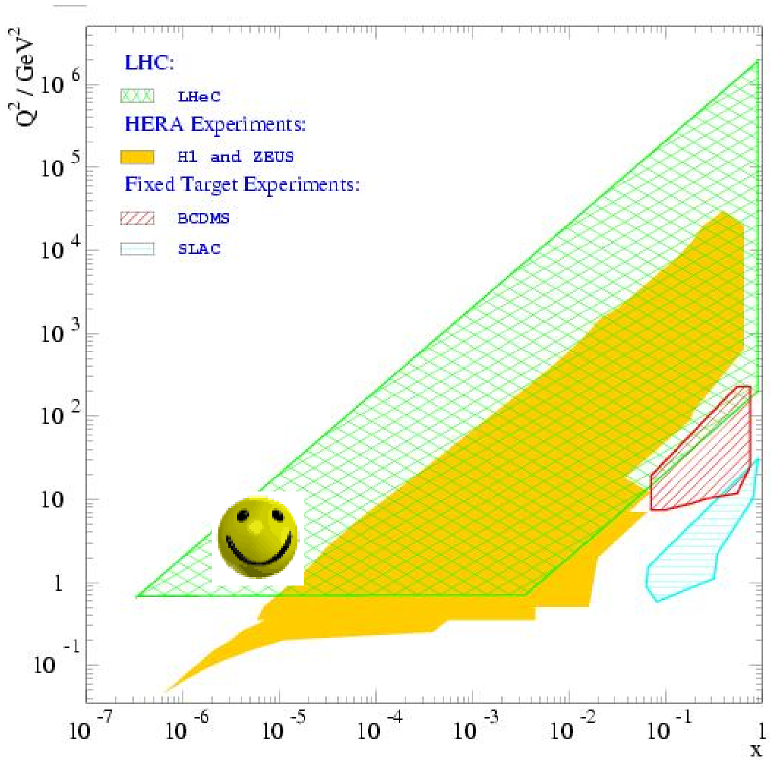
Low x and Diffractive ep and eA Physics

Paul Newman (Birmingham)

with Nestor Armesto, Brian Cole, Anna Stasto and the HPD group

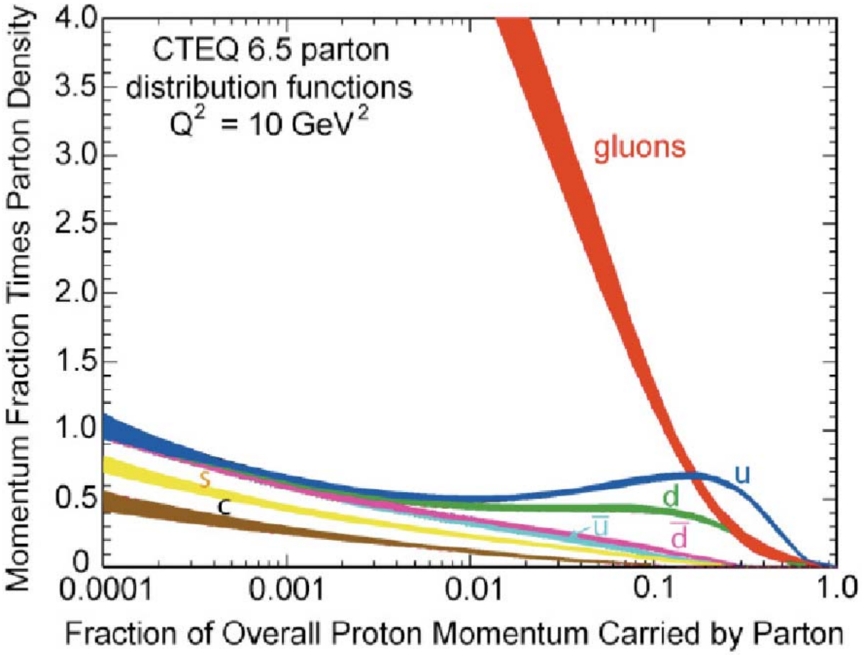
Divonne-II, 3 September 2009

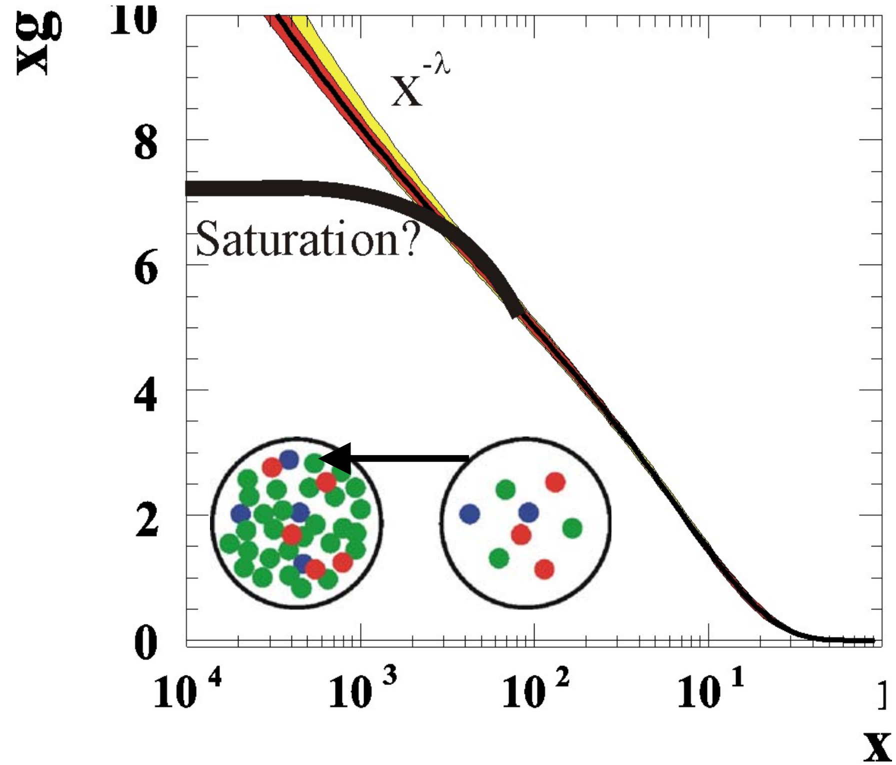
[Thanks to the many colleagues who contributed here and in a Other meetings in the past year]



- Intro: non-linear evolution
- Inclusive ep scattering
- Inclusive eA scattering
- Elastic Vector Mesons
- Inclusive Diffraction
- Forward Jet Production

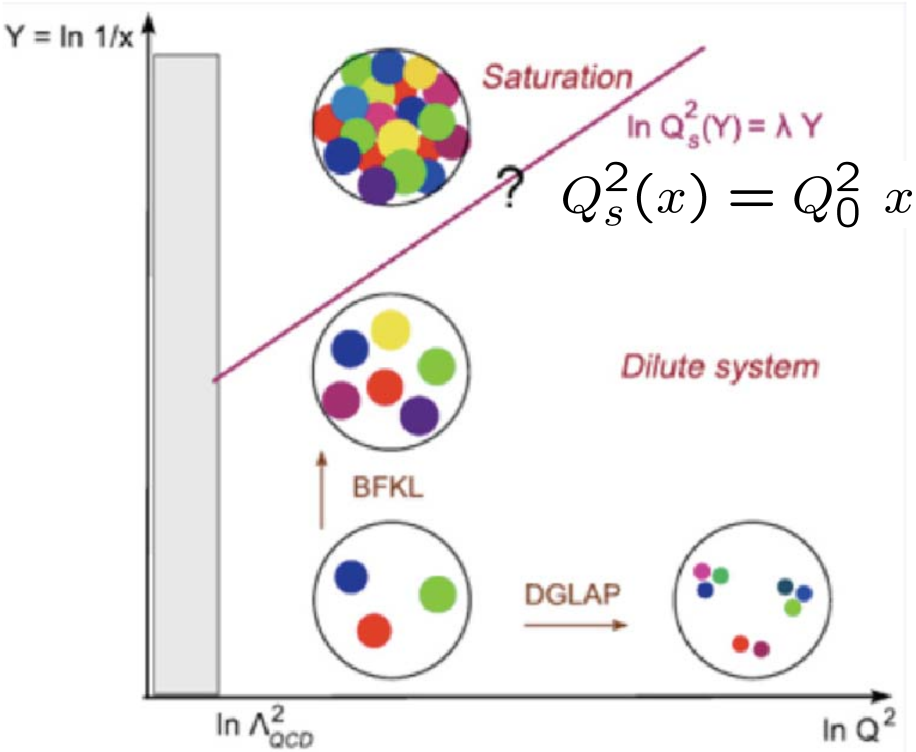
Low-x Physics and Non-linear Evolution





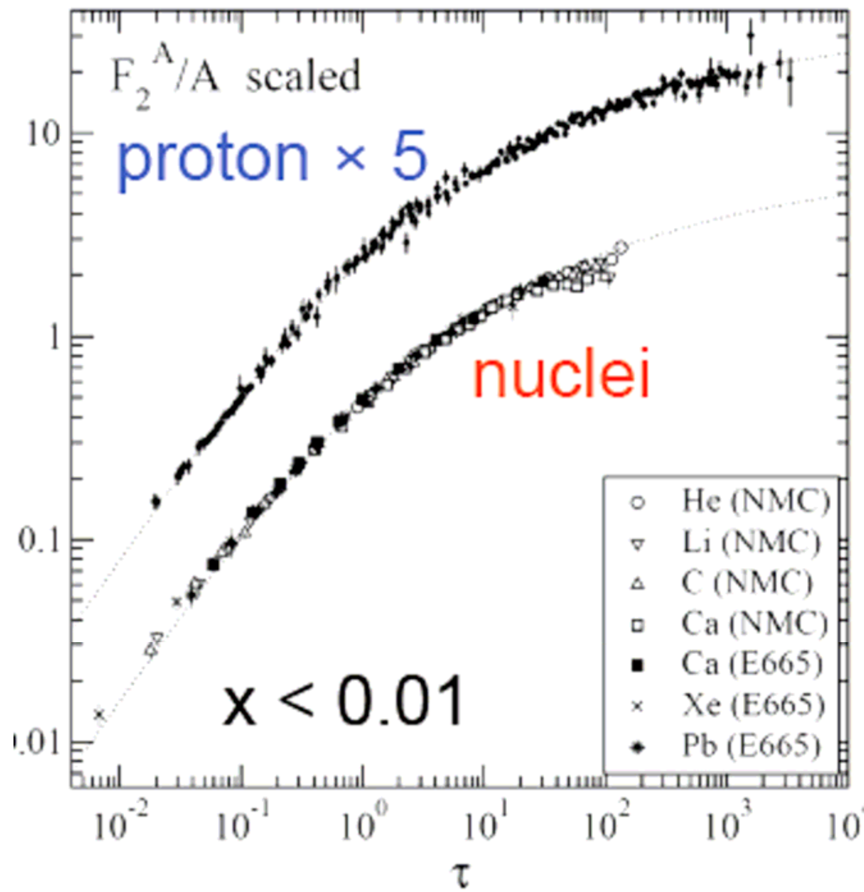
- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Dipole model language → **projectile $q\bar{q}$ multiply interacting**
- Parton level language → **recombination gg → g?**
- Usually characterised in terms of an x dependent "saturation scale", $Q^2_s(x)$, to be determined experimentally

Non-linear effects in HERA and eA Data



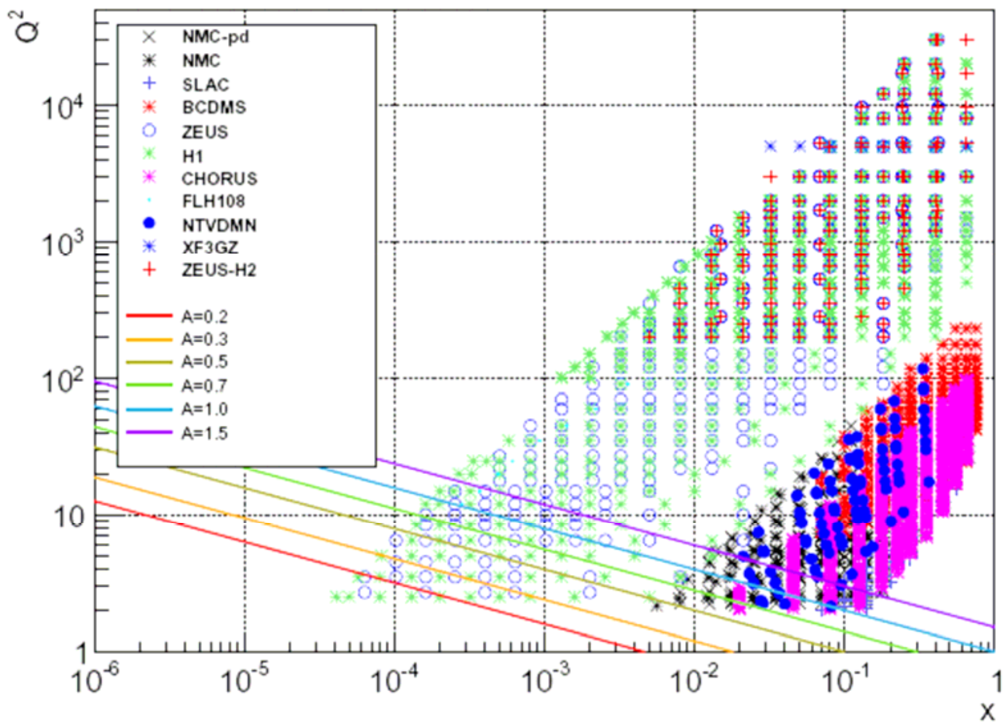
Lines of constant 'blackness' diagonal … … scattering cross section appears constant along them

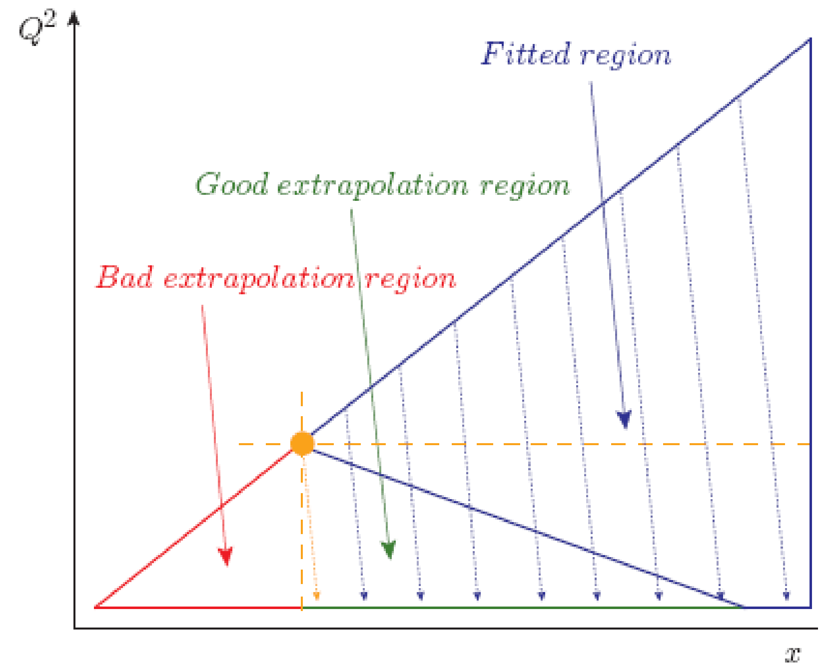
$$\sigma_{tot}^{\gamma^* h \to X}(x, Q^2) = \sigma_{tot}^{\gamma^* h \to X}(Q^2/Q_s^2(x))$$



Something appears to happen around $\tau = Q^2/Q^2_s = 1\ \text{GeV}^2$ (confirmed in many analyses)
BUT … Q^2 small for τ <~ 1 GeV^2
… not easily interpreted in QCD

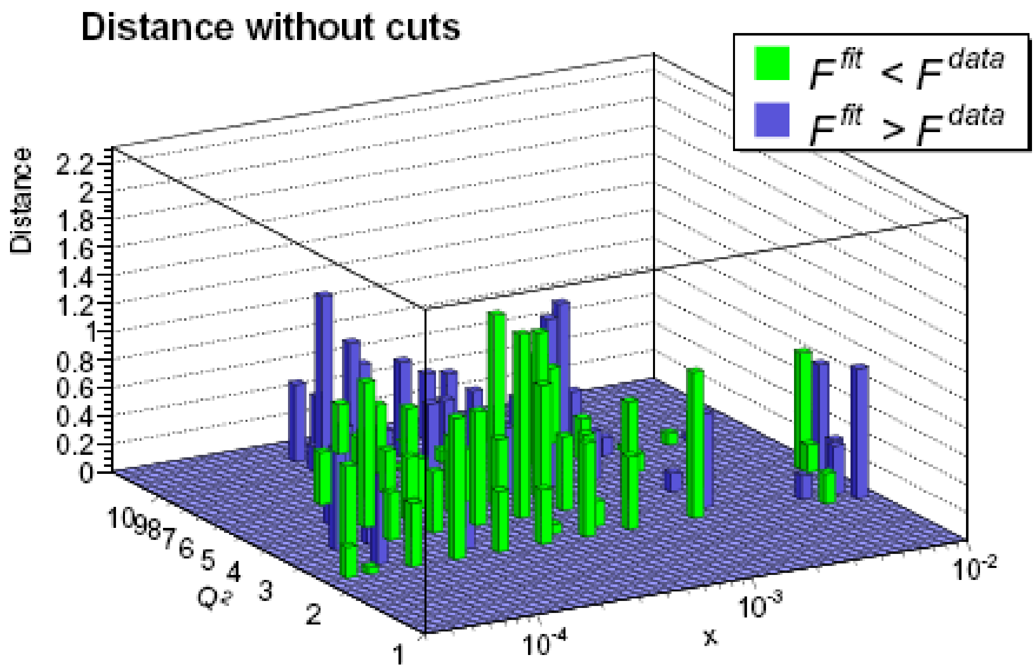
Confirmation in Study based on NNPDF (Caola)





- Fit HERA data in progressively reduced region above lines of $Q^2 > Ax^{-0.3}$ … using NNPDF1.2 → reliable errors
- Backwards evolve to lower scales
- Investigate quality of description as fitted region reduces and in `Good extrapolation' region connected via DGLAP evolution to fitted region

Confirmation in Study based on NNPDF (Caola)



Signed pulls show systematic effects in fitted region

Quality of backward evolution description in `safe' extrapolation region poor when data are excluded from fit

A	$\chi^2_{\text{without cuts}}/d.o.f.$	$\chi^2_{\text{cut}}/d.o.f$
0.5	19.68/25 = 0.79	106.22/25 = 4.25
1.0	54.41/44 = 1.24	138.24/44 = 3.14
1.5	62.31/59 = 1.06	860.65/59 = 14.6

"Evidence for deviations from NLO DGLAP @ HERA"

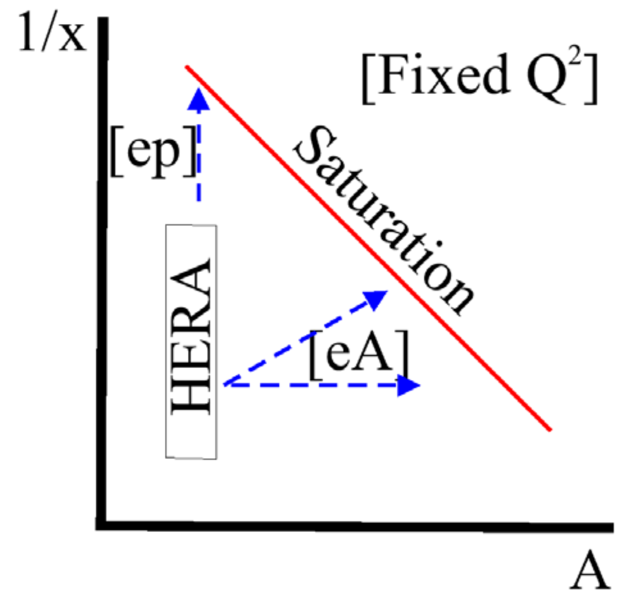
Effects go in wrong direction to be explained by NNLO
ln(1/x) resummation or non-linear evolution are candidates

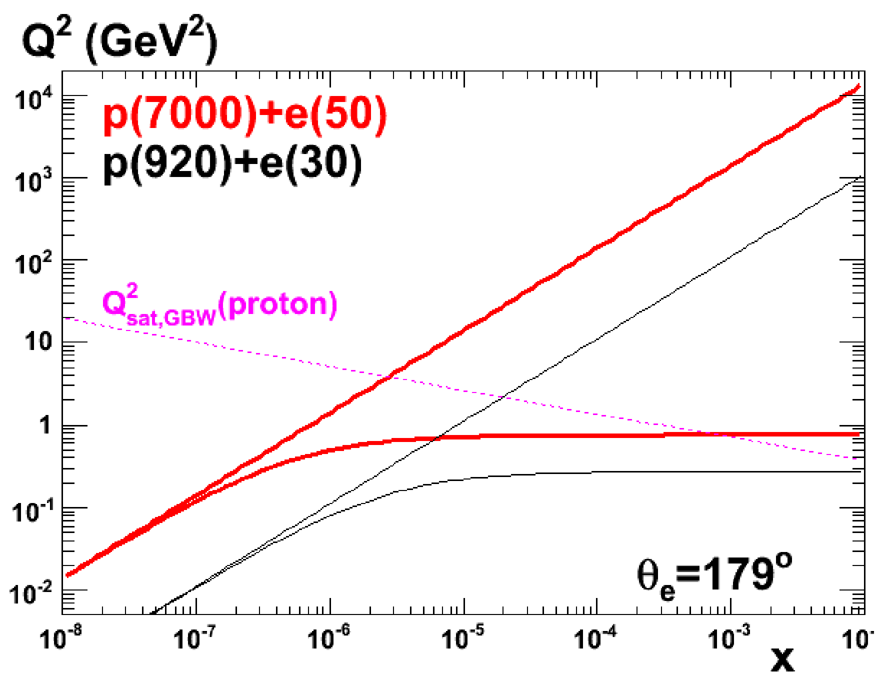
Going beyond HERA with Inclusive LHeC Data

