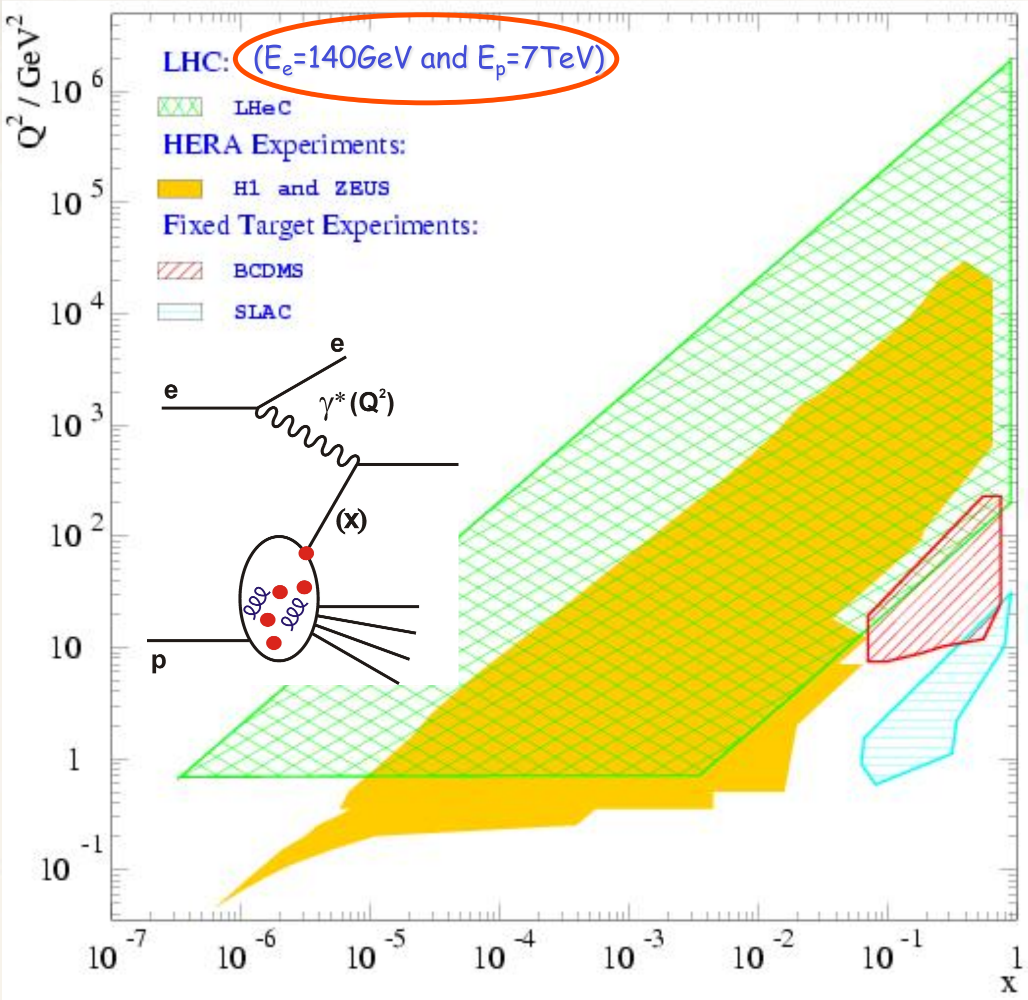


http://cern.ch/lhec

Small x physics at LHeC

Anna Staśto
Penn State University & BNL & INP Krakow

Overview of the project

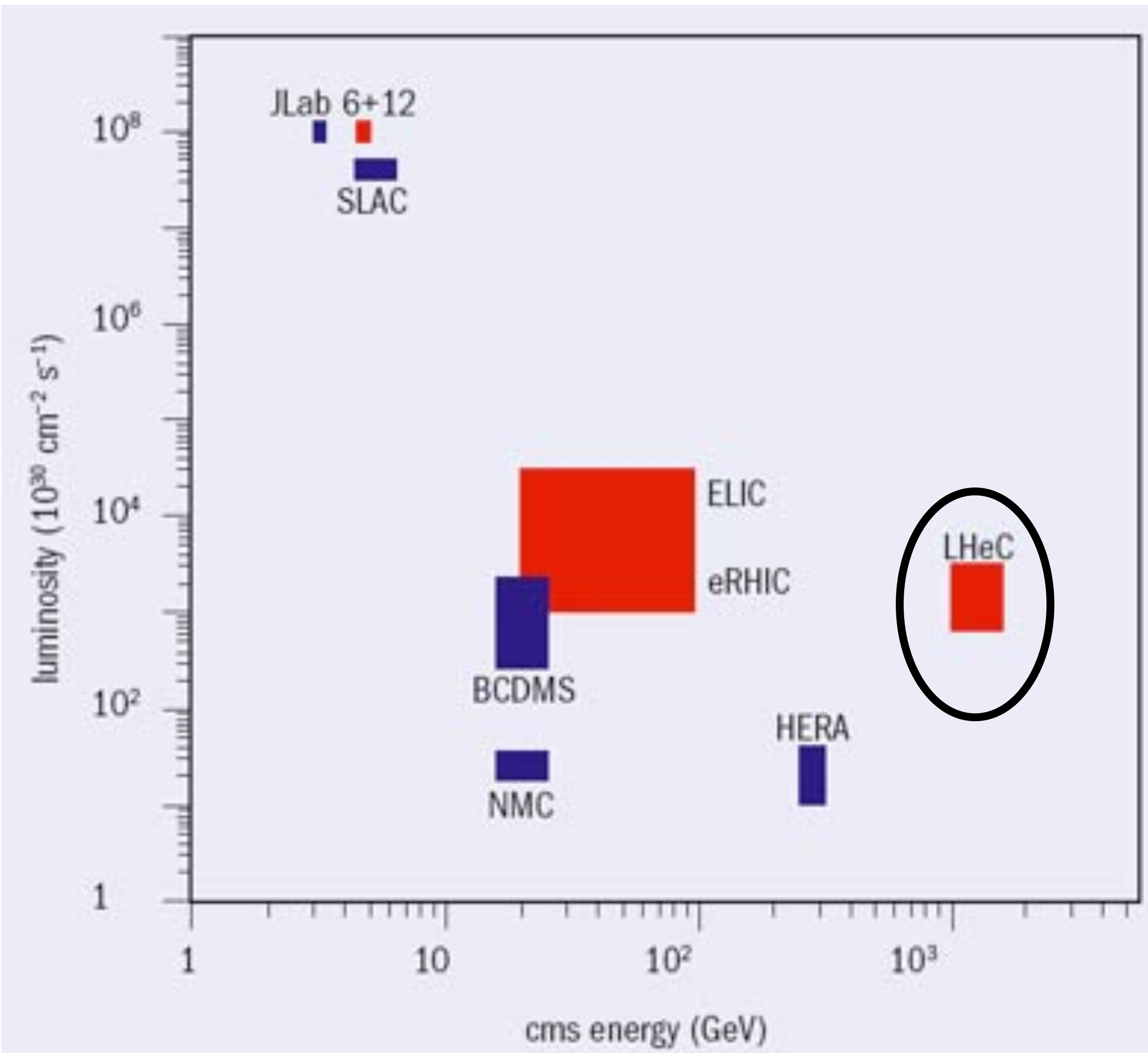
"Now we are entering the post-TeV era, jumping not one but two orders of magnitude to a lab equivalent of order 50 TeV at HERA. If the LHC is successfully commissioned in the LEP tunnel in 1997, then we may hope to see collisions between electrons from LEP and protons from the LHC in the next millenium giving a lab equivalent around 10 TeV (1 PeV). " F.Close Singapor 1990

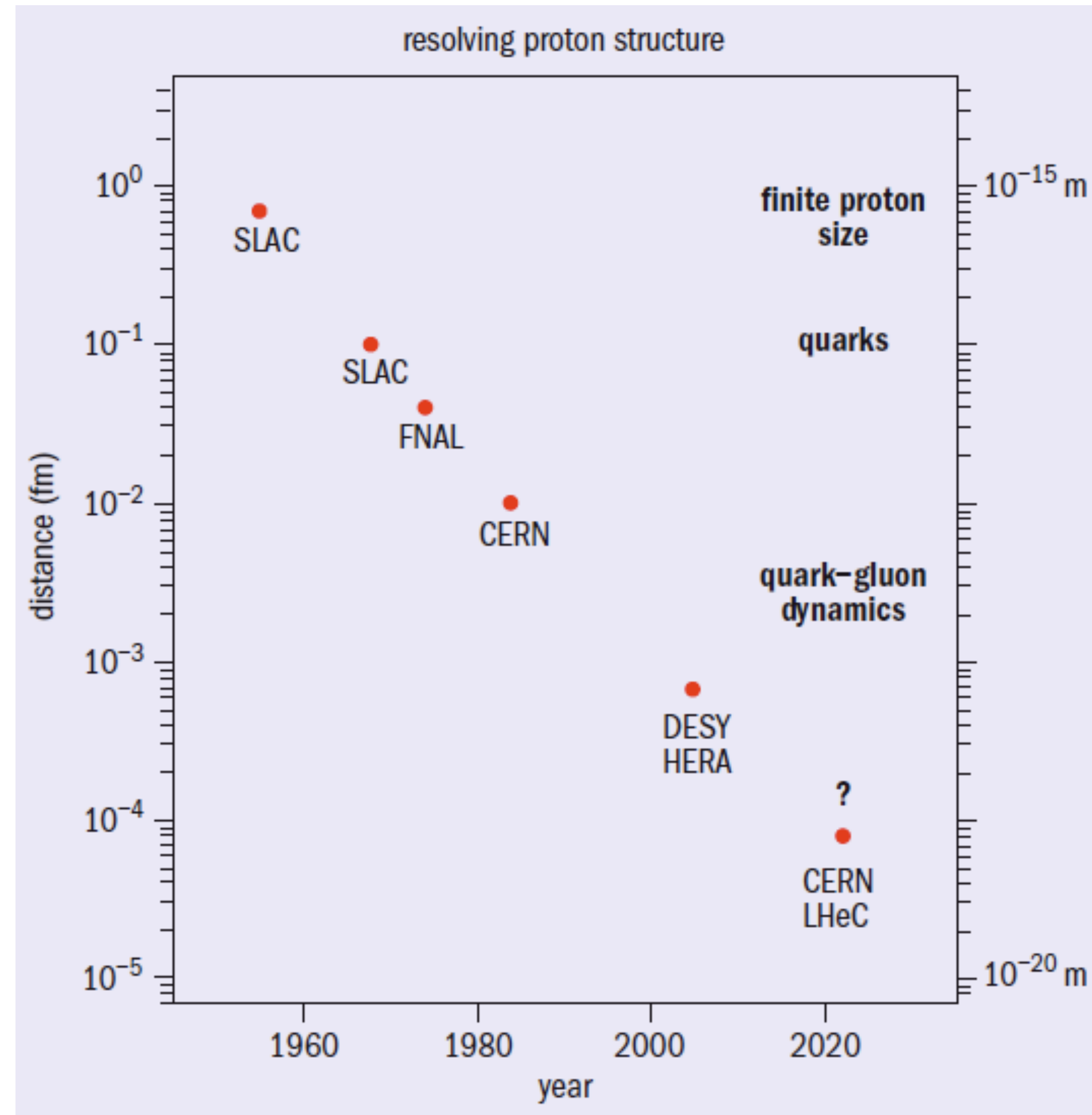
LHeC : Large Hadron Electron Collider

The LHeC is a proposed colliding beam facility at CERN, which will exploit the new world of energy and intensity provided by the LHC for lepton-nucleon scattering.

An existing 7 TeV LHC proton or heavy ion beam will collide with a new electron beam simultaneously with proton-proton or heavy ion collisions taking place at the existing LHC experiments.

LHeC vs other DIS experiments





Significantly higher luminosity than HERA.
TeV energy range using the LHC beam.

Physics possibilities at LHeC

Beyond Standard Model

Leptoquarks
Contact Interactions
Excited Fermions
Higgs in MSSM
Heavy Leptons
4th generation quarks
Z'
SUSY
???

QCD and EW precision physics

Structure functions
Quark distributions from direct measurements
Strong coupling constant to high accuracy
Higgs in SM
Gluon distribution in extended x range to unprecedented accuracy
Single top and anti-top production
Electroweak couplings
Heavy quark fragmentation functions
Heavy flavor production with high accuracy
Jets and QCD in photoproduction
Partonic structure of the photon
...

Small x and high parton densities

New regime at low x
Saturation
Diffraction
Vector Mesons
Deeply Virtual Compoton Scattering
Forward jets and parton dynamics
DIS on nuclei
Generalized/unintegrated parton distribution functions

Physics possibilities at LHeC

Beyond Standard Model

Leptoquarks
Contact Interactions
Excited Fermions
Higgs in MSSM
Heavy Leptons
4th generation quarks
Z'
SUSY
???

QCD and EW precision physics

Structure functions
Quark distributions from direct measurements
Strong coupling constant to high accuracy
Higgs in SM
Gluon distribution in extended x range to unprecedented accuracy
Single top and anti-top production
Electroweak couplings
Heavy quark fragmentation functions
Heavy flavor production with high accuracy
Jets and QCD in photoproduction
Partonic structure of the photon
...

Small x and high parton densities

New regime at low x
Saturation
Diffraction
Vector Mesons
Deeply Virtual Compoton Scattering
Forward jets and parton dynamics
DIS on nuclei
Generalized/unintegrated parton distribution functions

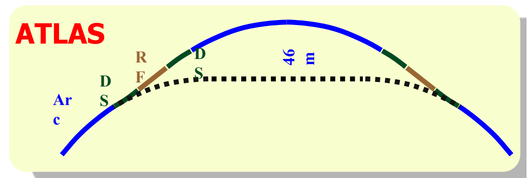
This talk

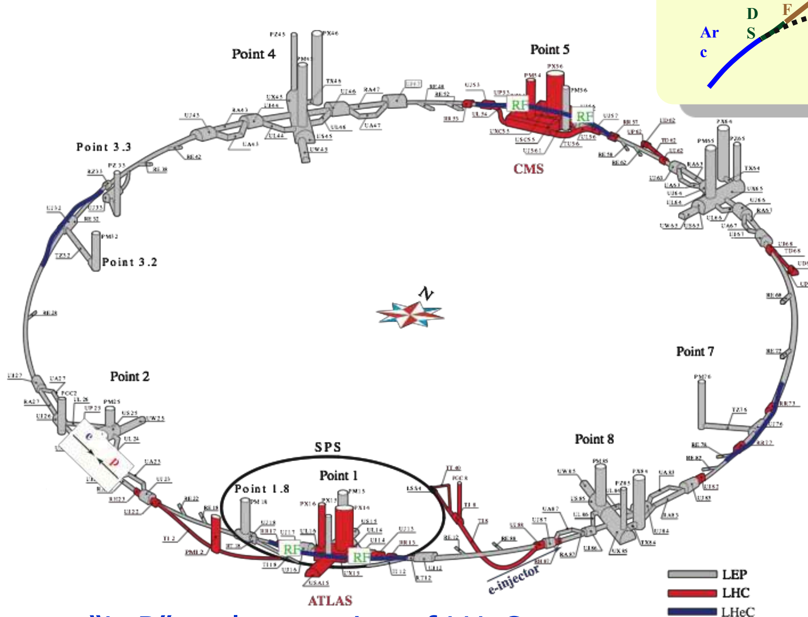
Machine design

Ring-Ring

Overall Layout and Bypasses

e-p/A experiment could be at IP2 (shown) or IP8





"LeR" = electron ring of LHeC

To be done:

Detailed design of CMS and ATLAS bypasses and integration into optics

Bypass design:

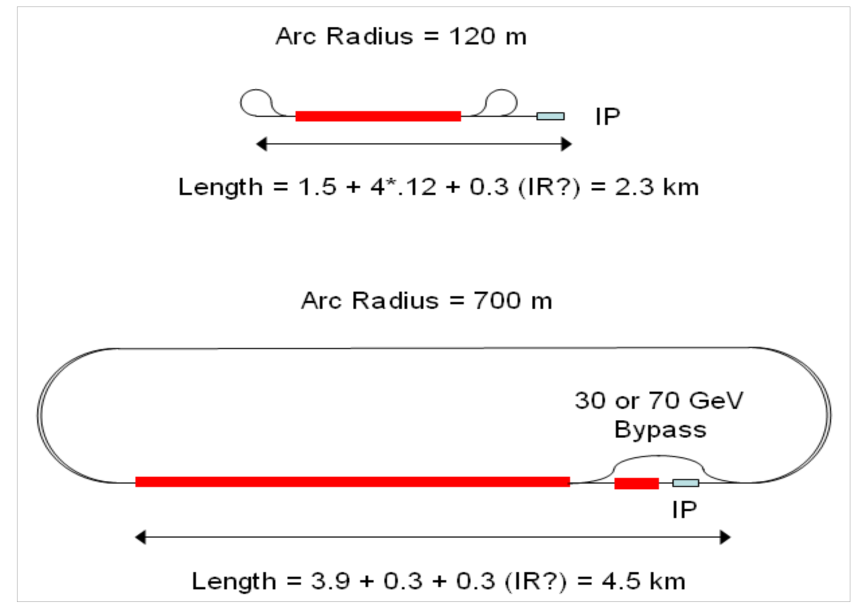
- shutdown time
- cost for tunnel
- match LHC and LeR circumference ? Or leave $\Delta C \sim 1$ m ?

