

**Vector Meson  
Electroproduction: from the  
universal pomeron to a  
paradigm for Exclusive  
Physics at an Electron-Ion  
Collider ?**

# The long and the short of Quark Interactions in a Hadron

**John Dainton**

Cockcroft Institute and the University of Liverpool, UK

1. Chromodynamic Landscape
2. Chromodynamics of Quarks in a Hadron?
3. Conclusion and Outlook?

# 1. Chromodynamic Landscape

# Chromodynamics

- rigorous  $SU(3)_{\text{colour}}$  non-abelian, gauge field theory
  - asymptotic freedom  $\leftrightarrow$  confinement  $\leftarrow$  sub fm
- cornerstone of the Standard Model - how exactly ?
  - QCD contribution to the vacuum
  - chirality ?
  - unification ?  $\leftarrow$  sub fm
- critical role in early Universe - how exactly ?
  - highest temperature/energy  $\leftarrow$  phase equilibria  
sub+super fm
- critical role in later Universe - how exactly ?
  - wide range of temperature/energy  $\leftarrow$  phase equilibria
  - wide range of chemical potential  $\leftarrow$  astrophysics  
super fm

# Chromodynamics with Hadrons

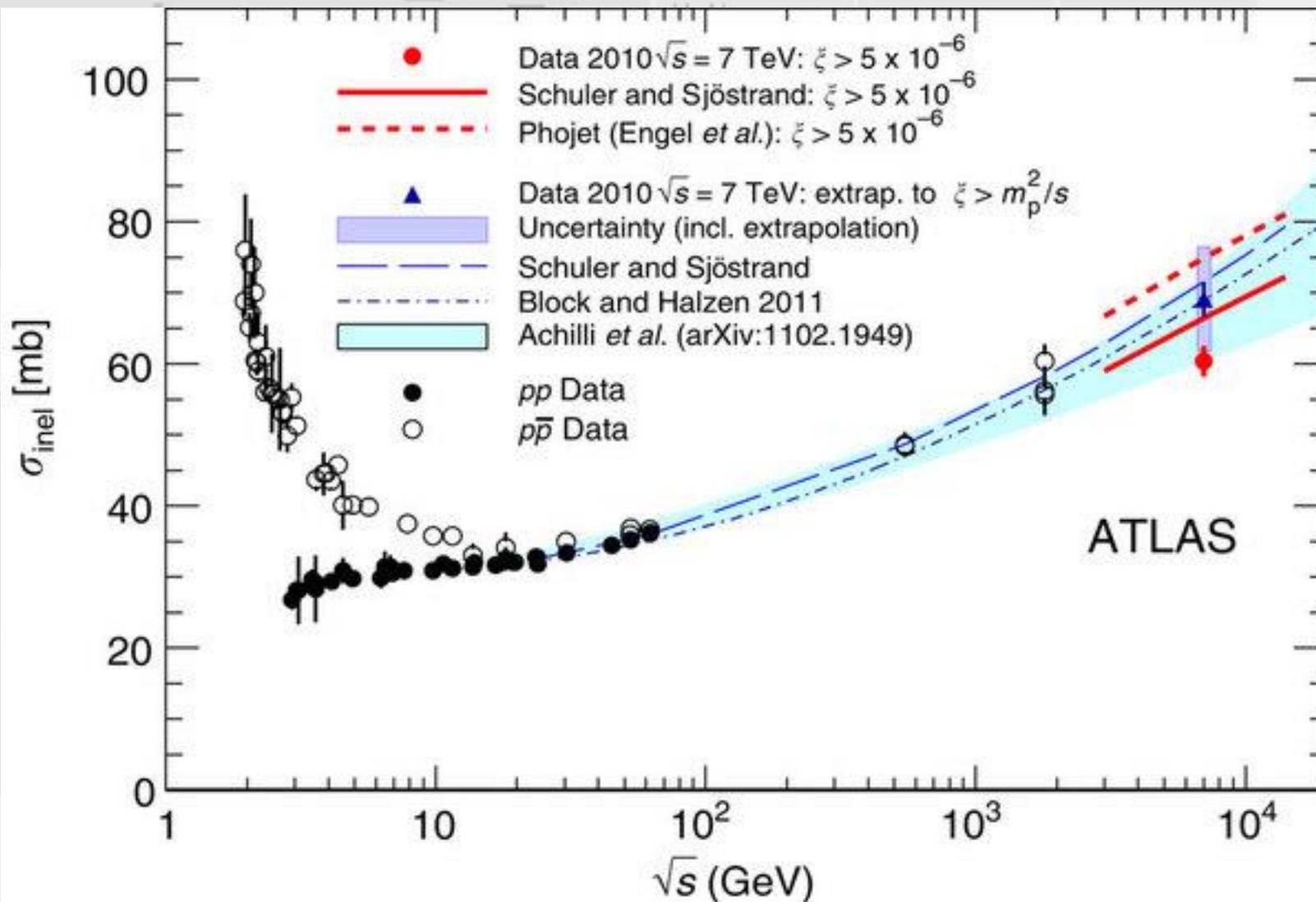


- rigorous  $SU(3)_{\text{colour}}$  non-abelian, gauge field theory
  - asymptotic freedom  $\leftrightarrow$  confinement
- cornerstone of the Standard Model
  - QCD contribution to the vacuum energy  $\leftarrow$  sub fm
  - chirality ?
  - unification ?
- precision measurements of hadronic interaction
  - in/exclusive: elastic + inelastic  $\leftarrow$  super fm
  - non-pQCD inv. + analyticity  $\leftarrow$  rigour
  - deep-inelastic inclusive: pQCD  $\leftarrow$  sub fm: rigour
  - deep-exclusive: elastic + inelastic  $\leftarrow$  sub fm + rigour
  - pQCD analyticity
- nuclear dynamics in QCD  $R = R_0 A^{1/3}$  ?  $\leftarrow$  sub fm

control of scale governs QCD field at work

# Inelastic Inclusive

- inelastic  $pp \rightarrow X$

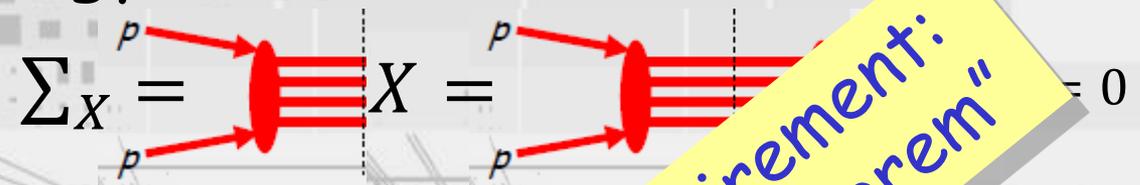


# Hadronic Interaction



- unitarity technology on  $pp \rightarrow X$

- optical theorem  $\sum_X = \dots$



↳  $\sigma_{pp}(s = W^2) = \frac{1}{W^2} \text{Im} T_{pp \rightarrow pp}(s = W^2, t = 0)$

forward elastic  $pp$  amplitude

- analyticity + rotational invariance of amplitude

↳  $T_{pp \rightarrow pp}(x) \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{1+\lambda(t)} \quad x_{\mathbb{P}} = \frac{m_p^2 - t}{s - m_p^2}$

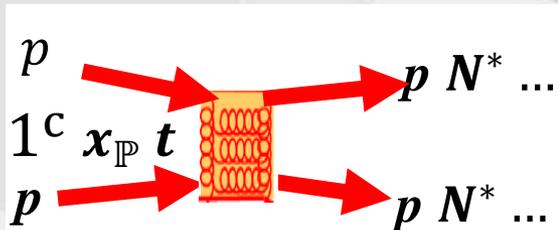
generalized Regge asymptotic limit  $\lambda(t) \lesssim 0.2$

**generic, robust and rigorous requirement:  
 Regge asymptotic limit + "optical theorem"**

- Regge asymptotic expansion  $\rightarrow$   
 $s$  or  $x_{\mathbb{P}}$  dependence of dynamics at fixed  $t$

# Elastic Exclusive

- elastic  $pp \rightarrow pp$   
 $19 \leq \sqrt{s} \leq 62 \text{ GeV}$



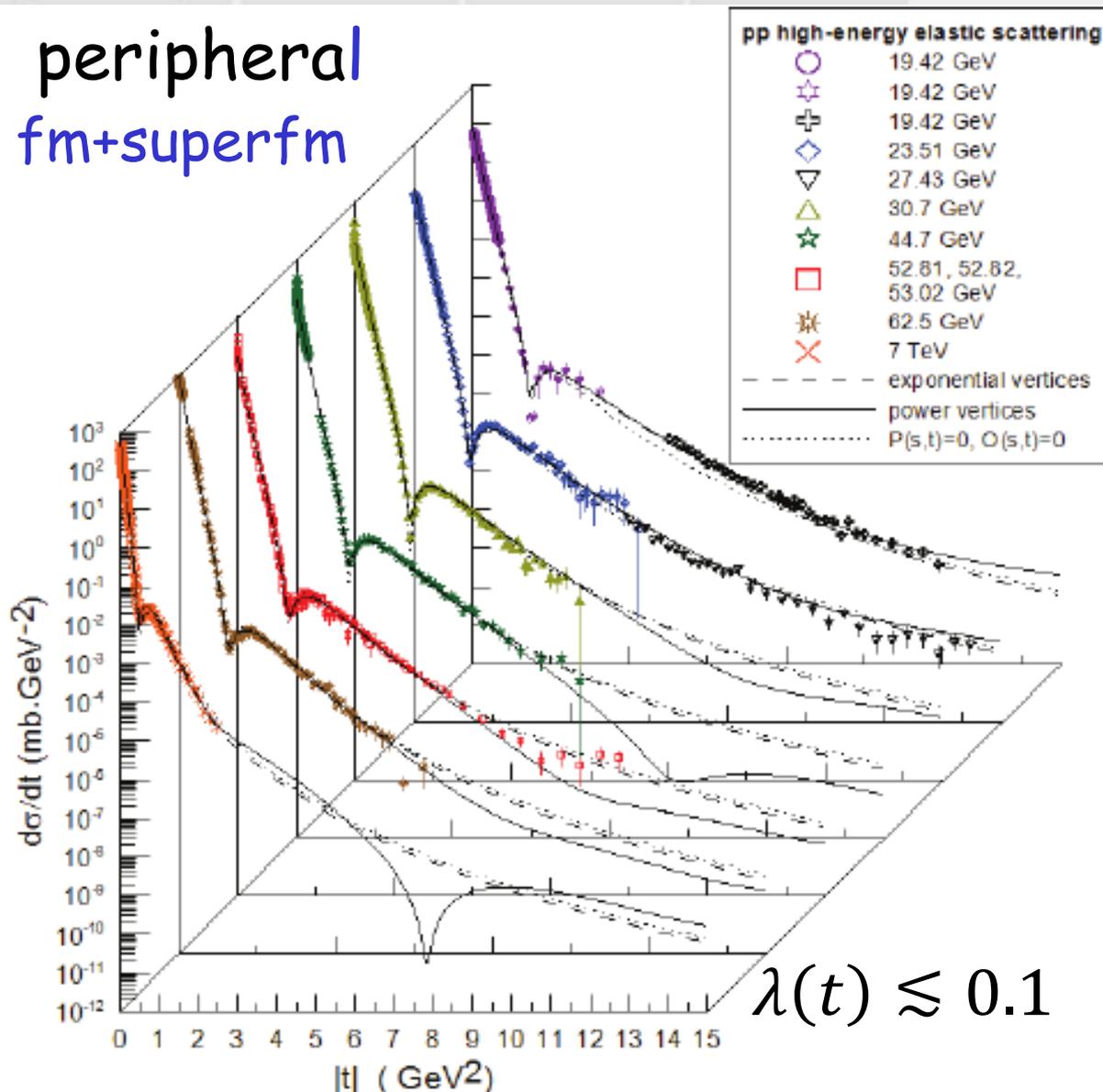
- analyticity  $\rightarrow$

$$\left(\frac{d\sigma}{dt}\right)_t \propto s^{2\lambda(t)}$$

$$|t| \lesssim 1 \text{ GeV}^2$$

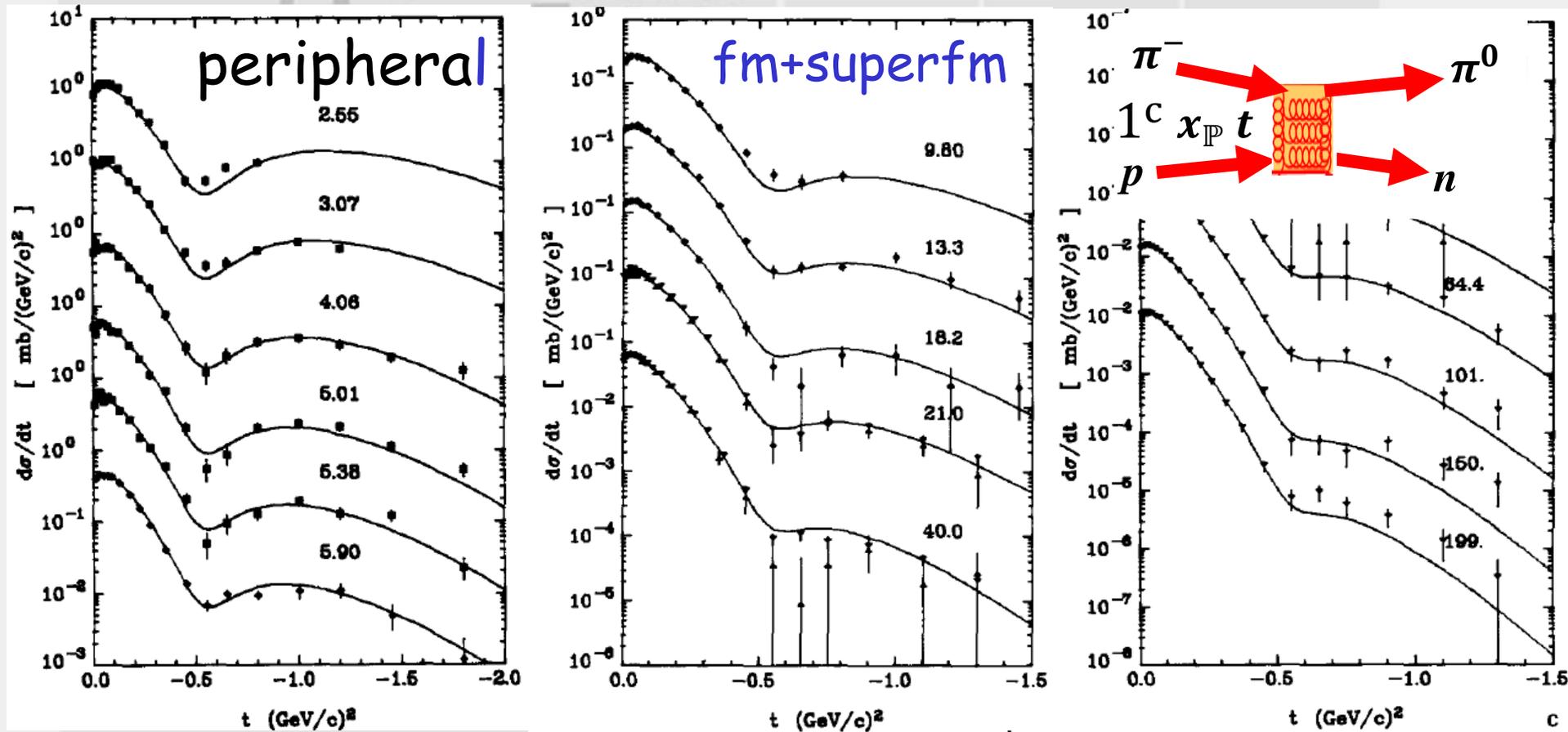
leading pole in  
 "Regge asymptotic  
 expansion"

peripheral  
 fm+superfm



# Inelastic Exclusive

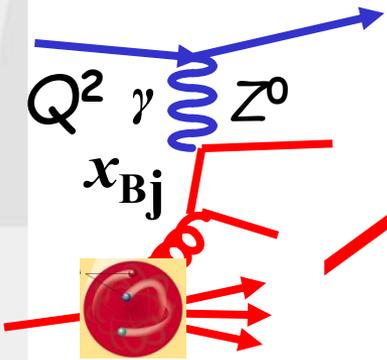
- inelastic  $\pi^- p \rightarrow \pi^0 n$   $2.5 \leq p_\pi \leq 200 \text{ GeV}/c$



- analyticity  $\rightarrow \left(\frac{d\sigma}{dt}\right)_t \propto s^{2\lambda(t)} \quad |t| \lesssim 1 \text{ GeV}^2 \quad \lambda(t) \lesssim -0.5$   
 leading pole (or more) in "Regge asympt<sup>tic</sup> expansion"

