Sub-femtoscopic Rutherford Scattering

"It's all down to that space-like quark" (JBD 1994 DESY

John Dainton

University of Liverpool, UK

Lepton-hadron interactions at the Fermi energy scale probe the structure of hadrons, the structure of the electro-weak interaction, and the structure of the hadronic interaction at the sub-femtoscopic distance scale. After setting a context in such terms with well-known, encyclopaedic, measurements of deeply inelastic, posit(elect)ron-proton scattering of centre-of mass energy ~100π GeV, the first steps in identifying in data the essential features which characterise sub-femtoscopic Rutherford scattering are reported.

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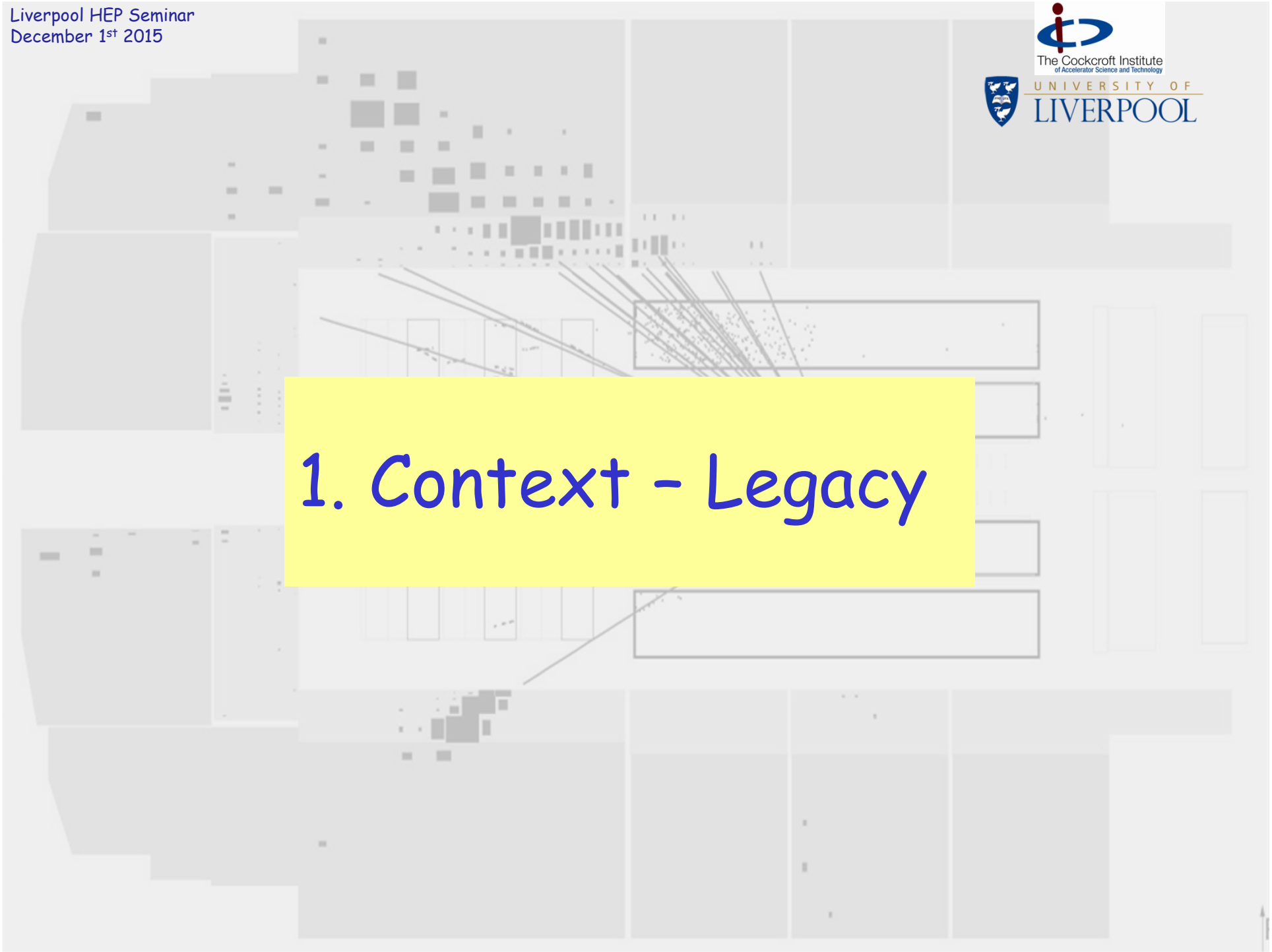
1. Context – Legacy
2. Chromodynamic
   Rutherford Scattering
3. Conclusion and Outlook

"It's all down to that space-like quark" JD
Coherent "head-shaking" and "tut-tutting"
Lonya Frankfurt, Mark Strikman et al. DESY-HH 1994

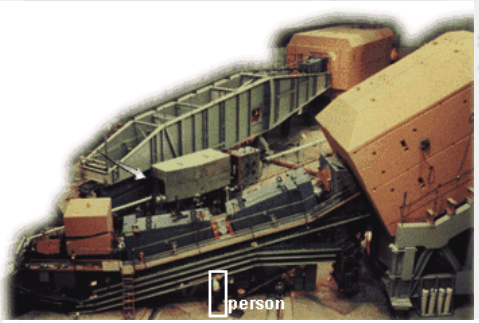
"Any chance of a summer project?"
Francis Bench Liverpool 2015



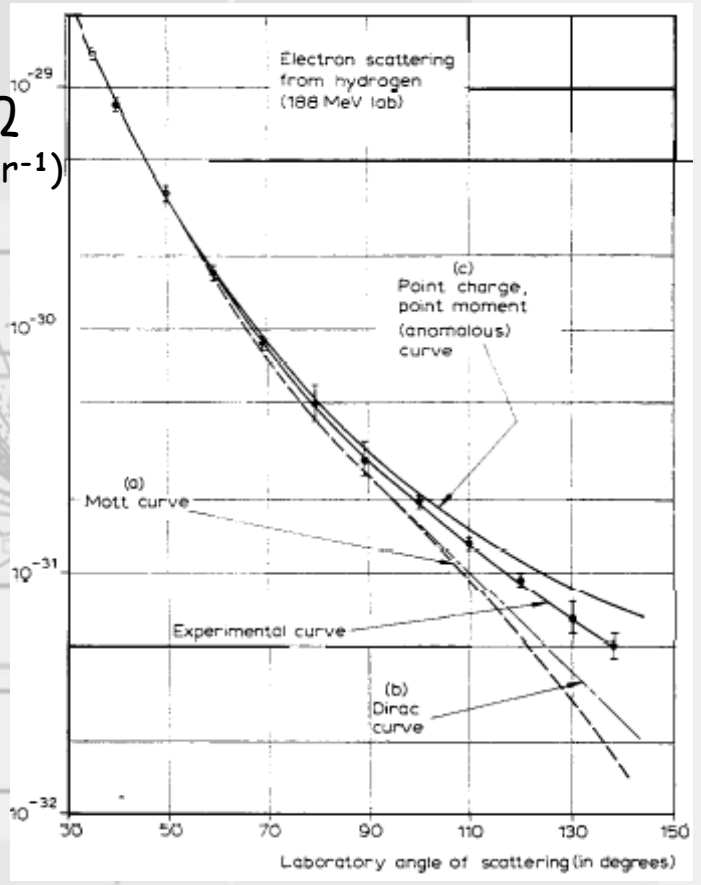
1. Context – Legacy

Constituents

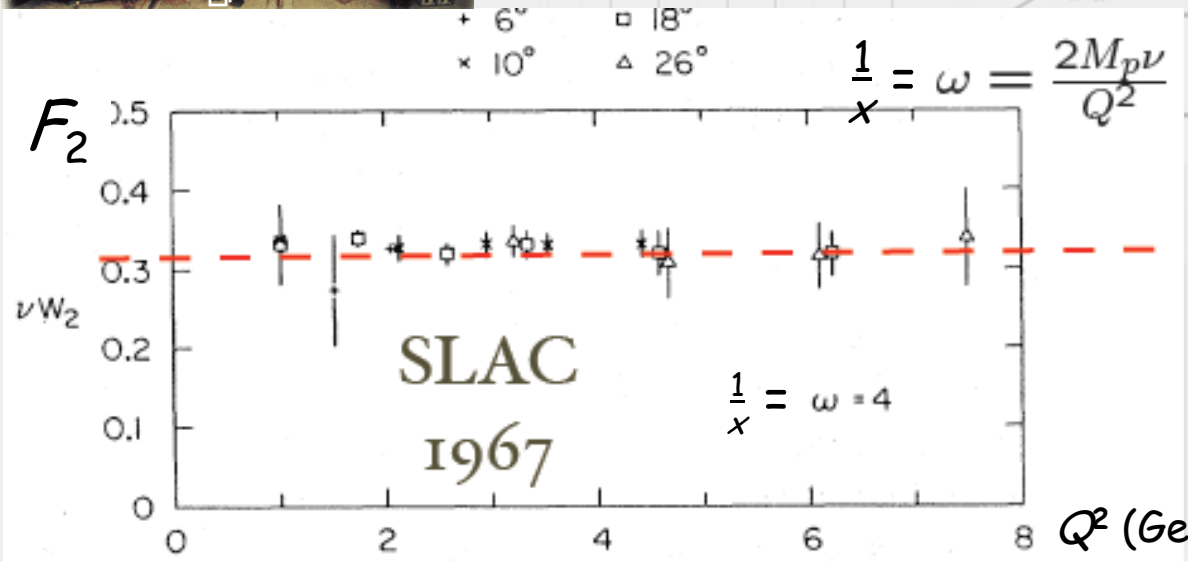
- SLAC end station:
  - 1959 nucleus size
    nucleon size — Hofstädter
  - 1967 quarks — Friedman Kendall Taylor

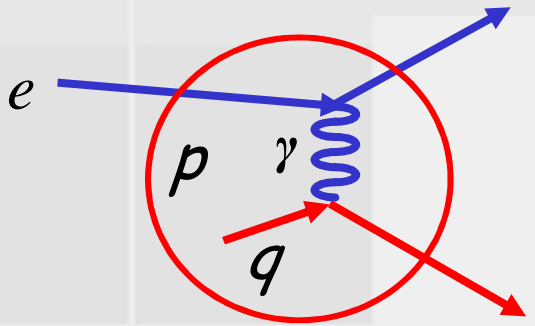


Proposal:
"A general survey of the basic cross sections which will be useful for future proposals"



$d\sigma/d\Omega$ (cm²ster⁻¹)





Constituents

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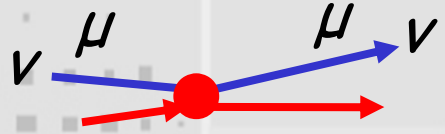
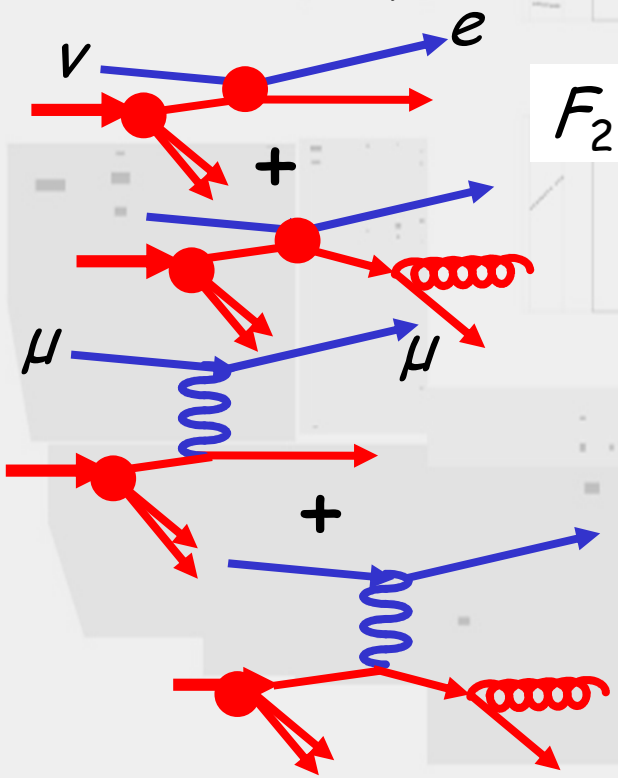
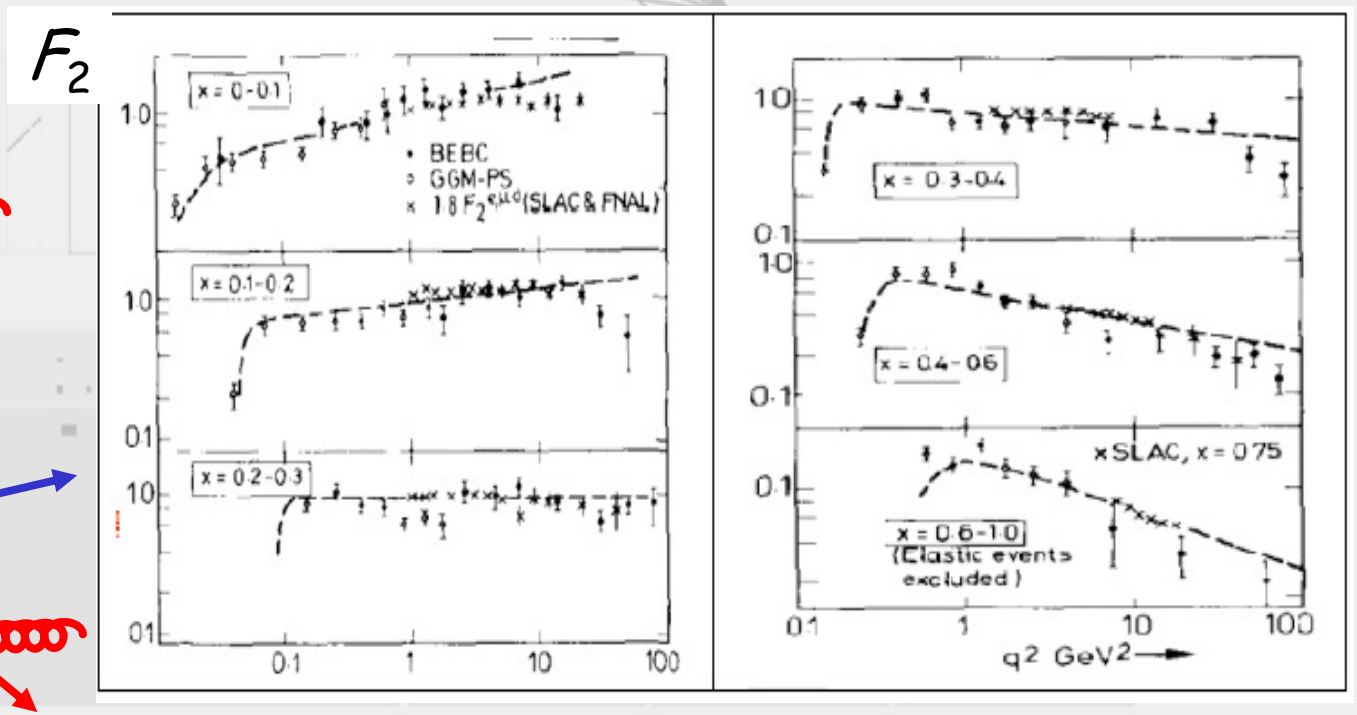
- CERN + Fermilab
  - fixed target
  - sub-fm ($Q \leq 20$ GeV)
  - 1972 weak NC
    1977 QCD



CERN (Perkins et al.)
Fermilab





Intermediate Vector Bosons

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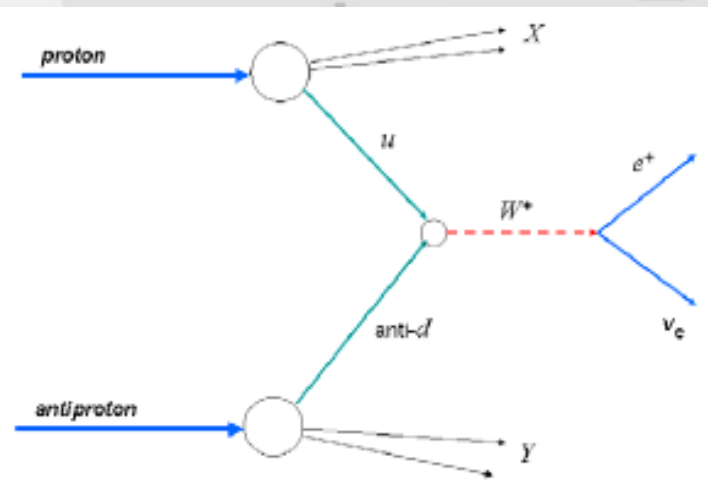
- $S\bar{p}pS$ @ CERN

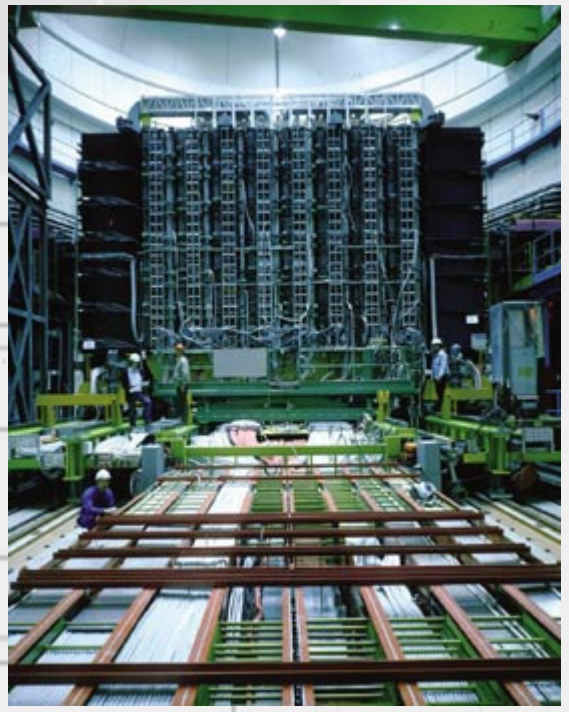
Nobel
Rubbia+van der Meer

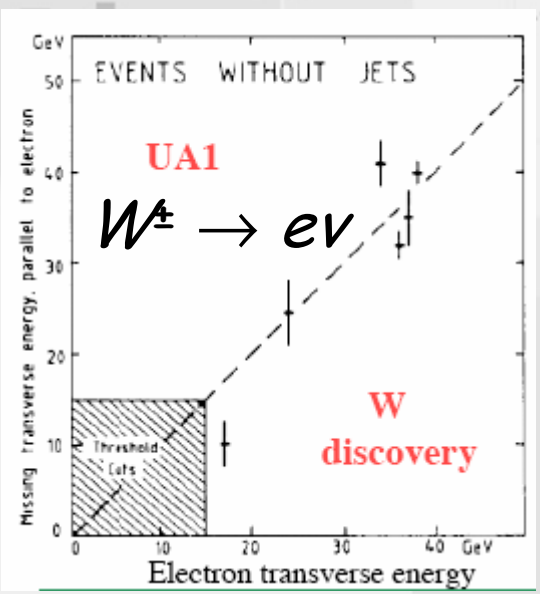


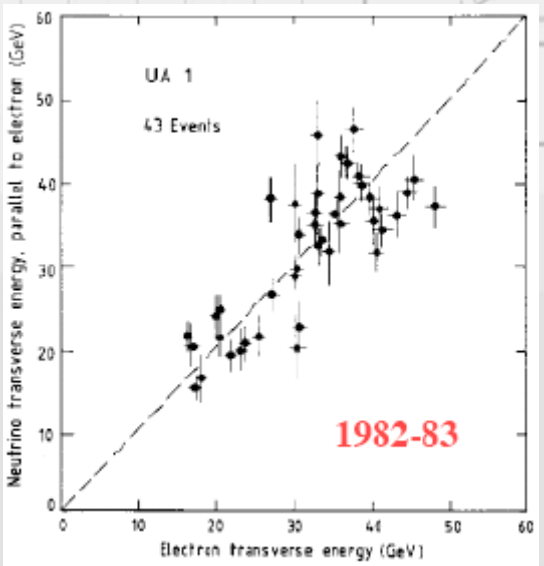
$pp \rightarrow X + Z^0 \rightarrow e^+e^-$

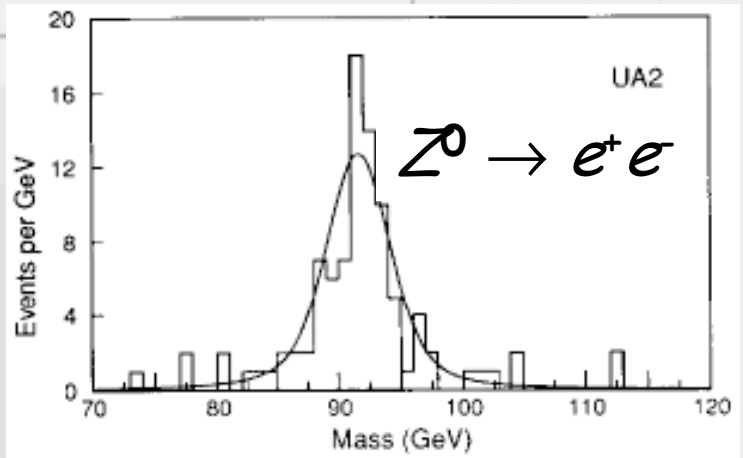
$\mu^+\mu^-$

$pp \rightarrow X + W^{\pm} \rightarrow \mu\nu$









A precision Fermiscale *ep* Collider HERA @ DESY

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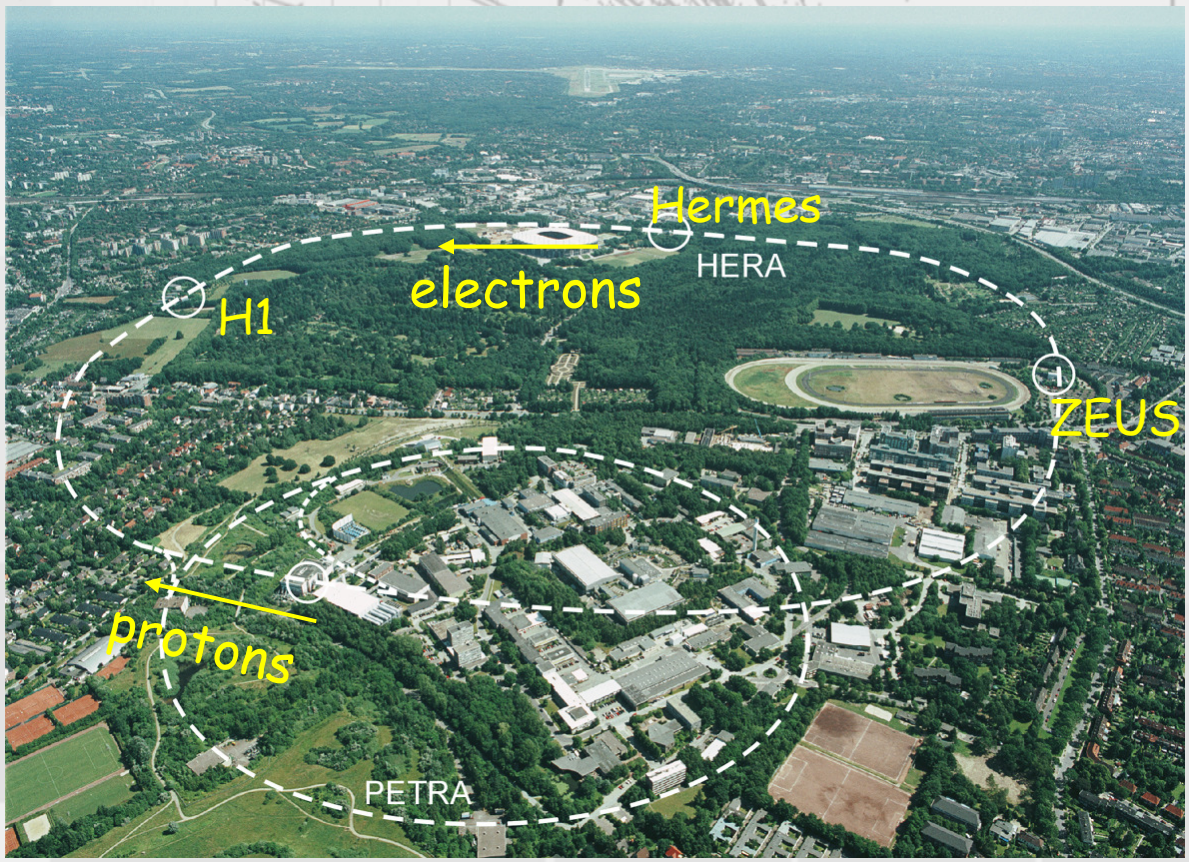
- challenge: different particle species *ep* in collision

27.6 GeV electrons + 920 GeV protons ← *uud* +"sea"

ep cm energy 314 GeV (100π)

lepton

HERA
DESY
Hamburg



HERA
+
H1
1992-2007
RIP

2007-?
legacy

Rotating Spin

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- stored e radiates

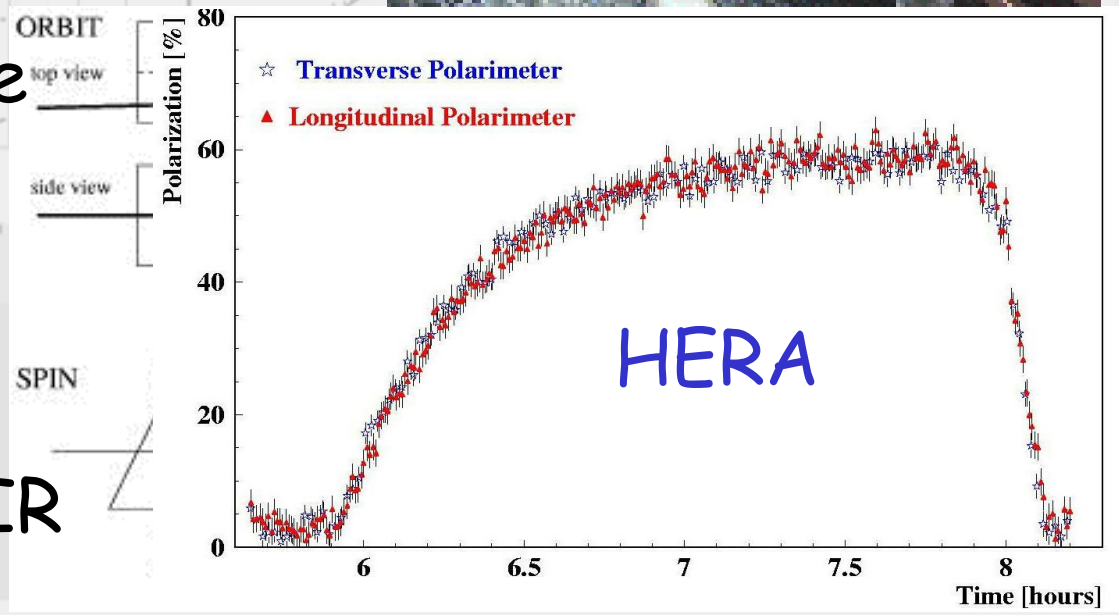
  $e \rightarrow e_T$ Sokolov-Ternov

  transversely polarised e

  synchrotron radiation

- "spin-rotator" Barber, Steffen
  - subtle and precise precession
  - "Siberian snake" insertion device

