AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

Ultra-peripheral collisions with ALICE

FAKT Workshop 2023

Roman Lavička

Feb 23, 2023, Bruck an der Mur, Austria

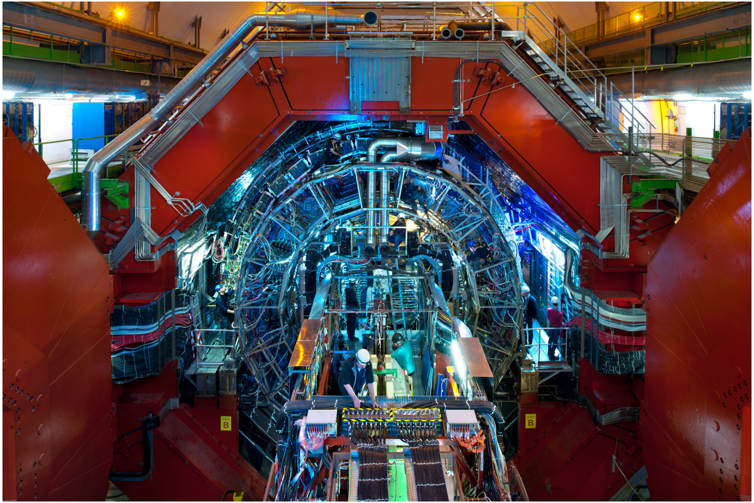
Content

1 Motivation

2 Current findings

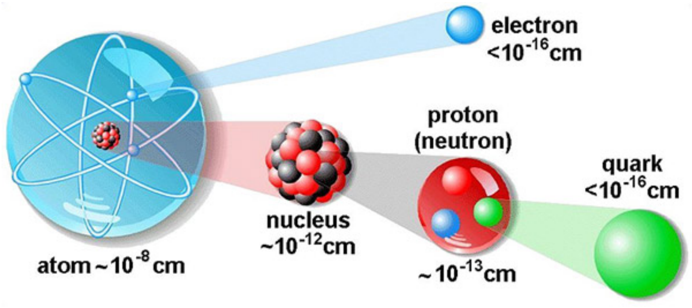
- Gluon saturation
- Nuclear shadowing
- Nucleus size
- Testing standard model

3 Summary



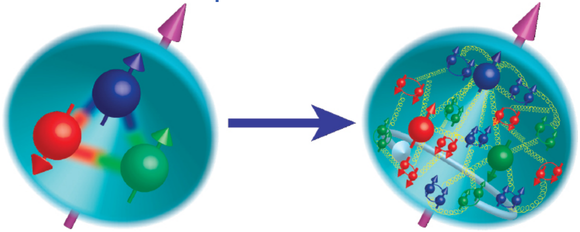
Motivation

What are we made of



- Idea of fundamental particles since ancient Greece and India (philosophy).
- Scientific exploration begun in 19th century (Dalton, later on Thompson, Rutherford...).
- Deep Inelastic Scattering (DIS) uses high-energetic virtual photons (small wavelength).
- Reveled that nucleons consists of quarks bounded with gluons.
- Several types of quarks and gluon described by Quantum Chromo Dynamic (QCD) theory.

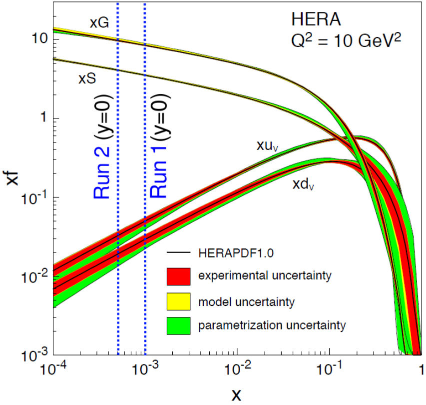
A very complicated structure of proton



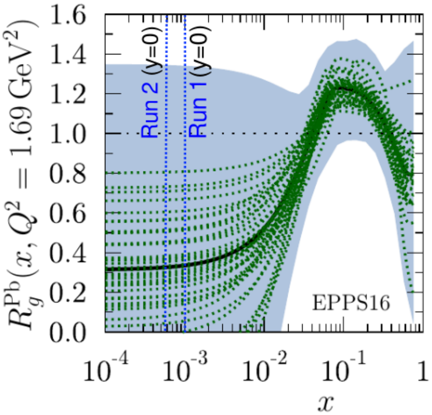
- The "valence" quarks carries only small part of nucleons mass.
- The rest is carried by "sea" quarks and gluons of different energies.
- Bjorken x: momentum fraction carried by constituent.
- Proportional to probe energy $-q^2 = Q^2$ as $s \sim Q^2/x$
- Smaller Bjorken $x \rightarrow$ smaller momenta fractions in the proton reached.
- By changing energy of your probe one can touch different objects inside target.
- What is the dynamics of all of this?

