A Estrutura do Próton: Compreensão Atual e Desafios

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SOCIEDADE BRASILEIRA DE FÍSICA

Niterói - RJ - Brazil
03 Dezembro 2025

Estrutura do Próton

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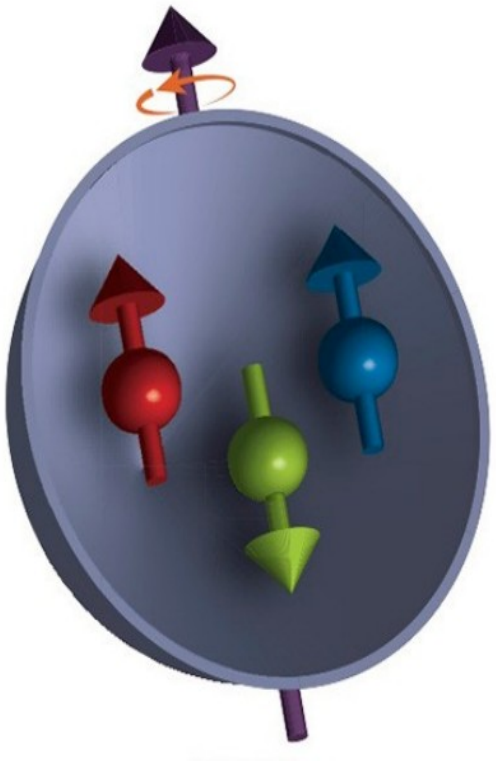
Década de 80:



Modelo de pártons:

Estrutura dominada por quarks de valência

Estrutura do Próton

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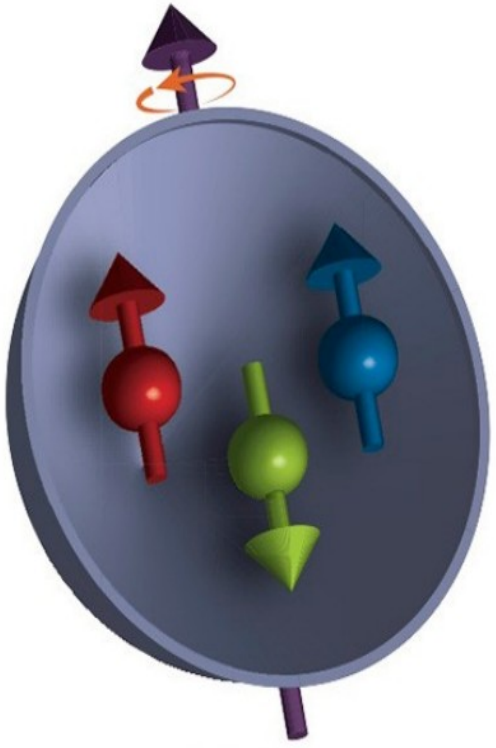
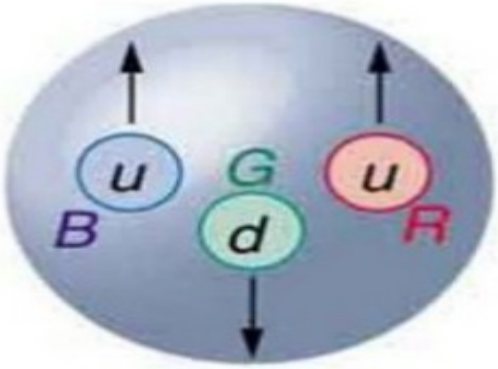


Modelo de pártons:
Estrutura dominada por quarks de valência

Descrição da carga e **spin** do próton:



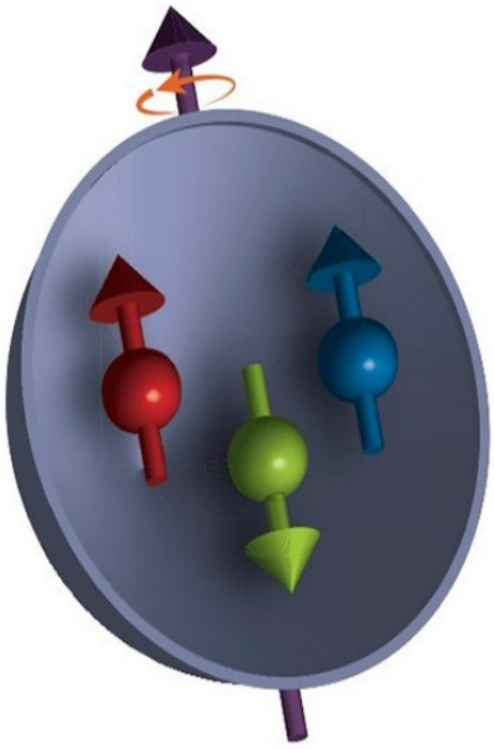
Proton

Spin $\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = \frac{1}{2}$

Charge $+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$

Estrutura do Próton

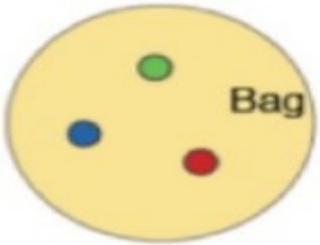
Década de 80:



Modelo de pártons:
Estrutura dominada por quarks de valência

Descrição da **massa** do próton:

❑ **Bag model:**



✧ Kinetic energy of three quarks: $K_q \sim 3/R$

✧ Bag energy (bag constant B): $T_b = \frac{4}{3}\pi R^3 B$

✧ Minimize $K_q + T_b$: $M_p \sim \frac{4}{R(\mathrm{fm})} 197.3(\mathrm{MeV fm})$

$$R(\mathrm{PDG}) = 0.8414(19)\ \mathrm{fm}$$

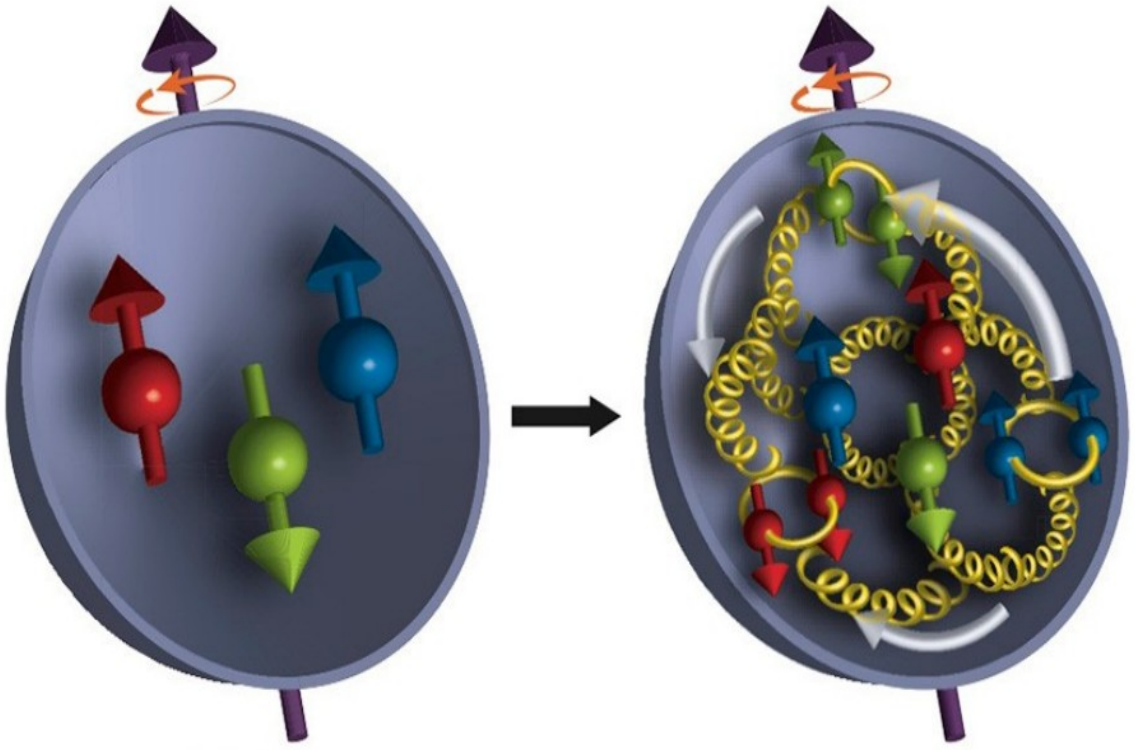
$$M_p \sim 936 - 940\ \mathrm{MeV}$$

$$M_p(\mathrm{PDG}) = 938.272\ \mathrm{MeV}$$

Estrutura do Próton

Década de 80:

Dias atuais:



Modelo de pártons:
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Cromodinâmica Quântica:
Estrutura dominada por quarks de mar e glúons

Estrutura do Próton

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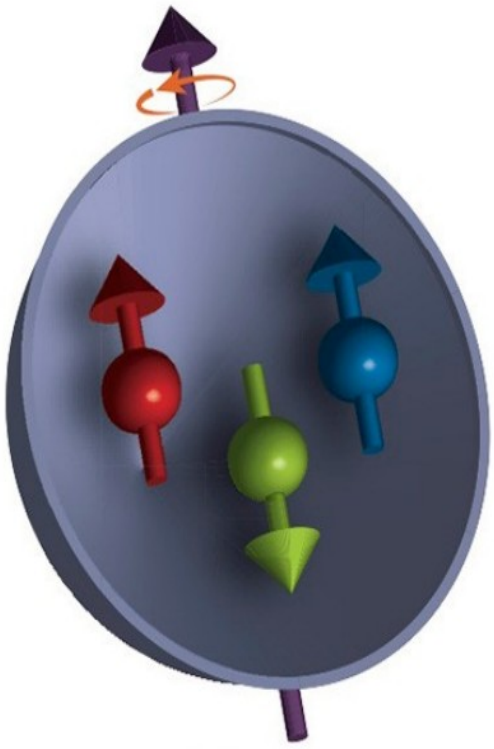

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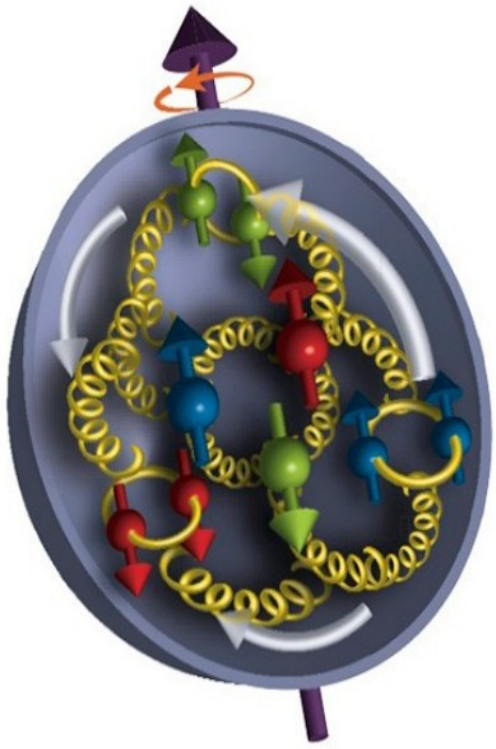

Cromodinâmica Quântica:
Estrutura dominada por quarks de mar e glúons

Descrição do **spin**:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Estrutura do Próton

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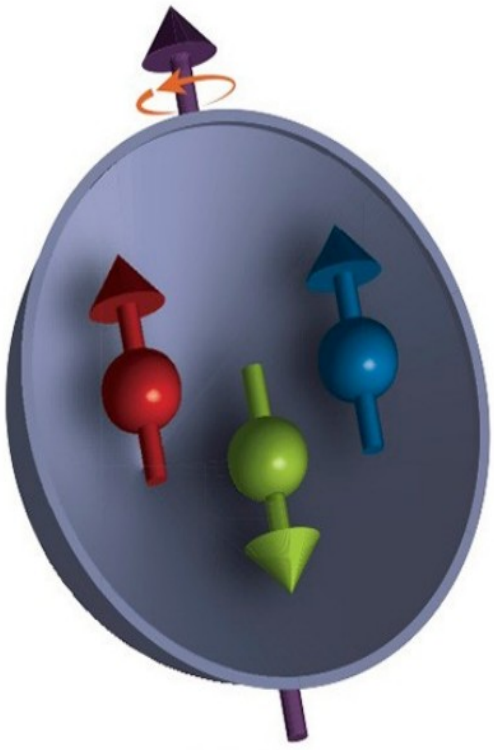

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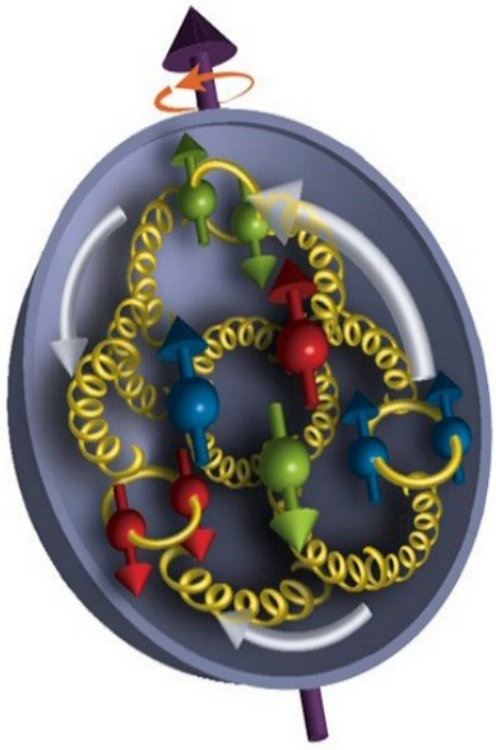

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Descrição do **spin**:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Estrutura do Próton

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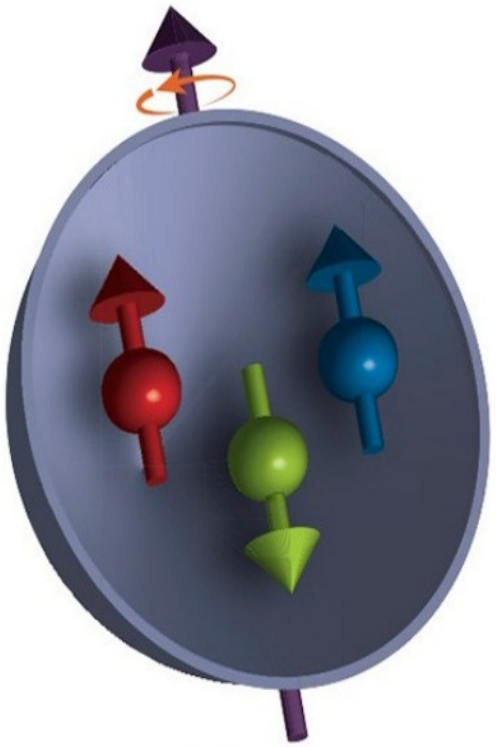

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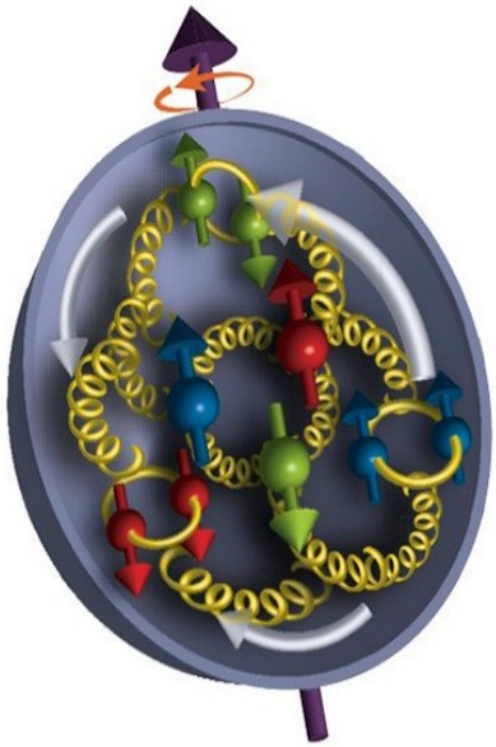

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$$\Delta G = \int dx \Delta g(x)$$

$$\sim 40\% (\text{with RHIC data})$$

Estrutura do Próton

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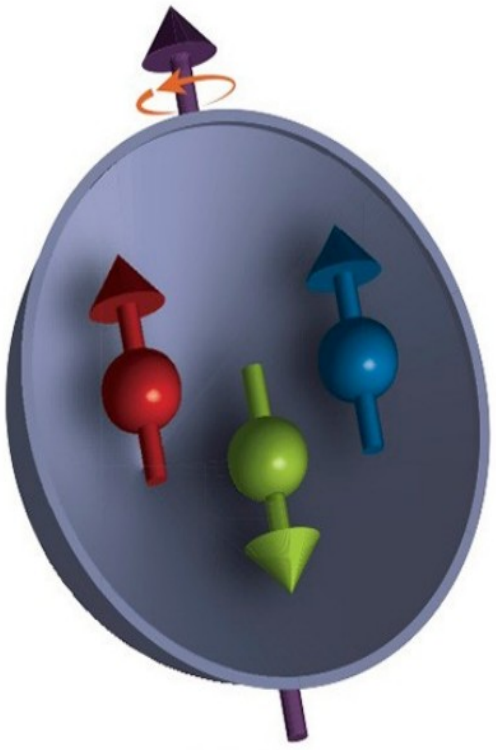

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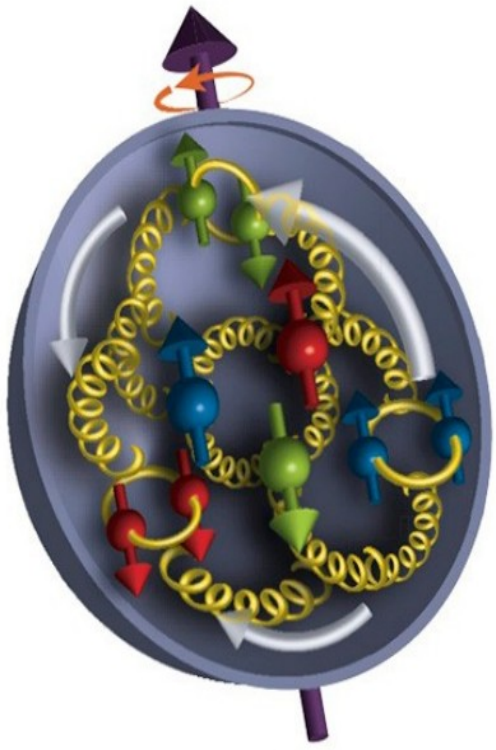

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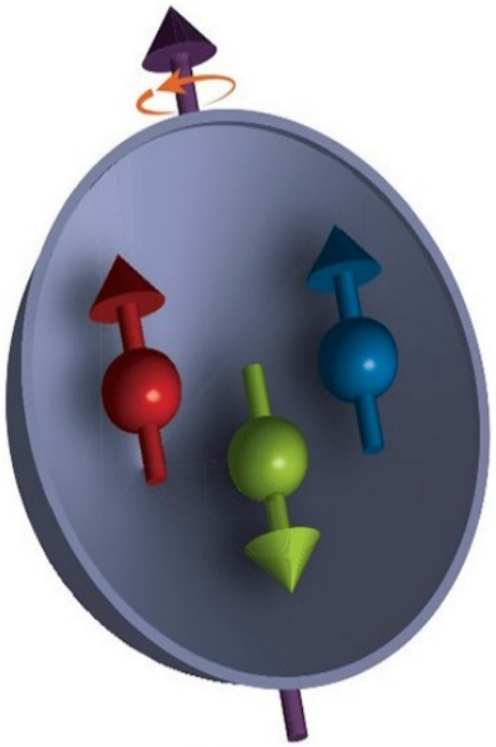

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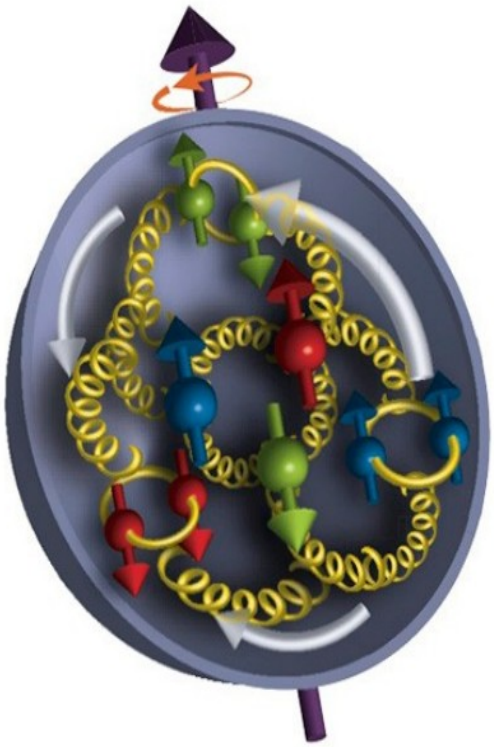

Cromodinâmica Quântica:
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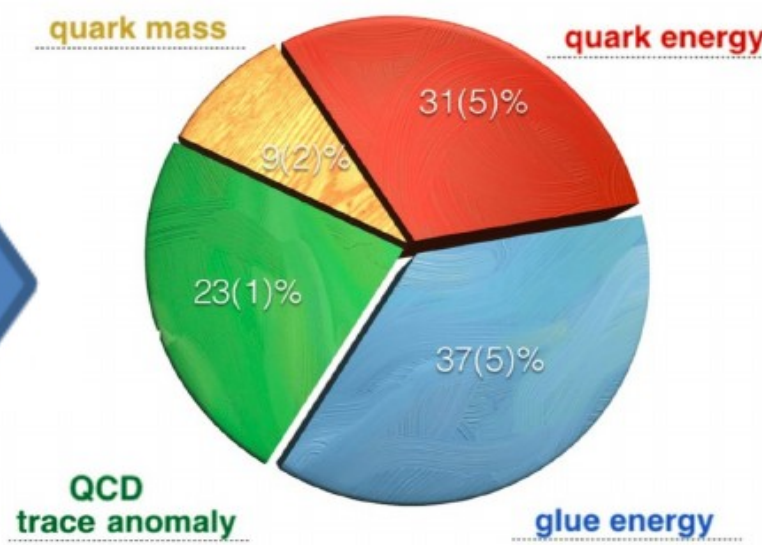
Descrição da **massa**:



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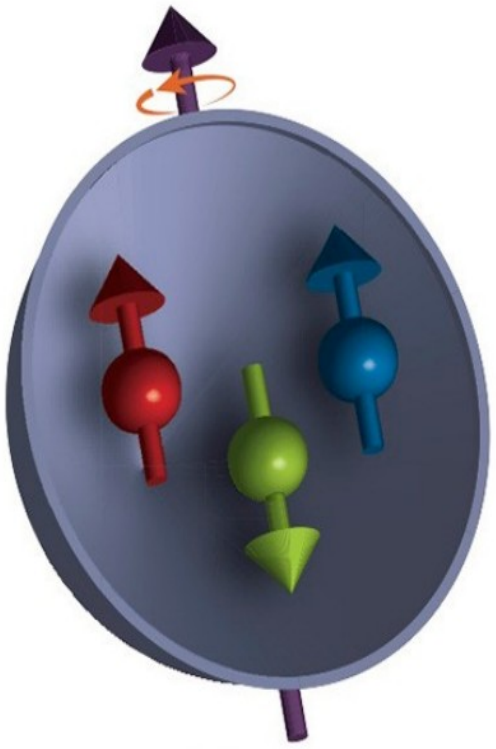

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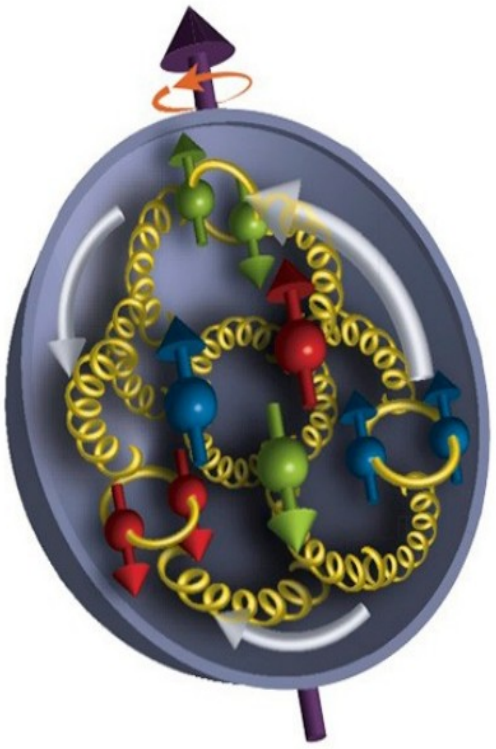

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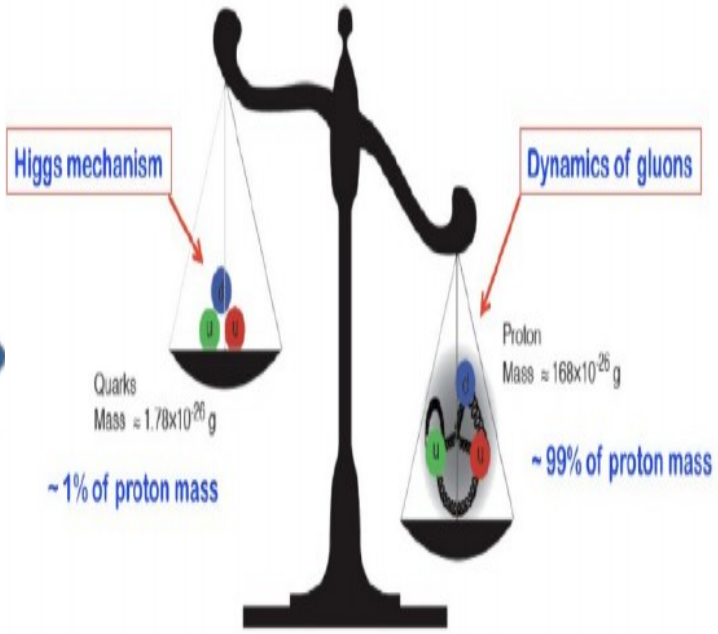
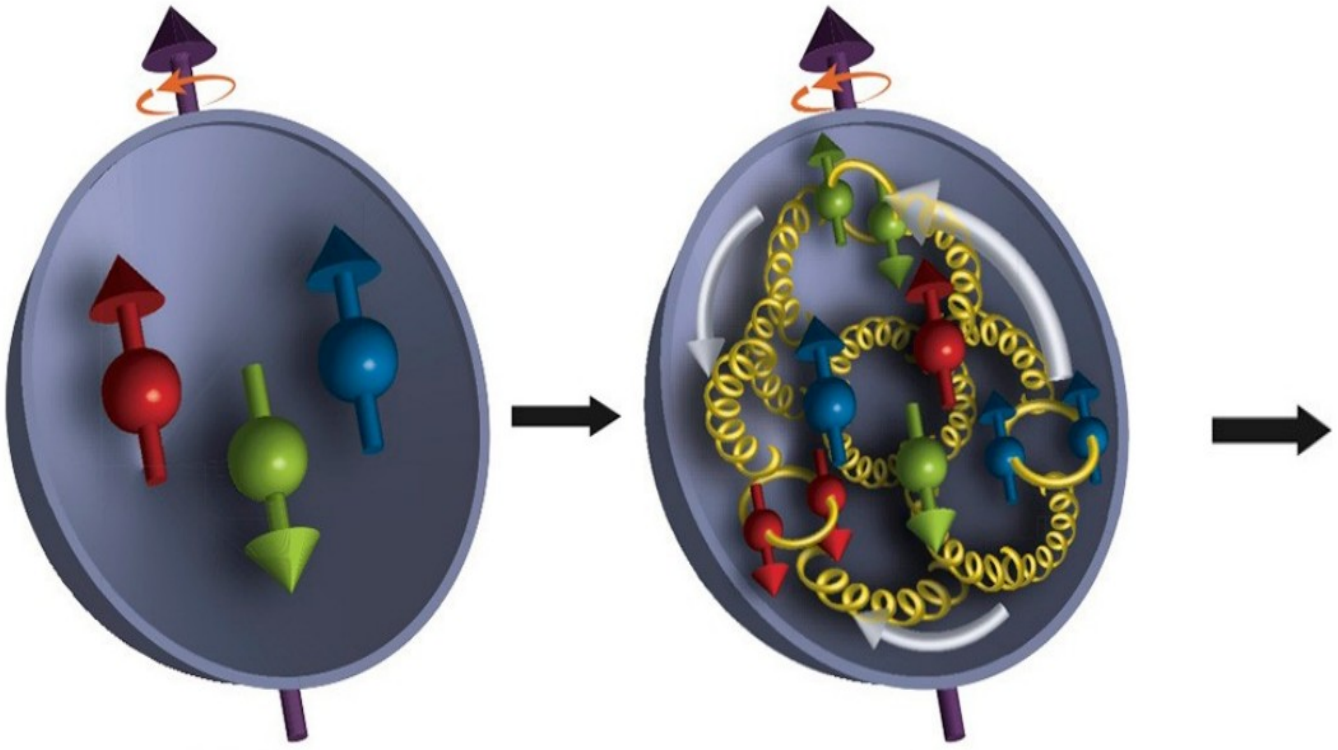


Estrutura do Próton

Década de 80:

Dias atuais:

Futuro:



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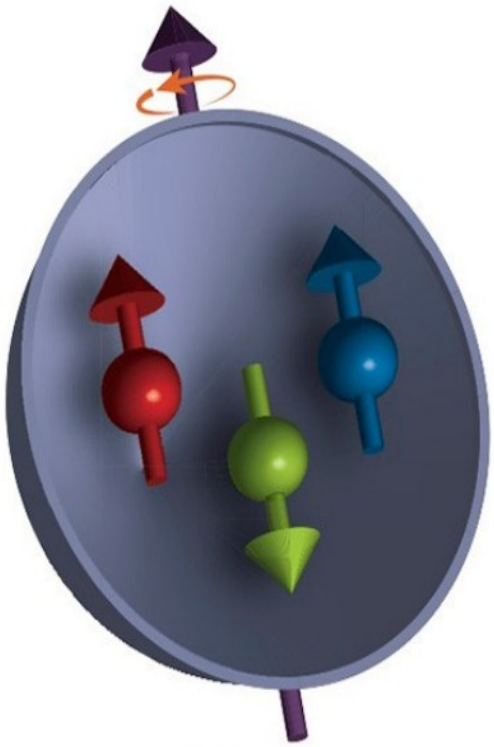

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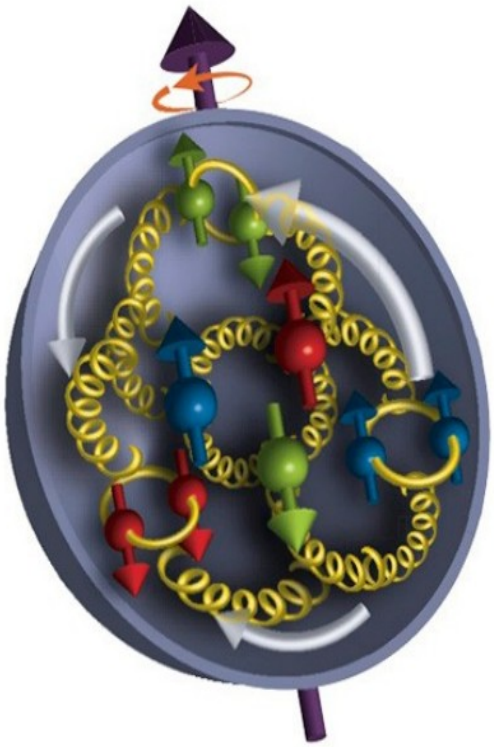

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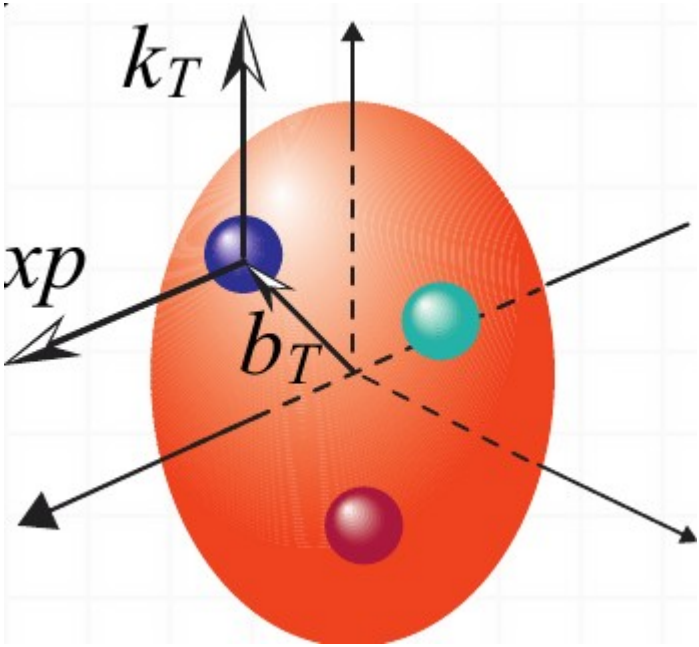


Imagem multi – dimensional do próton: Descrita em termos de uma distribuição de Wigner 5D

Neste seminário:

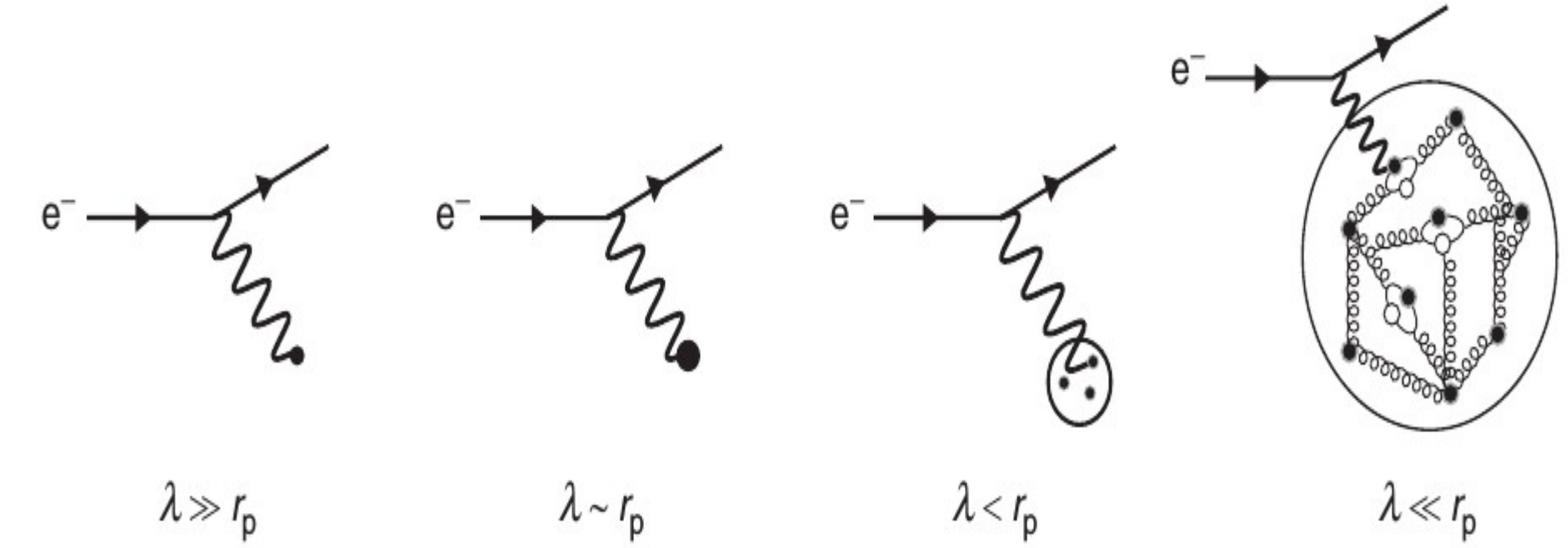
- Espalhamento elétron – proton

- Estrutura partônica do próton

- Perspectivas

Espalhamento lépton – próton:

ENERGIA



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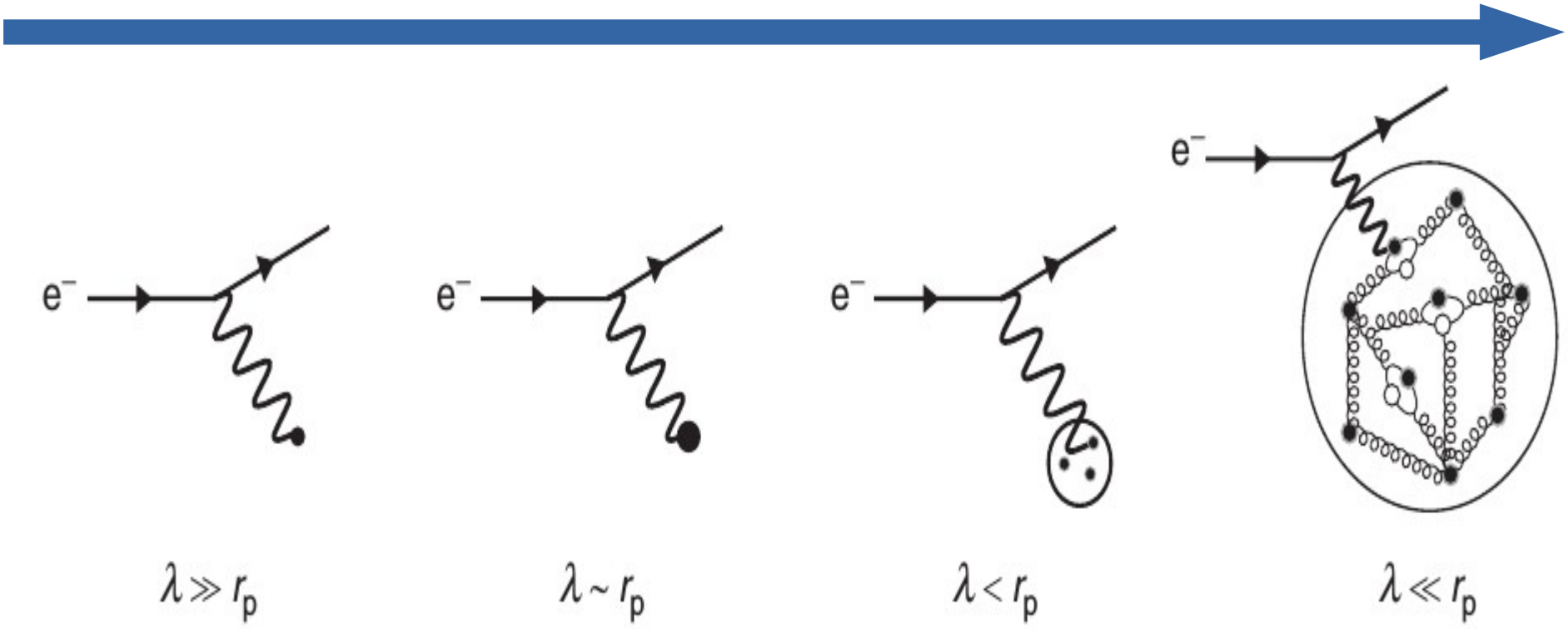
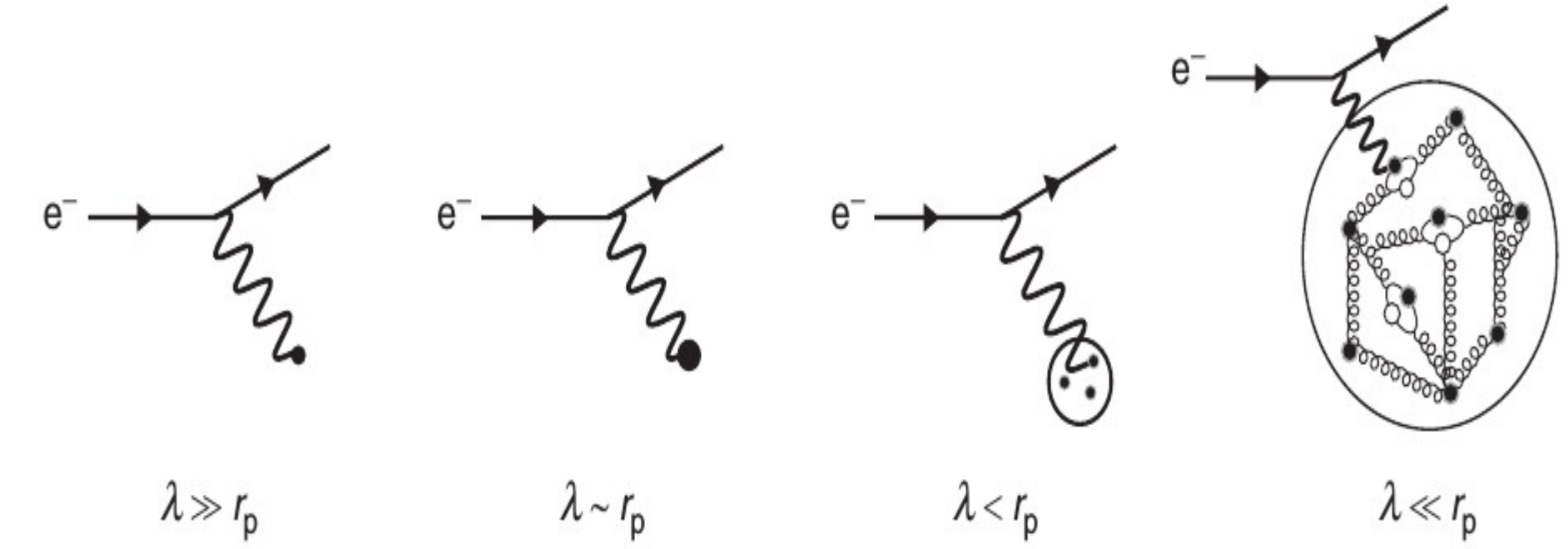


ESPALHAMENTO ELÁSTICO

ESPALHAMENTO INELÁSTICO

Espalhamento lépton – próton:

ENERGIA



$\lambda \gg r_p$

$\lambda \sim r_p$

$\lambda < r_p$

$\lambda \ll r_p$

Próton pontual

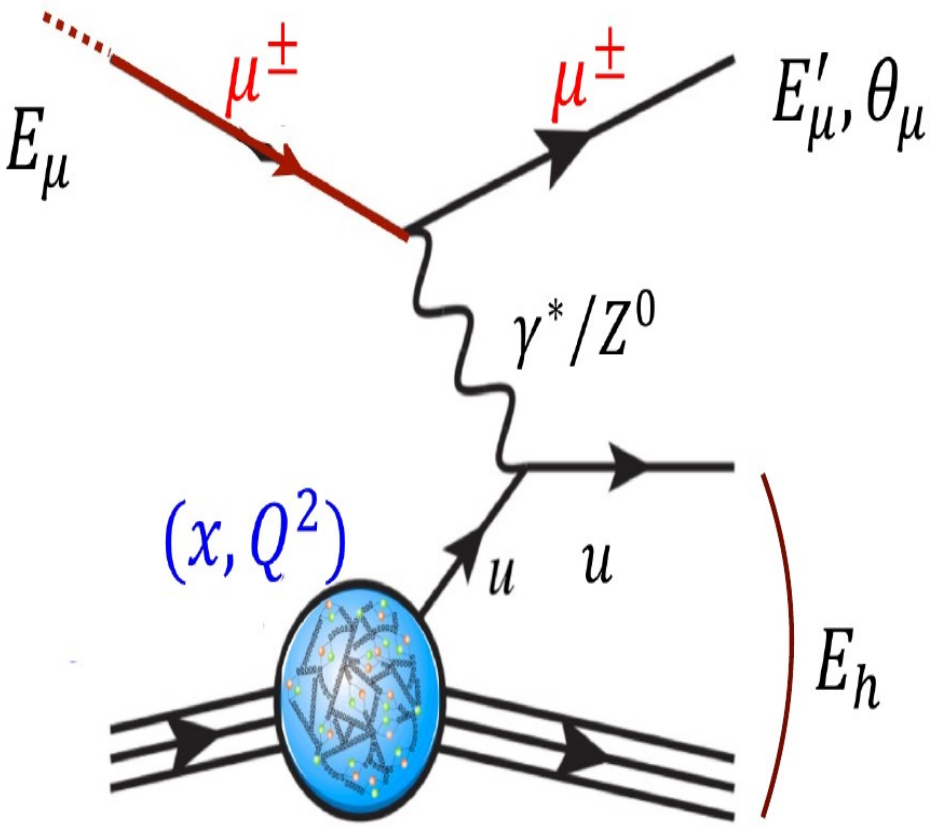
Sensível ao raio do Próton

Sensível a estrutura do Próton

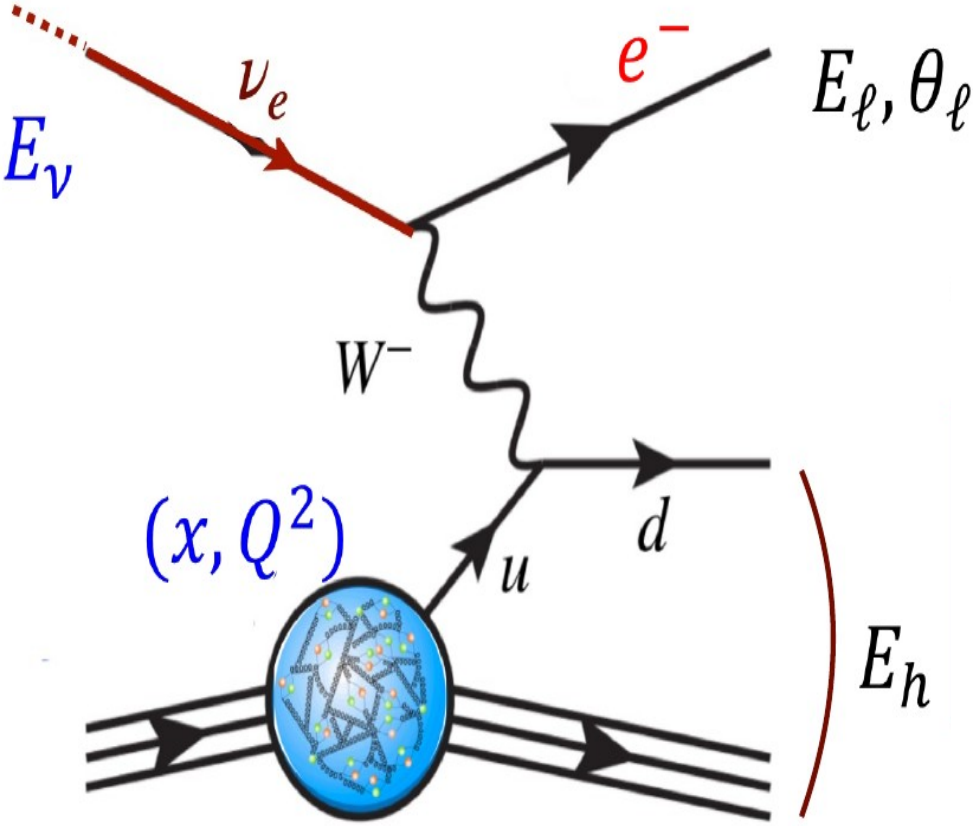
Sensível às flutuações quânticas

Espalhamento profundamente inelástico(DIS):

Lepton carregado - proton:

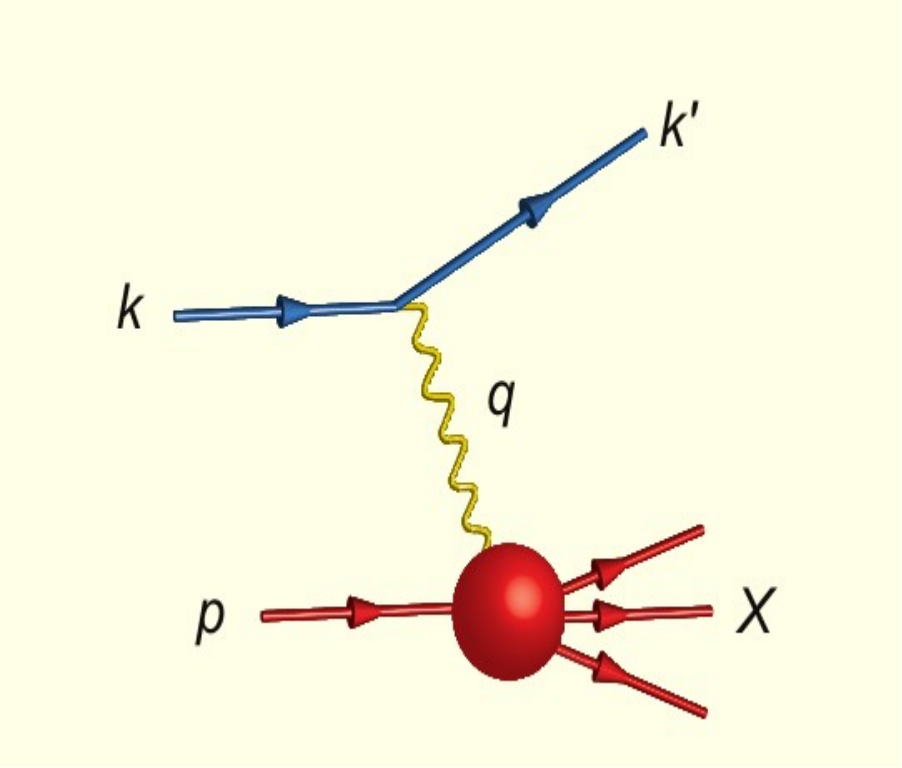


Lepton neutro - proton:



Espalhamento profundamente inelástico elétron – próton:

*** DIS Inclusivo Corrente Neutra:**



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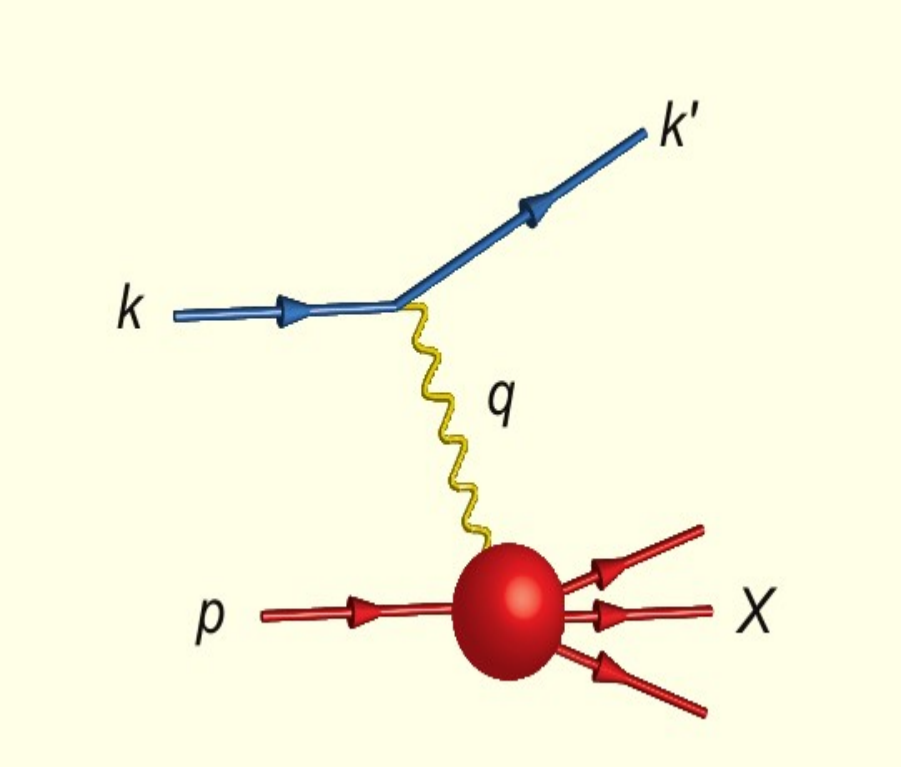

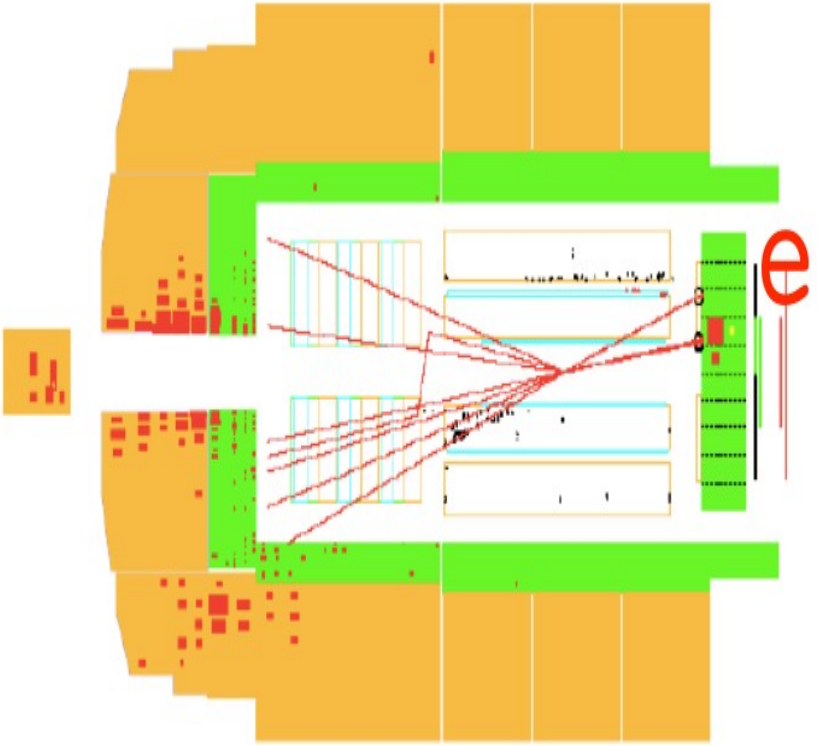

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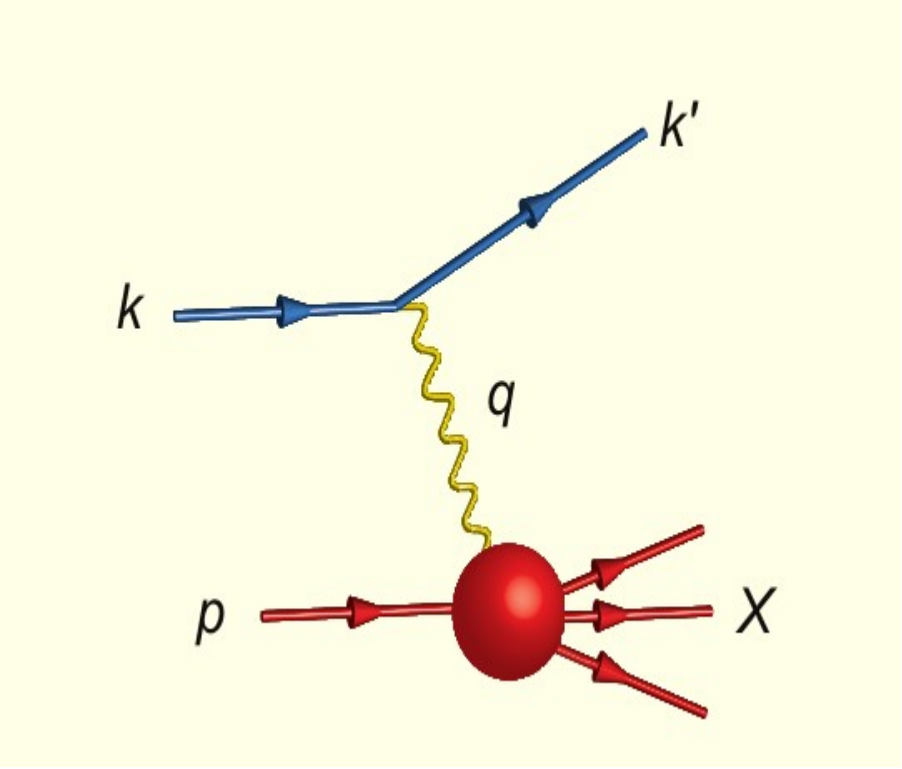
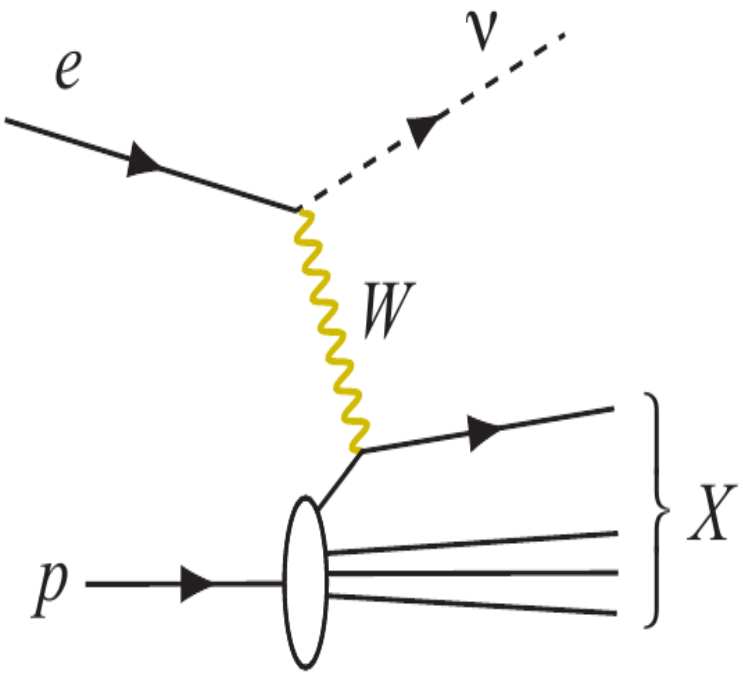


*** DIS Inclusivo Corrente Carregada:**



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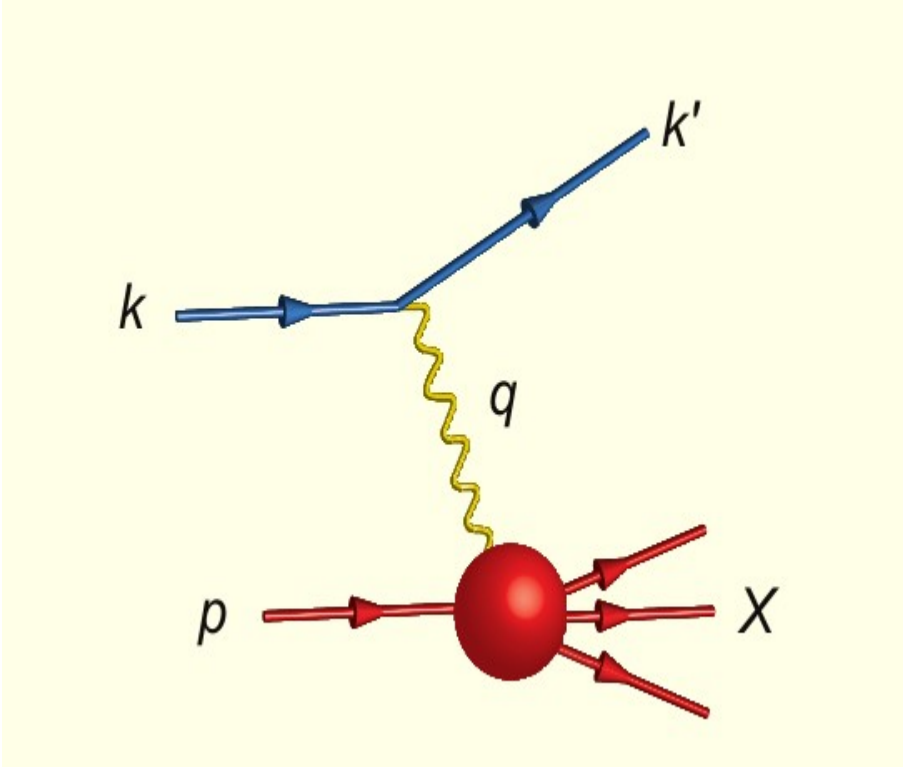
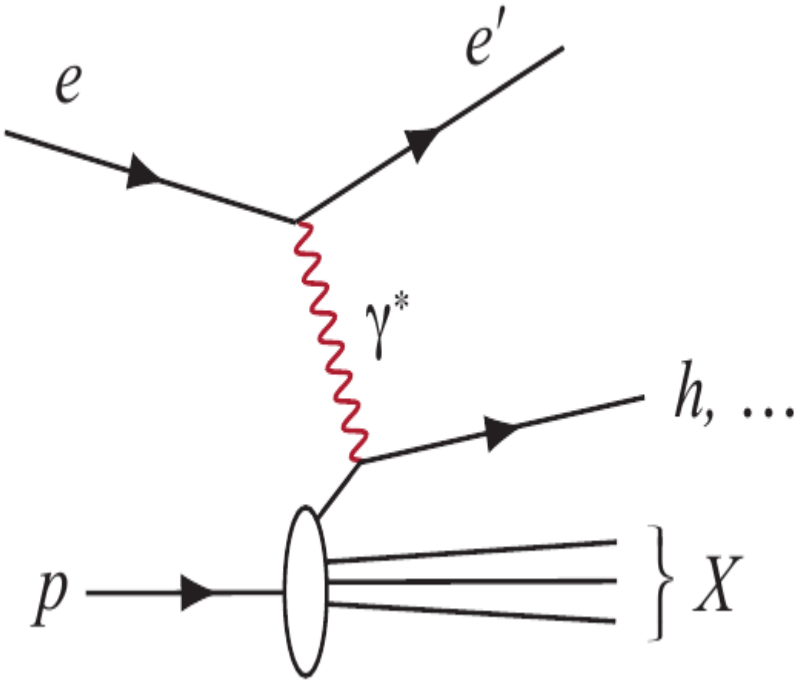
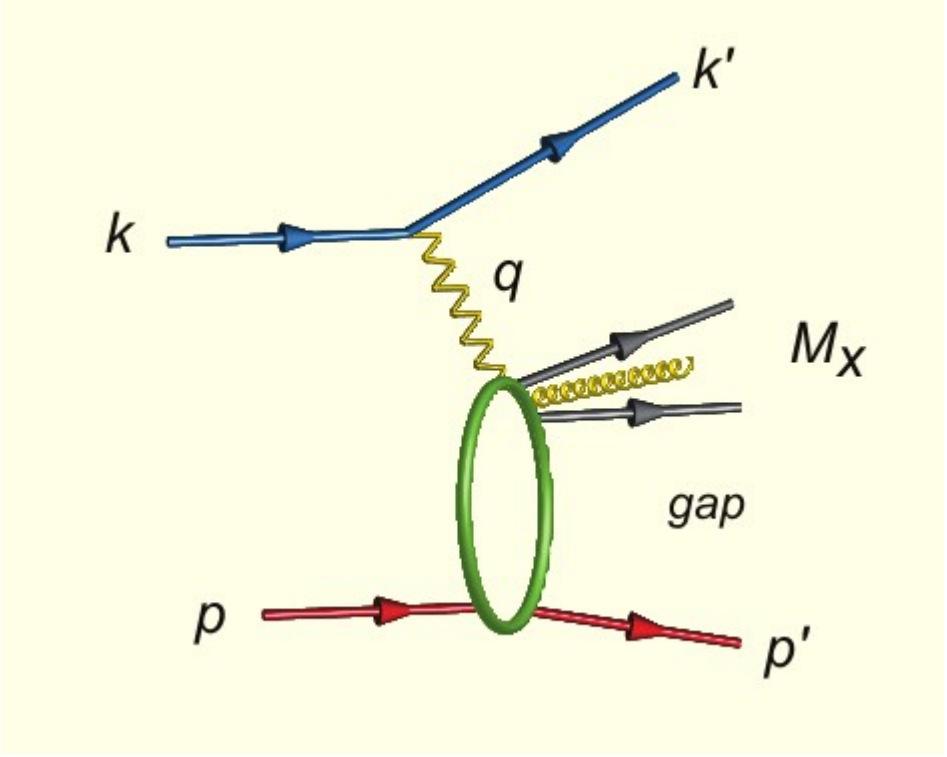


*** DIS Semi - Inclusivo:**



Espalhamento profundamente inelástico elétron – próton:

*** DIS Difrativo:**



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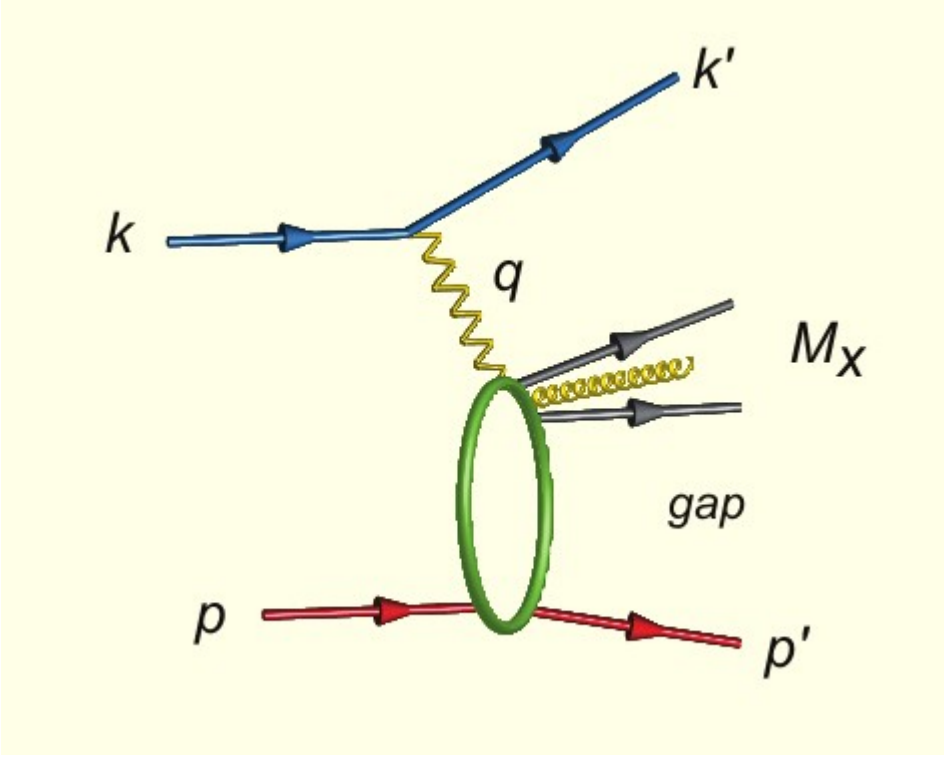

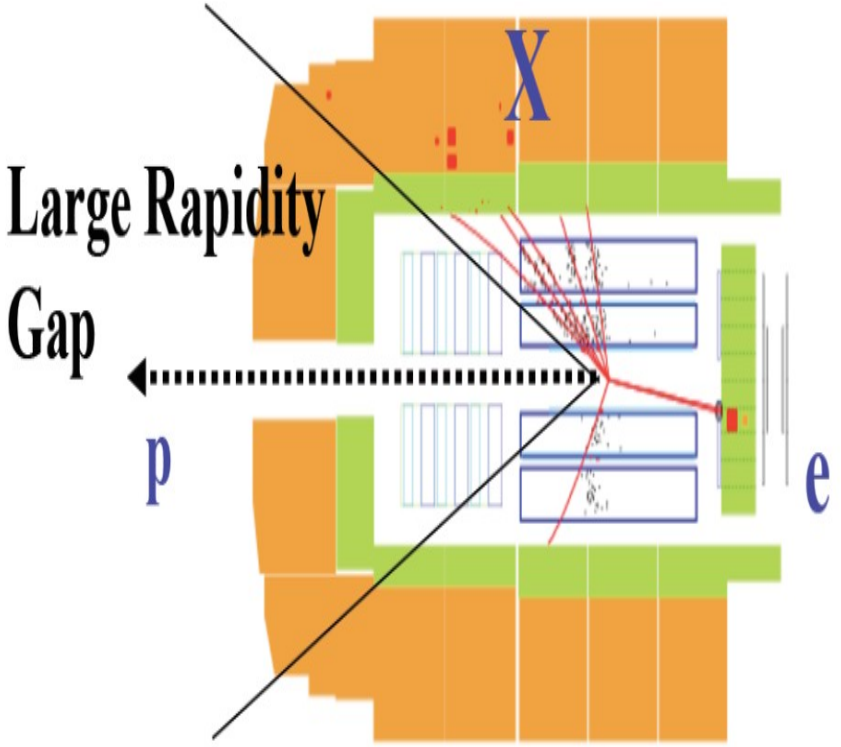

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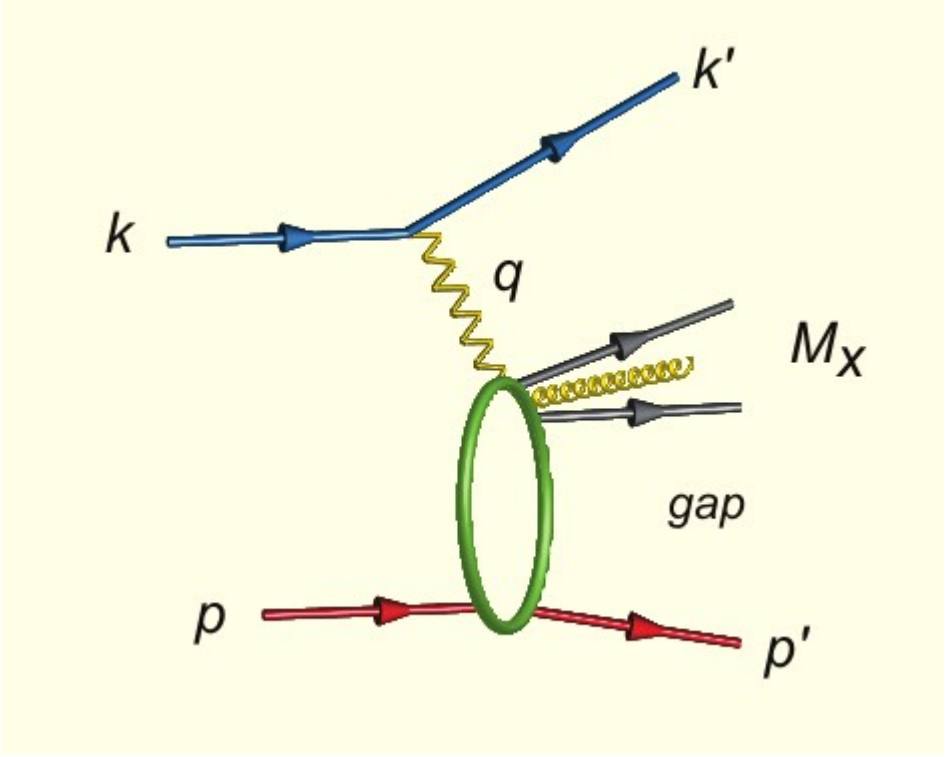

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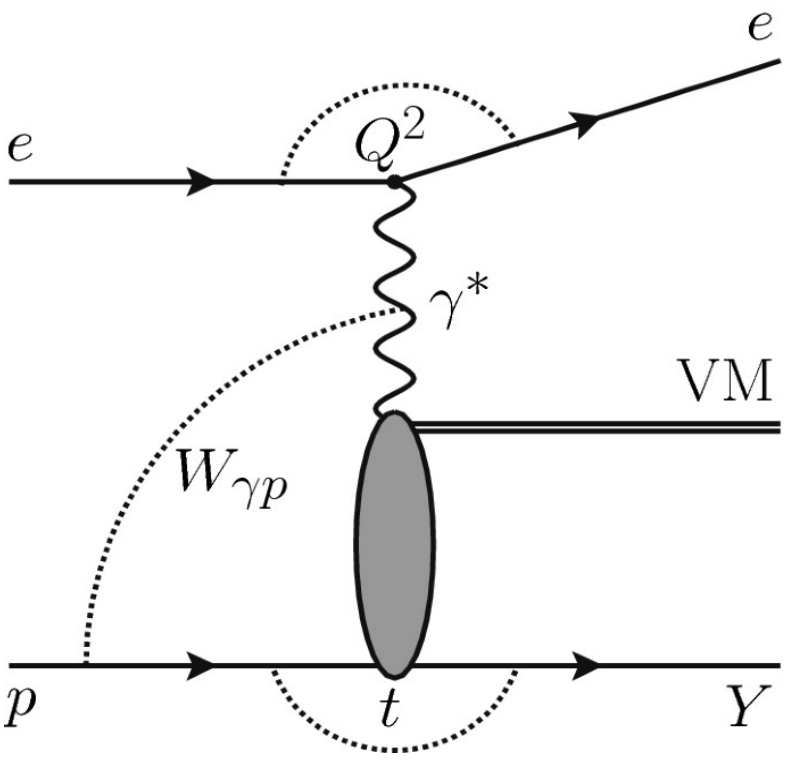
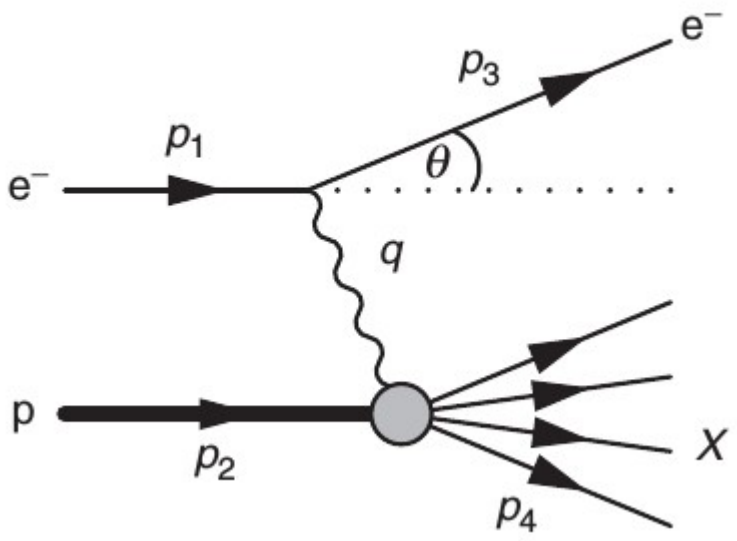


Espalhamento profundamente inelástico elétron – próton (inclusive DIS):



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$$x \equiv \frac{Q^2}{2p_2 \cdot q},$$ Variável de Bjorken

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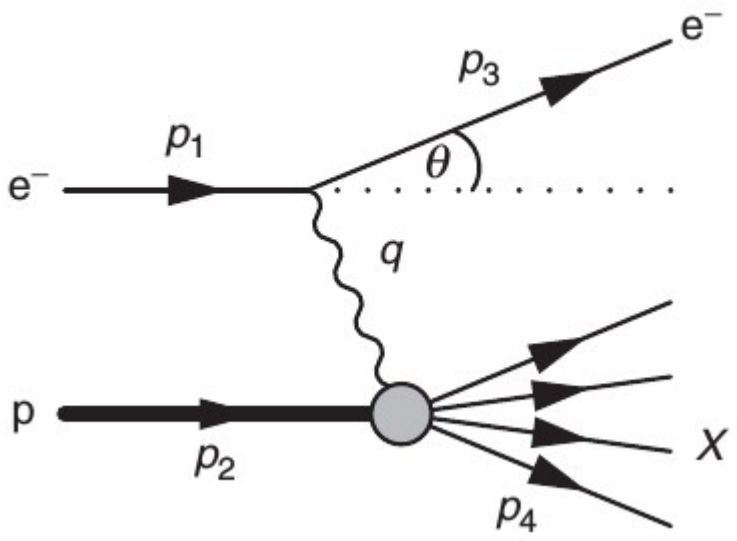

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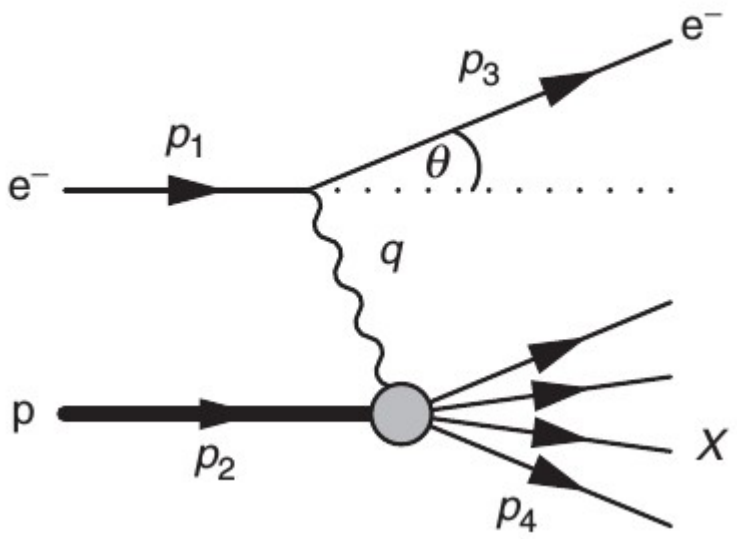
Reconstrução a partir da medida do elétron:

$$Q^2_{el} = 2E_e E'_e(1 - cos\theta'_e) \qquad y_{el} = \frac{Q^2_{el}}{s x_{el}}$$

$$x_{el} = x_0 \frac{E'_e(1 + \cos\theta'_e)}{2E_e - E'_e(1 - \cos\theta'_e)} \qquad x_0 = \frac{E_e}{E_p}$$

Espalhamento profundamente inelástico elétron – próton (inclusive DIS):



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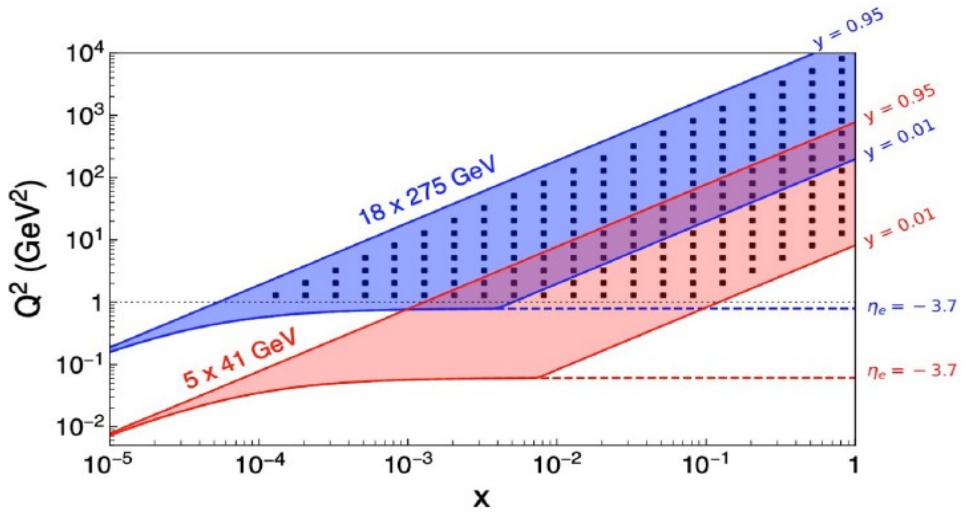

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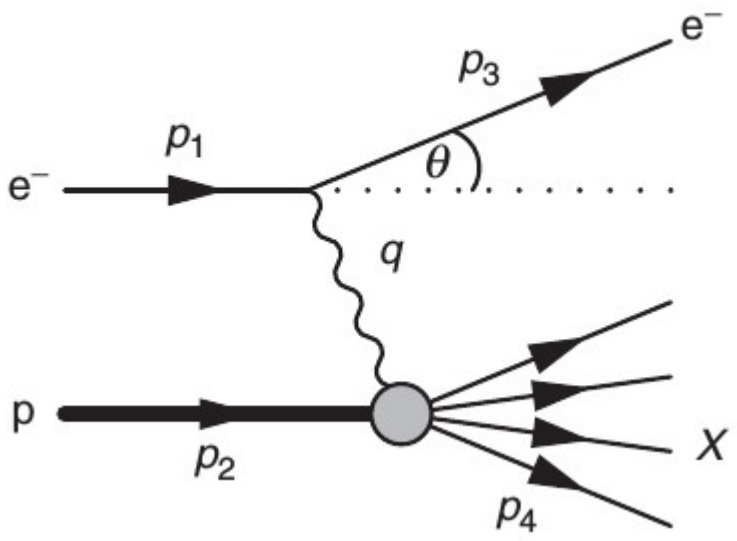

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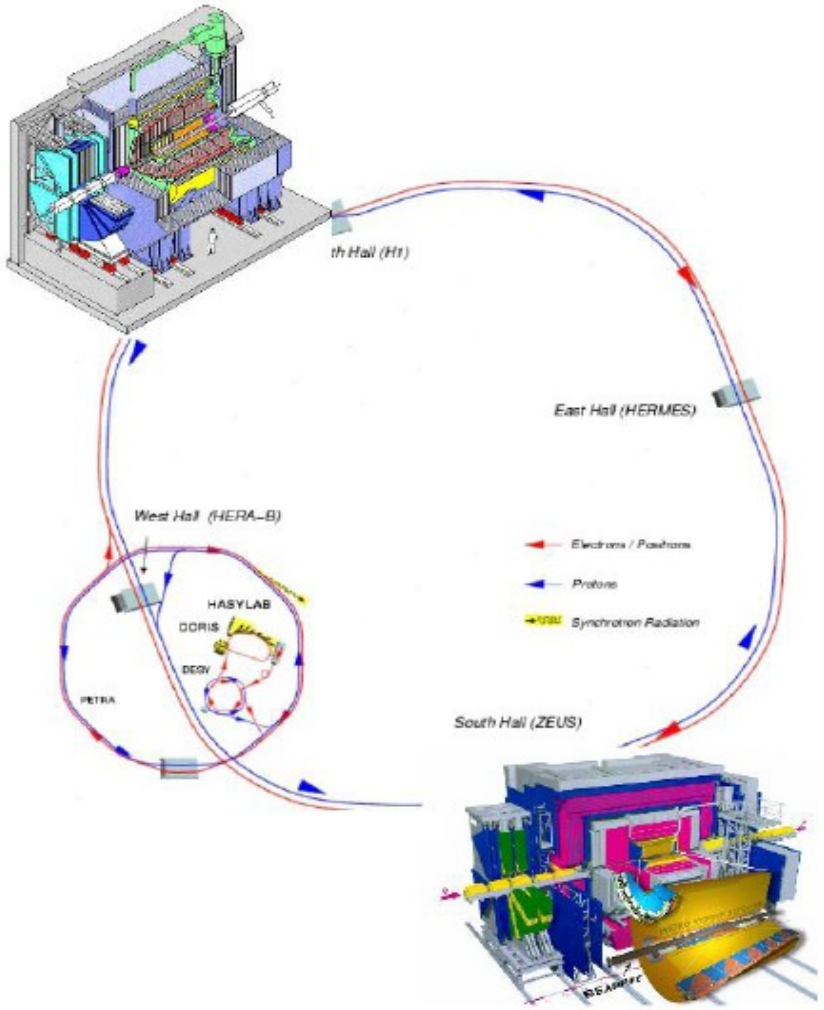
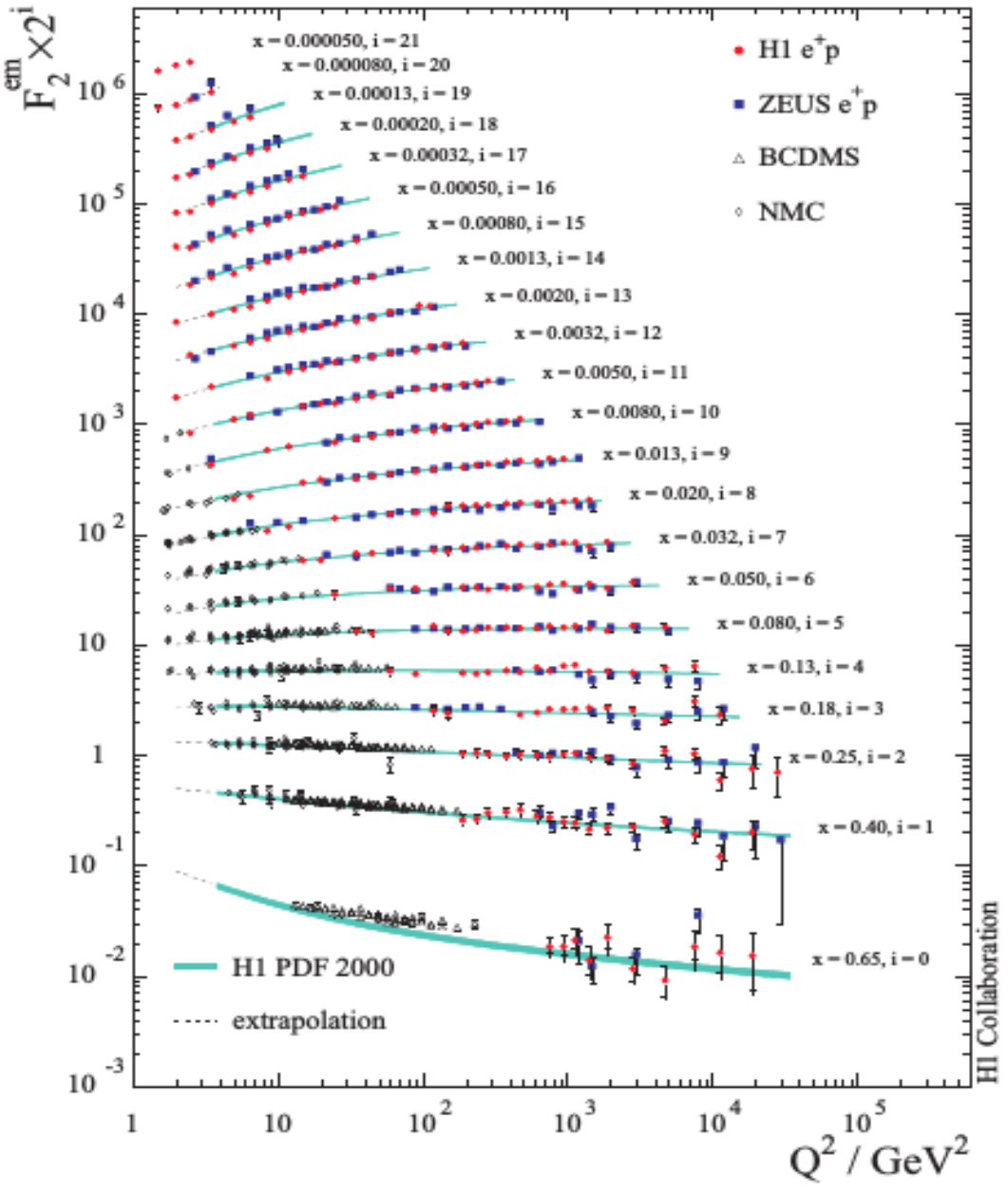
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha_{em}^2}{xQ^4}\left[(1+(1-y)^2)F_2(x,Q^2) - y^2 F_L(x,Q^2)\right]$$

