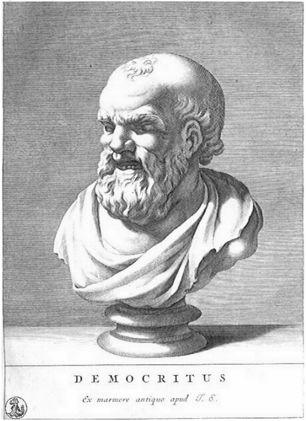
From Jefferson Lab to the LHC:
The quest to understand the building blocks of the universe

Nobuo Sato
University of Connecticut
Colloquium at ODU, Mar 2 2017

What is the universe made of?

- Democritus held that everything is composed of “atoms” (460 BC)



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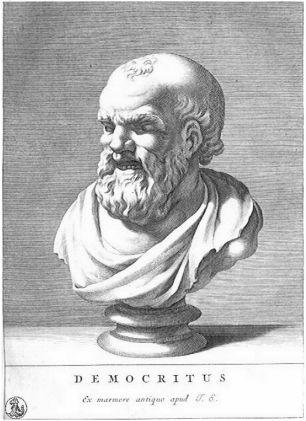

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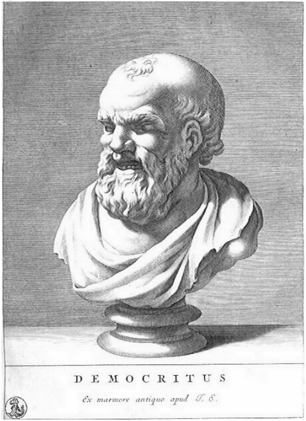

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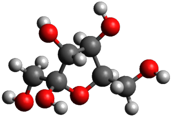
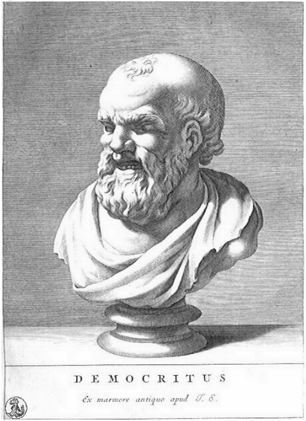


Fructose



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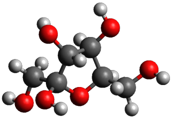

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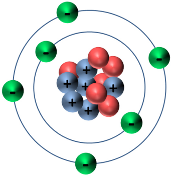

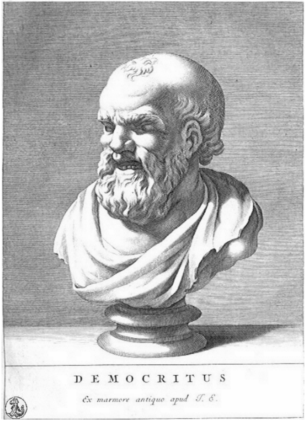

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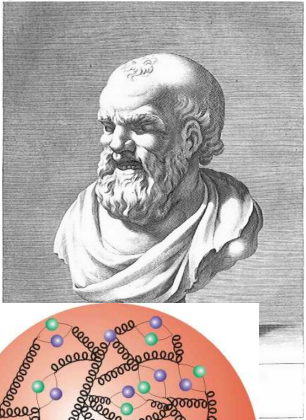

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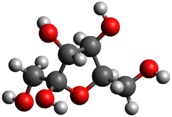

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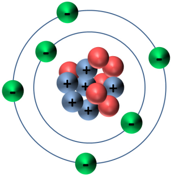

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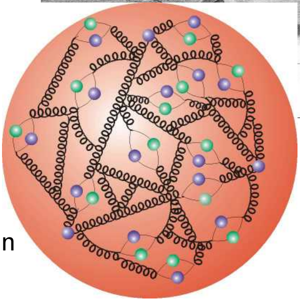

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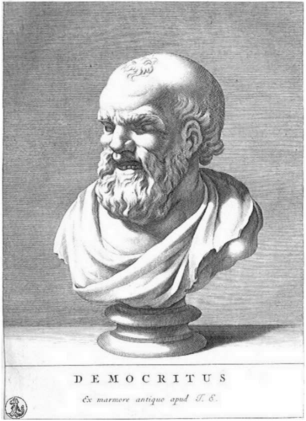

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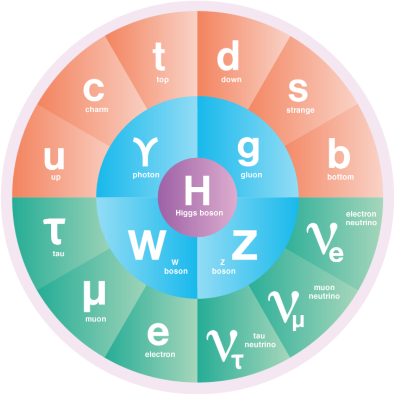

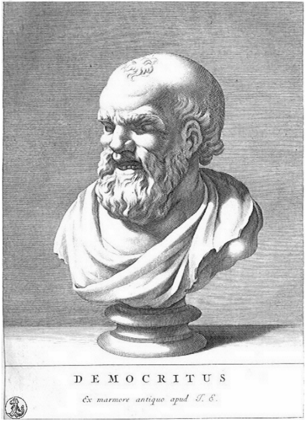

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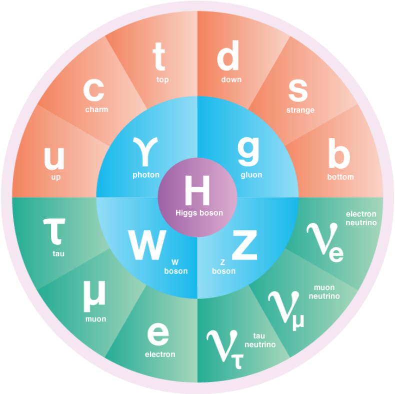

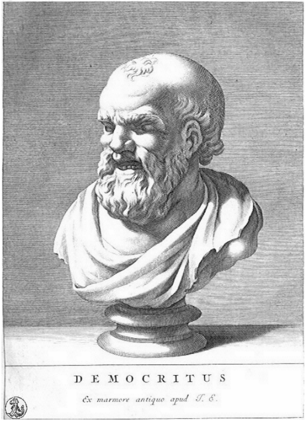

And we have a model for their interactions

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu$$

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2} \partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2} \partial_\mu H\partial_\mu H - \frac{1}{2} m_h^2 H^2$$

$$- \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)]$$

$$+ \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)]$$

$$- igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu$$

$$+ g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu]$$

$$- g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8} g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H$$

$$- \frac{1}{2} g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2} ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2} g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)]$$

$$+ \frac{1}{2} g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+)$$

$$+ igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4} g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \frac{1}{4} g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2} g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+)$$

$$- \frac{1}{2} ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2} g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2} ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^-$$

$$- g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)]$$

$$+ \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\frac{4}{3} s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\frac{8}{3} s_w^2-\gamma^5)d^\lambda_j)]$$

$$+ \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)]$$

$$+ \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j]$$

$$+ \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j)$$

$$+ \bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0)$$

$$+ igs_w W^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_w W^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_w Z^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-)$$

$$+ igs_w A_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) - \frac{1}{2} gM[\bar X^+ X^+ H + \bar X^- X^- H + \frac{1}{c_w^2}\bar X^0 X^0 H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+ X^0\phi^+ - \bar X^- X^0\phi^-]$$

$$+ \frac{1}{2c_w}igM[\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-] + igMs_w[\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-] + \frac{1}{2} igM[\bar X^+ X^+\phi^0 - \bar X^- X^-\phi^0]$$

$$\boxed{-\frac12\partial_\nu g^a_\mu\partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac14 g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac12 i g_s^2(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu}$$

$$-\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12\partial_\mu A_\nu\partial_\mu A_\nu - \frac12\partial_\mu H\partial_\mu H - \frac12 m_h^2 H^2$$

