Recent results on the hadronic final state at HERA

Daniel Britzger
for the H1 and ZEUS Collaborations

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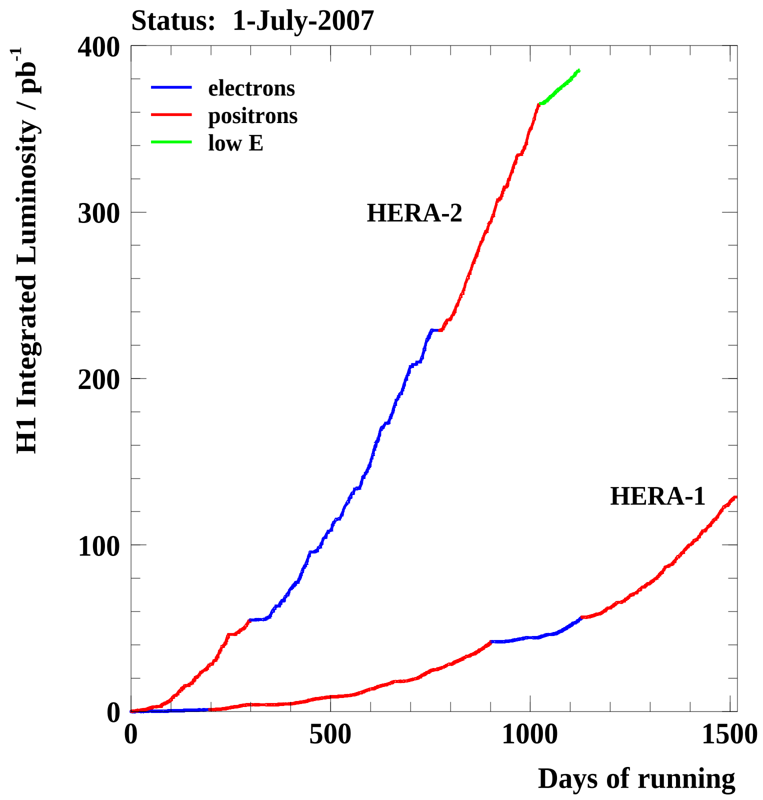
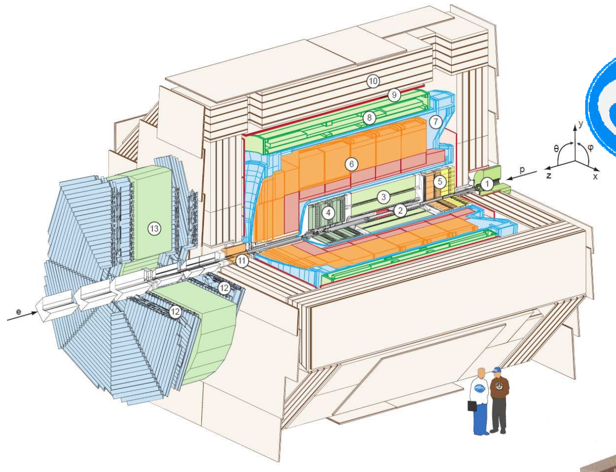
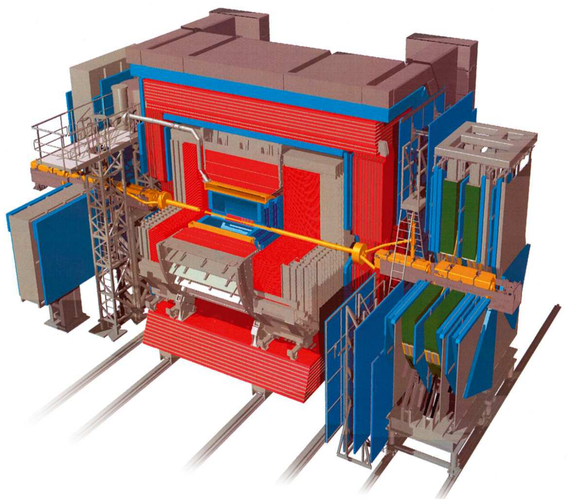
HERA with the H1 and ZEUS detectors

HERA e±p collider

- $\sqrt{s}$ = 319 GeV
  - E_e = 27.6 GeV
  - E_p = 920 GeV
- Operational until 2007







Two multi-purpose experiments: H1 and ZEUS

- Luminosity: ~ 0.5 fb^{-1} per experiment
- Excellent control over experimental uncertainties
  - Overconstrained system in DIS
  - Electron measurement: 0.5 – 1% scale uncertainty
  - Jet energy scale: 1%
  - Trigger and normalization uncertainties: 1-2 %
  - Luminosity: 1.8 – 2.5%

Inclusive deep-inelastic *ep* scattering (DIS)

***ep* scattering:** $e^{\pm}p \rightarrow e^{\pm} + X$

- Centre-of-mass energy

$$\sqrt{s} = \sqrt{(k+p)^2}$$

- Virtuality of exchanged boson

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

- Bjorken scaling variable

$$x_{\mathrm{Bj}} = \frac{Q^2}{2p \cdot q}$$

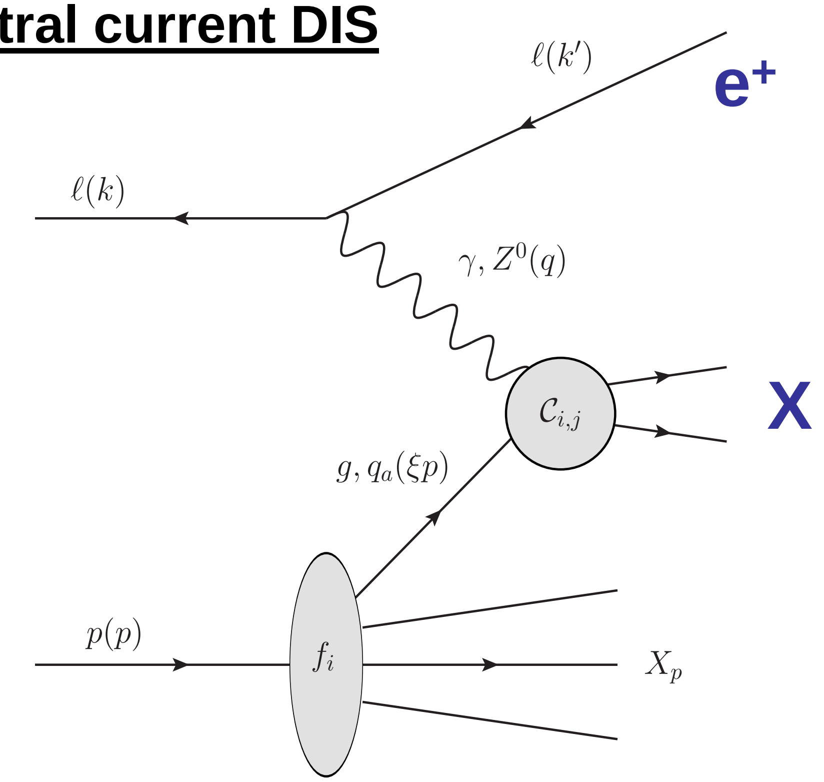
- Inealsticity

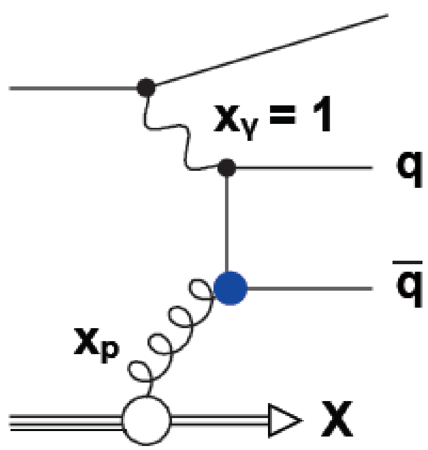
$$y = \frac{p \cdot q}{p \cdot k}$$

Cross section calculation

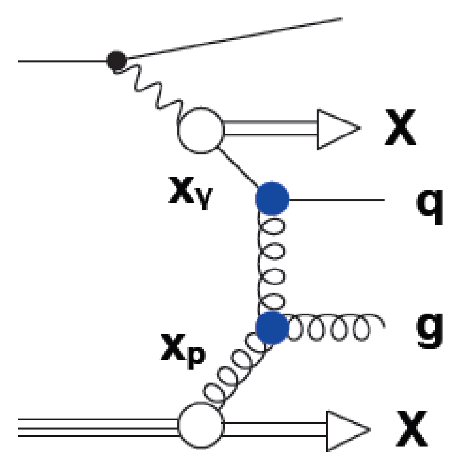
- Collinear factorisation
- Hard scattering calculable in QCD (pQCD)
  - Calculable up to NNLO for inclusive NC DIS
- PDFs have to be determined from experiment

Neutral current DIS





Direct photoproduction



Resolved photoproduction

Partonic momentum fraction of the photon

$$x_\gamma^{\mathrm{obs}} = \frac{E_T^{\mathrm{jet1}} e^{-\eta^{\mathrm{jet1}}} + E_T^{\mathrm{jet2}} e^{-\eta^{\mathrm{jet2}}}}{2yE_e}$$

Charged particle spectra in DIS

Measurement of hadron production in DIS constrain

- At small transverse momentum: hadronisation parameters
- At large transverse momentum: parton evolution

