The Cockcroft Institute of Accelerator Science and Technology

Lancaster University

QCDBSM: more than just a Standard Model Conundrum ?

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1. Landscape
2. Landmarks
3. Outlook
4. Horizon

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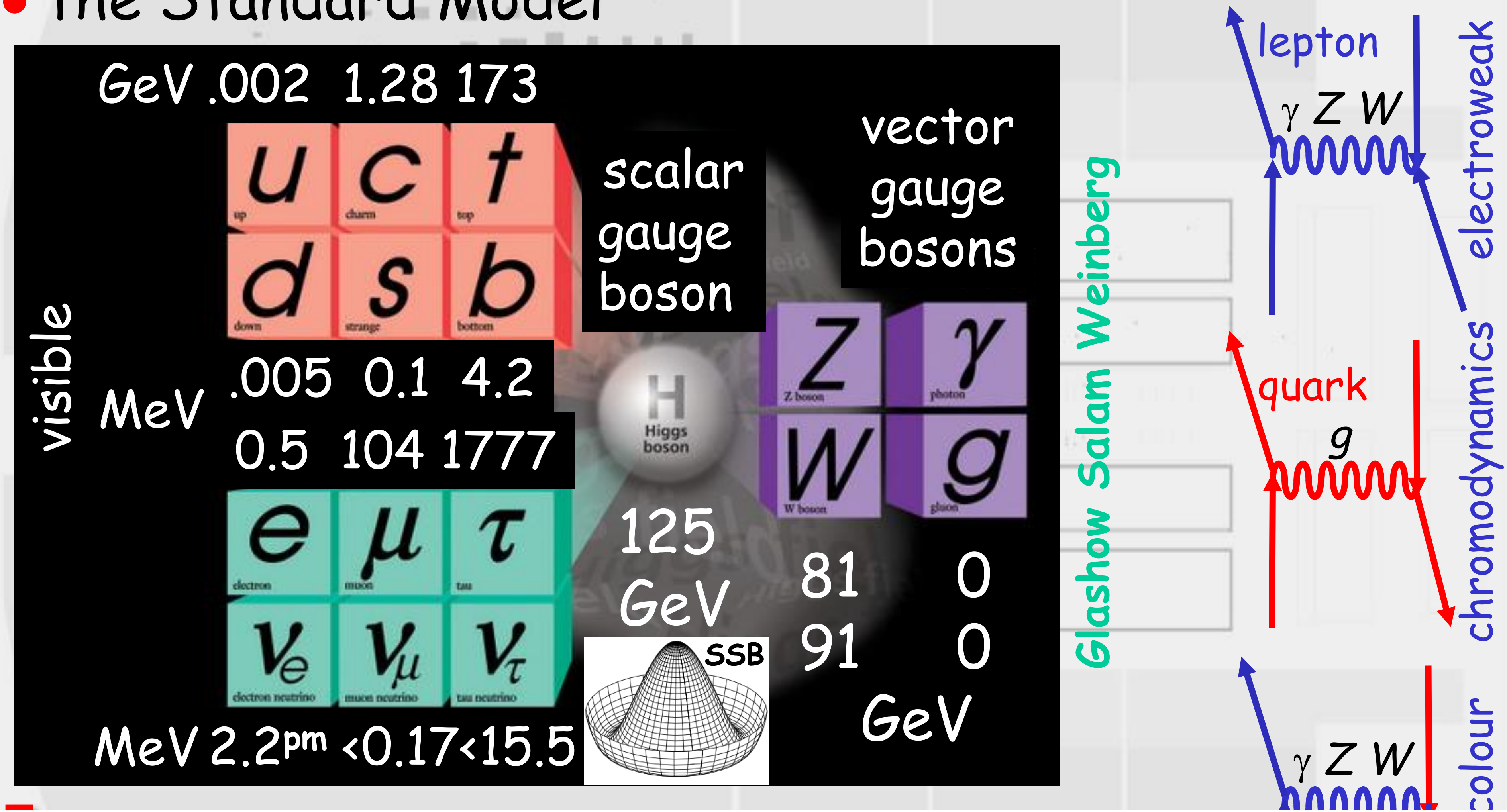
1. Landscape

Constituents and Currents

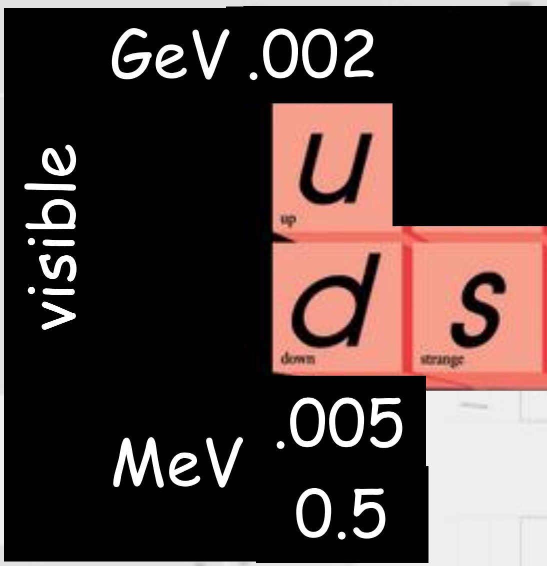
- the Standard Model

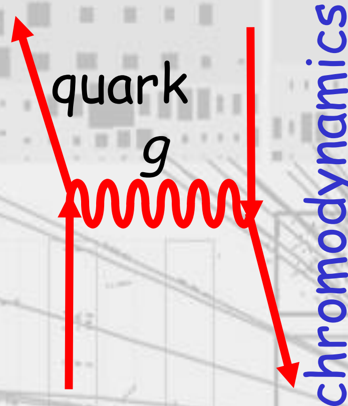


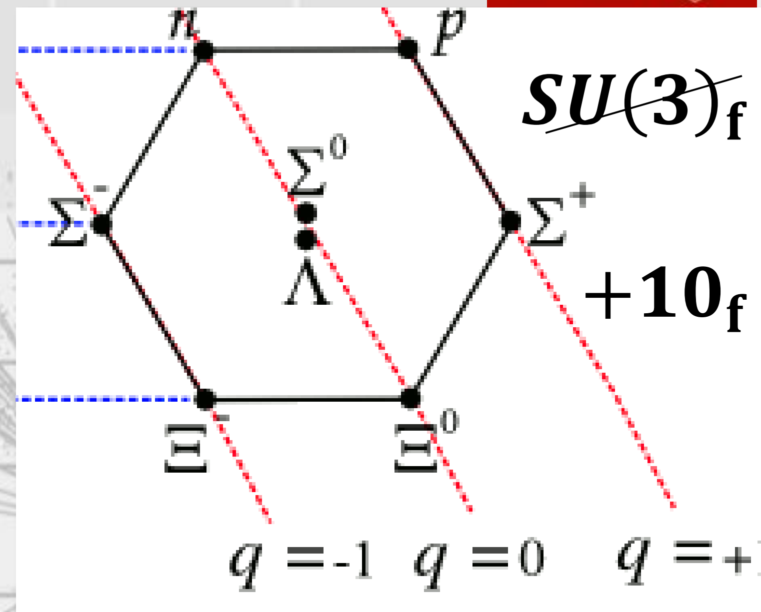
- Lamb-Retherford, CERN, BNL, ANL, SLAC, DESY, DL, RAL, Novosibirsk, Frascati, Fermilab, JParc …

Visible Hadronic Matter

- visible and temperate







- Dirac fermions $u\ d\ s$ in exact $SU(3)_c$ force = colour + eight gauge bosons g — mass = QCD $\lesssim 1$ fm
- confinement → $1_c\ p\ n\ \Sigma\ \Lambda\ \Xi$ force = "strong", saturates, range — Σ_{baryon} mass ~ 1 fm
- nuclei pn ... + hyper-nuclei $pn\Lambda$ ... → everyday matter — mass = A $\gtrsim A$ fm

QCD

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- stand-alone in SM

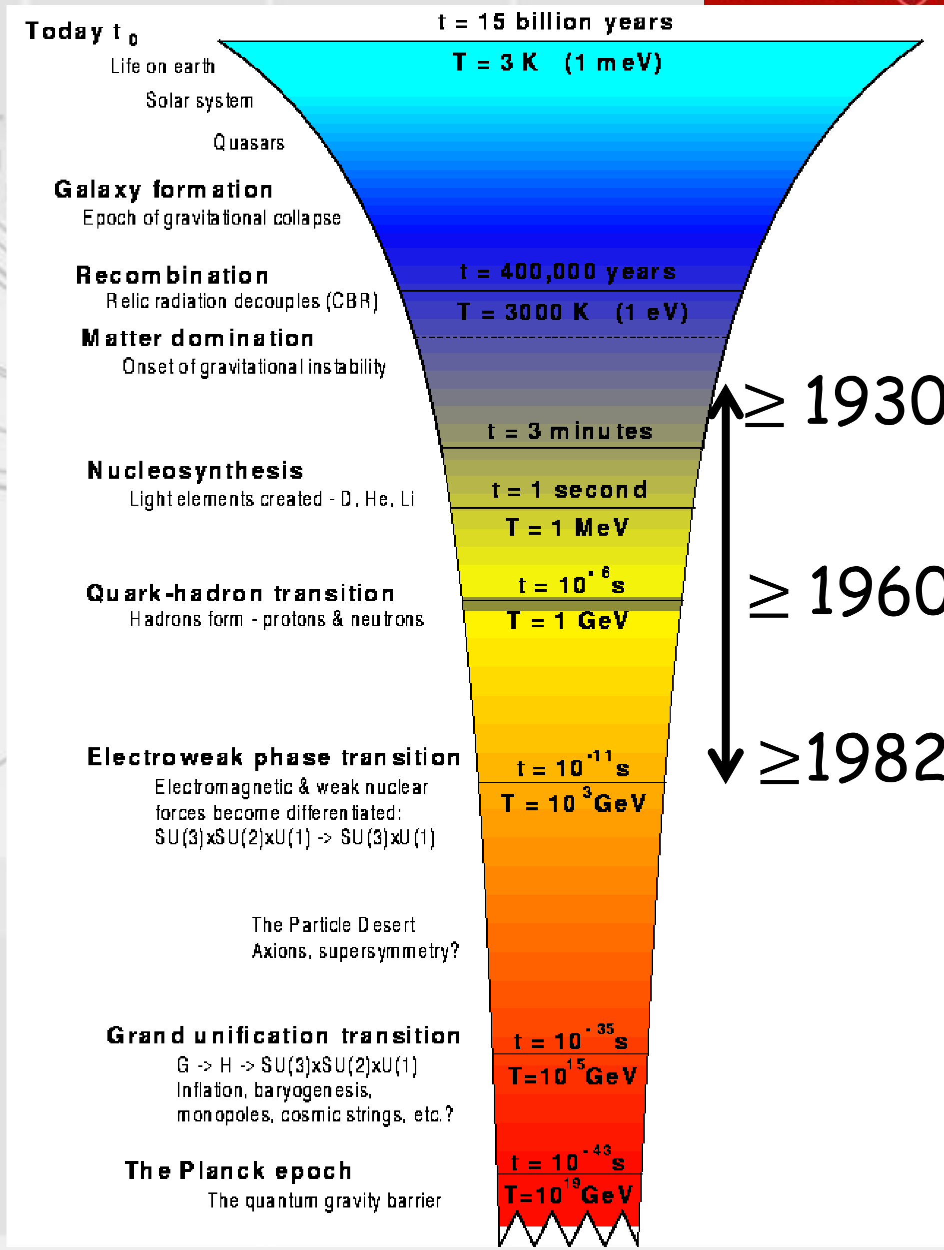
visible matter

GeV	.002	1.28	173
	u (up)	*c* (charm)	*t* (top)
	d (down)	*s* (strange)	*b* (bottom)
MeV	.005	0.1	4.2
	0.5	104	1777

- QCD $= u\; d\; s\; c\; b\; t$ $+ g +$ non-abelian $\mathbf{SU(3)}_c$

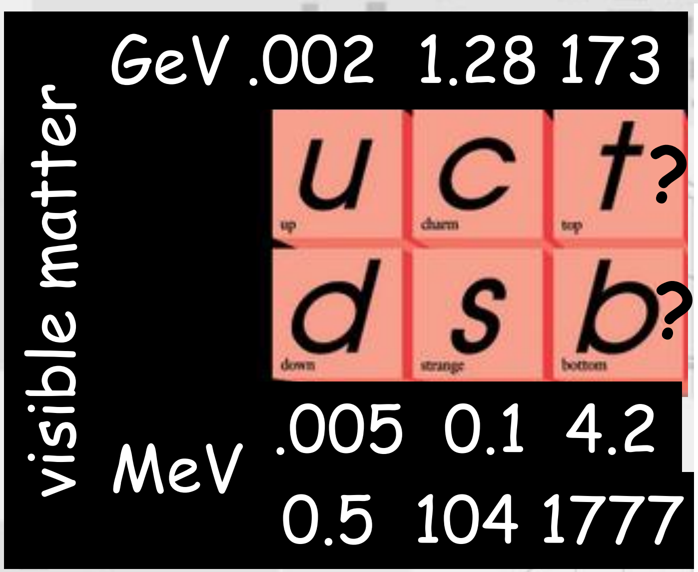
↳ asymptotic freedom confinement $\alpha_s(Q^2)$

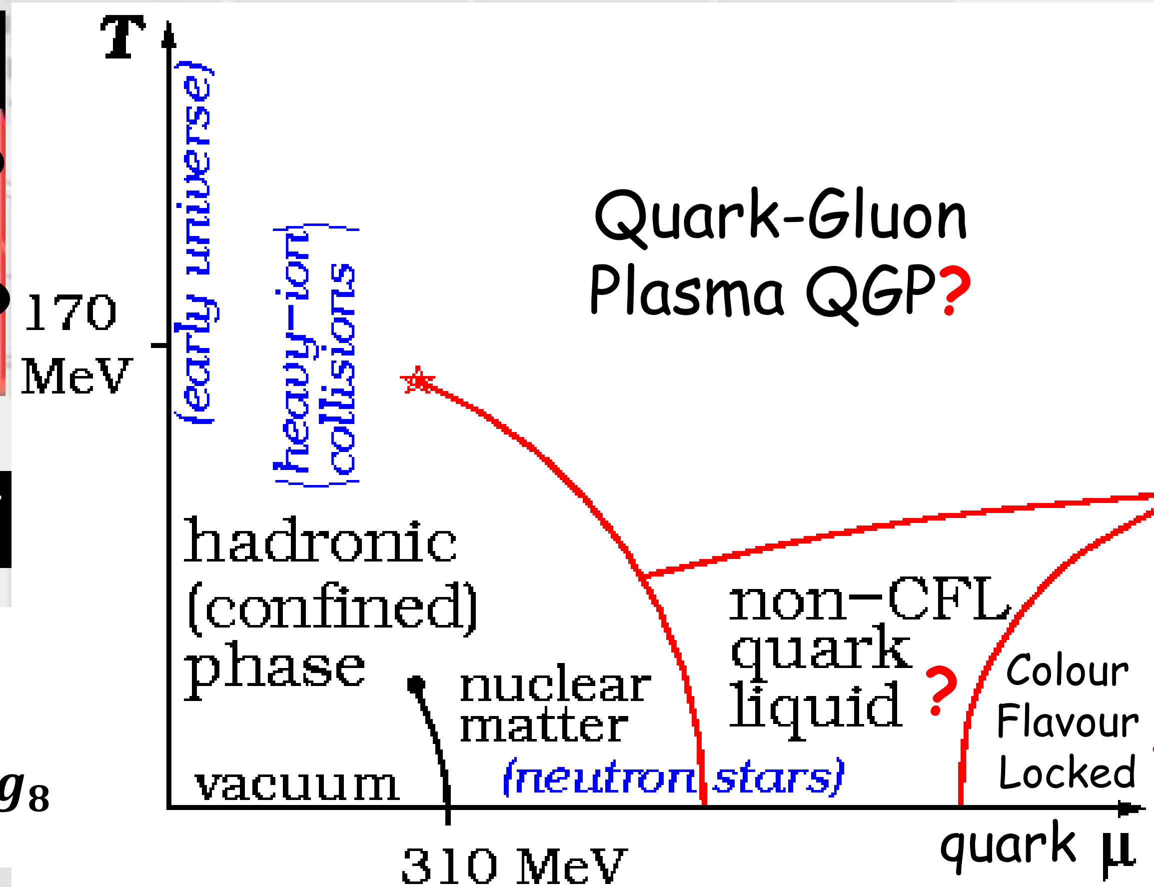
↳ lab for non-abelian QFT theory



Hot Hadronic Matter

- visible and hot → hadronic phase equilibria ?





- QGP

$$\overset{\longleftrightarrow}{SU(3)_c} \quad q = (u\, d\, s\, c\, b)_3, \quad \bar{q} = (\bar{u}\, \bar{d}\, \bar{s}\, \bar{c}\, \bar{b})_3 \quad + g_8$$

$$1_c \text{ confined} \xleftrightarrow[\text{energy}\equiv T]{} \text{deconfined}$$

vacuum condensate ↔ "$q\bar{q}g$ condensate" ?

Hot Hadronic Matter

- **hot** → high energy heavy ion collisions

visible matter

GeV	.002	1.28	173
	u (up)	*c* (charm)	*t* (top)
	d (down)	*s* (strange)	*b* (bottom)
MeV	.005	0.1	4.2
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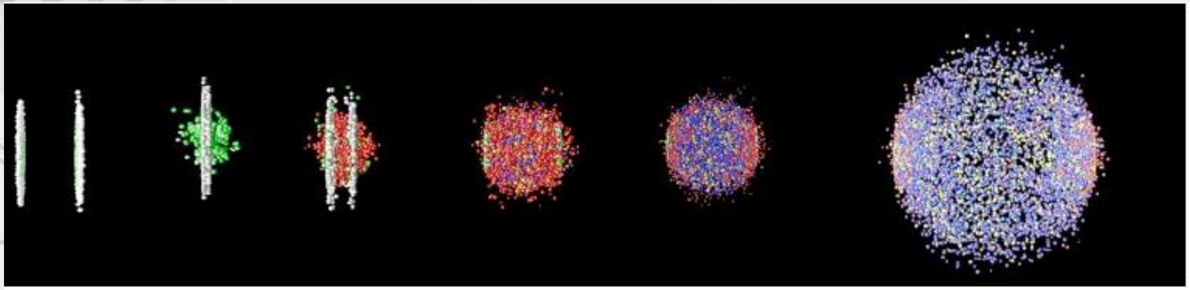


Thermalization (equilibrium established) | *Expansion* and *cooling* | Chemical and kinetic *freezout*

time ⟶

$$\ll \frac{1\ \text{fm}}{0.2\ \text{GeV}} \lesssim$$

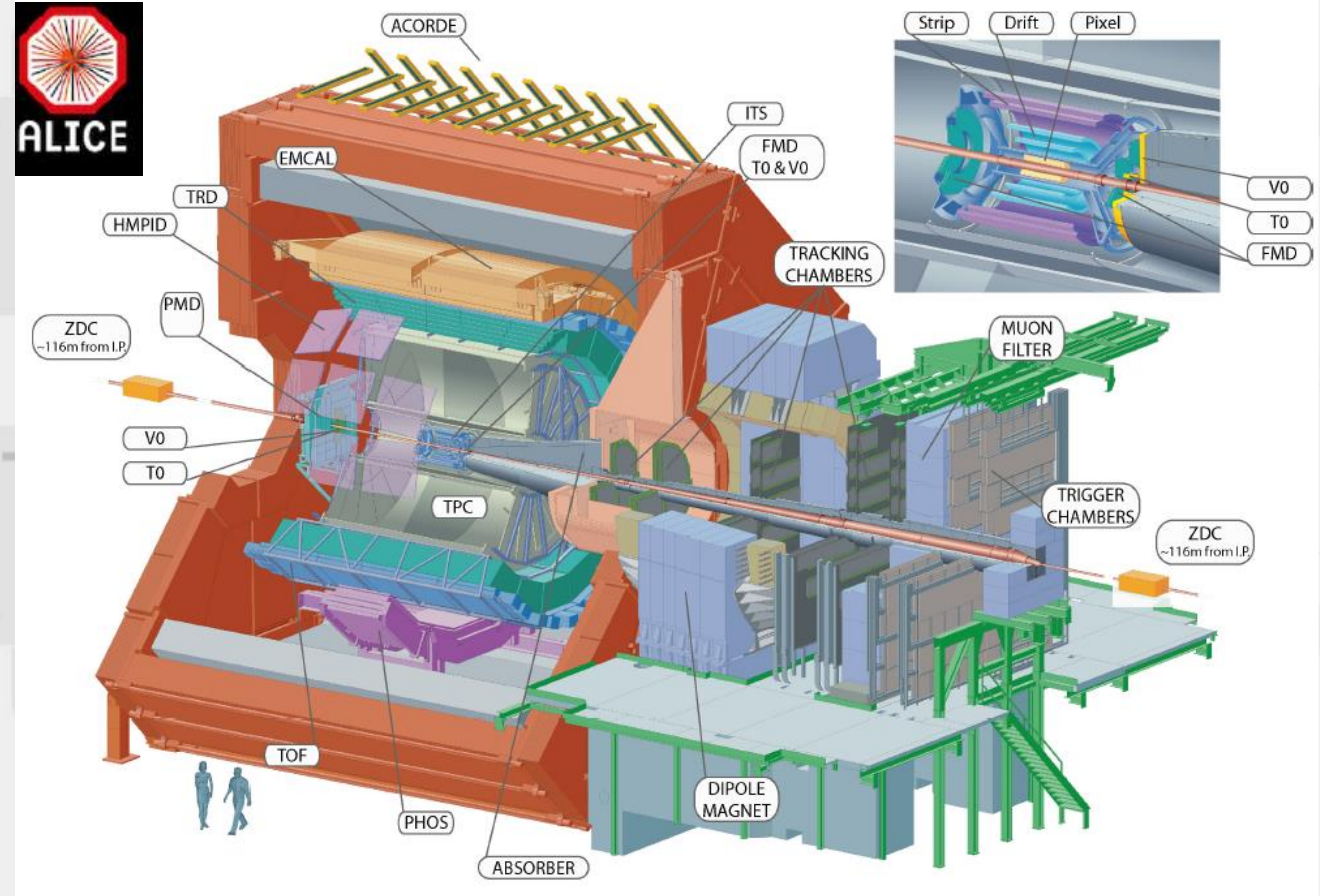
$$\text{QGP} = \begin{matrix} u+\bar{u} & d+\bar{d} \\ s+\bar{s} \quad c+\bar{c} & b+\bar{b} \end{matrix}\ g$$

$$\xrightarrow[\mathrm{SU(3)}_c]{} \mathbf{1}_c \quad \begin{matrix} \pi\ K \ldots\ p\ \ n\ \ \Sigma\ \Lambda\ \Xi \ldots \\ D\ (\Sigma\ \Lambda\ \Xi \ldots)_c \ldots B \ldots \end{matrix} + \text{KE}\ ?$$

↳ colour condensate $\xleftrightarrow[\text{Fermi} \gtrsim Q \gtrsim 0\ \text{GeV}]{}$ vacuum condensate

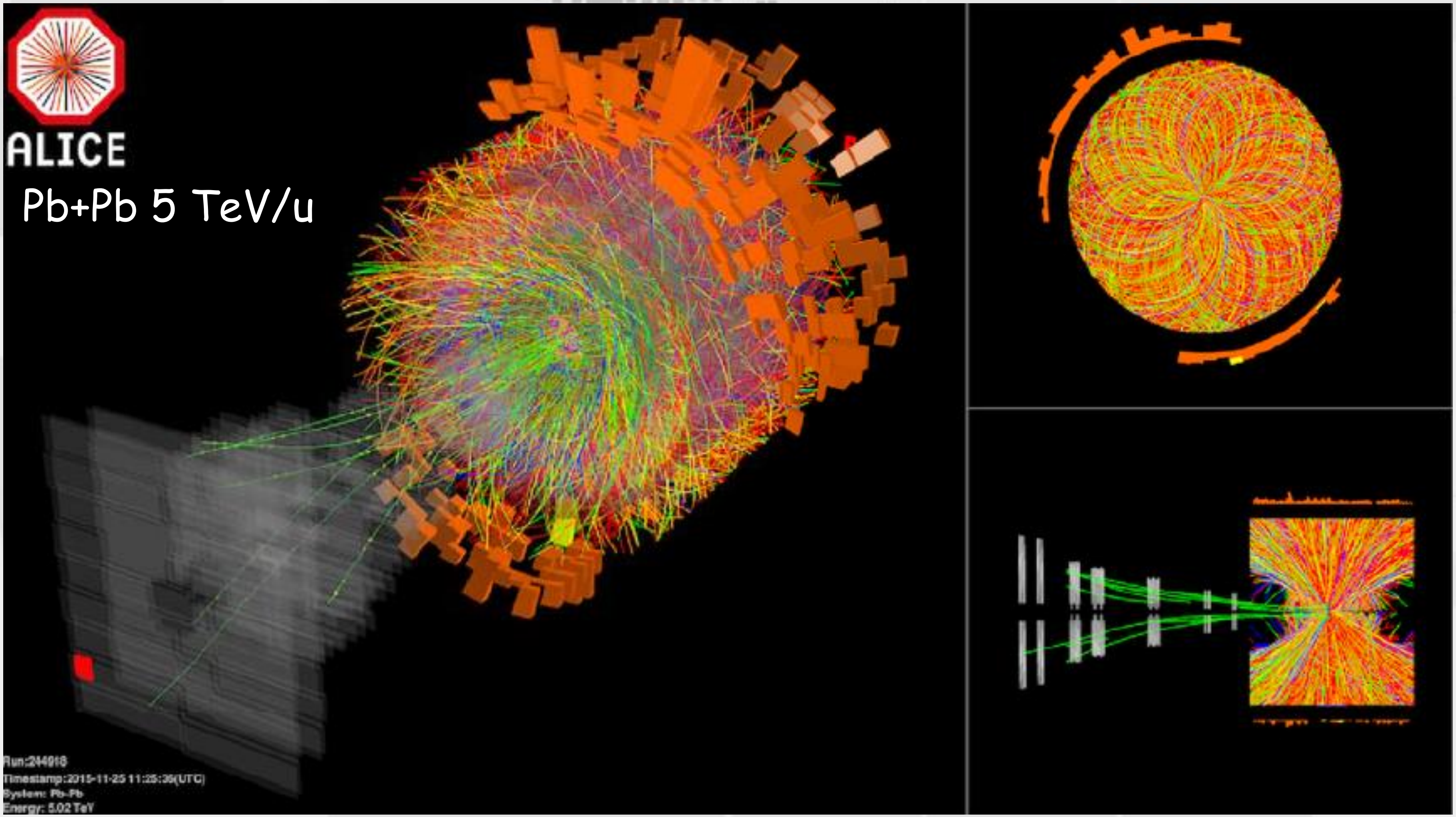
LHC: PbPb @ 13Z_{Pb} TeV CMS

LHC: PbPb @ 13Z_{Pb} TeV CM



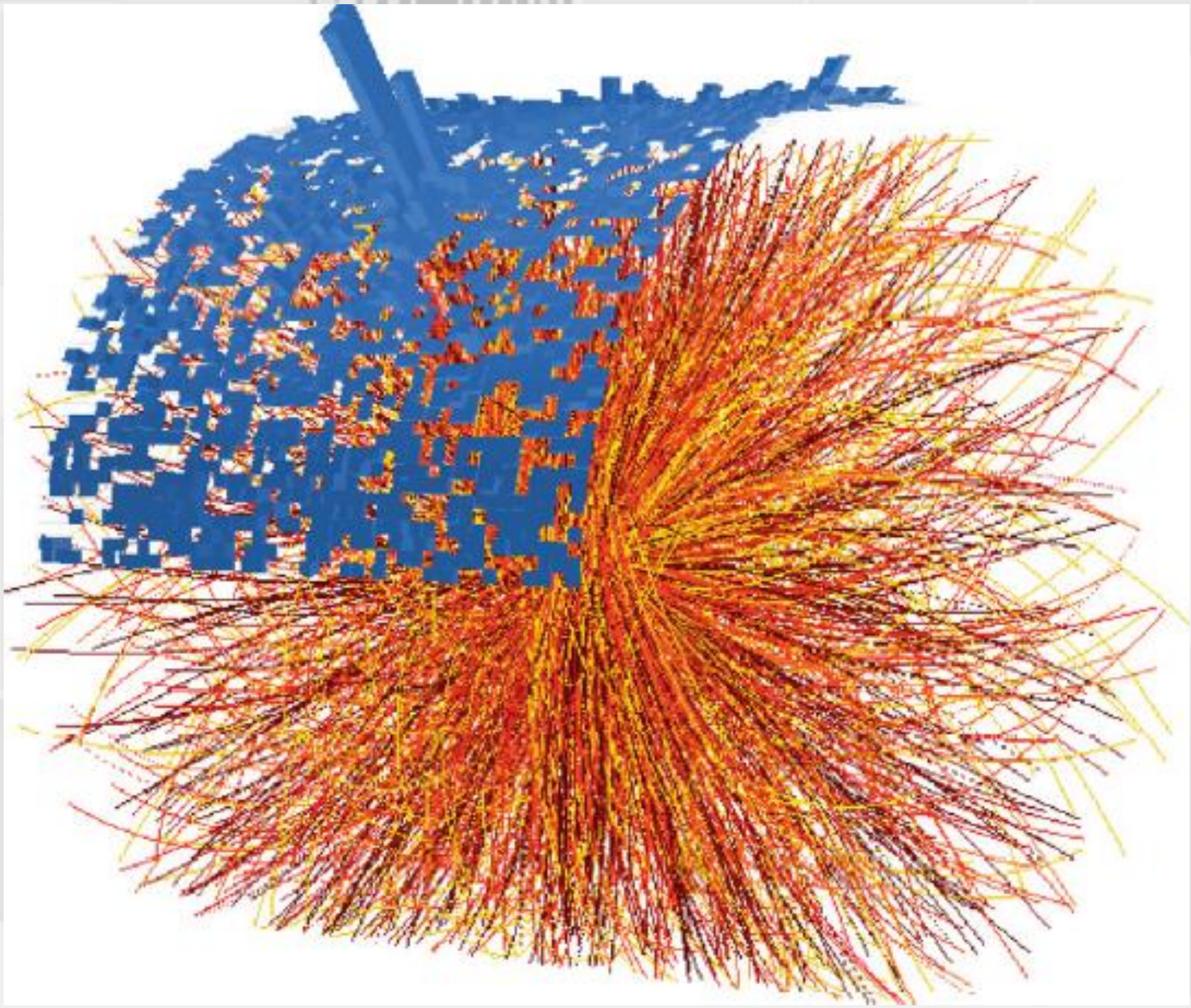
Experiment

- visible and hot: the experimental challenge



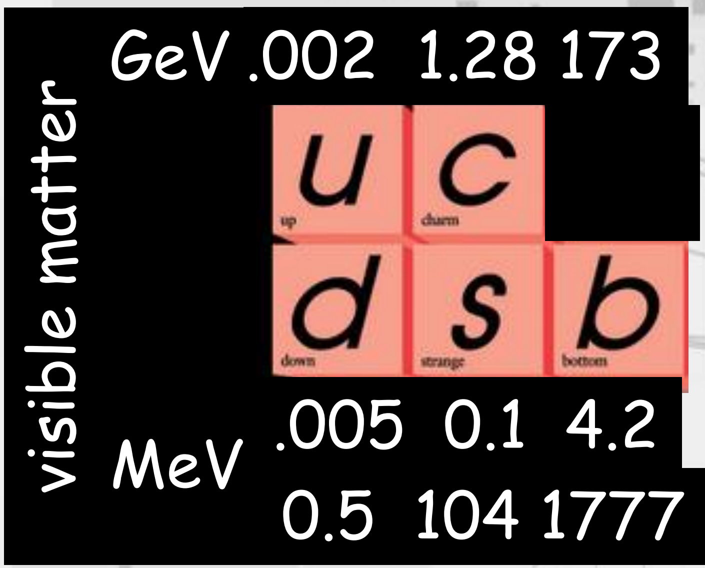
Experiment

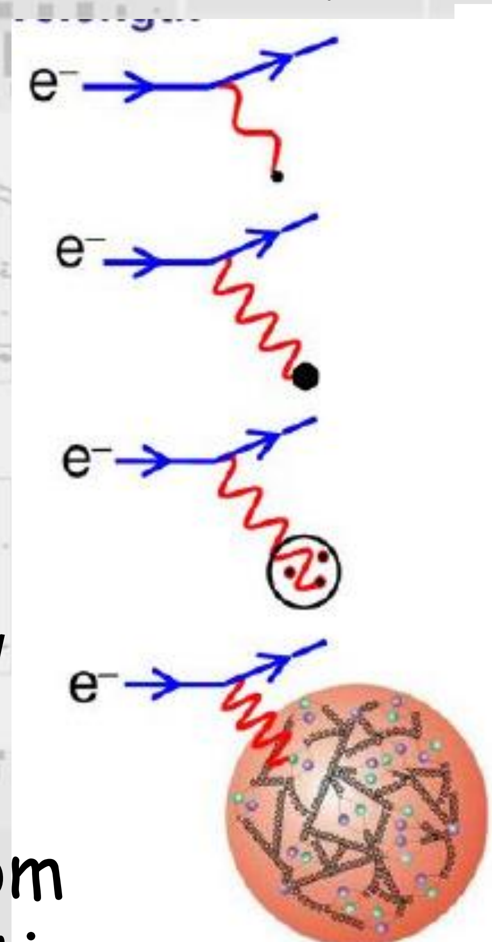
- visible and hot: not impossible
  jet(s) in "QGP condensate" ?