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$$+\frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)]$$

$$-igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu$$

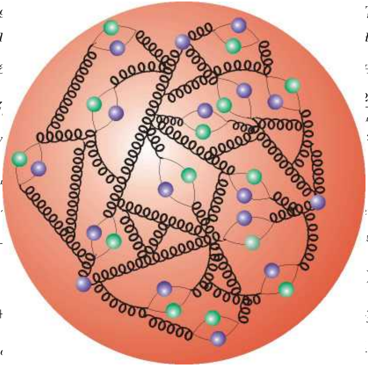
$+g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$ $- W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu]$

$-g\alpha[H^3+H\phi^0\phi^0+2H\phi^+\phi^-] - \frac18 g^2\alpha_h[H$ $^2] - gMW^+_\mu W^-_\mu H$

$-\frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-$ $) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)]$

$+\frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ$ $Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+)$

$+igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac14 g^2 W^+_\mu W$ $\phi^+\phi^-] - \frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+)$



$-\frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s$ $g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^-$

$-g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda$ $) + \frac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)]$

$+\frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2 -$ $)d^\lambda_j)]$

$+\frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+$ $)u^\lambda_j)]$

$+\frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+$ $C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j]$

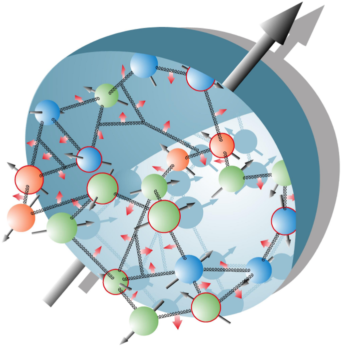
$+\frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa($ $\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j)$

$$+\bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0)$$

Theory of strong interactions

Key questions

- How do the quarks and gluons carry the spin of protons?



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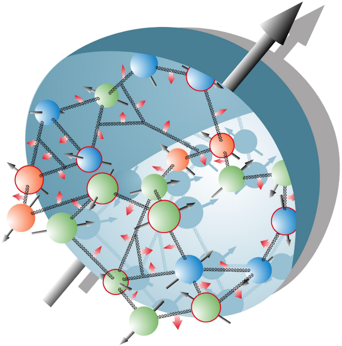

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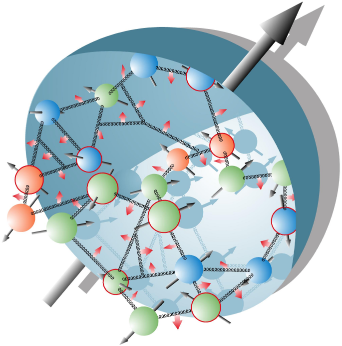
- How does confinement work?



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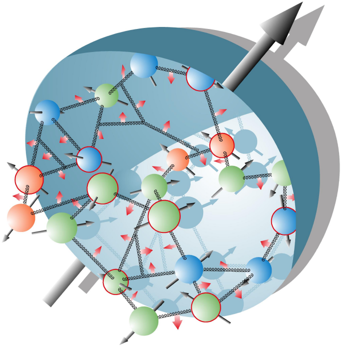
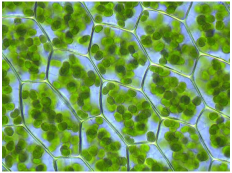


To answer these questions we need to look inside the hadrons

How to zoom in

Chloroplast Cells

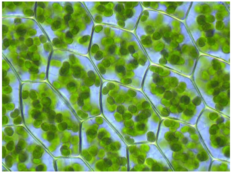


$10^{-6}\mathrm{m}$

Microscope

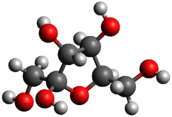
How to zoom in

Chloroplast Cells



10^{-6}m

Fructose



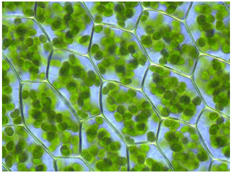
10^{-9}m

Microscope

Mass Spectrometer

How to zoom in

Chloroplast Cells



10^{-6}m

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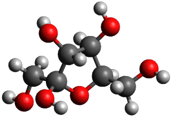
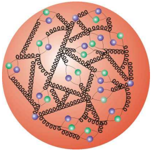


10^{-9}m

Hadron

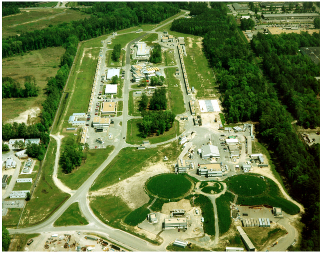


10^{-15}m

Microscope

Mass Spectrometer

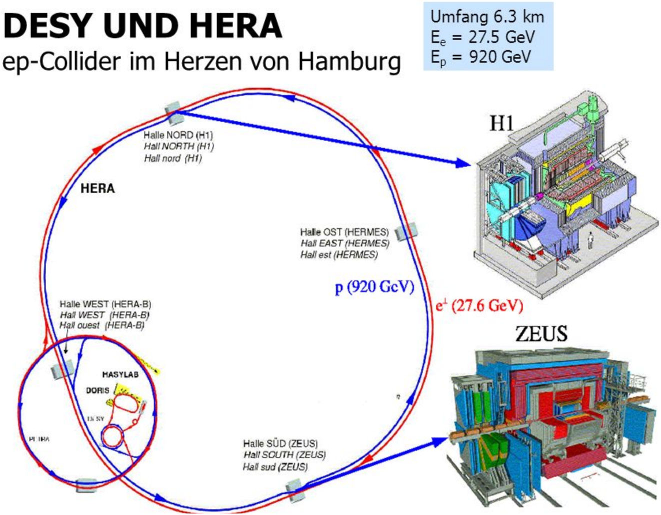
Particle accelerators



An example of a scattering experiment

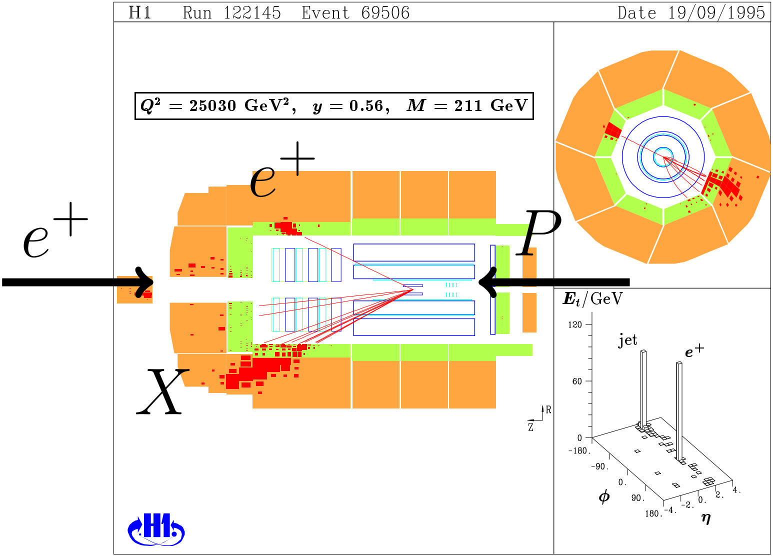
Deep inelastic scattering (DIS) at HERA

1992-2007



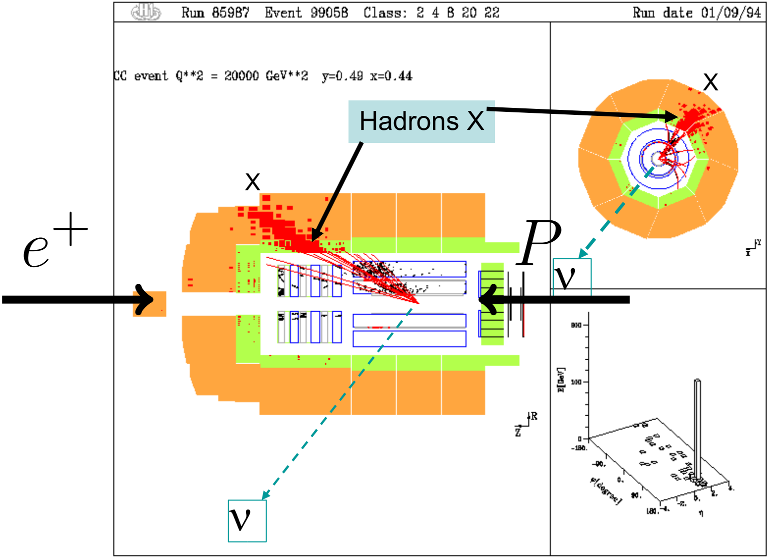
A DIS event: $e^+P \to e^+X$

ATTENTION: this is just a single event!