Advantage: high peak luminosity, no need to drill another tunnel.
Difficulty: building around existing LHC.
Electron beam energy and lifetime limited by synchrotron radiation

$$E \simeq 60\ \mathrm{GeV} \qquad \mathcal{L} \sim 3 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Linac-Ring

Two LINAC Configurations [CERN-SLAC]



60 GeV
31 MV/m, pulsed
two passes

60 GeV
13 MV/m CW ERL
4 passes

140 GeV
31 MV/m, pulsed
2 passes

Advantage: high energy, possibly high electron polarization. Low interference with existing LHC infrastructure.
Difficulty: lower peak luminosity, no previous experience

$$E \simeq 150\ \mathrm{GeV} \qquad \mathcal{L} \sim 3 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

LHeC Detector: version for low x

Muon chambers
(fwd,bwd,central)

Coil (r=3m l=11.8m, 3.5T)
[Return Fe not drawn]

Central Detector

Pixels
Elliptic beam pipe

Silicon (fwd/bwd+central)
[Strip or/and Gas on Slimmed Si Pixels]
[0.6m radius for 0.03% * p_t in 3.5T field]

El.magn. Calo (Pb,Scint. $30X_0$)
Hadronic Calo (Fe/LAr; Cu/Brass-Scint. 9-12λ)

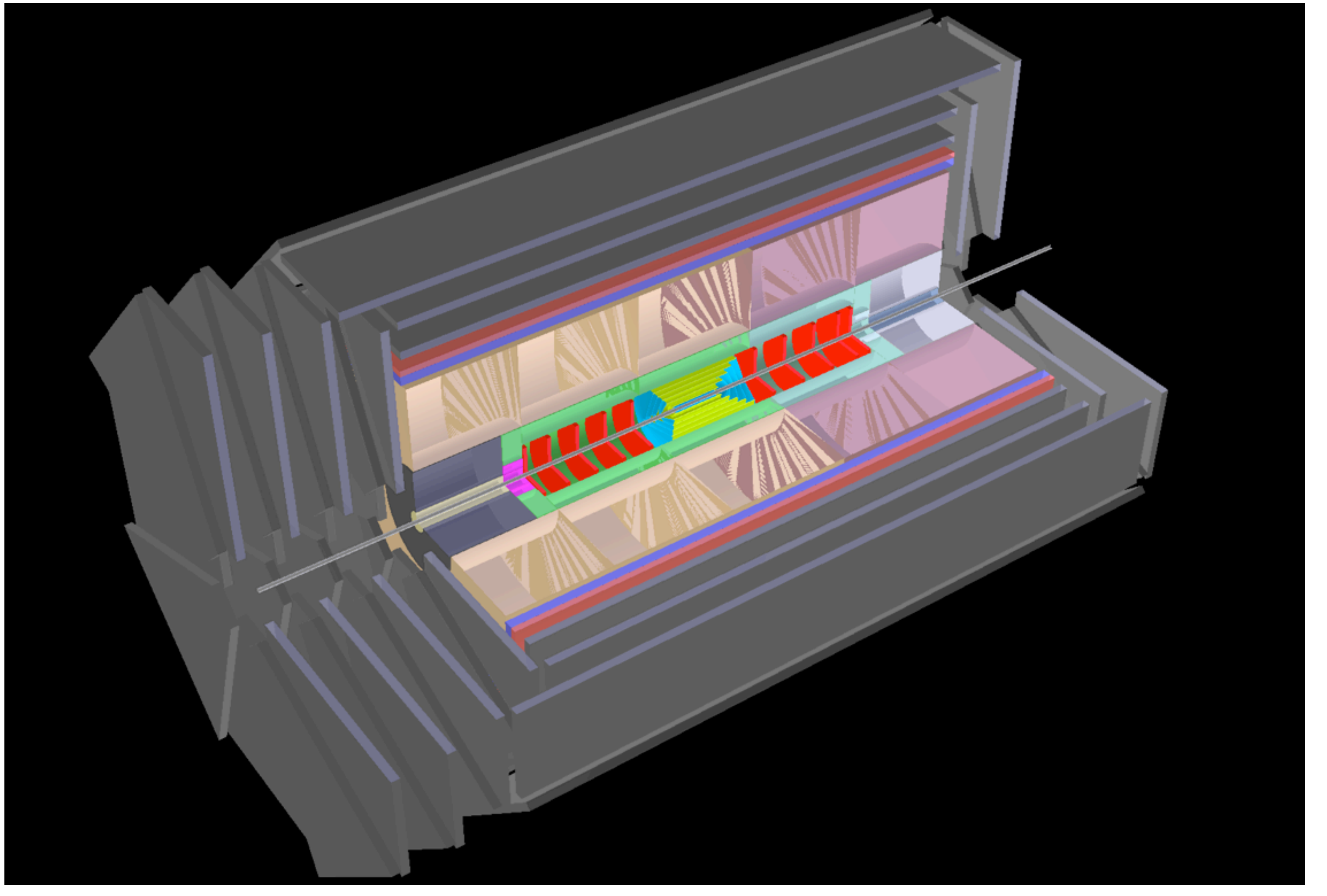
Fwd Detectors

(down to 1^o)
Silicon Tracker
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]

Calice (W/Si); dual ReadOut - Elm Calo
FwdHadrCalo:
Cu/Brass-Scintillator

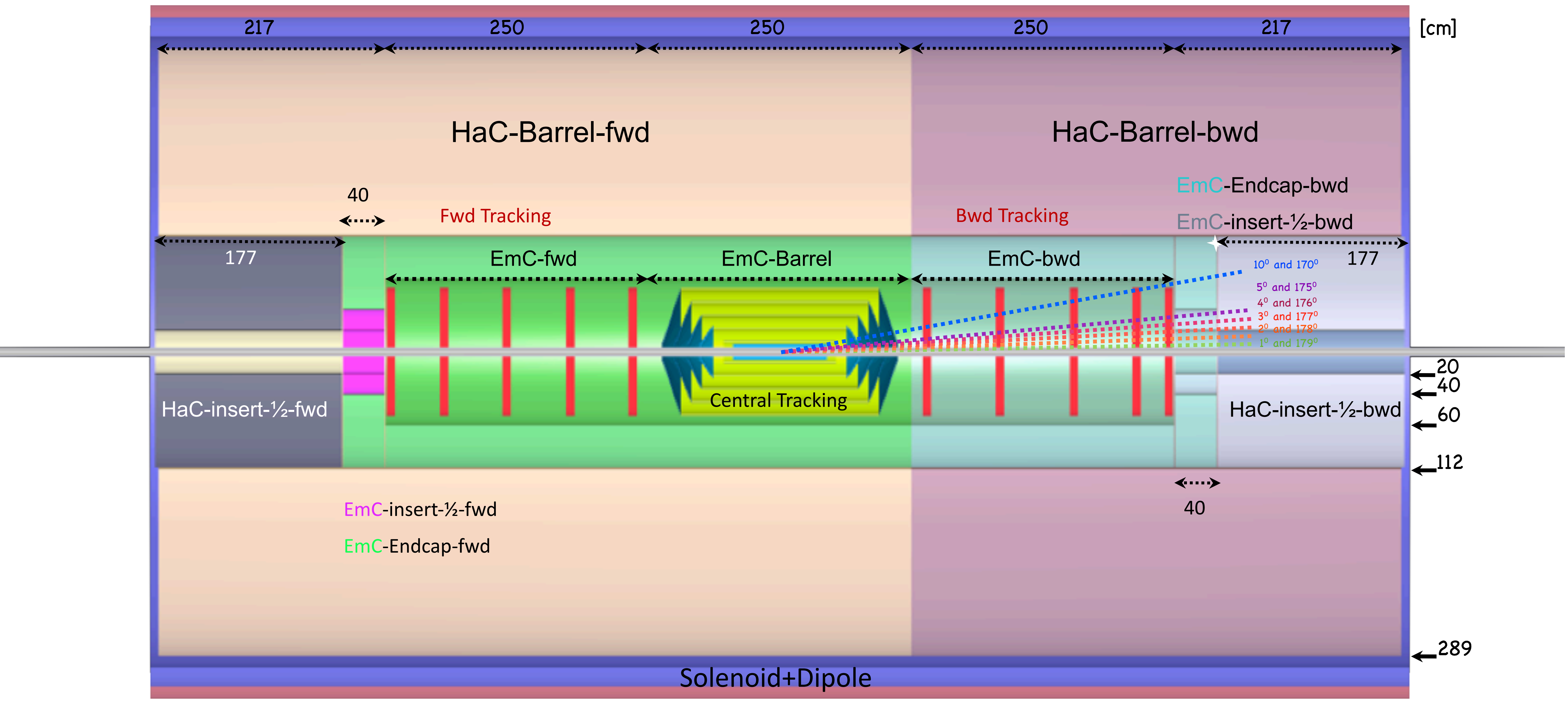
Bwd Detectors

(down to 179^o)
Silicon Tracker
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]
Cu/Brass-Scintillator,
Pb-Scintillator (SpaCal - hadr, elm)



Dimensions defined by beam pipe (Nomex/Be sandwich?) – work in progress.

The Detector - Low Q^2 Setup



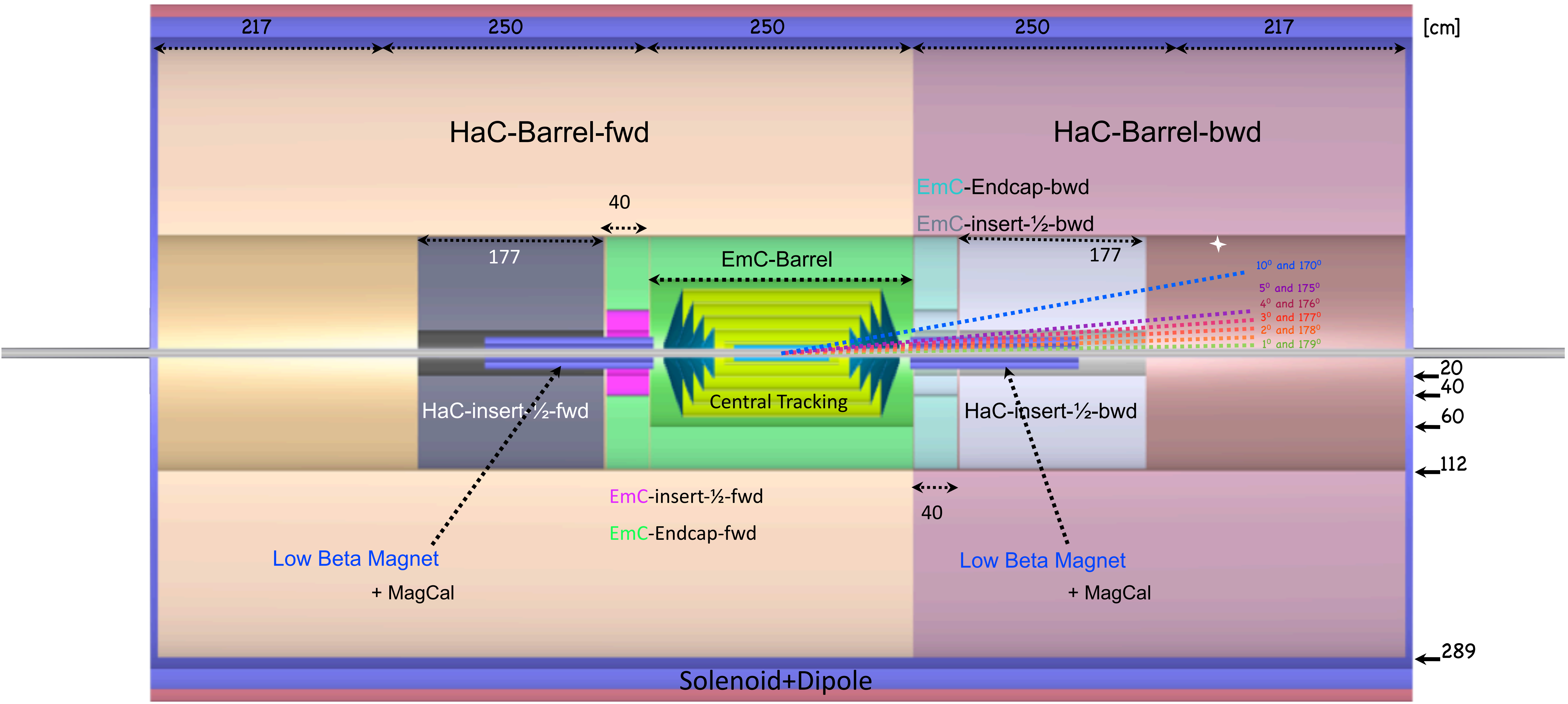
Fwd/Bwd asymmetry in energy deposited and thus in technology [W/Si vs Pb/Sc..]

28 Present dimensions: LxD =17x10m^2 [CMS 21 x 15m^2 , ATLAS 25 x 45 m^2]

Full angular coverage, acceptance down to 1 degree

Details of technologies under discussion

The Detector - High Q^2 Setup



Beam focusing magnets (lower angular acceptance)

Calorimeter inserts slide inwards

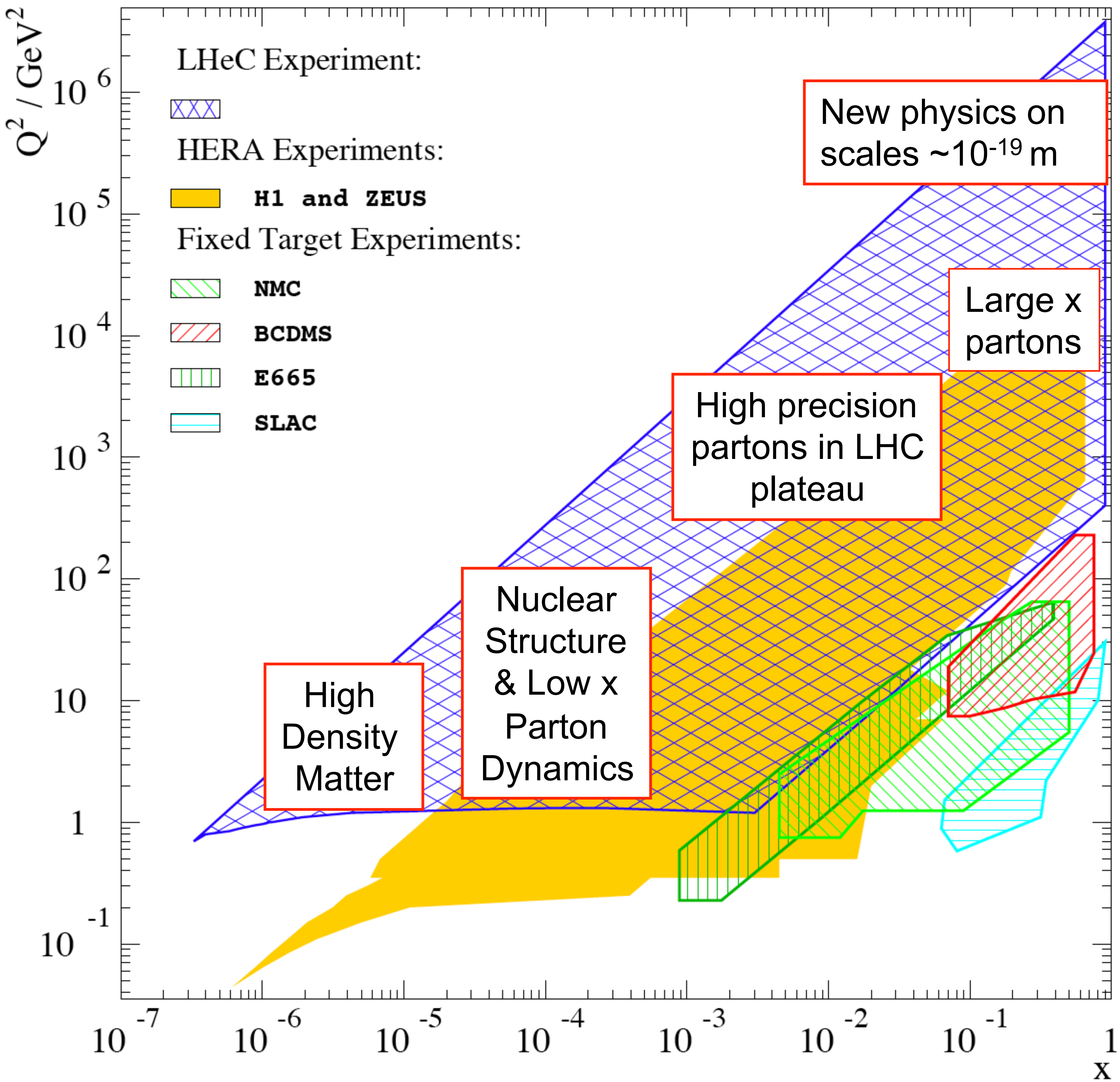
Two phases of operation (?)

Beam scenarios for first physics studies

config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	0.1	0.1	0.4	0.1	30	1	ePb
H	50	1	p	--	1	--	25	30	1	lowEp

ep Studies based on a 20-150 GeV electron beam and lumi of 1-10 fb^{-1} / year

Kinematics & Motivation (140 GeV x 7 TeV)



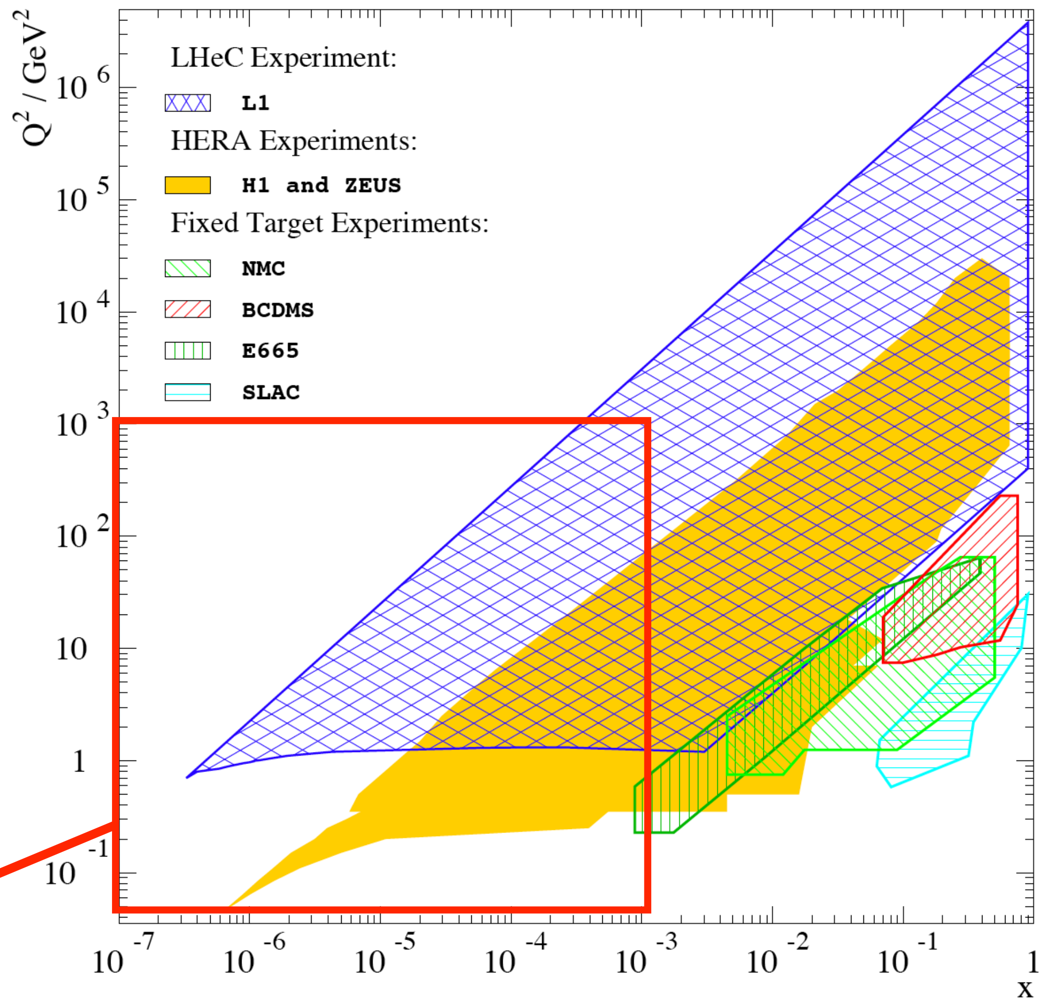
$\sqrt{s} = 2$ TeV

- High mass (M_{eq}, Q^2) frontier
- EW & Higgs
- Q^2 lever-arm at moderate & high x → PDFs
- Low x frontier → novel QCD …