Cold Hadronic Matter

- visible and cold → high energy eA collisions





$\lambda \gg r_A$ $\Delta Q \sim r_A$ $\Delta E \ll m_A$

$\lambda > r_A$ $\Delta Q \sim r_A$ $\Delta E < m_A$

$\lambda < r_A$ $\Delta Q \sim r_A$ $\Delta E > m_A$

$\lambda \ll r_A$ $\Delta Q \sim r_A$ $\Delta E \gg m_A$

- QCD $= u\ d\ s\ c\ b + g$
  non-abelian $SU(3)_c$

↳ asymptotic freedom
perturbative splitting

↳ size ↔ ΔQ + excitation ↔ ΔE large ↔ $q\bar{q}$ … gg …

A Precision Femtoscope
HERA *ep* Collider @ DESY

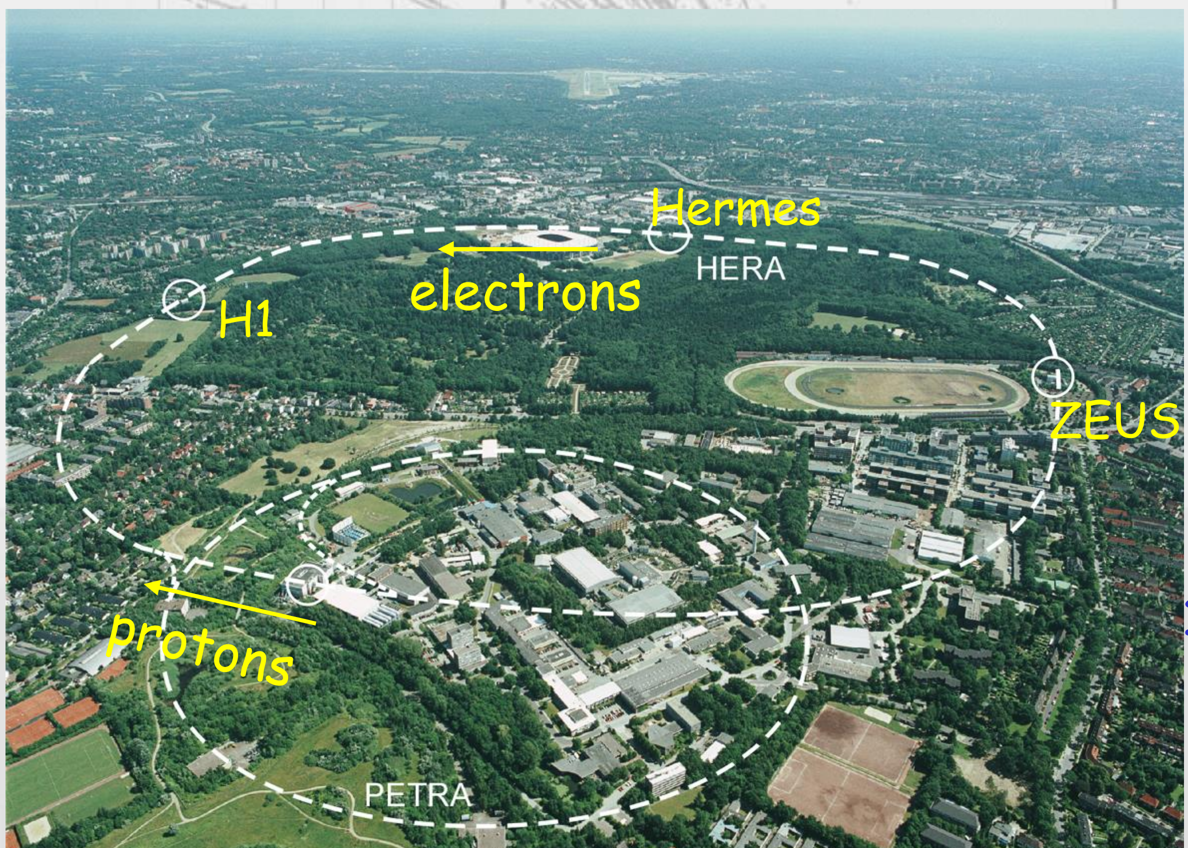
- challenge: different particle species *ep* in collision

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

lepton

ep cm energy 314 GeV

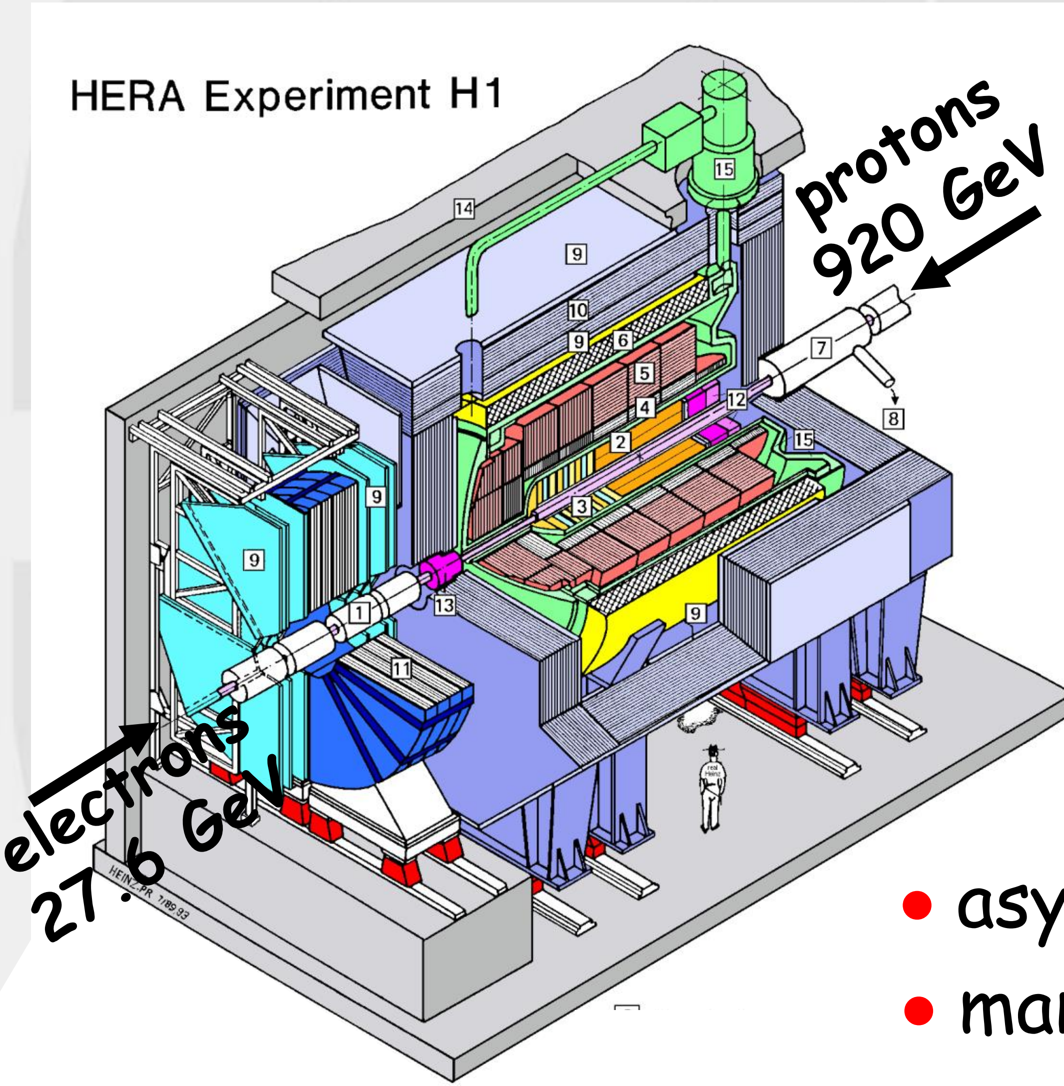
HERA
DESY
Hamburg

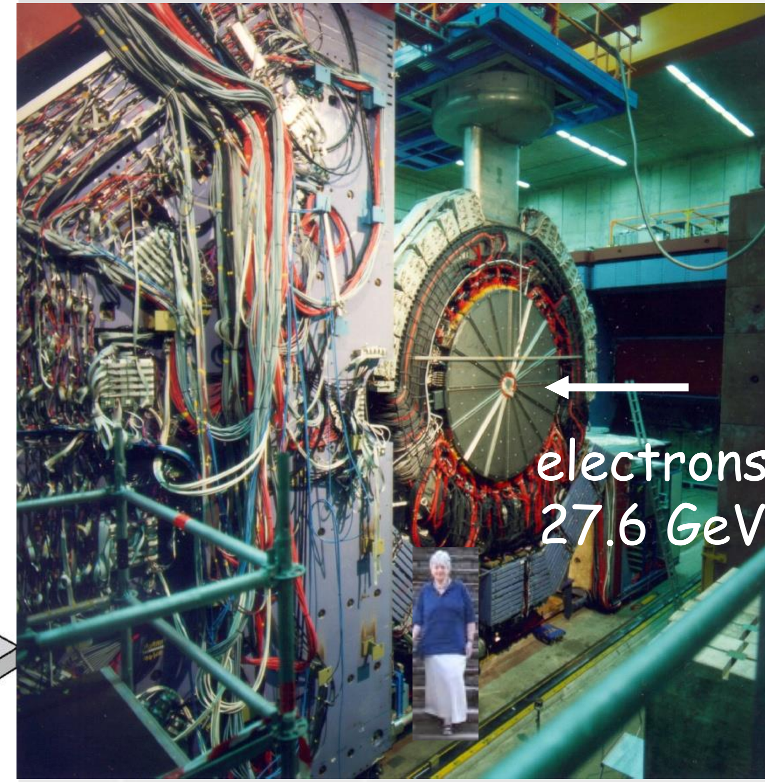


HERA
+

1992-2007
RIP

Experiment

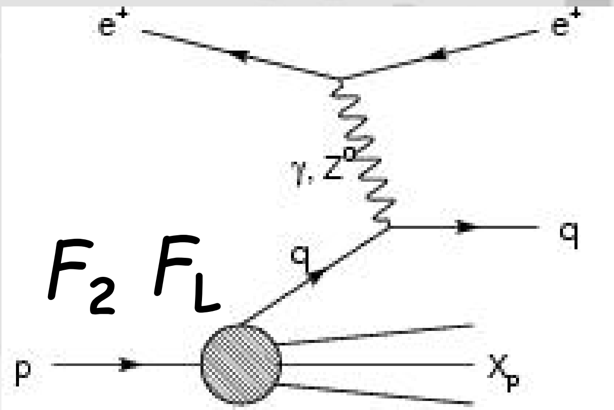


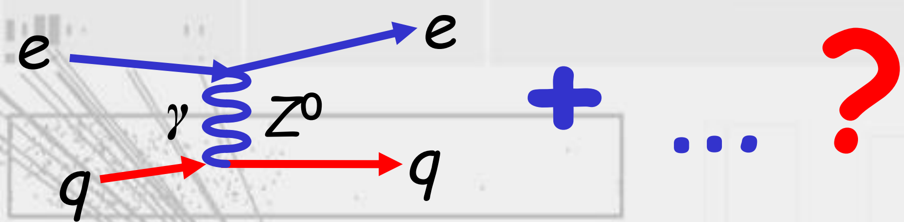


- asymmetric *e* and *p*
- many bunch Δt_{ep} = 75 ns
- p_T scale ~ 300 GeV (Fermi)

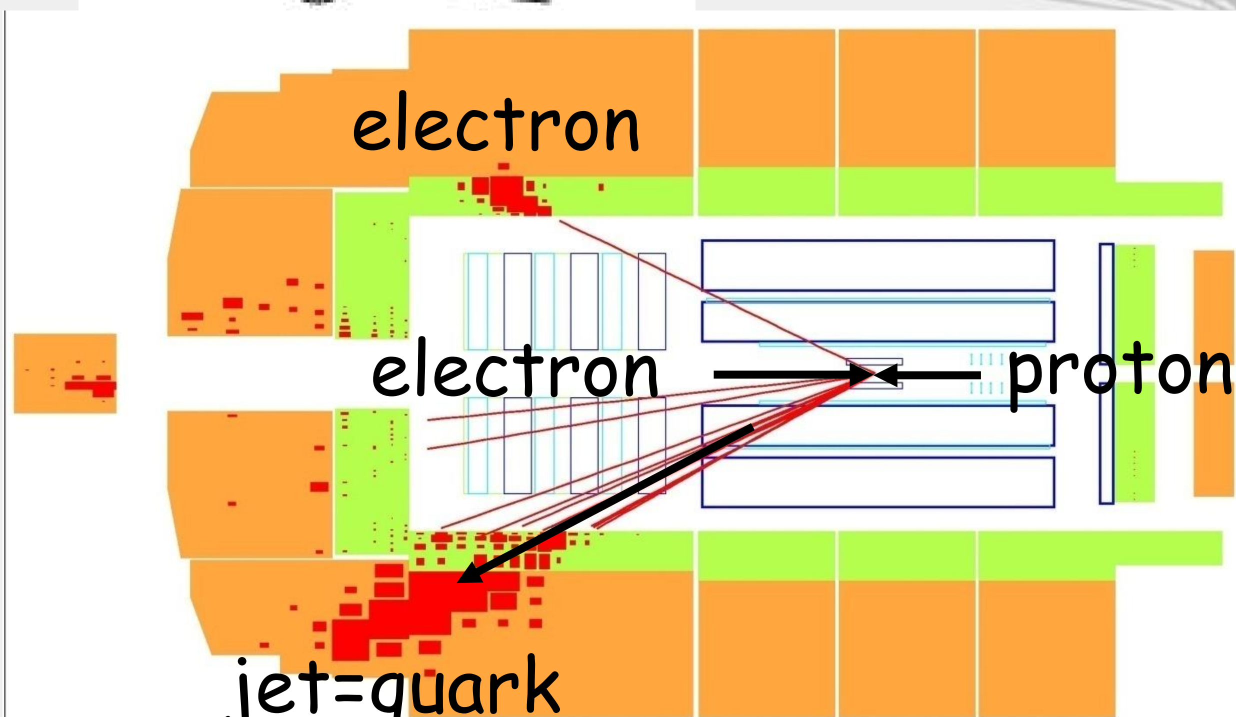
Constituents with Currents

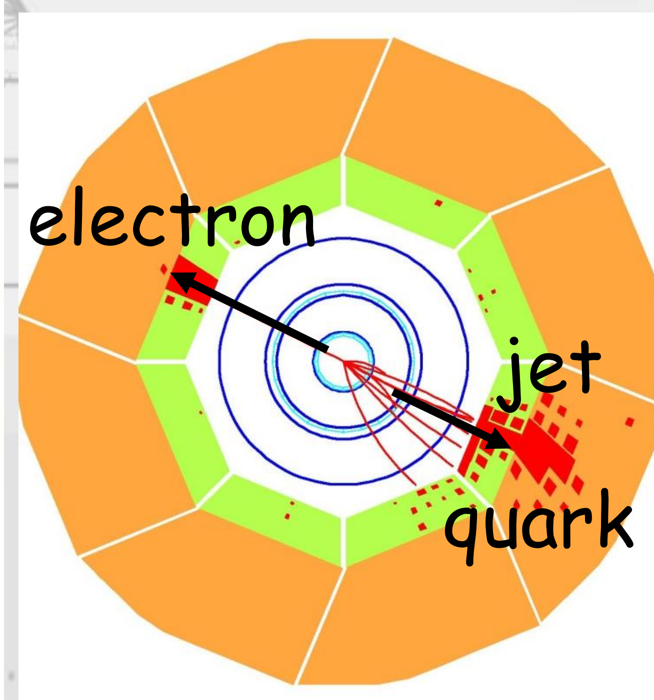
- >1992: Rutherford scattering at the Fermi scale





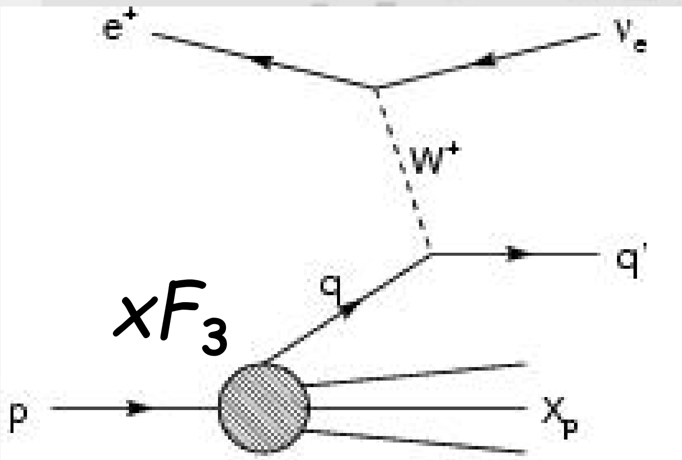
neutral current NC

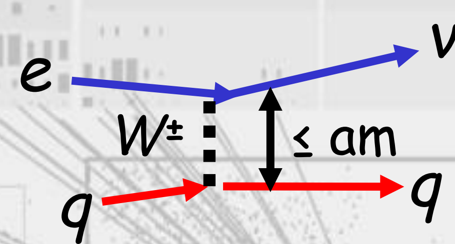




Constituents with Currents

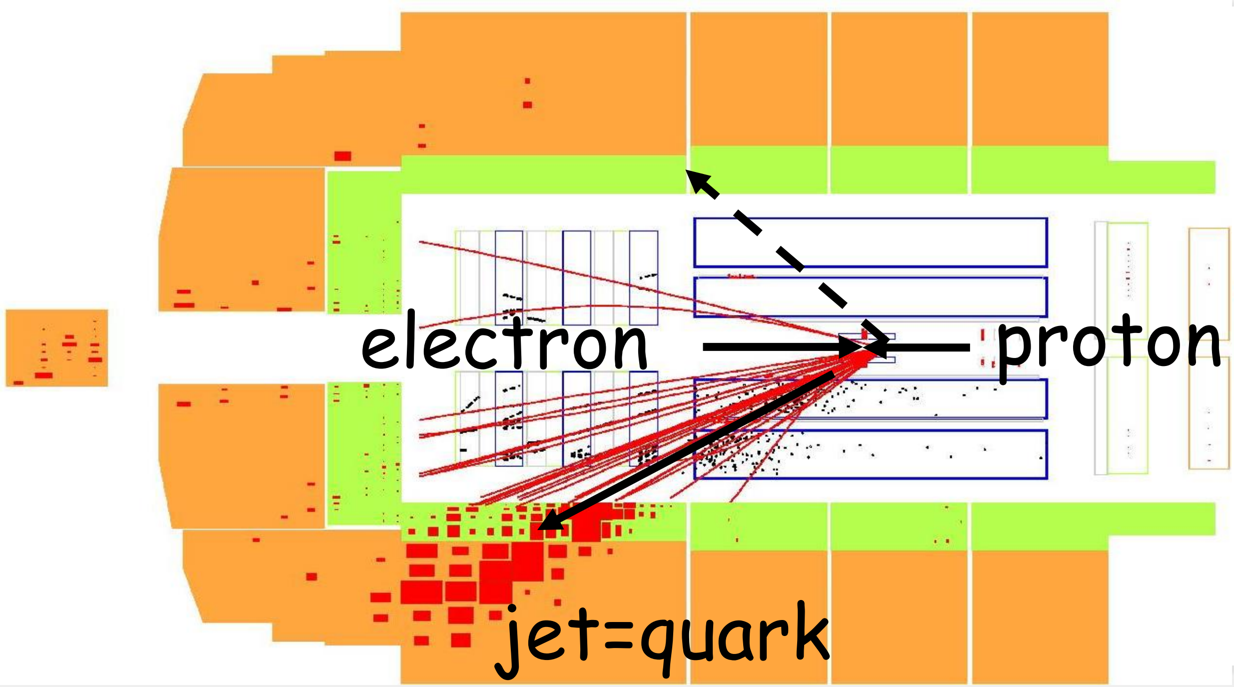
- >1992: inside Fermi's β-interaction

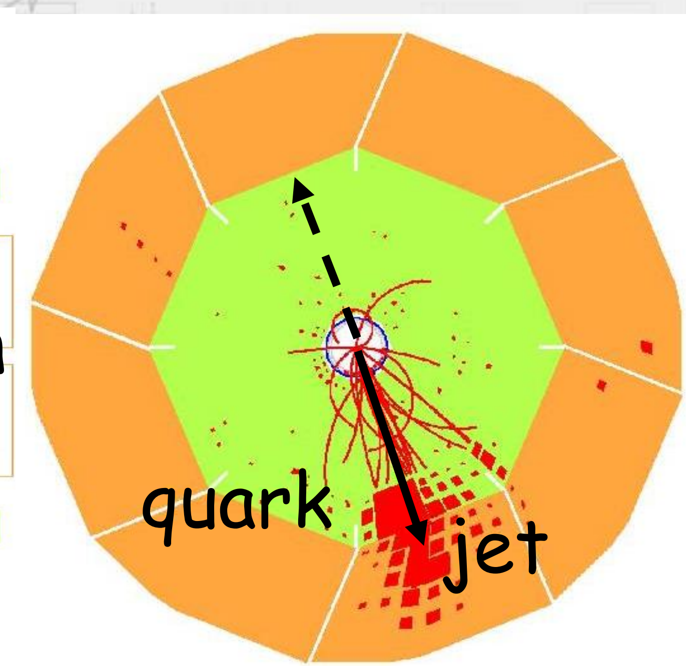




+ … ?

charged current CC

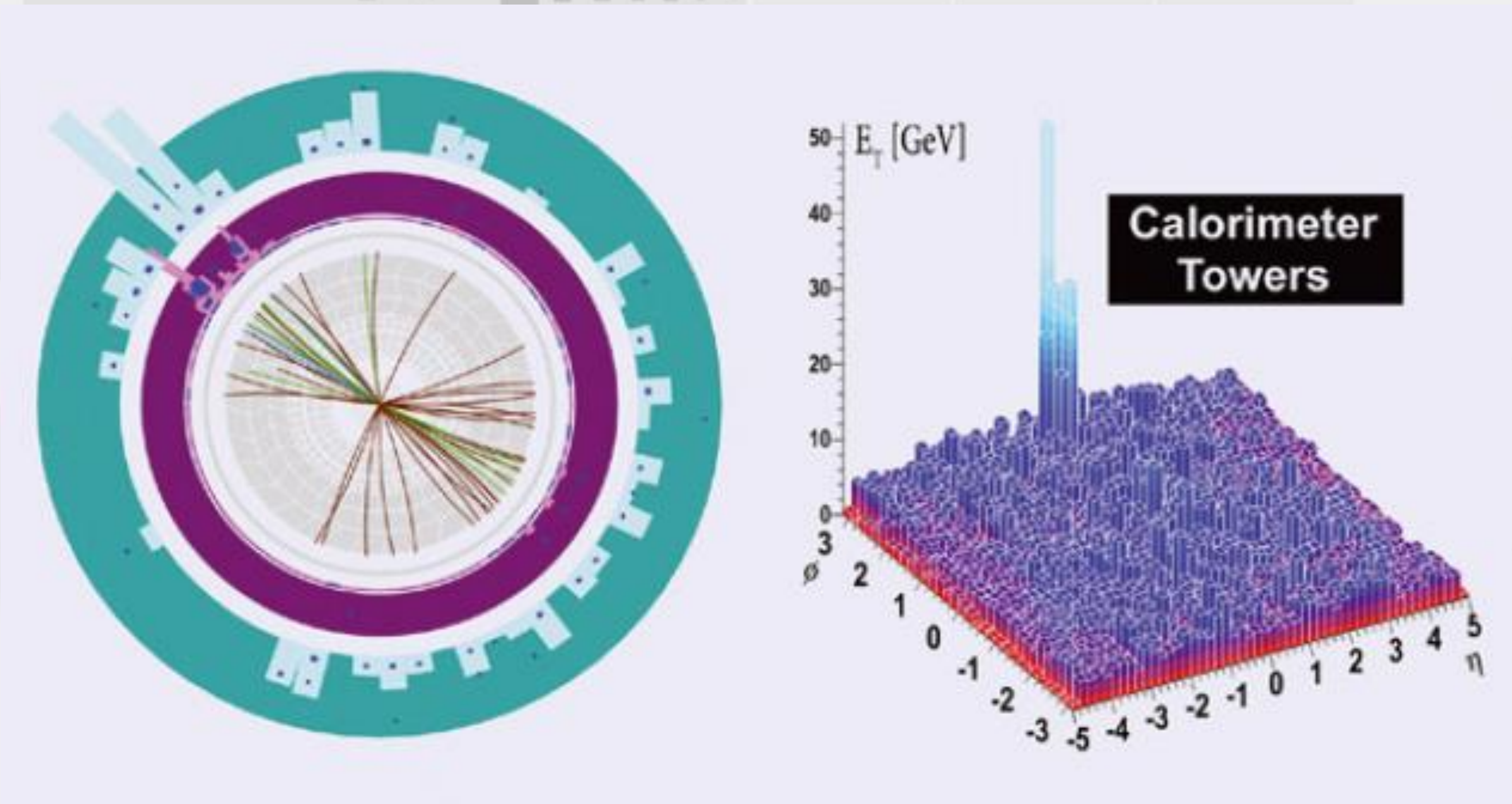




2. Landmarks

Jet in Open Colour?

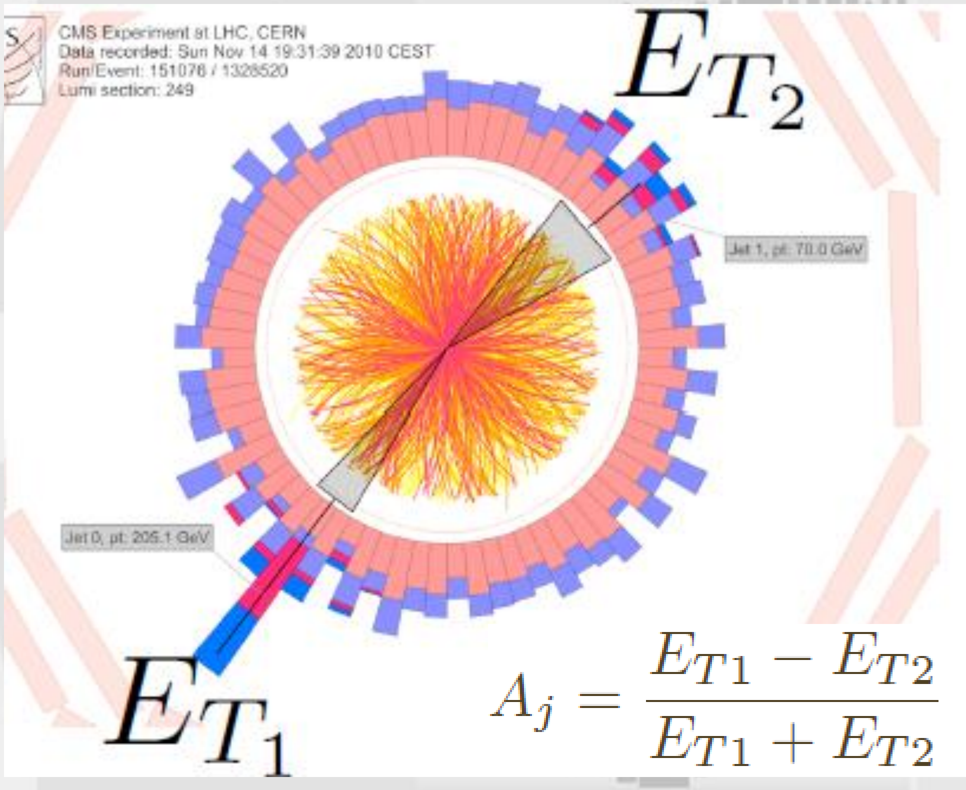
- di-jet visibility in hot matter



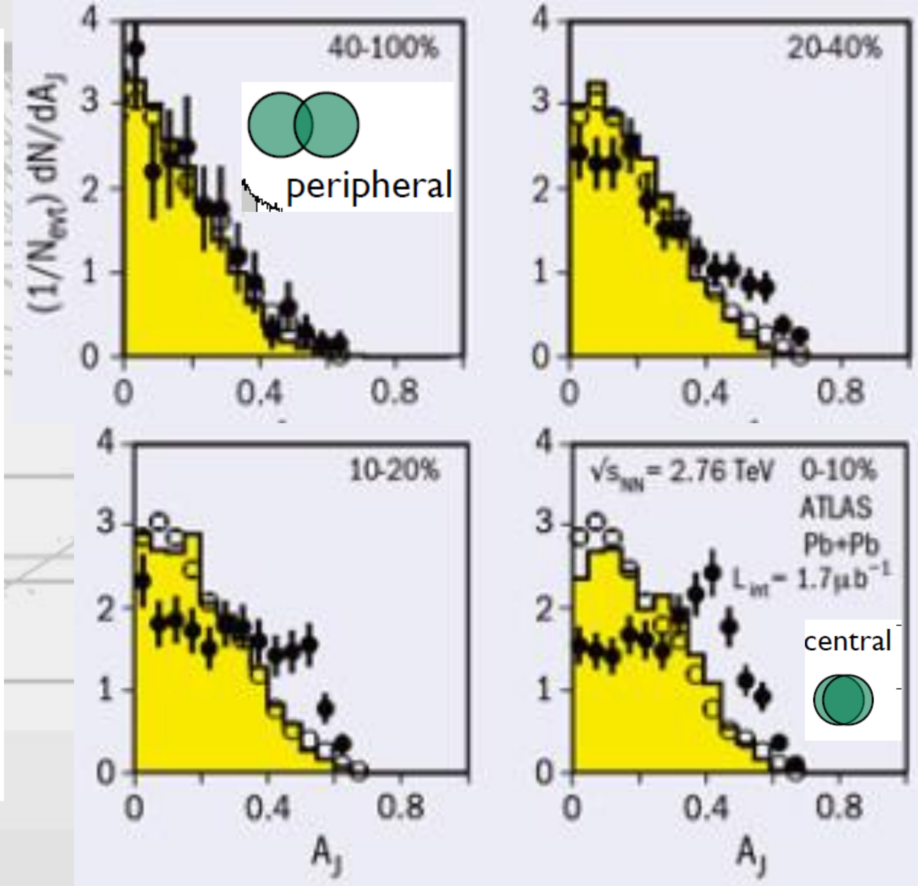
- jet "quenching" ?

Jet in Open Colour?

- jet energy asymmetry in hot matter



$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

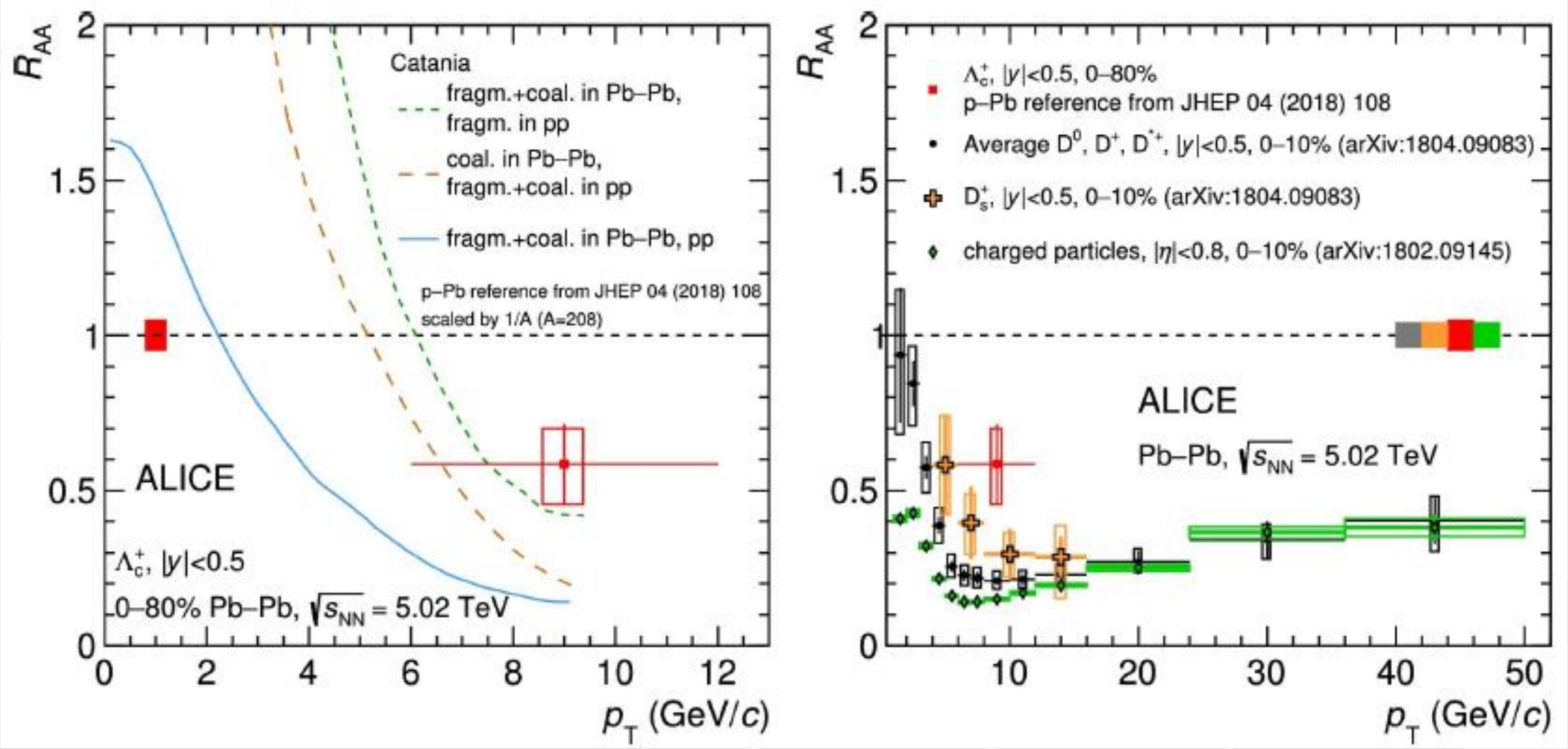


- "very dense as well as hot partonic system"
  production ⟵⟶ evolution ?
  factorisation

Heavy Flavour in Open Colour?

- charm $\Lambda_c(2286)$ production in hot matter

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle\,(1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$



- production ⟷ evolution

factorisation← $r_{\text{prod}\,\Lambda_c} \sim 0.1$ fm
recoil hadron topology ?

Hot QCD 2019

- hot chromodynamics in lab established
- di-jet → jet quenching
- inclusive jet → jet quenching central
  > jet quenching peripheral
- heavy flavour: observed $R_{AA}(p_T) < 1$

➥ beginnings of localised physics in QGP (cf 1970s)

➥ ALICE @ LHC upgrade
→ c and b acceptance and sensitivity
→ topological sensitivity → pQCD in QGP

LHC run 3
≥ 2021

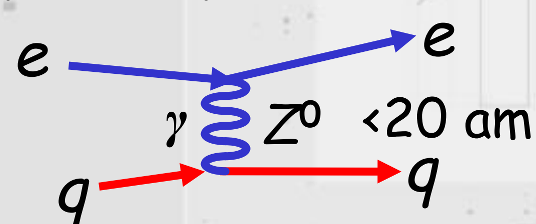
➥ "ALICE2": 2nd generation exp$^{\underline{t}}$ heavy ions

LHC
≥run 4
?

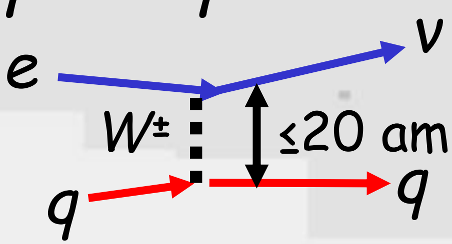
EW probe of Hadronic Matter

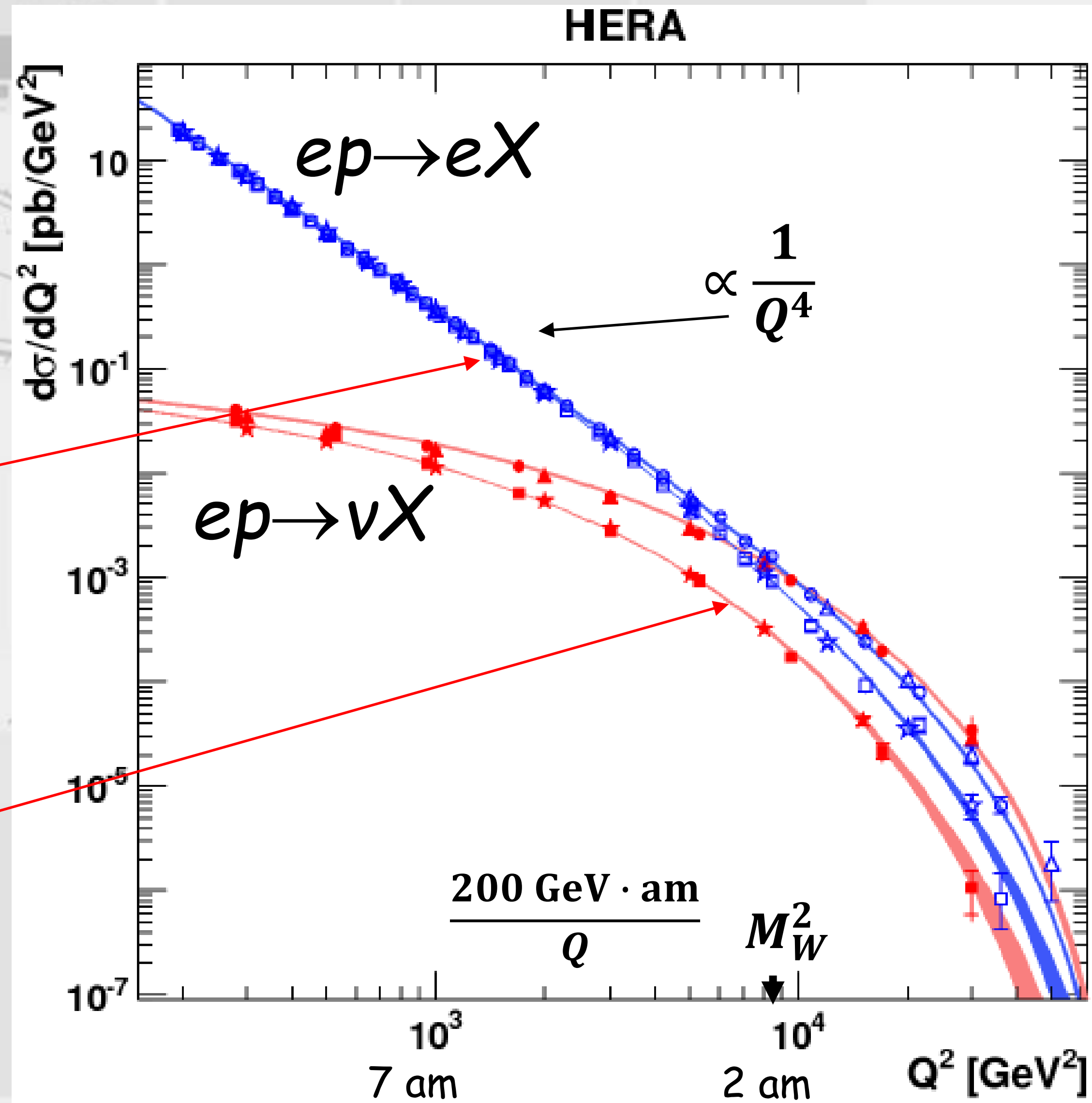
- GSW electron current
- structure of GSW $SU(2)_L \otimes U(1)$ force
- Rutherford scattering

