A PREVIEW

NEAR-THRESHOLD J/ψ PRODUCTION IN HALL C

007 $^{J/\psi}$

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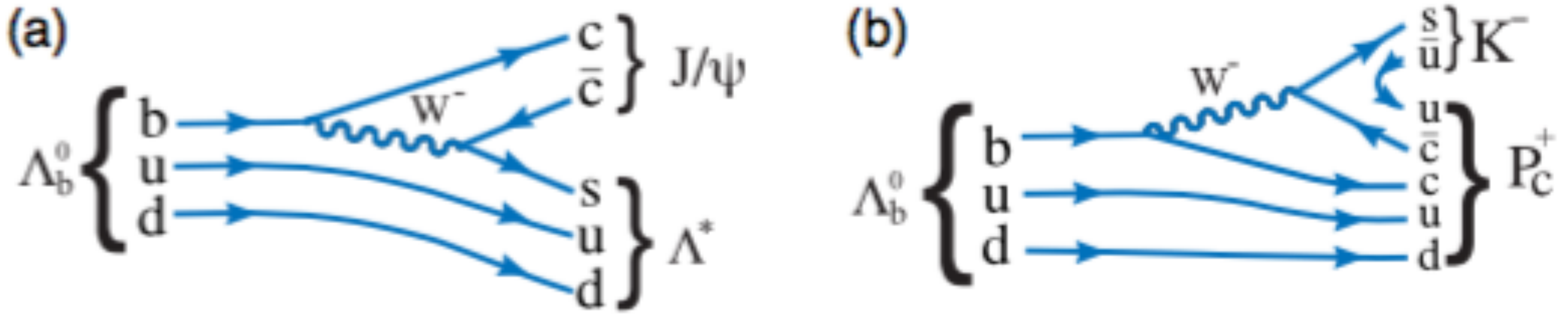
On behalf of the J/ψ-007 collaboration

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.

Jefferson Lab User's Group Meeting
June 23, 2020

DISCOVERY OF THE LHCB CHARMED PENTAQUARK



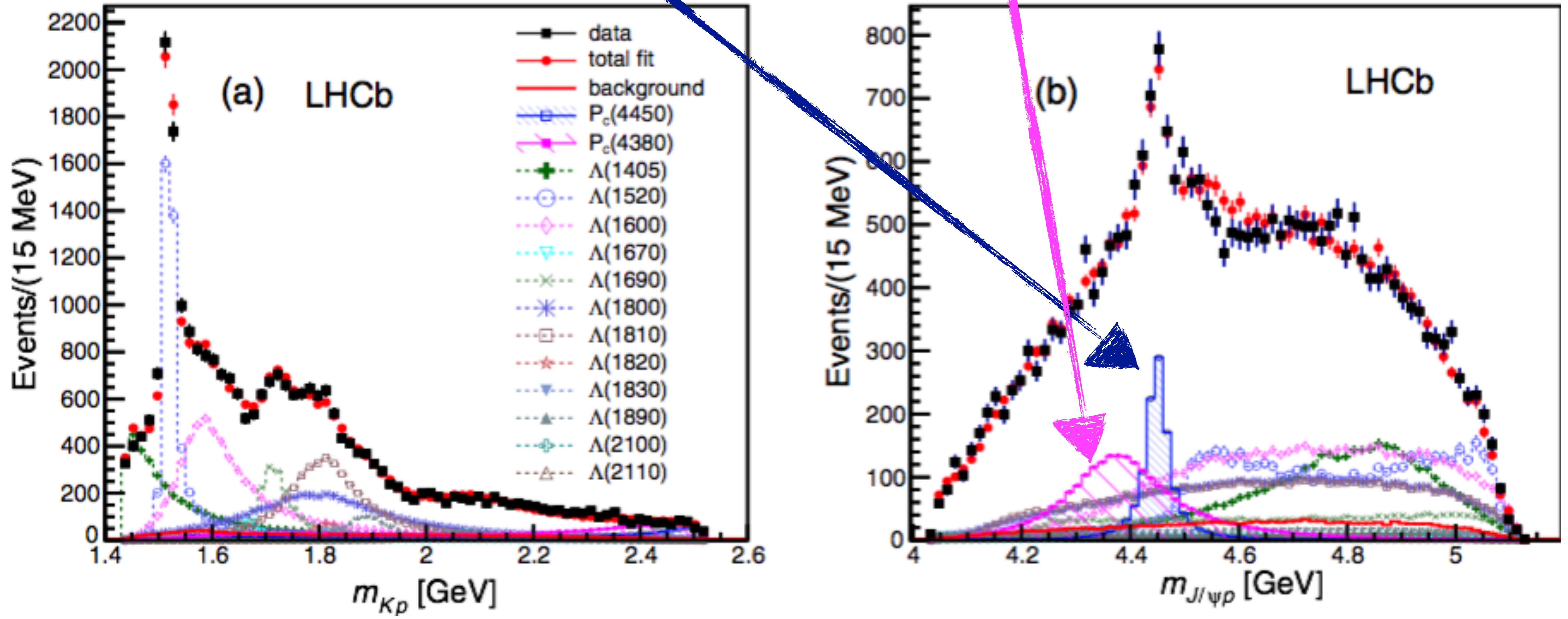
$$\Lambda_b \to \Lambda^* J/\Psi \to (K^- p) J/\Psi$$

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

narrow: P_c(4450) (12 σ)

wide: P_c(4390) (9σ)

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

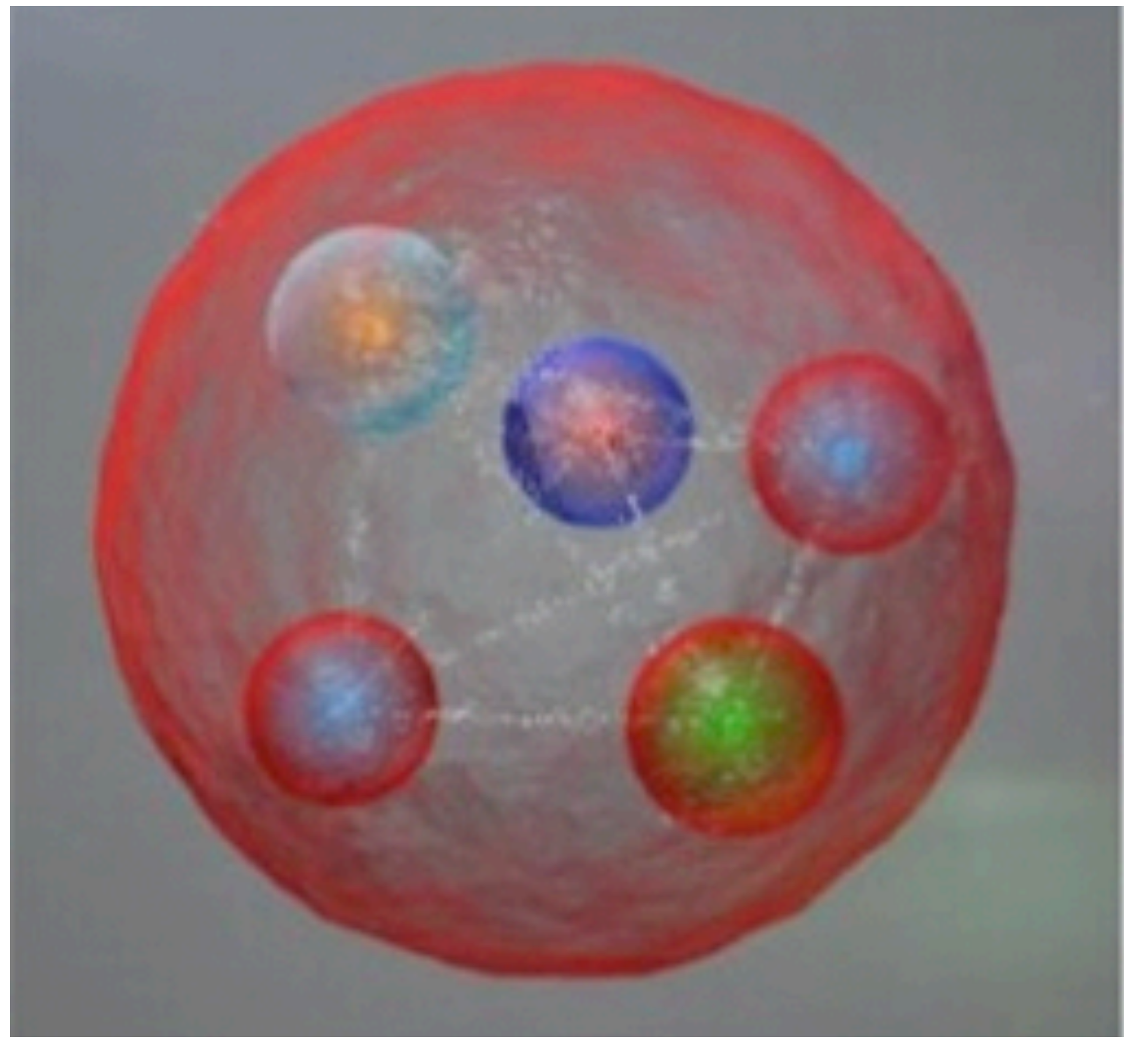


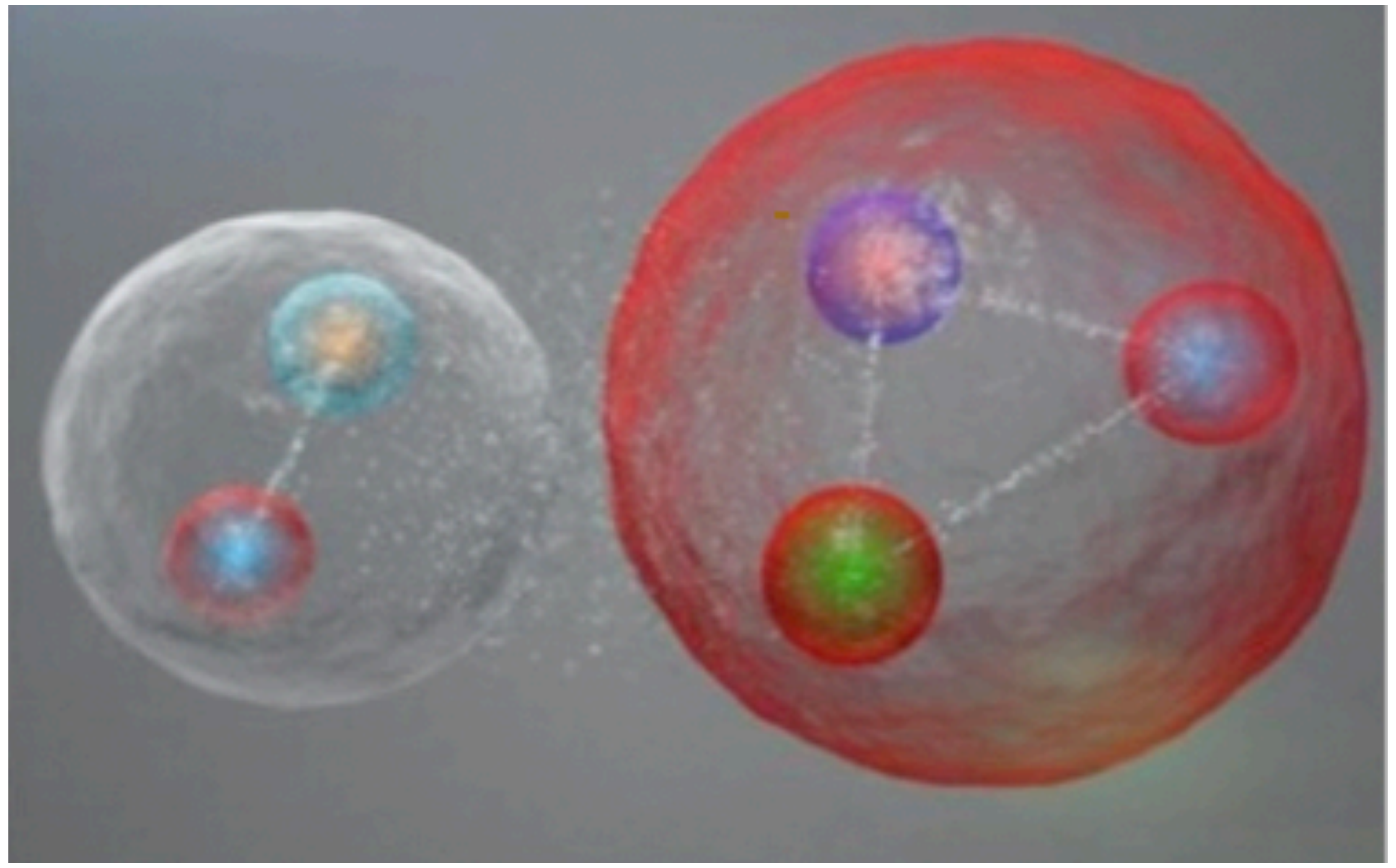
IS THIS A REAL PARTICLE?

We can confirm this at JLab!

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

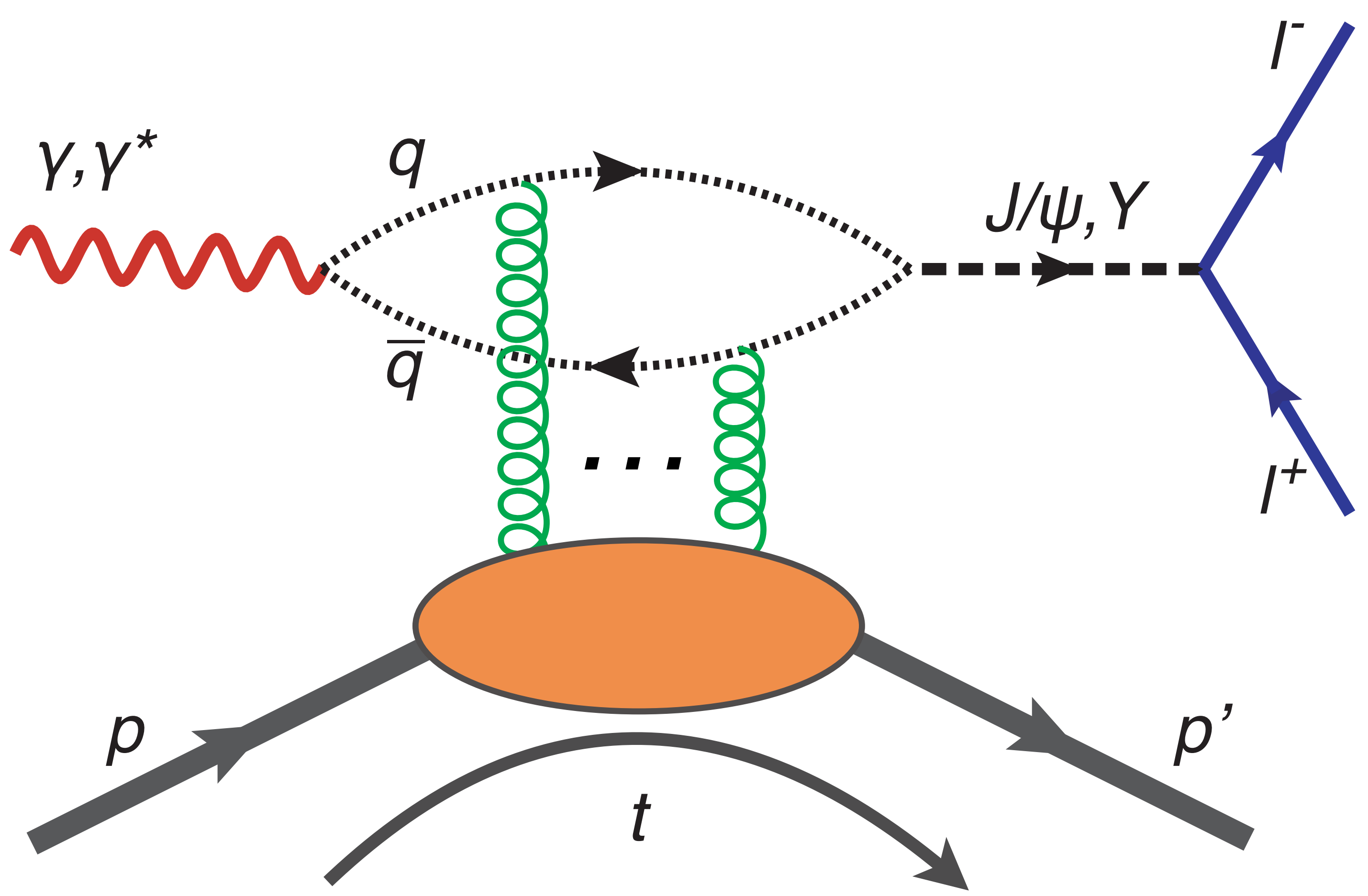
Jefferson Lab the perfect place to search for P_c





QUARKONIUM PHOTO-PRODUCTION

The basics

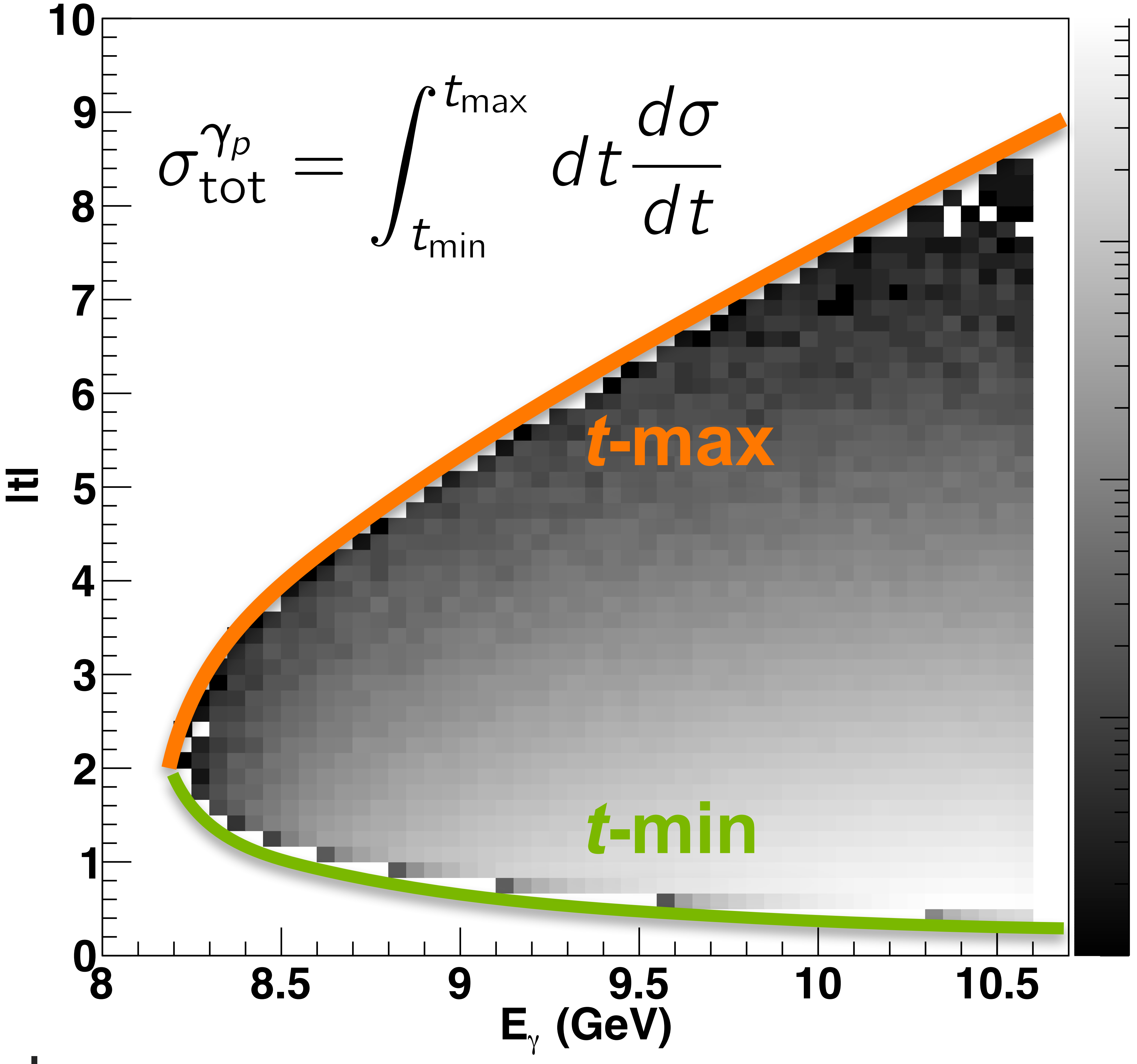


J/ψ threshold:

$W \approx 4.04\text{GeV}$

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

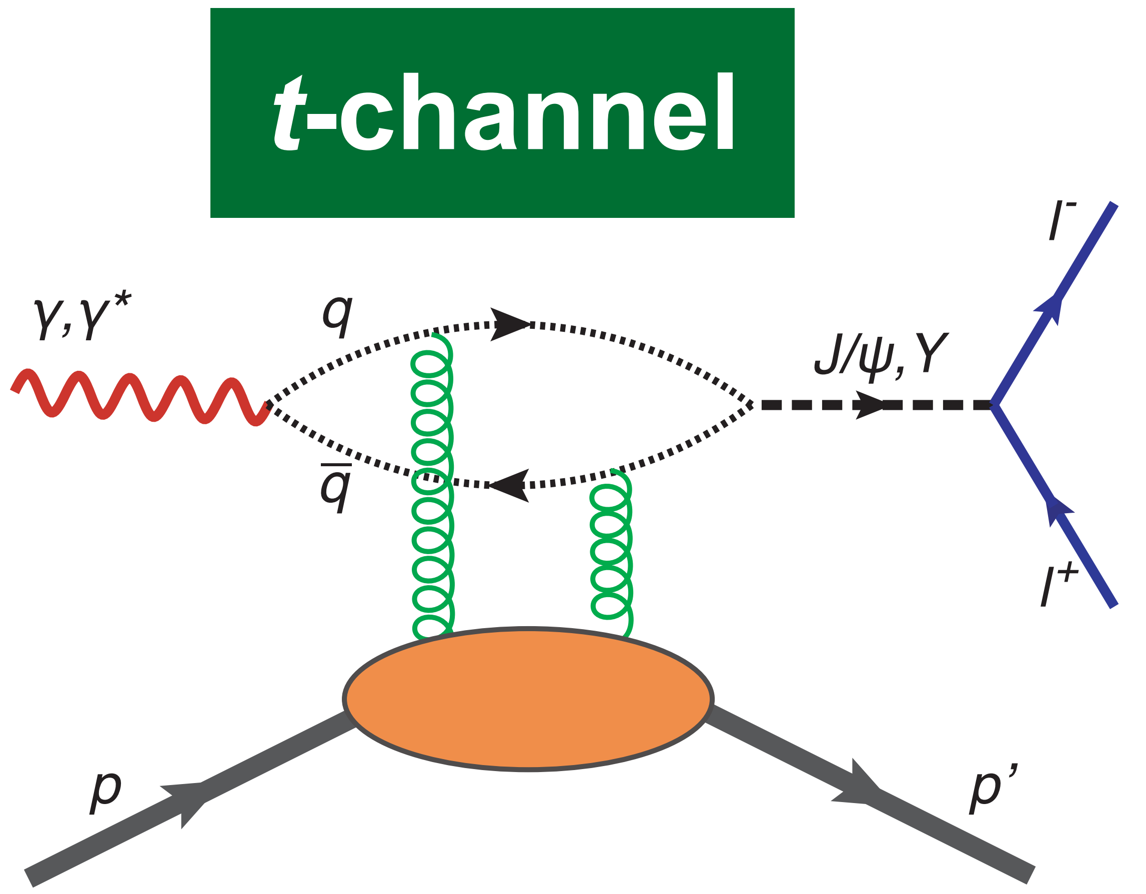
$t \approx -1.5\text{GeV}^2$

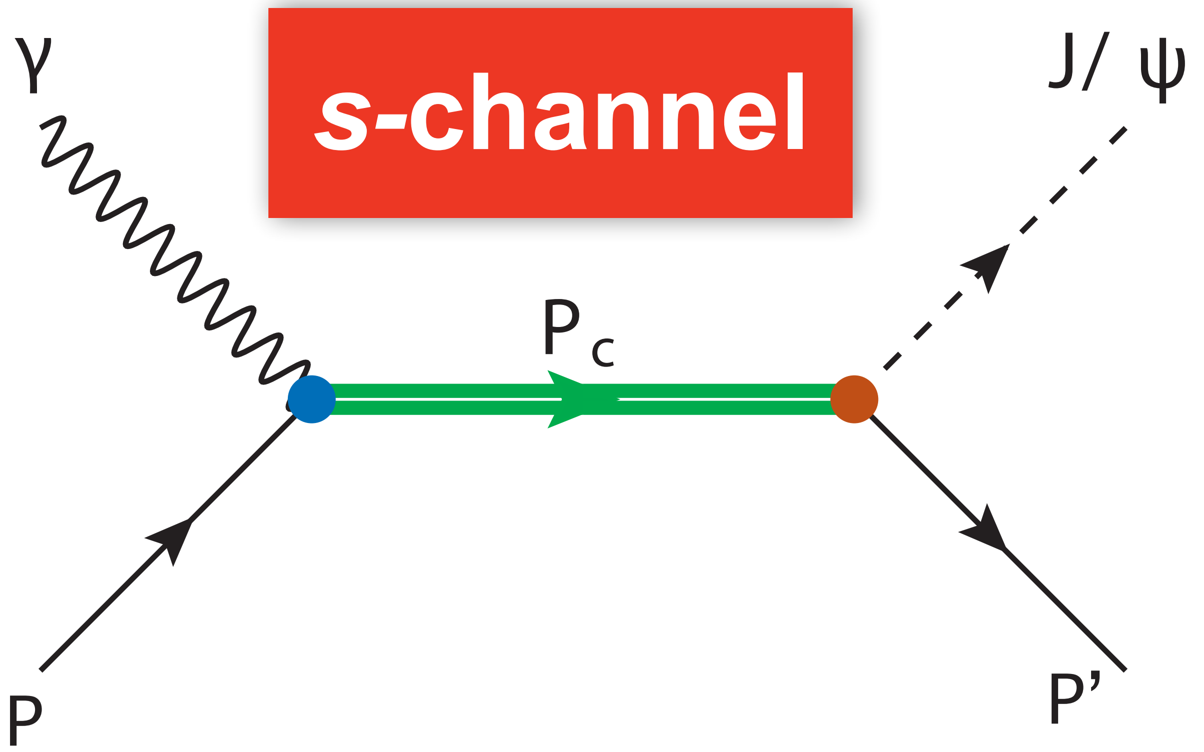


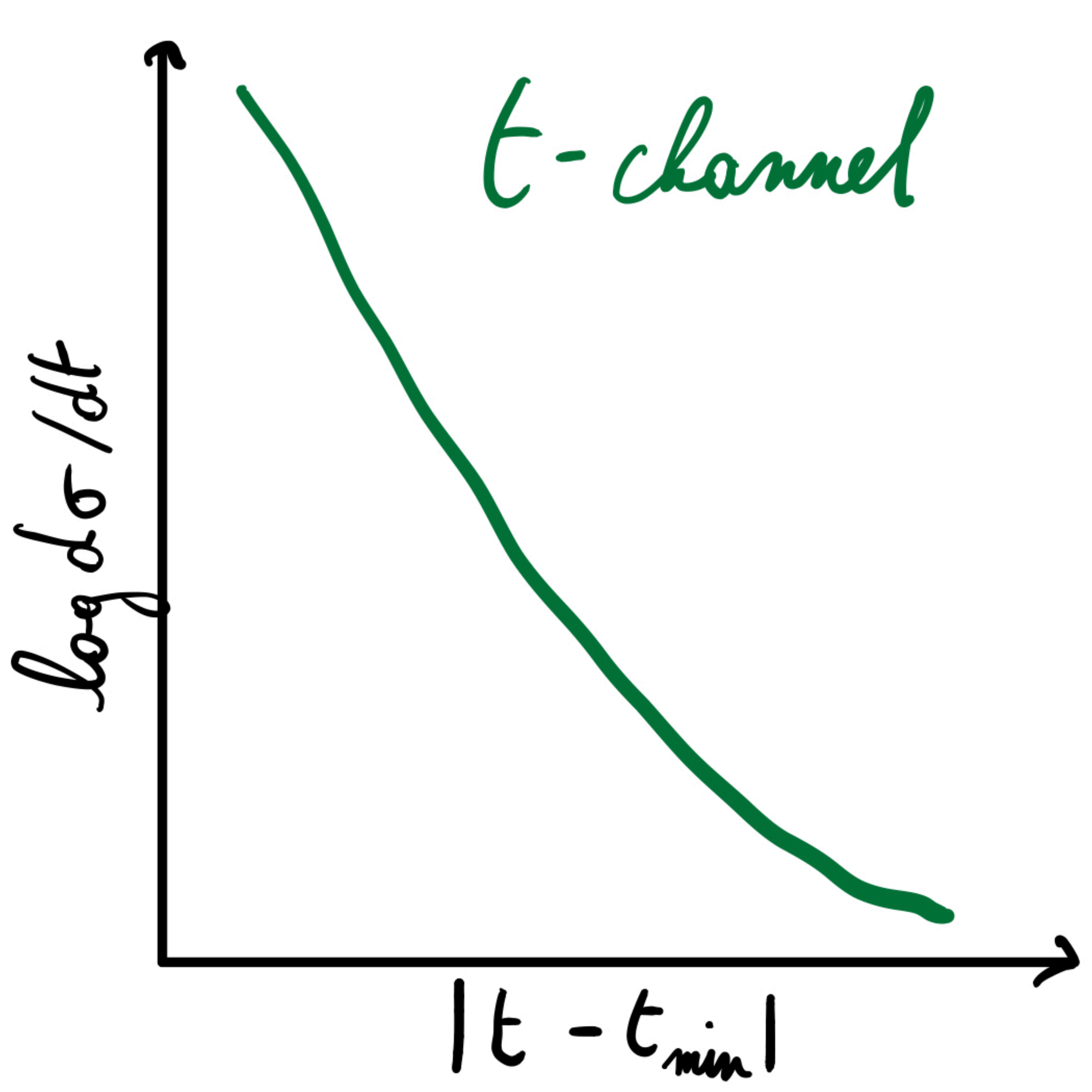
- Phase space limits defined by quarkonium direction
  - Forward (with photon): $t = t_{\min}$
  - Backward (with proton): $t = t_{\max}$
- Forward direction preferred: *t*-dependence ~exponential

