QFTHEP 2013

The XXI International Workshop High Energy Physics and Quantum Field Theory

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Recent Results from the H1 Experiment at HERA

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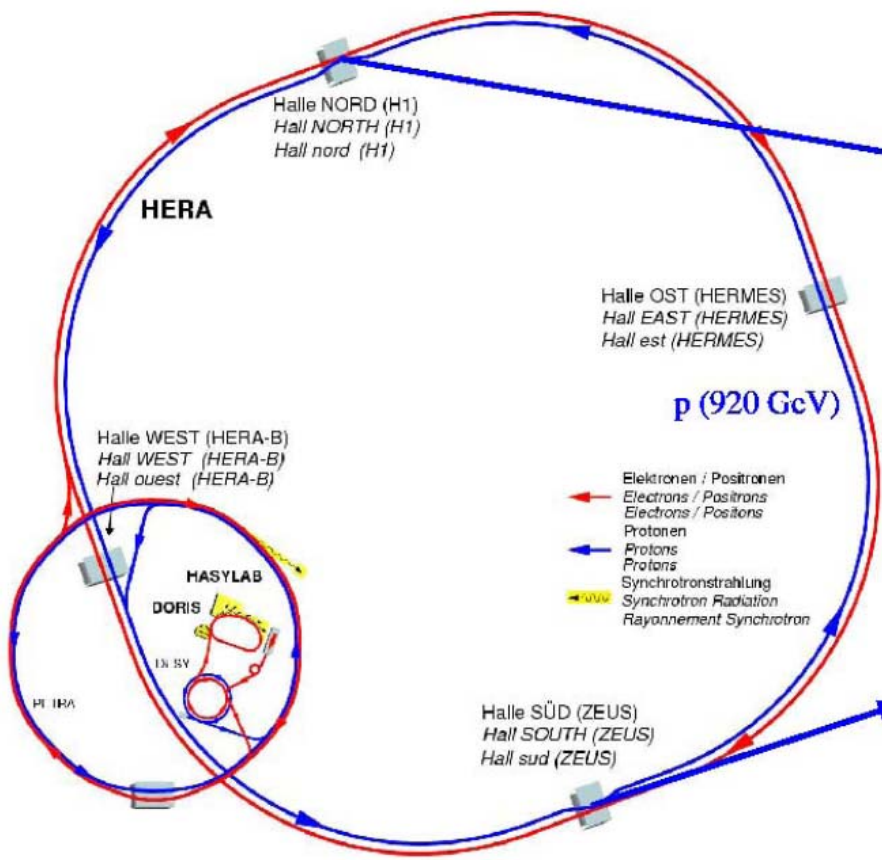
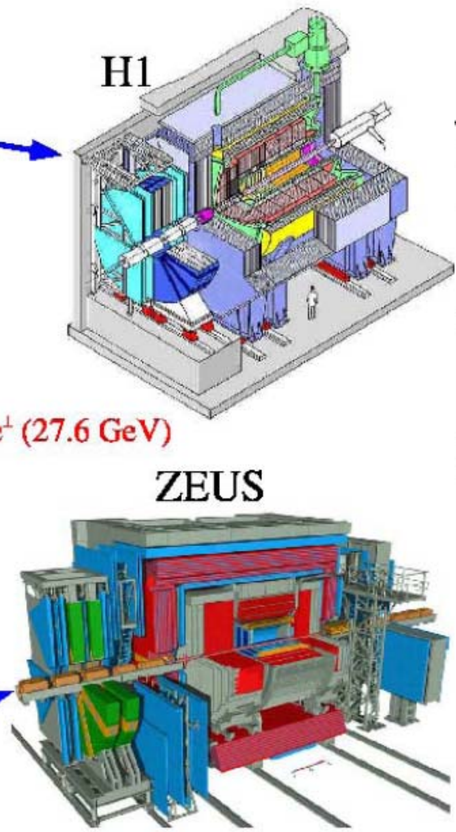
On behalf of the H1 Collaboration

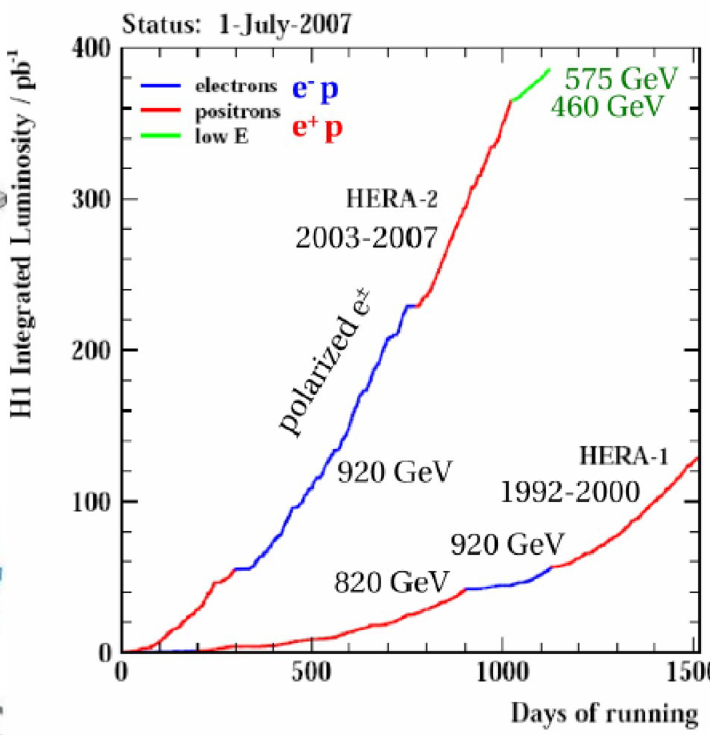
The world's only electron/positron-proton collider at DESY, Hamburg

E_e = 27.6 GeV E_p = 920 GeV (also 820, 460 and 575 GeV)

(total centre-of-mass energy of collision up to $\sqrt{s} \approx$ 320 GeV equivalent to $5 \cdot 10^{13}$eV photon beam on a stationary proton target)





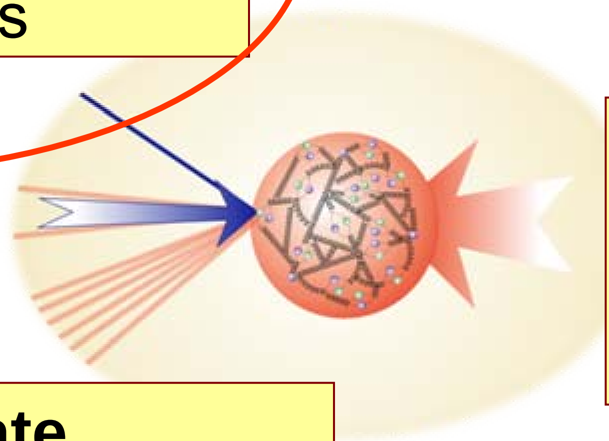


Two collider experiments: H1 and ZEUS

HERA-1: 1992 – 2000
HERA-2: 2003 - 2007
total lumi: 0.5 fb^{-1} per experiment

Recent H1 results

Inclusive measurements
proton structure, PDF
Electroweak effects

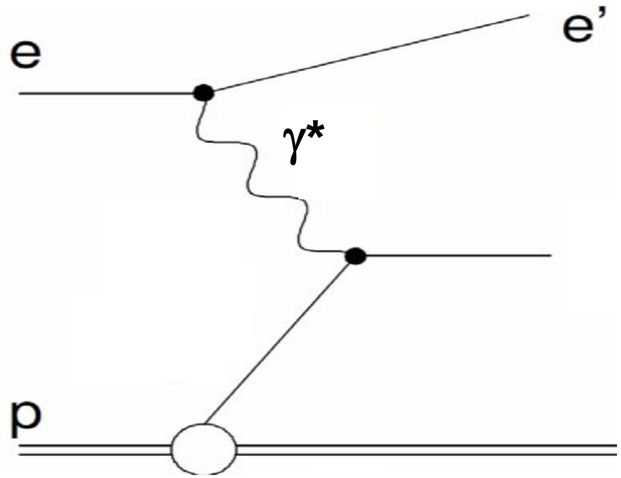


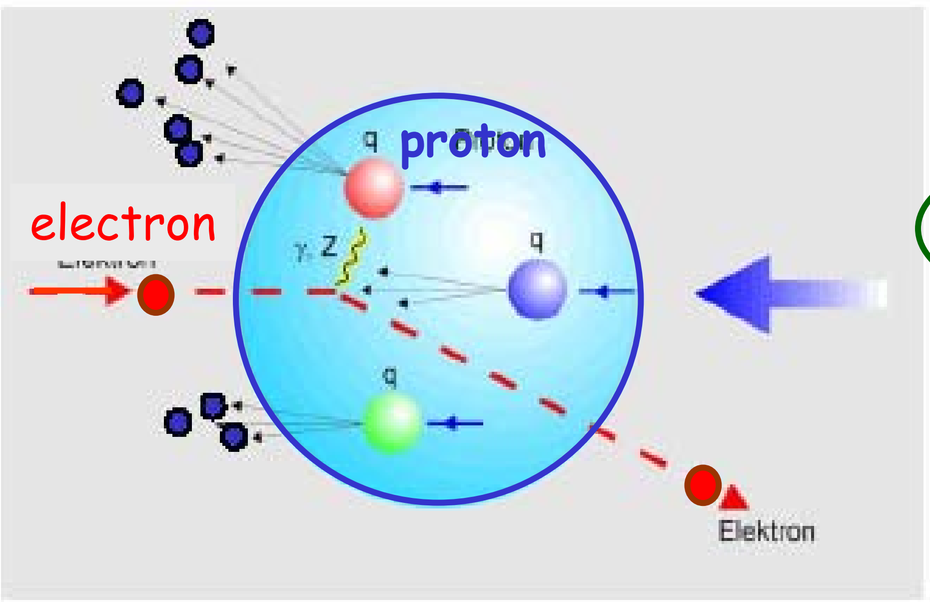
Hard diffraction
Diffractive DIS
elastic J/ψ production
diffractive jet production

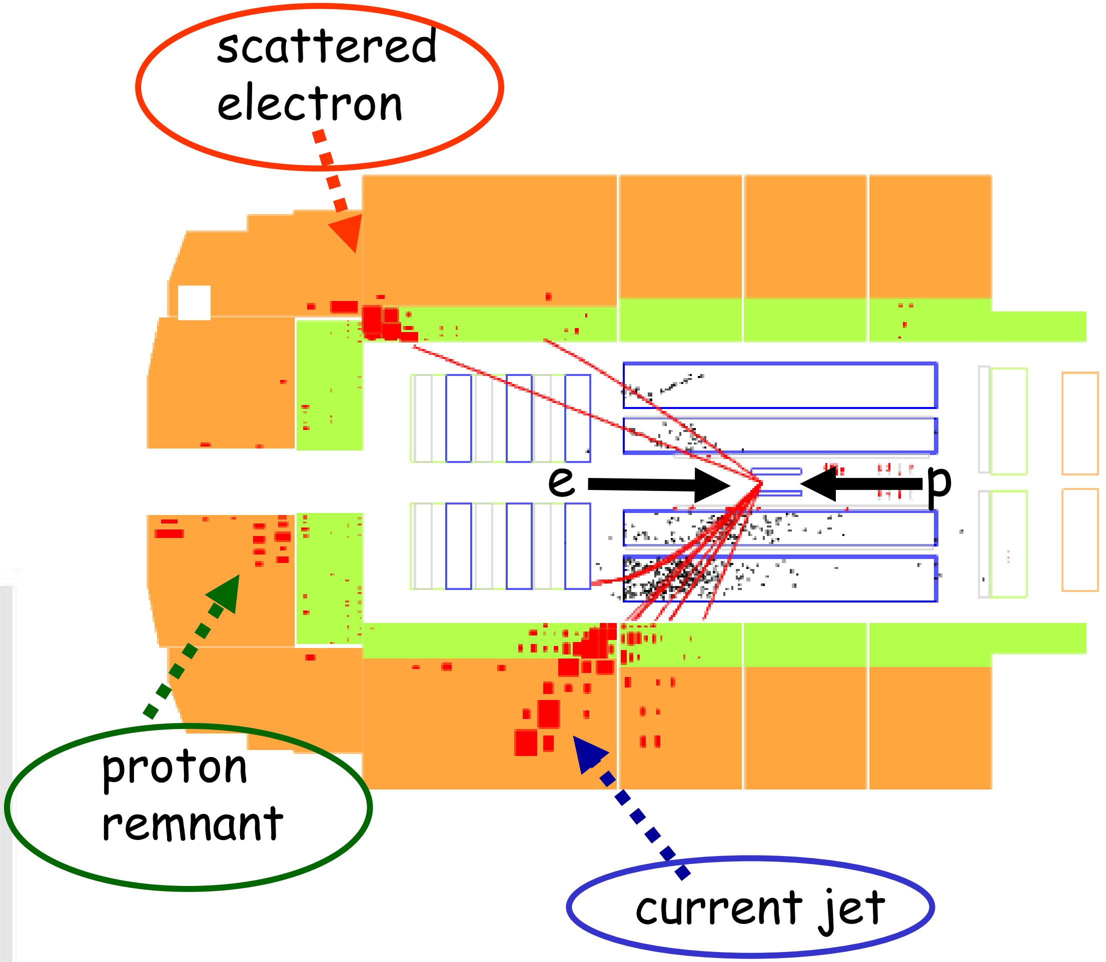
Hadronic final state
Charged particle densities
Strangeness, Jet production
Target fragmentation

Deep Inelastic electron-proton Scattering (DIS) at HERA

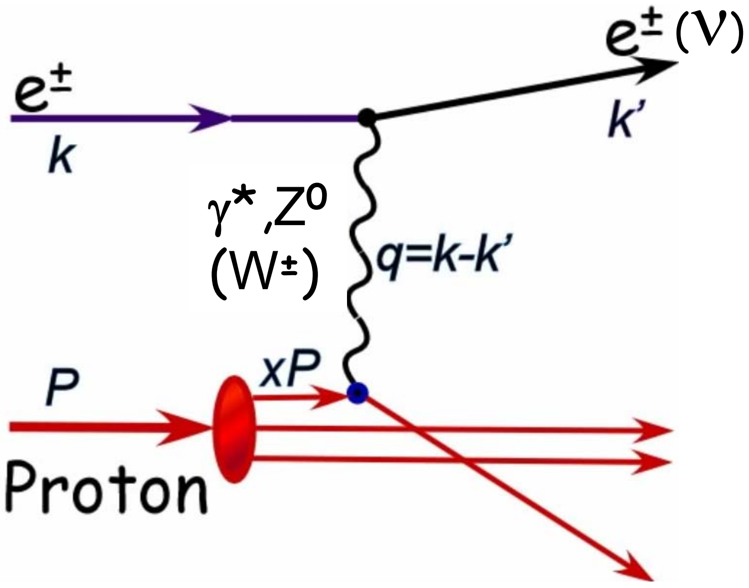
DIS - a probe of proton structure







Deep Inelastic electron-proton Scattering (DIS) at HERA

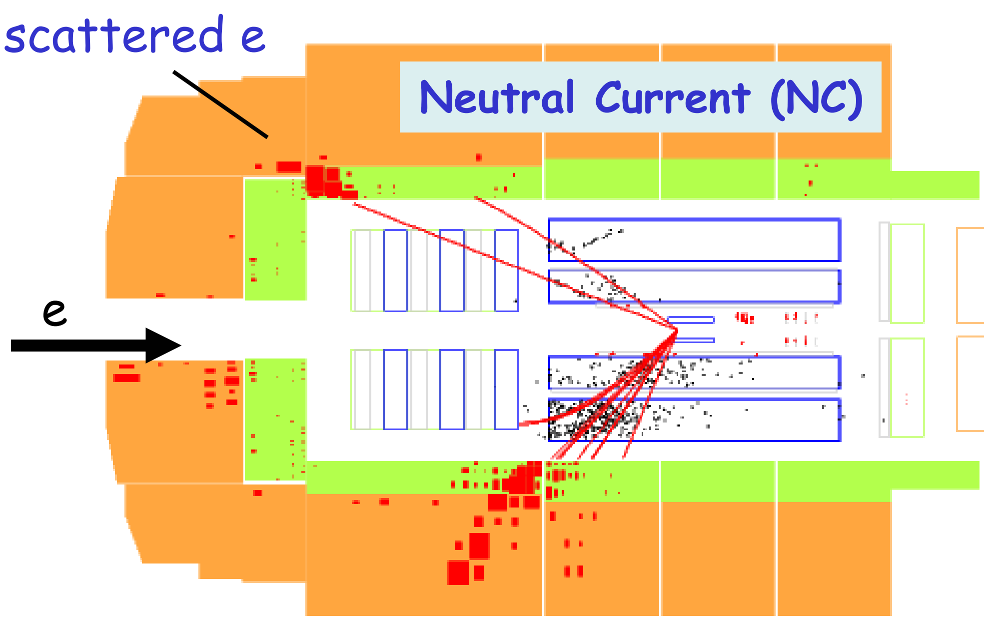


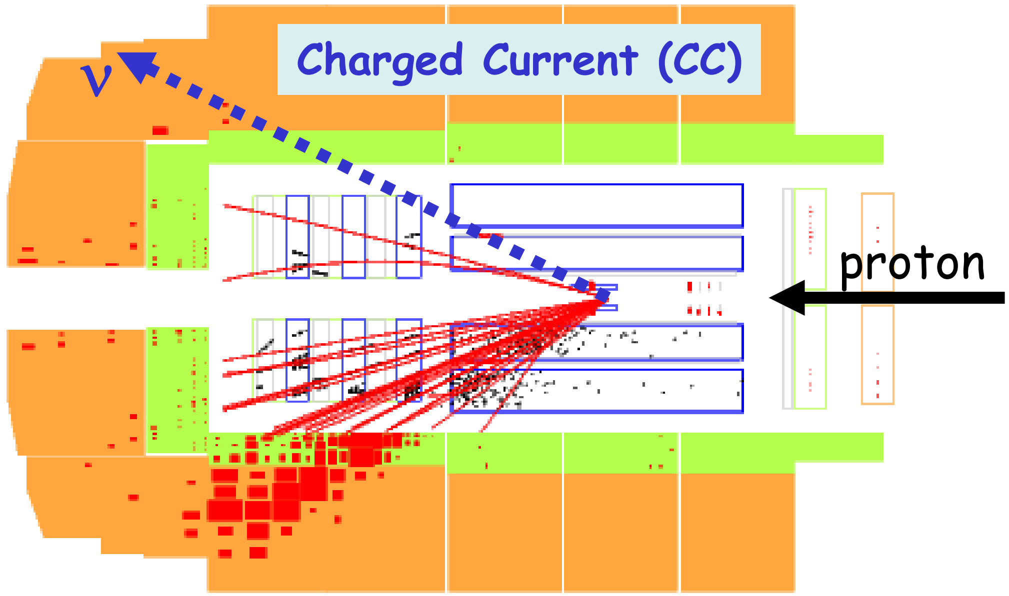
$Q^2=-(k-k')^2$ virtuality of exchanged boson: 'resolving power' of probe