Advantage over *pp*

- No minimum bias
- No underlying event

Observable η^*

pseudorapidity in hadronic centre-of-mass frame

Djangoh (CDM) gives best description

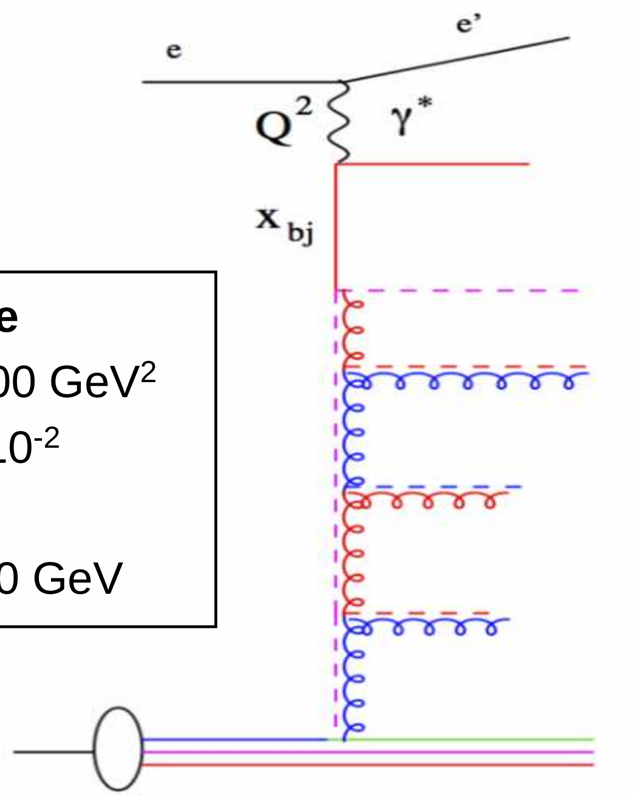
Phase space

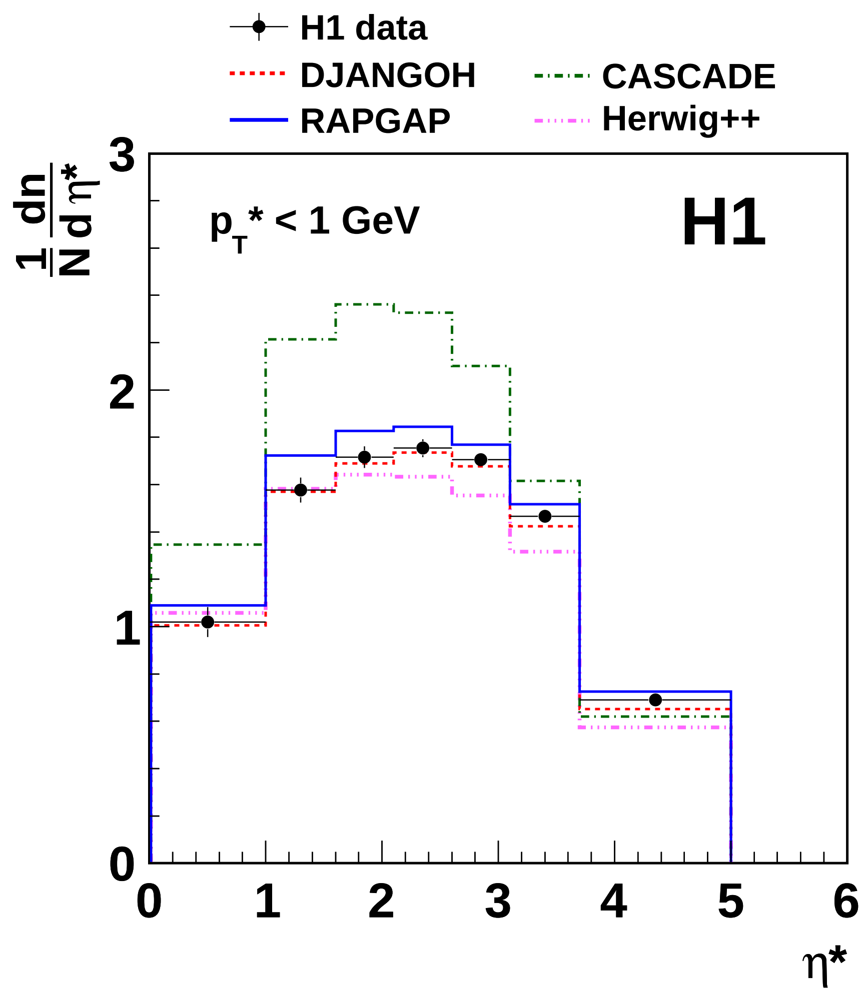
$5 < Q^2 < 100$ GeV^2

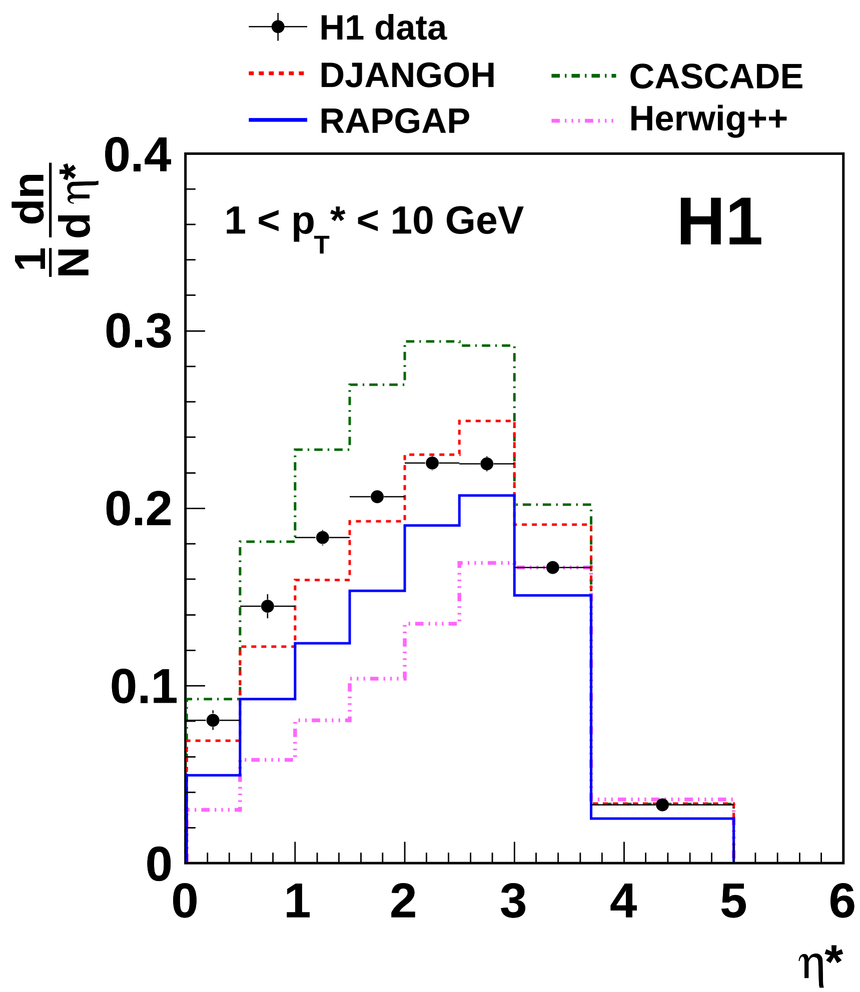
$10^{-4} < x < 10^{-2}$

$0 < \eta^* < 5$

$0 < p_T^* < 10$ GeV







Rapgap

virtually ordered collinear PS

HERWIG++

angular ordered collinear PS

CASCADE

angluar ordered small-x improved CCFM PS

DJANGOH

Color dipole model

Charged particle spectra in DIS

Charge particle spectra in 2 regions of η^*

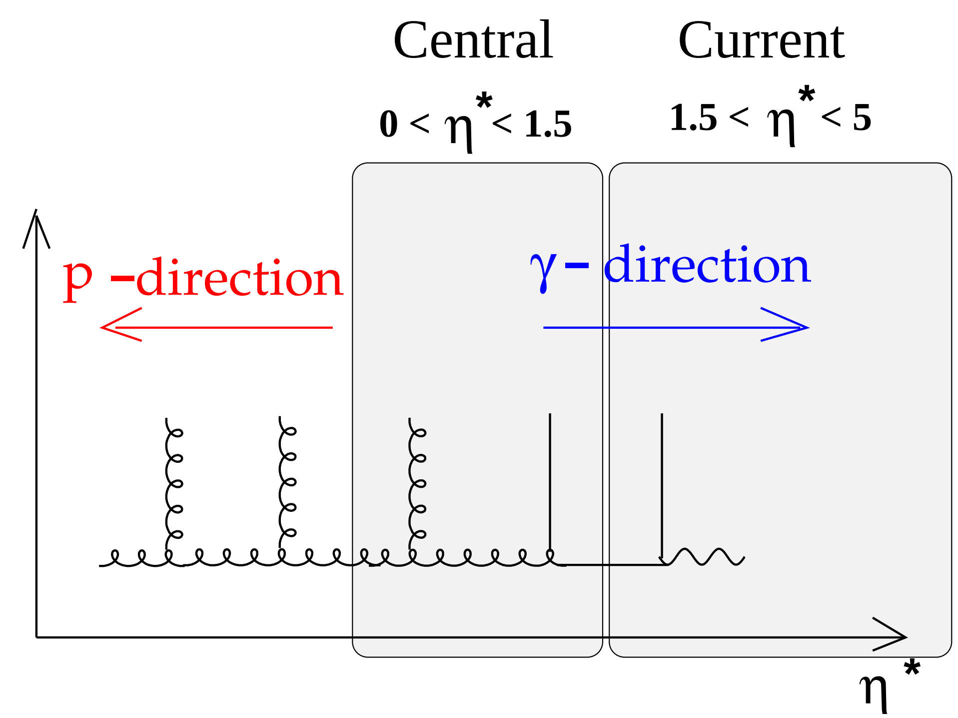
- Spectra as function of pt*:
  Constraints on hardness of parton in PS