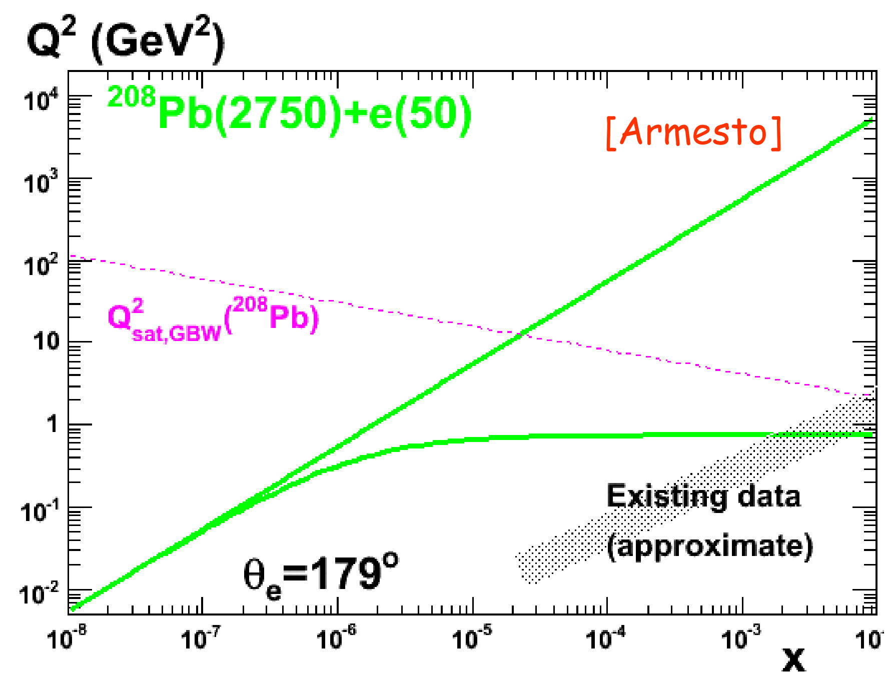
Enhance target `blackness' by:

1) Probing lower x at fixed Q^2 in ep

2) Increasing target matter in eA
… target density ~ $A^{1/3}$ ~ 6 for Pb

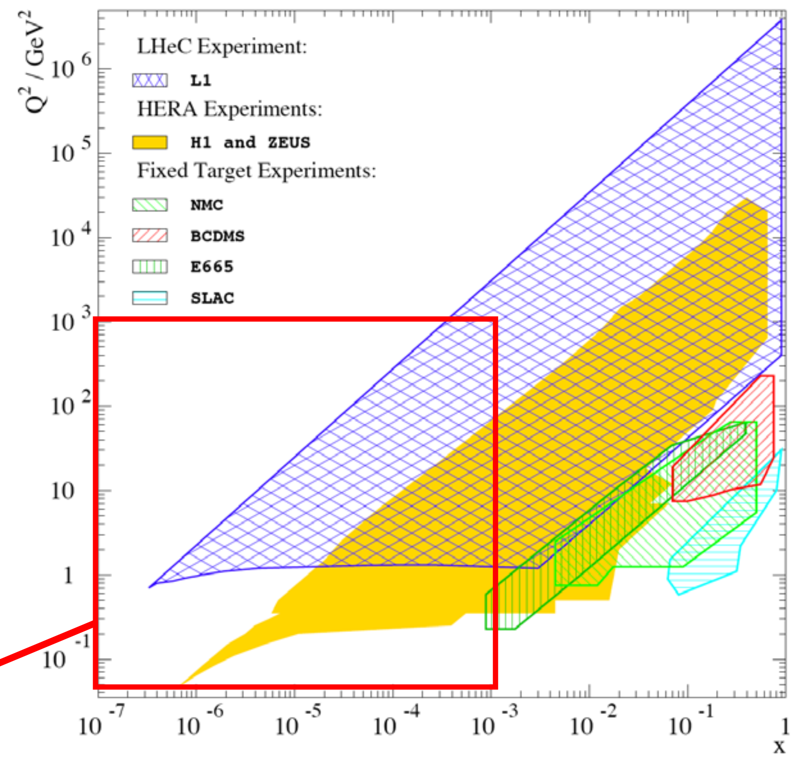




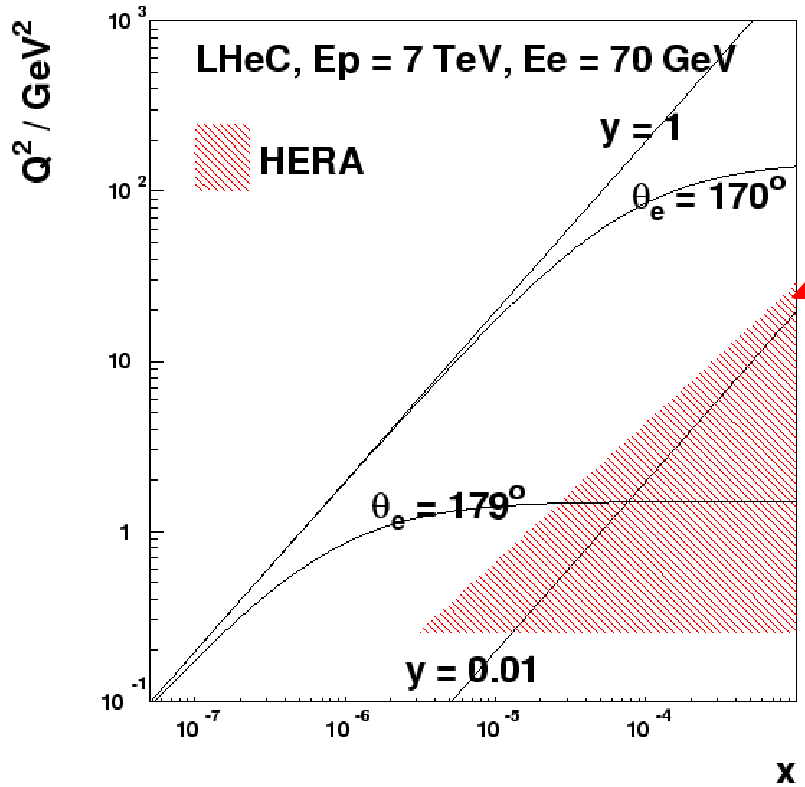


Basic Inclusive Kinematics / Acceptance

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



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

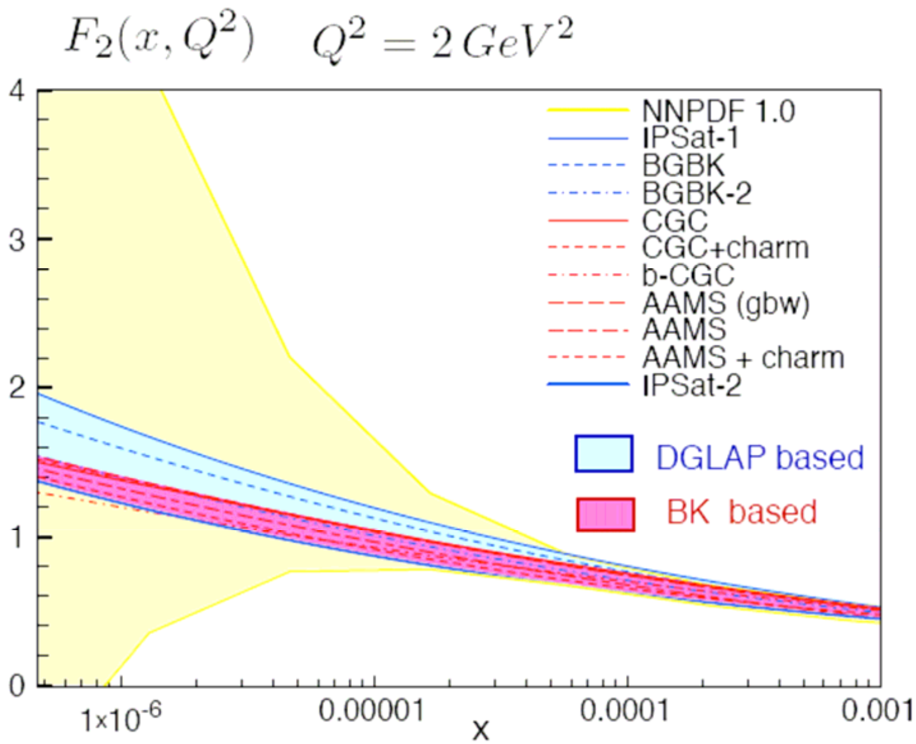


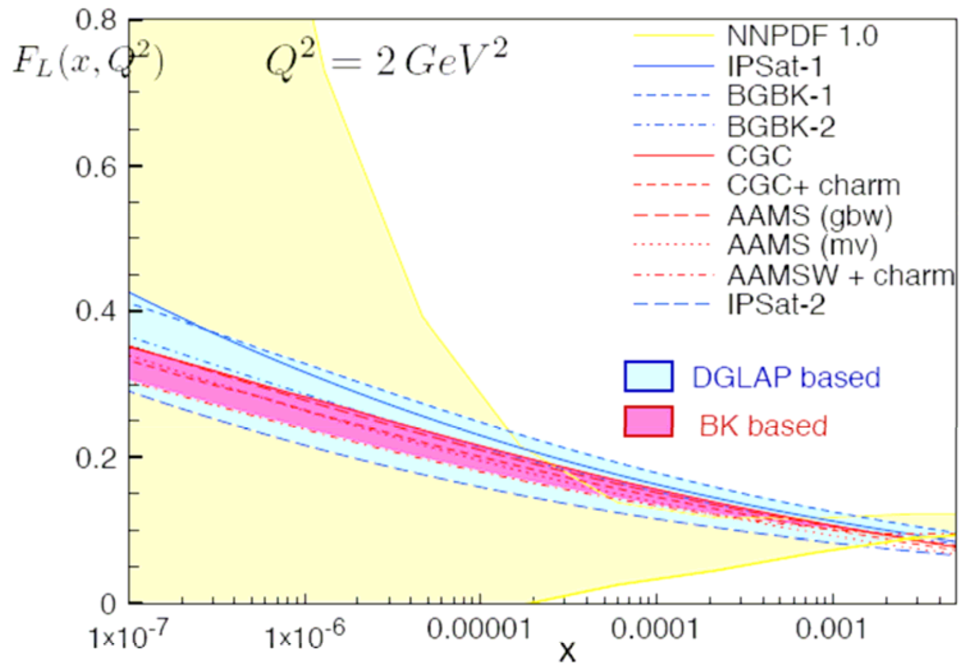
... luminosity in all scenarios ample for most low x processes

? Nothing sacred about 1° or 10°
... beyond 1° would be great!
... in between would need study

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

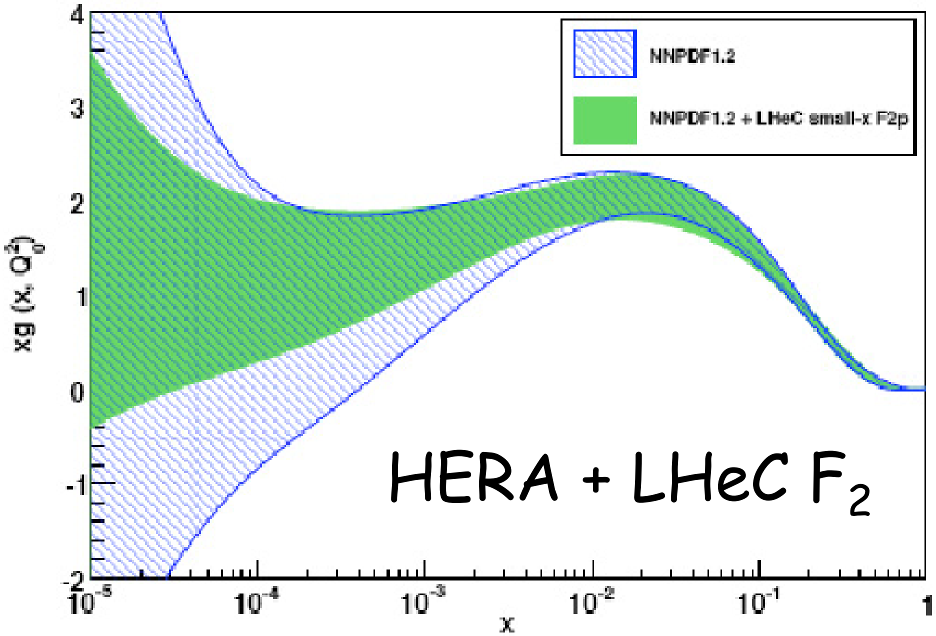


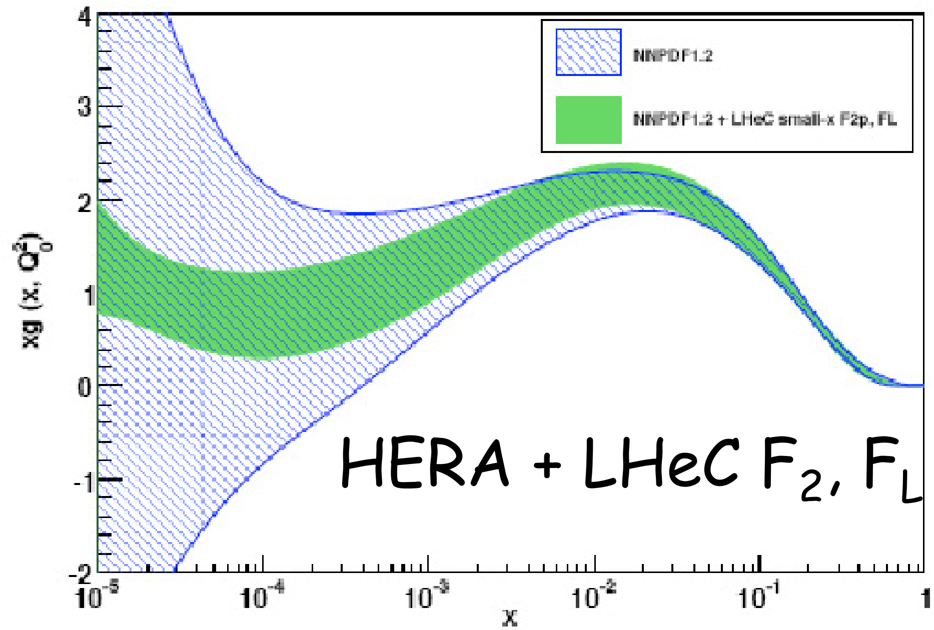


- 'Modern' dipole models, containing saturation effects & low x behaviour derived from QCD give a much narrower range
- c.f. 2% errors on LHeC F_2 pseudo-data, 8% on F_L pseudo-data

… we should be able to distinguish …

Fitting for the Gluon with LHeC F_2 and F_L (Gufanti, Rojo ...)





(Q^2 = 2 GeV^2)

Including LHeC data in NNPDF DGLAP fit approach ...

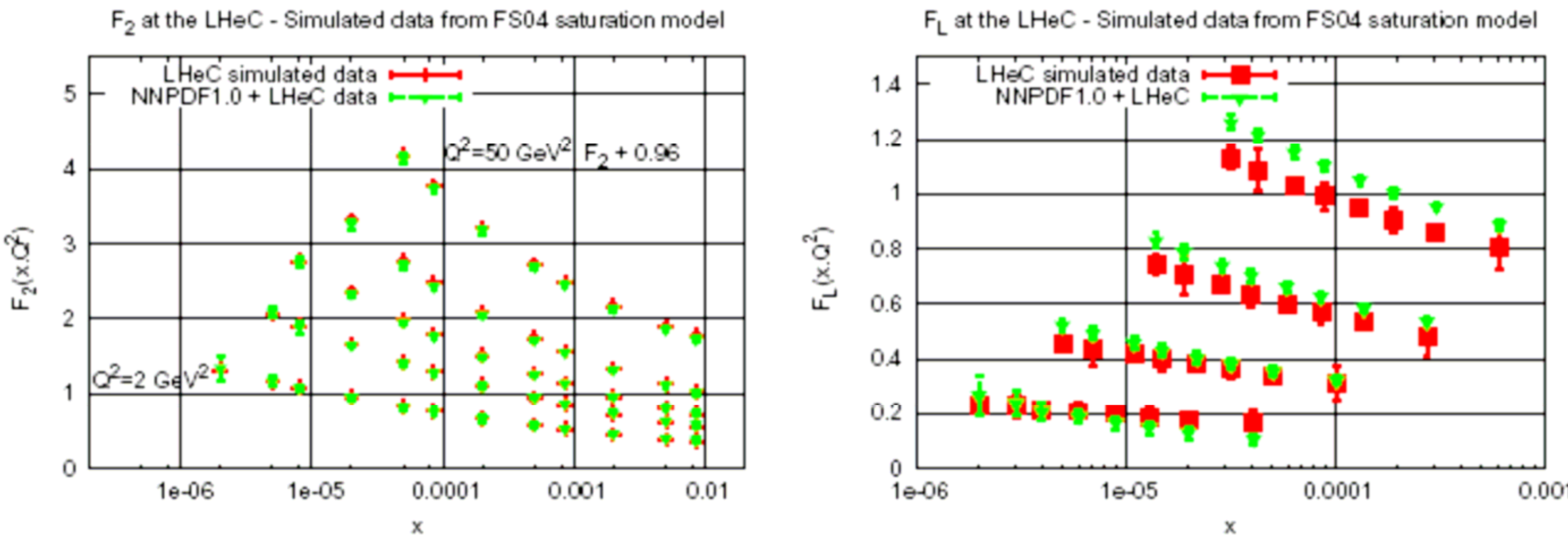
... sizeable improvement in error on low x gluon when both LHeC F_2 & F_L data are included.

... but would DGLAP fits fail if non-linear effects present?

Can Parton Saturation be Established @ LHeC?

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 … <u>next try F_2^c in place of F_L</u> …

What about eA?

Common misconception: Final states in DIS from nuclei are not significantly more complicated than in DIS from protons

→ scattered electron, current jet essentially identical

→ target remnant more complicated, but very forward

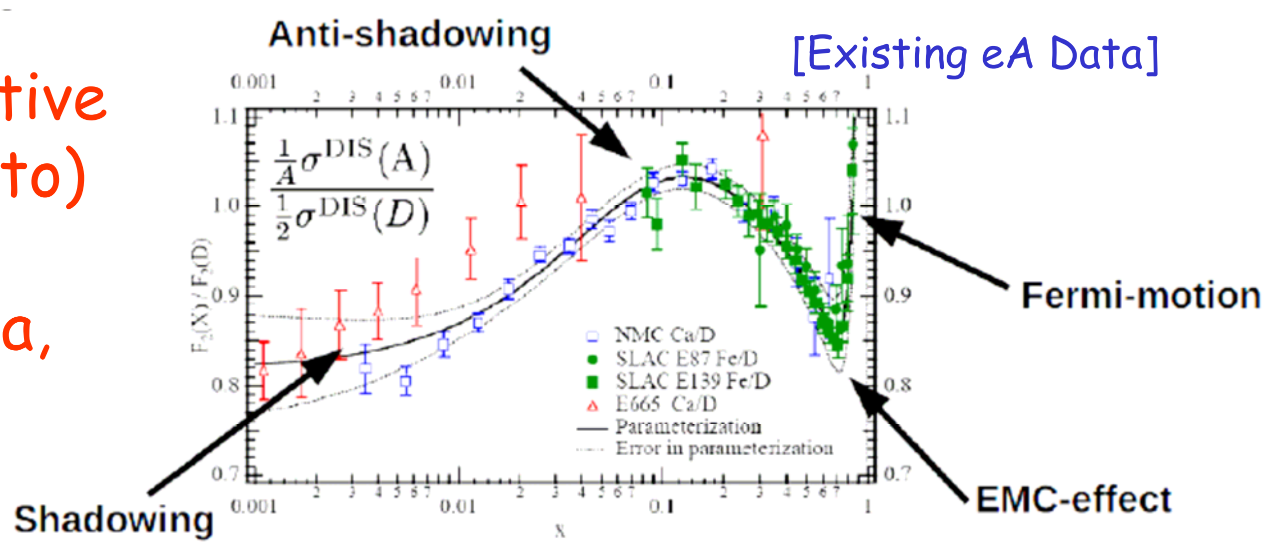
A highlight of this meeting: quantified impact of LHeC data on nuclear parton densities:

→ pseudo-data → precision and kinematic range (Klein)

→ dipole based model, including shadowing derived from diffractive ep scattering (Armesto)

→ fits for nuclear PDFs in EPS09 (Eskola, Paukkunen)

[Existing eA Data]



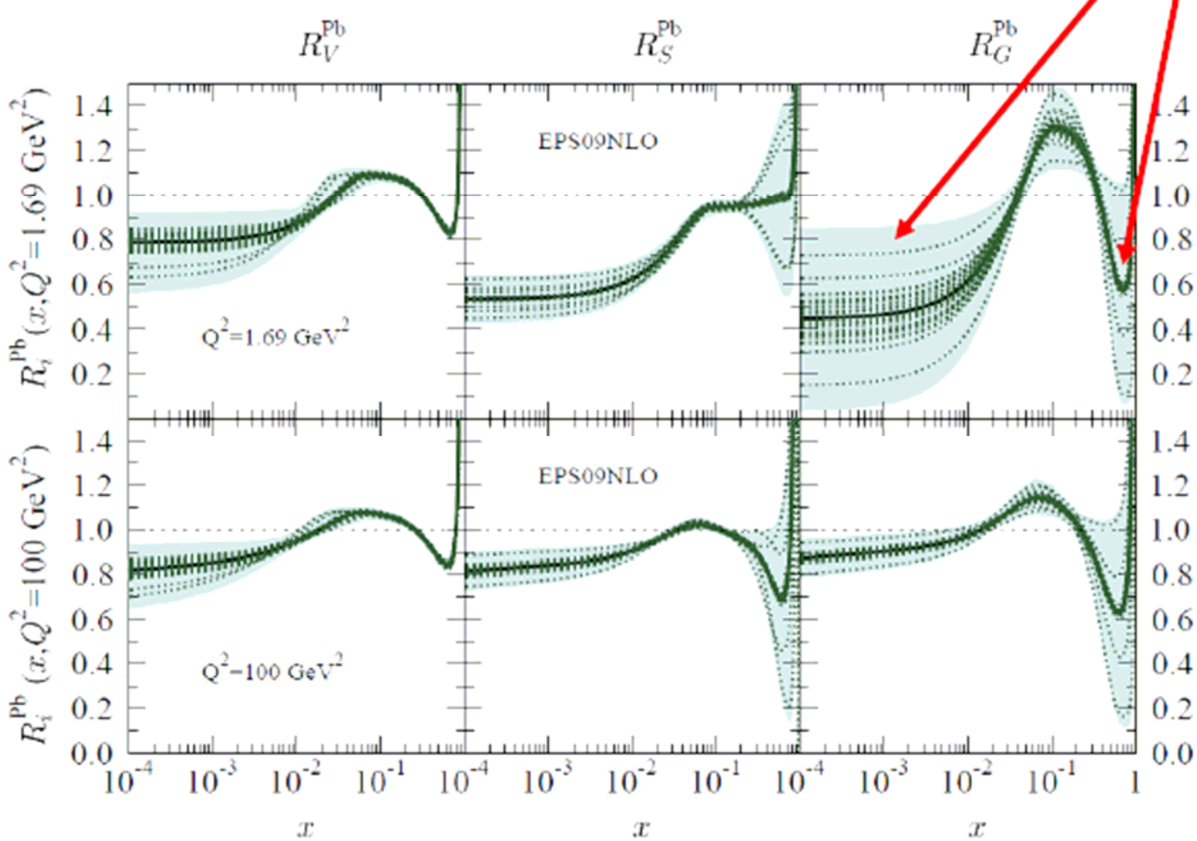
EPS'09 NLO DGLAP Fit for Nuclear PDFs

- Fit existing eA data with pA Drell-Yan and dA leading π^0
- Full Hessian error treatment