$eq \rightarrow eq$ NC



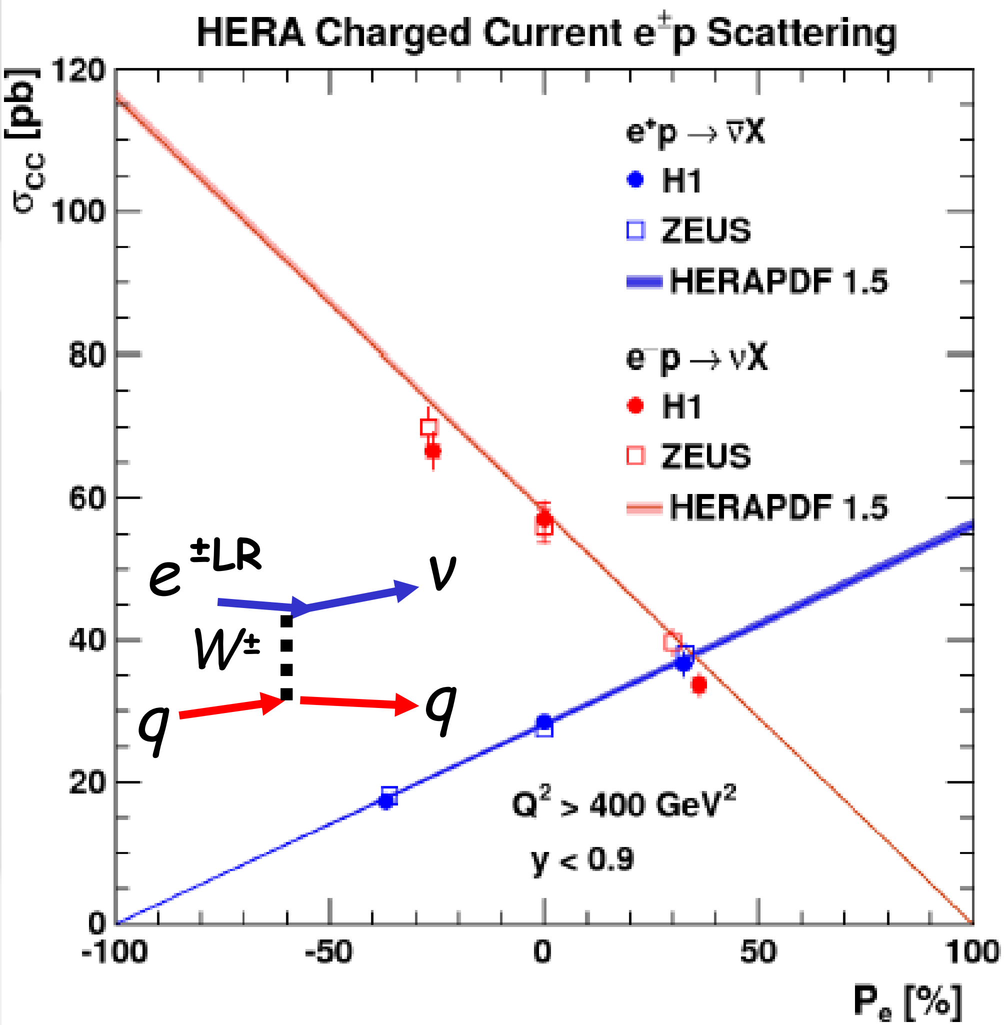
$eq \rightarrow \nu q$ CC



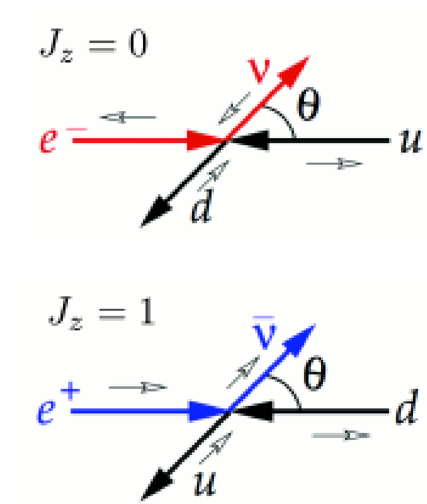


EW probe of Hadronic Matter

- GSW electron current
- "chirality" quarks / leptons L(R) Dirac (anti-)fermions



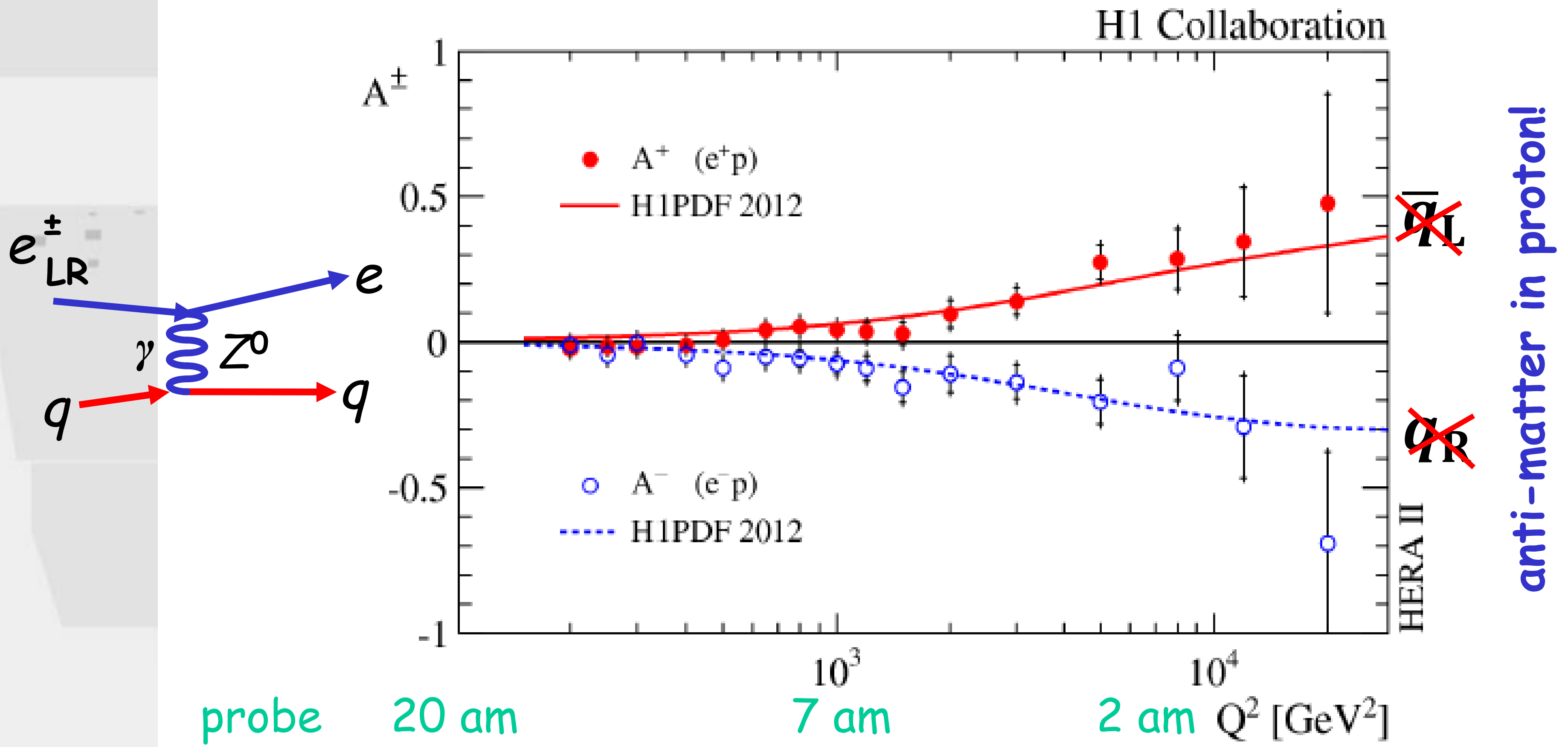
- Chiral structure of EW interactions probed
- No sign for right-handed currents



EW probe of Hadronic Matter

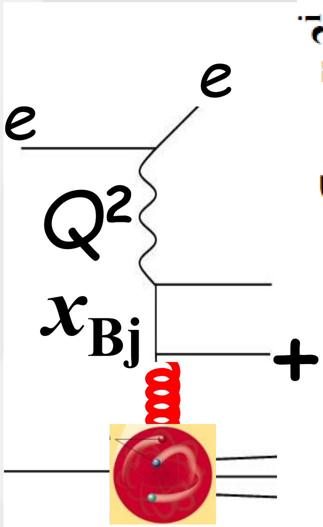
- GSW electron current
- polarisation asymmetry: $e^{\pm}q \rightarrow$ NC parity violation

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

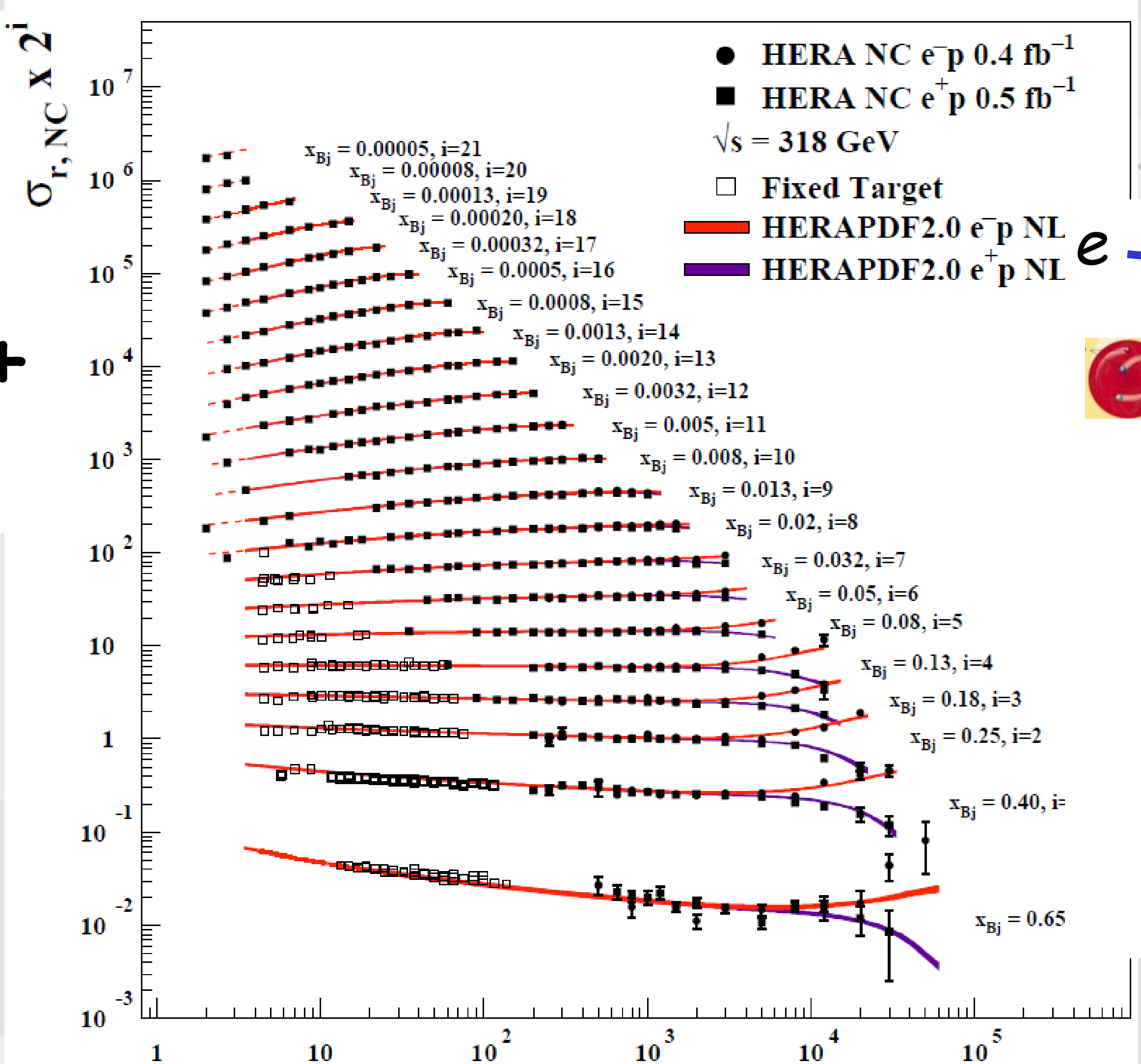


Hadron Structure: Proton

- EW probe of cold hadronic matter

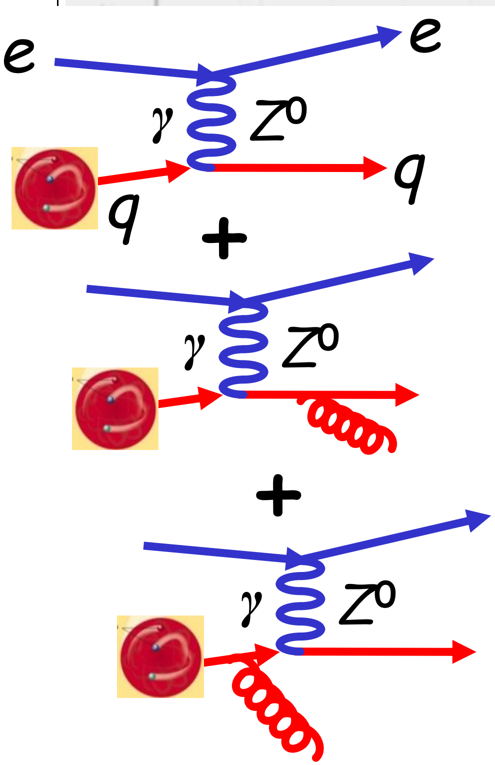


colour driven



probe 70 fm 20 am 7 am 2 am

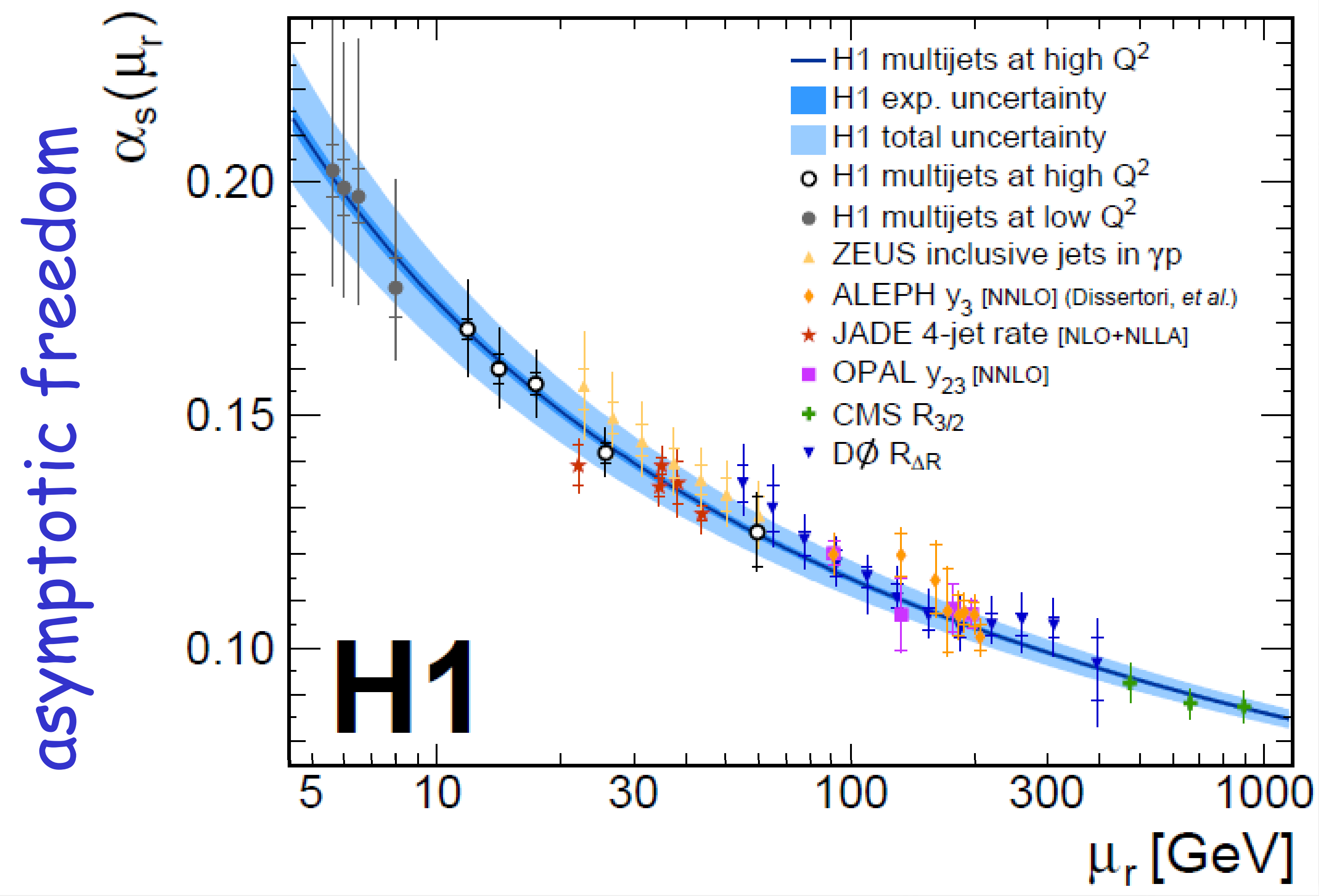
$F_2 \leftrightarrow \sigma_r$



valence driven

Hadronic Matter with Proton

- EW probe of cold hadronic matter
- QCD $= u\,d\,s\,c\,b\,t + g +$ non-abelian $\mathbf{SU(3)}_c$ + perturbative splitting $\rightarrow \alpha_s(Q^2)$



Hadronic Matter with Proton

- EW probe of cold hadronic matter
- QCD = $\boldsymbol{u\ d\ s\ c\ b\ t + g}$ + non-abelian $\mathbf{SU(3)}_{\boldsymbol{c}}$
  + perturbative splitting → partonic content

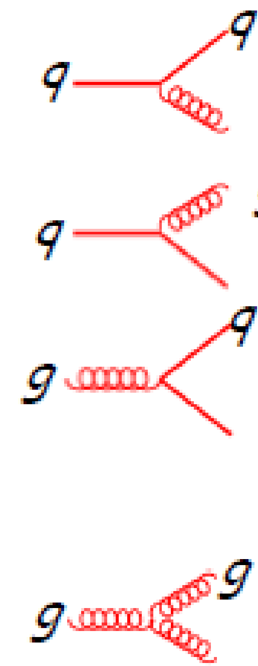
splitting functions

$$P_{qq} = \frac{4}{3}\left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\delta(1-x)\right] + o(\alpha_s) \rightarrow \frac{4}{3}\mathrm{d}x\frac{\mathrm{d}t}{t}$$

$$P_{gq} = \frac{4}{3}\frac{1+(1-x)^2}{x} + o(\alpha_s) \rightarrow \frac{4}{3}\frac{\mathrm{d}x}{x}\frac{\mathrm{d}t}{t}$$

$$P_{qg} = \frac{1}{2}\left[x^2 + (1-x)^2\right] + o(\alpha_s) \rightarrow \frac{1}{2}\mathrm{d}x\frac{\mathrm{d}t}{t}$$

$$P_{gg} = 6\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \frac{33-2n_f}{6}\delta(1-x) + o(\alpha_s) \rightarrow 6\frac{\mathrm{d}x}{x}\frac{\mathrm{d}t}{t}$$

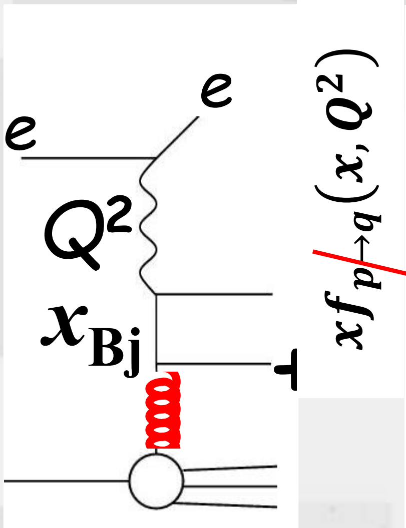


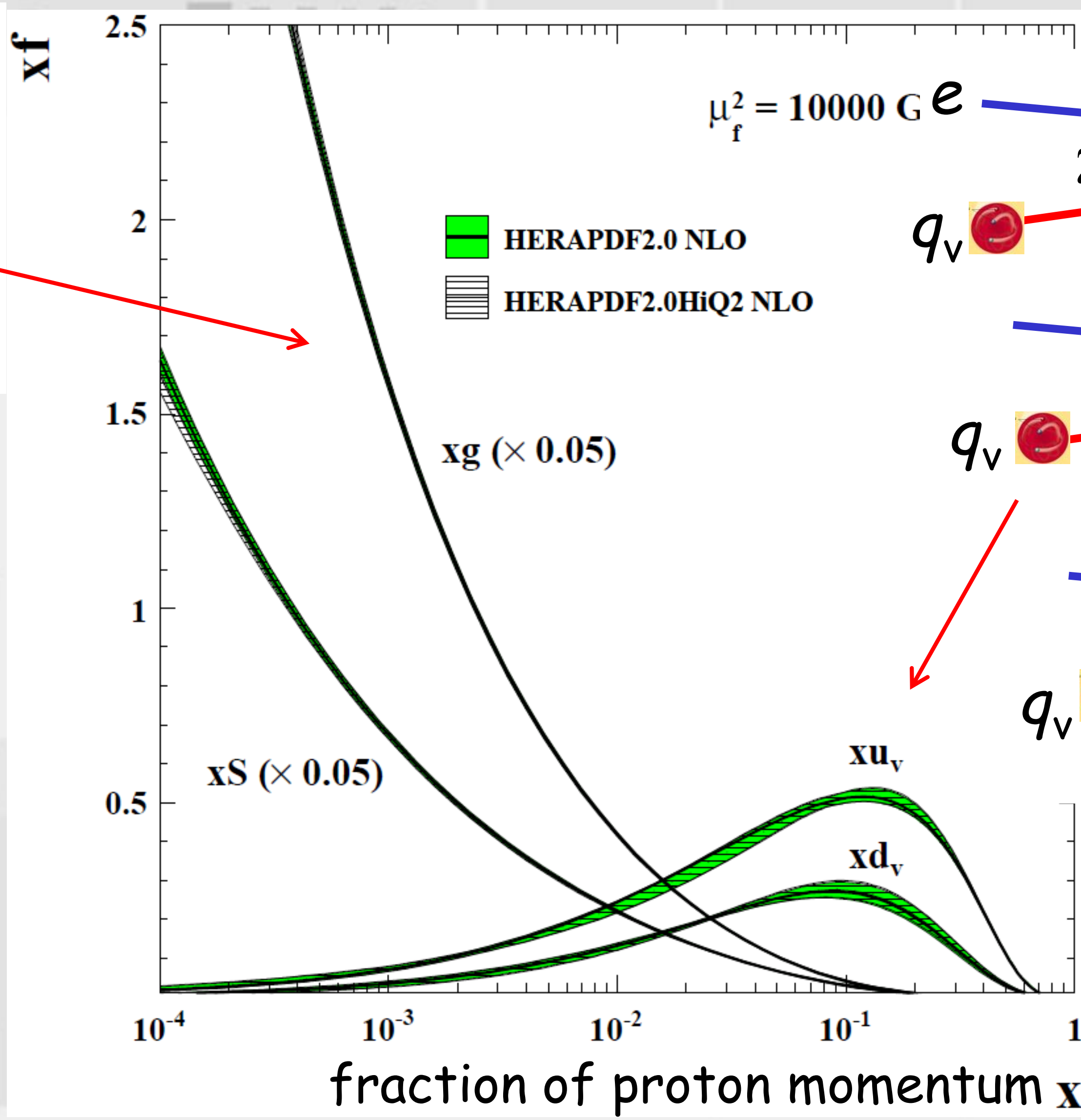
g→g dominates

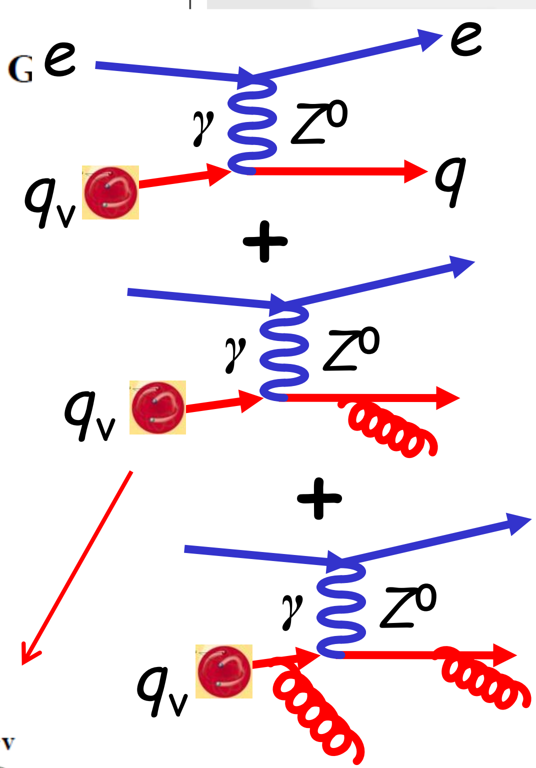
$$x = \frac{parent_\mu \cdot reference^\mu}{daughter_\mu \cdot reference^\mu}$$

Hadronic Matter with Proton

- EW probe of cold hadronic matter







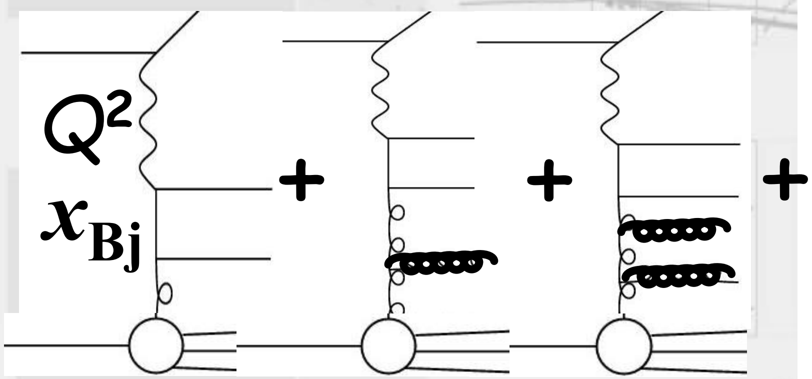
colour driven

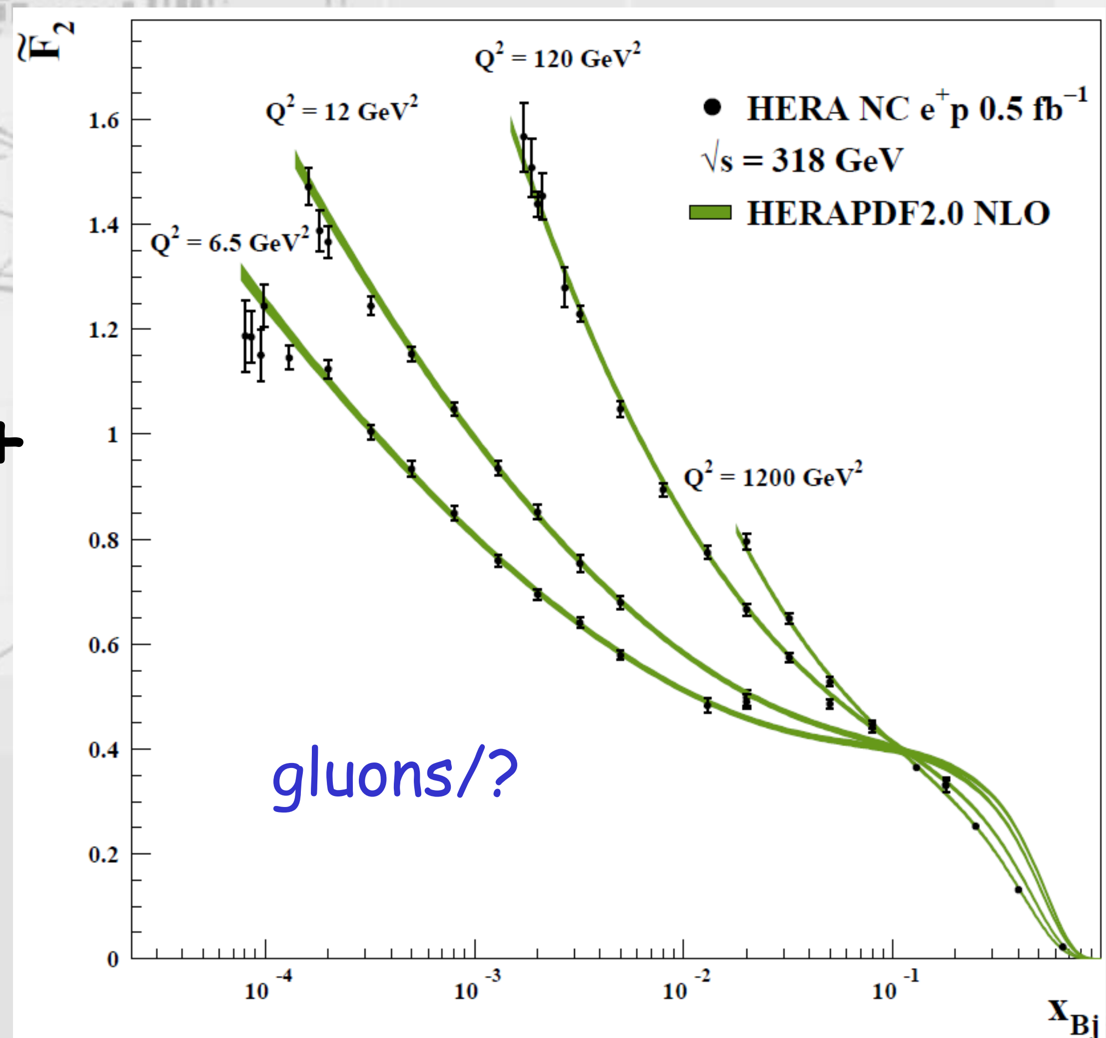
gluonic cold hadronic matter

valence driven

Hadronic Matter with Proton

- EW probe of cold hadronic matter
- QCD $= u\, d\, s\, c\, b\, t + g +$ non-abelian $\mathbf{SU(3)}_c$
- low x_{Bj} QCD
  $p \to g g g \ldots + q\bar{q}$





↳ "cold denser" hadronic matter

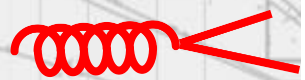
Hadronic Matter with Proton

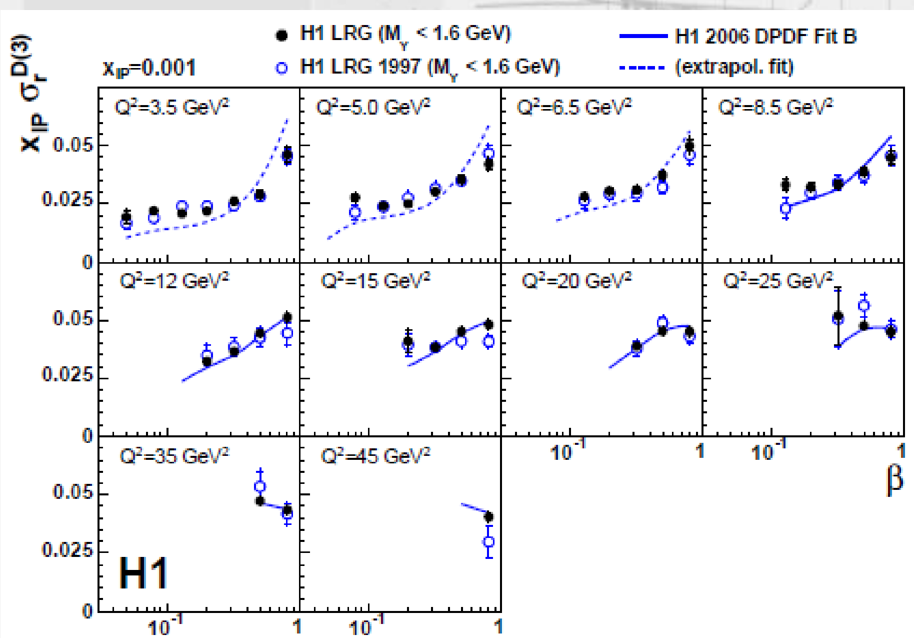
- EW probe of cold hadronic matter
- QCD $= \boldsymbol{u\ d\ s\ c\ b\ t} + \boldsymbol{g} +$ non-abelian $\mathbf{SU(3)}_c$
- low x_{Bj} QCD $\boldsymbol{p}$ interacts with structure $\boldsymbol{ggg} \ldots + \boldsymbol{q\bar{q}}$

- unquestionably dramatic: void ← 920 GeV proton

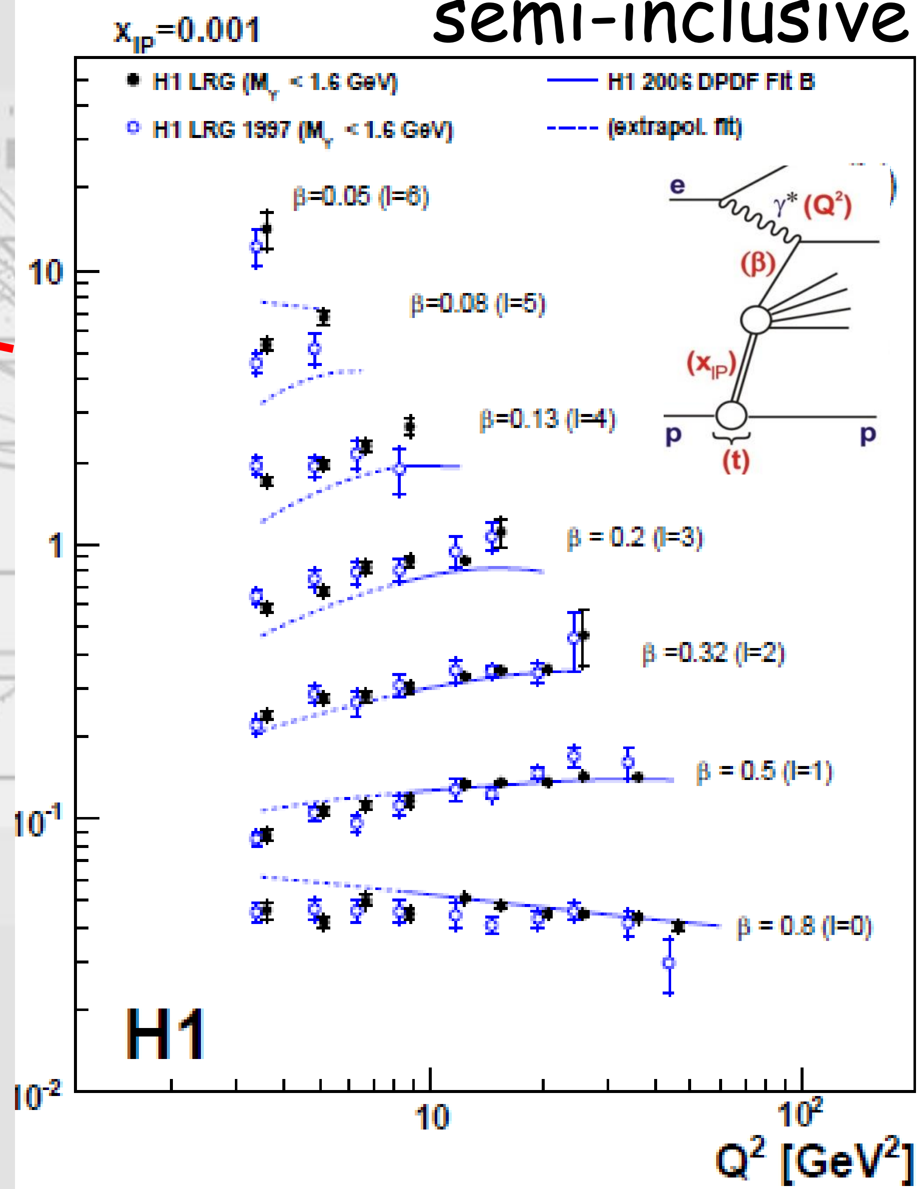
↳ non-abelian colour $\boldsymbol{g} \leftrightarrow \boldsymbol{g}$ builds colour singlet $\mathbf{1}_c$ in "cold denser" hadron matter

QCD of Inter-nucleon Force

- semi-inclusive $ep \to eXp$
  $F_2^{D(3)}(Q^2, \beta) \equiv 1_f$ (sea) $\equiv$ vector field quantum
  $g \to q\bar{q}$ splitting 



semi-inclusive



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

Cool Dense QCD 2019

- cool dense chromodynamics lab established with electroweak electron probe

- gluon-dominated proton structure

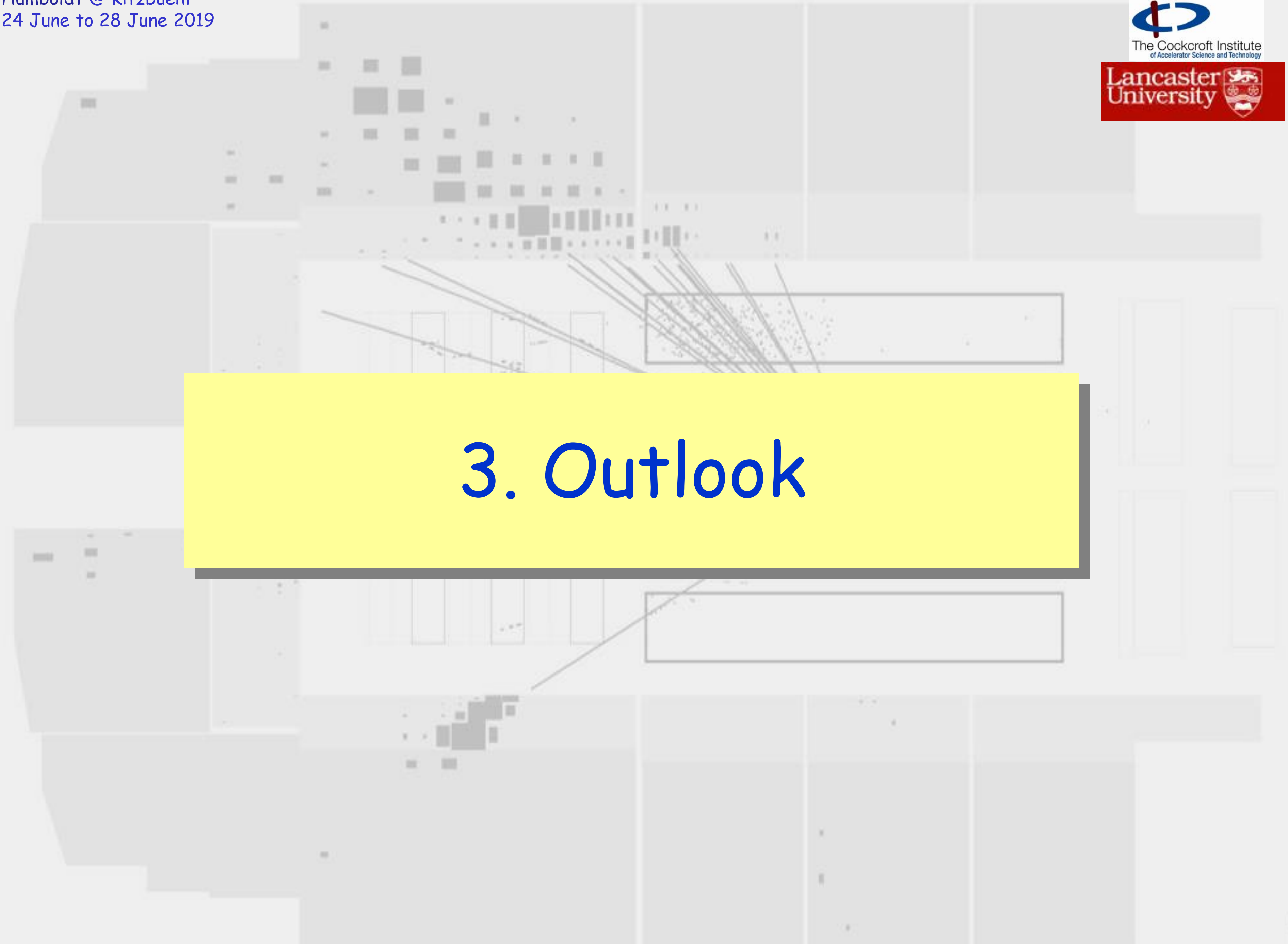
- low x_{Bj} p QCD structure builds pp interaction