Espalhamento profundamente inelástico elétron – próton (inclusive DIS):



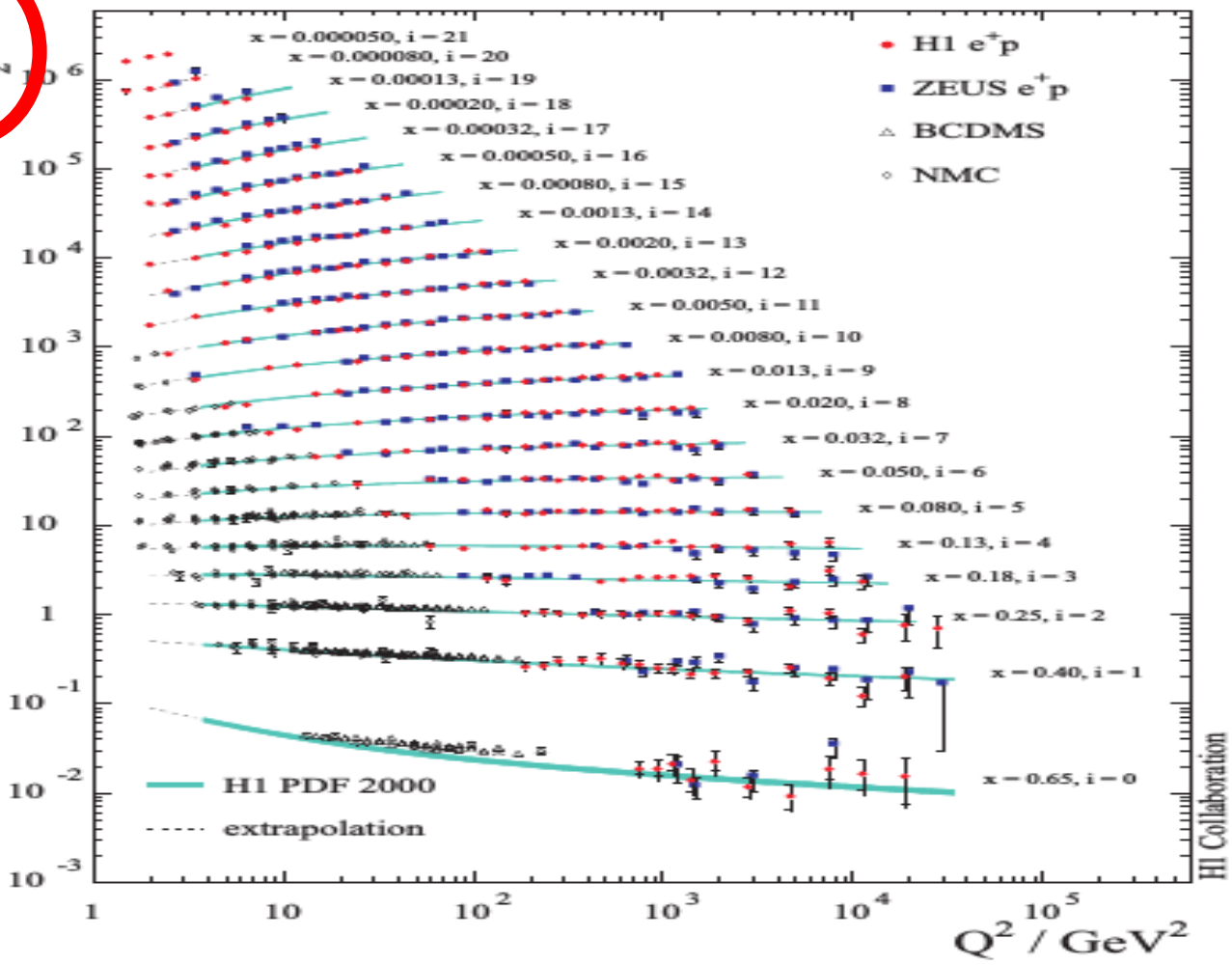
- E_p =920 GeV, E_e =27.6 GeV $\rightarrow$ $\sqrt{s}$ = 320 GeV

DESY – HERA (1992 - 2007)



Espalhamento profundamente inelástico elétron – próton (inclusive DIS):

Determina a quantidade de quarks com fração de momentum x para uma dada resolução



PODER DE RESOLUÇÃO

Espalhamento profundamente inelástico elétron – próton (inclusive DIS):

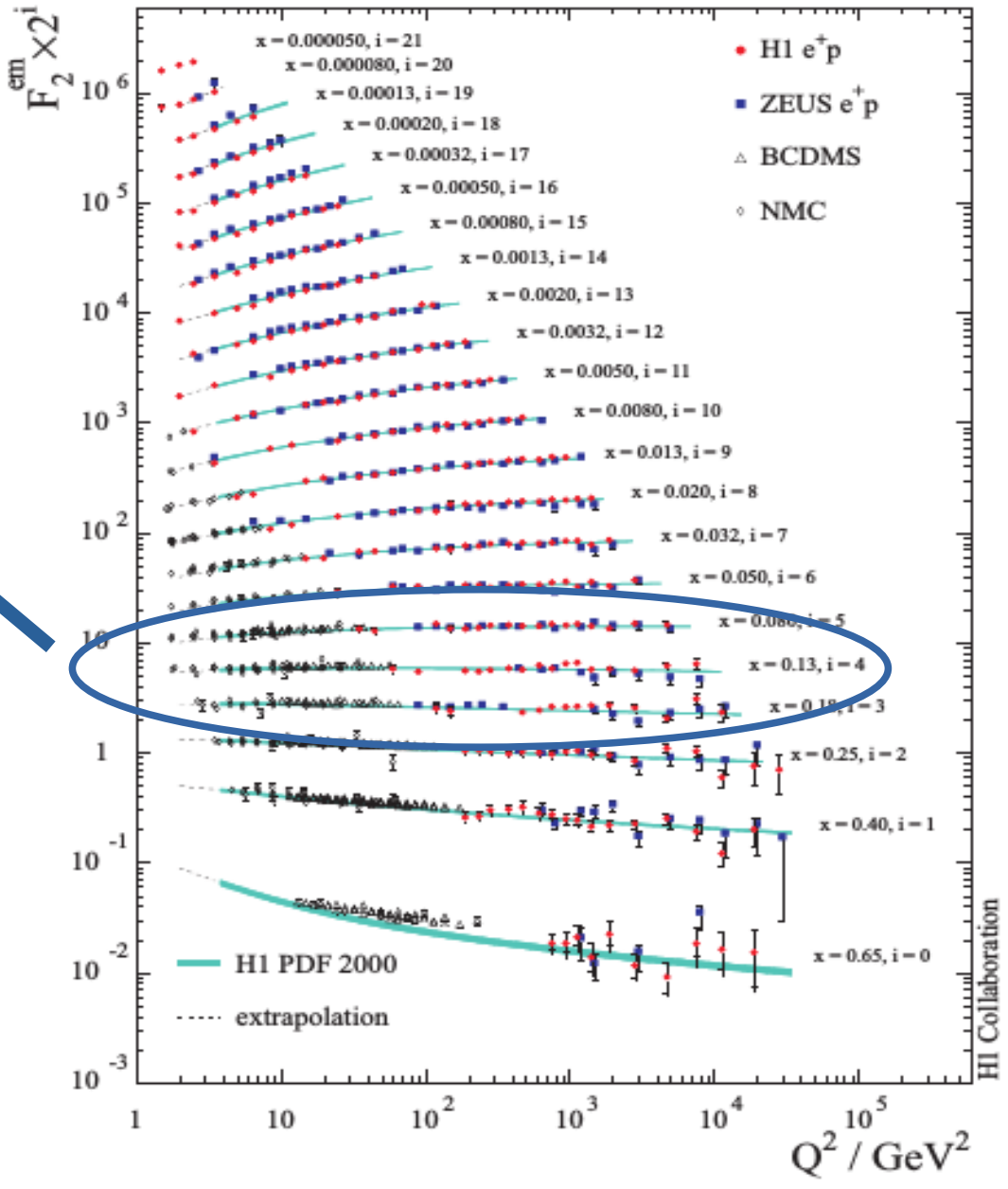
DADOS EXPERIMENTAIS:

Para x intermediário:

$$F_2(x,Q^2) = F_2(x)$$

Escalonamento de Bjorken

INDICATIVO DA INTERAÇÃO COM PARTÍCULAS PONTUAIS CARREGADAS ELETRICAMENTE DENTRO DO PRÓTON!



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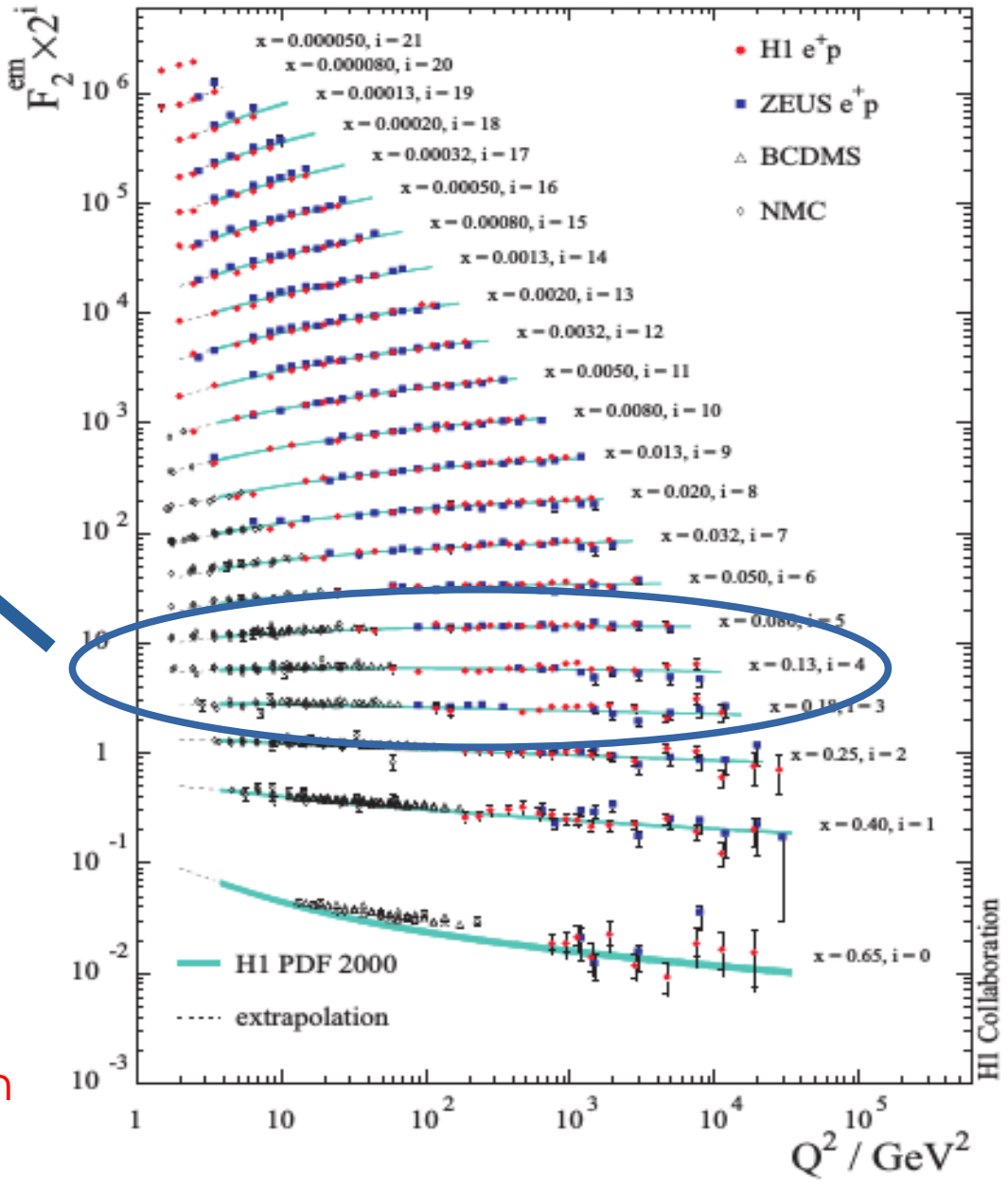
Escalonamento de Bjorken

INDICATIVO DA INTERAÇÃO COM PARTÍCULAS PONTUAIS CARREGADAS ELETRICAMENTE DENTRO DO PRÓTON!

x = Fração do momentum do próton portado pelos pártons!



Espalhamento profundamente inelástico elétron – próton (inclusive DIS):

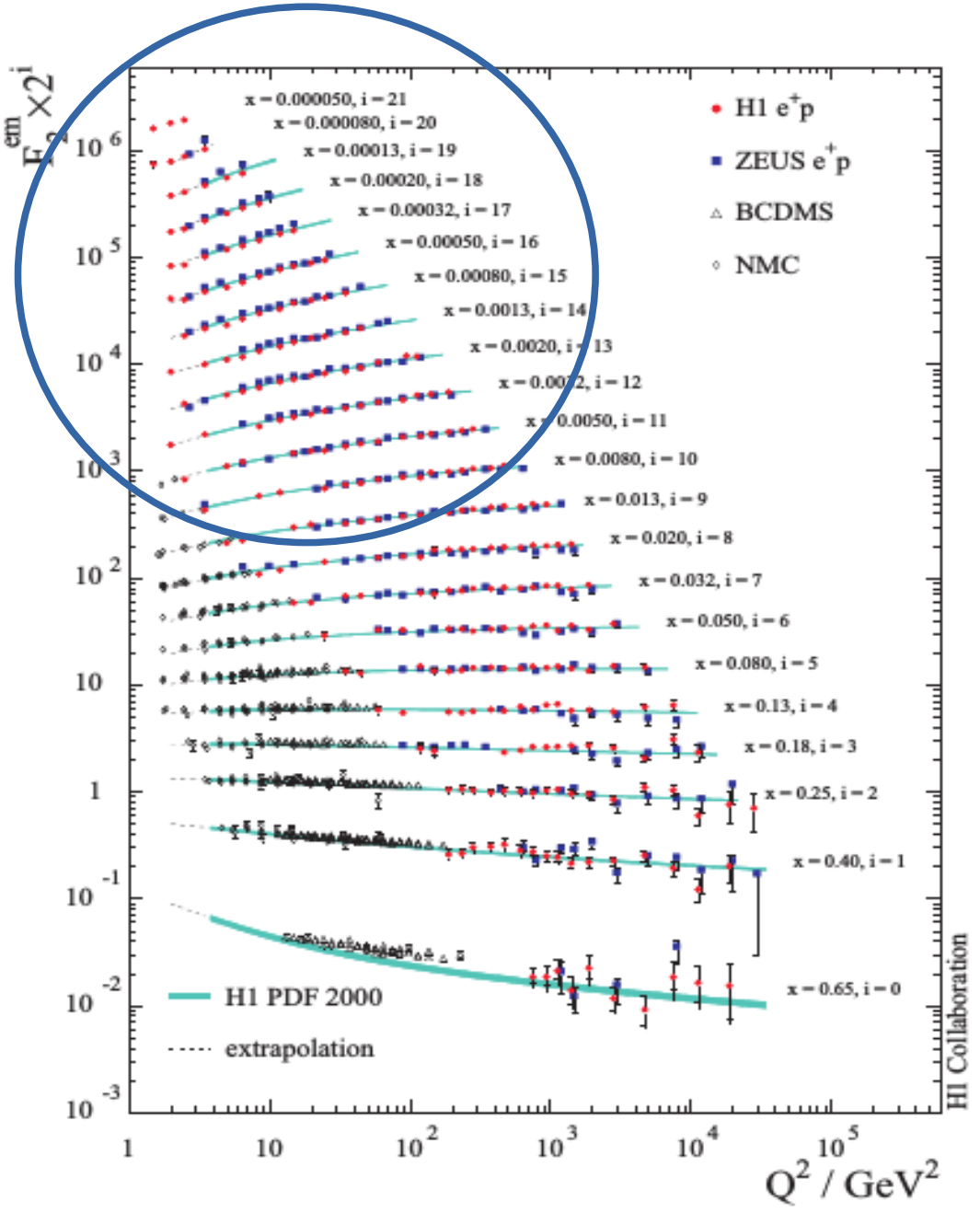
DADOS EXPERIMENTAIS:

Para pequeno – x:

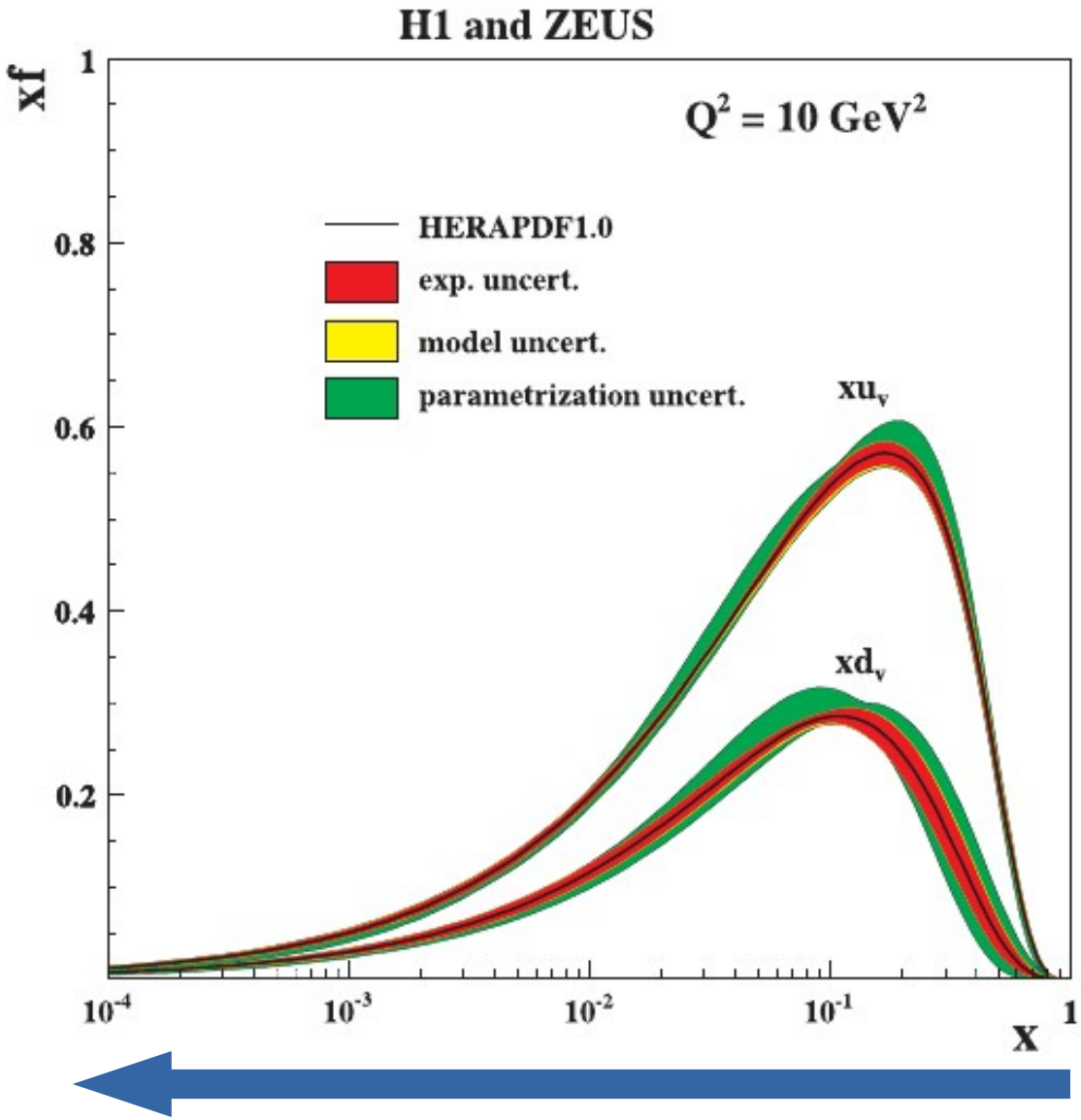
$F_2 = F_2(x,Q^2)$

Violações do Escalonamento de Bjorken.

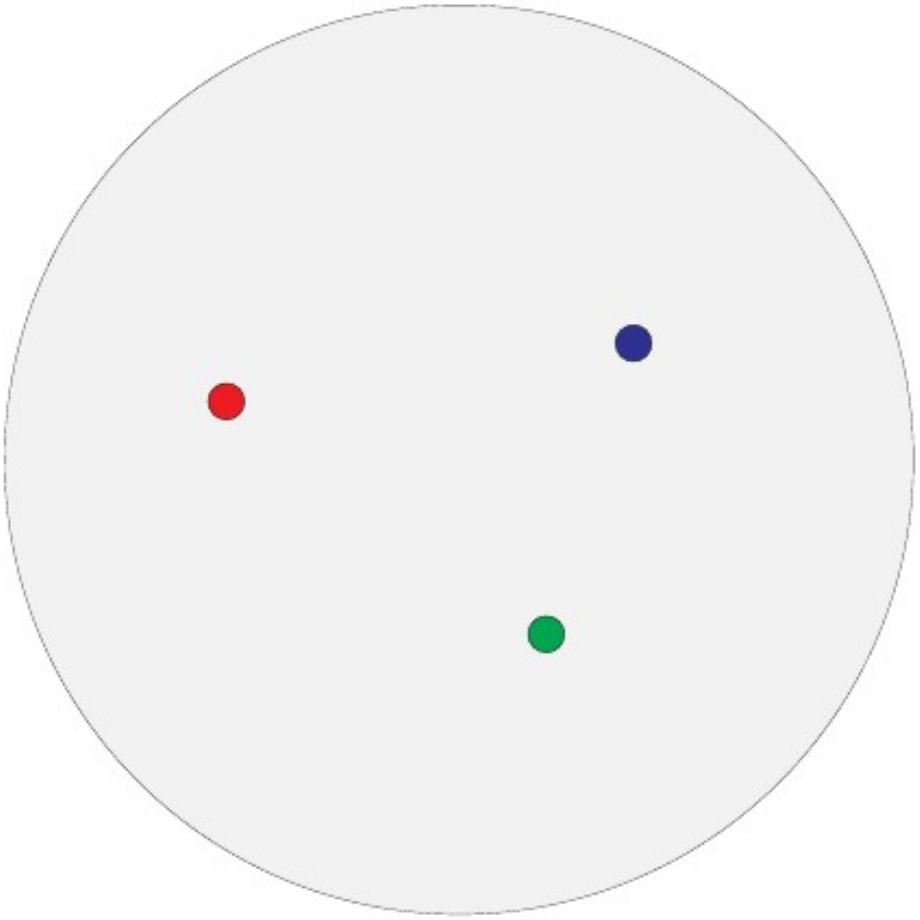
INDICATIVO DE UMA EVOLUÇÃO DINÂMICA DA ESTRUTURA DO PRÓTON (Descrita pela QCD!).