- Fit for valence & singlet quark and gluon densities
- Work in terms of $R_i^A(x,Q2) = f_i^A / A.f_i^p(CTeQ)$

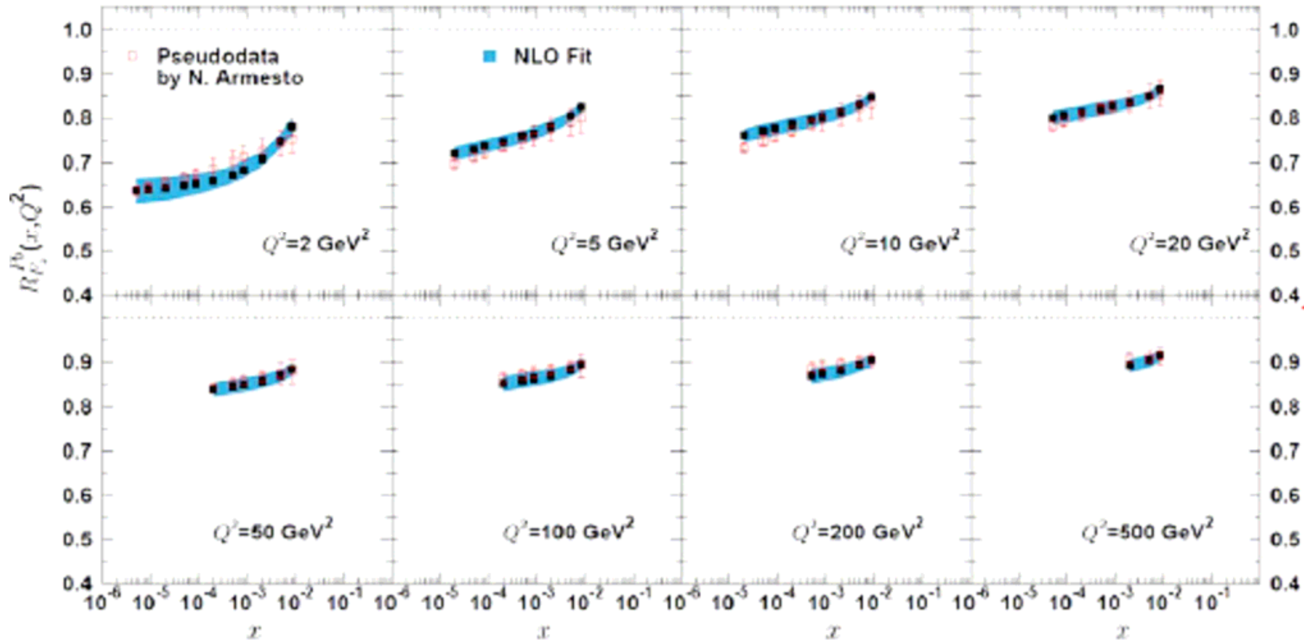
Largest uncertainties here

Good fit to existing data, but poor constraints on gluon density and at low x in particular



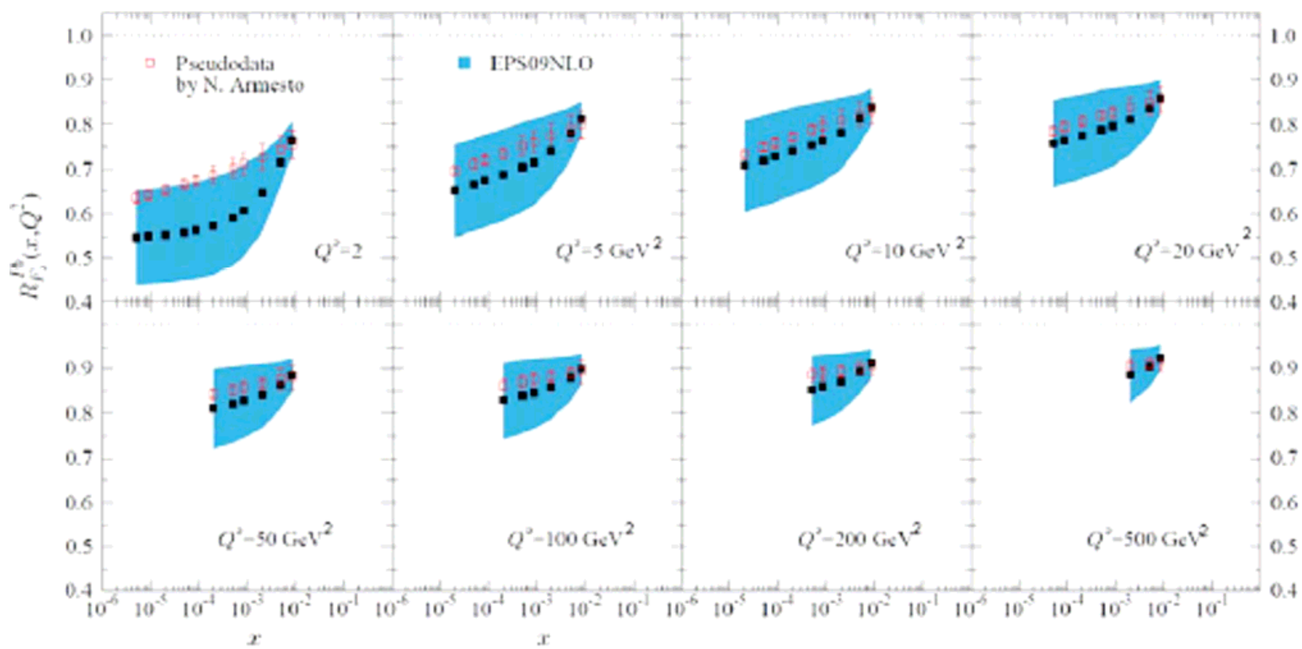
initial scale

higher scale



A=208

LHeC pseudodata included in the fit; uncertainties much smaller

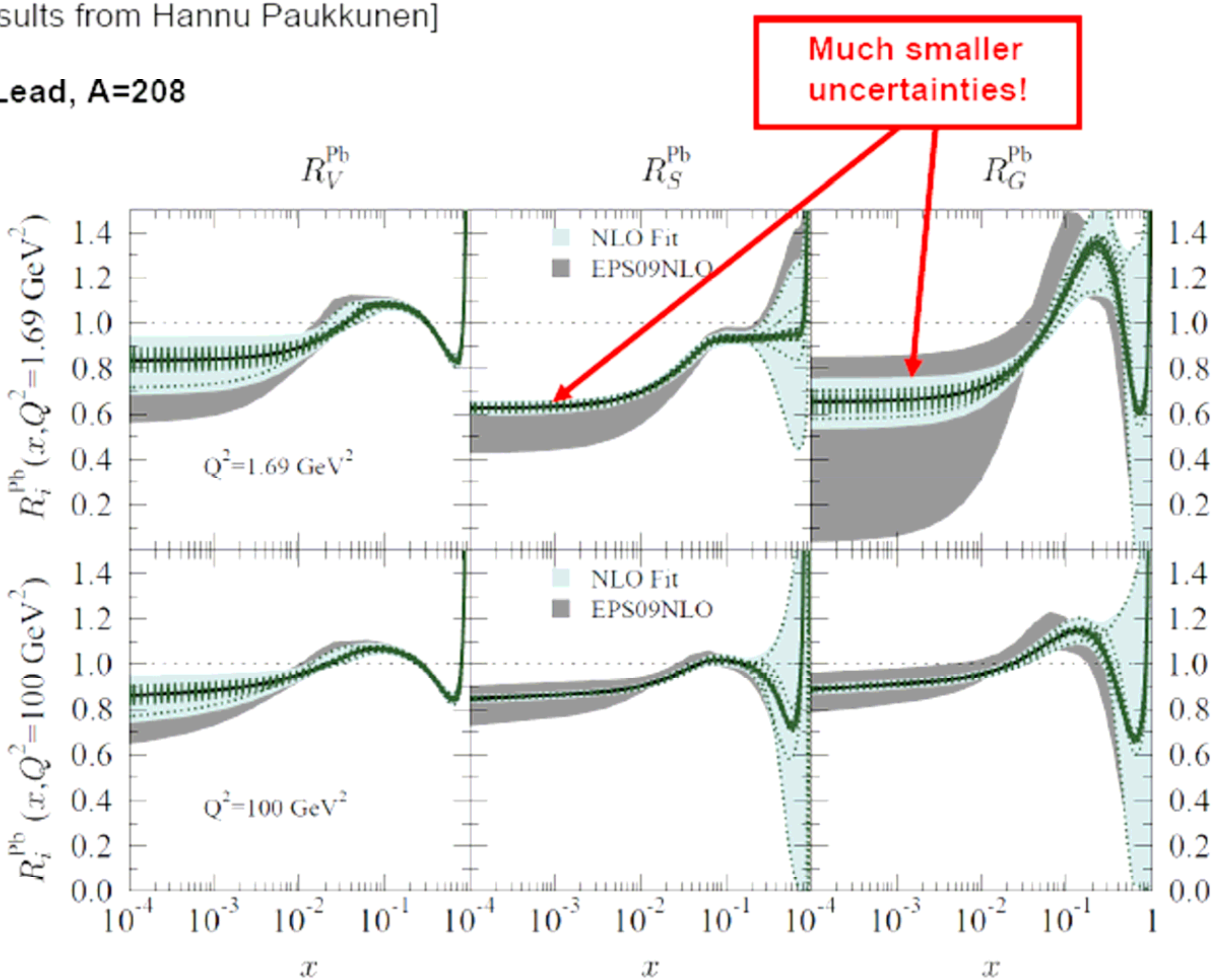


EPS09 –
LHeC pseudodata
not included

Global NLO fit with LHeC pseudodata [from N. Armesto] included

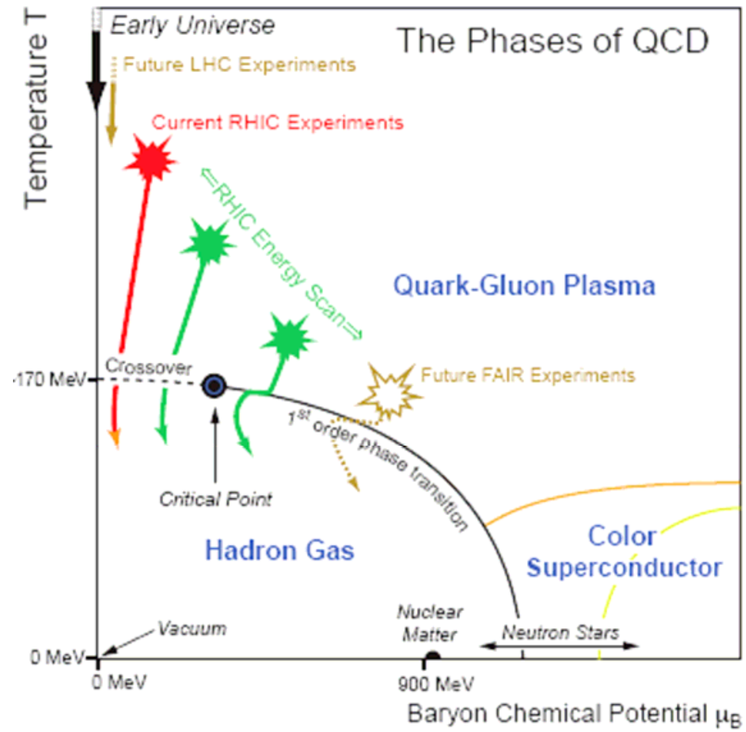
[results from Hannu Paukkunen]

Lead, A=208



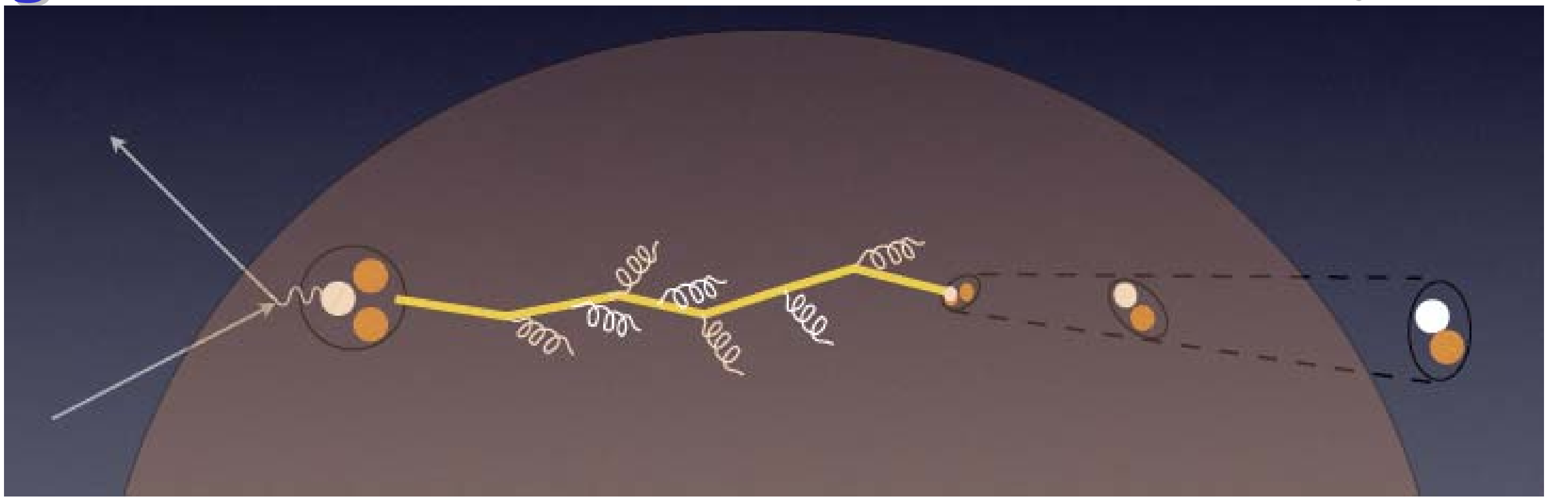
Many other reasons for eA (Ullrich)

As well as identifying non-linear dynamics, measuring nuclear effects in DIS will tell us lots about heavy ions / q-g plamsa:…
"Symbiotic Relationship between eA and AA" …



- Initial Conditions (saturation/CGC?)
  - impact on understanding of QGP properties (e.g. η/s)
- Thermalization (Glasma)
- Energy Loss (baseline/control) & Fragmentation
- Saturation & Multiplicity
- Understanding nuclear effects ((anti)-shadowing, EMC)

e.g. Final State Interactions in eA (Brooks)



Parton multiple scattering in medium
Hadron formation inside medium … can also interact …
Hadronis'n amplitudes inside & outside medium can interfere
Model of low energy data … several observable effects @ LHeC

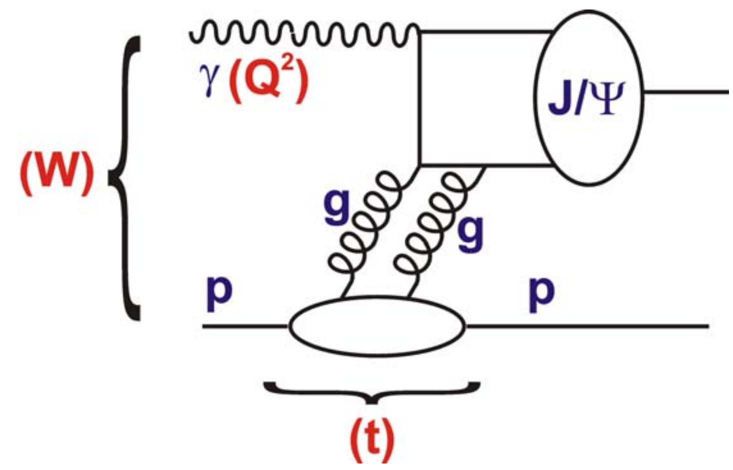
At ***HIGH ENERGIES***:

- Test the predicted universal breakdown of QCD factorization at large Feynman *x*
- Expect perturbative energy loss to be purely proportional to path length squared
- Expect increase in jet broadening and quark energy loss

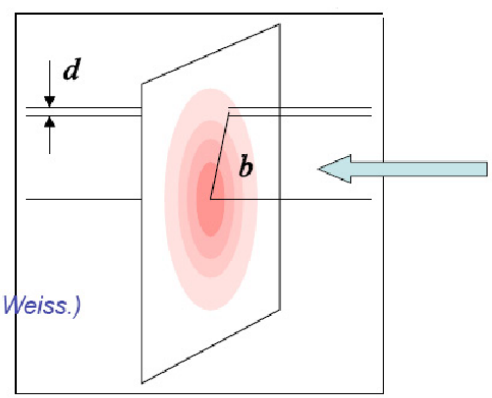
[Relation to jet quenching as a QGP signature?]

Diffractive Channels

Additional variable t gives access to impact parameter (b) dependent amplitudes

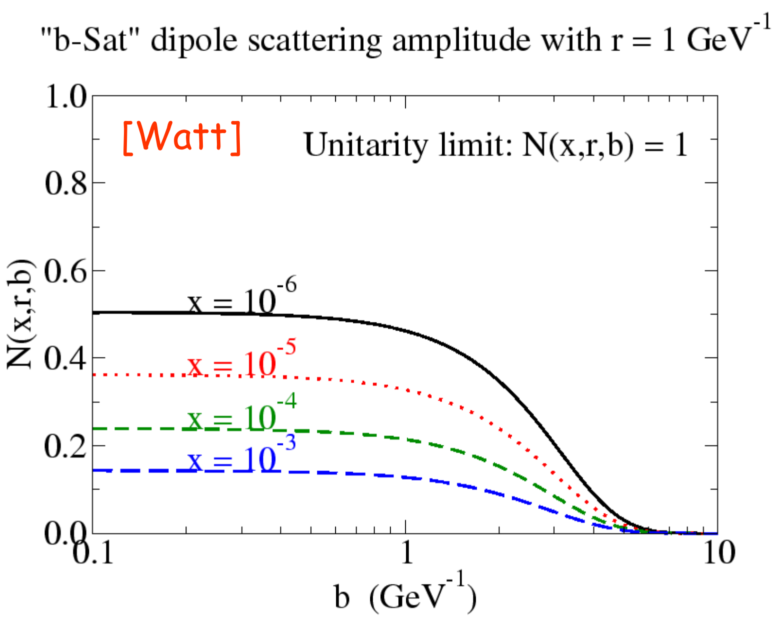


Large t (small b) probes densest packed part of proton … dipole scattering amplitude reaches large fraction of unitarity limit at low x values measurable at LHeC



(figure from C. Weiss.)

Central black region growing with decrease of x.