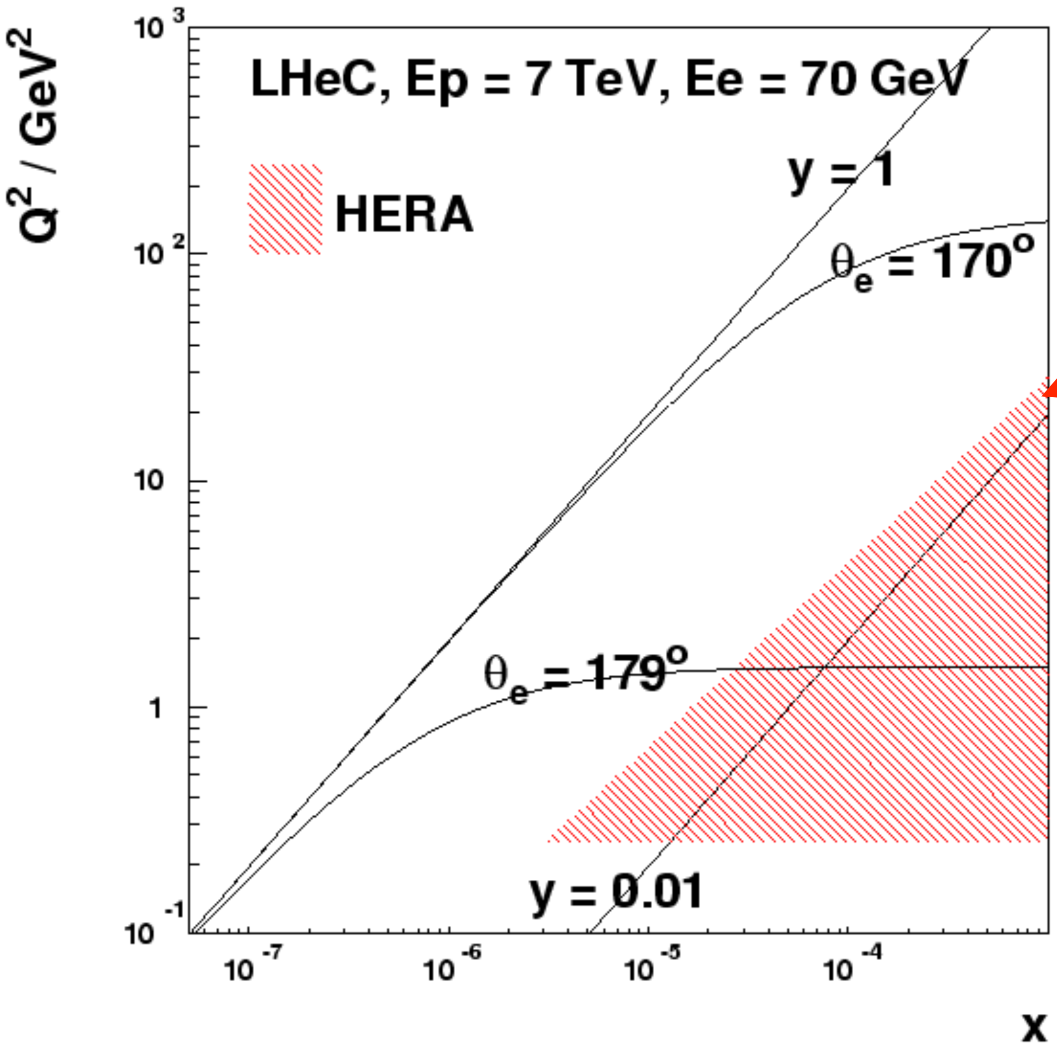
$x \geq 5.10^{-7}$ at $Q^2 \leq 1$ GeV^2

Basic Inclusive Kinematics / Acceptance

Access to Q^2=1 GeV^2 in ep mode for all x > 5 x 10^{-7} IF we have acceptance to 179^o (and @ low E_e')



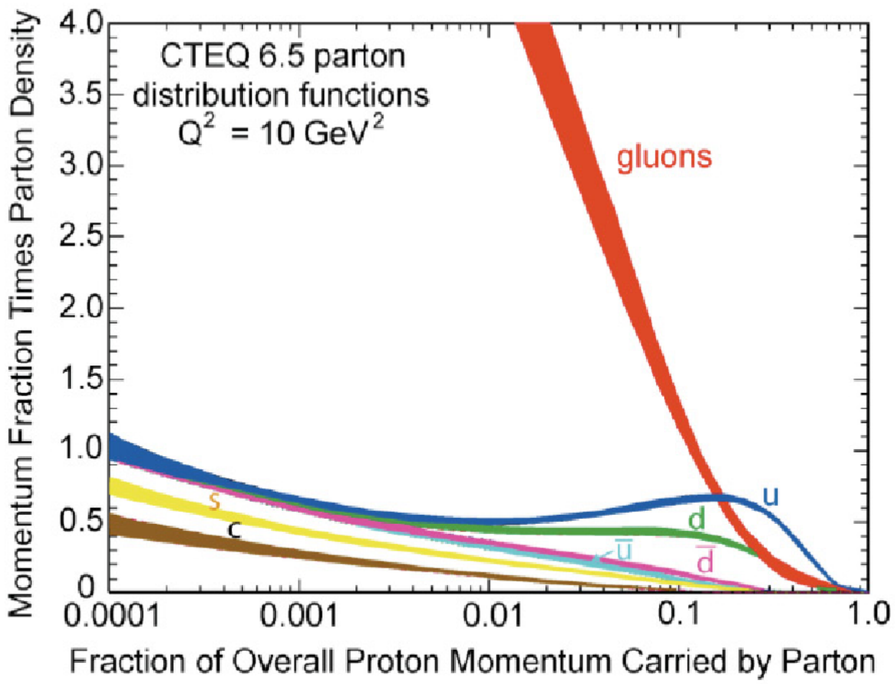
Nothing fundamentally new in LHeC low x physics with θ<170^o



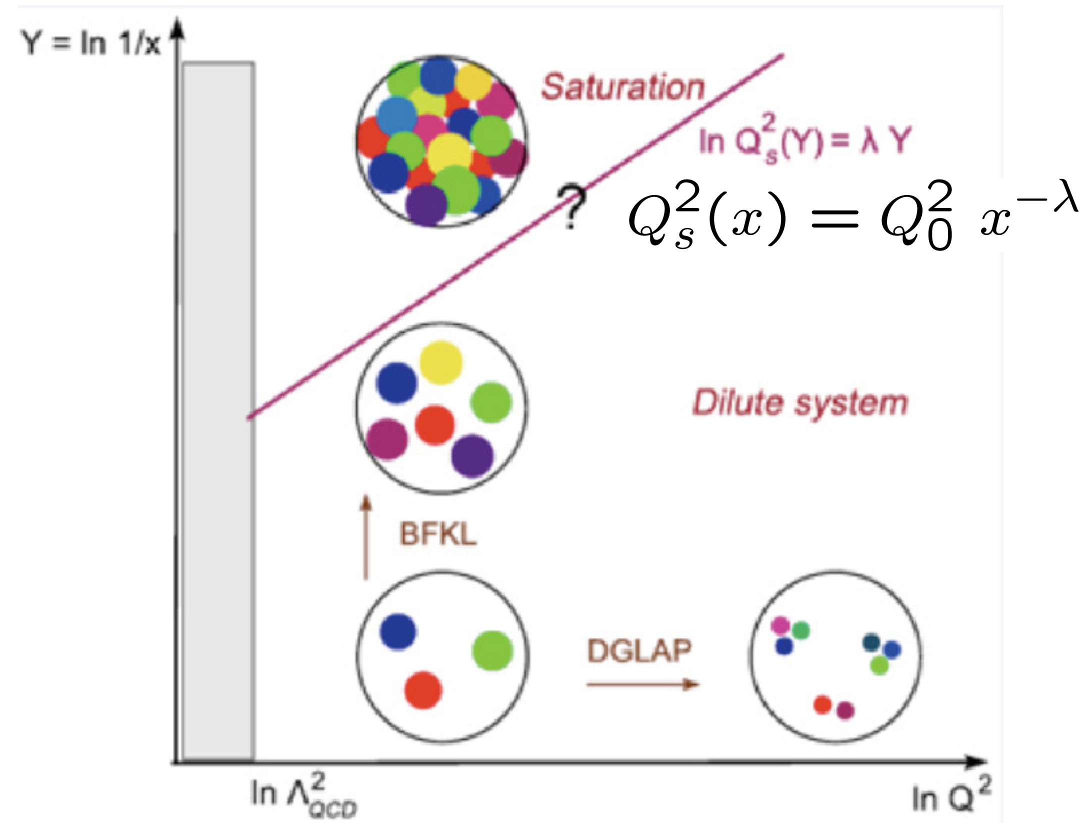
... low x cross sections are large!

... luminosity in all realistic scenarios ample for most low x measurements

Low x and saturation



HERA established strong growth of the gluon density towards small x
Unitarity must be preserved, but how it is realized in microscopic terms?
Parton saturation: recombination of gluons at sufficiently high densities leading to nonlinear modification of the evolution equations.
Emergence of a dynamical scale: saturation scale dependent on energy.



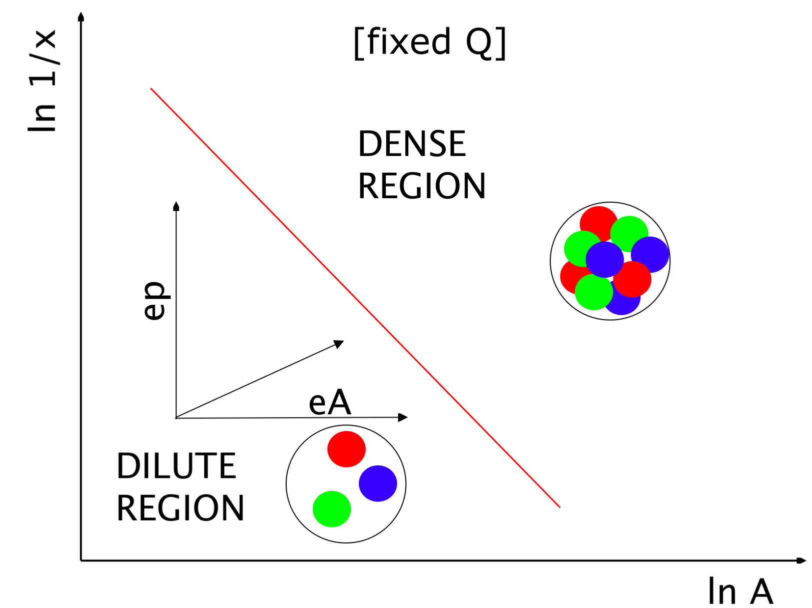
What we learned from HERA about saturation?

Linear DGLAP evolution works well at HERA.
Hints of saturation at low Q and low x: deterioration of the global fit in that region.
Large diffractive component.
Success of the dipole models in the description of the data.
The models point at the low value of the saturation scale
LHeC would provide an access to a kinematic regime where the saturation scale is perturbative

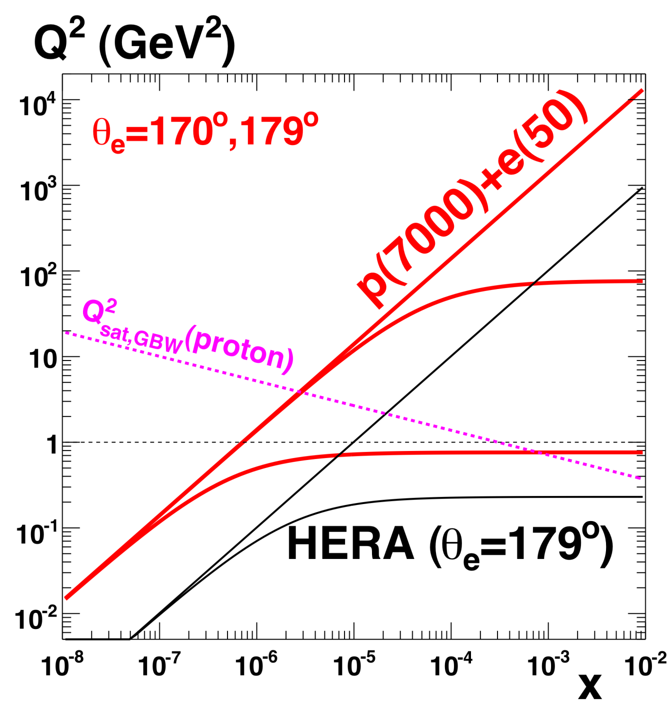
Strategy for making the target more black

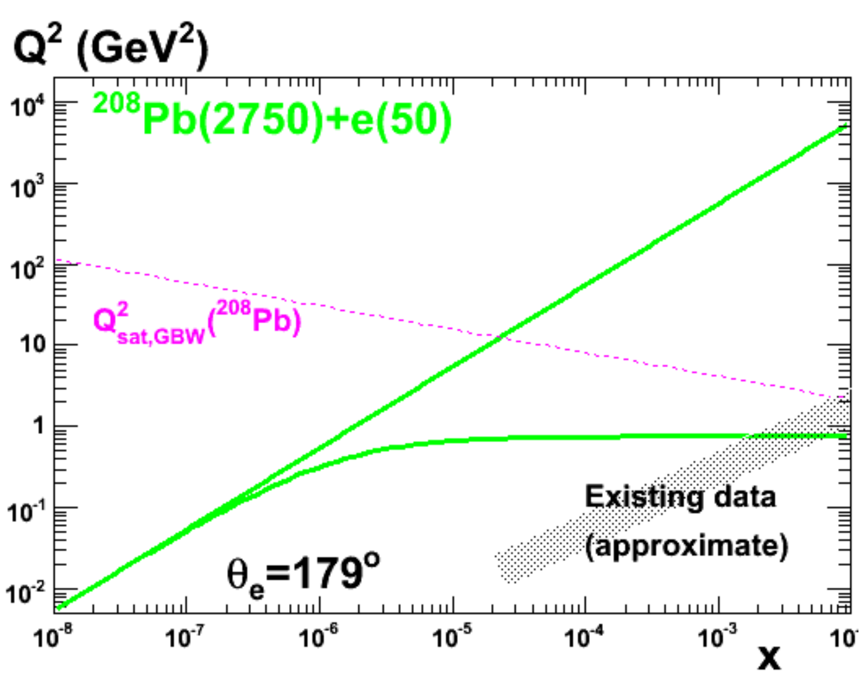
LHeC would deliver a two-pronged approach:

Probing lower x in ep. Evolution of a single source



More nucleons: eA scattering. Many sources overlapping in impact parameter .

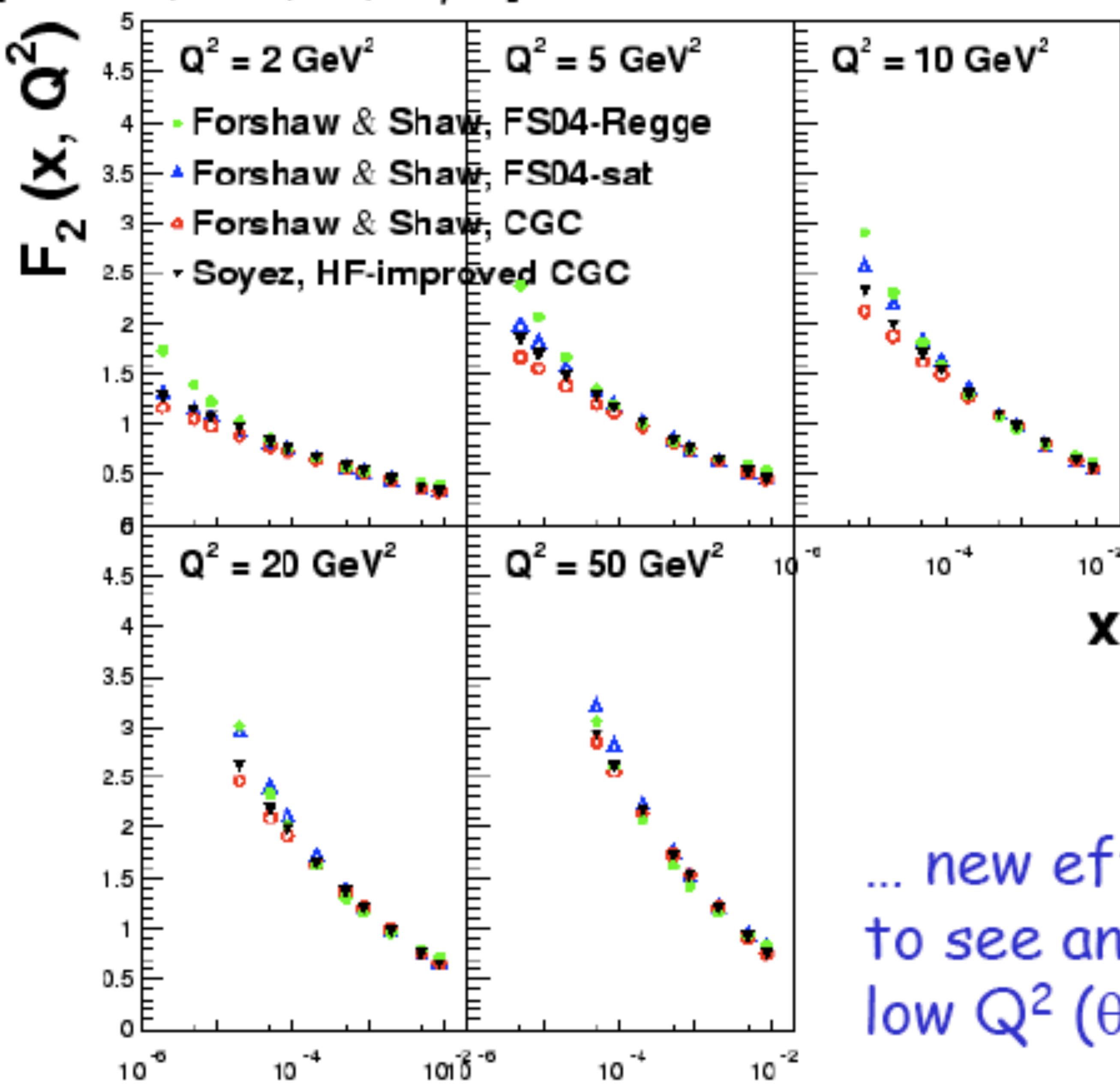




Some models of low x F_2 with LHeC Data

With 1 fb^{-1} (1 year at 10^{33} cm^{-2} s^{-1}), 1° detector:
stat. precision < 0.1%, syst, 1-3%

[Forshaw, Klein, PN, Soyez]



Precise data in LHeC region, x > ~10^{-6}

- Extrapolated HERA dipole models …
- FS04, CGC models including saturation suppressed at low x & Q^2 relative to non-sat FS04-Regge

… new effects may not be easy to see and will certainly need low Q^2 ($\theta \rightarrow 179°$) region …

F_L Simulation

Vary proton beam energy as recently done at HERA ?… 'direct' gluon measurement …

E_p (TeV)	Lumi (fb^{-1})
7	1
4	0.8
2	0.2
1	0.05
[0.45	0.01]