Estrutura partônica do próton:



ENERGIA



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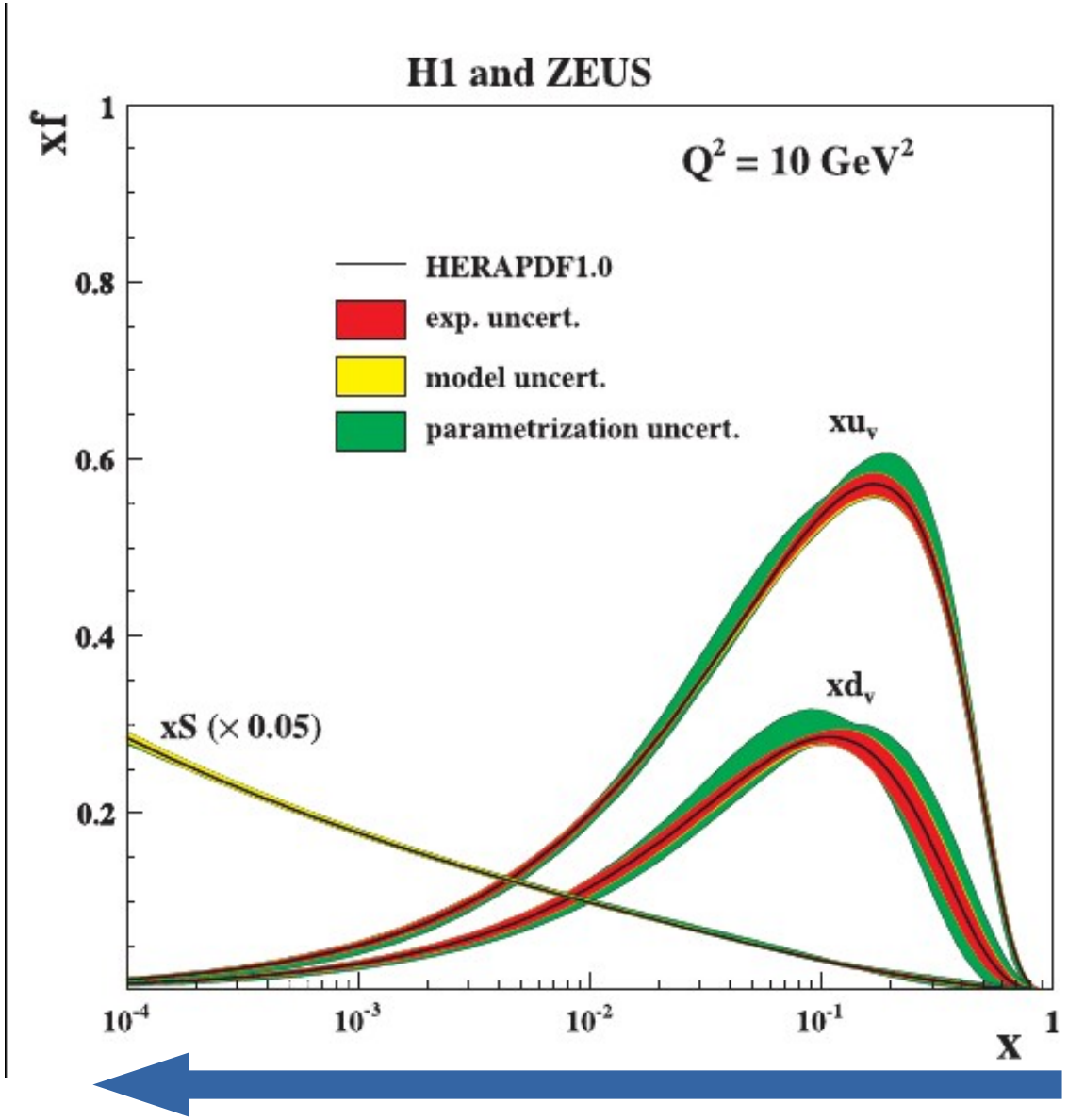

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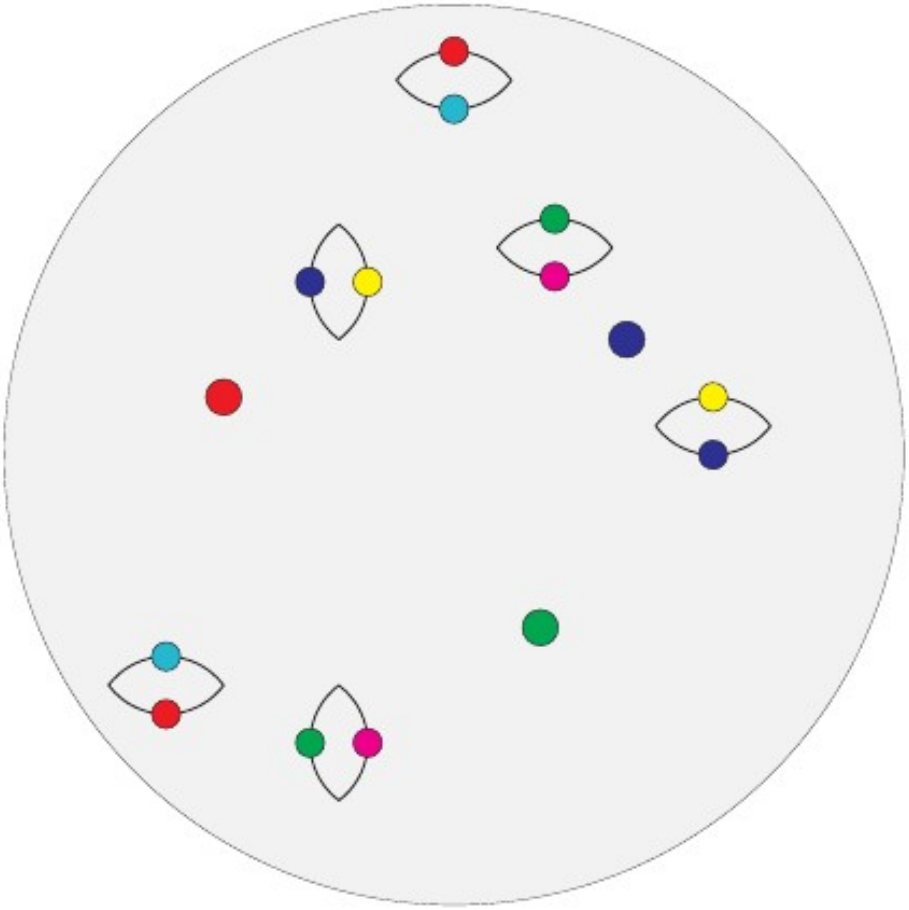

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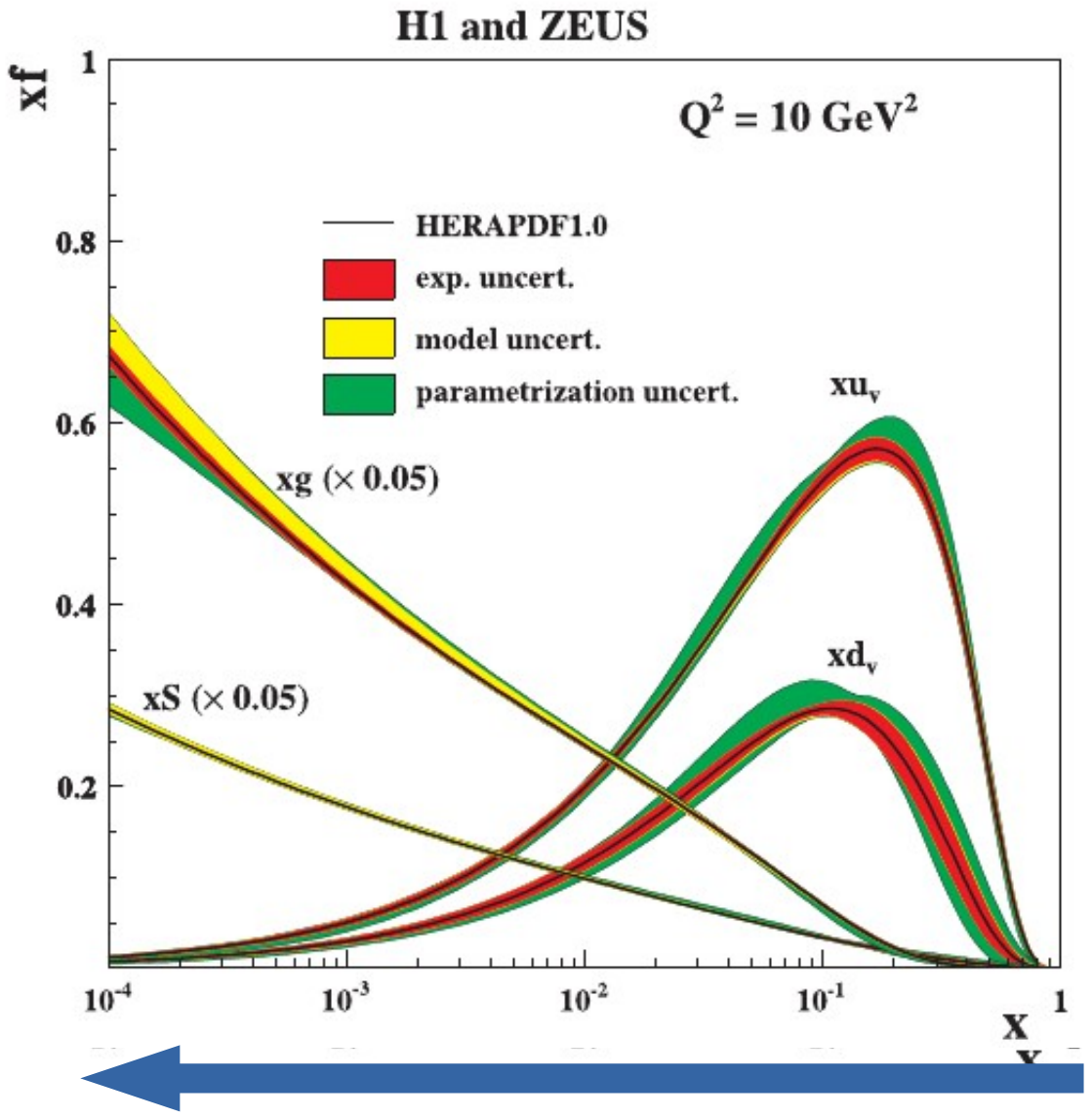

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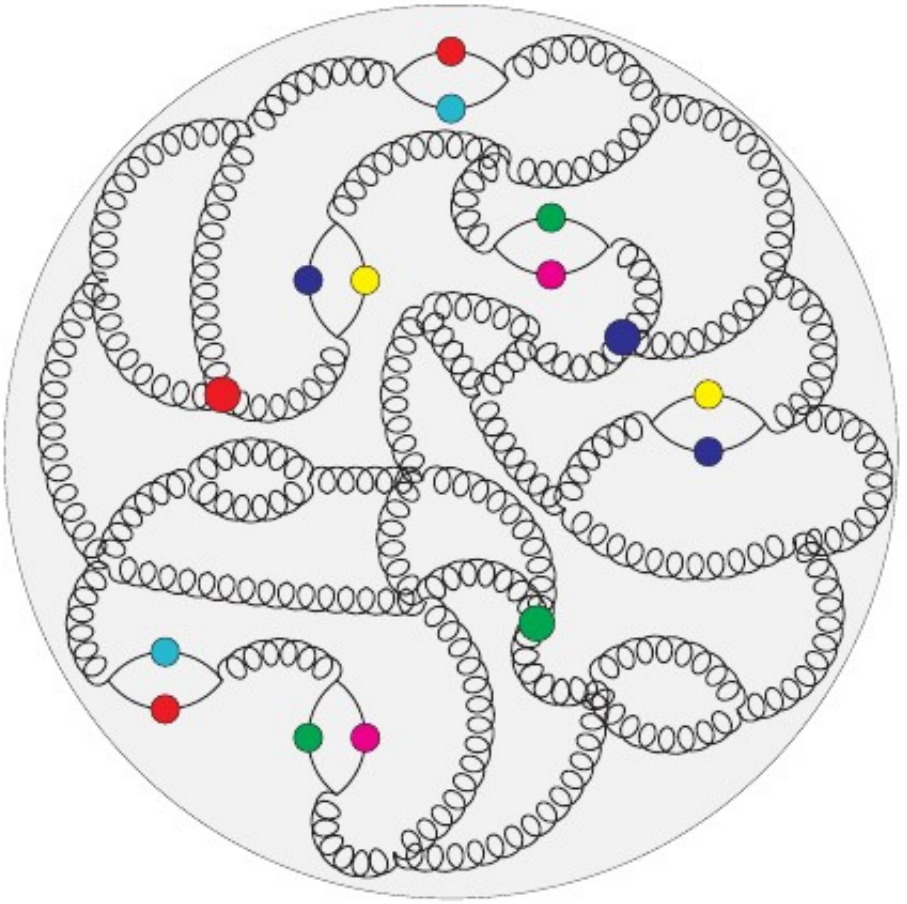

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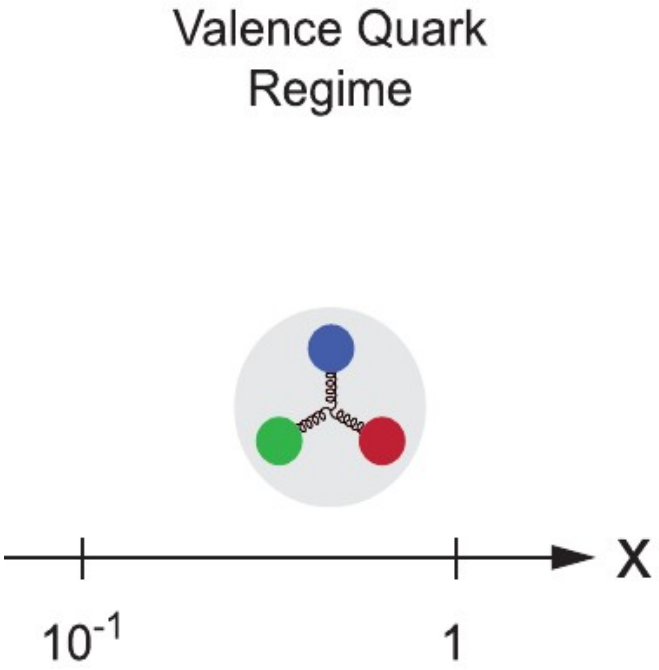

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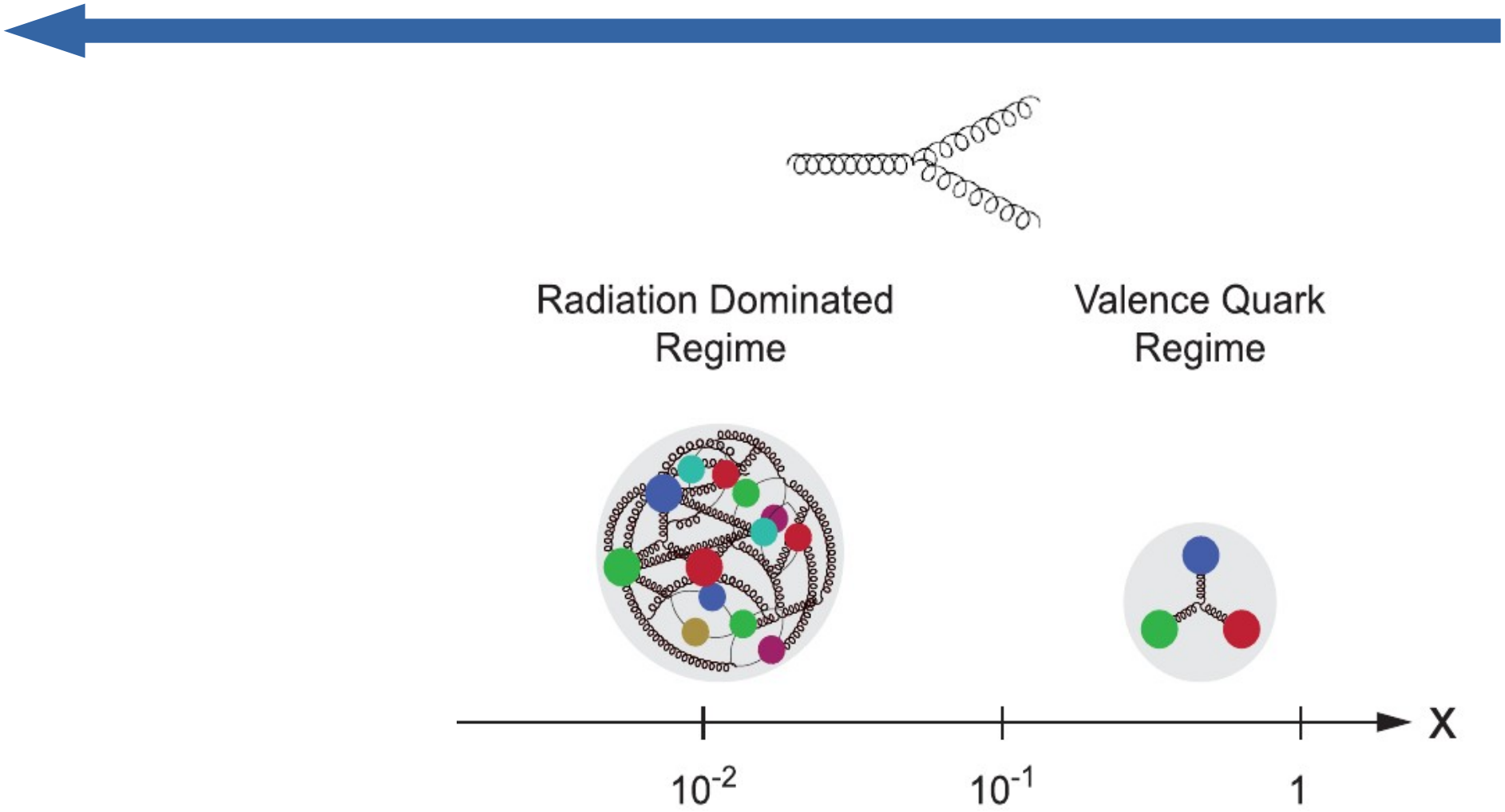