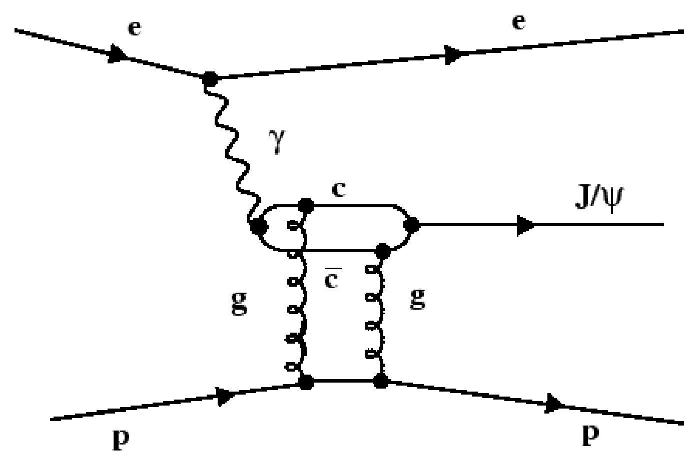
New Inclusive and VM Diffractive Pseudo-Data

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

[2 versions]

J/Ψ, Υ and inclusive diffraction pseudo-data made with 6 different configurations, including eA

Vector Mesons Advantages



Elastic J/Ψ production could be our `golden' channel …

→ Unlike inclusive diffraction, 'cleanly' inrterpreted as hard 2 gluon exchange coupling to qqbar

→Unlike light vector mesons, qqbar share energy equally and VM wavefunction issues are simplified

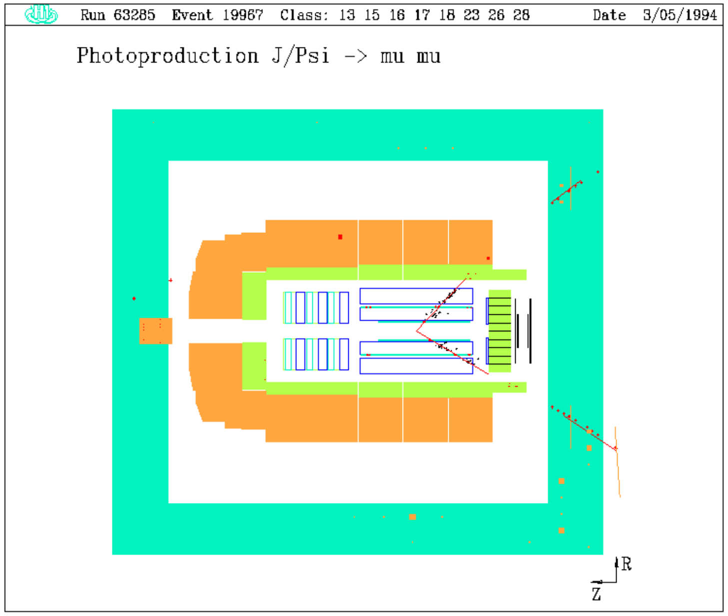
→Very clean experimental signature (just 2 leptons, small BG)

(MNRT etc) $x_g \sim (Q^2 + M_V^2) / (Q^2 + W^2)$ $\bar{Q}^2 = (Q^2 + M_V^2) / 4$

… lower x reach for J/Ψ than for Υ

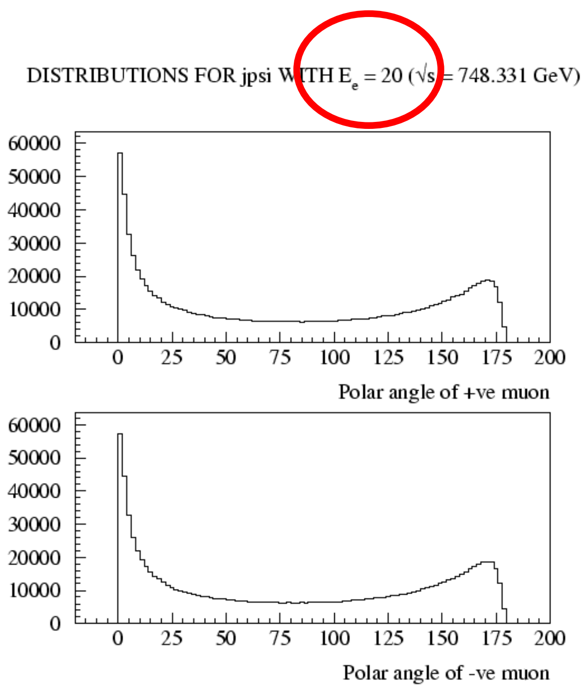
… Best sensitivity to non-linear effects

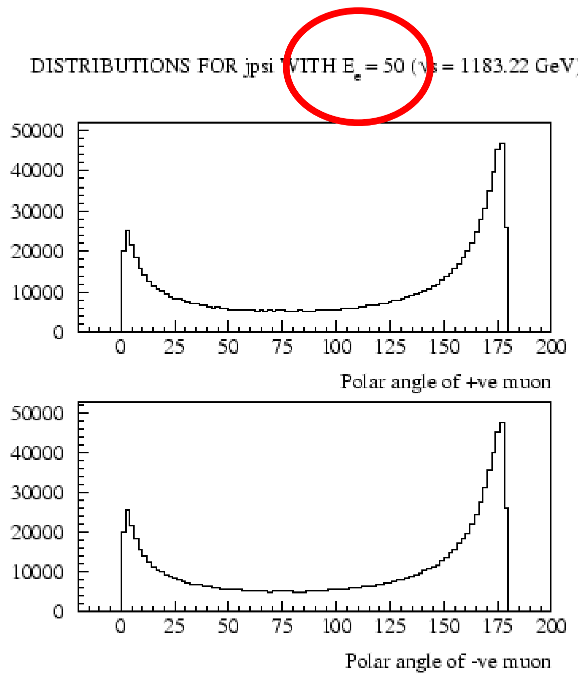
… Ideally require maximum W (minimum x) and good t measuerments to access small impact parameters

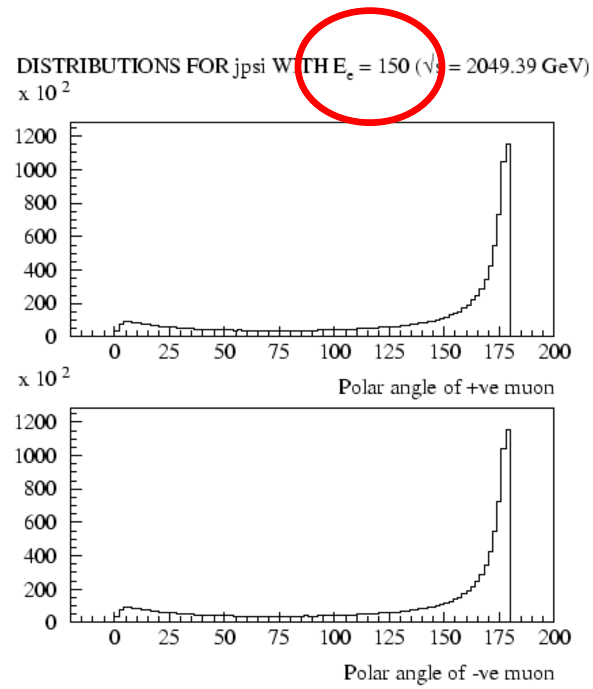


J/Ψ Decay Product Polar Angles

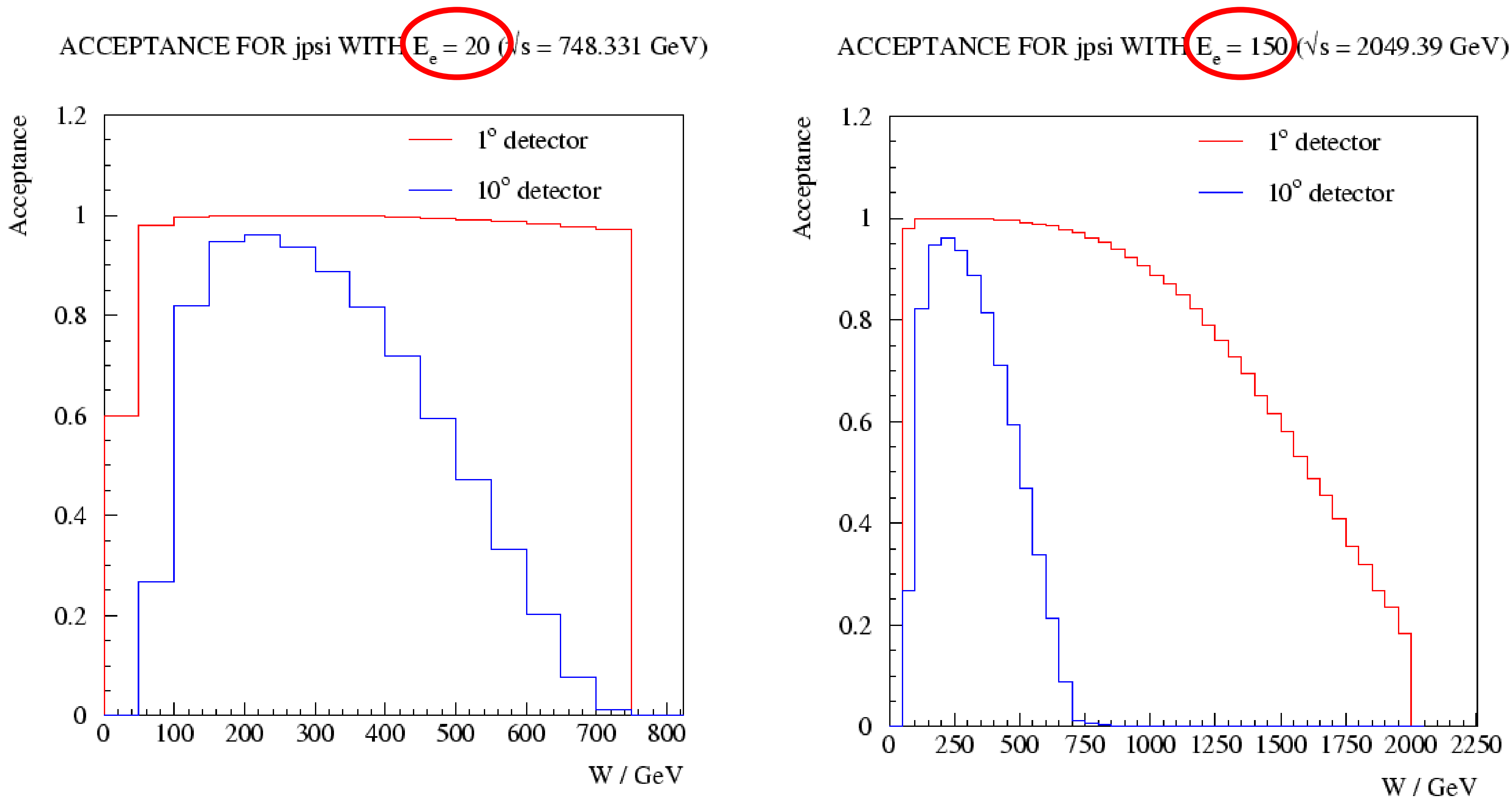
As Ee increases, leptons pushed further and further into outgoing electron beam direction (losing high W acceptance)





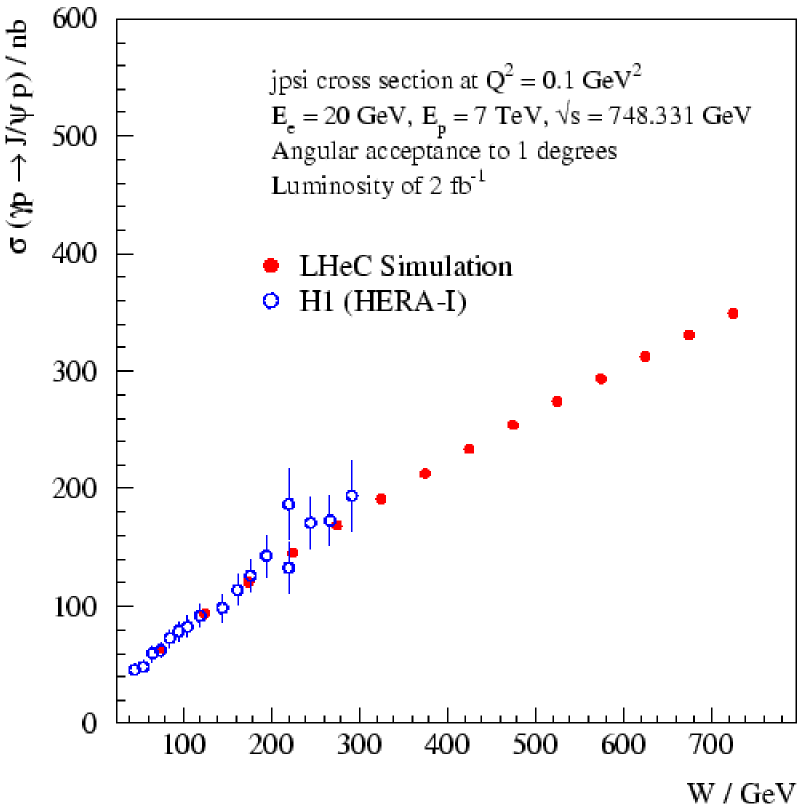


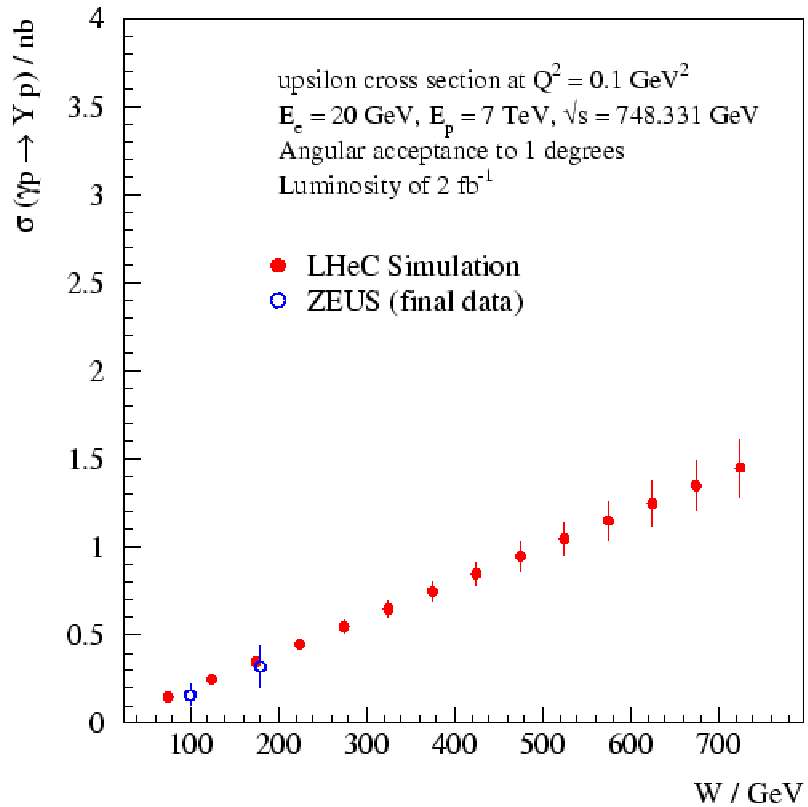
Acceptances for J/Ψ in Different Scenarios



- For a limited (170°) backward, geometrical acceptance in W does not improve beyond SPL scenario as E_e increases!
- For $\theta < 179°$, acceptance high at large E_e to kinematic limit

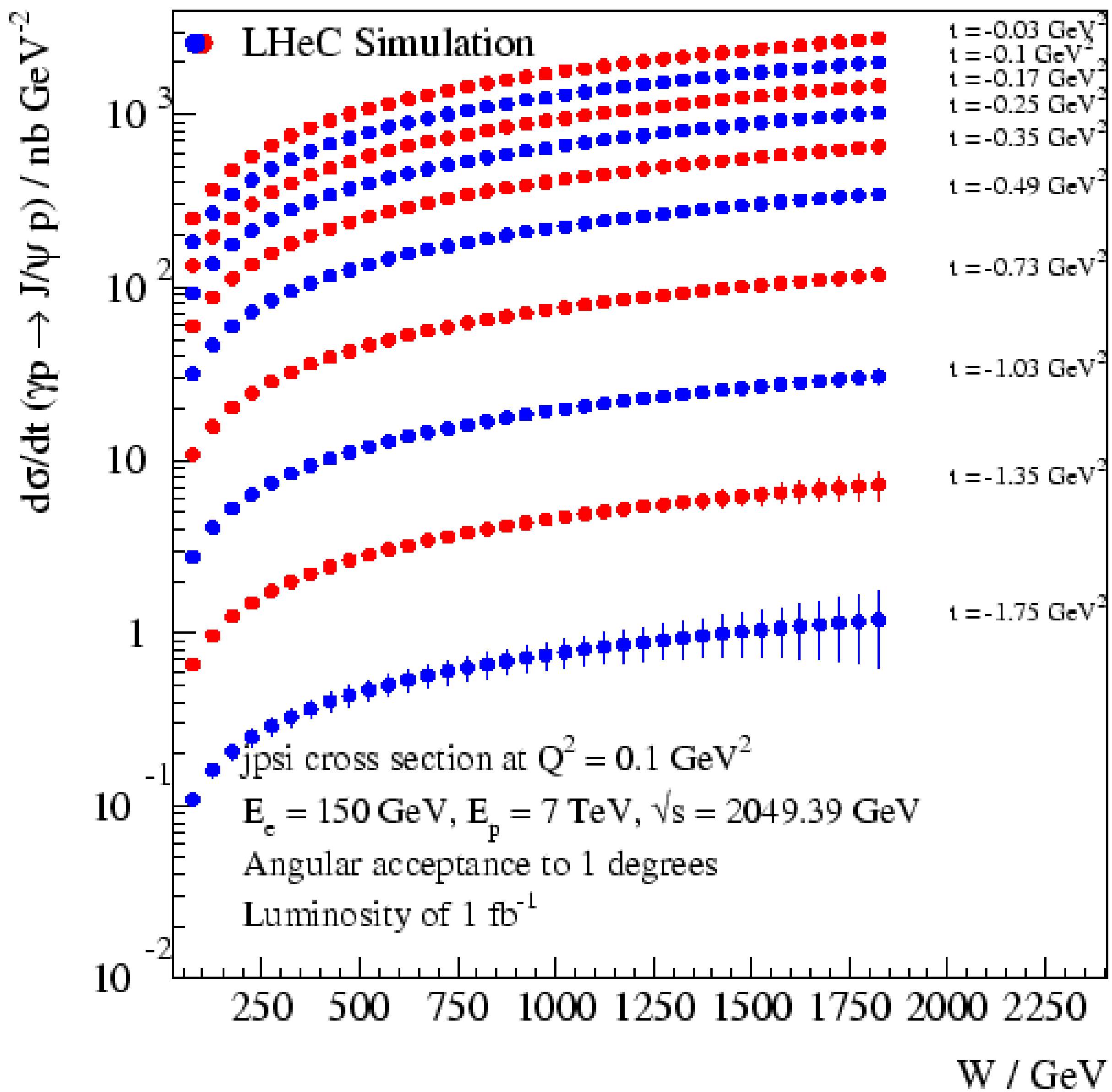
SPL Scenario - photoproduction cross secs





- 1^o acceptance yields cross sections almost to kinematic limit
- 2 fb^{-1} is already plenty of lumi - c.f. HERA-I based on 50 pb^{-1}
- Discussion with detector group → Muon acceptance very close to beam-line even with focusing magnets

Dedicated Low x Linac-Ring Scenario



Dream scenario!!!

J/ψ photoproduction double differentially in W and t, E_e=150 GeV
1^o acceptance

Probing x ~ 3.10^{-6} at eff Q^2 ~ 2.5 GeV^2

c.f. GB-W model x_s ~ 7.10^{-6} at Q^2 ~ 2.5 GeV^2

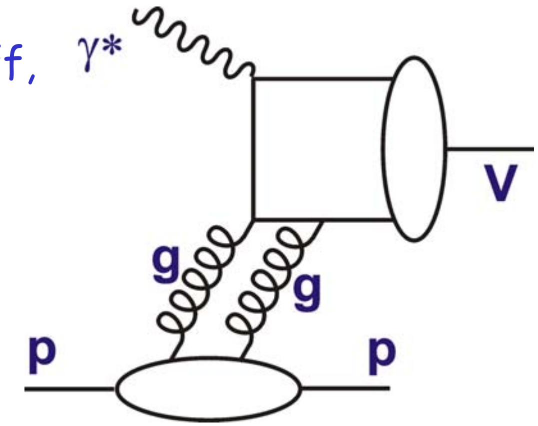
☺

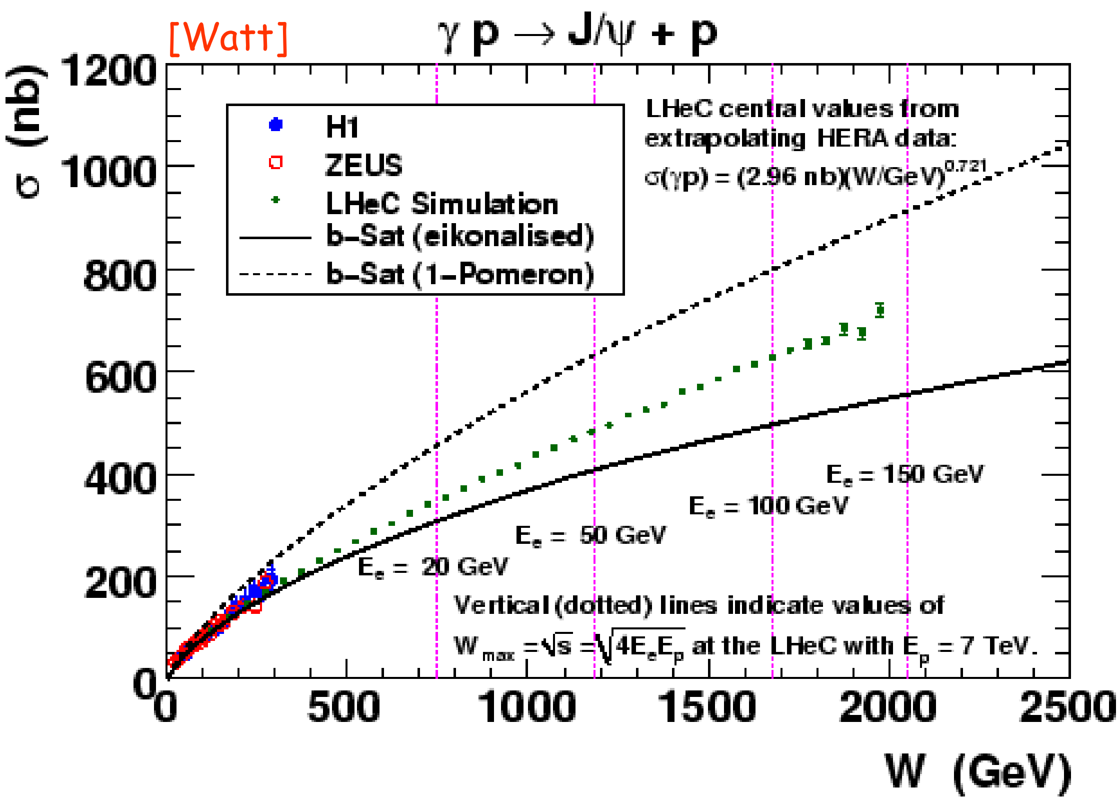
Dipole Model of J/ψ Photoproduction

e.g. "b-Sat" Dipole model [Golec-Biernat, Wuesthoff, Bartels, Teaney, Kowalski, Motyka, Watt] ...

"eikonalised": with impact-parameter dependent saturation

"1 Pomeron": non-saturating





- Significant non-linear effects expected even for t-integrated cross section in LHeC kinematic range.
- Data shown are extrapolations of HERA power law fit for E_e = 150 GeV…

→ Sat^n smoking gun?

