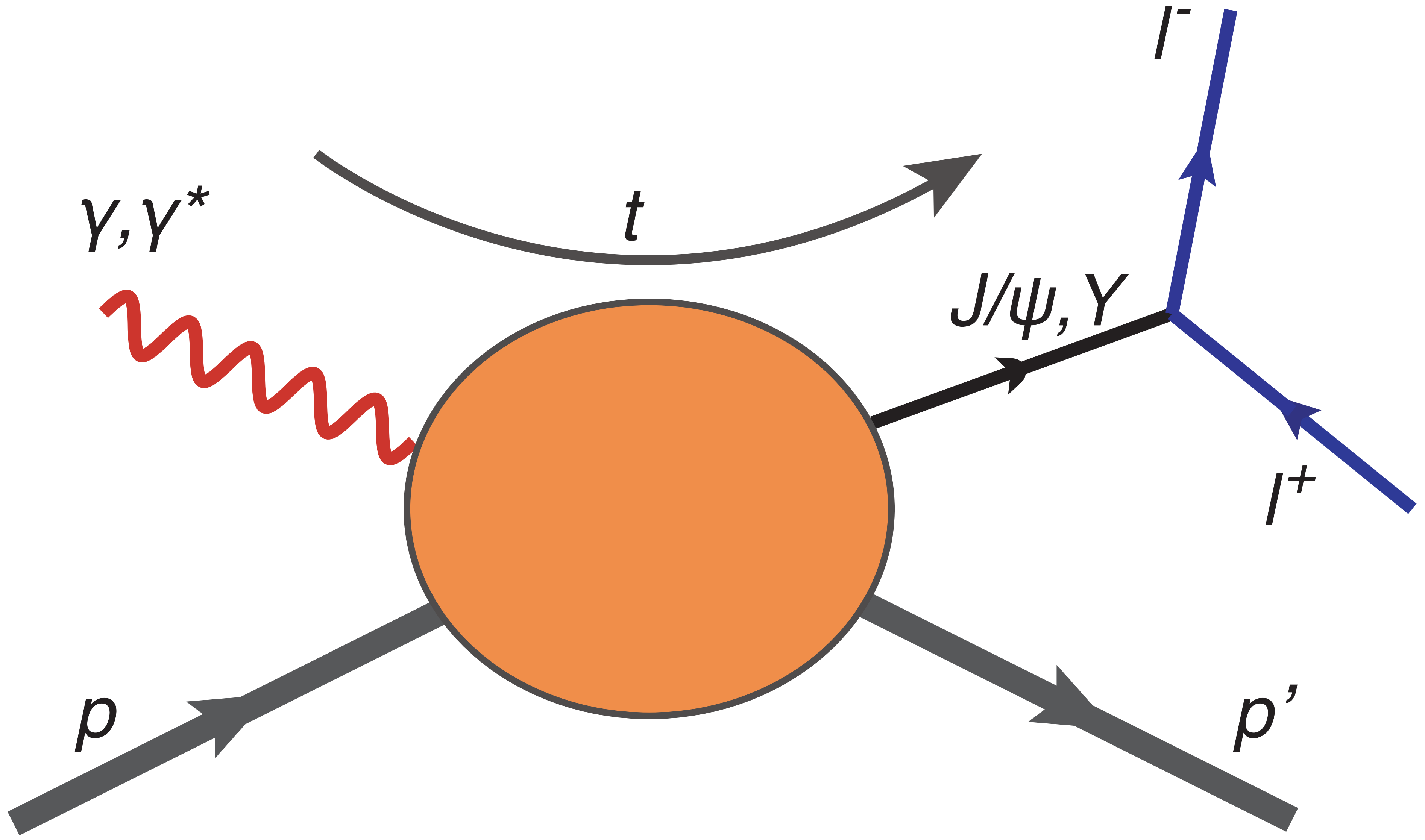
THE WHITE PAPER AND BEYOND

EXCLUSIVE VECTOR MESON PRODUCTION IN *e+p* COLLISIONS AT EIC



SYLVESTER JOOSTEN
sjoosten@anl.gov

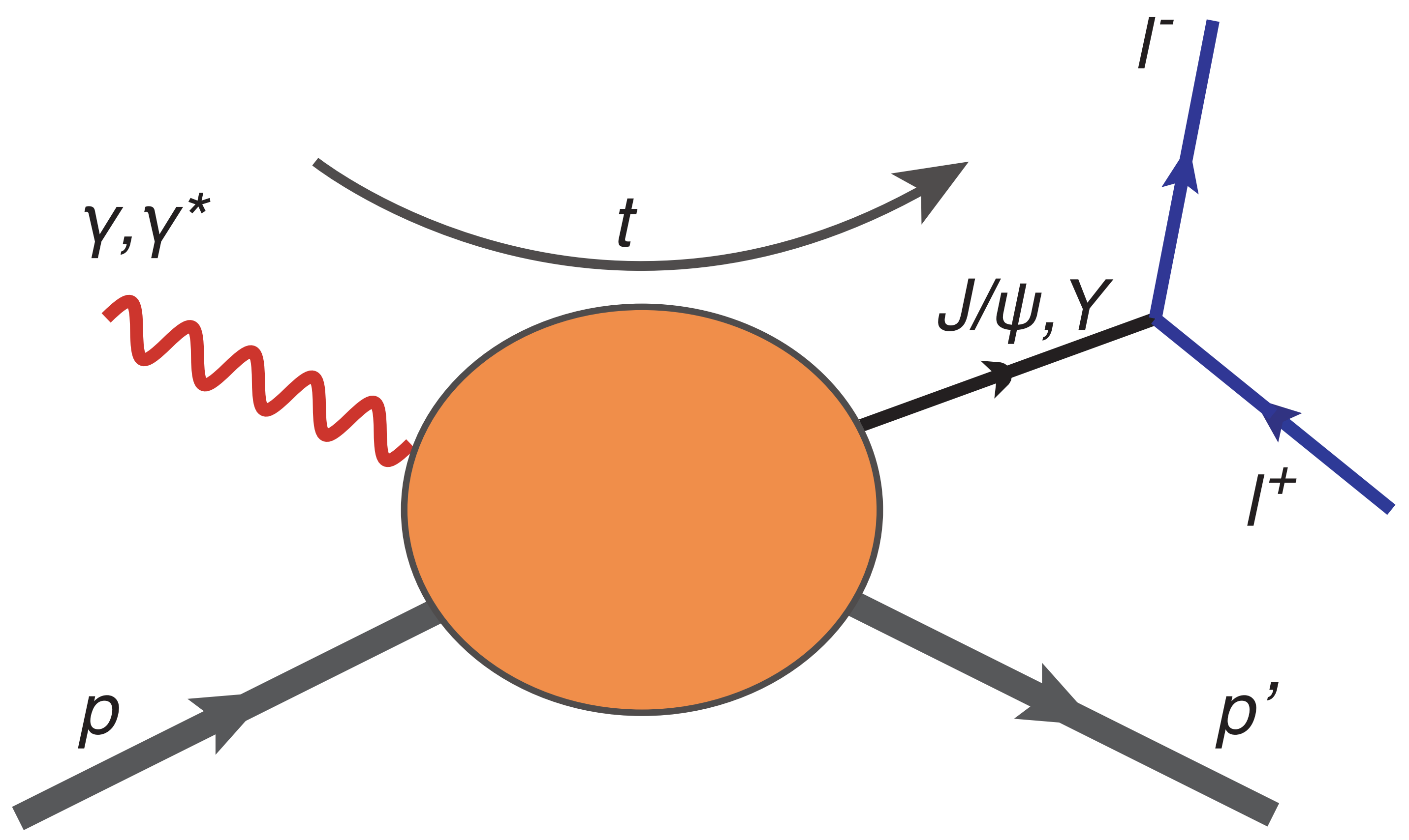
U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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

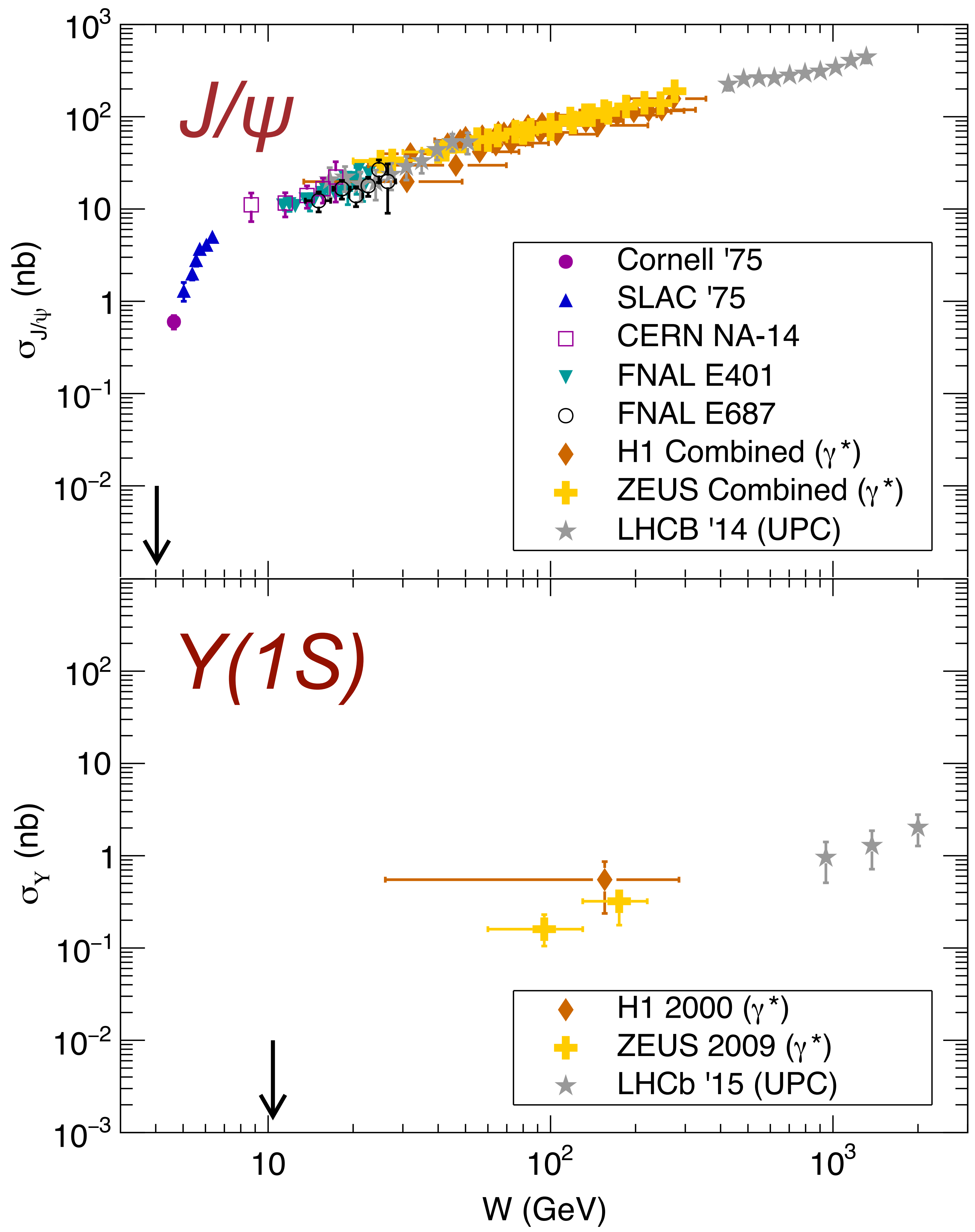
EICUG Yellow Report
Temple Meeting, March 19-21, 2020

QUARKONIUM PRODUCTION

What do we know?



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



- *J/ψ* photo-production constrained for high energies
- *Υ(1S)*: not much available
- **Almost no data near threshold**
- Momentum transfer t very large near threshold
- No real electro-production data available

QUARKONIUM 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

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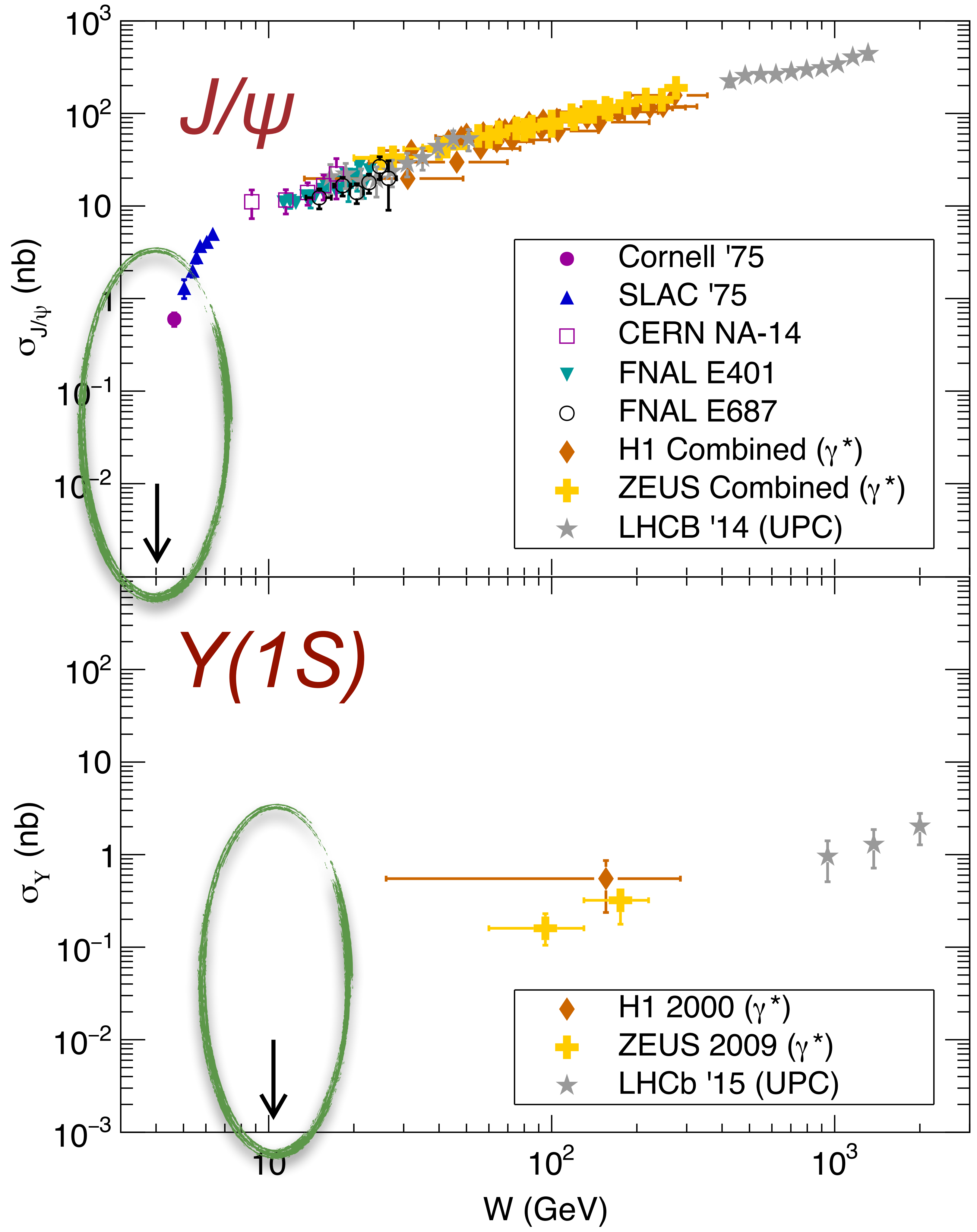
J/ψ at JLab

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

- J/ψ photo-production constrained for high energies
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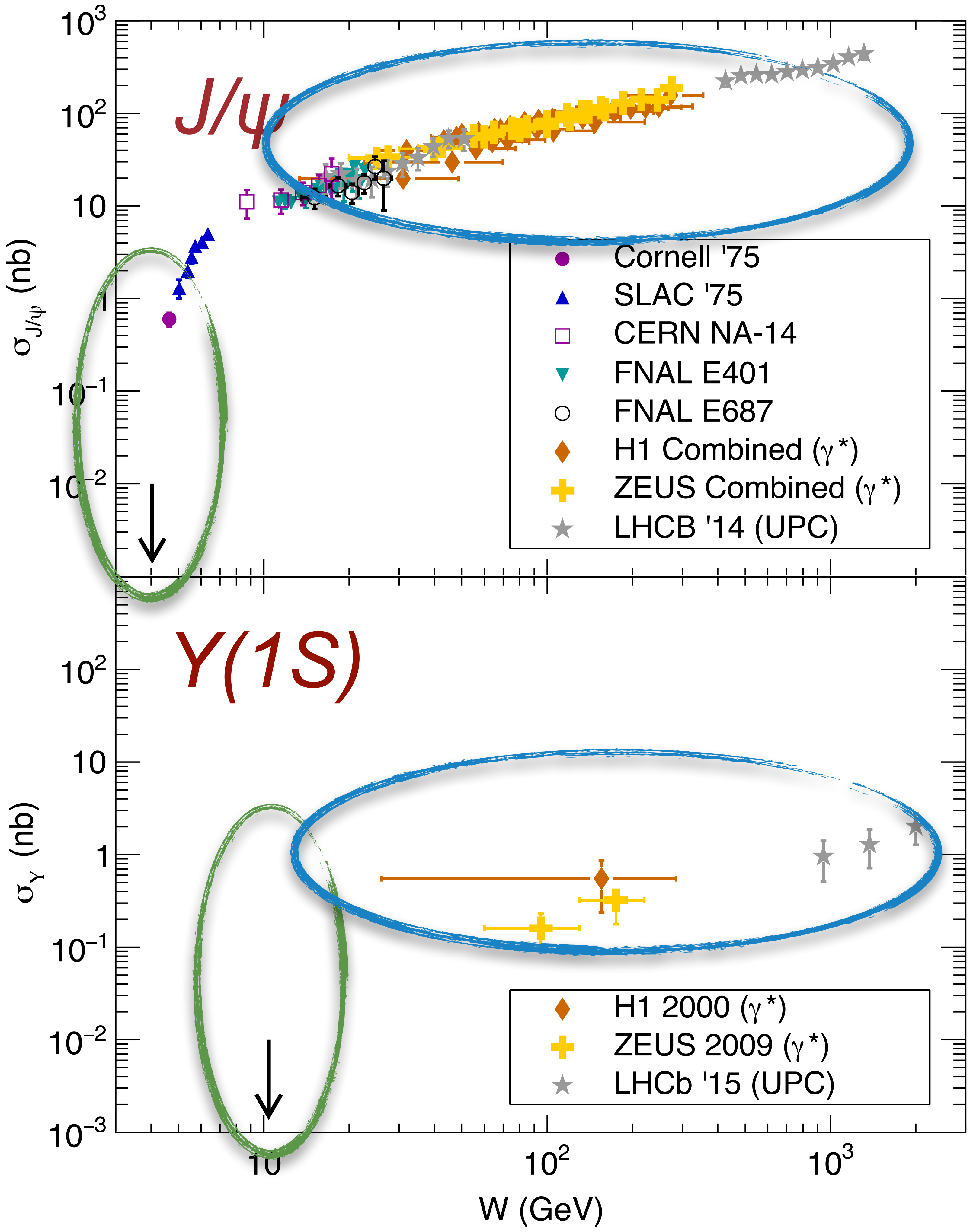
J/ψ at JLab
Y(1s) at EIC

J/ψ and
Y(1s) at EIC

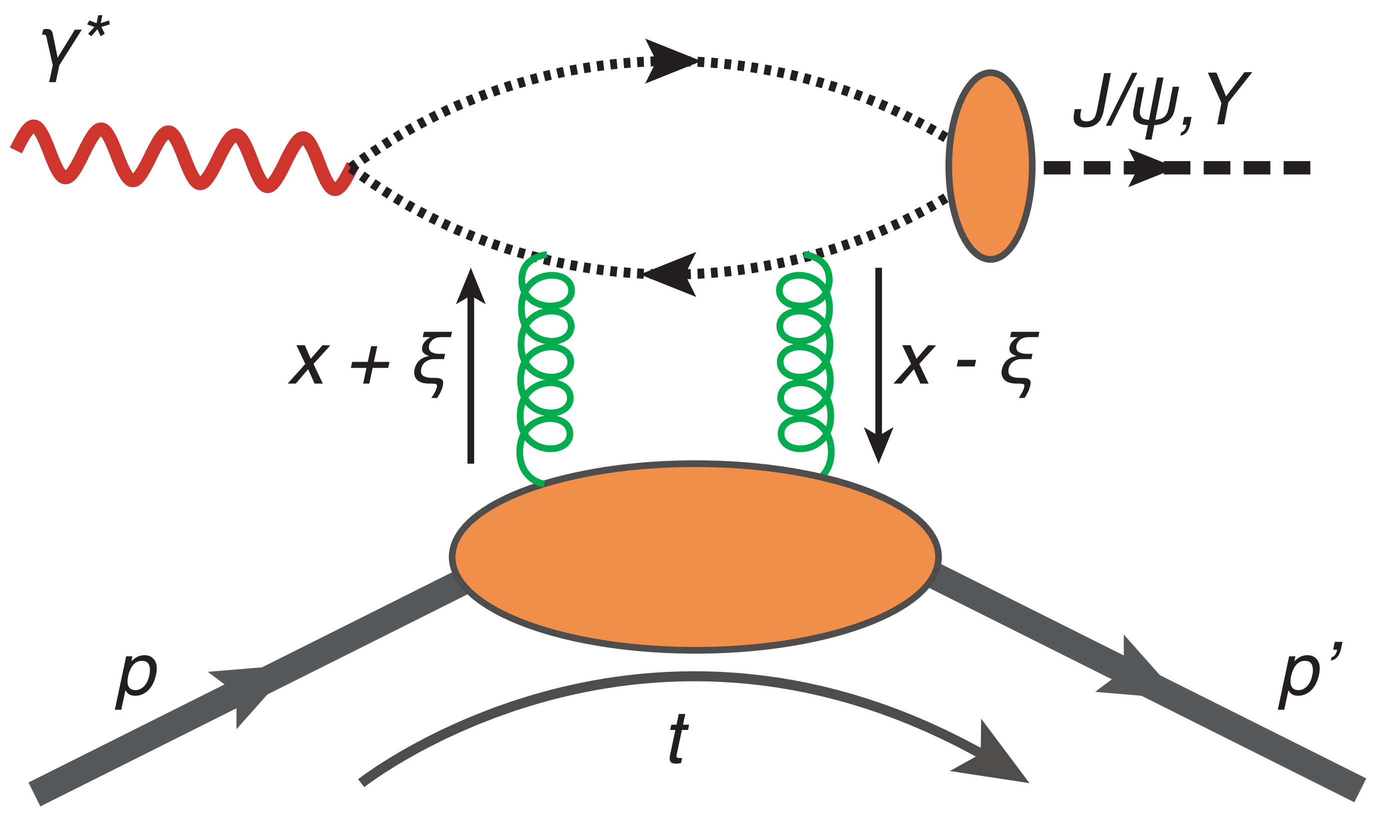


QUARKONIUM PRODUCTION AT HIGH ENERGIES

- 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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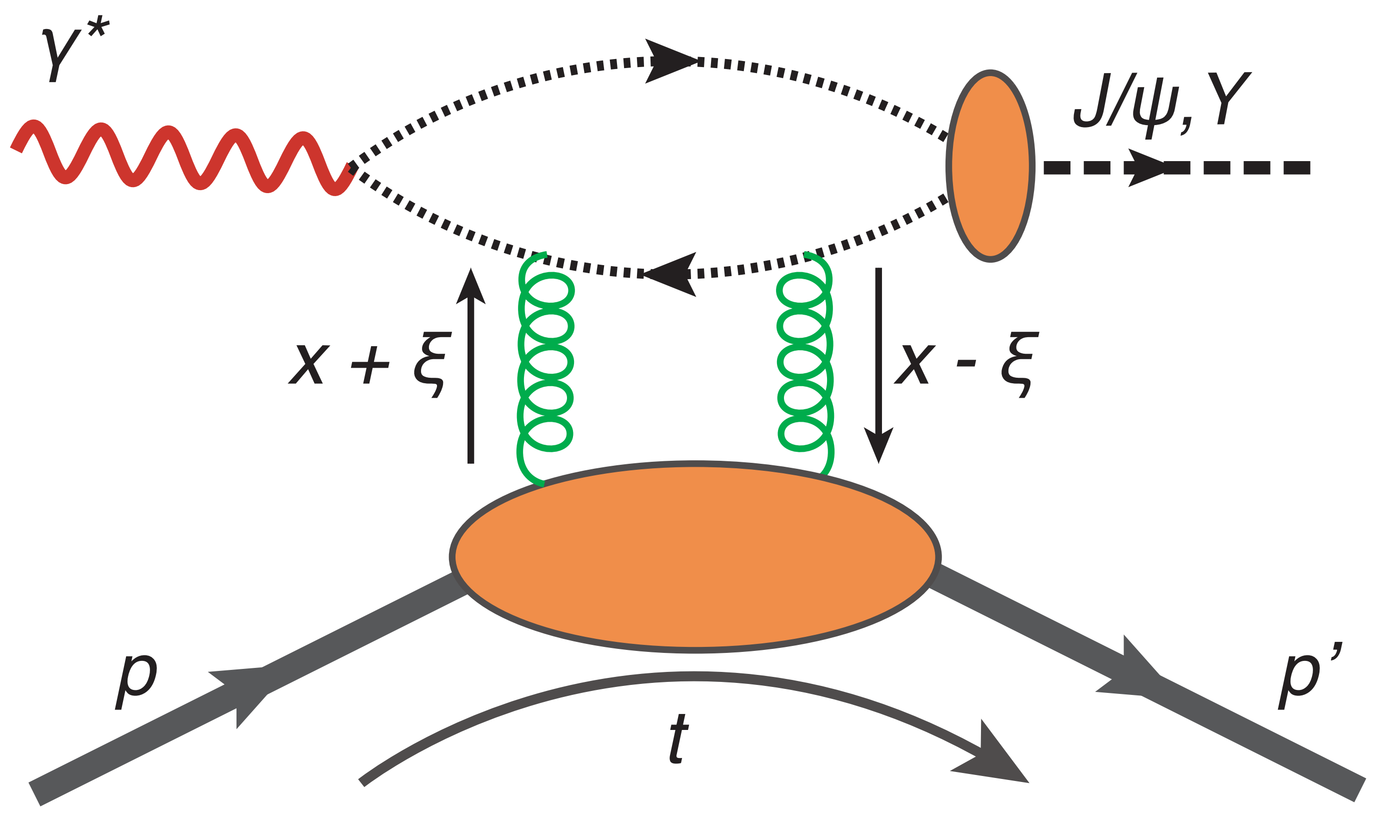

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average unpolarized gluon GPD related to *t*-dependent cross section (LO)

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

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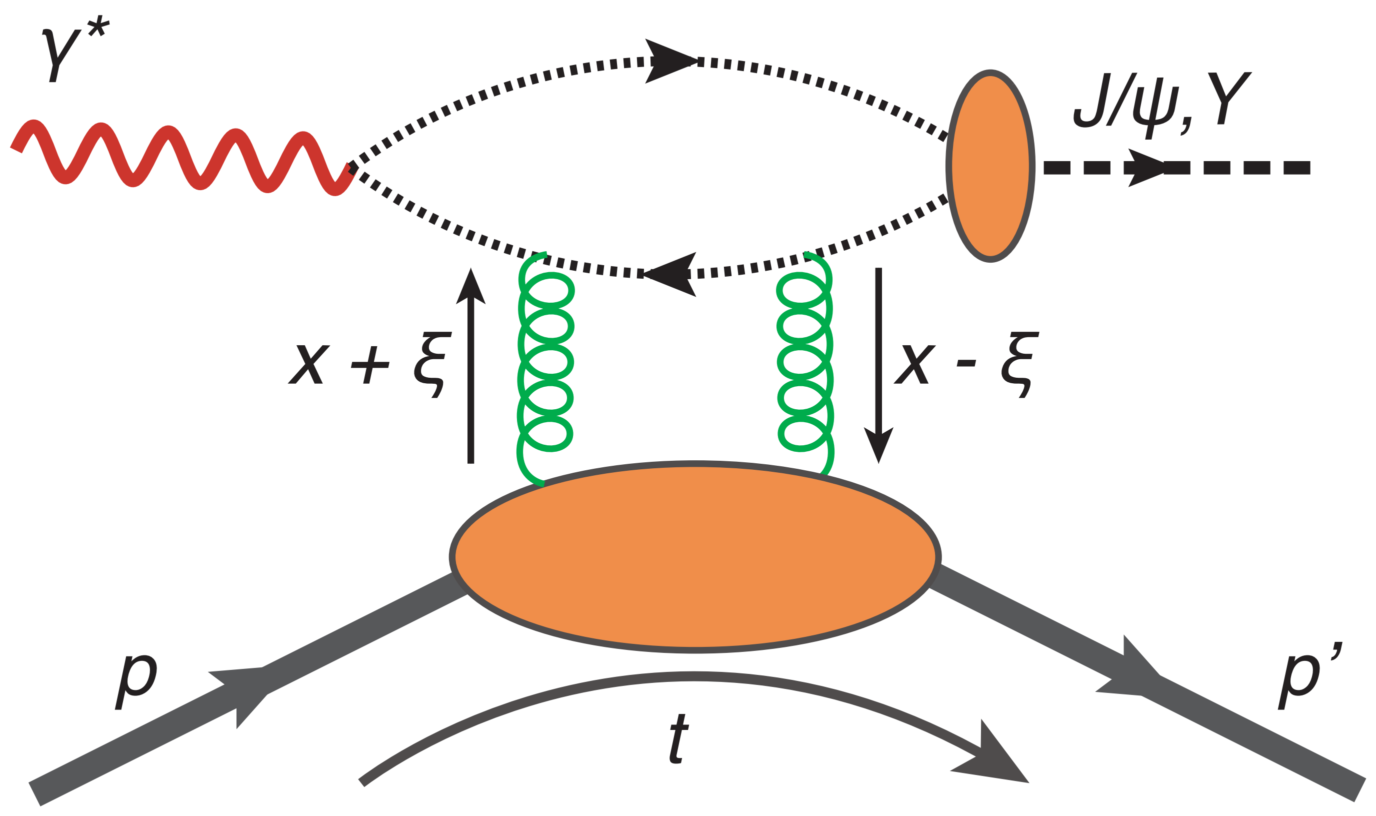

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Fourier transform:
transverse gluonic profile

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

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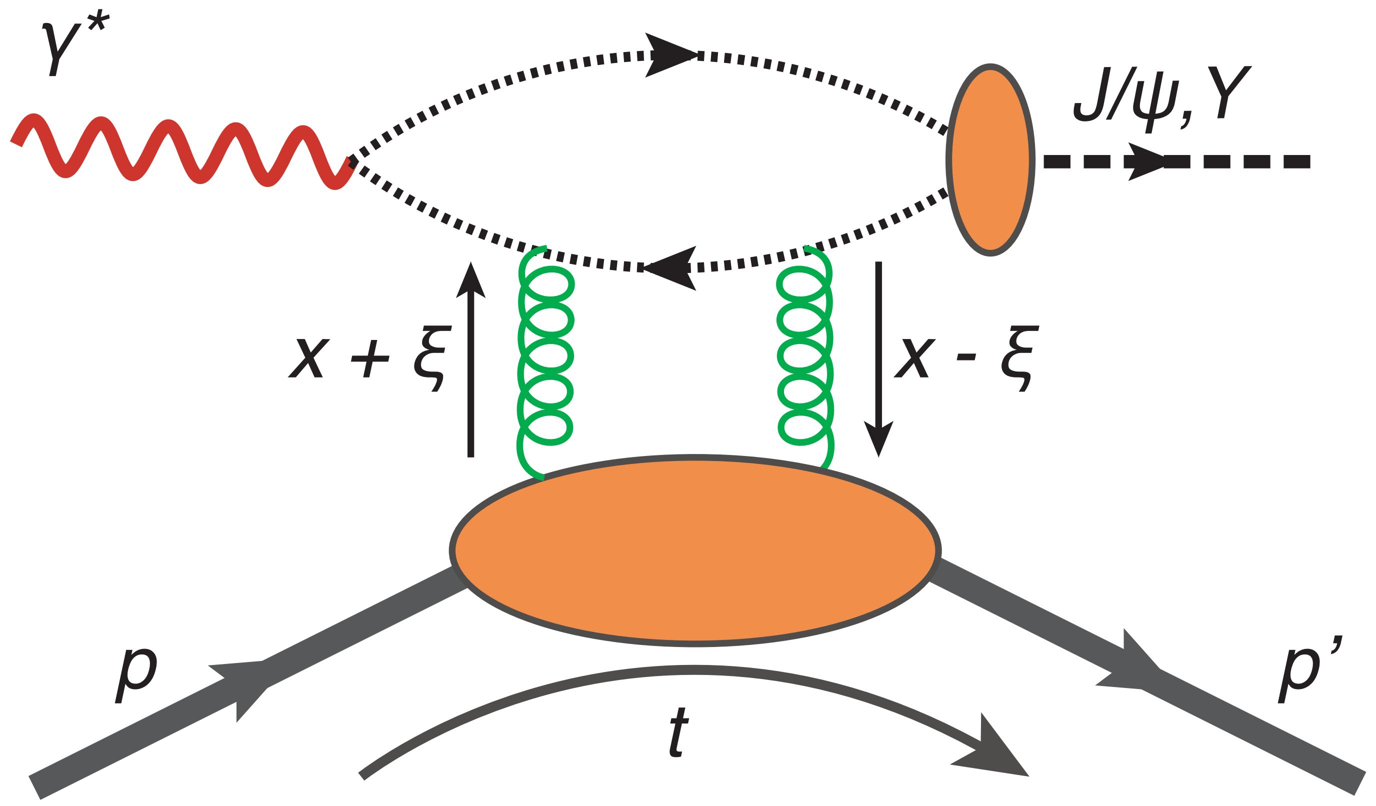

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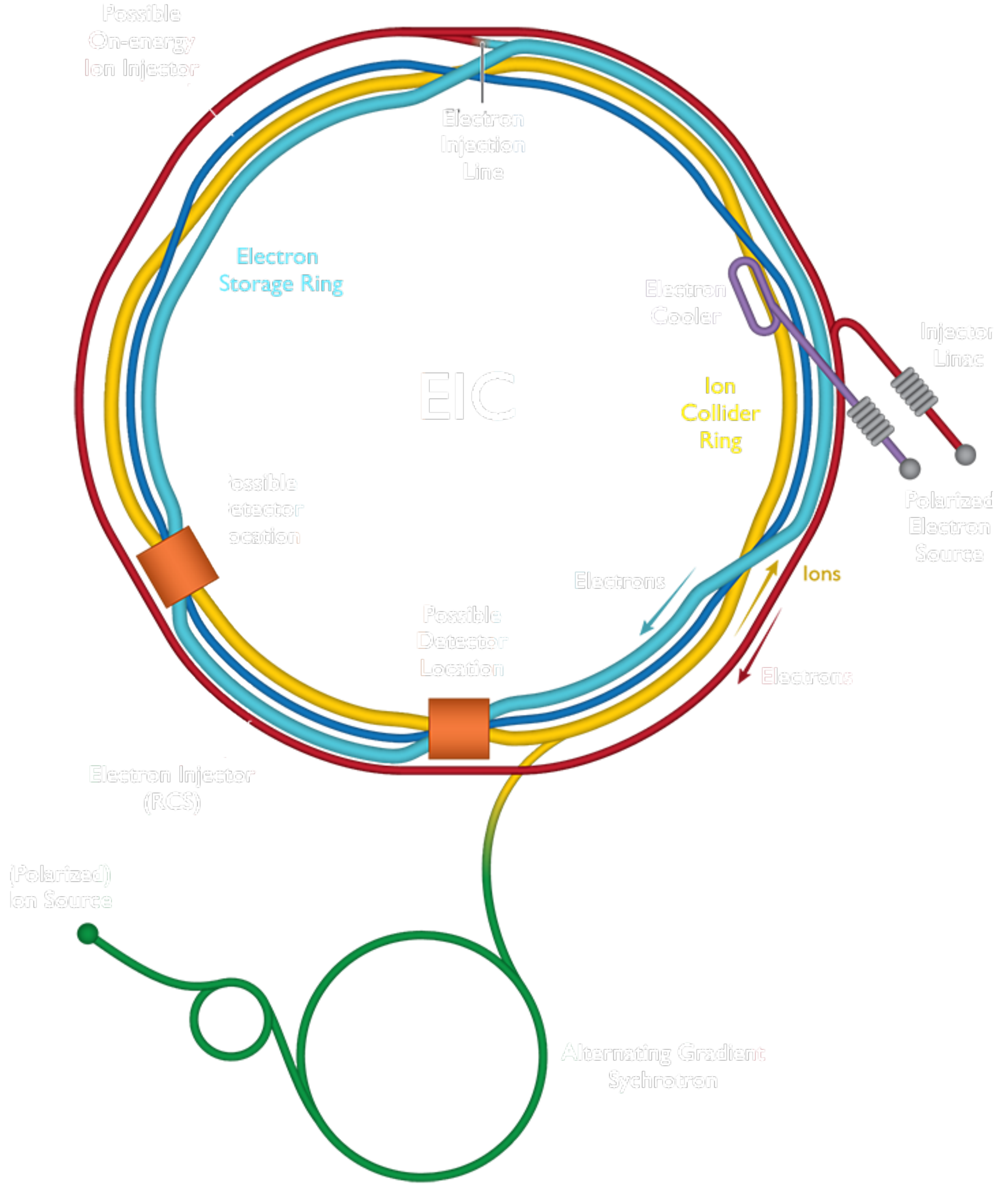
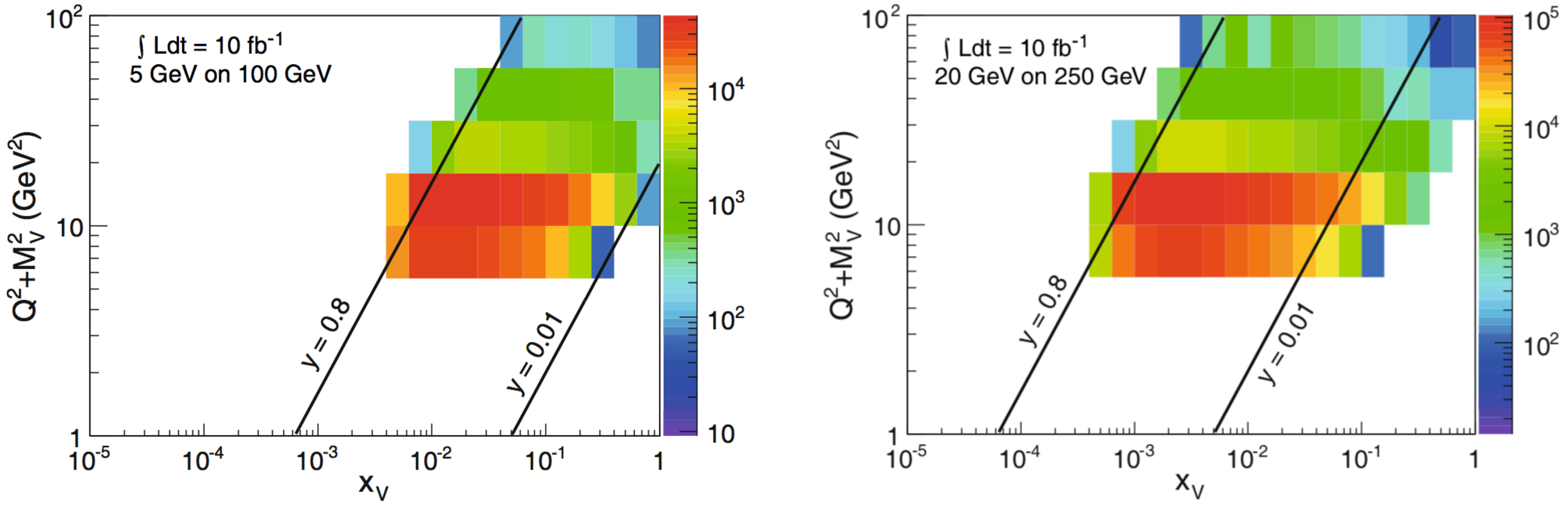
- Remarks:
  - **Simplest** possible GPD extraction
  - Intrinsic systematic uncertainty due to **extrapolation** outside of measured *t*-range
  - **NLO effects** could be significant
    - Corrections expected to be smaller for *Y(1s)* than for *J/ψ*

NOMINAL MACHINE/EXPERIMENT PARAMETERS

- Nominal parameters relevant to quarkonium production:
  - (Consistent with accelerator/detector specs from white-paper for J/ψ production)
  - **Luminosity: 10/100 fb^{-1}** (16/116 days @ 10^{34} cm^{-2}s^{-1})
  - **Acceptance**:
    - **Leptons**: pseudo-rapidity $|\eta| < 5$
    - **Recoil proton:** scattering angle $\theta > 3$ mrads
  - Resolution:
    - Angular < 0.5 mrad
    - Momentum < 1%



GLUON TOMOGRAPHY WITH *J/Ψ*



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

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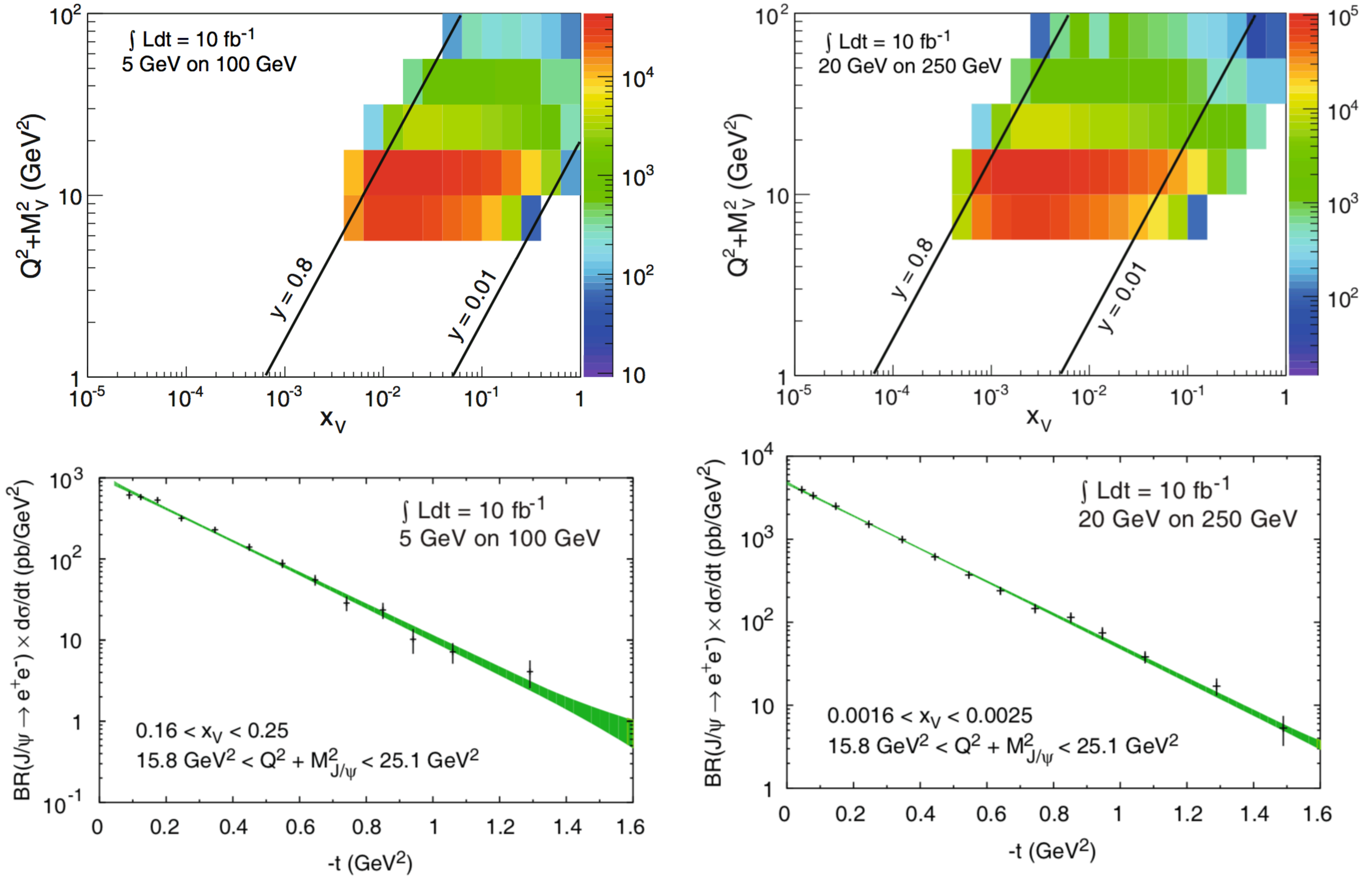

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***t*-spectra**

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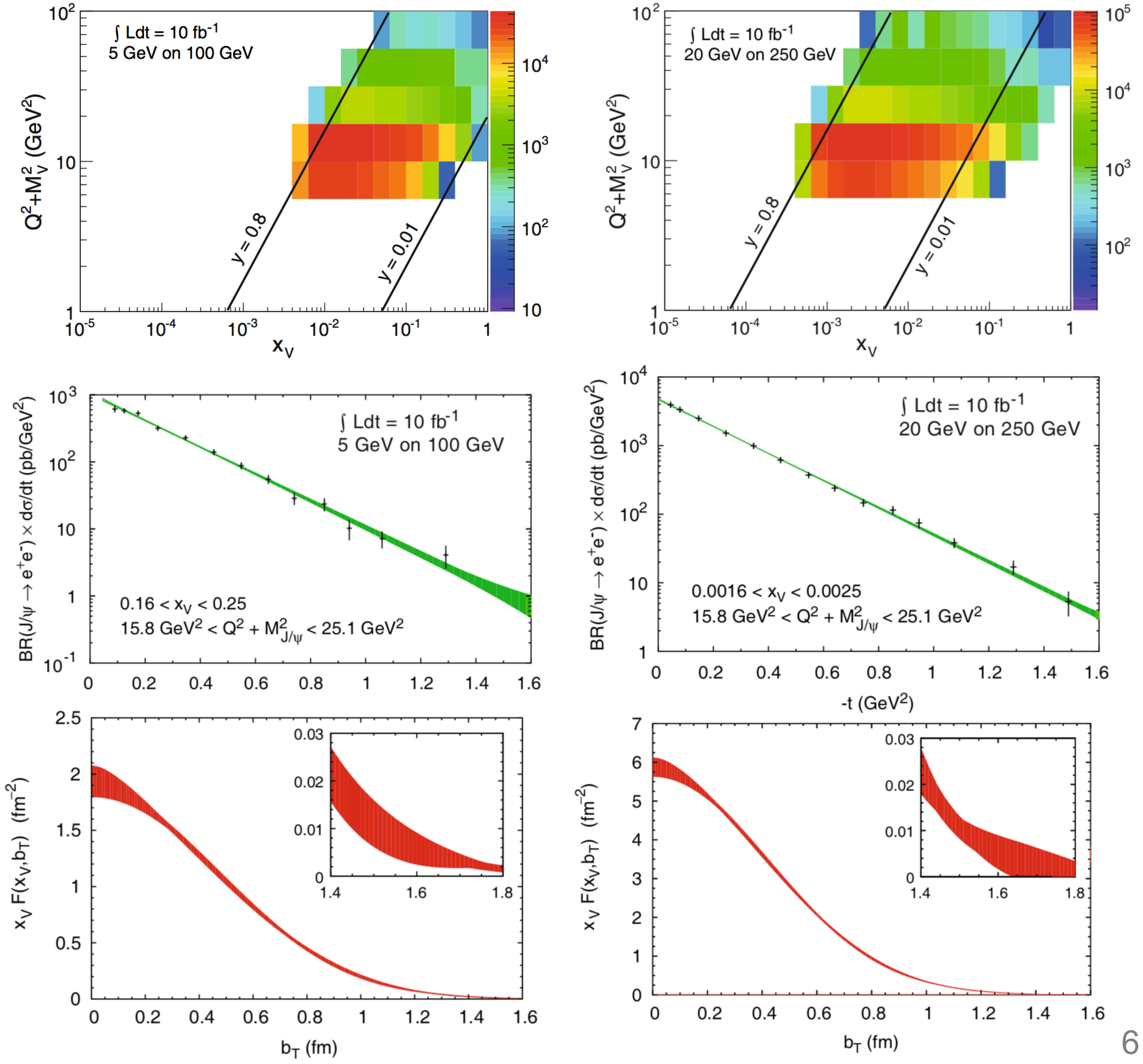

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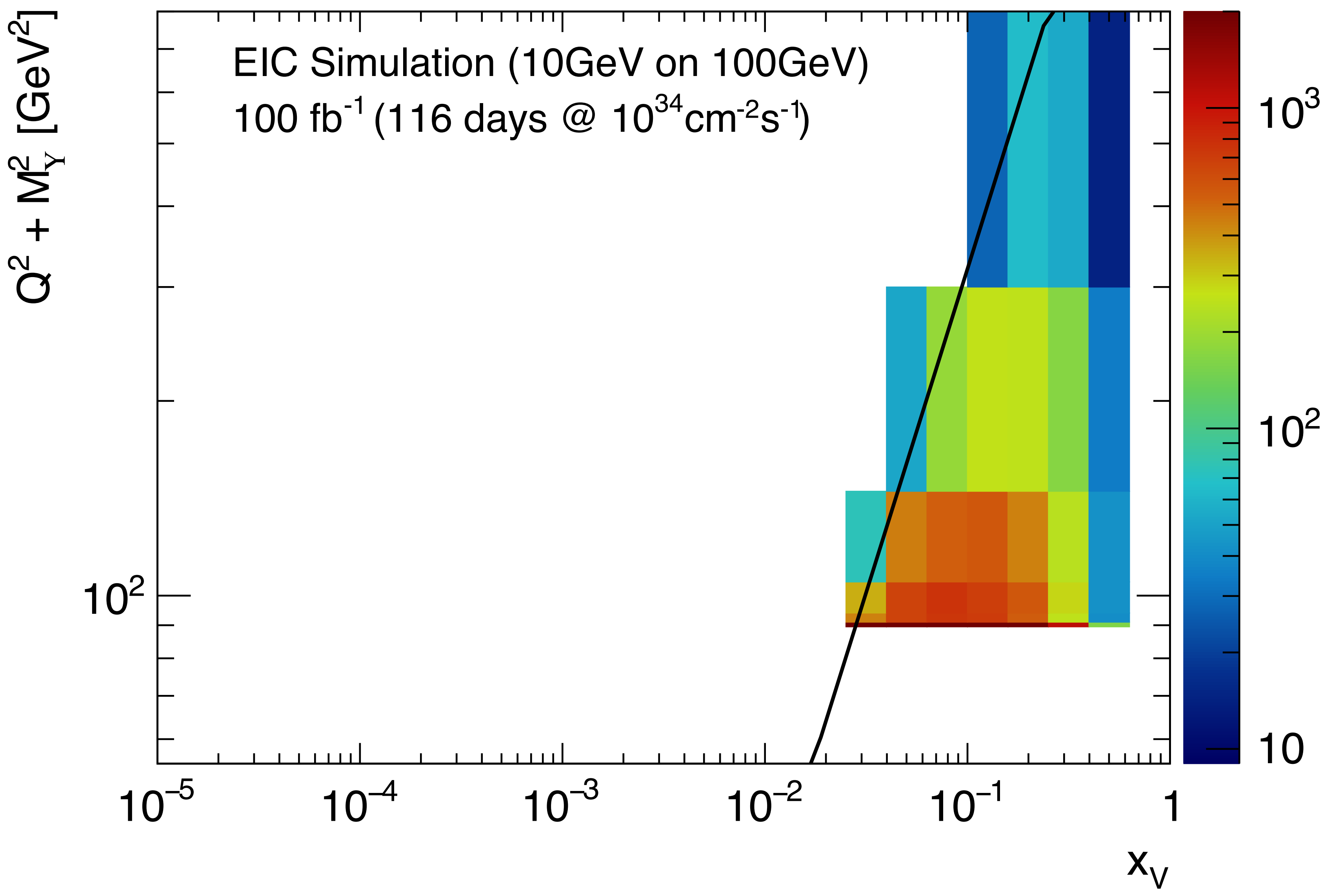
***t*-spectra**

