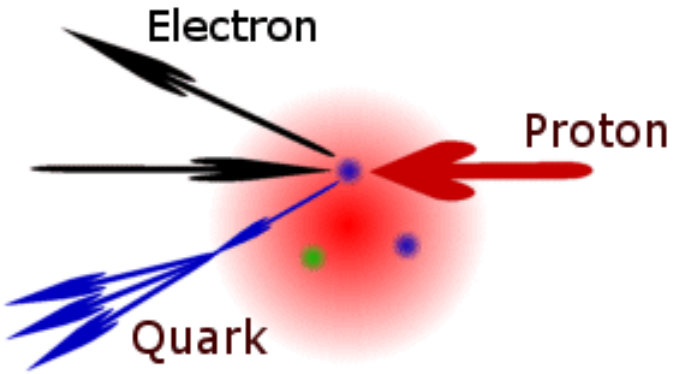
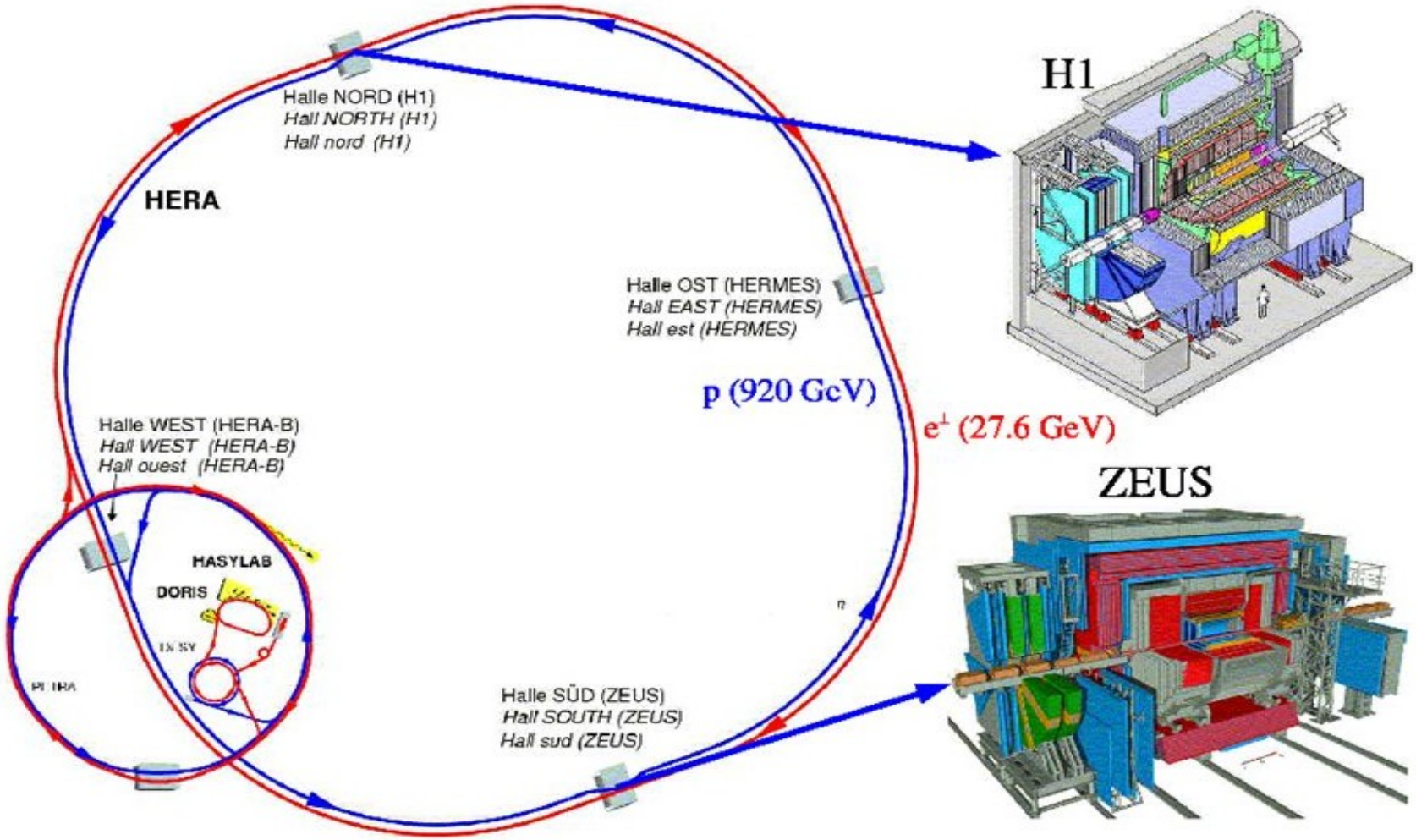


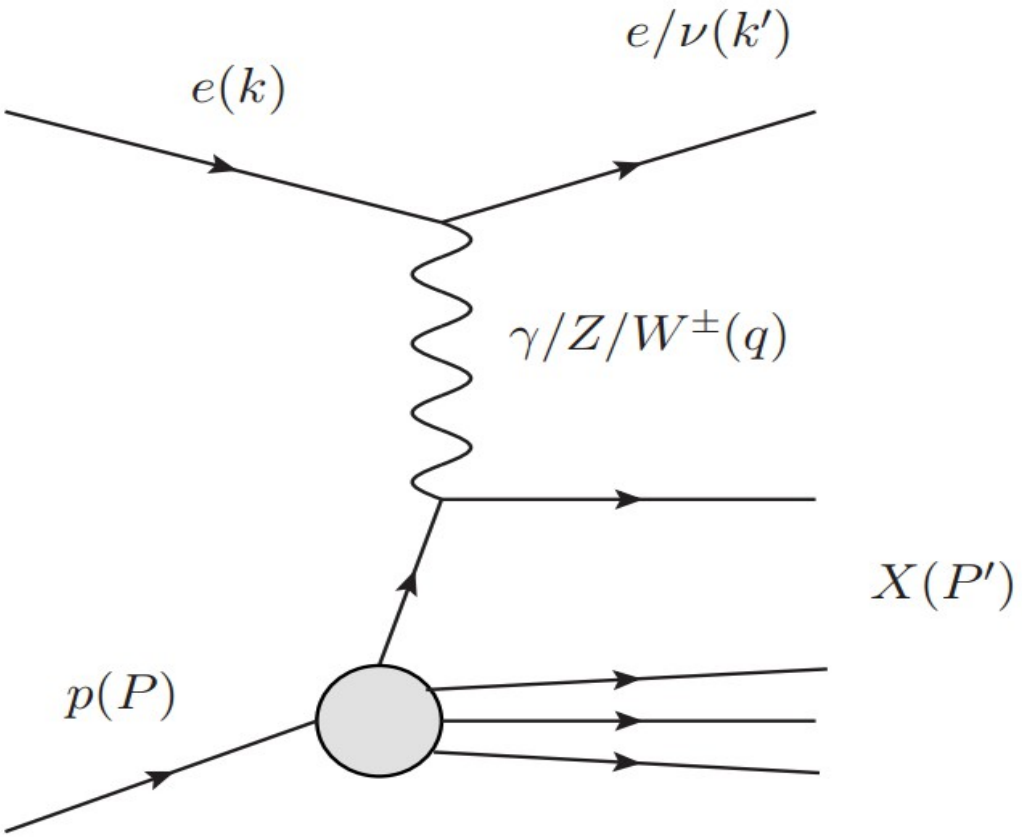
QCD @ HERA

Interplay between soft & hard physics



- HERA: ep collider in Hamburg
- Operation: 1992-2007
- Colliding experiments: H1 and ZEUS
- Collected ~1 fb^{-1} for both experiments together

ep Scattering at HERA



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

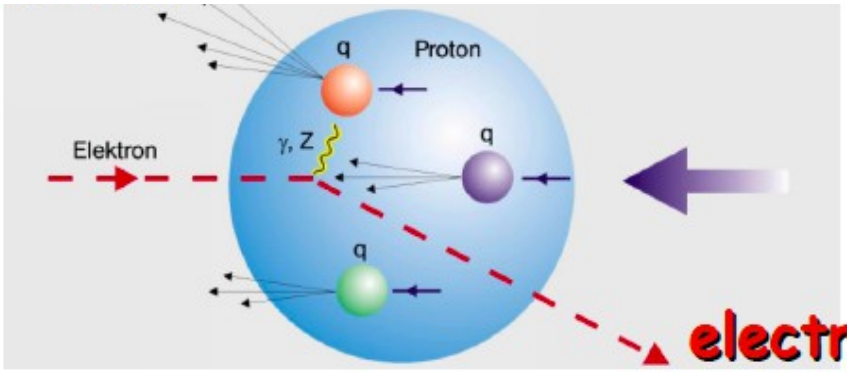
$$x_{Bj} = \frac{Q^2}{2\,pq} \qquad y = \frac{pq}{pk}$$

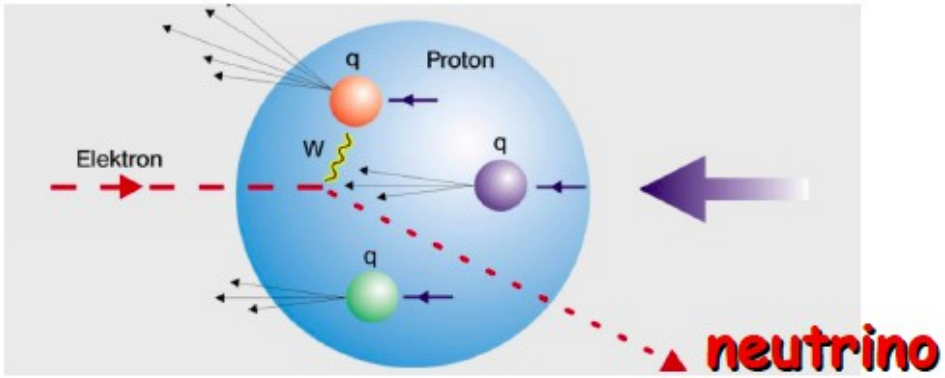
$$s = (p + k)^2 \qquad Q^2 = xys$$

$$W^2 = Q^2(1/x_{\mathrm{Bj}} - 1) + m_p^2$$

two regions: $Q^2 \approx 0$ GeV^2 — photoproduction
$Q^2 > 1$ GeV^2 — electroproduction (DIS)

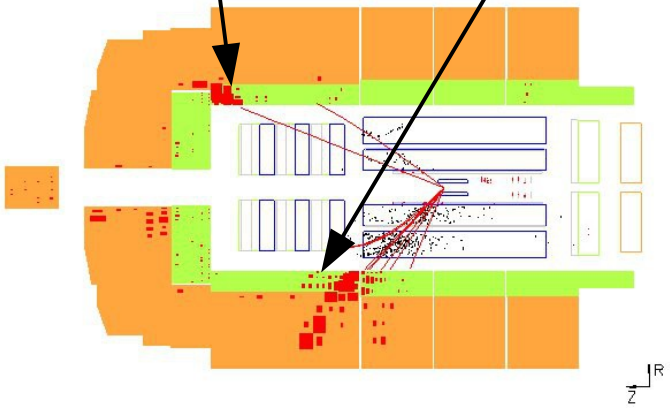
Deep Inelastic Scattering @ HERA





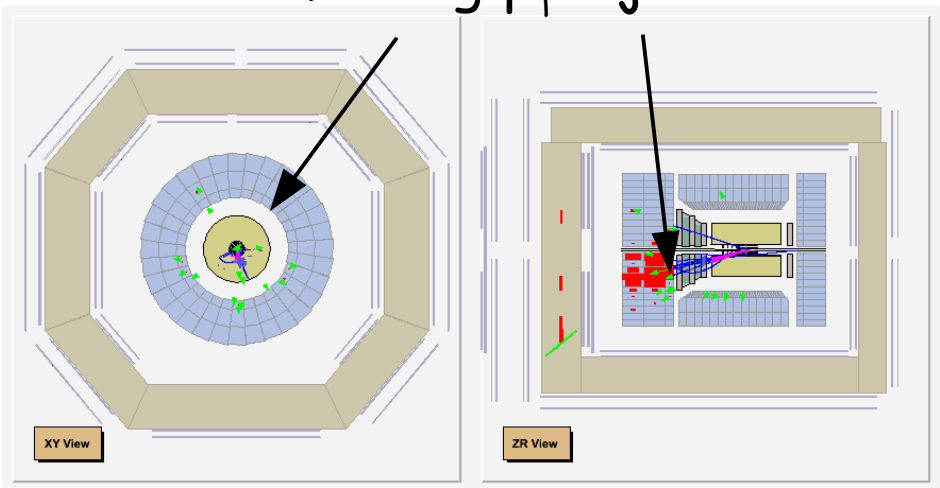
Neutral Current (NC): γ, Z exchange

electron + jet



Charge Current (CC): W exchange

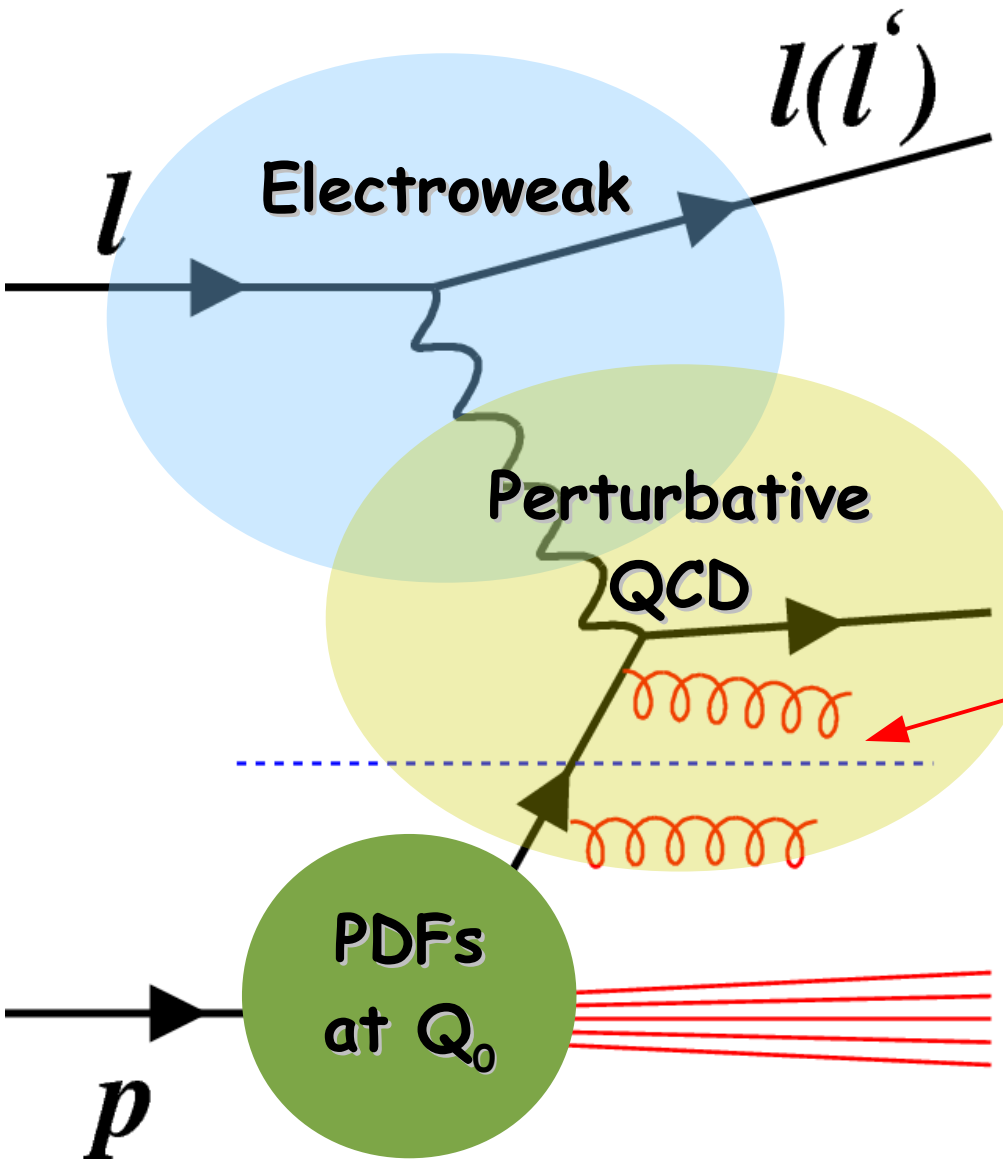
missing p_T + jet



- NC/CC cross section expresses in terms of structure functions

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

Deep Inelastic Scattering @ HERA

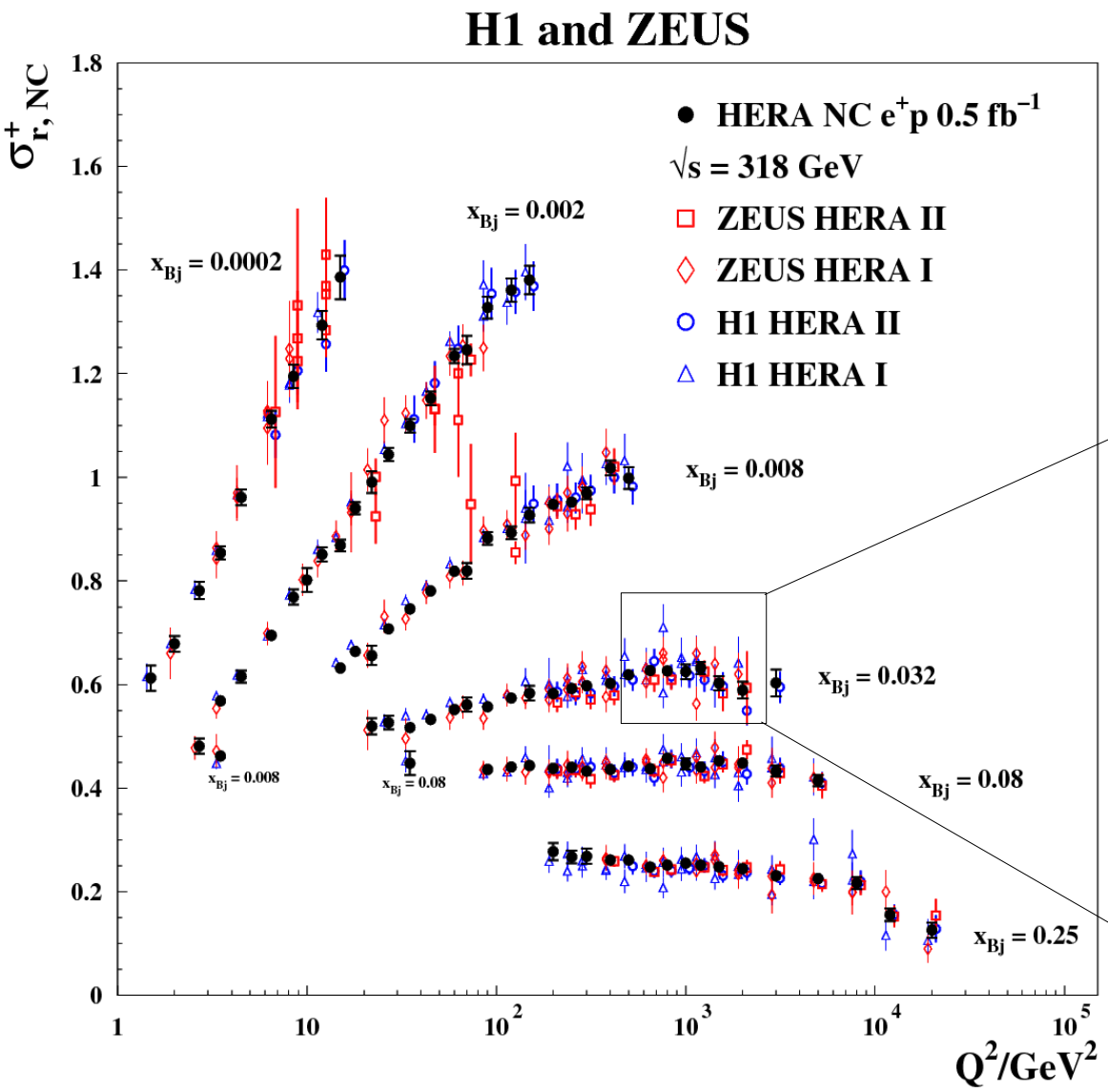


- Fix pQCD & PDFs
  ! Test Electroweak
- Fix Electroweak
  ! Test pQCD & PDFs

Factorisation

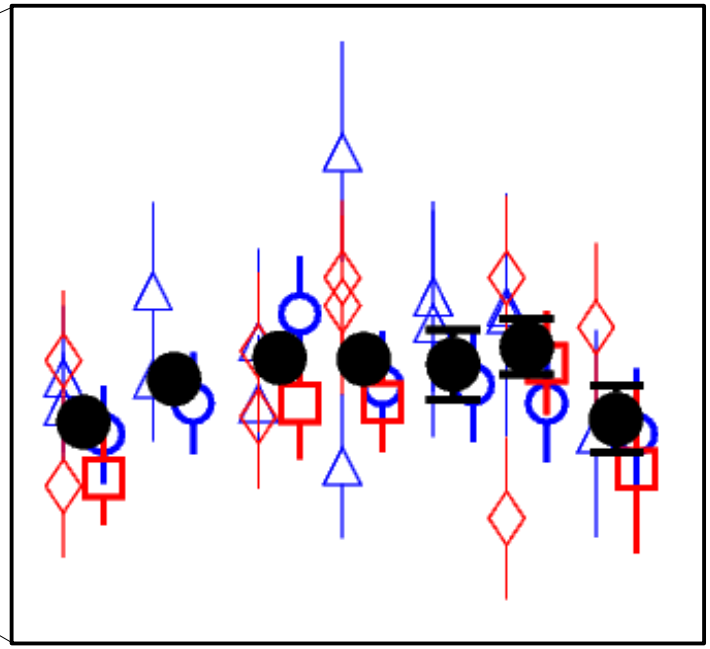
- Fix Electroweak & pQCD
  ! Determine PDFs

Combination of HERA inclusive DIS data



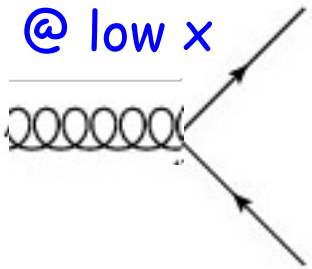
41 final data sets

- Neutral and charged current
- Electrons and positrons
- Four different CMEs

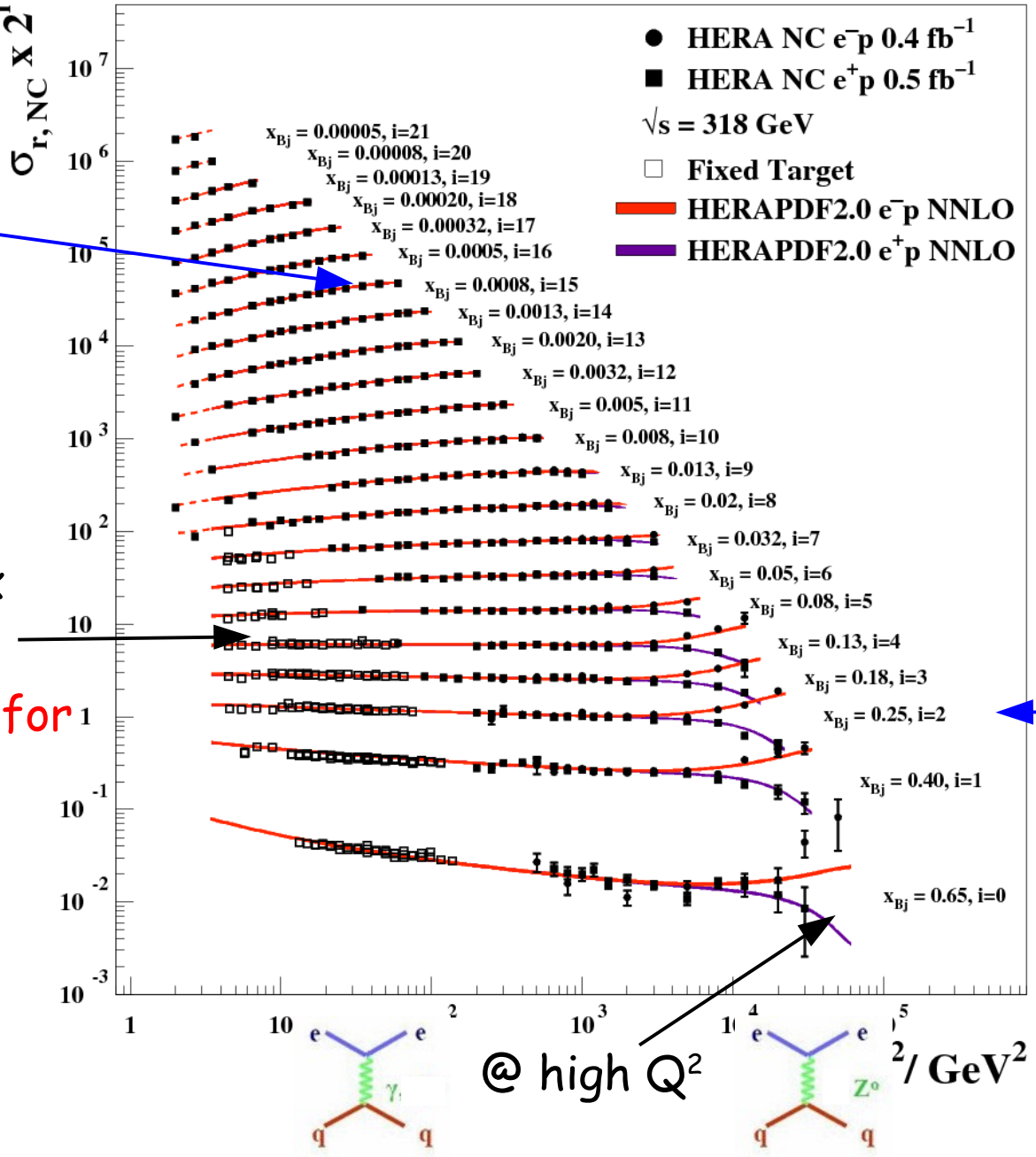


Eur. Phys. J. C 75 (2015) 580

Total of 2927 data points combined to 1307: chi2/ndf = 1.04

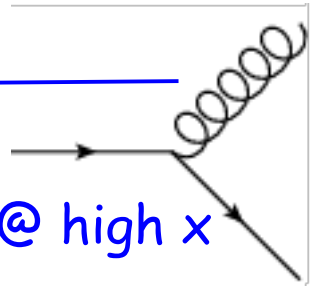


@ low x



electron-proton
positron-proton

@ moderate x
QCD scaling
2015 Wolf prize for
J. Bjorken!

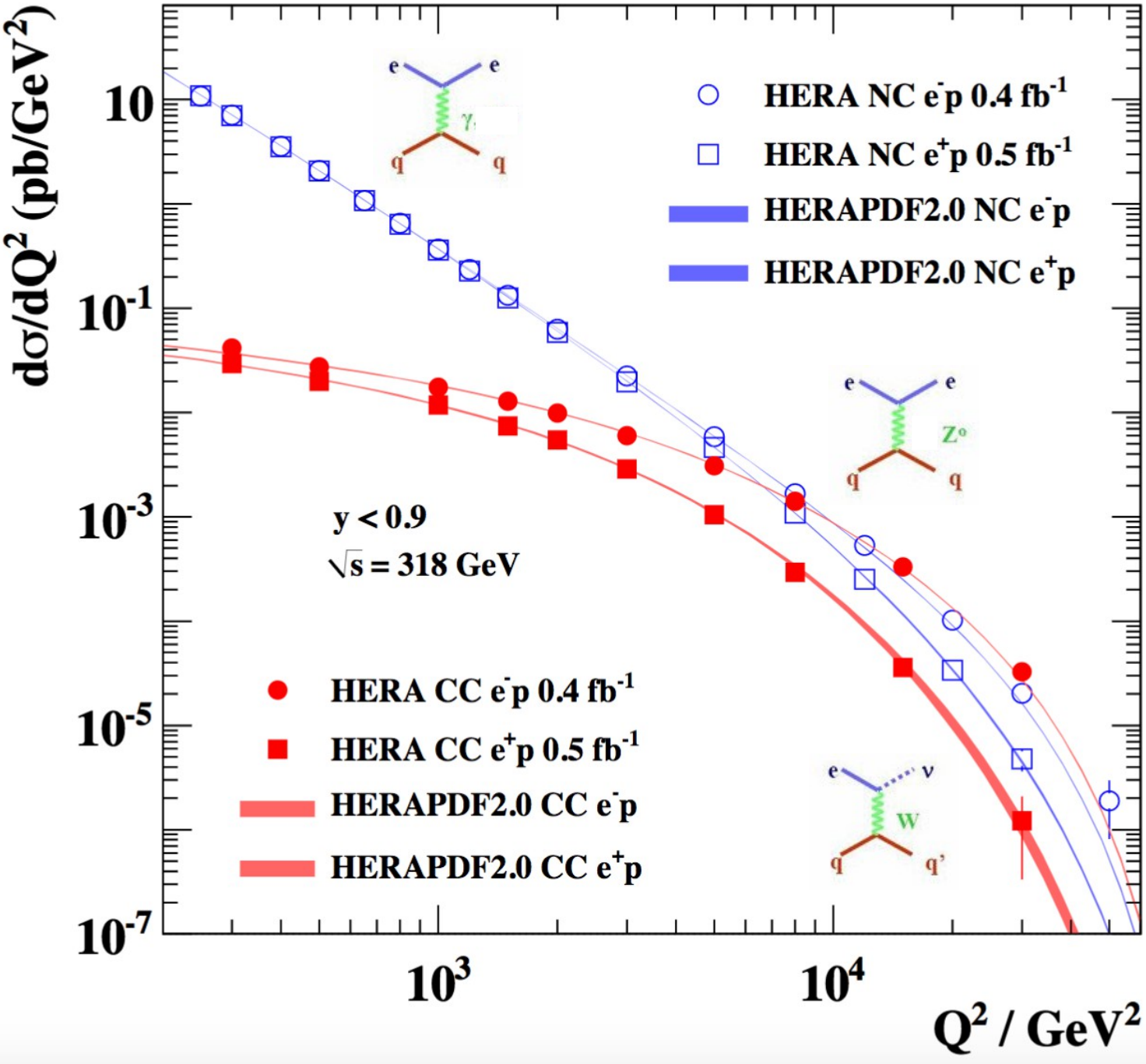


@ high x

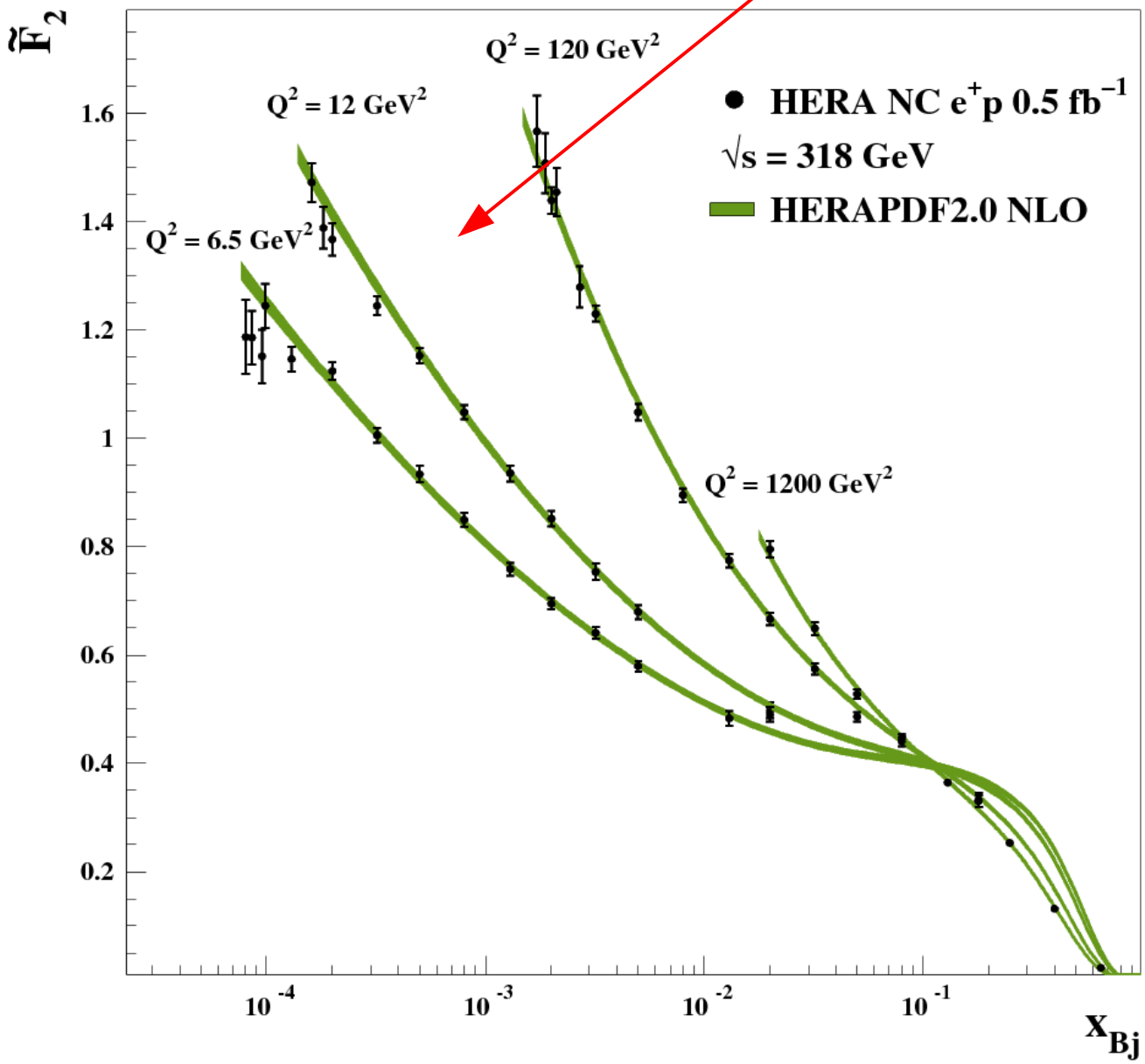
@ high Q^2

Text book plots of fundamental properties of particle interactions

Electroweak Unification



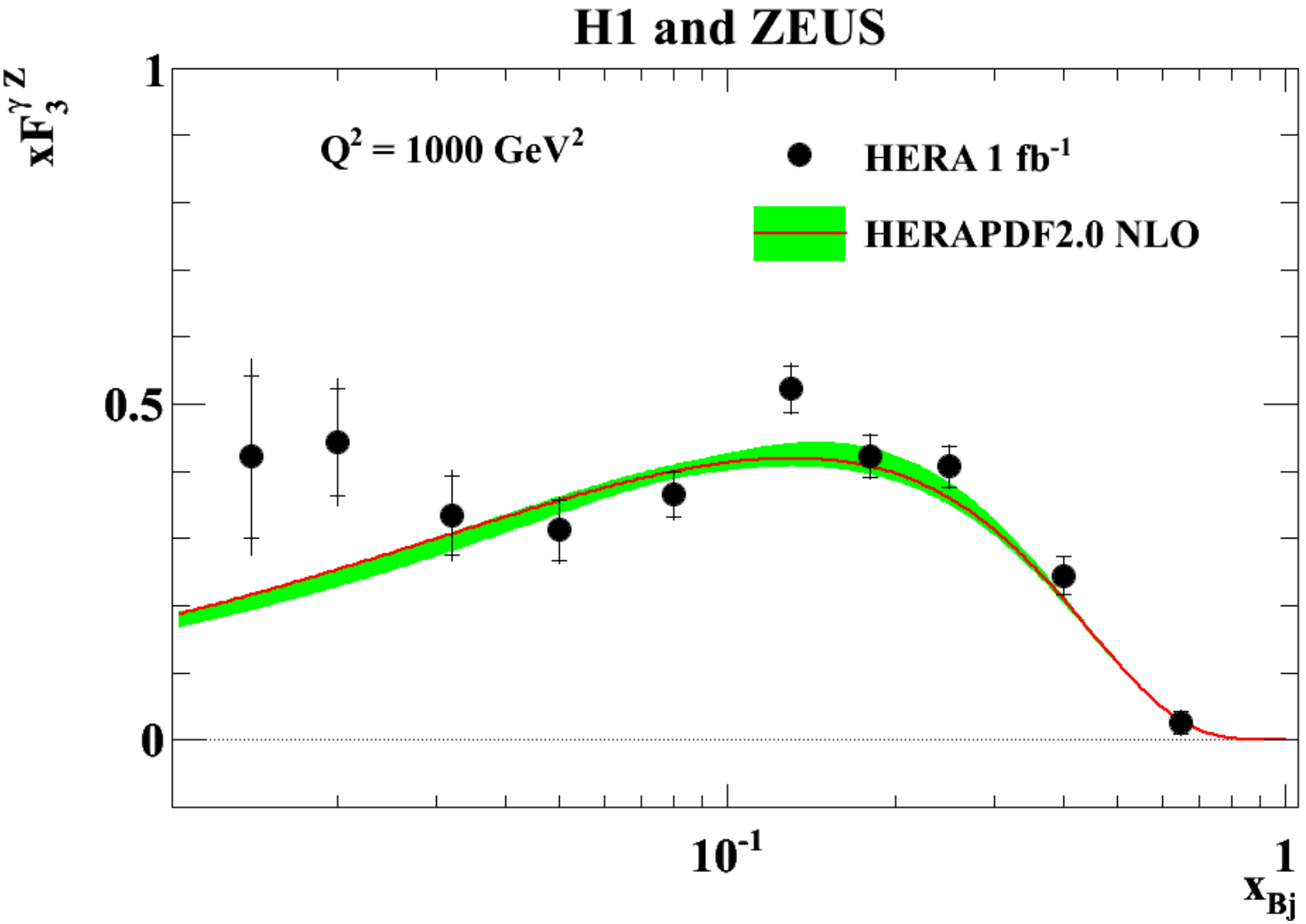
As expected: low-x rise of F_2



- F_2 extracted from red. σ using HERAPDF2.0 NLO predictions

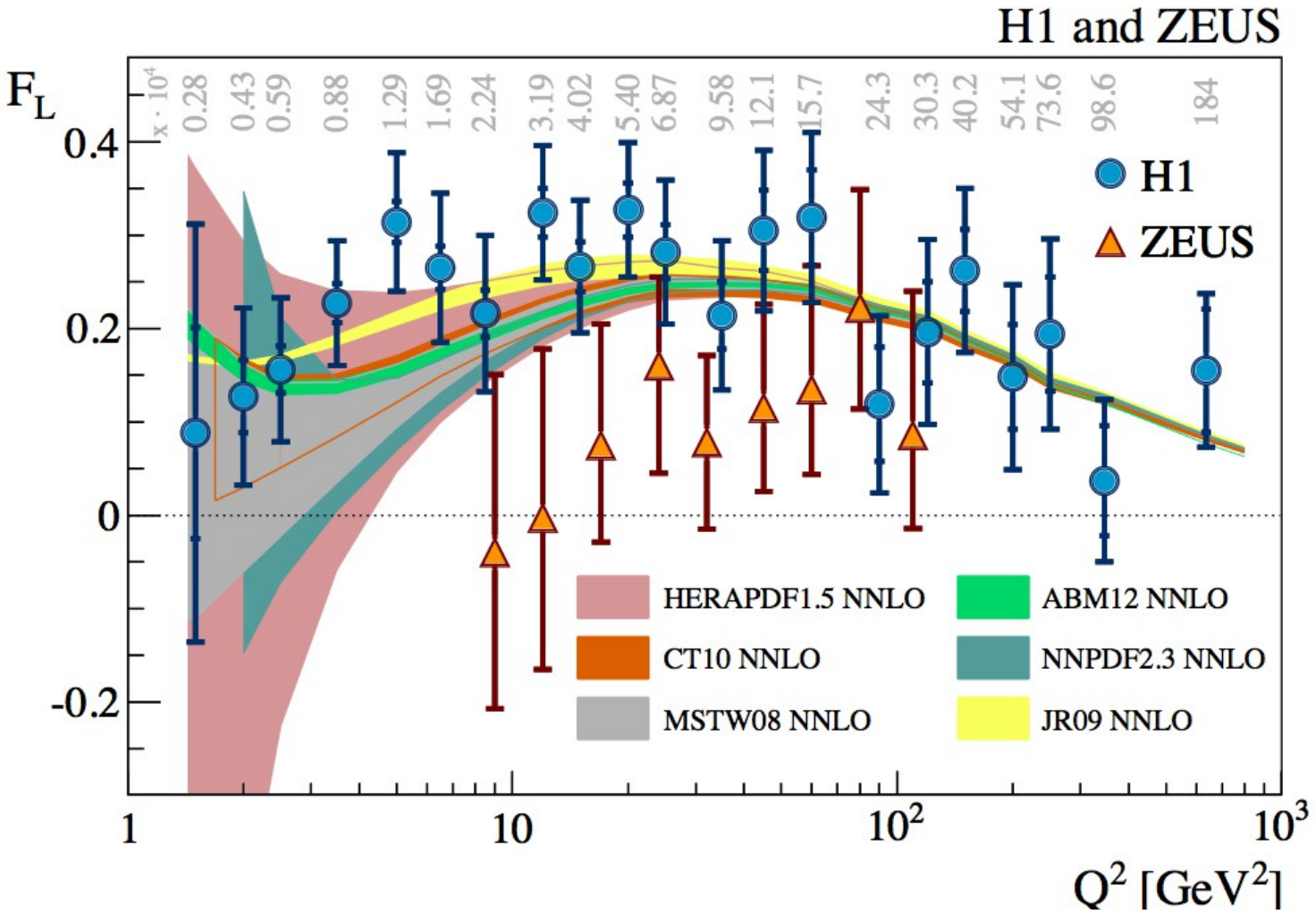
$xF_3^{\gamma Z}$ from combined data

- xF_3^{gZ} from subtracting the NC e^+p from the NC e^-p cross sections



F_L structure function

- F_L measured including low-energy data, separately by each experiment



Eur.Phys.J.C 74 (2014) 2814

Phys.Rev. D 90 (2014) 072002

Global analysis of parton distributions

Goal: determination of the ***input distributions*** (for light quarks and gluons):

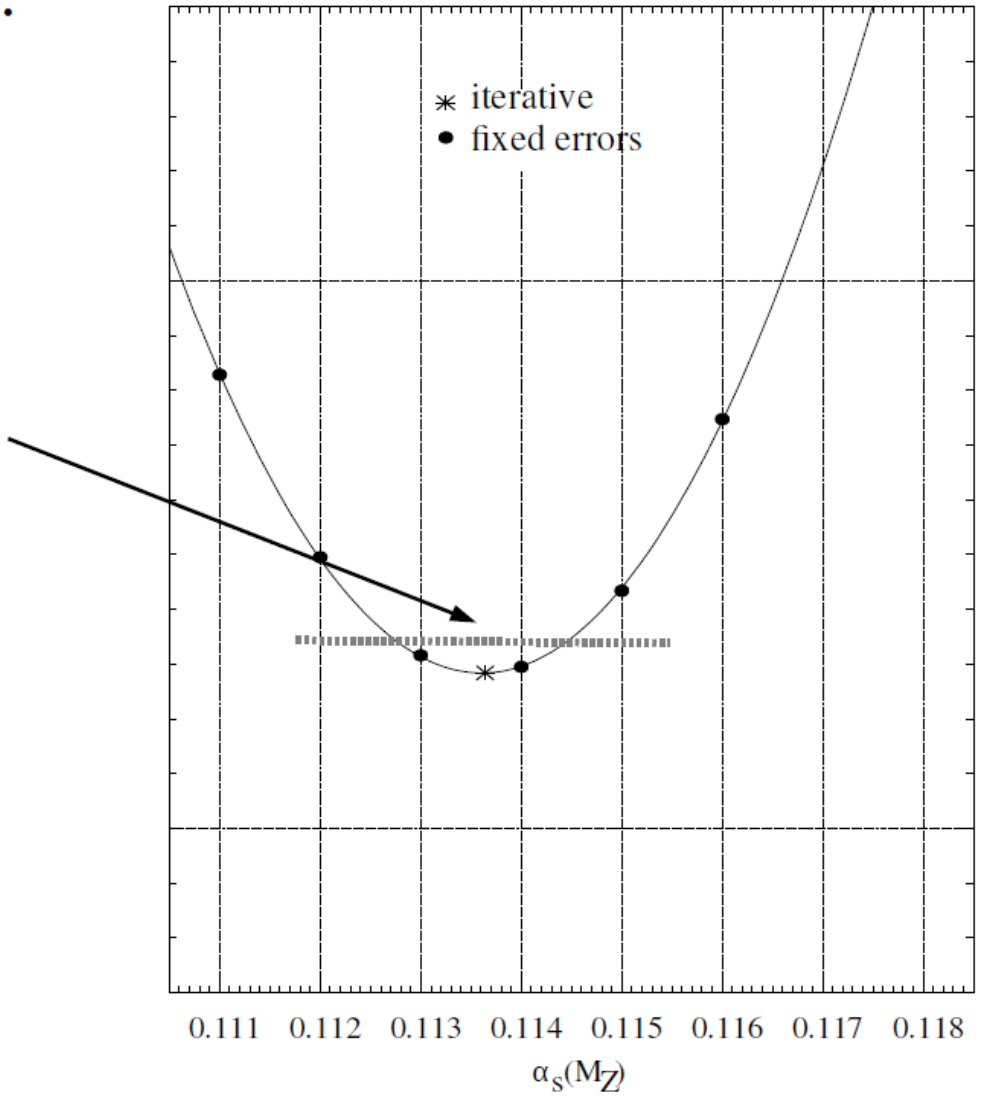
Method: Parametrizations $xf(x,Q_0^2) = Nx^a(1-x)^b\ \mathrm{function}(x)$
and usual *statistical estimation* (fits):

$$\chi^2(p) = \sum_{i=1}^{N} \left(\frac{\mathrm{data}(i) - \mathrm{theory}(i,p)}{\mathrm{error}(i)} \right)^2$$

Position of minimum gives the value and curvature gives the error (region within a certain "tolerance" $\Delta\chi^2 = 1$)

(Monte Carlo methods can also be used)

Usually the chi-square definition is more sophisticated, experimental correlations are also treated, etc.



