3rd Proton Mass Workshop: Origin and Perspective

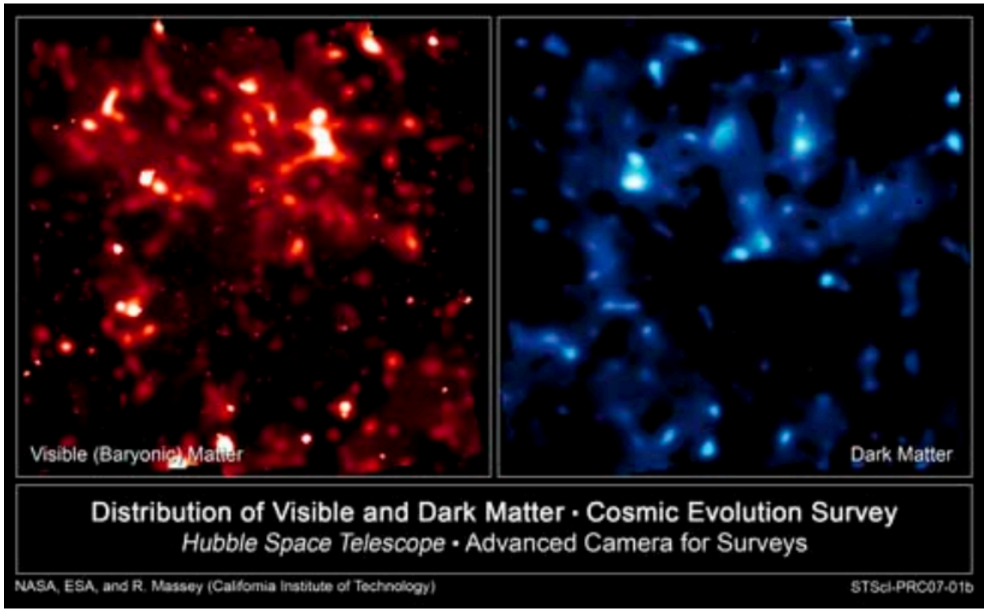
Argonne National Laboratory, January 14-16, 2021

J/ψ photoproduction near threshold and the proton mass distribution

D. Kharzeev

Supported by the Office of Science, US Department of Energy

Gravitational formfactors and the mass distribution



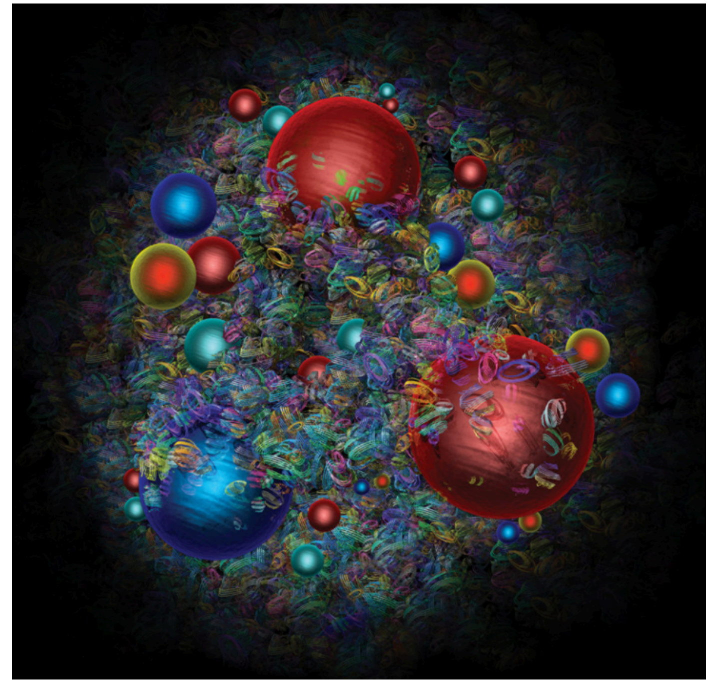


Image: CERN

What is the origin of the proton mass?

How is the mass distributed inside the proton?

Is it associated with quarks (“visible matter”) or with gluons (“dark matter”)?

How can we measure the mass distribution?

Outline

- Gravitational formfactors and the mass distribution
- Scale invariance and scale anomaly in QCD
- The origin of the proton mass
- Charmonium photoproduction near the threshold: measuring the mass distribution inside the proton

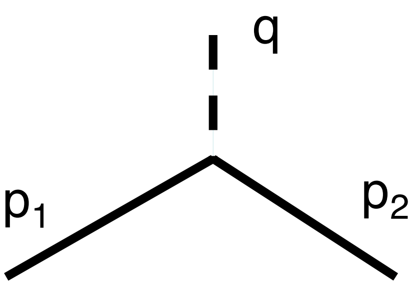
Gravitational formfactors and the mass distribution

The mass distribution is encoded in the gravitational formfactors.

For the spin ½ nucleon, 3 formfactors appear:

H. Pagels ‘66,
A. Pais, S. Epstein ‘49

$$\langle \mathbf{p}_1 | \theta_{\mu\nu} | \mathbf{p}_2 \rangle = \left(\frac{M^2}{p_{01}\ p_{02}} \right)^{1/2} \frac{1}{4M}\ \bar{u}(p_1, s_1) \Big[G_1(q^2)(p_\mu \gamma_\nu + p_\nu \gamma_\mu) +$$



$$+ G_2(q^2) \frac{p_\mu p_\nu}{M} + G_3(q^2) \frac{(q^2 g_{\mu\nu} - q_\mu q_\nu)}{M} \Big] u(p_2, s_2)$$

Energy-momentum conservation:

$$\partial^\mu \theta_{\mu\nu} = 0 \quad \Rightarrow \quad q^\mu \langle \mathbf{p}_1 | \theta_{\mu\nu} | \mathbf{p}_2 \rangle = 0;$$

Satisfied for on-shell nucleons (use Dirac equation)

$$p_1^2 = p_2^2 = M^2$$

Gravitational formfactors and the mass distribution

For the spin ½ nucleon, 3 formfactors appear: (no G_1 for spin 0)

$$\langle \mathbf{p}_1 | \theta_{\mu\nu} | \mathbf{p}_2 \rangle = \left(\frac{M^2}{p_{01}\ p_{02}} \right)^{1/2} \frac{1}{4M}\ \bar{u}(p_1, s_1) \left[G_1(q^2)(p_\mu \gamma_\nu + p_\nu \gamma_\mu) + \right.$$

$$\left. + G_2(q^2) \frac{p_\mu p_\nu}{M} + G_3(q^2) \frac{(q^2 g_{\mu\nu} - q_\mu q_\nu)}{M} \right] u(p_2, s_2)$$

Compare to
the macroscopic energy-momentum
tensor in relativistic hydrodynamics:

C. Eckart, 1940

The Thermodynamics of Irreversible Processes

III. Relativistic Theory of the Simple Fluid

CARL ECKART
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois

(Received September 26, 1940)

u_ν - matter velocity

$$\theta_{\mu\nu} = \underbrace{(w_\mu u_\nu + w_\nu u_\mu)}_{\text{Heat flow}} + \underbrace{w\ u_\mu u_\nu}_{\text{Energy density}} + \underbrace{w_{\mu\nu}}_{\text{Stress tensor}}$$

$$u_\mu\ w^\mu = 0 \qquad\qquad w \sim \epsilon$$

Gravitational formfactors and the mass distribution

For the spin ½ nucleon, 3 formfactors appear: (no G_1 for spin 0)

$$\langle \mathbf{p}_1|\theta_{\mu\nu}|\mathbf{p}_2\rangle = \left(\frac{M^2}{p_{01}\ p_{02}}\right)^{1/2} \frac{1}{4M}\ \bar{u}(p_1,s_1)\big[G_1(q^2)(p_\mu\gamma_\nu + p_\nu\gamma_\mu) + G_2(q^2)\frac{p_\mu p_\nu}{M} + G_3(q^2)\frac{(q^2 g_{\mu\nu} - q_\mu q_\nu)}{M}\big]u(p_2,s_2)$$

Zero momentum transfer $q \to 0$:

$$\langle \mathbf{p}|\theta_{\mu\nu}|\mathbf{p}\rangle = \left(\frac{M^2}{p_0^2}\right)^{1/2}\ \bar{u}(p,s)u(p,s)\ \frac{p_\mu p_\nu}{M^2}\,[G_1(0) + G_2(0)]$$

(no “stress” G_3)

In the rest frame of the nucleon:

the Hamiltonian

$$\langle \mathbf{p}=0|\theta_{00}|\mathbf{p}=0\rangle = M$$

$$\Downarrow$$

$$H = \int d^3x\,\theta_{00}(x)$$

$$G_1(0) + G_2(0) = M.$$

Formfactor of the trace of the energy-momentum tensor

Let us call it "scalar gravitational formfactor", as it would be a gravitational formfactor in a scalar model of gravity:

Nordstrom 1912
Einstein 1913

$$\theta \equiv \theta^\mu_\mu$$

$$\langle \mathbf{p}_1|\theta|\mathbf{p}_2\rangle = \left(\frac{M^2}{p_{01}\ p_{02}}\right)^{1/2} \bar{u}(p_1, s_1)u(p_2, s_2)\ G(q^2)$$

Scalar gravitational formfactor:

$$G(q^2) = G_1(q^2) + G_2(q^2)\left(1 - \frac{q^2}{4M^2}\right) + G_3(q^2)\frac{3q^2}{4M^2}$$

In the rest frame of the nucleon:

$$\langle \mathbf{p}=0|\theta|\mathbf{p}=0\rangle = \langle \mathbf{p}=0|\theta_{00}|\mathbf{p}=0\rangle = M$$

$$\Downarrow$$

$$G(0) = M$$

How to define the mass distribution in the nucleon?

