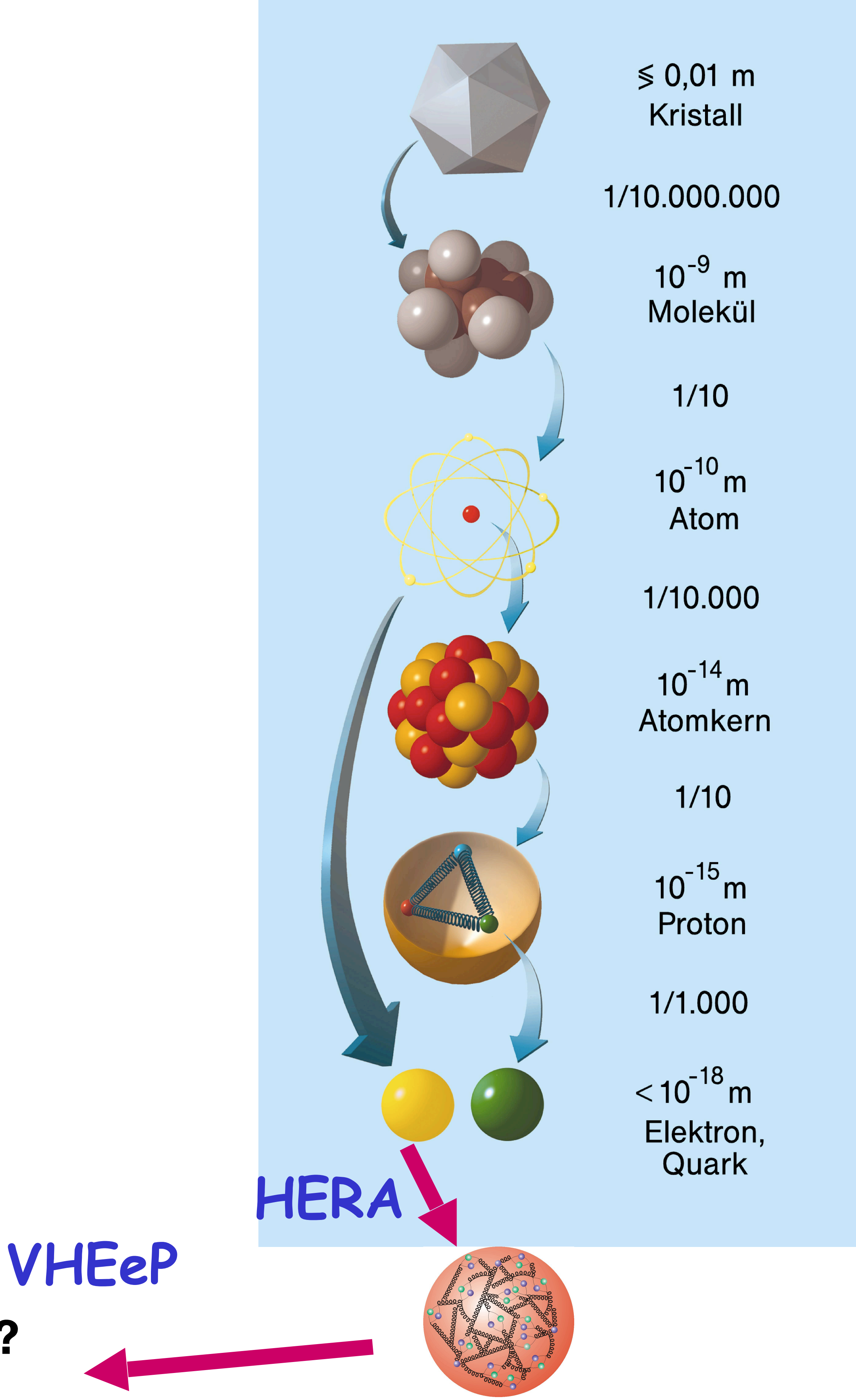
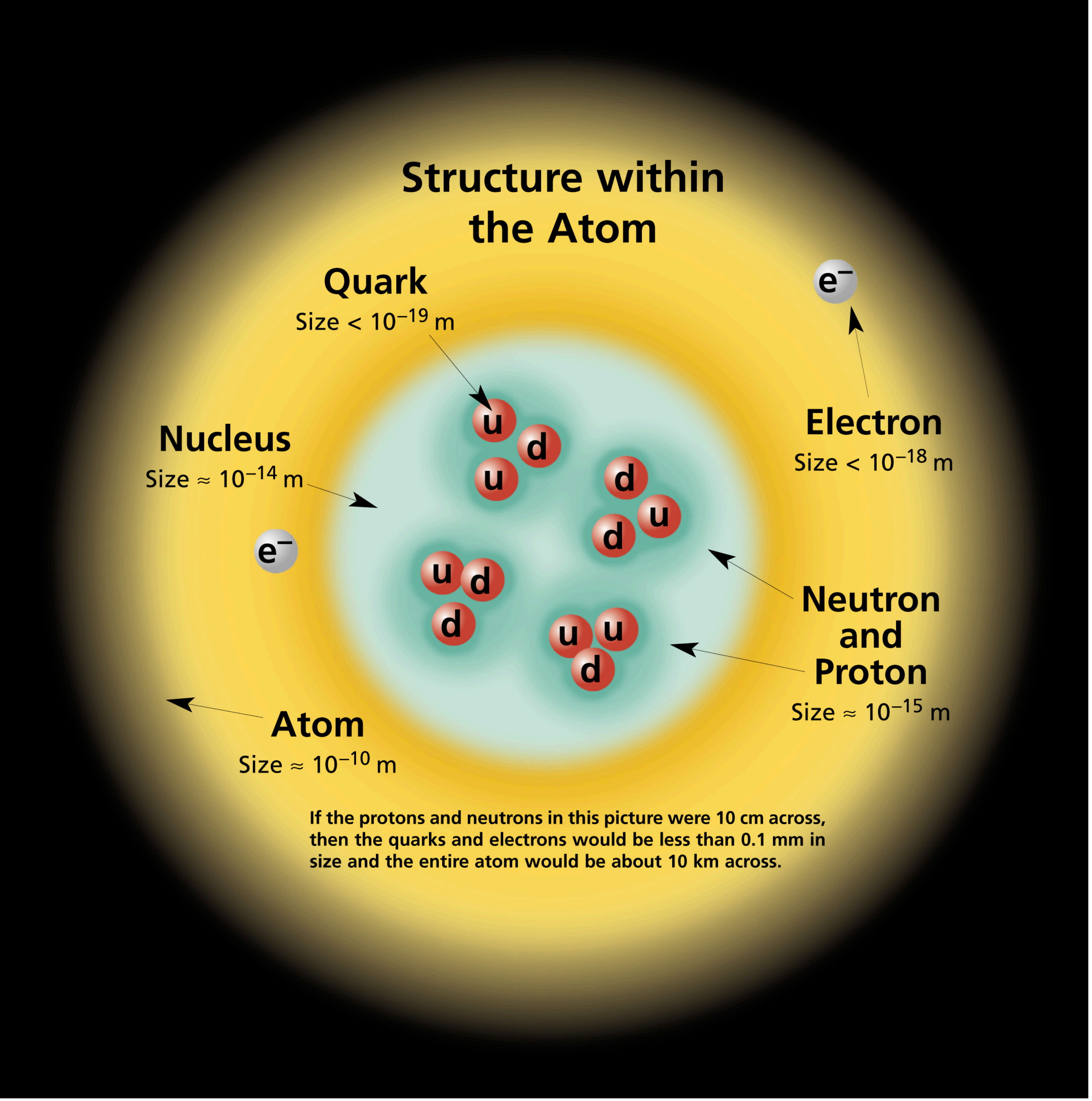
Physics case
high energy e/p and e/A collider

Allen Caldwell
Max Planck Institute for Physics

Alegro Workshop
CERN
March 26, 2019



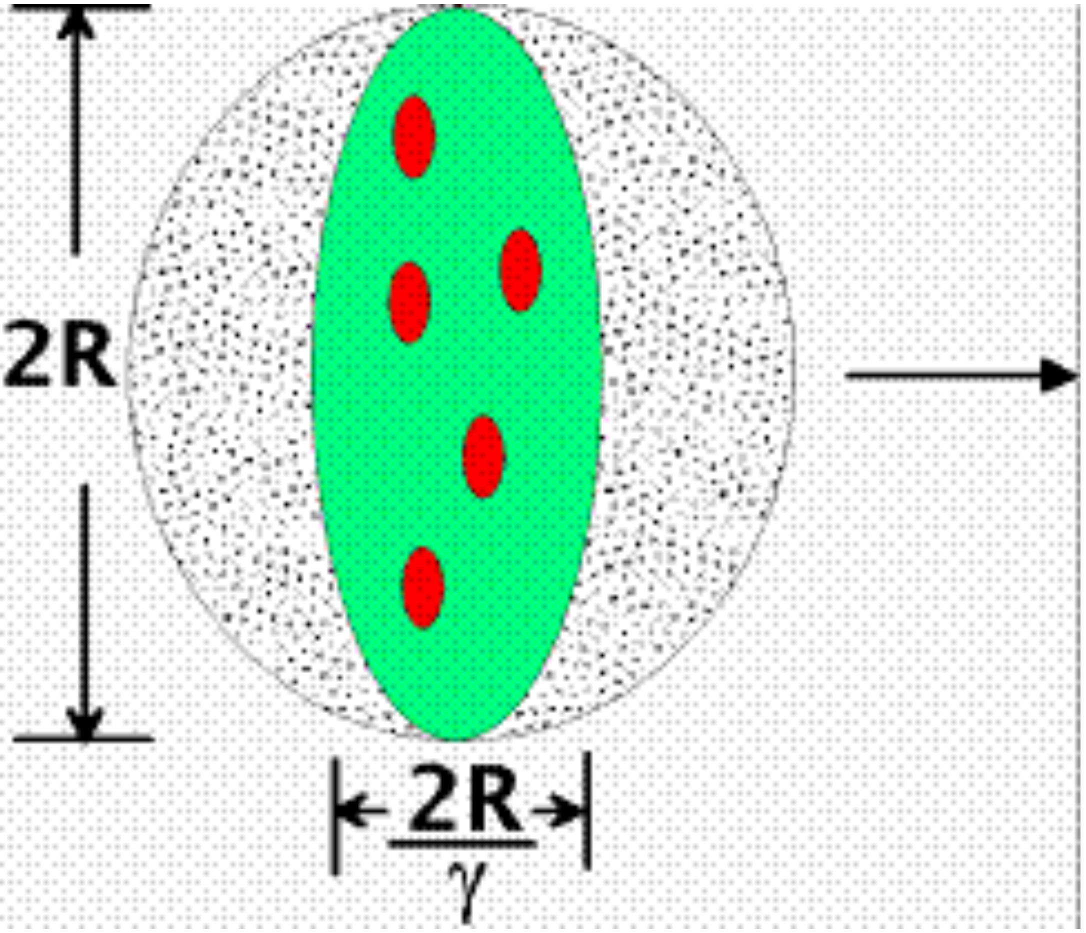
fundamental state of QCD matter?
relation to gravity?
color confinement?



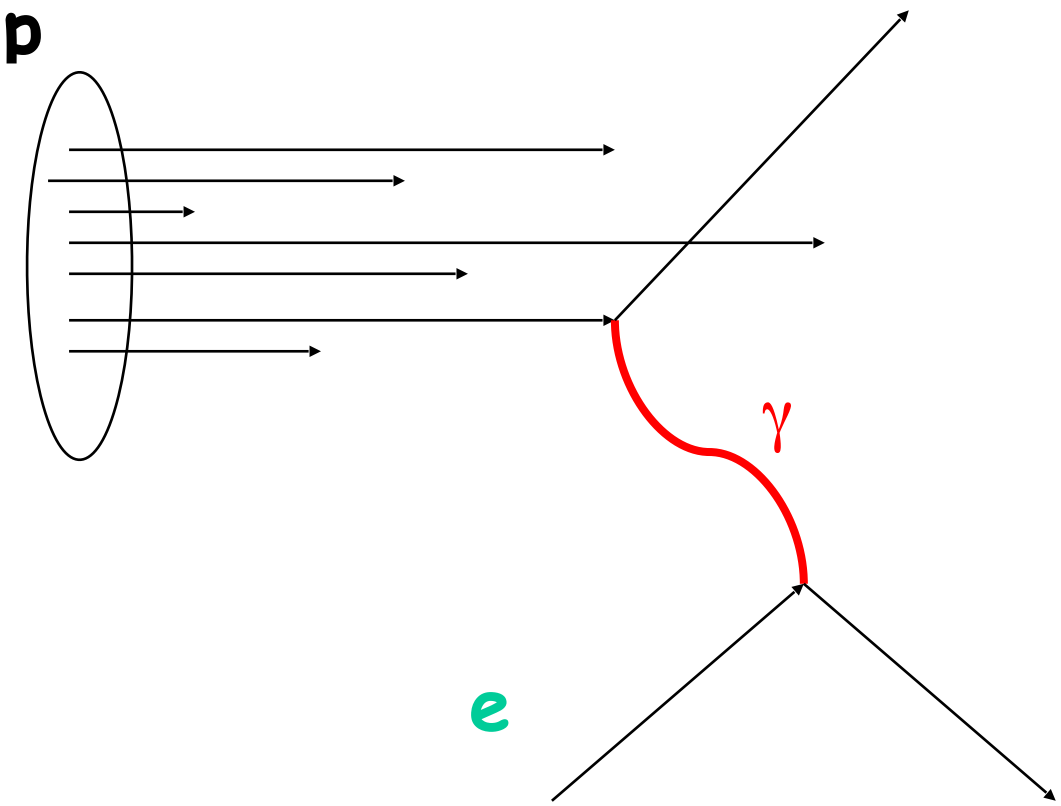
To the outside world, the proton is made of three quarks, two 'u' and a 'd'.

Other quarks which have been discovered: s,c,b,t

Feynman's Parton Model



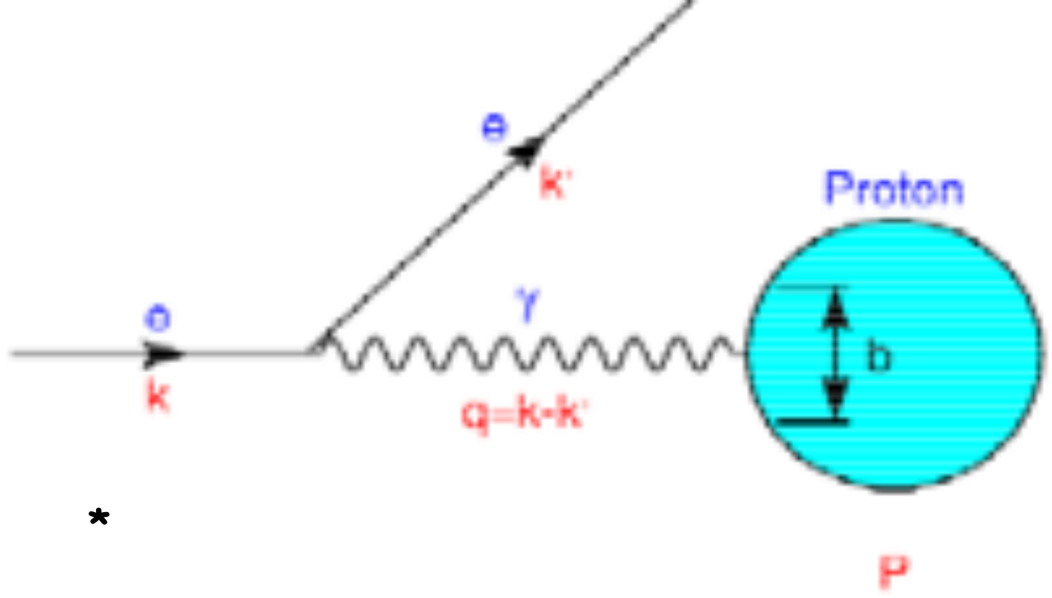
Imagine a very fast moving nucleon. Feynman asked us to think of it as a collection of point-like constituents- the partons- which are behaving incoherently.



All partons moving parallel to the nucleon. Assume massless and no significant transverse momentum. Parton carries fractional momentum $\sum_i x_i = 1$

Interactions between partons in this frame time-dilated, so wavefunction not changing during the time of the interaction.