  $e_T \rightarrow e_{RL} \rightarrow e_T$ at IR



A Precision Fermiscale Experiment @ HERA

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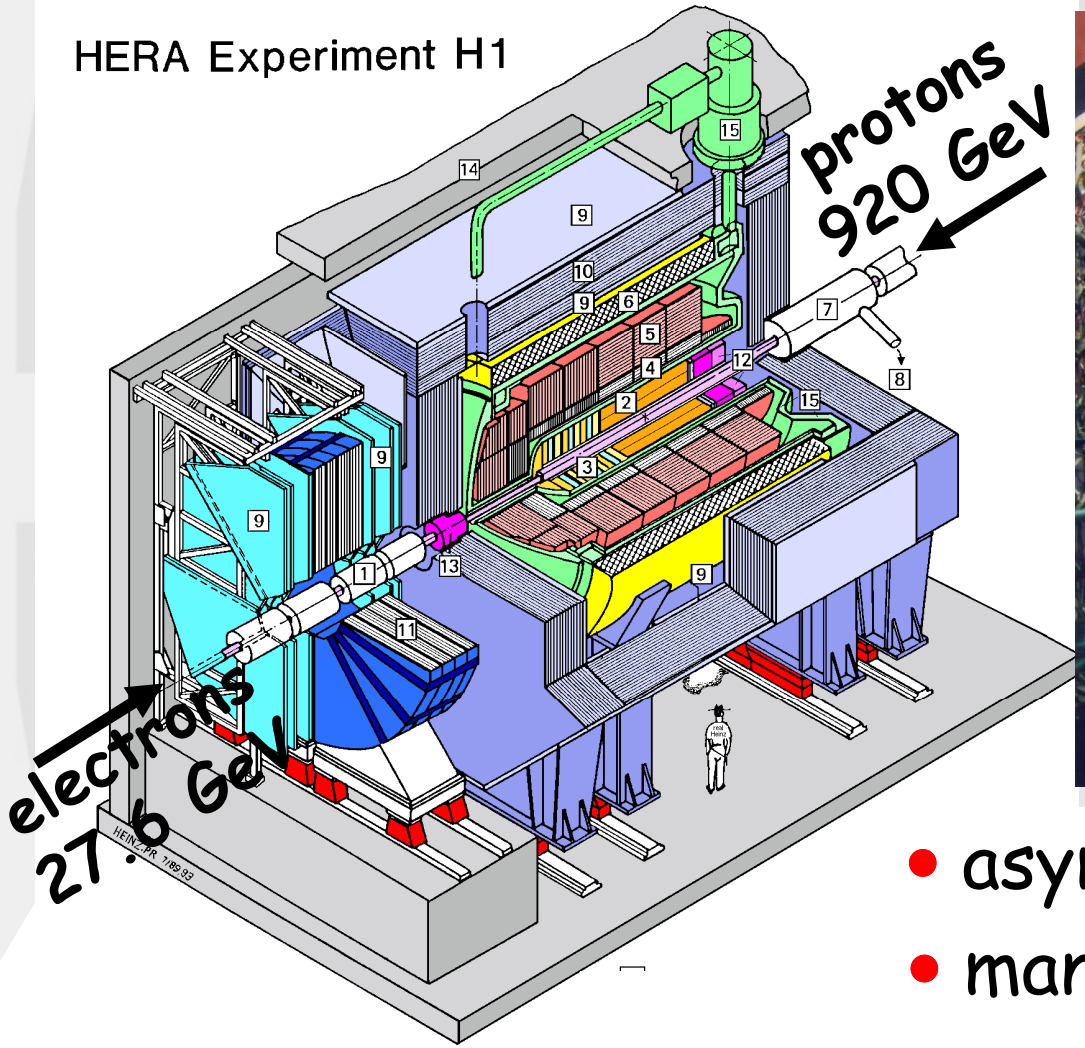

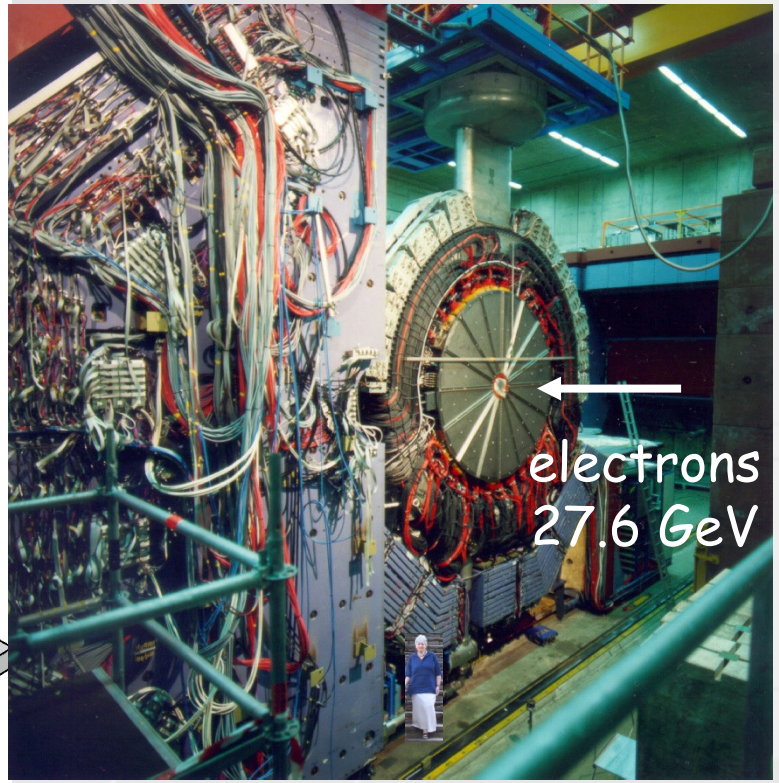

- asymmetric e and p
- many bunch Δt_{ep} = 75 ns
- p_T scale ≤ 300 GeV (Fermi)

Constituents with Currents

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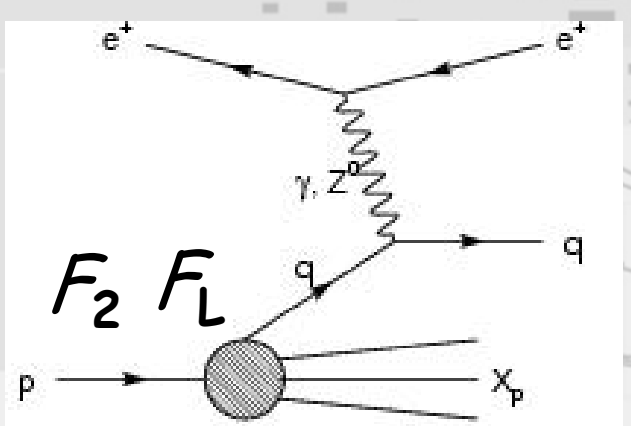
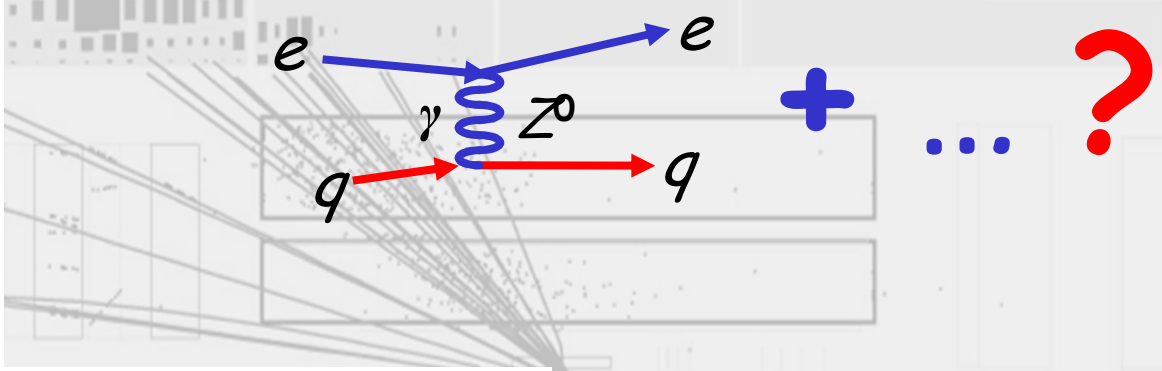
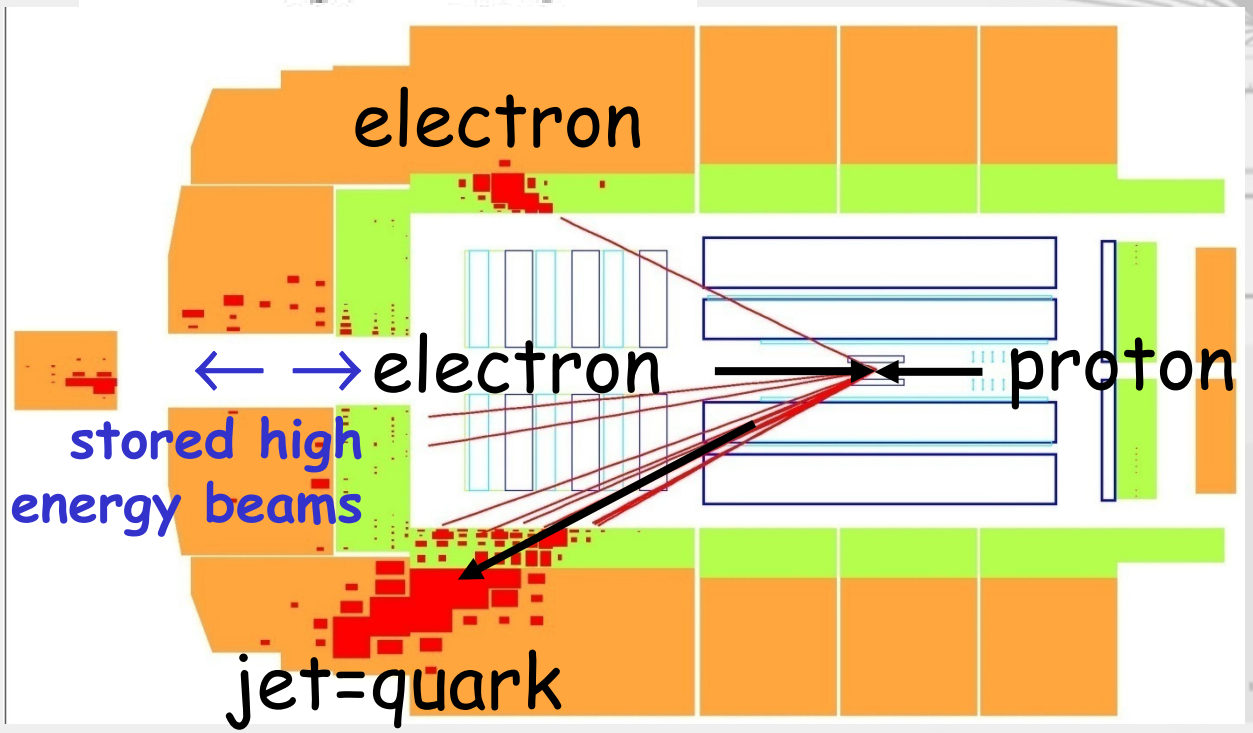
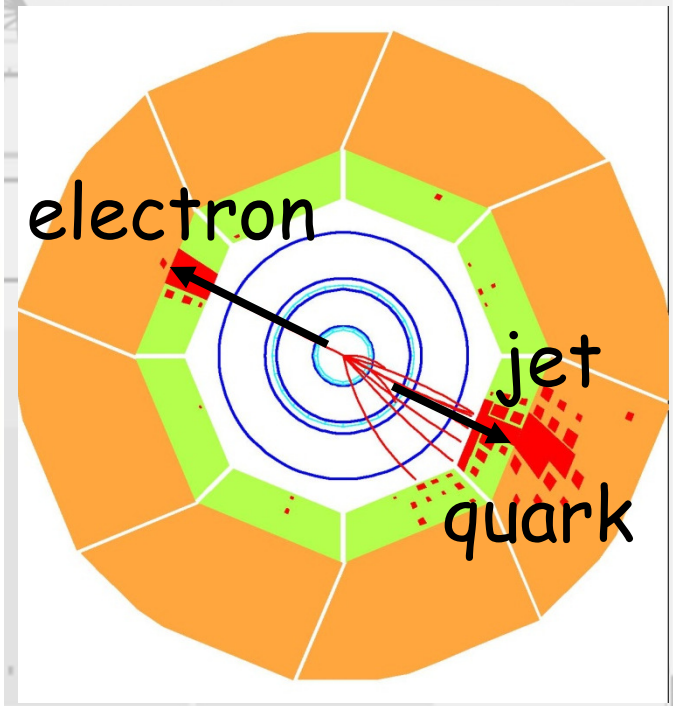
- "Rutherford-like" back-scattering at Fermi scale









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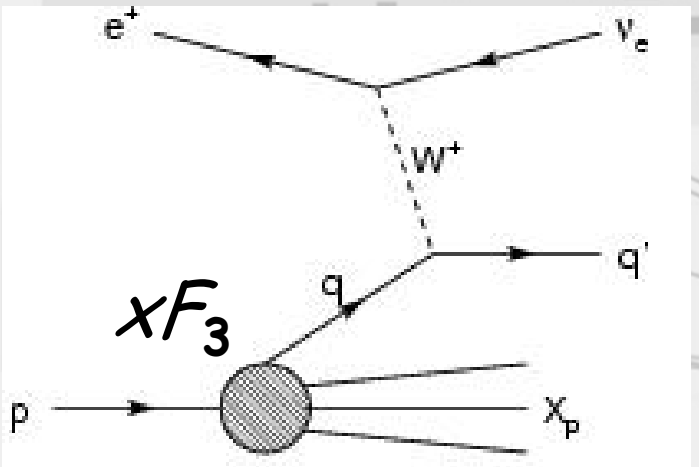
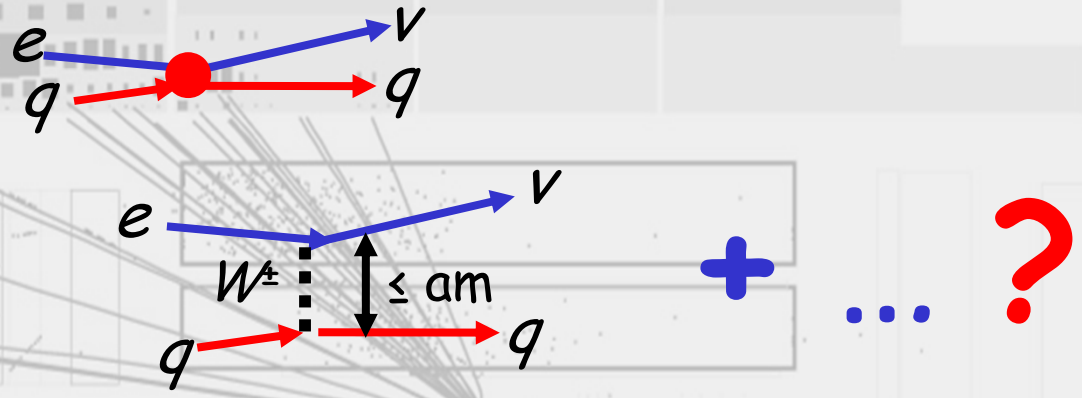
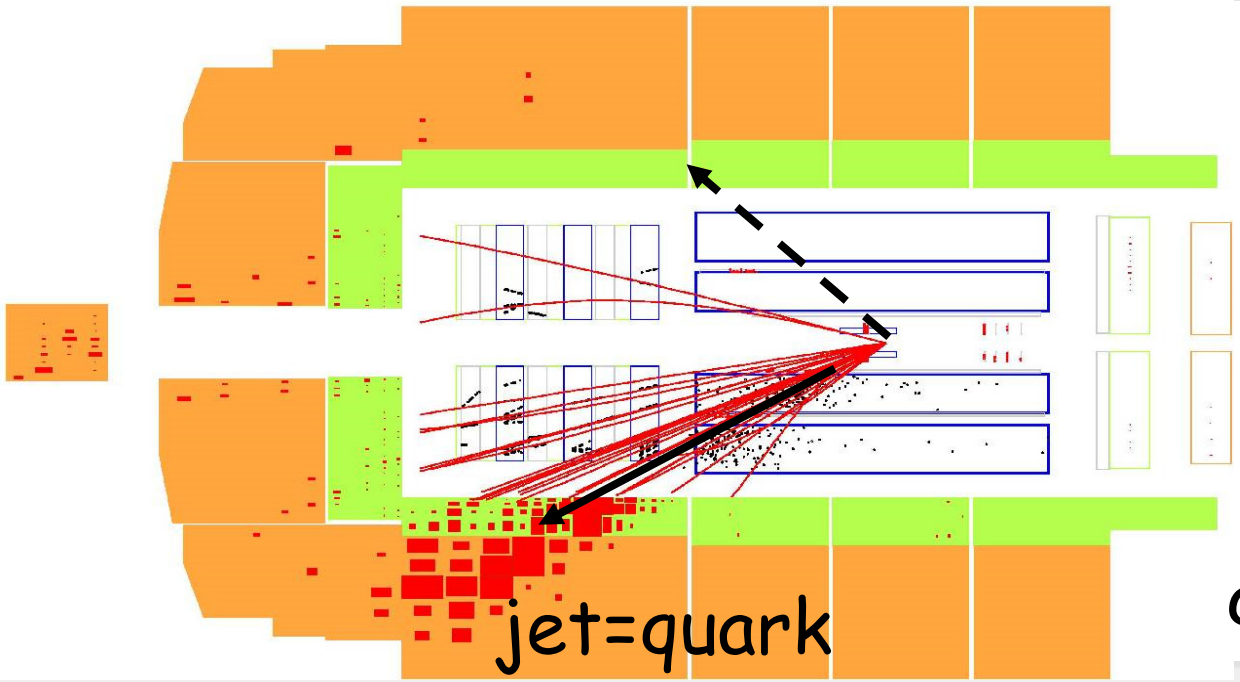
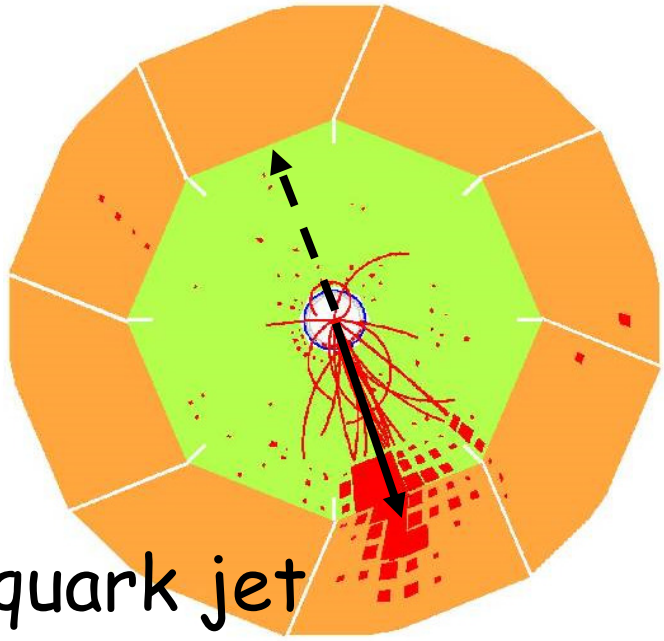
- >1992: inside Fermi's β-interaction









GSW Current

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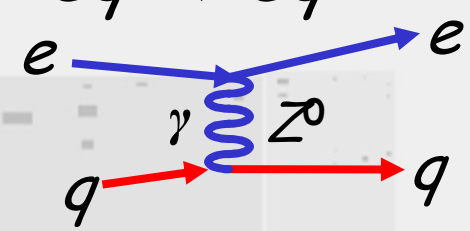
- now: resolved structure in GSW $SU(2)_L \otimes U(1)$

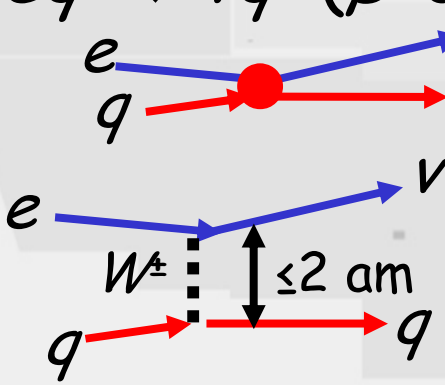
$$\Delta x \sim \frac{0.2\ \text{TeV·am}}{Q}$$

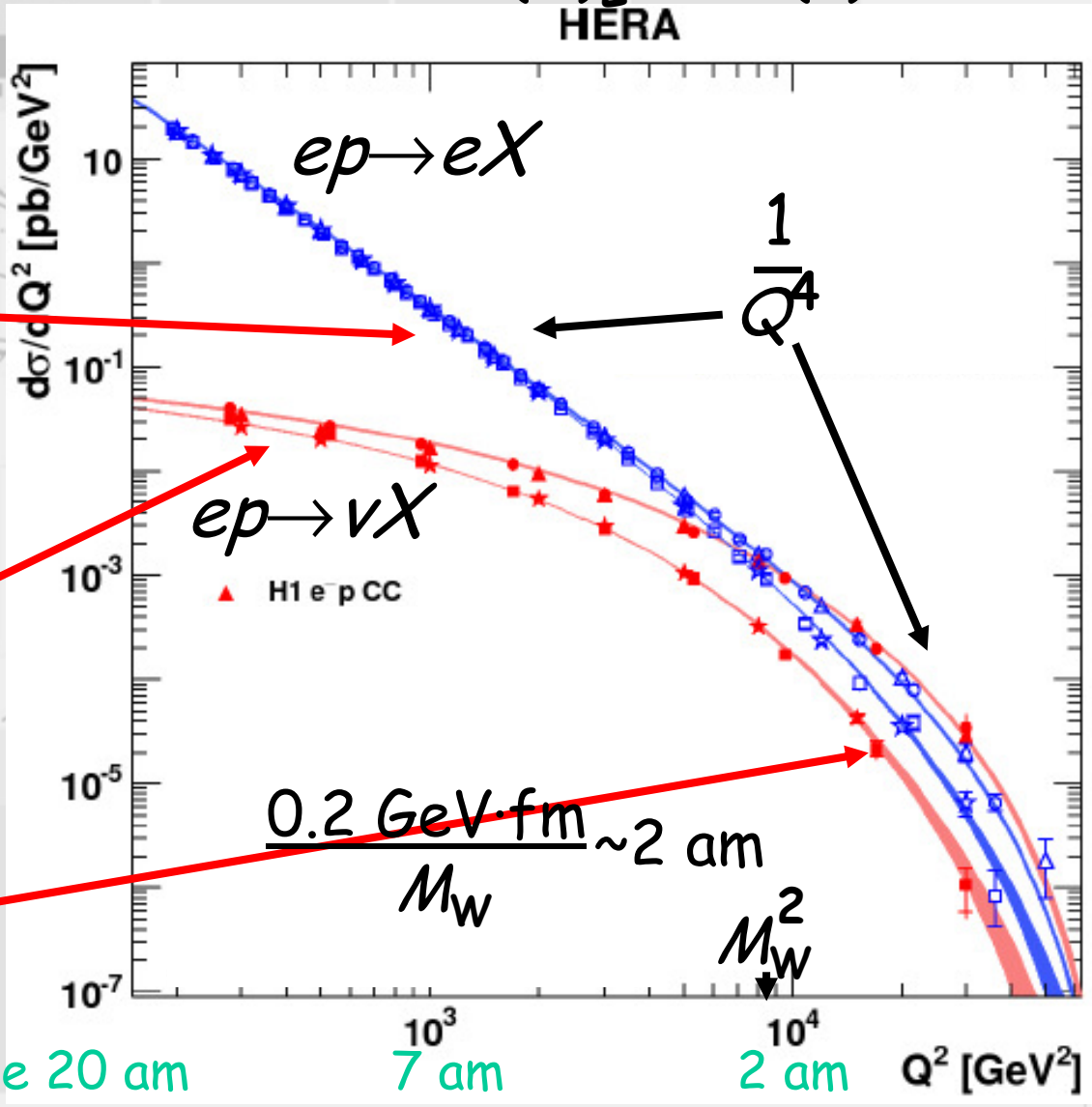
- "Rutherford scattering" -like

$eq \rightarrow eq$



$eq \rightarrow \nu q$ (β-decay)