$x=Q^2/2p\cdot q$ fraction of proton momentum carried by struck quark
At HERA $x\sim 10^{-6} - 1$

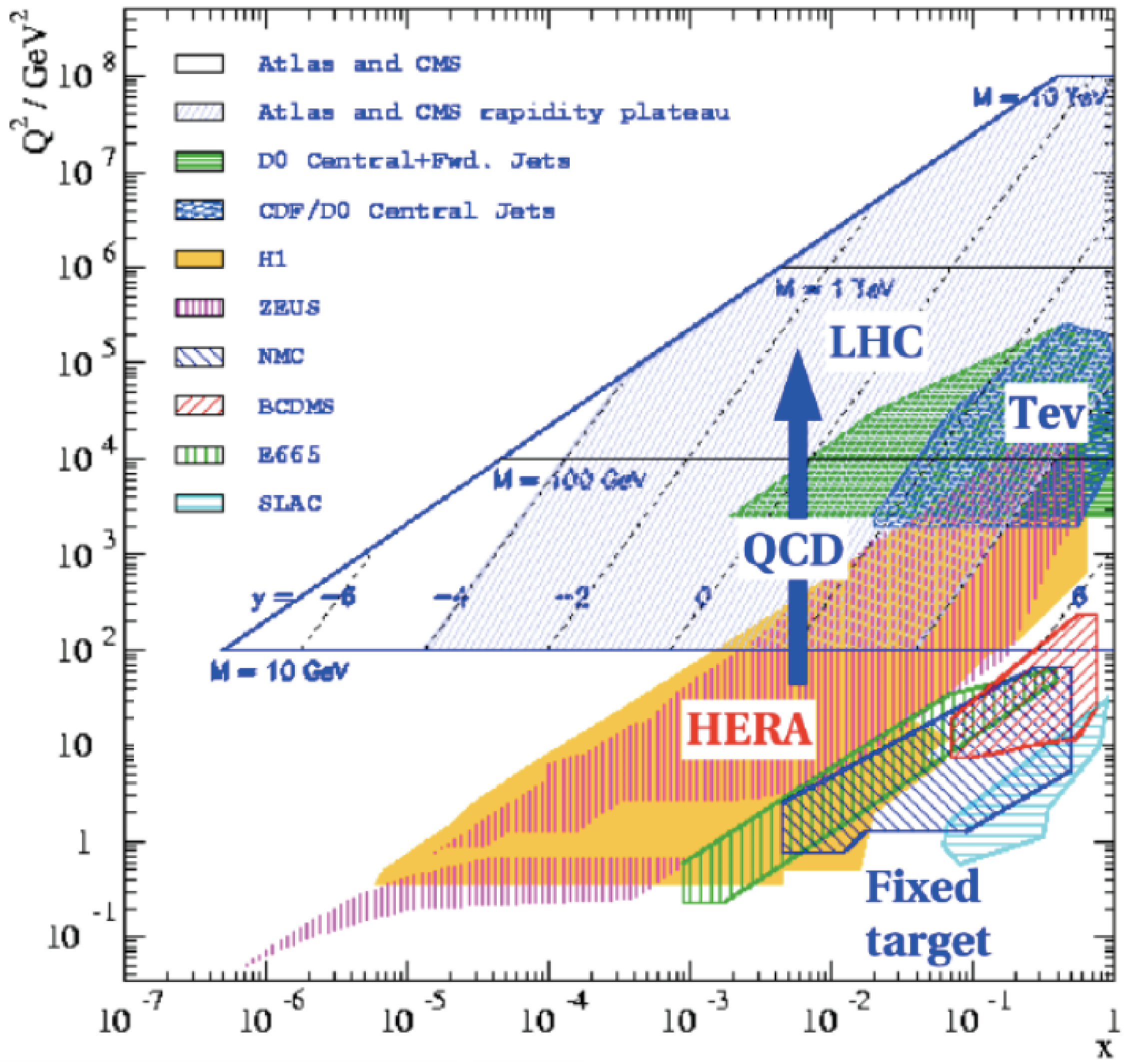
$y=p\cdot q/p\cdot k$ inelasticity variable: $y= Q^2/(s\cdot x)$

At fixed $\sqrt{s}$ only two independent kinematic variables, e.g. x and Q^2





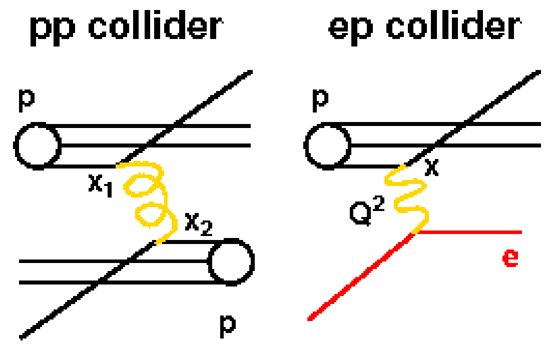
DIS at HERA: kinematic coverage



HERA: span 5 orders of magnitude in x and Q^2

HERA inclusive data are an indispensable input to modern PDF fits

Direct overlap with the LHC kinematics:
HERA covers x range of the LHC, evolution in Q^2 via DGLAP



σ_{HERA} = PDF $\otimes$ ME

σ_{LHC} = PDF $\otimes$ ME $\otimes$ PDF

Inclusive DIS cross sections at high Q^2

Final measurement of inclusive NC/CC cross sections at $\sqrt{s}$=319 GeV with H1 detector

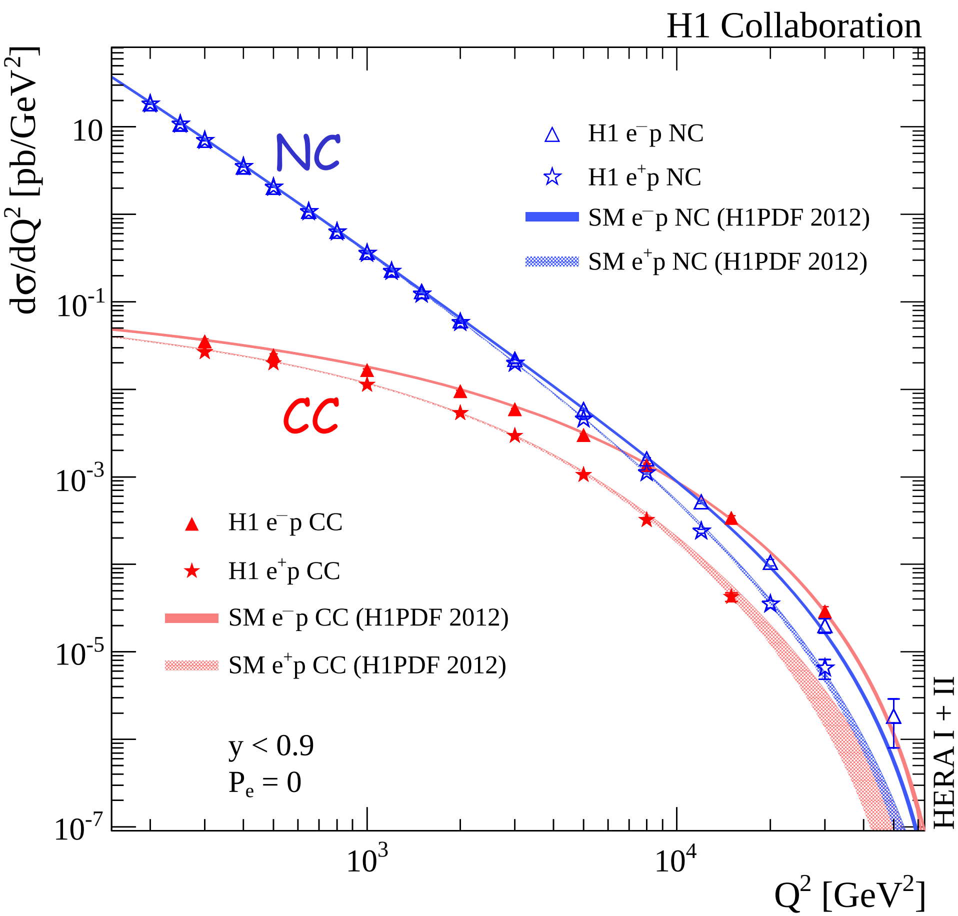
Data: e^-p and e^+p polarized $e^\pm$ beams
→4 distinct data sets
(all HERA-2 data at Ep=920 GeV)

	R	L
e^-p	$\mathcal{L} = 47.3\,\mathrm{pb}^{-1}$ $P_e = (+36.0 \pm 1.0)\%$	$\mathcal{L} = 104.4\,\mathrm{pb}^{-1}$ $P_e = (-25.8 \pm 0.7)\%$
e^+p	$\mathcal{L} = 101.3\,\mathrm{pb}^{-1}$ $P_e = (+32.5 \pm 0.7)\%$	$\mathcal{L} = 80.7\,\mathrm{pb}^{-1}$ $P_e = (-37.0 \pm 0.7)\%$

$60 < Q^2 < 50.000\ \mathrm{GeV}^2$, $0.0008 < x_{Bj} < 0.65$

Typical precision:
NC e^+ ~1.5% ; e^- ~2.0%
CC $e^\pm$ ~4%

$d\sigma/dQ^2$ cross sections of CC and NC



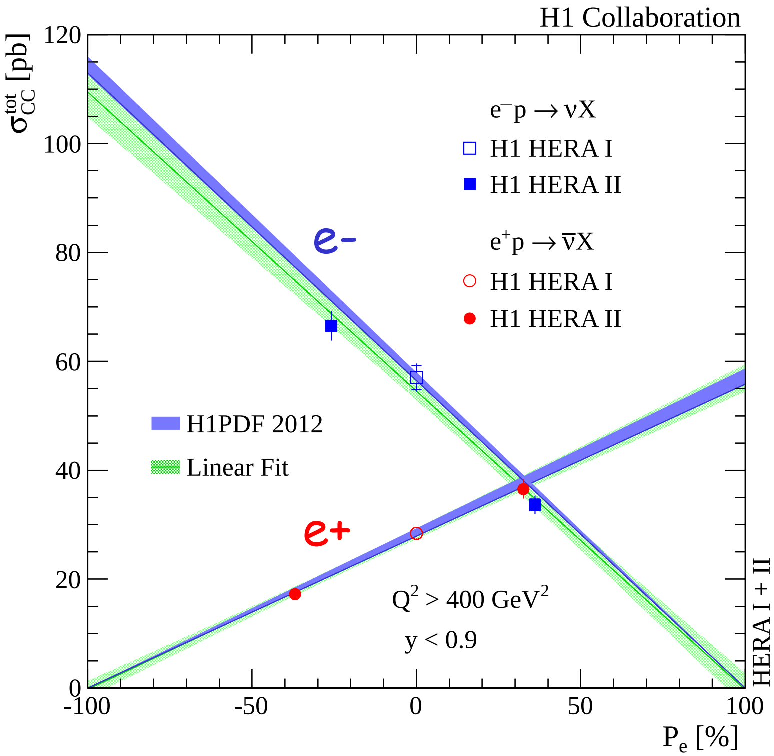
Text-book plot illustrating electroweak unification

JHEP 09 (2012) 061

Inclusive DIS polarised cross sections at high Q^2

Polarisation dependence of total CC cross sections

SM: $\sigma^{\pm}_{CC}(P_e) = (1 \pm P_e)\sigma^{\pm}_{CC}(0)$



Linear scaling with P_e

Extrapolated cross sections ≈ 0
- at Pe=+1 for e-
- at Pe=-1 for e+

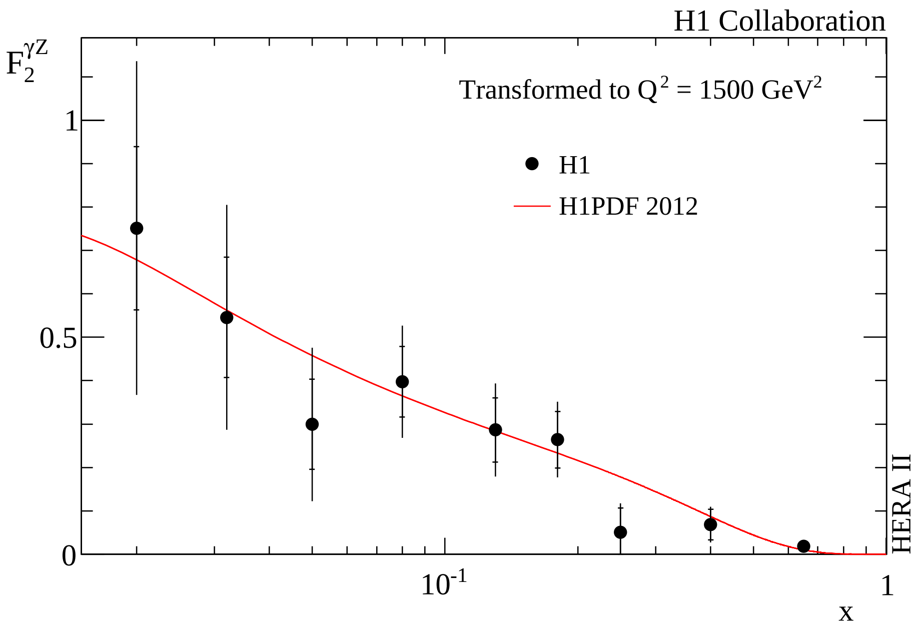
➔ **Text-book plot demonstrating the absence of right handed weak current**

NC polarisation asymmetry

SM: difference in the σ_{NC} for leptons with different helicity states (due to chiral structure of the neutral EW exchange)

Polarisation asymmetry of NC cross section is sensitive to γZ interference terms of structure functions

$$F_2^{\gamma Z} \sim [\sigma^-(P_L) - \sigma^-(P_R)] - [\sigma^+(P_L) - \sigma^+(P_R)]$$