Inclusive measurements from HERA are core of every parton density extraction

Final HERA data – exclusively - used as input to global QCD fit HERAPDF2.0

- Parton densities parametrised @ Q^2 = 1.9 GeV^2

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

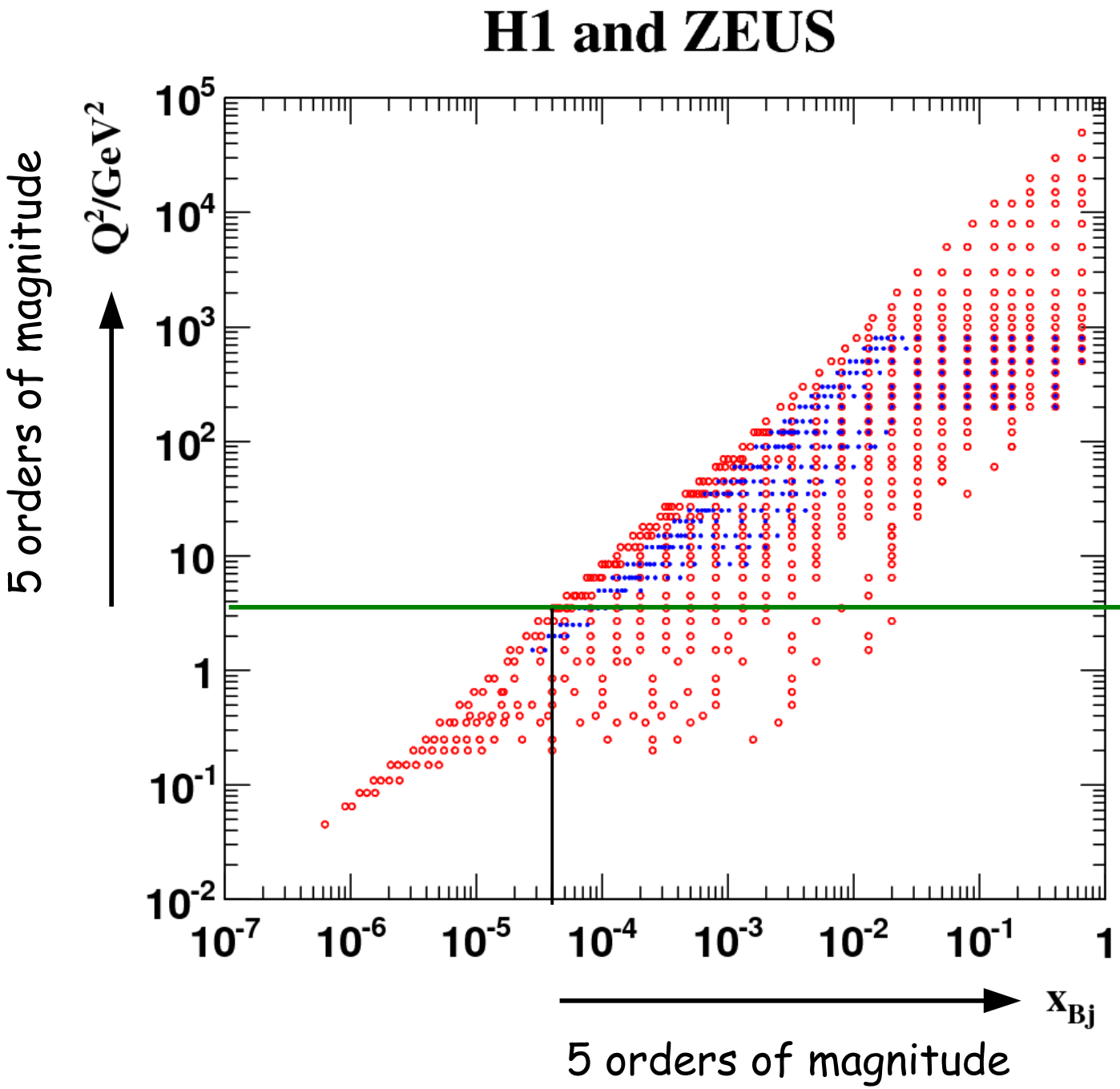
$$xg(x),\ xu_v(x),\ xd_v(x),\ x\bar{U}(x),\ x\bar{D}(x)$$

- Evolution using DGLAP equations
- 14 parameters determined in paramerisation scan
- Heavy quarks from Roberts-Thorne Variable Flavor Number Scheme

HERAFitter

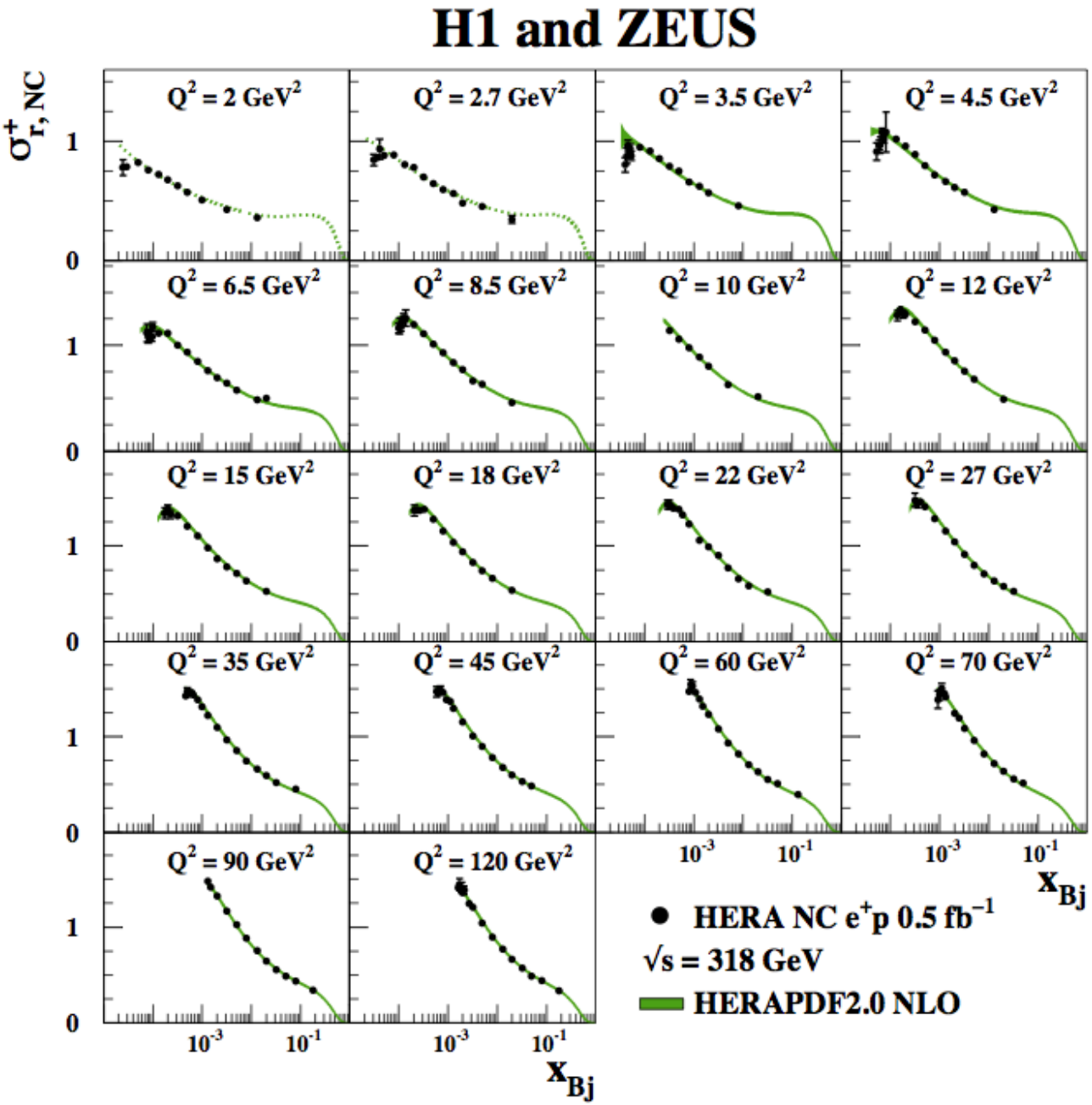
QCD fits performed using HERAFitter package www.herafitter.org

Data in PDF fit



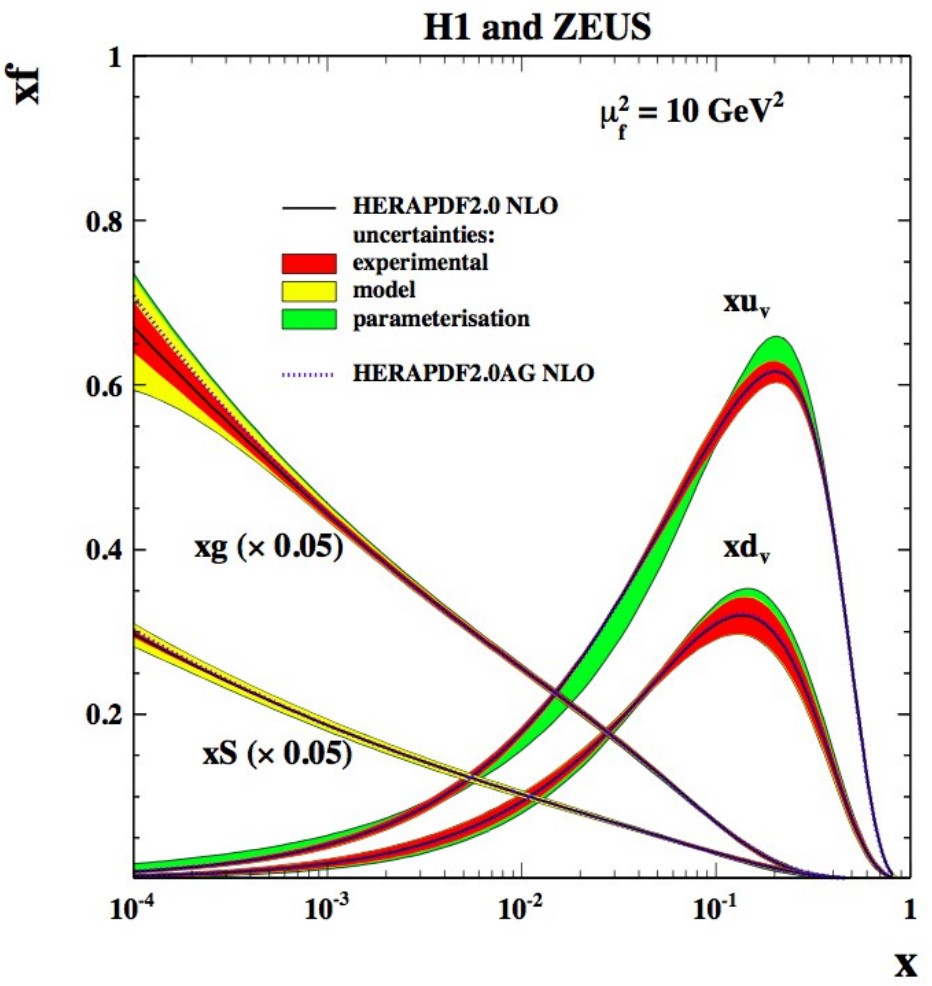
Q^2_{min} = 3.5 GeV^2

Surprisingly we can fit so low in Q^2

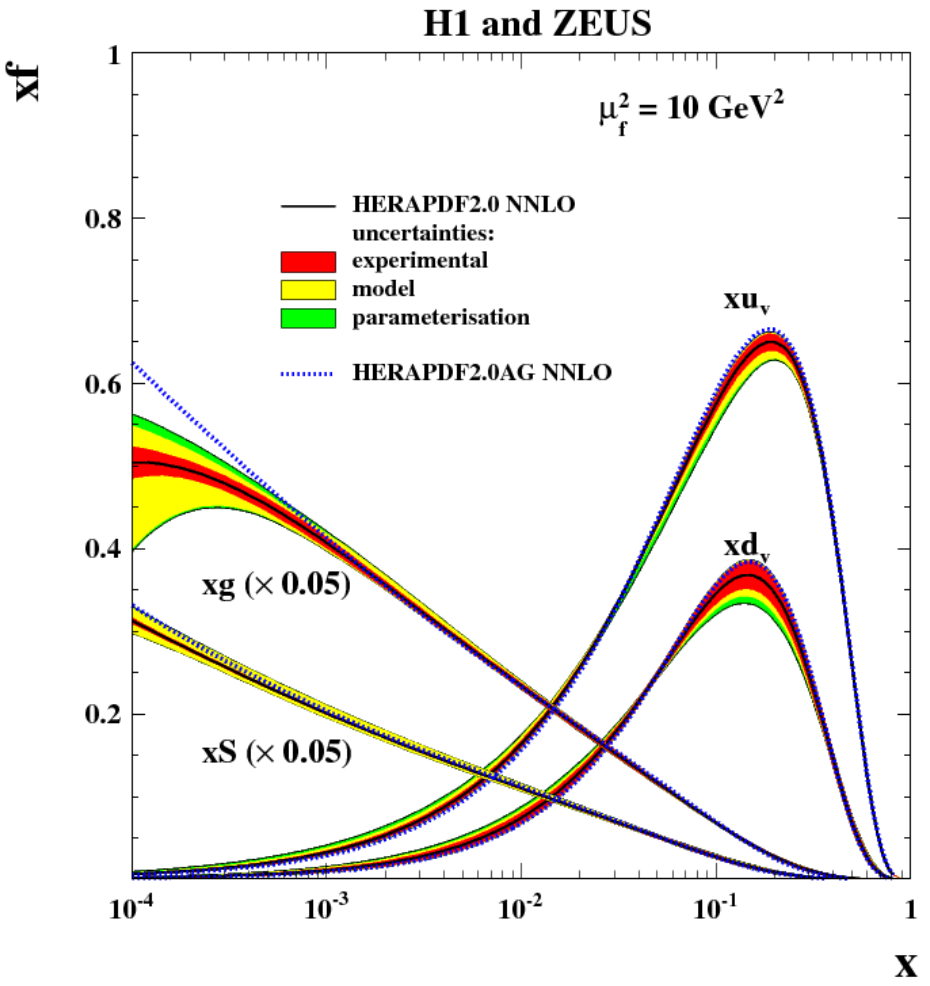


Reasonable description of NC, CC and low energy data for NLO and NNLO

NLO



NNLO



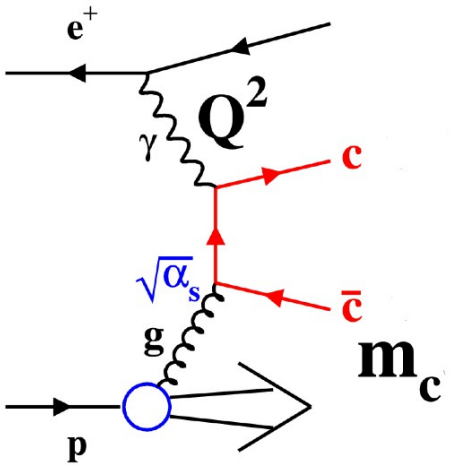
HERAPDF2.0 extracted

with experimental, model and parametrization uncertainties

Adding more HERA data

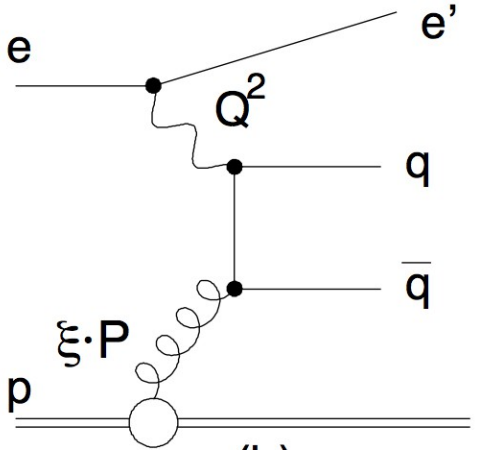
Charm and jet data from HERA

Charm production

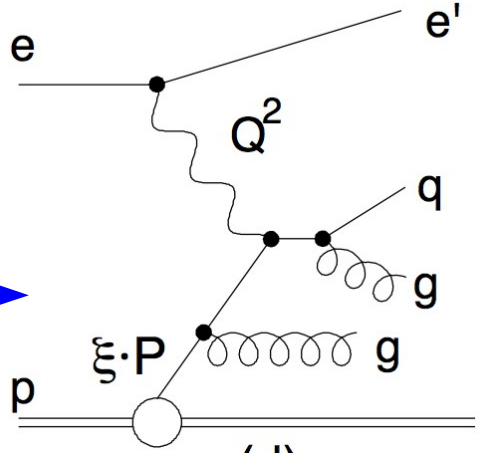


Boson-Gluon Fusion

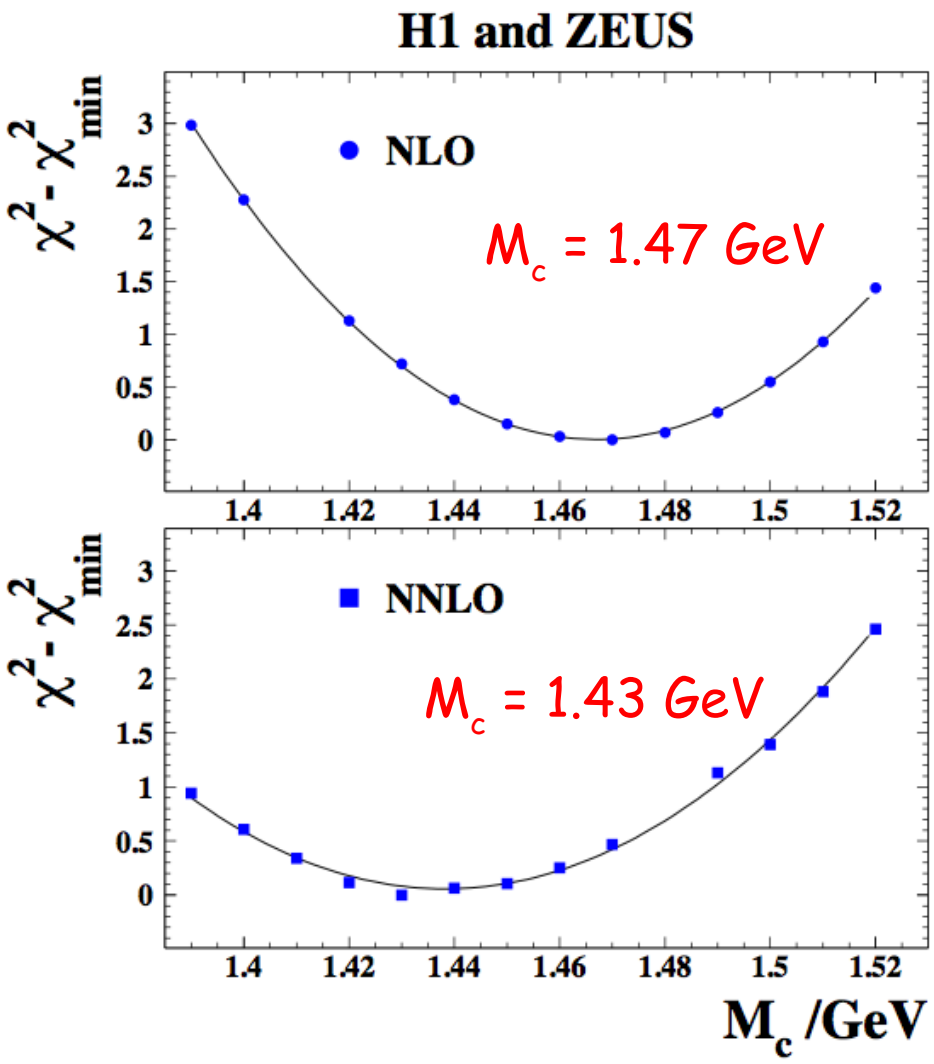
Jet production

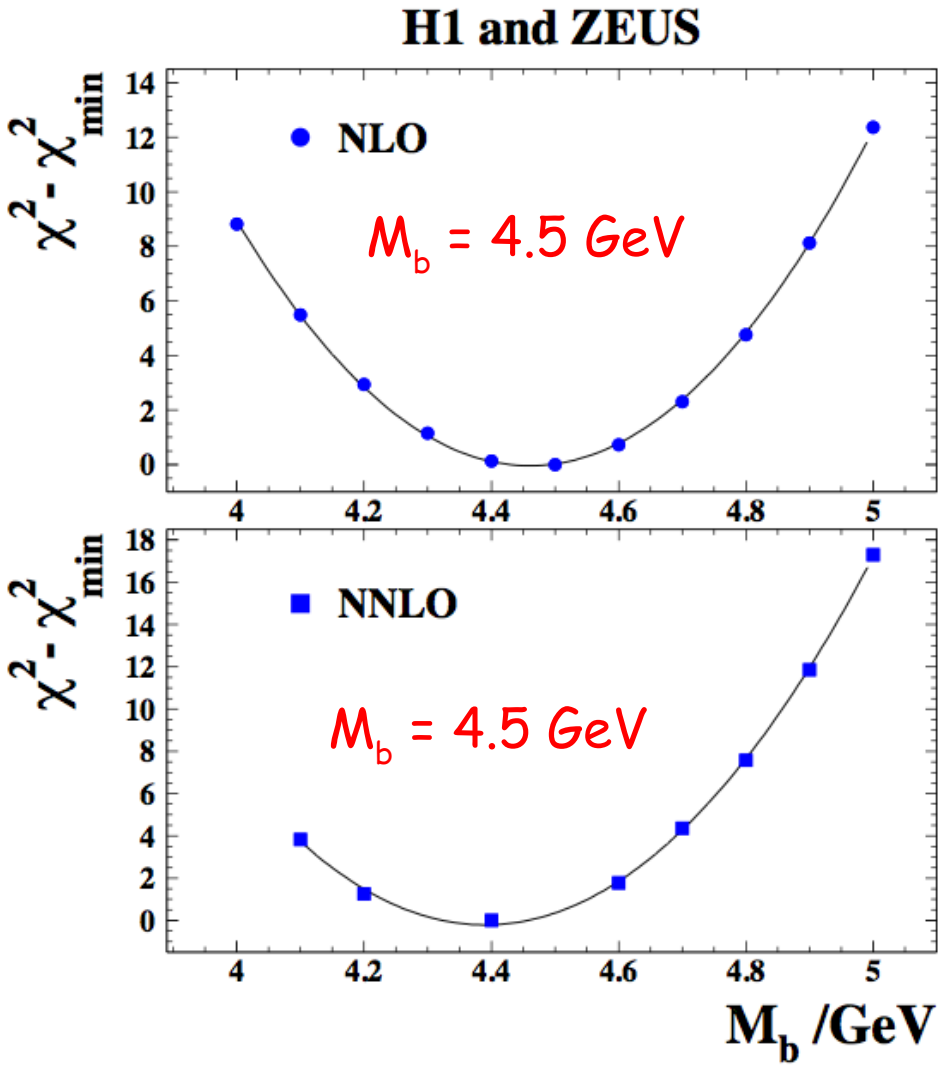


- Charm and jet data sensitive to gluon/α_s
  - @ high Q^2 up to 30-40% of charm
- Trijets most sensitive to α_s



Estimation of beauty and charm mass parameters

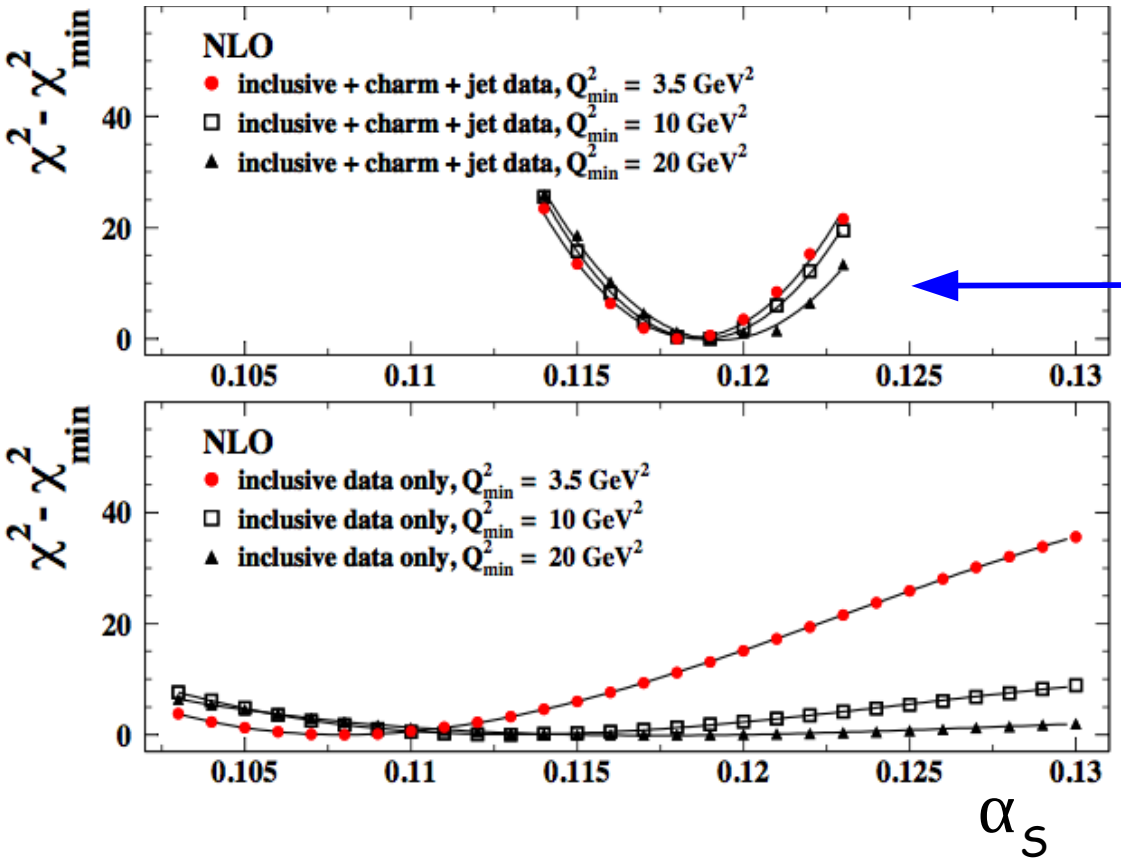




→ M_c/M_b determined from inclusive data + charm/beauty data

Method comes from the HERA charm combination (Eur. Phys. J. C73 (2013) 2311)

Including HERA jets in QCD global fits



- HERA multi-jet data added to see sensitivity to gluon/α_s
- Validated choice of α_s = 0.118
- Now let's use these data and fit α_s together with PDFs

α_s determined from QCD fit -> Experimental uncertainty below 1%

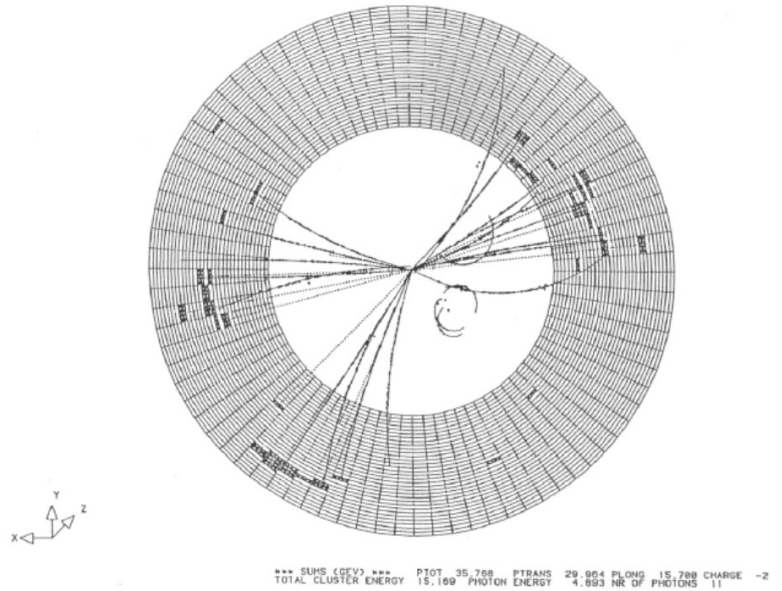
$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp}) \pm 0.0005(\text{model/parameterisation})$$
$$\pm 0.0012(\text{hadronisation}) \; {}^{+0.0037}_{-0.0030}(\text{scale})$$

Uncertainty dominated by theory → NNLO ep jet calculations needed

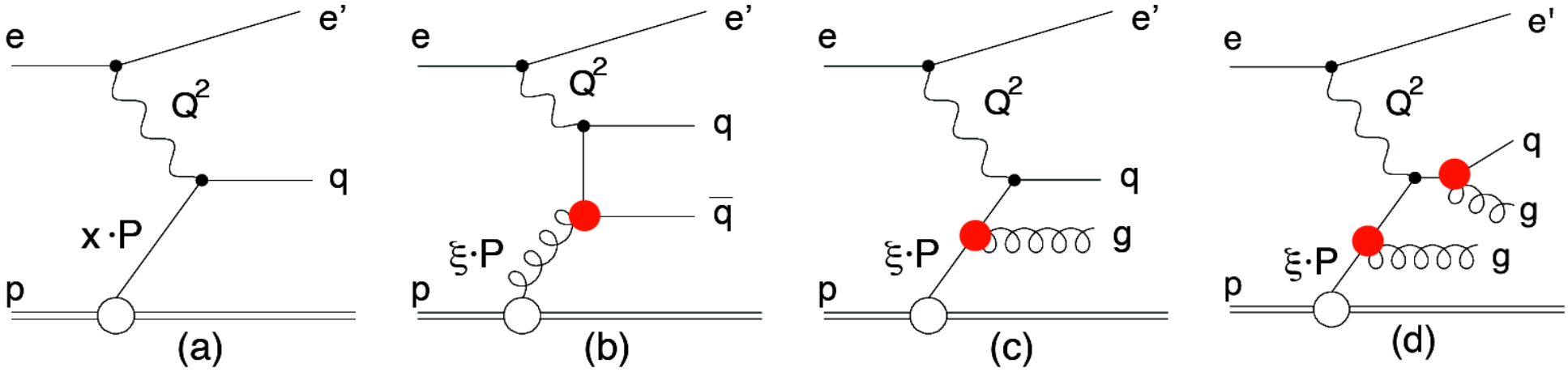
Jet production @HERA

Jets at PETRA, 1979

- Direct information on gluon distribution comes from jet production
- Possible simultaneous determination of parton densities and α_s



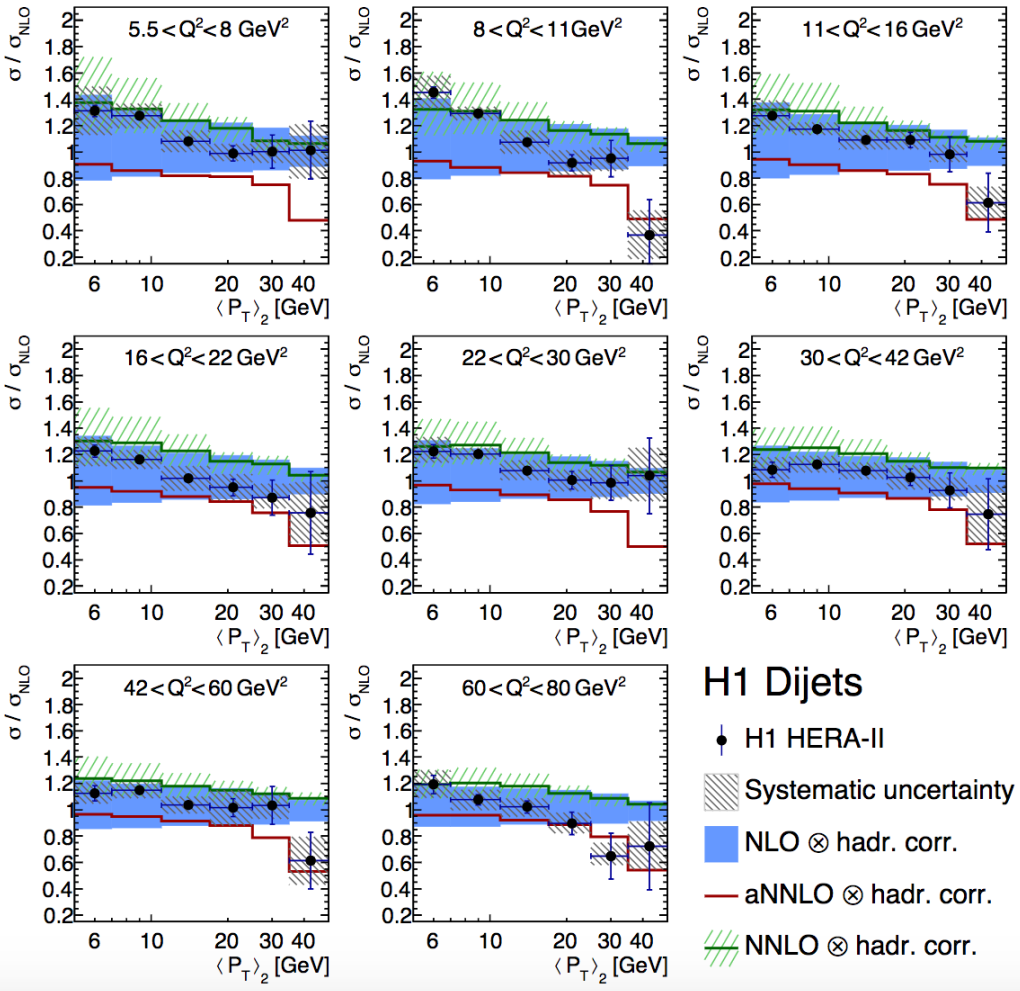
- Jets at HERA



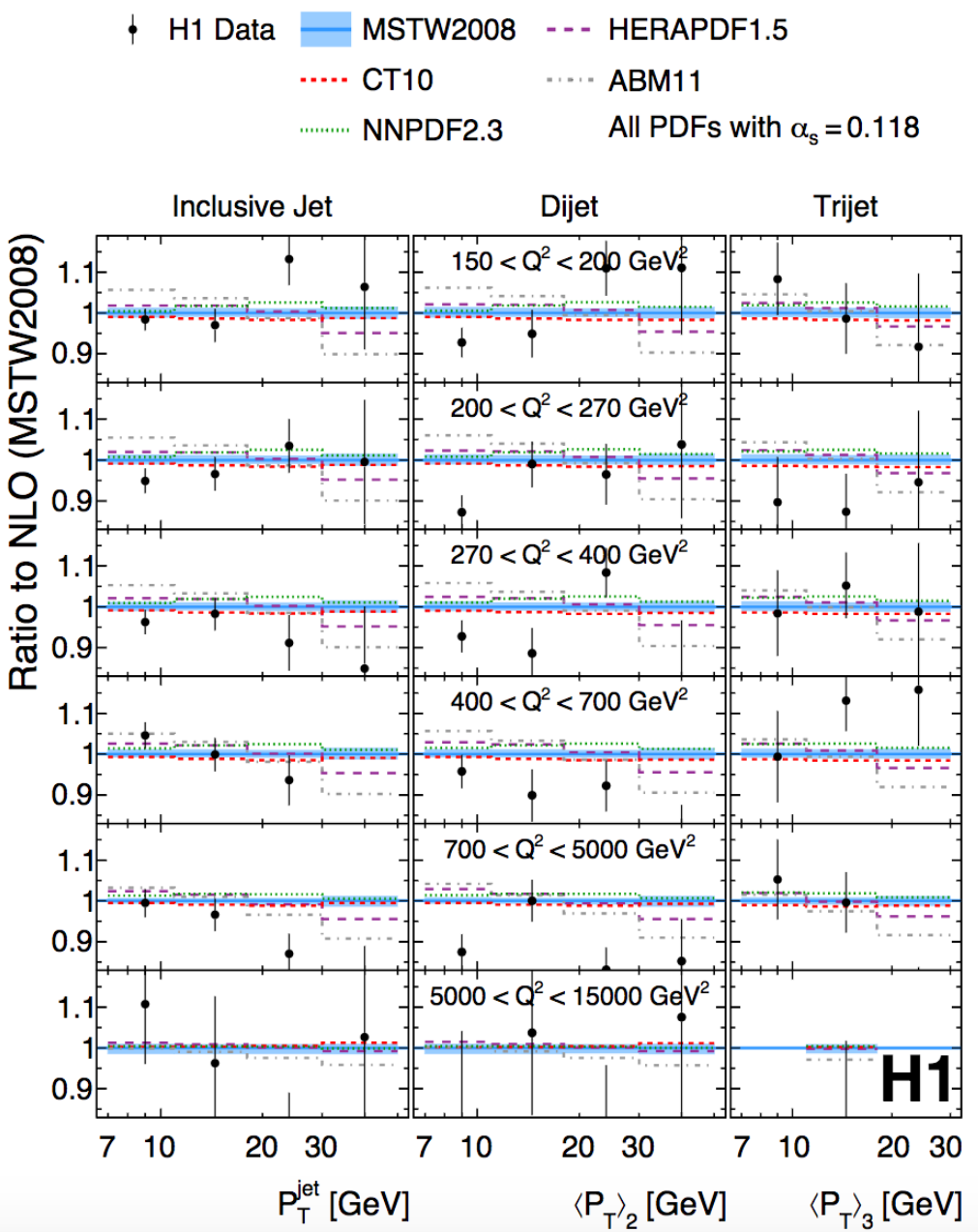
elweak coupling $\propto \alpha_S$ $\propto \alpha_S$ $\propto \alpha_S^2$

dijets trijets

Multi-jets from Q^2 of 5.5 to 15000GeV^2



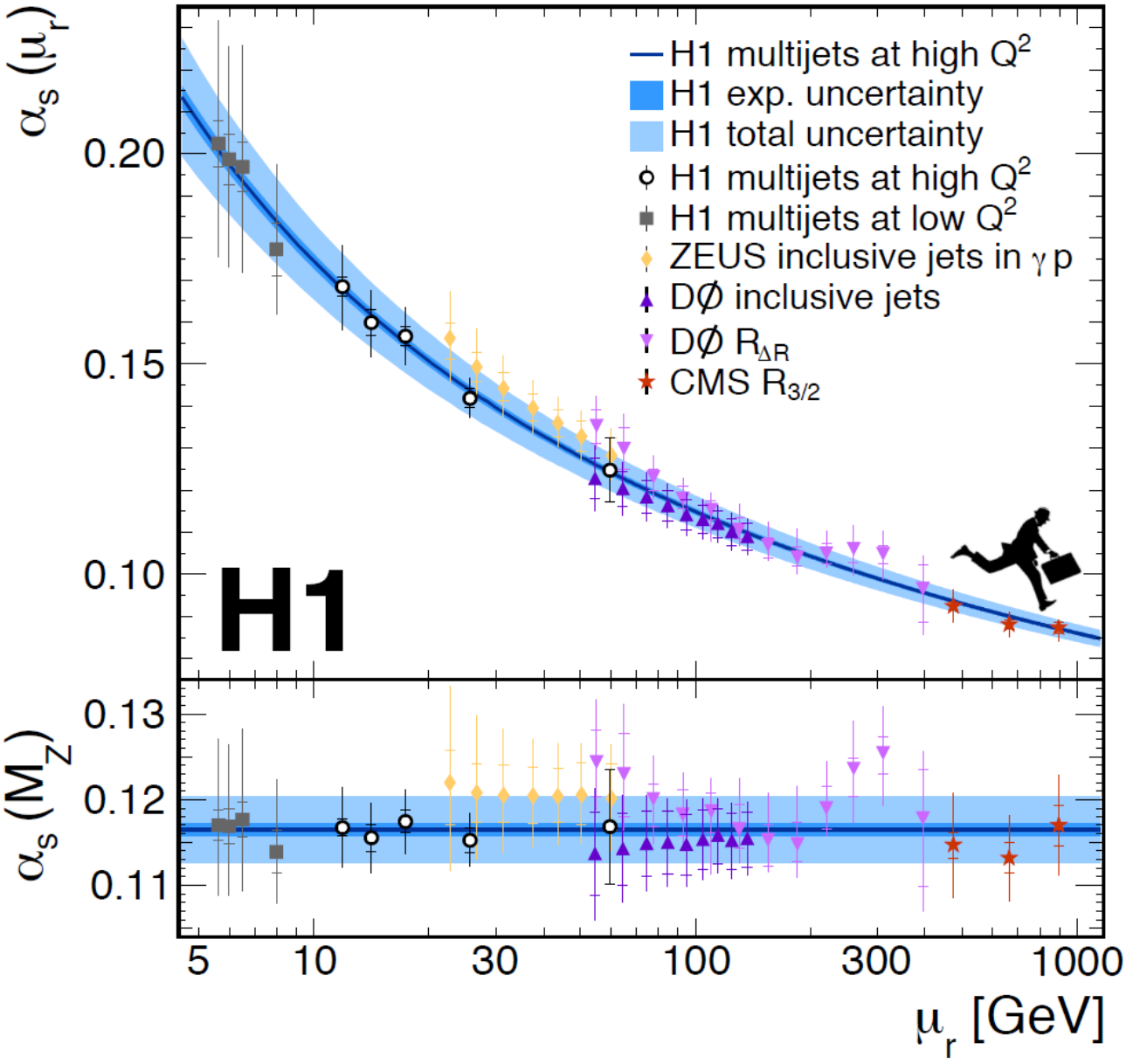
Eur.Phys.J.C77 (2017) 4, 215



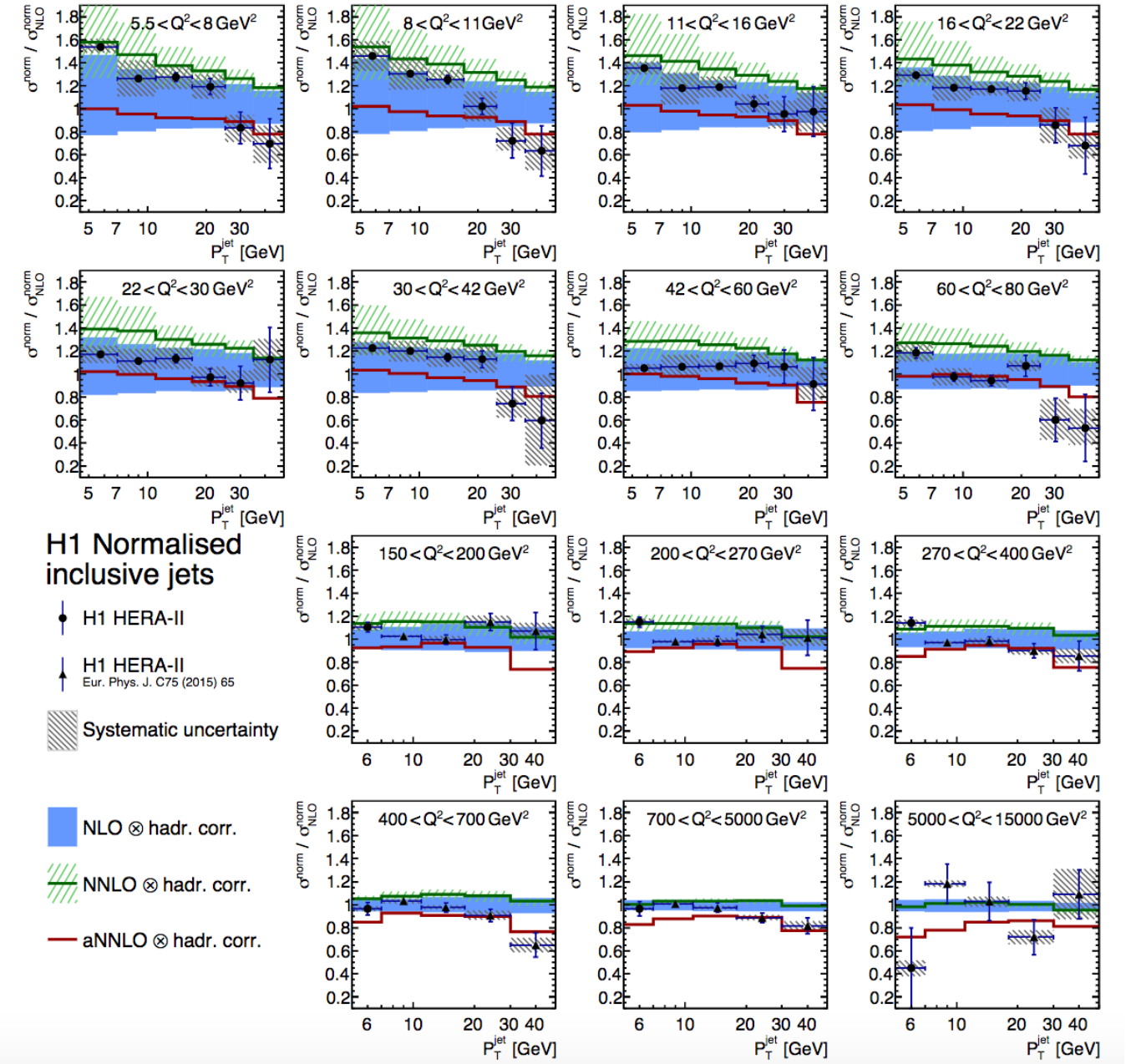
Eur.Phys.J.C75 (2015) 2, 65

α_s running from jet measurements @ NLO

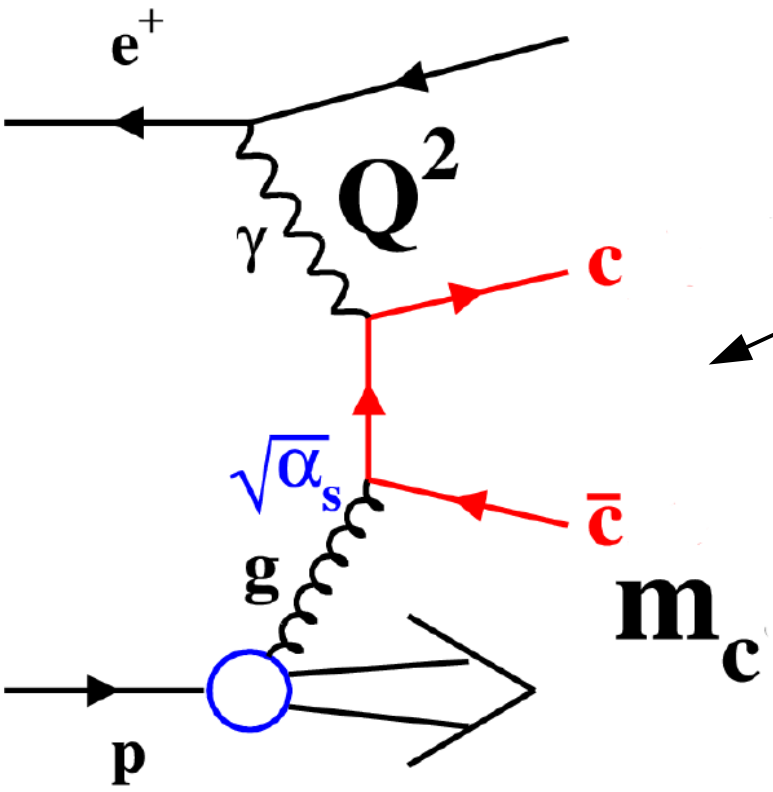
$$\alpha_s(M_Z) = 0.1172\,(4)_{\mathrm{exp}}\,(3)_{\mathrm{PDF}}\,(7)_{\mathrm{PDF}(\alpha_s)}\,(11)_{\mathrm{PDFset}}\,(6)_{\mathrm{had}}\,\left(^{+51}_{-43}\right)_{\mathrm{scale}}$$



