Dark matter detection in the DIS regime

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Numerical plots are preliminary

Motivation

- There may be dark particles χ floating around the galaxy.
- They may have some (but small) way to interact with hadrons.
- But suppose that they are light ($m_\chi < 5$ GeV).
- Then they carry too little momentum to easily see.
- Make some with high energy protons hitting a target.
- Then they have lots of energy and we can see them.
- *Eg.* Beam dump experiment E613.

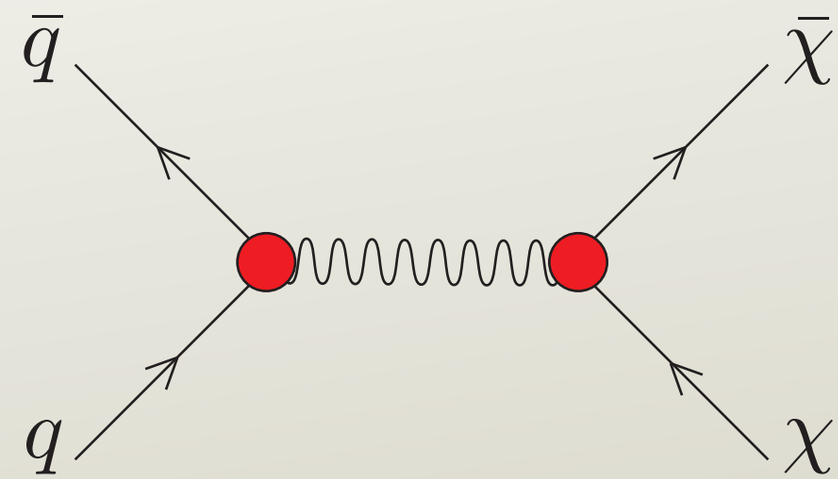
A simple model to consider

- A fermion χ with mass m_χ.
- A vector boson V ("dark photon") with small mass m_v.

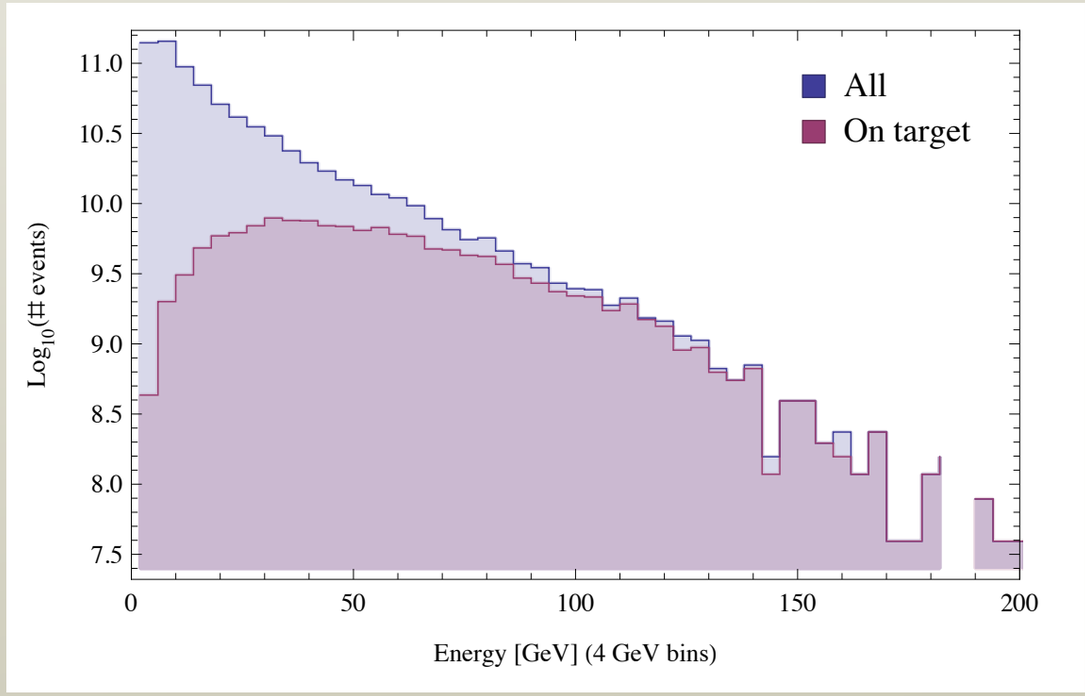
$$\mathcal{L}_{\mathrm{I}} = V_\mu \left(g_{q\bar{q}v} \sum_q \bar{q}\gamma^\mu q + g_{\chi\bar{\chi}v} \bar{\chi}\gamma^\mu \chi \right) .$$

Make some

- Follow E613.
- Use $pA \to \bar{\chi}\chi + X$.
- A is a tungsten nucleus.



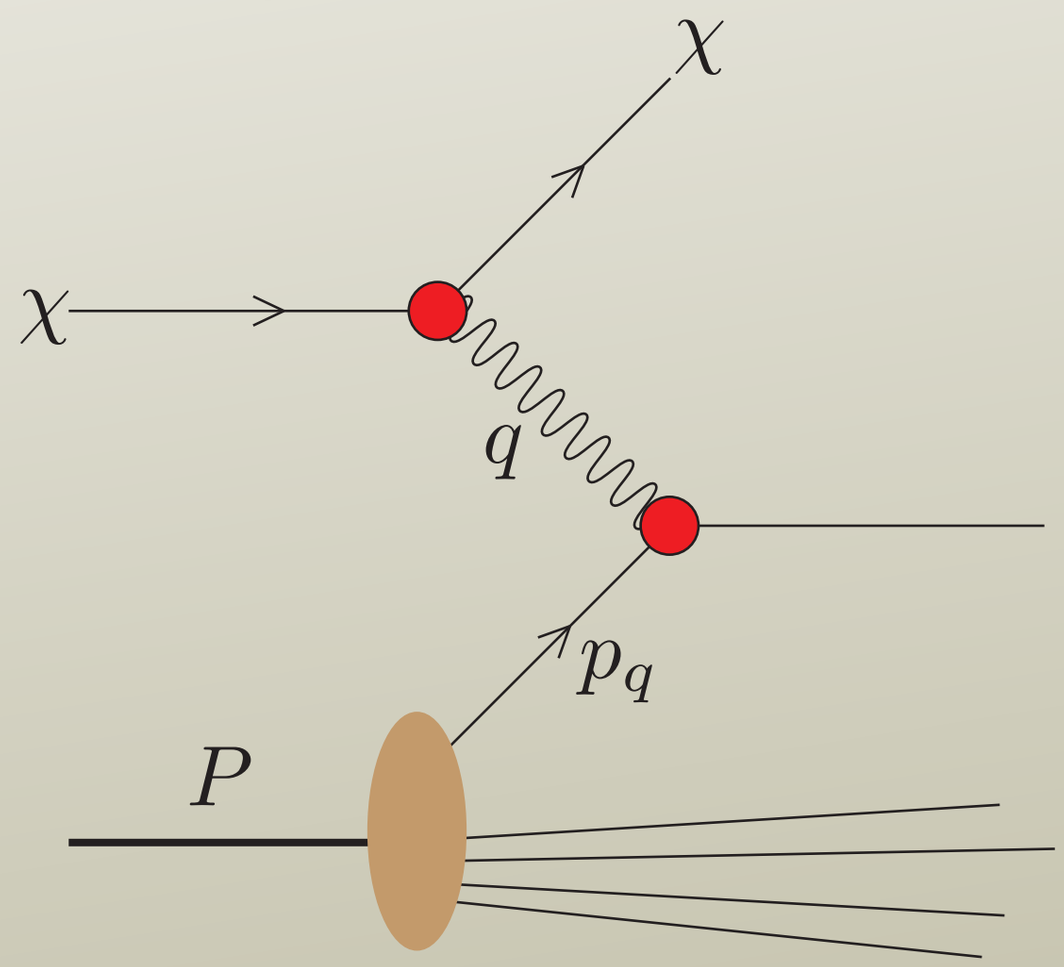
- Proton energy $E_{\mathrm{p}} = 400$ GeV



- Energy distribution of χs.
  - All angles.
  - Aimed at target.