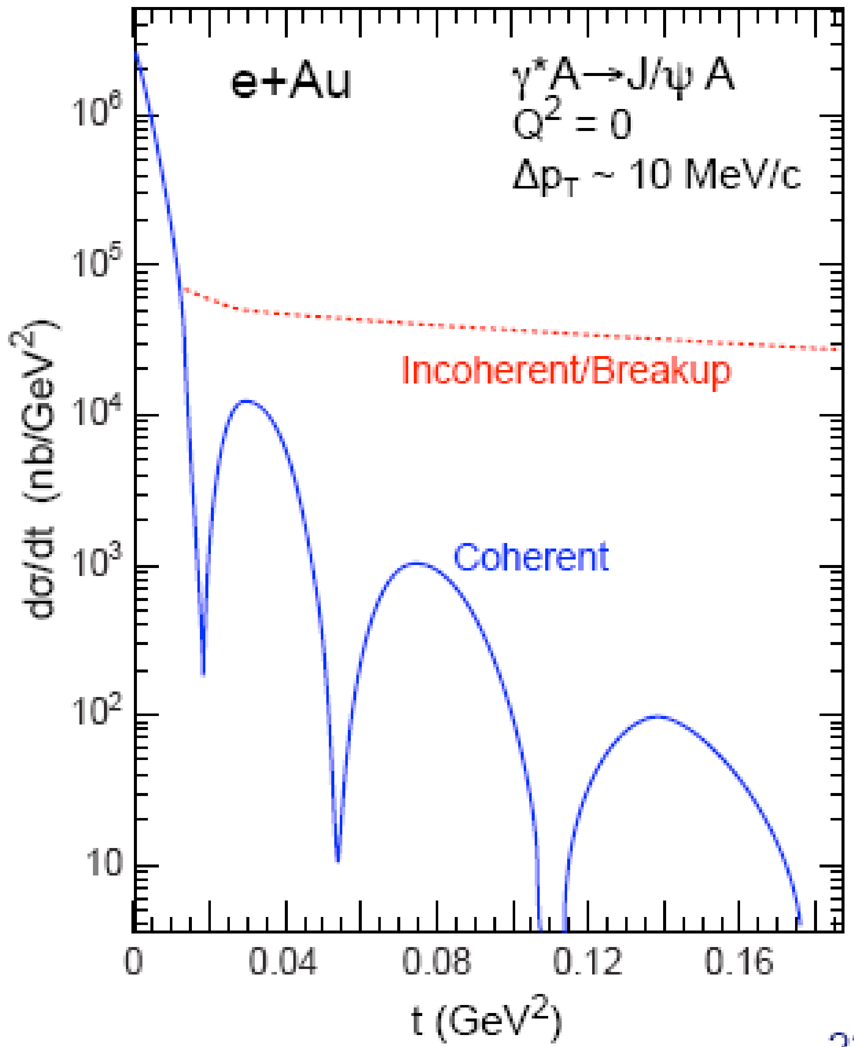
J/Ψ as Probe of Gluon in Nuclei (Kowalski)

- Coherent ($\gamma A \to J/\Psi\ A$) and incoherent ($\gamma A \to J/\Psi\ A'nnp...$) can both be studied.

- Coherent is the easier to interpret … Fourier transform of the nucleus … gluonic nuclear density / radius

- Incoherent gives info on 2-body correlations / interactions within nuclei

- To separate, need good forward proton and (especially) neutron detection

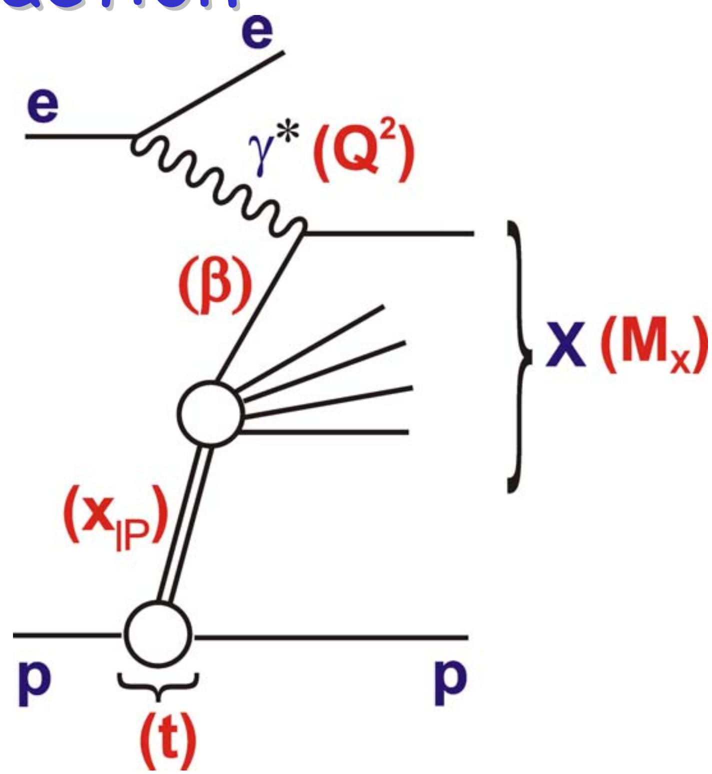


Inclusive Diffraction

Additional variables …

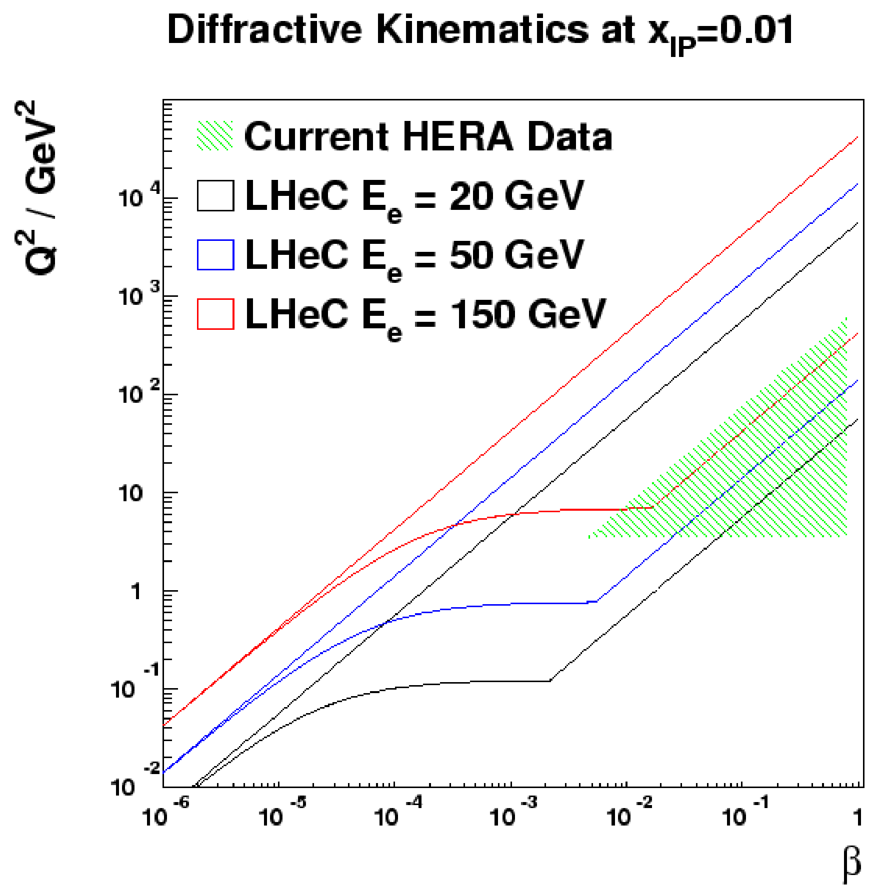
x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

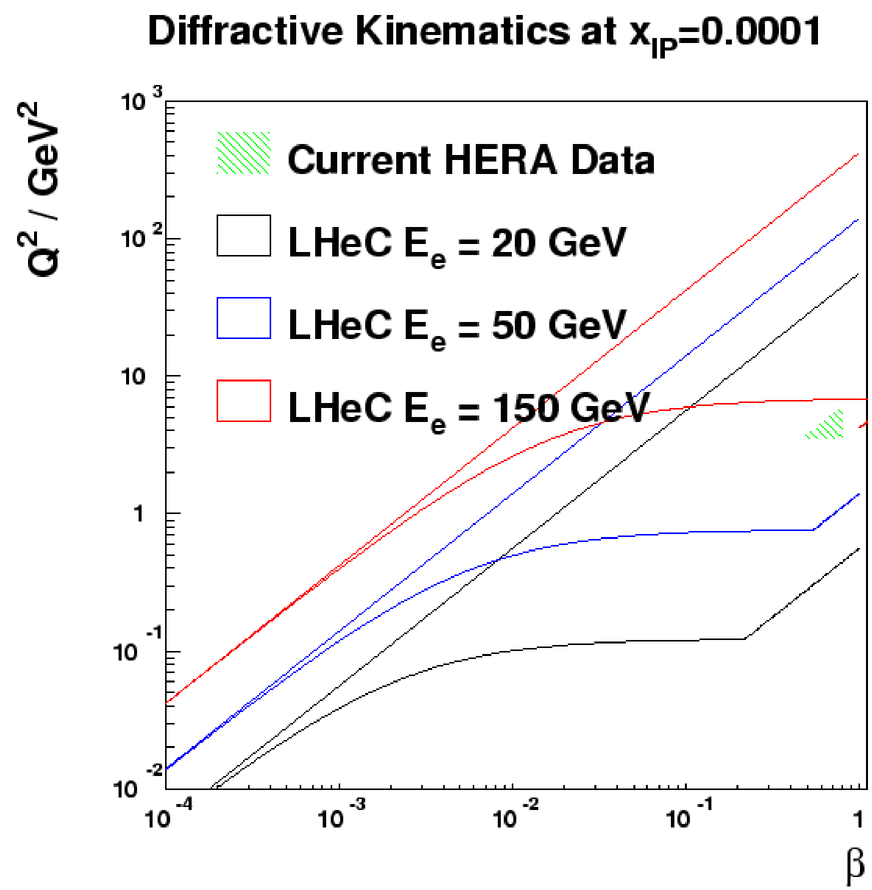
$\beta = x / x_{IP}$ (momentum fraction q / IP)



→ Further sensitivity to saturation phenomena
→ Diffractive parton densities in much increased range
→ Sensitivity to rapidity gap survival issues
→ Can relate ep diffraction to eA shadowing
… Link between ep and eA for interpreting inclusive data

Diffractive Kinematic Plane at LHeC

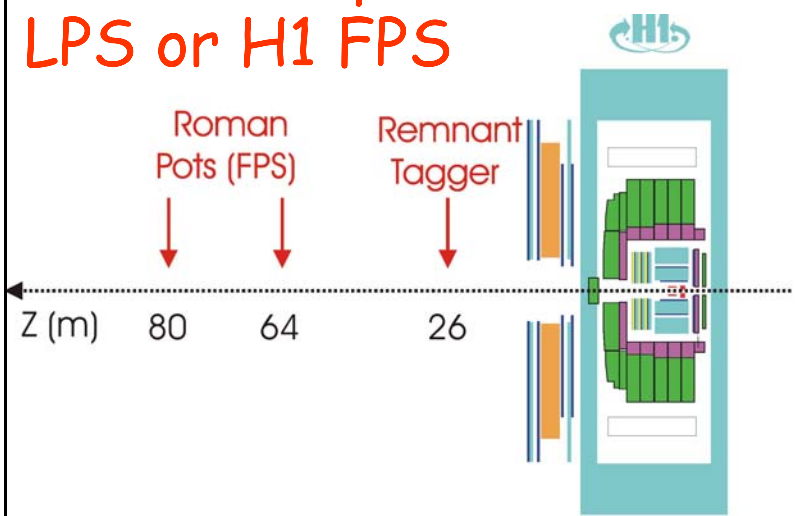




- Higher E_e yields acceptance at higher Q^2 (pQCD), lower x_{IP} (clean diffraction) and β (low x effects)
- Similar to inclusive case, 170° acceptance kills most of plane

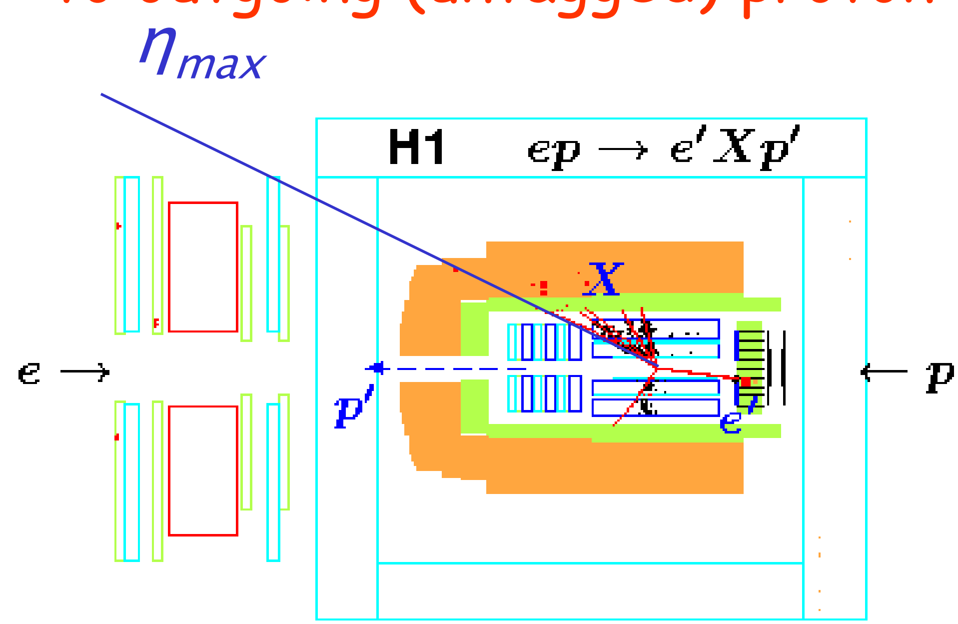
Signatures and Selection Methods at HERA

Scattered proton in ZEUS LPS or H1 FPS



- Allows t measurement
- Limited by stats and p-tagging systs

\`Large Rapidity Gap' adjacent to outgoing (untagged) proton



Limited by p-diss systs

Worked well: The methods have very different systs!
What is possible at LHeC?...

Large Rapidity Gap Selection

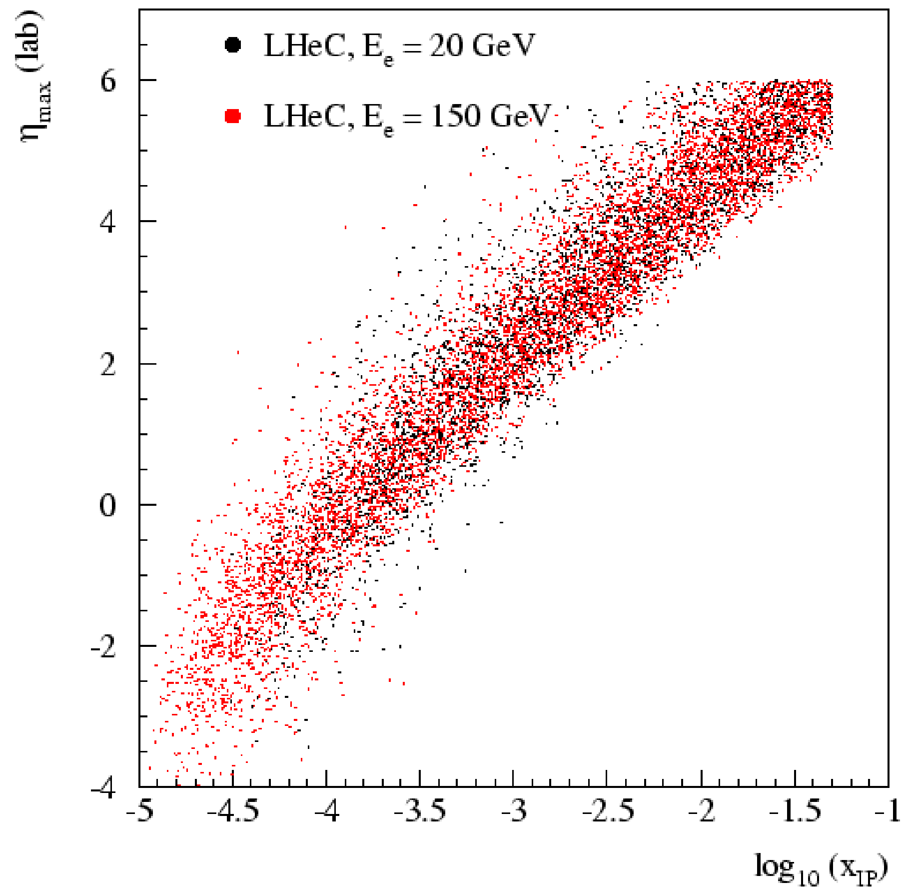
- For large rapidity gap method, life harder than HERA …

- x_{IP} = 1 – Ep' / Ep … correlation with η_{max} independent of E_e

- Reaching x_{IP} = 0.01 with rapidity gap method requires η_{max} cut around 5 … corresponds to $\theta > 1^{o}$ ☹

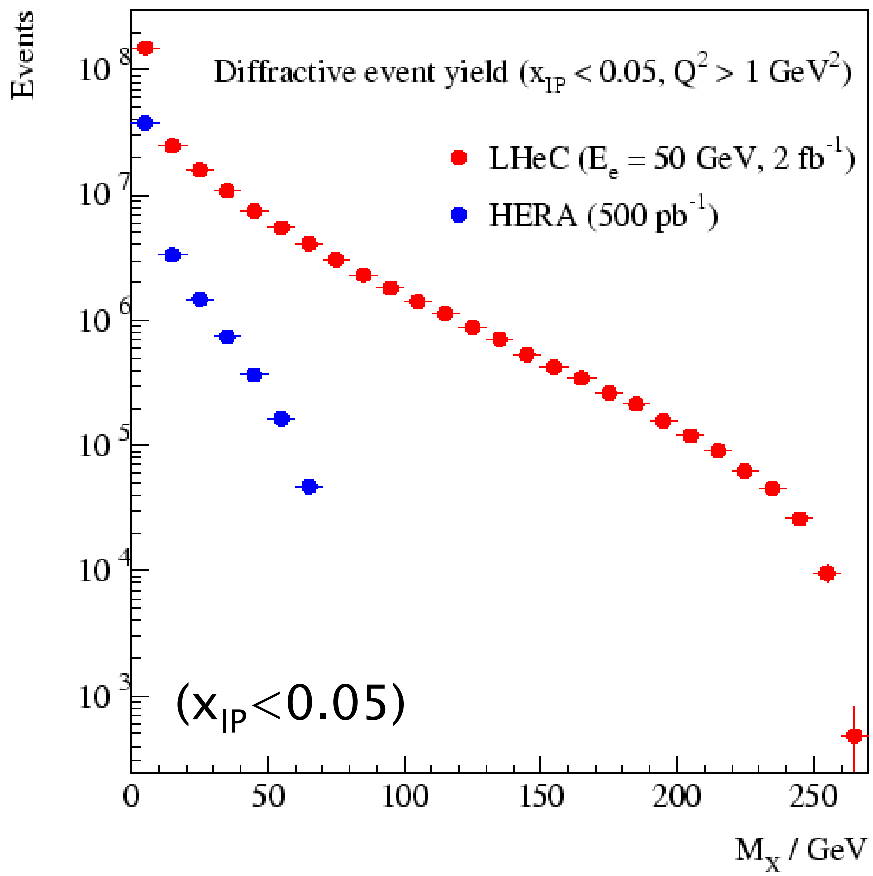
- For x_{IP} = 0.001 η_{max} cut around 3 … similar to H1 LAr cut … and still lots of data …
… but not the high M_x stuff

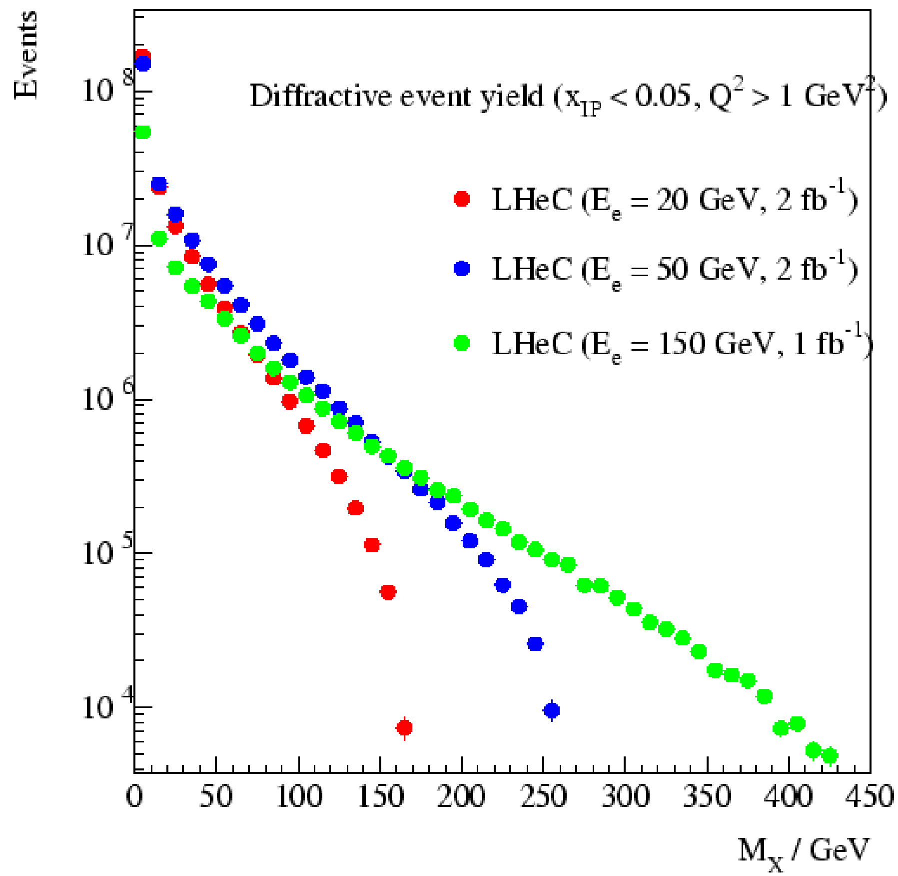
η_{max} from LRG selection …



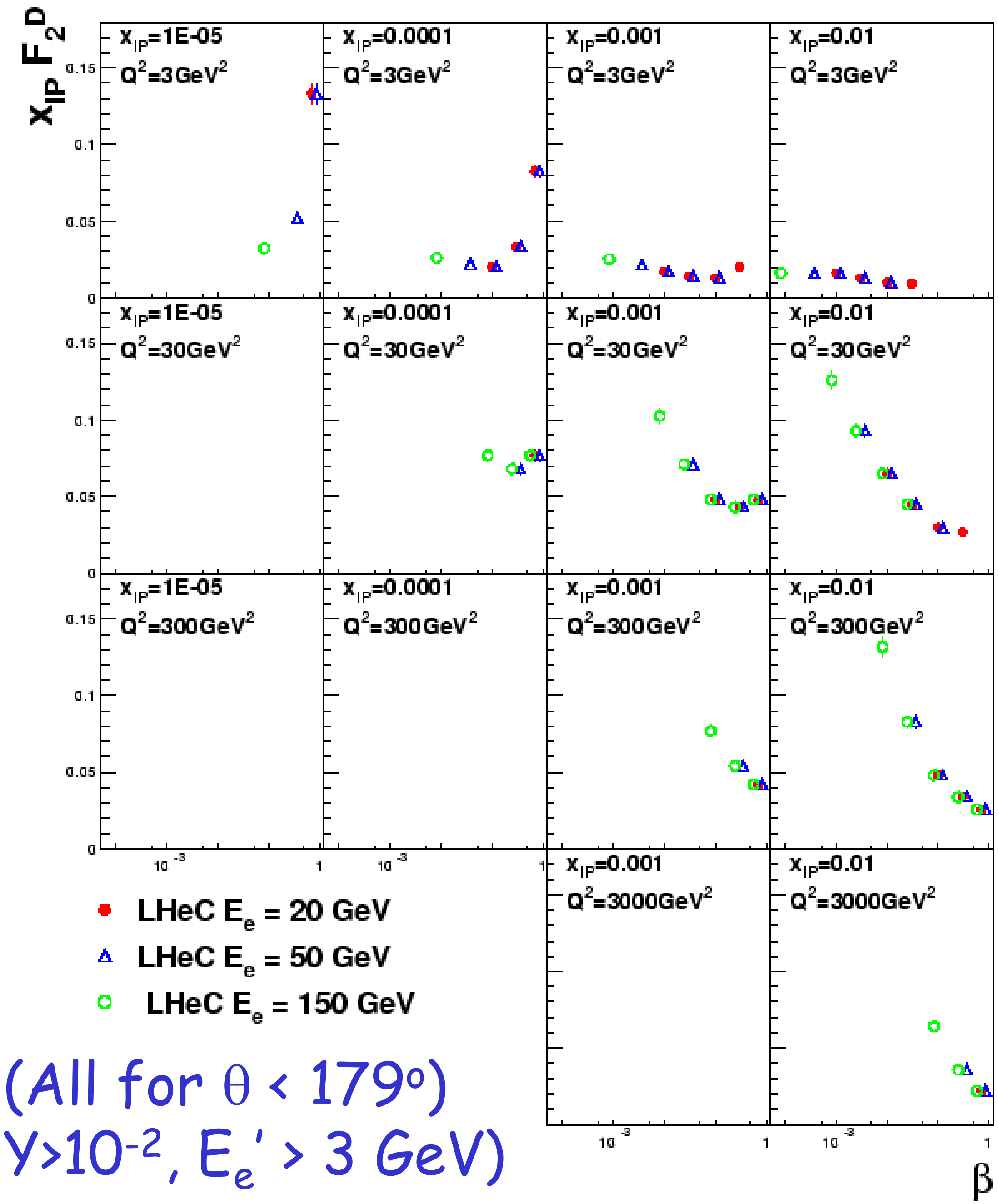
New region of Diffractive Masses

No alternative to proton spectrometer to select high M_x





- `Proper' QCD (e.g. large E_T) with jets and charm accessible
- New diffractive channels … beauty, W / Z / H(?) bosons
- Unfold quantum numbers / precisely measure new 1^{--} states