Very exciting results → NNLO calculation for DIS jets available now for inclusive and di-jets

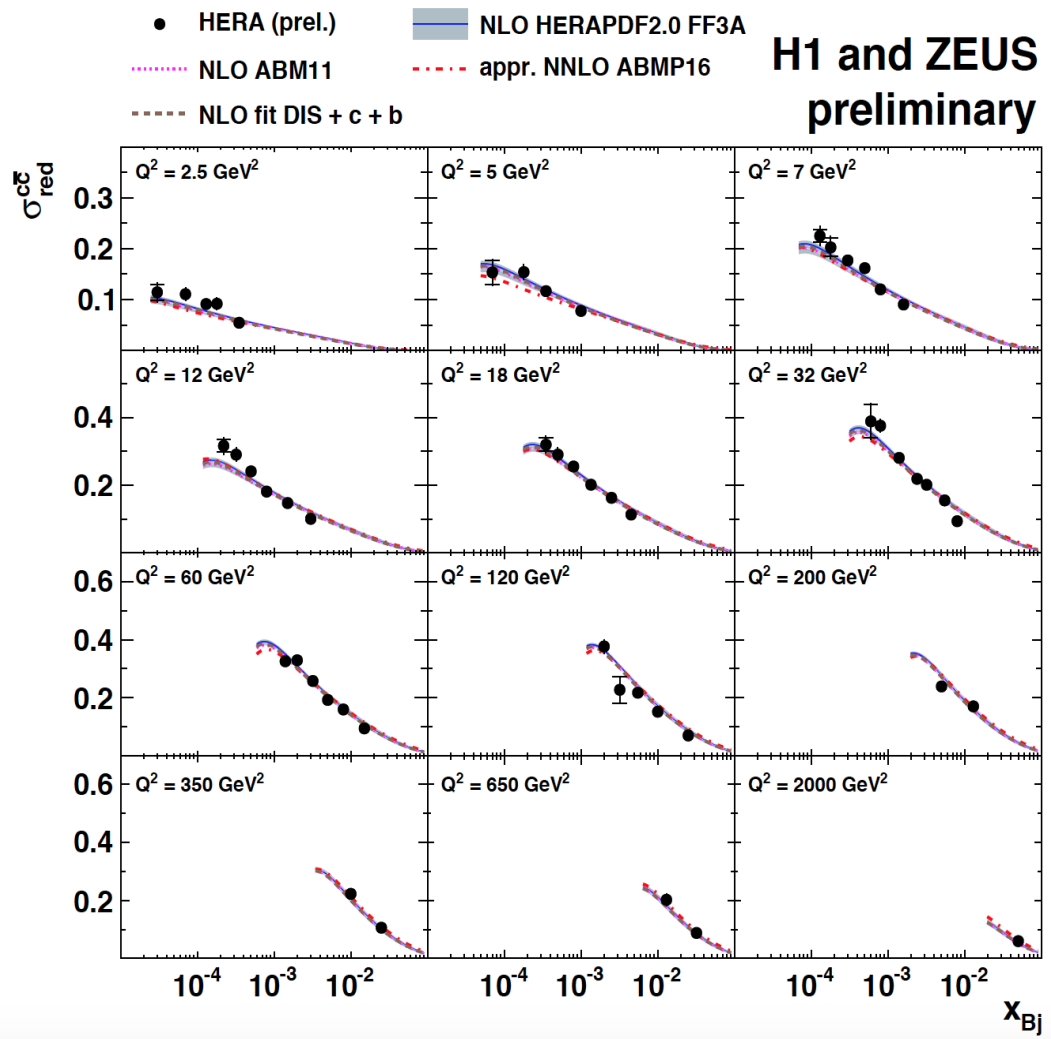


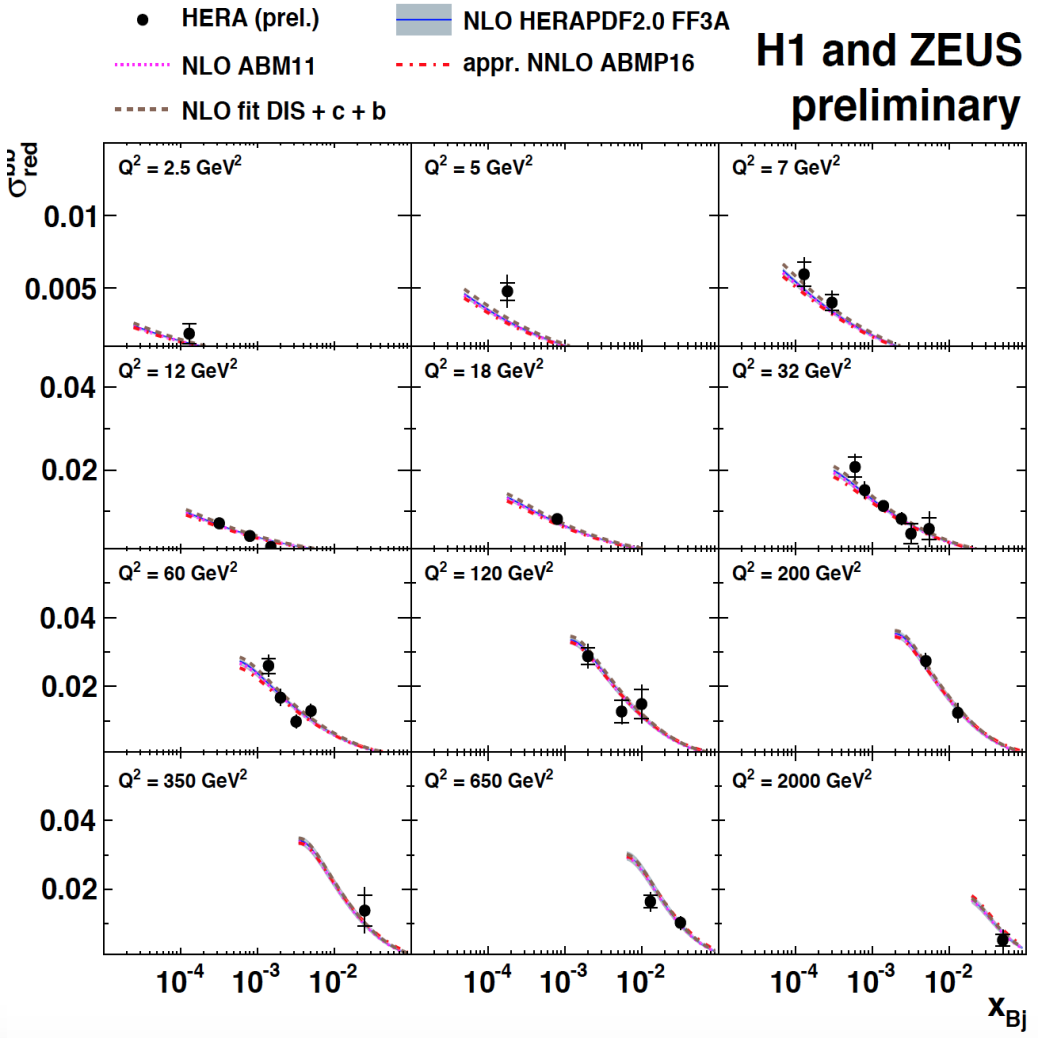
Heavy quark production @ HERA



- Heavy quarks @ HERA mostly produced in Boson-Gluon Fusion
- Heavy flavor structure functions
  - Sensitive to gluon parton densities
- Heavy-quark production most useful to
  - distinguish between different calculations for heavy quark production
  - fix values of the heavy quark mass parameters

Charm & beauty cross sections

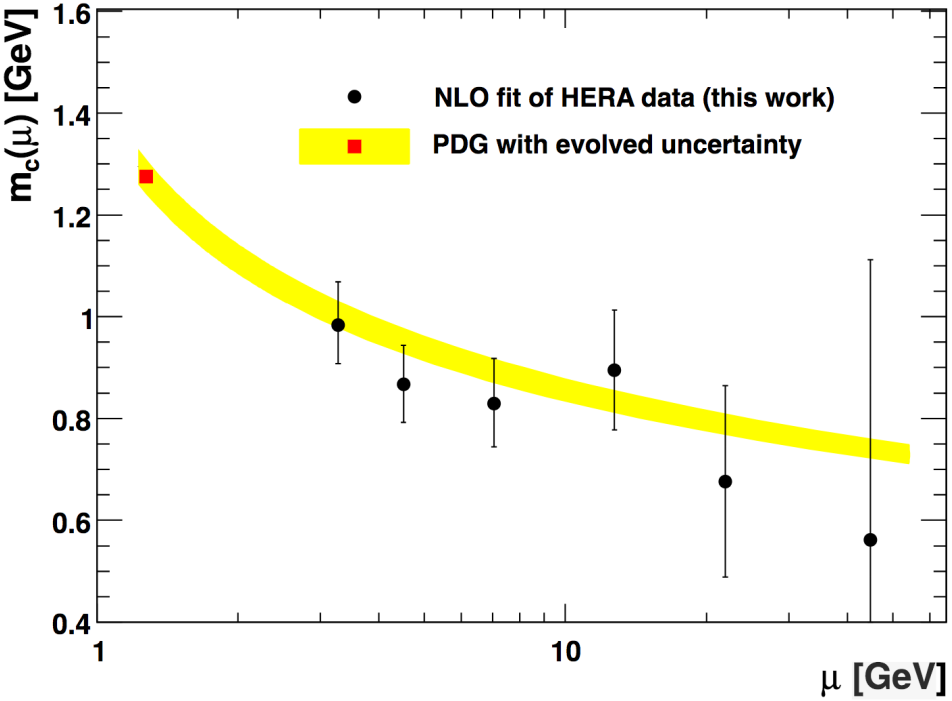


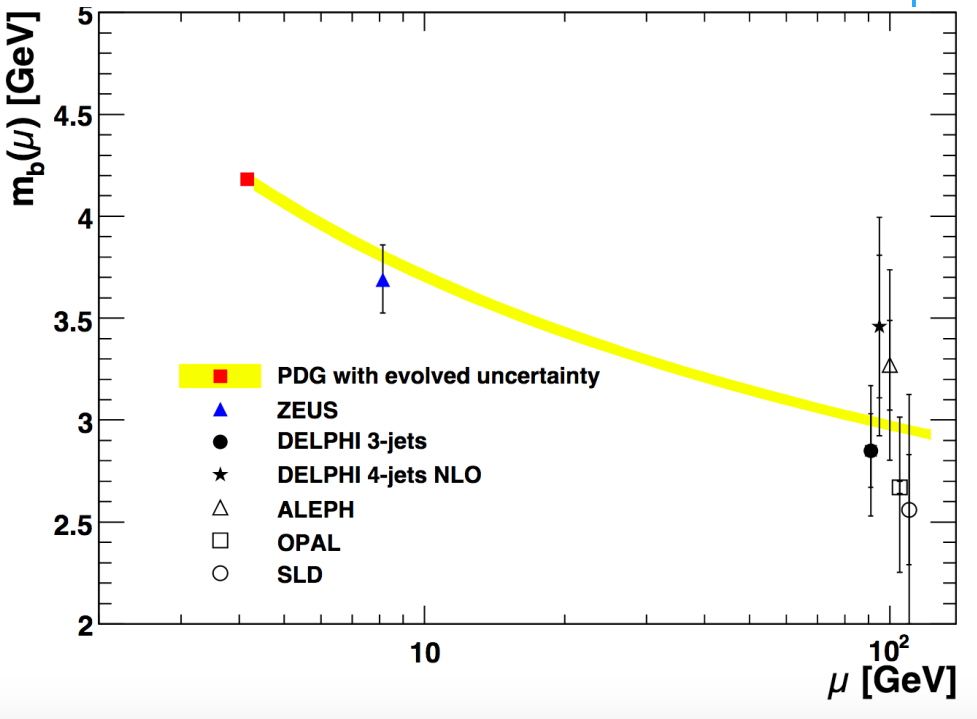


Measurements in good agreement with predictions

Charm & beauty mass running

arXiv:1705.08863

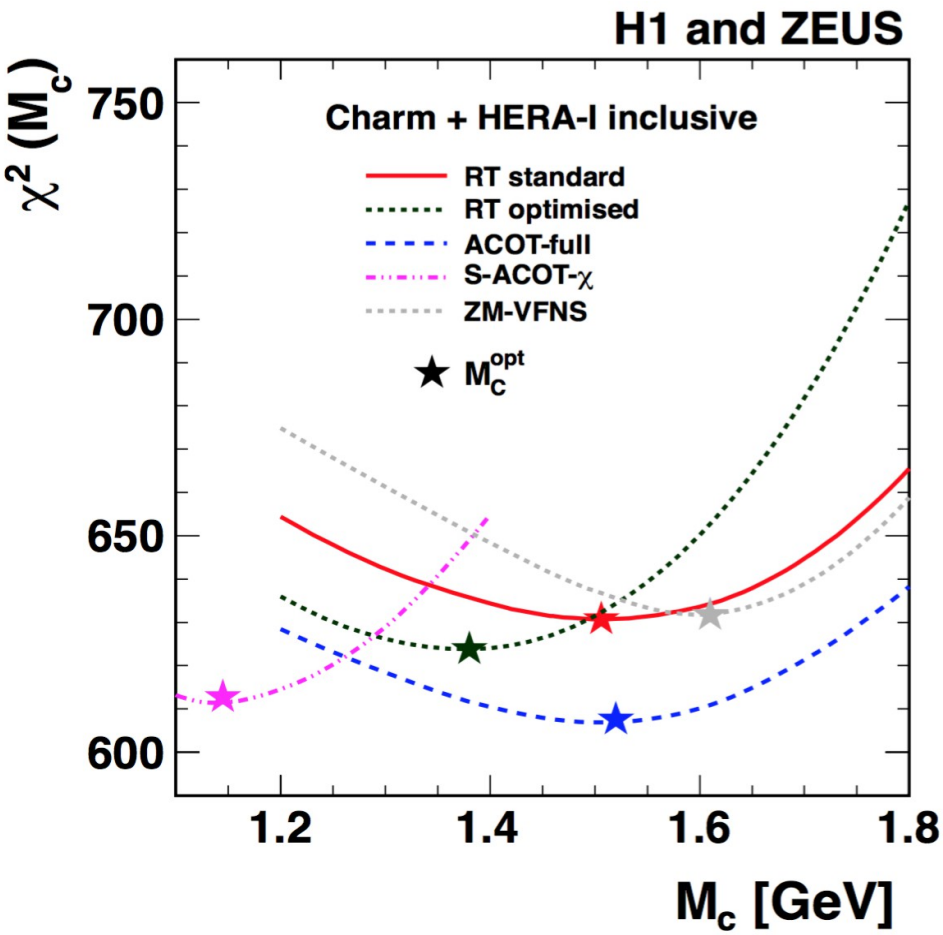


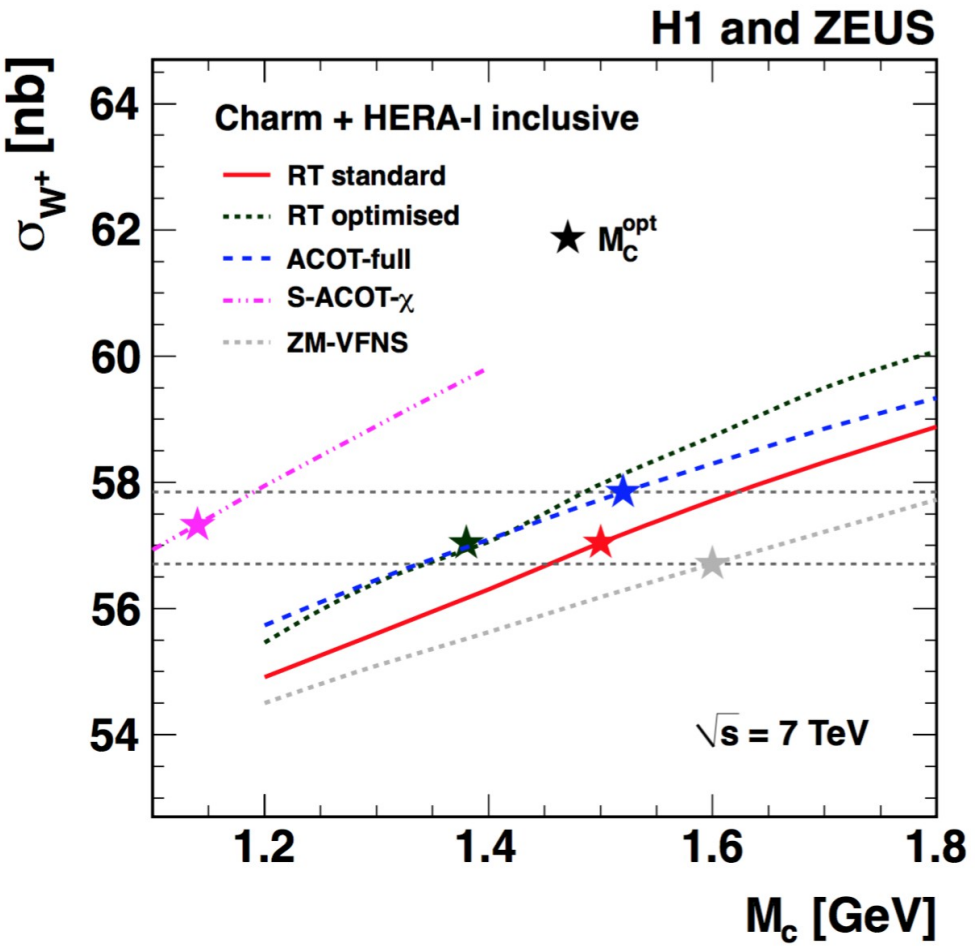


Heavy quark masses run in agreement with pQCD

Optimal charm value

Eur.Phys.J.C73 (2013) 2311



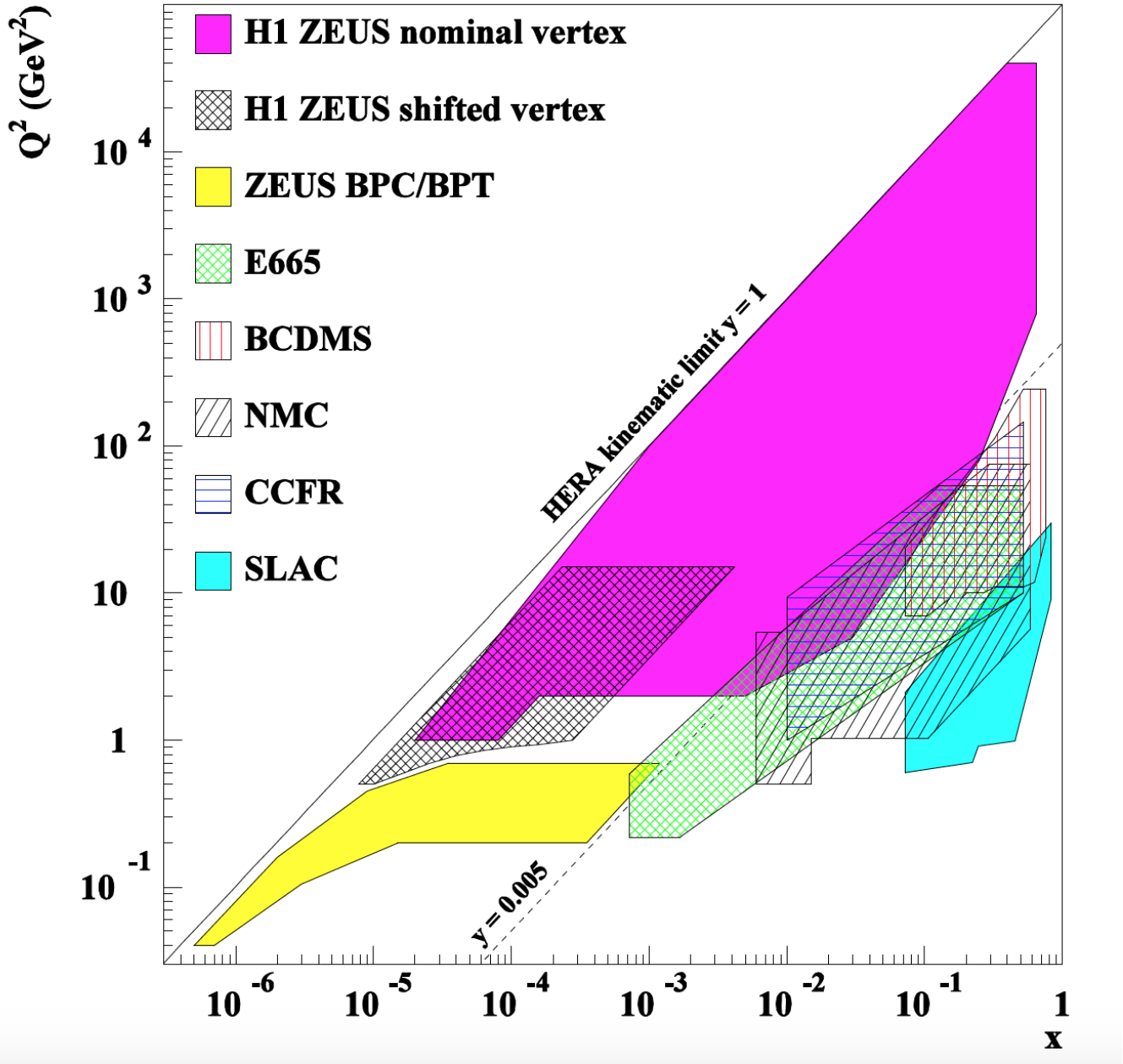


- M_c optained in global QCD fit
- different optimal effective masses for different VFNS schemes
- very similar fit quality

- Various PDFs use different schemes
- Using optimal mass parameter for each scheme reduces spread between predictions to <1%

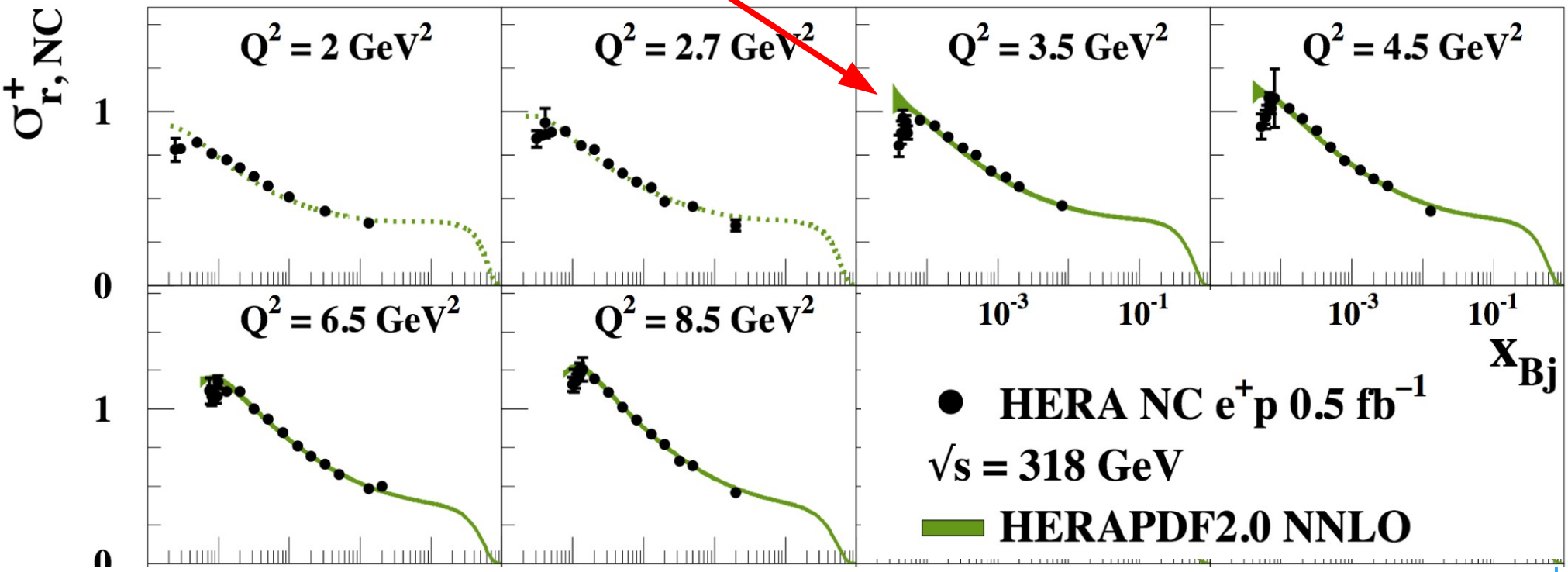
Let's go back to low-Q^2 region

@ HERA low $Q^2 \rightarrow$ low x

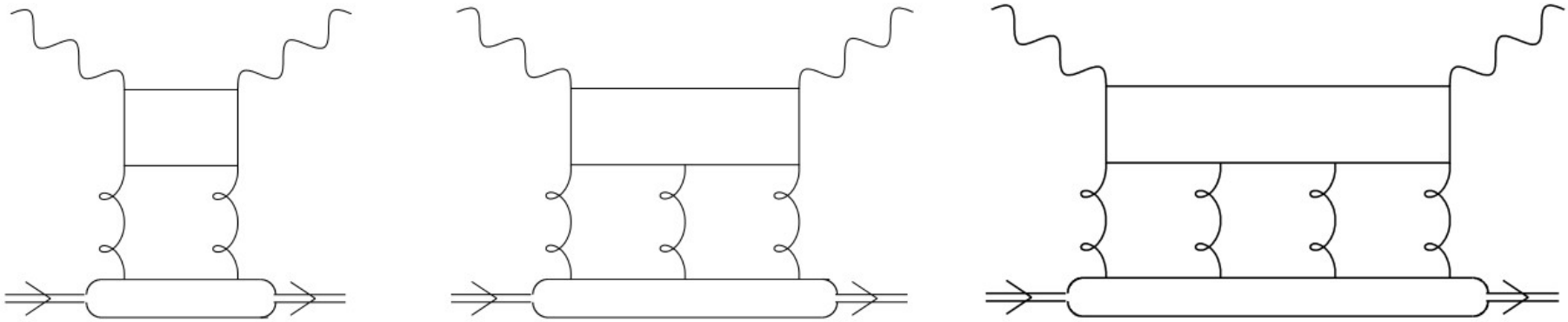


HERAPDF2.0 @ low Q^2 and low x

- Let's see how HERA low Q^2, low x data are described by predictions
  - Not that great...
  - Especially turn-over seen in data at low Q^2 and low x not described by predictions



Higher-twist corrections using HERAPDF2.0 approach



- higher twist terms acting at low-x considered
- their origin COULD be connected with the recombination of gluon ladders
- Bartels, Golec-Biernat, Peters suggested that such higher twist terms would cancel between σ_L and σ_T in F_2, but remain strong in F_L
- simplest possible modification to structure functions F_2 and F_L as calculated from HERAPDF2.0 formalism tried

$$F_2^{\mathrm{HT}} = F_2^{\mathrm{DGLAP}} \left(1 + A_2^{\mathrm{HT}}/Q^2\right)$$ has almost no effect

$$F_{\mathrm{L}}^{\mathrm{HT}} = F_{\mathrm{L}}^{\mathrm{DGLAP}} \left(1 + A_{\mathrm{L}}^{\mathrm{HT}}/Q^2\right)$$ helps a lot, A ~4-5 for (N)NLO

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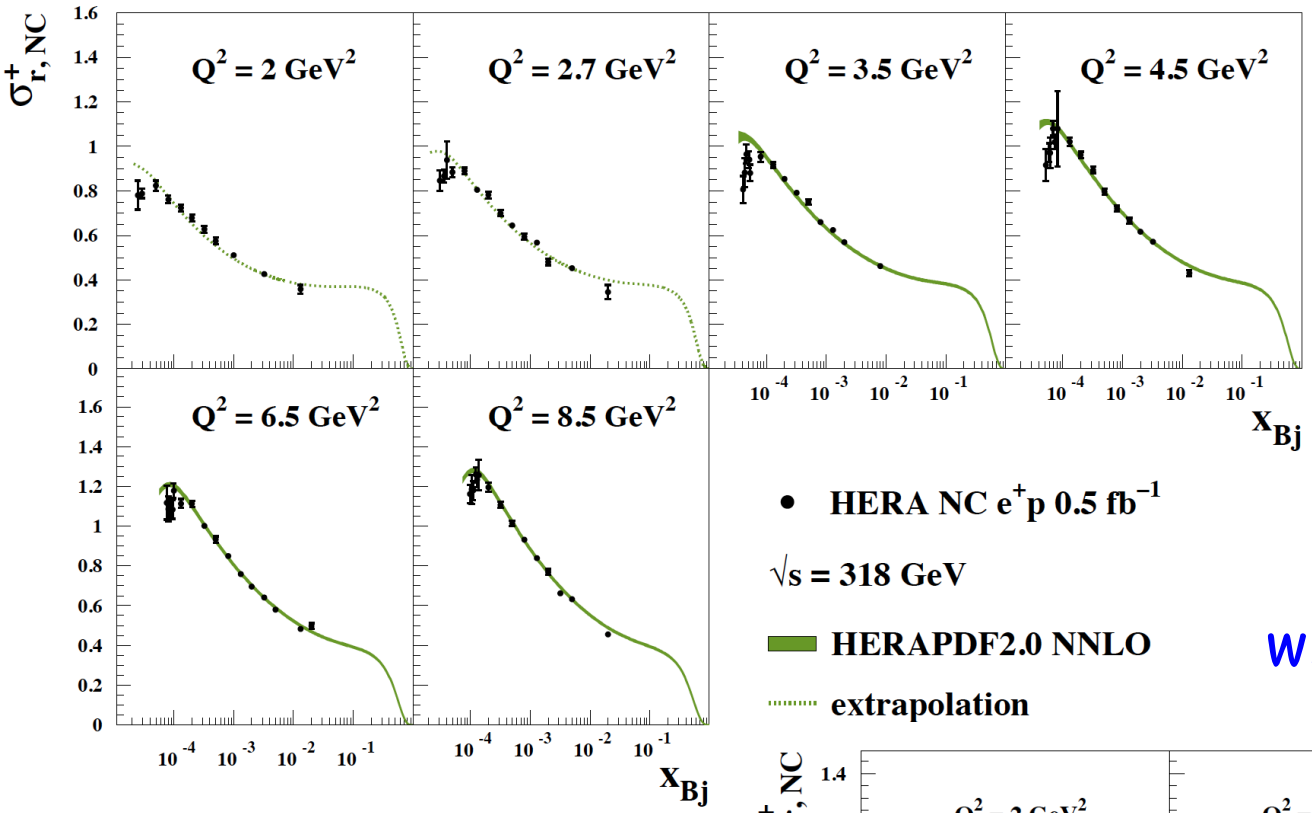


- HERA NC e^+p 0.5 fb^{-1}

$\sqrt{s}$ = 318 GeV

HERAPDF2.0 NNLO

extrapolation

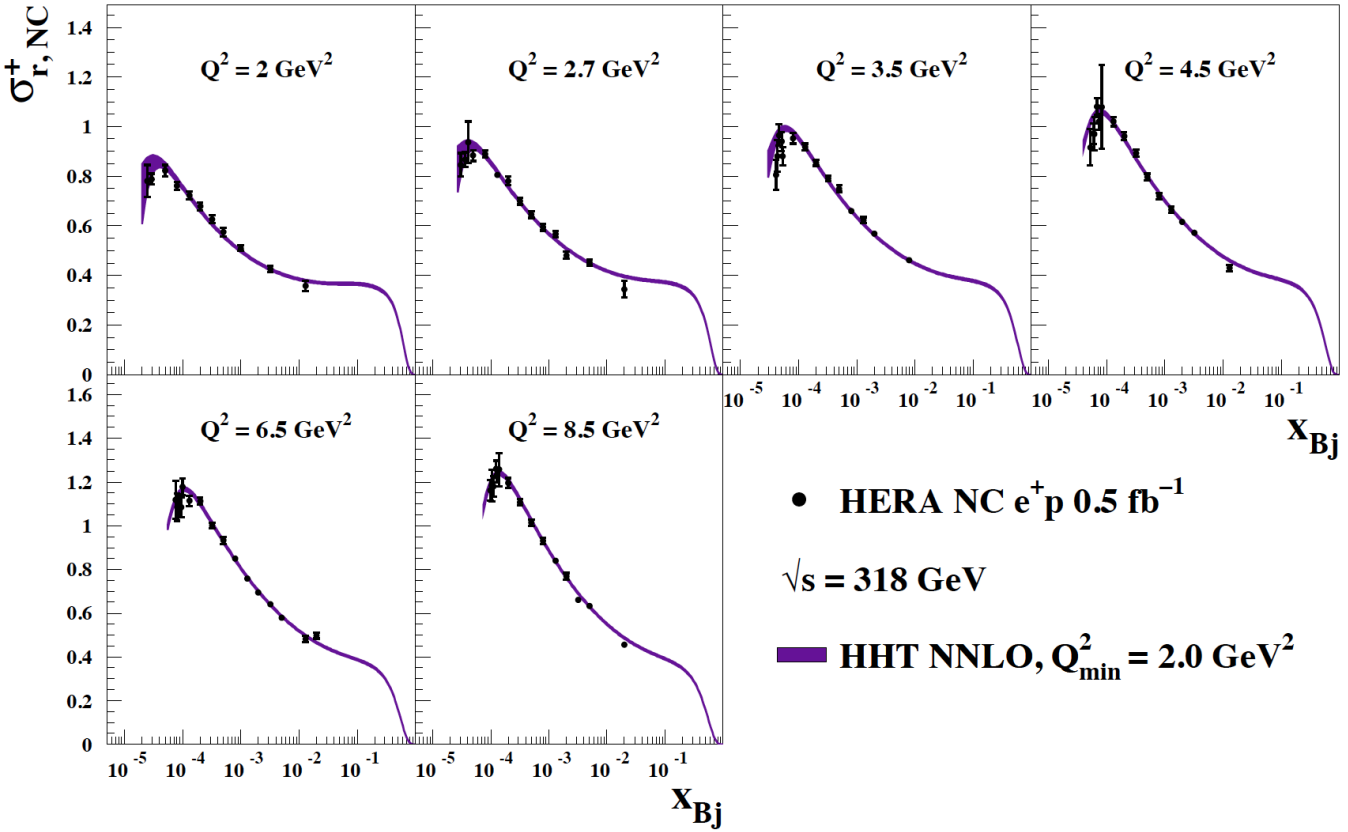
- Low-Q^2 data description is excellent down to Q^2 = 2 GeV^2

why HHT fits do so well?

- HHT describes turn-over slope better

$$\sigma_{red} = F_2 - y^2/Y_+ F_L$$

- data clearly wants larger F_L
  - this is what higher twist term provides

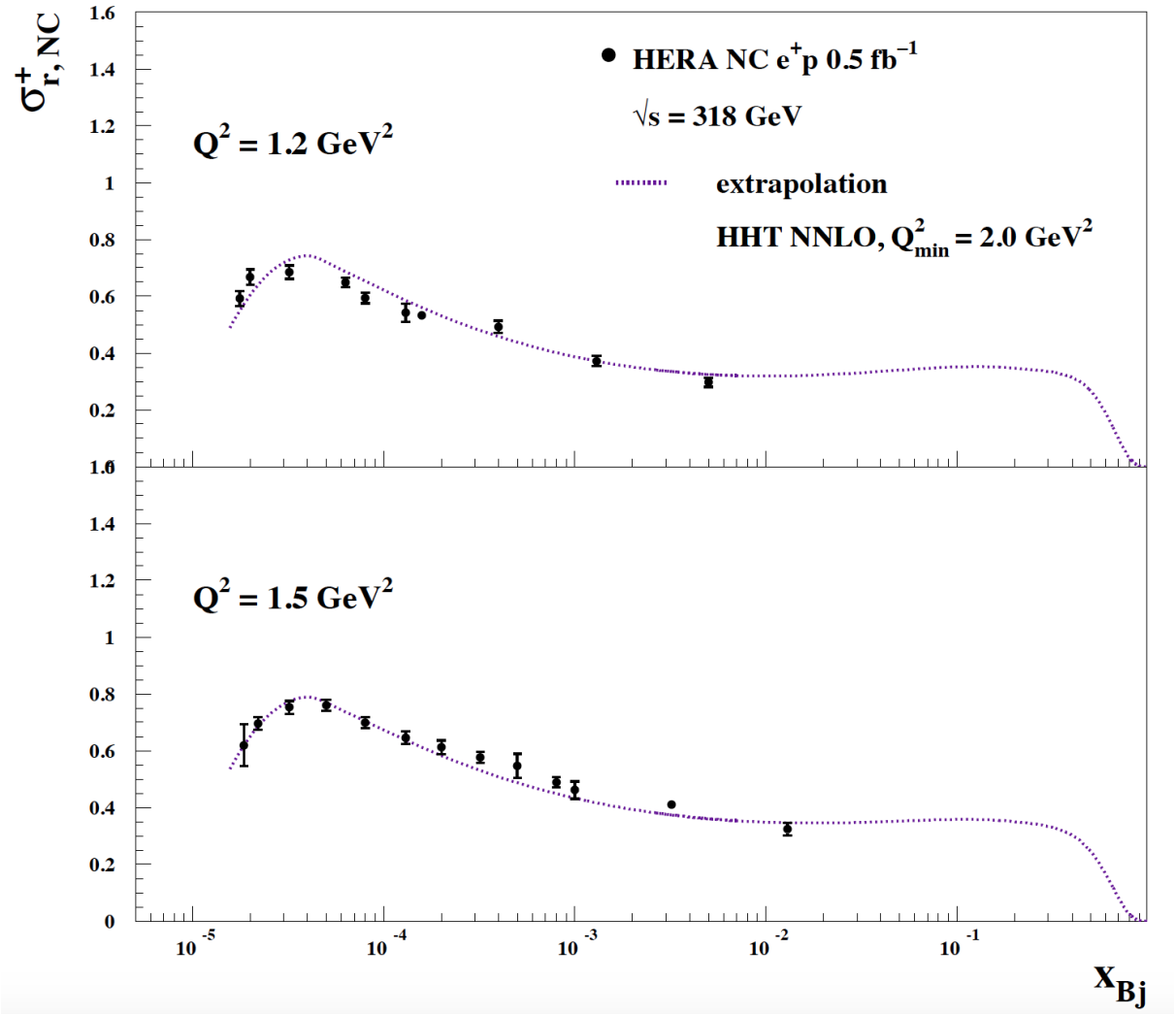


- HERA NC e^+p 0.5 fb^{-1}

$\sqrt{s}$ = 318 GeV

HHT NNLO, Q^2_{min} = 2.0 GeV^2

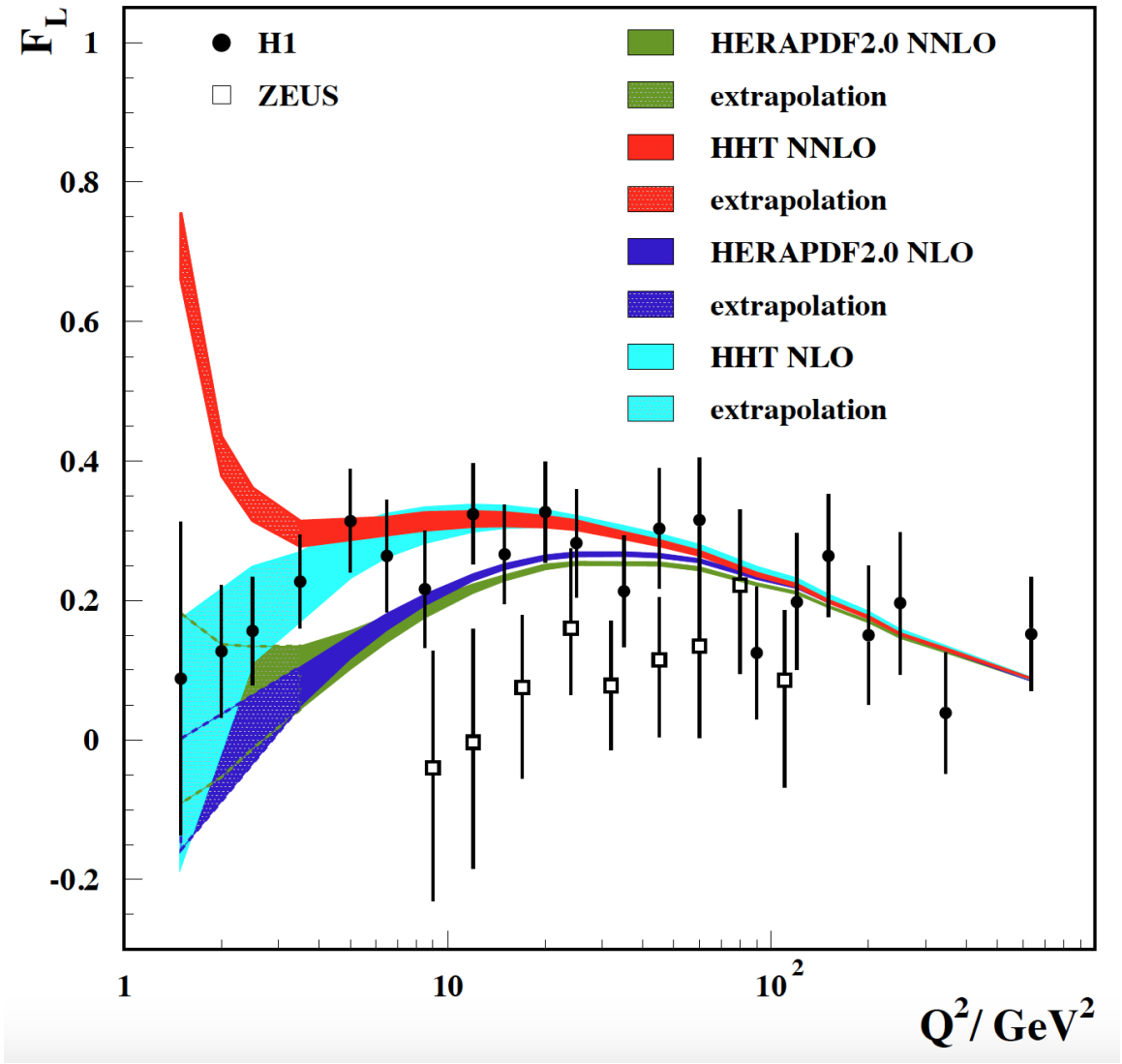
Extrapolation down to $Q^2 \sim 1$ GeV^2



But beware… is this actually reasonable?

