

# *QCD Dynamics*

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*CCSG Open Symposium 31/1/06*

*LAL, Orsay, Paris*

# QCD Dynamics

- Hadronic structure at low  $Q^2$
- Deep Inelastic Scattering studies
- High  $Q^2$  processes
- (*Hadron spectroscopy?*)

# *Fundamental questions in QCD*

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*Need to be answered before we can say we really understand the strong interaction*



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*Need to be answered in order to do the best physics with hadron (or lepton?) beams, CP physics, neutrinoless double beta decay, astrophysics...*

# *Operational questions in QCD*

**I have interpreted my brief as being to discuss the QCD-driven aspects of particle physics and how they may fit in a European strategy.**

**I am hoping that the need to understand QCD to do physics at LHC is already well known.**

# *How, when and where might these questions be addressed?*

- **A whistle-stop tour of realities, hopes & dreams**

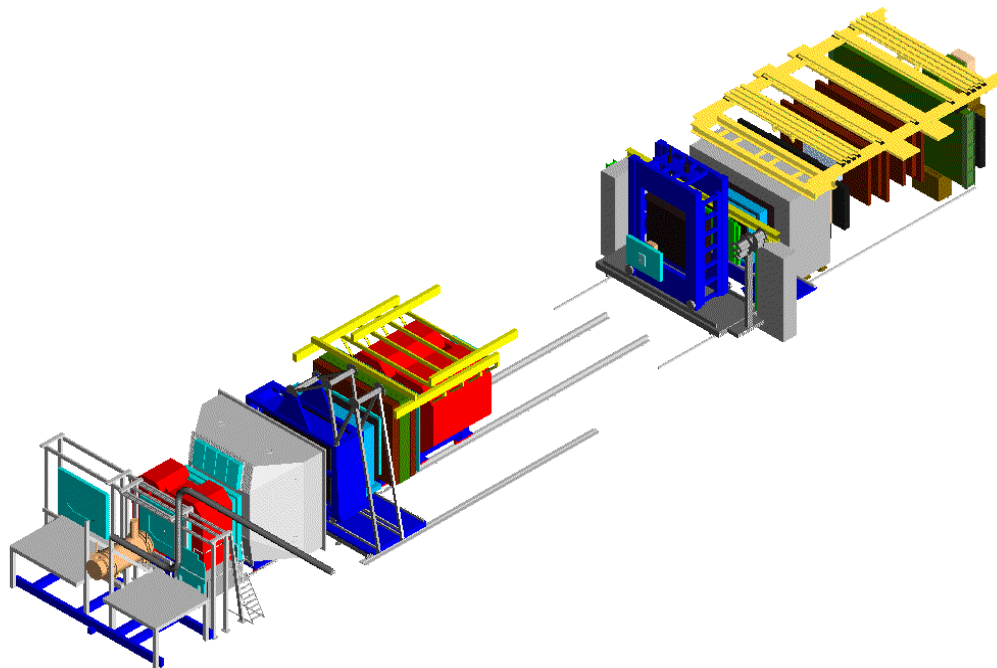


# Current facilities

- **HERA II**
  - *DESY, Hamburg*
  - *920 GeV p vs (polarized) 27.6 GeV e $\pm$  (320 GeV CME)*
  - *H1 and ZEUS, general purpose detectors*
  - *HERMES, polarized leptons vs polarized fixed target*
  - *Running until 2007, after which PETRA is given over to synchrotron light...*



# Current facilities



- **SPS**
  - *CERN, Geneva*
  - *COMPASS. 100-200 GeV polarized muon beam (and secondary hadron beams) vs fixed targets.*
  - *Running (on and off) 2001-2010(?)*
  - *See contribution from Bertini et al*

# Future facilities

- **LHC**
  - *ATLAS & CMS/TOTEM*
  - *LHCb*
  - *FP420 (Proposed proton tagging 420m from ATLAS and/or CMS)*
  - *ALICE (next talk)*



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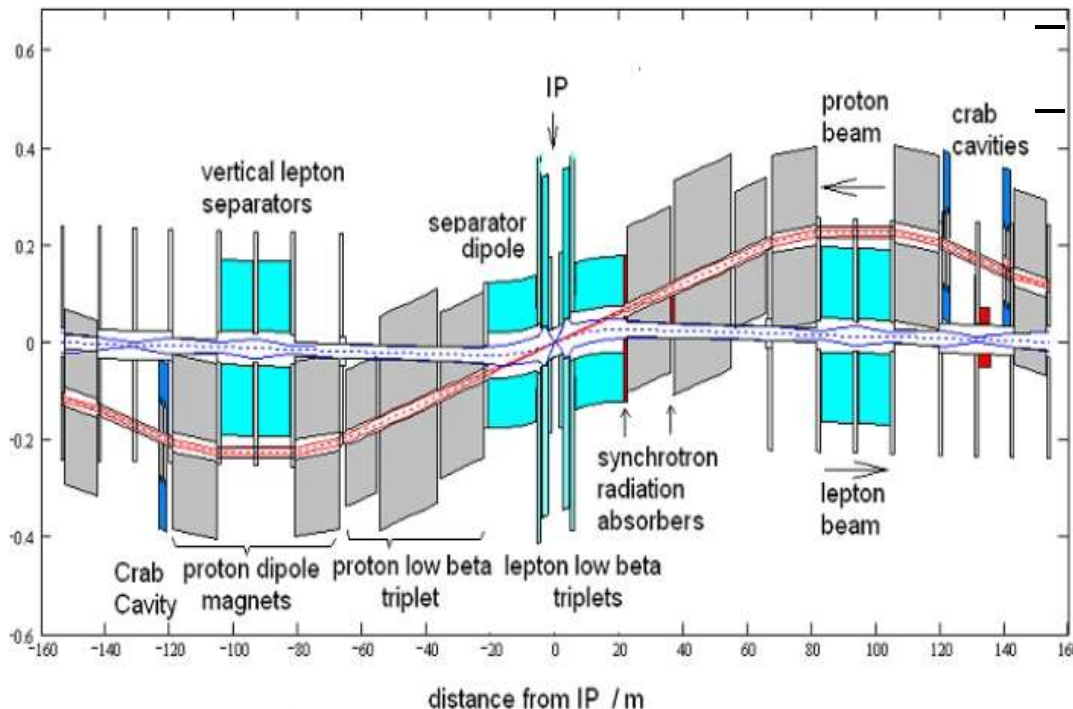
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- **eRHIC**
  - *250 GeV protons vs 10 GeV e+/-, both beams polarized.*
  - *Could also do eA.*
- **ILC and CLIC**
- **Experiments at High Intensity Neutrino beams**
  - *NUMI (Minerva), T2K, Neutrino factory...*