MAXIMIZING THE SENSITIVITY

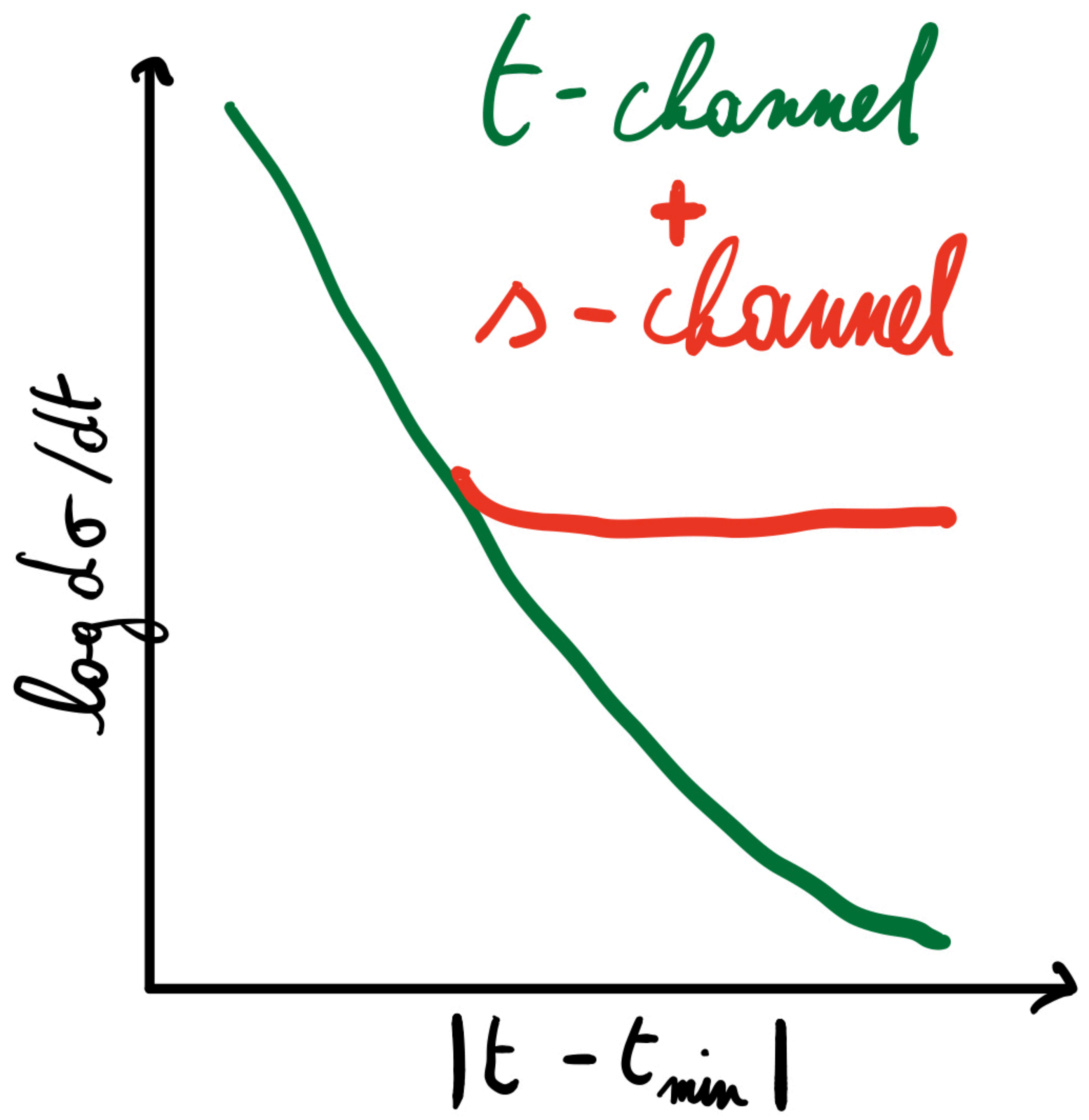
Maximum sensitivity for s-channel resonance at high *t*





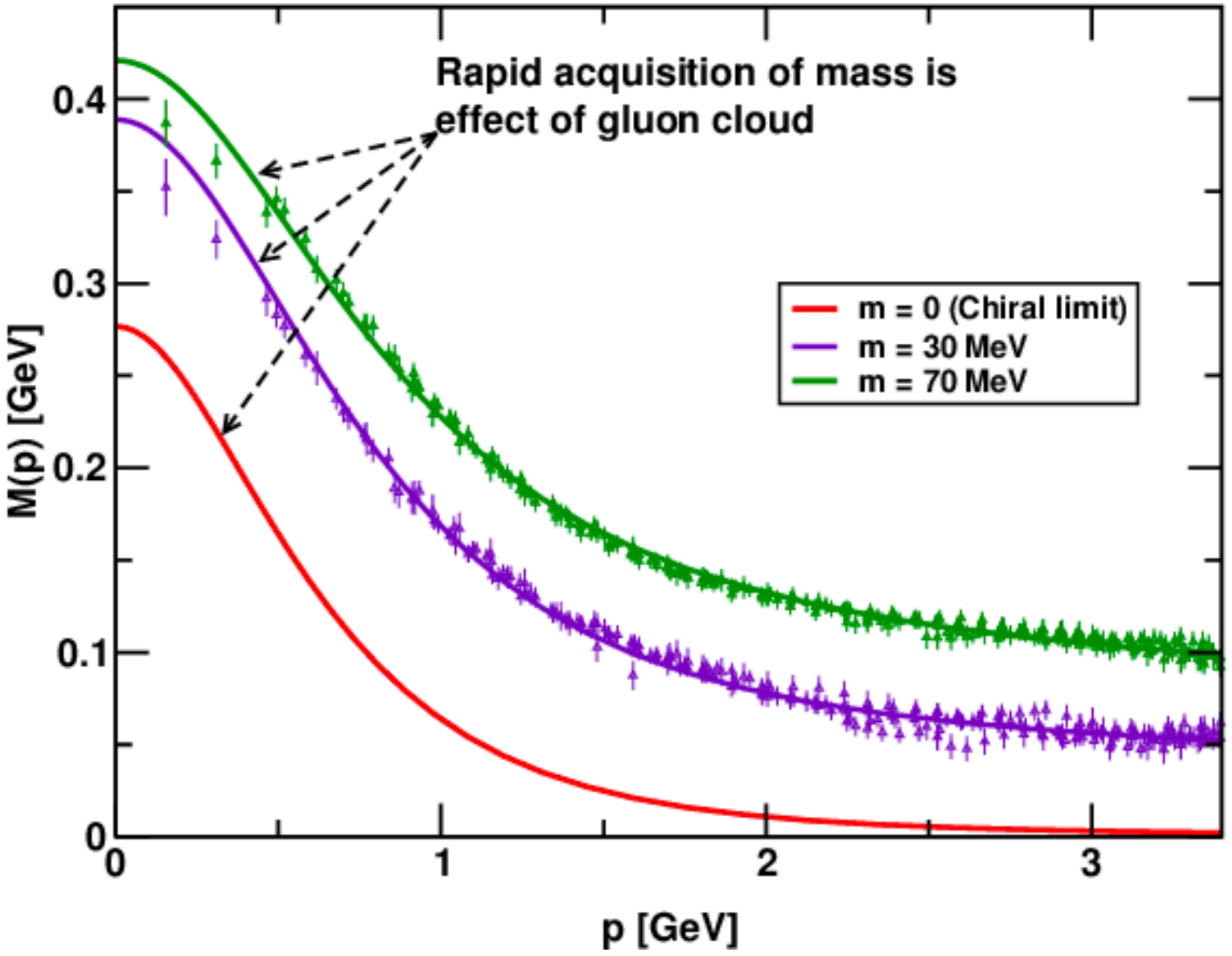


t-channel production mostly forward (exponential-like *t*-dependence)



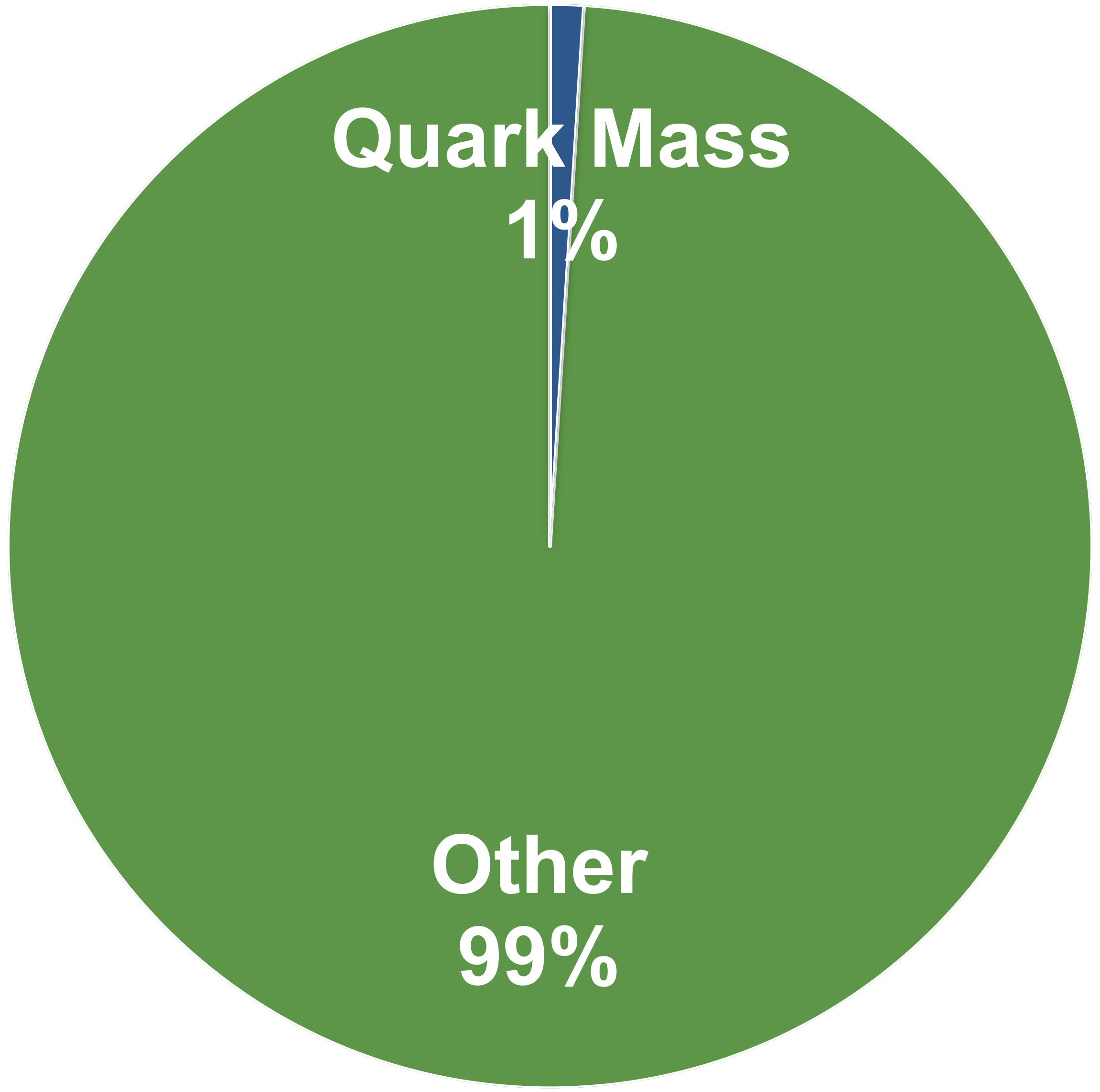
s-channel production more isotropic (flatter *t*-dependence)

NUCLEON MASS IS AN EMERGENT PHENOMENON



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

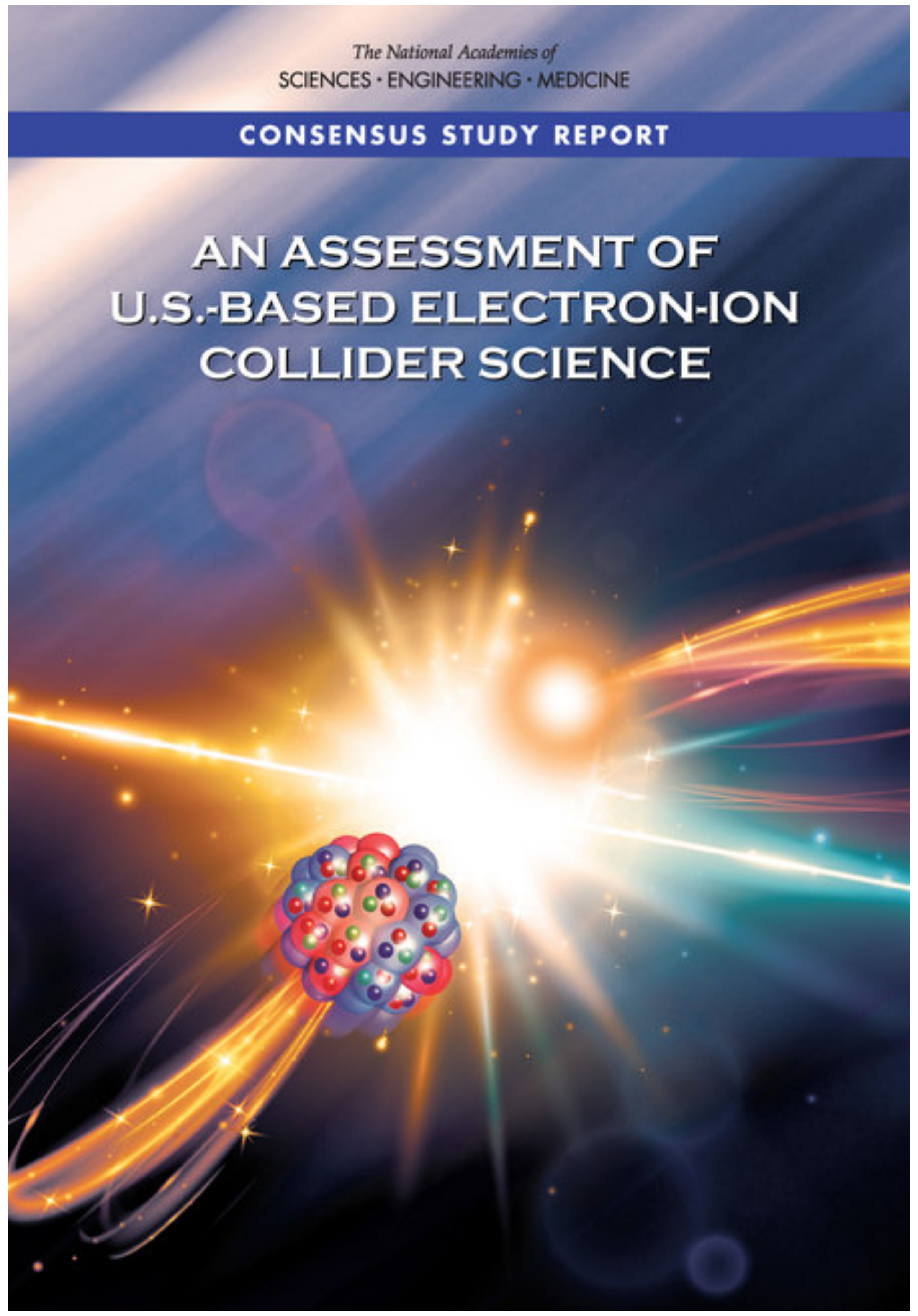
- From DSE and Lattice:
  - Low momentum gluons attach to the current quarks (DCSB)
  - Gluon field accumulates ~300MeV/constituent quark
  - Even in the chiral limit: **mass from nothing!**



The Higgs mechanism is largely irrelevant in "normal" matter!

NAS CHARGE FOR EIC

The proton mass… a hot topic!



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

PROTON MASS: TRACE DECOMPOSITION

Why is the proton mass non-vanishing?

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

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

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

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

Trace Anomaly **Light Quark Mass**

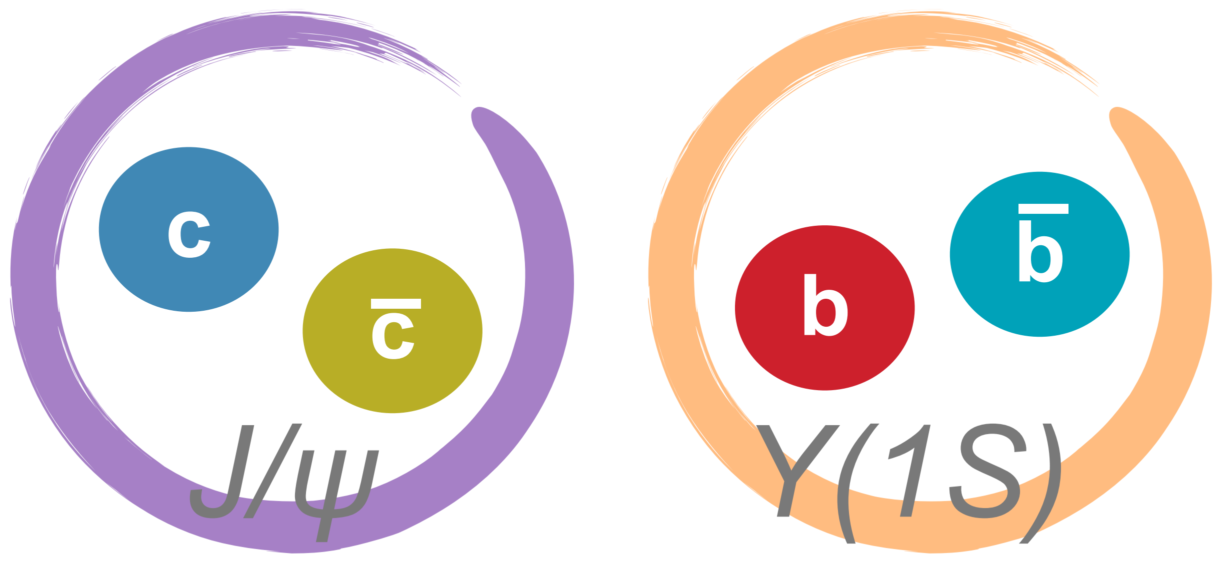
Trace anomaly dominant
"Proton mass result of the vacuum polarization induced by the presence of the proton."

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

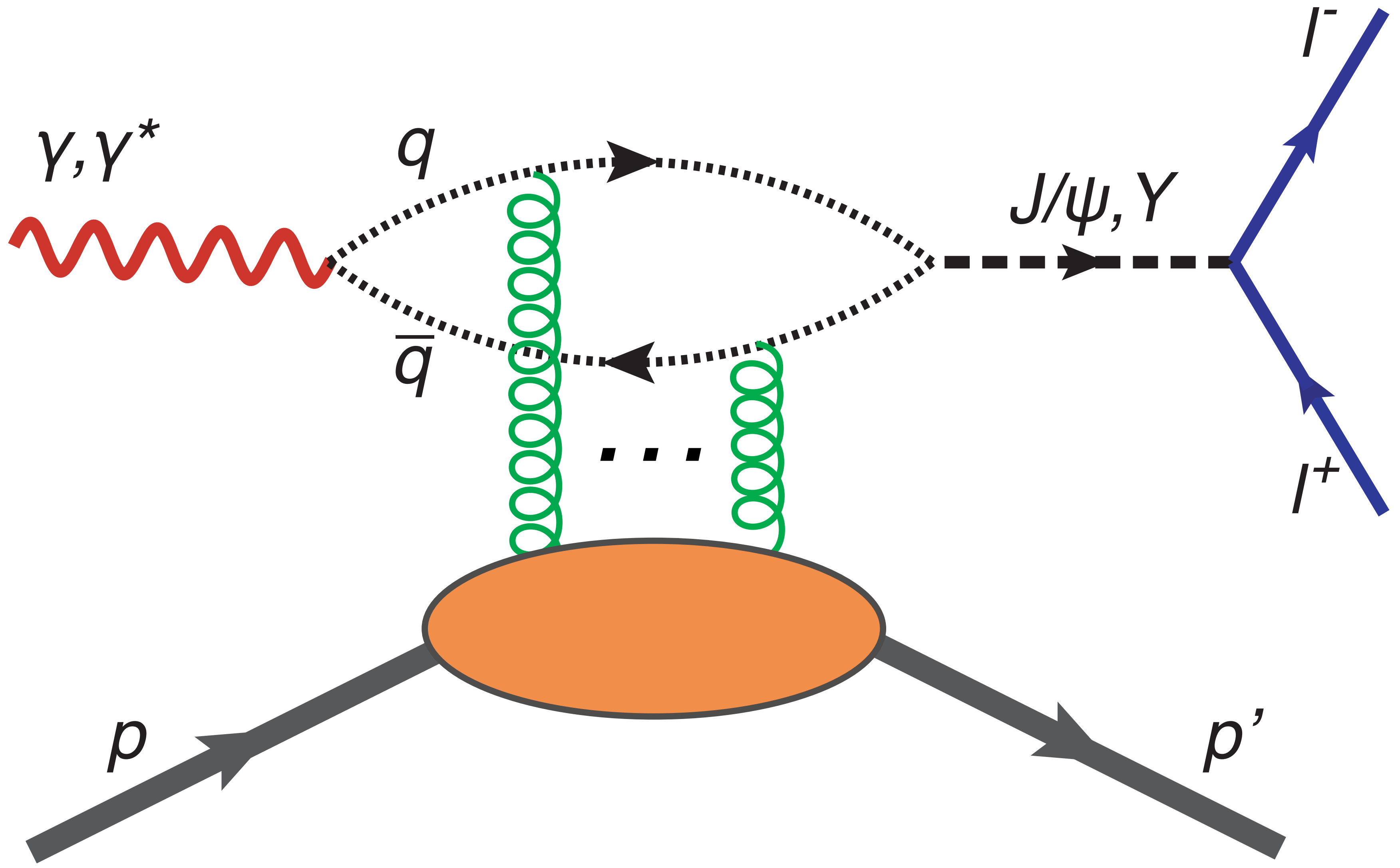
Trace anomaly intimately related to DCSB and the emergence of scale

CAN WE MEASURE THE TRACE ANOMALY?

…Quarkonium production near threshold!