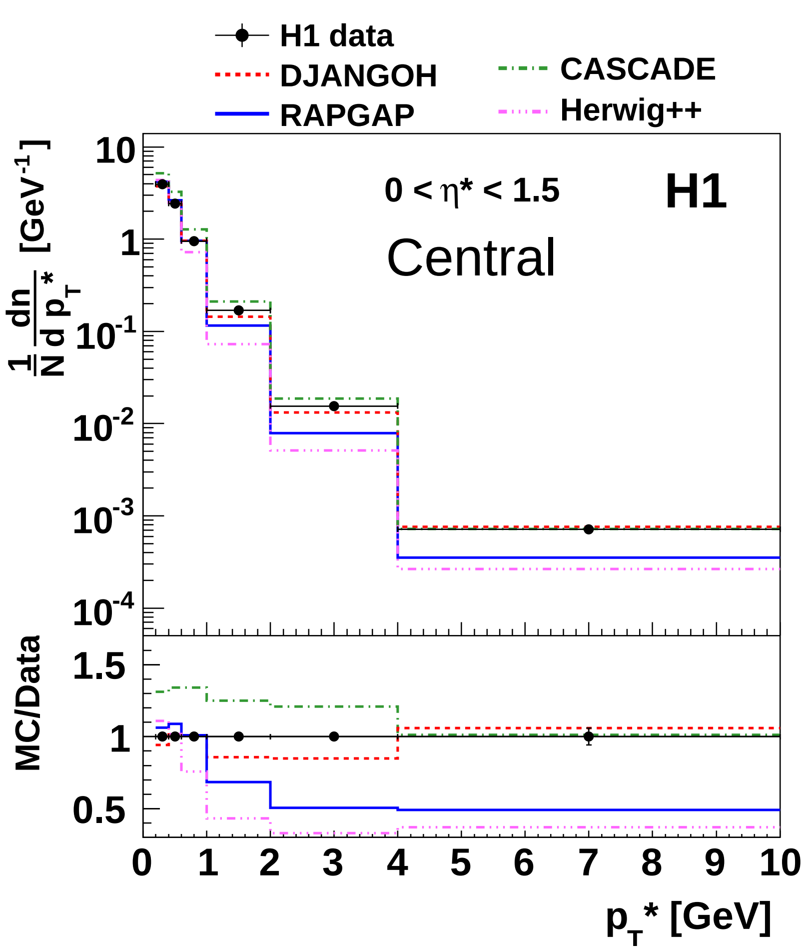
***Central*: $0 < \eta^* < 1.5$**

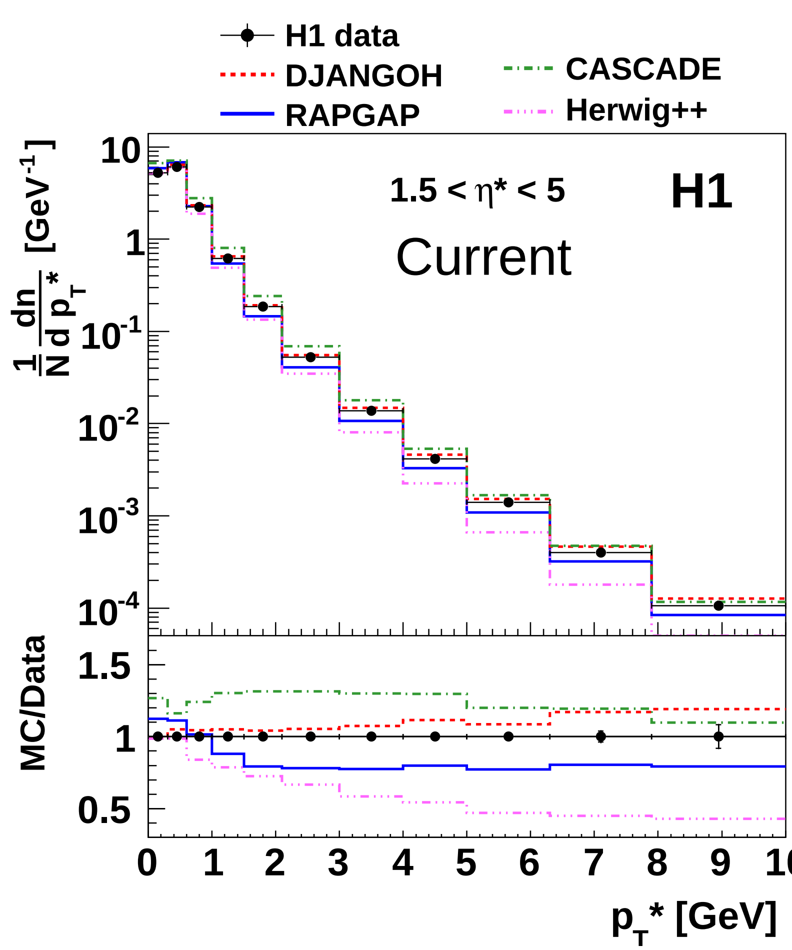
- Region sensitive to higher order radiation (PS)
- Data not described by collinear PS models

***Current*: $1.5 < \eta^* < 5$**

- Region sensitive to hard scattering
- Djangoh and Rapgap give best description







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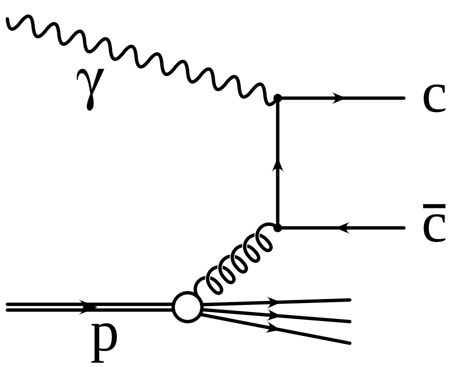
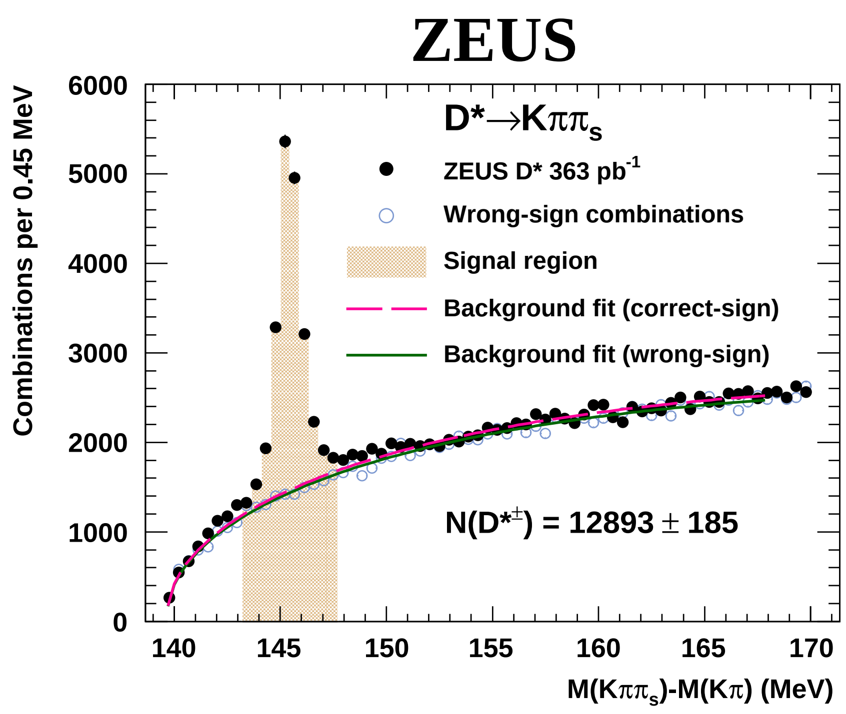
D* production in DIS

$D^{*\pm}$ production in DIS

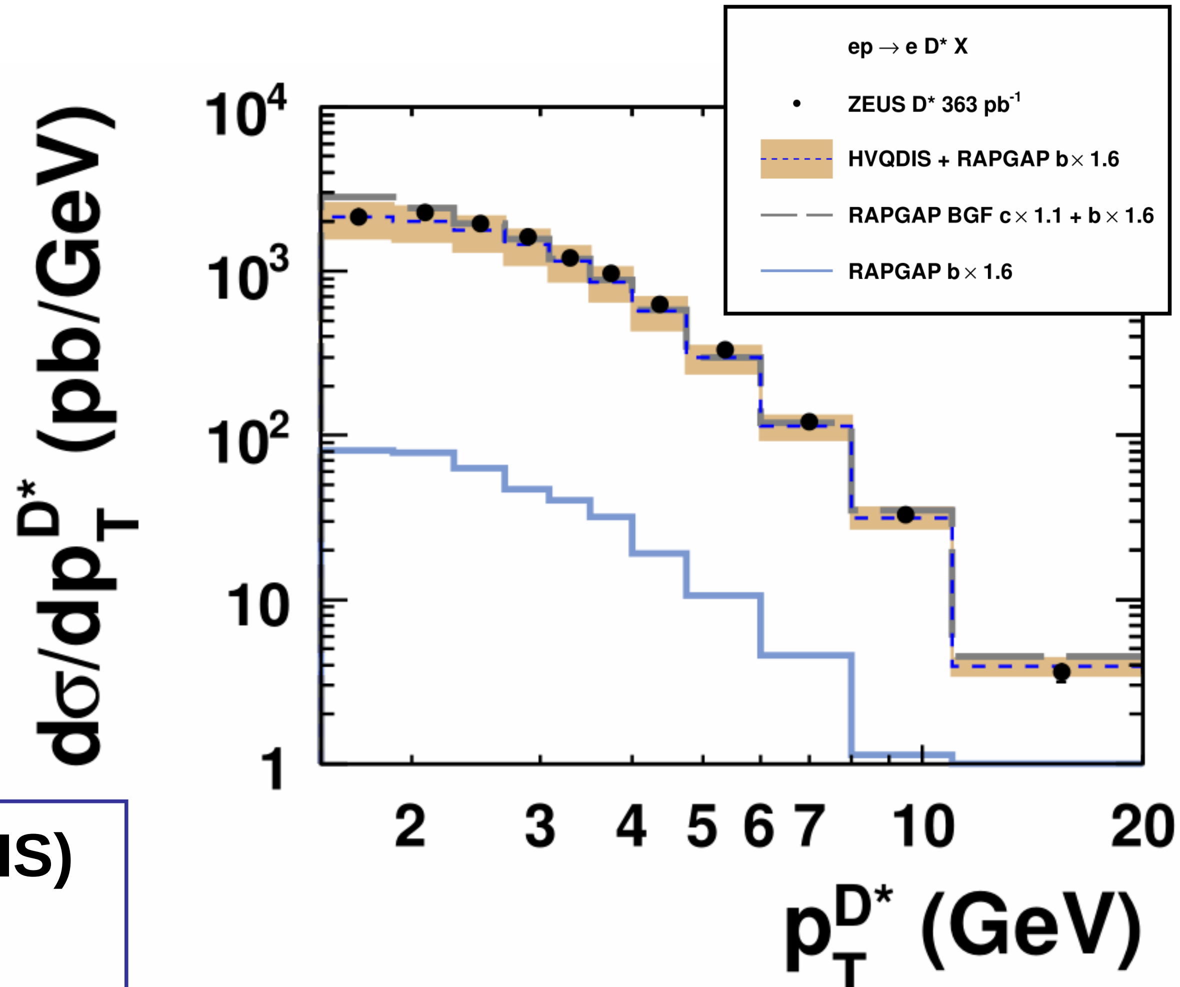
- Full HERA II data: 354 pb^{-1}
- $D^{*+} \rightarrow D^0\pi^+_s \rightarrow (K^-\pi^+)\pi^+_s$
- Clean D^{*+} signal in $M(K^-\pi^+\pi^+_s) - M(K^-\pi^+)$