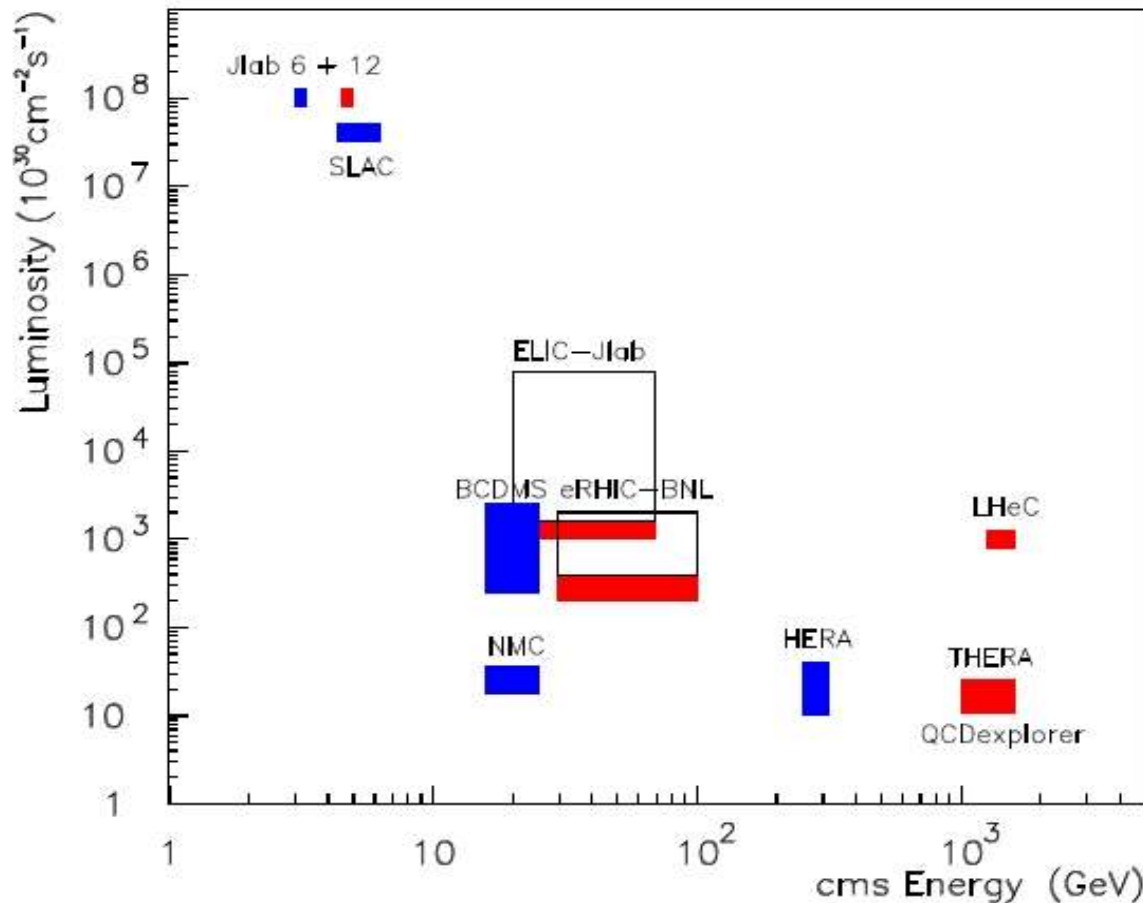
# Proposed and/or possible facilities

- **LHeC**
  - CERN, Geneva
  - 7 TeV protons vs 70 GeV e<sup>±</sup>
  - High luminosity ( $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ )
  - see contribution from *Dainton et al*

QCD Dynamics



# Facilities for Deep Inelastic Scattering





***So how far could we get  
with those questions?***

# *How does confinement work?*

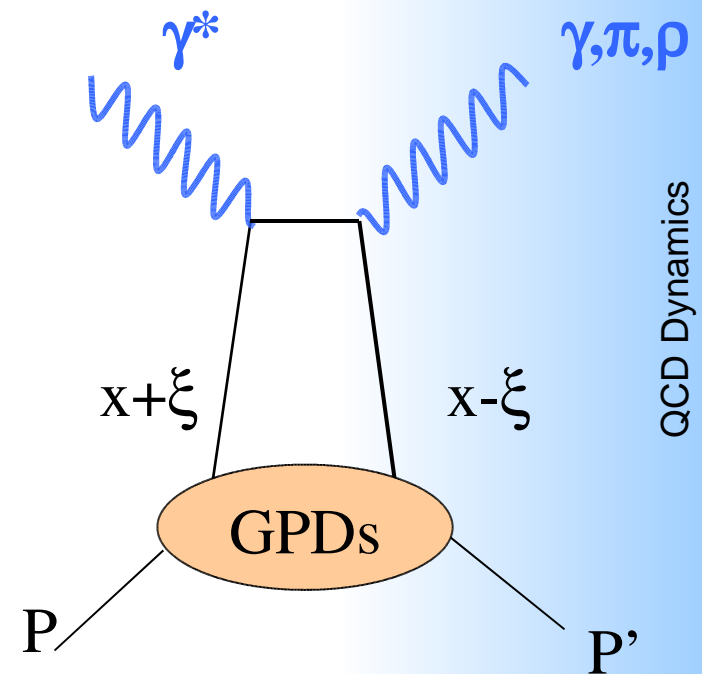
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## How does confinement work?

- **Hadron spectroscopy**
  - **COMPASS, e.g. double charmed baryons “molecule-like” excitation spectrum**
  - **Glueball spectrum, 1.5-2.5 GeV, and hybrid mesons.**
  - **A busy past few years with new states coming (and in some cases going) at *CLEO, BES, Belle, Babar, Daphne, HERA...* (see talk by A. Hocker)**
  - **Important area for validating lattice calculations.**

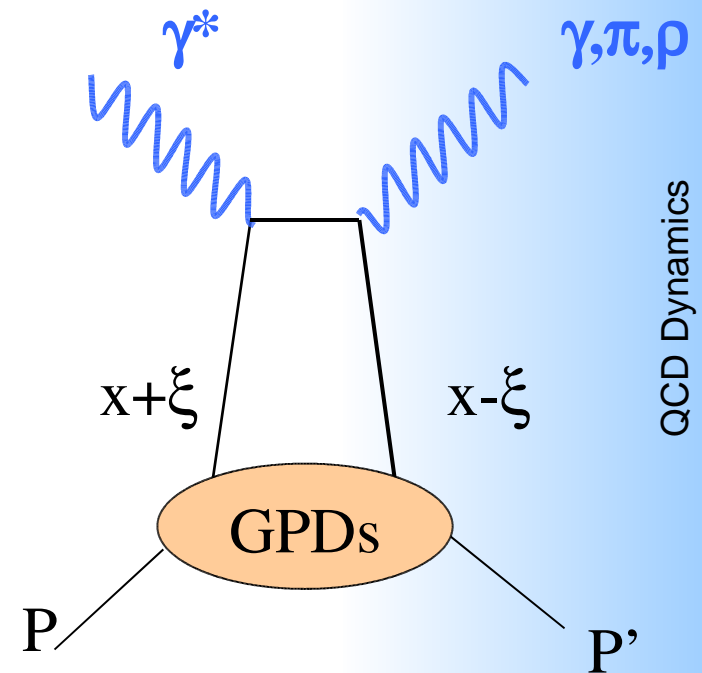
# How does confinement work?

- Generalised parton distributions (GPD)