At small momentum transfer $|q^2| \ll M^2$,

the formfactor of θ_{00} and the scalar gravitational formfactor coincide,

thus the scalar gravitational formfactor can be used to extract the mass

distribution at distances $r \gg \frac{1}{M} \simeq 0.2 \text{ fm}$; usual definition:

$$\langle R_s^2 \rangle = 6 \frac{dG}{dt} \Big|_{t=0}$$

In the relativistic region (mass -> energy), it is natural to consider the scalar gravitational formfactor, as θ is the Lorentz scalar

The trace of the energy-momentum tensor also plays a special role –

it is a generator of dilatations. Its formfactor thus carries information

about the Renormalization Group (RG) evolution inside the nucleon.

Scale invariance

Scale transformations (dilatations) are defined by

$$x \to e^{\lambda}\ x$$

the corresponding dilatational current is

$$s^{\mu} = x_{\nu}\ \theta^{\mu\nu}$$

Hermann Weyl
(1885-1955)

It is conserved
(a theory is scale-invariant)
if the energy-momentum is traceless:

$$\partial_{\mu} s^{\mu} = \theta^{\mu}_{\mu}$$

Scale invariance

A scale-invariant theory cannot contain massive particles, all particles must be massless

For example, in Maxwell electrodynamics with action

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

the energy-momentum is traceless: $\theta^{\mu}_{\mu} = 0$
(massless photons)

Note: because of this, in scalar gravity (e.g. Einstein, 1913) there would be no light bending by massive bodies!

Scale invariance and matrix element of θ

In a macroscopic theory,

energy density   pressure

$$\bar{\theta} \equiv \langle \mathrm{matter}|\theta|\mathrm{matter}\rangle = \epsilon - 3p$$

Ideal massless gas: $\epsilon = 3p$

$\bar{\theta} \neq 0$ - interaction measure, deviation from "conformality"

Usually, one expects $\bar{\theta} \geq 0$ See e.g. Landau, Lifshitz, v. 2, sect. IV

Can $\bar{\theta}$ be negative? Yes! May happen in the interior of neutron stars

Zel'dovich 1961

e.g. D.Podkowka et al arXiv:1807.01565

THE EQUATION OF STATE AT ULTRAHIGH DENSITIES AND ITS RELATIVISTIC LIMITATIONS

Ya. B. ZEL'DOVICH

Submitted to JETP editor May 31, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) 41, 1609-1615 (November, 1961)

Can this happen in some region inside the proton?

Scale invariance in QCD

The trace of the energy-momentum tensor in QCD (computed in classical field theory) is

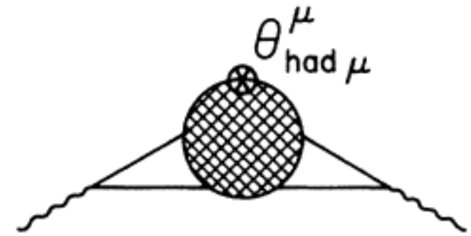
$$\Theta^\alpha_\alpha = \sum_{l=u,d,s} m_l \; \bar{q}_l q_l + \sum_{h=c,b,t} m_h \; \bar{q}_h q_h$$

Two problems:

1. Potentially large contribution from heavy quarks to the masses of light hadrons

2. If we forget about heavy quarks, all hadron masses must be equal to zero in the chiral limit

Scale anomaly in QCD



The quantum effects (loop diagrams) modify the expression for the trace of the energy-momentum tensor:

$$\Theta^{\alpha}_{\alpha} = \frac{\beta(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l (1+\gamma_{m_l}) \bar{q}_l q_l + \sum_{h=c,b,t} m_h (1+\gamma_{m_h}) \bar{Q}_h Q_h,$$

Running coupling -> dimensional transmutation -> mass scale

Gross, Wilczek; Politzer

$$\beta(g) = -b \frac{g^3}{16\pi^2} + \ldots, \;\; b = 9 - \frac{2}{3} n_h,$$

Ellis, Chanowitz; Crewther; Collins, Duncan, Joglecar; …

At small momentum transfer, heavy quarks decouple:

$$\sum_h m_h \bar{Q}_h Q_h \to -\frac{2}{3}\, n_h \, \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \ldots$$

so only light quarks enter the final expression

Shifman, Vainshtein Zakharov ’78

$$\Theta^{\alpha}_{\alpha} = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l,$$

The proton mass

At zero momentum transfer, the matrix element of the trace of the energy-momentum tensor defines the mass of the proton:

$$\langle \mathbf{p} = 0 | \theta | \mathbf{p} = 0 \rangle = \langle \mathbf{p} = 0 | \theta_{00} | \mathbf{p} = 0 \rangle = M$$

$$\Theta^{\alpha}_{\alpha} = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l ,$$

In the chiral limit, the entire mass is from gluons!

The proton mass

At finite quark mass, contribution from "sigma-terms"

$$\Sigma_{\pi N} = \hat{m}\langle p|\bar{u}u + \bar{d}d|p\rangle$$

can be extracted from pion-nucleon scattering or measured on the lattice

e.g. Y.-B.Yang et al arXiv:1511.09089

Sometimes interpreted as either

1. Contribution from quark masses

or

2. Contribution from chiral symmetry breaking

But the interpretation is more subtle

The proton mass

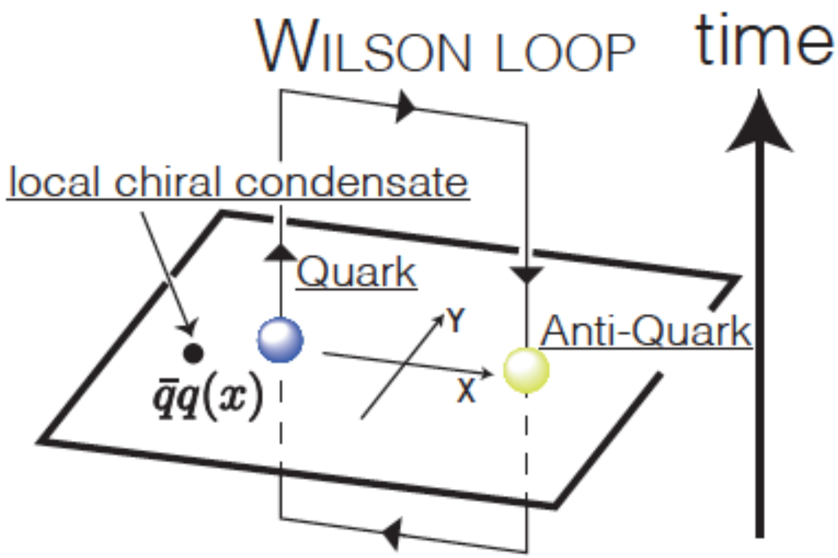
The matrix elements over a hadron state have to be understood as the **difference** of the value of the measured quantity in the hadron and in the vacuum, e.g.