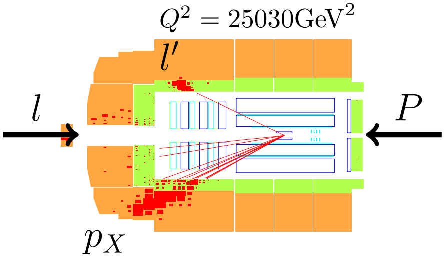


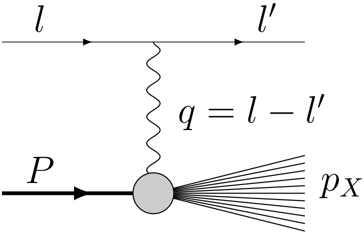
A DIS event: $e^+P \to \nu + X$

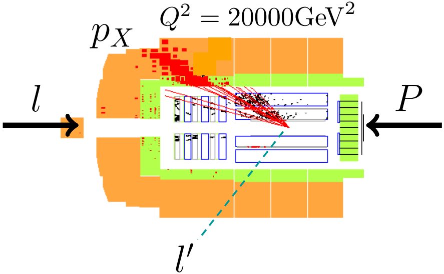
ATTENTION: this is just a single event!



Gauge bosons ($\gamma, Z, W^{\pm}$) as probes

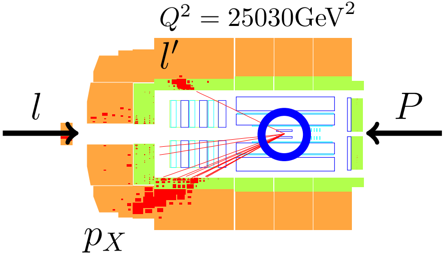


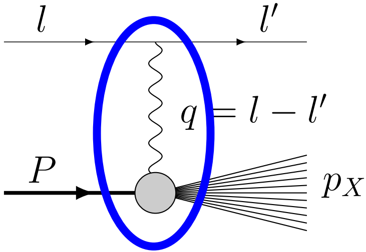


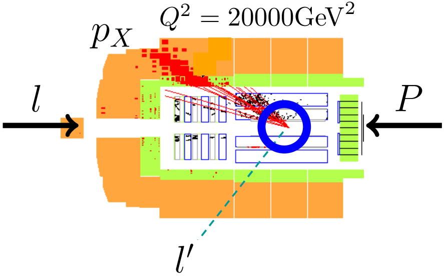


- $Q^2 \equiv -q^2$
- Bosons propagation length $\sim 1/Q$
- proton radius ~ 0.84 fm
- $1\ \text{GeV}^{-1} \sim 0.2\ \text{fm} = 0.2 \times 10^{-15}\ \text{m}$
- Interaction range $\ll 10^{-15}$ m

Gauge bosons ($\gamma, Z, W^{\pm}$) as probes







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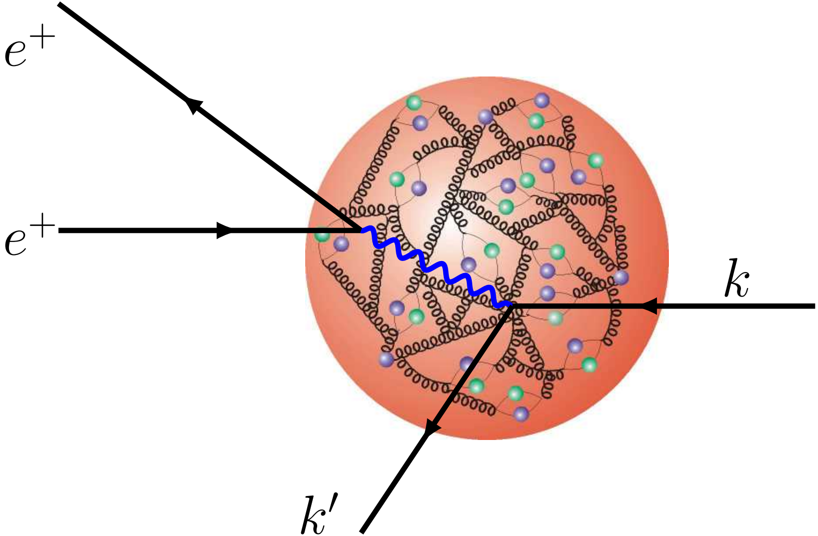
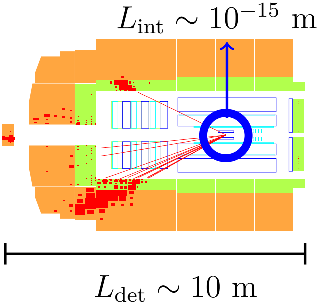
Intuitive picture

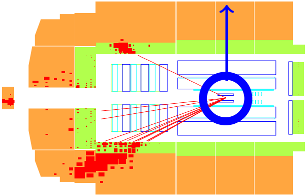


How small is $1 \text{ fm} = 10^{-15} \text{ m}$?



How small is $1\ \mathrm{fm} = 10^{-15}\ \mathrm{m}$?

$L_{\mathrm{int}} \sim 10^{-15}\ \mathrm{m}$



$L_{\mathrm{det}} \sim 10\ \mathrm{m}$

$L_{\mathrm{Earth}} \sim 10^{7}\ \mathrm{m}$

$L_{\mathrm{X}} \sim 10^{25}\ \mathrm{m}$

- $L_{\mathrm{X}} = (L_{\mathrm{det}}/L_{\mathrm{int}})L_{\mathrm{Earth}} \sim 10^{9}\ \mathrm{ly}$
- Diameter of Milky Way $\sim 10^{5}\ \mathrm{ly}$
- Distance to Andromeda $\sim 10^{6}\ \mathrm{ly}$
- High energy experiments allows one to resolve the inner structure of protons from far away detectors

How do we describe the data?

Events and cross sections

Number of events

Integrated Luminosity

Differential cross section

$$\frac{dN}{d\Omega} = \mathcal{L}\ \frac{d\sigma}{d\Omega}$$

Phase space volume

Events and cross sections

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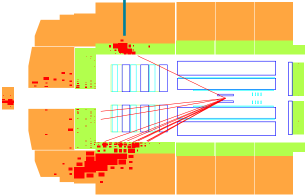
Phase space volume

i.e. $d\Omega = d\phi d\eta$



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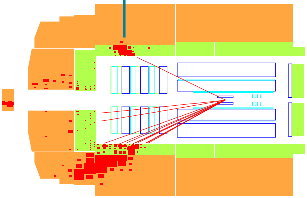
Phase space volume

Calculable using QCD



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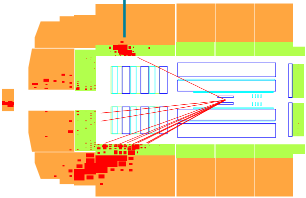


The events can separated into subprocesses

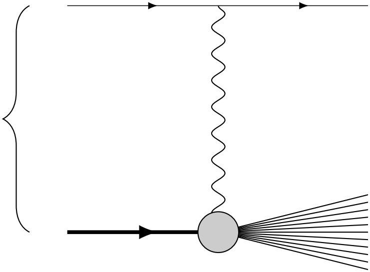
$$\frac{dN}{d\Omega} = \frac{dN^{(e^+P\to e^+X)}}{d\Omega} + \frac{dN^{(e^+P\to \nu X)}}{d\Omega} + \ldots$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{(e^+P\to e^+X)}}{d\Omega} + \frac{d\sigma^{(e^+P\to \nu X)}}{d\Omega} + \ldots$$