↳ foundation of QCD in hadronic physics

↳ understanding and phenomenology of q and g in atomic nuclei → QCD in cold nuclear matter

↳ precision less in/ex clusive $eA \to eXY$

? eIC begin 2020

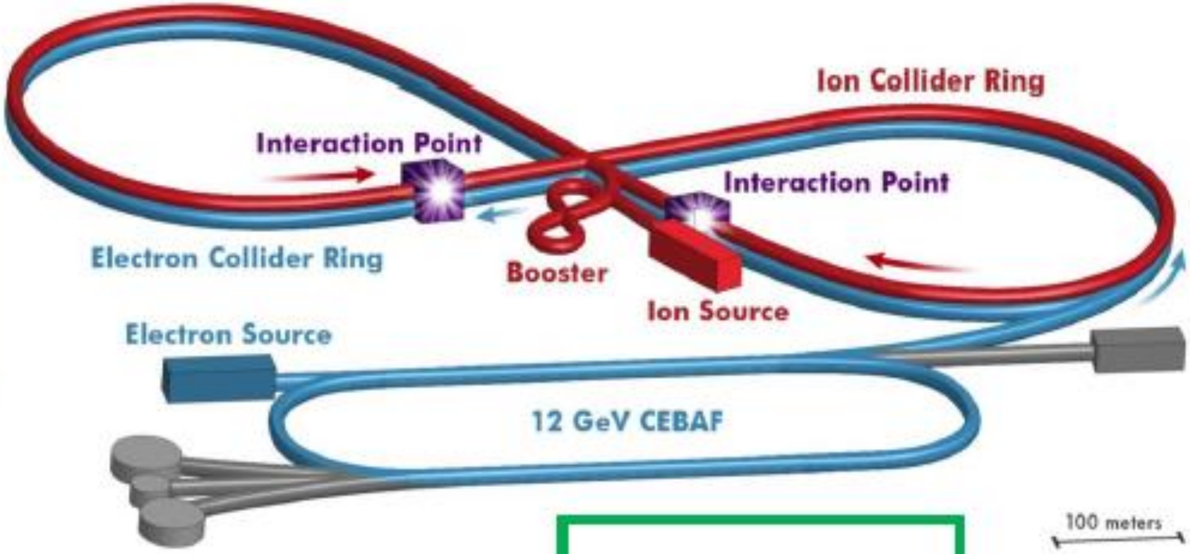


3. Outlook

Cool QCD

- second generation collider: JLeIC $e_{\mathrm{LR}}A \rightarrow eXY$

Energy range:
E_e: 3 to 12 GeV
E_p: 40 to 100–400 GeV
$\sqrt{s}$: 20 to 65–140 GeV
(upper limit depends on magnet technology choice)



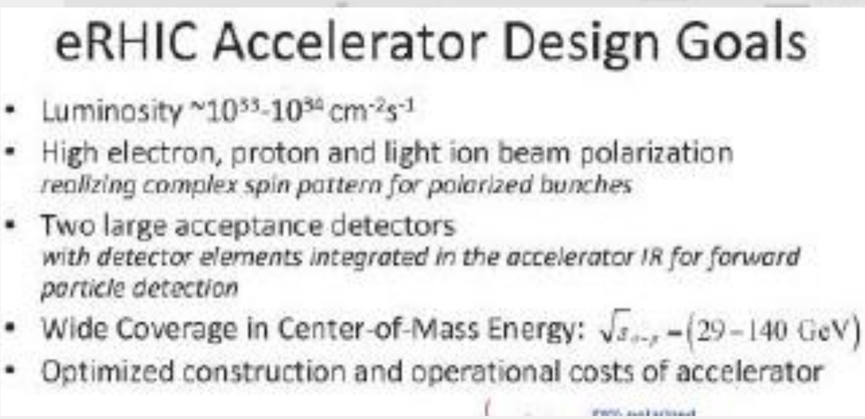
- Electron complex
  - CEBAF
  - Electron collider ring
- Ion complex
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring
- Fully integrated IR and detector
- DC and bunched beam coolers

arXiv:1504.07961

Cool QCD

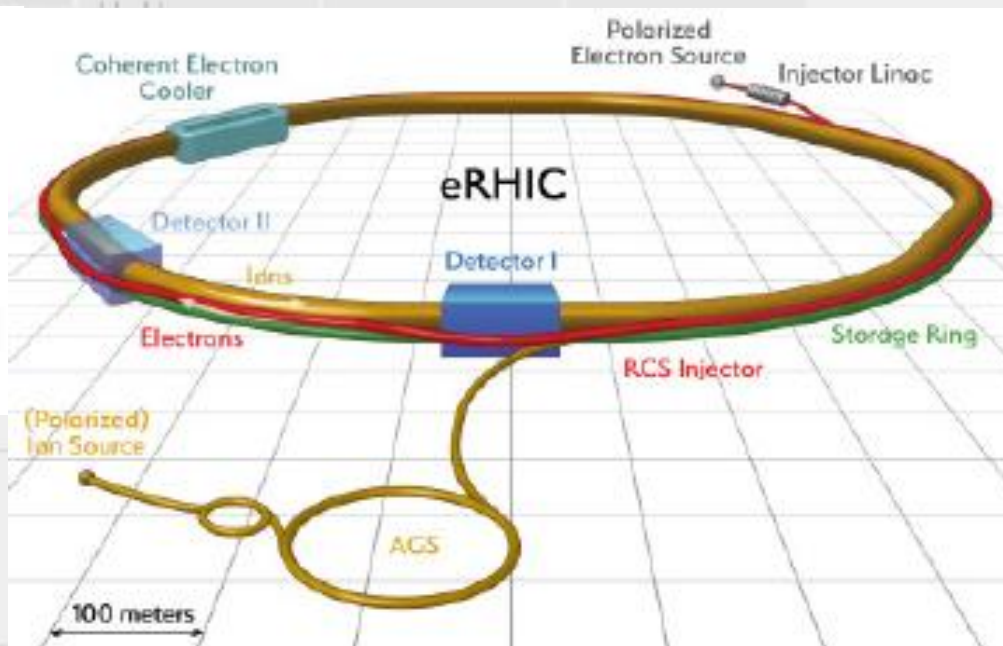
The Cockcroft Institute of Accelerator Science and Technology
Lancaster University

- second generation collider: eRHIC $e_{\mathrm{LR}}A \rightarrow eXY$



eRHIC Accelerator Design Goals

- Luminosity ~10^{33}-10^{34} $cm^{-2}s^{-1}$
- High electron, proton and light ion beam polarization
  realizing complex spin pattern for polarized bunches
- Two large acceptance detectors
  with detector elements integrated in the accelerator IR for forward particle detection
- Wide Coverage in Center-of-Mass Energy: $\sqrt{s_{e-p}} = (29 - 140\ \mathrm{GeV})$
- Optimized construction and operational costs of accelerator



- $L_{ep} \gtrsim 10^{34}$ polarisation cooling "final focus"

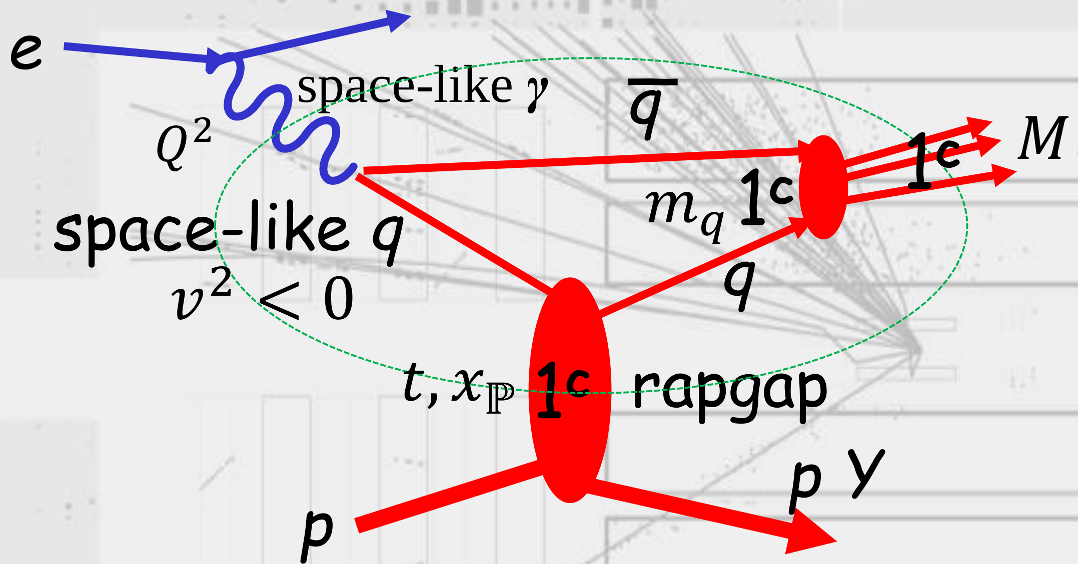
Hutton, Willeke …

- generation-2 experiments: on-line intelligence

Aschenauer, Yoshida …

Scale in Cold QCD

- measure and therefore specify mass M of system X
  - in→exclusive $ep \to eXp$, $ep \to eXY$: no radiation (g)



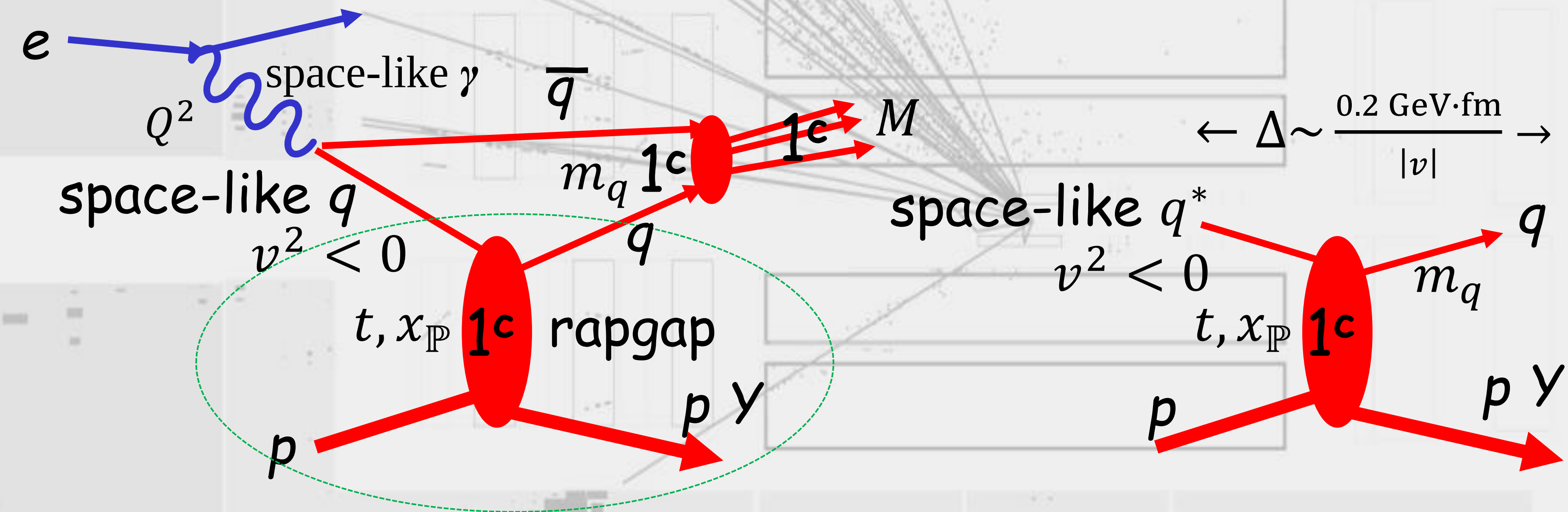
  - limits on quark "virtuality" $-v^2$ in quark splitting

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

- specific M → sensitivity to quark mass m_q inside hadronic QCD field (exclusive → no radiation)

Scale in $q^*p \to qp, qY$

- perspective in $q^*p \to qp, qY$

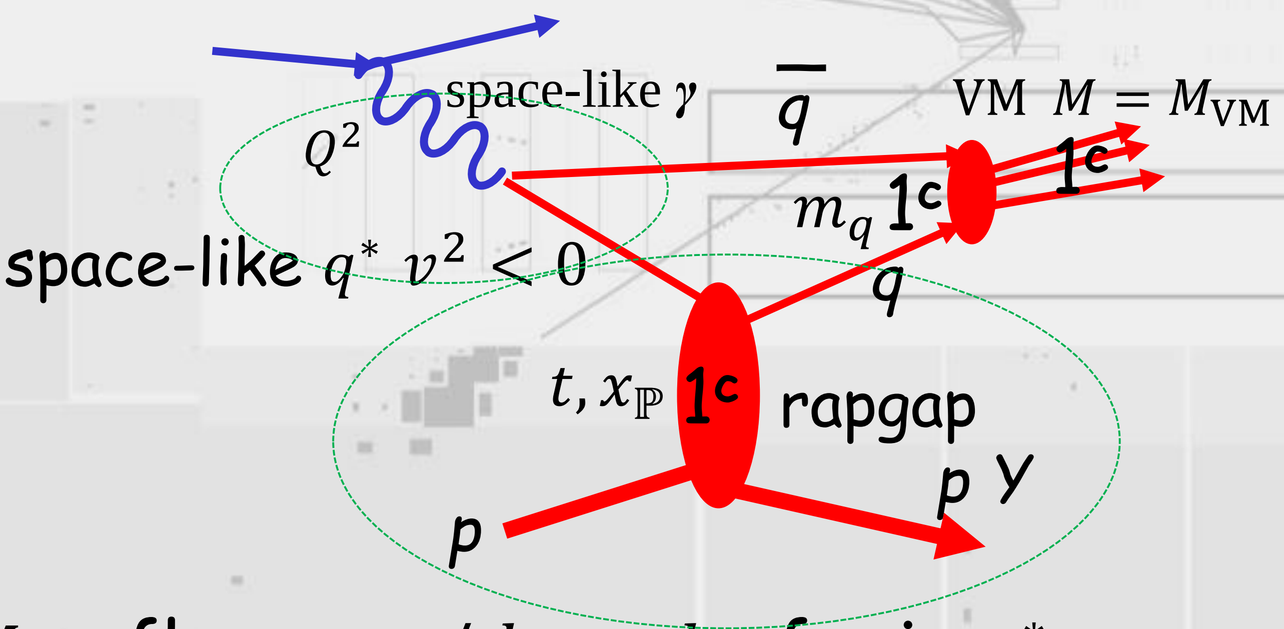


- quark "virtuality" $-v^2 \leftrightarrow$ length $\Delta \sim \frac{0.2 \text{ GeV}\cdot\text{fm}}{|v|}$ of collinear $q^*p \to qp, qY$

Flavour in Cold QCD

- specify system X as vector meson VM
- exclusive $ep \to e\mathrm{VM}p,\, ep \to e\mathrm{VM}Y\ \ M = M_{\mathrm{VM}}$
  $\mathrm{VM} = \rho(760)\ \omega(780)\ u/d\ \ \phi(1019)\ s$
  $J/\psi(3096)\ c\ \ \Upsilon(9460)\ b$

↳ defines Bethe-Heitler γ^*-splitting hypercharge



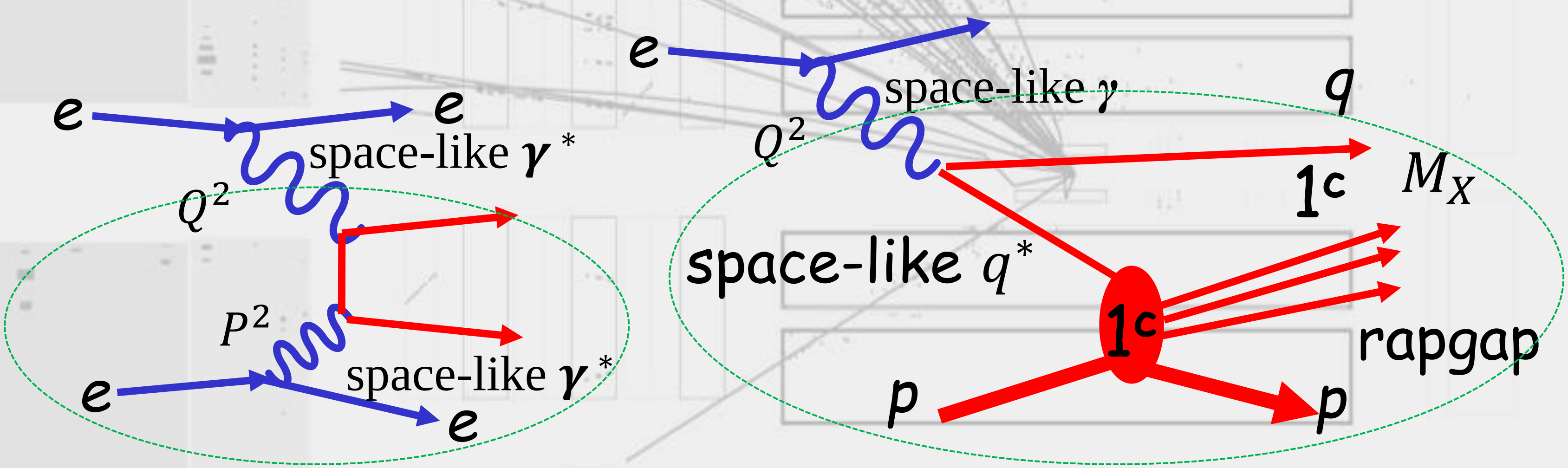
↳ $\mathrm{VM} \to$ flavour $u/d, s, c, b$ of q in $q^*p \to qp, qY$ QCD

QED Technology

- exclusive $e_{LR}A \to eVMY$: q in nuclear matter

+ deep-inelastic structure of the virtual photon in

$e^+e^- \to e^+e^- +$ hadrons $\qquad e\gamma^* \to e +$ hadrons

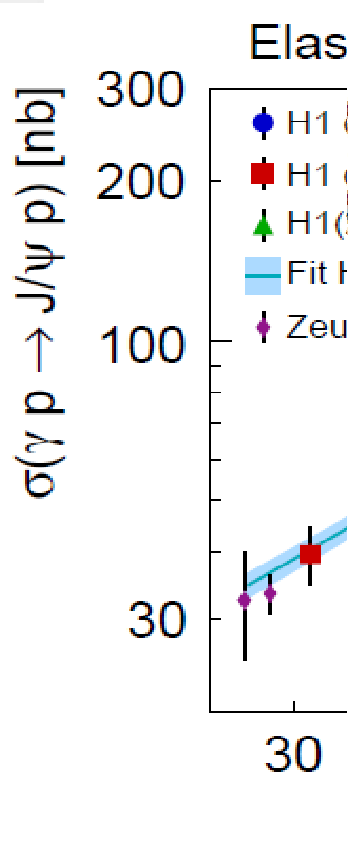


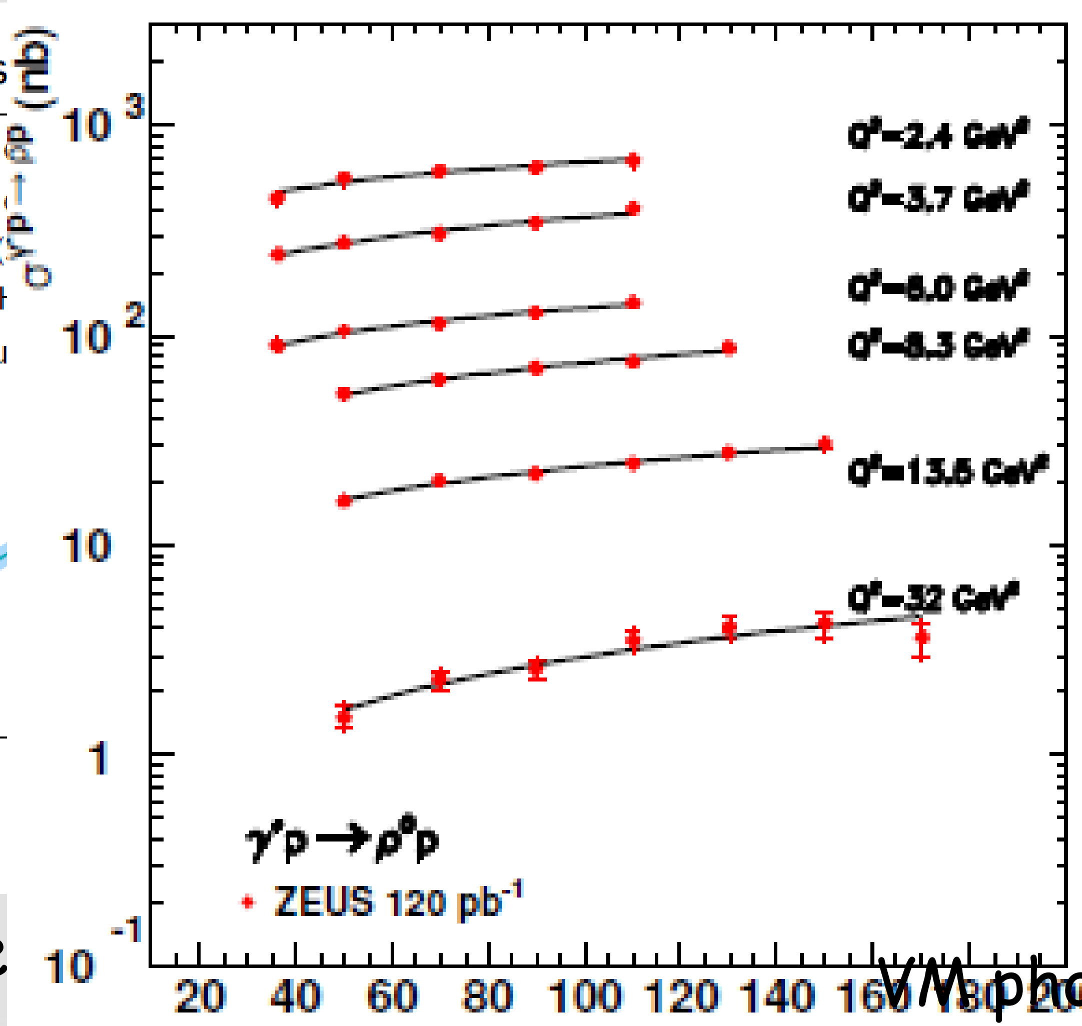
"drop" a quark into nuclear matter …
…and watch it interact!

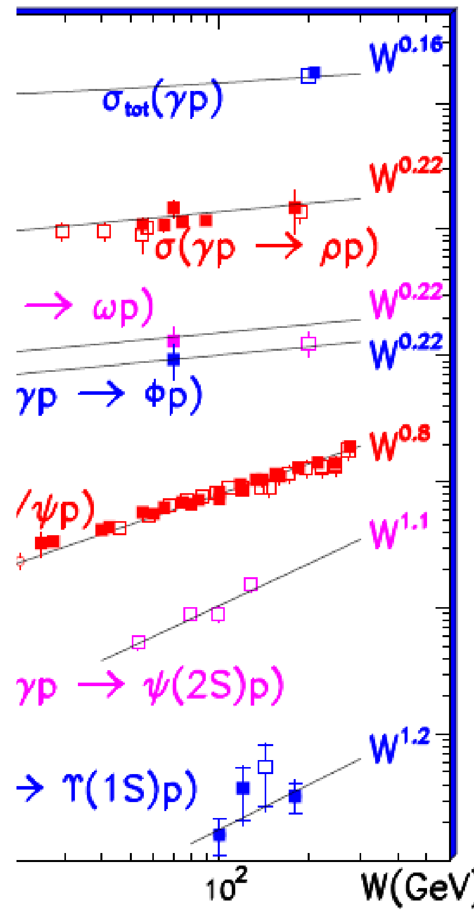
Francis Bench and John Dainton "Towards Sub-femtoscopic, Chromodynamic, Rutherford Scattering?"
http://pos.sissa.it/archive/conferences/265/168/DIS2016_168.pdf

Exclusive @ HERA ?

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







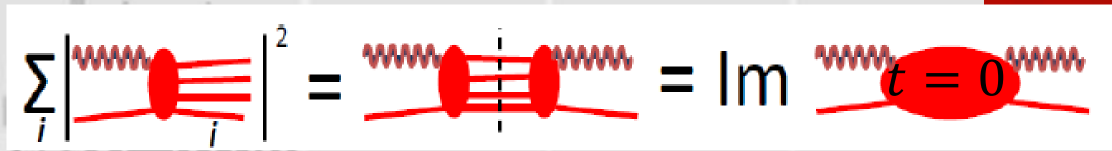
VM photoproduction

$\rho(760)$ electroproduction

- at face …
  … some

Unitarity Technology

- optical theorem

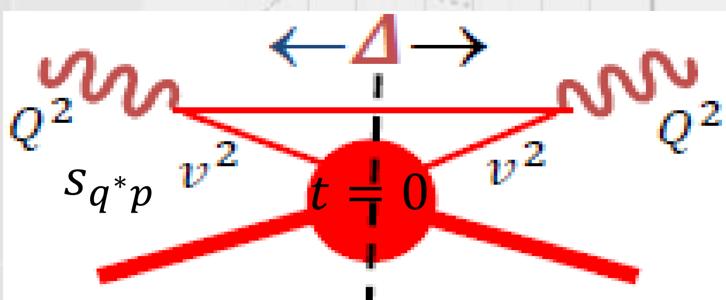


$$\sigma_{\gamma^* p}(W^2, Q^2) = \frac{1}{Q^2+W^2} \mathrm{Im} T_{\gamma^* p \to \gamma^* p}(W^2, t=0, Q^2)$$

$$\equiv \frac{x_{\mathrm{Bj}}}{Q^2} \mathrm{Im} T_{\gamma^* p \to \gamma^* p}(x_{\mathrm{Bj}}, t=0, Q^2) = \frac{4\pi^2 \alpha}{Q^2} F_2(x_{\mathrm{Bj}}, Q^2)$$

↳ $F_2(x_{\mathrm{Bj}}, Q^2) \xleftrightarrow[\text{fixed } Q^2]{}$ forward Compton amplitude $T_{q^* p \to q^* p}(s_{q^* p}, t=0, v^2)$

W^2



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

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

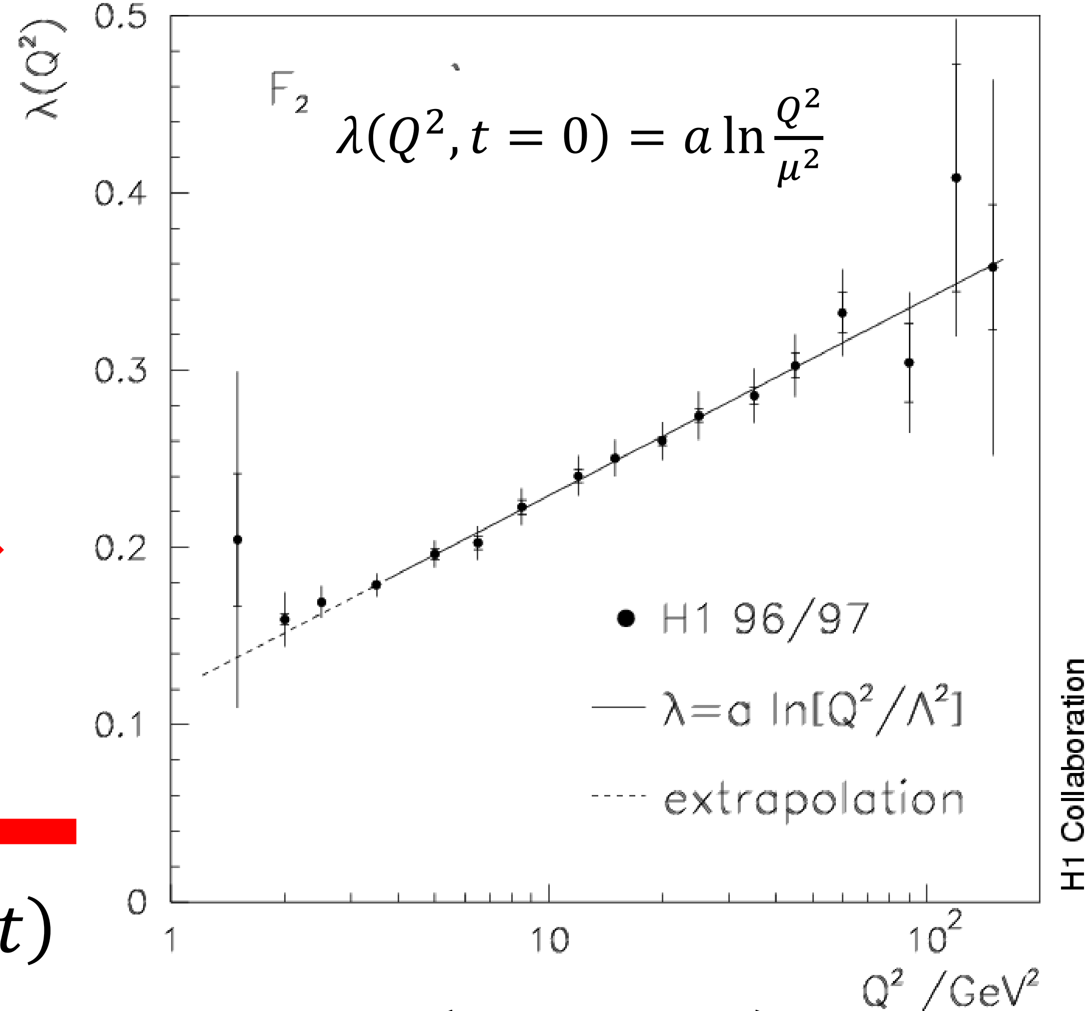
↳ forward $q^* p$ Rutherford scattering amplitude $T_{q^* p \to q^* p}(s_{q^* p}, t=0, v^2)$ embedded in $F_2(x_{\mathrm{Bj}}, Q^2)$

Unitarity and Analyticity

- universal but scale dependent pomeron $\mathbb{P}$?

$$\frac{4\pi^2\alpha}{Q^2}F_2\left(x_{\mathrm{Bj}},Q^2\right)$$
$$\propto x_{\mathrm{Bj}}^{-\lambda(Q^2,t=0)}$$
$$\left(x_{\mathrm{Bj}}<0.01\right)$$