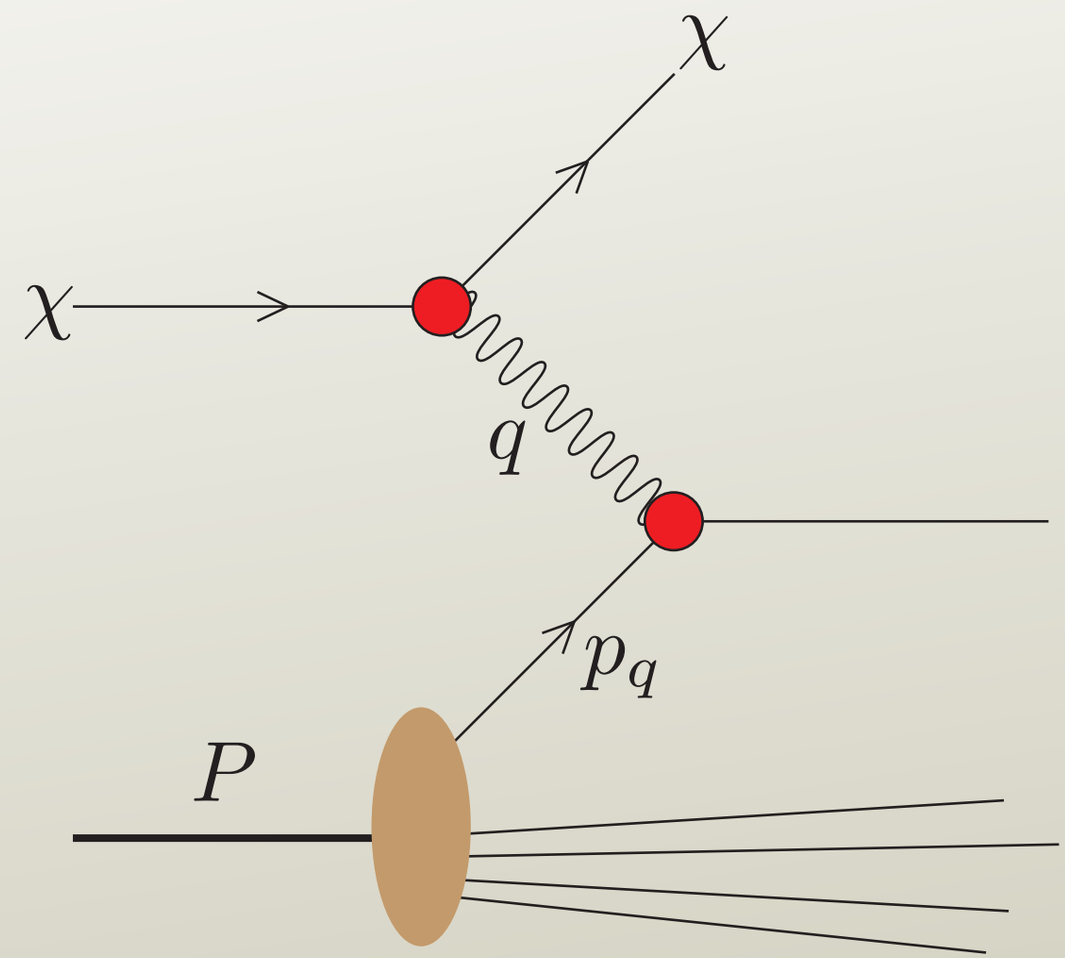
Detect the dark particle

- The target contains lead nuclei, each with momentum P.
- χ has energy E.
- It exchanges a dark photon carrying momentum q with the nucleus.
- Demand that at least energy E_{cut} is delivered to the nucleus.
- $E_{\text{cut}} = 20$ GeV for E613.



This is like DIS

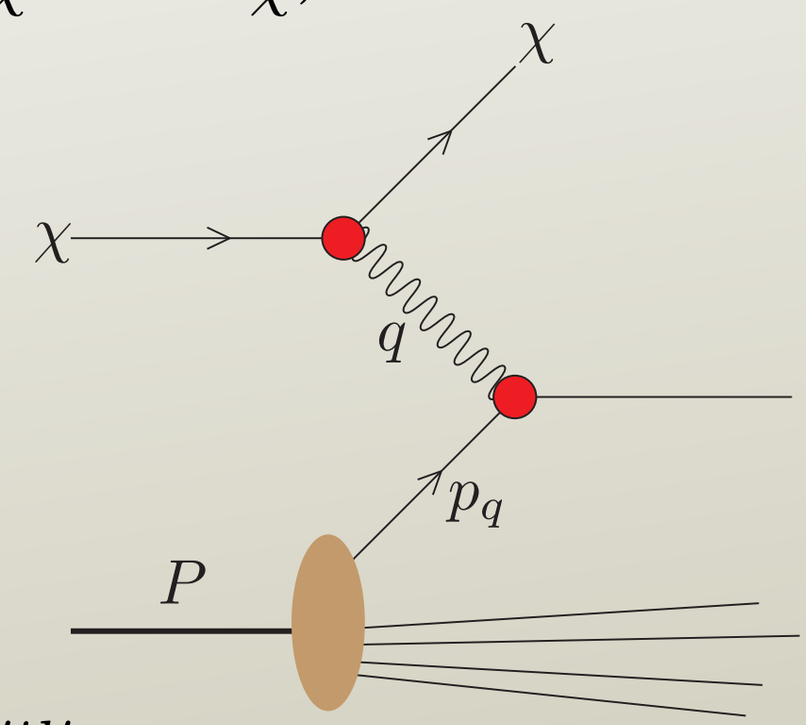
- $q^2 < 0$, $-q^2 = Q^2$.
- $q \cdot P = M\nu$.
- $x_{bj} = \dfrac{Q^2}{2M\nu}$



The cross section

$$d\sigma = \frac{1}{4M[E^2 - m_\chi^2]^{1/2}} (2\pi)^{-3} d^4 p'_\chi \; \delta({p'_\chi}^2 - m_\chi^2)$$

$$\times \frac{g^2_{\chi\bar{\chi}v} L^{\mu\nu} \; 4\pi g^2_{q\bar{q}v} W_{\mu\nu}}{(q^2 - m_v^2)^2}$$



where

$$L^{\mu\nu} = 8p^\mu_\chi p^\nu_\chi - 4(p^\mu_\chi q^\nu + q^\mu p^\nu_\chi) + 2q^2 g^{\mu\nu}$$

$$W_{\mu\nu} = \frac{1}{4\pi} \sum_X \langle P | J_\mu(0) | X \rangle \langle X | J_\nu(0) | P \rangle (2\pi)^4 \delta(P + q - p_X)$$

After a change of variables

$$d\sigma = \frac{g^2_{\chi\bar{\chi}v}\, g^2_{q\bar{q}v}}{16\pi M}\, \frac{d\nu\, dQ^2}{E^2 - m_\chi^2}\, \frac{L^{\mu\nu} W_{\mu\nu}}{(Q^2 + m_v^2)^2}$$

$$\nu < E - m_\chi$$

$$Q^2 < 2M\nu$$

$$2\mu^2(\nu) < Q^2 < 4[E(E-\nu) - m_\chi^2] - 2\mu^2(\nu)$$

where

$$\mu^2(\nu) = \frac{m_\chi^2 \nu^2}{[E(E-\nu) - m_\chi^2] + \sqrt{[E(E-\nu) - m_\chi^2]^2 - m_\chi^2 \nu^2}}$$

&

$$\nu > E_{\rm cut} = 20 \text{ GeV}$$

Define structure functions

$$W^{\mu\nu} = C_{\mathrm{T}}^{\mu\nu} F_{\mathrm{T}}(x_{\mathrm{bj}}, Q^2) + C_{\mathrm{L}}^{\mu\nu} F_{\mathrm{L}}(x_{\mathrm{bj}}, Q^2)$$

where

$C_{\mathrm{T}}^{\mu\nu} q_\nu = C_{\mathrm{L}}^{\mu\nu} q_\nu = 0$ current conservation

$C_{\mathrm{T}}^{\mu\nu} a_\nu = 0$ a_ν in q-P plane transverse polarization

$C_{\mathrm{L}}^{\mu\nu} a_\nu^\perp = 0$ $a_\nu^\perp \perp$ to q-P plane longitudinal polarization

So

$$W^{\mu\nu} = C_{\mathrm{T}}^{\mu\nu} F_{\mathrm{T}}(x_{\mathrm{bj}}, Q^2) + C_{\mathrm{L}}^{\mu\nu} F_{\mathrm{L}}(x_{\mathrm{bj}}, Q^2)$$

where

$$C_{\mathrm{T}}^{\mu\nu} = -g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2} + \frac{2x_{\mathrm{bj}}}{P\cdot q + 2x_{\mathrm{bj}}M^2}\left(P^\mu - \frac{P\cdot q}{q^2}\,q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2}\,q^\nu\right)$$

$$C_{\mathrm{L}}^{\mu\nu} = \frac{1}{P\cdot q + 2x_{\mathrm{bj}}M^2}\left(P^\mu - \frac{P\cdot q}{q^2}\,q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2}\,q^\nu\right)$$

The result

$$d\sigma = \frac{g^2_{\chi\chi v}\, g^2_{qqv}}{8\pi}\, \frac{d\nu\, dQ^2}{E^2 - m^2_\chi}\, \frac{1}{(Q^2 + m^2_v)^2}$$

$$\times \left\{ \left[\frac{\nu(2E-\nu)^2}{\nu^2 + Q^2} + \frac{\nu(Q^2 - 4m^2_\chi)}{Q^2} \right] 2x_{\rm bj} F_{\rm T}(x_{\rm bj}, Q^2) \right.$$

$$\left. + \frac{\nu[4E(E-\nu) - Q^2]}{\nu^2 + Q^2}\, F_{\rm L}(x_{\rm bj}, Q^2) \right\}$$

- We just need to know the structure functions.

