The LHeC project

INT workshop – Science case for an EIC
Seattle, WA, November 18, 2010

Olaf Behnke (DESY)

..Logo from the ongoing logo contest..

Need for LHeC

27.5 GeV x 920 GeV ep HERA

with integrated L~0.5 fb^{-1} was a

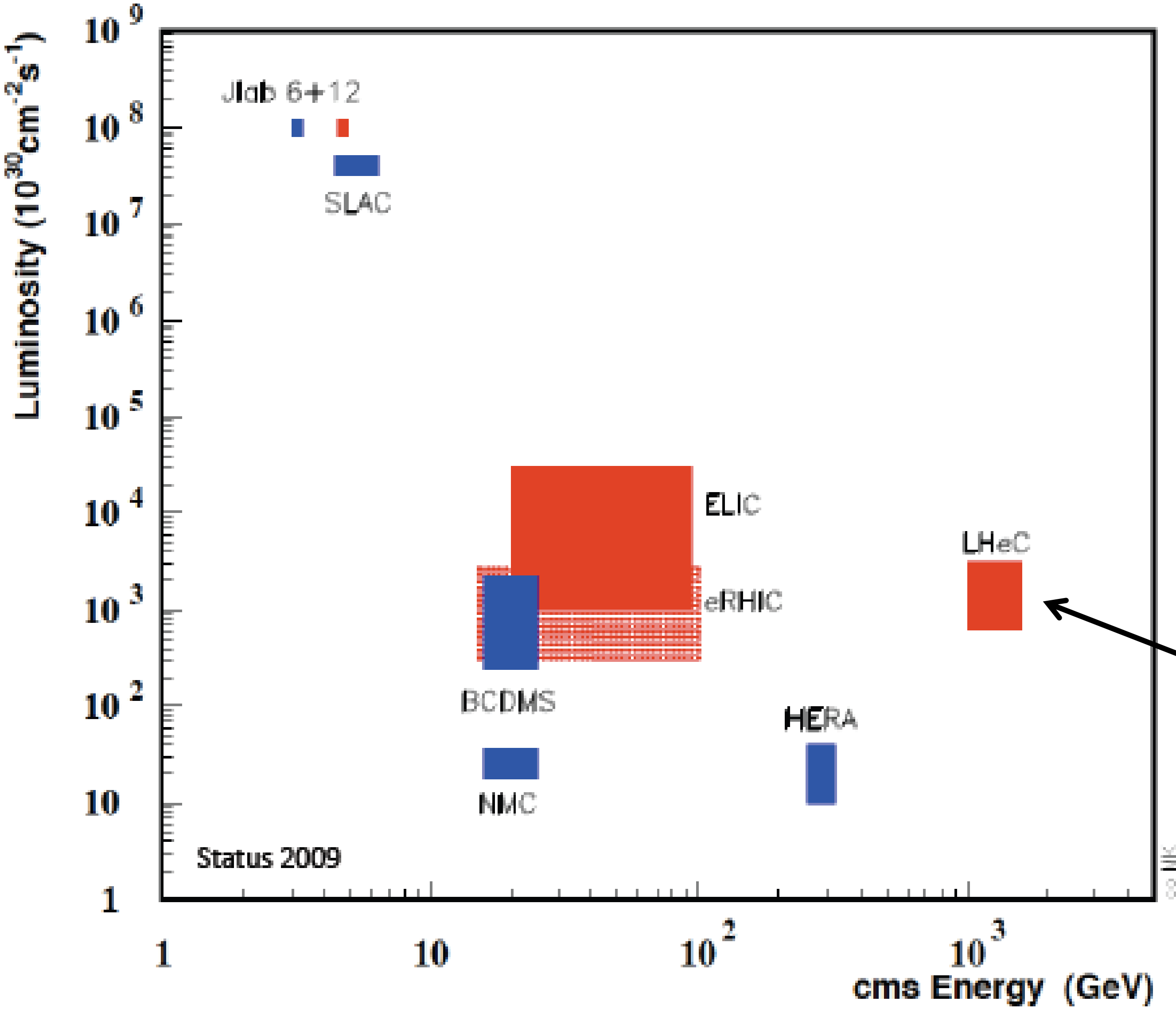
- ➢ high precision machine for QCD
- ➢ modest precision machine for electroweak physics

Where could we go with a

20-150 GeV x 7 TeV $e^{\pm}p$, also eA collider

with integrated L~1-100 fb^{-1} ?

Lepton proton scattering experiments

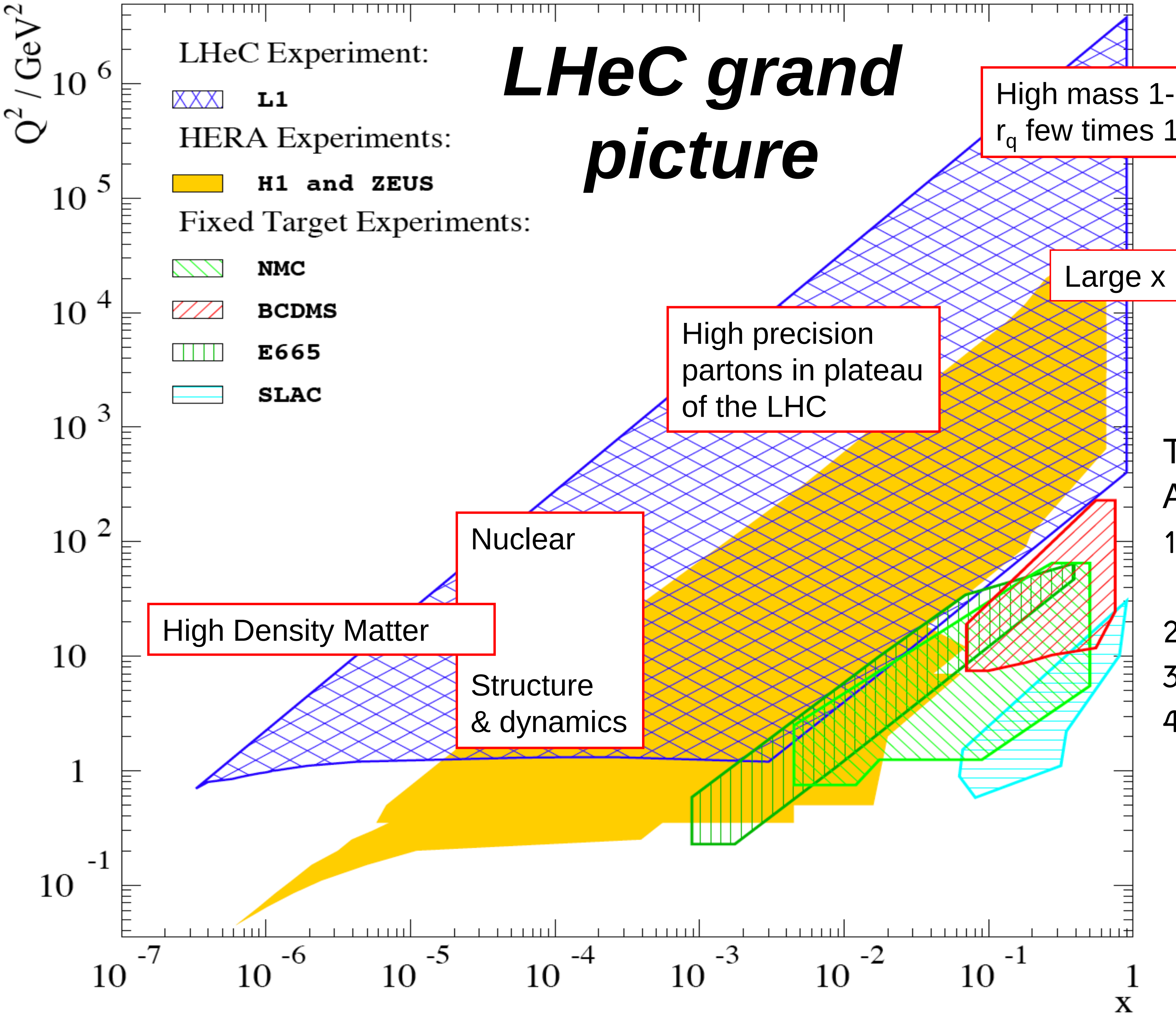


done

planned

LHeC = highest energy and high lumi

LHeC grand picture



Talk Content:

Accelerator

1. Inclusive DIS & PDFs
2. Jets, c,b,t
3. Low x, saturation
4. EW and BSM

LHeC Accelerator options

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta_{px(y)} = 1.8(0.5)m, \gamma = \frac{E_p}{M_p}$$

$$L = 8.2 \cdot 10^{32} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{m}{\sqrt{\beta_{px}\beta_{py}}} \cdot \frac{I_e}{50mA}$$

$$I_e = 0.35mA \cdot P[MW] \cdot (100 / E_e[GeV])^4$$

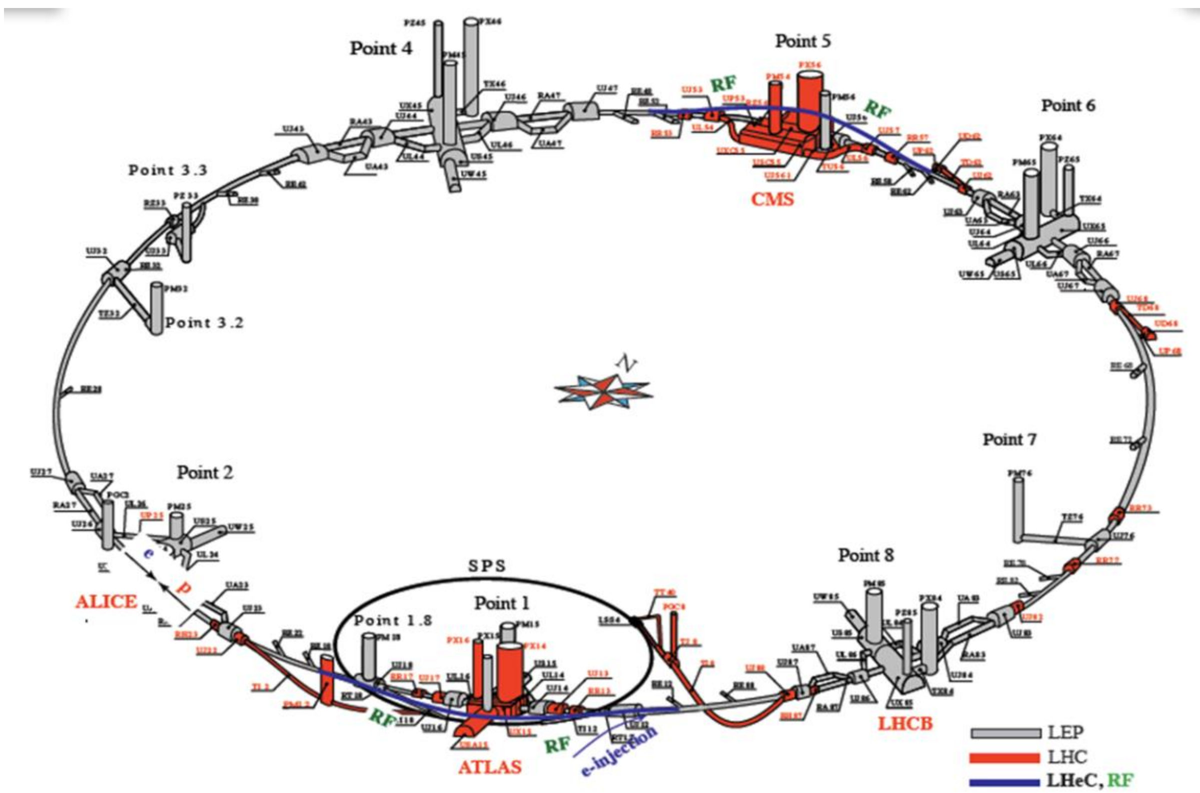
Ring-Ring

Power Limit of 100 MW wall plug

"ultimate" LHC proton beam

60 GeV $e^{\pm}$ beam

→L = 2 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}



LHeC Accelerator options

$$L = \frac{1}{4\pi} \cdot \frac{N_p}{\varepsilon_p} \cdot \frac{1}{\beta^*} \cdot \gamma \cdot \frac{I_e}{e}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta^* = 0.2m, \gamma = 7000/0.94$$

$$L = 8 \cdot 10^{31} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^*/m} \cdot \frac{I_e/mA}{1}$$

$$I_e = mA \frac{P/MW}{E_e/GeV}$$

LINAC Ring

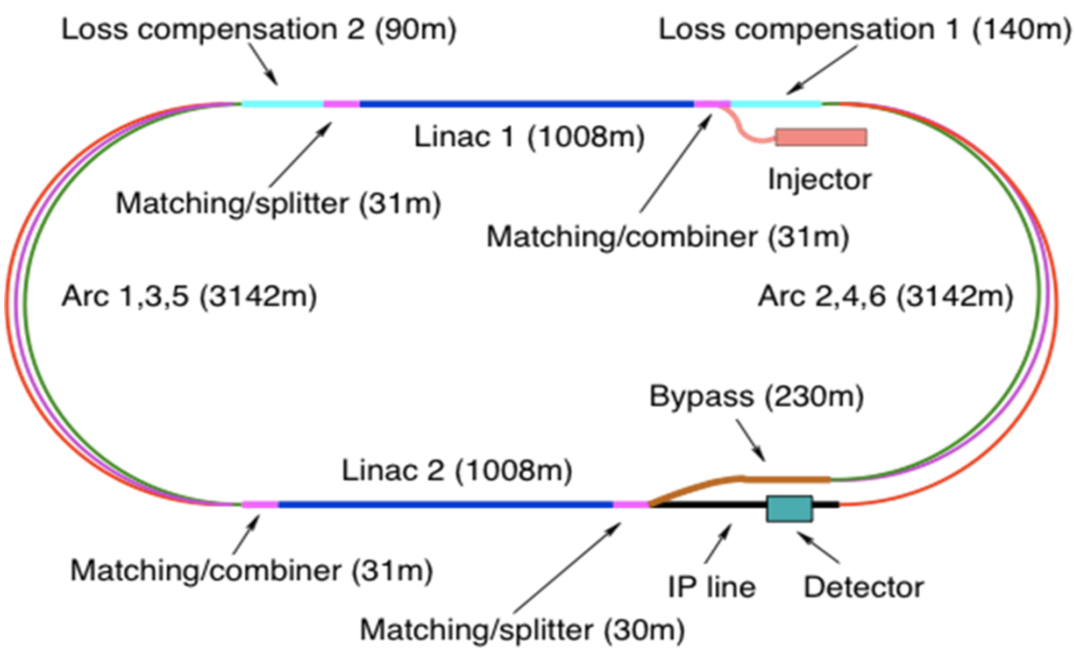
60 GeV "Circus Maximus" with

Energy recovery: $P = P_0/(1-\eta)$

$\beta^* = 0.1m$

$L = 10^{33}\ cm^{-2}s^{-1} \rightarrow O(100)\ fb^{-1}$

140 GeV LINAC few times 10^{32}



A 60 GeV Energy Recovery "LINAC"

A 140 GeV pulsed LINAC

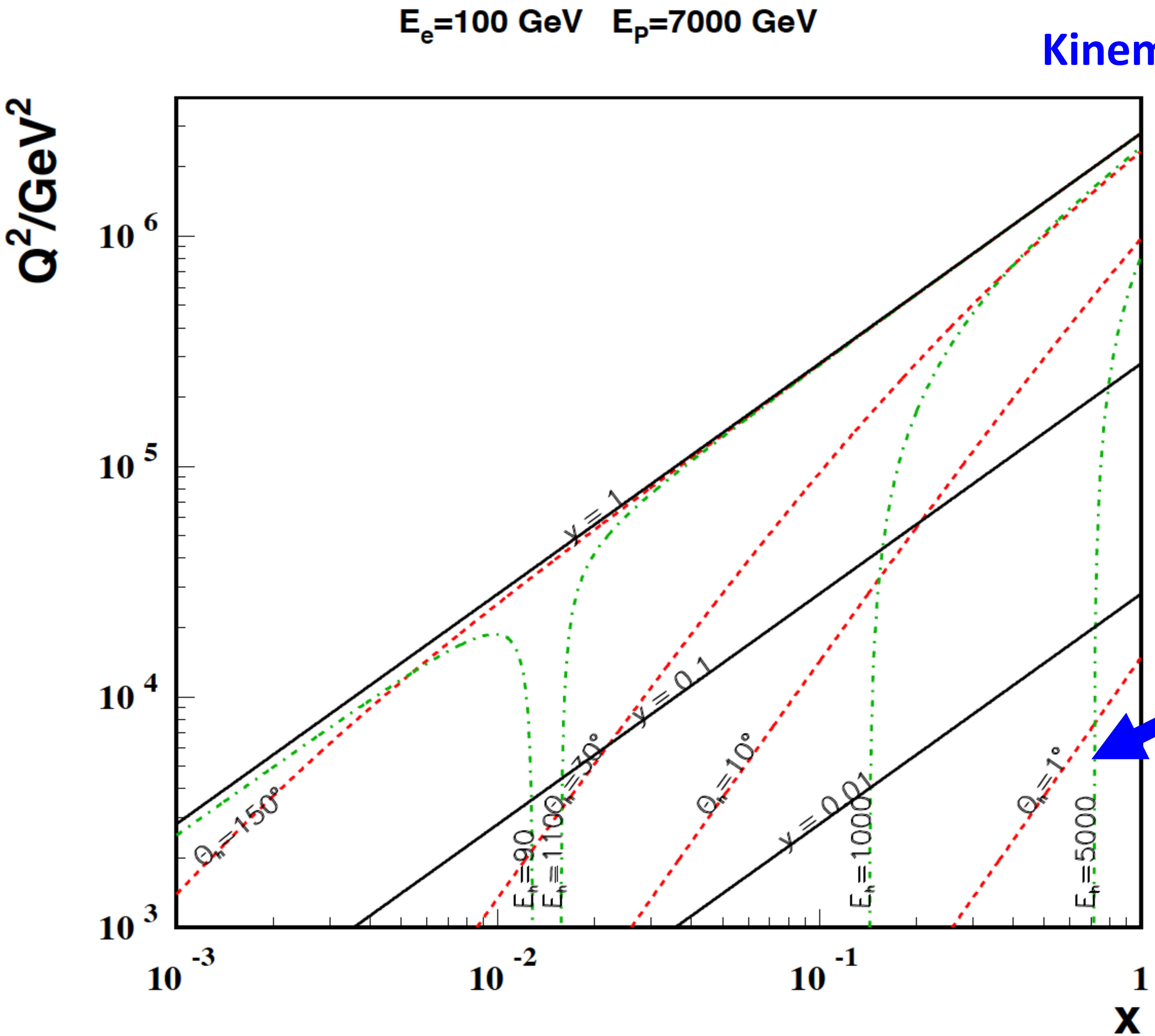
1. Inclusive NC & CC DIS: simulated Default Scenarios

http://hep.ph.liv.ac.uk/~mklein/simdis09/lhecsim.Dmp.CC, readfirst

Max Klein, LHeC

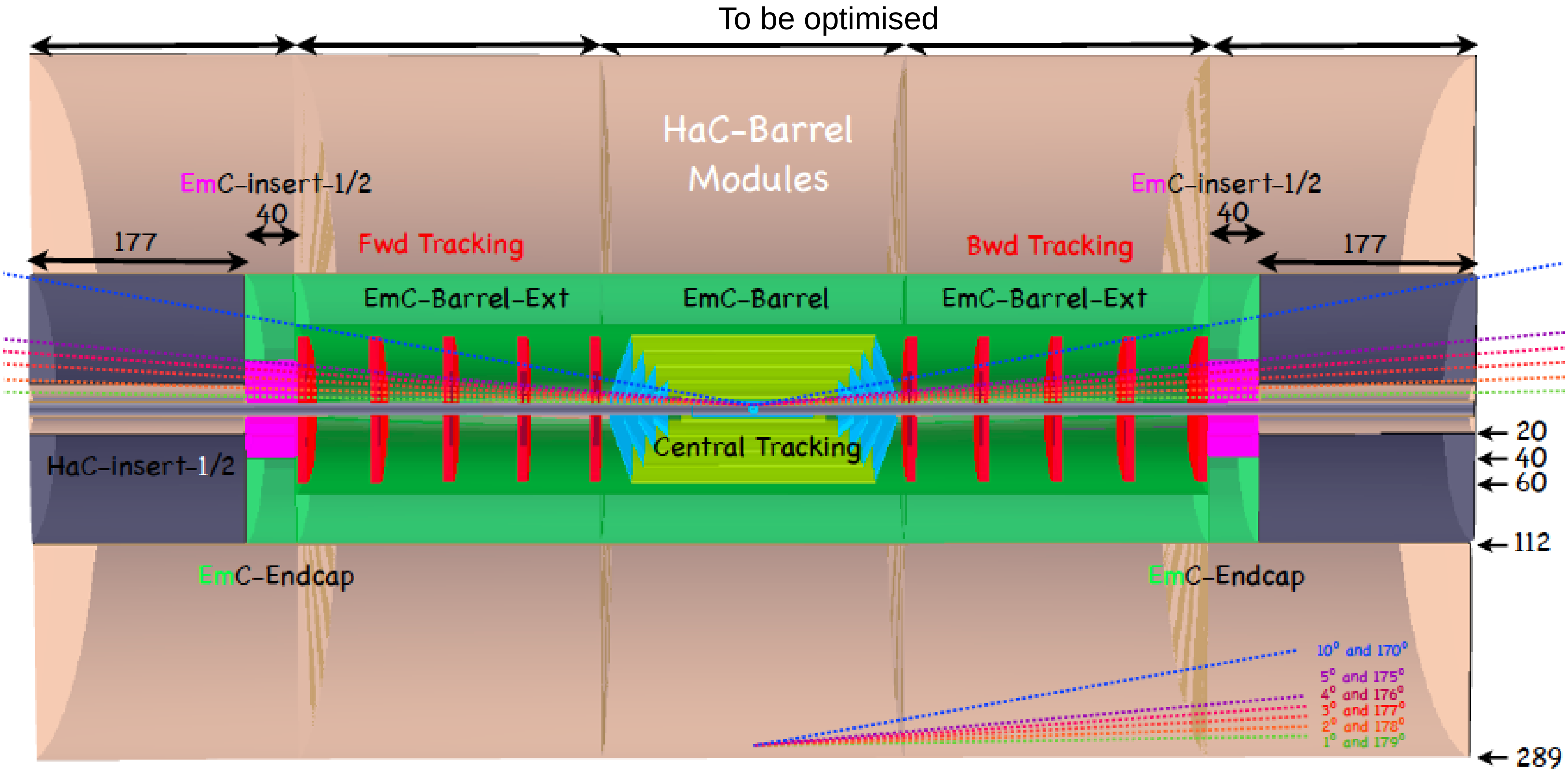
config.	E(e)	E(N)	N	$\int L(e^+)$	$\int L(e^-)$	|Pol|	$L/10^{32}$	P/MW	years	type
A	20	7	p	1	1	-	1	10	1	SPL
B	50	7	p	50	50	0.4	25	30	2	RR hiQ^2
C	50	7	p	1	1	0.4	1	30	1	RR lo x
→ D	100	7	p	5	10	0.9	2.5	40	2	LR
E	150	7	p	3	6	0.9	1.8	40	2	LR
F	50	3.5	D	1	1	--	0.5	30	1	eD
G	50	2.7	Pb	0.1	0.1	0.4	0.1	30	1	ePb ← Not simulated
H	50	1	p	--	1	--	25	30	1	lowEp