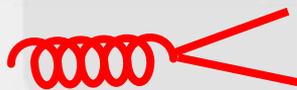
# Deep-Inelastic Inclusive

• inclusive  
 $ep \rightarrow eX$



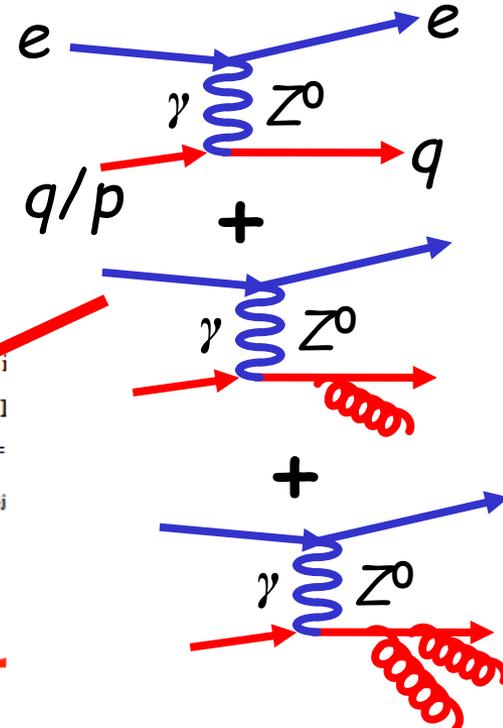
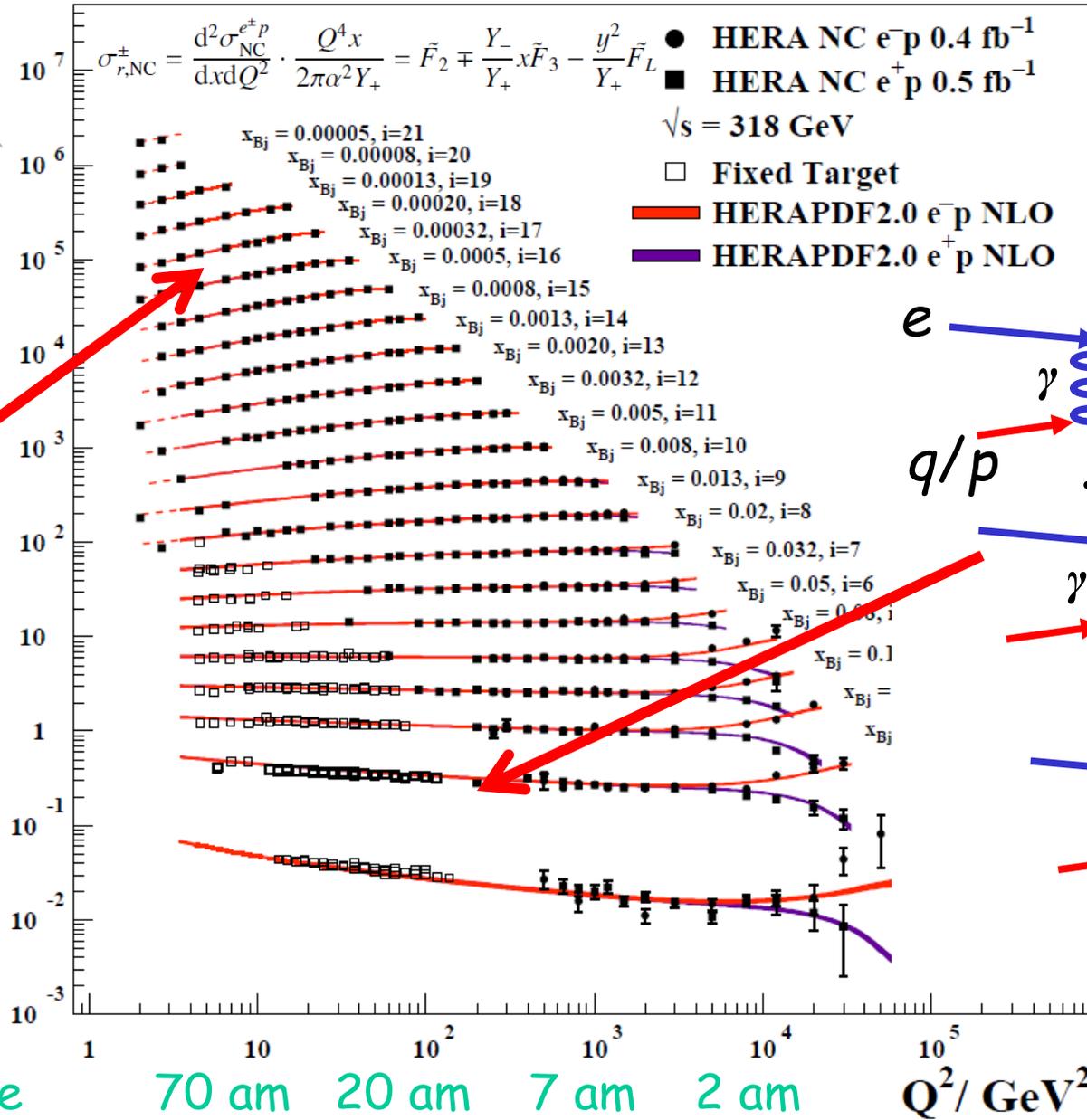
colour  
driven

$$g \rightarrow \bar{q}q$$



$$\propto \ln \frac{Q^2}{\Lambda^2} + \dots$$

sub fm probe



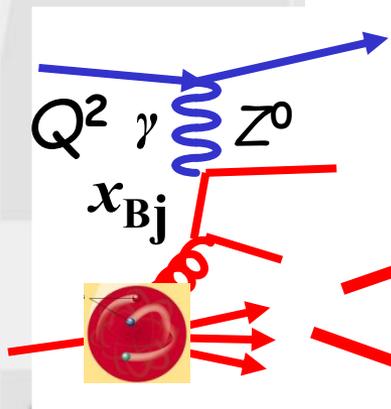
valence  
driven

70 am 20 am 7 am 2 am

$Q^2 / \text{GeV}^2$

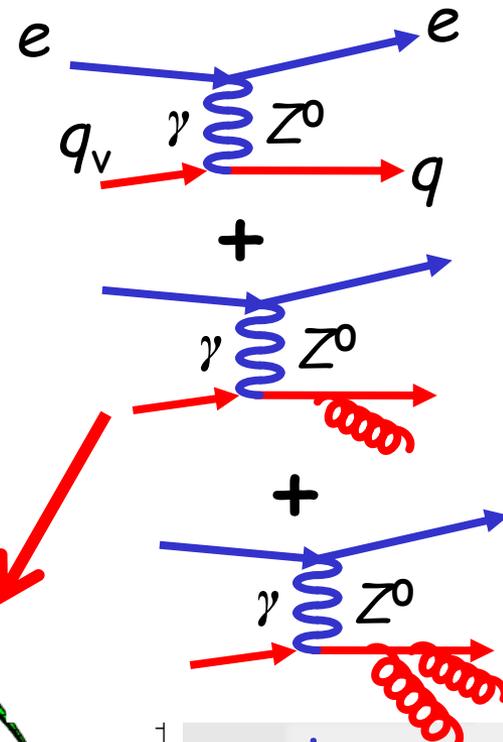
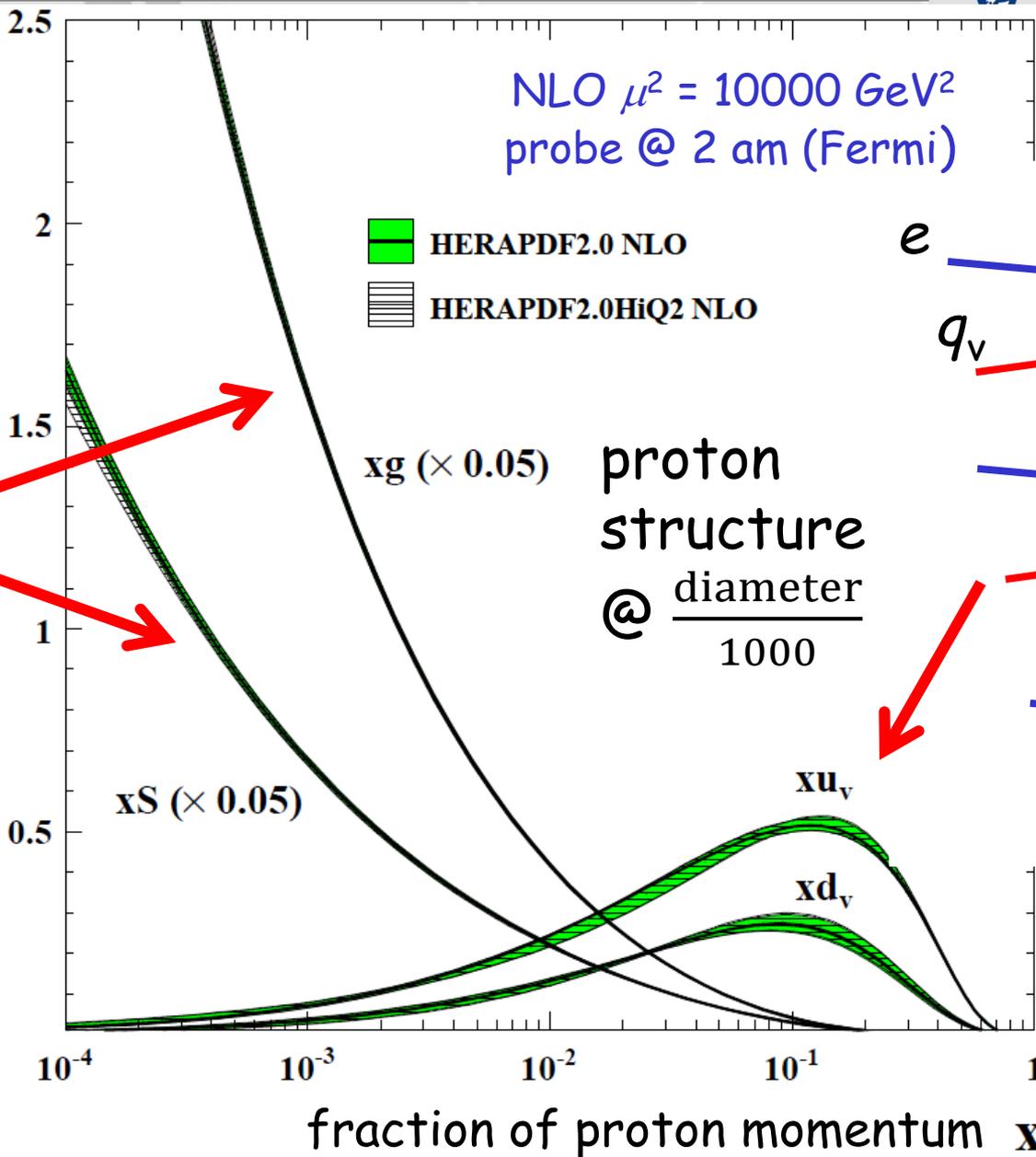
# Deep-Inelastic Inclusive

- inclusive  $ep \rightarrow eX$



colour driven  
 $g \rightarrow \bar{q}q$

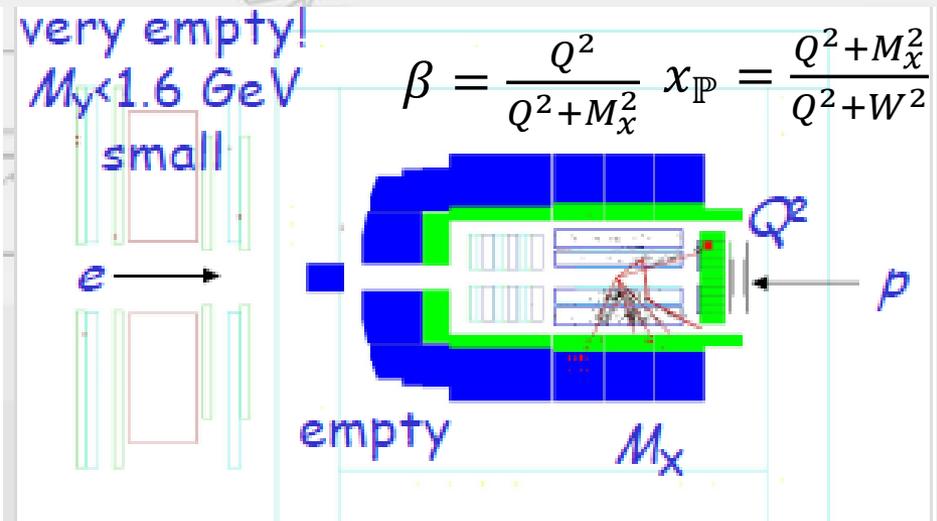
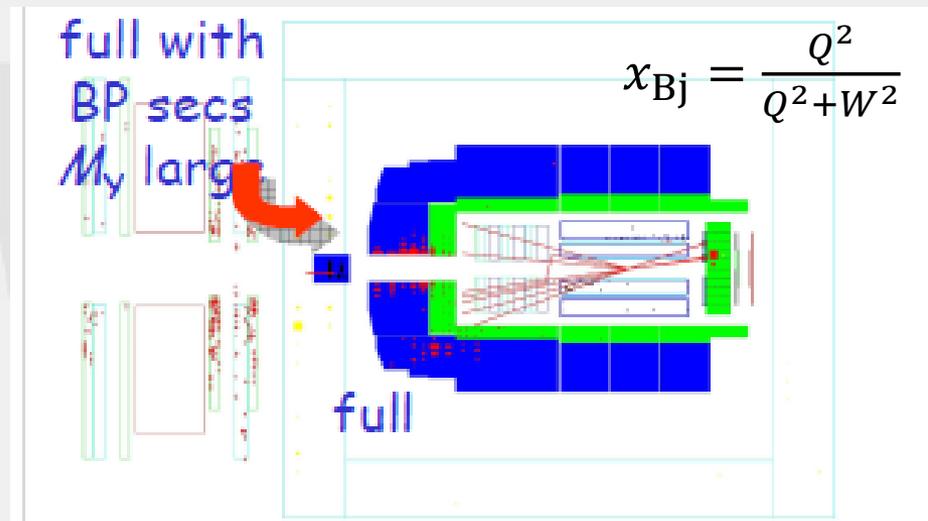
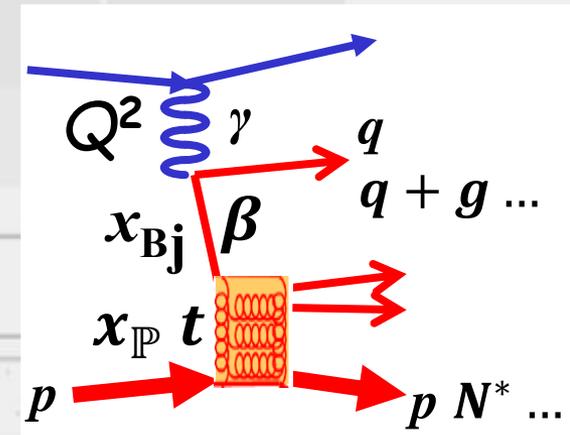
sub fm



valence driven

# Deep-Inelastic Semi-Inclusive

- semi-inclusive  $ep \rightarrow eXY$ 
    - $Y \geq p$  isolated in forward  $\eta \rightarrow$  gap
    - $Y$  forward hadron(s)
- ↳ deep-inelastic probe of hadronic interaction