Theoretical cross sections

$$d\sigma = \frac{1}{\text{flux}} |\Psi|^2 d\Omega$$

Ψ



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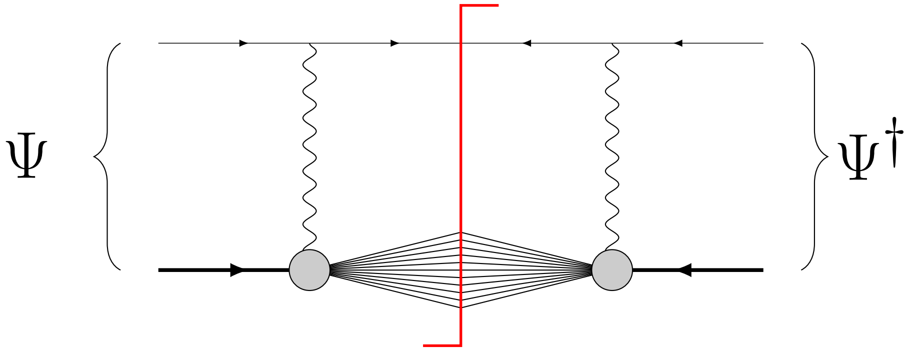

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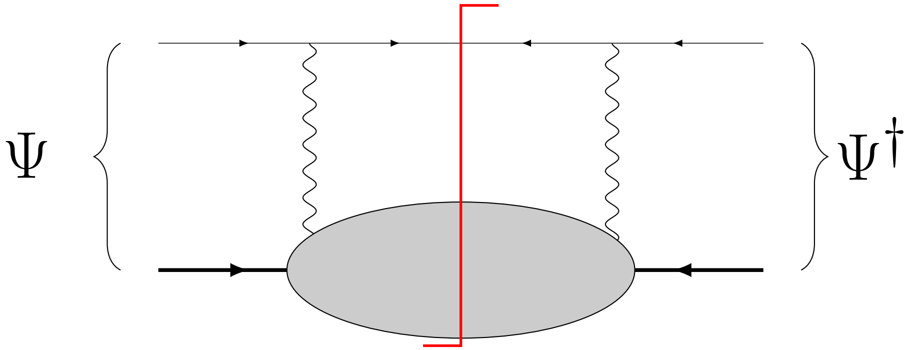

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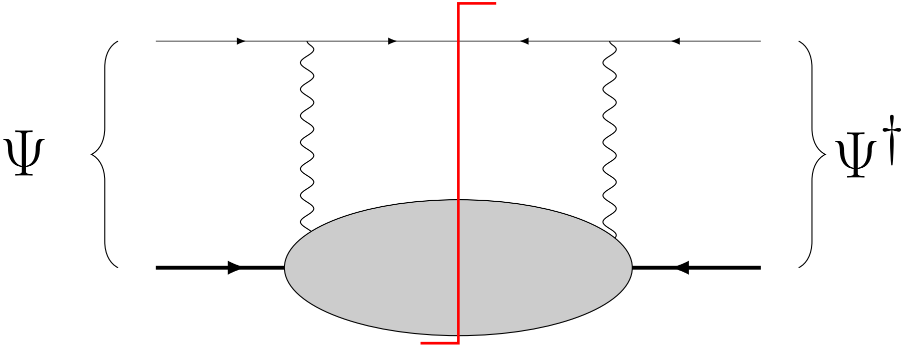
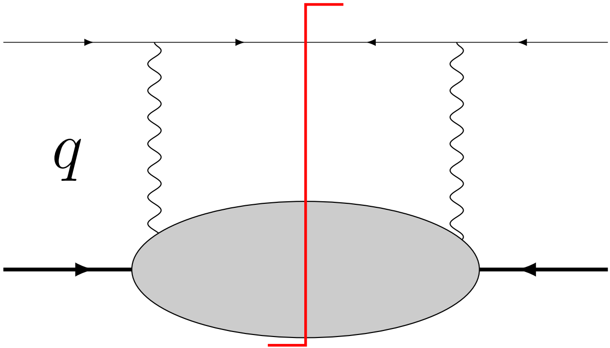


- The upper part of the diagram can be calculated using QED
- The lower part is more complicated $\rightarrow$ **Factorization**

Factorization in inclusive DIS



- The lower blob represents a collection of Feynman diagrams

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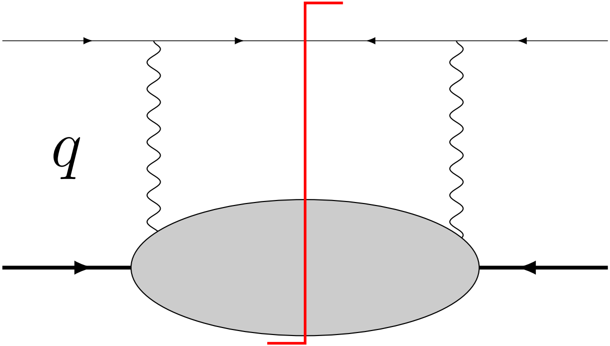
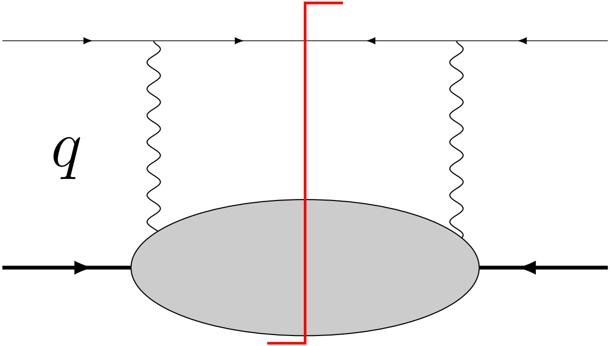


- The lower blob represents a collection of Feynman diagrams
- It is possible to identify the most relevant contributions to the blob classifying them into different regions (Libby-Sterman)

Factorization in inclusive DIS



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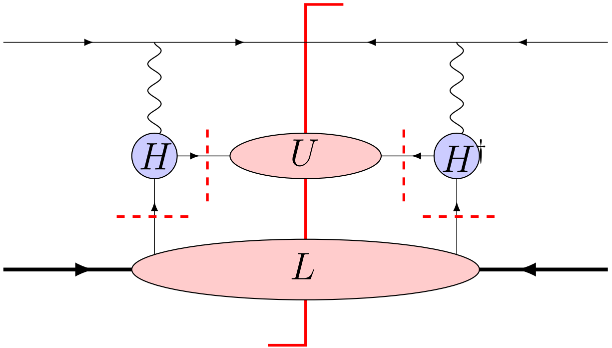

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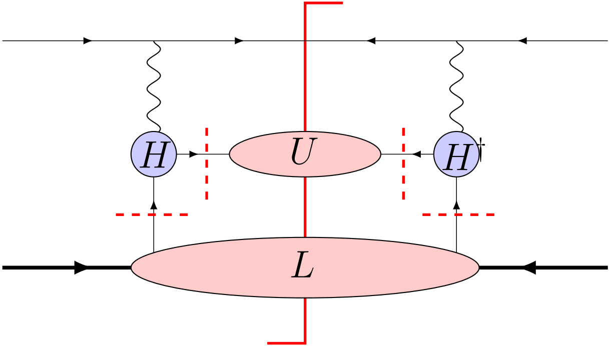
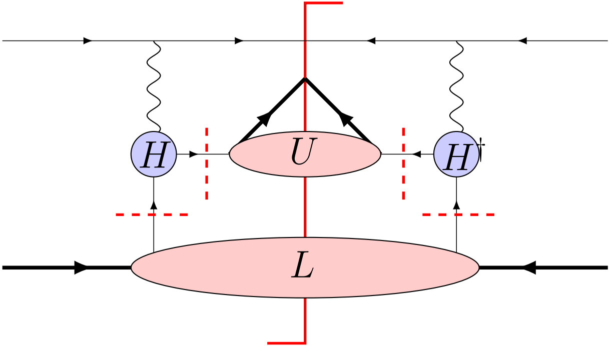


