Jets and Hadronization in a Nuclear Environment

Abhijit Majumder
Wayne State University

HUGS 2019, Jefferson Lab., June 10-11, 2019

Most of this material is in

The Theory and Phenomenology of Perturbative QCD Based Jet Quenching
A. Majumder (Ohio State U.), M. Van Leeuwen (Utrecht U.). Feb 2010. 77 pp.
Published in **Prog.Part.Nucl.Phys. 66 (2011) 41-92**
DOI: 10.1016/j.ppnp.2010.09.001
e-Print: **arXiv:1002.2206 [hep-ph] | PDF**

Higher twist jet broadening and classical propagation.
A. Majumder, Berndt Muller, (Duke U.) . May 2007. (Published May 2007). 16pp.
Published in **Phys.Rev.C77:054903,2008**.
e-Print: **arXiv:0705.1147** [nucl-th]

Hard collinear gluon radiation and multiple scattering in a medium
Abhijit Majumder (Ohio State U.). Dec 2009. 30 pp.
Published in **Phys.Rev. D85 (2012) 014023**
DOI: 10.1103/PhysRevD.85.014023
e-Print: **arXiv:0912.2987 [nucl-th] | PDF**

The In-medium scale evolution in jet modification.
A. Majumder, (Duke U. & Ohio State U.) . Jan 2009. 4pp.
e-Print: **arXiv:0901.4516** [nucl-th]

Multiple parton scattering in nuclei: Parton energy loss.
Xin-Nian Wang, (LBL, Berkeley) , Xiao-feng Guo, (Kentucky U.) . Feb 2001. 37pp.
Published in **Nucl.Phys.A696:788-832,2001**.
e-Print: **hep-ph/0102230**

Lecture 1: outline

The basic problem of jets and jet modification

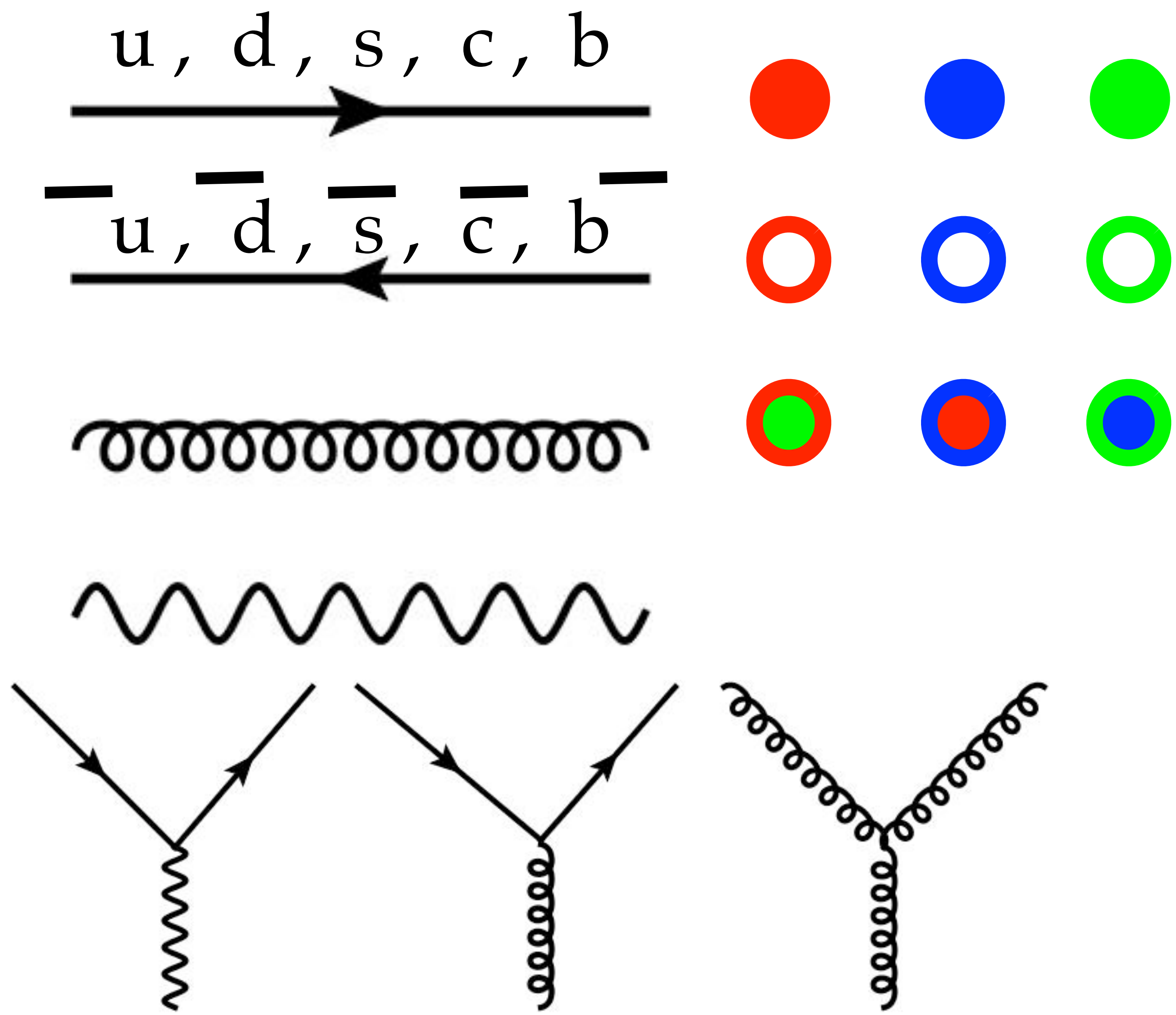
Deep-inelastic scattering, the theorists sandbox

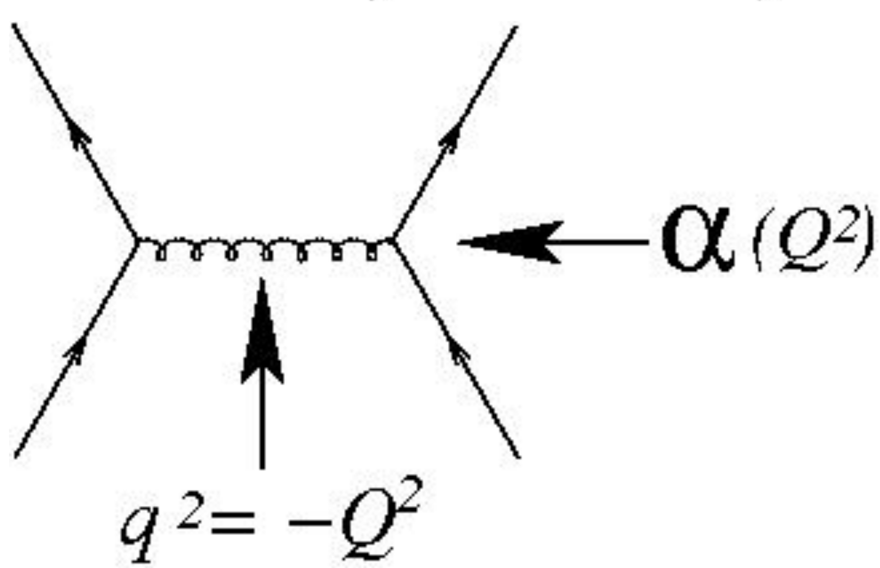
The variables, scales and notations involved

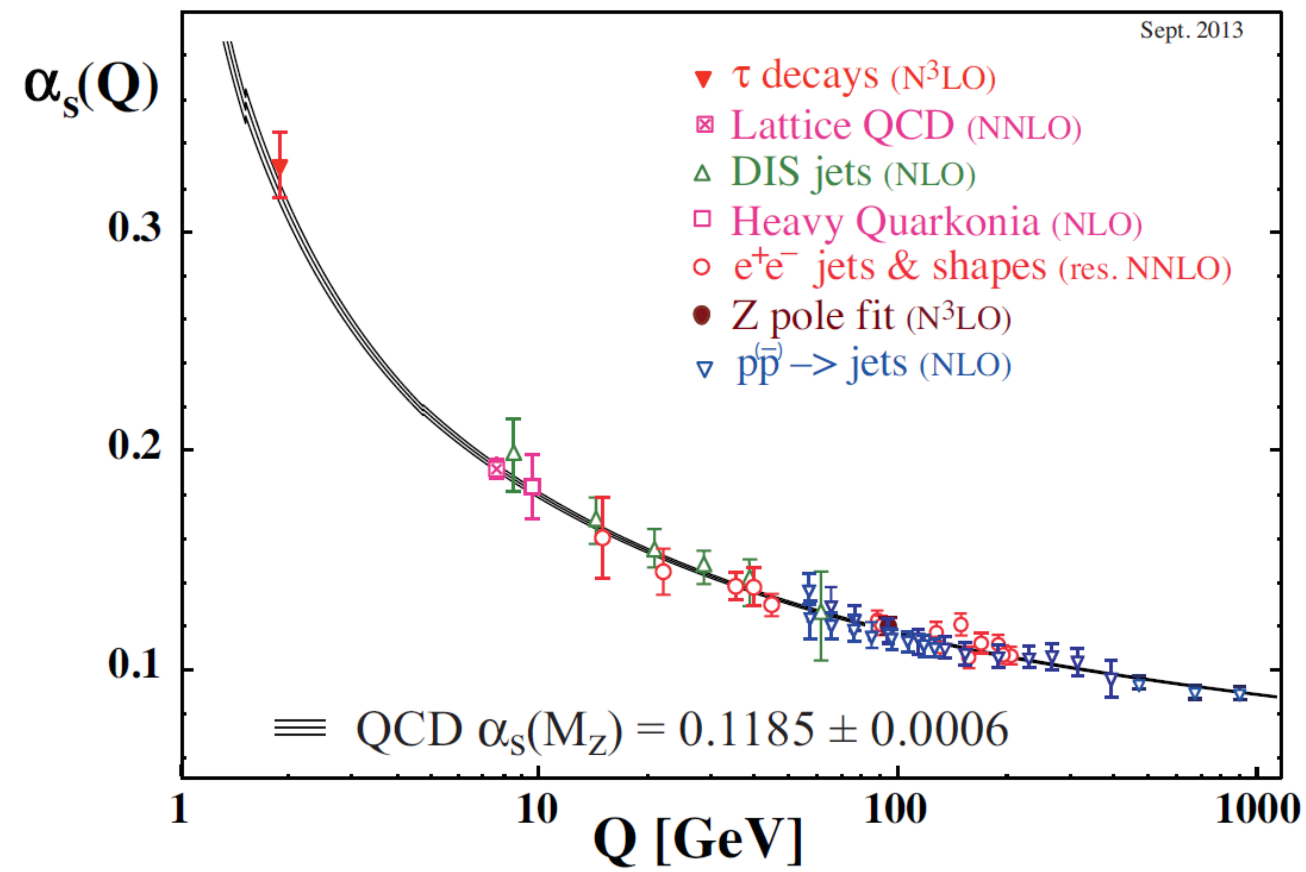
Leading twist (power) in DIS

Basic underlying physical picture

Quarks, Gluons, and the QCD coupling







coupling gets weaker at large momentum transfer

$Q^2 >> \Lambda^2_{QCD}$

What is a jet?

Many ways to answer the question

What we state:
A collection of particles combined by some jet clustering algorithm
(*regardless of source*)

What we want:

Theoretically: A collection of quarks and gluons produced in the decay of a single high energy parton, ***produced in a hard scattering.***

Experimentally: A collection of hadrons produced in the decay of a single high energy parton,

All together: the fate of a single hard parton produced in a hard interaction

Hard: $Q >> \Lambda_{QCD}$

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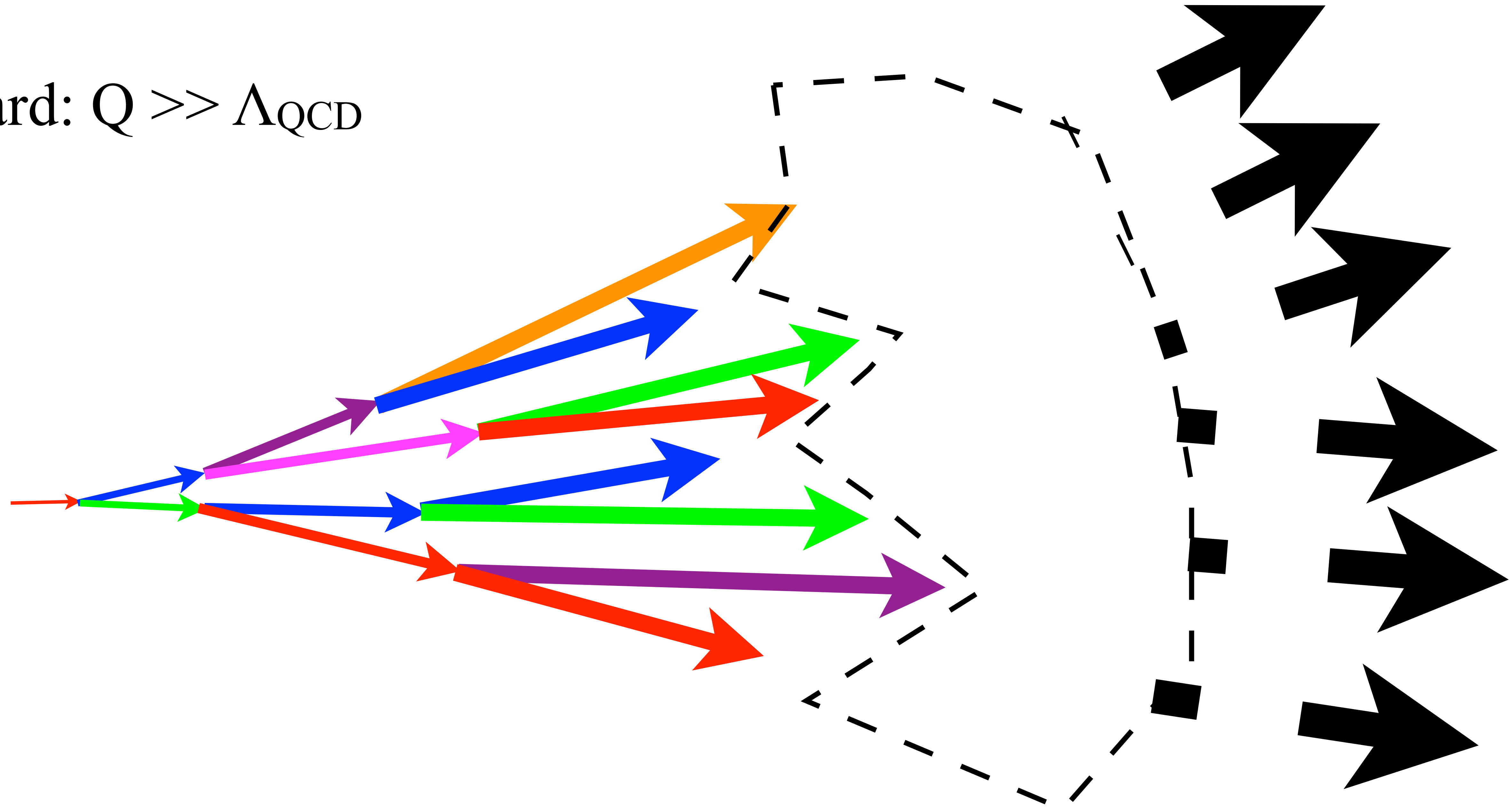

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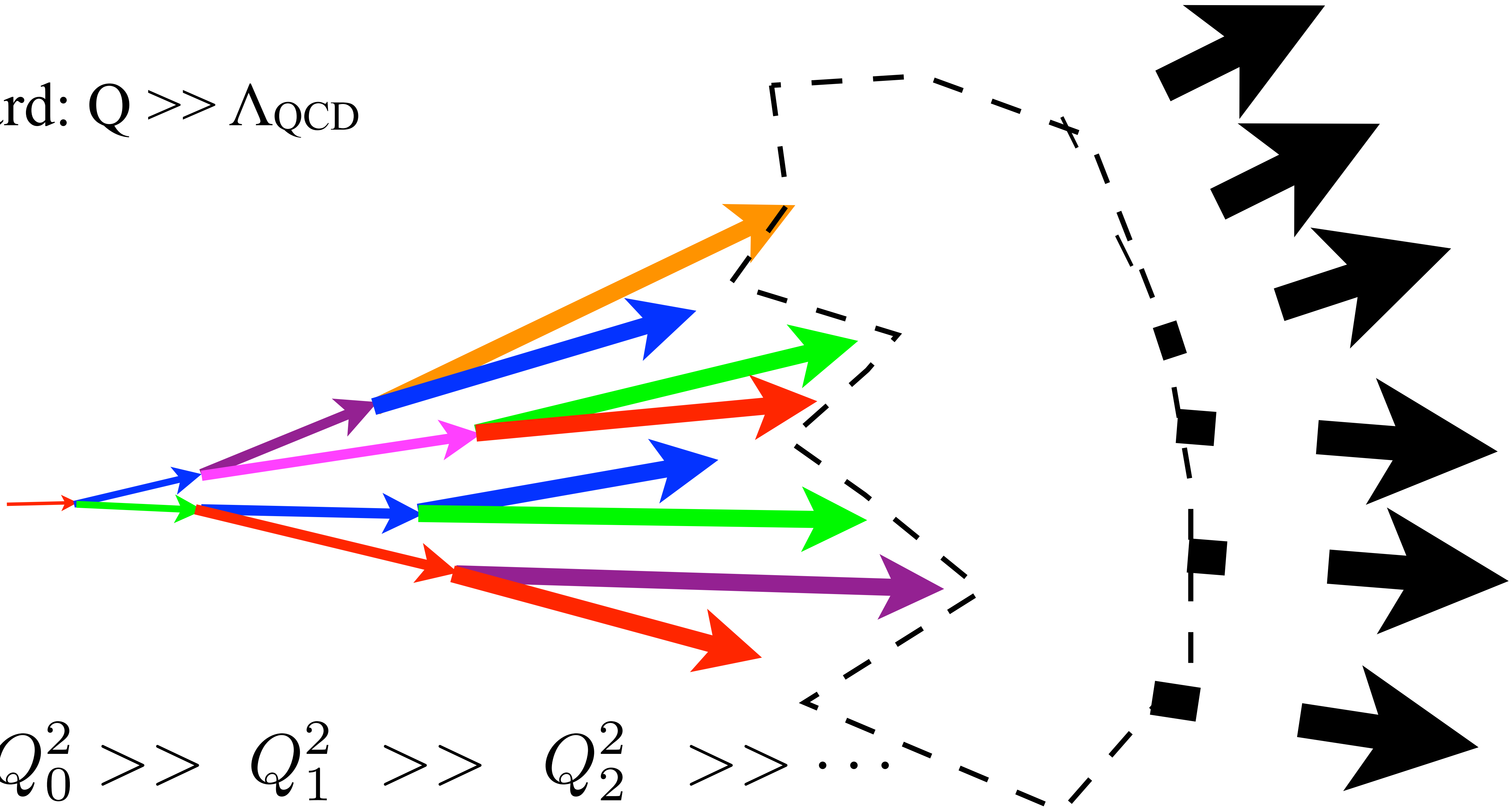

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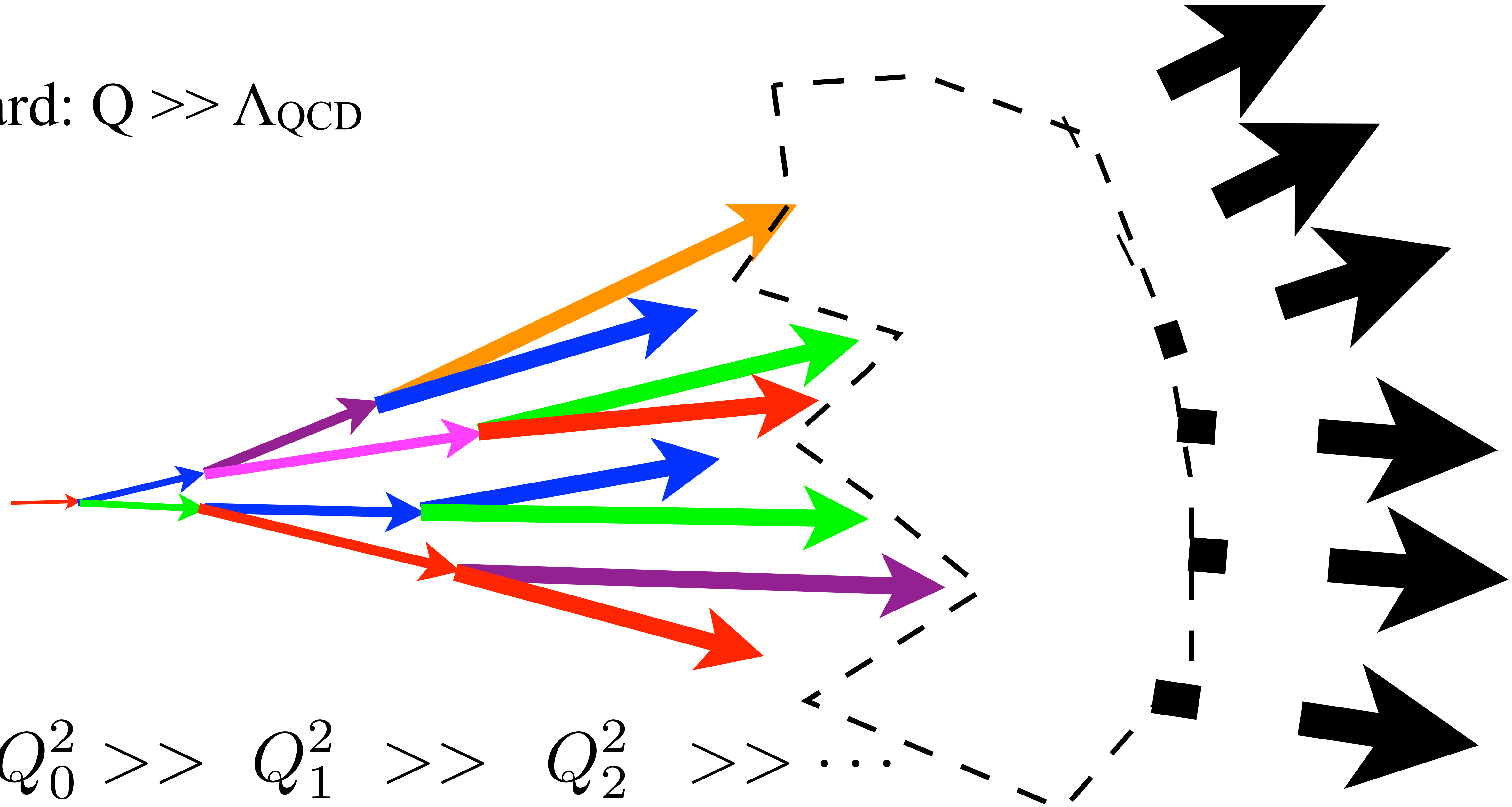

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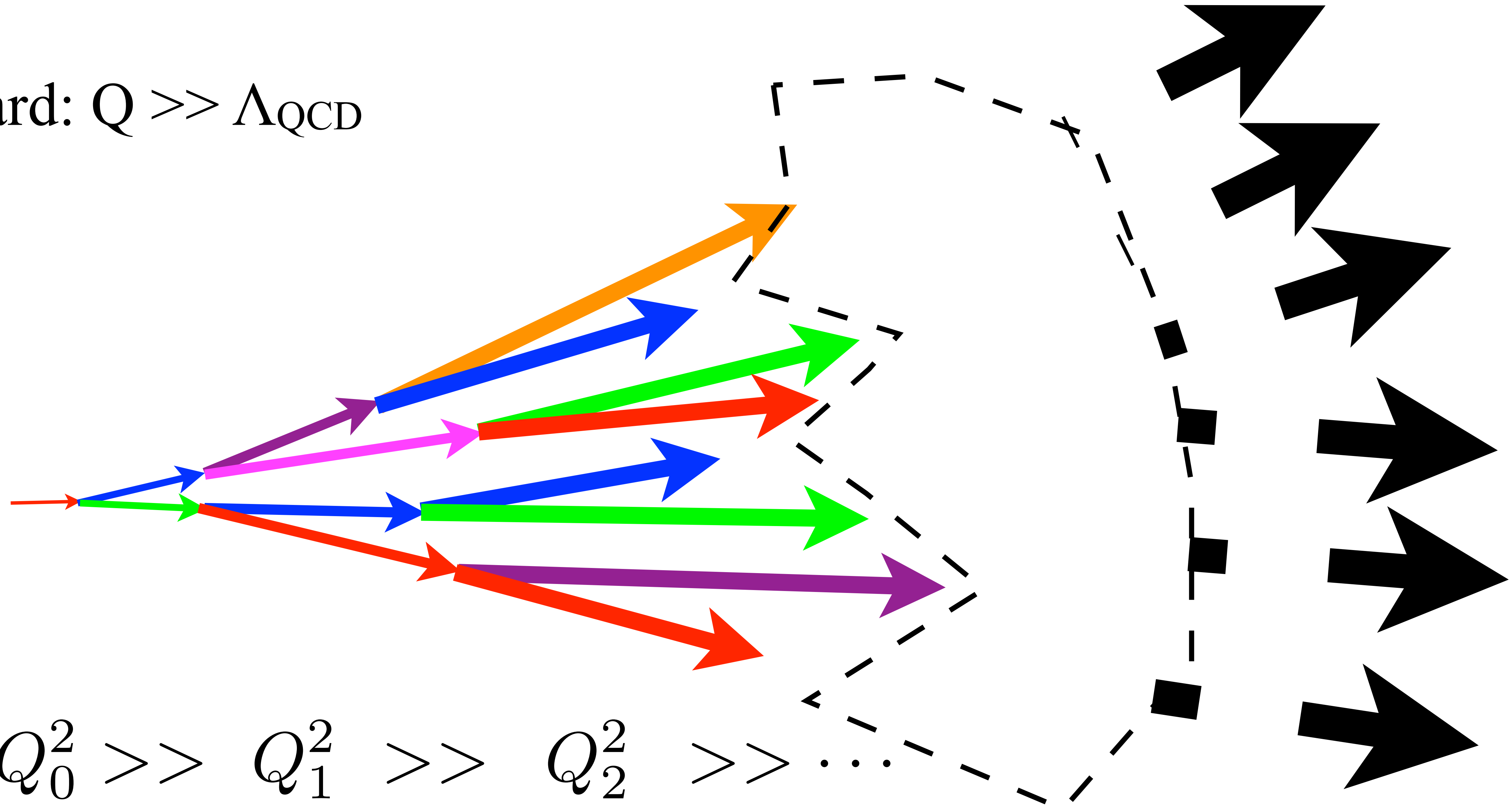

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perturbative QCD (pQCD)

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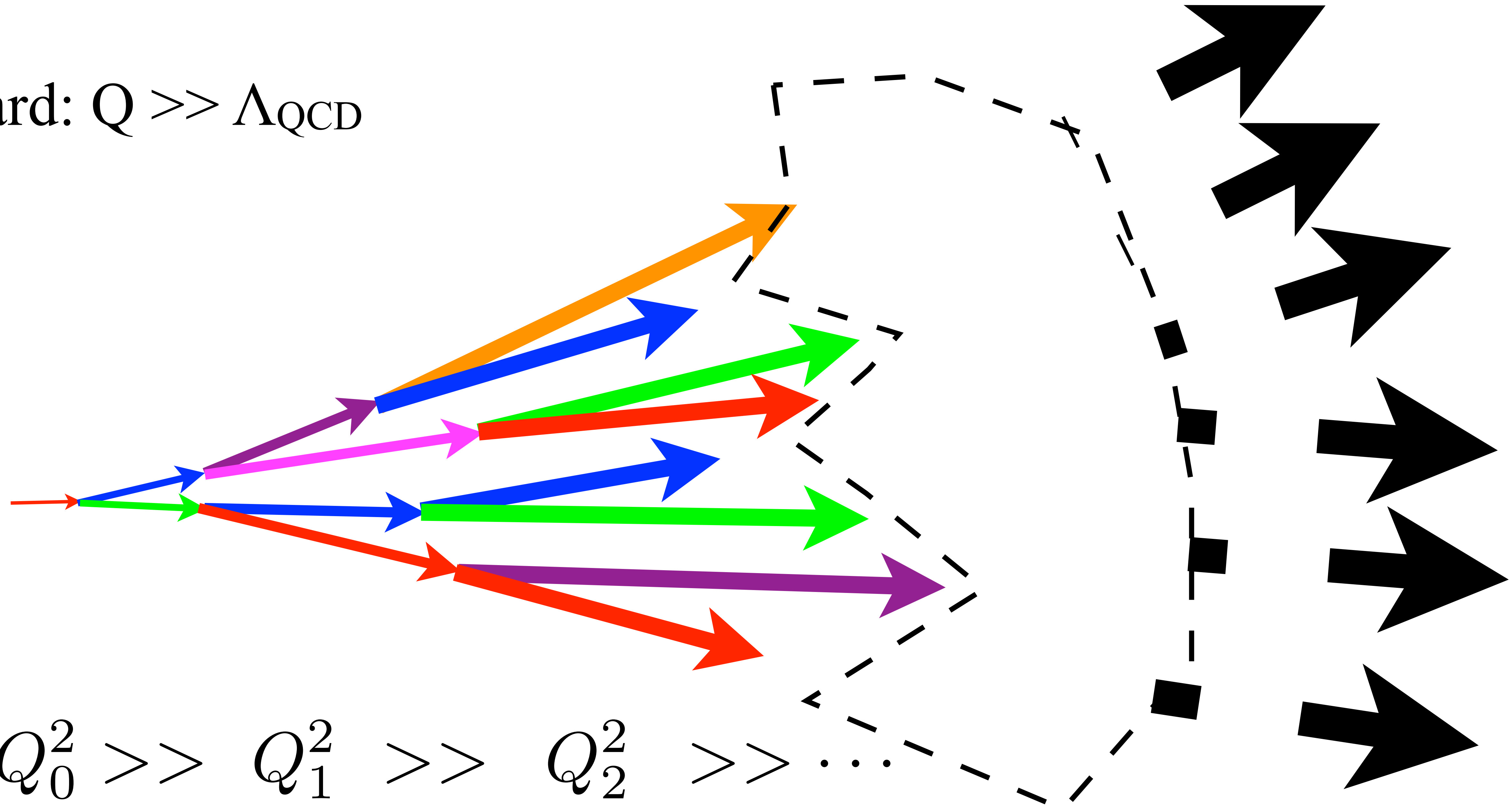

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Hadronization

All together: the fate of a single hard parton produced in a hard interaction

jet of hadrons

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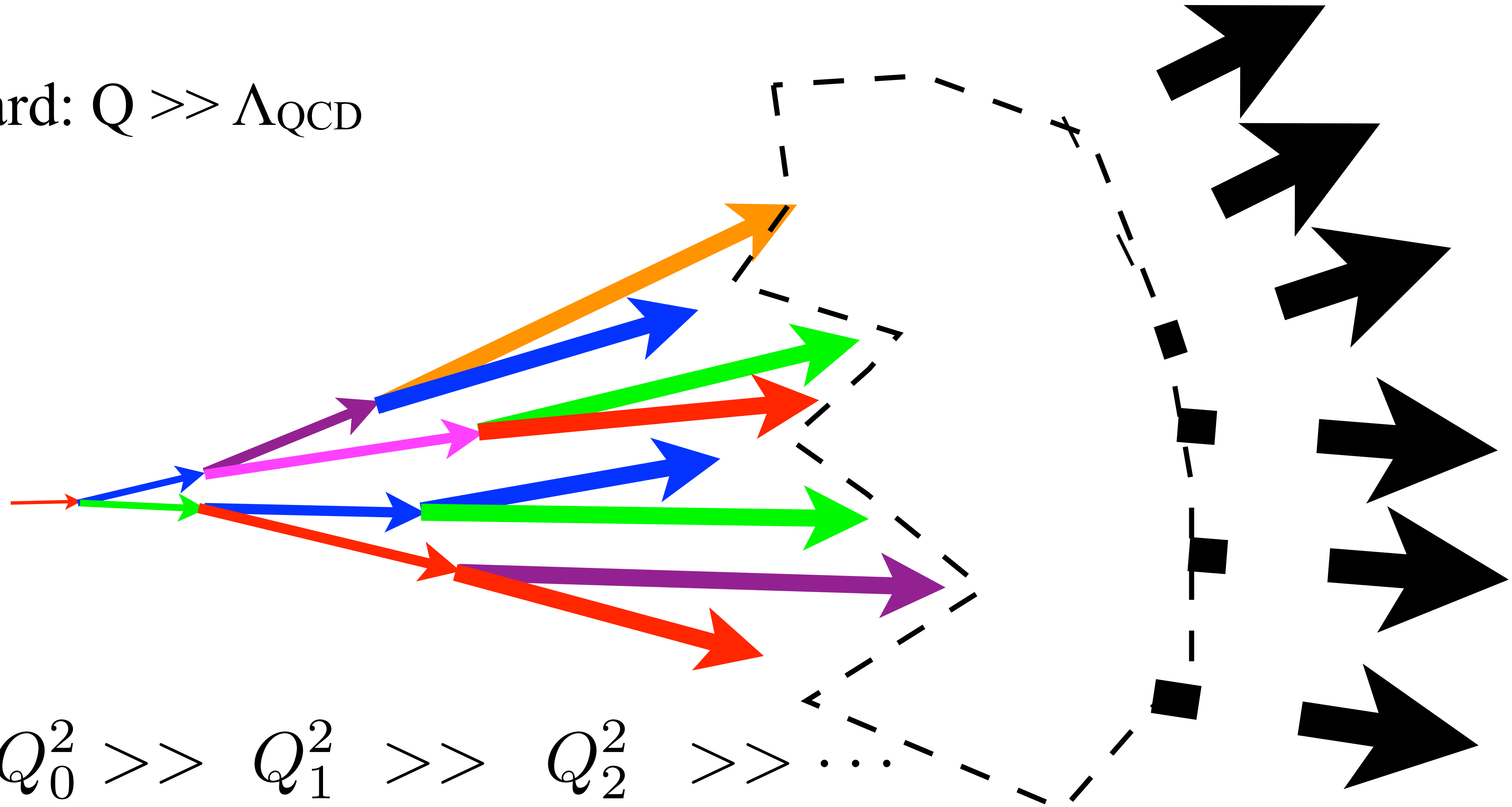