- *J/ψ* and *Υ(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)



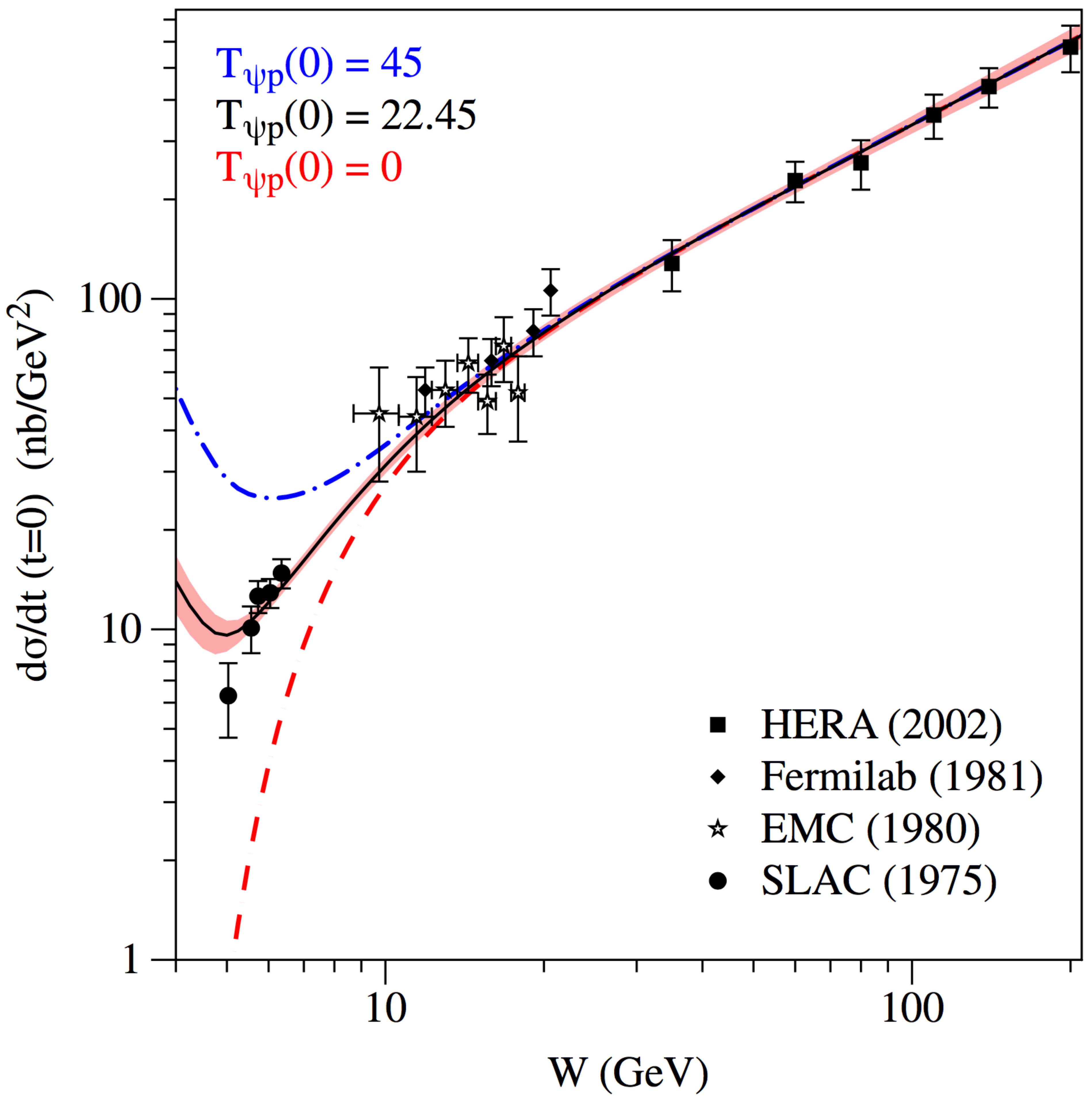
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)
S. R. Beane *et al.*, PRD 91, 114503 (2015)

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

The nature of the gluonic Van der Waals force

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

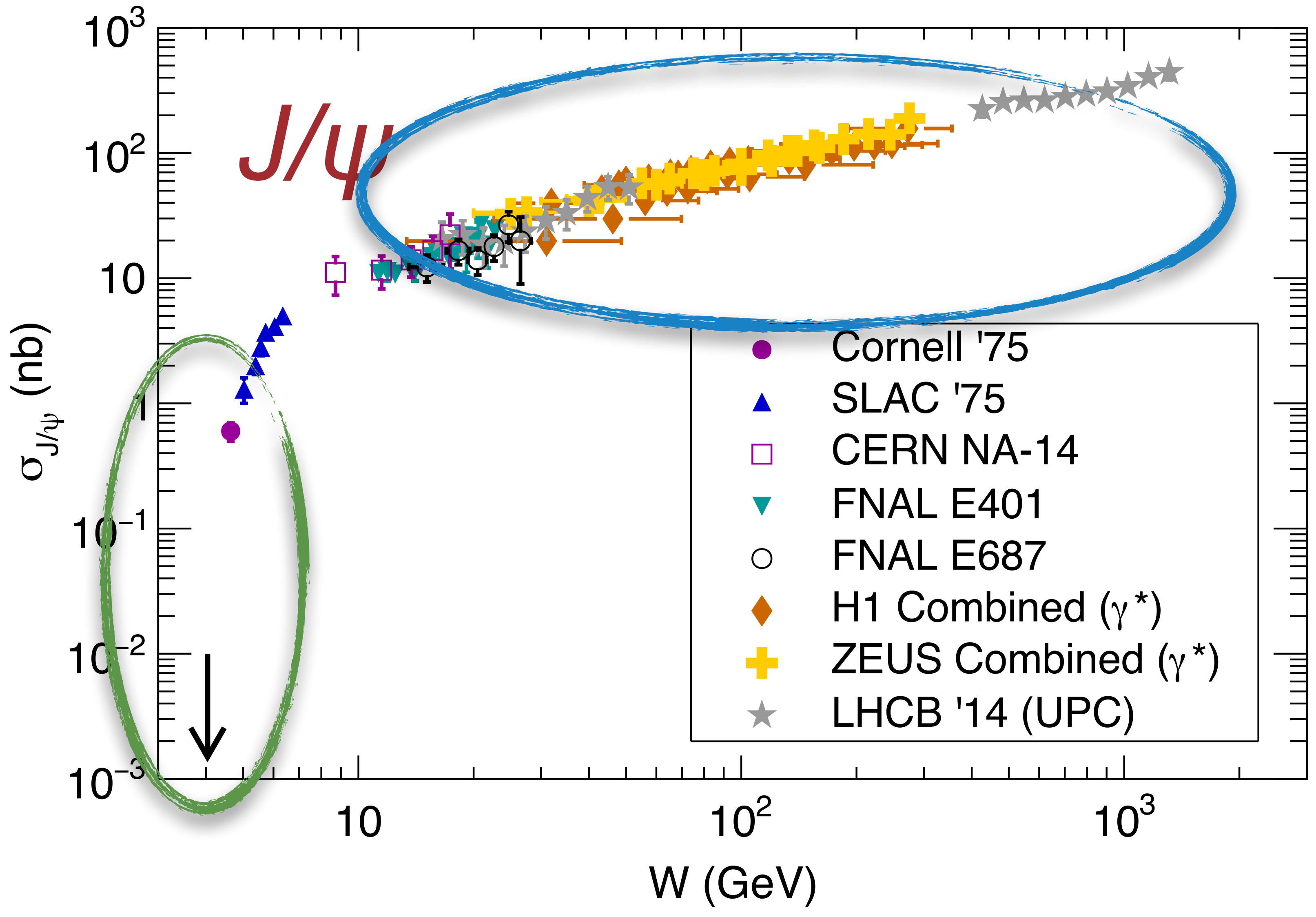
Need high-precision photo-production data near threshold



S. Joosten

QUARKONIUM PHOTO-PRODUCTION

What did we know before JLab?



- *J/ψ* well constrained for high energies
- No real electro-production data available
- **Almost no data near threshold**

Near Threshold:

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

J/ψ at JLab!

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

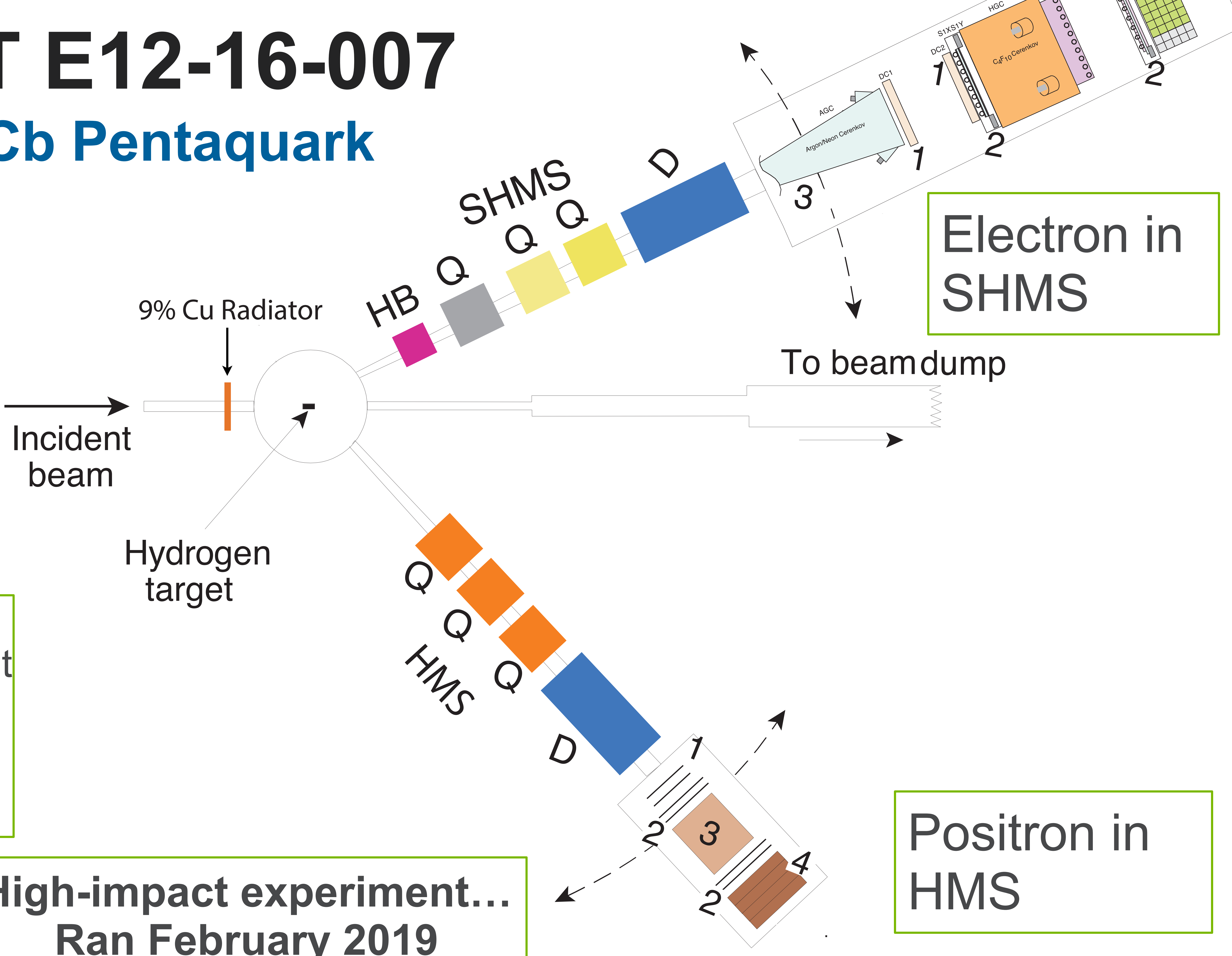
JLAB EXPERIMENT E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

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

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

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



Electron in SHMS

Positron in HMS

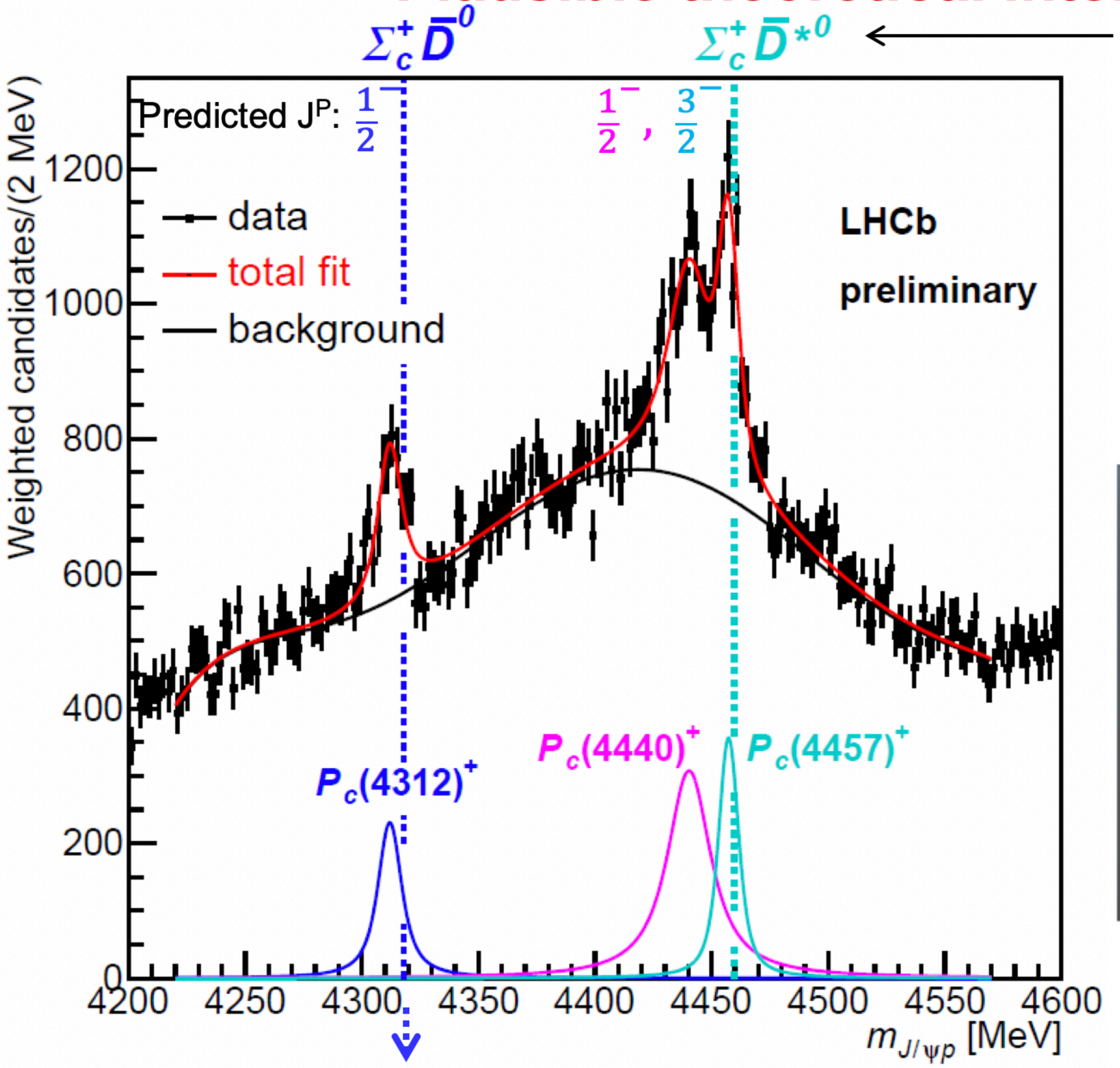
High-impact experiment…
Ran February 2019

The plot thickens…

NEW LHC-B RESULTS WITH 10X STATISTICS

Moriond QCD, Tomasz Skwarnicki, Mar 26, 2019 — 14

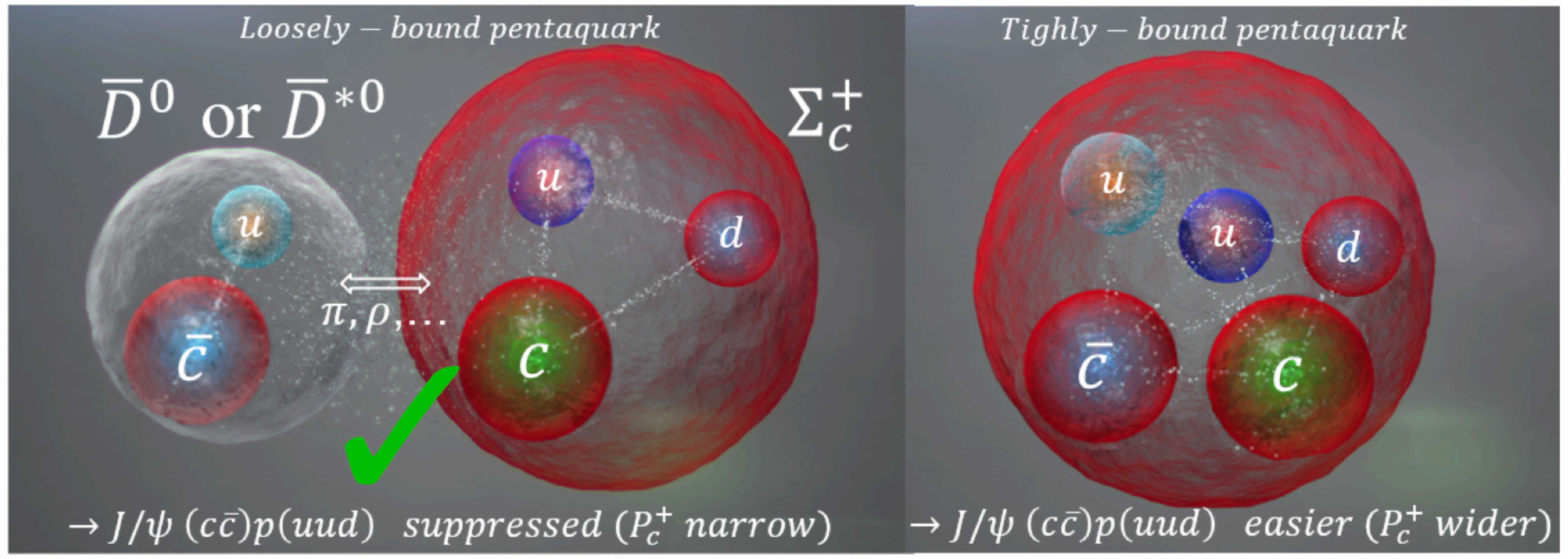
Plausible theoretical interpretation



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

LHCb-PAPER-2019-014 in preparation

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



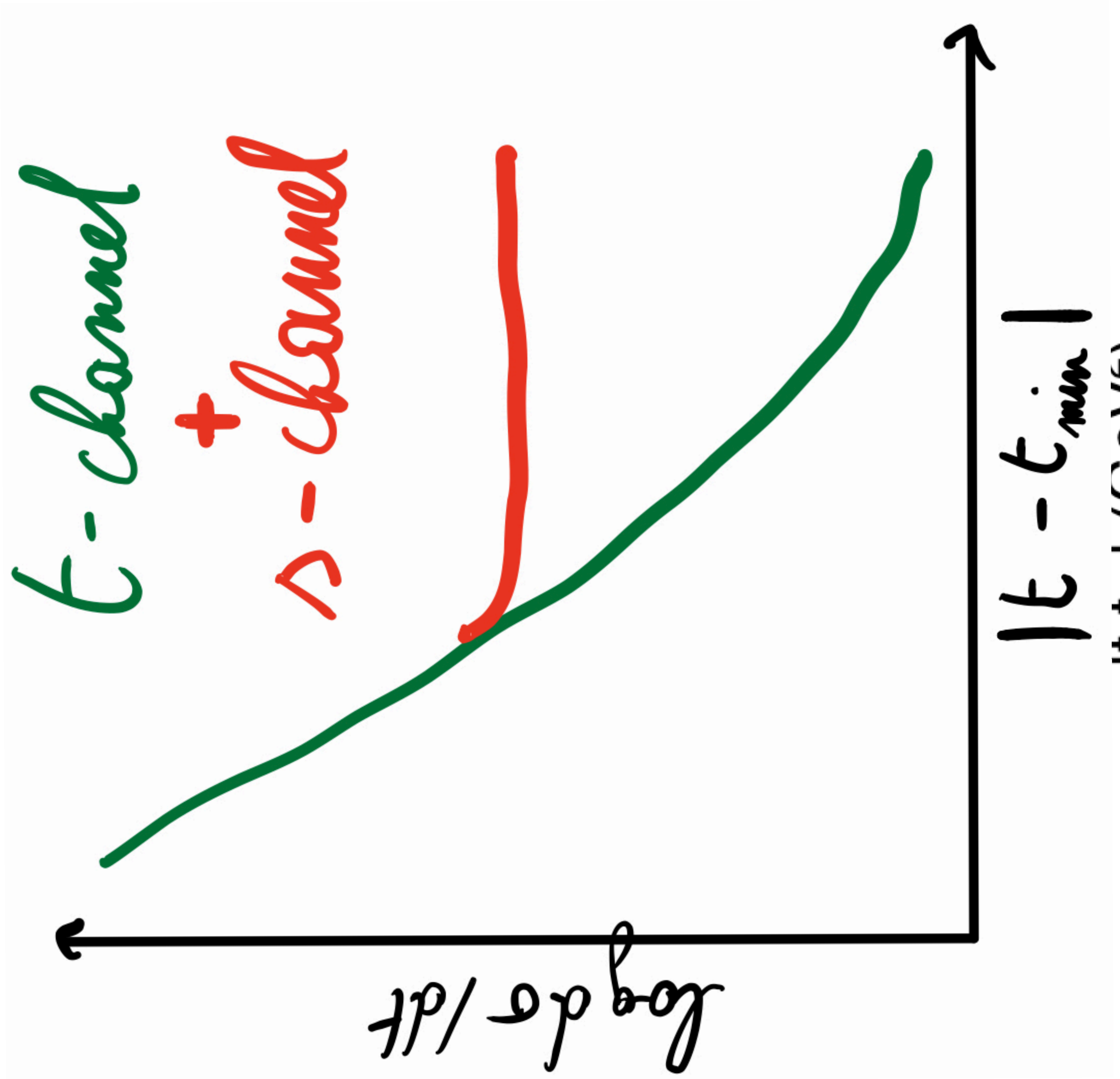
Existence of $\Sigma_c^+ \bar{D}^0$ molecule would imply importance of ρ-exchange

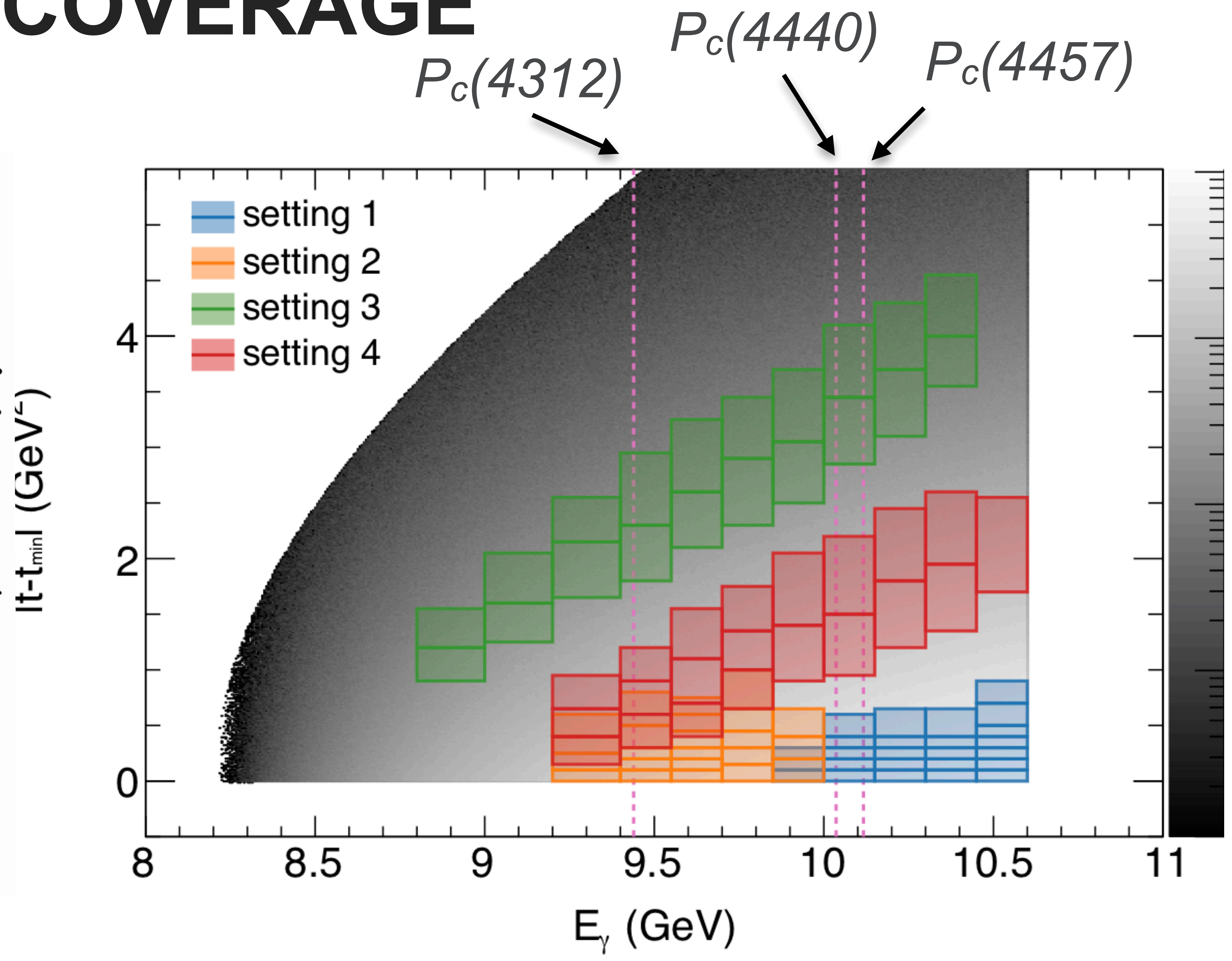
However, we need to measure J^Ps to confirm molecular hypothesis, find isospin partners, …

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

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

2D PHASE SPACE COVERAGE

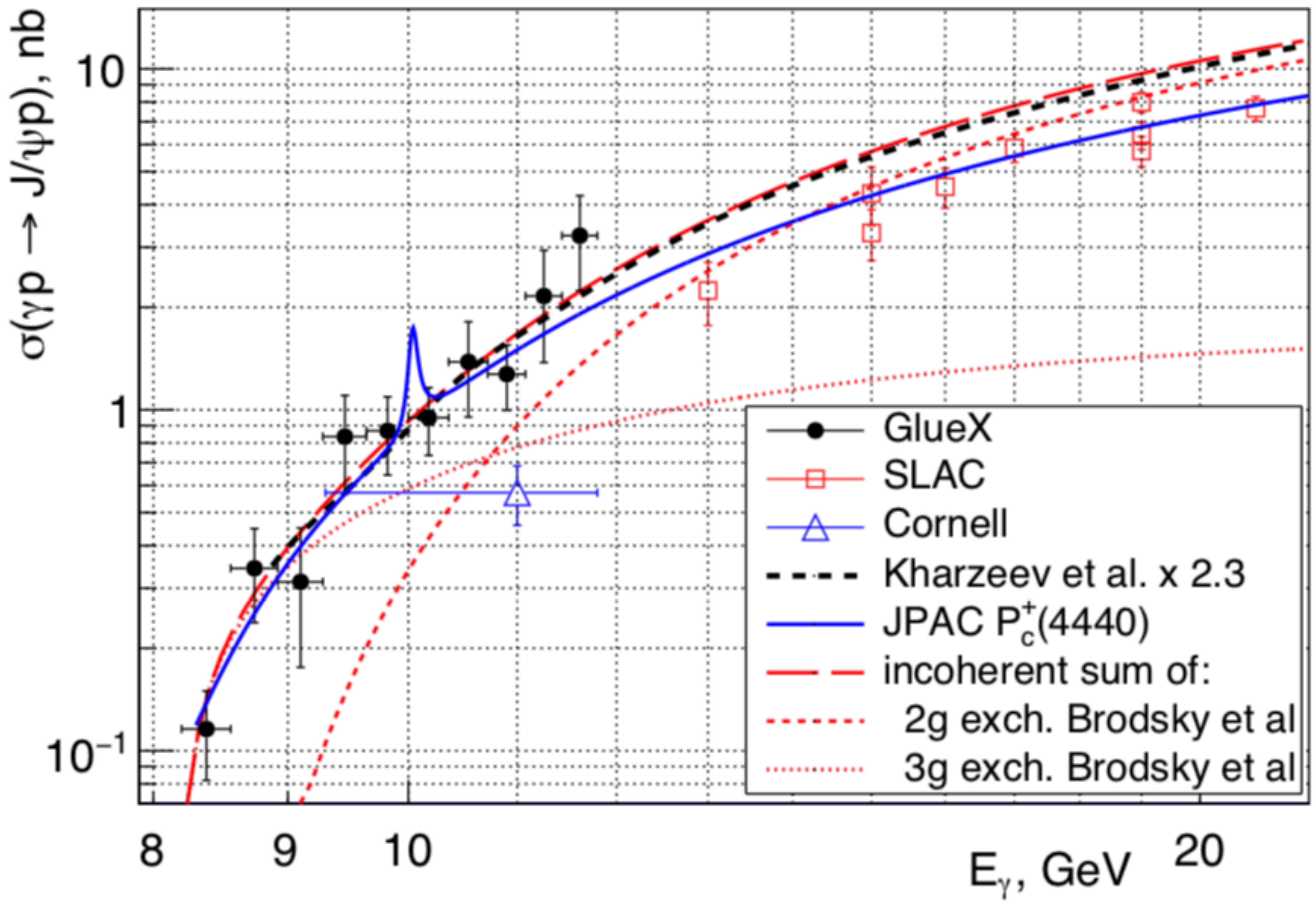




…MEANWHILE IN HALL D

First *J/ψ* results from Jefferson Lab, published in PRL (2019)