First measurement of $F_2^{\gamma Z}$ structure function

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Inclusive DIS cross sections

unpolarised NC cross e^-p and e^+p reduced cross sections

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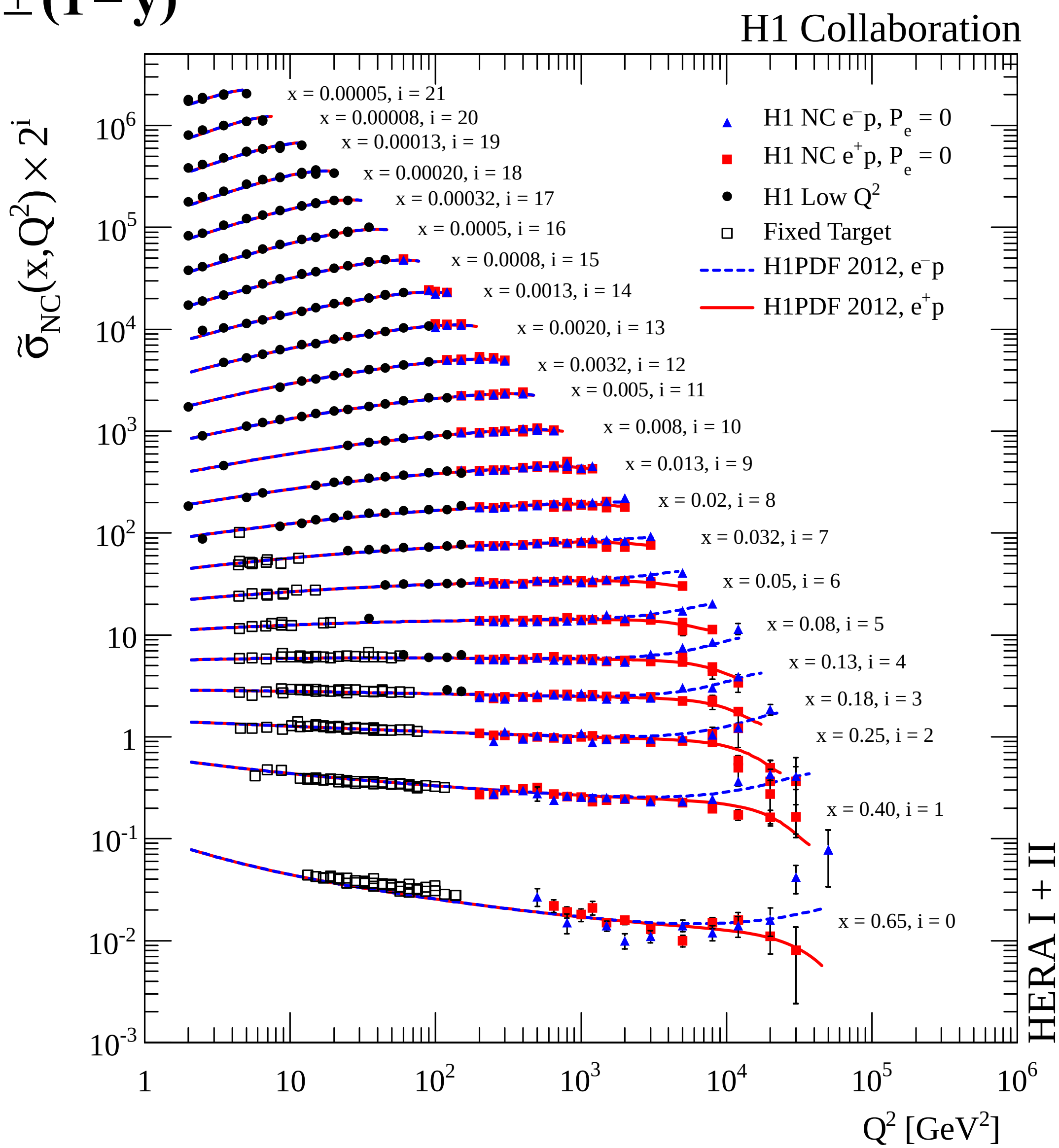
$$\frac{d^2\sigma^{NC}_{e^\pm p}}{dx\,dQ^2} = \frac{2\pi\alpha^2 Y_\pm}{xQ^4}\cdot\left(F_2 - \frac{y^2}{Y_\pm}F_L\right), \quad Y_\pm = 1 \pm (1-y)^2$$

reduced cross section $\equiv \sigma_r(x,Q^2)$

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

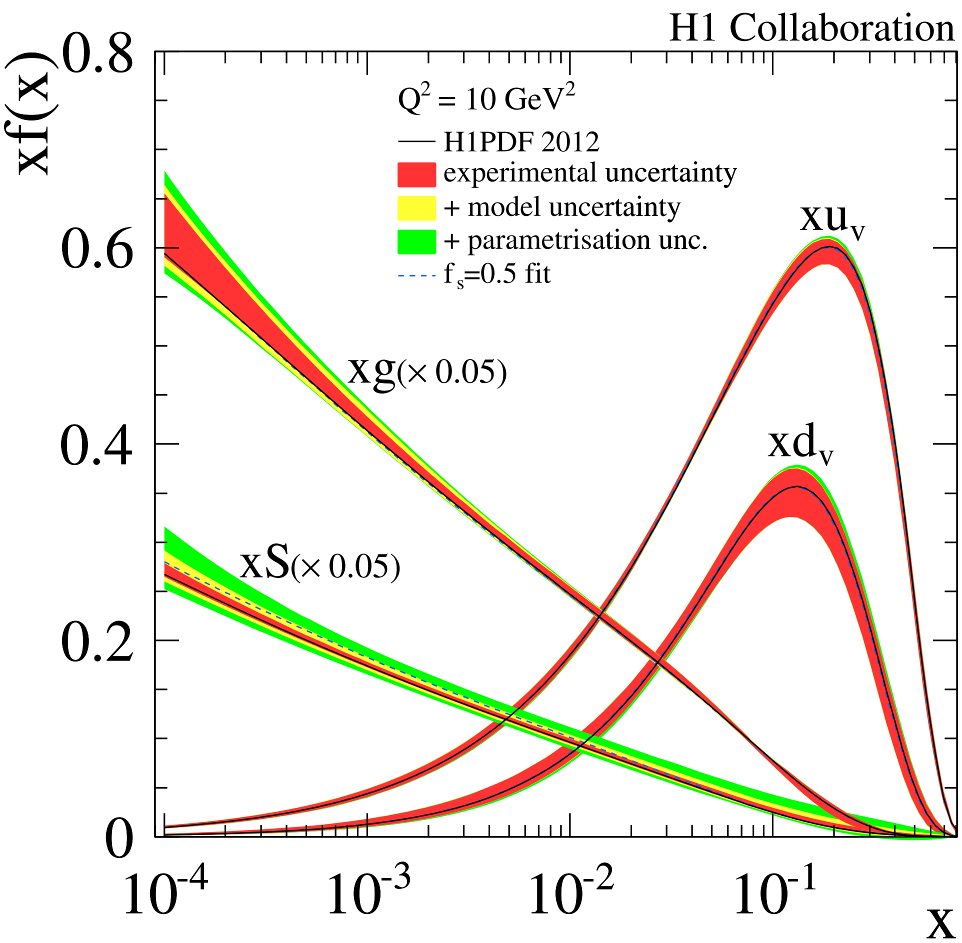
dominant contribution to cross section



- Very high precision
- Combined H1 data probe the proton over nearly 5 orders of magnitude
- Scaling violation

➔ Text-book measurement !

NLO QCD fit to all published NC and CC H1 data with **HERAFitter**



➔ H1PDF 2012

➔ Improvement in precision for all PDFs in the full x range

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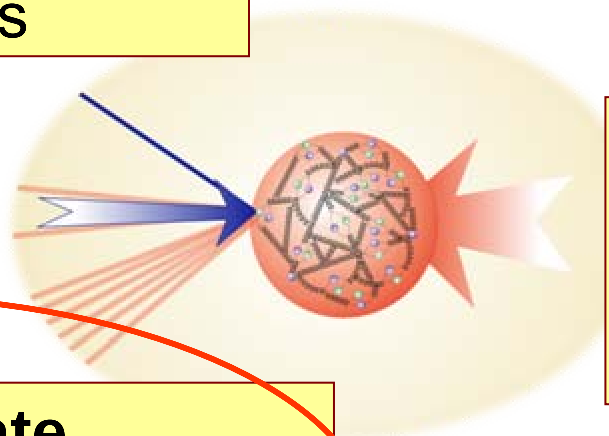
Inclusive measurements
proton structure, PDF
Electroweak effects



Hard diffraction
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diffractive jet production

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Charged particle densities
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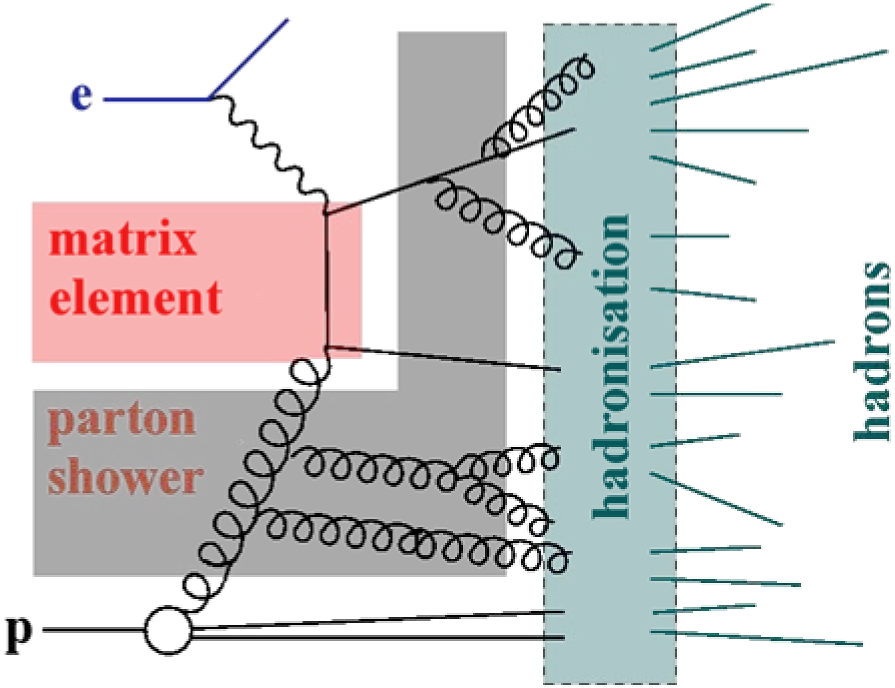
Charged particle densities in DIS

A large amount of the experimental data on charged particle production spectra has been accumulated during last decades. However the underlying dynamics of hadron production in high energy particle interaction is still not fully understood.



Several mechanisms contribute to hadron production

PDF $\otimes$ Parton dynamics $\otimes$ Hadronisation → HFS

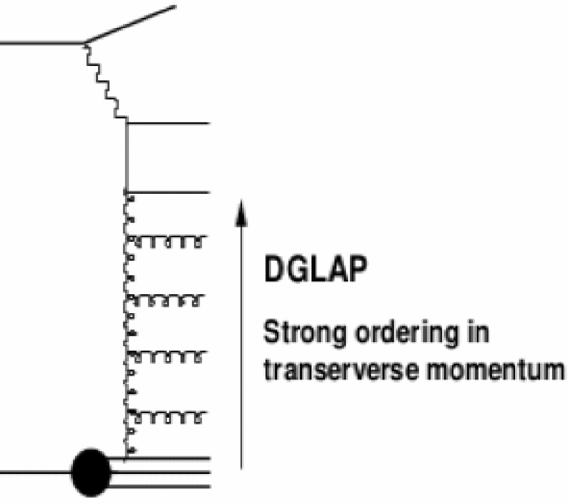
→ Different kinematic ranges sensitive to different effects

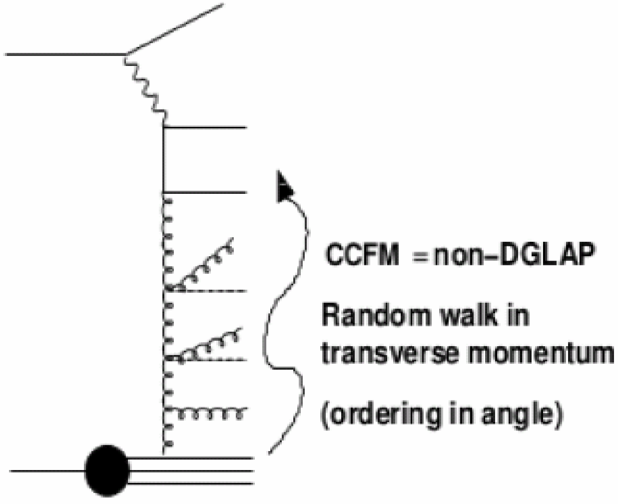
Low p_T region
- Hadronisation effects dominate

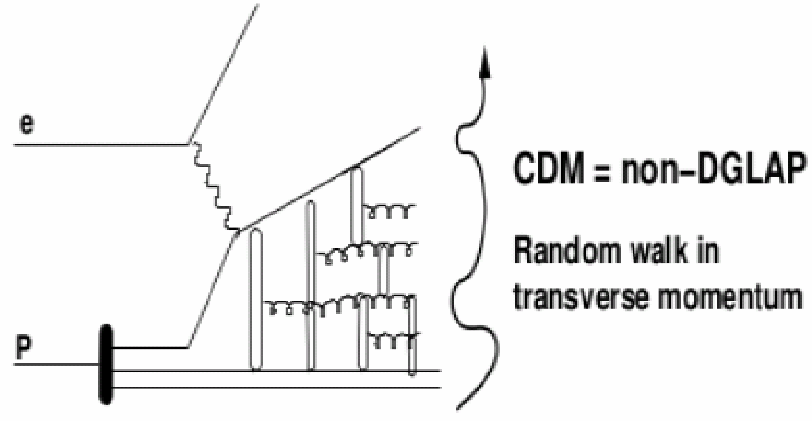
High p_T region
- Parton dynamics effects dominate

New H1 results on charged particle spectra:
with proton energy E_p =920 GeV ($\sqrt{s}$ = 319 GeV)
and proton energy E_p=460 GeV ($\sqrt{s}$ = 225 GeV)

Analyses performed in γ^*p frame (η^*, p_T^*)







DGLAP:

- strong k_T ordering

$k^2_{T0} \ll \ldots \ll k^2_{Ti} \ll \ldots \ll Q^2$

- matrix elements + parton showers
- valid when Q^2 is large and x not too small
- RAPGAP, Herwig++ MC

beyond DGLAP:

- random walk in k_T

- CCFM model
- valid for both: large and small x
- CASCADE MC

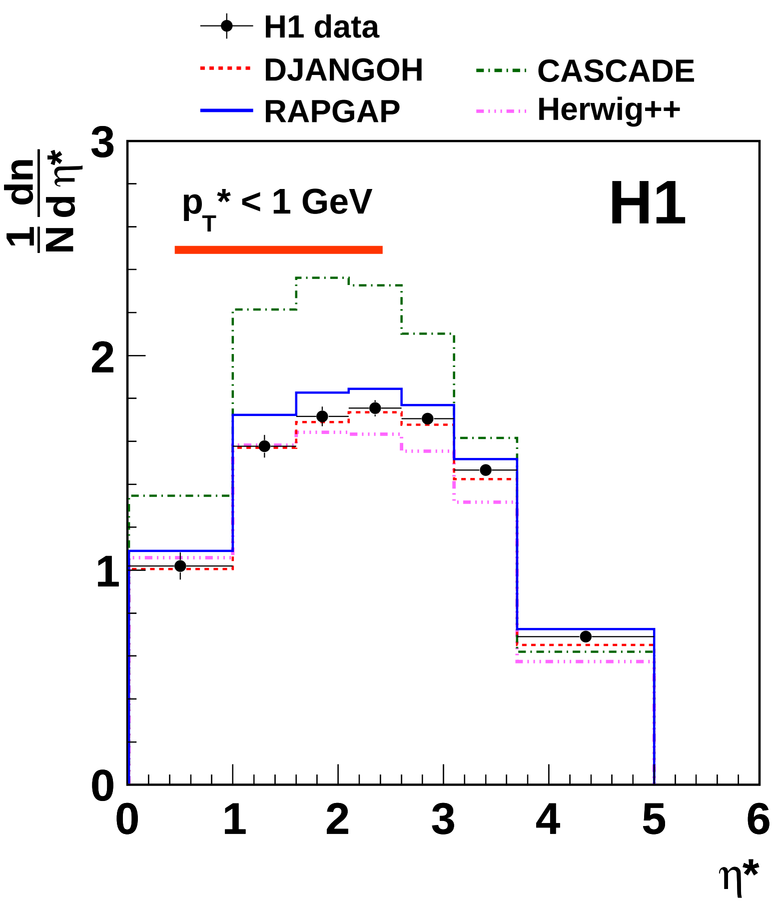
- Colour Dipole Model (CDM)
- BFKL like parton evolution)