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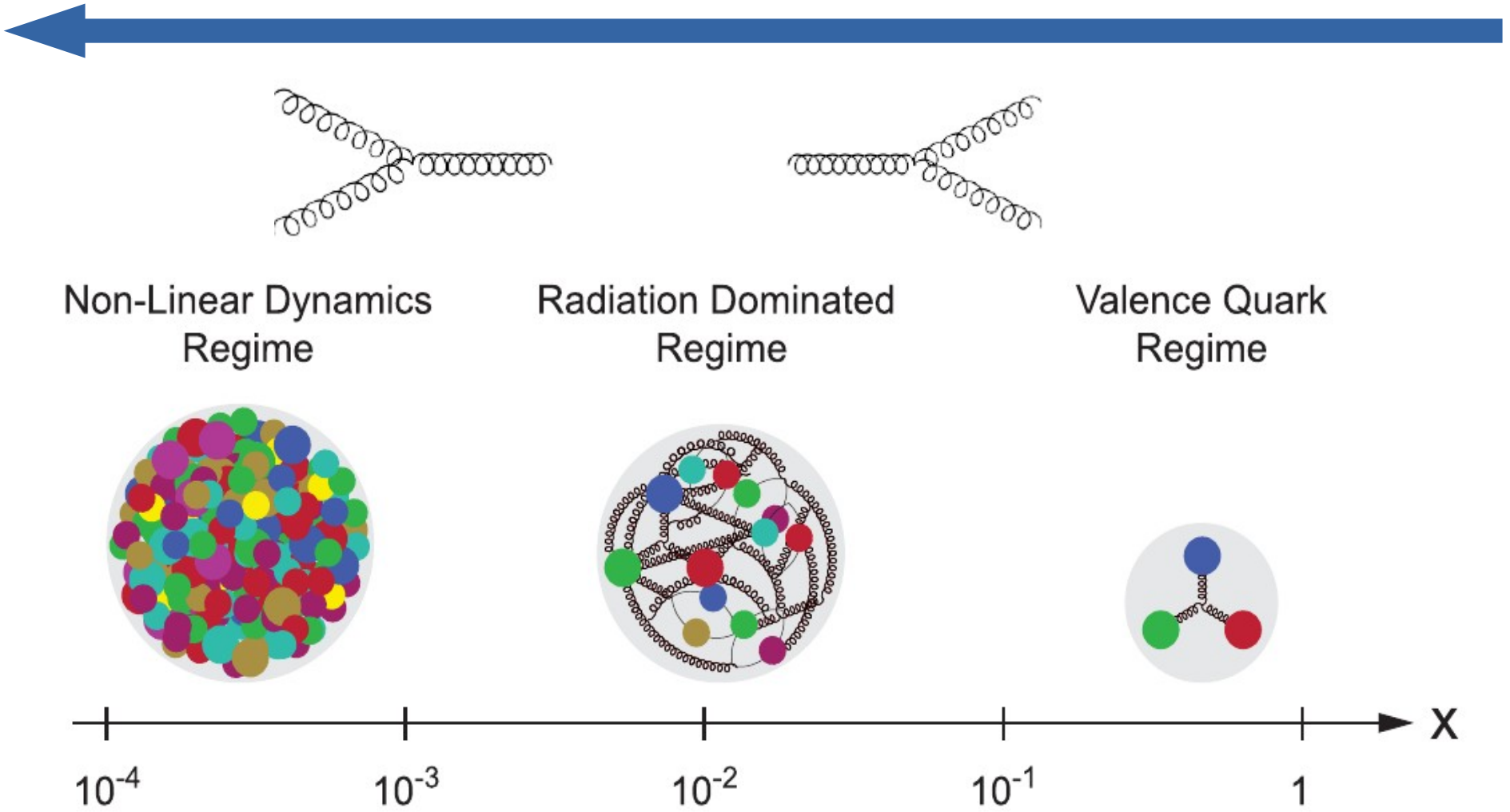
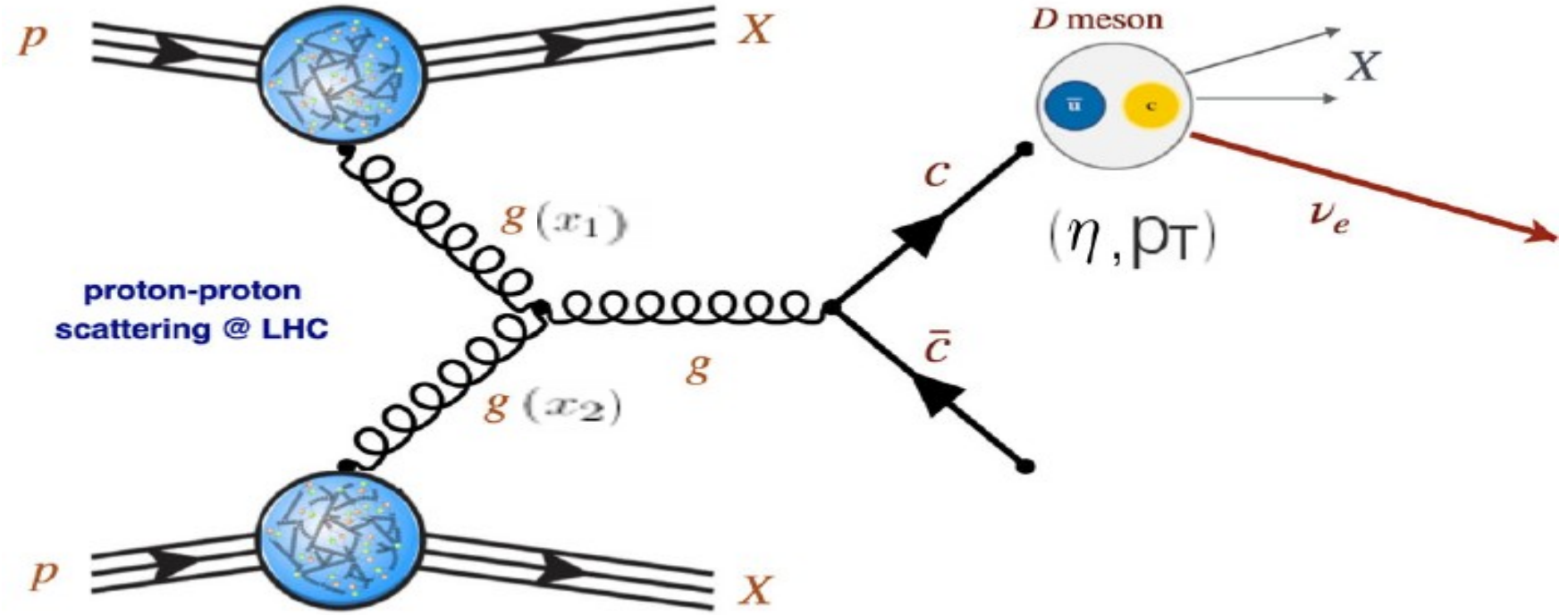


Para que altas energias (pequeno – x) a recombinação de glúons torna-se apreciável →
Efeitos não – lineares na dinâmica QCD!

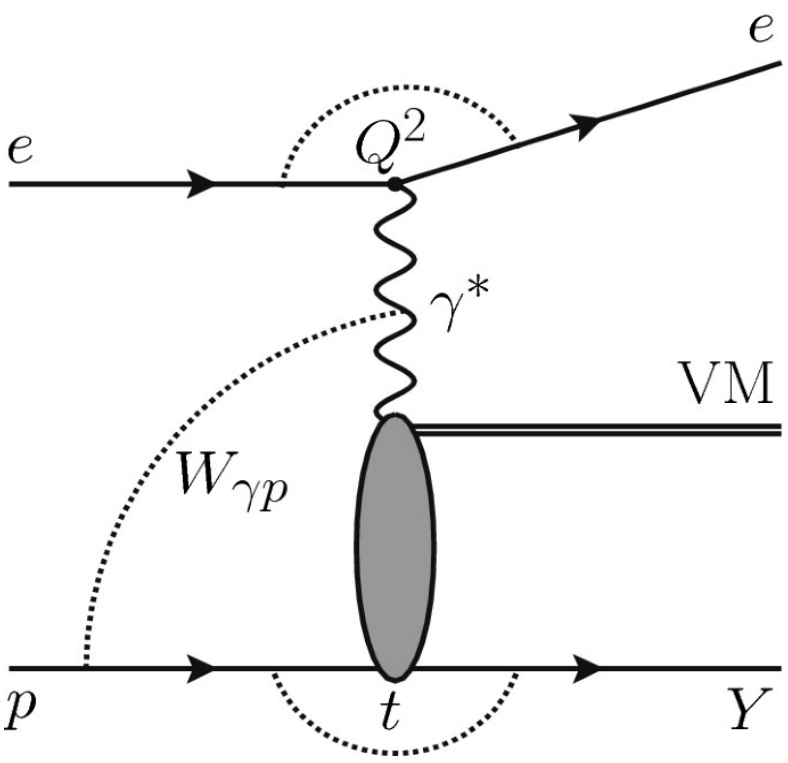
Um breve parênteses:
Produção de partículas no LHC



$$x_1 \propto \frac{p_T}{\sqrt{s}} \exp(+\eta)$$
$$x_2 \propto \frac{p_T}{\sqrt{s}} \exp(-\eta)$$

$$\eta \to +\infty \Rightarrow x_1 \to 1 \text{ and } x_2 \to 0$$

Espalhamento profundamente inelástico elétron – próton (exclusive DIS):



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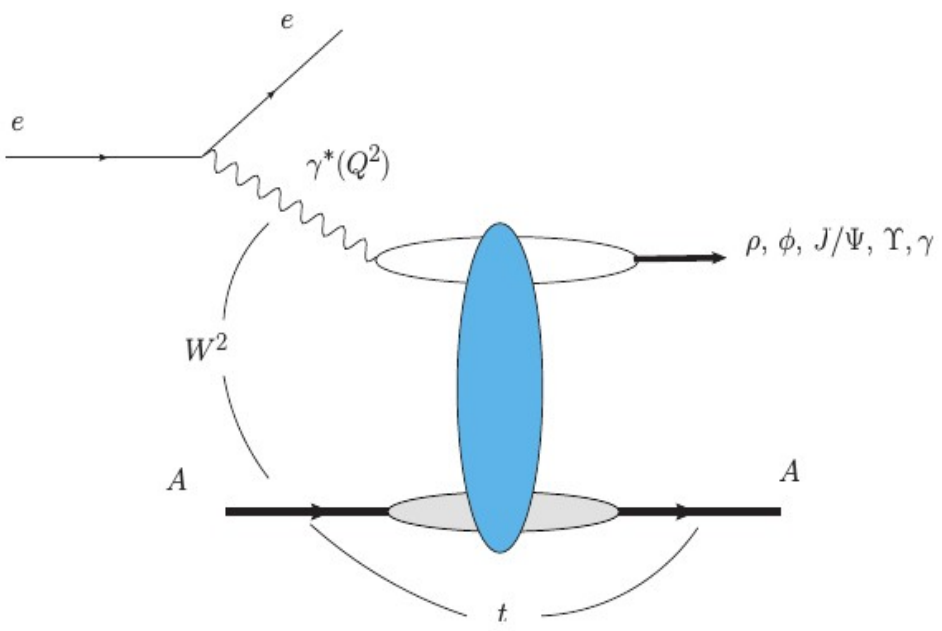
$t = (p - p')^2$ Quadrado do momentum transferido.

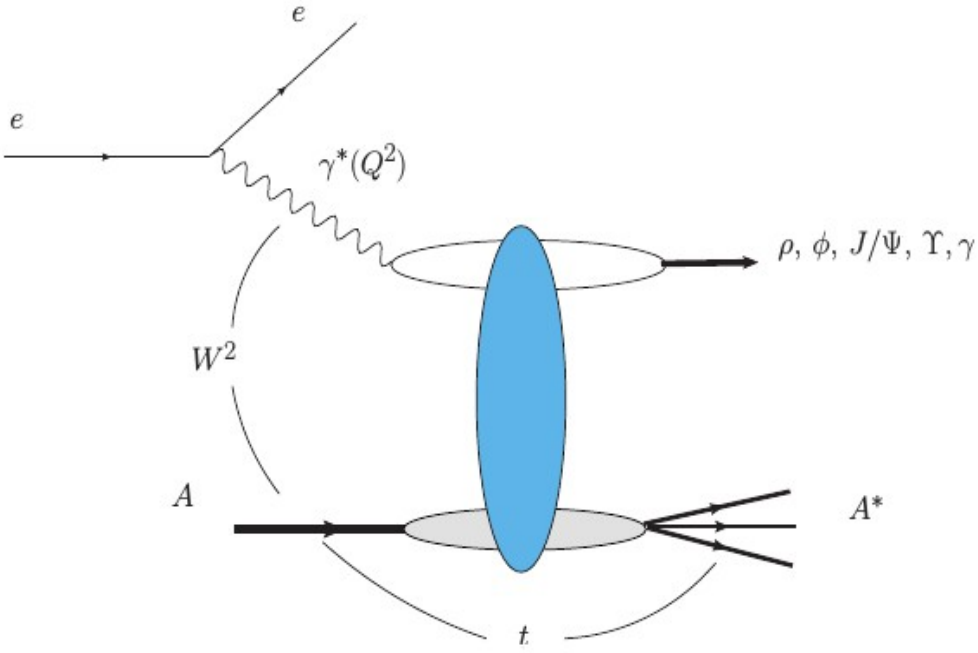
Espalhamento profundamente inelástico elétron – próton (exclusive DIS):

Interação coerente:



$$\left.\frac{d\sigma^{\gamma^* A\to V\,A}}{dt}\right|_{T,L}^{coh} = \frac{1}{16\pi}\left|\left\langle \mathcal{A}_{T,L}(x, Q^2, \Delta)\right\rangle\right|^2$$

Interação incoerente:

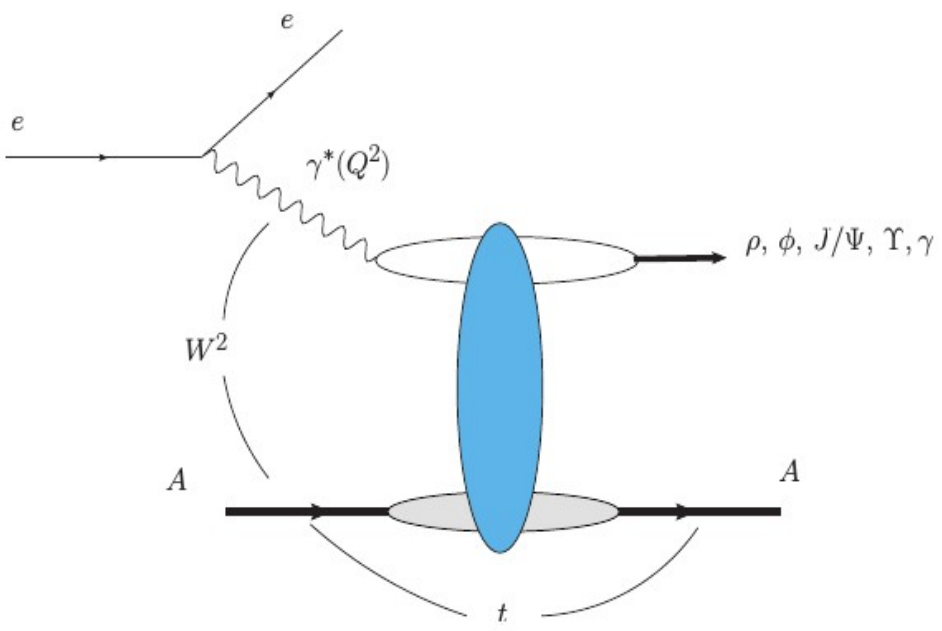


$$\left.\frac{d\sigma^{\gamma^* A\to V\,X}}{dt}\right|_{T,L}^{inc} = \frac{1}{16\pi}\left(\left\langle\left|\mathcal{A}_{T,L}(x, Q^2, \Delta)\right|^2\right\rangle - \left|\left\langle \mathcal{A}_{T,L}(x, Q^2, \Delta)\right\rangle\right|^2\right)$$

Média sobre as possíveis configurações da função de onda hadrônica.

Espalhamento profundamente inelástico elétron – próton (exclusive DIS):

Interação coerente:



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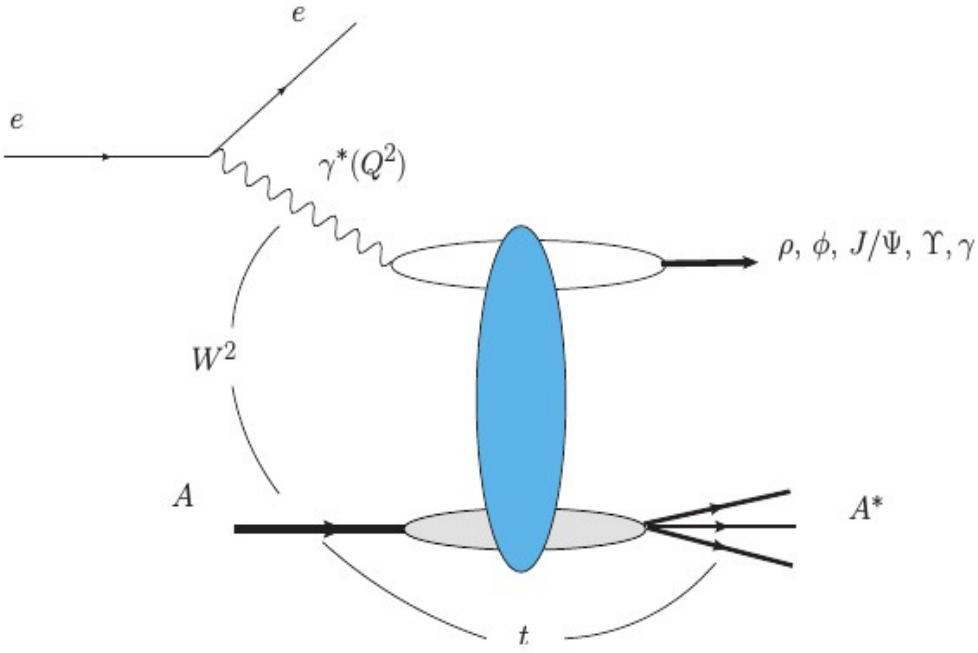

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A seção de choque destes processos é fortemente dependente:

- da descrição da dinâmica QCD;
- da descrição da distribuição espacial de partículas dentro do alvo.

Exemplo: Produção exclusiva de mésons em colisões elétron - núcleo

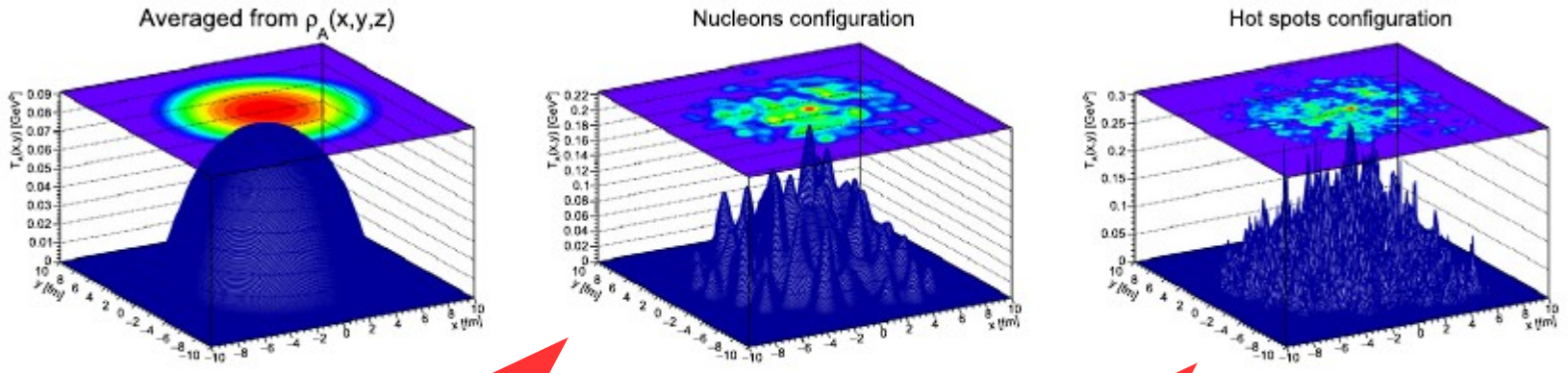


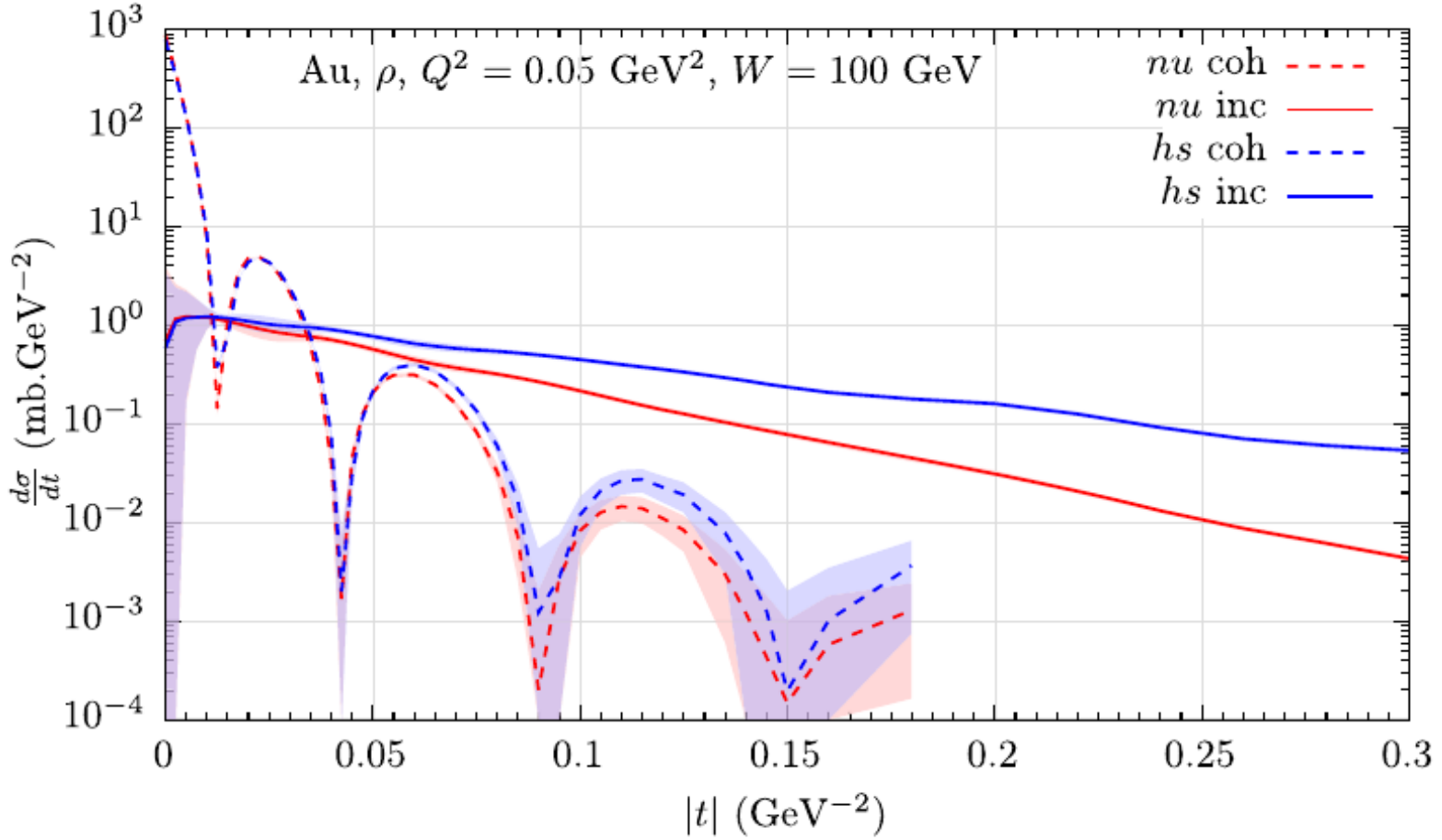
Fig. 2. Comparison of nuclear profiles, $T_A(b)$, calculated from nuclear density functio $\rho_A(\vec{r})$ (left), calculated using *nu* model where each nucleon is represented by Gaussian (center), and calculated using the hot shots model, where every nucleon from *nu* model is represented by a set of hot spots (right).

$$T_A(\boldsymbol{b}) = \frac{1}{2\pi B_p} \sum_{i=1}^{A} \exp\left[-\frac{(\boldsymbol{b}-\boldsymbol{b}_i)^2}{2B_p}\right]$$

$$T_A(\boldsymbol{b}) = \frac{1}{2\pi B_{hs}} \sum_{i=1}^{A} \frac{1}{N_{hs}} \sum_{j=1}^{N_{hs}} \exp\left[-\frac{(\boldsymbol{b}-\boldsymbol{b}_i-\boldsymbol{b}_j)^2}{2B_{hs}}\right]$$

Krelina, VPG, Cepila, NPA 989, 189 (2019).