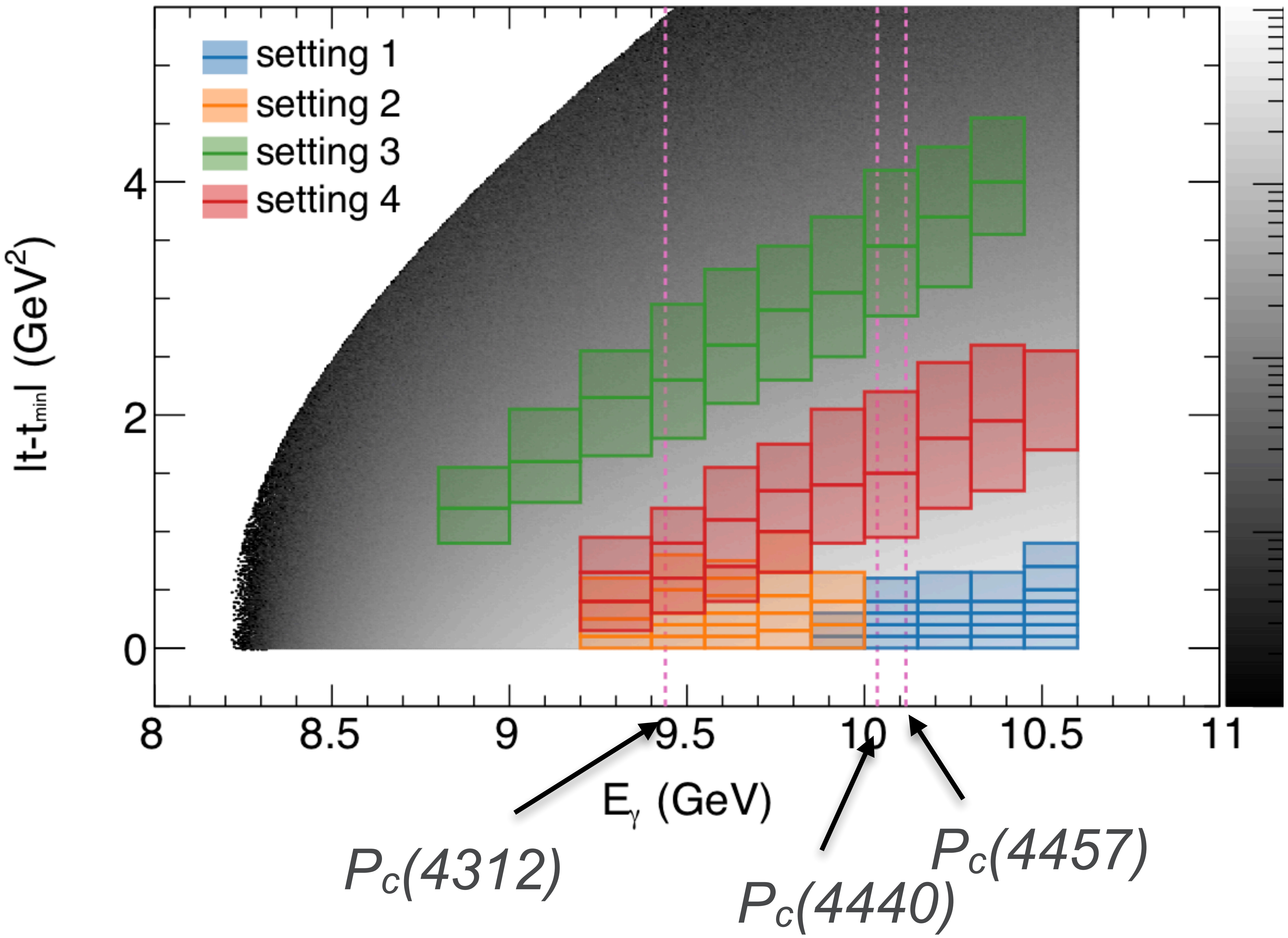
- 1D cross section (~469 counts)
- Also released 1D integrated *t*-dependence for photon energy between 10-11.8GeV
- Trends significantly higher than old measurements, but large 27% scale uncertainty
- Published upper limits for s-channel resonances at 90% confidence level
- Still consistent with molecular model



FEATURES OF HALL C MEASUREMENT

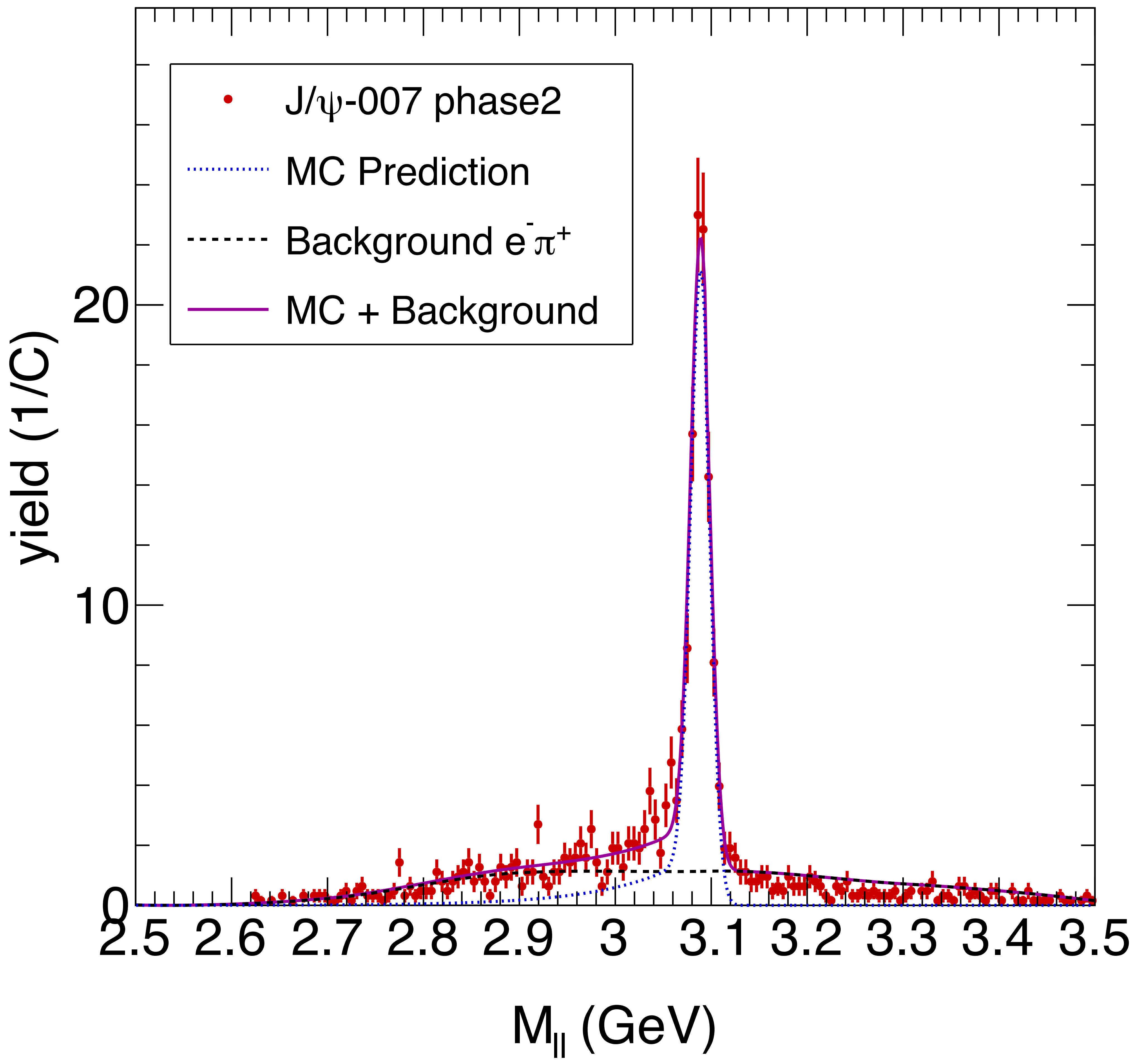
J/ψ in 2D

- 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!
- Combine data from all settings for maximal sensitivity to LHCb pentaquark
- Covers energy range of the three new LHCb pentaquark candidates



SIGNAL SHAPE WELL UNDERSTOOD

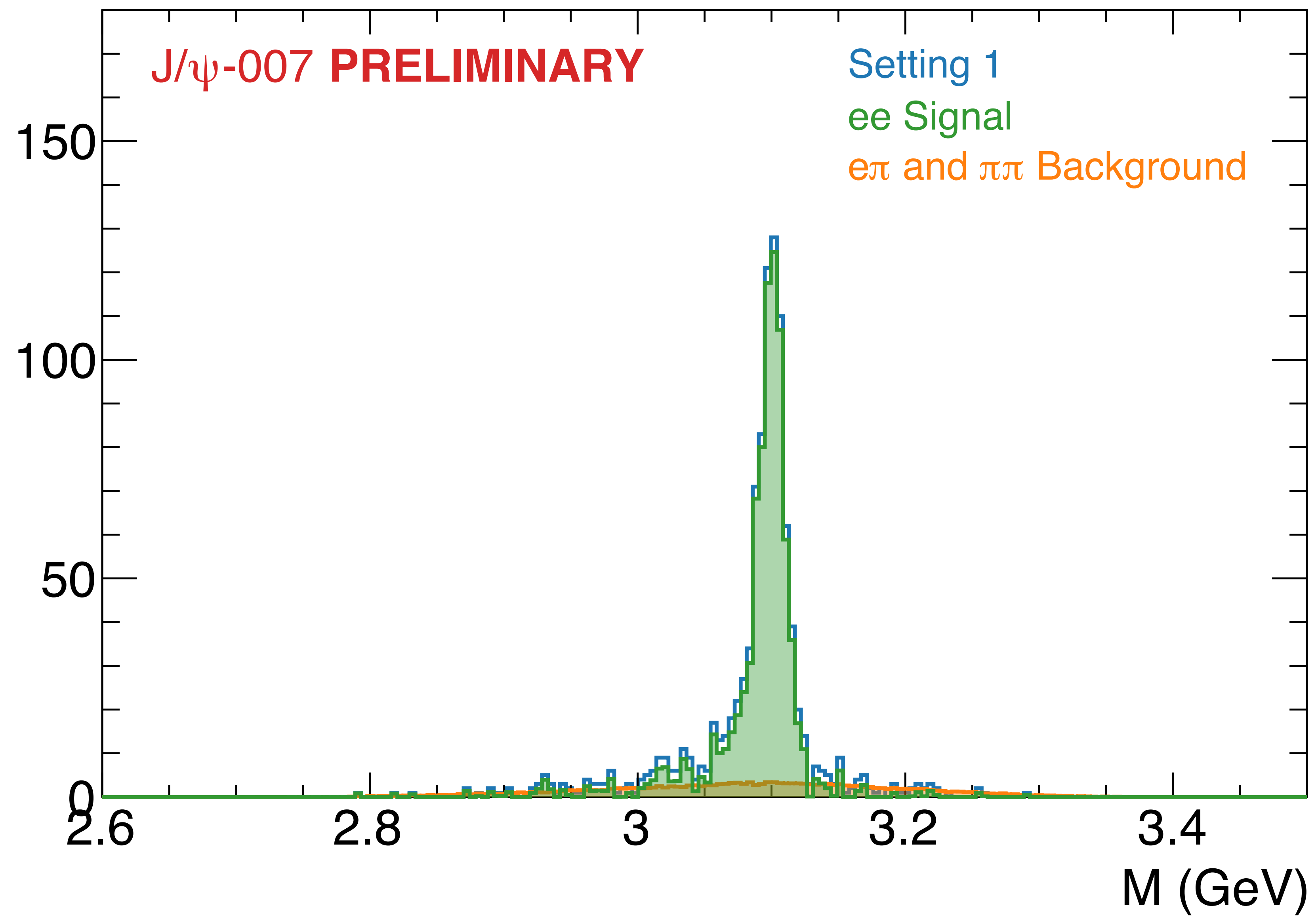
007$^{J/\psi}$

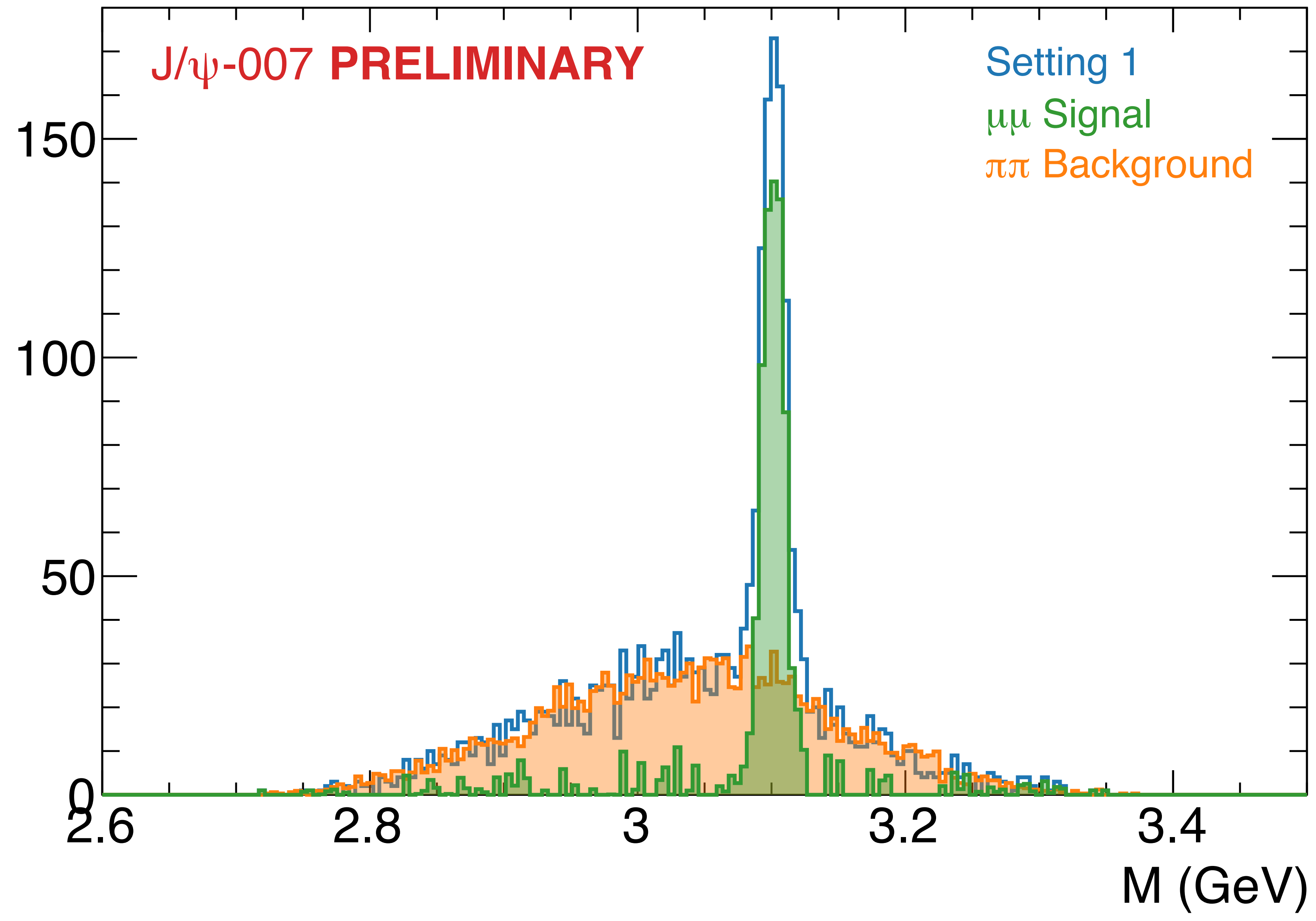


- MC has model of radiator, realistic target, detector and RC (using PHOTOS)
- Measured signal well described by MC for all settings.
- Background dominated by pion electro-production and 2-pion production
- Bethe-Heitler contamination very small due to large spectrometer angles
- Took data with open trigger: **background shape from real data!**

SIGNAL SHAPE WELL UNDERSTOOD

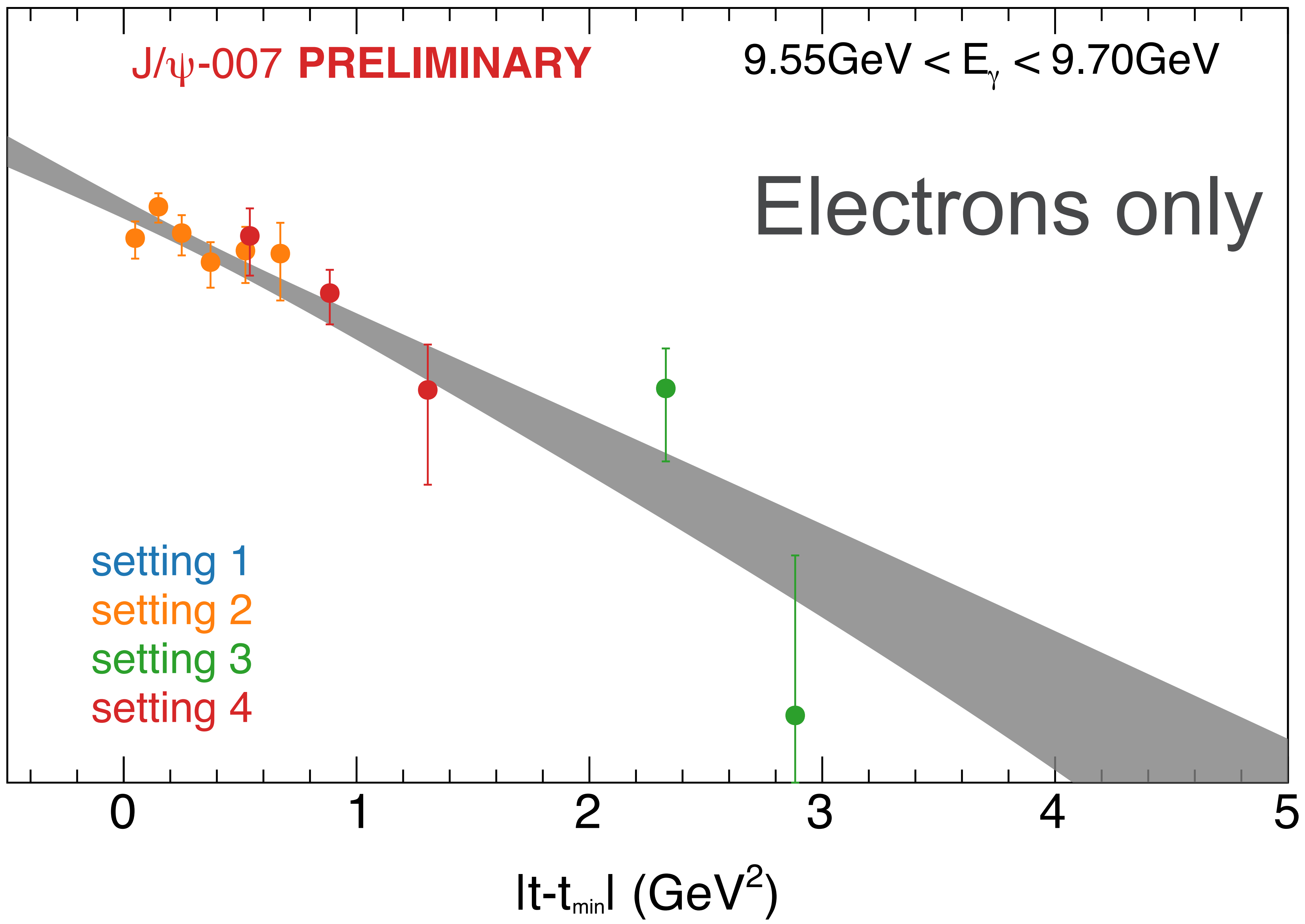
007$^{J/\psi}$

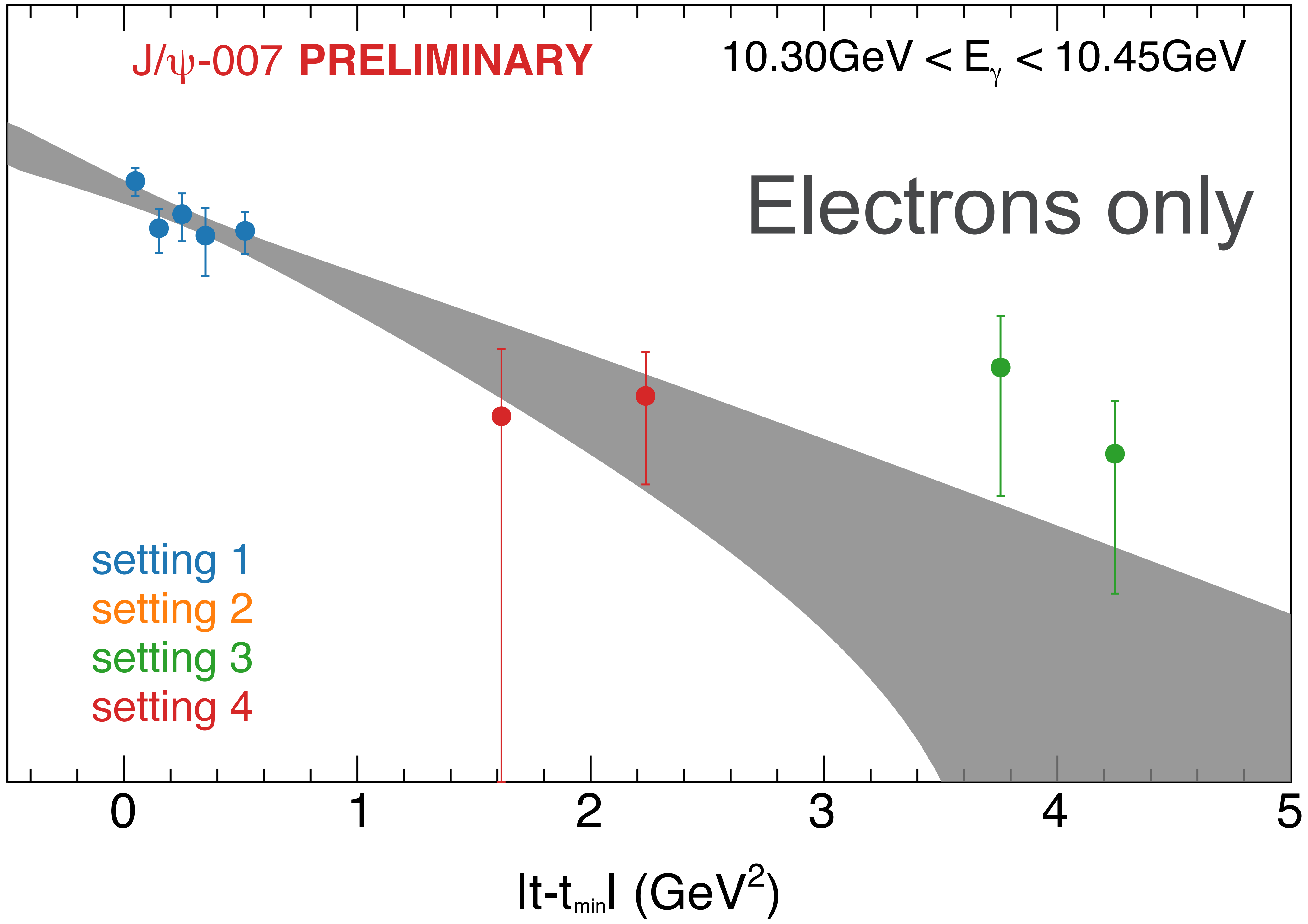




- **Electron and muon channels independent measurements, same statistics but different systematics**
- **Electrons:**
  - Low background with Cherenkov and ECAL for PID
  - Undergo multiple scattering and more sensitive to radiative losses
  - Slightly worse resolution (10MeV)
- **Muons**
  - More background using only ECAL (require coincidence MIP in 4 layers in HMS and 2 layers in SHMS), but still reasonable
  - Background dominated by 2-pion events, can get shape from dataset
  - Less sensitive to multiple scattering and radiative losses
  - Better resolution (8MeV)
- **Invariant mass posititionn *stable* between phases, well described by Monte Carlo!**

SNEAK PREVIEW OF RESULTS





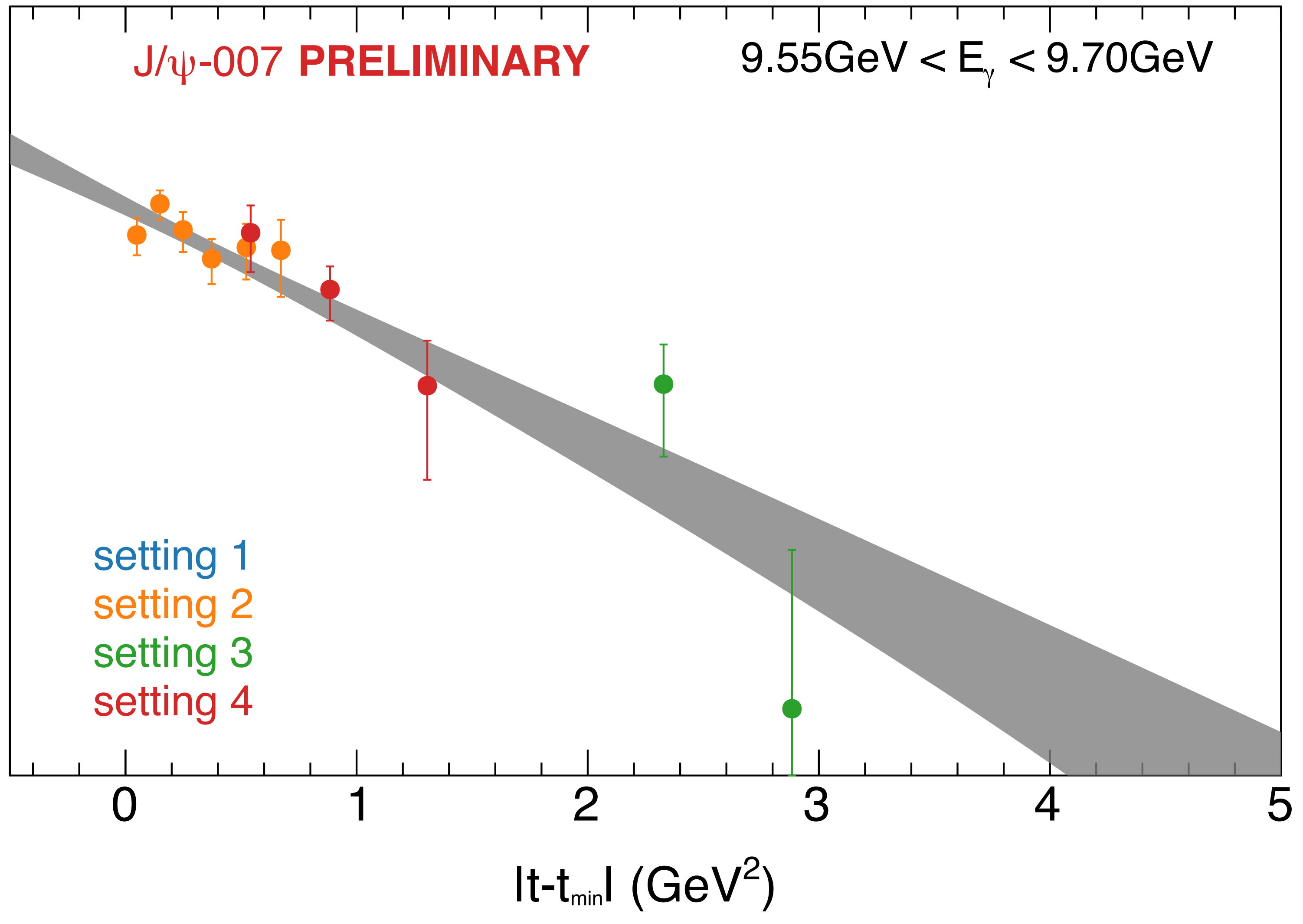
- First ever determination of t-dependence of the cross section in bins of 150MeV of photon energy between 9.1 and 10.6 GeV
- Highly sensitive to presence of s-channel resonance
- Only showing electron data, muon data is separate experiment with same statistics!