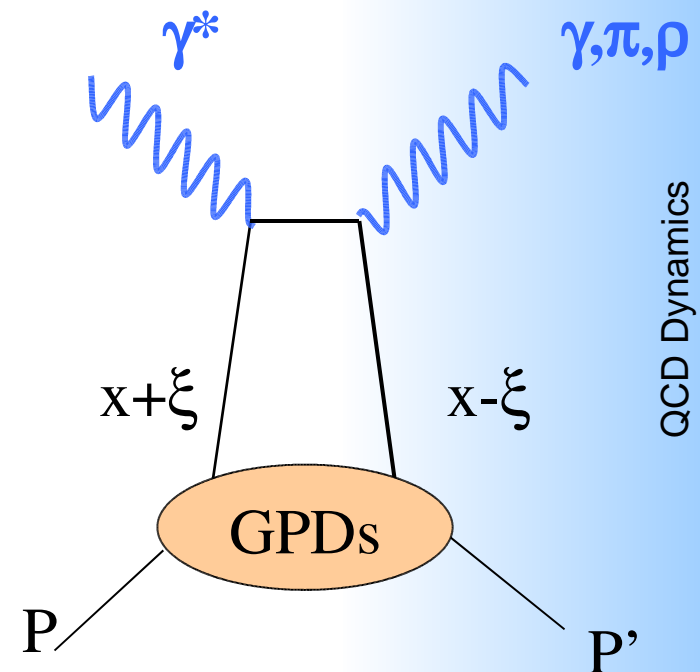
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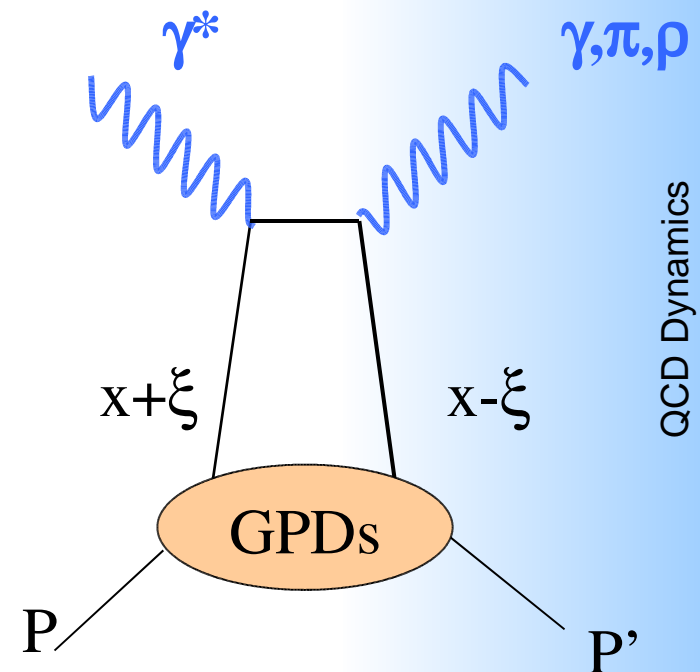
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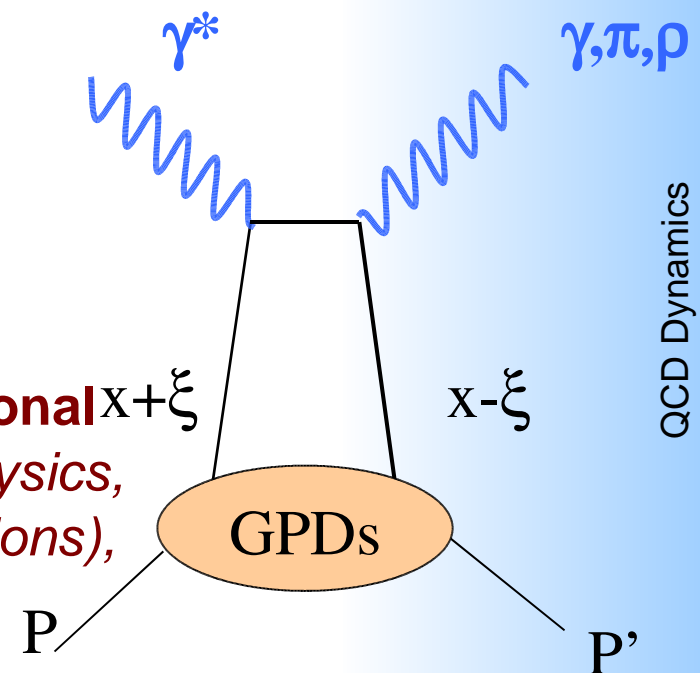
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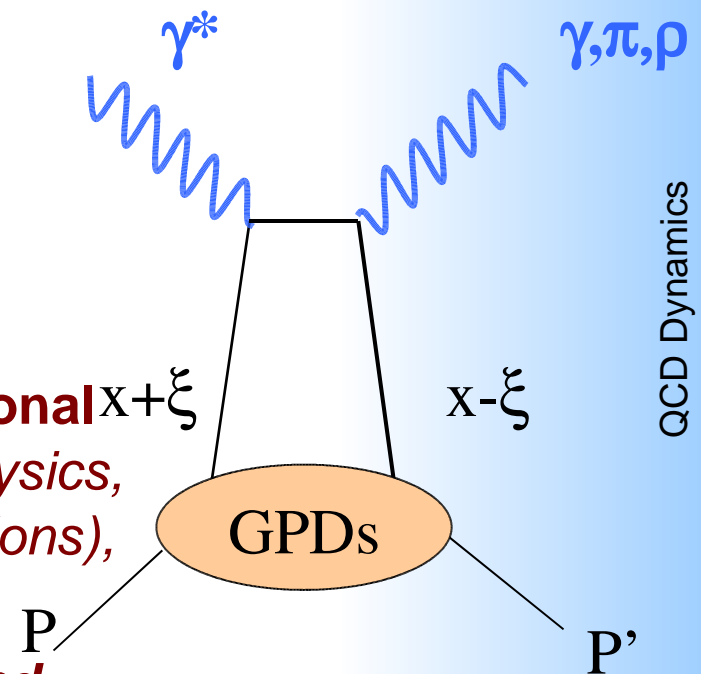
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  - **COMPASS (intermediate  $x$ ) H1, ZEUS and HERMES, FP420, LheC (low  $x$ ), maybe MINERVA.**



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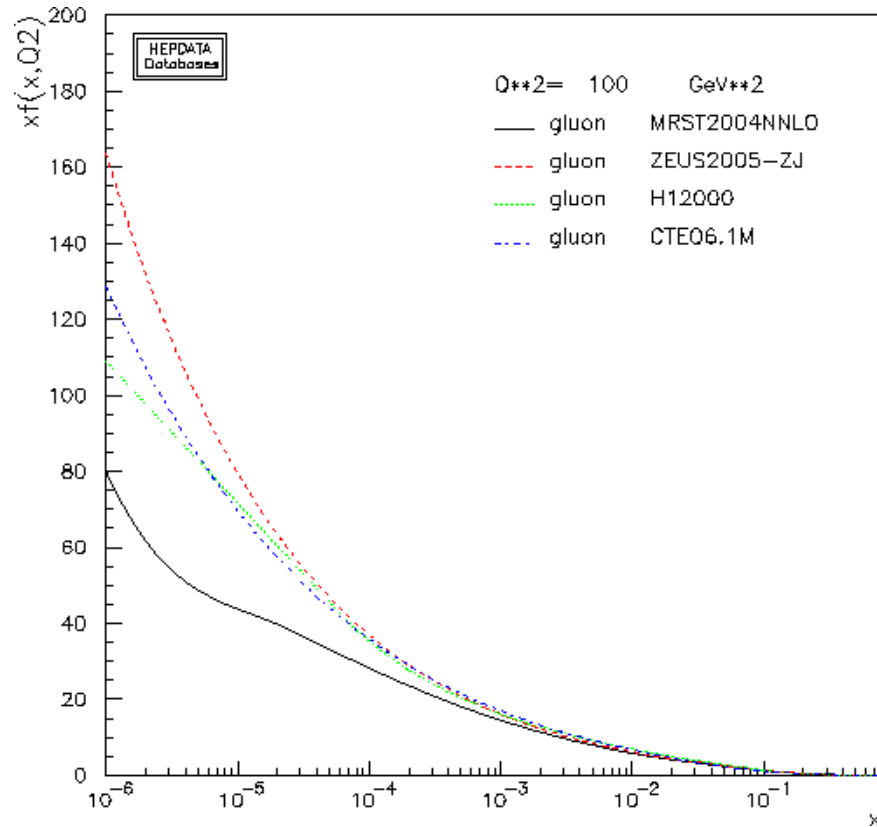
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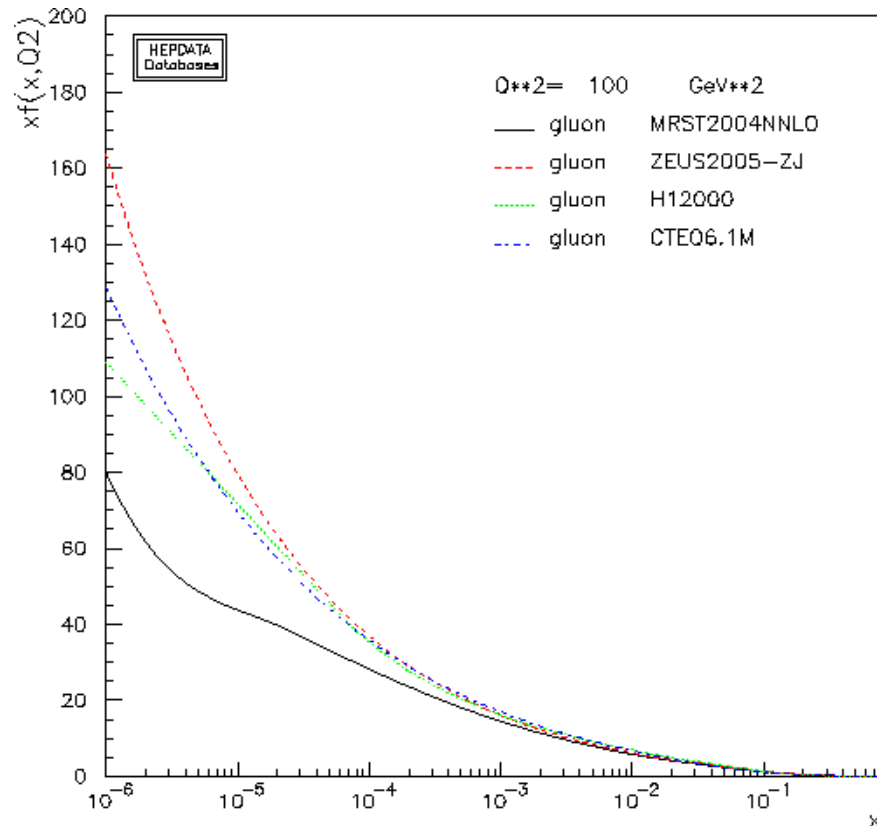
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- **NB Collins fragmentation function from Belle.**