Kinematics – high Q^2



Need excellent forward hadron calorimetry & calibration

The Detector 'that should do it': - Low Lumi (Low Q^2) Setup

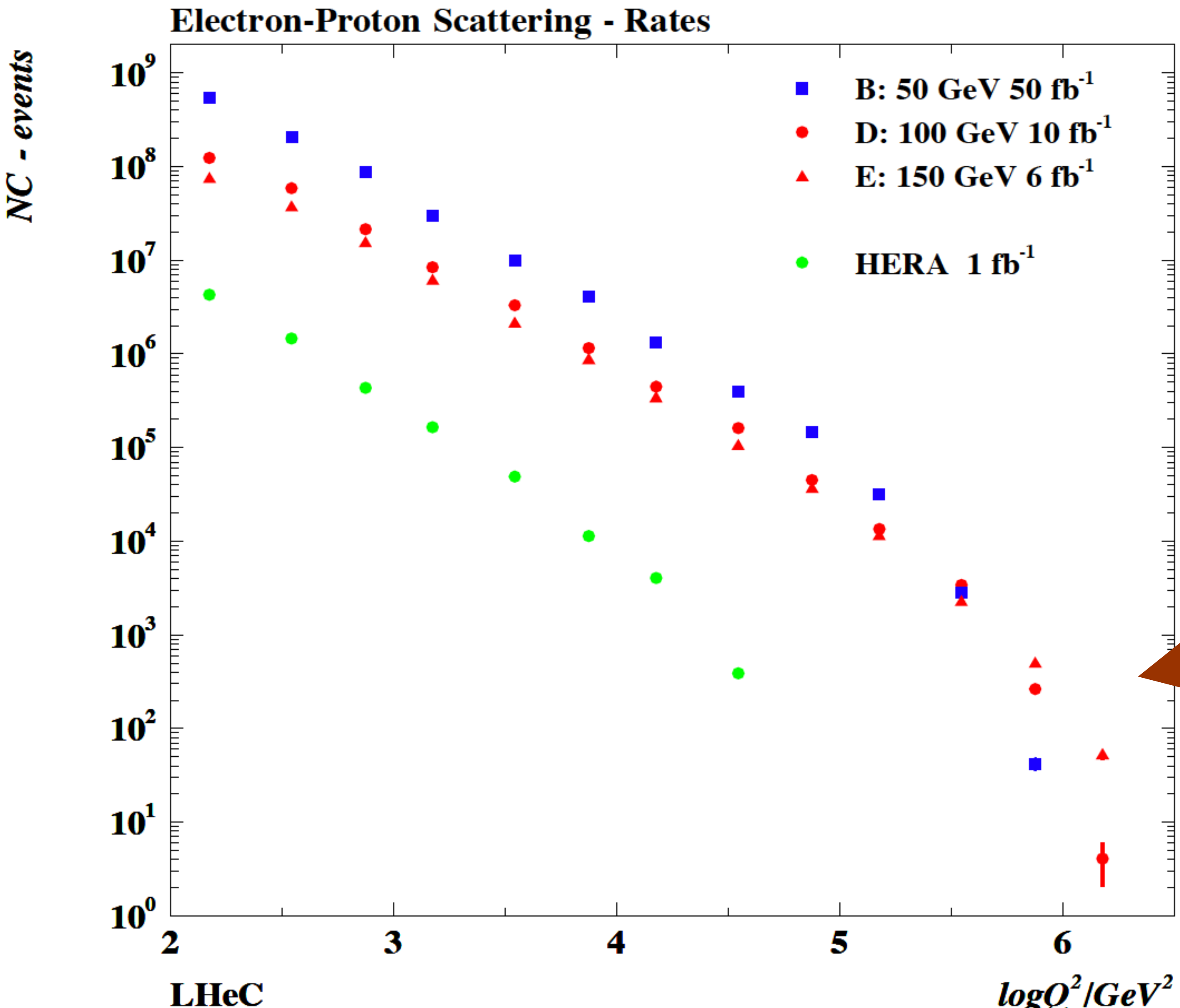


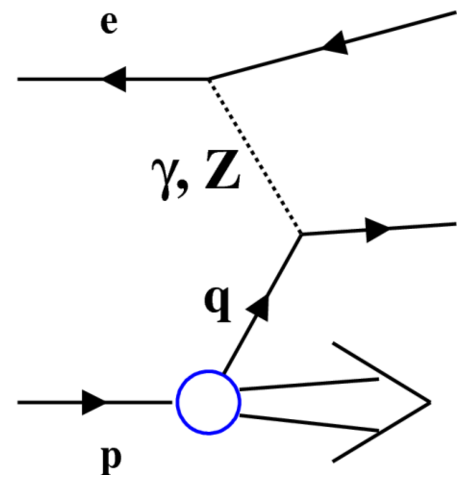
- Solenoid surrounding the HAC modules

-Outer detectors (HAC tailcatcher/muon detectors not shown)

to be discussed: very forward detector setup (proton taggers)

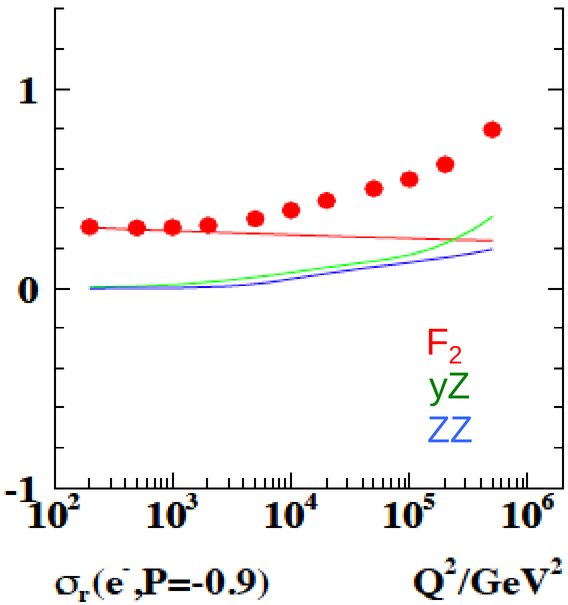
Pseudodata: Neutral Current Event Rates



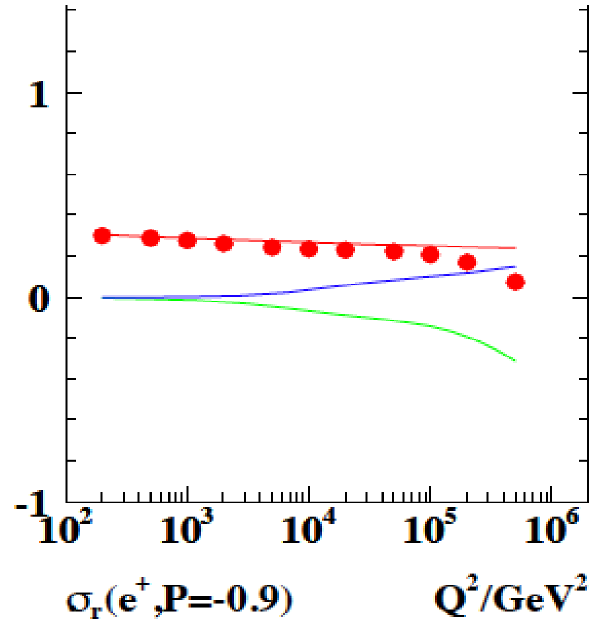


Trivial, but important: largest E_{lep} allows highest Q^2 scales

Photon and Z exchanges are 1:1



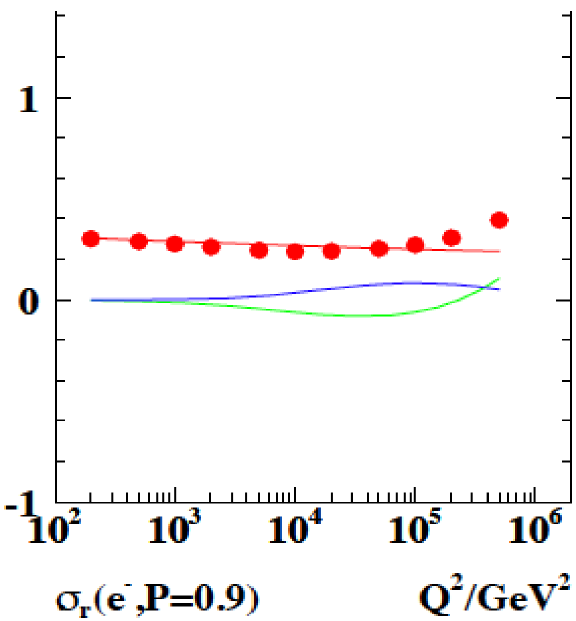
x=0.2
100 GeV
7000 GeV

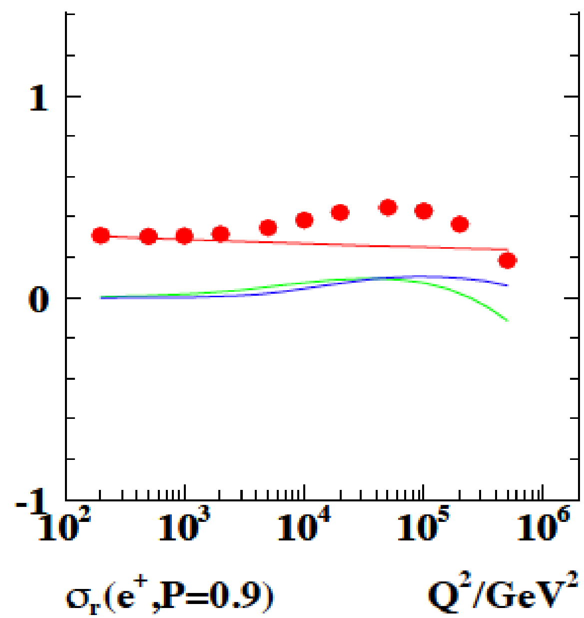


2 charges and
2 polarisations
very desirable

for electroweak
precision physics
and a
new spectroscopy
should that appear.

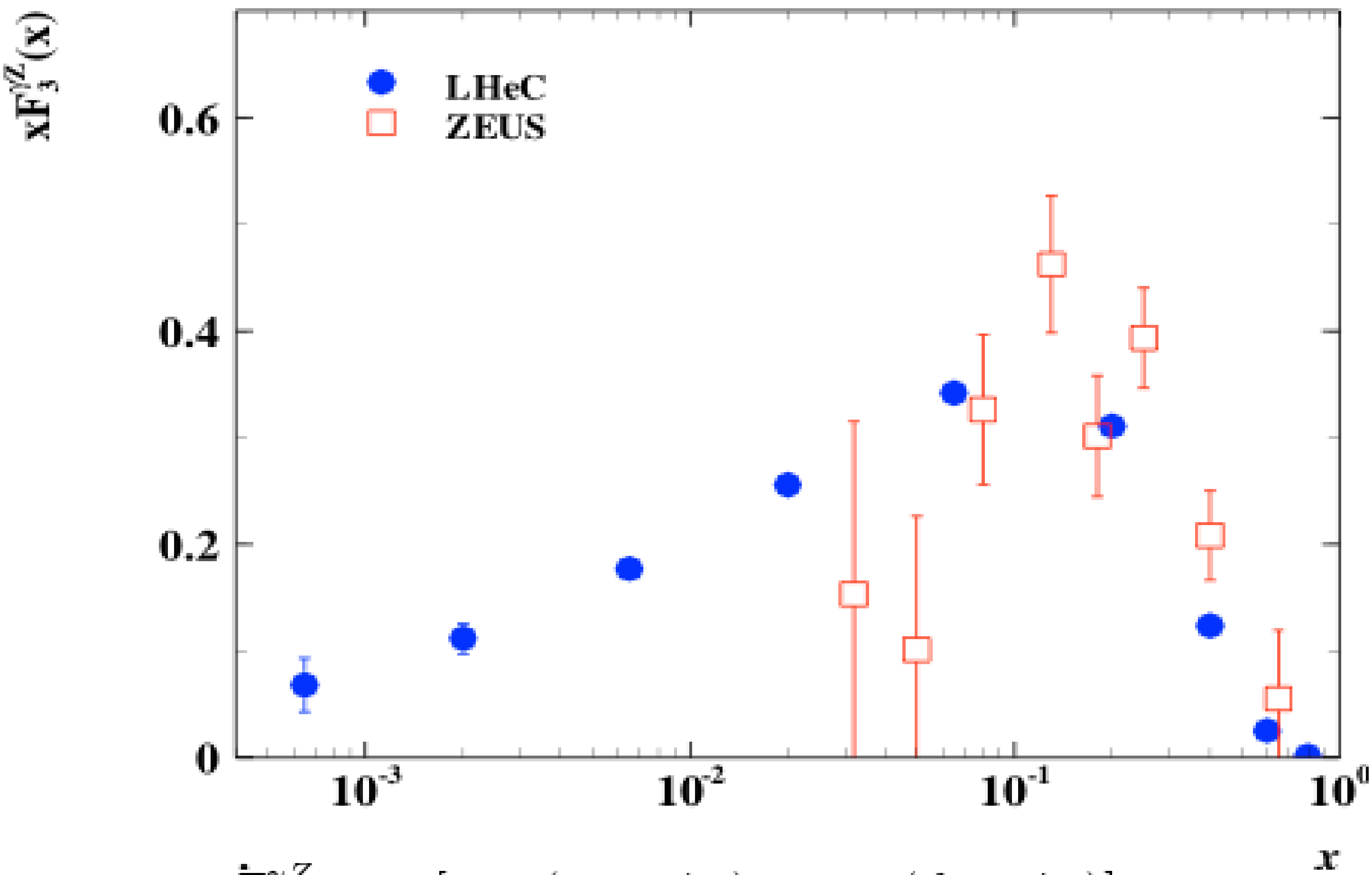
Z effects depend on lepton charge and polarisation.





Charge Asymmetry $xF_3^{\gamma Z}$

60x7000 GeV^2
P=0
10fb^{-1}



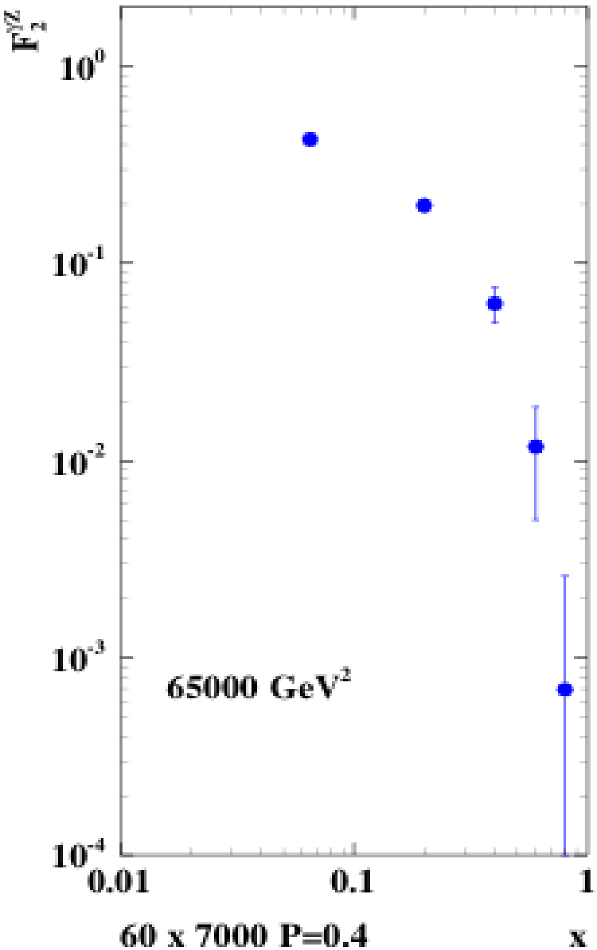
$$xF_3^{\gamma Z} = 2x[e_u a_u(u_v + \Delta_u) + e_d a_d(d_v + \Delta_d)]$$

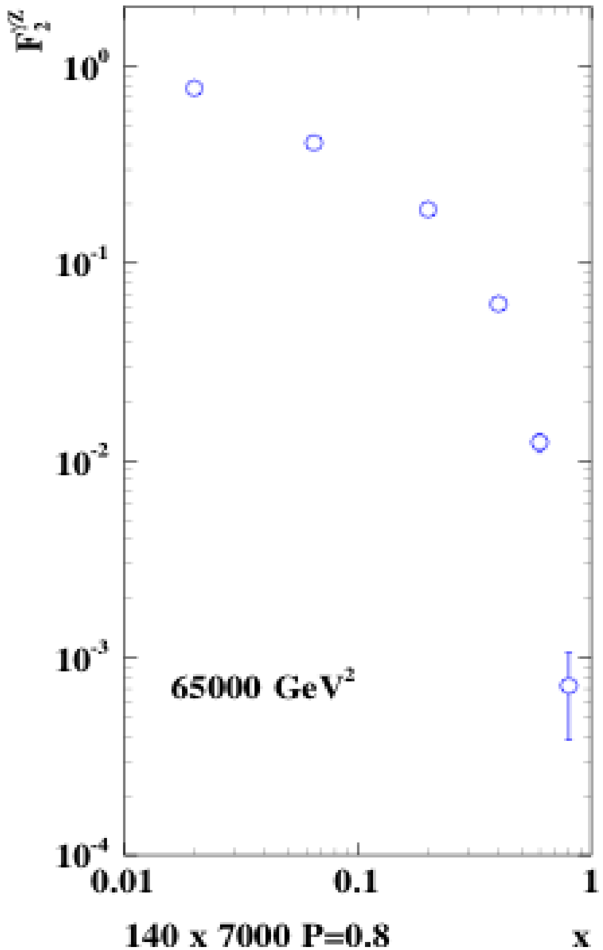
Get handle on valence quarks down to x~0.001

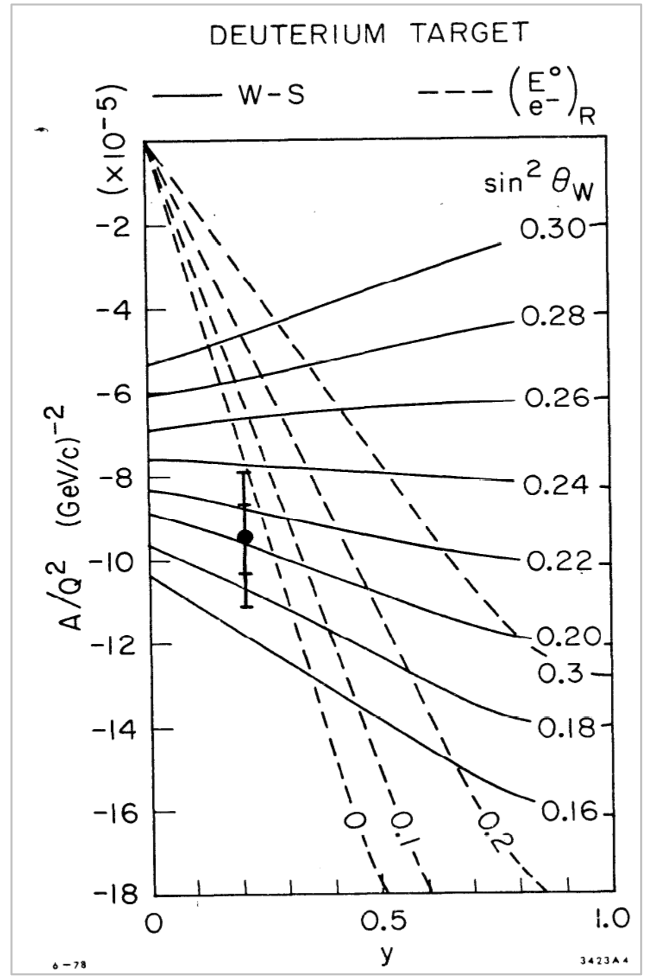
Parity violating polarisation asymmetries (for 60 GeV and 140 GeV lepton beams)

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

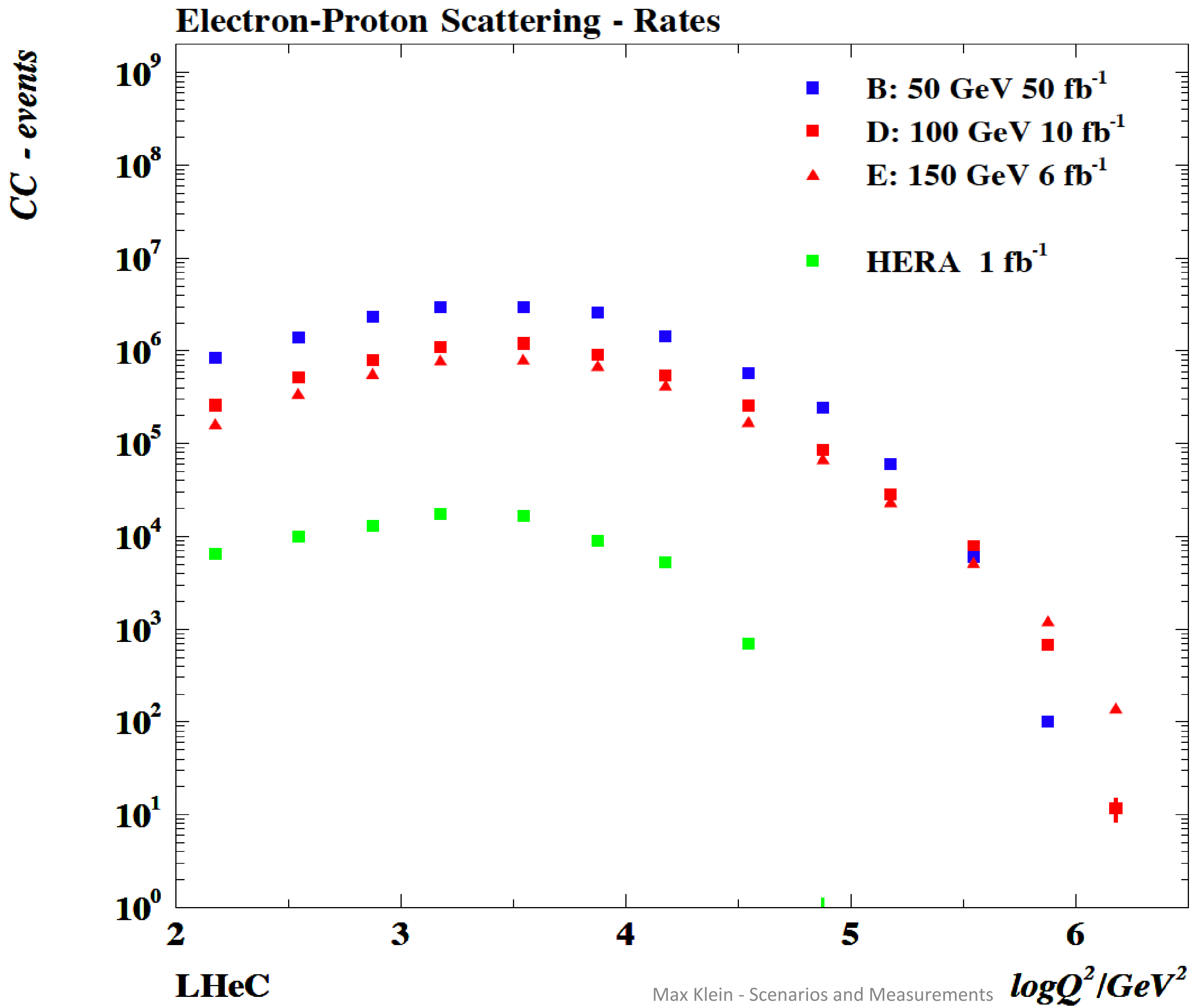


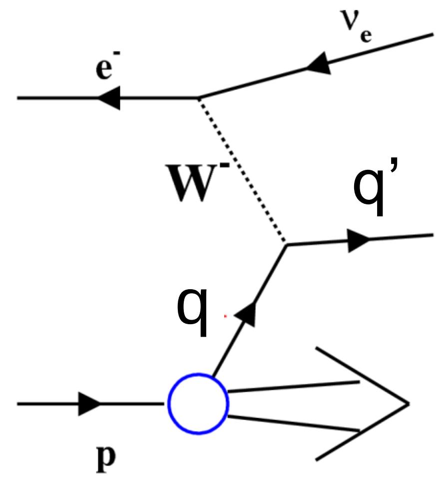




SLAC 1978

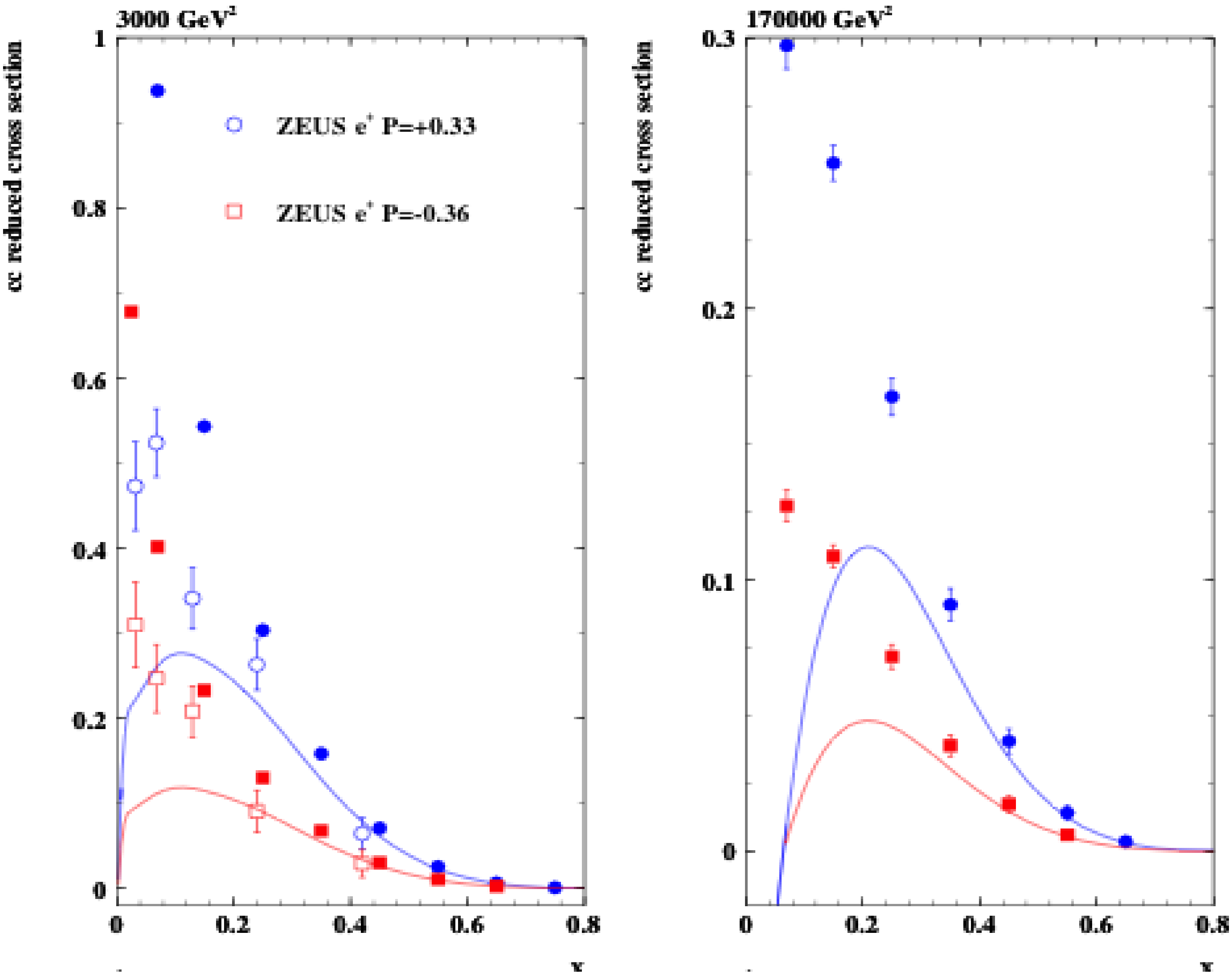
Pseudodata: Charged Current Event Rates





LHeC: expect ~ two orders of magnitude **more events** + better coverage for x>0.5

