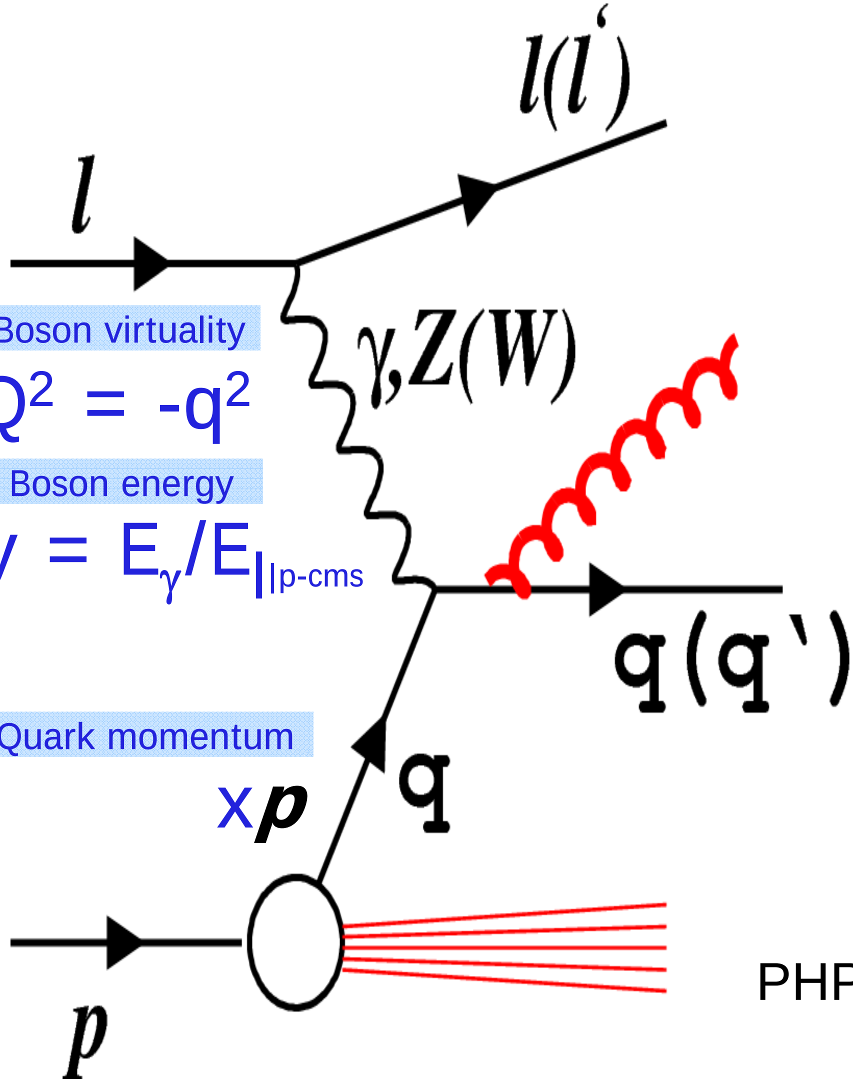
Precision QCD measurements in DIS

DIS 2013, Marseille
22th april 2013

Olaf Behnke (DESY)

Deep inelastic scattering: nucleon structure and QCD



Boson virtuality

$Q^2 = -q^2$

Boson energy

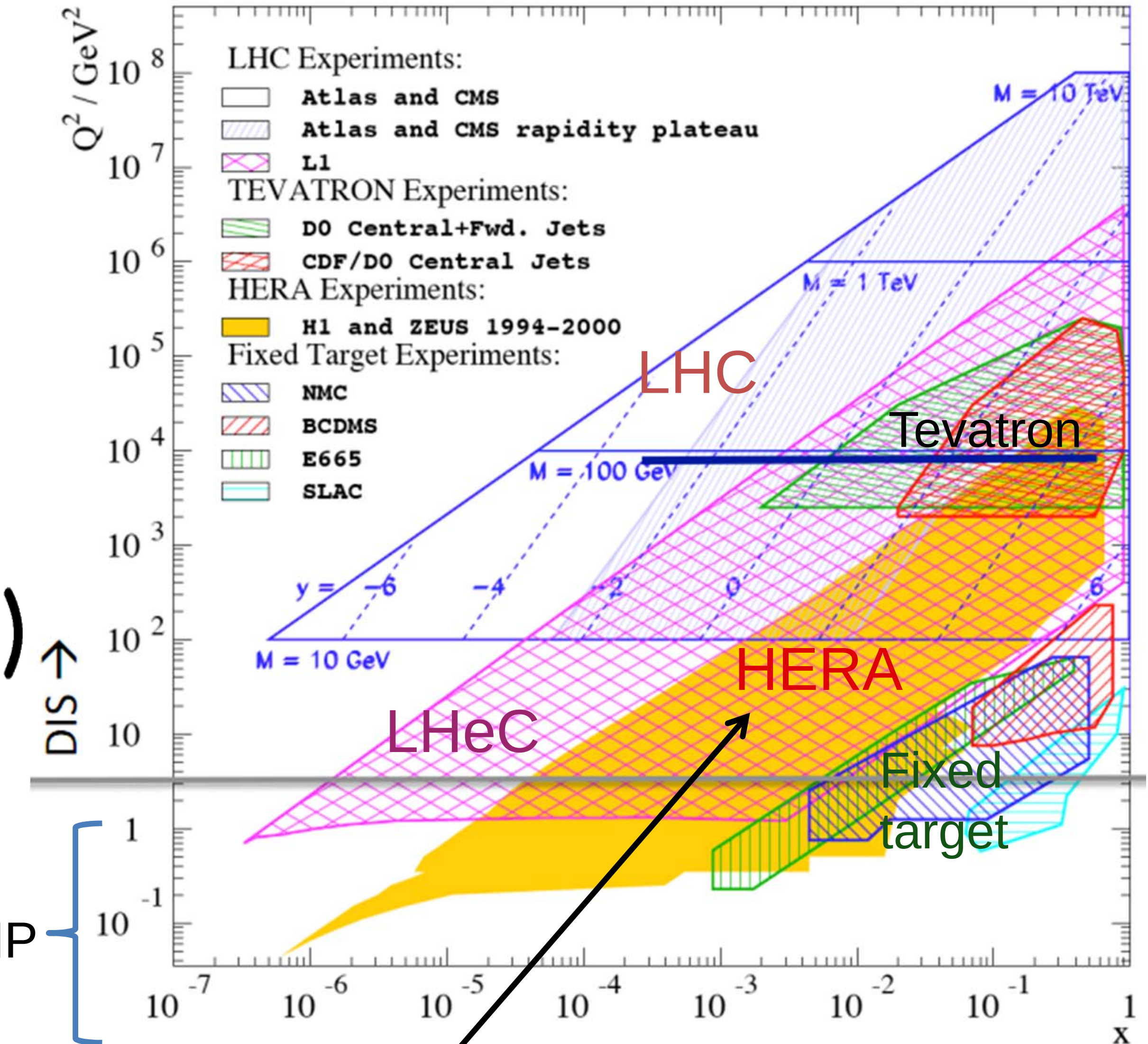
$y = E_\gamma / E_{l|p\text{-cms}}$

Quark momentum

$x\boldsymbol{p}$

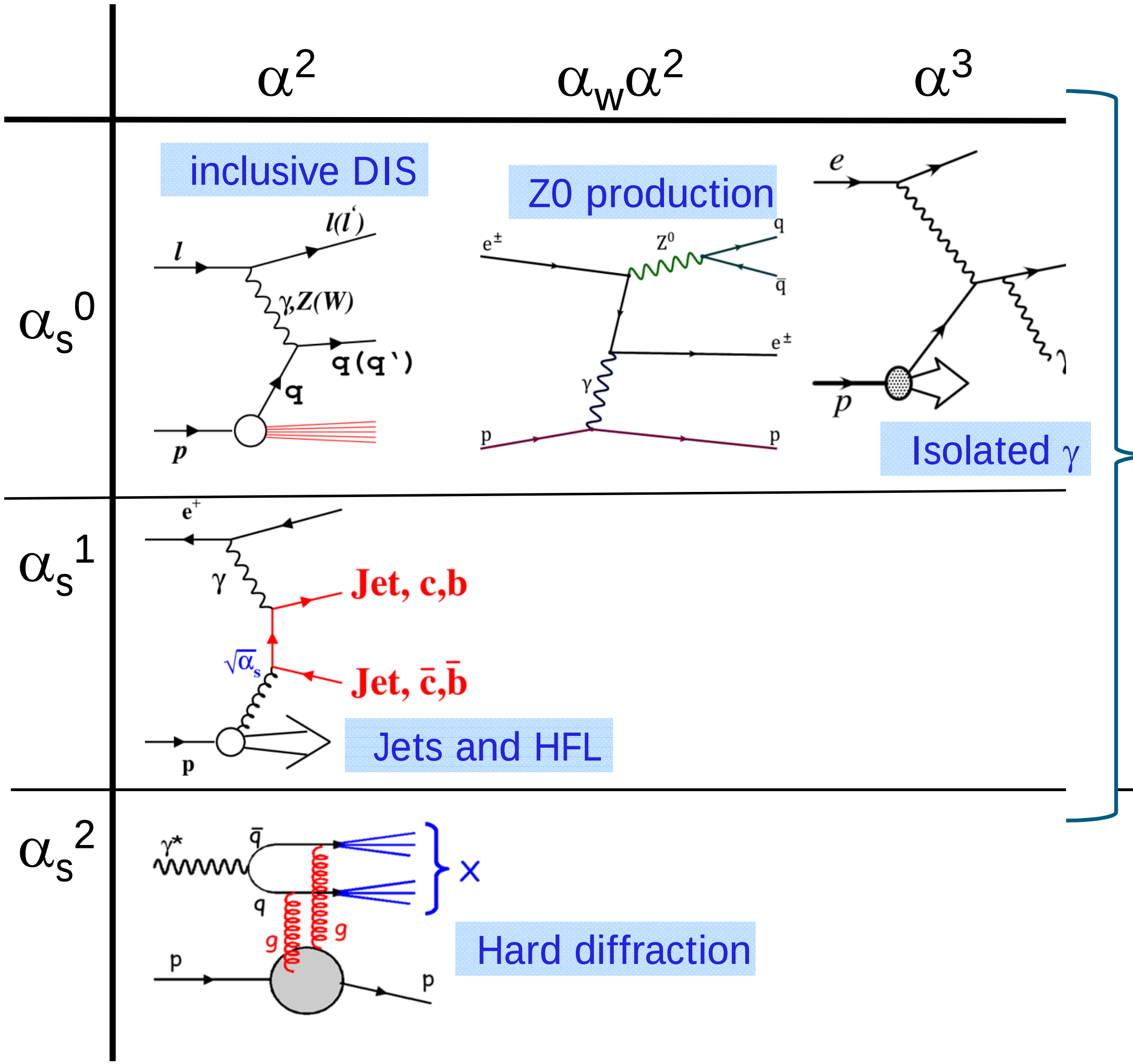
Constraint:

$Q^2 = sxy$



Today: Present new HERA QCD results

Todays HERA Tour through perturbation series:



Compare to N(NLO) calculations based on factorisation

$$\frac{d\sigma}{dx\,d\Phi} = \frac{1}{Q^d} f(\mu_F) \underset{x}{\otimes} C\left(\Phi, \frac{\mu_F}{Q}, \frac{\mu_R}{Q}, \alpha_s(\mu_R)\right)$$

Proton PDF

hard scattering kernel

Not covered: Charged particle spectra, Very forward neutron/photon production, strangeness production

Todays HERA Tour through perturbation series:

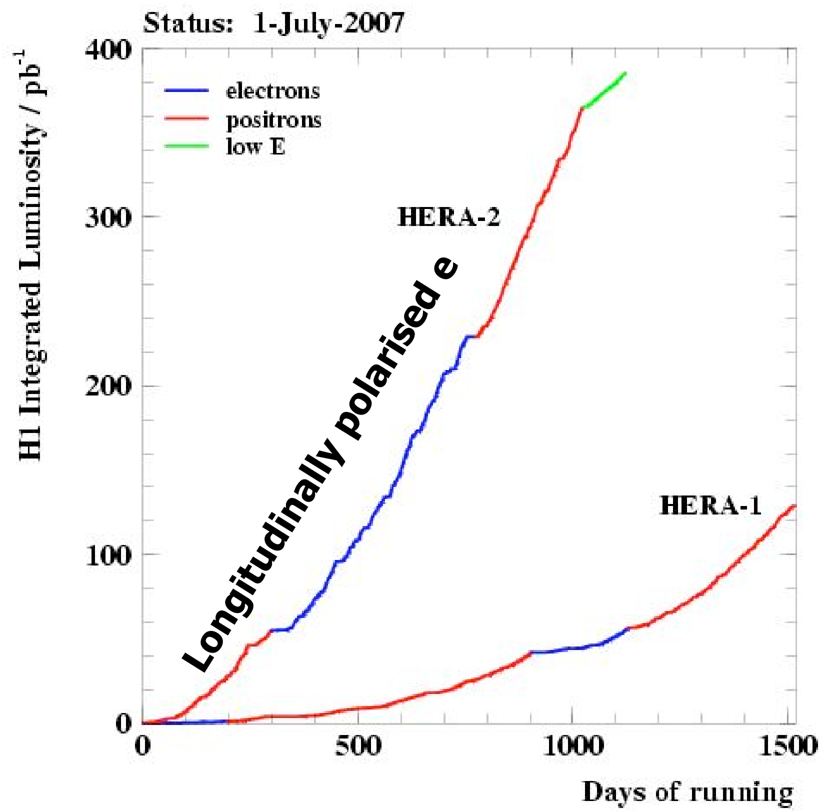
	α^2	$\alpha_w\alpha^2$	α^3
α_s^0	inclusive DIS JHEP 1209:061 (2012) PRD 87, 052014 (2013)	Z0 production PL B 718 (2013) 915	ZEUS-prel-13-001 Isolated γ
α_s^1	NPB 864 (2012) 1 H1prelim-12-031 Jets and HFL	EPJ C73 (2013) 2311 DESY-13-054 DESY-13-028 JHEP02 (2013) 071 EPJ C72 (2012) 2047 EPJ C72 (2012) 2148	
α_s^2		H1prelim-13-011 Hard diffraction	

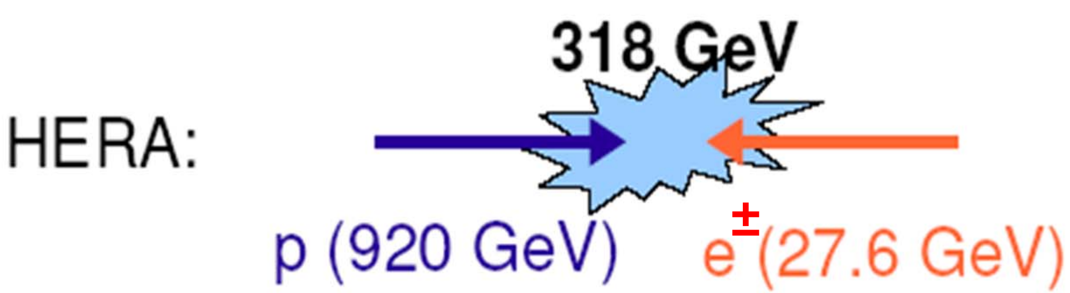
DESY-13-012
H1prelim-13-032

Not covered: Charged particle spectra, Very forward neutron/photon production, strangeness production

H1prelim-12-111, H1prelim-13-012
H1prelim-13-031, H1prelim-13-033

The HERA ep collider (1992-2007)

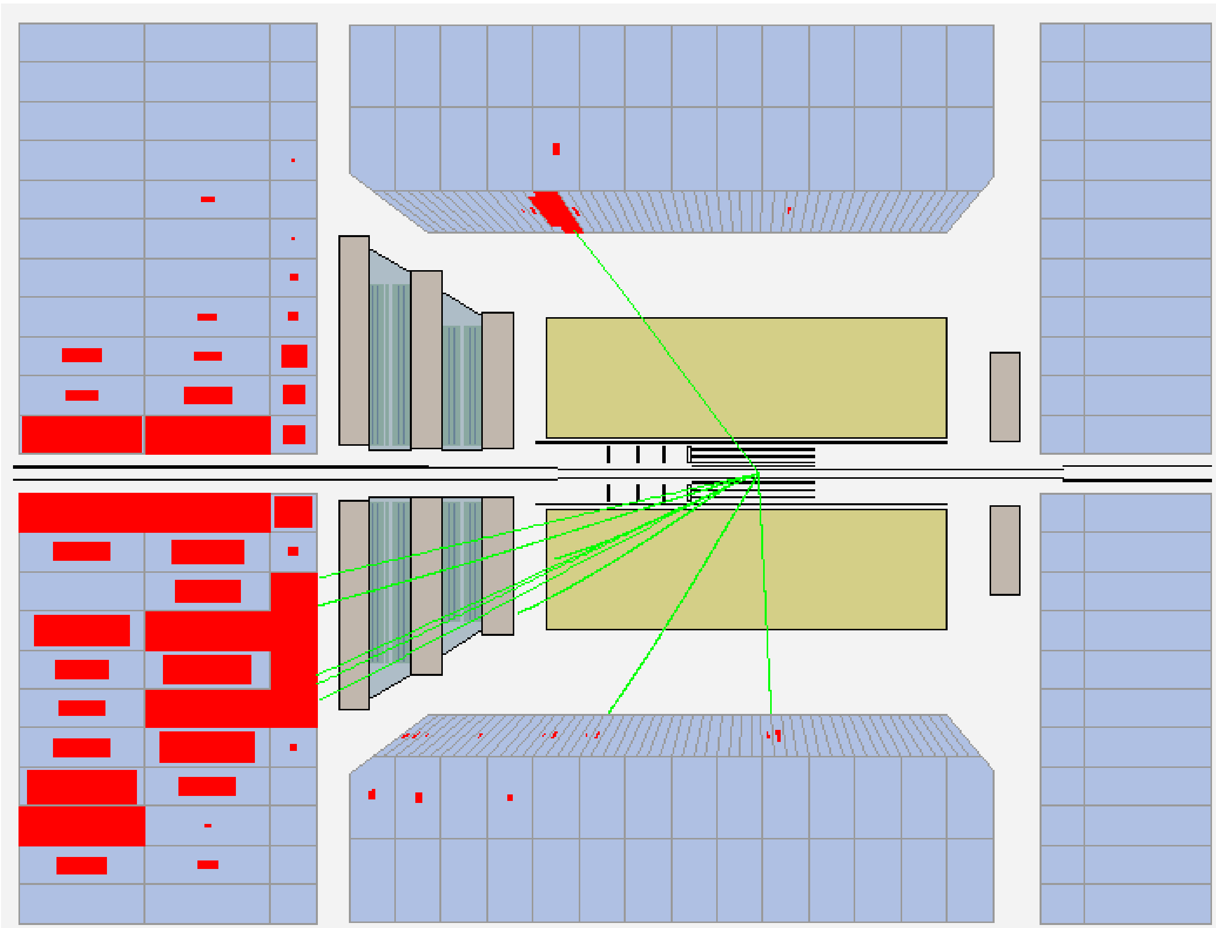


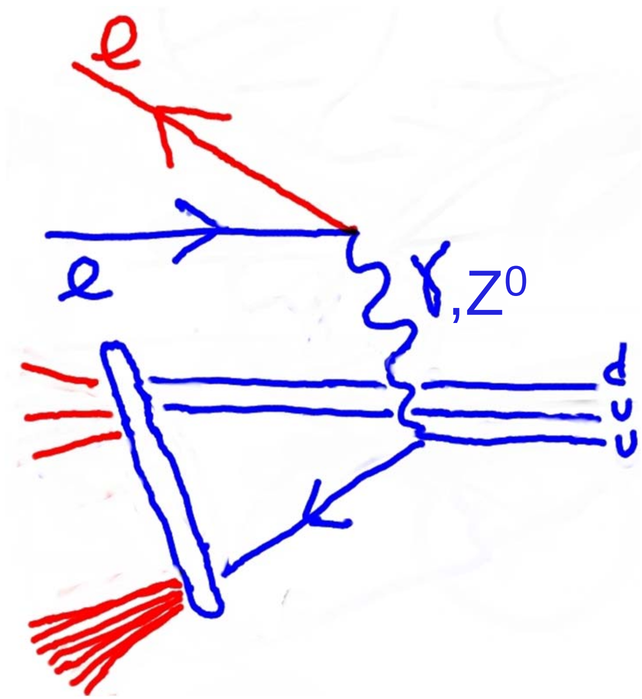


~0.5 fb^{-1} per experiment

Inclusive DIS at HERA (count every DIS event)