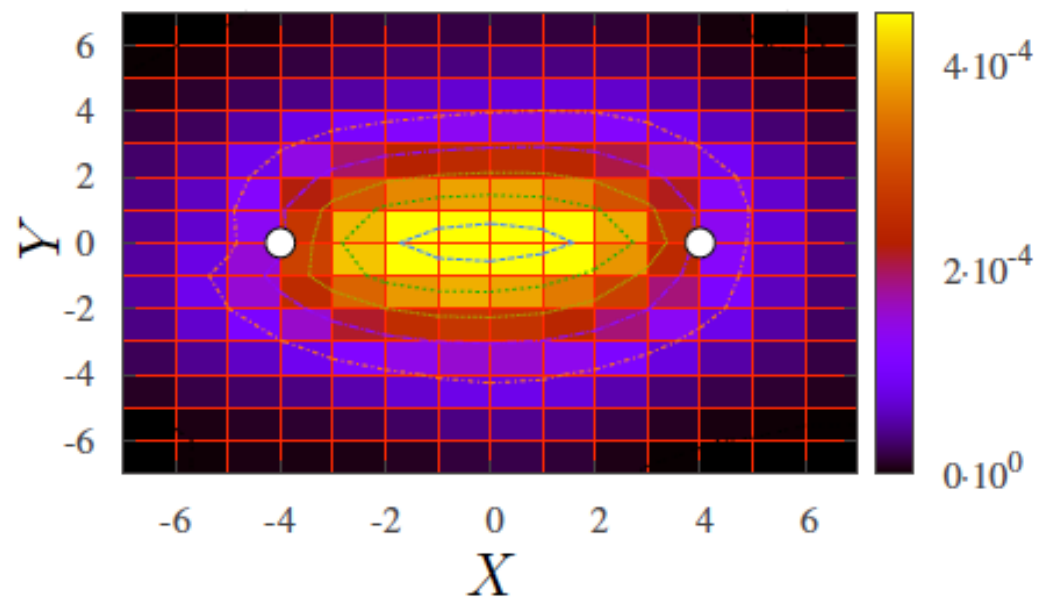
$$\langle P|\bar{q}q|P\rangle = \langle P|\int d^3x\ \bar{q}(x)q(x)|P\rangle - \langle 0|\bar{q}q|0\rangle V_P$$

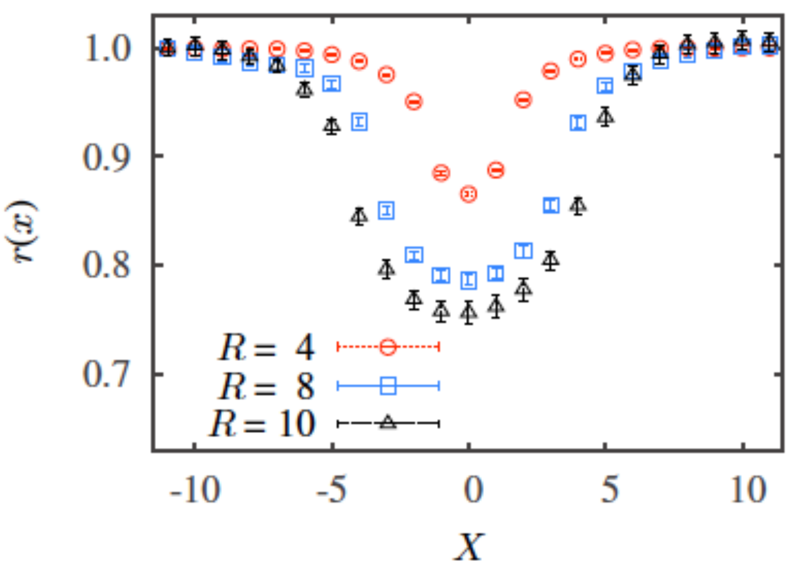
This difference results from the partial **restoration** of spontaneously broken chiral symmetry inside the hadron

e.g., Donoghue, Nappi ‘86

Partial restoration of chiral symmetry inside the nucleon



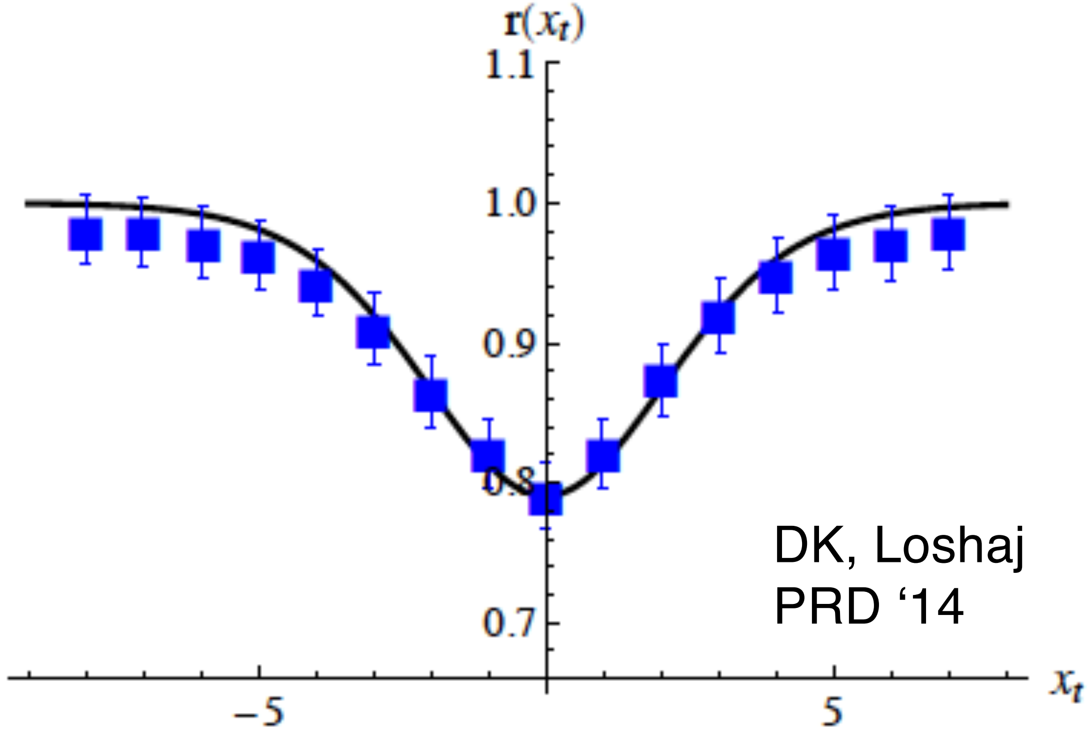




Significant suppression of the local quark condensate by the confining flux tube!

Iritani, Cossu, Hashimoto
arXiv:1502.04845 PRD[17]

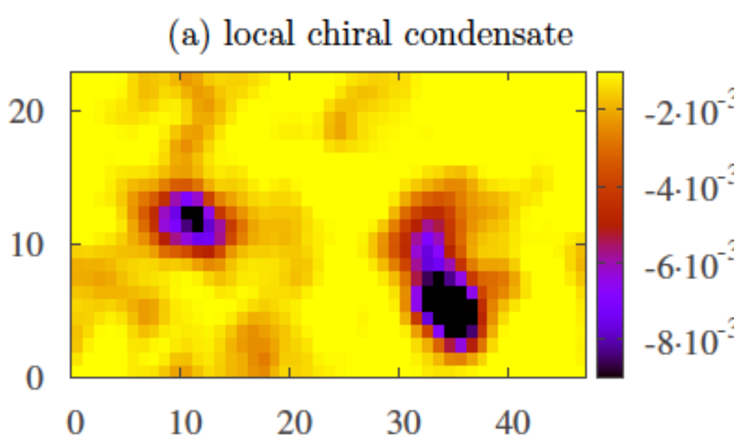
Partial restoration of chiral symmetry inside the nucleon

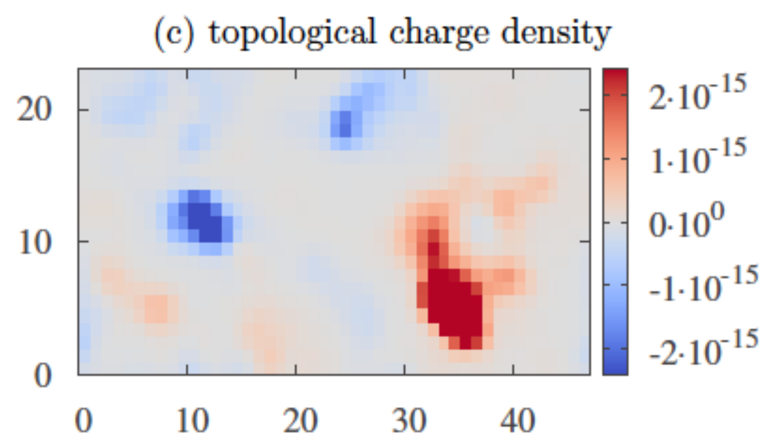


DK, Loshaj
PRD '14

A possible mechanism of chiral condensate suppression involves the chiral anomaly –

so the entire mass of the proton might originate from anomalies – scale and chiral !