Parton model

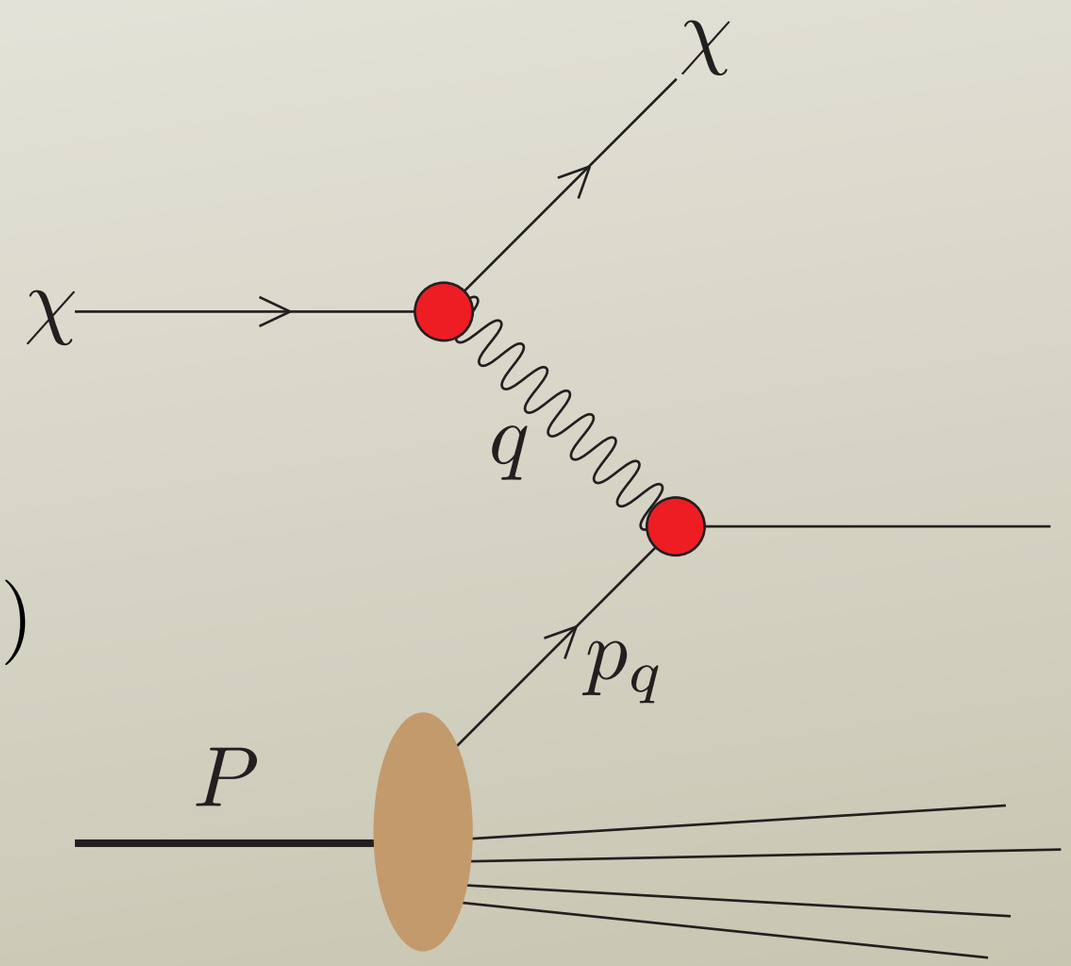
- If Q^2 is large, then we can use QCD factorization.

- Get a hard, partonic structure function convoluted with parton distribution functions.

- At lowest order,

$$F_{\mathrm{L}} = 0$$

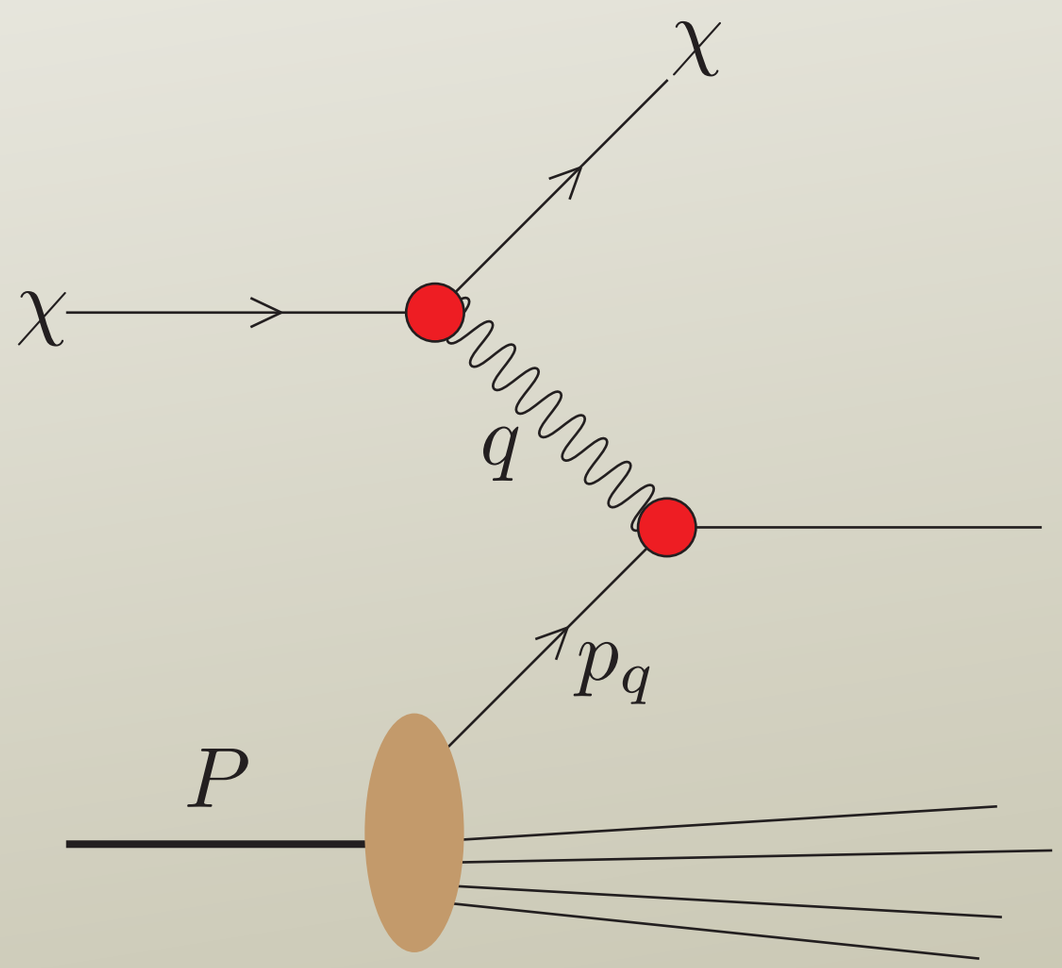
$$F_{\mathrm{T}} = \frac{1}{2x_{\mathrm{bj}}} \sum_q x_{\mathrm{bj}} f_{q/A}(x_{\mathrm{bj}}, Q^2)$$



A challenge

- We need large Q^2 to rely on this.

- But that we need something else for large ν but small Q^2.



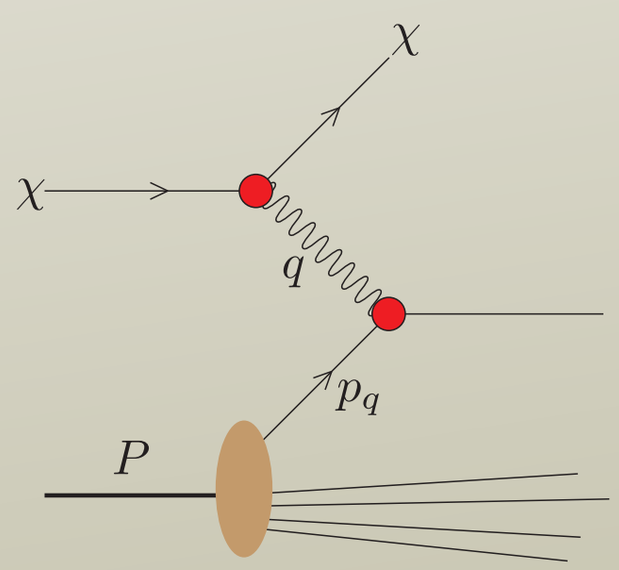
High energy picture

- In the nucleus rest frame, orient the axes so that $\vec{q}$ is along the negative z-axis.