$$\lambda(Q^2,t=0)$$



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

$$Q^2=v^2$$

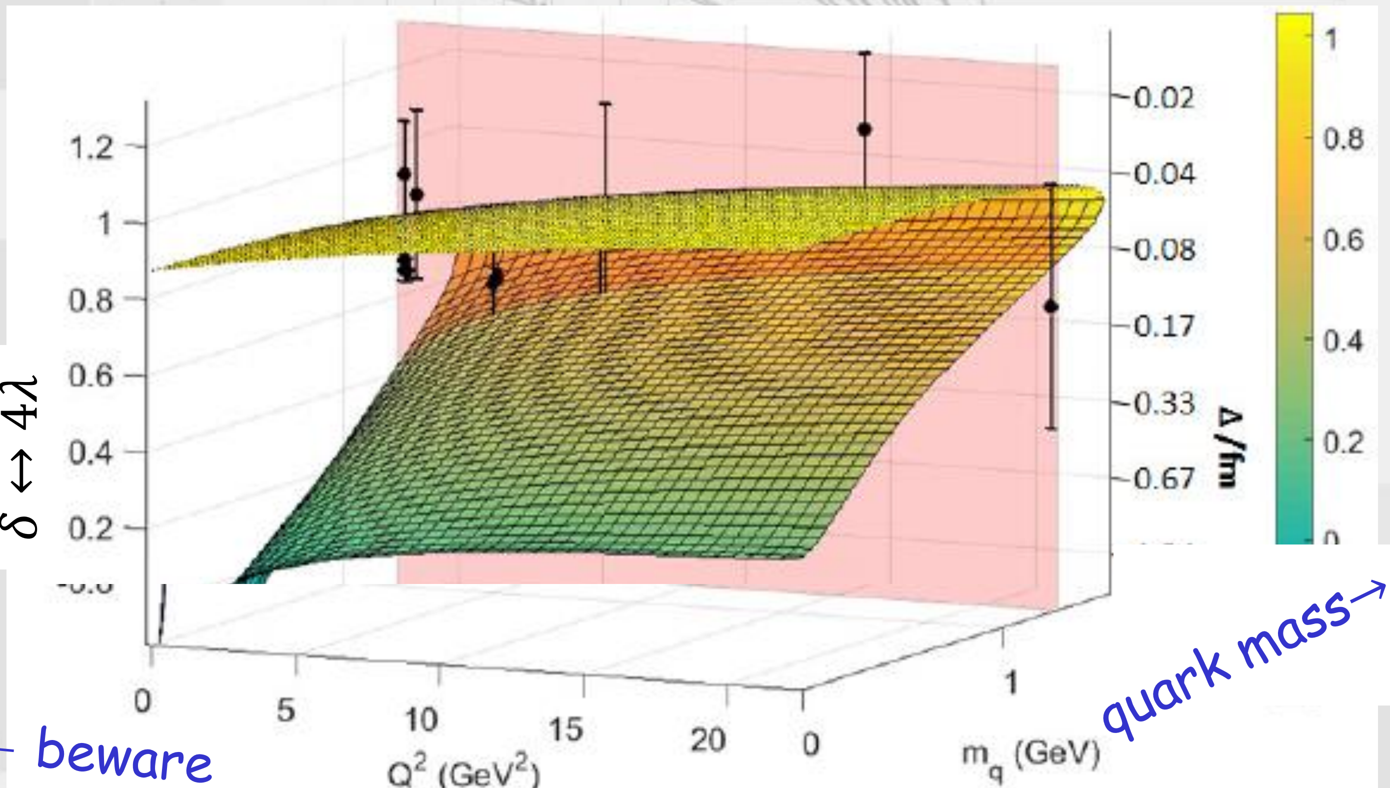
$$\lambda(v^2,t=0)\sim\lambda(v^2,t)$$

(Regge) analyticity for $T_{q^*p\to q^*p}\left(s_{q^*p},t,v^2\right)$

c-quark "dropped into" Proton

- electroproduction $\gamma^* p \to J/\psi\, p$

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



$\delta \leftrightarrow 4\lambda$

Regge scaale →

← beware $Q^2 < 1\ GeV^2$

quark mass→

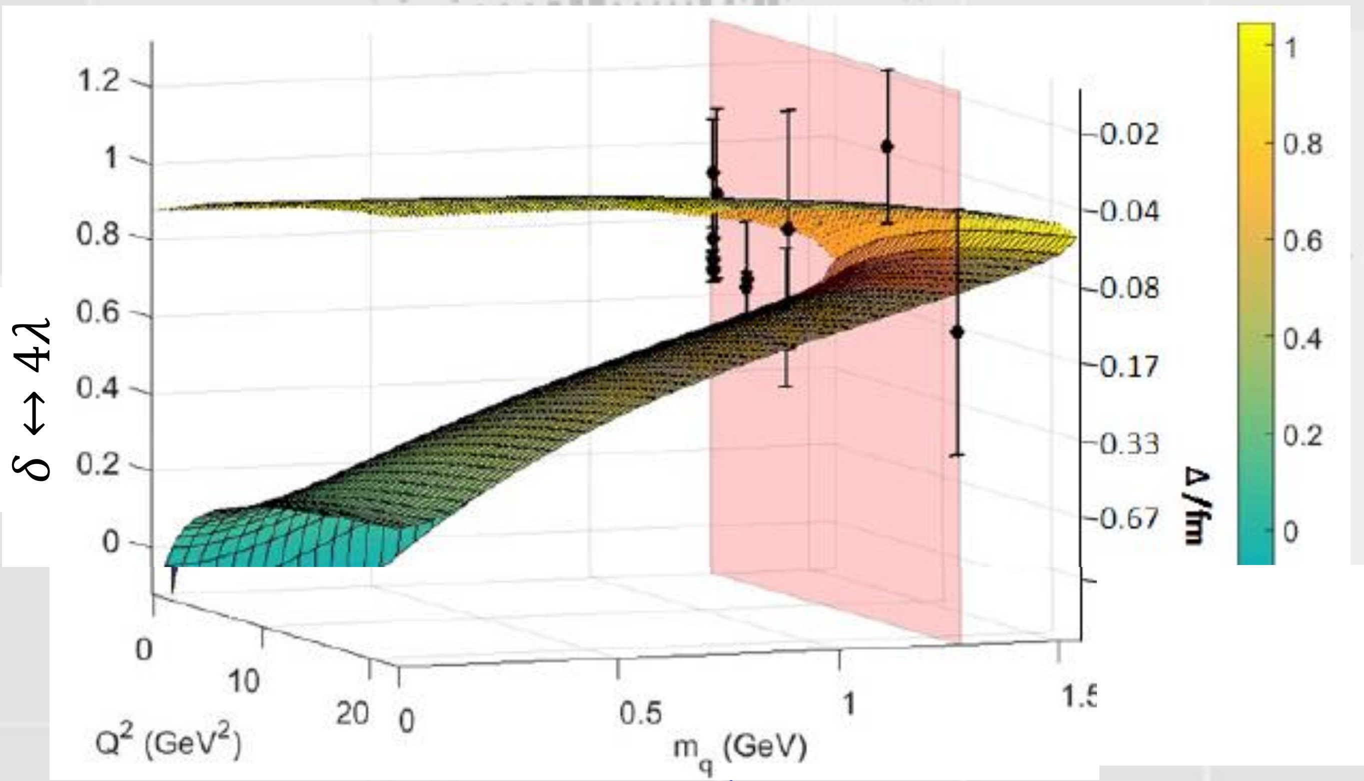
$|t| \ll M_{VM}^2 \lesssim Q^2 \ll W^2$

c-quark dropped in Proton

- electroproduction $\qquad \gamma^* p \to J/\psi\, p/Y$

Regge scale ↑

$\delta \leftrightarrow 4\lambda$

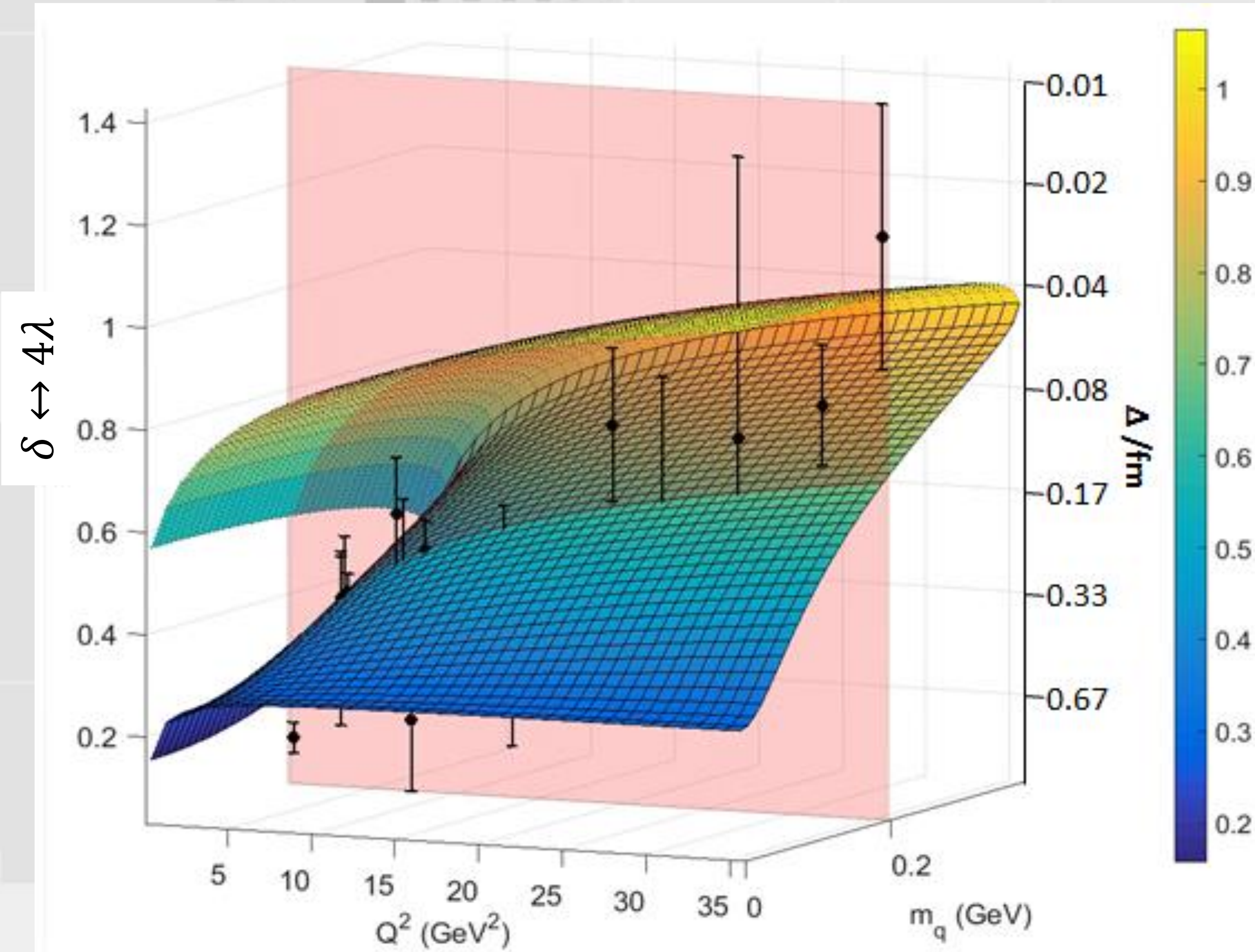


quark mass→

- current ~ constituent c-quark mass

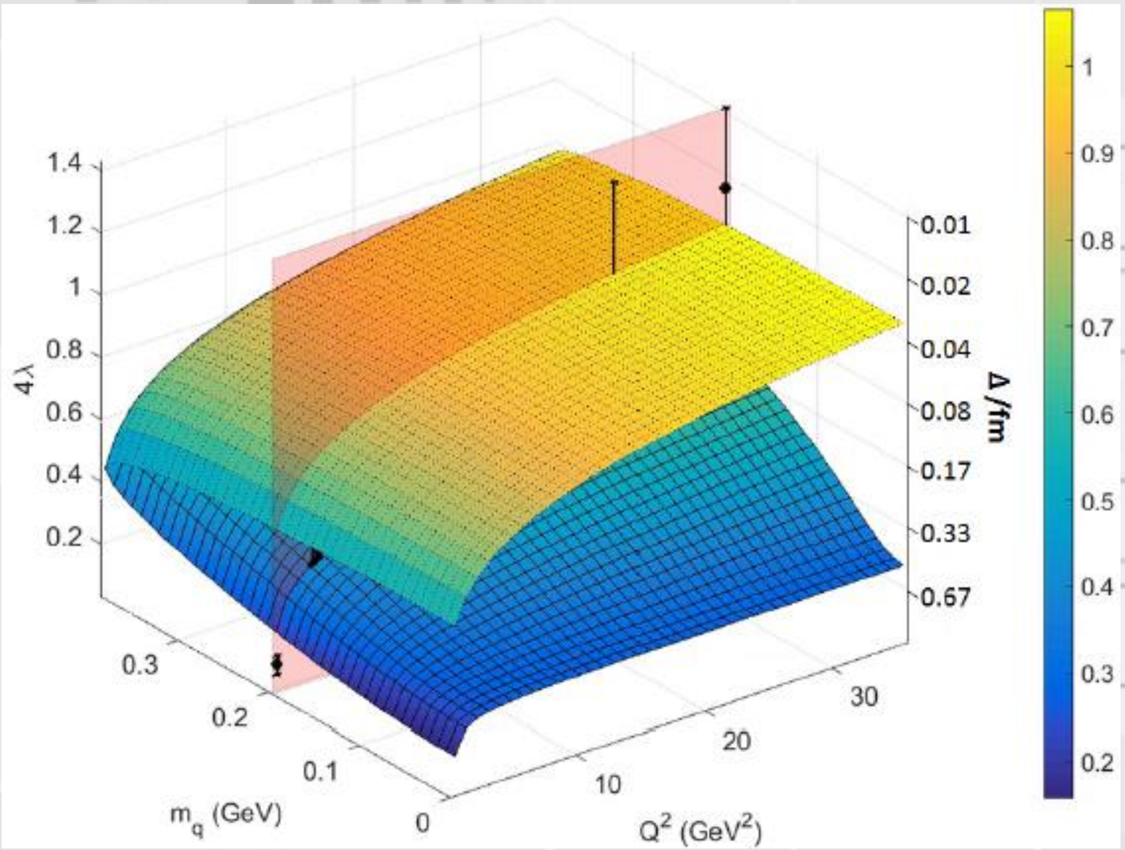
u/d-quark dropped in Proton

- electro/photoproduction $\gamma^* p \to \rho(760) p/Y$



u/d-quark dropped in Proton

- electroproduction $\gamma^* p \to \rho(760) p/Y$



$\delta \leftrightarrow 4\lambda$

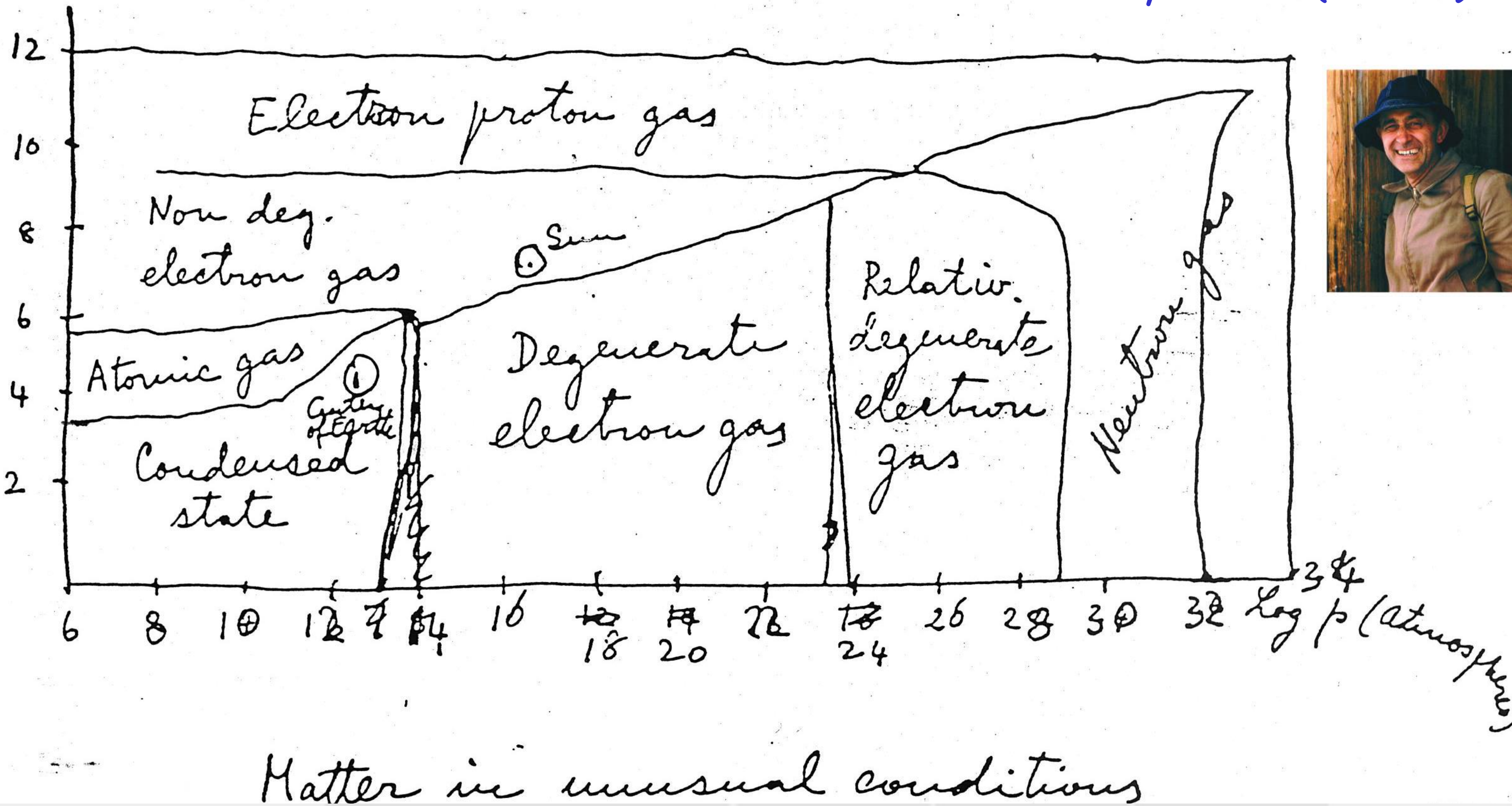
- inter-play of scales - constituent u/d-quark mass

↳ cold QCD @ eIC

Hot QCD

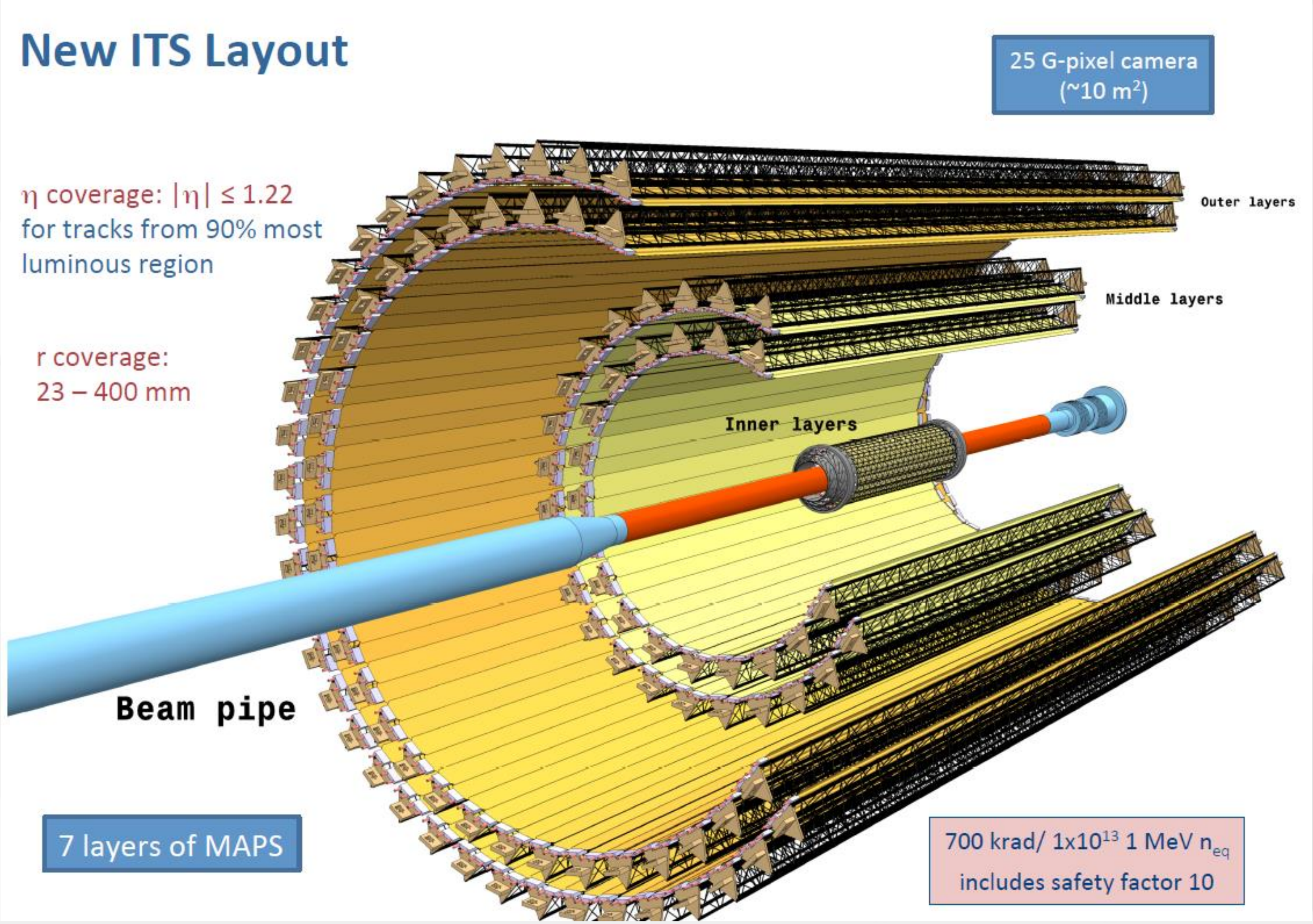
- the greats are always also ahead of their time

E Fermi lecture notes on Thermodynamics (~1950)



ALICE LHC Run 3

- ALICE @ LHC → c and b acceptance + recoil topology → pQCD + bulk flow in QGP

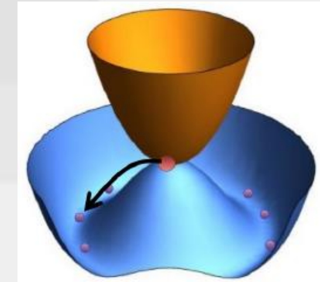


4. Horizon

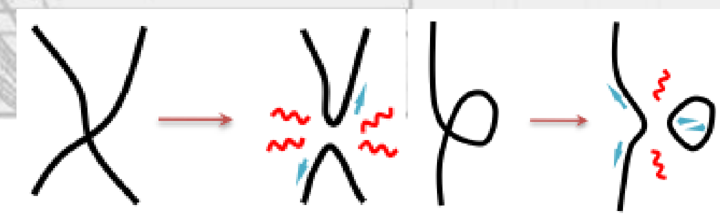
QCD meets Dark Matter ?

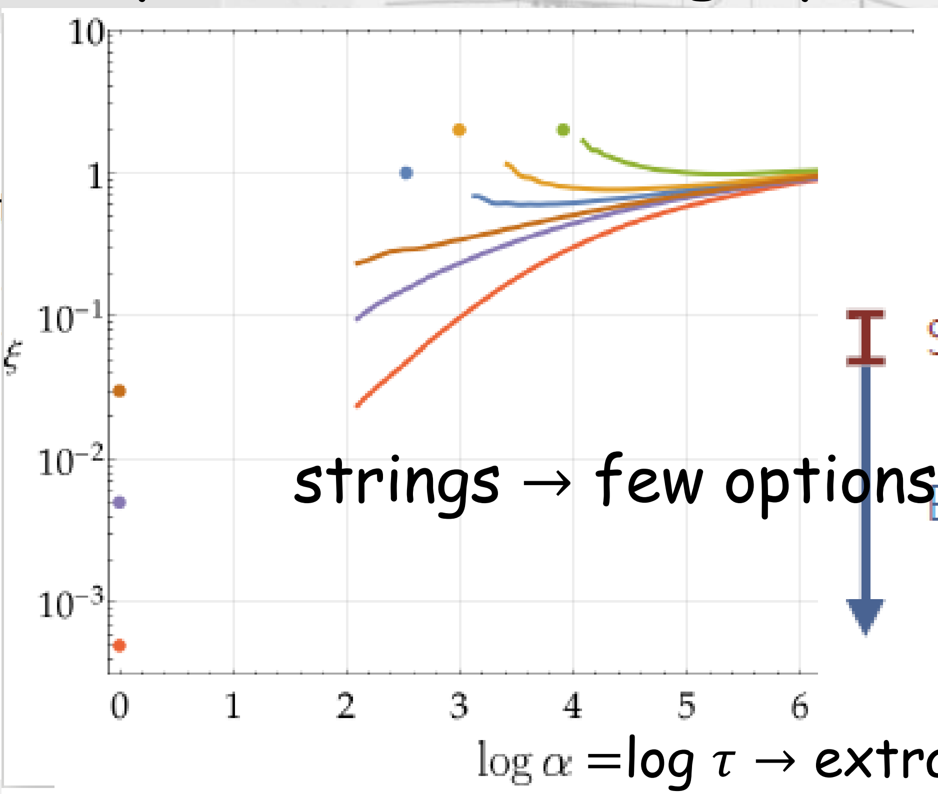
The Cockcroft Institute of Accelerator Science and Technology
Lancaster University

- chiral symmetry breaking ? Peccei Quinn
  - SSB $U(1) >$ inflation ← axion scalar field
  - low mass (≪ eV) axion scalar field
  - dark matter



- early Universe string dynamics





Infla
U(1
order

strings → few options

=log τ → extrapolation

Scale separation:
Simulation
10^3
Extrapolation
$\alpha \sim 10^{30}$

strings → scalar axions …
… + QGP +SSB = $\mathbf{1}_c$ hadron ?
visible ↔ invisible matter !
probe chirality ?

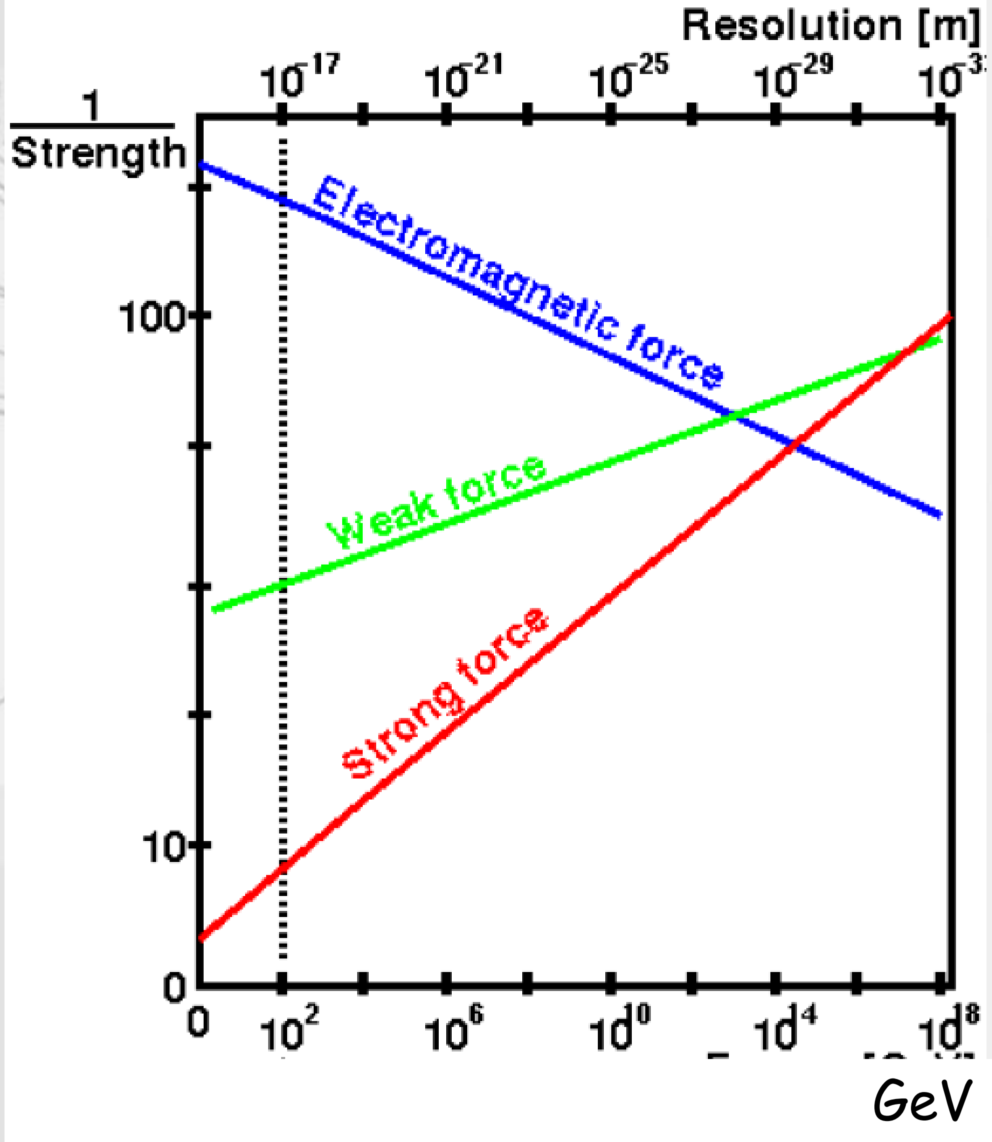
Hardy
Ghordetto
Villadoo

Unification QCD + EW ?

- unification:
  QCD + GSW ?
  - SSB ⟶ (phase equlibrium?) chiral symmetry ?
  - QCD portal to dark matter ?

➥ QCD is much more than just a Standard Model Conundrum

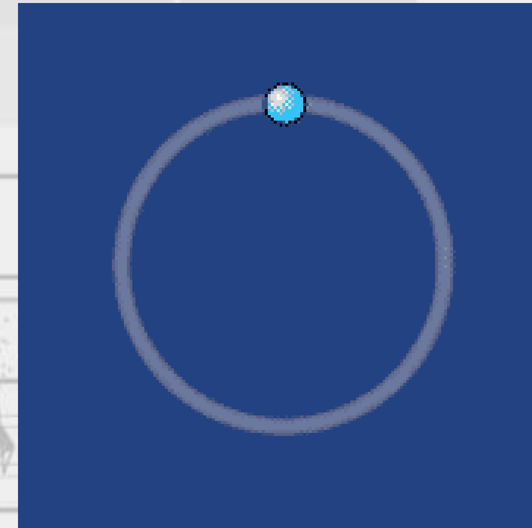
➥ new experiments *eA* and *AA* mandatory



Details in spares

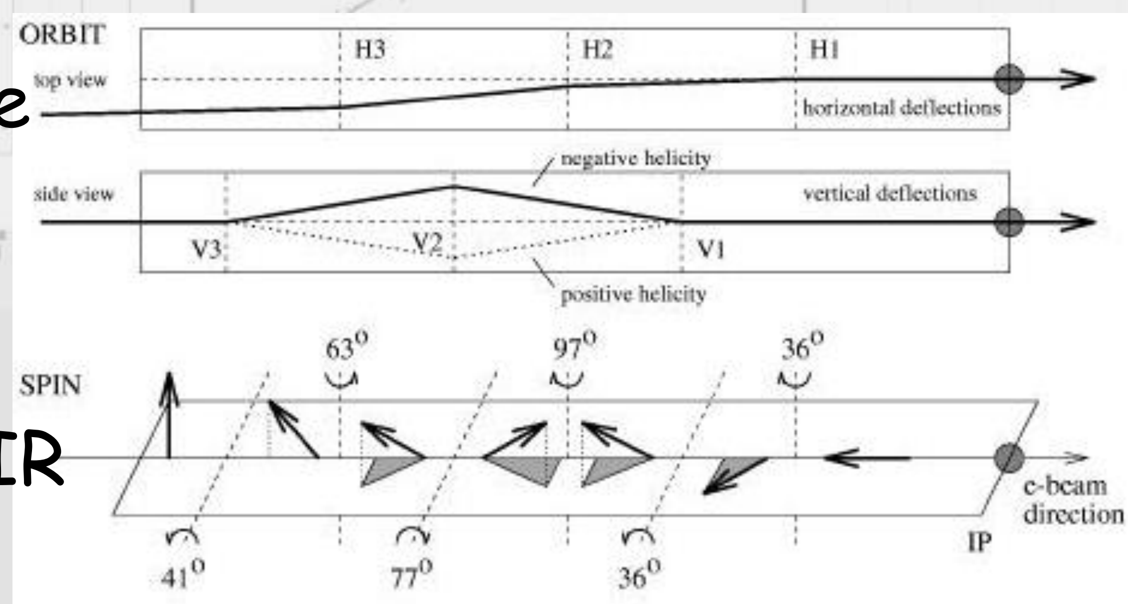
Precision: Rotating Spin

- stored e radiates
  $e \rightarrow e_T$ Sokolov-Ternov
  transversely polarised e
  synchrotron radiation



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

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



Barber, Steffen (DESY)

Rotating Spin

- stored e radiates
  $e \rightarrow e_T$ Sokolov-Ternov
  transversely polarised e
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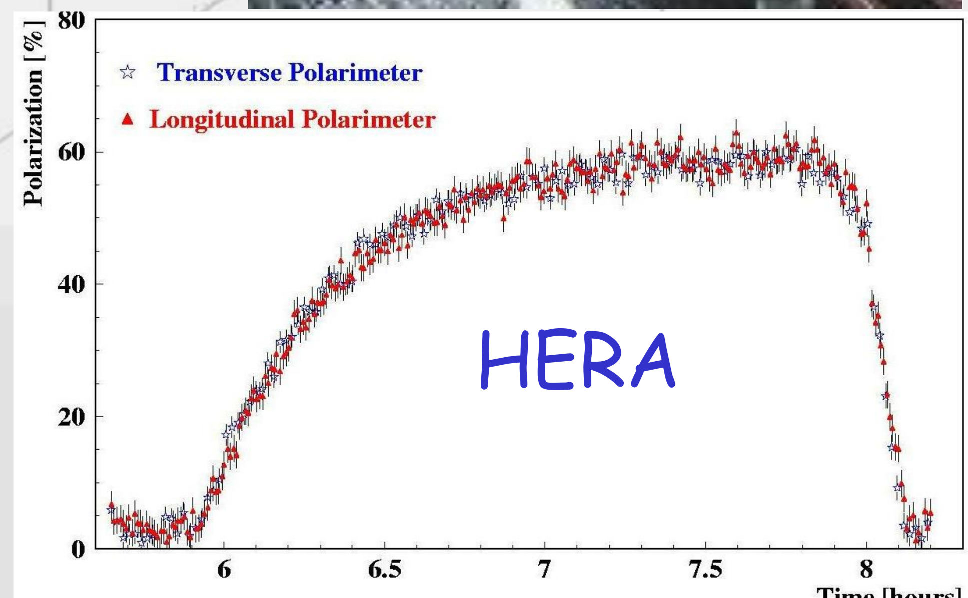
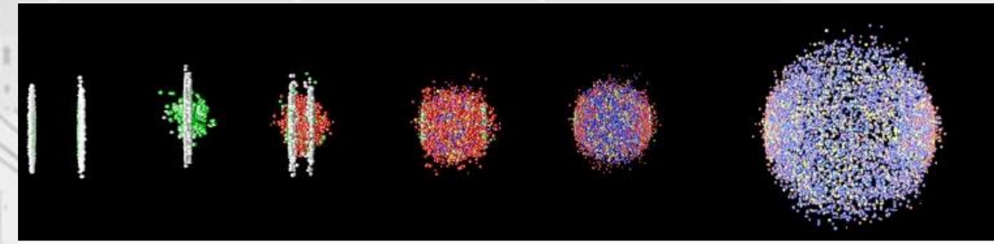


Barber, Steffen (DESY)

Heavy Ion Centrality

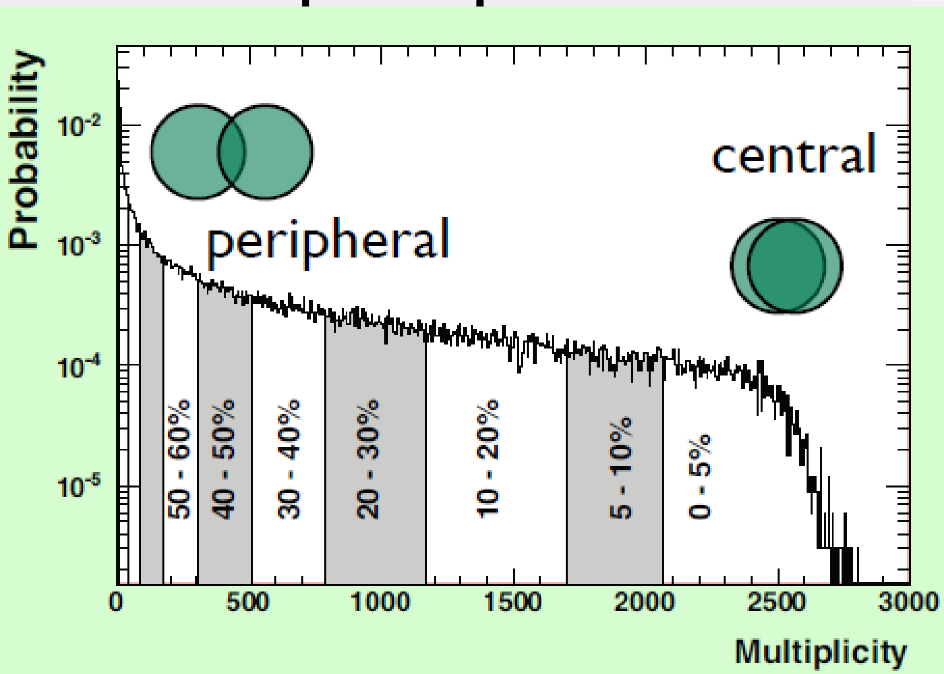
- hot → high energy heavy ion collisions
  FT @ CERN
  RHIC @ BNL
  ALICE @ CERN LHC
- "centrality" %
  = impact parameter ***b***

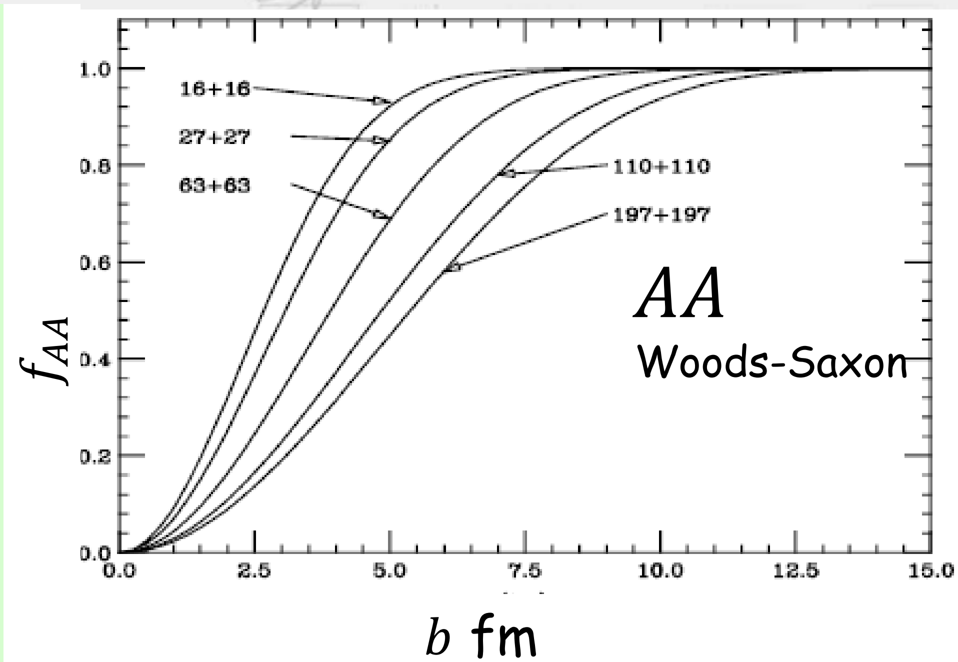


Thermalization (equilibrium established)

Expansion and *cooling*

Chemical and kinetic *freezout*





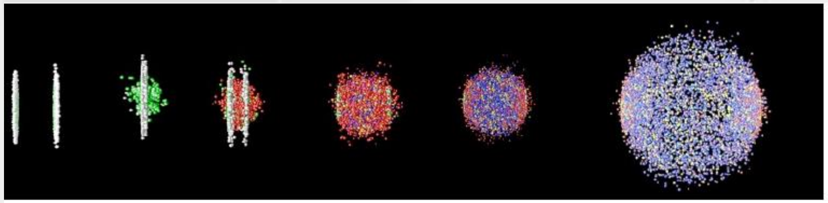
Nucleons in Nuclei

- **hot** → high energy heavy ion collisions
  "nuclear modification factor"

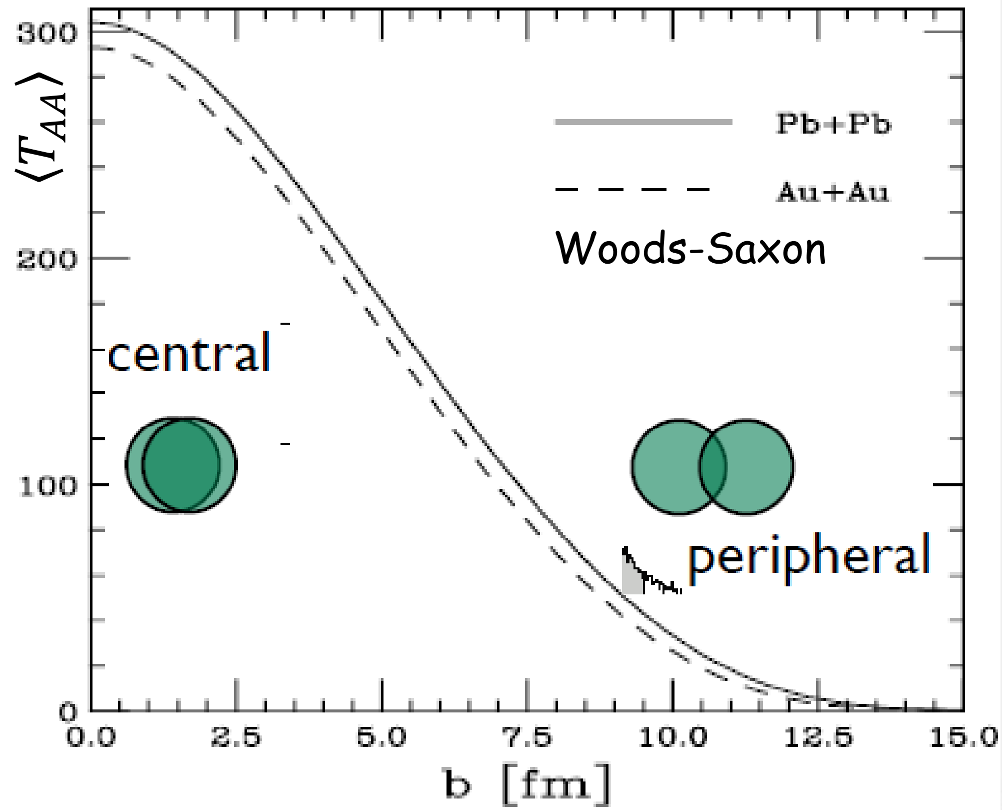
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$

- "nuclear overlap" $\langle T_{AA}\rangle$

$$\langle N_{coll}\rangle = \langle T_{AA}\rangle\, \sigma_{inel}^{NN}$$

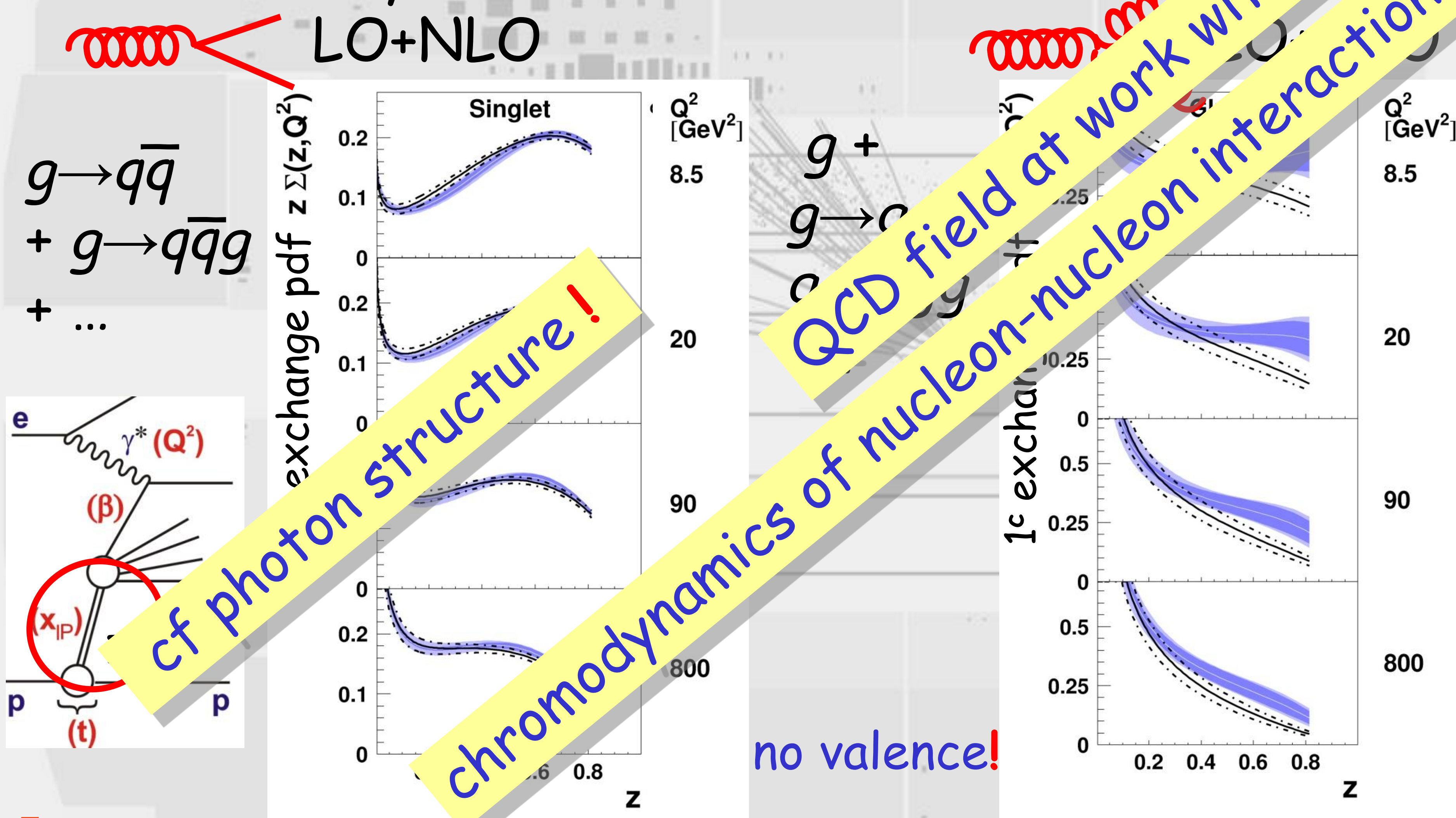


Thermalization (equilibrium established) | Expansion and cooling | Chemical and kinetic freezout



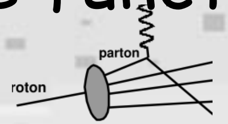
Colour Interaction Dynamics

- the colour dynamics of the nucleon interac...