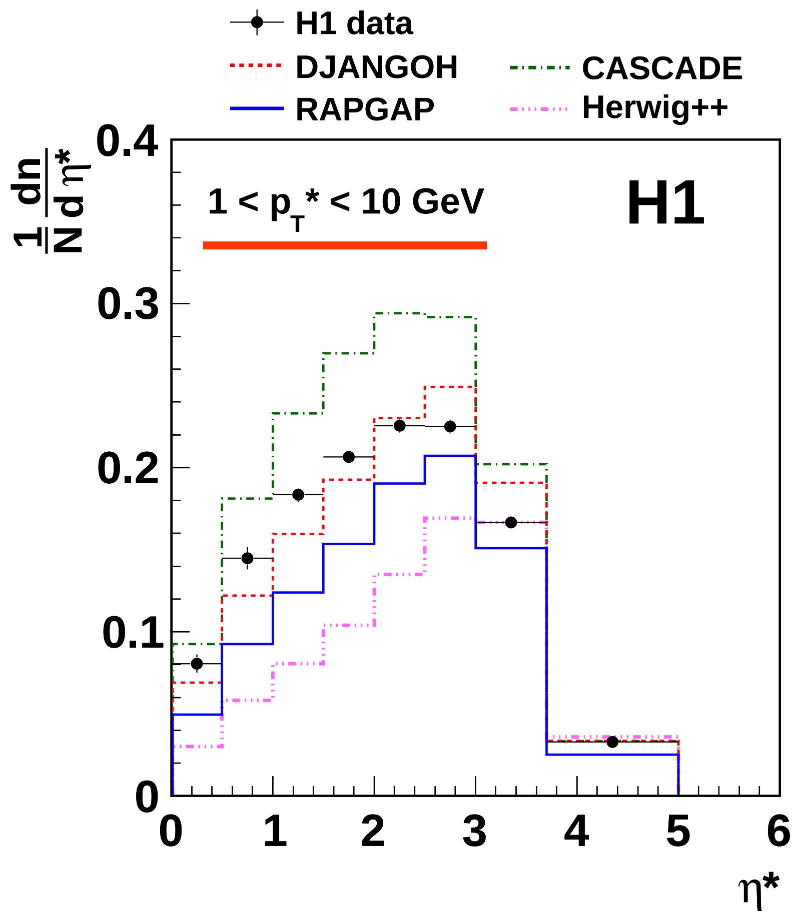
valid at low x and not large Q^2

- DJANGOH MC

Hadronisation parameters tuned to e^+e^- data (ALEPH tune)

Charged particle density: sensitivity to parton cascade models





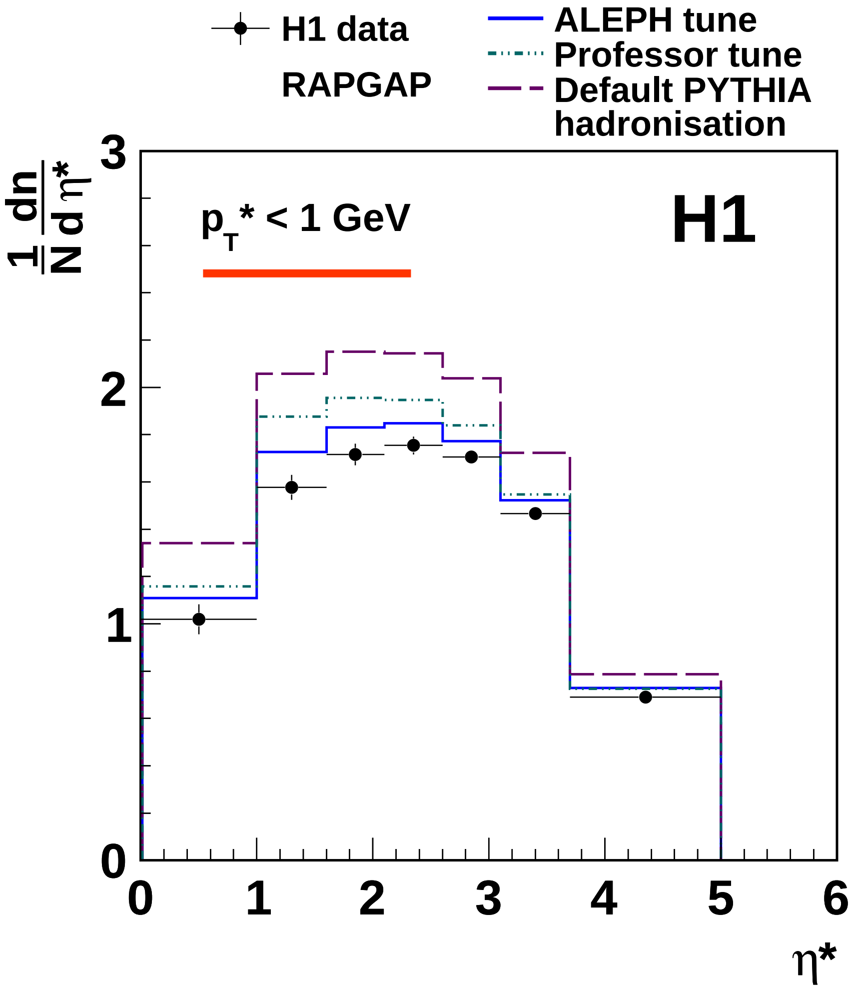
All models (except CASCADE) describe the data within PDF uncertainties

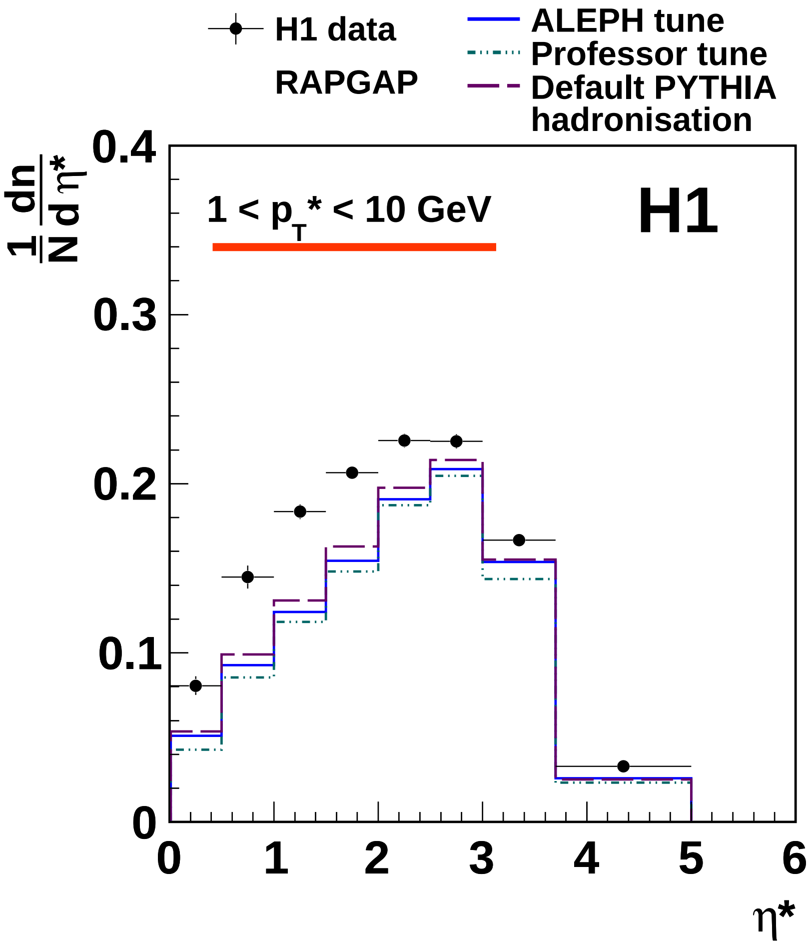
Strong sensitivity to parton dynamics at large p_T
DGLAP models (RAPGAP and HERWIG) underestimate the data for $\eta^*<3$

Best description at all p_T^* by DJANGOH (CDM)

EPJ C73 (2013) 2406

Charged particle density: sensitivity to hadronisation models



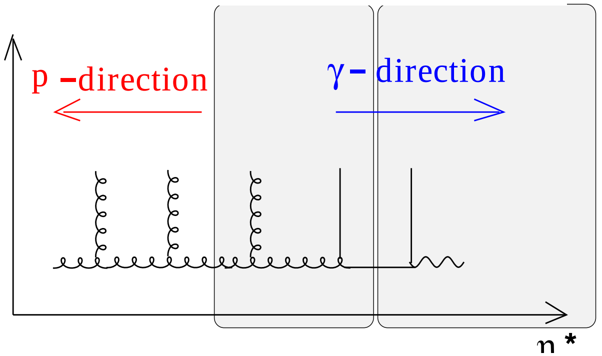


- Large sensitivity to the tuning of hadronisation parameters
- Data are best described by ALEPH tune (e+e-)

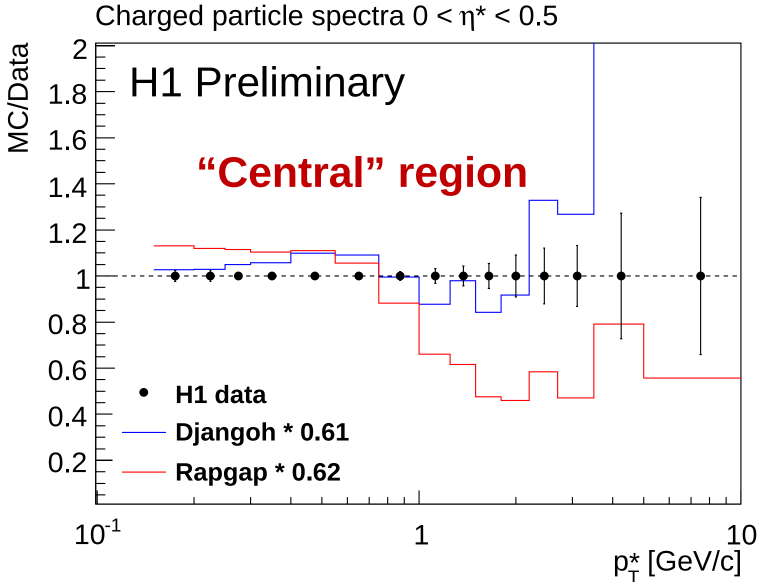
- Essentially no sensitivity to hadronisation expected
- None of the tunes describes the data

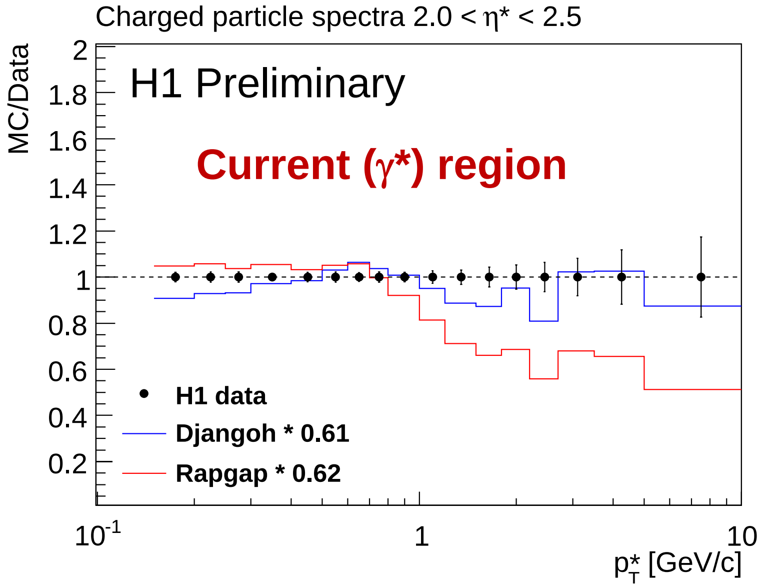
EPJ C73 (2013) 2406

Use data with reduced proton beam energy E_p = 460 GeV to achieve good acceptance and high resolution in η* closer to the central region



-low Q^2: $5 < Q^2 < 10$ GeV^2
- high y: $0.35 < y < 0.8$

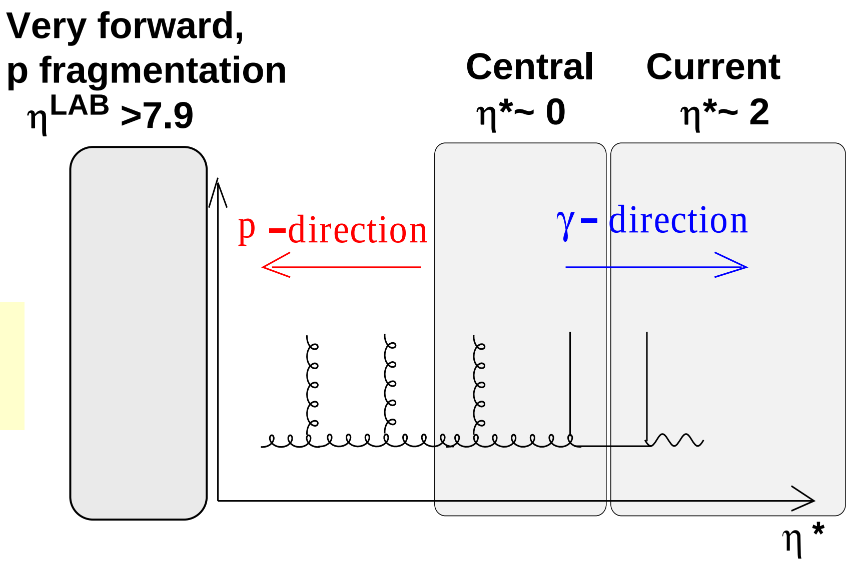




Models don't describe the p_T^*,η* double differential cross sections

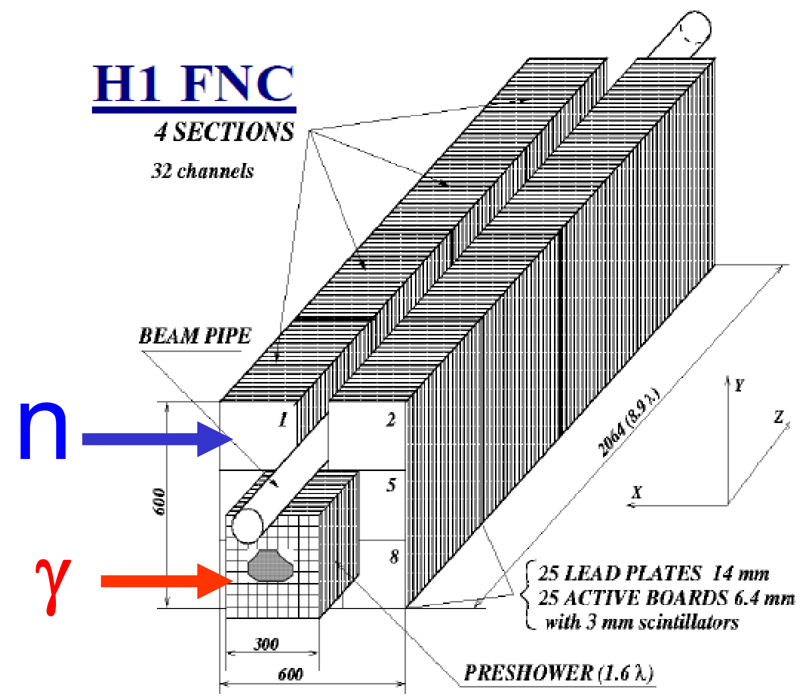
Measurements of Forward Particles are important for the understanding of proton fragmentation mechanisms, and, in particular, interesting for tuning hadron interaction in Cosmic Ray models.

ep collisions – a clean environment to study the proton fragmentation



- Forward Photons are produced mainly in π^0 decay from hadronisation of the proton remnant

- Forward Neutrons are produced in proton fragmentation and by the π-exchange mechanisms, $p \rightarrow n + \pi^+$

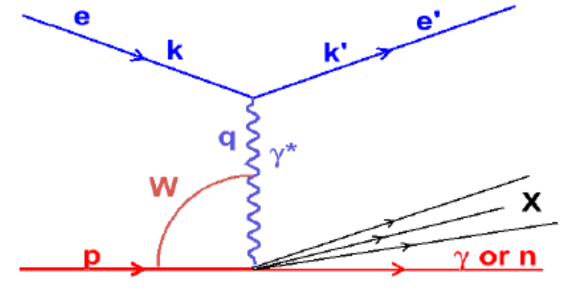


Forward photons and neutrons ($\eta^{Lab} > 7.9$) measured in the FNC Calorimeter (106m from IP)