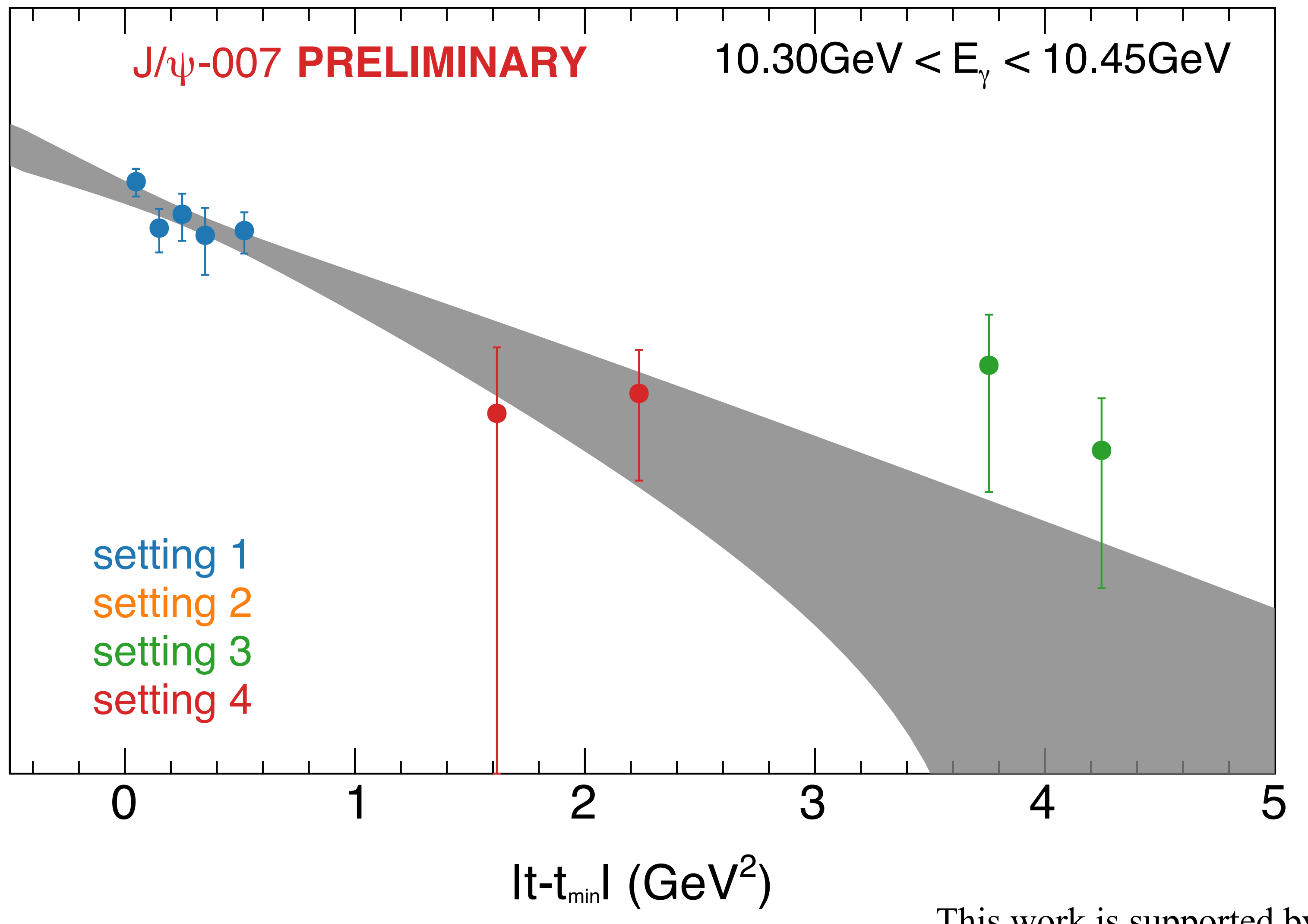
J/Ψ EXPERIMENTS IN JLAB IN A NUTSHELL

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.)	**469**	**2100 + 2100**	***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?

CONCLUSION





- **Quarkonium** production an important tool to study the **gluonic fields** in the nucleon
- **Threshold production** of quarkonium can shed light on the **trace anomaly,** quarkonium-nucleon **binding,** the LHCb **pentaquark** and the origin of the **proton mass**
- ***J/ψ-007*** perfectly positioned to **significantly contribute to these topics** with a 2D measurement of the *J/ψ* cross section near threshold
  - Evidence for pentaquark states?
  - Binding force between proton and *J/ψ?*
  - Understand apparent discrepancy between GlueX and SLAC/Cornell points

Analysis ready to undergo a collaboration review!

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.

Argonne NATIONAL LABORATORY

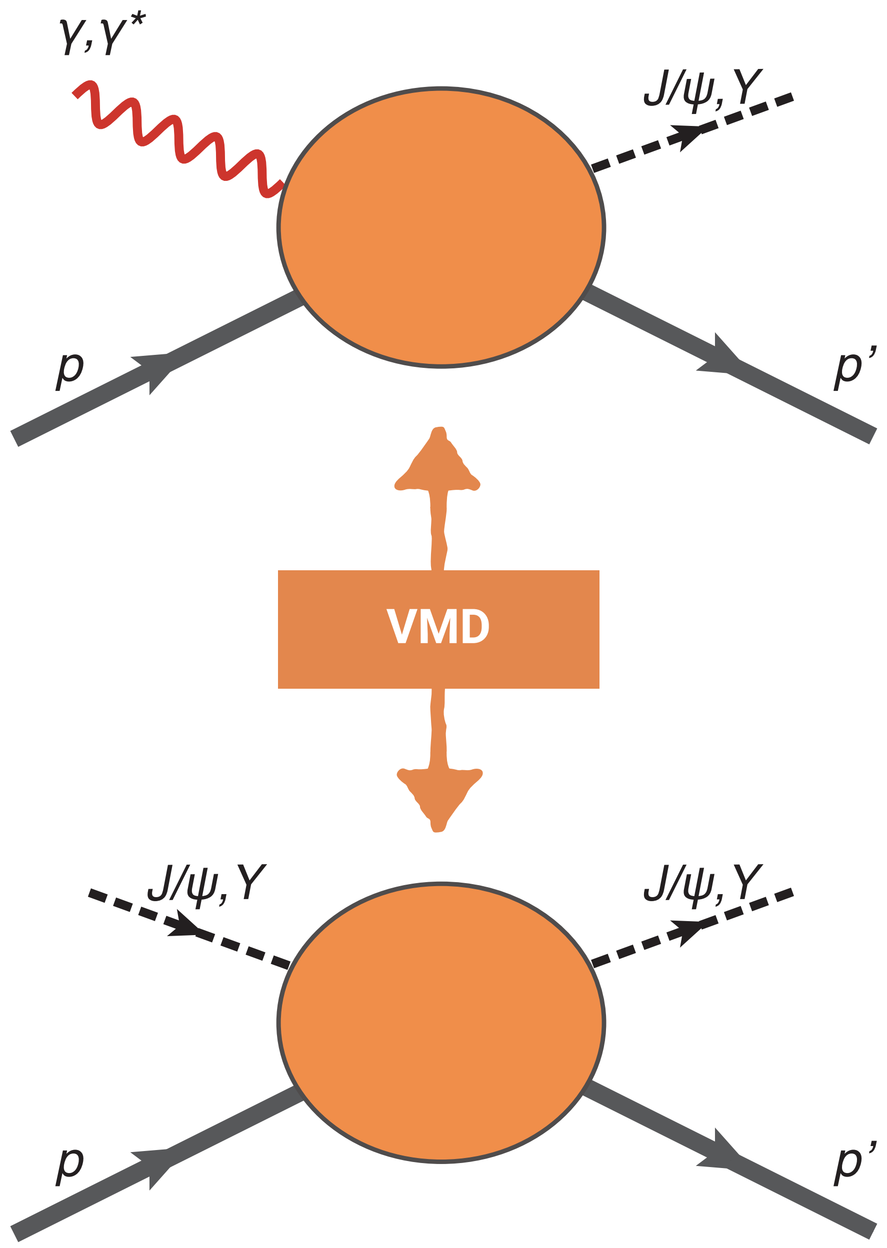
BACKUP

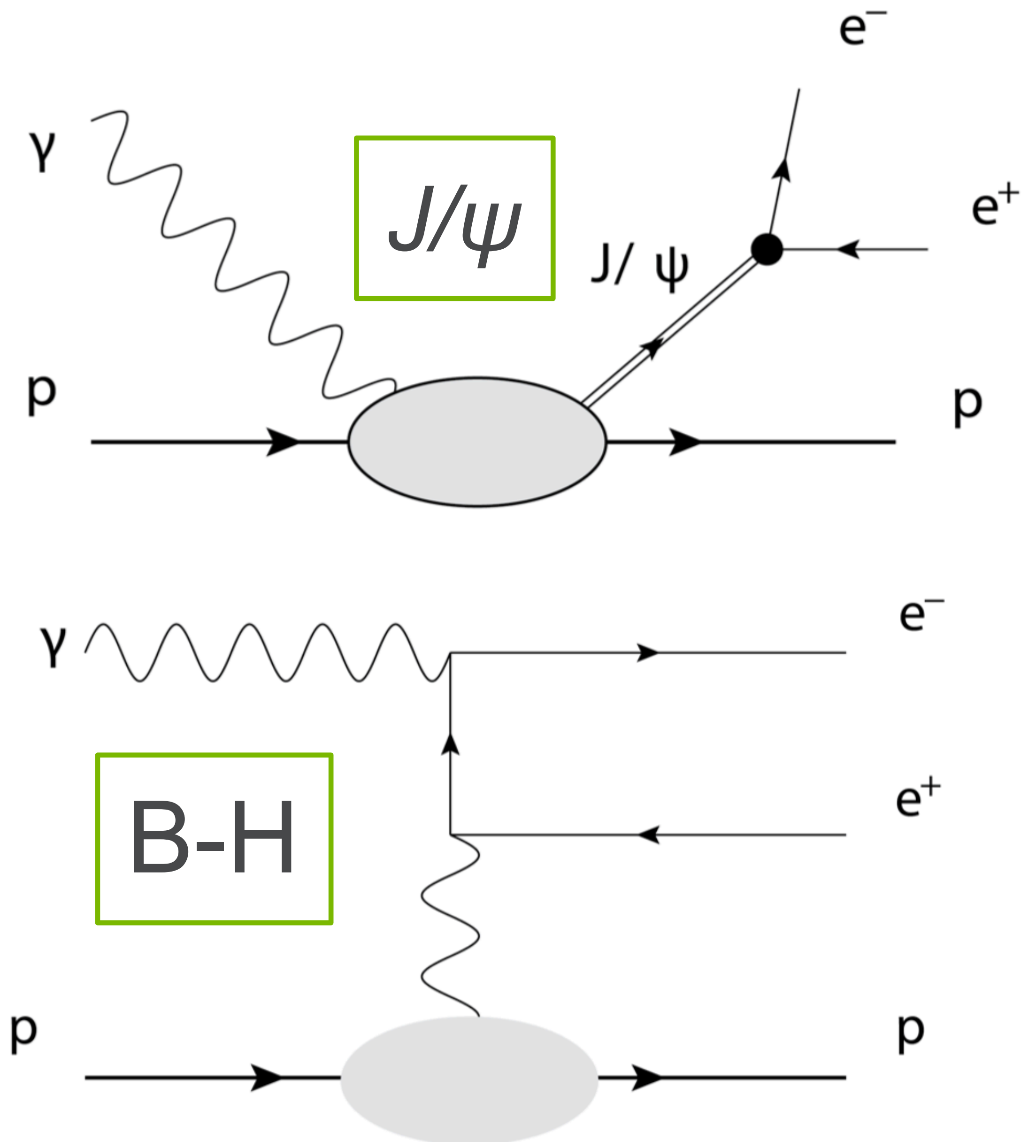
Three possible avenues for…

MEASURING THE TRACE ANOMALY

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

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



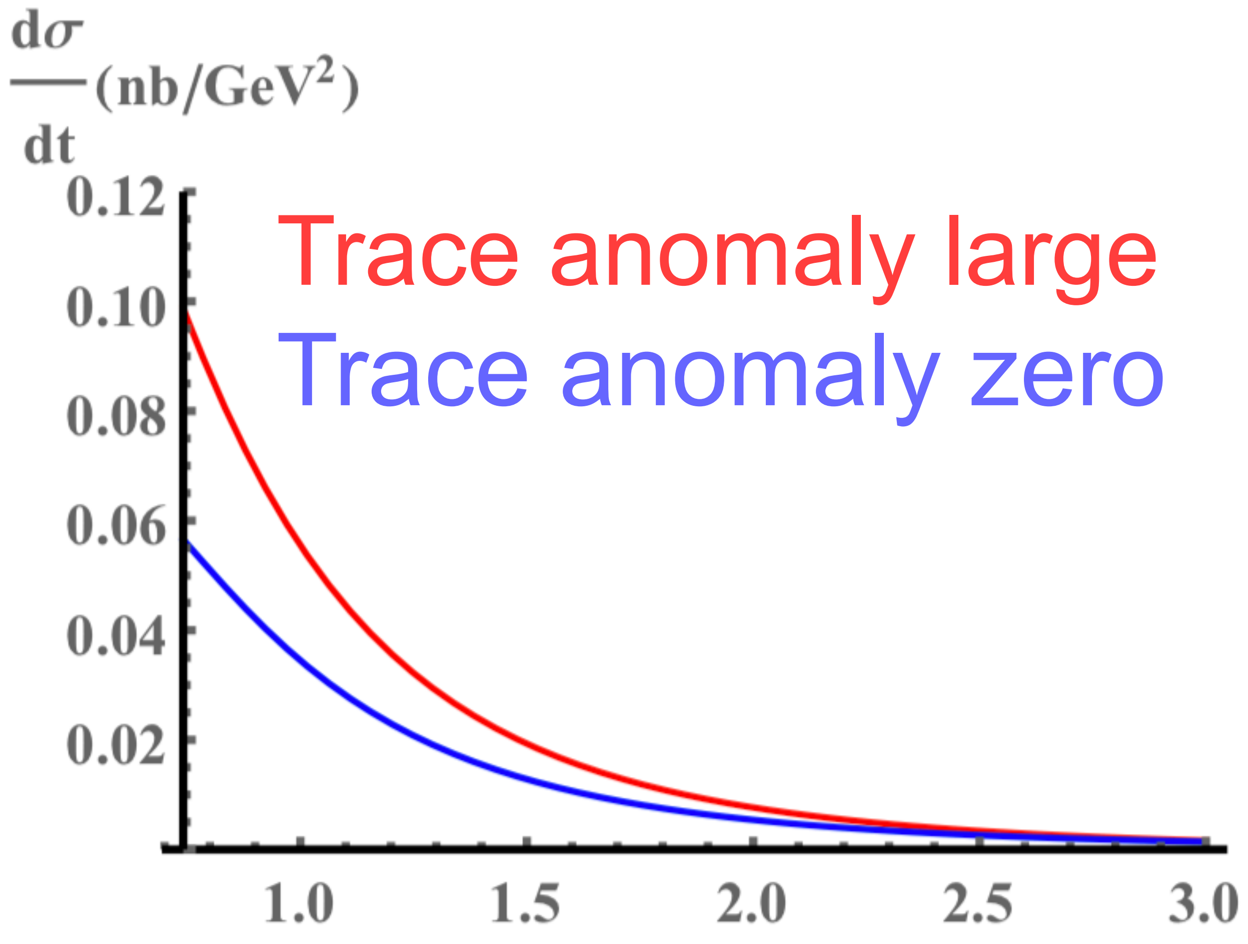


2. Interference with Bethe-Heitler
Interference between for *J/ψ* production and Bethe-Heitler near (but not at) threshold. Needs very high statistics. Possible at SoLID.

Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

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

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



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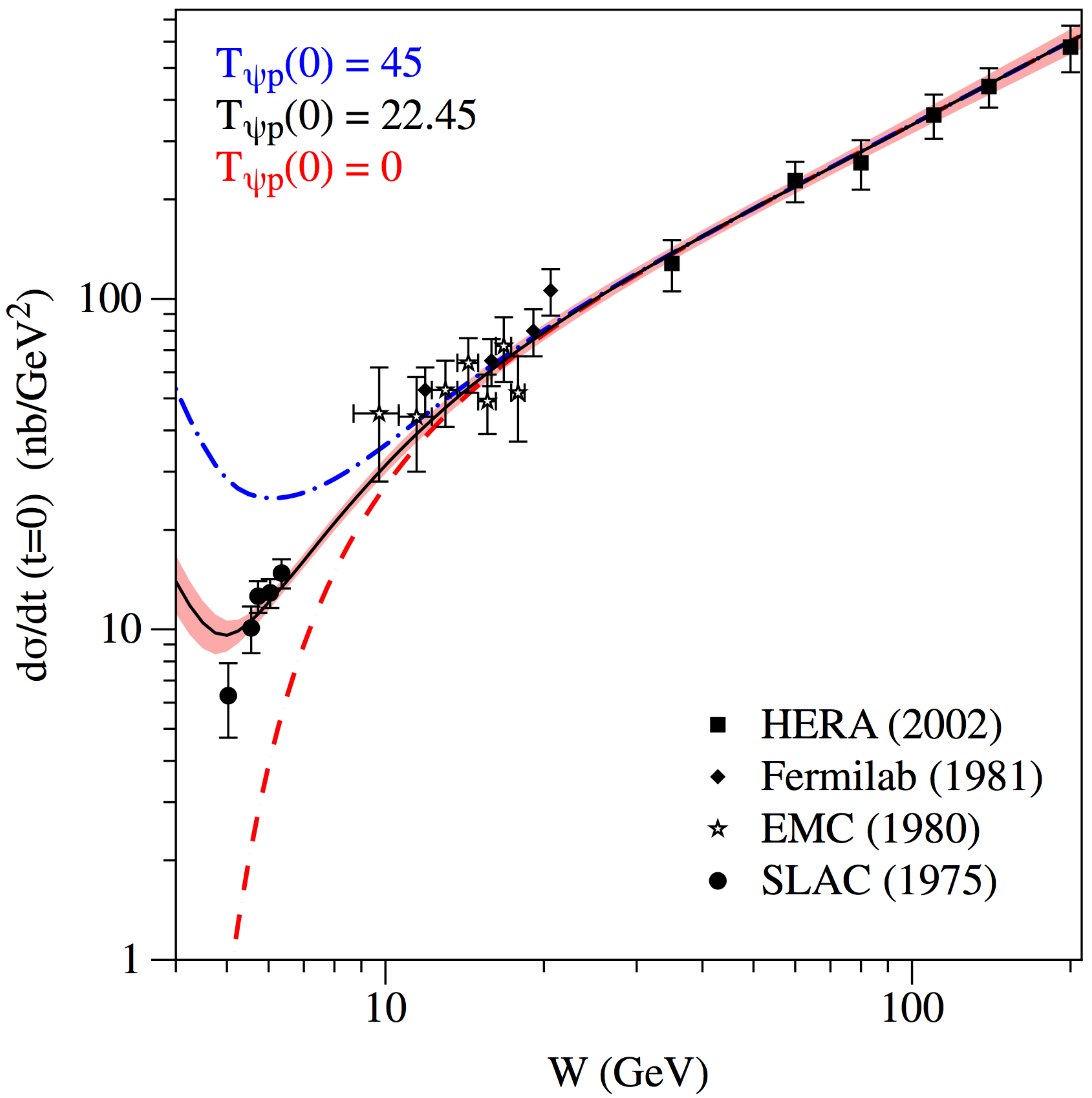
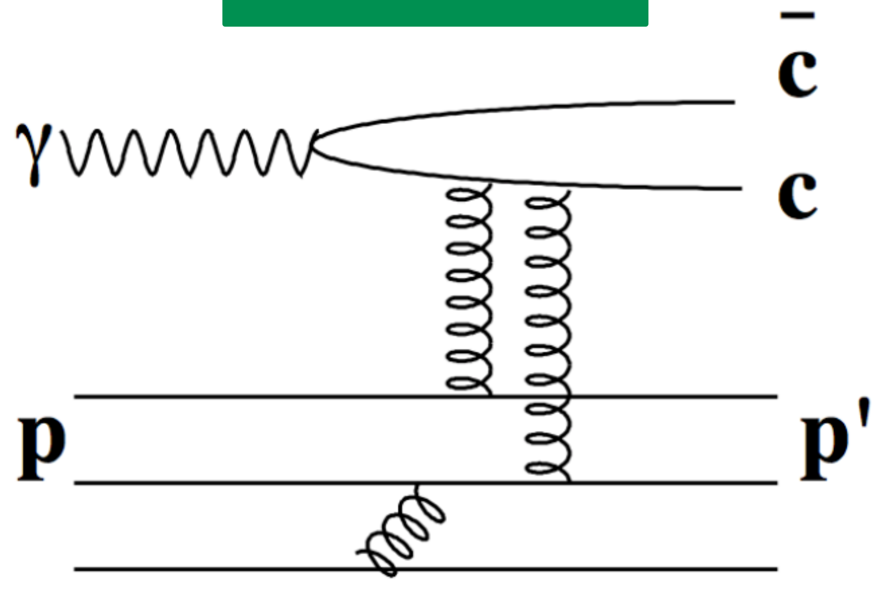
Need high-precision photo-production data near threshold



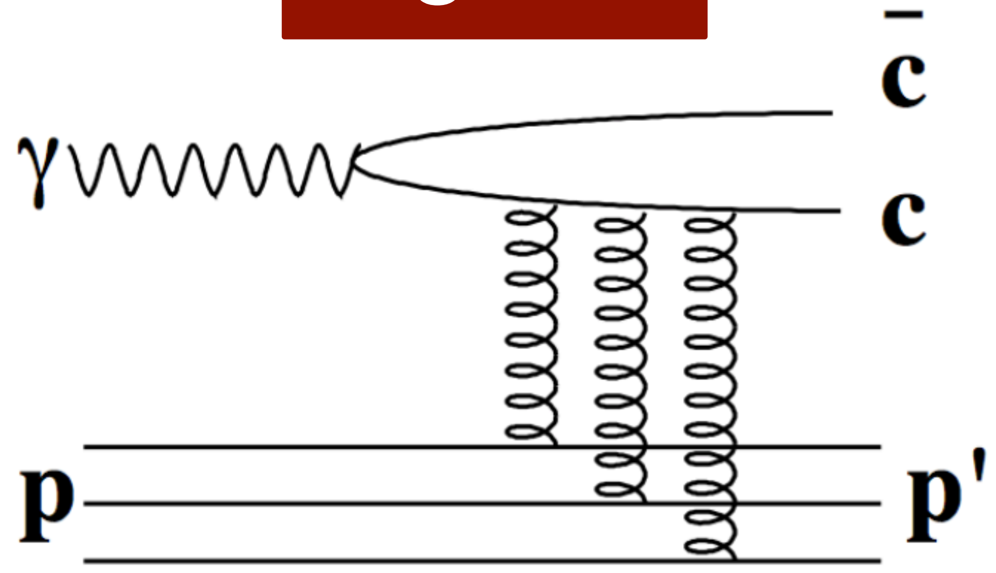
PRODUCTION MECHANISM NEAR THRESHOLD?