Where QCD is now

- The proton is mainly occupied by gluons for Bjorken $x < 10^{-2}$ (HERA).
- The LHC gives the possibility to measure the gluonic structure of the proton and nuclei to study saturation and shadowing at small Bjorken x.



Accardi *et. al.*: Eur.Phys.J.A 52 (2016) 9, 268



Eskola *et. al.*: Eur.Phys.J.C 77 (2017) 3, 163

QCD questions and how to answer them

QCD questions and how to answer them

What is the Bjorken-x evolution of the gluon structure?

Measure the rapidity and the impact parameter dependence.

QCD questions and how to answer them

What is the Bjorken-x evolution of the gluon structure?

Measure the rapidity and the impact parameter dependence.

Can we access the gluon distribution?

Measure the dependence on momentum transfer $|t|$.

QCD questions and how to answer them

What is the Bjorken-x evolution of the gluon structure?

Measure the rapidity and the impact parameter dependence.

Can we access the gluon distribution?

Measure the dependence on momentum transfer $|t|$.

How does the gluon distribution change with the atomic mass number?

Trace the evolution at a fixed energy by using different targets.

QCD questions and how to answer them

What is the Bjorken-x evolution of the gluon structure?

Measure the rapidity and the impact parameter dependence.

Can we access the gluon distribution?

Measure the dependence on momentum transfer $|t|$.

How does the gluon distribution change with the atomic mass number?

Trace the evolution at a fixed energy by using different targets.

Where are the limits of Standard Model?

Use high energies to see small object/heavy particles.

QCD questions and how to answer them

What is the Bjorken-x evolution of the gluon structure?

Measure the rapidity and the impact parameter dependence.

Can we access the gluon distribution?

Measure the dependence on momentum transfer $|t|$.

How does the gluon distribution change with the atomic mass number?

Trace the evolution at a fixed energy by using different targets.

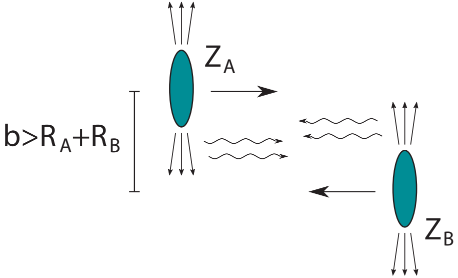
Where are the limits of Standard Model?

Use high energies to see small object/heavy particles.

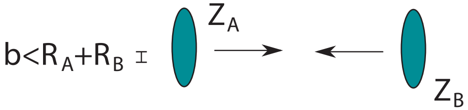
Let's see what ALICE can do about it.

Ultra-peripheral collisions (UPCs)

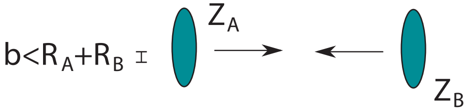
- Collisions with impact parameter $b > R_A + R_B$.
  - Hadronic interactions suppressed.
  - EM induced interactions remain.
- EM field of ultrarelativistic electrically charged particle $\sim$ flux of photons.
  - Flux intensity increasing with Z^2.