D^{*+} differential cross sections in $ep \rightarrow e'c\bar{c}X \rightarrow e'\, D^*X'$

- differential in:
  - Q^2,y, x
- Kinematic region
  - $5 < Q^2 < 1000$ GeV^2 ,
  - $1.5 < p_T(D^*) < 20$ GeV
  - $|\eta(D^\pm)| < 1.5$
  - $0.02 < y < 0.7$



Results compared to HVQDIS and to RAPGAP MC

Reduced cross sections derived further

Reasonable description by massive NLO (HVQDIS)
RAPGAP roughly reproduce data shape

H1+ZEUS D* combined cross sections

Combined H1+ZEUS D* differential visible cross sections in DIS

$5 < Q^2 < 1000$ GeV^2

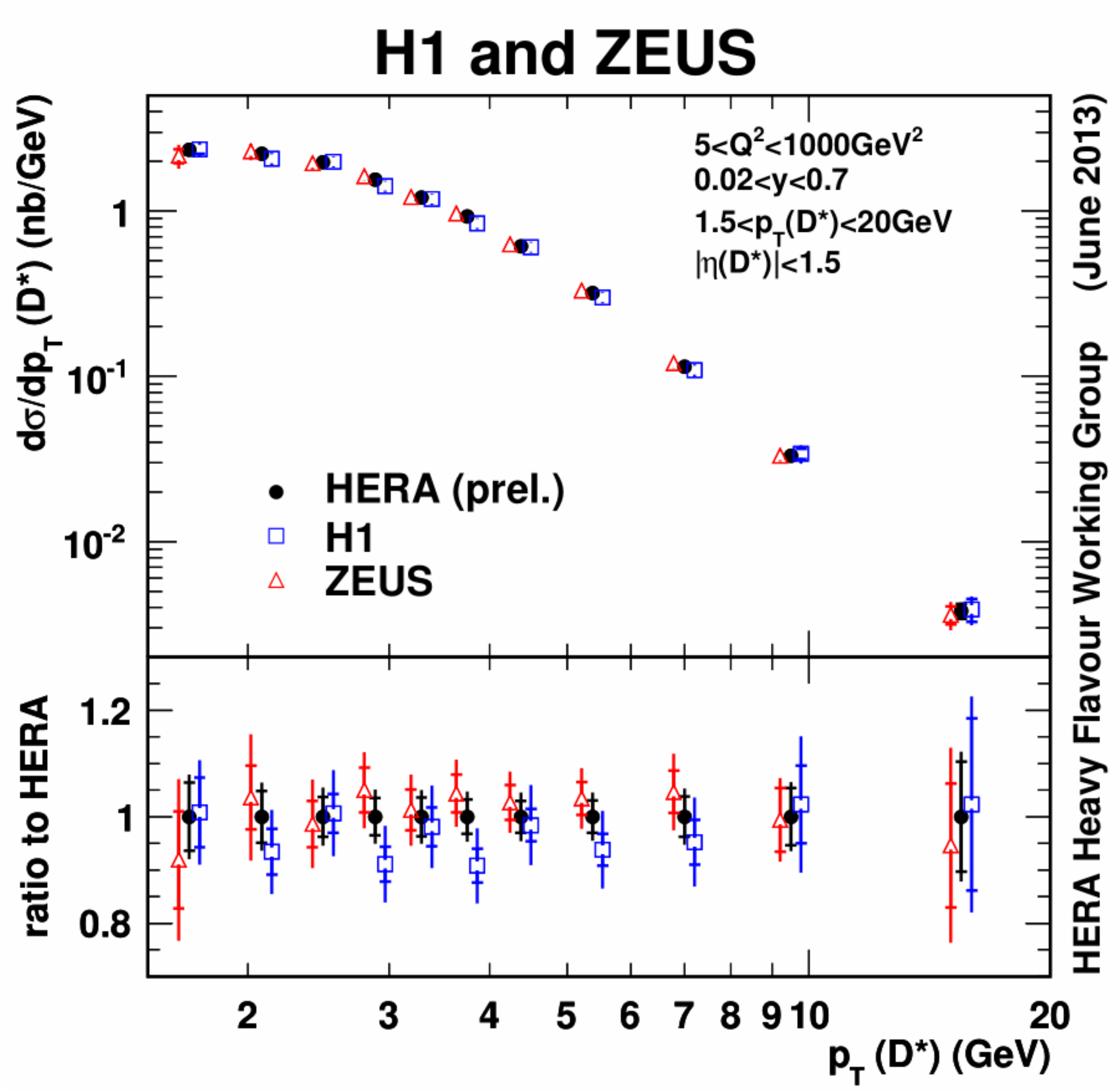
$1.5 < p_T(D^*) < 20$ GeV

H1 and ZEUS analyses performed in similar phase space and similar binning

Negligible uncertainty from swimming corrections

All relevant correlations are taken into account

HERAverager tool used



Single-differential visible cross sections

Q^2, y, pT(D*), η(D*), z(D*)

H1 and ZEUS data are well compatible

Impressive reduction of uncertainties in the combined results

H1+ZEUS D* combined cross sections

Data combination extends to HERA-I data

Increased range to lower values of Q^2

Double-differential cross sections

Further increase in precision

Compared to NLO calculations

HVQDIS with 3-flavor FFNS PDF

Double-differential visible cross sections

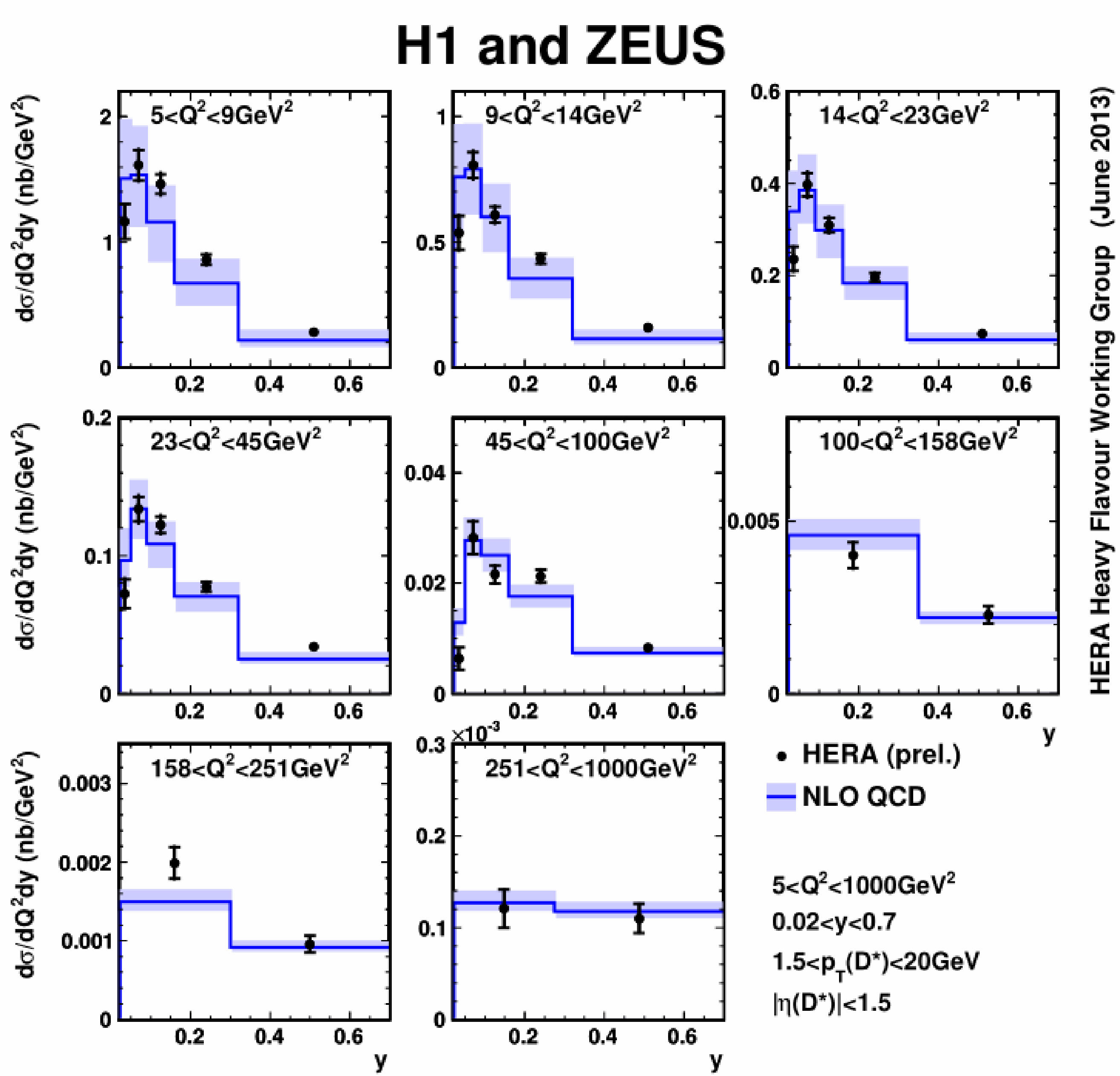
dQ^2dy

Data free from theoretical uncertainties

NLO theory describes data well

Data yields much higher precision than theory

NNLO calculations are welcome



Charm fragmentation fractions in photoproduction

Fragmentation fractions

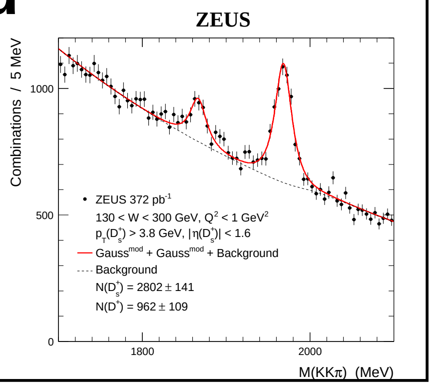
- Probability: c-quark hadronise into charm-hadron

$$f(c \rightarrow \text{charm hadron}) = \frac{\sigma(\text{charm hadron})}{\sigma(\text{total charm production})}$$