N-gluon exchange hard scattering

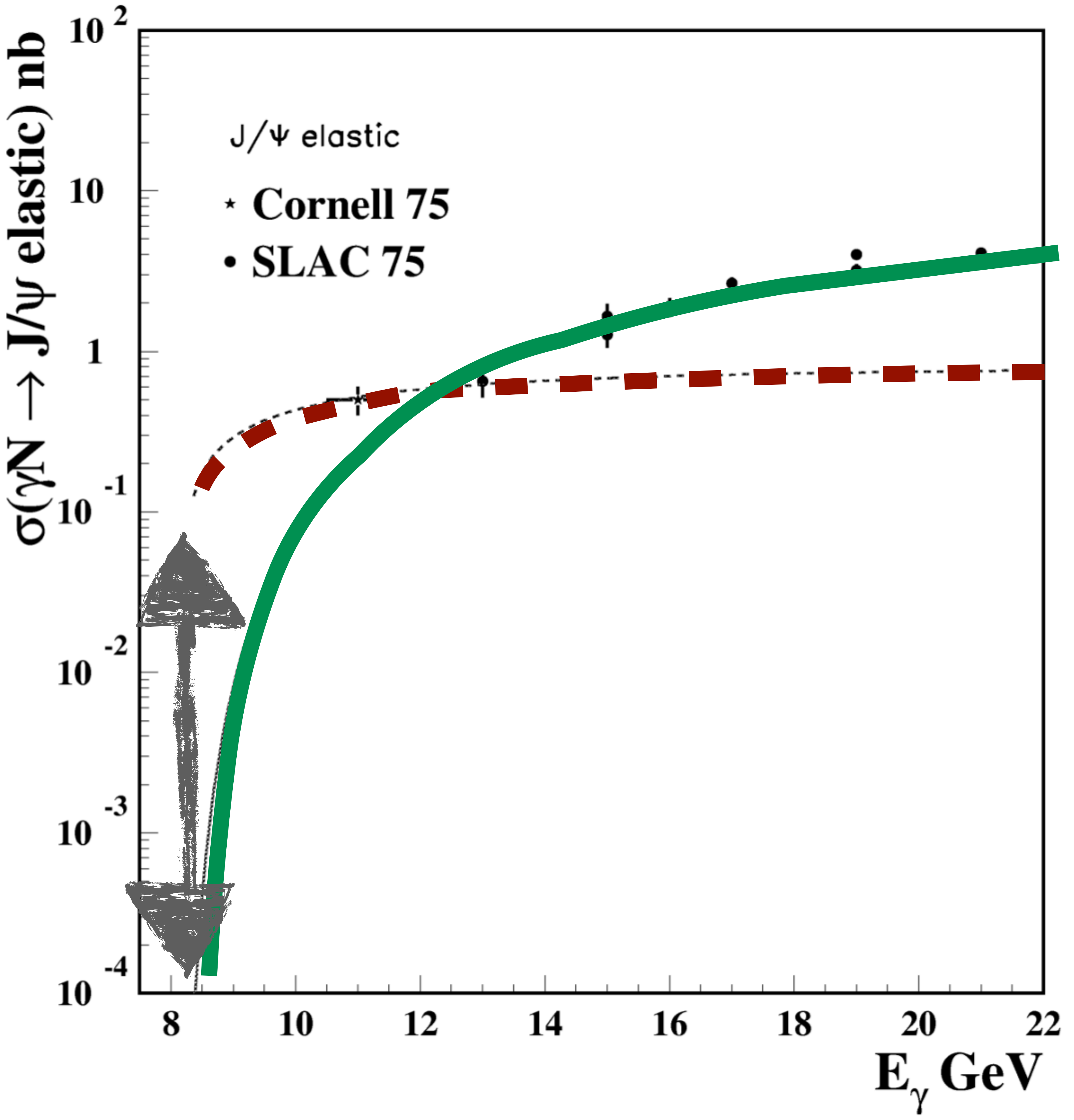
2-gluon



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**



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PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)

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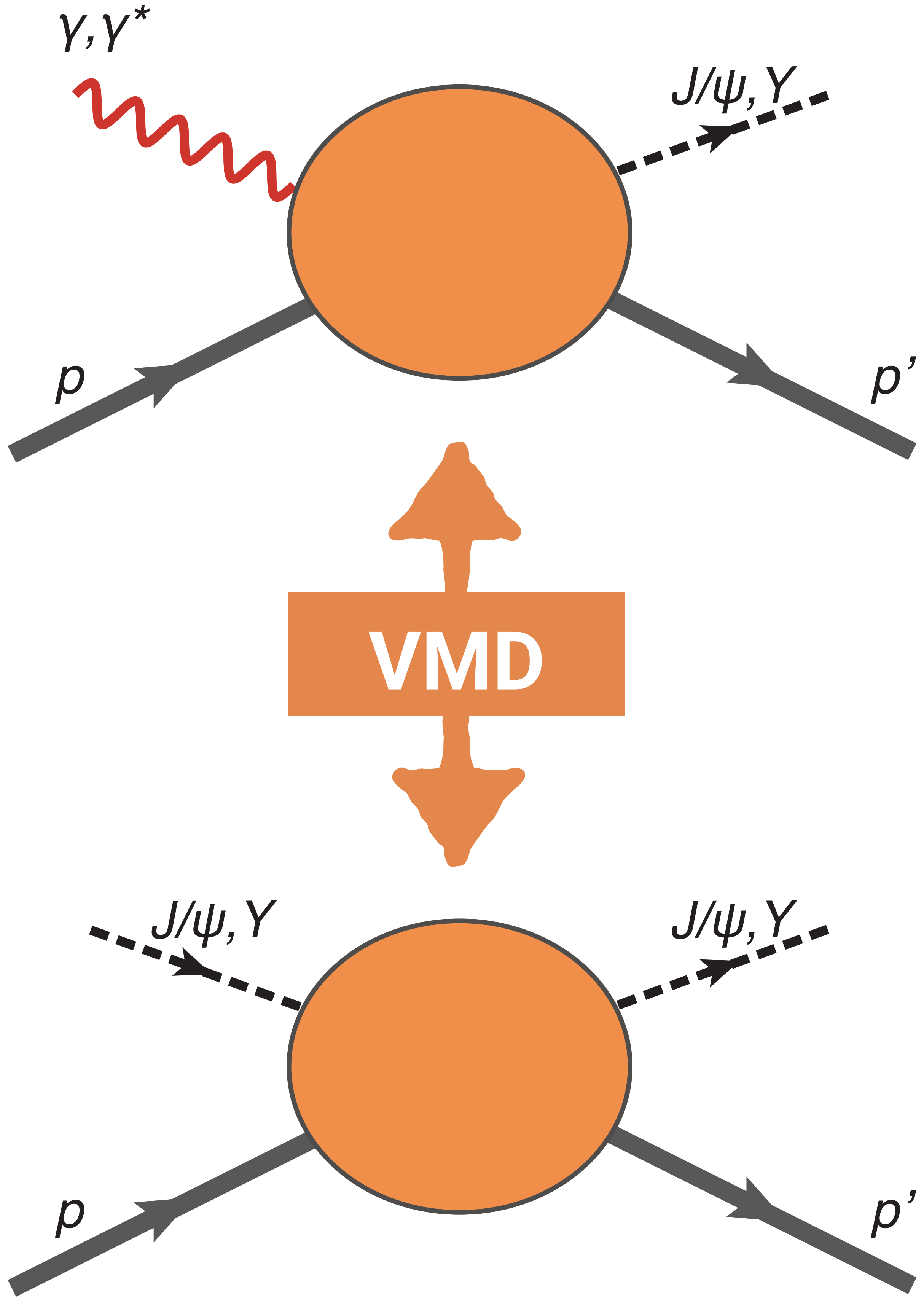
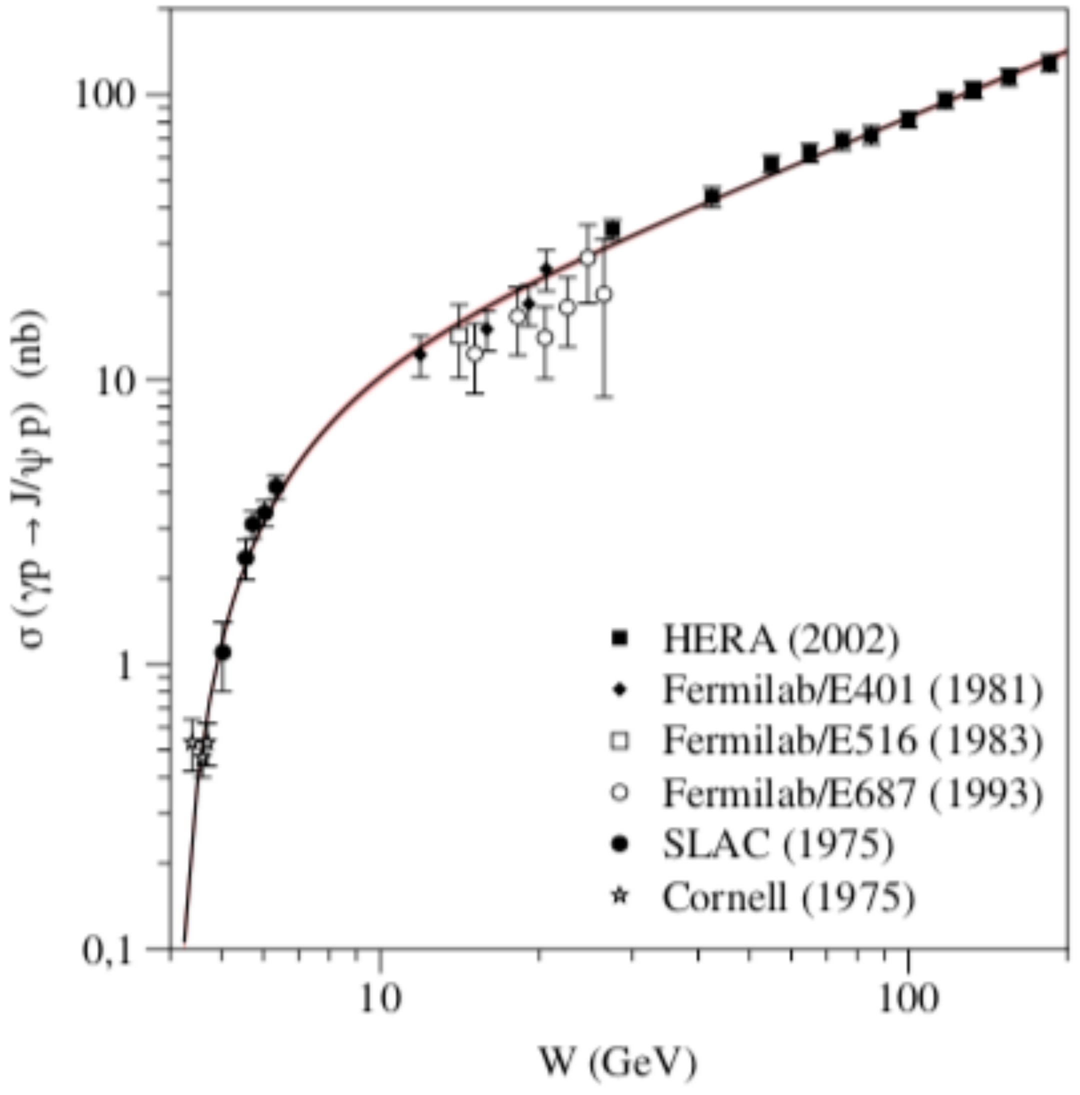
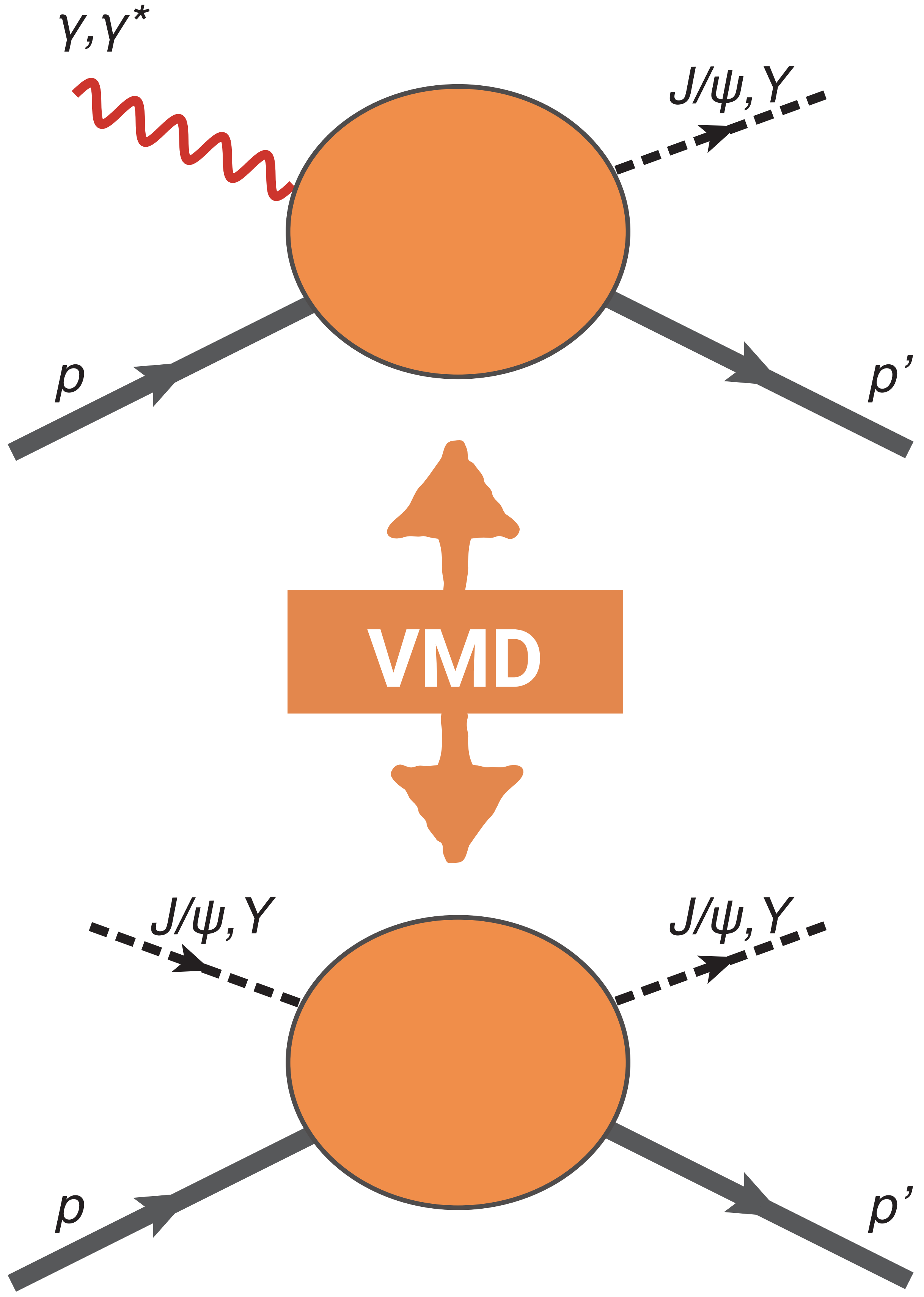


- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $T_{\psi p}$



PRODUCTION MECHANISM NEAR THRESHOLD?

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

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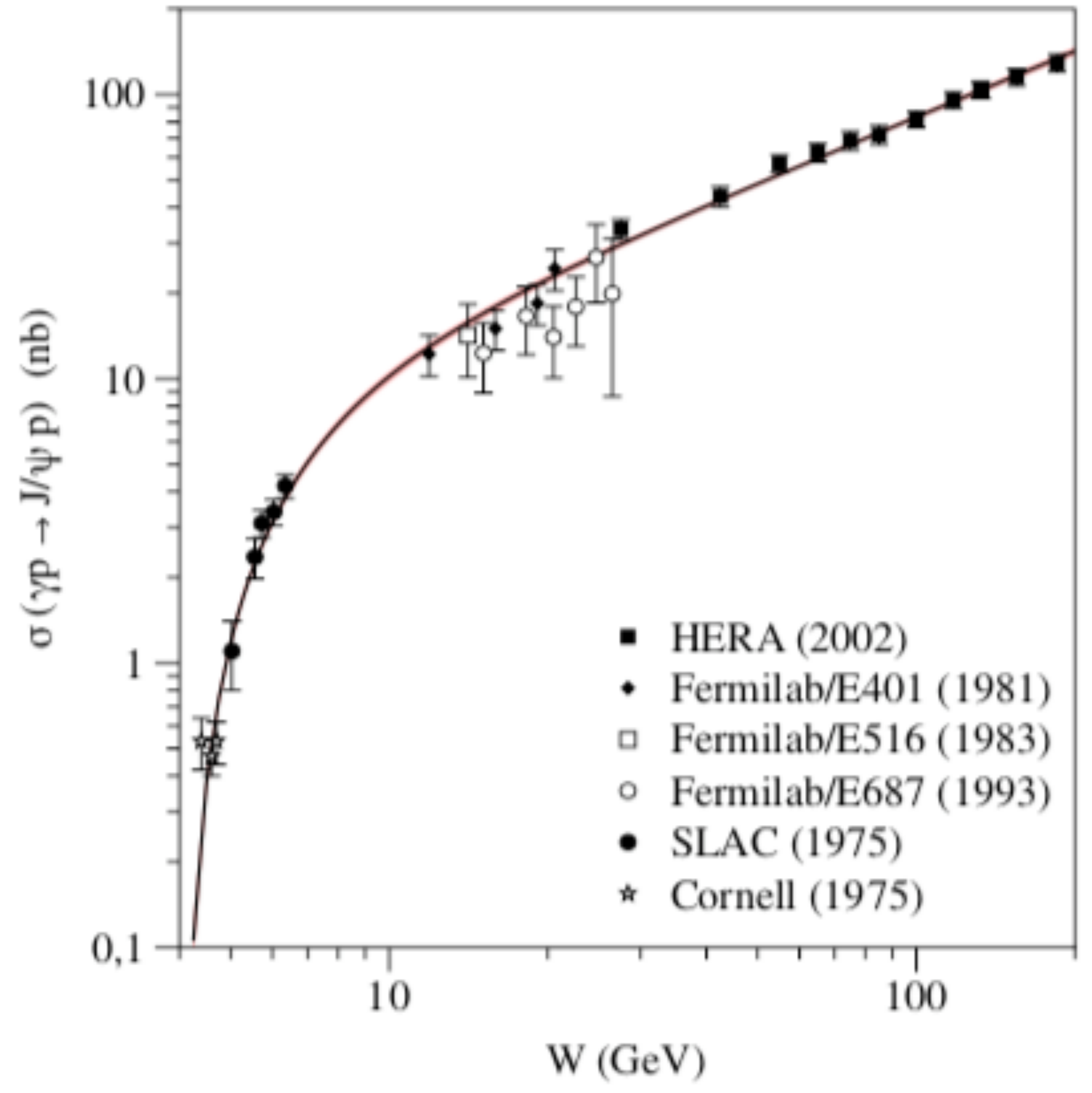
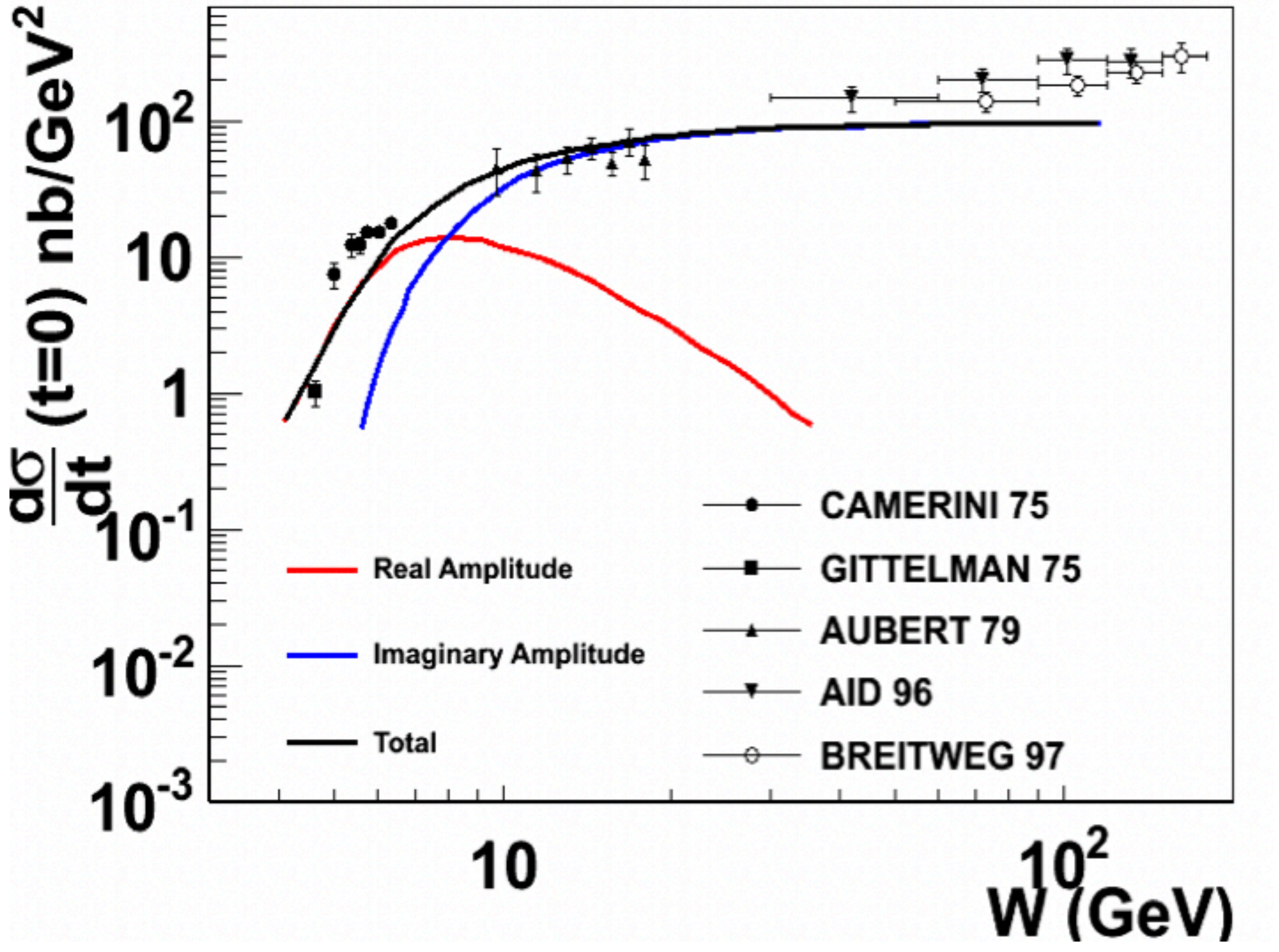
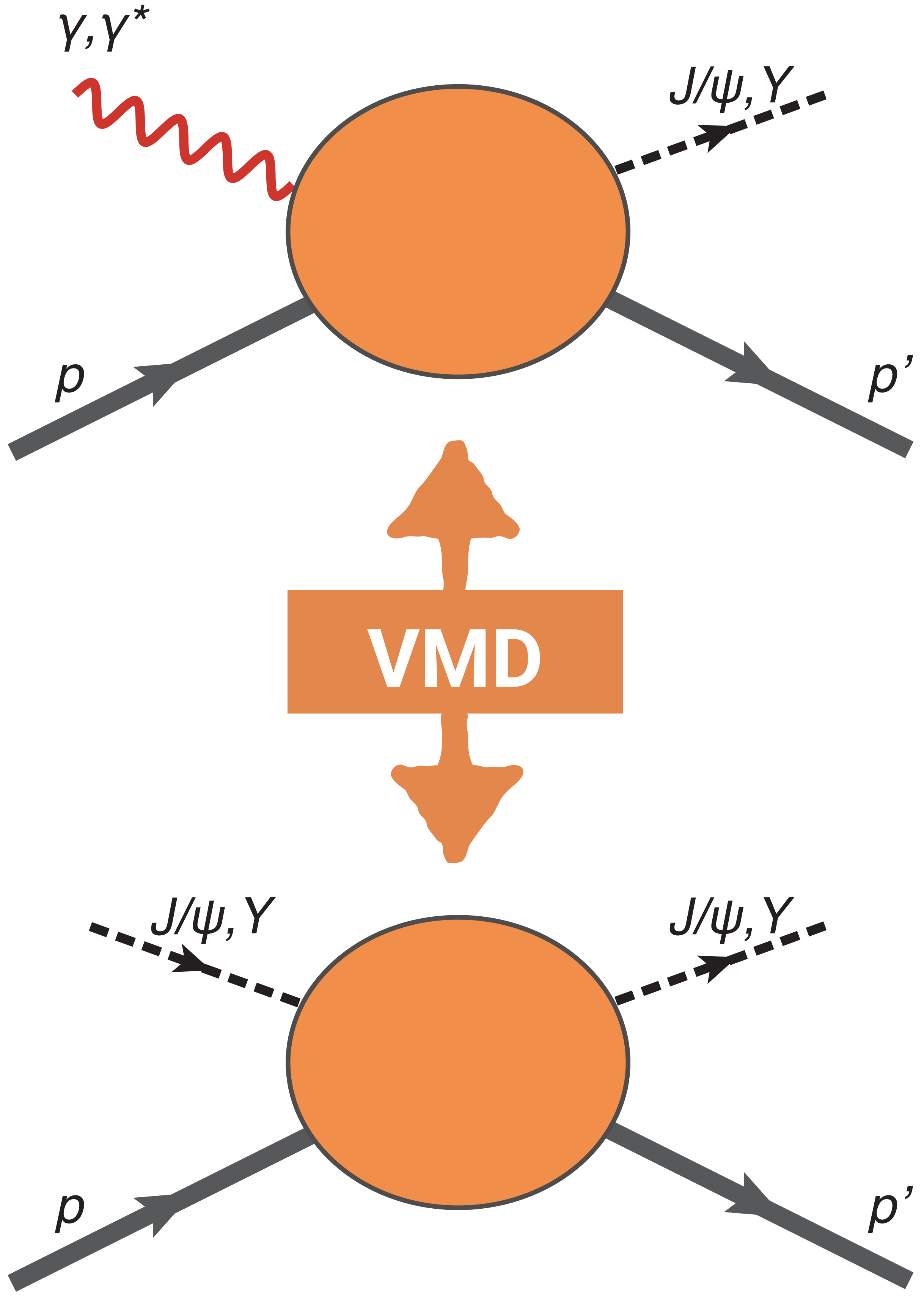




D. Kharzeev *et al.*, PLB 289 595-599 (1996), EPJ-C 9 459-462 (1999)
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)

PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)