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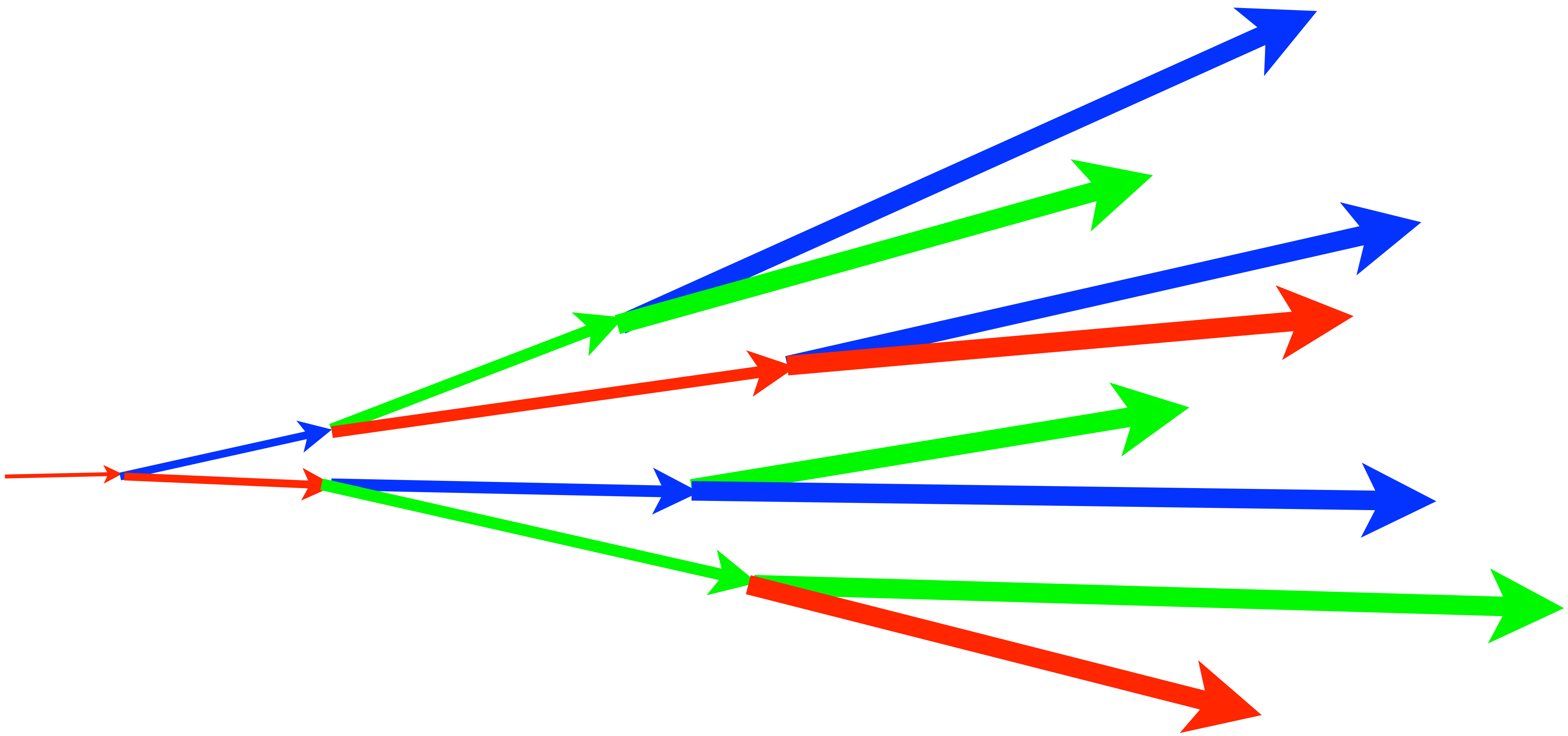

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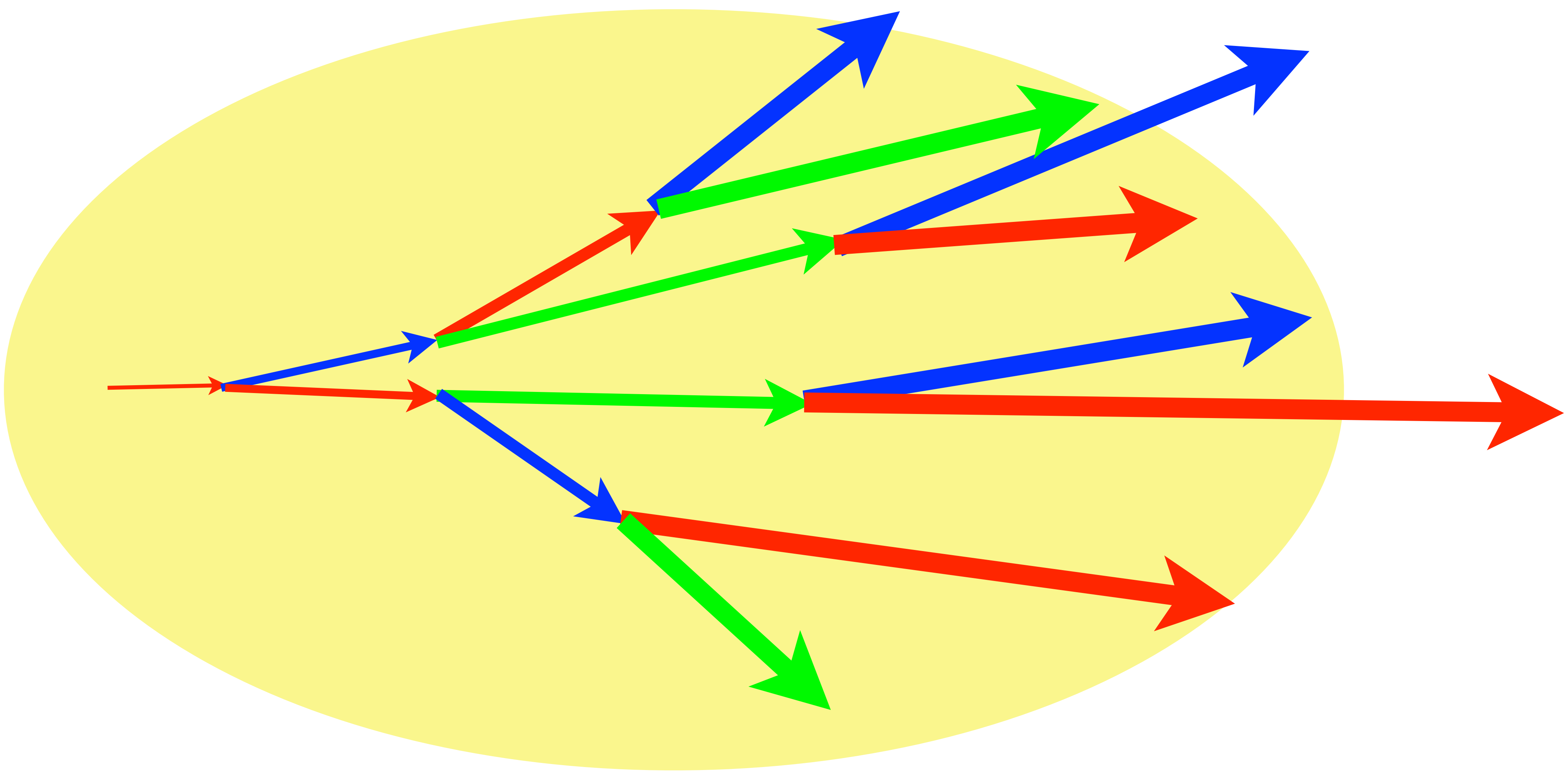

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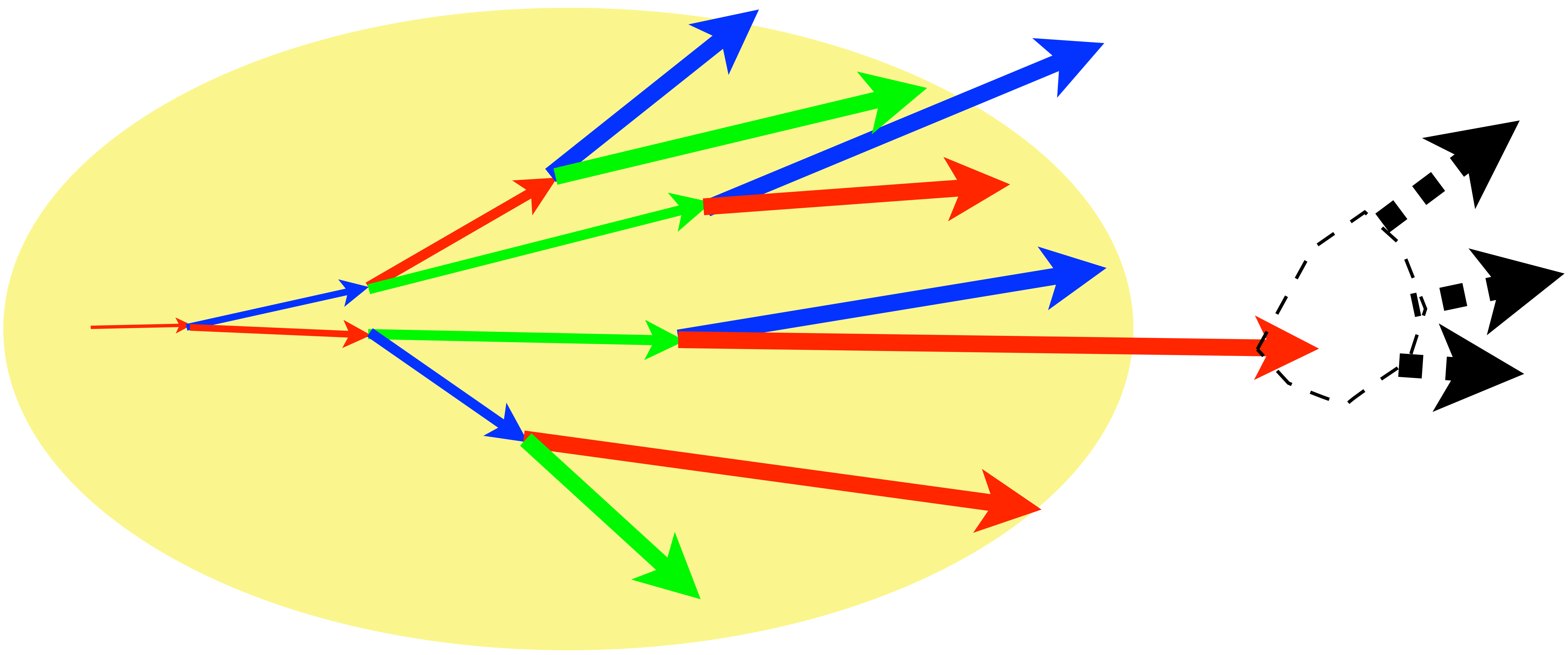

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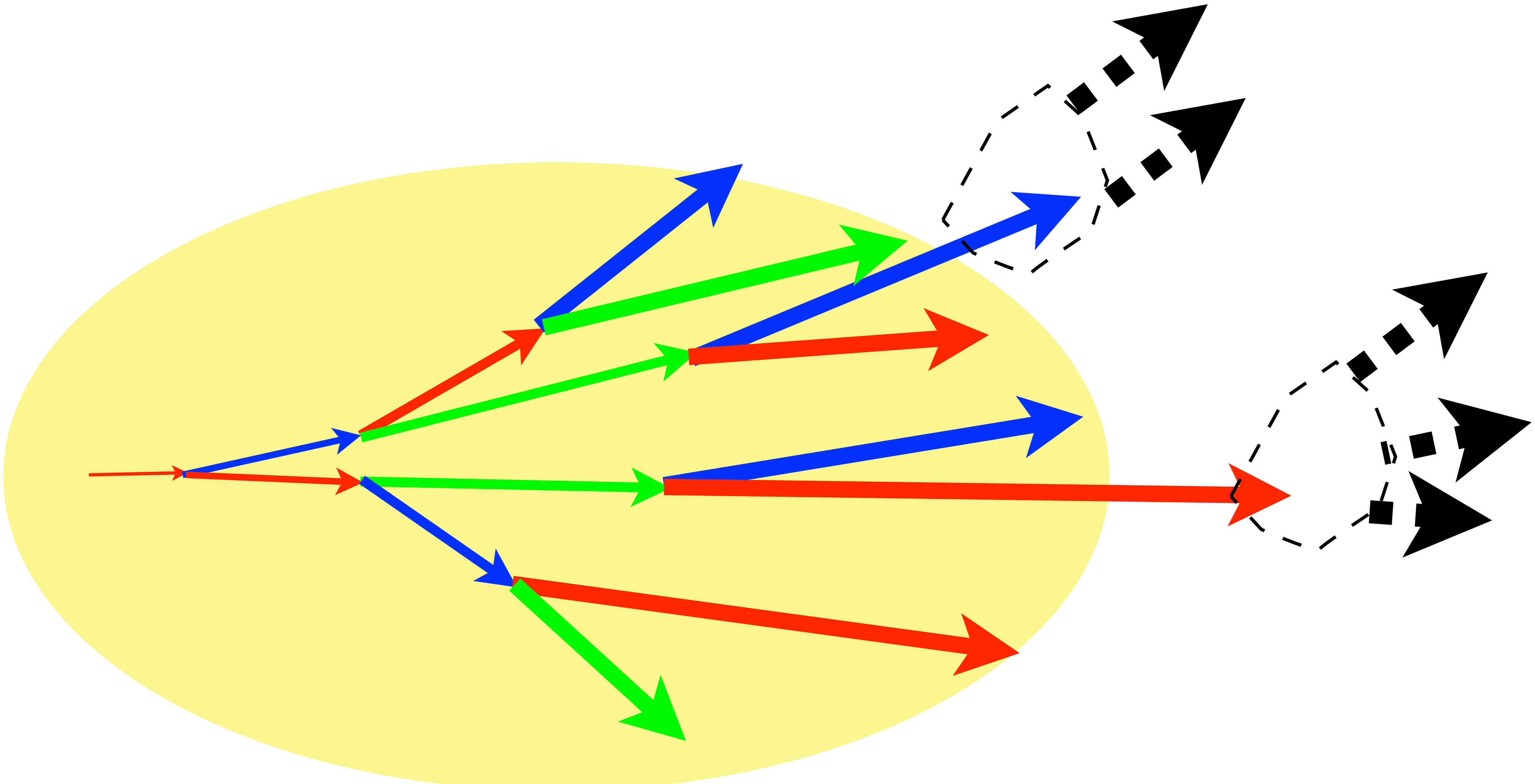

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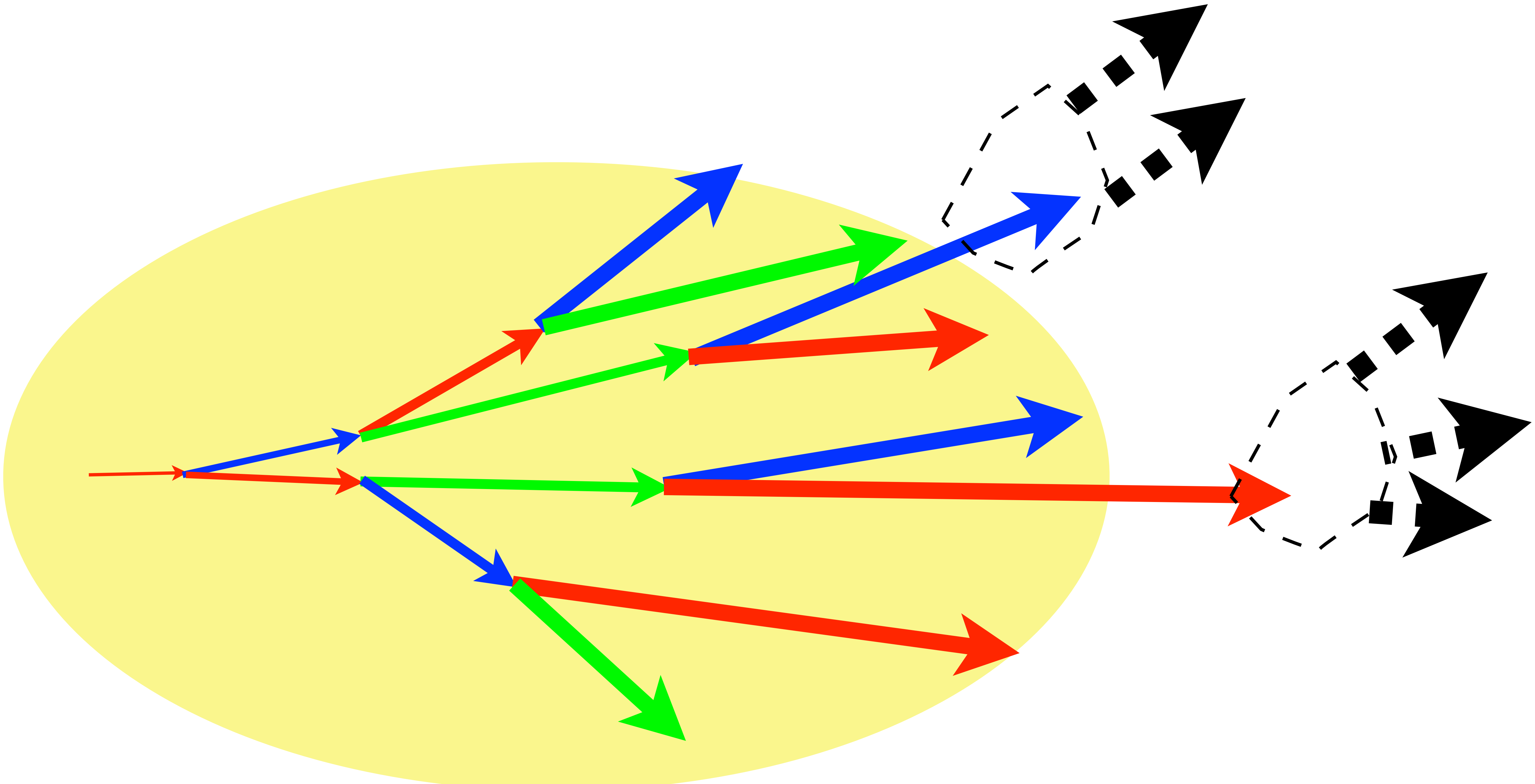

Compute the change of this shower if matter is in the way

Measure the change in this shower

Compare calculation to measurement and deduce properties of matter

I wish it was just that simple

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7) How controlled are any of the approximations ?

1) Placing a jet inside a medium

How to get a jet in vacuum?

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Well there are the classics!

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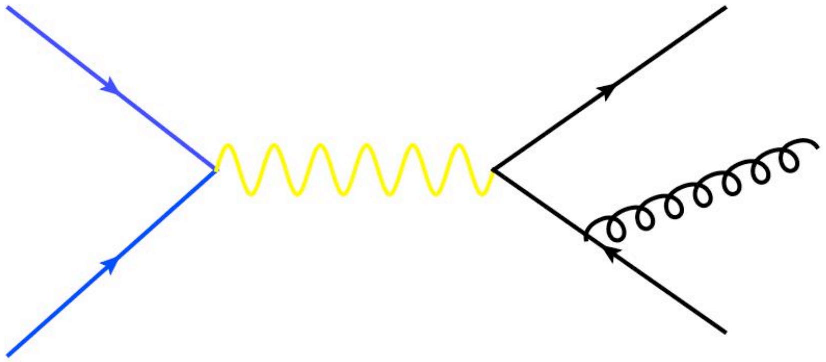
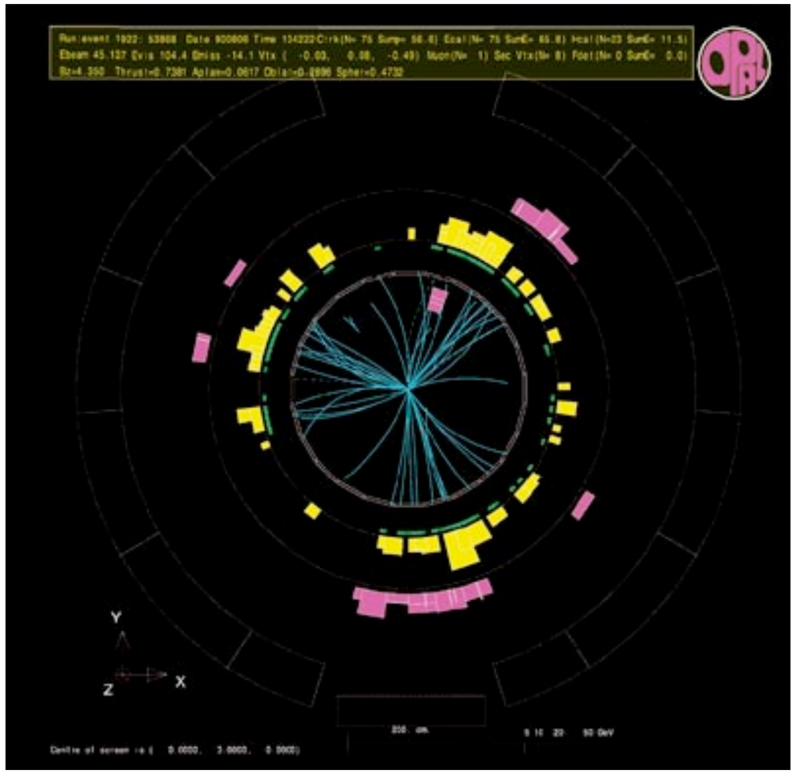
$e^+e^- \rightarrow$ Jets





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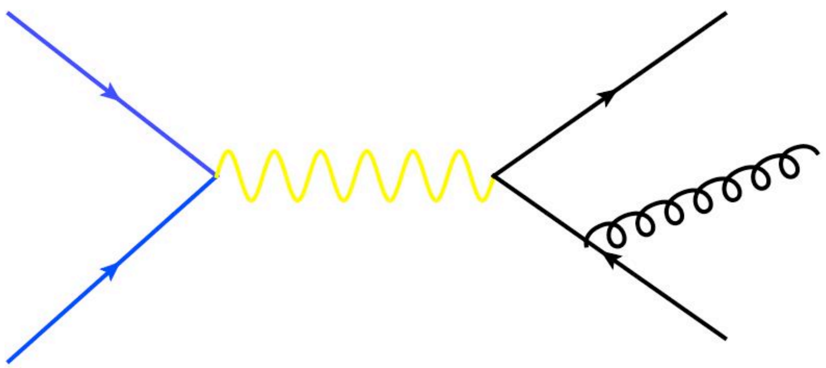
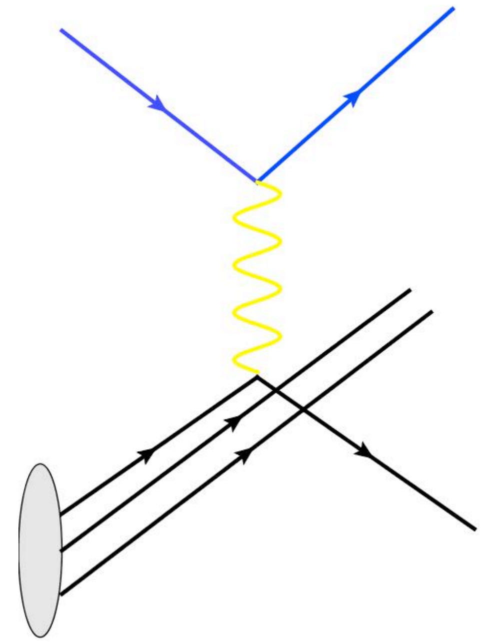
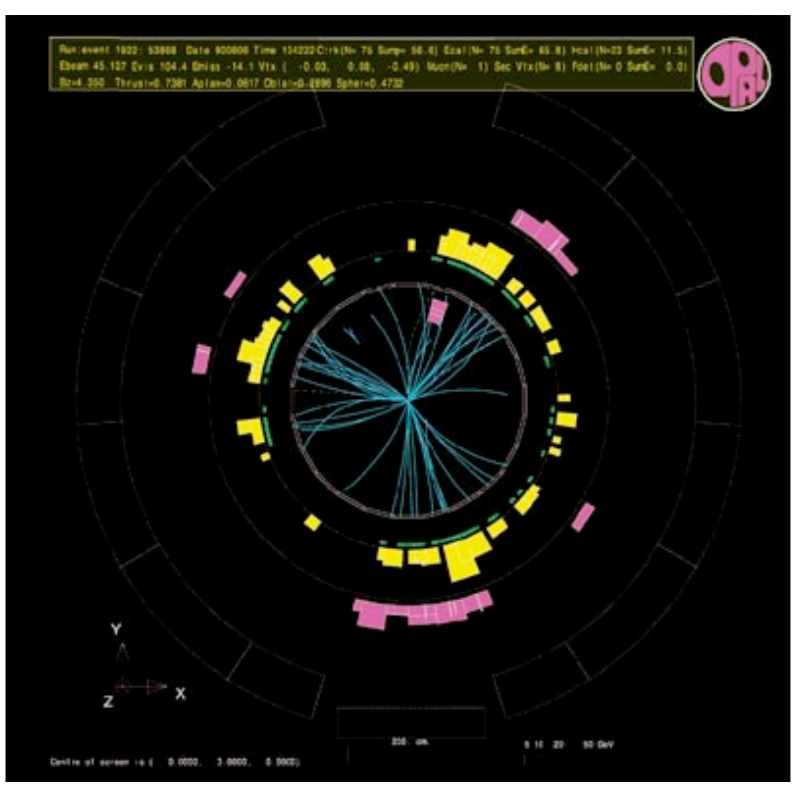
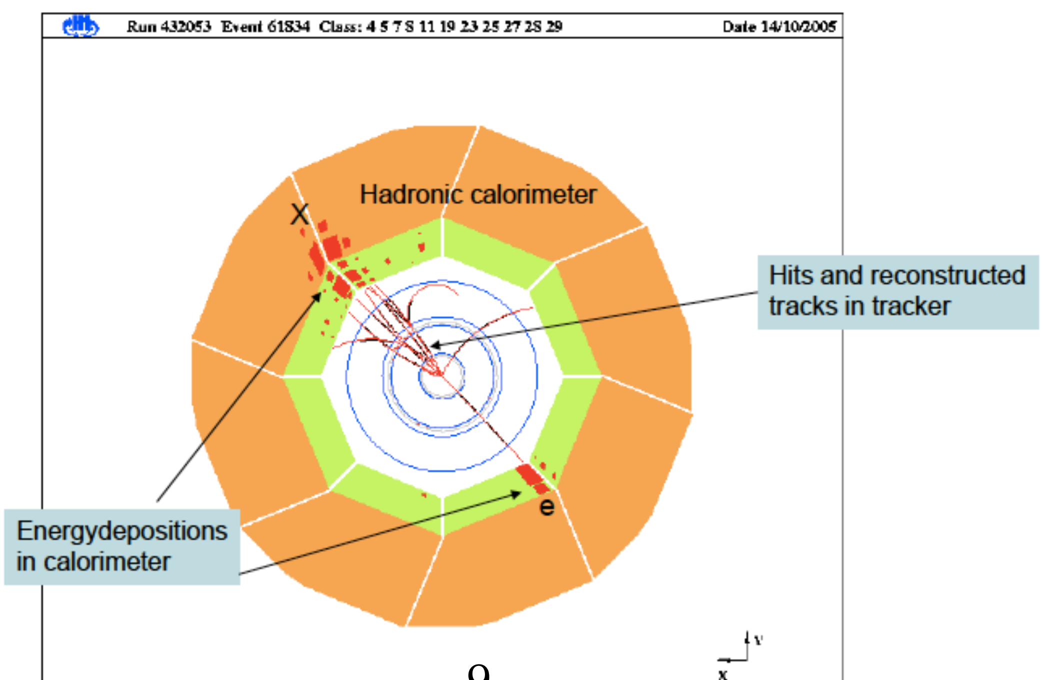


$e^- + p \longrightarrow$ Jets







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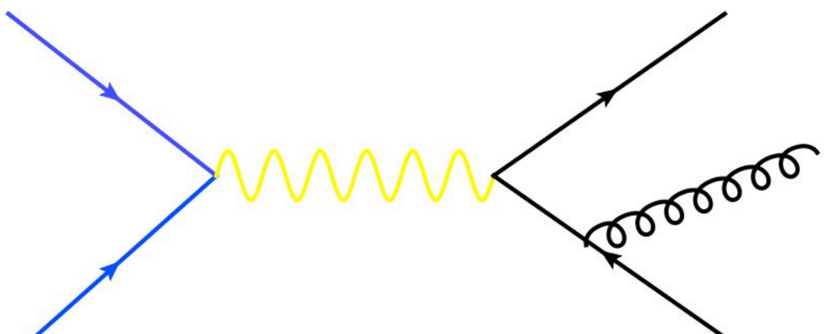

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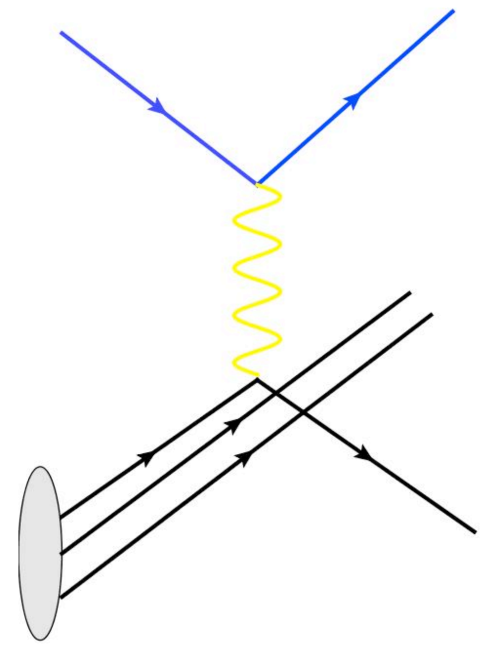

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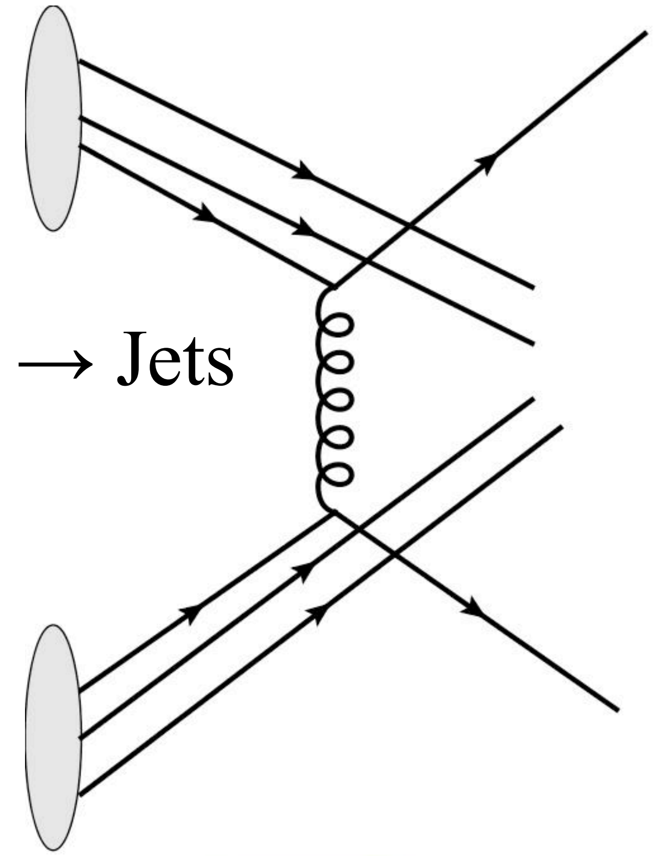