Glashow-Salam-Weinberg Quantum Flavour Dynamics

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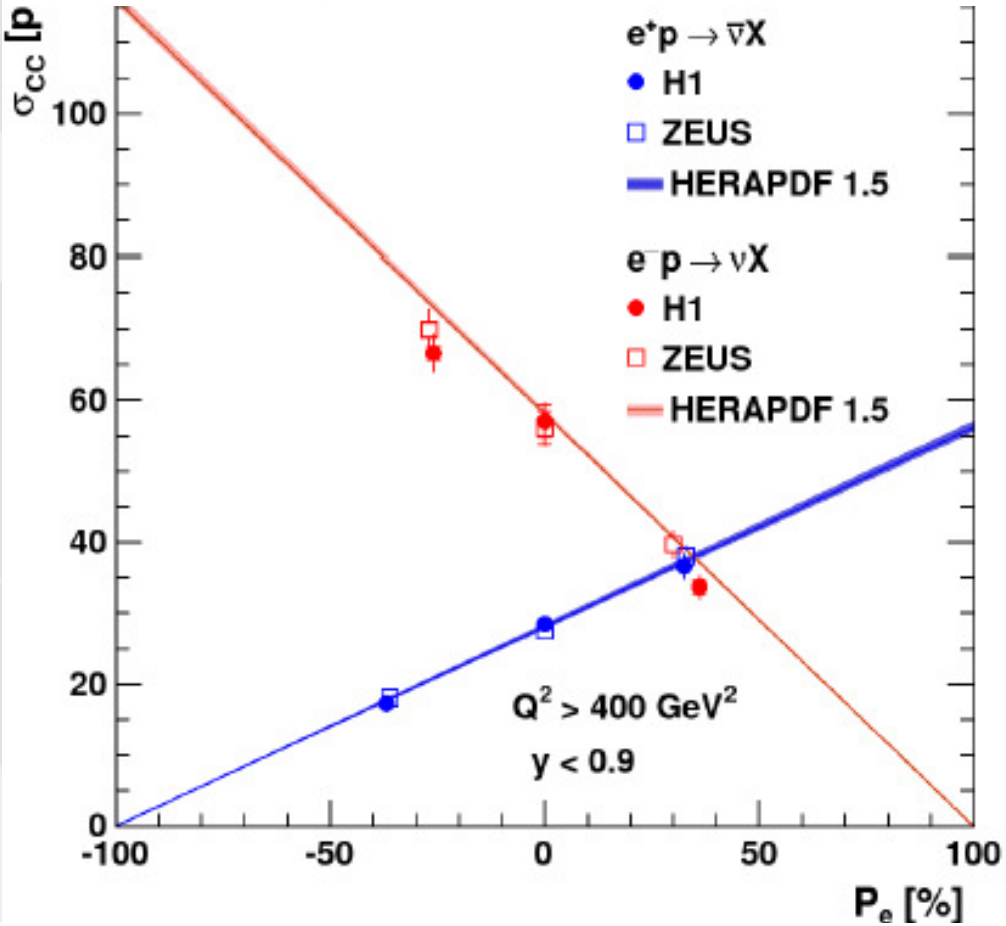
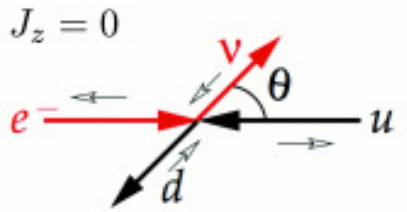
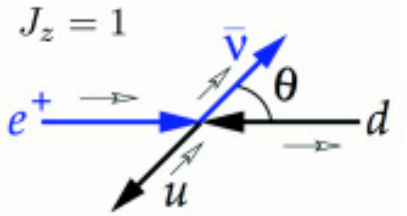
- quarks = LH Dirac fermions
  LH leptons RH anti-leptons



- Chiral structure of EW interactions probed
- No sign for right-handed currents





Fermi Scale NC ~~P~~

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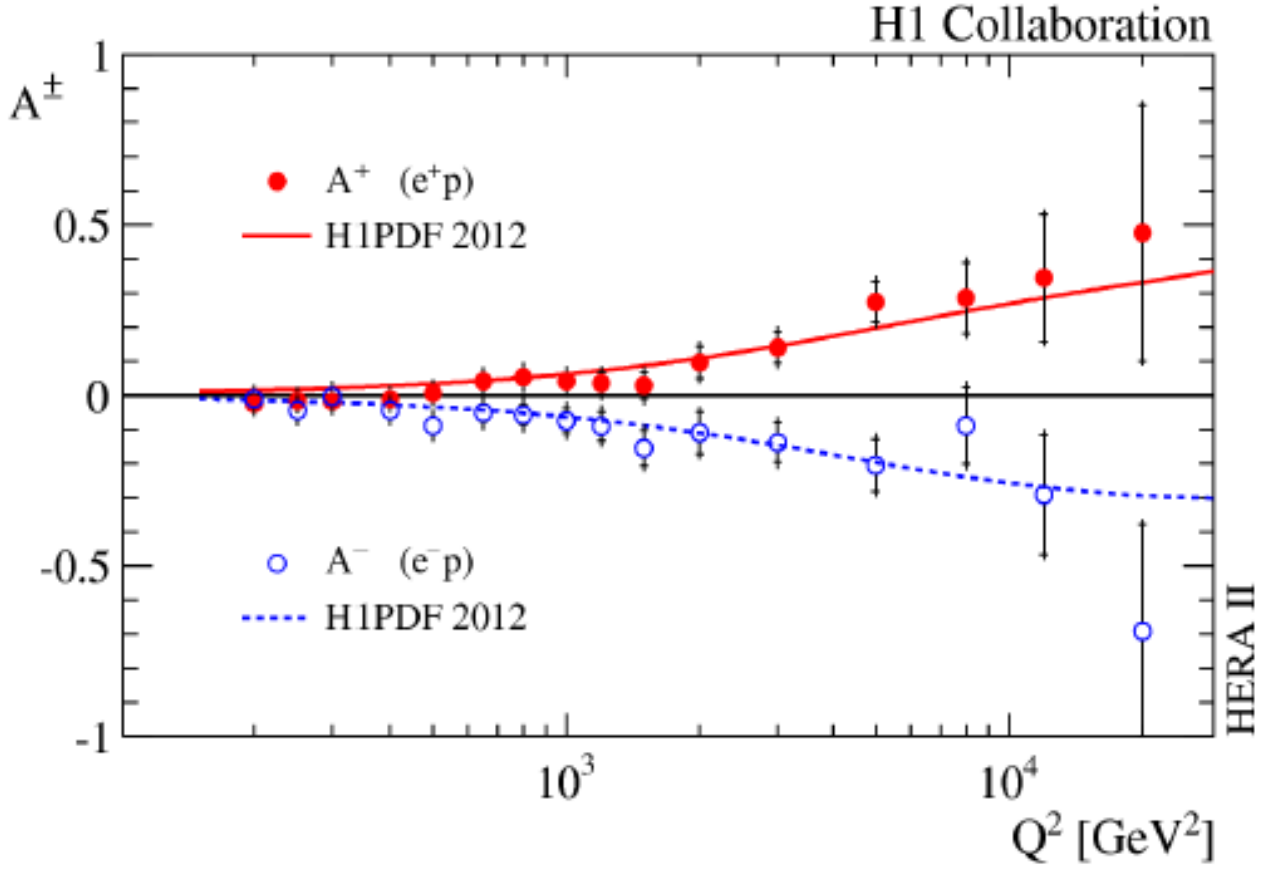
NC polarization asymmetry $A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$



Direct measure of parity violation effect in NC DIS

Fermi Scale Anti-matter

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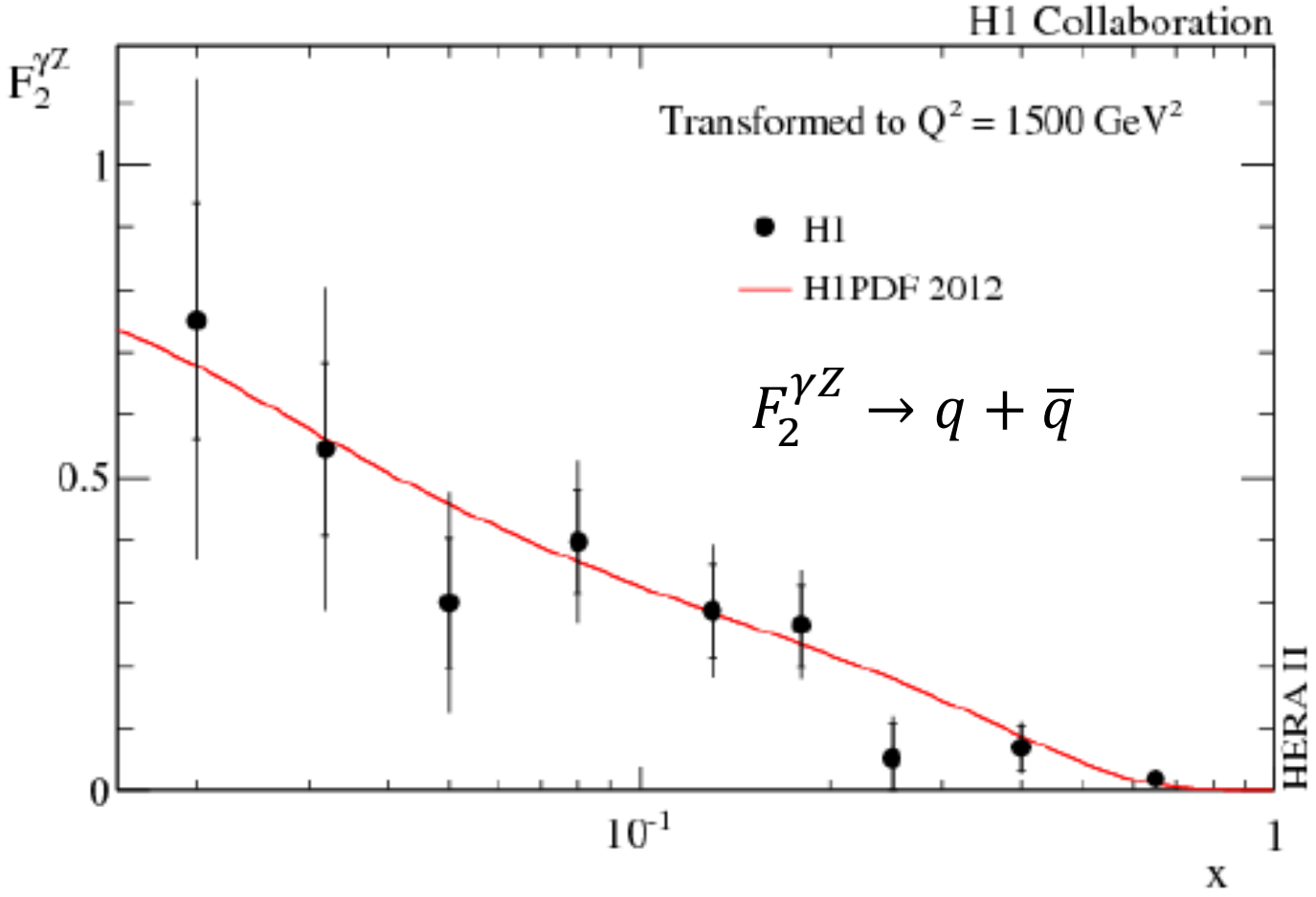
- chirality probes anti-matter

$$\frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{P_L^{\pm} - P_R^{\pm}} = \frac{\kappa Q^2}{Q^2 + M_Z^2}\left[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+}\frac{\kappa Q^2}{Q^2 + M_Z^2}(v_e^2 + a_e^2) x F_3^Z\right]$$



$$x_{\mathrm{Bj}} = \frac{\gamma \cdot q}{\gamma \cdot p} = \frac{m_q^2 + Q^2}{W^2 - m_p^2 + Q^2} \xrightarrow[\frac{m_{q,p}^2}{W^2} \to 0]{} \frac{Q^2}{W^2 + Q^2}$$

Fermi Scale Couplings

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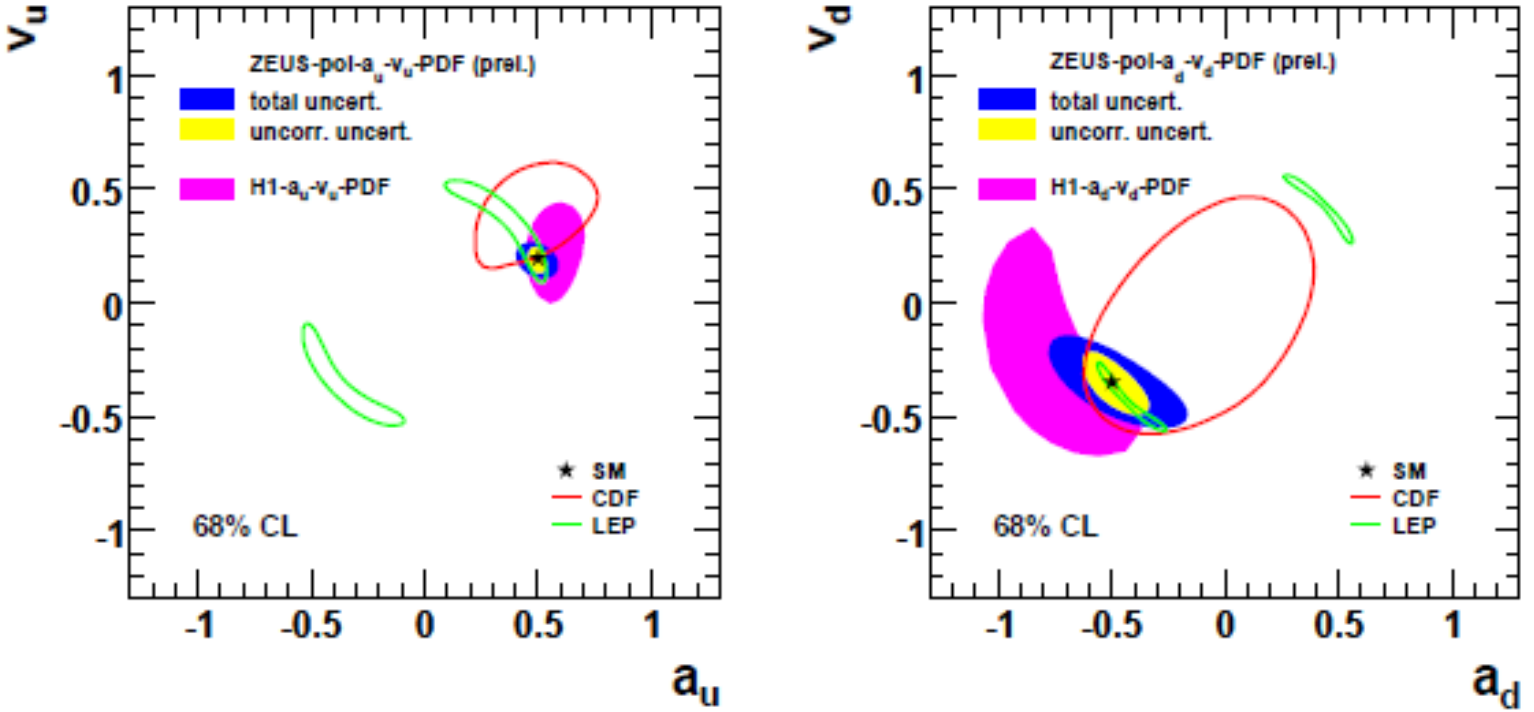
Measurement of sign and size of vector and axial quark couplings from $\gamma - Z$ interference and lepton polarisation.



Thorne

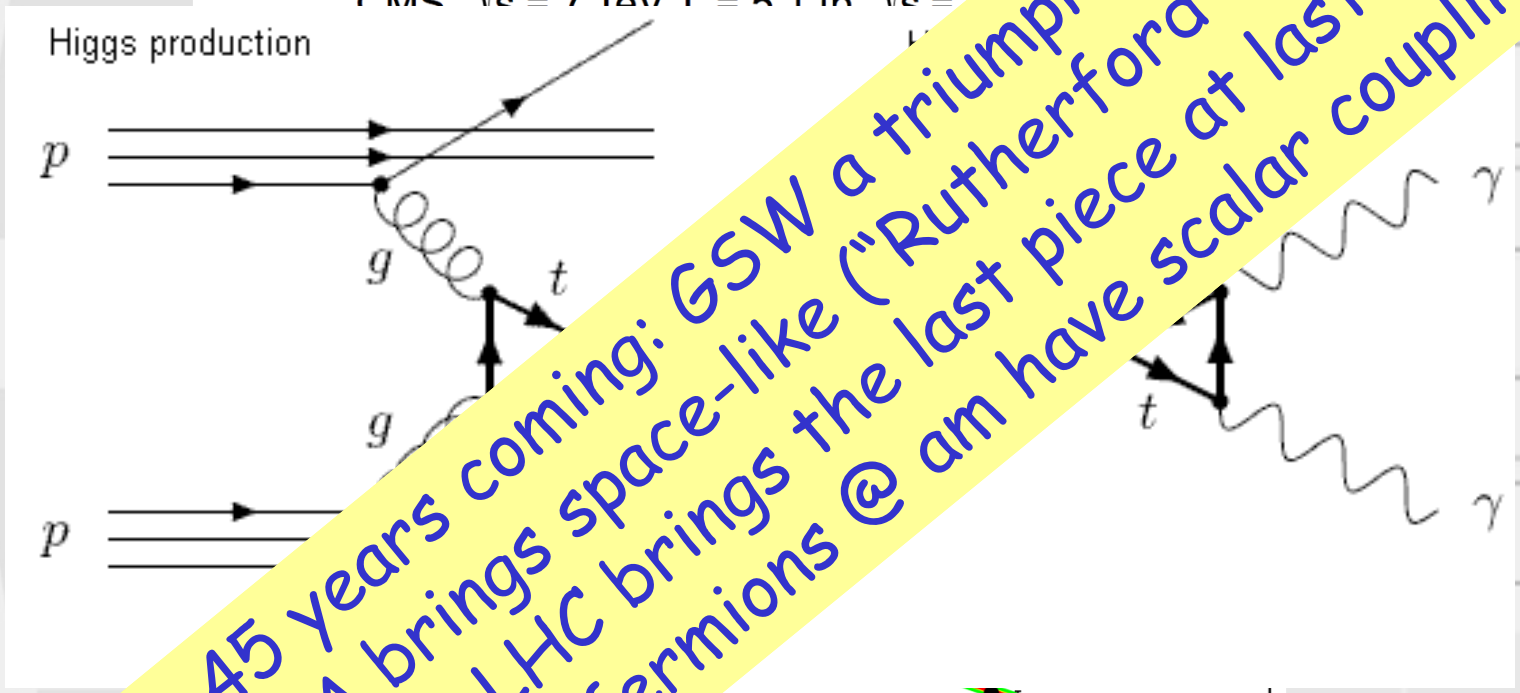
Similar to searches for BSM physics. Complementary behaviour.

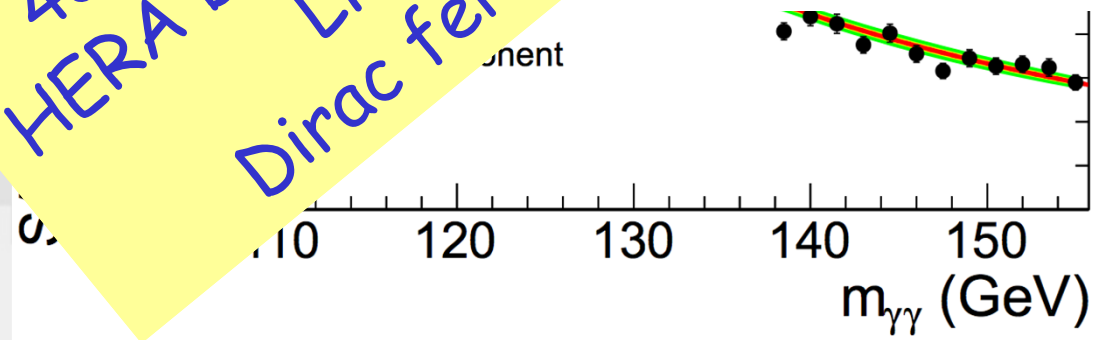
- beat? ! precision space-like SM – where else ?

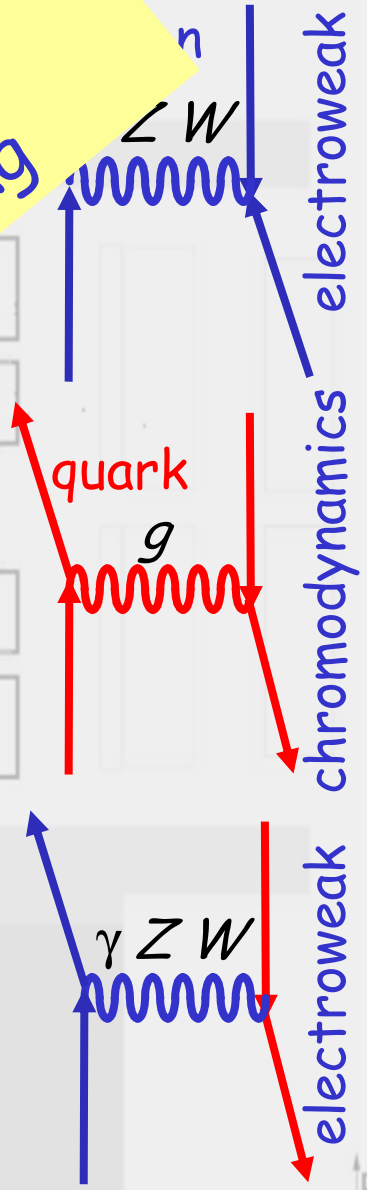
Fermi Scale – remainde

- Fermi scale complete: EW unifi

45 years coming: GSW a triumph of humanity
HERA brings space-like ("Rutherford"-like NC CC)
LHC brings the last piece at last!
Dirac fermions @ am have scalar coupling







Constituents with Currents

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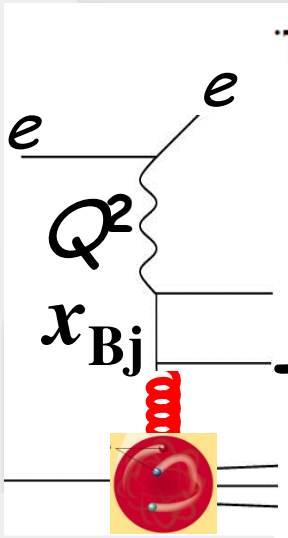
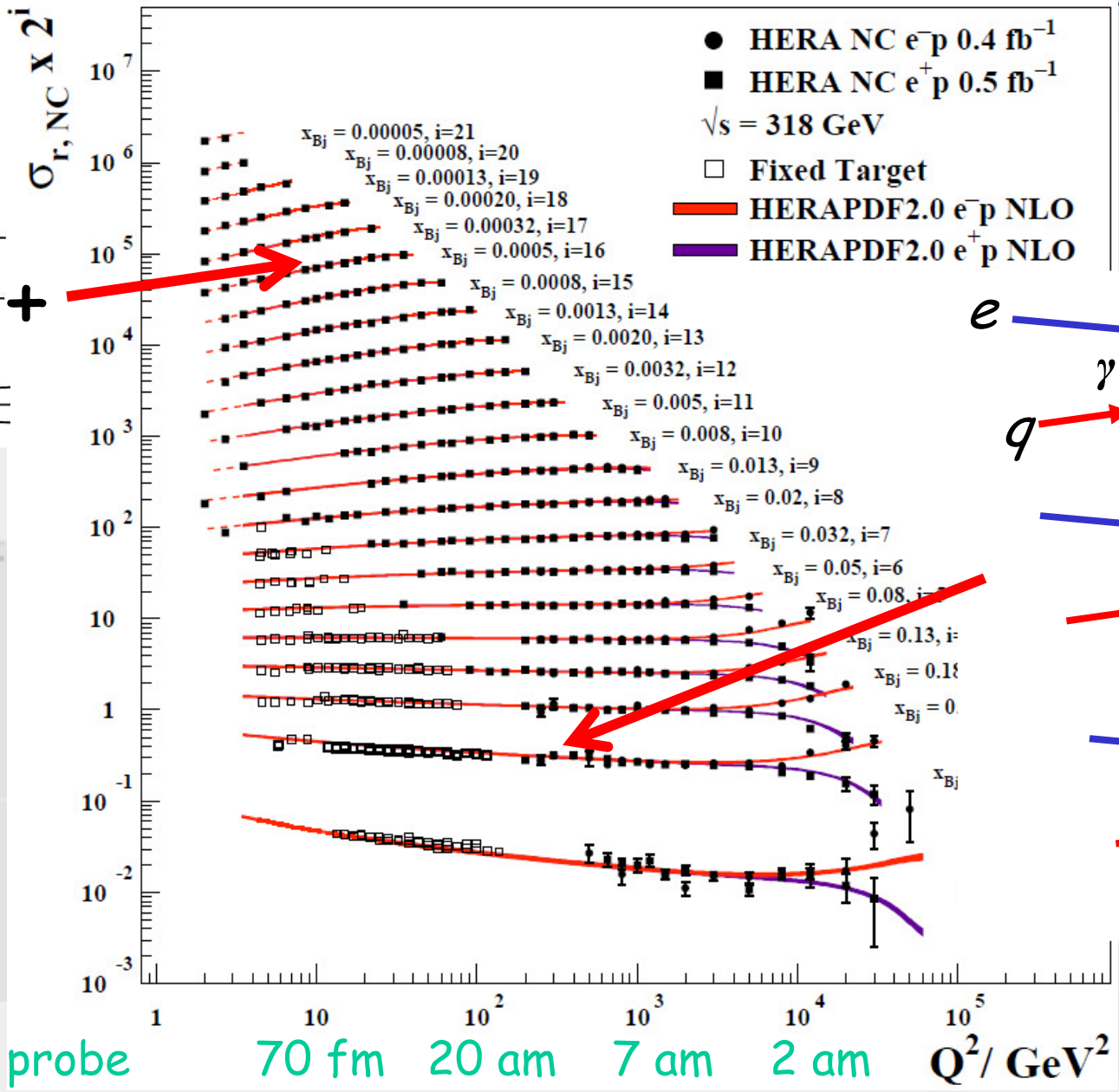
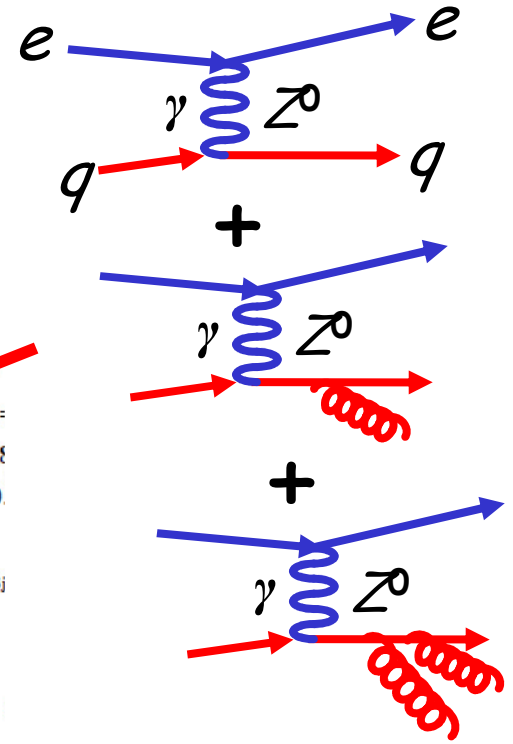