Schematically

$$d\sigma \sim \underbrace{|H|^2}_{\text{Hard}} \underbrace{\int dk^- dk^\perp L(xP^+, k^-, k^\perp)}_{\text{Parton densities}} \underbrace{\int dl^+ U(l^+)}_{\text{Jet function}} d\Omega$$

Factorization in SIDIS



- Additional information about the lower blob can be accessed by measuring hadrons in the final state (i.e., flavor separation, intrinsic transverse momentum)

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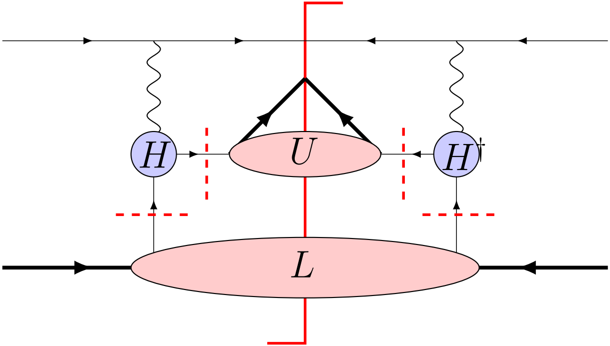

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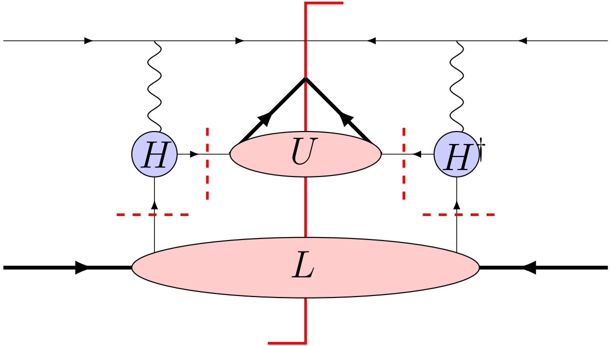
- The upper blob along with tagged hadrons characterizes formation of hadrons from partons

Factorization in SIDIS



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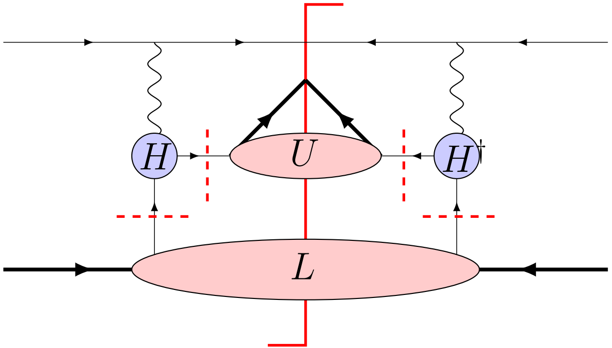
- The upper blob along with tagged hadrons characterizes formation of hadrons from partons
- Factorization of these regions assumes large $Q^2 = -q^2$

Factorization in SIDIS



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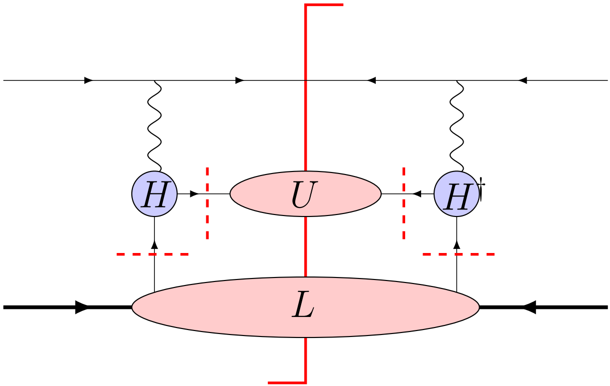
Extensions to hadron-hadron collisions

Extend the formalism to hadron-hadron collisions



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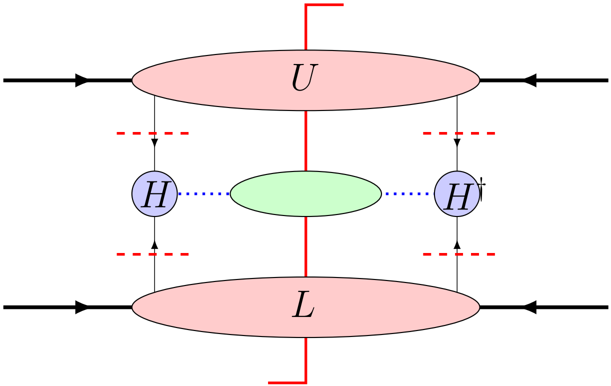

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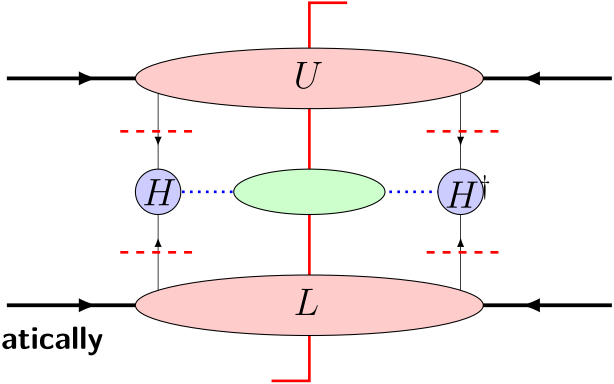

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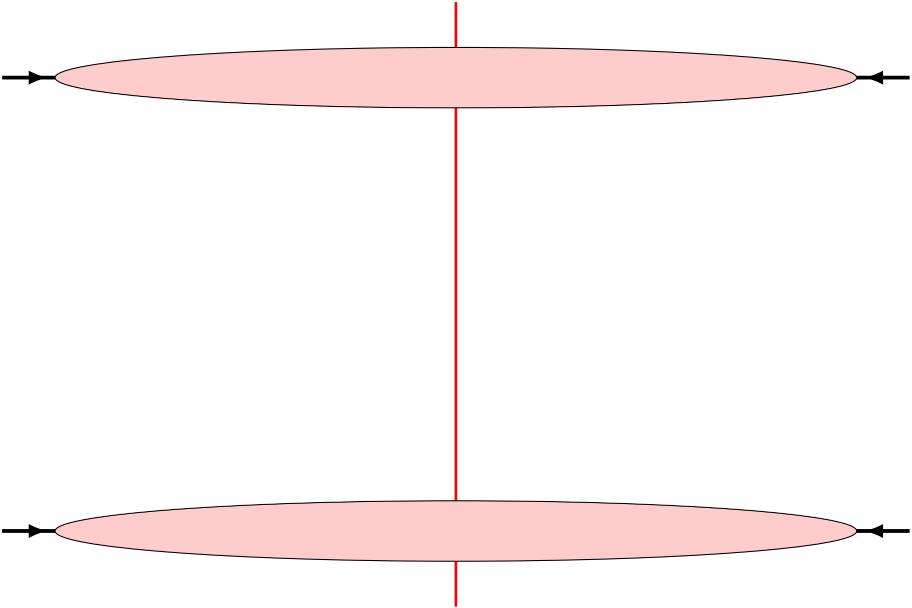
Example: The LHC and the Higgs