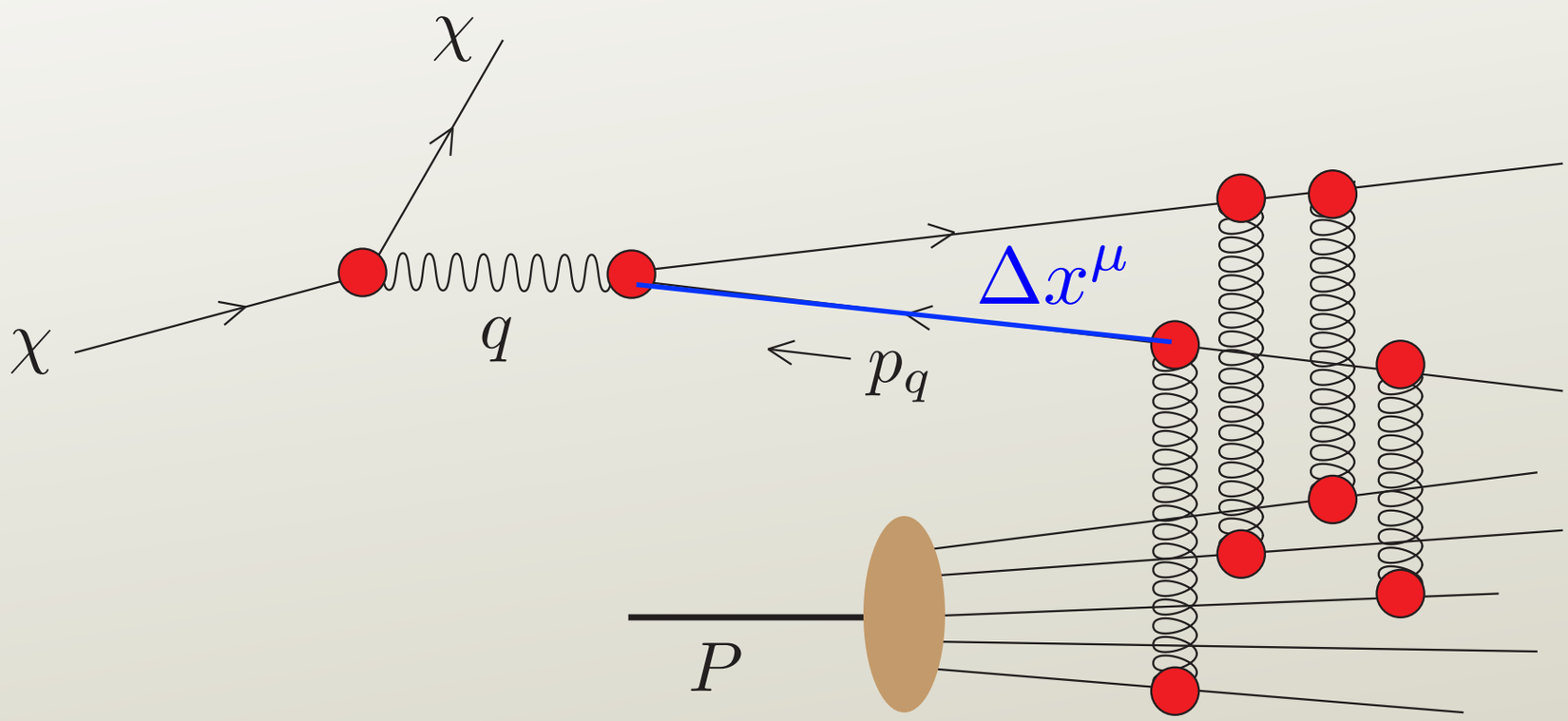
- Then when $\nu \gg Q^2/\nu$, we have large q^- and small $|q^+|$.

$$q^{\pm} = (q^0 \pm q^3)/\sqrt{2}$$

- The dark photon splits into a q and $\bar{q}$.



Space-time picture

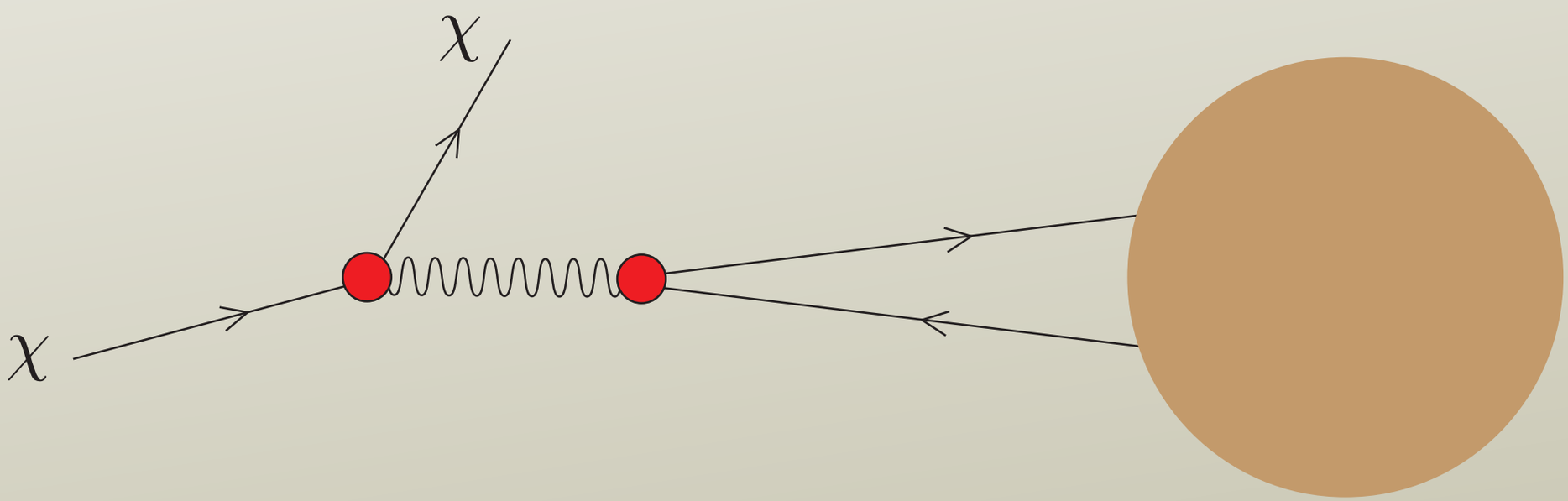


- $|p_q^-|$ is big and $|p_q^+|$ is small.
- Let the $\bar{q}$ propagate over a separation Δx^μ.
- Then Δx^- is very large.
- That is, the $q\bar{q}$ is created outside the nucleus.

Dipole model

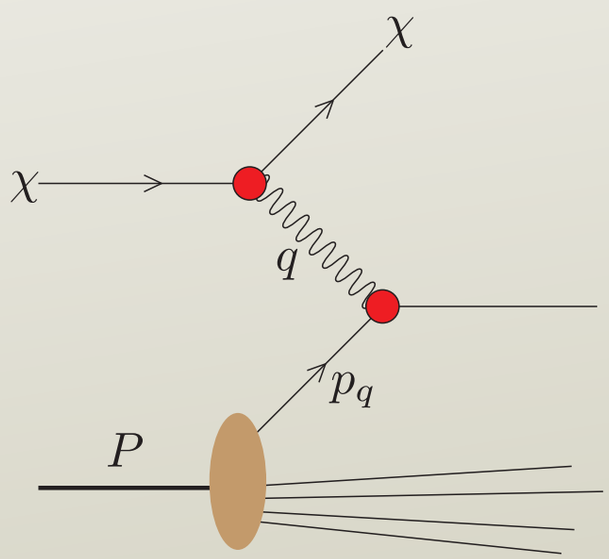
- We see that for $\nu \gg Q^2/\nu$, the dark photon creates a $q\bar{q}$ color dipole.

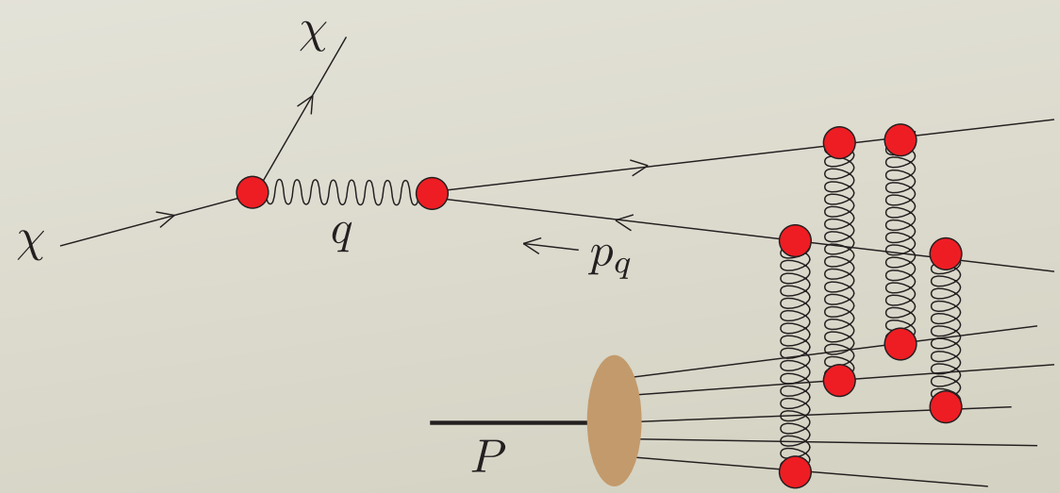
- Then the dipole hits the nucleus.



Dueling pictures

- When Q^2 is large and $\nu \gg Q^2/\nu$, the parton model picture and the dipole picture can both be right.





- They represent the same physics viewed from two reference frames.

Cross section in dipole model

- $F_{\mathrm{L}} \approx 0$.
  - $F_{\mathrm{L}} = 0$ at lowest order in parton model.
  - On shell massless vector bosons don't have longitudinal polarization.
- F_{T} needs a combination of calculation and modelling.