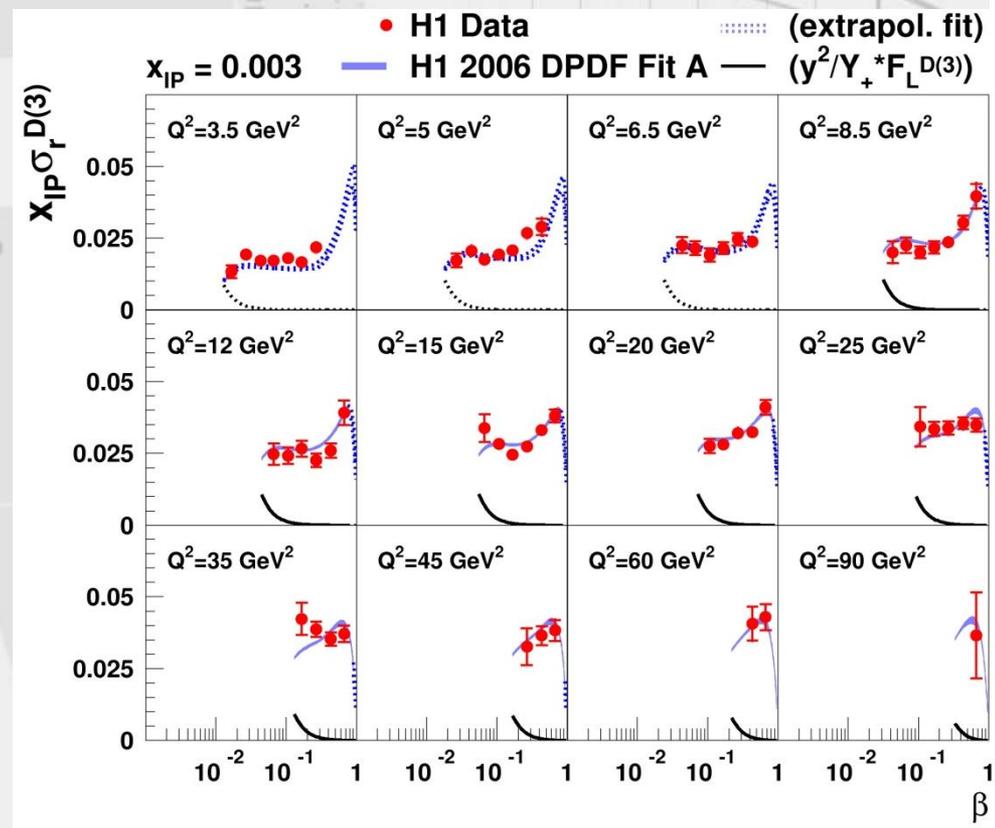
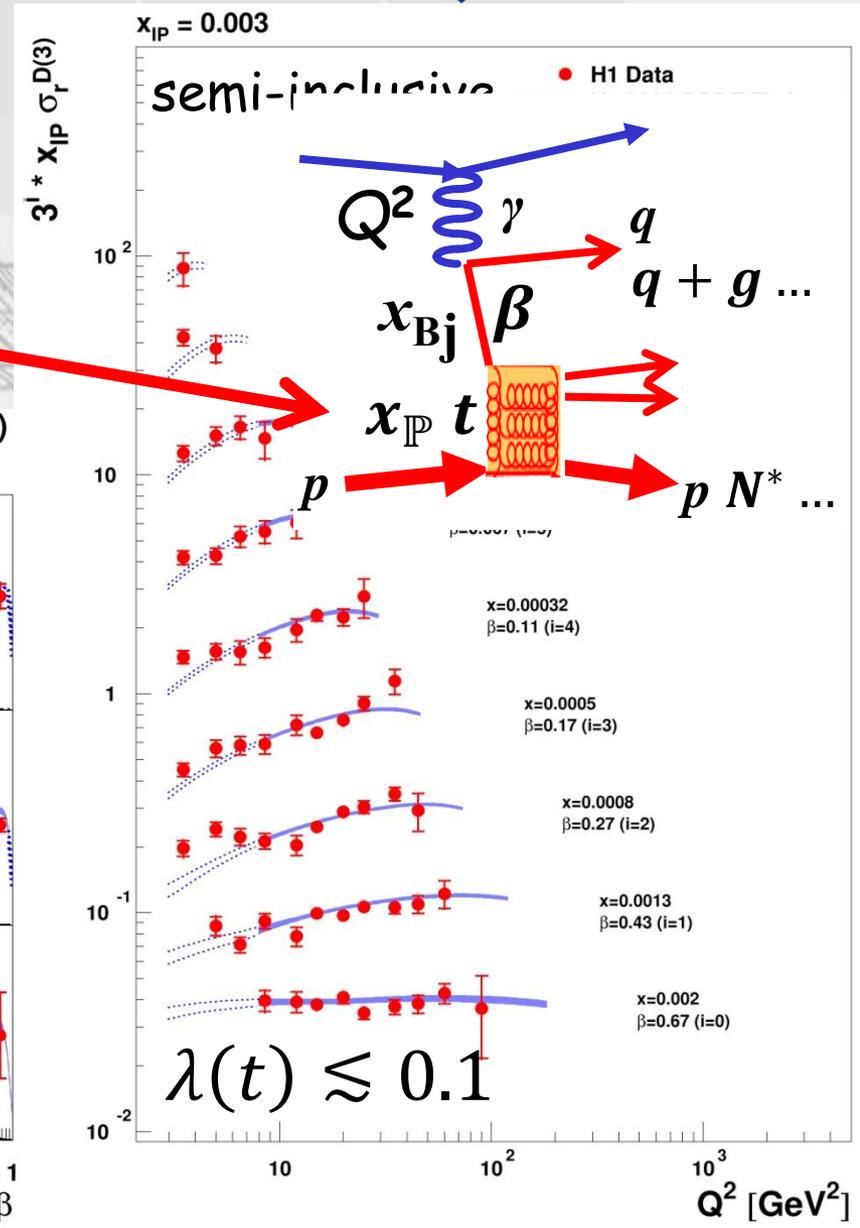


• unquestionably dramatic: void ← 920 GeV proton

# Deep-Inelastic Semi-Inclusive



- x-section  $x_{IP} \sigma_r \sim F_2(\beta, Q^2, x_{IP})$
- scaling violations  $\rightarrow$   $1_f(q_s)$  QCD evolution
- $\beta$  dep<sup>c</sup>  $\rightarrow g \rightarrow q\bar{q}$



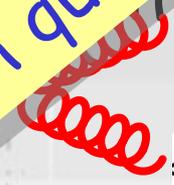
# Sub fm Colour Dynamics



- the colour dynamics of the nucleon and the interaction



LO+NLO



LO+NLO

$$g \rightarrow q\bar{q}$$

$$+ g \rightarrow q\bar{q}g$$

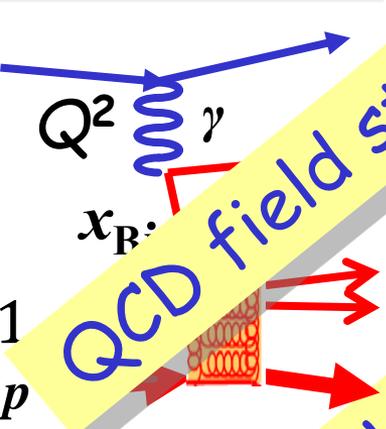
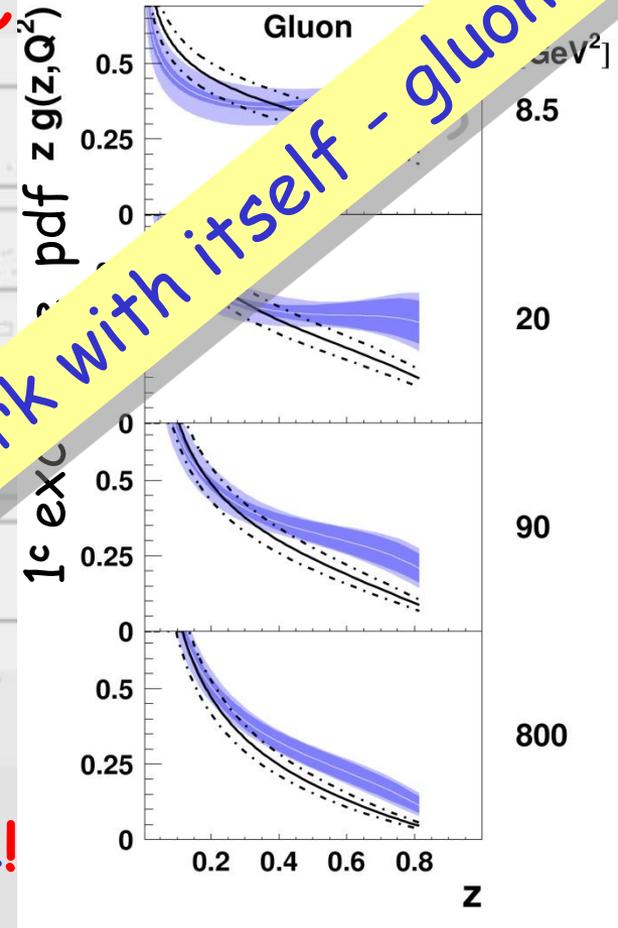
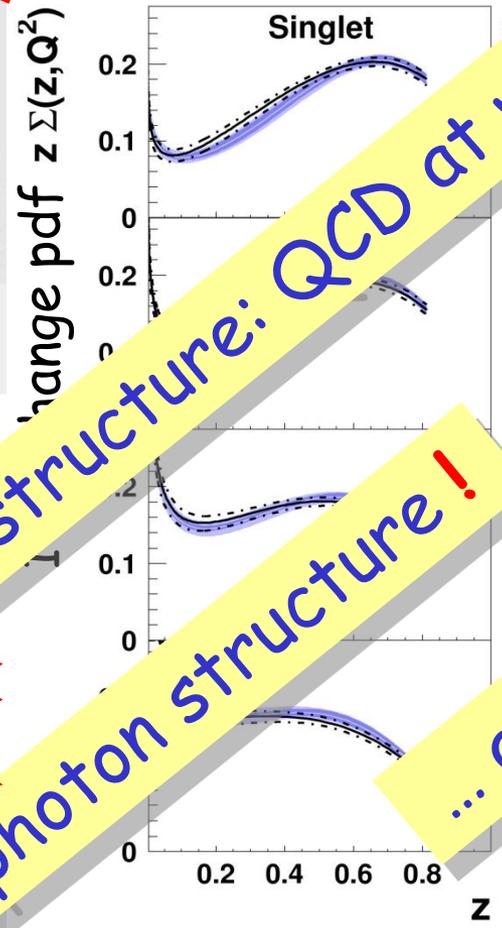
$$+ \dots$$

$$g +$$

$$g \rightarrow gg +$$

$$g \rightarrow ggg$$

$$+ \dots$$



QCD field structure: QCD at work with quarks ...  
cf photon structure!

... and QCD at work with itself - gluons

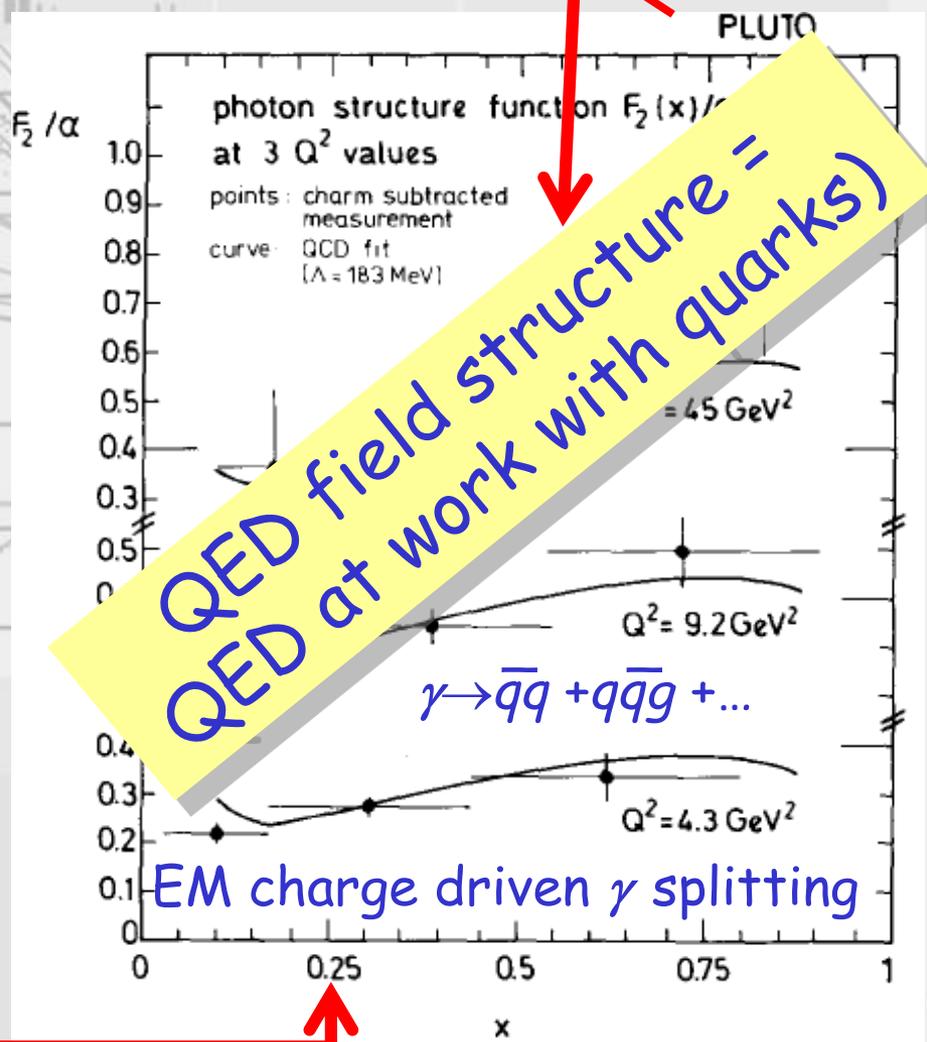
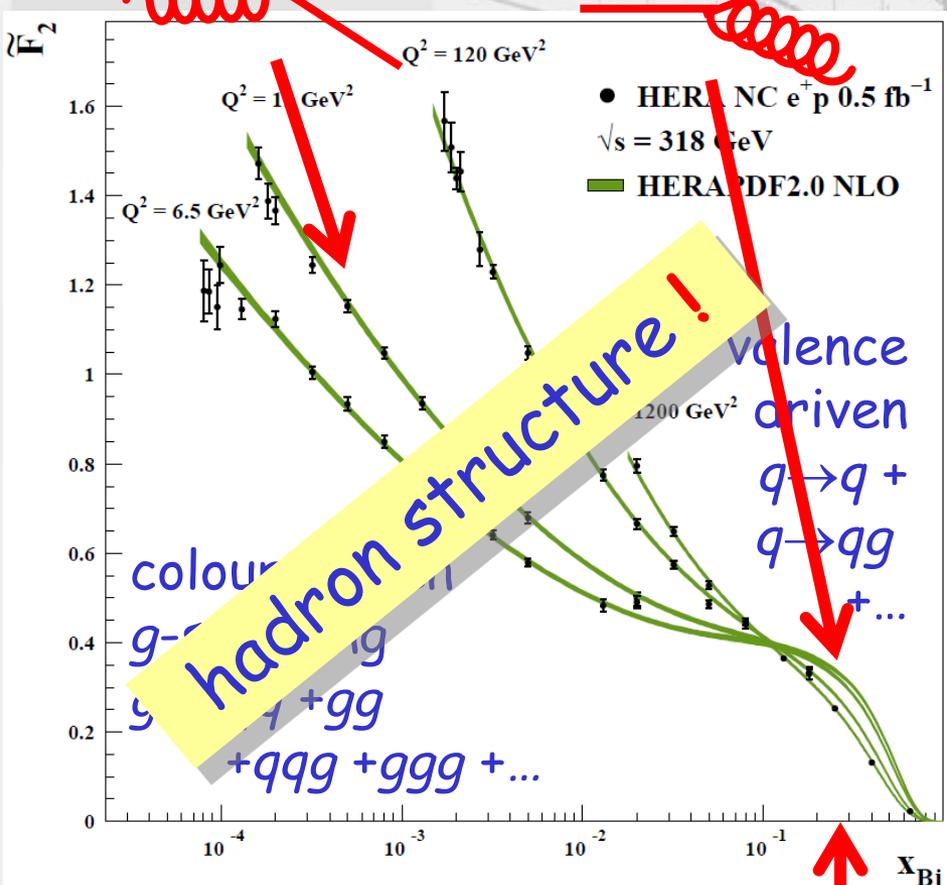
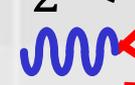
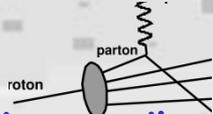
no valence!