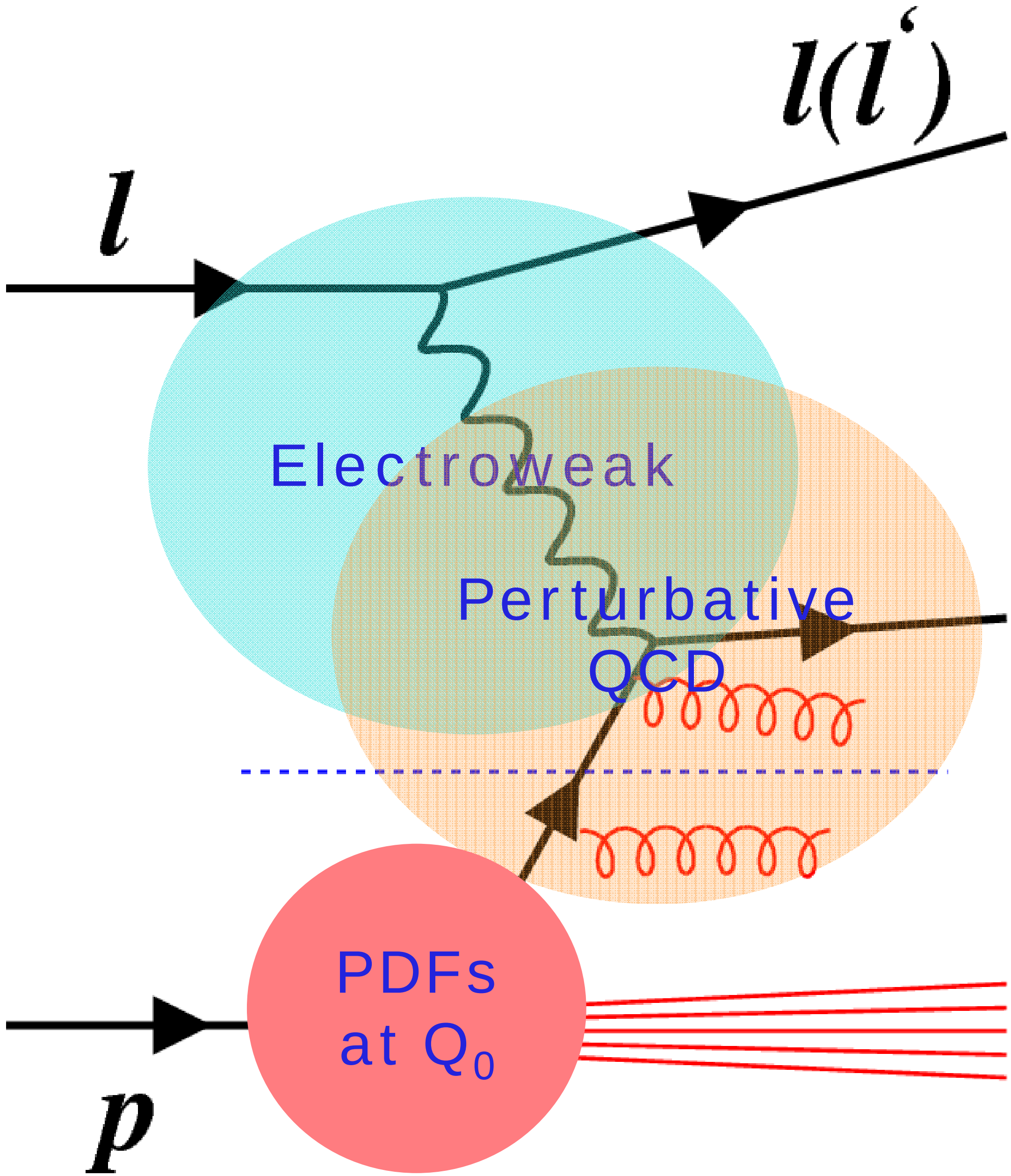
NC Event in ZEUS detector





Display produced from ROOT ntuple ("ZEUS common ntuple")

Inclusive DIS at HERA: three pieces

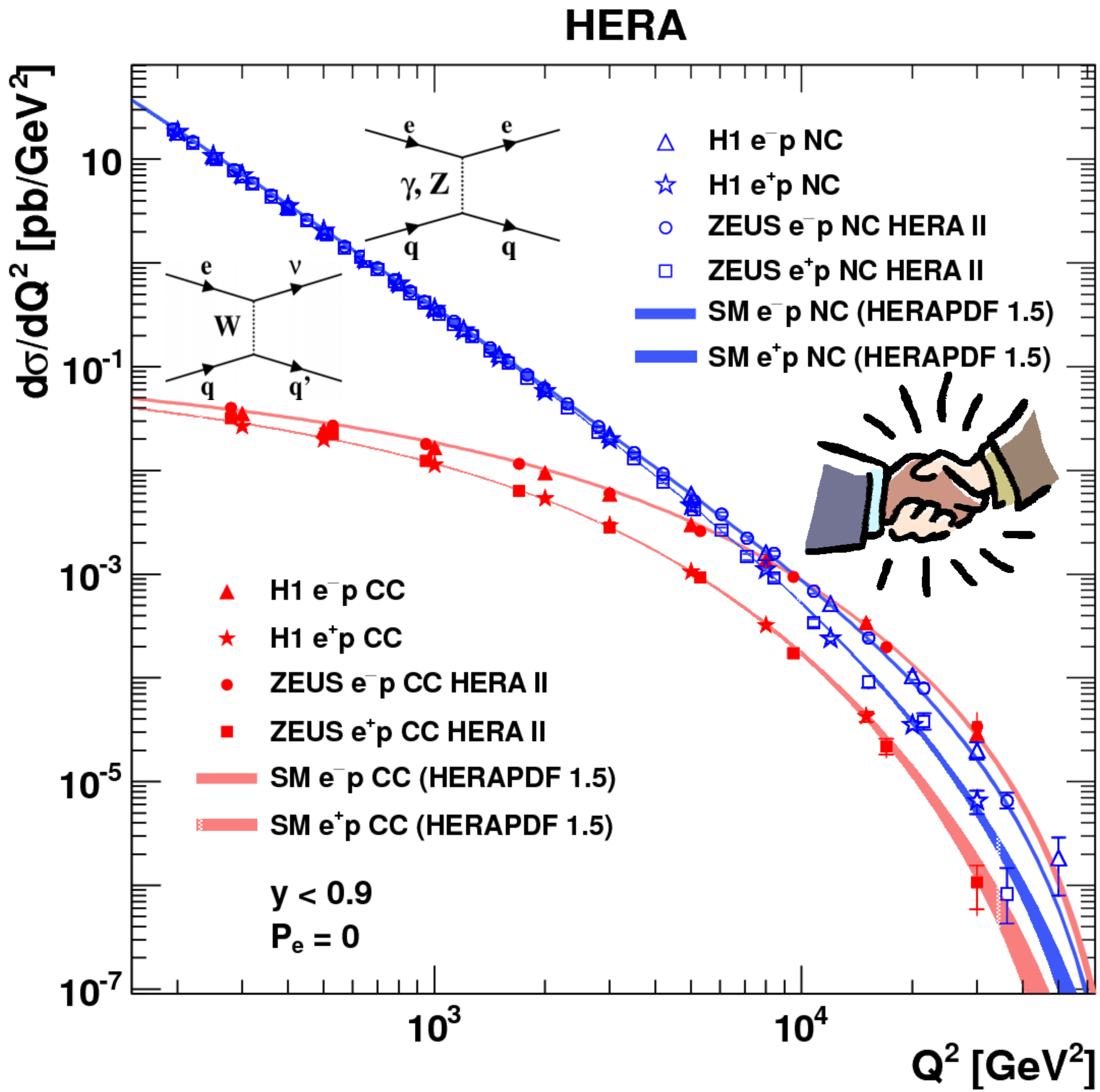


Fix Electroweak & pQCD
$\Rightarrow$ Determine PDFs
Voica Radescu talk

Fix Electroweak
$\Rightarrow$ Test pQCD $\otimes$ PDFs
Main talk topic!

Fix pQCD $\otimes$ PDFs
$\Rightarrow$ Test Electroweak
Next two slides

Electroweak unification



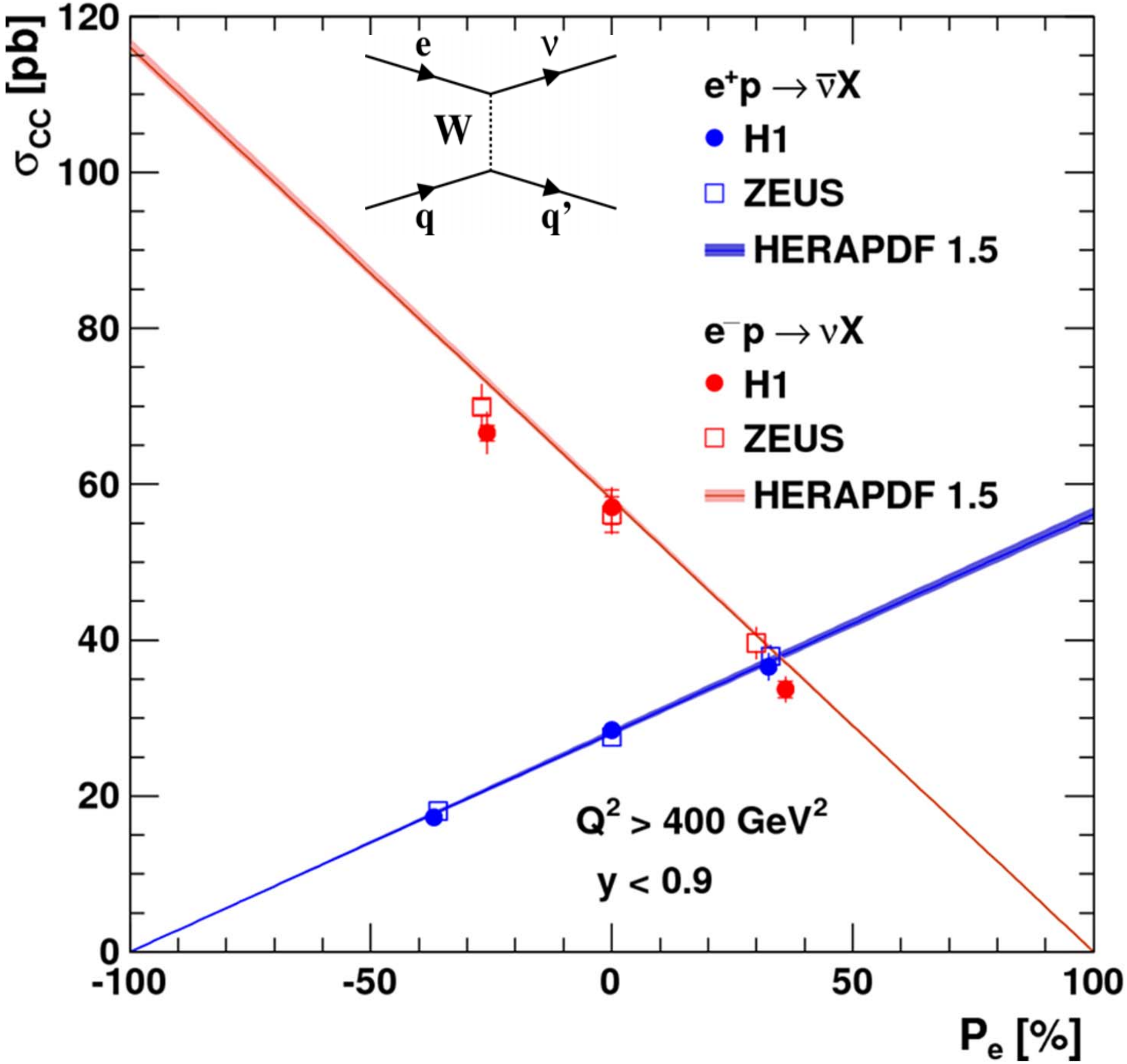
Using the full HERA II results completed by

JHEP 1209:061 (2012)

PRD 87, 052014 (2013)

➔ Textbook plot

Parity violation in charged current DIS

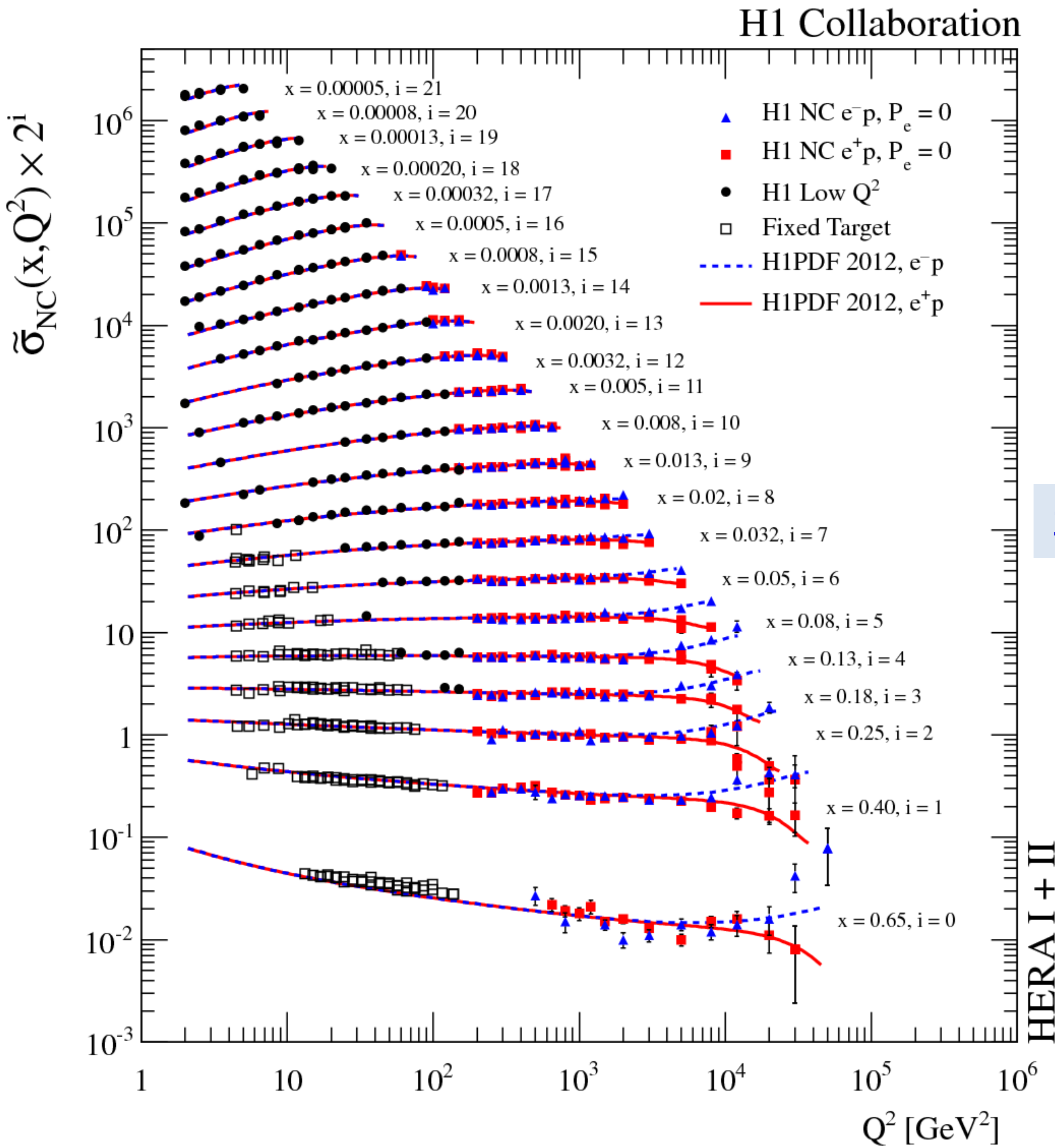


Using the full HERA II results completed by

JHEP 1209:061 (2012)

SM: zero cross section for RH e- and LH e+

➔ Data agree with SM
➔ Rules out W_R bosons under 200 GeV



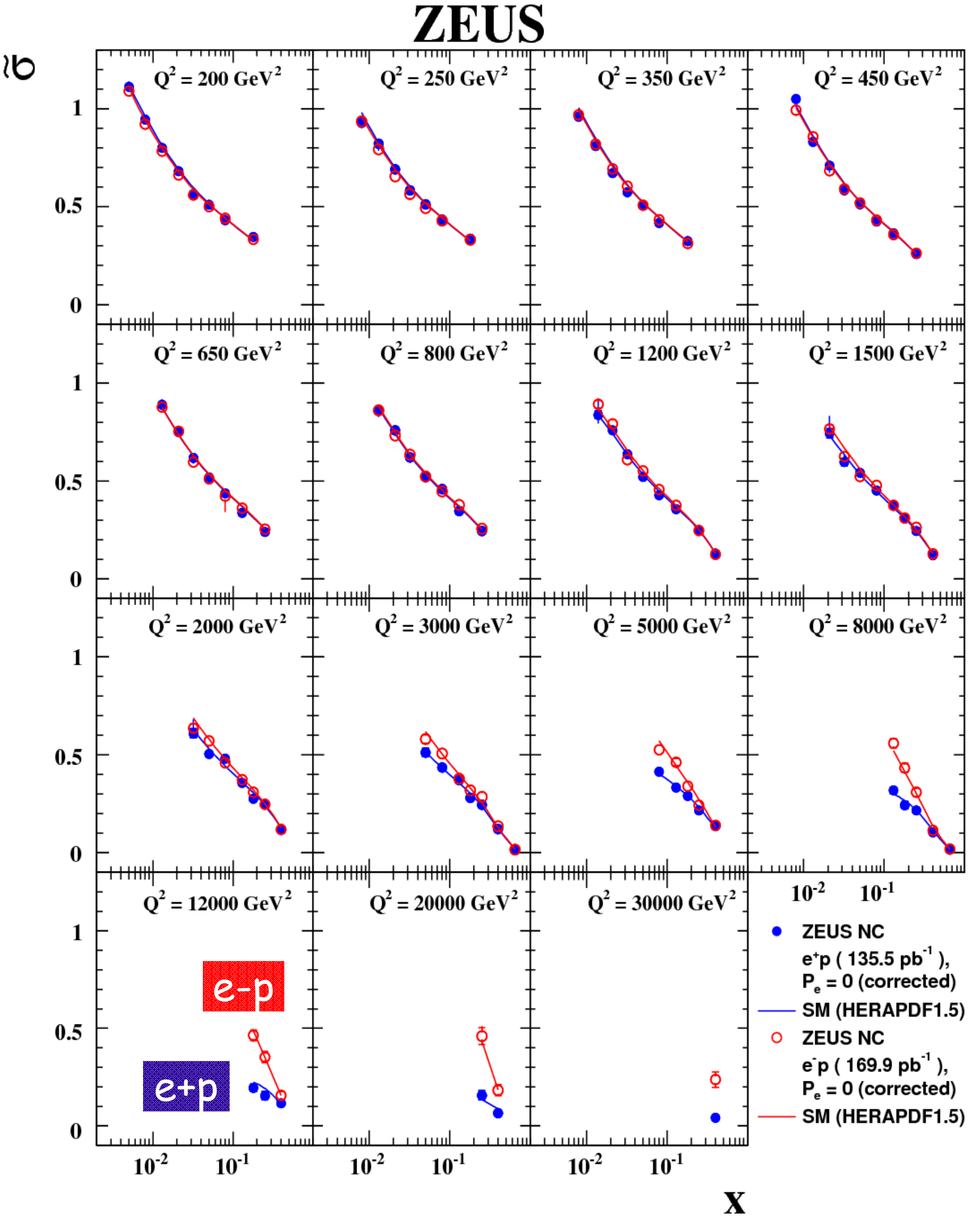
Reduced NC cross sections

Final H1 results

JHEP 1209:061 (2012)