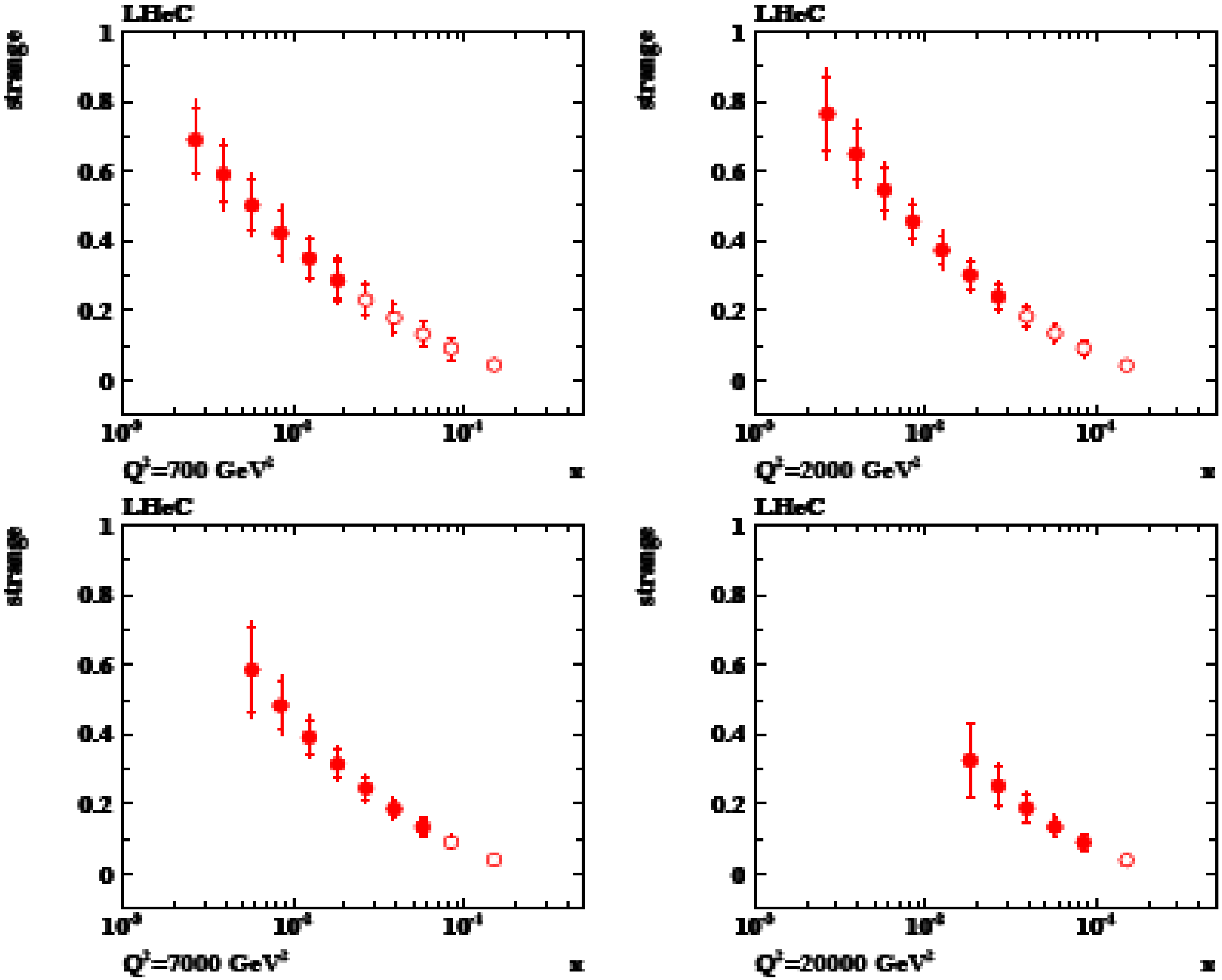
Charged Currents

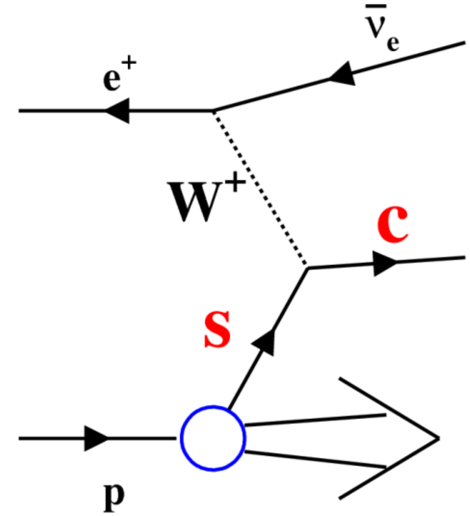


Valence quarks
up to x=0.8

Unfold U,D and
anti U,D

Strange =? Anti-strange quark density





$W^+ s \to c$

$1\, fb^{-1}$

$\varepsilon_c = 0.1$

$\varepsilon_q = 0.01$

$\delta_{syst} = 0.1$

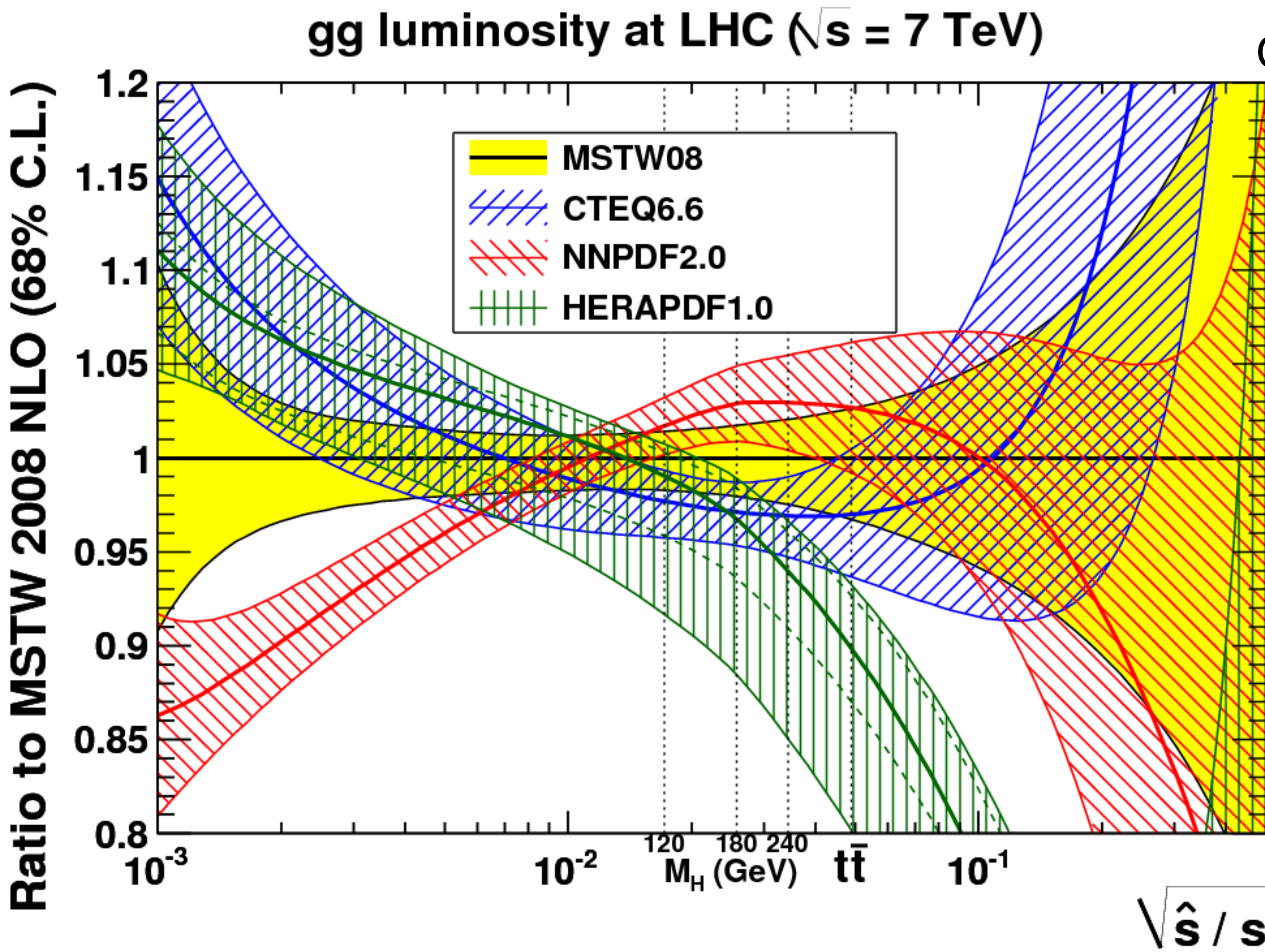
$\circ - \vartheta_h \geq 1^o$

$\bullet - \vartheta_h \geq 10^o$

→ Use e- p data for sbar

Some dimuon and K data, but never properly measured

How well do we know PDFs today? gg parton luminosities



G. Watt

Agree in region relevant for Higgs at LHC,
but diverge towards smaller/largest shat

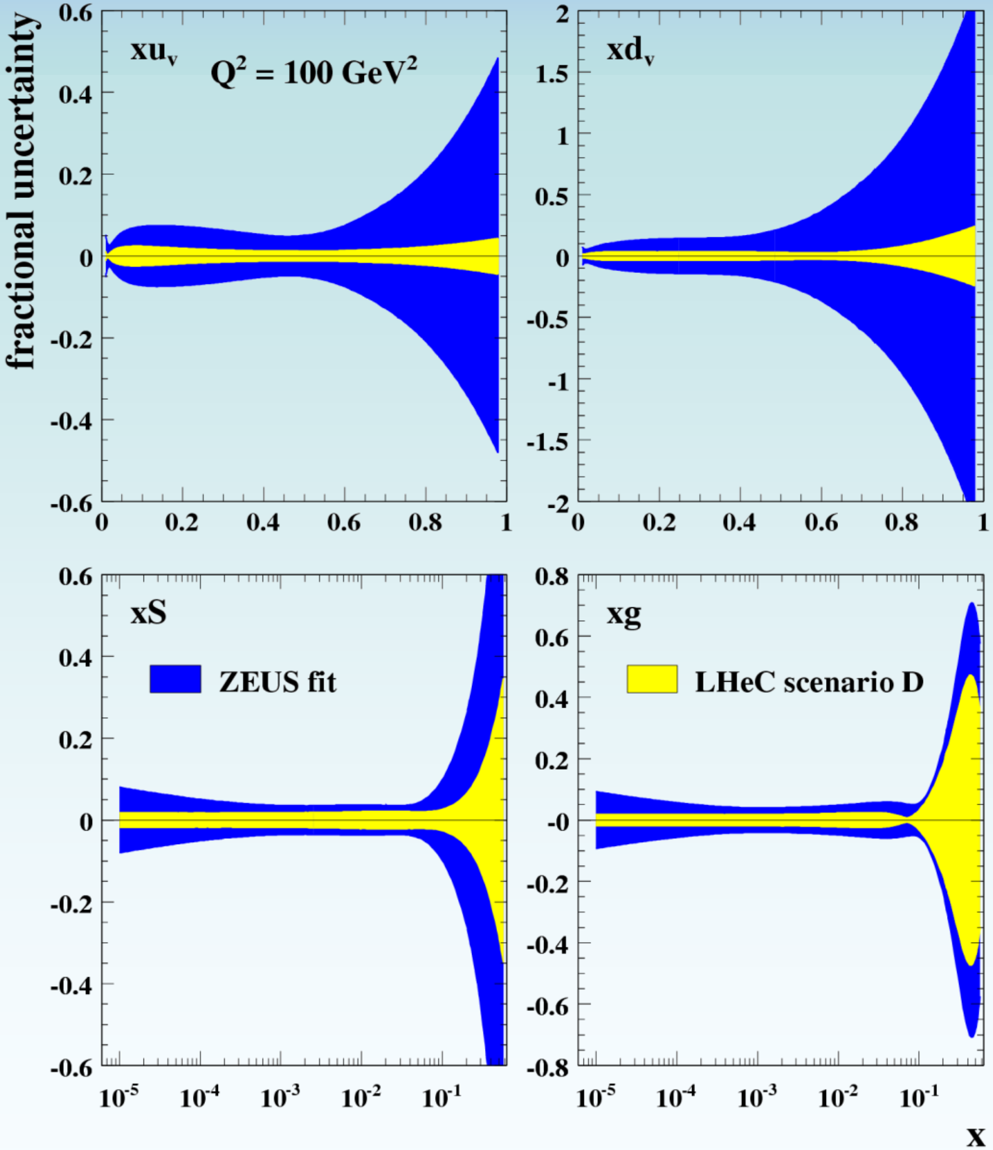
Proton PDF fit at LHeC

Claire Gwenlan

Q^2 = 100 GeV^2

Scenario D

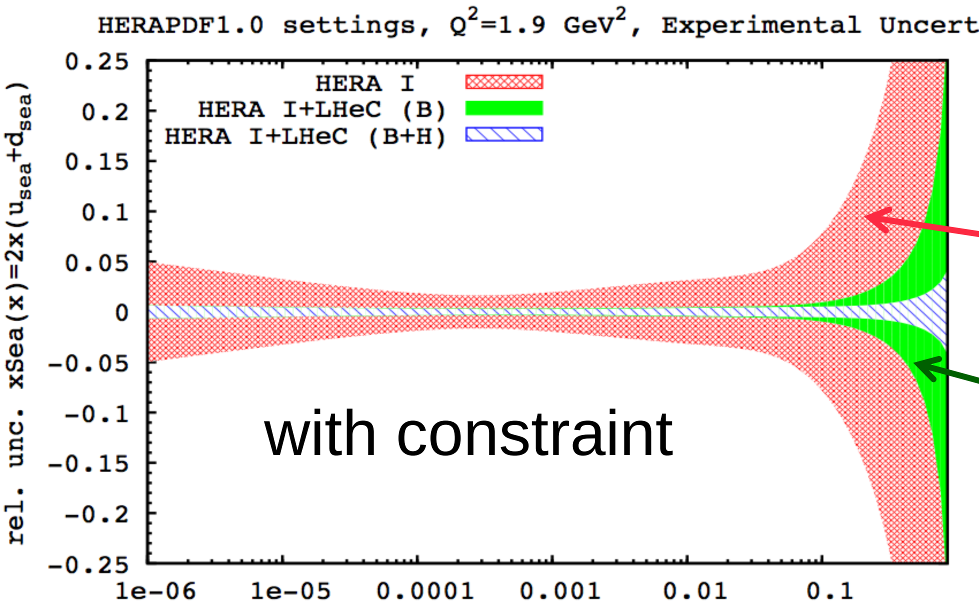
- <u>only</u> PDF parameters free (LHeC **NC** and **CC** $e^{\pm}p$ included)



Large improvements, model and parameterisation uncertainties to be studied

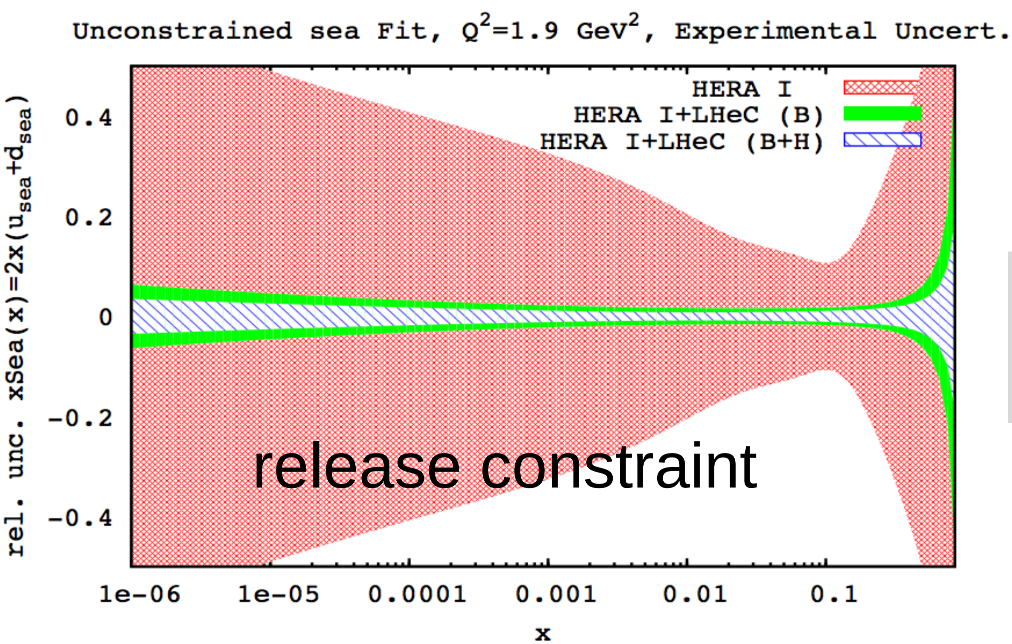
Sea quark uncertainties and usual constraint ubar=dbar for x→0

Voica Radescu



HERA only

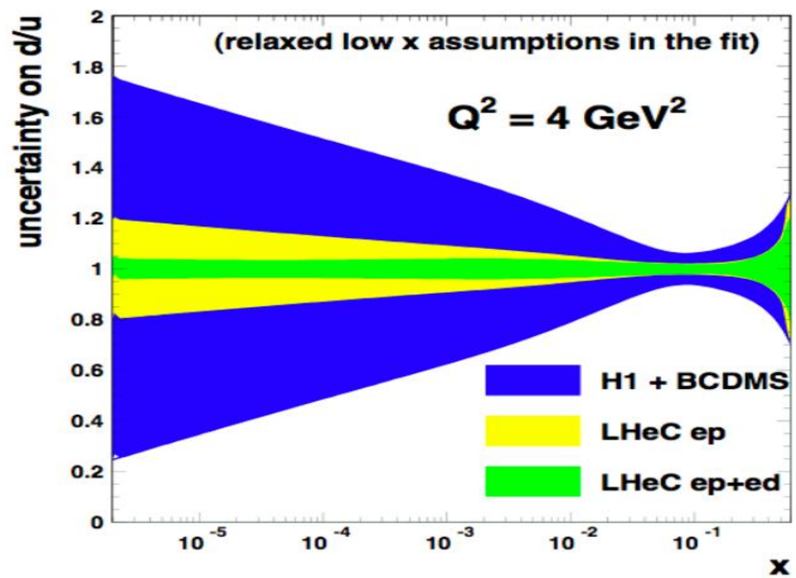
Adding LHeC



→ With LHeC can get rid of such assumptions

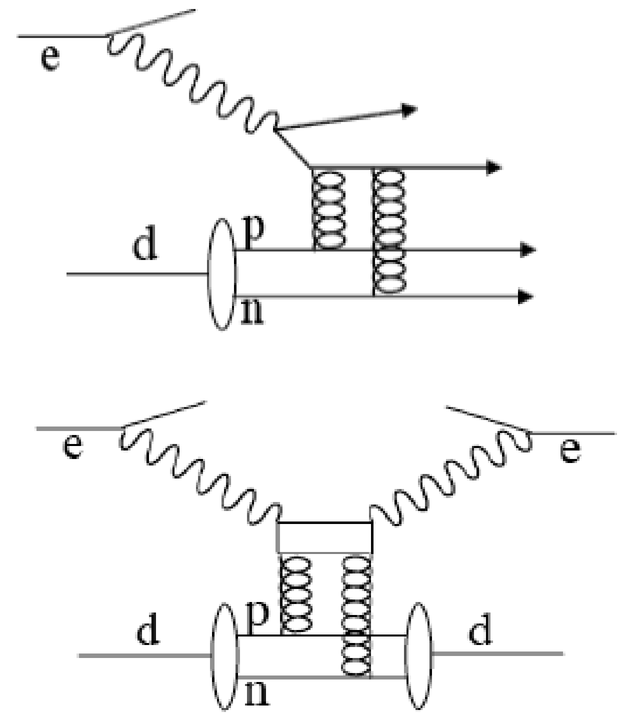
Further PDF improvements at LHeC with ep + eD

d/u at low x from deuterons



(13) There are five color-singlet combinations of the deuteron wavefunction in QCD, only one of which is the standard proton-neutron state. The "hidden color" [13] components will lead to high multiplicity final states in deep inelastic electron-deuteron scattering.

crucial constraint on evolution (S-NS), improved α_s

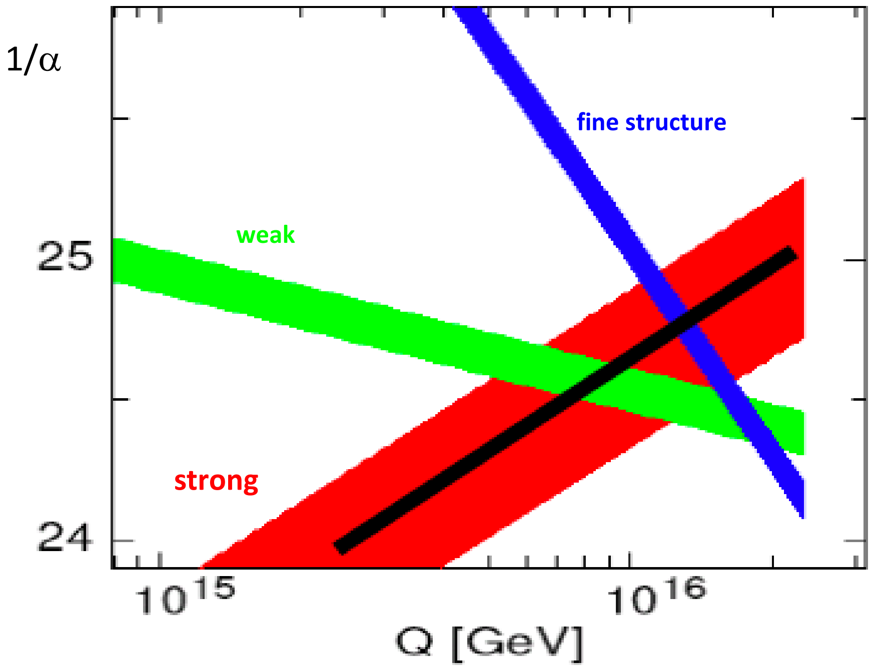


In eA at the collider, test Gribovs relation between shadowing and diffraction, control nuclear effects at low Bjorken x to high accuracy

Strong Coupling Constant from inclusive DIS

(sensitivity mainly from dF2/dln(Q2))

Simulation of α_s measurement at LHeC

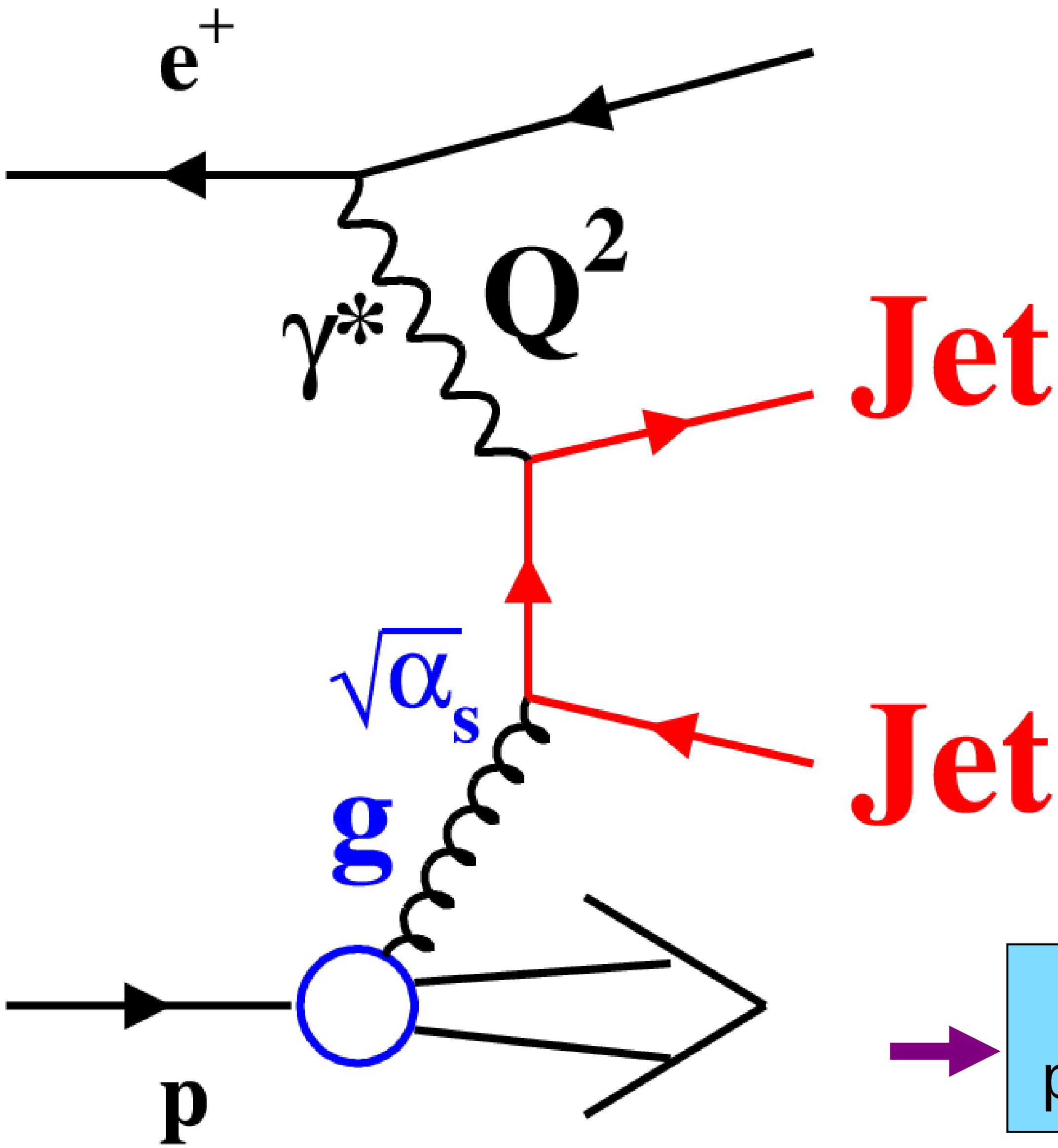


DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) $\gamma_h > 5°$	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