- VMD relates photo-production cross section to quarkonium-nucleon scattering amplitude $T_{\psi p}$
- Approach well-defined at **high energies:**
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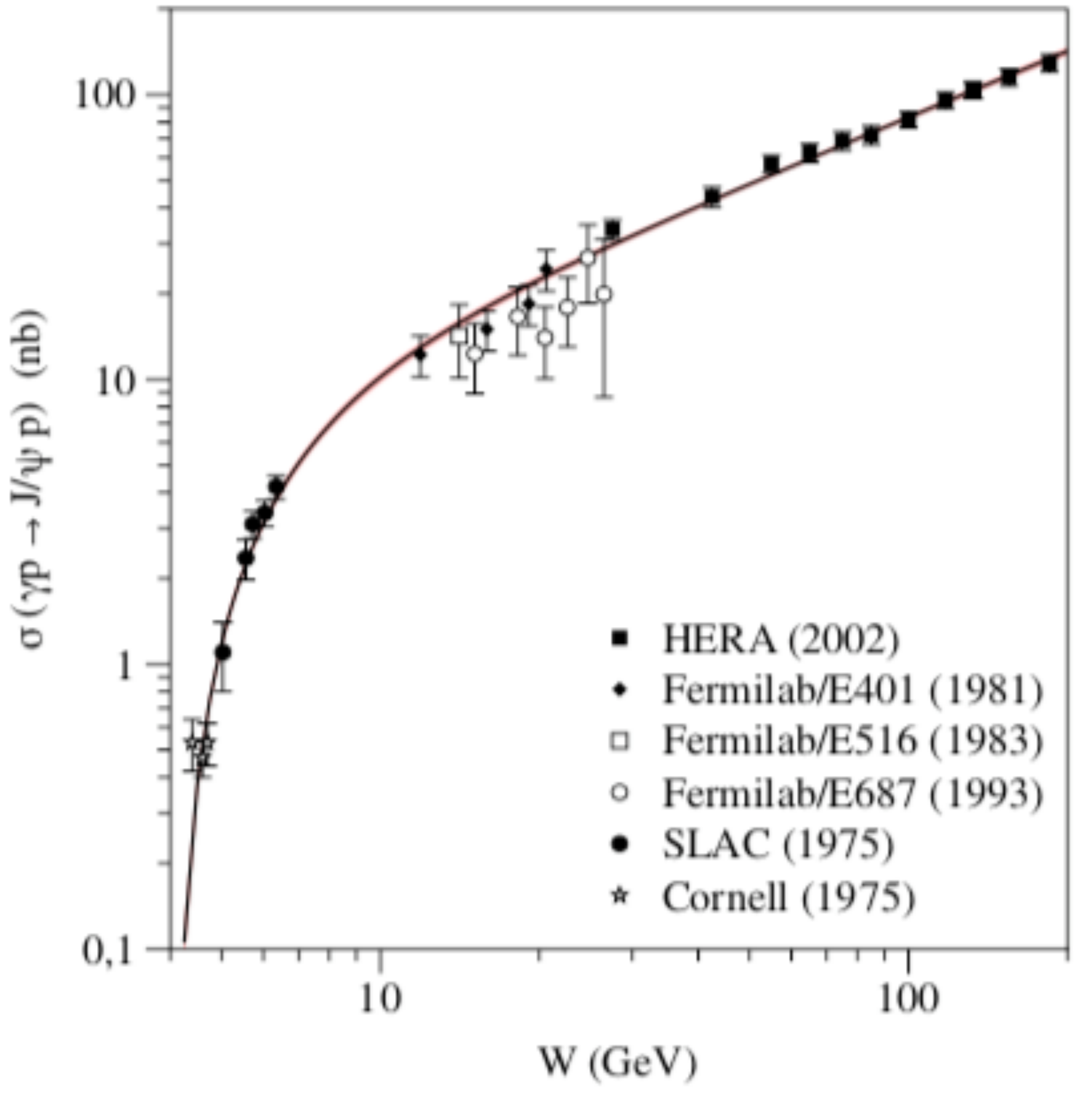
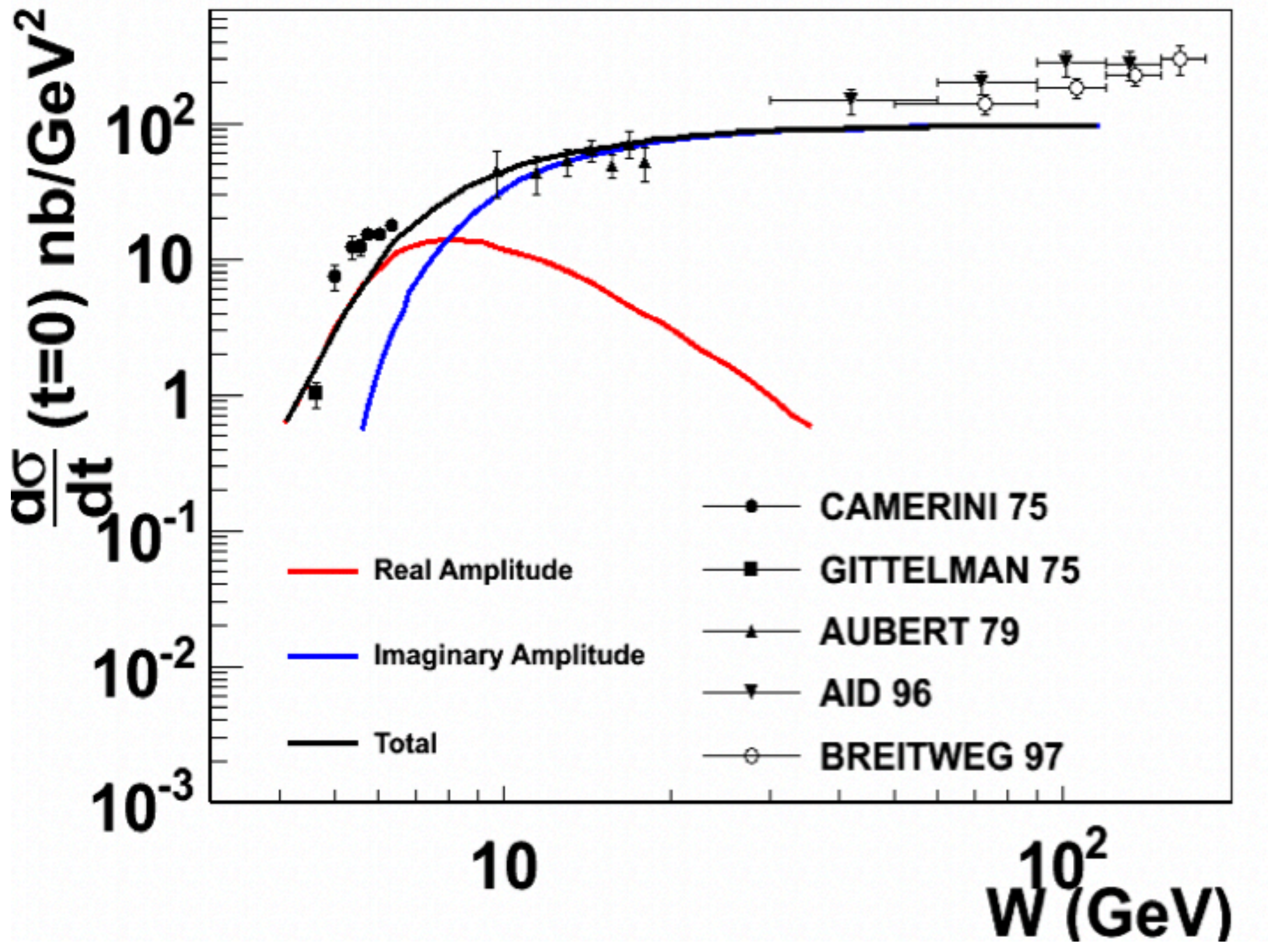
- Trace anomaly proportional to subtraction constant $\langle P \mid G^2 \mid P \rangle \sim T_{\psi p}(0)$

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





S. Joosten

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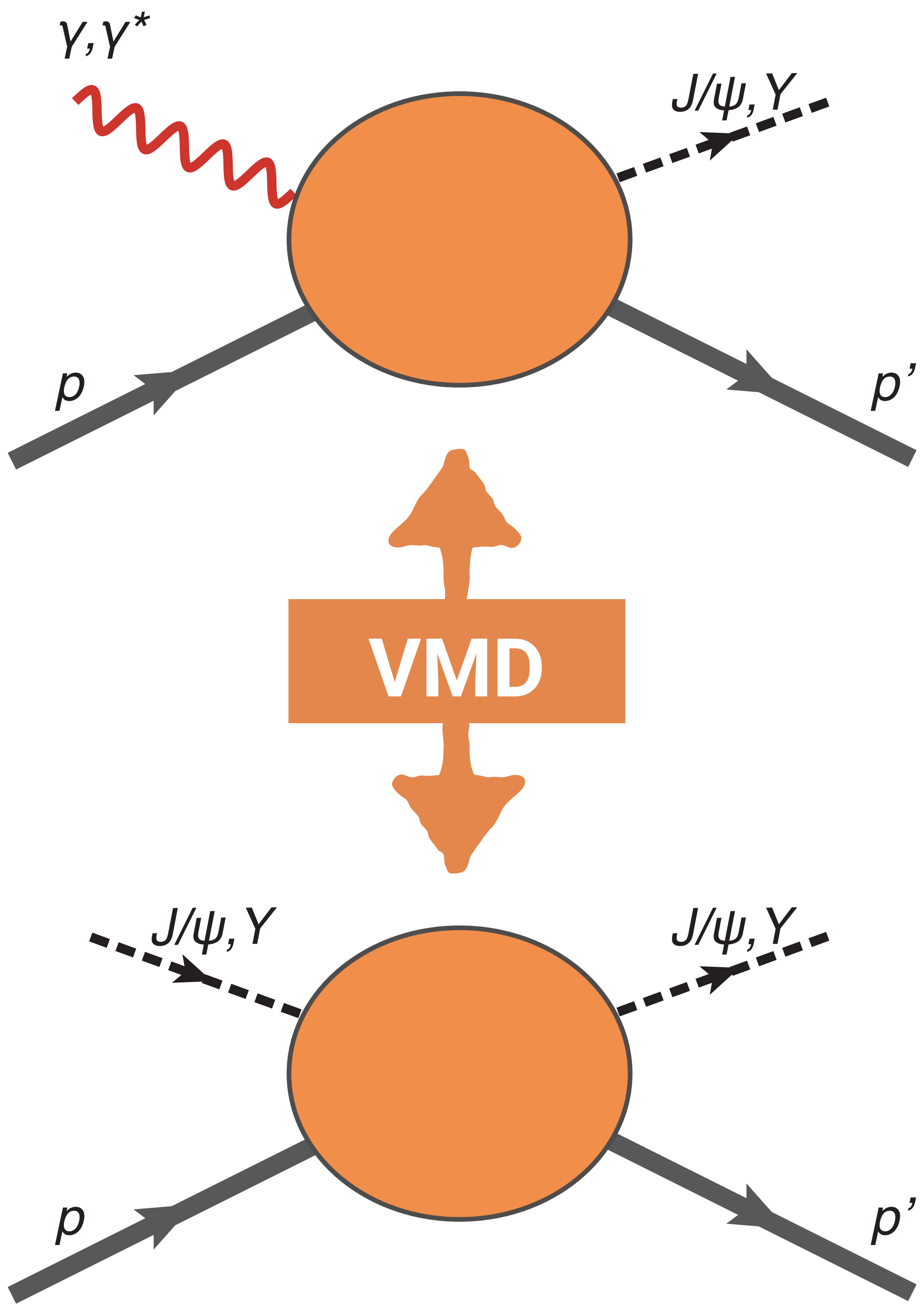

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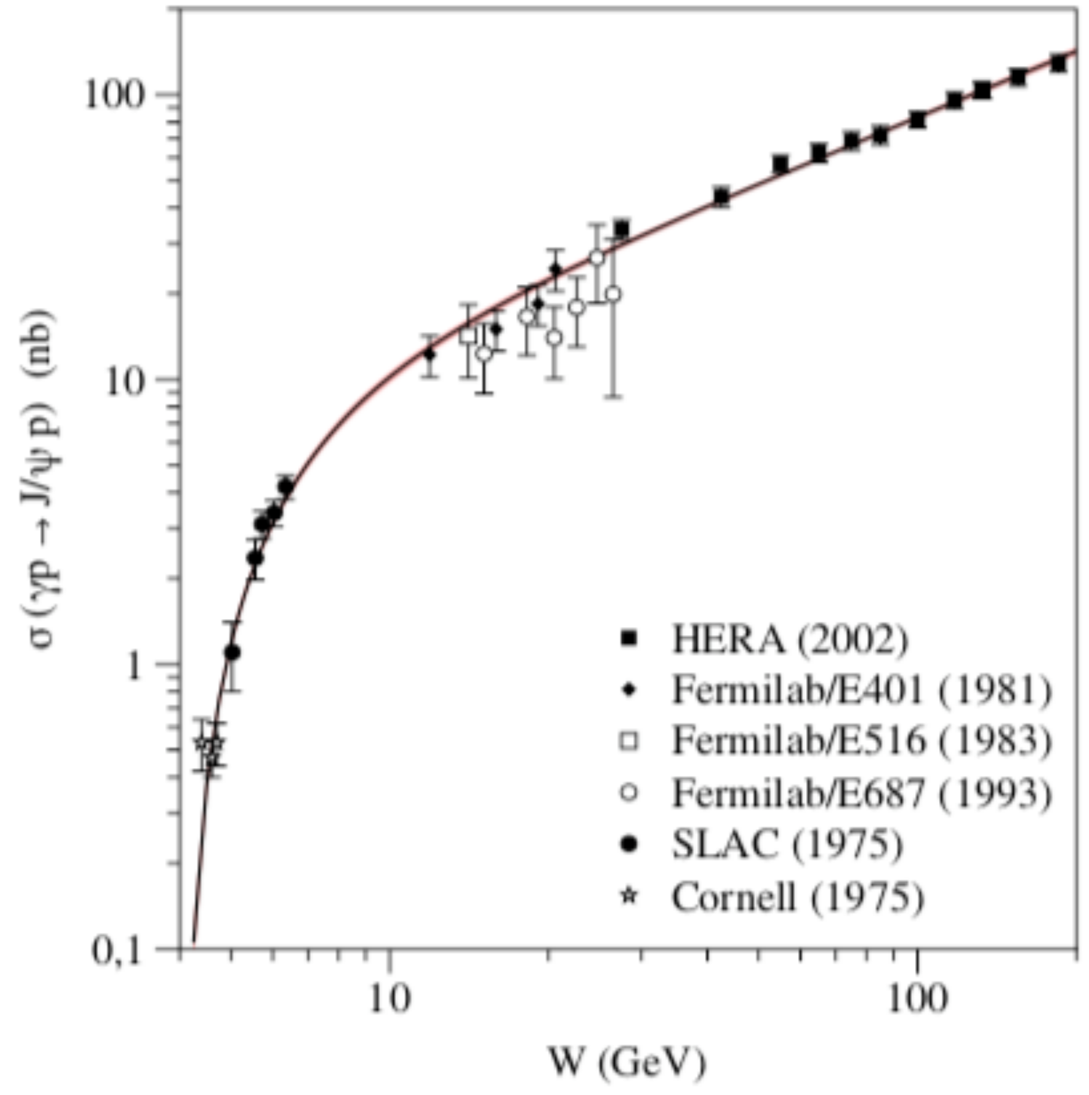
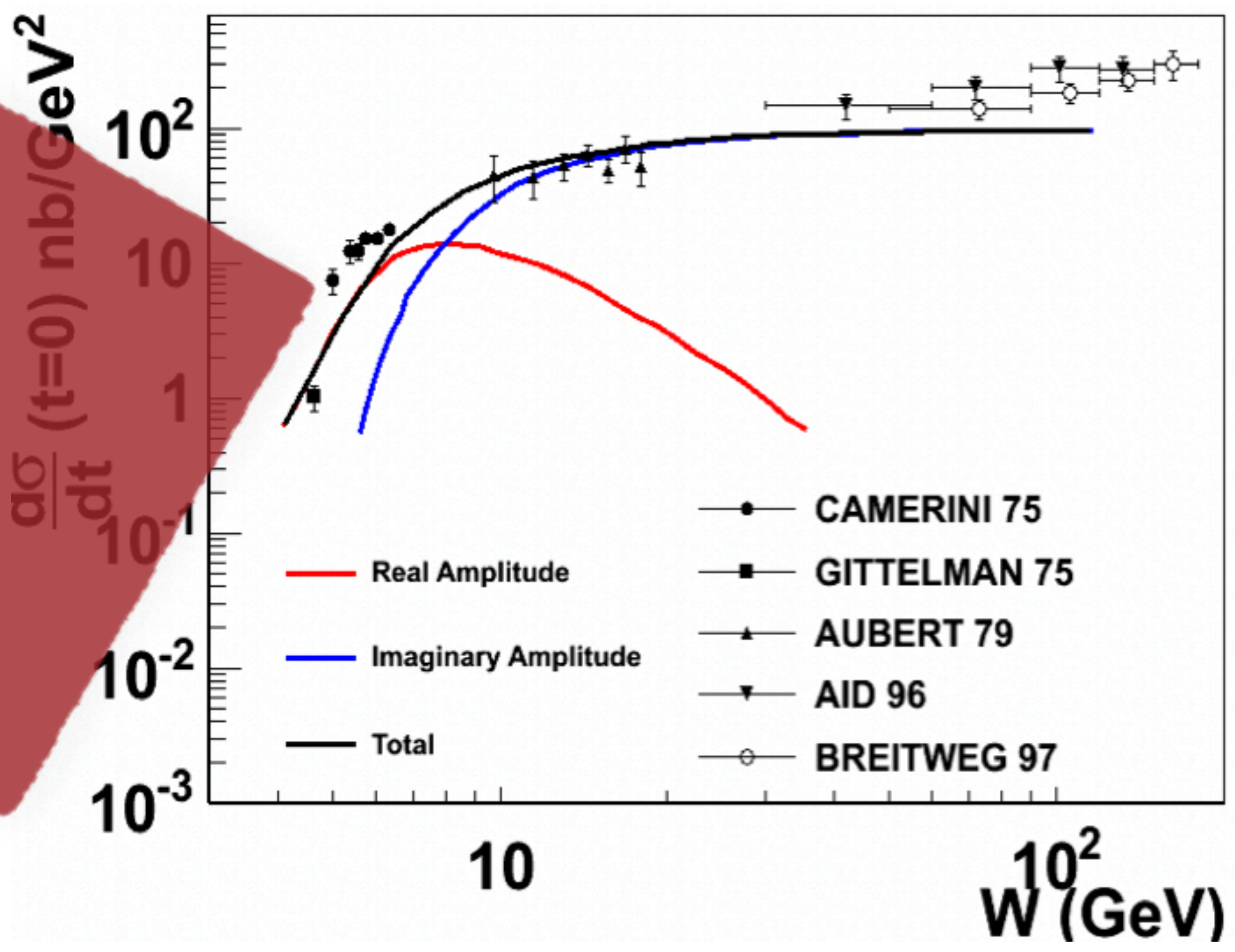
Experimental access to trace anomaly: *t*-dependence of quarkonium cross section *at* threshold

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





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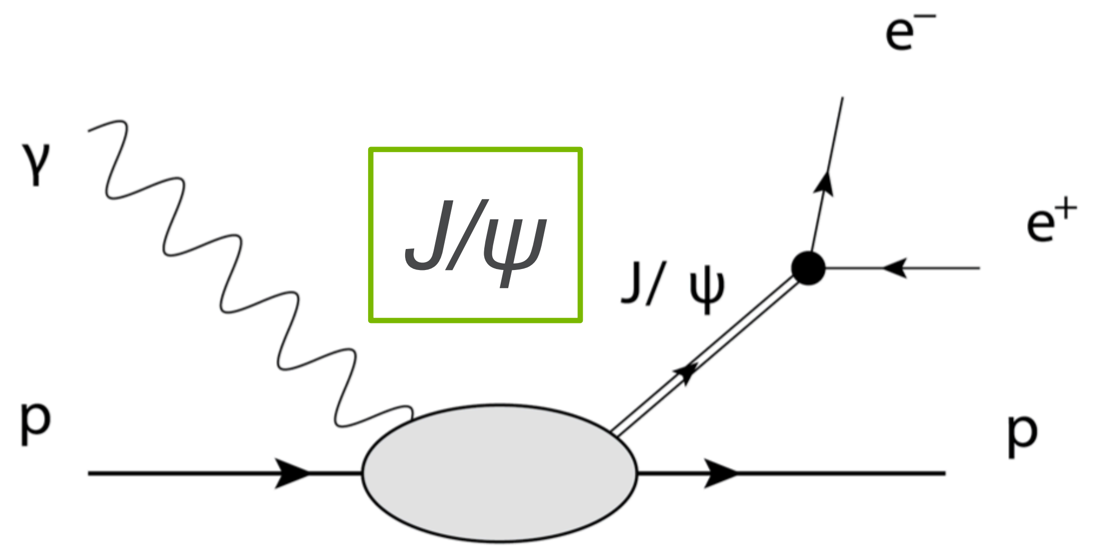
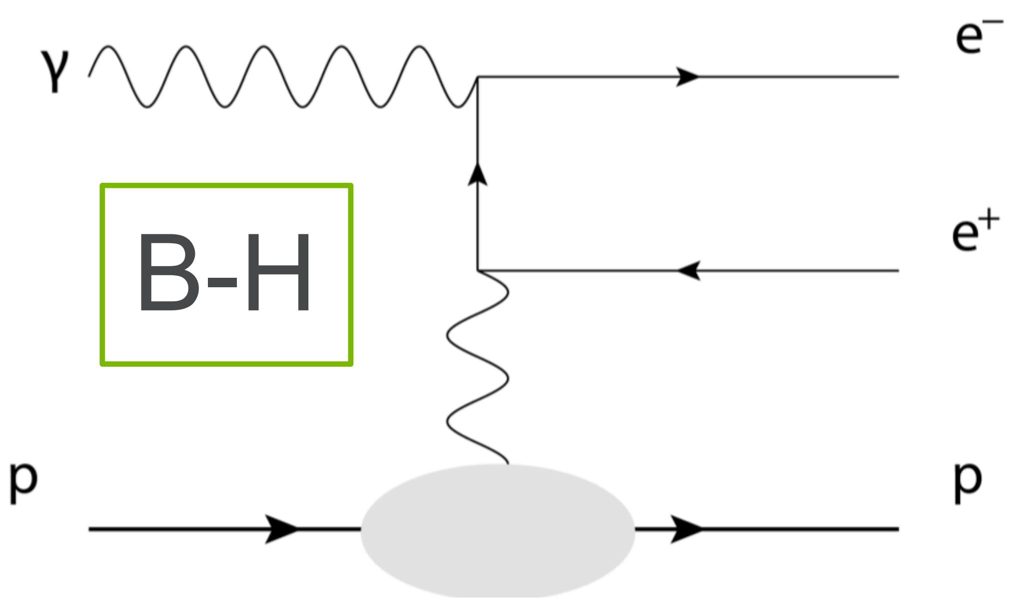
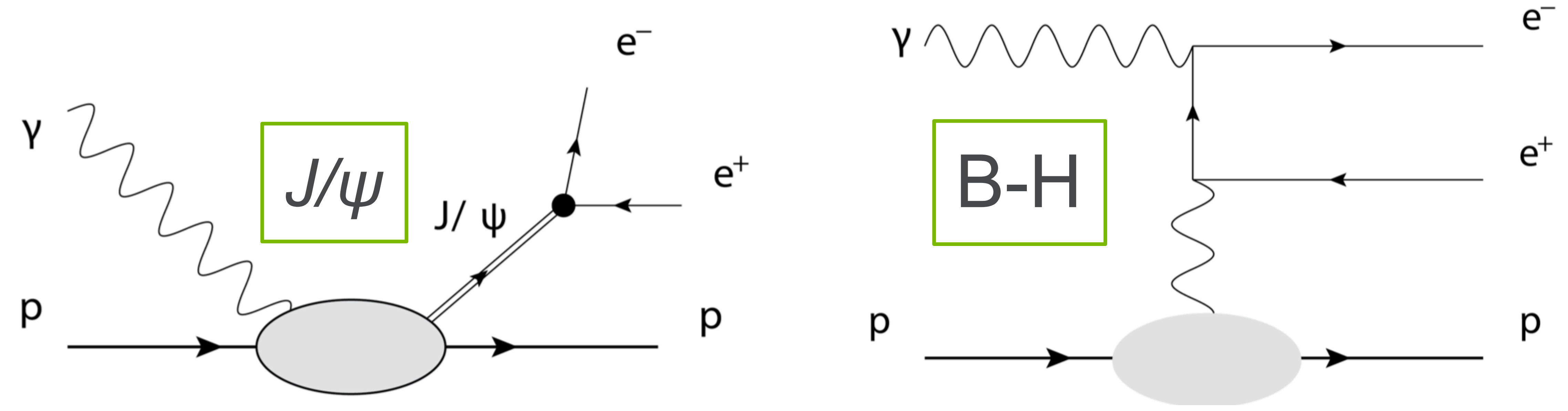




PRODUCTION MECHANISM NEAR THRESHOLD?

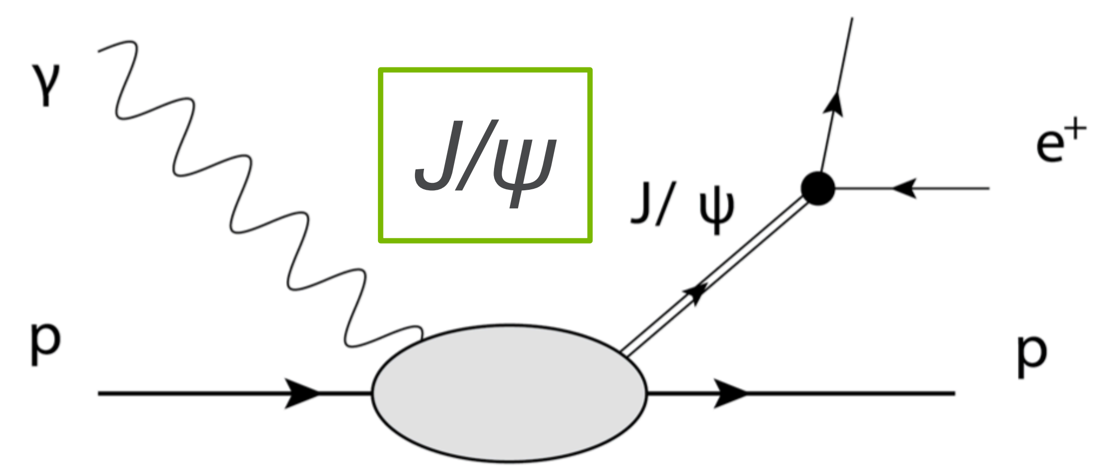
Vector meson dominance (dispersive framework)

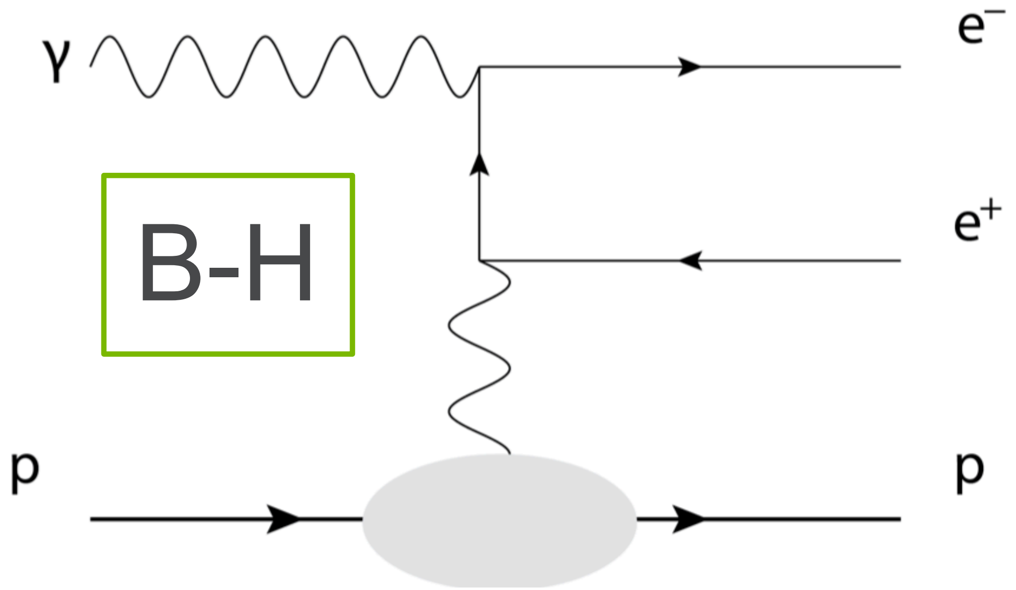


- Interference between elastic *J/ψ* production near threshold and Bethe-Heitler

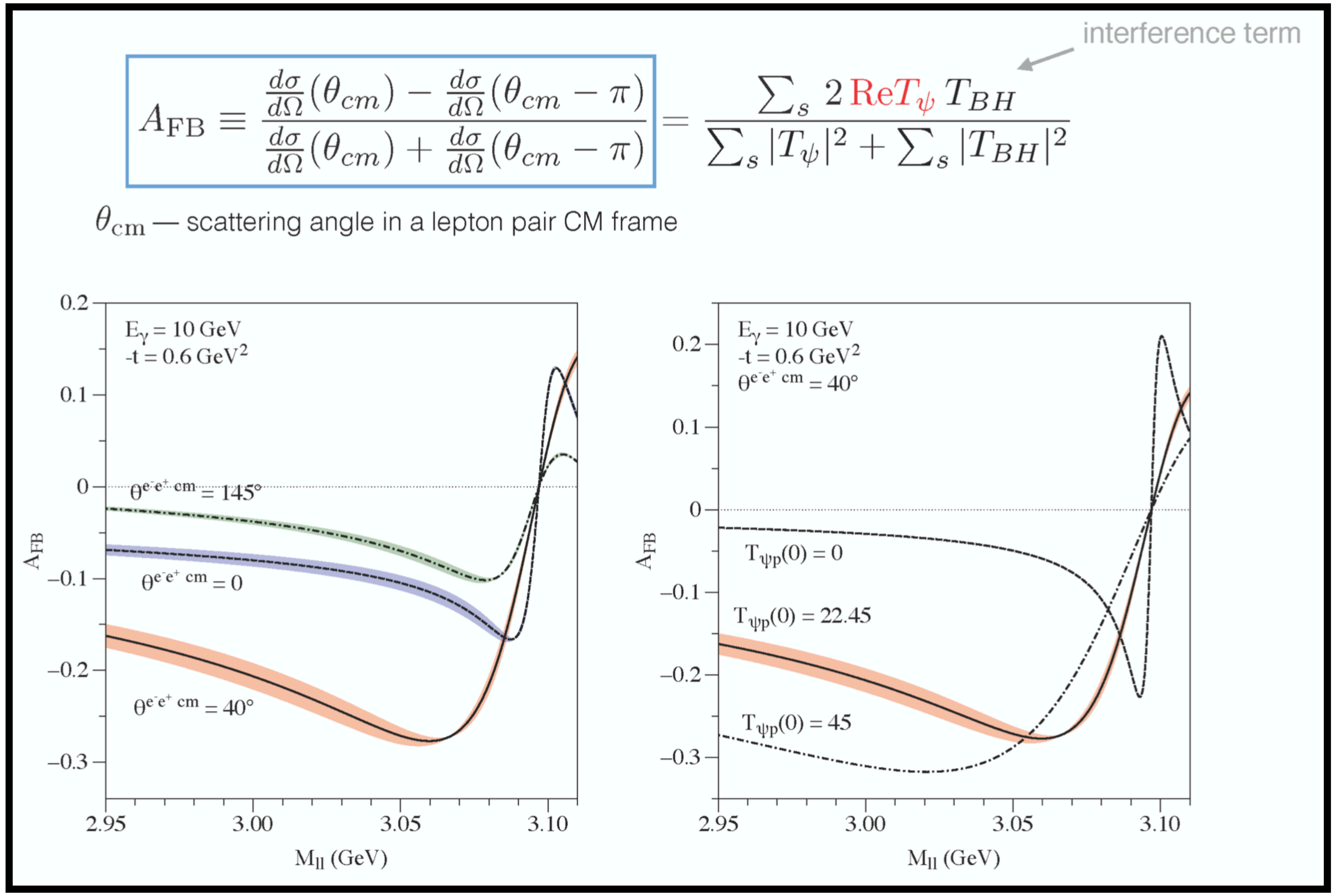
PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)





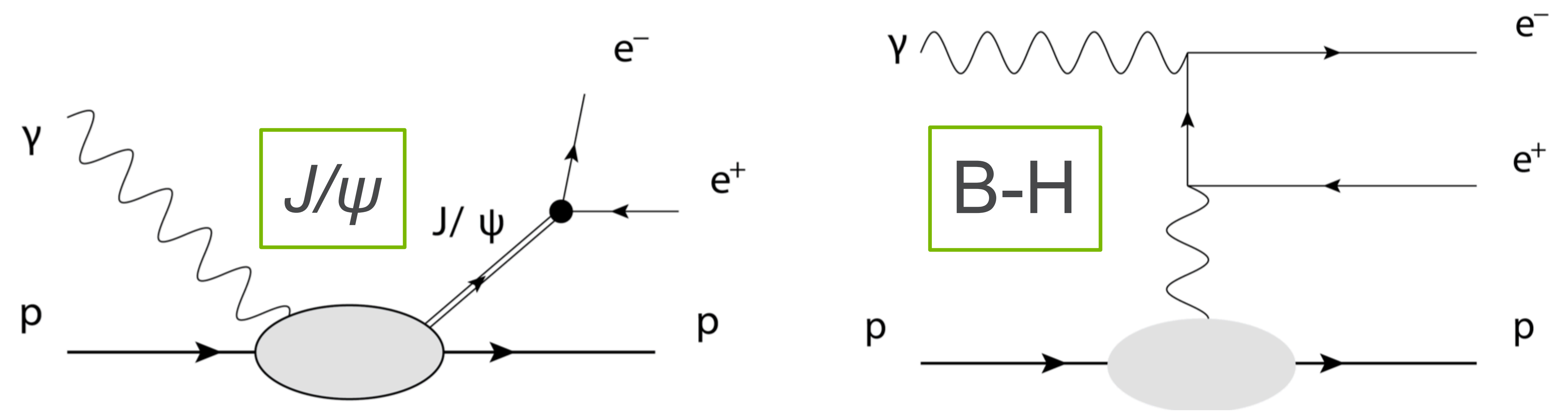
- Interference between elastic *J/ψ* production near threshold and Bethe-Heitler
- Forward-backward asymmetry near *J/ψ* invariant mass peak proportional to **Re(*$T_{\psi p}$*)**



Slide from O. Gryniuk

PRODUCTION MECHANISM NEAR THRESHOLD?