1.5% precision for $Q^2<500$ GeV^2

➔ Data well described by DGLAP NLO QCD



Reduced NC cross sections

ZEUS final

high Q^2 HERA II *results*

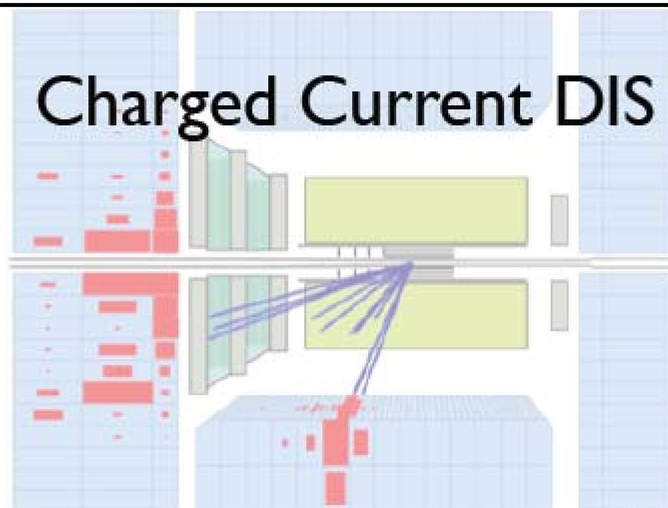
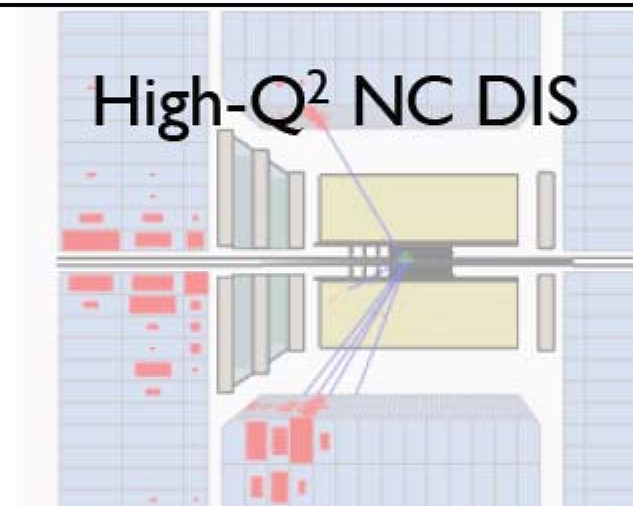
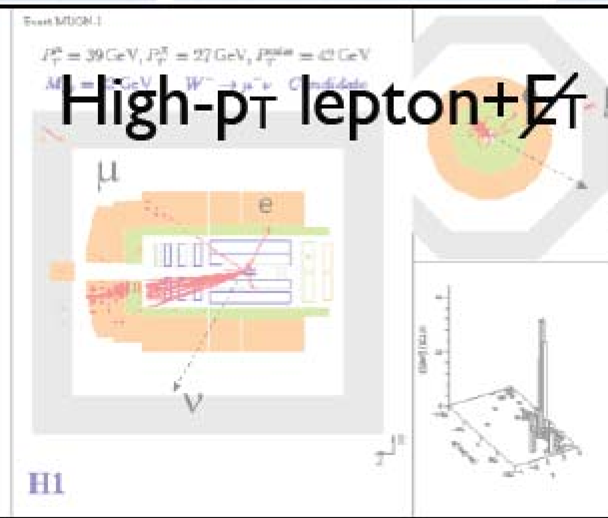
completed by e+p NC data

PRD 87, 052014 (2013)

Best precisions of ~1.5%

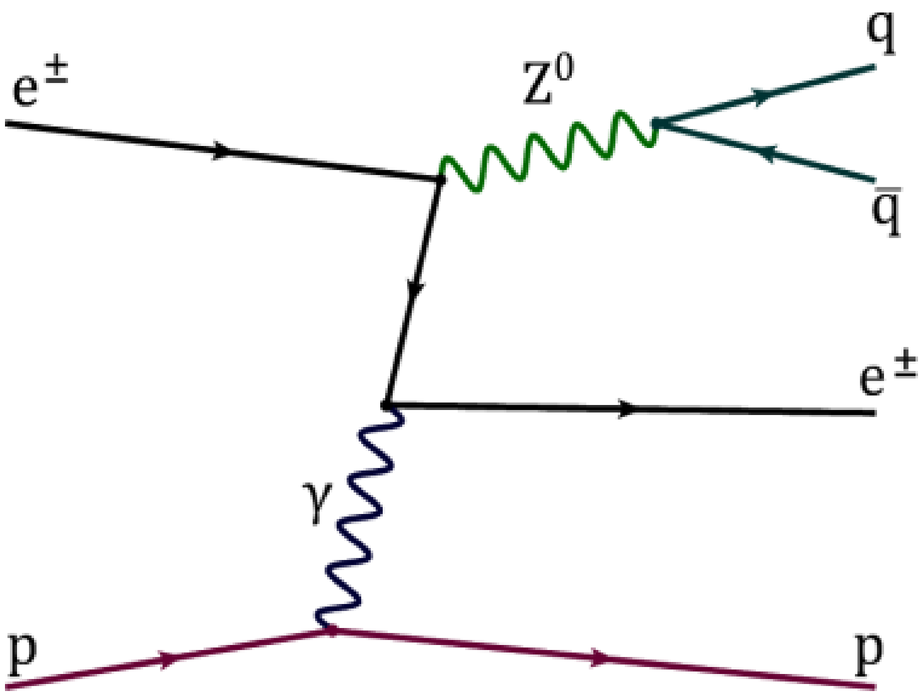
→ Data well described by DGLAP NLO QCD

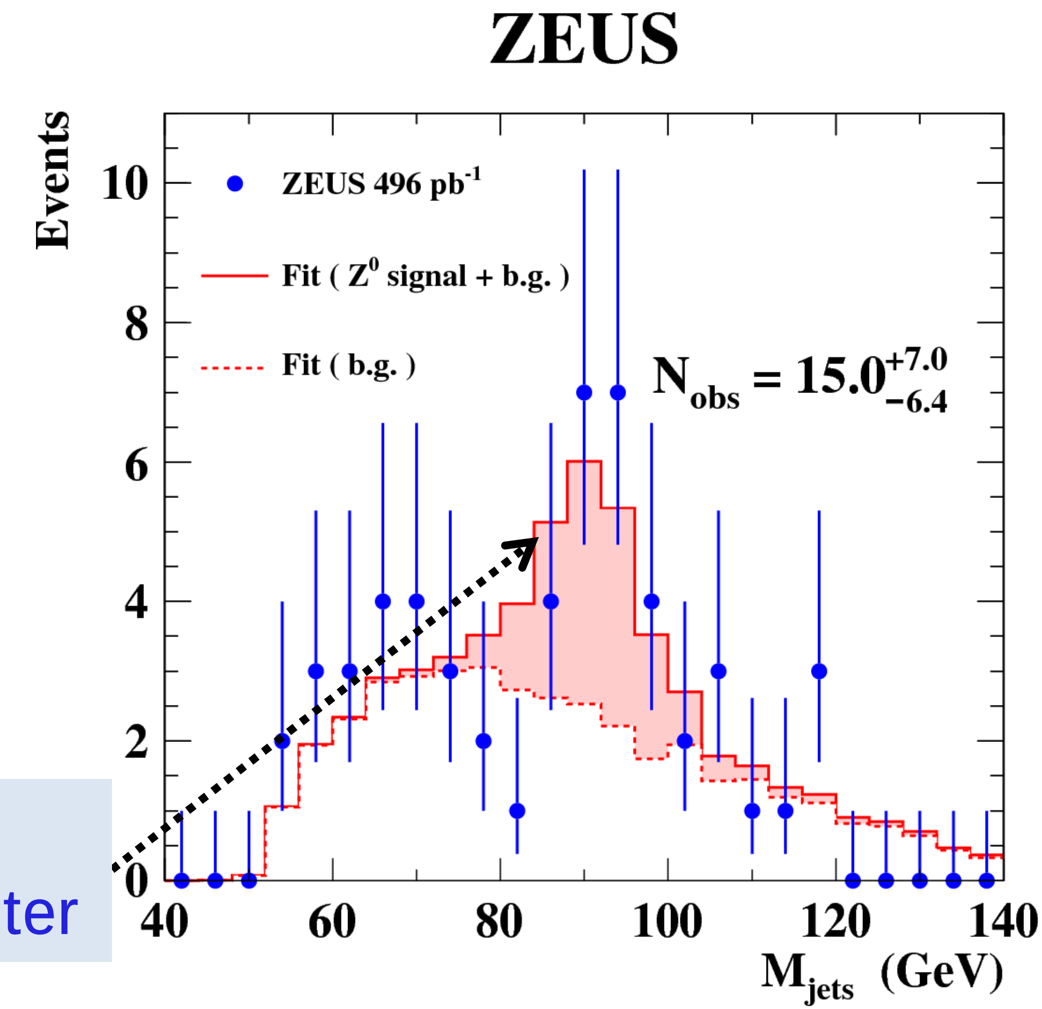
Electroweak Bosons at HERA

	W	Z
Virtual	 Charged Current DIS	 High-Q^2 NC DIS
Real	 High-p_T lepton+$\not{E}_T$	**Missing piece in HERA EW program?**

Elastic Z^0 production

PL B 718 (2013) 915





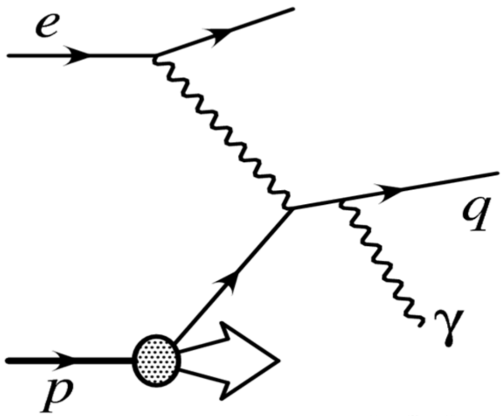
shows excellent $\sigma_E^{hadronic}$ of ZEUS Uranium scintillator calorimeter

$$\sigma_{obs}\left(ep \rightarrow ep^{(*)} Z^0\right) = 0.133^{+0.060}_{-0.057}\,(\text{stat.})^{+0.049}_{-0.038}\,(\text{syst.})\ \text{pb}$$

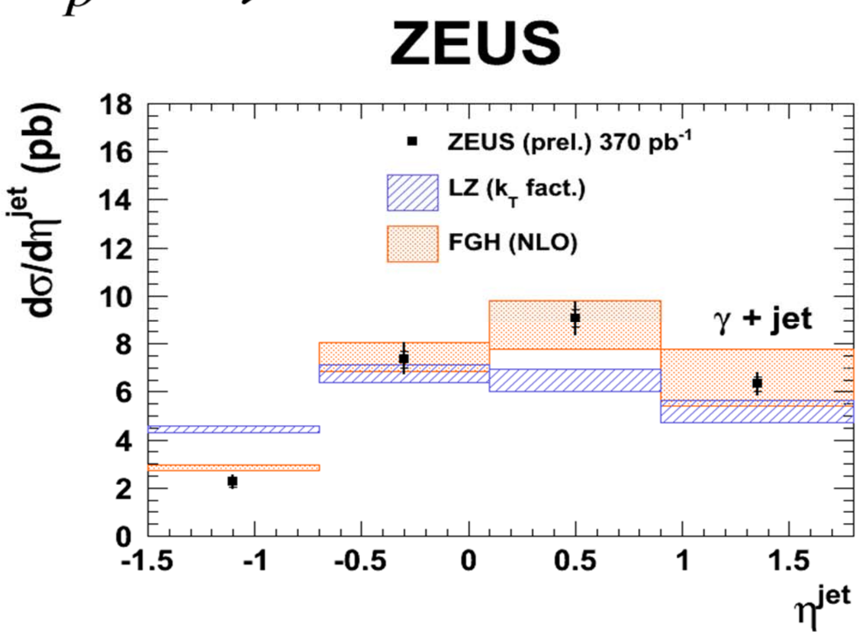
The result agrees with SM cross section of 0.16pb

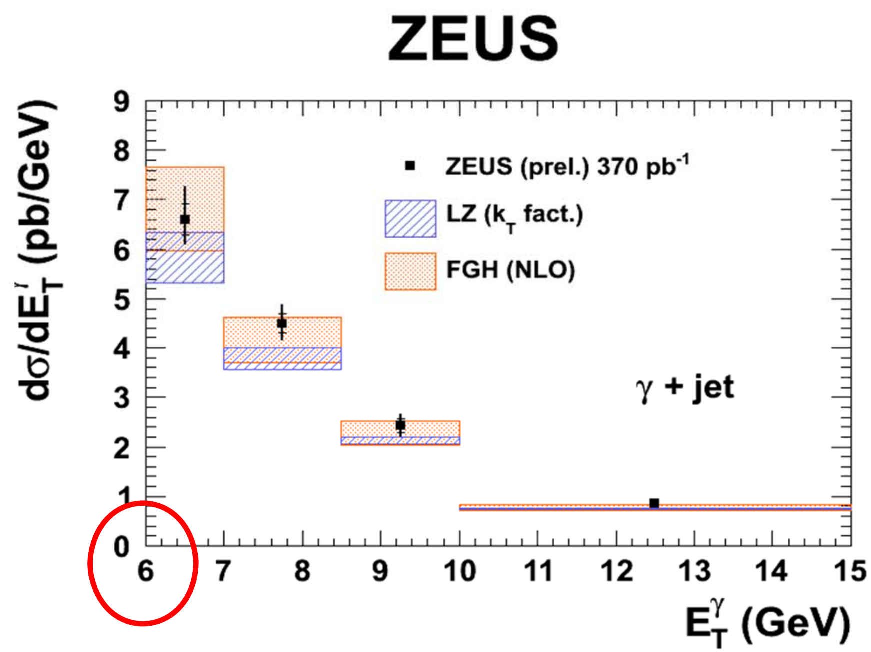
Isolated γ+jets in photoproduction

ZEUS-prel-13-001



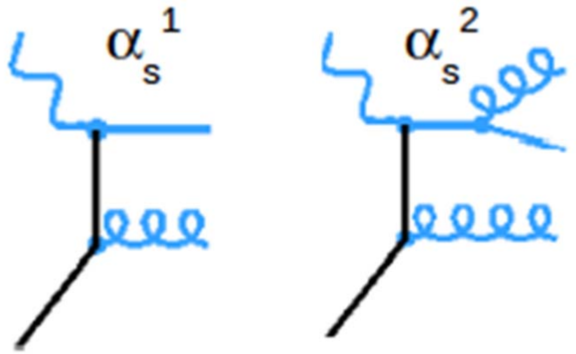
γ emissions are not affected by hadronisation
=> direct probe of the parton dynamics



