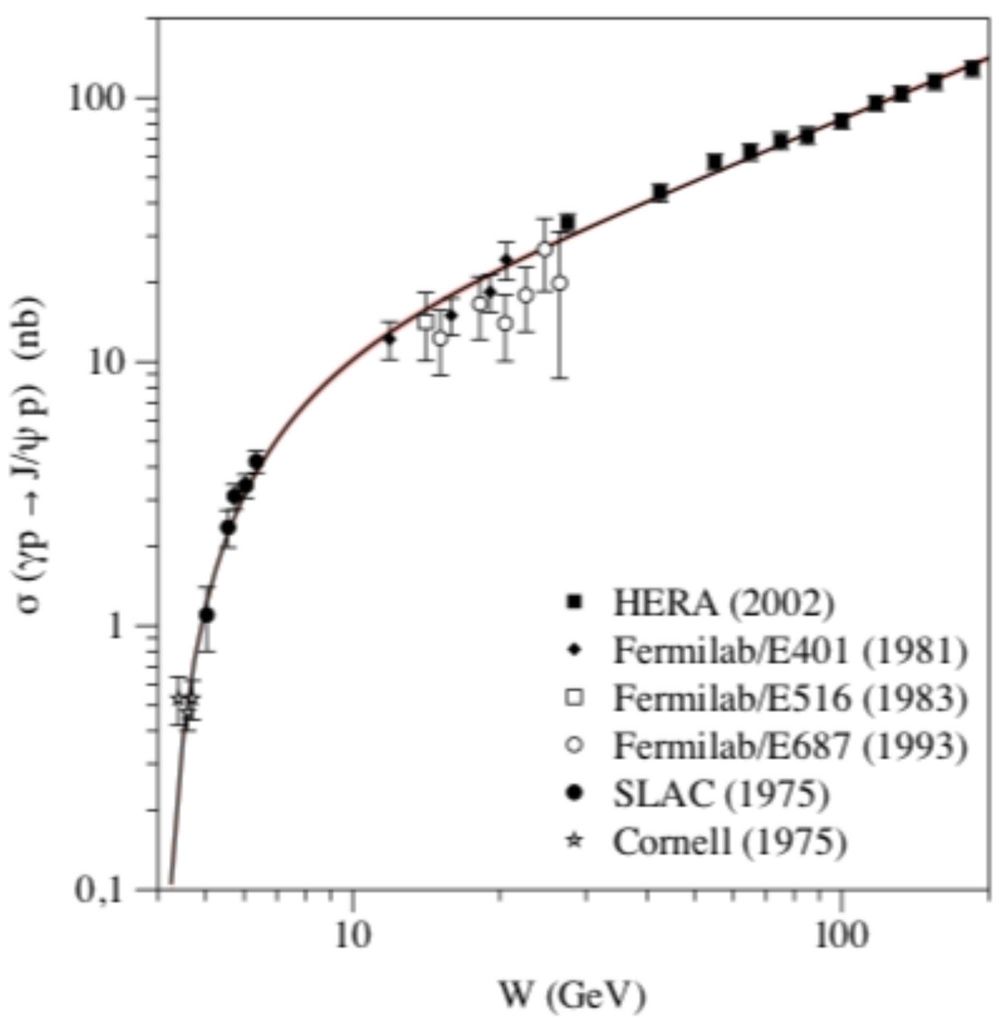


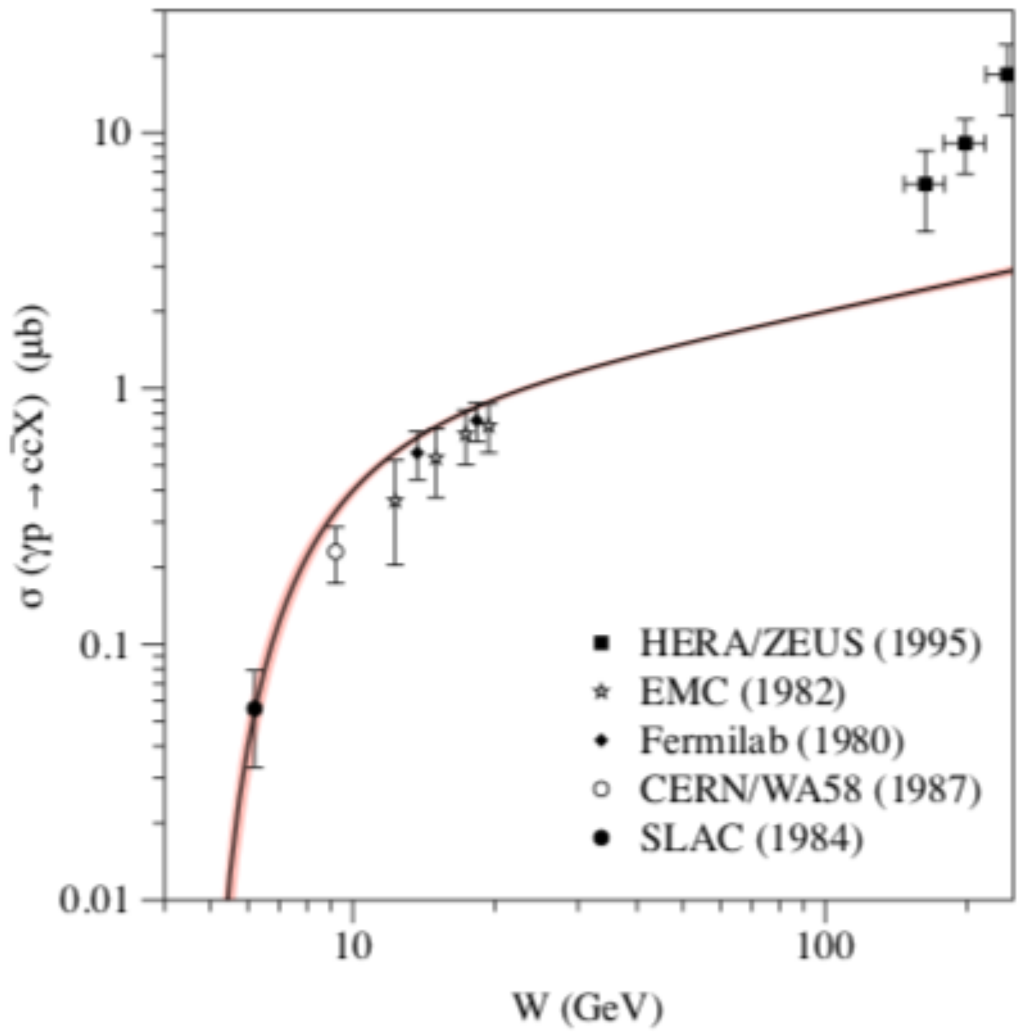
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)
S. R. Beane *et al.*, PRD 91, 114503 (2015)

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

The nature of the gluonic Van der Waals force

- Binding energy $B_{\psi p}$ can be derived from s-wave scattering length $a_{\psi p}$ at threshold
  - $T_{\psi p} = 8\pi(M + M_\psi)a_{\psi p}$
  - Currently constrained through fit to *J/ψ* and open-charm production + dispersion relations
  - For direct measurement need threshold *J/ψ*
  - Note: *link with trace anomaly*!
- Lattice QCD (at large pion mass): $B_{\psi p}$ < 40 MeV
- Current estimates between 0.05-0.30fm (3-20MeV)





S. Joosten

Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)
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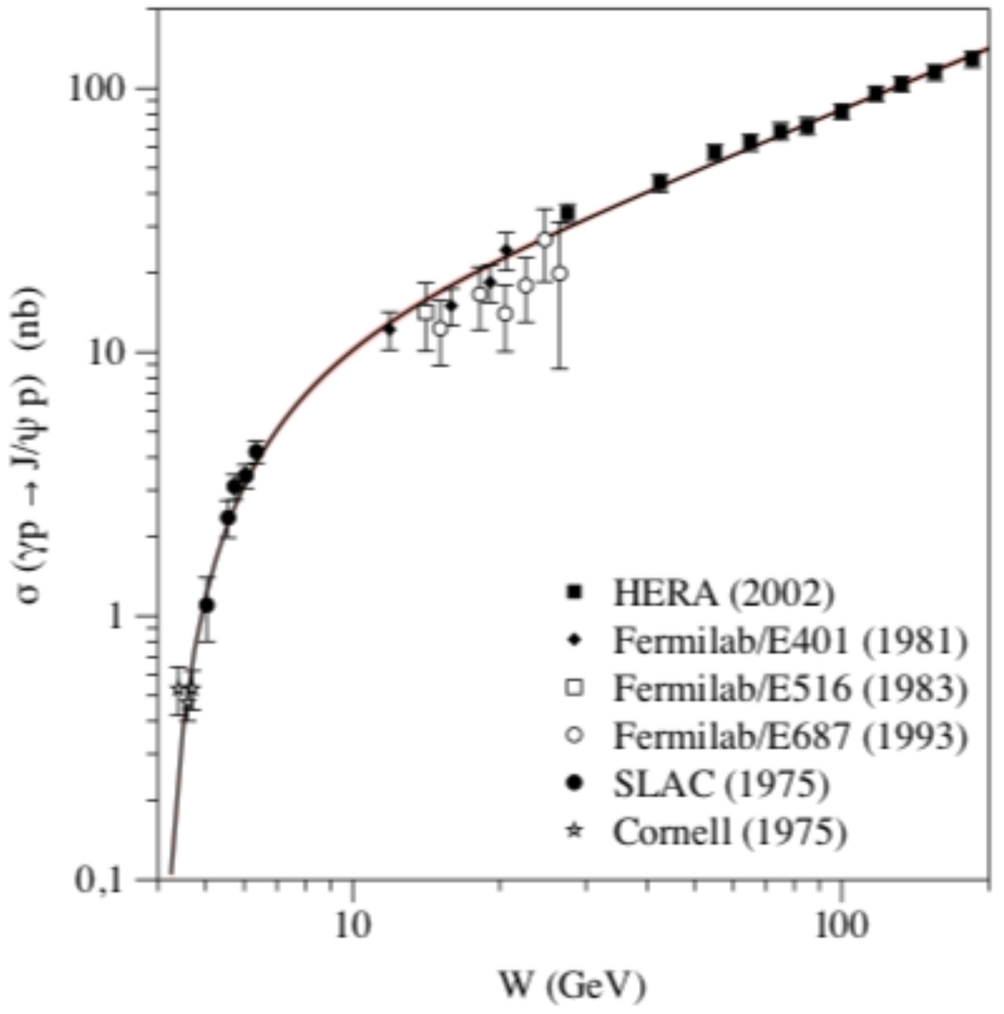
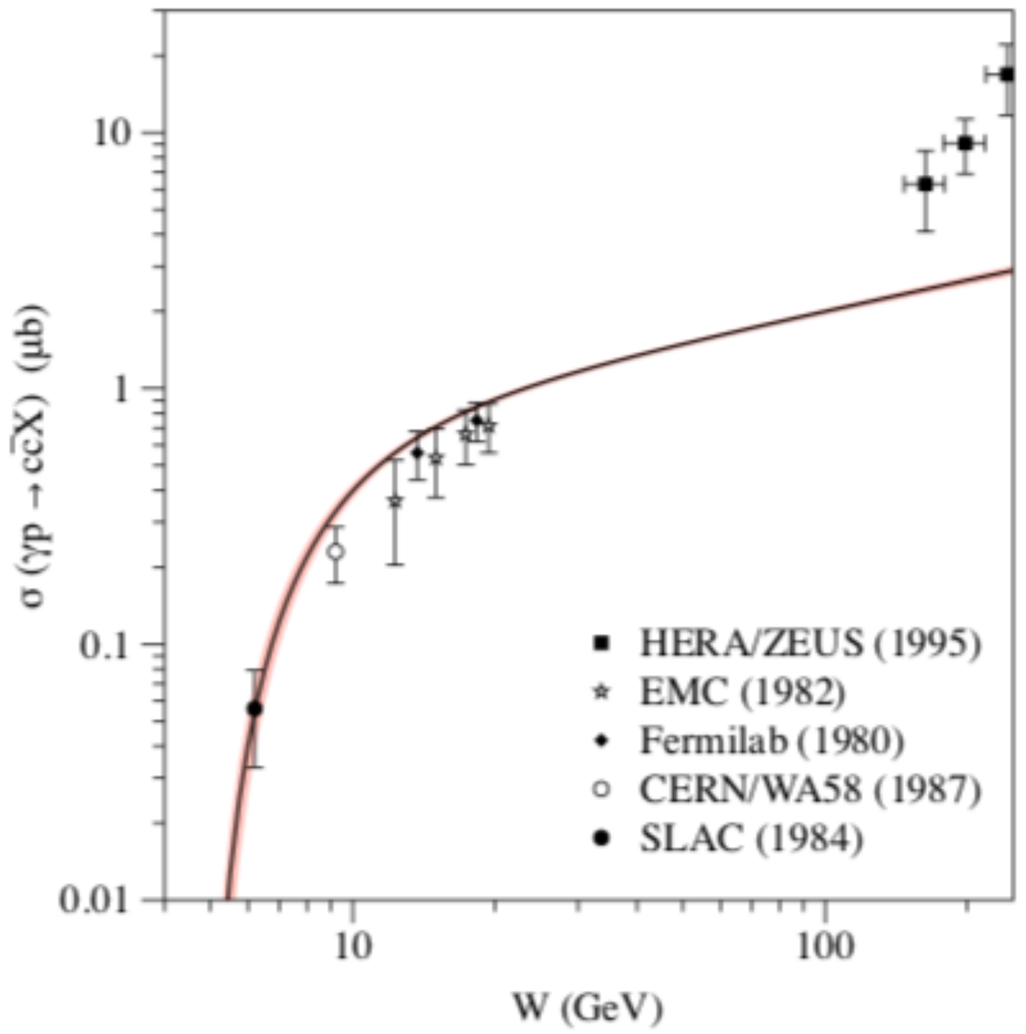
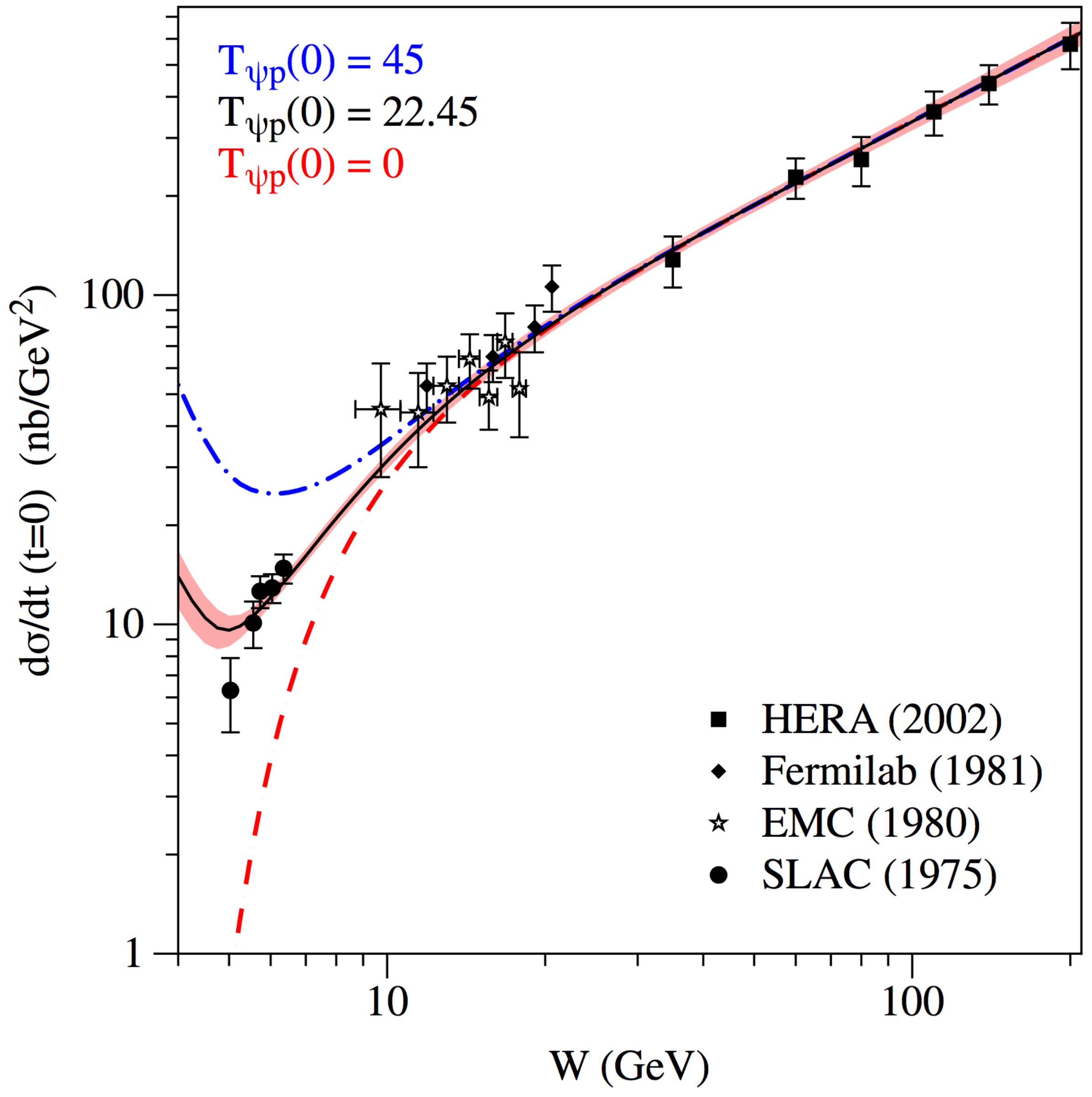
Need high-precision photo-production data near threshold



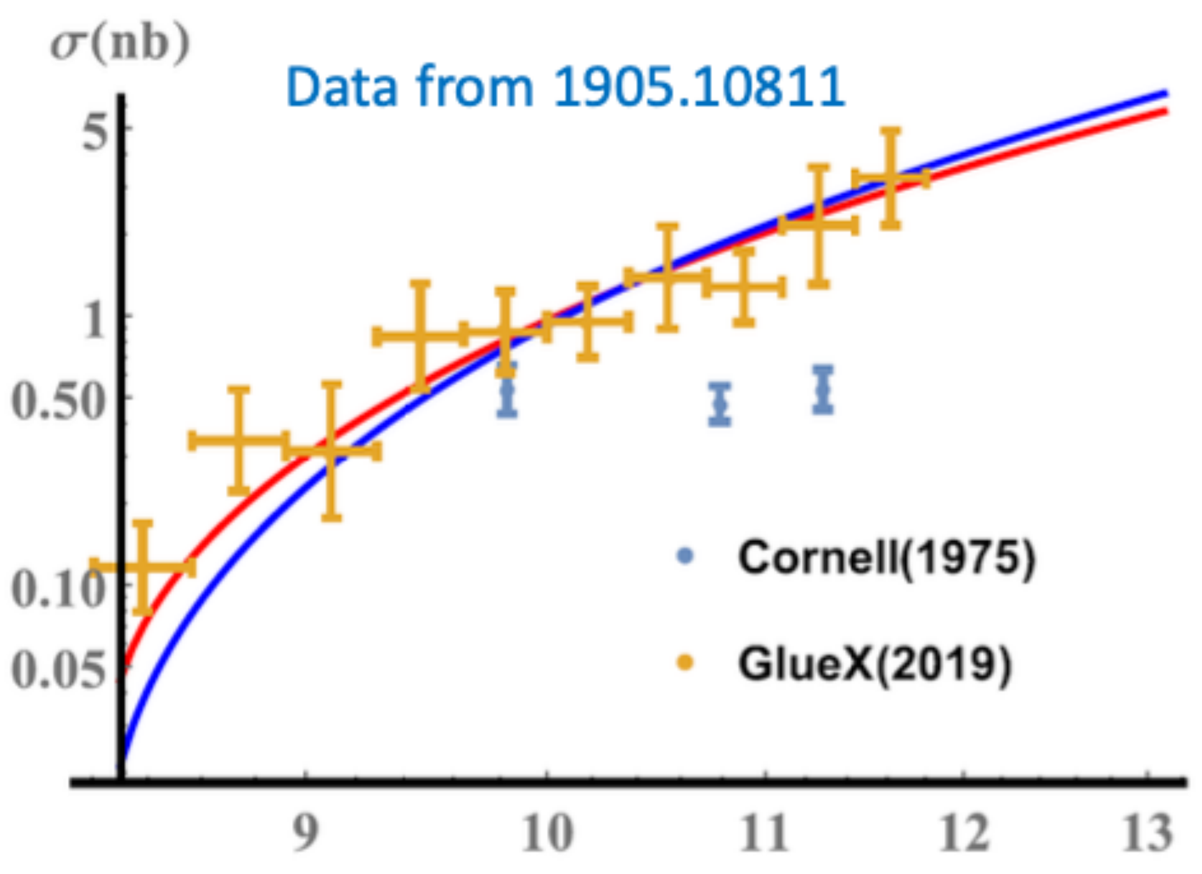


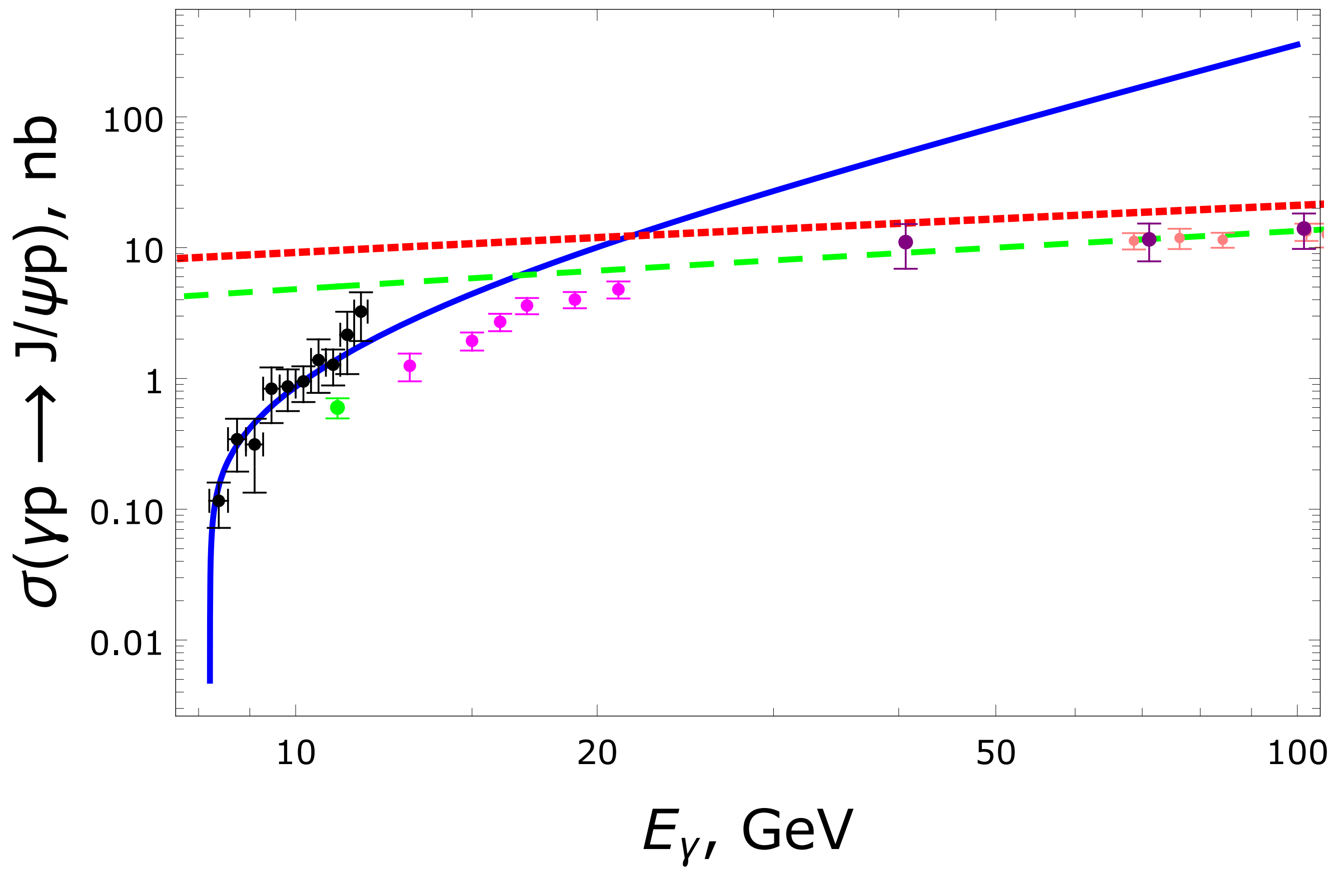


HOW TO MEASURE THE TRACE ANOMALY

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 $F^{\mu\nu}F_{\mu\nu}$)
- Predicts largest sensitivity to trace anomaly near threshold at low *t*
- Still very new development.





bottom-line: predicts strong sensitivity to the trace anomaly for quarkonium production near threshold.

Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)
Y. Hatta *et al.*, 1906.00894 (2020)
K. Mamo & I. Zahed, PRD 101, 086003 (2020)

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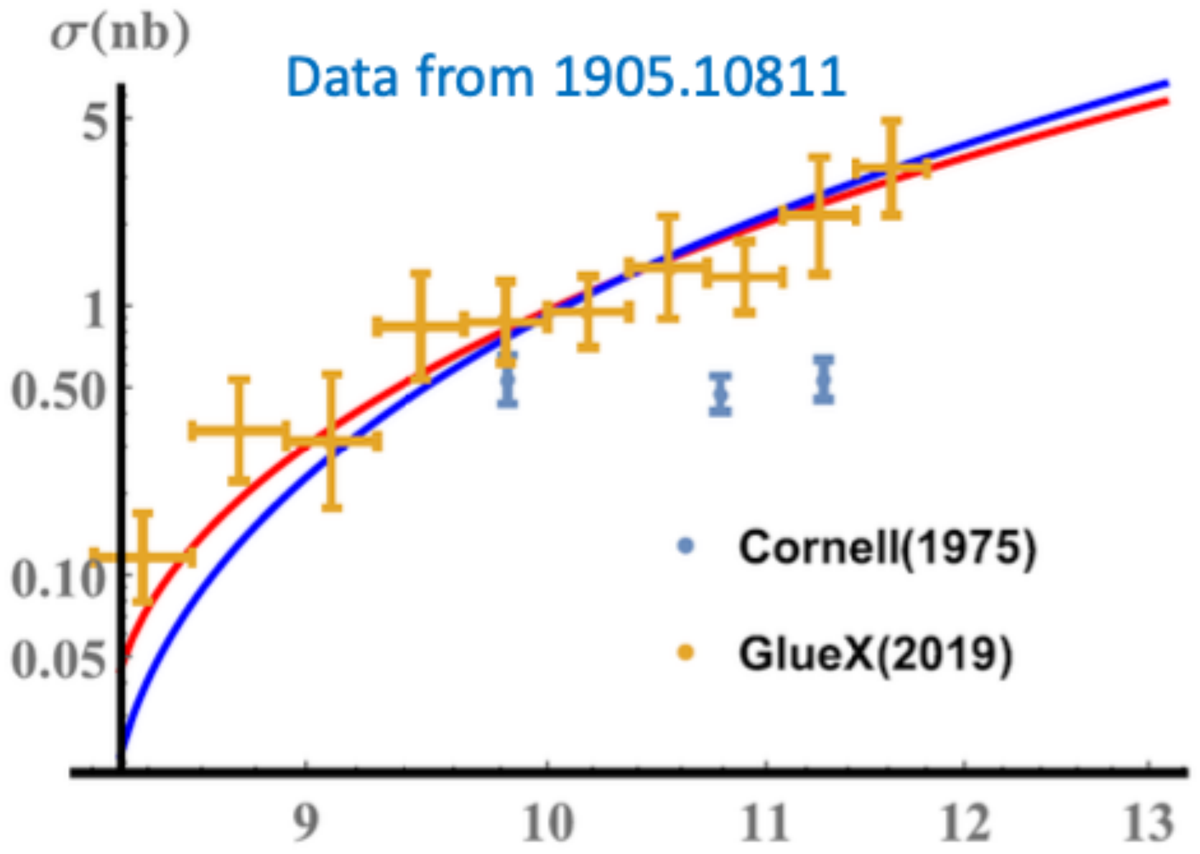
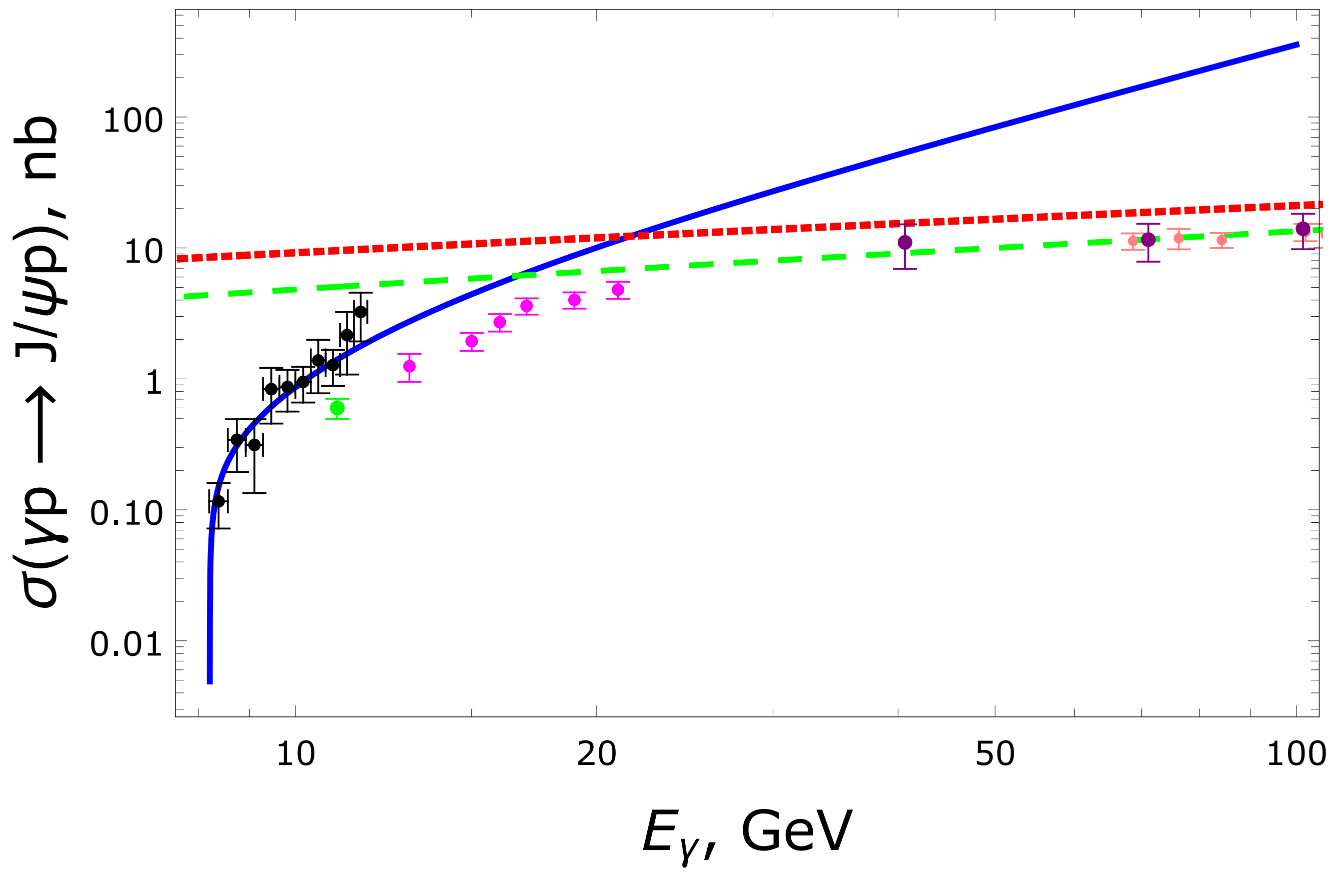
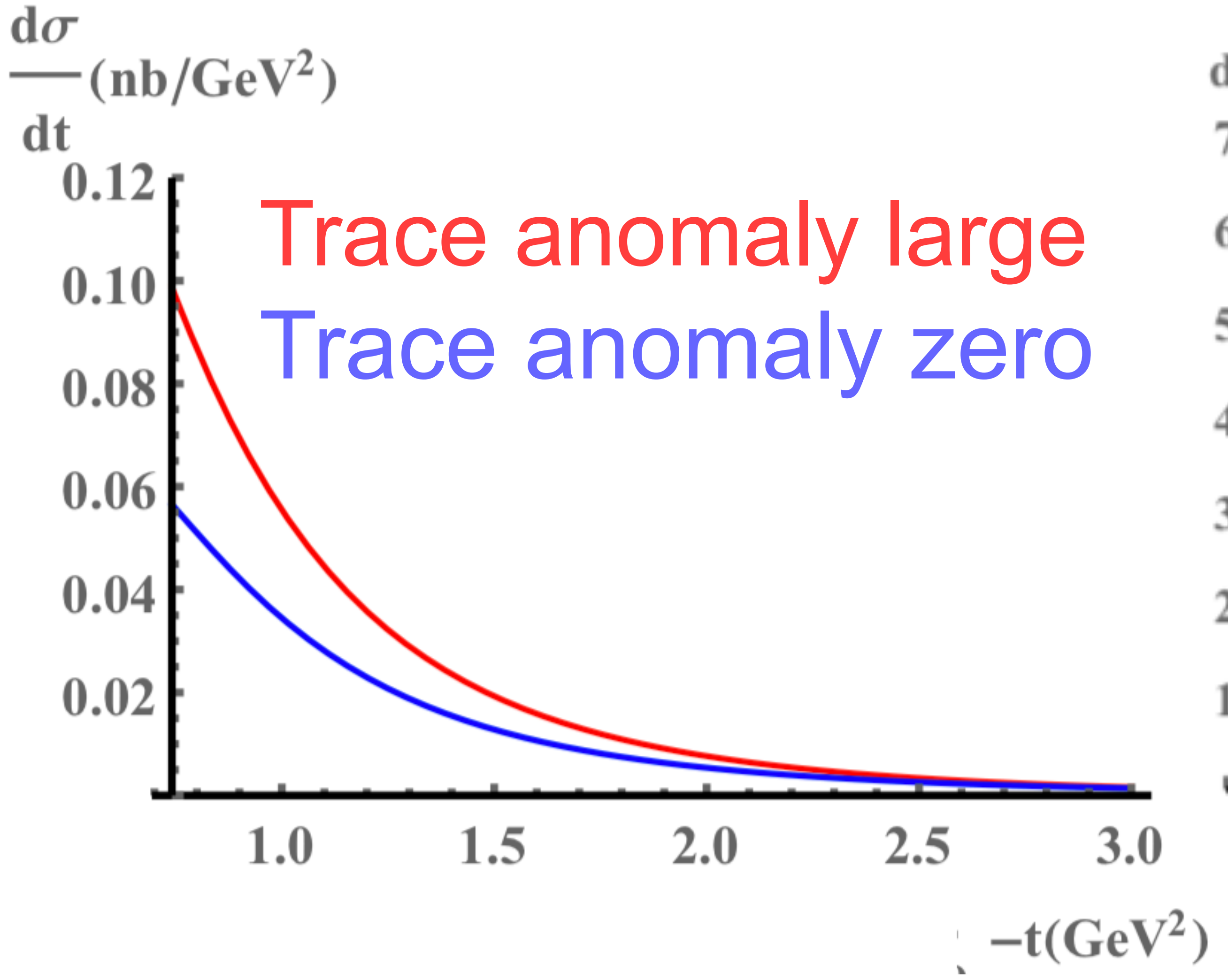
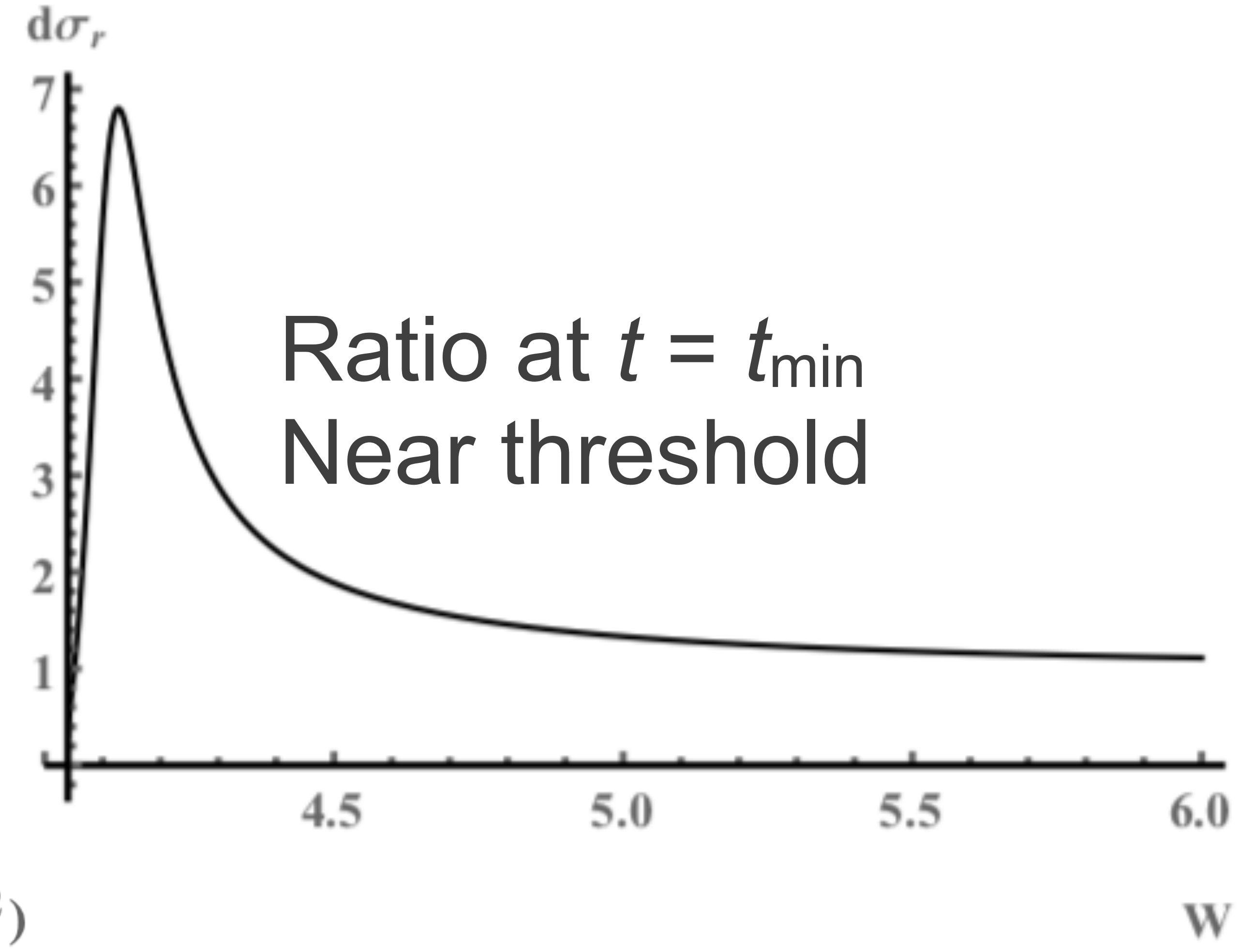




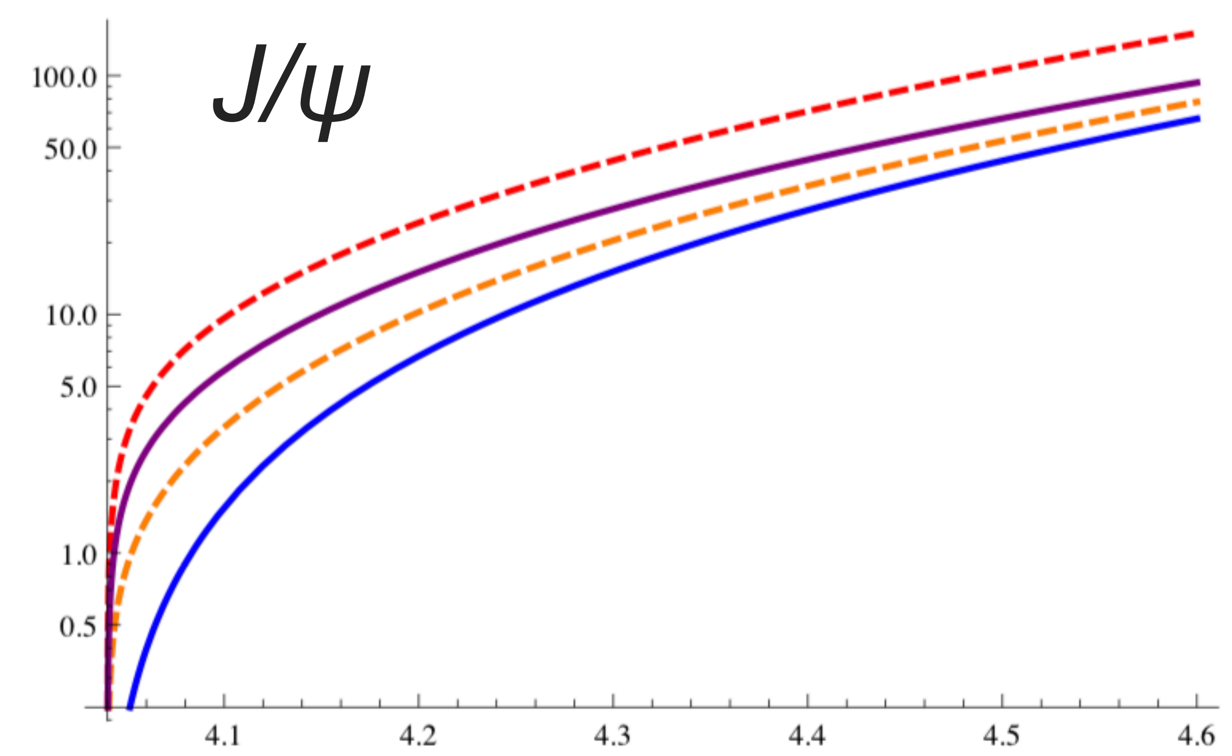




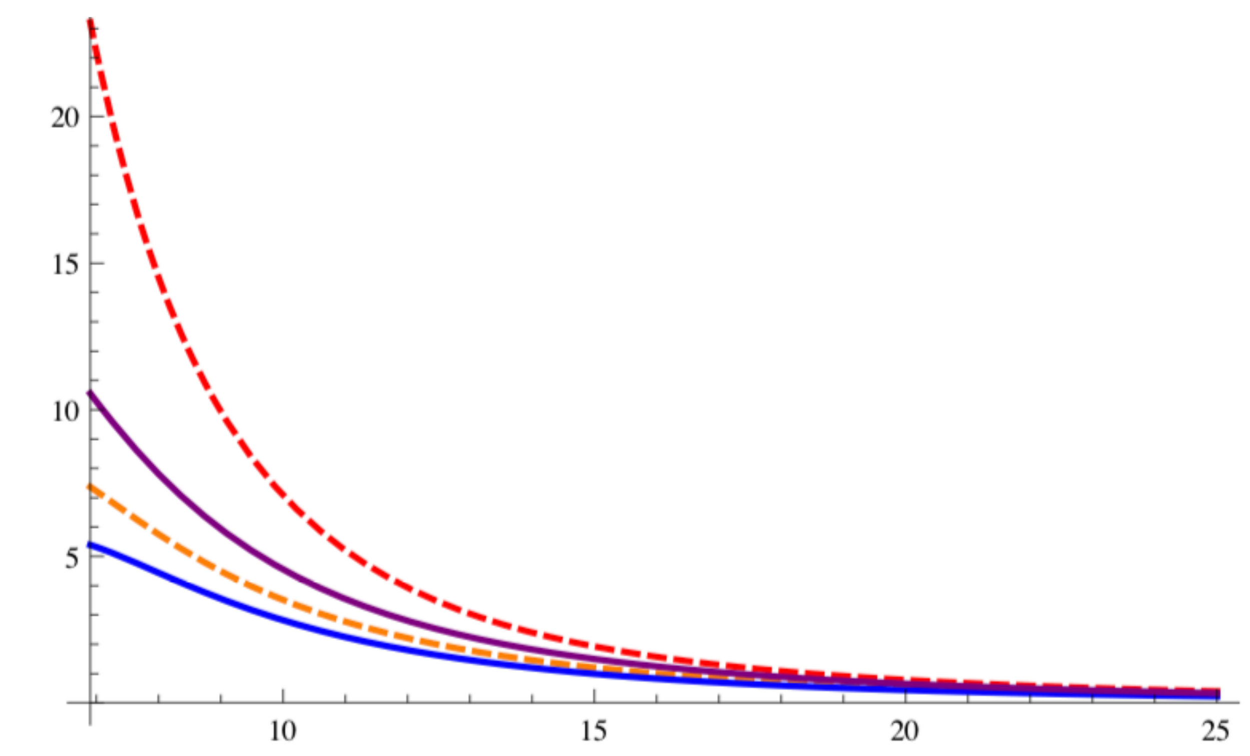
R. Boussarie and Y. Hatta, PRD 101 (2020) 11, 114004

HOW TO MEASURE THE TRACE ANOMALY

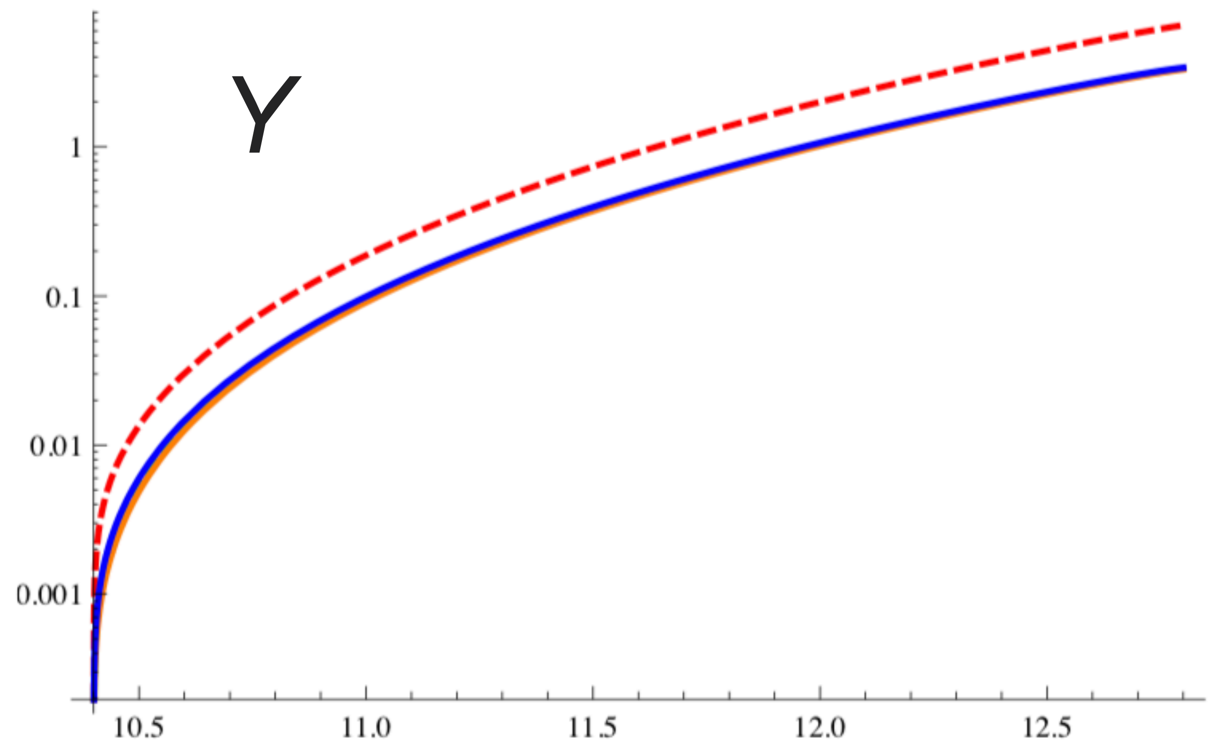
Quarkonium production at high Q^2



(a) Total cross section (in fb) as a function of W (in GeV).