- Needed to go from *partonic* QCD to *hadronic* cross sections
- Not predictable in pQCD

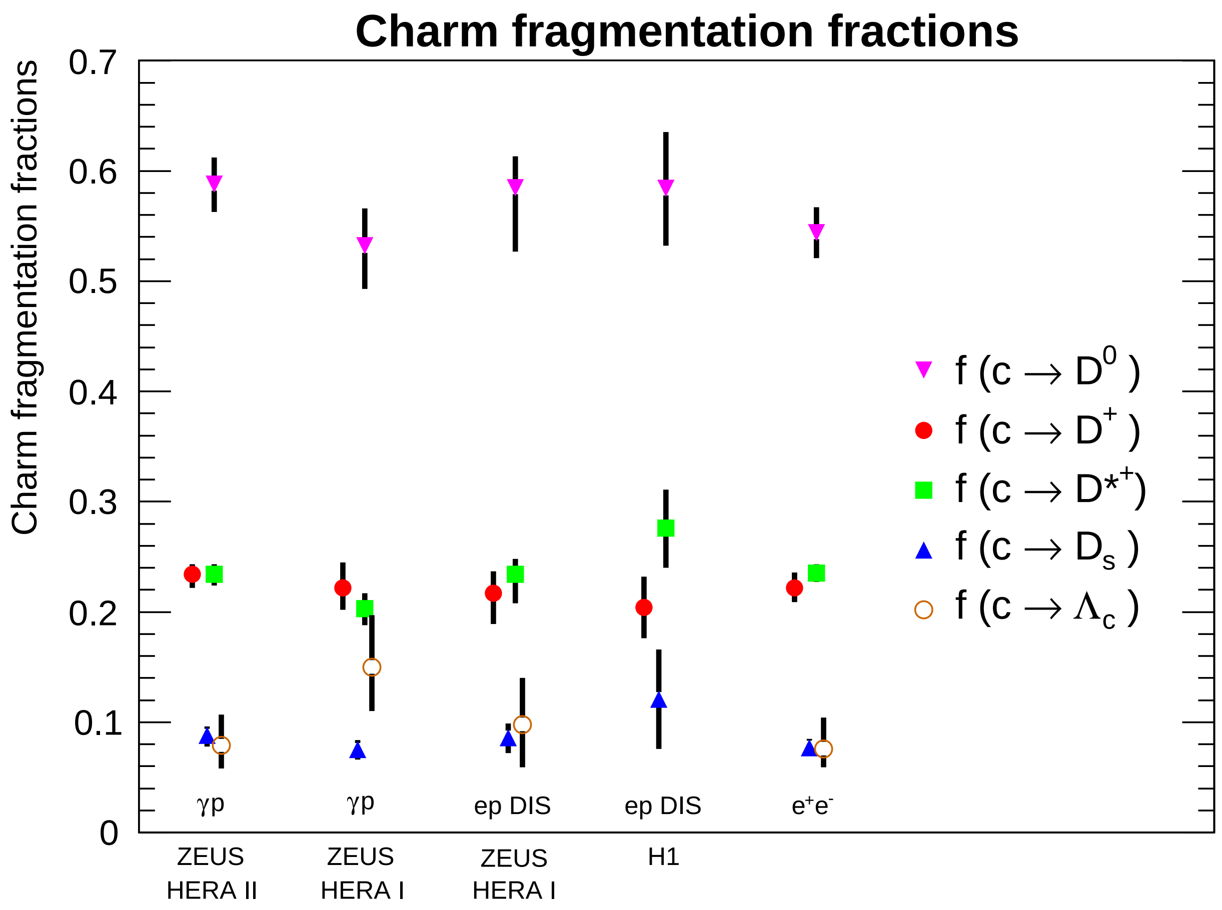
Charm hadrons measured

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+_s \rightarrow K^- \pi^+ \pi^+_s$
- $D^+_s \rightarrow \varphi\pi^+$
- $\Lambda^+_c \rightarrow K^- p\pi$



Measurement in photoroduction $Q^2 < 1\text{GeV}^2$

- Charm hadrons
  - $p_T > 3.8$ GeV
  - $|\eta| < 1.6$
  - $130 < W_{\gamma p} < 300$ GeV
- Silicon-strip detector used for charm vertices

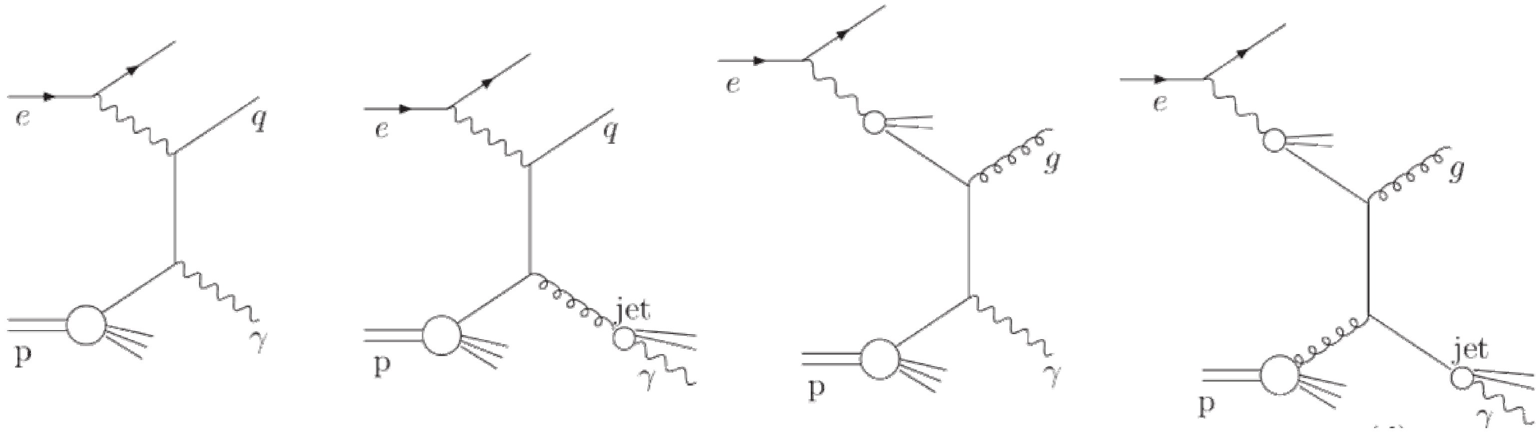


Results in good agreement with previous results

Precision competitive with combined e^+e^- LEP results

Support hypothesis of universality of heavy-quark fragmentation

Prompt photons in γp: ep → γ+X (+j) [+e]