Normalized average gluon density

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

GLUON TOMOGRAPHY WITH *Υ(1S)*



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

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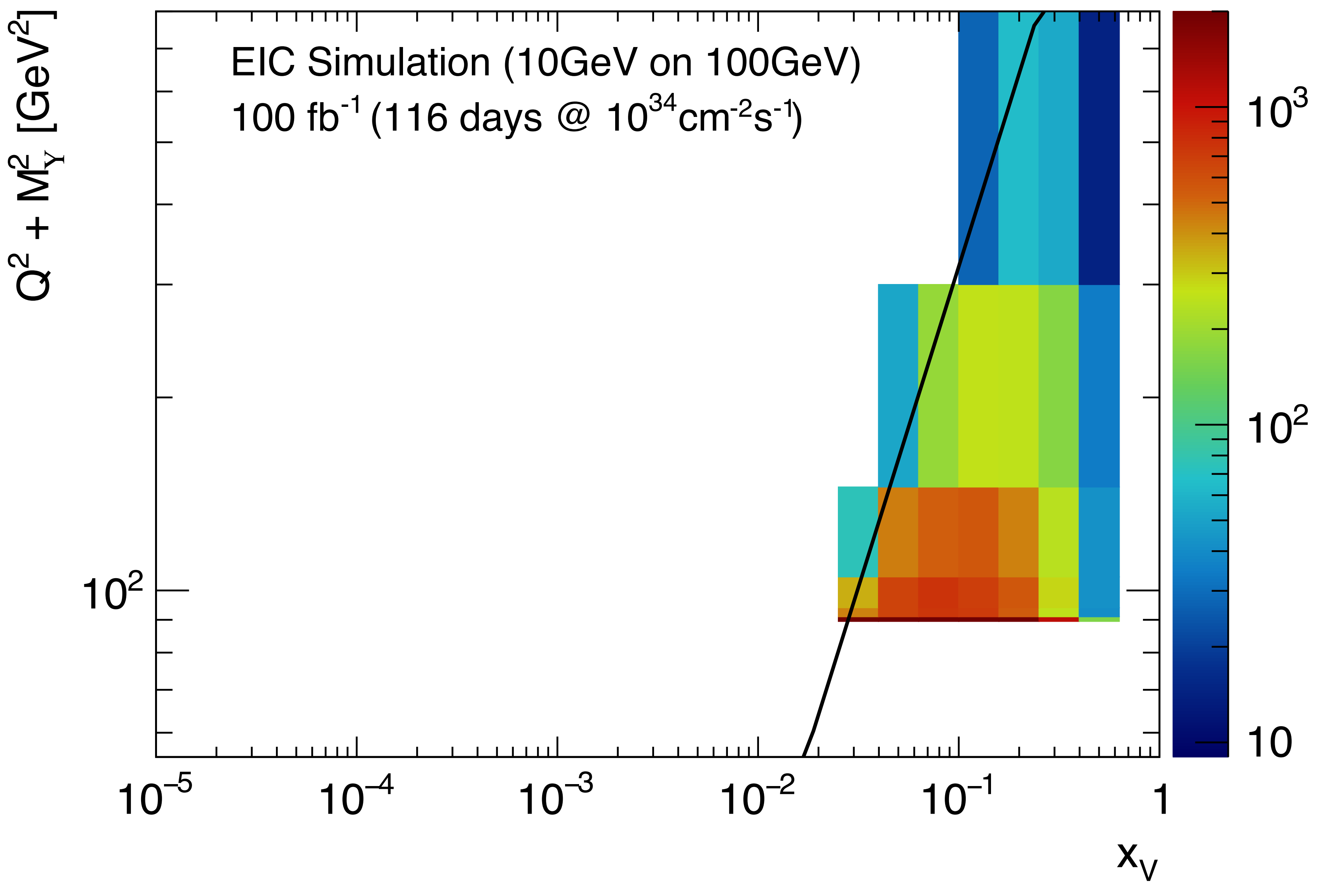
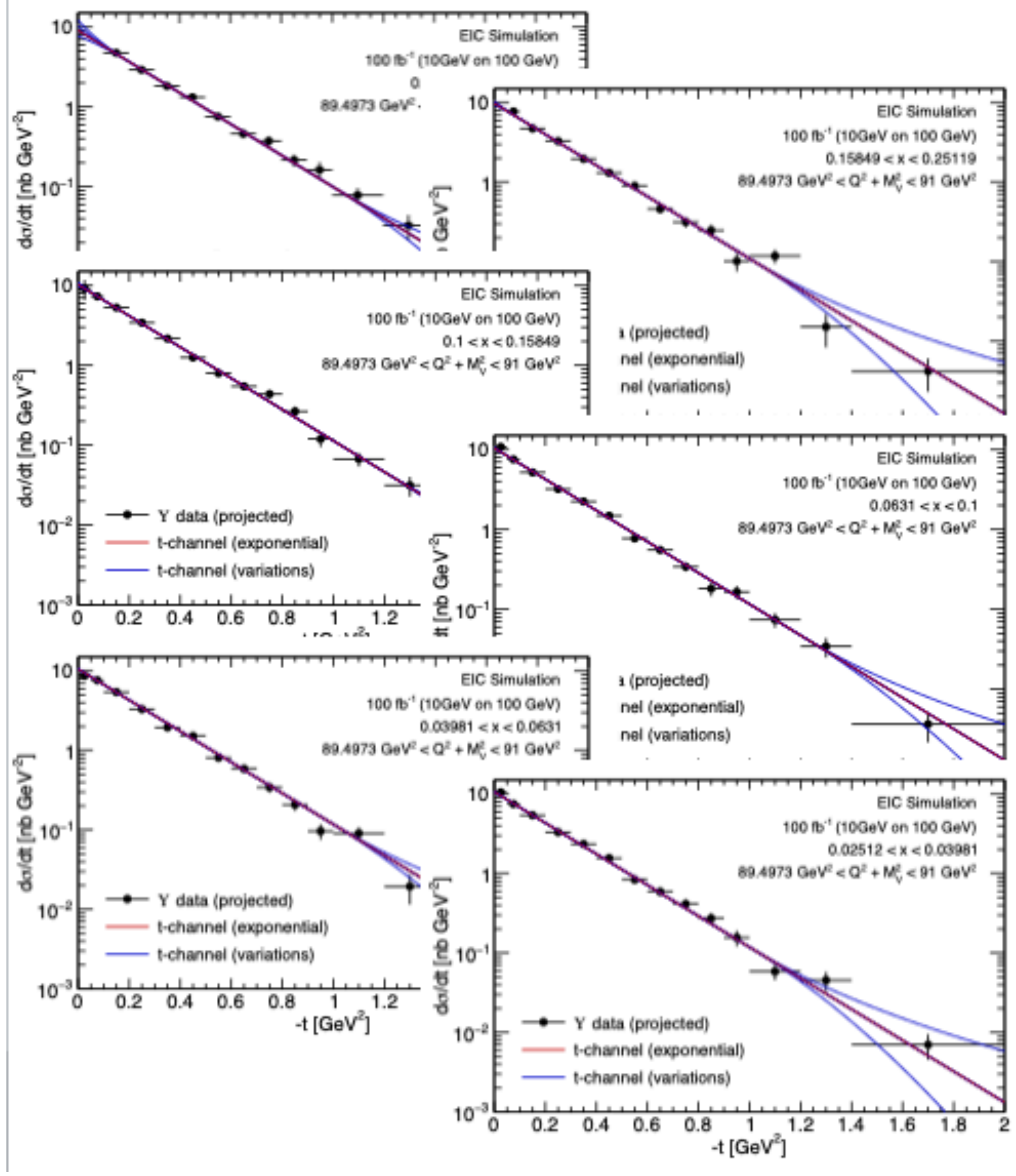
GLUON TOMOGRAPHY WITH *Y(1S)*





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***t*-spectrum**

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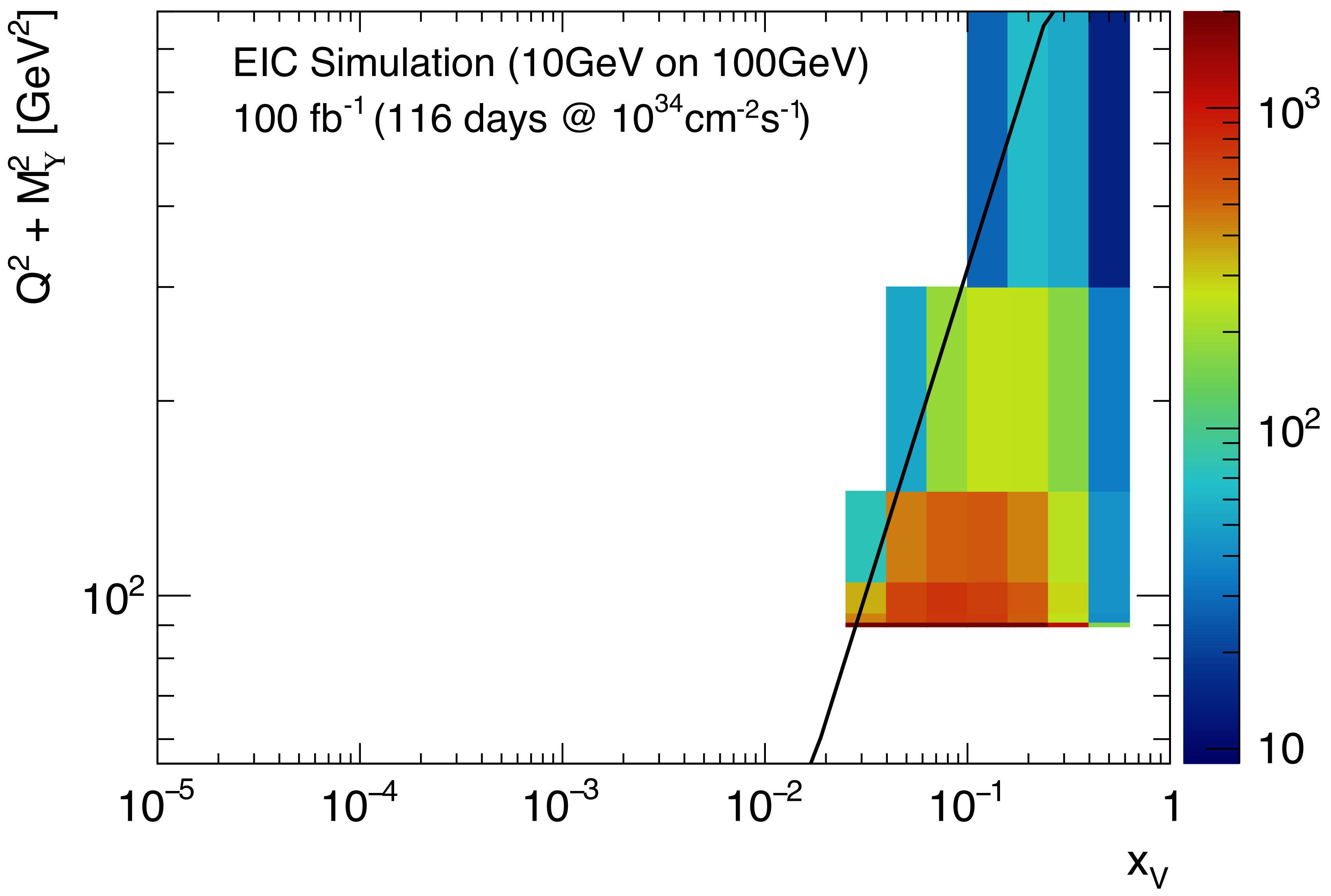

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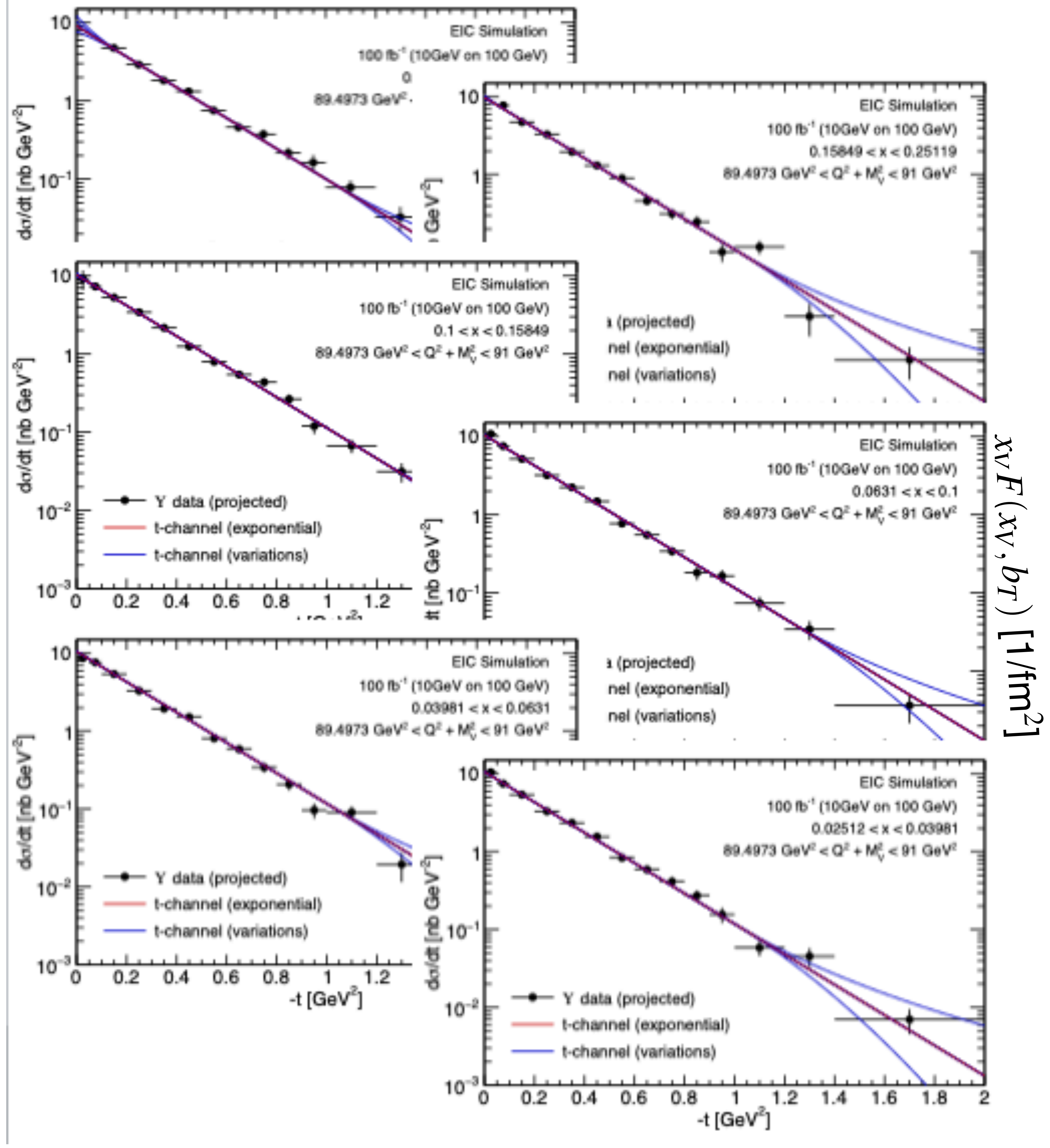
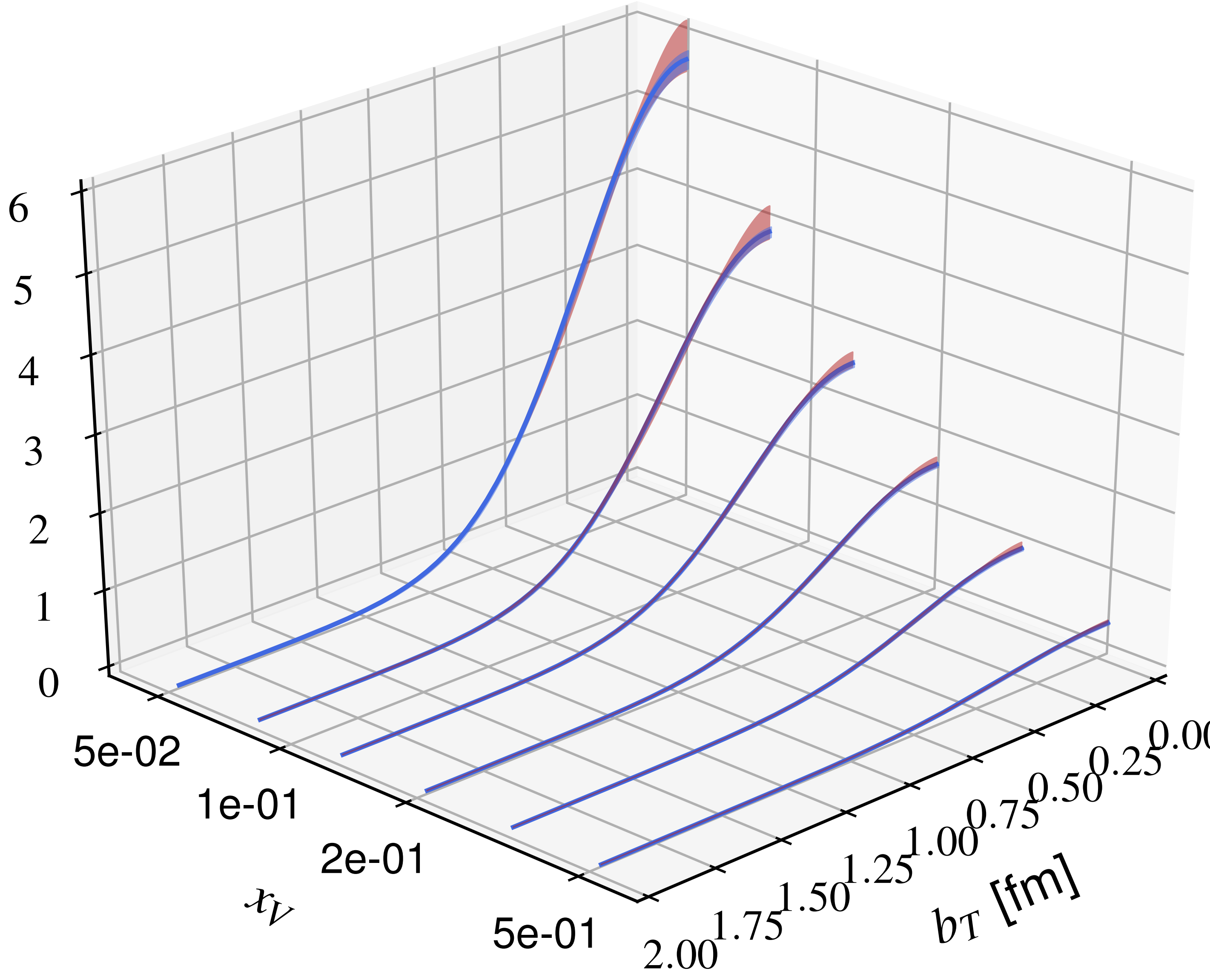
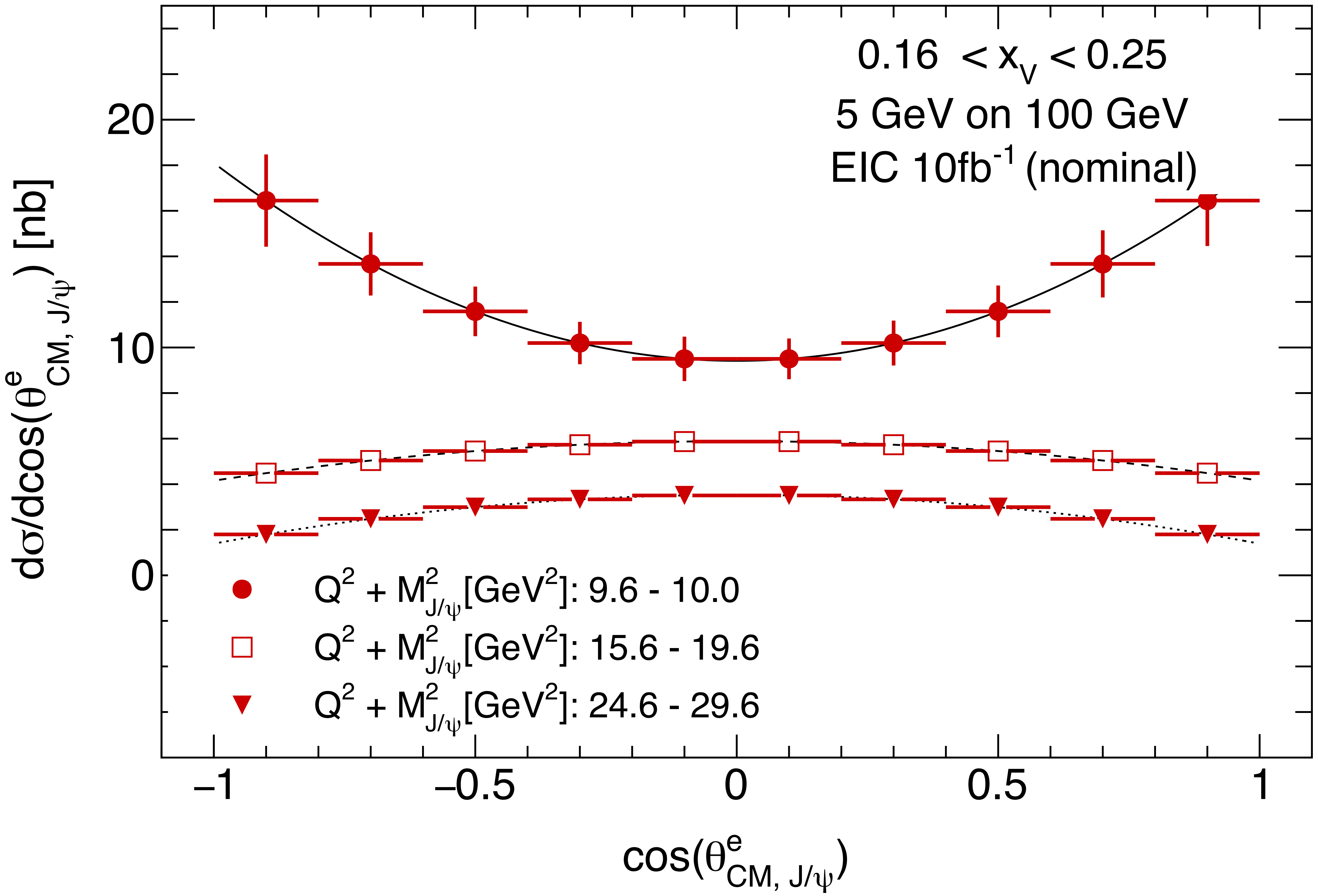




***t*-spectrum** → **Average gluon density**

L-T SEPARATION AND Q² DEPENDENCE OF R

Using S-channel helicity conservation



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

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

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

MONTE-CARLO GENERATOR

lAger l/A event generator

- Meant to be a general purpose generator
- Currently implements various models for J/ψ and Υ production
- Available to the public

I/A-event Generator

This is the Argonne generic l/A-event generator (`lAger`), a flexible MC generator system to simulate electro- and photo-production off nucleons and nuclei.

Below you can find an overview of the release versions, as well as a short tutorial and copyright notice. If you use lAger to generate data used in a presentation or an article in a scientific publication, please cite:

S. Joosten, Argonne l/A-event Generator (2020), GitLab repository, https://eicweb.phy.anl.gov/monte_carlo/lager

Versions

- v3.1.0 First stable release version of `lAger` .

Tutorial

Setup of the lager singularity container on your system:

The default mode to run the generator is through singularity. To setup the generator on your system, first ensure singularity is installed. Then follow these instructions:

1. Clone this repository and checkout the desired stable release (e.g. v3.1.0)

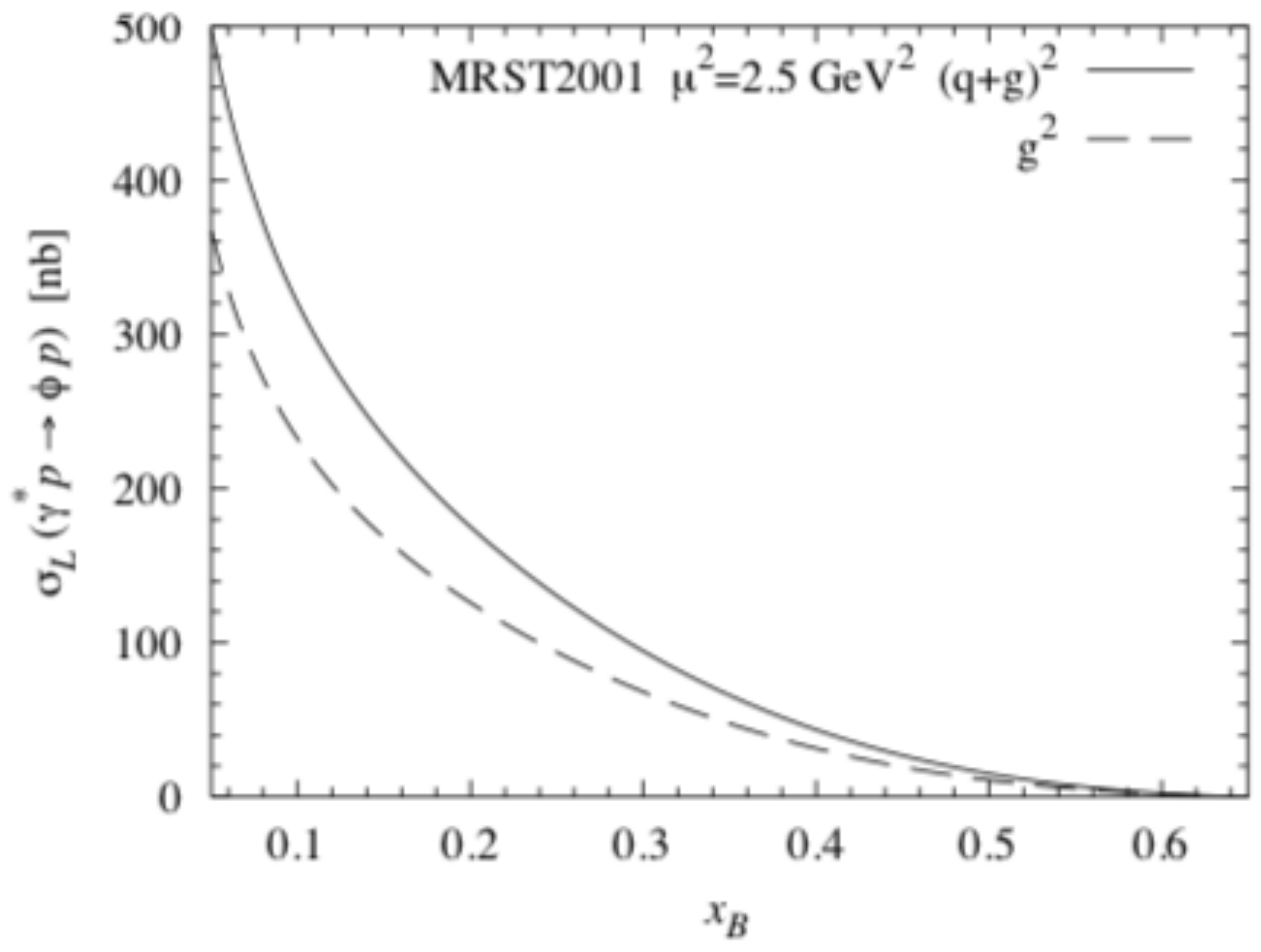
```
git clone https://eicweb.phy.anl.gov/monte_carlo/lager.git
cd lager && git checkout v3.1.0
```

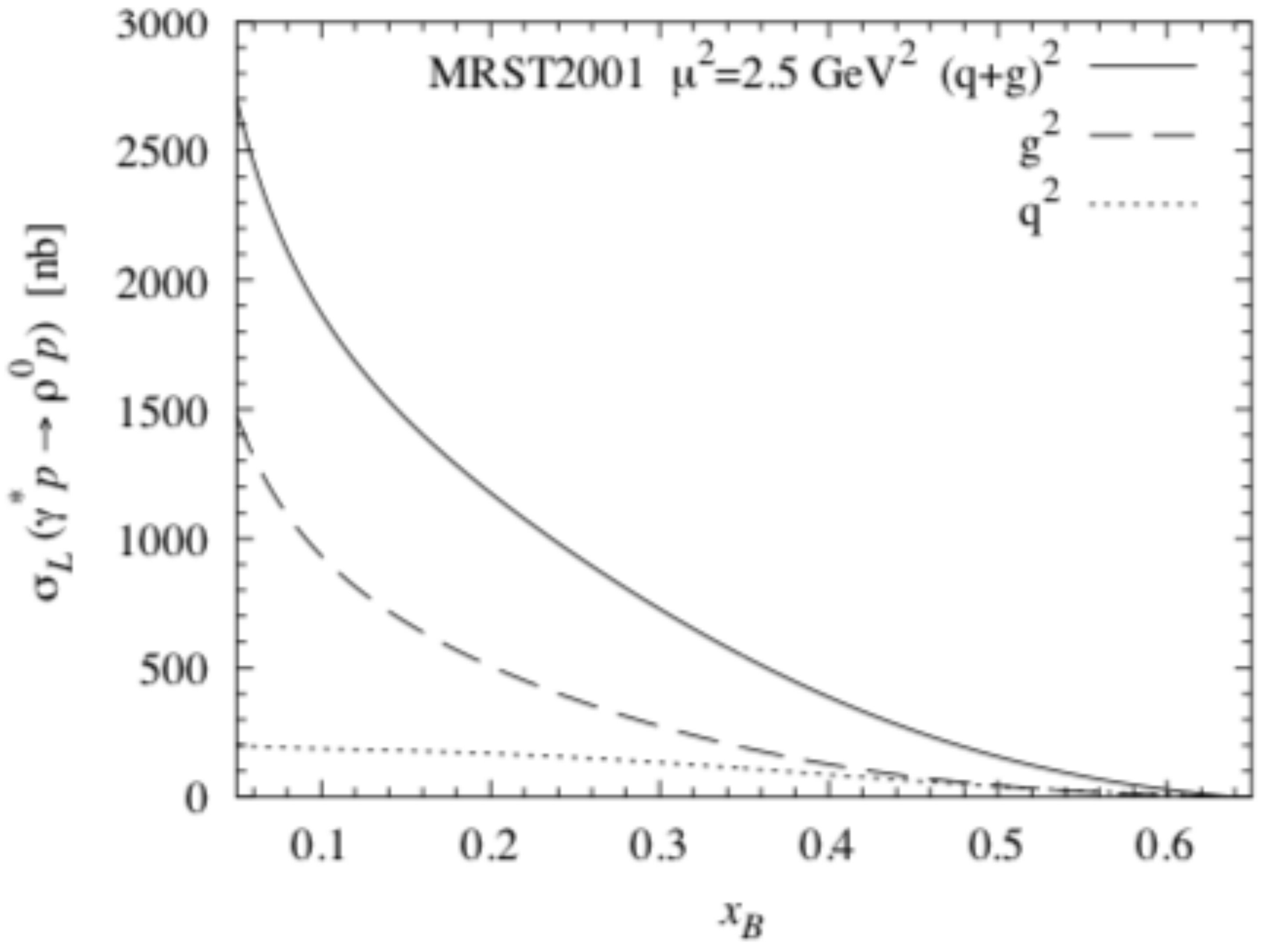
2. Run the `deploy.py` script to install the container to a prefix of your choice, e.g. `$HOME/local/opt/lager` .

```
./deploy.py $HOME/local/opt/lager
```

https://eicweb.phy.anl.gov/monte_carlo/lager

VECTOR MESON PRODUCTION BEYOND QUARKONIA





M. Diehl, *et al.*, PRD 72, 034034 (2005)

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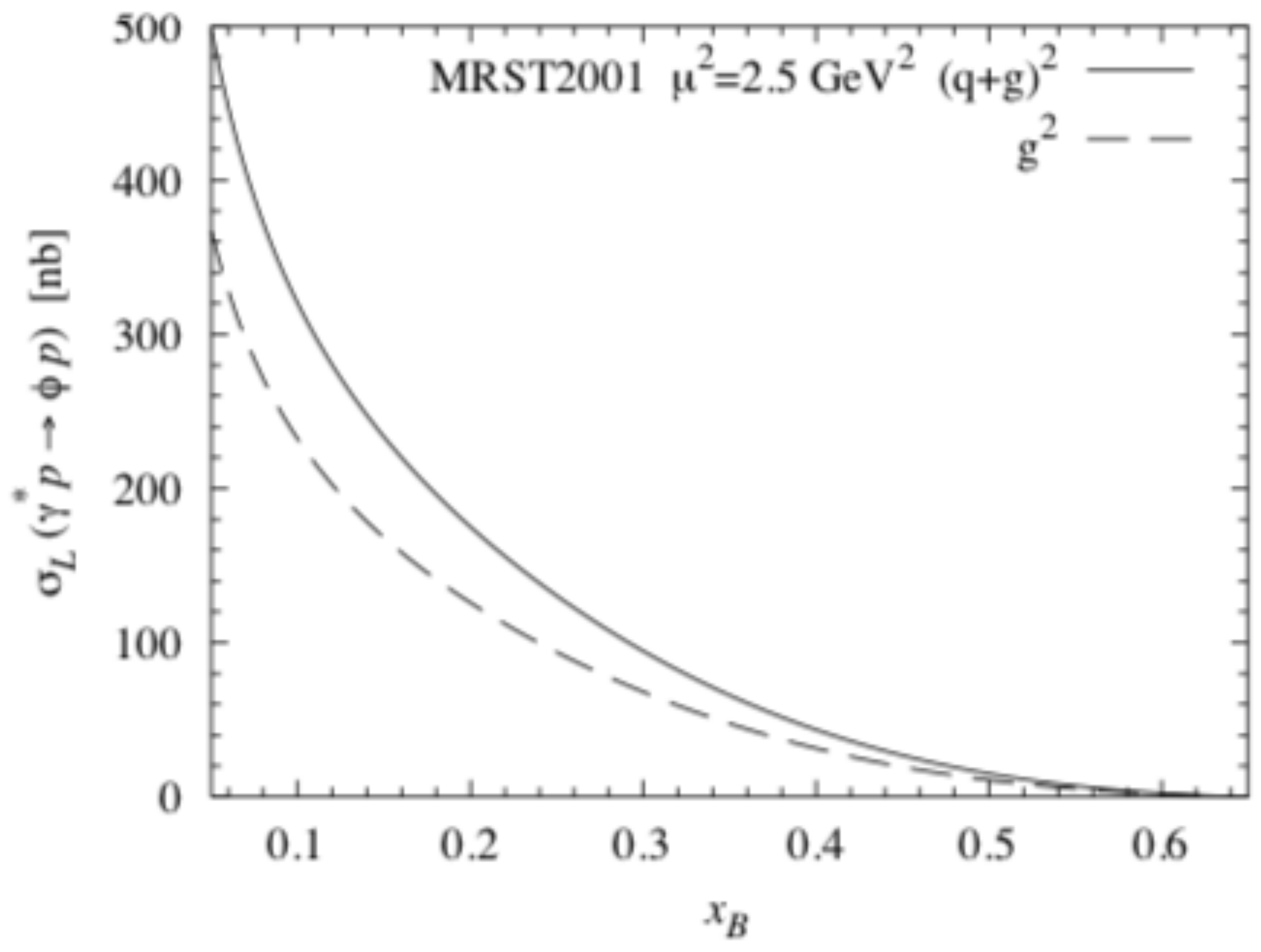
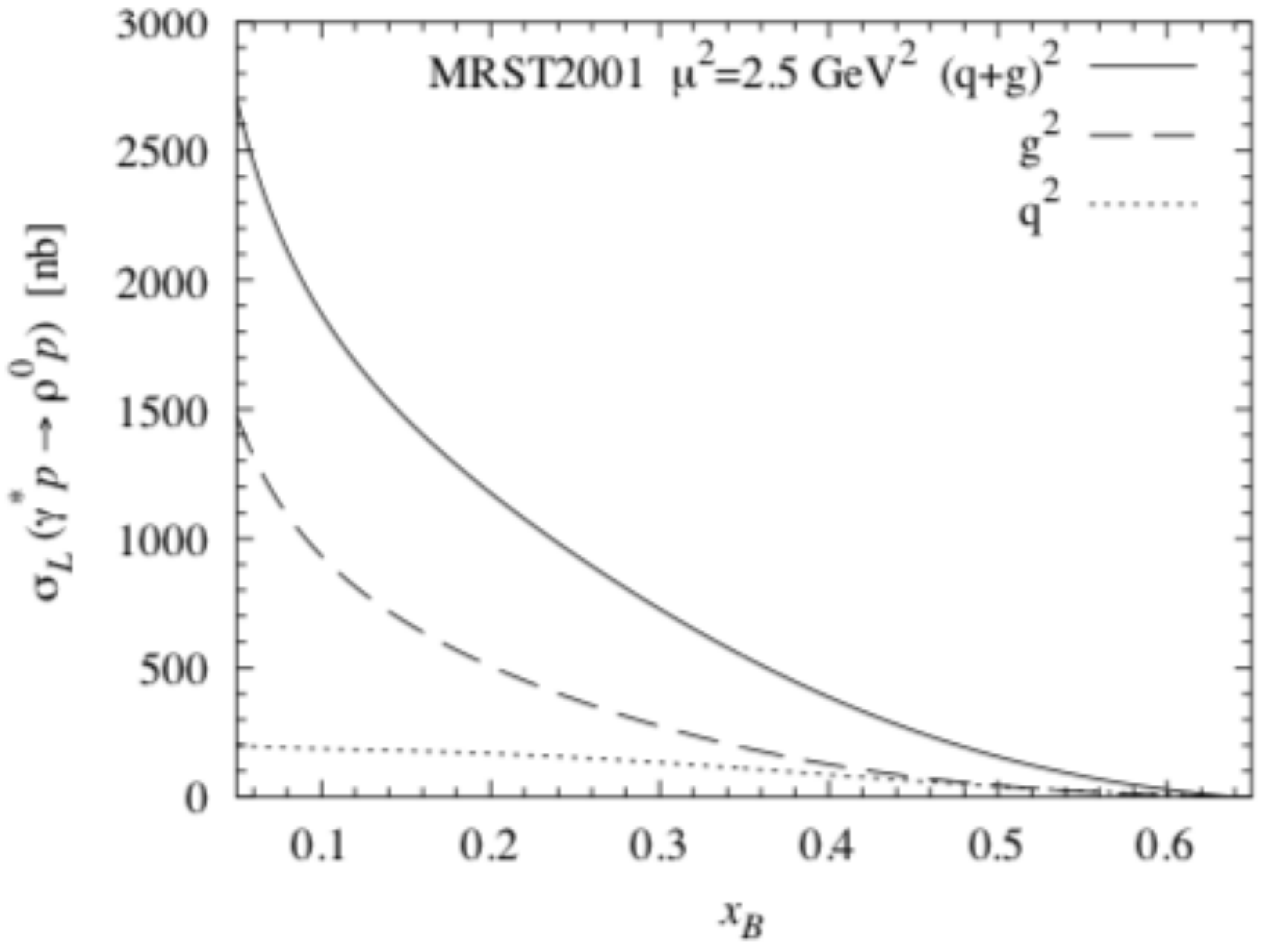
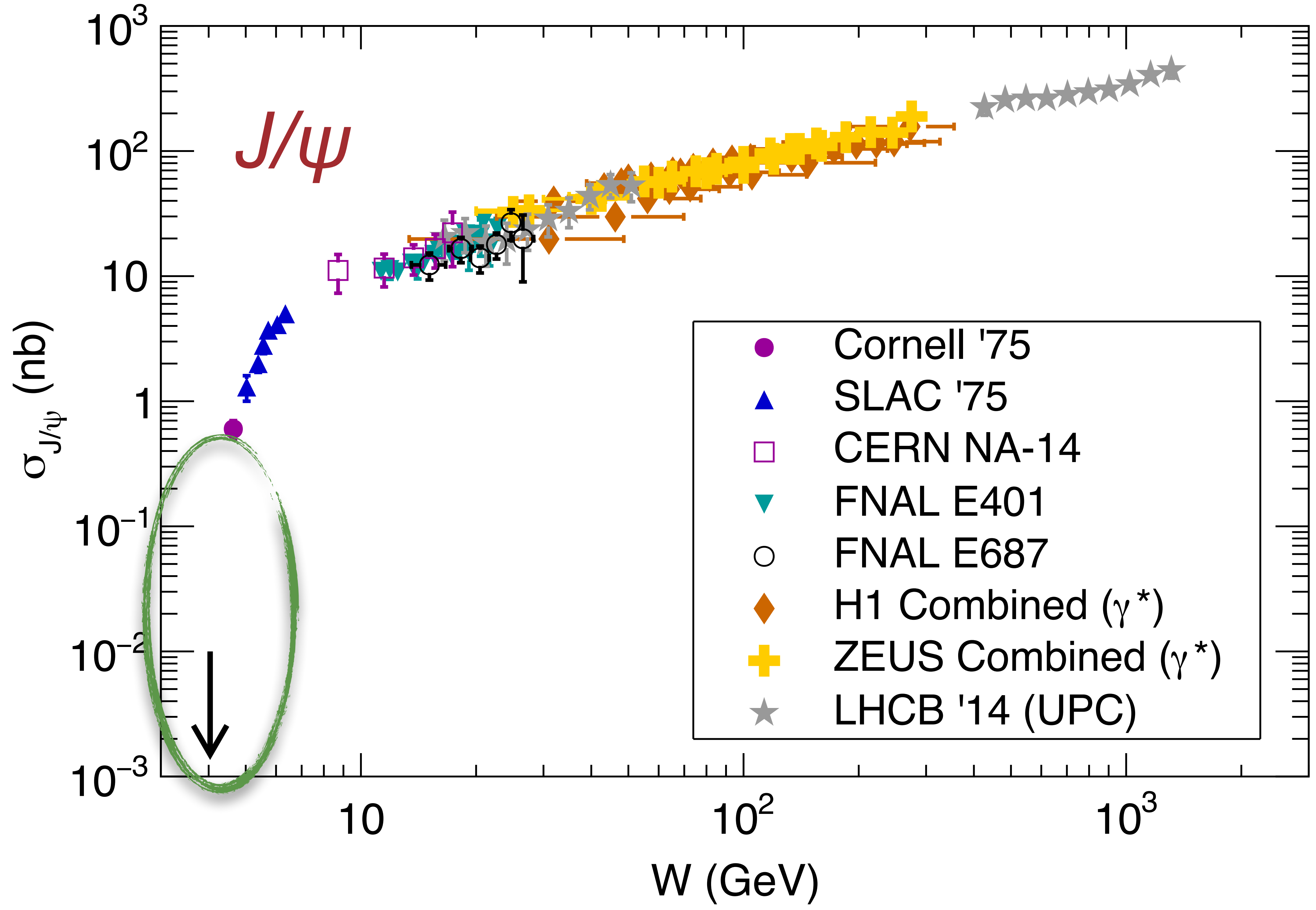
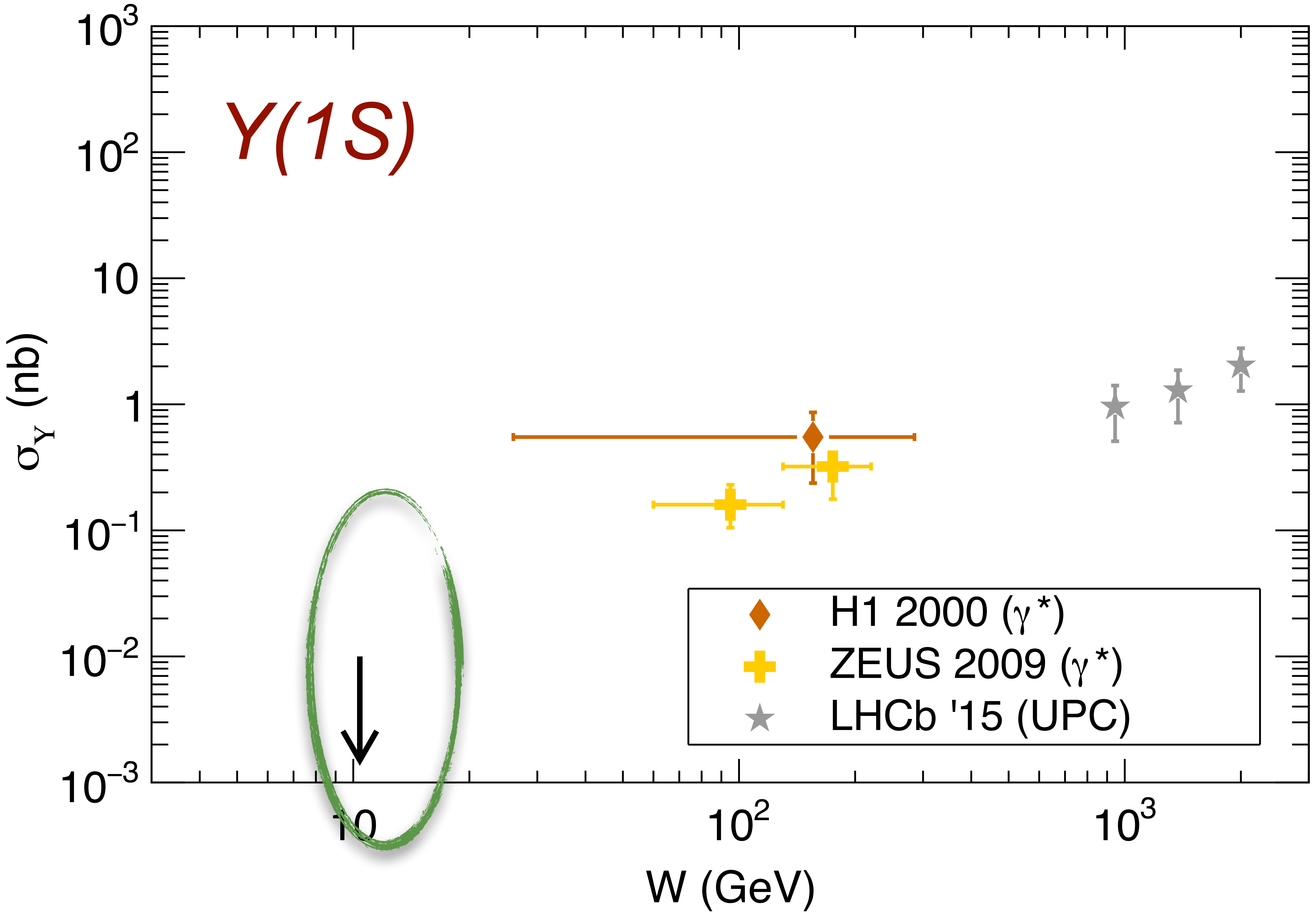




M. Diehl, *et al.*, PRD 72, 034034 (2005)

- Exclusive *ρ, ω* and *φ* production uniquely sensitive to different combinations of quarks and gluons
- Extra independent lever-arm for imaging
- Should be produced plenty (cross section much higher than that for quarkonia)
- PID requirements for final states similar to SIDIS experiments