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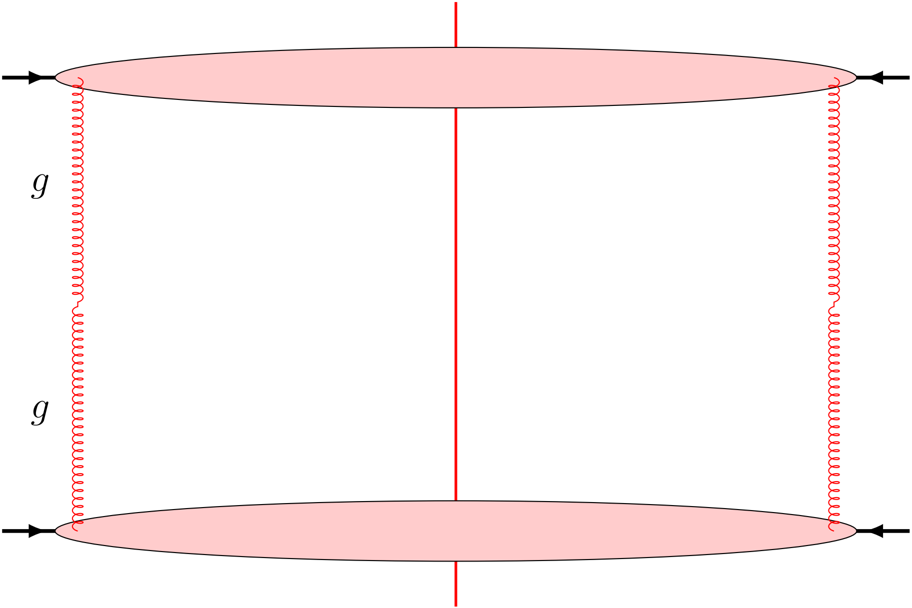

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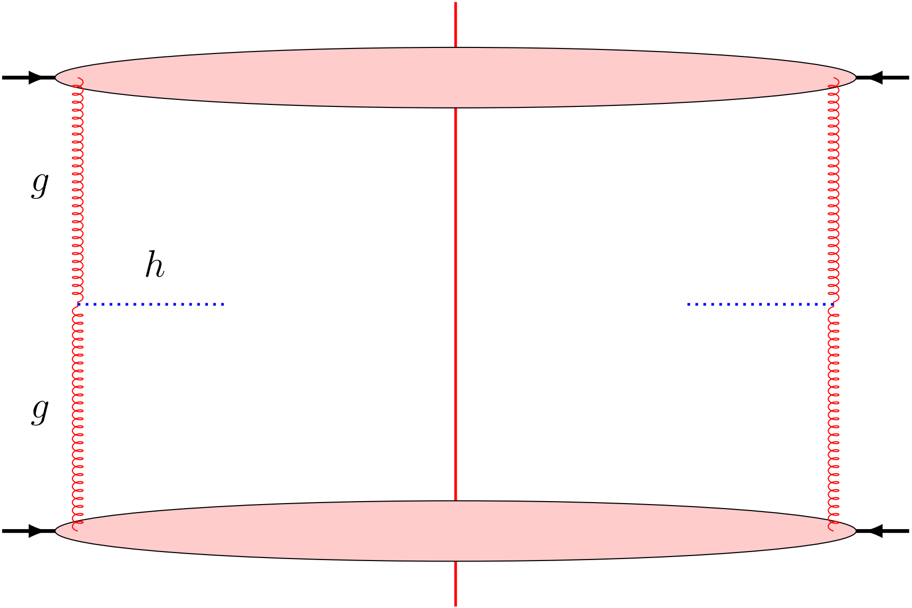

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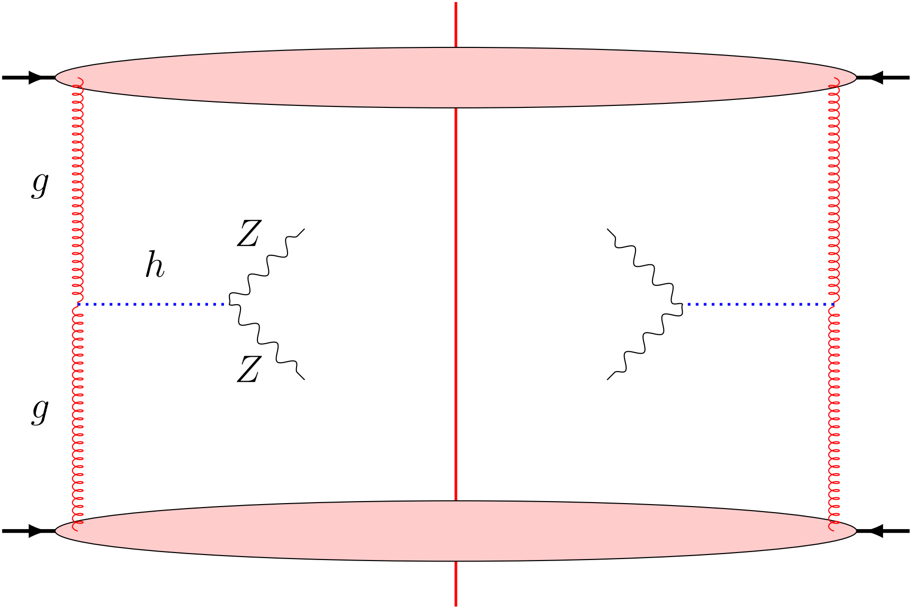

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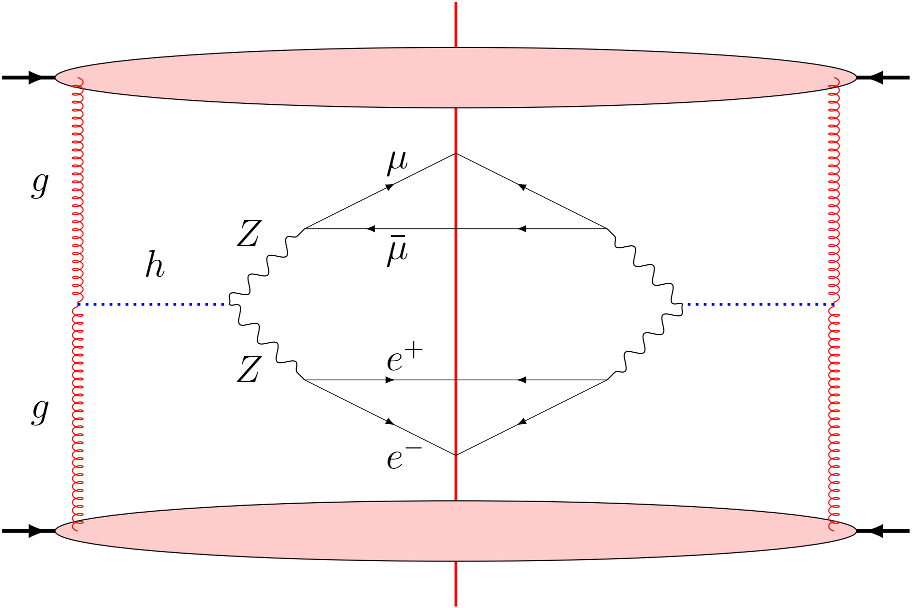
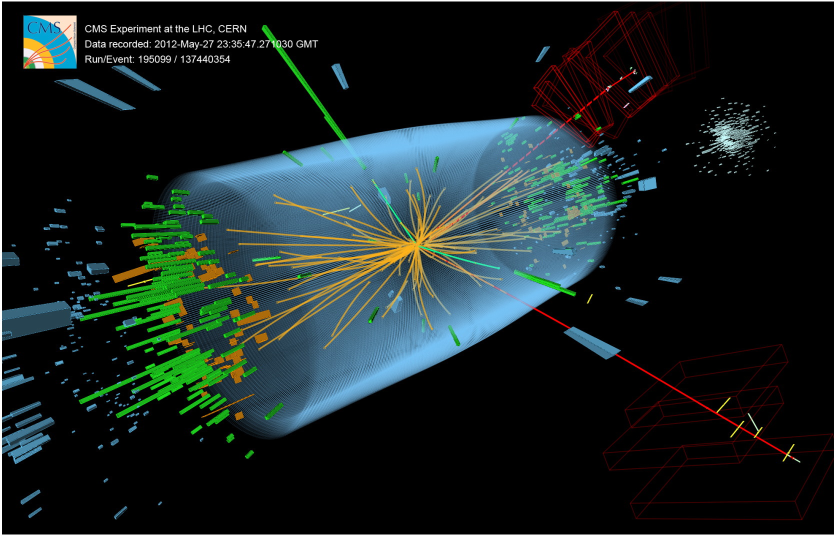