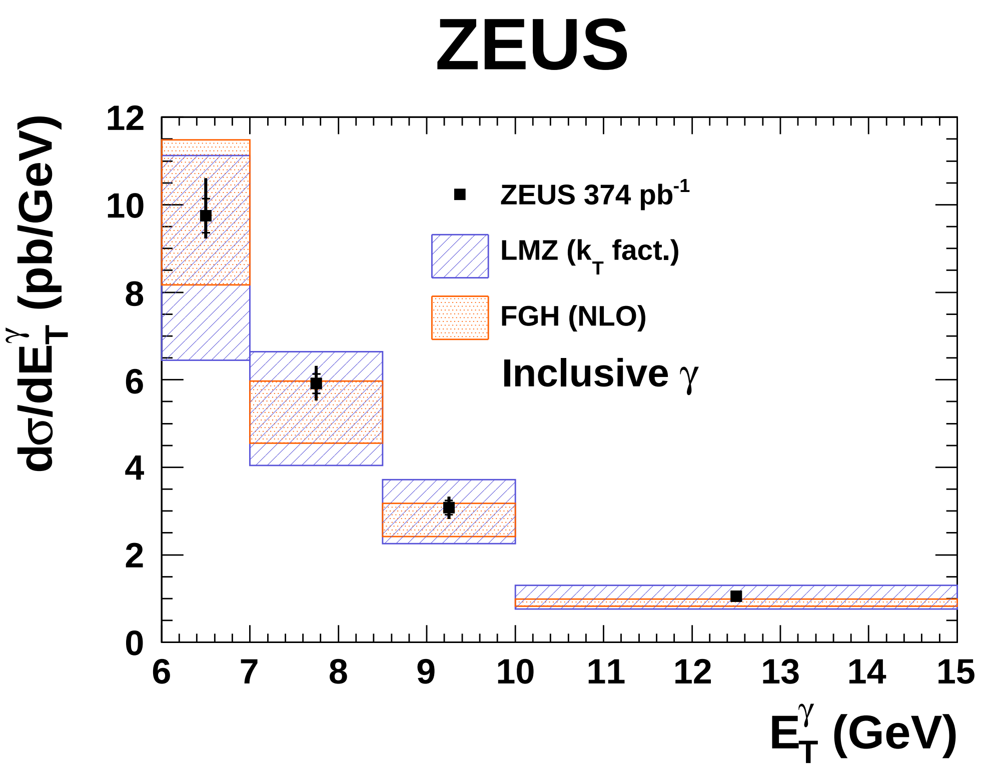


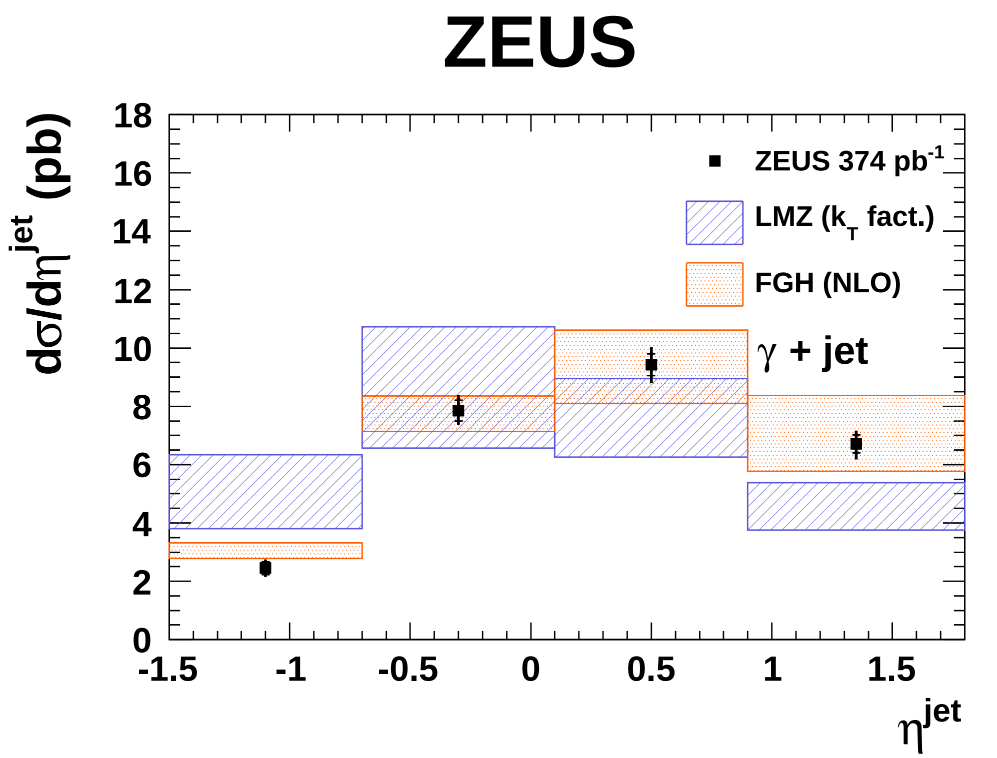
Prompt photons in photoproduction Q^2<1 GeV^2

Direct and resolved processes

Prompt radiation and fragmentation

Measured *with* and *without* accompanying jet





Theory

FGH: NLO with fragmentation functions ($O(\alpha^3\alpha_s^2)$)

- Data well described within theory uncertainties

LMZ: k_T factorization with unintegrated parton densities

- Data well described within uncertainties
- Less good at low η^{jet} and low resolved region in γ+jet ($x_\gamma^{meas} \to 1$)

Complementary process: photons + jets in DIS was measured in Phys Lett B 715 (2012) 88

Diffractive dijet photoproduction

History

- Suppression w.r.t. to NLO observed by H1
- No indication observed by ZEUS

Complementary method to large-rapidity-gap method (LRG)

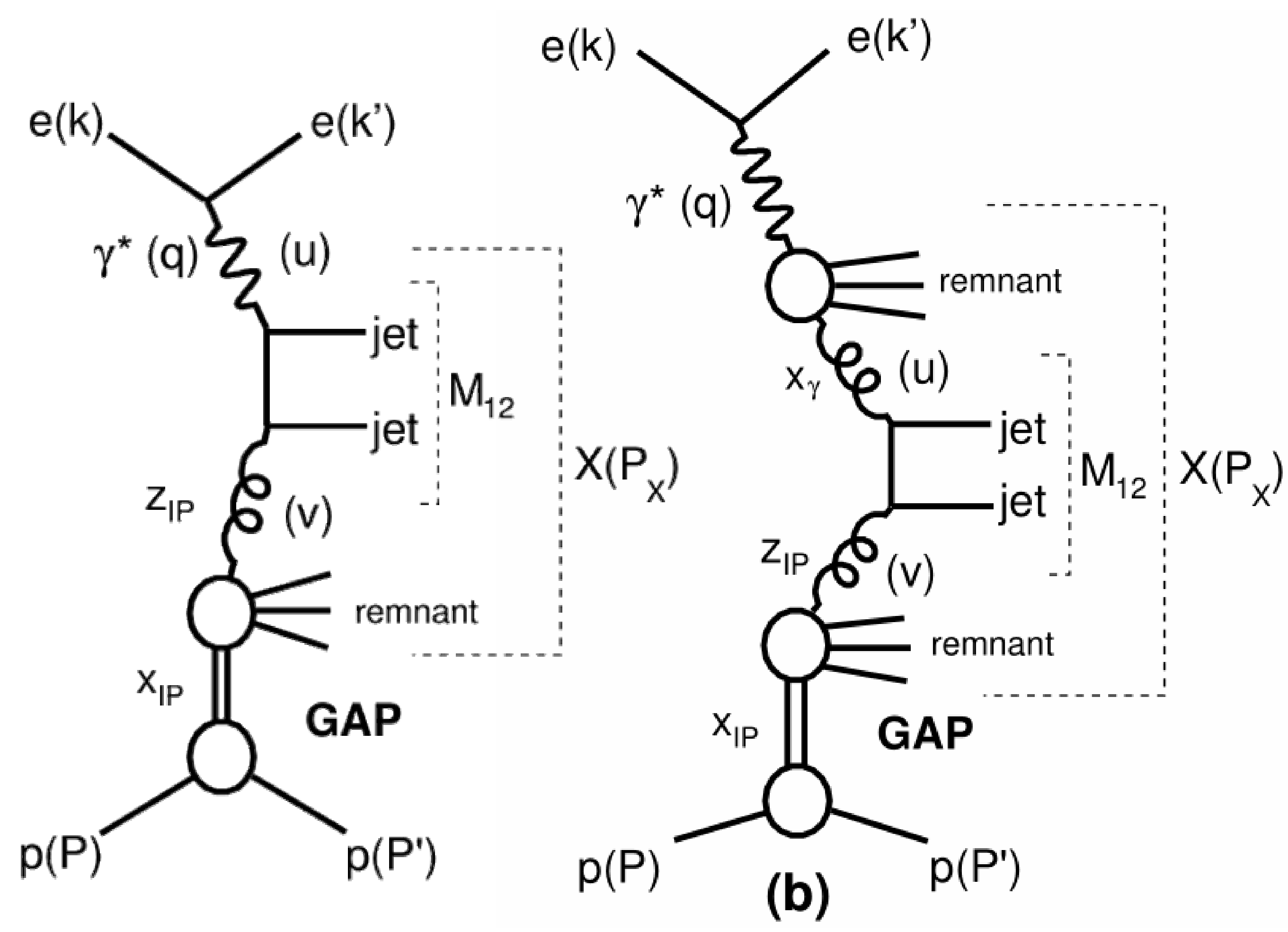
Tag leading proton

- Very forwad proton spectrometer (VFPS)
- At 220m from interaction point

Two measurements of dijets in

- DIS
- Photoproduction

PHP	DIS
$Q^2 < 2\,\mathrm{GeV}^2$	$4\,\mathrm{GeV}^2 < Q^2 < 80\,\mathrm{GeV}^2$
Common Cuts	
$0.2 < y < 0.7$	
$E_T^{*\mathrm{jet1}} > 5.5\,\mathrm{GeV}$	$E_T^{*\mathrm{jet2}} > 4.0\,\mathrm{GeV}$
$-1 < \eta^{\mathrm{jet1}} < 2.5$	$-1 < \eta^{\mathrm{jet2}} < 2.5$
$\vert t\vert < 0.6\,\mathrm{GeV}^2$	$0.010 < x_{I\!P} < 0.024$
$z_{I\!P} < 0.8$	