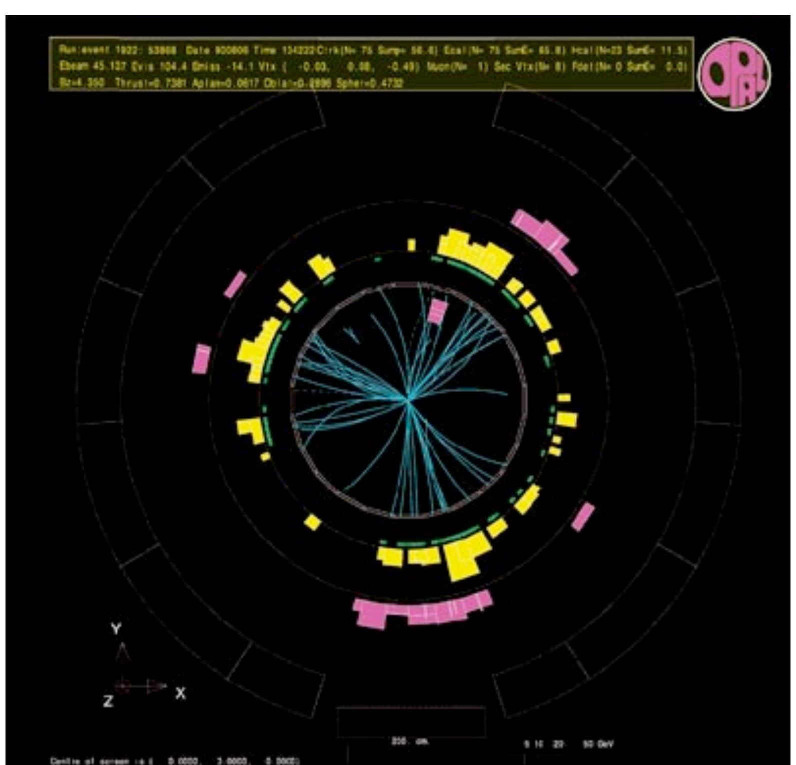

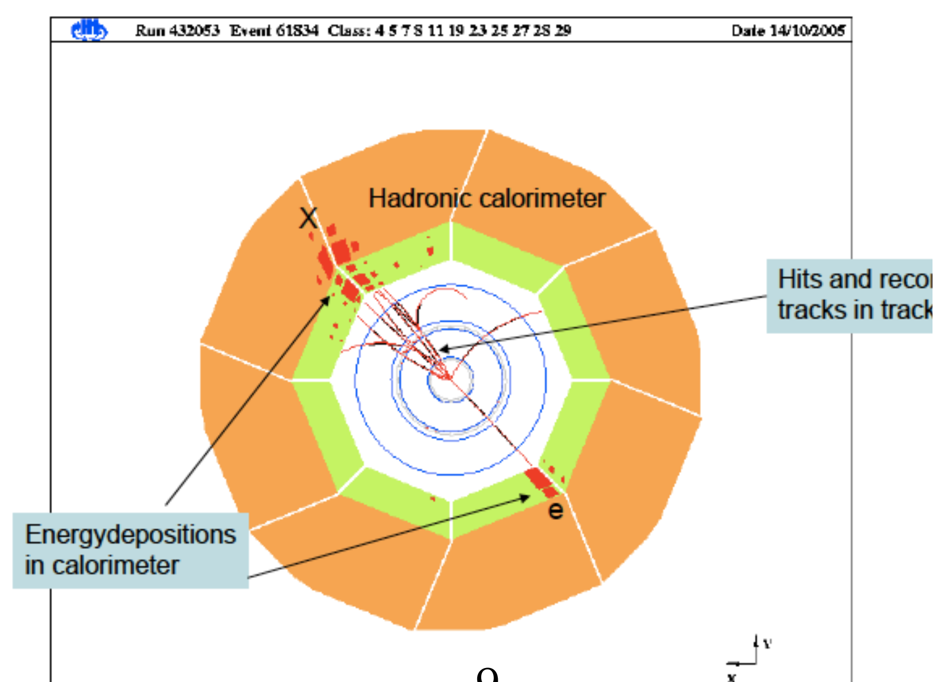

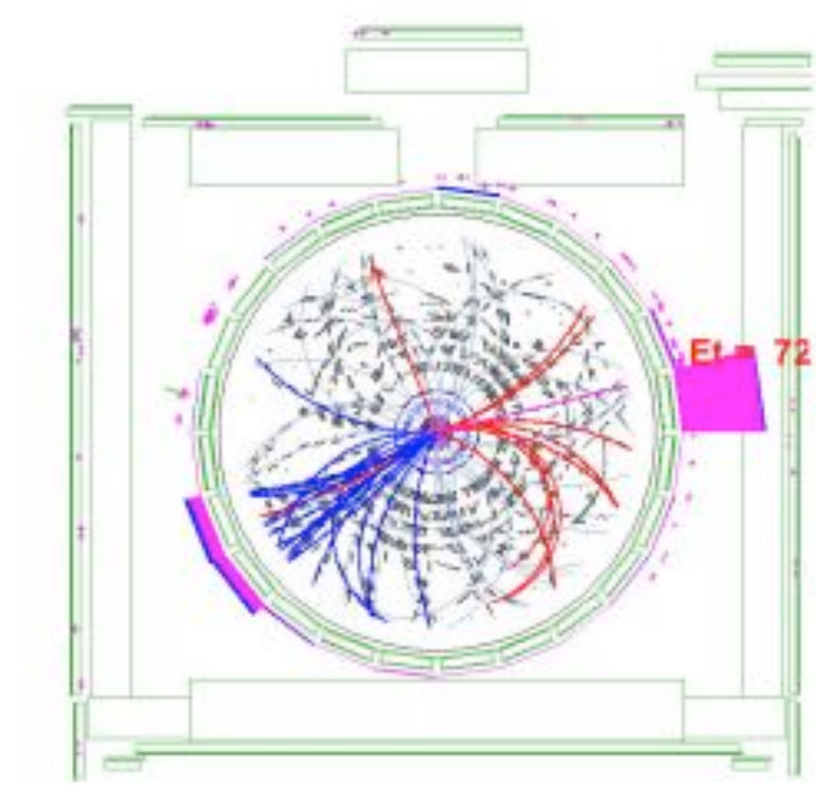

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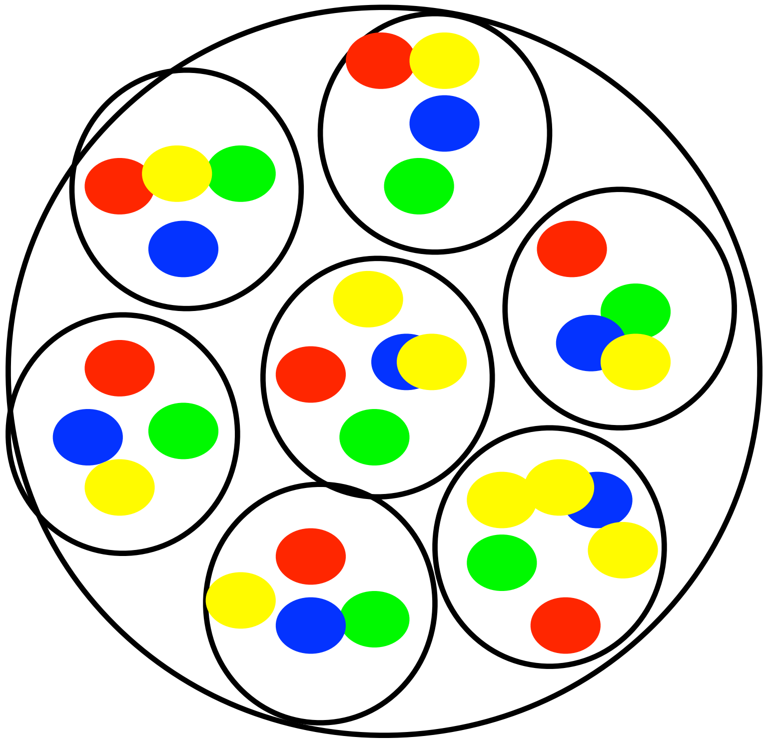

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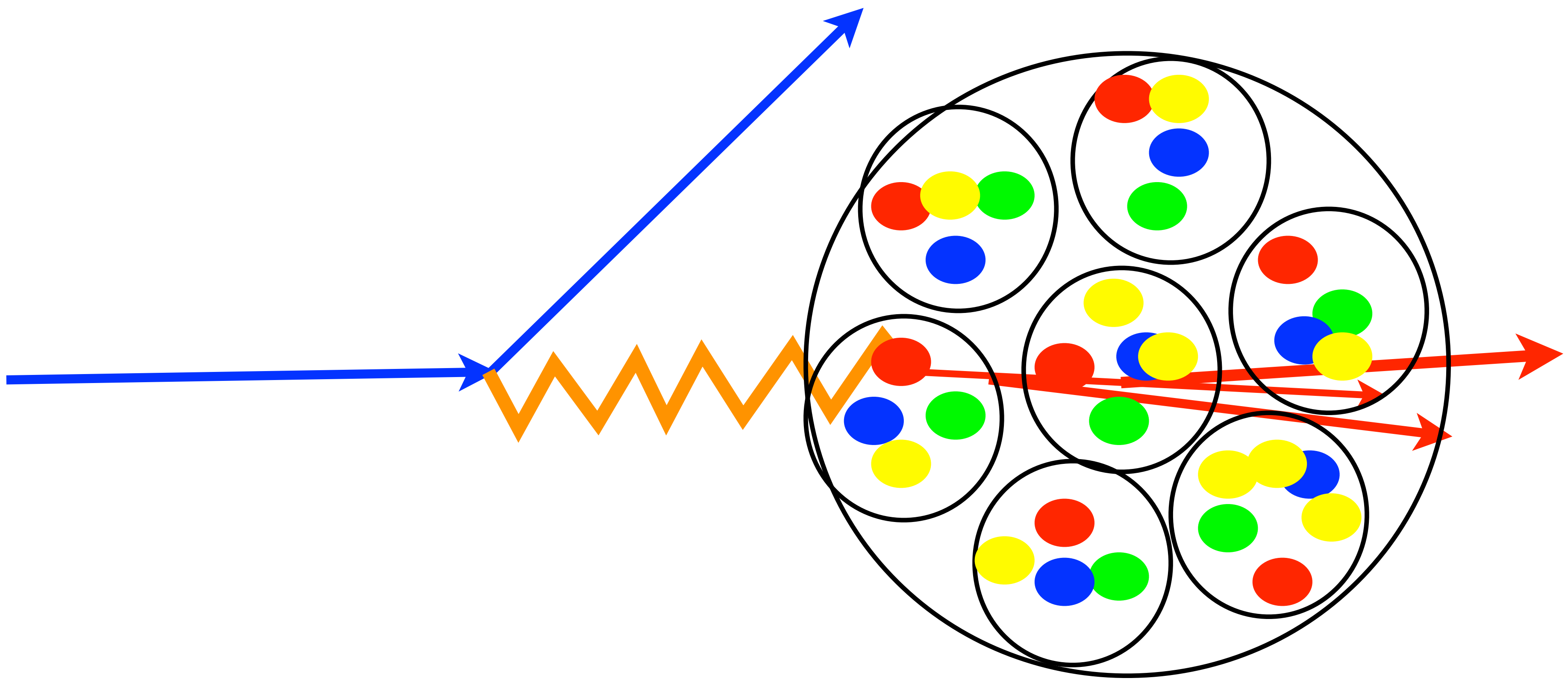

DIS on a large nucleus

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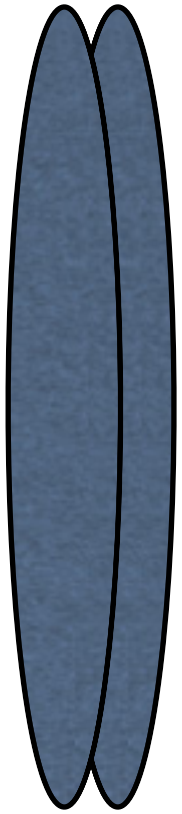

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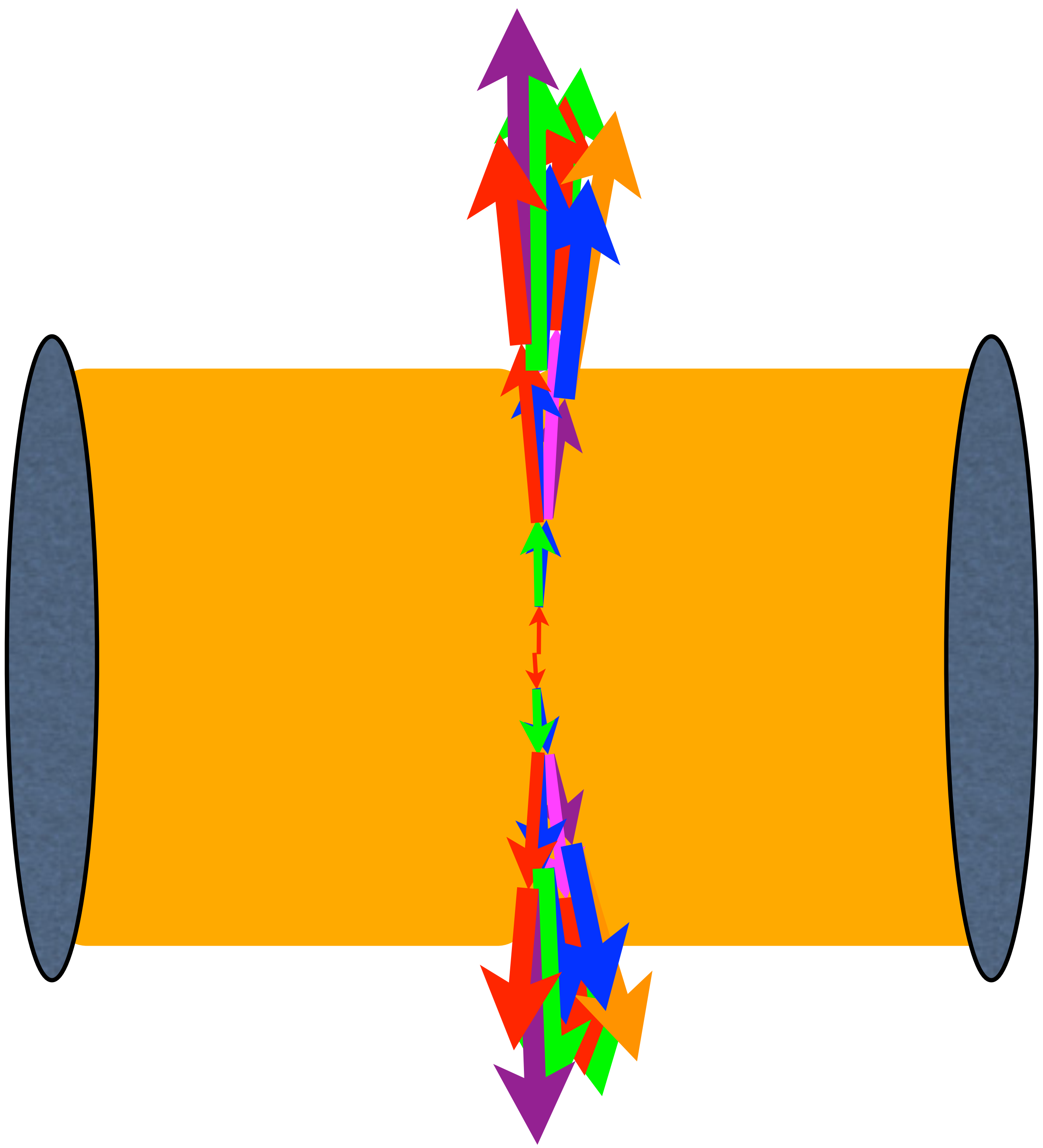

Jets in high energy heavy-ion collisions

Focussing on A-DIS

Among the 2 experiments DIS on a nucleus is definitely simpler!

Half of the process is Electro-Magnetic

The medium remains static over jet propagation timescale

The d.o.f. of the medium are ``known'': nucleons

The struck parton is almost always a quark

40+ years of DIS on nucleon and nuclei have given us
a lot of confidence on our understanding of PDFs

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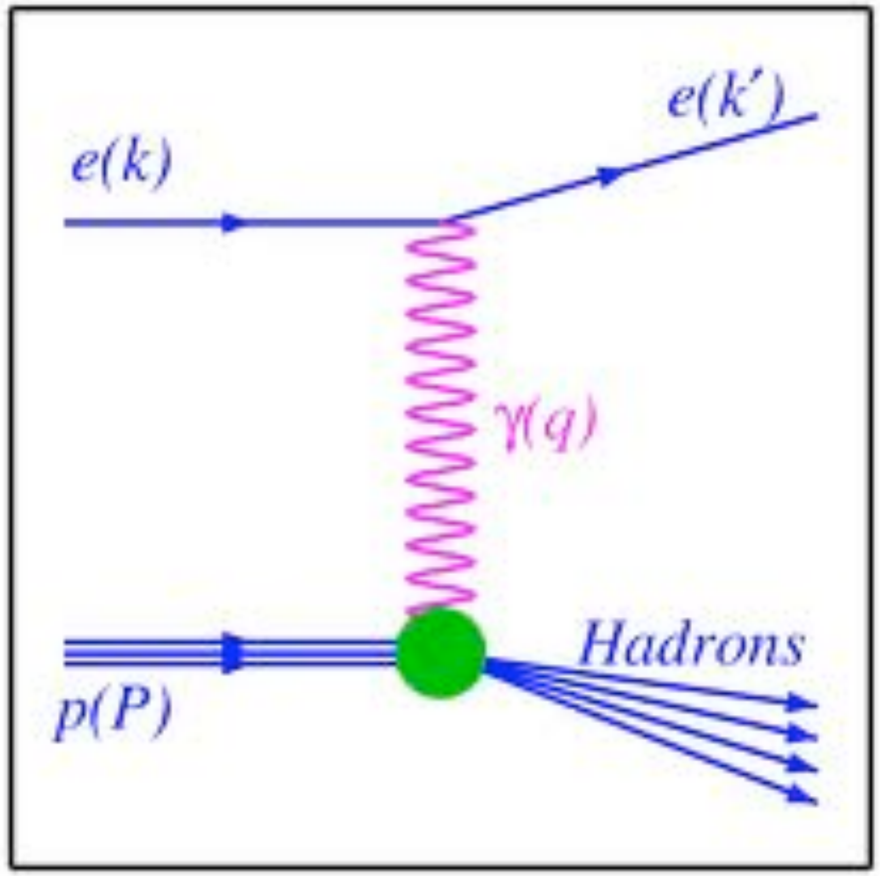
We will study jets in A-DIS in detail and then extend to heavy-ion collisions

Even simpler: DIS on a nucleon



very high energy electron scatters off a proton and shatters it

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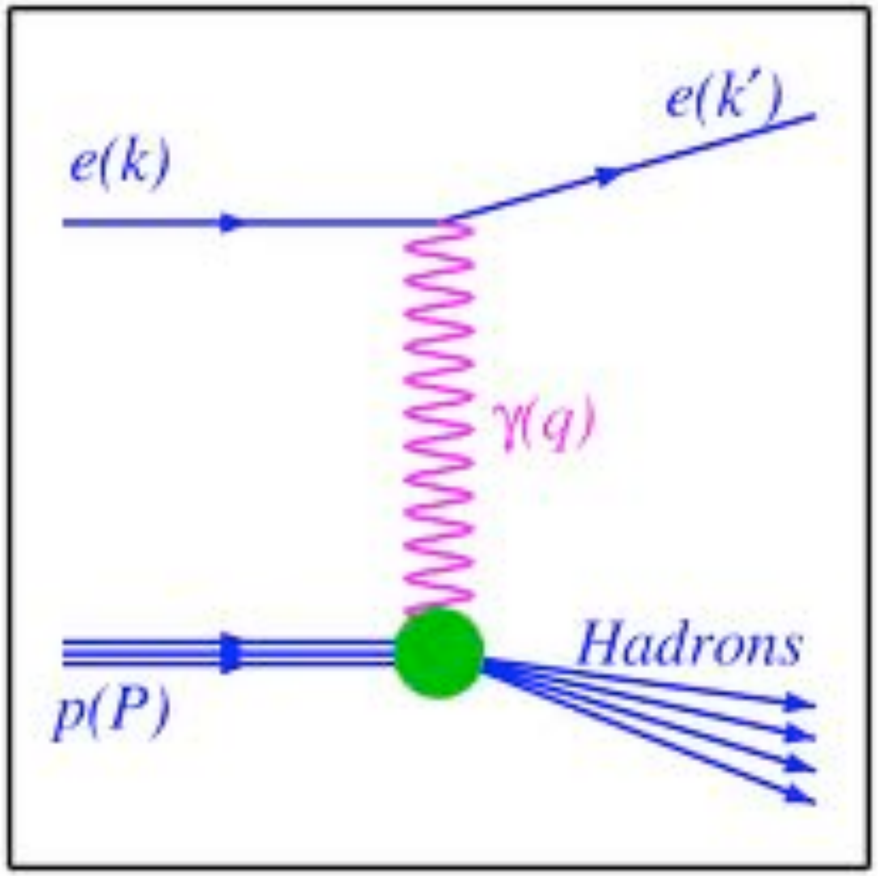

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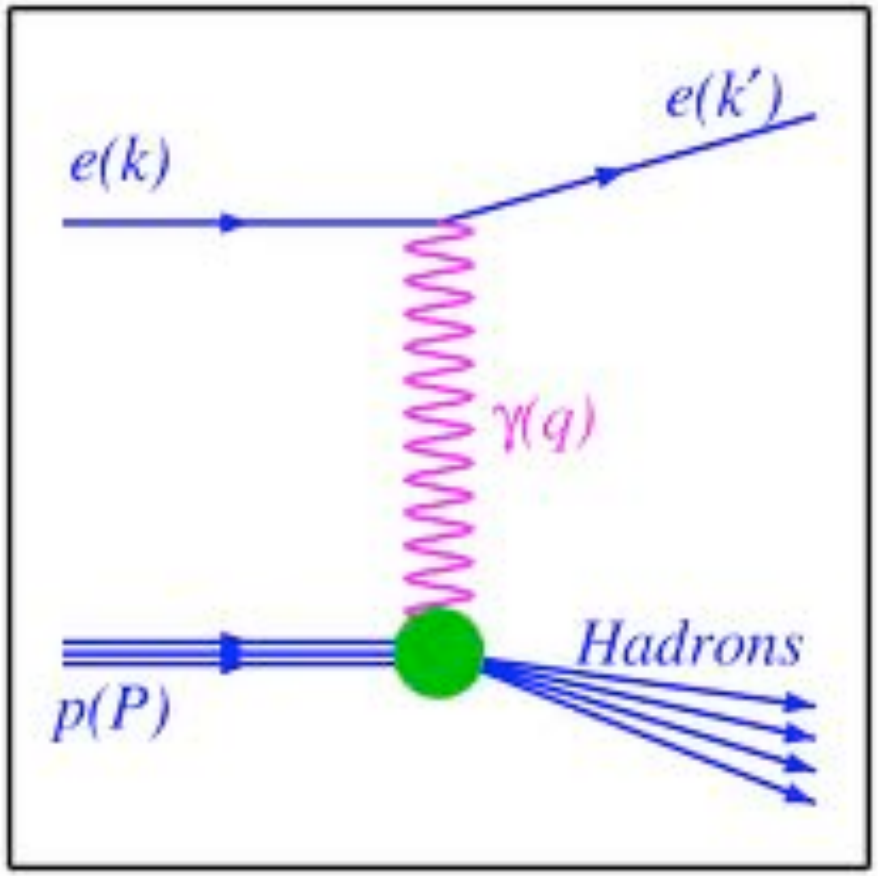

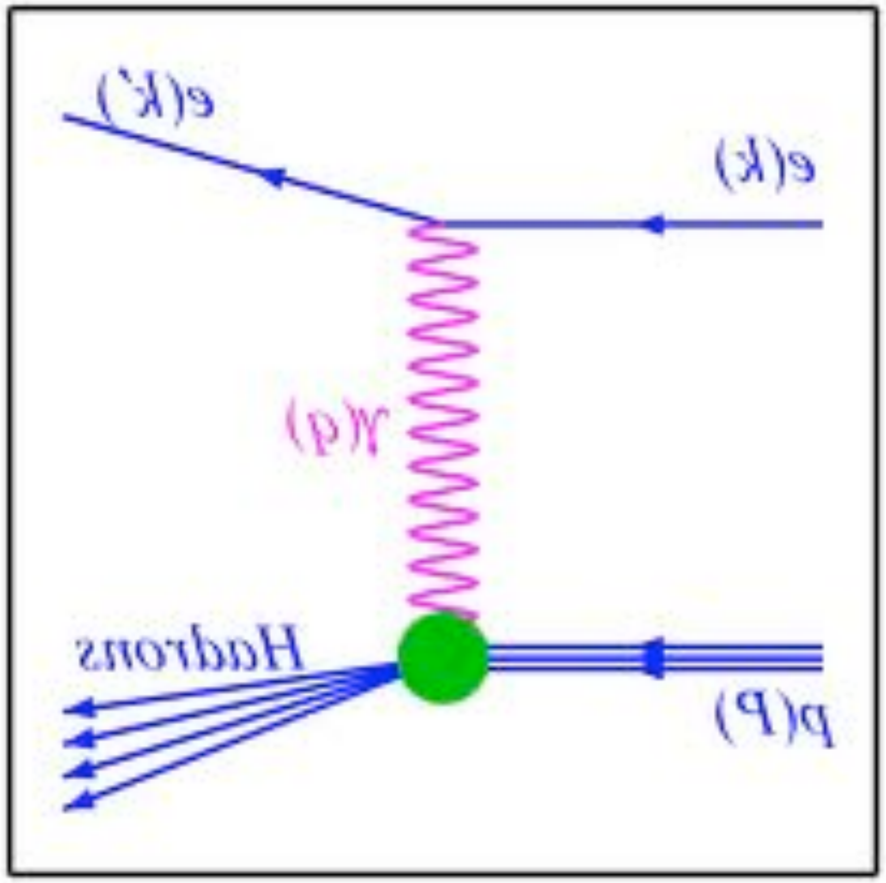

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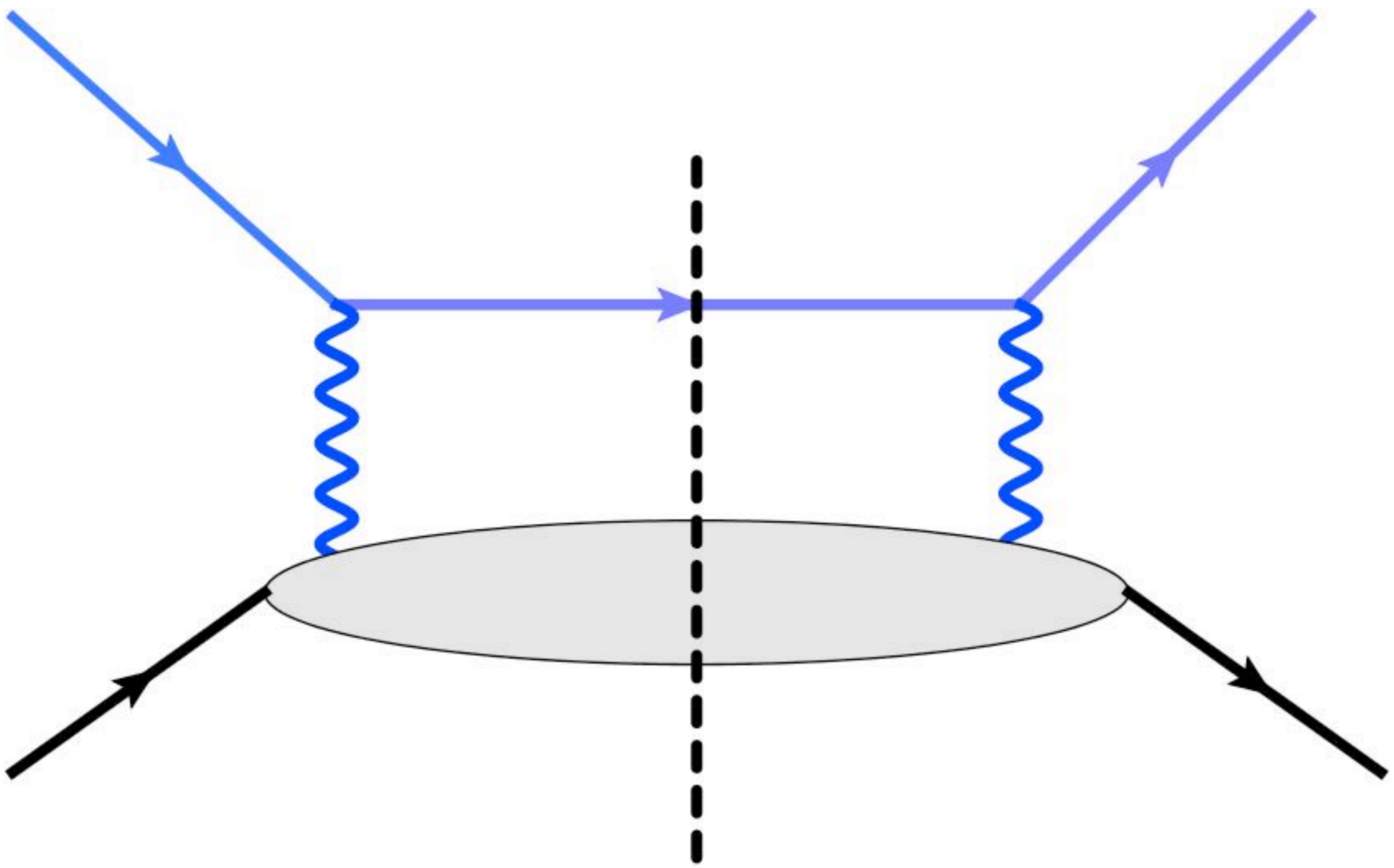

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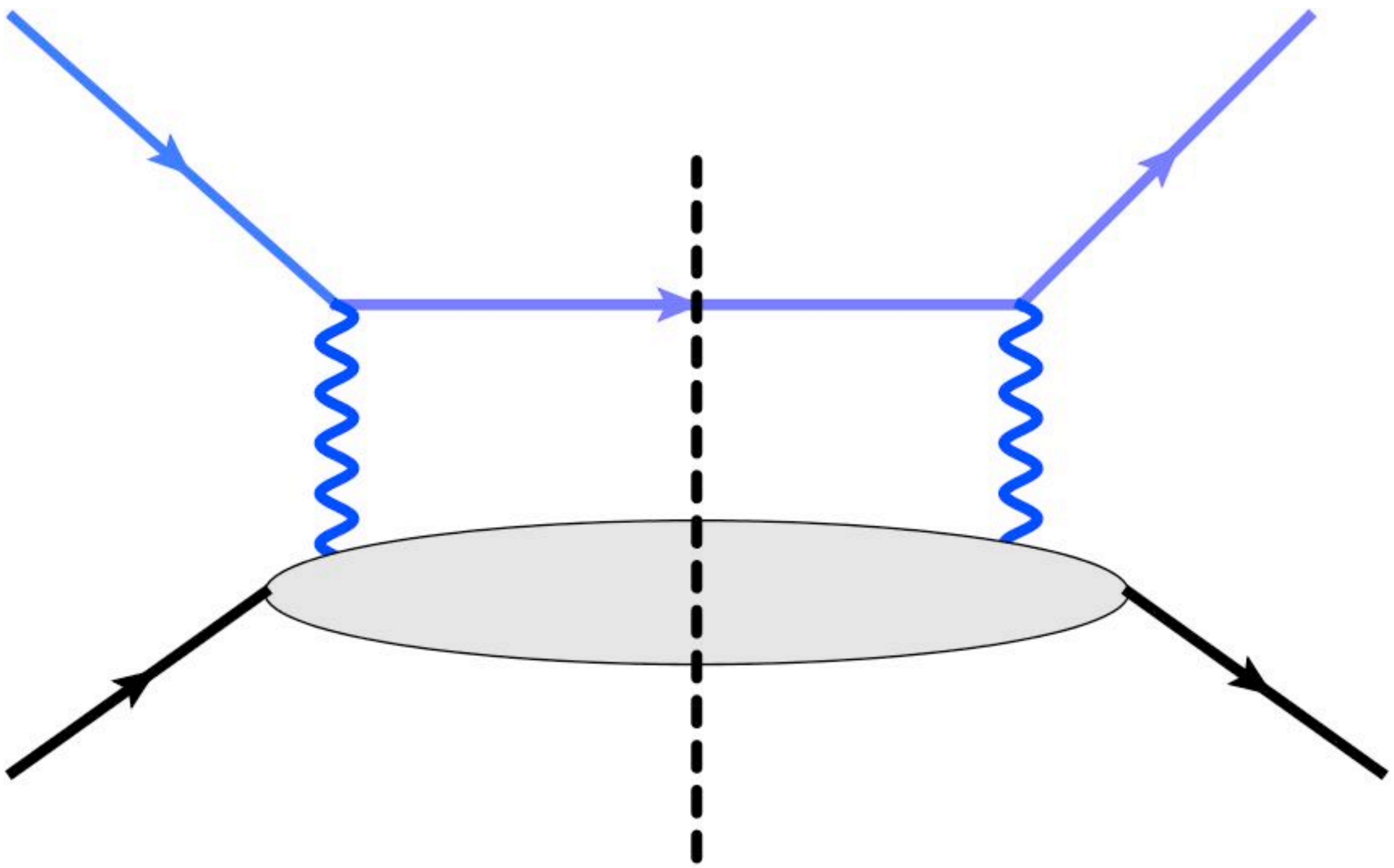

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2 frames will be important: rest frame of proton & infinite momentum frame

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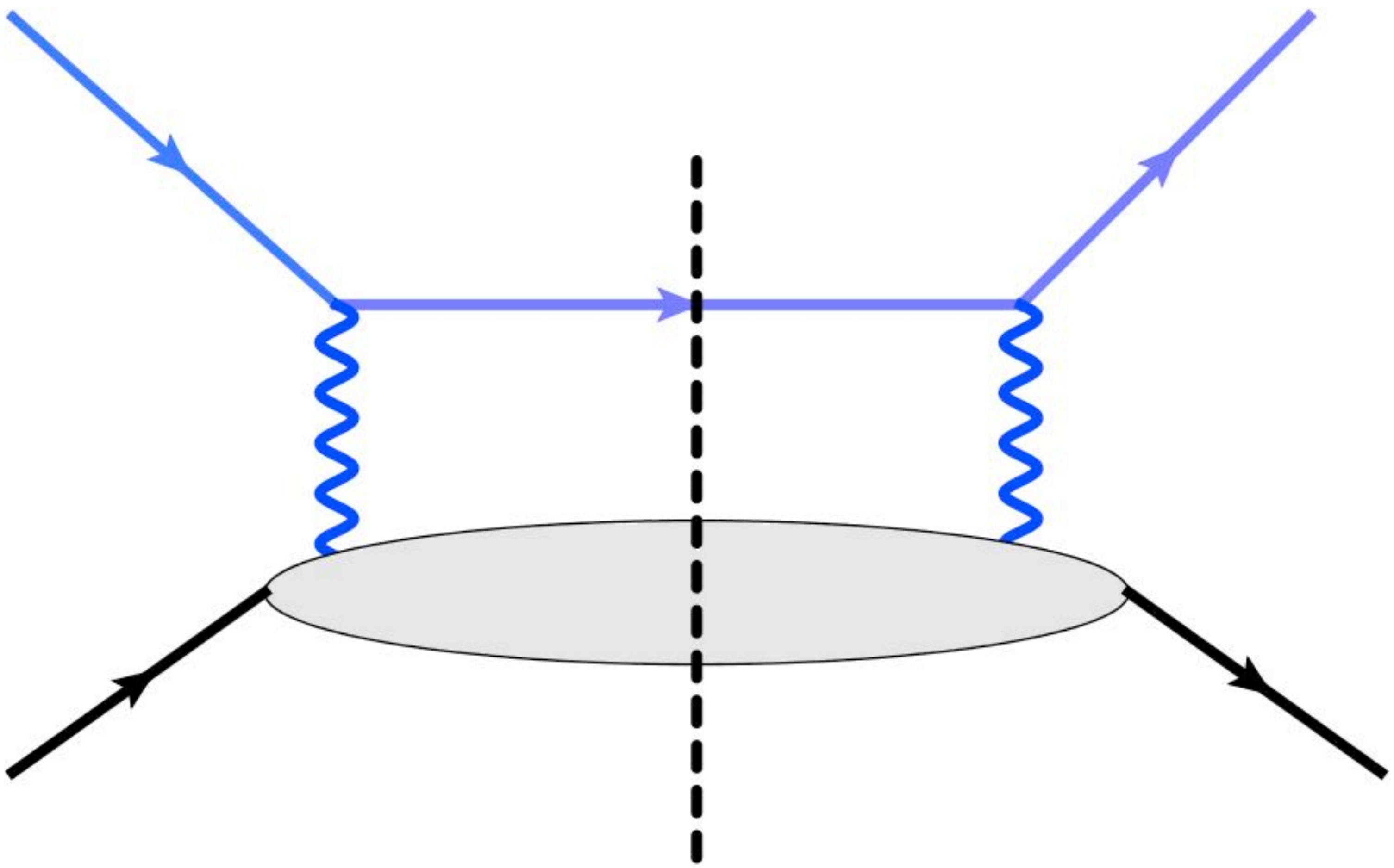