"hard" (~70%) g with  $g \rightarrow gg$  and  $g \rightarrow q\bar{q}$  splitting

# Hadronic Structure



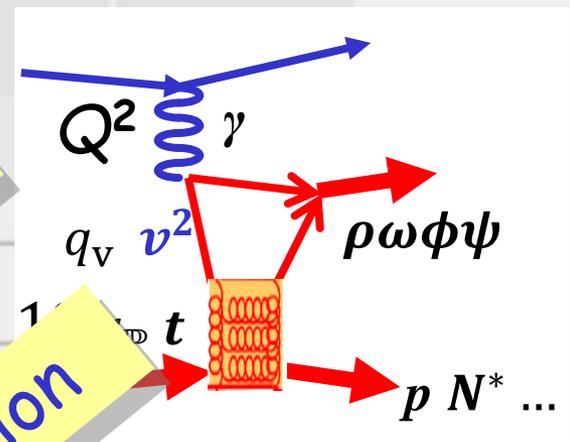
- structure functions  $F_2(x, Q^2 \text{ fixed})$  and  $F_2^\gamma(x, Q^2 \text{ fixed})$
- hadron + QCD "g-splitting"
- photon + QCD "γ-splitting"



# Deep-Elastic Exclusive



- exclusive  $ep \rightarrow eXY$ 
  - $X, Y = 1_c$  hadron isolated in  $\eta$
  - eg deep-elastic exclusive  
 $X = \rho\omega\phi\psi \quad Y = p N^* \dots$



- embedded Bethe-Heitler  $\gamma^* 1_c \rightarrow$  QCD  
 virtual photon splits into  $q\bar{q}$
- QCD dynamics  $\rightarrow$  Dirac  $\rightarrow$  gluons  
 embedded  $\rightarrow$   $q\bar{q}$  Rutherford scattering

- QCD scattering set by  $M^2, \rho\omega\phi\psi, m_q^2 \rightarrow |v^2| \gg |t|$

$$m_q^2 - v_{\min}^2 = \frac{M^2}{2} \left( 1 \mp \sqrt{1 + 4 \frac{Q^2 t}{(M^2 + Q^2 - t)^2}} \cdot \sqrt{1 - 4 \frac{m_q^2}{M^2}} \right)$$

$m_q$  = quark inertia in hadron chromodynamic field

quark and gluons in hadron = in p A  
 no chromodynamic radiation

# Deep-Elastic Exclusive

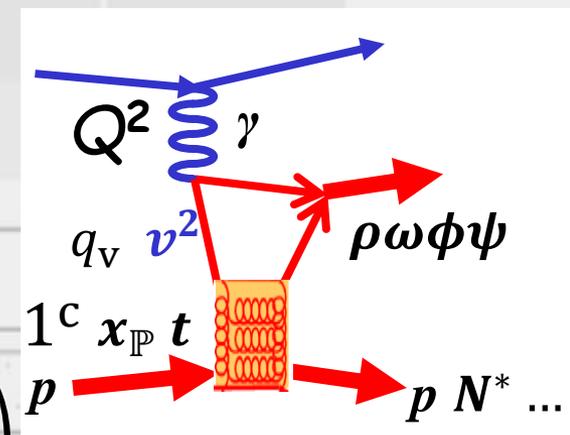


- quark flavour  $u/d, s, c, b \leftrightarrow \rho/\omega, \phi, \psi, Y$

- QCD scale  $v$  ?

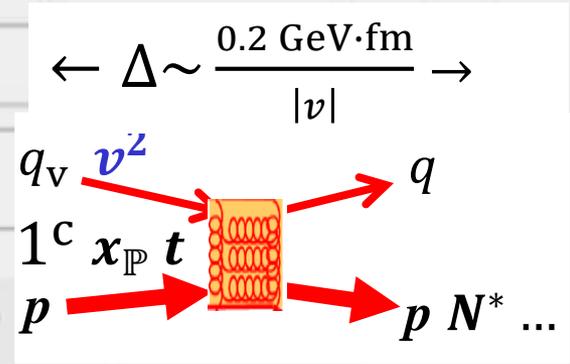
$$m_q^2 - v_{\min}^2 \leq v \leq v_{\max}^2$$

$$= \frac{M^2 + Q^2 - t}{2} \left( 1 \mp \sqrt{1 + 4 \frac{Q^2 t}{(M^2 + Q^2 - t)^2}} \cdot \sqrt{1 - 4 \frac{m_q^2}{M^2}} \right)$$



quark "virtuality"

$-v^2 \leftrightarrow$  length  $\Delta \sim \frac{0.2 \text{ GeV}\cdot\text{fm}}{|v|}$  of collinear  $q^* p \rightarrow qp, qY$



long and short elastic  $q_v p \rightarrow qp$  scattering  
 long and short  $q_v p \rightarrow qp$  Rutherford scattering

# Deep-Elastic Exclusive



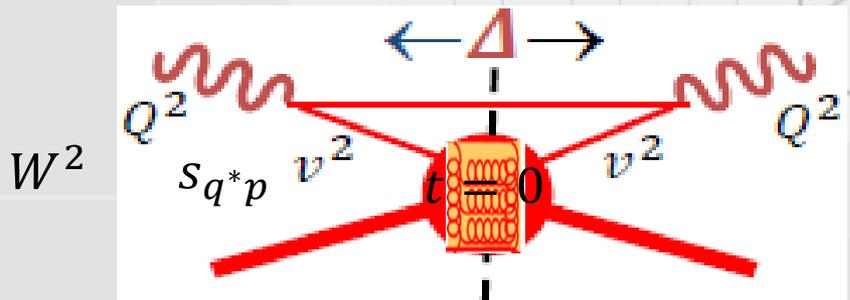
- unitarity technology on  $\gamma^* p \rightarrow X$

- optical theorem

$$\sum_i \left| \text{Diagram}_i \right|^2 = \text{Diagram} = \text{Im} \text{Diagram}_{t=0}$$

$$\begin{aligned} \sigma_{\gamma^* p}(W^2, Q^2) &= \frac{1}{Q^2 + W^2} \text{Im} T_{\gamma^* p \rightarrow \gamma^* p}(W^2, t=0, Q^2) \\ &\equiv \frac{x_{\text{Bj}}}{Q^2} \text{Im} T_{\gamma^* p \rightarrow \gamma^* p}(W^2, t=0, Q^2) = \frac{4\pi^2 \alpha}{Q^2} F_2(x_{\text{Bj}}, Q^2) \end{aligned}$$

$\hookrightarrow F_2(x_{\text{Bj}}, Q^2) \xleftrightarrow{\text{fixed } Q^2} T_{\gamma^* p \rightarrow \gamma^* p}(x_{\text{Bj}}, t=0, Q^2)$ 
forward Compton amplitude



$$x_{\text{Bj}} = \frac{m_q^2 + Q^2 - t}{Q^2 + W^2 - m_p^2}$$

$$x_{\text{P}} = \frac{-t}{W^2 + Q^2 - m_p^2} \equiv \frac{-t}{s_{q^*p} - v^2 - m_p^2}$$

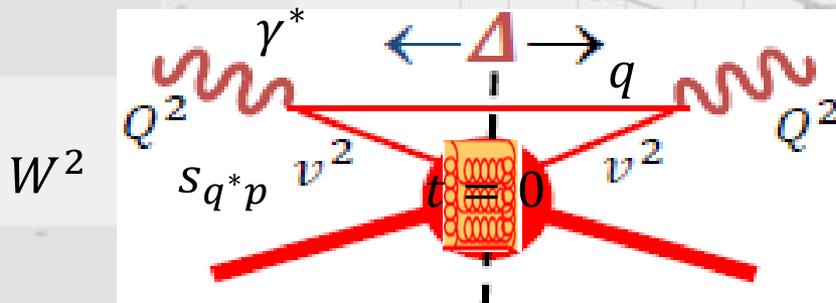
- forward  $q^* p$  Rutherford scattering amplitude

$$T_{q_{\text{v}p} \rightarrow q_{\text{v}p}}(s_{q^*p}, t=0, v^2) \text{ embedded in } F_2(x_{\text{Bj}}, Q^2)$$

# Deep Forward Exclusive

- virtuality  $v^2$  of quark in forward  $q_{\nu}p \rightarrow q_{\nu}p$ 
  - rest frame of time-like  $q$  in B-H splitting

$$E_{\gamma}^* = \frac{m_q^2 - Q^2 - v^2}{2M_q} > 0 \quad E_{\nu}^* = \frac{m_q^2 + v^2 + Q^2}{2M_q} > 0$$



$$x_{\text{Bj}} = \frac{m_q^2 + Q^2 - t}{Q^2 + W^2 - m_p^2}$$

$$x_{\mathbb{P}} = \frac{-t}{W^2 + Q^2 - m_p^2} \rightarrow \frac{-t}{s_{q^*p} - v^2 - m_p^2}$$

↳  $m_q^2 > v^2 + Q^2 > -m_q^2 \xrightarrow{m_q^2 \rightarrow 0} v^2 = -Q^2 !$

↳ for  $q_{\nu} = u/d$  quark virtuality = photon ( $\gamma^*$ ) virtuality

↳ forward  $q_{\nu}p$  Rutherford scattering amplitude  
 $T_{q_{\nu}p \rightarrow q_{\nu}p}(s_{q_{\nu}p}, t=0, v^2)$  embedded in  $F_2(x_{\text{Bj}}, Q^2) !$

# Deep Forward Exclusive

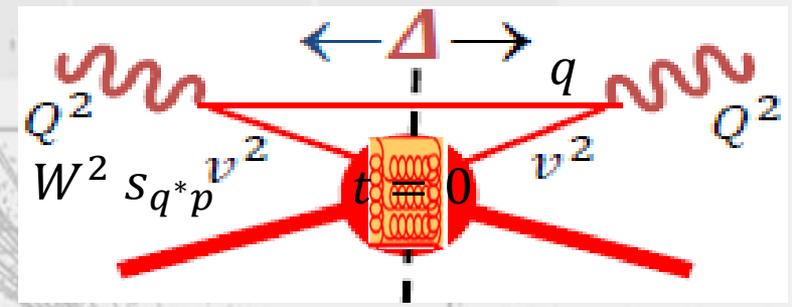


- analyticity applied to forward scattering  $q_{\nu}p \rightarrow q_{\nu}p$

$$T_{q_{\nu}p \rightarrow q_{\nu}p}(x_{\mathbb{P}}, t = 0, v^2)$$

$$\xrightarrow[x_{\mathbb{P} \rightarrow 0}]{\text{Regge}} \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{1+\lambda(Q^2, t=0)} \quad \lambda \lesssim 0.2$$

sub fm ?



- "Regge asymptotic" limit  $\leftarrow W^2 \gg |v^2| \gg |t|, m_p^2, m_q^2$

- independent of  $q$  flavour

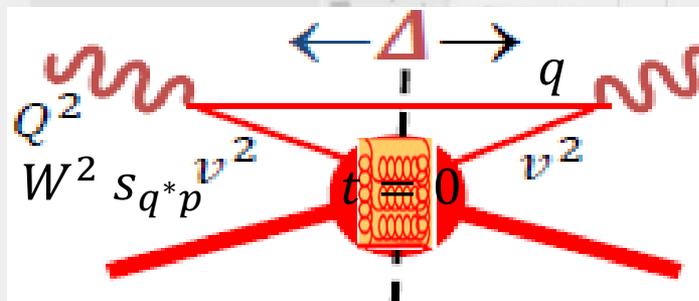
$\hookrightarrow$  structure function  $F_2(x_{Bj}, Q^2 = -v^2)$  + analyticity  $\rightarrow$  forward scattering amplitude  $T_{q_{\nu}p \rightarrow q_{\nu}p}(x_{\mathbb{P}}, t = 0, v^2)$

$\hookrightarrow$  (low)  $x_{Bj}$  dependence of  $F_2(x_{Bj}, Q^2)$  at fixed  $Q^2$

where  $\frac{1}{x_{Bj}} = \frac{W^2 + Q^2}{Q^2} \xrightarrow[\text{Regge}]{W^2} \infty$

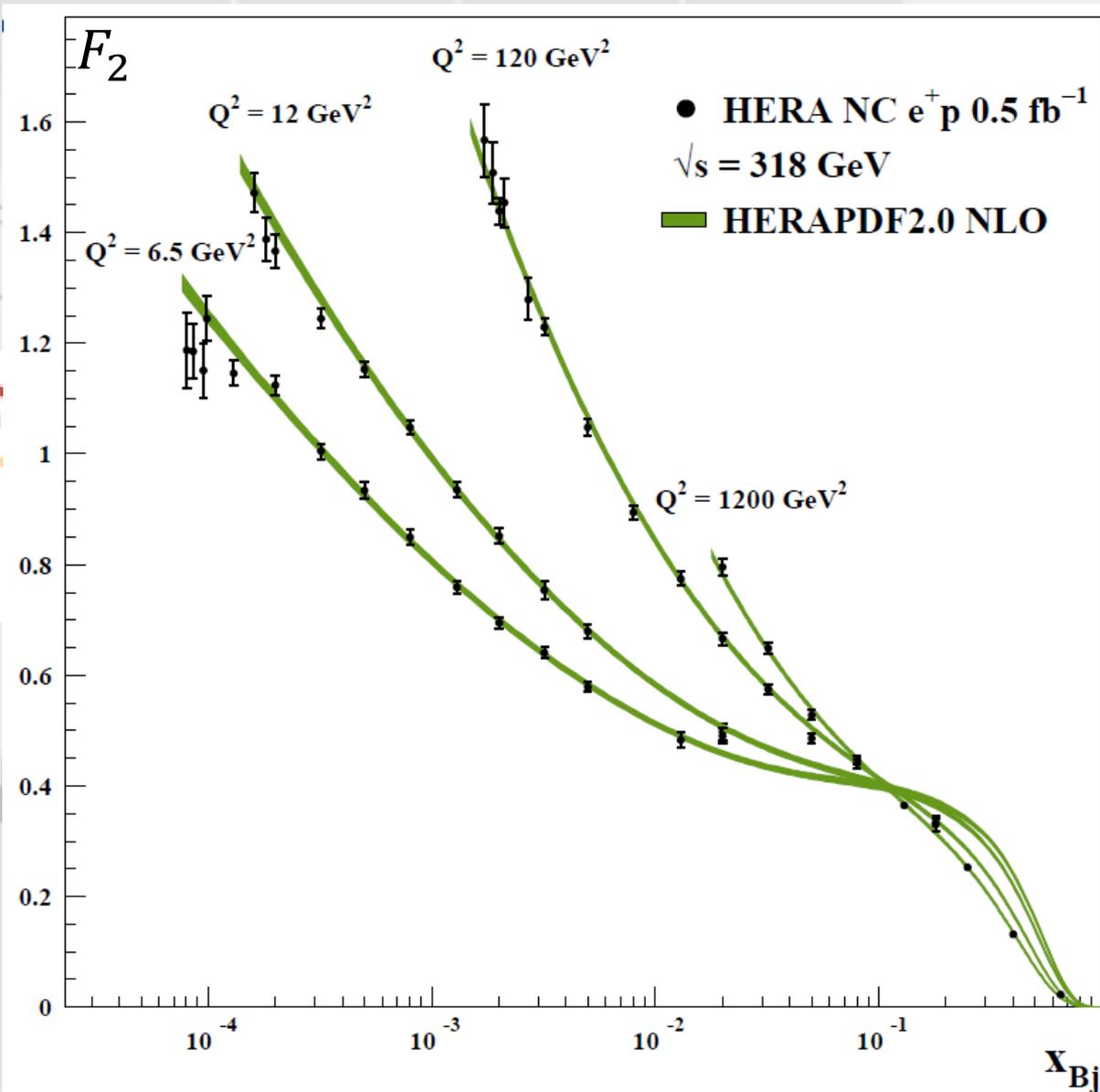
# Deep Forward Exclusive

- (low)  $x_{Bj}$  dependence of  $F_2(x_{Bj}, Q^2)$  at fixed  $Q^2$



$$\sigma_{\gamma^* p \rightarrow X}(W^2, Q^2) = \frac{4\pi^2\alpha}{Q^2} F_2(x_{Bj}, Q^2)$$