Diffractive dijet photoproduction

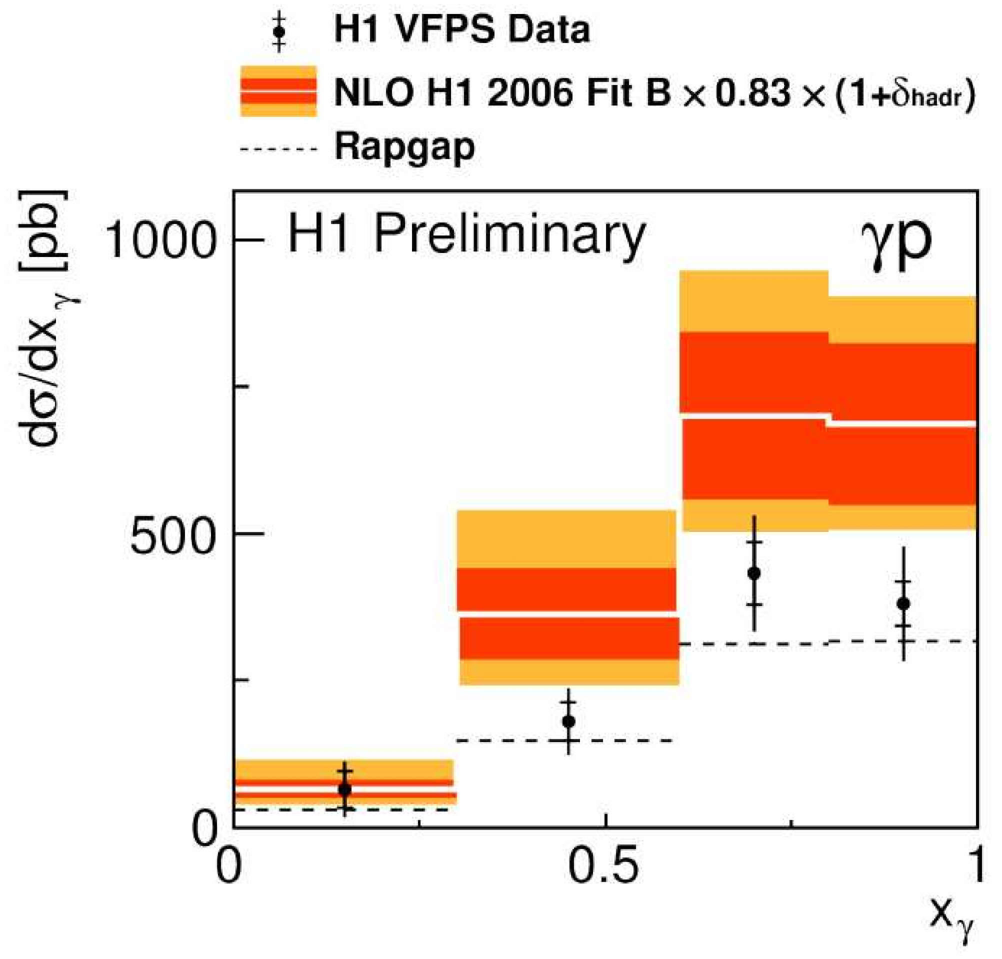
Dijet in photoproduction

NLO calculations

- Frixione et al.
- DPDF: H1 2006 Fit B
- γ-PDF: GRV

NLO overestimates data

Rapgap describes data

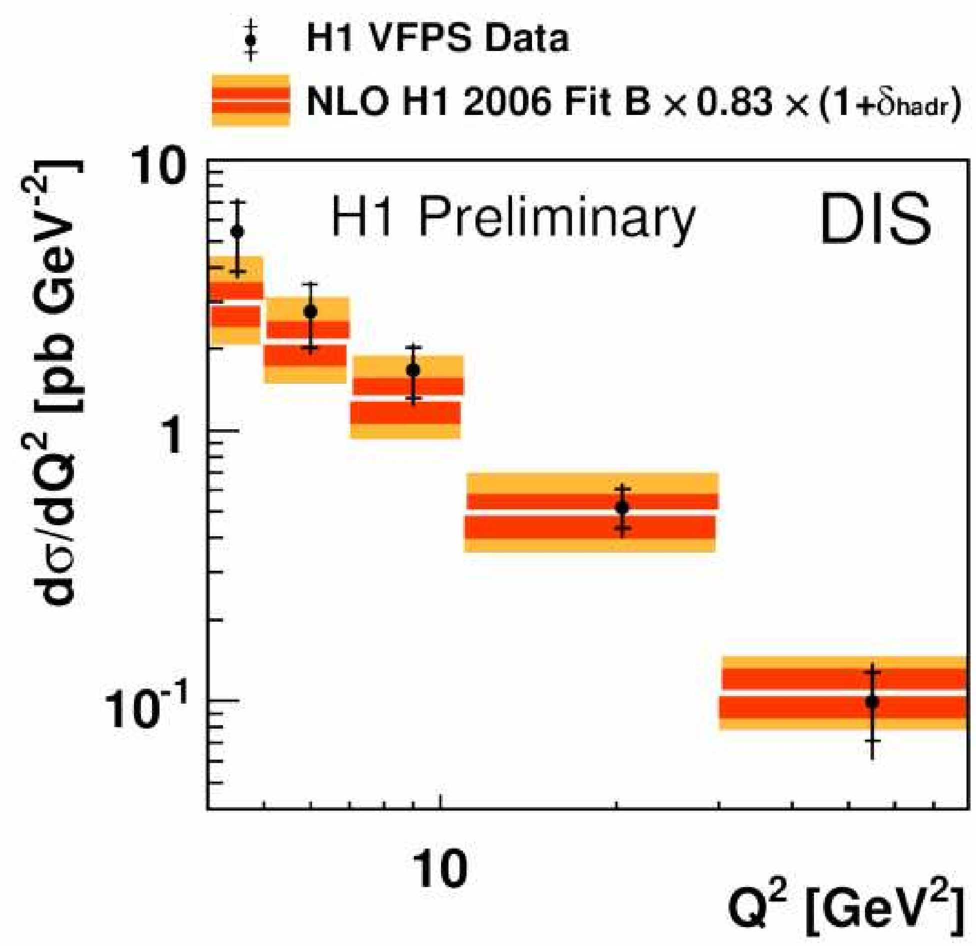


Dijet in NC DIS

NLO calculations:

- NLOJET++
- DPDF: H1 2006 Fit B

Data well described by theory



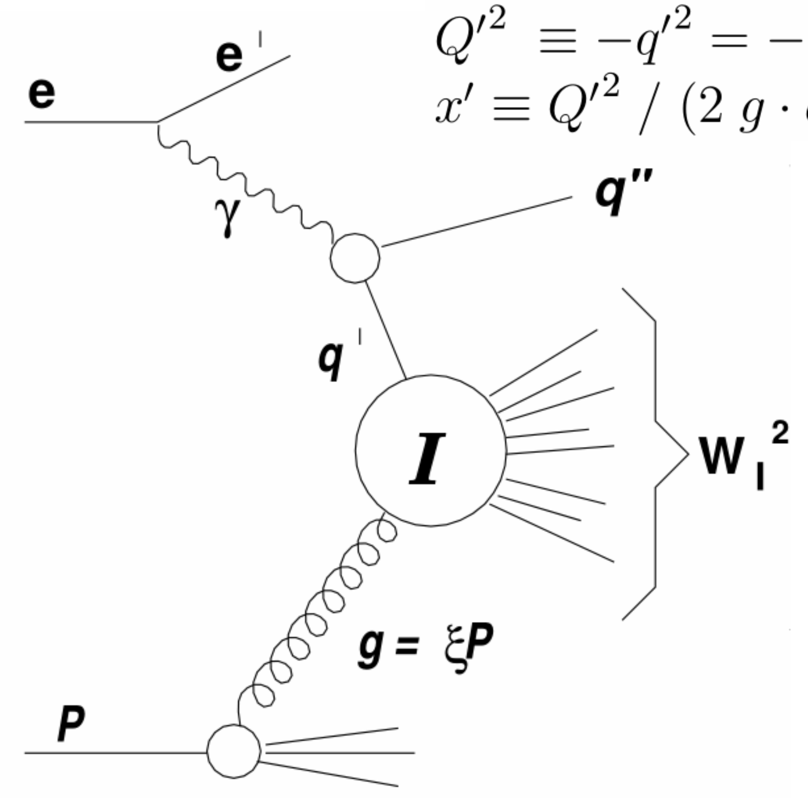
New analysis confirms previous results from H1 with complementary experimental method

QCD Instantons

Variables of I-subprocess:

$$Q'^2 \equiv -q'^2 = -(\gamma - q'')^2$$

$$x' \equiv Q'^2 \,/\, (2\, g \cdot q')$$



QCD Instantons

- Solution to Yang-Mills equation of motion
- Physical interpretations:

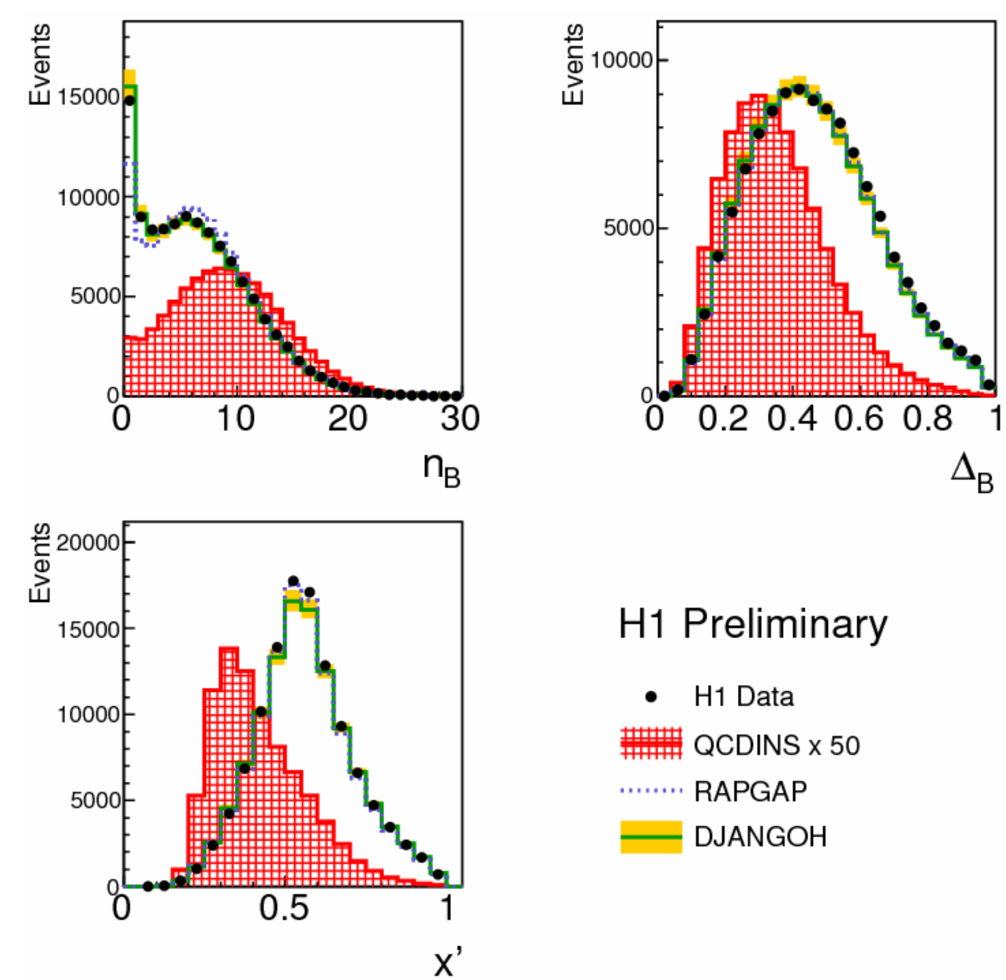
  Pseudo-particle or tunneling process between topologicaly different vacuum states