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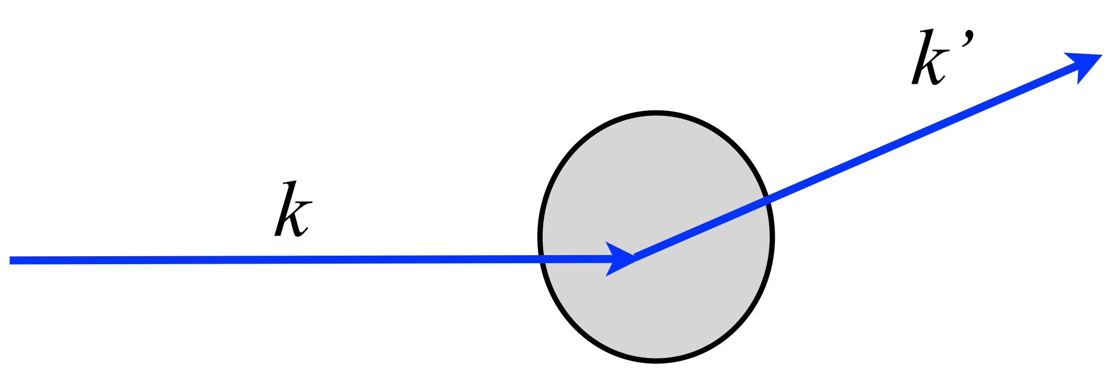

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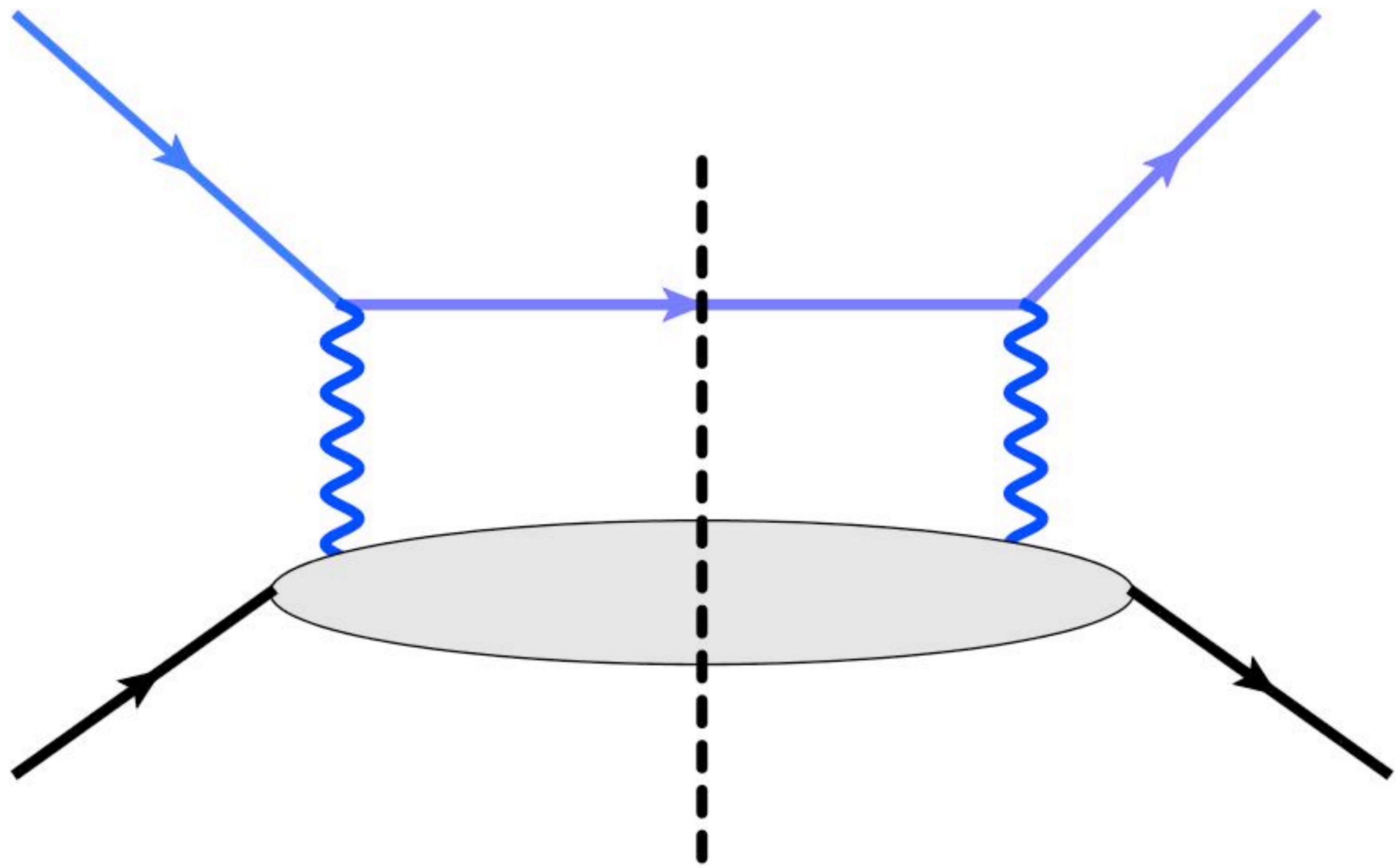

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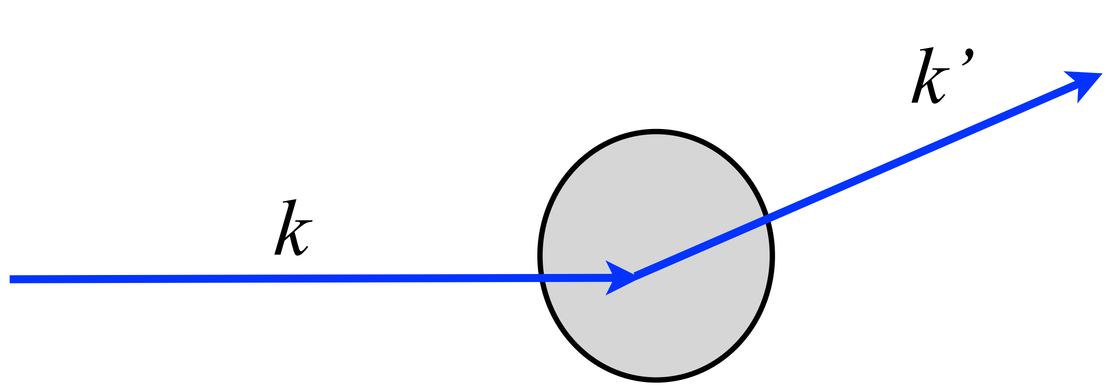
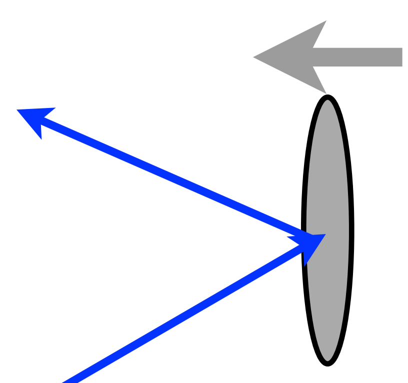




The variables

Incoming electron k, outgoing electron k', Proton P, photon $q = k - k'$

Invariants: $$q^2 = (k - k')^2 = -4E_k E_{k'} \sin^2(\theta/2) = -Q^2$$

$$s = (k + P)^2 = M^2 + 2k \cdot P \simeq 2k \cdot P$$

$$W = (q + P)^2 = -Q^2 + M^2 + 2q \cdot P$$

What if the photon hits a massless particle with momentum fraction, x and that exits as a massless particle

$$(q + xP)^2 = 0 \Longrightarrow x = \frac{-q^2}{2P \cdot q} = \frac{Q^2}{2P \cdot q}$$

Often referred to as Bjorken-x and written as x_B
in the rest frame of the proton

$$P \cdot q = M\nu \Longrightarrow \nu = E_k - E_{k'}$$

Physical condition $\nu > 0$, $W > 0$, $Q^2 >> M^2$

The variables

Incoming electron k, outgoing electron k', Proton P, photon $q = k - k'$

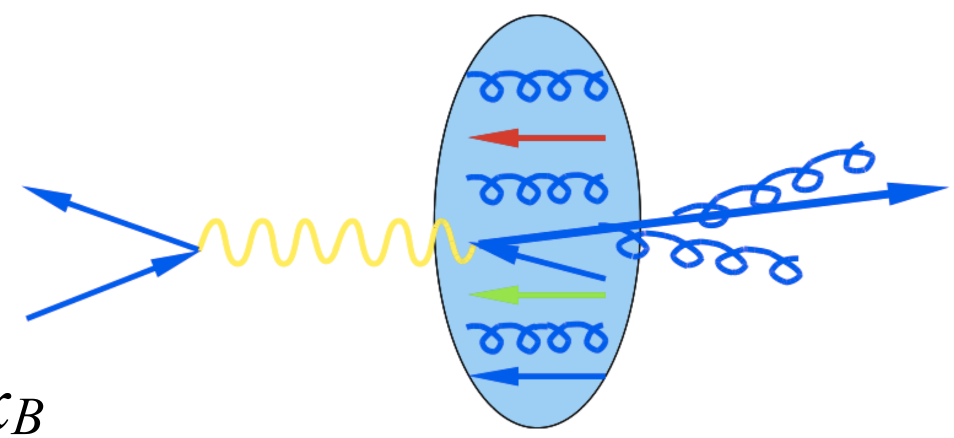
Invariants: $$q^2 = (k-k')^2 = -4E_k E_{k'} \sin^2(\theta/2) = -Q^2$$

$$s = (k+P)^2 = M^2 + 2k\cdot P \simeq 2k\cdot P$$

$$W = (q+P)^2 = -Q^2 + M^2 + 2q\cdot P$$

What if the photon hits a massless particle with momentum fraction, x and that exits as a massless particle

$$(q+xP)^2 = 0 \Longrightarrow x = \frac{-q^2}{2P\cdot q} = \frac{Q^2}{2P\cdot q}$$



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Working out the matrix element

$$\mathcal{M} = \langle k', r'| \otimes \langle X| \int d^4x d^4y - e^2 J^\alpha(y) A_\alpha(y) \bar{\psi}_e(x) \gamma^\mu A_\mu(x) \psi_e(x) |k, r\rangle \otimes |P, \lambda\rangle$$

| k , r > : incoming electron with momentum k , spin r
< k', r' | : outgoing electron with momentum k' , spin r'

J : a current in the proton with which the photon can couple

$$\psi(x)|k, r\rangle = u^r(k) e^{-ik\cdot x} \qquad \langle k', r'|\bar{\psi}(x) = \bar{u}^{r'}(k') e^{ik'\cdot x}$$

$$A^\mu(y) A^\nu(x) = \int \frac{d^4q}{(2\pi)^4} \frac{-ig^{\mu\nu} e^{-iq\cdot(y-x)}}{q^2 + i\epsilon}$$ photon propagator

$$\langle X|J(y)|P\rangle = \langle X|e^{i\hat{P}\cdot y} J(0) e^{-i\hat{P}\cdot y}|P\rangle = \langle X|J(0)|P\rangle e^{i(P_X - P)\cdot y}$$

Integrating out x, y we get : $(2\pi)^4 \delta^4(q - k + k')(2\pi)^4 \delta^4(q + P - P_X)$

$$\therefore \mathcal{M} = \mathcal{T} (2\pi)^4 \delta(k + P - k' - P_X)$$

From matrix element to diff. cross section

$$2k'^0 \frac{d\sigma}{d^3k'} = \frac{1}{4k\cdot P}\frac{1}{(2\pi)^3}\frac{1}{4}\sum_{r,r',\lambda}|\mathcal{T}|^2(2\pi)^4\delta(k+P-k'-P_X)$$

$$= \frac{1}{k\cdot P}\frac{\alpha_{EM}^2}{(q^2)^2}\mathcal{L}^{\mu\nu}W_{\mu\nu}$$

$$\mathcal{L}^{\mu\nu} = \frac{1}{2}\sum_{r,r'}\bar{u}(k)\gamma^\mu u(k')\bar{u}(k')\gamma^\nu u(k) = \frac{1}{2}Tr[\not{k}\gamma^\mu \ \not{k}'\gamma^\nu]$$

(Leptonic tensor)

$$W^{\mu\nu} = \frac{1}{2\pi}\int d^4x e^{iq\cdot x}\langle P|J^\mu(x)\sum_X|X\rangle\langle X|J^\nu(0)|P\rangle$$

$$= \frac{1}{2\pi}\int d^4x e^{iq\cdot x}\langle P|J^\mu(x)J^\nu(0)|P\rangle$$ (Hadronic tensor)

$$= \frac{Disc.}{2\pi i}\left[\int d^4x e^{iq\cdot x}\langle P|\mathcal{T}[J^\mu(x)J^\nu(0)]|P\rangle\right]$$

Where: $\langle P|\mathcal{O}|P\rangle = \frac{1}{2}\sum_\lambda\langle P,\lambda|\mathcal{O}|P,\lambda\rangle$ *and q = k - k'*

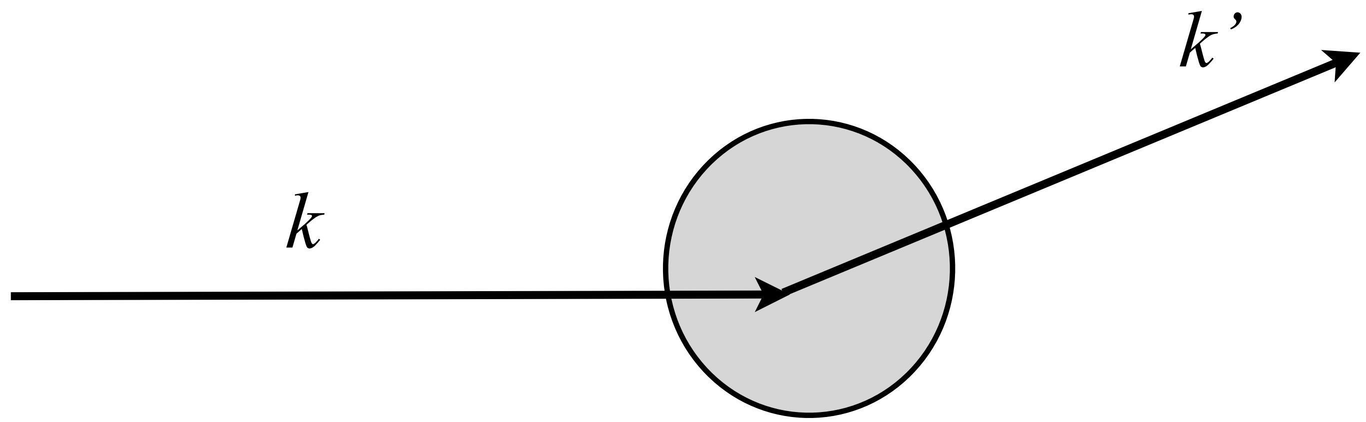
All of the QCD is in $W^{\mu\nu}$

Are the currents probed by the photon from quarks inside the nucleon?

How do you know the photon is probing inside the nucleon ?

Question of scales !

Consider the problem in the rest frame of the proton.



k is known, *k'* is measured

$$W^{\mu\nu} = \frac{1}{2\pi}\int d^4x e^{iq\cdot x}\langle P|\left[J^\mu(x), J^\nu(0)\right]|P\rangle \Longrightarrow x^2 \geq 0$$

Causality!

consider the phase factor in the frame where *q* defines the *z*-direction

$$q\cdot x = \nu x^0 - \sqrt{\nu^2+Q^2}x_z \simeq \nu(x^0 - x_z) - \frac{Q^2}{2\nu}x_z$$

$$\therefore (x^0 - x_z) \sim \frac{1}{\nu} \text{ and } x_z, x^0 \sim \frac{2\nu}{Q^2} \qquad \Longrightarrow x_\perp^2 \lesssim 1/Q^2$$

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In the OPE method one expands the OP above to an infinite series of operators and identifies those with the least suppression in $1/Q^2$
These turn out to be those with least "twist"= dimensionality - maximum spin

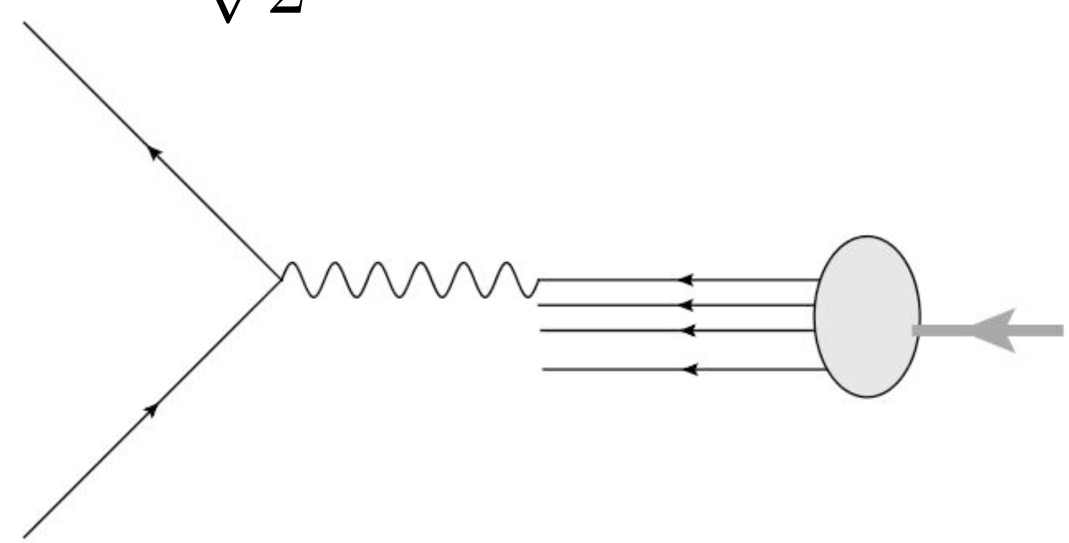
Diagram method: Boosting to the Breit frame.

and using light-cone coordinates

Photon momentum $q = [q^0, \vec{q}] \equiv [q^+, q^-, \vec{q}_\perp]$

Proton momentum $P = [P^0, \vec{P}] \equiv [P^+, P^-, \vec{P}_\perp]$

with $x^+ = \dfrac{x^0 + x_z}{\sqrt{2}}$ and $x^- = \dfrac{x^0 - x_z}{\sqrt{2}}$



In the Breit frame:

$$q_\perp = 0,\ P_\perp = 0,\ q^2 = 2q^+q^-,\ P^- = M^2/2P^+ \to 0$$

Struck quark has momentum $p = \left[x_B P^+, \dfrac{p_\perp^2}{2x_B P^+}, \vec{p}_\perp\right]$ and $q^+ = -x_B P^+$

We will ignore terms which go as $\sim \dfrac{M^2}{2P^+q^-} = \dfrac{M^2 x_B}{Q^2}$ i.e., power corrections

In the high-energy collinear limit

We can approximate:

$$\sum_X \langle P|\bar{\psi}(x)|X\rangle\langle X|\psi(0)|P\rangle \simeq \frac{\not{P}}{2}\langle P|\bar{\psi}(x)\frac{\gamma^+}{2P^+}\psi(0)|P\rangle + \#\frac{p_\perp^2}{Q^2}$$

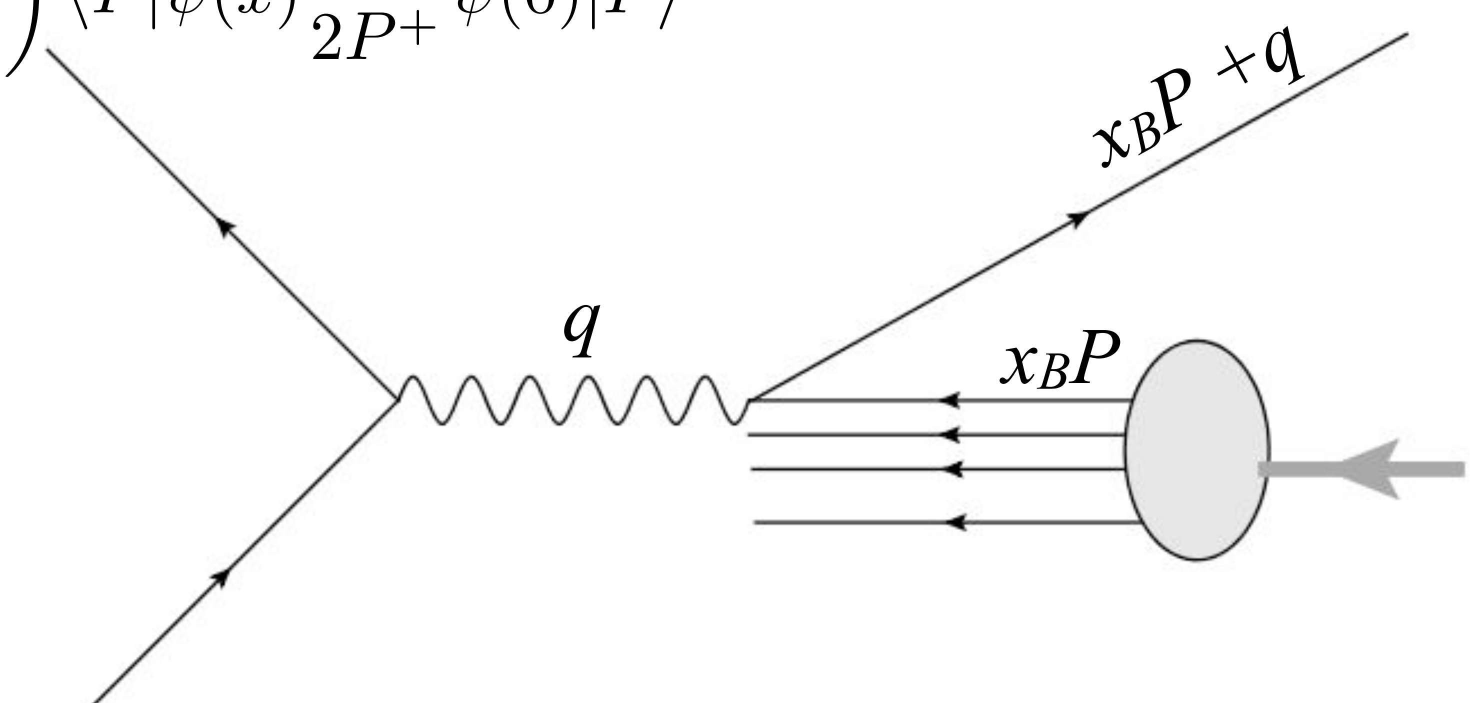
At large Q^2 can ignore all power corrections (higher twist corrections), and get The leading twist or leading power term as,

$$W^{\mu\nu} = \frac{1}{4x_B\nu}Tr\left[x_B\ \not{P}\gamma^\mu(\not{q}+x_B\ \not{P})\gamma^\nu\right]F(x_B) \quad \equiv W_h^{\mu\nu} = \hat{\sigma}(p,q)F(x_B)$$

Where

$$F(\xi) = \int \frac{d^4p}{(2\pi)^4}d^4x e^{-ix\cdot p}\delta\left(\xi - \frac{p^+}{P^+}\right)\langle P|\bar{\psi}(x)\frac{\gamma^+}{2P^+}\psi(0)|P\rangle$$

Is the non-perturbative parton distribution function



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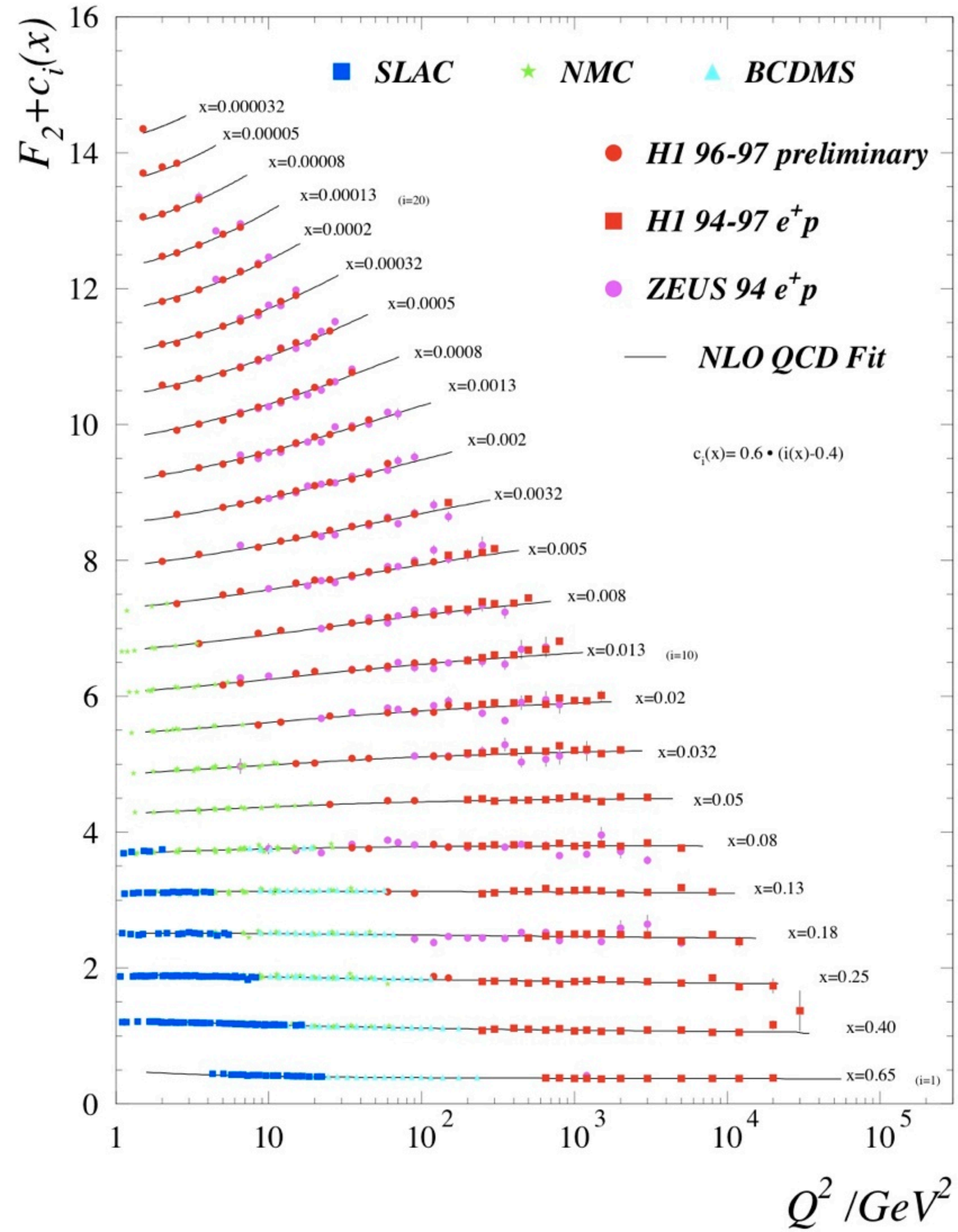

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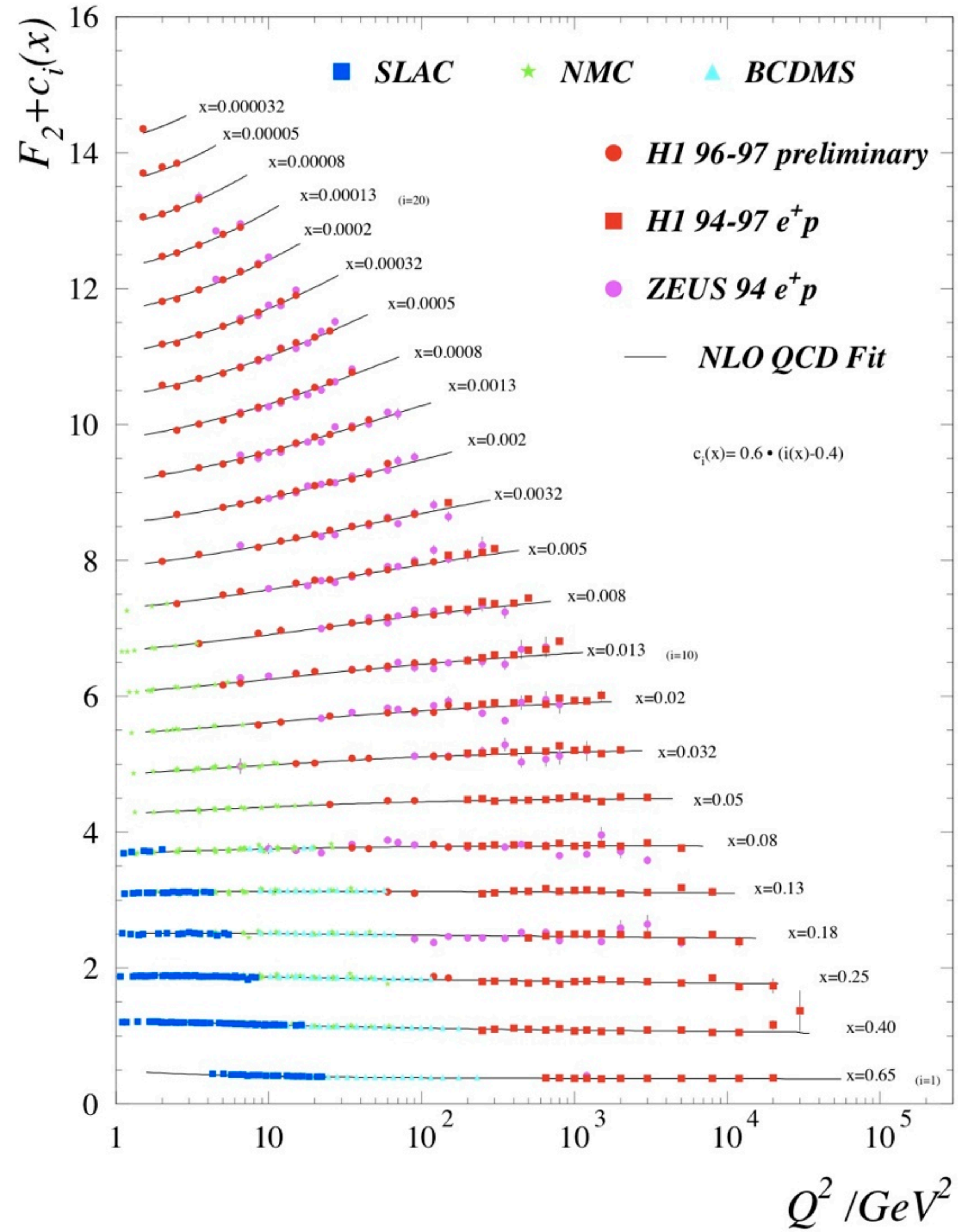

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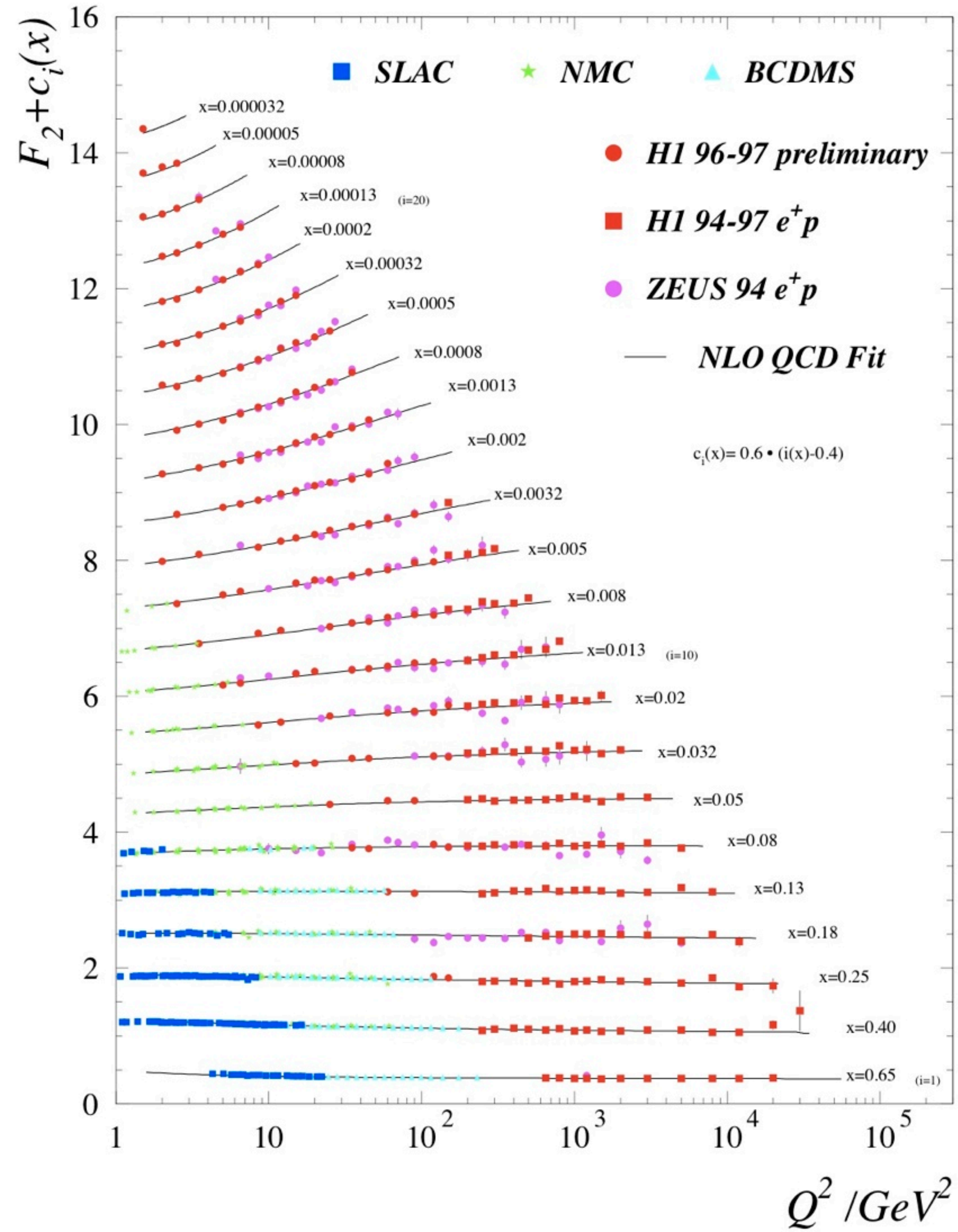