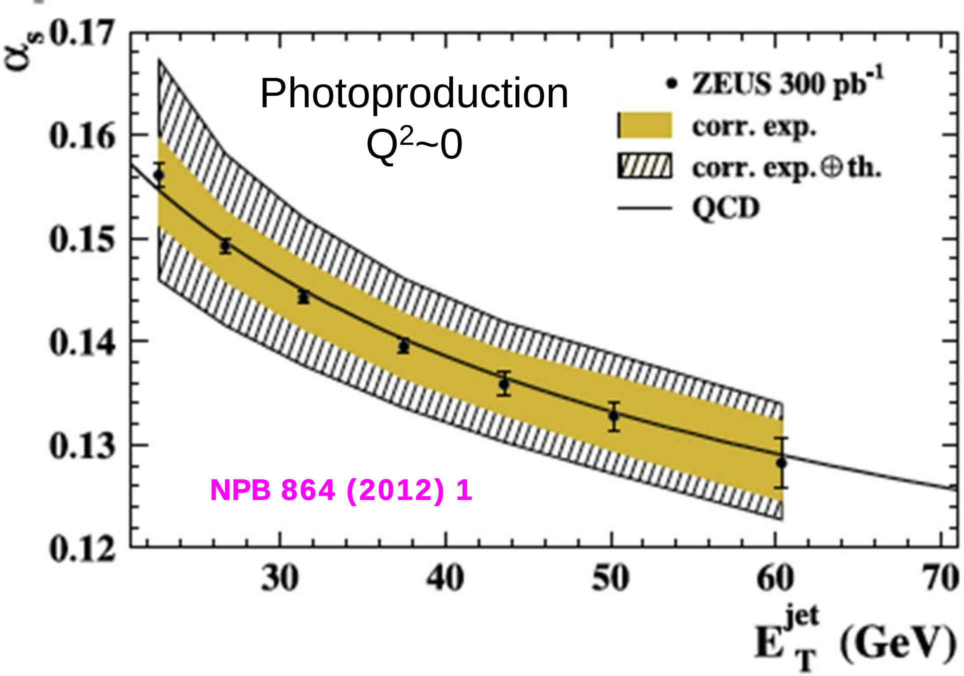


➔ Both predictions ~reasonable, but room for improvements

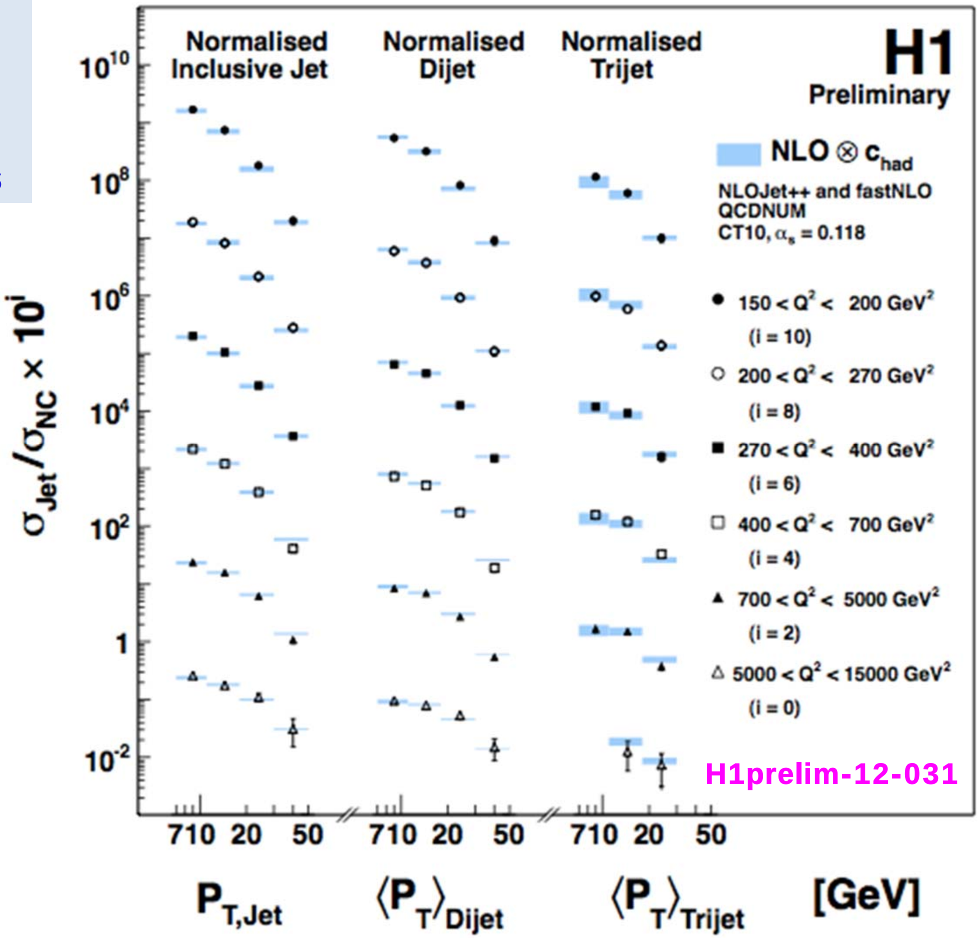
Jets at HERA



(Multi) jets directly sensitive to α_s



DIS, 150 GeV^2 < Q^2 < 15000 GeV^2



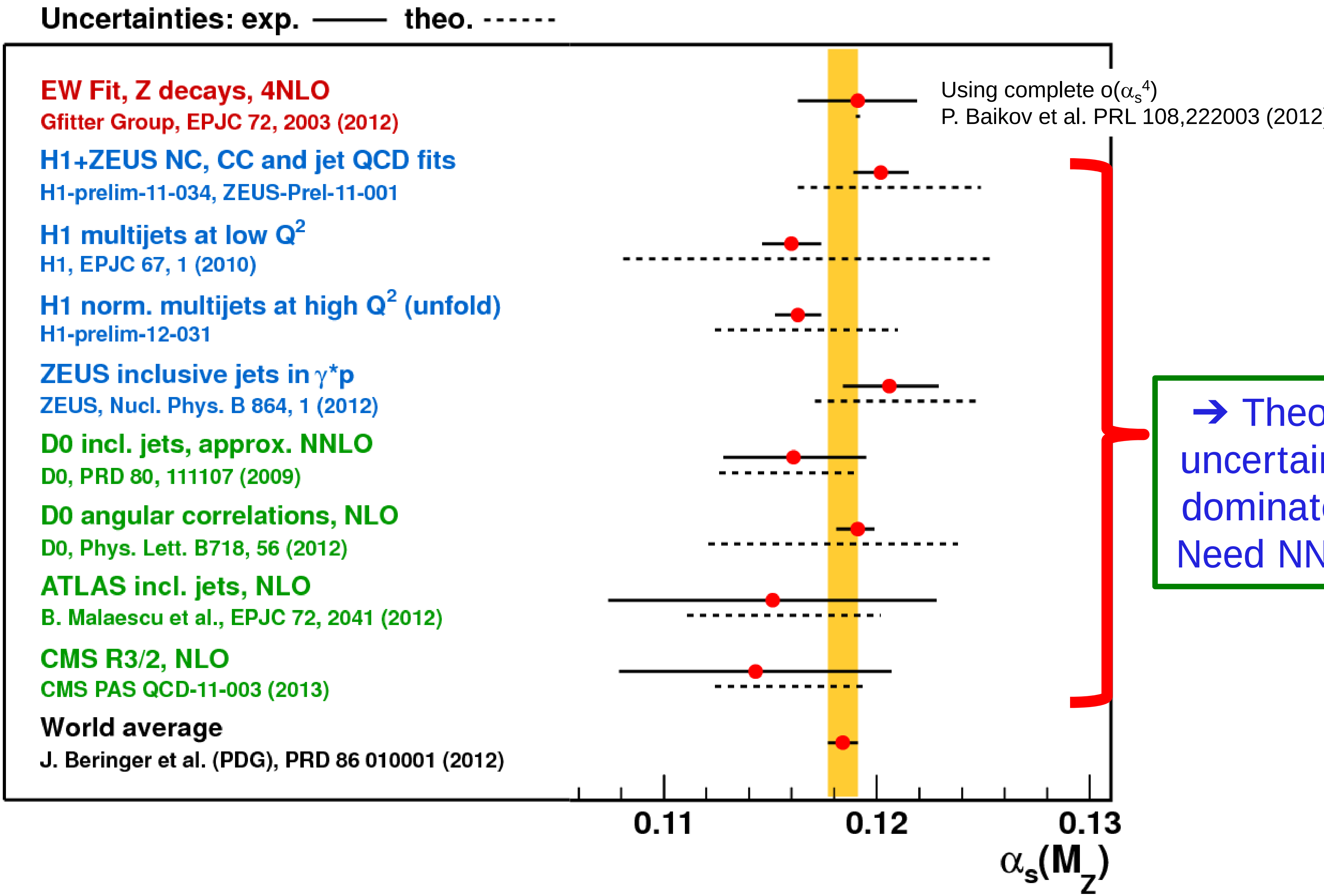
$\alpha_s(M_Z) = 0.1206^{+0.0023}_{-0.0022}$ (exp) $^{+0.0042}_{-0.0035}$ (theory)

$\alpha_s(M_Z) = 0.1163^{+0.0011}_{-0.0011}$ (exp) $^{+0.0042}_{-0.0042}$ (theory)

➔ Higher order theory uncertainties dominate → need NNLO calculations!

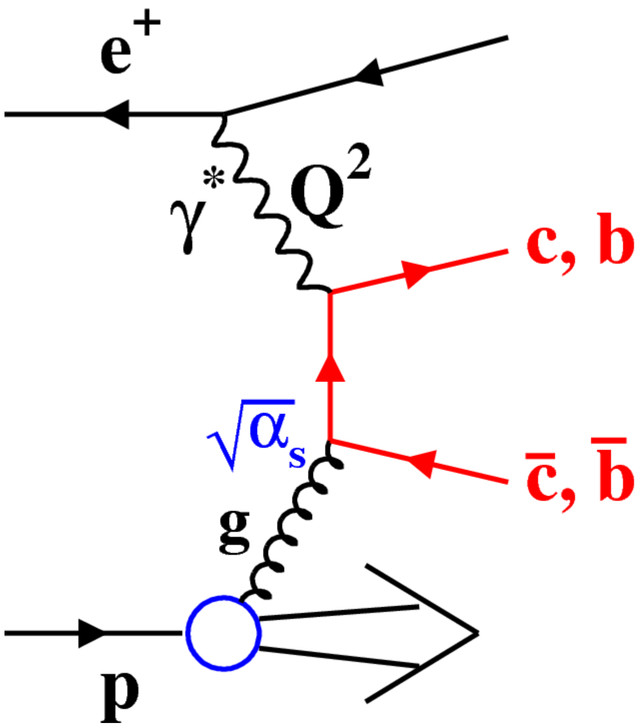
Comparison of recent $\alpha_s(M_Z)$ values

Compiled by R. Kogler



➔ Theory uncertainty dominates, Need NNLO

Charm and Beauty production at HERA

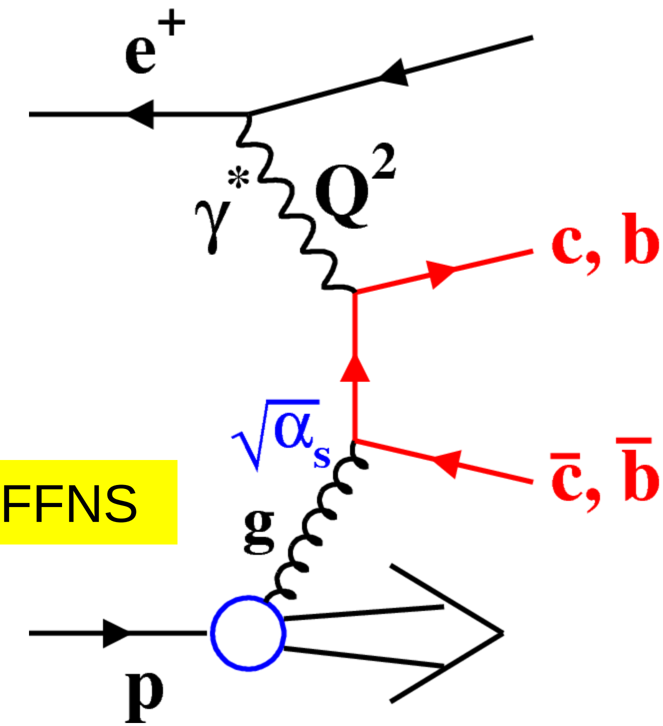


- ❑ Large contributions to incl. DIS
- ❑ Sensitive to g(x)

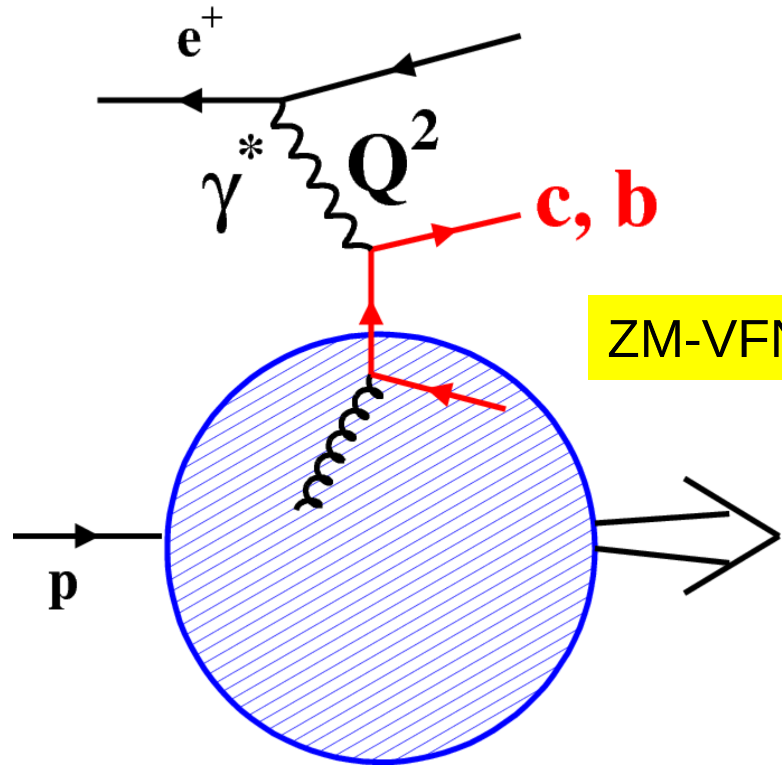
HFL schemes

Massive scheme: $Q^2 \sim m_c^2$

Massless scheme: $Q^2 >> m_c^2$



FFNS

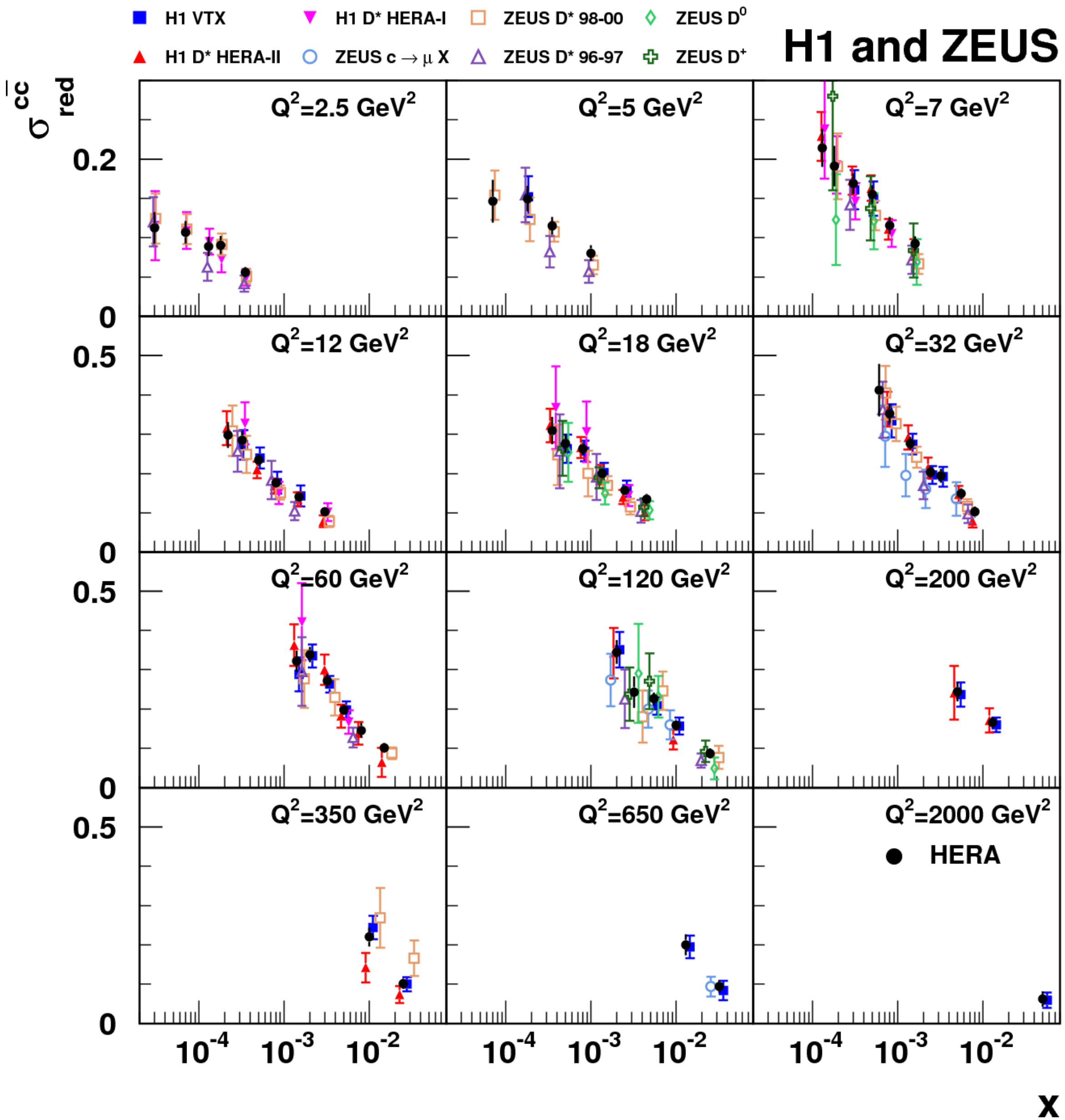


ZM-VFNS

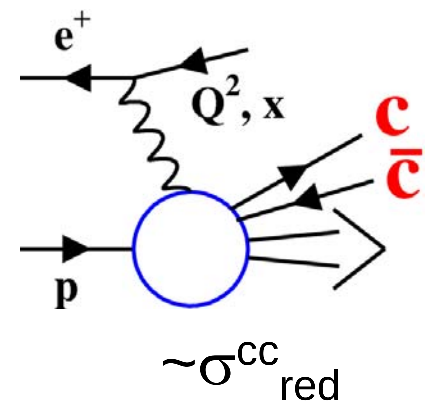
Mixed schemes: interpolate, but how to do transition? → numerous variants GM-VFNS

HERA Charm data combination

EPJ C73 (2013) 2311

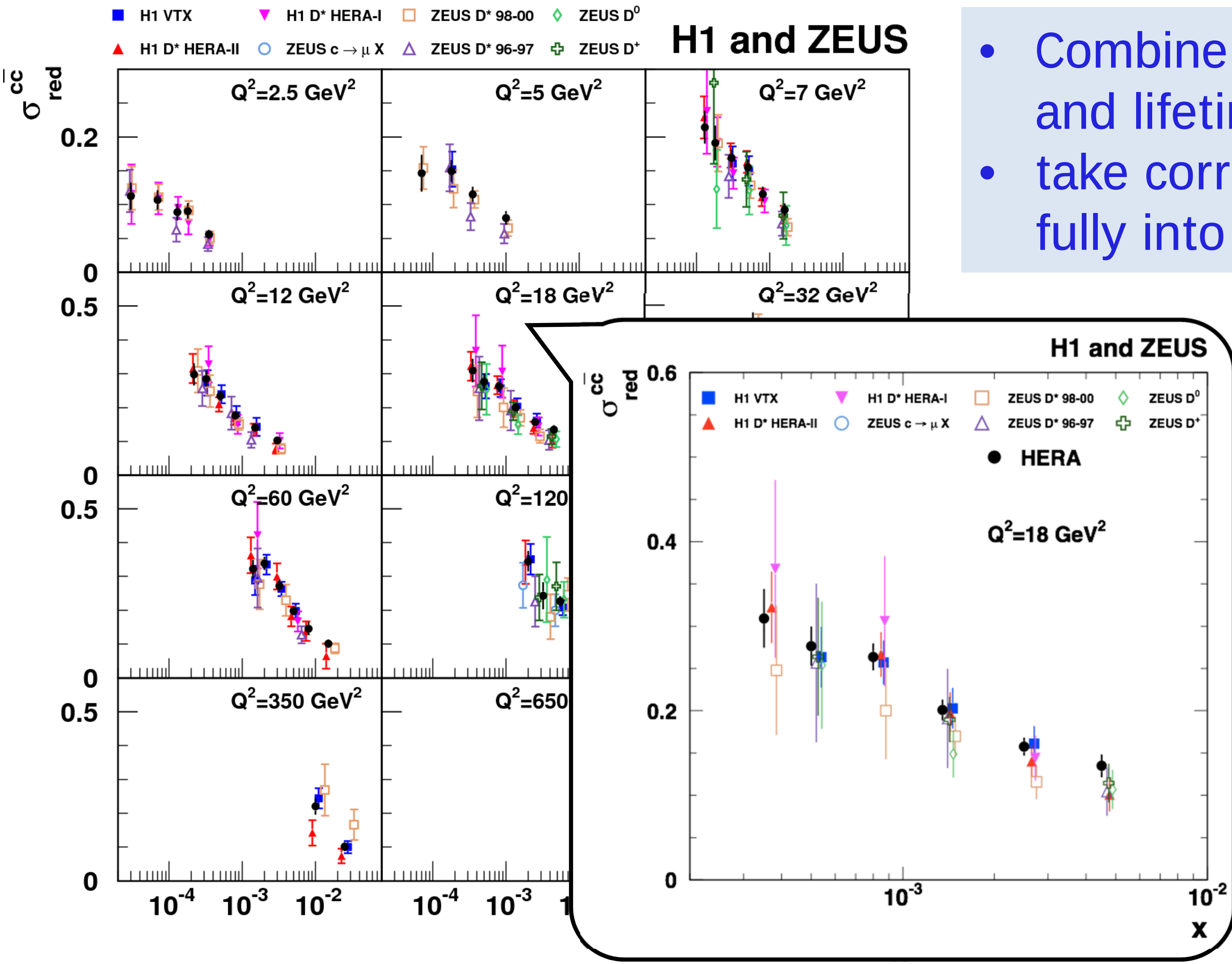


- Combine D^*, D^+, D^0, μ and lifetime tag data
- take correlated syst. fully into account



HERA Charm data combination

EPJ C73 (2013) 2311



- Combine D^*, D^+, D^0, μ and lifetime tag data
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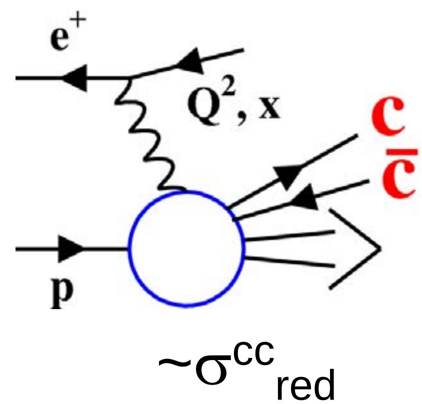
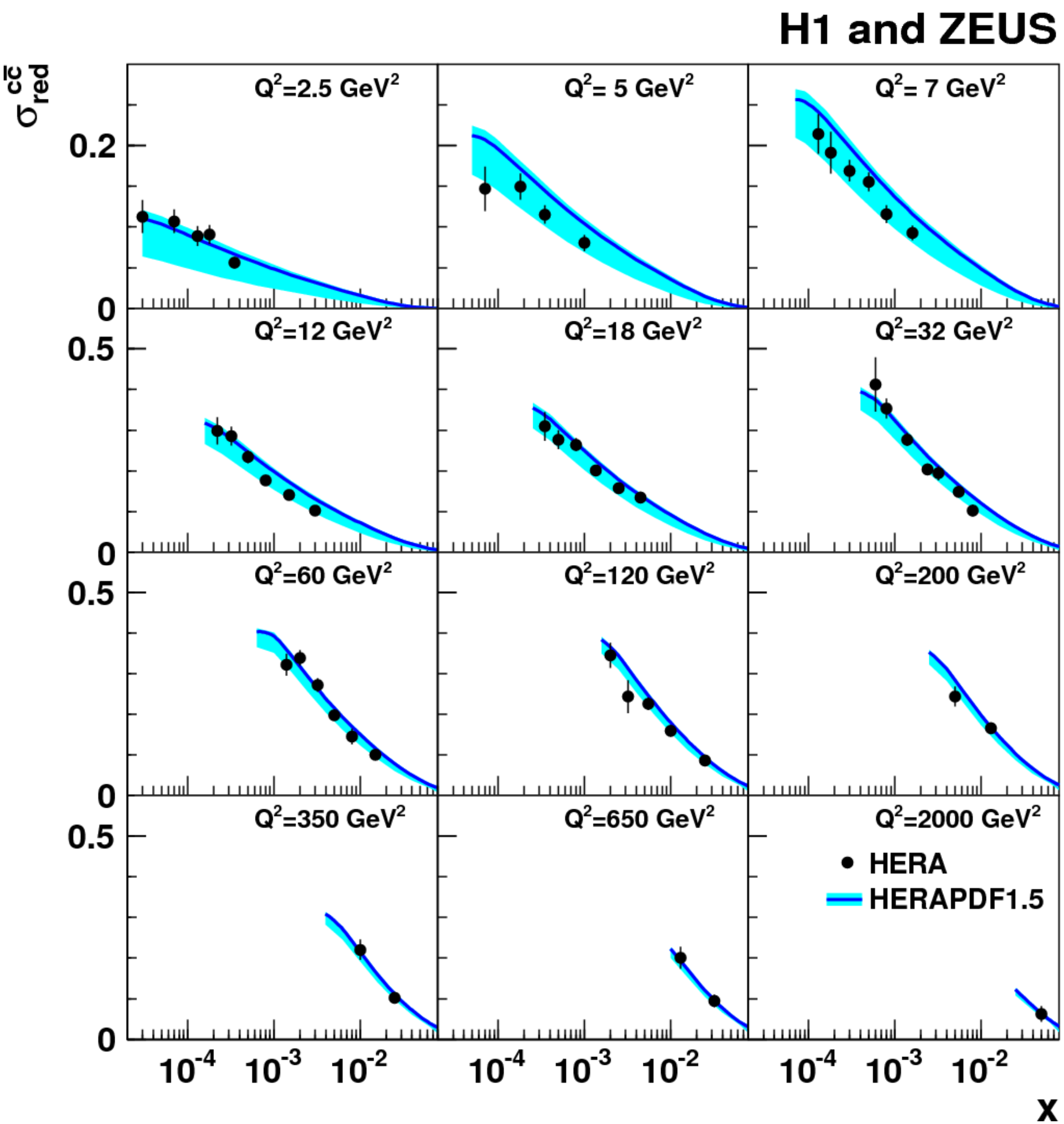