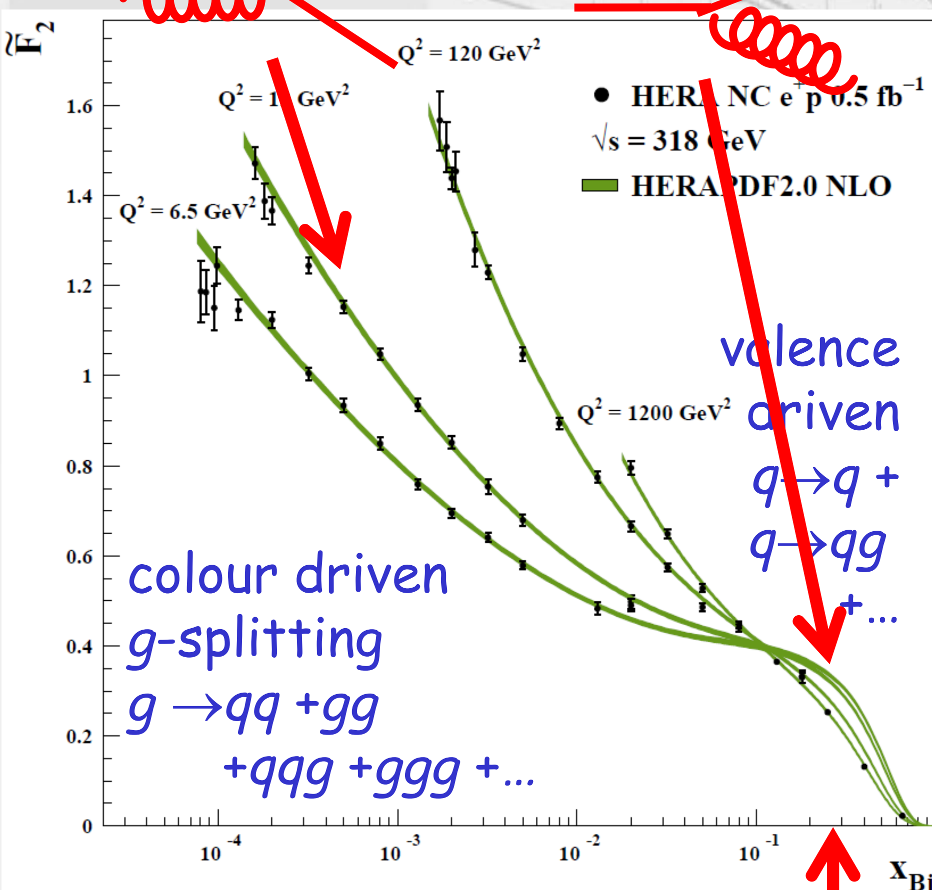


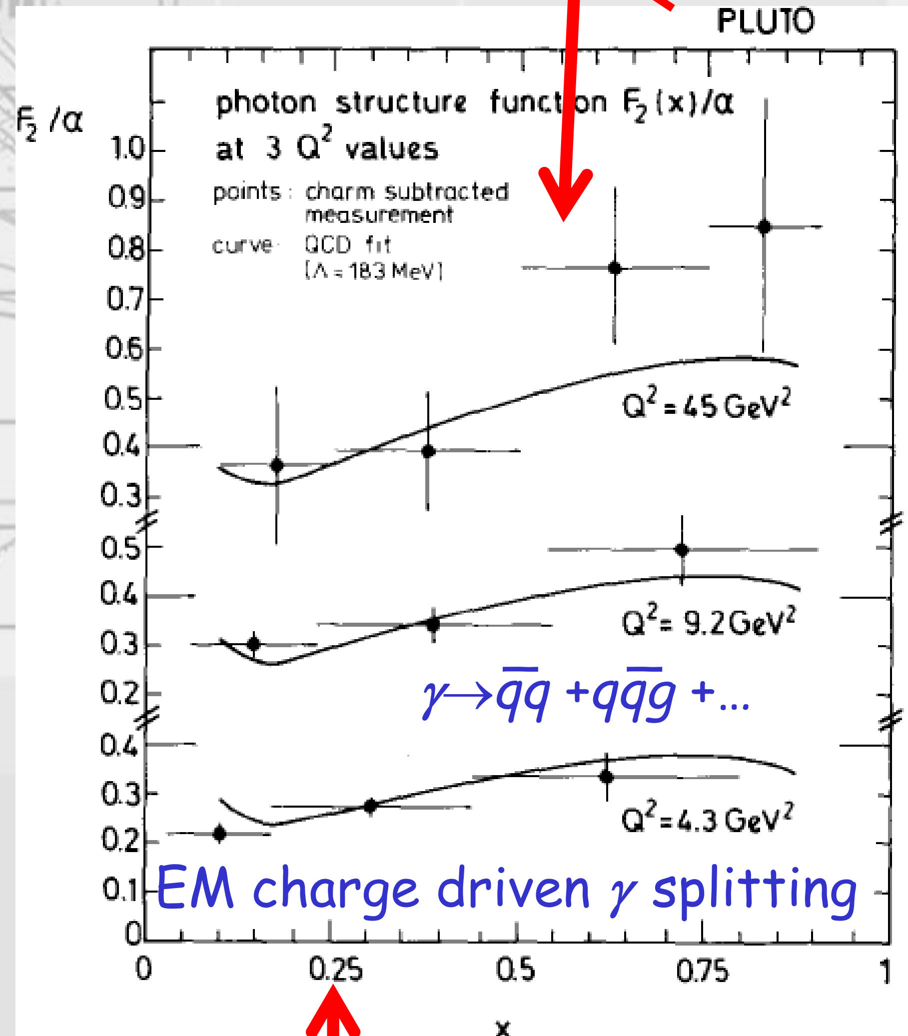
↳ "hard" (~70%) g with $g \to gg$ and $g \to q\bar{q}$ splitting

Hadron and Photon Structure

- structure functions $F_2(x,Q^2)$ and $F_2^\gamma(x,Q^2)$
  - hadron  + QCD "γ-splitting" + QCD

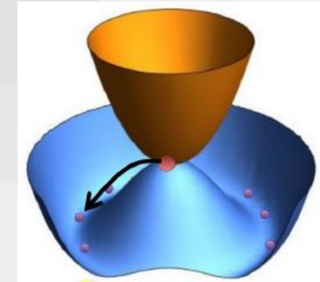
"g-splitting" "q-splitting"



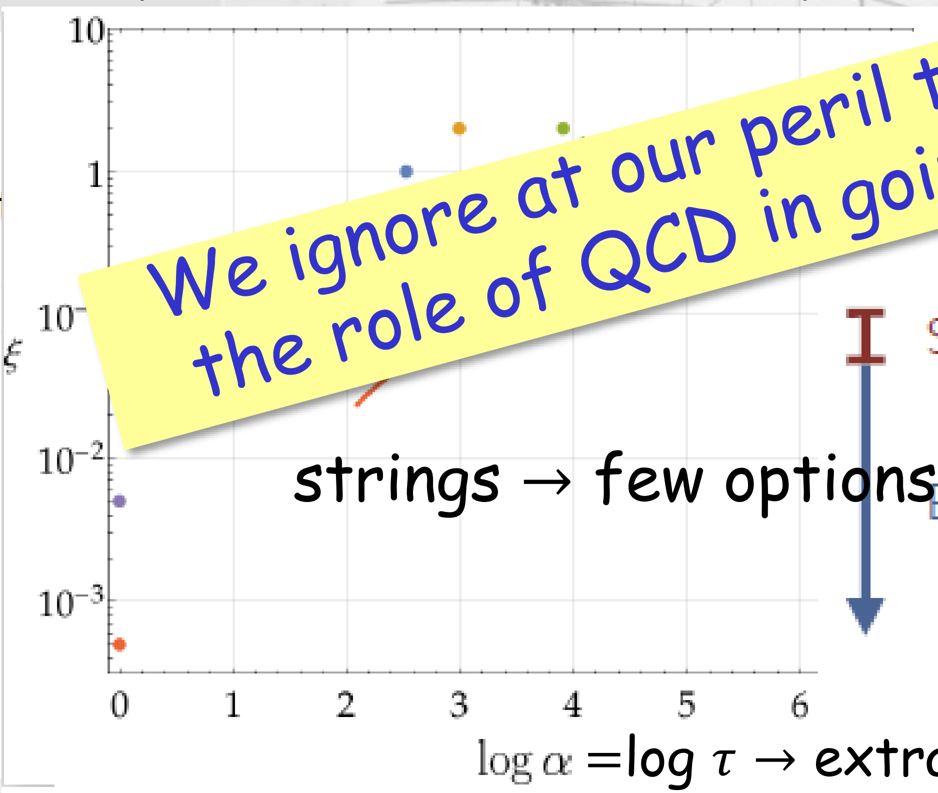


QCD meets Dark Matter ?

- chiral symmetry breaking ? **Peccei Quinn**
  - SSB $U(1) >$ inflation ← axion scalar field
  - low mass (≪ eV) axion scalar field
  - dark matter



- early Universe string dynamics



order

We ignore at our peril the importance of the role of QCD in going beyond the SM

strings → few options

strings → scalar axions …

… + QGP +SSB = $\mathbf{1}_c$ hadron ?

visible ↔ invisible matter !

probe chirality ?

$\log \alpha = \log \tau$ → extrapolation

Hardy Ghordetto Villadoo

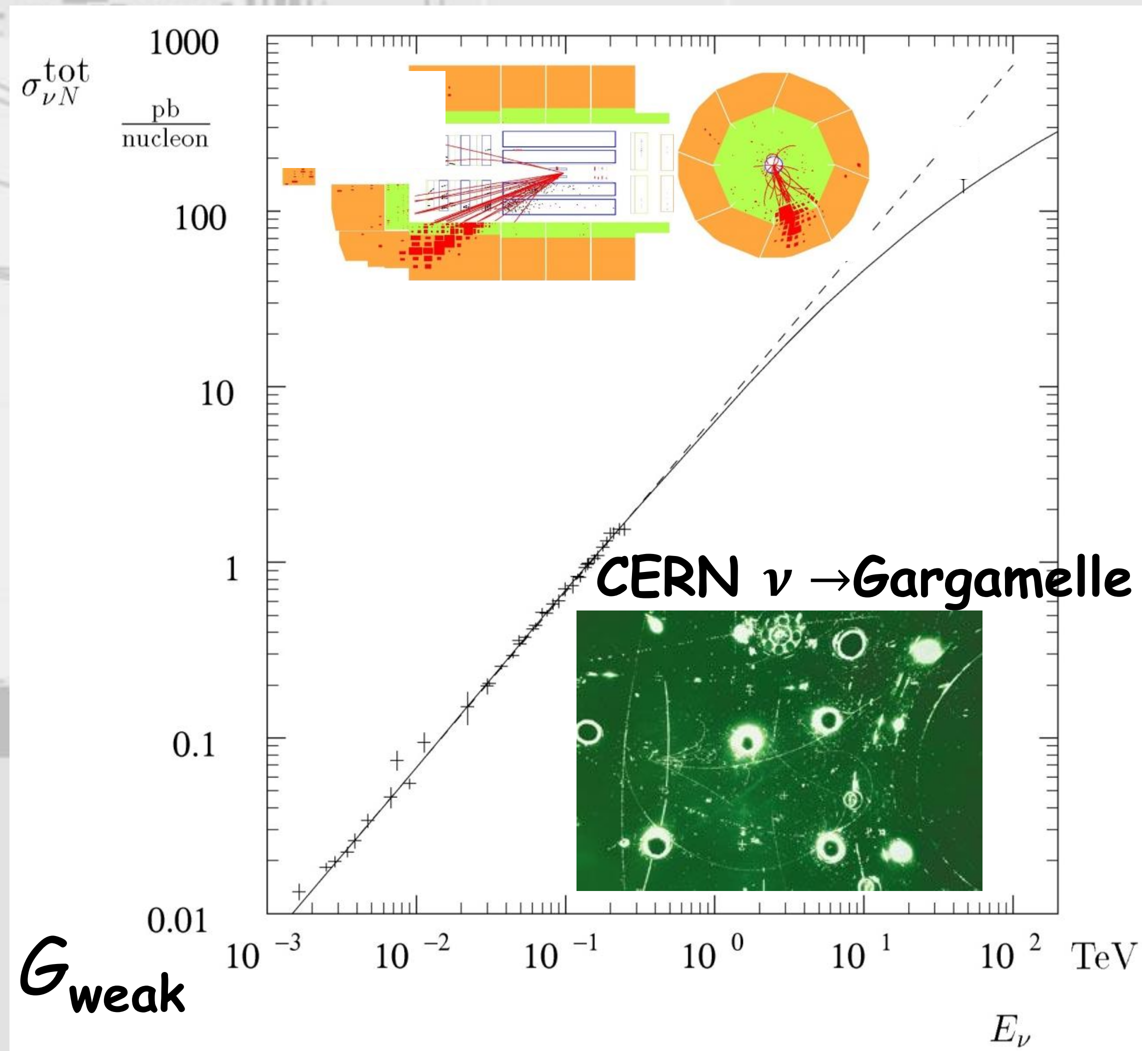
GSW Current

- then: point-like Fermi-β $\sigma^{\nu N}_{tot}(E_\nu) \propto E_\nu$
  1993: hint of weak unitarity = GSW unification ?

- from $ep \to \bar{\nu}X$

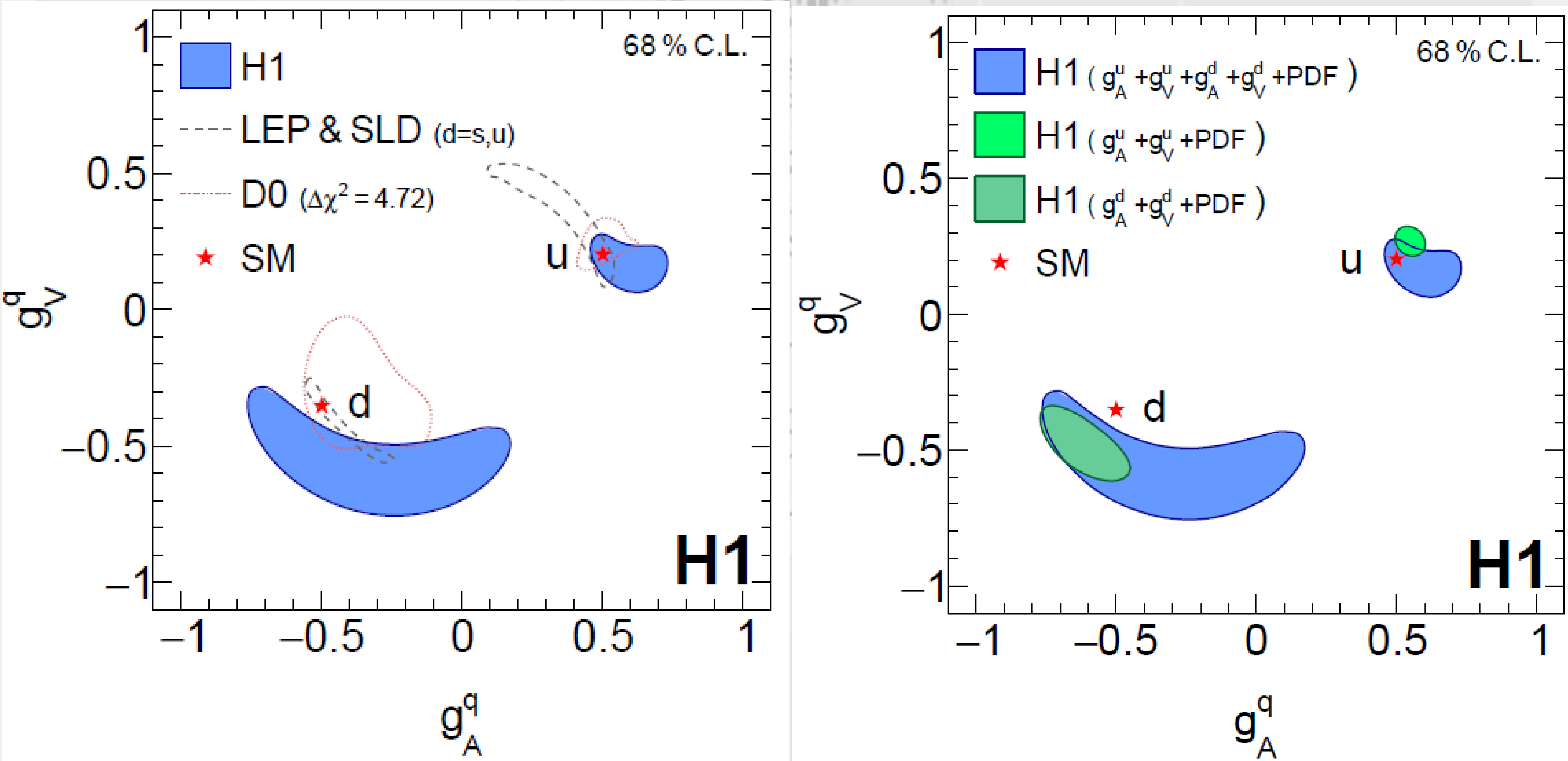
to $\nu p \to eX$

- IVB in CC
- EW probe
- structure of Fermi constant G_{weak}



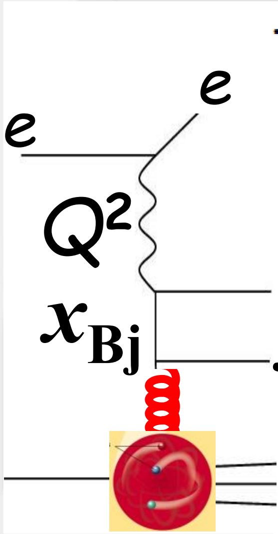
Current Quark GSW Couplings

- EW probe of cold hadronic matter
  $V + A$ current quark couplings: e pol$^{\underline{n}}$ $+\gamma^* Z$ int$^{\underline{frnce}}$

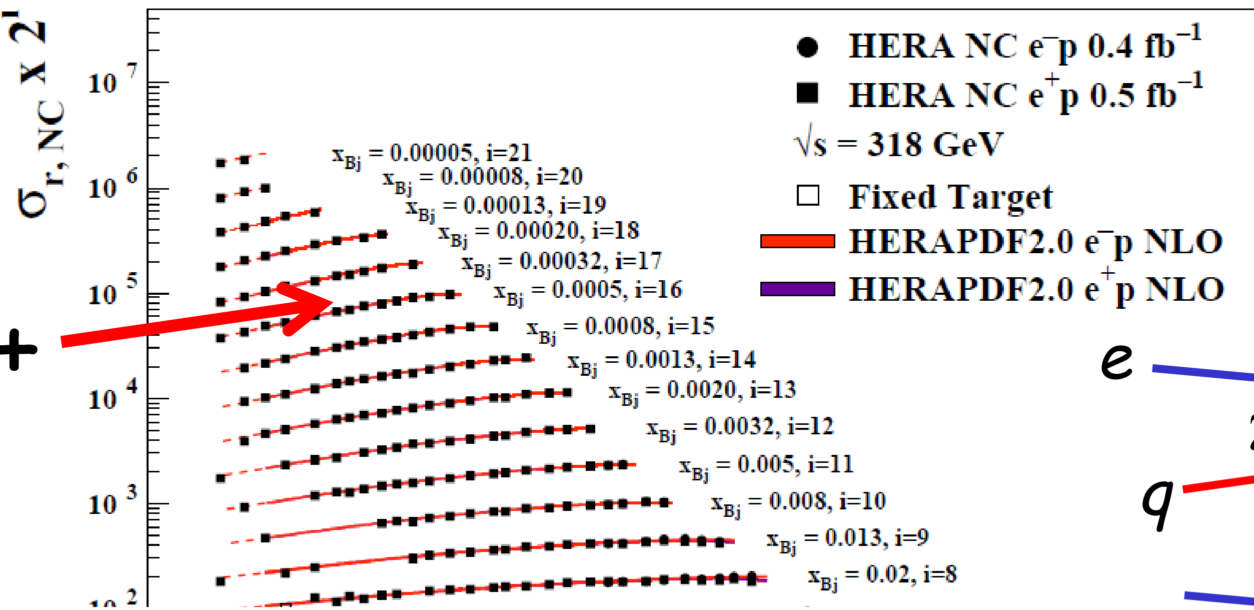


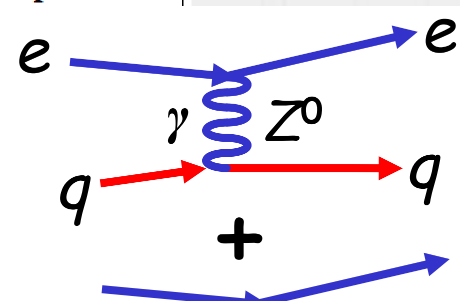
- space (HERA) and time (LEP+Tevatron)-like = SM

Constituents with GSW Currents



colour





$$\sigma^{\pm}_{r\mathrm{NC}}(x,Q^2) = \frac{Q^4 x}{2\pi\alpha^2_{\mathrm{em}} Y_+}\frac{\mathrm{d}^2\sigma^{e^\pm p}_{rNC}}{\mathrm{d}x\mathrm{d}Q^2} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_\mathrm{L} \mp \frac{Y_-}{Y_+} x\tilde{F}_3$$

$$\tilde{F}_2 = F_2 - \kappa_Z v_e F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_2^Z$$

$$\tilde{F}_\mathrm{L} = F_\mathrm{L} - \kappa_Z v_e F_\mathrm{L}^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2) F_\mathrm{L}^Z$$

$$x\tilde{F}_3 = -\kappa_Z a_e F_3^{\gamma Z} + 2\kappa_Z^2 v_e a_e F_\mathrm{L}^Z$$

$$\kappa_Z(Q^2) = \frac{1}{4\sin^2\theta_W \cos^2\theta_W}\frac{Q^2}{Q^2+M_Z^2}$$

$$y = \frac{\gamma\cdot p}{e\cdot p} \quad x = \frac{Q^2}{\gamma\cdot p} \quad Y_\pm = 1 \pm (1-y)^2$$

$\tilde{F}_{2,\mathrm{L},3}$, $W^{\pm}_{2,\mathrm{L},3}$ $\leftrightarrow$ parton density

Colour Driven

- precision $\sigma_{\mathrm{r}}^{ep\mathrm{NC}}(x, Q^2)$: quarks in quantum field quarks and gluons in chromodynamics

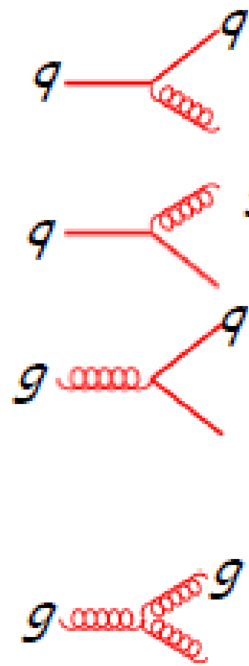
splitting functions

$$P_{qq} = \frac{4}{3}\left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\delta(1-x)\right] + o(\alpha_s) \rightarrow \frac{4}{3}\mathrm{d}x\frac{\mathrm{d}t}{t}$$

$$P_{gq} = \frac{4}{3}\frac{1+(1-x)^2}{x} + o(\alpha_s) \rightarrow \frac{4}{3}\frac{\mathrm{d}x}{x}\frac{\mathrm{d}t}{t}$$

$$P_{qg} = \frac{1}{2}\left[x^2 + (1-x)^2\right] + o(\alpha_s) \rightarrow \frac{1}{2}\mathrm{d}x\frac{\mathrm{d}t}{t}$$

$$P_{gg} = 6\left[\frac{x}{(1-x)_+} + \frac{1-x}{x} + x(1-x)\right] + \frac{33-2n_f}{6}\delta(1-x) + o(\alpha_s) \rightarrow 6\frac{\mathrm{d}x}{x}\frac{\mathrm{d}t}{t}$$



g→g dominates

$$x = \frac{parent_\mu \cdot reference^\mu}{daughter_\mu \cdot reference^\mu}$$

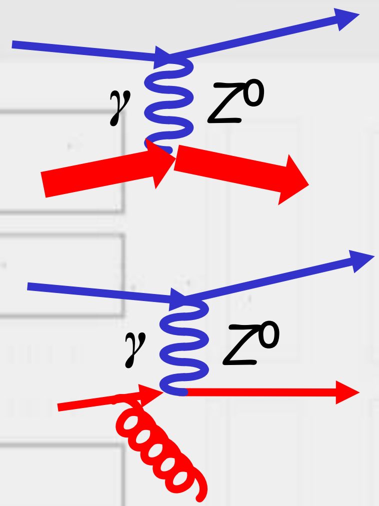
- parton densities $f_{p\rightarrow q,g}(x, Q^2) \propto \left(\ln Q^2 + \cdots\right)_x$

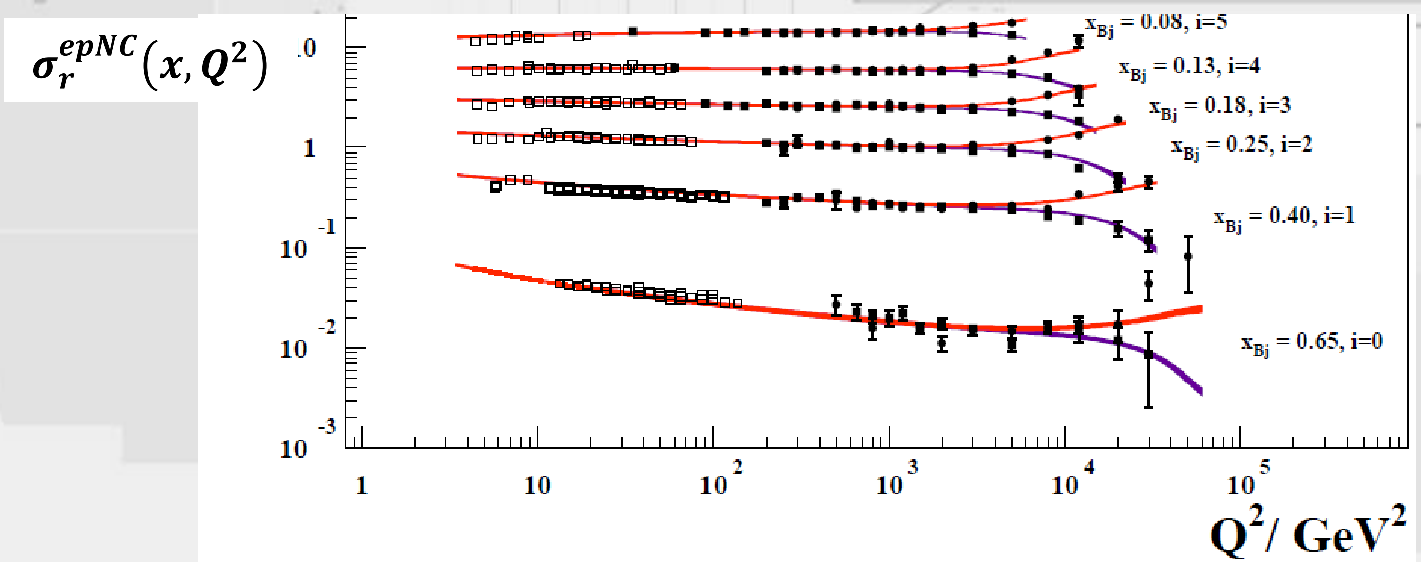
Valence Driven

- precision $\sigma_r^{epNC}(x, Q^2)$ at larger x :

  low Q^2: valence q presence, but not structure, resolved

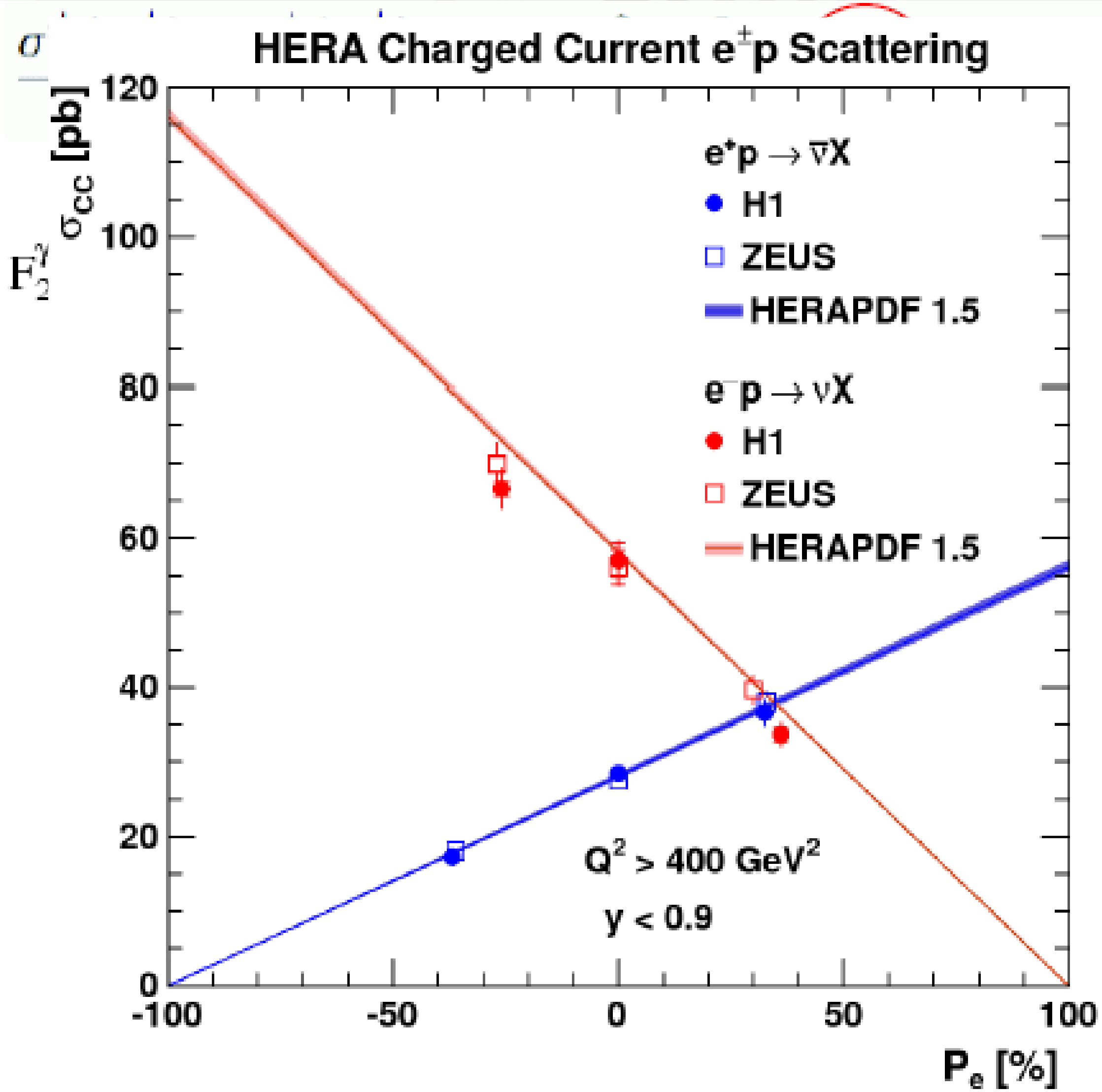
  larger Q^2: valence q "field structure" resolved, therefore "struck q" at lower x



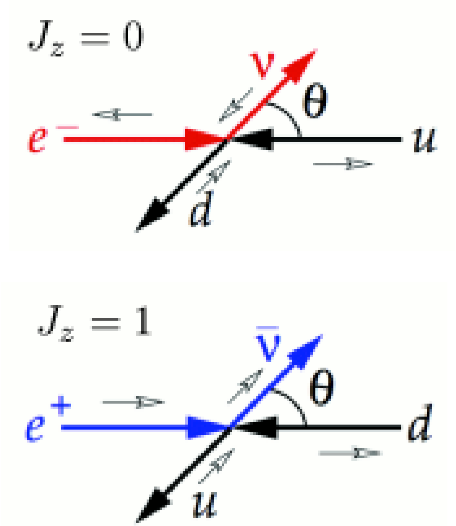


GSW Current → Proton Anti-matter

- in *ep* interaction chirality probes anti-matter in *p*

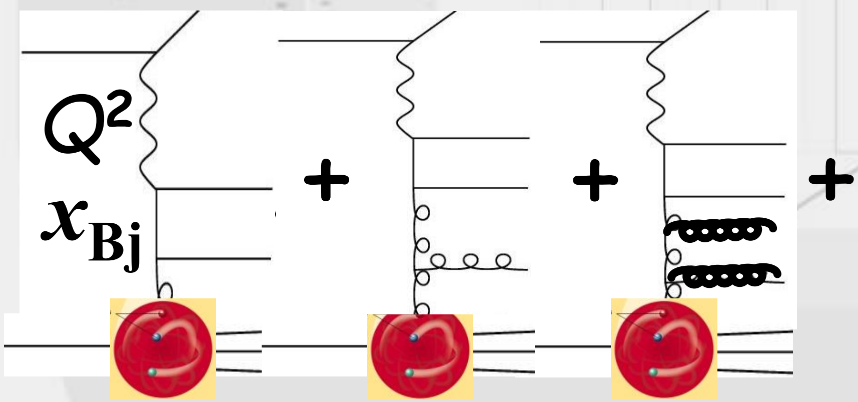


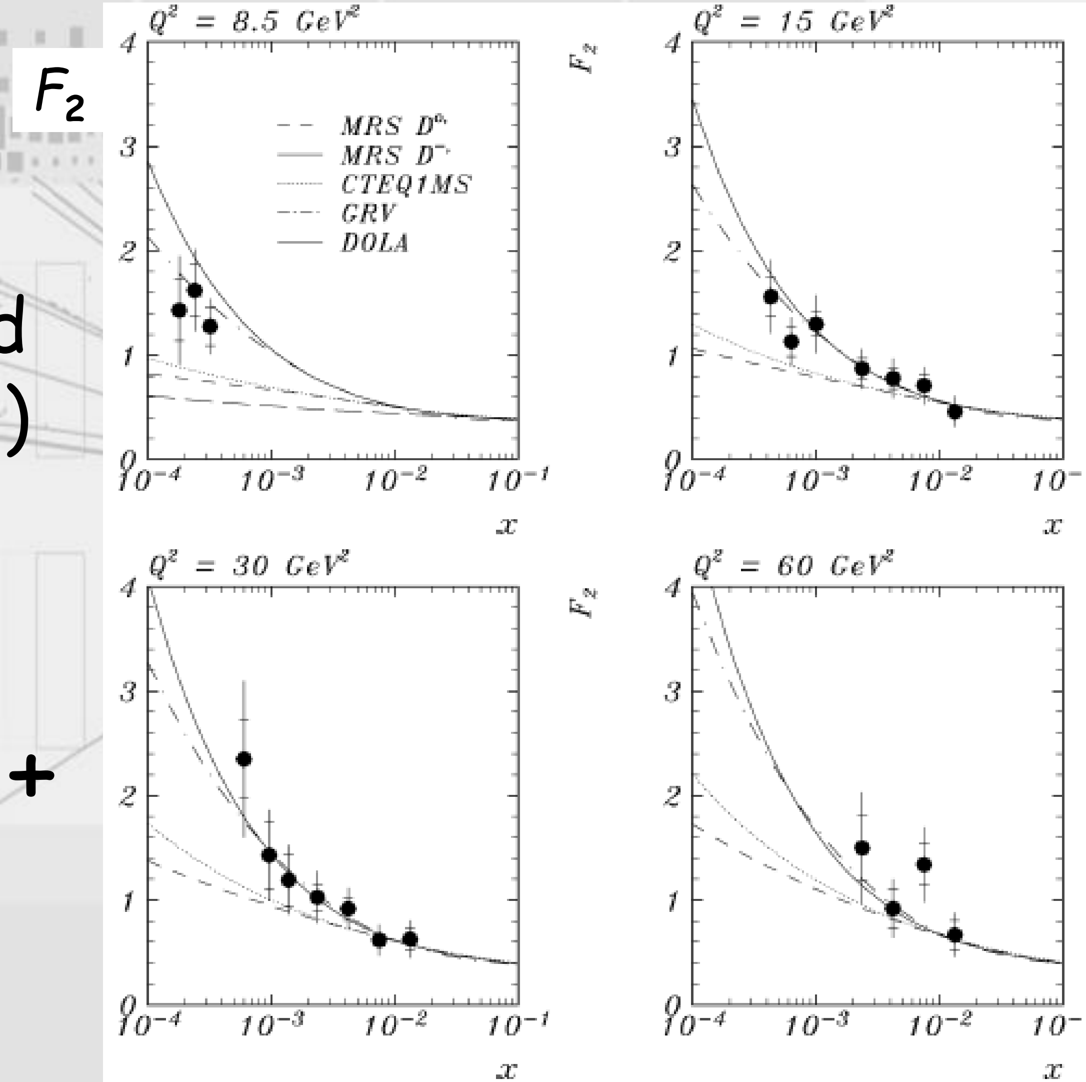
- Chiral structure of EW interactions probed
- No sign for right-handed currents



Colour Field Constituents

- 1993: rise to low x of proton structure function F_2
  - now: the gauge field theory QCD (gluons) **is** proton structure

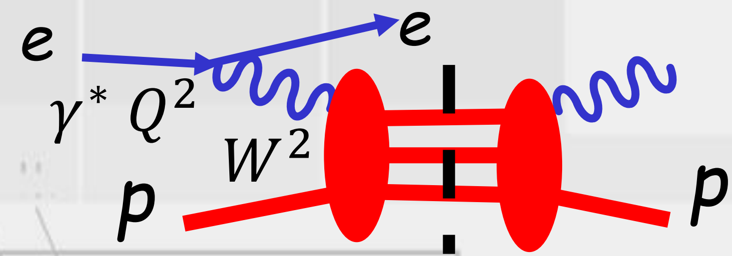




↳ discovery: **we** are (>99%) chromodynamic energy

Multi-gluons in F_2 at low-x

- data $ep \to eX$ and $\gamma^* p \to X$
  - total cross-section



$$\sigma_{\gamma^* p \to X}(Q^2, W^2) \xrightarrow[\substack{\text{large } W^2 \\ \text{low } x_{\text{Bj}}}]{} \frac{4\pi^2 \alpha_{\text{em}}}{Q^2} F_2(Q^2, x_{\text{Bj}})$$

$$\sigma_{\gamma^* p \to X}(Q^2, W^2) \xrightarrow[\substack{\text{optical} \\ \text{theorem}}]{} \frac{1}{W^2+Q^2} \operatorname{Im} A_{\gamma^* p \to \gamma^* p}(Q^2, W^2, t=0)$$

$$\propto \frac{1}{W^2+Q^2} (W^2 + Q^2)^{1+\lambda(t=0)}$$

↳ proton structure function

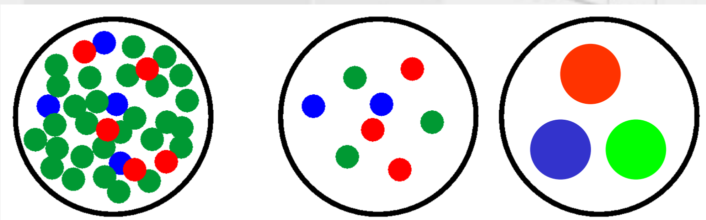
Regge asymptotic ↔ Lipatov multi-gluons

$$F_2(Q^2, x)_{\text{low } x} \propto \left[\left(\frac{1}{x}\right)^{\lambda}\right]_{Q^2} \sim \left[\left(\frac{W^2}{Q^2}\right)^{\lambda} \propto \sigma_{\text{tot}}^{\gamma^* p}(\sim W^2)\right]_{Q^2} \qquad x = \frac{\boldsymbol{Q^2}}{\boldsymbol{\gamma \cdot p}} = \frac{Q^2}{W^2+Q^2}$$

↳ "Regge intercept" $1 + \lambda$ from $[F_2(Q^2, x)]_{Q^2}$

Colour Conundrum

- F_2 @ low x
  - saturation in $F_2 \propto x^{-\lambda}$?