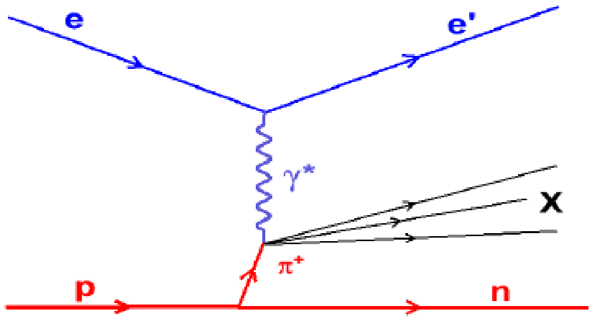
Monte Carlo Models

MC models:
- inclusive DIS:
  LEPTO - LO matrix elements+leading log parton shower
  ARIADNE - LO matrix elements+color dipole model (CDM)

- Pion exchange model: RAPGAP-π



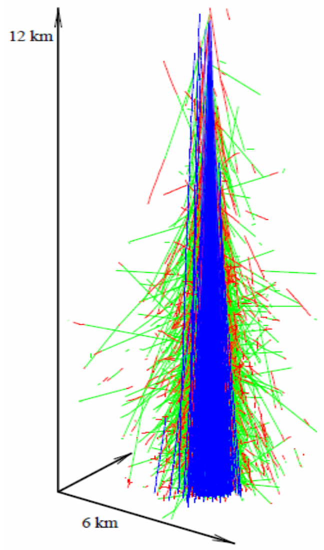
γ or n production in proton fragmentation



n production via π^+ - exchange

Hadronic interaction Cosmic Rays (CR) models:
QGSJET 01, QGSJET II-03: (Kalmykov, Ostapchenko)
EPOS 1.9: (Pierog, Werner)
SIBYLL 2.1: (Engel, Fletcher, Gaisser, Lipari, Stanev)

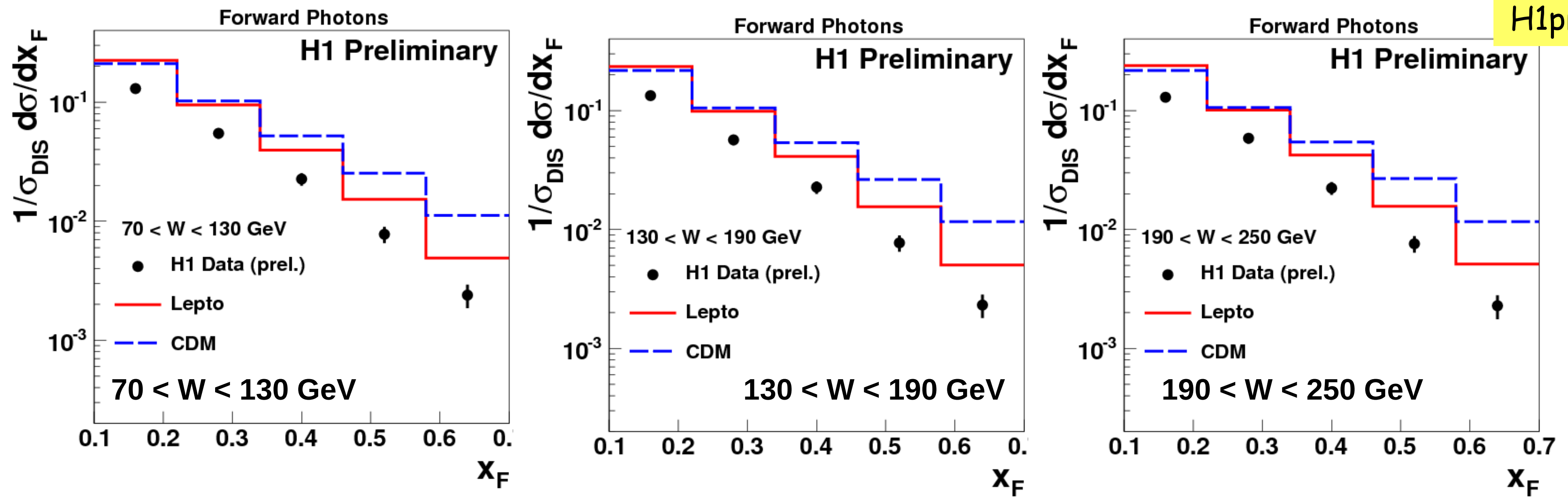
Differences in modeling - mini-jet production, formation of color strings and fragmentation, treatment of saturation effects, multiparton interaction, treatment of hadron remnants.



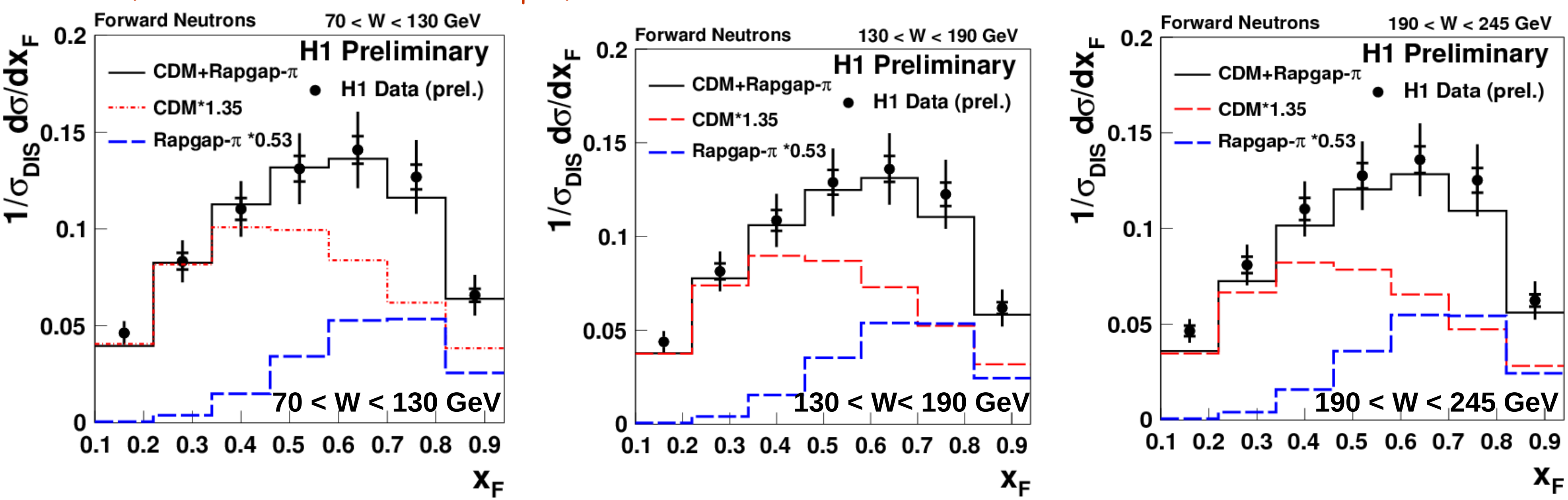
study the energy (W) dependence of $x_F=2p^*_{||}/W$ distributions

Very forward photons and neutrons: $1/\sigma_{DIS}\, d\sigma/dx_F$ distributions vs W

H1prelim-13-012

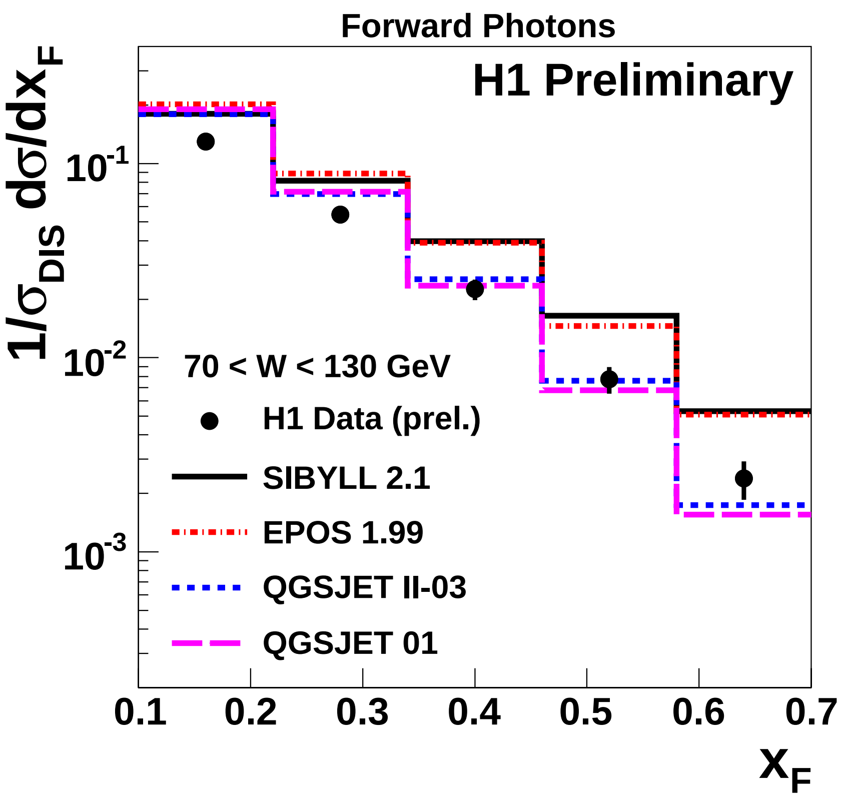


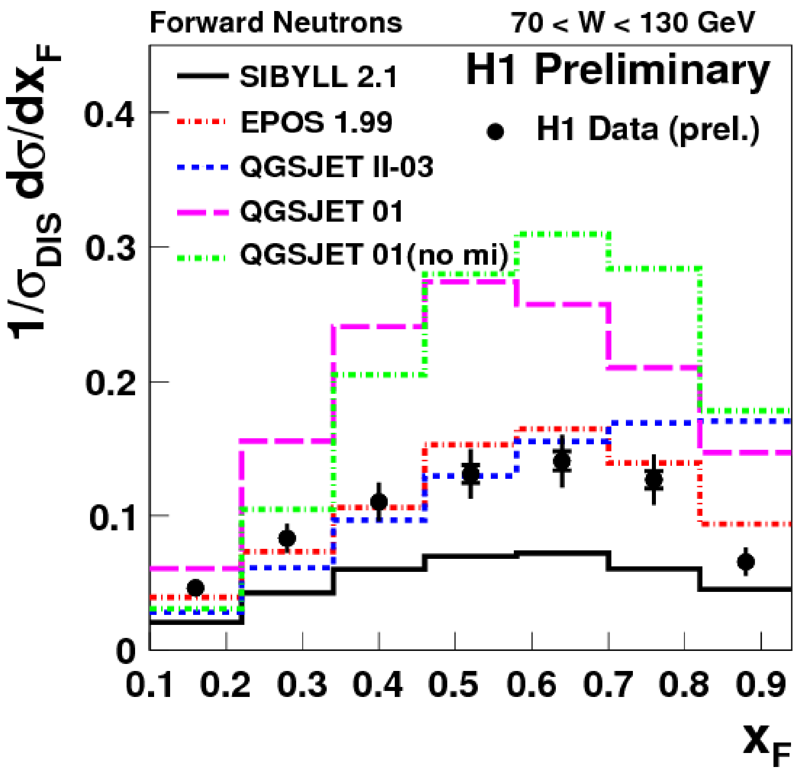
- Photon rate in all MC models used is significantly (70%) higher than in the data at all W
- CDM predict much harder x_F spectra



Neutron rate described by combination of π-exchange (RAPGAP) and 'standard' fragmentation models

Very forward photons and neutrons: comparison with the Cosmic Ray hadronic interaction models

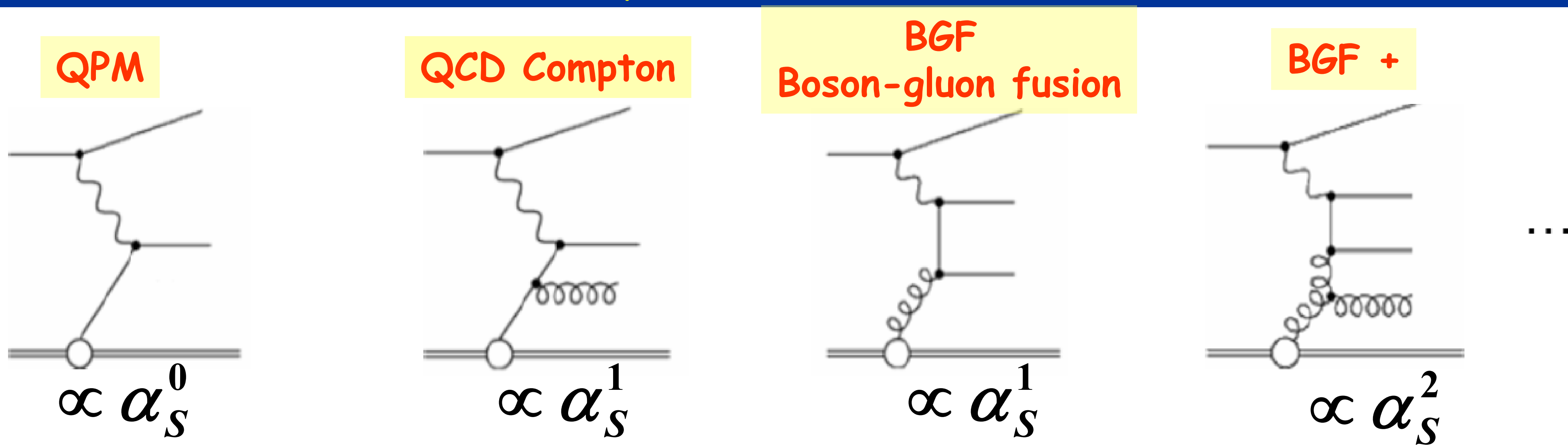




- Large differences between the Cosmic Ray model predictions
- None of models describes simultaneously the photon and neutron measurements

H1prelim-13-012

Jet production in DIS



- Measurements of jets provide a powerful ground for precision QCD test

  Cross section depends on: QCD matrix elements, strong coupling α_s, PDF of the proton

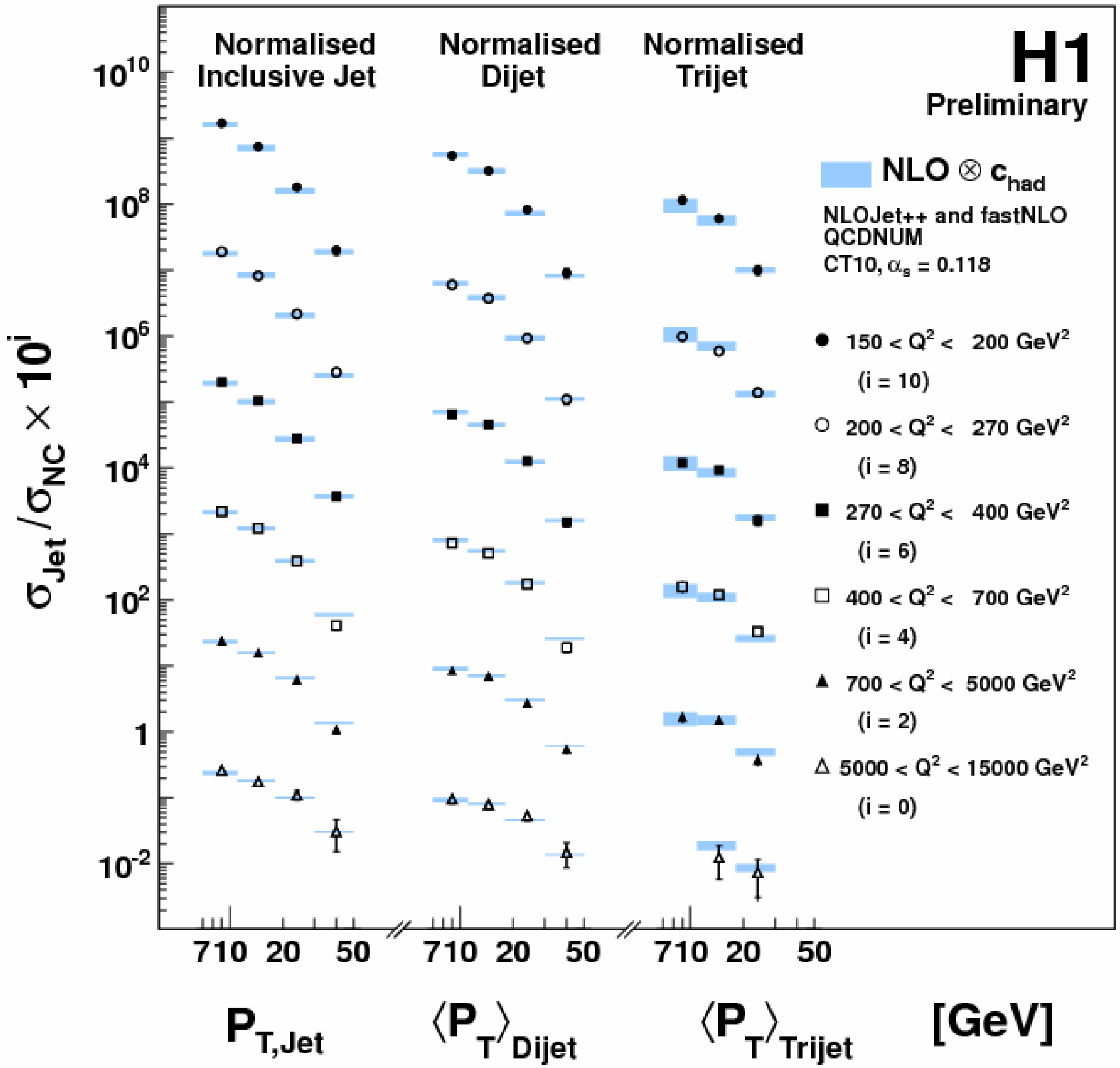
Jets are directly sensitive to α_s and gluons already in LO: $\sigma \sim \alpha_s \cdot g(x)$