What does F_L itself look like?

F_L measurements & predictions

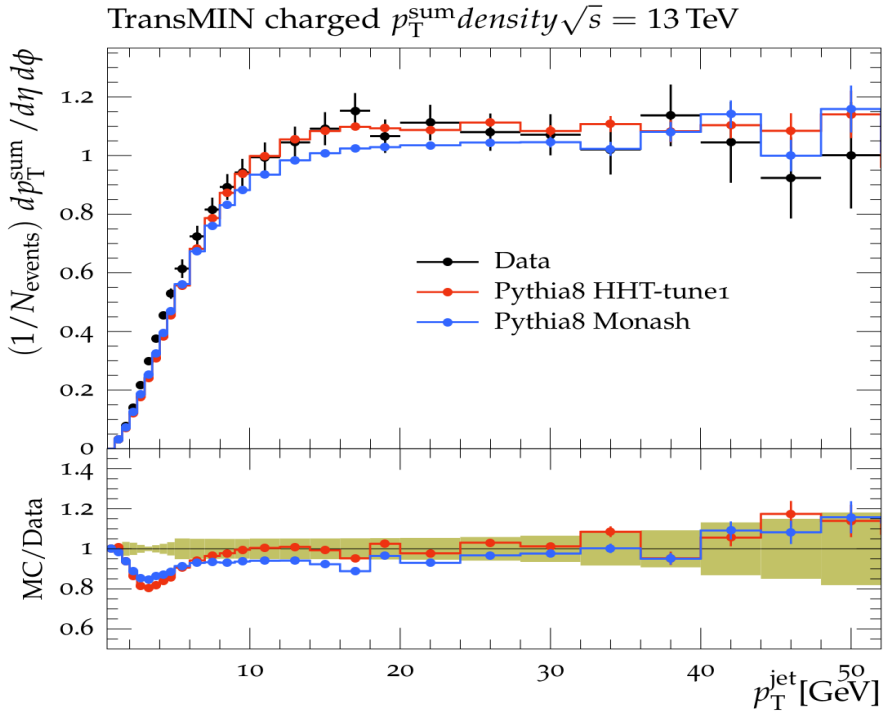


- NNLO HHT FL prediction untamed at low Q^2
- this approach cannot be pushed too far
- this comes from NNLO coeff. functions and the $1/Q^2$ term makes it worse

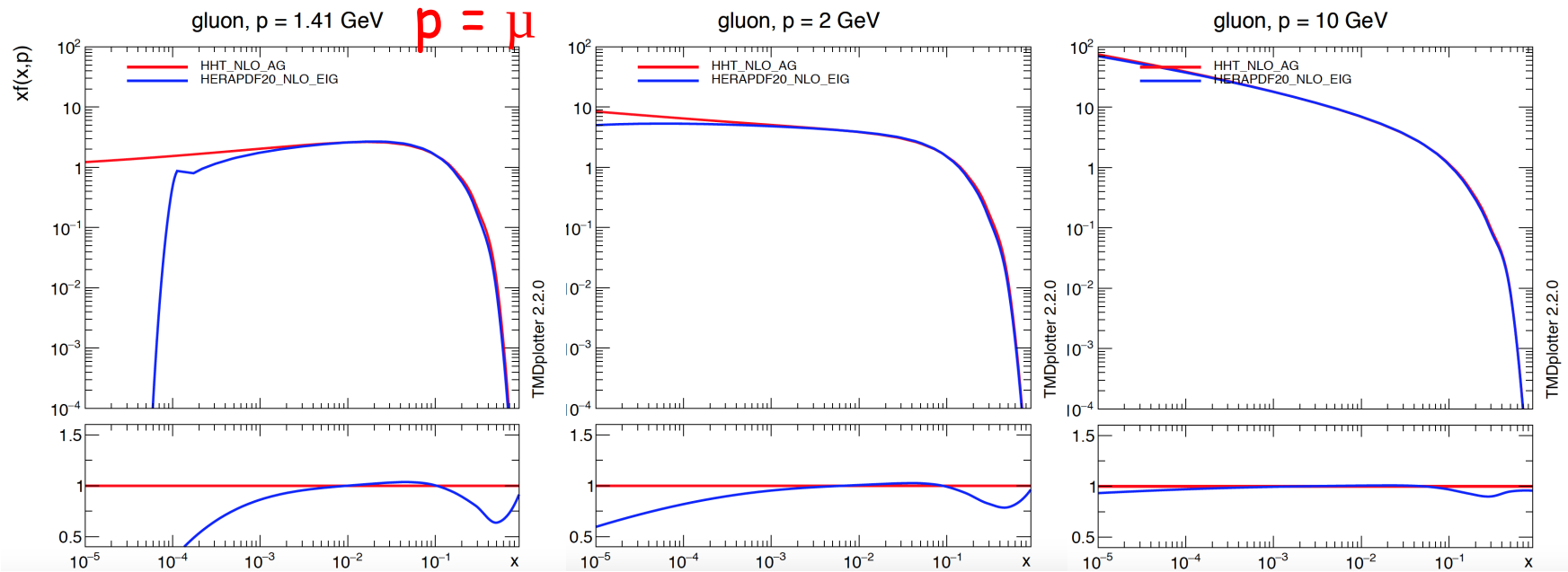
Started to be used in MC tuning: underlying event

- Interest in MC community for PDF describing data well down to lowest possible Q^2: HHT NLO
  - First use: tune for underlying event, private work in CMS

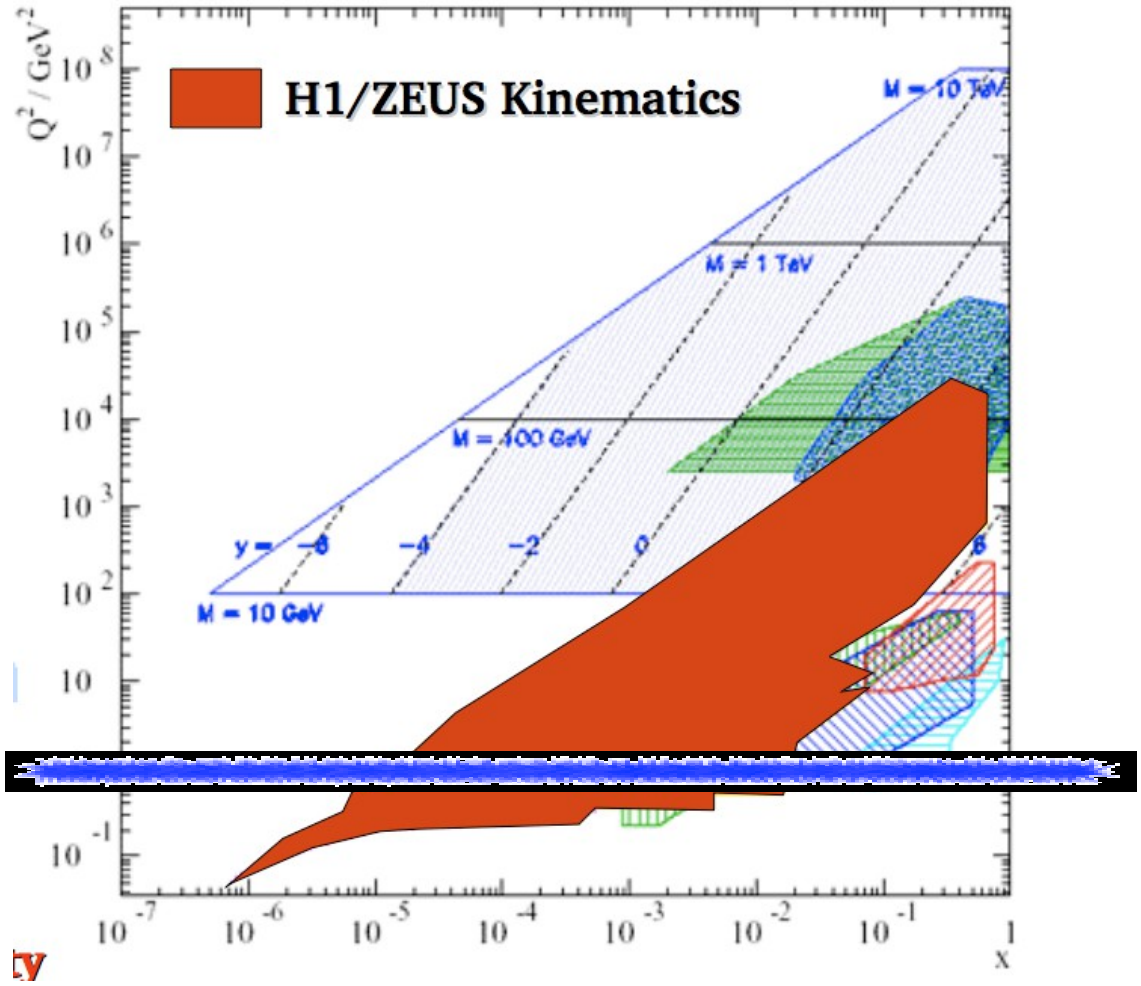
P. Gunnellini, private communication



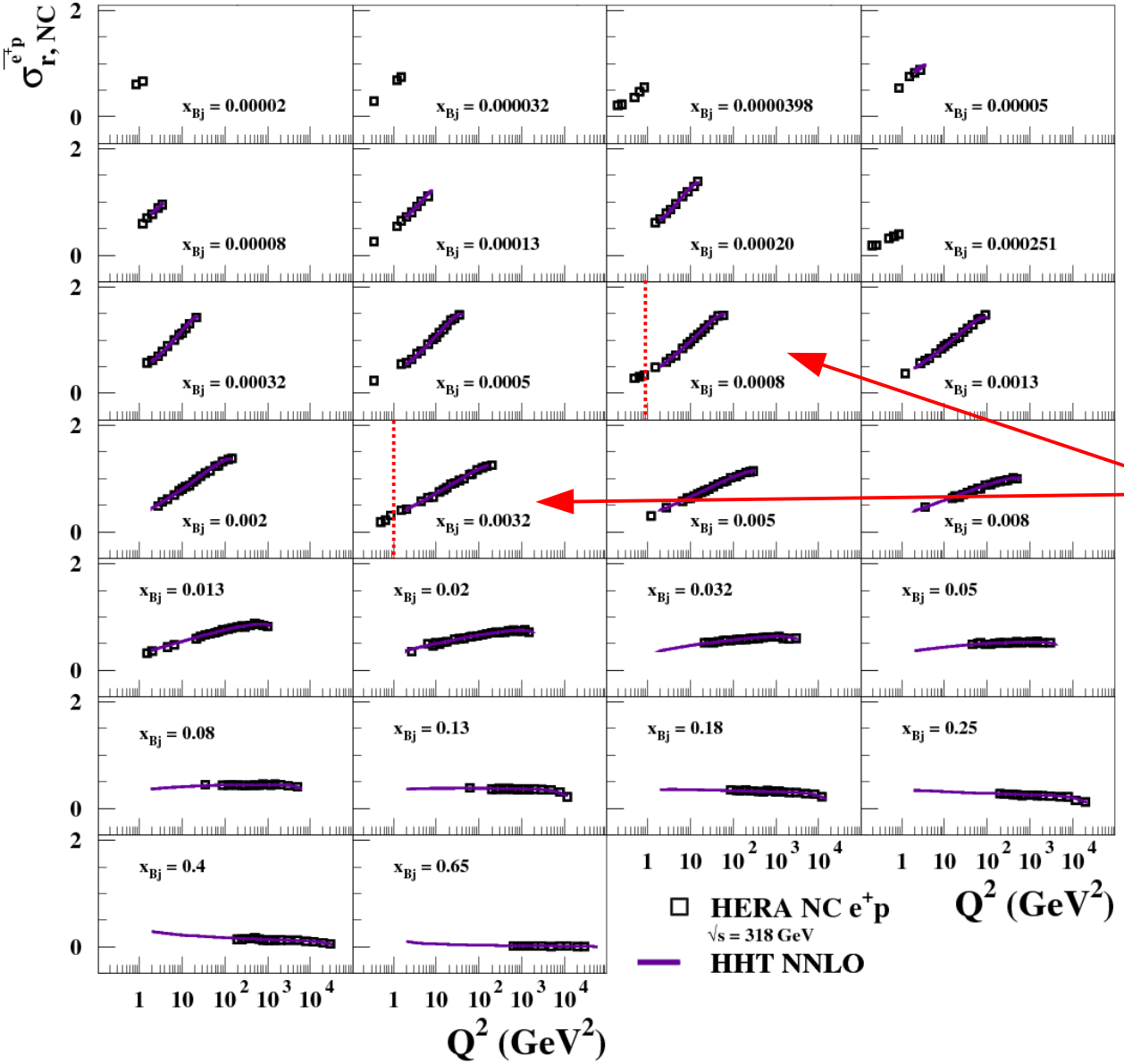
H. Jung



Let's go now to even lower Q^2: transition region



Reduced cross sections



- Scaling violations well established

→ good description by pQCD

- No dramatic change observed around transition point ~ 1 GeV^2

Nature seems not to know about perturbation theory

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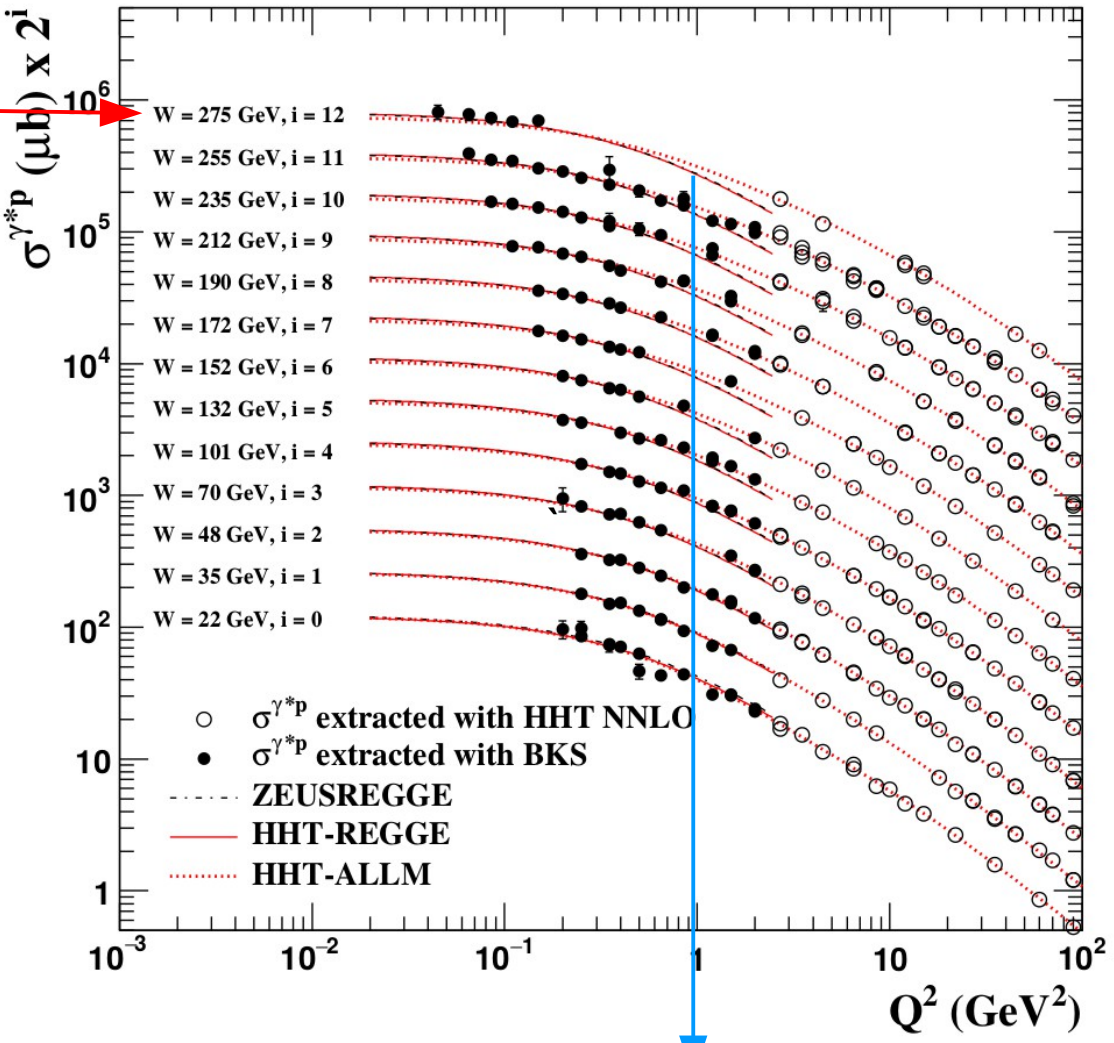
Transition region

$$W^2 = Q^2(1/x_{\mathrm{Bj}} - 1) + m_p^2$$

Square of photon-proton center-of-mass energy

- cross section for virtual photon exchange, $\sigma^{\gamma^* p}$
  - From very low to very high Q^2 → possibility to look at transition region between hard and soft QCD – expected somewhere around 1 GeV^2
  - Can we actually see this transition in the data?
  - … not really, smooth transition



smooth transition region between hard and soft: ~1 GeV^2

ALLM parameterisation

@ $Q^2 \sim 0$ GeV^2 : photopoduction
Photon considered a hadronic object

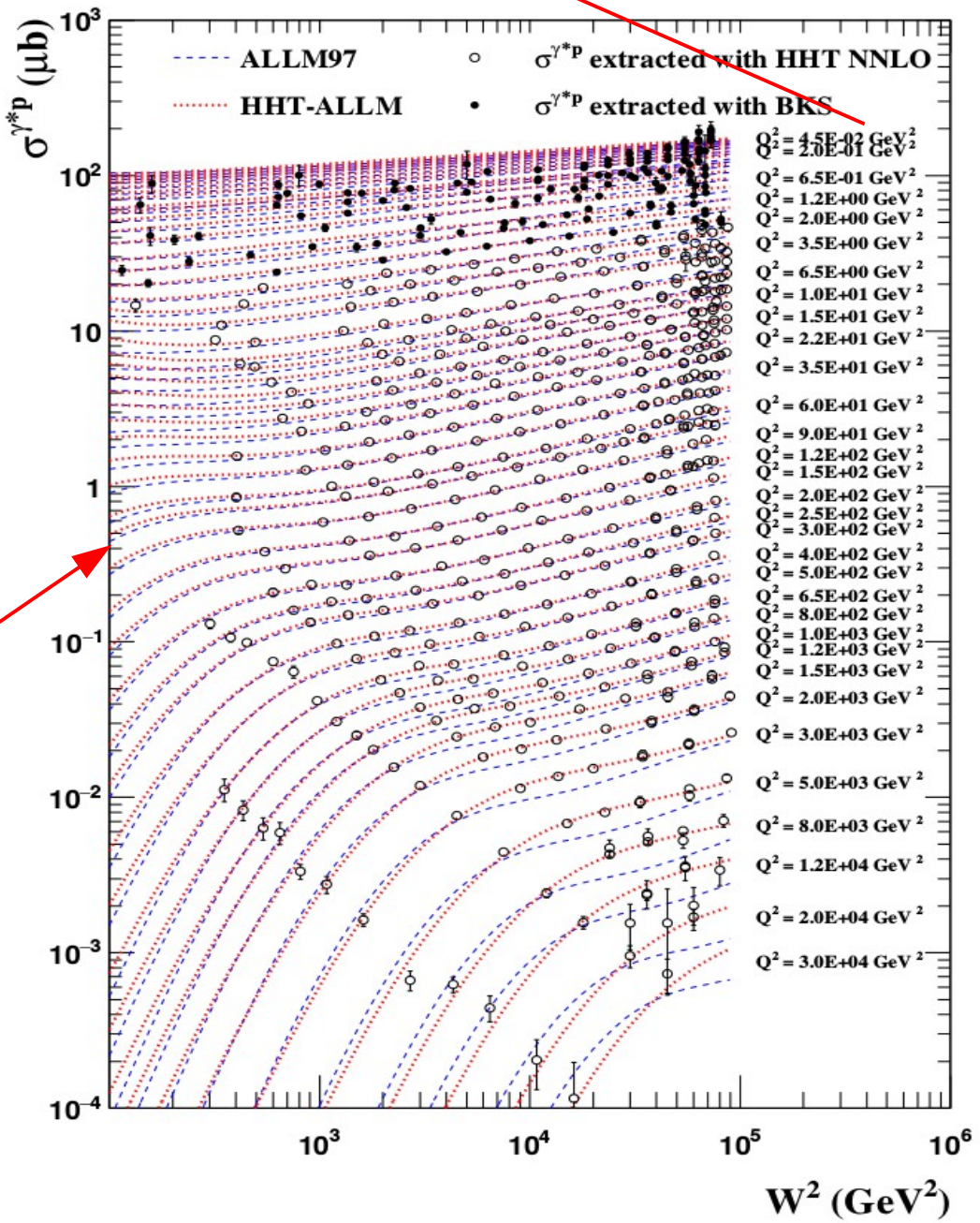
- Inspired by Regge theory
- Incorporates ideas of pQCD

$$F_2 = \frac{Q^2}{Q^2 + m_0^2} \cdot (F_2^{I\!P} + F_2^{I\!R})$$

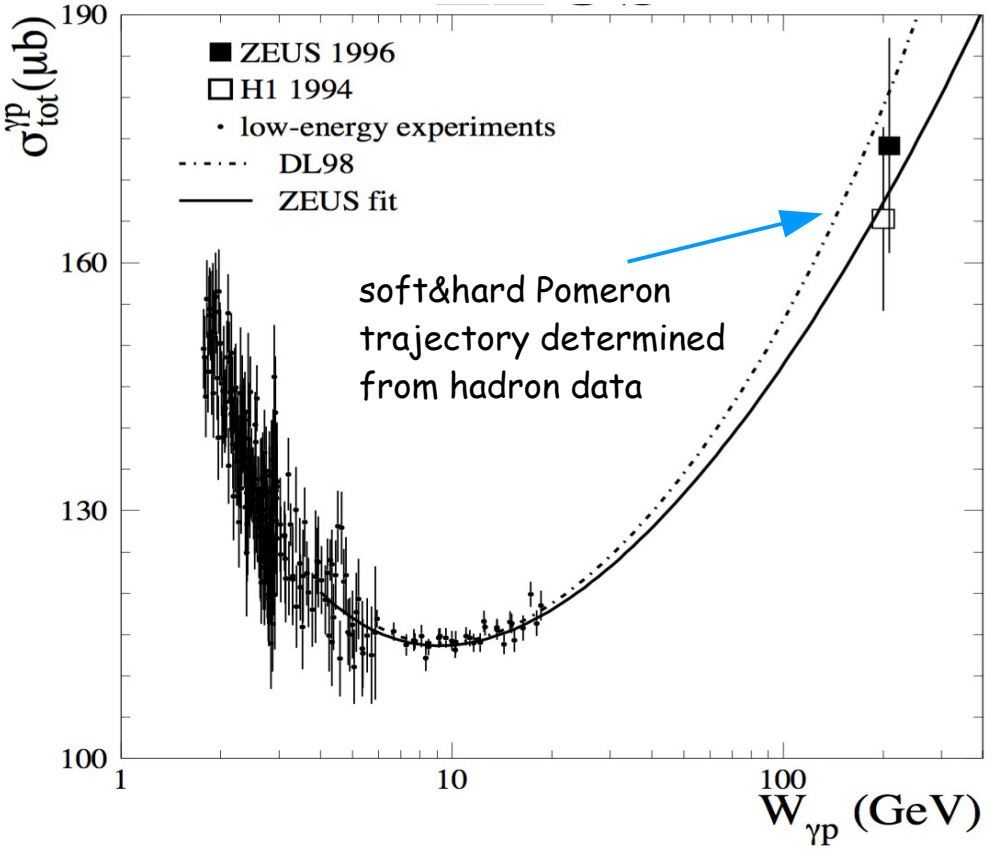
proton mass

- Overall 23 free parameters

Describes data well across the whole kinematic range



Going down to Q^2 = 0 GeV^2: photoproduction → test of asymptotic behavior of total cross sections



Indication of universality of energy dependence of photon-proton total cross section with respect to hadron-proton total cross sections

- BN model based on QCD minijets and soft-gluon resummation and ansatz that infrared gluons limit rise of total cross section
- Introduced into MC AIRES to simulate extended air-showers initiated by cosmic ray photons

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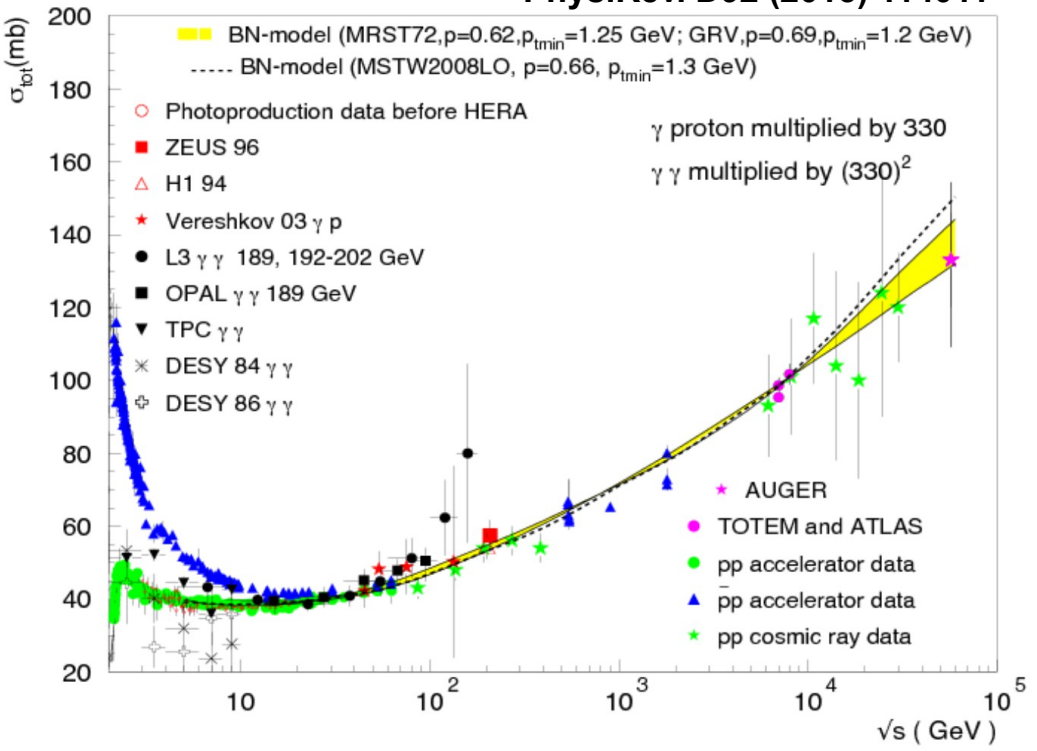
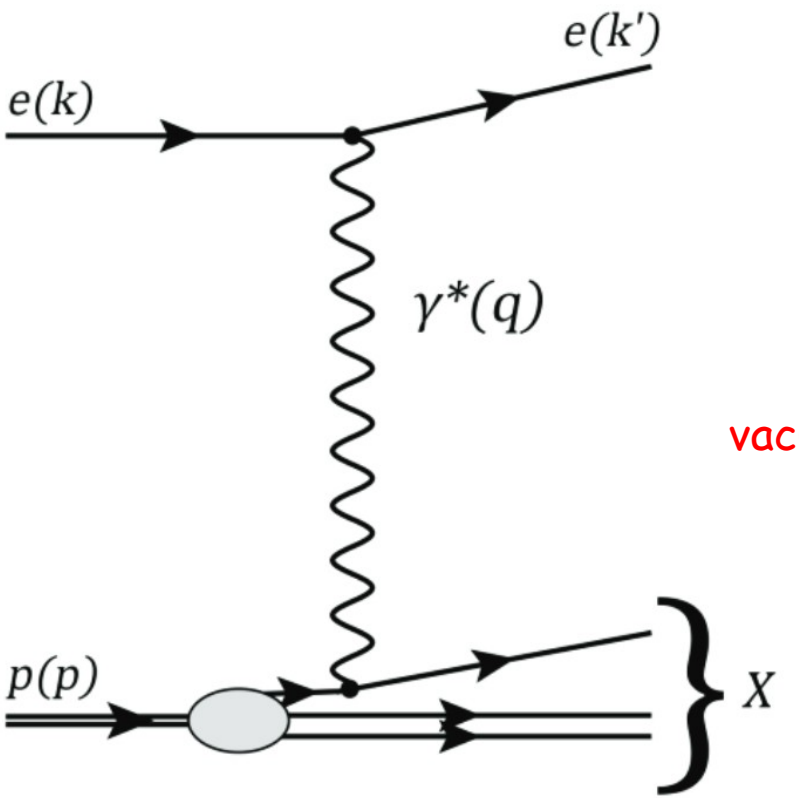


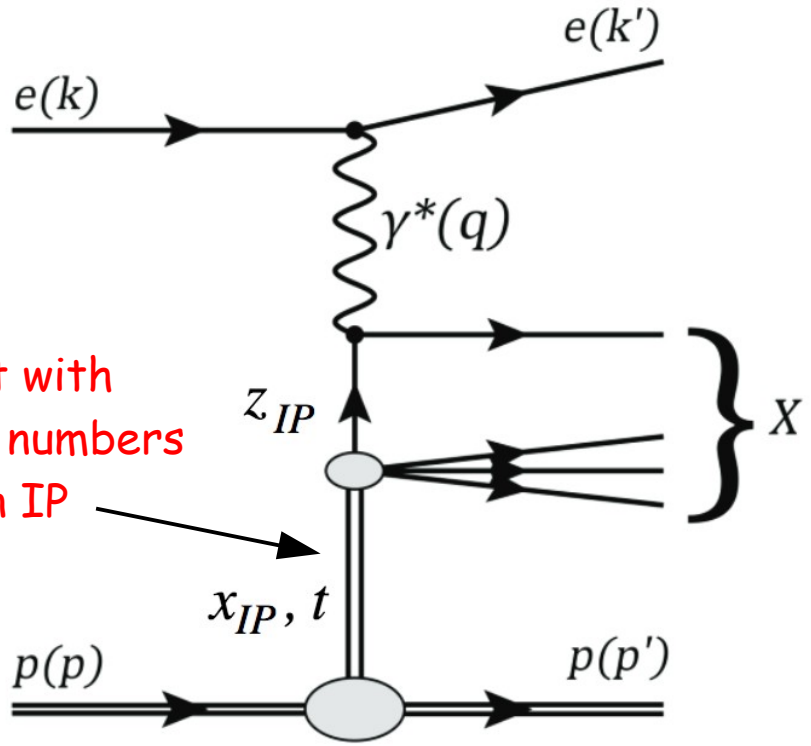
Let's talk about diffraction now

DIS

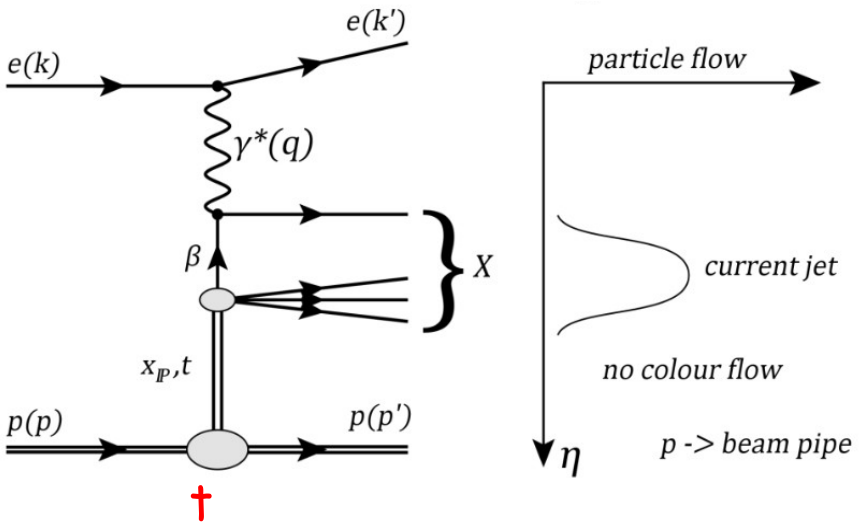


Diffractive DIS (DDIS)

colour singlet with
vacuum quantum numbers
→ pomeron IP



Diffractive Scattering

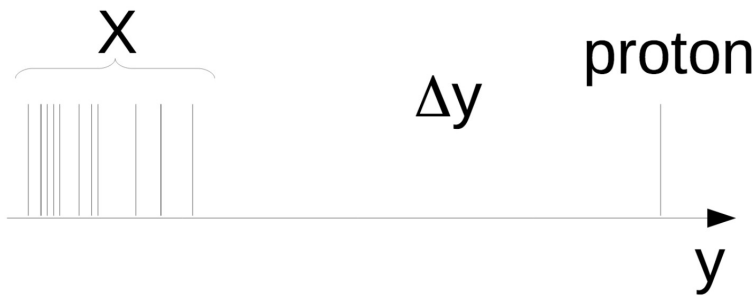


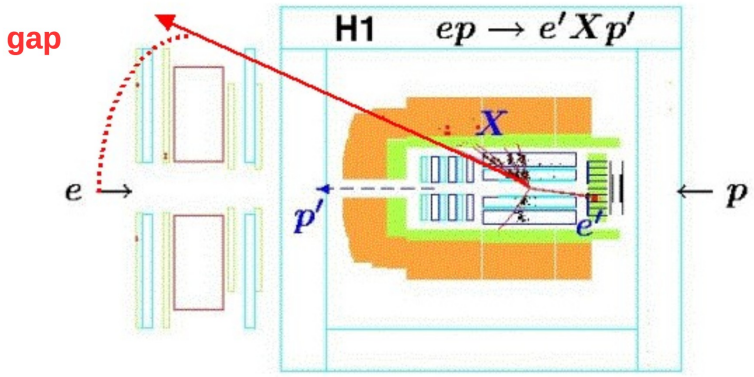
- due to vacuum quantum exchange

→ leading particle at relatively small t

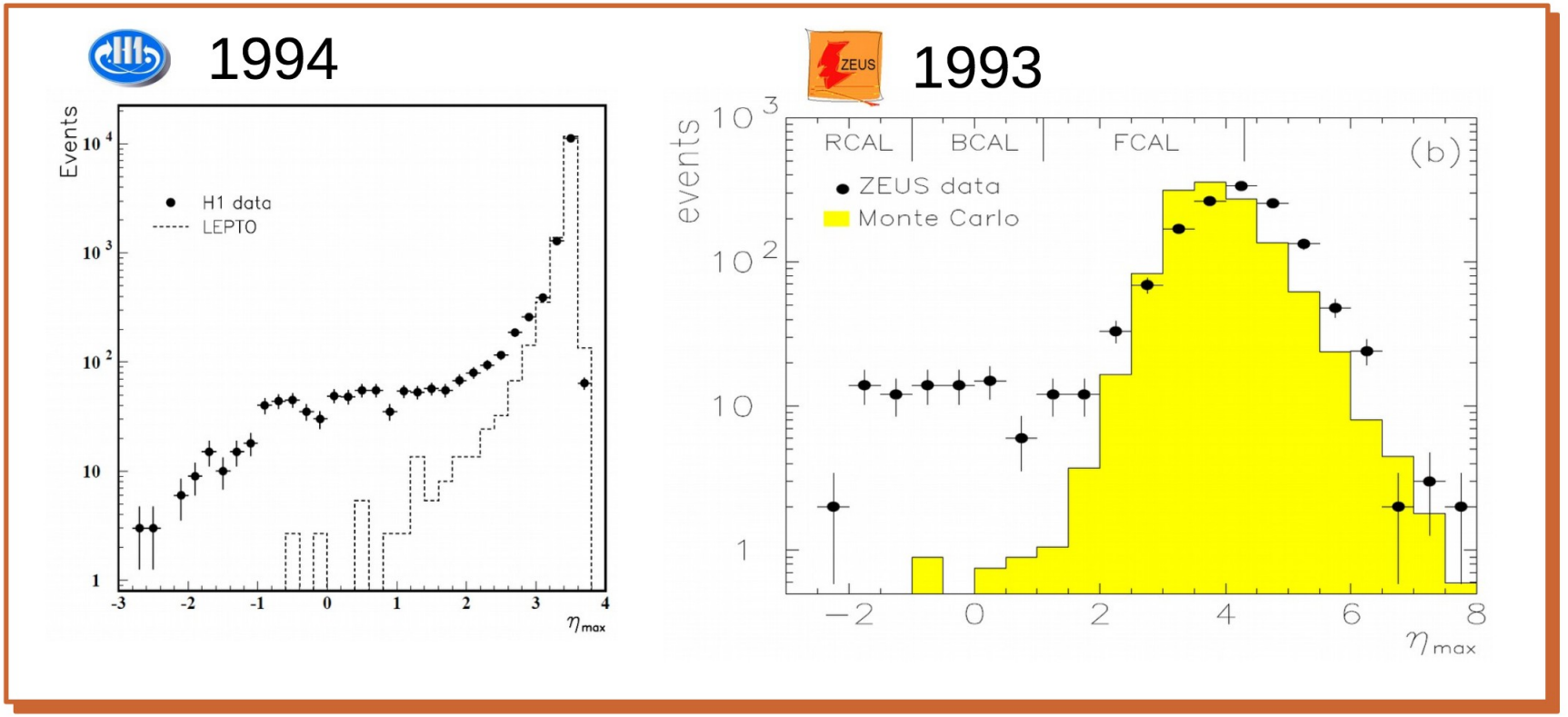
→ rapidity distributions of final state separated from leading particle by non-exponentially suppressed gaps – Large Rapidity Gap (LRG)

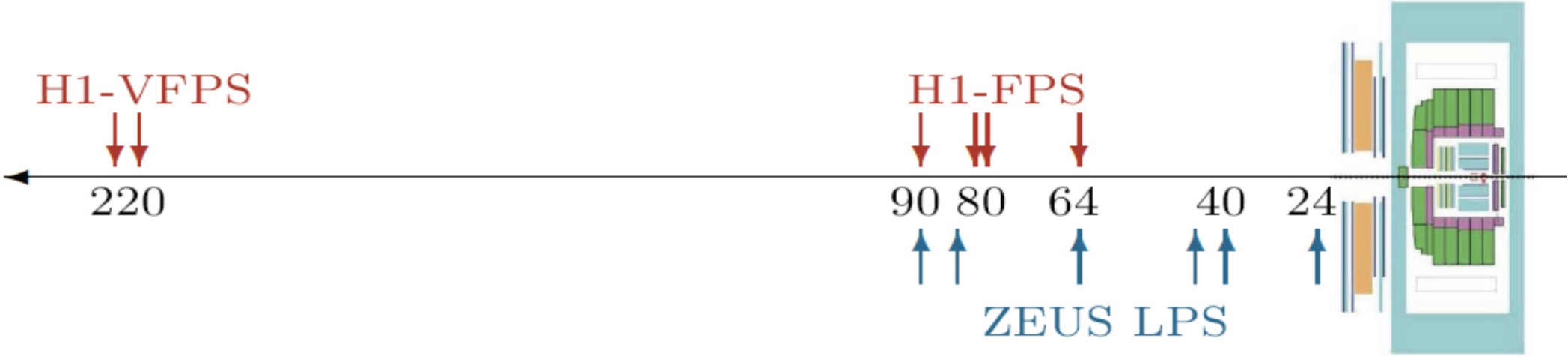
- $x_{I\!P}$ - fraction of proton's momentum carried by exchanged color singlet
- $t = (p - p')^2$- four momentum transfer squared at proton vertex
- $\beta = x/x_{I\!P}$ - fraction of Pomeron momentum "seen" by the photon



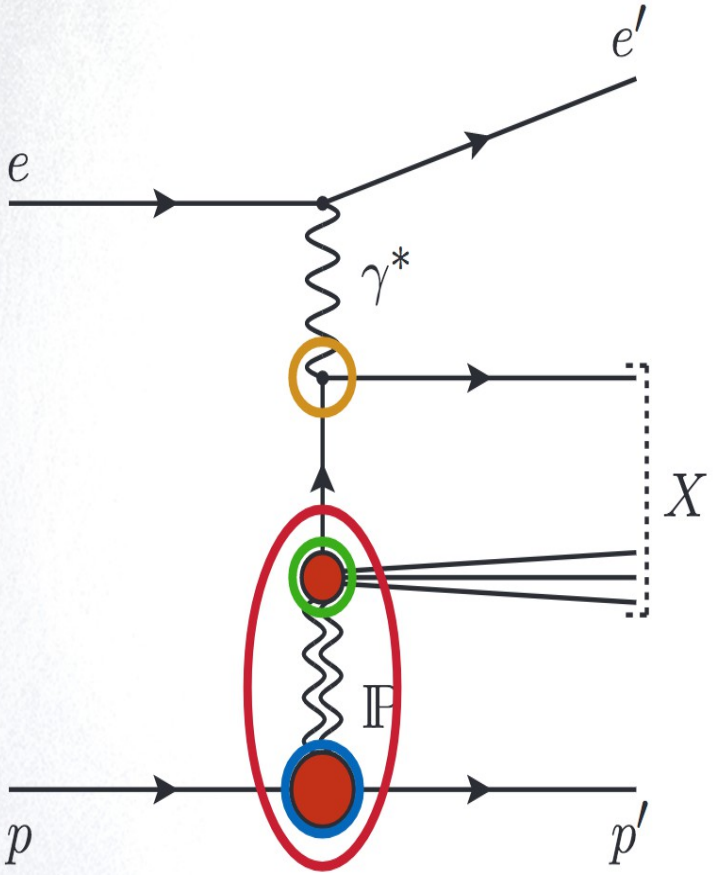


Diffraction @ HERA





Factorisation theorem in diffractive scattering



collinear factorisation: (proven for DDIS by J. Collins)

$$\sigma^D(\gamma^* p \to Xp) = \sum_i^{partons} \hat{\sigma}(z_{IP}, Q^2) \otimes f_i^D(z_{IP}, Q^2, x_{IP}, t)$$