colour driven





valence driven

Constituents with Currents

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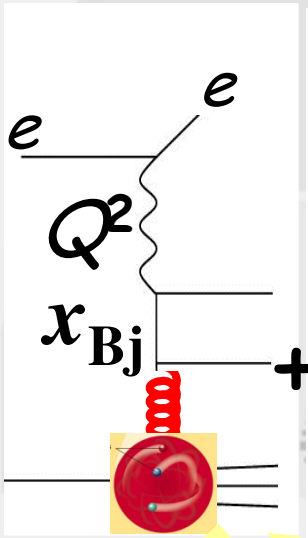
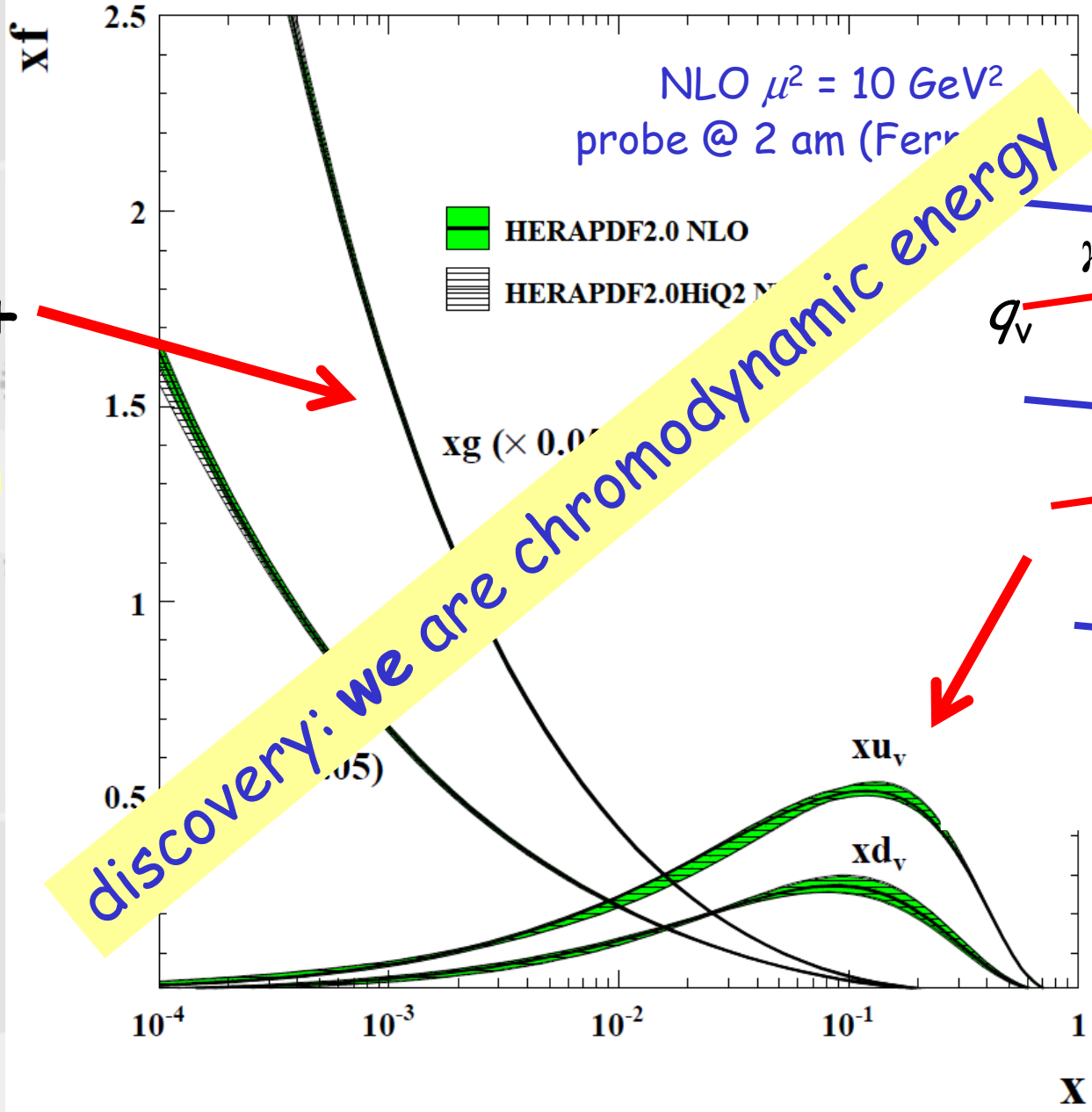
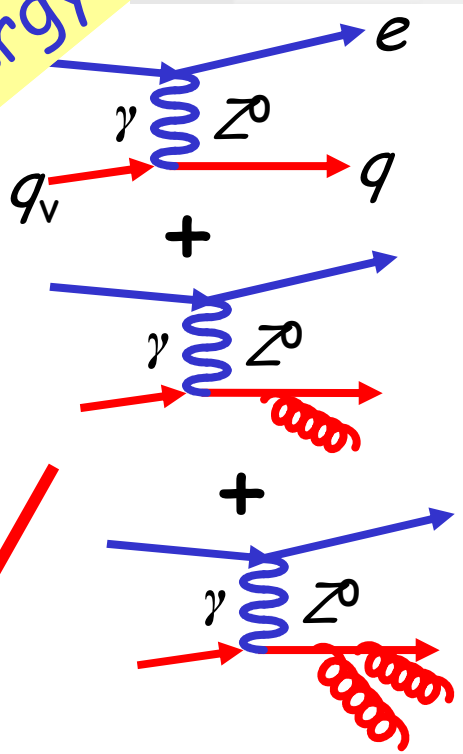


colour driven

Guido Altarelli
1941-2015



discovery; we are chromodynamic energy



valence driven

Colour Conundrum

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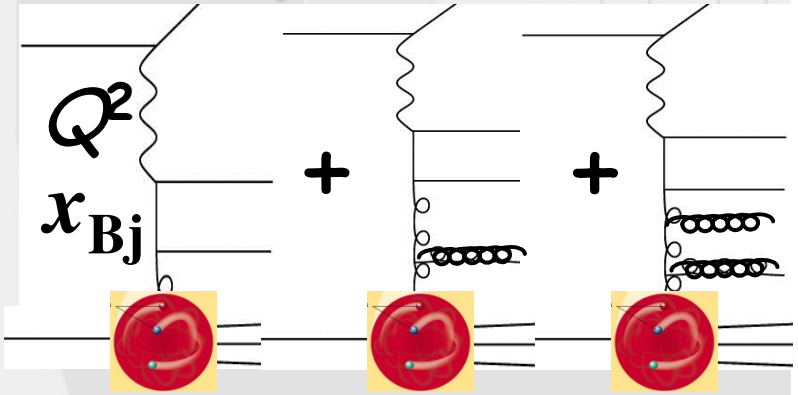
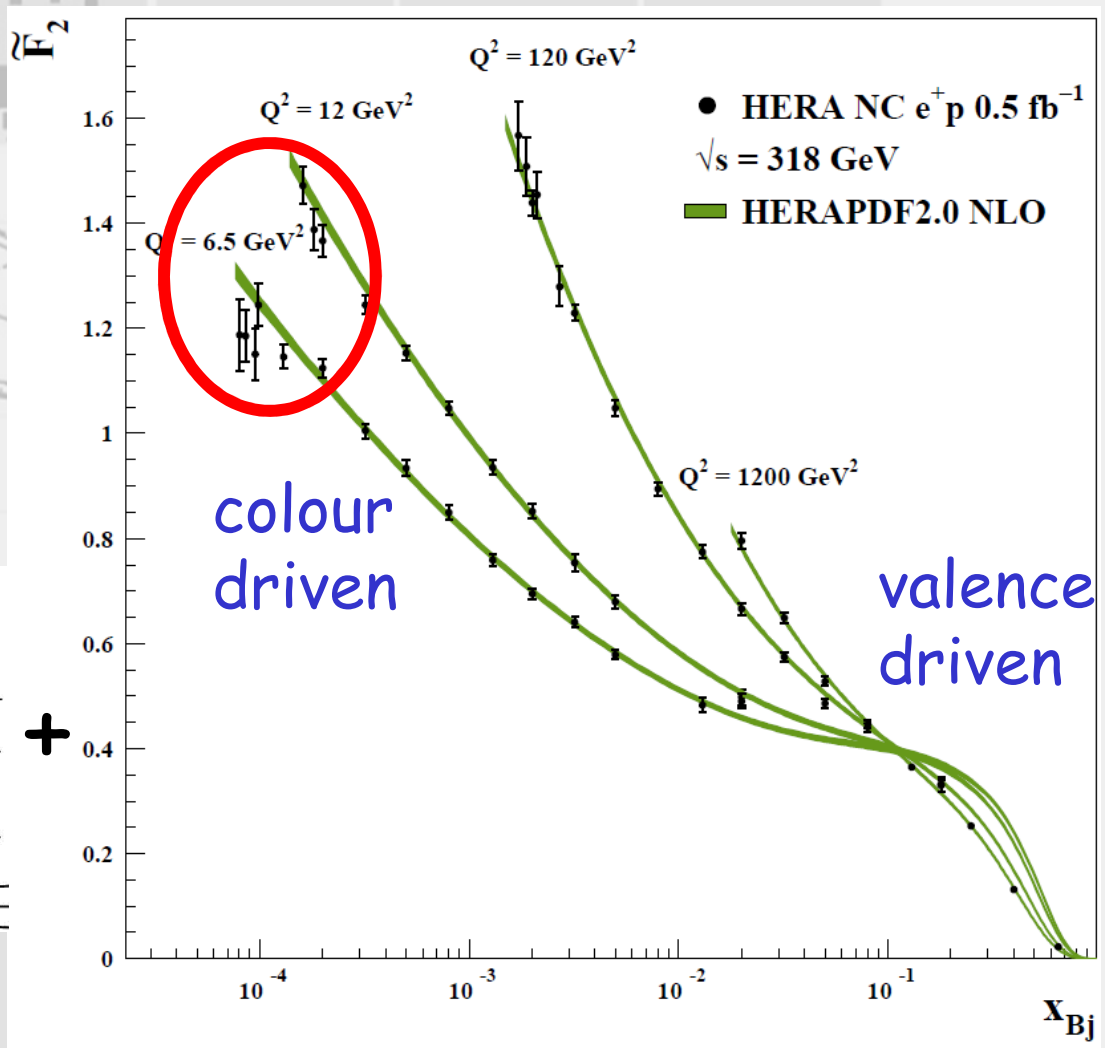
- 2015: rise to low x of proton structure function F_2
  - the gauge field theory QCD **is** proton structure





↳ discovery: but we don't understand why: $\ln\frac{1}{x}$?

Constituents and Currents

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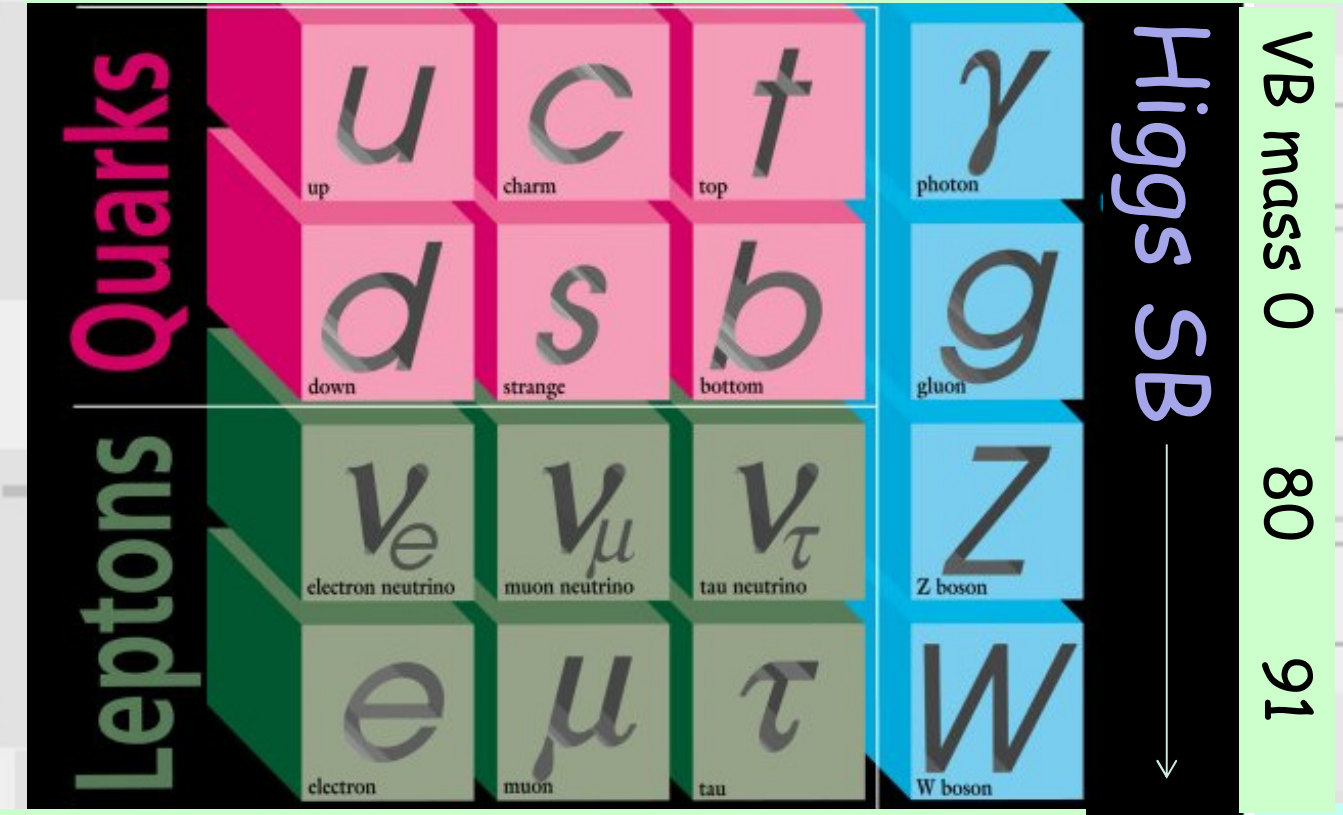
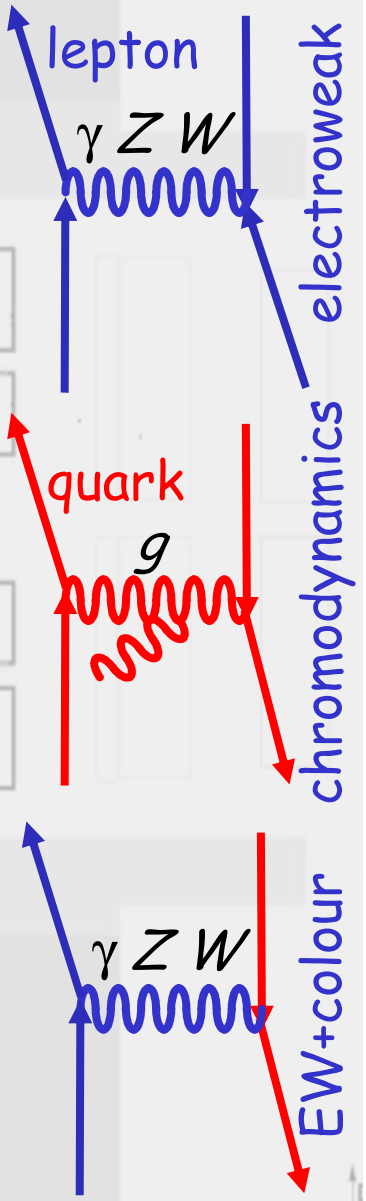
- the Standard Model landscape

mass <15 MeV *s*<0.3 *c* ~1.5 *b* ~4 *t* ~170 GeV ?



mass *e* =0.5 MeV *μ* =0.1 *τ* =1.8 GeV

matter = Dirac fermions
force = colour, charge, gauge SB VB



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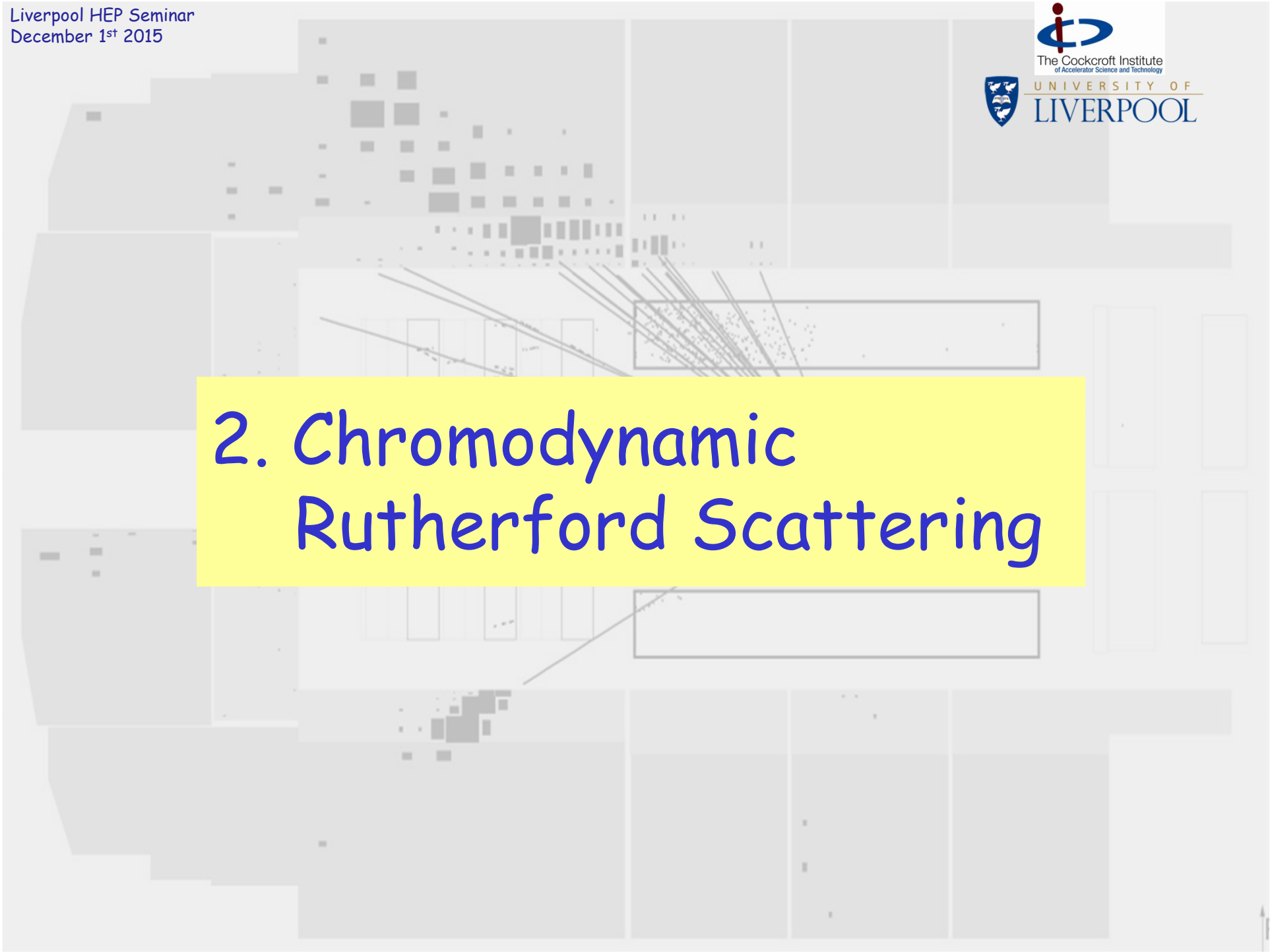

2. Chromodynamic Rutherford Scattering

Colour Interaction Dynamics

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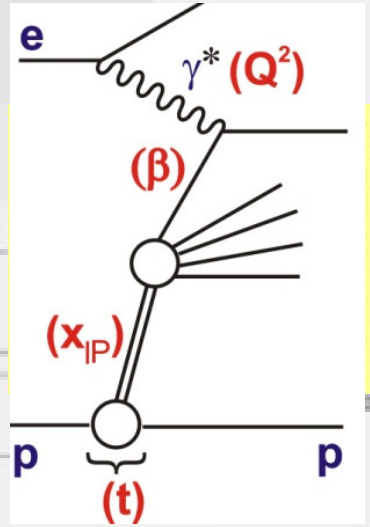
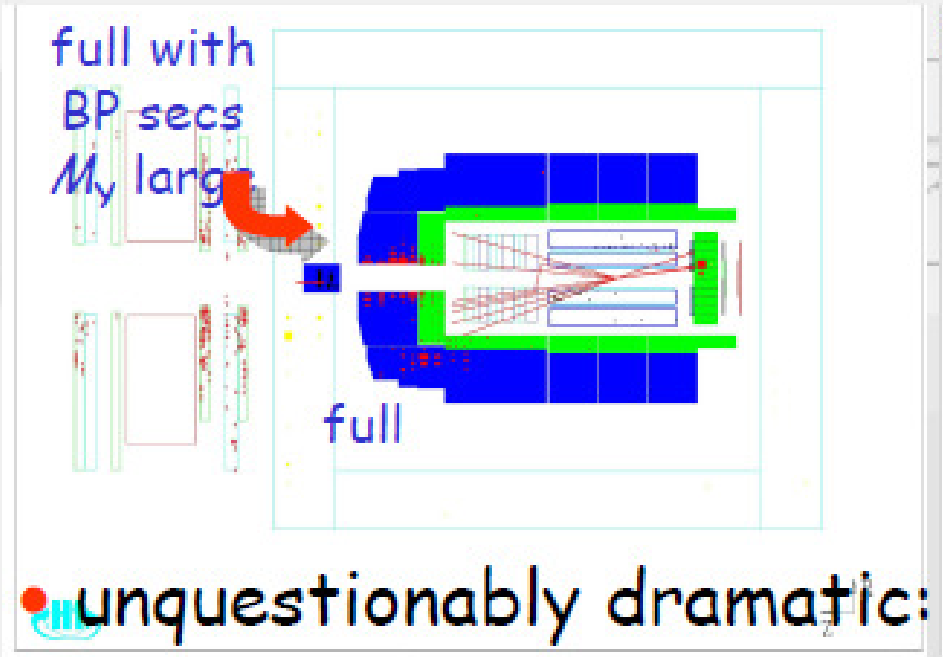
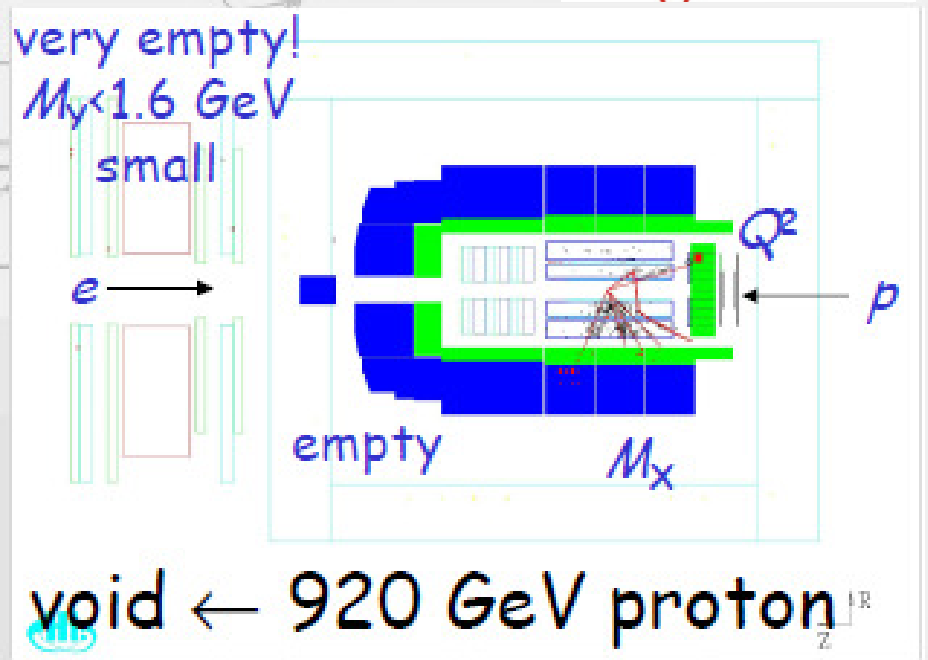
- experiment $ep \rightarrow epXY$
  - p isolated in rapidity
  - forward hadrons $M_Y^2 < 2.5$ GeV^2 } gap
    isolated in rapidity
  - probe hadronic interaction