# What happens at high quark and gluon density?

- **Gluon dynamics dominate the mass of the proton, and hence the visible mass of the universe.**

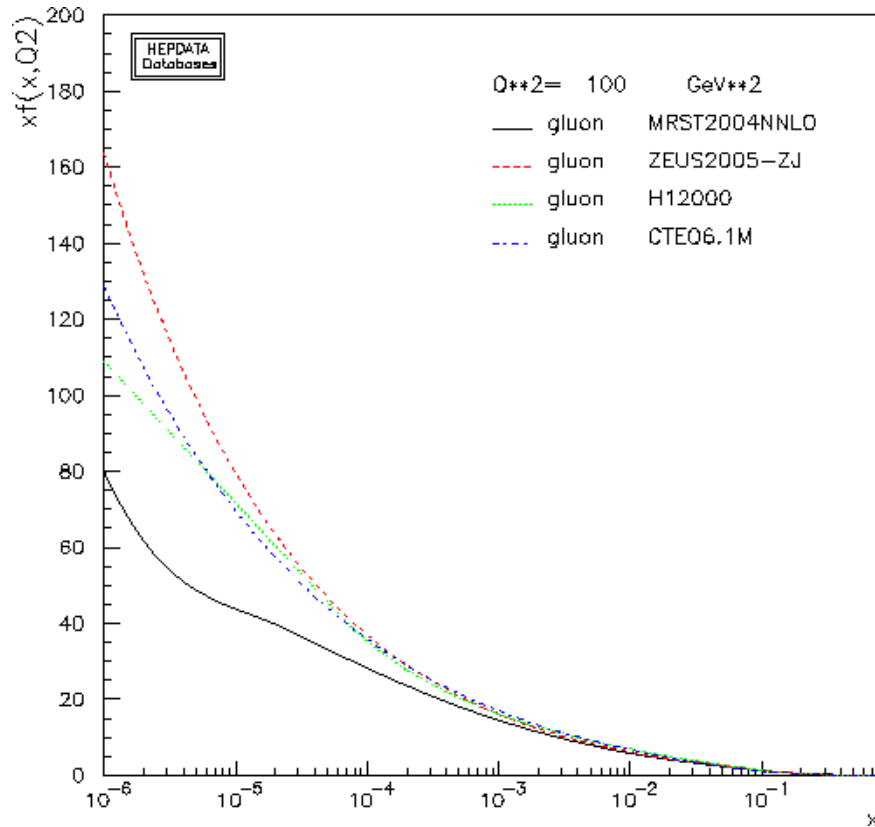


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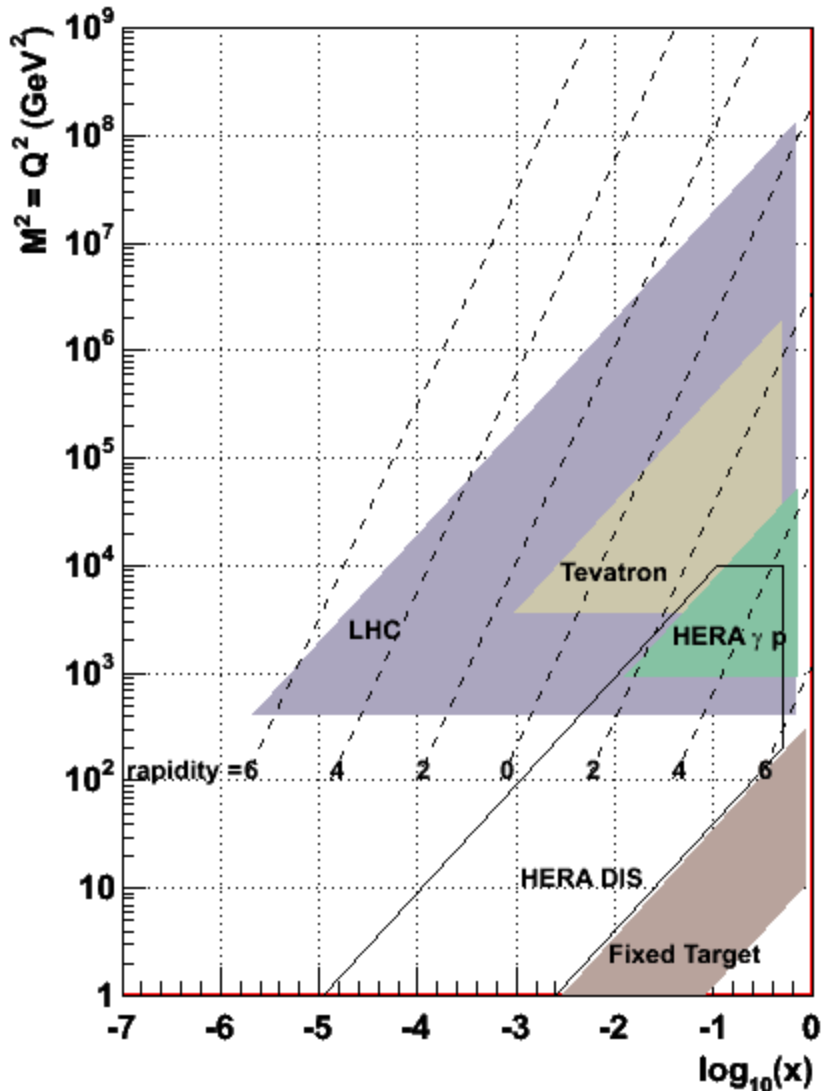
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- **Possible new state of matter at high density and low coupling - “Colour Glass Condensate”.**