(All for θ < 179°)
$y>10^{-2}$, $E_e' > 3$ GeV)

New pseudo-data

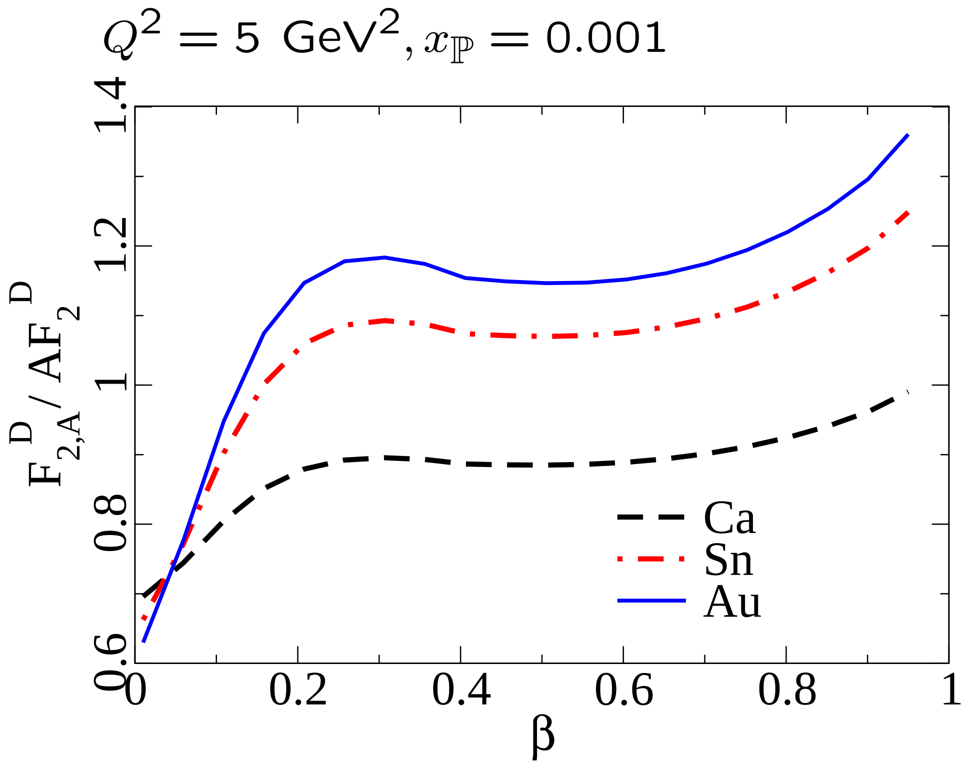
Binning currently designed to emphasise β dependence

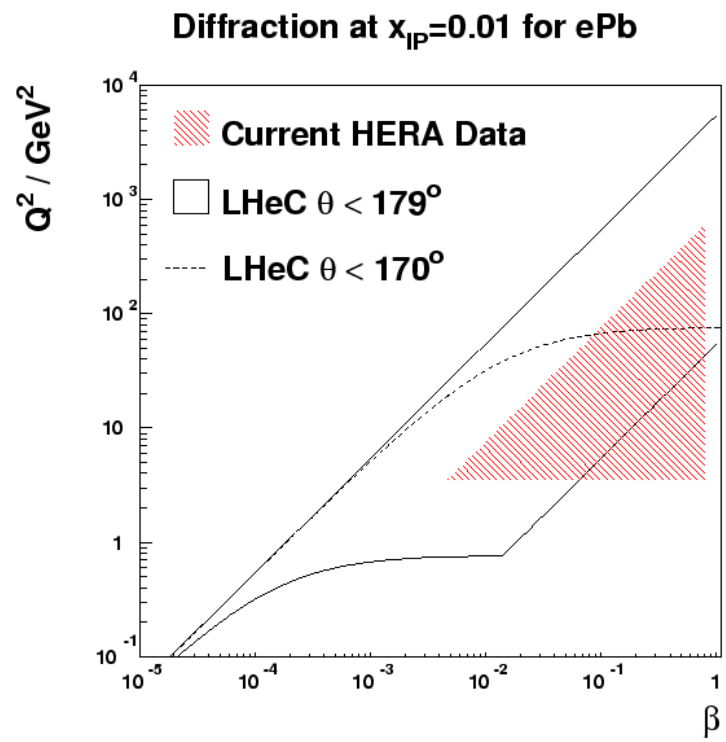
Statistical precision not an issue … phase space runs out before data

Sysytematics fixed to 5% guesstimate …
… depends crucially on forward detectors

To be implemented in models and fits

Diffraction in eA





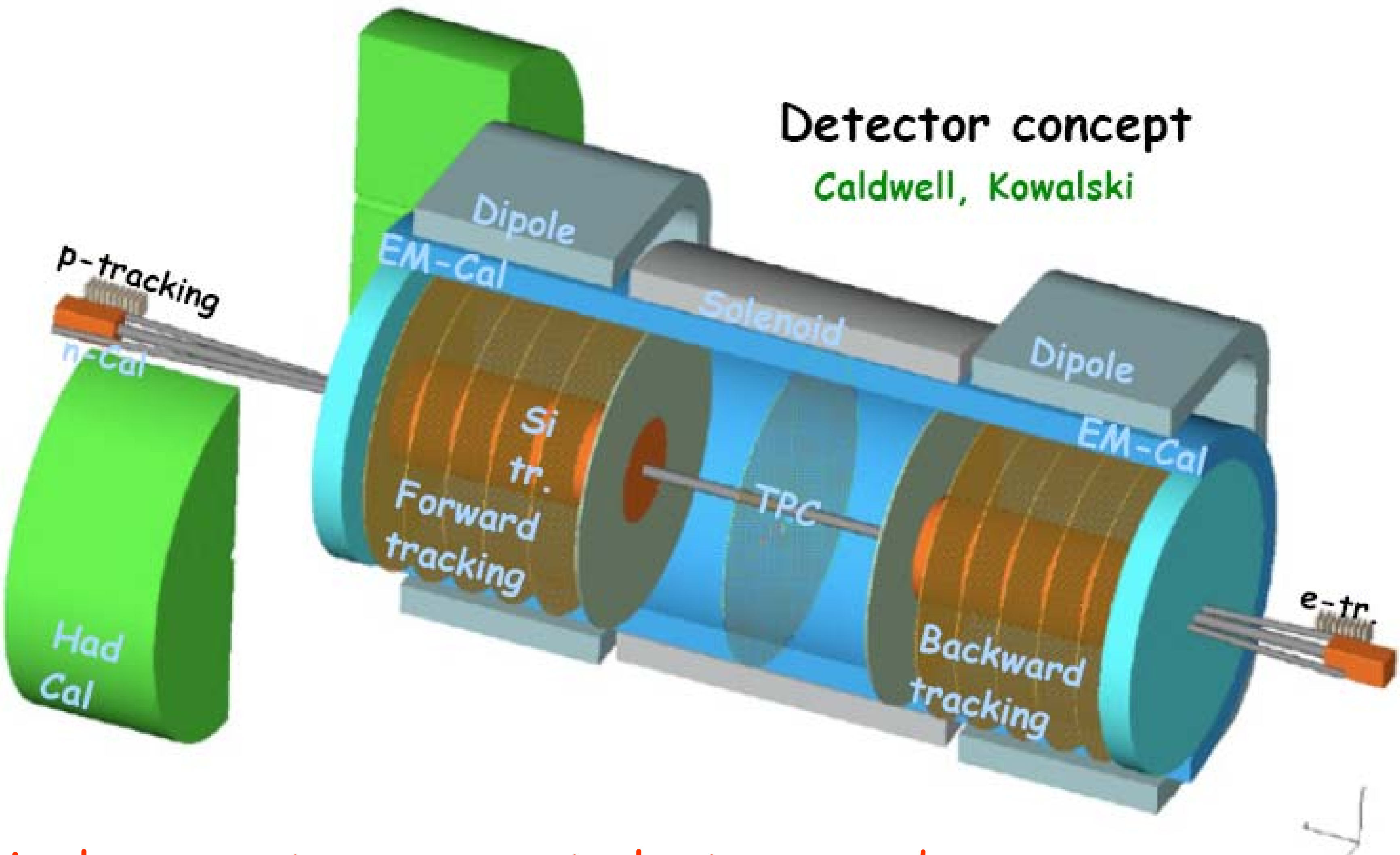
Dipole based model now exists for nuclear (anti-) shadowing in diffraction [Kowalski, Lappi, Marquet, Venugopalan]

→ Nuclear effects give high β enhancement (qqbar dipole)

→ Nuclear effects suppress low β (qqbarg dipole)

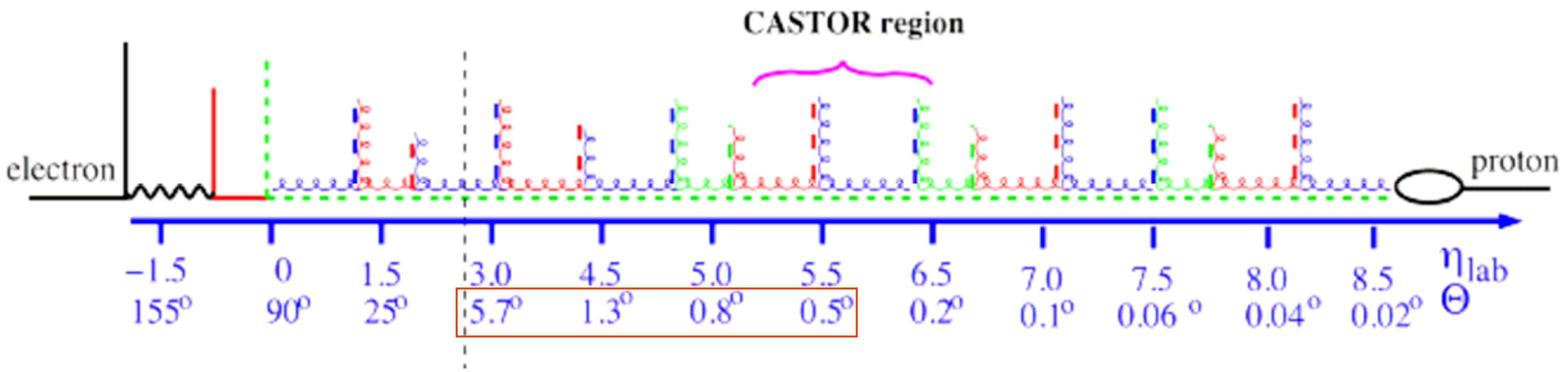
Crucial to detect nuclear break-up (beamline p,n detectors)

Another Low x Detector Concept



Dipole magnets sweep out electrons and forward going hadrons scattered at very low angles

Forward Instrumentation and Jets

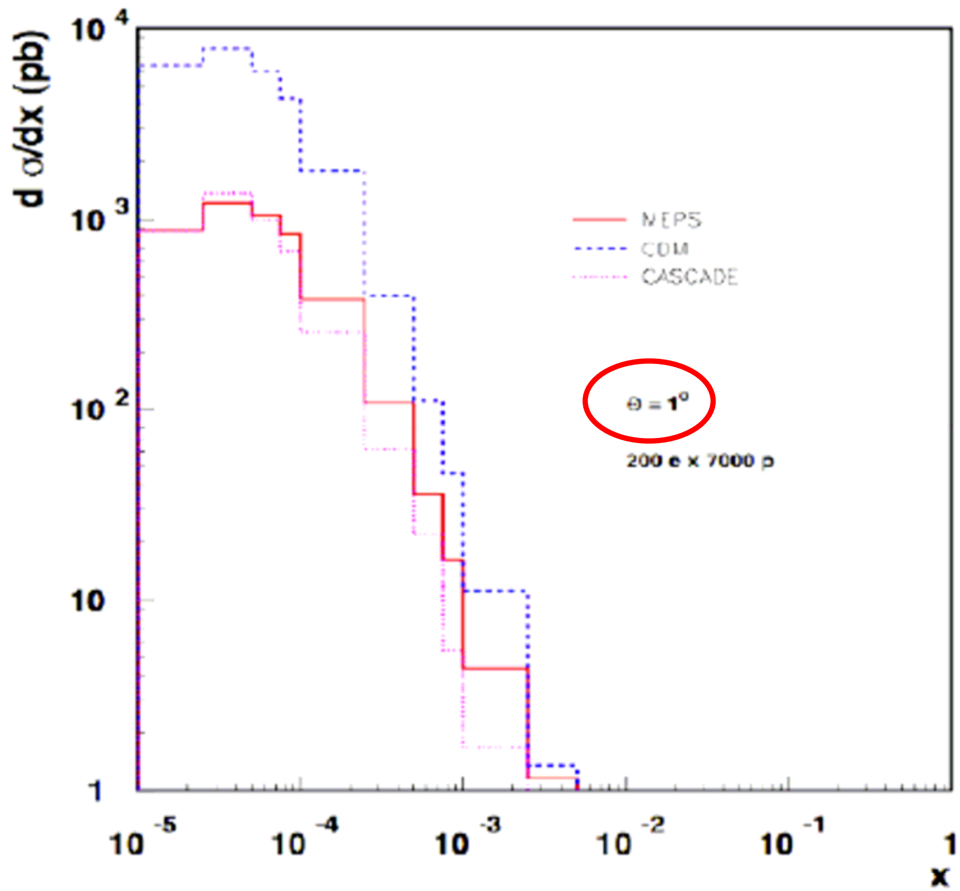


[Jung, Kutak]

- DIS and forward jet:

$$x_{jet} > 0.03$$

$$0.5 < \frac{p_{t\,jet}^2}{Q^2} < 2$$



x range (and sensitivity to novel QCD effects) strongly depend on θ cut

Similar conclusions for Δφ decorrelations between jets

Summary

- Now have calculations / pseudo-data for most important channels

- Biggest obstacle is now to define final geometrical acceptances and systematics

- Still some areas missing or needing more work
  - F2c
  - Forward jets and parton cascade dynamics
  - DVCS
  - Final states in diffraction
  - Radiative corrections
  - Dipole + Solenoid detector idea

- Next step towards CDR is to define short-list of most essential plots and arguments
  - Further meetings planned over next few months

Back-Ups Follow

Questions and Comments

- Achievable precision, background rejection θ and E_e' ranges for scattered electron in low Q2 DIS?
- Magcal and other more exotic ideas to be pursued?
- Tracking precision and noise rejection for vector mesons?
- What acceptance is achieavble for muon detection?
- Forward tracking / calorimetry for rapidity gap identification and forward jets?
- Other rapidity gap identifiers (scintilators round beampipe?)
- Hadronic calorimtery / Eflow algorithm resolution for M_x rec, jets …
- Proton (and ion?) spectrometry and forward neutrons?
- Low angle electron tagging?… Tagged photoproduction

Scenario for Experimental Precision

To date, we worked with crude assumptions on systematics based on improving on HERA by a factor ~ 2

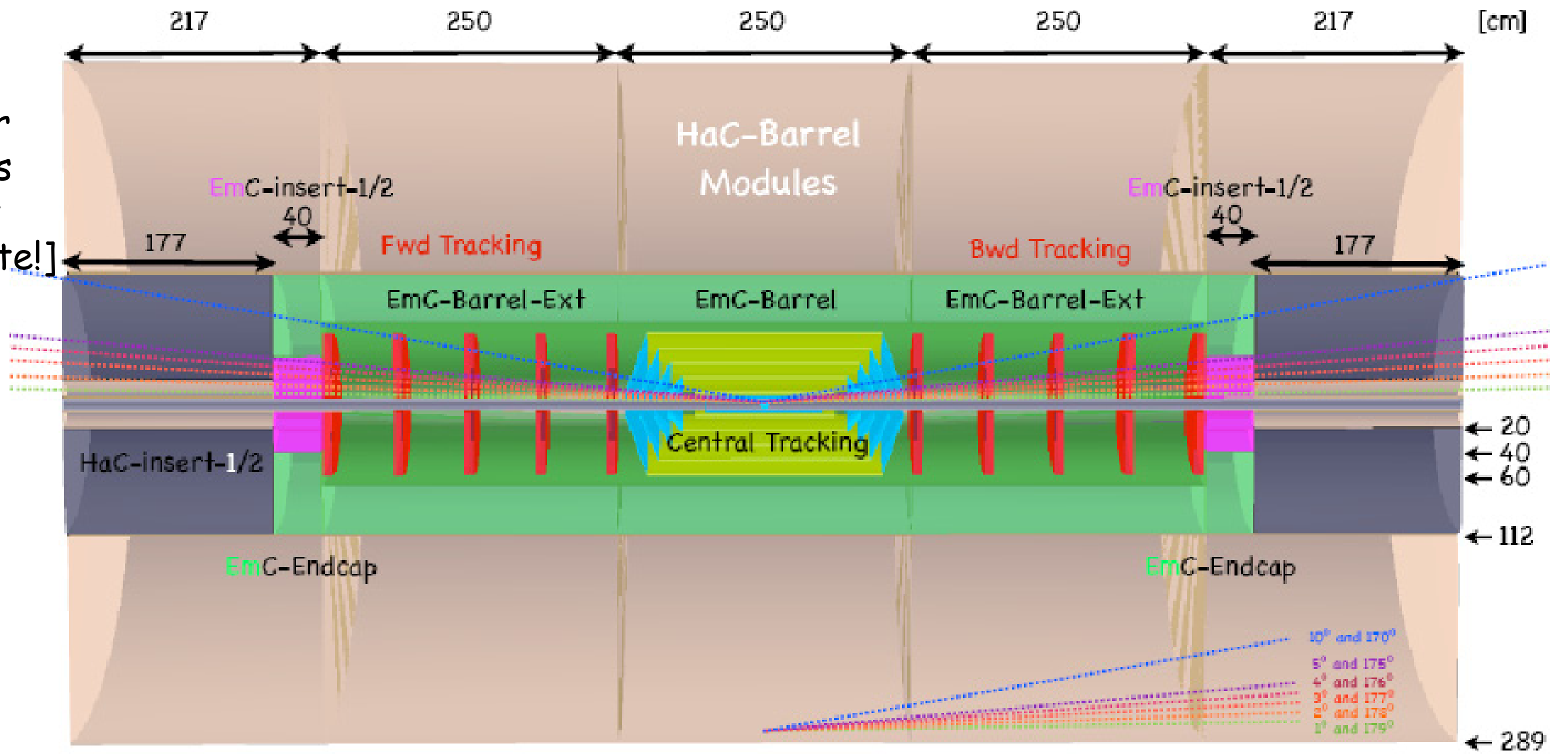
Lumi = 10^{33} cm^{-2} s^{-1}	(HERA 1-5 x 10^{31} cm^{-2} s^{-1})
Acceptance 10-170^{o} (→179^{o}?)	(HERA 7-177^{o})
Tracking to 0.1 mrad	(HERA 0.2 – 1 mrad)
EM Calorimetry to 0.1%	(HERA 0.2-0.5%)
Had Calorimtry to 0.5%	(HERA 1%)
Luminosity to 0.5%	(HERA 1%)

First `pseudo-data' for F_2, F_L, F_2^D … produced on this basis
Now need to go further

→ More realistic approach to inclusive scattering

→ First serious look at systematics for diffraction and other final state measurements

Low x Detector Design



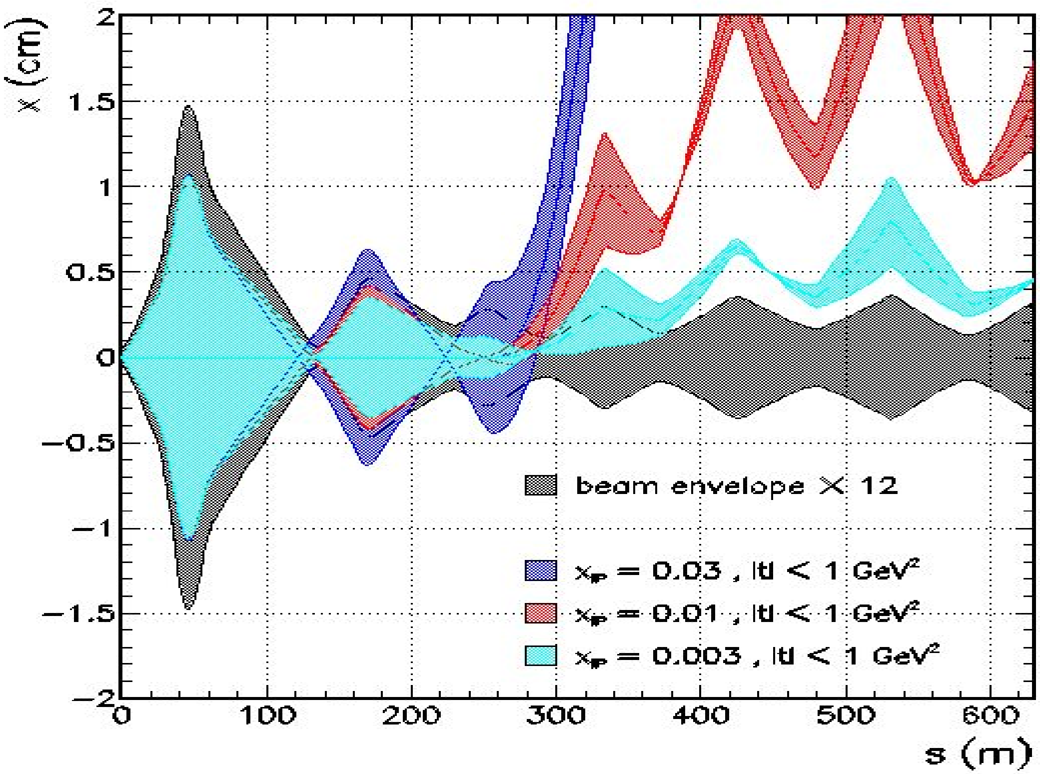
[Detector Convenors … already out of date!]