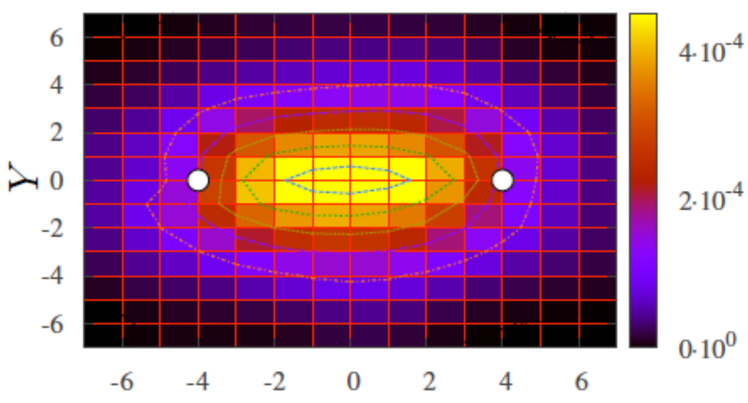


The proton mass as a result of the vacuum polarization induced by the presence of the proton

$$\Theta^{\alpha}_{\alpha} = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G^{a}_{\alpha\beta} + \sum_{l=u,d,s} m_l \bar{q}_l q_l ,$$

Polarization of the gluon field;

~ 90% of the proton's mass ?



Polarization of the quark condensate;

numerically, ~ 80 MeV using

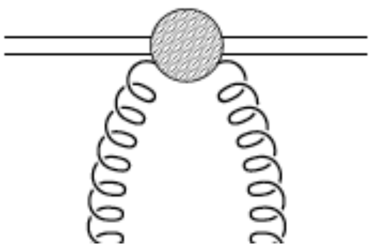
Y.-B.Yang et al
arXiv:1511.09089

How to measure the mass distribution inside the proton?

No dilatons available…
next best thing: a heavy quarkonium

QCD multipole expansion:

Voloshin '78; Appelquist, Fischler '78; Gottfried '78;
Peskin '79; Novikov, Shifman '81; Leutwyler '81, …



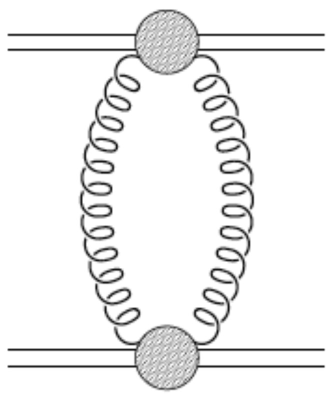
M.B. Voloshin
1953-2020

$$g^2\mathbf{E}^{a2} = \frac{g^2}{2}(\mathbf{E}^{a2} - \mathbf{B}^{a2}) + \frac{g^2}{2}(\mathbf{E}^{a2} + \mathbf{B}^{a2})$$

$$= -\frac{1}{4}g^2 G^a_{\alpha\beta}G^{a\alpha\beta} + g^2(-G^a_{0\alpha}G^{a\alpha}_0 + \frac{1}{4}g_{00}G^a_{\alpha\beta}G^{a\alpha\beta}) = \frac{8\pi^2}{b}\theta^\mu_\mu + g^2\theta^{(G)}_{00}$$

$$\theta^\mu_\mu \equiv \frac{\beta(g)}{2g}G^{a\alpha\beta}G^a_{\alpha\beta} = -\frac{bg^2}{32\pi^2}G^{a\alpha\beta}G^a_{\alpha\beta}\ , \quad \theta^{(G)}_{\mu\nu} \equiv -G^a_{\mu\alpha}G^{a\alpha}_\nu + \frac{1}{4}g_{\mu\nu}G^a_{\alpha\beta}G^{a\alpha\beta}$$

Quarkonium interactions at low energy



Perturbation theory:

at large distances,
the Casimir-Polder
interaction (retardation)

Bhanot, Peskin '78

$$V^{\mathrm{pt}}(R) = -g^4 \left(\bar{d}_2 \frac{a_0^2}{\epsilon_0} \right)^2 \frac{23}{8\pi^3} \frac{1}{R^7}$$

Fujii, DK '99

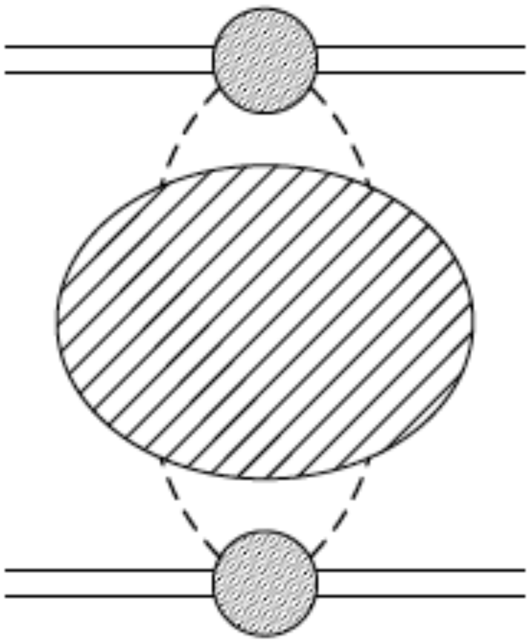
$23 = 15 + 8$

scalar 0^{++} tensor 2^{++}

Beyond perturbation theory, scalar is strongly enhanced due to scale anomaly

Quarkonium interactions at low energy and the scale anomaly

But, at very large distances, the interaction must be dominated by the lightest physical states - pions



conversion of gluons to pions is a (hopeless?) non-perturbative problem

…but, can use scale anomaly matching!

Voloshin, Zakharov '80

Quarkonium interactions at low energy and the scale anomaly

Use RG invariance to match the EMT computed in QCD and in the chiral theory:

$$\theta^\mu_\mu = -2\,\frac{f_\pi^2}{4}\,\mathrm{tr}\,\partial_\mu U \partial^\mu U^\dagger \;-\; m_\pi^2 f_\pi^2\,\mathrm{tr}\left(U + U^\dagger\right)$$

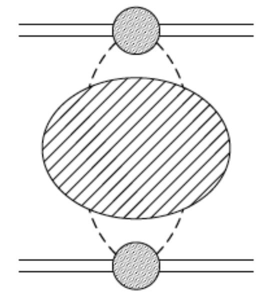
to lowest order in the pion field

$$\theta^\mu_\mu = -\partial_\mu \pi^a \partial^\mu \pi^a + 2 m_\pi^2 \pi^a \pi^a + \cdots$$

In the chiral limit scale anomaly yields:

$$\langle \pi^+ \pi^- | \theta^\mu_\mu | 0 \rangle = q^2$$

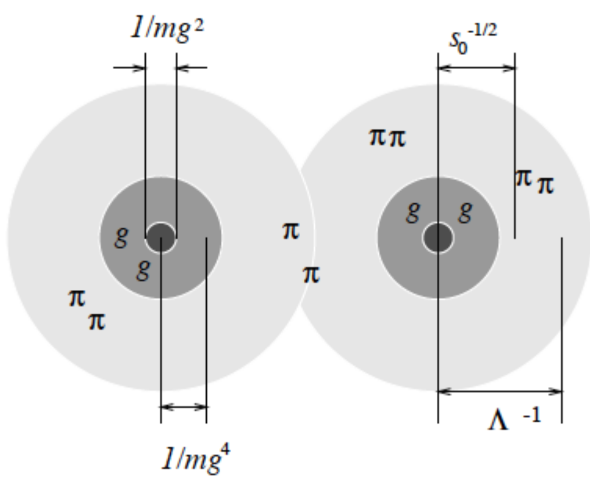
Quarkonium interactions at low energy and the scale anomaly



The result (long distances):

$$V^{\pi\pi}(R) \rightarrow -\left(\bar{d}_2 \frac{a_0^2}{\epsilon_0}\right)^2 \left(\frac{4\pi^2}{b}\right)^2 \frac{3}{2}(2m_\pi)^4 \frac{m_\pi^{1/2}}{(4\pi R)^{5/2}} e^{-2m_\pi R}.$$

Fujii, DK, PRD'99



1. Not a Yukawa potential (retardation)
2. The QCD coupling has disappeared at large distance (but not b from the beta-function)
3. Entirely due to scalar 0^{++} exchange

Probing the proton mass

The quarkonium-proton scattering amplitude

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} \underbrace{d_n}_{\text{Wilson coefficients}} \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

$$d_n^{(1S)} = \left(\frac{32}{N}\right)^2 \sqrt{\pi}\, \frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+5)}$$

M.Peskin '78

$$d_n^{(2S)} = \left(\frac{32}{N}\right)^2 4^n \sqrt{\pi}\, \frac{\Gamma(n+\frac{5}{2})}{\Gamma(n+7)} (16n^2 + 56n + 75)$$

$$d_n^{(2P)} = \left(\frac{15}{N}\right)^2 4^n 2\sqrt{\pi}\, \frac{\Gamma(n+\frac{7}{2})}{\Gamma(n+6)}$$

DK, '96

nucl-th/9601029

Quarkonium-proton interaction

$$F_{\Phi h} = r_0^3 \epsilon_0^2 \sum_{n=2}^{\infty} d_n \langle h | \frac{1}{2} G_{0i}^a (D^0)^{n-2} G_{0i}^a | h \rangle$$