- unquestionably dramatic: void ← 920 GeV proton

Colour Interaction Dynamics

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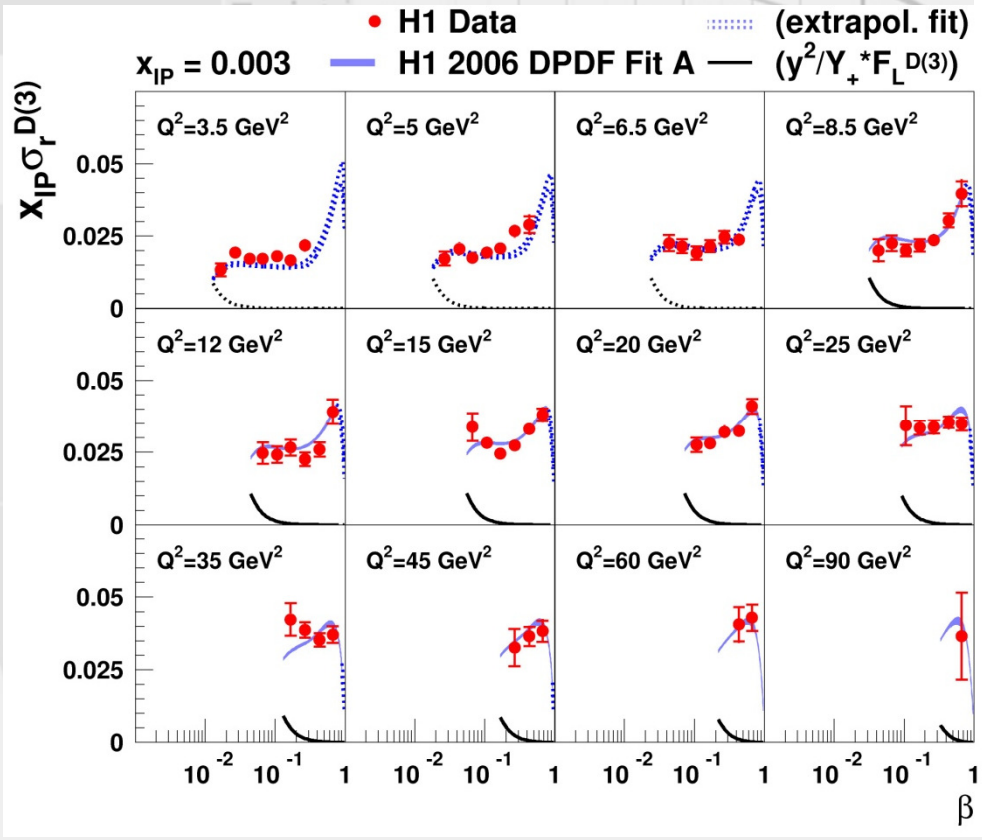
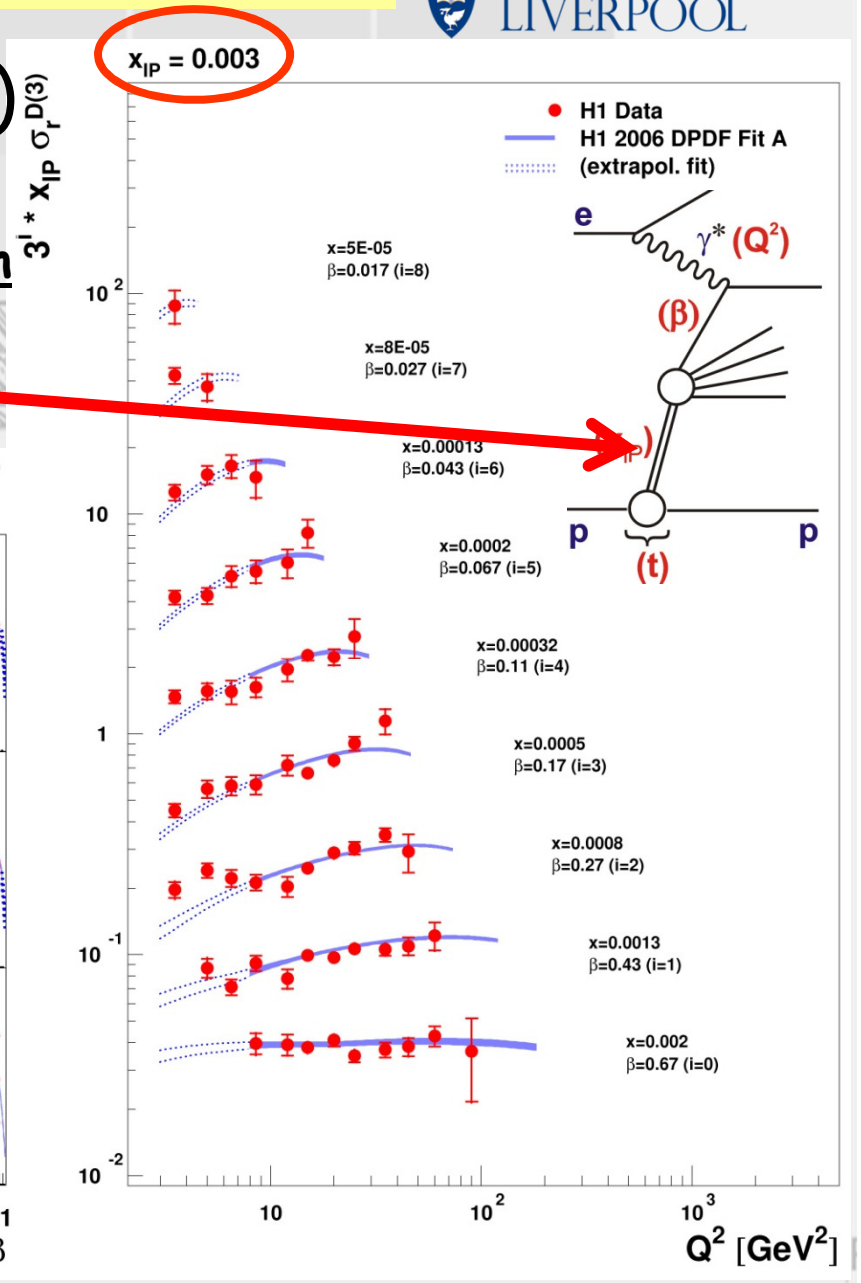
- x-section $x_{IP}\sigma_r \sim F_2^D(\beta, Q^2, x_{IP})$
  - scaling violations → flavour singlet q_s QCD evol^n
  - β dep^c → $g \to q\bar{q}$





Colour Interaction Dynamics

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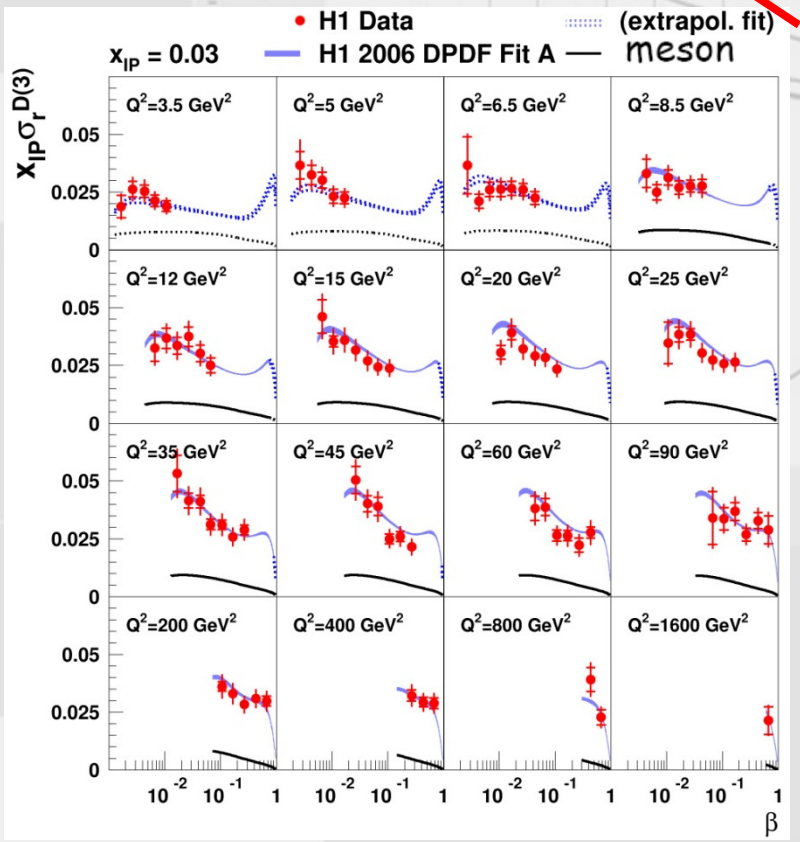
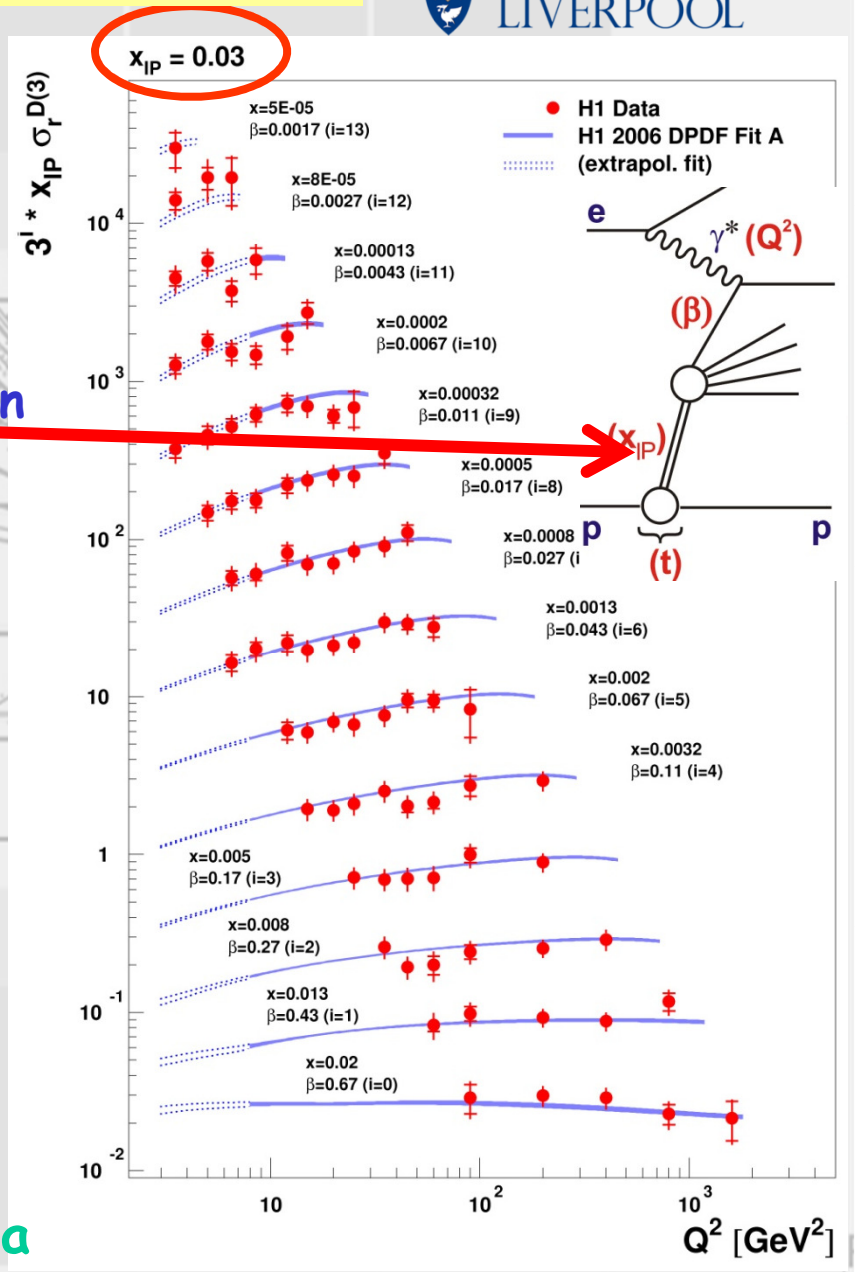
- x-section $x_{I\!P}\sigma_r$ @ larger $x_{I\!P}$
  - scaling violations → flavour singlet q_S evol^{n}
  - β dep^{c} ~ $1^{c}_{g\to q\bar{q}}$ + q_{meson}





Ruspa

Photon Structure

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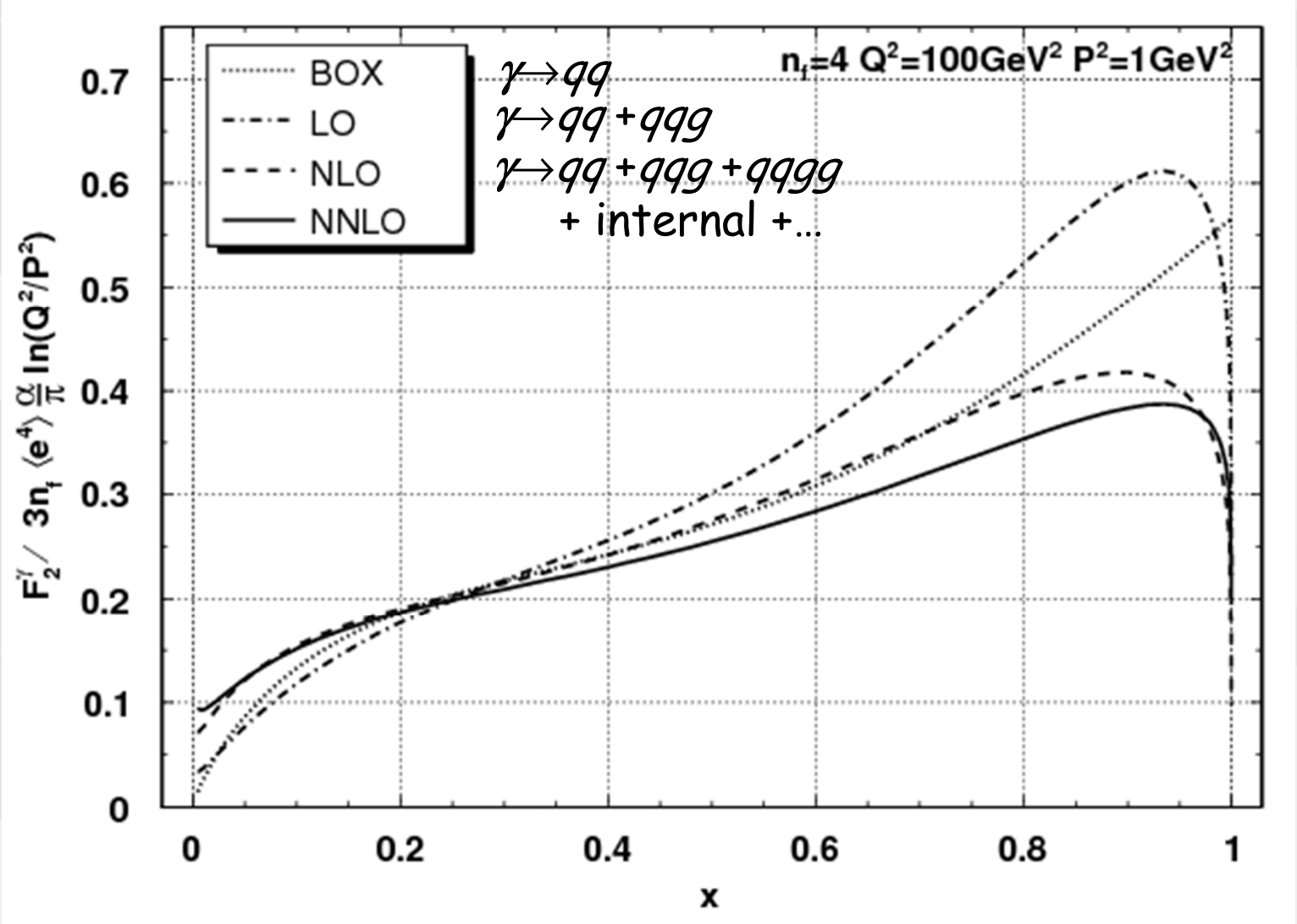
- Photon structure function $F_2(x, Q^2)$



Hadronic Structure

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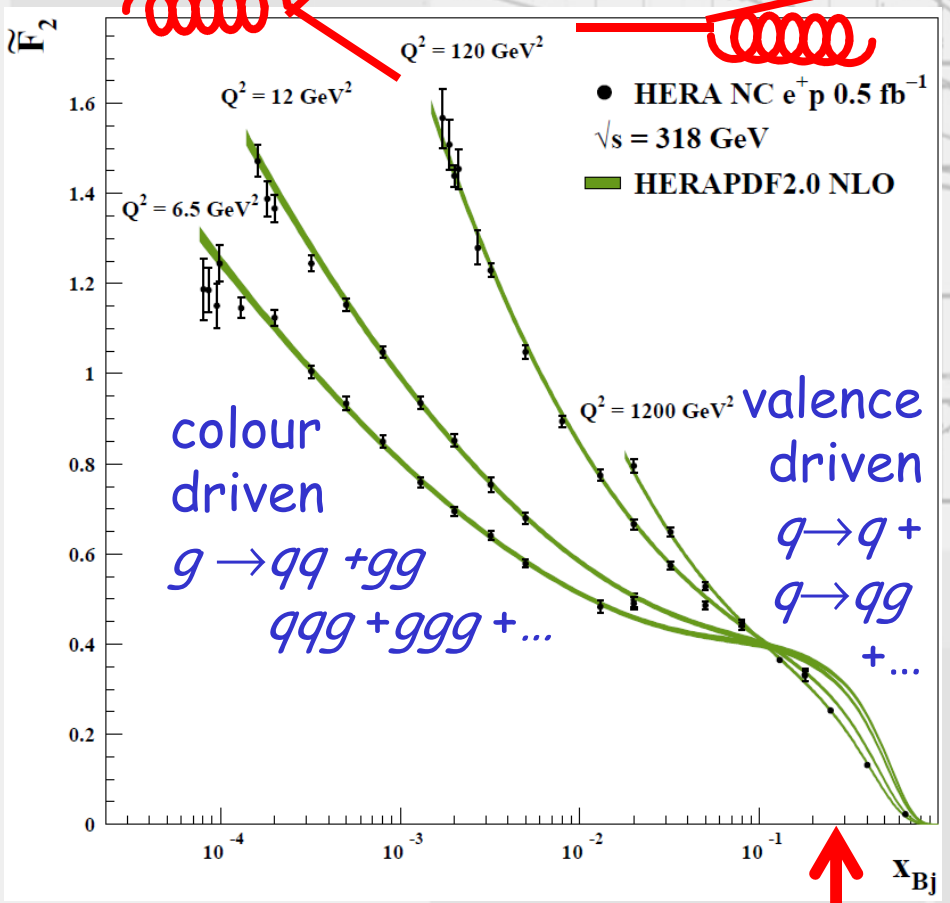
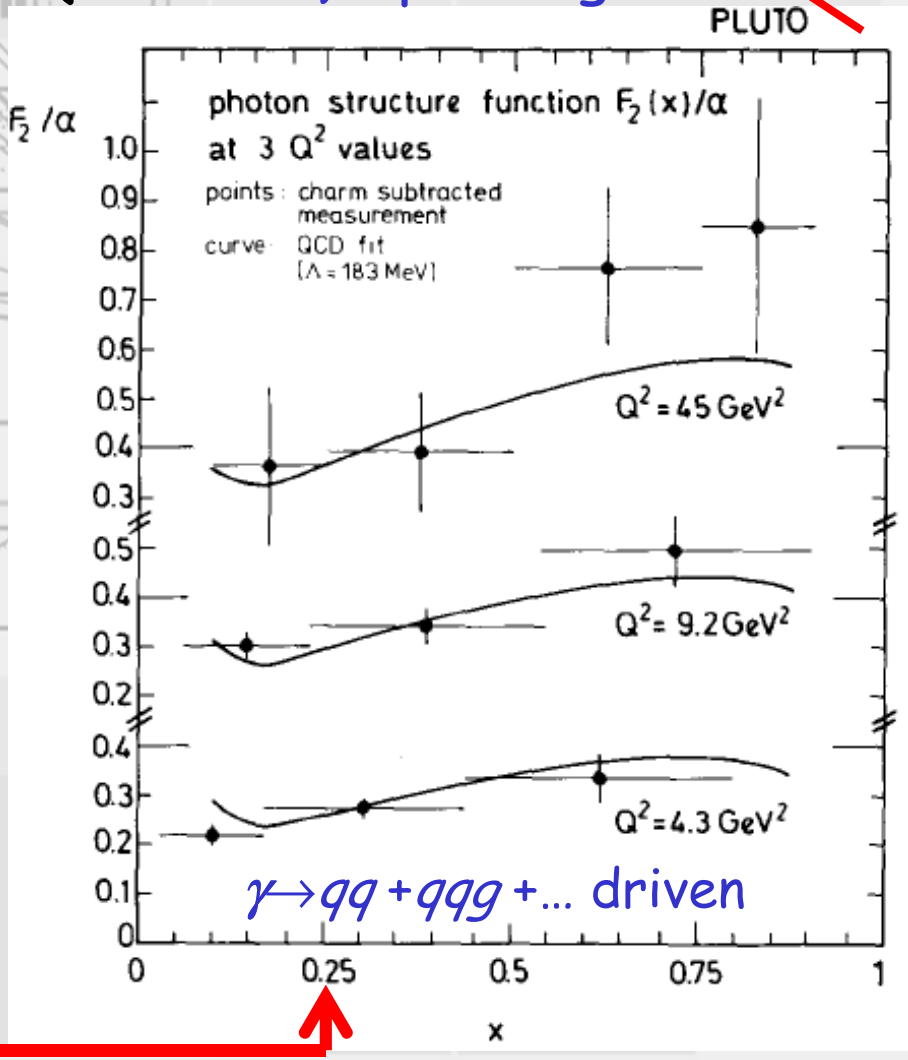
- structure function $F_2(x, Q^2)$
  - QCD
  - QED

"g-splitting"

"q-splitting"

"γ-splitting"





Colour Interaction Dynamics

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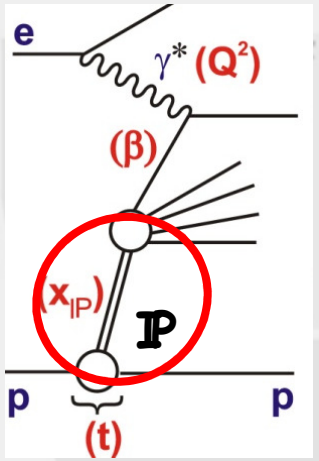
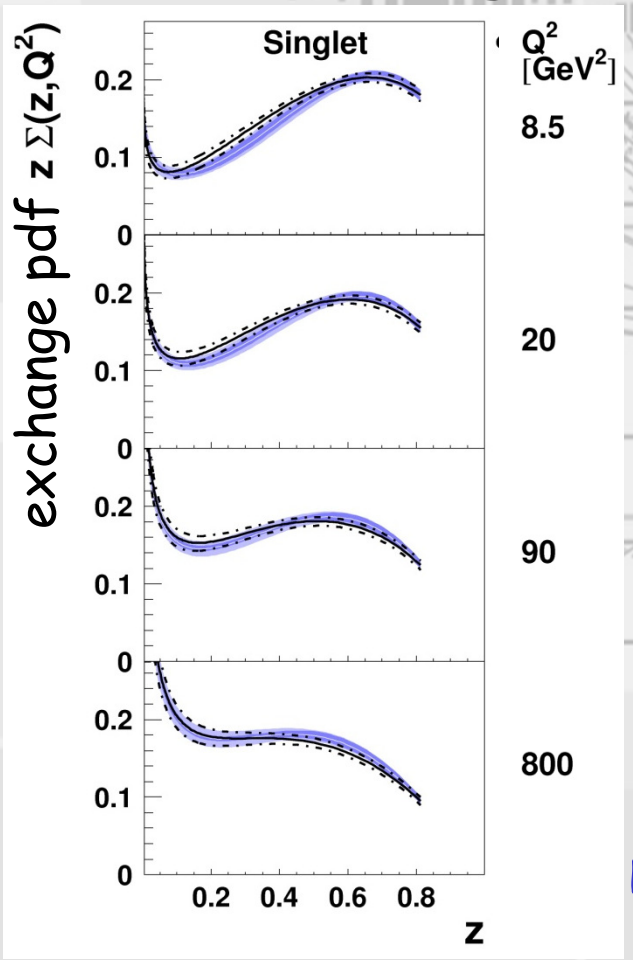
- the colour dynamics of the nucleon interaction
  - NLO $\rightarrow$ 1^c colour singlet inelastic q interaction

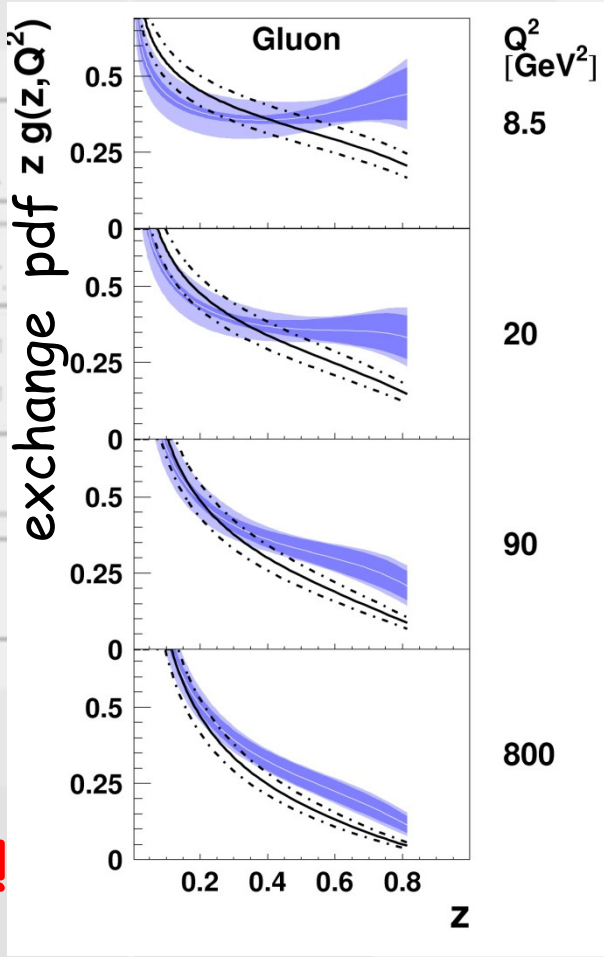
$g \rightarrow q\bar{q}$
$+ g \rightarrow q\bar{q}g$
$+ \ldots$





$g +$
$g \rightarrow gg +$
$g \rightarrow ggg$
$+ \ldots$

no valence!