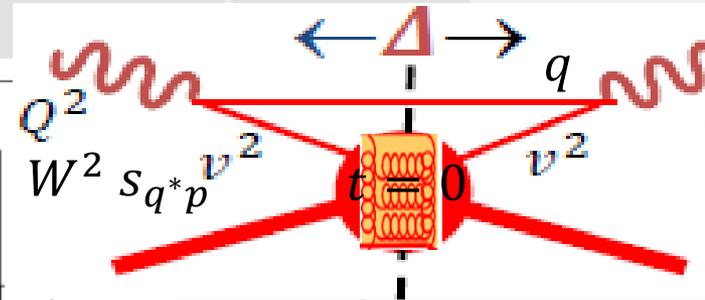
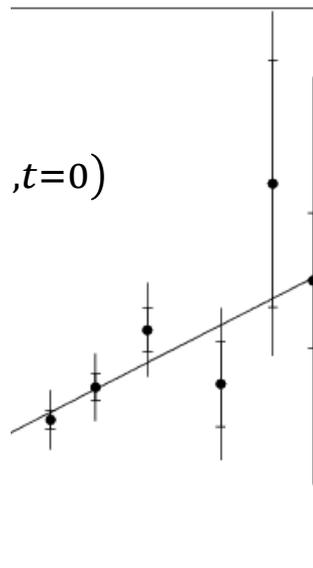
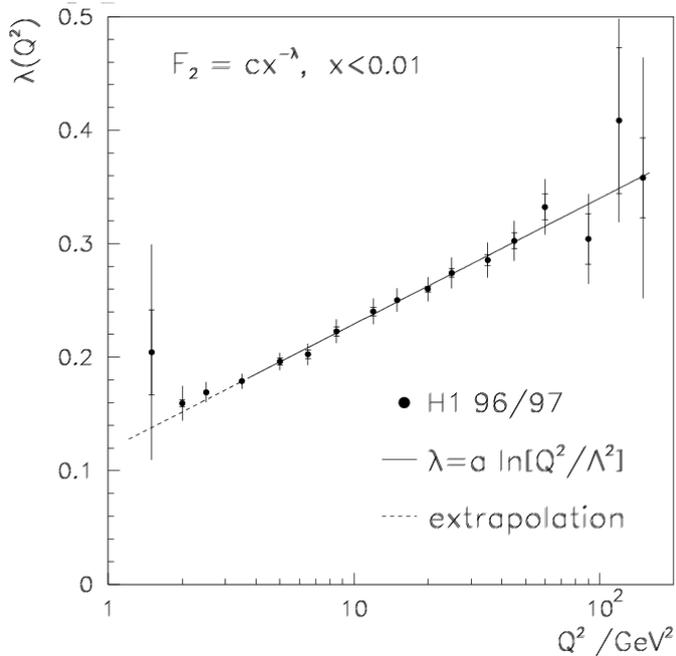
Regge  $\longrightarrow \propto x_{Bj}^{-\lambda(Q^2, t=0)}$



# Deep Forward Exclusive



- the universal pomeron  $\mathbb{P}$  ?



$$x_{Bj} = \frac{m_q^2 + Q^2 - t}{Q^2 + W^2 - m_p^2}$$

$$x_{\mathbb{P}} = \frac{-t}{W^2 + Q^2 - m_p^2}$$

$$\rightarrow \frac{-t}{s_{q*p} - v^2 - m_p^2}$$

$$\lambda(Q^2, t=0) = a \ln \frac{Q^2}{\Lambda^2}$$

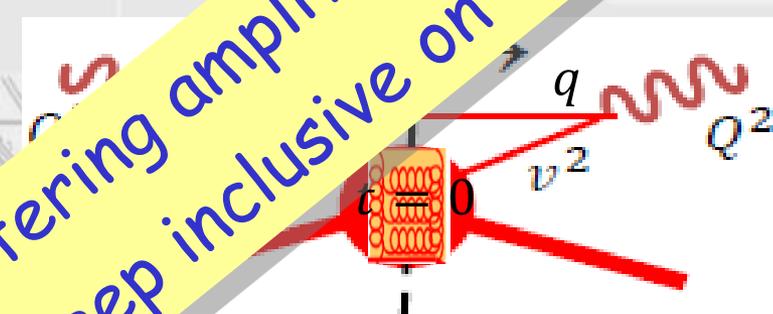
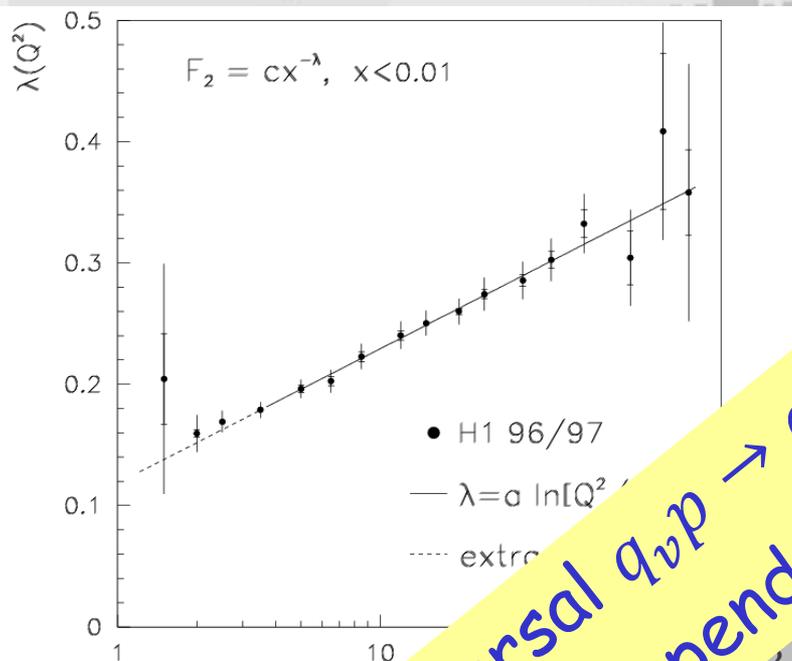
$$a = 0.0481 \pm 0.0013(\text{stat}) \pm 0.0037(\text{syst})$$

$$\Lambda = 0.292 \pm 0.020(\text{stat}) \pm 0.0051(\text{syst}) \text{ GeV}$$

H1 Collaboration, Phys. Lett. **B598** (2004) 159

# $q_{\nu}p \rightarrow q_{\nu}p$ in Proton

- $q_{\nu}p \rightarrow q_{\nu}p$  elastic scattering ?



universal  $q_{\nu}p \rightarrow q_{\nu}p$  scattering amplitude  
 universal dependence for deep inclusive on  $-v^2$  ?

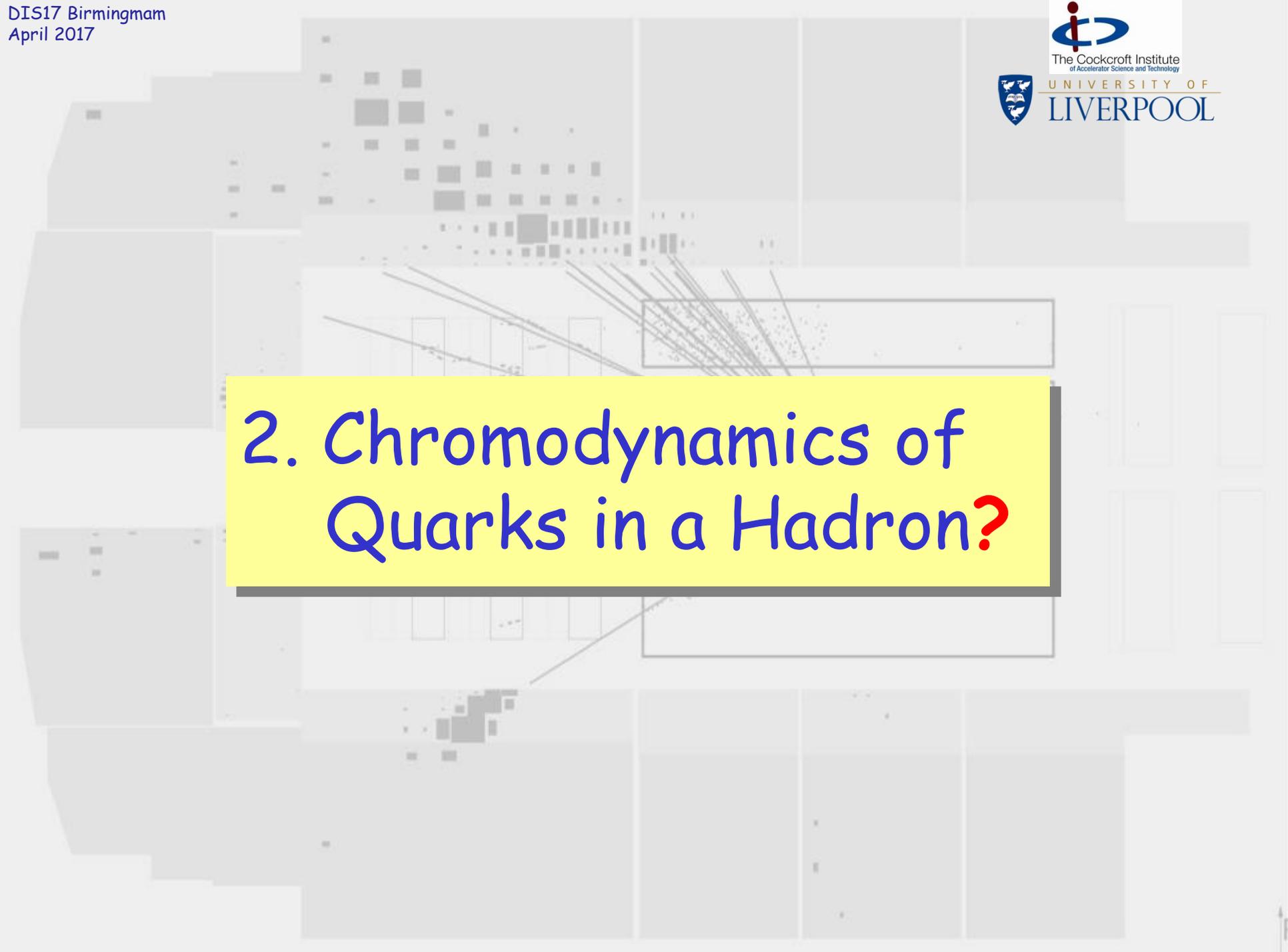
$$\sigma_{q_{\nu}p \rightarrow q_{\nu}p}(x_{\mathbb{P}}, t = 0, v^2) \xrightarrow{x_{\mathbb{P}} \rightarrow 0} \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{1+\lambda(v^2, t \gg -1 \text{ GeV}^2)}$$

Regge

$$\Lambda \rightarrow \Lambda (v^2, t \gg -1 \text{ GeV}^2) = a \ln \frac{-v^2}{\Lambda^2}$$

$$a = 0.0481 \pm 0.0013(\text{stat}) \pm 0.0037(\text{syst})$$

$$\Lambda = 0.292 \pm 0.020(\text{stat}) \pm 0.0051(\text{syst}) \text{ GeV}$$



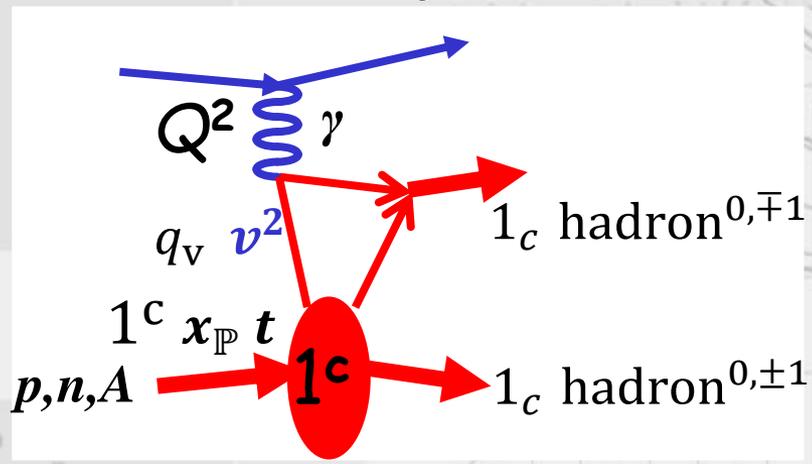
## 2. Chromodynamics of Quarks in a Hadron?

# HERA: Quarks in Proton



- quarks in hadrons

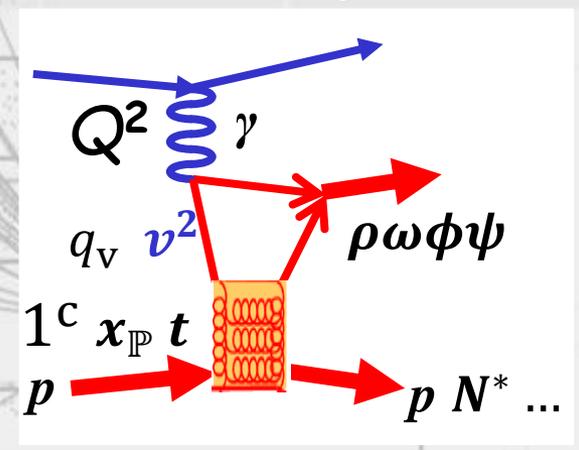
$$ep, A \rightarrow eX_{1_c} p, n, A^Z$$



- quarks in proton ?

$$ep \rightarrow eVM_{u/dsc} p N^* \dots$$

H1  
 Zeus



- $ep \rightarrow eXp$  to  $\sigma_{tot}(\gamma^* p) \rightarrow Xp + \gamma^* \rightarrow q\bar{q}$

- splitting  $dP_{\gamma^* \rightarrow q\bar{q}} = e_q \frac{\alpha}{2\pi} [y^2 + (1-y)^2] \frac{dP^2}{m_q^2 + P^2} dy$   $y = \frac{q \cdot \gamma^*}{Q \cdot \gamma^*}$

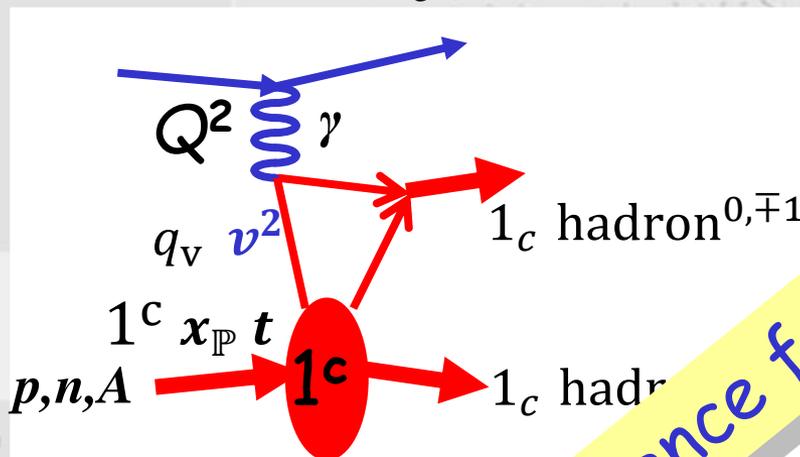
- appropriate  $q_v p$  phenomenology

$$T_{q_v p \rightarrow q_v p}(x_P, t=0, v^2) \xrightarrow[x_P \rightarrow 0]{\text{Regge}} \propto \left(\frac{1}{x_P}\right)^{1+\lambda(v^2, t \gg -1 \text{ GeV}^2)}$$

# HERA: Quarks in Proton

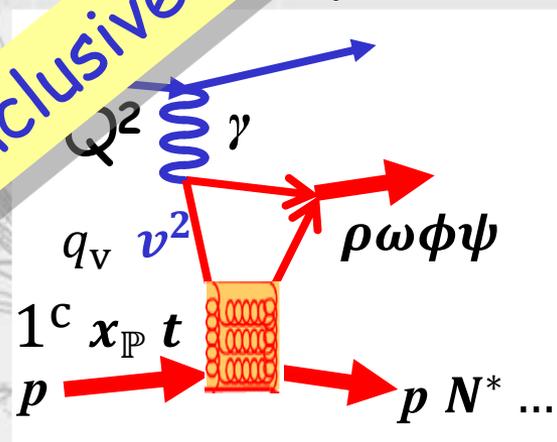
- quarks in hadrons

$$ep, A \rightarrow eX_{1c} p, n, A^Z$$



- quarks in hadron ?

$$ep \rightarrow e u/dsc p N^* \dots$$



universal dependence for deep inclusive on  $-v^2$  ?