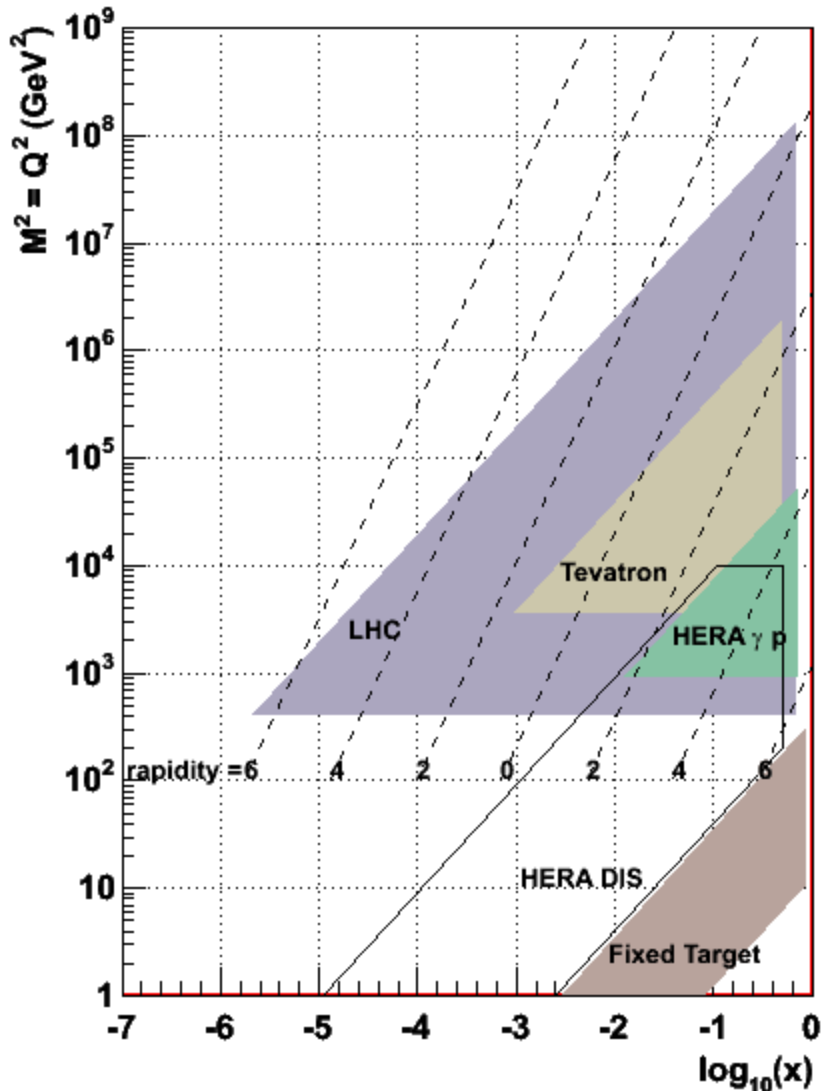


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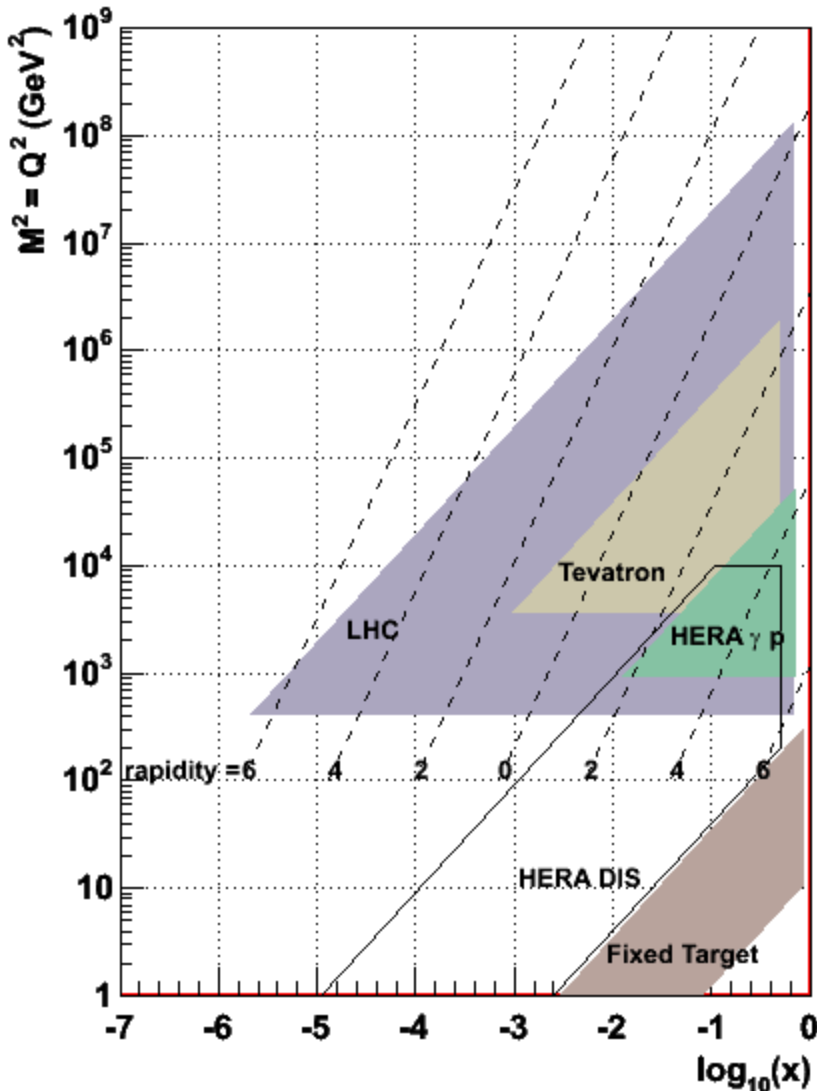
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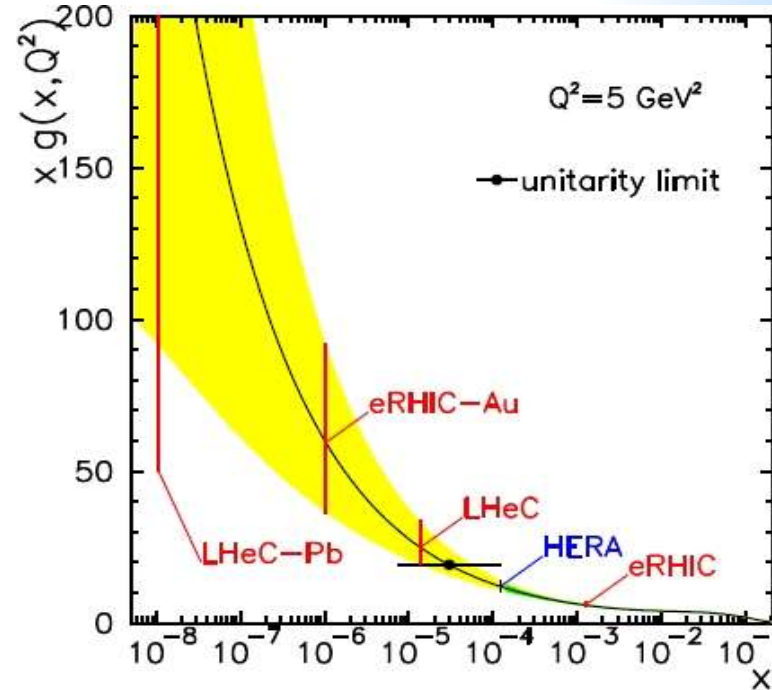


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# What happens at high quark and gluon density?



- LHC will be sensitive to this physics.
- Important data from HERA II
- eRHIC and LHeC could make excellent measurements



## *What happens at high quark and gluon density?*

- **“Unintegrated” partons densities needed at low  $x$** 
  - $F(x, Q^2, k_T)$
  - **Correlated with transverse spin? With radial position in proton?**