The LHC and the Higgs $P, P \to h \to ZZ \to \nu\bar{\nu}, e^+e^-$



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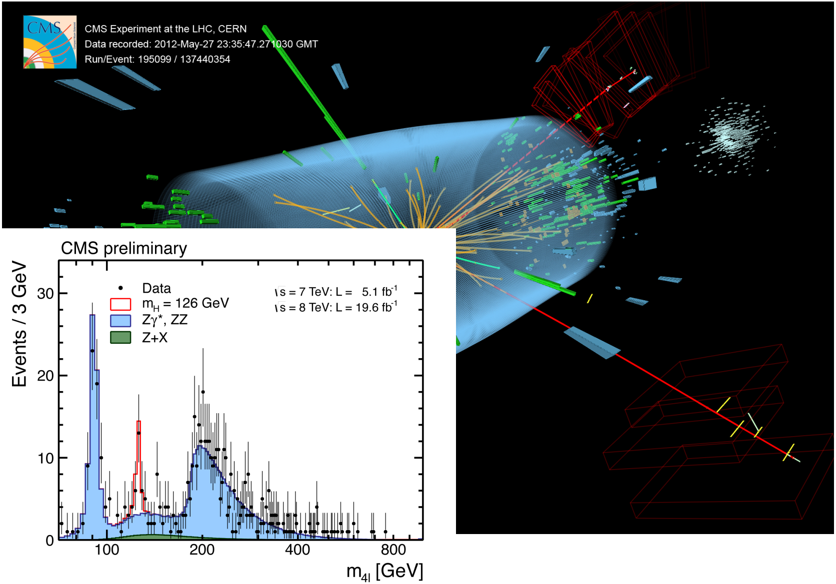

The parton densities and nucleon structure

- Factorization allows us to characterize nucleon structure

$$f(x) = \int dk^- dk^\perp L(xP^+, k^-, k^\perp)$$

$f(x)$: Probability of finding a quark/gluon with momentum fraction $x = k^+/P$

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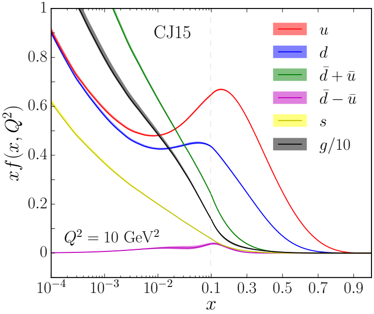

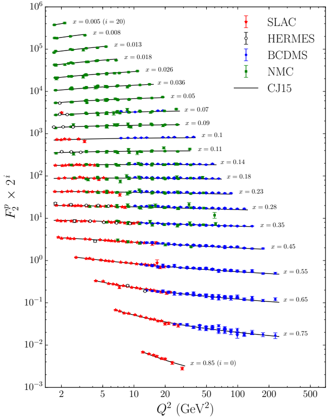

PDFs and LHC

$H \rightarrow ZZ$

Systematics

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.7 %
Lepton identification/reconstruction efficiencies	4 – 9 %
Background related uncertainties	
QCD scale ($q\bar{q} \rightarrow ZZ$, $gg \rightarrow ZZ$)	3 – 10 %
PDF set ($q\bar{q} \rightarrow ZZ$, $gg \rightarrow ZZ$)	3 – 5 %
Electroweak corrections ($q\bar{q} \rightarrow ZZ$)	1 – 15 %
$gg \rightarrow ZZ$ K factor	10 %
Reducible background (Z+X)	40 – 90 %
VBF tagging efficiency (experimental)	7 – 14 %
VBF tagging efficiency (theoretical)	15 – 25 %
Signal related uncertainties	
QCD scale ($q\bar{q} \rightarrow$ VBF/VH, $gg \rightarrow H/t\bar{t}H$)	3 – 10 %
PDF set ($q\bar{q} \rightarrow$ VBF/VH, $gg \rightarrow H/t\bar{t}H$)	3 – 4 %
Acceptance	2 %
BR($H \rightarrow ZZ \rightarrow 4\ell$)	2 %
Lepton energy scale	0.04 – 0.3 %
Lepton energy resolution	20 %
VBF tagging efficiency (experimental)	2 – 7 %
VBF tagging efficiency (theoretical)	5 – 15 %

The parton densities and nucleon structure

- Helicity distributions

$$f(x) = f^{\uparrow}(x) + f^{\downarrow}(x)$$

$$\Delta f(x) = f^{\uparrow}(x) - f^{\downarrow}(x)$$

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$$\Delta f(x) = f^{\uparrow}(x) - f^{\downarrow}(x)$$

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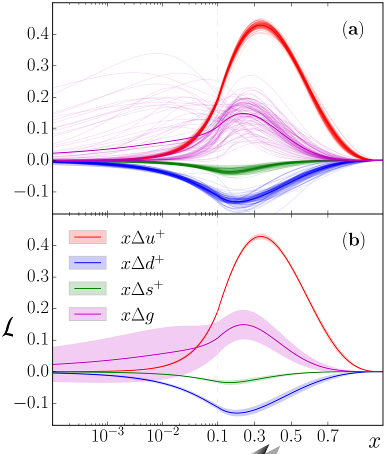
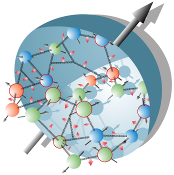
$$\frac{1}{2} = \int_0^1 dx \left(\frac{1}{2}\Delta\Sigma(x) + \Delta g(x)\right) + \mathcal{L}$$





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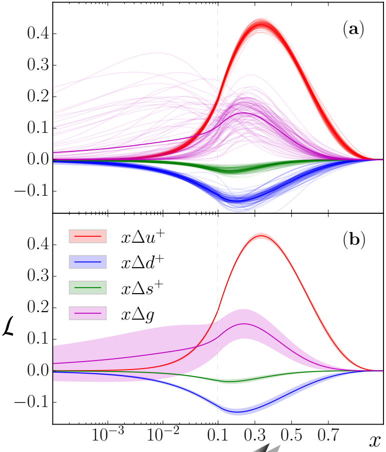
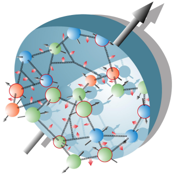
- From existing analysis
  - $\Delta\Sigma^{(1)} = 0.28 \pm 0.04$
  - $\Delta g^{(1)} = 1 \pm 15$



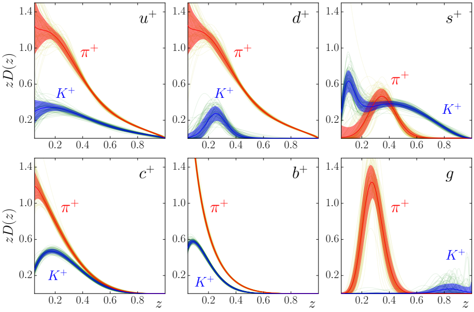


Fragmentation functions

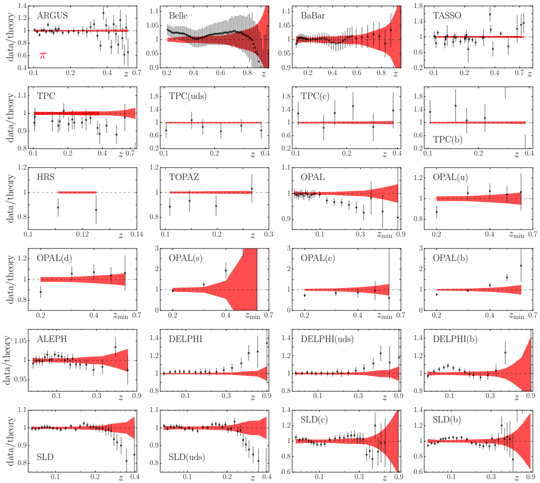
- Factorization allows us to characterize nucleon structure

$$D(z) = \int dk_h^+ dk_h^\perp U(k_h^+, zk_h^-, k_h^\perp)$$

$D(z)$: Probability of finding a hadron from quark with momentum fraction $z = P_h^- / k^-$