Exemplo: Produção exclusiva de mésons em colisões elétron - núcleo



Krelina, VPG, Cepila, NPA 989, 189 (2019).

Perspectivas:

Colisões elétron – próton nas próximas décadas

LHeC and FCC – eh at CERN

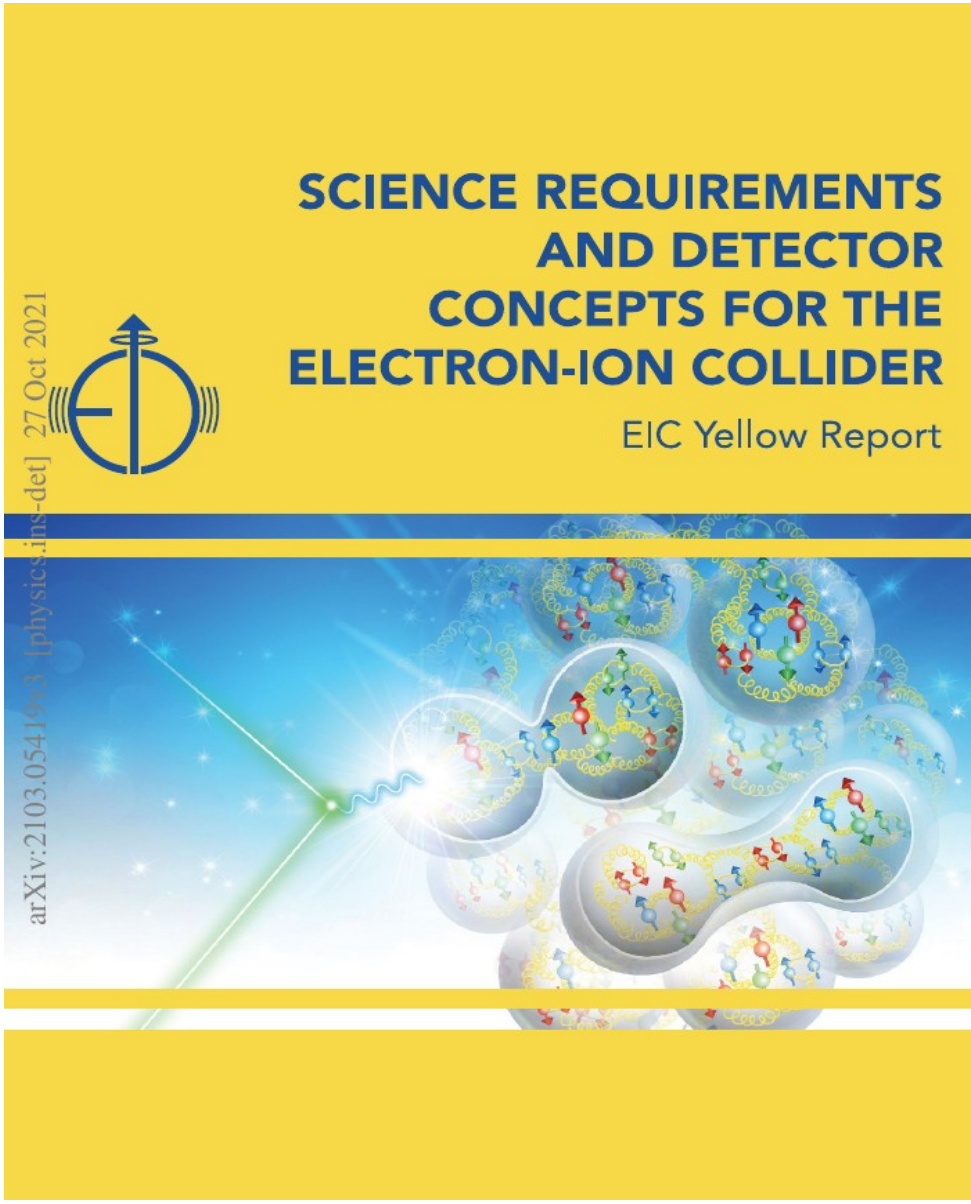
CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

To be submitted to J. Phys. G

EIC at BNL



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ArXiv:2007.14491 (hep-ex)

J. Phys. G48 (2021) 1105501

373 páginas

300 autores

156 Instituições

3 do Brasil (UFPel, UFRN e UFRGS)

Proposto

Funcionamento: ?????

Colisões elétron – próton nas próximas décadas

EIC at BNL

ArXiv:2103.05419 (physics.ins-det)

Nuc. Phys. A 1026 (2022) 122447

902 páginas

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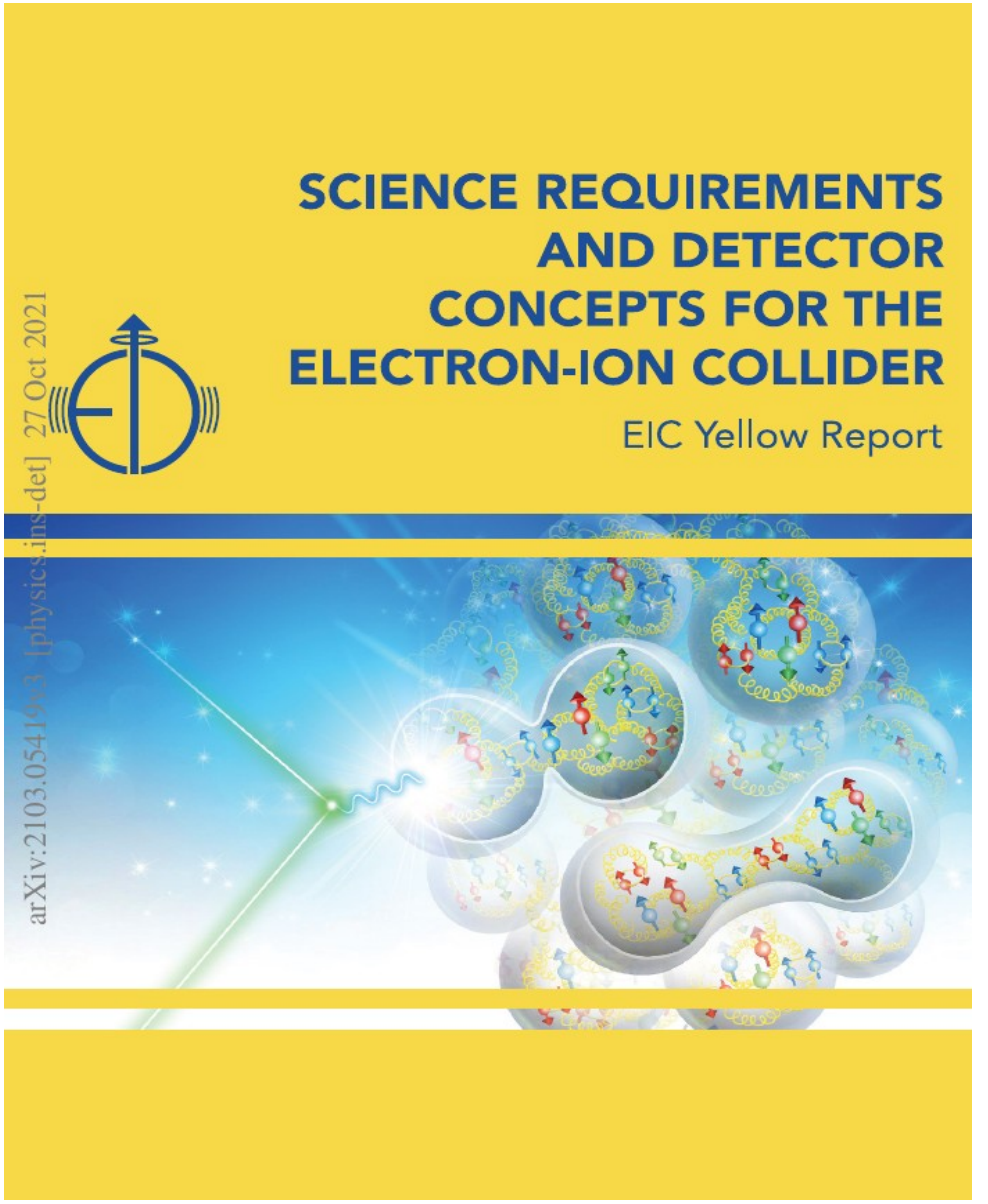
151 Instituições

3 do Brasil (UFPel,ITA e UFRGS)

Aprovado pelo DOE/EUA

Previsão de funcionamento: 2032 ->



Worldwide Interest in EIC

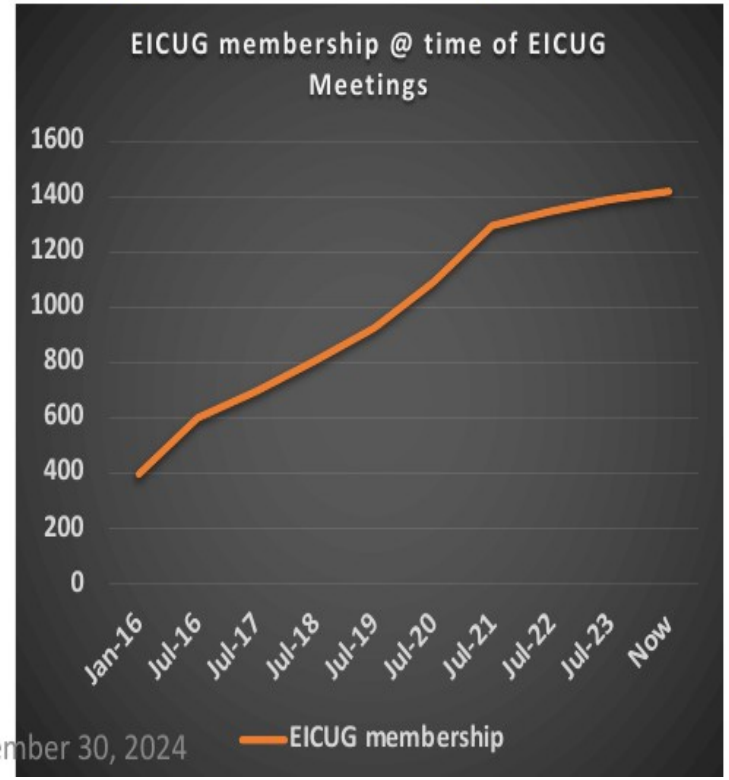
The EIC User Group:
https://eicug.github.io/

Formed 2016 – (with 700 enthusiasts)

- **1450+ collaborators,**
- **~40 countries,**
- **290+ institutions**

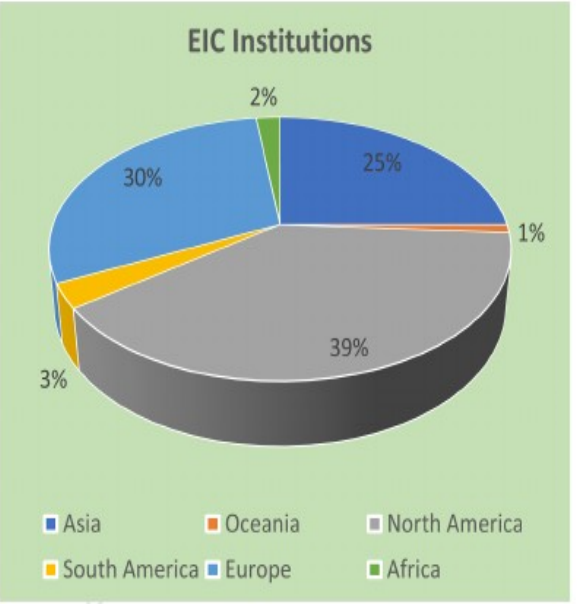
as of May, 2024.

Strong International Participation.



Annual EICUG meeting

2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 FIU, Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland
2024 Lehigh U, PA



Extraído do seminário ministrado por Abhay Deshpande, EIC Science Director, no IWSHO2024

Uma alternativa proposta recentemente ...

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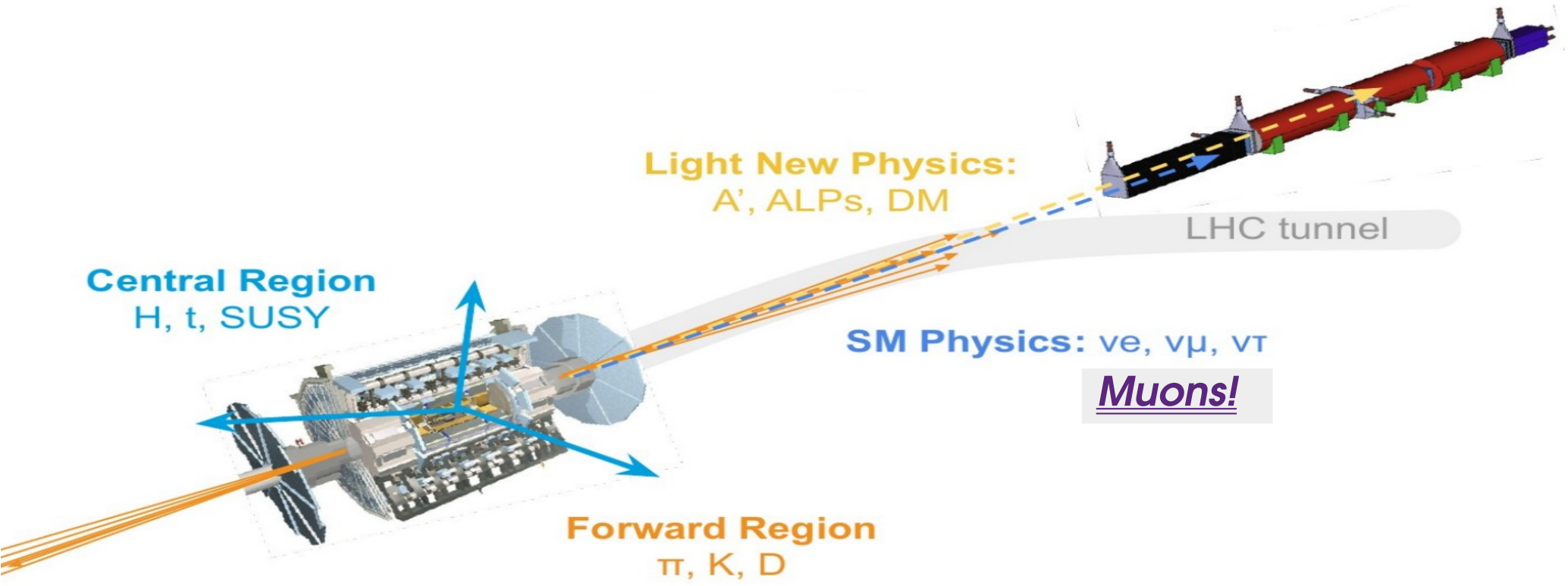
Deep-Inelastic Scattering at TeV Energies with LHC Muons

Reinaldo Francener[1,2,3], Victor P. Gonçalves[4], Felix Kling[5,6], Peter Krack[2,3] and Juan Rojo[2,3]

arXiv:2506.13889v1 [hep-ph] 16 Jun 2025



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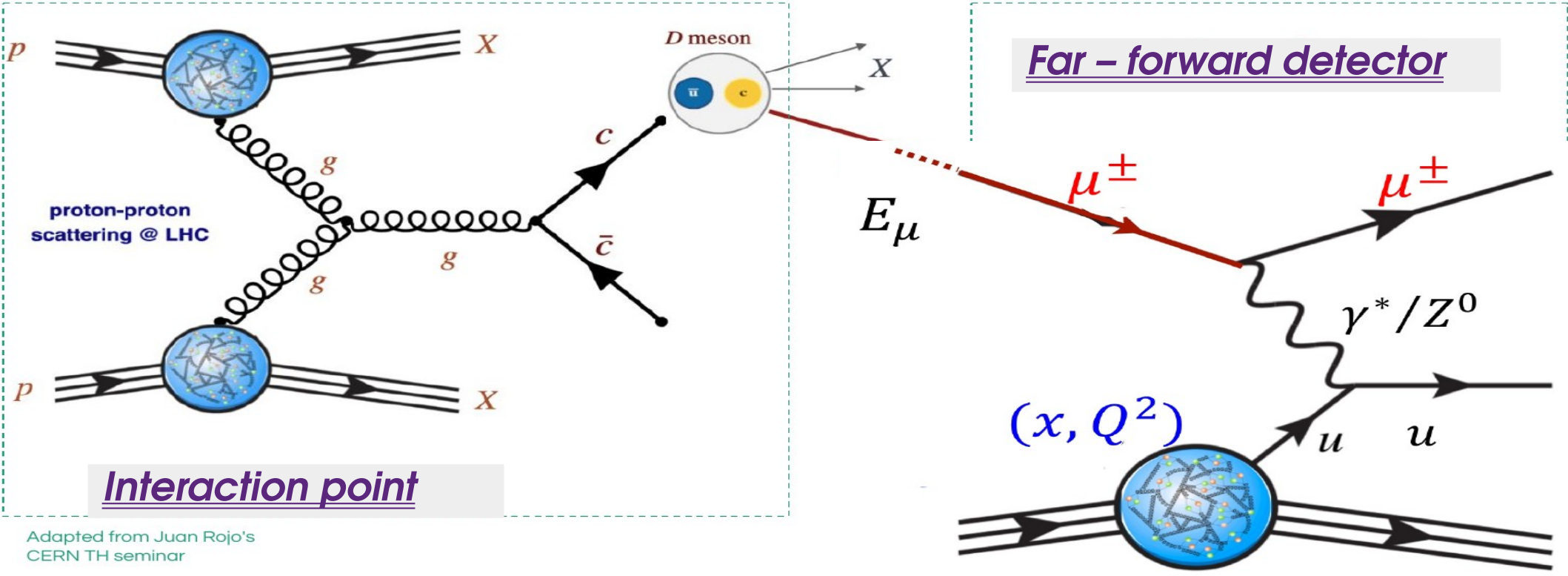
arXiv:2506.13889v1 [hep-ph] 16 Jun 2025



Adapted from Juan Rojo's CERN TH seminar

Uma alternativa proposta recentemente ...

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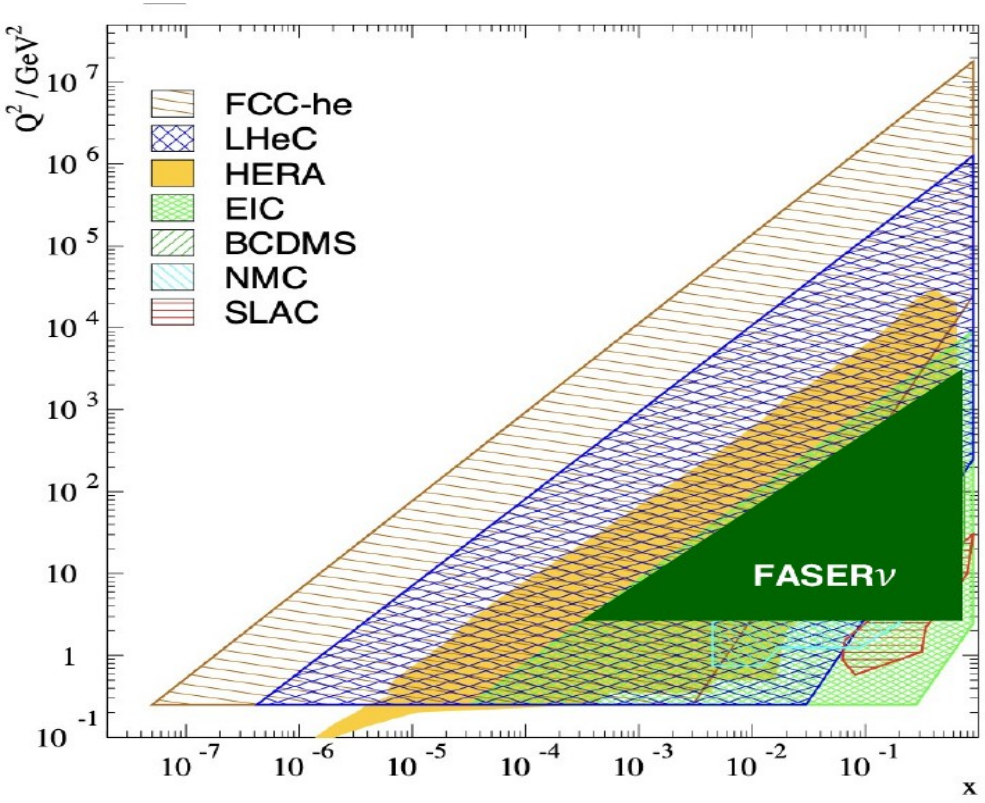

- Região cinemática provada semelhante àquela do EIC!

- Experimento DIS com múons em laborário mais energético de todos os tempos.

Ao invés de conclusões...

Questões em aberto:

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#1: Qual é o RAIO do próton?

#2: Qual é a ESTRUTURA do próton?

#3: Como é o SPIN do próton descrito a partir de seus constituintes?

#4: Como é a MASSA do próton descrita a partir de seus constituintes?

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Continuamos na luta ...

Muito obrigado pela atenção!