Kinematics



$s=(k+P)^2$ CM energy squared

$Q^2=-(k-k')^2$ virtuality

$W^2=(q+P)^2$ γ^*P CM energy squared

$$x \approx \frac{Q^2}{W^2}$$

Transverse distance scale probed: $b \approx \dfrac{\hbar c}{Q}$

McAllister, Hofstadter	Ee=188 MeV	b_{min}=0.4 fm
Bloom et al.	10 GeV	0.05 fm
CERN, FNAL fixed target	500 GeV	0.007 fm
HERA	54 TeV	0.0007 fm
LHeC/PEPIC	900 TeV	0.0002 fm
VHEeP	45000 TeV	0.00003 fm

McAllister and Hofstadter 1956

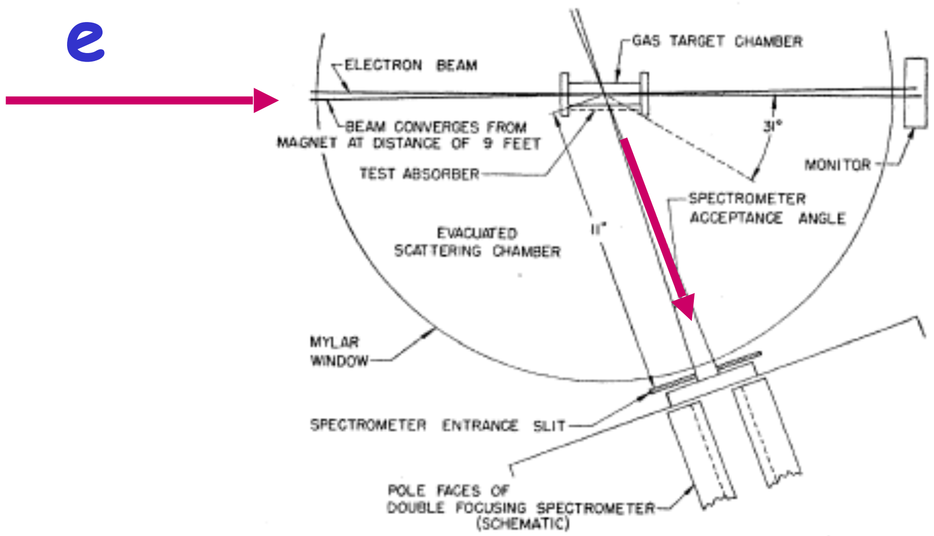
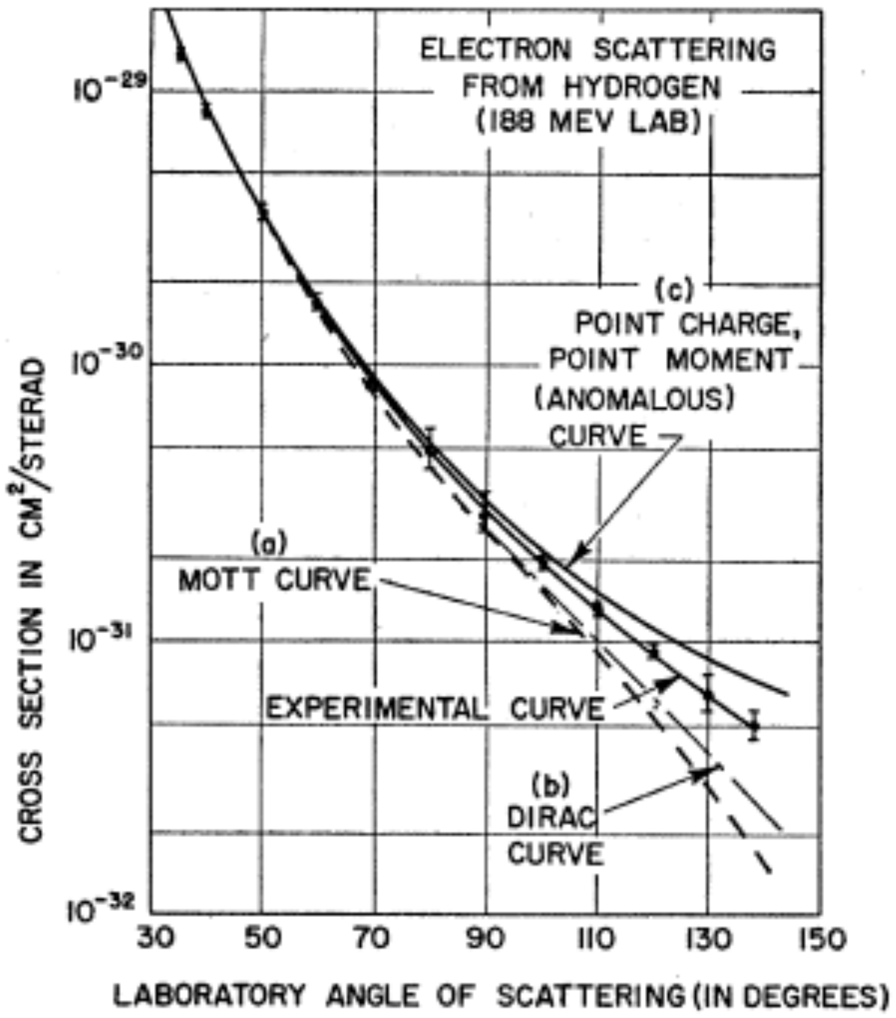


FIG. 2. Arrangement of parts in experiments on electron scattering from a gas target.

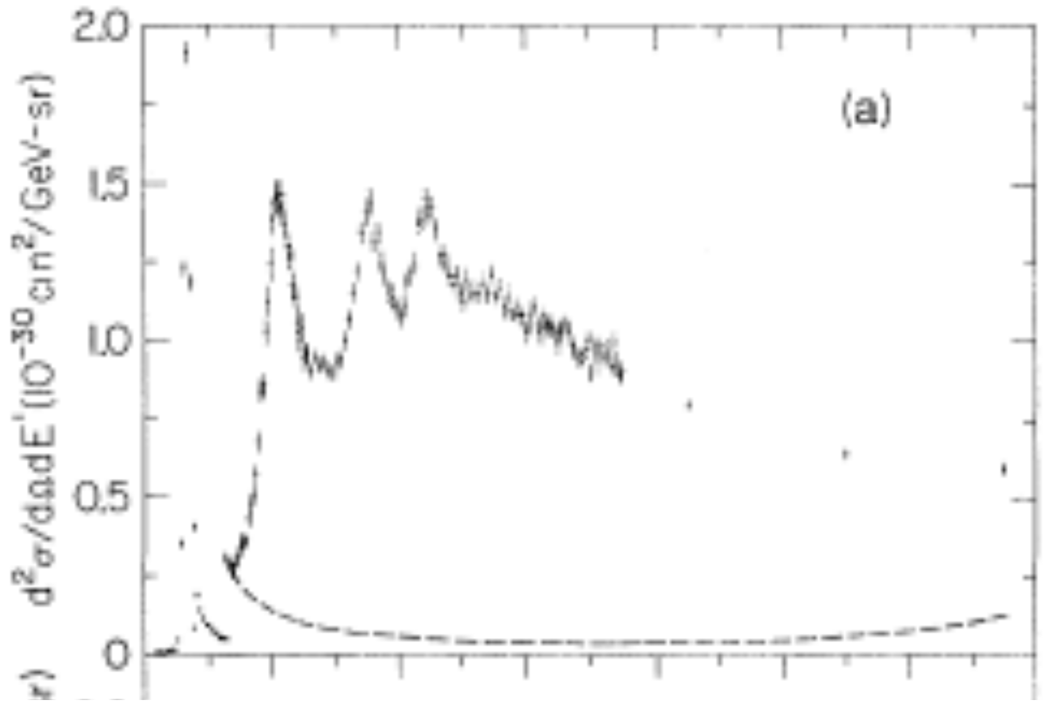
188 MeV and 236 MeV electron beam from linear accelerator at Stanford

Conclusion:

radius of proton 0.7-0.8 fm



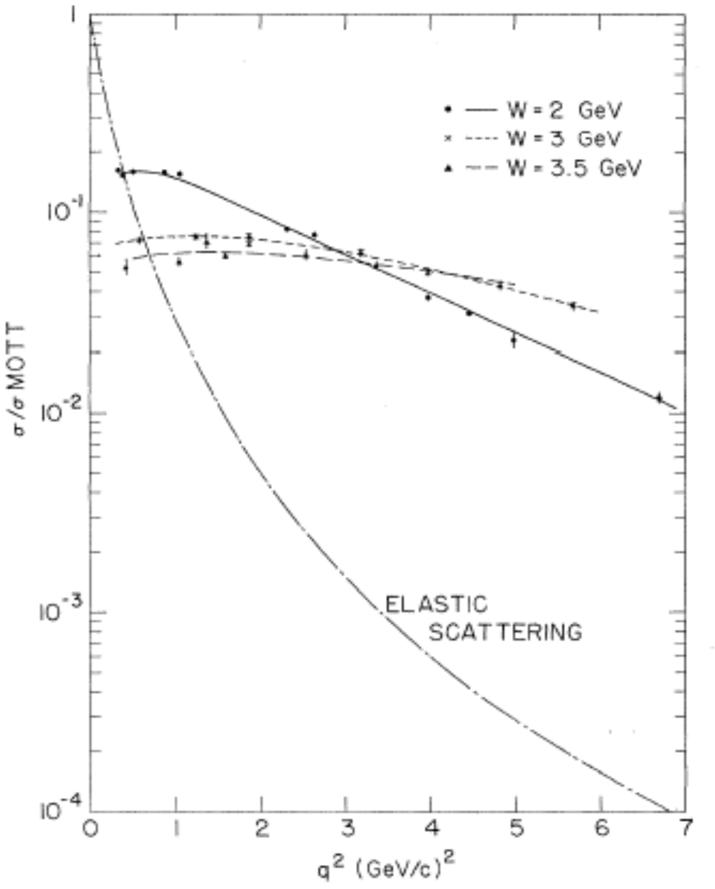
Bloom et al. (SLAC-MIT group) in 1969 performed an experiment with high-energy electron beams (7-18 GeV).



At small W, see proton and resonances.

W=0.8

2.0



The data did not fall with Q^2 as expected for elastic scattering on an extended nucleus. Rather, data looks like elastic scattering on a point charge (Mott).

SEARCH & DISCOVERY

FRIEDMAN, KENDALL AND TAYLOR WIN NOBEL PRIZE FOR FIRST QUARK EVIDENCE

The 1990 Nobel Prize in Physics has been awarded to Jerome Friedman and Henry Kendall of MIT and Richard Taylor of SLAC "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics." The prize of $710 000, which the three recipients shared equally, was awarded in Stockholm on 10 December.

Friedman, Kendall and Taylor were honored for a series of experiments from 1967 and 1973 that used the then-new two-mile electron linear accelerator at Stanford to study deep inelastic scattering of electrons from protons and neutrons. The SLAC experiments were somewhat analogous to the experiment by Ernest Rutherford that gave evidence for a hard core within the atom: Just as Rutherford's observation of large numbers of alpha particles being scattered at large angles led him to postulate a nucleus within the atom, the SLAC finding of unexpectedly large numbers of electrons being scattered at large angles provided clear evidence for pointlike constituents within nucleons. These constituents are now understood to be quarks.

Quarks had been predicted in 1964 by Murray Gell-Mann and independently by George Zweig at Caltech. Until the SLAC–MIT experiments no one had produced convincing dynamical evidence from experiment for the existence of quarks inside the proton or neutron. In fact during that period many theorists were not sure about the role played by quarks in the theory of hadrons. As Cecilia Jarlskog said at the Nobel ceremony when (on behalf of the Nobel committee for physics) she presented the winners to the king of Sweden, "the quark hypothesis was not alone. There was, for example, a model called 'nuclear democracy' where no particle had the right to call itself elementary. All particles were equally fundamental and consisted of each other."

The 1990 Nobel laureates join hands at a SLAC fest following the announcement of the award. From left: Richard Taylor, Henry Kendall and Jerome Friedman.

SLAC and its detectors

In 1962 construction began on the large Stanford linac, which had a proposed energy of 10–20 GeV; eventually it reached 50 GeV over a series of many steps. Two years later SLAC director Wolfgang Panofsky enlisted the help of several young physicists he had worked with when he was director of the Stanford High-Energy Physics Laboratory. Among these was Taylor, who had returned to Stanford in 1962. He agreed to take charge of the beam switchyard, which linked the accelerator proper with the experimental areas. Around the same time the laboratory established a number of experimental teams, one of which was headed by Taylor.

Soon he was joined by Friedman and Kendall, who were by then on the MIT faculty. They had been doing electron scattering experiments at the 5-GeV Cambridge Electron Accelerator, which had limited capacity and "was a circular machine, with all that that limitation meant," Kendall recalls. But at Stanford there was to be a 20-GeV machine going on line with an "absolutely ferocious beam," high current density and external beam, and immediate availability for experimental use. A group from Caltech led by Barry Barish, Jerome Pine and Charles Peck joined the collaboration but concentrated its work on the comparison of electron–proton with positron–proton scattering.

A large team of experimenters from SLAC, MIT and Caltech decided to build two spectrometers. Stanford experimenters included Panofsky, Taylor and their collaborators, who were interested in electron scattering; Burton Richter and his collaborators, who were interested in photoproduction; and David Ritson, who eventually built a third spectrometer at 1.6

PHYSICS TODAY JANUARY 1991 17

Scaling observed

Predicted by **Bjorken** (1967). Implies electron scattering on point-like objects.

After discovery of quarks, a period of inelastic lepton-nucleon studies ensued:

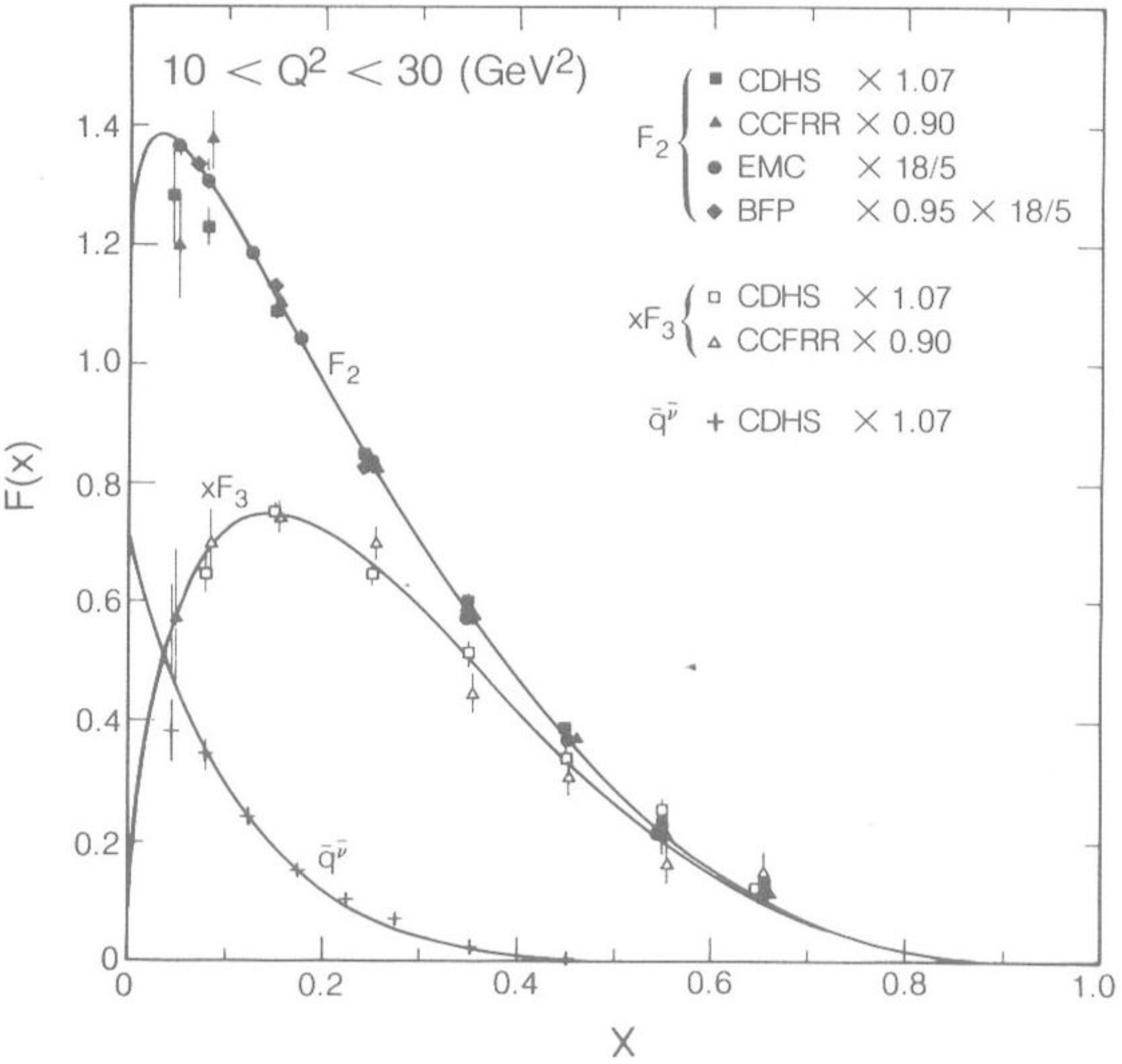
Beams: electron,muon, neutrino

Targets: p, D, heavy targets

Main results: There is something else in the proton than quarks – gluons !

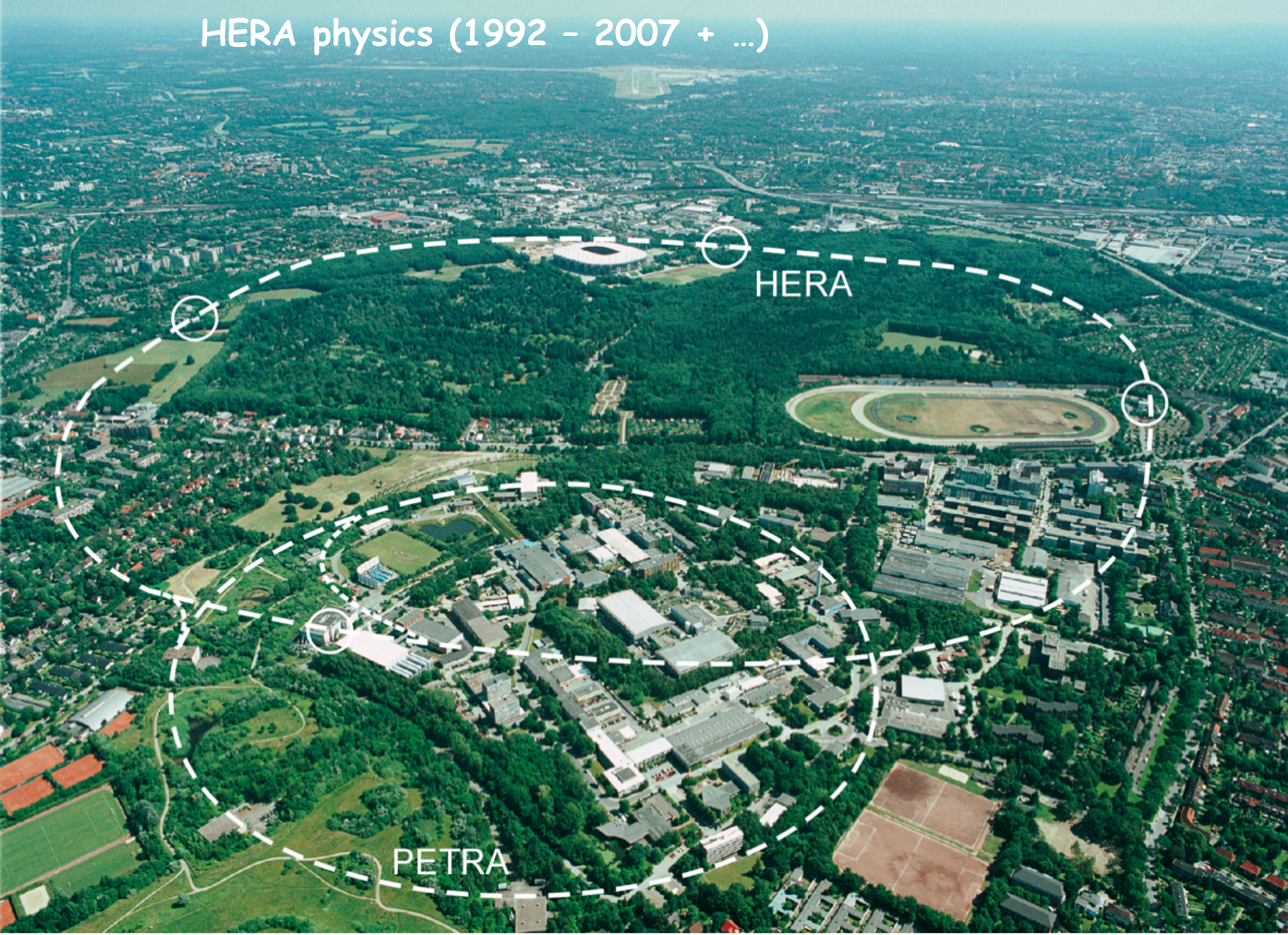
$$\boxed{\int x \sum_{q} \left[\bar{q}(x) + q(x) \right] dx < 1}$$

QCD was established as the correct description of the strong interactions.