(b) Differential cross section (in fb/GeV^2) at $W = 4.4$ GeV as a function of $|t|$ (in GeV^2).



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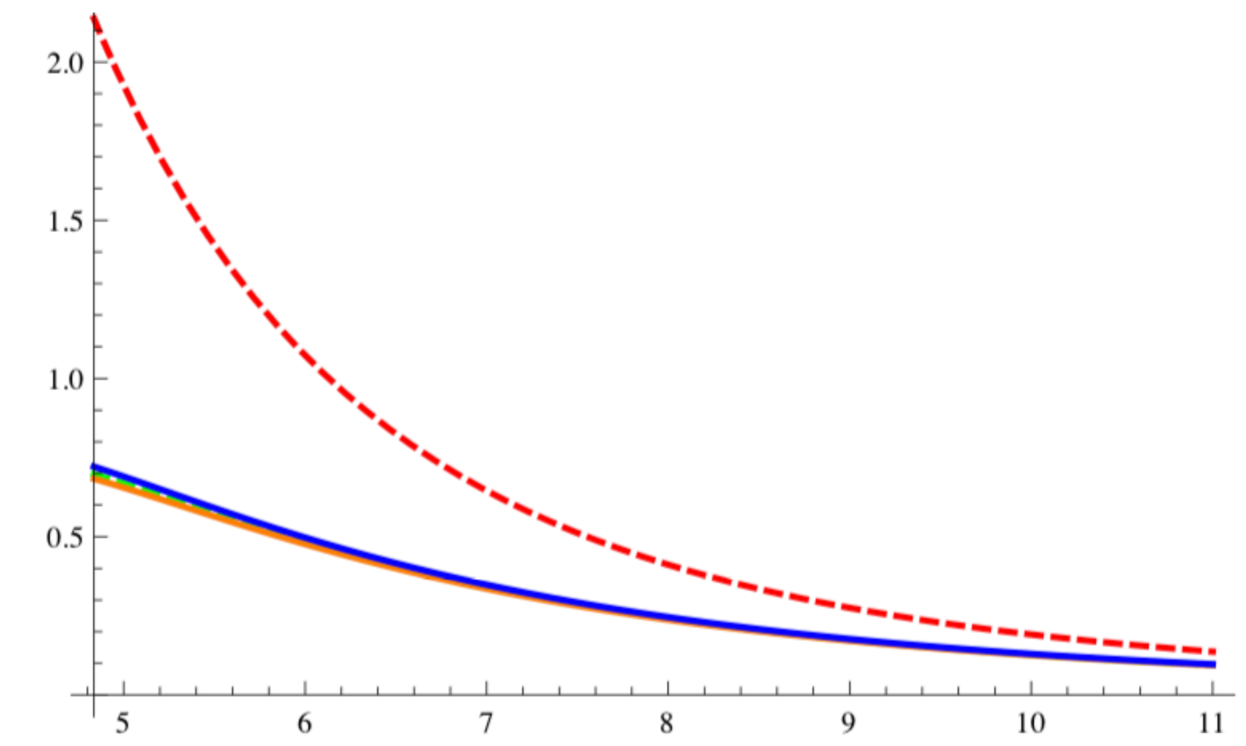
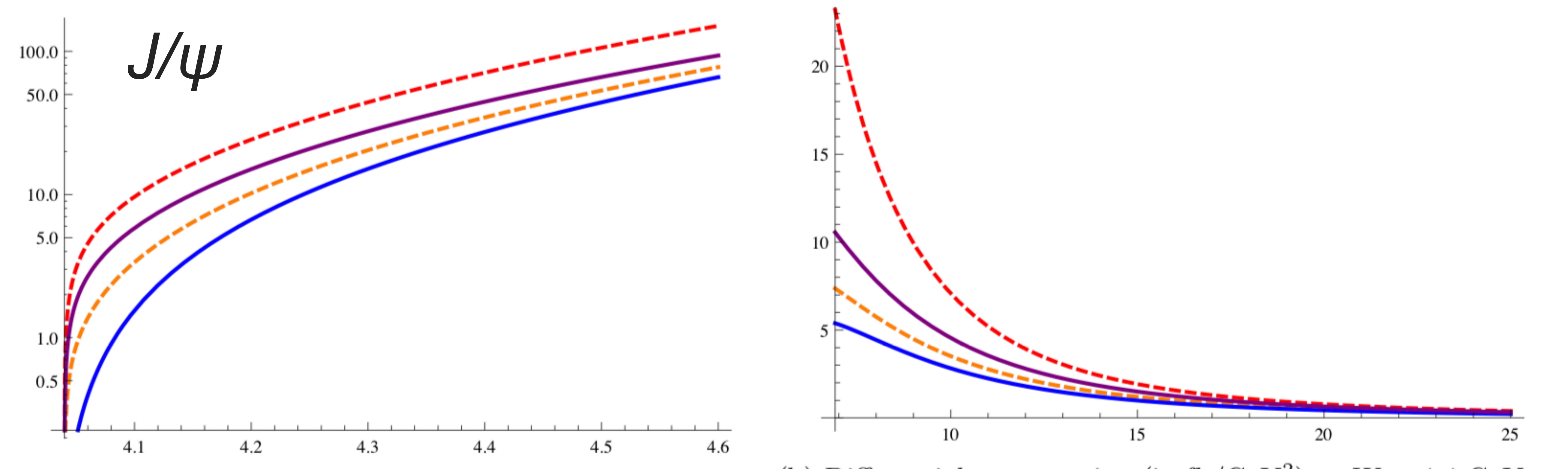


(b) Differential cross section (in fb/GeV^2) at $W = 12.5$ GeV as a function of $|t|$ (in GeV^2).

HOW TO MEASURE THE TRACE ANOMALY

Quarkonium production at high Q^2

- New development: posible to access the trace anomaly through quarkonium lepto-production at threshold with large Q^2 (much larger than M^2)
- Approach also sensitive to gluon D-term
- Requires very high luminosity, can only be done at EIC.
- New development: simulations not available yet.



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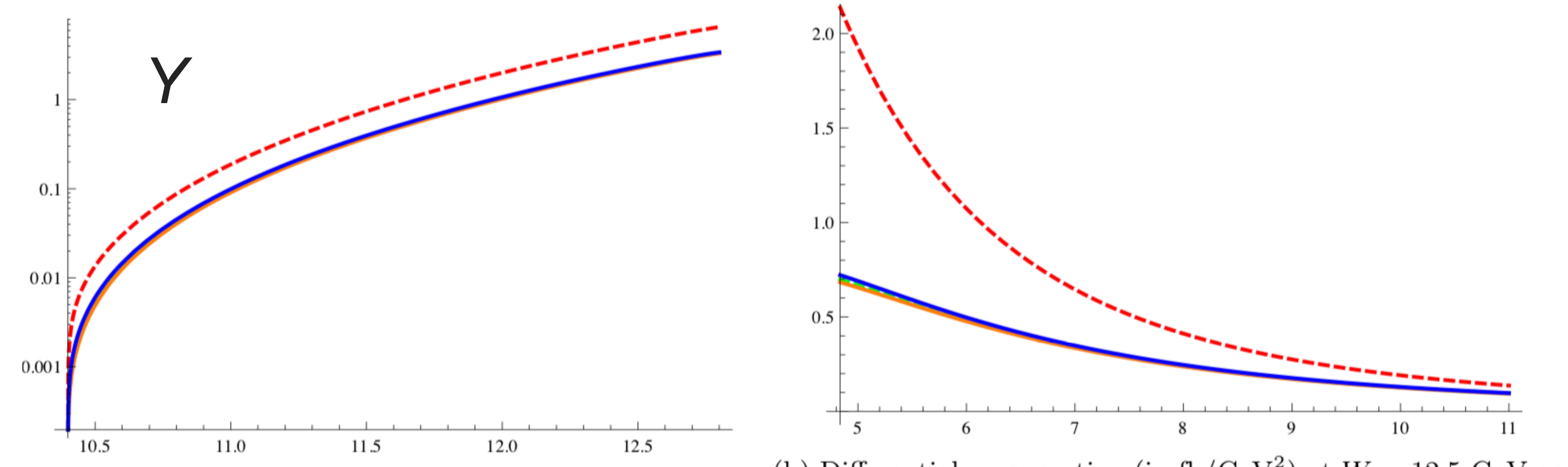

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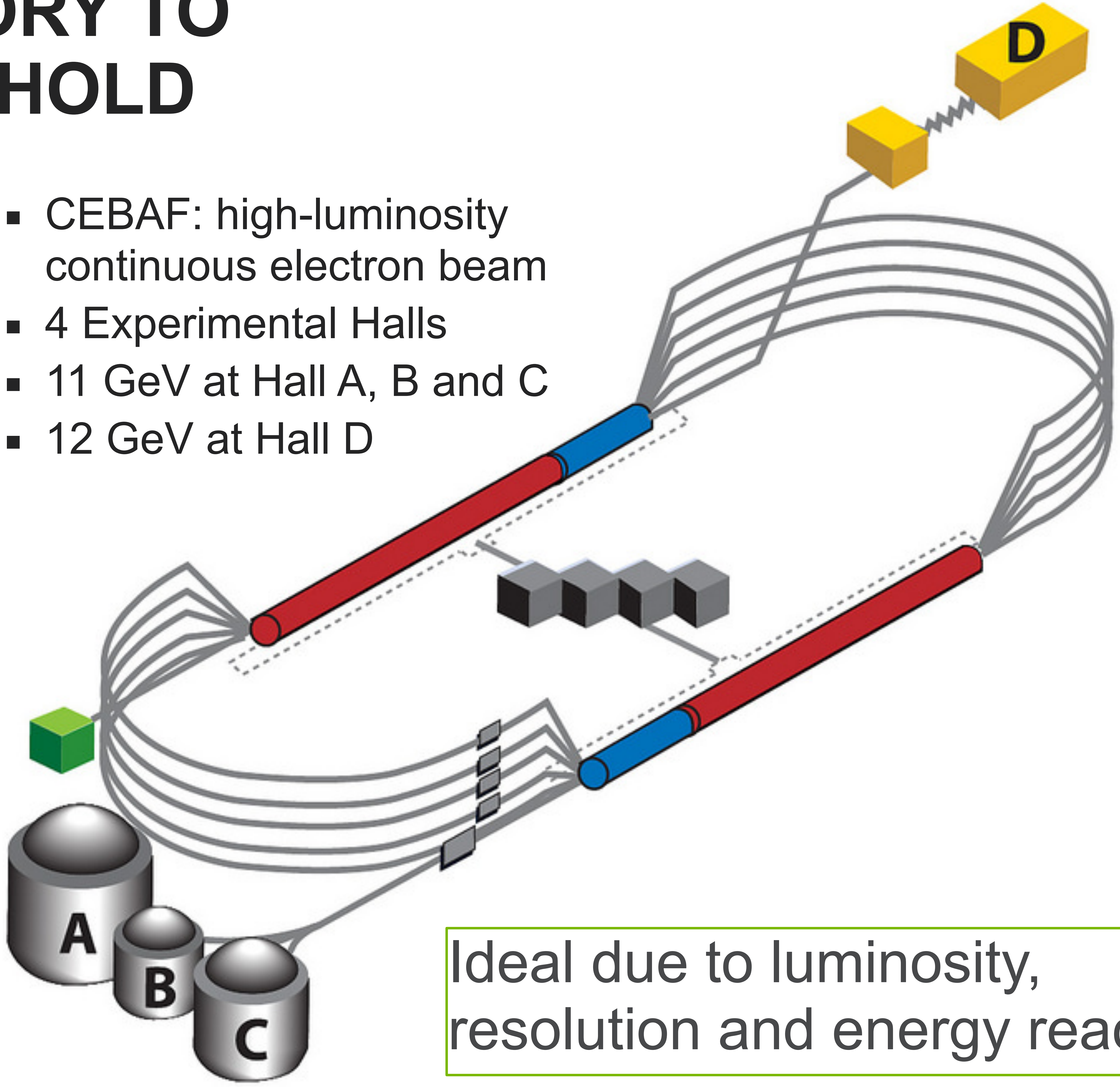
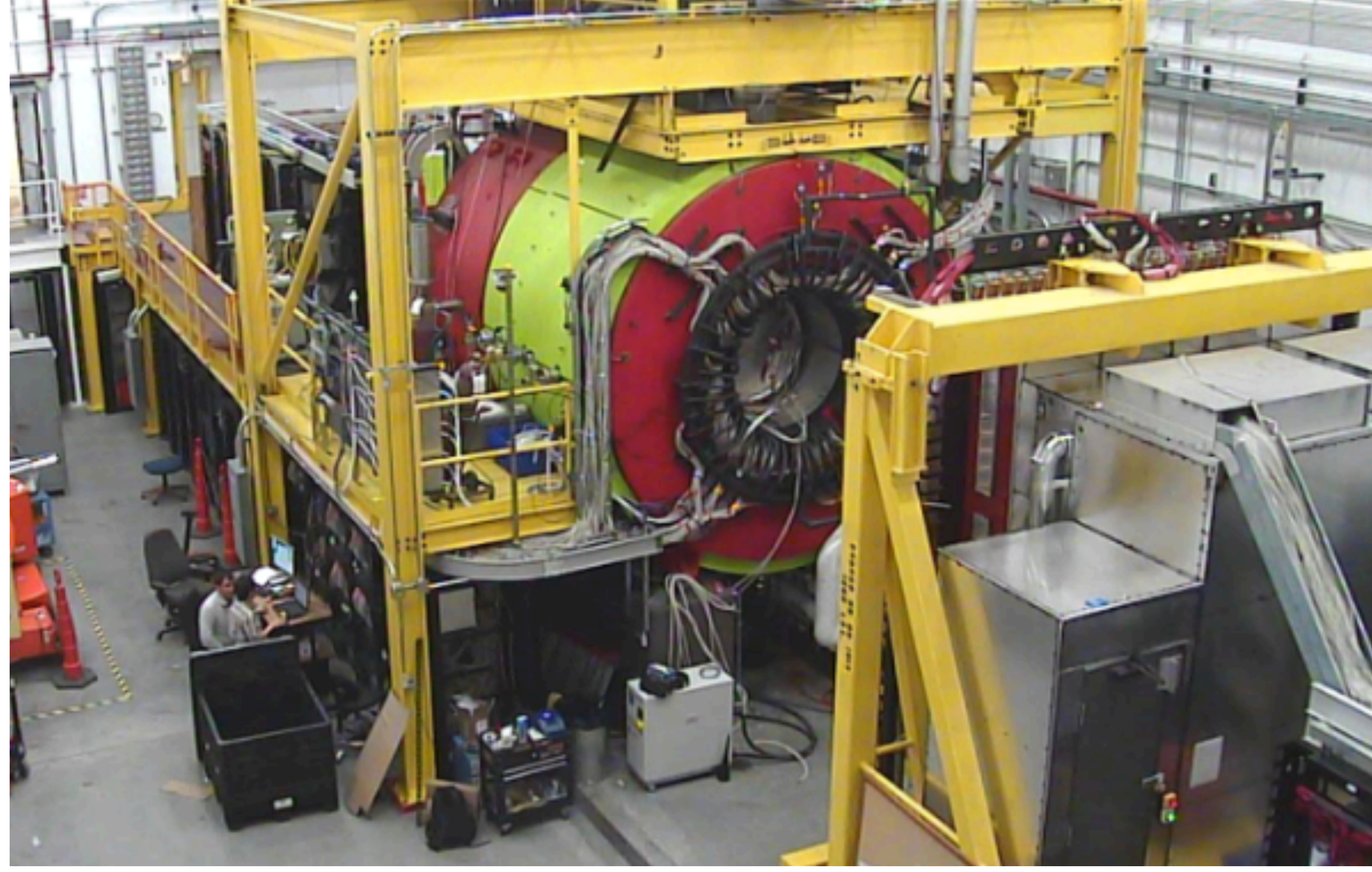
JLAB: THE IDEAL LABORATORY TO MEASURE *J/Ψ* NEAR THRESHOLD

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



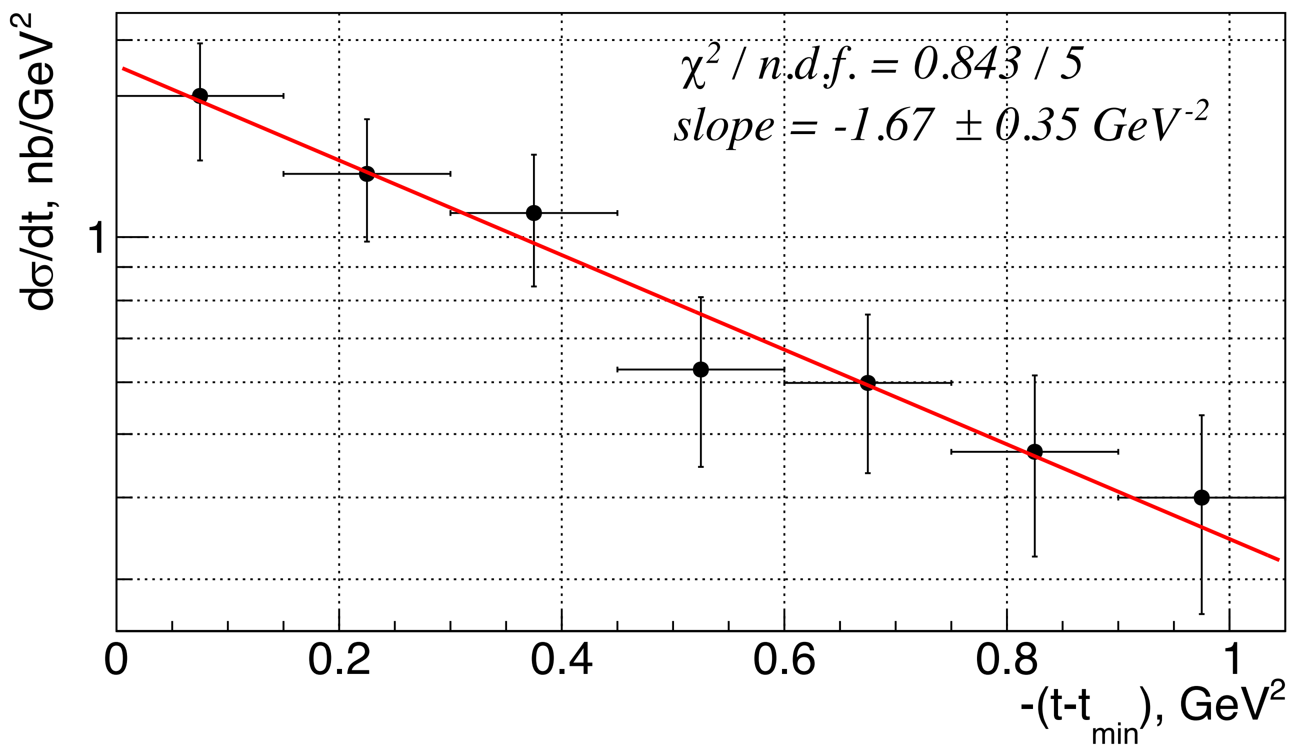
Ideal due to luminosity, resolution and energy reach

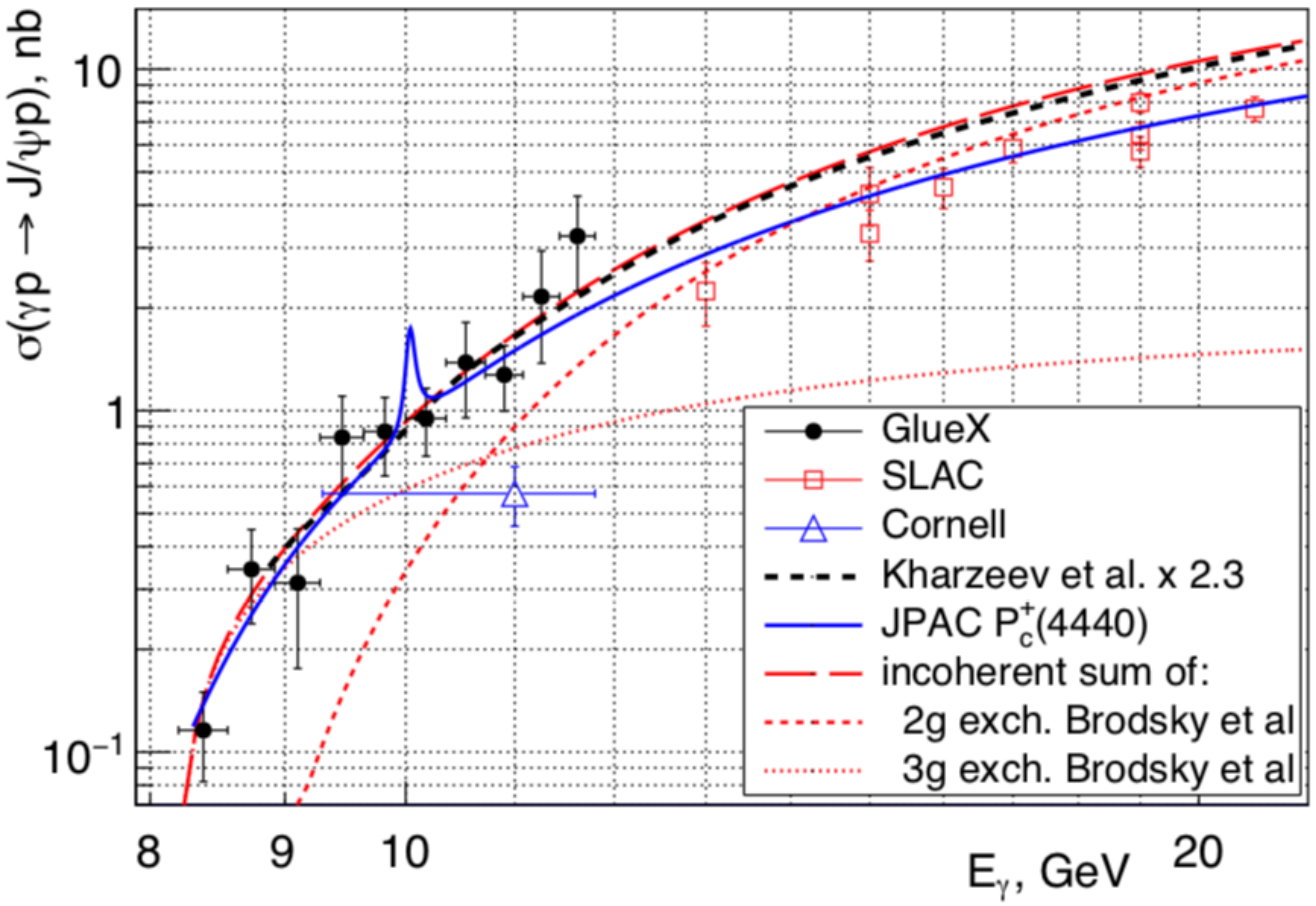
J/ψ IN HALL D/GLUEX



First J/ψ results from JLab, published in PRL (2019)