→ hard subprocess matrix element, calculable in pQCD

→ universal diffractive parton distribution functions (DPDFs)

proton-vertex factorisation assumption: experimental fact (supported by H1 and ZEUS data)

$$f_i^D(z_{IP}, Q^2, x_{IP}, t) = f_{IP/IR}(x_{IP}, t)\, f_i^{IP/IR}(z_{IP}, Q^2)$$

→ flux parametrisation, Pomeron/Reggeon PDFs

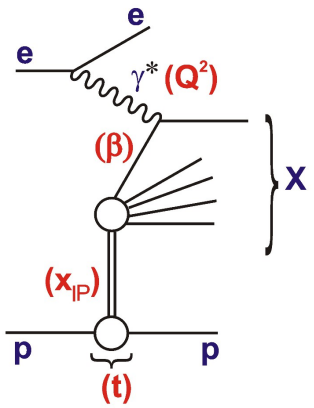
Test of factorization:

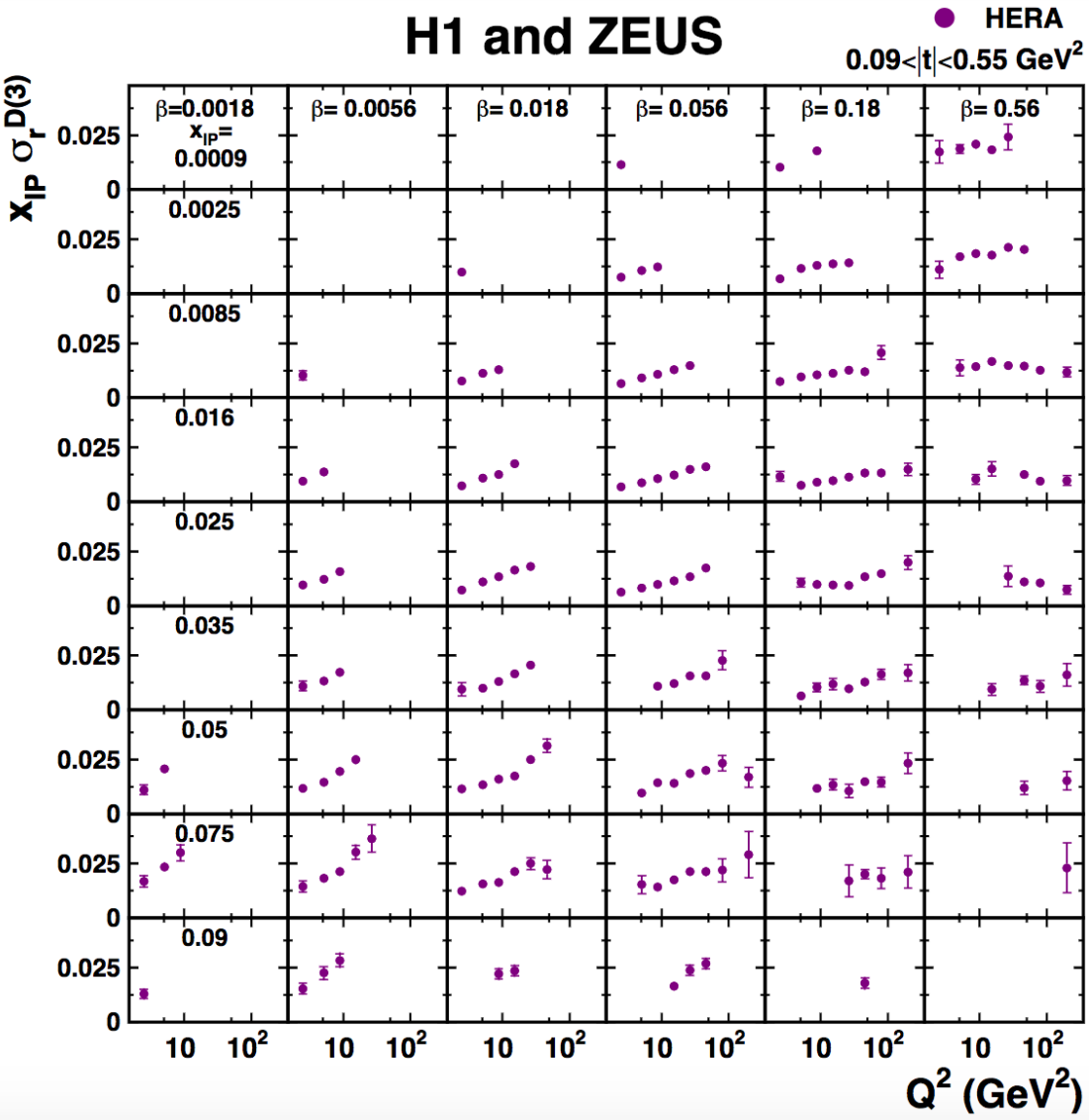
- use NLO calculations and universal DPDFs to predict and confront with measurement the cross sections for particular diffractive final state

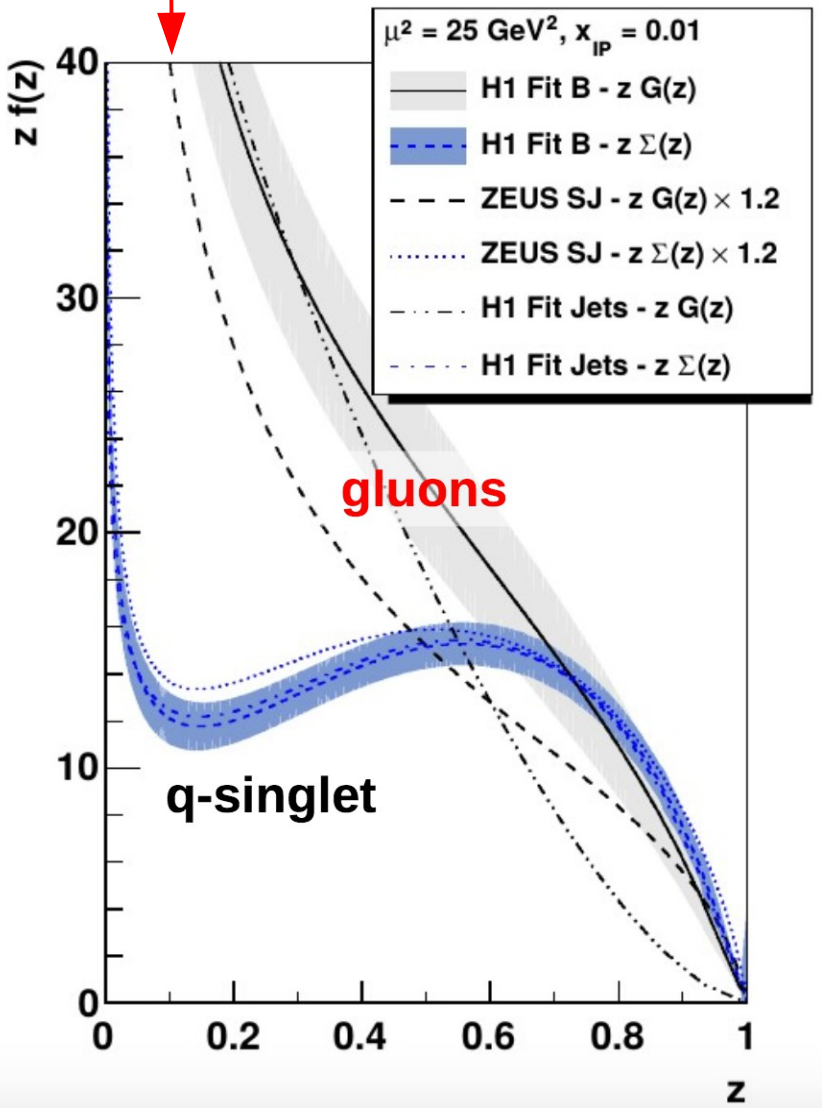
Diffractive cross sections & DPDFs

$$\sigma_r^{D(4)}(\beta, Q^2, x_{IP}, t) = F_2^{D(4)} - \frac{y^2}{Y_+} F_L^{D(4)} \sim F_2^{D(4)}$$

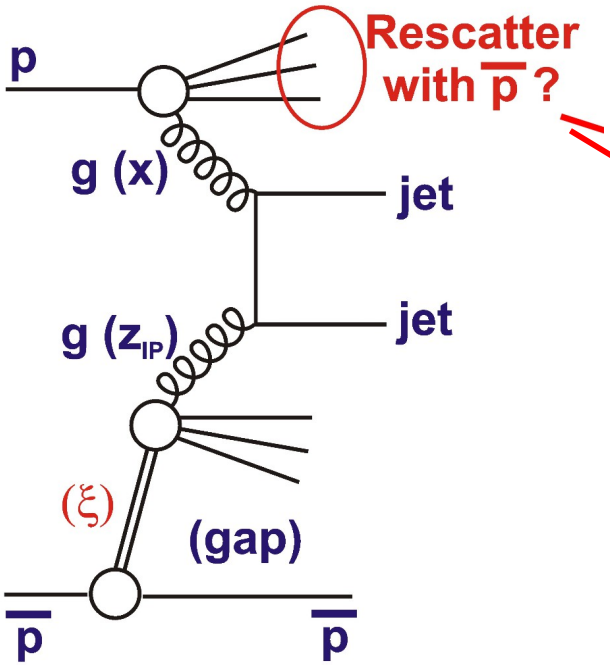
dominated by gluons



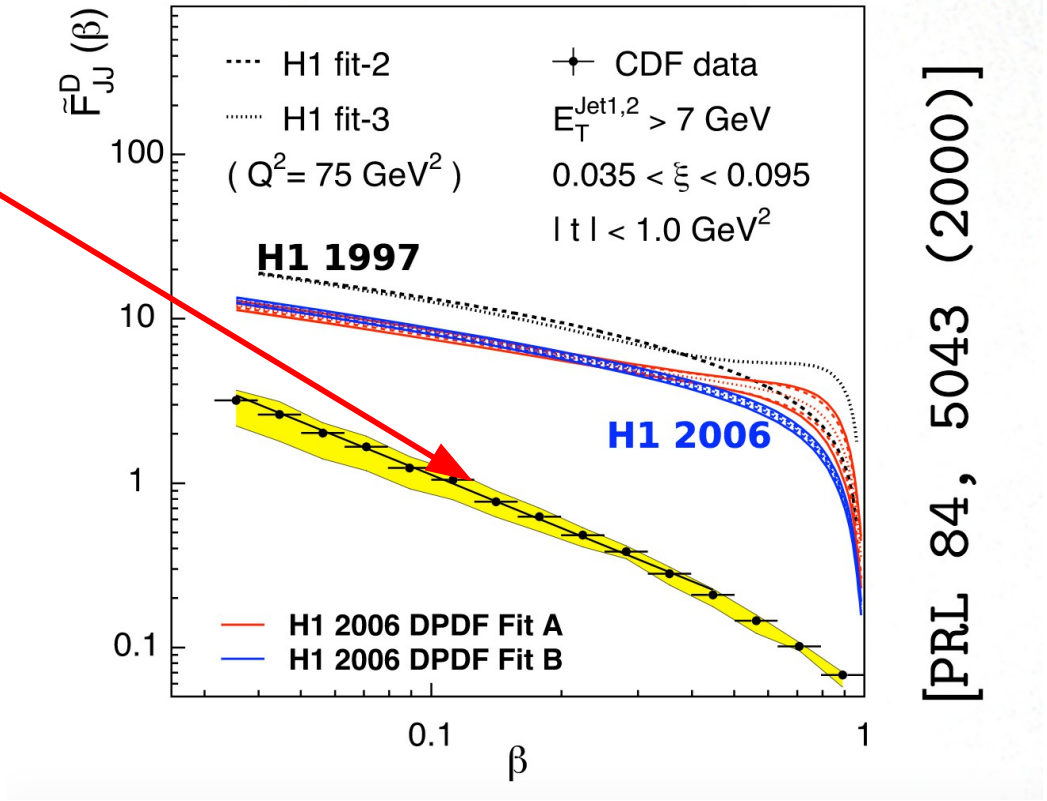




Predicting TeVatron data



CDF: dijets in diffractive $p\bar{p}$

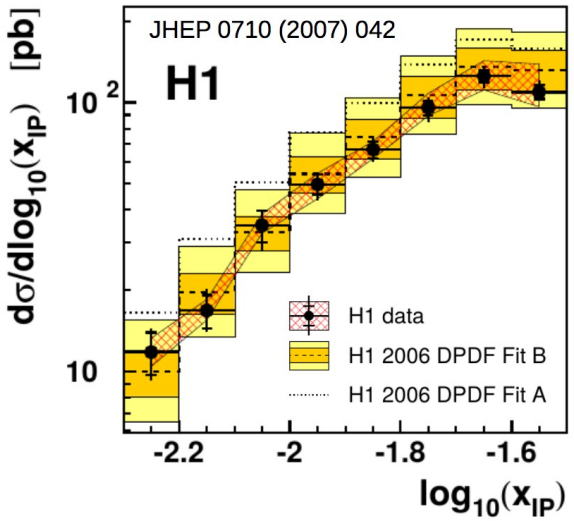


- factorisation is broken in hadron-hadron scattering at TeVatron and LHC with HERA DPDFs

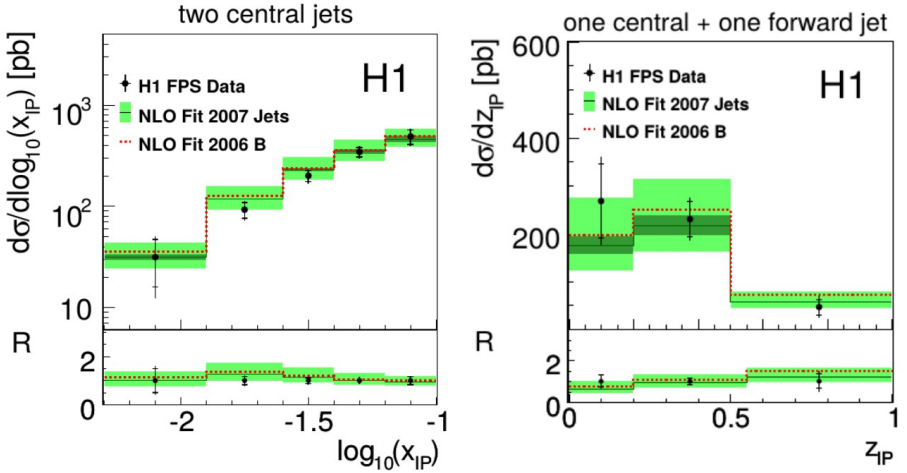
  ... usually explained by soft interactions or multi-pomeron exchange between the hadrons and/or rescattering phenomena which destroy gaps

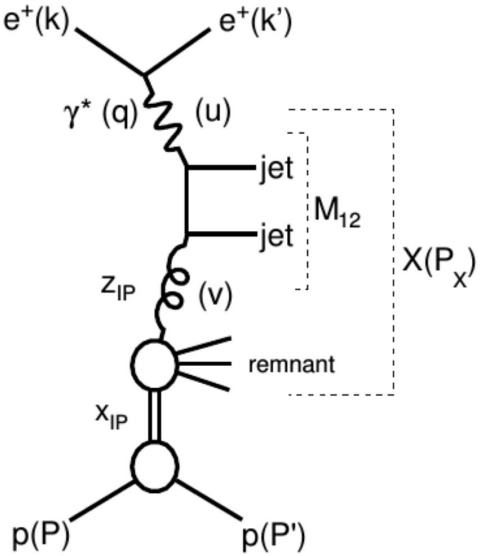
→ **how does that look @ HERA itself?**

Diffractive di-jets in DDIS

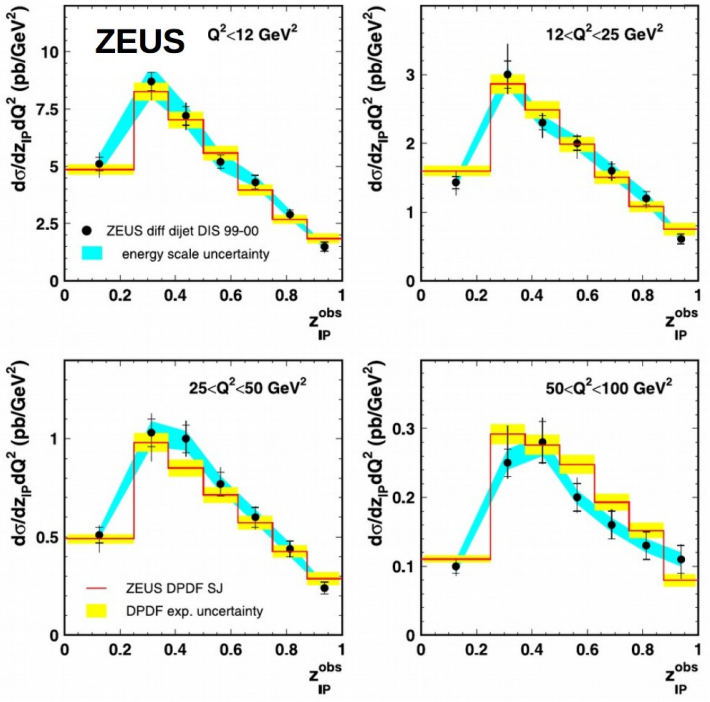


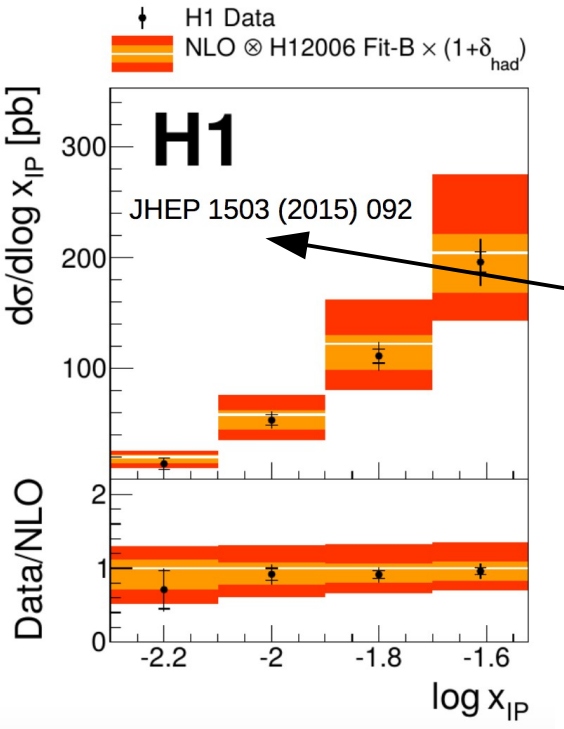
Eur.Phys.J. C72 (2012) 1970





Nucl. Physics B 831 (2010) 1-25



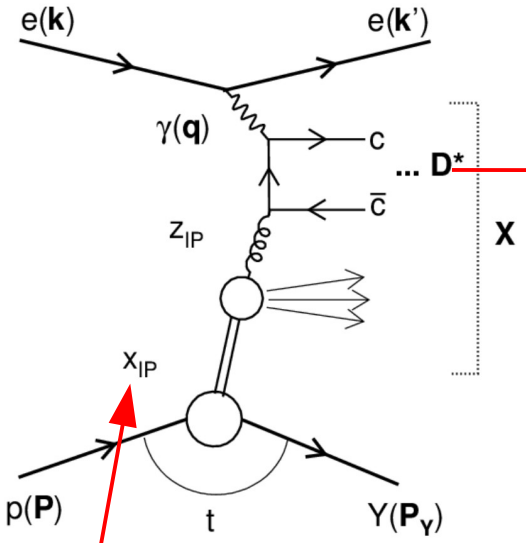


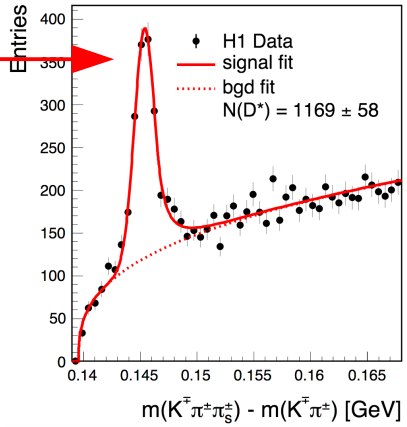
first measurement of α_s in DDIS

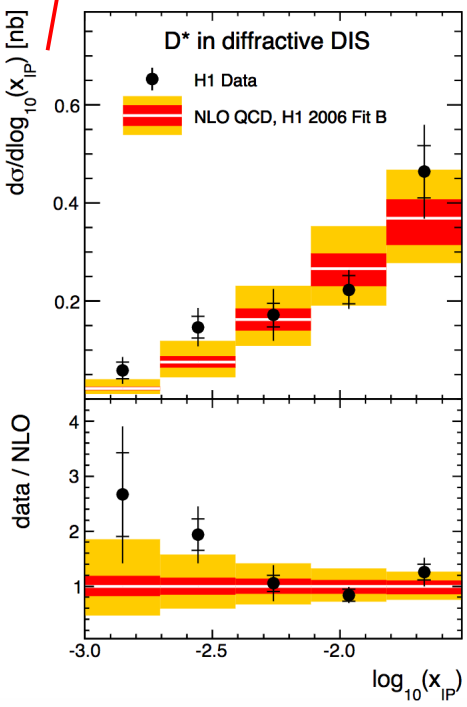
$$\alpha_s(M_Z) = 0.119 \pm 0.004(exp) \pm 0.012(DPDF,\ theo)$$

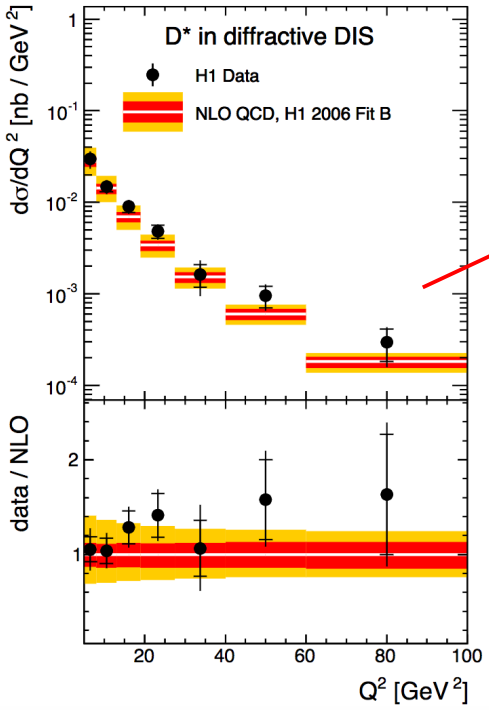
Factorisation holds in DDIS jets

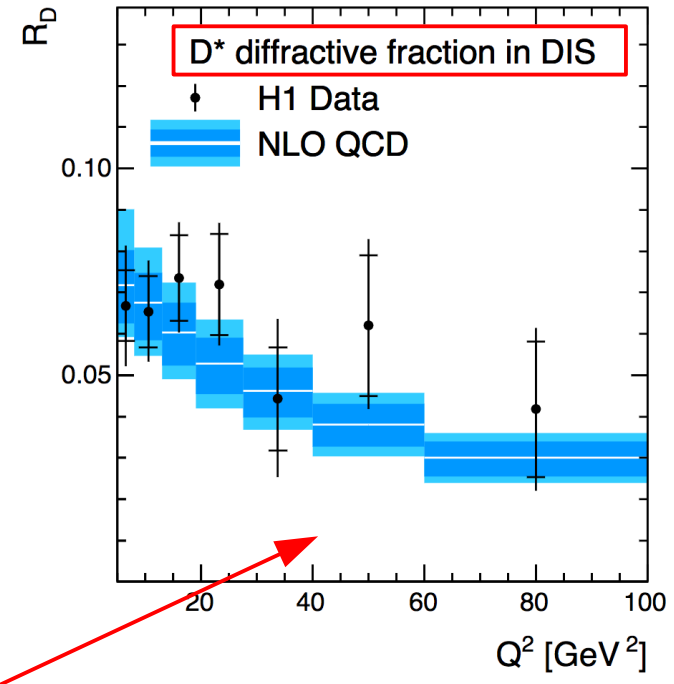
Open charm production in DDIS



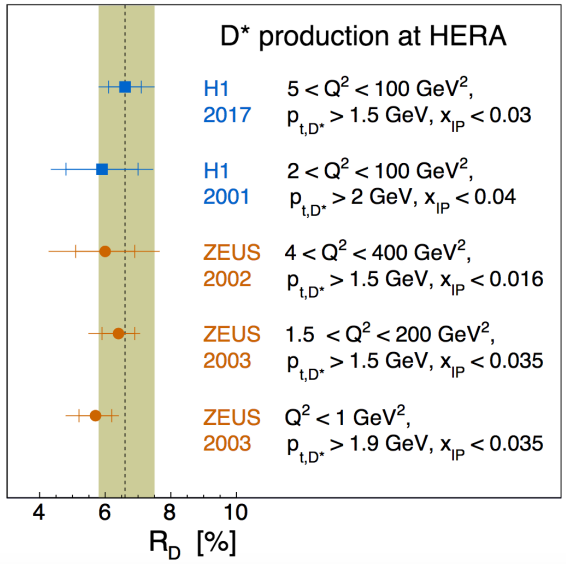








Diffractive fraction

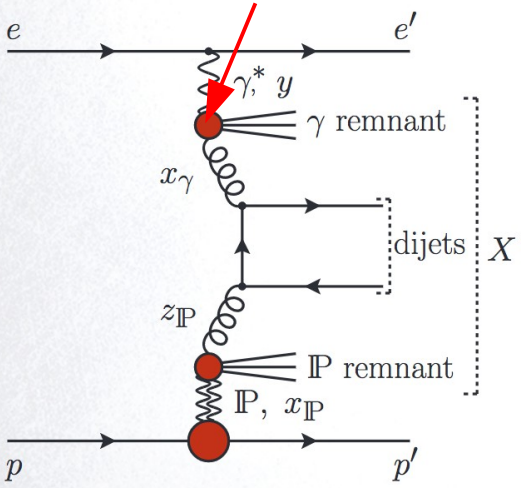


Factorisation holds in D* DDIS and photoproduction

Eur.Phys.J.C77 (2017), 340

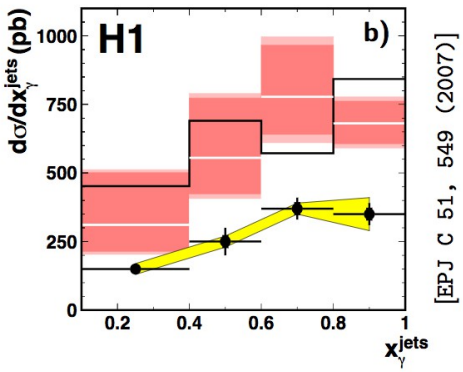
Diffractive di-jets in photoproduction

real photon has hadronic structure

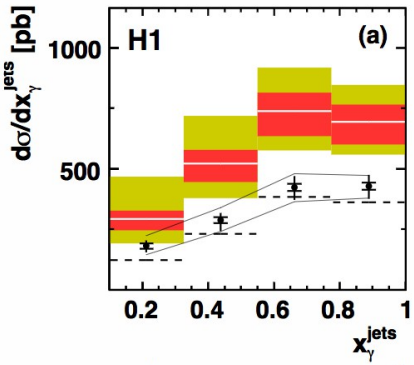


H1: fact. holds

"suppression" w.r.t. NLO observed in γp



[EPJ C 51, 549 (2007)]

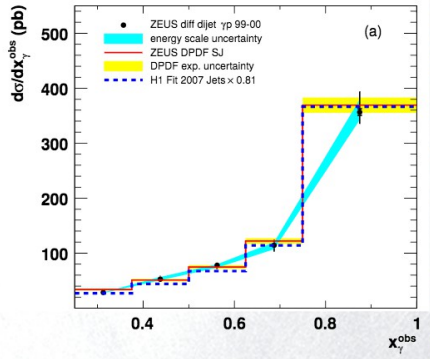


[EPJ C 70, 15 (2010)]

fact. broken

ZEUS:

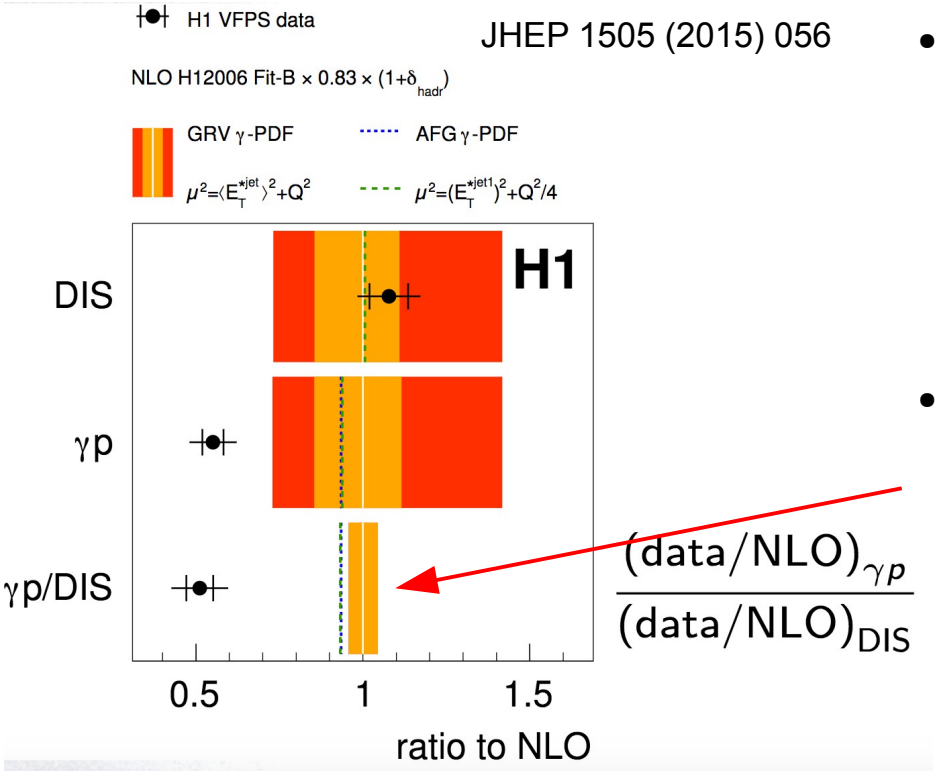
no indication of suppression



[Nucl.Phys. B 831, 1 (2010)]

2 LRG+γ-tag analyses (L = 18 pb^{-1} & L = 47 pb^{-1})

LRG analysis



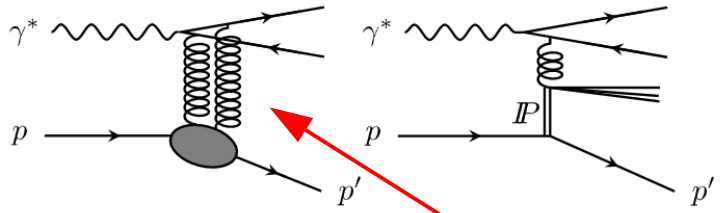
$$\frac{(\text{data/NLO})_{\gamma p}}{(\text{data/NLO})_{\text{DIS}}}$$

- Diffractive di-jet results in photoproduction from HERA inconclusive
  - H1 observes factorisation breaking
  - Not seen in ZEUS
- New H1 results, using different method confirm factorisation breaking seen in previous H1 measurement

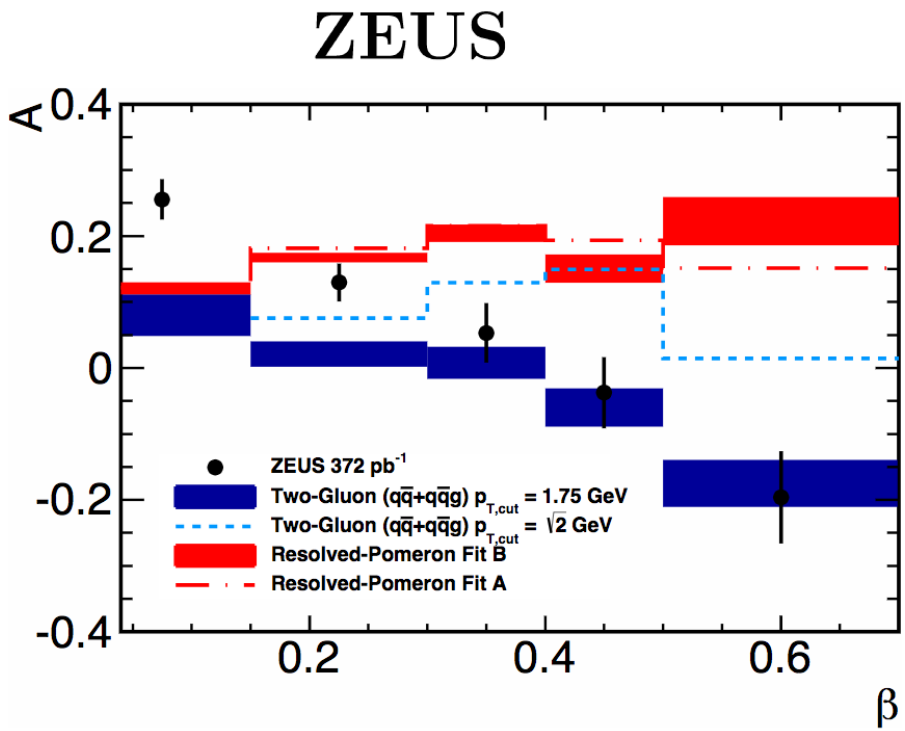
Still inconclusive results from HERA

Exclusive di-jet production in DIS → another test of QCD in diffraction

- select two hard jets $p_t > 2$ GeV to allow comparison to pQCD models



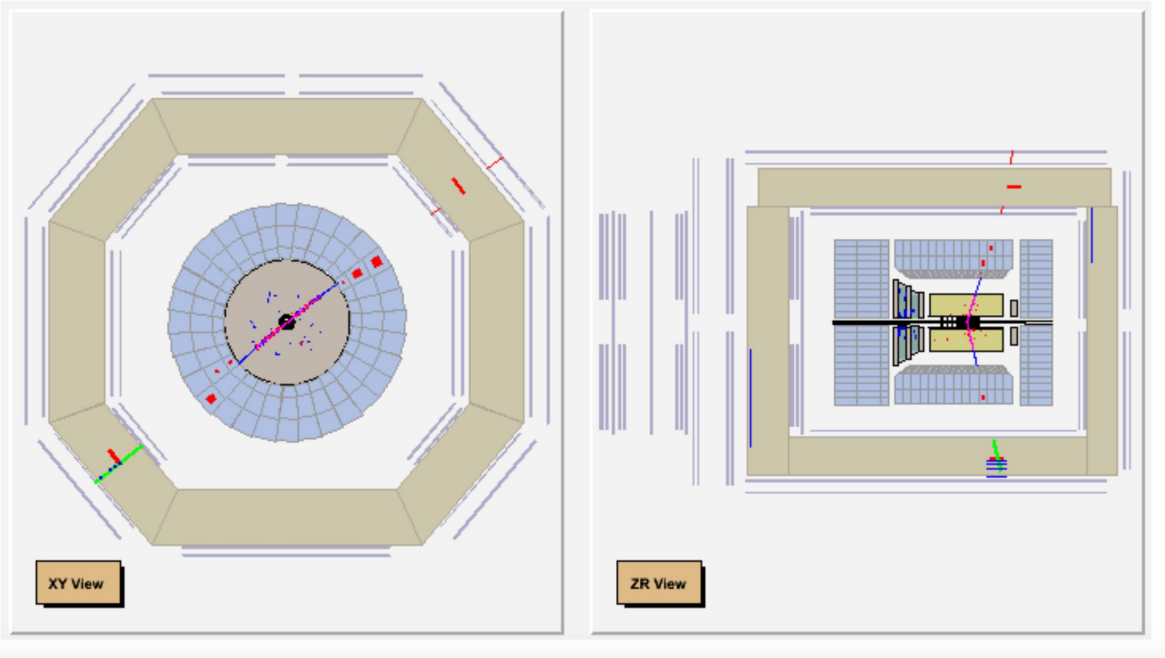
- Two-gluon exchange model (J. Bartels and H. Jung et al.)
- Resolved Pomeron model (G.Ingelman and P.Schlein et al.)
- models predict different shape for dijet azimuthal angular distribution $d\sigma/d\phi \propto 1 + A\cos(2\phi)$

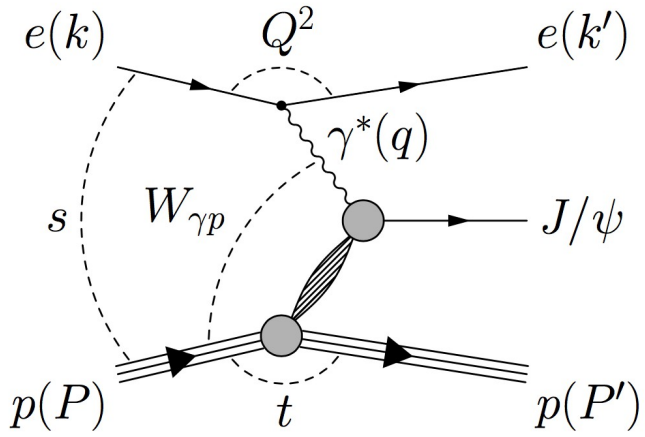


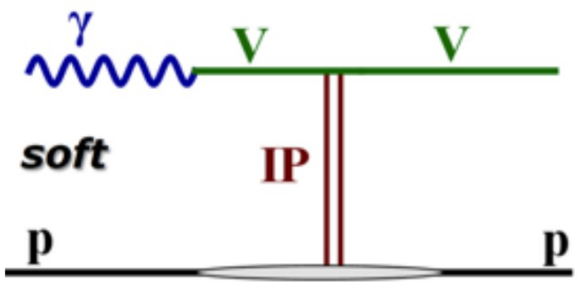
- data favor the two-gluon exchange model prediction
- The Resolved Pomeron model (BGF) does not describe this data

Eur. Phys. J. C 76 (2016) 16

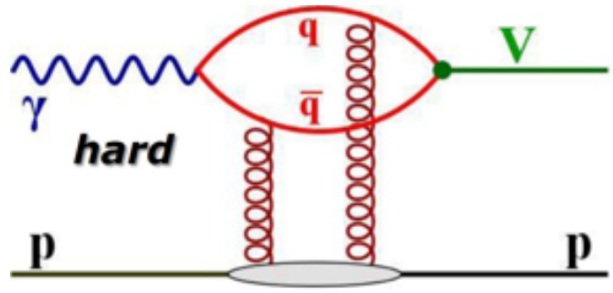
Diffractive vector mesons: switching perturbative QCD on or off



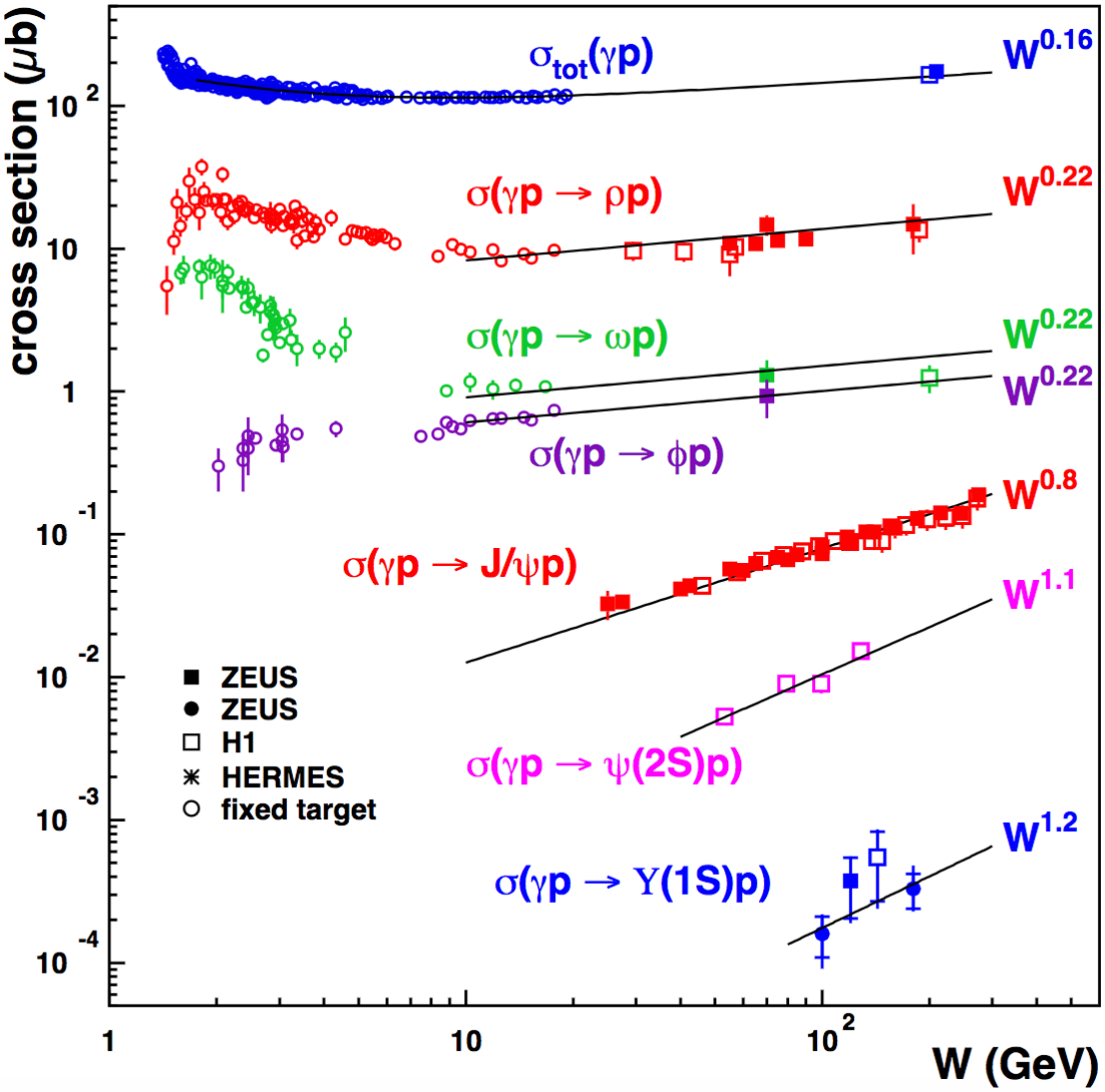




Vector Mesons



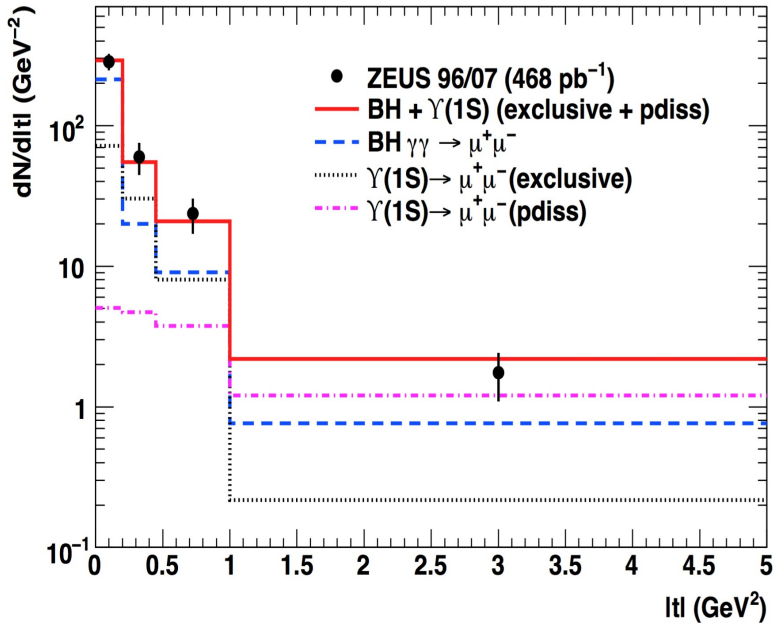
VM cross section as a function of W

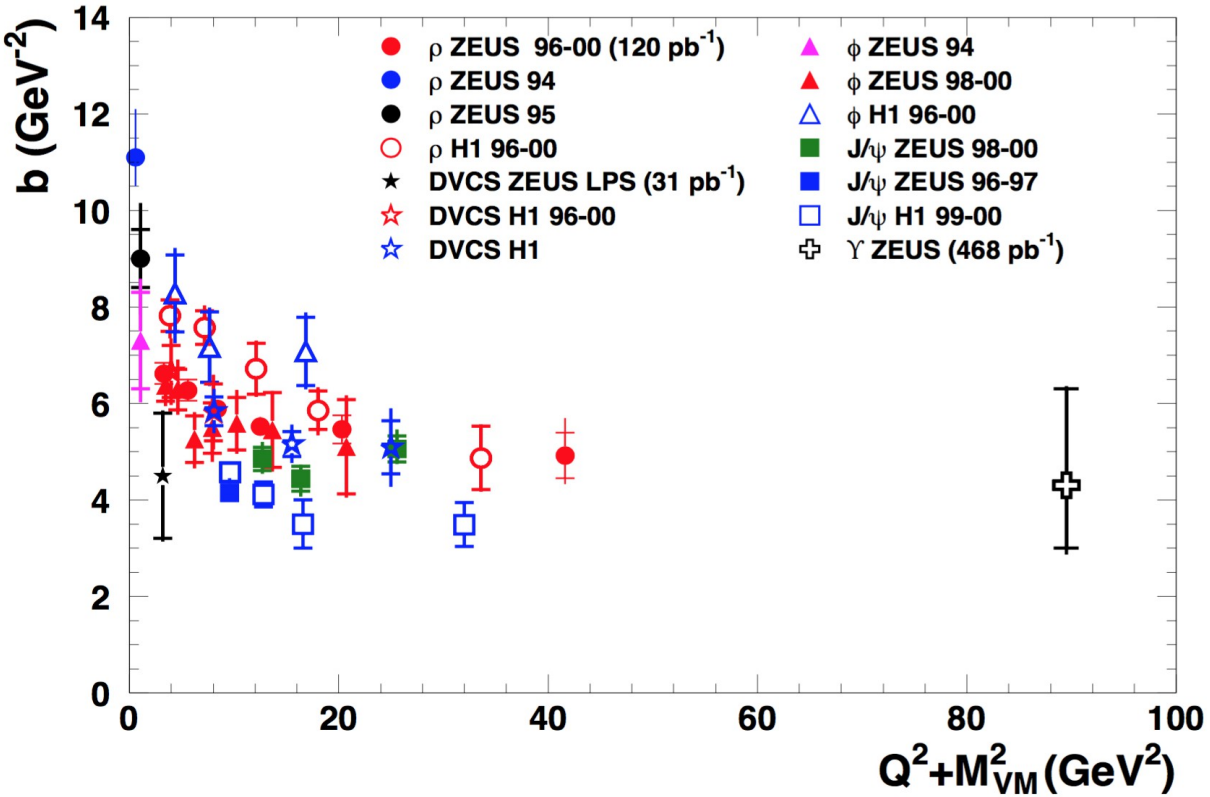


- total cross sections σ_{VM} for VM photoproduction spans over 6 orders of magnitude!
- σ_{VM} rises with γp c.m. energy W as W^{δ} (for heavy VMs expected from the gluon behaviour in the proton → probing small x)
- Power δ rises with M_V^2
  - from "soft" (δ≈0.22)
  - to "hard" (δ≈1.2) processes