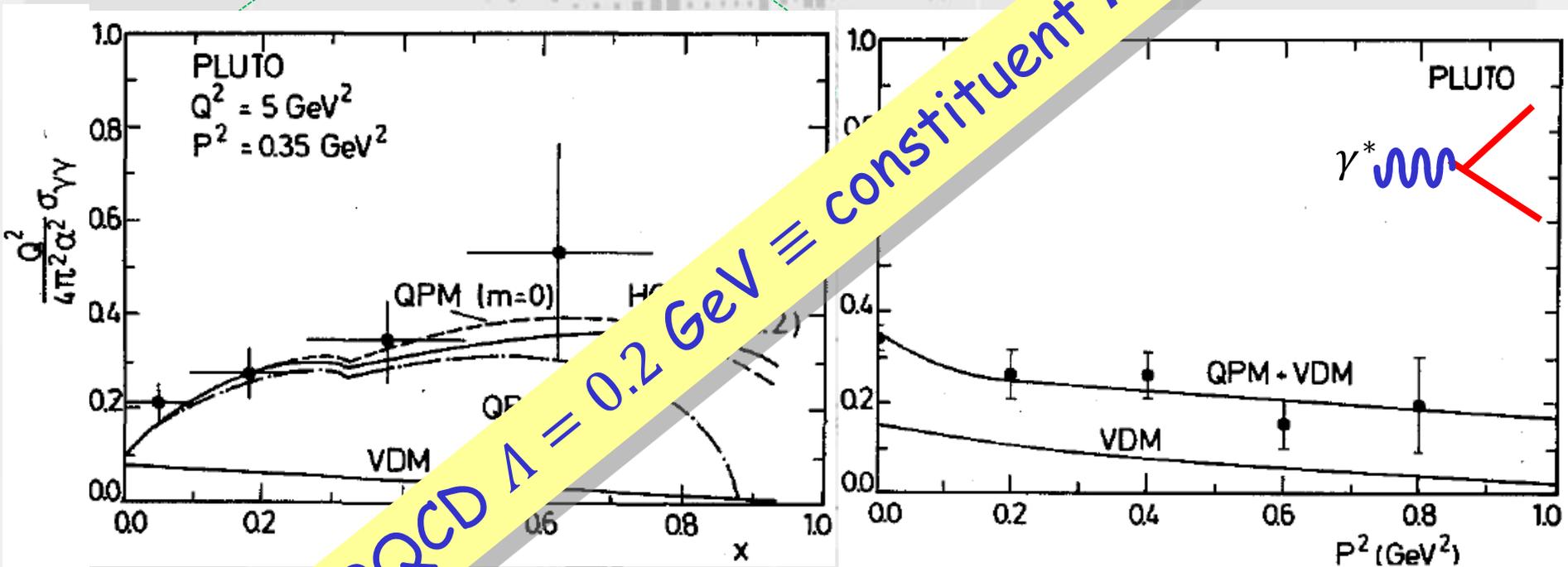
- kinematics  $\rightarrow 1_c$  hadron mass  $M$

limiting quark "virtuality"  $-v^2$  in quark splitting

$$1_{c\bar{q}} - v_{\min}^2 = \frac{M^2 + Q^2 - t}{2} \left( 1 \mp \sqrt{1 + 4 \frac{Q^2 t}{(M^2 + Q^2 - t)^2}} \cdot \sqrt{1 - 4 \frac{m_q^2}{M^2}} \right)$$

# Virtual Photon Splitting

- deep-inelastic structure of the virtual photon in  $e^+e^- \rightarrow e^+e^- + \text{hadrons}$  and  $e\gamma^* \rightarrow \text{hadrons}$



PLUTO Collaboration, Phys. Lett. B142 (1984) 120

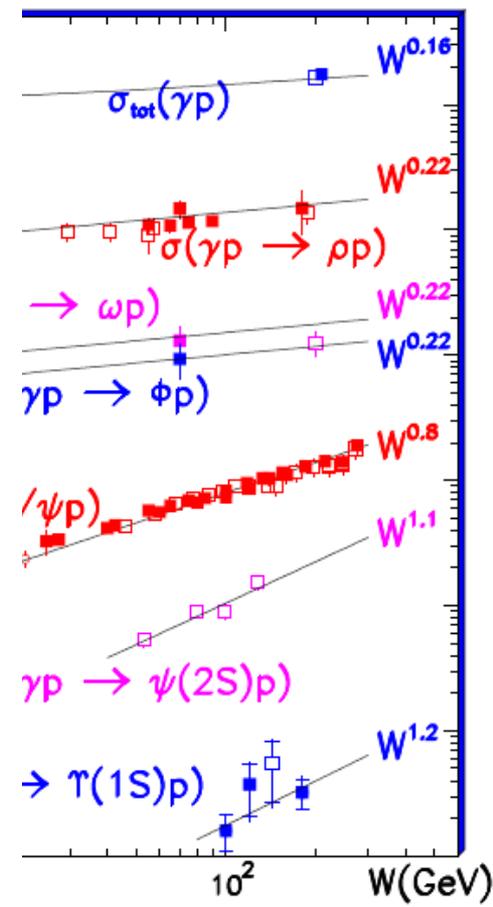
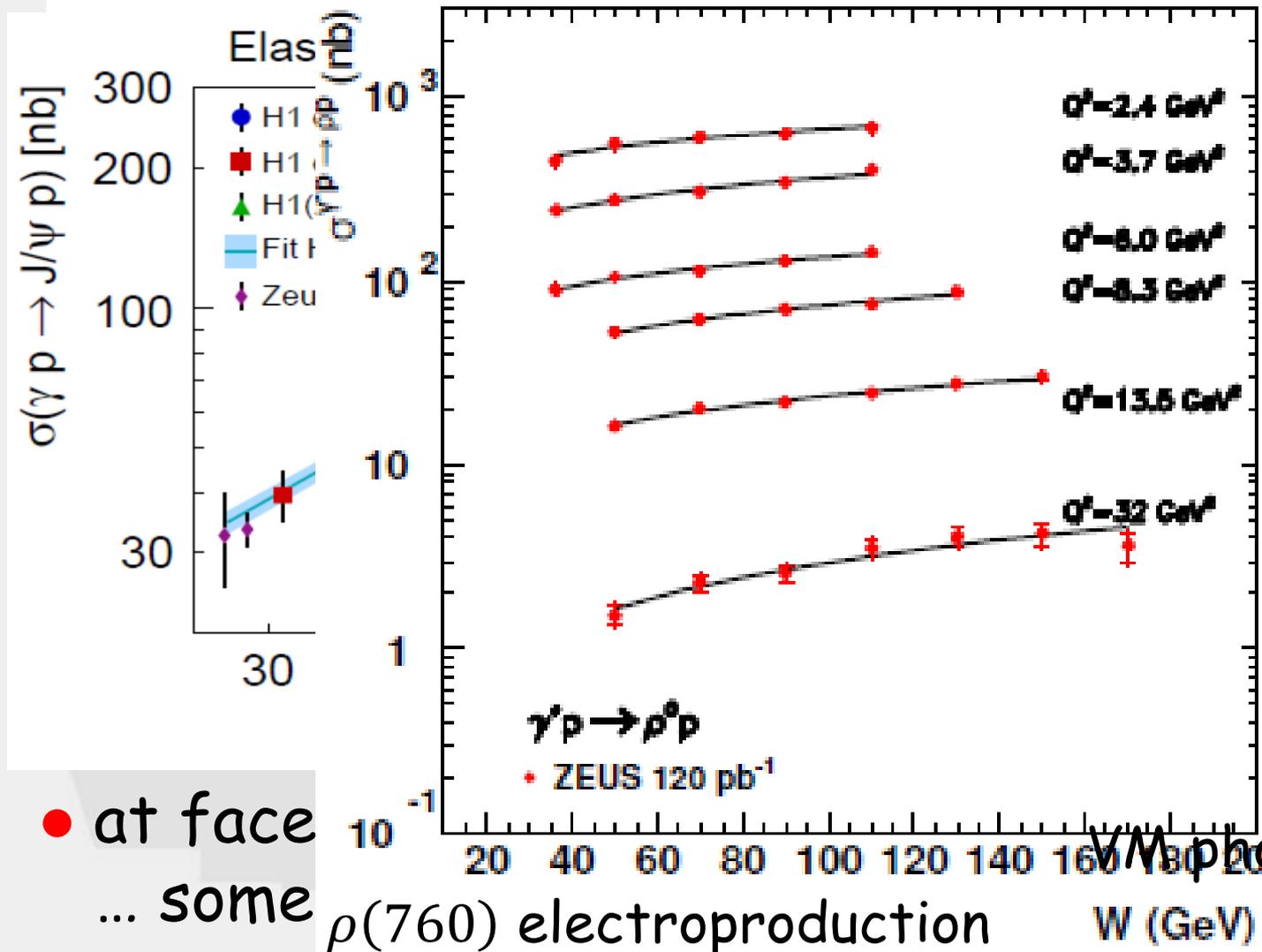
$F_2^{\gamma^*}$  consistent with (QFD) splitting  $\gamma^* \rightarrow q\bar{q}$  ( $u, d, s, c$ )

$$\frac{1}{y} F_2^{\gamma^*} = dP_{\gamma^* \rightarrow q^* \bar{q}} = e_q \frac{\alpha}{2\pi} [y^2 + (1-y)^2] \frac{dP^2}{m_q^2 + P^2} dy \quad y = \frac{q \cdot \gamma^*}{Q \cdot \gamma^*}$$

# Measurements



- H1 and Zeus  $\sigma_{\gamma^* p \rightarrow VMp, Y}(W^2, Q^2) \propto W^\delta(Q^2)$



- at face ... some

$\rho(760)$  electroproduction  
 VM photoproduction  
 W (GeV)

# Implementation: Quarks in Proton

- for  $Q^2$  evolution of  $\delta(Q^2)$  in

$$\sigma_{\gamma^* p \rightarrow VMp, Y}(W^2, Q^2) = \int_t \frac{d\sigma_{\gamma^* p \rightarrow VMp, Y}(W^2, Q^2, t)}{dt} dt \sim W \delta(Q^2)$$

$$\left[ d\sigma_{\gamma^* p \rightarrow VMp}(Q^2, t) \right]_{|t| \ll M_{VM}^2 + Q^2} \propto \frac{\alpha}{2\pi} \beta_{p \leftrightarrow \mathbb{P}^* N}(t, m_p^2) \beta_{q^* \mathbb{P}^* \leftrightarrow q}(t, m_q^2) \frac{dt}{t} \\ \cdot \frac{M_{VM} \Gamma}{(M_{VM}^2 + Q^2)^2} \int_{z_{\min}}^{z_{\max}} \frac{z^2 + (1-z)^2}{z} \left[ \frac{W^2 + Q^2 - m_p^2}{M_{VM}^2 + Q^2} \left( 1 + \frac{t}{M_{VM}^2 + Q^2} \right) \right]^{2\alpha_{\mathbb{P}}(-v^2, t)} dz$$

where  $\alpha_{\mathbb{P}}(-v^2, t=0) - 1 \sim \alpha_{\mathbb{P}}(-v^2, t) - 1 = a \ln \frac{-v^2}{\Lambda^2}$  and  $\frac{W^2 + Q^2 - m_p^2}{M_{VM}^2 + Q^2} - 1 \sim \frac{W^2 + Q^2 - m_p^2}{\Lambda^2}$

$$a = 0.0481 \pm 0.0013(\text{stat}) \pm 0.0037(\text{syst}) \quad \Lambda = 0.292 \pm 0.020(\text{stat}) \pm 0.0051(\text{syst}) \text{ GeV}$$

$$z_{\min}^{\max} = \frac{m_q^2 - v_{\min}^2 - t}{M_{VM}^2 + Q^2 - t} = \frac{1}{2} \left[ 1 \mp \sqrt{1 + 4 \frac{Q^2 t}{(M_{VM}^2 + Q^2)^2} - 4 \frac{m_q^2}{M_{VM}^2}} \right] - \frac{t}{M_{VM}^2 + Q^2 - t}$$

$$\xrightarrow{|t| \ll M_{VM}^2 + Q^2} \frac{1}{2} \left[ 1 \mp \sqrt{1 + 4 \frac{Q^2 t}{(M_{VM}^2 + Q^2)^2} - 4 \frac{m_q^2}{M_{VM}^2}} \right] - \frac{t}{M_{VM}^2 + Q^2}$$

$\mathcal{O}\left(\frac{t}{M_{VM}^2 + Q^2}\right) \leq 1$

read off-line; fits underway!

↪ 2-scale dependence on  $Q^2$  and  $m_q^2$  (3-scale with  $t$ )

# Universal $q\nu p \rightarrow q\nu p$ at work ?

- universal  $q\nu p \rightarrow q\nu p$  scattering amplitude

$$T_{q\nu p \rightarrow q\nu p}(x_{\mathbb{P}}, t = 0, \nu^2) \xrightarrow[x_{\mathbb{P} \rightarrow 0}]{\text{Regge}} \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{1+\lambda(\nu^2, t \gg -1 \text{ GeV}^2)}$$

↳ dependence  $\sigma_{\gamma^* p \rightarrow \nu MY}(W^2, Q^2) \propto W^{\delta(Q^2)} \leftarrow \text{data!}$

$$\lambda(\nu_{\min}^2) \leq \frac{\delta}{4} = \lambda(\nu^2) \leq \lambda(\nu_{\max}^2) \quad ?$$

$$m_q^2 - \nu_{\min \max}^2 = \frac{M^2 + Q^2 - t}{2} \left( 1 \mp \sqrt{1 + 4 \frac{Q^2 t}{(M^2 + Q^2 - t)^2}} \cdot \sqrt{1 - 4 \frac{m_q^2}{M^2}} \right)$$

↳ 2-scale dependence of  $\lambda\left(\nu_{\min \max}^2\right) = 4\delta$

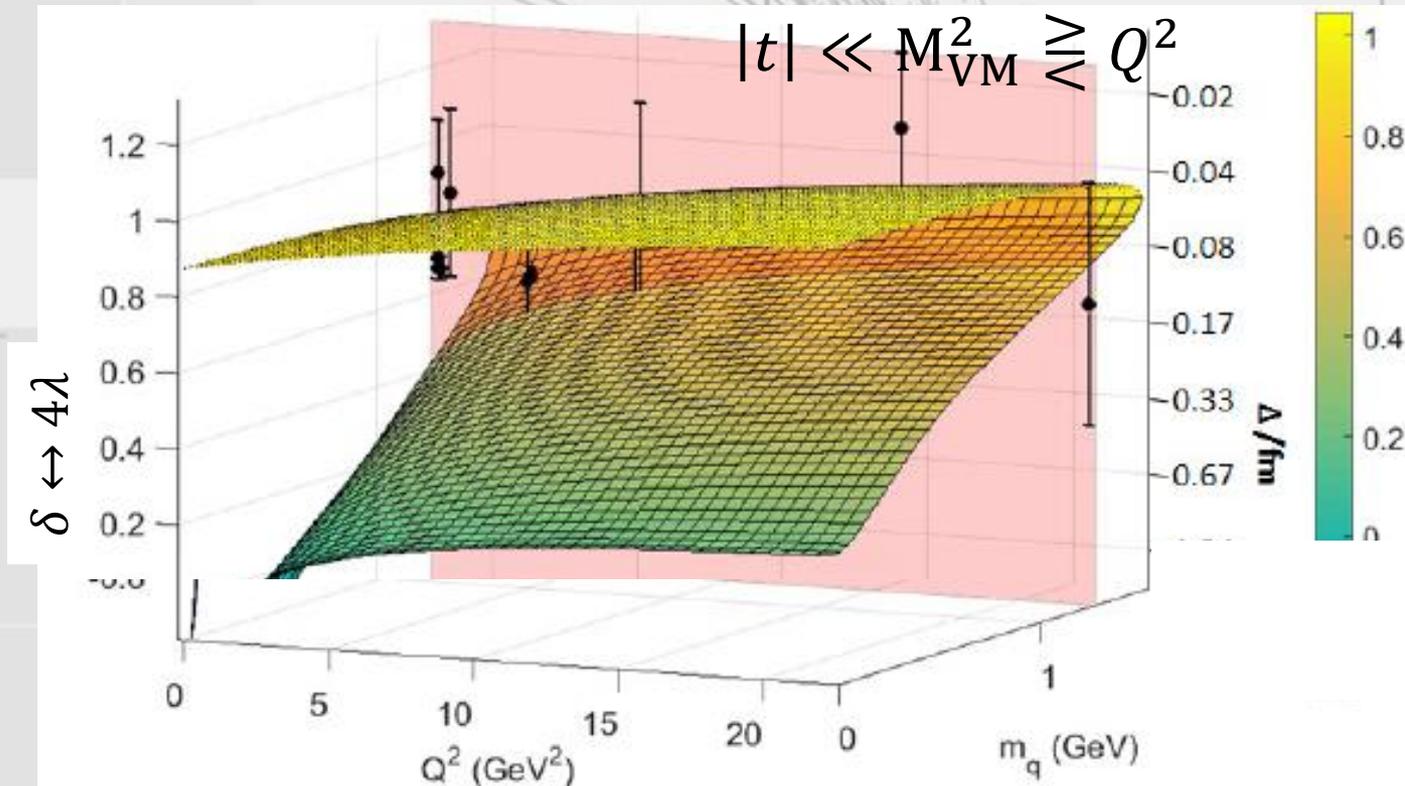
on  $Q^2$   $m_q^2$  ( $|t|$  small)