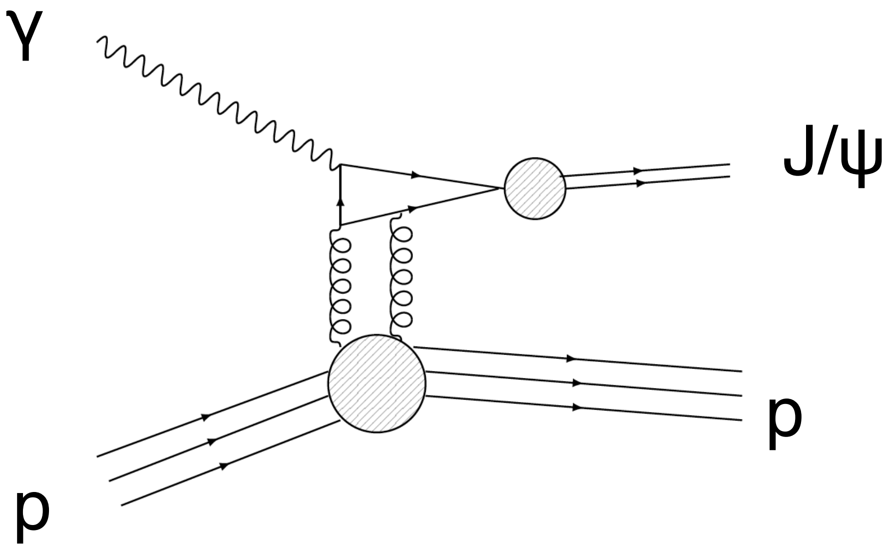
1. Interaction is attractive (VdW force of QCD)

S.Brodsky, I.Schmidt, G. de Teramond '90

2. For n=2 (low energy) the amplitude is proportional to the trace of the energy-momentum tensor

M.Luke, A.Manohar, M.Savage '92

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton



Near threshold, dominance of

$$g^2\mathbf{E}^{a2} = \frac{8\pi^2}{b}\theta^{\mu}_{\mu} + g^2\theta^{(G)}_{00}$$

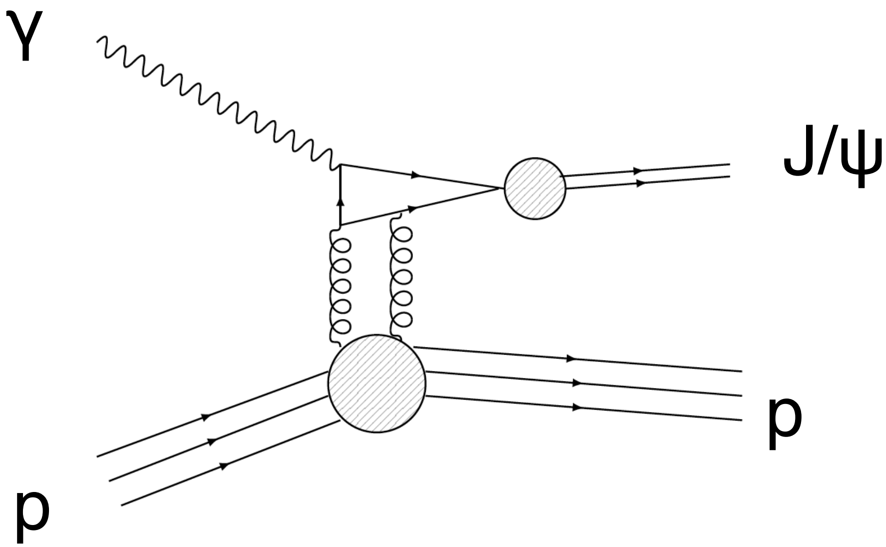
Assuming the validity of vector meson dominance, can relate photoproduction to quarkonium scattering amplitude and probe the mass of the proton

DK, Satz, Syamtomov, Zinovjev '99

Other approaches to threshold photoproduction:

Hatta, Yang '18; Hatta, Rajan, Yang '19; Mamo, Zahed '19

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton

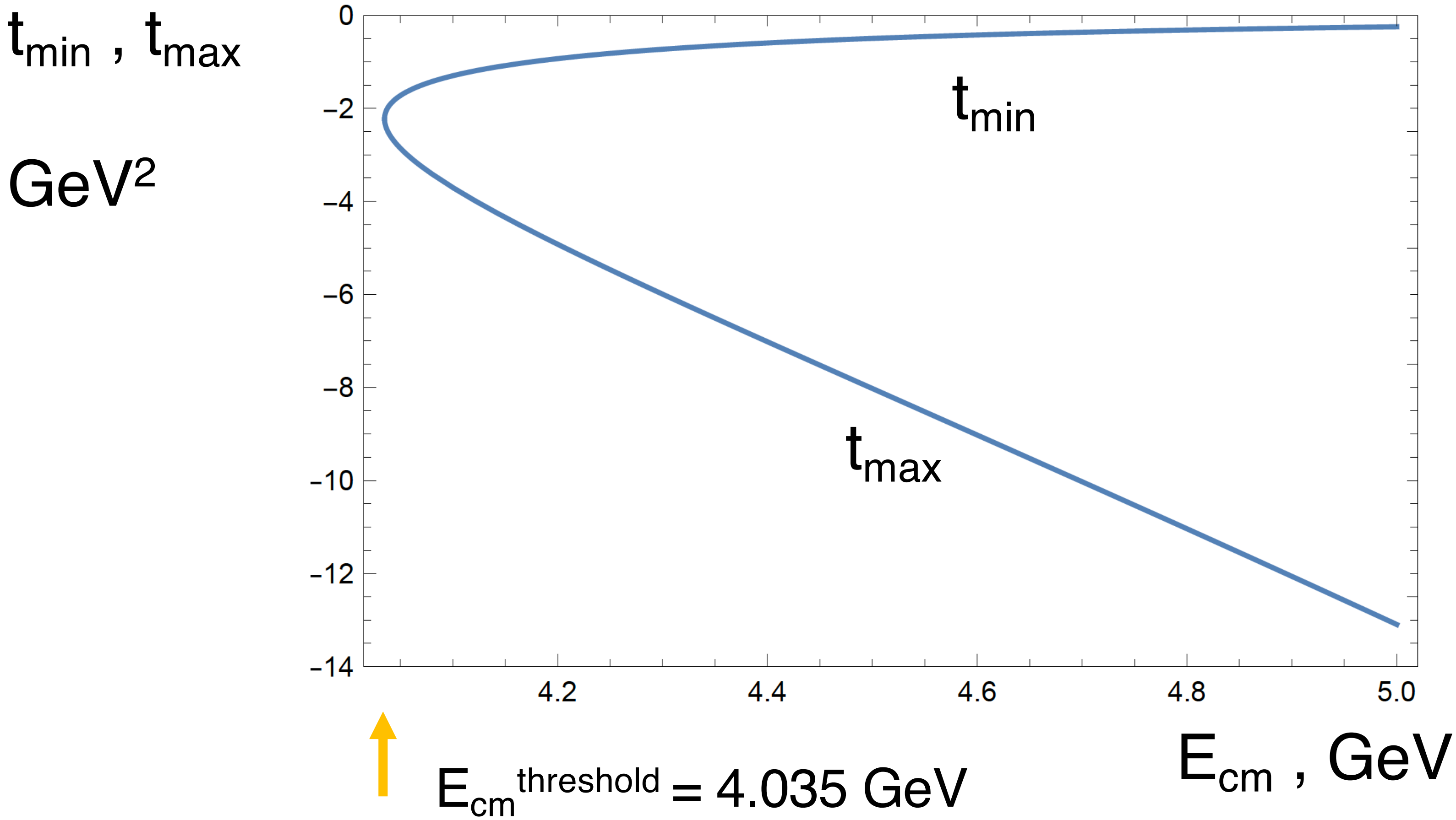


Large minimum momentum transfer at threshold:

$$t_{min} = -\frac{M_\psi^2 M}{M_\psi + M} \simeq -2.23\ \mathrm{GeV}^2 \simeq -(1.5\ \mathrm{GeV})^2$$

–> VDM questionable.
but, scanning the energy range near the threshold, we measure the scalar gravitational formfactor – can extract the proton mass distribution!