VM cross section as a function of |t|

- measurement of VM production cross section to test the transition between soft and hard physics
- $d\sigma/d|t| \sim \exp(-bt)$
  - b~10 GeV^{-2} for soft physics
  - b~4-5 GeV^{-2} pQCD



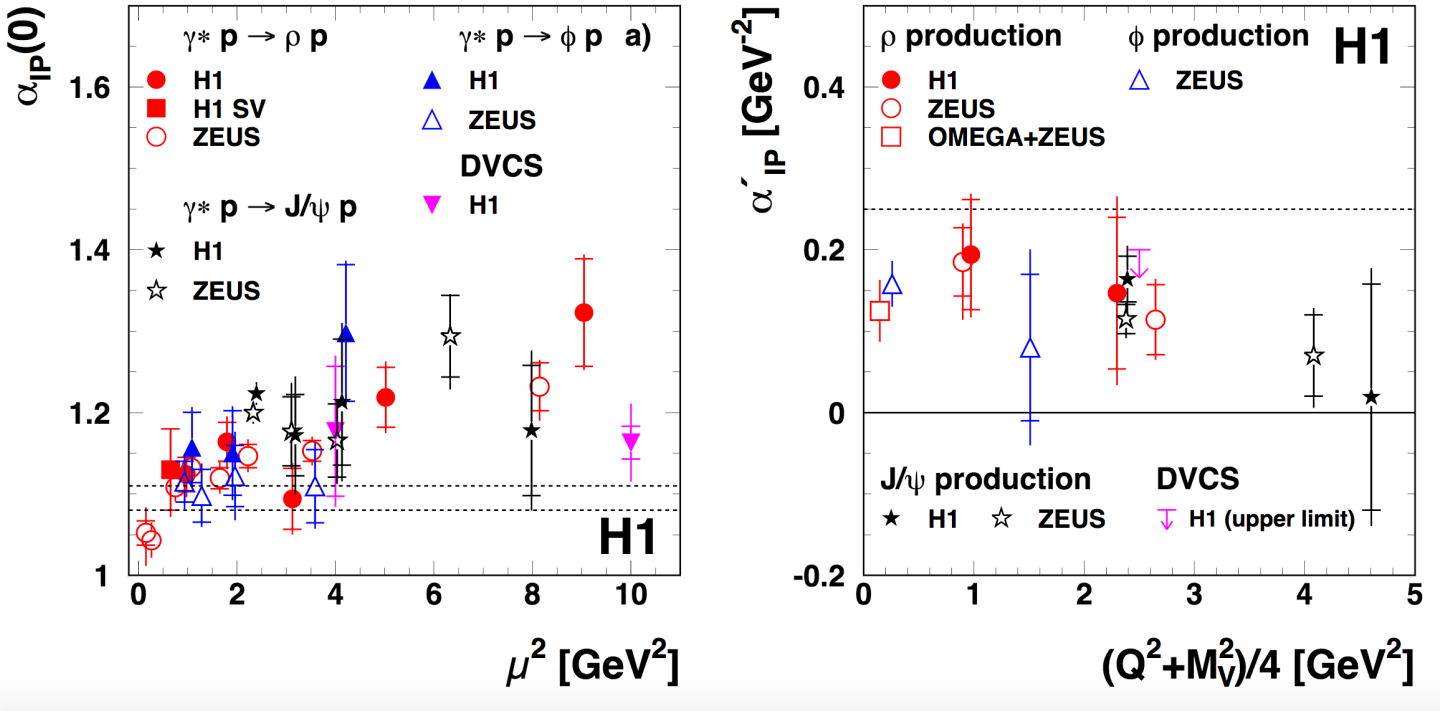


b slope decreases with scale as expected by smooth transition from soft to hard physics

t-slope, b, decreases with scale $Q^2 + M^2_V$

VM cross section as a function of scale μ^2

- effective Pomeron trajectory: $\alpha(t) = \alpha(0) + \alpha' t$
- $\alpha(0)$: energy dependence of the total xsec: $\sigma_{tot} = W^{\delta} = W^{2(\alpha(0)-1)}$
  δ: 0.2 ↗ 1.2
- α': shrinkage of the diffractive peak: $\frac{d\sigma}{d|t|} = e^{-b|t|}$, $b(W) = b_0 + 4\alpha' ln(W/W_0)$
  b: 10 ↘ 5 GeV^{-2}, α': 0.25 ↘ 0.1 GeV^{-2}



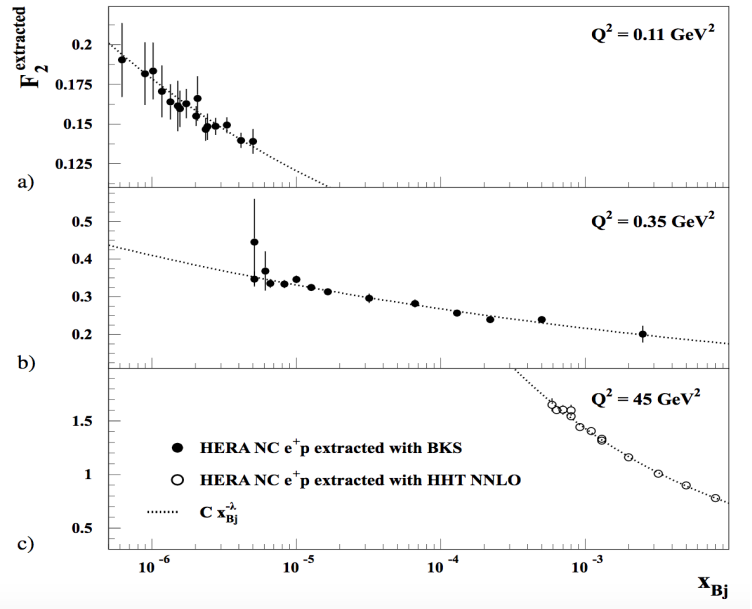
Clear transition from soft to hard QCD with scale
→ evidence for "hard Pomeron"

One last thing - back to DIS again

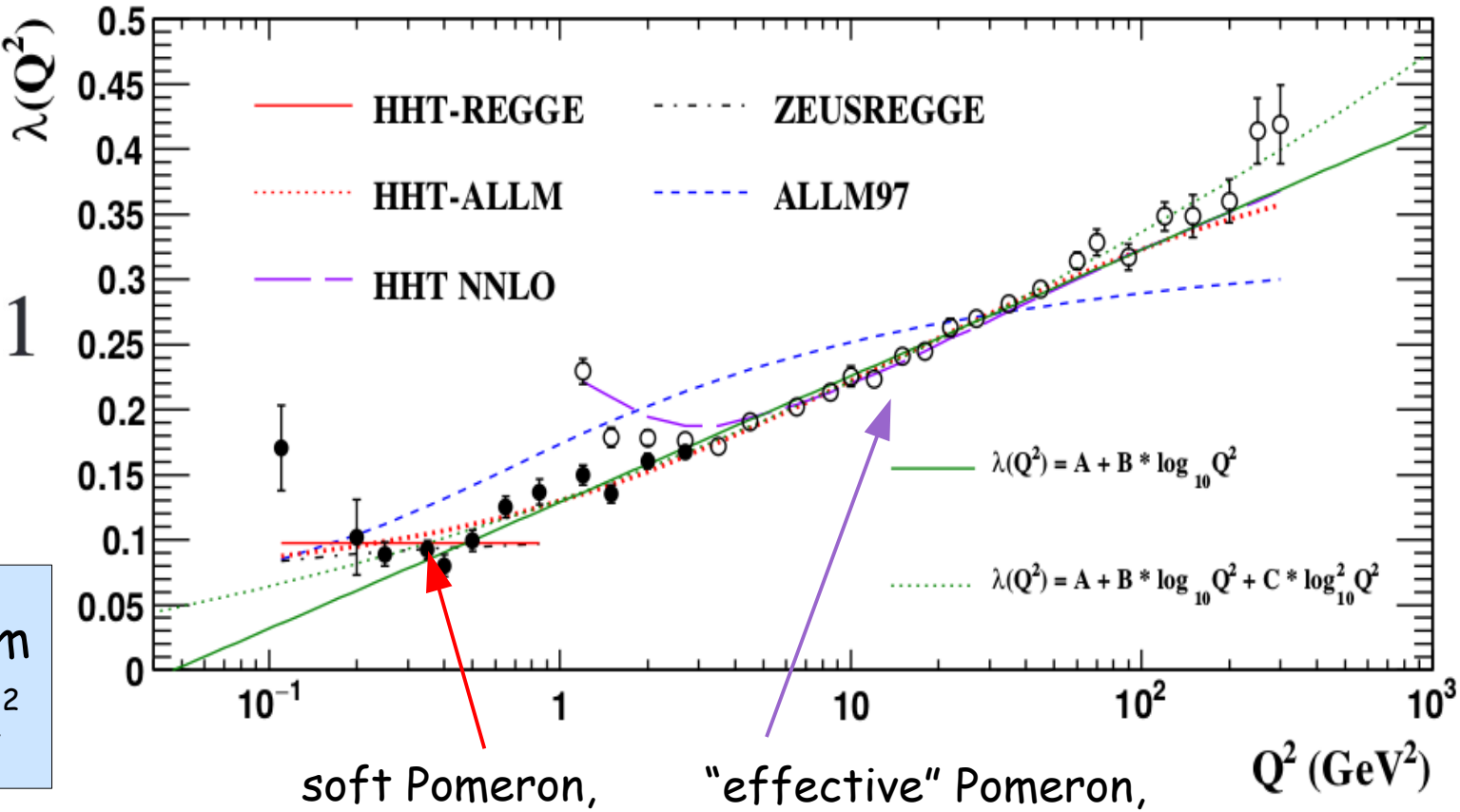
$\rightarrow \alpha_{IP}(0)$ from F_2

$$F_2 = C(Q^2) x_{Bj}^{-\lambda(Q^2)} \qquad x_{Bj} < 0.01$$

region where gluon dominates



$$\lambda = \alpha_{IP}(0) - 1$$



soft Pomeron, constant

"effective" Pomeron, changes with scale

Again transition from soft to hard with Q^2

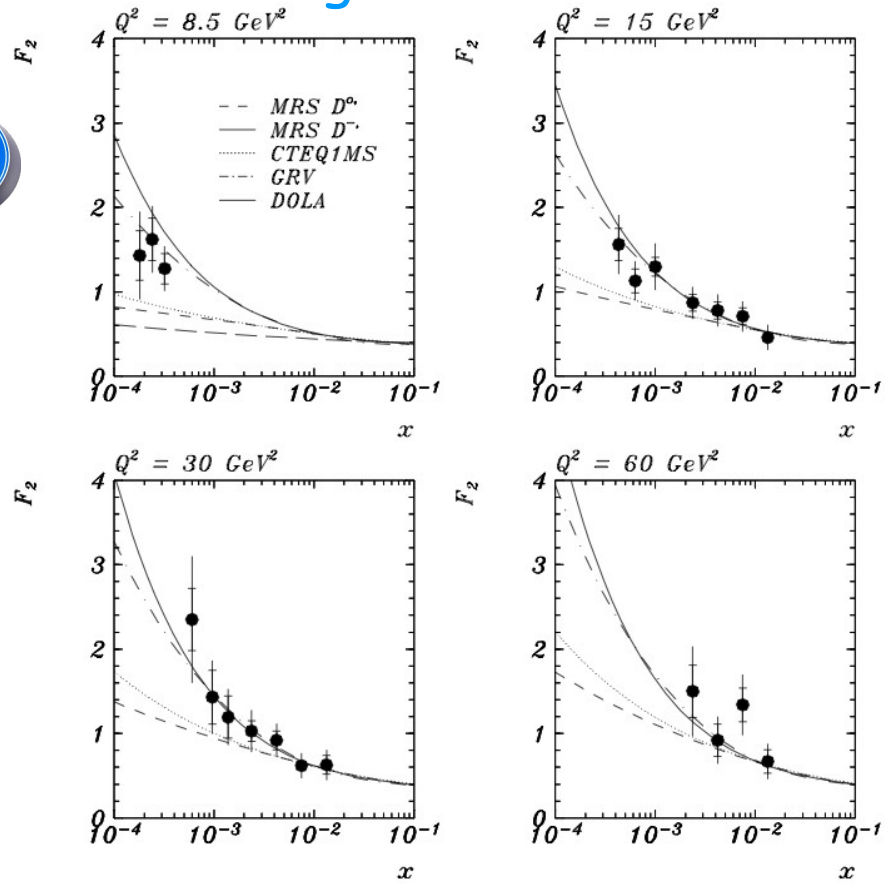
Instead of summary:
thank you for your patience :)

Extra slides

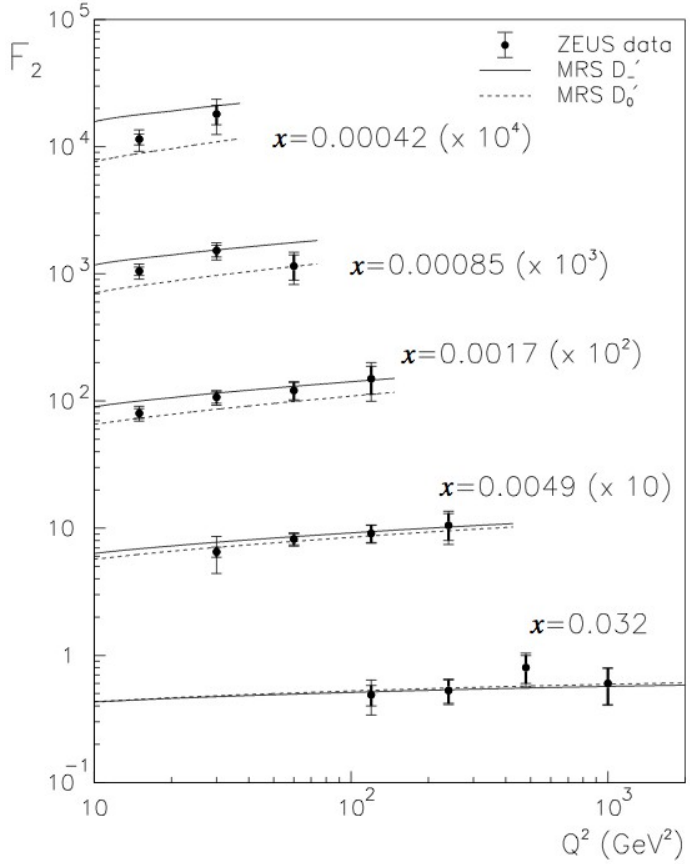
First F_2 measurements @ HERA: 1993

~20 nb^{-1} ⟹ 1 fb^{-1}

August 25th



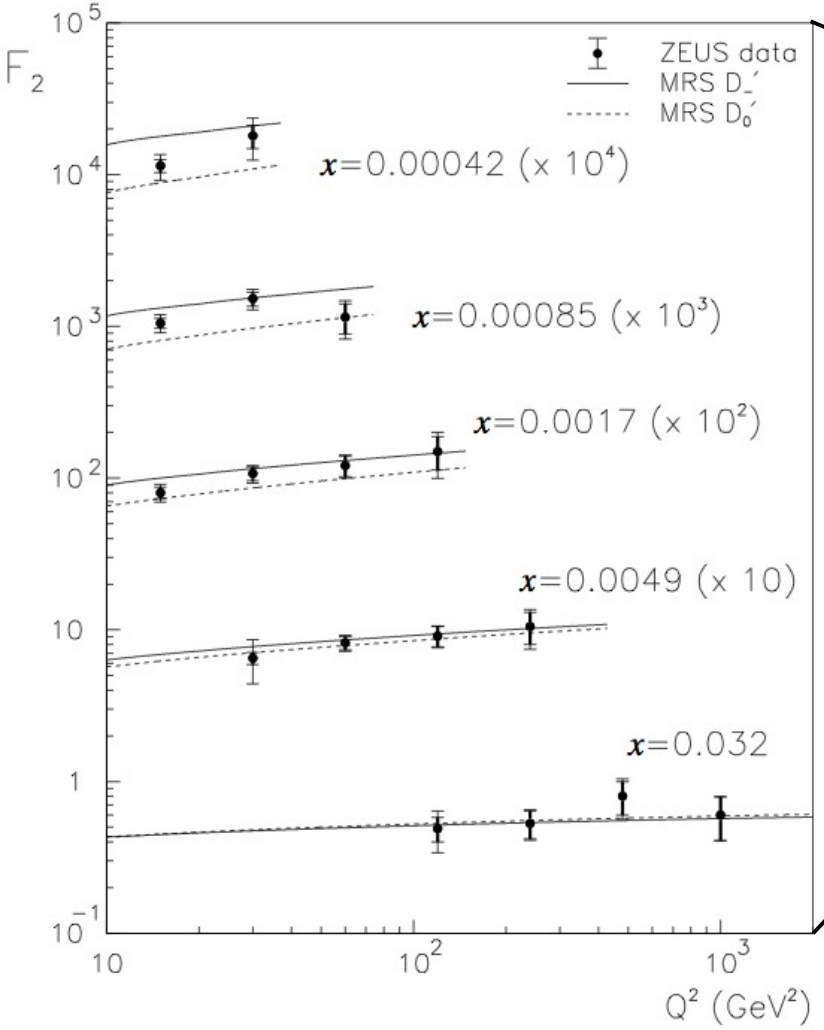
August 13th

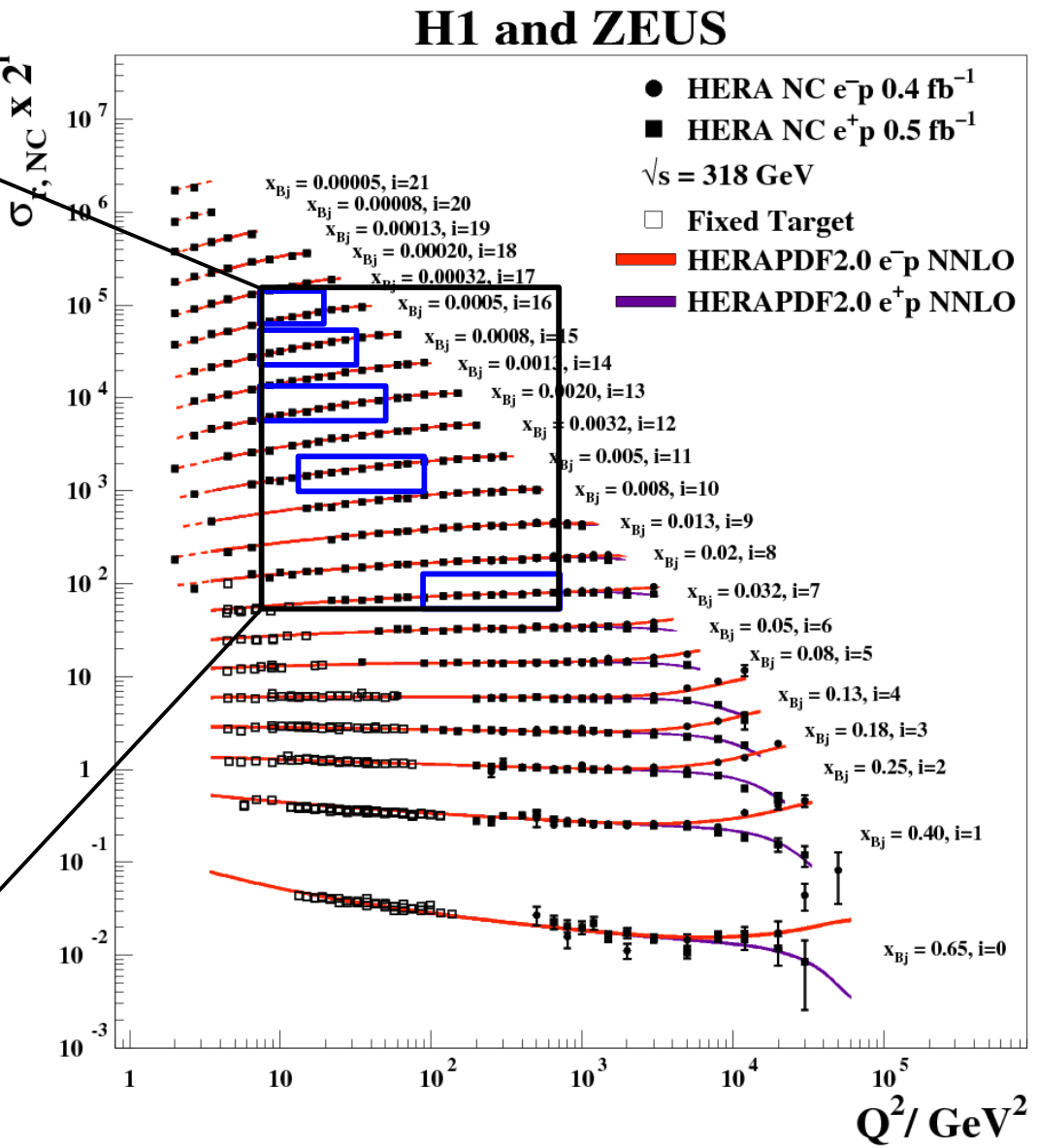


The F_2 structure function increases rapidly as x decreases.

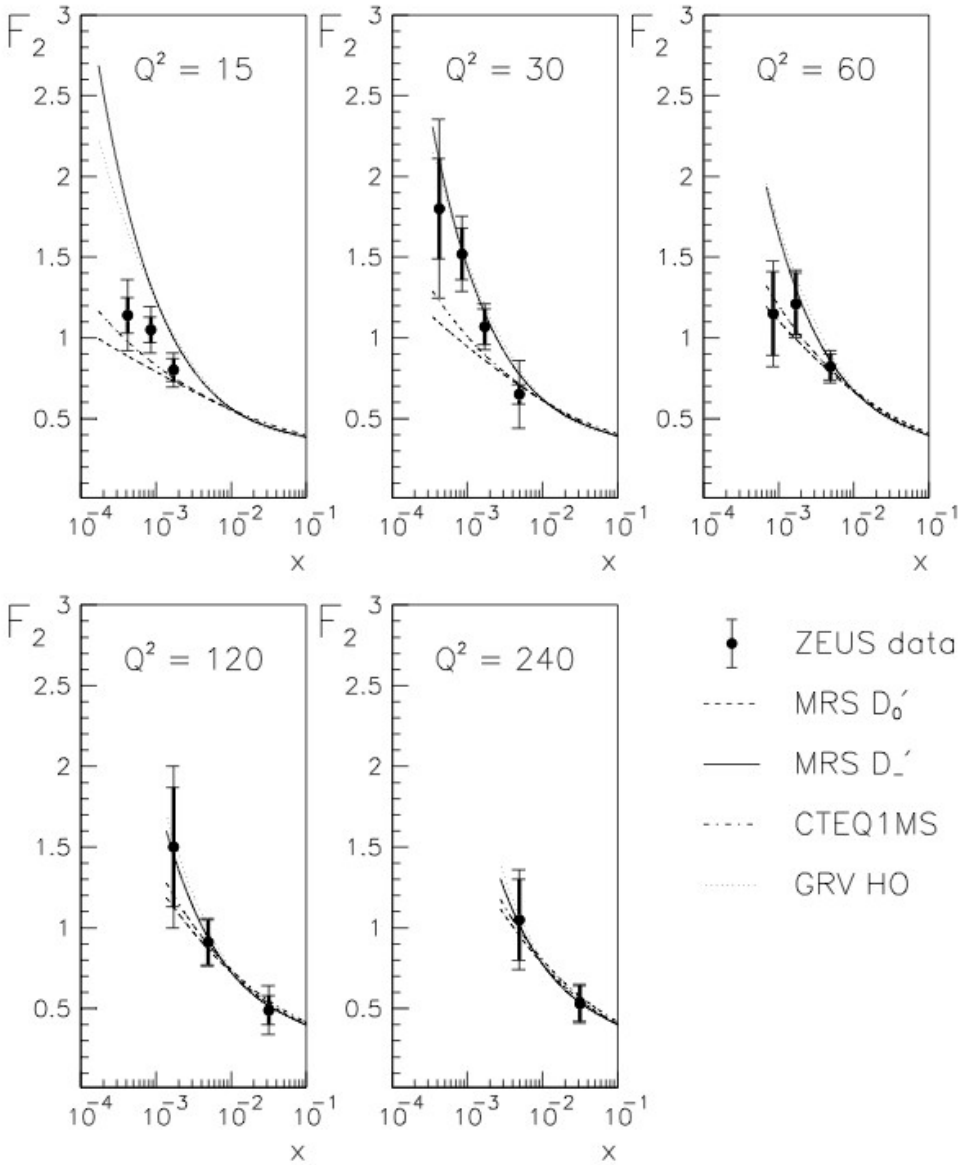
it is exciting to see F_2 rise at small x.

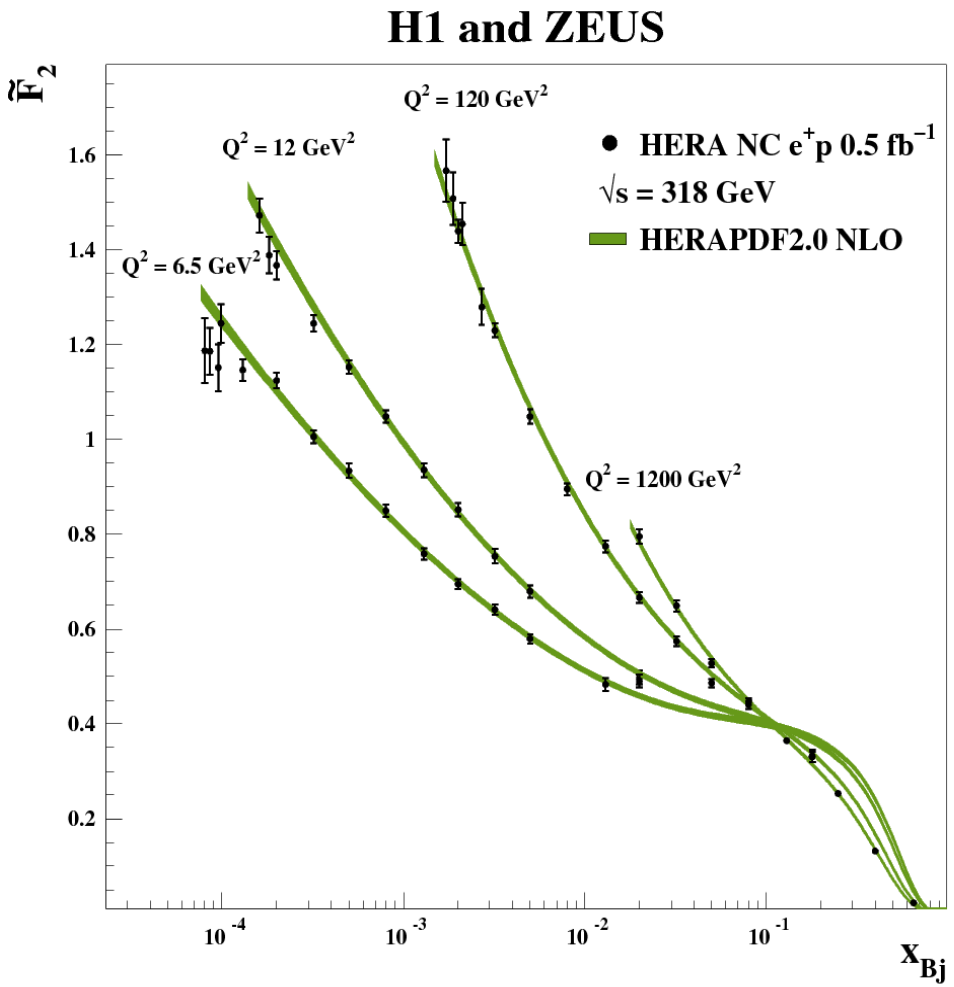
First → Final


F2
ZEUS data
MRS D_'
MRS D0'
x=0.00042 (x 10^4)
x=0.00085 (x 10^3)
x=0.0017 (x 10^2)
x=0.0049 (x 10)
x=0.032
Q^2 (GeV^2)


H1 and ZEUS
HERA NC e⁻p 0.4 fb⁻¹
HERA NC e⁺p 0.5 fb⁻¹
√s = 318 GeV
Fixed Target
HERAPDF2.0 e⁻p NNLO
HERAPDF2.0 e⁺p NNLO
σ_r,NC x 2^i
Q²/ GeV²

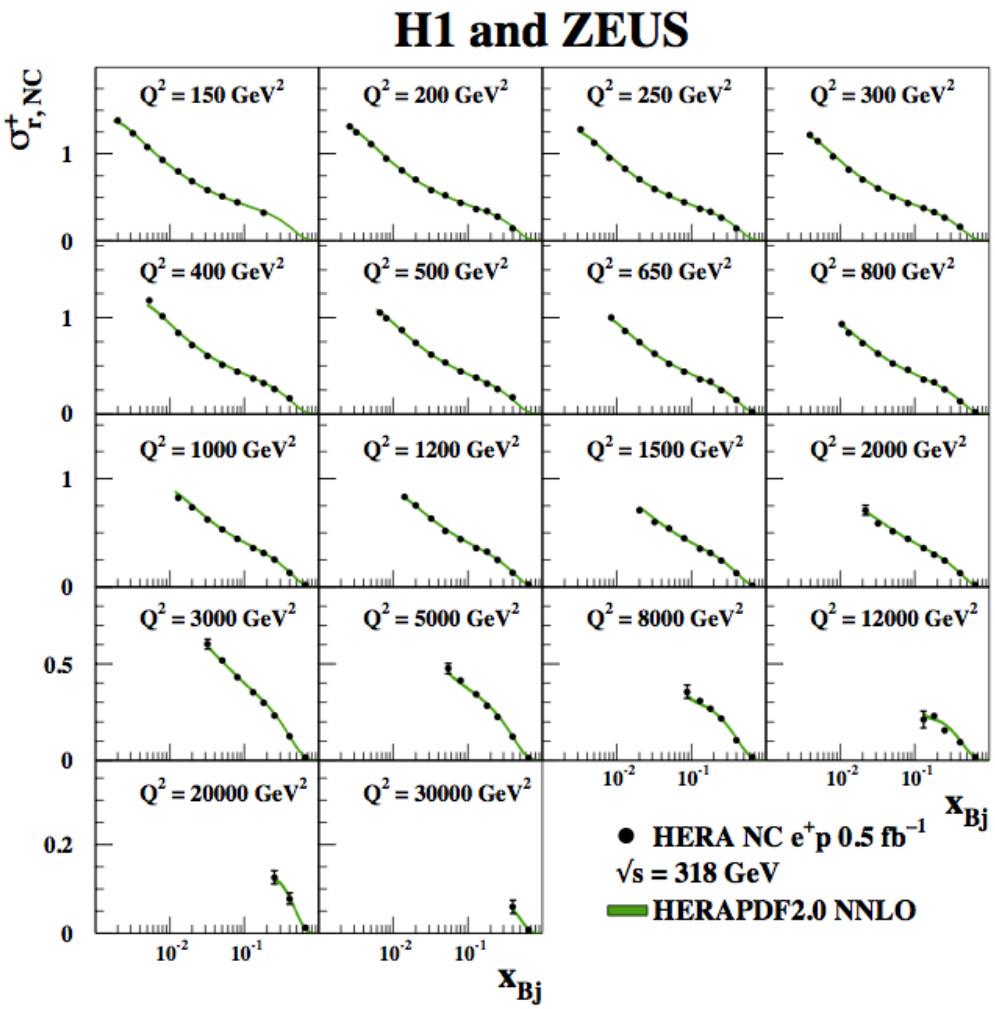
1993 → 2015


F_2
Q^2 = 15
Q^2 = 30
Q^2 = 60
Q^2 = 120
Q^2 = 240
x
ZEUS data
MRS D_0'
MRS D_-'
CTEQ1MS
GRV HO


H1 and ZEUS
$\tilde{F}_2$
Q^2 = 120 GeV^2
Q^2 = 12 GeV^2
Q^2 = 6.5 GeV^2
Q^2 = 1200 GeV^2
HERA NC e^+p 0.5 fb^{-1}
$\sqrt{s}$ = 318 GeV
HERAPDF2.0 NLO
x_{Bj}

Neutral Current

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$



Proton structure functions

$$F_2 = x\sum e_q^2[q(x) + \bar{q}(x)]$$

- Sensitive to quarks

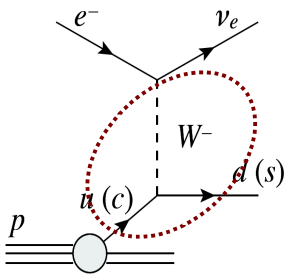
$$xF_3 = x\sum 2e_q a_q[q(x) - \bar{q}(x)]$$

- Sensitive to valence distributions

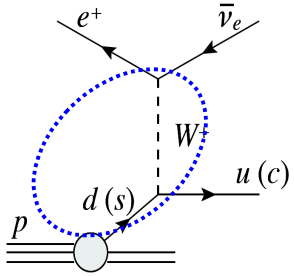
$$F_L \sim \alpha_S \, x \, g$$

- Sensitive to gluon

- Gluon also from scaling violation and charm+jet data

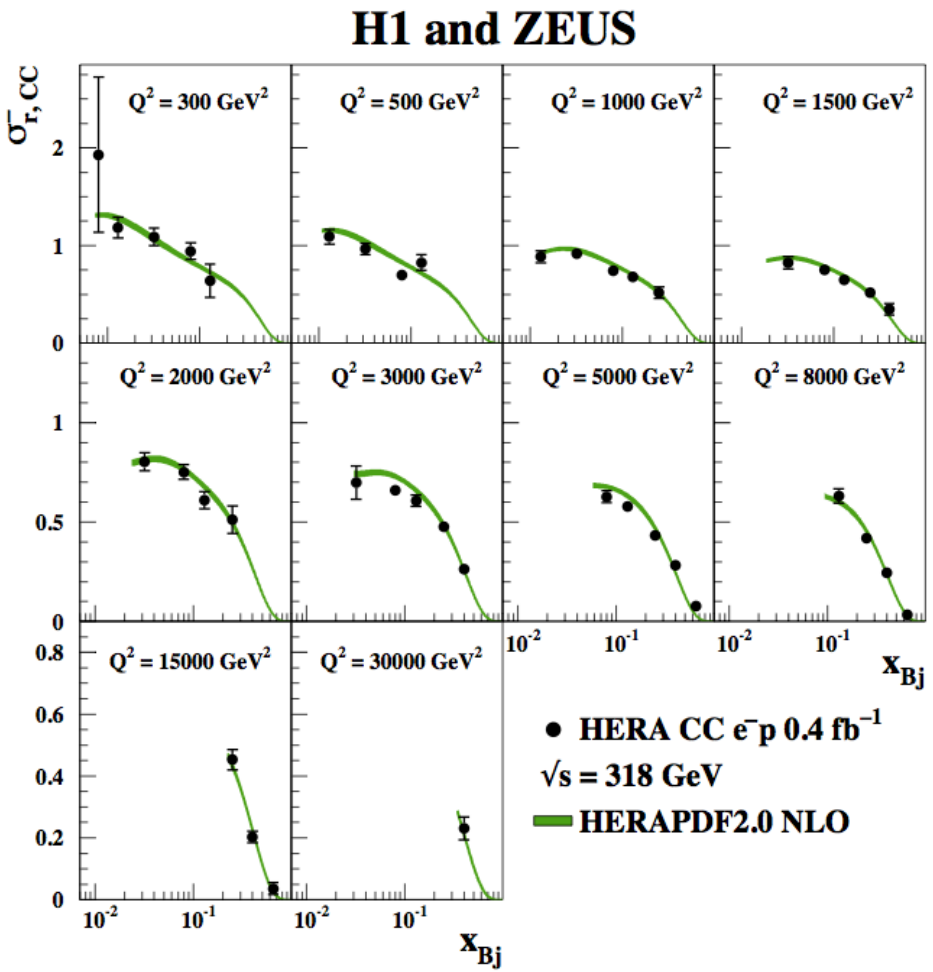


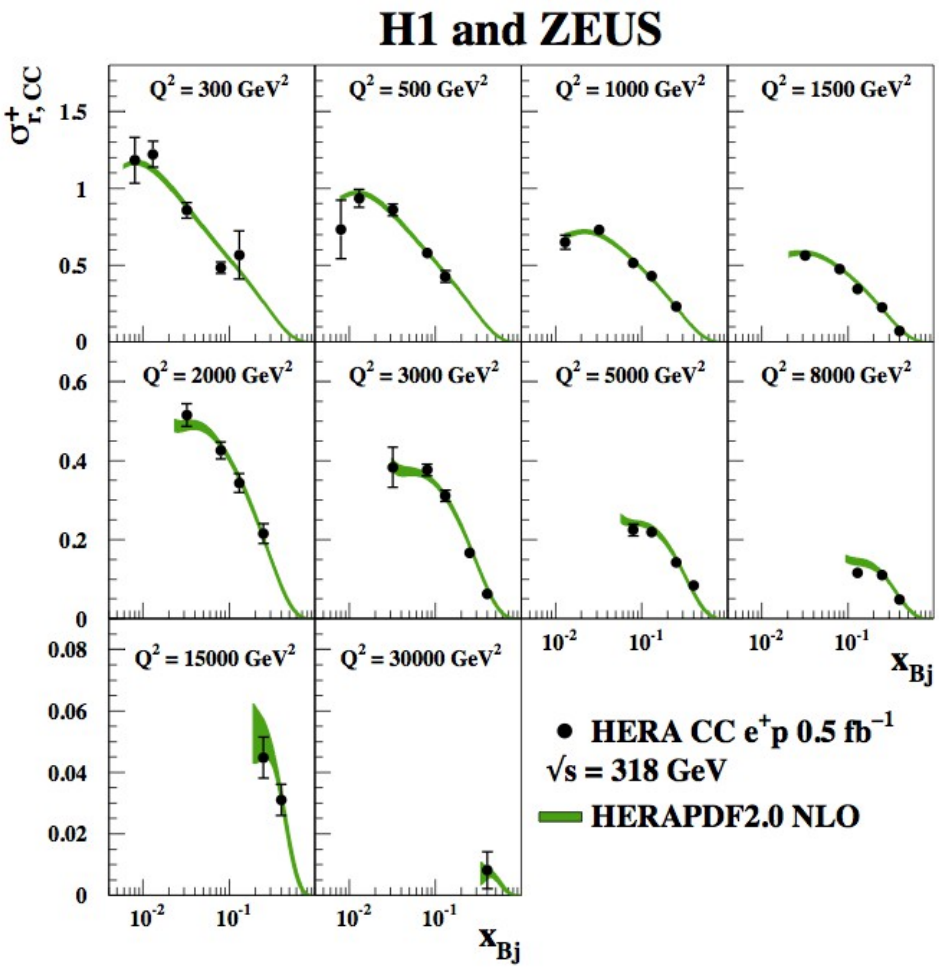
Charge Current: flavor decomposition



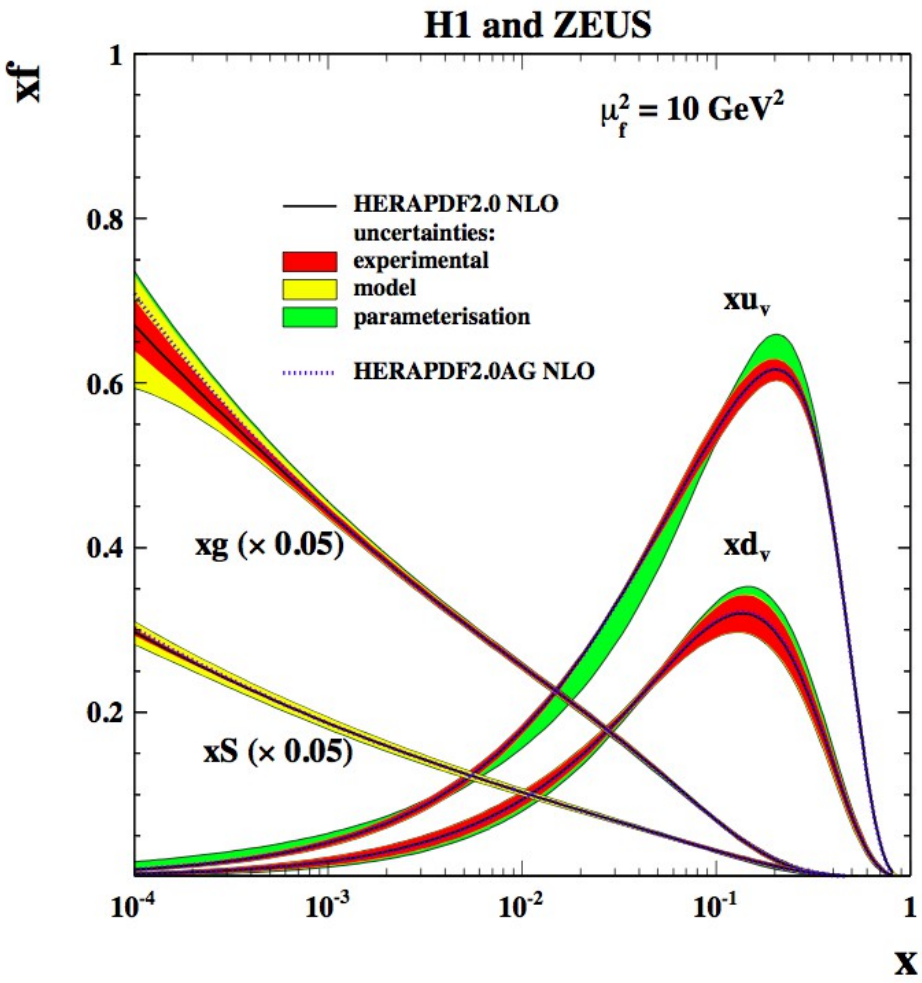
$$\sigma^{-}_{CC} \sim x[u + c] + x(1 - y)^2[\bar{d} + \bar{s}]$$

$$\sigma^{+}_{CC} \sim x[\bar{u} + \bar{c}] + x(1 - y)^2[d + s]$$





Color decomposition of uncertainties



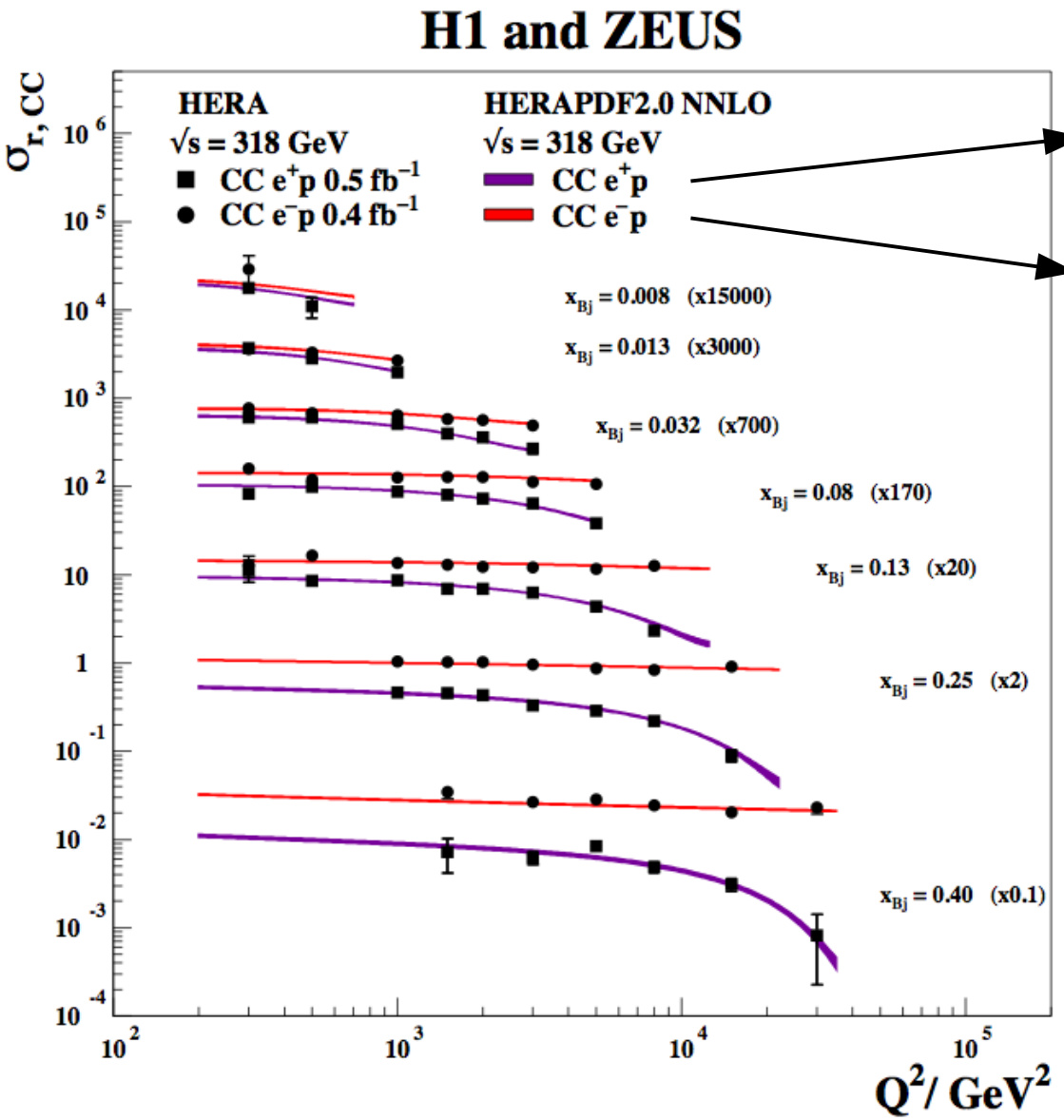
- Experimental uncertainties:
  - Hessian method
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