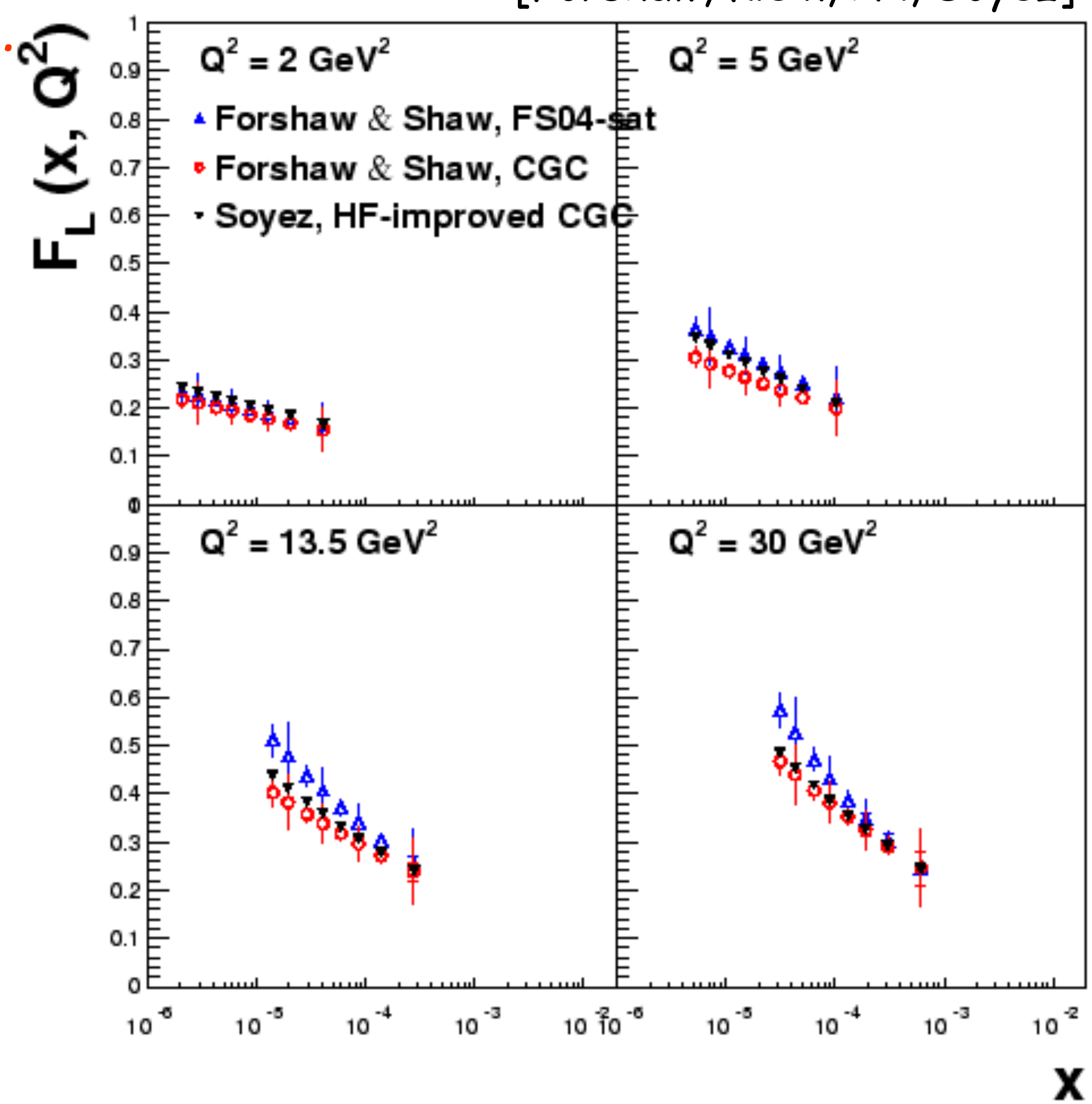
… precision typically 5%

… stats limited for $Q^2 > 1000\ GeV^2$

… could also vary E_e …

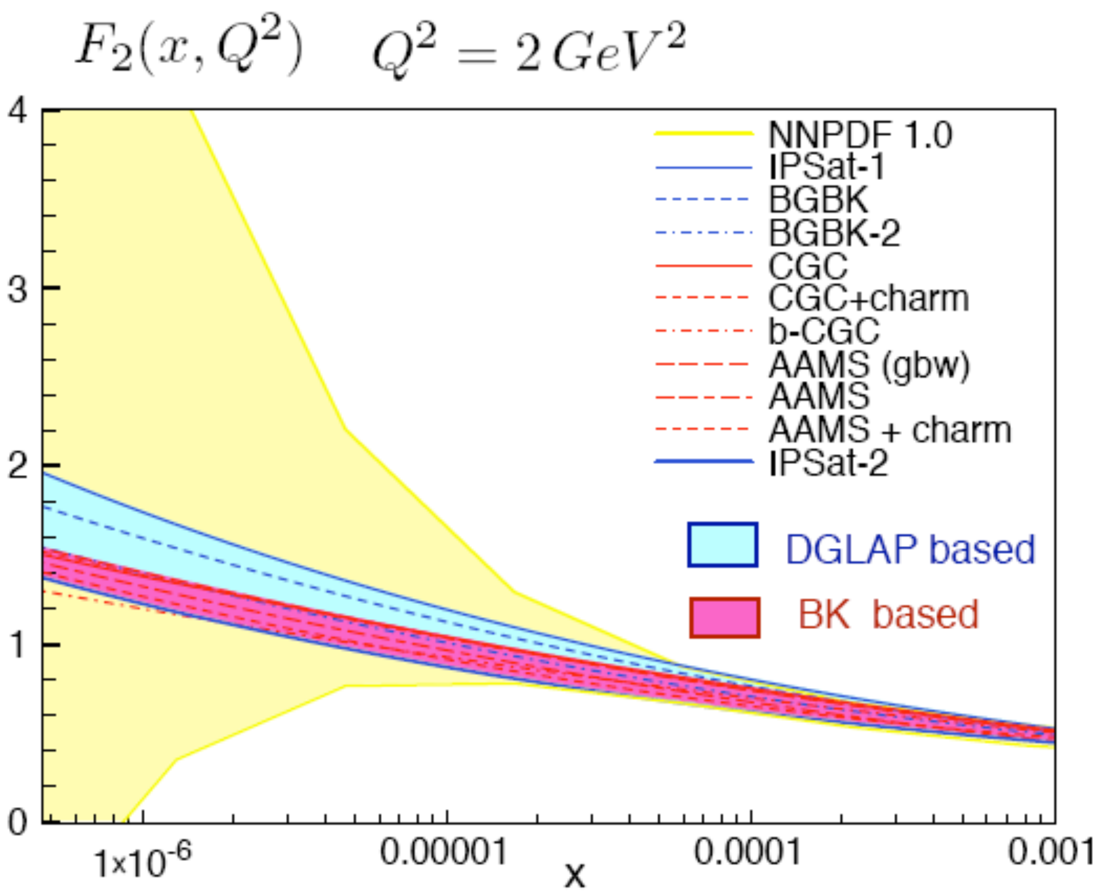
… selected lowest x data compared with 3 dipole models including saturation …

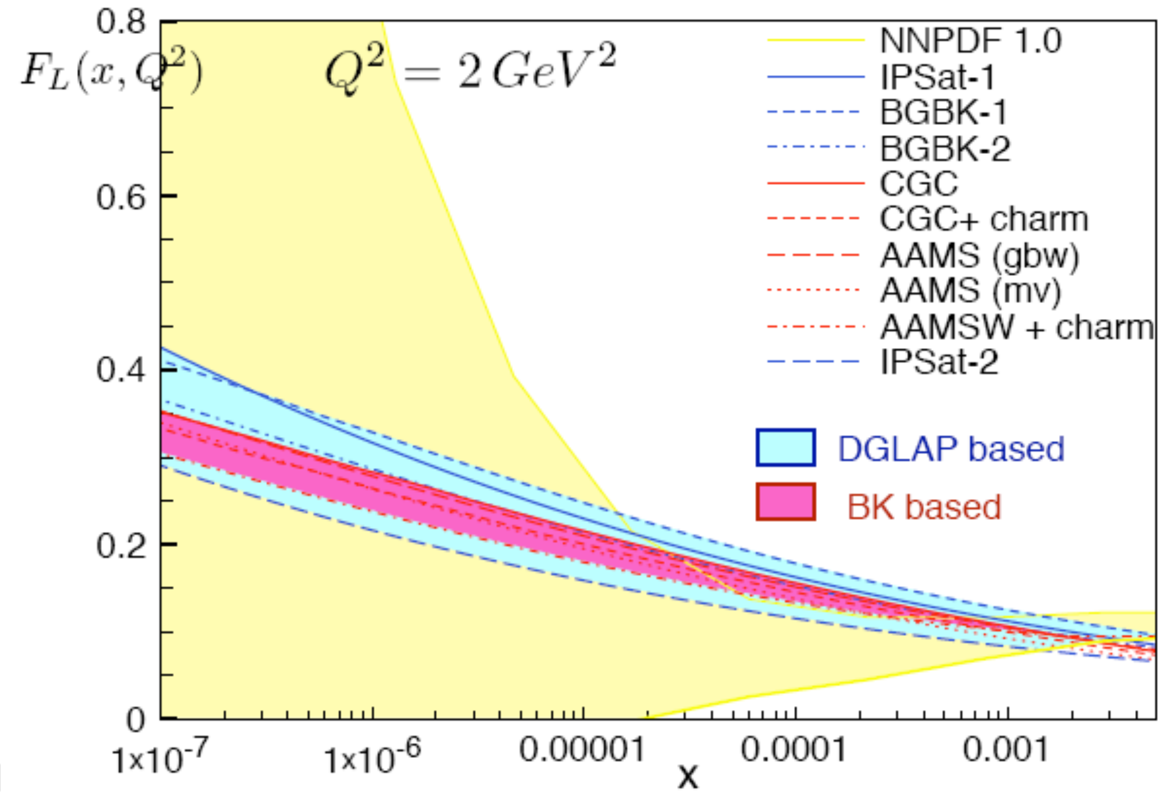
[Forshaw, Klein, PN, Soyez]



Extrapolating HERA models of F_2 (Albacete)

NNPDF NLO DGLAP uncertainties explode @ low x and Q^2
Formally, wide range of possibilities allowed, still fitting HERA





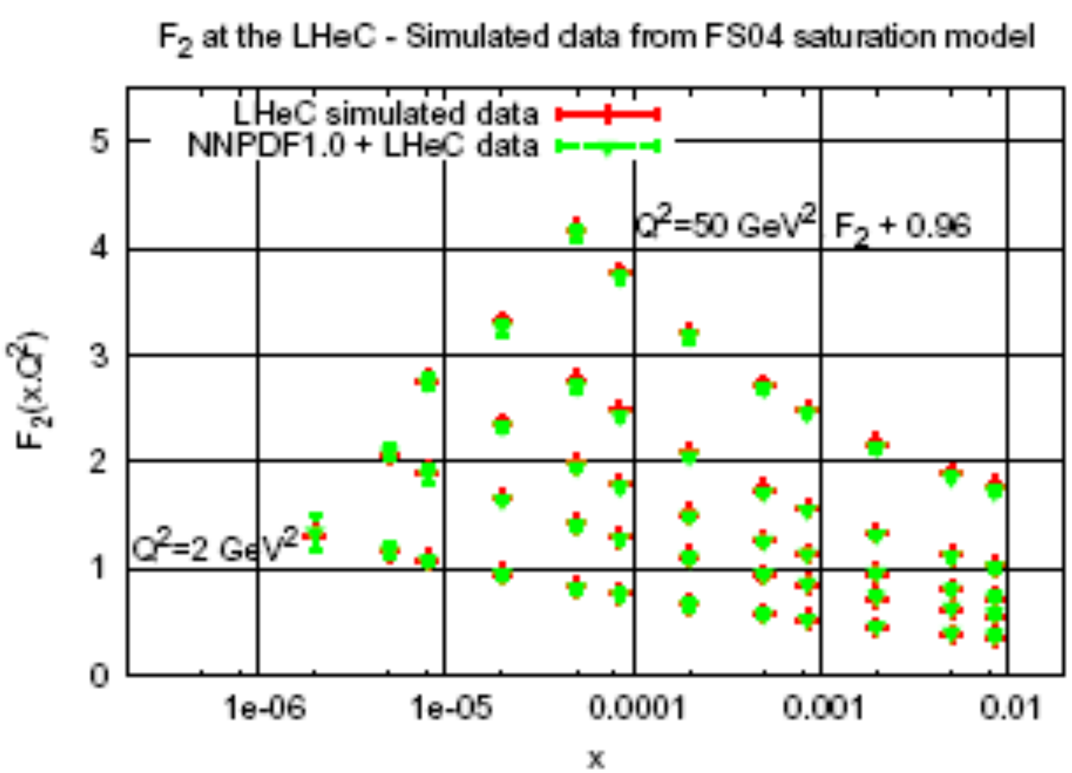
Interestingly, rather small band of uncertainties for models based on saturation as compared with the calculations based on the linear evolution. Possible cause: the nonlinear evolution washes out any uncertainties due to the initial conditions, or too constrained parametrization used within the similar framework.

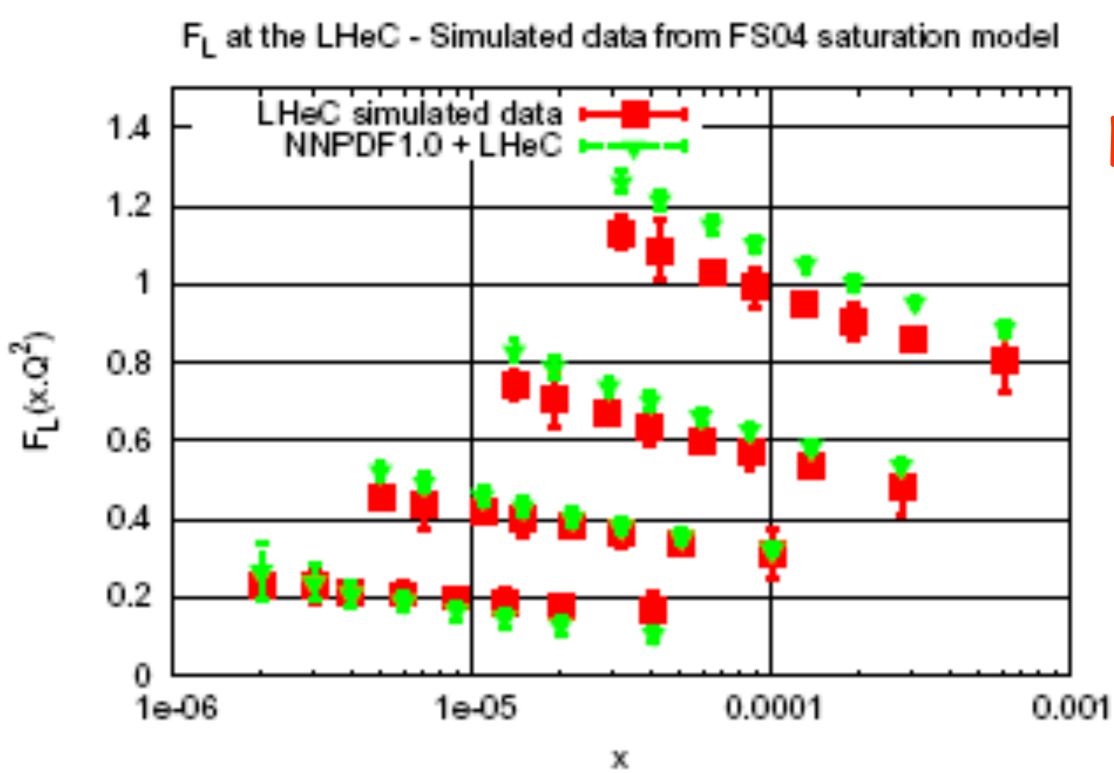
approx. 2% error on the F2 pseudodata, and 8% on the FL pseudodata ,should be able to distinguish between some of the scenarios.

Can saturation be finally established at ep collider?

Simulated LHeC F_2 and F_L data based on a dipole model containing low x saturation (FS04-sat)…

… NNPDF (also HERA framework) DGLAP QCD fits cannot accommodate saturation effects if F_2 and F_L both fitted

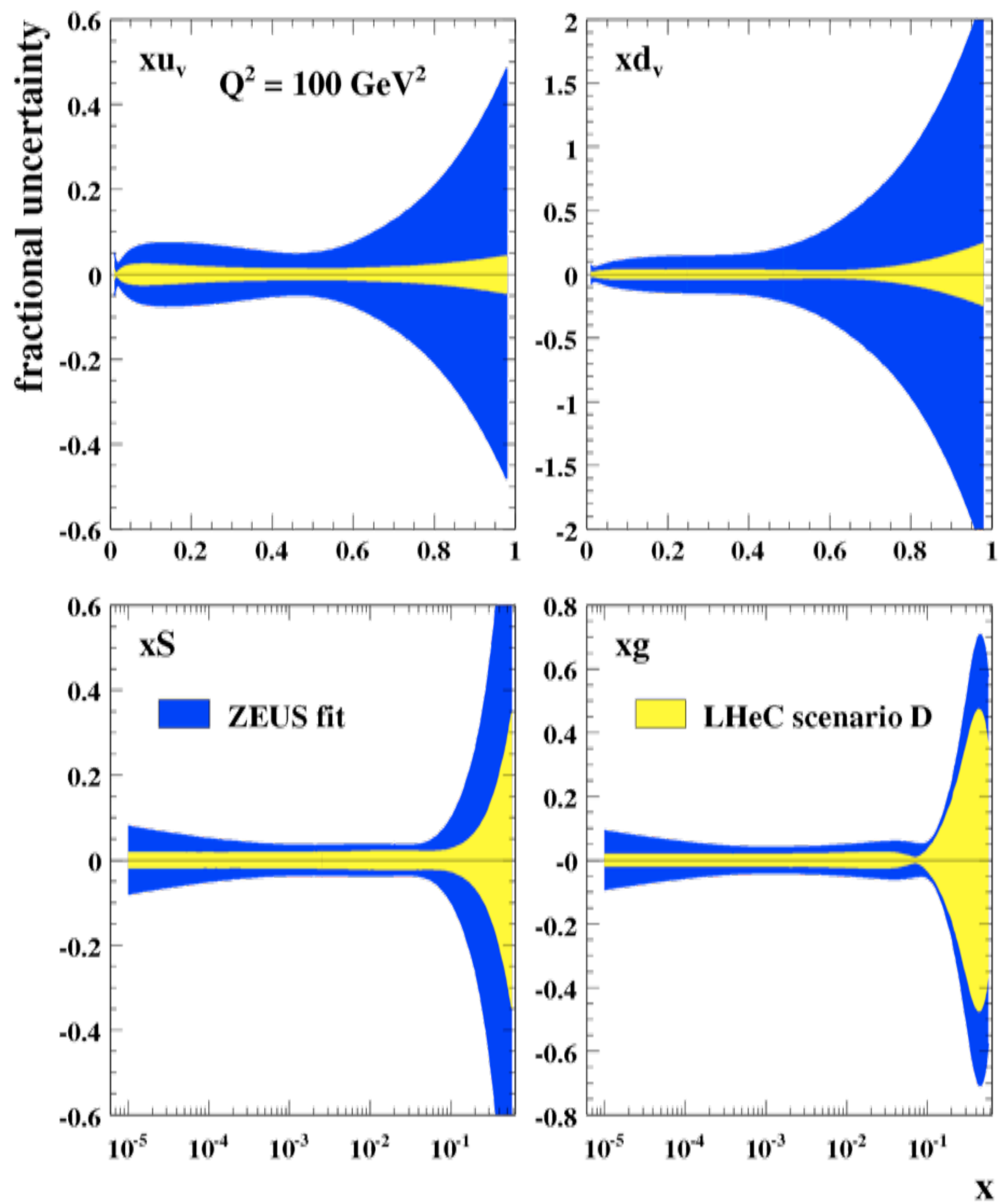




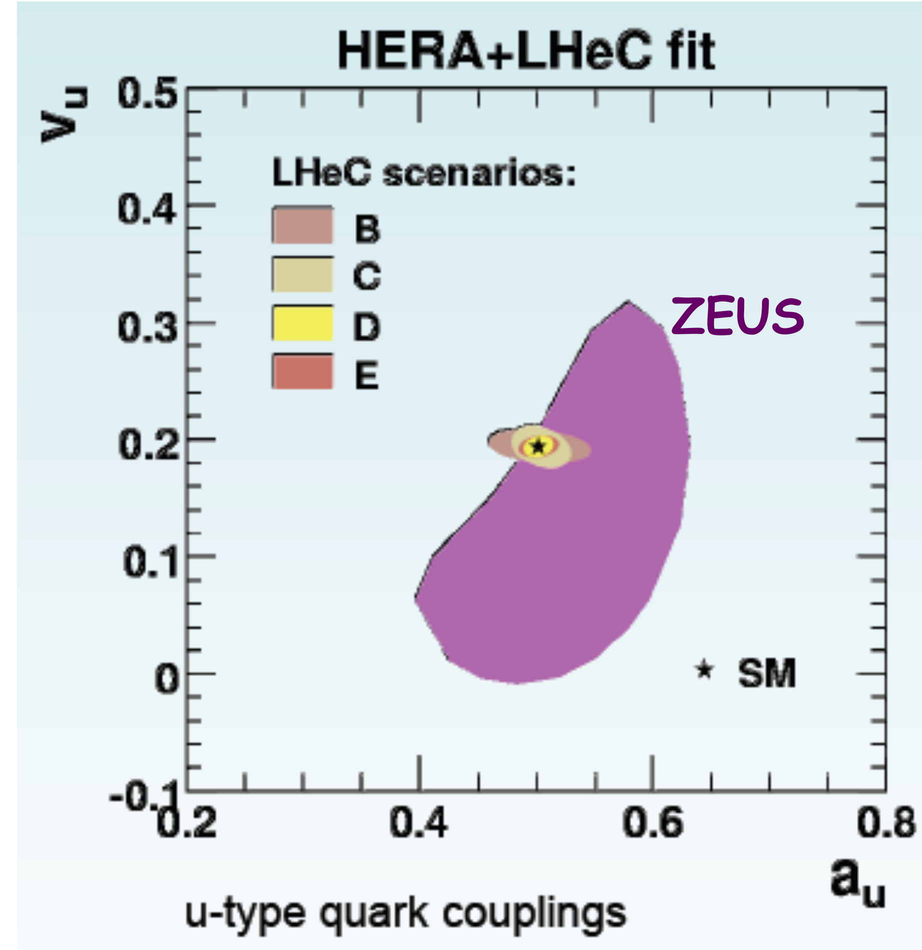
[Rojo]