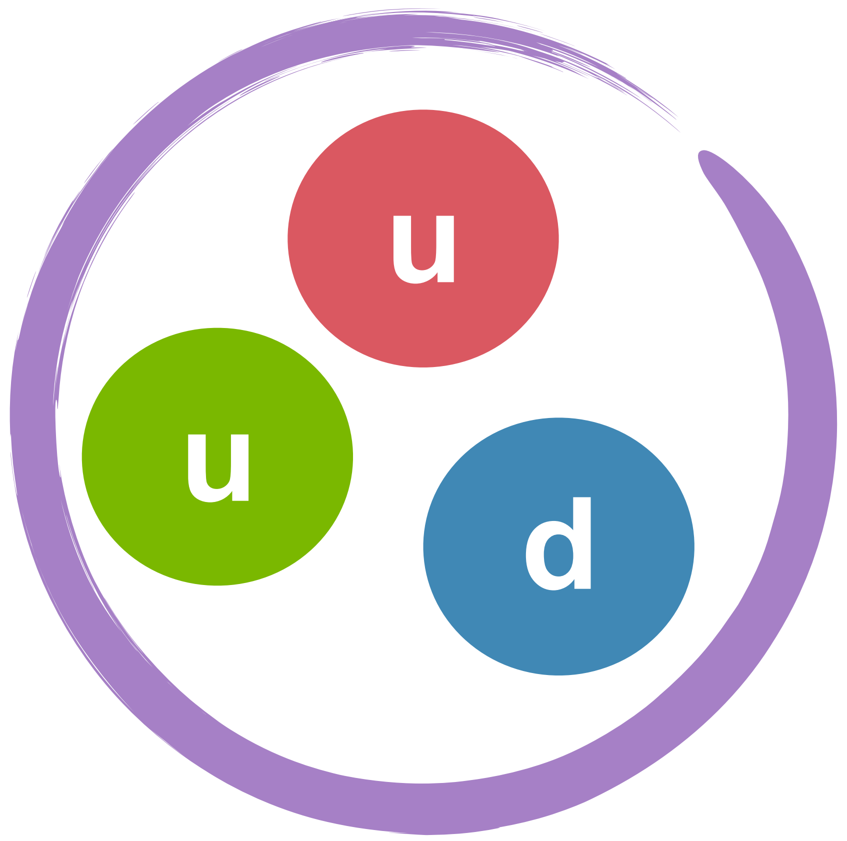


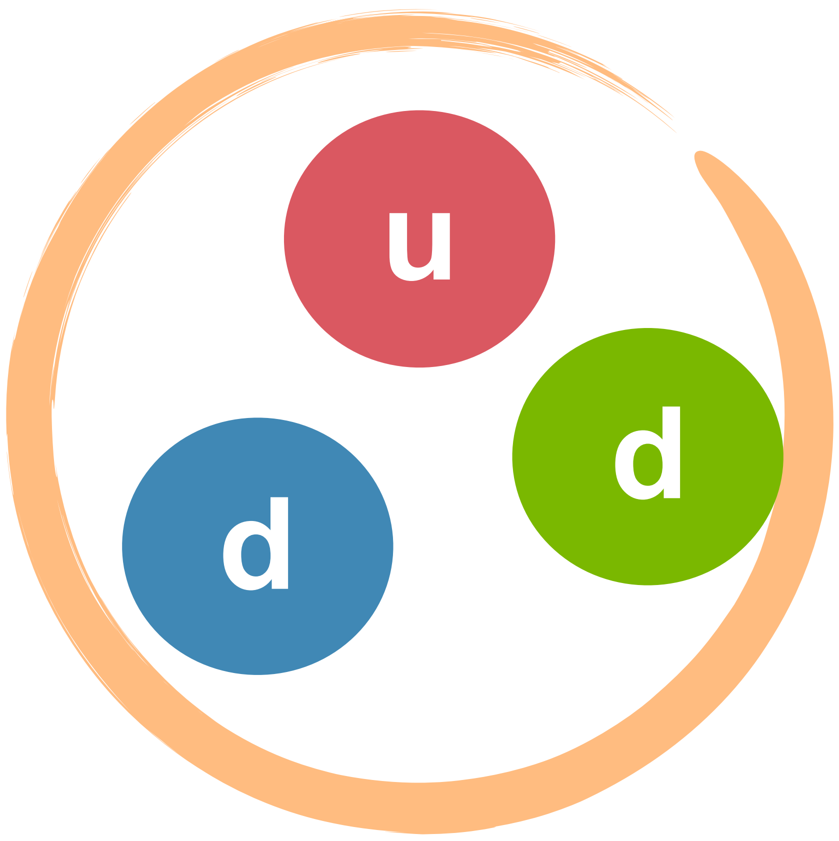


QUARKONIUM PRODUCTION NEAR THRESHOLD

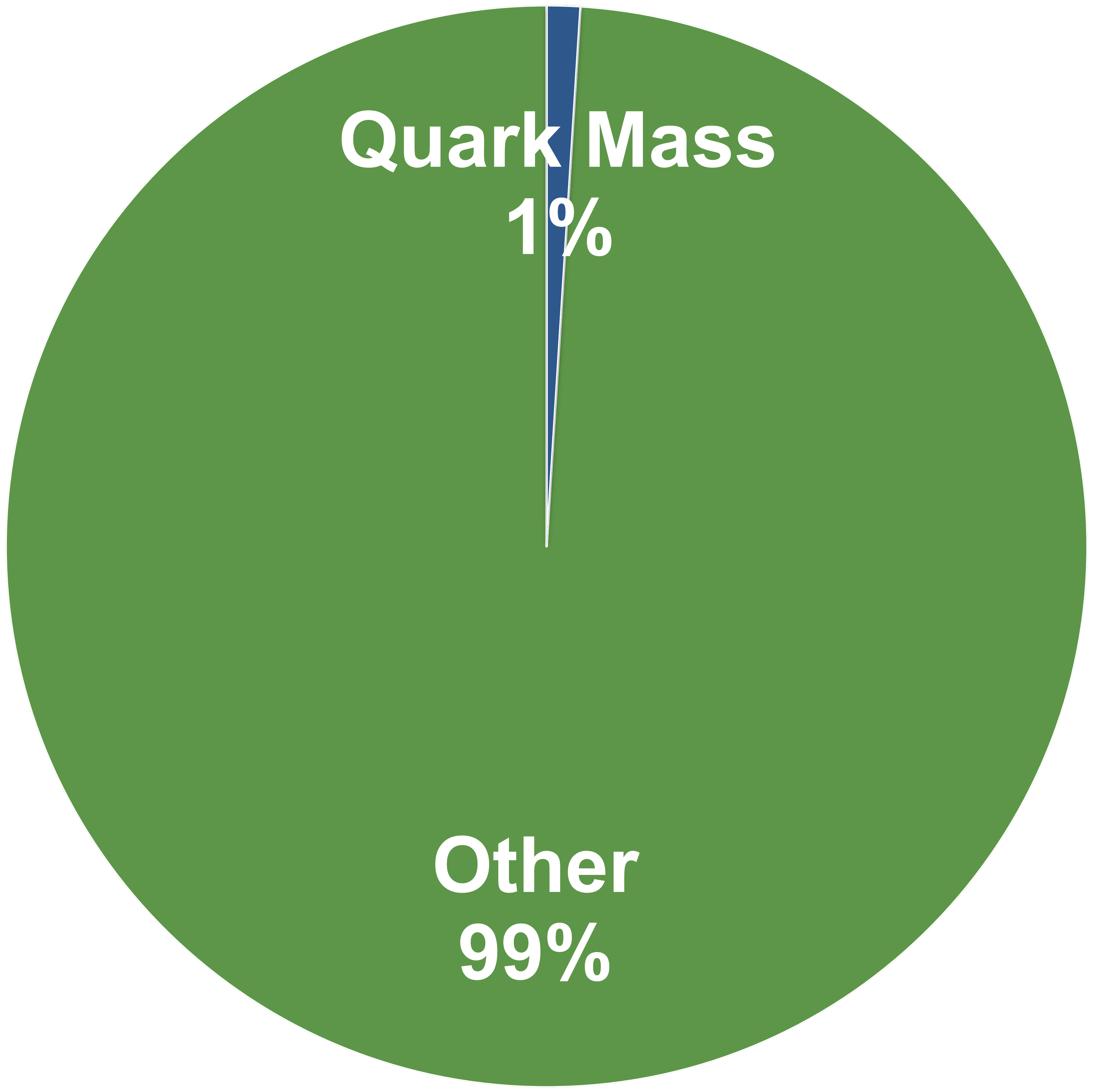
THE NUCLEON IN QCD

99% of the mass of the visible universe

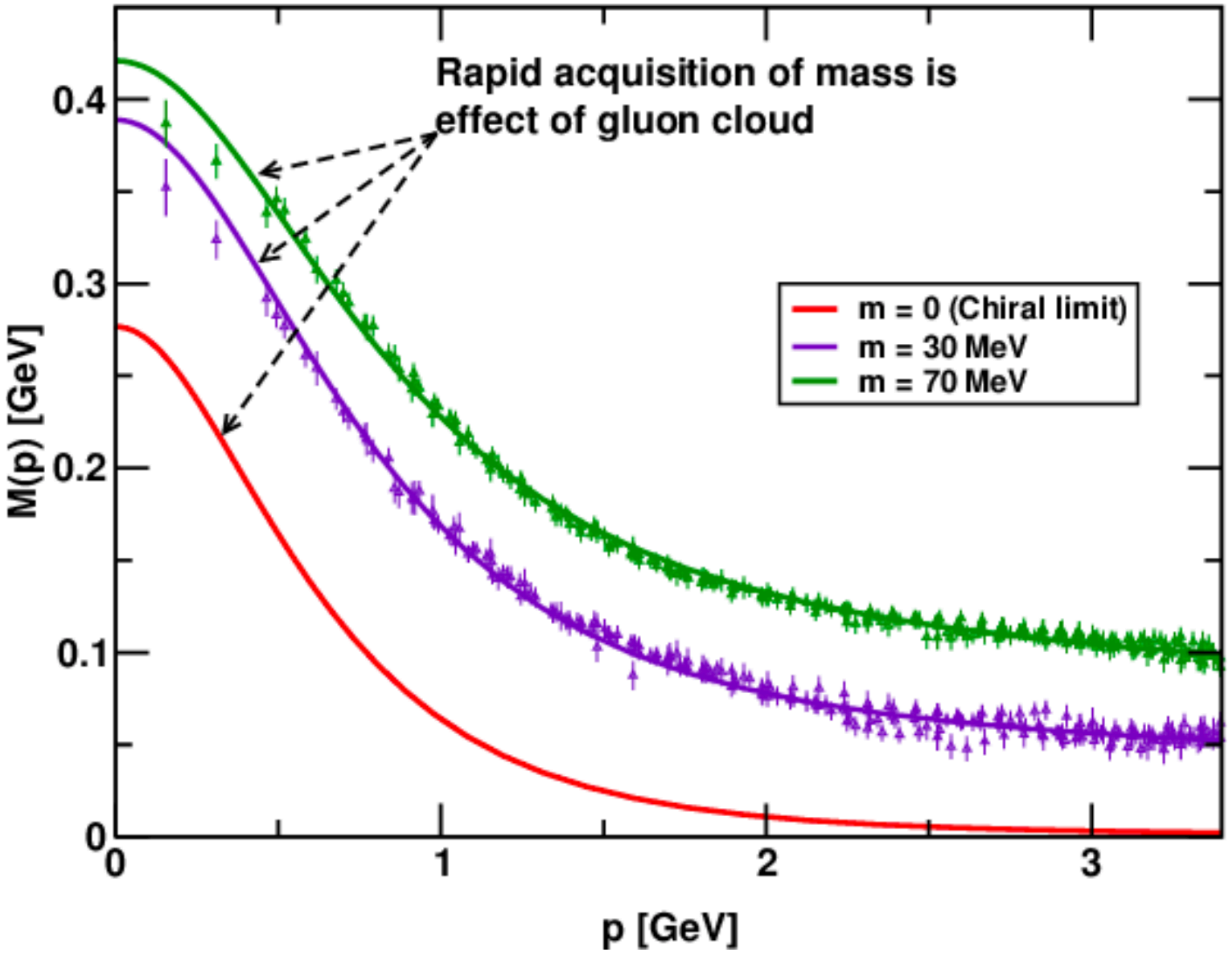




- Fundamental building blocks of matter
- Bound states of QCD Lagrangian
- Three **valence quarks** needed to define quantum numbers **contribute only ~1% of its mass**



NUCLEON MASS IS AN EMERGENT PHENOMENON



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

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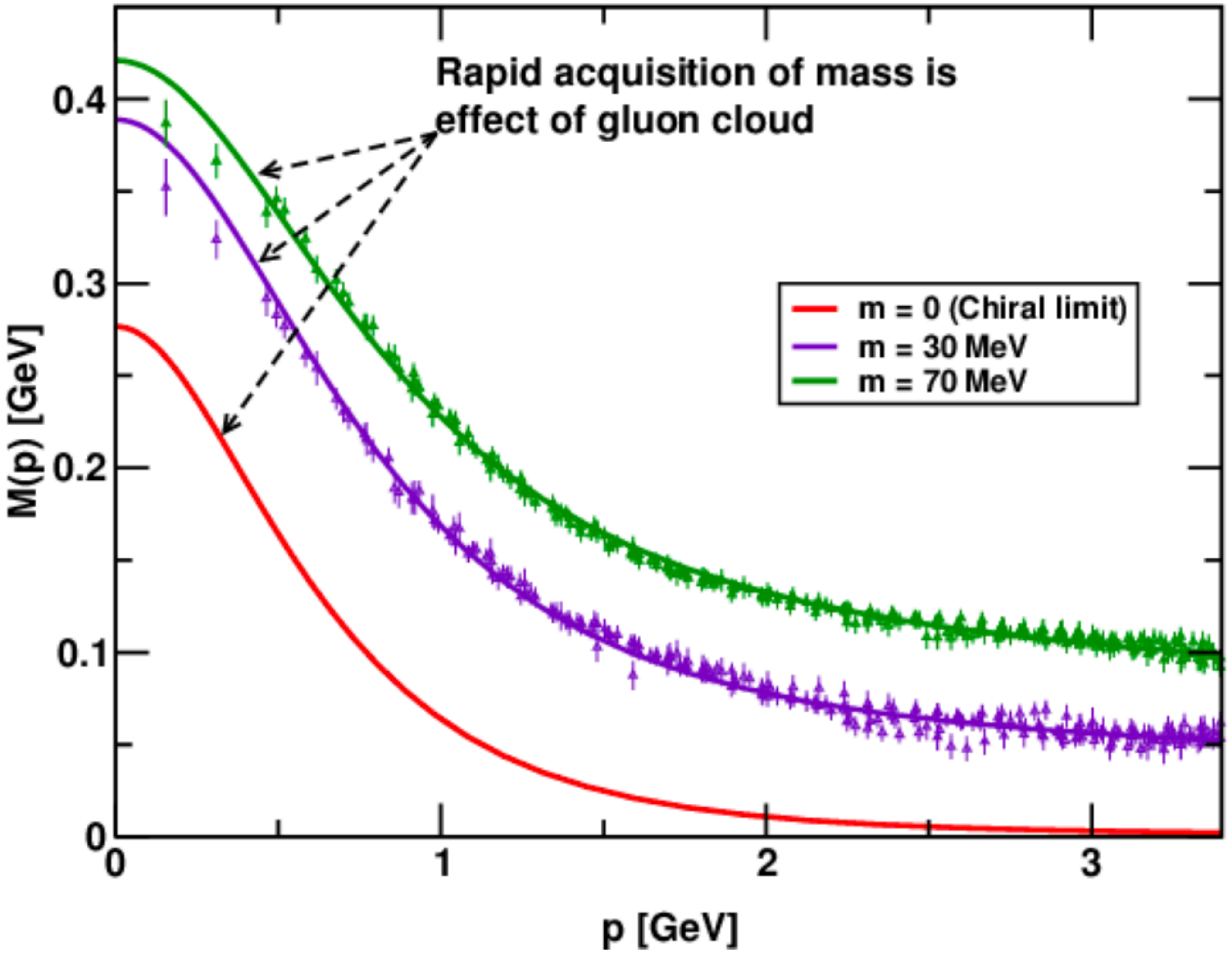

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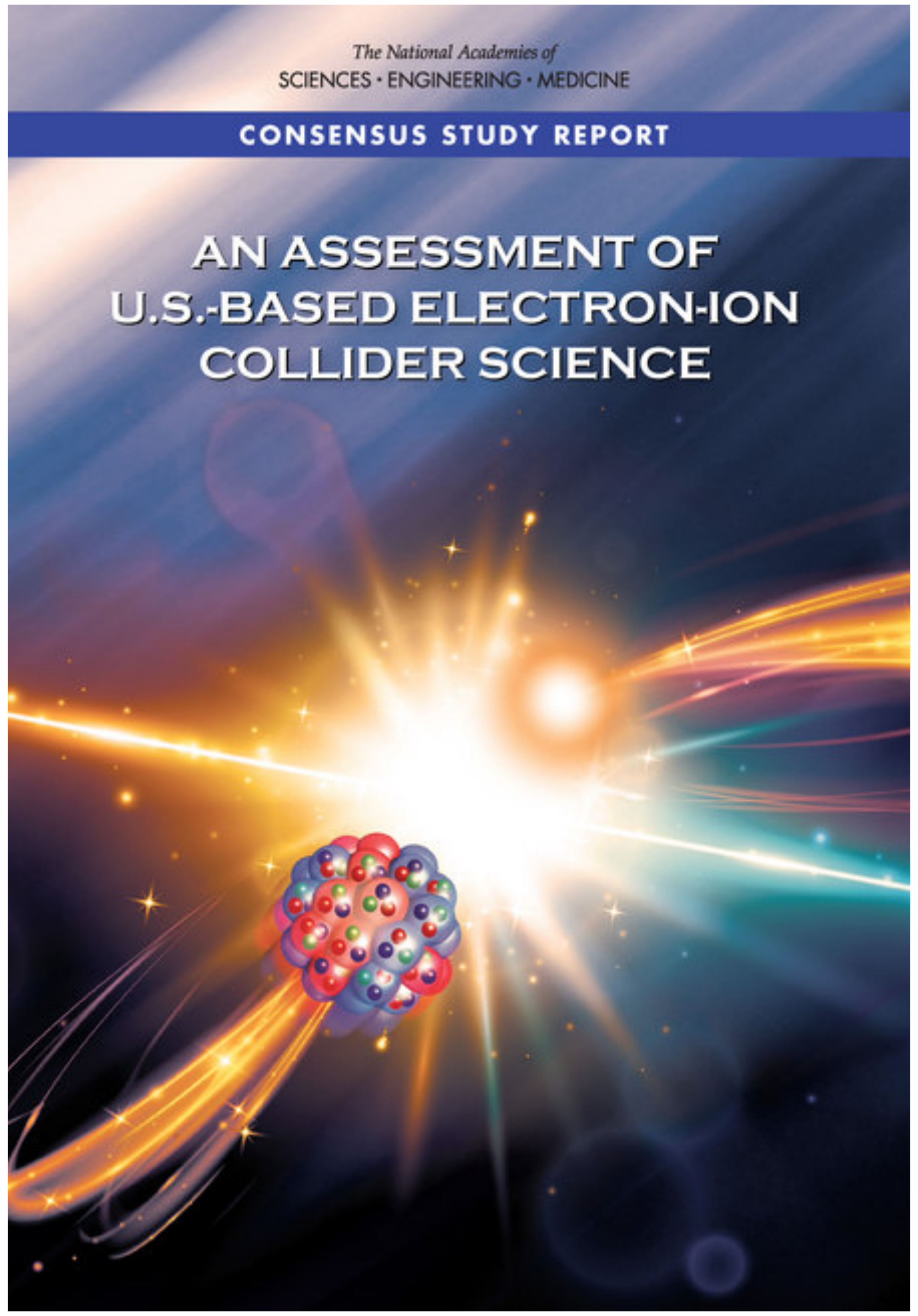
The Higgs mechanism is largely irrelevant in “normal” matter!

NAS CHARGE FOR EIC



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

PROTON MASS: TRACE DECOMPOSITION

Why is the proton mass non-vanishing?

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

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

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

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

Trace Anomaly **Light Quark Mass**

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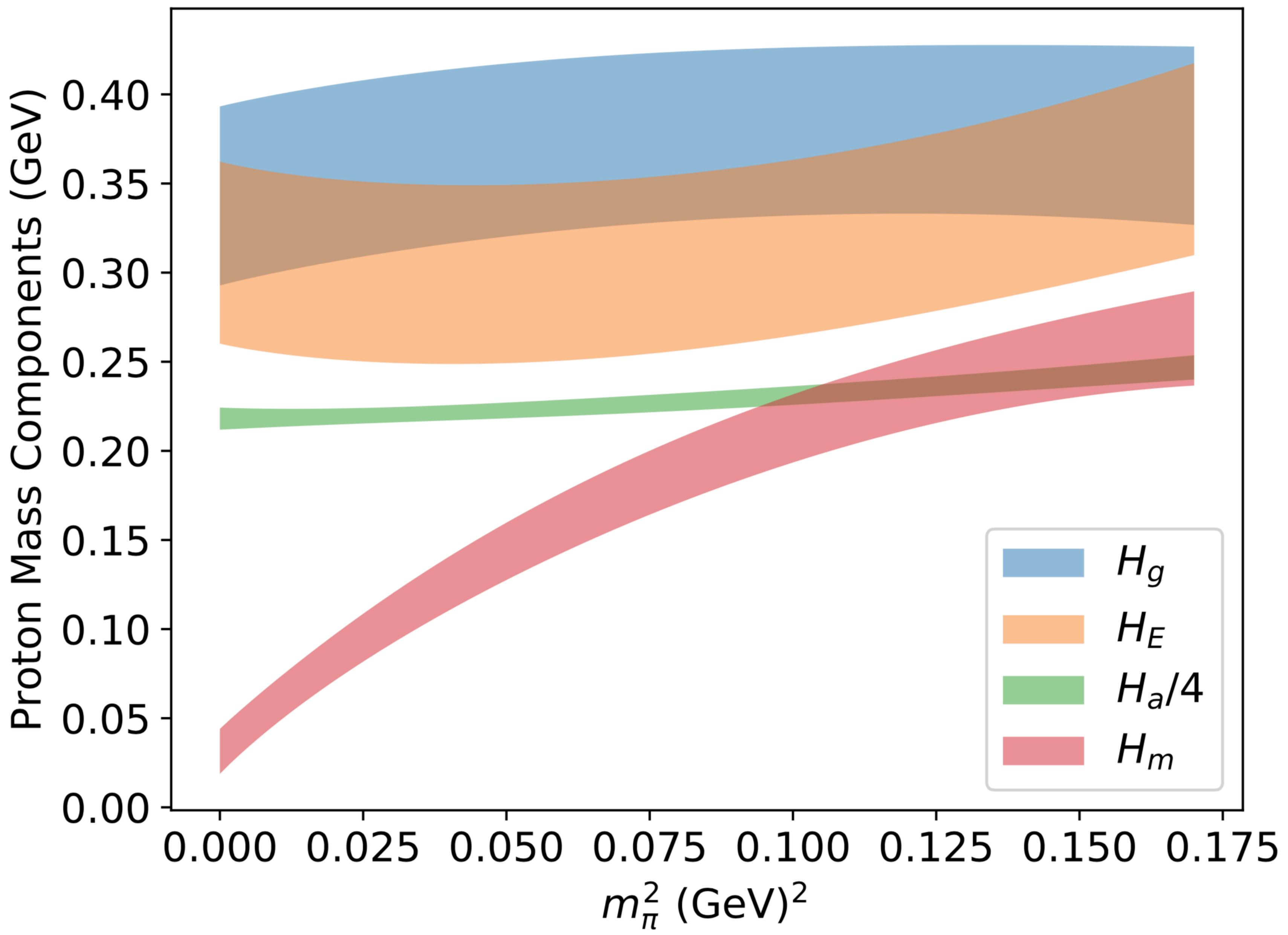
Trace anomaly dominant
"Proton mass result of the vacuum polarization induced by the presence of the proton."

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

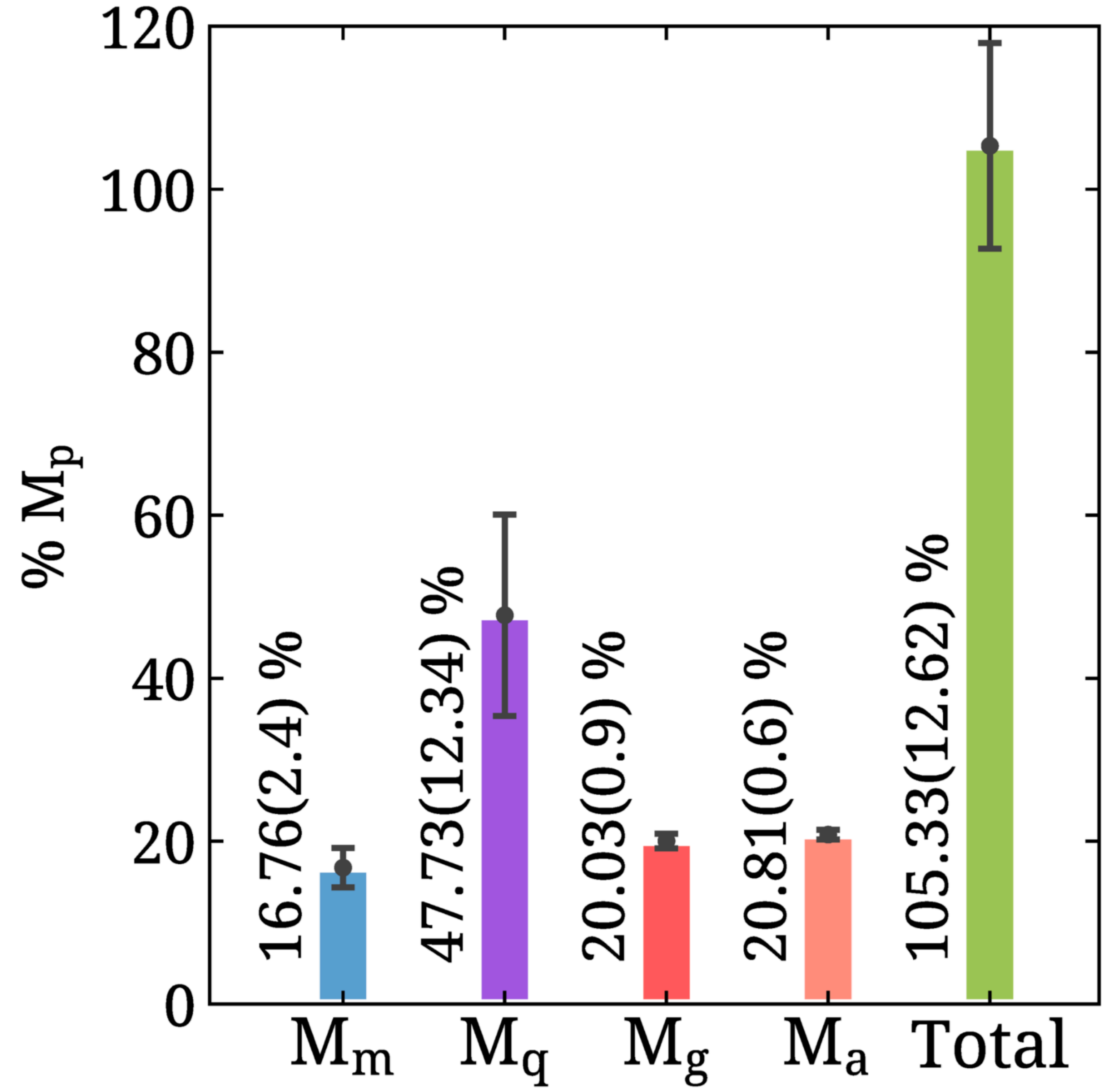
Trace anomaly intimately related to DCSB and the emergence of scale

PROTON MASS ON THE LATTICE

No direct calculation of trace anomaly to date.



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

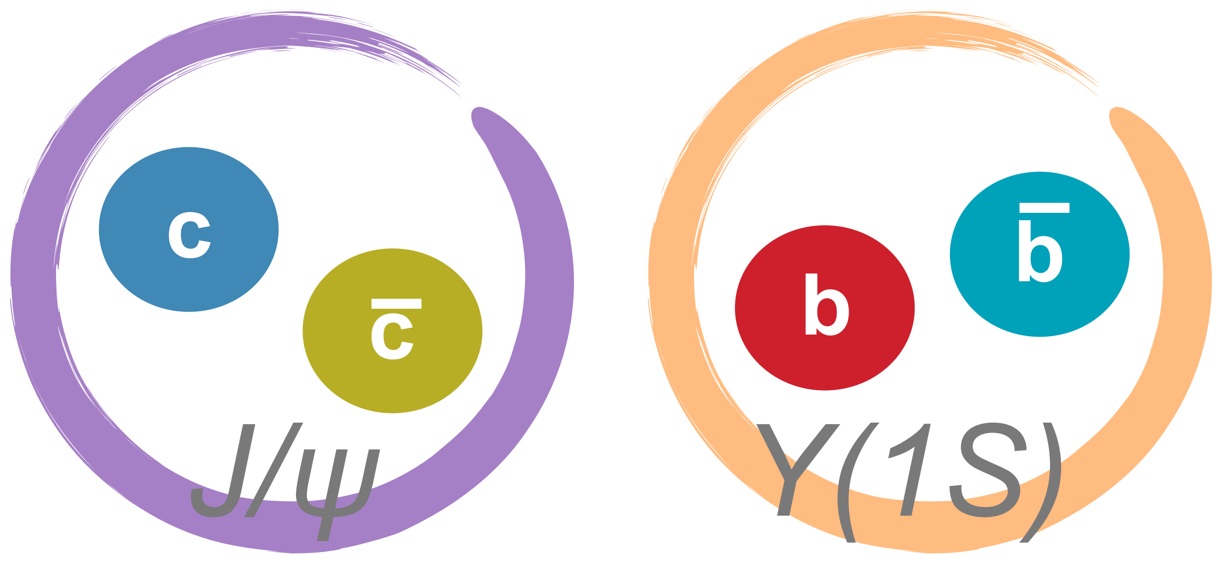


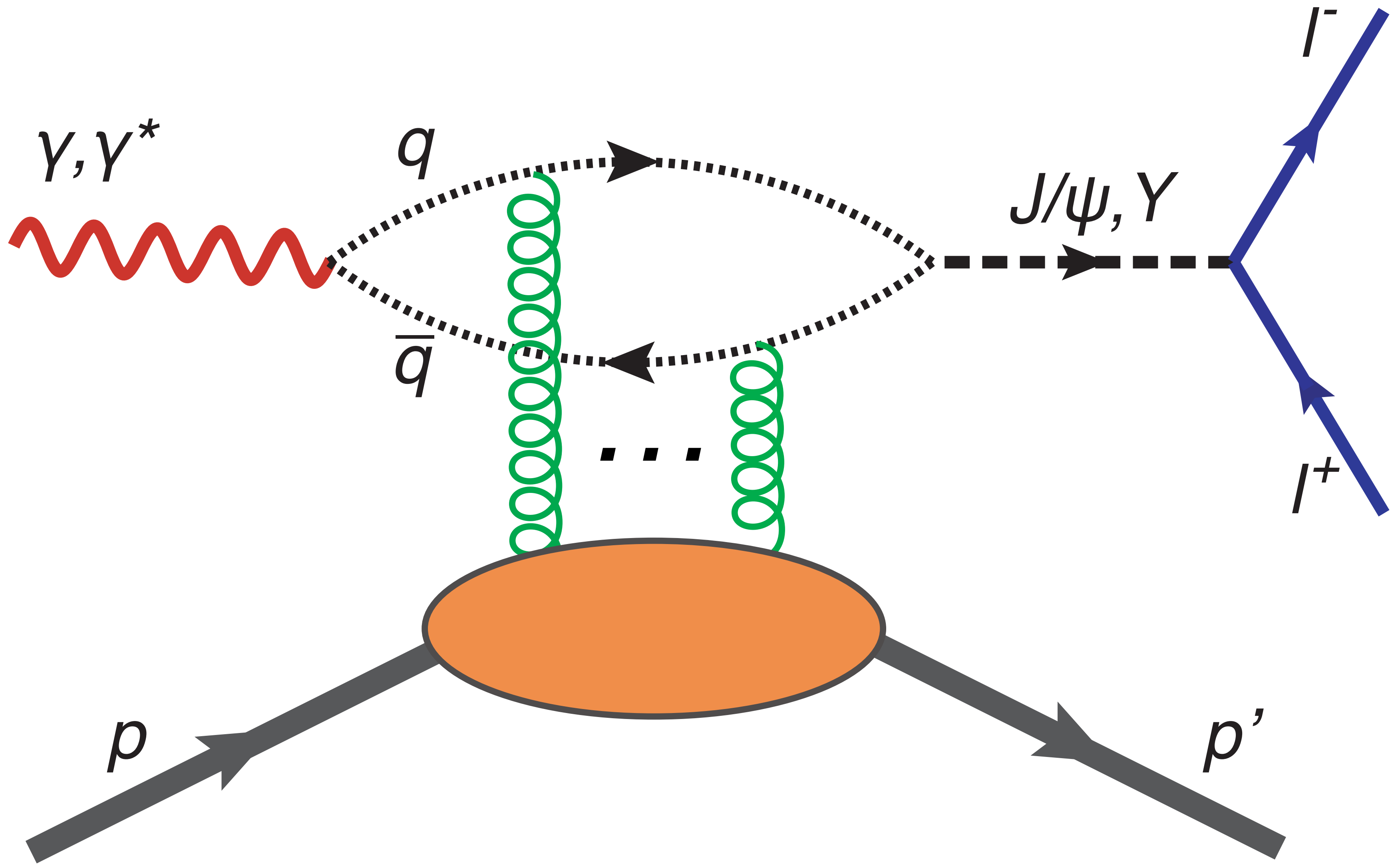
C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)
C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

Trace anomaly only constrained through sum-rules

CAN WE MEASURE THE TRACE ANOMALY?

…Quarkonium production near threshold!





M. Luke *et al.*, PLB 288 355-359 (1992)
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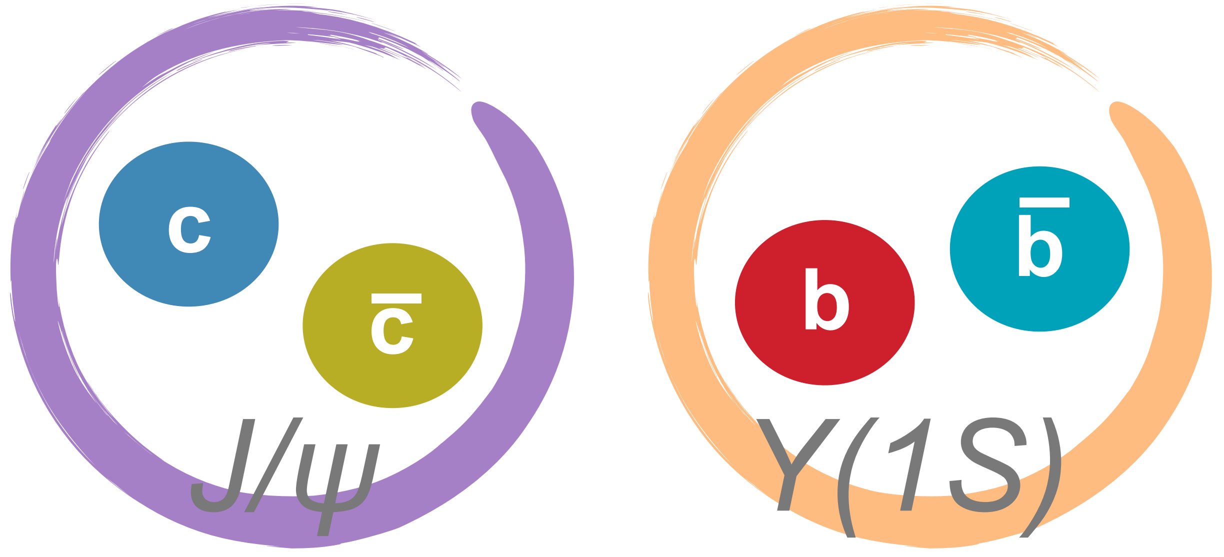
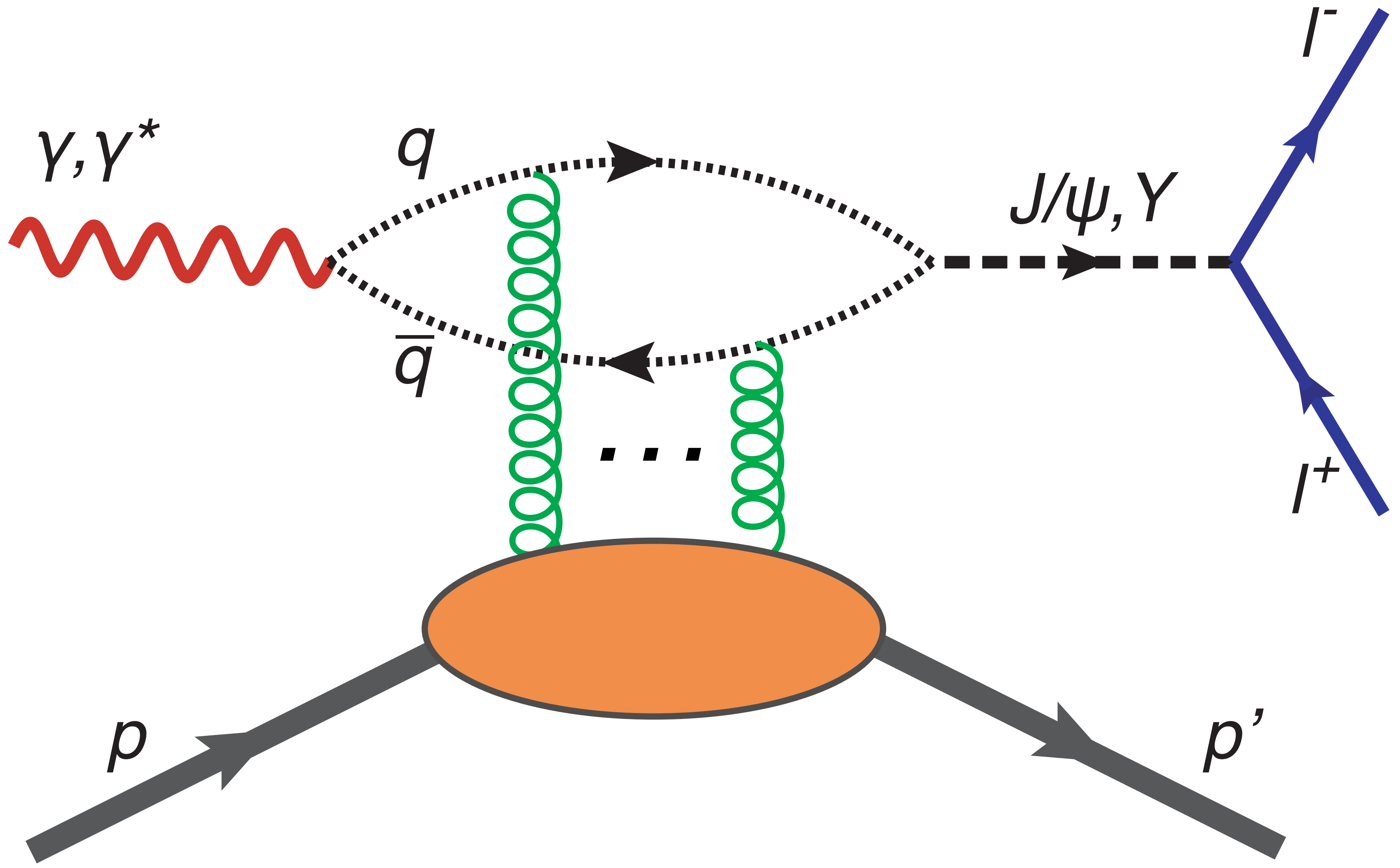


- *J/ψ* and *Y(1S)* only couple to gluons, not light quarks
- Sensitive to gluonic structure of the proton



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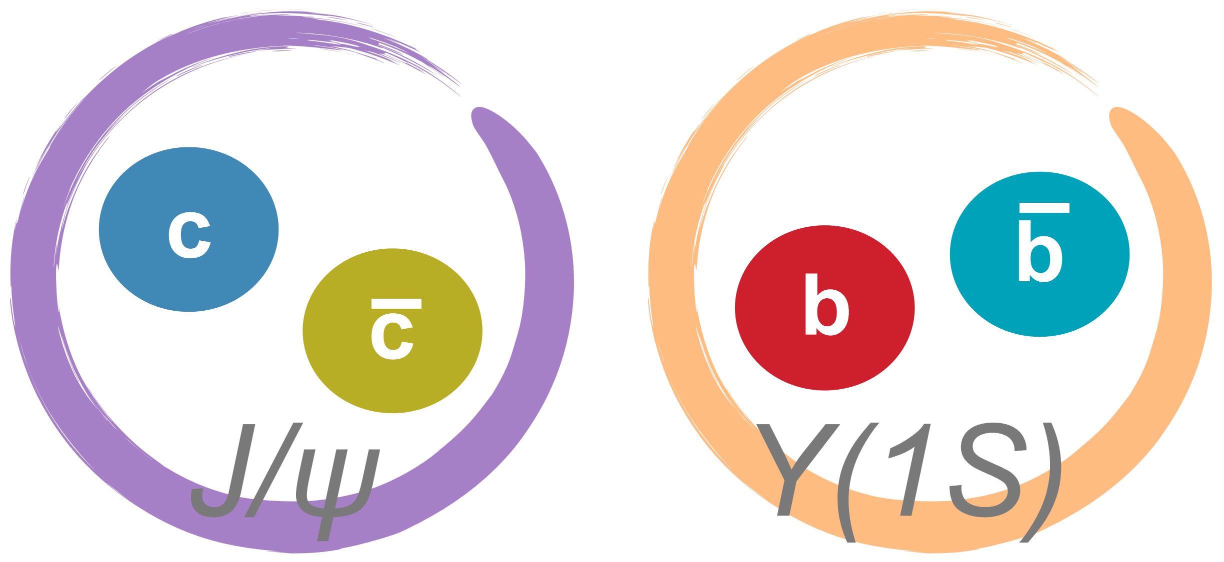
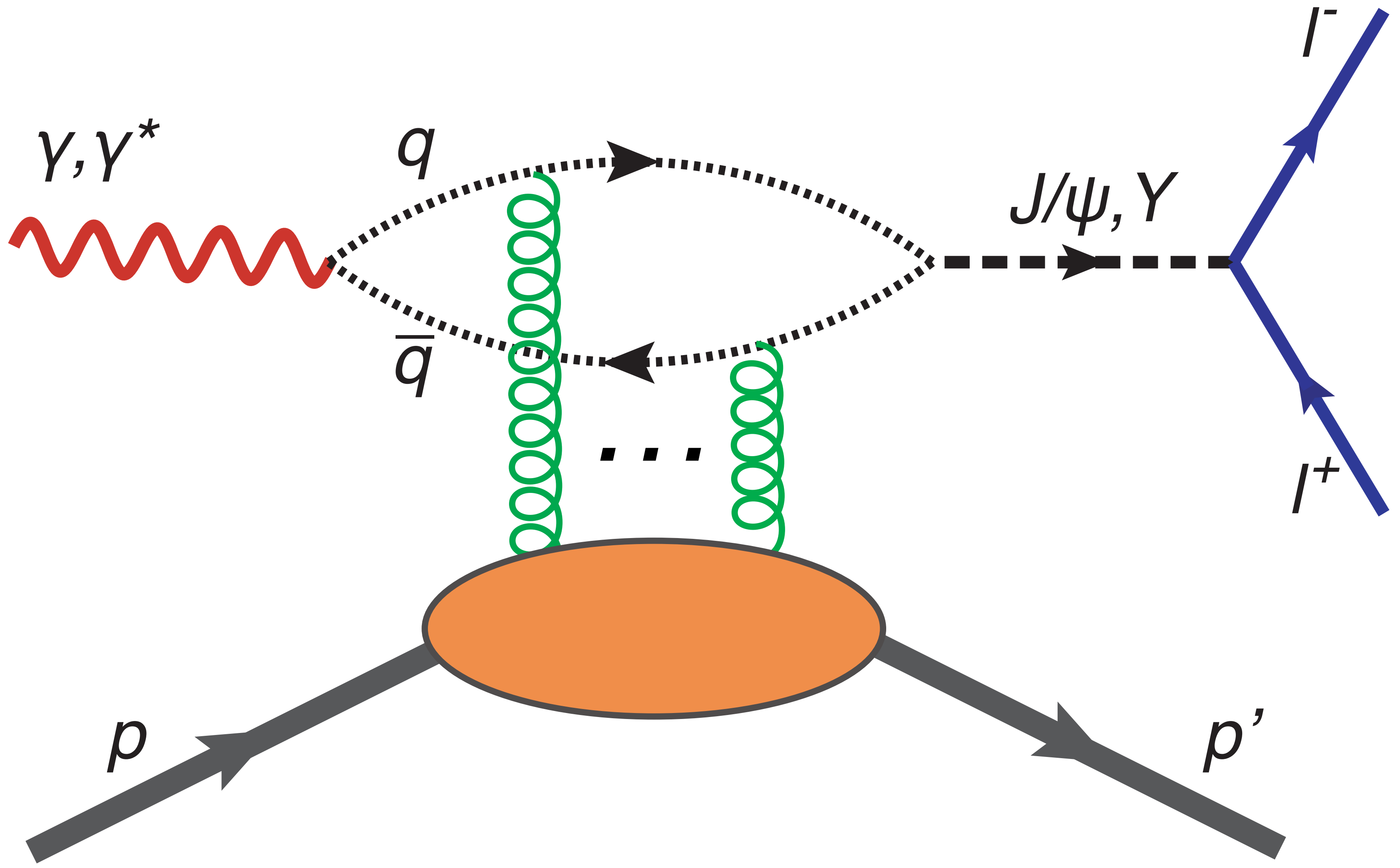


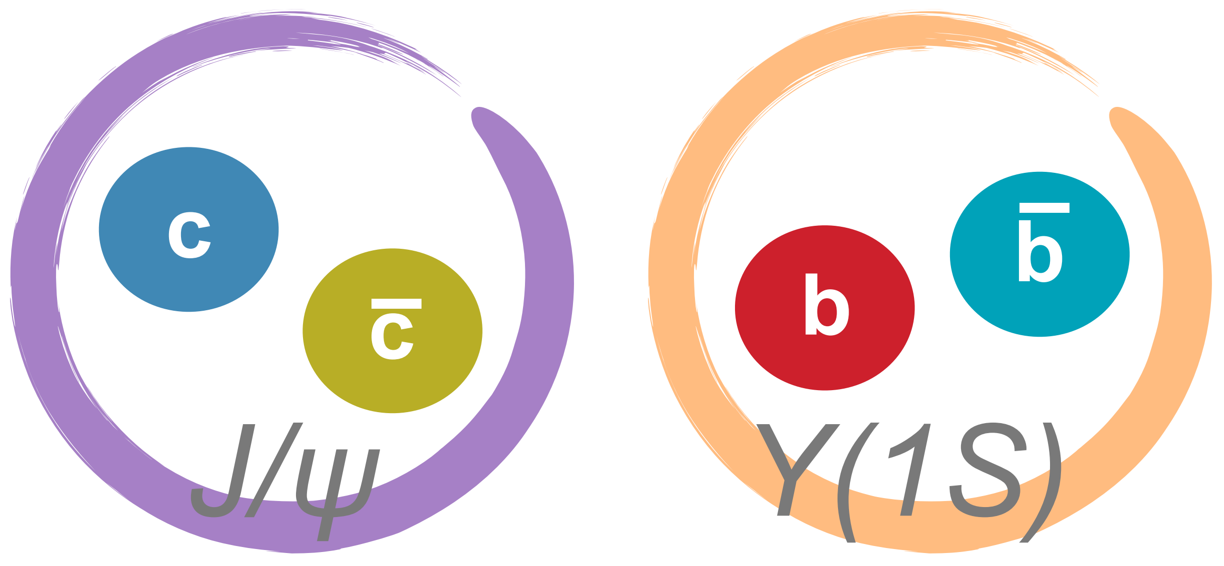
- *J/ψ* and *Y(1S)* only couple to gluons, not light quarks
- Sensitive to gluonic structure of the proton
- Trace-anomaly operator twist-four:
  - Highly suppressed in high-energy scattering
  - QCD Factorization not yet established



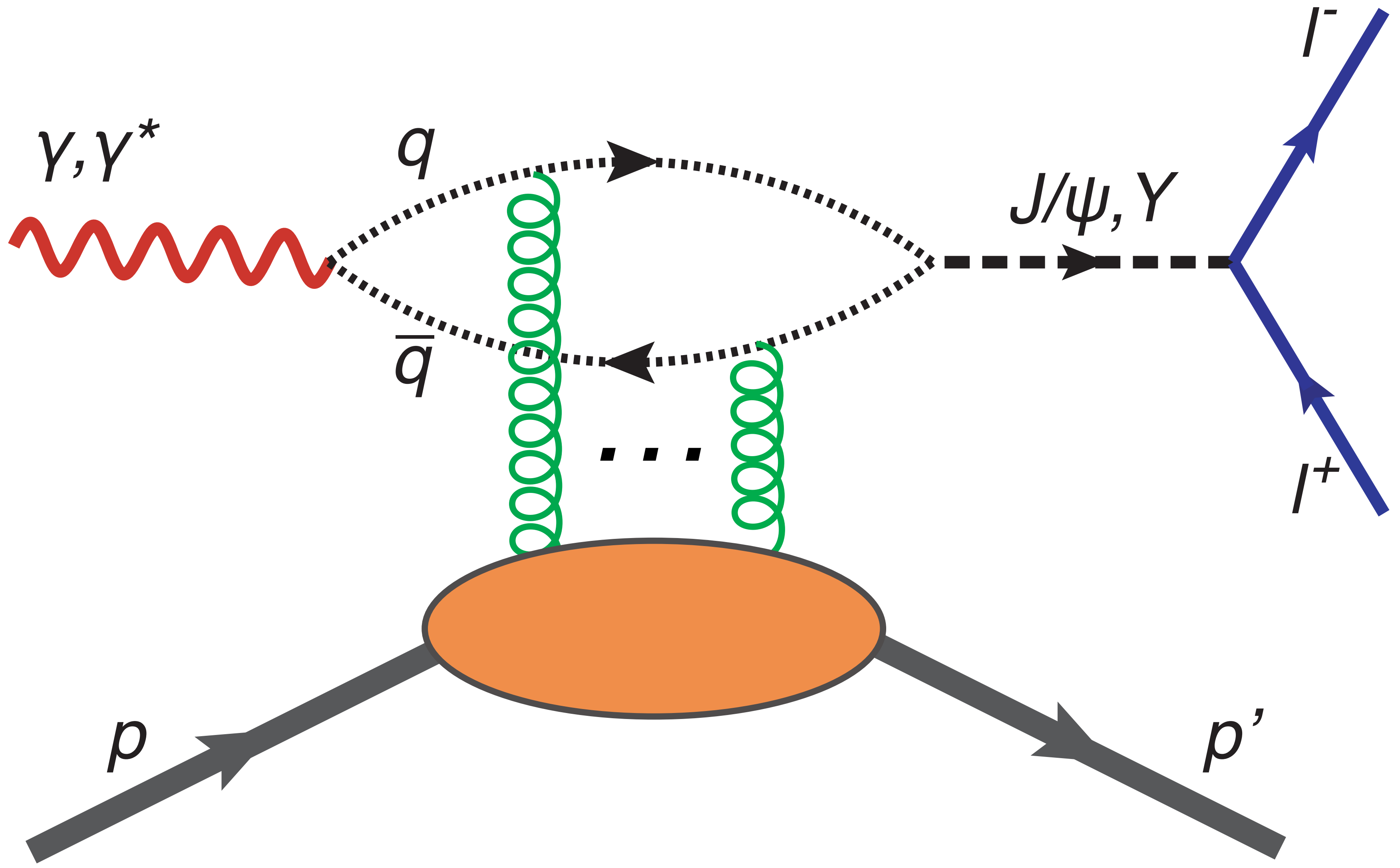
M. Luke *et al.*, PLB 288 355-359 (1992)
D. Kharzeev, Proc.Int.Sch.Phys.Fermi 130 105-131 (1996)

CAN WE MEASURE THE TRACE ANOMALY?

…Quarkonium production near threshold!



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



Three possible avenues for…

MEASURING THE TRACE ANOMALY

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

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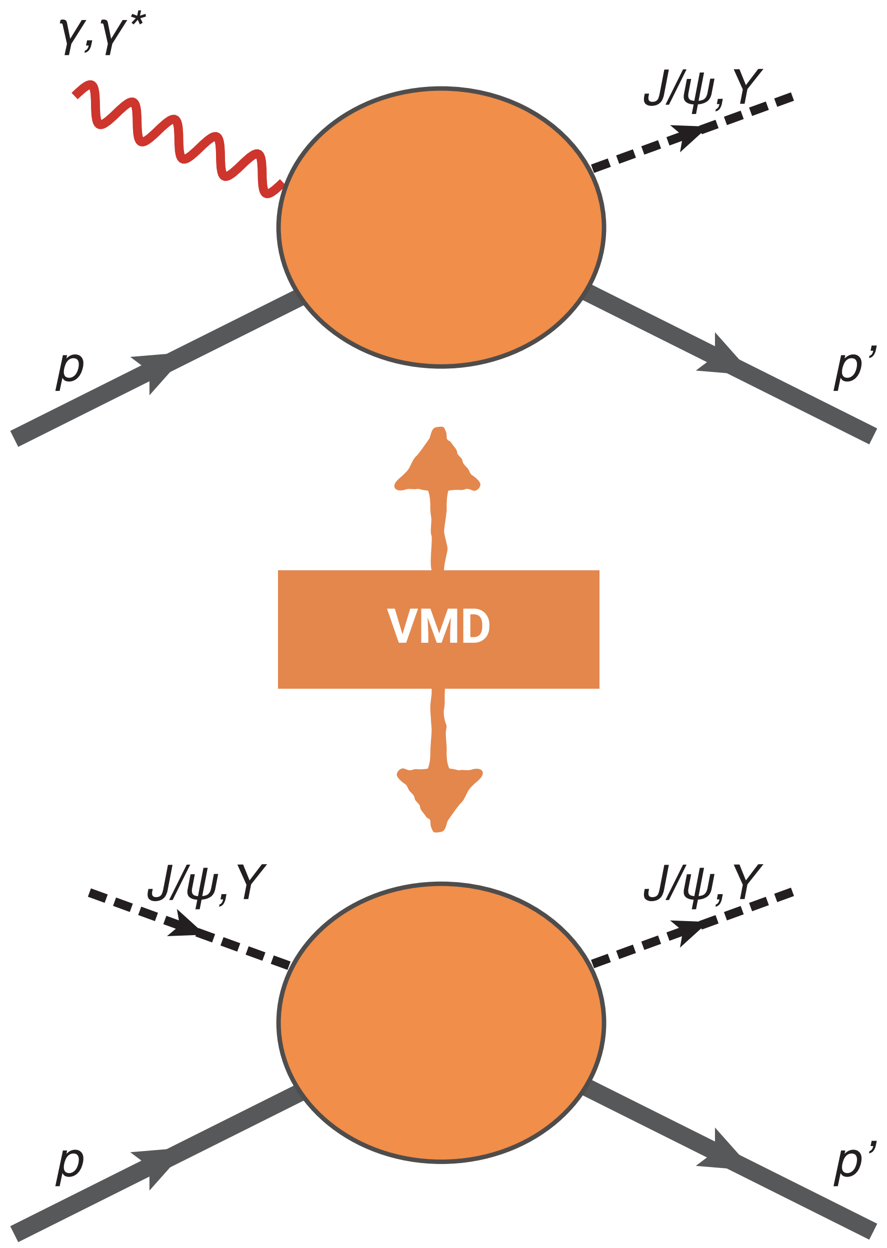

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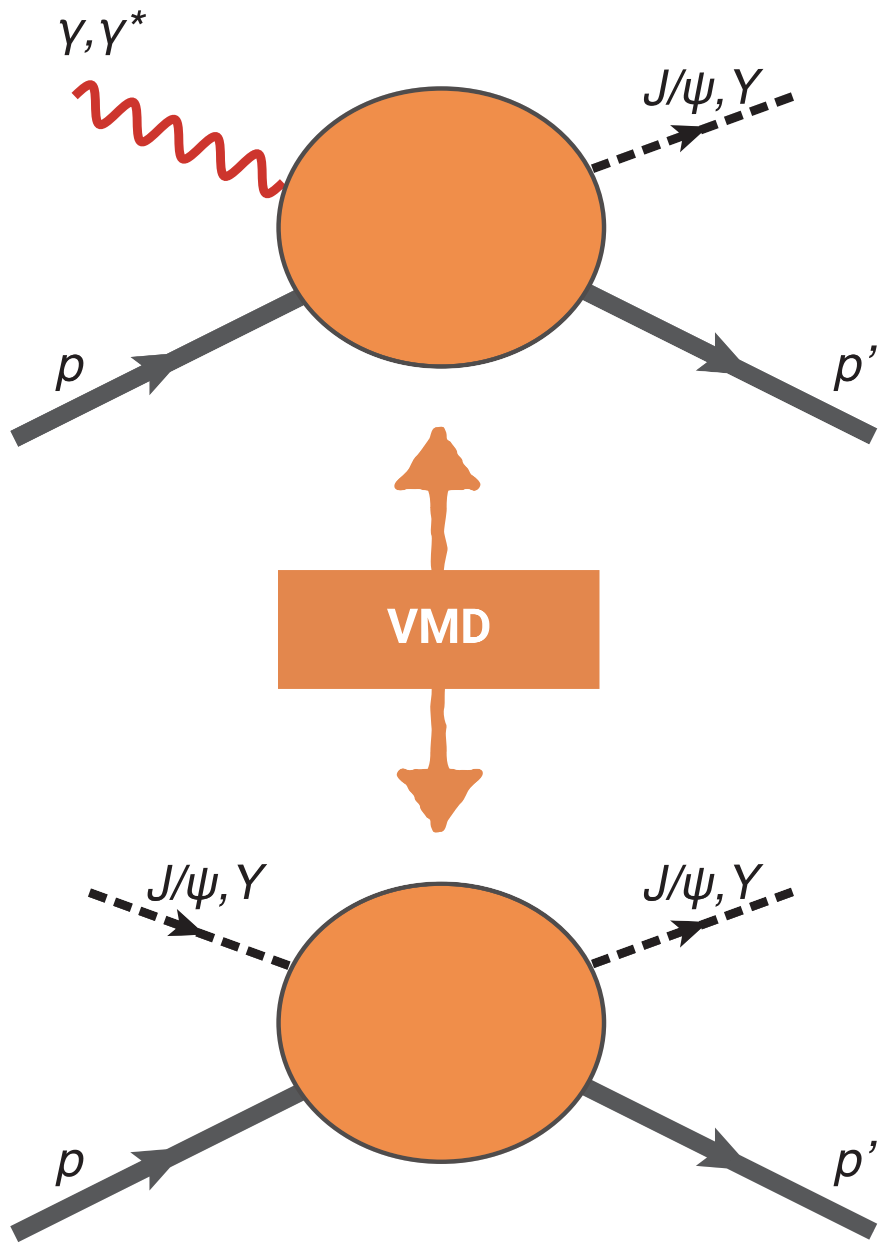

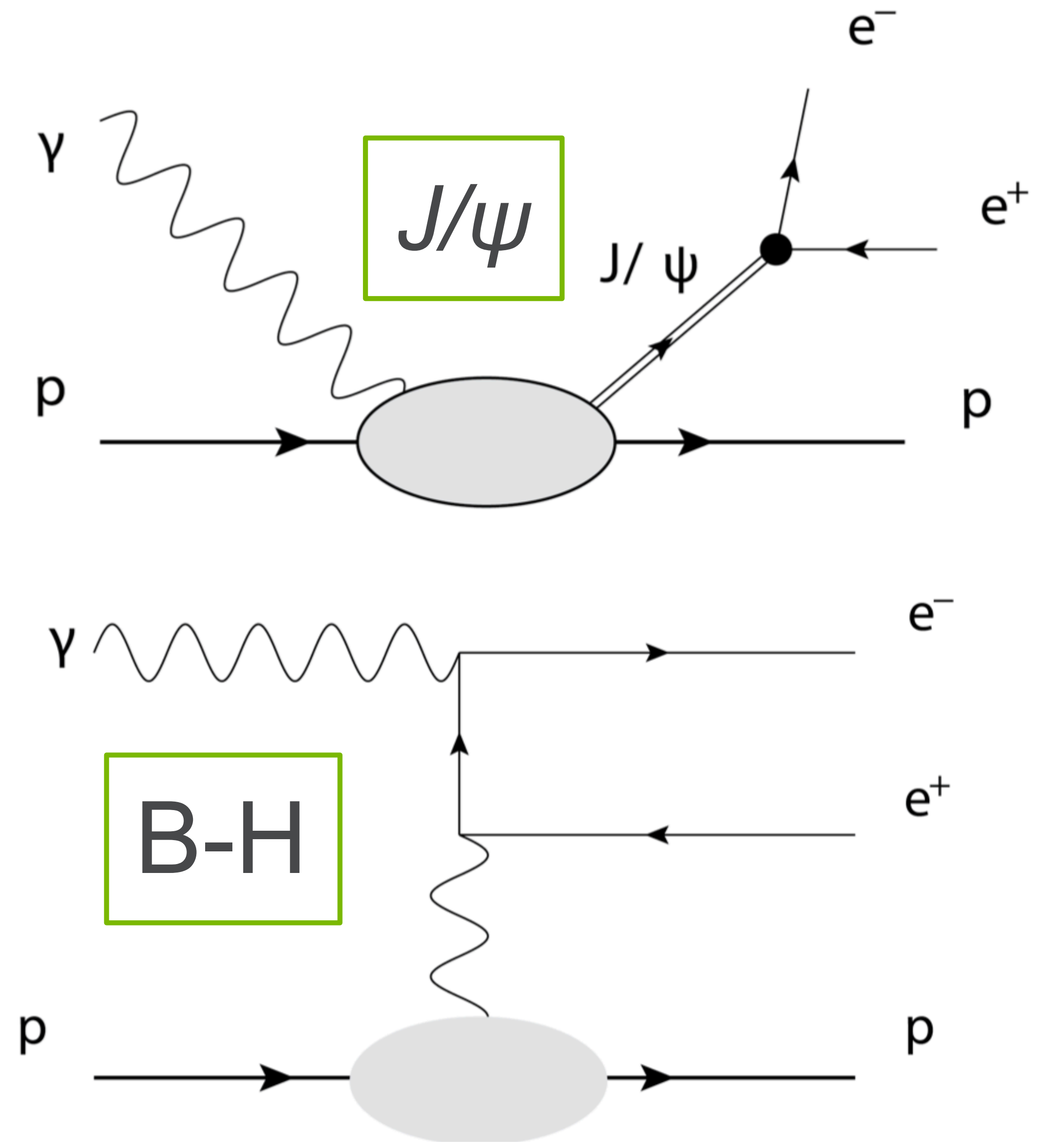

2. Interference with Bethe-Heitler
Interference between for *J/ψ* production and Bethe-Heitler near (but not at) threshold. Needs very high statistics. Possible at SoLID.

Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

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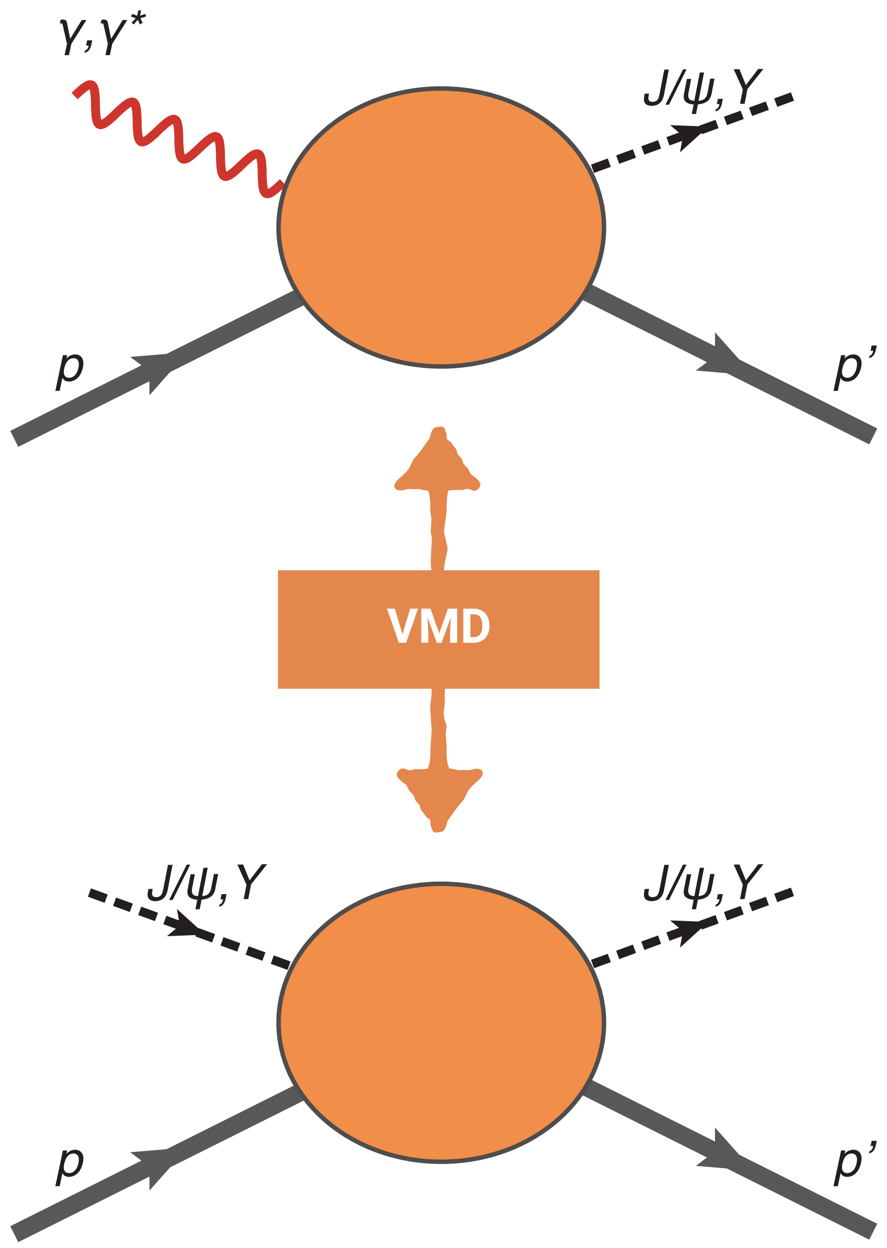

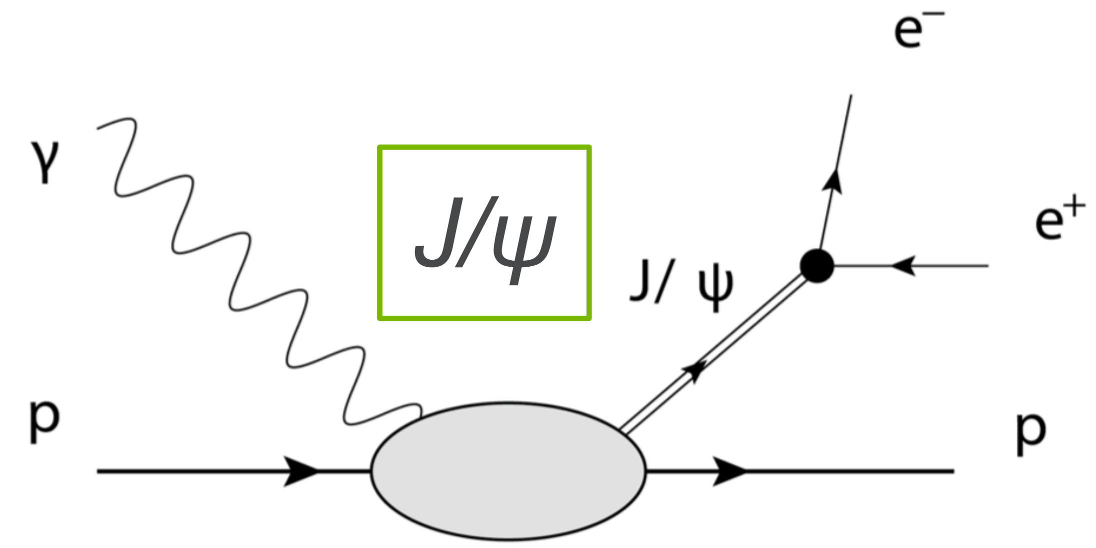

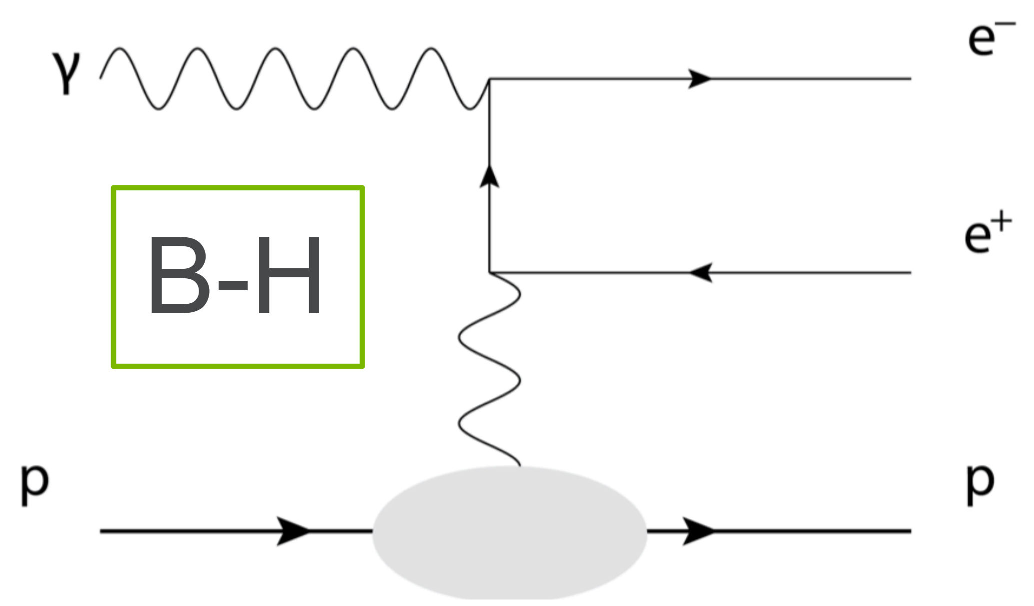

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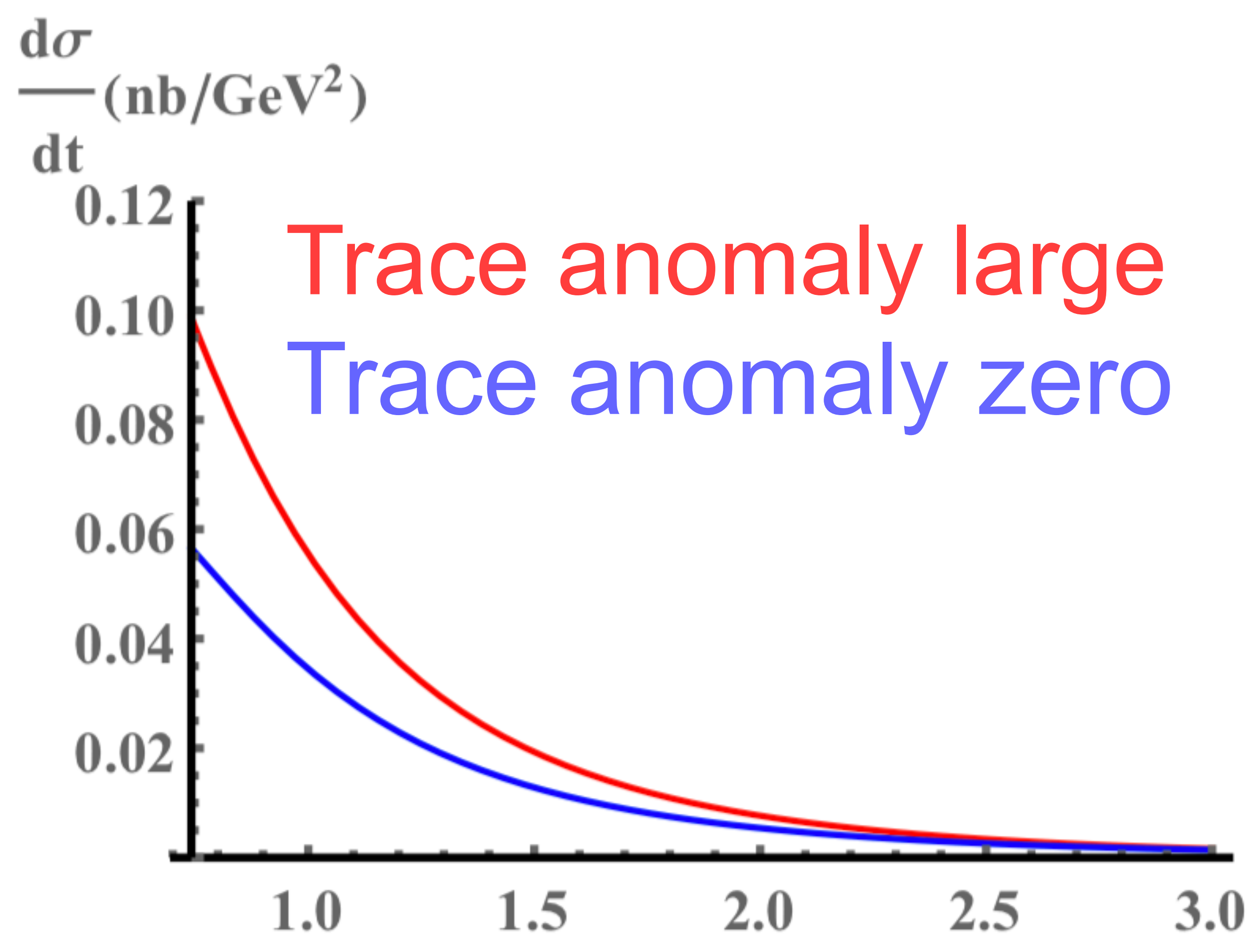
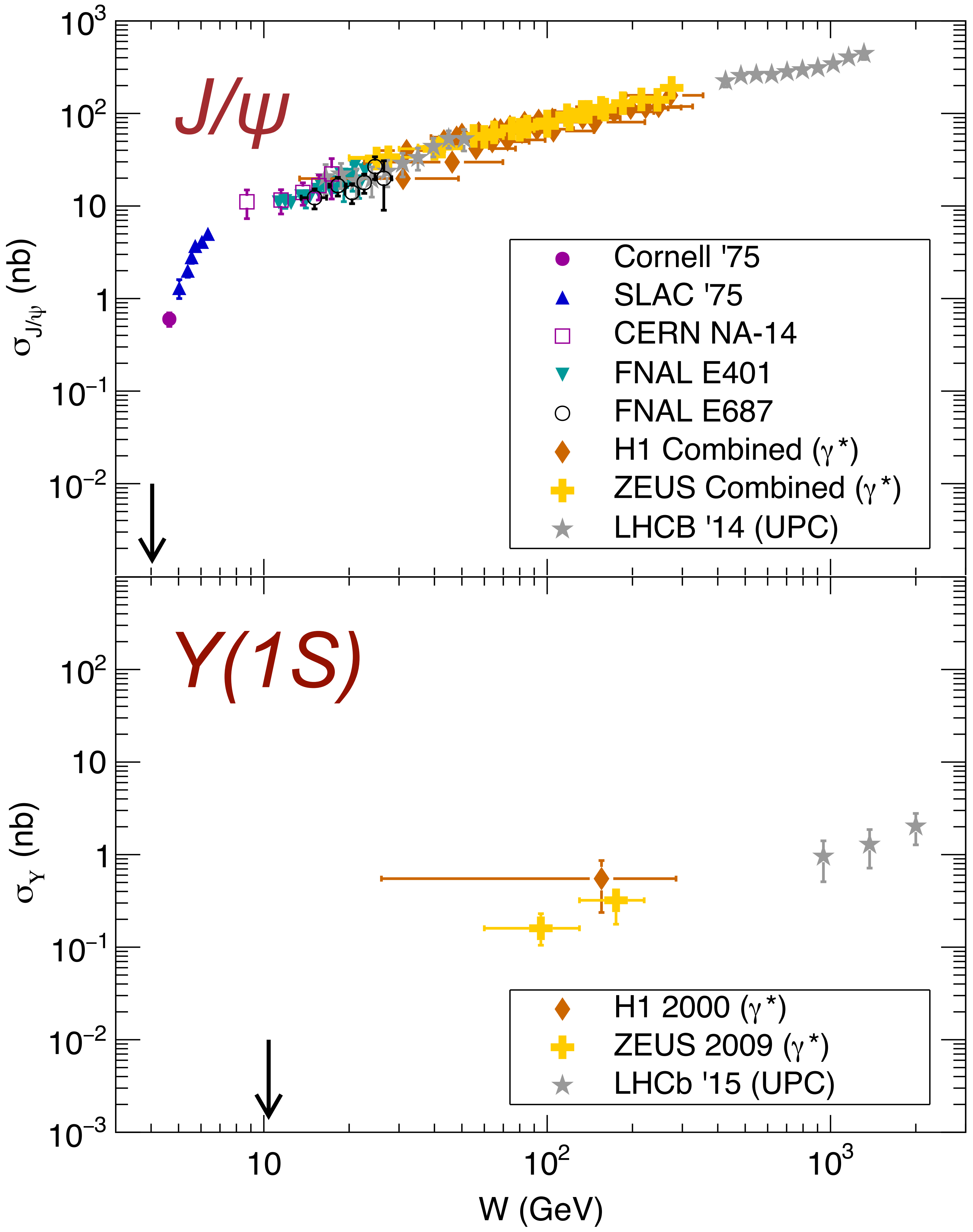
3. Holographic approach:
Non-perturbative approach using AdS/CFT gauge-string duality. New development. Predicts sensitivity for *J/ψ* production near threshold.

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



Y(1S): THE OPTIMAL GLUONIC PROBE

…but a challenging measurement

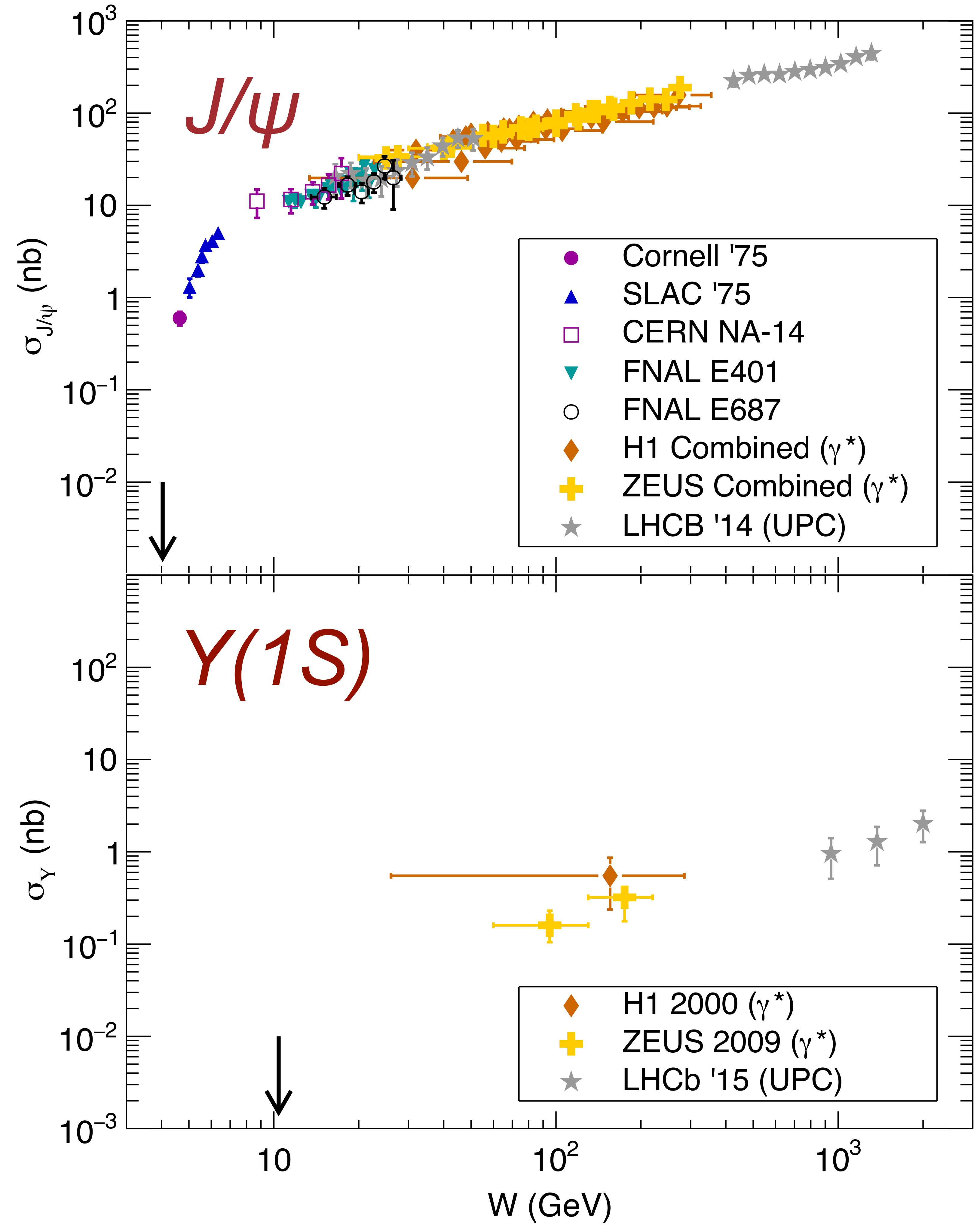


Υ(1S): THE OPTIMAL GLUONIC PROBE

…but a challenging measurement

- Jefferson Lab experiments will map out the *J/ψ* threshold region in great detail.
  - Accessing the *J/ψ* threshold region at higher Q^2 possible at EIC, potentially important for factorization.

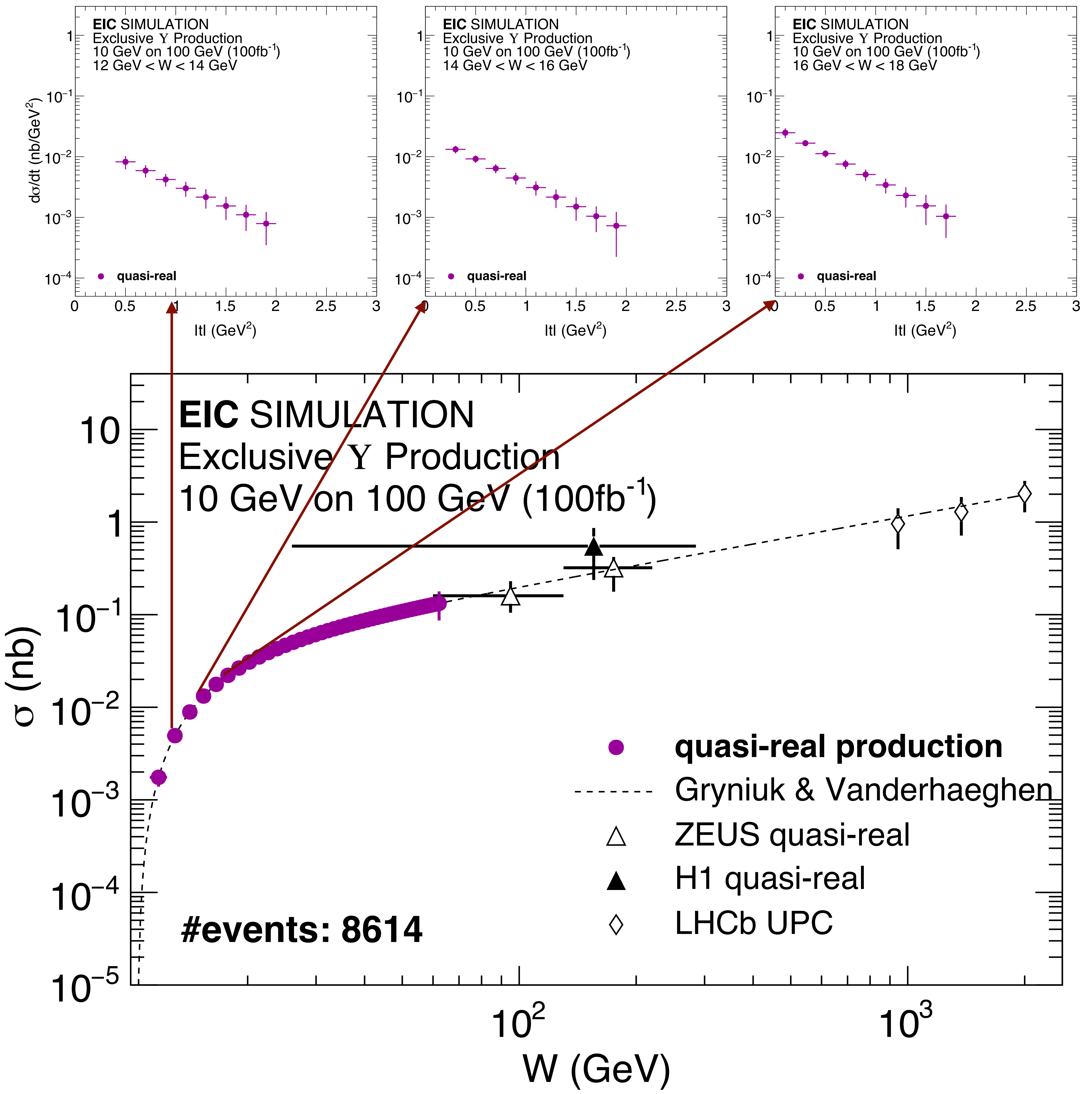
- *Υ(1S)* is a heavier (smaller) probe than *J/ψ*
  - *Υ(1S)* production near threshold crucial to **universality**
  - Cross section very small (2 orders of magnitude smaller than *J/ψ*)
  - Measurement can (only) be done at EIC



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**



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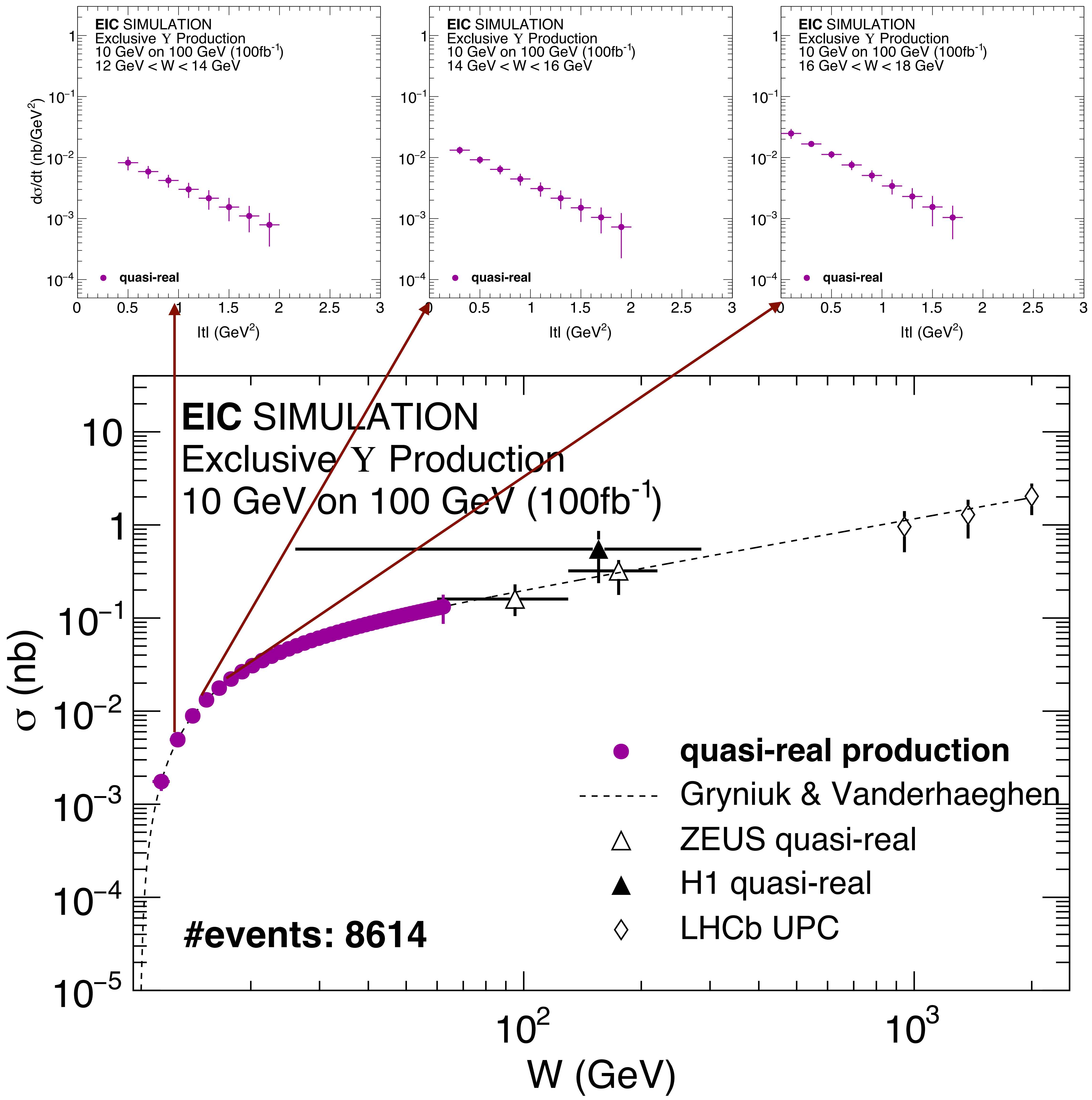
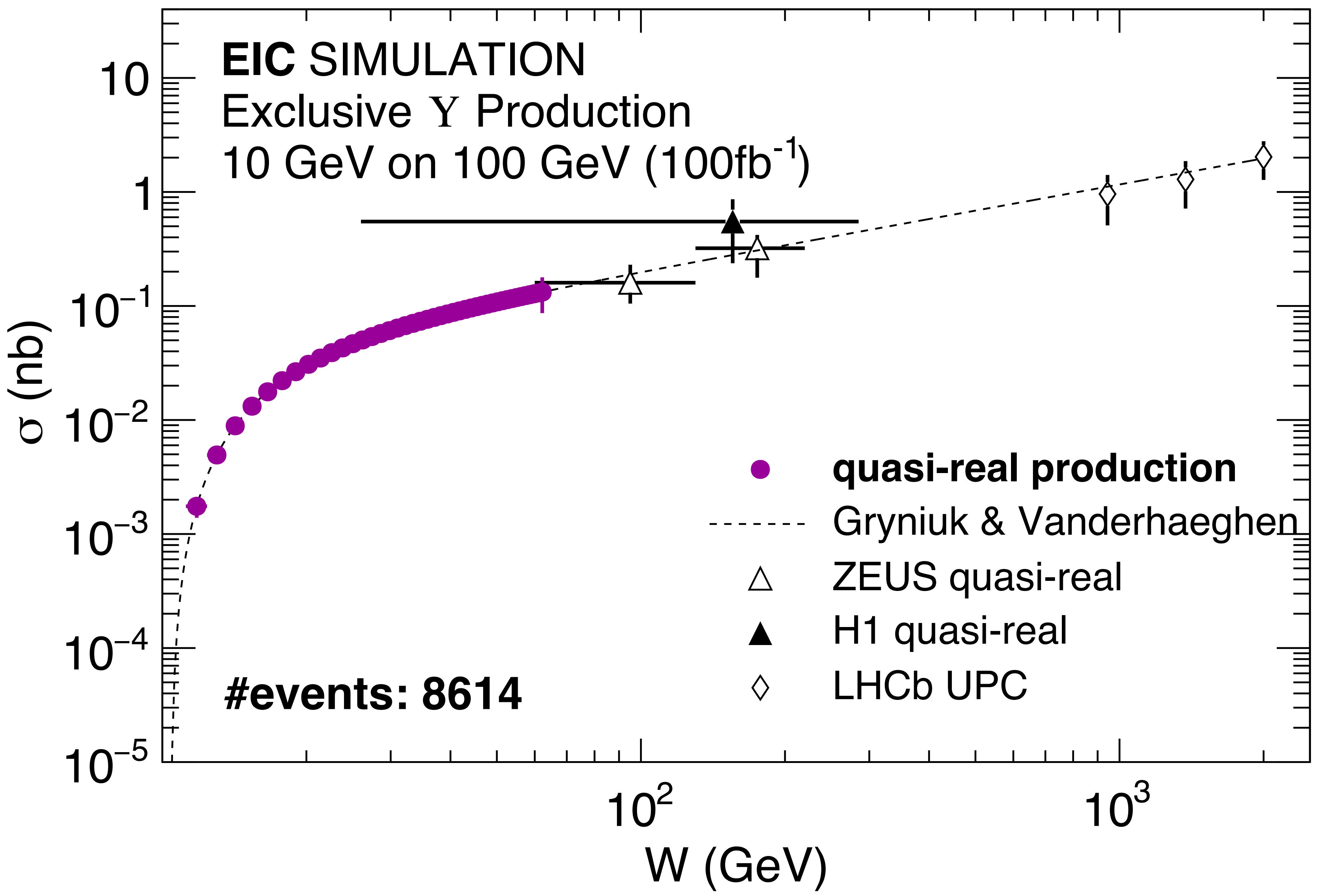
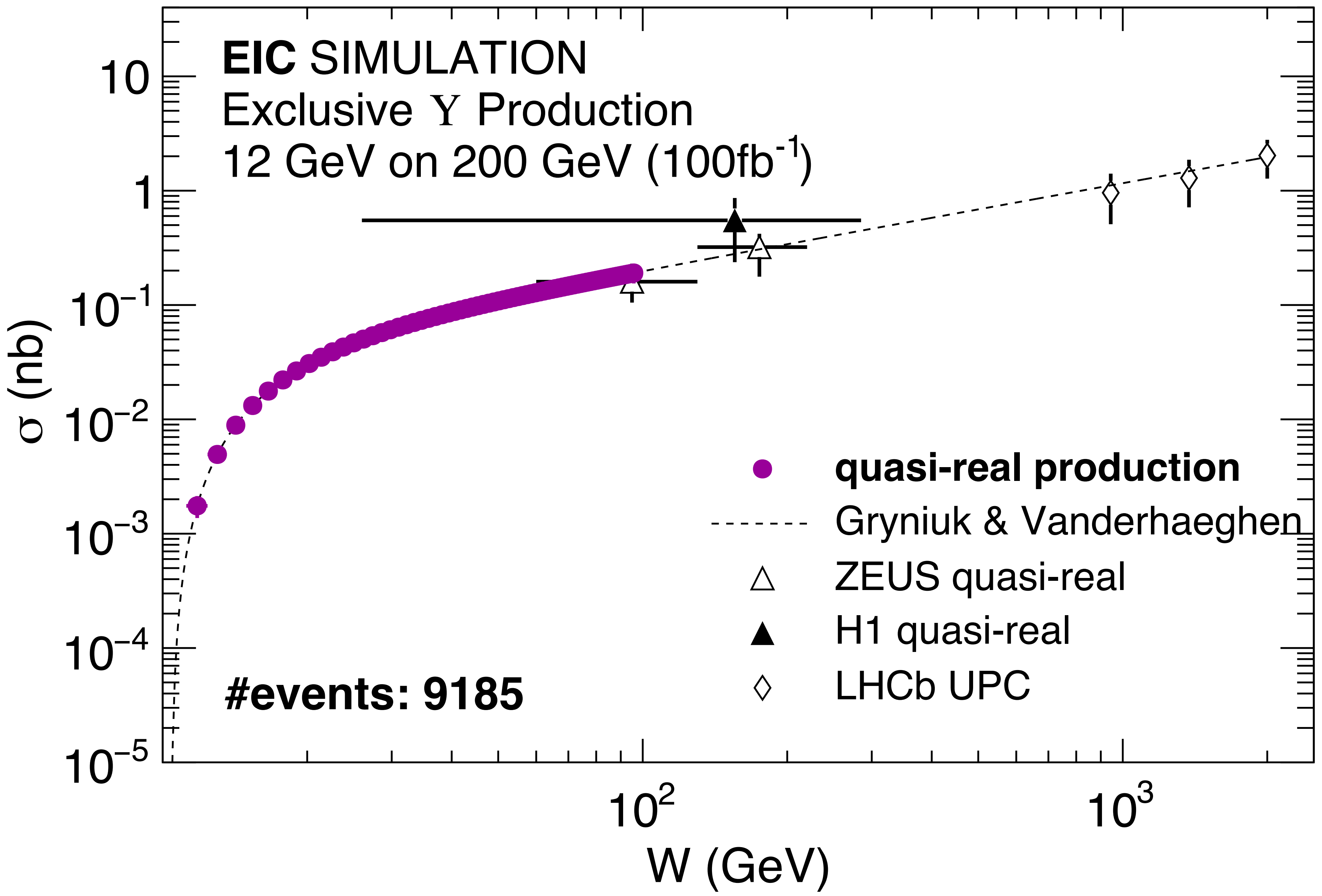


- ***Y(1s)*** production possible at threshold!
  - Provides measure for **universality,** complimentary to threshold *J/ψ* program at JLab12
  - Are there a "beautiful" pentaquarks?
- Sensitivity down to ~10^{-3} nb!

DETECTOR REQUIREMENTS FOR MASS

Trade-off between energy and ability to reach threshold





Higher energy better due to 1/y dependence of virtual photon flux
… as long as we can still detect the events!

CONCLUSION

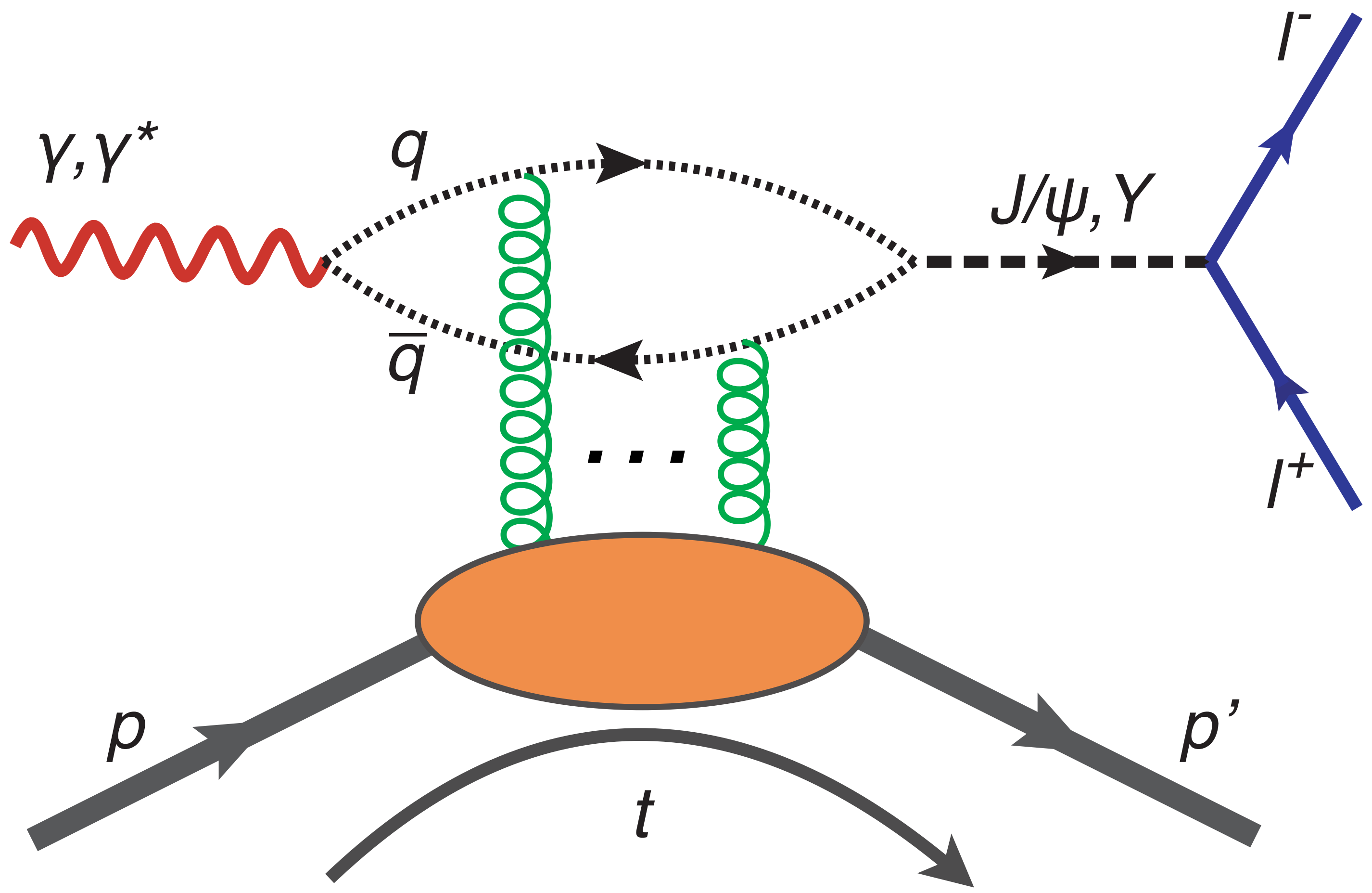
- ☑ **Quarkonium** production an important tool to study the **gluonic fields** in the nucleon
- ☑ **Threshold production** of quarkonium can shed light on the **trace anomaly,** quarkonium-nucleon **binding**, **SRC universality**, and **proton mass**
- ☑ At **high energies***:* possible to access **gluon GPDs**, and study the gluonic degrees of freedom of SRCs.
- ☑ Can **test universality by comparing** Υ **to** J/ψ
- ☑ **EIC** 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

QUARKONIUM PHOTO-PRODUCTION

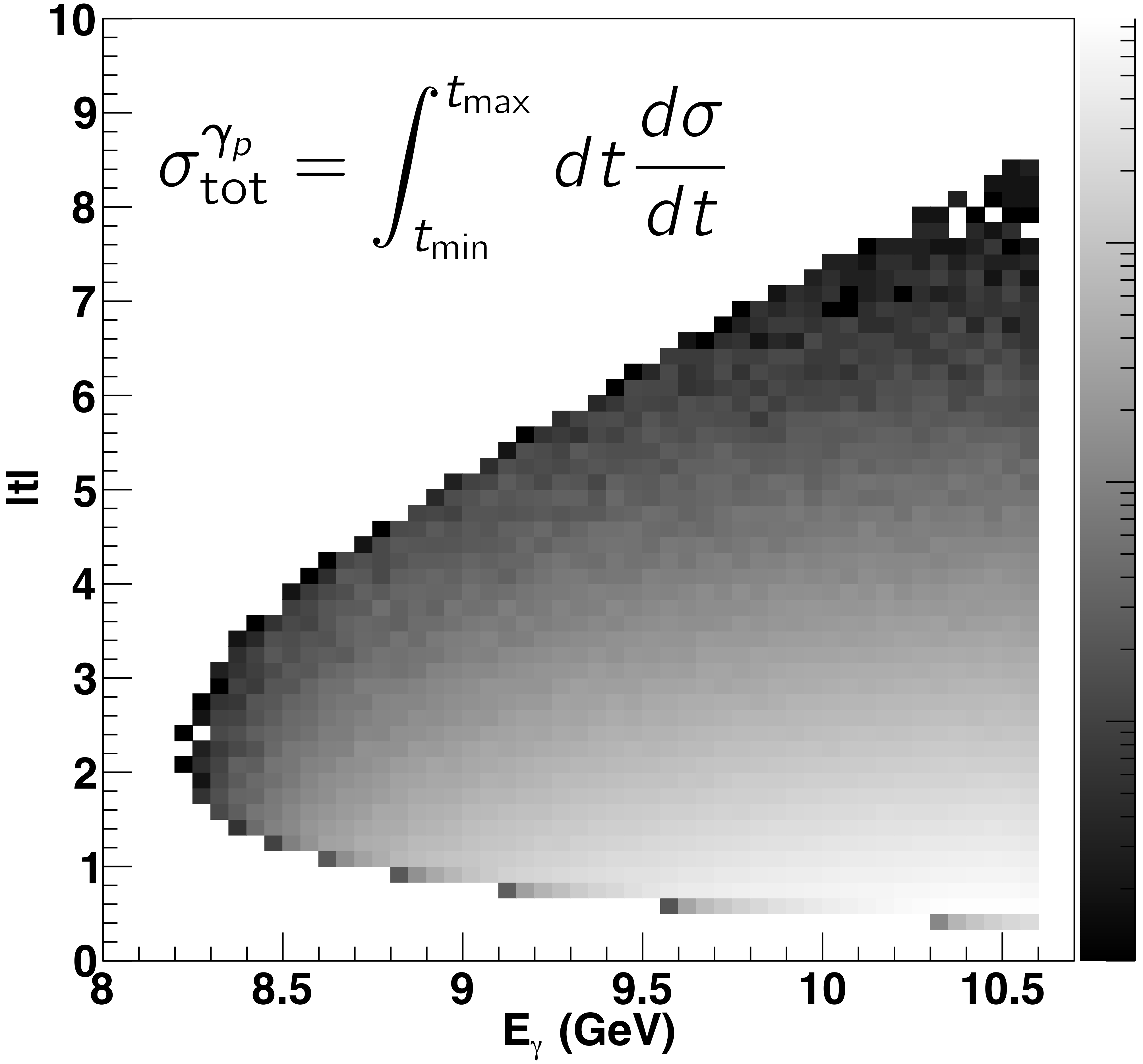
The basics



Υ(1S) threshold:

$W \approx 10.4\text{GeV}$

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



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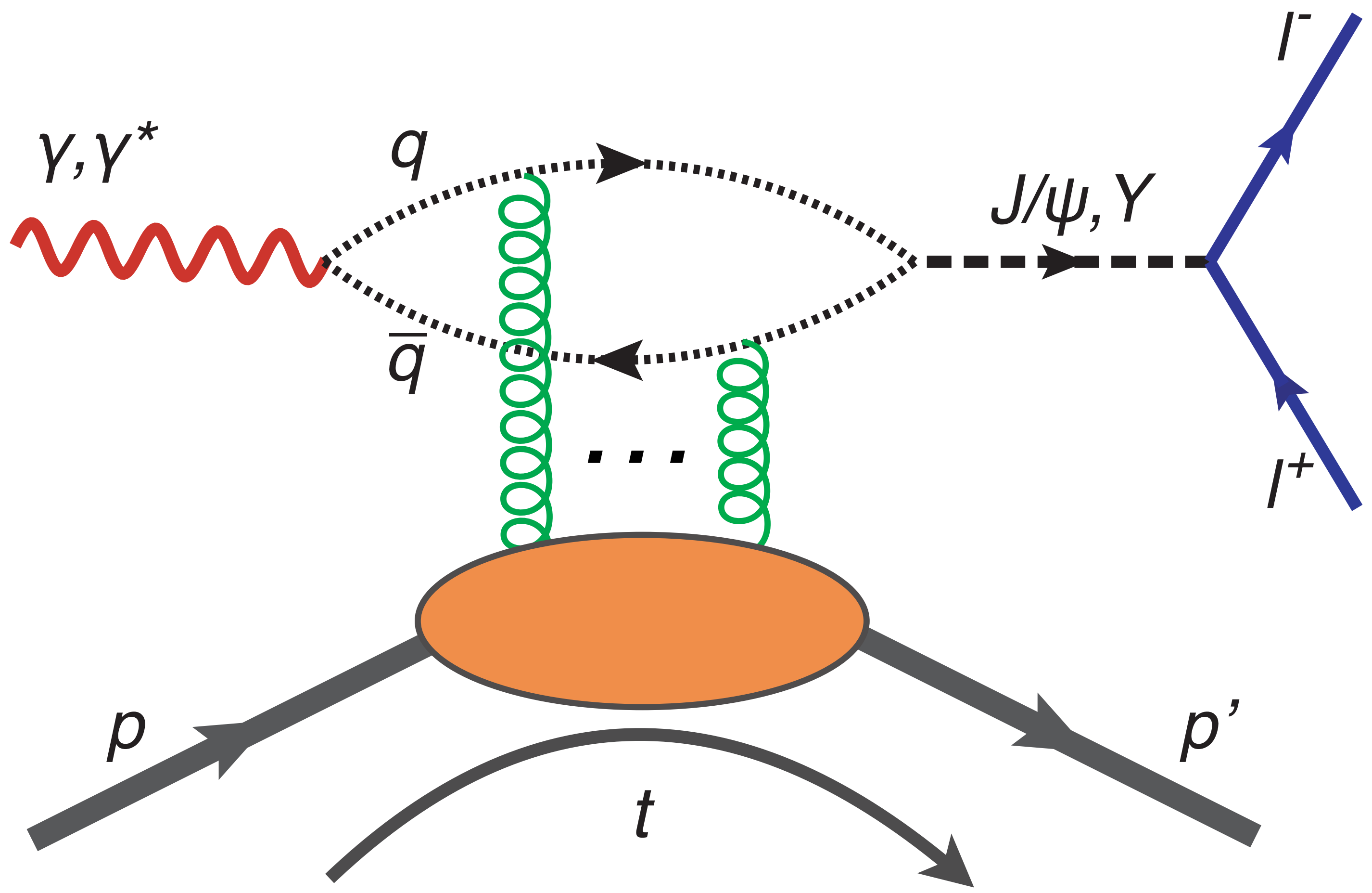