Improve at LHeC to
~ permille precision level

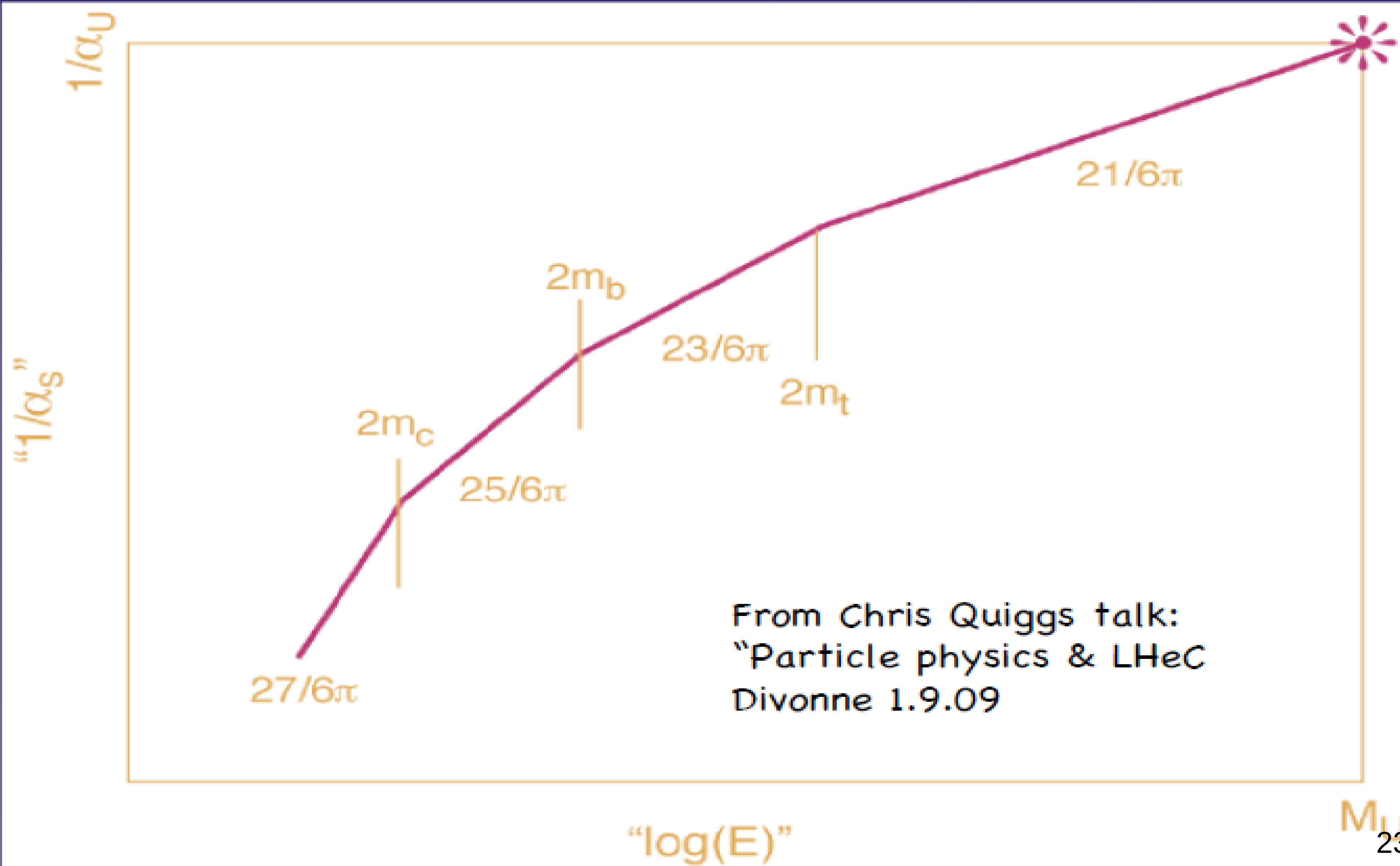
T.Kluge/M.Klein Divonne 09

2. High pt Jets



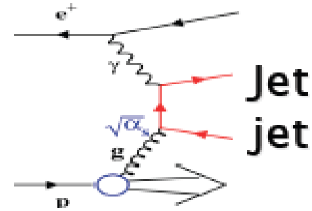
sensitive to g(x), photon structure and α_s

Measure change in slope at top threshold?

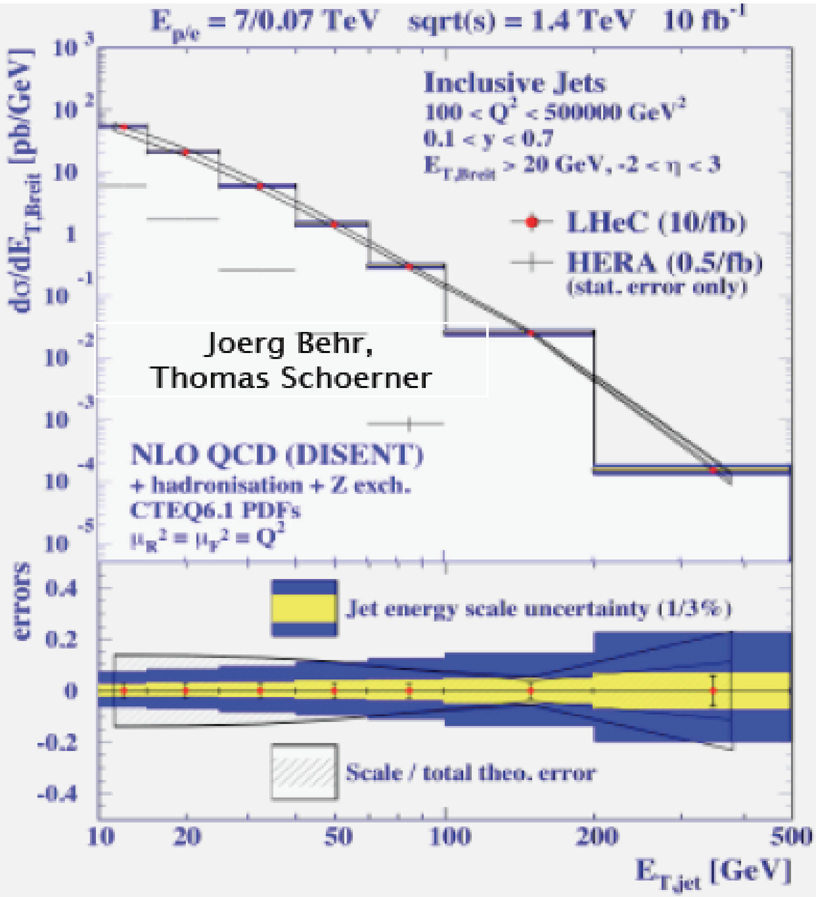


From Chris Quiggs talk:
"Particle physics & LHeC
Divonne 1.9.09

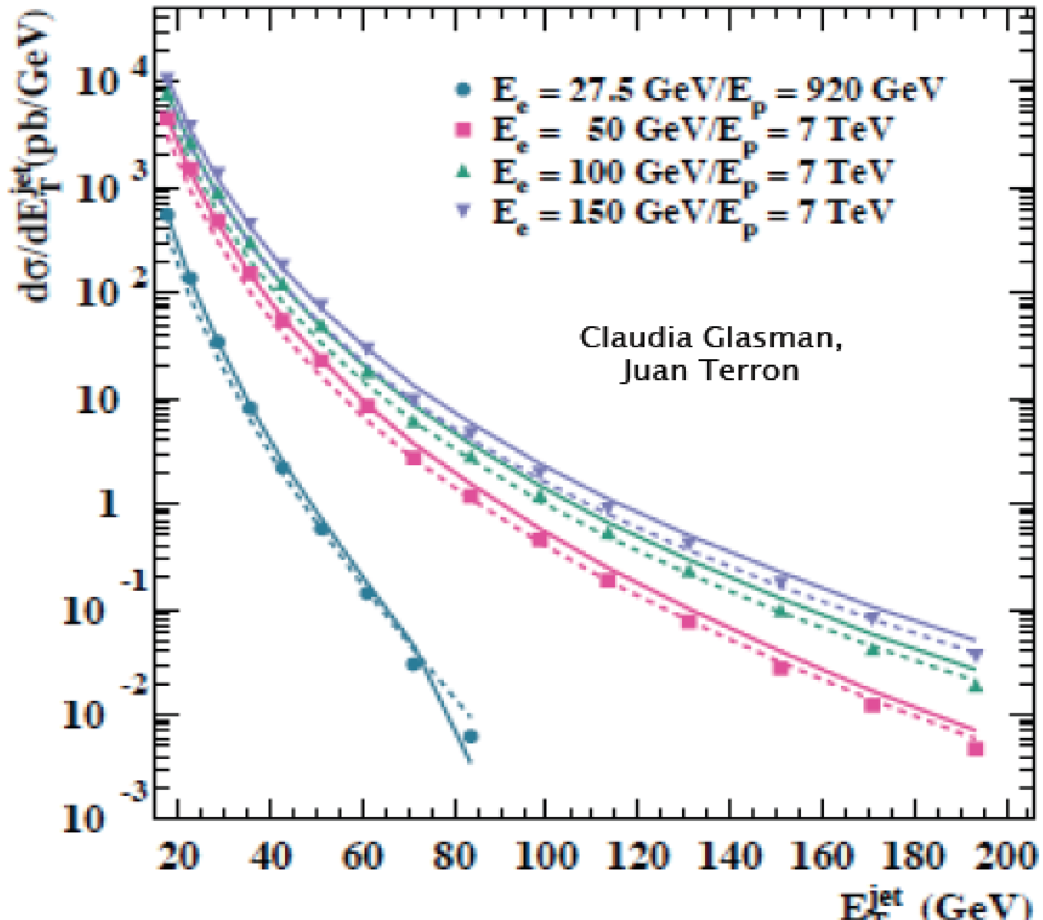
Jet production



DIS



Photoproduction



Reach scales up to $2m_{top}$ where change of $1/\alpha_s$ slope is expected

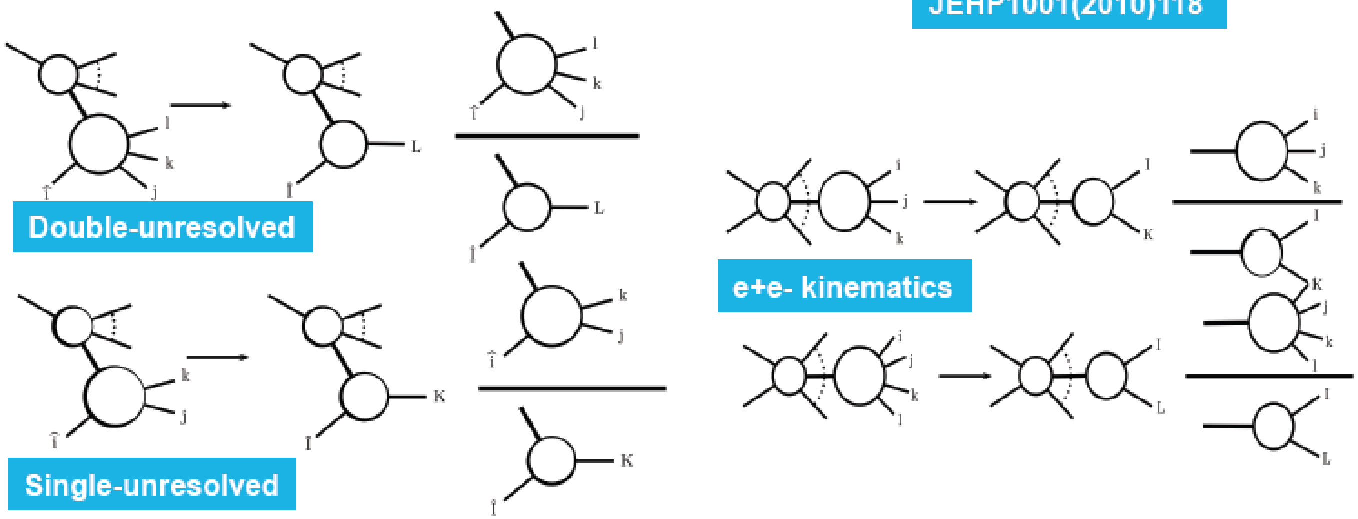
NNLO THEORY (T. Gehrmann et al.) $O(\alpha_s^3)$

- NNLO calculations are ongoing. Matrix elements are either
  - already derived (NLO corrections to 3-jet production in DIS, Z. Nagy, NLOJET++) or
  - Contained in work by Gehrmann/Glover (for the two-loop 2-parton final state).

PLB676(2009)146

- Required: subtraction method!
  - Gehrmann et al.: antenna subtraction method (for DIS).

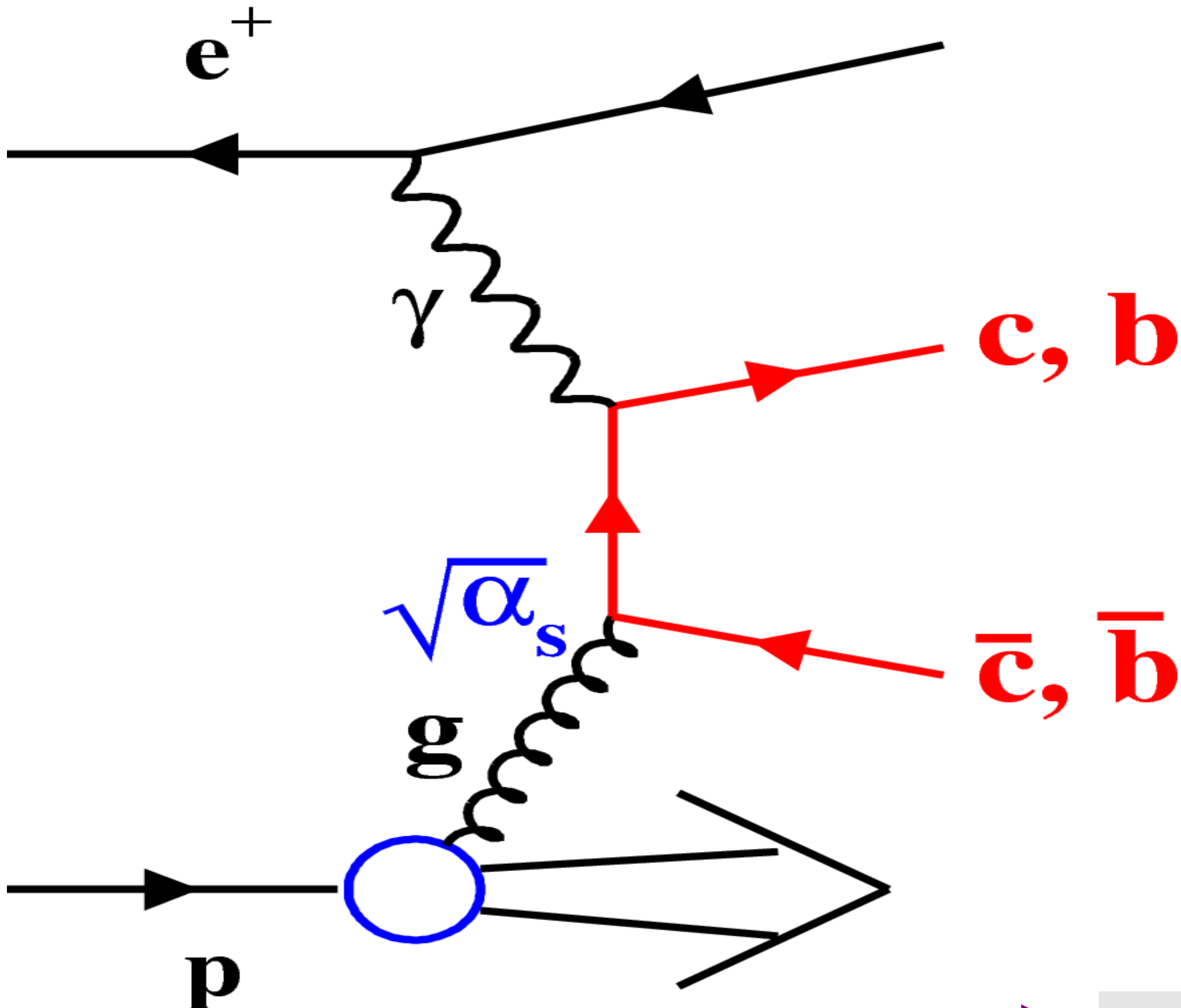
JHEP0704*2007)016
JEHP1001(2010)118



- Currently implementing method into program for DIS jet production.

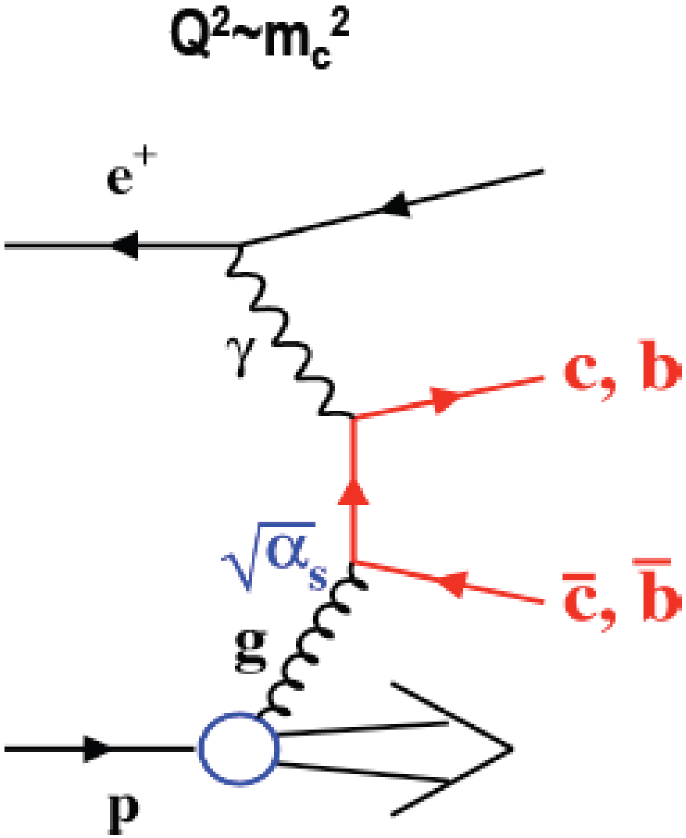
Will reduce significantly theory (higher order) uncertainty for α_s extraction from jet data

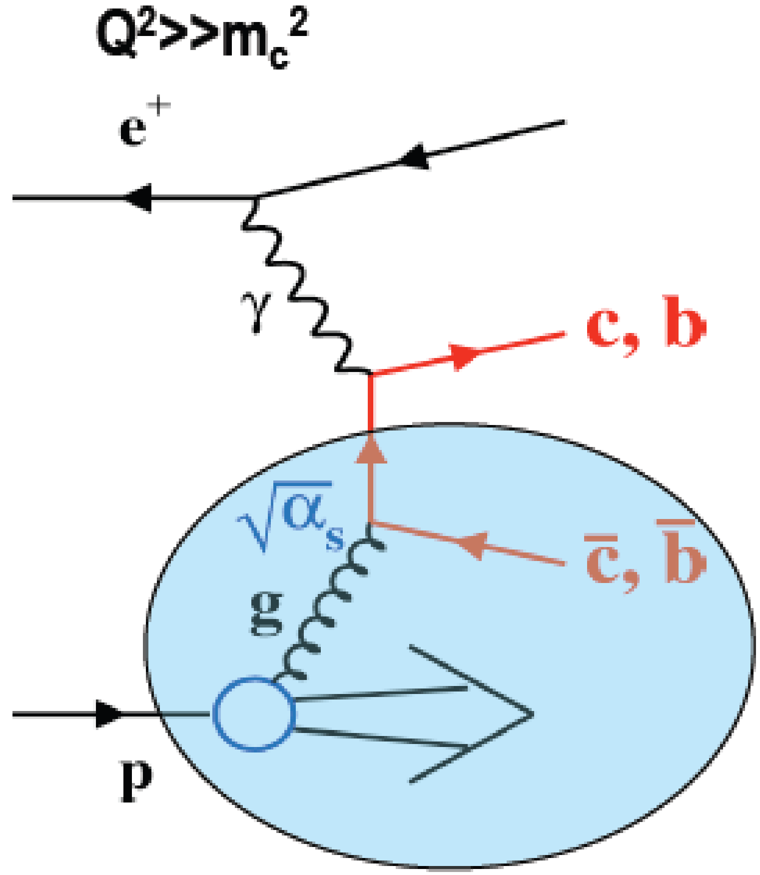
2. Charm & beauty



→ sensitive to g(x)

Subtle topic: correct treatment of heavy flavour masses in pQCD

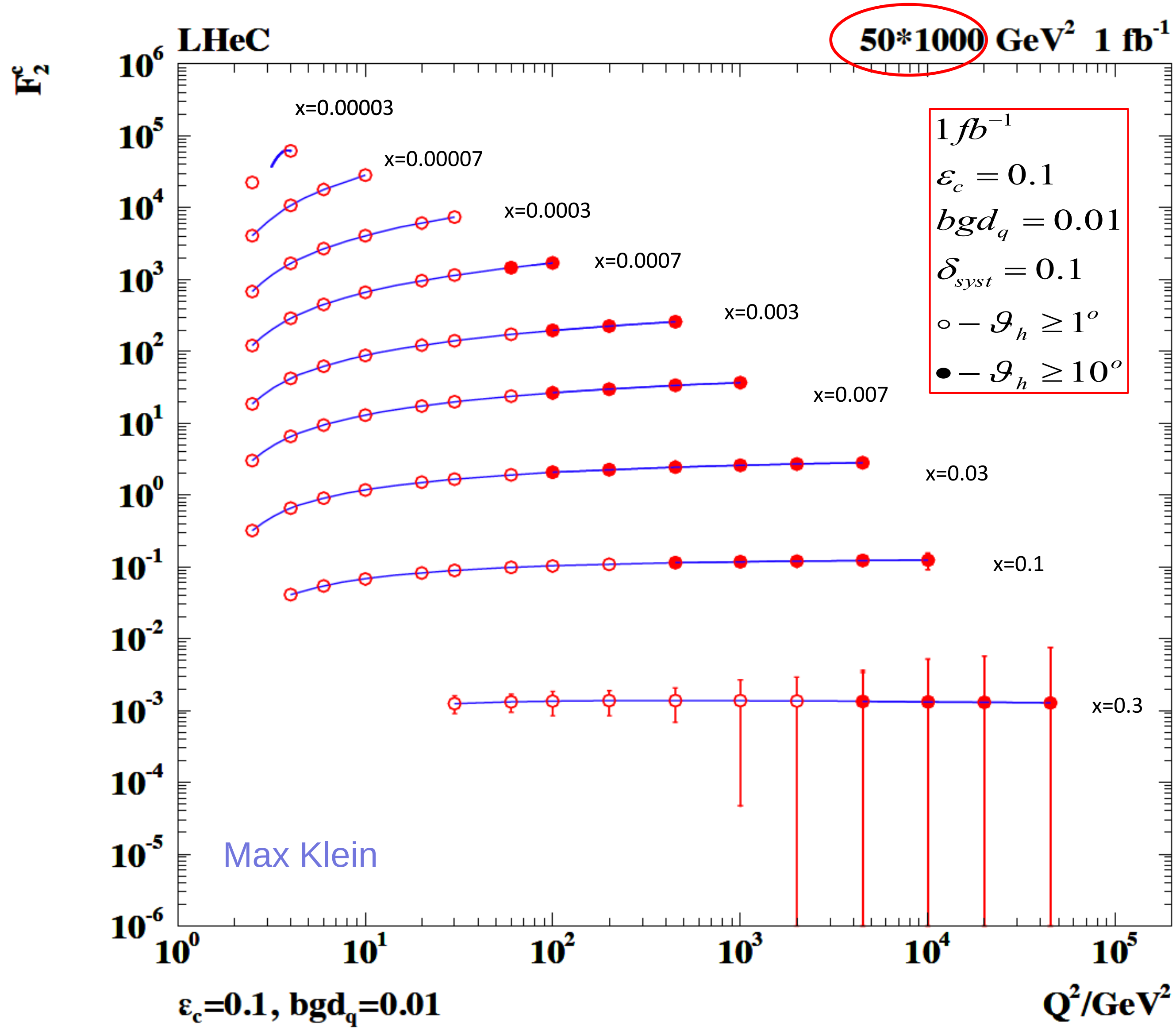


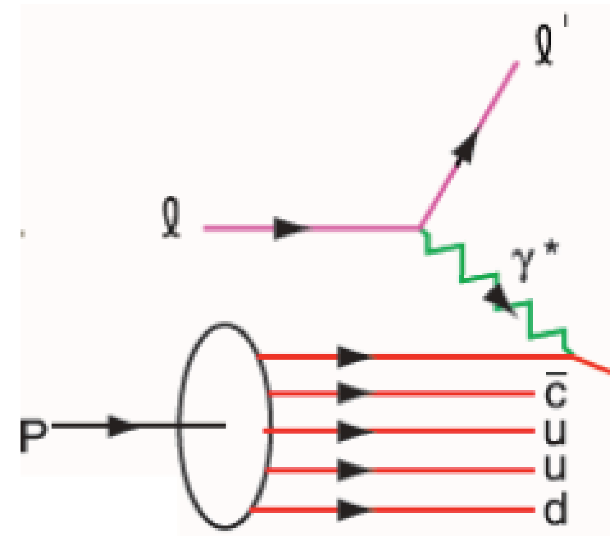


Sea quark like c,b

How to make properly the transition from left to right picture is a longstanding problem **for PDF fits**