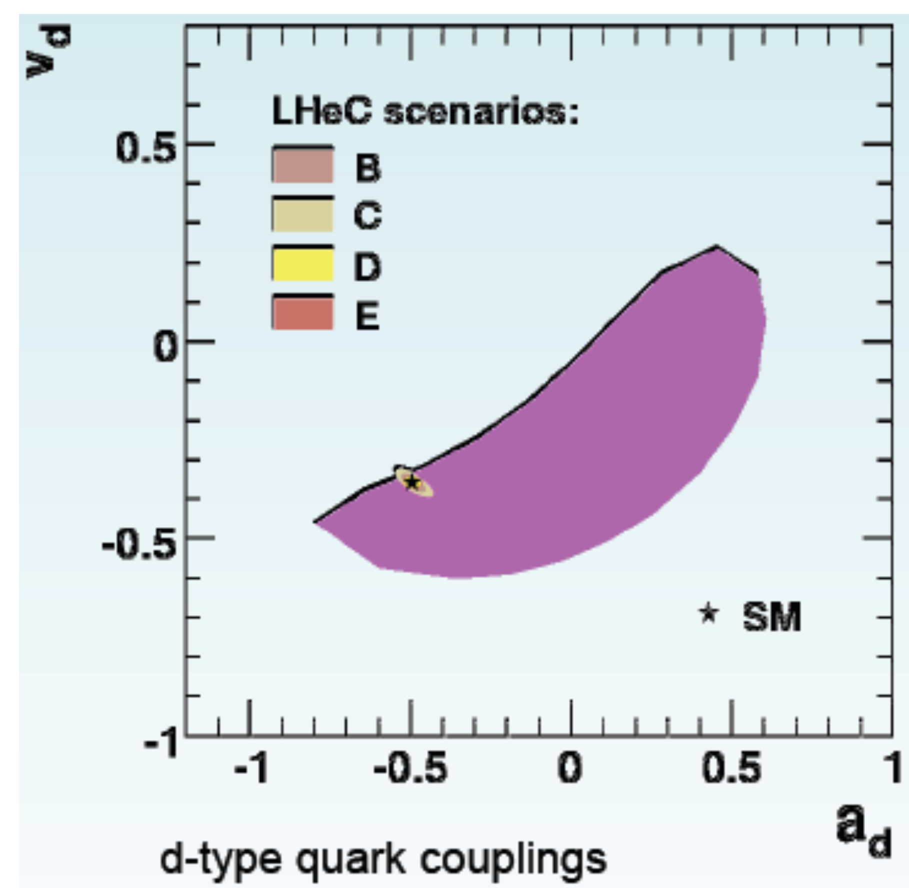
Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … (F_2^c may work in place of F_L)…

PDFs & EW Couplings



[Gwenlan]

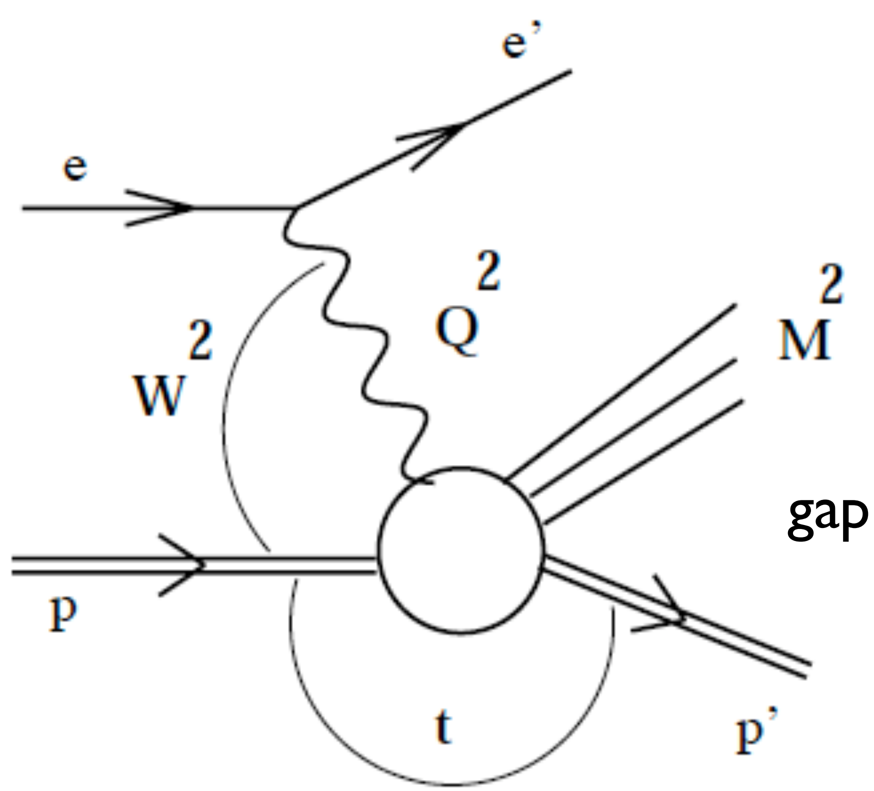




Using ZEUS fitting code, HERA + LHeC data … EW couplings free

E_e = 100 GeV, L = 10+5 fb^{-1}, P = +/- 0.9

Diffraction



$$e + p \rightarrow e' + p' + X$$

Proton stays intact and separated by a rapidity gap

M^2 diffractive mass

$t = (p - p')^2$ momentum transfer

$\Delta\eta = \ln 1/x_{I\!P}$ Rapidity gap

$$x_{I\!P} = \frac{Q^2 + M^2 - t}{Q^2 + W^2}$$

momentum fraction of the Pomeron with respect to the hadron

$$\beta = \frac{Q^2}{Q^2 + M^2 - t}$$

momentum fraction of the struck parton with respect to the Pomeron

$$x = x_{I\!P}\,\beta$$

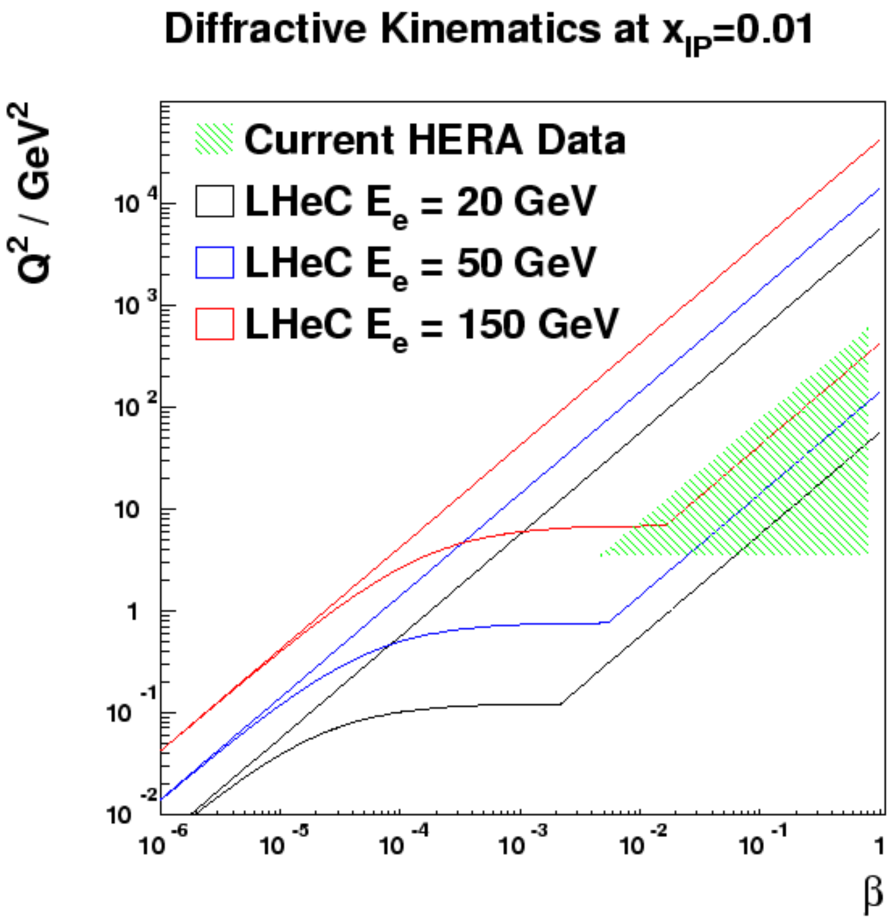
Bjorken x

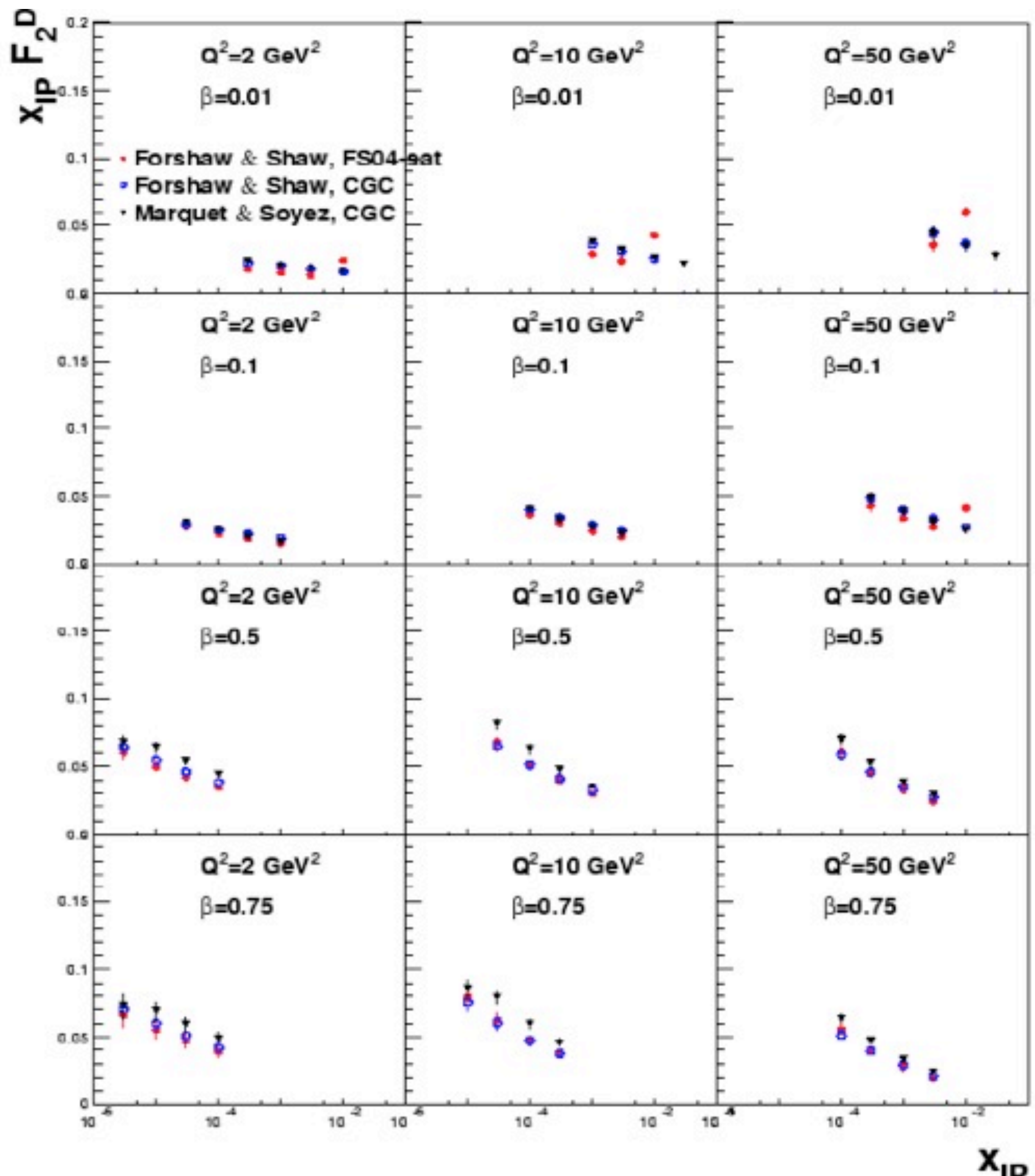
Diffraction

- Enhanced sensitivity to semi-hard regime
- Explore relation with saturation at unprecedented low x
- Test factorization (or lack of it)
- Gap survival issues
- Additional momentum transfer dependence allows access to measure the impact parameter profile of the interaction region

LHeC has the potential to address these problems in an extended kinematic regime

Diffraction at LHeC: new possibilities





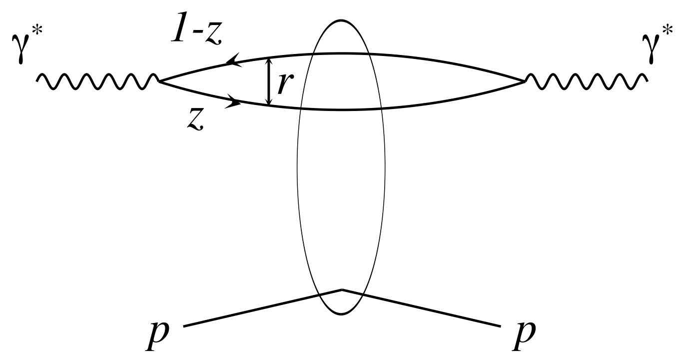
- Studies with 1 degree acceptance,
- Diffractive-PDFs
- Factorization (tests) in much bigger range
- Diffractive masses $M_X \sim 100\text{GeV}$ with $x_{I\!P} = 0.01$
- X can include W,Z,b

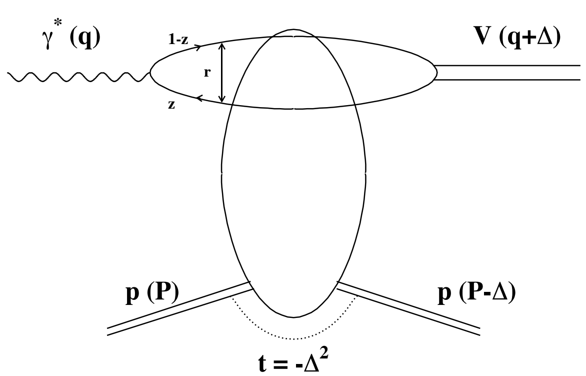
Forshaw, Marquet, Newman

Diffraction and saturation

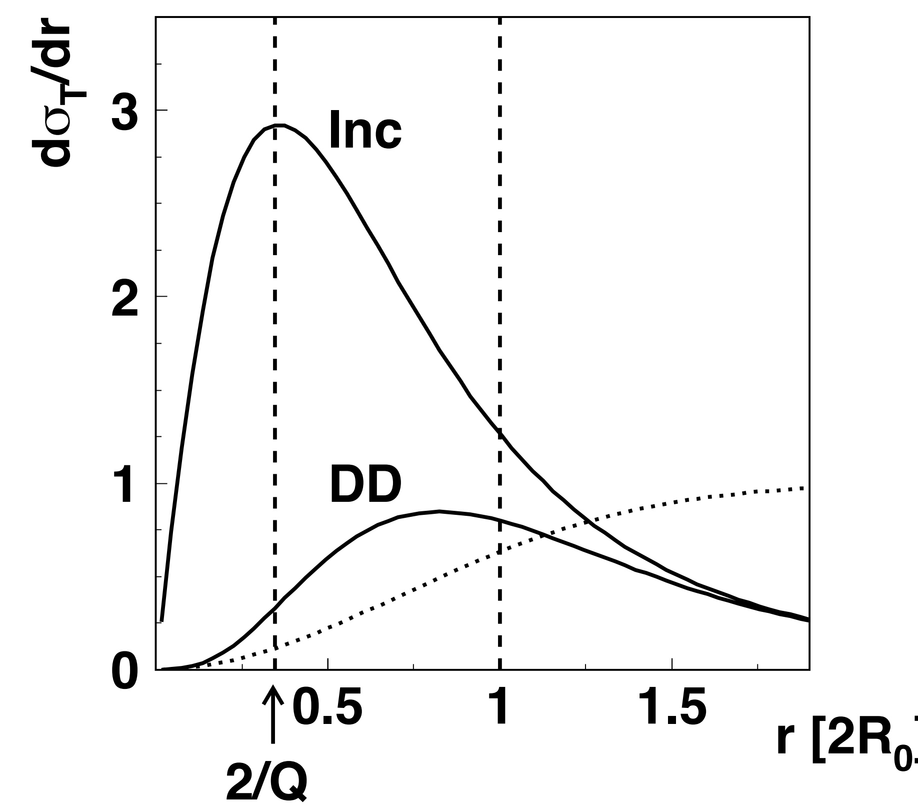
Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r} \int_0^1 dz\; \sum_f \;|\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2\; \hat\sigma(x,\mathbf{r})\,.$$