# Experiment: Charm Quark

- electroproduction

$$\gamma^* p \rightarrow J/\psi p/Y$$

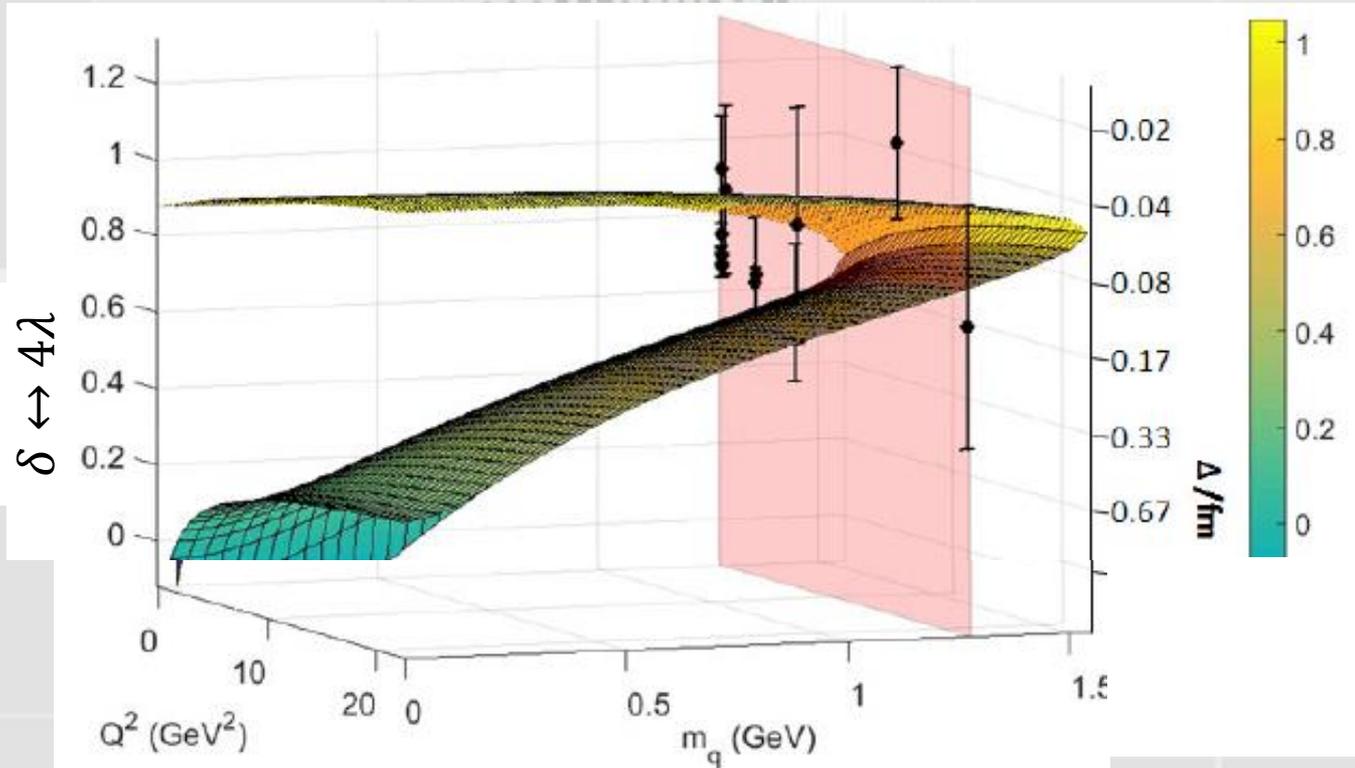


← beware  $Q^2 < 1 \text{ GeV}^2$  !

# Experiment: Charm Quark

- electroproduction

$$\gamma^* p \rightarrow J/\psi p/Y$$



# Experiment: Charm Quark

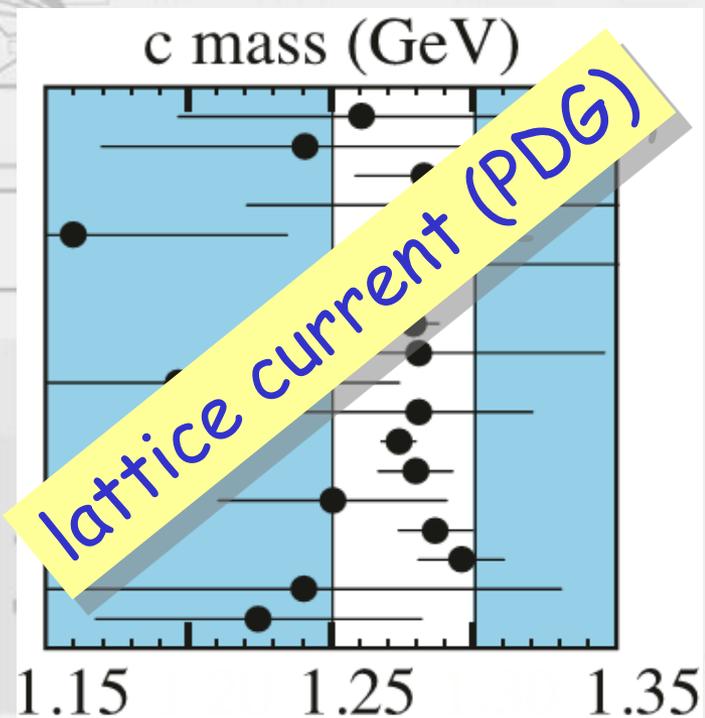
- electroproduction  $\gamma^* p \rightarrow J/\psi p/Y \quad |t| \ll M_{J/\psi}^2 \lesseqgtr Q^2$

$$m_c^2 - v_{\min}^2 = \frac{M_{J/\psi}^2}{2} \left( 1 \mp \sqrt{1 - 4 \frac{m_c^2}{M_{J/\psi}^2}} \right)$$

consistent with

$$T_{c^* p \rightarrow cp}(x_{\mathbb{P}}, t, v^2) \propto \left( \frac{1}{x_{\mathbb{P}}} \right)^{\lambda(v^2, t)}$$

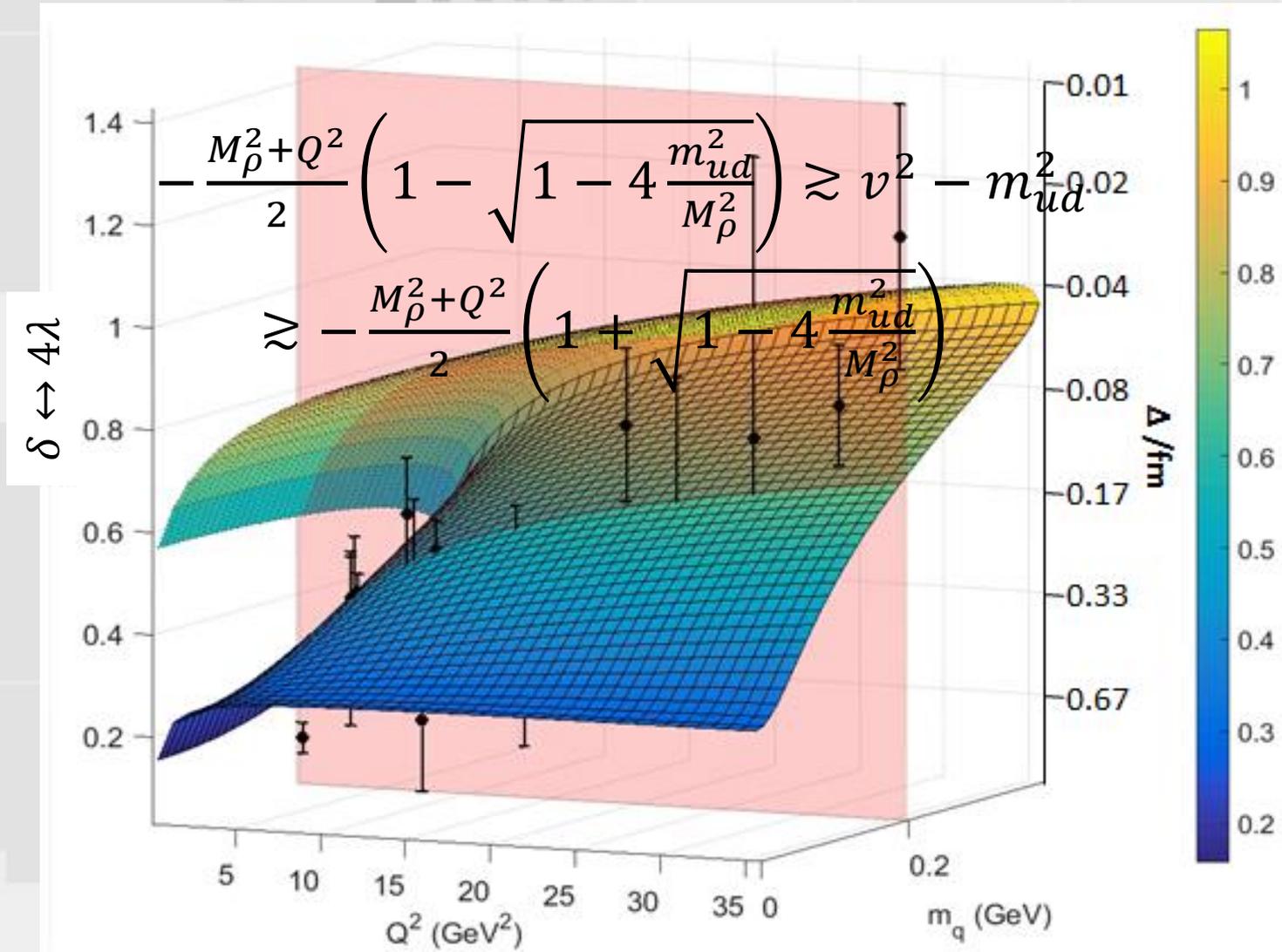
- driven by current  $1.28 \text{ GeV}/c^2$   
~ constituent mass
- "sub-fm" means  $\Delta \sim 0.08 \text{ fm}$



# Experiment: $u/d$ Quarks

- electroproduction

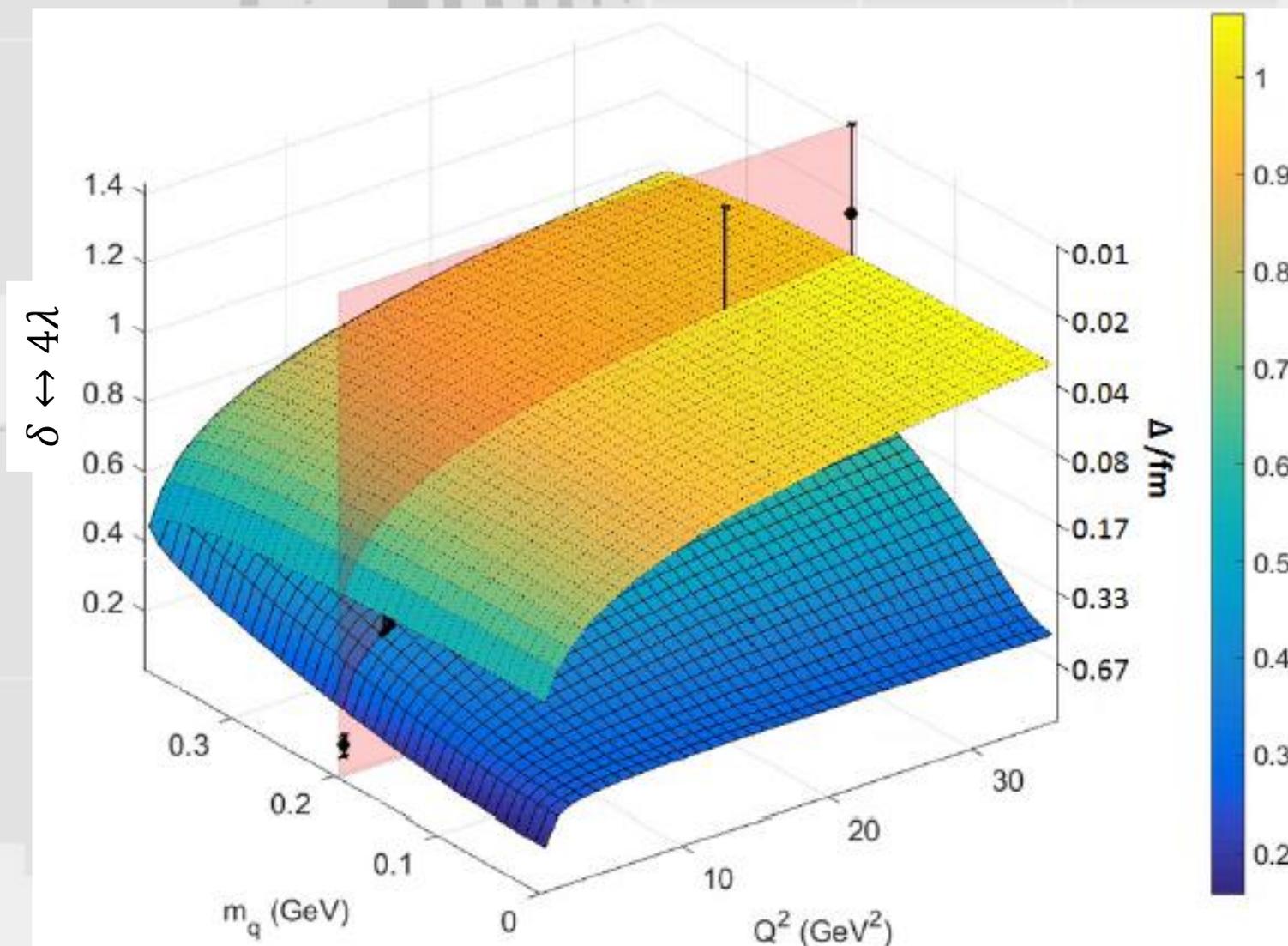
$$\gamma^* p \rightarrow \rho(760)p/Y$$



# Experiment: $u/d$ Quarks

- electroproduction

$$\gamma^* p \rightarrow \rho(760)p/Y$$



# Experiment: $u/d$ Quarks

- electroproduction  $\gamma^* p \rightarrow \rho(760)p/Y$   $|t| \lesssim M_\rho^2 \lesssim Q^2$

$$-\frac{M_\rho^2 + Q^2}{2} \left( 1 - \sqrt{1 - 4 \frac{m_{ud}^2}{M_\rho^2}} \right)$$

$$\gtrsim v^2 - m_{ud}^2 \gtrsim -\frac{M_\rho^2 + Q^2}{2} \left( 1 + \sqrt{1 - 4 \frac{m_{ud}^2}{M_\rho^2}} \right)$$

- consistent with  $T_{u/d^* p \rightarrow u/dp}(x_{\mathbb{P}}, t, v^2) \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{\lambda(v^2, t)}$

- driven by mix of  $Q^2$  and  $M_\rho^2$

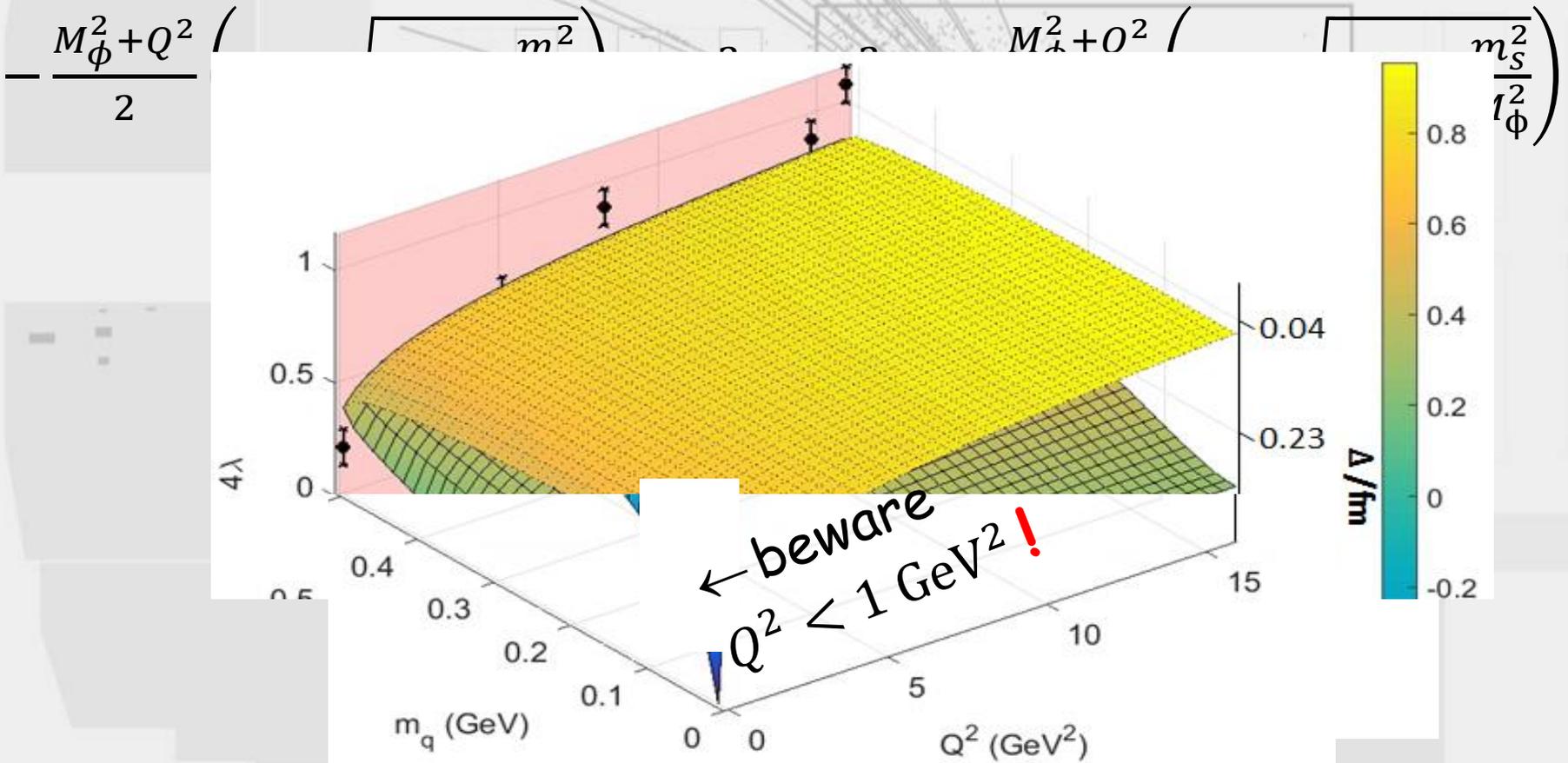
- constituent  $u/d$  mass  $\lesssim 0.2 \text{ GeV}/c^2$

$$0 \gtrsim v^2 \gtrsim -(M_X^2 + Q^2) \quad \text{so} \quad \Delta \gtrsim \frac{1}{\sqrt{M_X^2 + Q^2}}$$