J/ψ threshold:

$$W \approx 4.04\text{GeV}$$
$$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$$
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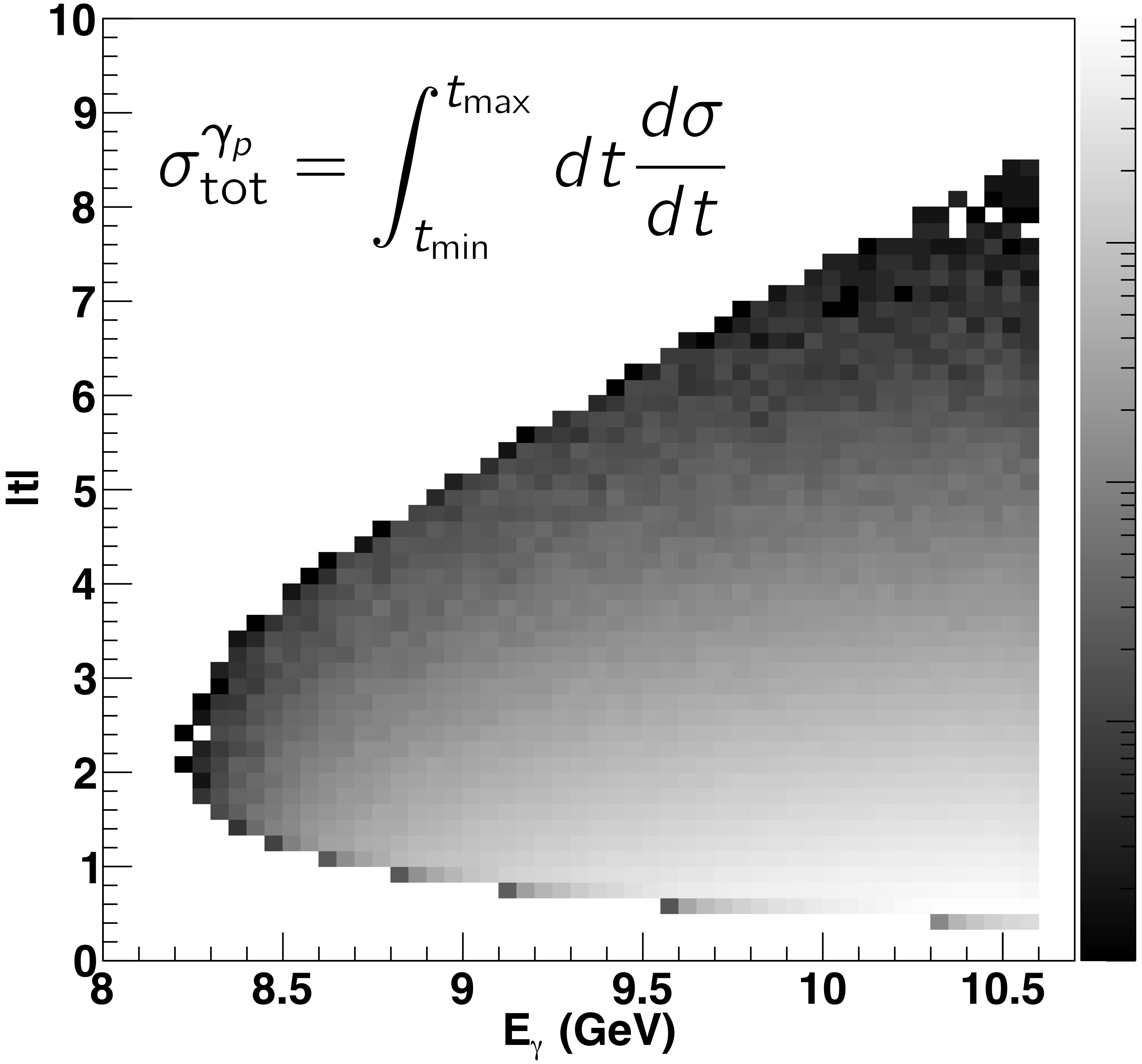
- Phase space limits defined by quarkonium direction

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



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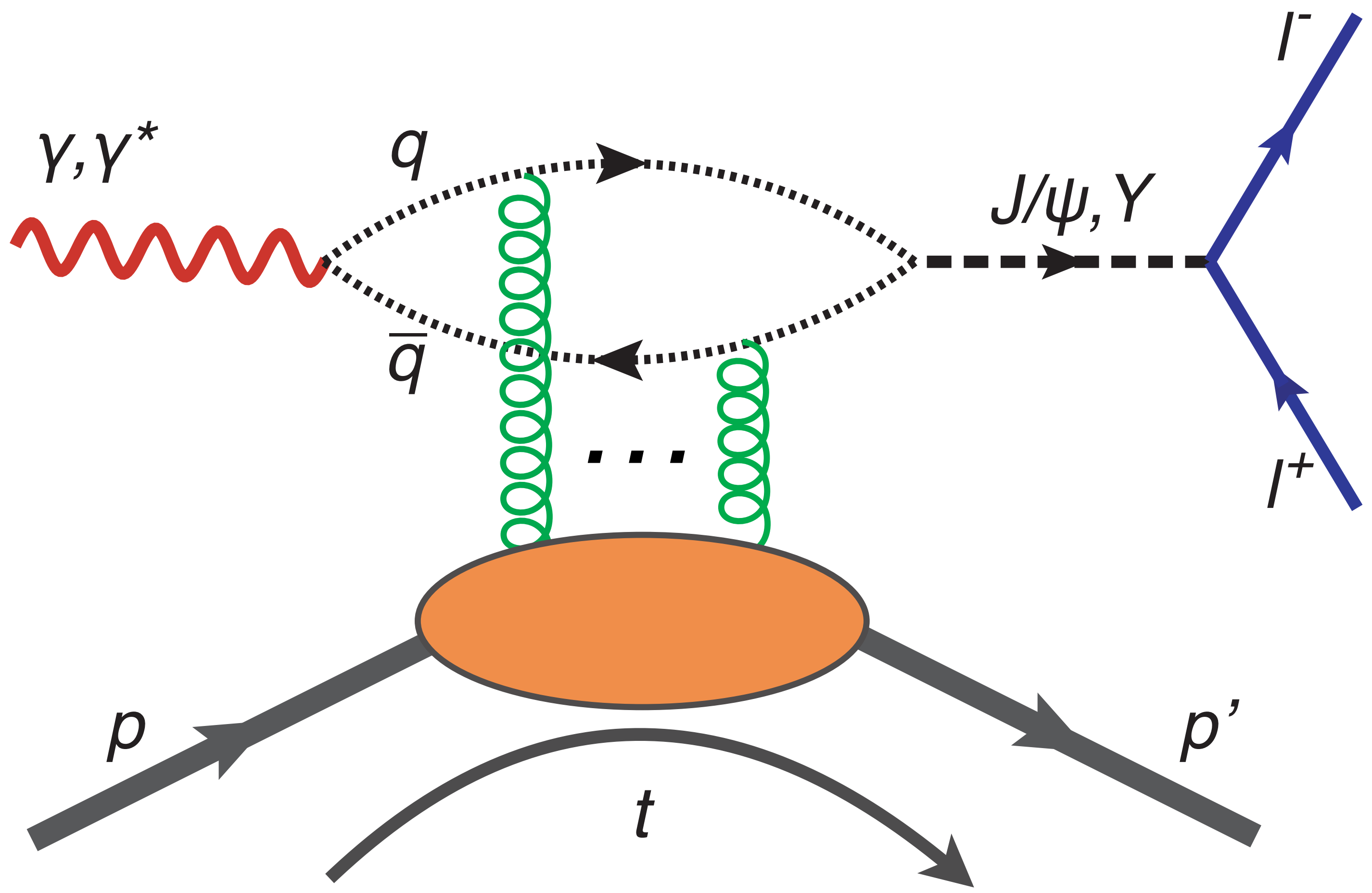

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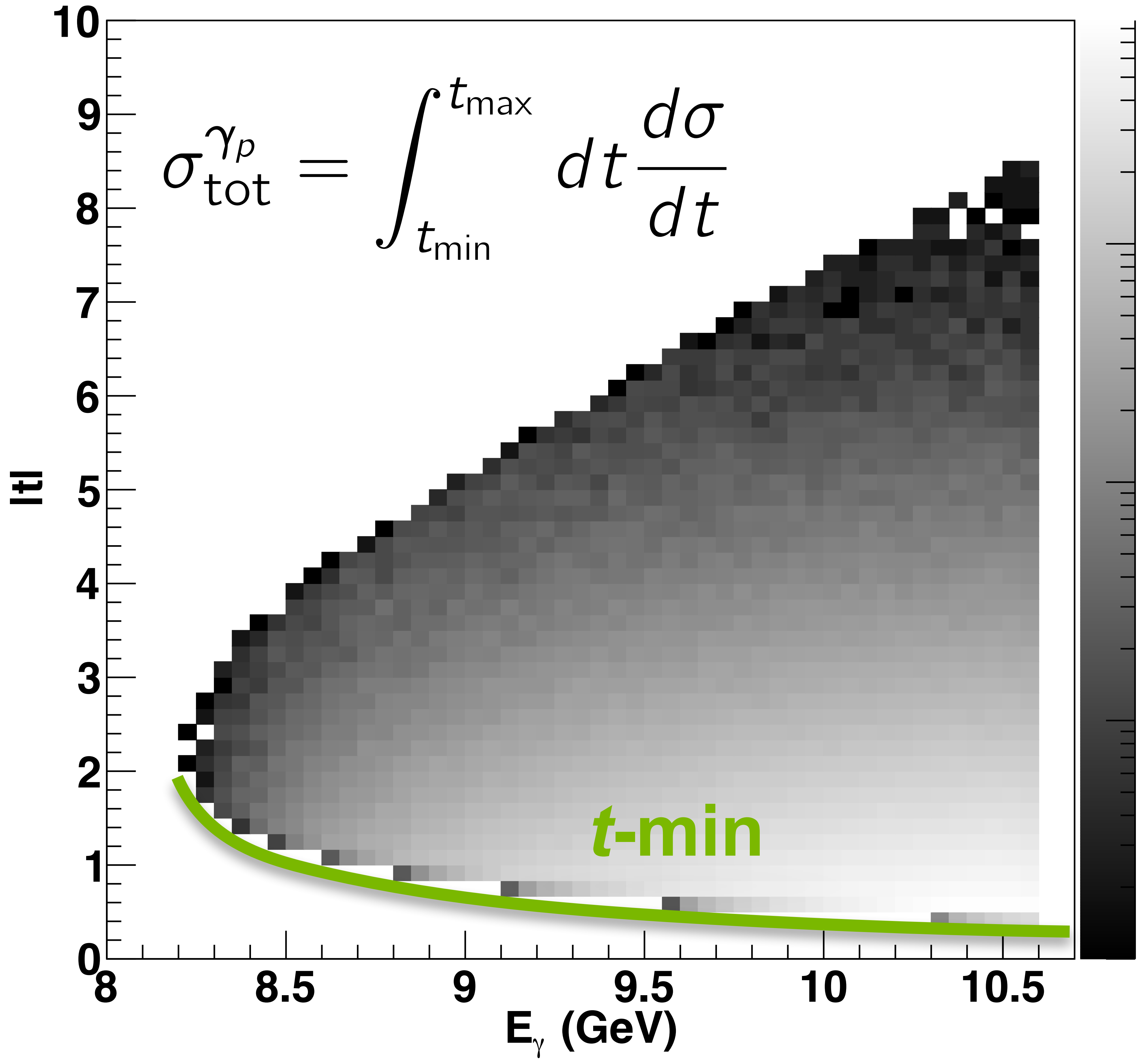

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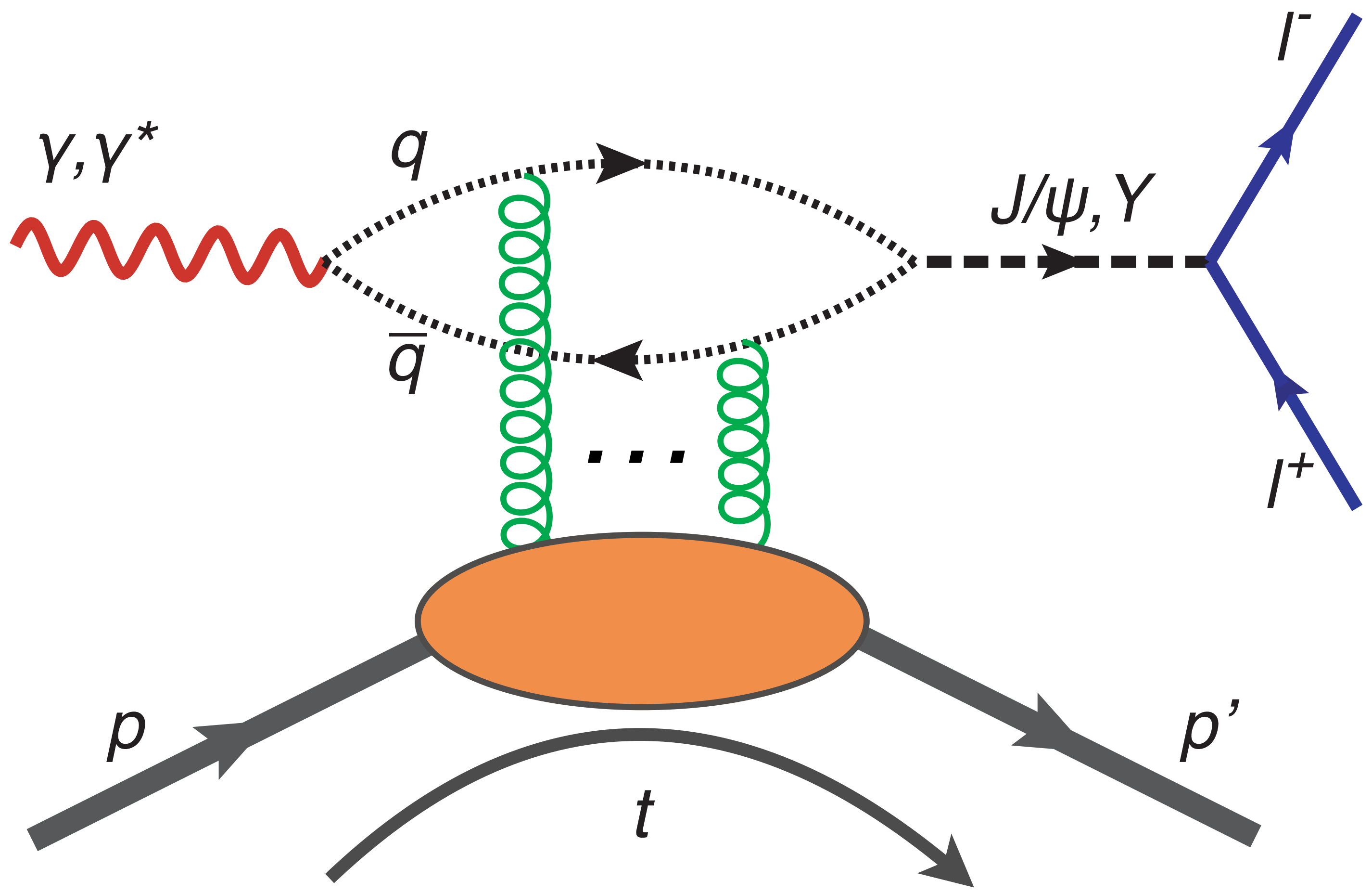

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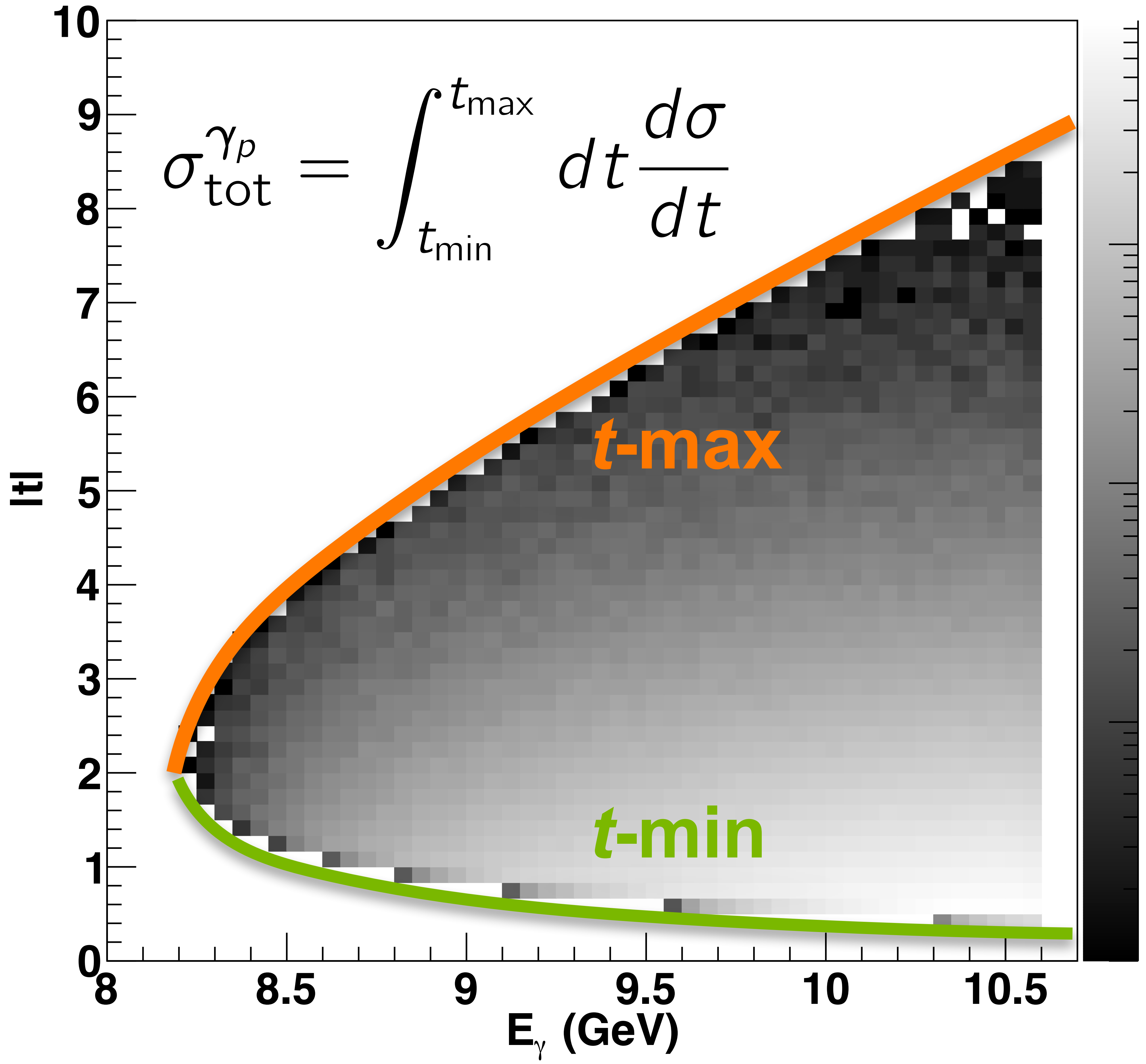

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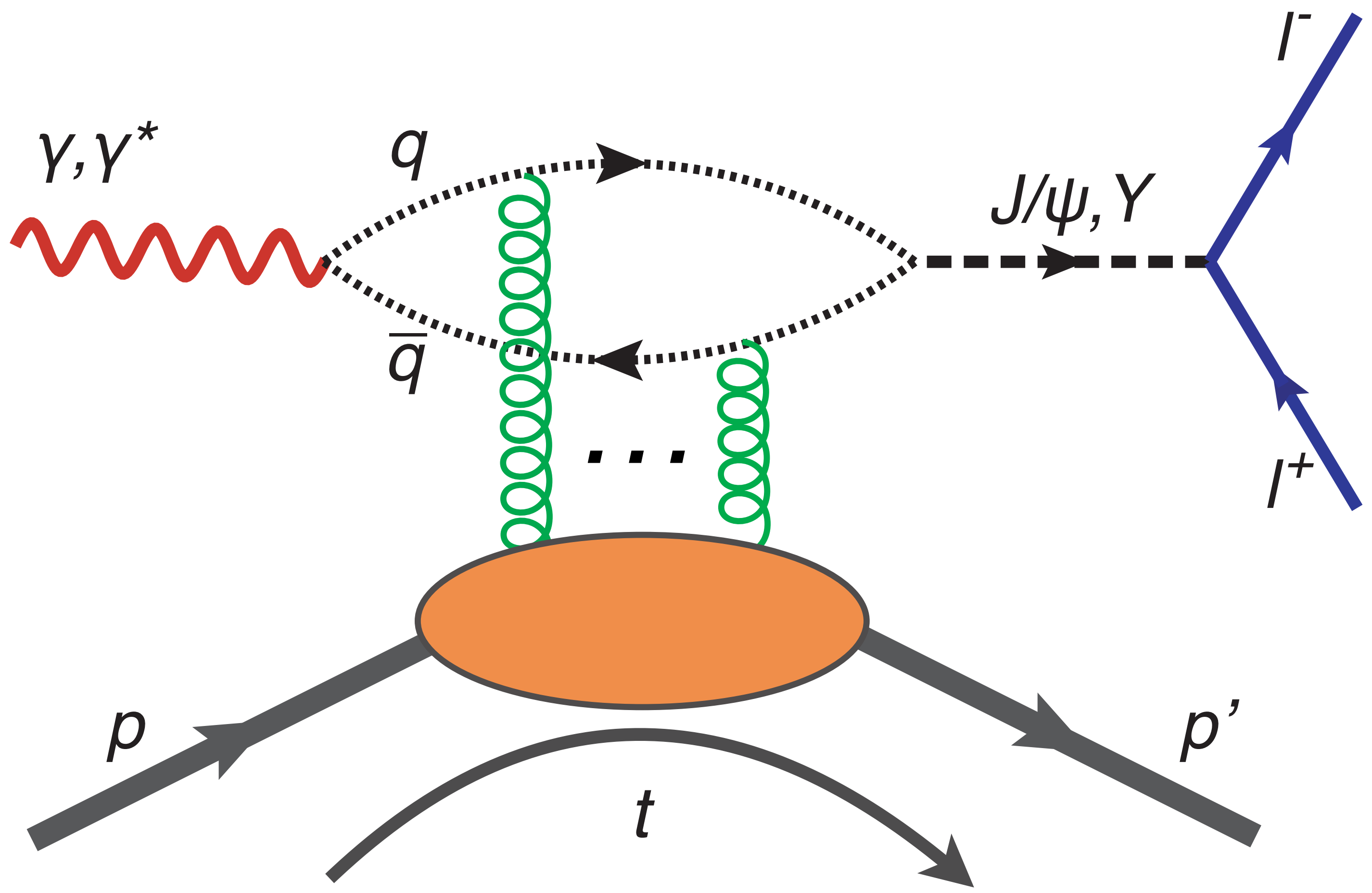

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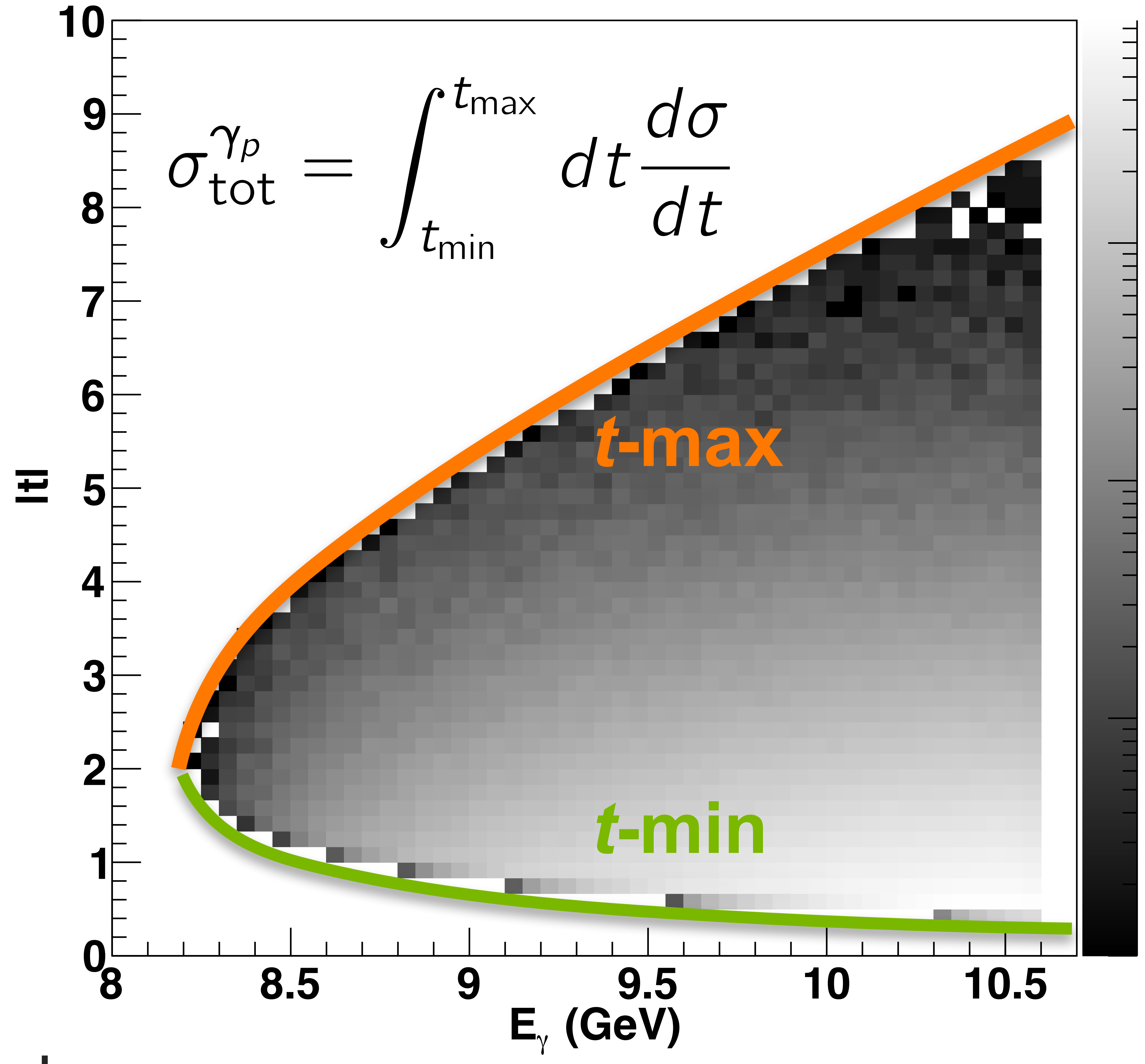

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  - Forward (with photon): $t = t_{min}$
  - Backward (with proton): $t = t_{max}$
- Forward direction preferred: *t*-dependence ~exponential

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

$$
\begin{aligned}
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:

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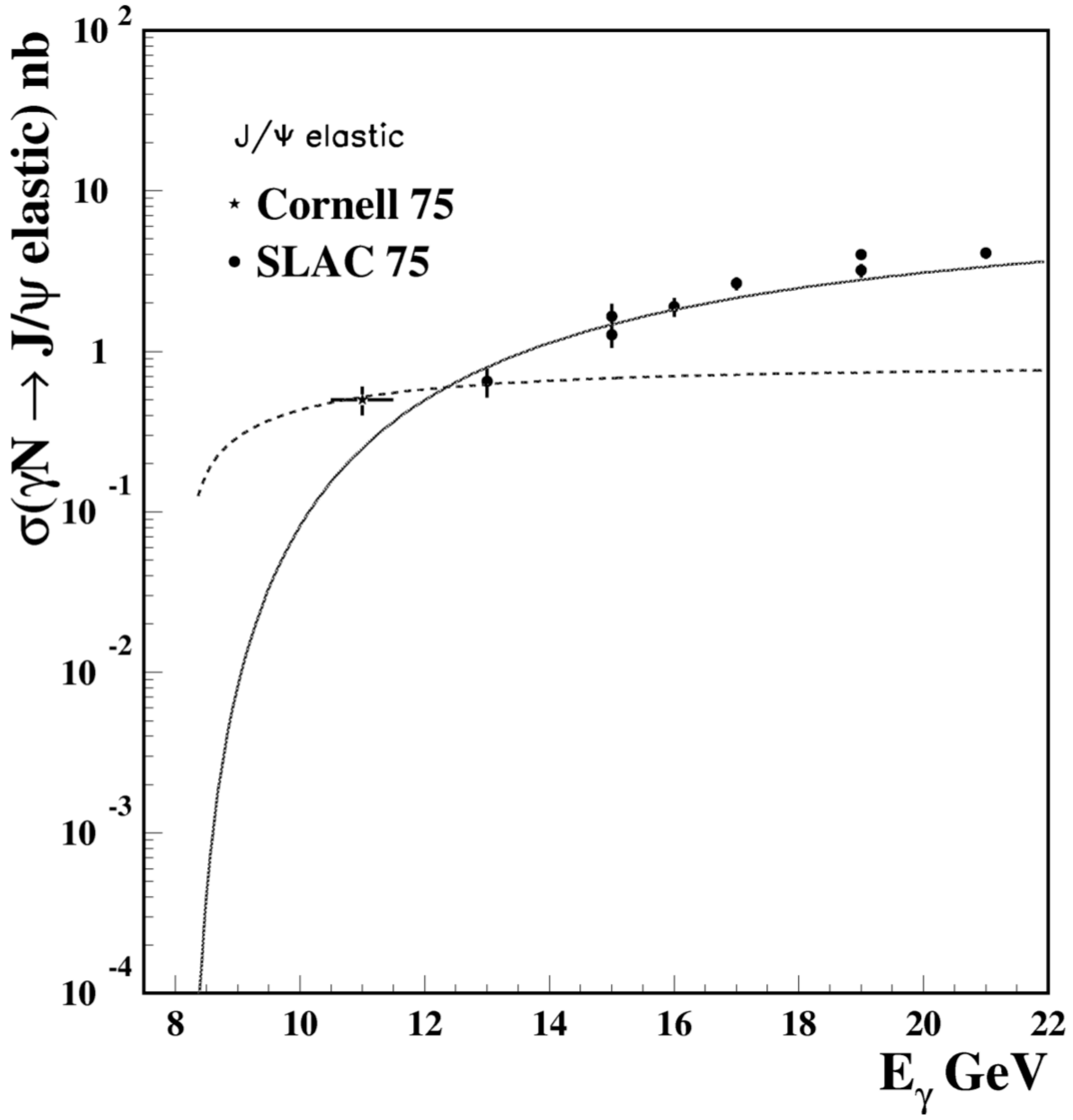
a(μ) related to PDFs, well constrained

b(μ) related trace anomaly, unconstrained

PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering



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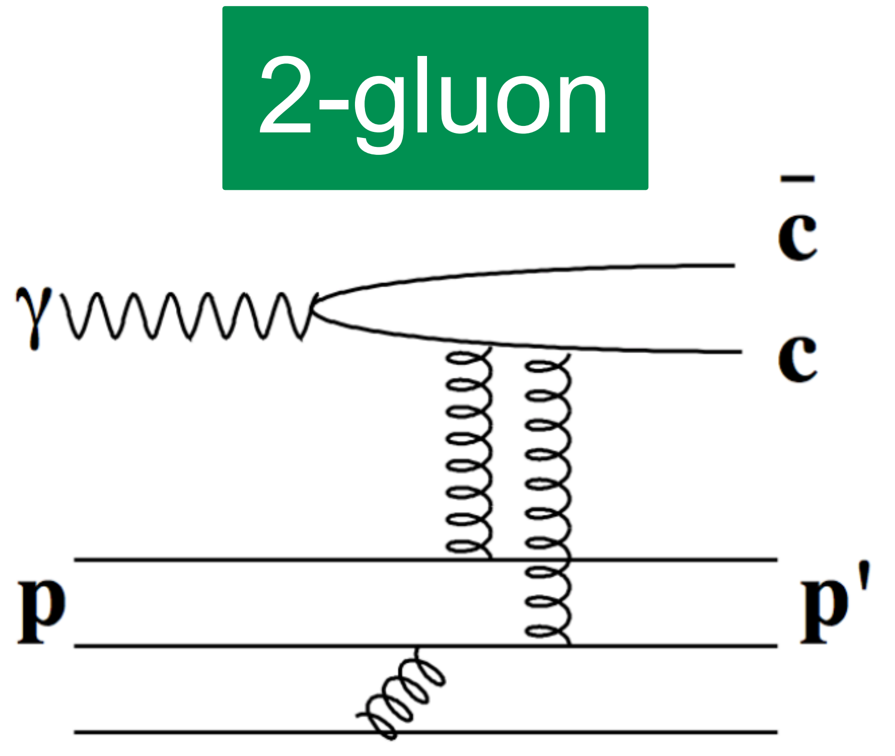

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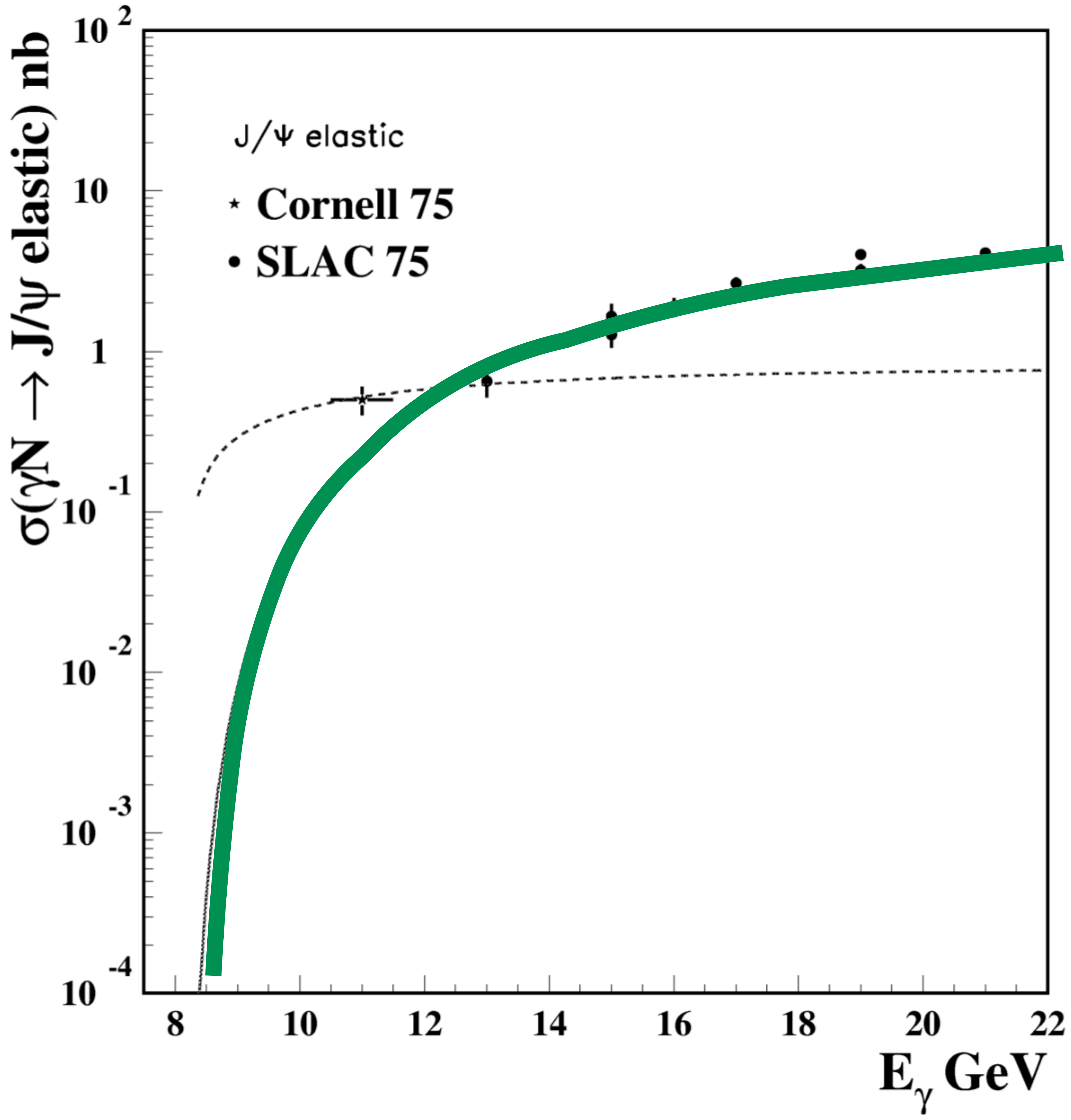

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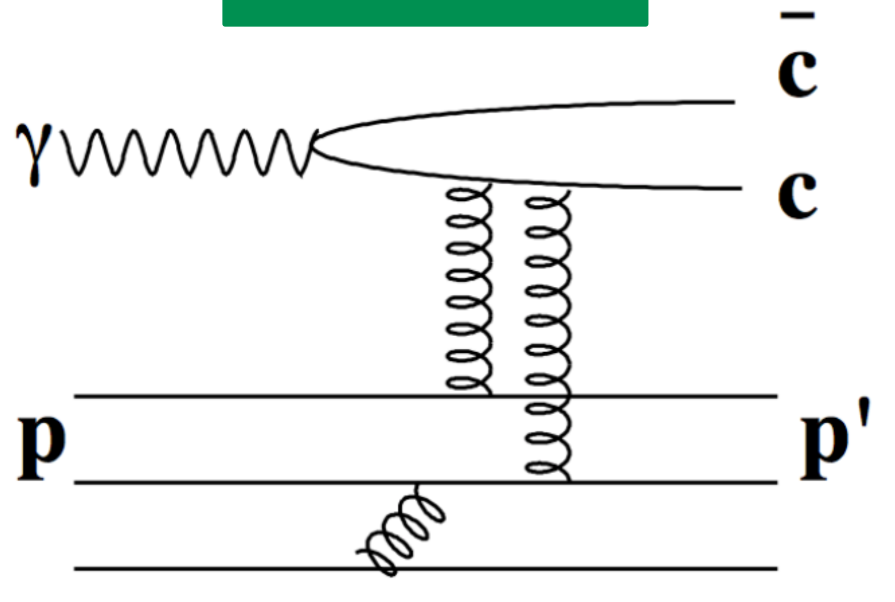
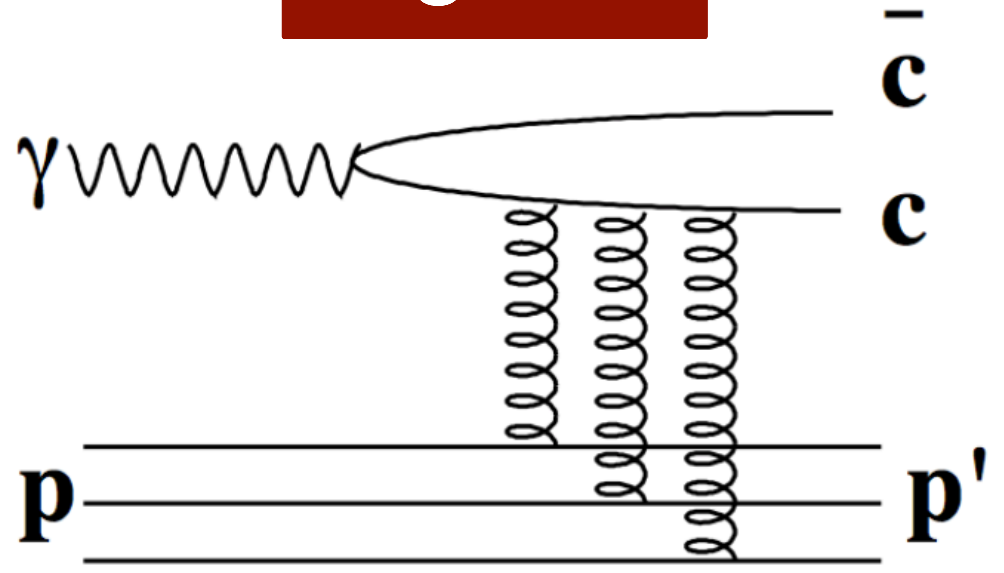


3-gluon



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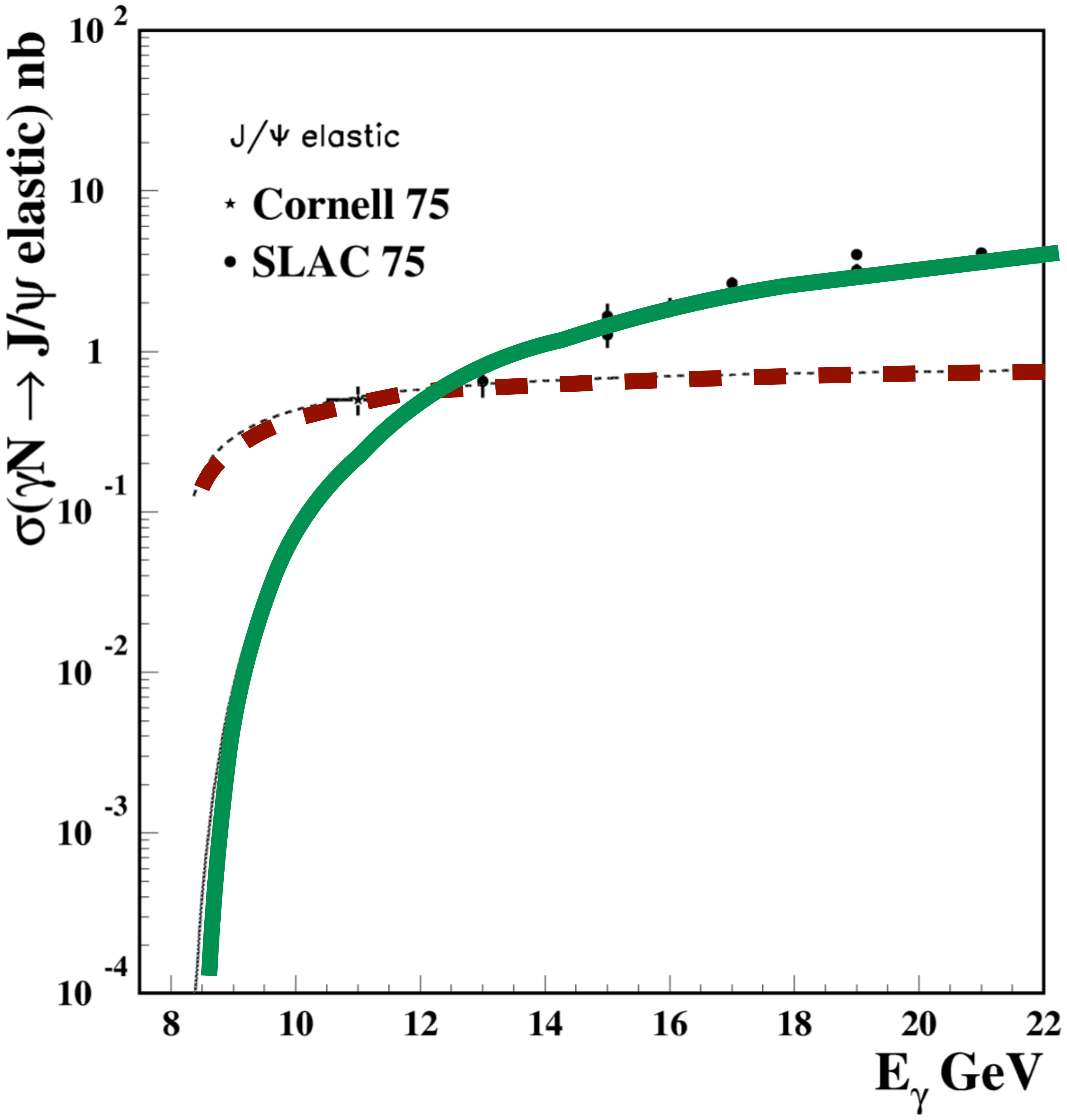

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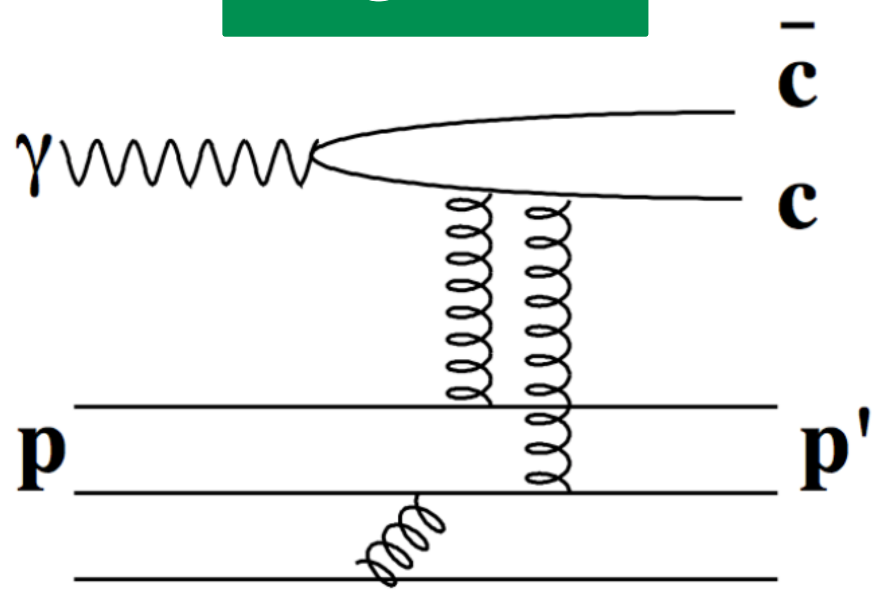

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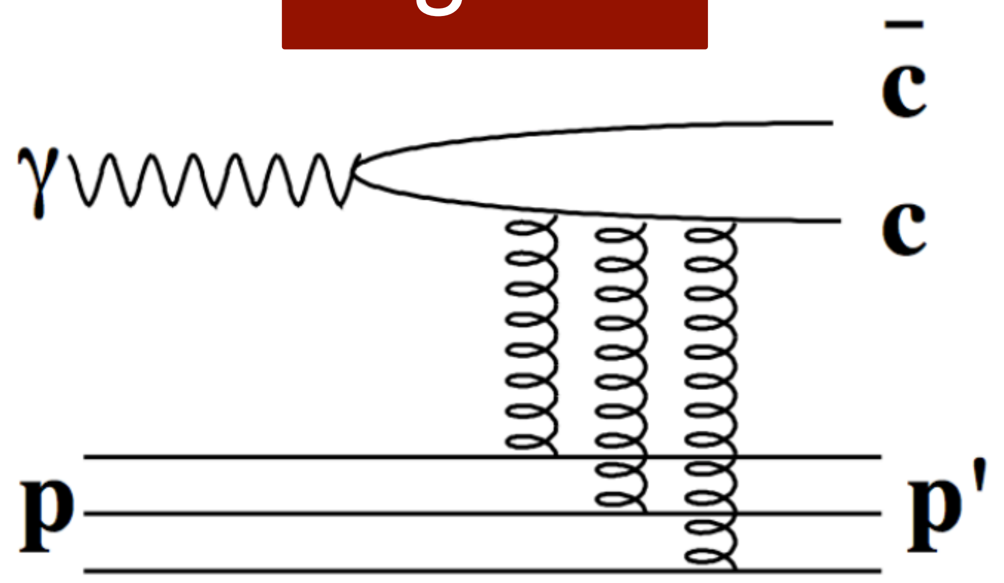

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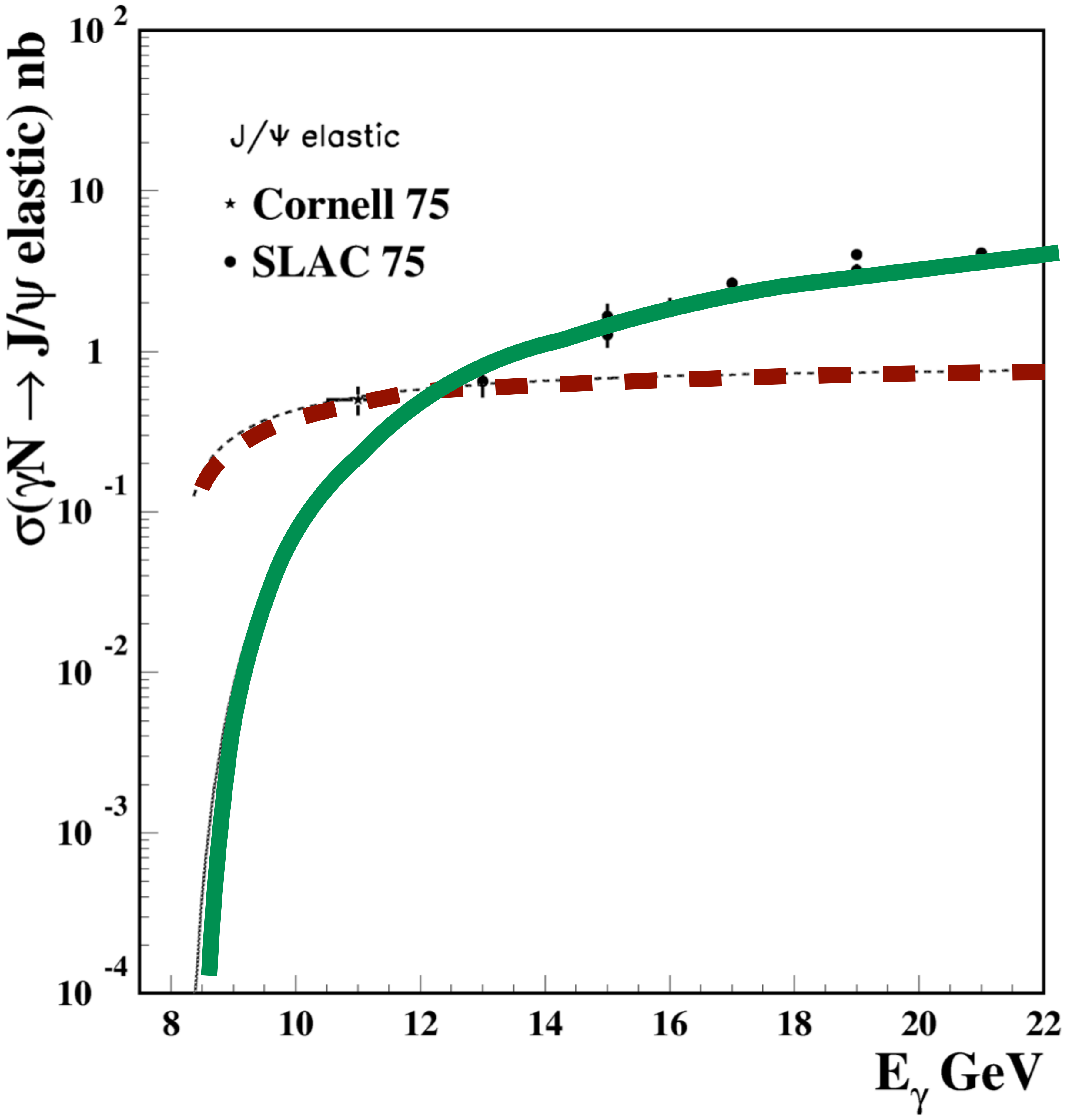

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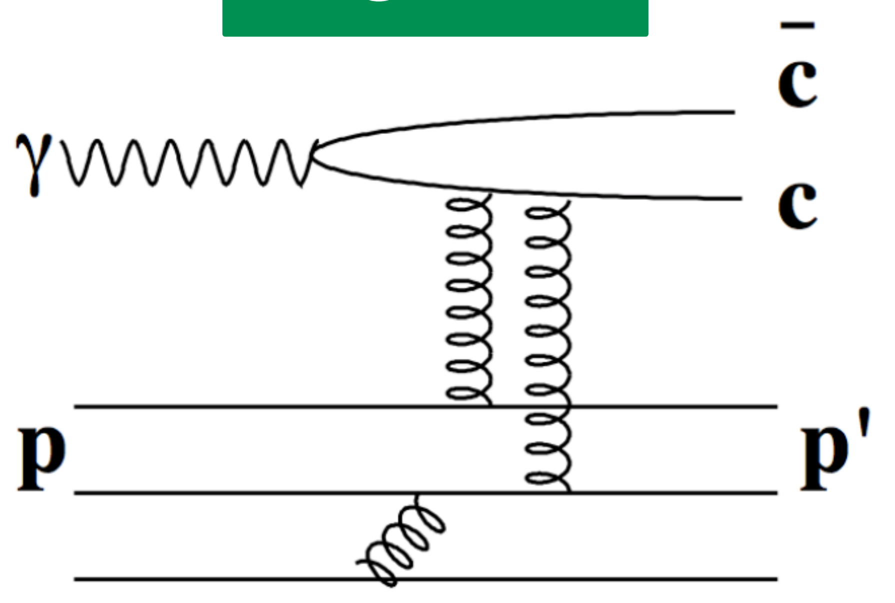

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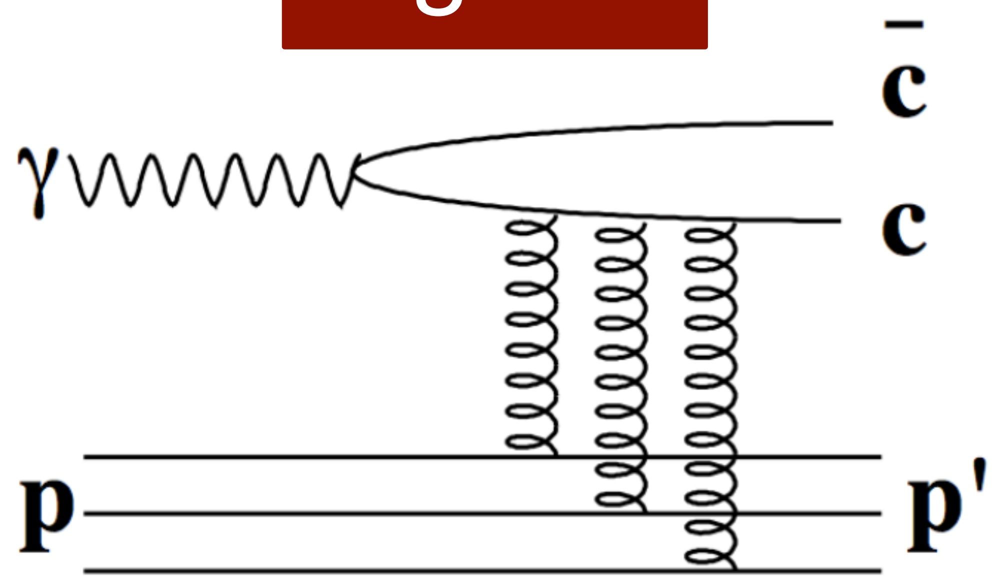