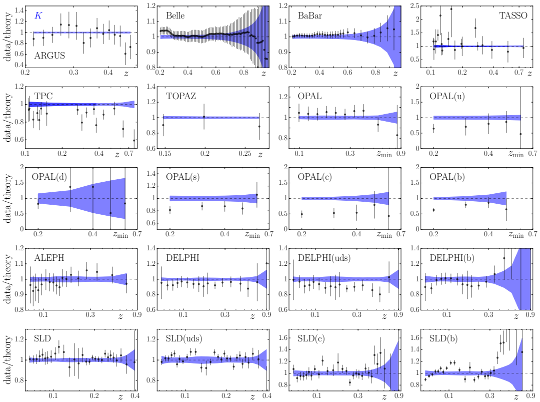


π analysis $\quad (\chi^2/N_{\text{npts}} = 1.31)$



- $z_{\text{cut}} > 0.1$ for low energies
- $z_{\text{cut}} > 0.05$ for high energies
- We use BaBar prompt data set
- Belle data set needs 10% normalization
- Good agreement at low–z for inclusive data sets
- Data inconsistencies at large–z for $Q^2 = M_z^2$

K analysis $(\chi^2/N_{\rm npts} = 1.01)$



- $z_{\rm cut} > 0.2$ for low energies to avoid hadron mass corrections
- $z_{\rm cut} > 0.05$ for high energies
- Smaller χ^2 that π due to larger errors
- Consistent shapes across all z
- Inconsistencies mostly due to normalizations

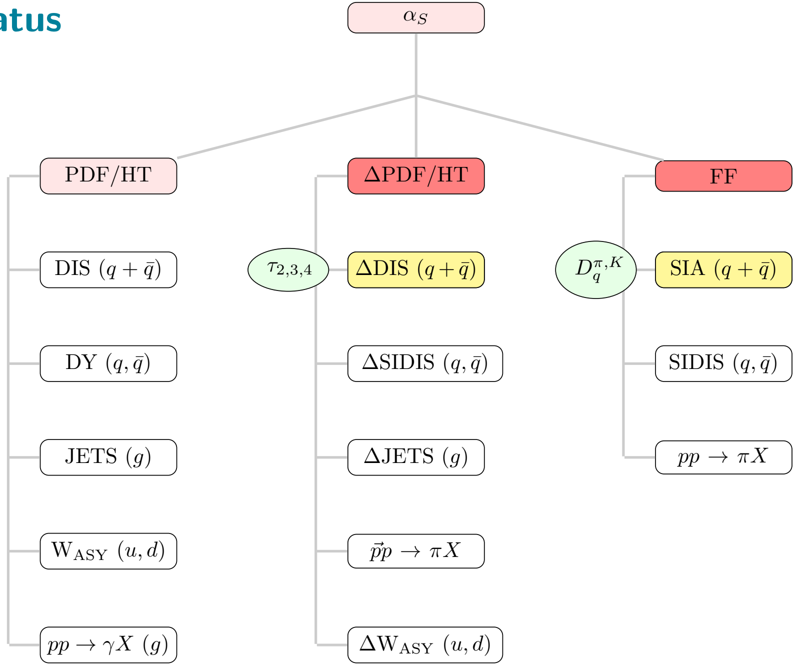
The collinear master plan

- Extract reliable collinear polarized and unpolarized parton distribution functions (PDFs) and fragmentation functions (FFs)

- Improvements in fitting methodology:
  Iterative Monte Carlo

- Reliable description of q_T integrated SIDIS data.

Status



α_S
PDF/HT
DIS $(q+\bar{q})$
DY $(q,\bar{q})$
JETS (g)
$\mathrm{W_{ASY}}\ (u,d)$
$pp \to \gamma X\ (g)$
ΔPDF/HT
$\tau_{2,3,4}$
ΔDIS $(q+\bar{q})$
ΔSIDIS $(q,\bar{q})$
ΔJETS (g)
$\vec{p}p \to \pi X$
$\Delta\mathrm{W_{ASY}}\ (u,d)$
FF
$D_q^{\pi,K}$
SIA $(q+\bar{q})$
SIDIS $(q,\bar{q})$
$pp \to \pi X$

Milestones

- Global analysis of all inclusive polarized DIS data

Iterative Monte Carlo analysis of spin-dependent parton distributions

Nobuo Sato,[1] W. Melnitchouk,[1] S. E. Kuhn,[2] J. J. Ethier,[3] and A. Accardi[4,1]
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PHYSICAL REVIEW D **94,** 114004 (2016)

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- Invited talk in FCCee workshop

Parton Radiation and Fragmentation from LHC to FCC-ee

Workshop Proceedings, CERN, Geneva, Nov. 22nd–23th, 2016

Editors

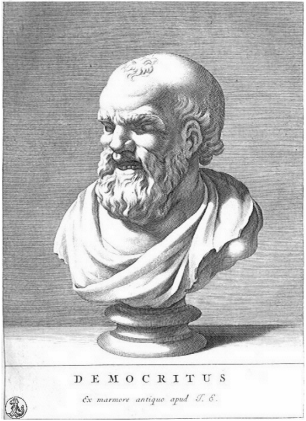
David d'Enterria (CERN), Peter Z. Skands (Monash)

Authors

D. Anderle (U. Manchester), F. Anulli (INFN Roma), J. Aparisi (IFIC València), G. Bell (U. Siegen), V. Bertone (NIKHEF, VU Amsterdam), C. Bierlich (Lund Univ.), S. Carrazza (CERN), G. Corcella (INFN-LNF Frascati), D. d'Enterria (CERN), M. Dasgupta (U. Manchester), I. García (IFIC València), T. Gehrmann (U. Zürich), O. Gituliar (U. Hamburg), K. Hamacher (B.U. Wuppertal), A.H. Hoang (U. Wien), N.P. Hartland (NIKHEF, VU Amsterdam), A. Hornig (LANL Los Alamos), S. Jadach (IFJ-PAN Krakow), T. Kaufmann (U. Tübingen), S. Kluth (T.U. München),

Summary and outlook

- Factorization is a powerful framework to study nucleon structure



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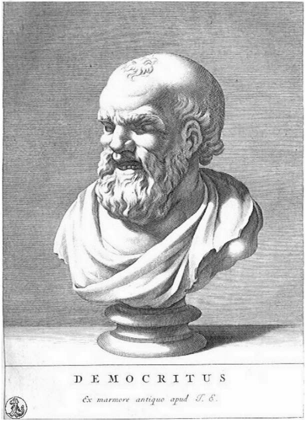
- It allows to separate short distance scales from the long distance scales so that nonperturbative scales can be studied.



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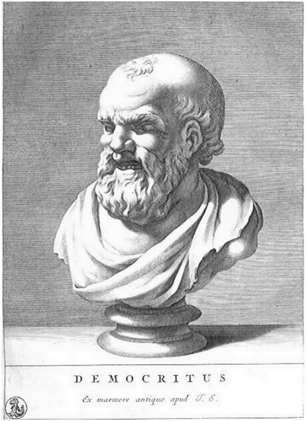

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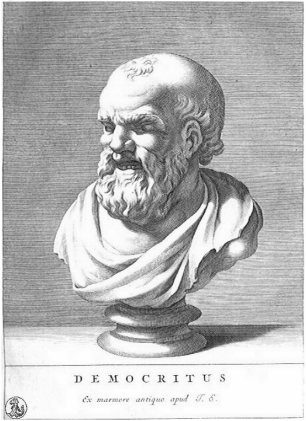

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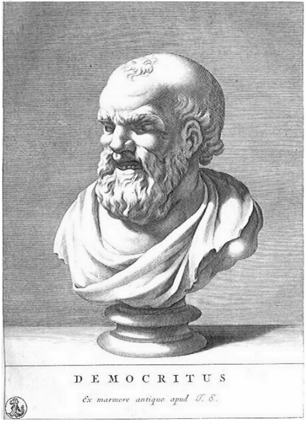

- JLab 12 has just started and the new theoretical and analysis innovations will allow the nucleon's quark structure to be reveled in unprecedented detail