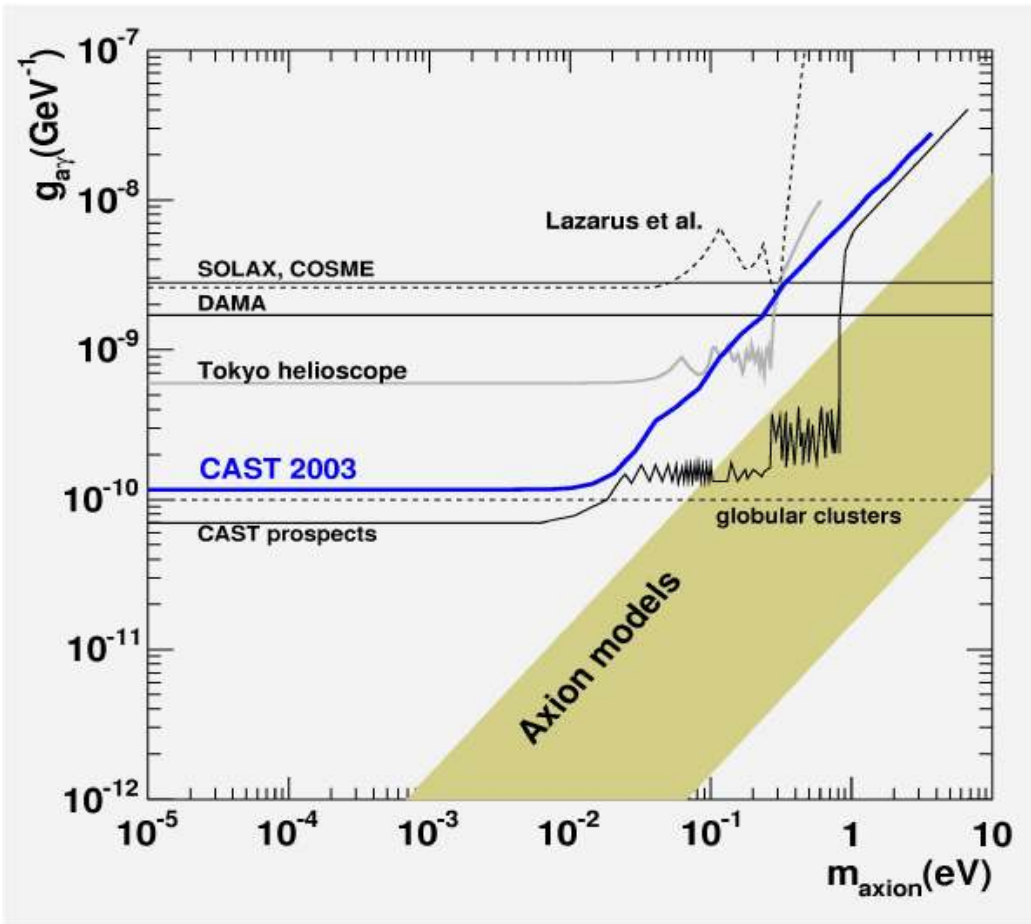
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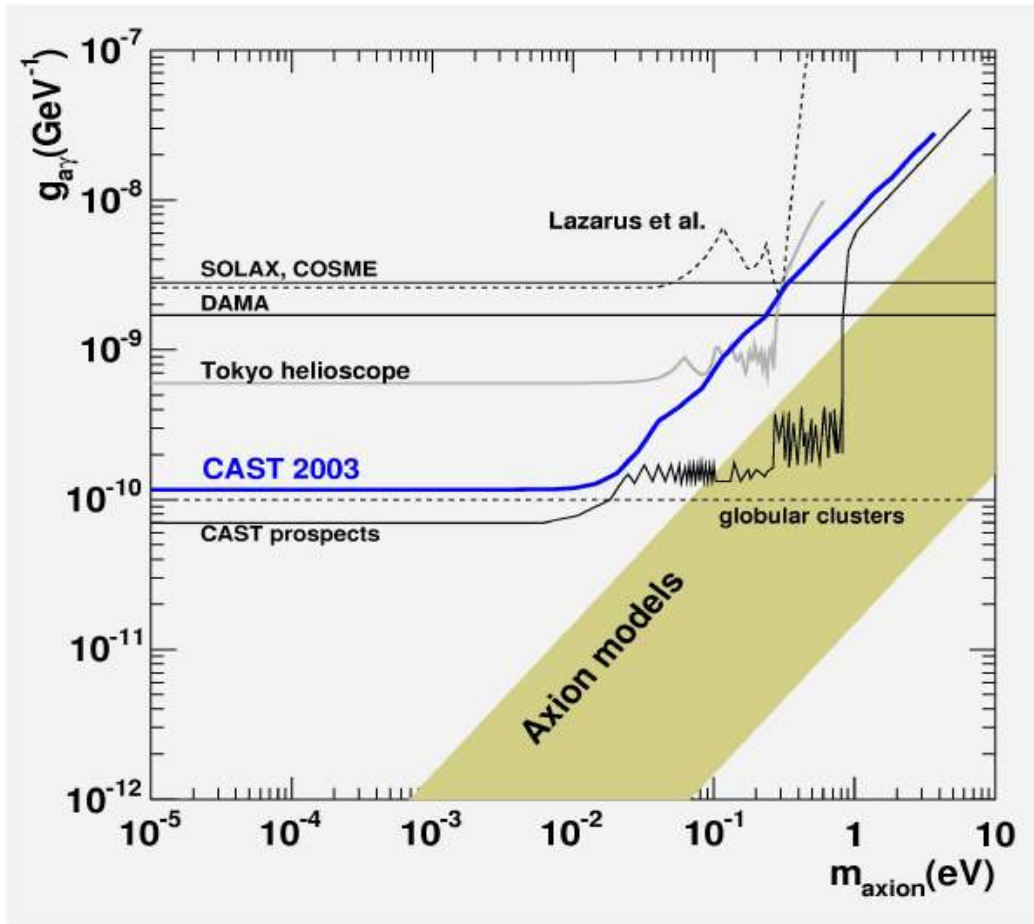
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- *More from HERA II; also eRHIC and LHeC*

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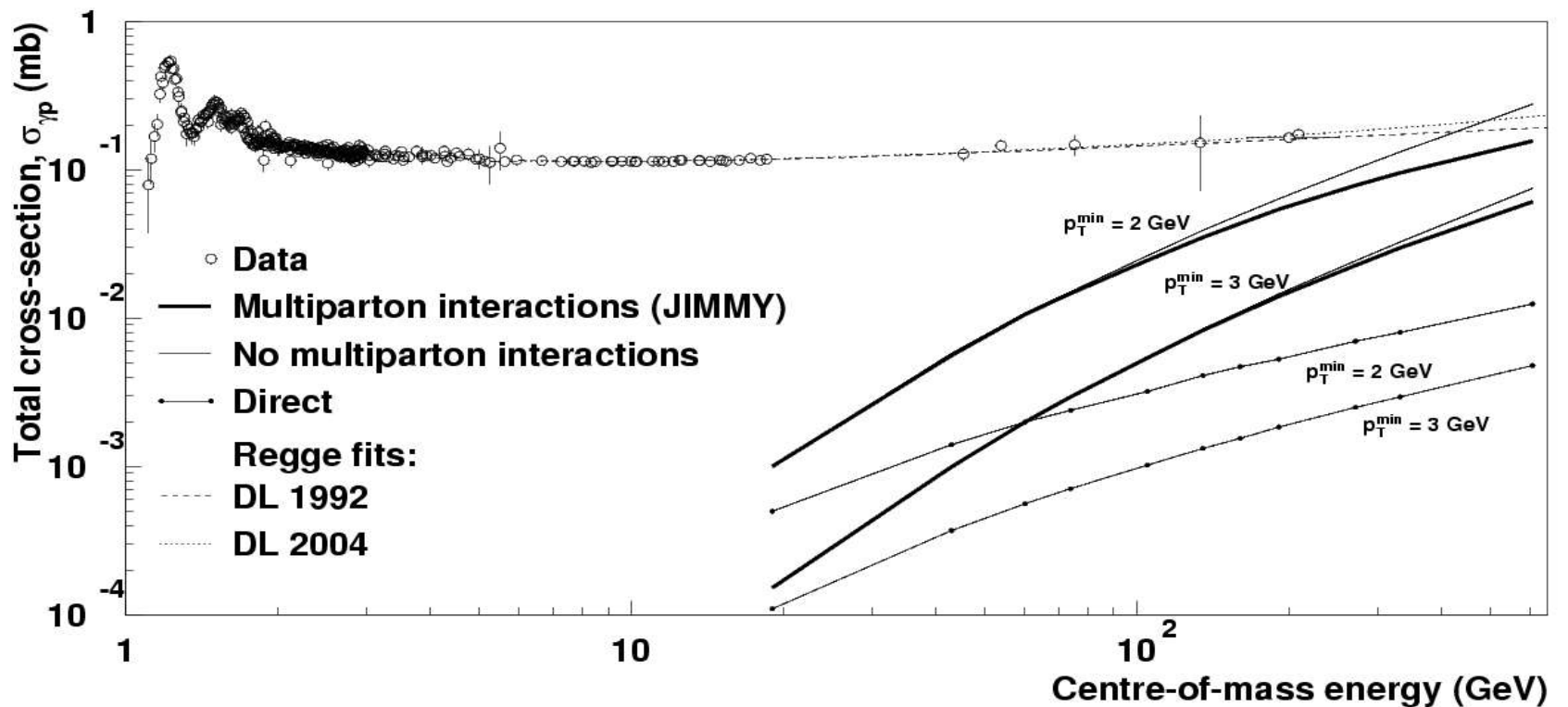


- **Find an axion?**
  - e.g. CERN Axion Solar Telescope (CAST) 2005-2007
- **Find an EDM**
  - If the neutron has one, is it QCD or something else?
  - Can it be unravelled, does it predict an axion mass?
  - Electron EDM?



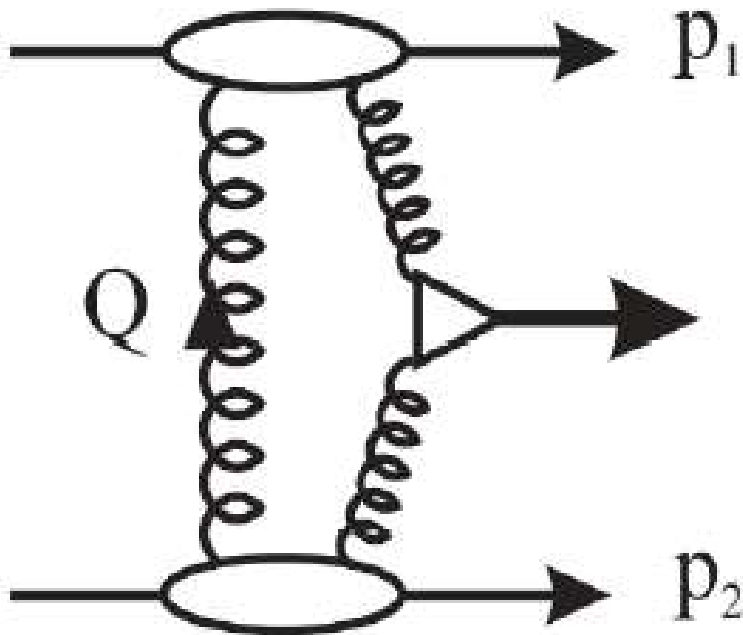
# Why do high energy hadronic cross sections behave the way they do?