→ extract strong coupling α_s with high precision

→ combined inclusive DIS and jet analyses help to improve constraining gluon density

Normalised Jet Cross Sections in DIS at high Q^2

H1prelim-12-031



Inclusive jet, 2-jet, 3-jet production

- photon virtuality $150 < Q^2 < 15000$ GeV²

longitudinally invariant k_T jet algorithm in the Breit frame → collinear and infrared safe

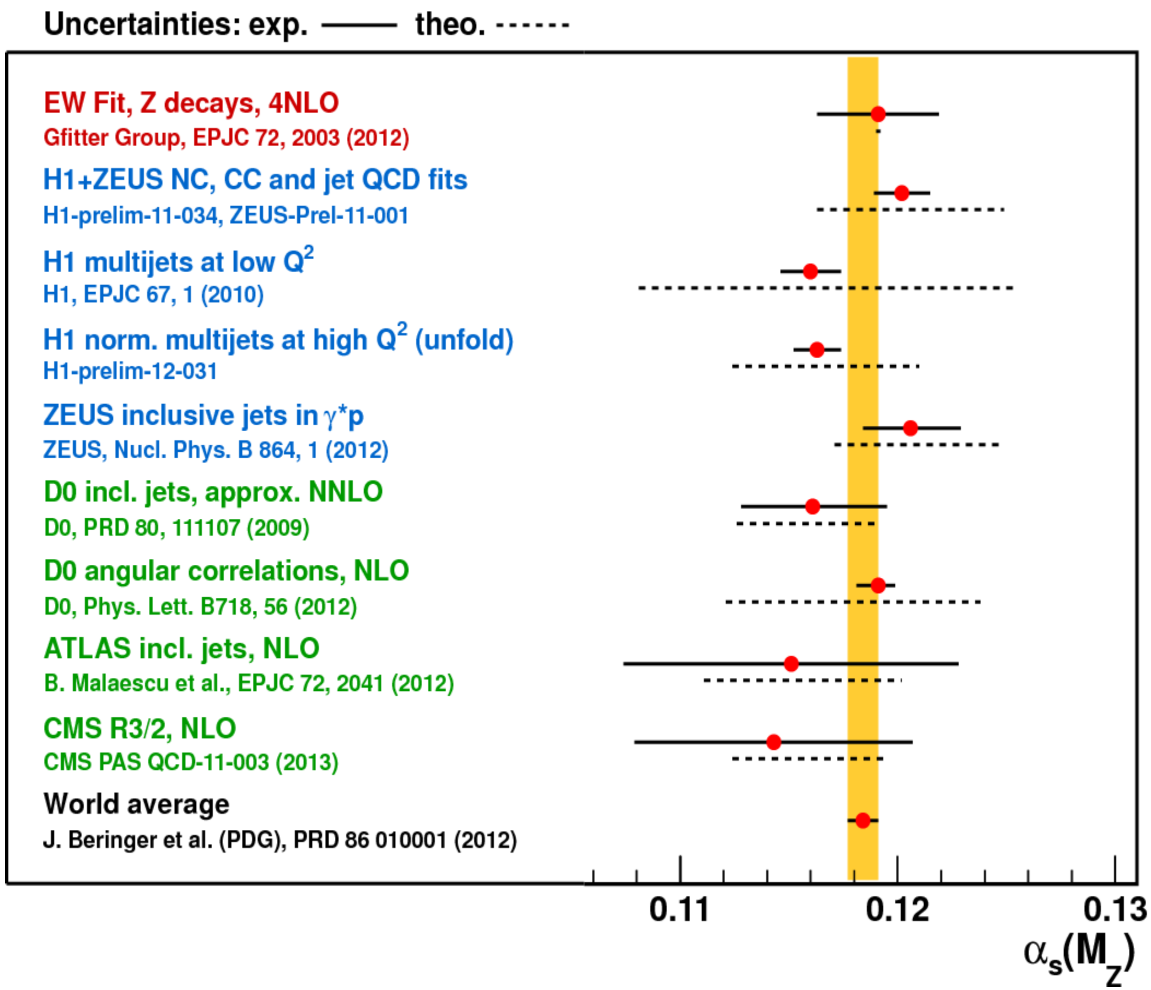
- high precision- 1% jet energy scale uncertainty

- data are well described by NLO calculation

Combined NLO fit to normalised inclusive, dijet and trijet cross sections

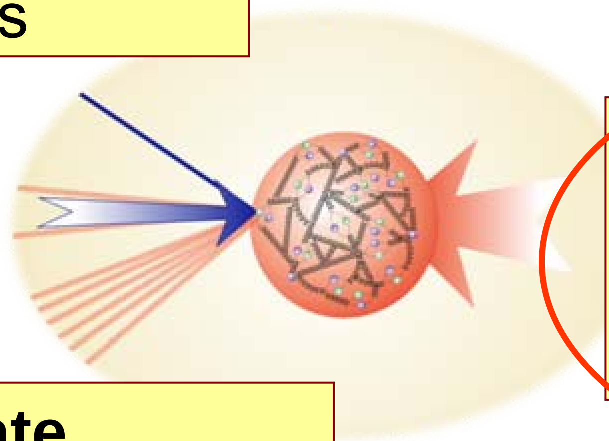
$\alpha_S(M_Z)$=0.1163 ± 0.0011 (exp) ± 0.0014 (PDF) ± 0.0008 (had) ± 0.0039 (theory)

Comparison of recent $\alpha_s(M_Z)$ values



- HERA jet data among the most precise data for precision test of QCD
- pQCD calculations in general describe the data
- extractions of as(Mz) yield values consistent with the world average and having an experimental precision competitive with other extraction methods
- Theory uncertainty dominate → NNLO needed

Inclusive measurements
proton structure, PDF
Electroweak effects



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diffractive jet production

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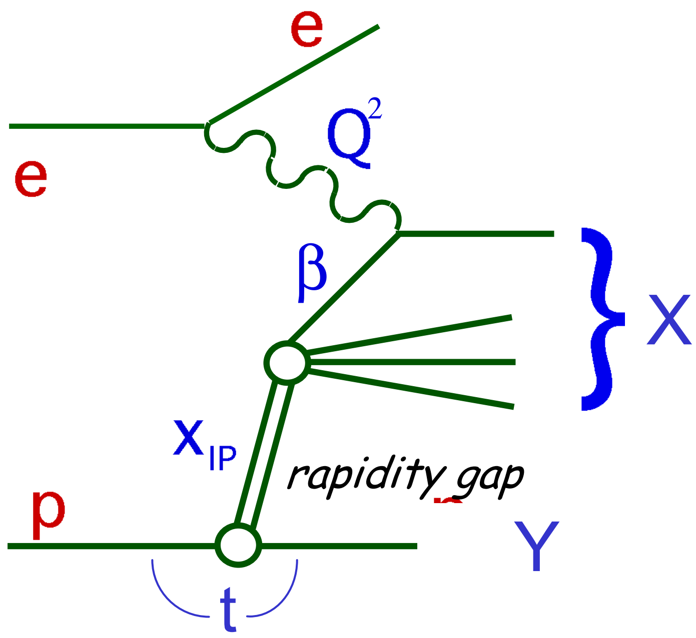
Diffraction in ep collisions

One of first HERA surprises: ~10% of DIS events have no activity in proton direction, i.e. they are from *diffractive interactions*

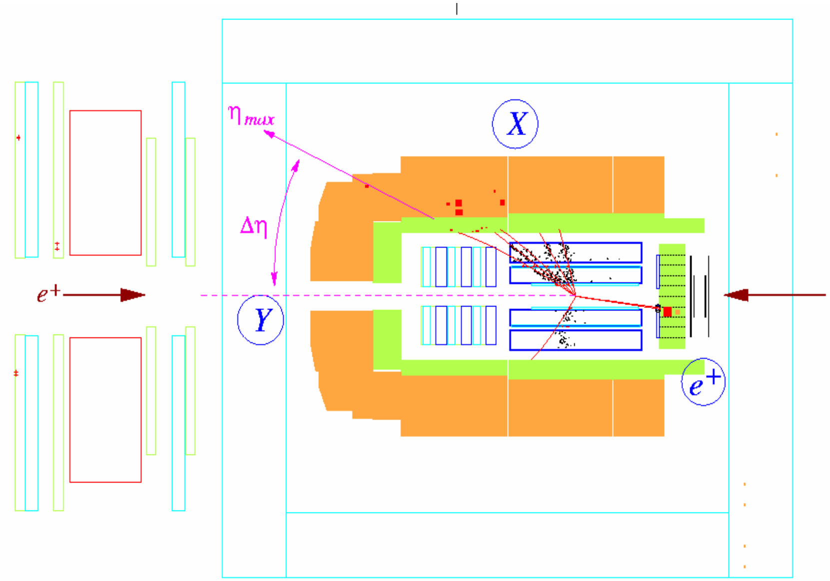


- t-channel exchange of vacuum quantum numbers
- proton survives the collision intact or dissociates to low mass state, $M_Y \sim O(m_p)$

  → large rapidity gap

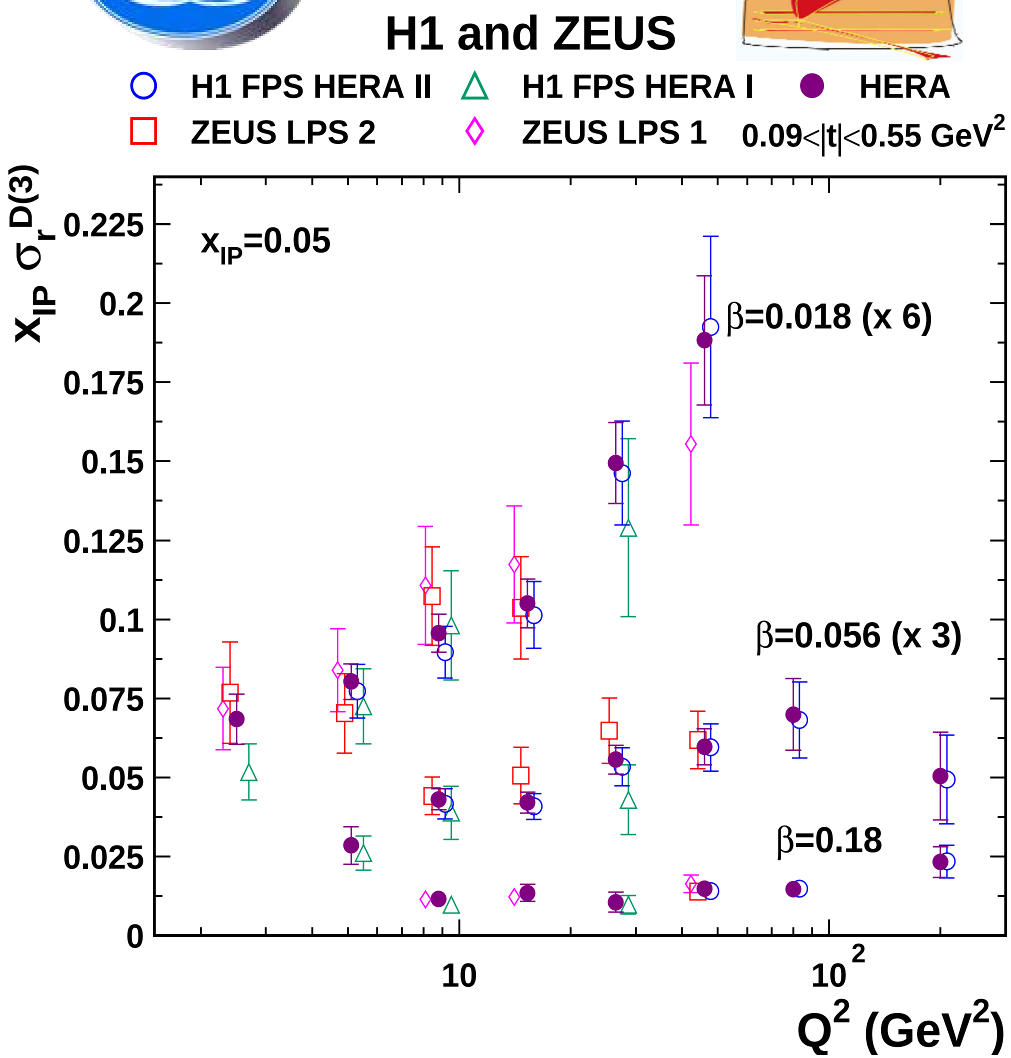
- small t (four-momentum transfer), small x_{IP} (fraction of proton momentum); $M_X \ll W$

- access to the structure of the colour-singlet exchange
- description in terms of diffractive parton densities
- different experimental methods to tag diffraction:
  - leading proton tagging
  - large rapidity gap



H1/ZEUS Combined Inclusive Diffractive DIS Cross Sections measured with forward proton spectrometers

EPJ C72 (2012) 2175



Proton Spectrometer data in $0.09<|t|<0.55$ GeV^2

➔ Consistency between H1 and ZEUS data sets

➔ Combination method uses iterative χ^2 minimization and include full error correlations

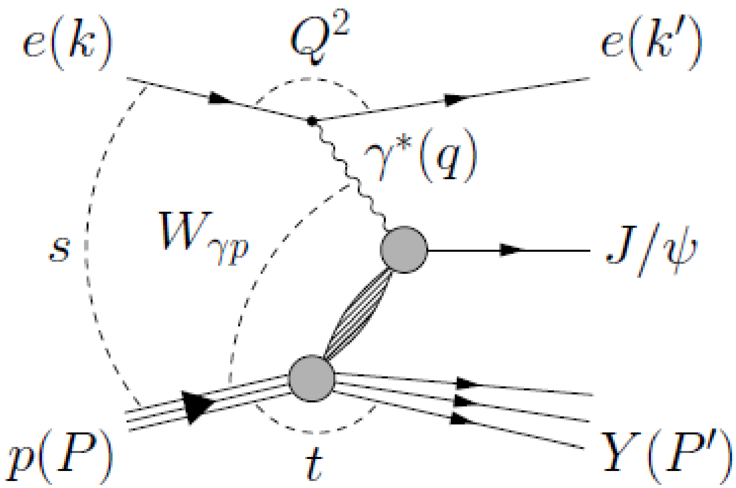
➔ Profit from different detectors: Two experiments 'calibrate' each other resulting in reduction of systematic uncertainties

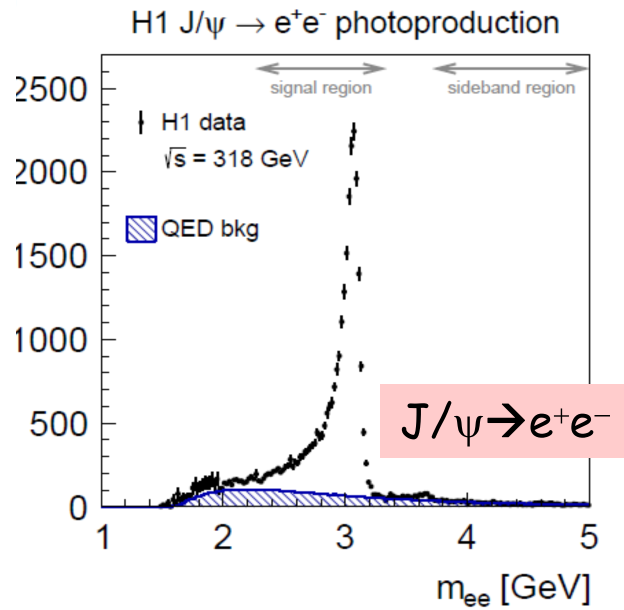
Combined data have ~25% smaller uncertainties then the most precise data alone