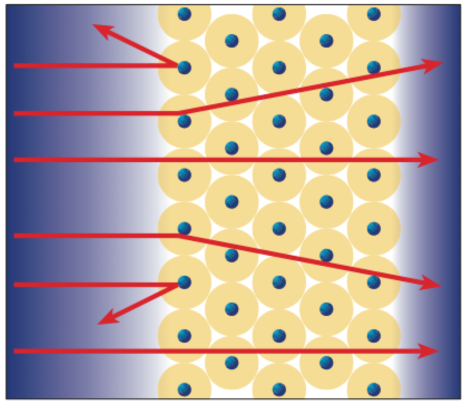
from the **Review of Particle Properties, Phys. Lett., 170B (1986) 79.**

HERA physics (1992 – 2007 + …)

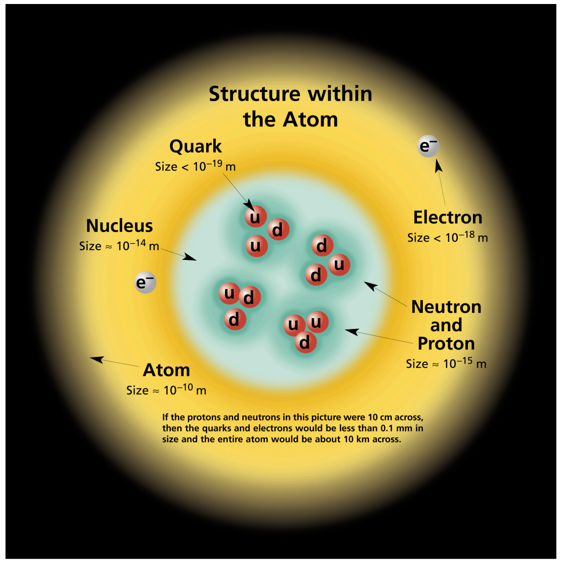


HERA Highlights

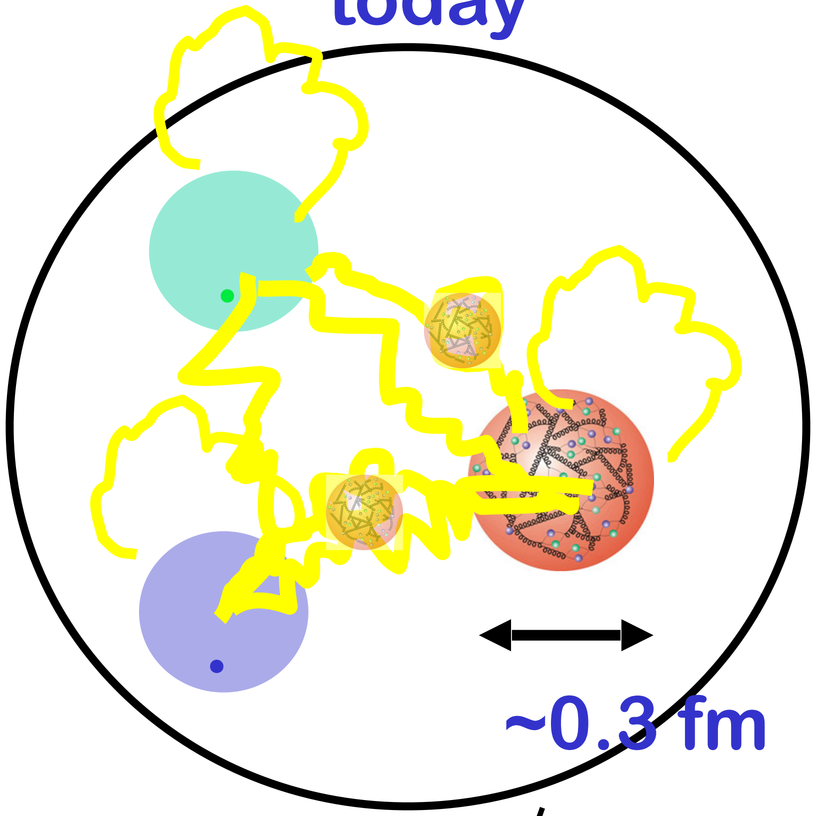
~1900



~1970

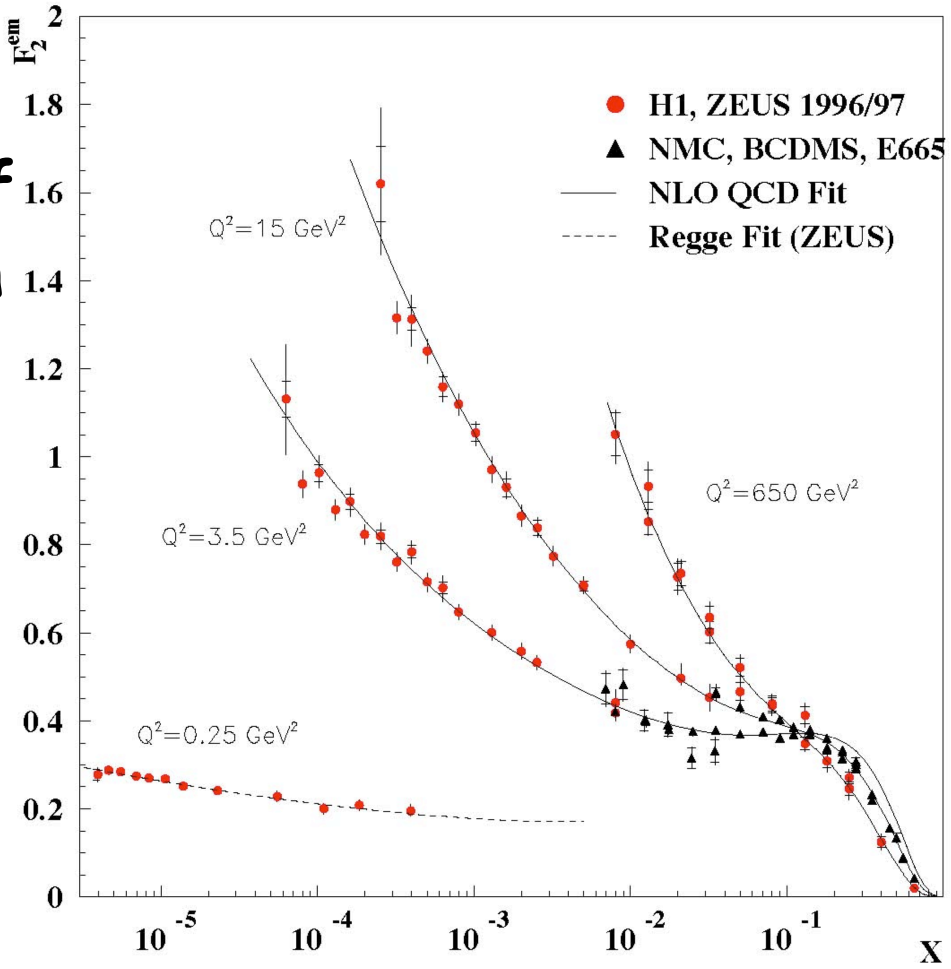


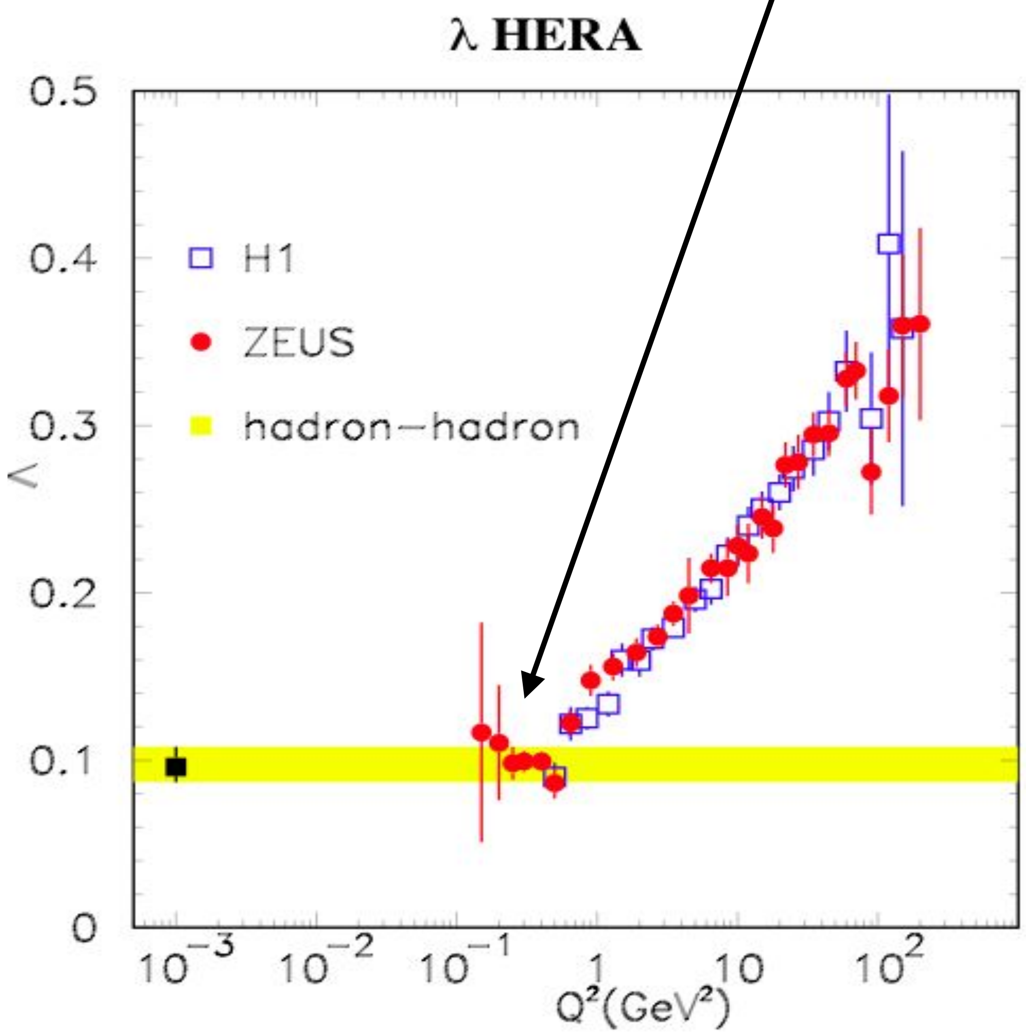
today

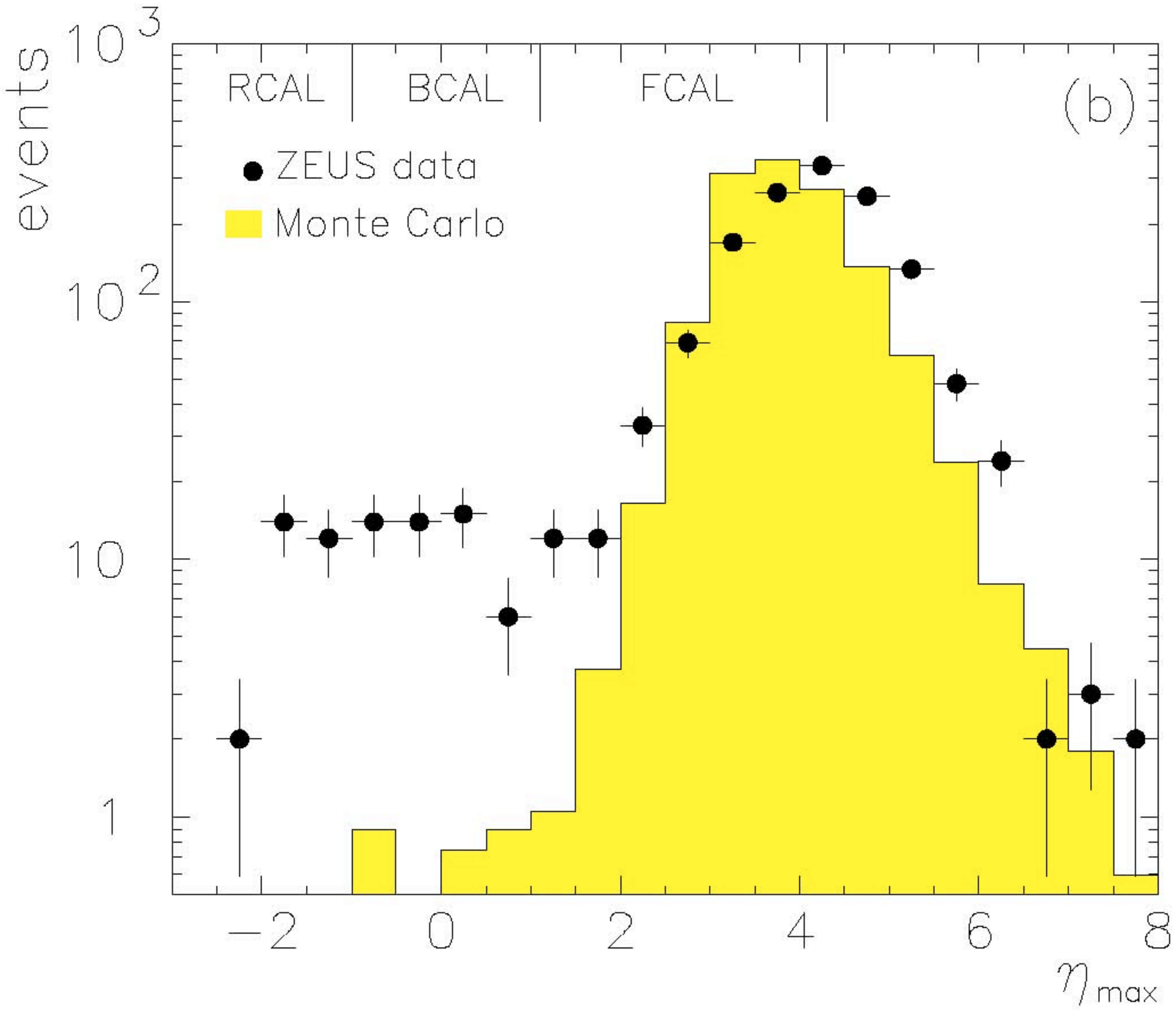


F_2 structure function

Proton full of partons when viewed with high resolution probe!