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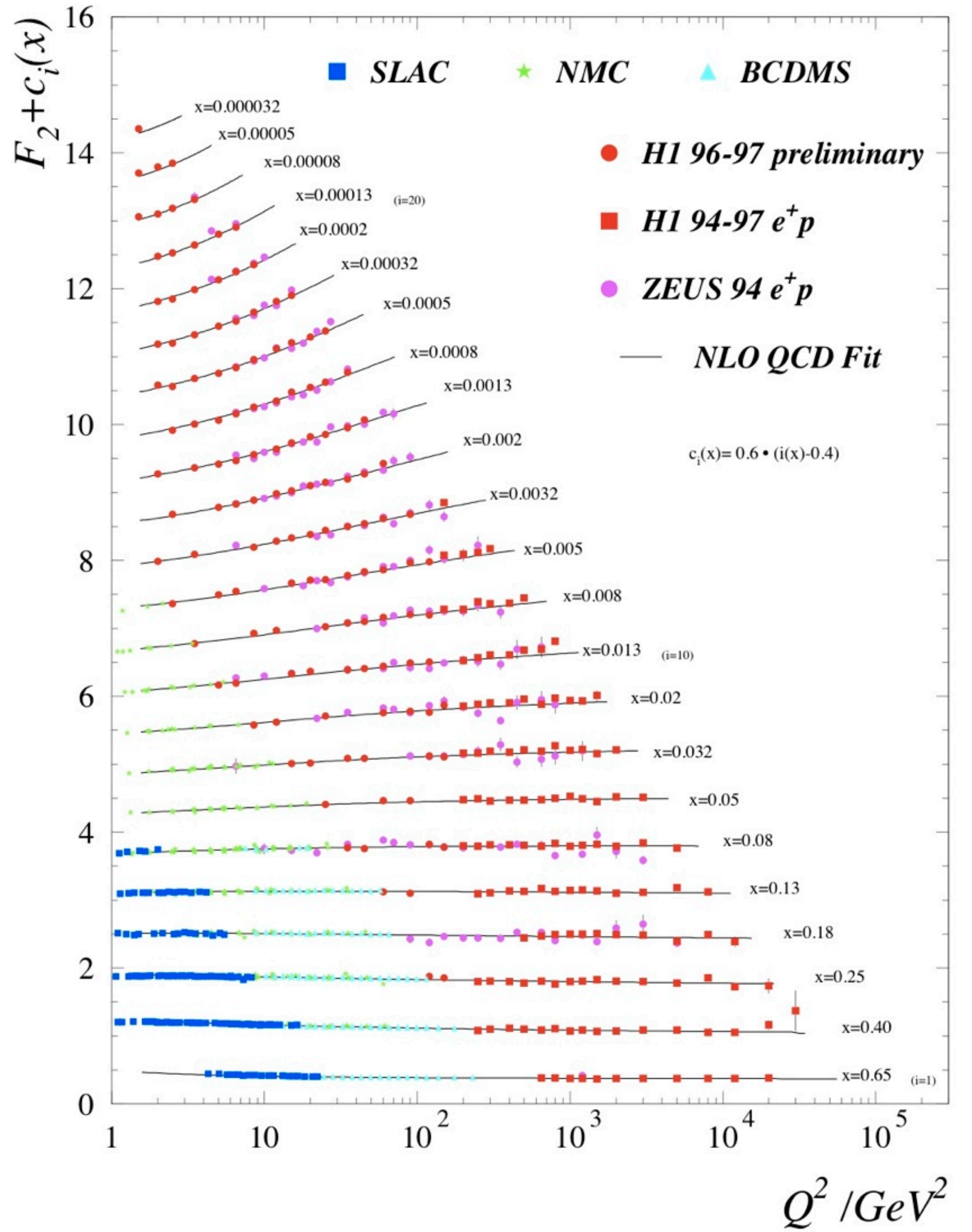

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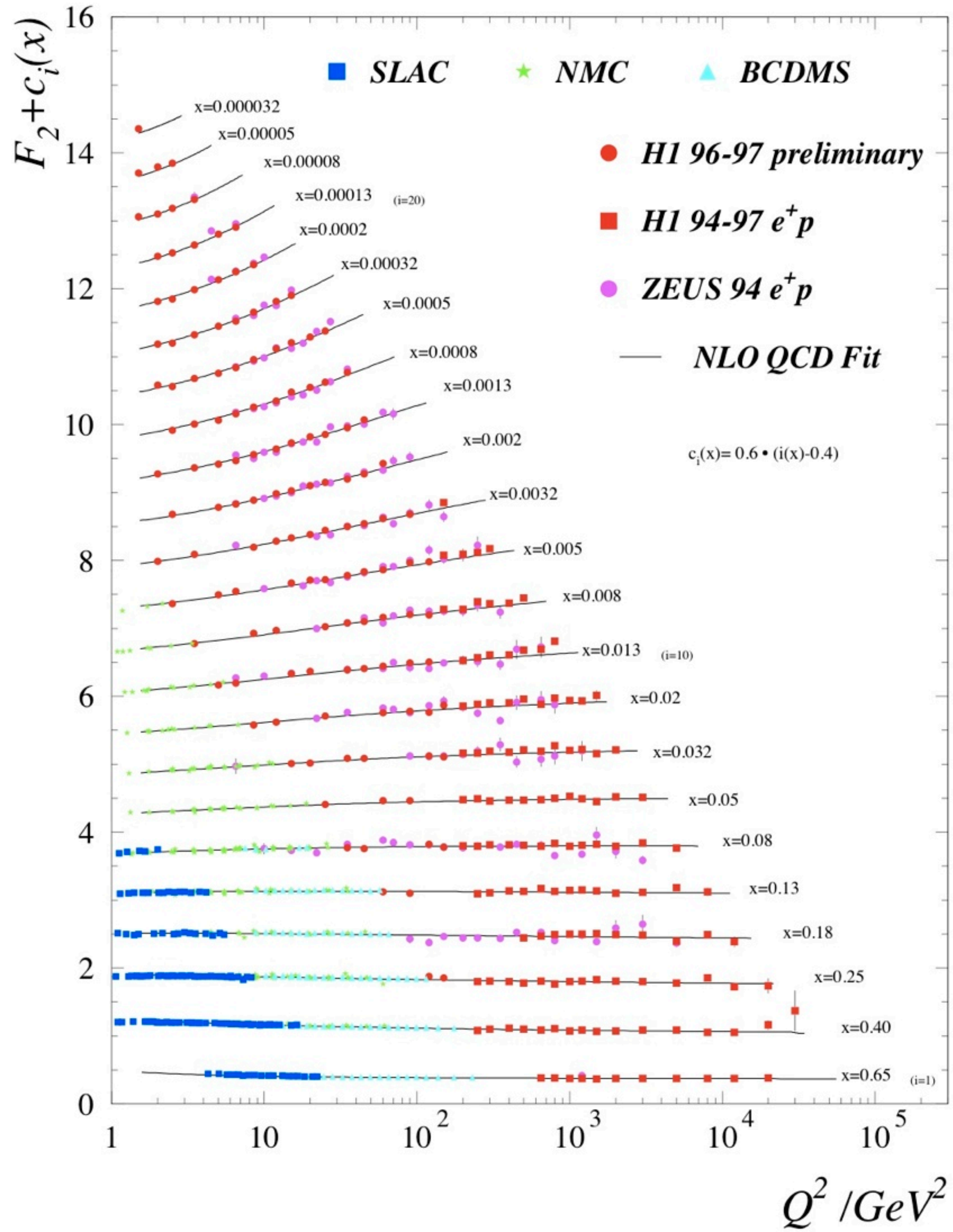

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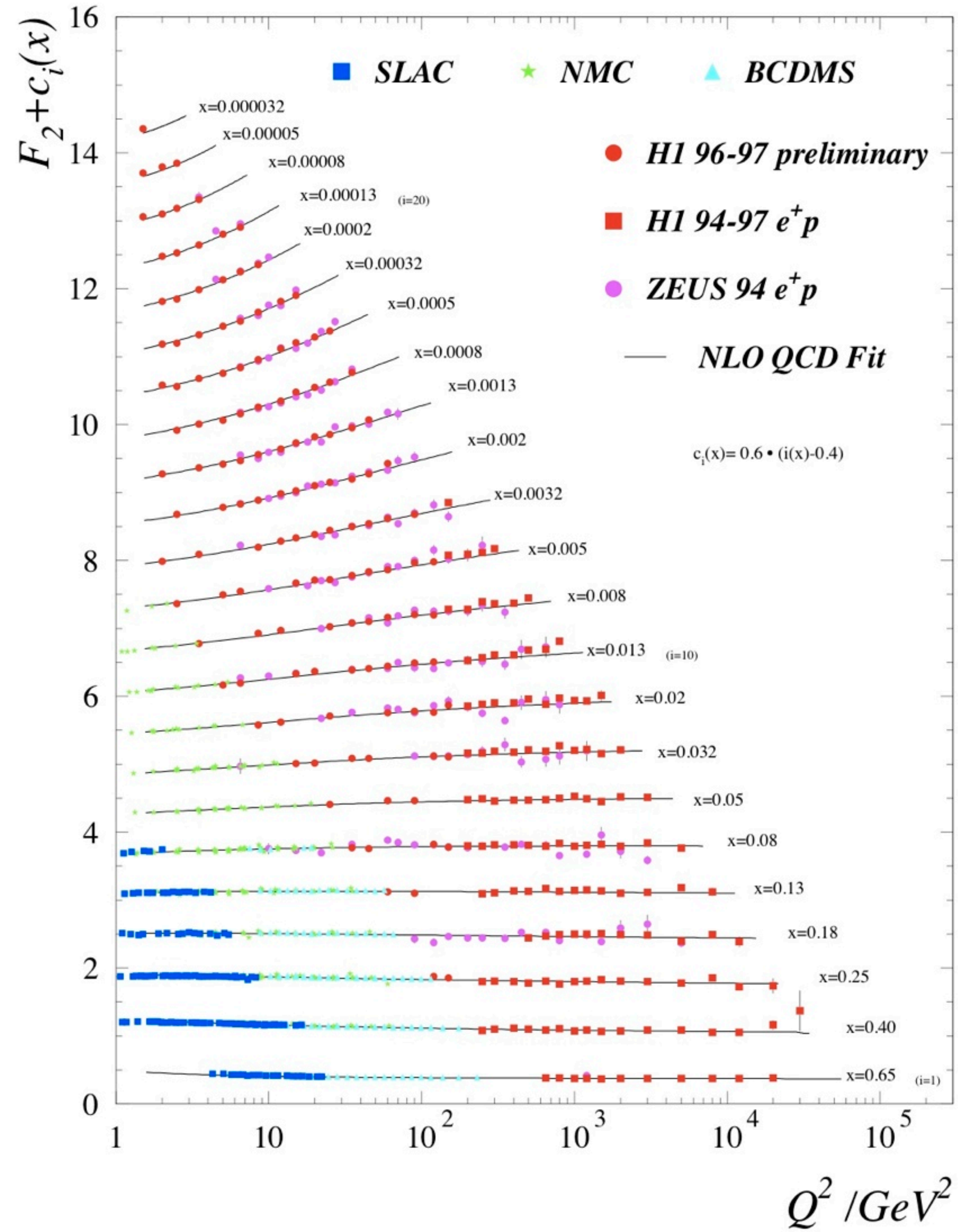

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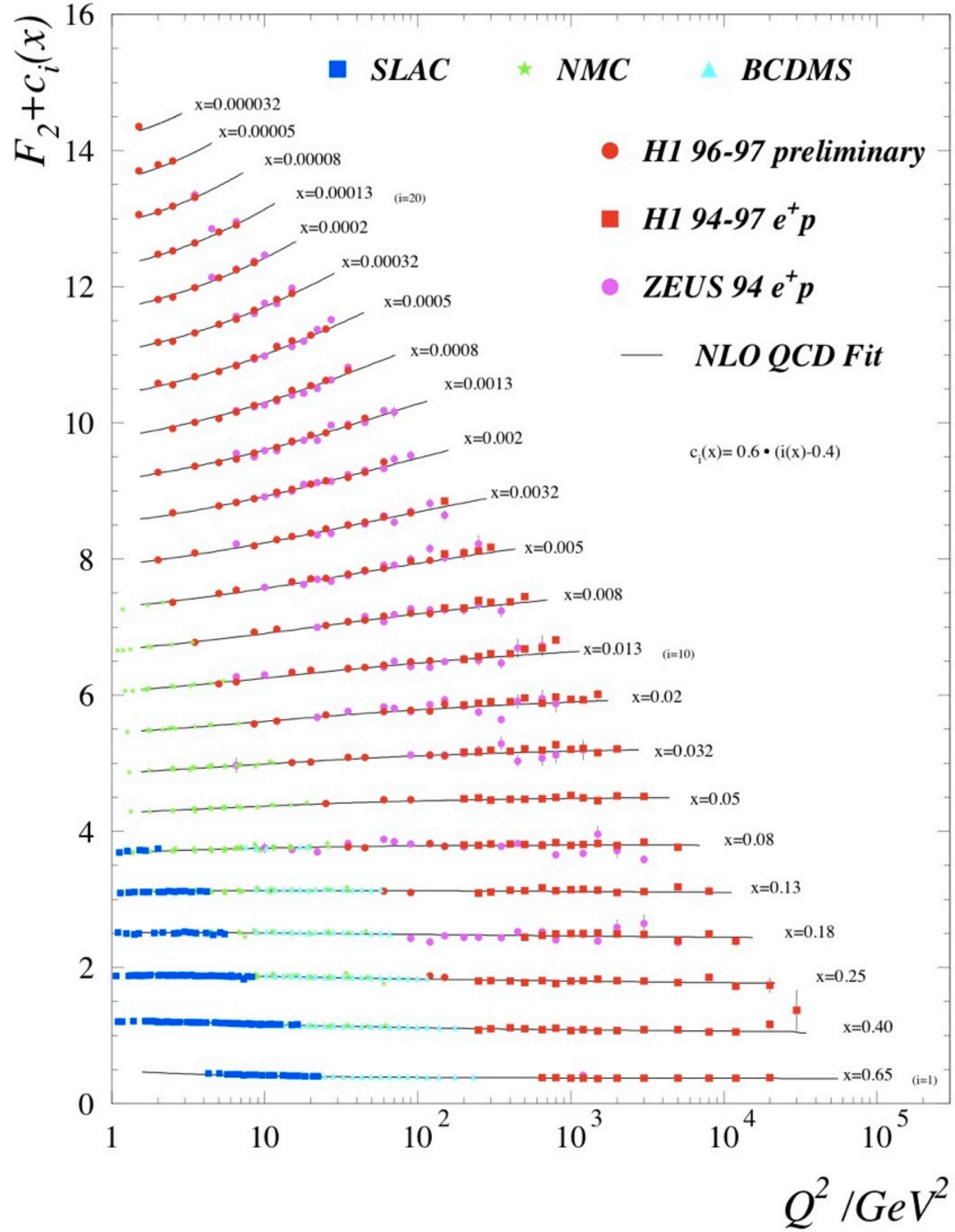

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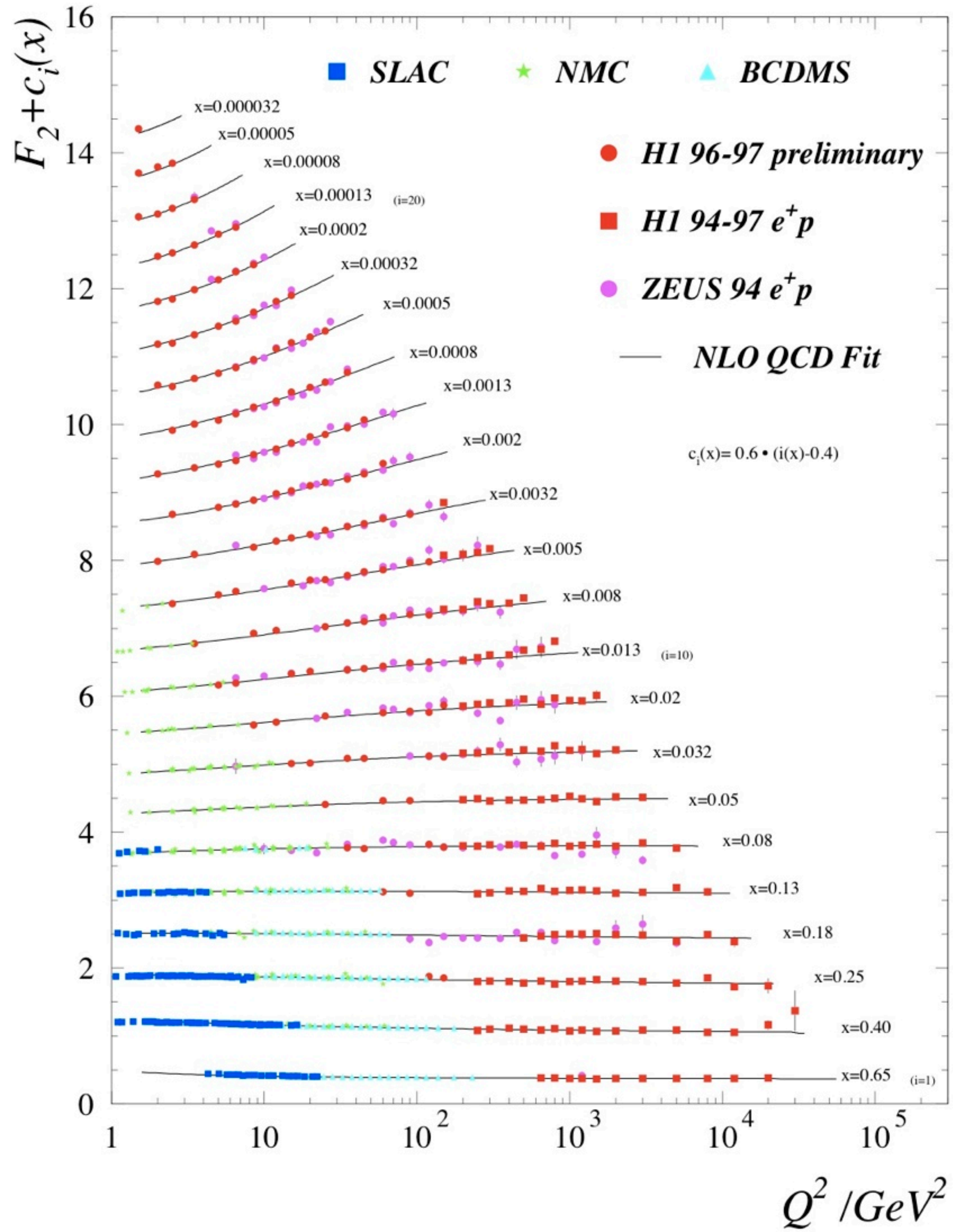

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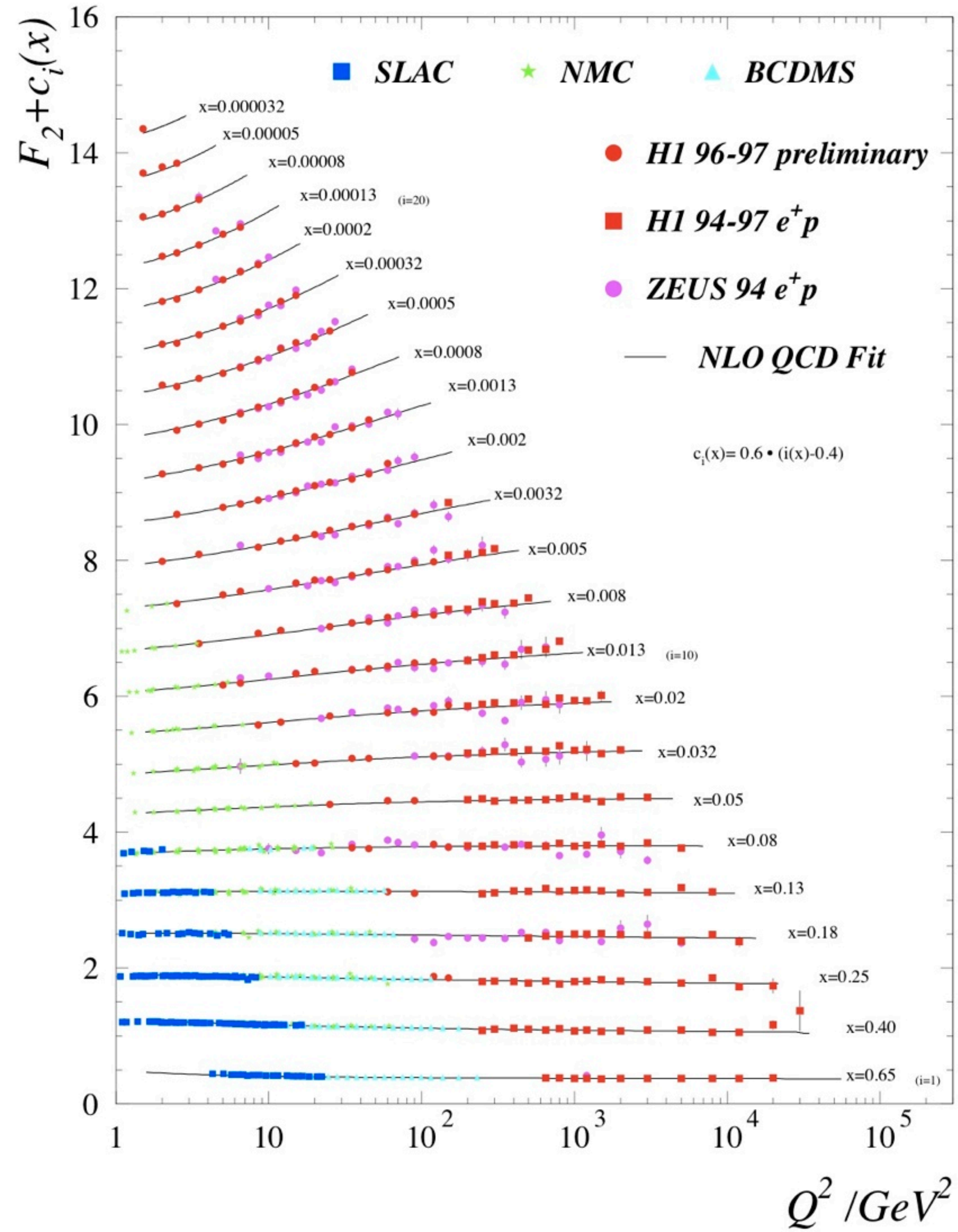

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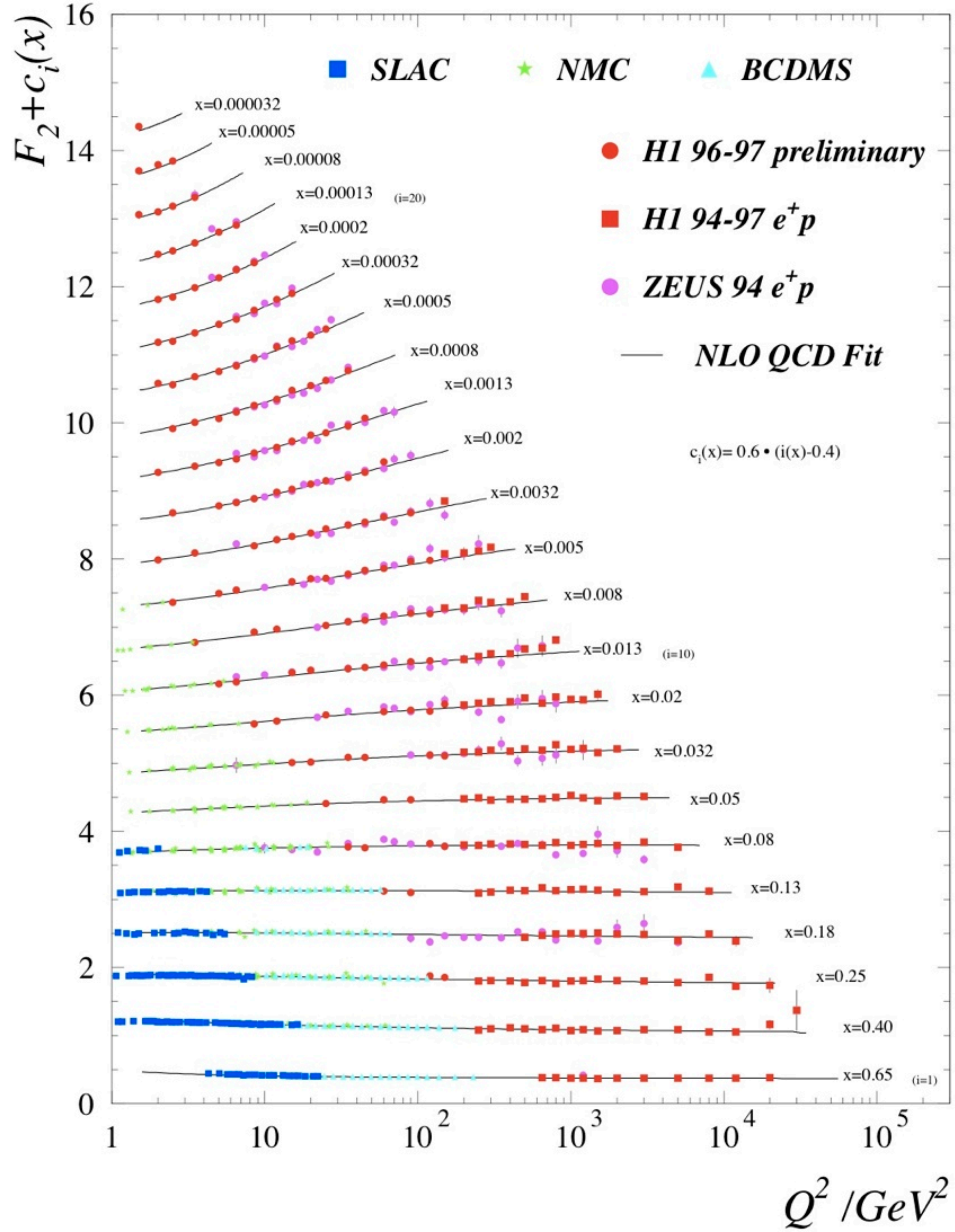

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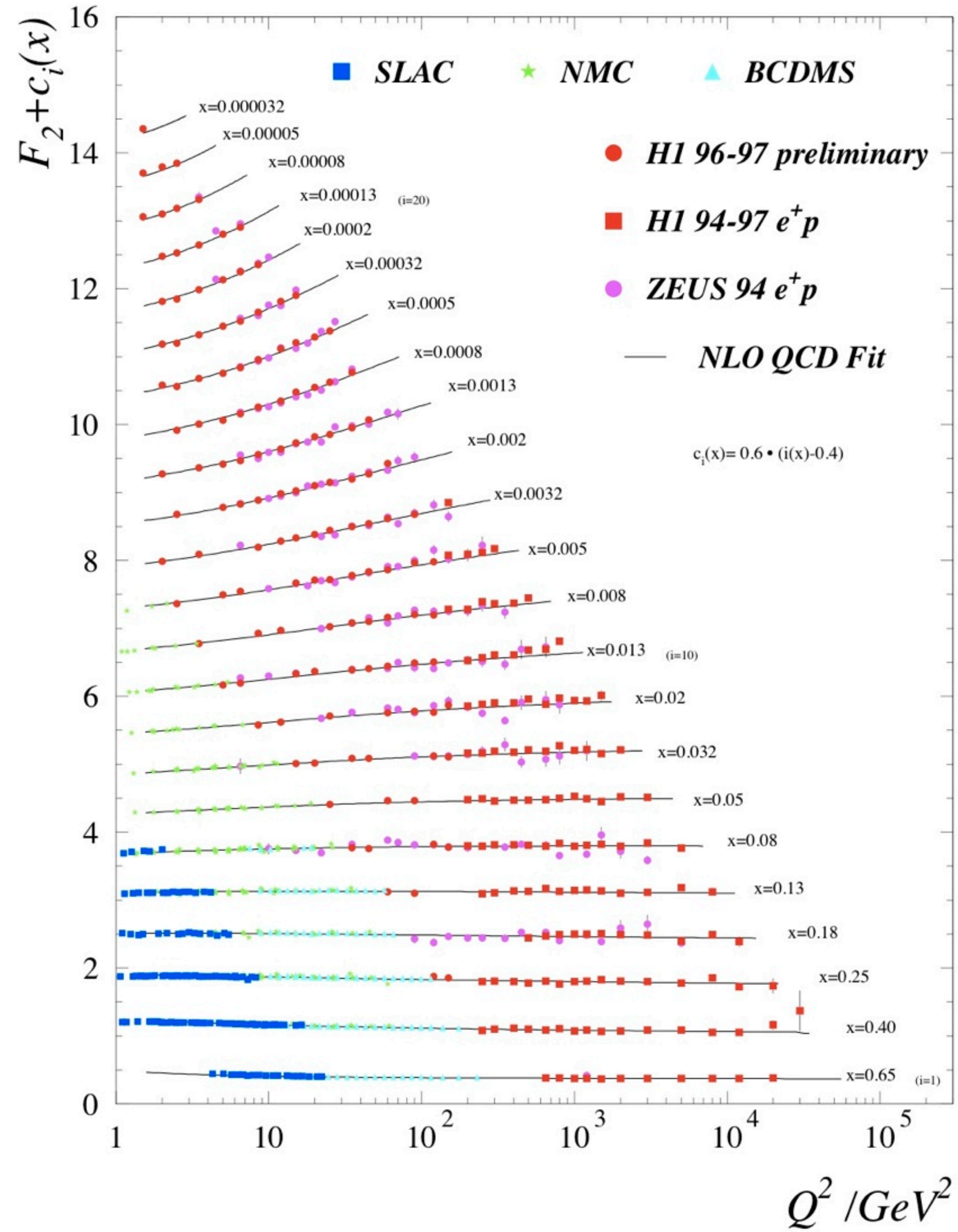

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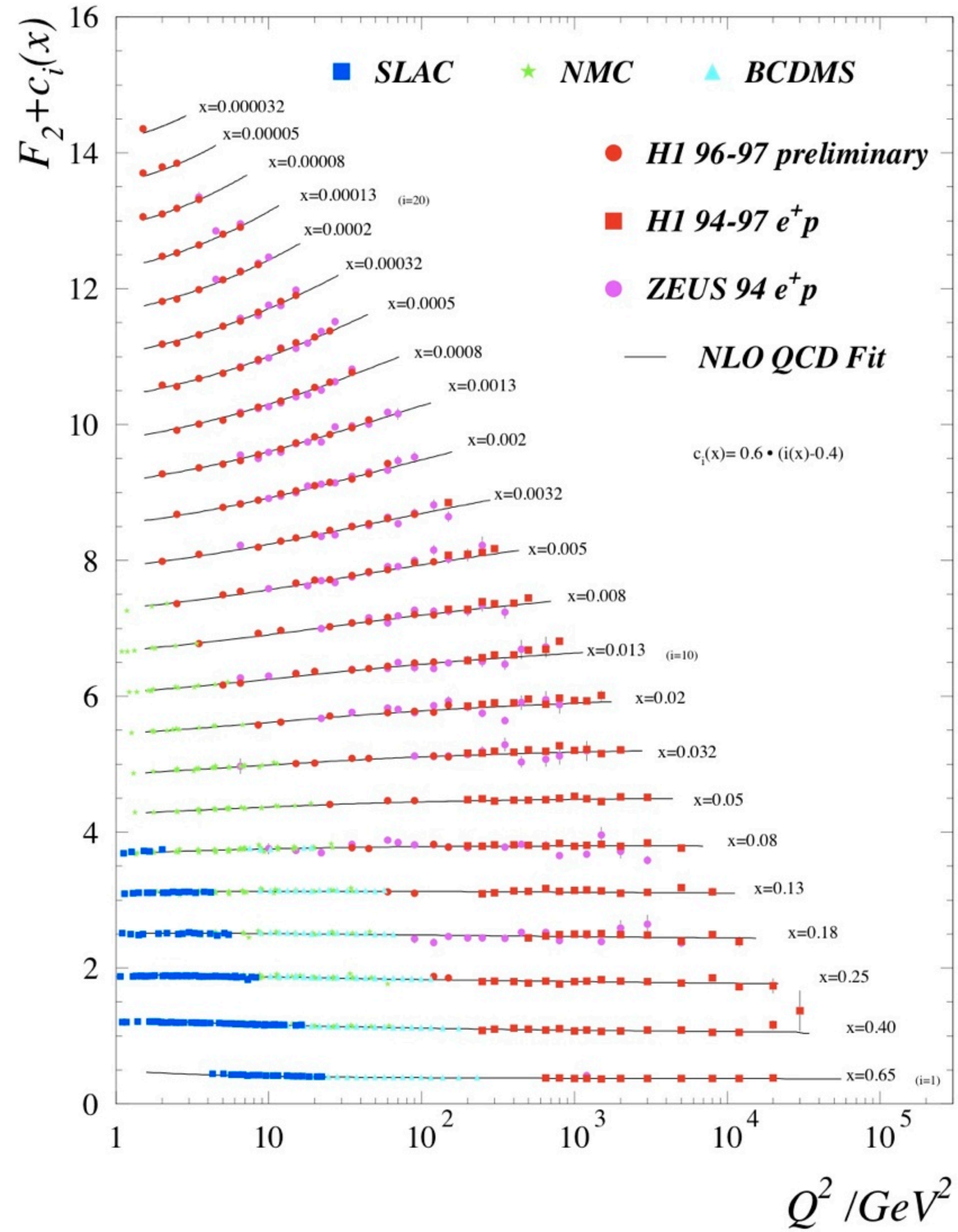