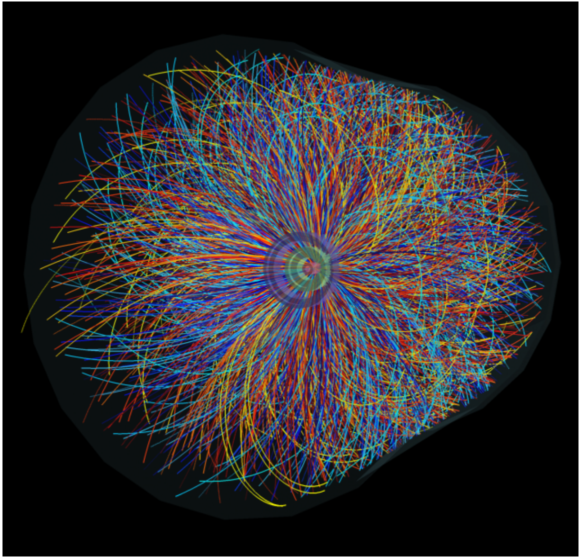


What was ALICE designed for

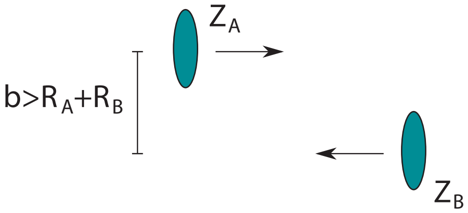


What was ALICE designed for

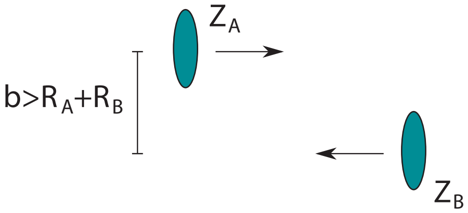


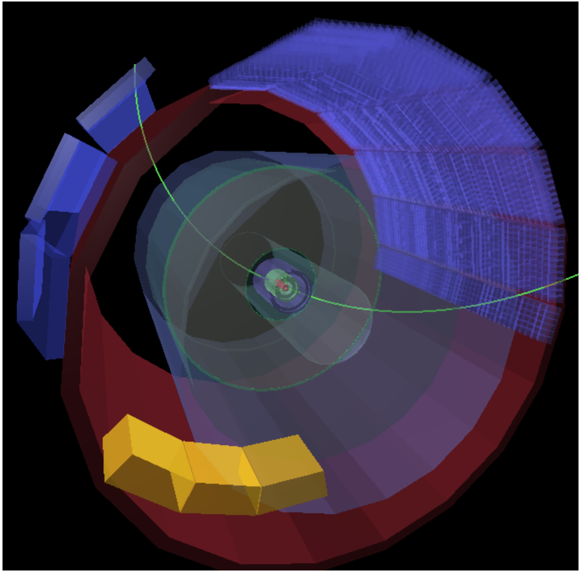


How we actually use it

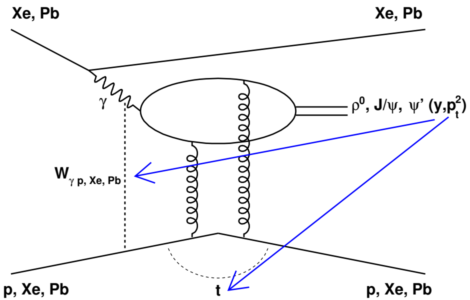


How we actually use it





UPCs as a tool to use light to study gluons



Coherent ρ^0, J/ψ and ψ' photoproduction:

- $Q^2 \sim m_V^2/4$
  (ρ^0 is semi-hard; J/ψ and ψ': pQCD valid)
- Large cross sections.
- Clean experimental signals.
- Provides information on gluon saturation in the proton and shadowing in nuclei at low-x (corresponding to large $W_{\gamma p,\mathrm{Pb}}$).

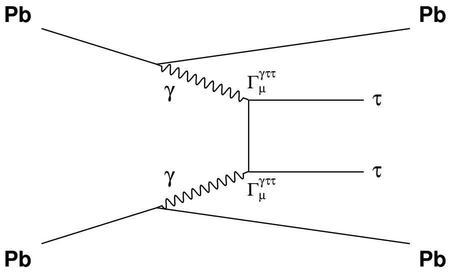
At leading order in the collinear approach:

$$\left.\frac{d\sigma_{\gamma A \to J/\psi A}}{dt}\right|_{t=0} = \frac{M_{J/\psi}^3 \Gamma_{ee} \pi^3 \alpha_s^2(Q^2)}{48 \alpha_{em} Q^8} \left[x g_A(x, Q^2)\right]^2$$

Ryskin: Z. Phys. C 57, 89 (1993)

UPCs as a tool to use light to study anomalous magnetic moment of τ

- τ is the heaviest lepton.
  - The best sensitivity to new physics.
- a_τ poorly know.
  - Short lifetime $\rightarrow$ cannot be stored.
- $\gamma\tau\tau$ vertex is sensitive to a_τ.