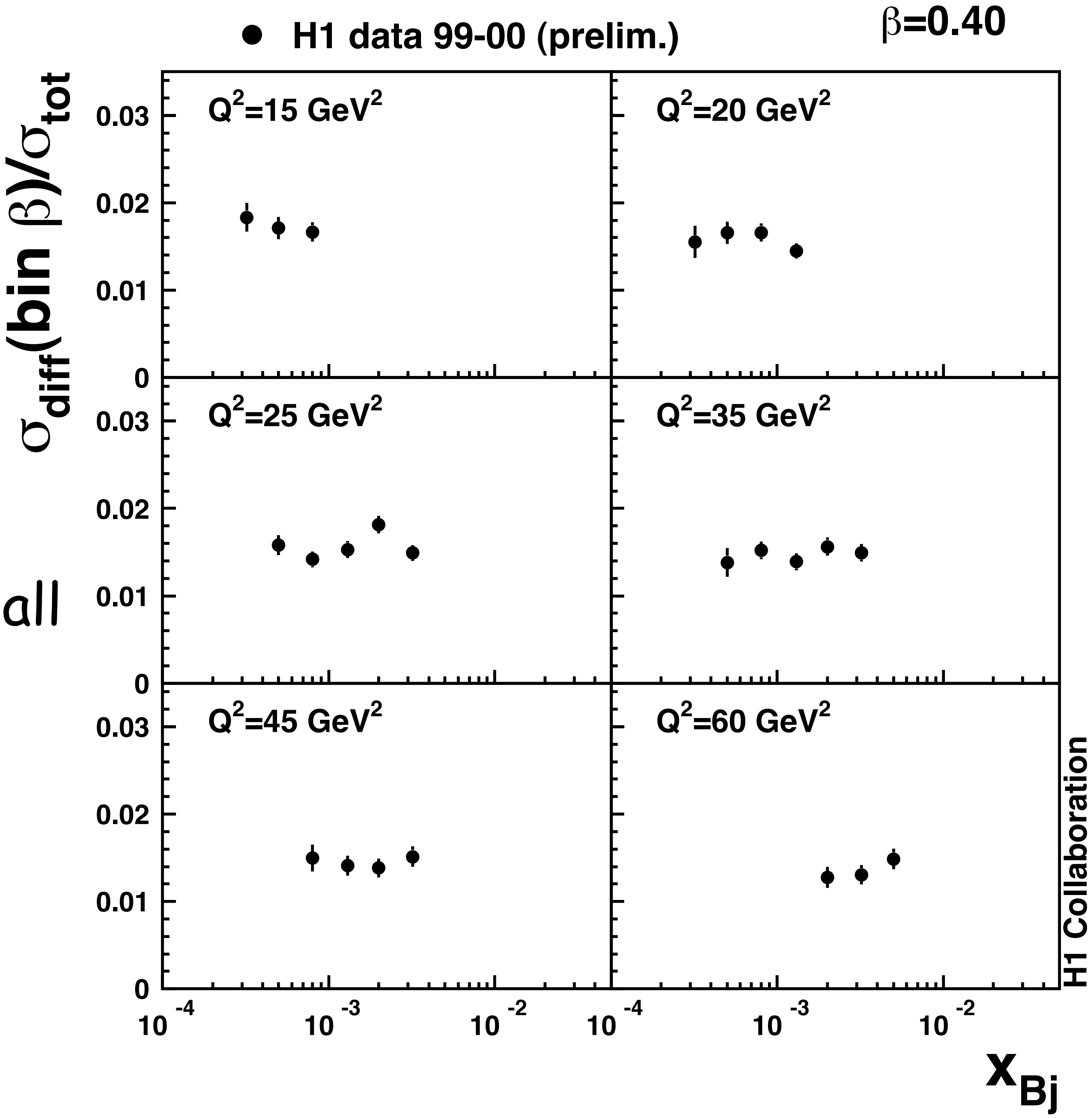




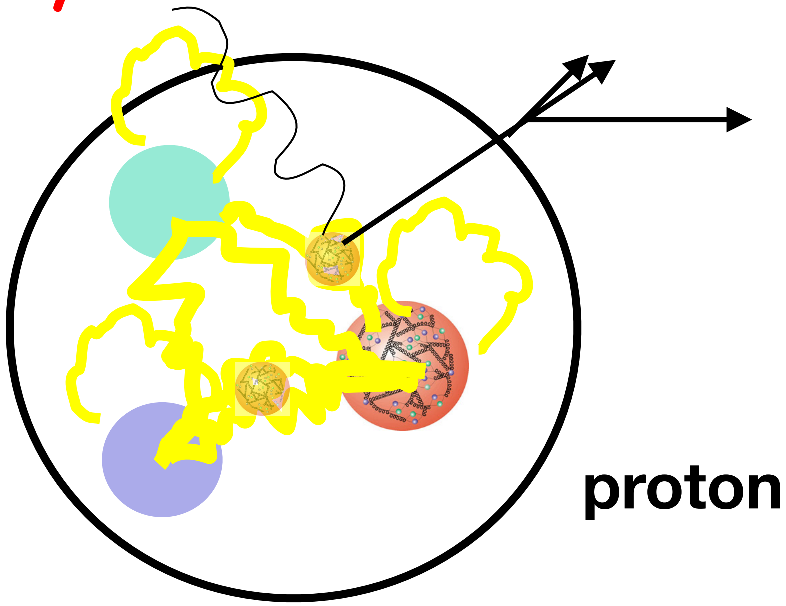


$\eta \approx y$

≥10% of events, protons survive collision! Implies scattering on color neutral cluster: at least two gluons. Sometimes called 'Pomeron'.

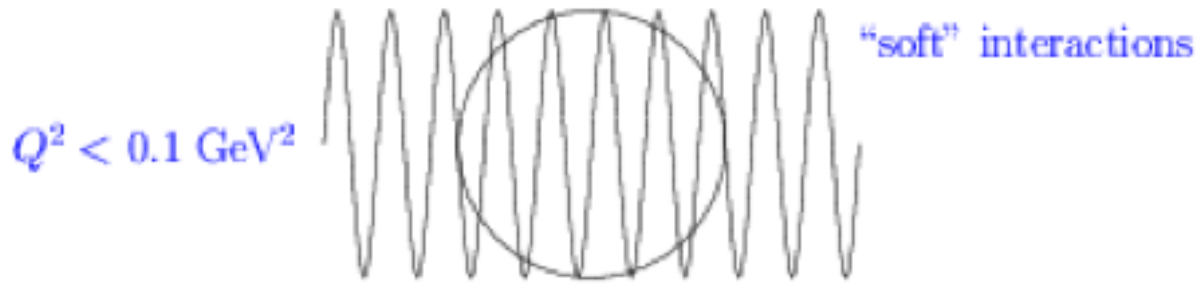


Ratio of diffractive/total independent of x at small x. **Small-x physics is universal.**

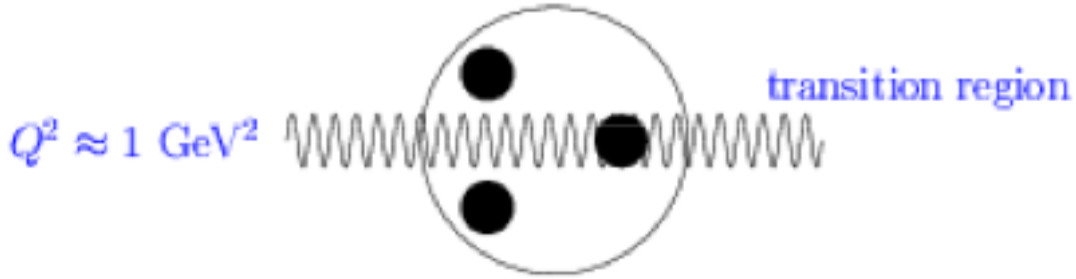


proton survives collision

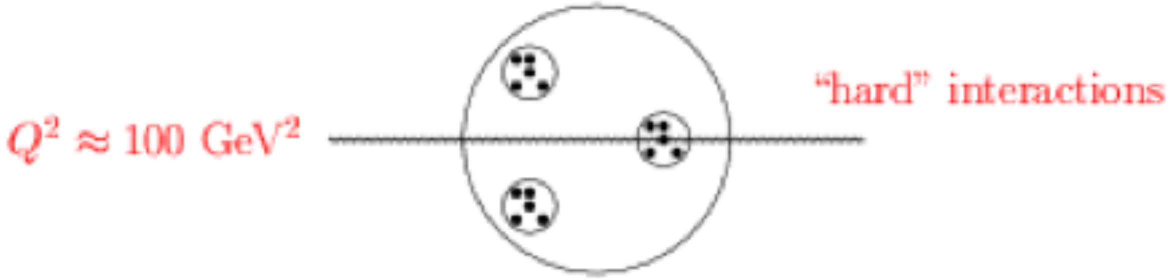
Higher energy allows finer probe



Not sensitive to details of proton structure



Start to see quarks – the valence quarks



See that valence quarks have complicated structure

What's next ?

New Physics in QCD

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

color confined ?
mass of the proton = 1 GeV ?
spin of the proton = 1/2 ?
asymptotic freedom ?

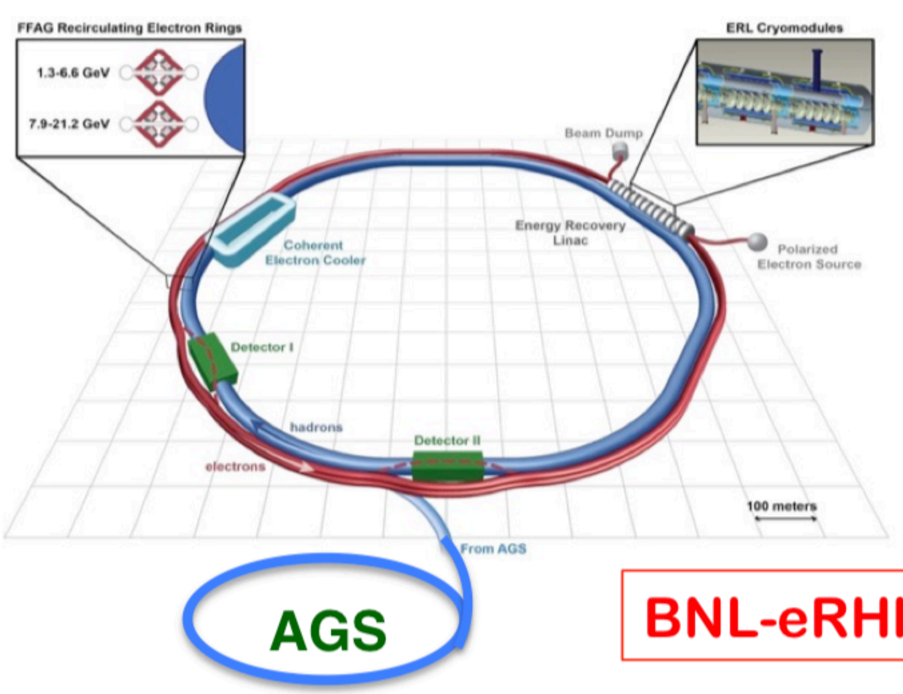
The interesting features of QCD are not apparent from the QCD Lagrangian - emergent features

Fundamental to understand how they emerge:

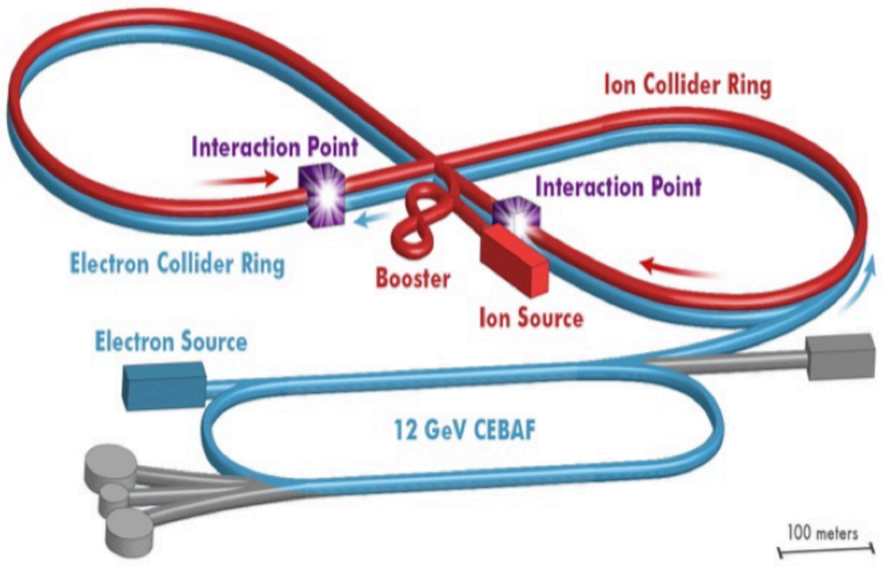
- most of the visible mass of the universe comes from QCD binding energy
- QCD is at the heart of everything (photons, electrons,…). What does matter look like in the high energy limit ?
- confinement of color at 1fm distance scale and spin structure - result of complicated multi particle nonlinear interactions

New ep/A colliders tasked with bringing insight into these important questions

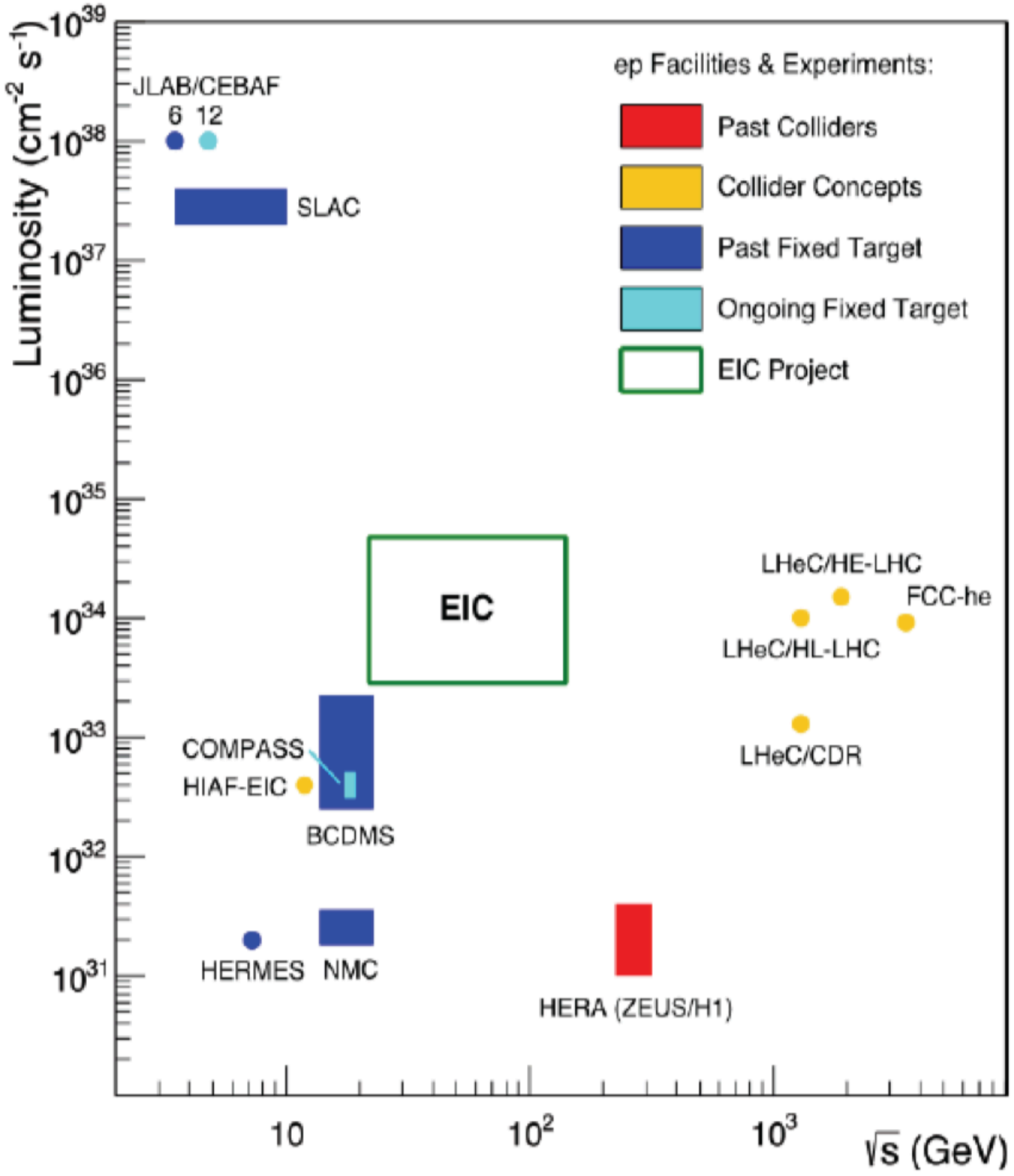
Future Collider Options - EIC



BNL-eRHIC



JLab-JLEIC



Will be the first eA collider
First time both e,p polarized
high luminosity. Realization: late 2020s

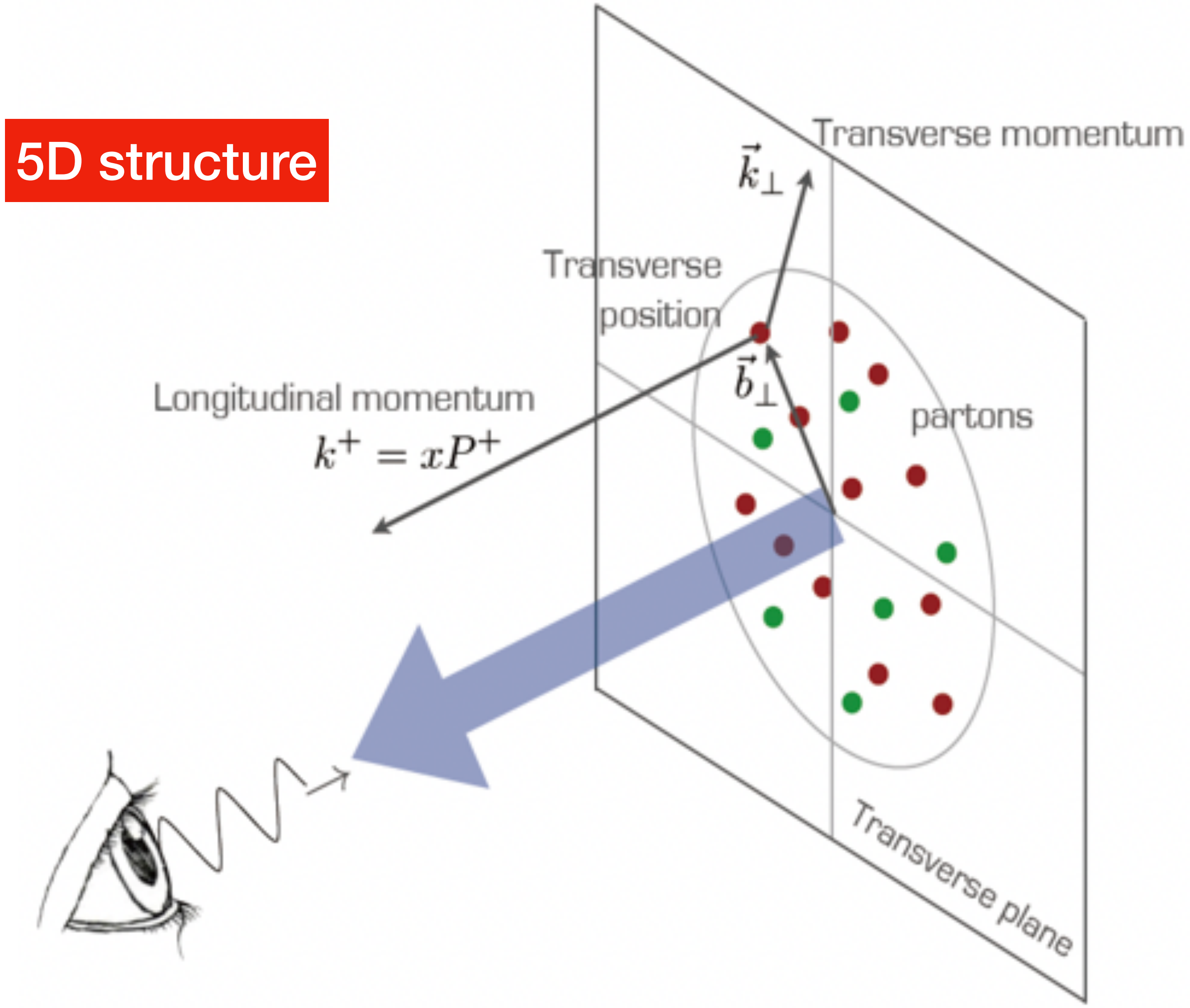
Future Collider Options - EIC

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q_f^2) + \Delta G(Q_f^2) + L_{Q+G}(Q_f^2)$$