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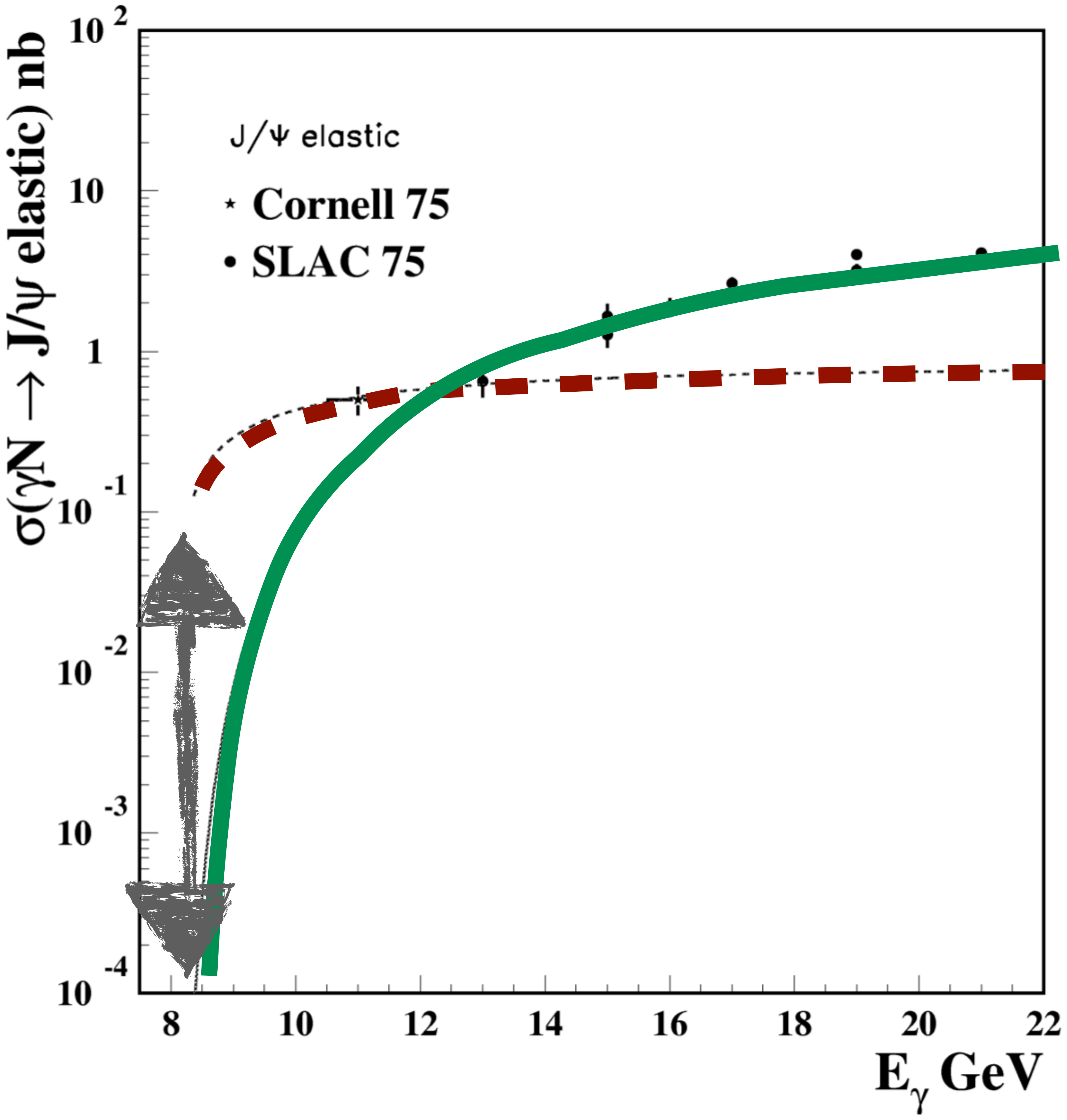

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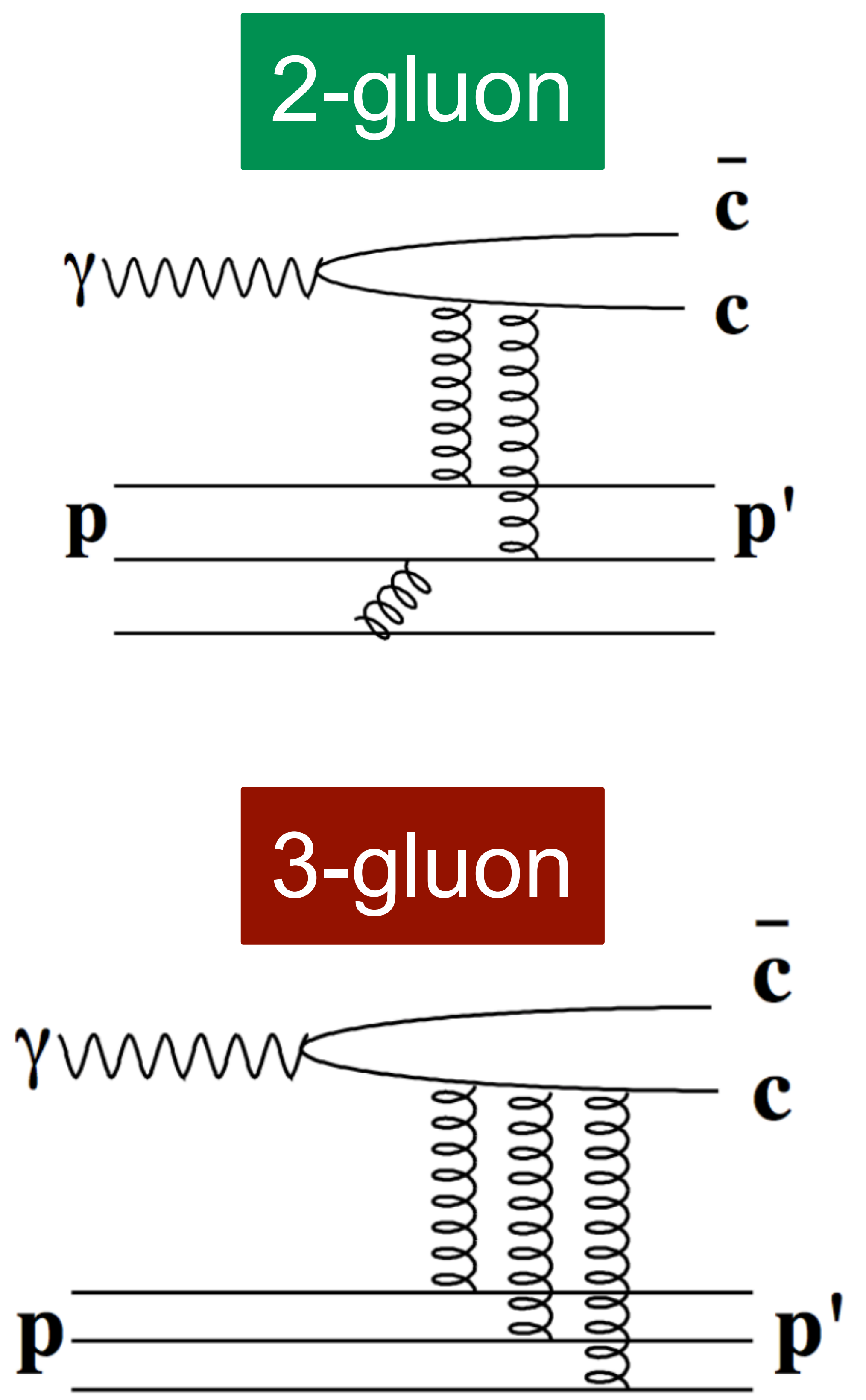

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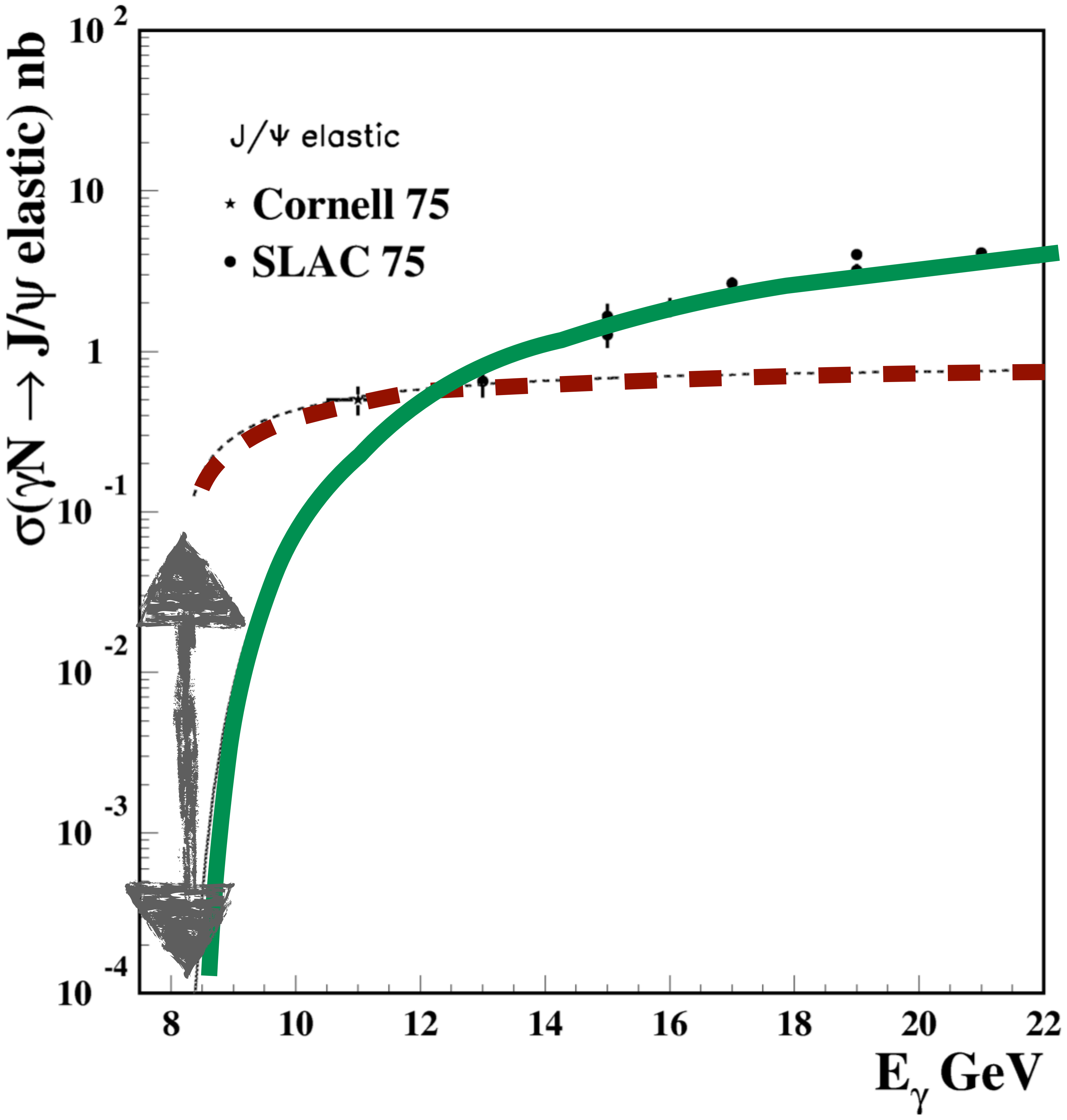
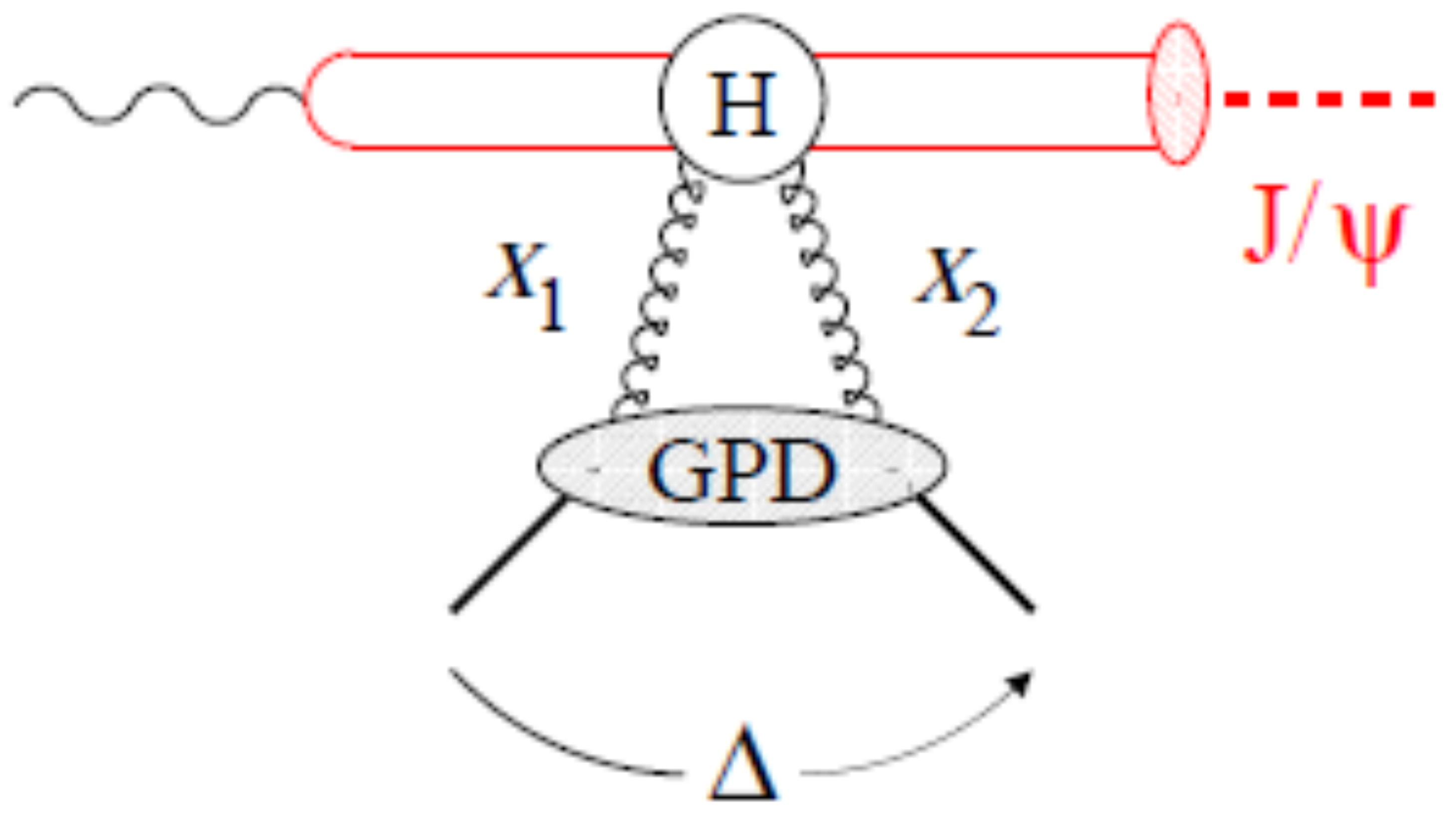
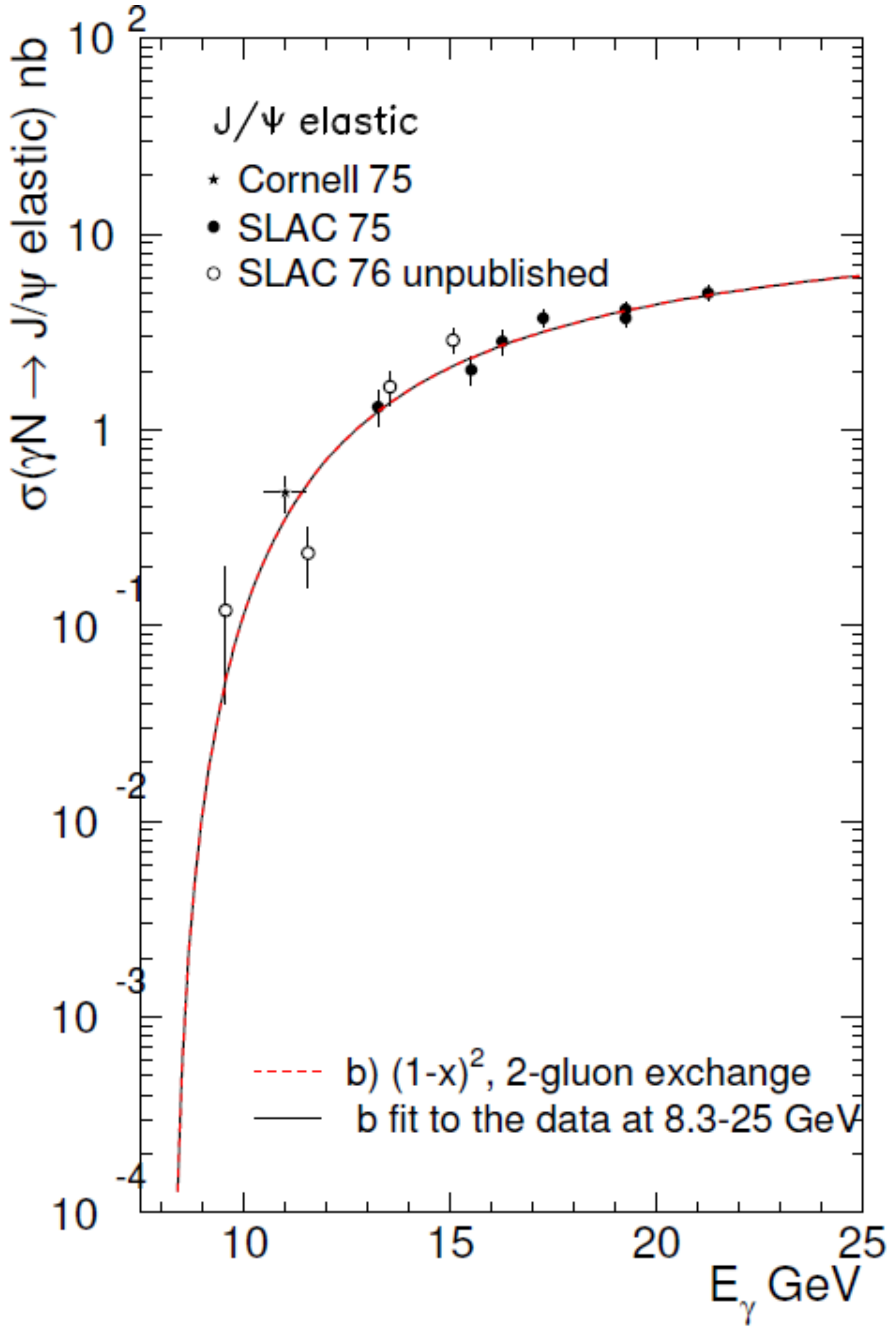


PRODUCTION MECHANISM NEAR THRESHOLD?

Partonic soft mechanism





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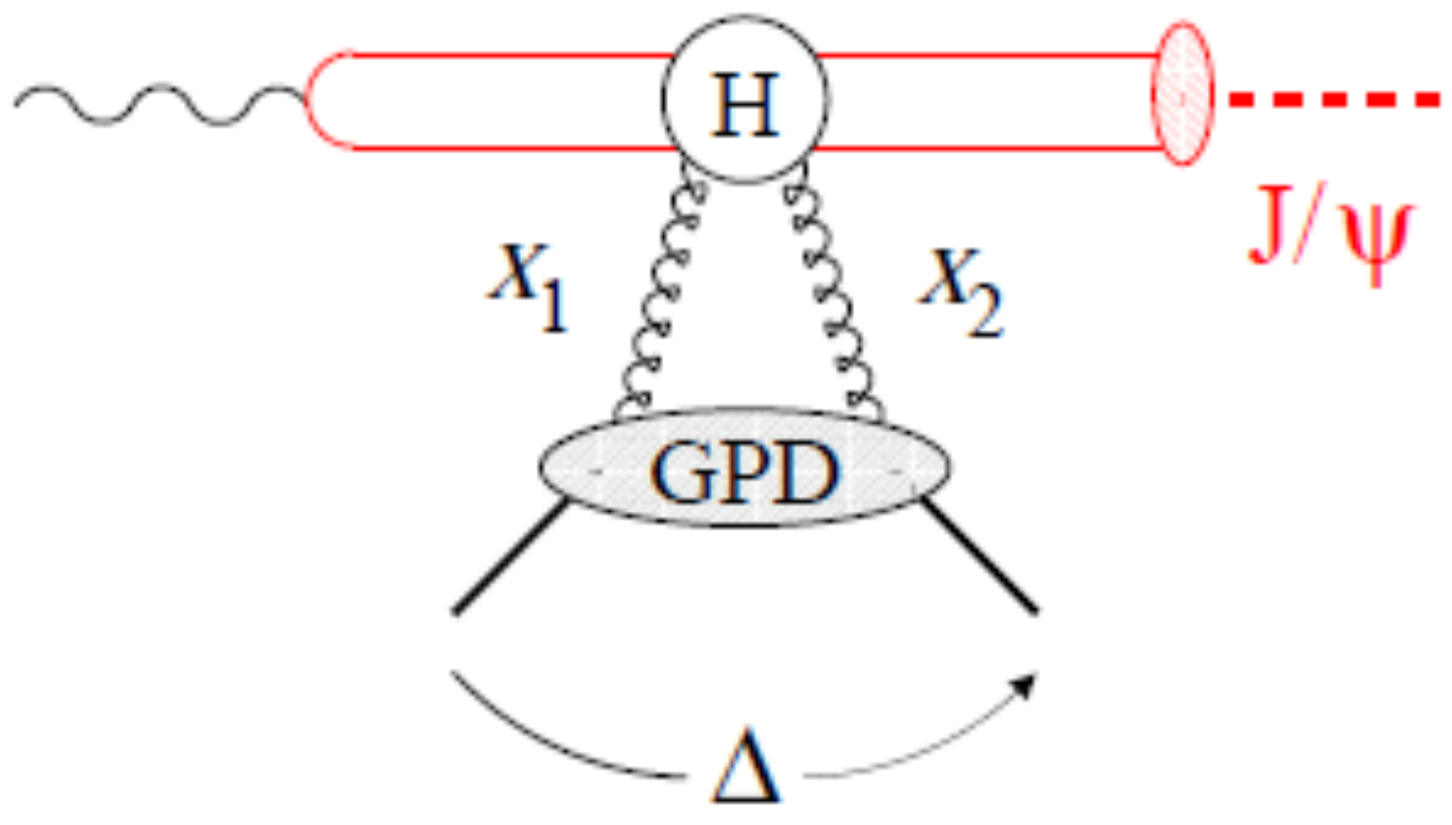

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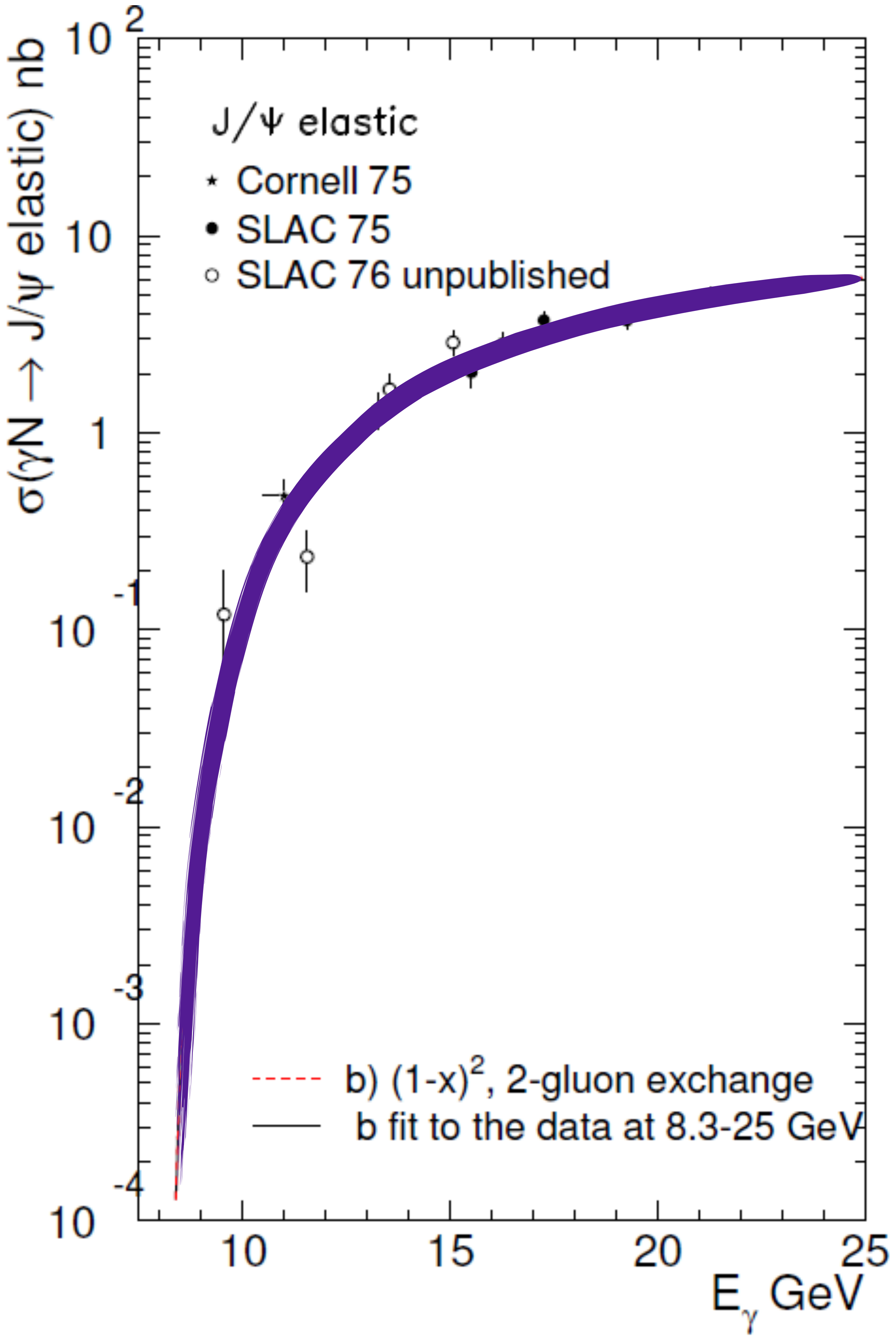

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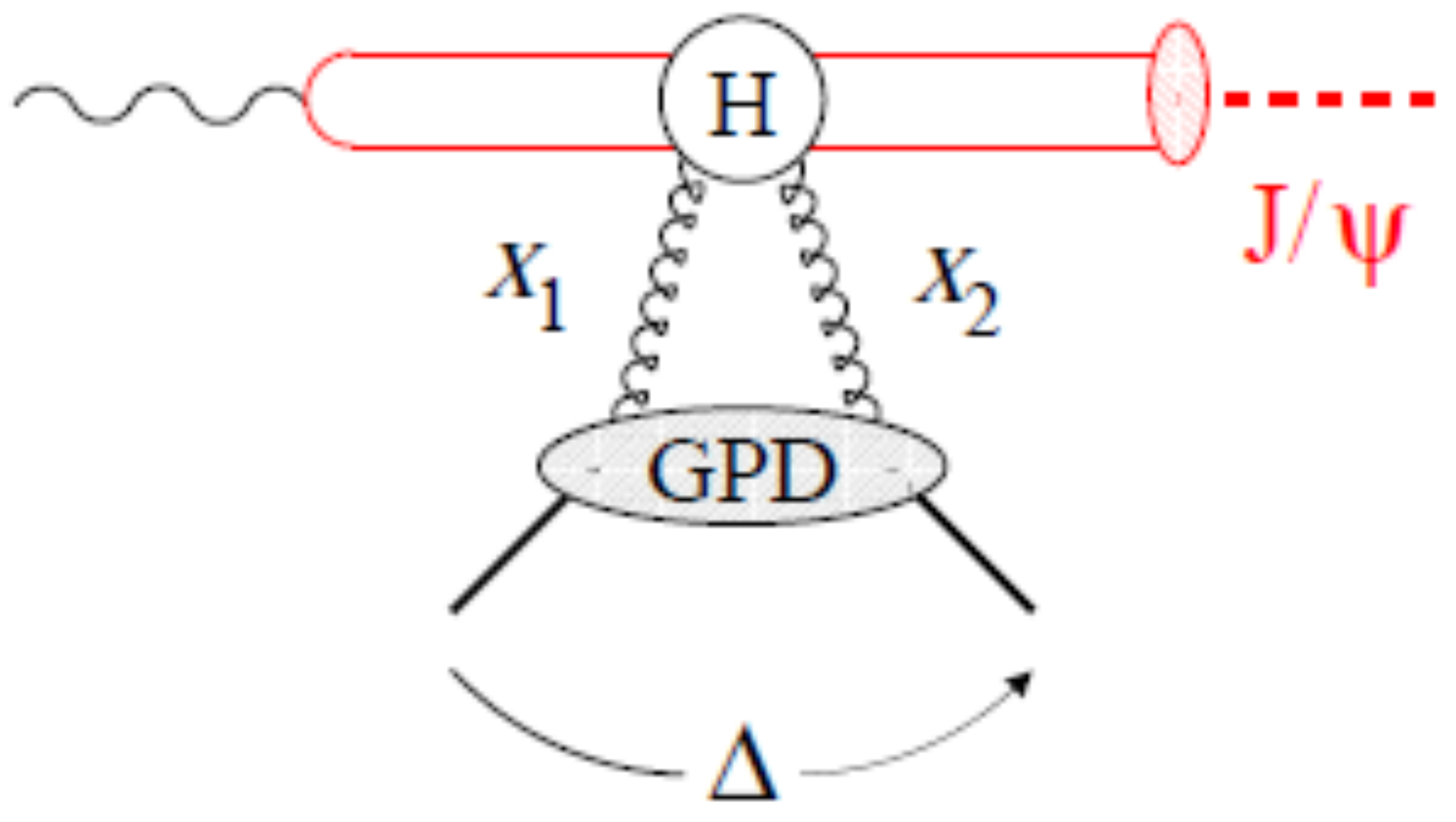

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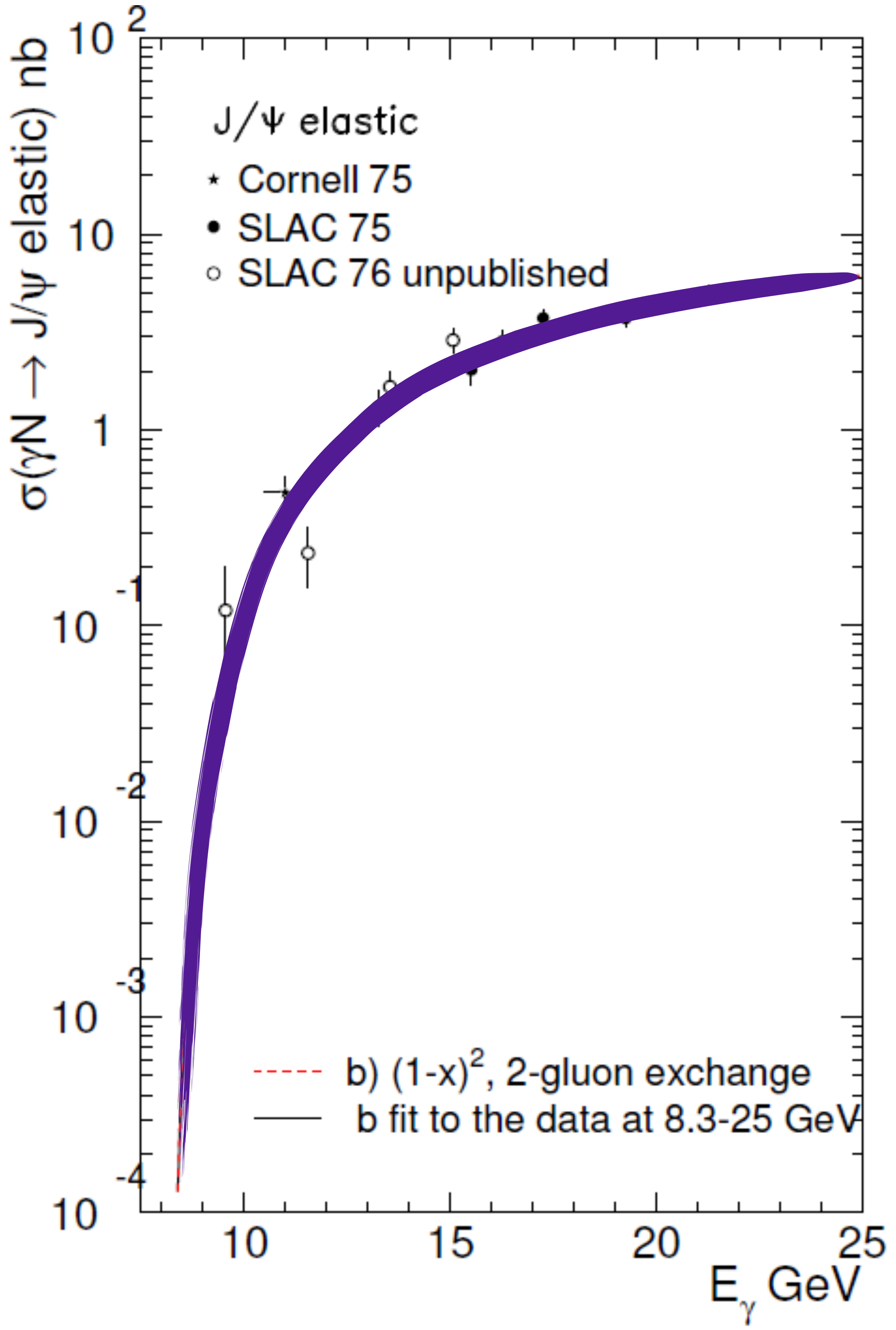

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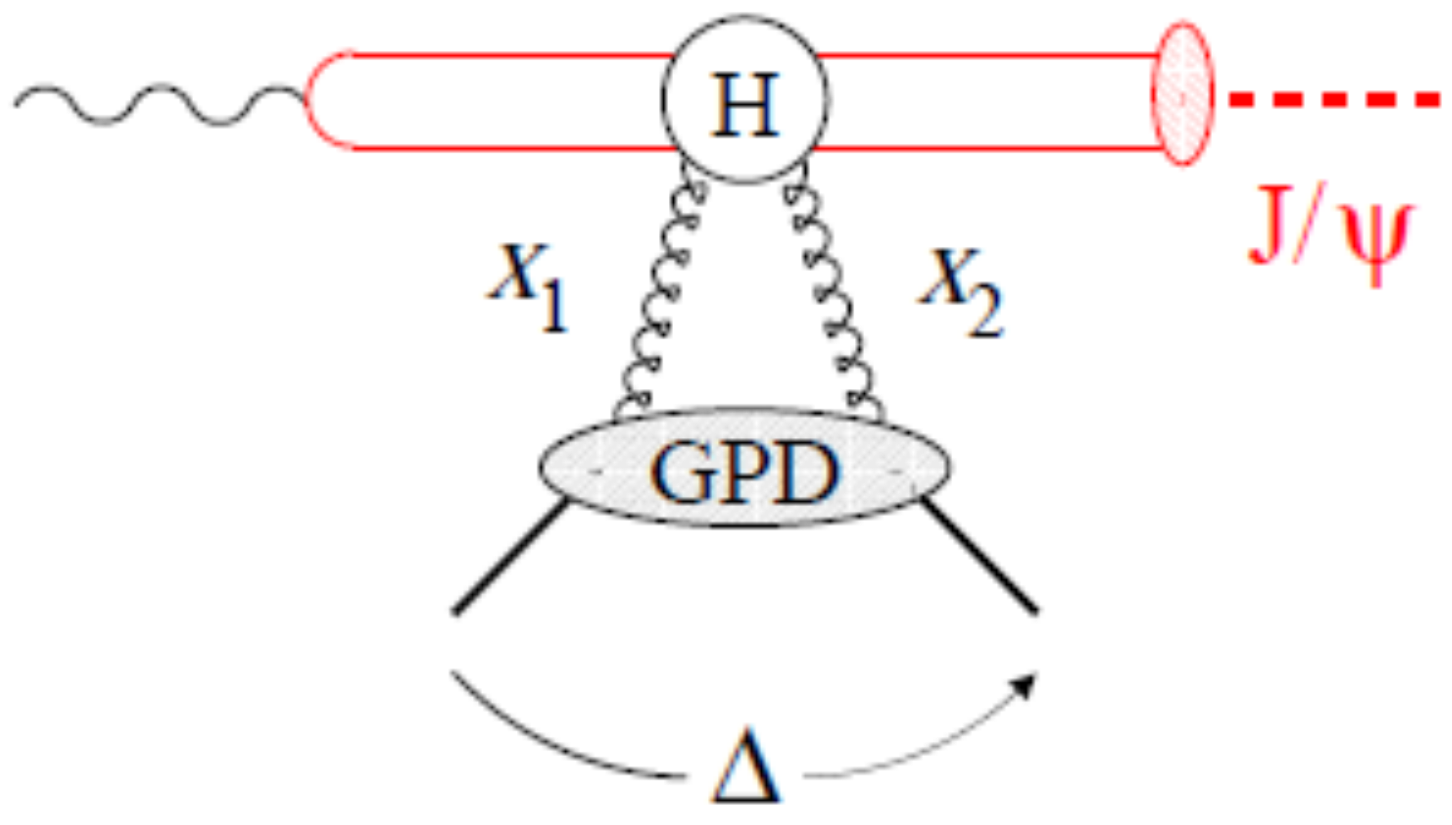

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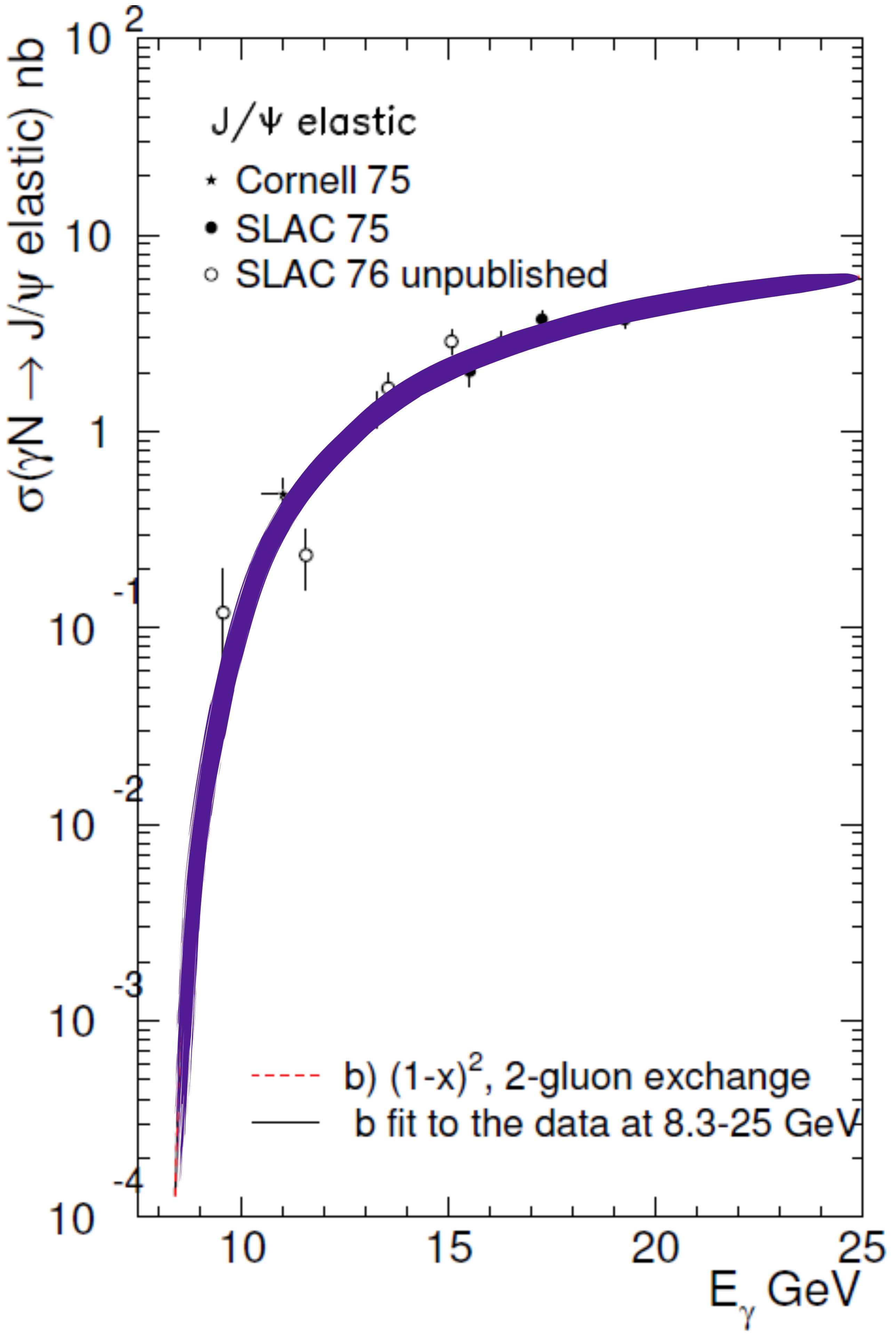

D. Kharzeev *et al.*, PLB 289 595-599 (1996), EPJ-C 9 459-462 (1999)
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)

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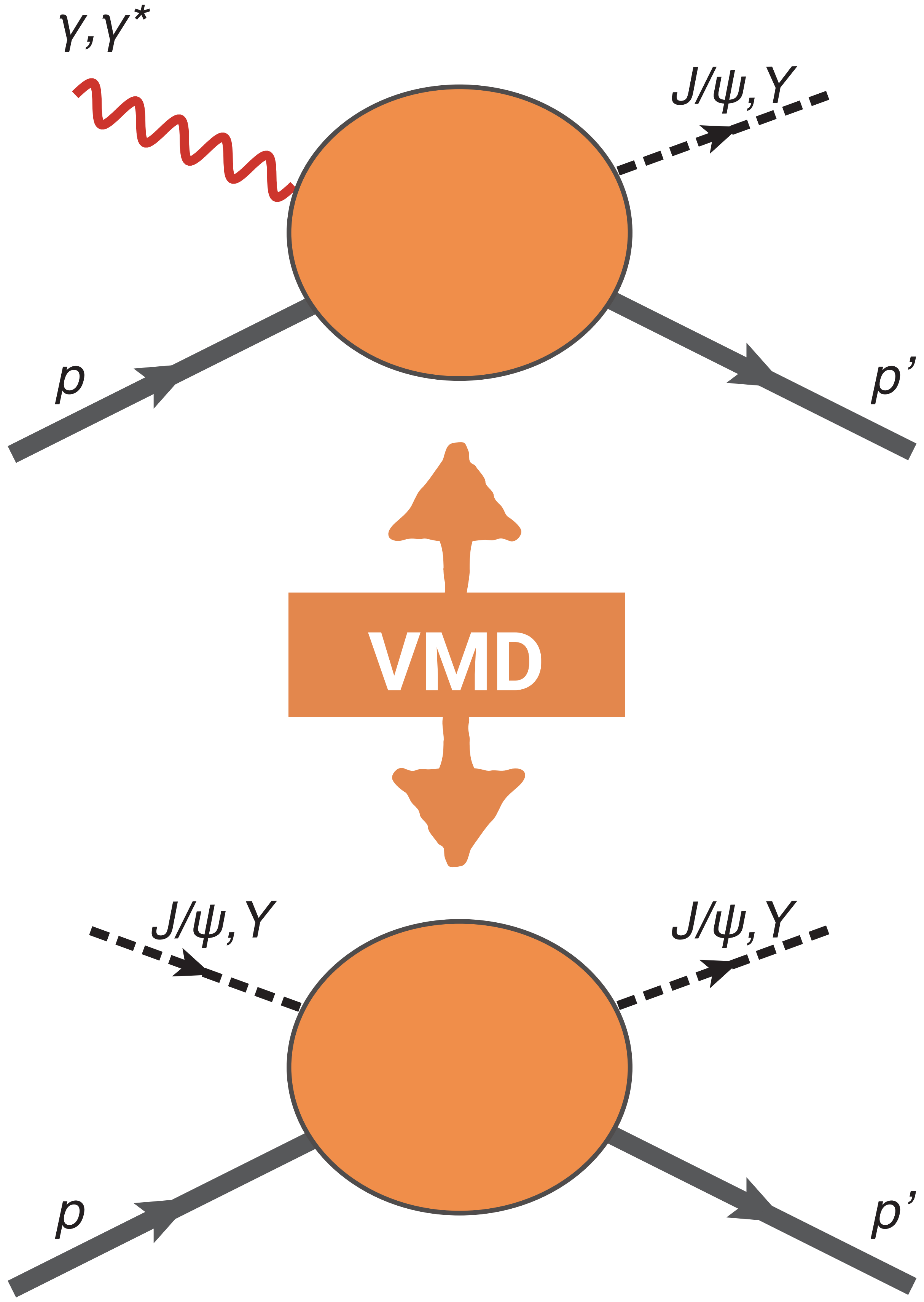

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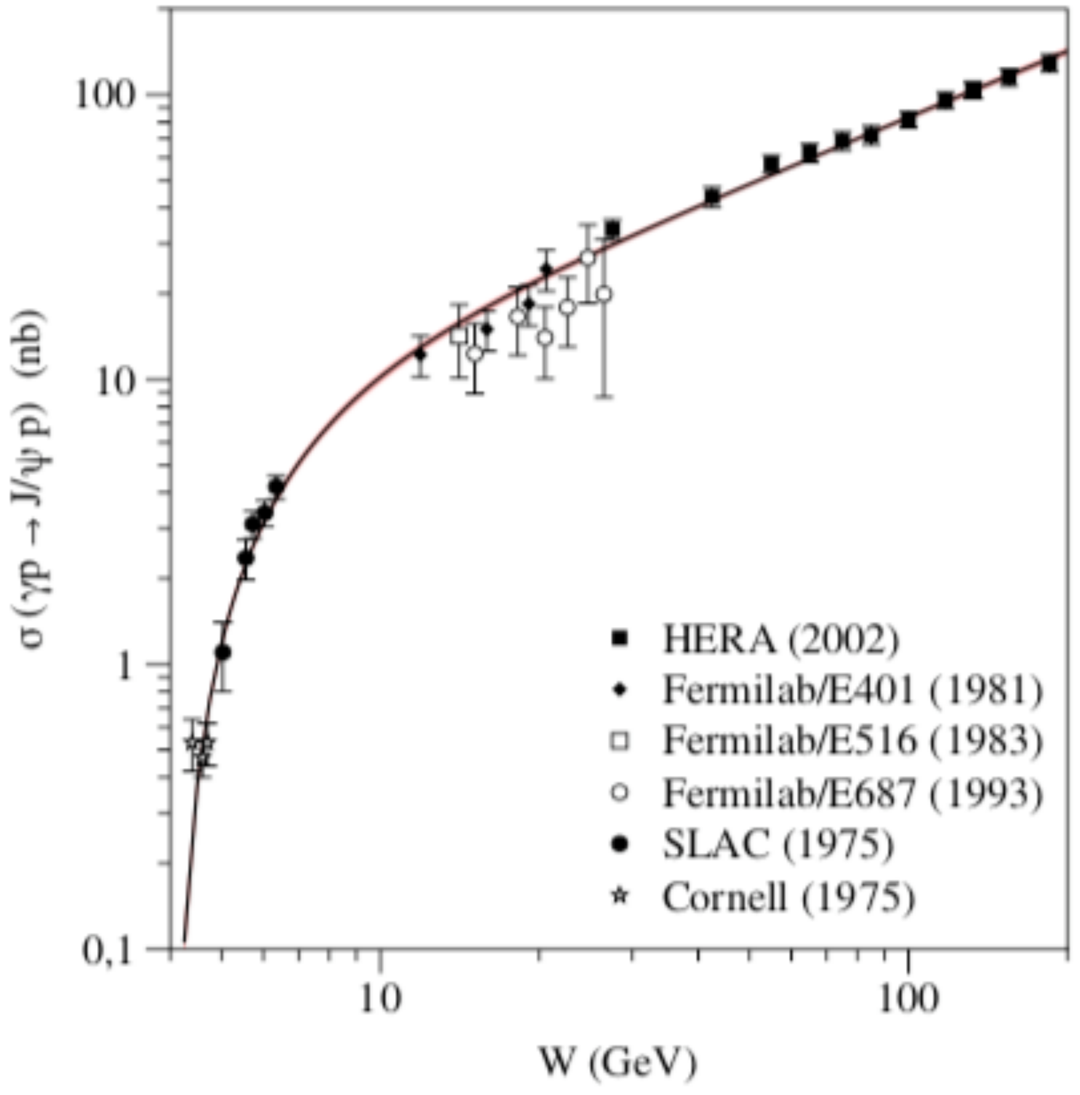

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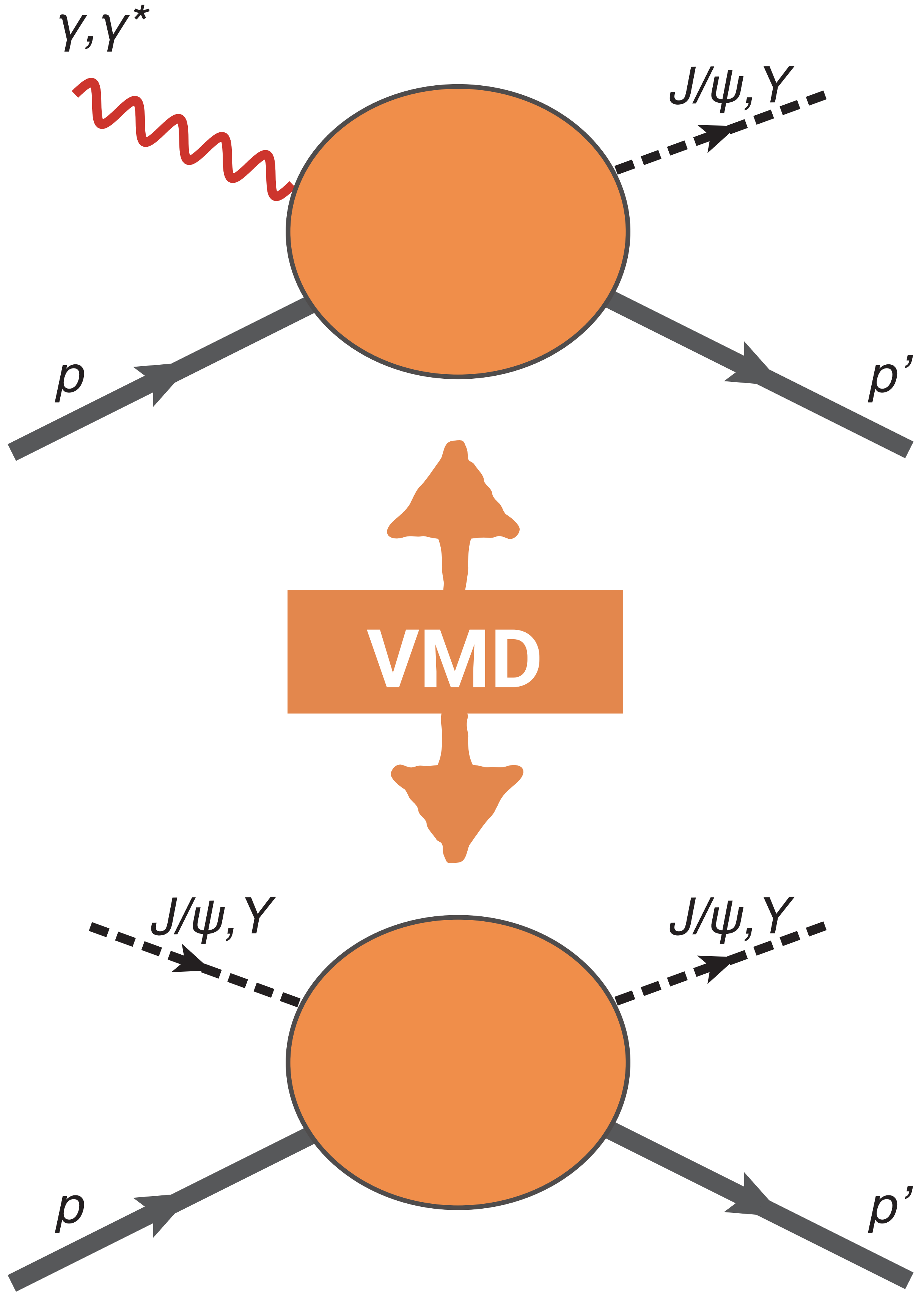