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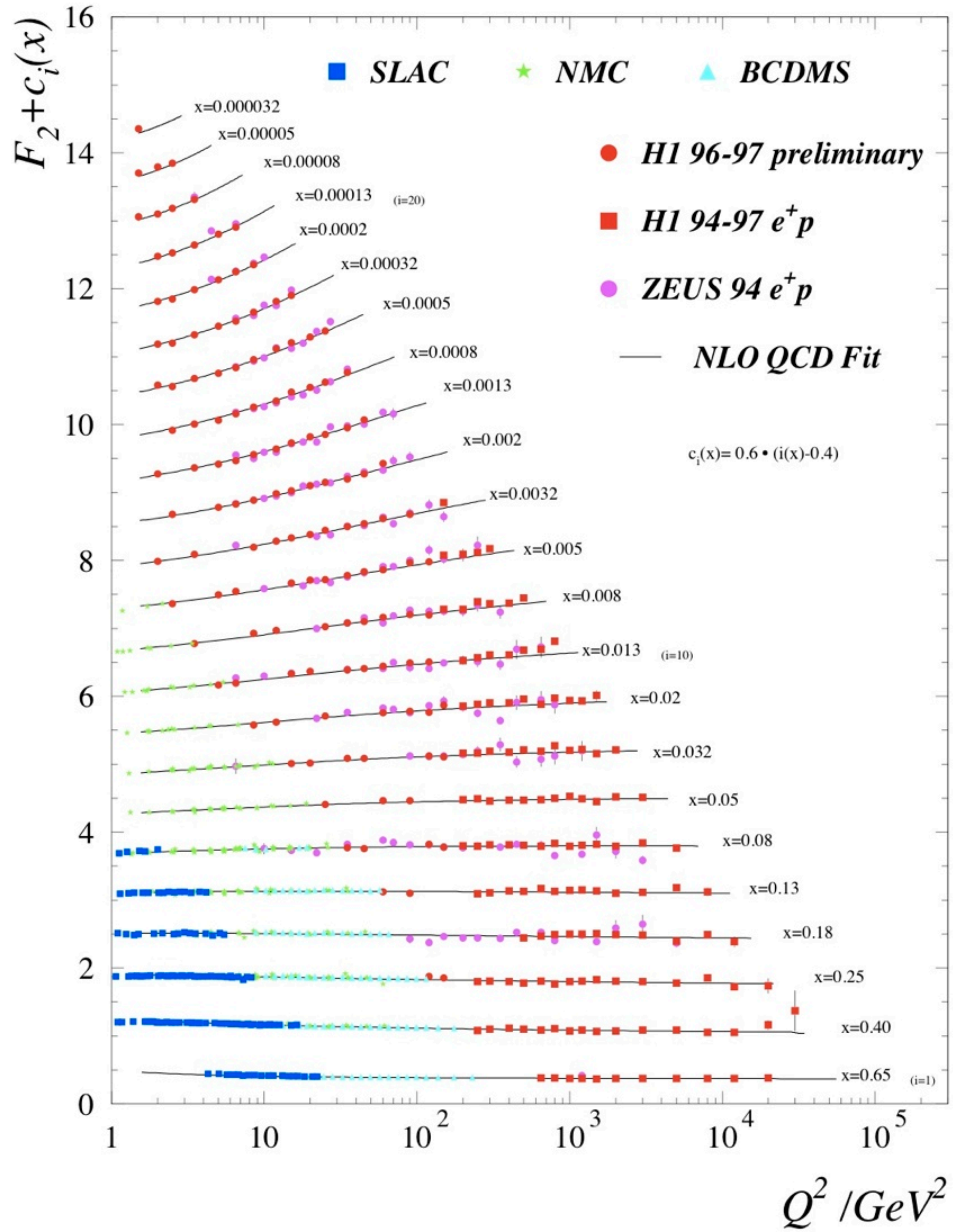

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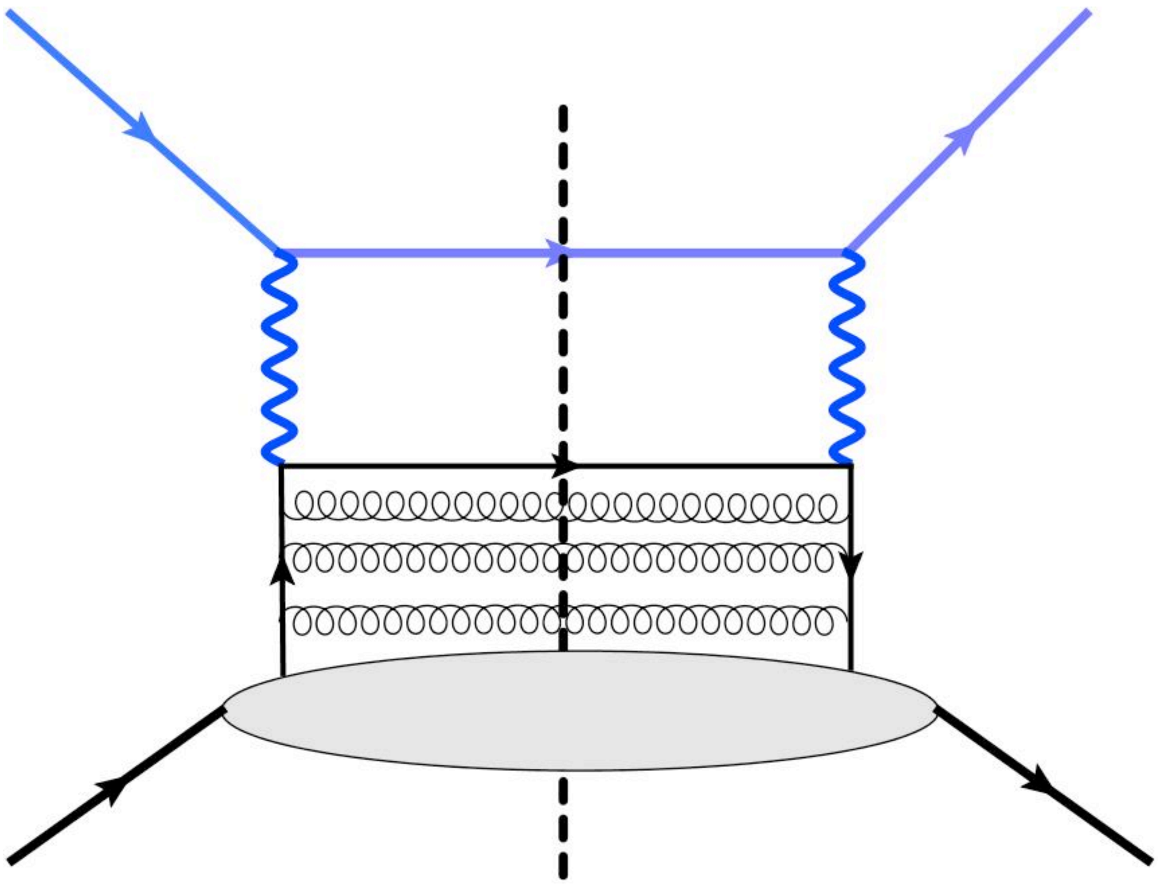

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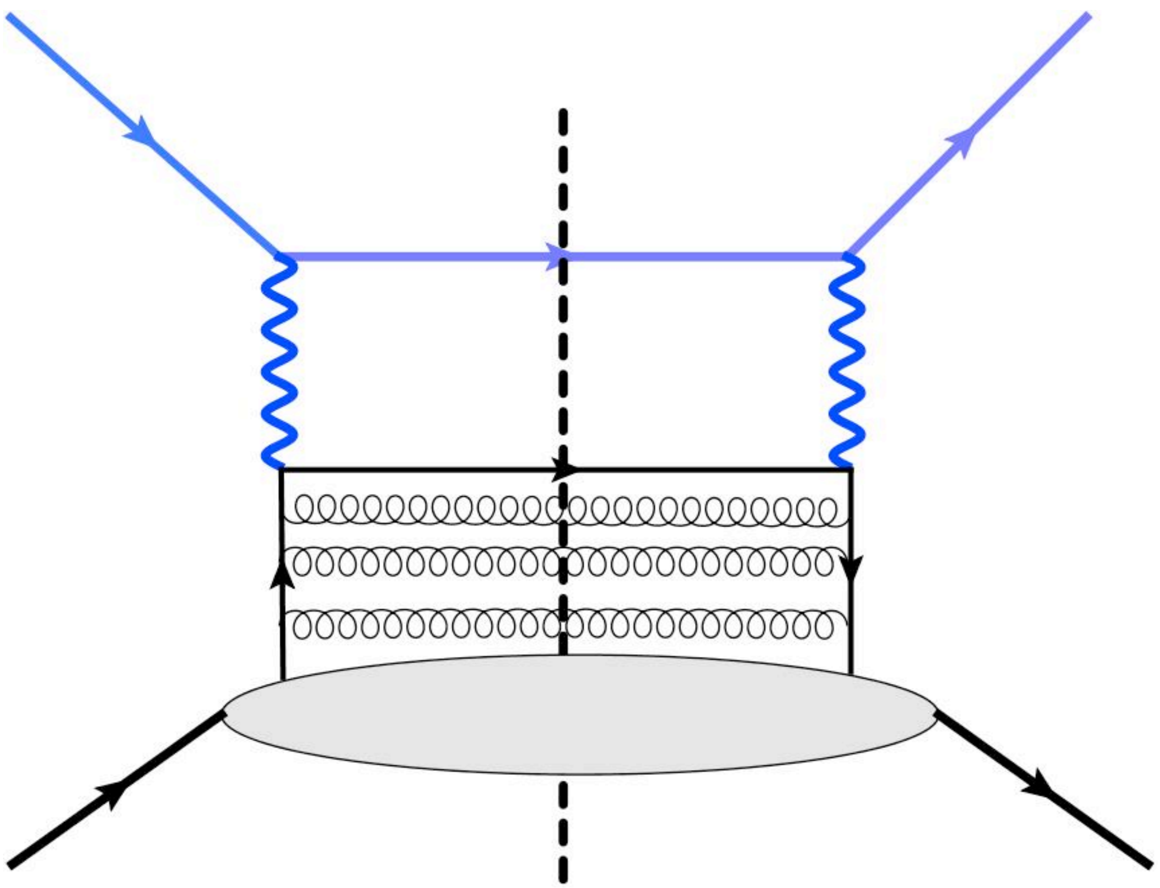

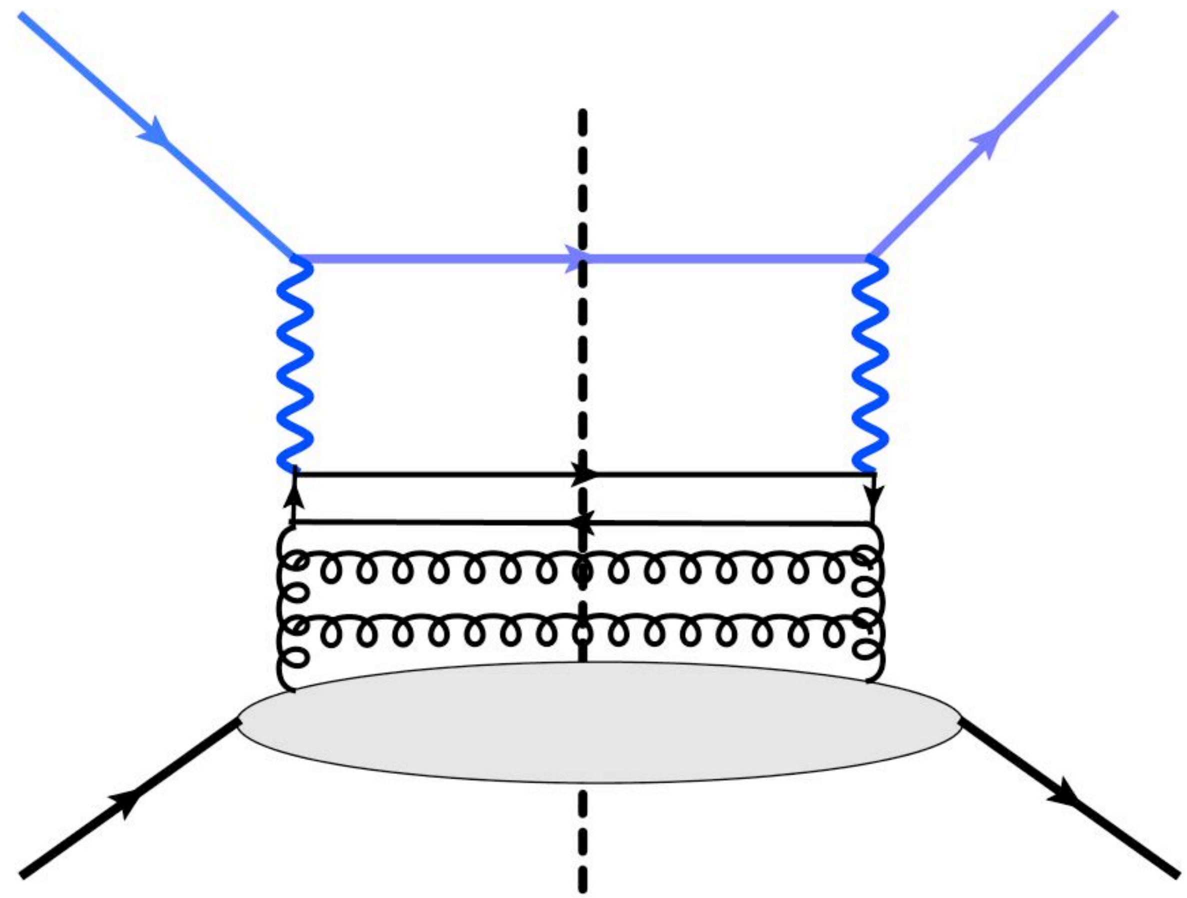

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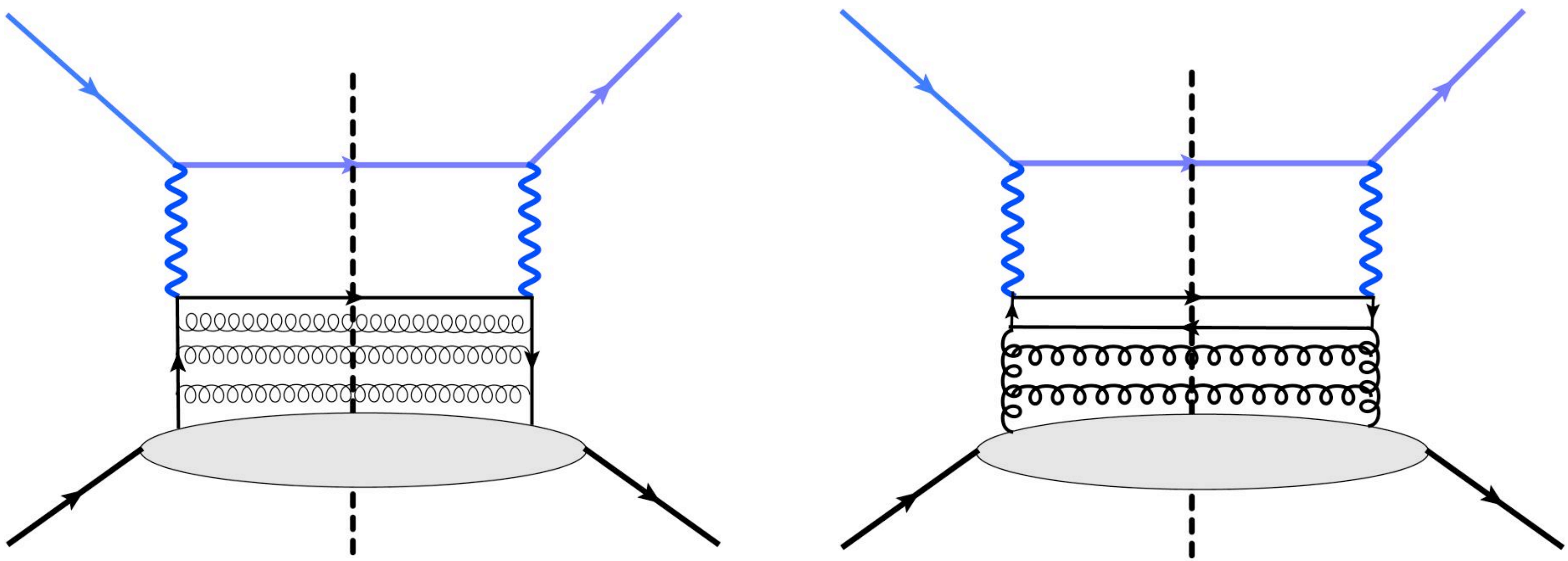
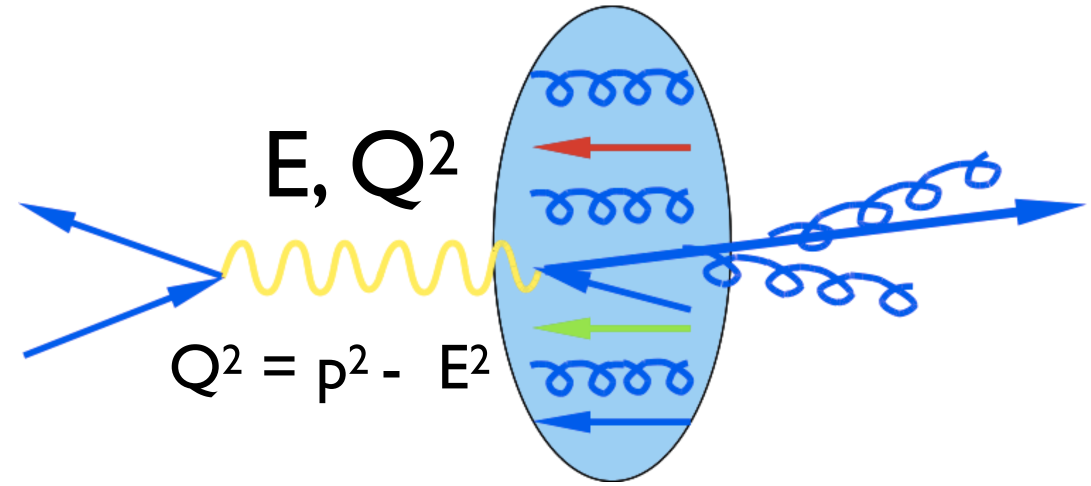
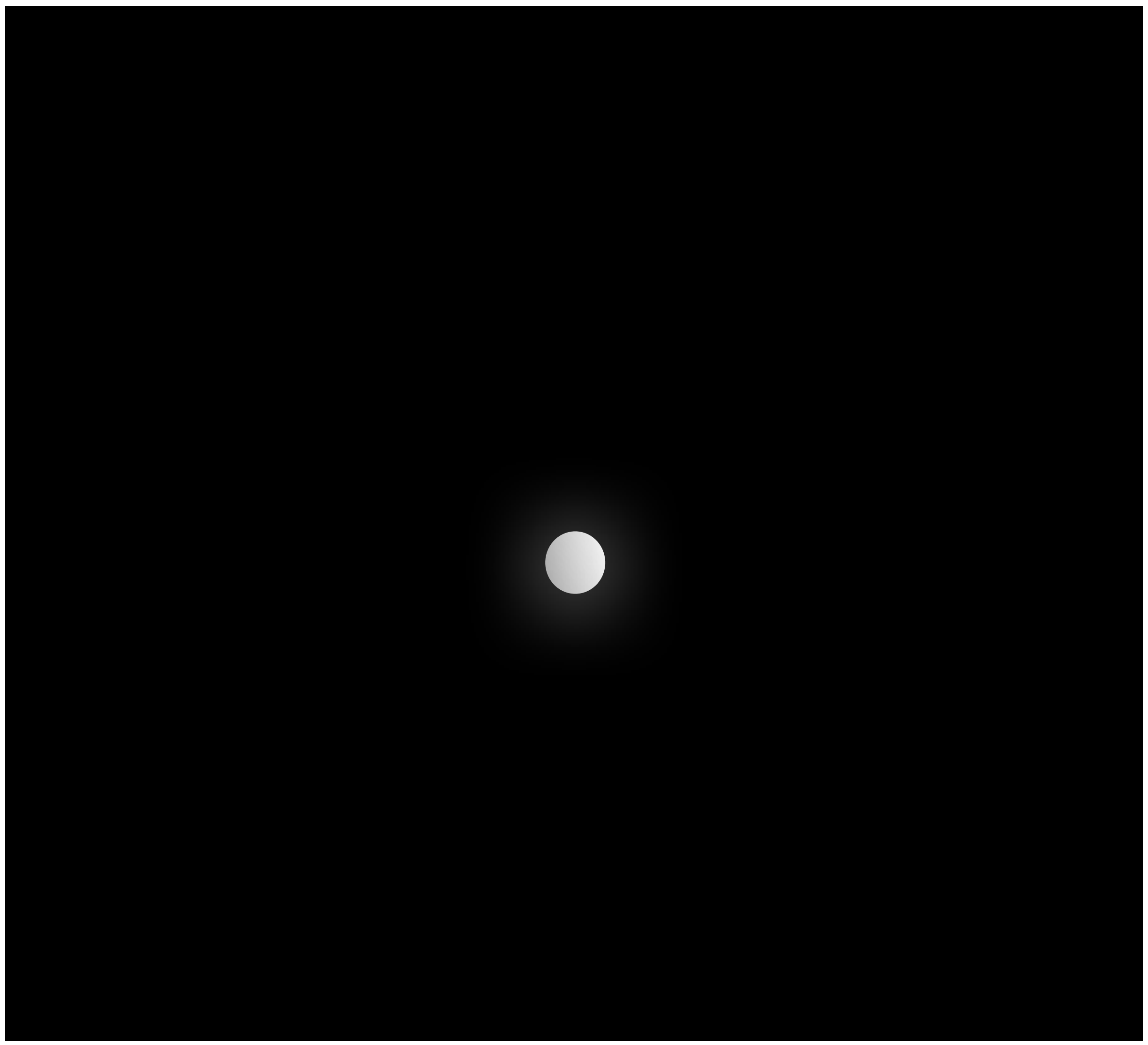
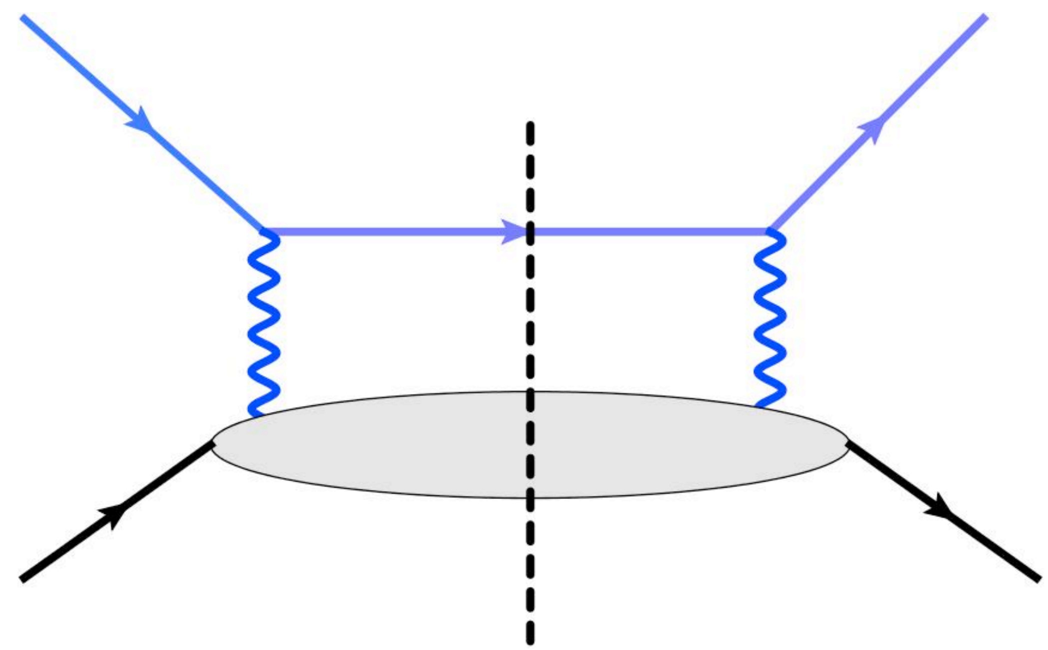


$$
\begin{aligned}
\frac{dF(x,\mu^2)}{dlog\mu^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y} P_{q\rightarrow q}(y) F\left(\frac{x}{y},\mu^2\right) \\
&+ \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y} P_{g\rightarrow q}(y) G\left(\frac{x}{y},\mu^2\right)
\end{aligned}
$$

What the electron sees, depends on E, Q^2







Increasing energy E = boosting nucleon
Increasing Q^2 = getting closer to nucleon

$$x = \frac{p}{P_h}$$

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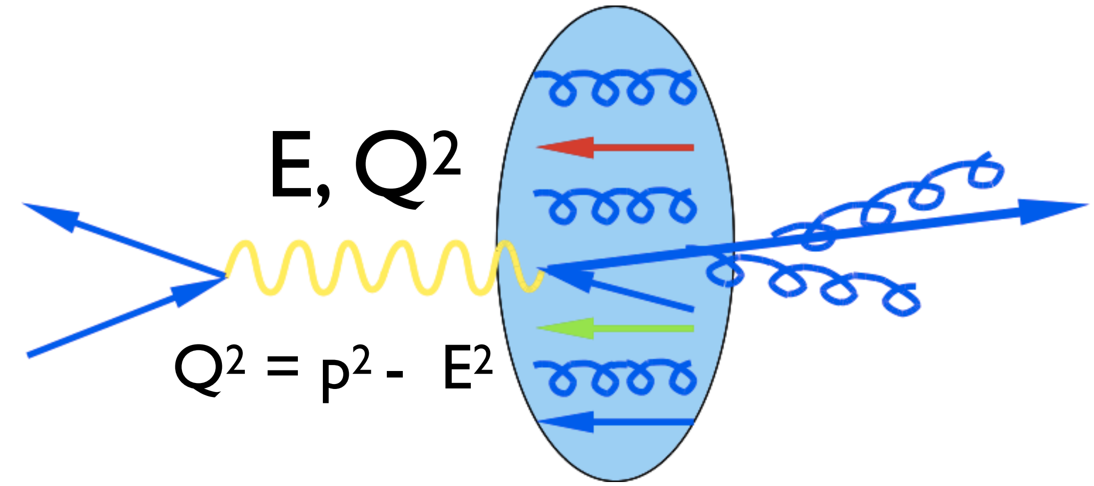

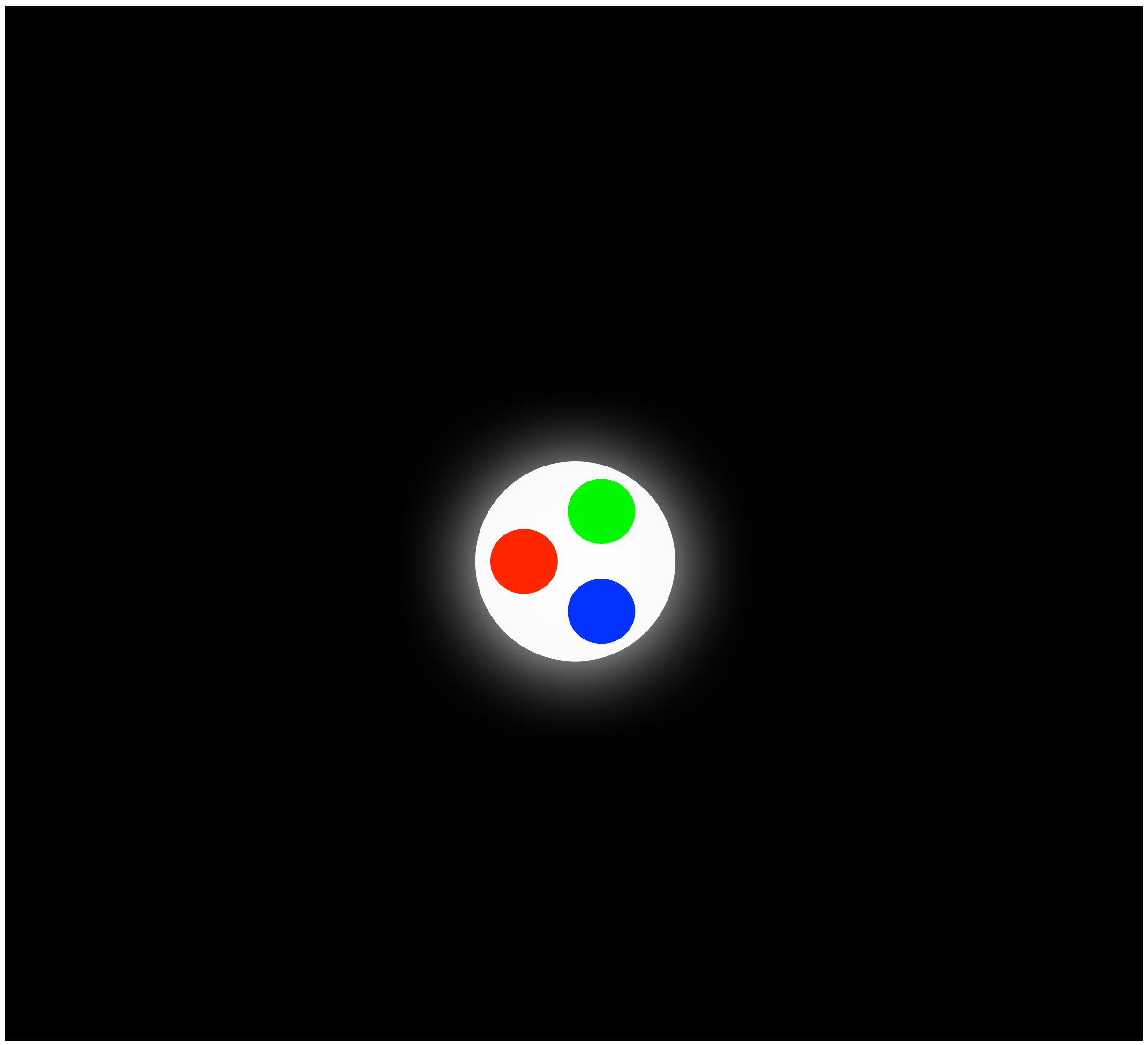

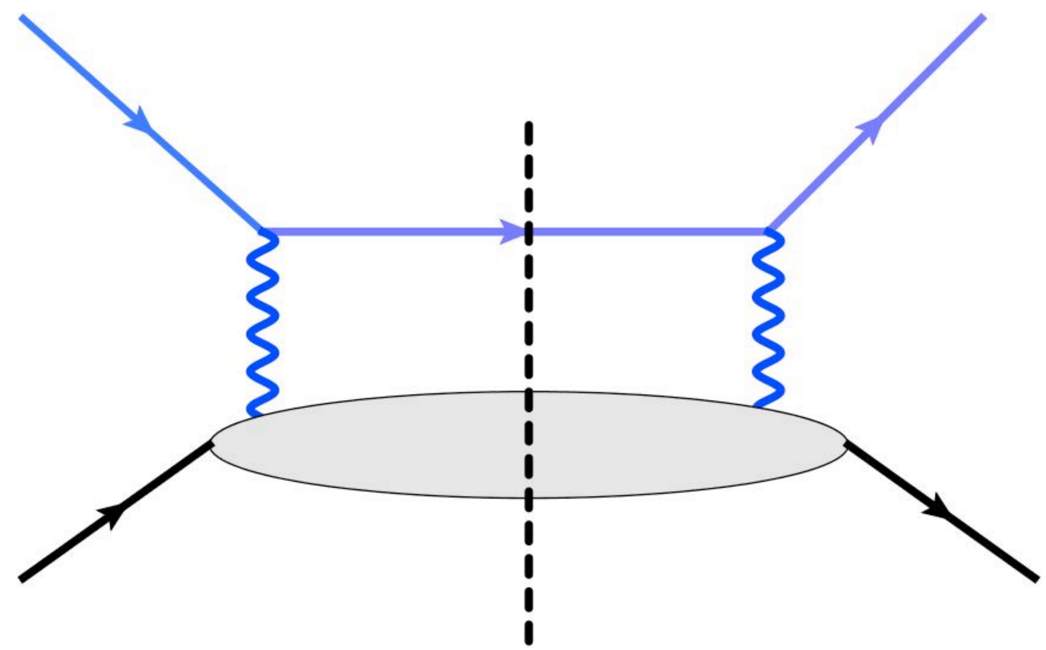

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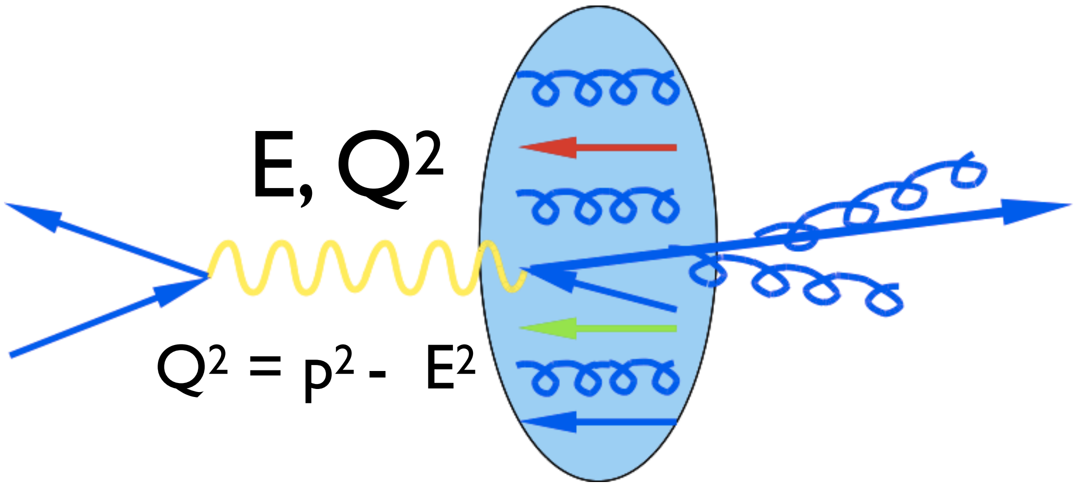