Study spin structure

How does spin 1/2 emerge from quark, antiquark, gluon and orbital angular momentum?
Key: both beams polarized, lots of events, small-x

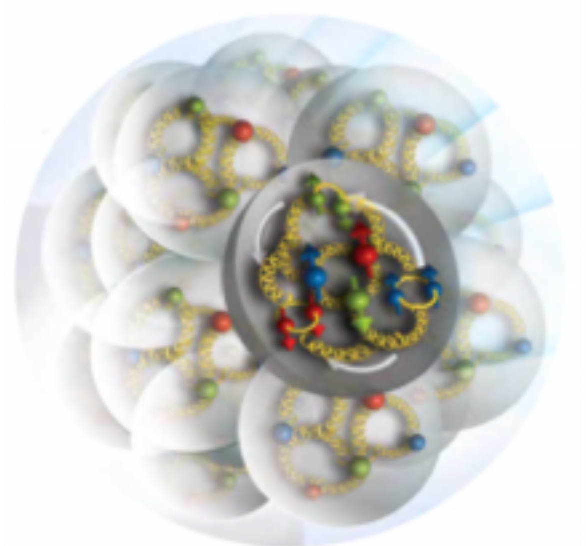
5D structure



Key: lots of events, full acceptance detector

small-x in nuclei

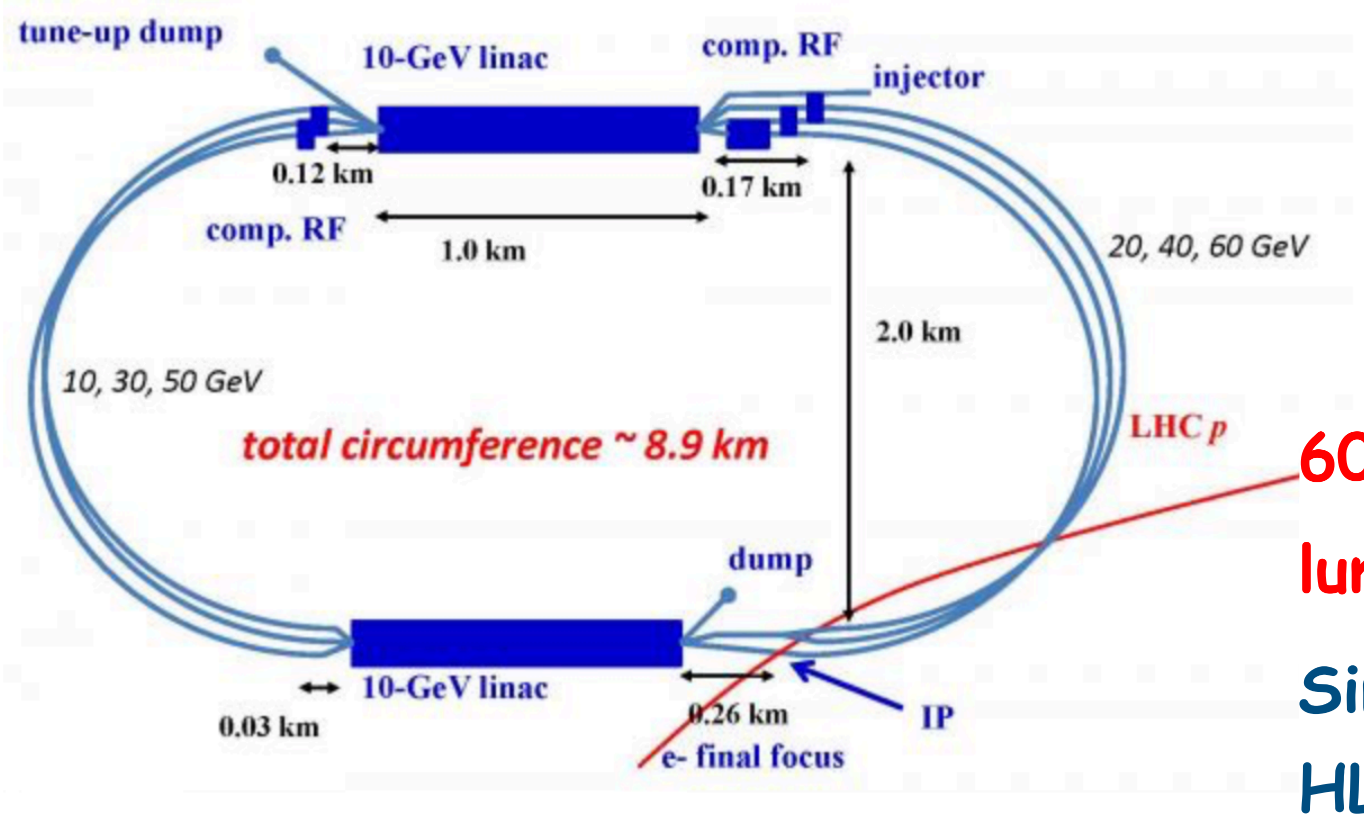
Probe scatters off partons from different nuclei:"oomph factor".
Key: maximum energy



borrowed from J. Qiu DIS 2017, Kobe, Japan

Future Collider Options - LHeC

LHeC



60 GeV electrons x LHC protons/ions high luminosity 10^{34} cm^{-2} s^{-1}

Simultaneous running with ATLAS / CMS in HL-LHC period ?

Broad physics program:

Small x; novel QCD / unitarity
Medium x: precision Higgs and EW

High x:new particle mass frontier

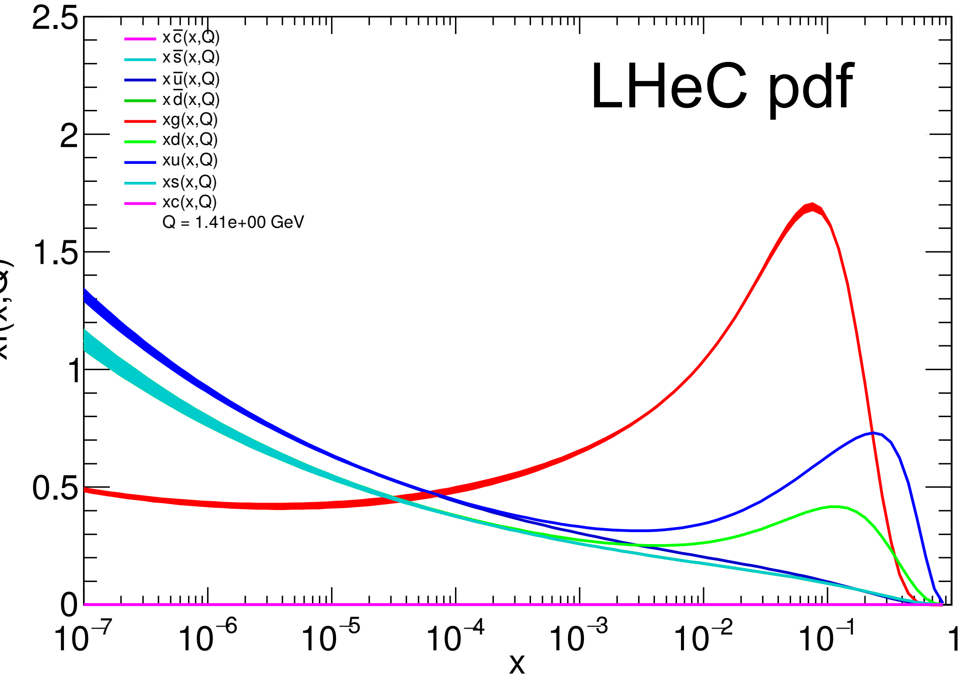
Per-mille experimental precision on α_S

1) CDR 2012

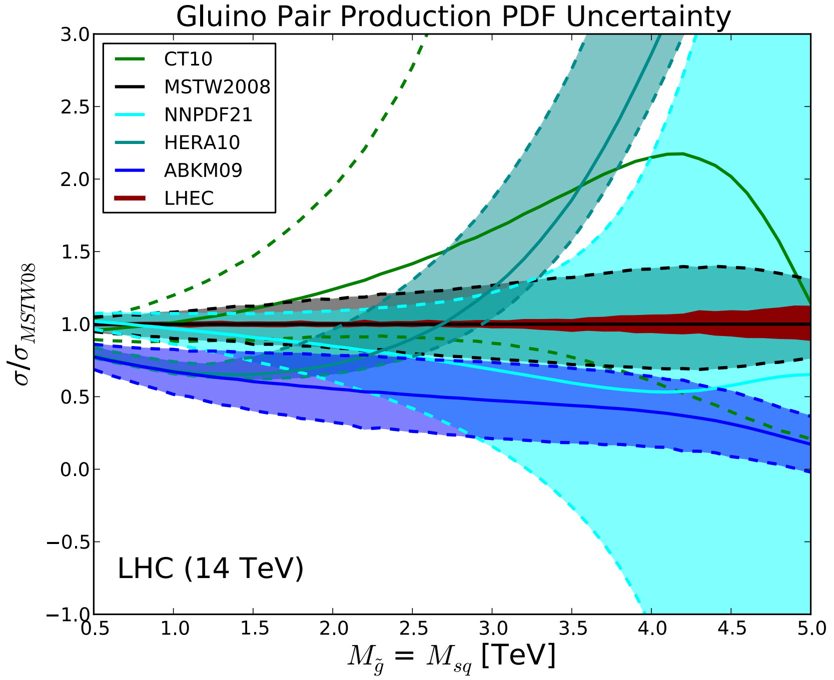
2) TDR for PERLE

3) Further development of FCC eh

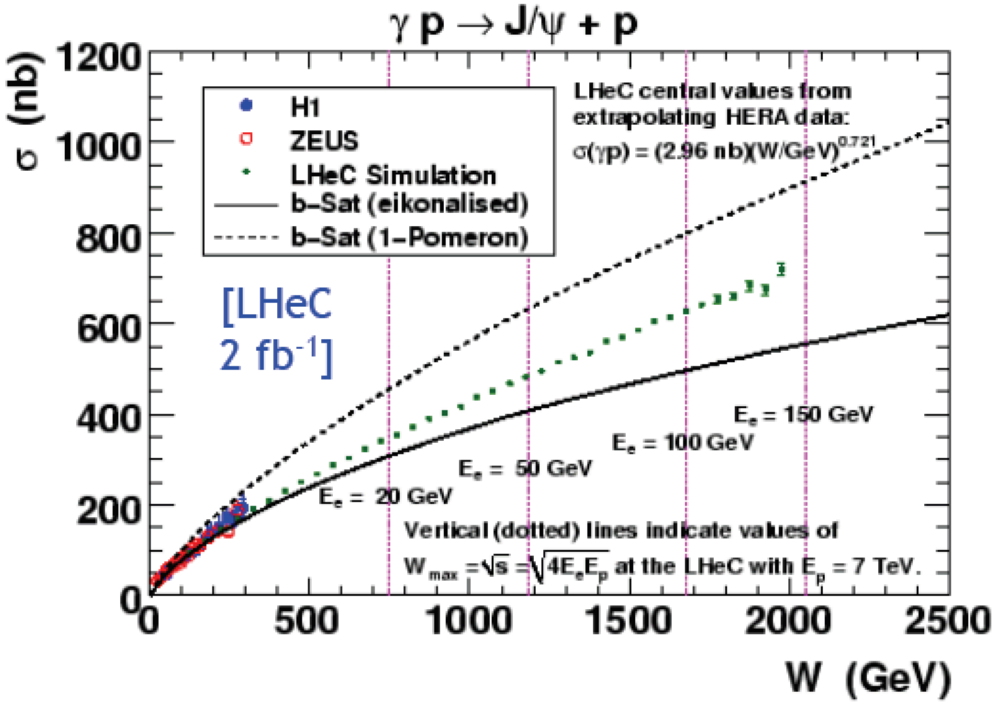
Future Collider Options - LHeC

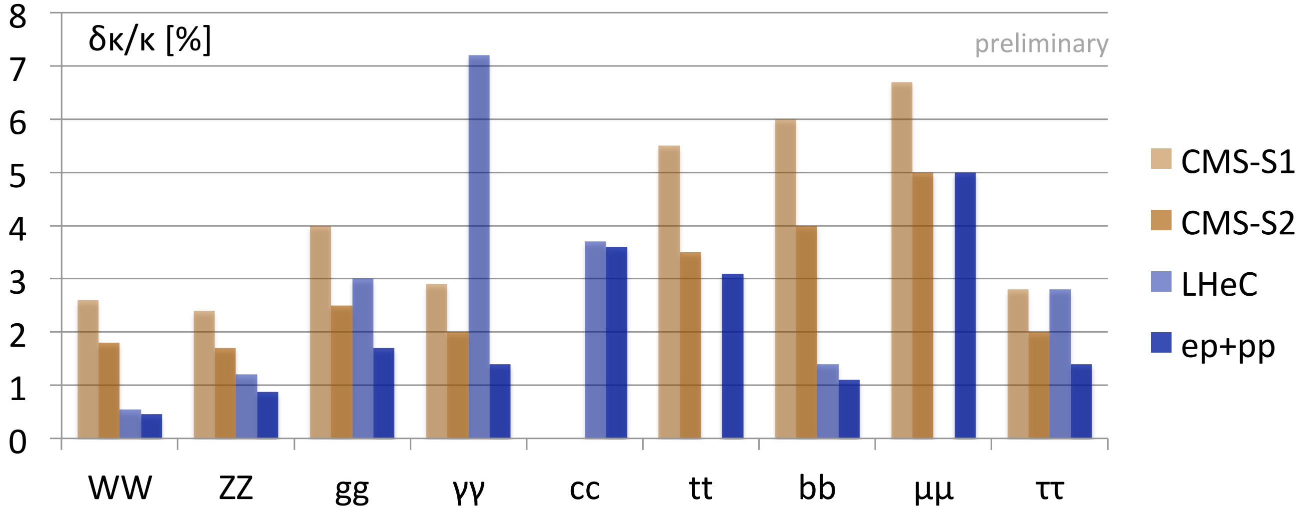


Precision proton structure functions important in recognizing new physics



small-x physics: vastly extended
high lumi: exclusive observables !



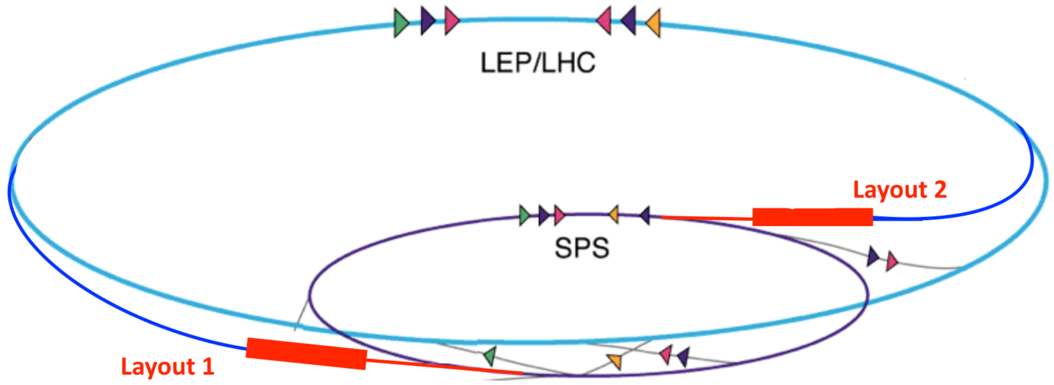


High lumi: sensitivity to Higgs couplings

eA will also be possible

Future Collider Options - PEPIC

PEPIC



Create ~50 GeV beam within 50–100 m of plasma driven by SPS protons

luminosity expected to be << 10^{30} cm^{-2} s^{-1}. Focus on QCD

Studied within Physics Beyond Colliders workshop @ CERN.