Vector meson dominance (dispersive framework)



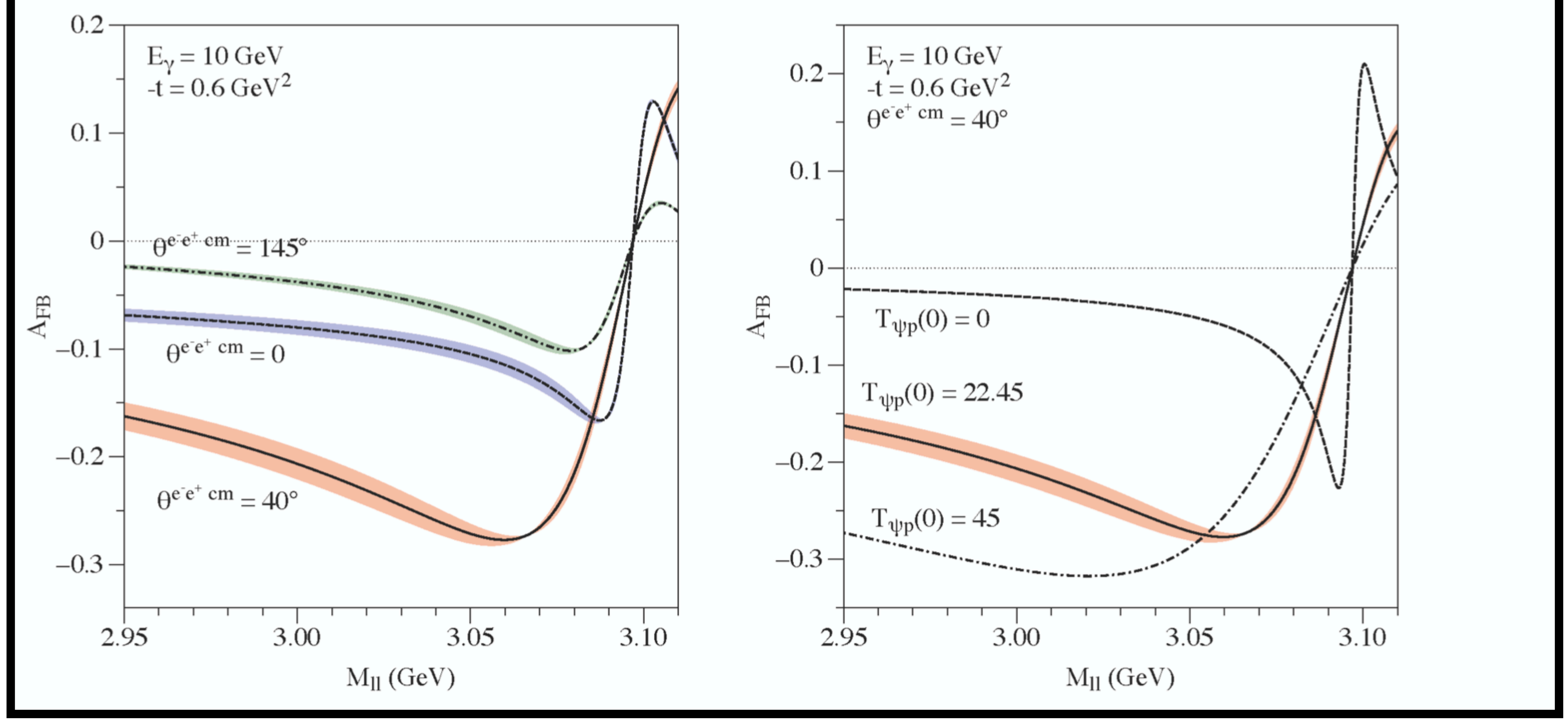
- Interference between elastic *J/ψ* production near threshold and Bethe-Heitler
- Forward-backward asymmetry near *J/ψ* invariant mass peak proportional to **Re($T_{\psi p}$)**

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

$$A_{FB} \equiv \frac{\frac{d\sigma}{d\Omega}(\theta_{cm}) - \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)}{\frac{d\sigma}{d\Omega}(\theta_{cm}) + \frac{d\sigma}{d\Omega}(\theta_{cm}-\pi)} = \frac{\sum_s 2\,\mathrm{Re}T_\psi\, T_{BH}}{\sum_s |T_\psi|^2 + \sum_s |T_{BH}|^2}$$

interference term

θ_{cm} — scattering angle in a lepton pair CM frame

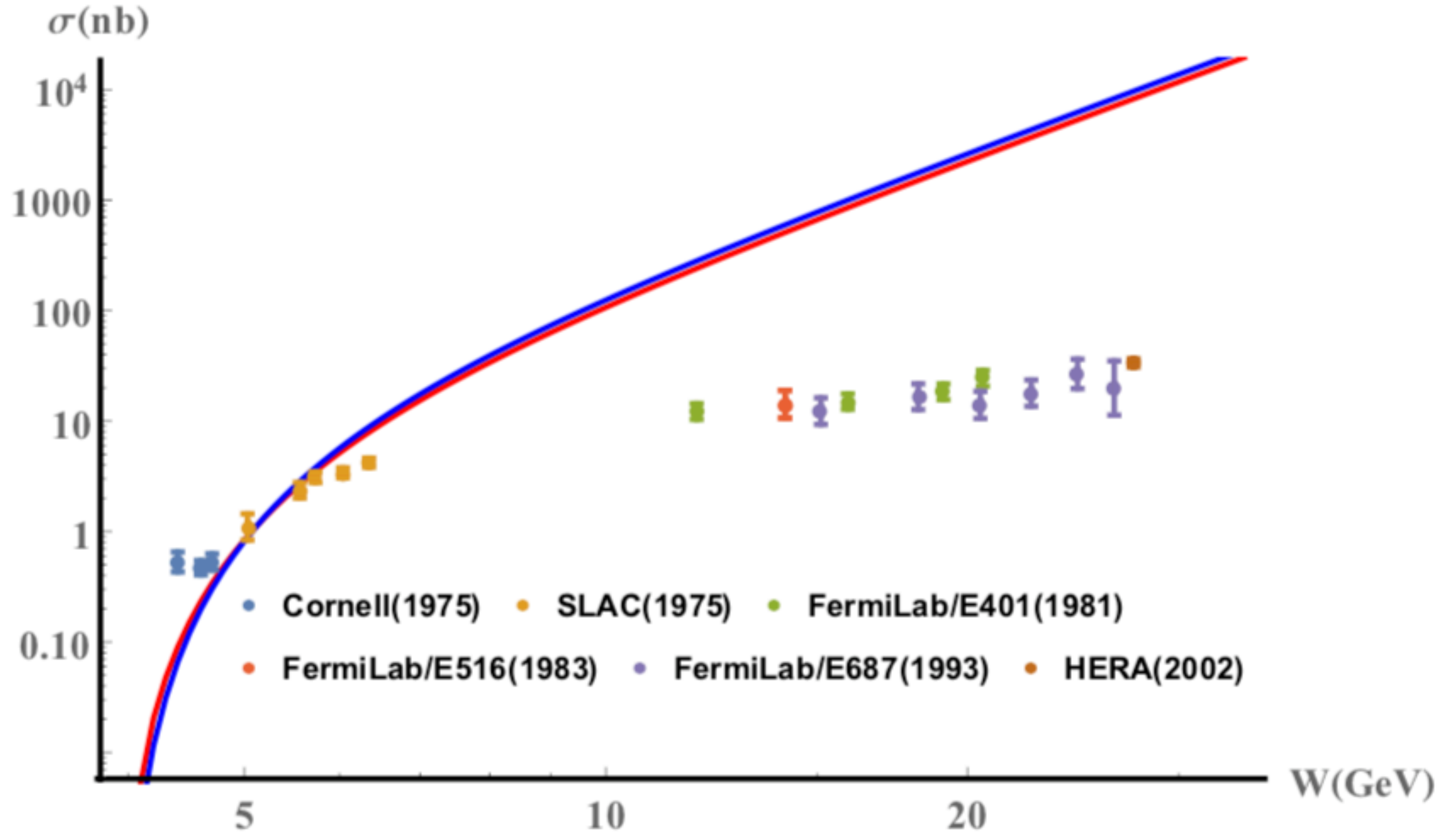


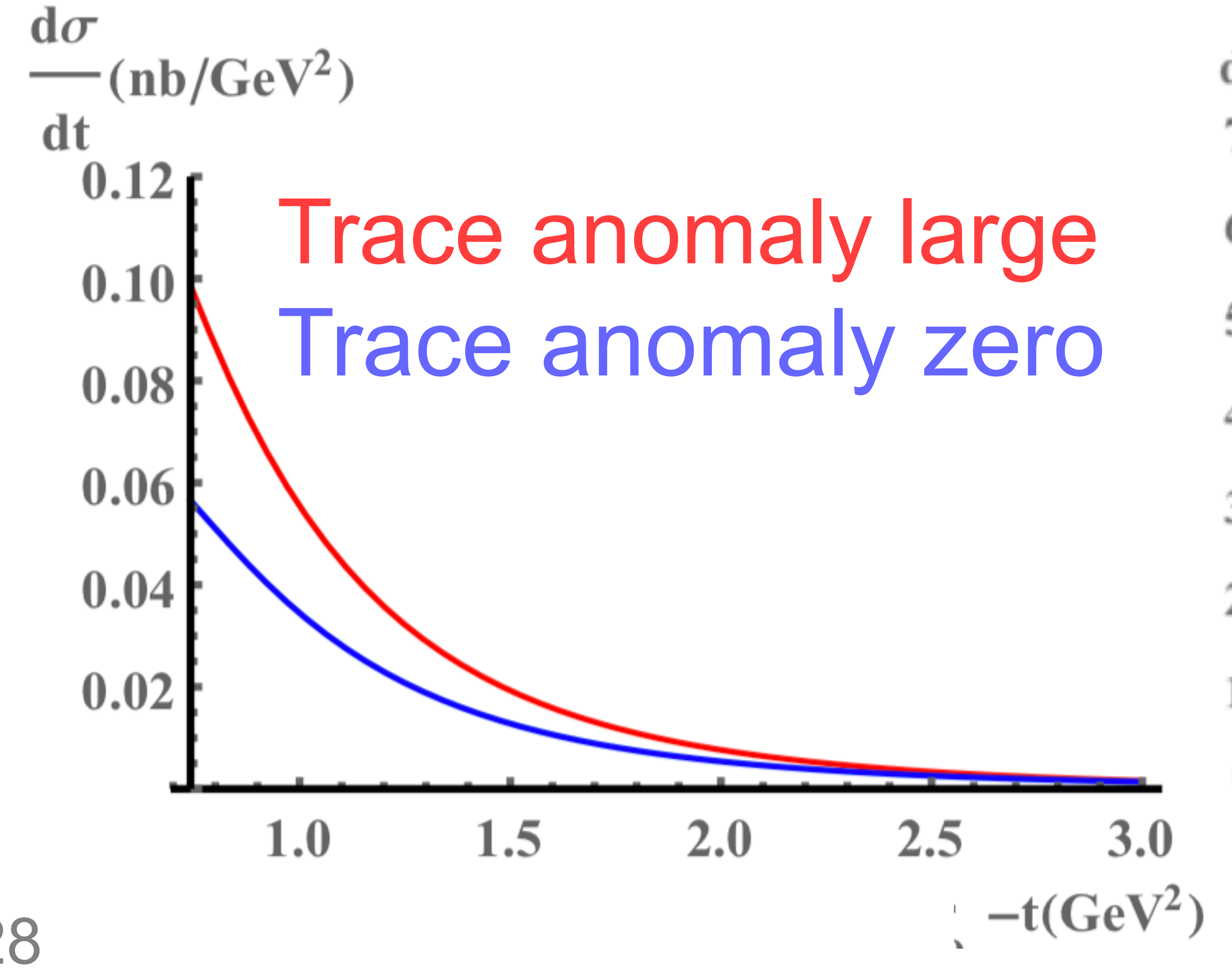
Slide from O. Gryniuk

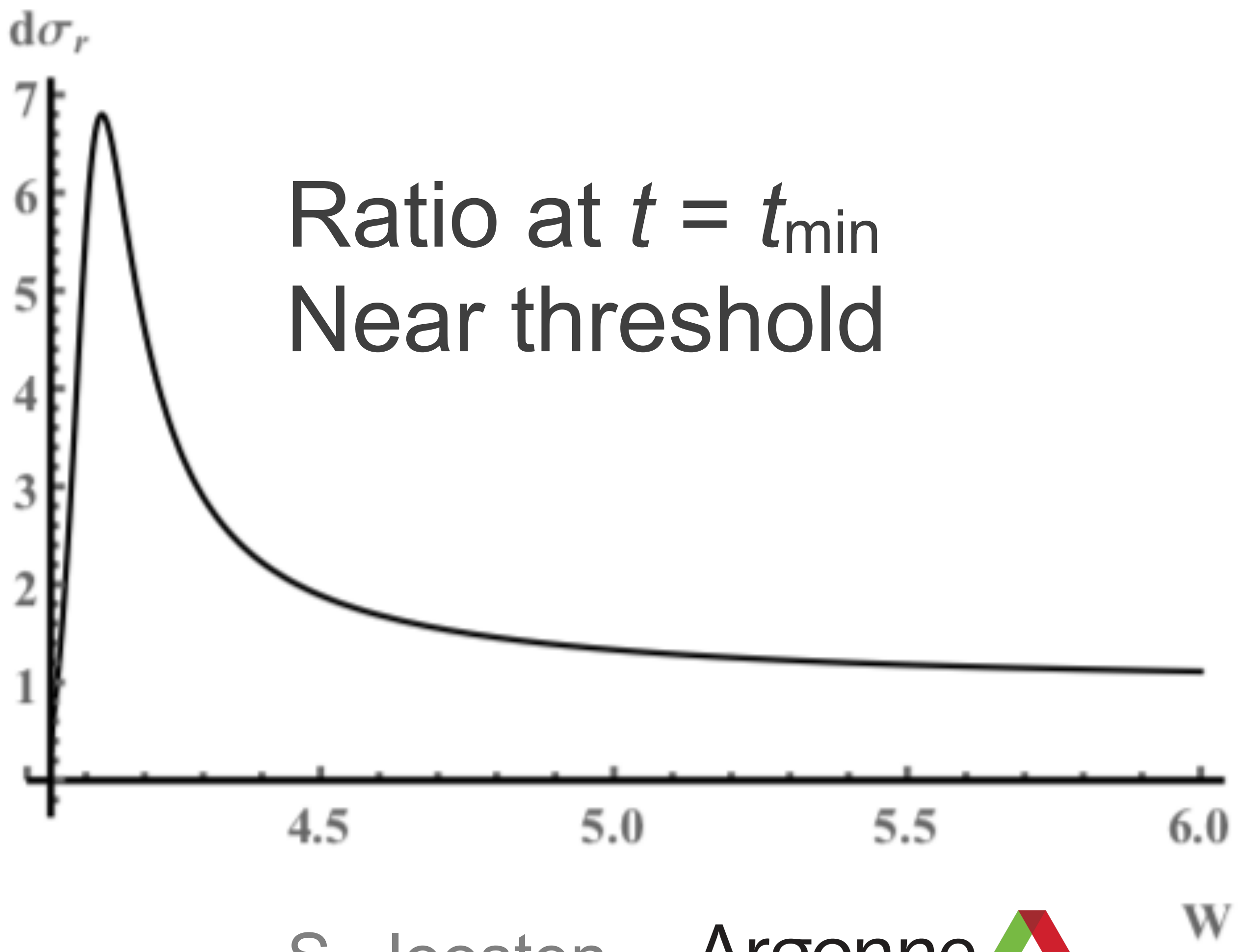
PRODUCTION MECHANISM NEAR THRESHOLD?

Holographic approach

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



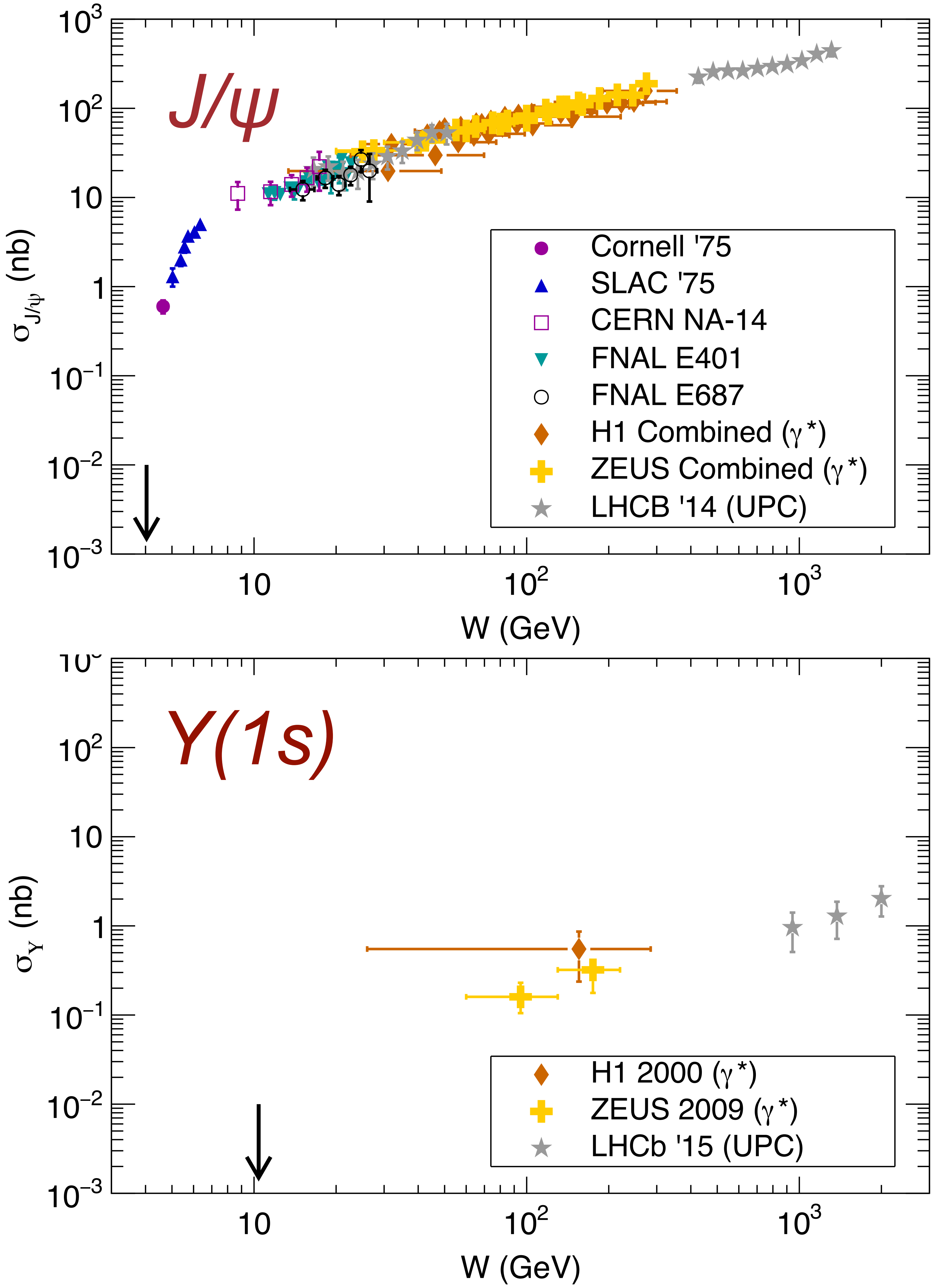




Υ(1S): THE OPTIMAL GLUONIC PROBE

…but a challenging measurement

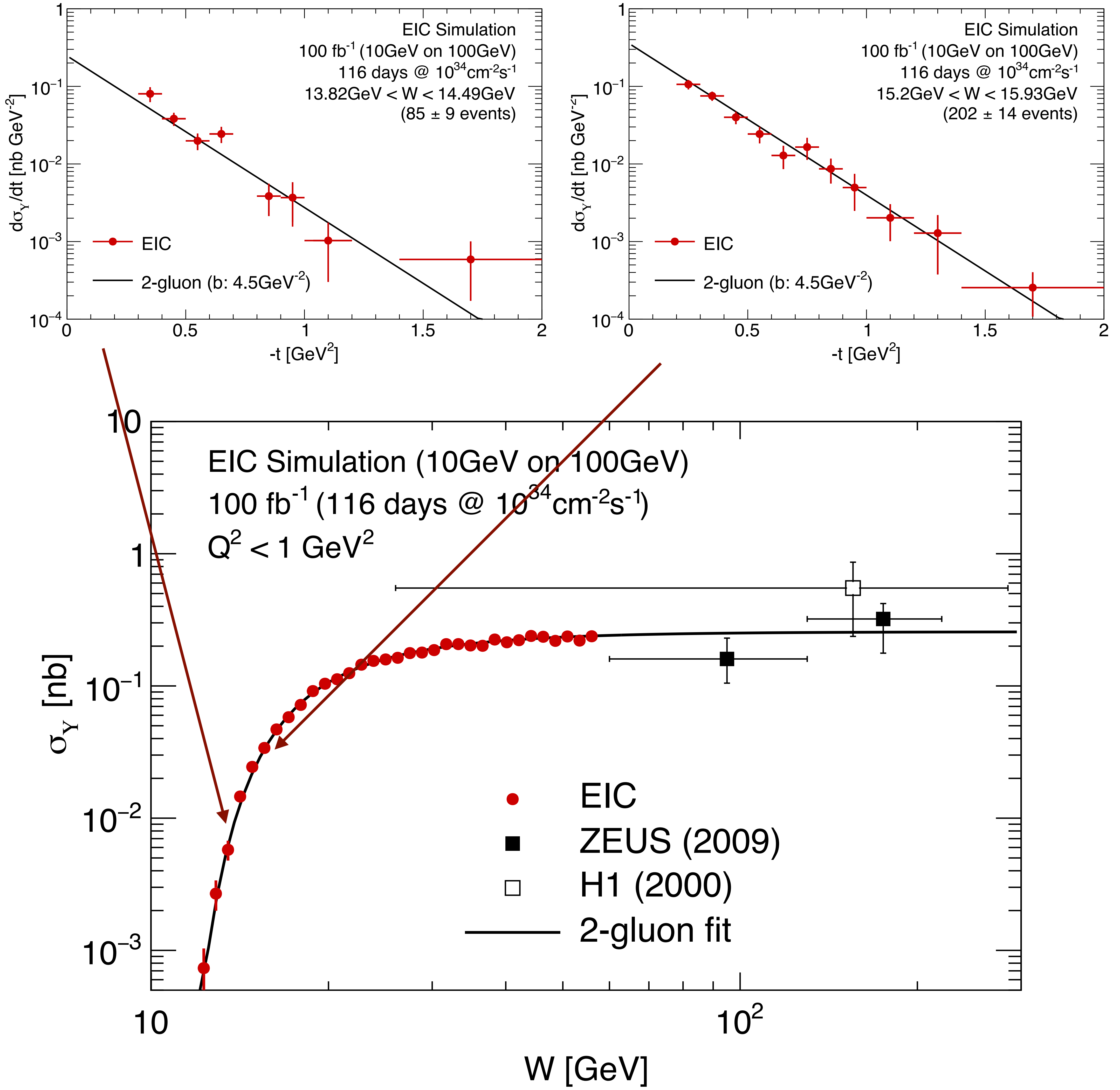
- *Υ(1S)* is a heavier (smaller) probe than *J/ψ*
  - *Υ(1S)* production near threshold crucial to **universality**
- Cross section very small (2 orders of magnitude smaller than *J/ψ)*
- If possible, measurement can (only) be done at EIC



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**



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