Need to translate specifications into physics studies …

- How many radiation lengths is backward EMC insert (defined by kinematic peak, which depends on E_e?)
- What about electron energy, angle resolution?
- Other ideas still alive? … 2 detectors? … Instrument inside beampipe? …Dipoles a la EIC? … Magcal?

A High Acceptance Proton Spectrometer?

[van Mechelen]

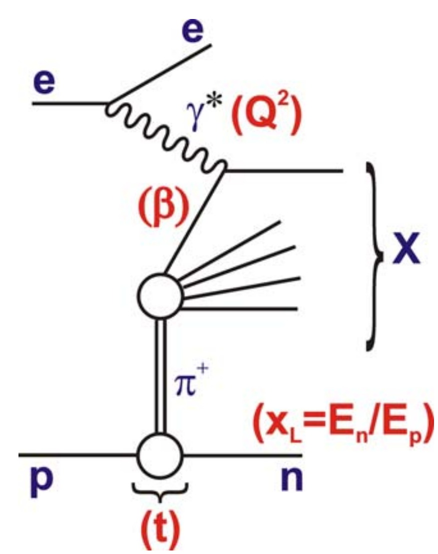


With `FP420'-style proton spectrometer, could tag and measure elastically scattered protons with high acceptance over a wide x_{IP}, t range

? Any complications if there's a finite crossing angle?
? Dependence on proton beampipe appertures near IP?
? Further pots closer to the IP?

→ Crucial to pursue these questions further … we need this!

What about Leading Neutrons?

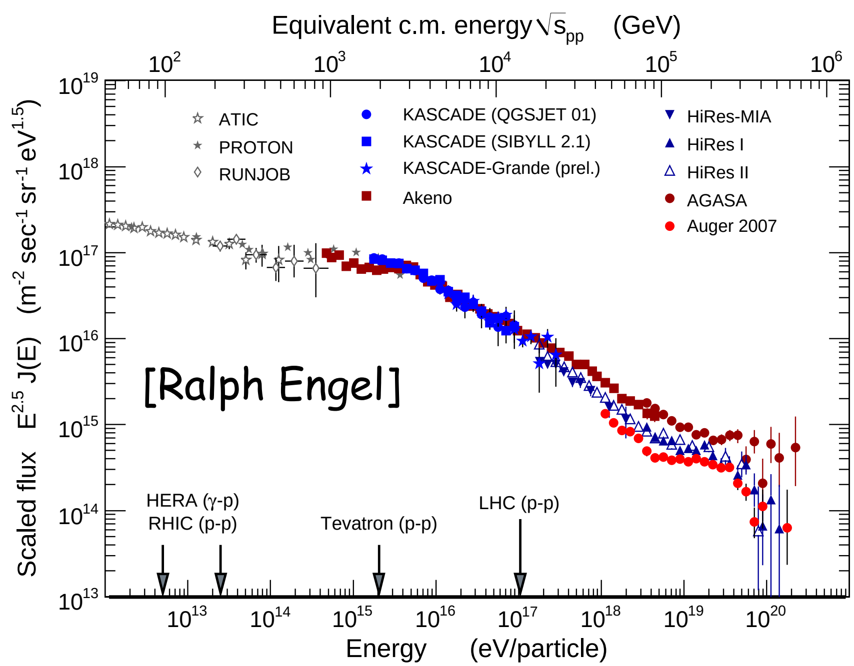


Interesting in ep for π structure function, absorptive / gap survival effects and related to cosmic ray physics

Crucial in inclusive ed, to distinguish scattering from p or n

Crucial in diffractive eA, to distinguish coherent from incoherent diffraction

Both HERA expts had a FNC



Very radiation hard detectors needed for LHC environment c.f. Similar detectors (ZDCs) at ATLAS and CMS

Leading Neutron Ideas (Buyatyan, Lytkin)

- Size & location determined by available space in tunnel and beam-line appertures
- Requires a straight section at $\theta \sim 0^o$ after beam is bent away.
- H1 version → 70x70x200cm Pb-scintillator (SPACAL) @ 100m →θ<0.8mrad (p_t <~ 500 MeV)

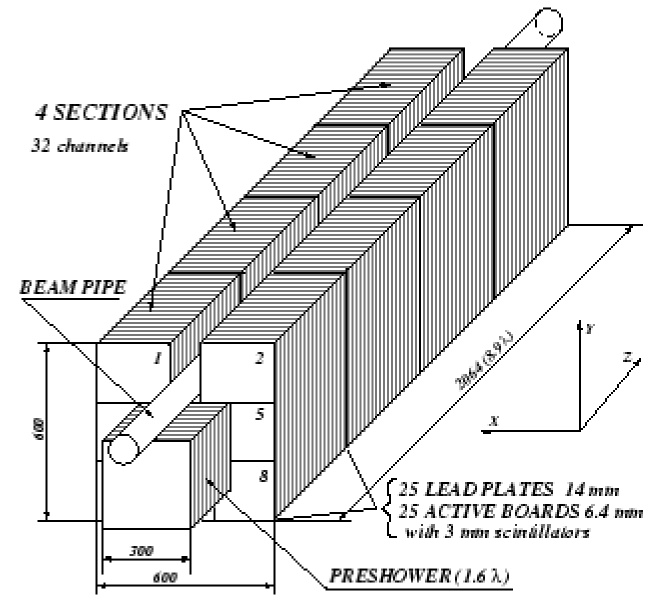
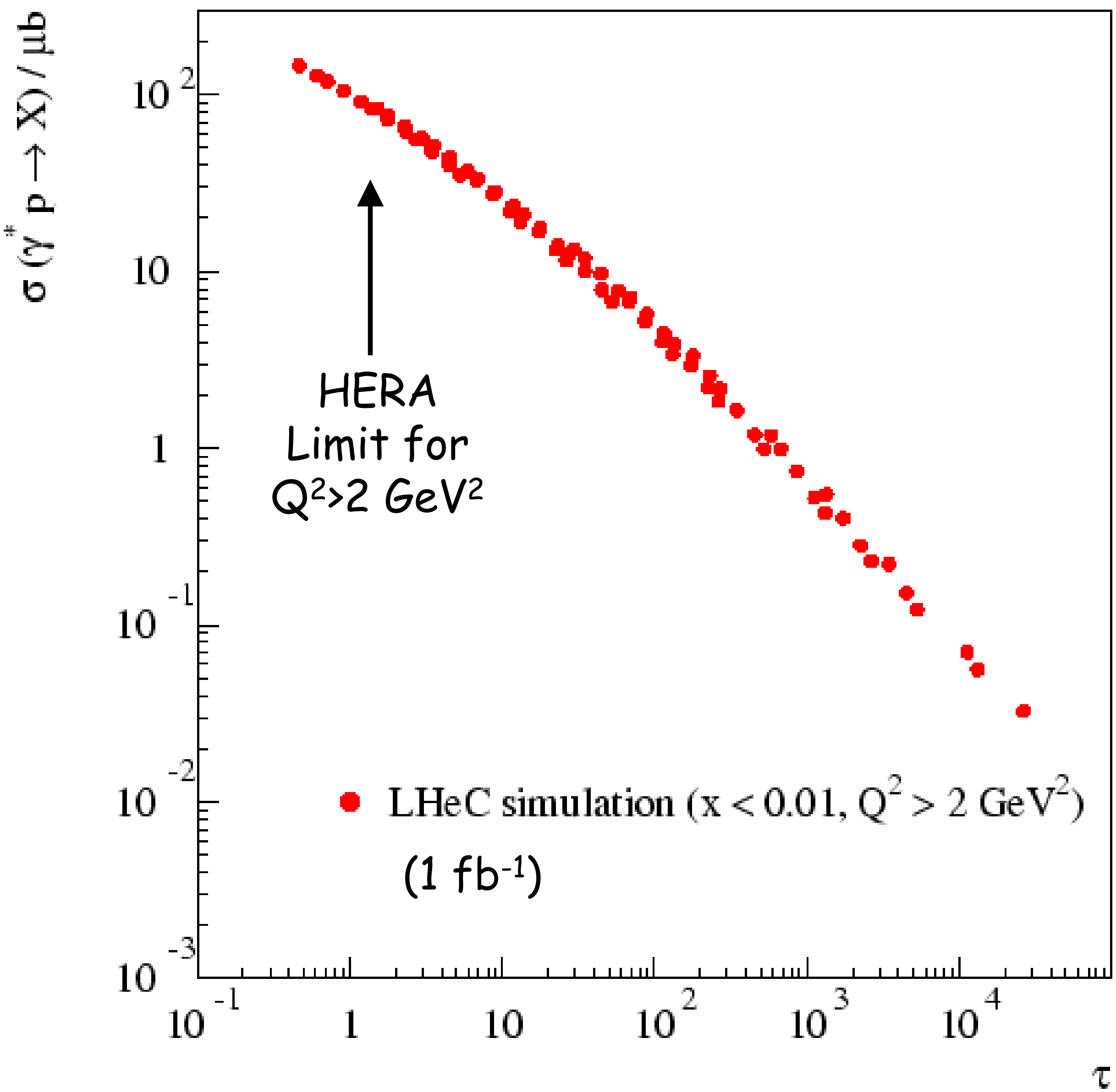


Figure 5: General view of the H1-FNC calorimeter

- LHeC: aim for similar θ range?… more would be nice!
- Need ~ 10λ to contain 95% of 7 TeV shower
- 2λ high granularity pre-sampler to reject EM showers from photon background and get impact point
- Main calorimeter coarser with 4-5 longitudinal segments?
- Achievable resolution could be $\sigma/E \sim 60\%/\text{sqrt}(E)$

Geometric Scaling at the LHeC



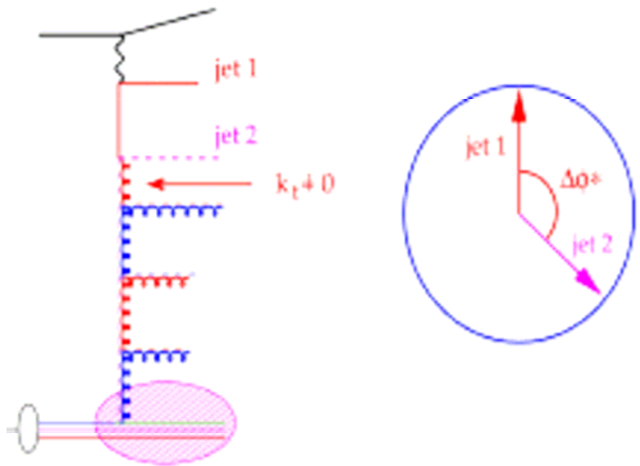
LHeC reaches $\tau \sim 0.15$ for Q^2=1 GeV^2 and $\tau \sim 0.4$ for Q^2=2 GeV^2

Some (though limited) acceptance for $Q^2 < Q^2_s$ with Q^2 "perturbative"

Could be enhanced with nuclei.

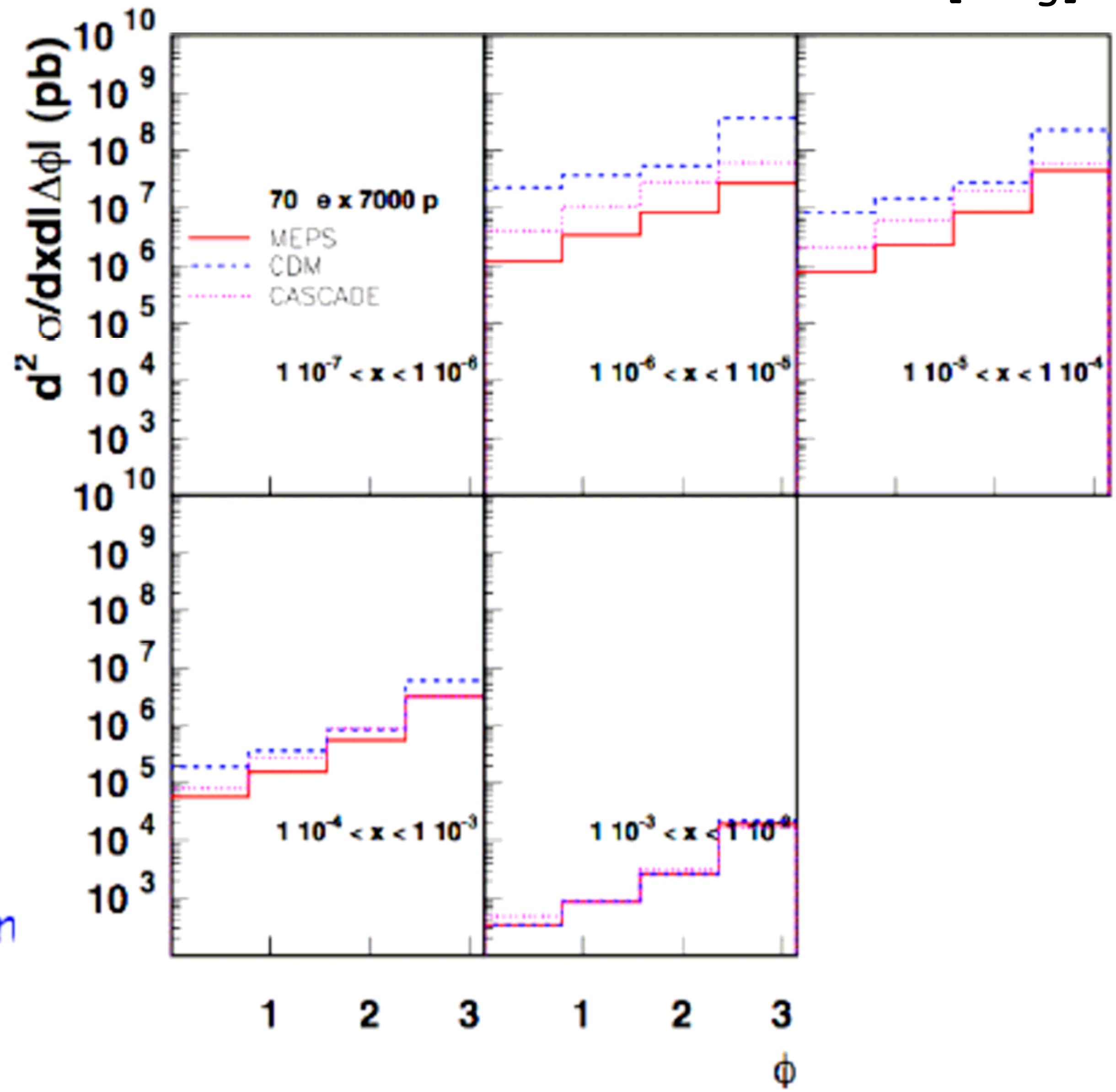
$Q^2 < 1$ GeV^2 accessible in special runs?

Azimuthal (de)correlations between Jets



- $5 < Q^2 < 100\ \mathrm{GeV}^2$
  $-1 < \eta < 2.5$
  $E_T > 5\ \mathrm{GeV}$
- small $k_t \rightarrow \Delta\phi \sim 180$
- large k_t from evolution

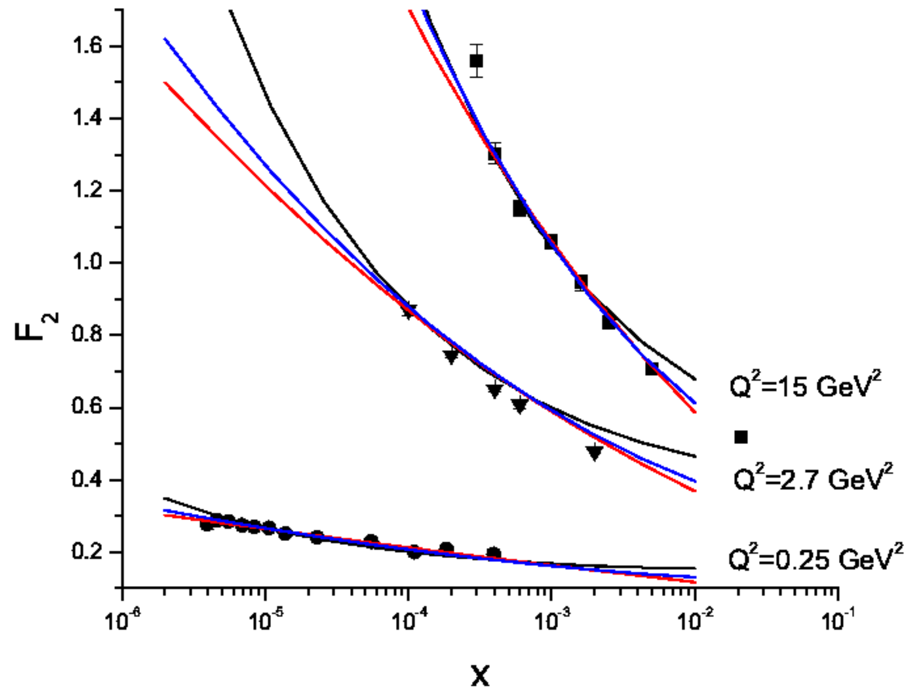
[Jung]



Parton Saturation after HERA?

e.g. Forshaw, Sandapen, Shaw
hep-ph/0411337,0608161
… used for illustrations here

Fit inclusive HERA data
using dipole models
with and without parton
saturation effects



FS04 Regge (~FKS): 2 pomeron model, <u>no saturation</u>

FS04 Satn: <u>Simple implementation of saturation</u>

CGC: <u>Colour Glass Condensate version of saturation</u>

- All three models can describe data with $Q^2 > 1\text{GeV}^2$, $x < 0.01$
- Only versions with saturation work for $0.045 < Q^2 < 1\ \text{GeV}^2$

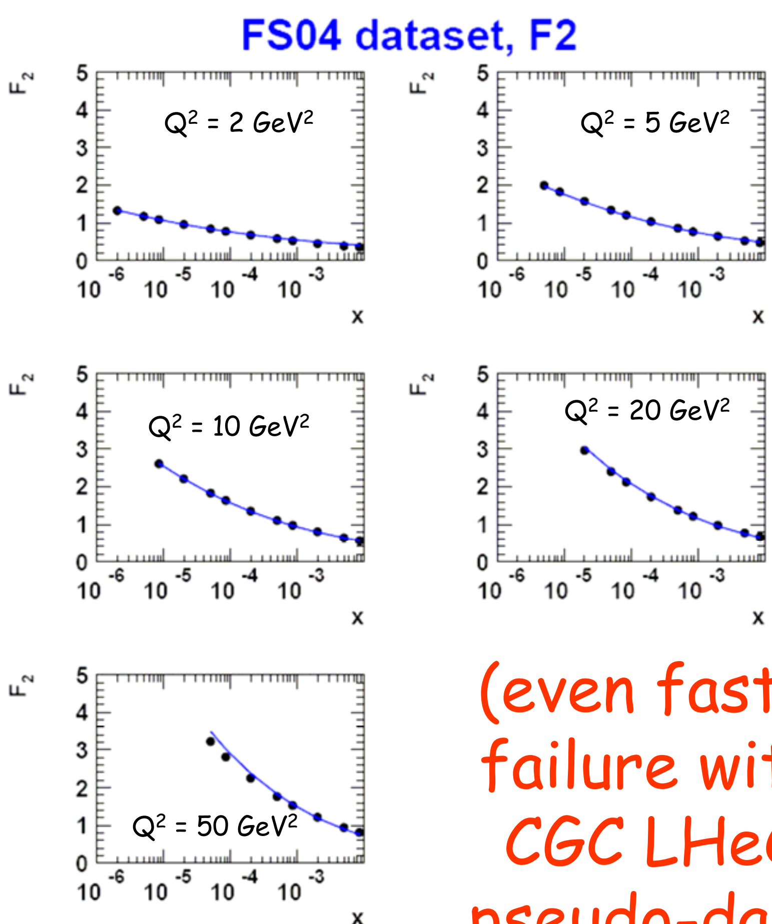
<u>… any saturation at HERA not easily interpreted partonically</u>

Can DGLAP adjust to fit LHeC sat models?