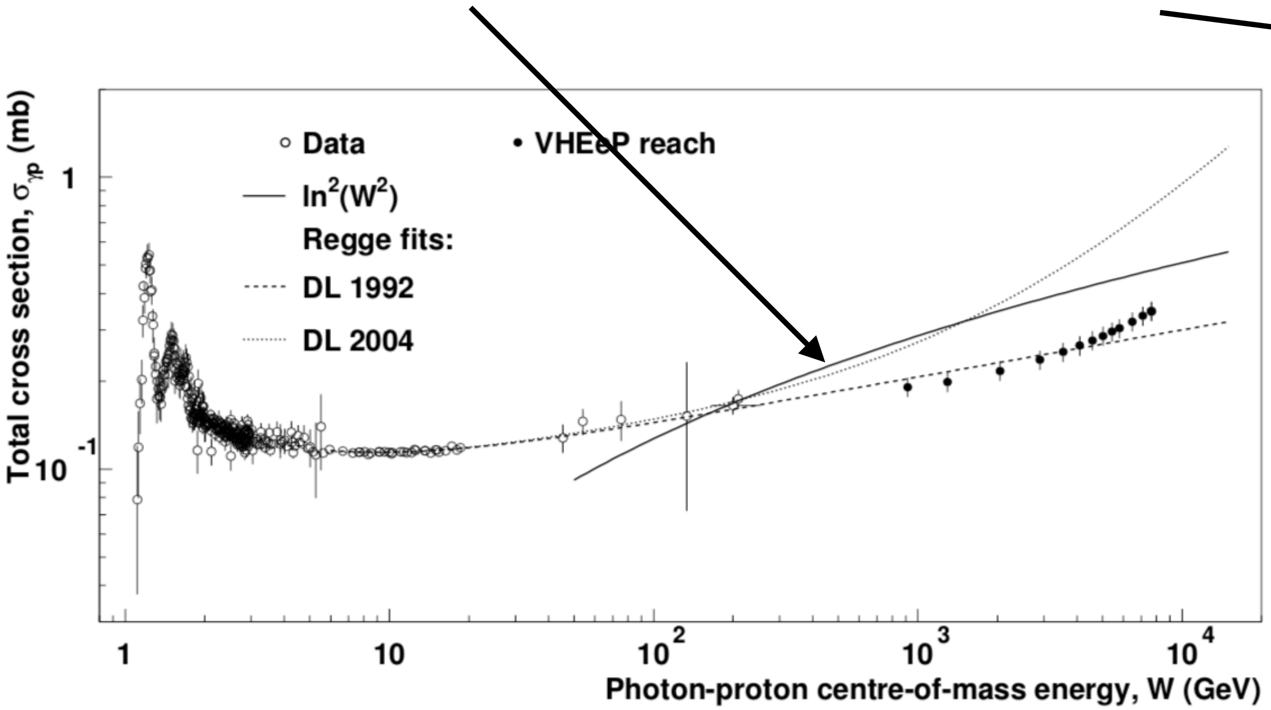
Relatively inexpensive first application of PWA ?

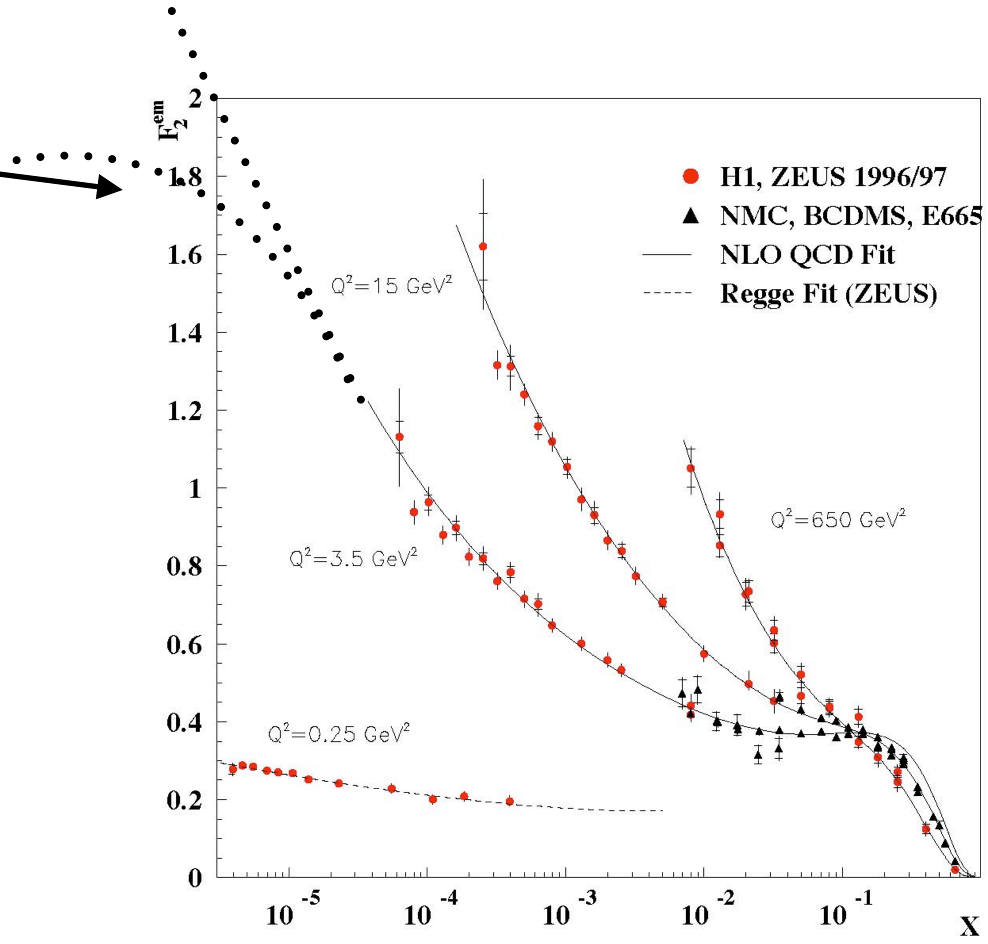
Physics: focus on QCD processes

large cross sections, growing with energy -> luminosity requirement modest

See Froissart behavior ?

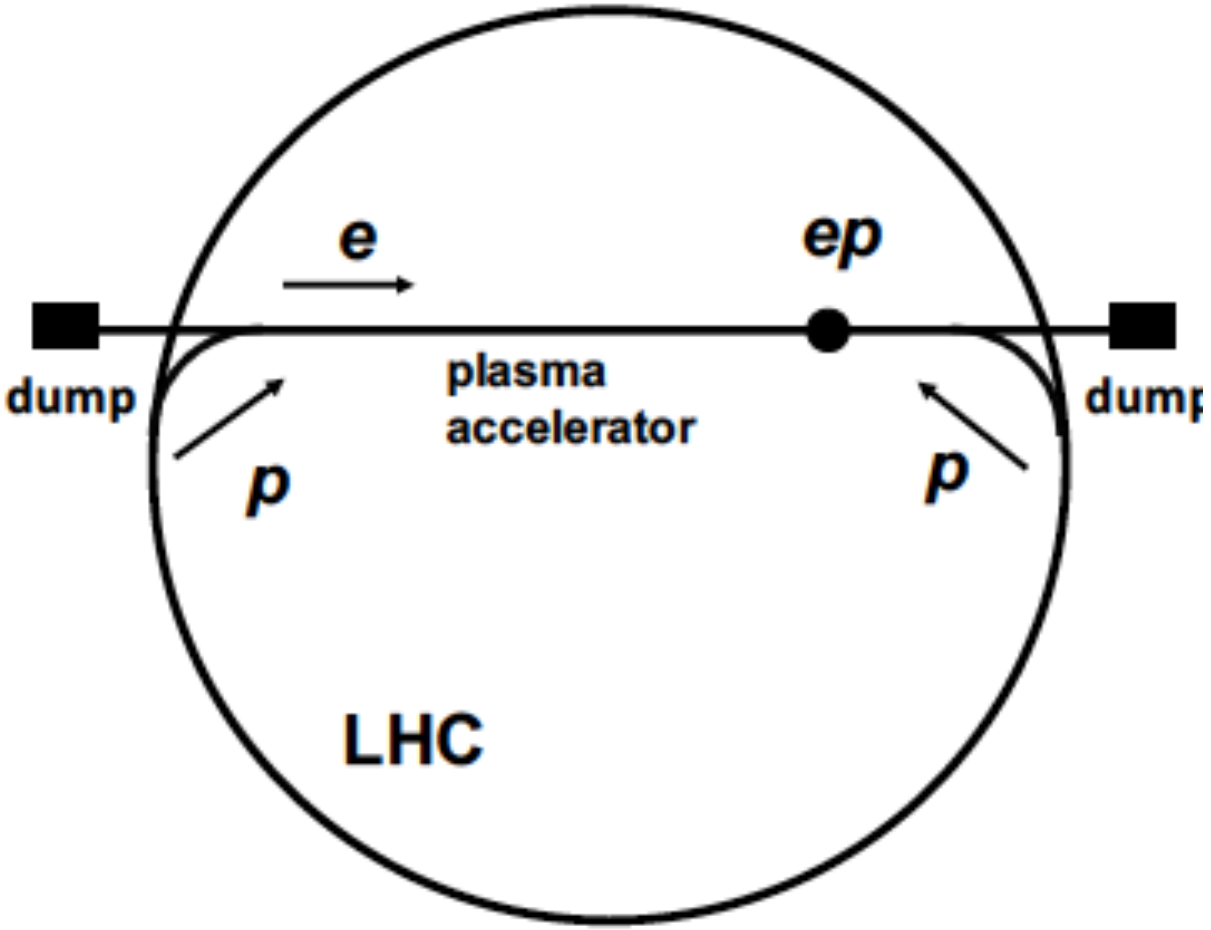
saturation?





VHEeP

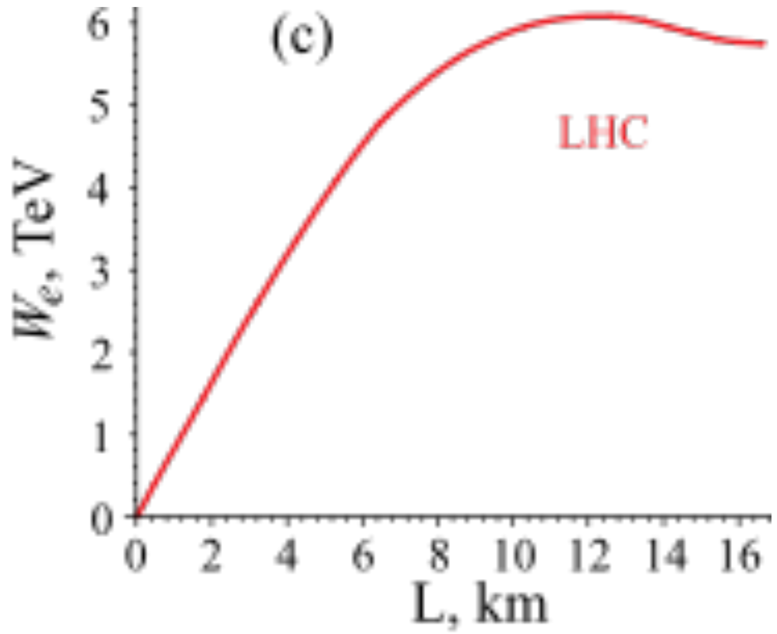
(Very High Energy electron-Proton collider)



One proton beam used for electron acceleration to then collide with other proton beam

Luminosity ~ $10^{28} - 10^{29}$ cm^{-2} s^{-1} gives ~ 1 pb−1 per year. Studies on achievable luminosity ongoing.

Electron energy from wakefield acceleration by LHC bunch

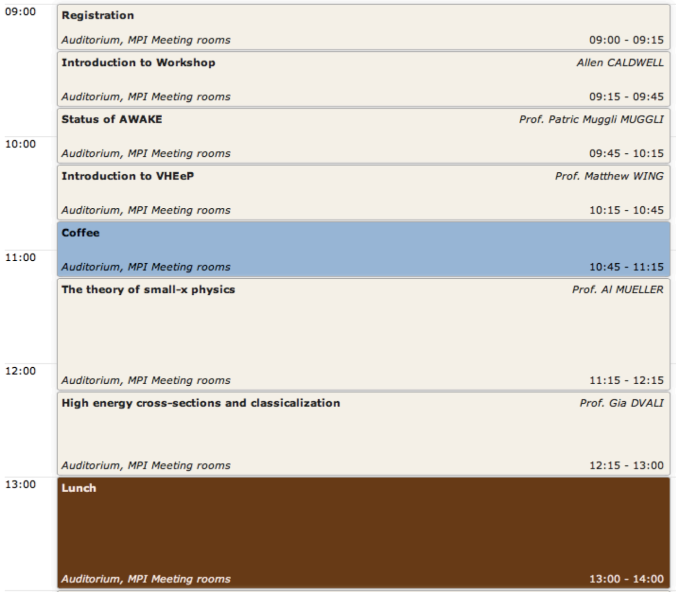


Choose E_e = 3 TeV as a baseline for a new collider with E_p = 7 TeV yields $\sqrt{s}$ = 9 TeV. Can vary.

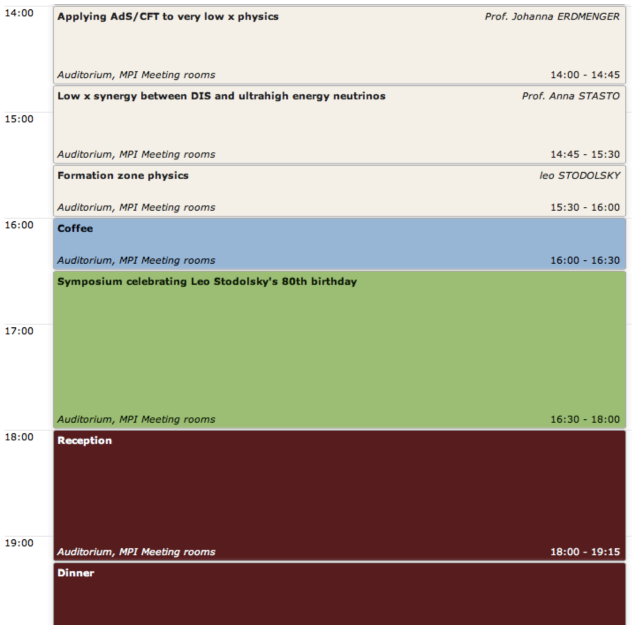
- Centre-of-mass energy ~30 higher than HERA.
- Reach in (high) Q^2 and (low) Bjorken x extended by ~1000 compared to HERA.
- Opens new physics perspectives

Prospects for a very high energy eP and eA collider

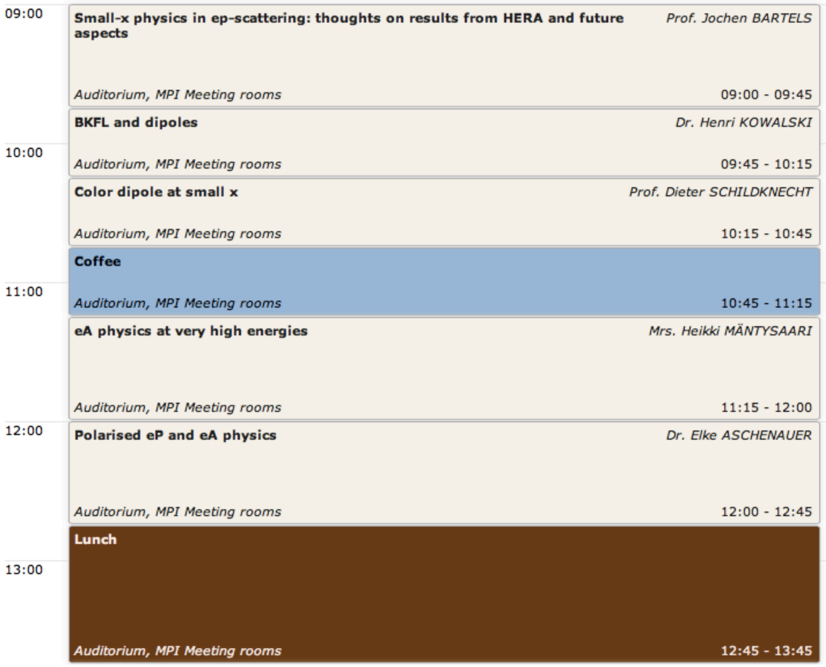
June 1,2 2017
Max Planck Institute for Physics



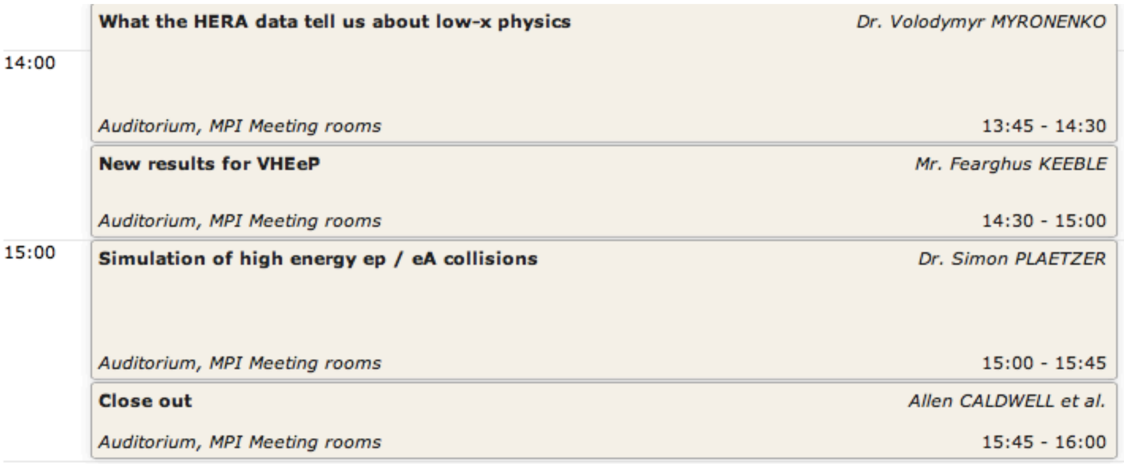
Event	Speaker	Location	Time
Registration		*Auditorium, MPI Meeting rooms*	09:00 - 09:15
Introduction to Workshop	*Allen CALDWELL*	*Auditorium, MPI Meeting rooms*	09:15 - 09:45
Status of AWAKE	*Prof. Patric Muggli MUGGLI*	*Auditorium, MPI Meeting rooms*	09:45 - 10:15
Introduction to VHEeP	*Prof. Matthew WING*	*Auditorium, MPI Meeting rooms*	10:15 - 10:45
Coffee		*Auditorium, MPI Meeting rooms*	10:45 - 11:15
The theory of small-x physics	*Prof. Al MUELLER*	*Auditorium, MPI Meeting rooms*	11:15 - 12:15
High energy cross-sections and classicalization	*Prof. Gia DVALI*	*Auditorium, MPI Meeting rooms*	12:15 - 13:00
Lunch		*Auditorium, MPI Meeting rooms*	13:00 - 14:00