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

Colour Interaction Dynamics

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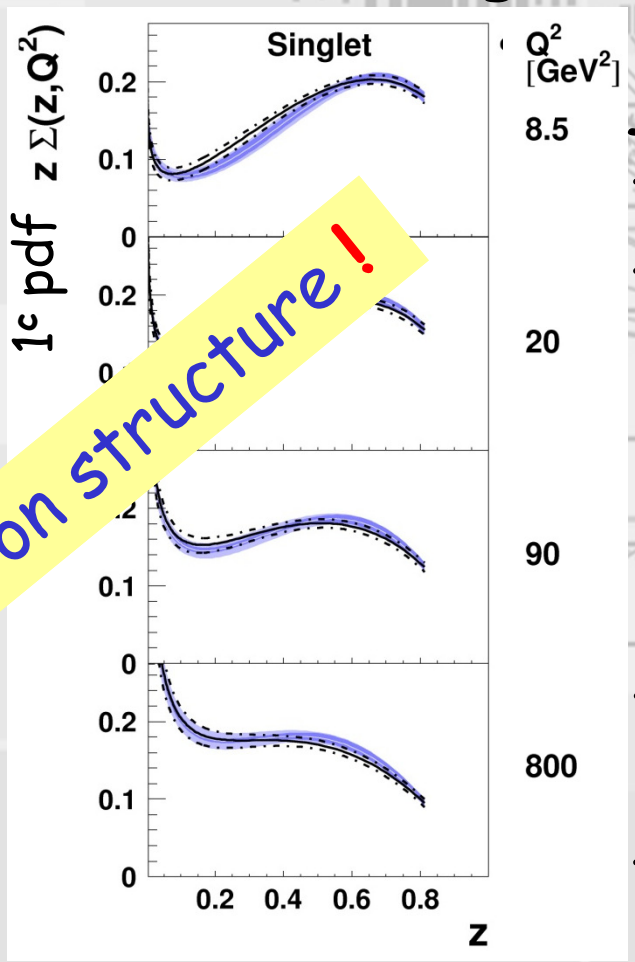
- the colour dynamics of the nucleon interaction
  - NLO $\rightarrow$ 1^c colour singlet inelastic q interaction

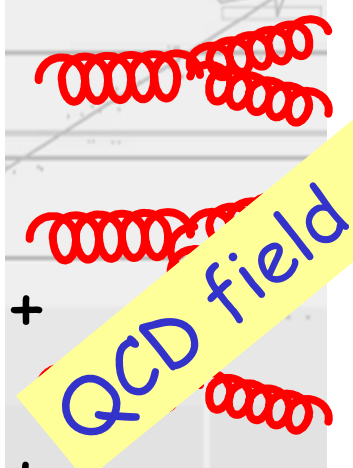
$g \rightarrow q\bar{q}$
$+ g \rightarrow q\bar{q}g$
$+ \ldots$

$+ \ldots$

cf photon structure !

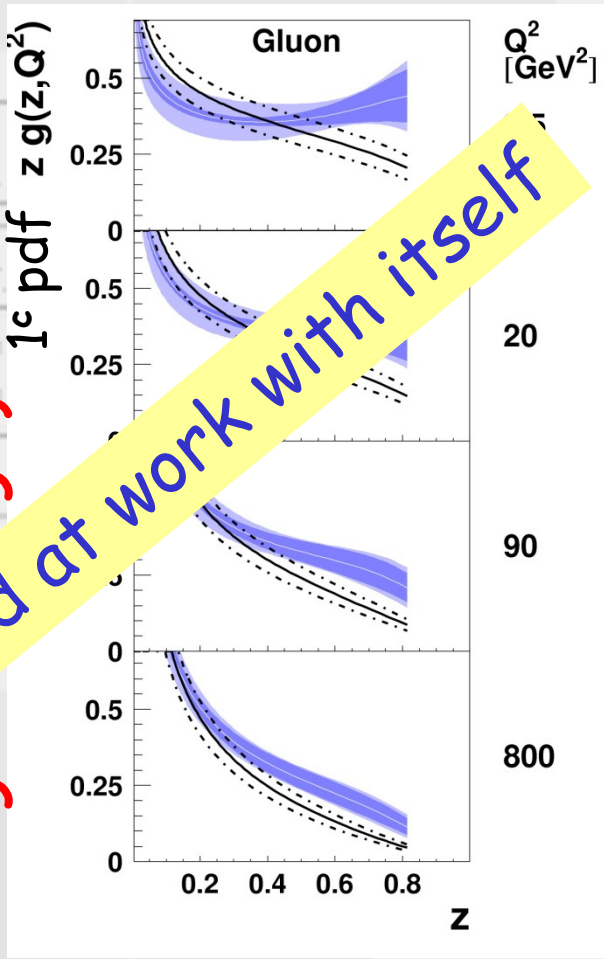


$g \rightarrow gg$
$+ g \rightarrow ggg$
$+ \ldots$



$+ \ldots$

QCD field at work with itself



$\hookrightarrow$ internucleon interaction = gluons = $\frac{\text{gluon splitting}}{\text{quark splitting}} = \frac{9}{4}$ LO

Photon Structure

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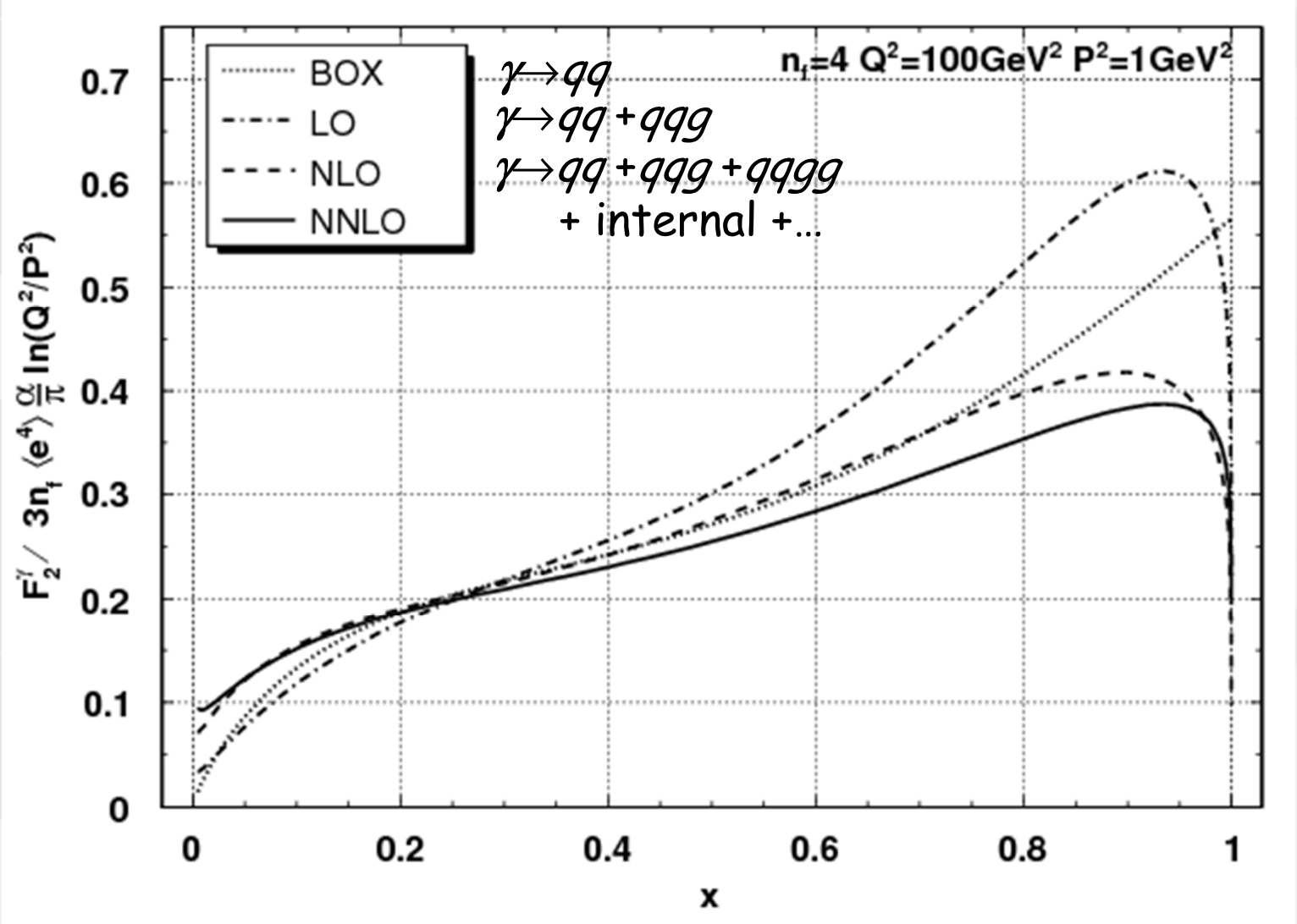
- photon structure function $F_2(x, Q^2)$



Deep-Inelastic Diffraction

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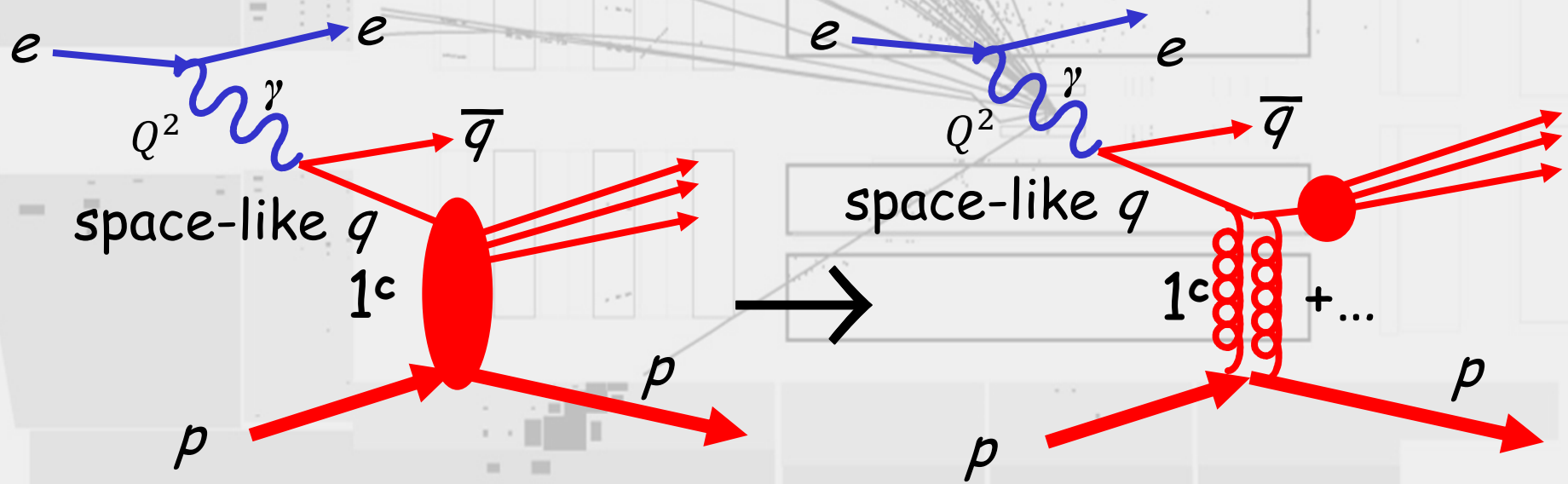
- flavour probe (electric charge) of 1^c interaction
  - space-like photon "probes for quark flavour in diffractive interaction of proton



↳ high energy hadron-hadron interaction
= exchange of (coloured gluons)$_{1^c}$

Deep-Inelastic Diffraction

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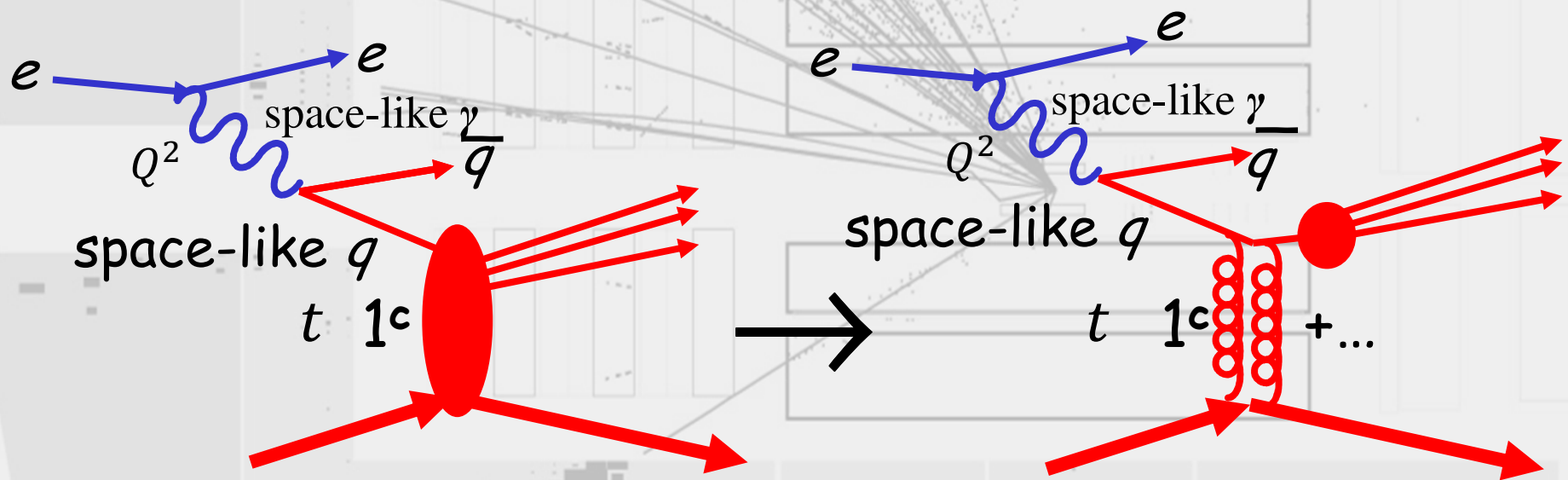
- *in*elastic (dissociative) quark diffraction
  → 1^c q inelastic interaction ?
  - space-like virtual photon → space-like quark+p



↳ high energy quark-hadron interaction
= exchange of (coloured gluons in 1^c)
- small < space-like q virtuality < large

Elastic Quark Scattering

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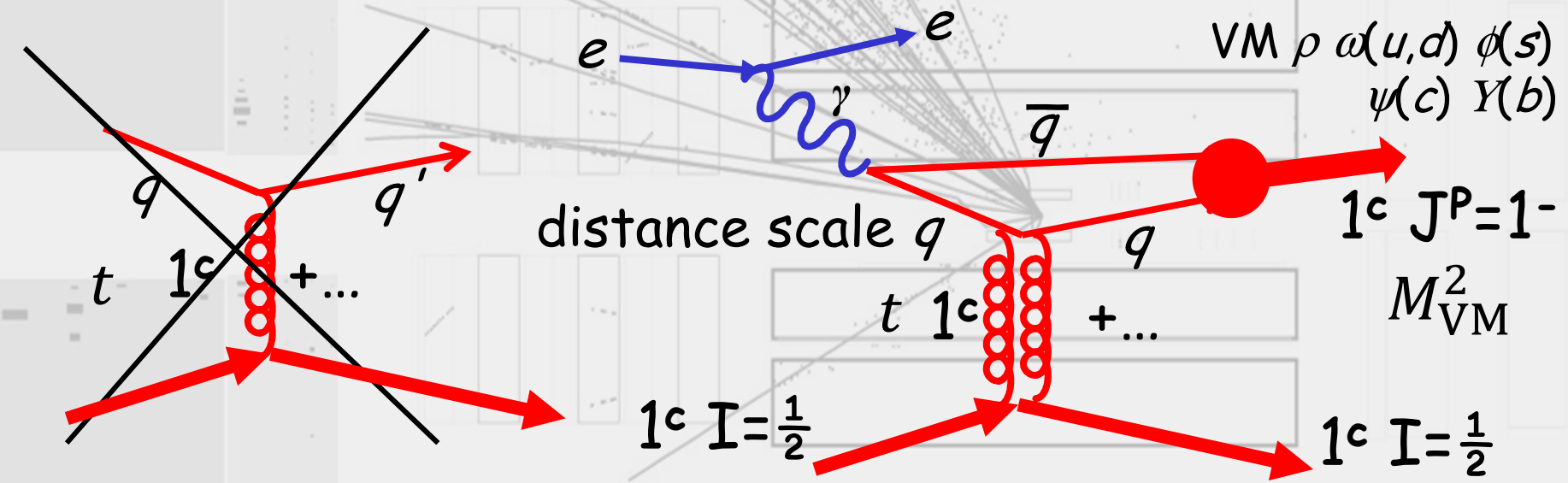
- elastic quark diffraction
  → *qp* elastic interaction with 1^c singlet exchange ?
  - space-like virtual photon → space-like *q*



- exclusive VM electroproduction: $ep \to e\mathrm{VM}p$
  - (embedded) sub-fm Rutherford scattering
  - quark virtuality $\leftrightarrow Q^2\ M^2_{\mathrm{VM}}\ m^2_{\mathrm{quark}}\ t$ u d s c
    $\leftrightarrow$ size of elastic interaction

Elastic Quark Scattering

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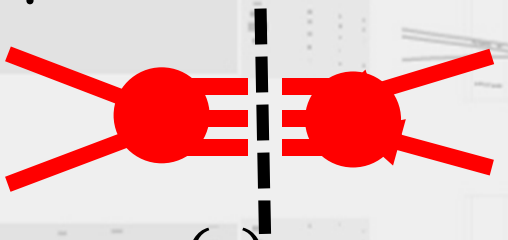
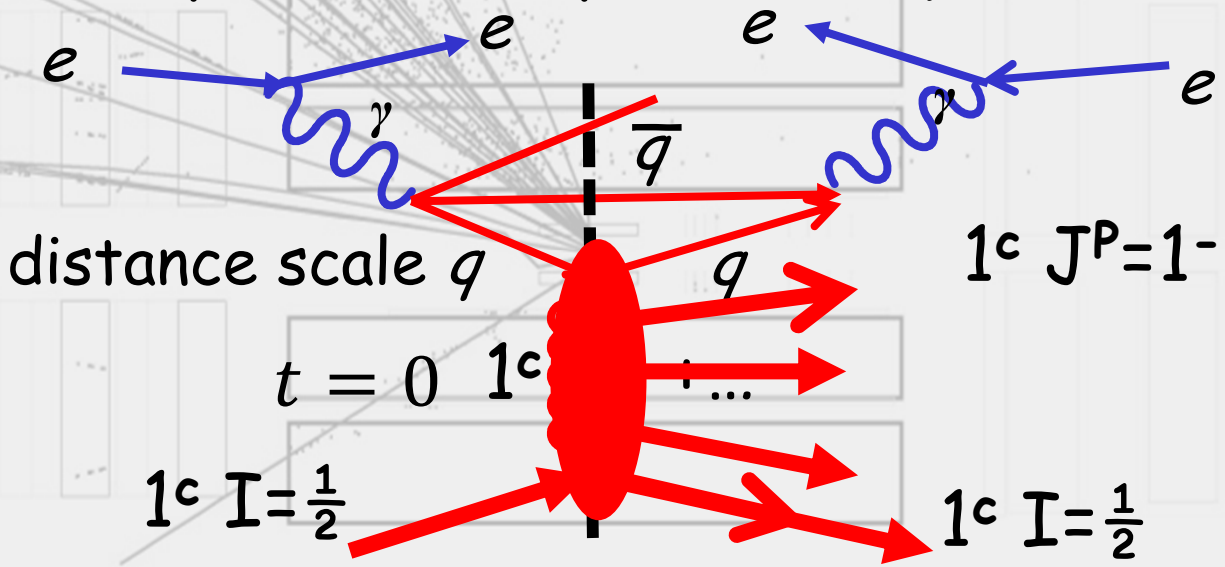
- elastic quark diffraction
  → *qp* elastic interaction with 1^c singlet exchange?
  - space-like virtual photon → space-like *q*

optical theorem



$\sigma_{12\to\text{all}}(s)$

$\frac{1}{s}\,\text{Im}\,A_{12\to12}(s,t=0)$



- "exclusive" $\gamma^* p \to \gamma^* p$ elastic virtual photon-proton
  - sub-fm Rutherford scattering $\text{Im}\,A_{12\to12}(s,t=0)$
  - quark virtuality $\leftrightarrow Q^2$ $t=0$ *u d s c*
    $\leftrightarrow$ size of elastic interaction

Size of Elastic Scattering

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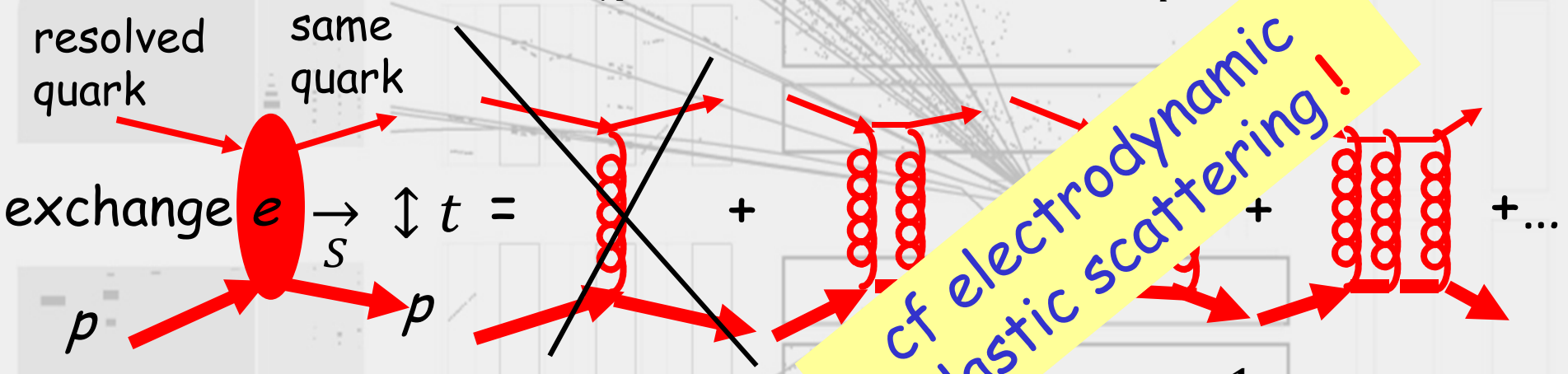
- size of elastic interaction
  - transverse resolves and defines quark $\propto \frac{1}{Q}$
  - longitudinal $\propto \frac{1}{x_{ex/p}}$ $x_{ex/p} = \frac{ex \cdot quark}{p \cdot quark} = \frac{m_q^2 - t - v^2}{\hat{s} - m_p^2 - v^2}$



cf electrodynamic elastic scattering !

smaller ← time-like phase space $\propto \frac{1}{x_{ex/p}}$ → larger

smaller ← time-like phase space ∝ quark size → larger

quark size = interaction size $\propto \frac{1}{\text{quark virtuality}}$

small perturbative ← interaction size = quark size = $\frac{1}{\text{quark virtuality } v}$ → large non-perturbative

Rutherford Scattering

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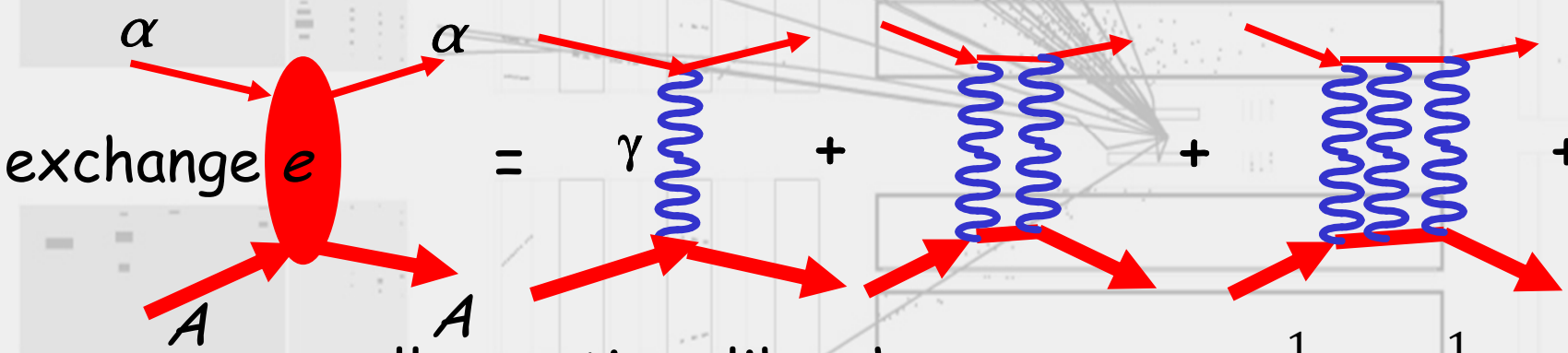
- size of elastic interaction
  - transverse $\propto \frac{1}{Q}$ resolves (defines) structure in A
  - longitudinal $\propto \frac{1}{x_{ex/A}}$ $x_{ex/A} = \frac{ex \cdot \alpha}{A \cdot \alpha} = \frac{Q^2}{s - m_\alpha^2 - m_A^2}$



smaller ← time-like phase space $\propto \frac{1}{x_{ex/A}} \propto \frac{1}{Q^2}$ → larger

α_{em} small

small ← interaction size $\propto \frac{1}{Q}$ → large

perturbative ← interaction size $\propto \frac{1}{Q}$ → non-perturbative

- $A \rightarrow A\gamma$ splitting $\propto \frac{dx_{ex/A}}{x_{ex/A}} \cdot F_A(Q^2) \frac{dQ^2}{Q^2} \rightarrow \frac{d\sigma_{\alpha A \rightarrow \alpha A}}{dQ^2}(s, Q^2) \propto \frac{F_A(Q^2)}{Q^4}$

Theory of Elastic Scattering

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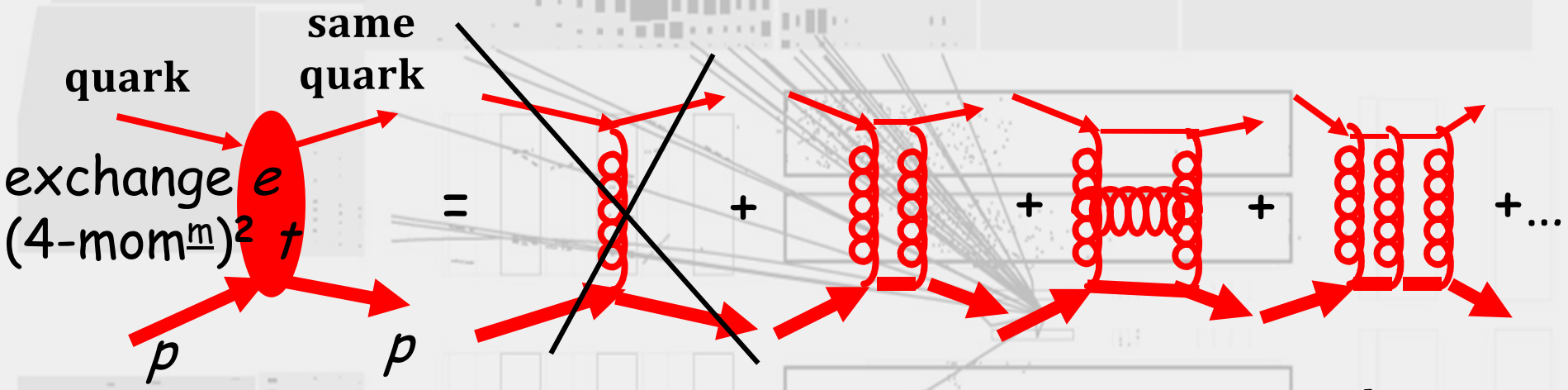
small perturbative $\leftarrow$ interaction size = quark size $= \frac{1}{\text{quark virtuality } v} \rightarrow$ large non-perturbative