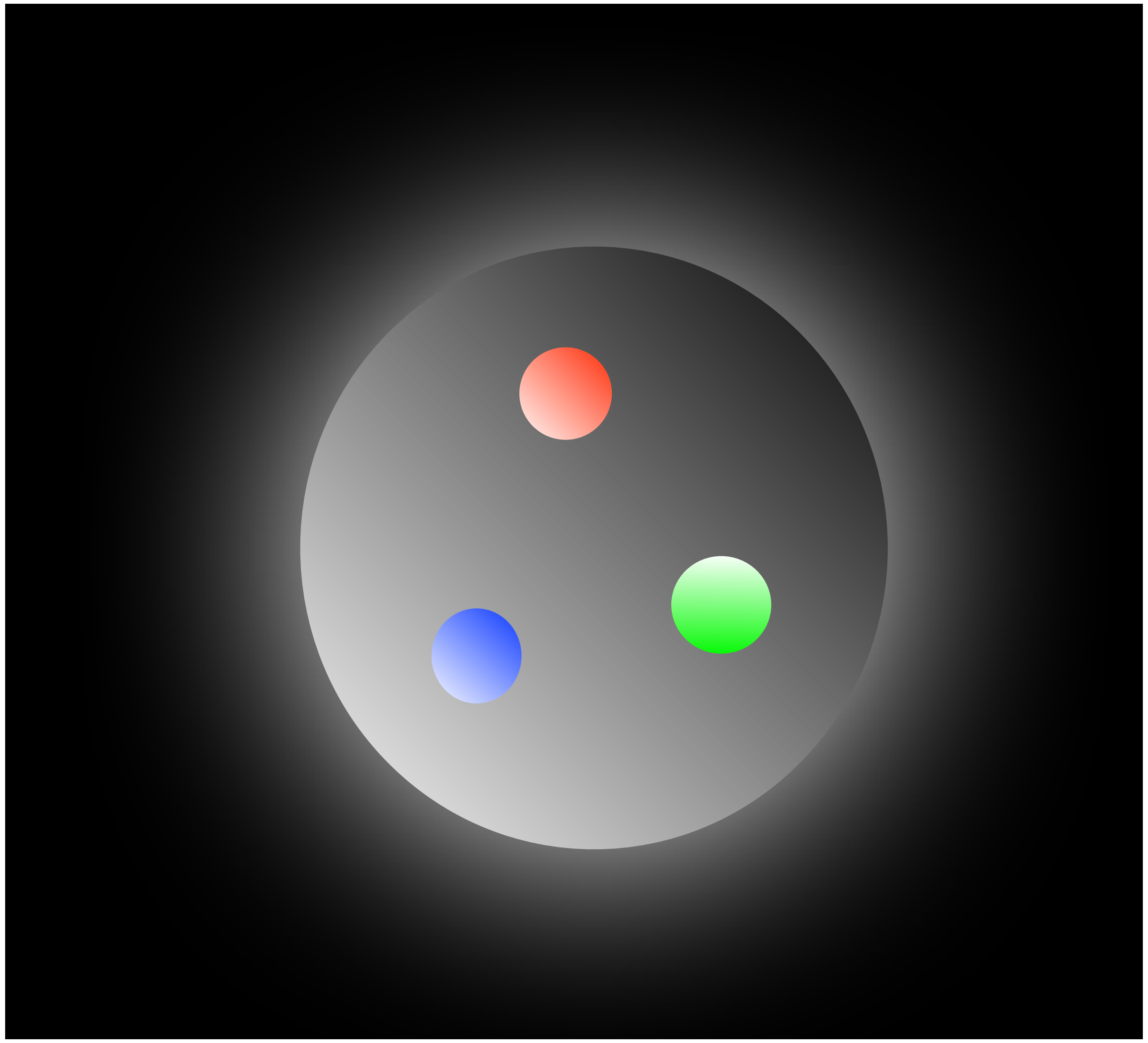

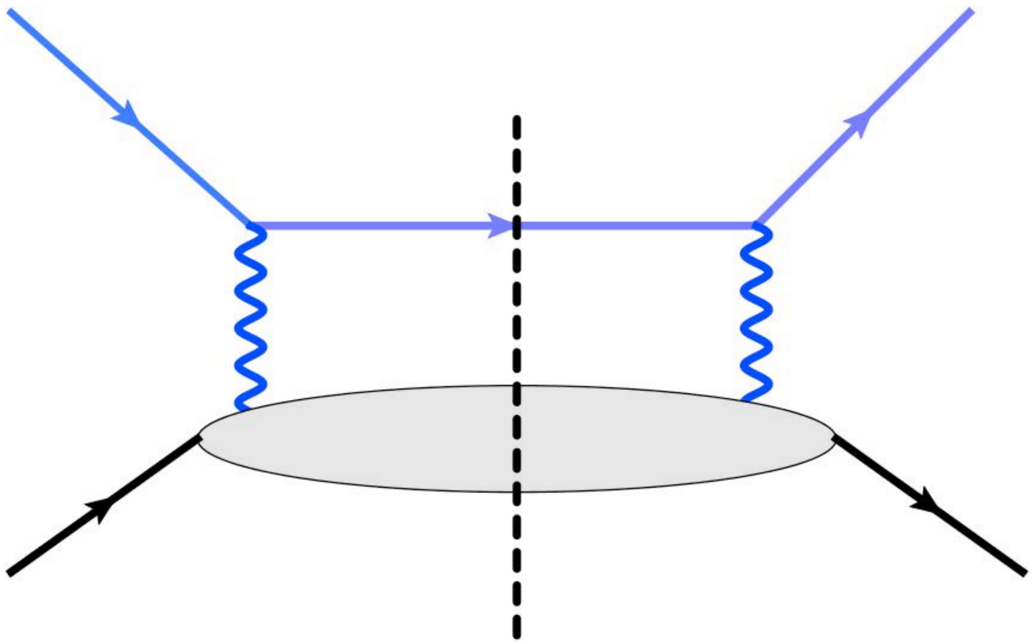

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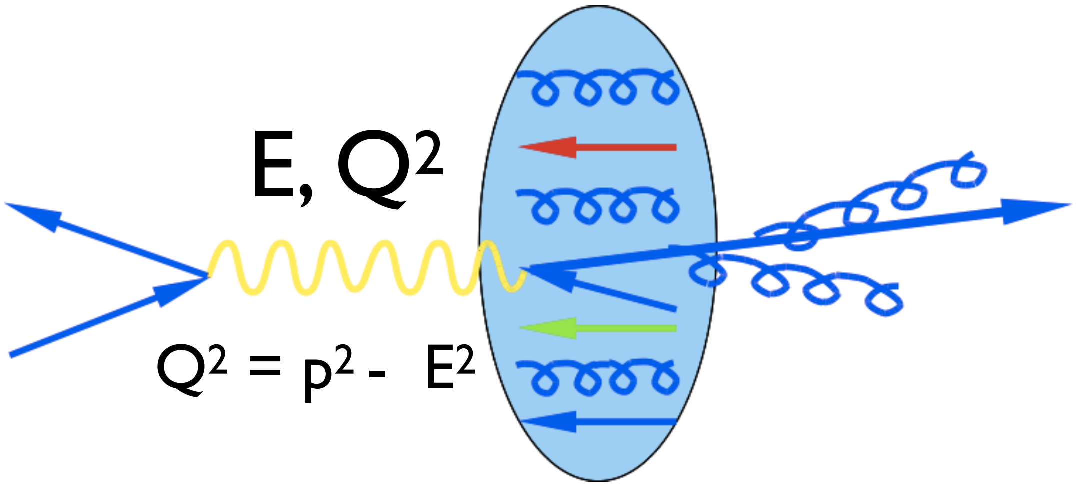

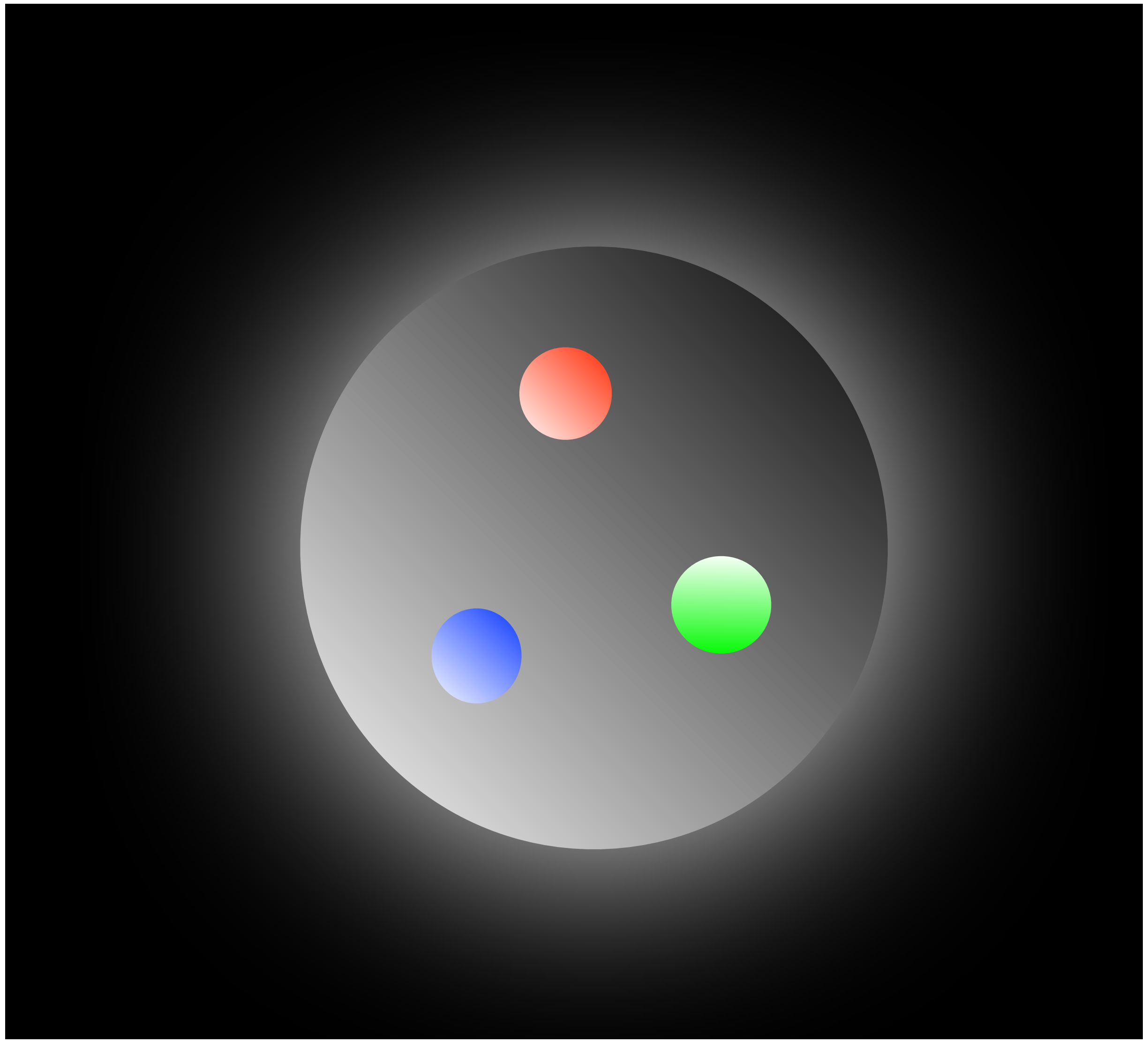

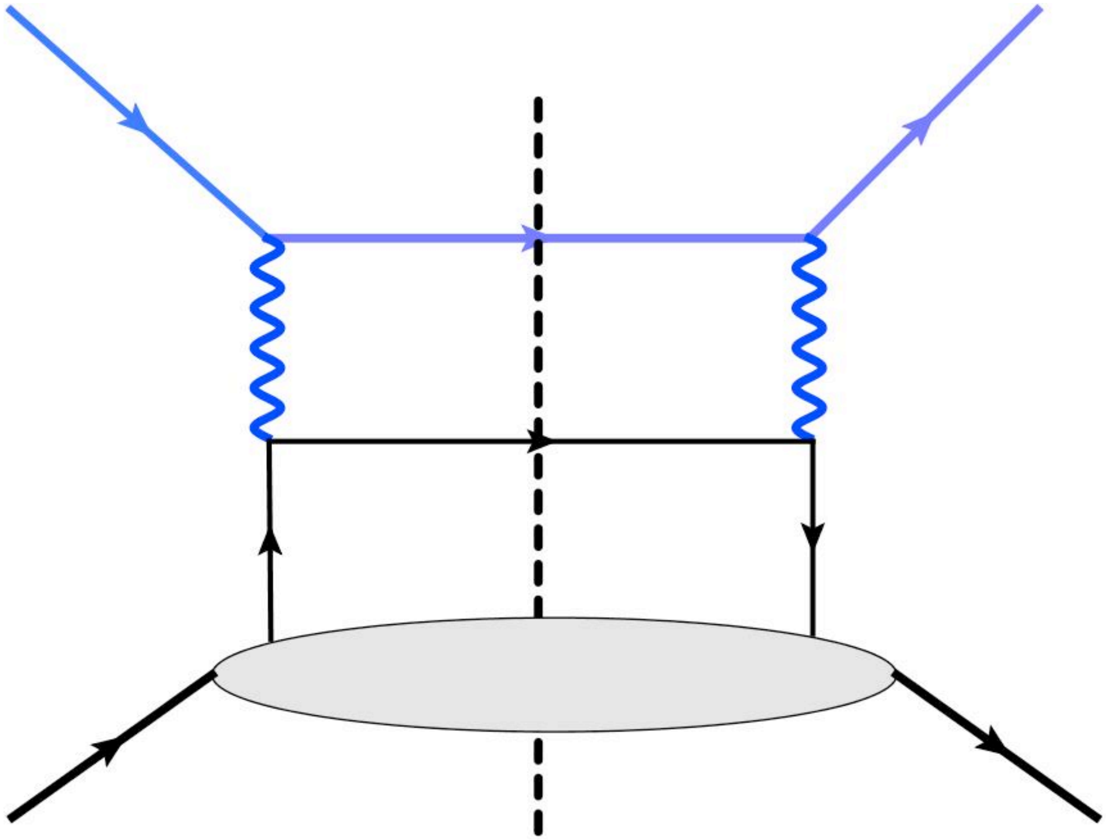

Increasing energy E = boosting nucleon
Increasing Q^2 = getting closer to nucleon

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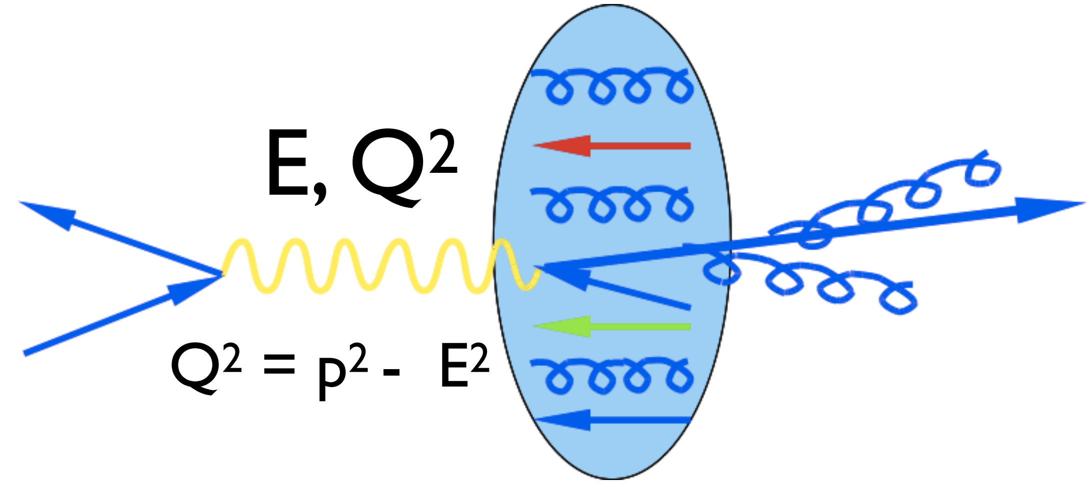

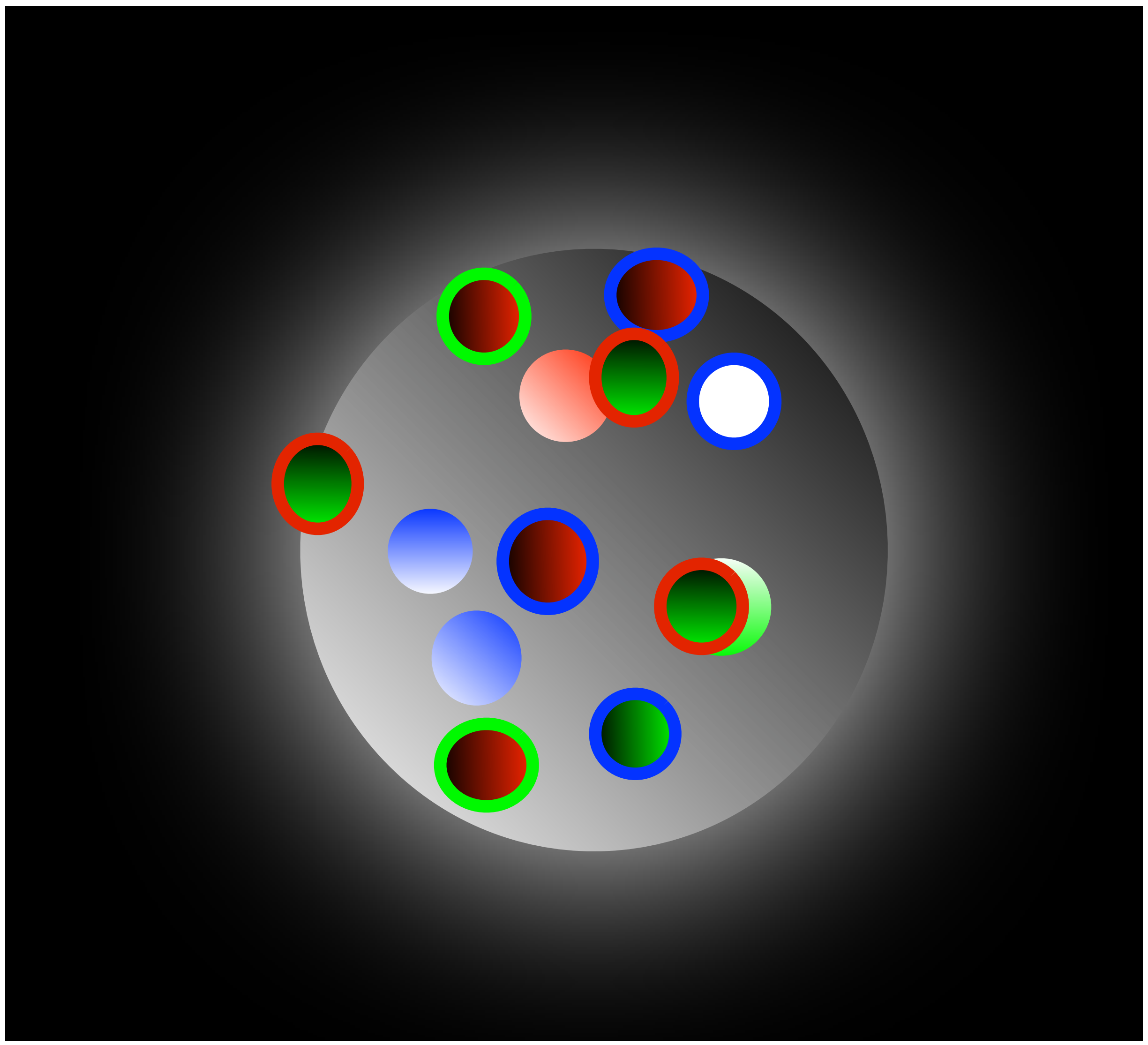

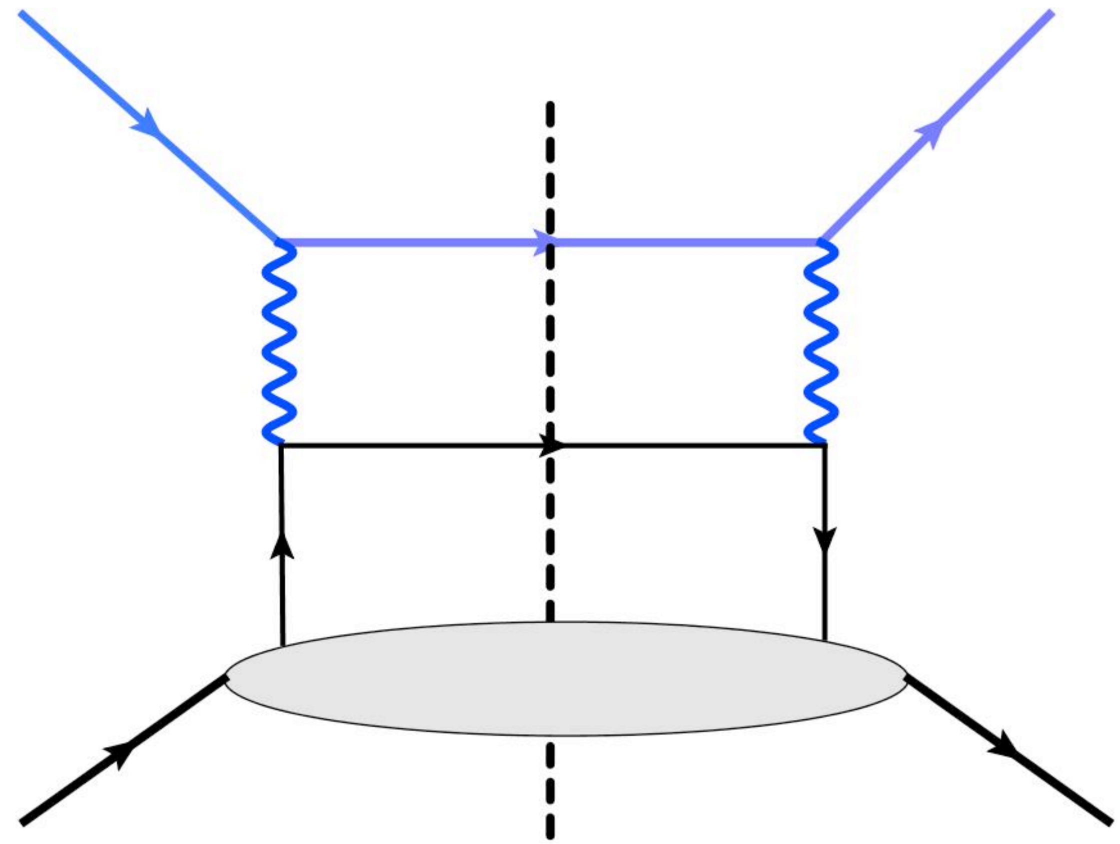

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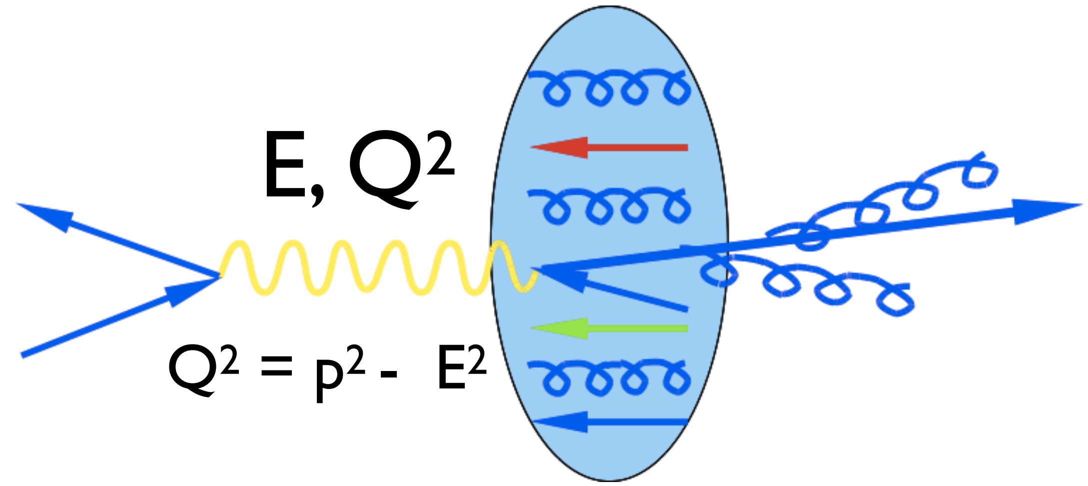

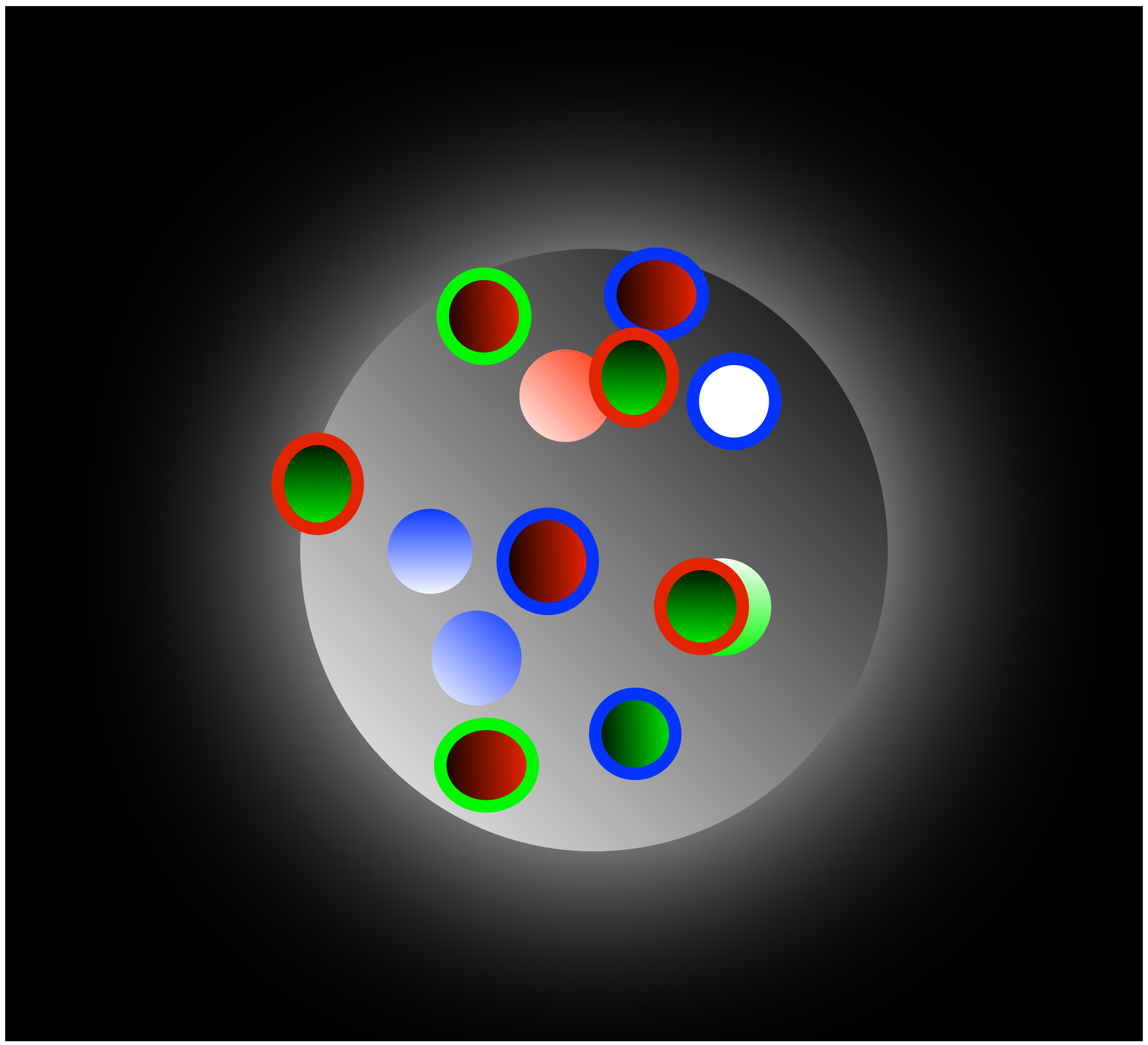

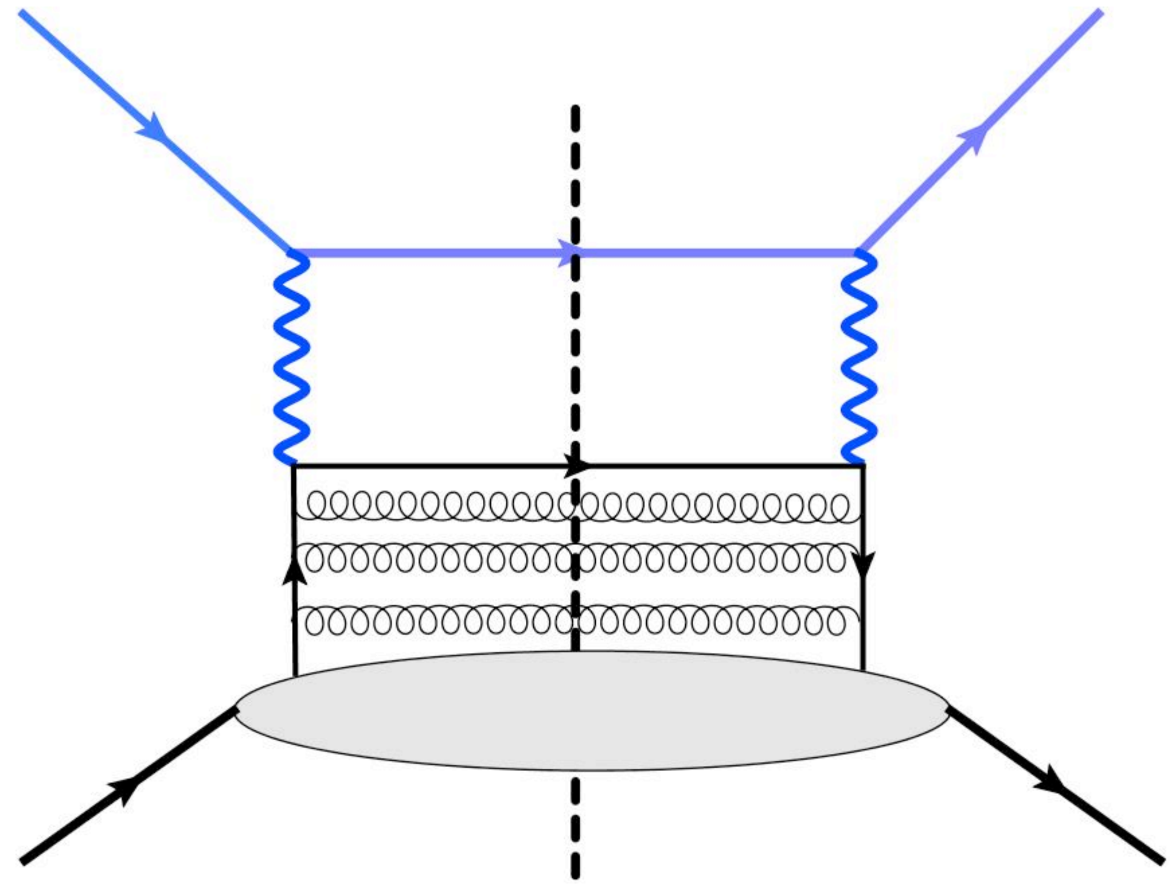

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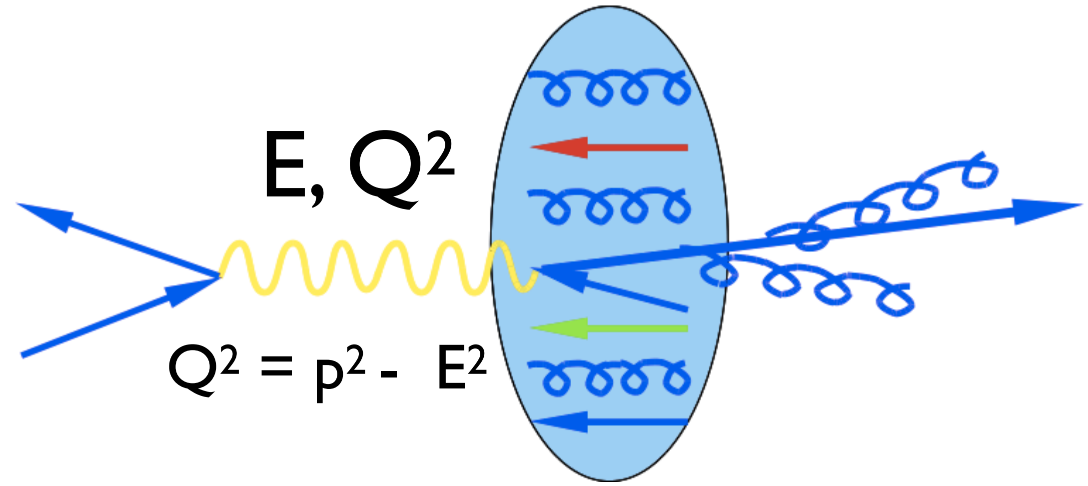