Event	Speaker	Location	Time
Applying AdS/CFT to very low x physics	*Prof. Johanna ERDMENGER*	*Auditorium, MPI Meeting rooms*	14:00 - 14:45
Low x synergy between DIS and ultrahigh energy neutrinos	*Prof. Anna STASTO*	*Auditorium, MPI Meeting rooms*	14:45 - 15:30
Formation zone physics	*leo STODOLSKY*	*Auditorium, MPI Meeting rooms*	15:30 - 16:00
Coffee		*Auditorium, MPI Meeting rooms*	16:00 - 16:30
Symposium celebrating Leo Stodolsky's 80th birthday		*Auditorium, MPI Meeting rooms*	16:30 - 18:00
Reception		*Auditorium, MPI Meeting rooms*	18:00 - 19:15
Dinner			



Event	Speaker	Location	Time
Small-x physics in ep-scattering: thoughts on results from HERA and future aspects	*Prof. Jochen BARTELS*	*Auditorium, MPI Meeting rooms*	09:00 - 09:45
BKFL and dipoles	*Dr. Henri KOWALSKI*	*Auditorium, MPI Meeting rooms*	09:45 - 10:15
Color dipole at small x	*Prof. Dieter SCHILDKNECHT*	*Auditorium, MPI Meeting rooms*	10:15 - 10:45
Coffee		*Auditorium, MPI Meeting rooms*	10:45 - 11:15
eA physics at very high energies	*Mrs. Heikki MÄNTYSAARI*	*Auditorium, MPI Meeting rooms*	11:15 - 12:00
Polarised eP and eA physics	*Dr. Elke ASCHENAUER*	*Auditorium, MPI Meeting rooms*	12:00 - 12:45
Lunch		*Auditorium, MPI Meeting rooms*	12:45 - 13:45



Event	Speaker	Location	Time
What the HERA data tell us about low-x physics	*Dr. Volodymyr MYRONENKO*	*Auditorium, MPI Meeting rooms*	13:45 - 14:30
New results for VHEeP	*Mr. Fearghus KEEBLE*	*Auditorium, MPI Meeting rooms*	14:30 - 15:00
Simulation of high energy ep / eA collisions	*Dr. Simon PLAETZER*	*Auditorium, MPI Meeting rooms*	15:00 - 15:45
Close out	*Allen CALDWELL et al.*	*Auditorium, MPI Meeting rooms*	15:45 - 16:00

Mini-workshop on QCD and Gravity
December 12,13
Max Planck Institute for Physics

2018

Wednesday, December 12

14:15-15:15	Raju Venugopalan ‘A many-body theory of QCD in the Regge limit’
15:30-16:00	Eran Palti ‘News on Swampland’
16:00-16:30	Stephan Stieberger ‘QCD meets Gravity’
16:30-17:00	Johanna Erdmenger ‘AdS/CFT and very small x’
17:00-17:30	Angnis Schmidt-May ‘News from bimetric gravity’
17:30-18:30	Discussion time
19:00-	Dinner somewhere

Thursday, December 13

9:00-10:00	Gia Dvali et al ‘Proof of the Axion?’
10:00-10:30	Discussion time
10:30-11:00	Henri Kowalski ‘BFKL analysis of HERA data’
11:00-11:30	Agustin Sabio Vera ‘The Regge limit in QCD, SUSY and gravity’
12:00-14:00	lunch and discussion

2 workshops to discuss novel physics with very high energy eP/eA collider.

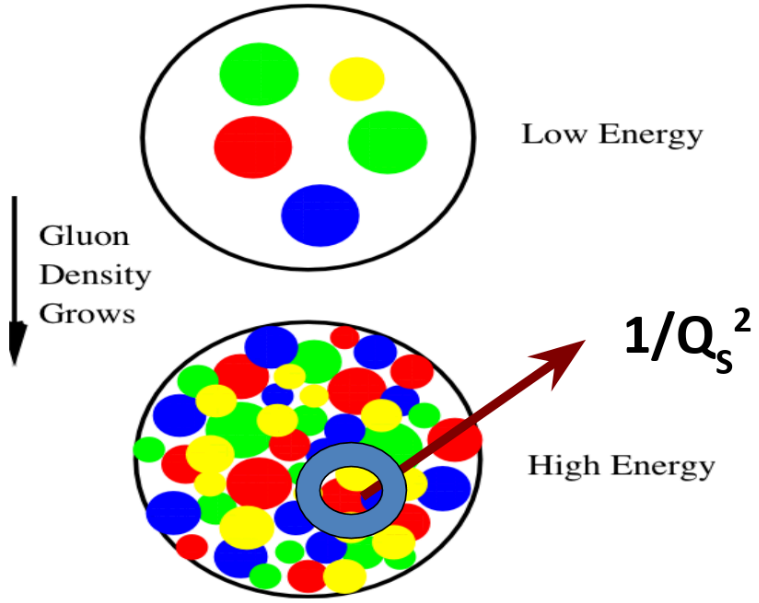
Second - focus on relation between QCD and gravity.

Small-x physics and color confinement. One of the key unsolved questions in physics.

How?

R. Venugopalan, Mini-workshop on QCD and Gravity
December 12,13 Max Planck Institute for Physics

The boosted proton viewed head-on

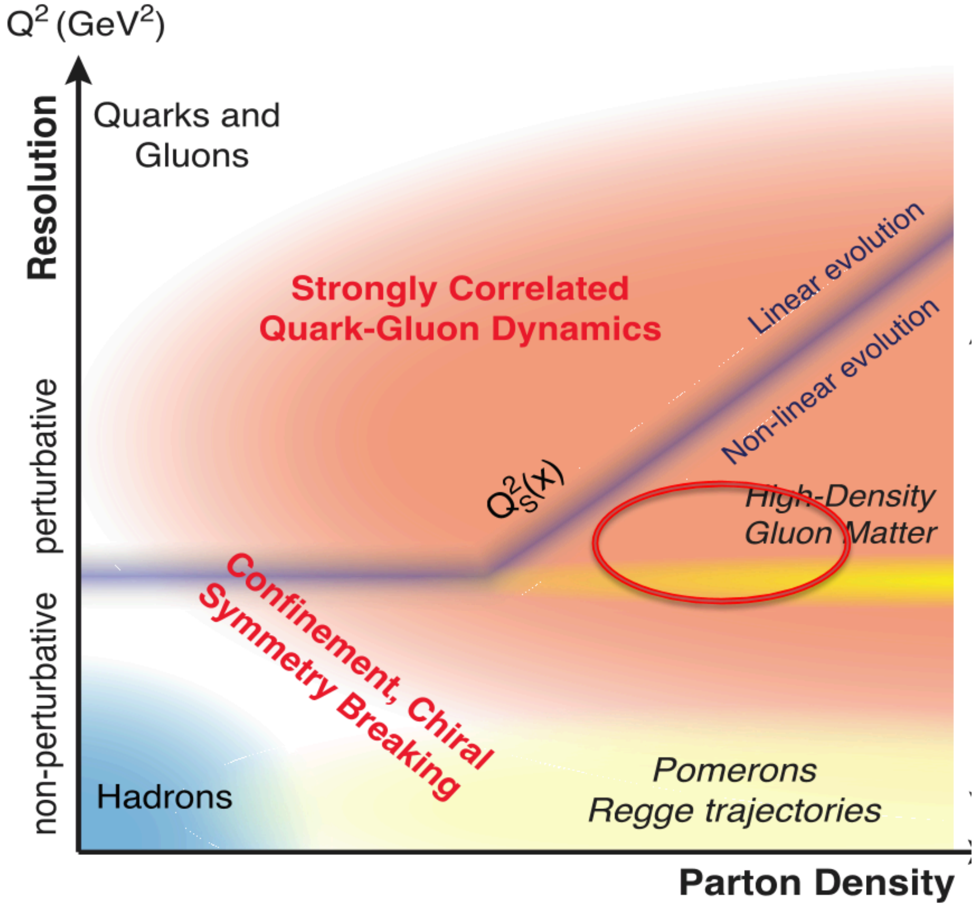


When occupancies become large ~ $1/\alpha_S$, gluons resist further close packing by recombining and screening their color charges -- leading to gluon saturation

Emergent semi-hard scale dynamical scale $Q_S(x) >> \Lambda_{QCD}$

Asymptotic freedom! $\alpha_S(Q_S) << 1$ provides weak coupling window into infrared

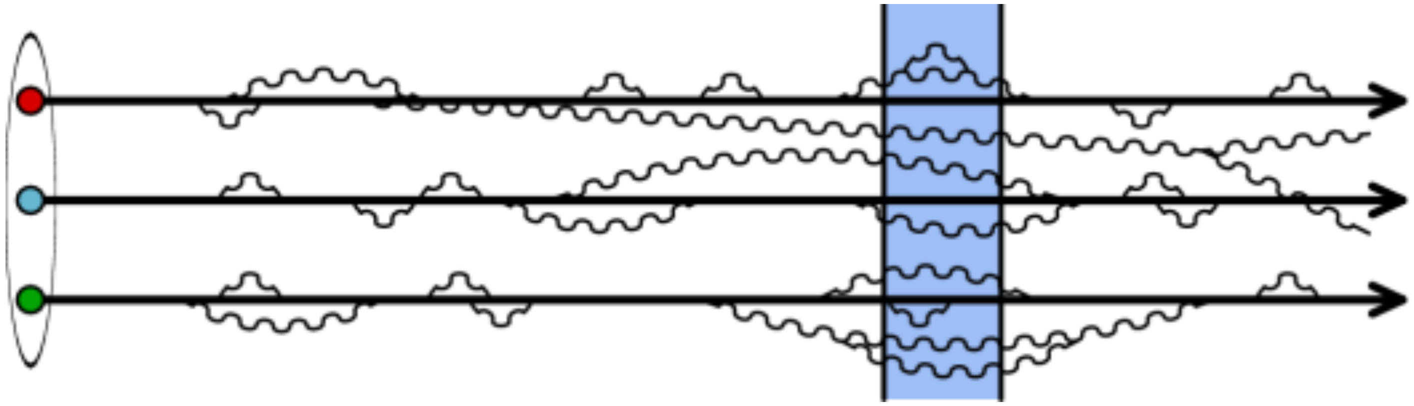
Saturation in the QCD landscape



From the physics we know - these are the strongest fields that can be achieved in nature

New: perturbative approach to infrared physics! Relevant equations very similar to fundamental statistical mechanics equations. Strong overlap with quantum description of black holes.

At high energy, see short-lived fluctuations due to time dilation



Courtesy: **R. Venugopalan**

Markovian process leads to power law growth of gluon distribution at small x

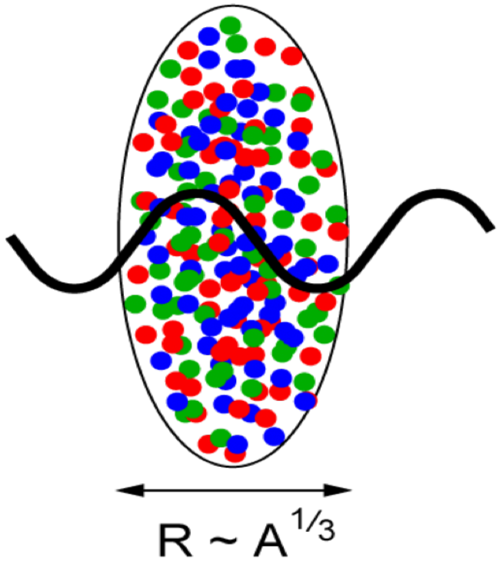
Violates Froissart bound asymptotically

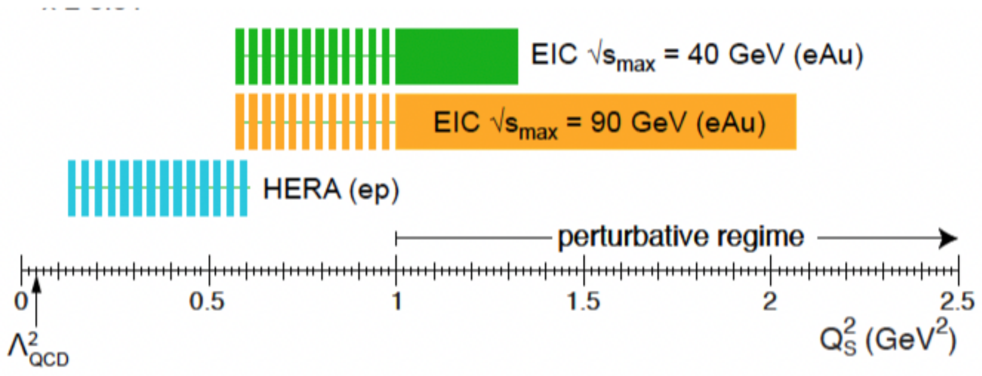
A fascinating equilibrium of splitting and recombination should eventually result. It is a considerable theoretical challenge to calculate this equilibrium in detail…

F. Wilczek, Nature (1999)

"oomph factor" from Nuclei

$Q_S^2 \sim A^{1/3}$ since "wee" gluons couple coherently for $x << A^{-1/3}$





VHEeP

with VHEeP and eA, we will be in a region where the saturation scale is well into the perturbative region. Allows detailed probing of this new physics: high density & weak coupling !

QCD and Gravity: more than math ?

Consider: the visible mass is largely due to baryons. The mass of baryons is largely due to QCD (not the Higgs mechanism). Gravity couples to mass ....

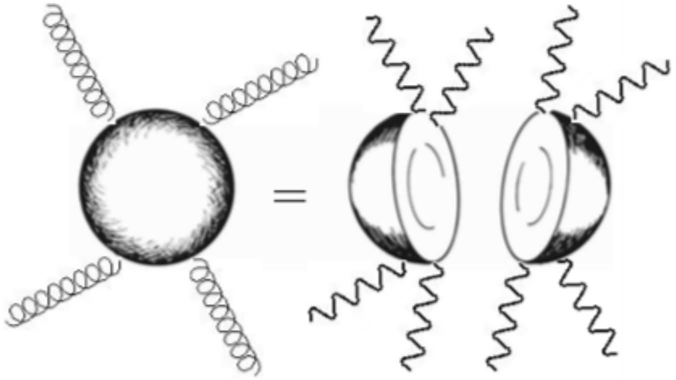
S. Stieberger, Mini-workshop on QCD and Gravity December 12,13 Max Planck Institute for Physics

Can gravity be described by YM-theory ?

do we see some generic or unifying structures in scattering amplitudes?

G : spin 2 $\qquad\qquad$ γ : spin 1

graviton as composite particle ?



Alert: graviton cannot be a composite particle in a relativistic quantum field theory (Weinberg, Witten)

proof relies on the construction of a conserved and Lorentz-covariant stress tensor

$$T^{\mu\nu}(x) = (-g)^{-1/2}\,\frac{\partial}{\partial g_{\mu\nu}(x)}\,S[g]$$

theorem holds for any known renormalizable field-theory, e.g. QCD

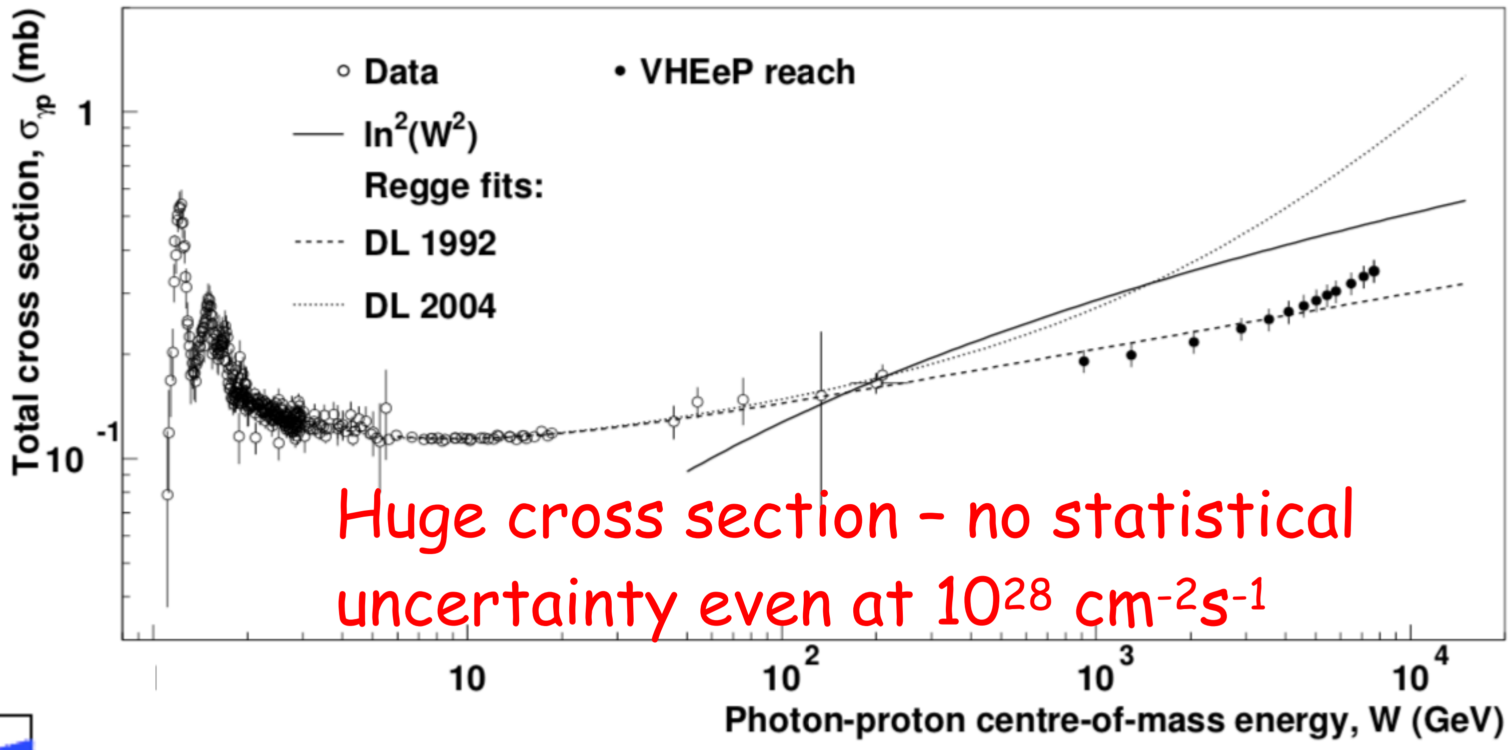
However there are many ways out:
massive gravity, conformal field theory, string theory, ...