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton

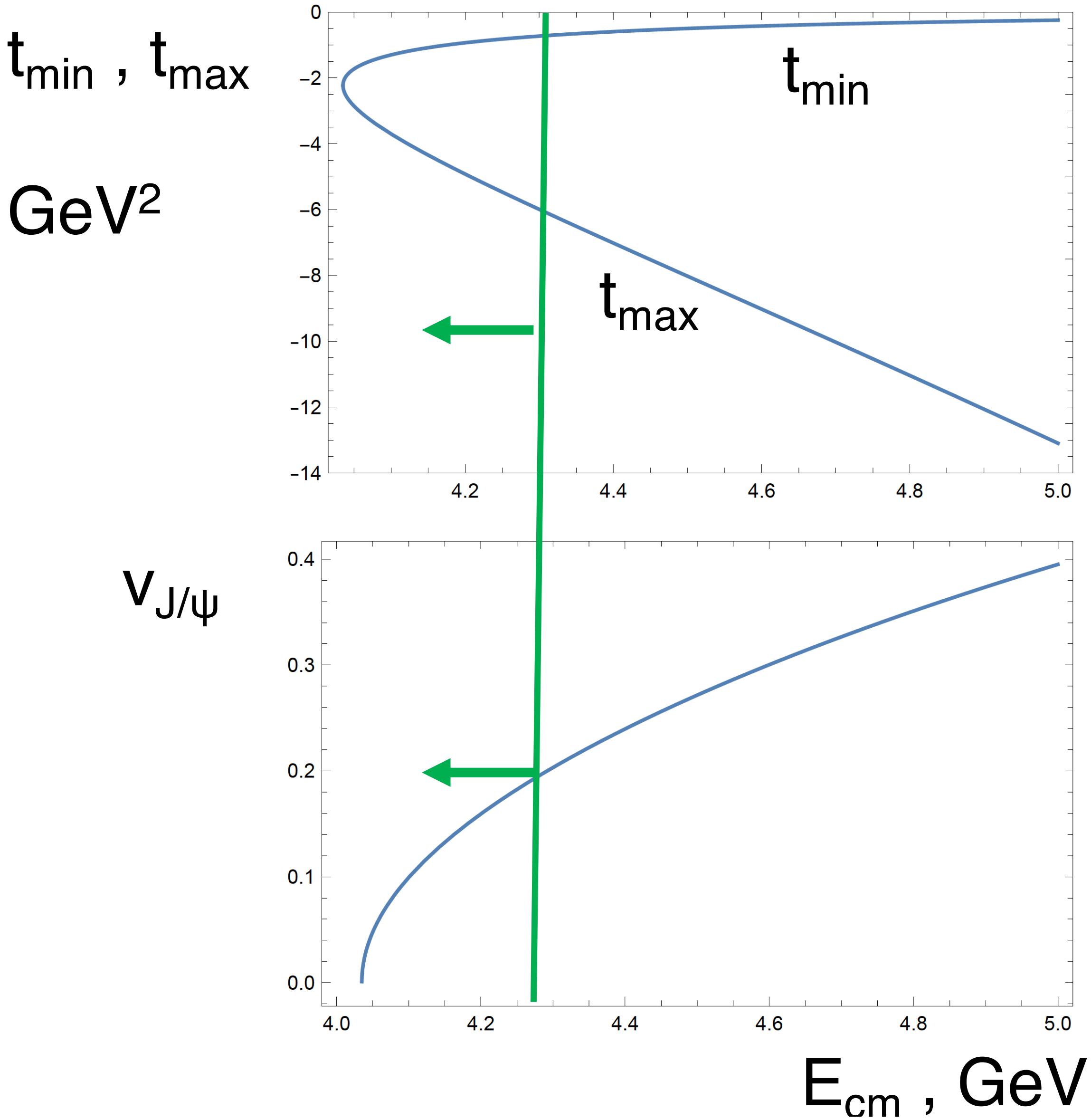


Can measure scalar gravitational formfactor in a broad kinematical domain!

At threshold:

$$t_{min} = -\frac{M_\psi^2 M}{M_\psi + M} \simeq -2.23 \text{ GeV}^2 \simeq -(1.5 \text{ GeV})^2$$

Threshold photoproduction of quarkonium as a probe of mass distribution inside the proton



The scalar operator dominates for small velocity of heavy quarkonium;

Limiting $v_{J/\psi} < 0.2$, (corrections ~ $v_{J/\psi}^2$) the optimal kinematical region is:

$E_{cm} < 4.25$ GeV
$E_\gamma < 9.2$ GeV

$-t < 6$ GeV^2

PHYSICAL REVIEW LETTERS **123,** 072001 (2019)

Editors' Suggestion

First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton

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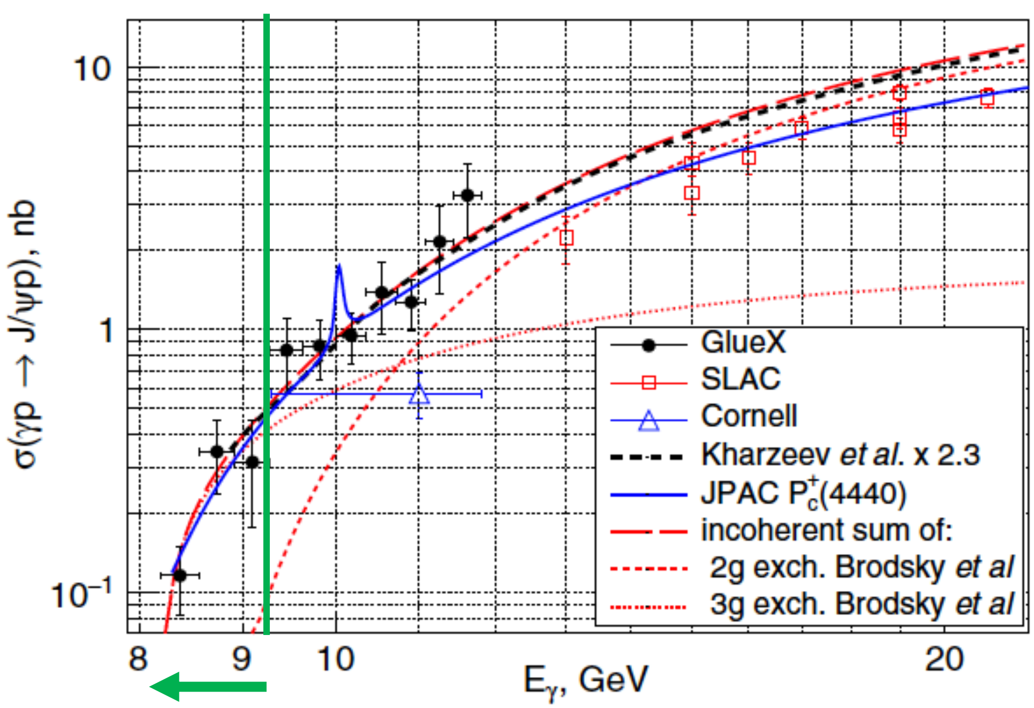
(GlueX Collaboration)



Need to focus on the threshold region!

$E_{cm} < 4.25$ GeV
$E_\gamma < 9.2$ GeV

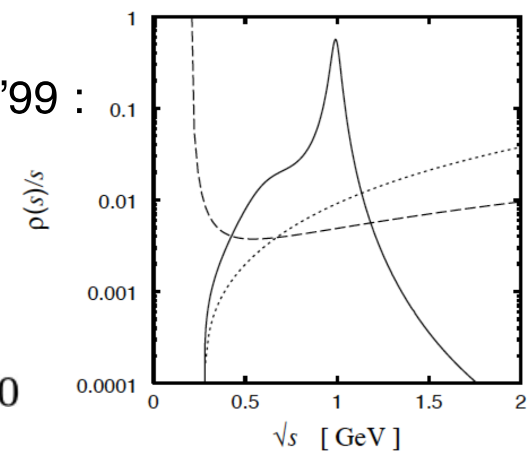
Threshold photoproduction of quarkonium: the effect of the scalar gravitational formfactor

The scalar gravitational formfactor can be constrained theoretically by using:

i) dispersion relations;
ii) low-energy theorems of broken scale invariance;
iii) experimental data on ππ phase shifts and scalar mesons

However, as a first step, can try a simple dipole formfactor of the type used for electromagnetic formfactor:

See e.g. Fujii, DK'99 :