Adding D and E parameters to each PDF

- Parametrisation uncertainties
  - largest deviation
- Model uncertainties
  - all variations added in quadrature

CC: helicity effects

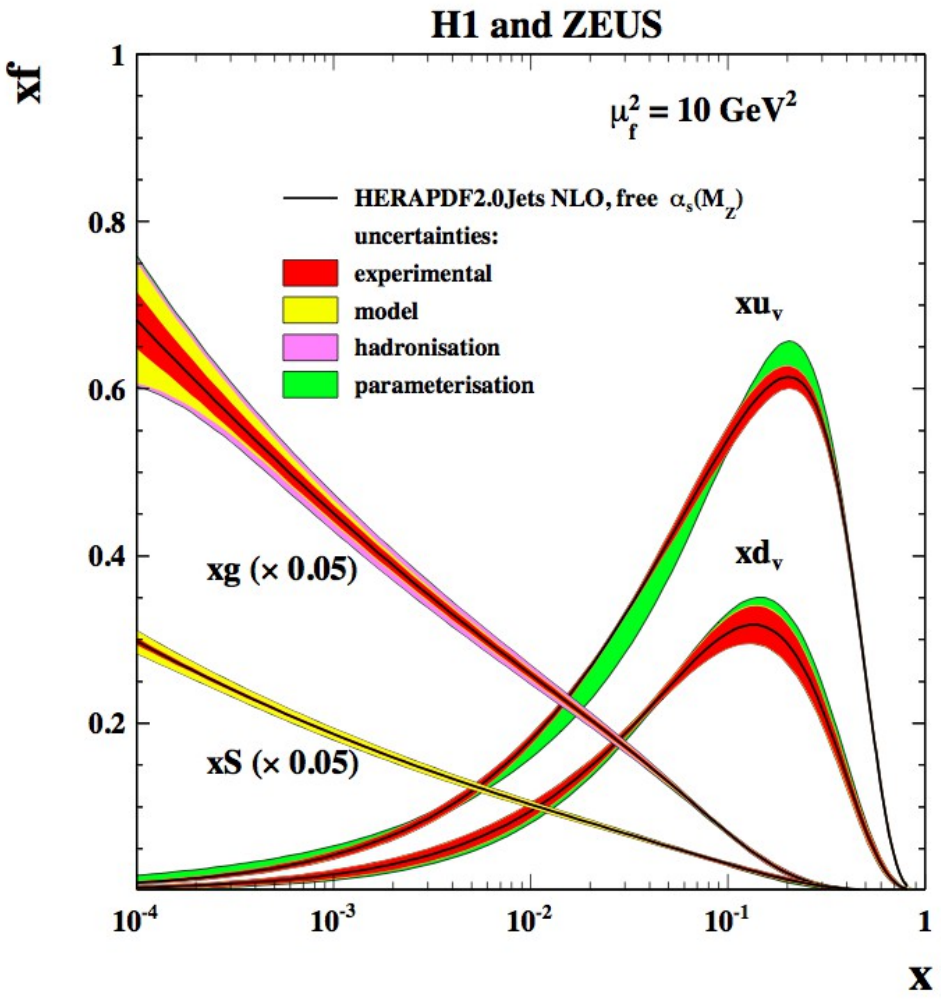


$$\sigma^{+}_{CC} \sim x[\bar{u} + \bar{c}] + x(1-y)^2[d + s]$$

$$\sigma^{-}_{CC} \sim x[u + c] + x(1-y)^2[\bar{d} + \bar{s}]$$

- e^+p: d_V quarks are suppressed at high Q^2
- e^-p: helicity factor applies to sea quarks only

HERAPDF2.0Jets α_s free



α_s determined from QCD fit

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0009(\text{exp})$$

Experimental uncertainty below 1%

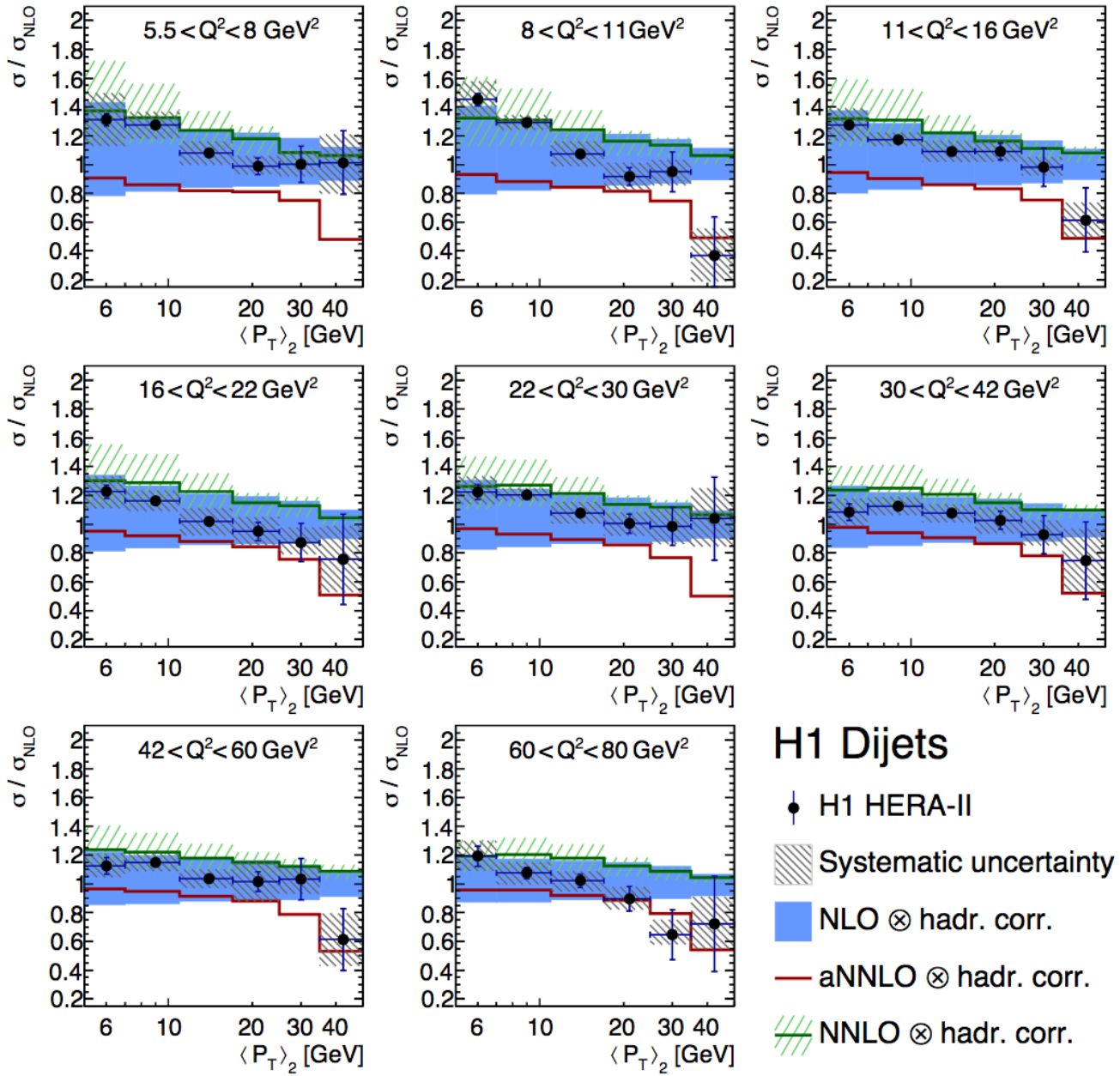
$$\pm\, 0.0005(\text{model/parameterisation})$$

$$\pm\, 0.0012(\text{hadronisation})$$

$$^{+0.0037}_{-0.0030}(\text{scale})$$

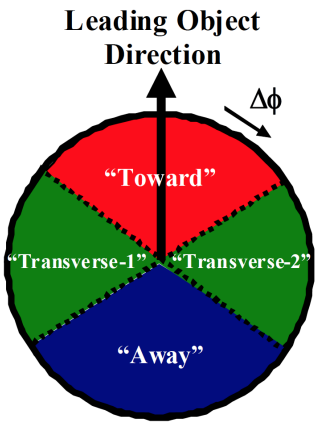
Uncertainty dominated by theory
NNLO ep jet calculations needed

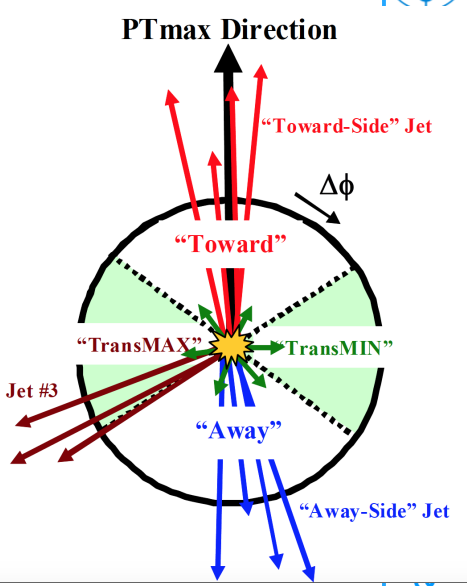
H1 dijets with NNLO predictions



Used in MC tuning: underlying event

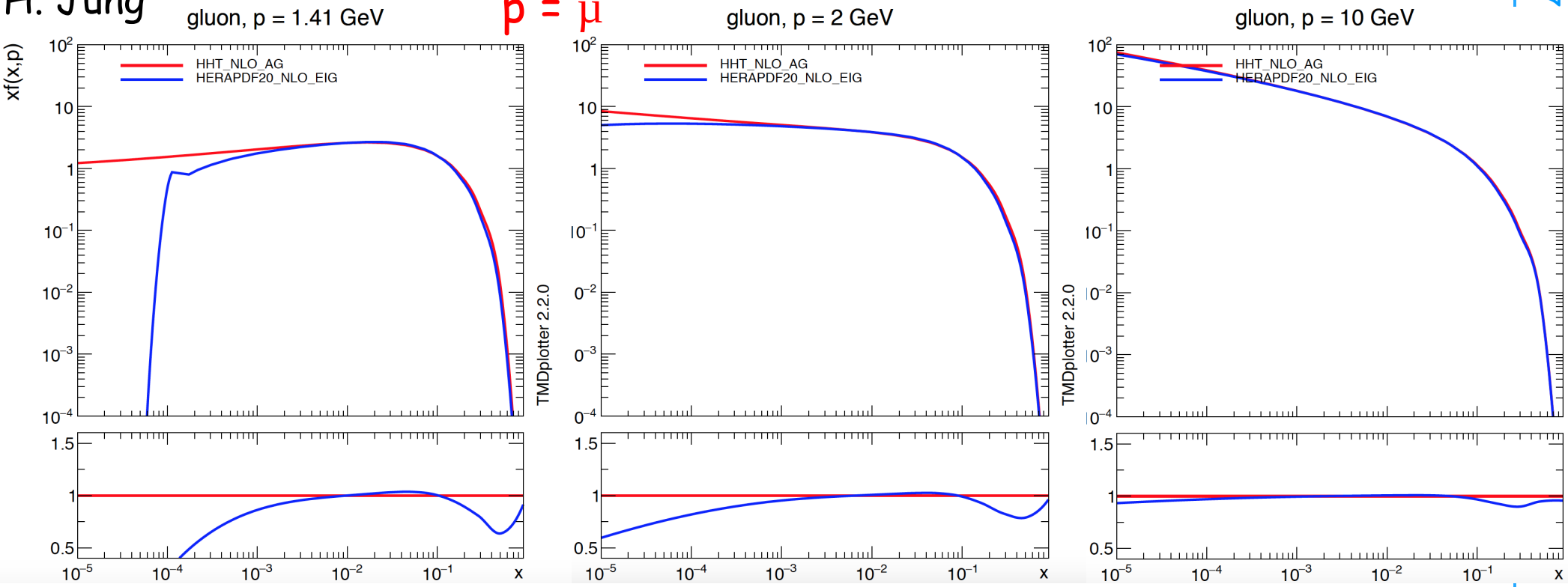
- Interest in MC community for PDF describing data well down to lowest possible Q^2
  - HHT NLO AG can be used → AG (alternative gluon): no negative gluon term
  - First use: tune for underlying event, private work done in CMS





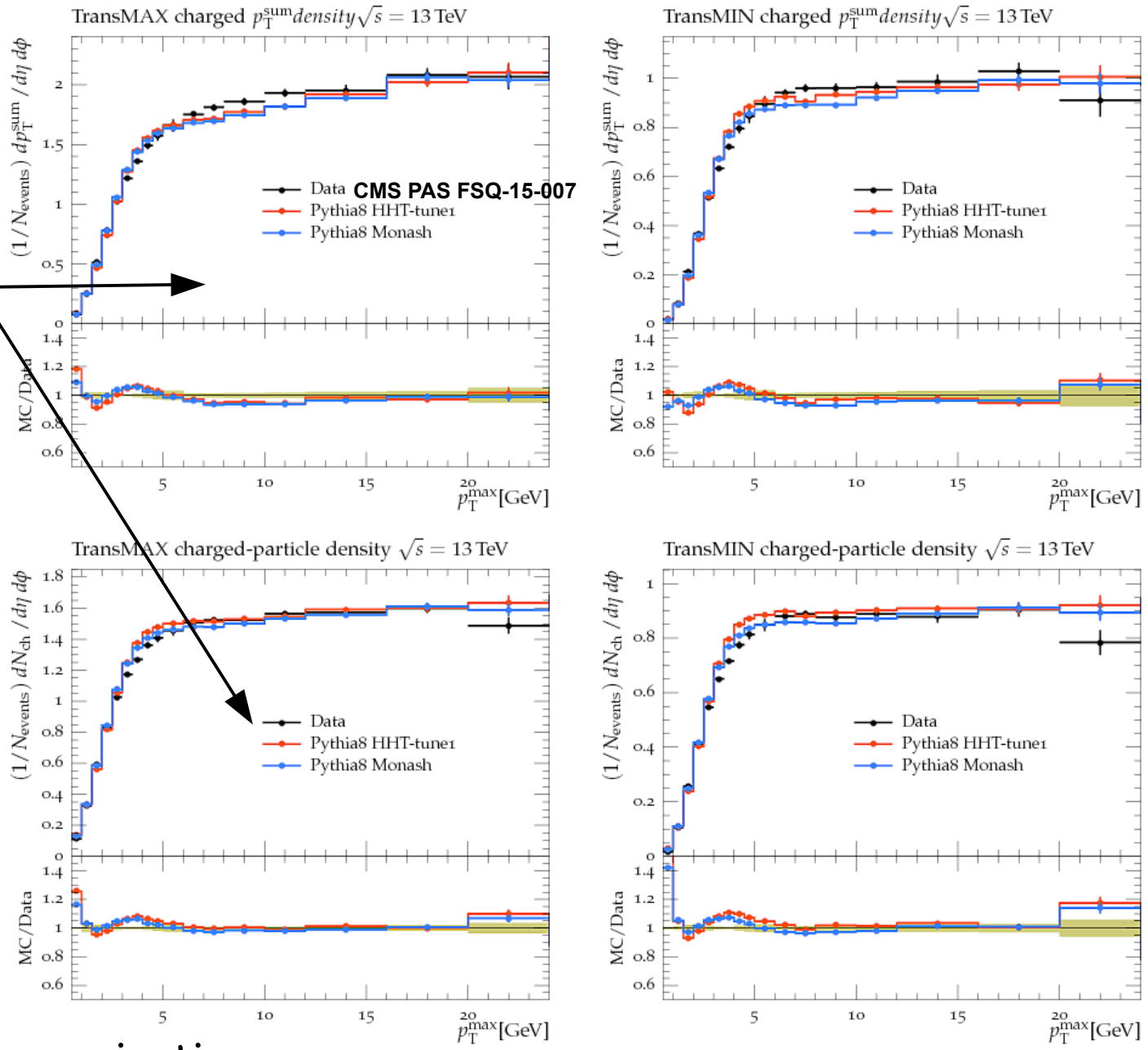
H. Jung

p = μ



MC tuning: underlying event

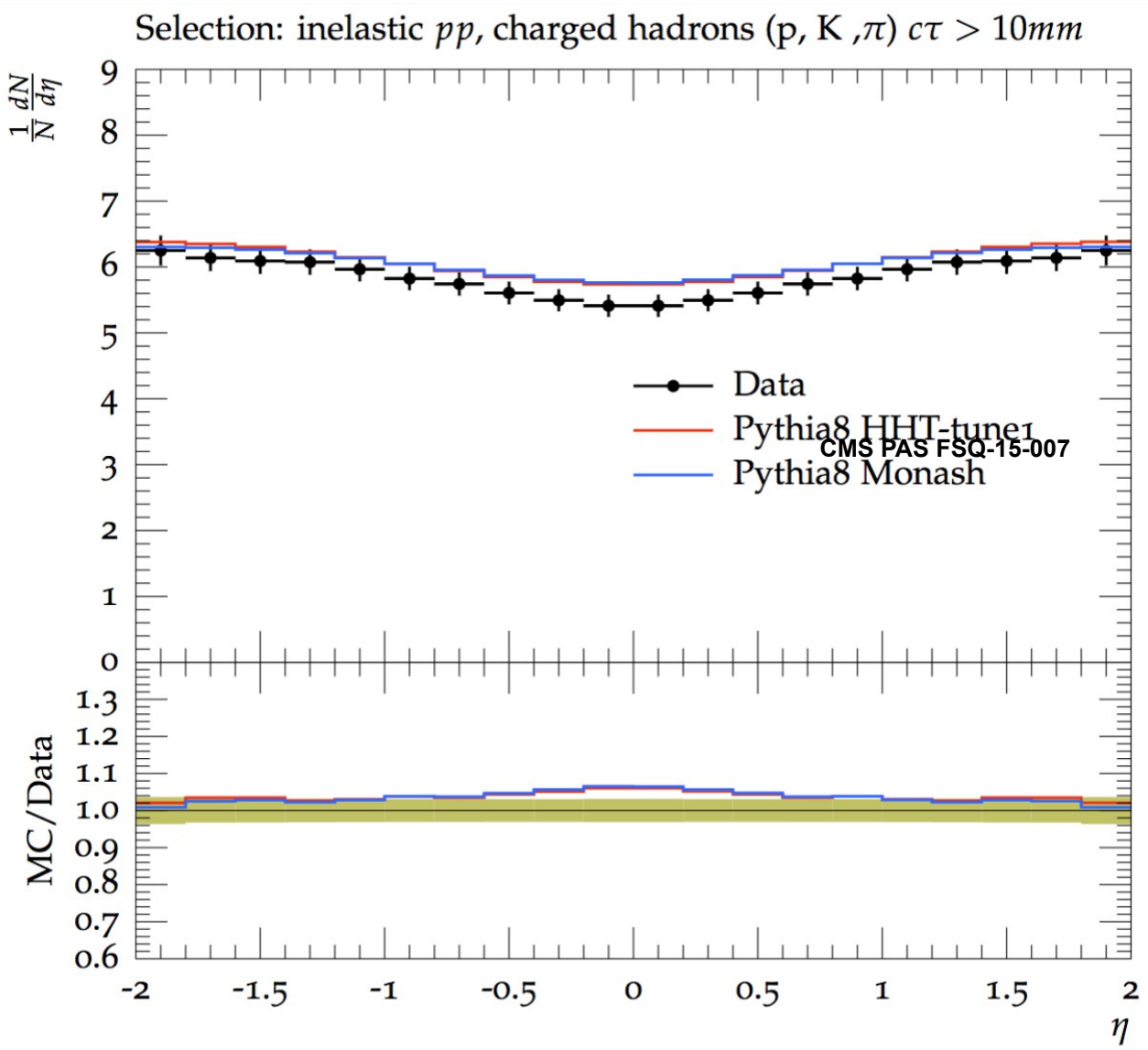
- 4 tuned variables
- 1 tuned parameter



P. Gunnellini, private communication

MC tuning

- Global variable: compares well with standard Monash tune with NNPDF

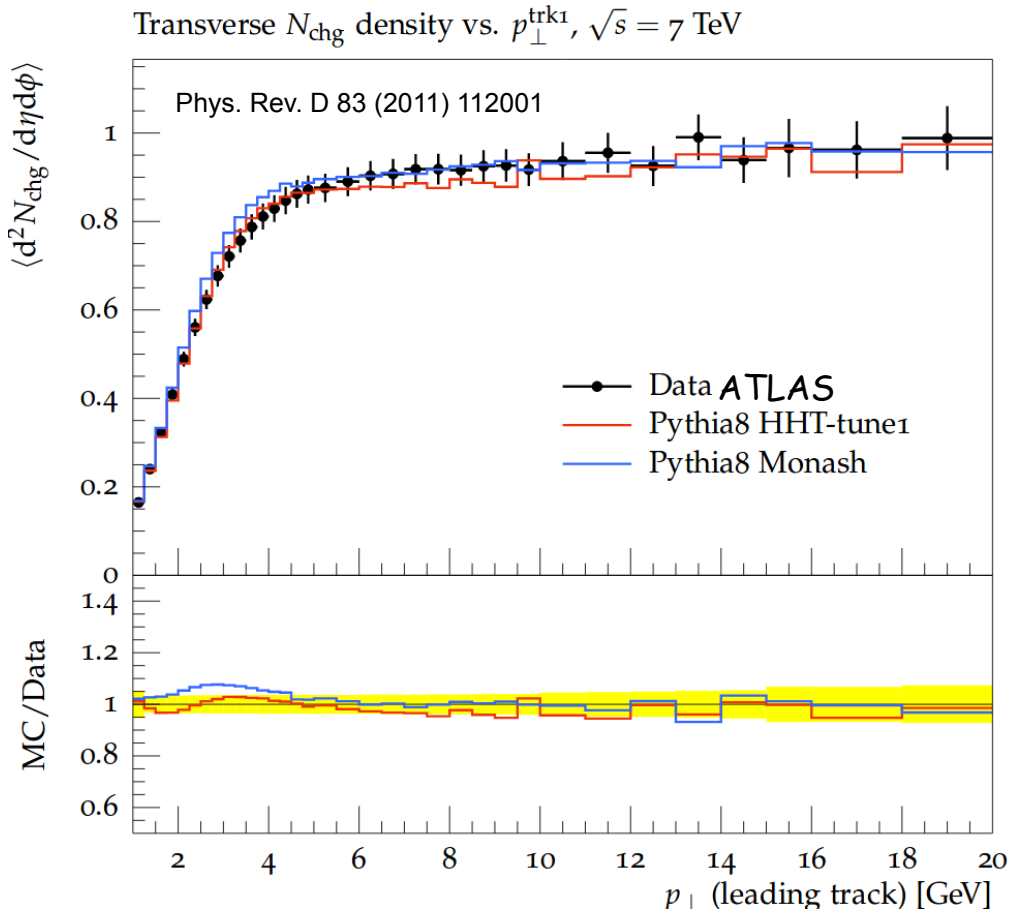


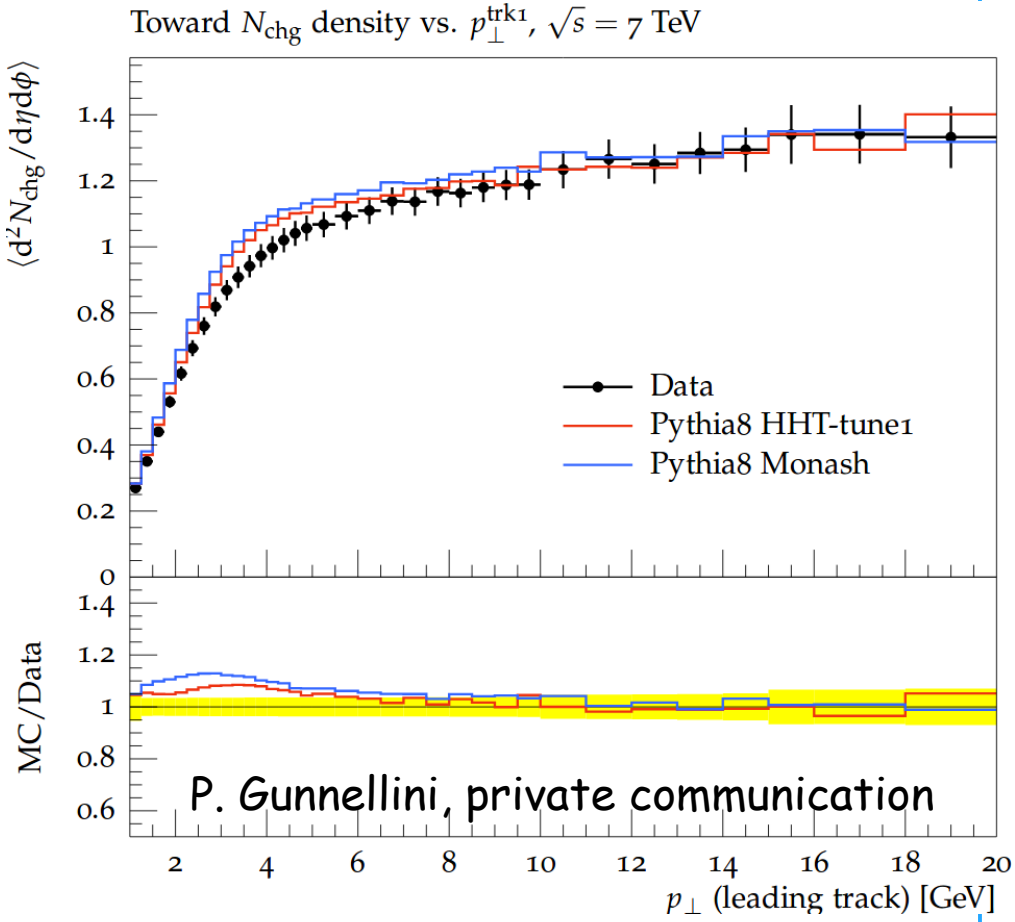
P. Gunnellini, private communication

MC tuning: comparison to ATLAS data

Phys. Rev. D 83 (2011) 112001

- Compares well with standard Pythia Monash tune
  - Sometimes better / sometimes a bit worse

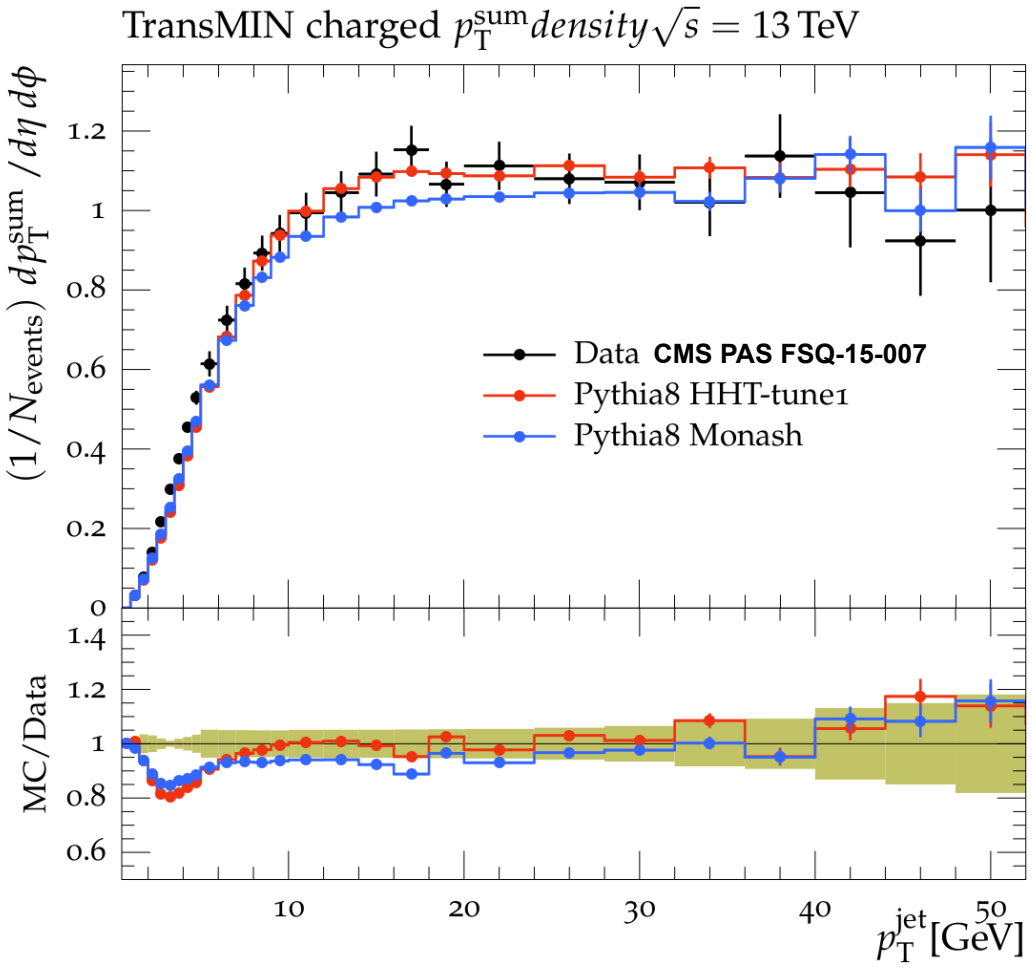


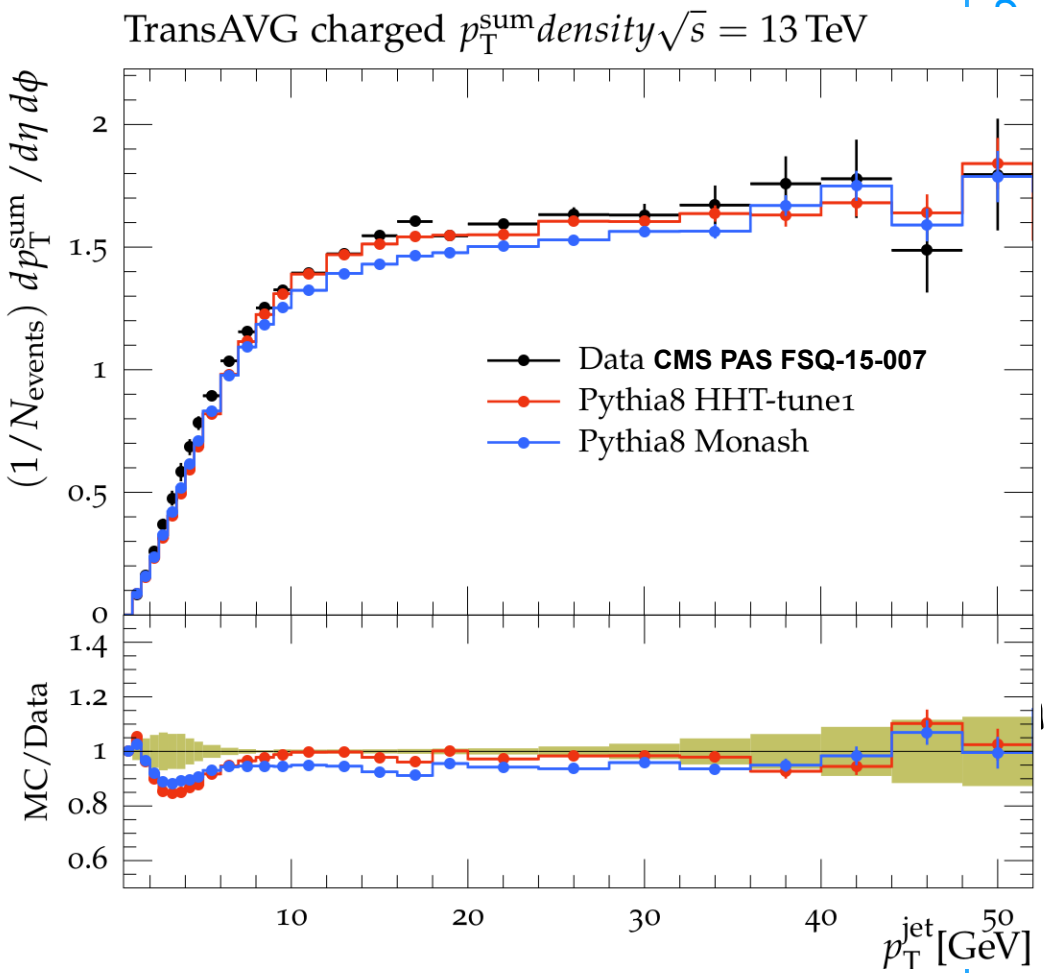


- Work in progress → hope that for tunes with lower energies PDF better describing low Q^2 will be beneficial

MC tuning

- Compares well with standard Pythia Monash tune – with NNPDF
  - Examples of better description for some variables

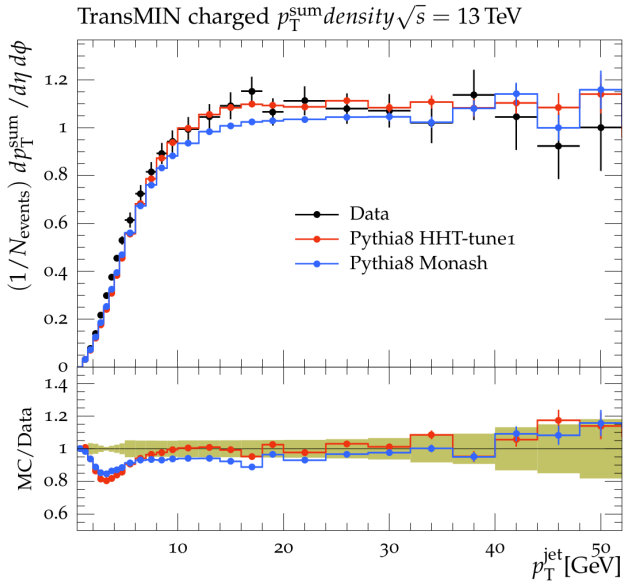




P. Gunnellini, private communication

Summary & Prospects

- Study of adding higher twist terms to the HERAPDF2.0 analysis of combined HERA data for NLO and NNLO fits presented
  Phys. Rev. D 94, 034032 (2016), arXiv:1604.02299
- Such terms are significant in F_L for $2 < Q^2 < 50$ GeV^2
- χ^2 improved significantly
  - NNLO fits clearly better than NLO
- Higher twist terms important for low x, Q^2
- Simple approach fails for $Q^2 < 2$ GeV^2



- HHT NLO AG released to MC community
  - PDF solid down to low p_T
  - This is something that should be used in MC tuning for underlying event
  - There is also newer higher-twist calculation by L. Motyka et al. that gives PDFs down to 1 GeV^2: arXiv1707.05992
  - As low in x, Q^2 as possible → to avoid any assumption and extrapolation of PDFs → reduction of uncertainties

F_2 and $\sigma^{\gamma^* p}$

$$\sigma_{r,\mathrm{NC}}^{e^+p} = F_2 - \frac{y^2}{Y_+} F_\mathrm{L}$$

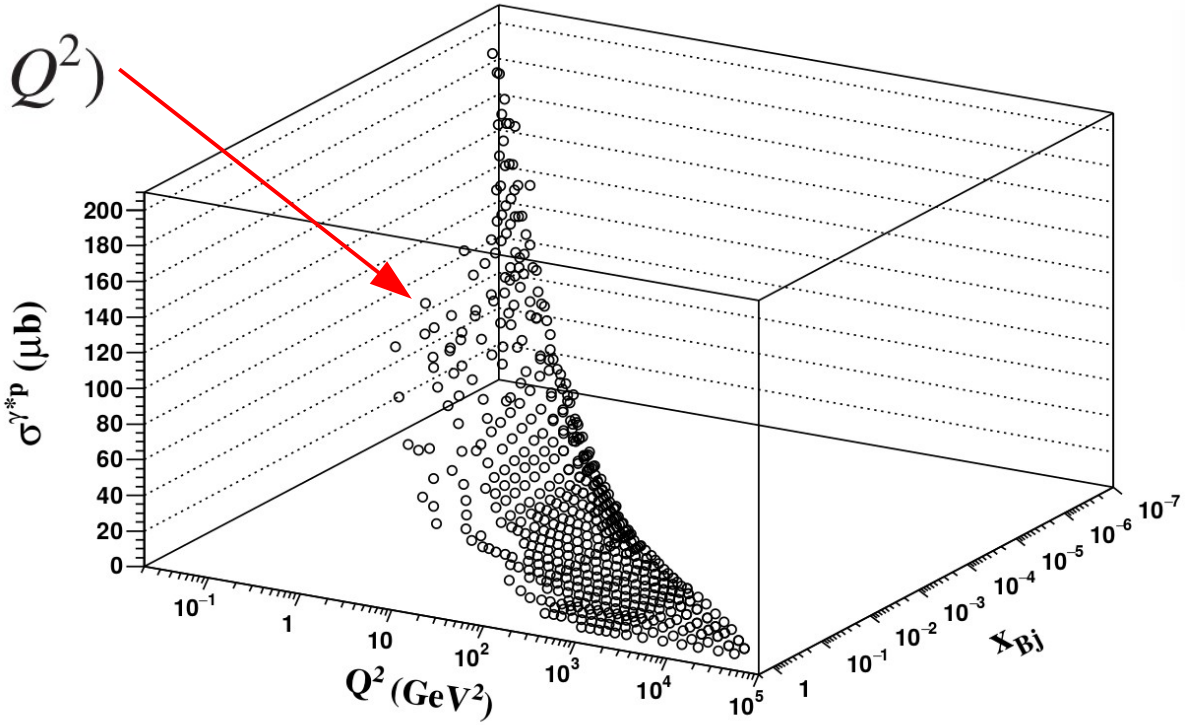
- Extracting F_2 tricky – no unbiased way exists

$$F_2^{\mathrm{extracted}} = F_2^{\mathrm{predicted}} \frac{\sigma_r^{\mathrm{measured}}}{\sigma_r^{\mathrm{predicted}}}$$

- Low Q^2: Regge inspired BKS
- **High Q^2: pQCD HHT NNLO**

- Extracting cross section for virtual photon exchange, $\sigma^{\gamma^* p}$, tricky

$$\sigma^{\gamma^* p}(x_{\mathrm{Bj}}, Q^2) = \frac{4\pi^2\alpha}{Q^2} F_2(x_{\mathrm{Bj}}, Q^2)$$



$\sigma^{\gamma^* p}$ forms smooth plane
→ no abrupt features around transition point ~ 1 GeV^2

How about Regge phenomenology?