→ Best precision: ~5%

Combined charm data vs NLO GMVFNS

EPJ C73 (2013) 2311



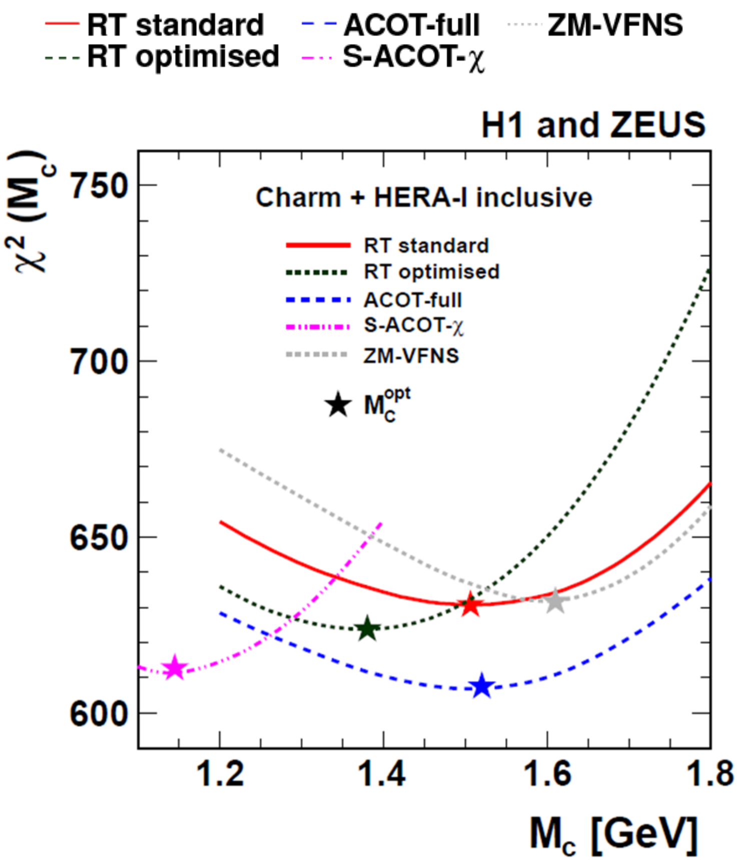
HERAPDF1.5:
- only inclusive DIS data
- RT standard scheme

→ NLO GM-VFNS ok ☺

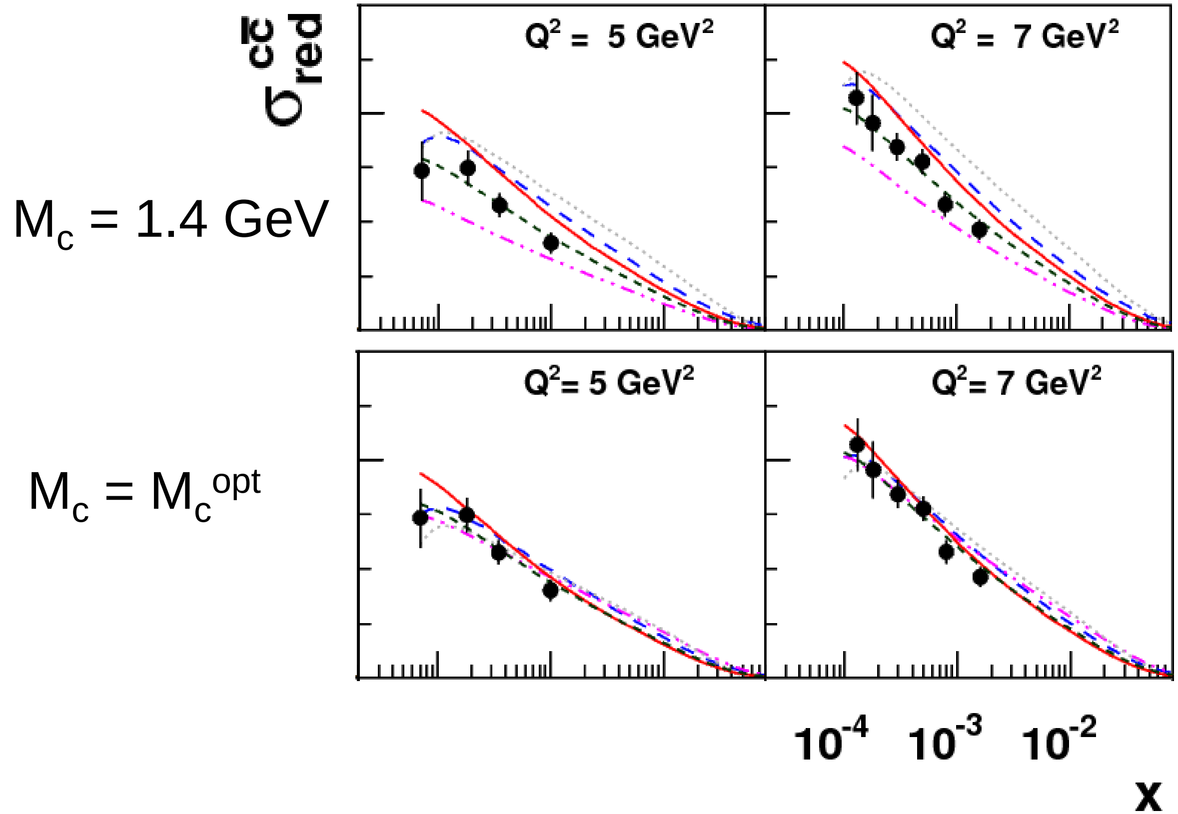
→large theory uncertainty dominated by m_c variation ☹

PDF plus charm mass param. fit

EPJ C73 (2013) 2311



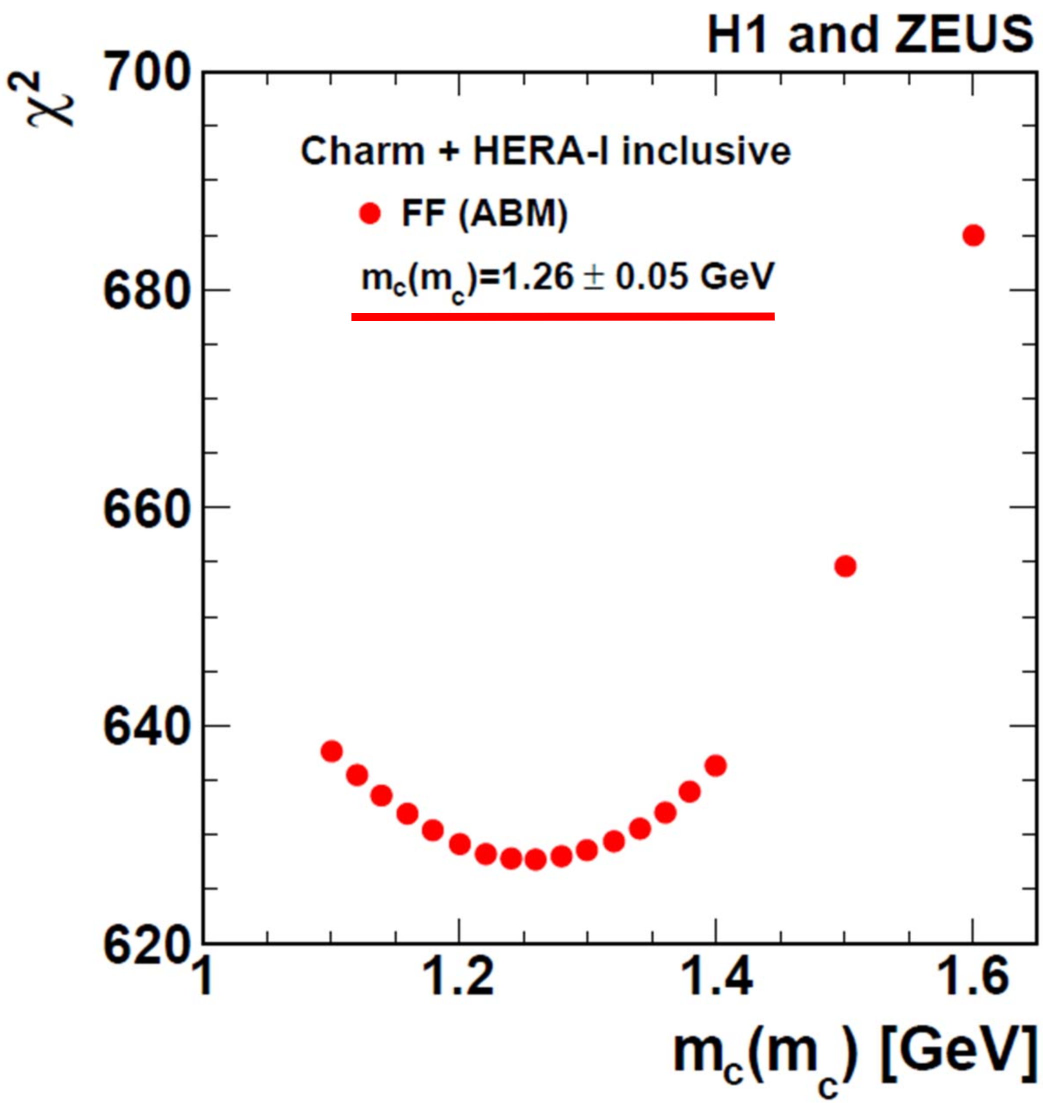
- Fit **combined charm** and inclusive DIS data
- GMVFN-schemes with **charm mass parameter M_c**



→ **Various GM-VFNS: interpolate differently between massive and massless schemes**
→ **different quality of charm data description for fixed M_c → compensate by M_c^{opt} values**
→ **stabilises flavour mixture in PDF → stabilises LHC predictions (W,Z)** (see talk V. Radescu)

PDF plus *running charm mass* fit

EPJ C73 (2013) 2311

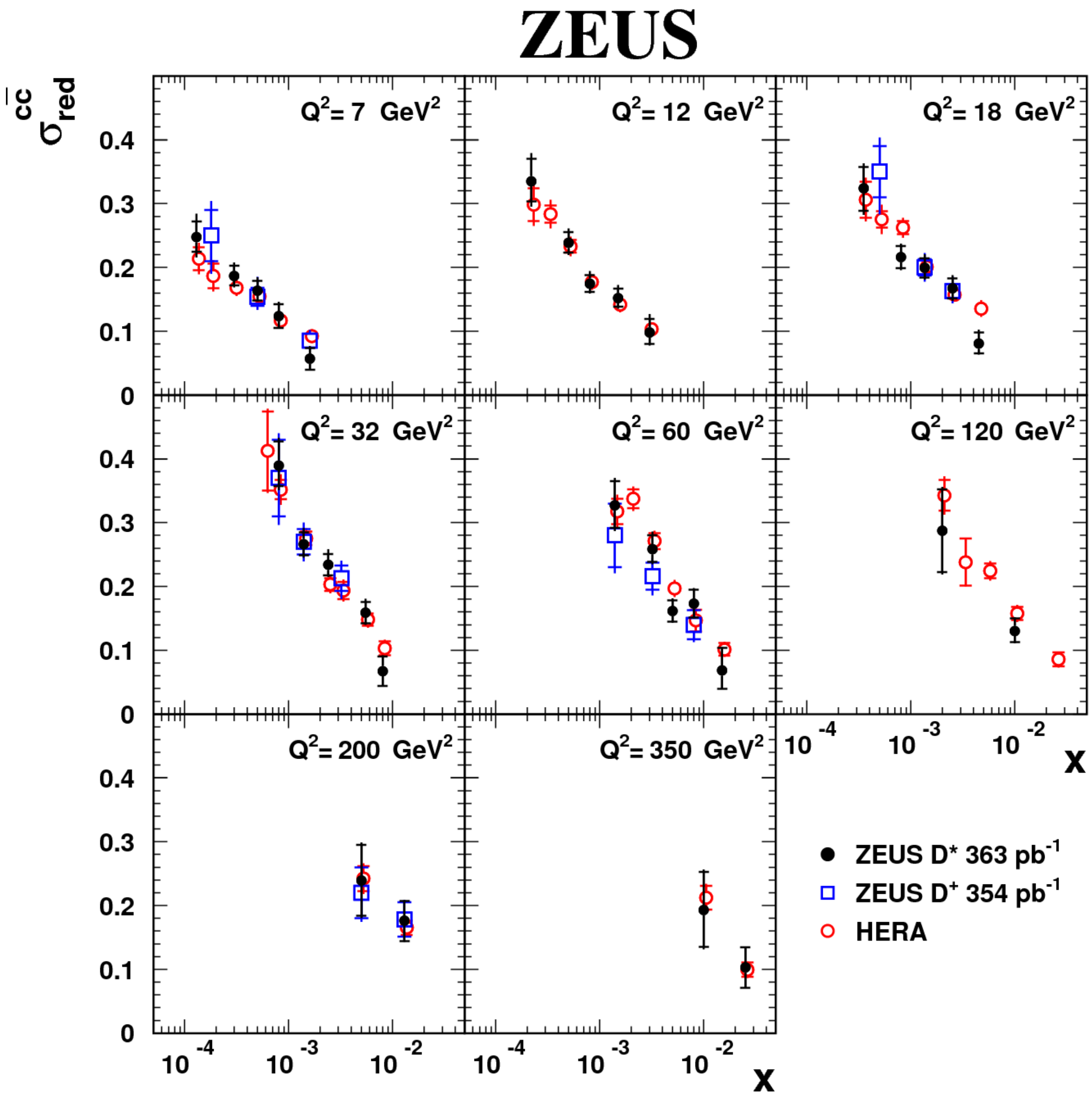


- Fit to the same data
- Massive scheme (FF ABM)

➔ Consistent with world average: $m_c(m_c) = 1.275 \pm 0.025$ GeV

Brand new charm results in DIS: D* and D+

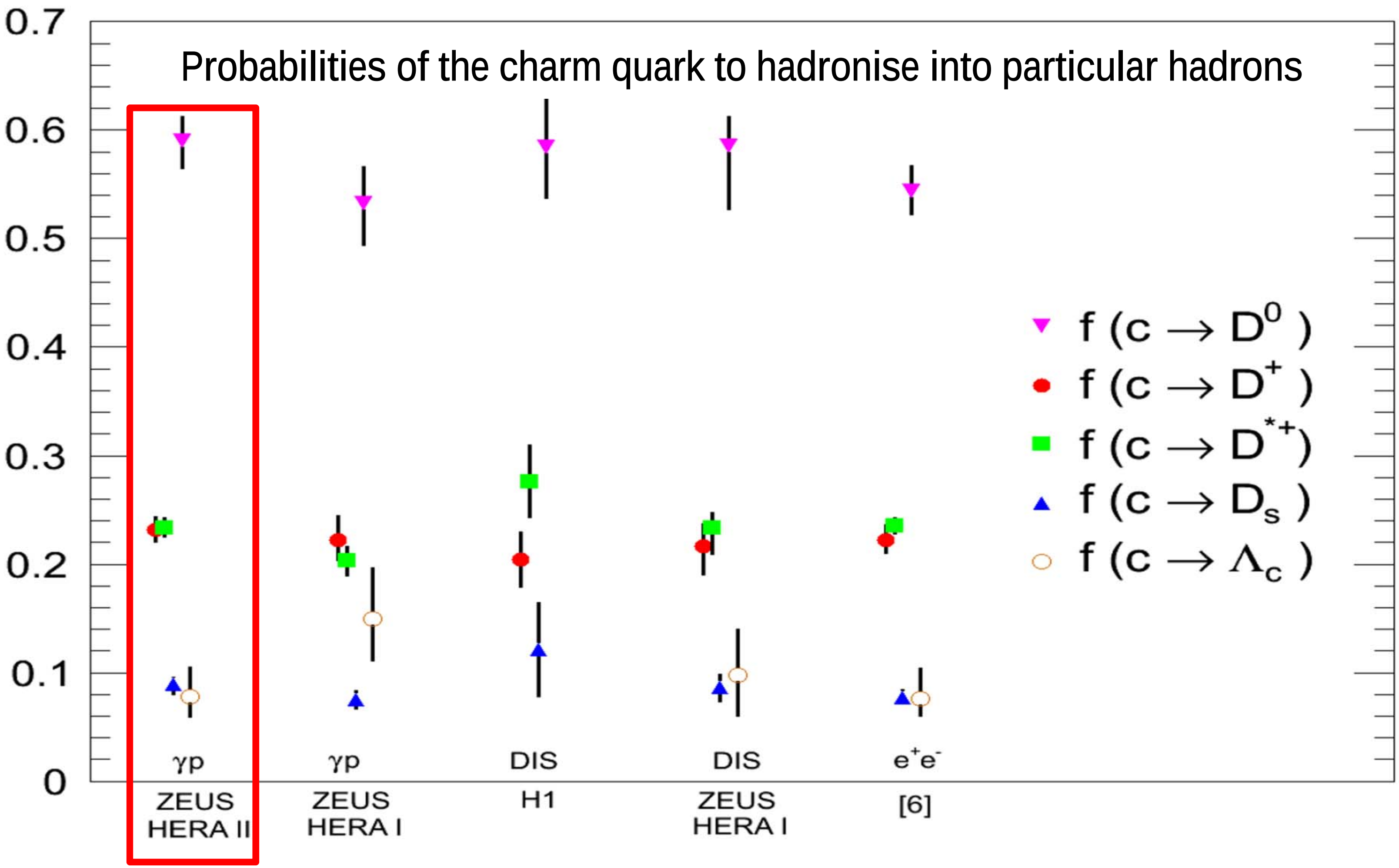
DESY-13-054
DESY-13-028



➔ Consistent findings
➔ New ZEUS results will **improve** combination, PDF and m_c fits