Charm in DIS: test intrinsic charm in p



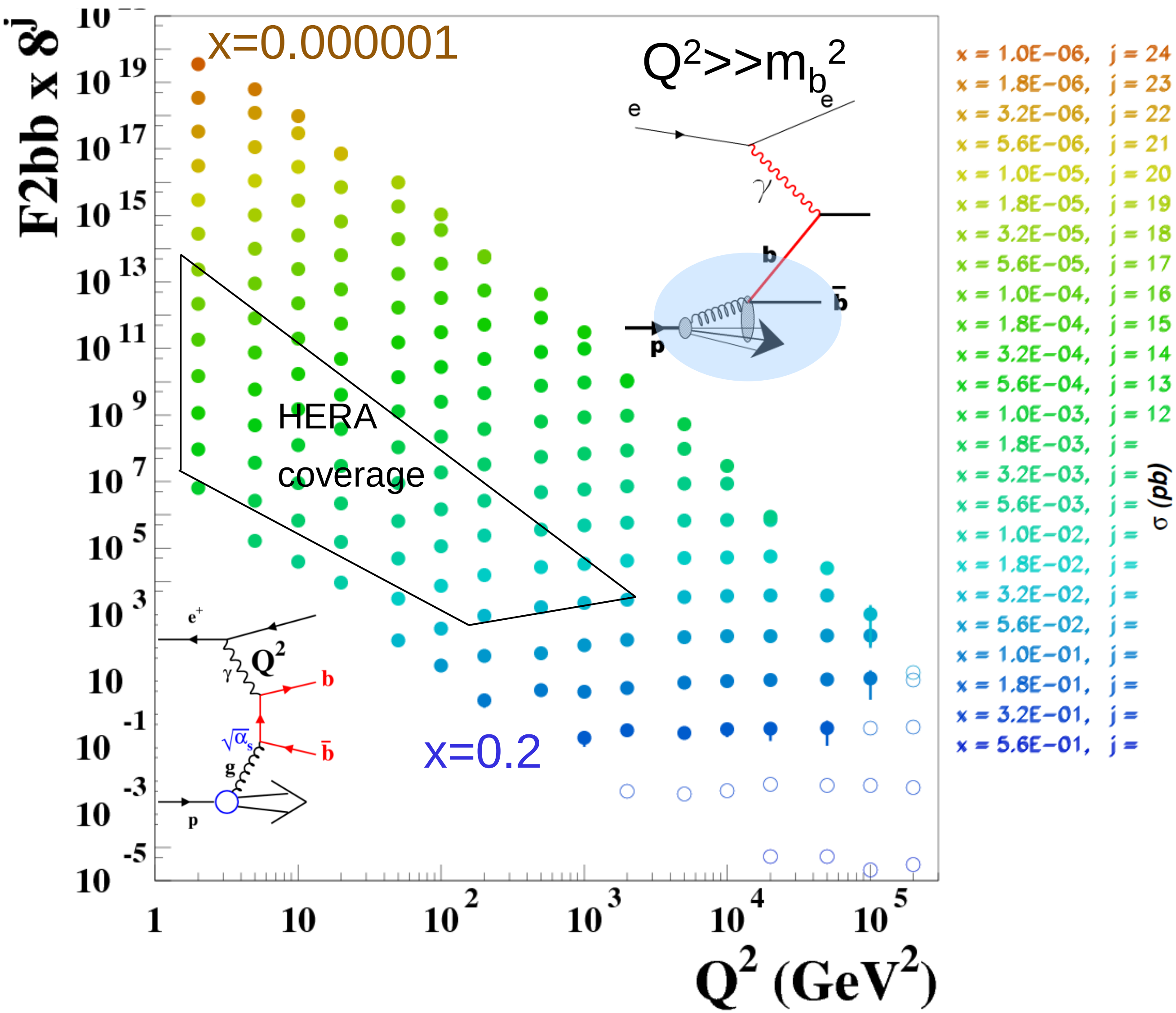


Expected to show up at $x_b > 0.1$

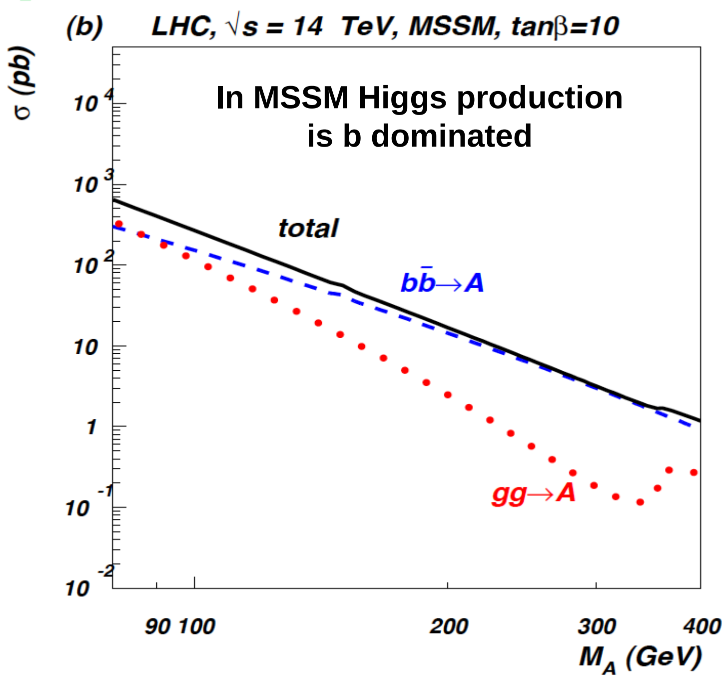
➡ Requires c-tagging in very foward direction (θ~1 deg.)

Beauty in DIS: → determine b-density in proton

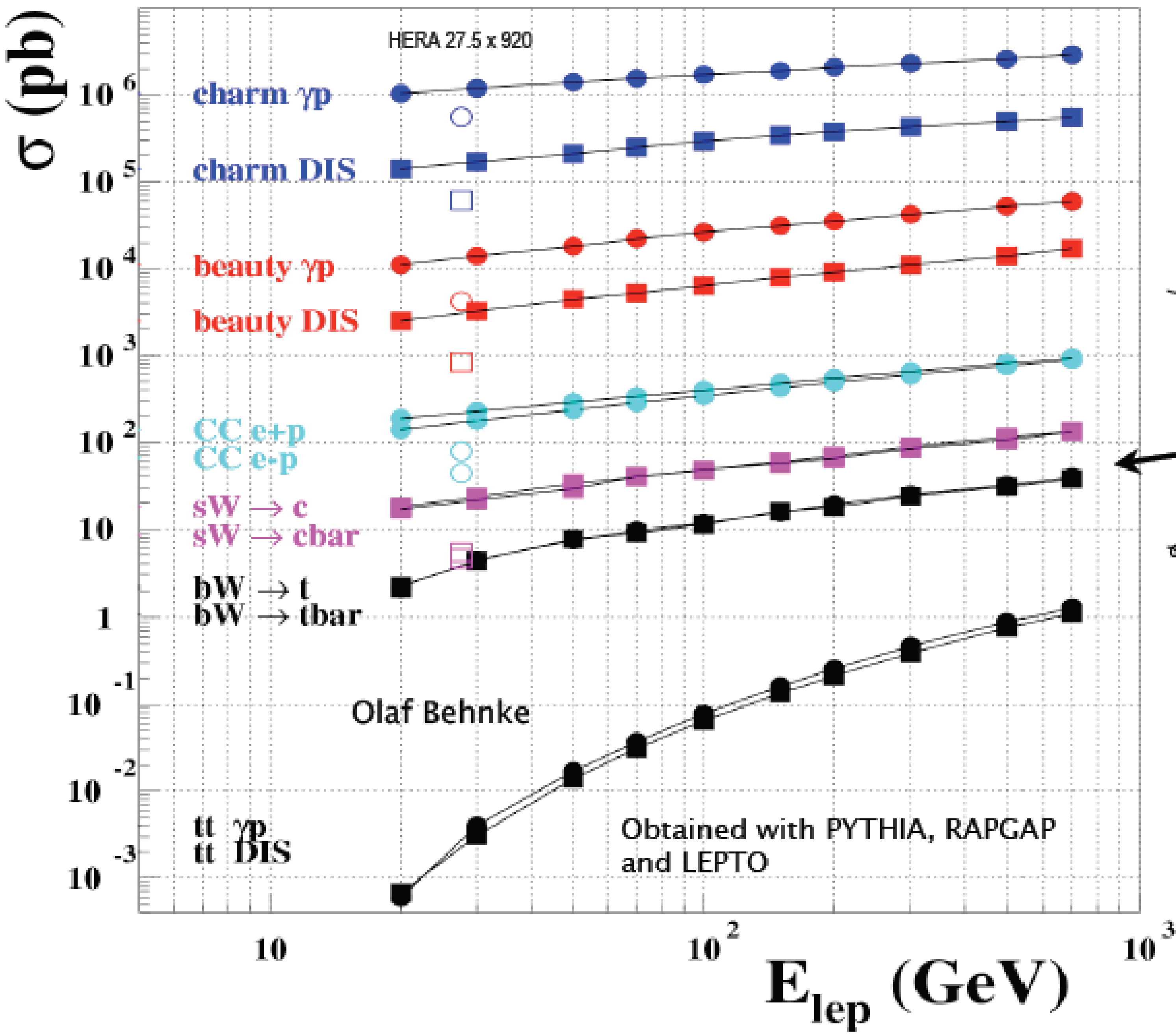
O.Behnke

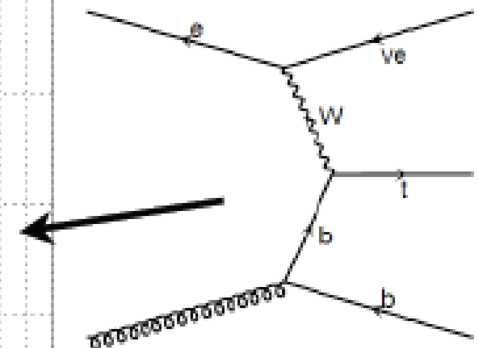


Use for LHC predictions



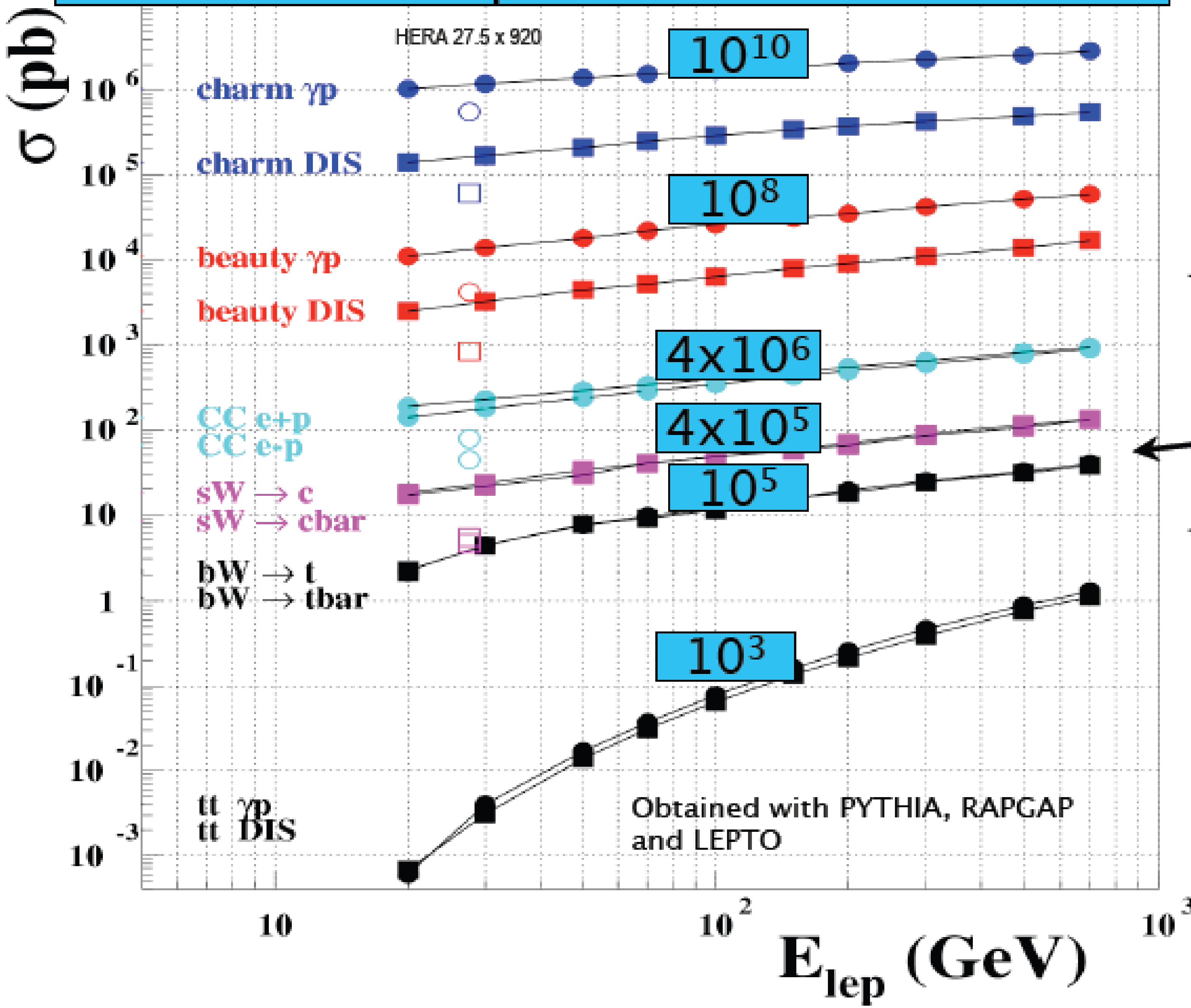
LHeC total cross sections (MC simulated)

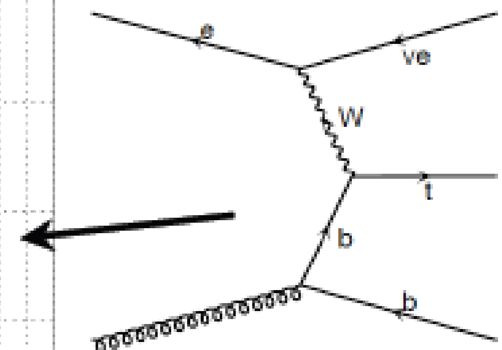




LHeC is a flavour factory

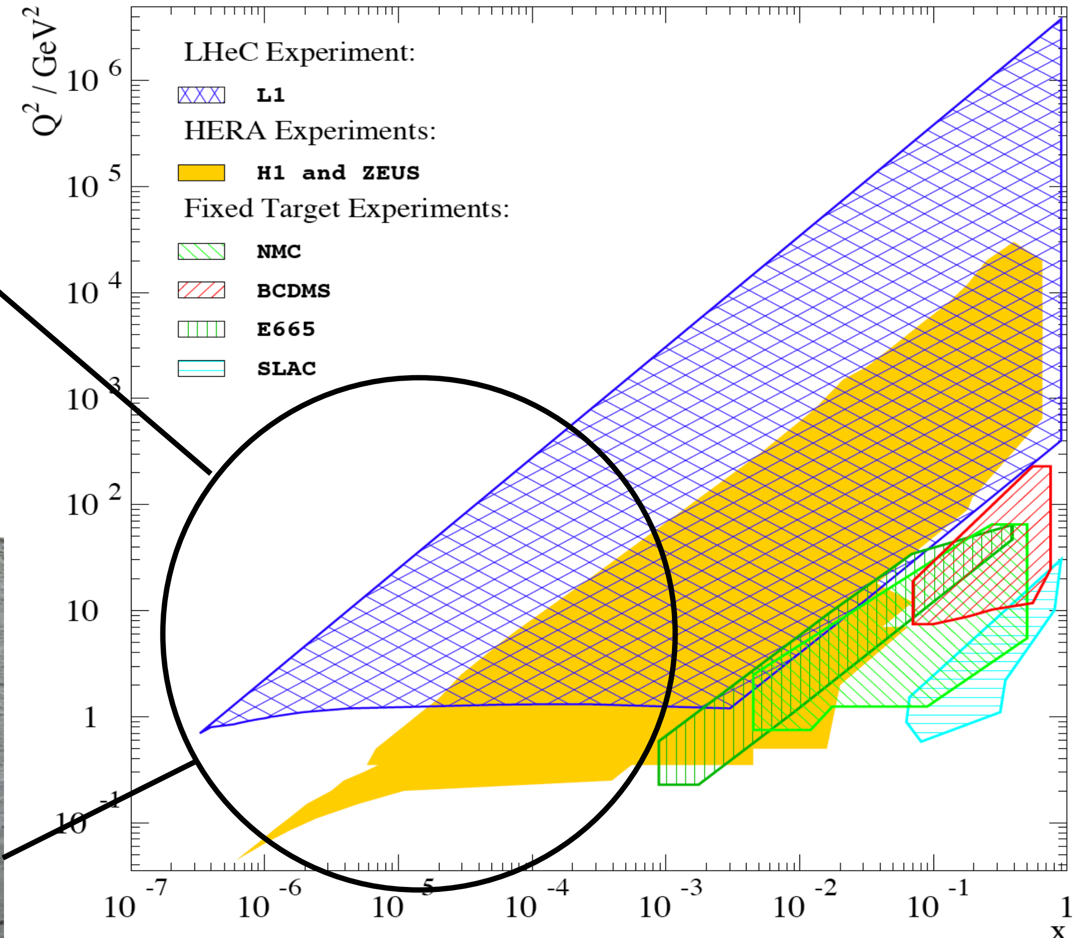
Events per 10 fb-1 Lumi



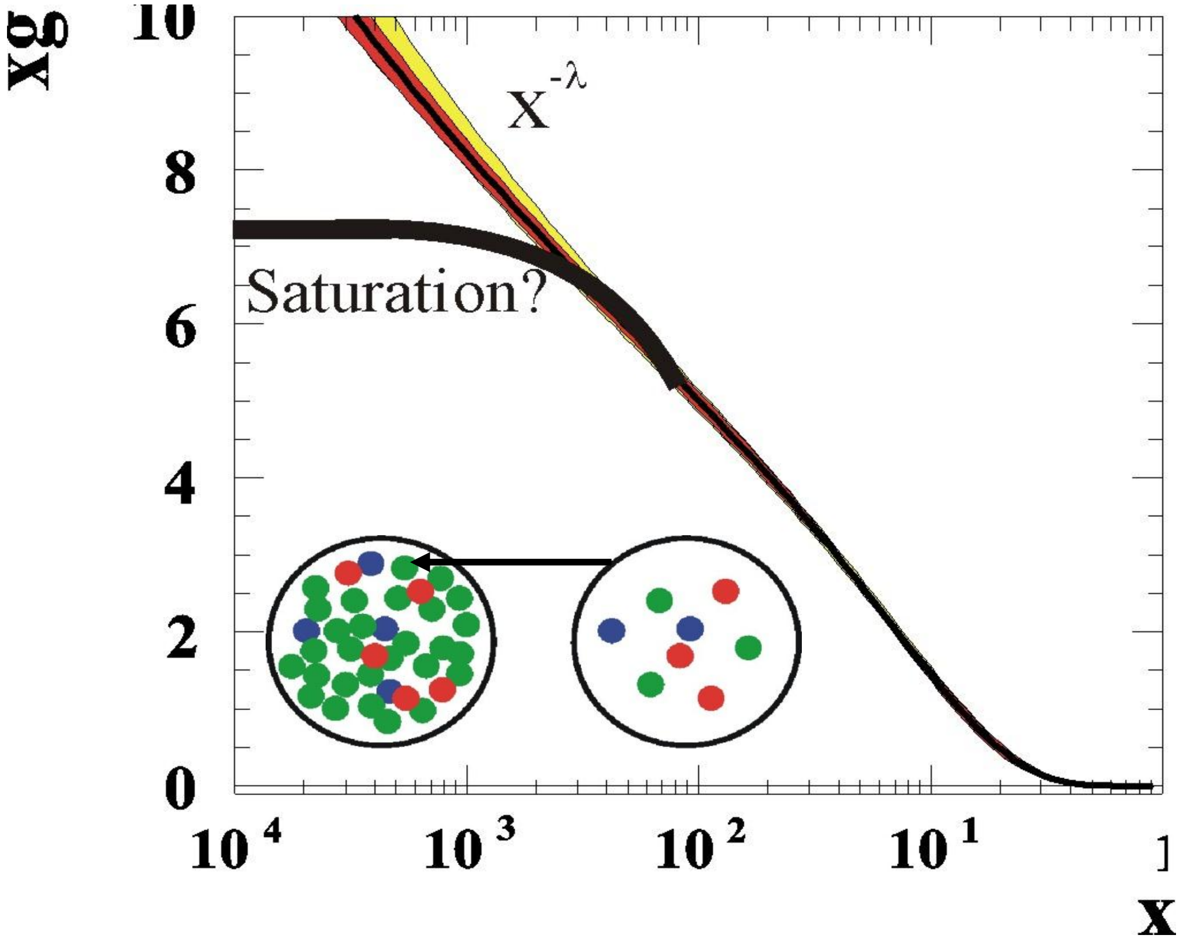


LHeC is a flavour factory

3. Entering the mysterious world of low x physics



Low-x Physics and Non-linear Evolution



Note: This and following slides Courtesy Paul Newman or Anna Statso

- Somewhere & somehow, the low x growth of cross sections must be tamed to satisfy unitarity … non-linear effects
- Usually characterised in terms of an x dependent "saturation scale", $Q^2_s(x)$, to be determined experimentally

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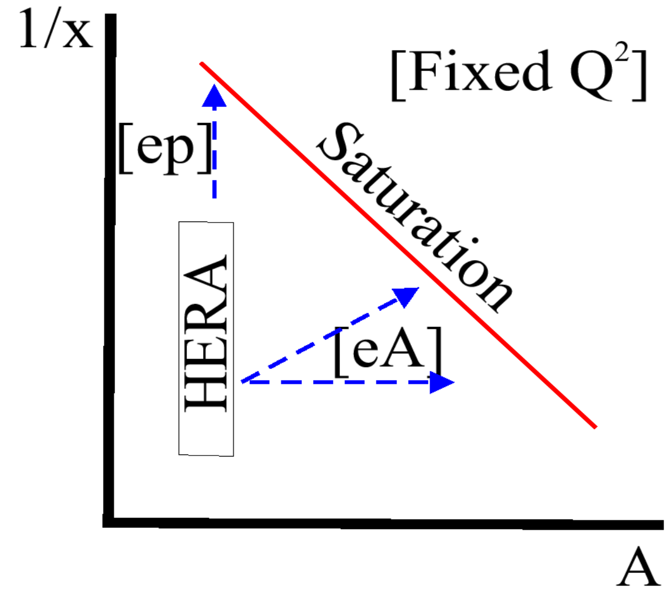
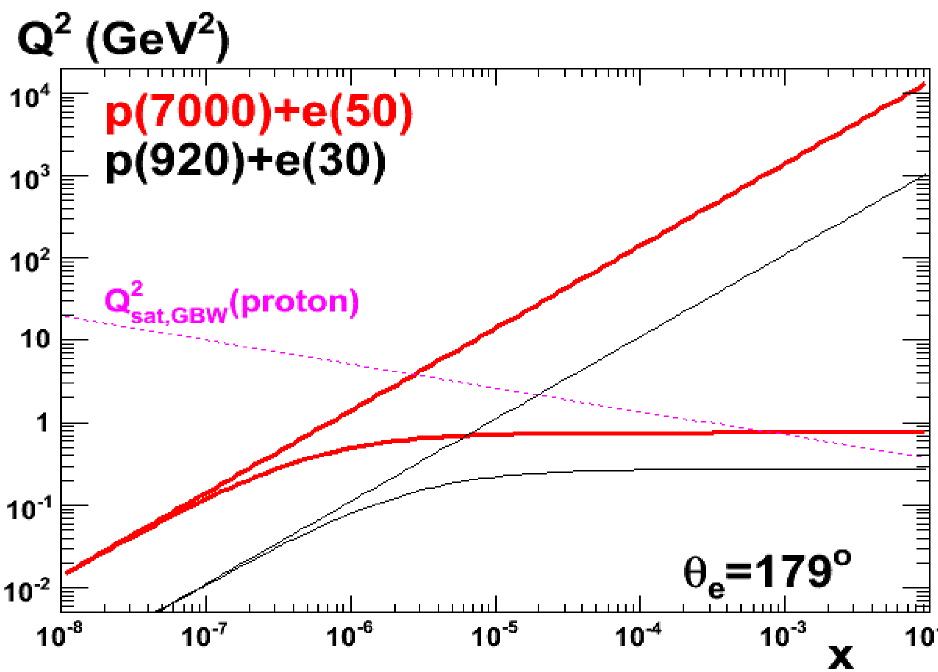
Going beyond HERA with Inclusive LHeC Data