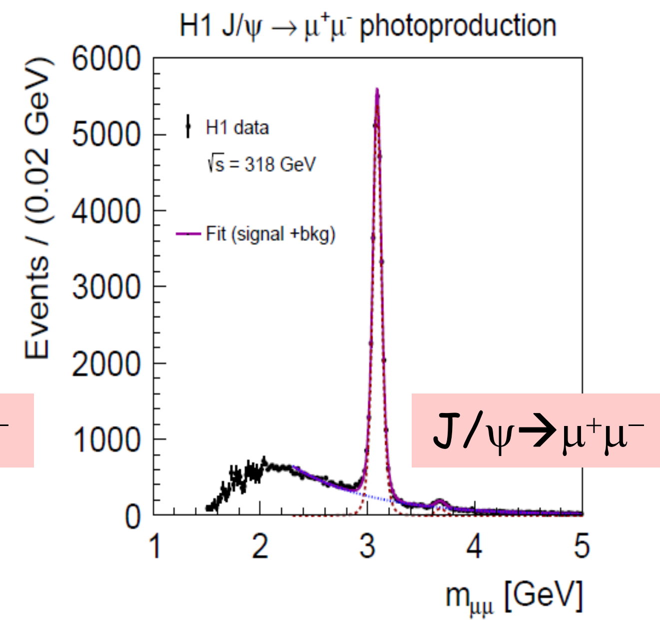
Important input to diffractive PDFs

Diffractive Photoproduction of J/ψ mesons

EPJ C73 (2013) 2466

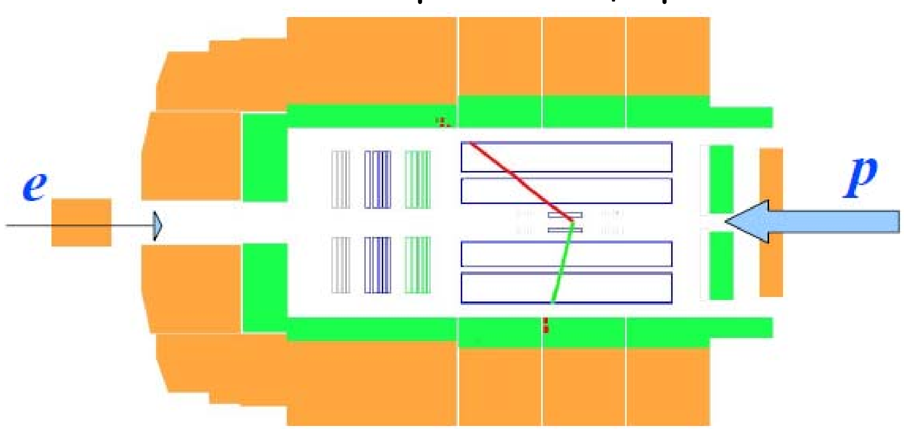






- clean experimental signature

Elastic: ep→ e+ J/ψ +p



Proton dissociation : ep→ e+ J/ψ +Y

J/ψ elastic and p-diss. photoproduction cross sections vs $W_{\gamma p}$

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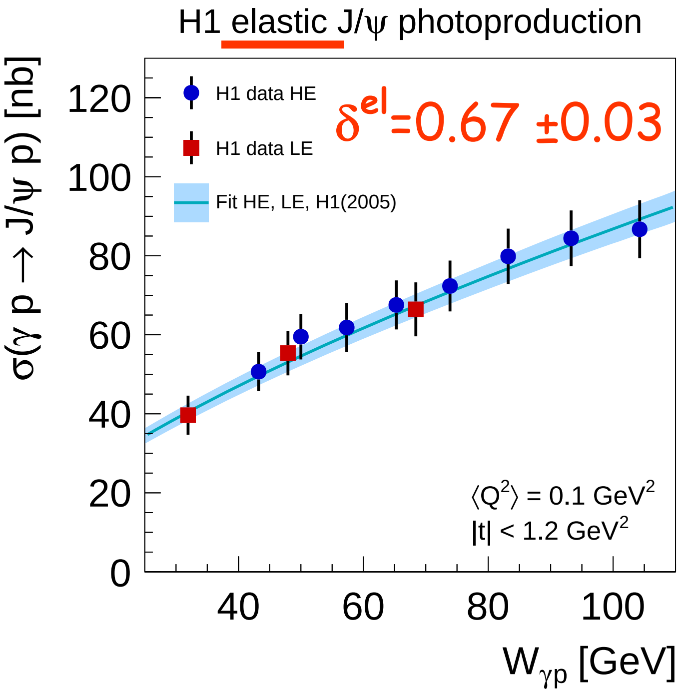
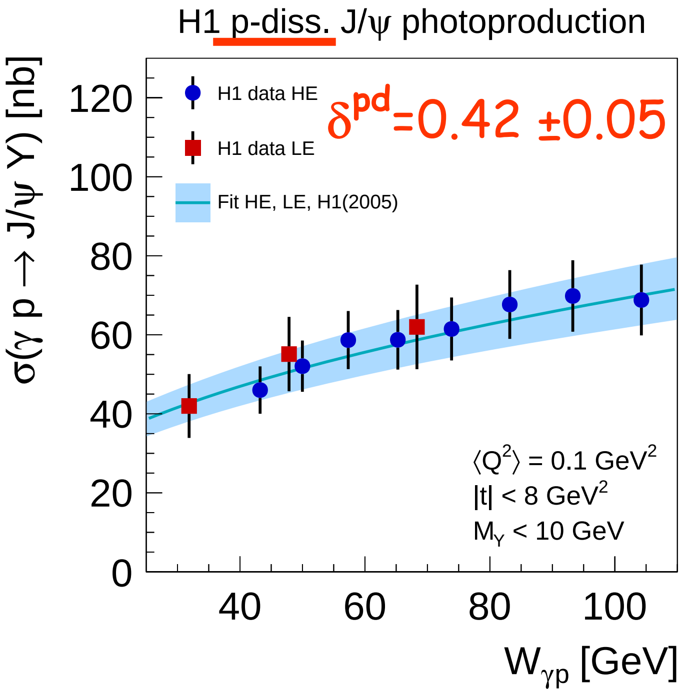
Elastic and proton-dissociation cross sections measured simultaneously using Regularised Unfolding

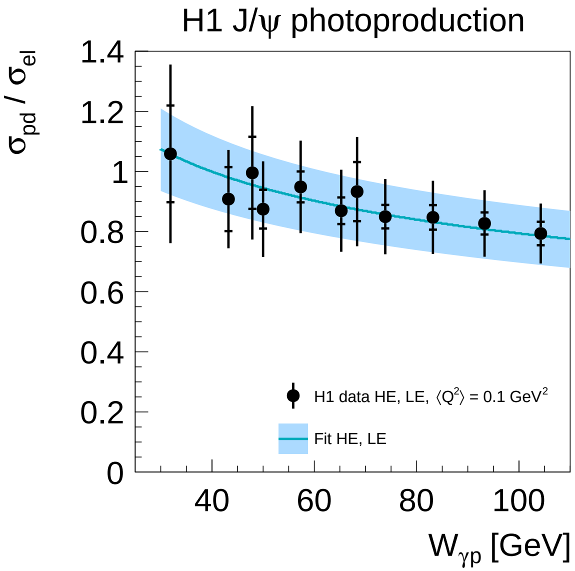
- Simultaneous fit to $W_{\gamma p}$ distributions, taking into account correlations between elastic and p-diss. cross sections

$$\sigma = N\left(\frac{W_{\gamma p}}{W_0}\right)^{\delta}$$

$W_0 = 90$ GeV







➔ Ratio σ_{pd}/σ_{el} slowly decreasing with $W_{\gamma p}$

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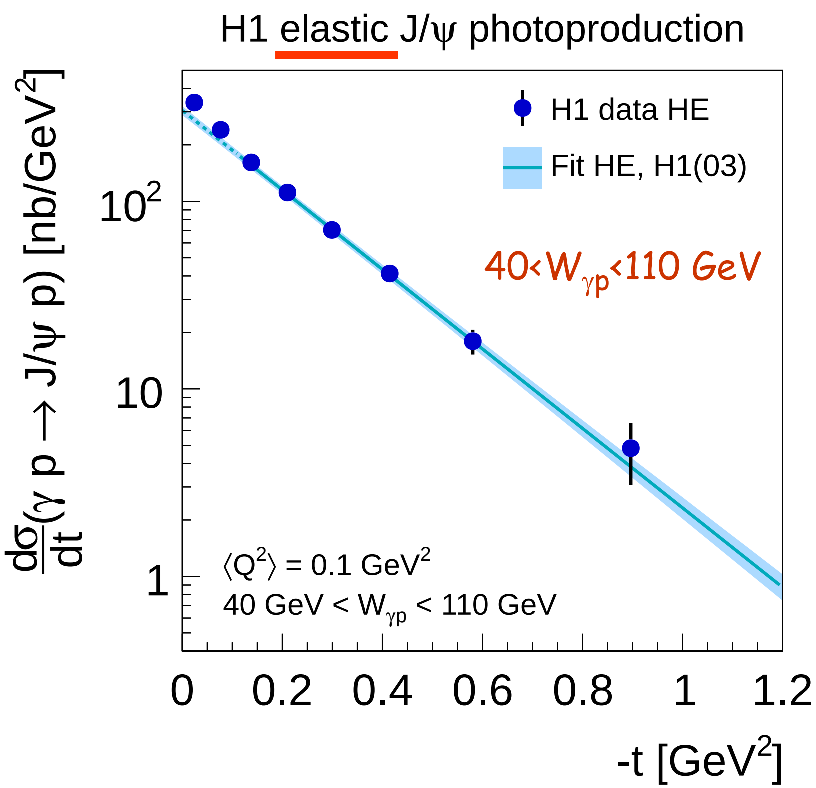
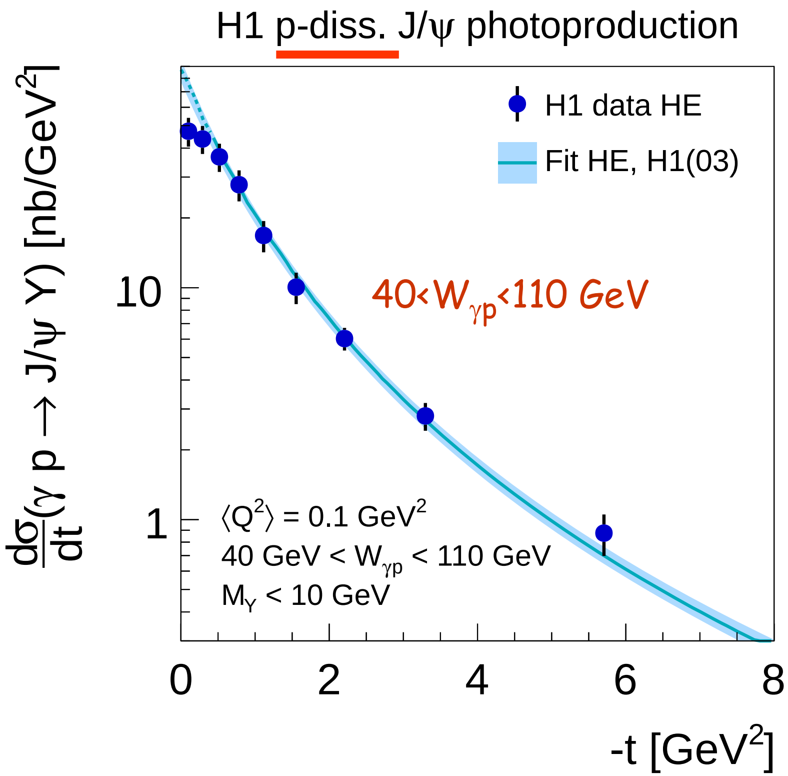
t –momentum transfer squared at the proton vertex





$$\frac{d\sigma}{dt} \sim e^{-b_{el}|t|}$$

b_{el}= 4.88 ± 0.15 GeV^2

$$\frac{d\sigma}{dt} = N_{pd}\left(1+\frac{b_{pd}}{n}|t|\right)^{-n}$$

b_{pd}= 1.79 ± 0.12 GeV^2

b is related to the transverse size of interaction: b_{pd} is significantly lower than b_{el}

J/ψ elastic photoproduction cross sections vs t

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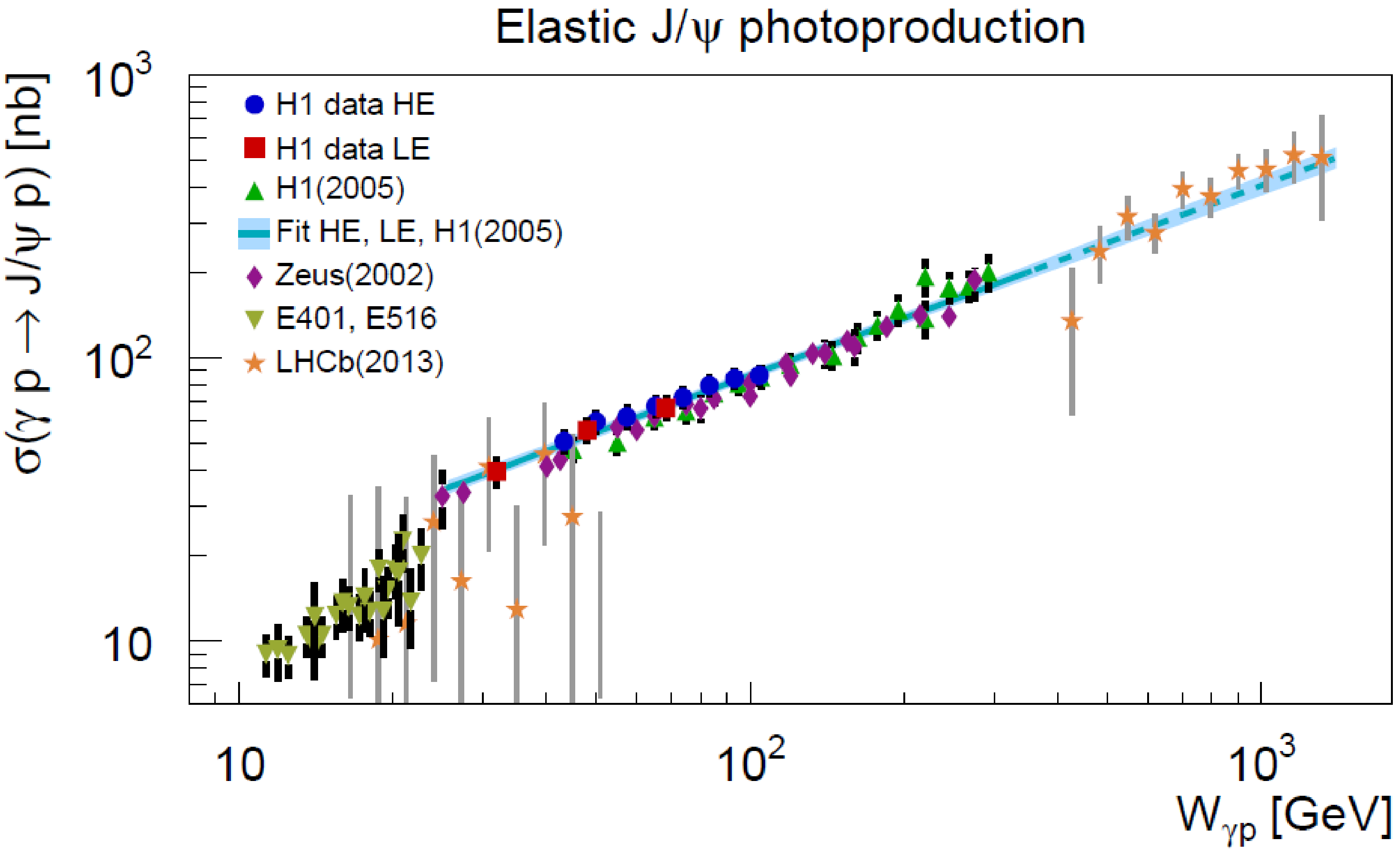


New H1 measurement- two energy ranges: $W_{\gamma p}$=40-110 GeV and $W_{\gamma p}$=25-80 GeV

- Transition region from fixed target to previous HERA data
- Good agreement with previous HERA measurements
- Fixed target data: steeper slope, lower normalisation
- Extrapolation of H1 data to high W agrees with LHCb measurement

Conclusions

Six years after the end of data taking, H1 is an active experiment producing valuable results in a broad area of physics.