Signatures

- One hard jet (not originating from instanton)
- Densily populated narrow band, flat in φ
- Large particle multiplicities

Strategy I

- Find jets in hadronic center of mass frame
  - Remove hardest jets from HFS
- Boost to instanton rest frame and define variables
  - Topological: Sphericity, Fox-Wolfram moments, azimuthal isotropy (Δ_B)…
  - Number of charged particles in band (n_B)
  - Energy of band ($E_{Inst.}$), …
- Variables are input to MVA



QCD Instantons

Multivariate analysis

Probability density estimator with range search (PDERS)

Training

- Rapgap, Django
- QCDINS (Ringwald, Schremp)

Good description of discriminator in background region

Signal region

D > 0.86

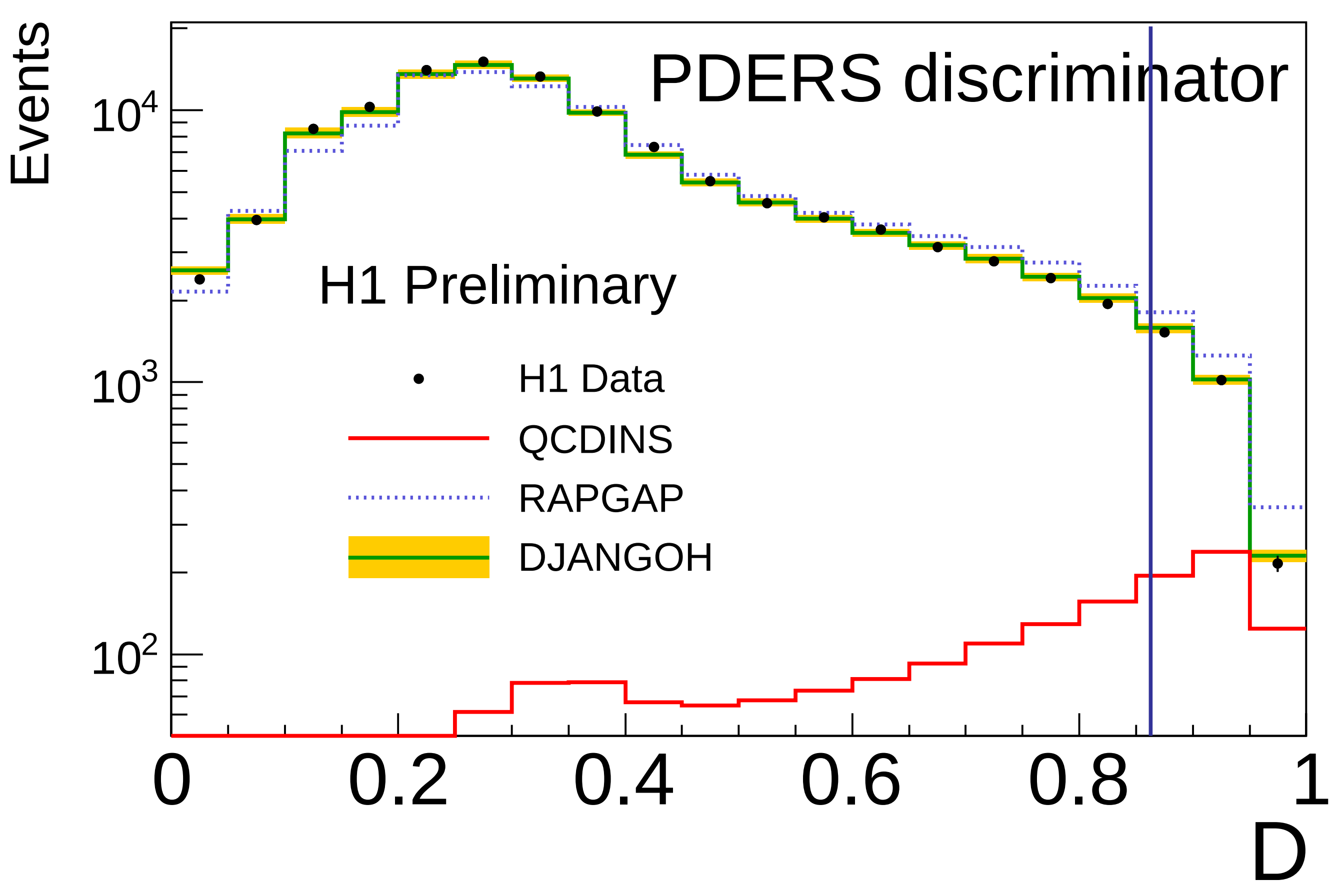
Input for limit calculation

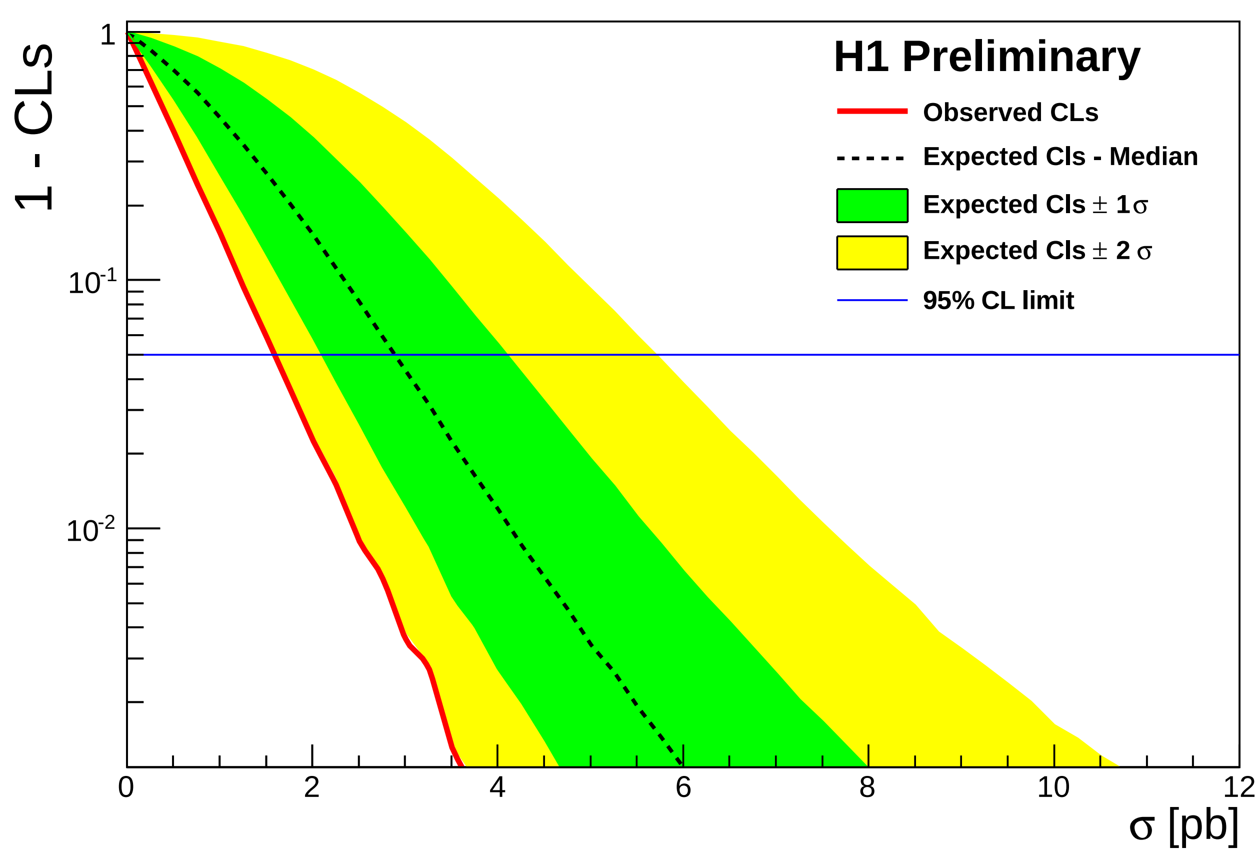
QCD Instanton cross section: 10 ± 2 pb

Uncertainties: Systematic and model

Upper limit for 95% CL: 1.6pb

- Data are consistent with background
- No evidence for QCD Instantons
- Upper limit suggests exclusion of the Ringwald-Schremmps‘ predictions for HERA QCD instantons.





Summary

Many new interesting QCD results from the HERA experiments

- Often valuable complementary information to LHC experiments
- H1 and ZEUS (still) very active collaborations

Selected topics

- Charge particle spectra → Color dipole model gives best PS description
- D* production cross sections
- Combined D* cross sections → Great benefit in precision from combination
- Charm fragmentation functions → Universality hypothesis confirmed
- Photons in photoproduction → NLO and k_t-factorization give good description
- Diffractive dijet → Complemenatary method confirms old H1 results
- QCD Instanton → Ringwald-Schrempp' solution appears to be excluded

Many QCD topics not covered in this short summary

- $D^{\pm}$ production in DIS (*JHEP 05 (2013) 023*)
- K^0 production (*H1prelim-13-033*)
- Lamda Baryon production (*H1prelim-13-031*)
- J/ψ in elastic and proton-dissociation photoproduction (*EPJ C73 (2013) 2466*)
- Feynman Scaling of Photon and Neutron Production in the Very Forward Direction (*H1prelim-13-012*)
- Inclusive jet, dijet and trijet production and $\alpha_s(M_Z)$ (*H1prelim-12-031*)
- Charged particle production at sqrt{s}=225 GeV (*H1prelim-13-032*)
- PDF fits including jet data and charm data (→ HERAPDF2.0)
- Inclusive jet in photoproduction and $\alpha_s(M_Z)$ (*Nucl. Phys. B 864 (2012) 1*)
- Photon + jet in DIS (*Phys. Lett. B 715 (2012) 88*)

More results from H1 and ZEUS still to come soon …