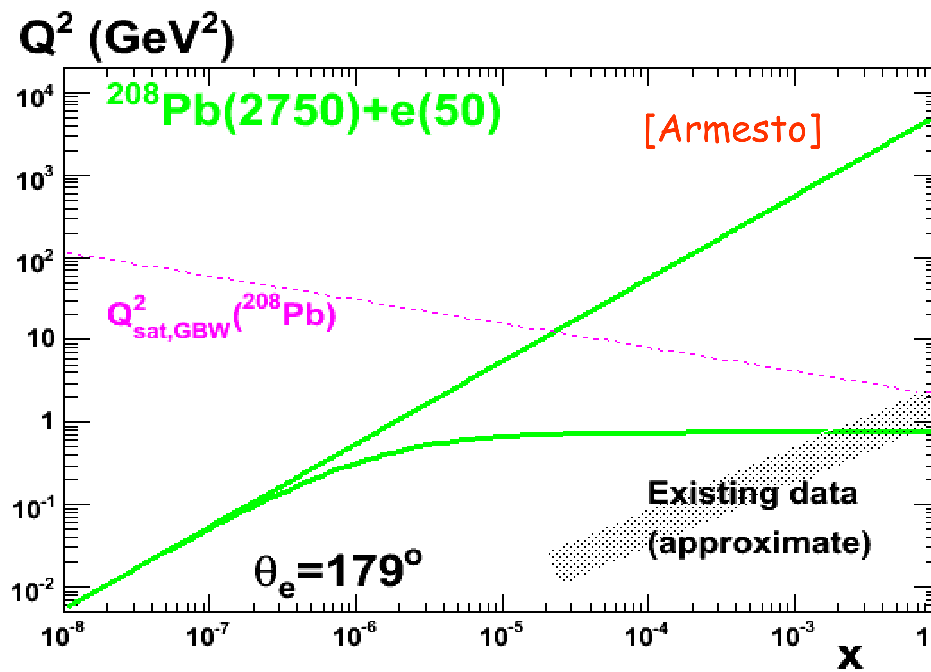
Enhance target 'blackness' by:

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

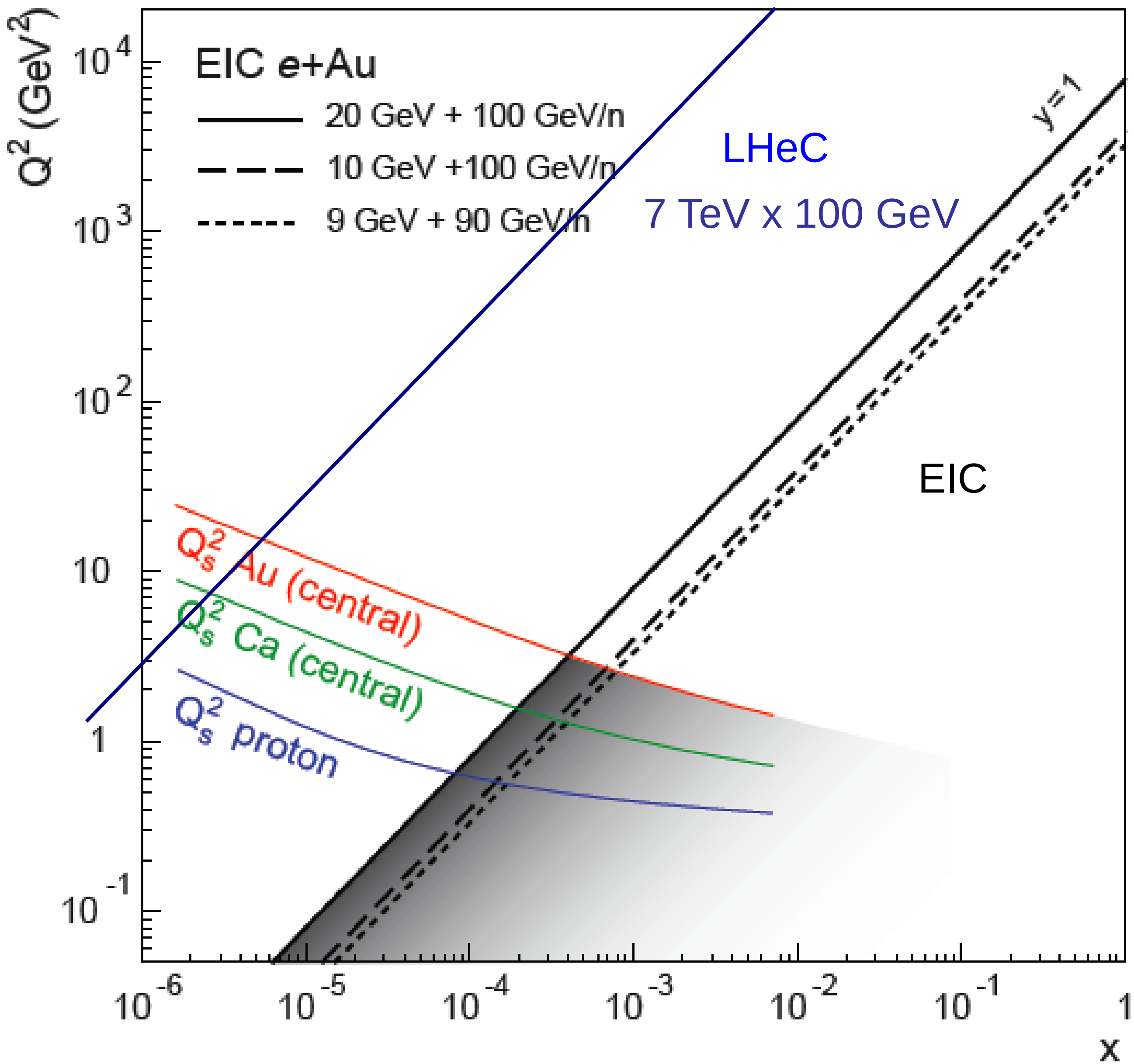
2) Increasing target matter in eA
… target density ~ $A^{1/3}$ ~ 6 for Pb







Saturation region reach: LHeC vs EIC



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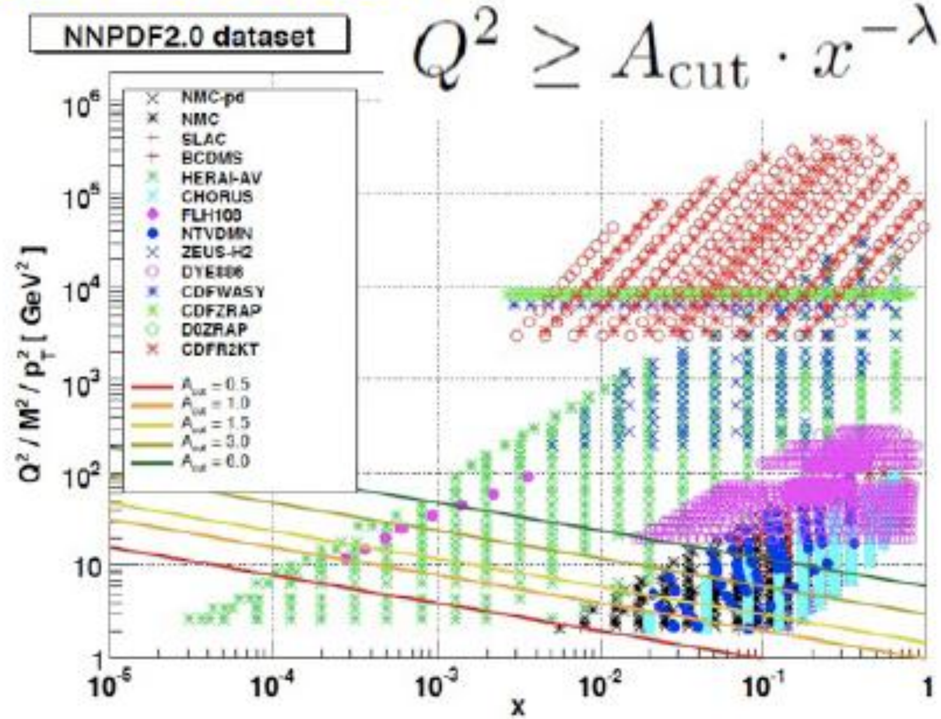
NON DGLAP Hints from HERA

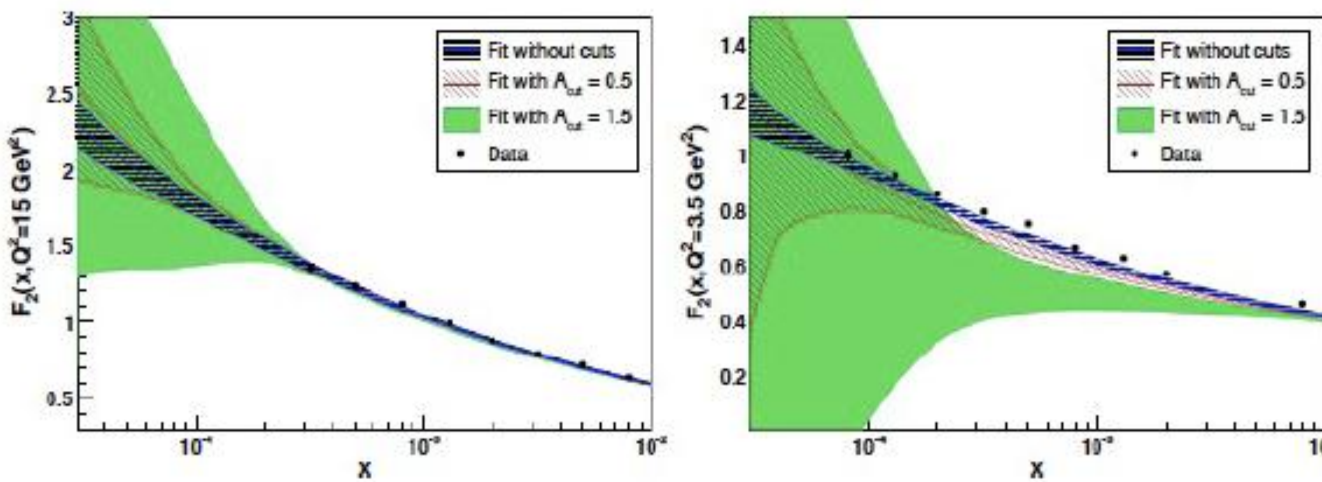
- Tension in data at small x and Q^2 when introduced in a global fit (NNPDF2.0).

- Deviation incompatible with NNLO → resummation or non-linear effects.

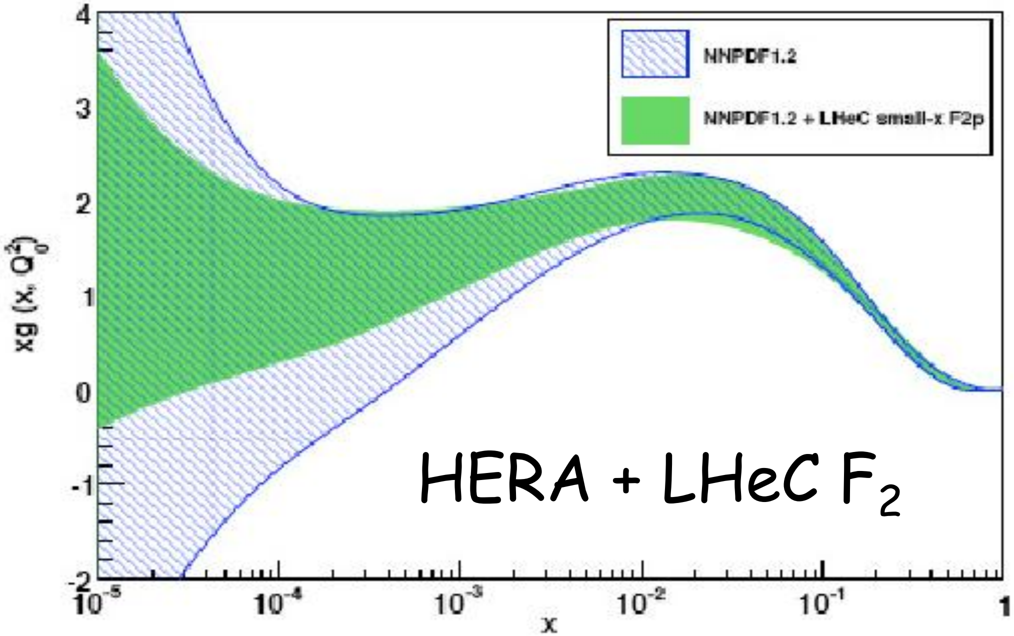
$$Q^2 \geq A_{\rm cut} \cdot x^{-\lambda}$$

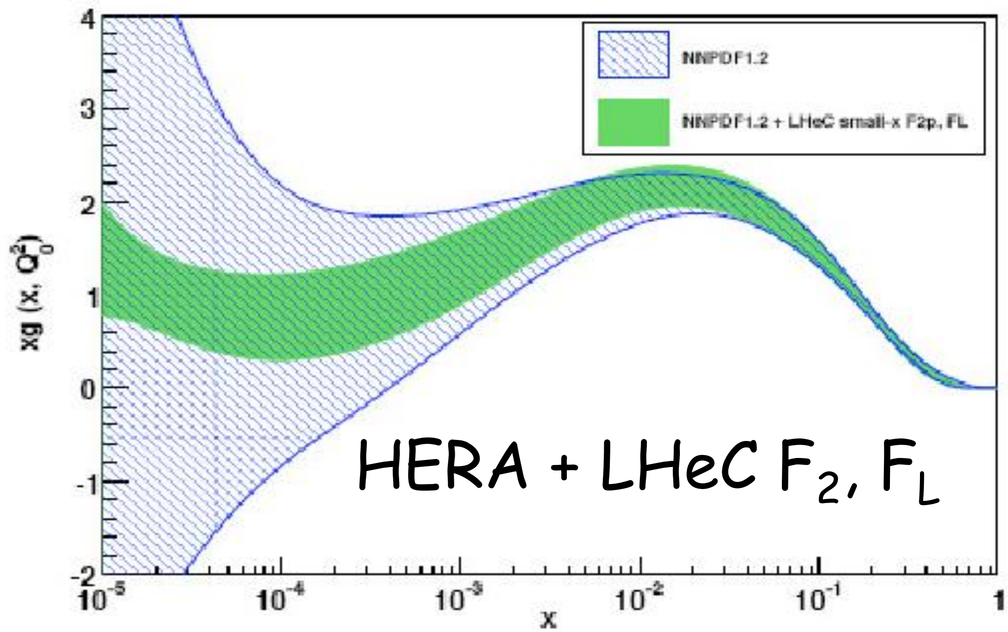


Forte,Rojo



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 …

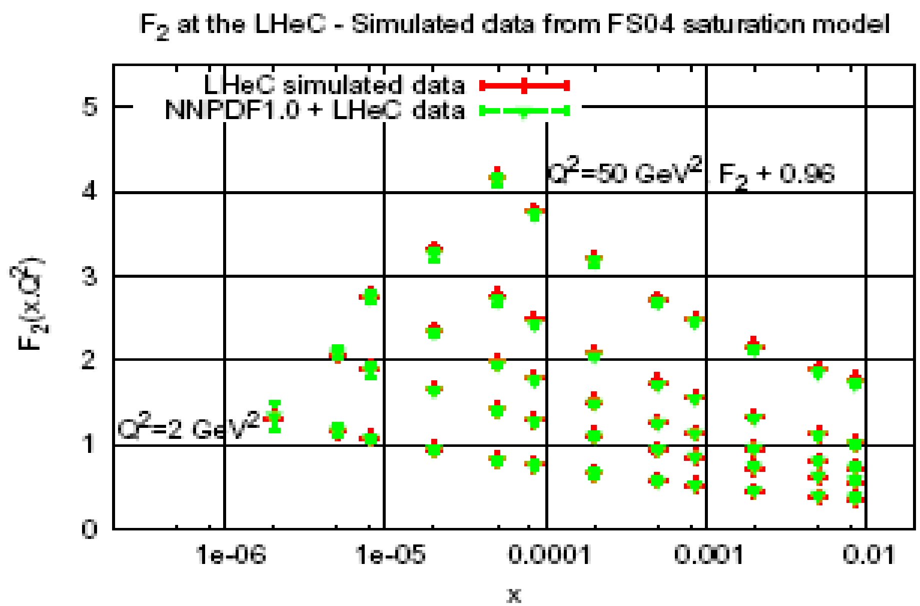
… sizeable improvement in error on low x gluon when both LHeC F_2 & F_L data are included.

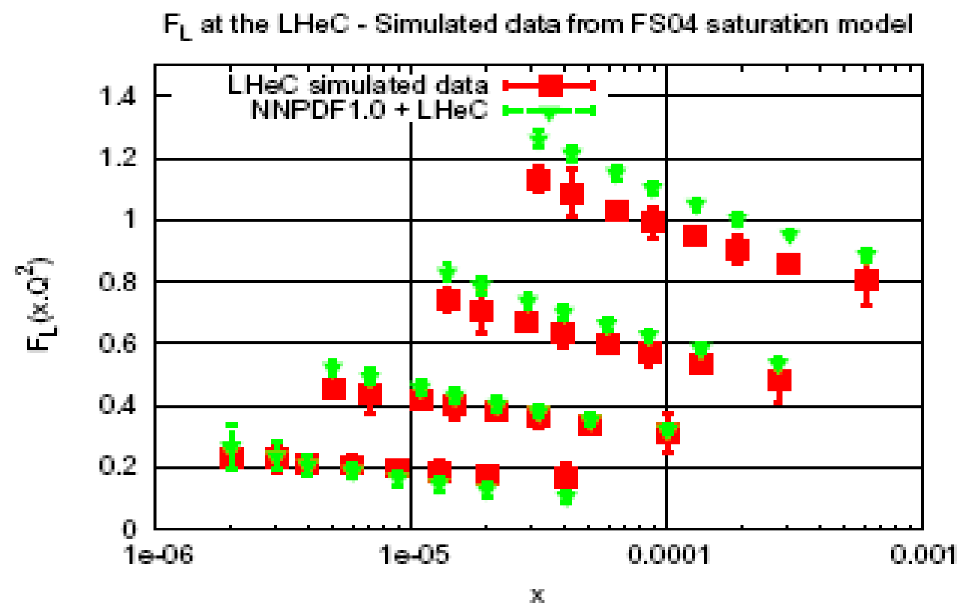
… but would DGLAP fits fail if non-linear effects present?

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]

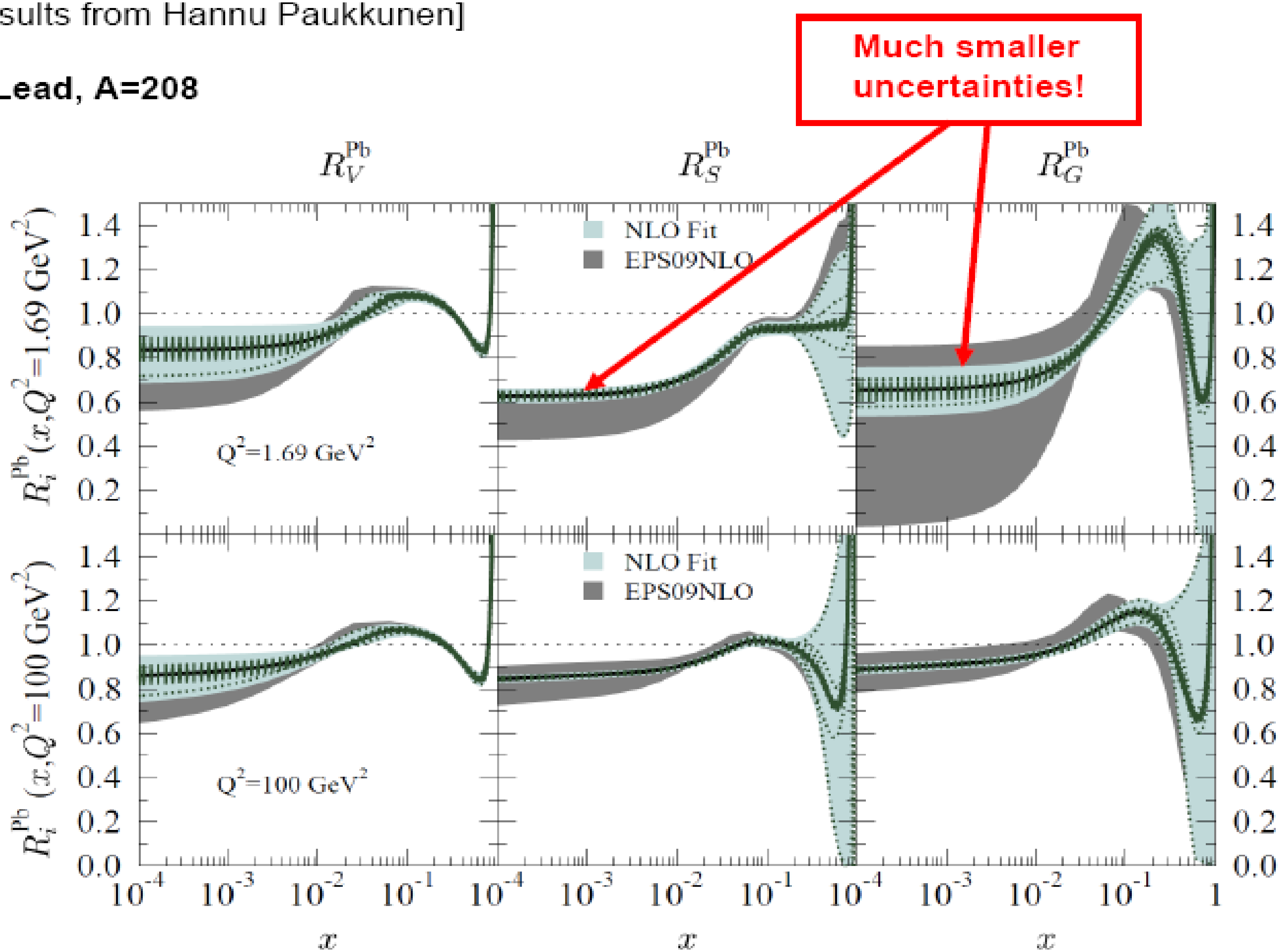
Conclusion: clearly establishing non-linear effects needs a minimum of 2 observables … <u>next try F_2^c in place of F_L</u> …

eA: Impact of LHeC data on nuclear parton densities

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

[results from Hannu Paukkunen]