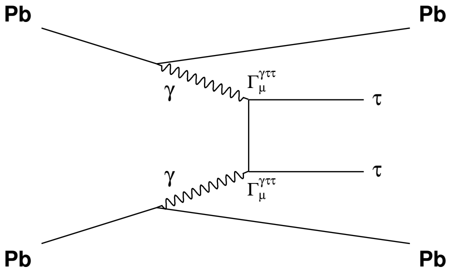
UPCs produce quazi-real photon ($q^2 \rightarrow 0$) !

$$i\Gamma_\mu^{(\gamma\tau\tau)}(q) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\tau}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\tau}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right] \qquad F_2(q^2 \rightarrow 0) = a_\tau$$

Dyndal *et al.*: Phys. Lett. B 809, (2020) 135682

UPCs as a tool to use light to study anomalous magnetic moment of τ

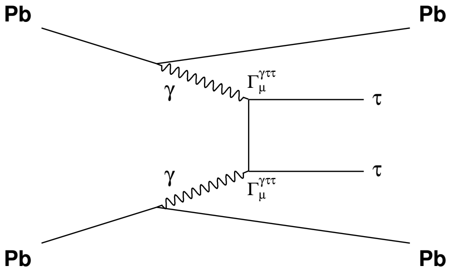
- τ is the heaviest lepton.
  - The best sensitivity to new physics.
- a_τ poorly know.
  - Short lifetime $\rightarrow$ cannot be stored.
- $\gamma\tau\tau$ vertex is sensitive to a_τ.



No useful data, yet :(

UPCs as a tool to use light to study anomalous magnetic moment of τ

- τ is the heaviest lepton.
  - The best sensitivity to new physics.
- a_τ poorly know.
  - Short lifetime $\rightarrow$ cannot be stored.
- $\gamma\tau\tau$ vertex is sensitive to a_τ.



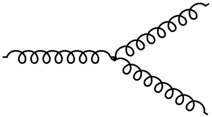
No useful data, yet :(

We should have them this year!

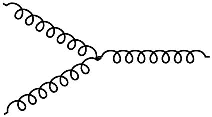
Current findings

Gluon saturation

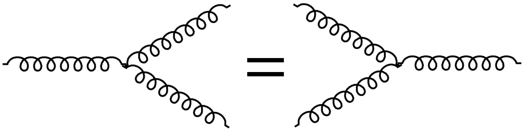
When gluons abundance saturate



Gluon splitting



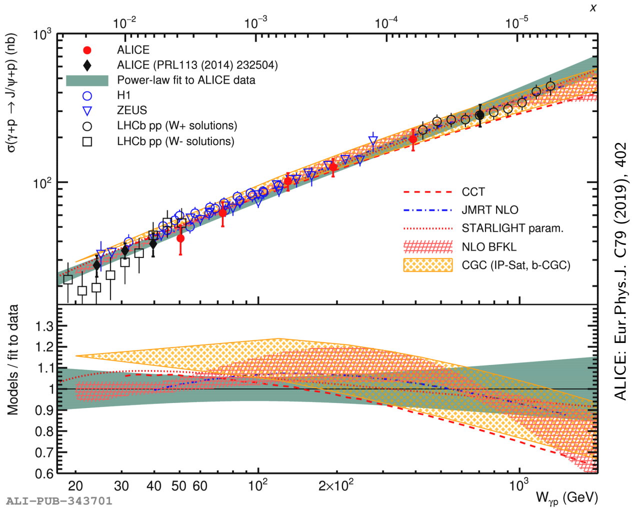
Gluon recombination



Gluon saturation

- QCD allows gluons-only vertex.
- Gluon abundance different at different scales.
- When splitting dominates, gluons rises.
- With higher energies, probability of gluon recombination increases.
- At some point, these two processes should equal and gluons stops rising with energy.
- $\rightarrow$ gluon saturation.

Looking inside proton

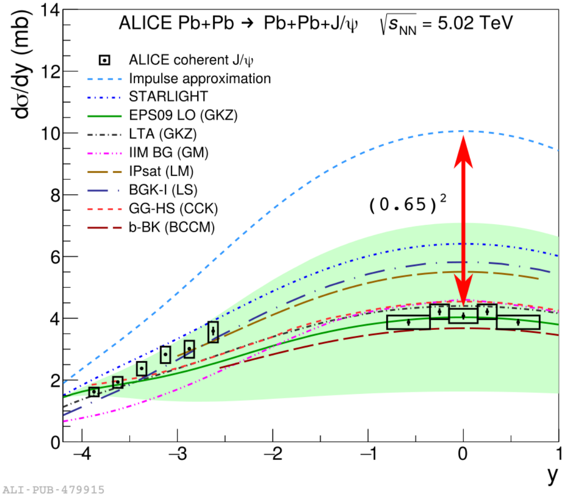


- Measurement in a single experiment from 20 GeV to 700 GeV corresponding to 3 orders of magnitude in x from 10^{-2} to 10^{-5}.
- If the cross section stops rising with energy, saturation is on.
- Currently, no such behaviour is visible $\rightarrow$ no experimental evidence for saturation
- We can also look into lead ions:
  - Possibility to reach higher energies.
  - Experimentally difficult.
  - No published results, yet.