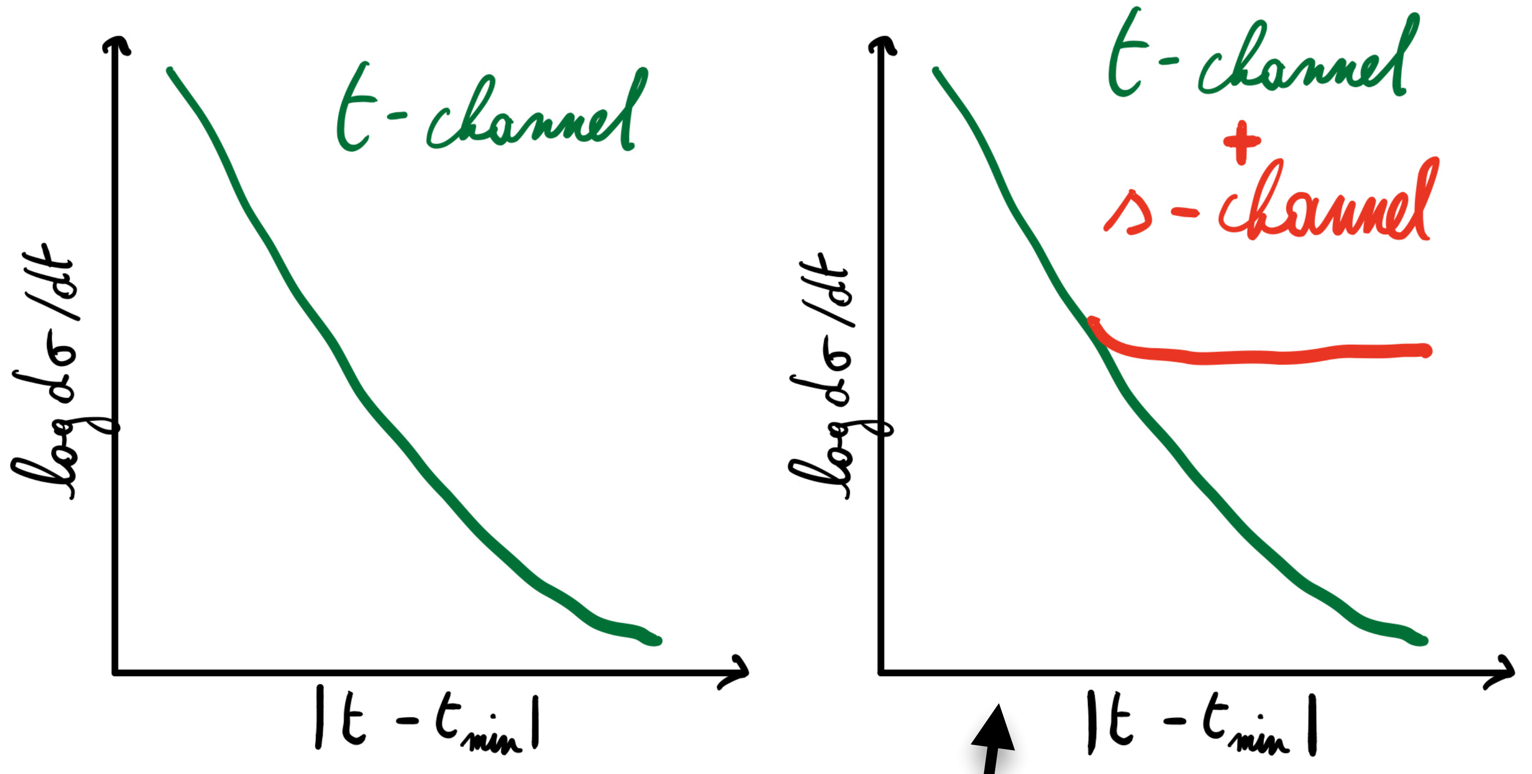
- 1D cross section (~469 counts)
- Also released 1D integrated *t*-dependence for photon energy between 10-11.8GeV
- Trends significantly higher than old measurements, but large 27% scale uncertainty



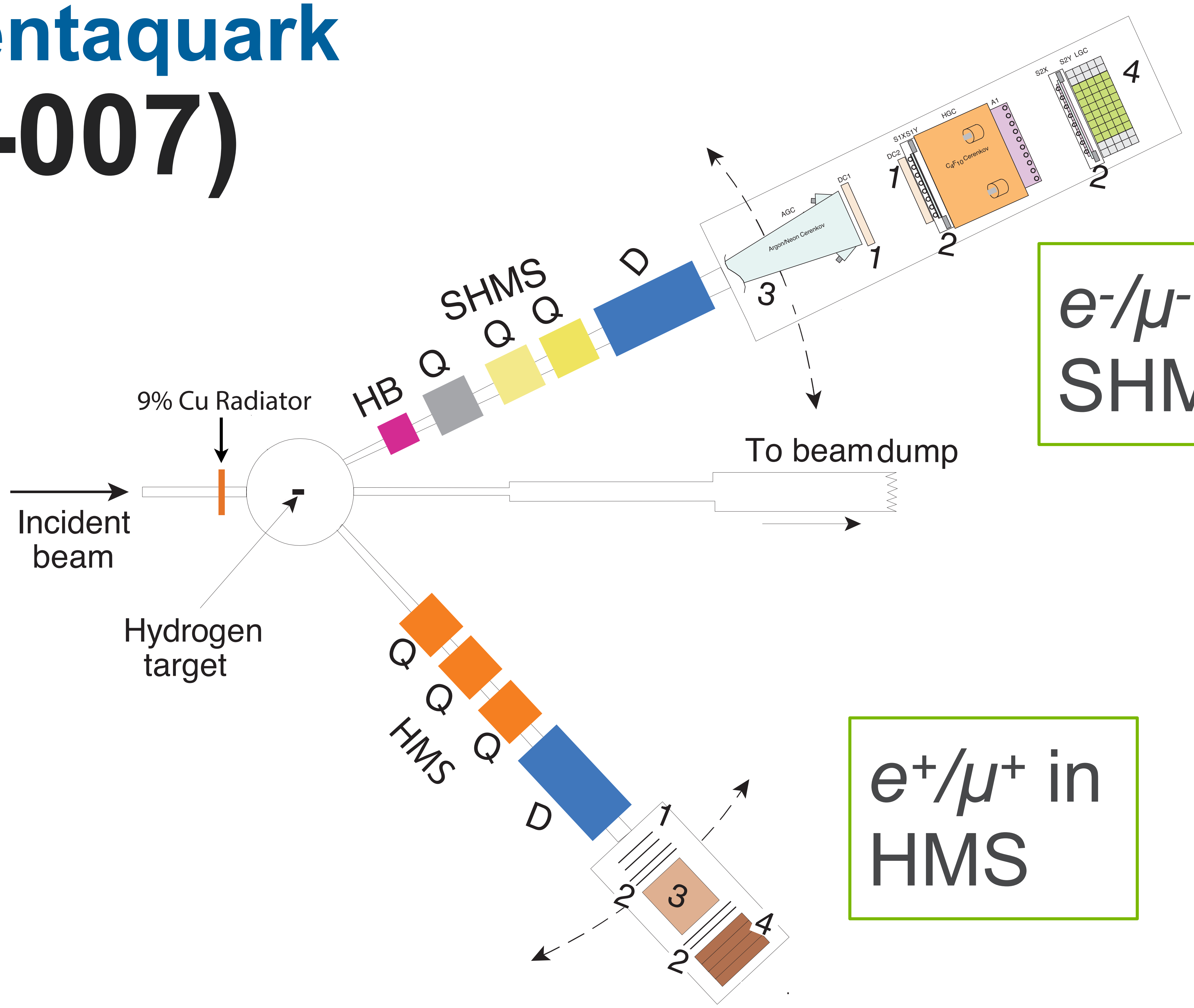


J/ψ-007: Search for the LHCb Pentaquark

J/ψ IN HALL C (E12-16-007)



Signature for P_c



e^-/μ^- in SHMS

e^+/μ^+ in HMS

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

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

High-impact experiment…
Ran February 2019

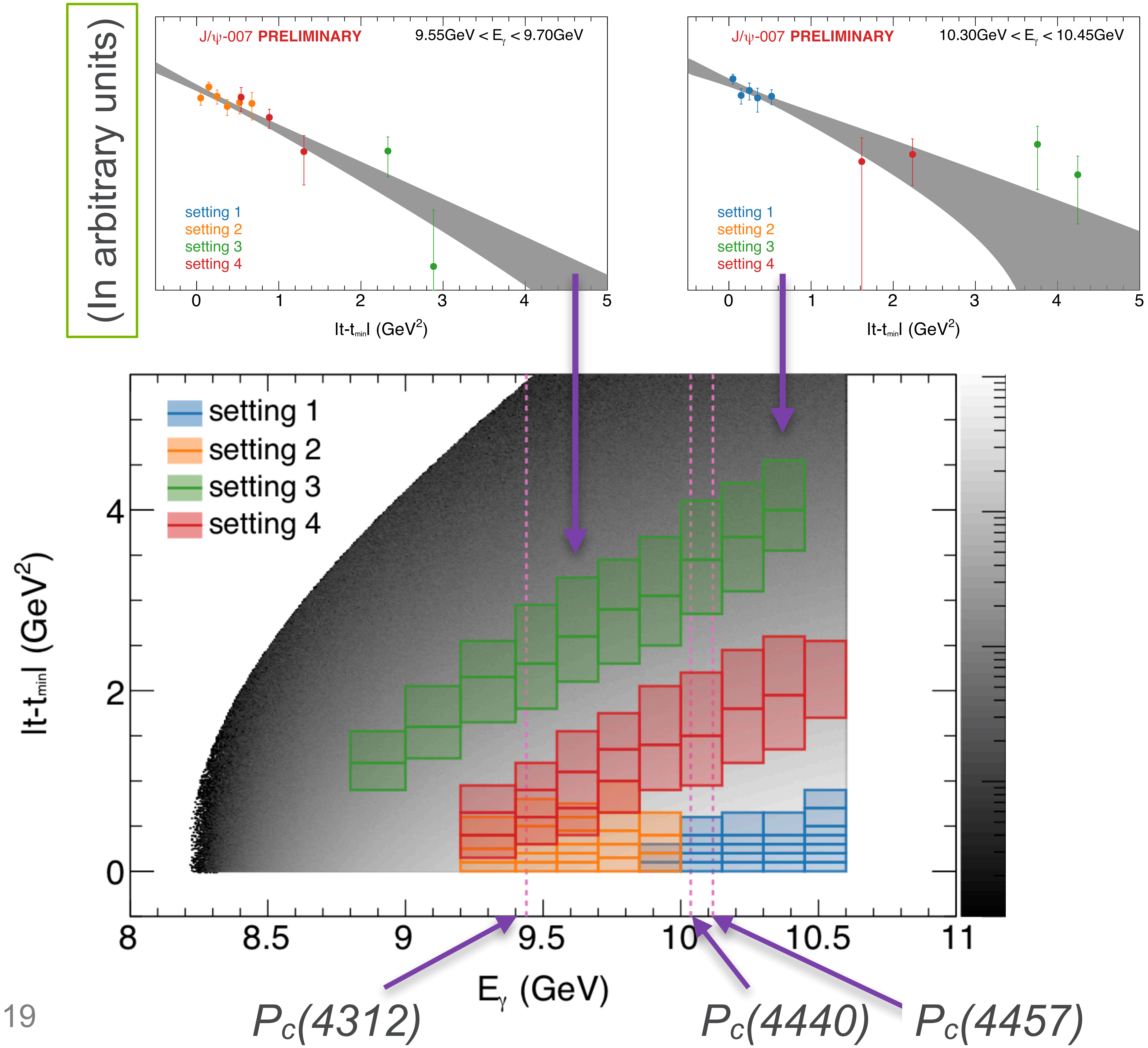
- Very high luminosity: high intensity real photon beam (9% copper radiator) on 10cm LH_2 target
- Detect *J/ψ* decay leptons in coincidence
  - Bremsstrahlung photon energy fully constrained

Near-threshold *J/ψ* in 2D

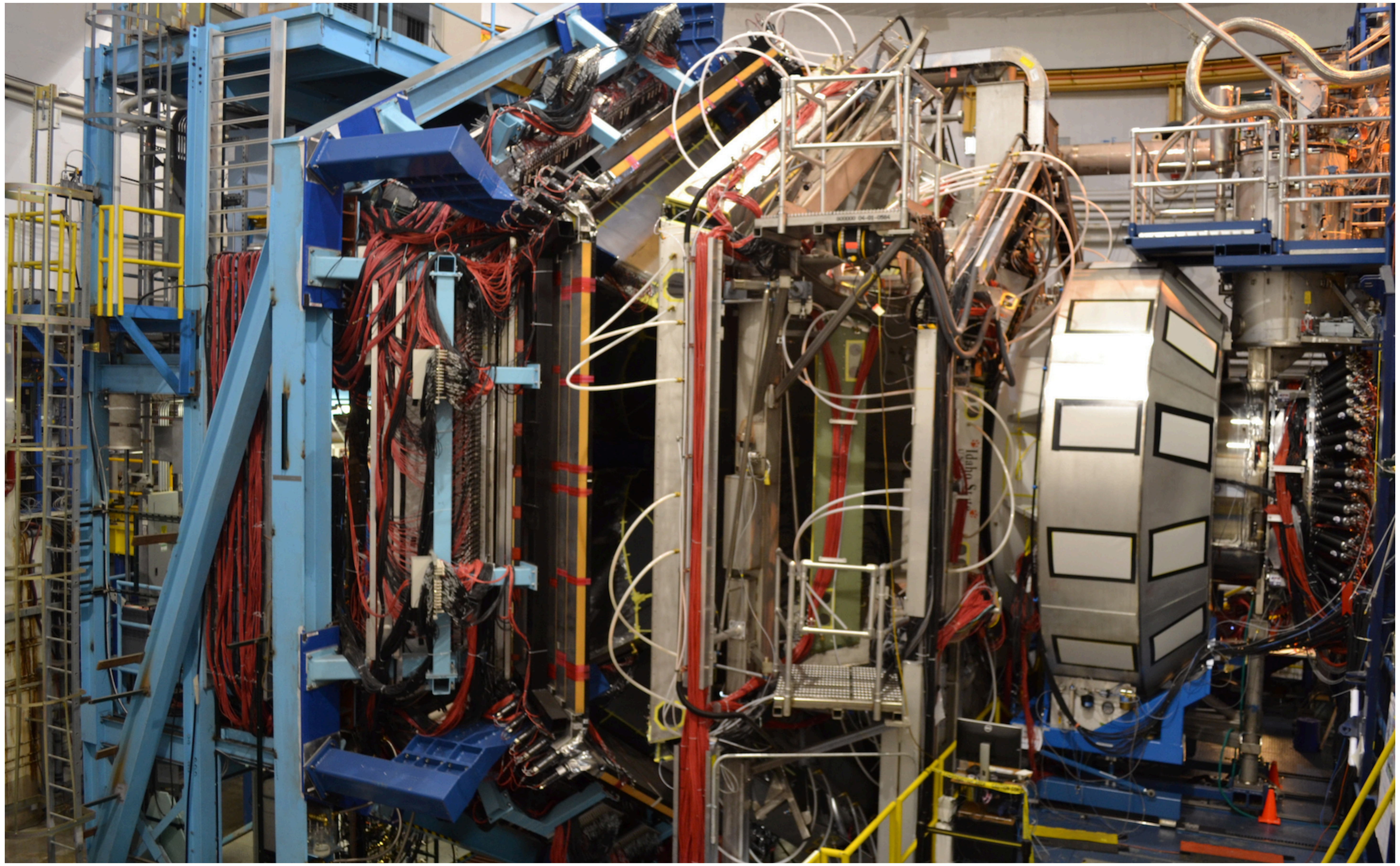
FEATURES OF THE HALL C MEASUREMENT

- Largest dataset (~4000 counts) of *J/ψ* produced with a real photon beam.
- Independent electron and muon channels.
- 2D photo-production cross section between 9.1-10.6 GeV
- 4 settings cover entire phase space
- High-*t* "enriched" sample, only possible at Hall C!

Status: finalizing systematics, results very soon.



J/Ψ IN HALL B/CLAS 12



- TCS + *J/ψ* measurements in photo-production on the proton (E12-12-001) and deuterium (E12-11-003B).
- Expected daily yield: 45*J/ψ* for 130 days for the pronto experiment
- Analysis on both datasets underway.
- Expect first results in ~1year

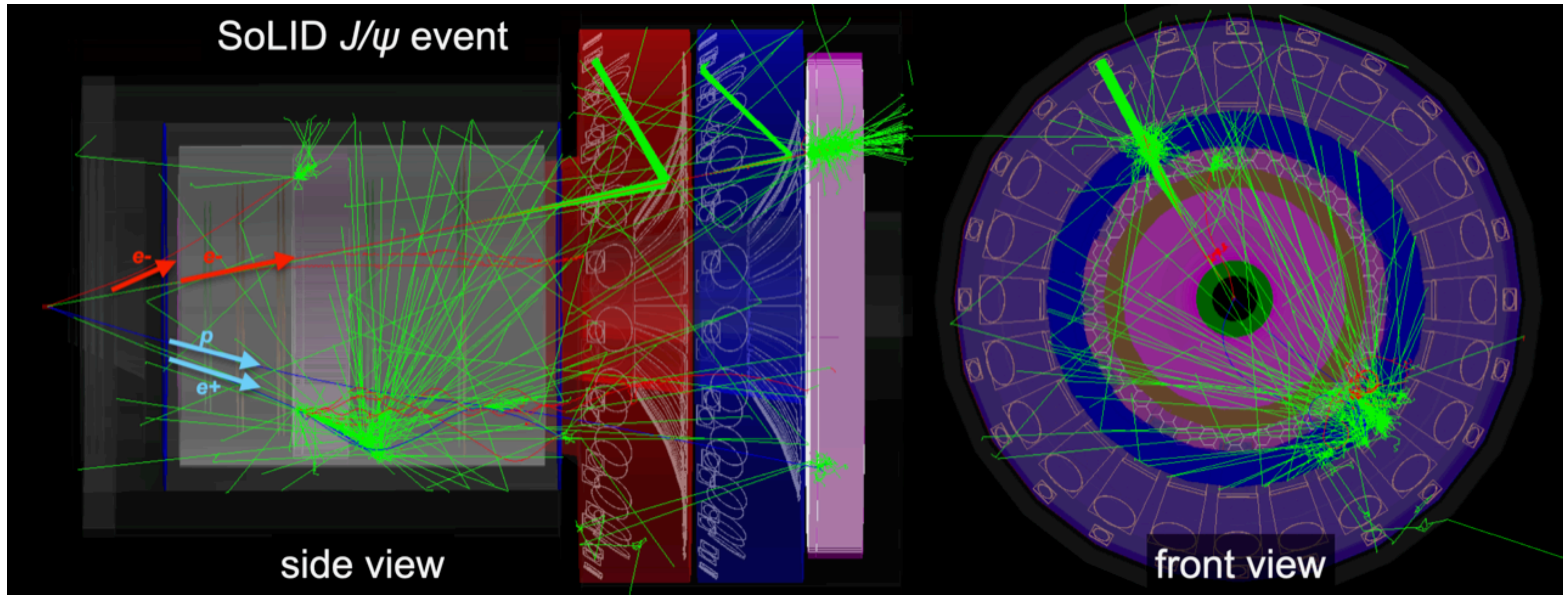
See K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141 and references therein

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

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



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

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J/Ψ EXPERIMENT E12-12-006 AT SOLID

SoLID SOLENOIDAL LARGE INTENSITY DEVICE

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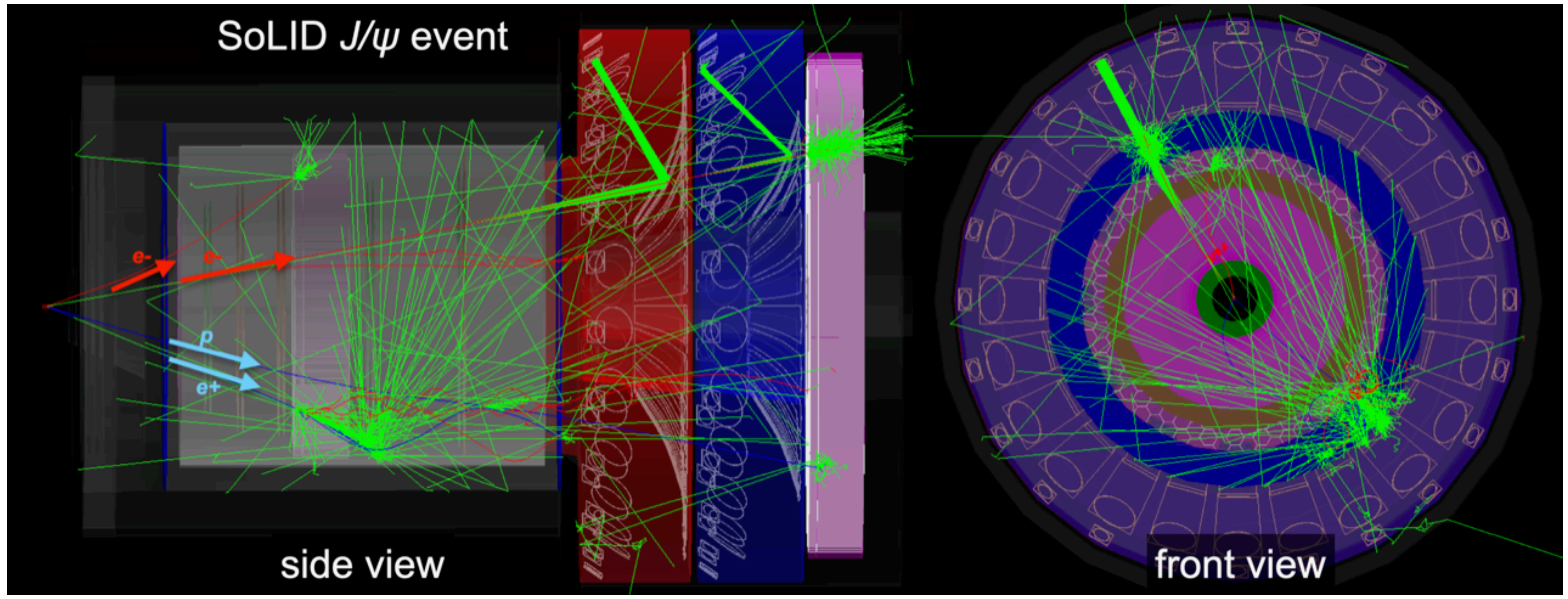