Charm fragmentation fractions in PHP

to be submitted soon for DESY preprint

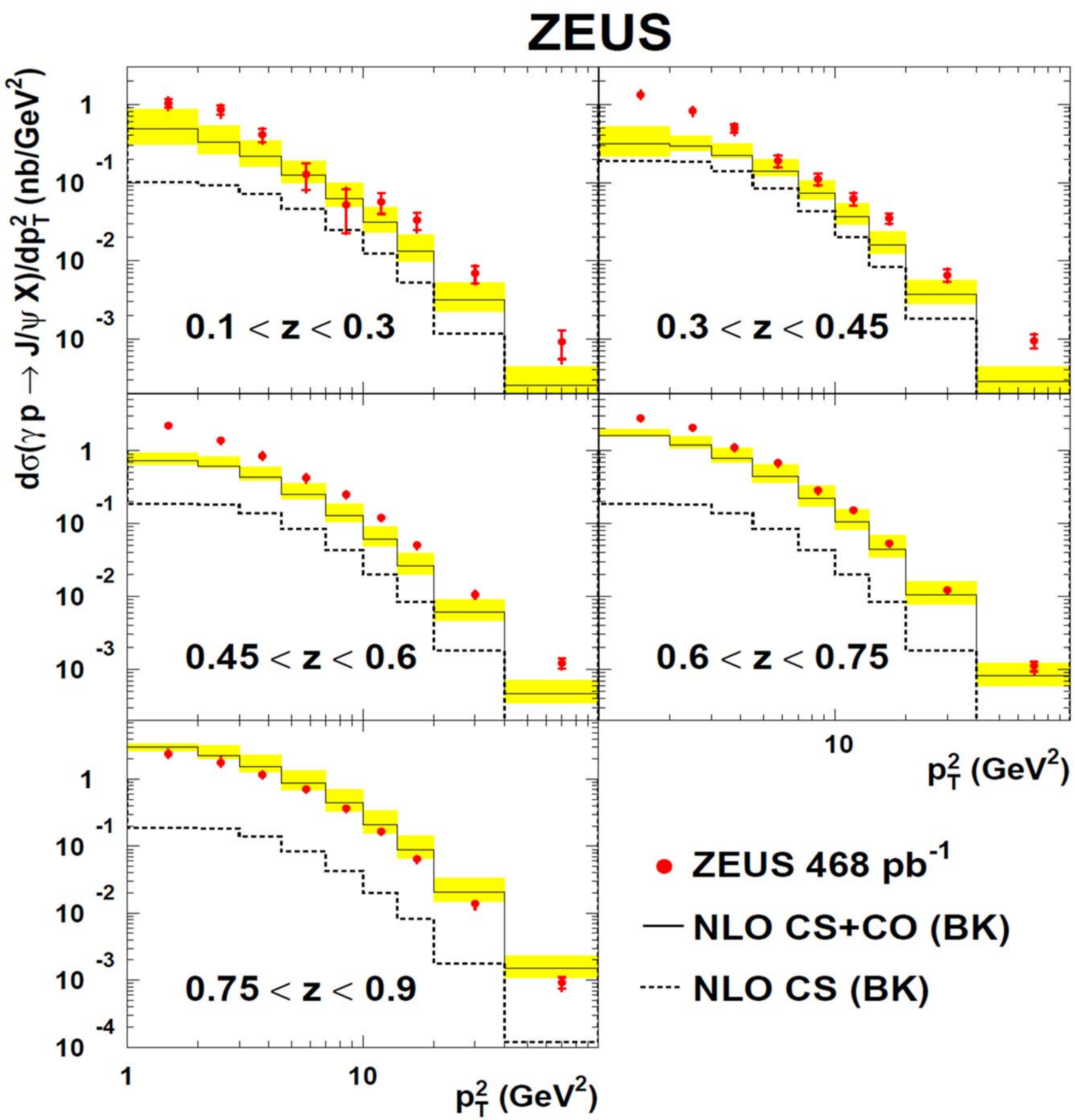


➔ Competitive precision to e+e- data

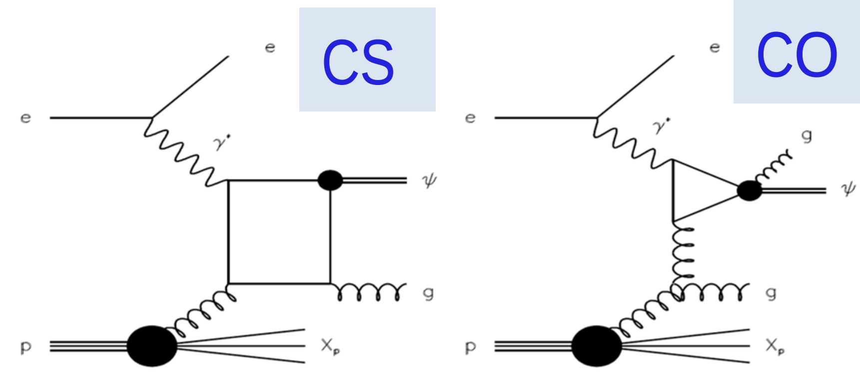
➔ Confirm ***universality*** of charm fragmentation

Inelastic J/ψ production in PHP

JHEP02 (2013) 071



Non relativistic QCD



$$z = \frac{(E\text{-}p_z)_{J/\Psi}}{(E\text{-}p_z)}$$

NLO calculation:

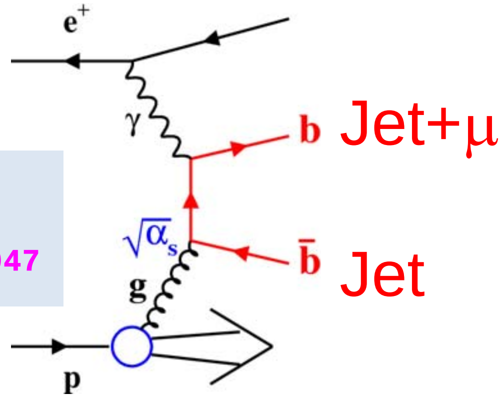
➔ **Rough** data description

➔ Color octet contribution is essential

Beauty: HERA photo- vs LHC hadroproduction

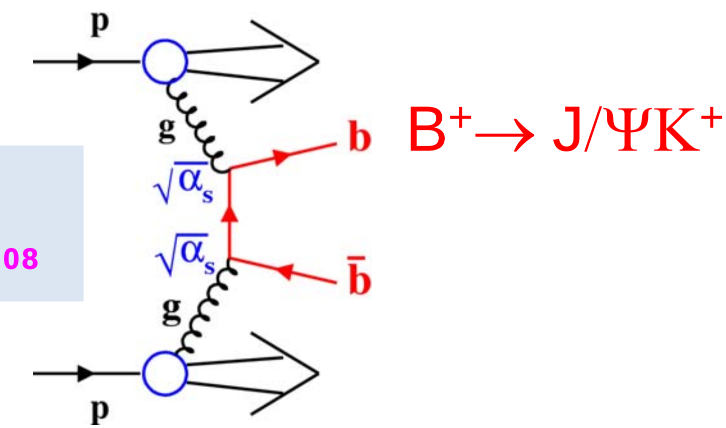
HERA

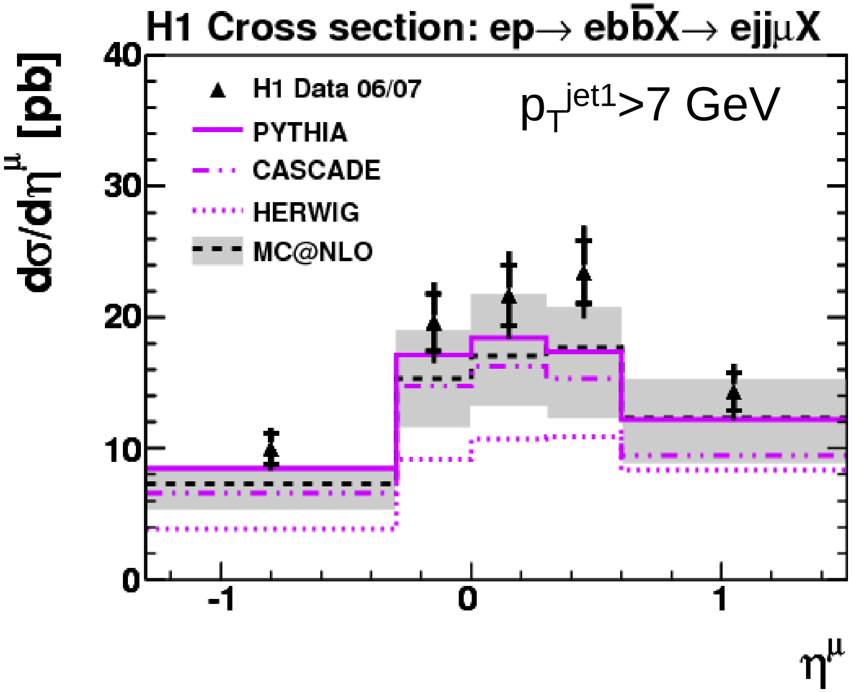
EPJ C72 (2012) 2047

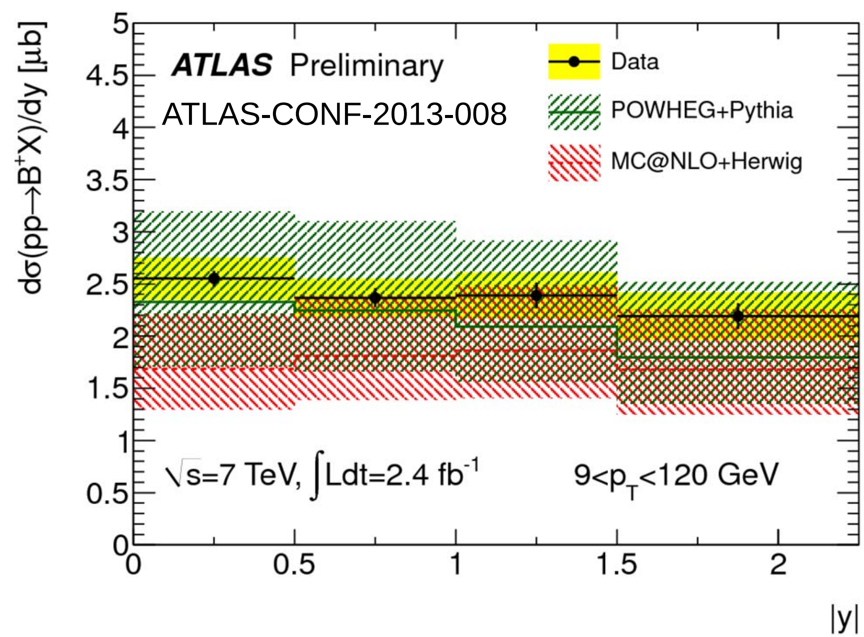


LHC

ATLAS-CONF-2013-008



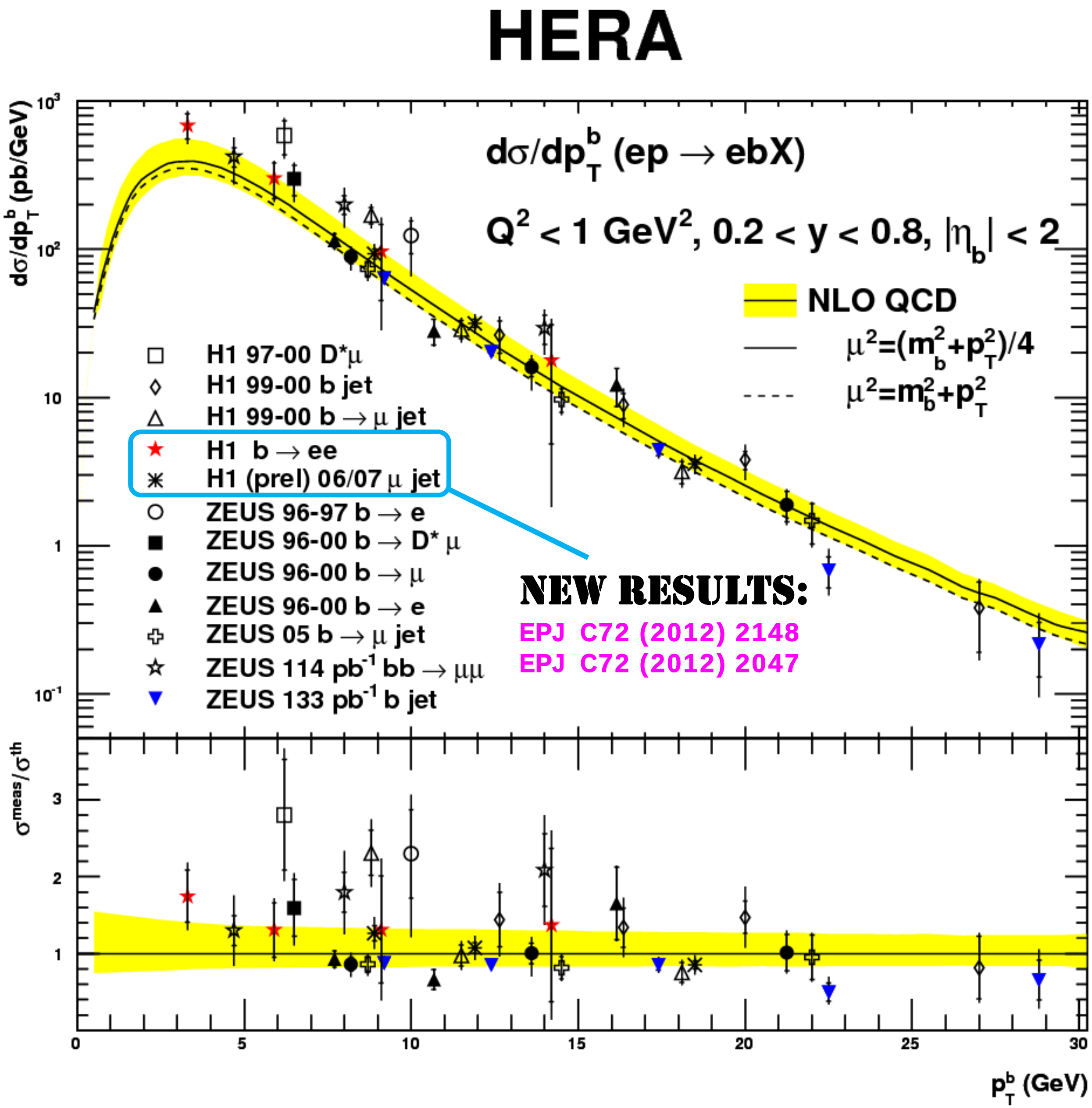


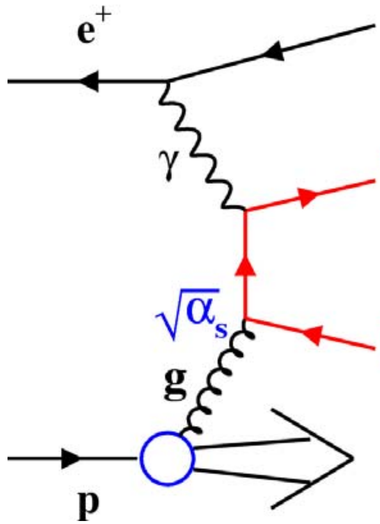


MC@NLO: - describes both data reasonably (however fails ATLAS $d^2\sigma/dpt/dy$)

- comparable (rather large) theory uncertainties

Beauty photoproduction vs p_T^b

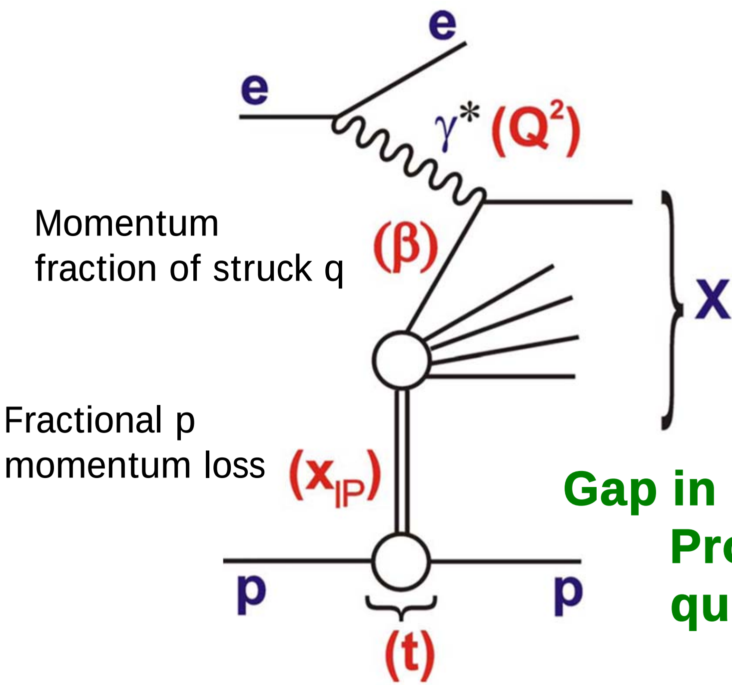




Data vs massive NLO (FMNR)

➔ Reasonable description ***from threshold to high momenta***

Hard Diffraction



Gap in rapidity

Proton is intact or quasi-intact

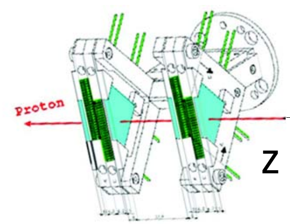
at HERA start: ~10% of DIS events are diffractive!

Experimental tagging:

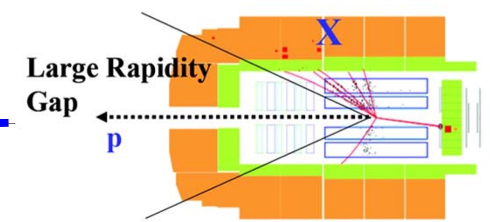
Very Forward Proton Spectrometer

z = 220 m

Forward Proton Spectrometer

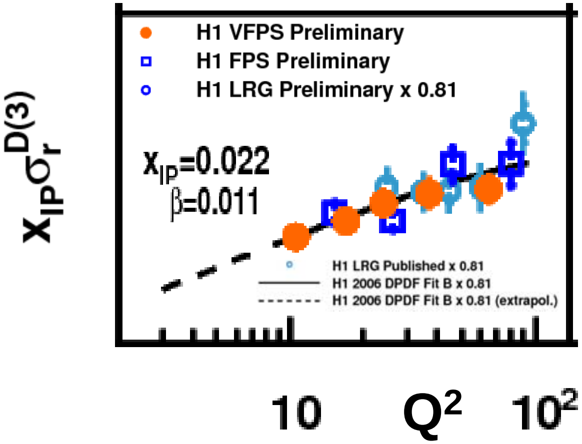


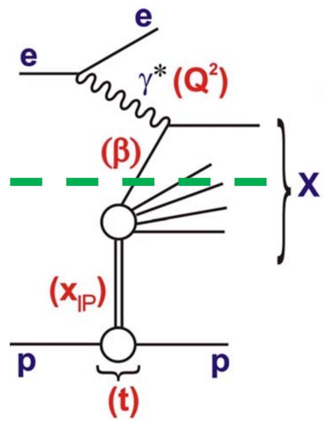
z = 64 m p



- ➔ Last year: Final H1 HERA II Large Rapidity Gap inclusive data EPJ C72 (2012) 2074
- ➔ Today: focus on H1 results with VFPS

Diffraction: VFPS Results

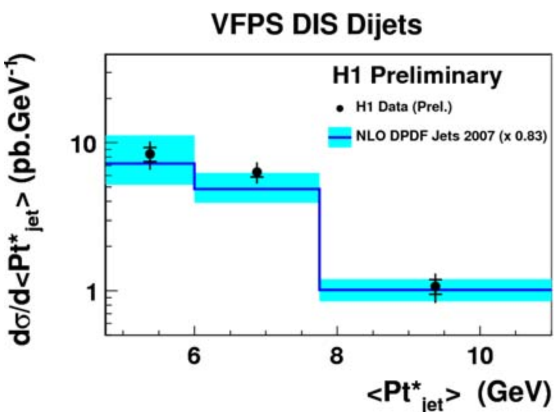




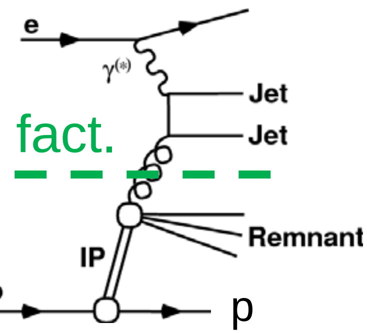
Inclusive

H1prelim-10-014

➔ agree with LRG data



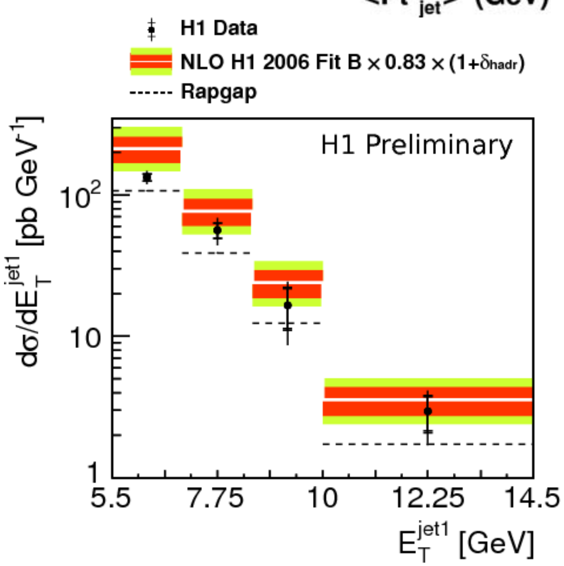
QCD fact.