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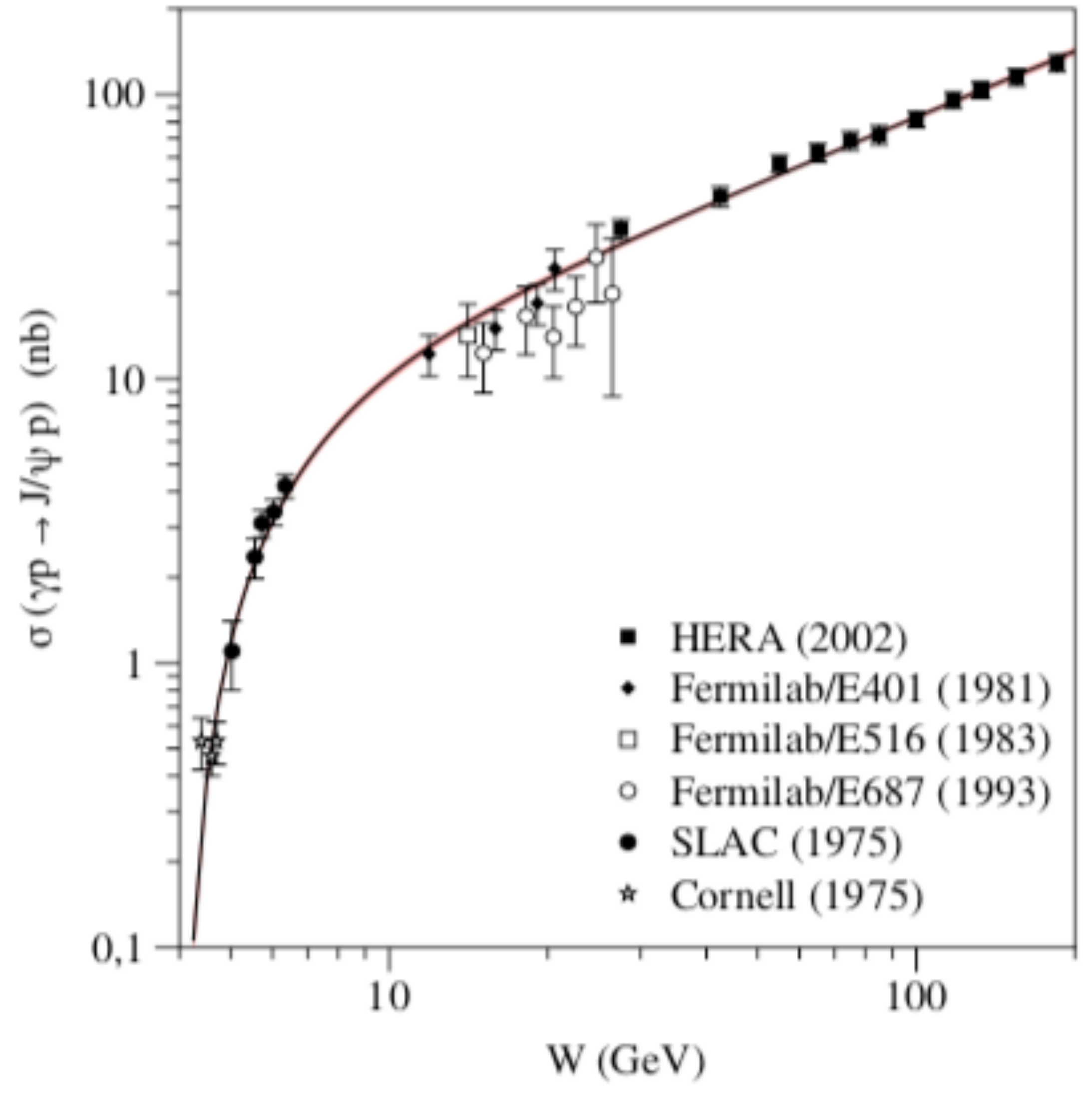

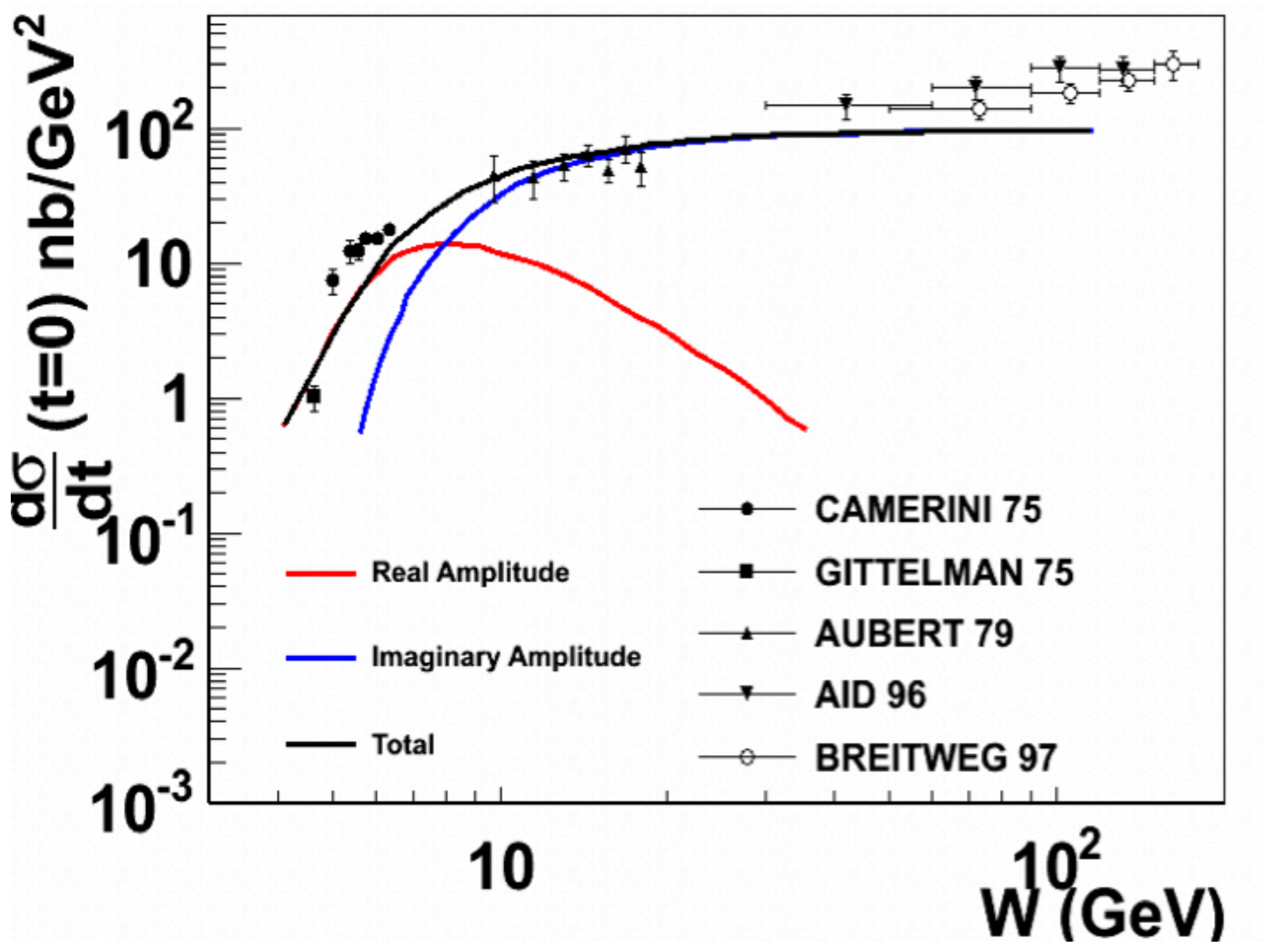

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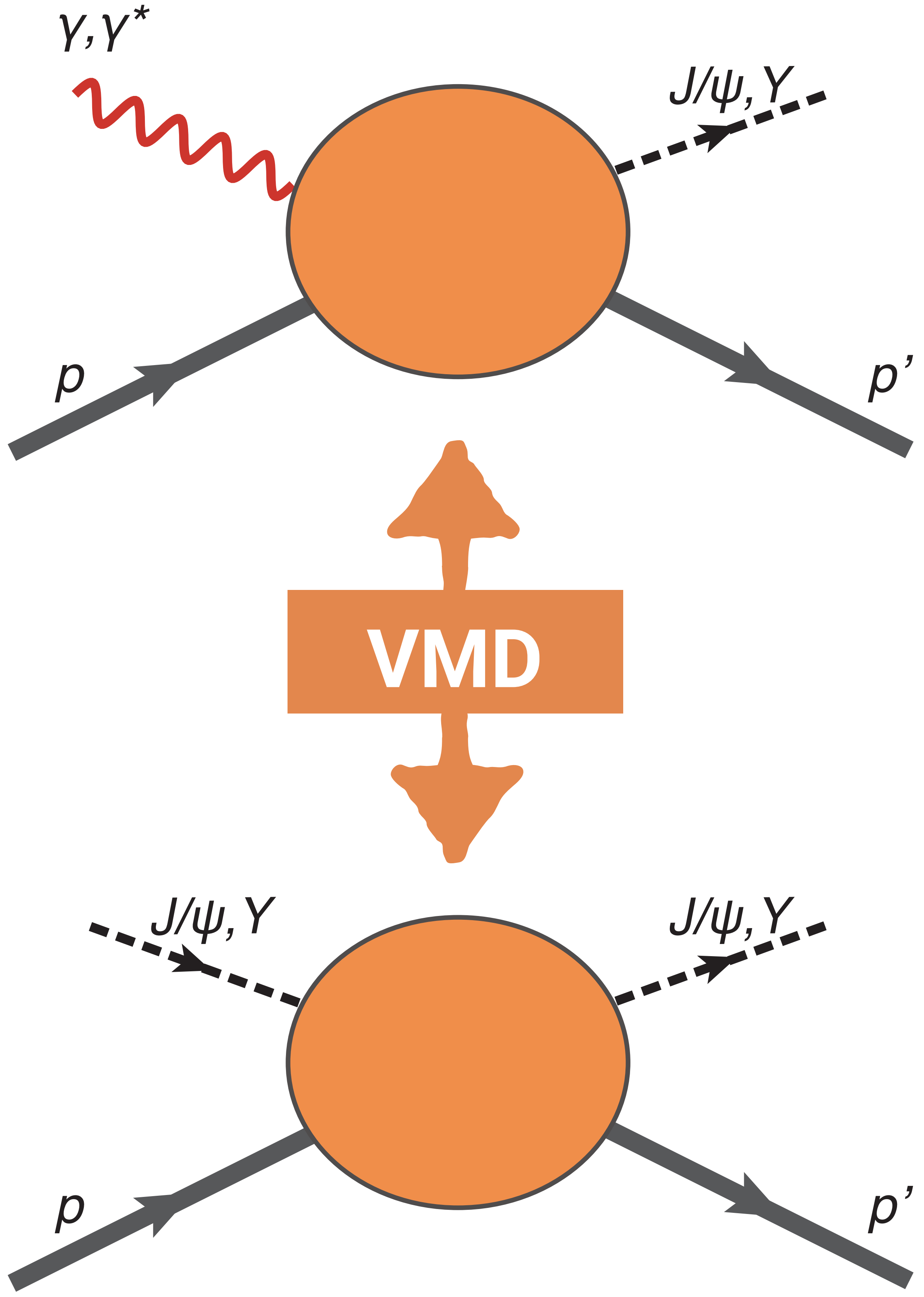

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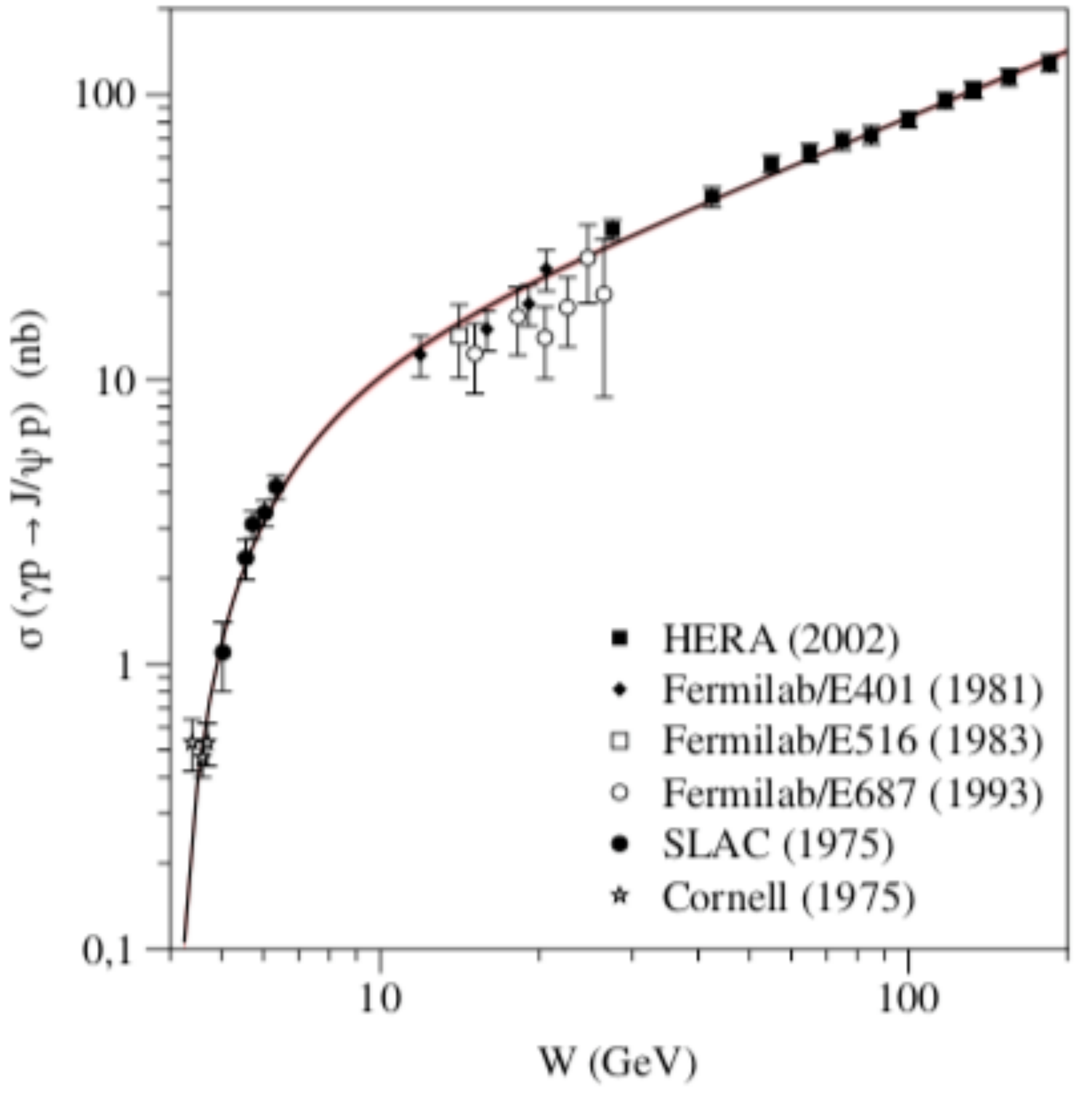

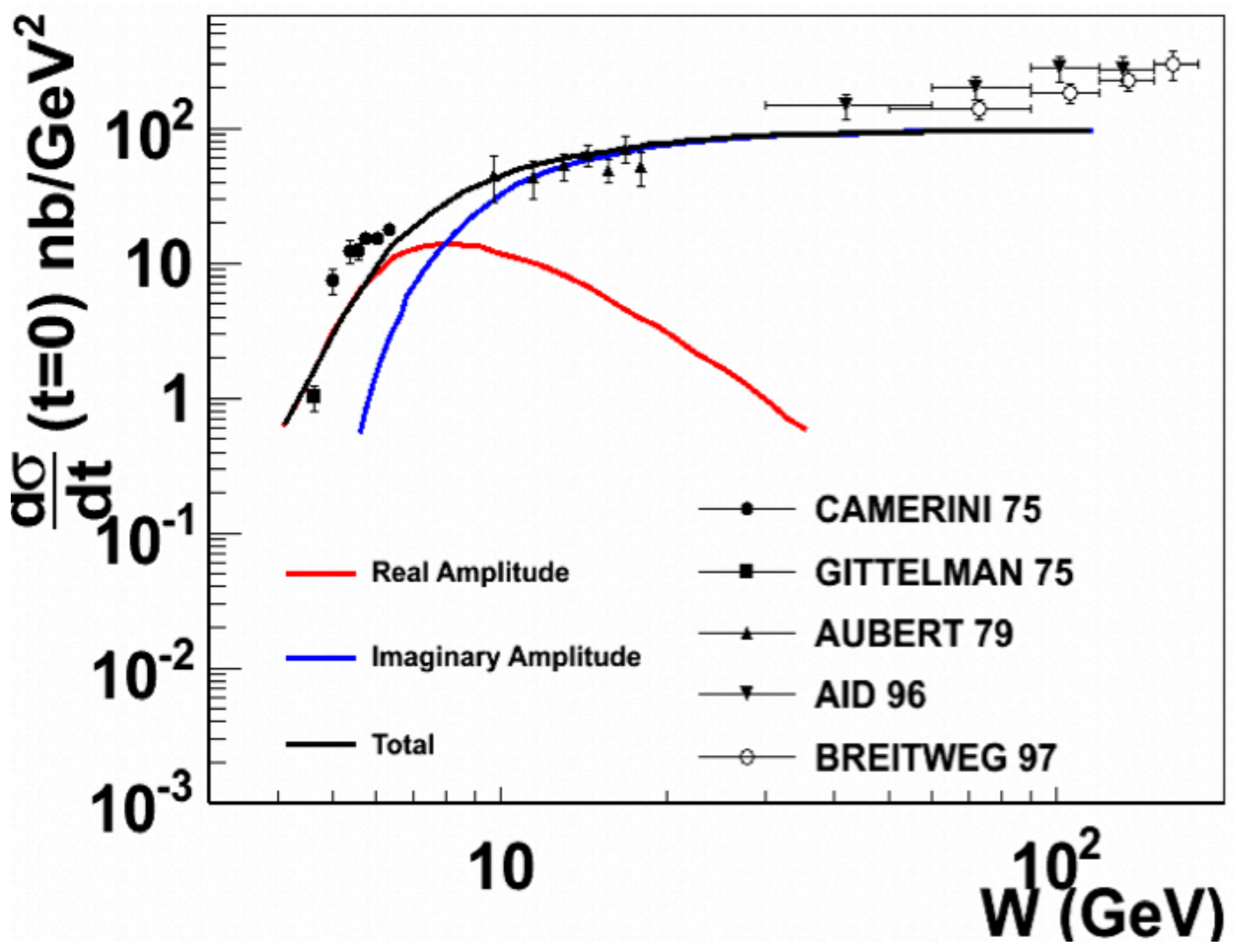

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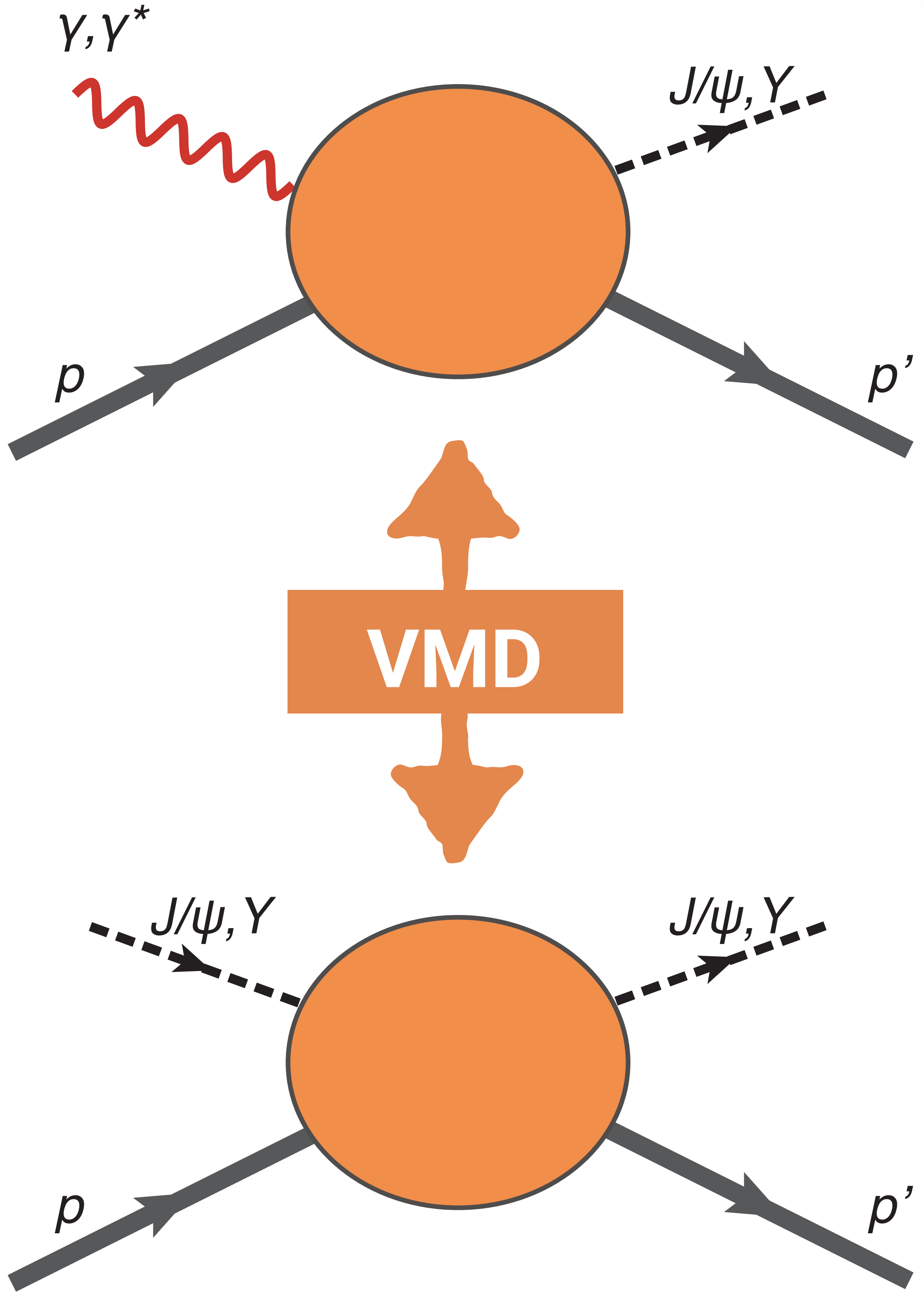

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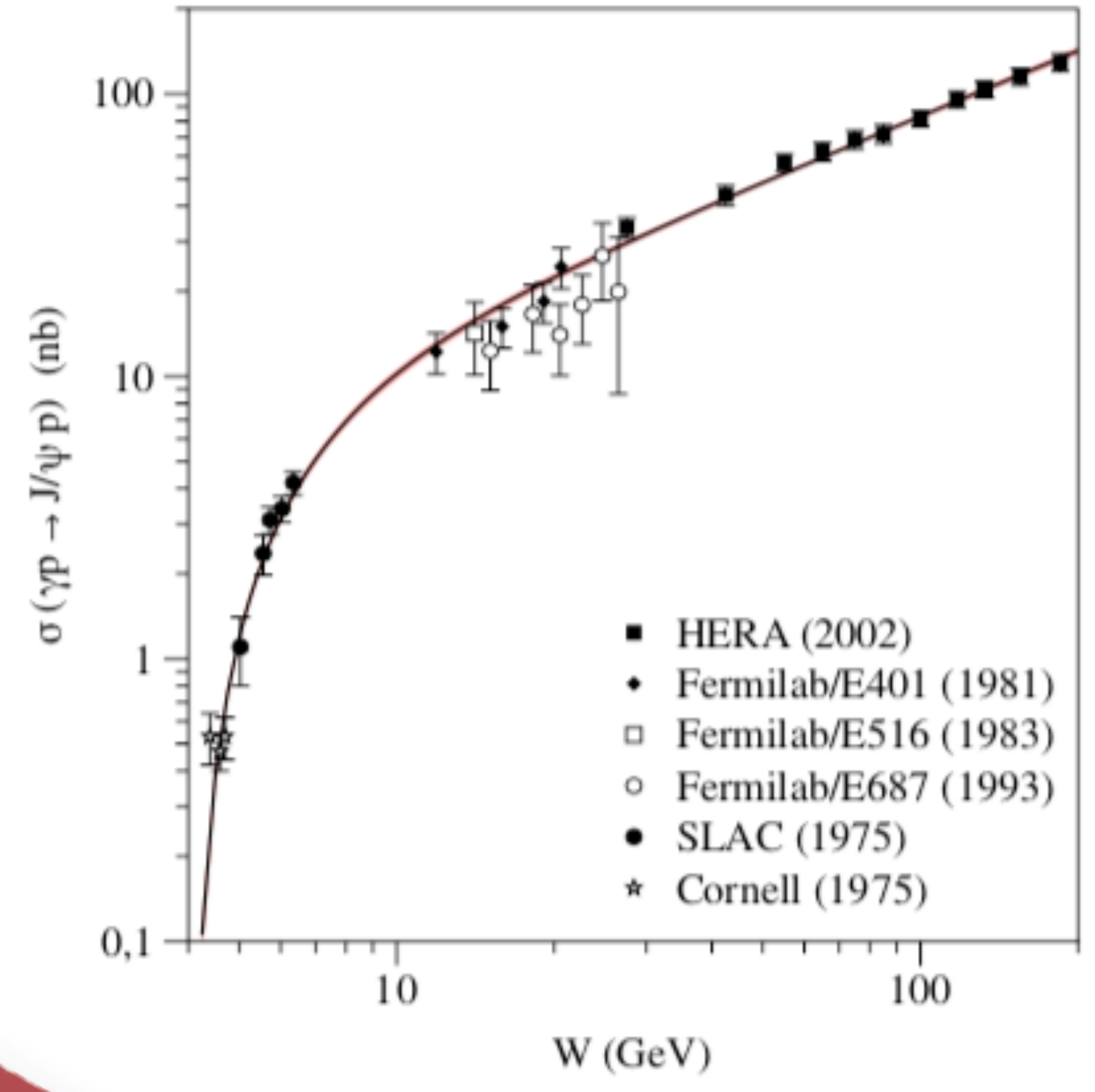
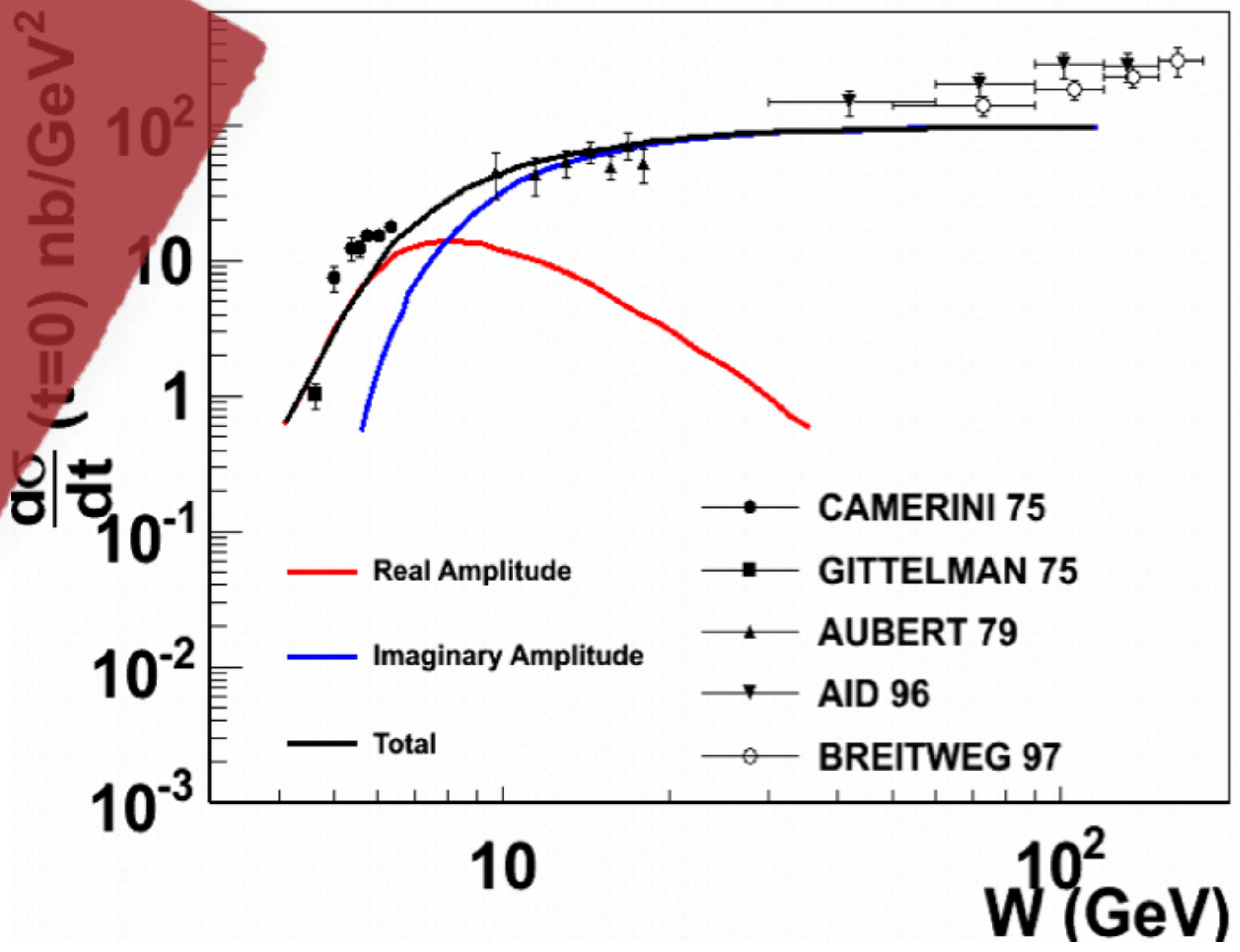
WARNING LABEL: Keep in mind, no rigorous factorization theorem (yet)!





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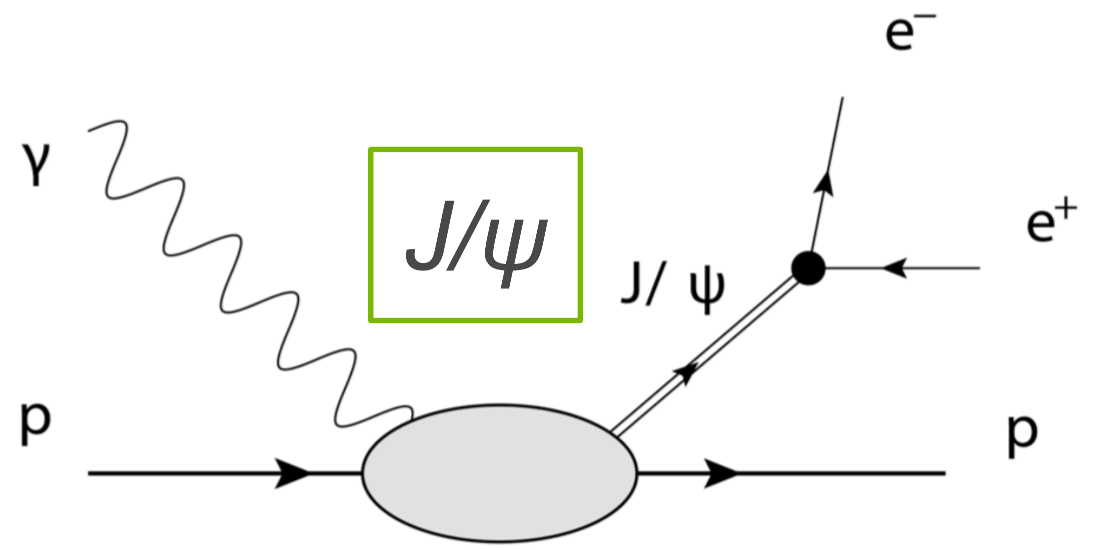

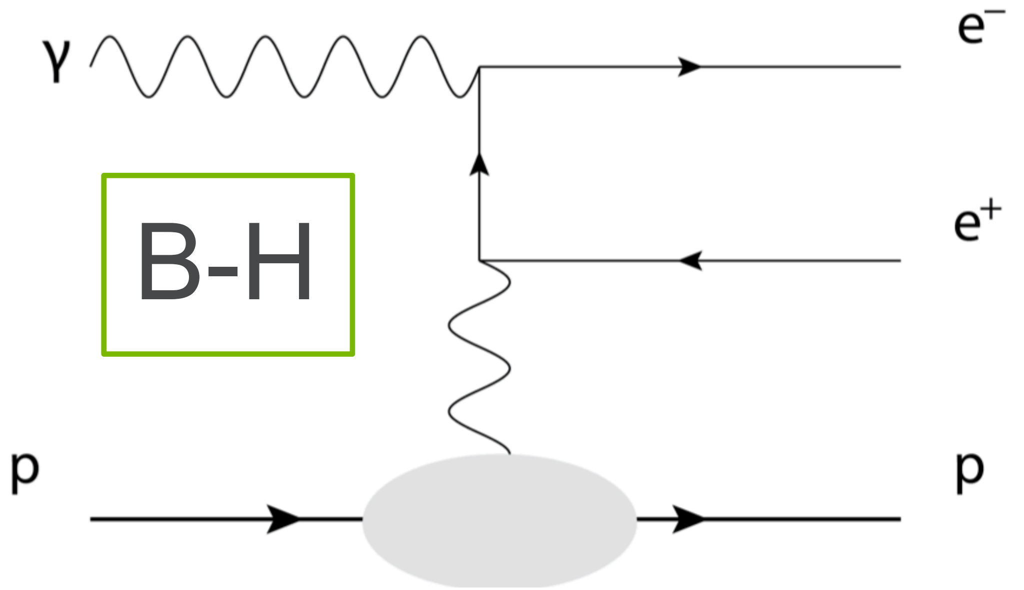

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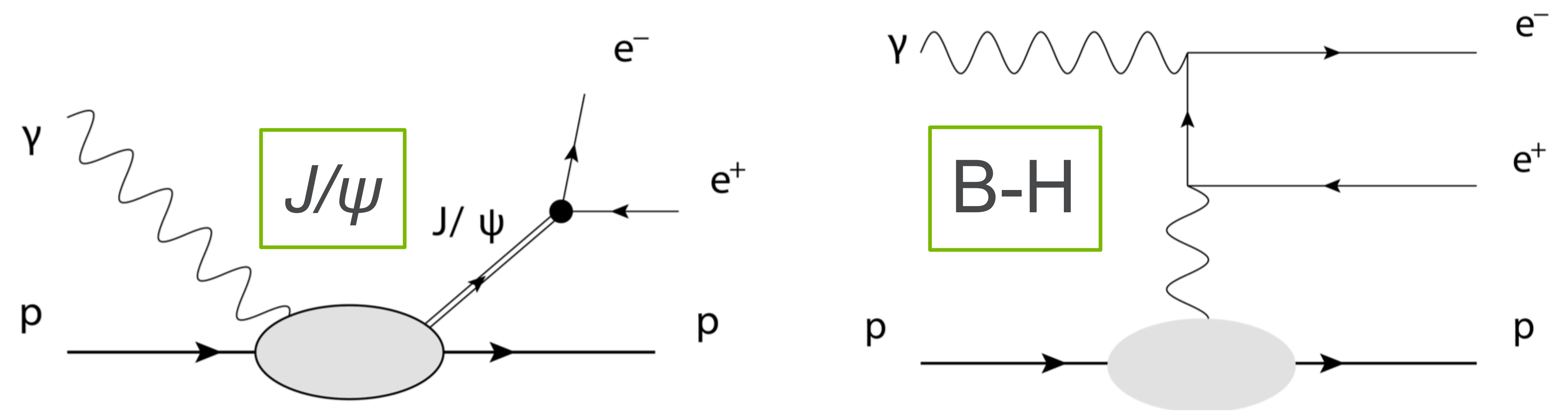

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Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

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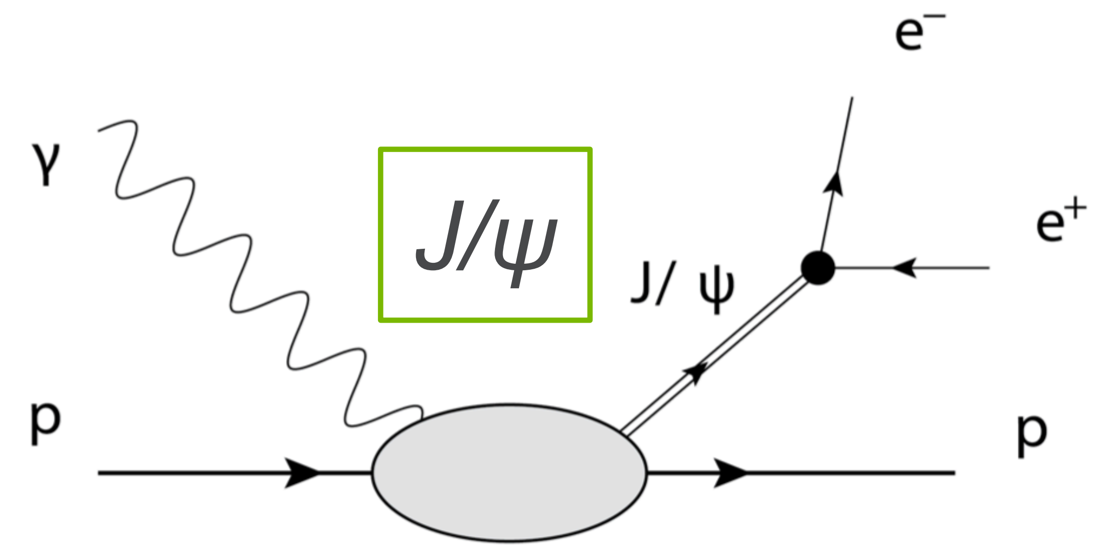
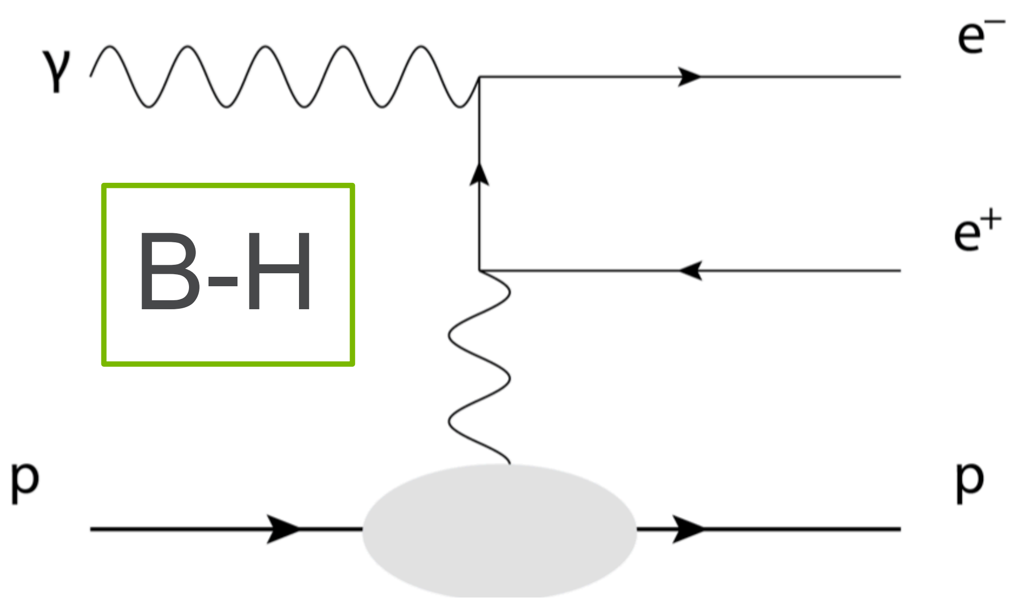
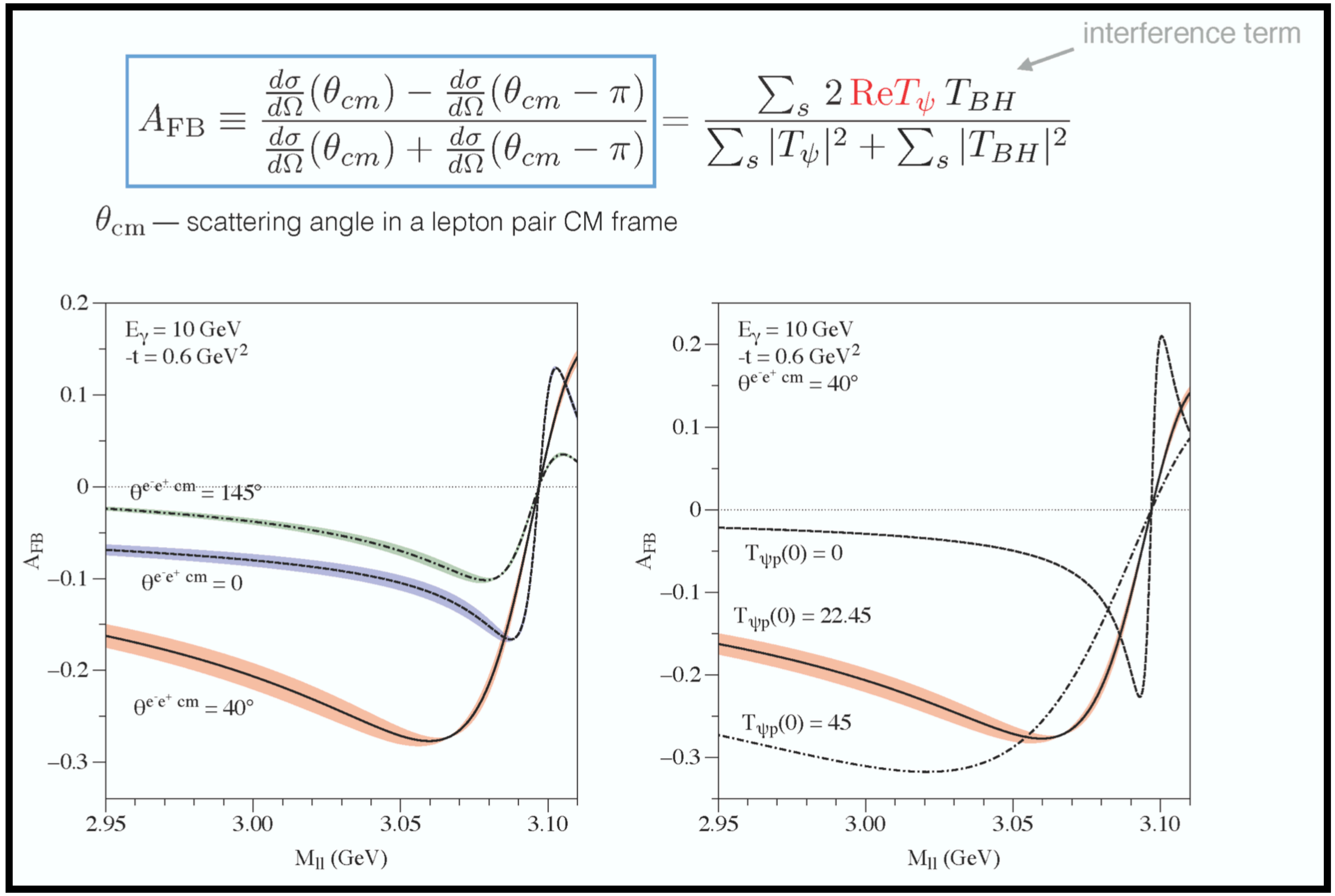




- Interference between elastic *J/ψ* production near threshold and Bethe-Heitler
- Forward-backward asymmetry near *J/ψ* invariant mass peak proportional to **Re(*T*$_{\psi p}$)**

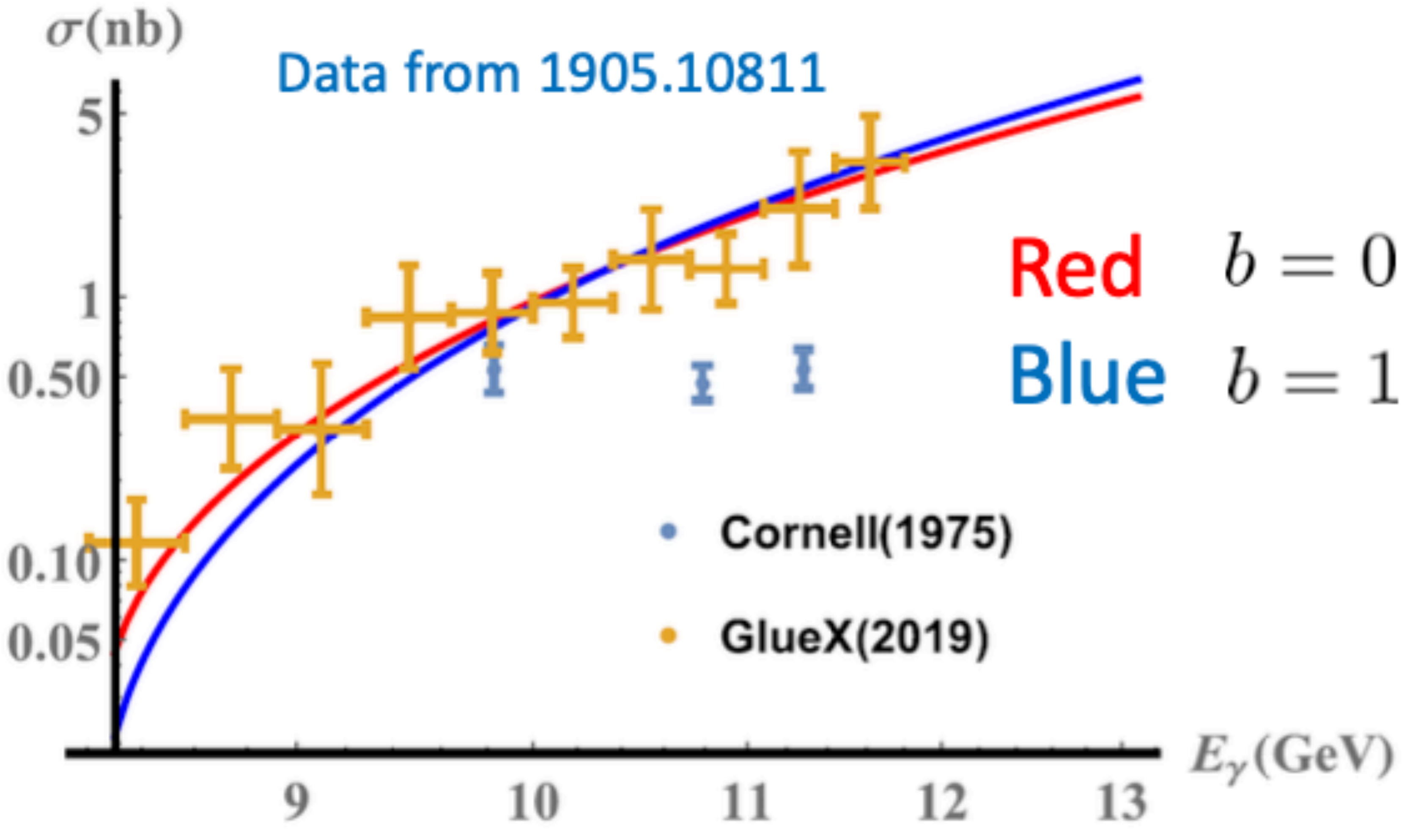
Independent channel to constrain **Re(*T*$_{\psi p}$)** and trace anomaly



Slide from O. Gryniuk

PRODUCTION MECHANISM NEAR THRESHOLD?