Concluding remarks

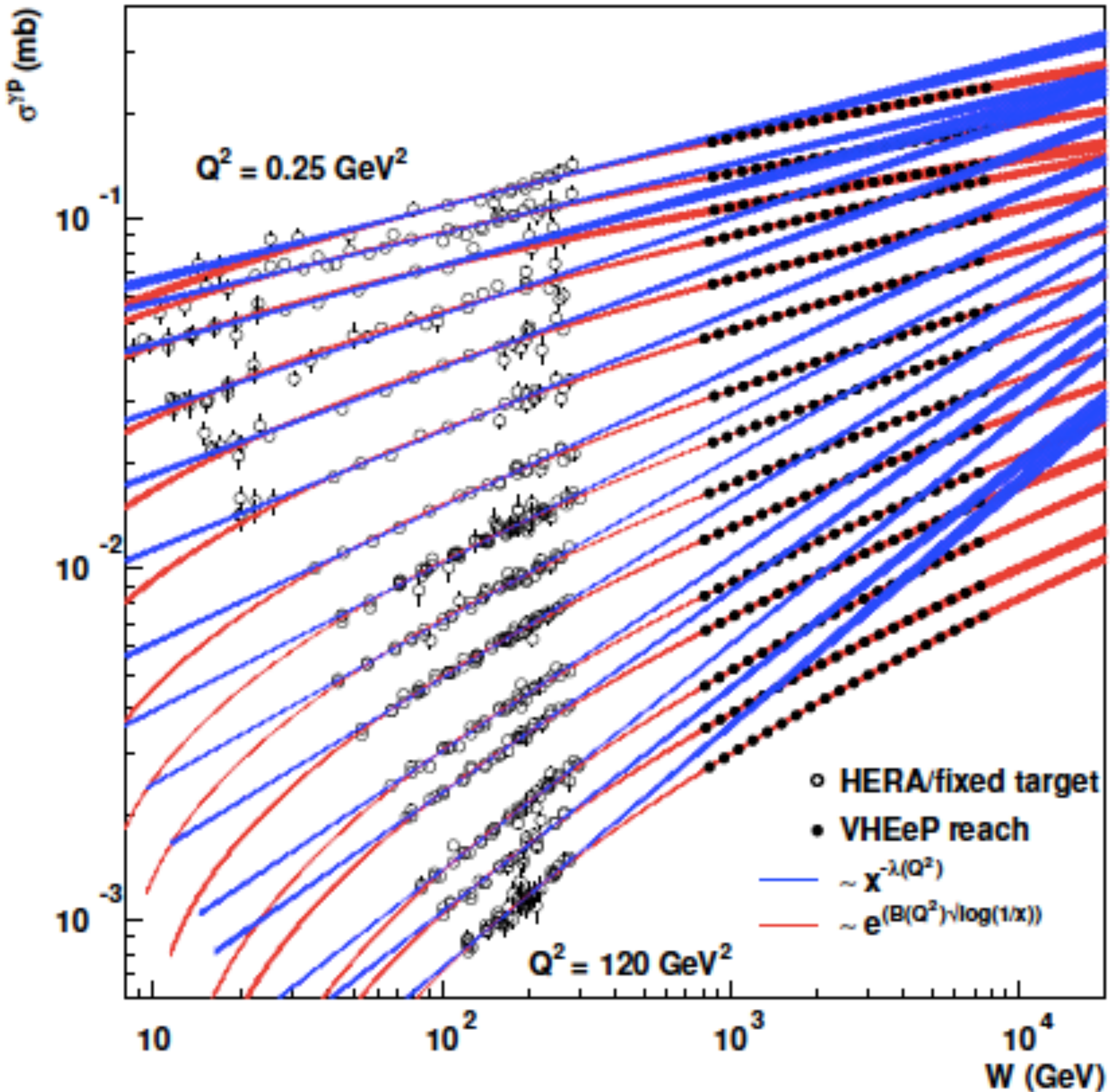
- growing set of **interconnections** between open & closed amplitudes with gauge theory and supergravity amplitudes
- indication for the existence of some **gauge structure** in **quantum gravity**

What will we measure and why will it help?

Total photoproduction cross section – energy dependence ?
See approach to Froissart bound ?
Impact on cosmic ray physics

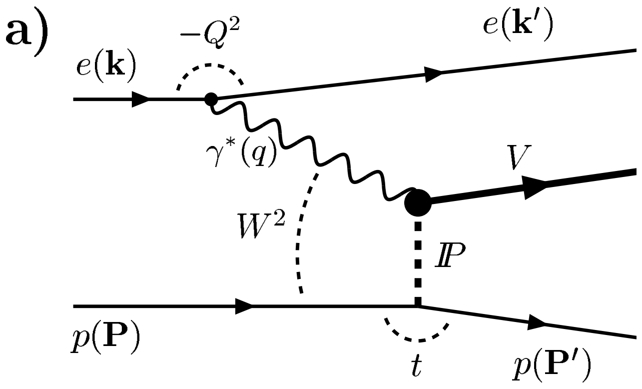


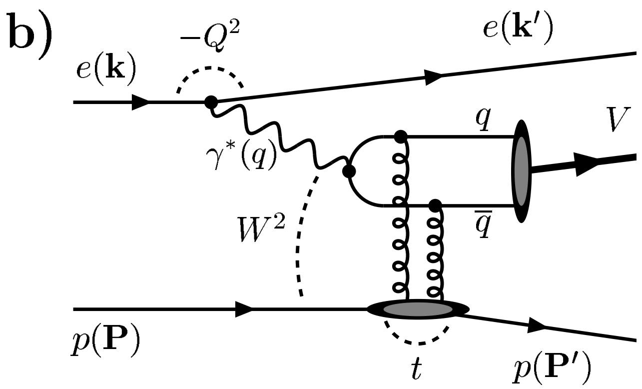
Huge cross section – no statistical uncertainty even at 10^{28} cm^{-2}s^{-1}

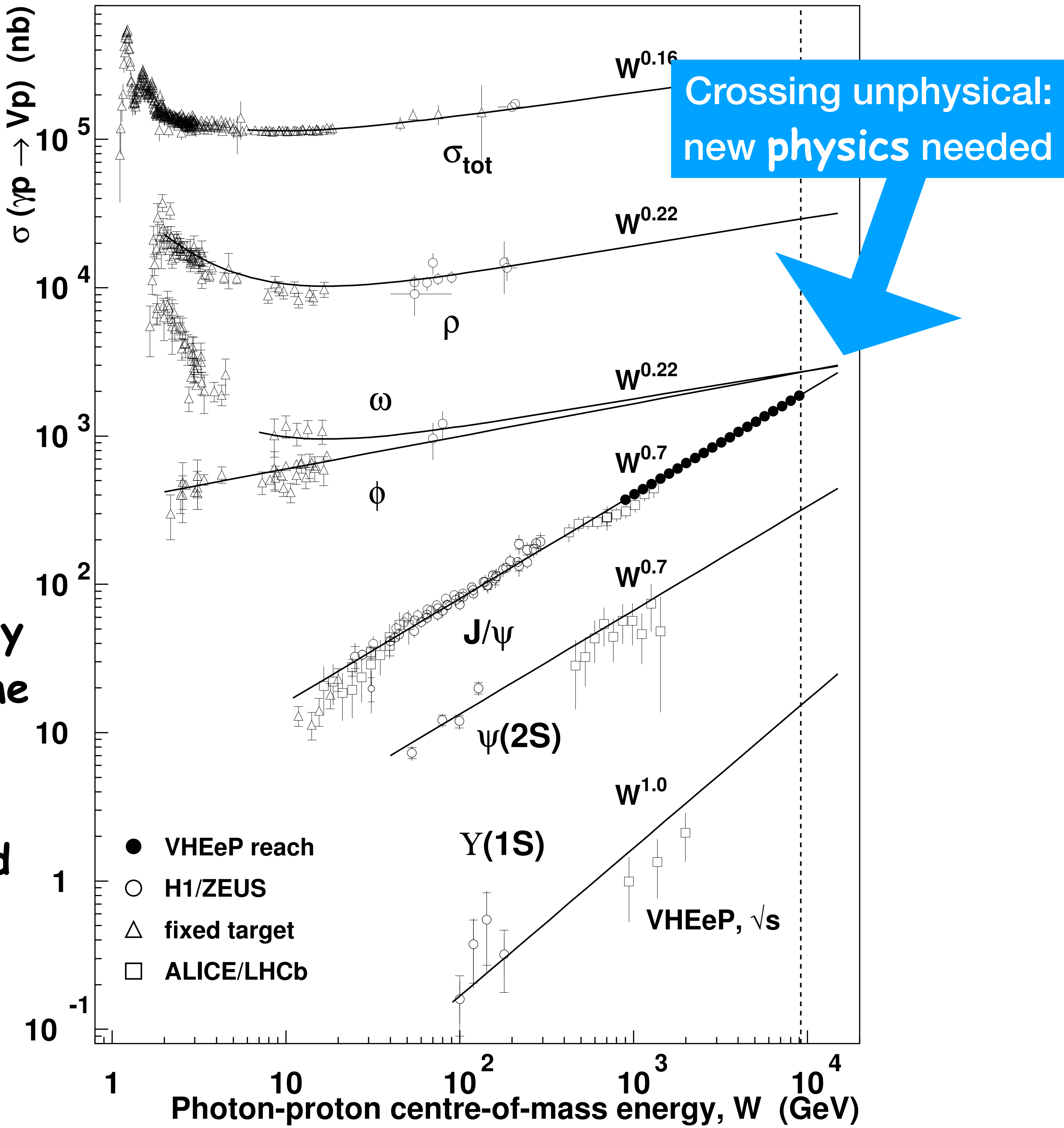


Virtual photon cross section: unphysical extrapolation of cross sections -> observation of saturation of parton densities ?

With the three orders of magnitude extension in the range at small-x, expect to see signs of the fundamental saturated regime.







Crossing unphysical:
new **physics** needed

Exclusive processes:

Sensitive to square of gluon density

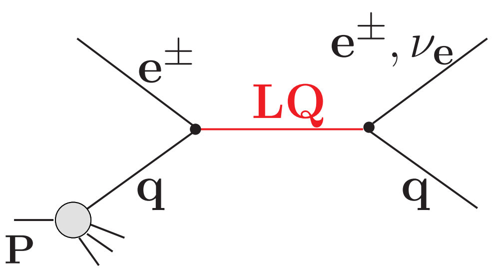
Early signs of new saturated regime

Good opportunity to see the fundamental high-energy saturated state!

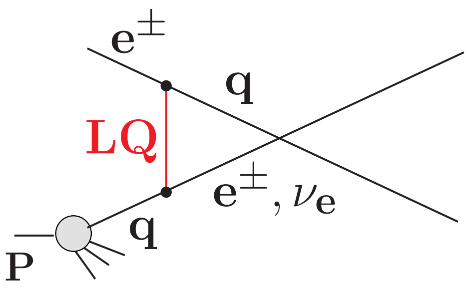
eA possibility will make this physics even more dramatic "oomph"-factor again

At high energy - leptoquarks appear ?

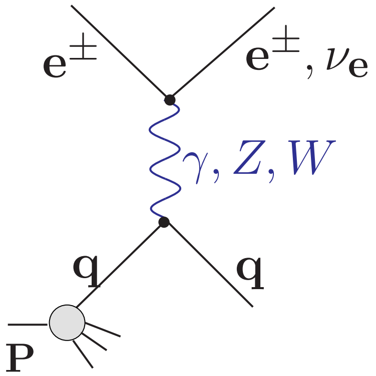
tailor-made for eP Collider



(a)

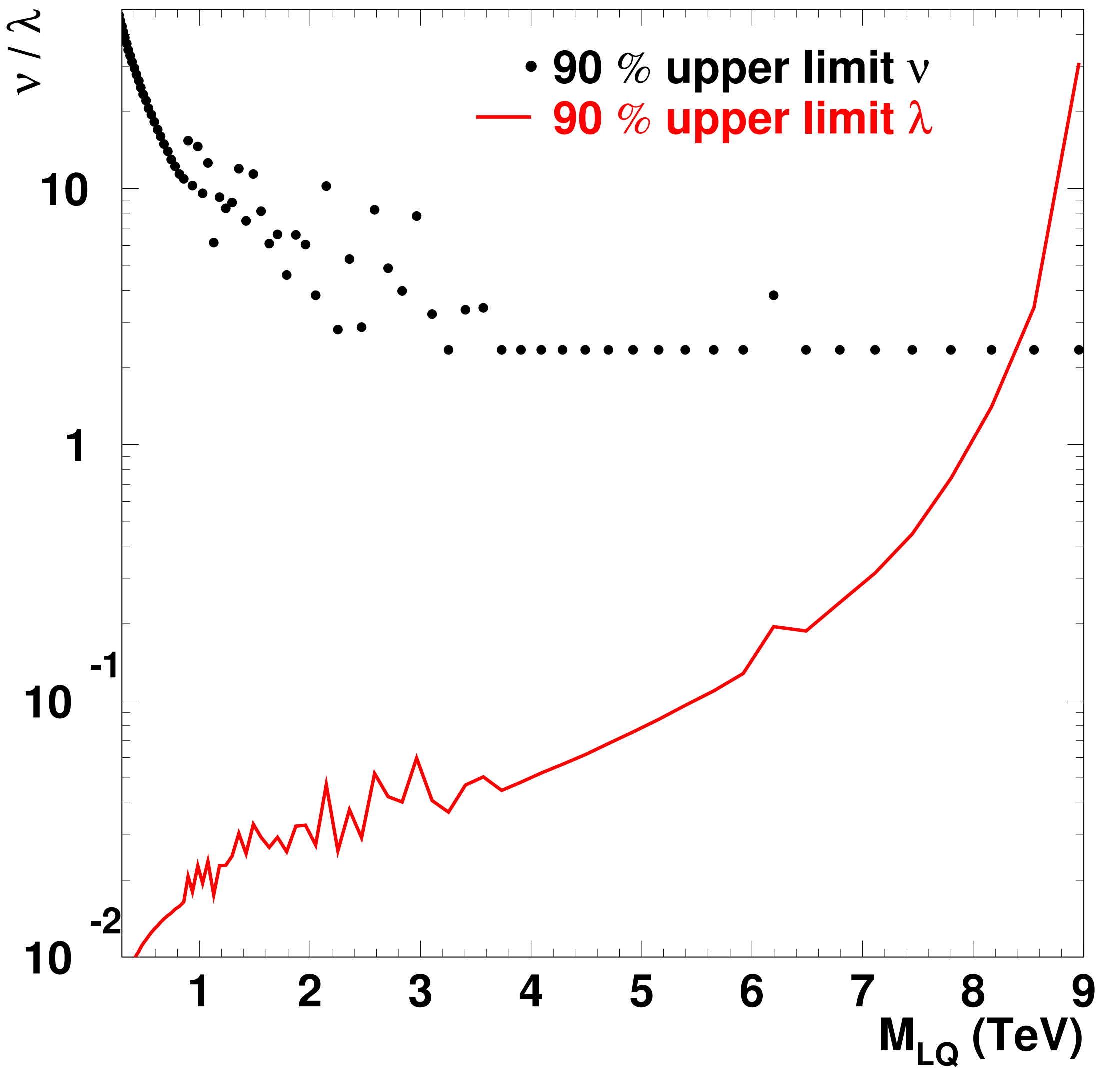


(b)

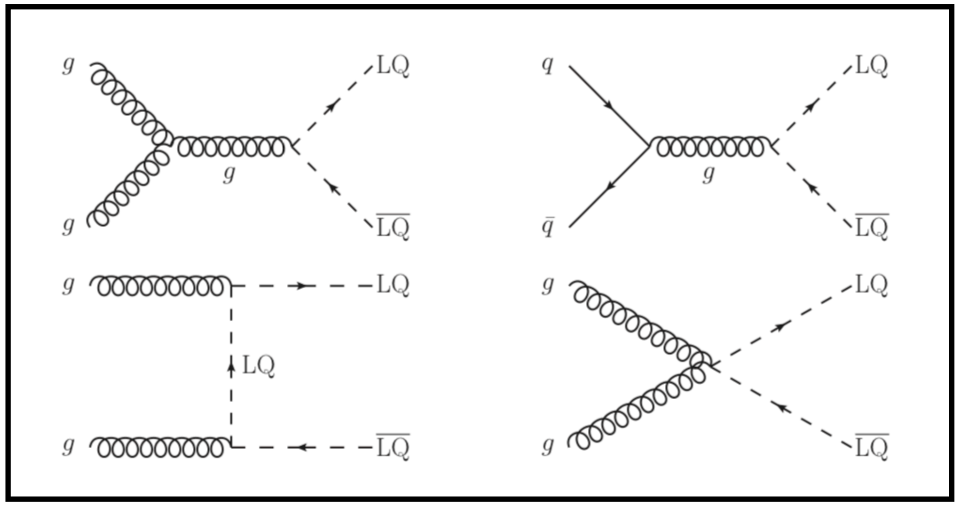


(c)

Simulation study: 100 pb^{-1}



Sensitivity well beyond expected reach of LHC



High energy electron-proton and electron-ion collider

new conceptual breakthroughs, (probably) not new particles

- where mass comes from (saturated high energy state of QCD matter).
- approach color confinement via large saturation scale
- connections to gravity may become apparent
- and lot’s of ‘bread-and-butter’ physics