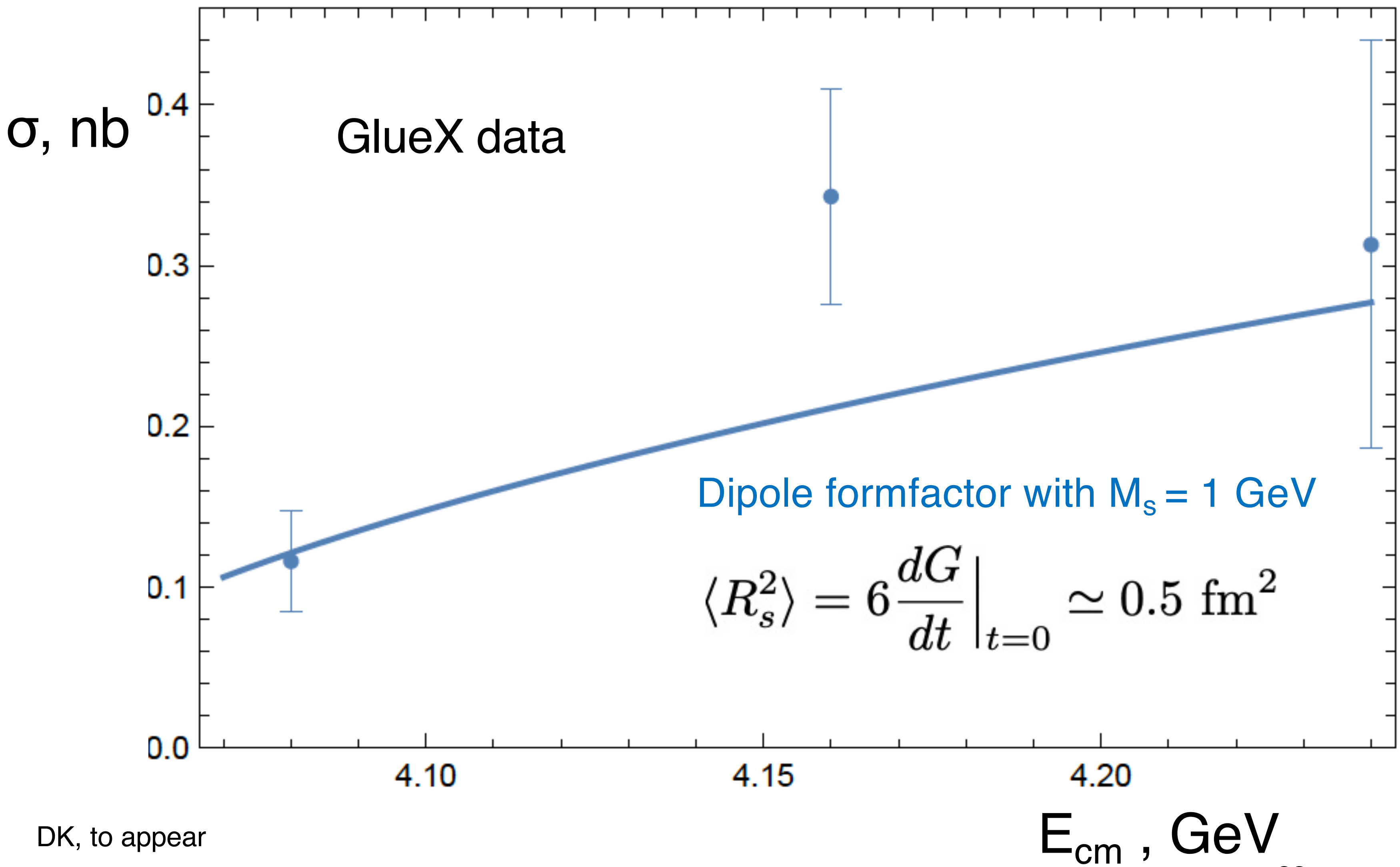


$$G(t) = \frac{M}{(1 - t/M_s^2)^2}$$ radius $$\langle R_s^2 \rangle = 6 \frac{dG}{dt}\Big|_{t=0}$$

Dipole formfactor was also used for 2-gluon coupling in perturbative models

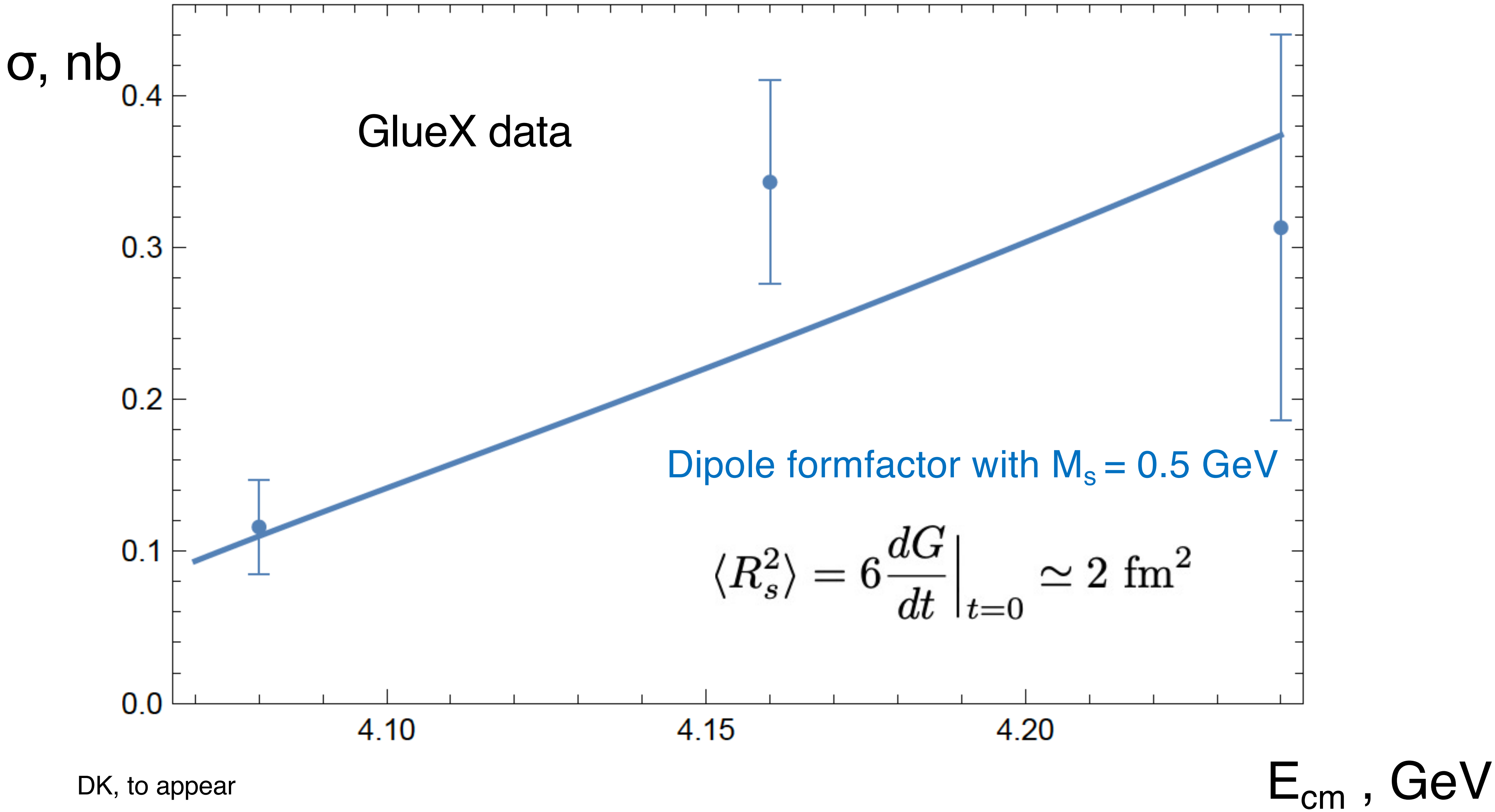
See e.g.
Frankfurt, Strikman '02

The cross section is sensitive to the formfactor due to the energy dependence of t_{min}



DK, to appear

Threshold photoproduction of J/ψ as a probe of mass distribution inside the proton