- Electro-production
  - Measure scattered electron and decay leptons
  - t-channel J/ψ rate: 100-400/day
  - Clean signal (less background)
  - Closer to threshold

- Photo-production
  - Measure decay leptons and recoil proton
  - t-channel J/ψ rate: 1600-7000/day
  - Ultra-high rate

ATHENNA Collaboration

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

J/Ψ EXPERIMENT E12-12-006 AT SOLID

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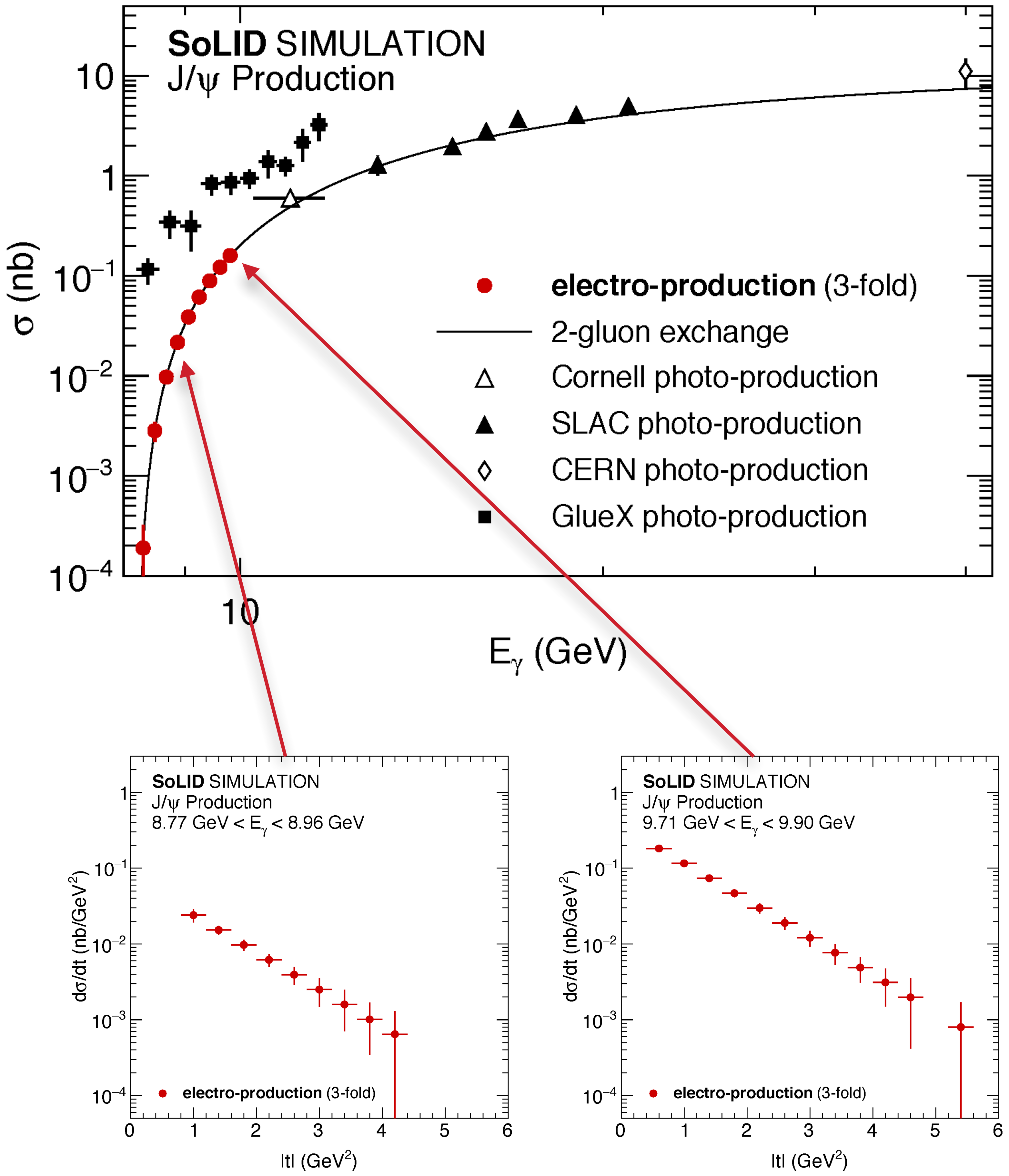
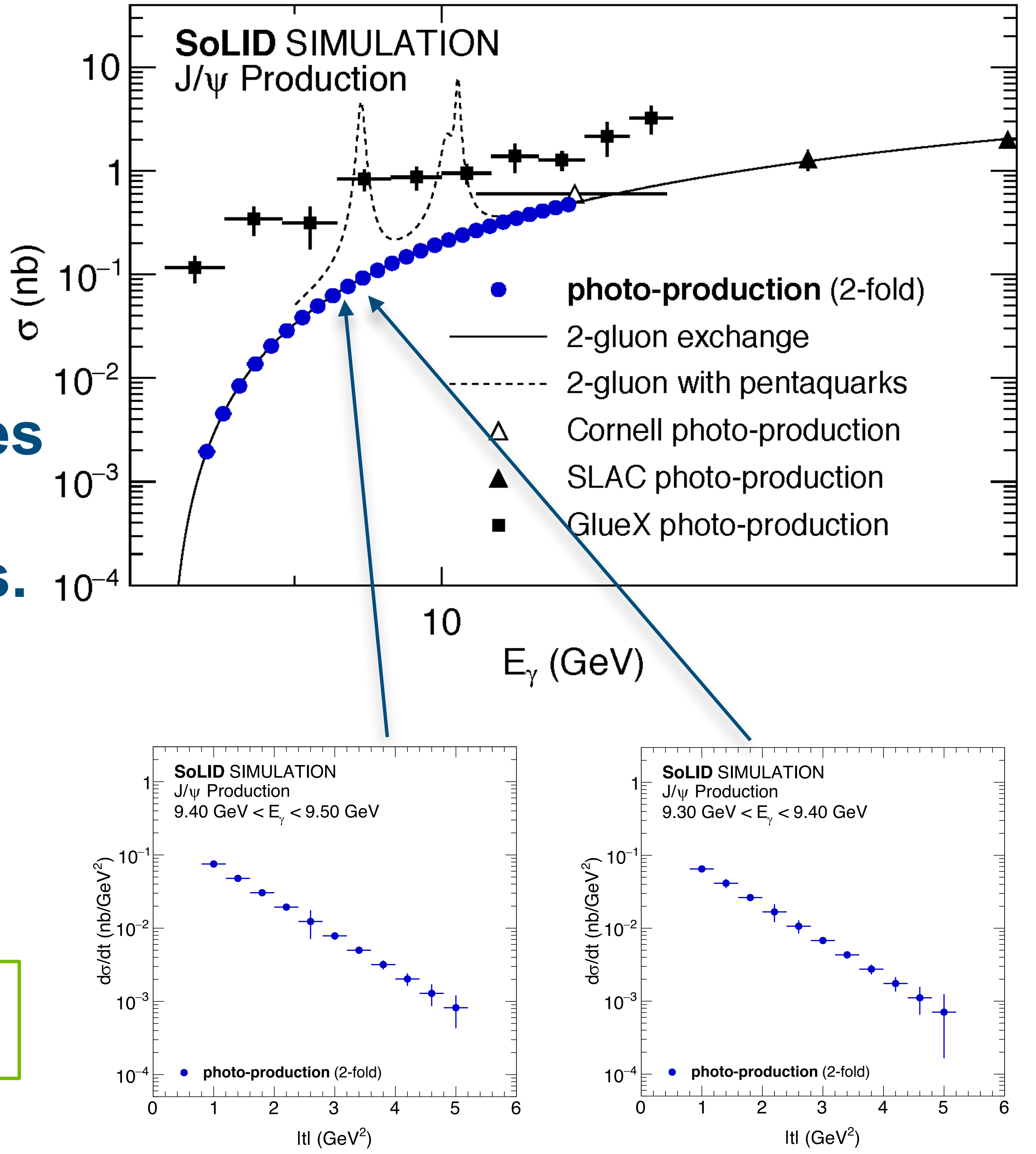


Electro-production allows measurement at threshold

Photo-production provides very high statistics, and access to higher energies.



Sensitivity below 10^{-3} nb!

J/Ψ EXPERIMENTS IN JLAB IN A NUTSHELL

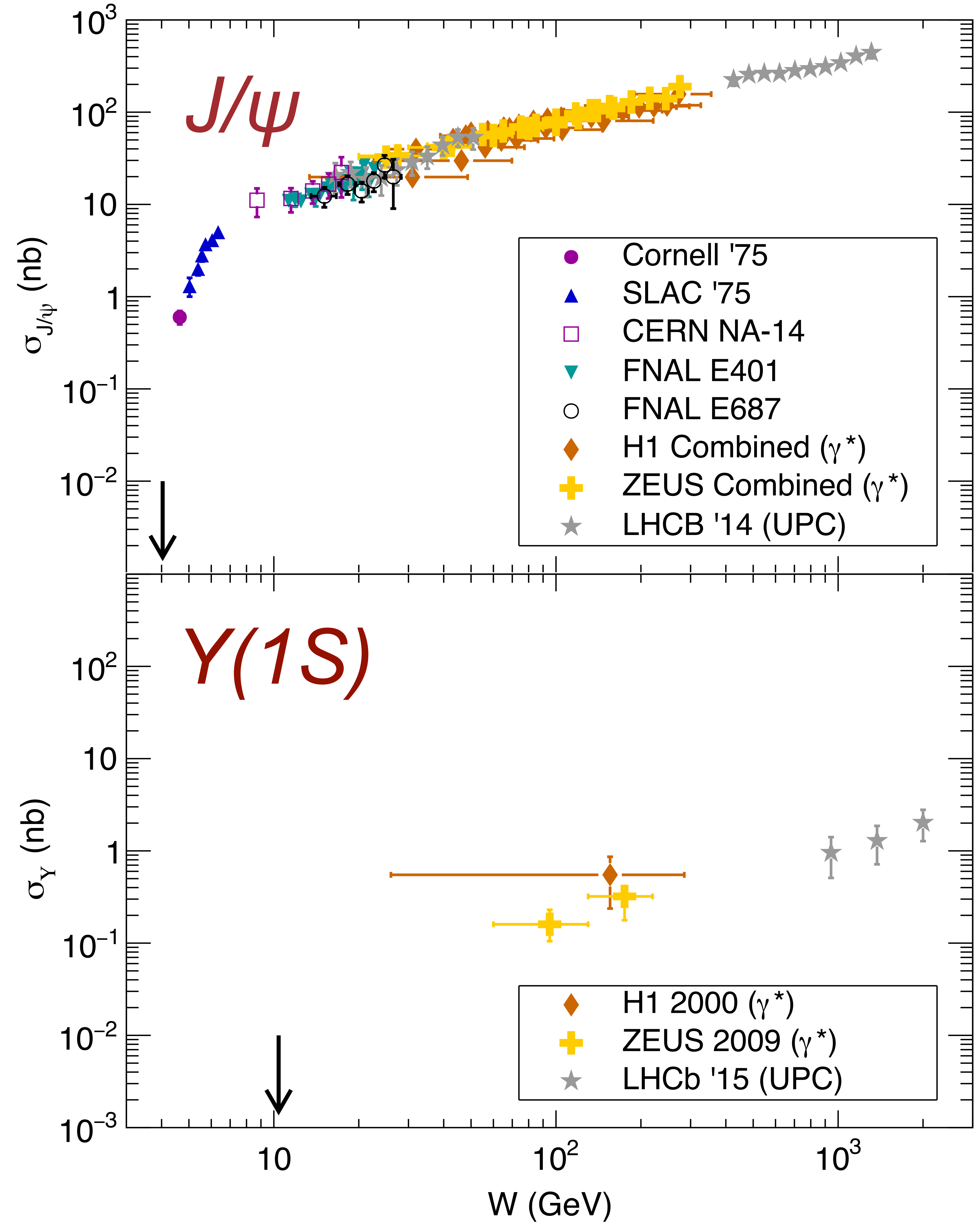
Exciting times for J/ψ near threshold!

	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	~400 published	2100 electrons 2100 muons	45*180/day	1600-7000/day
J/ψ Rate (electro-prod.)				100-400/day
Experiment		E12-16-007	E12-12-001 E12-11-003B	E12-12-006
PAC days		9+2	130	50
When?	Finished	Finished	Ongoing	~10 years?

+ new letter-of-intent to measure J/ψ double polarization with SBS in Hall A

Y(1S): THE OPTIMAL GLUONIC PROBE

…but a challenging measurement



What limits threshold physics at EIC?

- Reach toward lower values of *W* limited by experimental resolution, which imposes a lower limit on $y = P.q/P.k \sim 0.01$.
- This makes threshold *J/ψ* nearly impossible, and limits sensitivity to threshold *Y* at higher beam energies.

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**
- Cross section very small (2 orders of magnitude smaller than *J/ψ)*
- Sensitive to "beautiful" pentaquark states!
- Measurement can (only) be done at EIC

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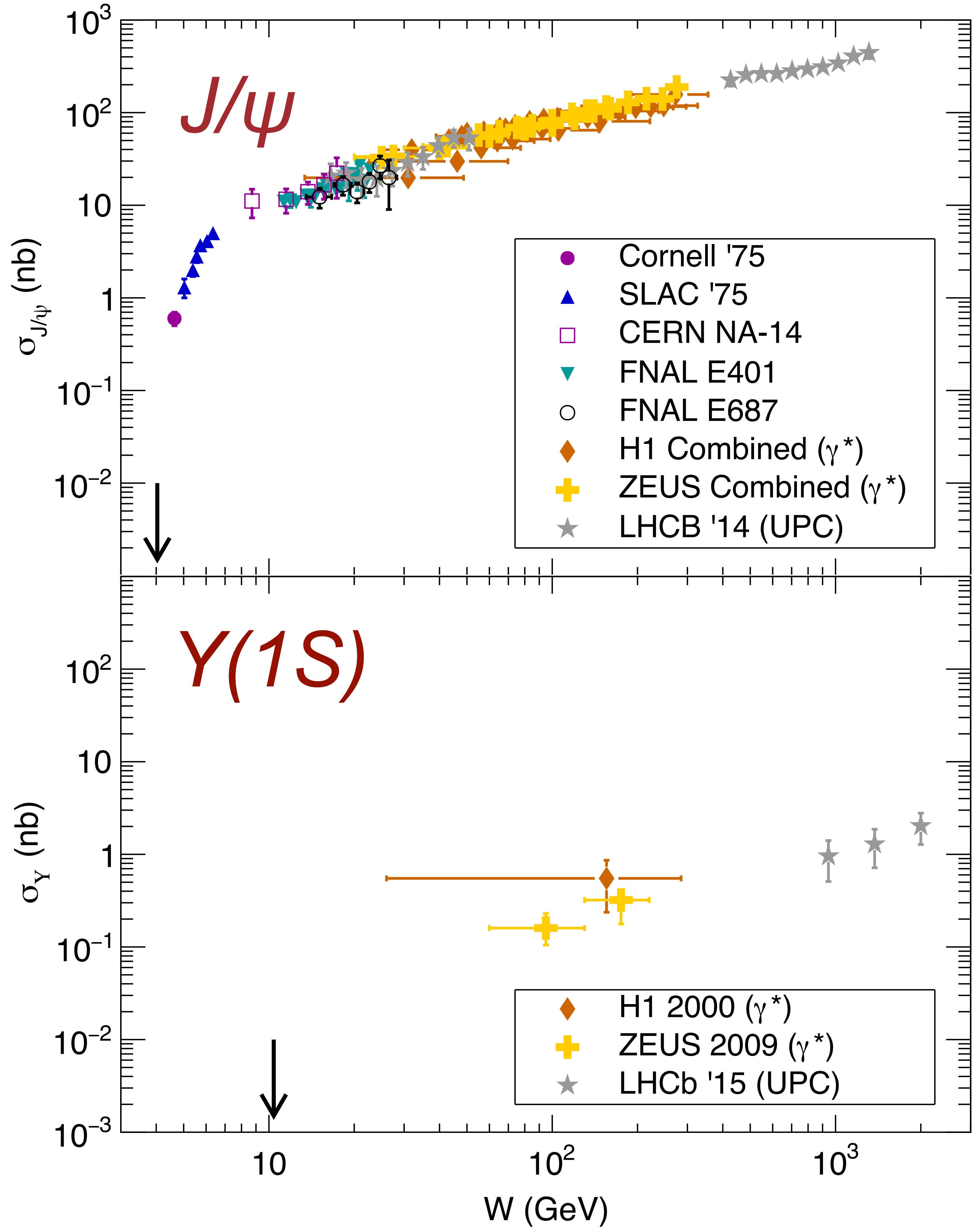
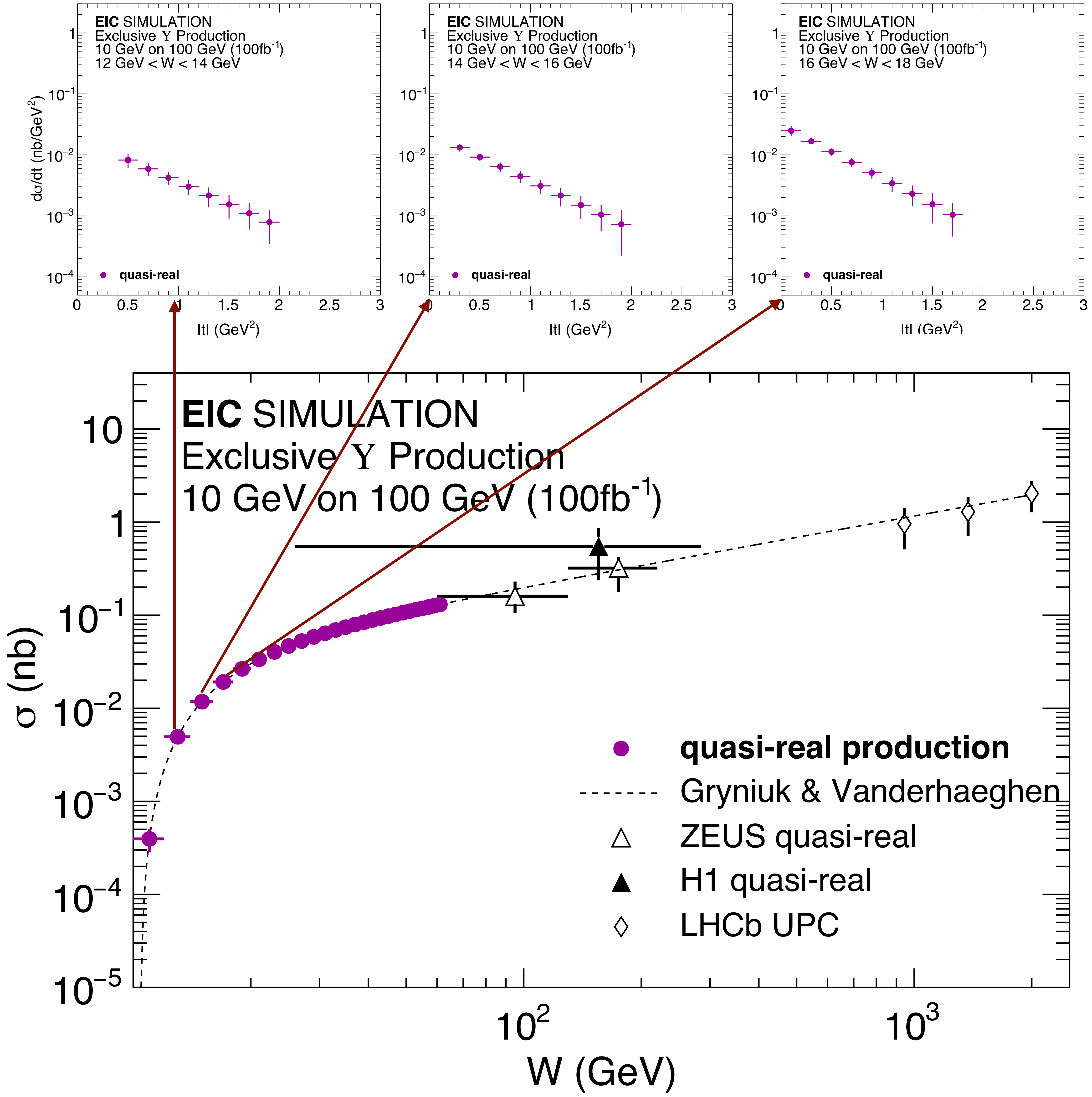


Υ(1S) PHOTO-PRODUCTION AT EIC

…Threshold measurement possible!