[Forshaw, Klein, PN, Perez]

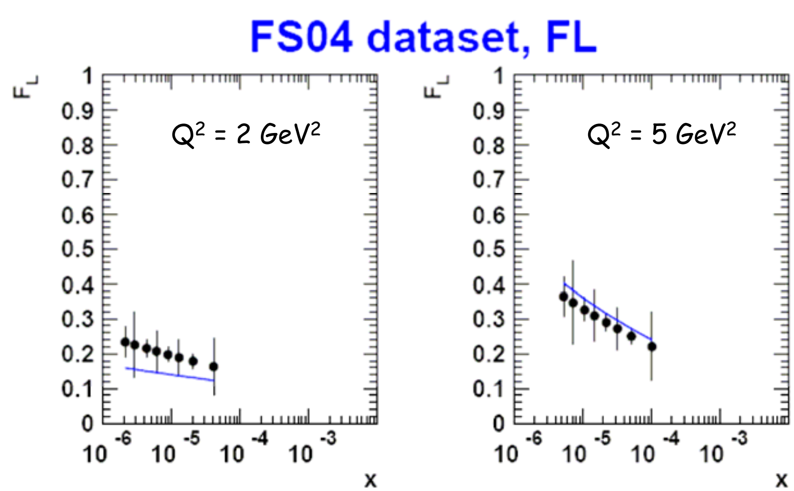
- Attempt to fit ZEUS and LHeC saturated pseudo-data in increasingly narrow (low) Q^2 region until good fit obtained
- Use dipole-like (GBW) gluon parameterisation at Q_0^2

$$xg(x,Q_0^2) = A_g\left(1-\exp\left[-B_g\log^2\left(\frac{x}{x_0}\right)^{\lambda}\right]\right)(1-x)^{C_g}$$



- Fitting F_2 only, a good fit cannot be obtained beyond the range $2 < Q^2 < 20$ GeV^2
- This fit fails to describe F_L

(even faster failure with CGC LHeC pseudo-data)



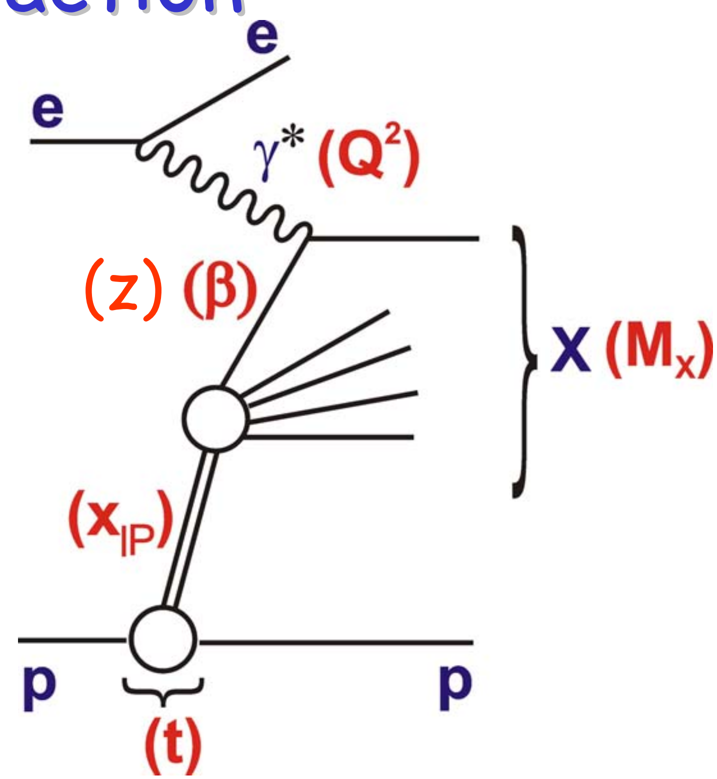
Inclusive Diffraction

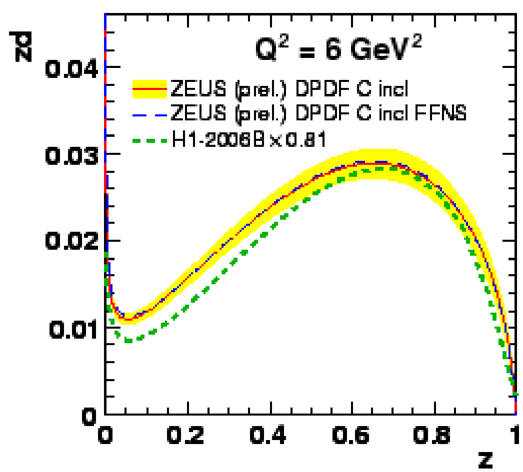
Additional variables ...

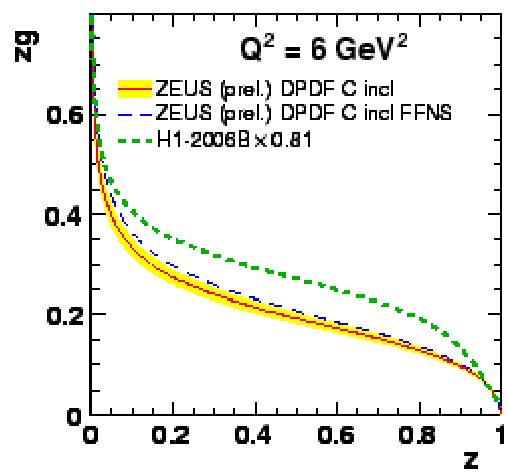
x_{IP} = fractional momentum loss of proton (momentum fraction IP/p)

$\beta = x / x_{IP}$ (momentum fraction q / IP)

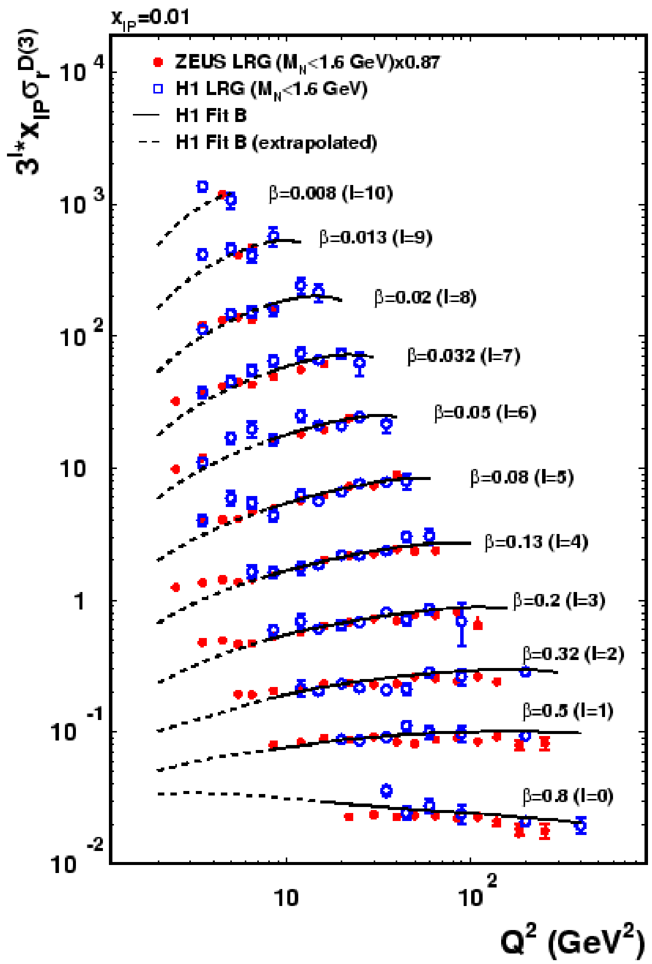
... both obtained from Mx





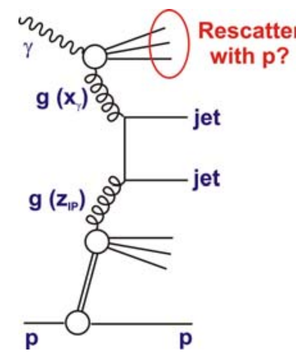


QCD analysis leads to diffractive parton densities of the proton



Inclusive Diffraction @ HERA

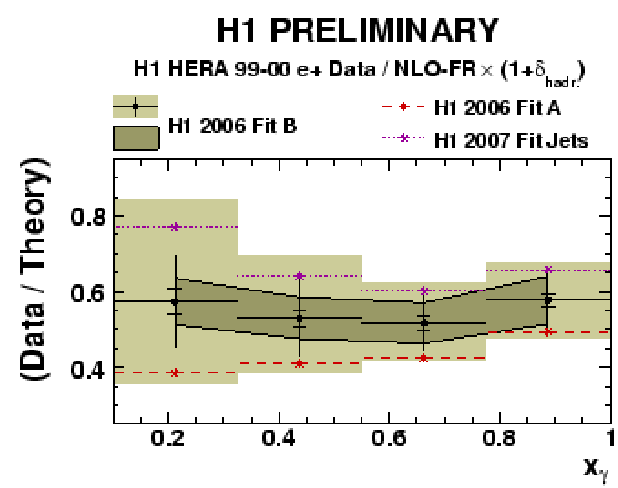
- Unexpectedly big story @ HERA
- Diffractive parton densities and factorisation now 'mature' subject
- Sensitivity to non-linear effects
- Rapidity gap survival dynamics



Still some unexplained features …

→ Low Q^2 flattening of F_2^D?

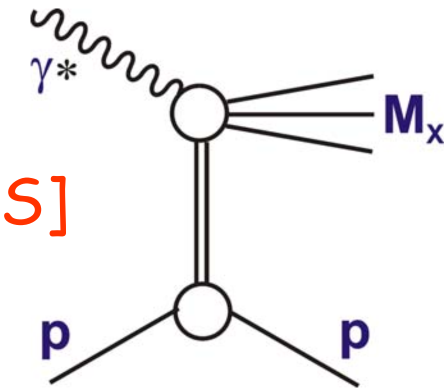
→ Anomalous survival probabilitiy in resolved photoproduction?

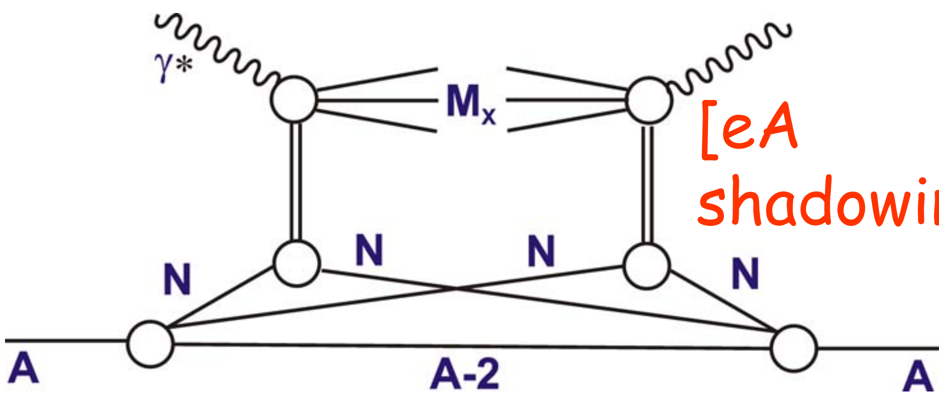


F_2^D and Nuclear Shadowing

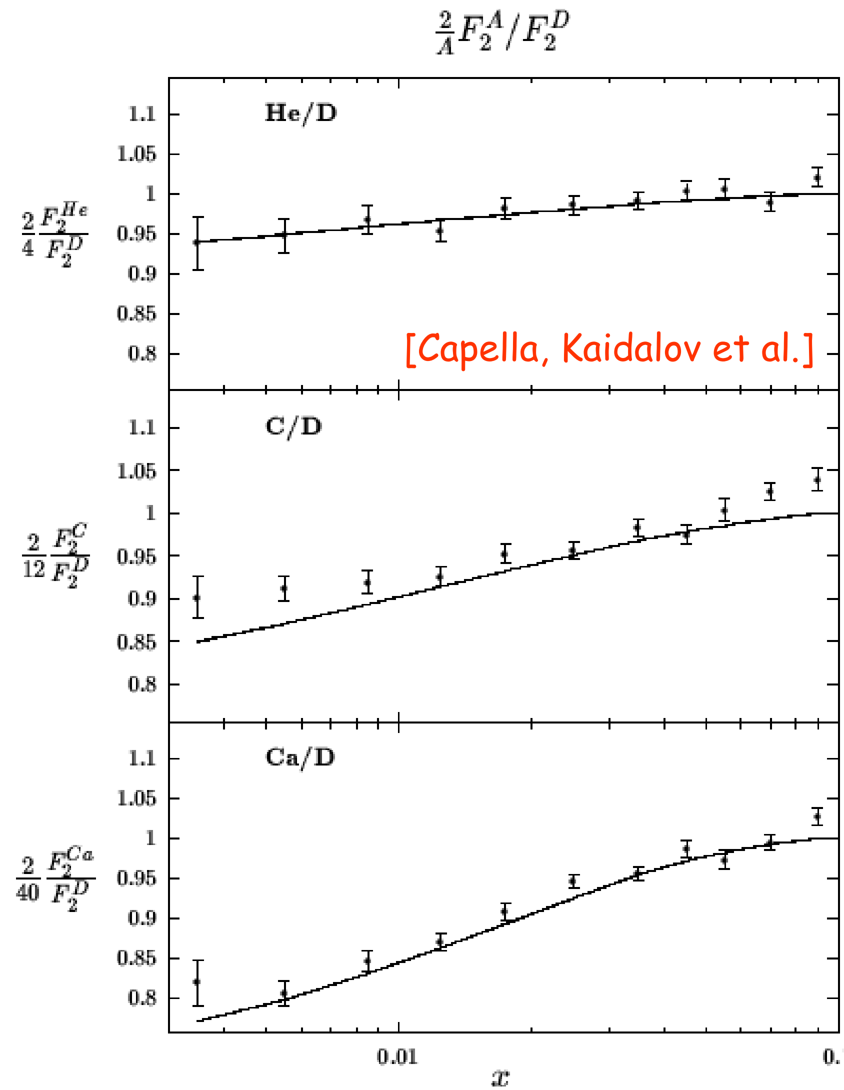
Nuclear shadowing can be described (Gribov-Glauber) as multiple interactions, starting from ep DPDFs

[Diff DIS]



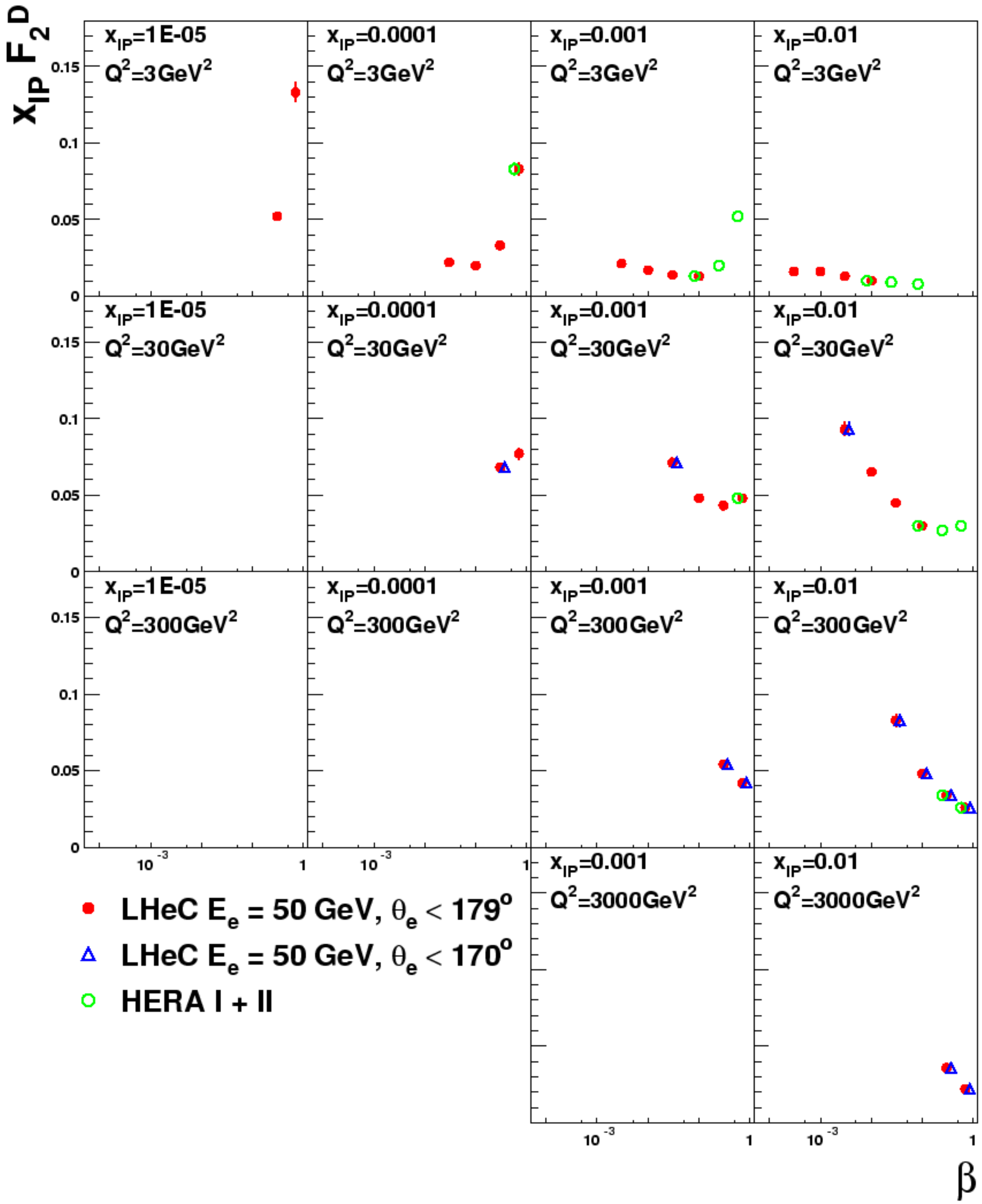


[eA shadowing]



... starting point for Extending precision LHeC studies into eA collisions

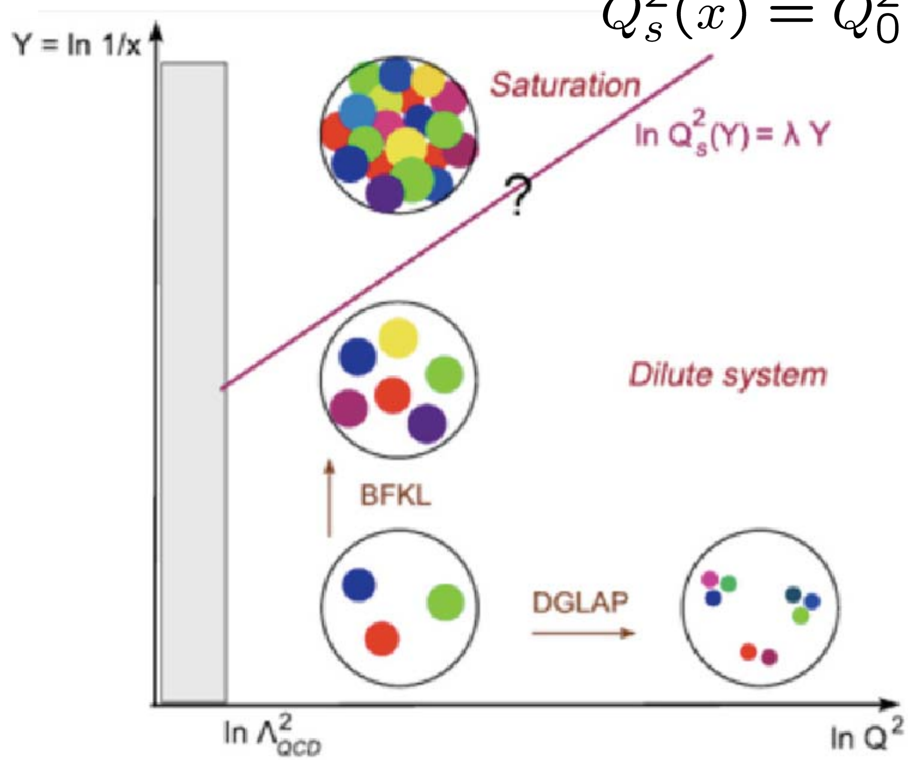
New pseudo-data



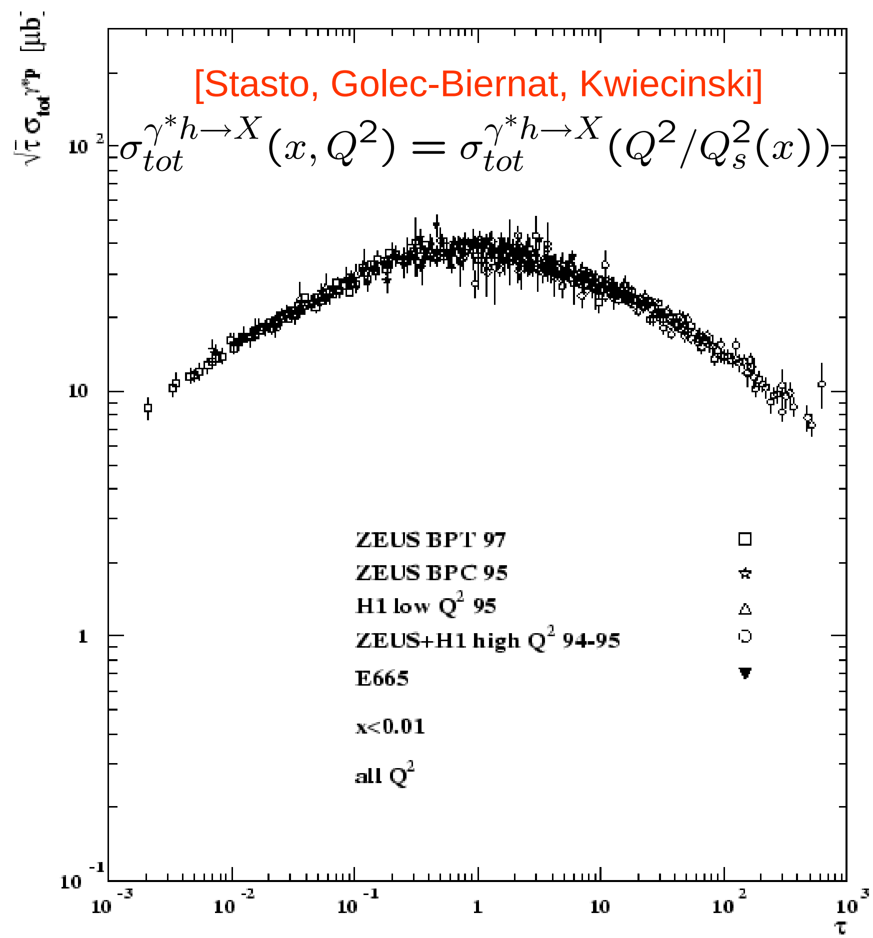
- With $\theta < 170^o$, limited coverage, separated from HERA range
- With $\theta < 179^o$, 50 GeV data overlap nicely with HERA and extend to lower β, lower x_{IP} and higher Q^2

Non-linear effects @ HERA

$$Q_s^2(x) = Q_0^2 \; x^{-\lambda}$$



Lines of constant density are diagonal …
… scattering cross section appears constant along them



Something appears to happen around $\tau = Q^2/Q^2_s = 1$ GeV^2 (confirmed in many analyses)
BUT … Q^2 small for τ <~ 1 GeV^2
… not easily interpreted in QCD