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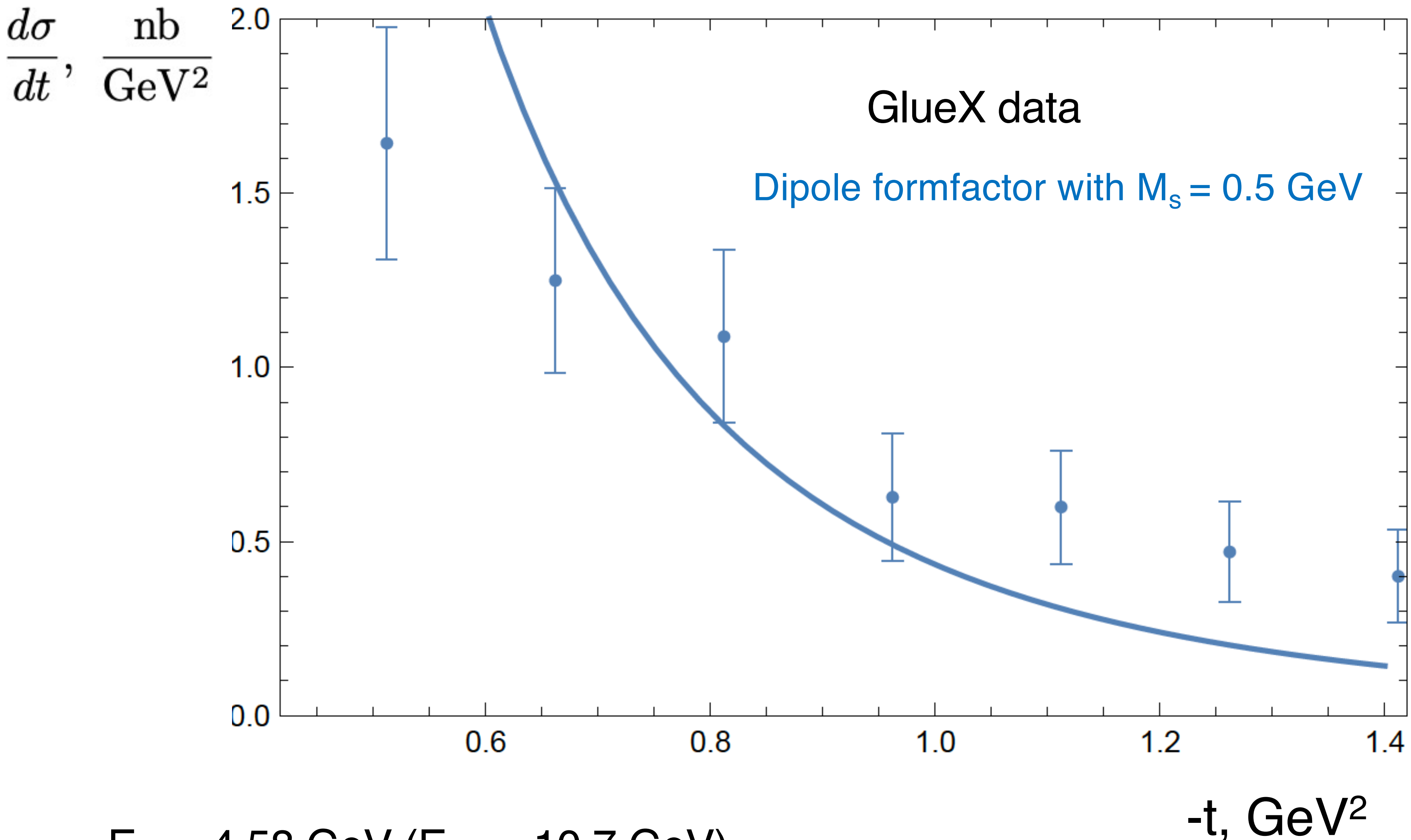
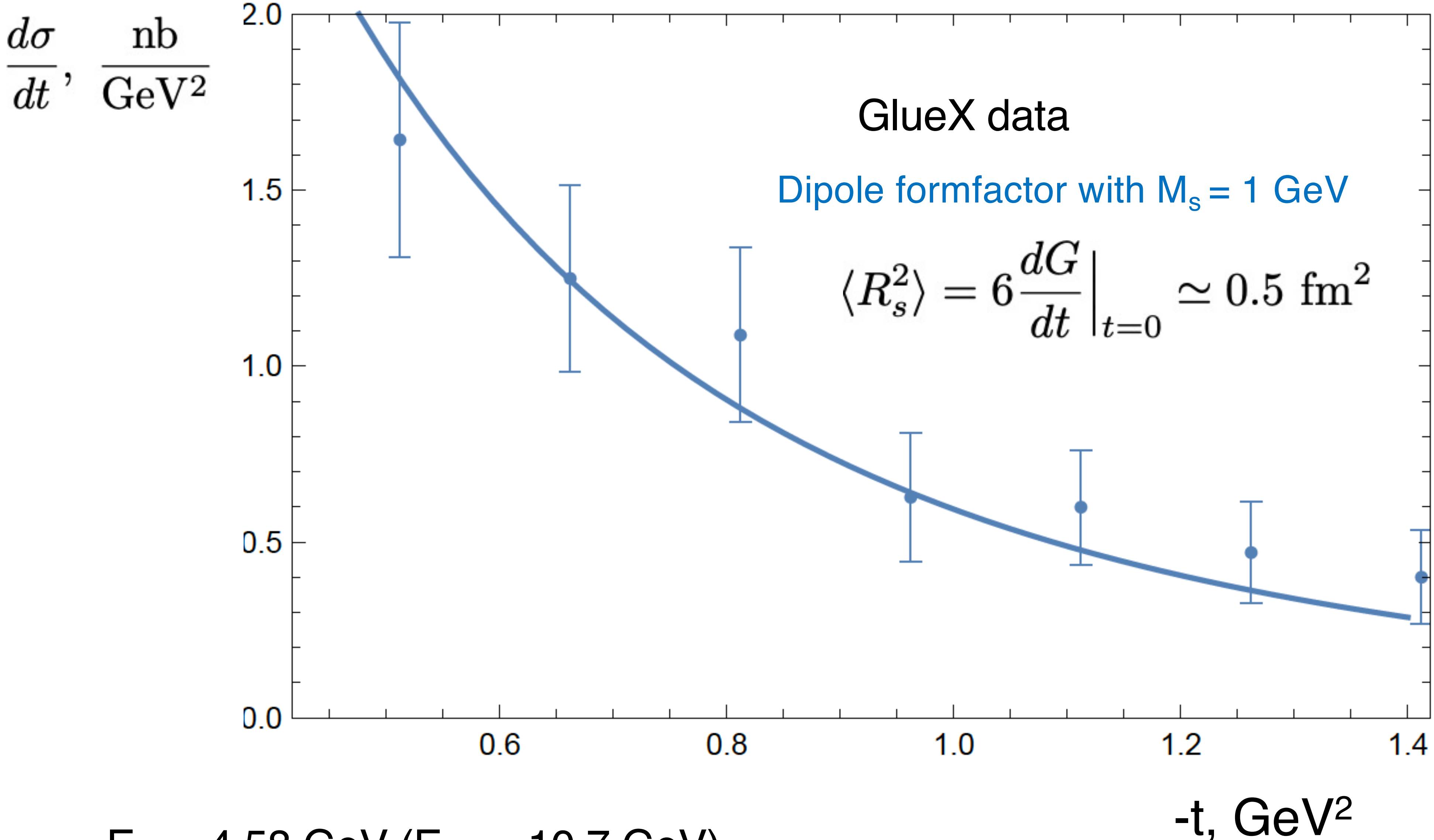
Differential cross section



E_{cm}= 4.58 GeV (E_{lab} = 10.7 GeV)

DK, to appear

Differential cross section



E_{cm}= 4.58 GeV (E_{lab} = 10.7 GeV)

DK, to appear

The proton mass radius

My estimate of the r.m.s. “proton mass radius” from GlueX data:

$$\bar{\mathrm{R}}_{\mathrm{m}} \equiv \sqrt{R_s^2} = 0.7 \pm 0.2 \quad \mathrm{fm}$$

DK, to appear

Compare to the proton charge radius:

$$\bar{\mathrm{R}}_{\mathrm{c}} \equiv \sqrt{R_c^2} = 0.8409 \pm 0.0004 \quad \mathrm{fm}$$

Perhaps, a hint for a more compact mass distribution? Need more data!

VALUE (fm)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.8409 ± 0.0004	**OUR AVERAGE**			
0.833 ±0.010	1 BEZGINOV	2019	LASR	2S-2P transition in H
0.831 ±0.007 ±0.012	2 XIONG	2019	SPEC	$e\,p \to ep$ form factor
0.84087 ±0.00026 ±0.00029	ANTOGNINI	2013	LASR	μp -atom Lamb shift
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.877 ±0.013	3 FLEURBAEY	2018	LASR	1S-3S transition in H
0.8335 ±0.0095	4 BEYER	2017	LASR	2S-4P transition in H
0.8751 ±0.0061	MOHR	2016	RVUE	2014 CODATA value
0.895 ±0.014 ±0.014	5 LEE	2015	SPEC	Just 2010 Mainz data
0.916 ±0.024	LEE	2015	SPEC	World data, no Mainz
0.8775 ±0.0051	MOHR	2012	RVUE	2010 CODATA, ep data
0.875 ±0.008 ±0.006	ZHAN	2011	SPEC	Recoil polarimetry
0.879 ±0.005 ±0.006	BERNAUER	2010	SPEC	$e\,p \to ep$ form factor

2020 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Some day:
p MASS RADIUS in PDG?

Summary

- The proton mass to large extent originates from quantum anomalies

- The threshold photoproduction of J/ψ probes the mass distribution inside the proton; current data and a simple dipole model favor

$$\bar{\mathrm{R}}_{\mathrm{m}} \equiv \sqrt{R_s^2} = 0.7 \pm 0.2 \quad \mathrm{fm}$$

- We need a quantitative theory of the scalar gravitational formfactor and precise data at $E_{cm} < 4.3$ GeV to understand the mass distribution inside the proton, and the origin of the proton mass!