Current findings

Nuclear shadowing

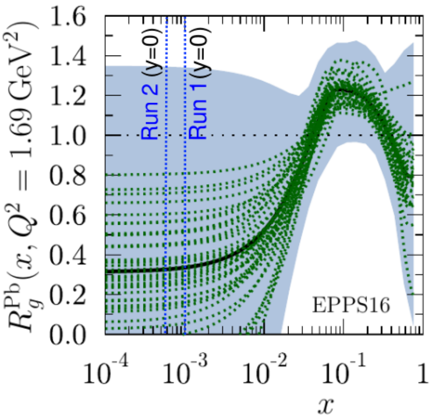
Measuring the transparency of the lead nucleus



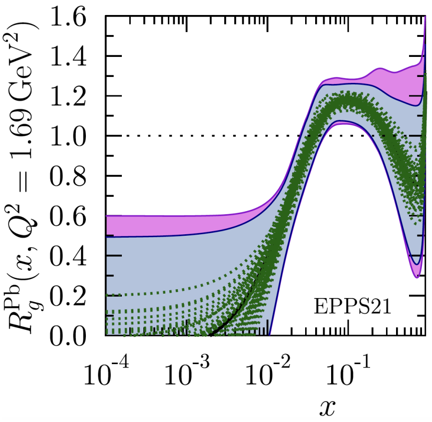
Eur.Phys.J.C 81 (2021) 8, 712

- Interplay between nucleons inside nucleus.
- Impulse approximation (IA) represents situation when nucleons do not interact with each other.
- Comparison of data to IA implies $S_{\mathrm{Pb}}(x \sim 10^{-3}) = 0.65 \pm 0.03$.
- No model can satisfactory explain all measured data points.

Immidiate impact on the precision of models



Eskola *et. al.*: Eur.Phys.J.C 77 (2017) 3, 163

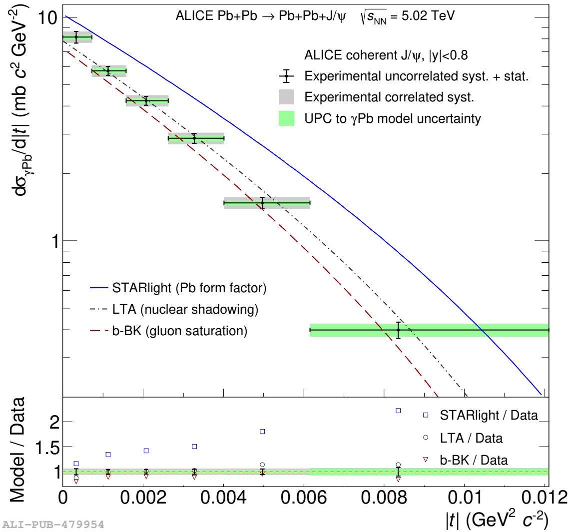


Eskola *et. al.*: Eur.Phys.J.C 82 (2022) 5, 413

Current findings

Nucleus size

Scanning the size of ultra-relativistic nucleus



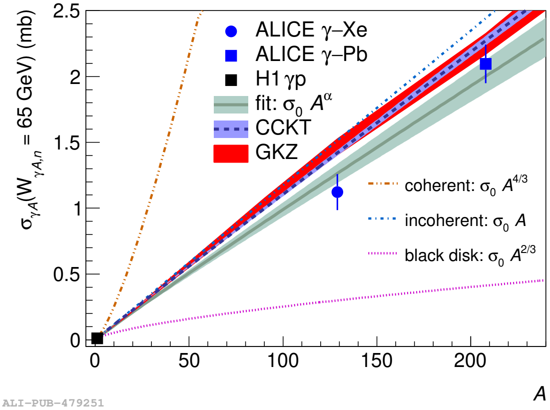
Phys.Lett.B 817 (2021) 136280

- $|t|$-dependence related by a 2D Fourier transform to the distribution of gluons in the impact-parameter plane.
- Steeper distribution → thicker nucleus.
- The Pb form factor prediction expects the same size as when at rest.
- Comparison of data implies existence of QCD dynamical effects.
- Roughly speaking, nucleons collective behaviour stronger than expected.