- perturbative field action $q \rightarrow qg$ splitting $\propto \frac{dx_{g/q}}{x_{g/q}} \cdot \frac{dt}{t}$
- time-ordering of field action $\rightarrow$ exponentiation
  $\rightarrow$ sum to all orders (α_S?) + 1c Dyson, Lipatov et al.
  $\rightarrow q \rightarrow q + ex$ splitting $\xrightarrow[x_{ex/A} \gtrsim 0]{} \left(\frac{1}{x_{ex/A}}\right)^{1+2\lambda(t)} e^{bt} dx_{e/A} dt$

$\underset{\text{small}}{0.5} \geq \lambda(t) \gtrsim \underset{\text{large}}{0.1}$ $b \sim 6\ \text{GeV}^{-2}$

experiment + (challenging) theory

Optical Theorem

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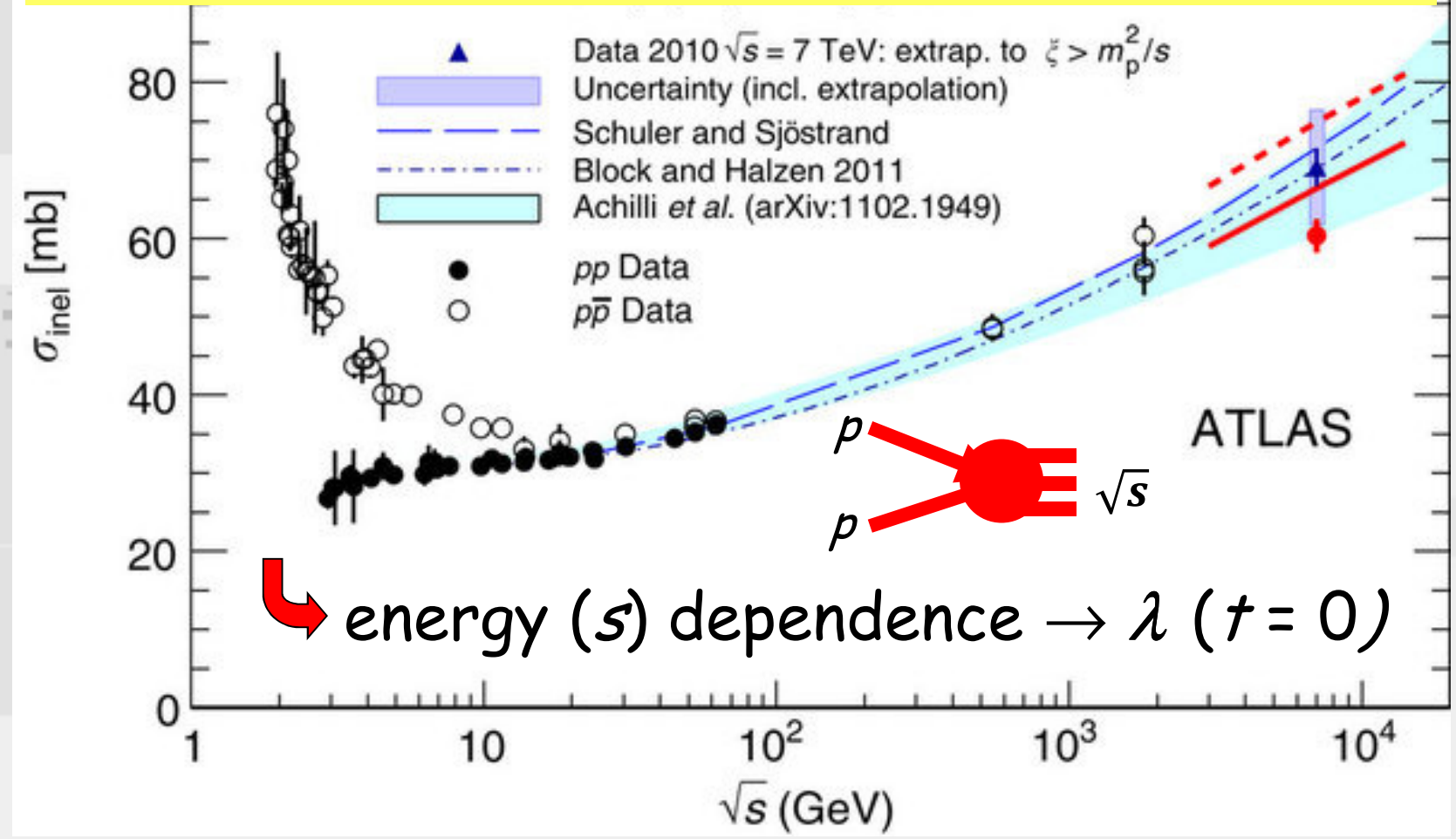
- hadron-hadron: $pp \to X$ $\lambda\,(t=0) \sim 0.1$

$$\frac{1}{s}\,\mathrm{Im}\,A_{12\to 12}(s,t=0) = \sigma_{12\to \mathrm{all}}(s) \propto \frac{1}{s}\left(\frac{1}{x_{ex/p}}\right)^{1+\lambda(t=0)} \sim \left(\frac{s}{-t}\right)^{\lambda(t=0)}$$



↳ energy (s) dependence → $\lambda\,(t=0)$

Elastic *pp* Scattering

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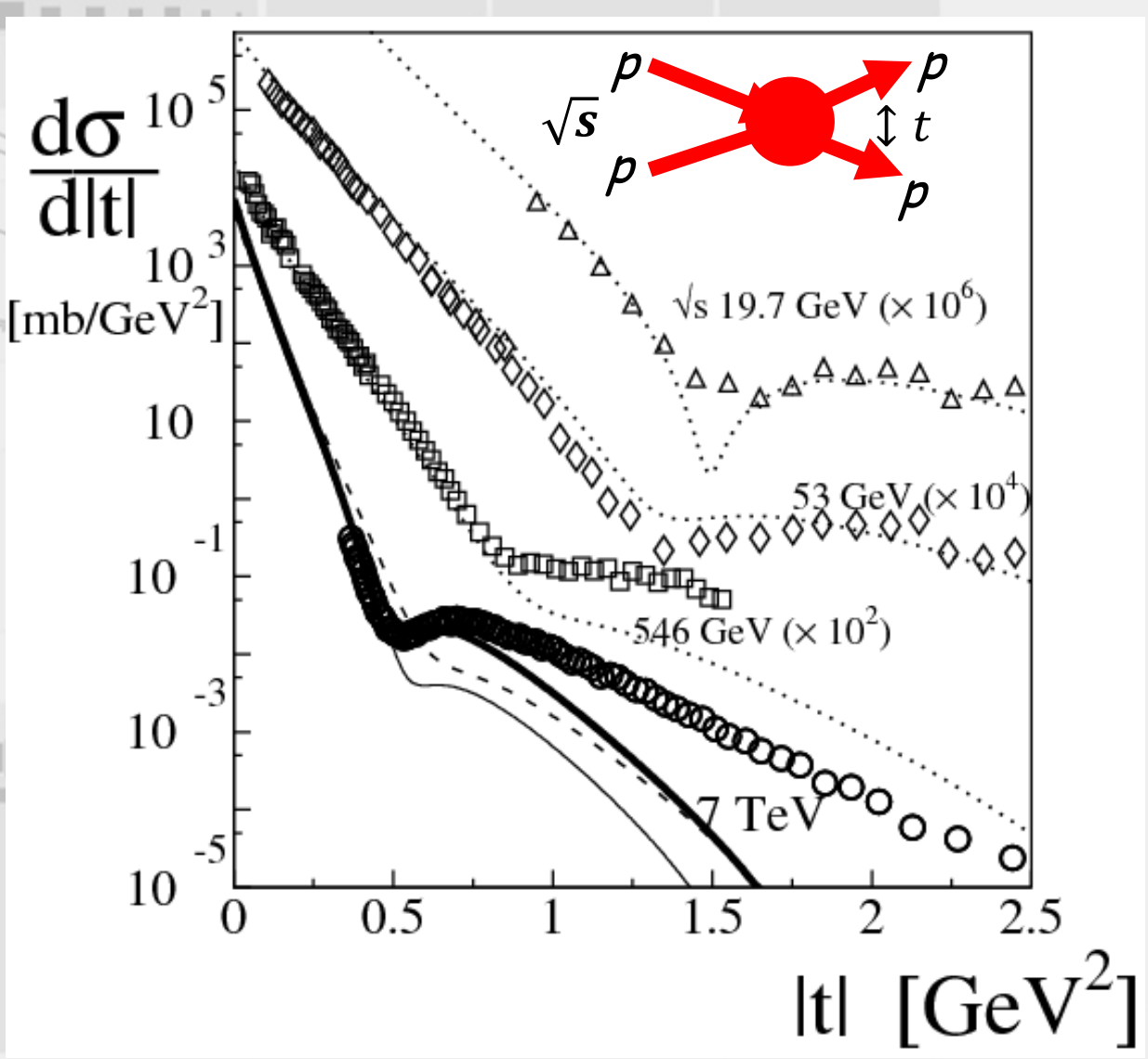
- hadron-hadron: $pp \to pp \quad \lambda\,(t)$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(s, t=0) \propto \frac{1}{s}\left(\frac{1}{x_{ex/p}}\right)^{1+2\lambda(t)} \sim \left(\frac{s}{-t}\right)^{\lambda(t)}$$

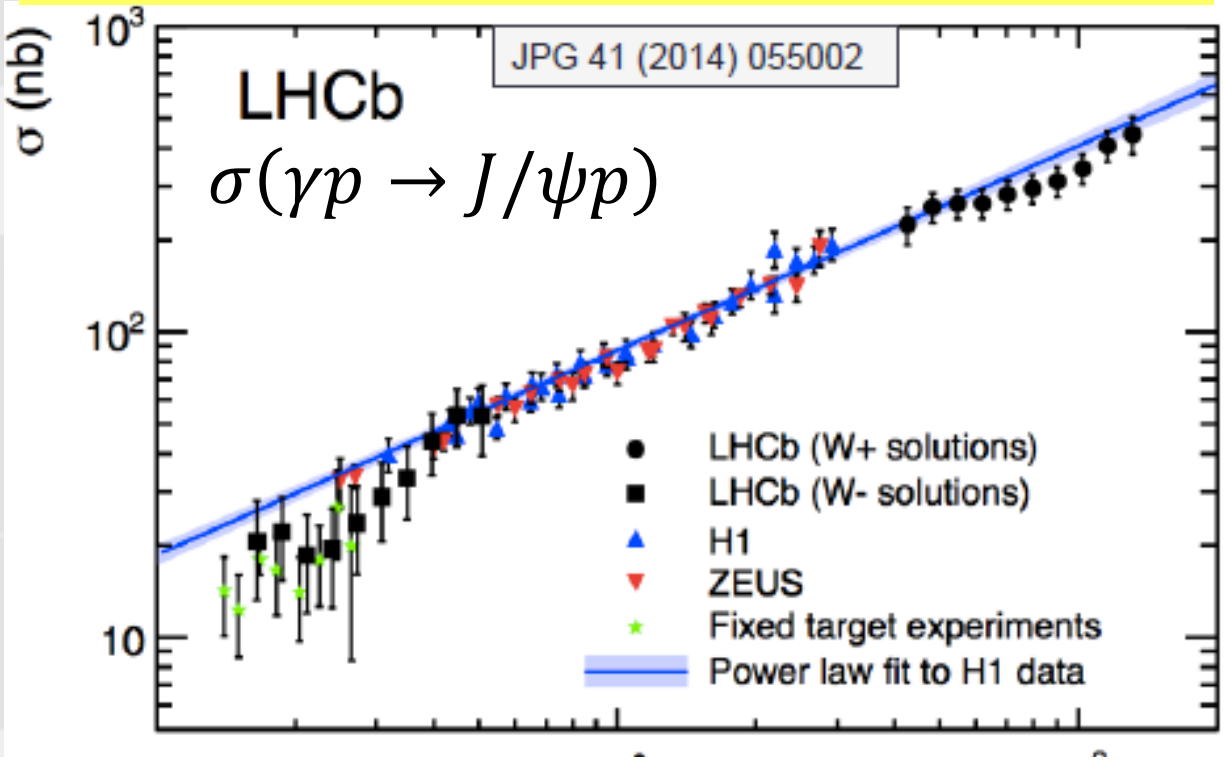
↳ energy (s) dependence at fixed t $\to \lambda\,(t)$

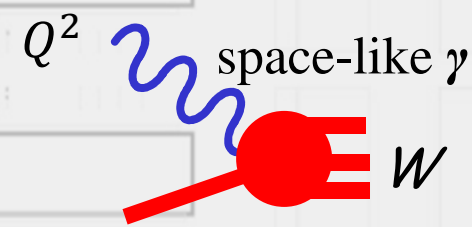


VM "Photo"production

- photon-hadron: $\gamma p \to \mathrm{VM}p \quad \lambda(t)$
  - q -flavour (m^2_{quark}) sensitivity of W-dependence

$$\sigma(W^2) \propto \frac{1}{s}\left(\frac{1}{x_{ex/p}}\right)^{1+2\langle\lambda\rangle_t} \sim \left(\frac{W^2 - M^2_{\mathrm{VM}}}{m_p^2}\right)^{2\langle\lambda\rangle_t}$$





↳ energy (W) dependence $\to \lambda$ (t = 0)

VM "Photo"production

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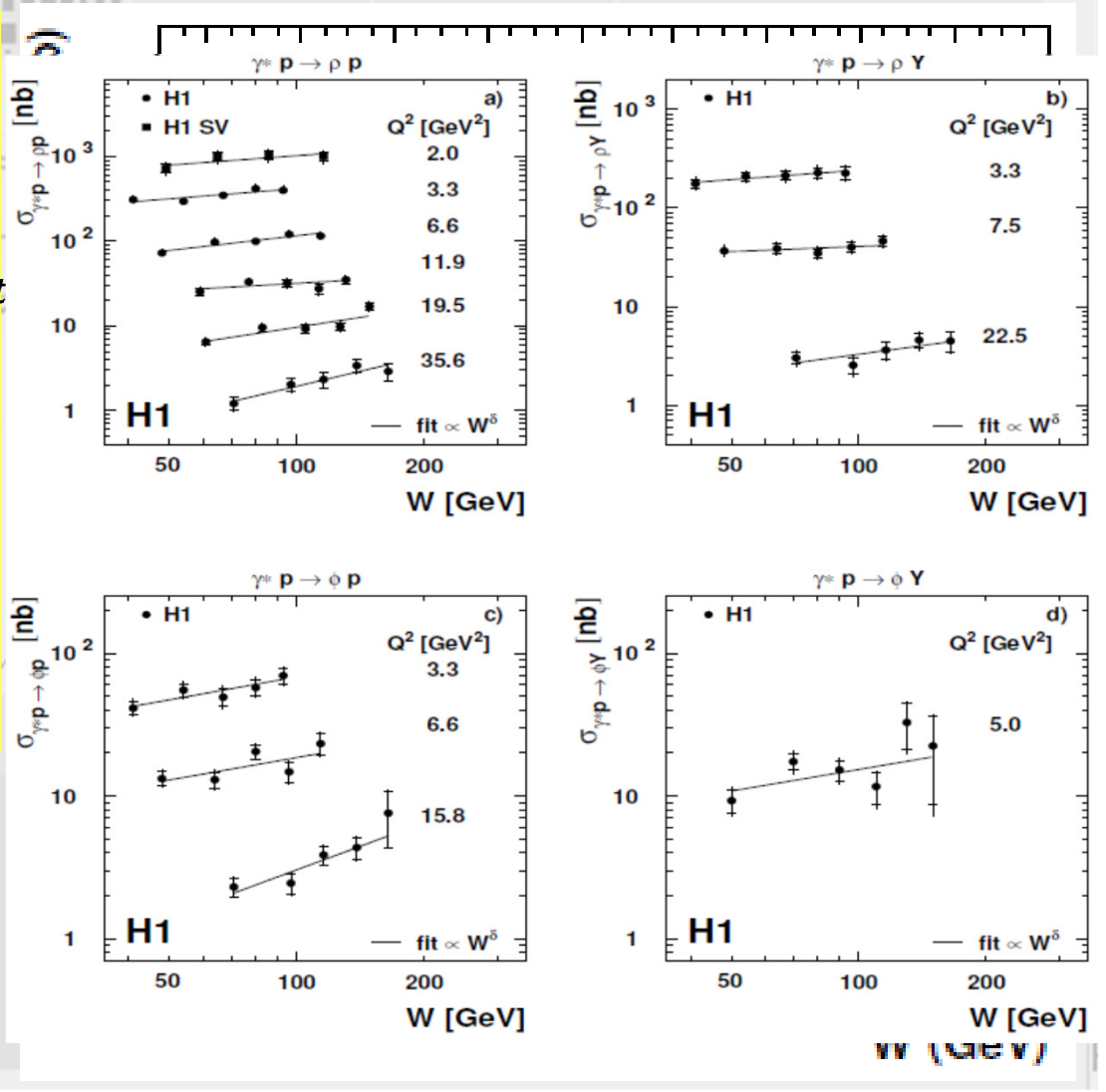
- virtual photon-hadron: eg $\gamma p \to \rho(u,d)p$ $\lambda(t)$
  - Q^2 sensitivity

$$\sigma(Q^2, W^2) \propto \frac{1}{s}\left(\frac{1}{x_{ex}}\right)^{1+2\langle\lambda\rangle_t}$$

$$\sim \left(\frac{W^2 + Q^2 - M_{\mathrm{VM}}^2}{m_p^2}\right)^{2\langle\lambda(Q^2)\rangle_t}$$

$$\xrightarrow[W^2 \gg M_{\mathrm{VM}}^2]{W^2 \gg Q^2} \left(\frac{W^2}{m_p^2}\right)^{2\langle\lambda(Q^2)\rangle_t}$$

↳ $< W$ dependence$>_t$
$\to < \lambda\,(Q^2) >_t$

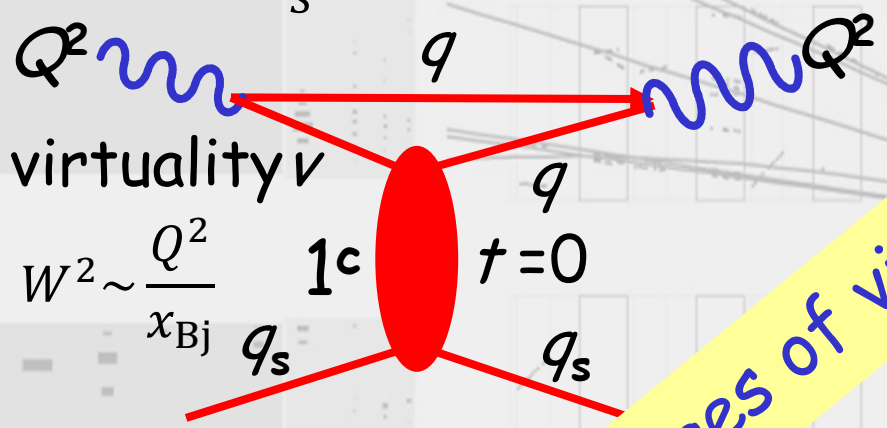


VM "Photo"interaction

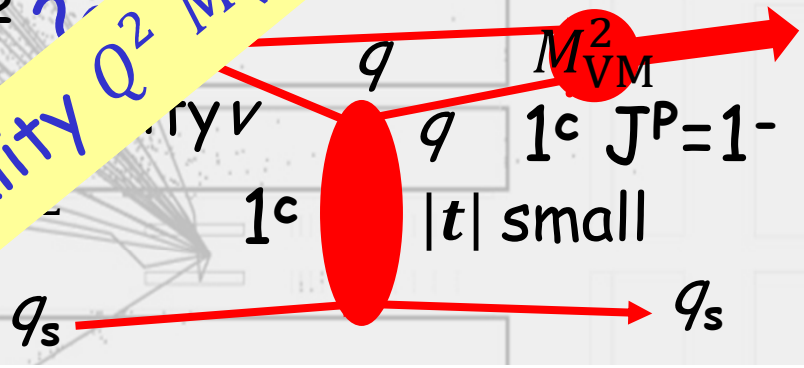
- kinematics and virtuality ν of elastic q ering

total $\gamma^* p$ cross-section

$$\propto F_2 \propto \frac{1}{s}\,\mathrm{Im}\,A_{12\to 12}(s, t=0)$$



elastic ... sociative vector-... electropruction



Kinematics → ranges of virtuality Q^2 M^2_{VM} m^2_{quark} t

$$-m_q^2 - Q^2 > \nu^2 > -m_{...}^2$$

quark mas...

$$\nu^2 ...$$

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

$$F_2(x,Q^2) \sim ...^{\lambda(\ln Q^2)}_{Bj} \xrightarrow[W^2 \gg Q^2]{} \left(\frac{W^2}{Q^2}\right)^{\lambda(\ln Q^2)}$$

$$\sigma(Q^2, W^2) \xrightarrow[W^2 \gg Q^2, M^2_{VM}]{} \left(\frac{W^2}{m_p^2}\right)^{2\langle\lambda(\ln Q^2)\rangle_t}$$

$\gamma^* p$ Forward Scattering

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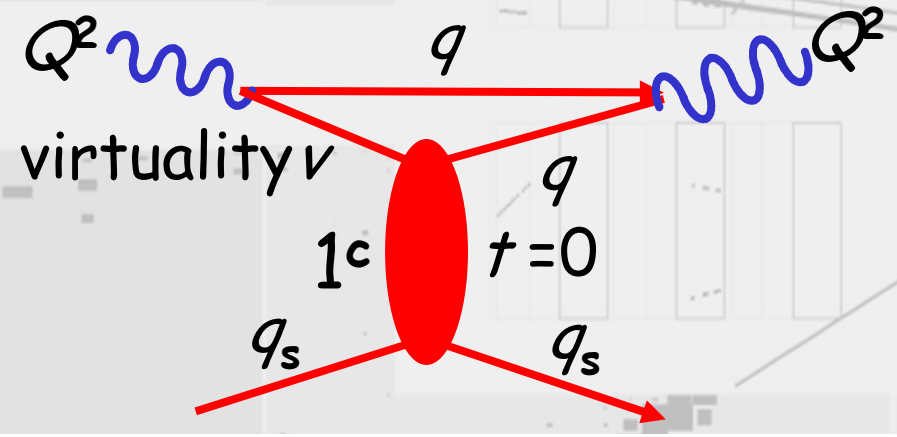
- forward elastic $\gamma^* p$ cross-section

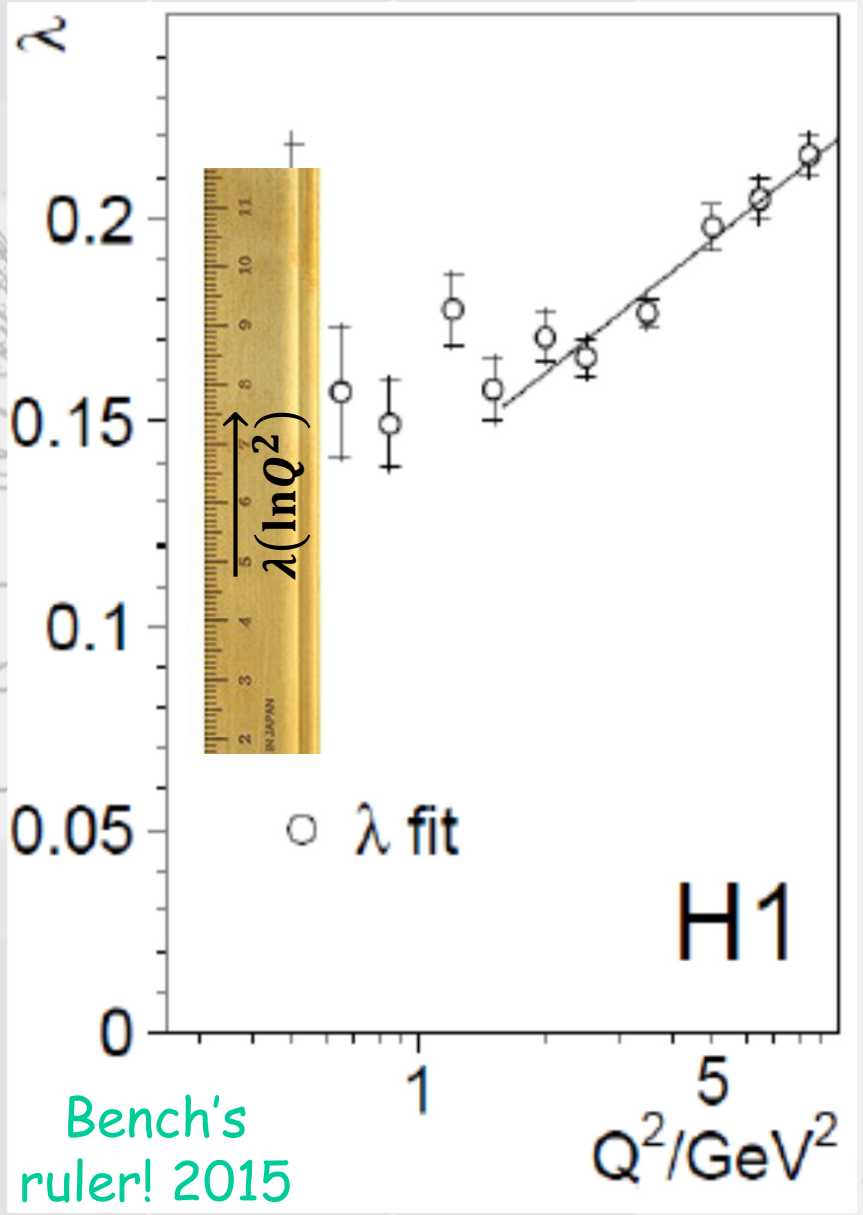
$$F_2(x,Q^2) \sim x_{\mathrm{Bj}}^{-\lambda(\ln Q^2)} \xrightarrow[W^2 \gg Q^2]{} \left(\frac{W^2}{Q^2}\right)^{\lambda(\ln Q^2)}$$



$$\lambda(\mathrm{size}) \sim 0.14 \pm 0.01 - \frac{0.15}{2.303} \ln \frac{\mathrm{size\ fm}}{0.2}$$

$$\mathrm{size} \propto \frac{\hbar = 1}{\nu}$$

$$-m_q^2 - Q^2 > \nu^2 > -m_q^2 - Q^2$$



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VM "Photo"production

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$W^{\delta(Q^2)}$ dependences