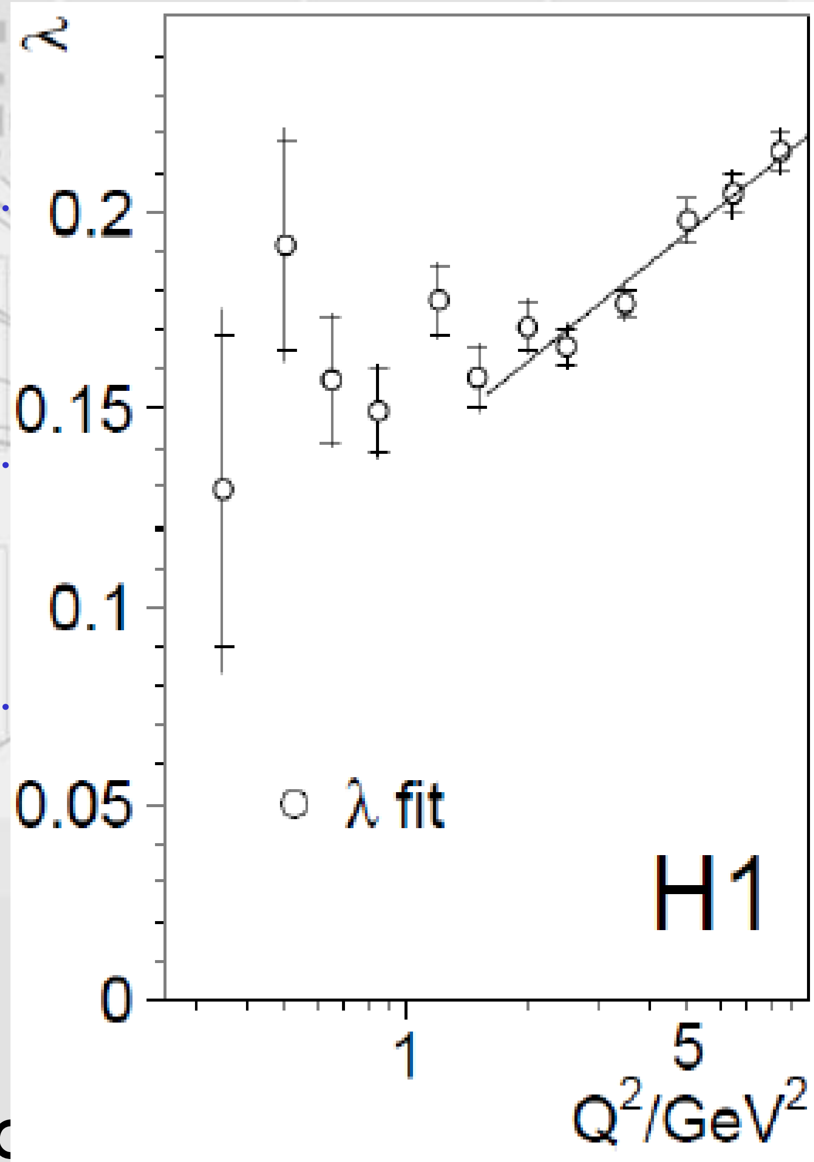


lower x higher x

$$\lambda = -(\partial \ln F_2 / \partial \ln x)_{Q^2}$$

smaller λ larger ?

- experiment → observation in measurements?
- unitarity in colour field



?

Colour Conundrum

- F_2 @ low x
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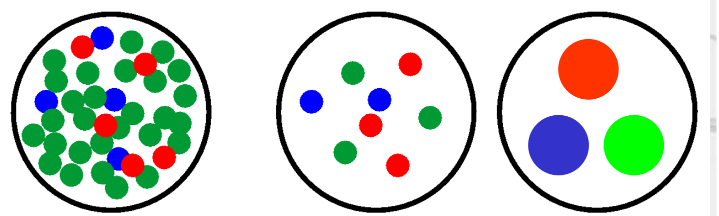

$$\lambda = -(\partial \ln F_2/\partial \ln x)_{Q^2}$$

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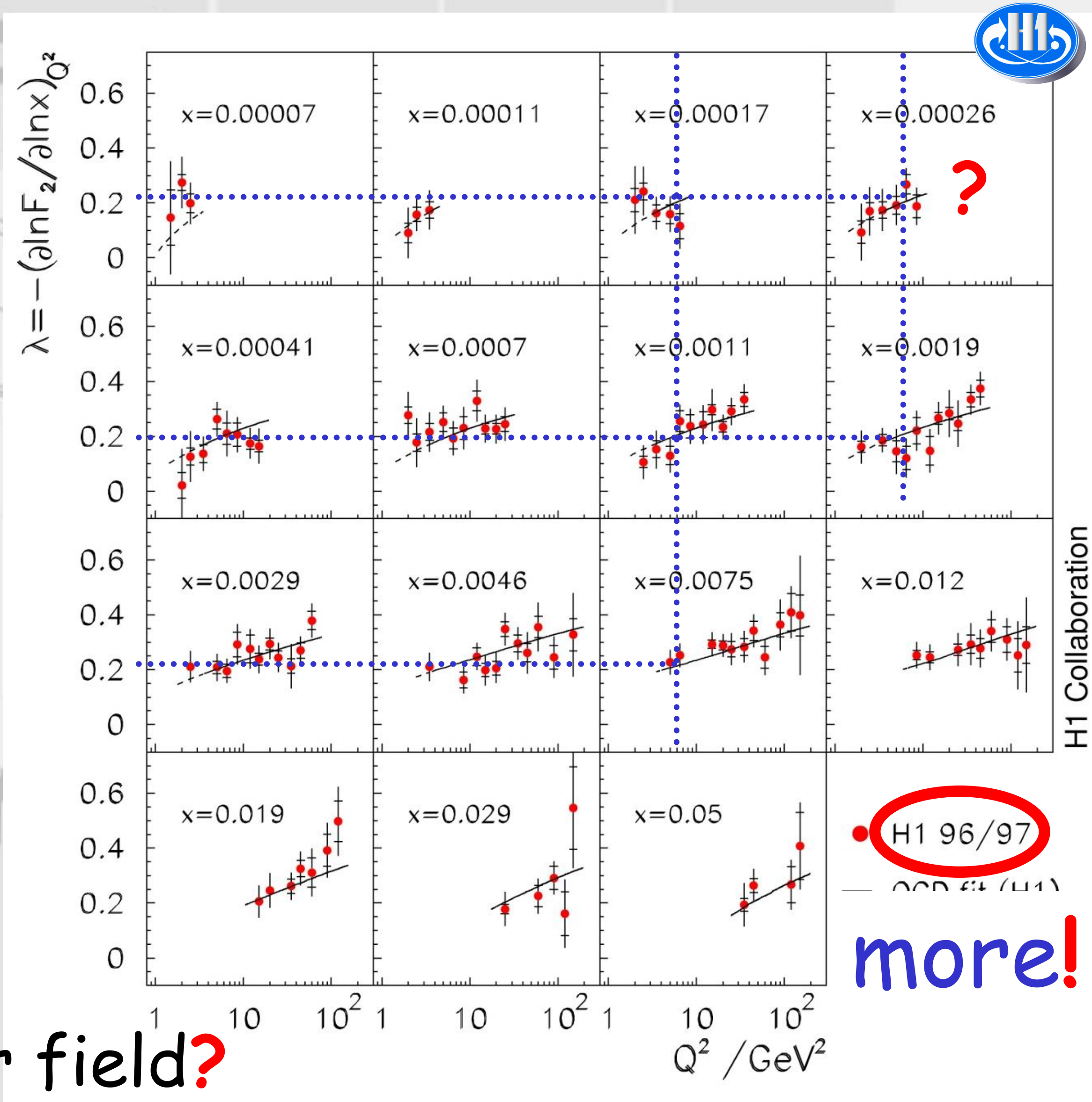


Colour Dynamics

- experiment $ep \to eXY$ with $Q^{-1} < 50$ am
  - p isolated in rapidity
  - forward hadrons $M_Y^2 < 2.5$ GeV² isolated in rapidity

} gap ➡ precisely defined x-section

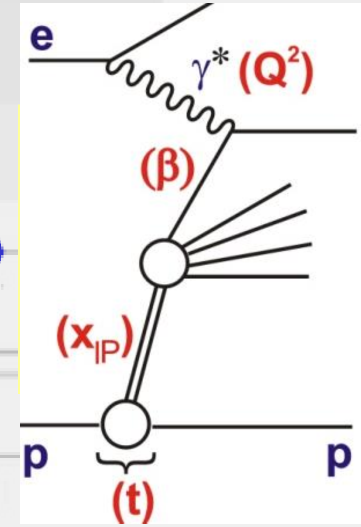
- unquestionably dramatic: void ← 920 GeV proton

Colour Dynamics

- experiment $ep \to eXY$ with $Q^{-1} < 50$ am
  - p isolated in rapidity
  - forward hadrons $M_Y^2 < 2.5$ GeV² isolated in rapidity

  } gap ➡

↳ probe hadronic interaction

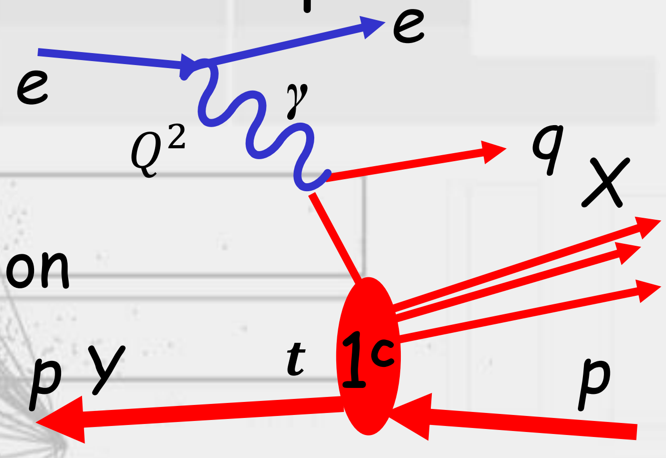


- unquestionably dramatic: void ← 920 GeV proton

Experiment

- high energy for precision "Rutherford" probe
  - deep ($Q^2 \gg m_p^2$) inelastic ($s \gg m_p^2$)
  - $ep \to e + X + p$
  - space-like factorisation

q from hadronic interaction



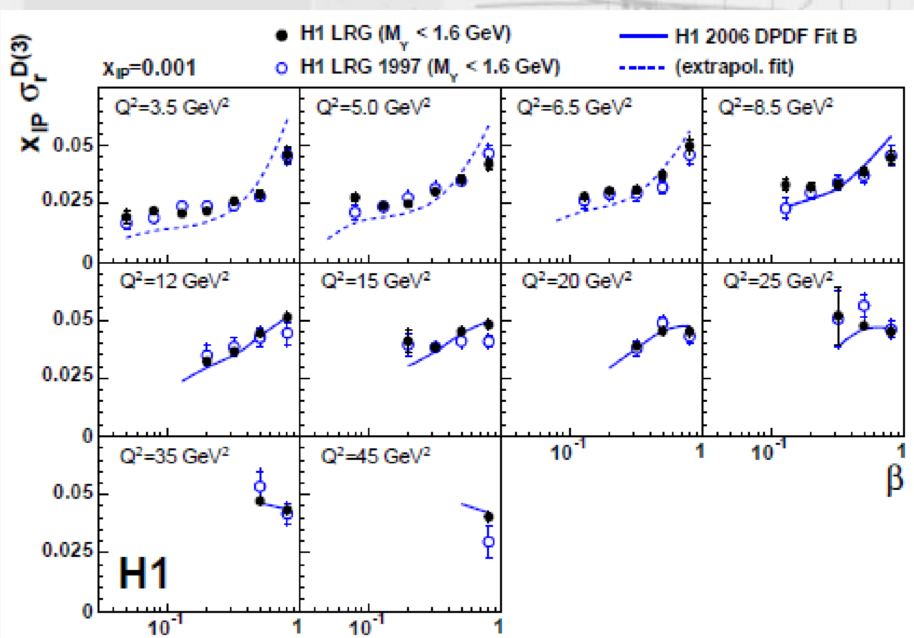
$$\sigma_r^{D(4)}(\beta, x_{IP},, t, Q^2) = \frac{Q^4 \beta}{2\pi\alpha_{em}^2 Y_+} \frac{d^2\sigma_r^{D(4)}}{d\beta dx_{IP} dt dQ^2} = F_2^{D(4)} - \frac{y^2}{Y_+} F_L^{D(4)}$$

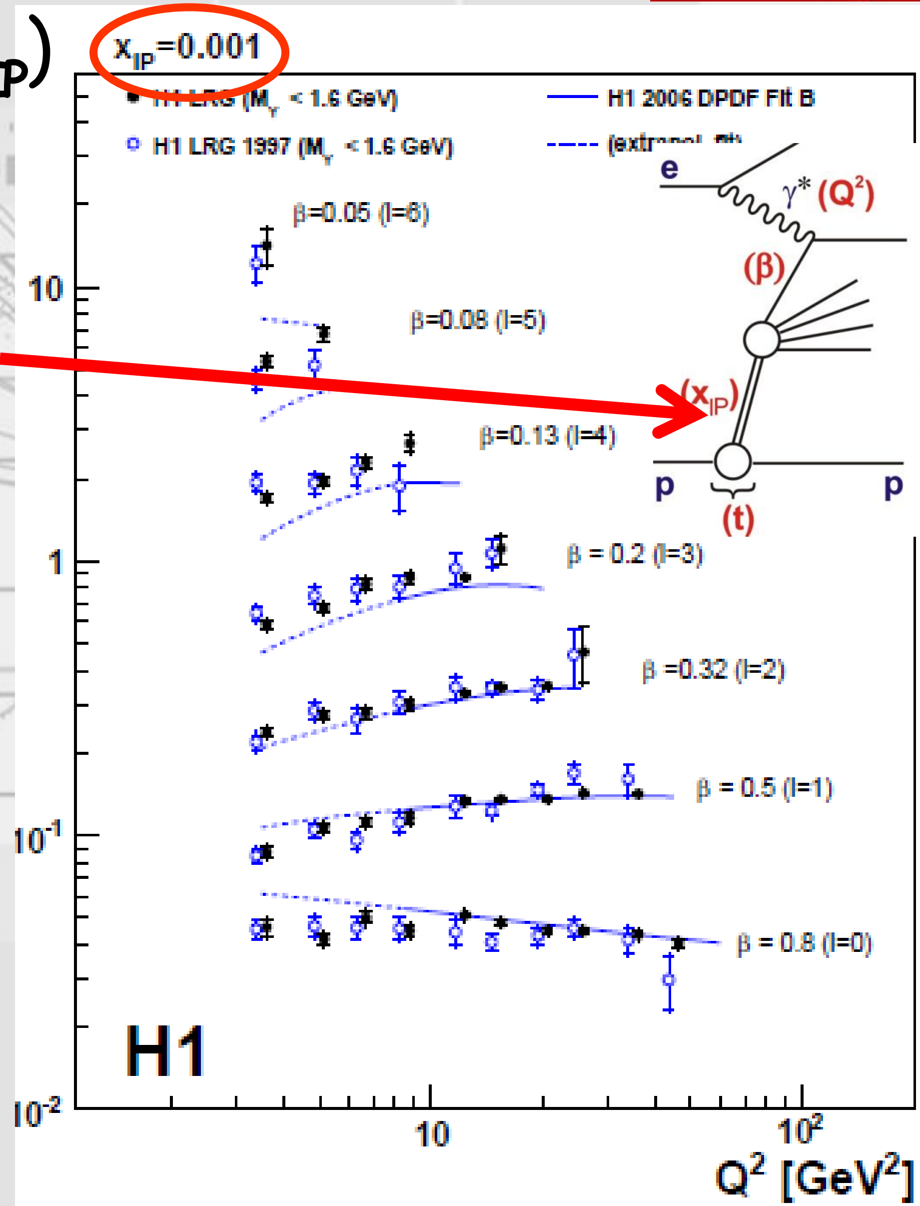
$F_2^{D(4)} \leftrightarrow$ diffractive parton density

- structure of high energy proton interaction = QCD composition of inter-nucleon force
- remnant in beam-pipe $\to$ rapidity gap

Colour Interaction Dynamics

- x-section $x_{I\!P}\sigma_r \sim F_2\,(\beta, Q^2, x_{I\!P})$
  - scaling violations → $1_f\ (q_s)$ QCD evolution
  - β dep$^{\underline{c}}$ → $g \rightarrow q\bar{q}$





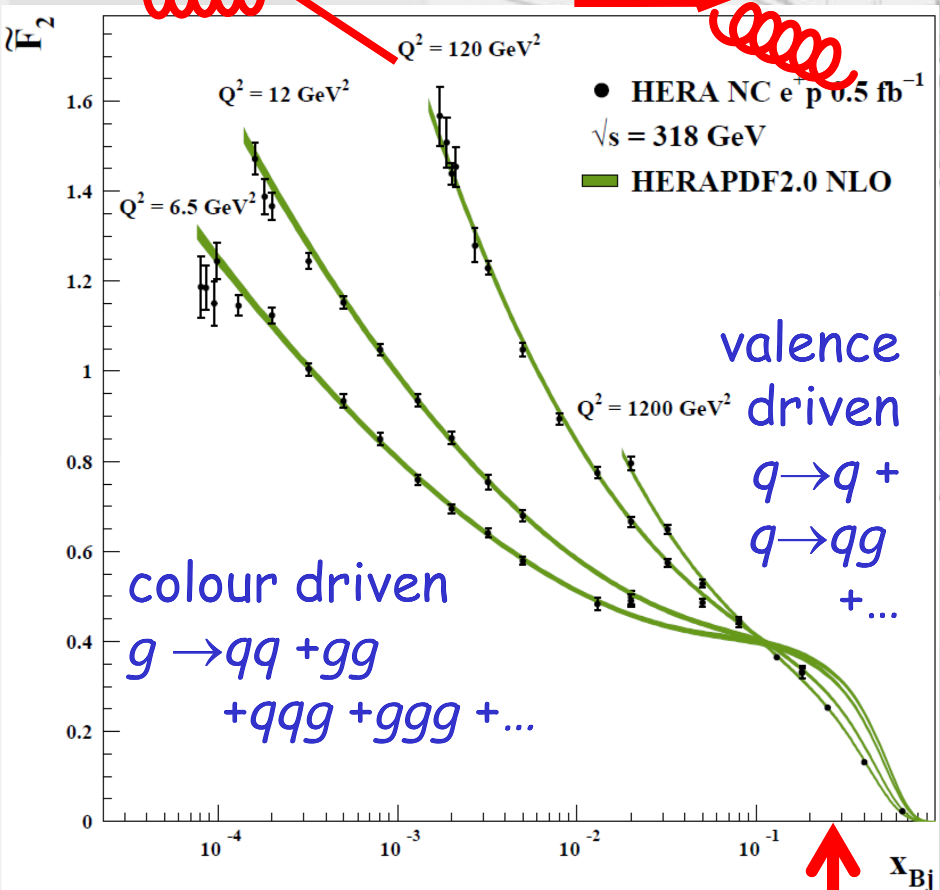
Hadronic Structure

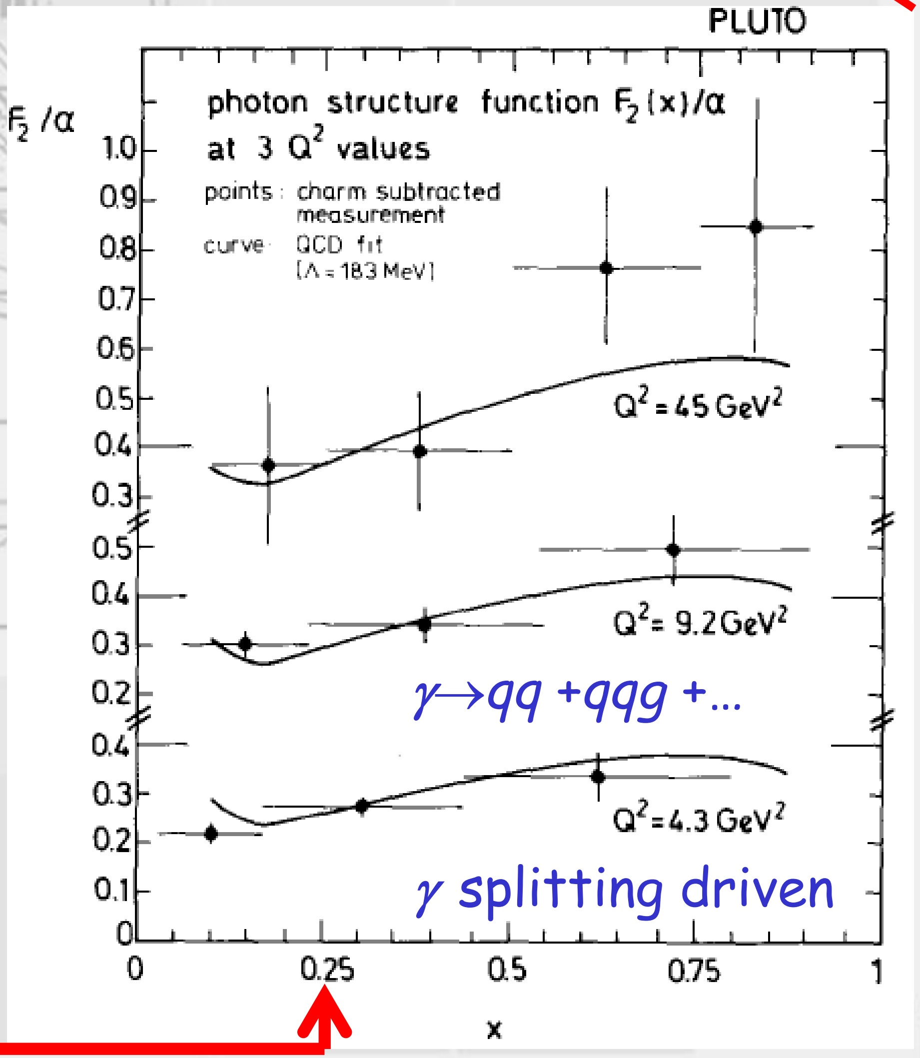
- structure function $F_2(x, Q^2)$
  - QCD and hadron

QFD field + QCD

"γ-splitting"

"g-splitting" "q-splitting"





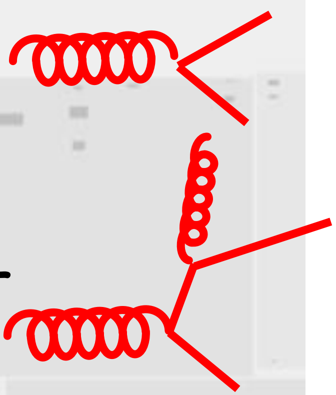
1_c Interaction Dynamics

- the colour dynamics of the nucleon interaction
  - NLO → 1^c colour singlet inelastic q interaction

$g \rightarrow q\bar{q}$

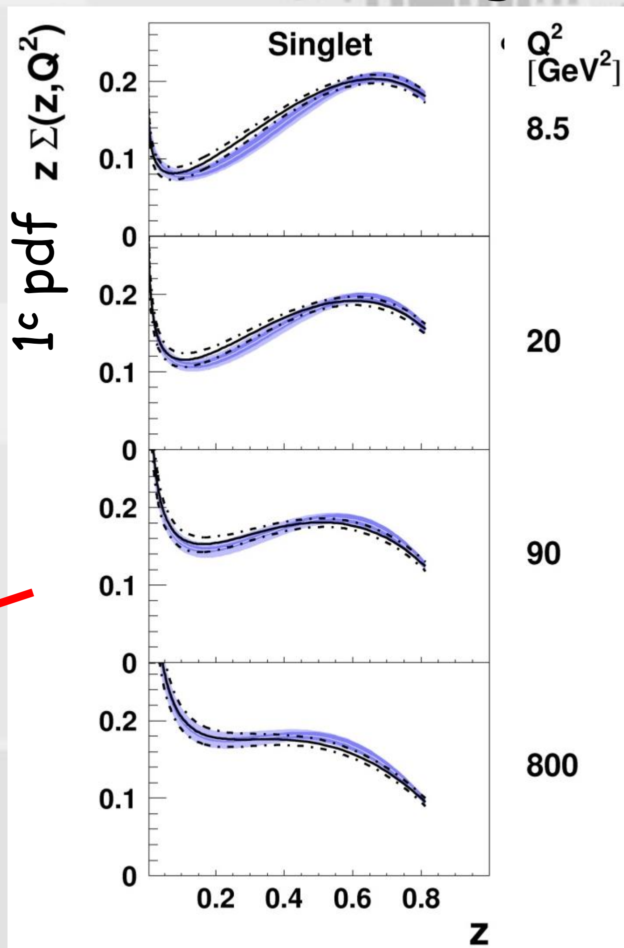
$+\ g \rightarrow q\bar{q}g$

$+\ \ldots$



$+$

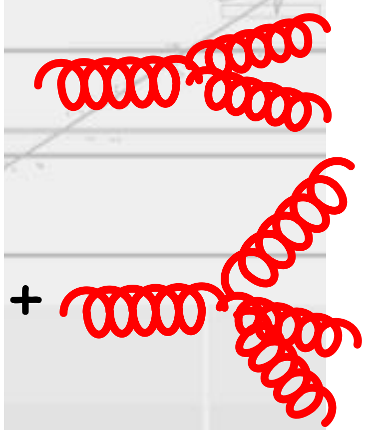
$+\ \ldots$



$g \rightarrow gg$

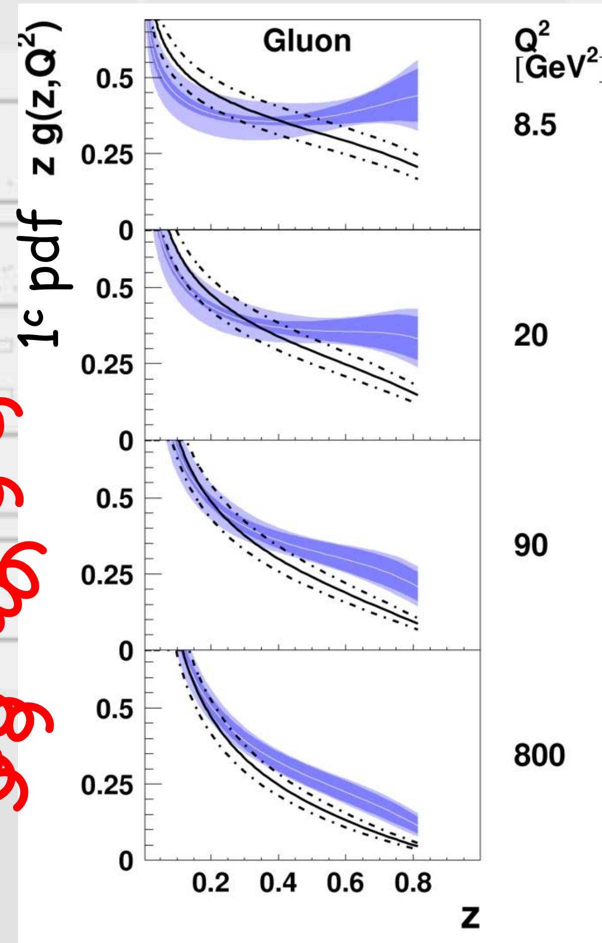
$+\ g \rightarrow ggg$

$+ \ldots$



$+$

$+\ \ldots$



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

1_c Interaction Dynamics

- the colour dynamics of the nucleon interac[tion]
  - NLO → 1^c colour singlet inelastic q int[eraction]

$g \to q\bar{q}$

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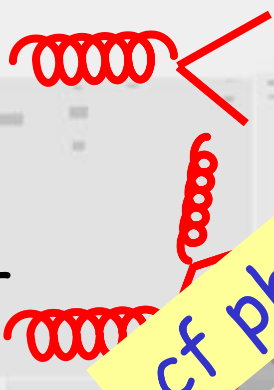
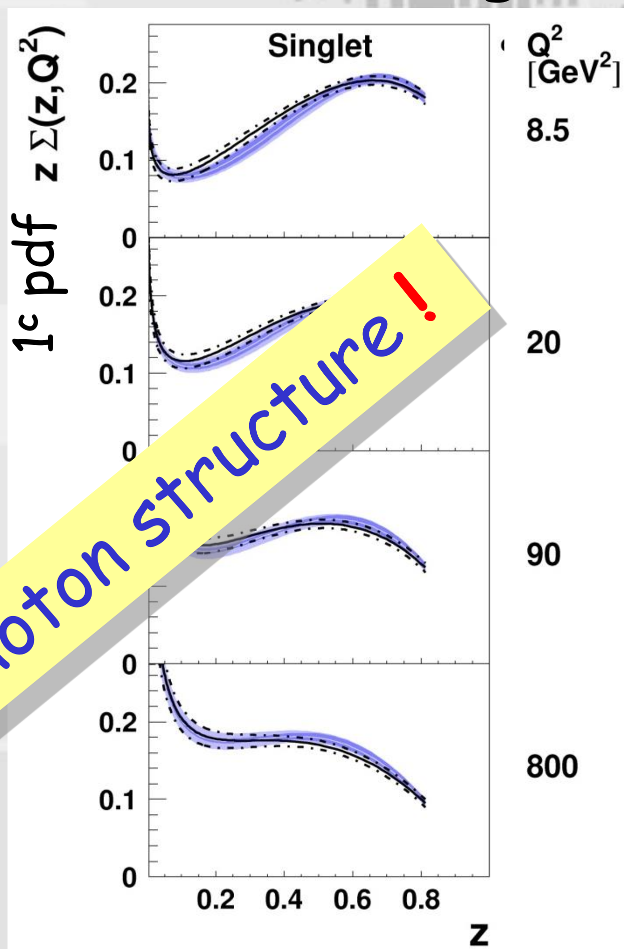


$+$

$+\ \ldots$

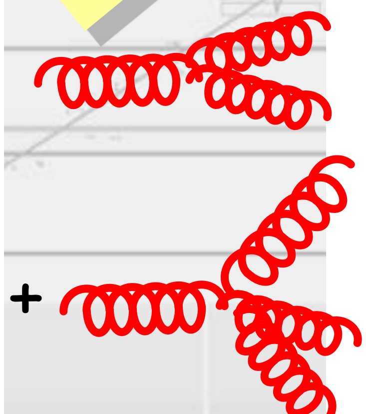


cf photon structure !