- How does the Regge behaviour emerge from the QCD lagrangian?

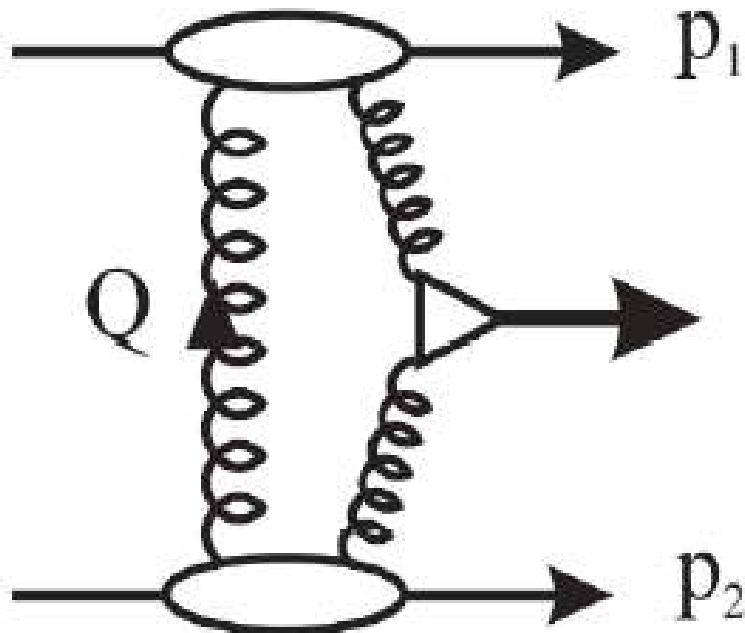


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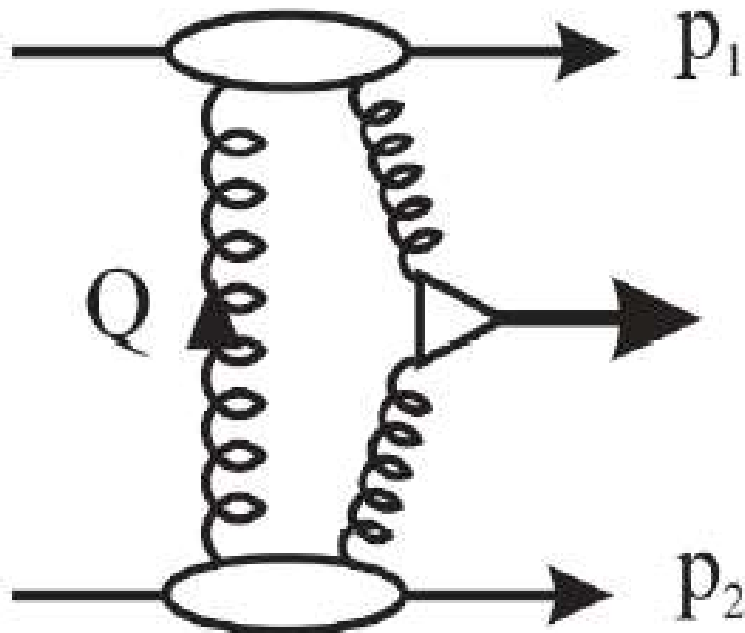


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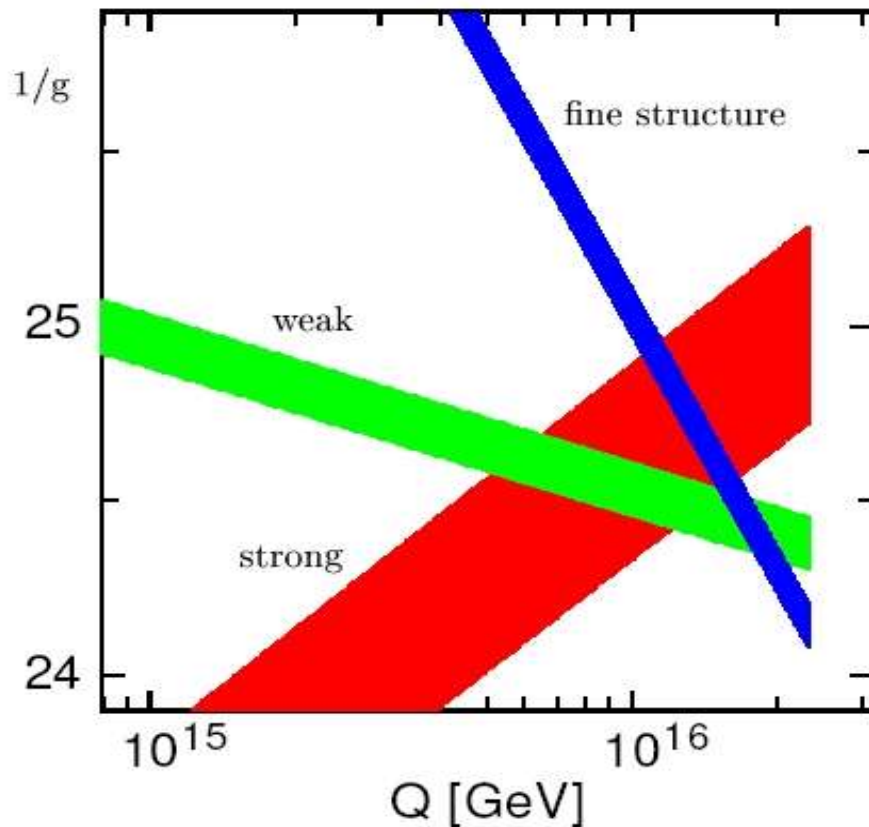
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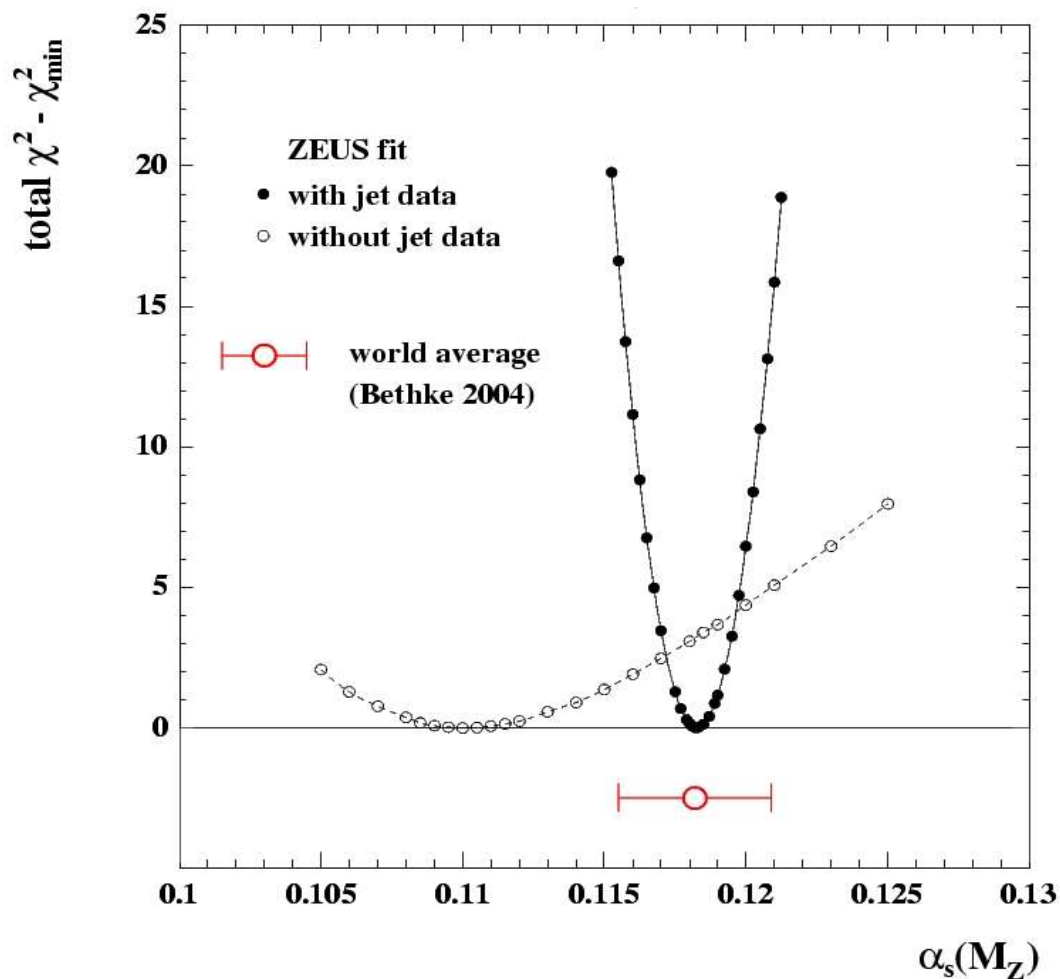
- High energy pp cross section at LHC (TOTEM/FP420)
- Diffractive physics, vector meson production, rapidity gaps *HERA II, LHC, LHeC., eRHIC...*
- Transition between perturbative and non-perturbative QCD. *HERA, LheC, eRHIC, neutrino beams*