Model from Golec-Biernat and Wusthoff (hep-ph/9807513 & hep-ph/9903358)

Also Mueller (hep-ph/9904404)

I follow Hautmann & Soper (hep-ph/0702077)

Transverse structure function

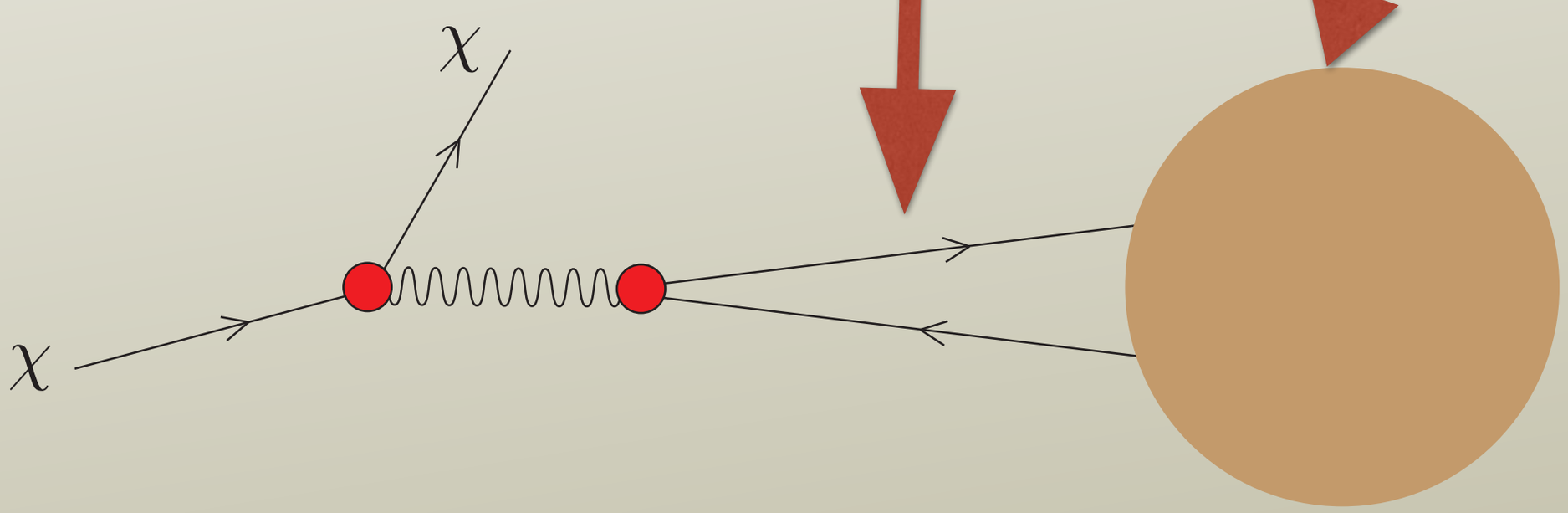
$$2x_{\mathrm{bj}}F_{\mathrm{T}} = \frac{1}{4\pi}\sum_f \frac{24Q^2}{(2\pi)^3}\int d\boldsymbol{b}\int d\boldsymbol{\Delta}\,\frac{G(\sqrt{Q^2+\Lambda_\rho^2}\,\Delta)}{\Delta^2}\,\Xi(\boldsymbol{b},\boldsymbol{\Delta})$$

$\boldsymbol{b}$ = impact parameter

$\boldsymbol{\Delta}$ = transverse size of dipole

dipole squared wave function

dipole scattering probability

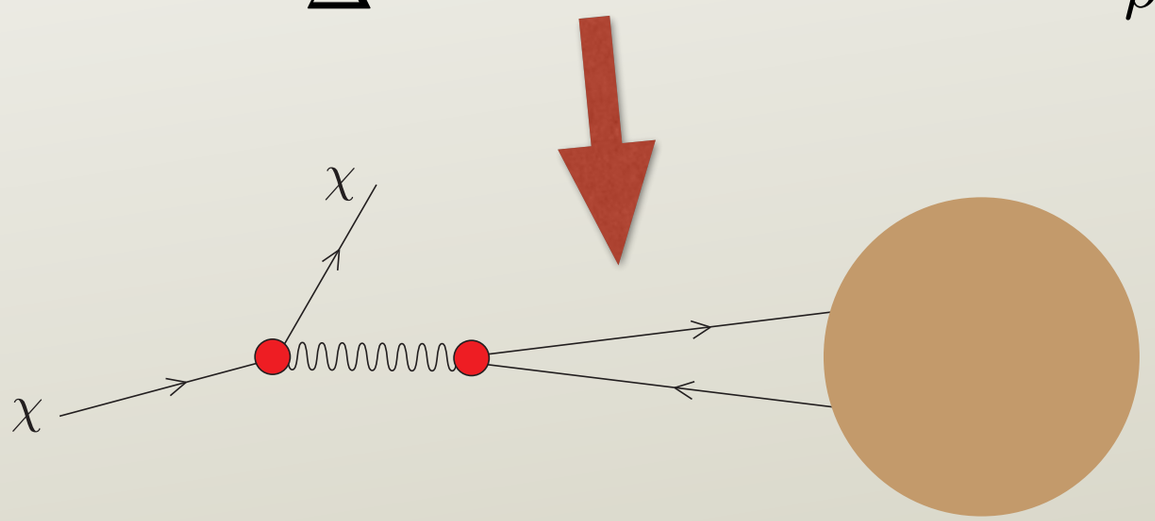


Dipole wave function

$$\frac{G(\sqrt{Q^2+\Lambda_\rho^2}\,\Delta)}{\Delta^2}$$

Our model:

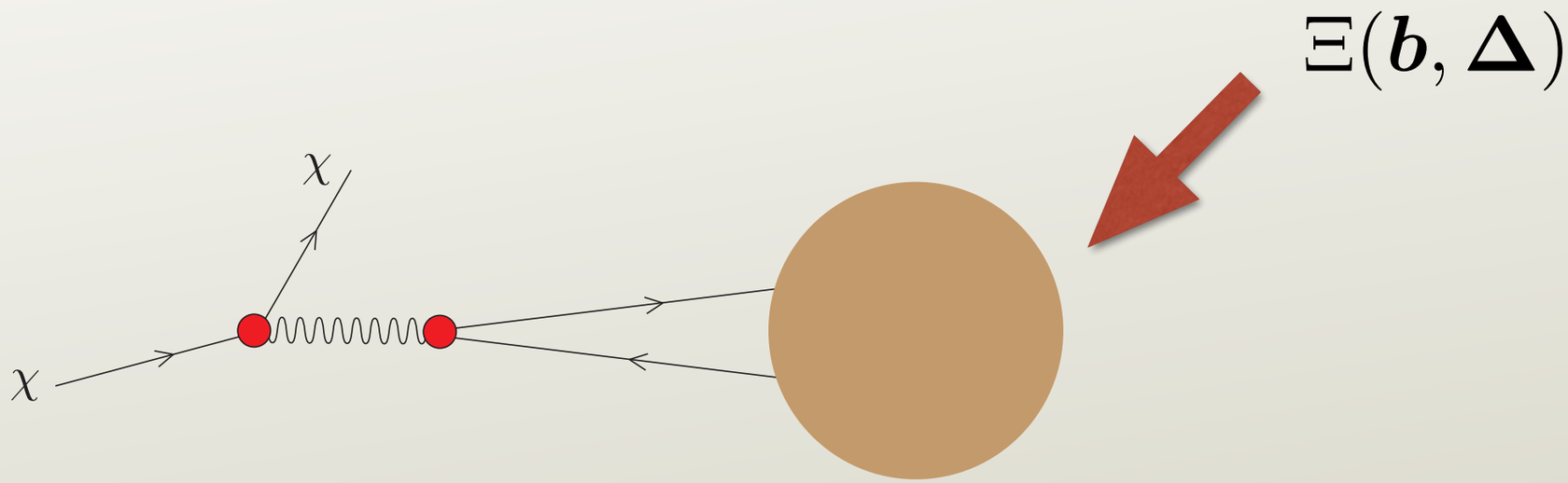
$$\Lambda_\rho \approx 1/(1\ \text{fm}) \approx 200\ \text{MeV}$$



$$G(z) = \int_0^1 d\alpha\ [1-2\alpha(1-\alpha)]\left[\sqrt{\alpha(1-\alpha)}\,z\,K_1(\sqrt{\alpha(1-\alpha)}z)\right]^2$$

$$G(z) \approx \frac{2}{3[1+z^2/4]}$$

Scattering probability

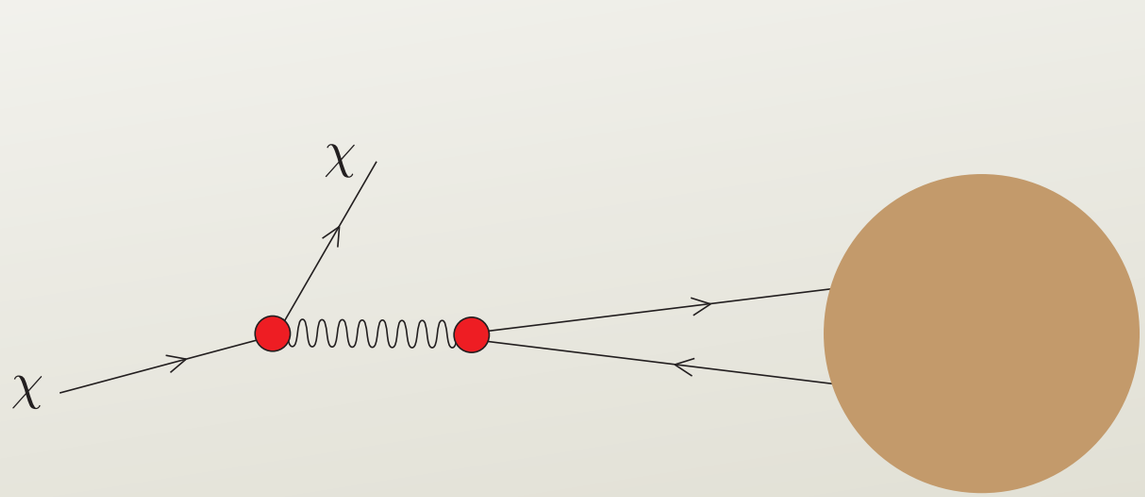


$$\Xi(\boldsymbol{b}, \boldsymbol{\Delta}) = 1 - e^{-\Delta^2 Q_{\mathrm{s}}^2(b)/4}$$