$g \to gg$

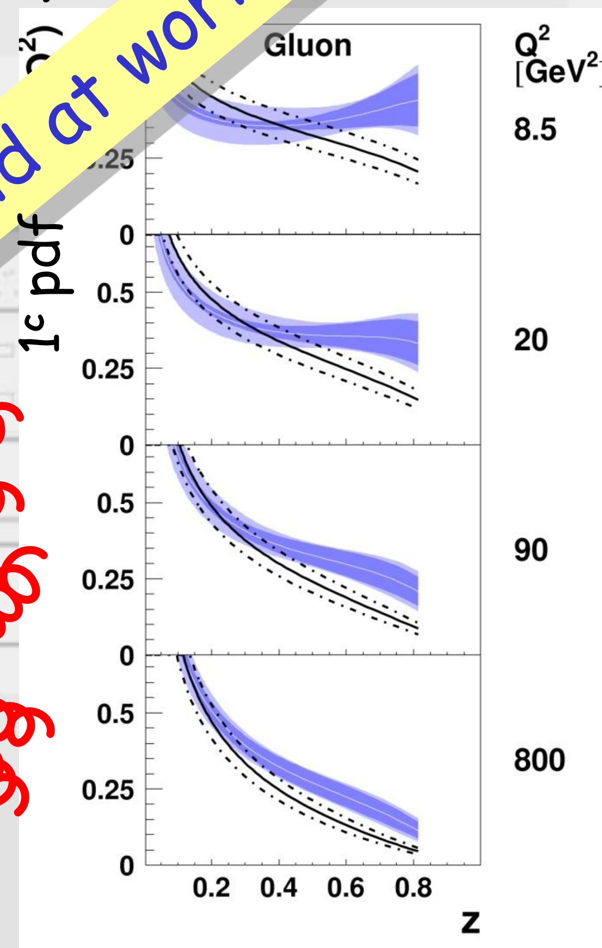
$+\ g \to$ …

$+\ \ldots$



$+$

$+\ \ldots$

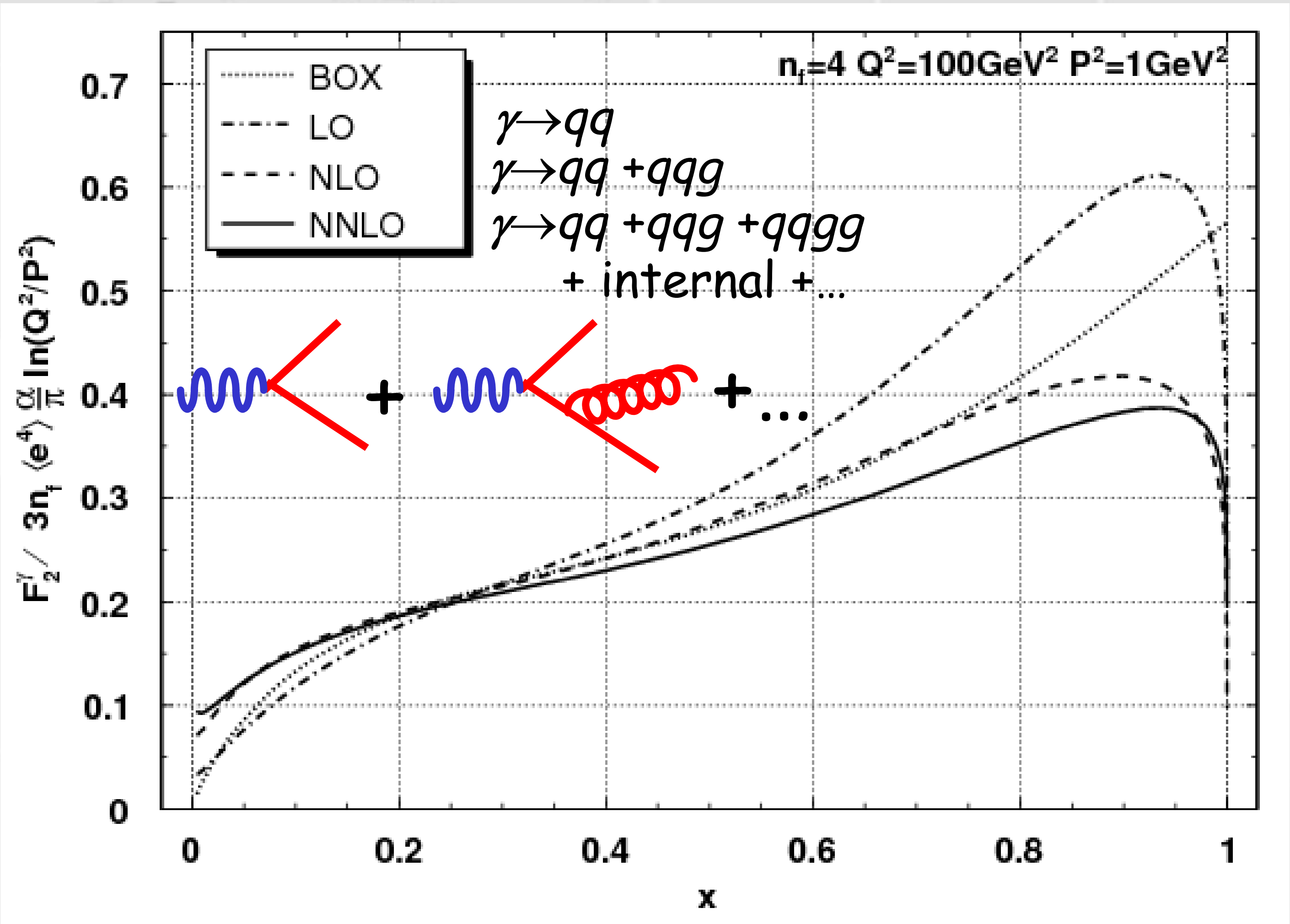


QCD field at work with itself

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

1_c Interaction Dynamics

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

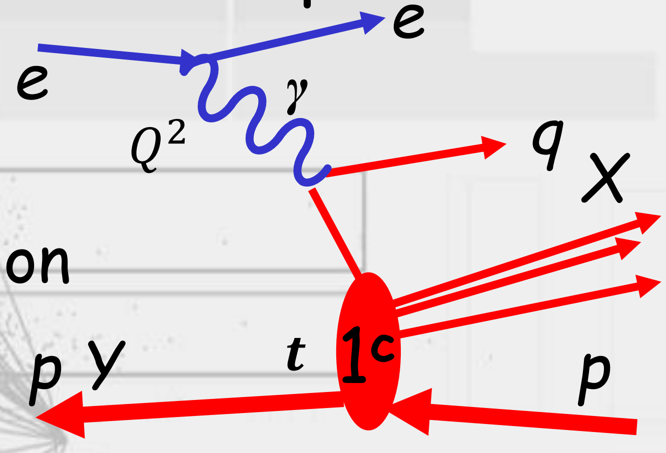


↳ QFD+QCD structure = gauge-invariant vector field

1_c Interaction Dynamics

- high energy for precision "Rutherford" probe
  - deep ($Q^2 \gg m_p^2$) inelastic ($s \gg m_p^2$)
  - $ep \rightarrow e + X + p$
  - space-like factorisation

q from hadronic interaction



$$\sigma_r^{D(4)}(\beta, x_{IP}, t, Q^2) = \frac{Q^4\beta}{2\pi\alpha_{em}^2 Y_+}\frac{d^2\sigma_r^{D(4)}}{d\beta\, dx_{IP}\, dt\, dQ^2} = F_2^{D(4)} - \frac{y^2}{Y_+}F_L^{D(4)}$$

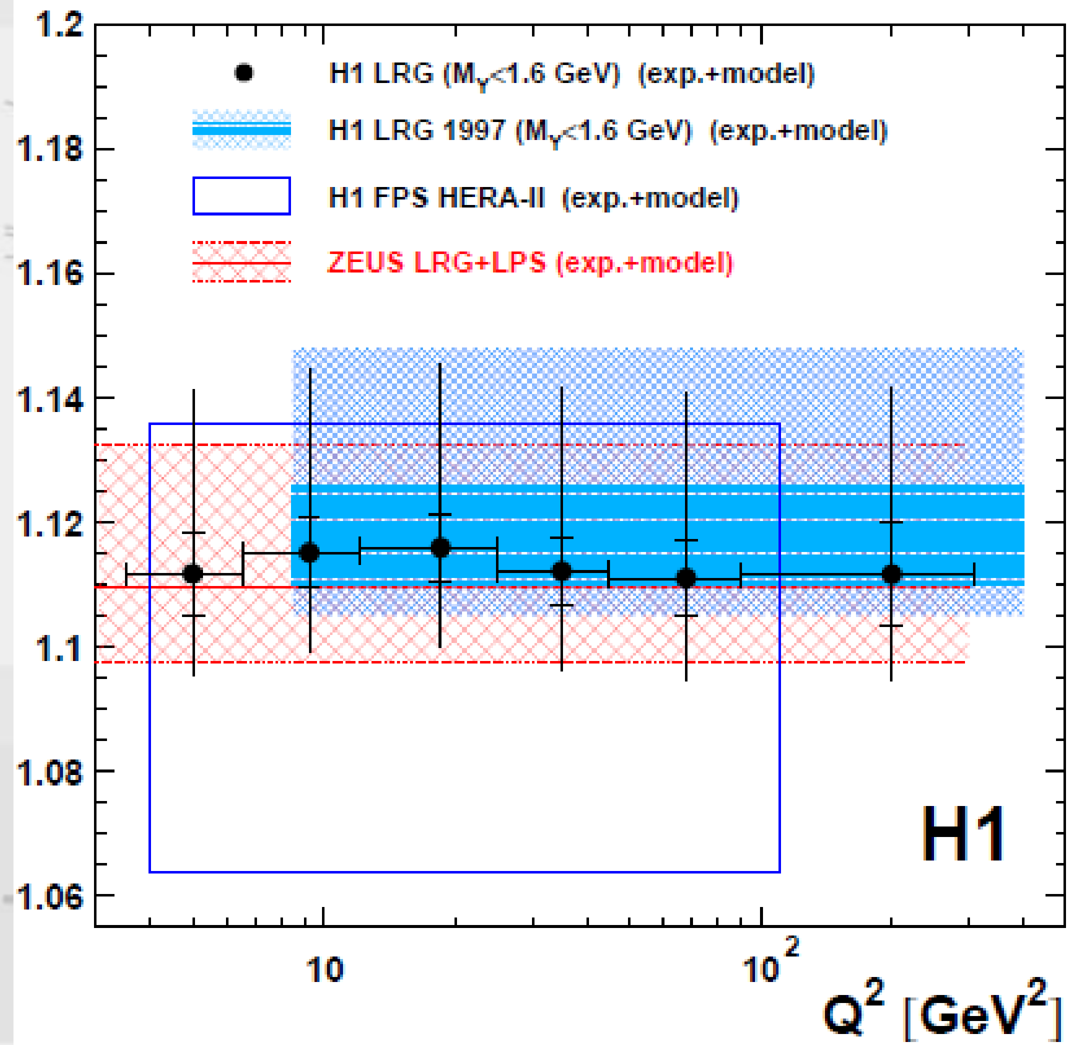
$$\langle\sigma_r^{D(3)}(\beta, x_{IP}, Q^2)\rangle_\beta \propto \langle\left(\frac{1}{x}\right)^{\lambda(Q^2)}\rangle_\beta$$

- structure of high energy proton interaction = QCD composition of inter-nucleon force
  - multi-gluon exchange ?

1_c Interaction Dynamics

- 1_c dynamics ≡ multi-gluons ~ 8_c dynamics ≡ Lipatov

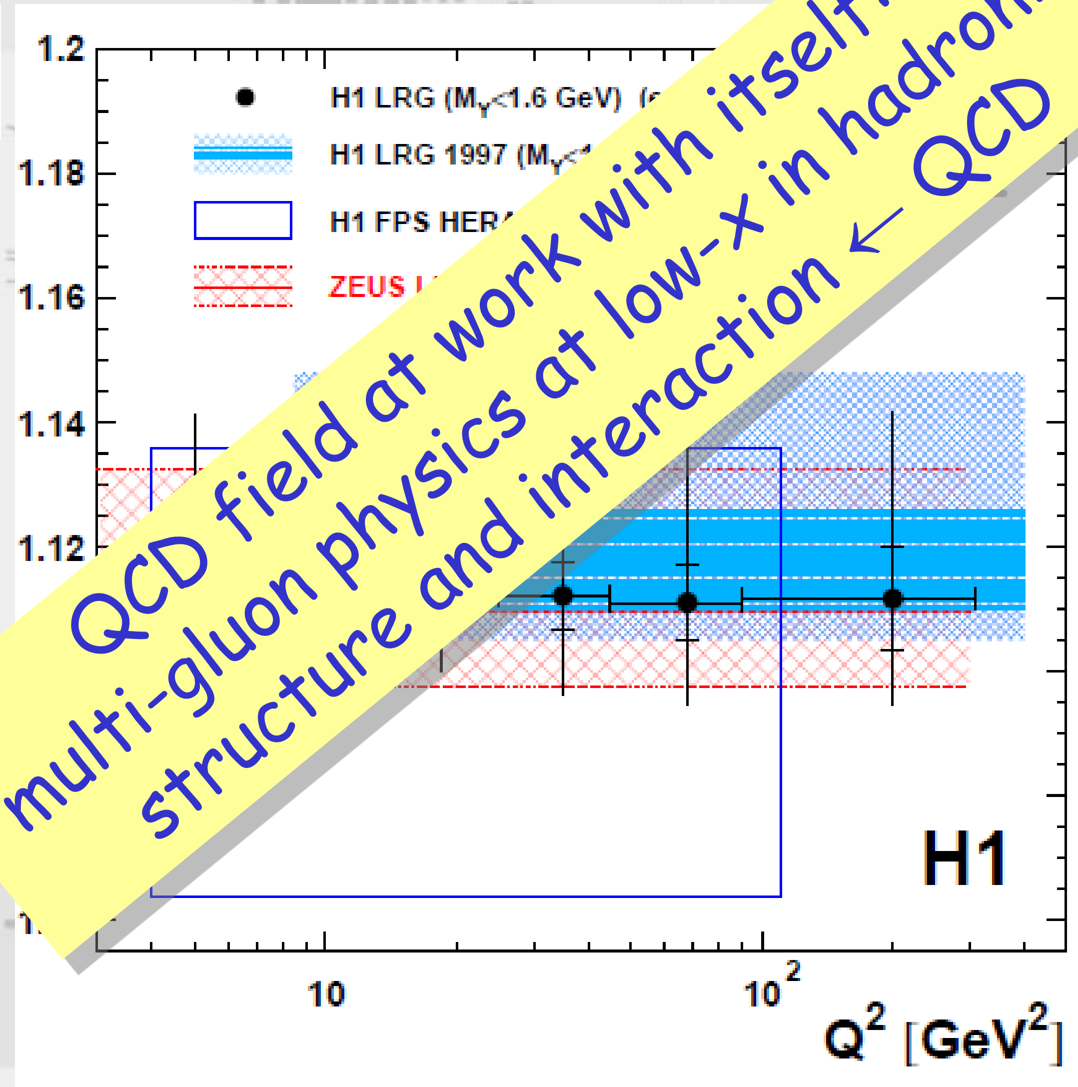
$\langle 1 + \lambda(Q^2) \rangle_\beta$



1_c Interaction Dynamics

- 1_c dynamics ≡ multi-gluons ~ 8_c dyna… ≡ Lipatov

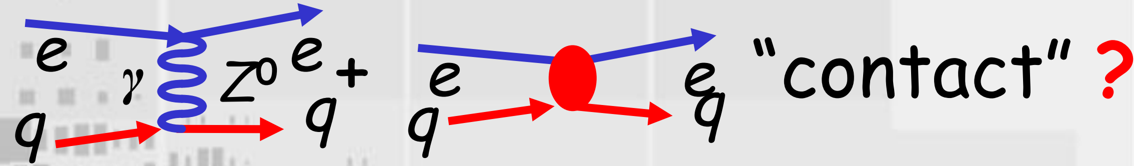
$\langle 1 + \lambda(Q^2) \rangle_\beta$

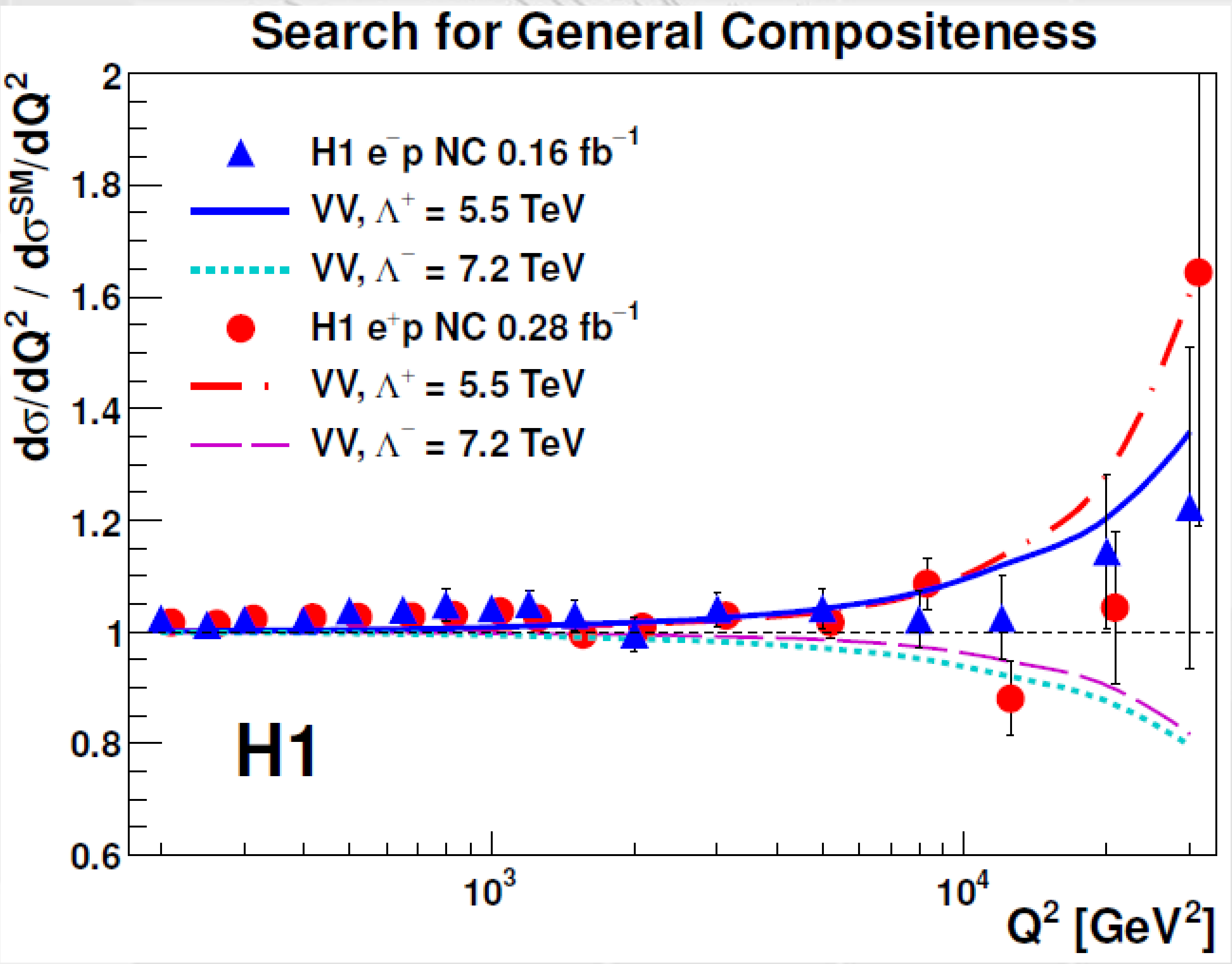


QCD field at work with itself:
multi-gluon physics at low-x in hadronic
structure and interaction ← QCD

Shortest Distance

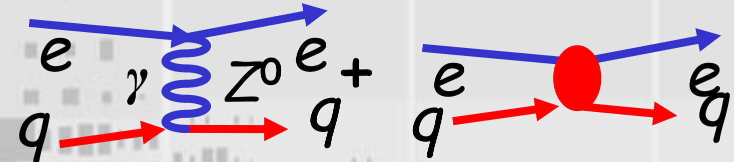
- beyond Dirac quark

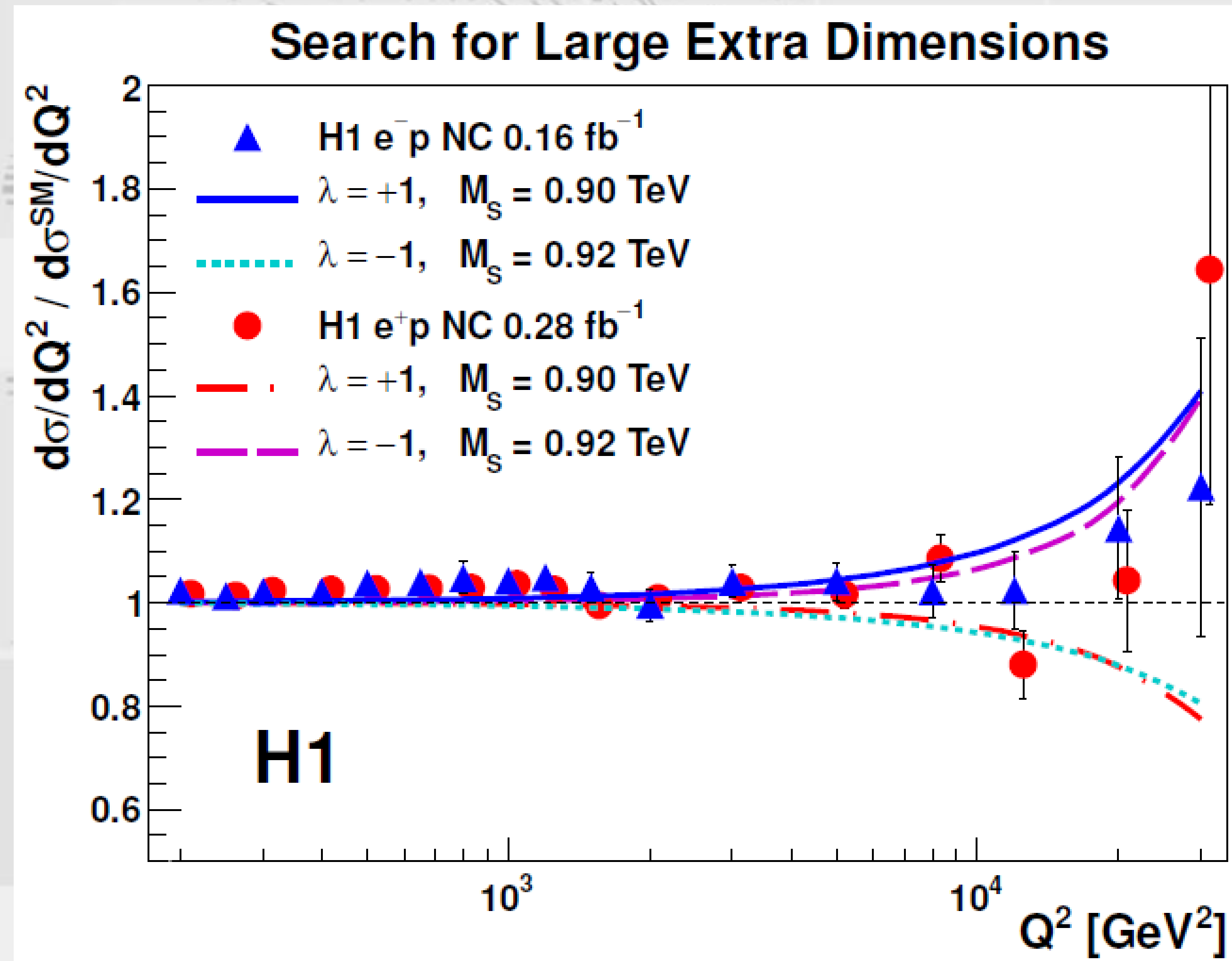




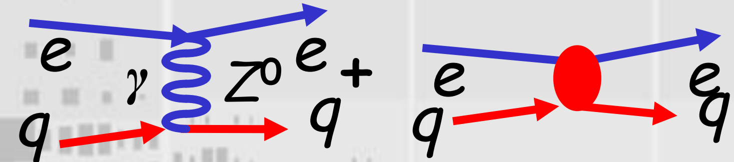
Shortest Distance

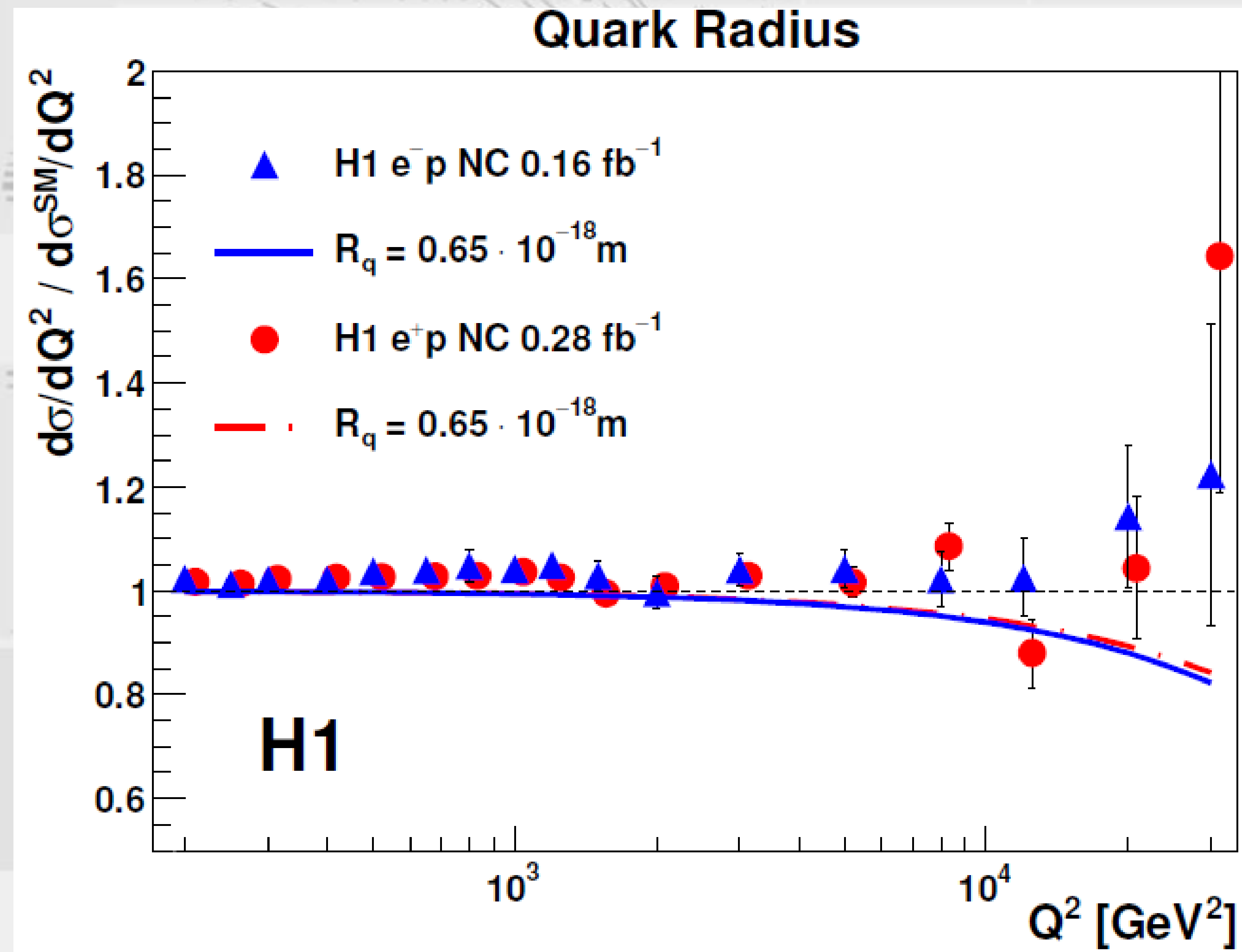
- beyond Dirac quark





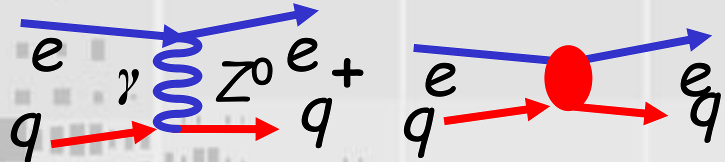
Shortest Distance

- beyond Dirac quark  “contact” ?

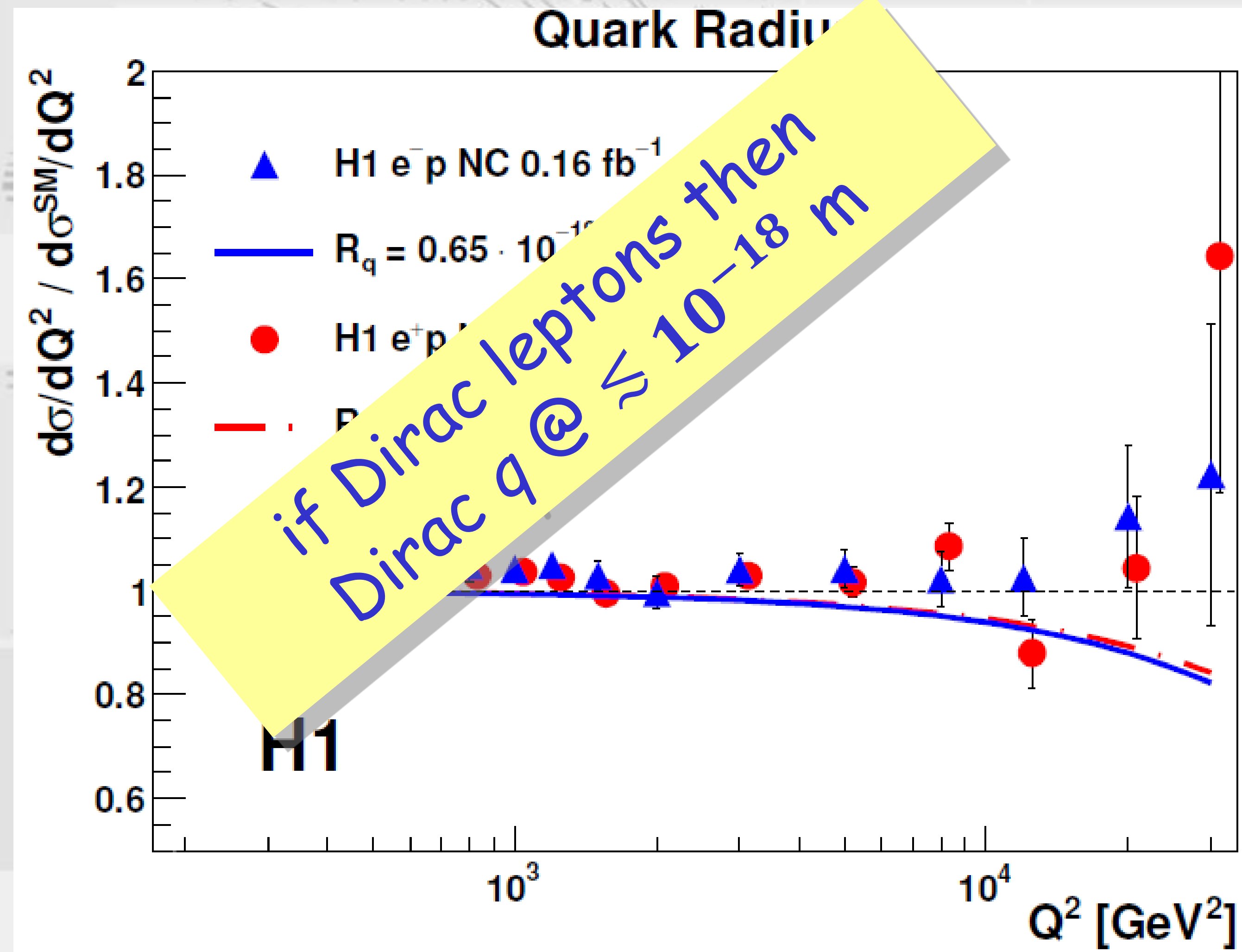


Shortest Distance

- beyond Dirac quark



“contact” ?



if Dirac leptons then
Dirac q @ ≲ 10^{-18} m

Landmarks

- discoveries reveal the landscape
- measurement defines the landmarks

"(The) history of science has shown that even during that phase of her progress in which she devotes herself to improving the accuracy of the numerical measurements of quantities long familiar, she is preparing the materials for the subjection of new regions, which would have remained unknown if she had been contented with the rough methods of her earlier pioneers."

James Clerk Maxwell

- landmarks signpost and define new discoveries
- paradigm hitherto:
  constituents, currents and colour

With today's Paradigm ?

The Cockcroft Institute of Accelerator Science and Technology
Lancaster University

- example: why leptons and quarks ?

THE UNCONFINED QUARKS AND GLUONS

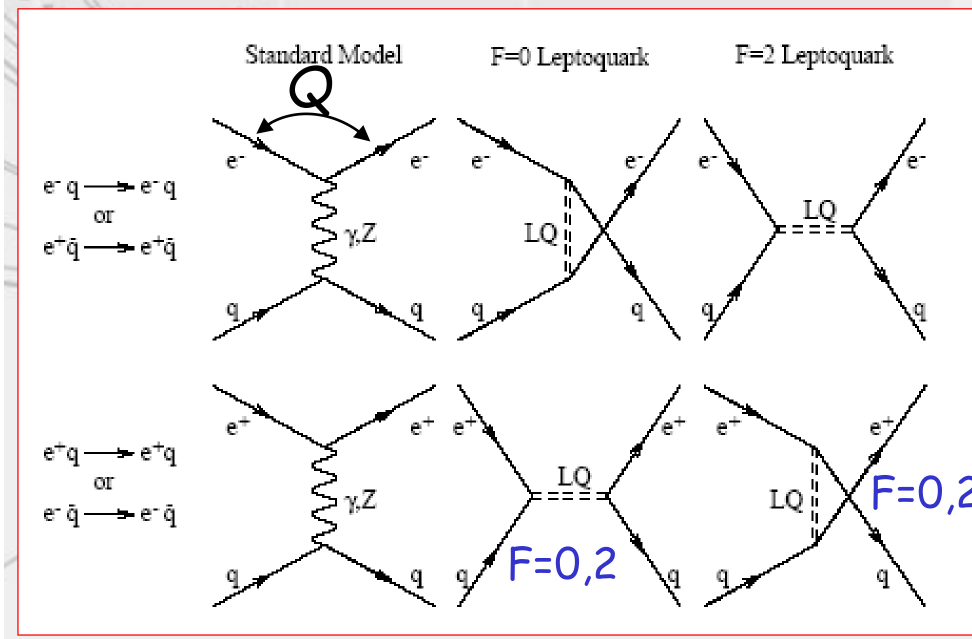
Abdus Salam

International Centre for Theoretical Physics, Trieste, Italy and Imperical College, London, England

1. Introduction

Leptons and hadrons share equally three of the basic forces of nature: electromagnetic, weak and gravitational. The only force which is supposed to distinguish between them is strong. Could it be that leptons share with hadrons this force also, and that there is just one form of matter, not two?

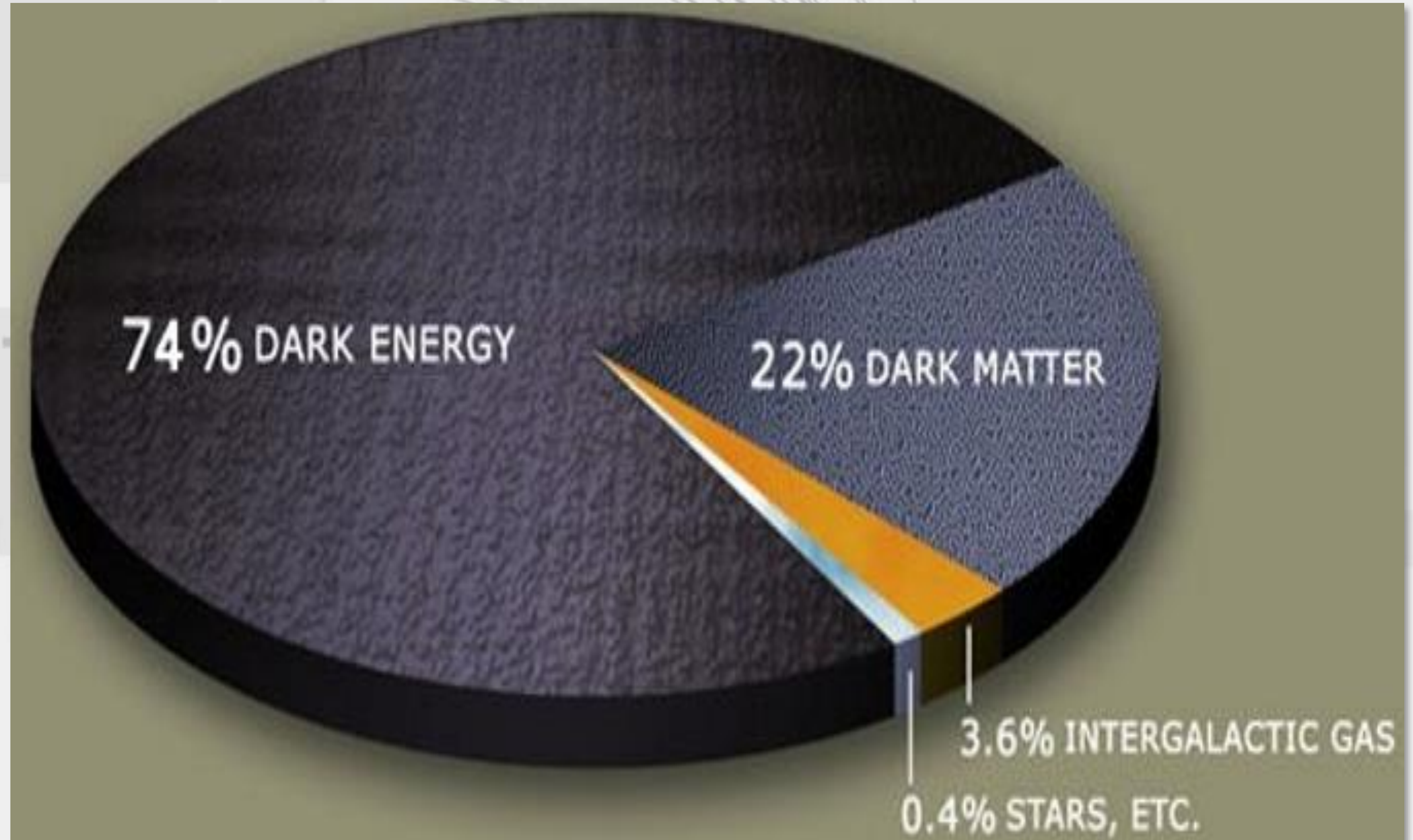
ICHEP76 Tbilisi



- further pursuit of landmarks
  - energy frontier
  - intensity frontier

Beyond today's Paradigm ?

- dark constituents and dark currents ?
- beyond constituents and currents ?



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Lancaster University

Beyond 1947's Paradigm

- Dirac 1928
  (*n* integer *j* ½-integer)

$$E_{nj} = \frac{mc^2}{\sqrt{1+\left[\frac{1}{\hbar c}\left(\frac{Ze}{n-\left|j+\frac{1}{2}\right|}\right)^2+\sqrt{\left|j+\frac{1}{2}\right|^2-\frac{Z^2e^2}{\hbar c}}\right]^2}}$$

- Lamb-Retherford 1947
  - Dirac+3 ppm observed
  - 3 ppm = 1 GHz splitting

↳ relativity + electron + field quantisation → mode $E_\nu = \left(n+\frac{1}{2}\right)h\nu$

integer → n "Zitterbewegung"

↳ relativistic quantum field