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



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

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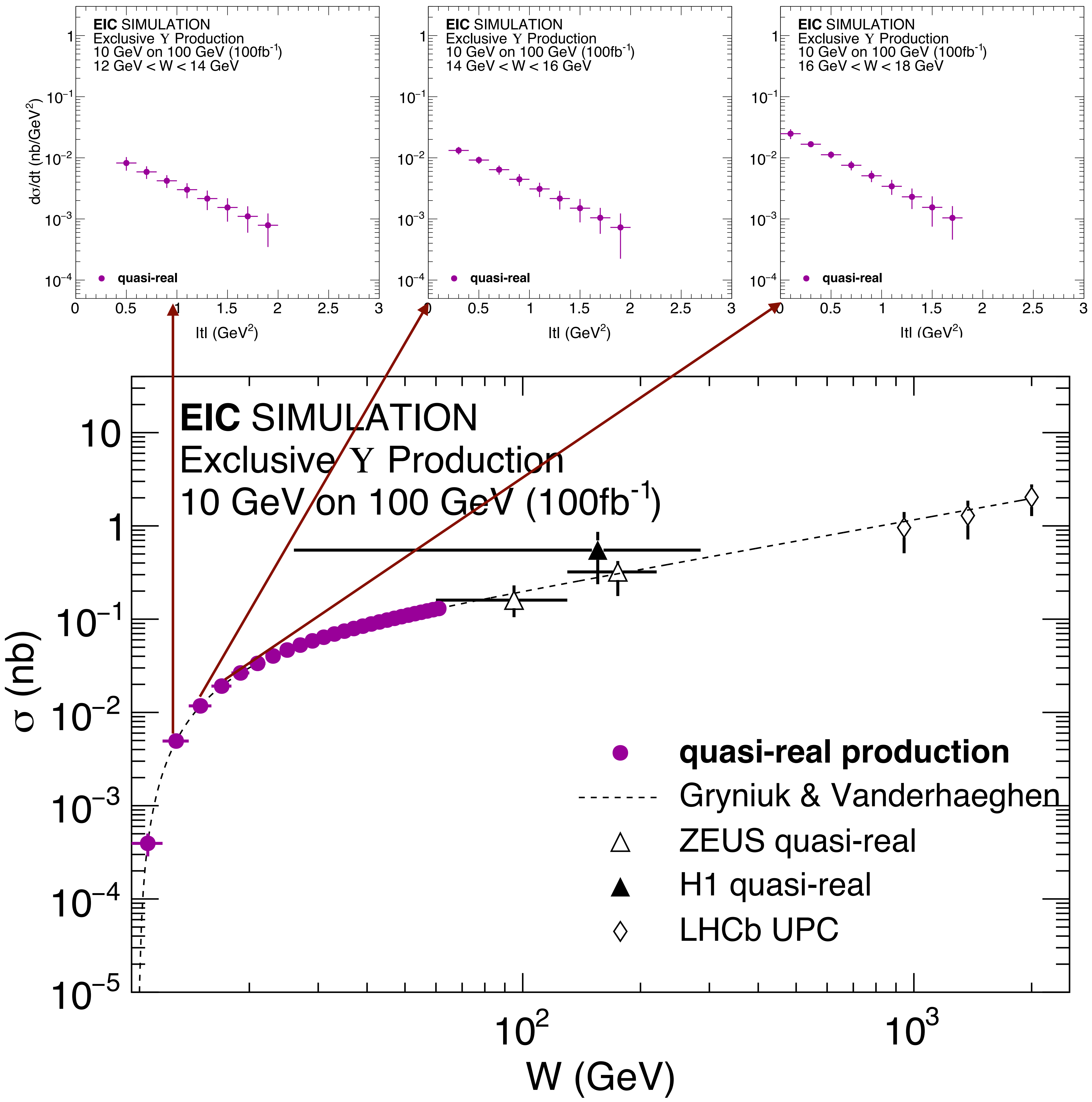


- ***Y(1s)*** production possible at threshold!
  - Provides measure for **universality,** complimentary to threshold *J/ψ* program at JLab12
- Sensitivity down to ~10^{-3} nb!

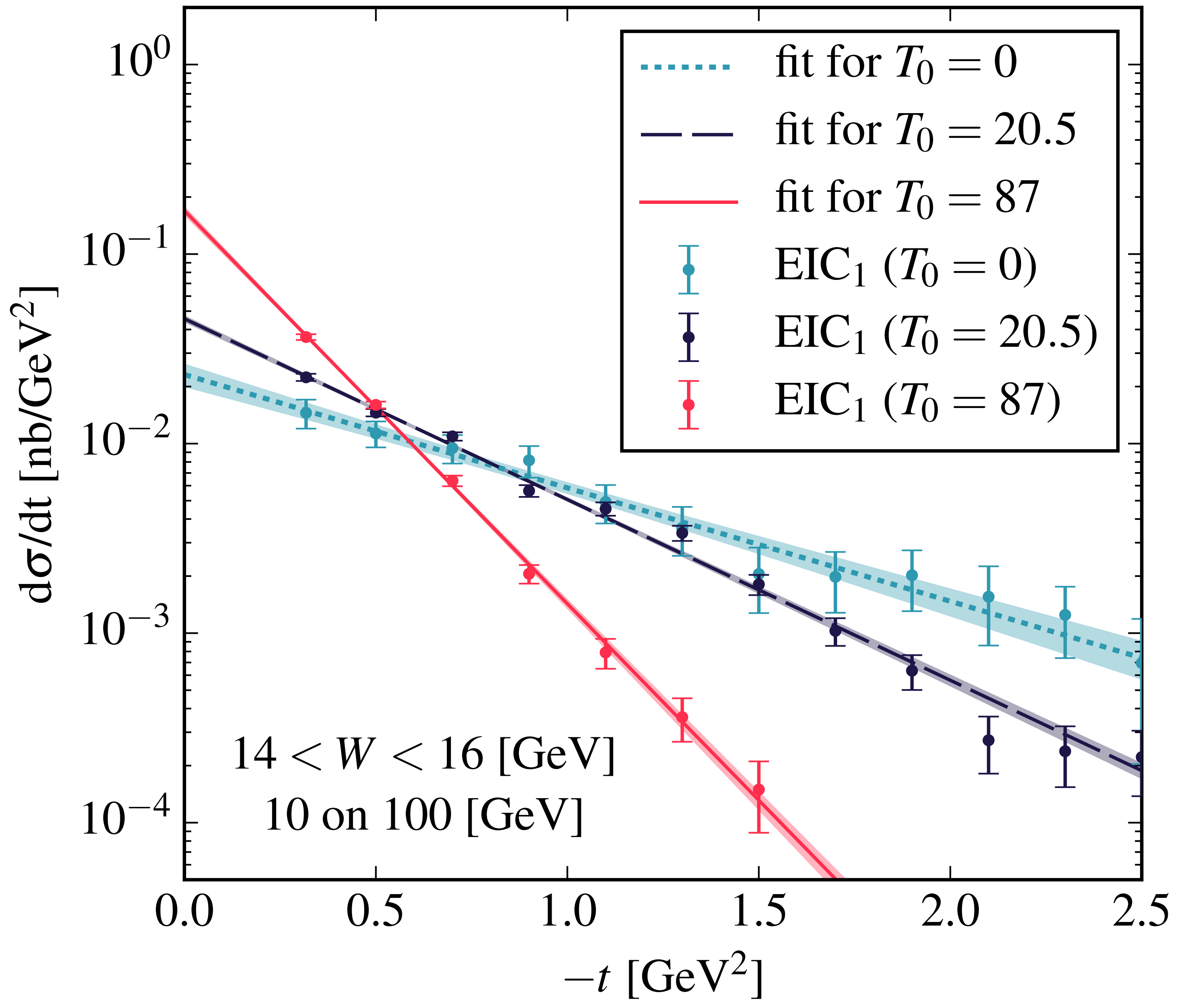
FROM EIC SCENARIOS TO SCATTERING LENGTH

Step 1: extrapolate to the forward limit

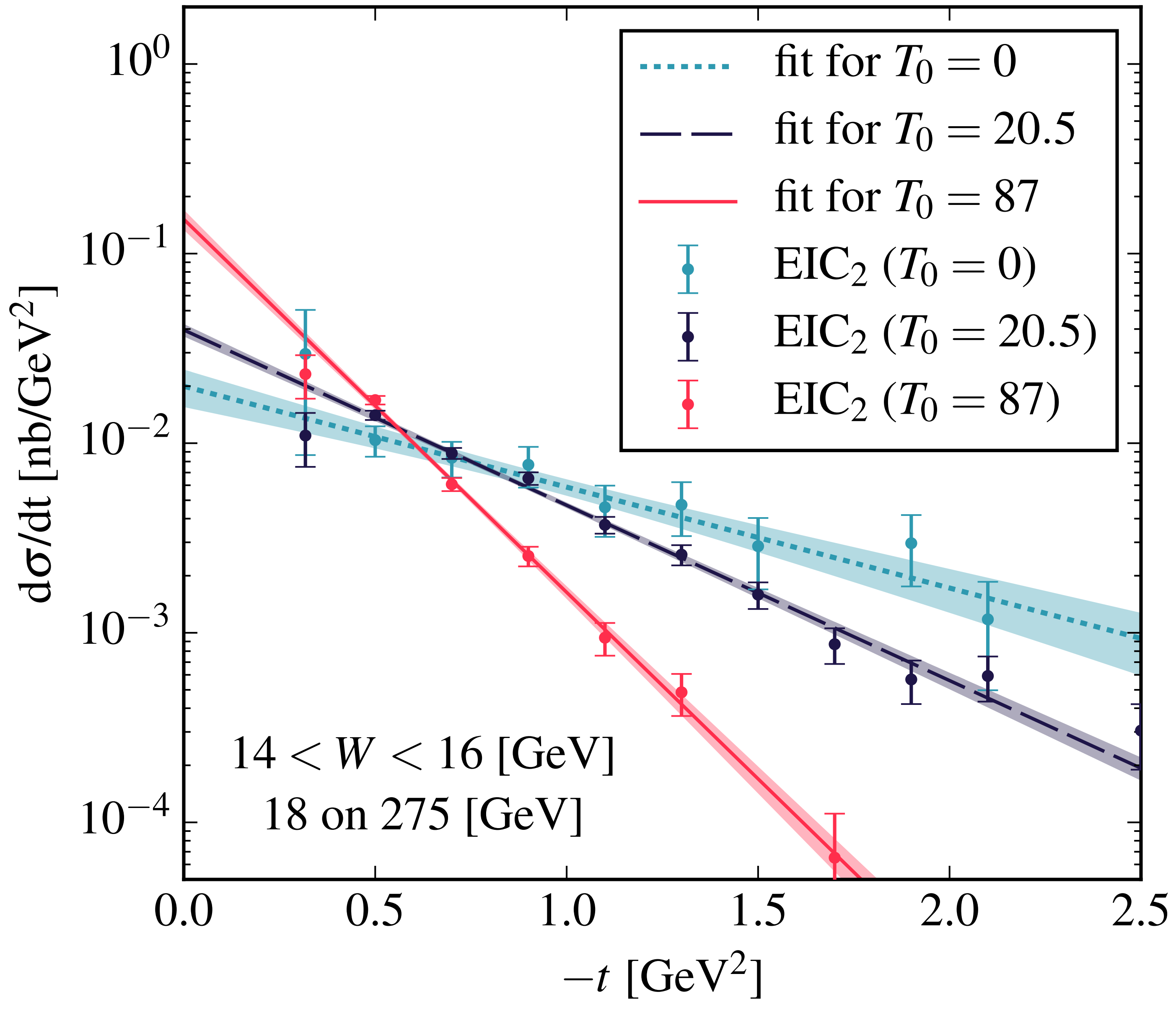
- Optimal rates near threshold for medium-energy 10 GeV electron on 100 GeV proton configuration
- **Subtraction constant** in dispersive analysis related to **scattering length, binding (and trace anomaly!)**
- Different colors show projected results for different values of the subtraction constant

$$\Re T_{\Upsilon p}(\nu) = T_{\Upsilon p}(0) + \frac{2}{\pi}\nu^2 \int_{\nu_{el}}^{\infty} d\nu' \frac{1}{\nu'} \frac{\Im T_{\Upsilon p}(\nu')}{\nu'^2 - \nu^2}$$

$$\left.\frac{d\sigma}{dt}\right|_{t=0}(\gamma p \to \Upsilon p) = \left(\frac{e f_\Upsilon}{M_\Upsilon}\right)^2 \frac{1}{64\pi s q_{\gamma p}^2} |T_{\Upsilon p}(\nu)|^2$$



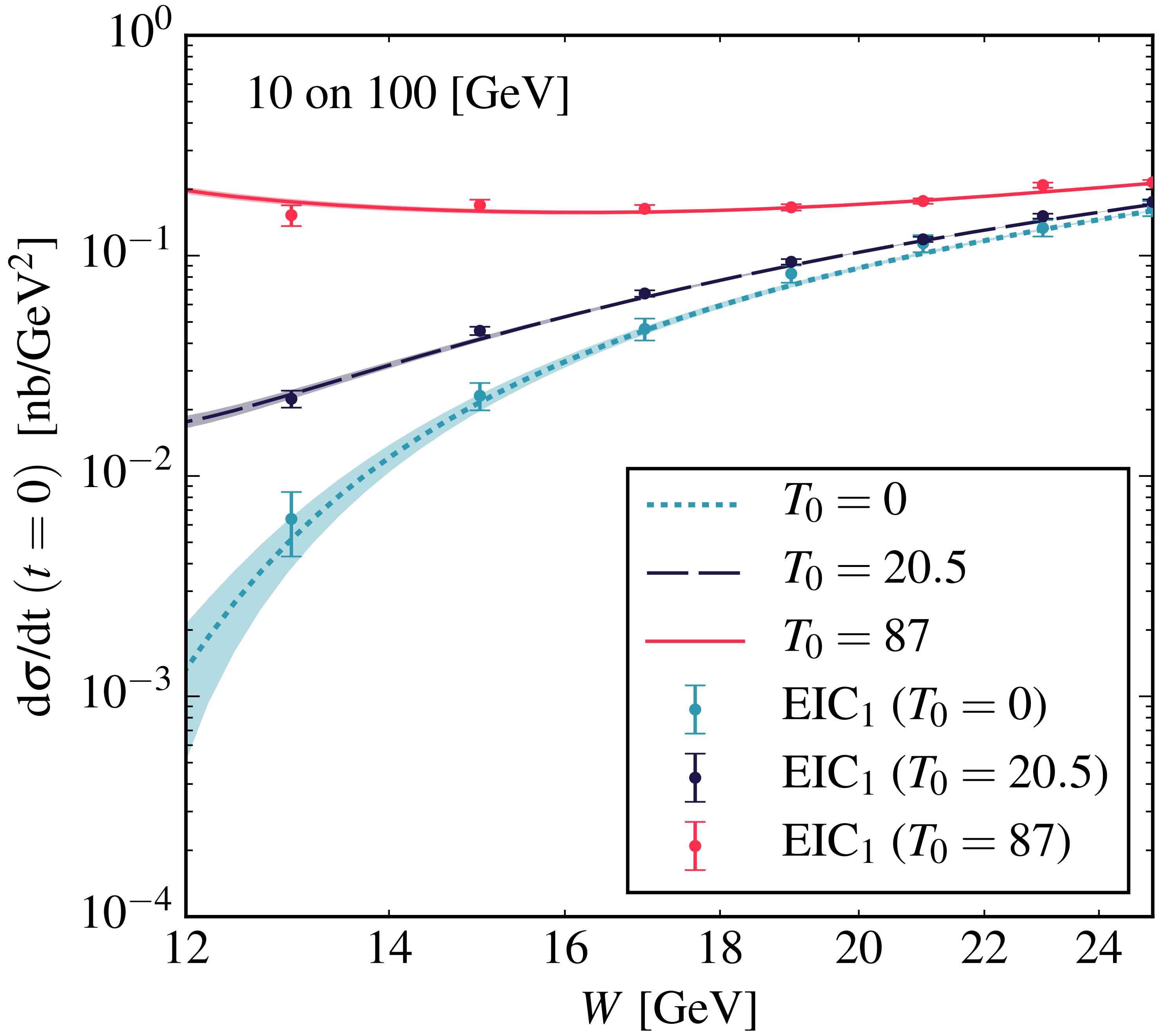
Setting 1: 10 on 100 GeV
Medium-energy configuration



Setting 2: 18 on 275 GeV
High-energy configuration

FROM EIC SCENARIOS TO SCATTERING LENGTH

Step 2: extract scattering length from fit to differential cross section



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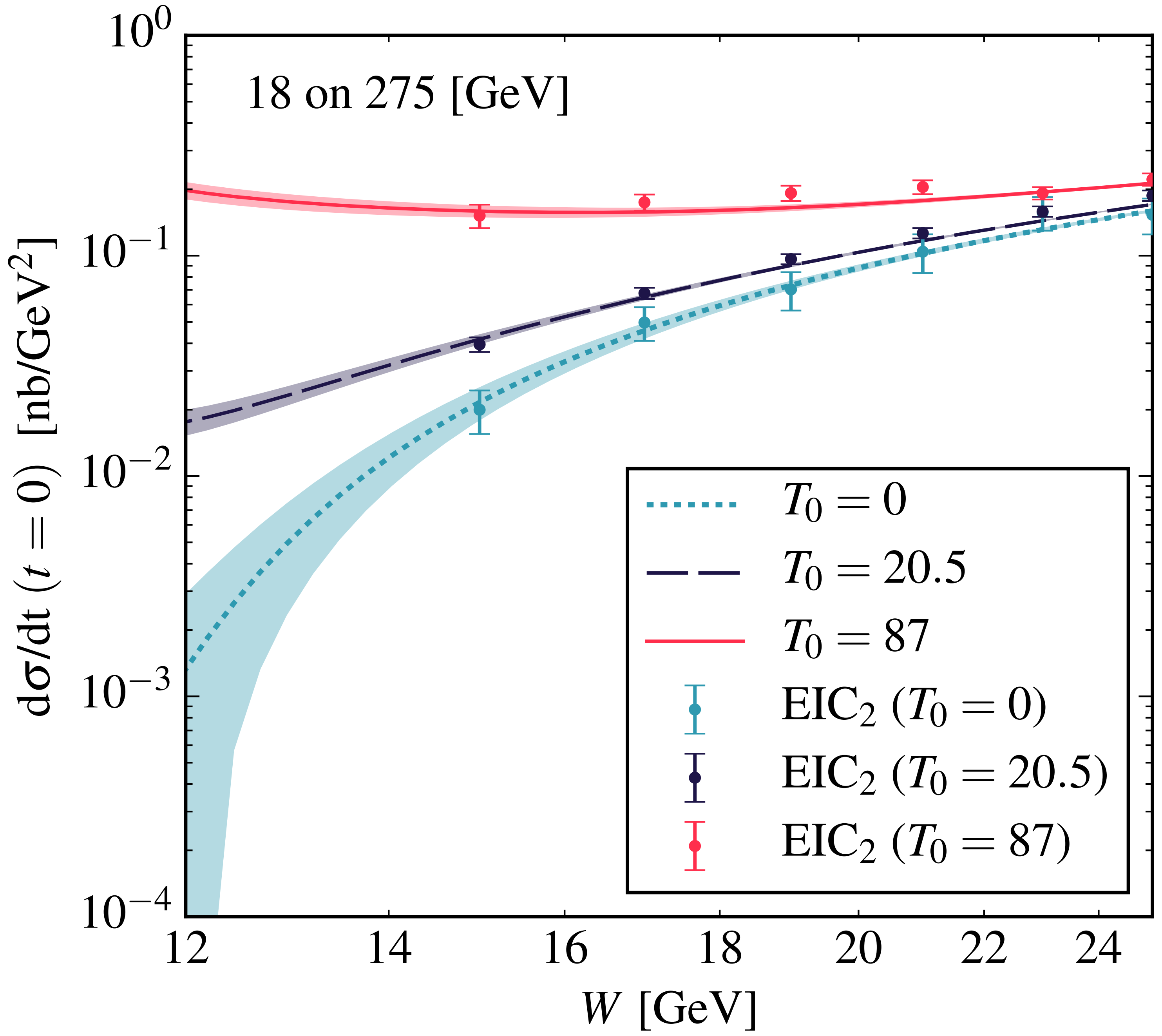


Setting 2: 18 on 275 GeV
High-energy configuration

$$T_{\Upsilon p}(\nu = \nu_{el}) = 8\pi(M + M_\Upsilon)a_{\Upsilon p}$$

$$B_\Upsilon \simeq \frac{8\pi(M + M_\Upsilon)a_{\Upsilon p}}{4MM_\Upsilon}\rho_{nm}$$

Setting	$T_{\Upsilon p}(0)$	$a_{\Upsilon p}$ (in fm)	B_Υ (in MeV)
1	0	$\simeq 0$	$\simeq 0$
	20.5 ± 0.9	0.016 ± 0.001	0.78 ± 0.03
	87 ± 2	0.066 ± 0.001	3.23 ± 0.06
2	0	$\simeq 0$	$\simeq 0$
	20.5 ± 1.9	0.016 ± 0.001	0.78 ± 0.07
	87 ± 4	0.066 ± 0.003	3.23 ± 0.16

Good sensitivity to scattering length and binding energy for both nominal EIC configurations.

QUARKONIUM CORNUCOPIA

New workshops coming up soon!

Proton Mass Workshop 3: Origin of hadron masses workshop (January 2021), will be announced soon!

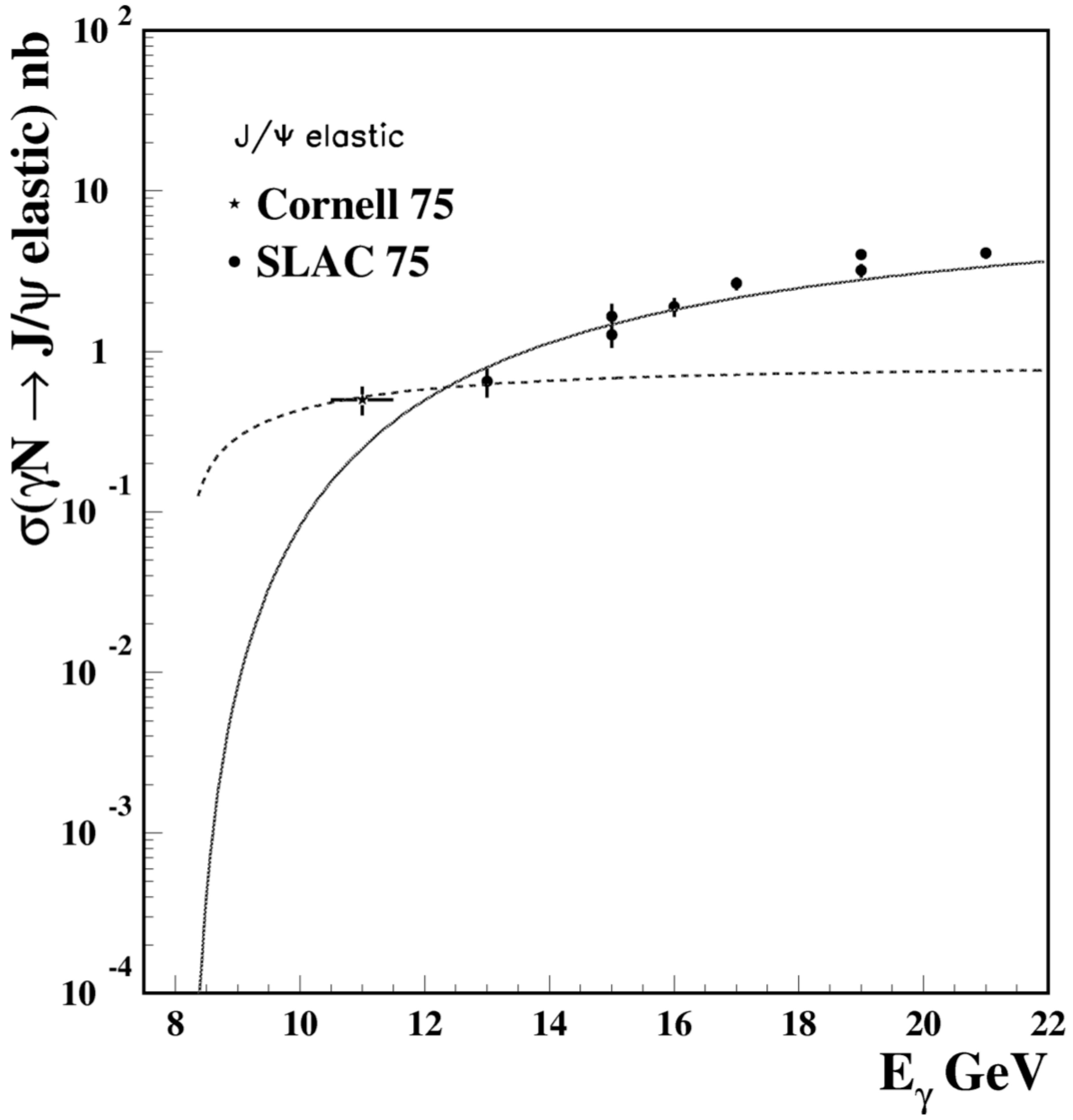
Proton Mass Workshop p4: INT, Winter 2022

- **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 *Υ* to *J/ψ*** results
- **JLab12 and the EIC** are (will be) perfectly positioned to **significantly contribute to these topics**

BACKUP

PRODUCTION MECHANISM NEAR THRESHOLD?