- "sub-fm" means  $0.08 \lesssim \Delta \text{ fm}$

# Experiment: Strange Quark

- electroproduction  $\gamma^* p \rightarrow \phi(1019) p / Y \quad |t| \lesssim M_{VM}^2 \lesssim Q^2$

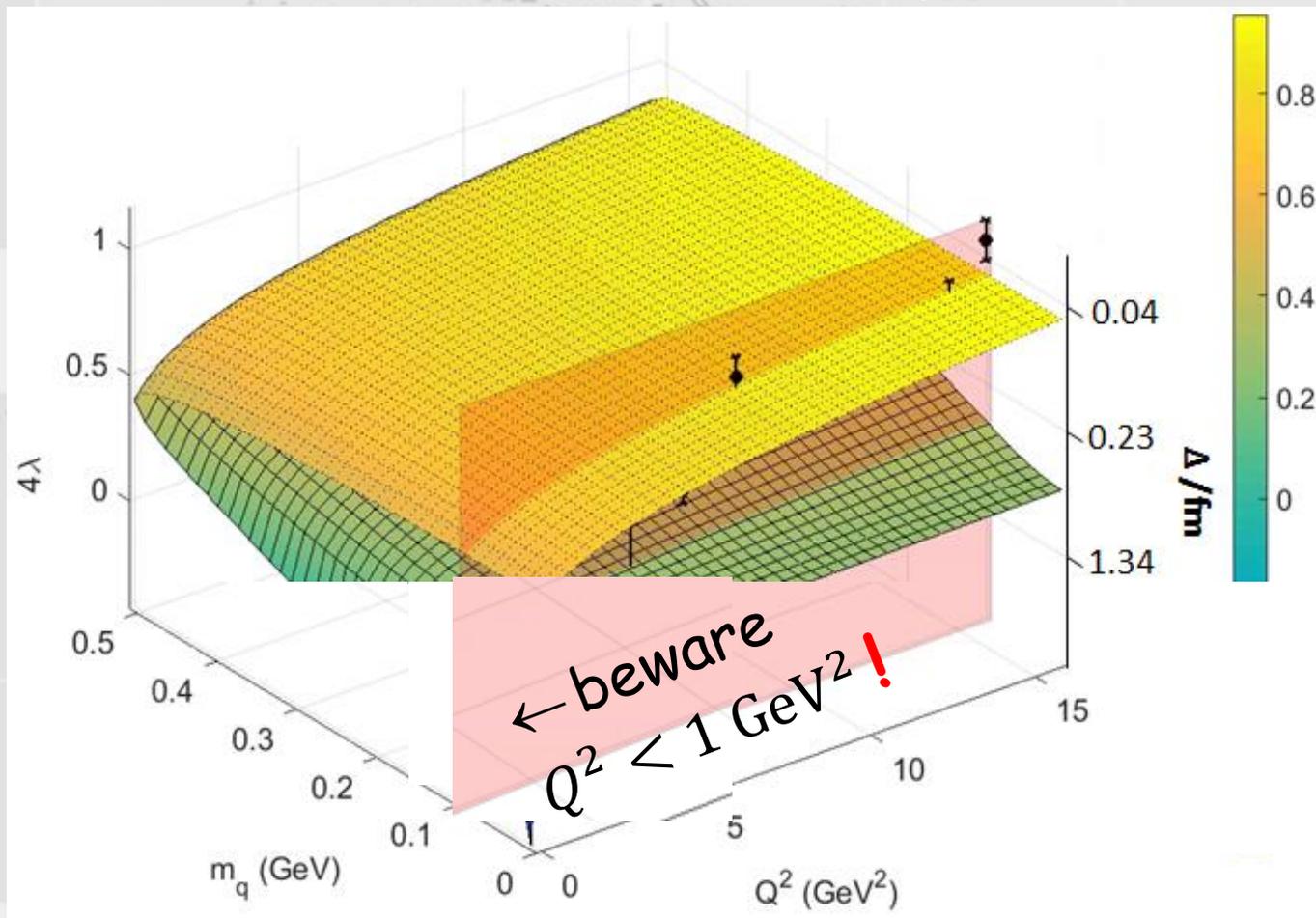


# Experiment: Strange Quark

- electroproduction

$$\gamma^* p \rightarrow \phi(1019)p/Y$$

$$|t| \lesssim M_{VM}^2 \lesssim Q^2$$

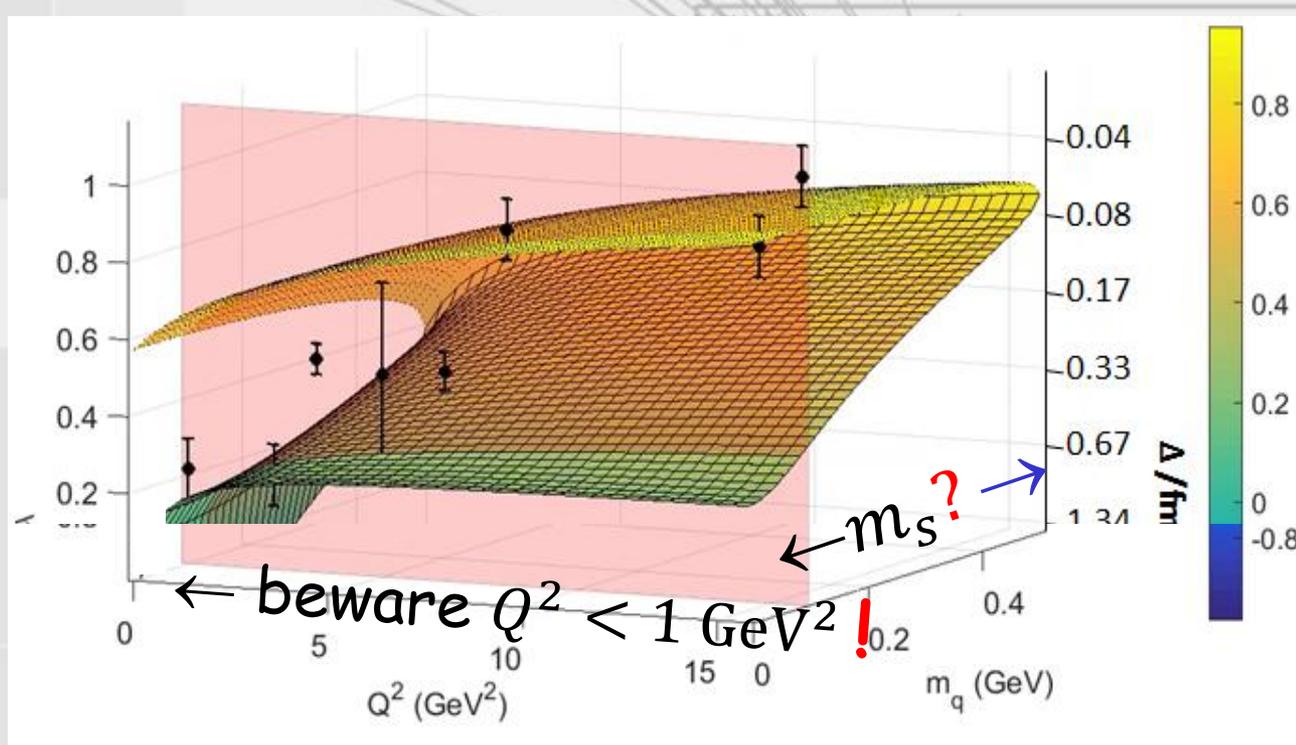


# Experiment: Strange Quark

- electroproduction

$$\gamma^* p \rightarrow \phi(1019)p/Y$$

$$|t| \lesssim M_{VM}^2 \lesssim Q^2$$



# Experiment: Strange Quark

- electroproduction  $\gamma^* p \rightarrow \phi(1019)p/X$   $|t| \lesssim M_\phi^2 \lesssim Q^2$

$$-\frac{M_\phi^2 + Q^2}{2} \left( 1 - \sqrt{1 - 4 \frac{m_s^2}{M_\phi^2}} \right) \gtrsim$$

$$v^2 - m_s^2 \gtrsim -\frac{M_\phi^2 + Q^2}{2} \left( 1 + \sqrt{1 - 4 \frac{m_s^2}{M_\phi^2}} \right)$$

↳ consistent with  $T_{s^*p \rightarrow sp}(x_{\mathbb{P}}, t, v^2) \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{\lambda(v^2, t)}$

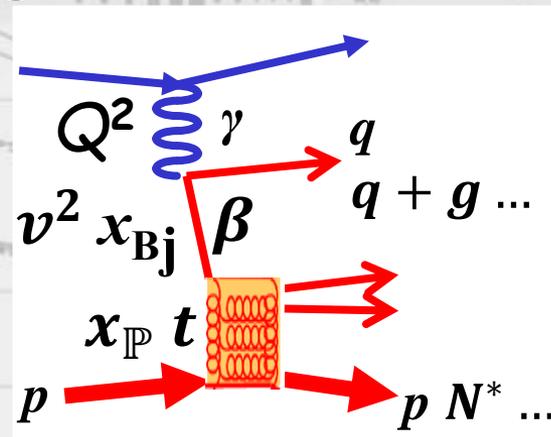
- driven by mix of  $Q^2$  and  $M_\phi^2$
- constituent  $s$  mass  $\lesssim 0.5 \text{ GeV}/c^2$  (unconstrained!)

↳ "sub-fm" means  $0.08 \lesssim \Delta \text{ fm}$  (unconstrained!)

## 3. Conclusion and Outlook ?

# Conclusion

- exclusive VM electroproduction at high energy probes quark degrees of freedom in hadronic matter

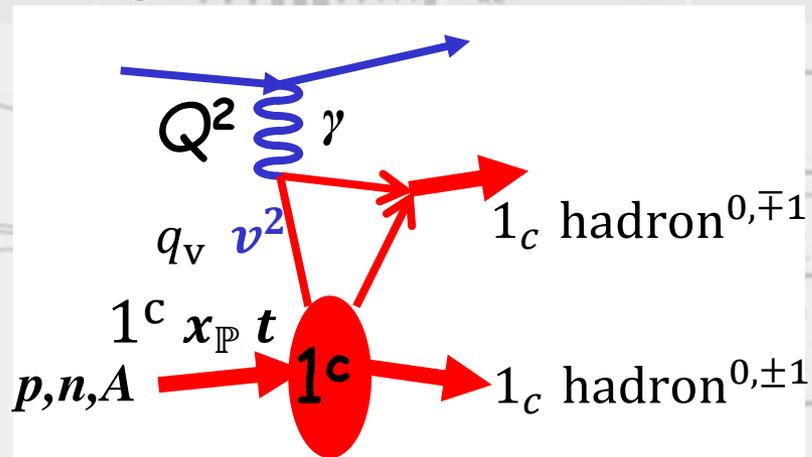


- VM flavour for Bethe-Heitler  $\gamma^* \rightarrow q_v \bar{q}$  flavour
- Regge asymptotic phenomenology for  $q_v p \rightarrow qp N^* \dots$
- universal  $\lambda(t, v^2) \leftrightarrow$  "diffractive" leading  $\mathbb{P}$  pole
- fit  $\sigma_{ep \rightarrow eVMp}$  for flavour independence of  $\sigma_{q_v p \rightarrow qp N^*}$   
stat limitation of HERA data

# Outlook



- exclusive hadronic electroproduction at high energy probes quark degrees of freedom in hadronic matter

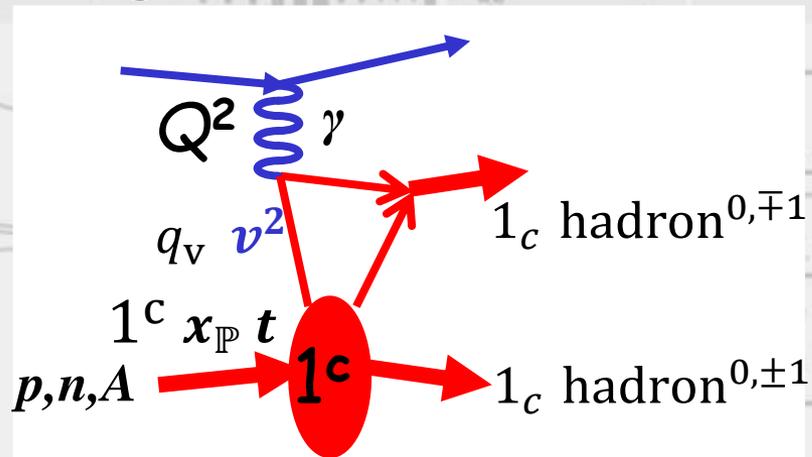


- hadron flavour for Bethe-Heitler  $\gamma^* \rightarrow q_v \bar{q}$  flavour
- phenomenology for  $q_v$  hadron  $\rightarrow q$  hadron' eg Regge asymptotic expansion for small  $|t|$
- "diffractive"  $\sigma_{ep \rightarrow eVMp}$  @ HERA  $\xrightarrow{\text{low lumi}}$  consistency
- towards quark dynamics in hadronic matter

# Outlook



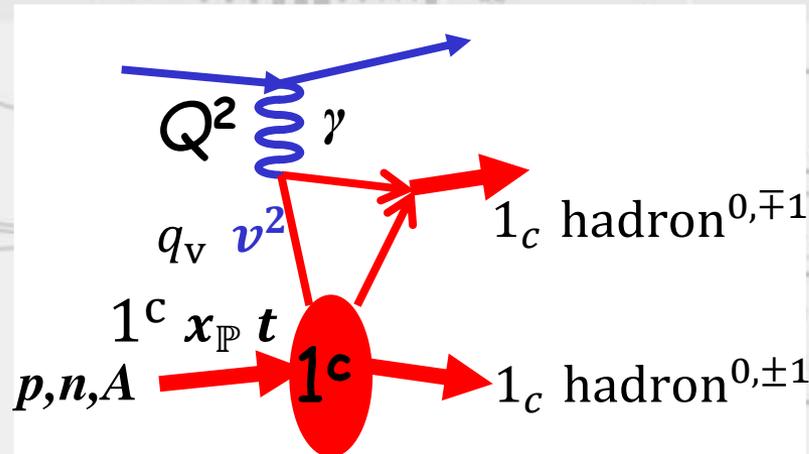
- exclusive hadronic electroproduction at high energy probes quark degrees of freedom in hadronic matter



- hadron flavour for Bethe-Heitler  $\gamma^* \rightarrow q_v \bar{q}$  flavour
- phenomenology for  $q_v$  hadron  $\rightarrow q$  hadron' eg Regge asymptotic expansion for small  $|t|$
- "diffractive"  $\sigma_{ep \rightarrow eVMp}$  @ HERA  $\xrightarrow{\text{low lumi}}$  consistency
- towards quark dynamics in hadronic matter

# Outlook

- exclusive hadronic electroproduction at high energy probes quark degrees of freedom in hadronic matter



- small  $\sigma_{ep \rightarrow e 1_c 1_c}$  require large luminosity
  - develop better phenomenology for  $q_v \text{ hadron} \rightarrow q \text{ hadron}'$
- towards quark dynamics in hadronic matter ...  
... at a high energy + lumi eIC (JLeIC, eRHIC ?)