$\gamma^* p \to \phi(1.019) p$ [H1,Zeus] $\Delta = \frac{0.2}{\sqrt{1+2Q^2(\mathrm{GeV}^2)}}$ $t_{\min} = m_p^2 \frac{1-Q^2(\mathrm{GeV}^2)}{W^2}$ $b \sim 6\ (\mathrm{GeV}^{-2})$ $\Delta_{\gamma^* p} \sim 0.7$ fm	0†									
	2.2									
	3.3									
	6.6	~0.16	0.06	0.22	0.88	$0.52 \pm 0.05 \pm 0.02$				
	8.2		0.05	0.23	0.92	~0.90 (est.)‡				
	14.7		0.04	0.24	0.98	~0.90 (est.)‡				
	15.8		0.04	0.24	0.96	$1.09 \pm 0.08 \pm 0.02$				
$\gamma^* p \to \phi(1.019) Y$ [H1] $\Delta = \frac{0.2}{\sqrt{1+2Q^2(\mathrm{GeV}^2)}}$ $t_{\min} = m_Y^2 \frac{1-Q^2(\mathrm{GeV}^2)}{W^2}$ $b \sim 2\ (\mathrm{GeV}^{-2})$ $\Delta_{\gamma^* p} \sim 0.4$ fm	5.0	~0.5	0.06	0.22	0.88	$0.50 \pm 0.24^{+0.16}_{-0.20}$				
$\gamma^* p \to \psi(3.1) p$ [H1,Zeus] $\Delta = \frac{0.2}{\sqrt{9.6+2Q^2(\mathrm{GeV}^2)}}$ $t_{\min} = m_p^2 \frac{9.6-Q^2(\mathrm{GeV}^2)}{W^2}$ $b \sim 4\ (\mathrm{GeV}^{-2})$ $\Delta_{\gamma^* p} \sim 0.56$ fm	0	~0.25	0.06	0.22	0.88	$0.92 \pm 0.14 \pm 0.10$				
	0		0.06	0.22	0.88	$0.695 \pm 0.021 \pm 0.028$				
	0		0.06	0.22	0.88	$0.67 \pm 0.03 \pm 0.05$				
	0.05		0.06	0.22	0.88	$0.75 \pm 0.03 \pm 0.03$				
	0.1		0.06	0.22	0.88	0.67 ± 0.03				
	0.4		0.06	0.22	0.88	$0.87 \pm 0.22^{+0.04}_{-0.01}$				
	3.1		0.05	0.23	0.92	$0.65 \pm 0.17^{+0.16}_{-0.05}$				
	3.2		0.05	0.23	0.92	$0.67 \pm 0.02 \pm 0.14$				
	6.8		0.04	0.24	0.96	$0.60 \pm 0.18^{+0.04}_{-0.1}$				
	7.0		0.04	0.24	0.96	$0.83 \pm 0.31 \pm 0.15$				
	16.0		0.03	0.26	1.04	$1.12 \pm 0.20^{+0.03}_{-0.16}$				
	22.4		0.03	0.26	1.04	$0.69 \pm 0.32 \pm 0.14$				
$\gamma p \to \psi(3.1) Y_{z>0.95}$ [H1,Zeus] $\Delta = \frac{0.2}{\sqrt{9.6+2\lvert t\rvert}}$ $t_{\min} = m_Y^2 \frac{9.6-Q^2(\mathrm{GeV}^2)}{W^2}$	0									
		2.2	0.05	0.23	0.92	$0.38 \pm 0.10^{+0.11}_{-0.06}$				
		2.7	0.05	0.23	0.92	$0.70 \pm 0.15 \pm 0.10$				
		3.4	0.05	0.23	0.92	$0.39 \pm 0.13^{+0.08}_{-0.07}$				
		4.5	0.05	0.23	0.92	$0.72 \pm 0.18^{+0.08}_{-0.07}$				
		5.7	0.04	0.24	0.96	$0.70 \pm 0.21 \pm 0.12$				
		7.2	0.04	0.24	0.96	$1.38 \pm 0.46^{+0.37}_{-0.34}$				
		9.2	0.04	0.24	0.96	$0.78 \pm 0.38^{+0.6}_{-0.12}$				
		14.2	0.03	0.26	1.04	$0.82 \pm 0.44^{+0.34}_{-0.08}$				
$\gamma^* p \to \Upsilon(9.46) p$ [H1,Zeus] $\Delta = \frac{0.2}{\sqrt{89.5+2Q^2(\mathrm{GeV}^2)}}$ $t_{\min} = m_Y^2 \frac{89.5-Q^2(\mathrm{GeV}^2)}{W^2}$ $b \sim 4\ (\mathrm{GeV}^{-2})$ $\Delta_{\gamma^* p} \sim 0.56$ fm	0	~0.25	0.02	0.29	1.16	1.2 ± 0.8				

† signifies the insertion in the table of the expectation for the energy dependence of forward, elastic, photon-proton Compton scattering deduced from the application of the optical theorem to the total photon-proton interaction cross-section.

‡ signifies an estimate which is extracted from publications.

(GeV^2)	t or $\langle\lvert t\rvert\rangle$ (GeV^2)	Quark Diffractive Interaction dimension Δ (fm)	Intercept $\lambda = 0.14 - 0.15 \log_{10}\left(\frac{\Delta\ \mathrm{fm}}{0.2}\right)$ from $\gamma^* p \to \gamma^* p$ ($\pm 20\%$ not included)	Asymptotic Regge $(W^2)^{2\lambda(t)}$ 4λ	Fitted W^δ dependence $(W^2)^{\frac{\delta}{2}} \cong \left(\frac{Q^2}{x_{\mathrm{Bj}}}\right)^{\frac{\delta}{2}}$ δ
†		1†	0.09†		
0	0	0.20	0.14		
0		0.09	0.19		
.0		0.06	0.22		
†		1†	0.09†	0.36†	soft hadronic
.7	~0.1	≳ 0.20	≲ 0.14	≲ 0.56	$0.12 \pm 0.03 \pm 0.08$
4		≳ 0.12	≲ 0.17	≲ 0.68	$0.321 \pm 0.035^{+0.068}_{-0.043}$
3	~0.13	≳ 0.10	≲ 0.18	≲ 0.72	$0.40 \pm 0.08 \pm 0.06$
5		≳ 0.10	≲ 0.18	≲ 0.72	$0.40 \pm 0.12 \pm 0.12$
7		≳ 0.10	≲ 0.18	≲ 0.72	$0.412 \pm 0.036^{+0.039}_{-0.035}$
0		≳ 0.08	≲ 0.19	≲ 0.76	$0.400 \pm 0.052^{+0.048}_{-0.045}$
6		≳ 0.08	≲ 0.19	≲ 0.76	$0.57 \pm 0.11 \pm 0.06$
0	~0.16	≳ 0.07	≲ 0.20	≲ 0.80	$0.45 \pm 0.15 \pm 0.07$
3		≳ 0.07	≲ 0.20	≲ 0.80	$0.503 \pm 0.057^{+0.047}_{-0.041}$
.0		≳ 0.05	≲ 0.23	≲ 0.92	$0.41 \pm 0.19 \pm 0.10$
.5		≳ 0.05	≲ 0.23	≲ 0.92	$0.28 \pm 0.15 \pm 0.05$
.5		≳ 0.04	≲ 0.24	≲ 0.96	$0.77 \pm 0.15 \pm 0.05$
.0		≳ 0.04	≲ 0.24	≲ 0.96	$0.76 \pm 0.55 \pm 0.60$
.6		≳ 0.03	≲ 0.26	≲ 1.04	$1.17 \pm 0.26 \pm 0.04$
.0		≳ 0.03	≲ 0.26	≲ 1.04	$0.834 \pm 0.118^{+0.043}_{-0.112}$
†		1†	0.09†	0.36†	soft hadronic
0		≳ 0.07	≲ 0.20	≲ 0.80	~0.5
3		≳ 0.10	≲ 0.18	≲ 0.72	$0.32 \pm 0.17^{+0.08}_{-0.09}$
5	~0.5	≳ 0.07	≲ 0.20	≲ 0.80	$0.17 \pm 0.14^{+0.07}_{-0.09}$
.5		≳ 0.04	≲ 0.24	≲ 0.88	$0.58 \pm 0.29^{+0.10}_{-0.13}$

DRAFT

VM "Photo"production

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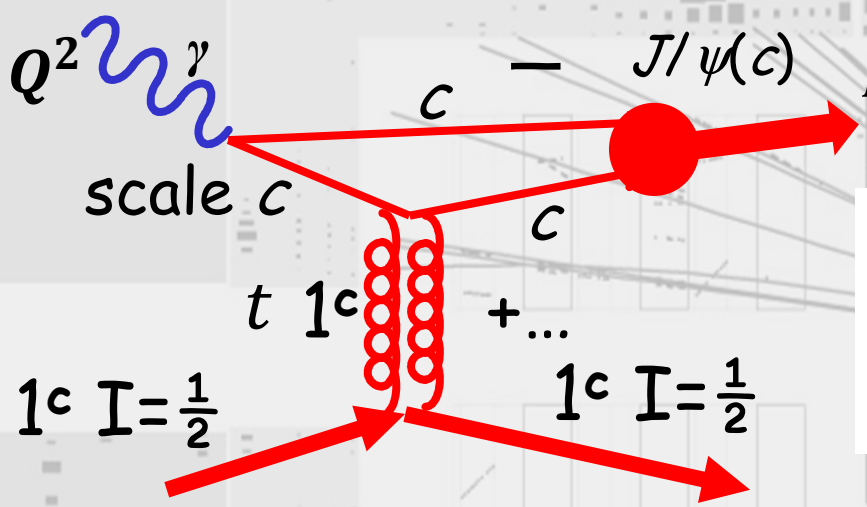
- electro/photoproduction $ep \to eJ/\psi p$



$$\lambda(\text{size}) \sim 0.14 \pm 0.01 - \frac{0.15}{2.303} \ln \frac{\text{size fm}}{0.2}$$

$$\text{size} \propto \frac{\hbar = 1}{v}$$

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

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

J/ψ "Photo"production

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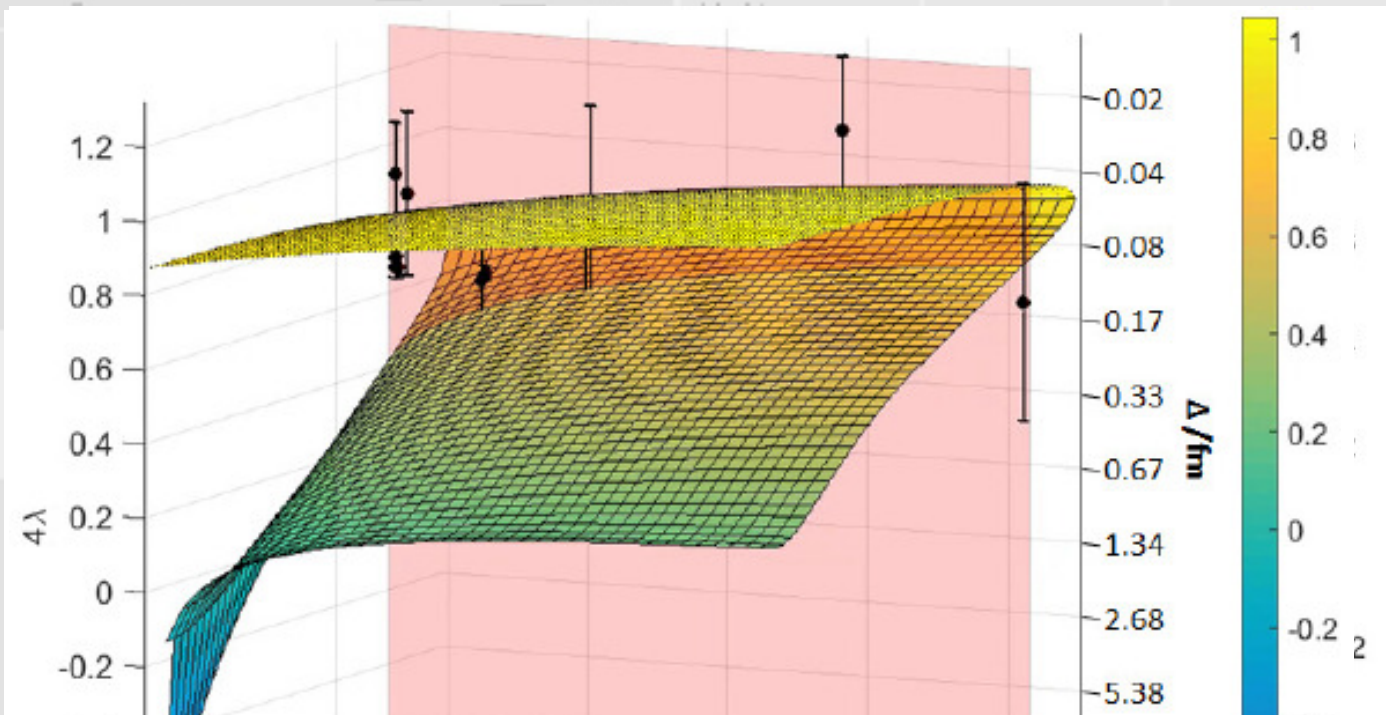
- electro/photoproduction $\gamma^* p \to J/\psi p$



- consistent with Bench ruler if *c*-mass ~ 1.5 GeV
  ≡ current *c*-mass
- size ~ 0.13 fm of $cp \to cp$ elastic interaction set by current *c*-mass

ρ "Photo"production

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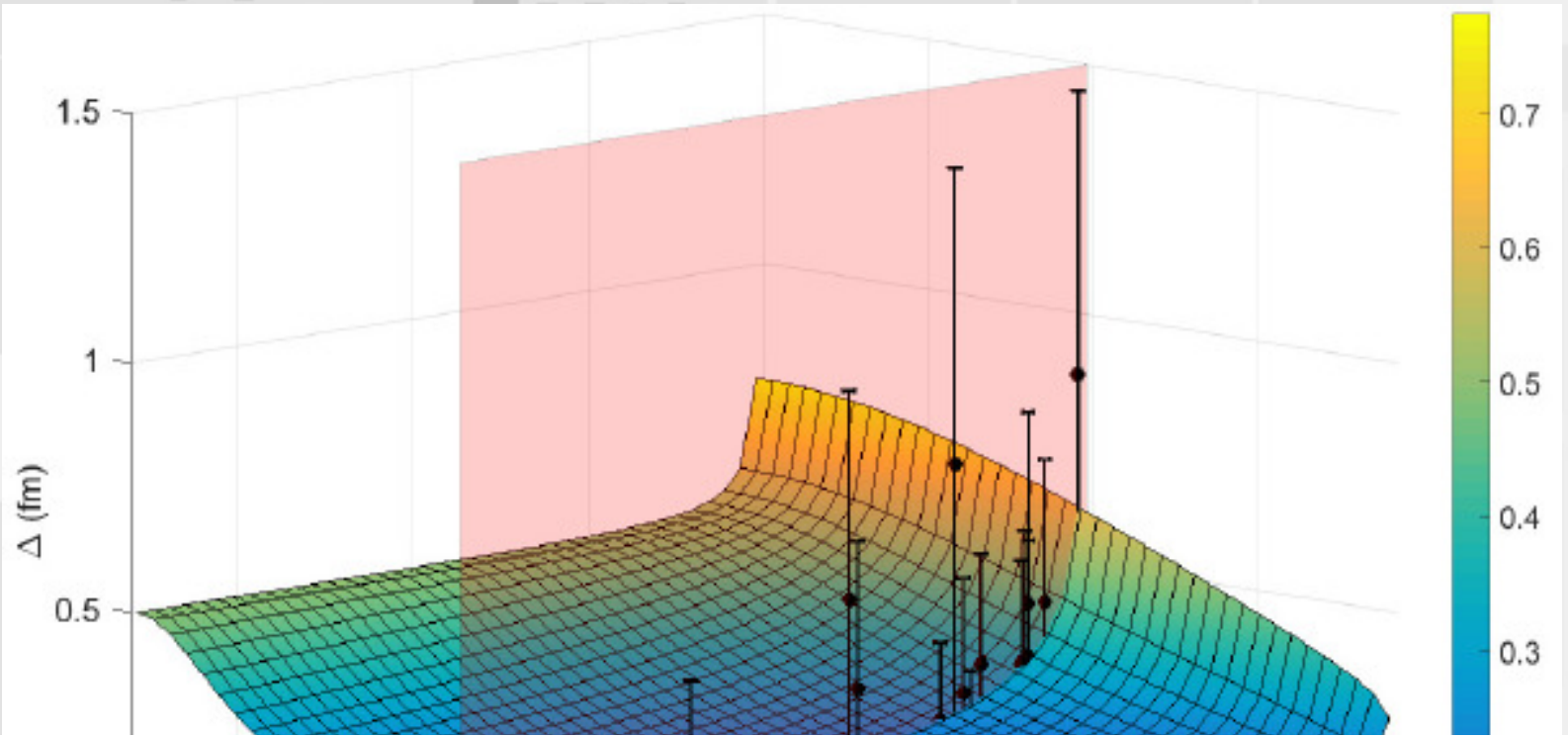
- electro/photoproduction $\gamma^* p \to \rho p$



- consistent with Bench ruler if *u/d -q* mass ≤ 0.2 GeV
  » current *u/d -q* mass
- 0.6 fm ≥ size ≥ 0.15 fm of *u / d p* elastic interaction with requirement of influence of Q^2

ϕ "Photo"production

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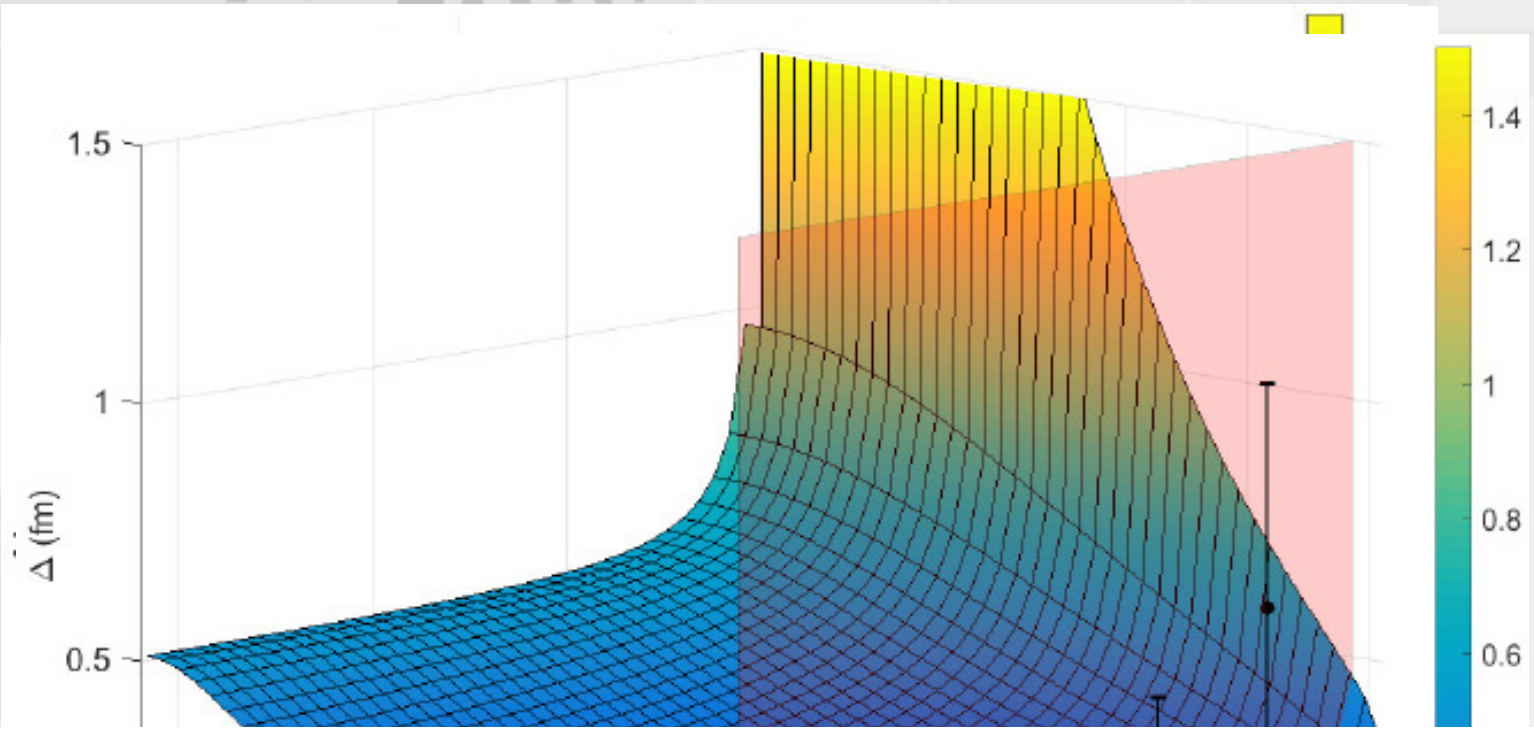
- electro/photoproduction $\gamma^* p \to \phi p$



- consistent with Bench ruler if s-q mass ≤ 0.5 GeV
  ≥ current s-q mass
- ~0.4 fm ≥ size ≥ ~0.5 fm of sp elastic interaction with suggestion of influence of Q^2

QCD Rutherford Scattering

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- asymptotic freedom ↔ confinement
  - current ↔ constituent
  - multiple scales at work
  - size of elastic interaction … definitive … ?
  - overall fit to all possible flavour cross-sections
  - phenomenology ↔ QCD calculation … ?
- fundamental to quark matter ?
  - lepton+nucleon/nuclei exclusive
  - "hot QCD" → exclusive

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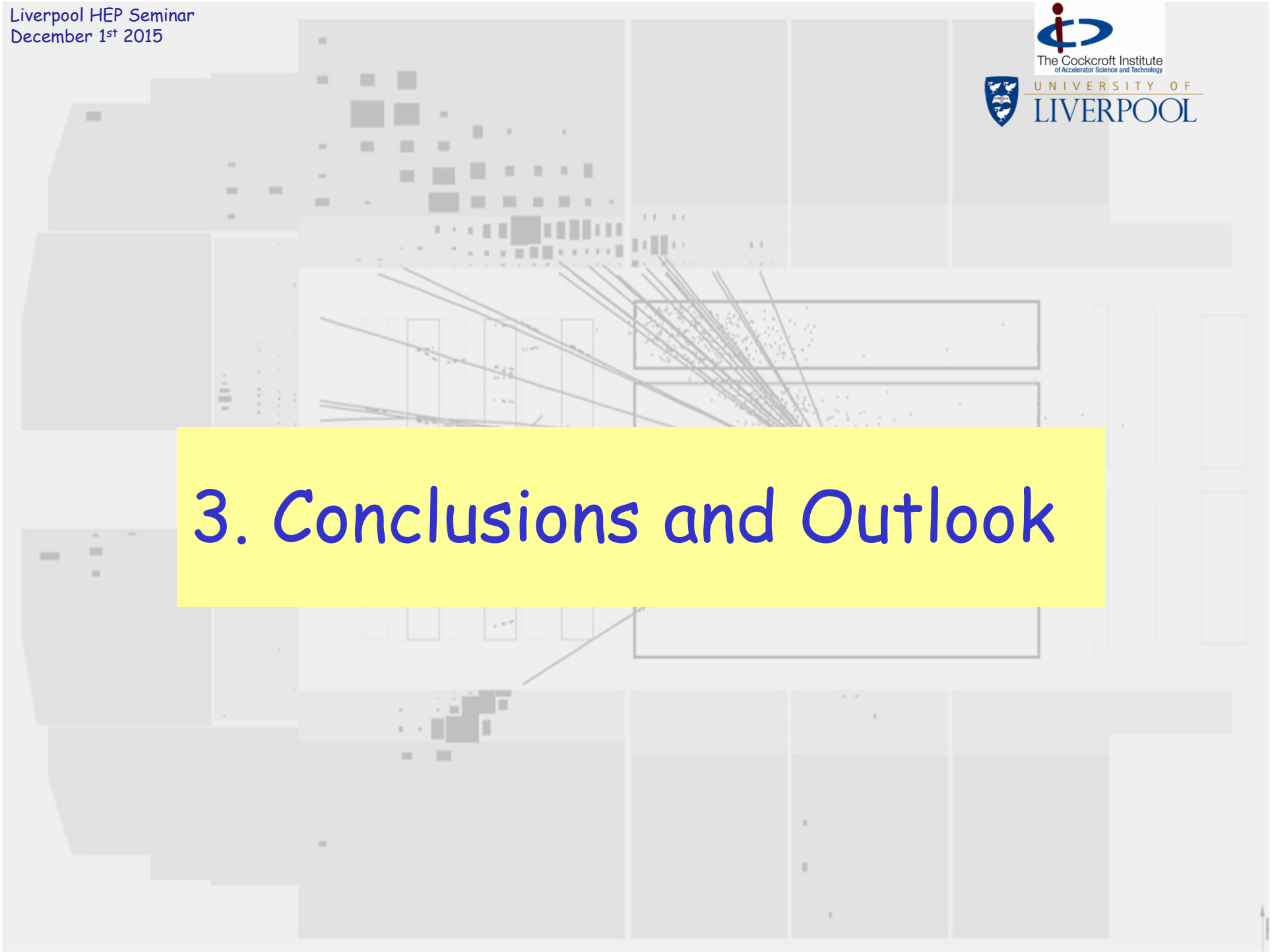

3. Conclusions and Outlook

Sub-femtoscopic Rutherford Scattering

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- so far … size matters in the way that chromodynamics says that it should !

HERA

+

- the  legacy lives on ….

1992-2007
RIP

2007-?
legacy

ALICE@LHC … +eIC? +eRHIC?

now "the" physics of the nucleus?

"Any chance of an MPhil student?"
John Dainton Liverpool 2015