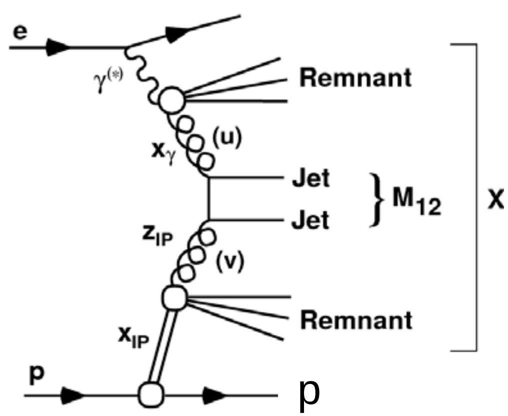


Dijets in DIS

H1prelim-11-013

➔ Confirm QCD factorisation





Dijets in PHP

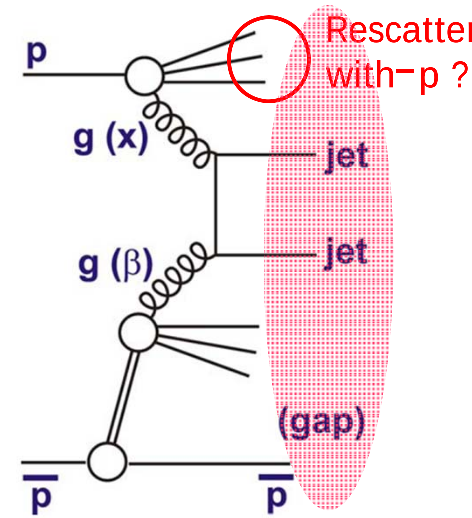
H1prelim-13-011

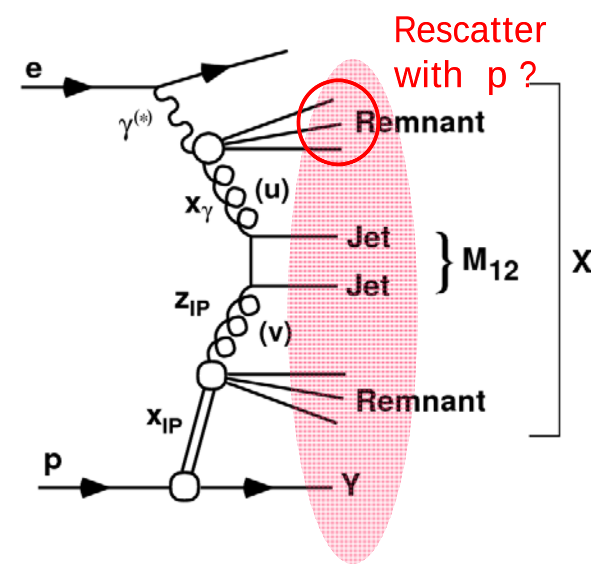
➔ Hints for suppression = factorisation breaking (but rather large syst. Uncertainties)

Status report

Factorisation breaking in diffractive dijets

			Data/NLO
- TEVATRON:	CDF	PRL 84 (2000) 5043	~0.1
	CDF	PRD 86 (2012) 032009	kinematic studies
- LHC:	CMS	PRD 87 (2013) 012006	~0.1
- HERA PHP:	H1	H1prelim-13-011	~0.7
	H1	EPJC 70 (2010) 15	~0.6
	ZEUS	EPJC 55 (2008) 177	compatible with 1





→ HERA results not fully conclusive

→ need future experiments to clarify (LHeC)

Conclusions

- HERA provides precision measurements in many QCD areas

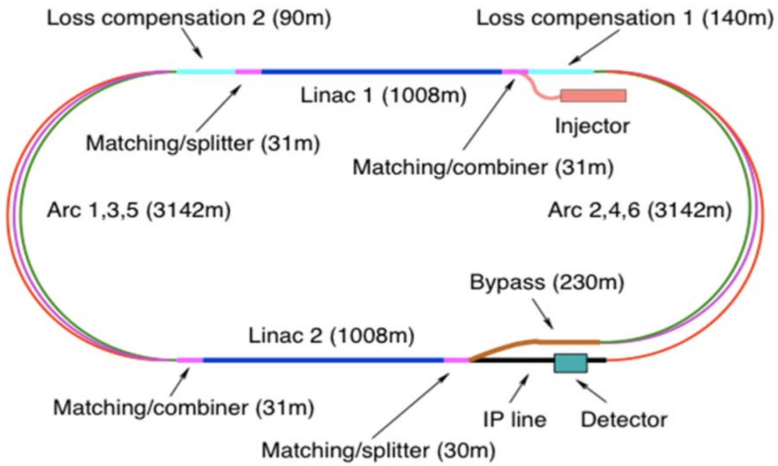
	Best precision	Recent highlight
Inclusive DIS	1%	Complete HERA II high Q^2data
Jets	1-2%	α_s from inclusive or multijets
c and b	5%	$m_c(m_c)$ determination
Diffraction	Few %	Dijets with proton tagged data

- Plus nice results with final states: Z^0, γ, charged particles, strange particles, neutrons
- Theory: pQCD works great, but almost everywhere large uncertainties due to missing NNLO calculations

Outlook

- Still numerous precise HERA QCD results (also combined) to come, stay tuned!
- Future experiments:
  - JLAB@12 GeV (Valence quarks)
  - longer term: LHeC and EIC would be ideal/complementary large scale facilities

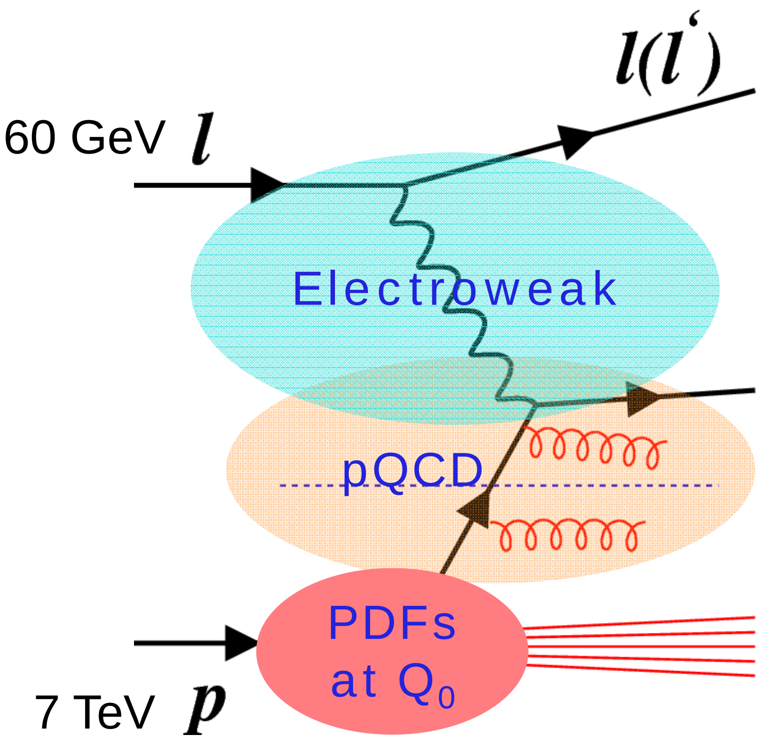
collide the LHC protons with electrons

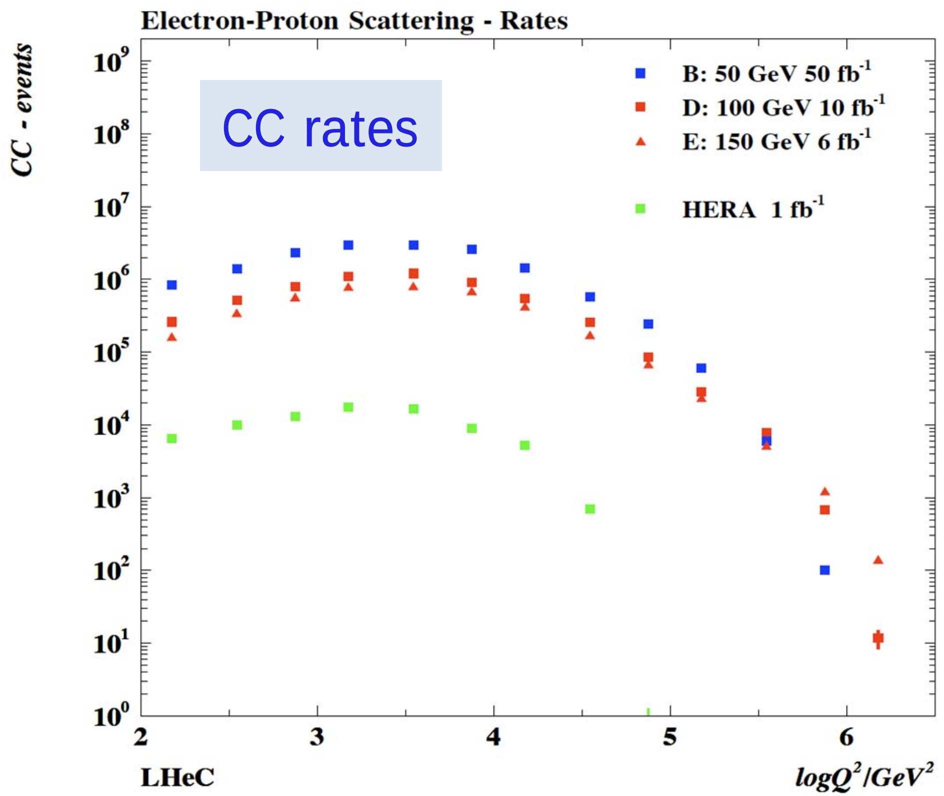


Electrons: LINAC Ring

60 GeV race track with Energy recovery

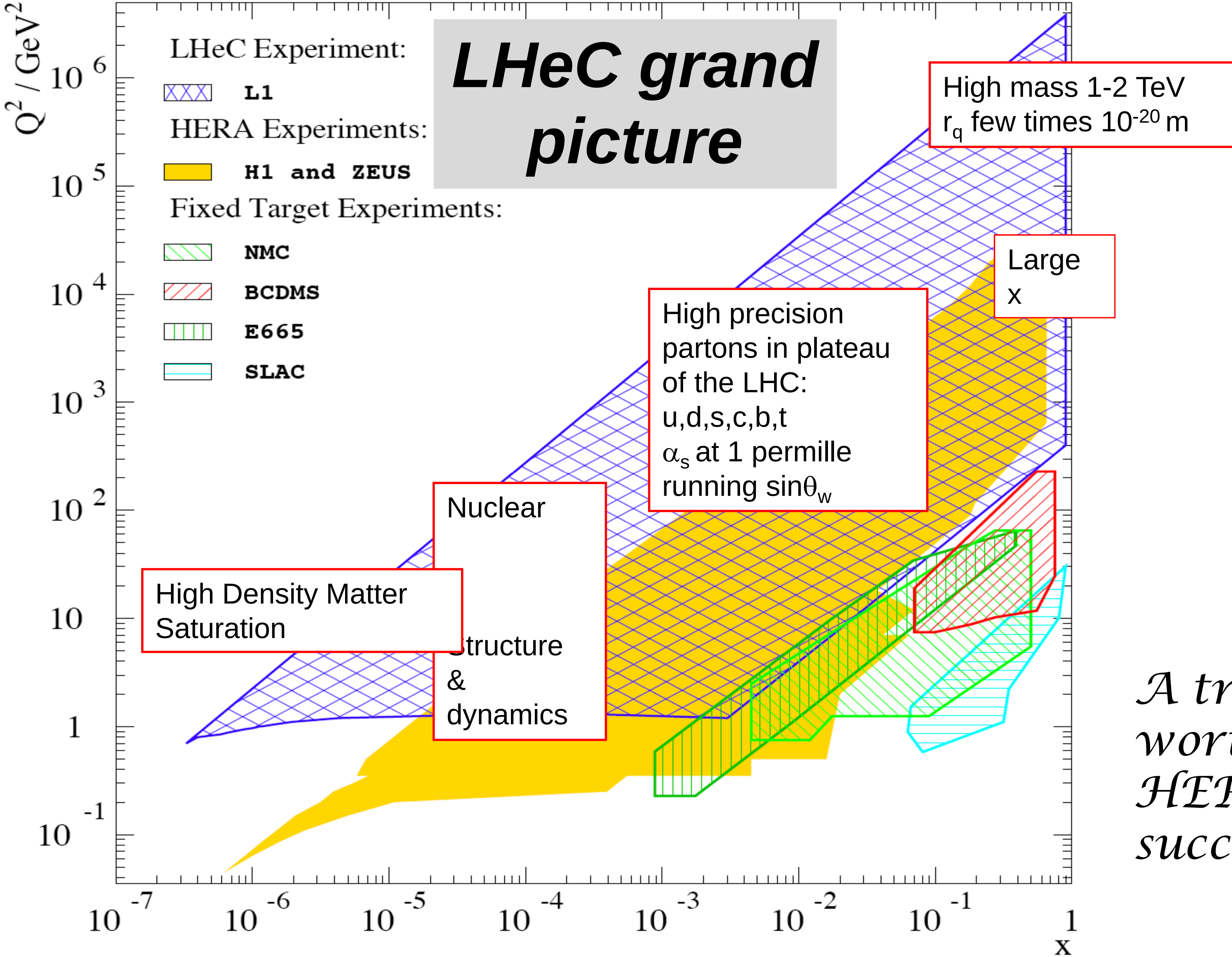
L = 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}





→ Electroweak part much enhanced at LHeC
→ helps for all three pieces

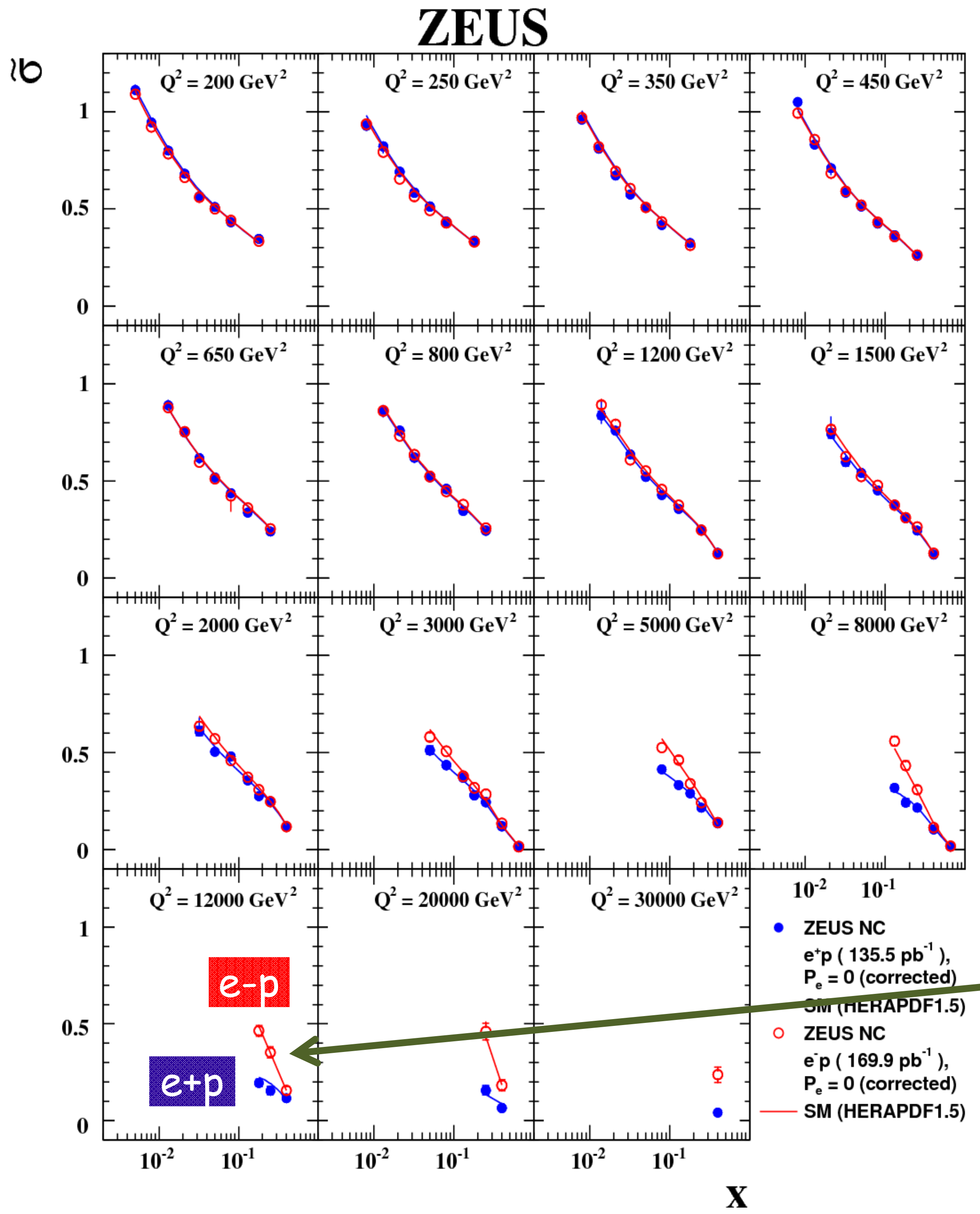
LHeC grand picture



A truly worthy HERA successor

Backup slides

Reduced NC cross sections



Final ZEUS
high Q^2 HERA II *results*

PRD 87, 052014 (2013)