# What, precisely, is the coupling constant and where does it meet the others?

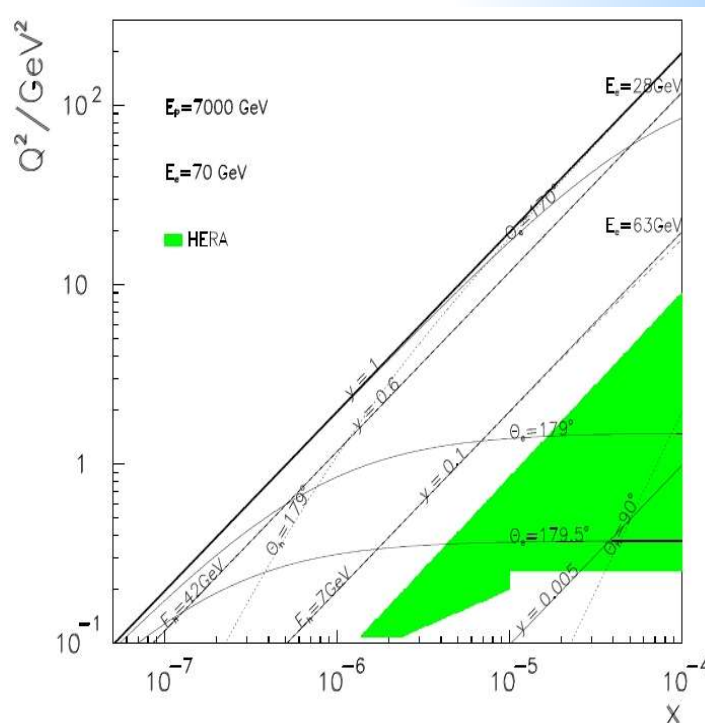


- $\alpha_s$  is known to 1-2%.  
 Compare to the EM, weak and gravitational ( $\sim 10^{-9}$ ,  $10^{-5}$ ,  $10^{-3}$ )

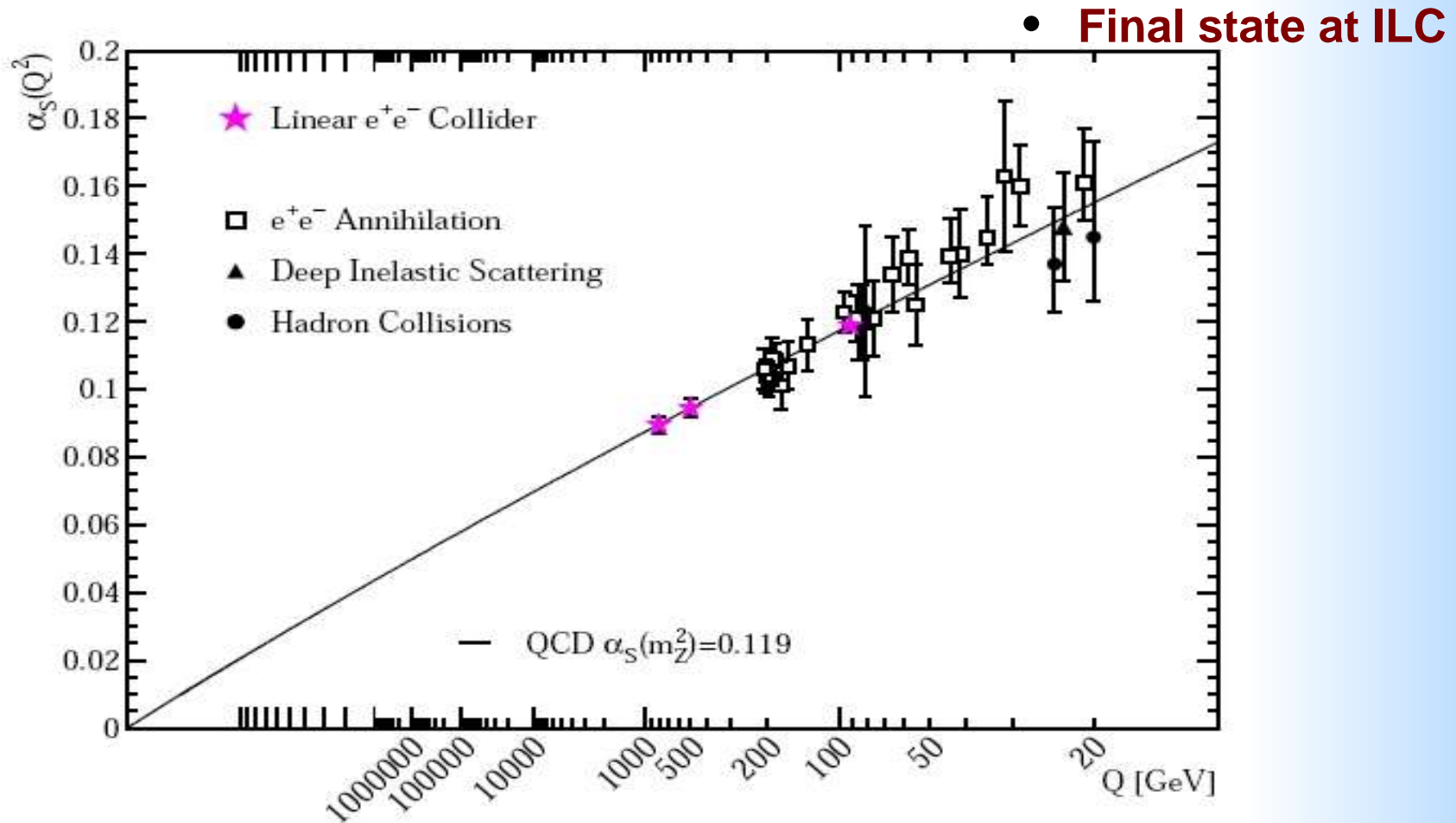
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- **QCD fits at LHeC**



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- *High x proton structure – HERA II, DIS at neutrino beams, W, Z, photon production at LHC.*
- *Testing/development of Lattice calculations for nuclear matrix elements and hadron decay Babar, Belle, COMPASS, Daphne, etc*

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- **Much of our understanding of QCD final states (jets, charm, beauty....) at colliders is best encapsulated in Monte Carlo generators. *Need access to large data sets (LEP, HERA, Tevatron, SPS; eventually LHC and ILC) to validate these and improve the next generation of measurements and models (virtuous cycle).***

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- **Precise measurements of jets, Charm- and Beauty-tagged cross sections from HERA II and Tevatron to come.**

# *Discussion...*

Acknowledgements to: E. Aschenauer, E. Burtin, A. Caldwell, B. Cox, J. Dainton, J. Ellis, D. Hasch, M. Klein, G. Mallot, J. Morfin, R. Thorne, M. Wing and many others...