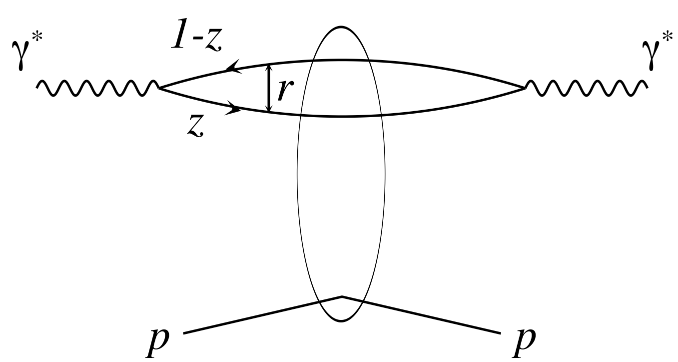
overlap function in the dipole model
typical dipole sizes involved in the process



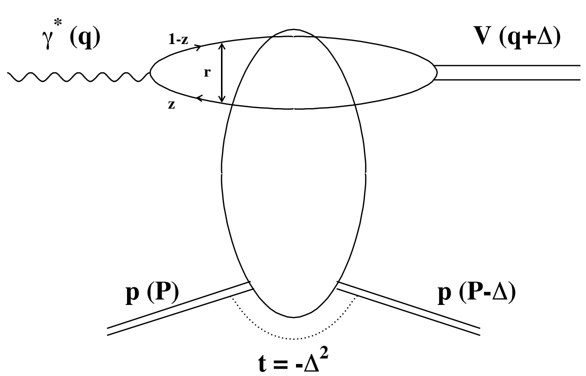
Diffraction and saturation

Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

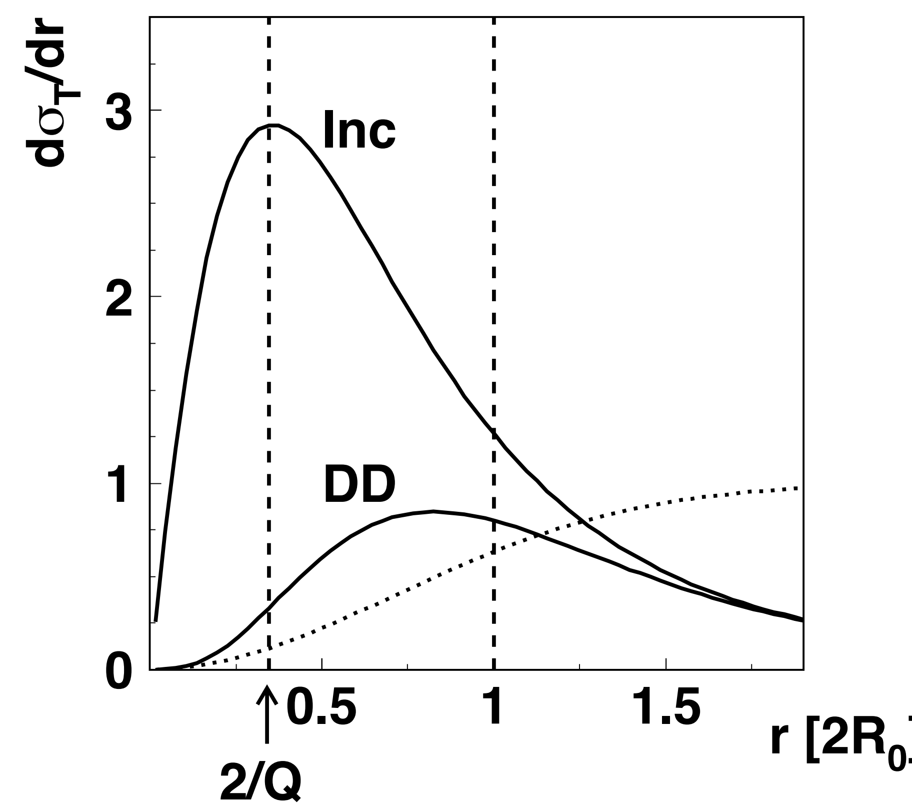
$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r} \int_0^1 dz \;\sum_f\; |\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2 \;\hat{\sigma}(x,\mathbf{r})\,.$$



Inclusive: dominated by relatively hard component



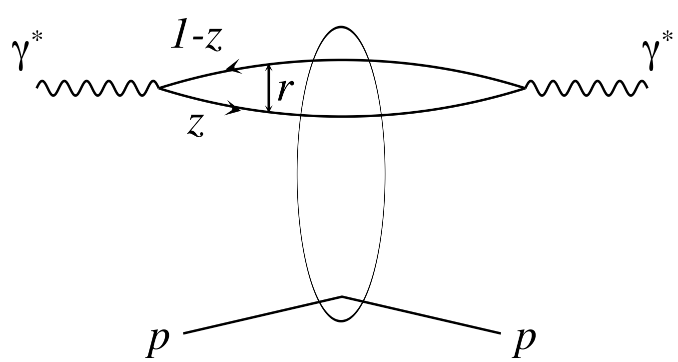
overlap function in the dipole model
typical dipole sizes involved in the process



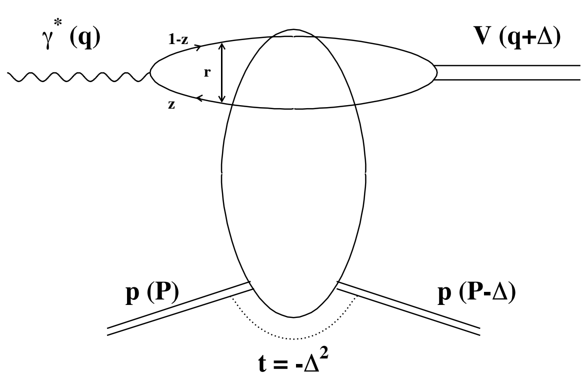
Diffraction and saturation

Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r}\int_0^1 dz\;\sum_f\;|\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2\;\hat{\sigma}(x,\mathbf{r})\,.$$

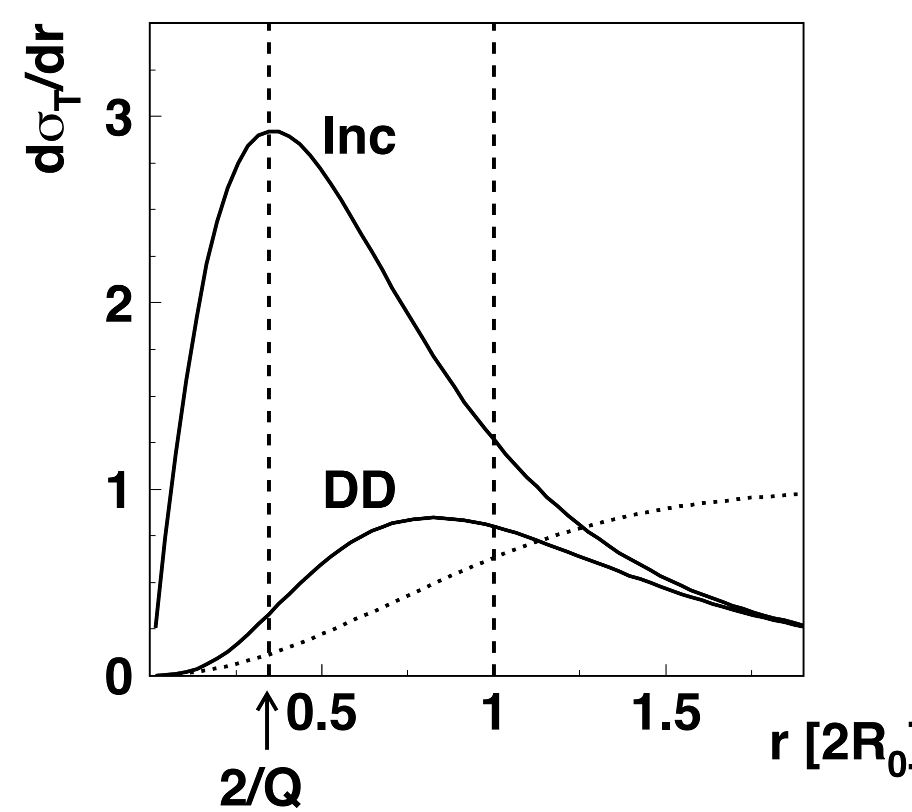


Inclusive: dominated by relatively hard component



Diffractive: dominated by the semi-hard momenta

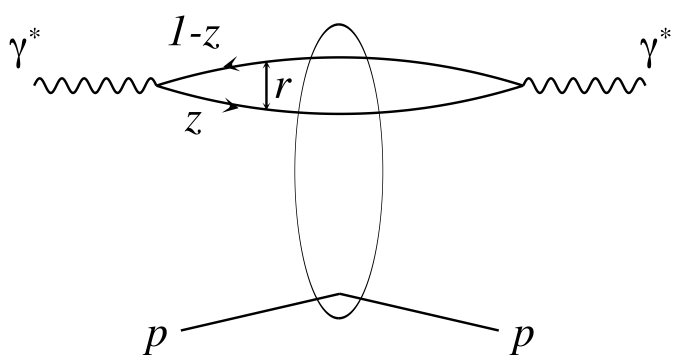
overlap function in the dipole model
typical dipole sizes involved in the process



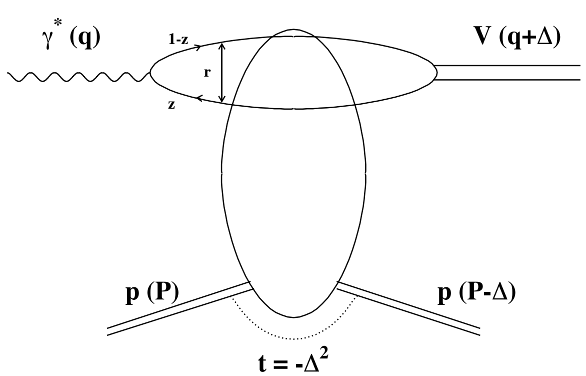
Diffraction and saturation

Dipole model at high energy: photon fluctuates into qqbar pair and undergoes an interaction with the target

$$\sigma_{T,L}(x,Q^2) \;=\; \int d^2\mathbf{r} \int_0^1 dz \;\sum_f\; |\Psi^f_{T,L}(\mathbf{r},z,Q^2)|^2 \;\hat{\sigma}(x,\mathbf{r})\,.$$

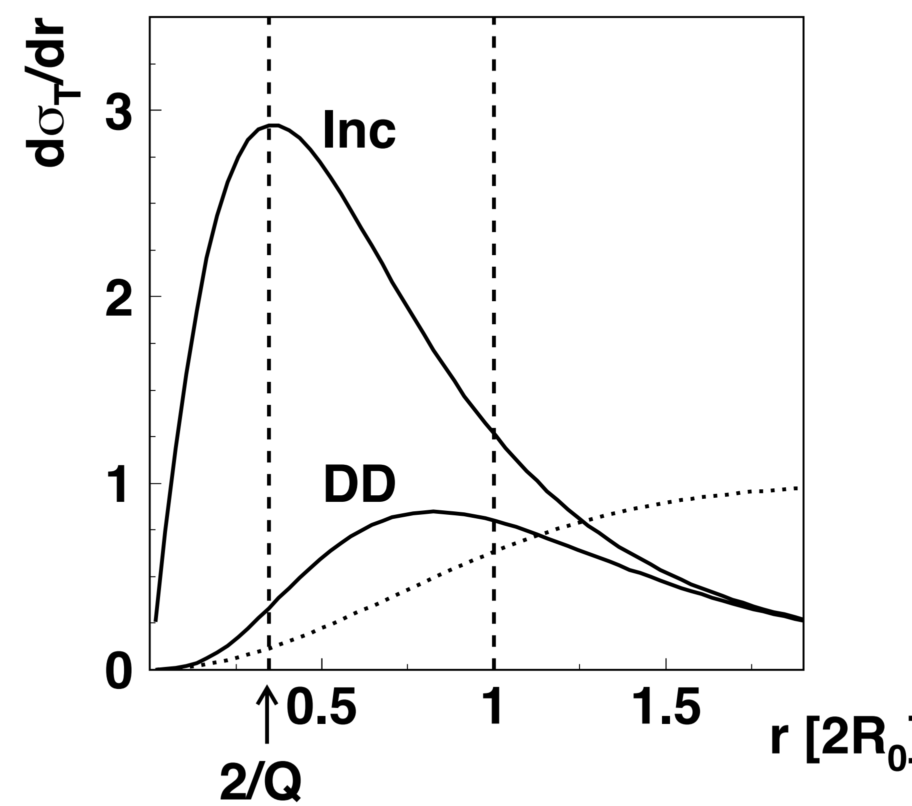


Inclusive: dominated by relatively hard component



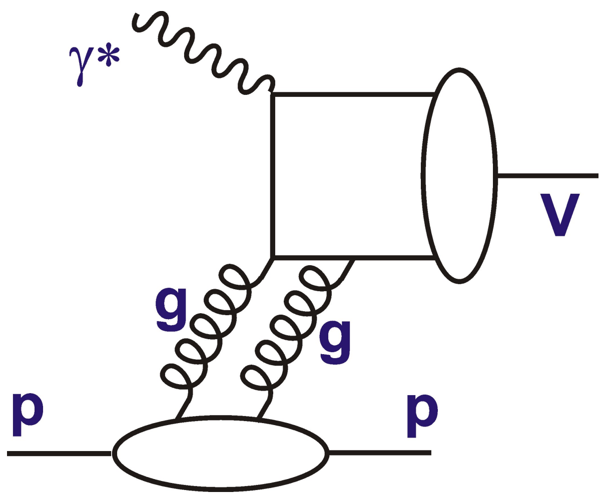
Diffractive: dominated by the semi-hard momenta

overlap function in the dipole model
typical dipole sizes involved in the process

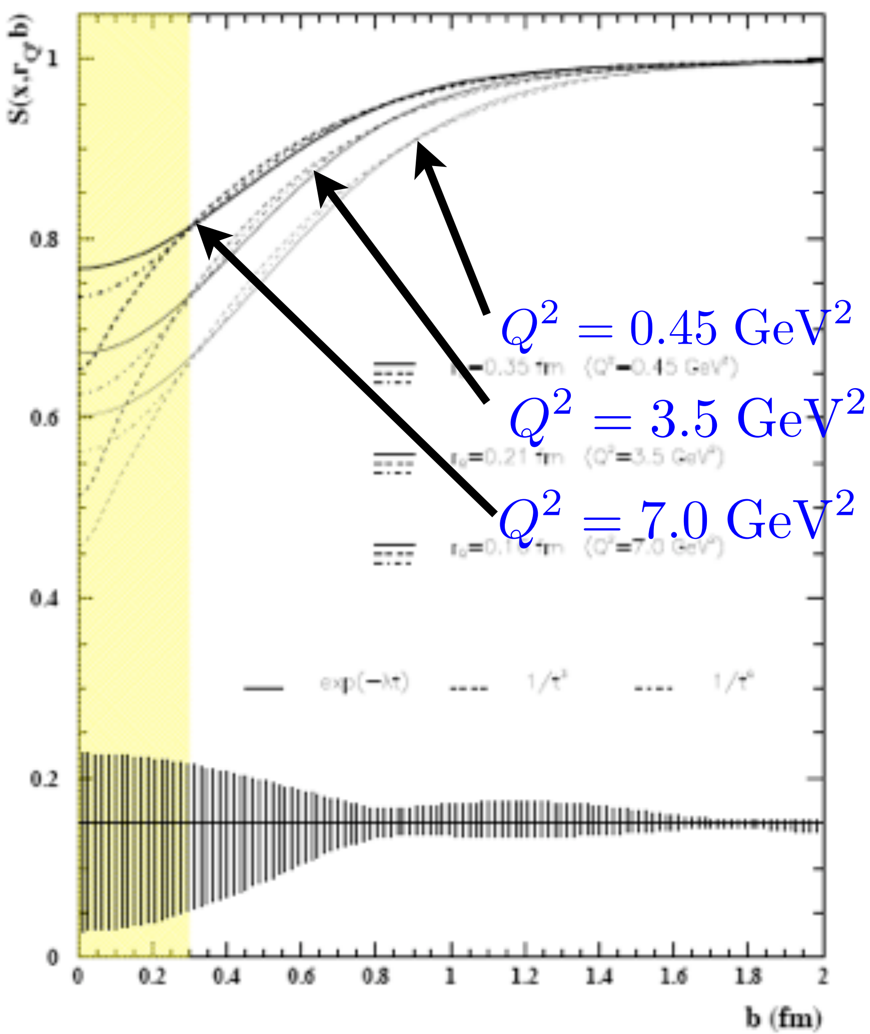


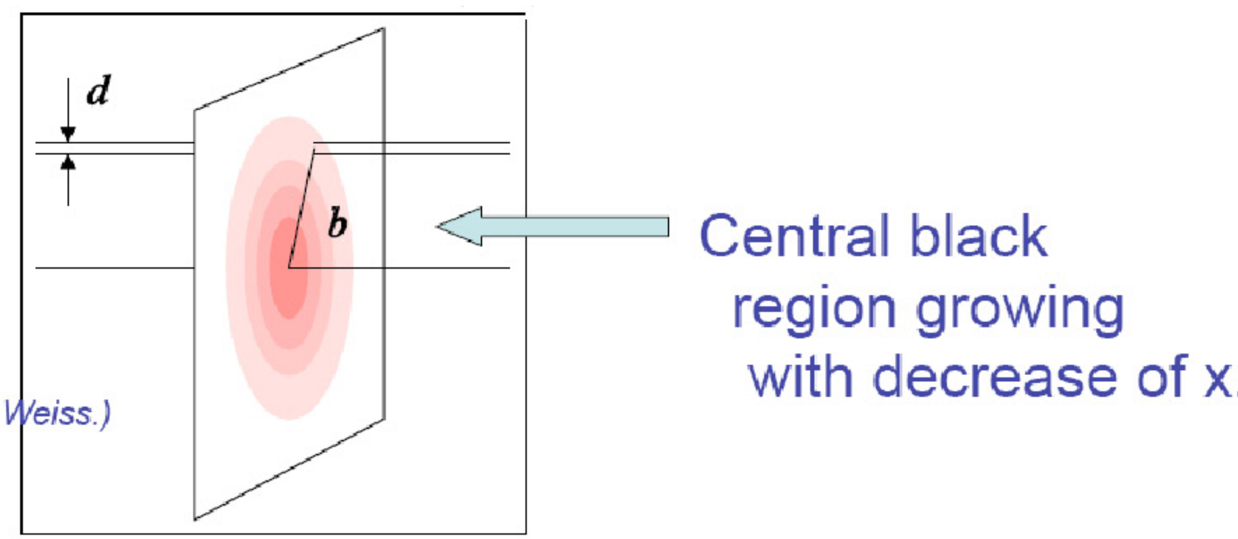
Diffraction is a collective phenomenon. Explore relation with saturation.

Exclusive diffraction



- Exclusive diffractive production of VM is an excellent process for extracting the dipole amplitude
- Suitable process for estimating the 'blackness' of the interaction.
- t-dependence provides an information about the impact parameter profile of the amplitude.