Current findings

Testing standard model

Unique Xe–Xe collisions opens A-dependence studies



Phys. Lett. B 820 (2021) 136481

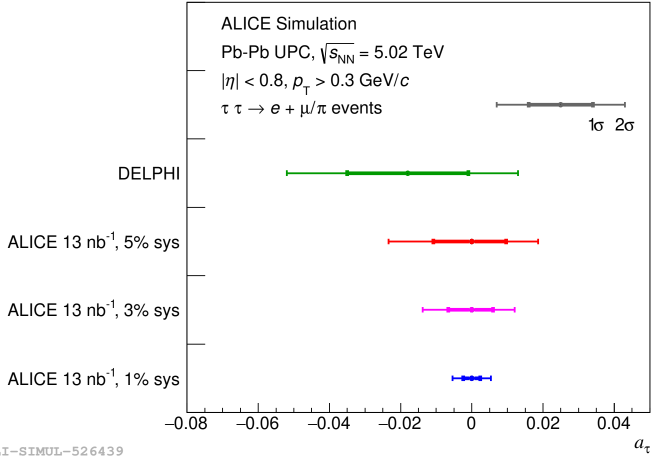
- First measurement with Xe nucleus → first study of A dependence.
- Study of nuclear shadowing with different A shows power-law behaviour with a slope of 0.96 ± 0.02. Models do a reasonable job in description of the data.
- Black disk limit = moment, when investigated medium is not transparent.

~~Current~~ Future findings

Testing standard model

a_τ limits from p_T-differential measurement

- Combining the cross section ratios of different p_T intervals.
- Currently not enough collected data at the LHC.
- LHC and ALICE improved in the last years promising much more data.
- Limits improvement looks feasible.
- SMI heavily involved in this.



Summary

(partial) answers to QCD questions

(partial) answers to QCD questions

What is the Bjorken-x evolution of the gluon structure?

Gluons keep rising with Bjorken-x $\rightarrow$ no signs of saturation in proton.

Bjorken-x dependence of shadowing in Pb $\rightarrow$ shadowing factor is around 0.65 at $x \approx 10^{-3}$.

(partial) answers to QCD questions

What is the Bjorken-x evolution of the gluon structure?

Gluons keep rising with Bjorken-x $\rightarrow$ no signs of saturation in proton.

Bjorken-x dependence of shadowing in Pb $\rightarrow$ shadowing factor is around 0.65 at $x \approx 10^{-3}$.

Can we access the gluon distribution?

Yes, in 2D; sensitivity to QCD dynamical effects demonstrated.

(partial) answers to QCD questions

What is the Bjorken-x evolution of the gluon structure?

Gluons keep rising with Bjorken-x $\rightarrow$ no signs of saturation in proton.

Bjorken-x dependence of shadowing in Pb $\rightarrow$ shadowing factor is around 0.65 at $x \approx 10^{-3}$.

Can we access the gluon distribution?

Yes, in 2D; sensitivity to QCD dynamical effects demonstrated.

How does the gluon distribution changes with the atomic mass number?

Power-law behaviour consistent with models.

Black-disc limit not yet reached.

(partial) answers to QCD questions

What is the Bjorken-x evolution of the gluon structure?

Gluons keep rising with Bjorken-x $\rightarrow$ no signs of saturation in proton.

Bjorken-x dependence of shadowing in Pb $\rightarrow$ shadowing factor is around 0.65 at $x \approx 10^{-3}$.

Can we access the gluon distribution?

Yes, in 2D; sensitivity to QCD dynamical effects demonstrated.

How does the gluon distribution changes with the atomic mass number?

Power-law behaviour consistent with models.

Black-disc limit not yet reached.

(partial) answers to QCD questions

What is the Bjorken-x evolution of the gluon structure?

Gluons keep rising with Bjorken-x $\rightarrow$ no signs of saturation in proton.
Bjorken-x dependence of shadowing in Pb $\rightarrow$ shadowing factor is around 0.65 at $x \approx 10^{-3}$.

Can we access the gluon distribution?

Yes, in 2D; sensitivity to QCD dynamical effects demonstrated.

How does the gluon distribution changes with the atomic mass number?

Power-law behaviour consistent with models.
Black-disc limit not yet reached.

Where are the limits of Standard Model?

Need more data to look for physics beyond Standard Model.