New results presented:

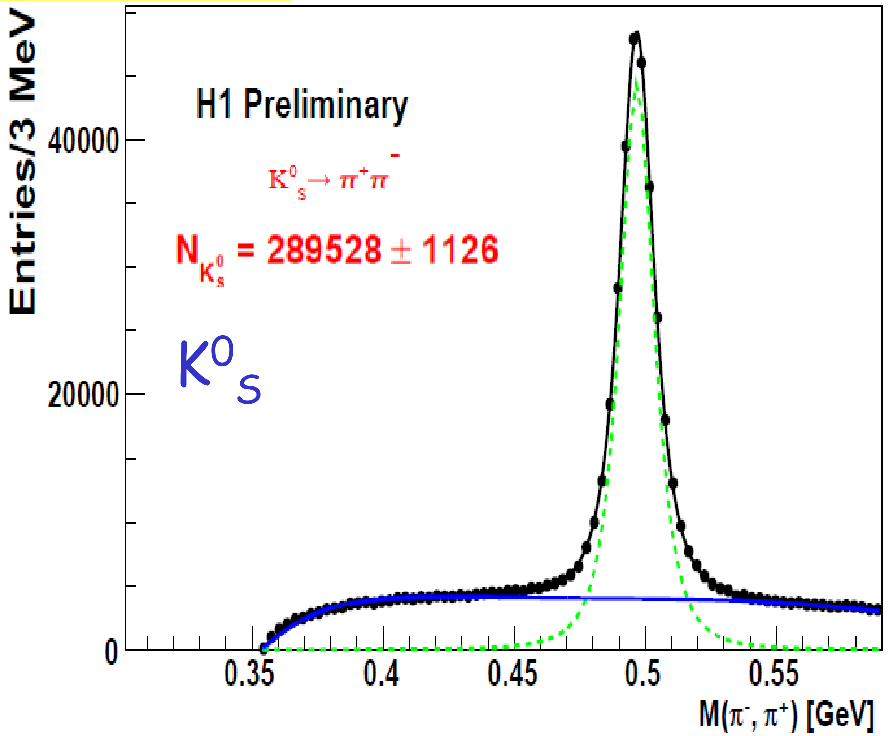
- Final measurement of inclusive NC/CC cross sections
- Several new measurements of hadronic final state and particle production
- Combined H1/ZEUS measurement of inclusive diffractive DIS with leading proton

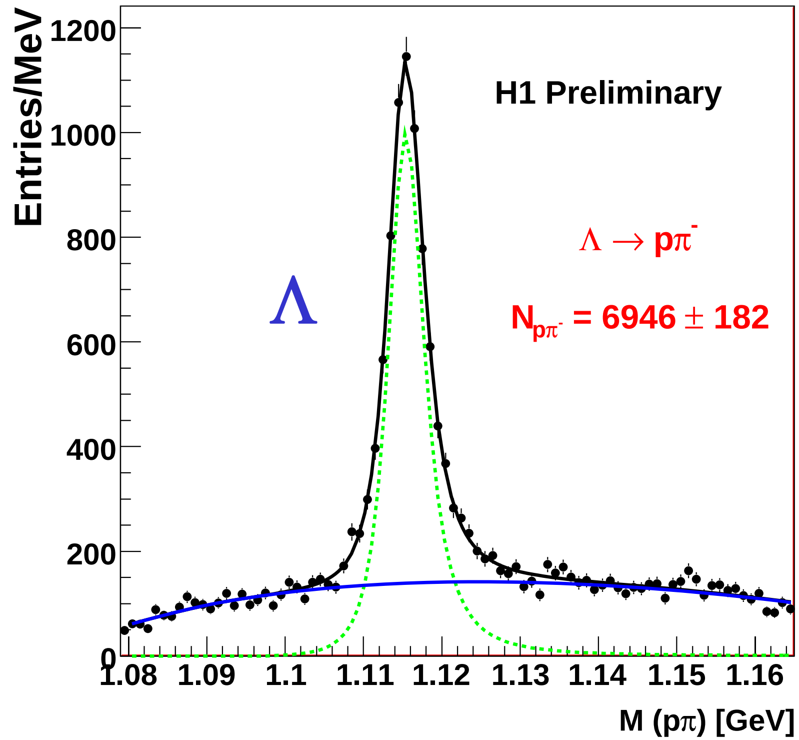
HERA has a rich physics program that has to be completed !

Strangeness production in DIS: visible cross sections for K^0_S and Λ

H1prelim-13-033

H1prelim-13-031





$7 < Q^2 < 100$ GeV^2 , $0.1 < y < 0.6$

$145 < Q^2 < 20000$ GeV^2 , $0.2 < y < 0.6$

$$\sigma_{vis}(ep \rightarrow eK^0_S X) = 10.66 \pm 0.04(stat.)^{+0.50}_{-0.53}(sys.)\,nb$$

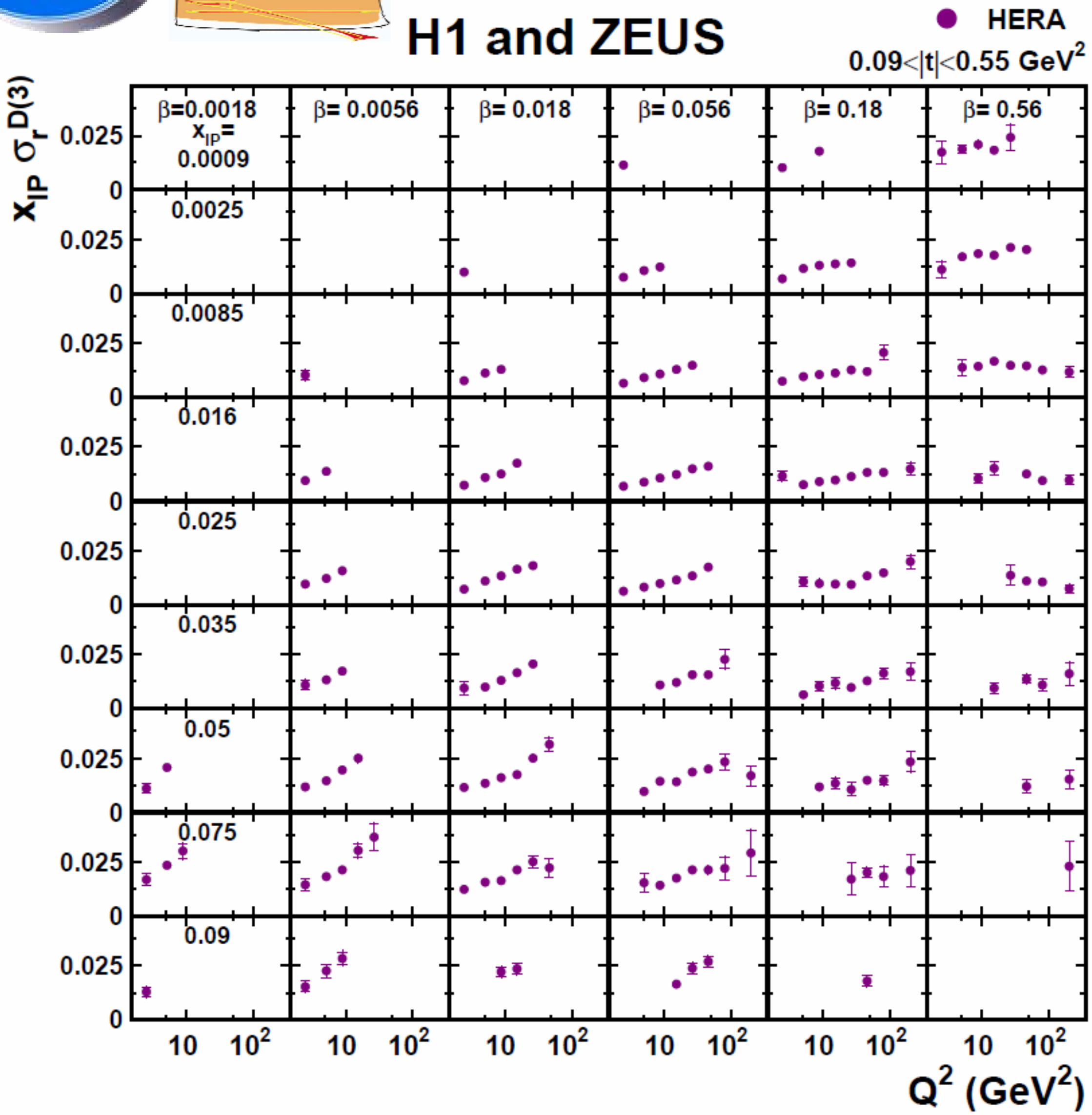
$$\sigma_{vis}(ep \rightarrow e\Lambda X) = 144.7 \pm 4.7(stat.)^{+9.4}_{-8.5}(sys.)\,pb$$

λ_s	0.286
$\sigma_{vis}(ep \rightarrow eK^0_s X)$ CDM	9.88 nb
$\sigma_{vis}(ep \rightarrow eK^0_s X)$ MEPS	10.93 nb

λ_s	0.220	0.286
$\sigma_{vis}(ep \rightarrow e\Lambda X)$ CDM	136 pb	161 pb
$\sigma_{vis}(ep \rightarrow e\Lambda X)$ MEPS	120 pb	144 pb

Combined Inclusive Diffractive DIS Cross Sections measured with forward proton spectrometers

Proton Spectrometer data in $0.09<|t|<0.55$ GeV^2



➔first combination of H1 and ZEUS diffractive data !

Diffractive Jet Photoproduction with a Leading Proton

2006-2007 data, integrated luminosity 30pb^{-1}

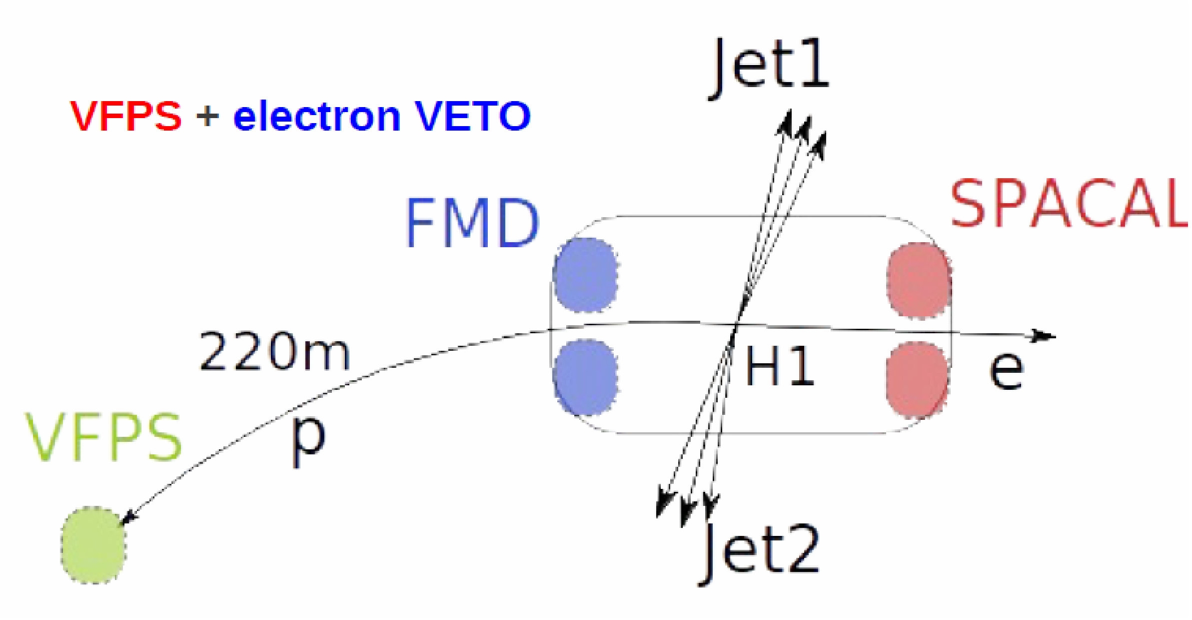
Leading proton measured in the Very Forward Spectrometer (VFPS):
two stations at 218m and 222m; reconstruction efficiency >96% ; background <1%

Two jets with E_T>5.5 (4) GeV

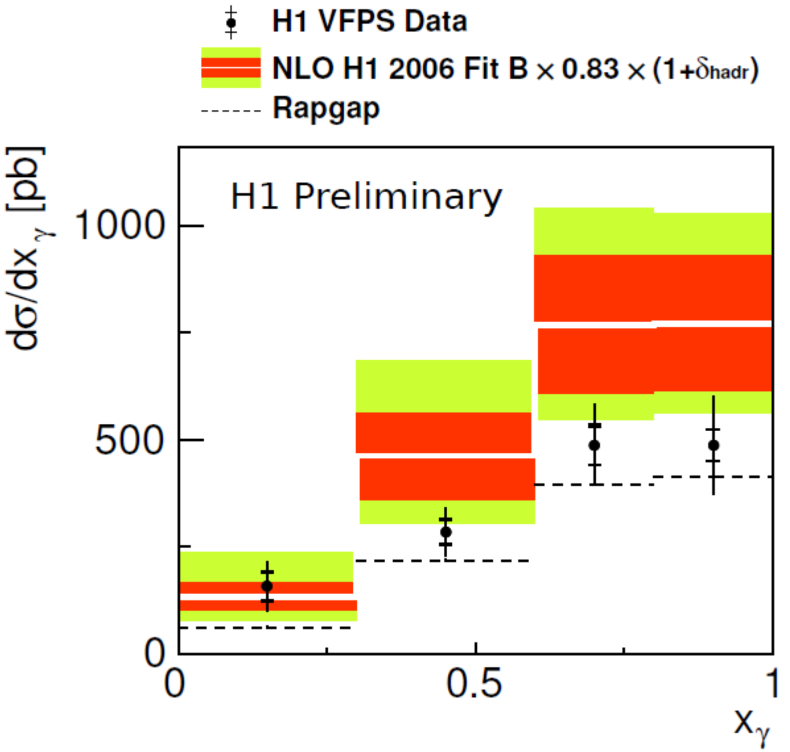
$0.01<x_{IP}<0.024$, $|t|<-0.6$ GeV^2

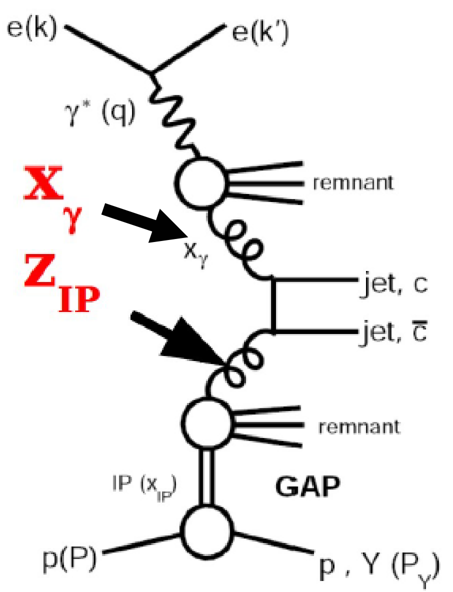
➔ ~4800 events selected

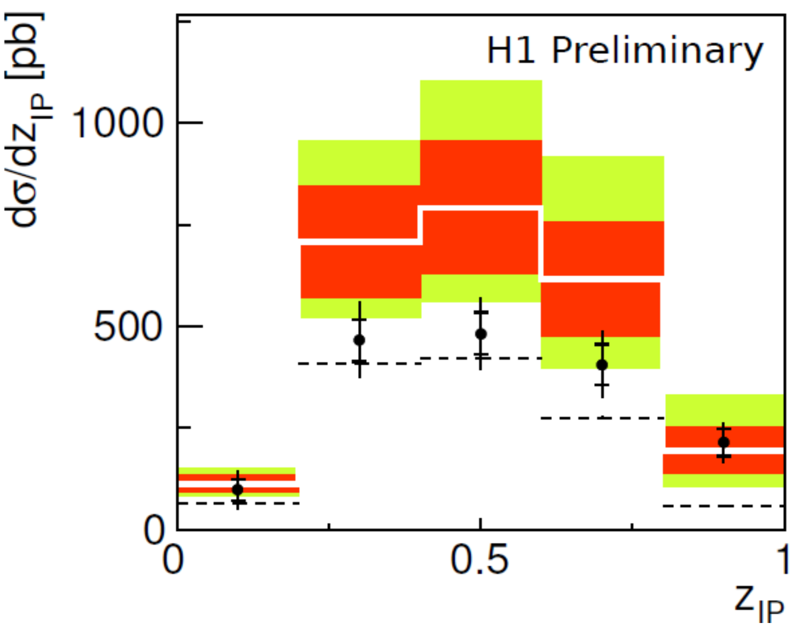
Data unfolded to hadron level
using Singular Value Decomposition
of the response matrix



Diffractive Jet Photoproduction with a Leading Proton







Data suppressed in comparison with NLO QCD by factor 0.67

$\sigma_{data}/\sigma_{nlo}$=0.67 ±0.04 (stat)±0.09 (sys)±0.20 (scale)±0.14(pdf)

No obvious dependence of suppression on x_γ

Large theoretical uncertainties connected with the DPDF uncertainty and scale variation