Lead, A=208



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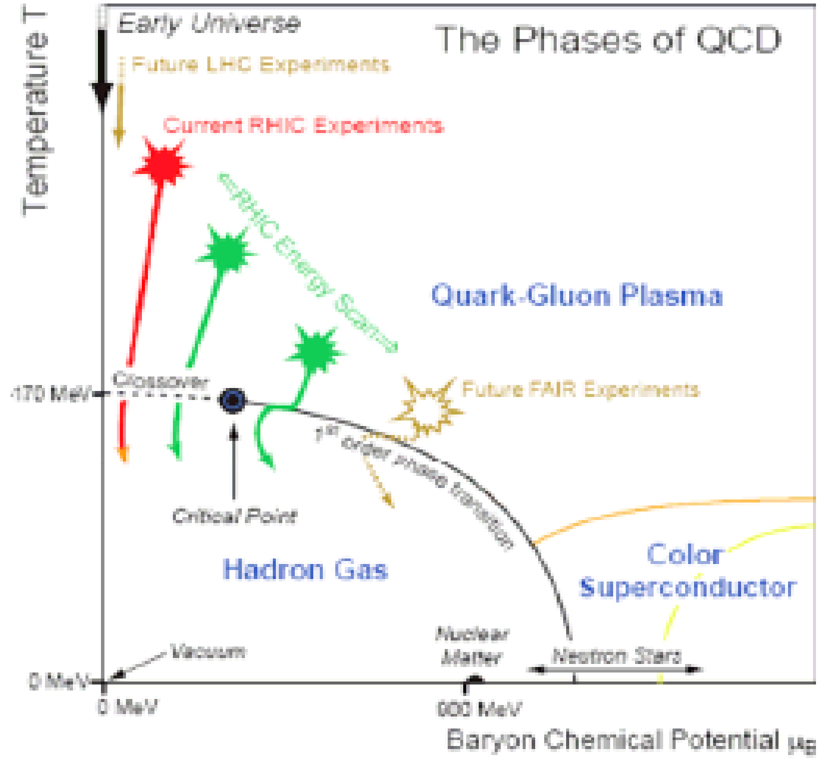
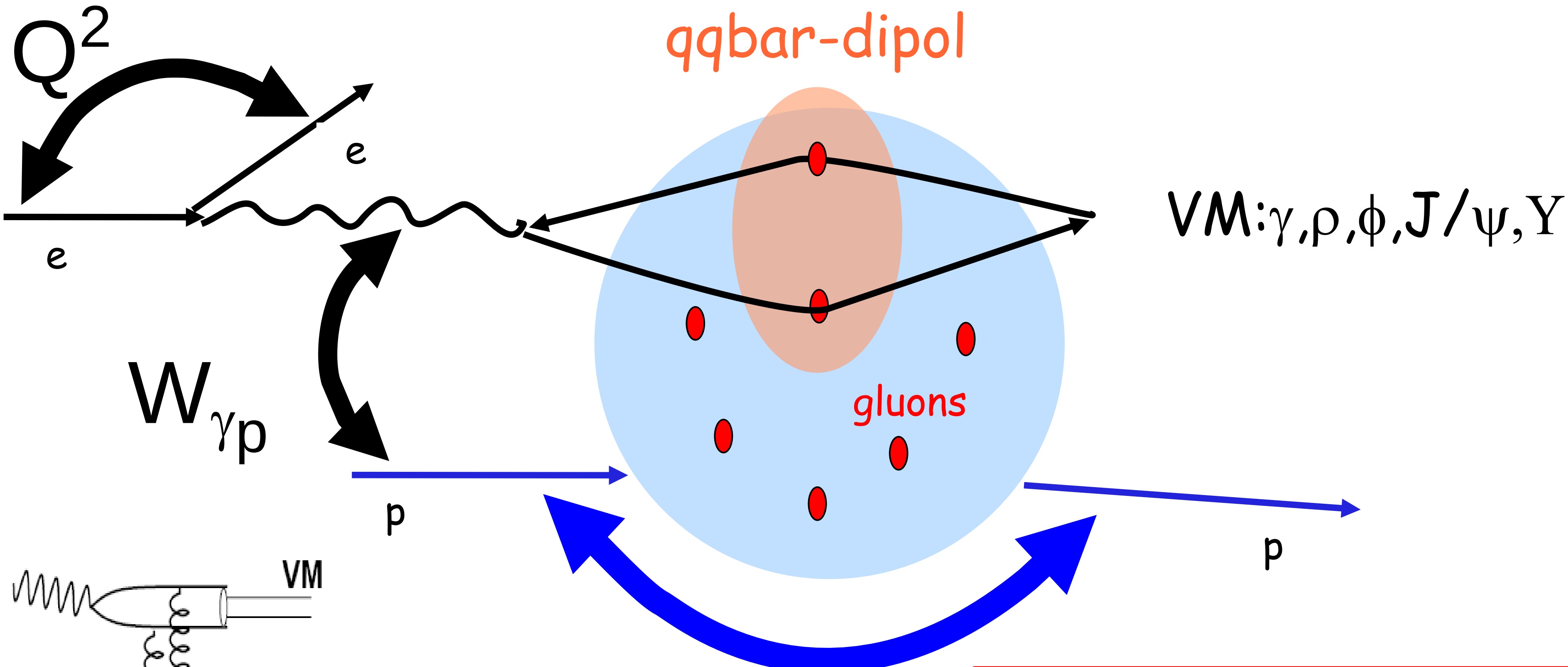
Many other reasons for eA (Ullrich)

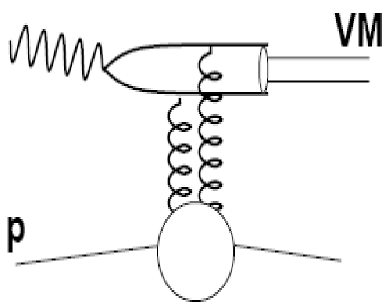


As well as identifying non-linear dynamics, measuring nuclear effects in DIS will tell us lots about heavy ions / q-g plamsa:...
"Symbiotic Relationship between eA and AA" ...

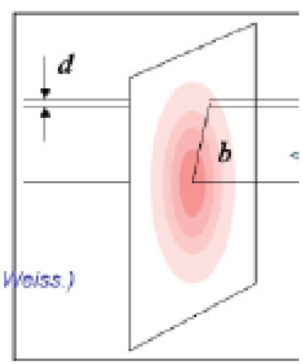
- Initial Conditions (saturation/CGC?)
  - impact on understanding of QGP properties (e.g. η/s)
- Thermalization (Glasma)
- Energy Loss (baseline/control) & Fragmentation
- Saturation & Multiplicity
- Understanding nuclear effects ((anti)-shadowing, EMC)

Elastic Vector meson production in ep scattering





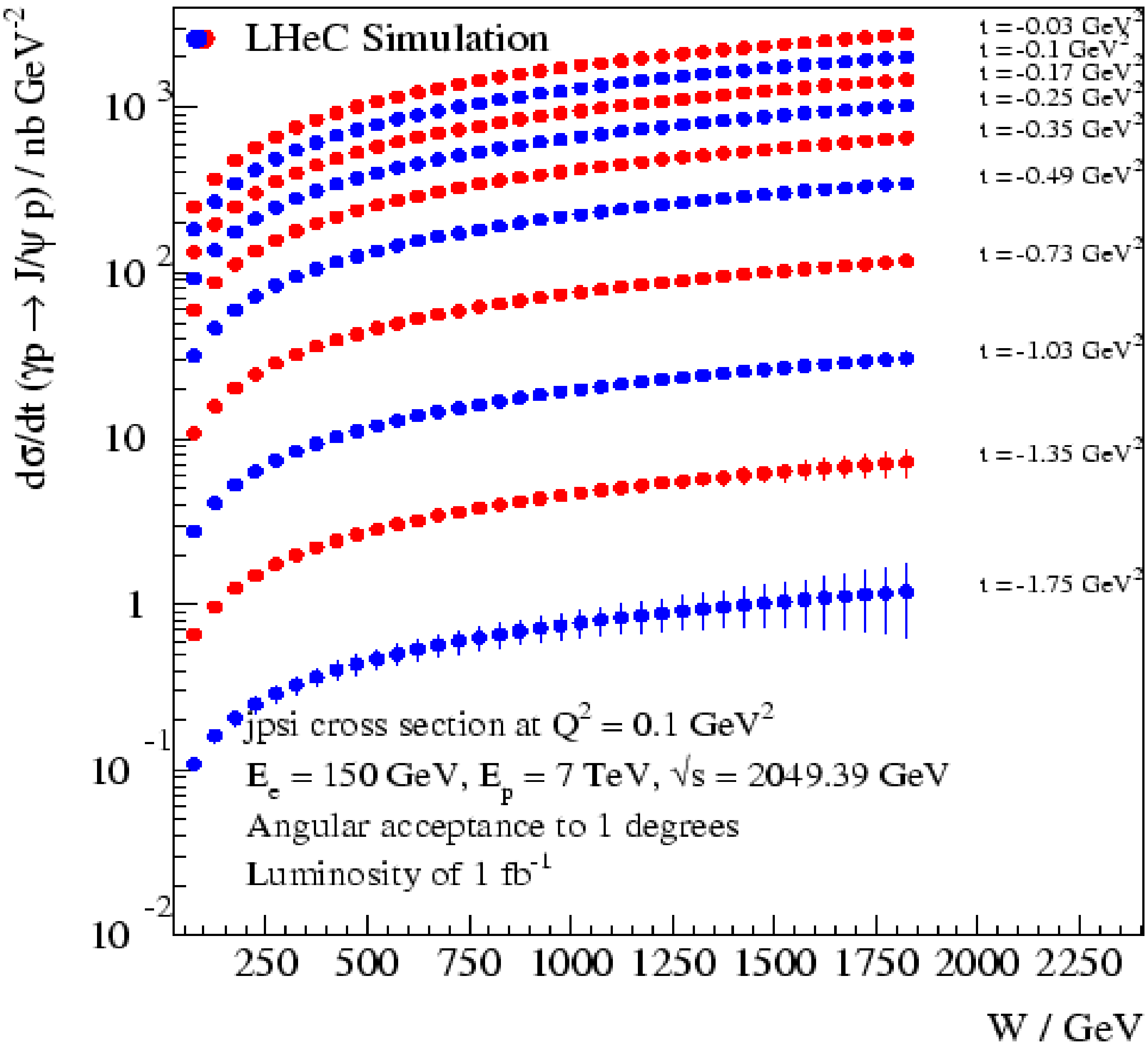
→ Obtain 3d-picture of proton



(figure from C. Weiss.)

Large t probe densest part of proton

Dedicated Low x Linac-Ring Scenario



Dream scenario!!!

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

☺

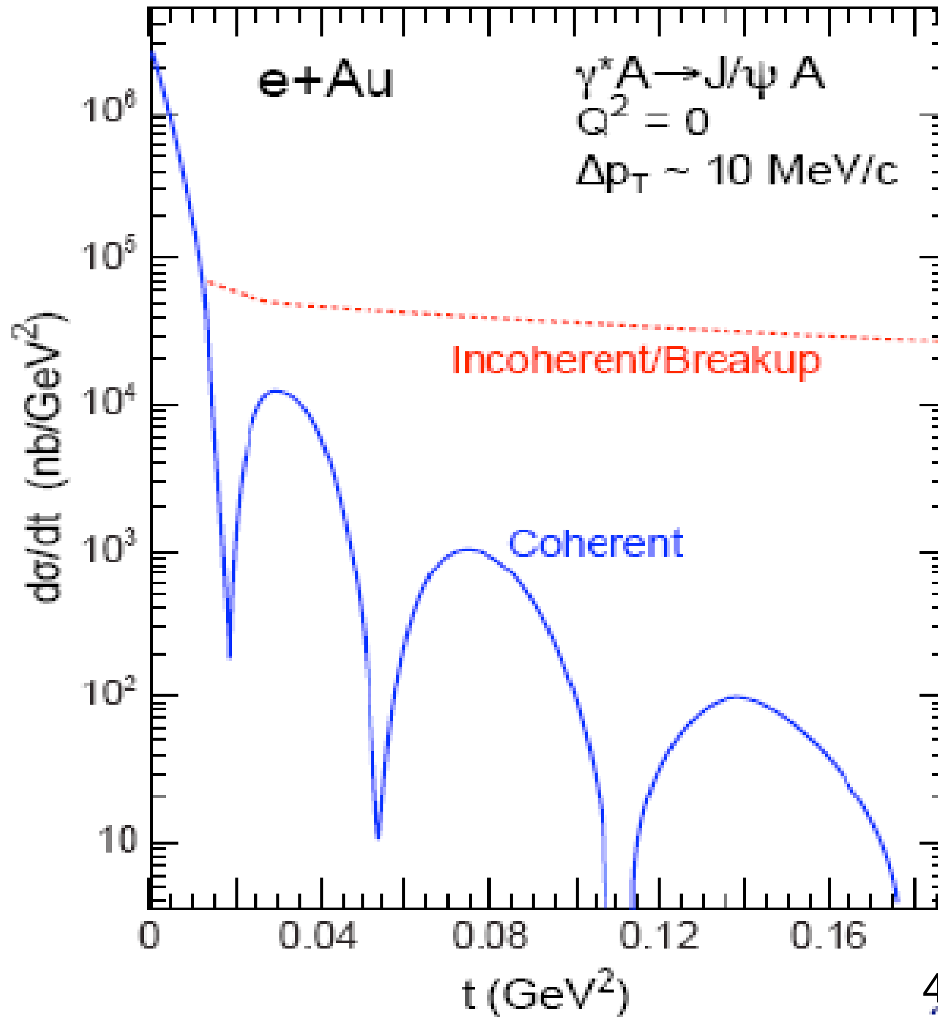
J/Ψ as Probe of Gluon in Nuclei (Kowalski)

- Coherent ($\gamma A \rightarrow J/\Psi\ A$) and incoherent ($\gamma A \rightarrow J/\Psi\ A'nnp...$) 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

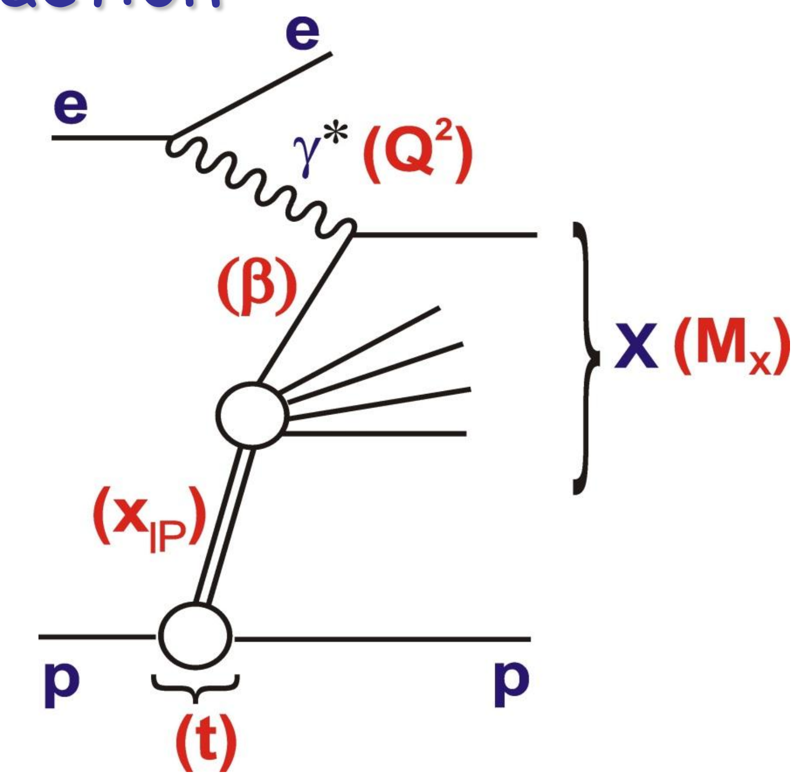


Inclusive Diffraction

Additional variables …

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

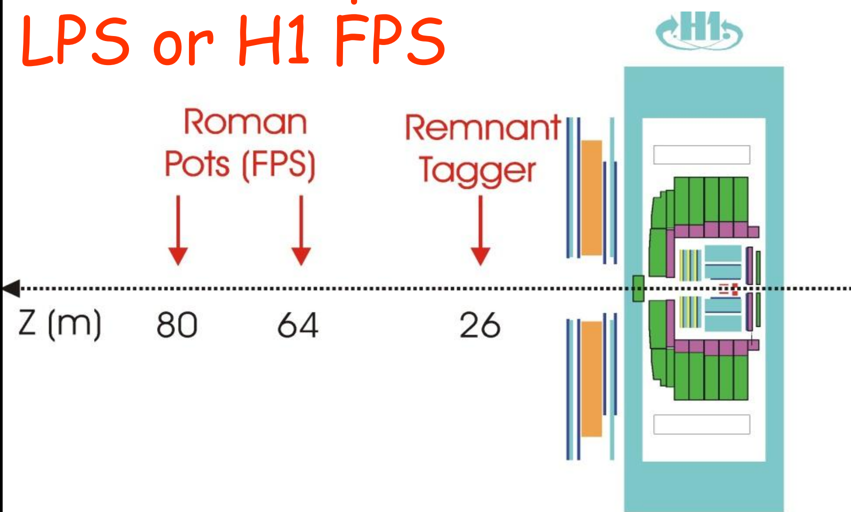
$\beta = x / x_{IP}$ (momentum fraction q / IP)



→ 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

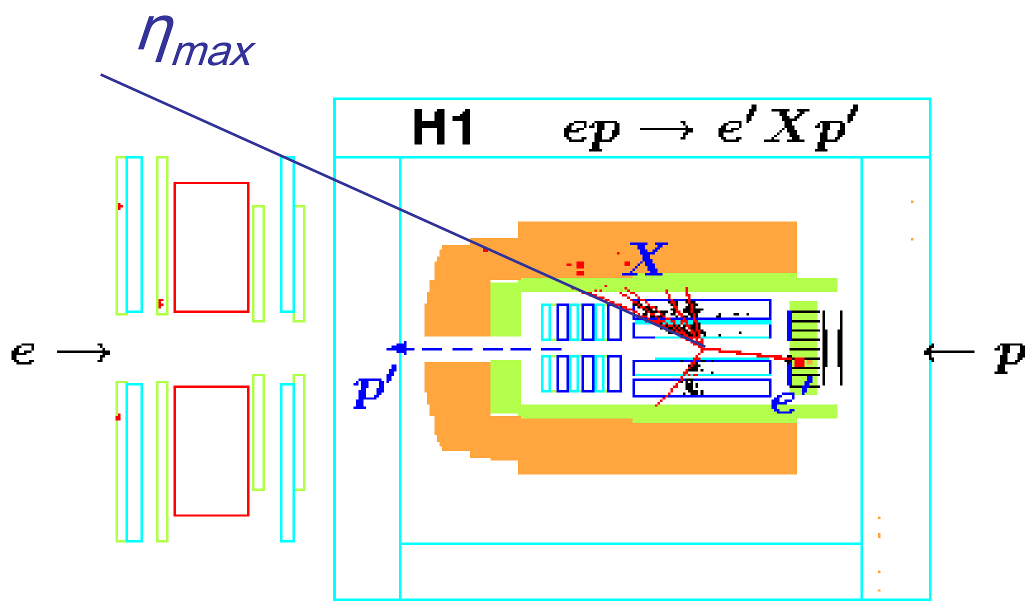
Signatures and Selection Methods at HERA