- $\Xi \to 0$ for $\Delta \to 0$ (color transparency)
- $Q_{\mathrm{s}}^2 =$ saturation scale

The logic of this

$$\Xi(\boldsymbol{b}, \boldsymbol{\Delta}) = 1 - e^{-\Delta^2 Q_{\mathrm{s}}^2(b)/4}$$



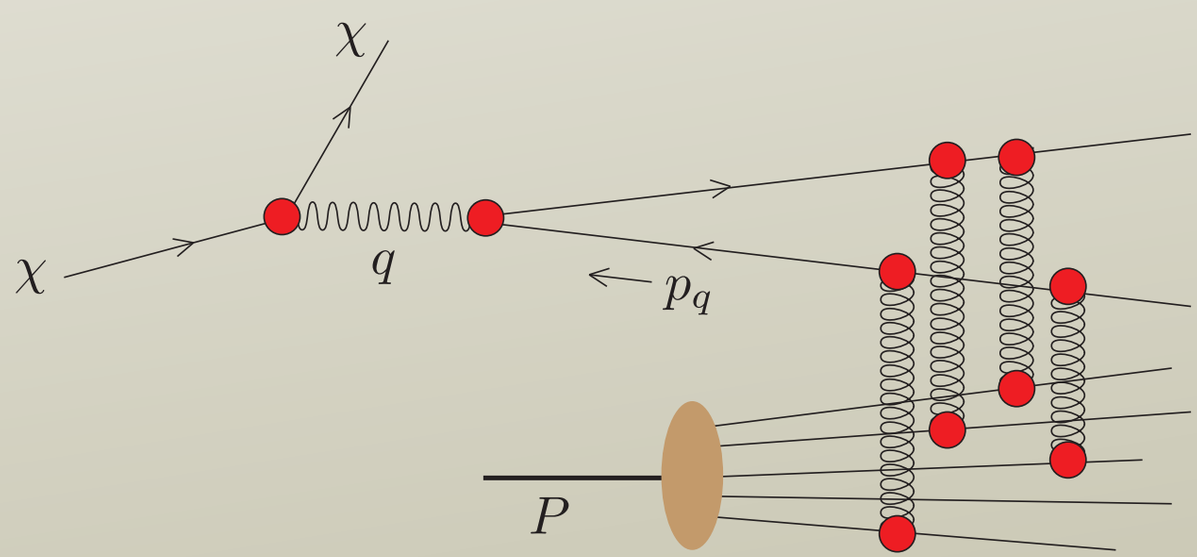
- If dipole misses the nucleus, need $\Xi = 0$.
  - Then need $Q_{\mathrm{s}}^2(b) = 0$.
- For small Δ, match to perturbation theory.
  - $\Xi \propto \Delta^2 \times$ gluon distribution.
- For large Δ, scattering probability is $\Xi \approx 1$

The saturation scale

$$Q_{\rm s}^2(b) = \frac{2\pi^2\alpha_{\rm s}(\mu^2)}{3}\, xG(x,\mu^2)\,\phi(b)$$

$$\phi(b) = \frac{3}{2\pi R_A^3}\sqrt{R_A^2 - b^2}\,\Theta(b^2 < R_A^2)$$

$$G(x,\mu^2) = \text{gluon distribution function}$$



Parameter choices

$$Q_{\rm s}^2(b) = \frac{2\pi^2\alpha_{\rm s}(\mu^2)}{3}\, xG(x,\mu^2)\,\phi(b)$$

$G(x,\mu^2)$ from HKNlo parton distributions for lead

$$\mu^2 = \frac{C}{\Delta^2} + \mu_0^2$$ (Bartels, Golec-Biernat, and Kowalski hep-ph/0203258)

$$\mu_0^2 = 1\ \mathrm{GeV}^2 \qquad C = 0.26$$

$$x = \frac{Q^2 + 4m_q^2}{2M\nu}$$ (Bartels, Golec-Biernat, and Kowalski hep-ph/0203258)