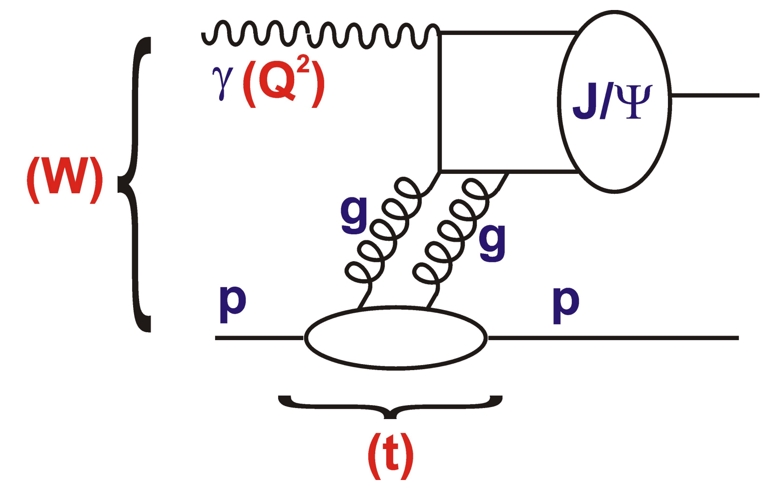


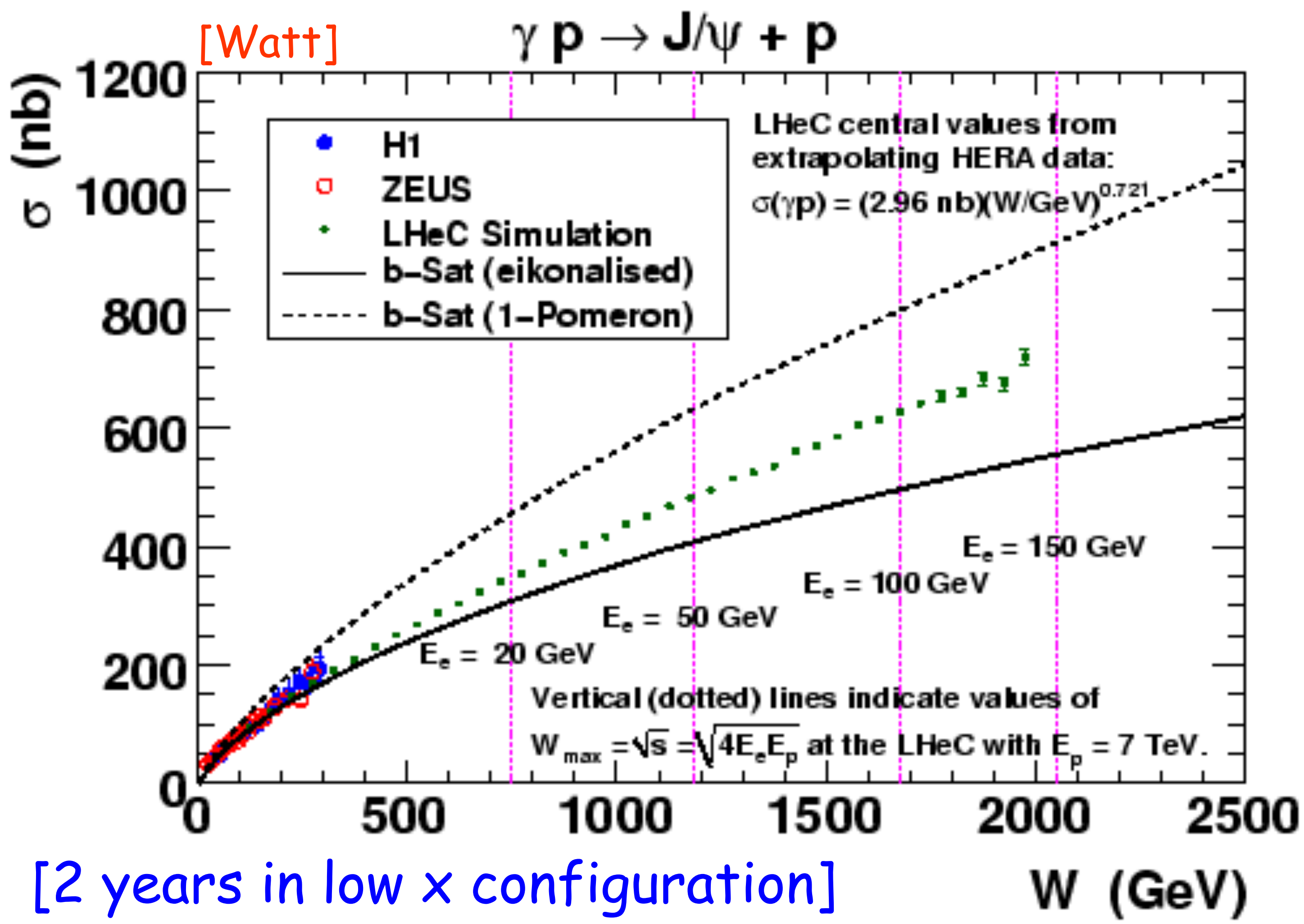
(figure from C. Weiss.)

$1 - S^2$ probability that a dipole passing the proton will induce an inelastic reaction at the given impact parameter

Exclusive diffraction in dipole model

- b-Sat dipole model (Golec-Biernat, Wuesthoff, Bartels, Motyka, Kowalski, Watt)
- eikonalised: with saturation
- 1-Pomeron: no saturation



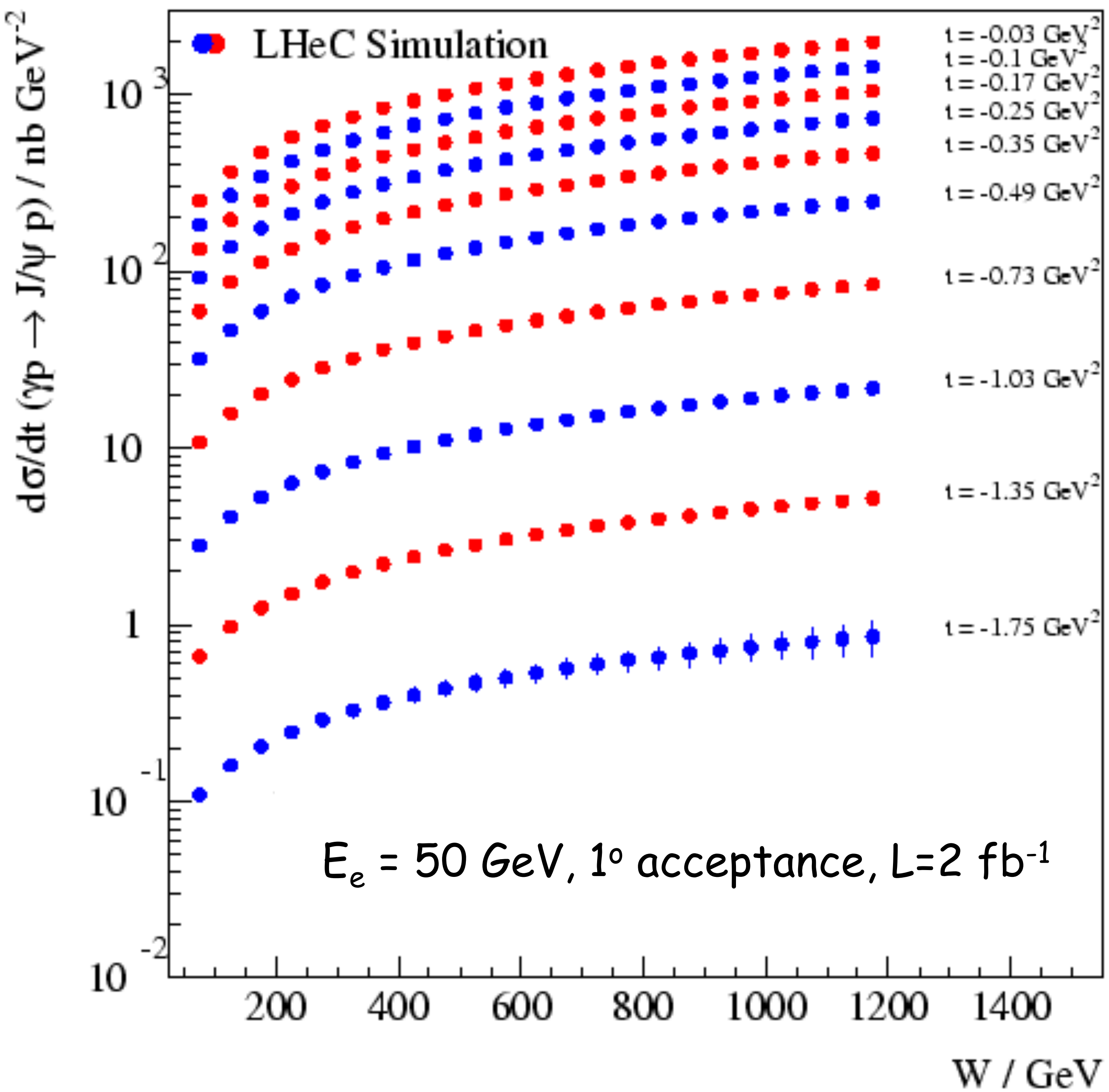


[2 years in low x configuration]

- Significant effects even for the t-integrated observable.
- Different W behavior depending whether saturation is included or not.
- Simulated data are from extrapolated fit to HERA data

Exclusive diffraction in dipole model

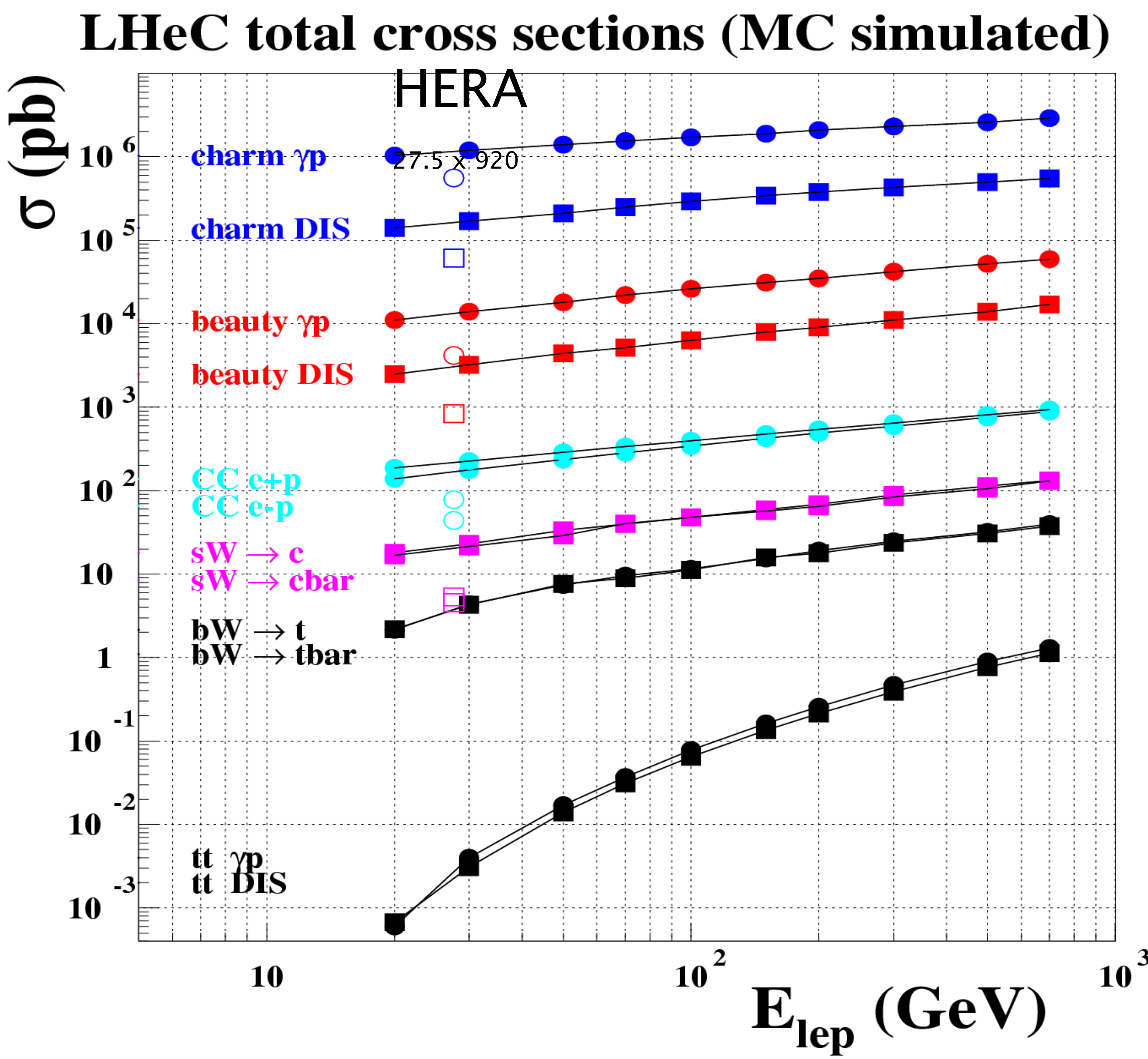
differential cross section in bins of t



- photoproduction cross section double differential in W and t
- small x of the gluon probed
- precise t-dependence can help us map the impact parameter profile
- possible also in DIS for several Q bins and other states like Upsilon and for DVCS process.

Physics with heavy flavors

Luminosity
$10\ fb^{-1}$



Charm [Behnke]

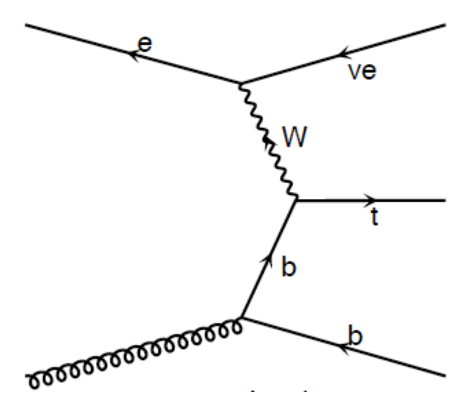
Beauty

cc

sW-> c

bW->top

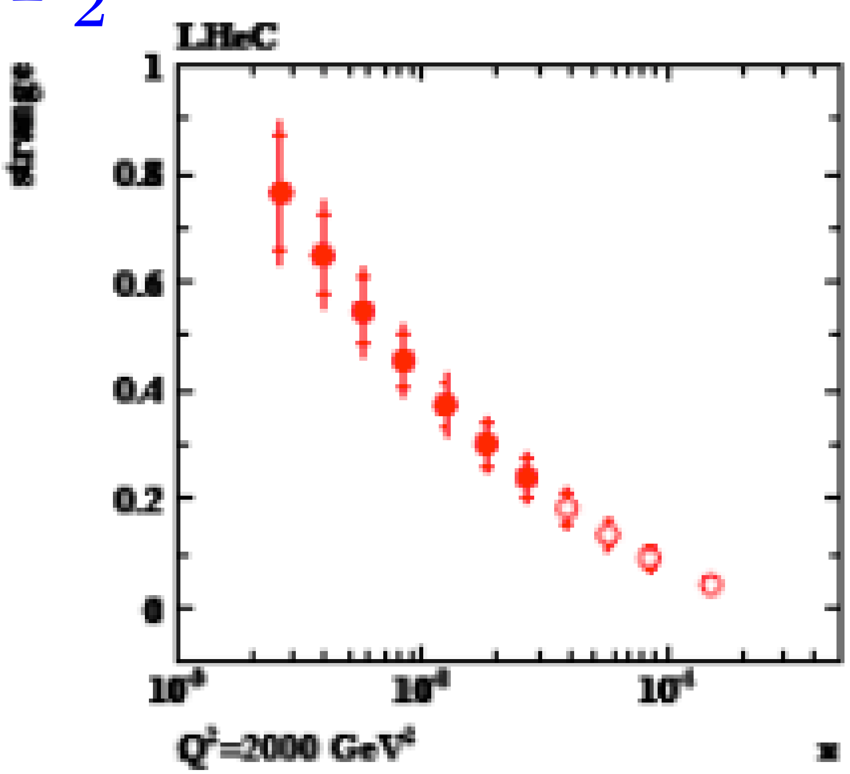
ttbar

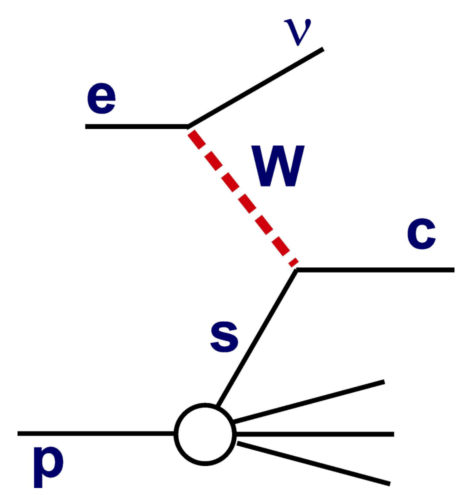


LHeC is a flavor factory!

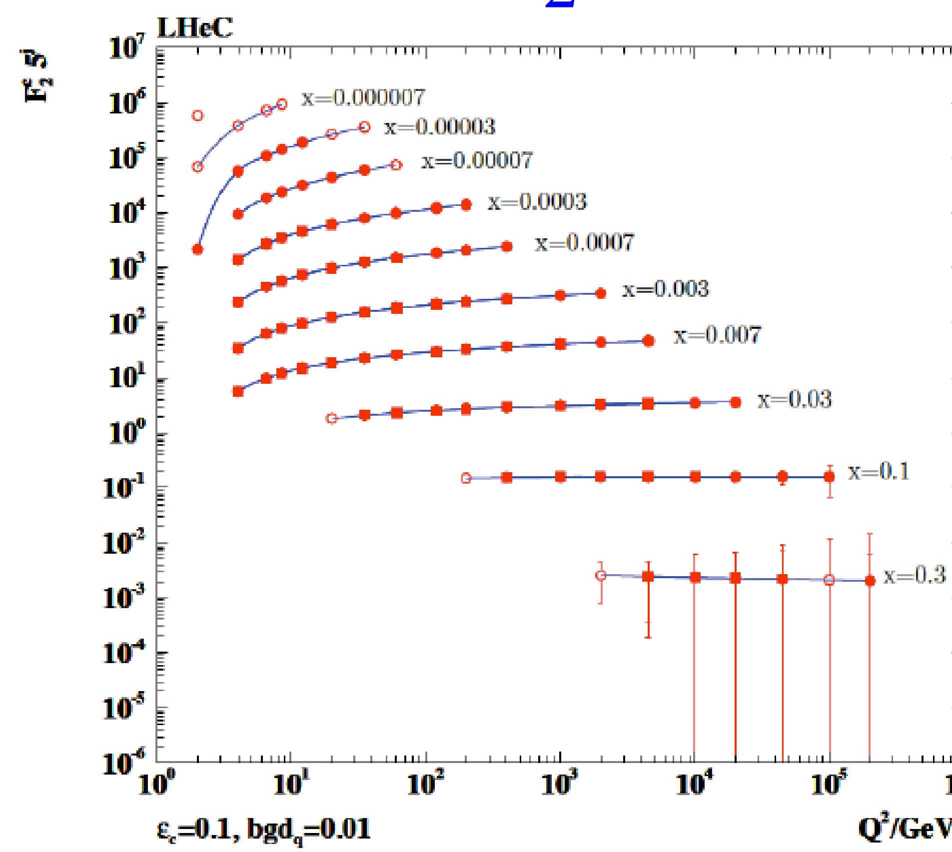
Flavor decomposition

F_2^{strange}





F_2^{charm}



Systematic error dominates (so far 3%)