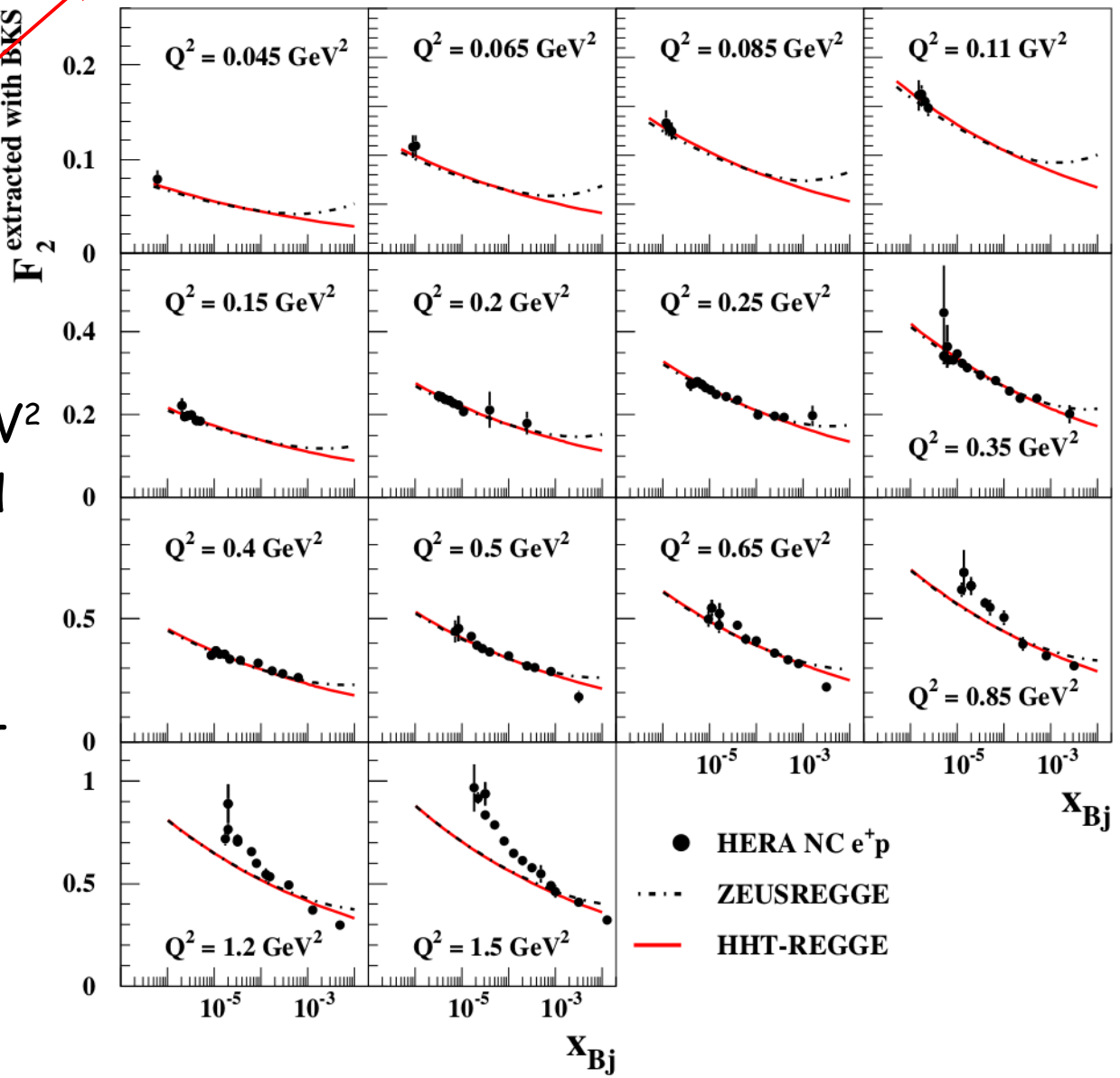
$$F_2(x_{\mathrm{Bj}}, Q^2) = \frac{Q^2}{4\pi^2\alpha} \cdot \frac{M_0^2}{M_0^2 + Q^2} \cdot \left(A_{I\!P} \left(\frac{Q^2}{x_{\mathrm{Bj}}} \right)^{\alpha_{I\!P}(0)-1} + A_{I\!R} \left(\frac{Q^2}{x_{\mathrm{Bj}}} \right)^{\alpha_{I\!R}(0)-1} \right)$$

GVMD

- HHT-REGGE
  - 3 parameters fitted to P
  - $Q^2 \lesssim 0.65\,\mathrm{GeV}^2$
- Good description to ~0.65 GeV²
  - Regge formalism expected to break around that Q²
- Various fits tested

→ All fits compatible with soft Pomeron expectations

$$\alpha_{I\!P}(0) \approx 1.08$$

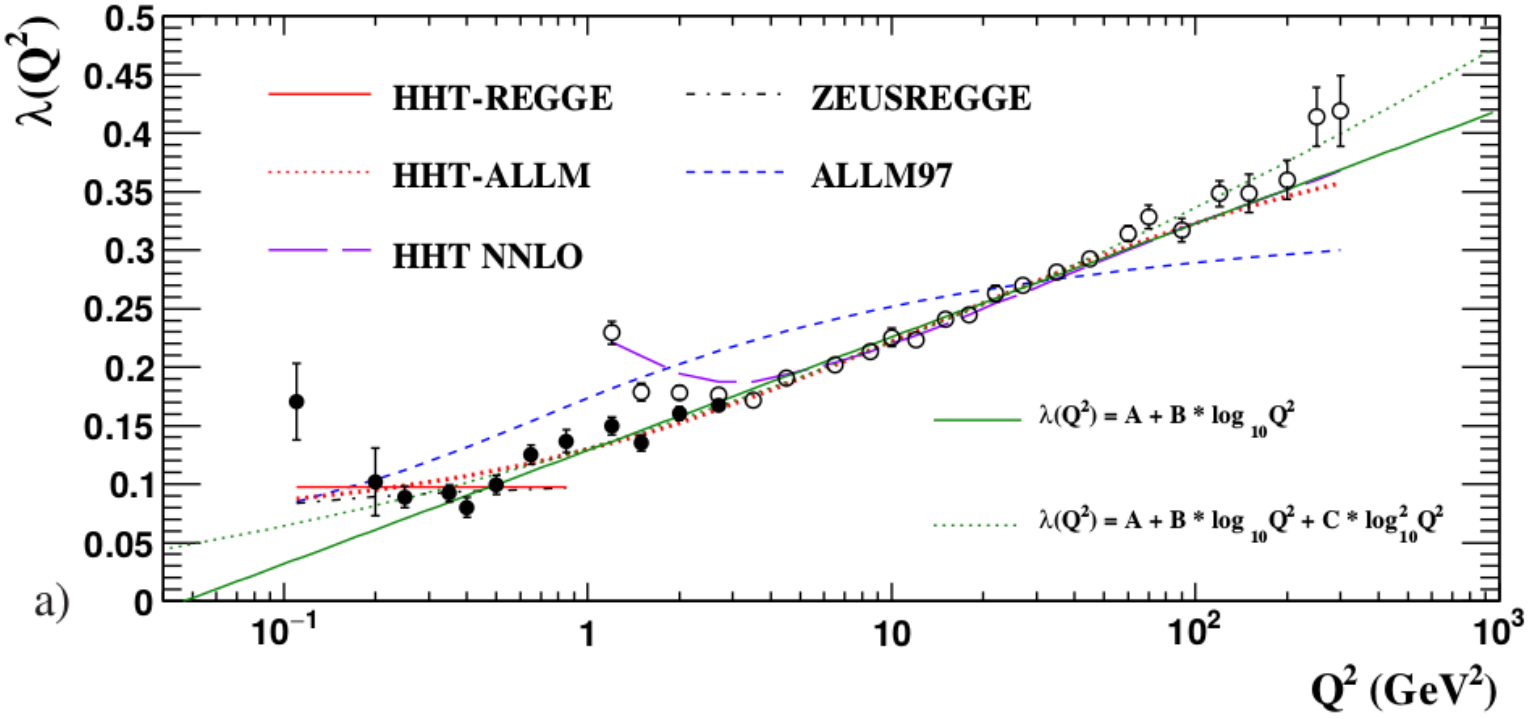


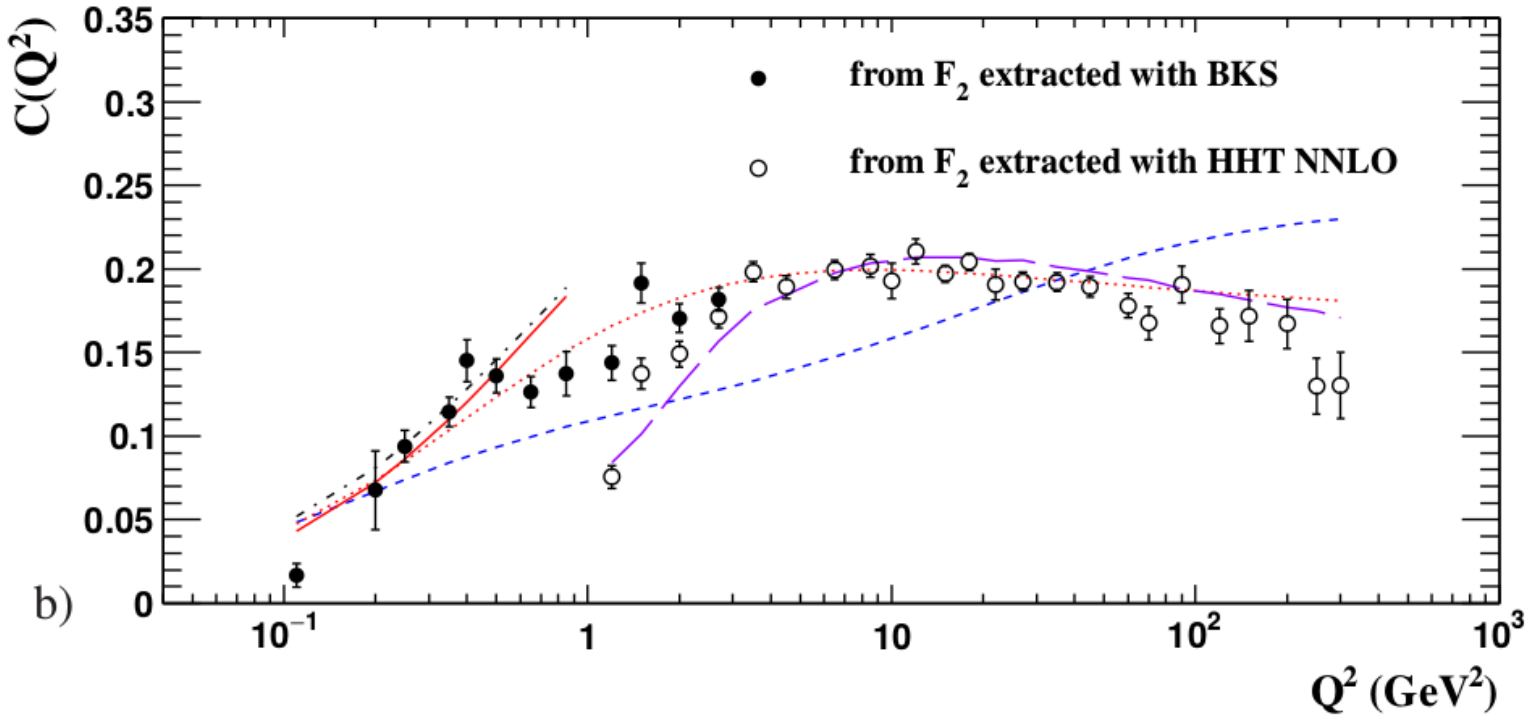
Regge fits

Name of Fit	Fit Parameters					χ^2/ ndf
	M_0^2 (GeV^2)	$A_{I\!P}$ (μb)	$\alpha_{I\!P}(0)$	$A_{I\!R}$ (μb)	$\alpha_{I\!R}(0)$	
HHT-REGGE	0.50 ±0.03	66.3 ± 3.2	1.097 ± 0.004	fixed to 0	–	0.83
3p-.85	0.58 ±0.03	58.5 ± 2.5	1.105 ± 0.003	fixed to 0	–	1.13
4p	0.49 ±0.03	78.5 ± 7.1	1.082 ± 0.008	−230 ±105	fixed to 0.5	0.78
FT-4p	0.50 ±0.02	77.4 ± 5.6	1.083 ± 0.006	−217 ± 60	fixed to 0.5	0.75
PHP-5p	0.52 ±0.01	57.0 ± 4.7	1.110 ± 0.007	193 ± 51	0.50 ±0.11	1.16
PHP-FT-5p	0.48 ±0.01	58.9 ± 3.0	1.110 ± 0.005	263 ± 69	0.39 ±0.09	1.35
ZEUSREGGE	fixed to 0.53	63.5 ± 0.9	1.097 ± 0.002	145 ± 2	fixed to 0.5	1.12
update	0.52 ± 0.04	62.0 ± 2.3	1.102 ± 0.007	148 ± 5	fixed to 0.5	–

Pomeron trajectory $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$

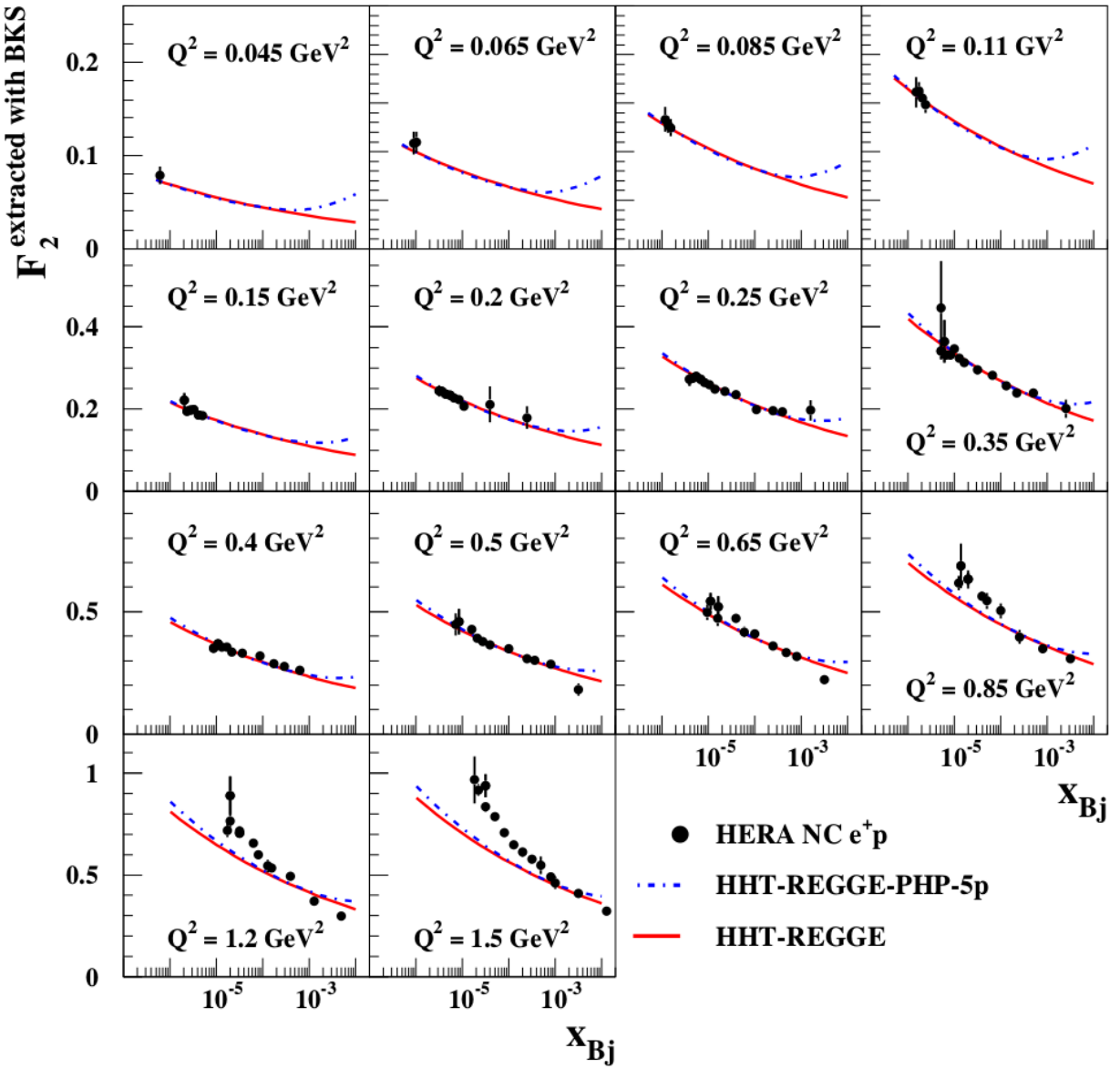
soft Pomeron: $\alpha_{I\!P}(0) \approx 1.08$


λ(Q²)
HHT-REGGE
ZEUSREGGE
HHT-ALLM
ALLM97
HHT NNLO
λ(Q²) = A + B * log 10 Q²
λ(Q²) = A + B * log 10 Q² + C * log²10 Q²
a)
Q² (GeV²)


C(Q²)
from F2 extracted with BKS
from F2 extracted with HHT NNLO
b)
Q² (GeV²)

HHT-REGGE fits

- With addition of low-W PhP data Reggeon parameters can be constrained
- Within kinematic range of HERA data description the same
- Adding fixed target data does not improve fits

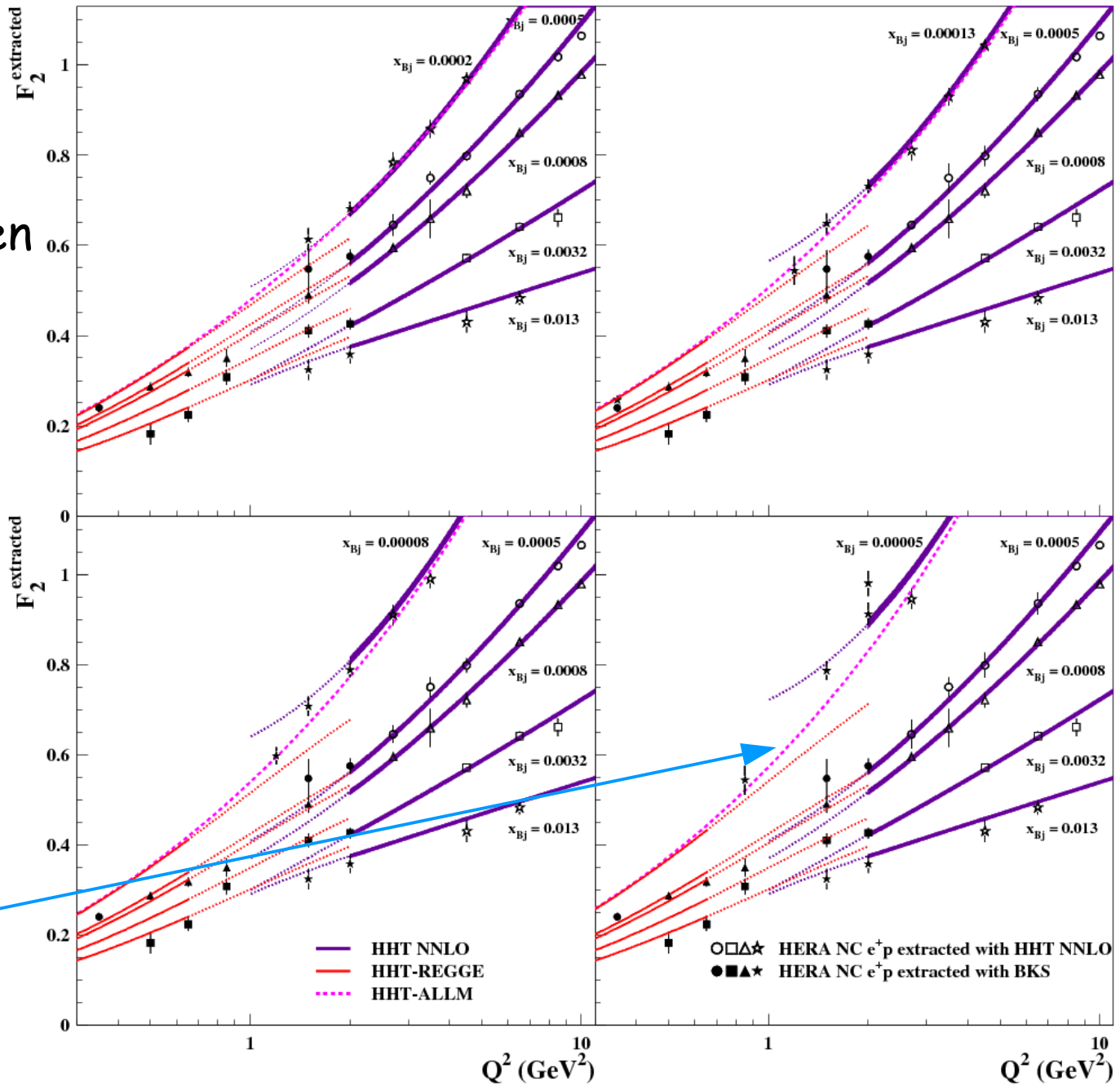


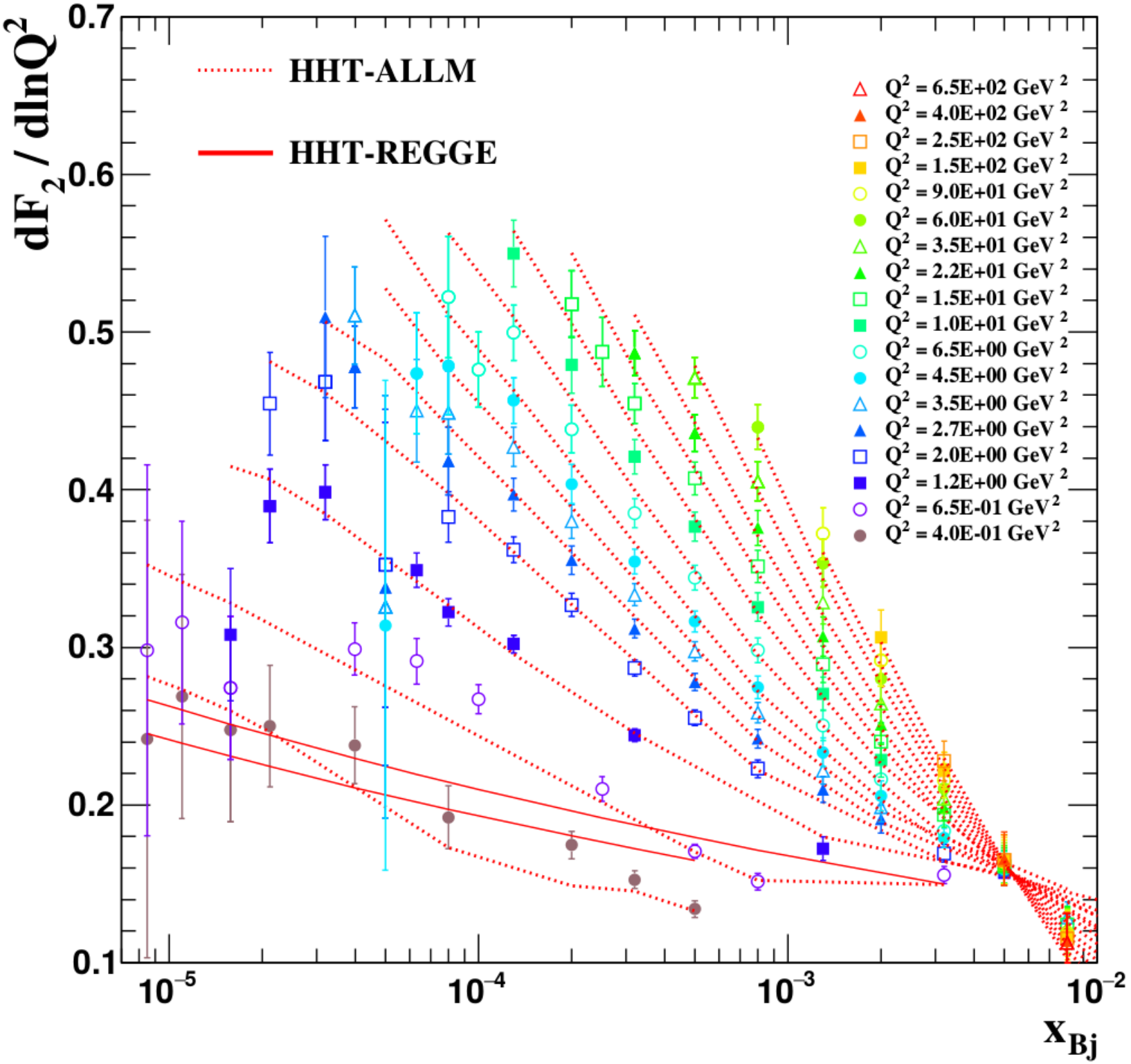
F_2 at lowest x_{Bj}

- As x_{Bj} falls, growing gap opens up between pQCD and Regge extrapolations in transition region

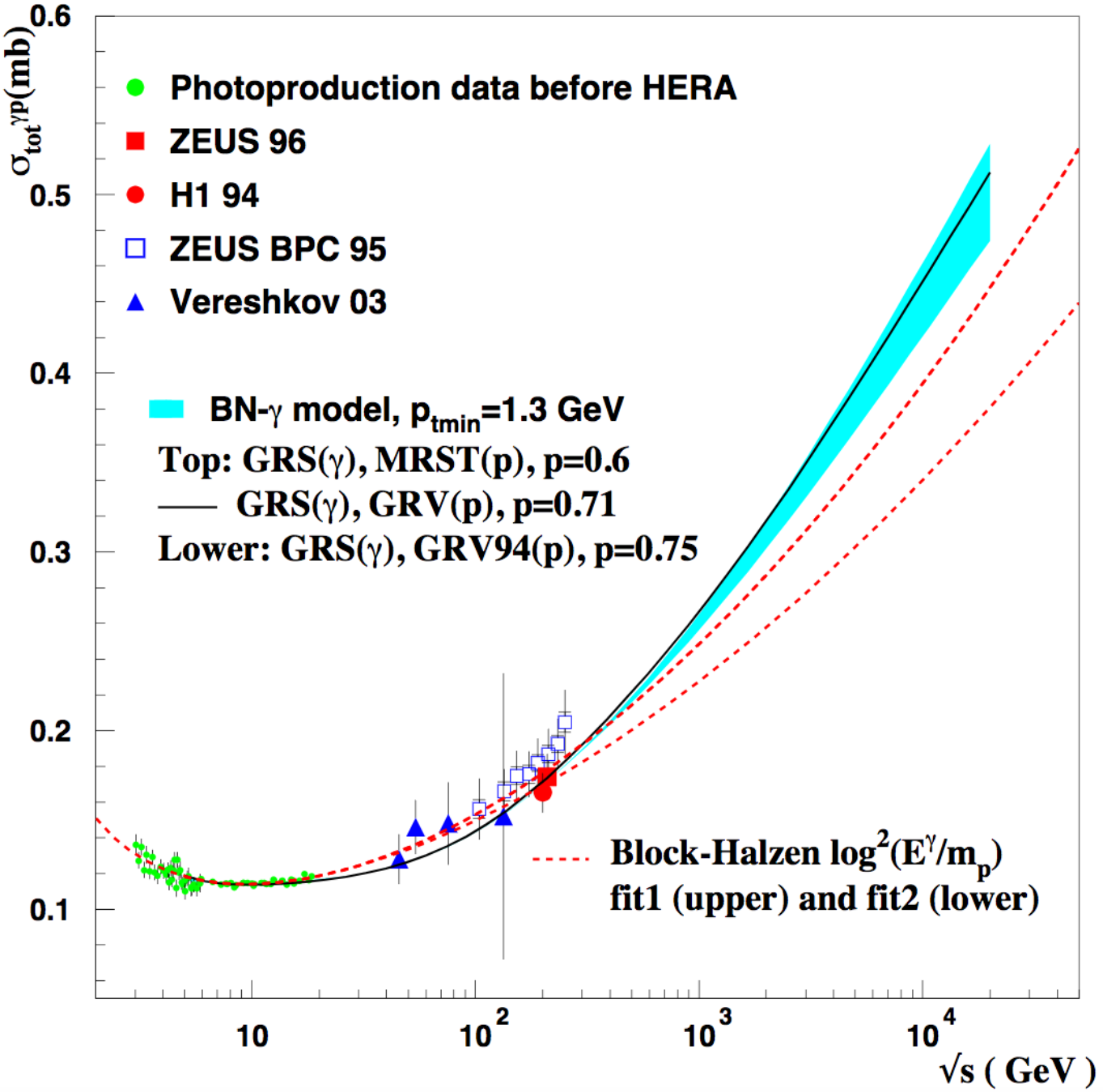
This gap is smoothly bridged by data!

- Region of very low x_{Bj} pinpointed

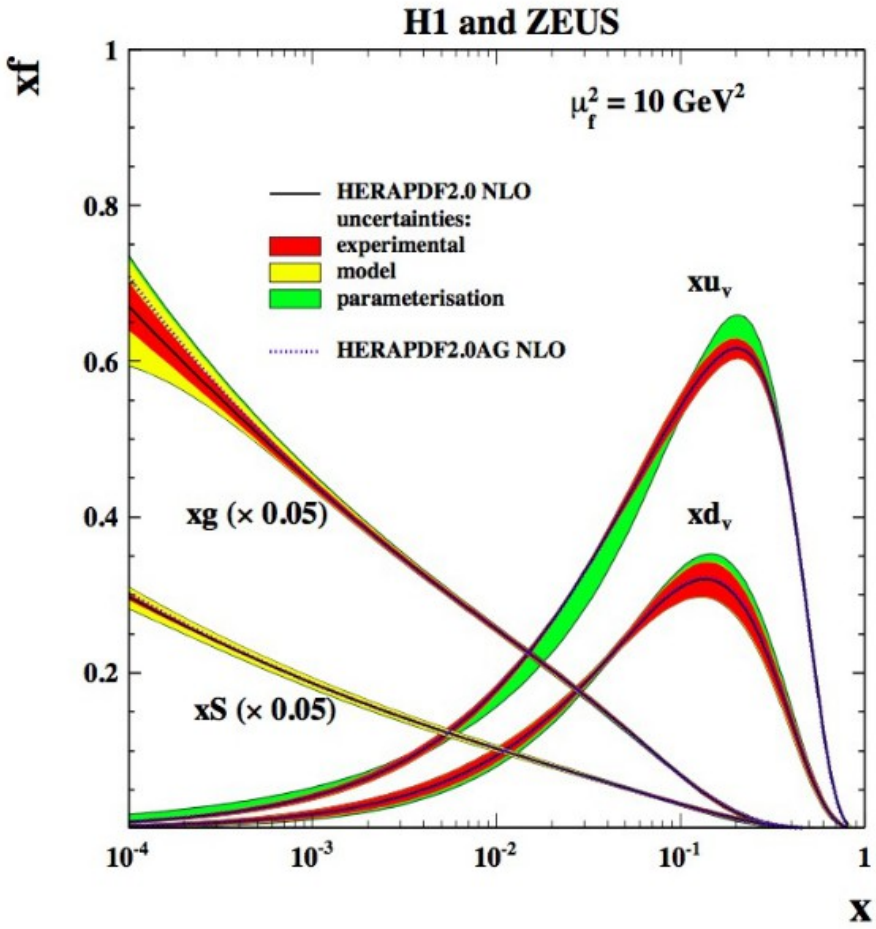



HHT-ALLM
HHT-REGGE
$dF_2 / d\ln Q^2$
x_{Bj}
Q^2 = 6.5E+02 GeV^2
Q^2 = 4.0E+02 GeV^2
Q^2 = 2.5E+02 GeV^2
Q^2 = 1.5E+02 GeV^2
Q^2 = 9.0E+01 GeV^2
Q^2 = 6.0E+01 GeV^2
Q^2 = 3.5E+01 GeV^2
Q^2 = 2.2E+01 GeV^2
Q^2 = 1.5E+01 GeV^2
Q^2 = 1.0E+01 GeV^2
Q^2 = 6.5E+00 GeV^2
Q^2 = 4.5E+00 GeV^2
Q^2 = 3.5E+00 GeV^2
Q^2 = 2.7E+00 GeV^2
Q^2 = 2.0E+00 GeV^2
Q^2 = 1.2E+00 GeV^2
Q^2 = 6.5E-01 GeV^2
Q^2 = 4.0E-01 GeV^2

Total cross section & BN model



Color decomposition of uncertainties



- Experimental uncertainties:
  - Hessian method
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

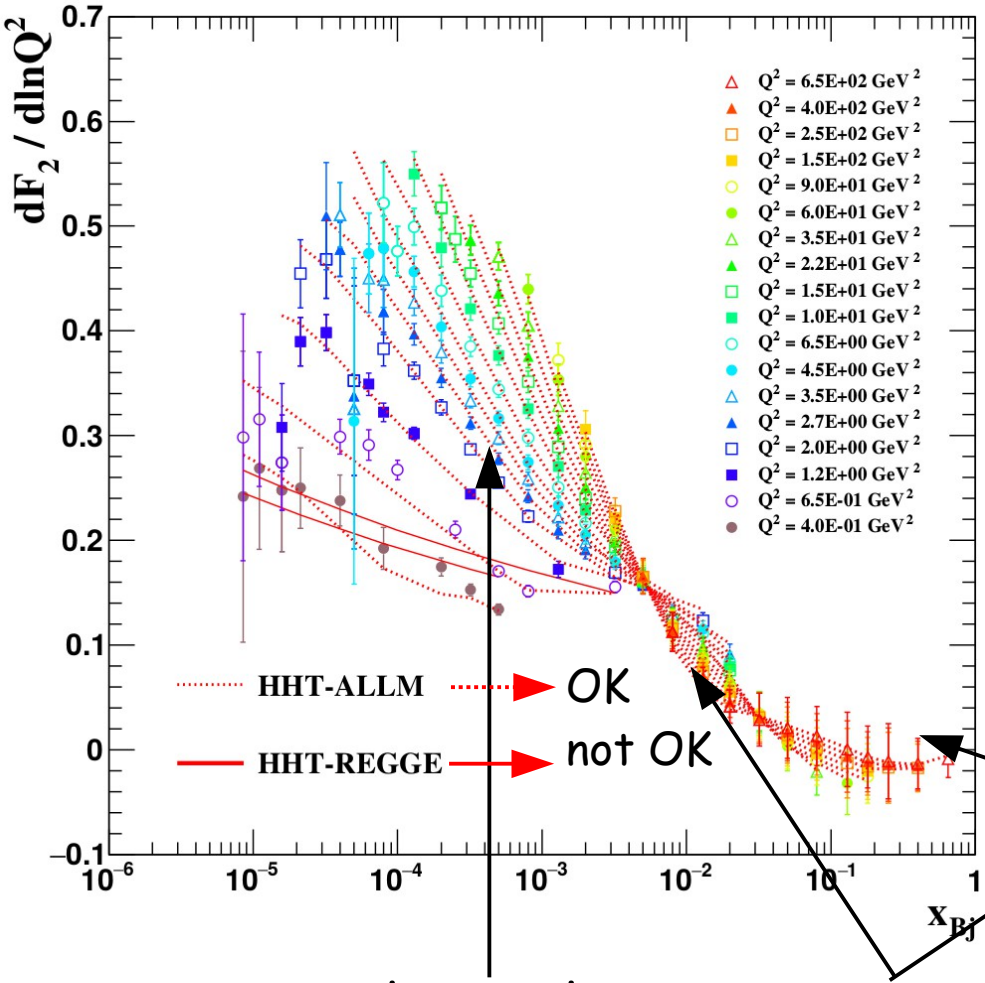
Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

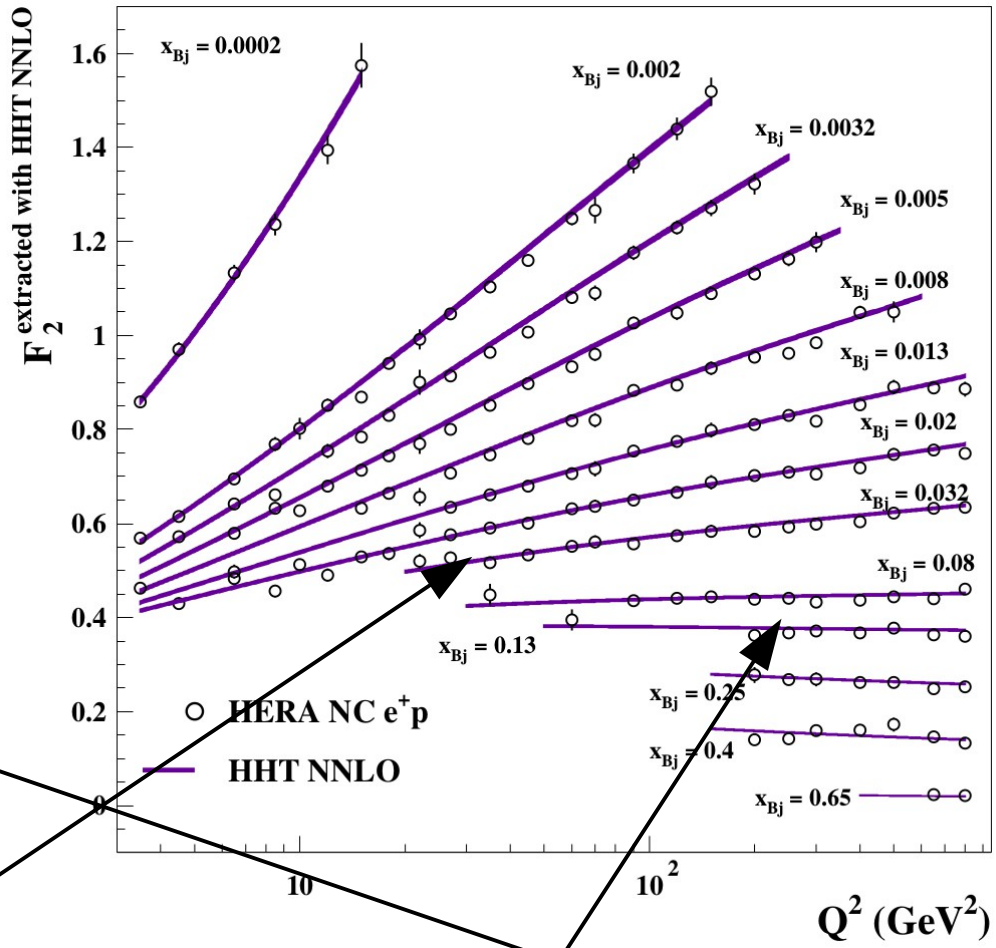
Adding D and E parameters to each PDF

- Parametrisation uncertainties
  - largest deviation
- Model uncertainties
  - all variations added in quadrature

F_2 derivatives $dF_2/d\ln Q^2 \rightarrow$ info on gluon

- Fits to extracted F_2 $\quad F_2 = A(x_{Bj}) + B(x_{Bj}) \ln Q^2 + C(x_{Bj}) \ln^2 Q^2$





strong scaling violation
depends on Q^2

scaling violation
depends on $\alpha_s(Q^2)$

scaling

Low-x twist-4 terms in HHT (HERA data only)

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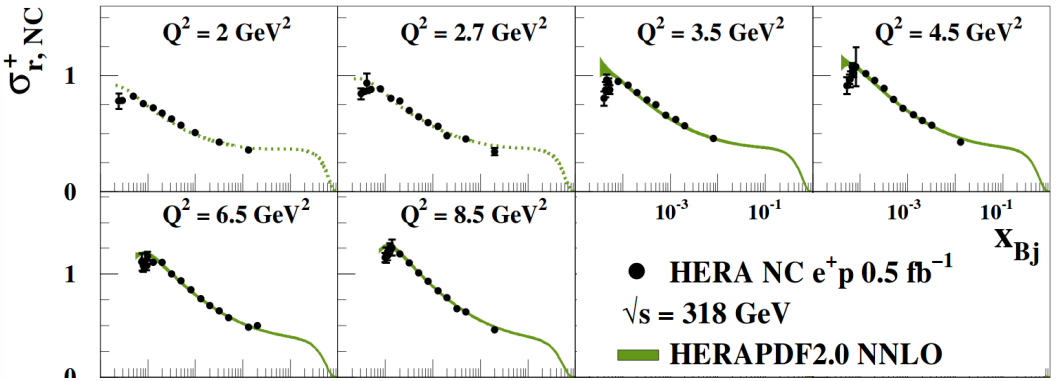
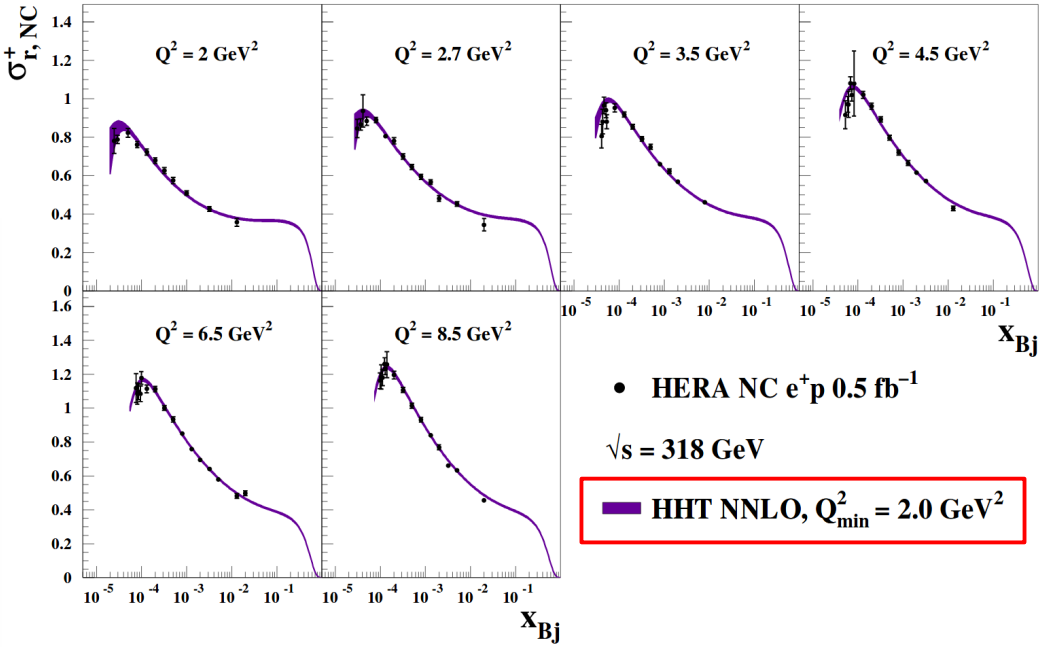
- Description of low-Q^2 low-x region improved by adding twist-4 terms

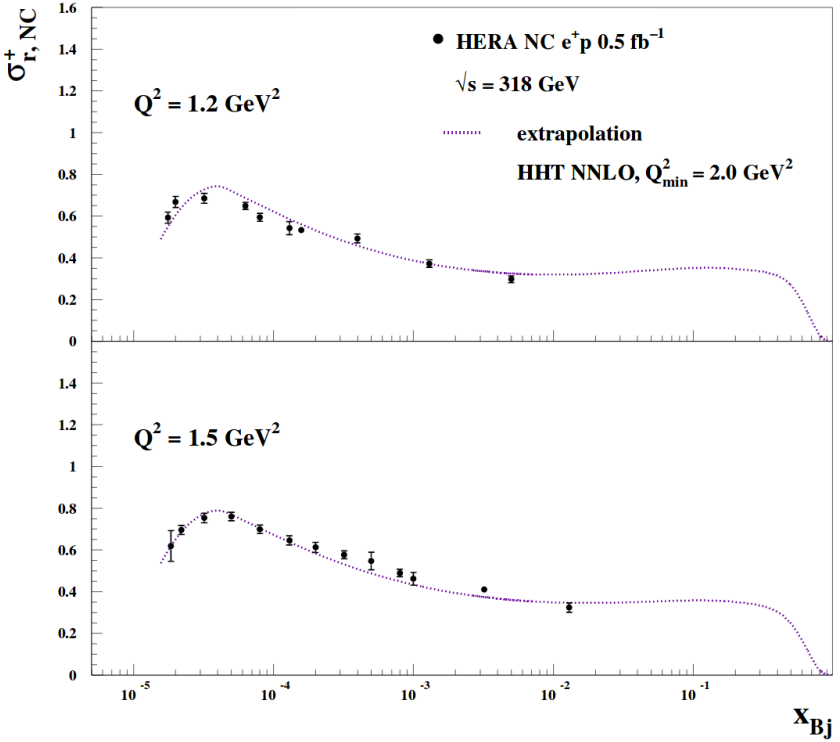
$$F_L^{HT} = F_L^{DGLAP} (1 + A_L^{HT}/Q^2)$$

H1 and ZEUS





extrapolation works down to 1 GeV^2 but F_L becomes unphysical in this



good description of data down to ~1 GeV^2

Higher-twist effects

HERAPDF2.0

NLO $\frac{\chi^2}{ndf} = \frac{1356}{1131} \approx 1.20$

NNLO $\frac{\chi^2}{ndf} = \frac{1363}{1131} \approx 1.21$

→ Introducing $F_2^{HT} = F_2^{DGLAP}\left(1 + \frac{A_2^{HT}}{Q^2}\right)$ has almost no effect

HHT@F_2

NLO $\frac{\chi^2}{ndf} = \frac{1354}{1130} \approx 1.20$

NNLO $\frac{\chi^2}{ndf} = \frac{1357}{1130} \approx 1.20$

A_2^{HT} = 0.14 ± 0.10 GeV²

A_2^{HT} = 0.12 ± 0.07 GeV²

factors consistent with 0

→ Introducing $F_L^{HT} = F_L^{DGLAP}\left(1 + \frac{A_L^{HT}}{Q^2}\right)$ helps a lot

HHT@F_L

NLO $\frac{\chi^2}{ndf} = \frac{1329}{1130} \approx 1.18$

NNLO $\frac{\chi^2}{ndf} = \frac{1316}{1130} \approx 1.16$

$\Delta\chi^2 = 27$

$\Delta\chi^2 = 47$

A_L^{HT} = 4.2 ± 0.7 GeV²

A_L^{HT} = 5.5 ± 0.6 GeV²

→ Trying to F_L and F_2 together gives the same conclusion