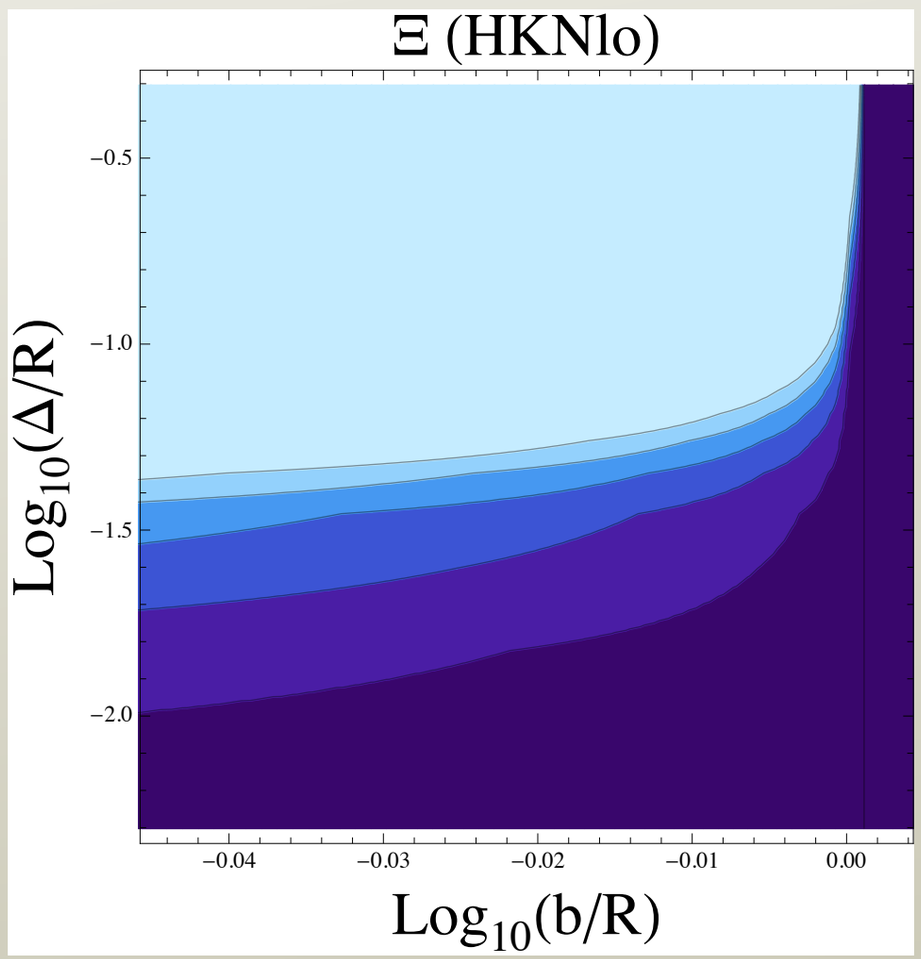
$$m_q = 140\ \mathrm{MeV}$$

Result for scattering probability

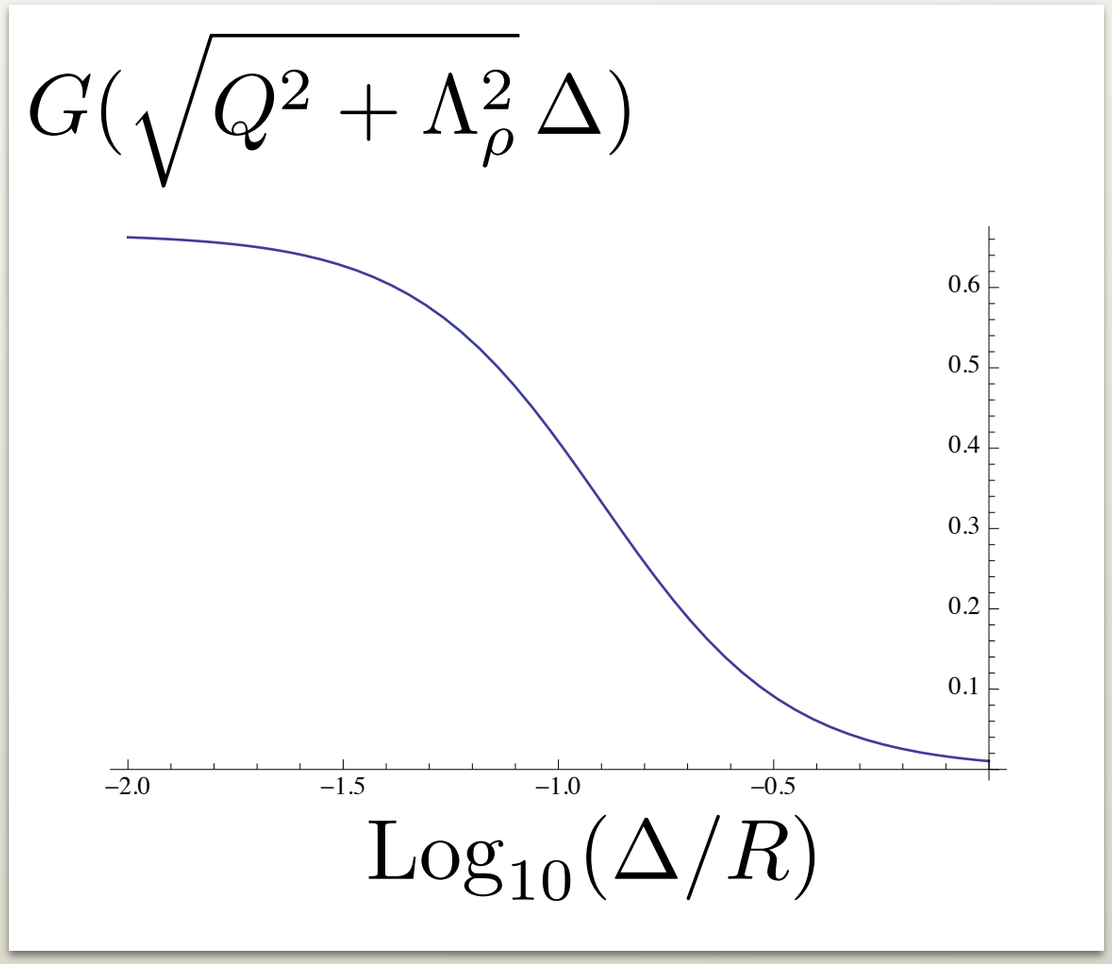
edge of nucleus

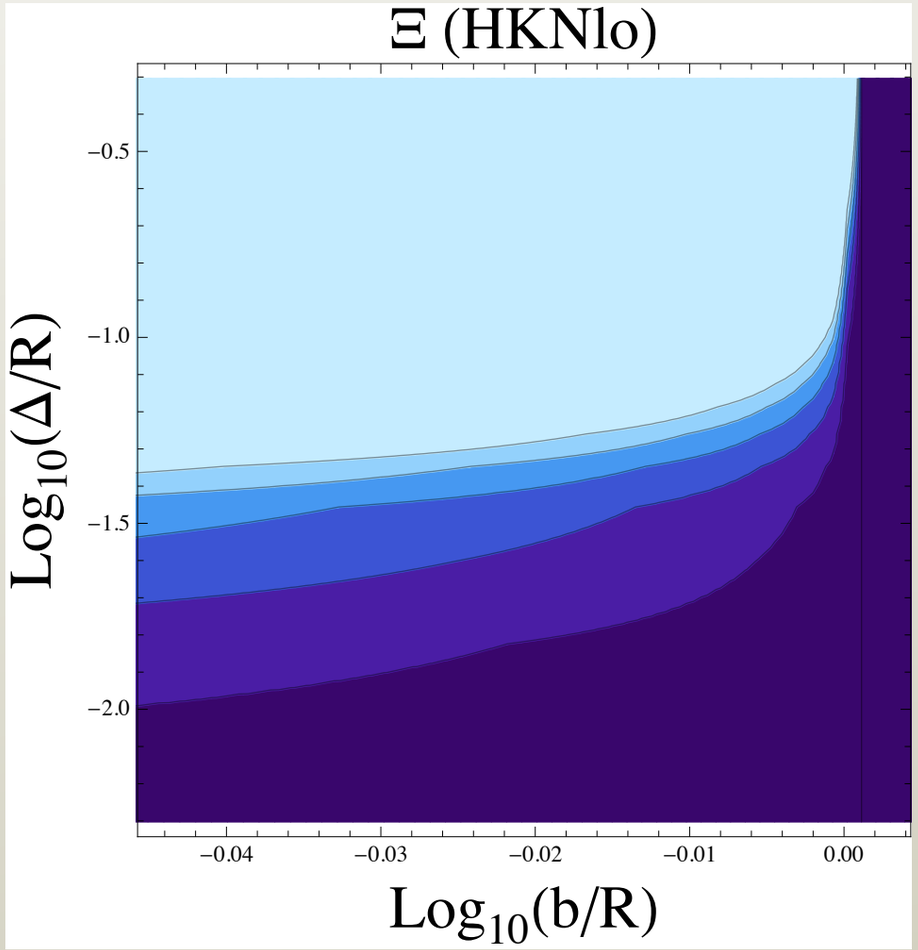
$\Xi = 1$

perturbative



Multiply factors





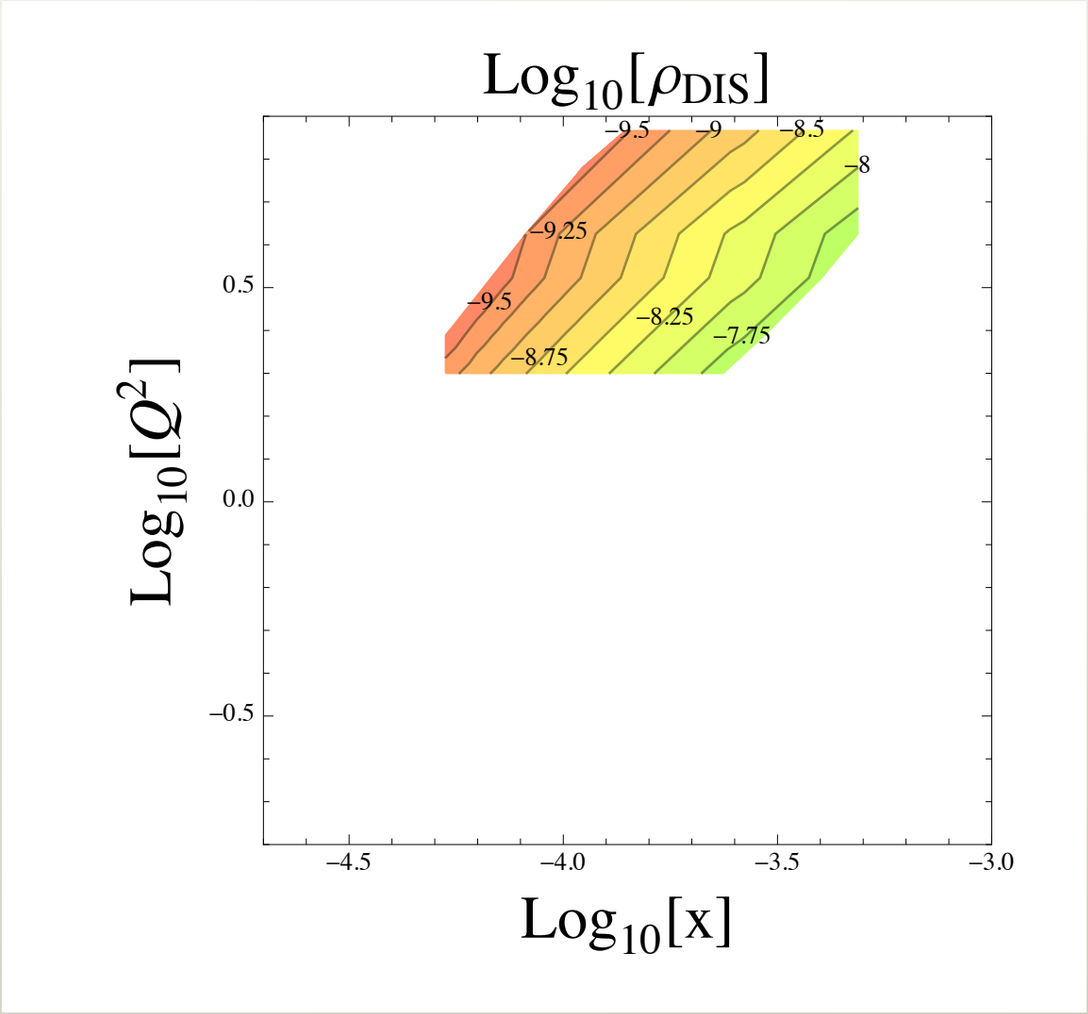
$$\Lambda_\rho = 0.2 \text{ GeV}$$

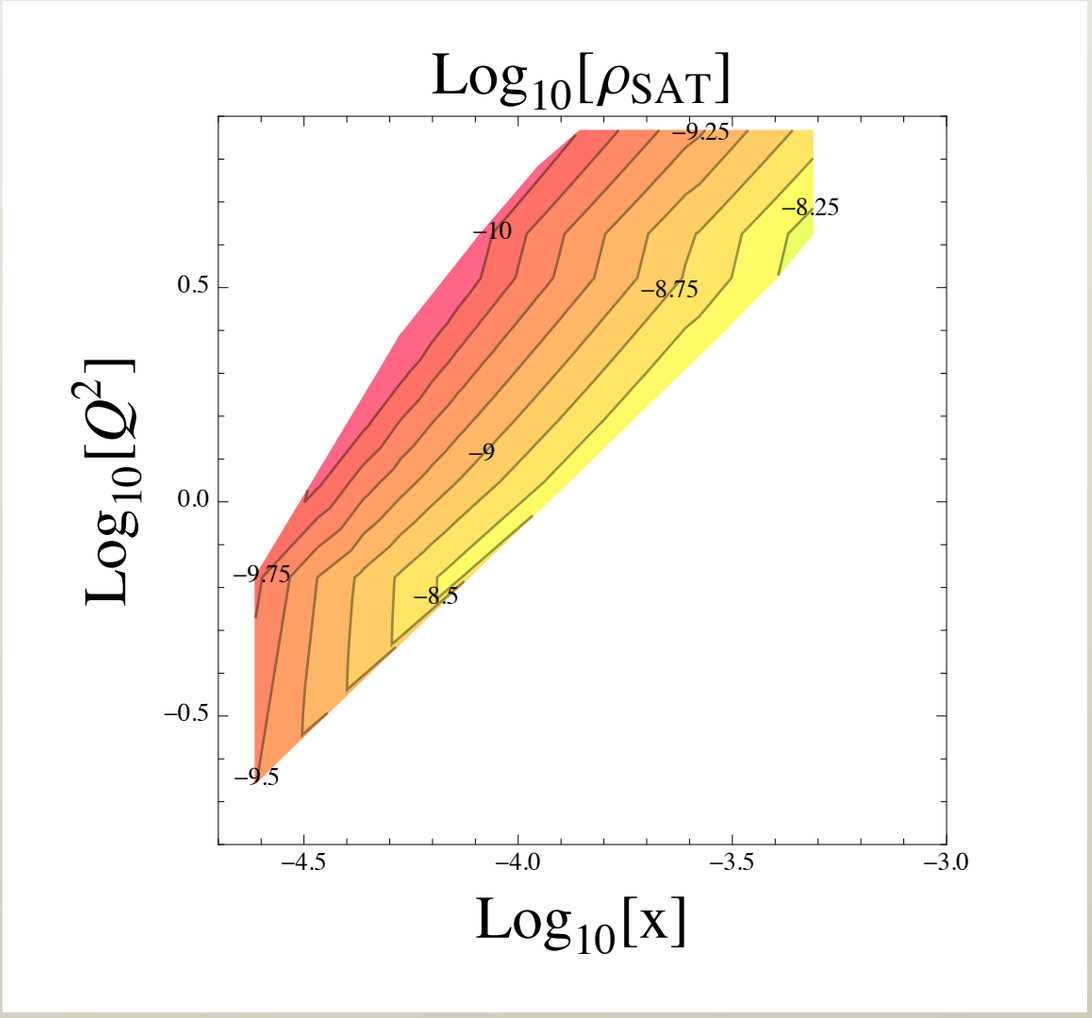
$$Q = 0.5 \text{ GeV}$$

Integrand in the two models

$$d\sigma = \rho(x, Q^2)\frac{dx_{\rm bj}}{x_{\rm bj}}\frac{dQ^2}{Q^2}$$

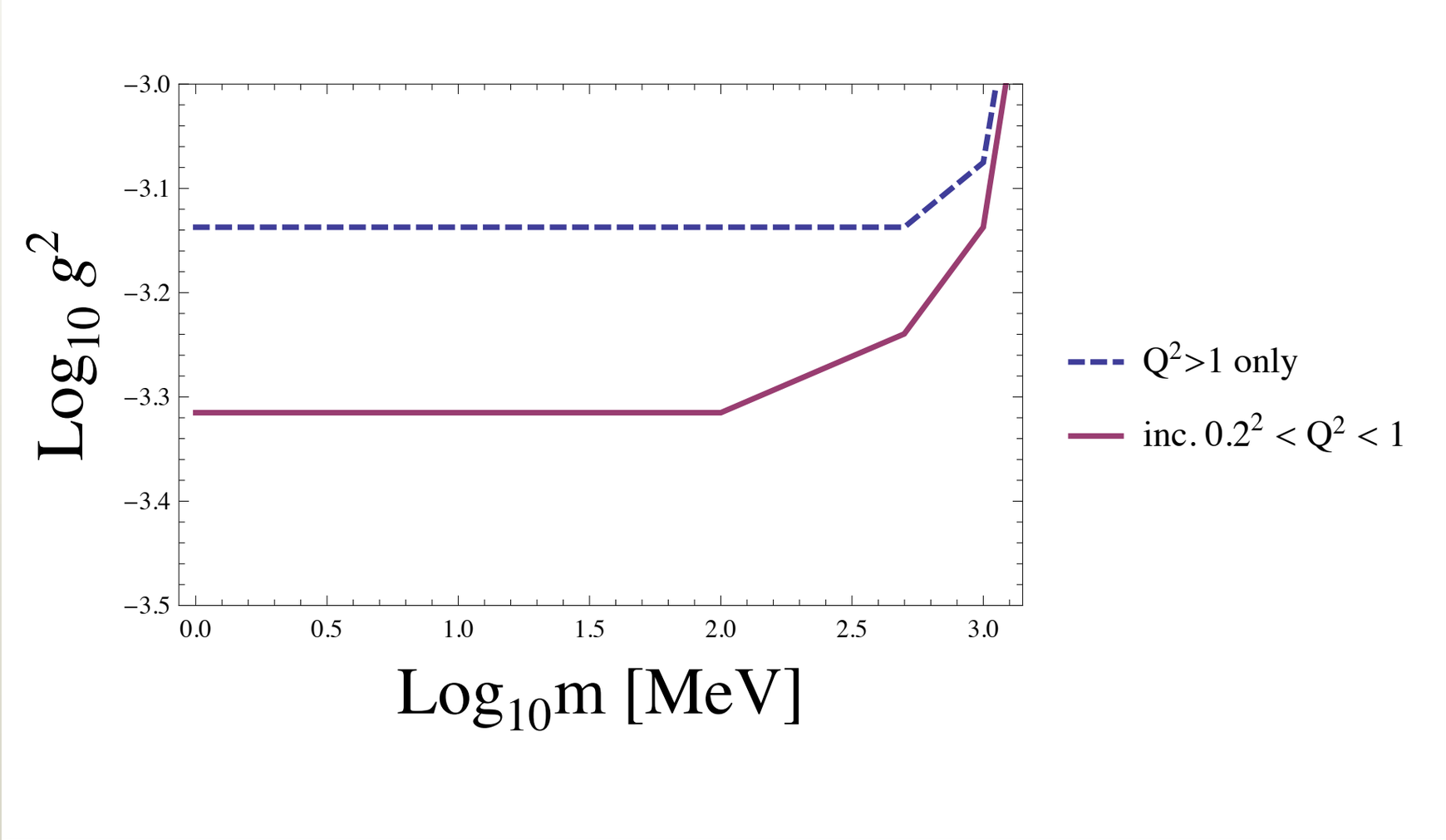