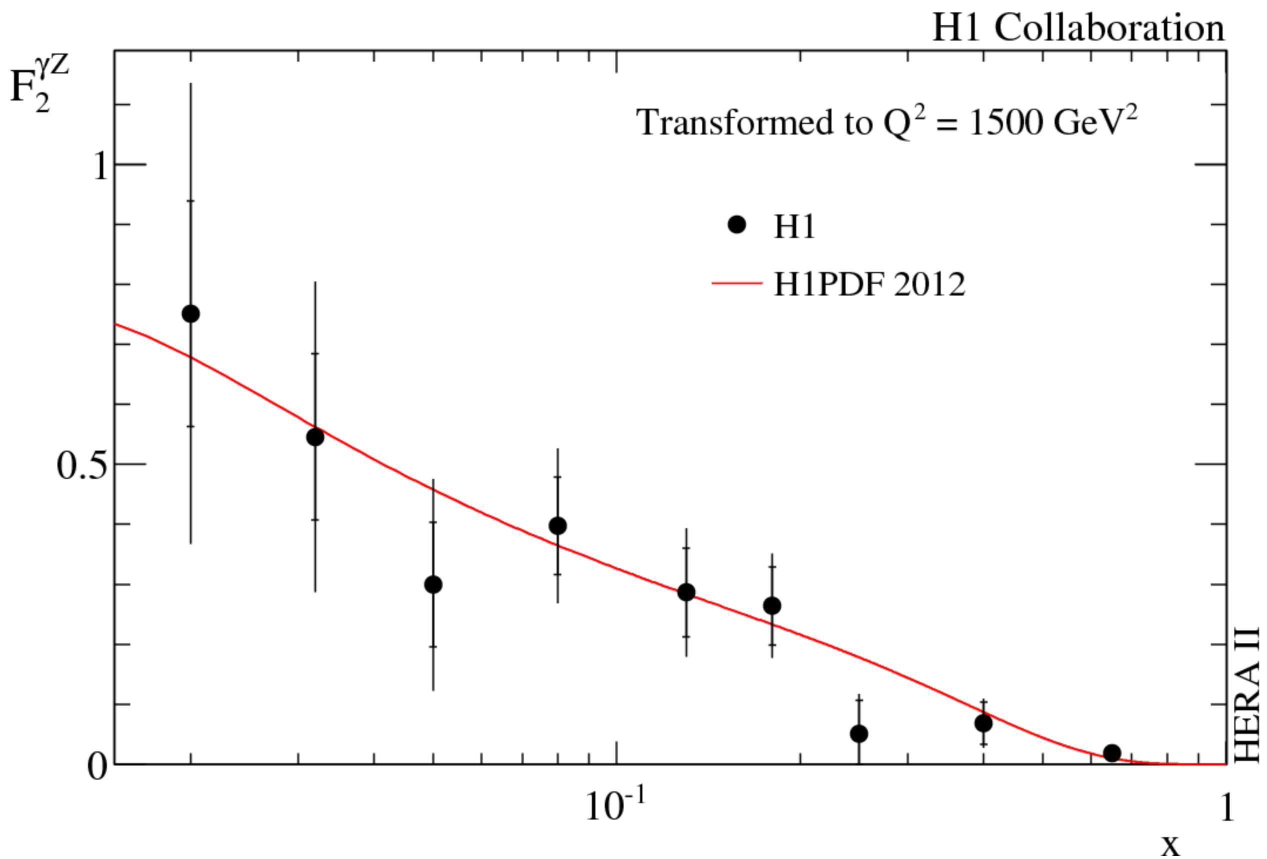
Best precisions of ~1.5%

→ Data well described by DGLAP NLO QCD

→ e^+p and e-p differ due to γZ interference → extract $xF_3^{\gamma Z}$
see V. Radescu talk

Reduced NC cross sections: $F_2^{\gamma Z}$

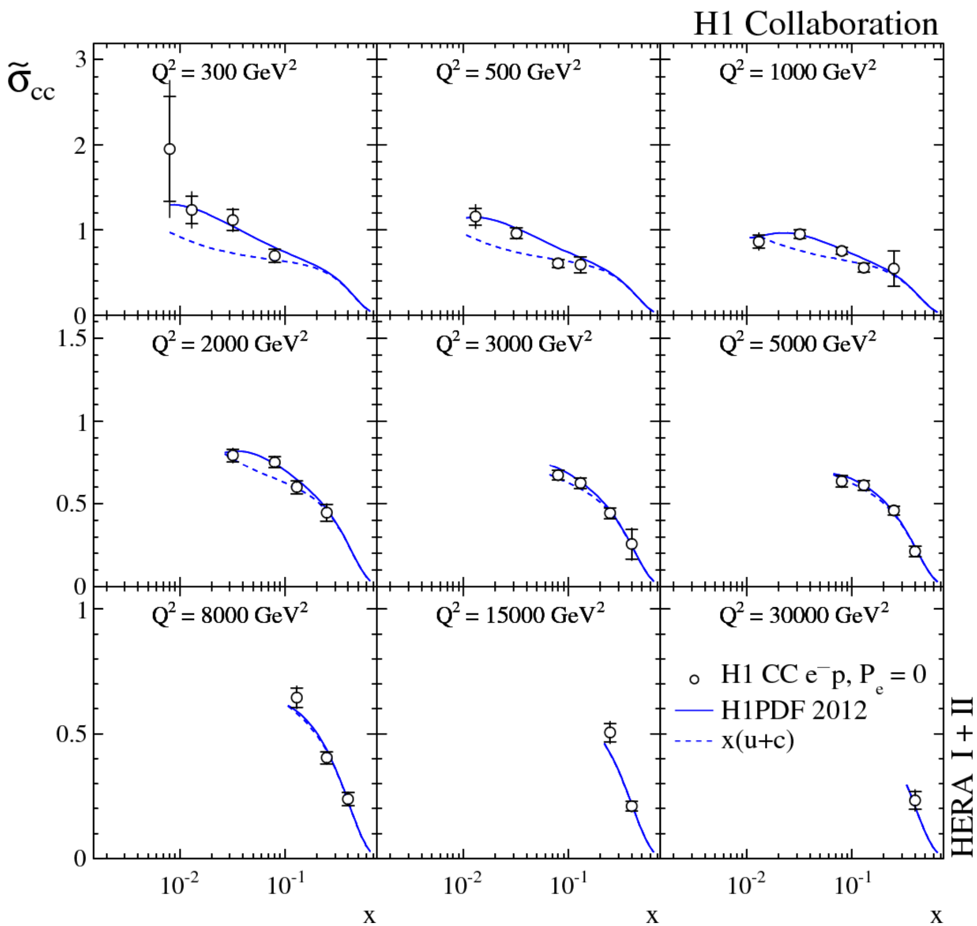
JHEP 1209:061 (2012)

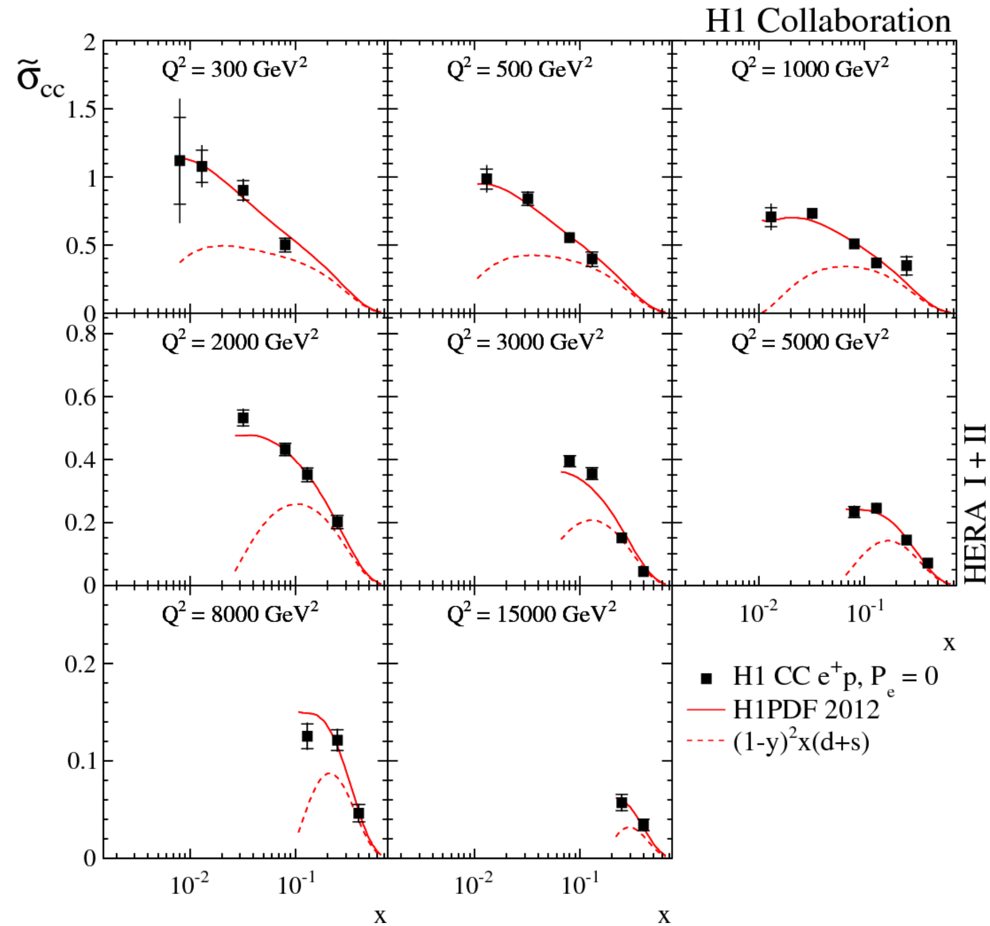


➔ Data well described by DGLAP NLO QCD

Reduced CC cross sections

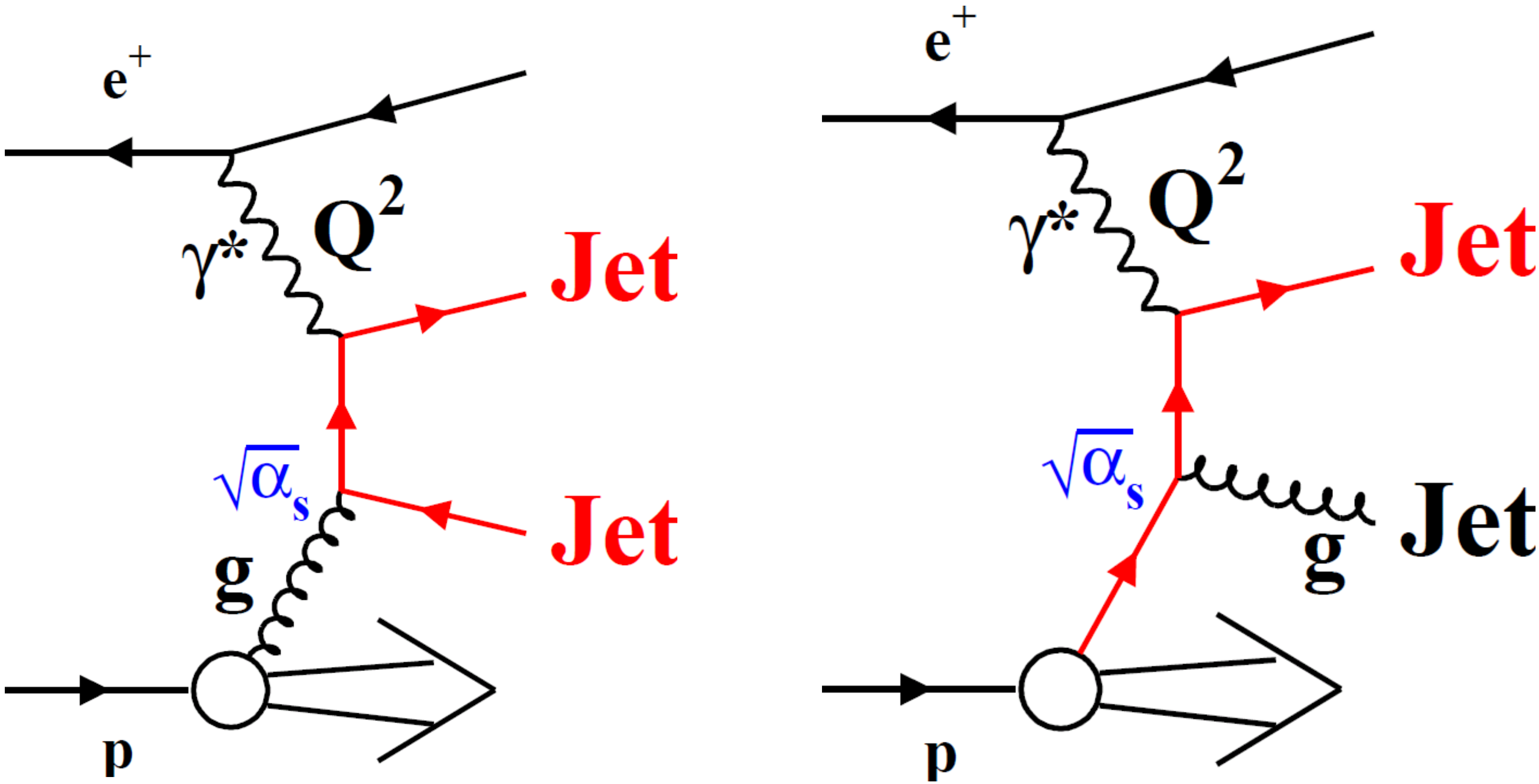
JHEP 1209:061 (2012)





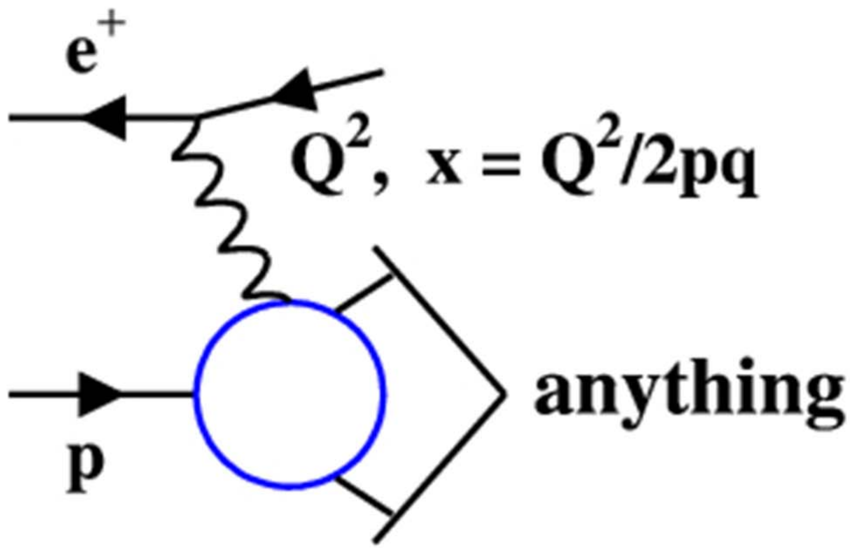
➔ Data well described by DGLAP NLO QCD

Jet production at HERA

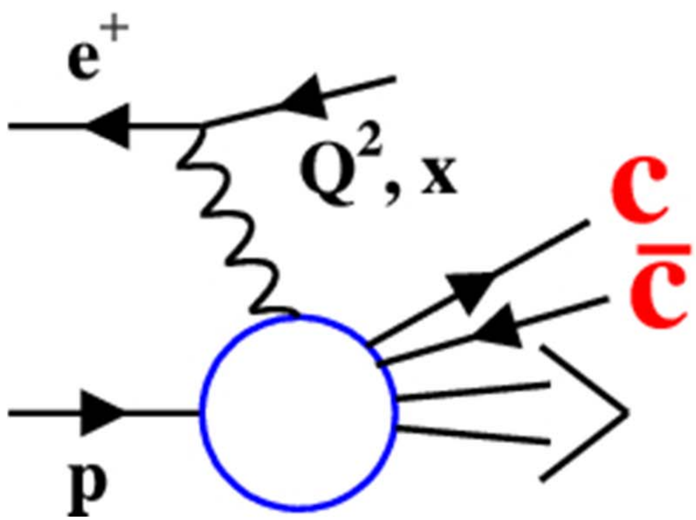


→ Different processes allow to disentangle g(x) and α_s

Charm contribution to DIS: F_2^{cc}

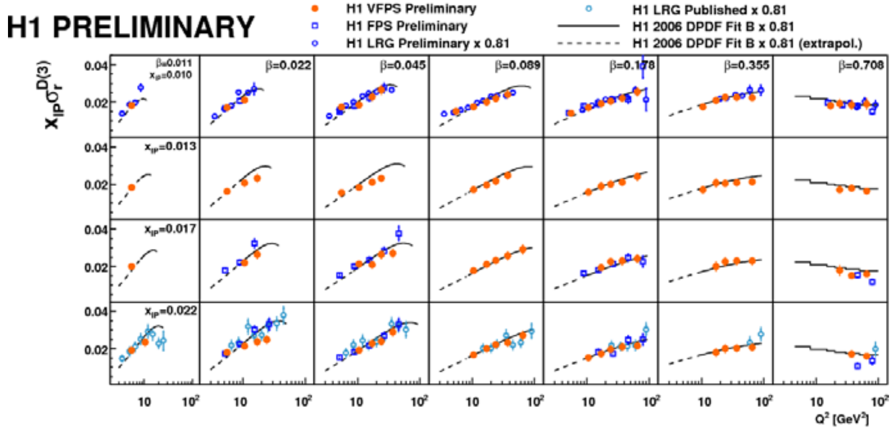


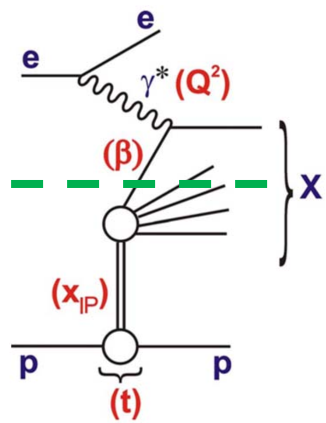
$$\frac{d^2\sigma^{ep}}{dQ^2dx} \propto F_2(x, Q^2)$$



$$\frac{d^2\sigma^{ep\to c\bar{c}x}}{dQ^2dx} \propto F_2^{c\bar{c}}(x, Q^2)$$

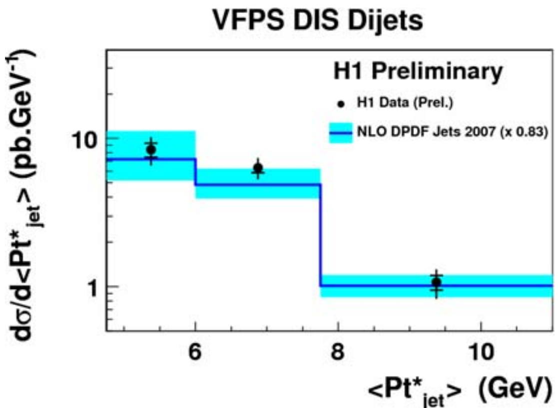
Diffraction: Results with VFPS

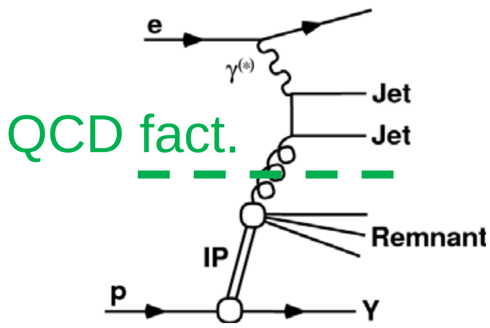




Inclusive H1prelim-10-014

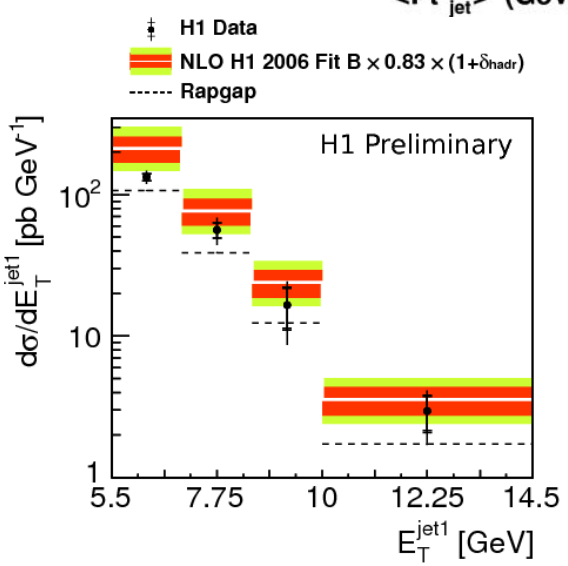
➔ agree with LRG data

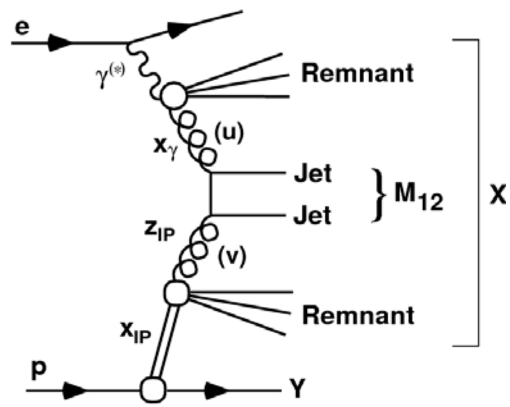




Dijets in DIS H1prelim-11-013

➔ Confirm QCD factorisation





Dijets in PHP H1prelim-13-011

➔ Hints for suppression = factorisation breaking (but rather large syst. Uncertainties)