Precise measurement near threshold and up to 10^5 GeV^2

F_2^{cc} will become precision testing ground for QCD and proton structure

open: 1°

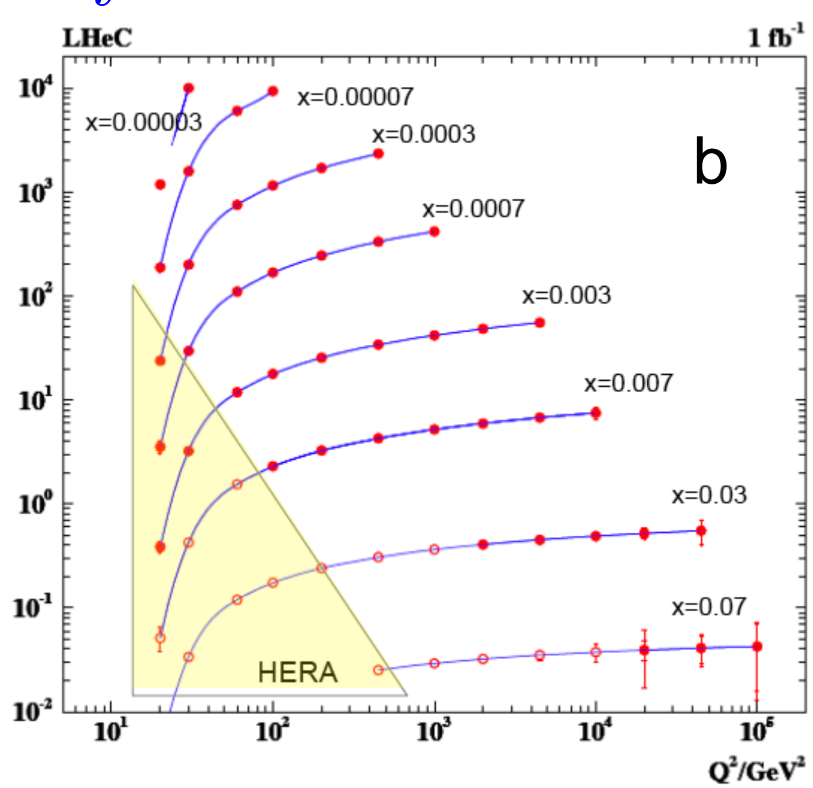
closed: 10°

box: 1 TeV

● LHeC 10° acceptance

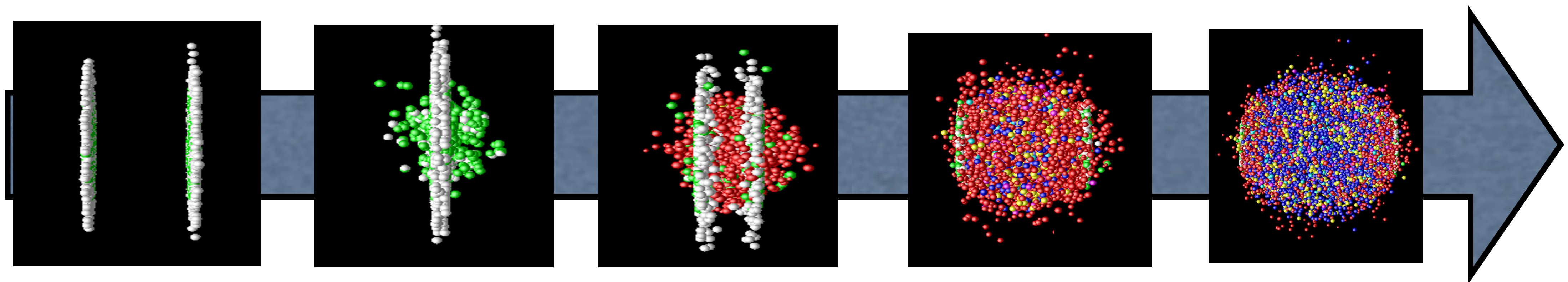
○ LHEC 1° acceptance

F_2^{beauty}



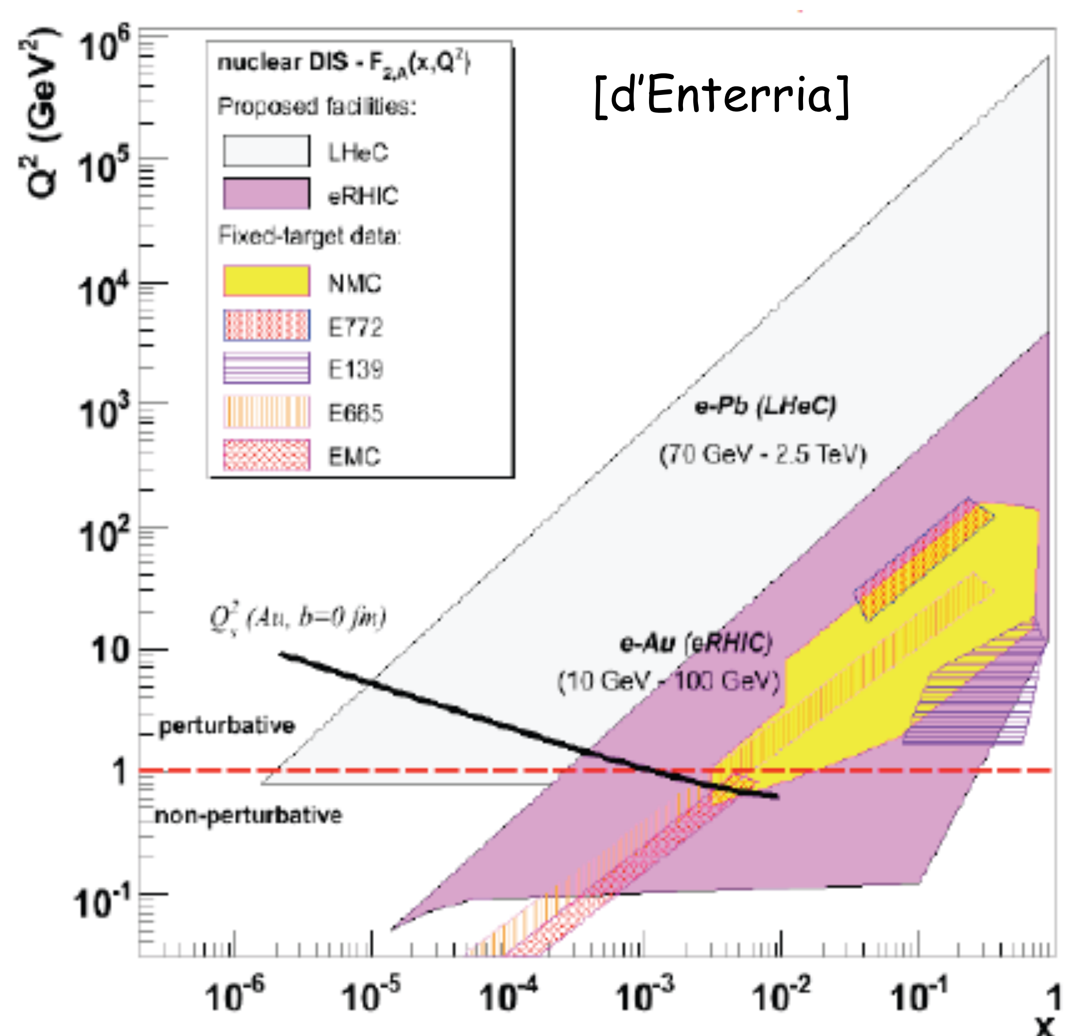
- High precision c,b measurements
- Possible s (and sbar) from charged current
- b is a small x observable
- Also possible $Wb \rightarrow t$

electron-ion collisions

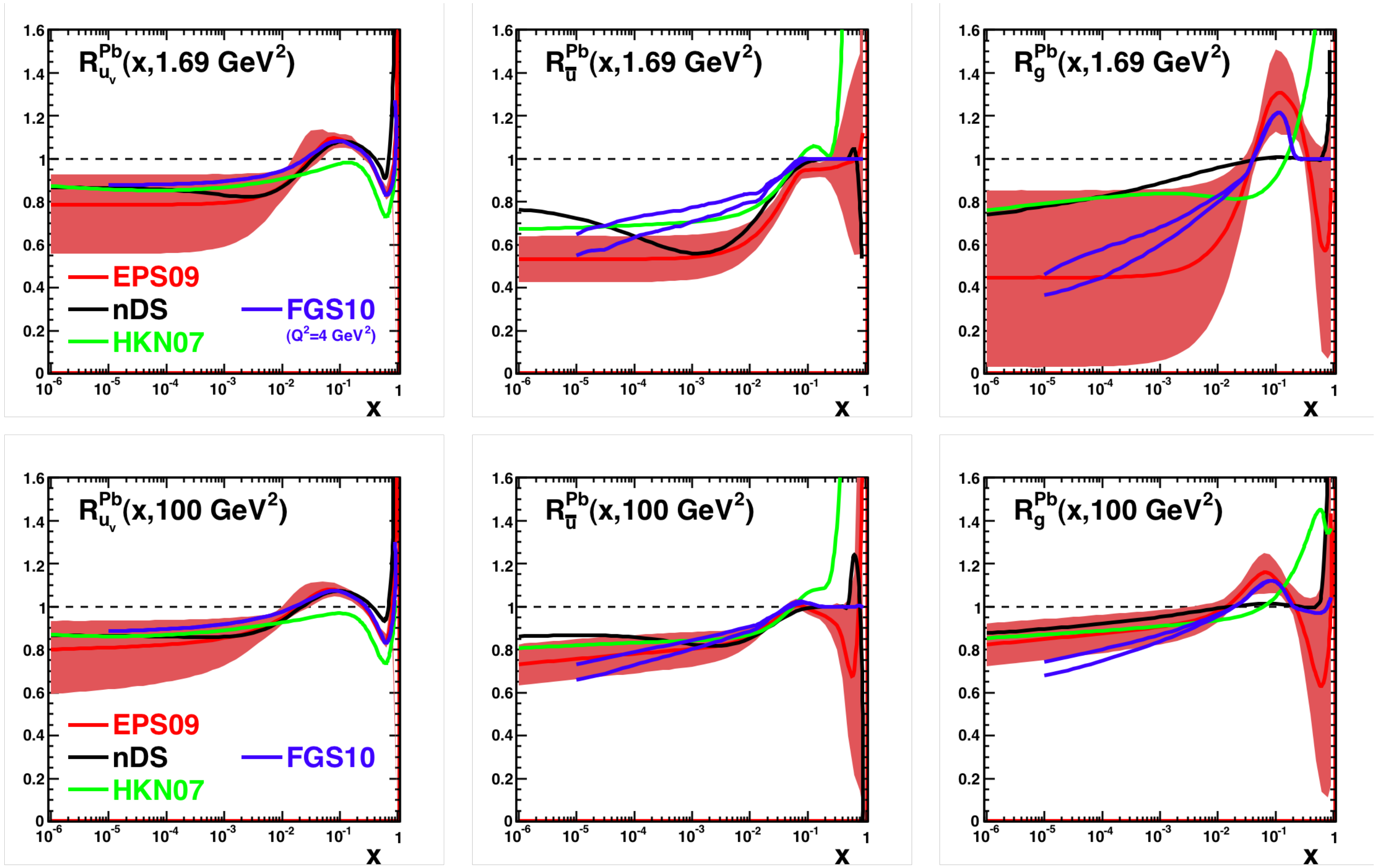


Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Measurement of eA essential for understanding the initial stage in the heavy ion collisions.
- So far limited kinematical range known
- Gluon in nucleus is not very well constrained
- LHeC can extend the range in x by 4 orders of magnitude as compared with existing data, and by 2 orders of magnitude as compared with planned eRHIC machine



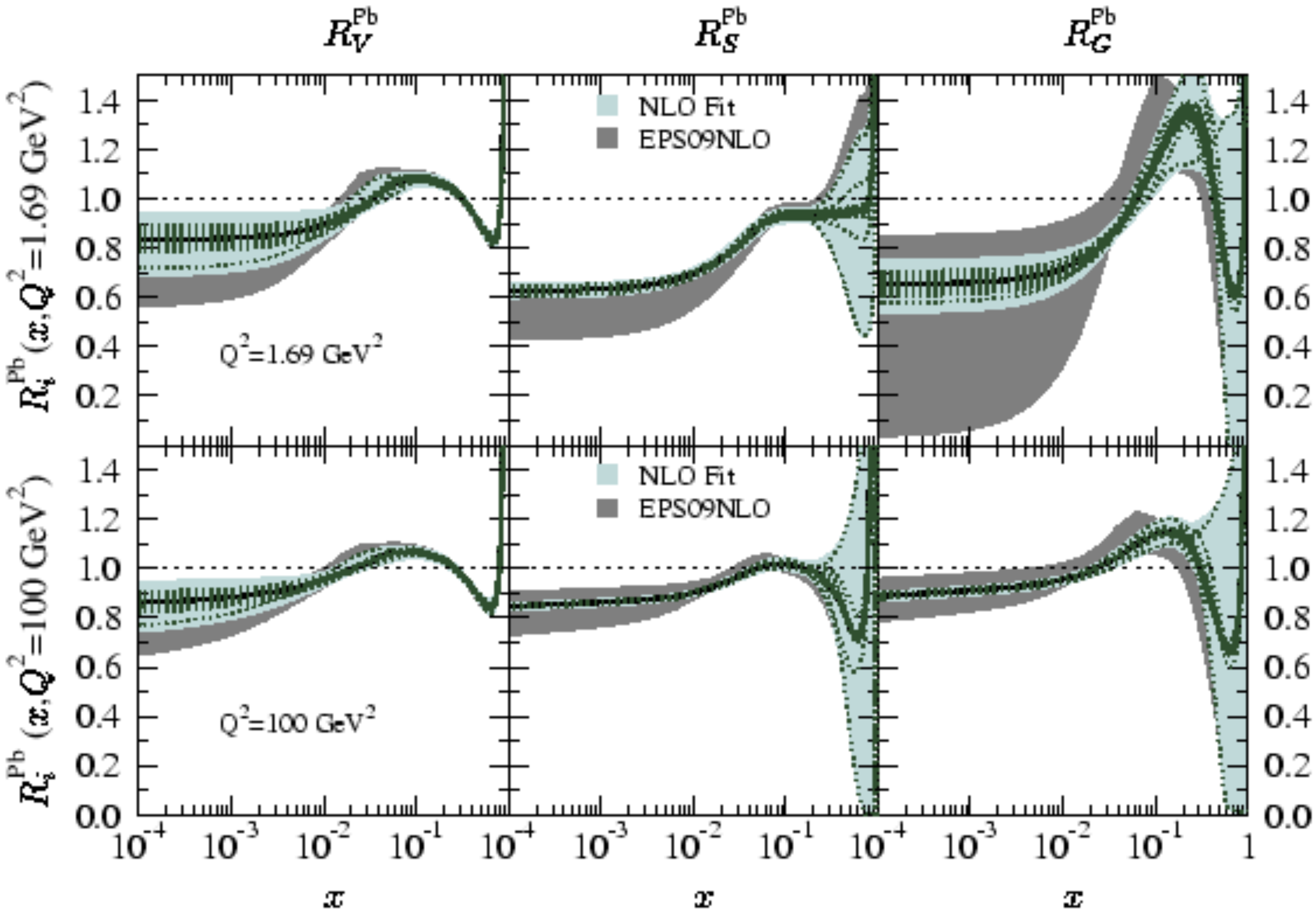
Extrapolation of nuclear parton densities



R_i = Nuclear PDF i / (A * proton PDF i)

Current status: nuclear parton distribution functions are poorly known at small x. Especially gluon density, below x=0.01 can be anything between 0 and 1....

Impact of LHeC on nuclear parton distributions



- Very large constraint on the low x gluons and sea quarks.
- Large x region remains unconstrained
- Work in progress: full flavor decomposition

Organization of the Conceptual Design Report

Scientific Advisory Committee

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
Stan Brodsky (SLAC)
Allen Caldwell -chair (MPI Munich)
Swapan Chattopadhyay (Cockcroft)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (CERN)
Joel Feltesse (Saclay)
Lev Lipatov (St.Petersburg)
Roland Garoby (CERN)
Roland Horisberger (PSI)
Young-Kee Kim (Fermilab)
Aharon Levy (Tel Aviv)
Karlheinz Meier (Heidelberg)
Richard Milner (Bates)
Joachim Mnich (DESY)
Steven Myers, (CERN)
Tatsuya Nakada (Lausanne, ECFA)
Guenther Rosner (Glasgow, NuPECC)
Alexander Skrinsky (Novosibirsk)
Anthony Thomas (Jlab)
Steven Vigdor (BNL)
Frank Wilczek (MIT)
Ferdinand Willeke (BNL)

Steering Committee

Oliver Bruening	(CERN)
John Dainton	(Cockcroft)
Albert DeRoeck	(CERN)
Stefano Forte	(Milano)
Max Klein - chair	(Liverpool)
Paul Laycock (secretary)	(L'pool)
Paul Newman	(Birmingham)
Emmanuelle Perez	(CERN)
Wesley Smith	(Wisconsin)
Bernd Surrow	(MIT)
Katsuo Tokushuku	(KEK)
Urs Wiedemann	(CERN)
Frank Zimmermann	(CERN)

Working Group Convenors

Accelerator Design [RR and LR]
Oliver Bruening (CERN),
John Dainton (CI/Liverpool)

Interaction Region and Fwd/Bwd
Bernhard Holzer (DESY),
Uwe Schneeekloth (DESY),
Pierre van Mechelen (Antwerpen)

Detector Design
Peter Kostka (DESY),
Rainer Wallny (UCLA),
Alessandro Polini (Bologna)

New Physics at Large Scales
George Azuelos (Montreal)
Emmanuelle Perez (CERN),
Georg Weiglein (Durham)

Precision QCD and Electroweak
Olaf Behnke (DESY),
Paolo Gambino (Torino),
Thomas Gehrmann (Zuerich)
Claire Gwenlan (Oxford)

Physics at High Parton Densities
Nestor Armesto (Santiago),
Brian Cole (Columbia),
Paul Newman (Birmingham),
Anna Stasto (PSU)

http://cern.ch/lhec

Schedule and remarks

- Proposal to start operation by 2020/2022 (new phase of LHC)
  - This is possible. HERA: proposal 1984-operation 1992. LEP: proposal 1983 - operation 1989.
- Major technologies for the detector and accelerator do exist. This machine can be built.
- Cost is modest in terms of major HEP experiments (part of the machine, LHC is already there)
- Next steps:
  - CDR fall 2010/early 2011
  - Evaluation by CERN, ECFA
  - If successful, set up professional structure to complete the TDR by 2013/2014
- In an optimistic long term perspective a super-LHC' beam of 16 TeV could be collided with a 140 GeV electron beam to give a CMS energy of 3 TeV and reaching down to $x \sim 10^{-7}$

Summary

- LHeC offers an access to a new world of luminosity and energy in lepton-hadron interactions.
- ep complementing next generation of ee and pp colliders.
- Already lots of interest among experimental and theoretical colleagues. Many tests and simulated data are available. Technical design under discussion.
- Still need a lot of work for the preparation of the CDR.
- Next major workshop, Divonne, October 2010.
- Ideas/suggestions and involvement are welcome!

http://cern.ch/lhec

Summary

- LHeC offers an access to a new world of luminosity and energy in lepton-hadron interactions.
- ep complementing next generation of ee and pp colliders.
- Already lots of interest among experimental and theoretical colleagues. Many tests and simulated data are available. Technical design under discussion.
- Still need a lot of work for the preparation of the CDR.
- Next major workshop, Divonne, October 2010.
- Ideas/suggestions and involvement are welcome!

> It would be a waste not to exploit the 7 TeV beams for eP and eA physics at some stage during the LHC time

G. Altarelli
Divonne 08

http://cern.ch/lhec