$$m_\chi = 1 \text{ GeV}$$
$$E_\chi = 150 \text{ GeV}$$





- Reasonable agreement for $Q^2 > 1$ GeV^2.
- Saturation model extends to smaller Q^2.

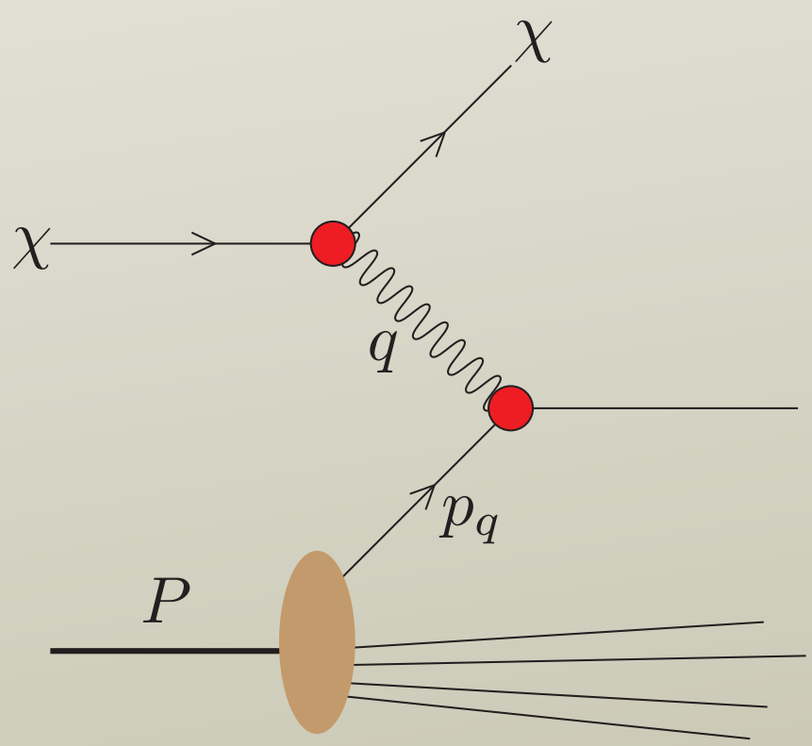
Bounds on DM coupling



- Including $Q^2 < 1$ GeV gives a tighter bound on the dark matter coupling g^2.

Summary

- Dark matter detection in beam dump style experiments for light dark matter is similar to inelastic lepton scattering.

- The "parton/DIS" picture applies for large Q^2.

- The "dipole/saturation" picture can apply for smaller Q^2.