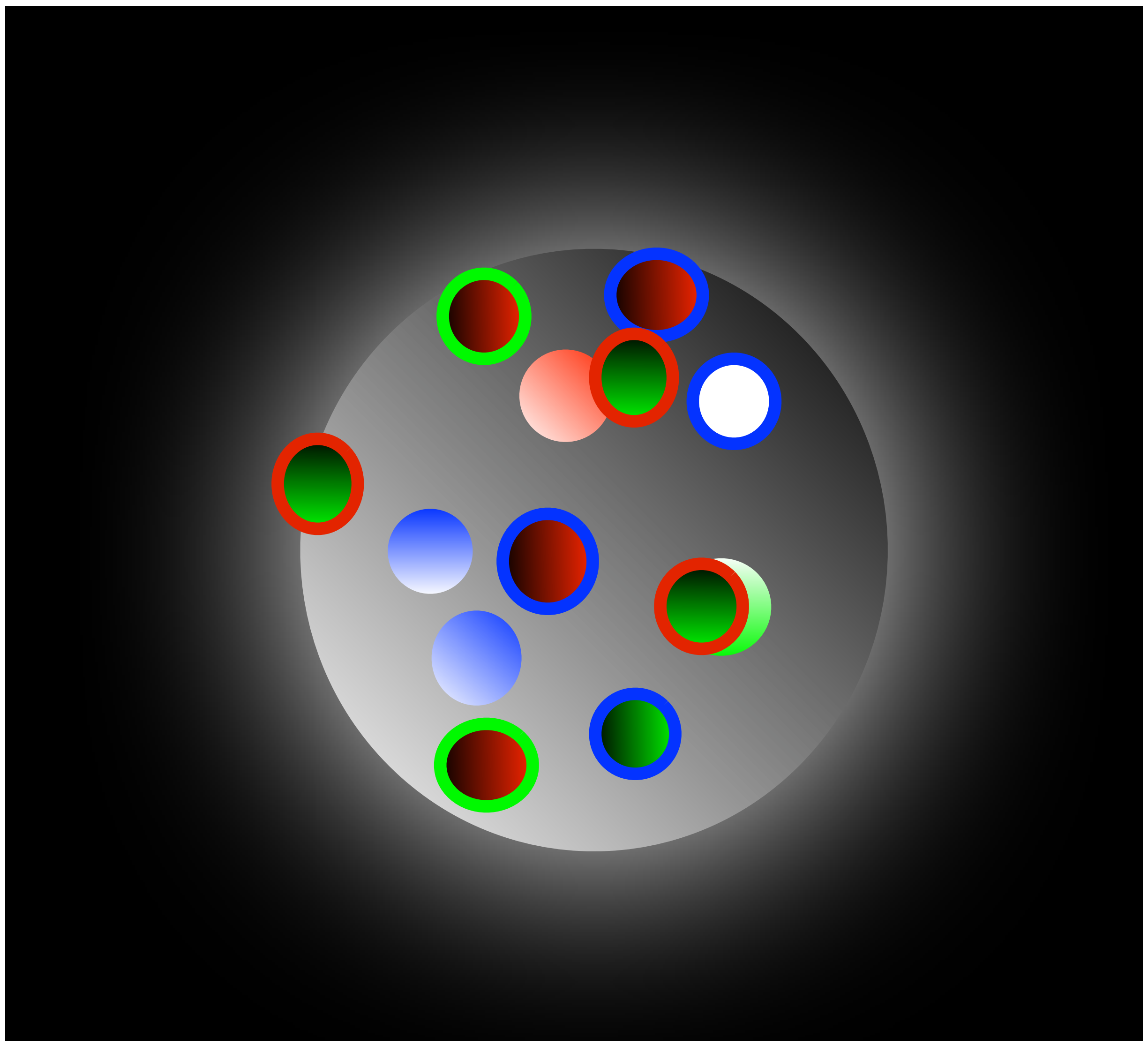

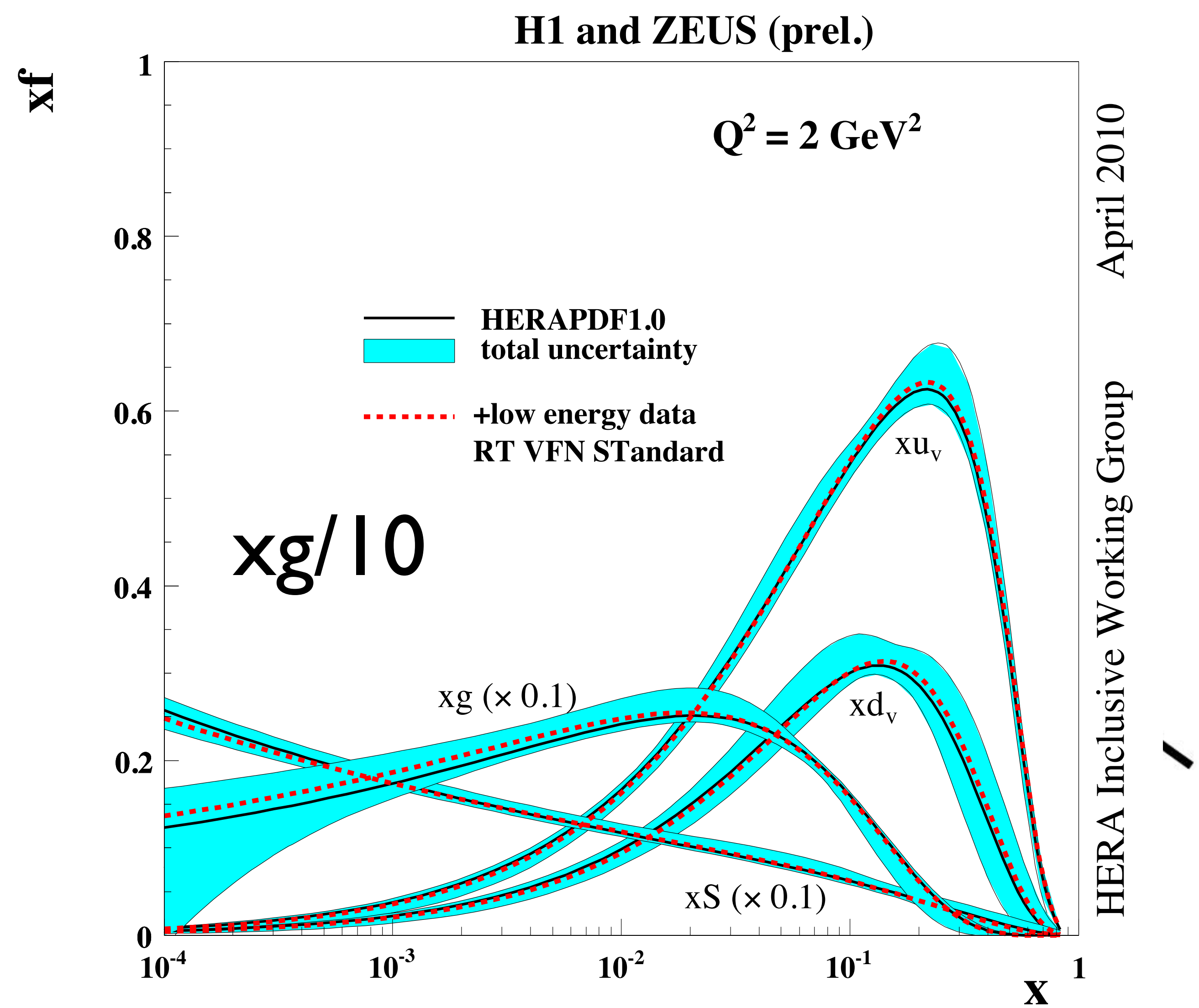

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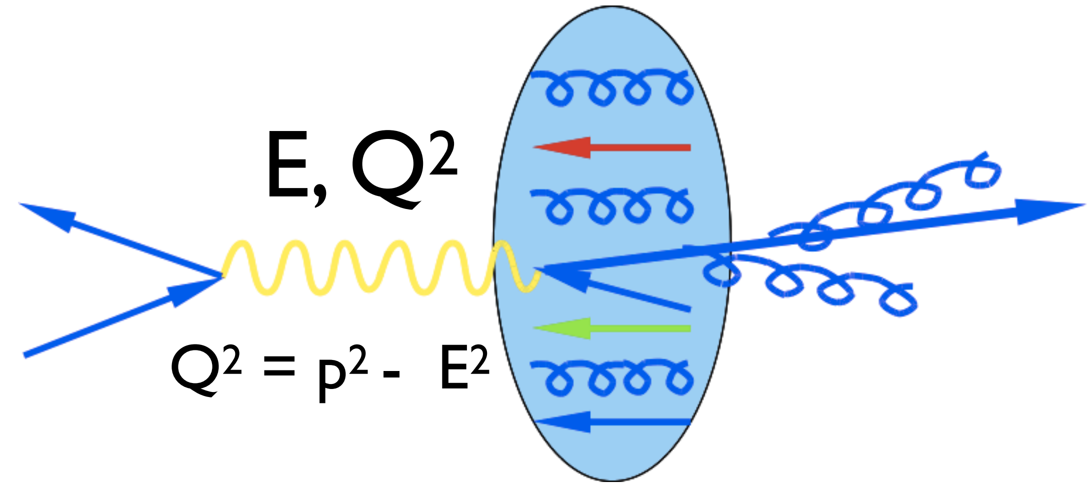

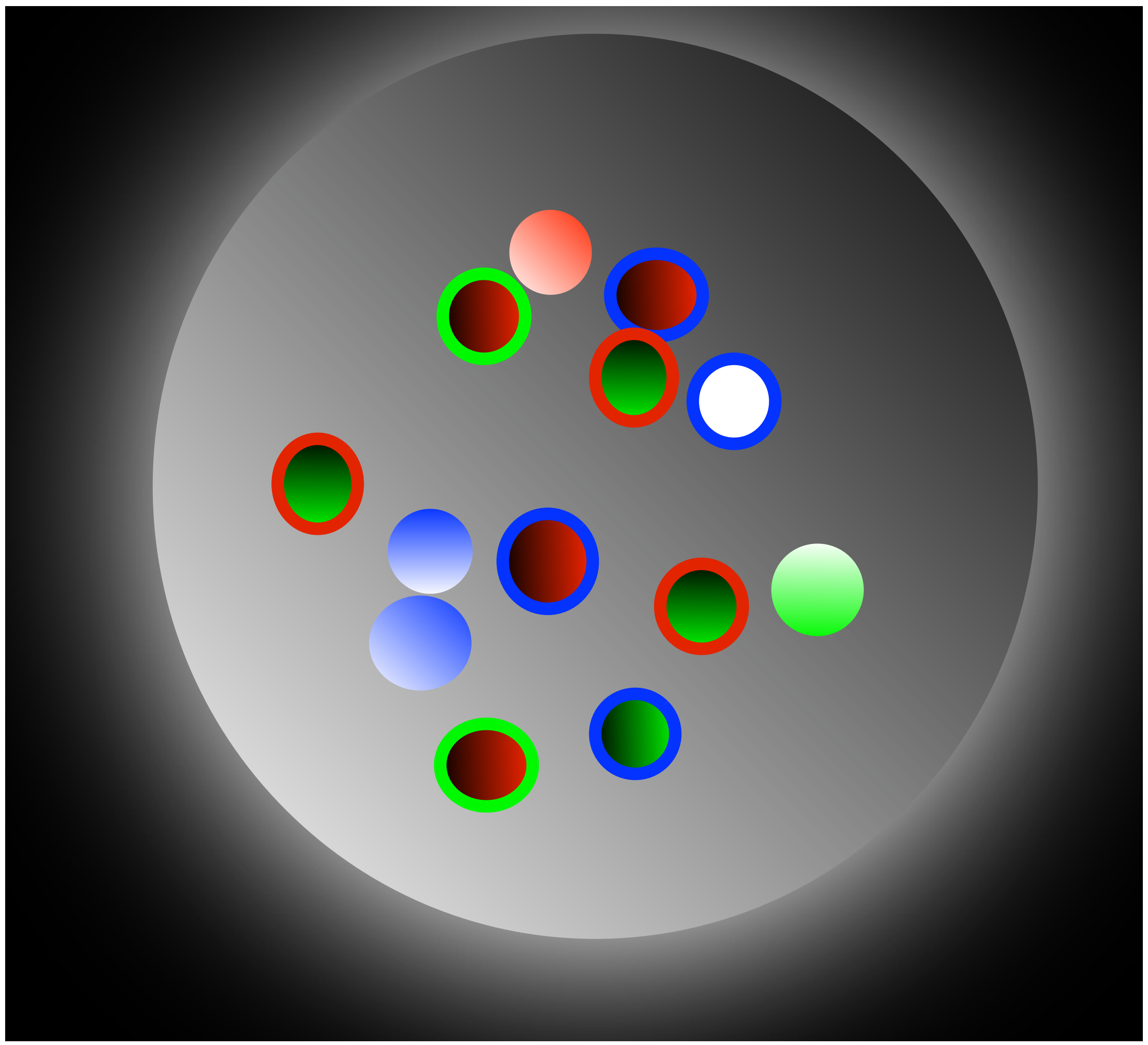

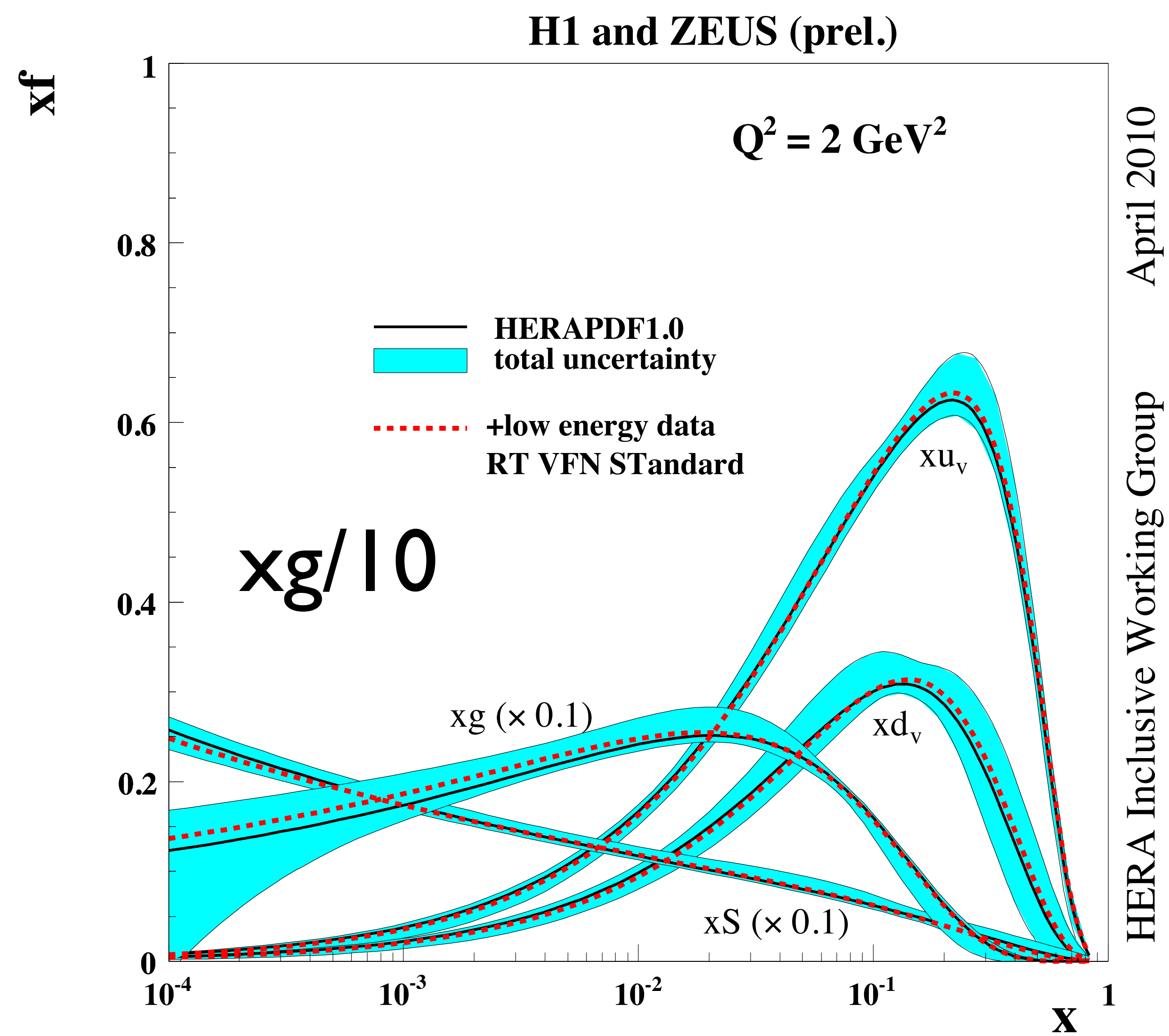

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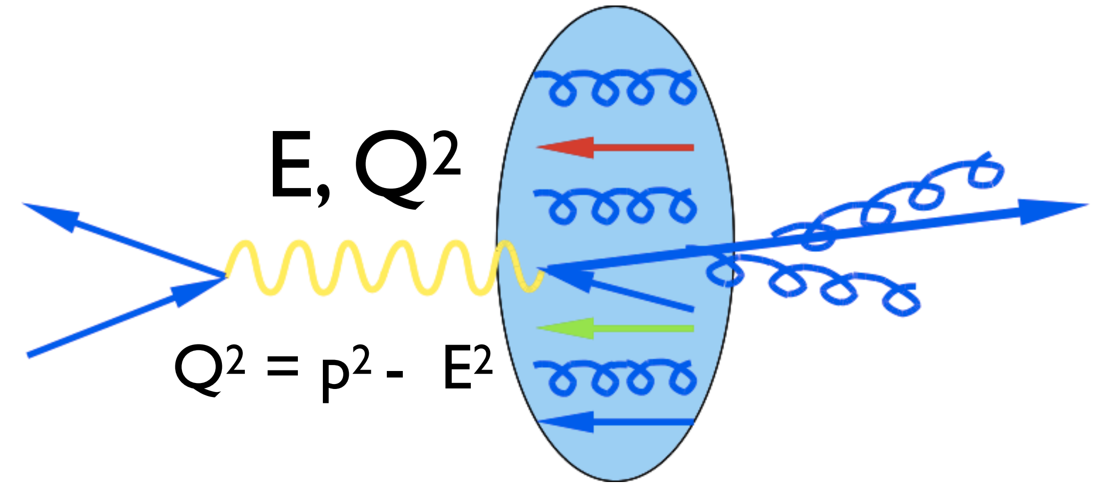

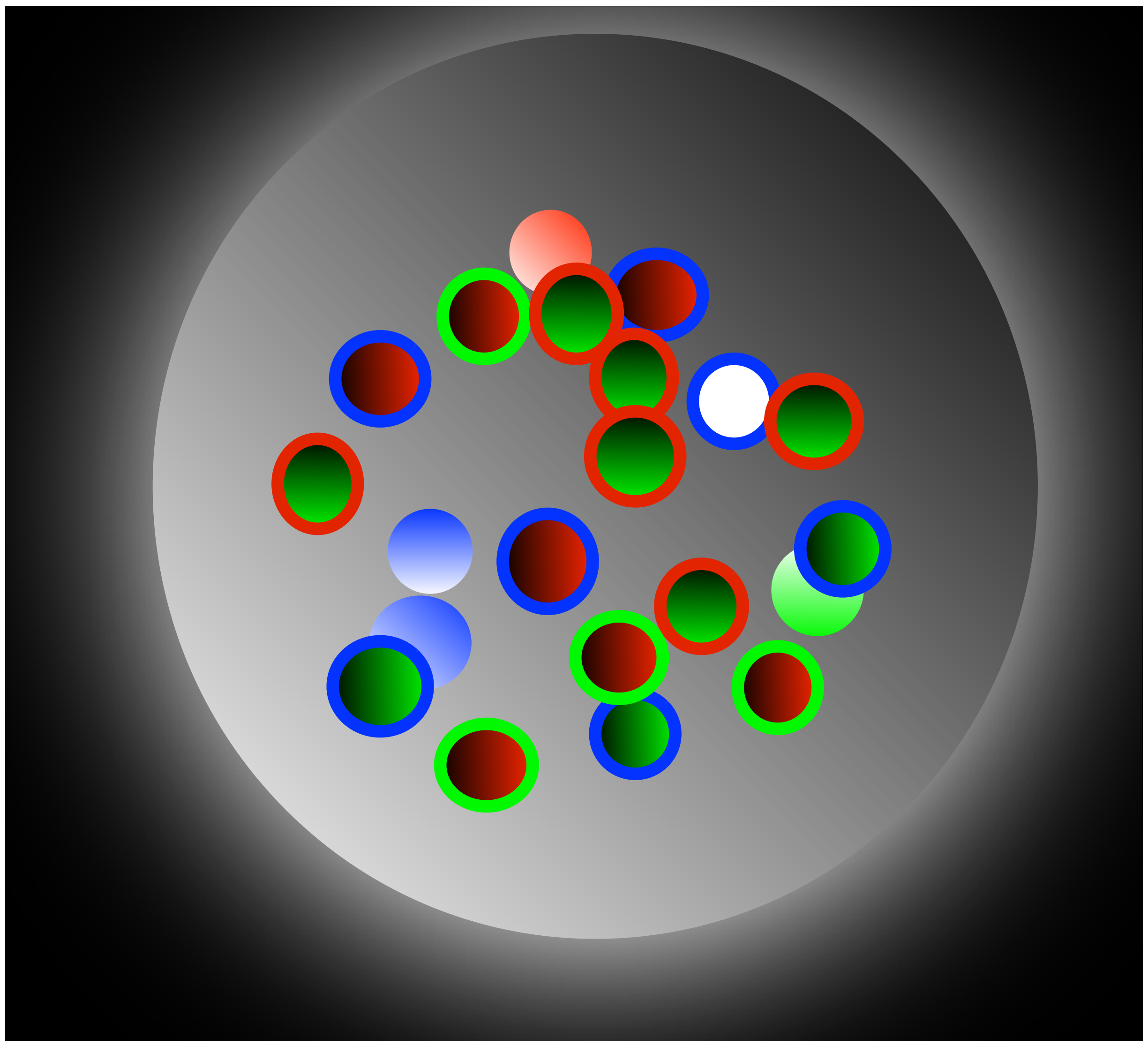

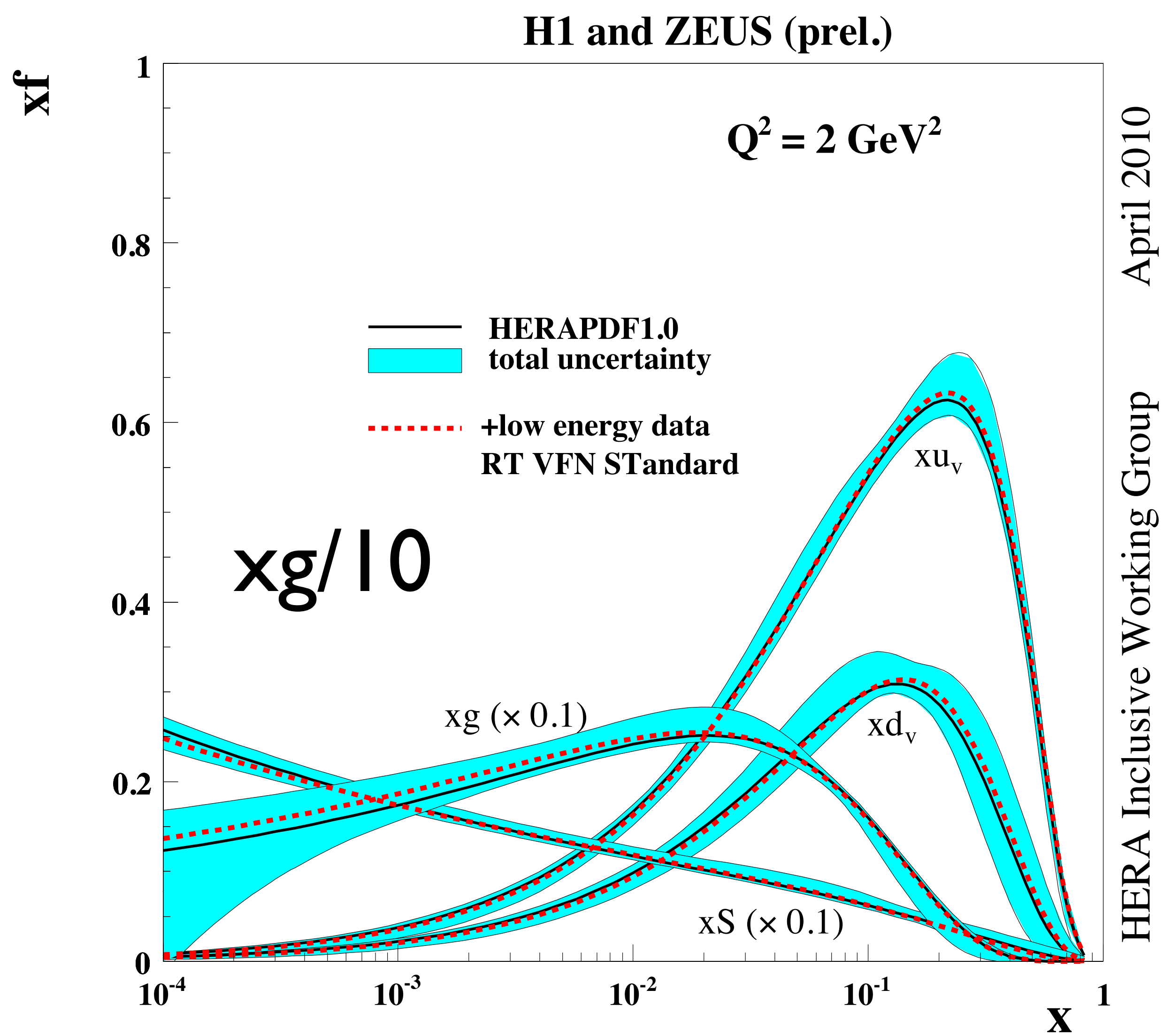

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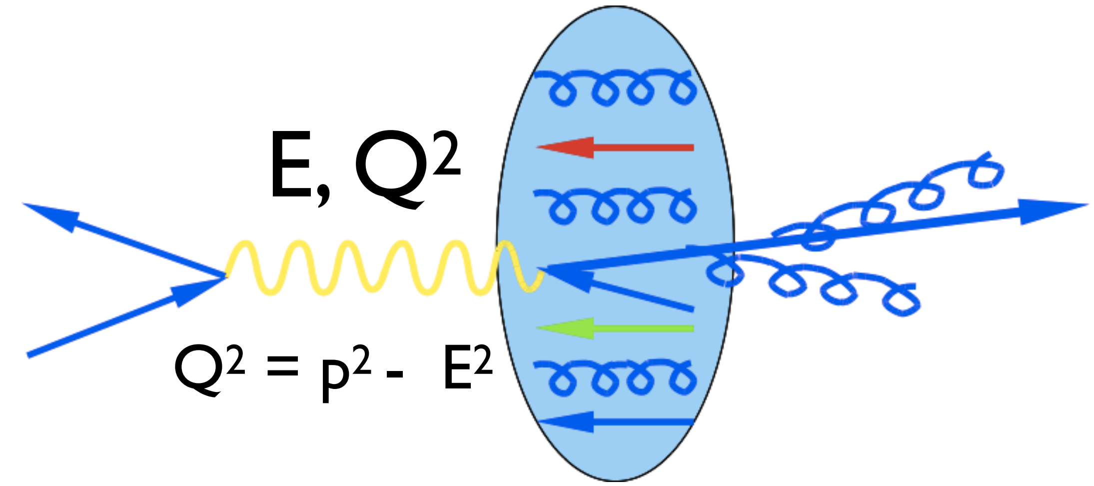

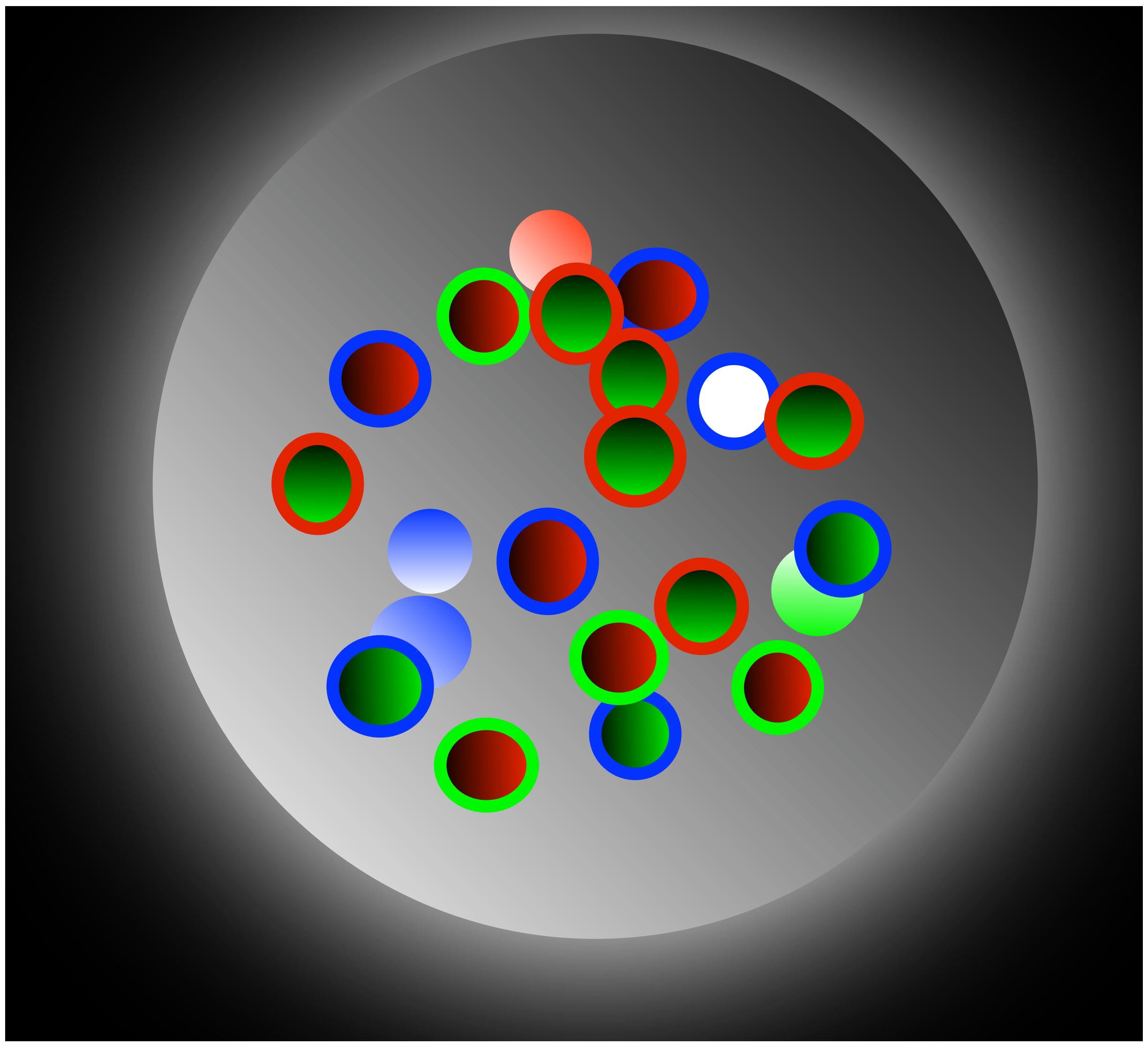

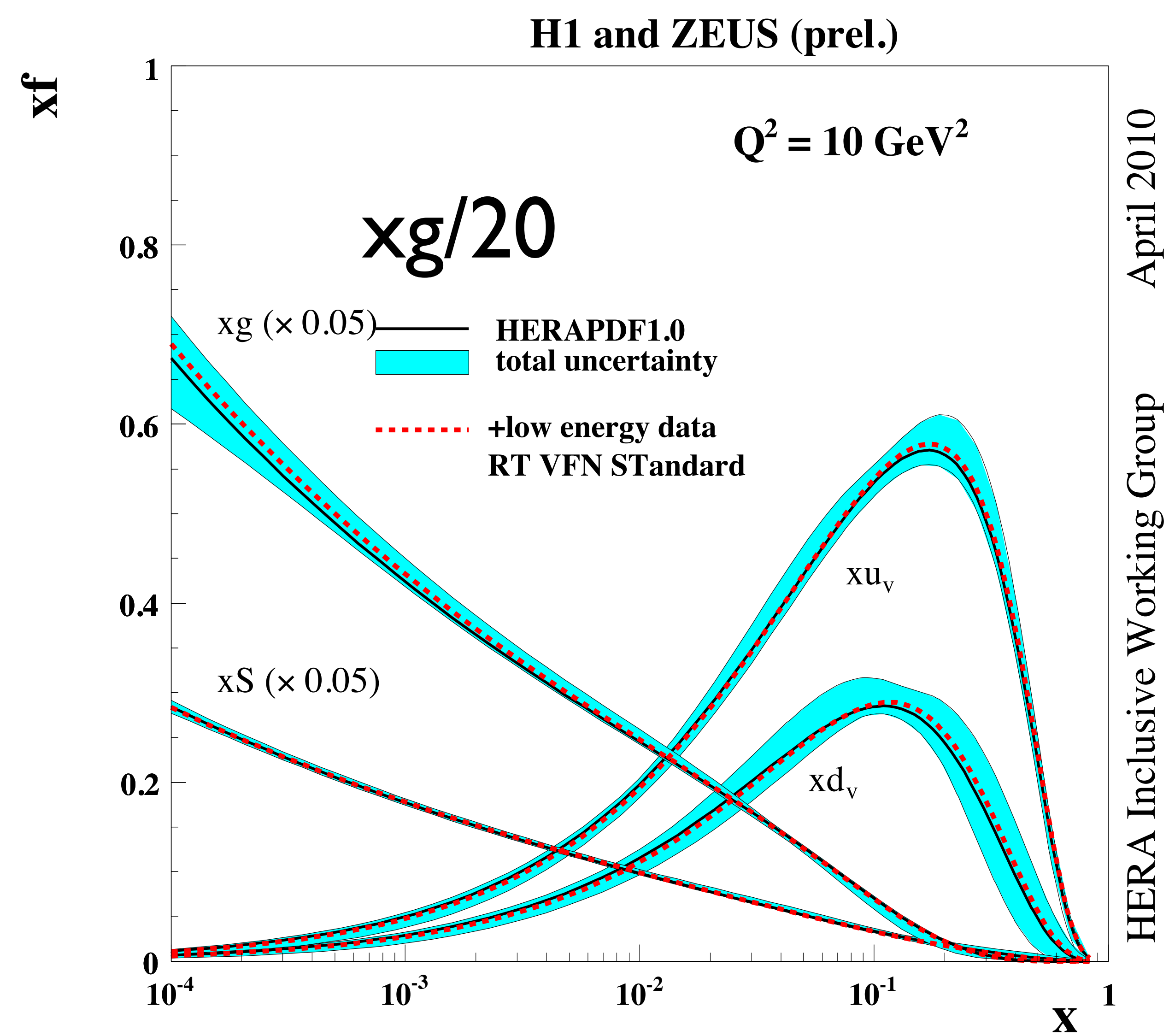

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