Holographic approach



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  (no factorization for twist-4 trace anomaly operator)
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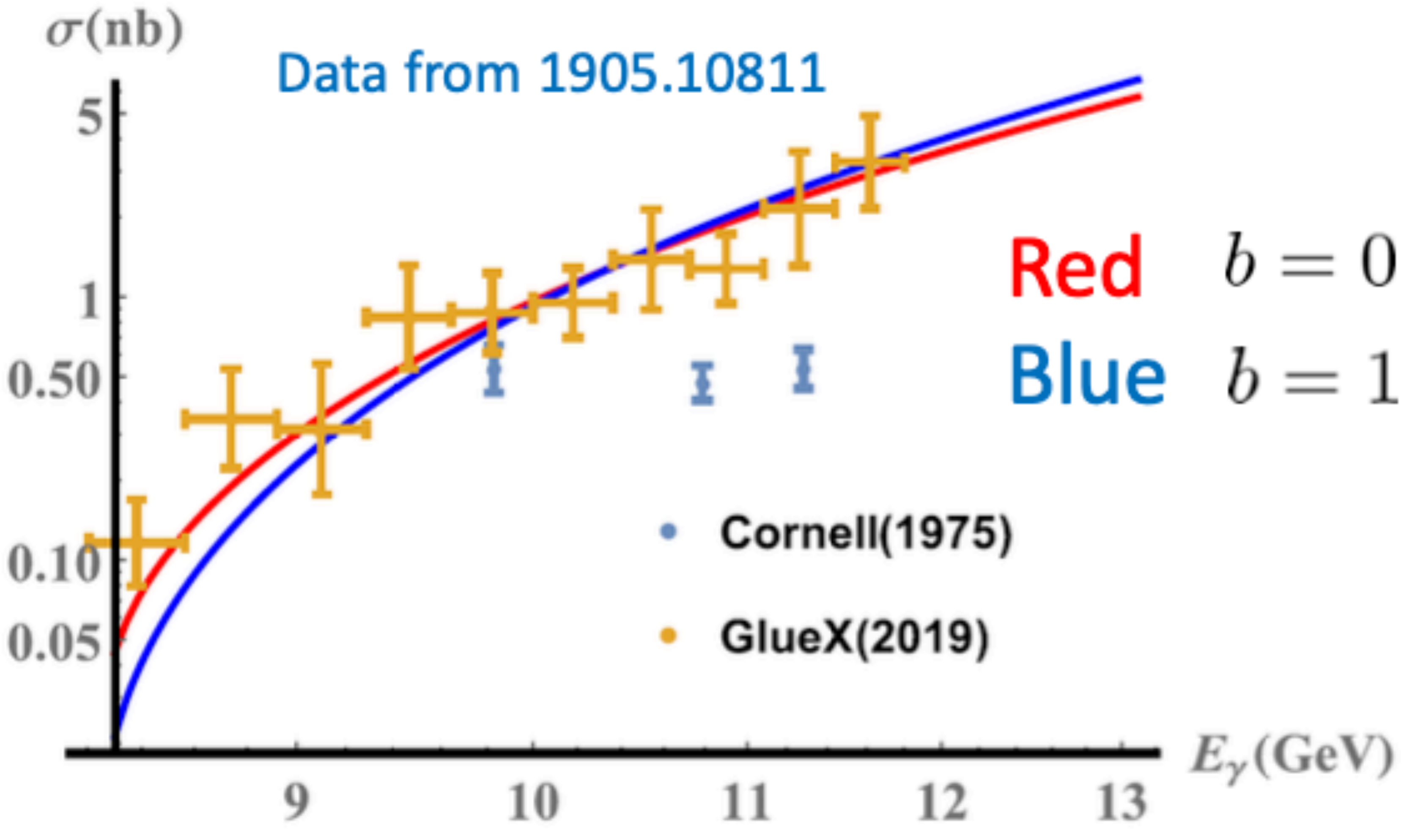

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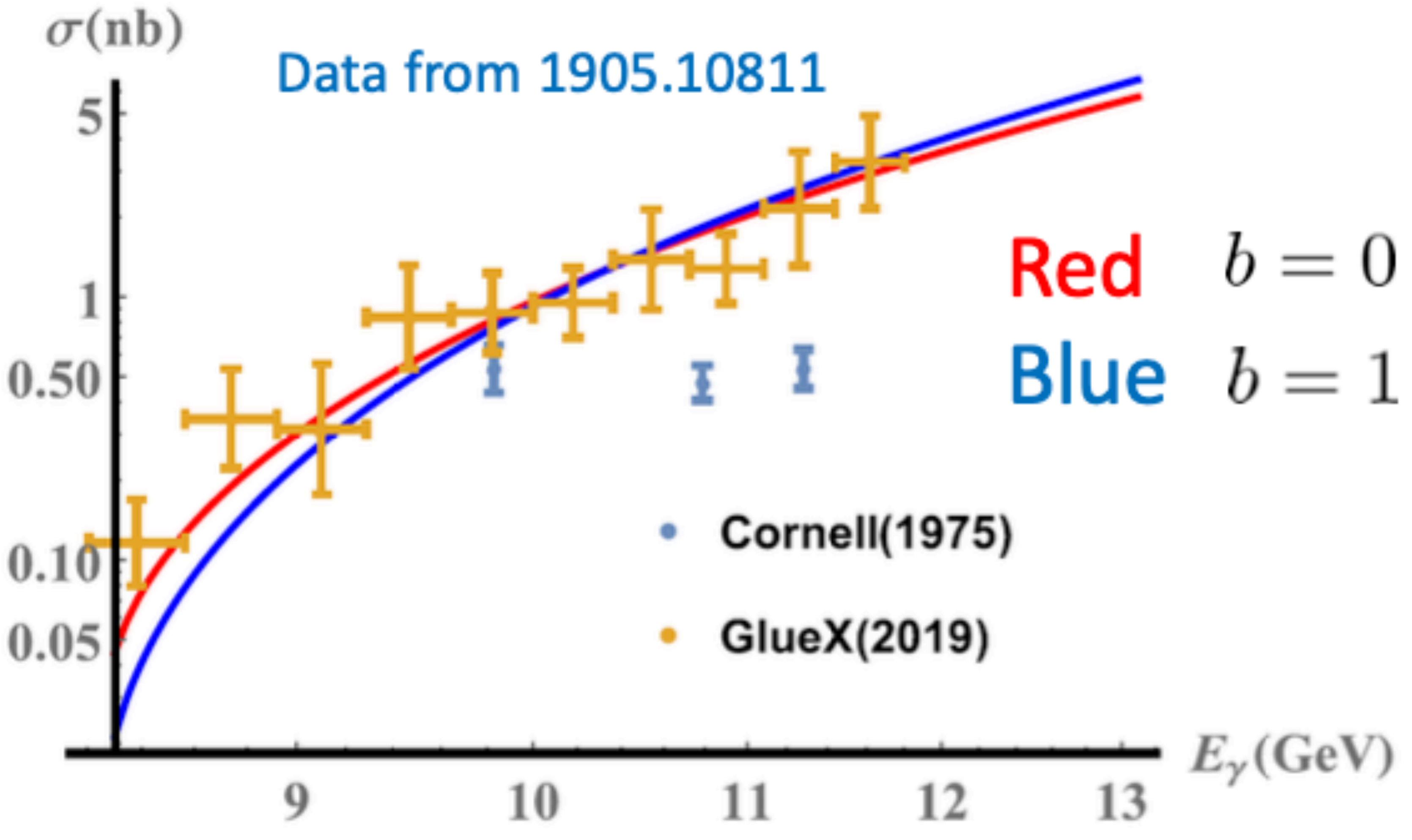

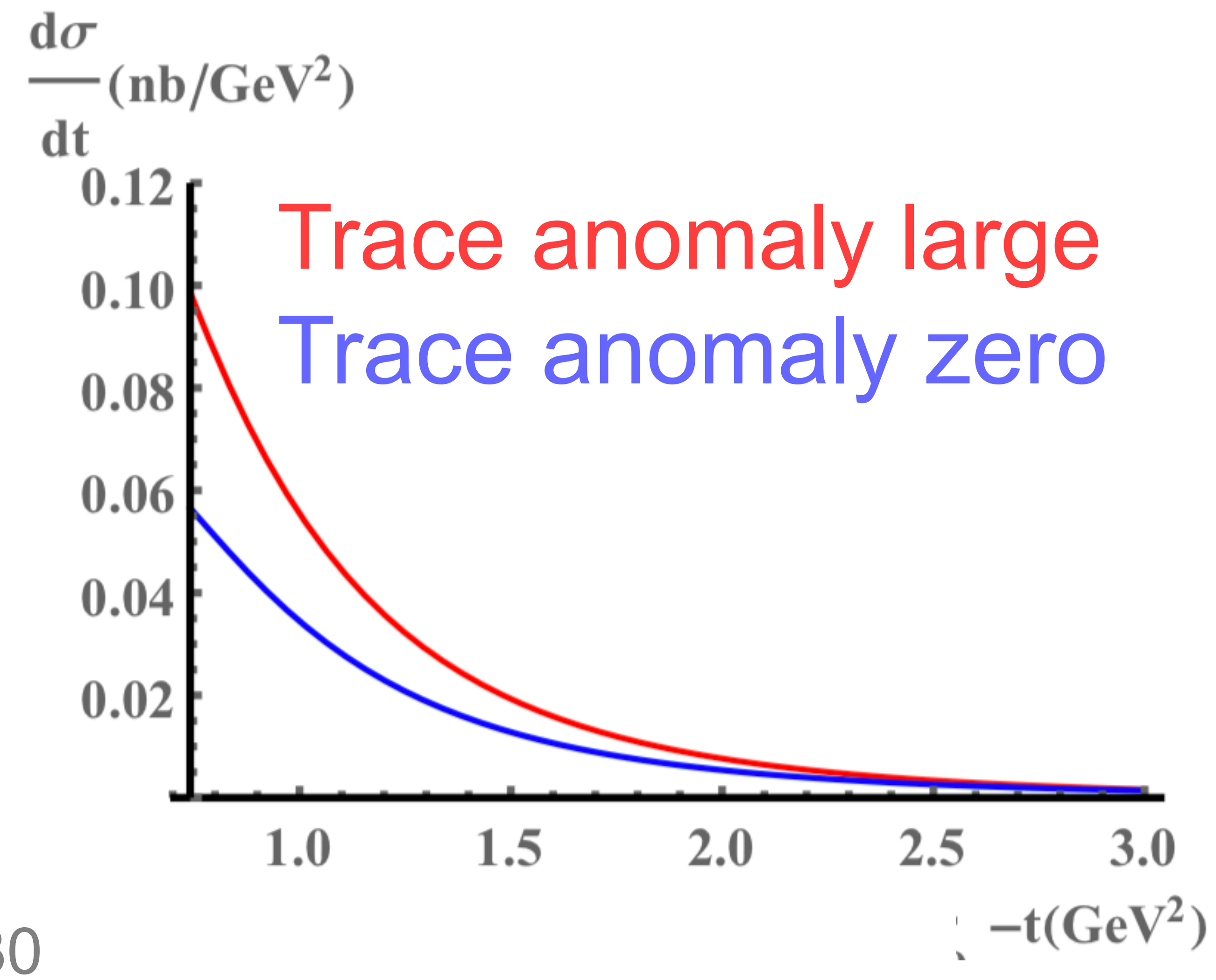

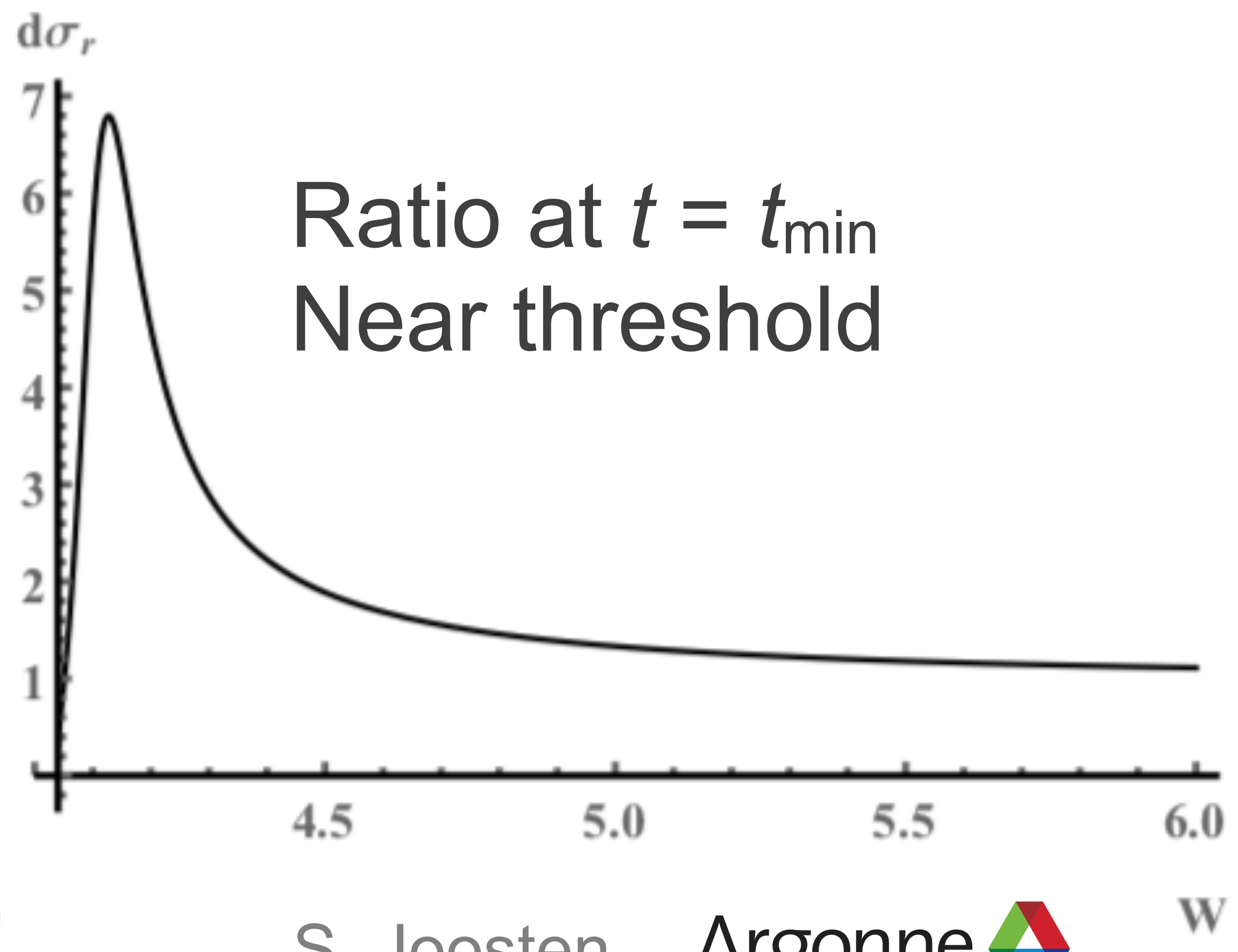

Y. Hatta *et al.*, PRD 98 no. 7, 074003 (2018)
Y. Hatta *et al.*, 1906.00894 (2019)

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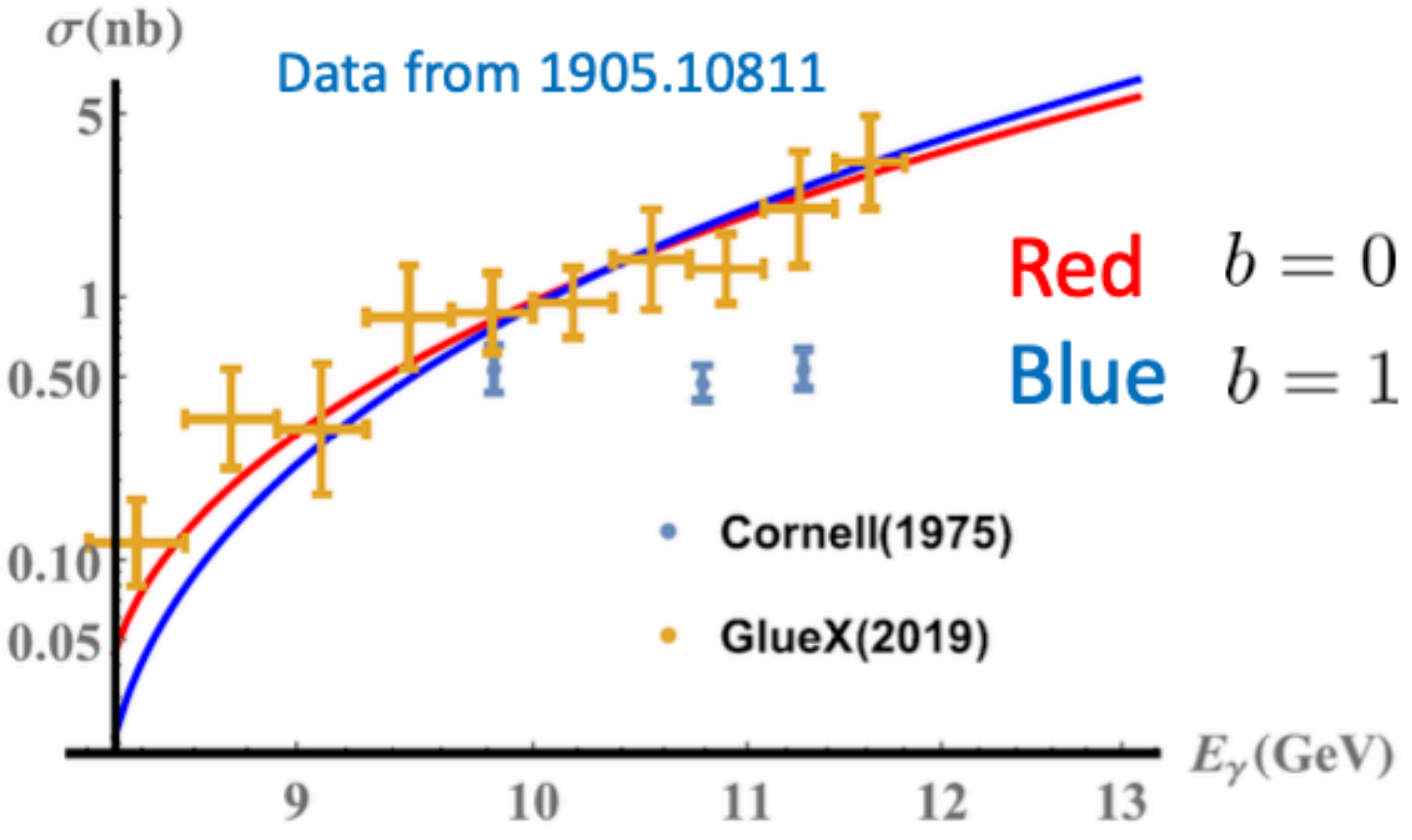
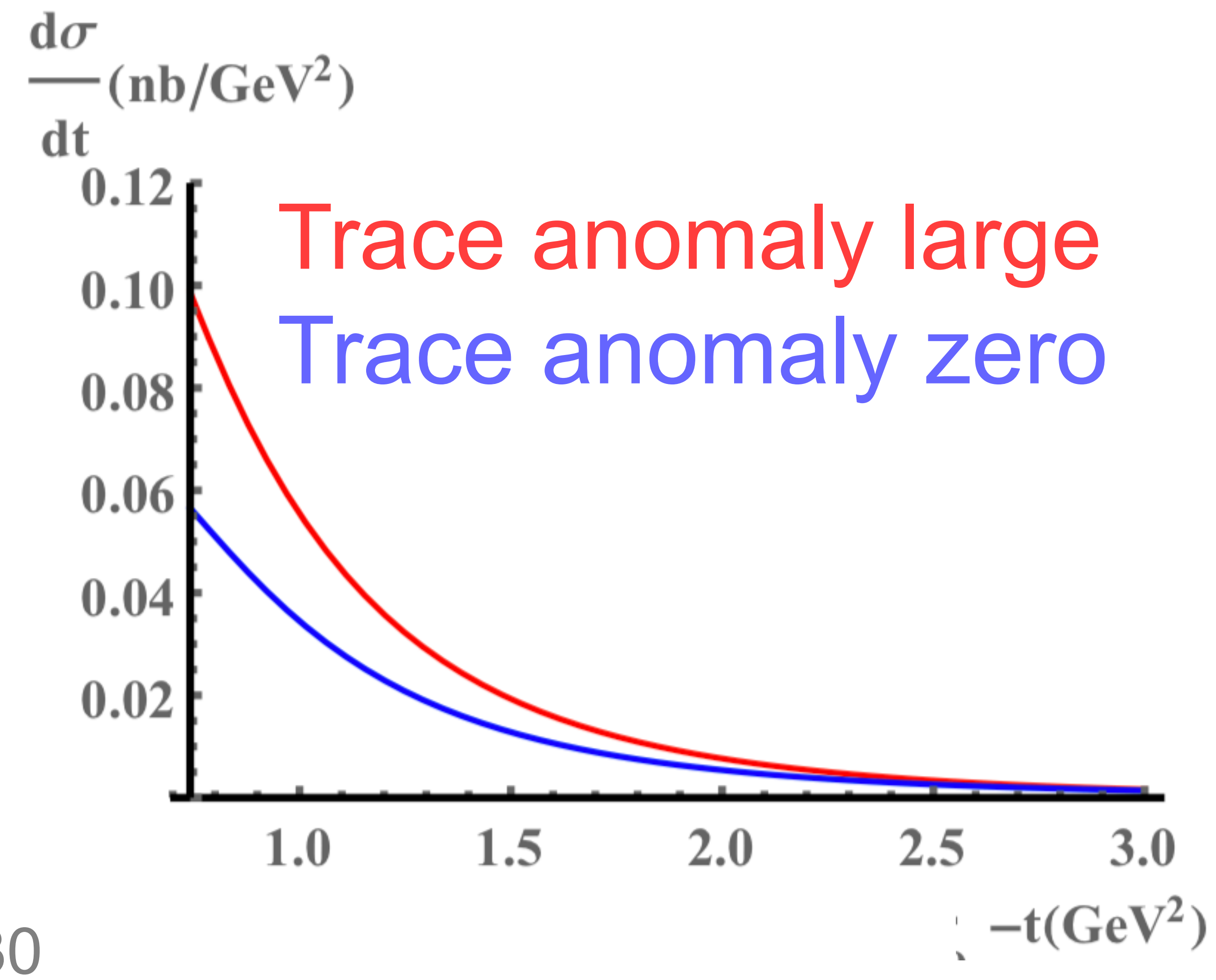
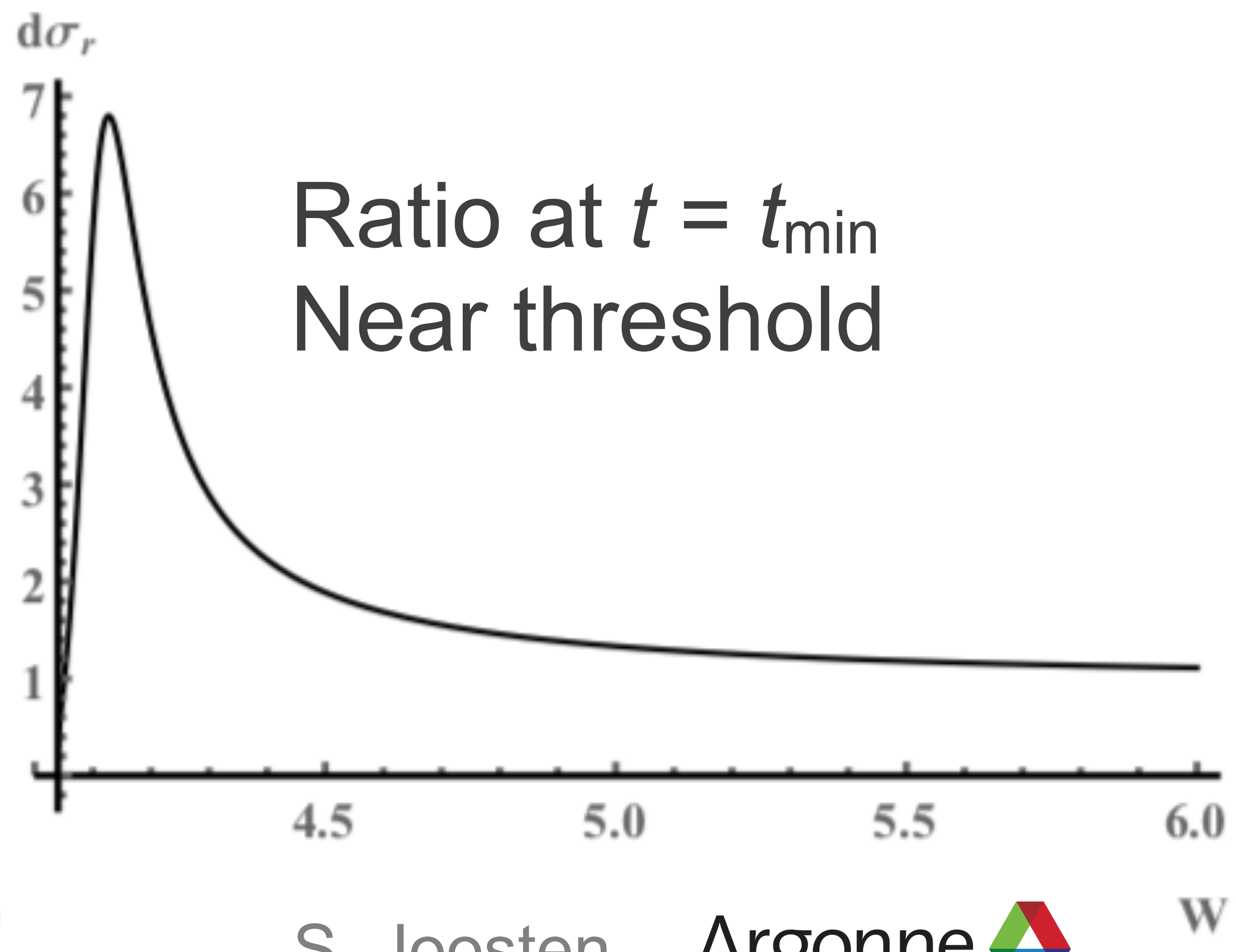
- New development, numerical predictions cary large model uncertainties



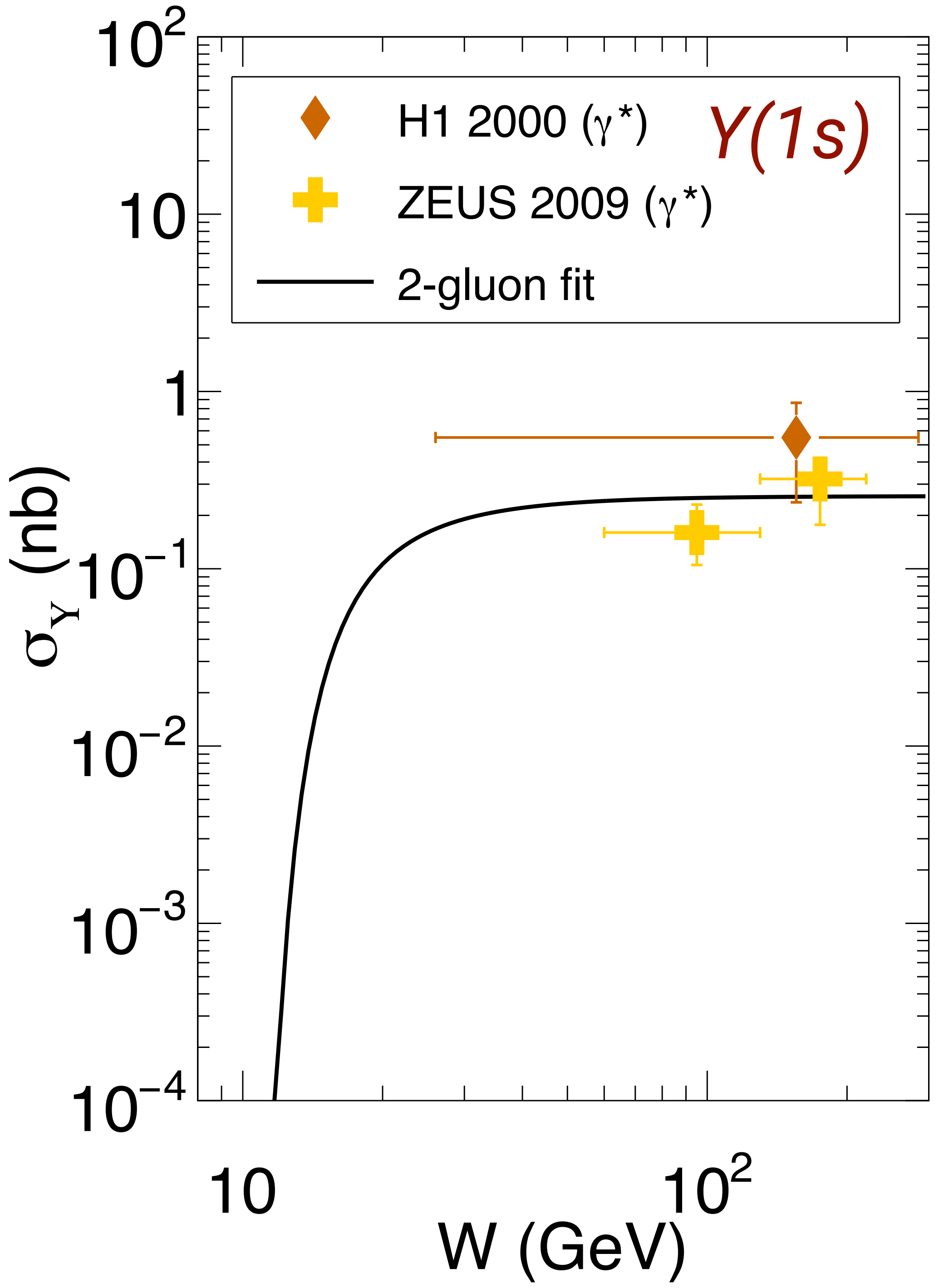




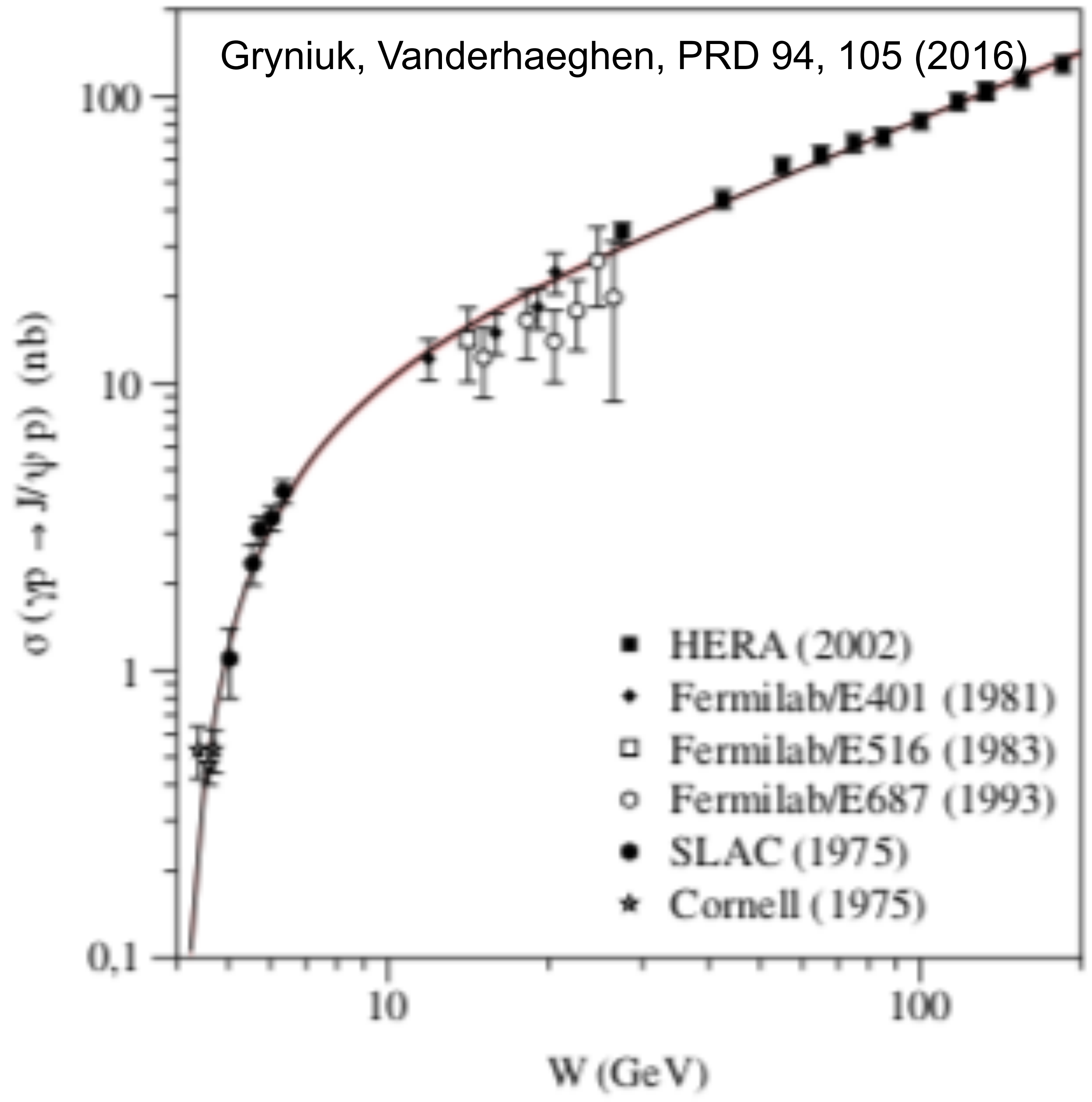
MODELING THE CROSS SECTION

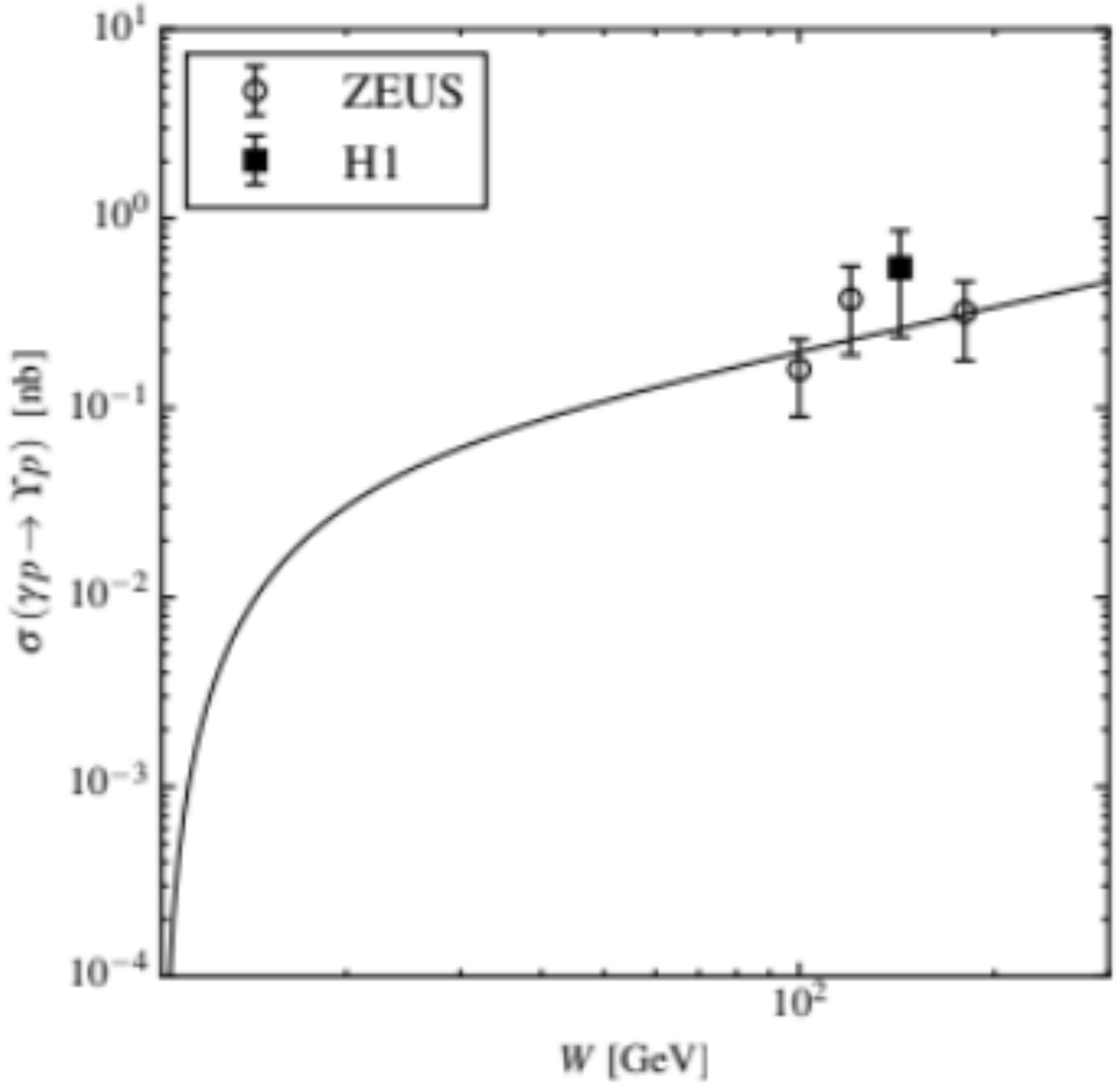
Need realistic model near threshold

Naive: 2-gluon
Fast drop-off near threshold



More realistic: dispersive framework
Includes binding effects near thresholds





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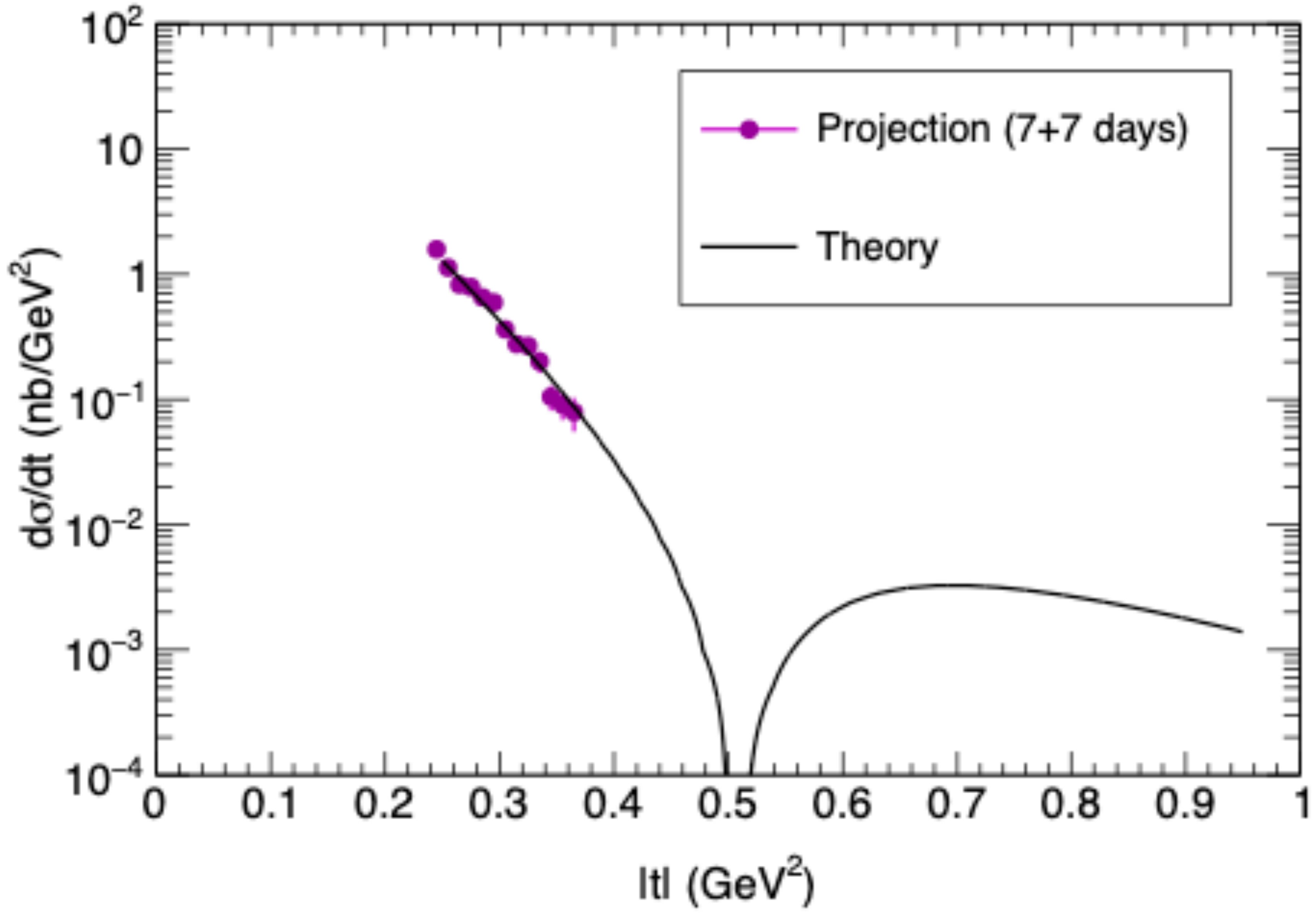

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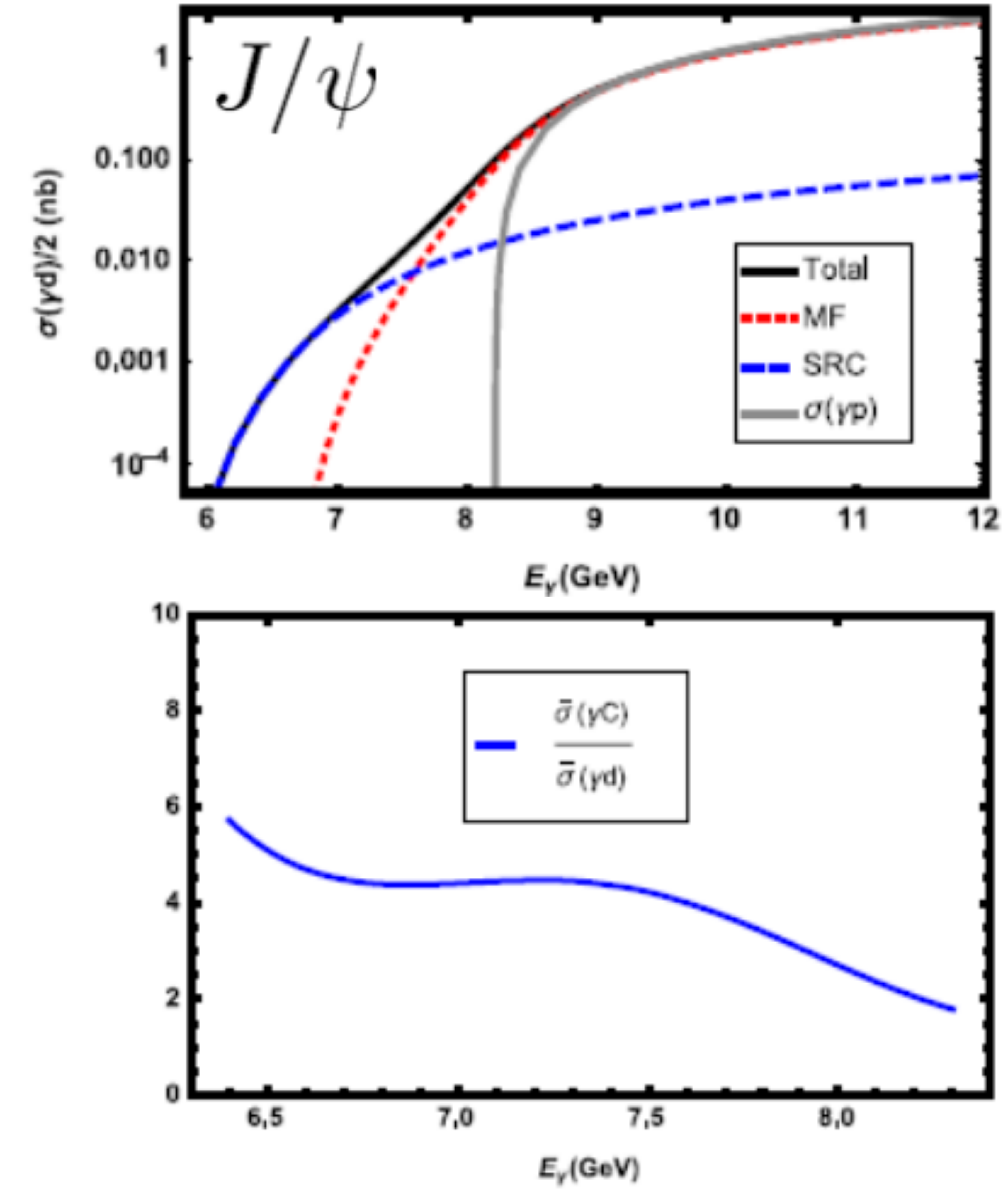
- New LOI for PAC47 to start constraining the gluonic form-factor of ^{4}He through direct photo-production in Hall C

JLab LOI12-19-007 (Hall C)

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

INDEPENDENT PROBE FOR SRC UNIVERSALITY

Through incoherent sub-threshold quarkonium production



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

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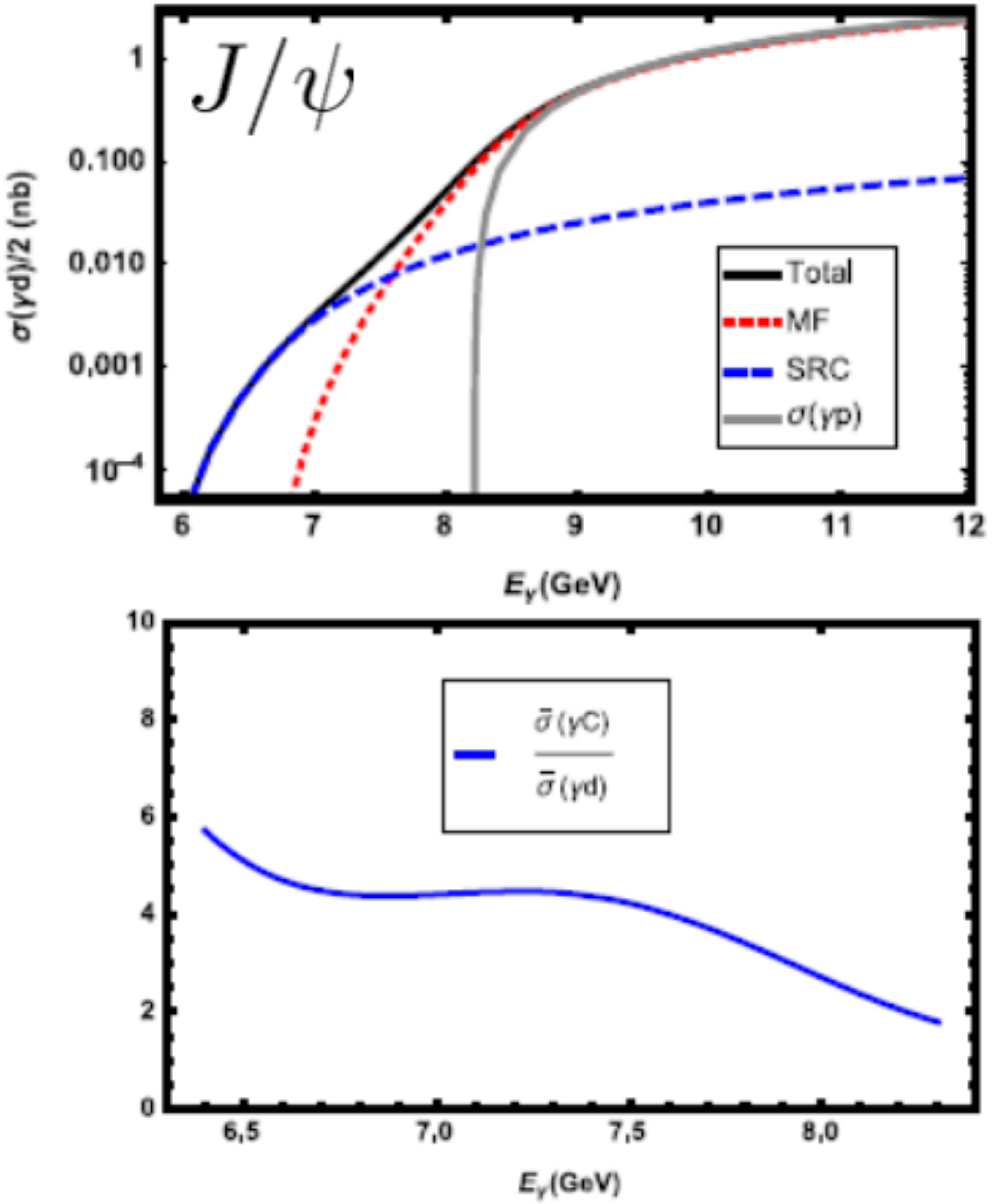

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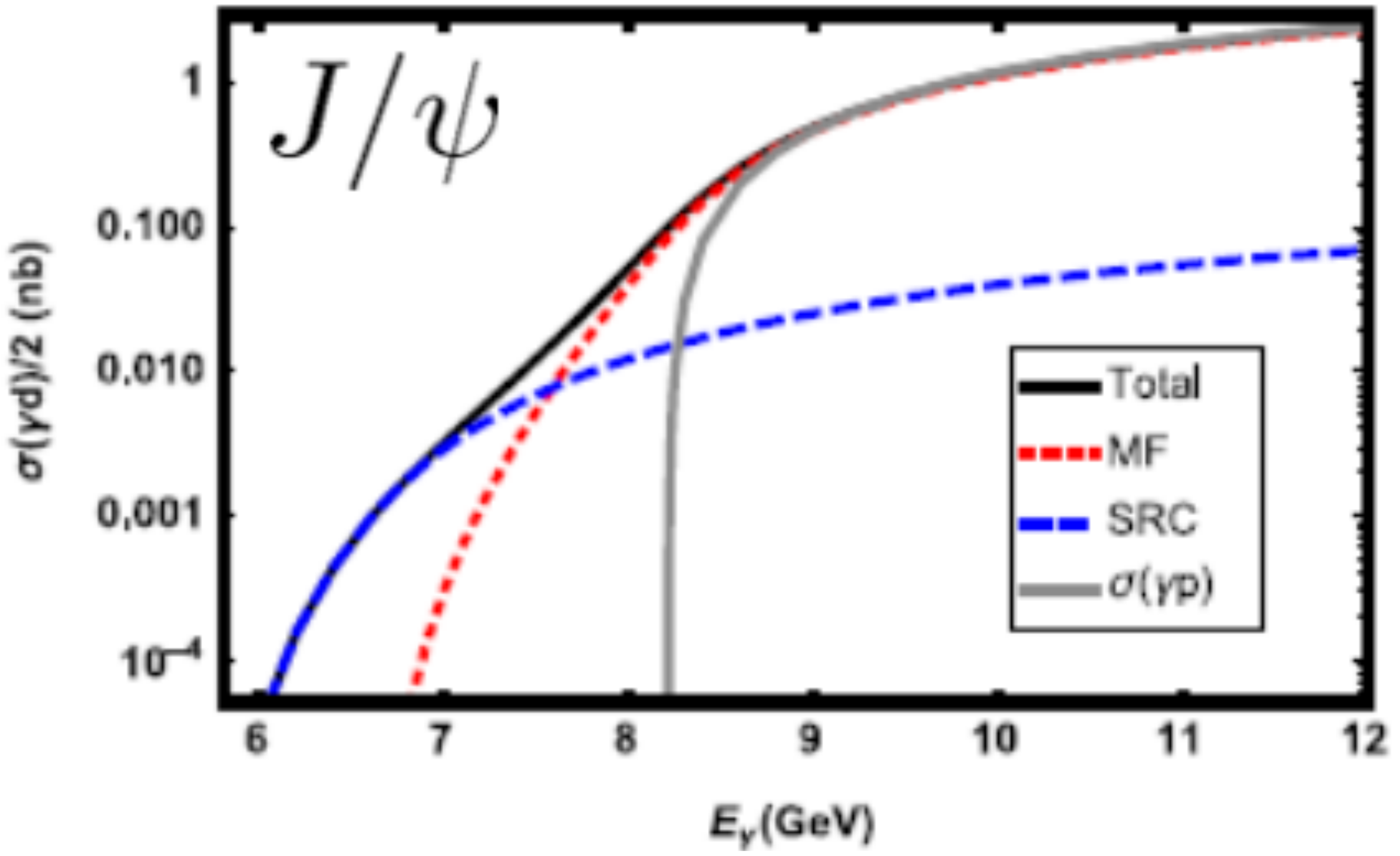

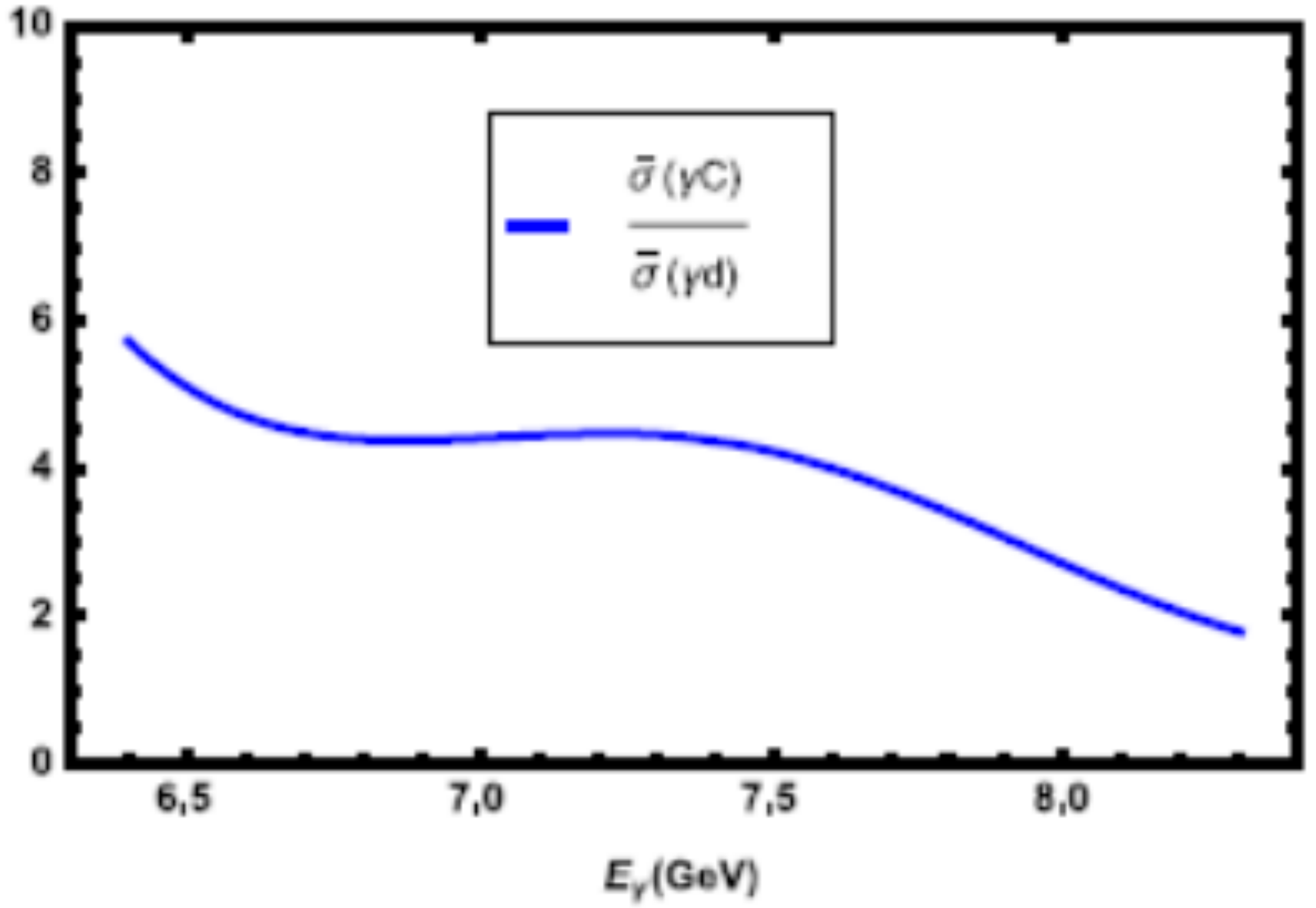

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- Sub-treshold measurement requires very high luminosity.