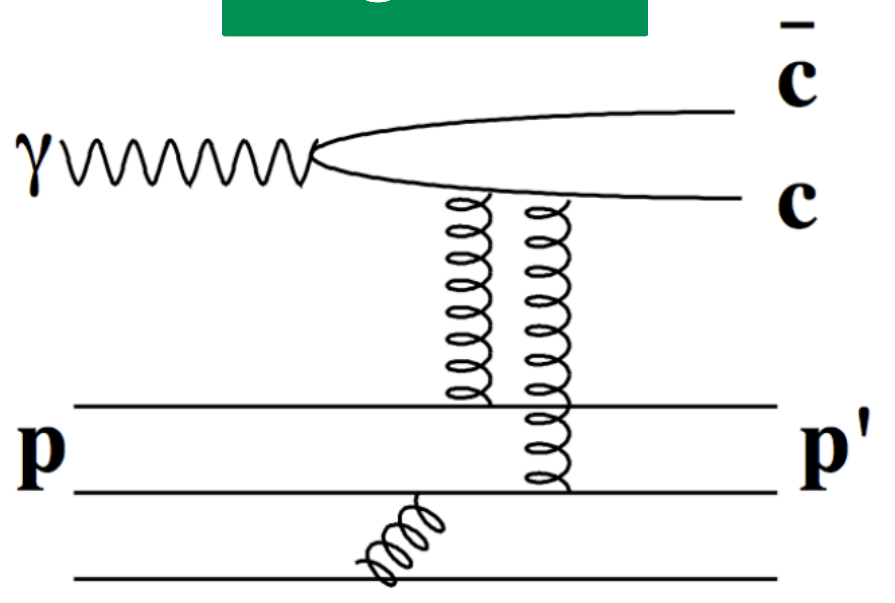
N-gluon exchange hard scattering



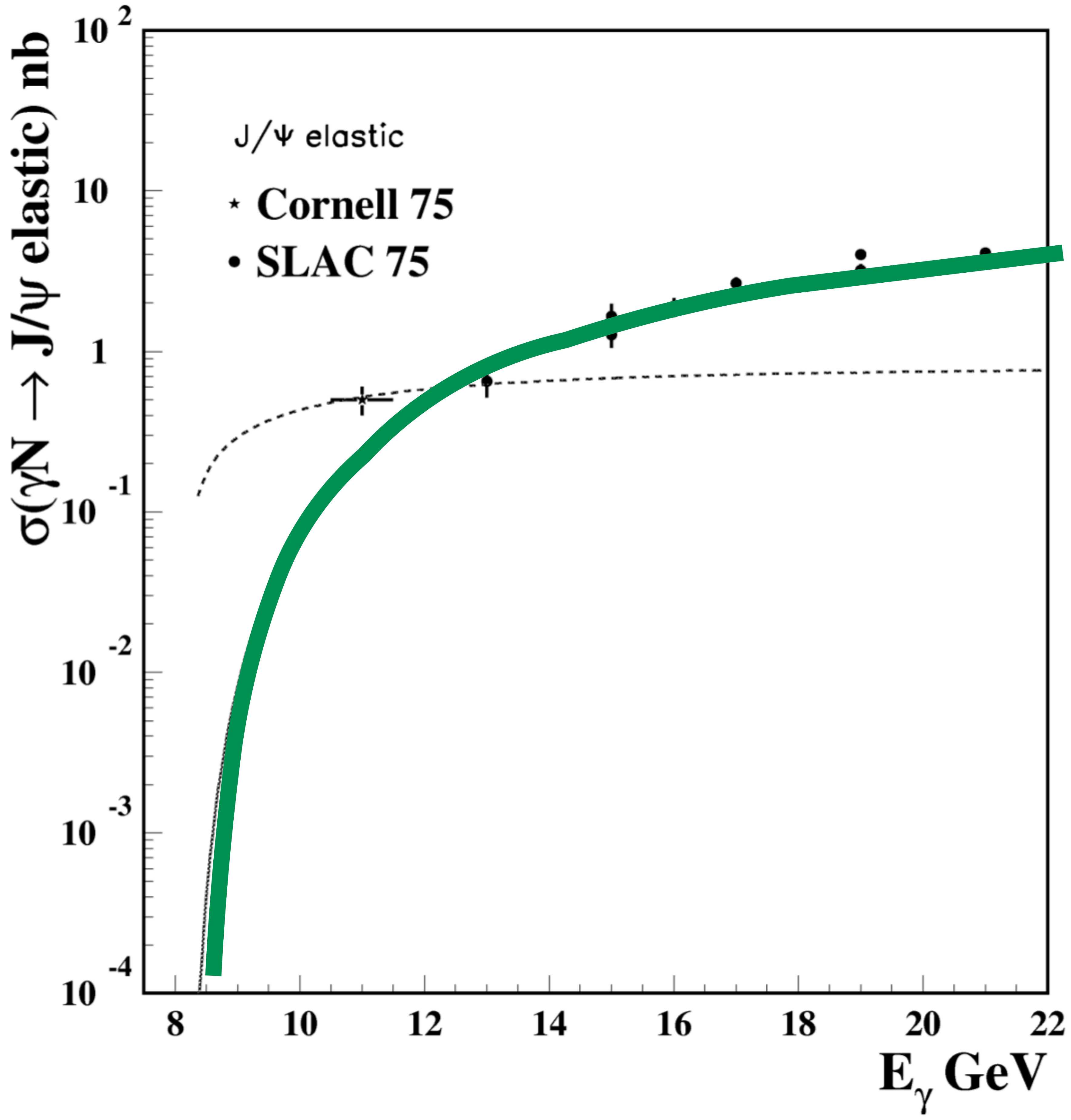
PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

2-gluon



- 2-gluon exchange works well at higher energies



PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

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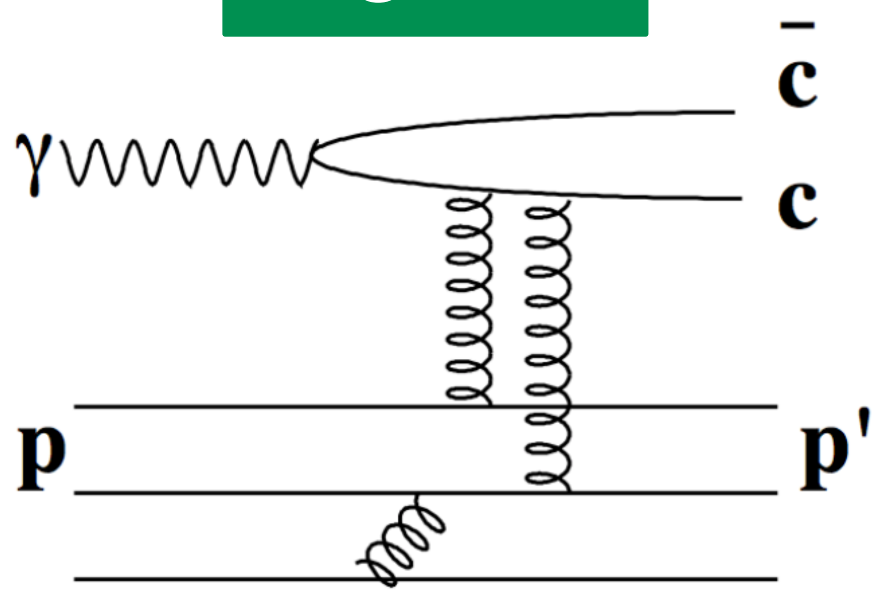
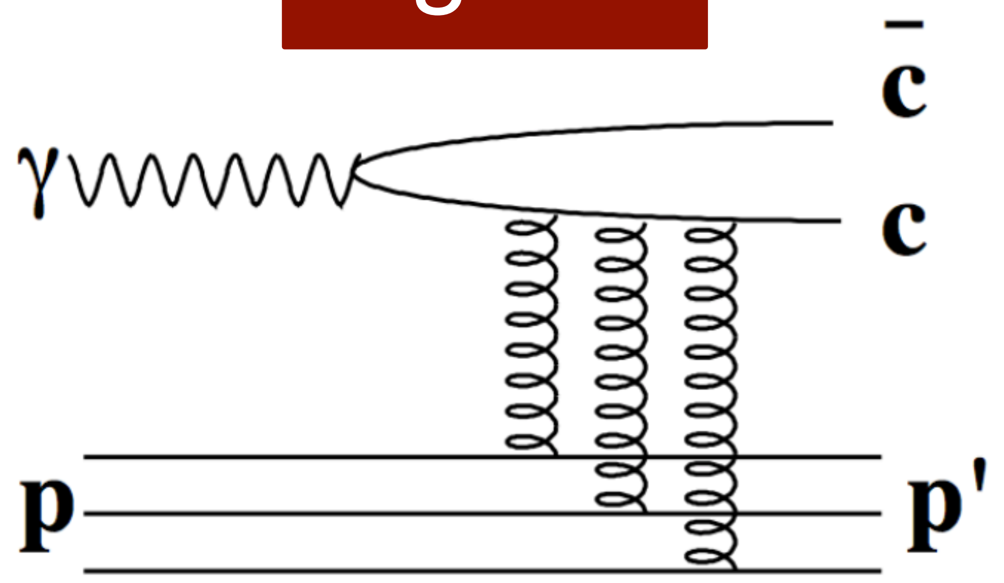
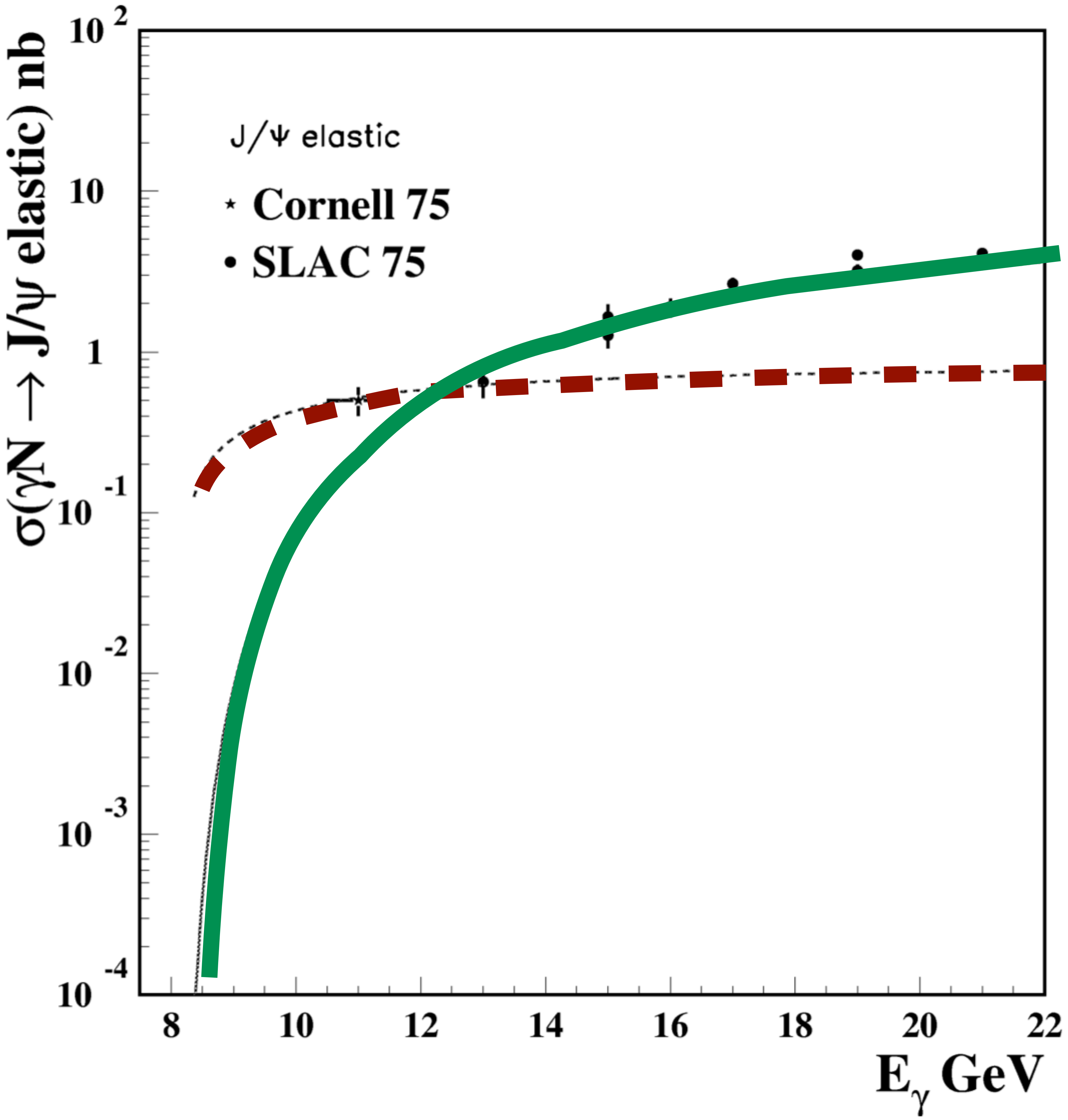


3-gluon



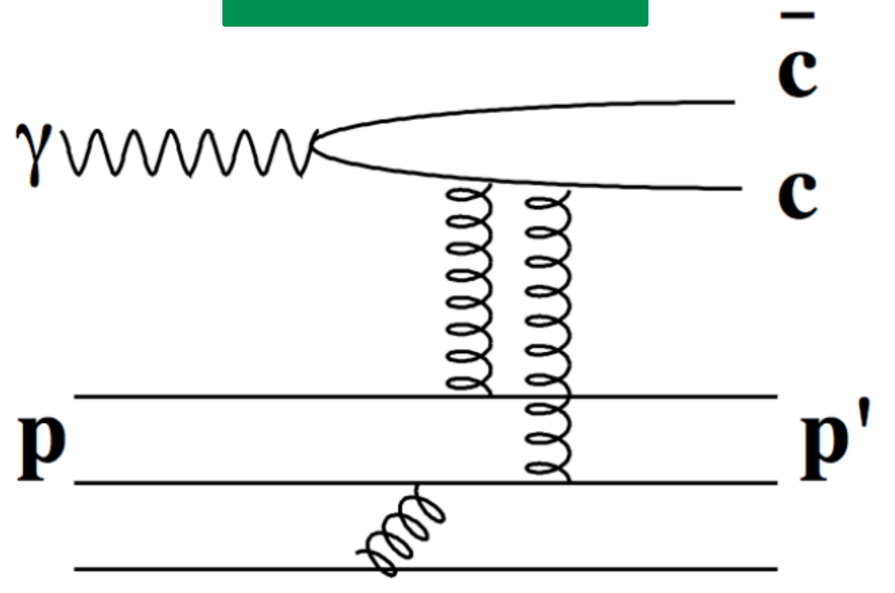
- 2-gluon exchange works well at higher energies
- Higher order gluon exchange expected to play role near threshold
  - Larger 3-gluon exchange contribution related to binding



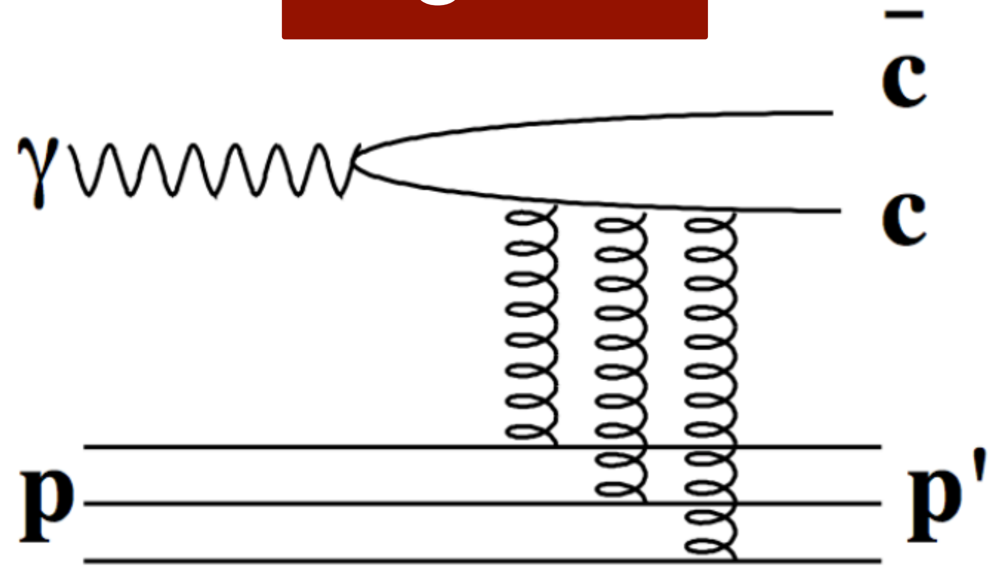
PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

2-gluon



3-gluon



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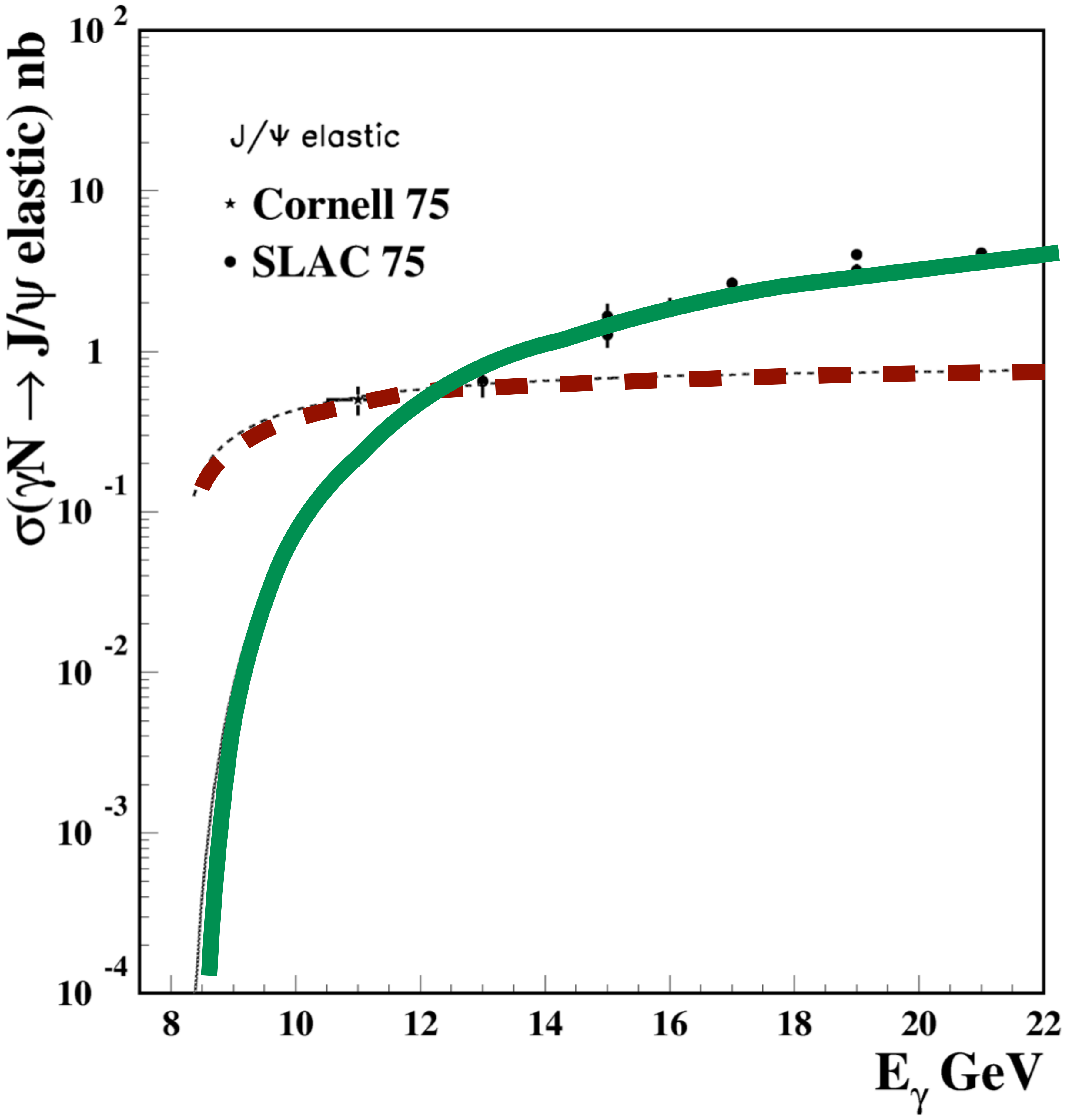
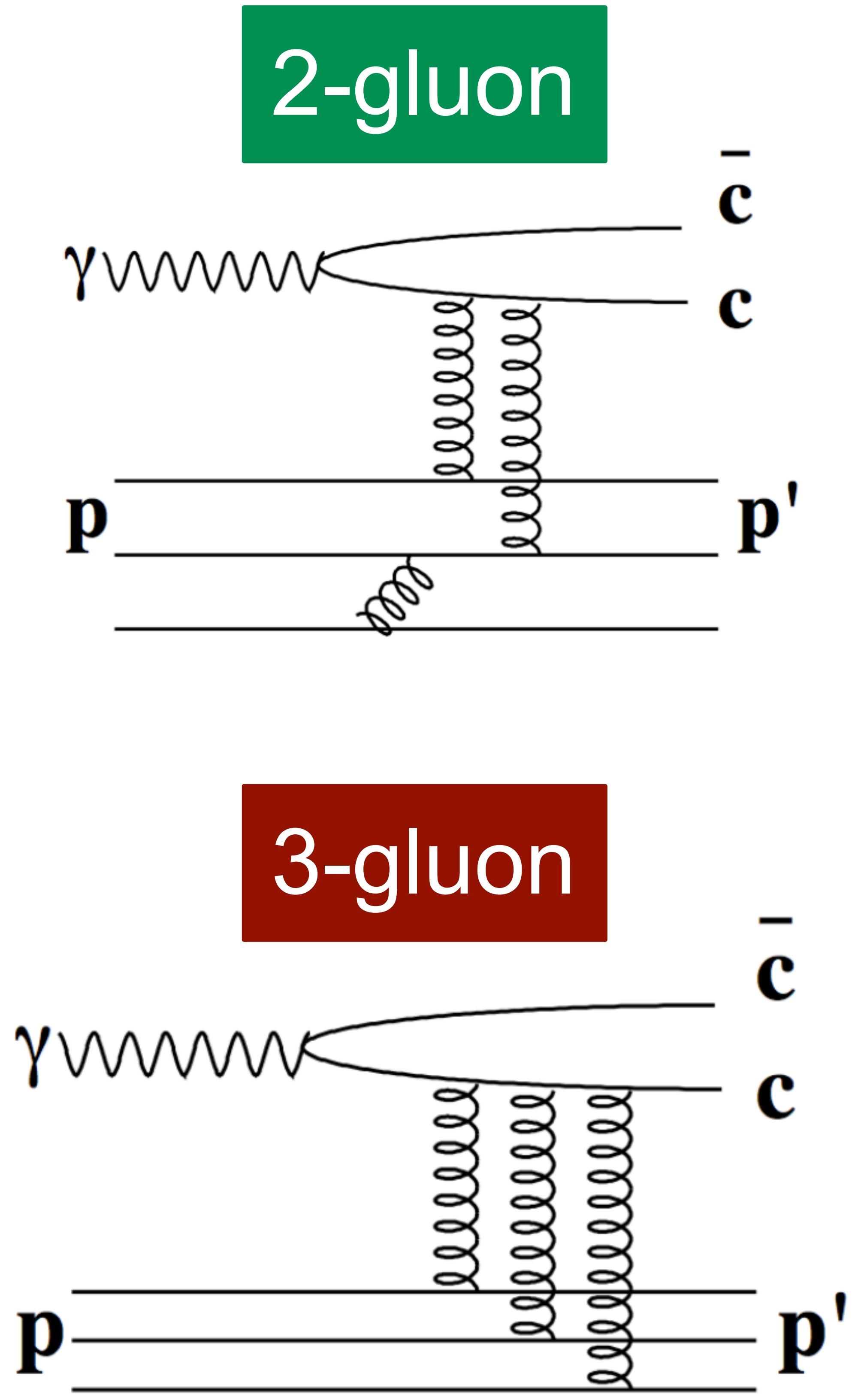
- Exponential *t*-dependence (or dipole)



PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering



- 2-gluon exchange works well at higher energies
- Higher order gluon exchange expected to play role near threshold
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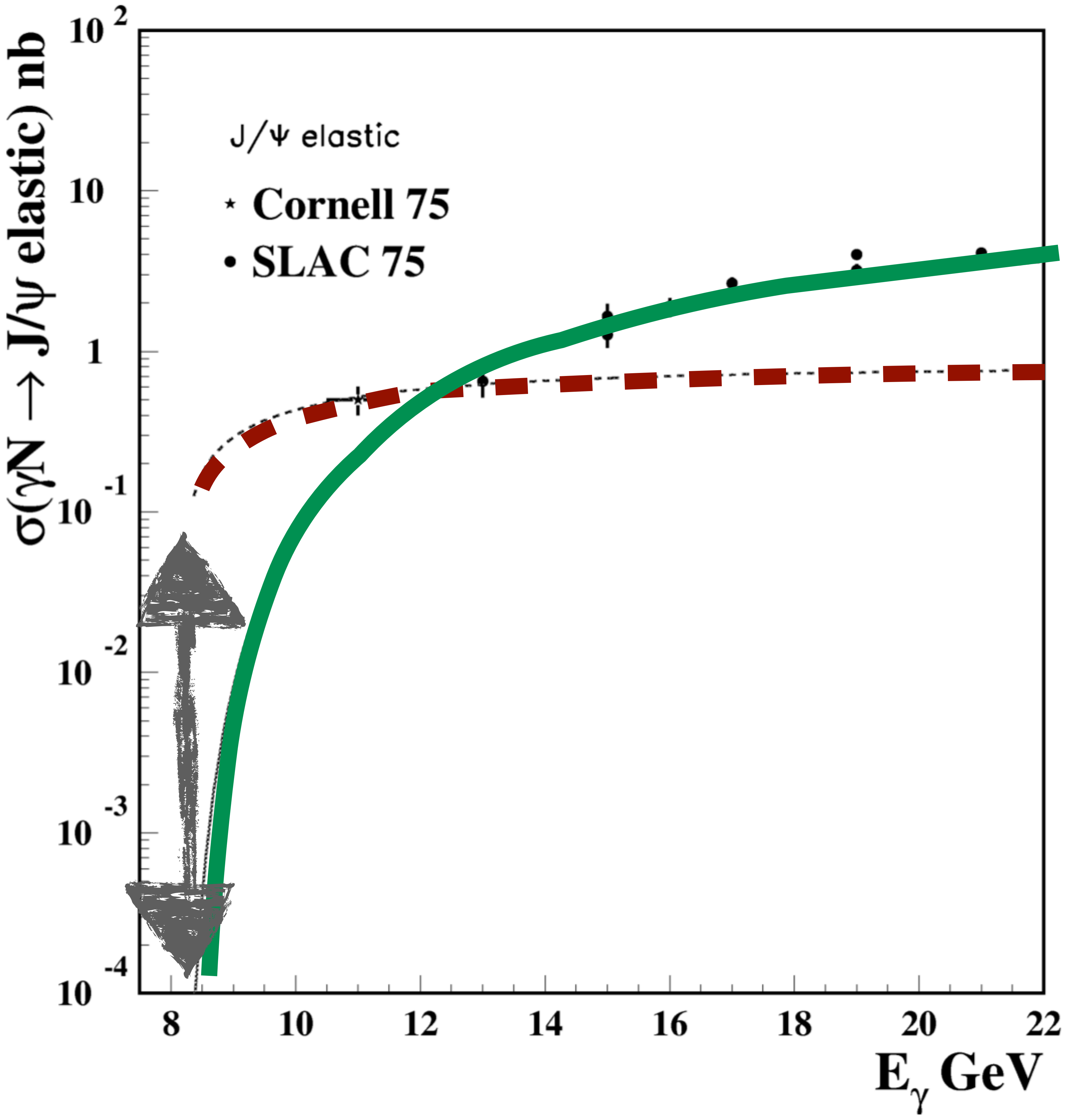
- Orders of magnitude difference between predictions: **threshold region still unknown**

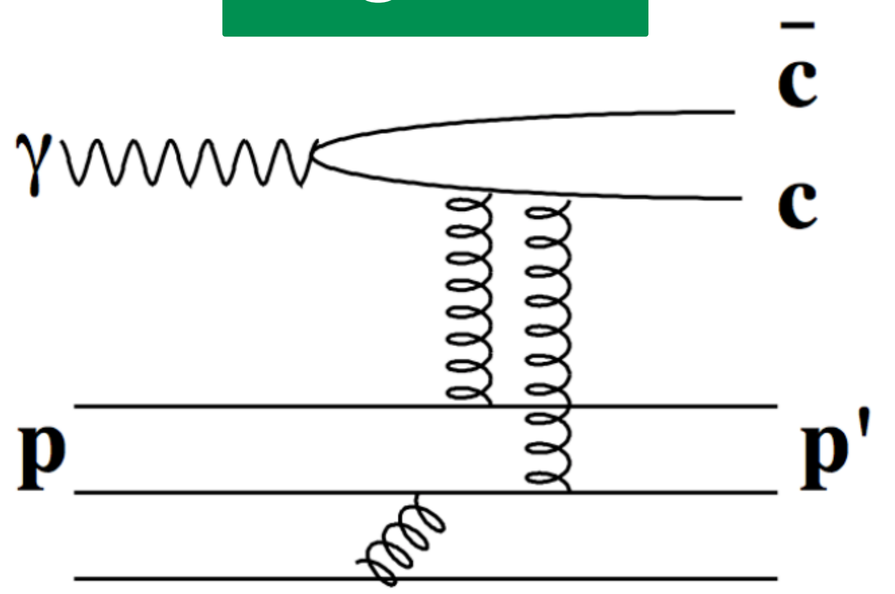


S.J. Brodsky, *et al.*, PLB 498, 23-28 (2001)

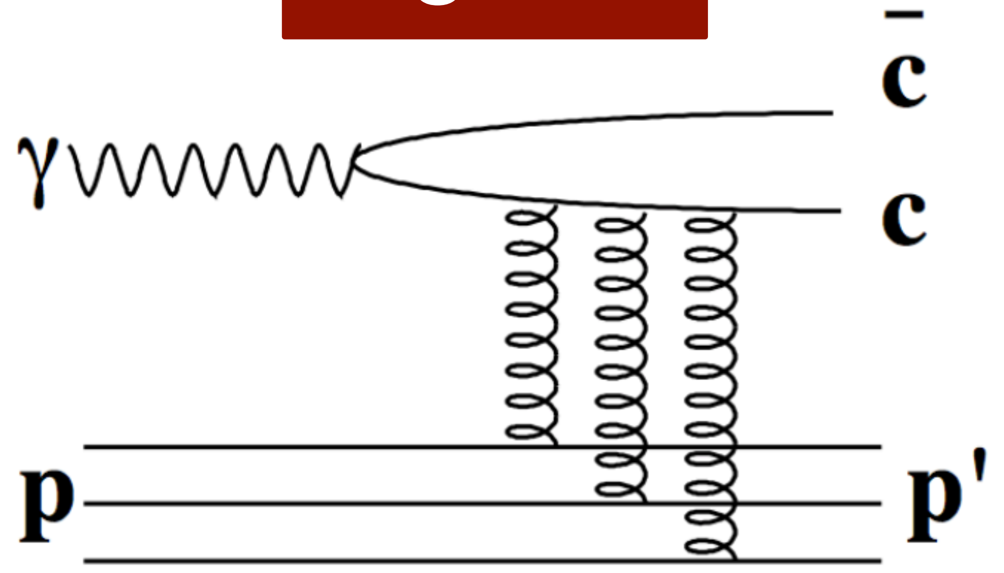
PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

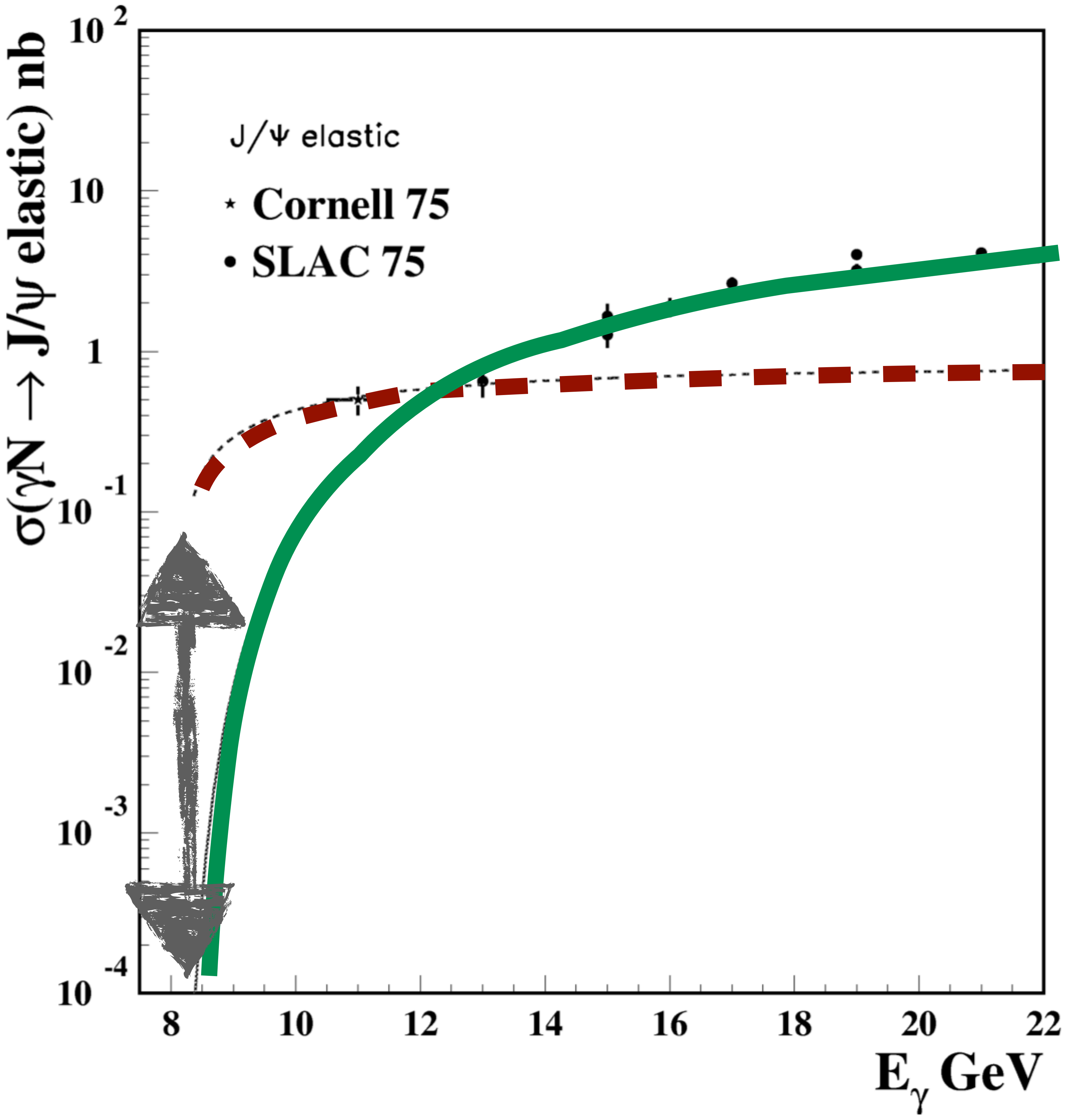
2-gluon



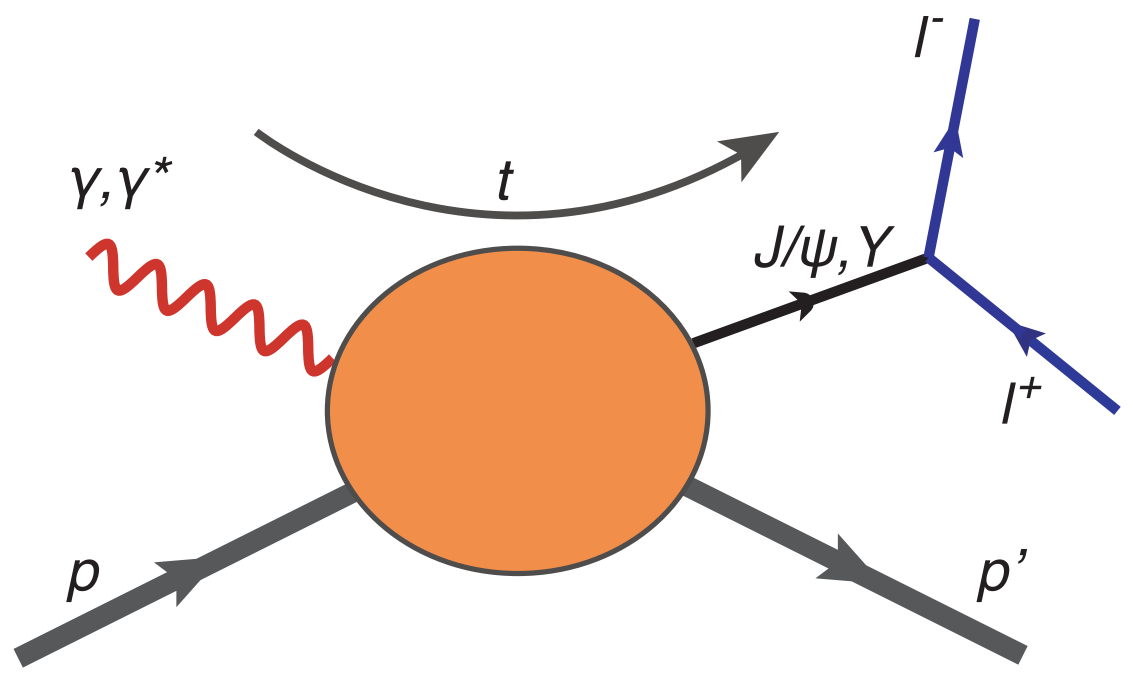
3-gluon



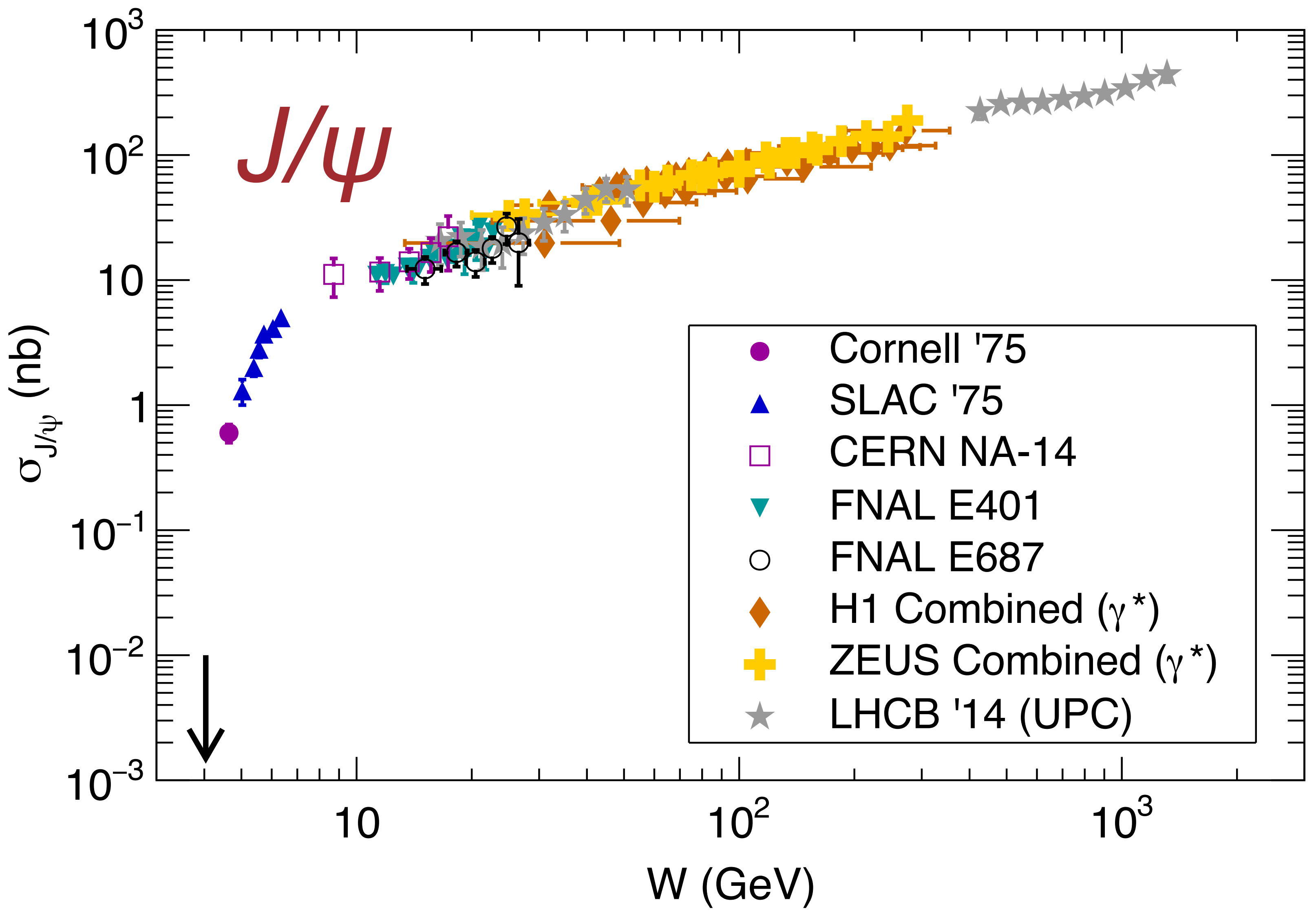
- 2-gluon exchange works well at higher energies
- Higher order gluon exchange expected to play role near threshold
  - Larger 3-gluon exchange contribution related to binding
- Exponential *t*-dependence (or dipole)
- Orders of magnitude difference between predictions: **threshold region still unknown**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

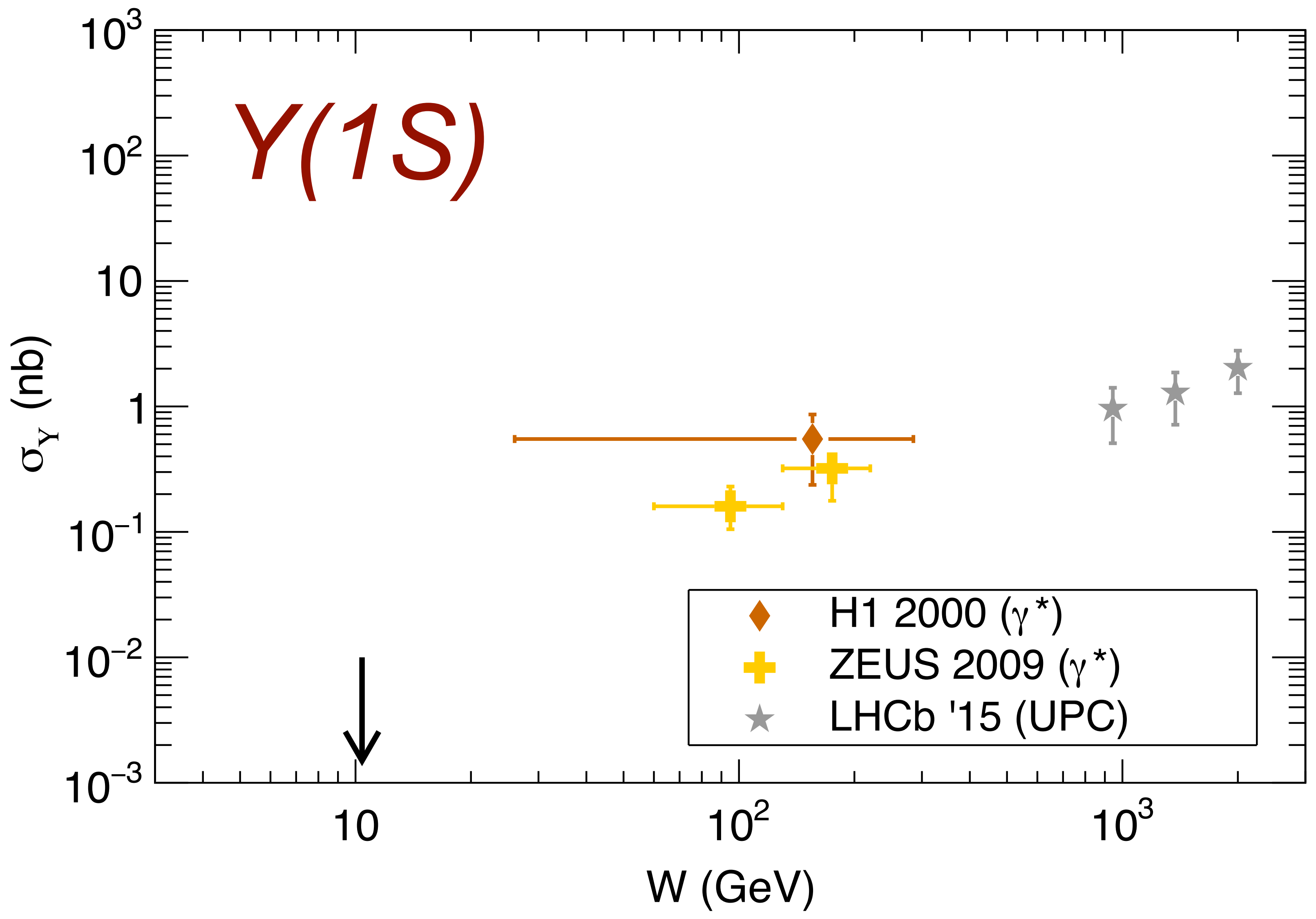


QUARKONIUM PHOTO-PRODUCTION: WHAT DO WE KNOW?



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





- **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*)