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

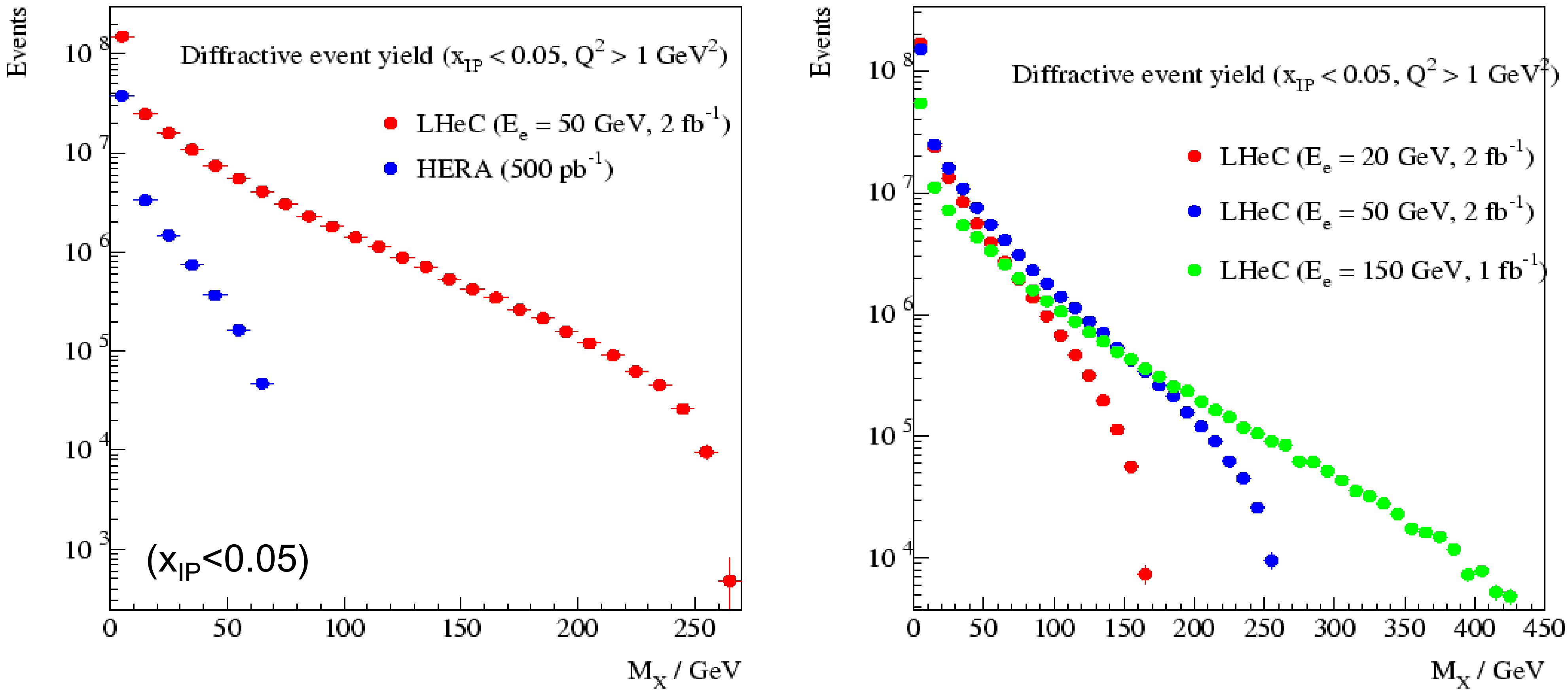


Limited by p-diss systs

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

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

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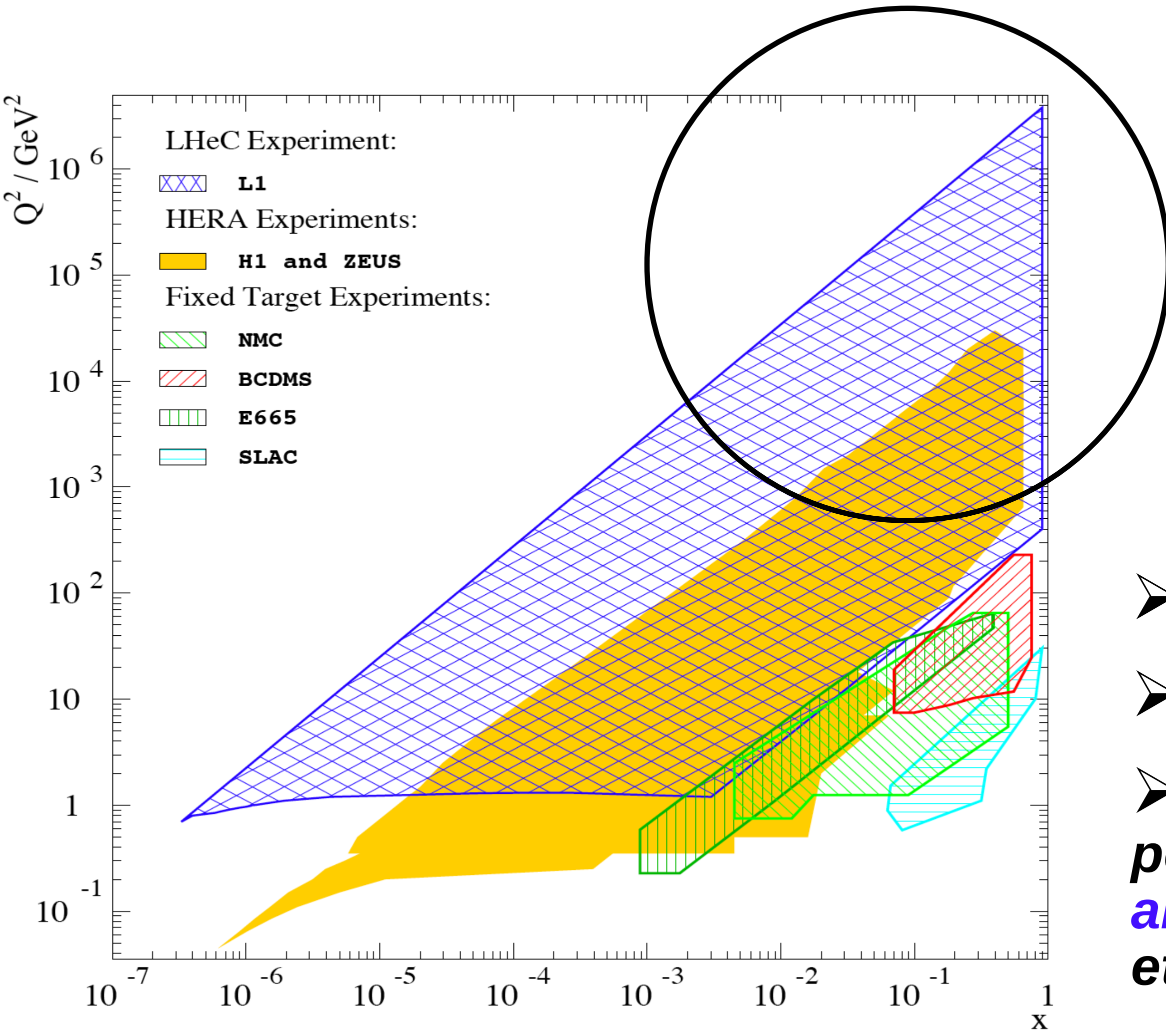
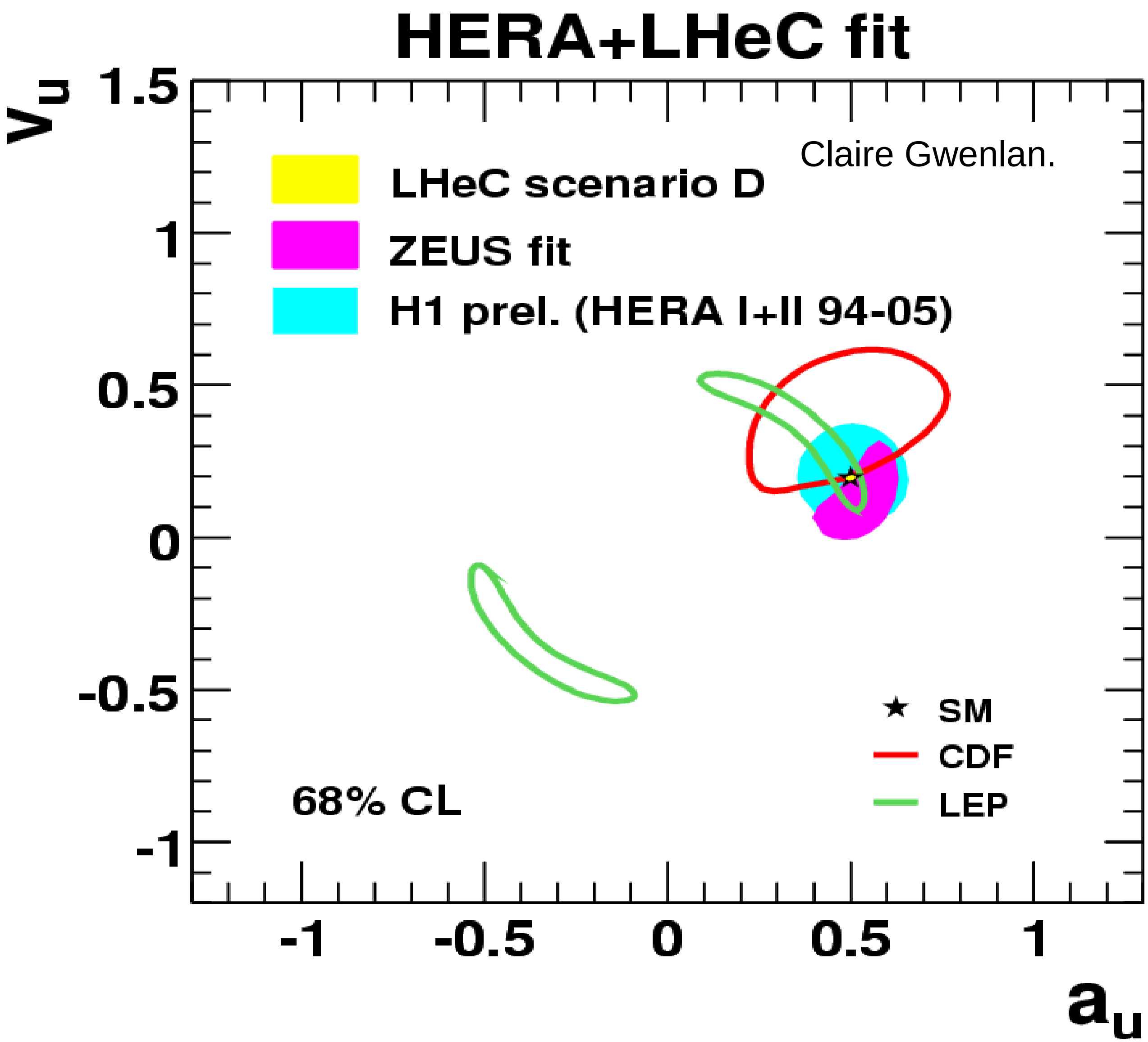
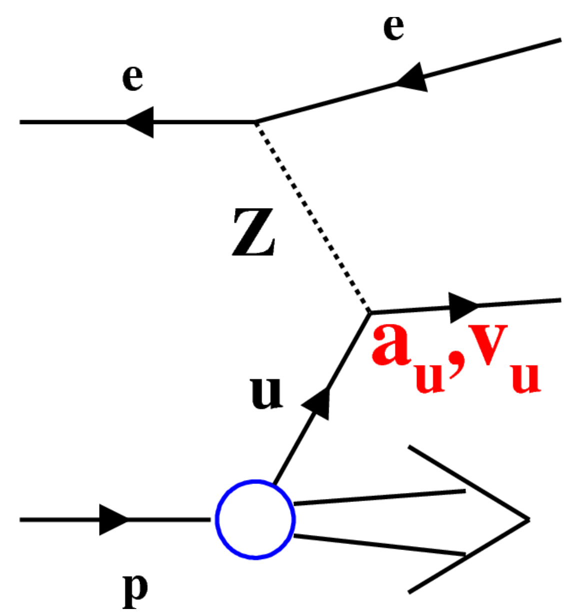
4. SM electroweak and new physics at the high energy frontier



- ***Light quark couplings to Z***
- ***SM Higgs production***
- ***Leptoquarks** + many other possibilities, e.g. excited leptons, anomalous single top production, etc.*

Fermion couplings to Z boson



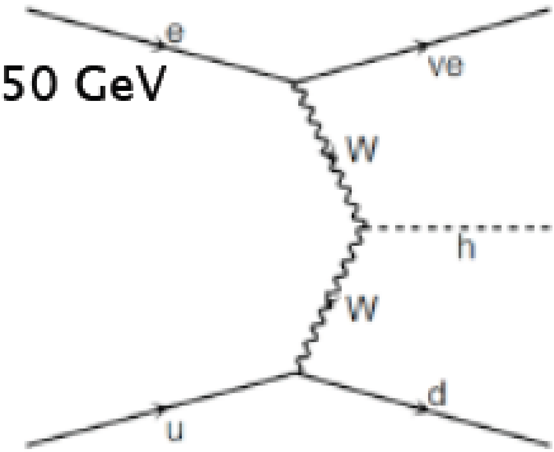


LHeC could measure u and d couplings with ~1% precision

Higgs production at LHeC

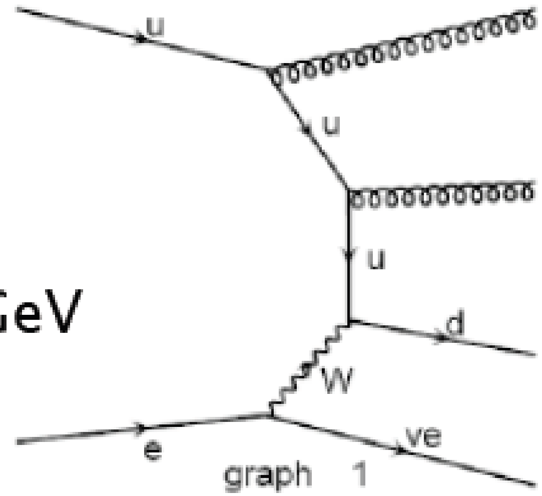
Dominating process

150 GeV



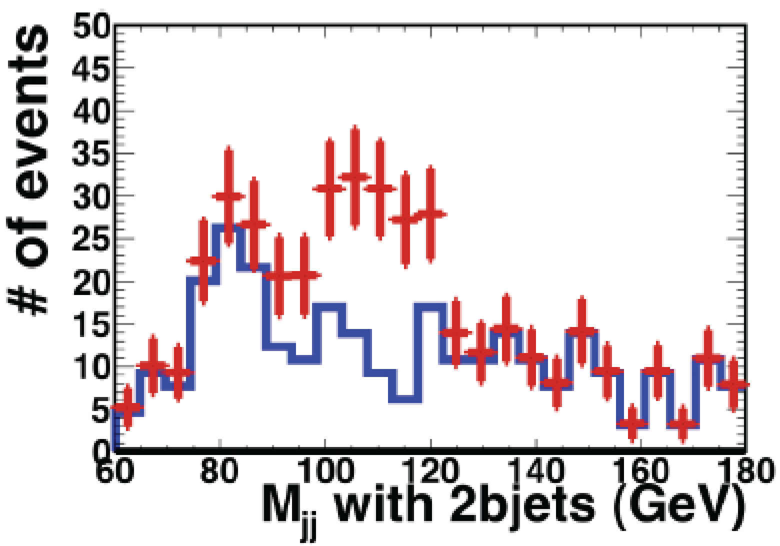
σ~160 pb
for mH=120 GeV

Beware of backgrounds



+ many many others

Motivation: Measure H→bb coupling

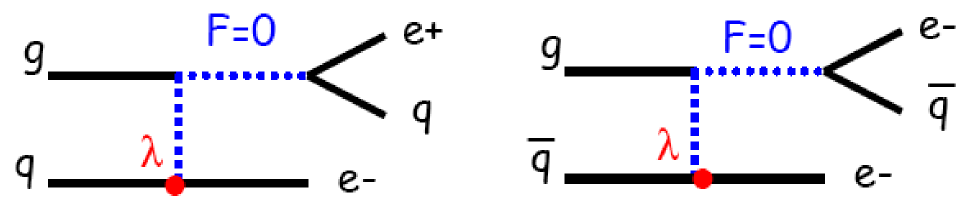


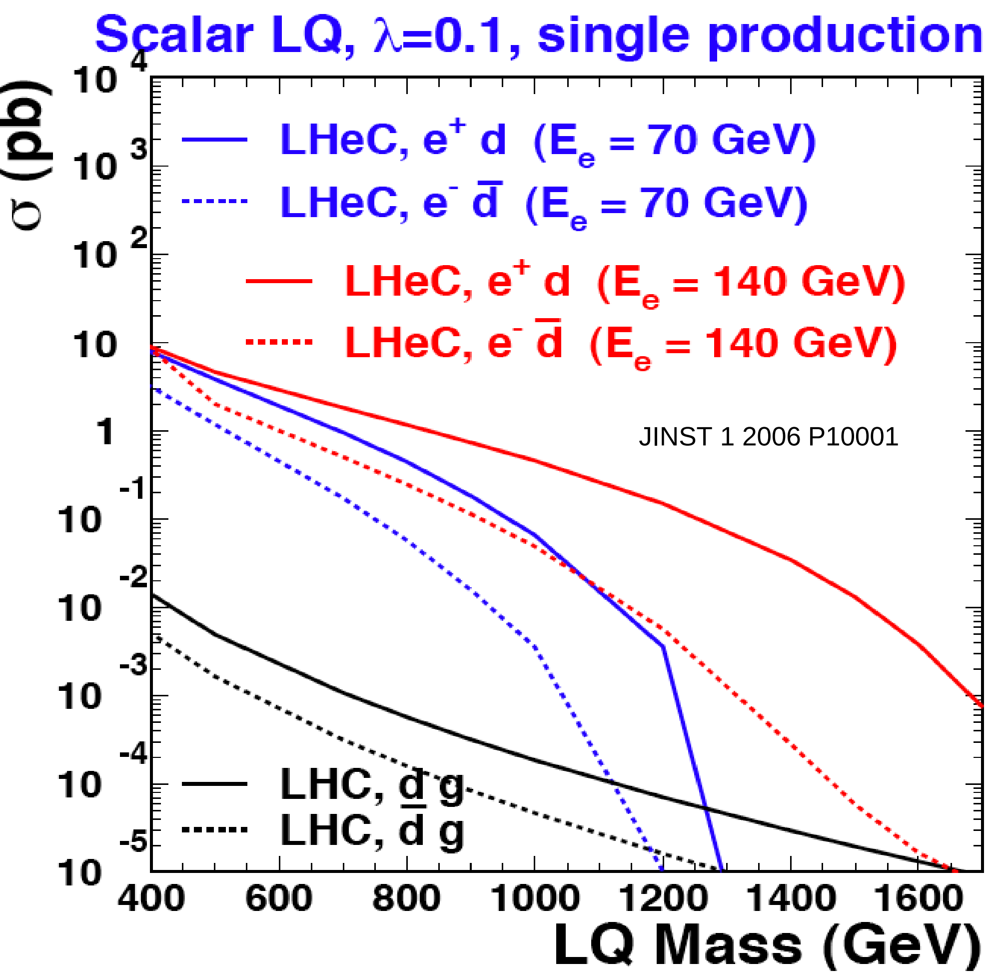
E_e = 150 GeV,
m_H = 120 GeV
10 fb^{-1}

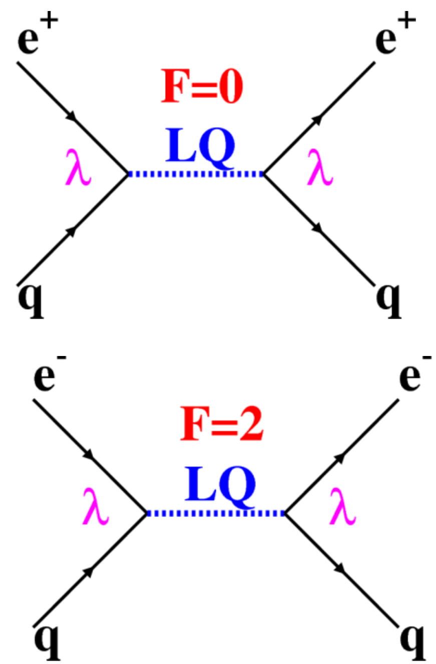
Excellent b tagging needed to suppress large backgrounds

New physics example
Leptoquarks: determine quantum Numbers at LHeC

Single LQ production at LHC







Single LQ production at LHeC

e-p vs e+p asymmetries at LHeC will reveal the Fermion number F

Summary

The LHeC has potential to completely unfold the partonic content of the proton: u,d, c,s, t,b for the first time and in an unprecedent kinematic range. This is based on inclusive NC, CC cross sections complemented by heavy quark identification.

Puzzles as u/d at large x or a strange-antistrange asymmetry will be solved.

Precision measurements are possible of xg (up to large x) and the beauty density which are of particular relevance for the LHC. The (almost) whole p structure which the LHC assumes to know will become accurately known.

Determine α_s with permille level precision

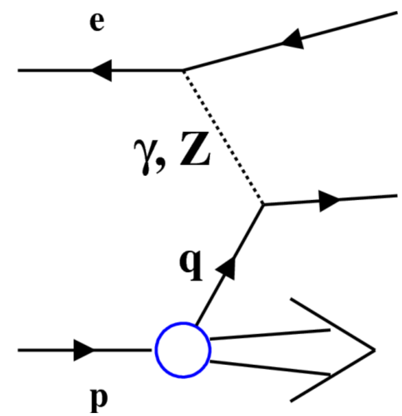
Wealth of QCD tests with final states (not much discussed in this talk : Jets (study also photon structure), heavy flavours, prompt photons, other identified particles

Low x and diffractive physics with ep and eA: Measuring multiple observables (F2, Fl, F2c, F2D, Vector mesons…) in ep and eA can lead to a microscopic understanding of non-linear evolution, unitarity constraints and parton saturation

Electroweak and new physics
- Light quark couplings to Z at ~1% level
- SM Higgs production for H-> bb coupling
- New physics: Leptoquarks and quantum numbers, quark radius, leptons* and more!

Backup slides

Master formulae for NC DIS



$$\sigma_{r,NC} = \frac{d^2\sigma_{NC}}{dxdQ^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \mathbf{F_2} + \frac{Y_-}{Y_+}\mathbf{xF_3} - \frac{y^2}{Y_-}\mathbf{F_L}$$

$$\begin{aligned}
\mathbf{F_2^\pm} &= F_2 + \kappa_Z(-v_e \mp P a_e)\cdot F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2P v_e a_e)\cdot F_2^Z \\
\mathbf{xF_3^\pm} &= \kappa_Z(\pm a_e + P v_e)\cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2 v_e a_e - P(v_e^2 + a_e^2))\cdot xF_3^Z
\end{aligned}$$

$$\begin{aligned}
(F_2, F_2^{\gamma Z}, F_2^Z) &= x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q}) \\
(xF_3^{\gamma Z}, xF_3^Z) &= 2x\sum(e_q a_q, v_q a_q)(q - \bar{q}),
\end{aligned}$$

$$F_L(x) = \frac{\alpha_s}{4\pi}x^2\int_x^1 \frac{dz}{z^3}\cdot\left[\frac{16}{3}F_2(z) + 8\sum e_q^2\left(1 - \frac{x}{z}\right)zg(z),\right]$$

Vary charge and polarisation and beam energy to disentangle contributions

Charged Currents

$$\sigma_{r,CC} = \frac{2\pi x}{Y_+ G_F^2} \left[\frac{M_W^2 + Q^2}{M_W^2} \right]^2 \frac{\mathrm{d}^2 \sigma_{CC}}{\mathrm{d}x \mathrm{d}Q^2}$$

$$\sigma_{r,CC}^{\pm} = \frac{1 \pm P}{2} \left(W_2^{\pm} \mp \frac{Y_-}{Y_+} x W_3^{\pm} - \frac{y^2}{Y_+} W_L^{\pm} \right)$$

$$W_2^+ = x(\overline{U} + D),\ xW_3^+ = x(D - \overline{U}),\ W_2^- = x(U + \overline{D}),\ xW_3^- = x(U - \overline{D})$$

$$U = u + c \qquad \overline{U} = \overline{u} + \overline{c} \qquad D = d + s \qquad \overline{D} = \overline{d} + \overline{s}$$

$$\sigma_{r,CC}^{+} \sim x\overline{U} + (1-y)^2 xD,$$

$$\sigma_{r,CC}^{-} \sim xU + (1-y)^2 x\overline{D}$$

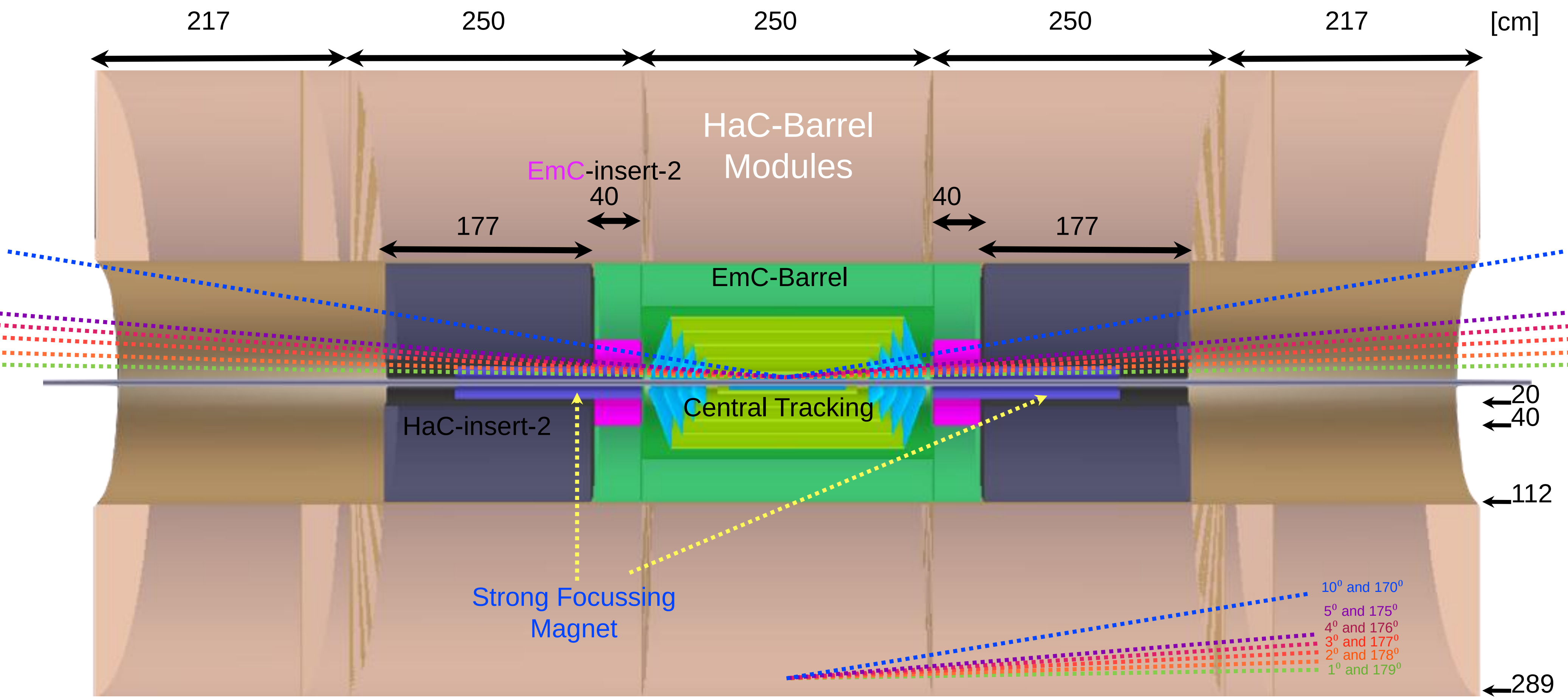
$$\sigma_{r,NC}^{\pm} \simeq [c_u(U + \overline{U}) + c_d(D + \overline{D})] + \kappa_Z [d_u(U - \overline{U}) + d_d(D - \overline{D})]$$

with $c_{u,d} = e_{u,d}^2 + \kappa_Z(-v_e \mp P a_e) e_{u,d} v_{u,d}$ and $d_{u,d} = \pm a_e a_{u,d} e_{u,d}$,

Complete unfolding of all parton distributions to unprecedented accuracy

The High Lumi (High Q²) Setup

(to be optimised)

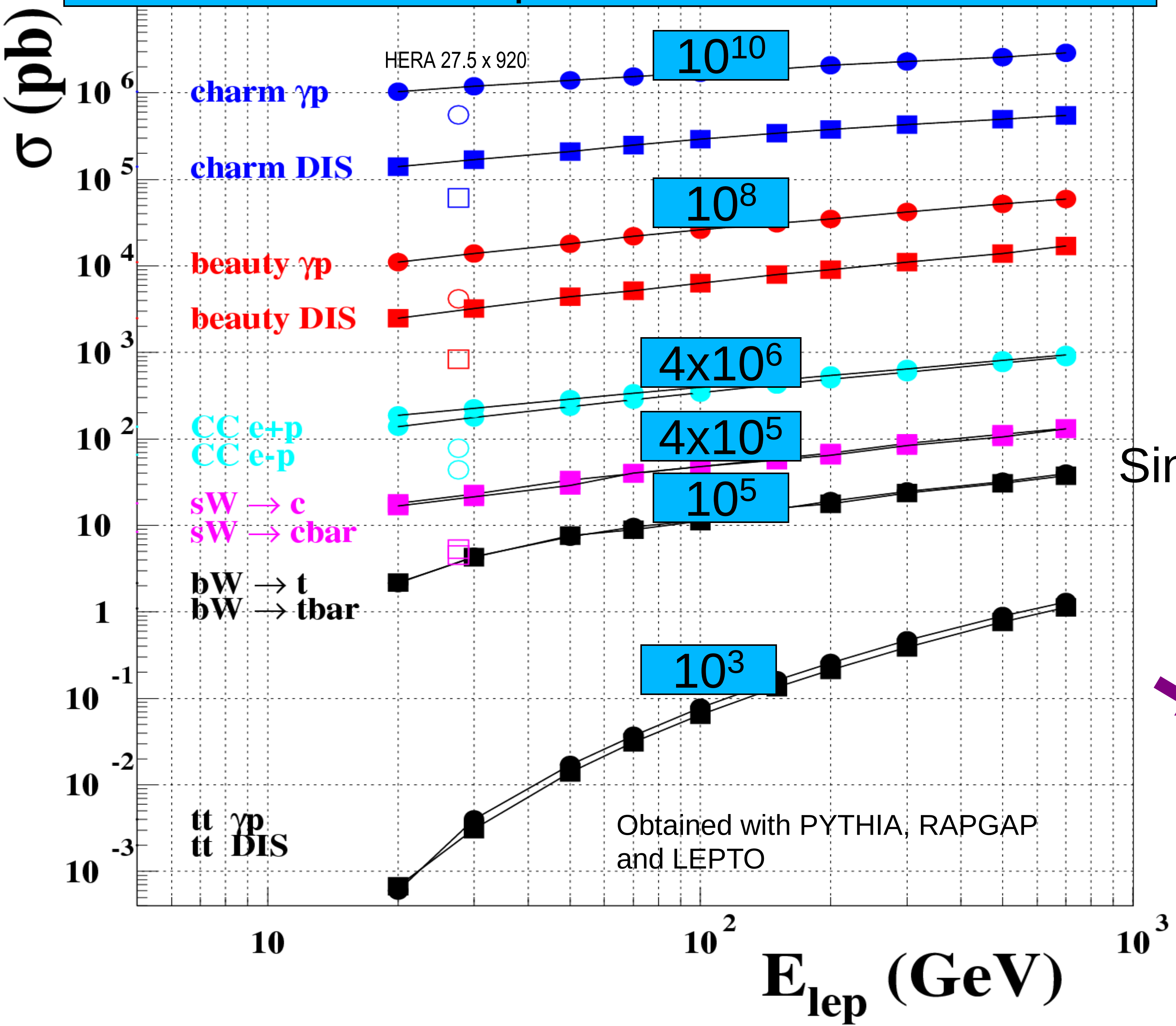


L1 Low Q² SetUp → High Q² SetUp

- Fwd/Bwd Tracking & EmC-Extensions, HaC-Insert-1 removed
- Calo-Inserts in position
- Strong Focussing Magnet installed

Events per 10 fb-1 Lumi

O.B.



Single Top

LHeC is a *multi flavour factory*