Low x Final States at HERA

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Introduction

General Properties of the Hadronic Final State

Jets at HERA

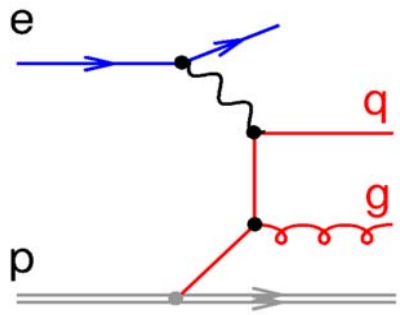
Open Charm and Beauty Production

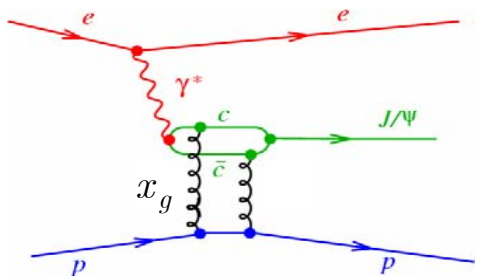
Prompt Photons

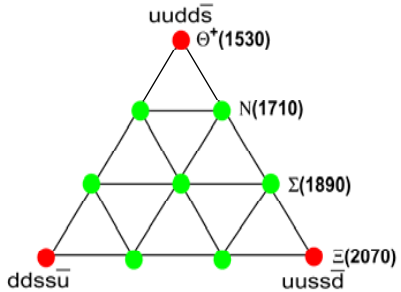
Exclusive Final States (Hidden Charm)

Spectroscopy: Pentaquarks

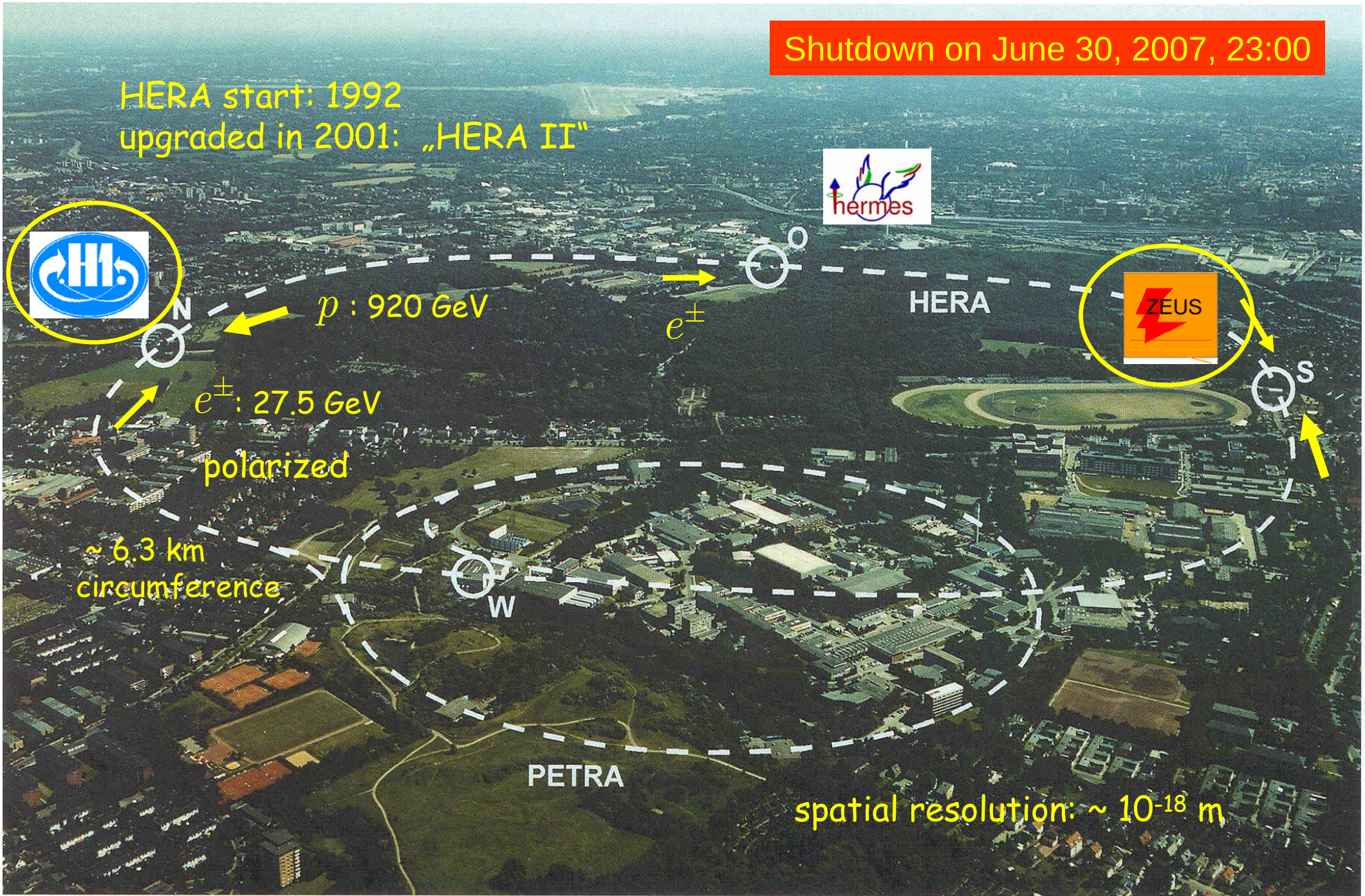
Summary and Conclusions



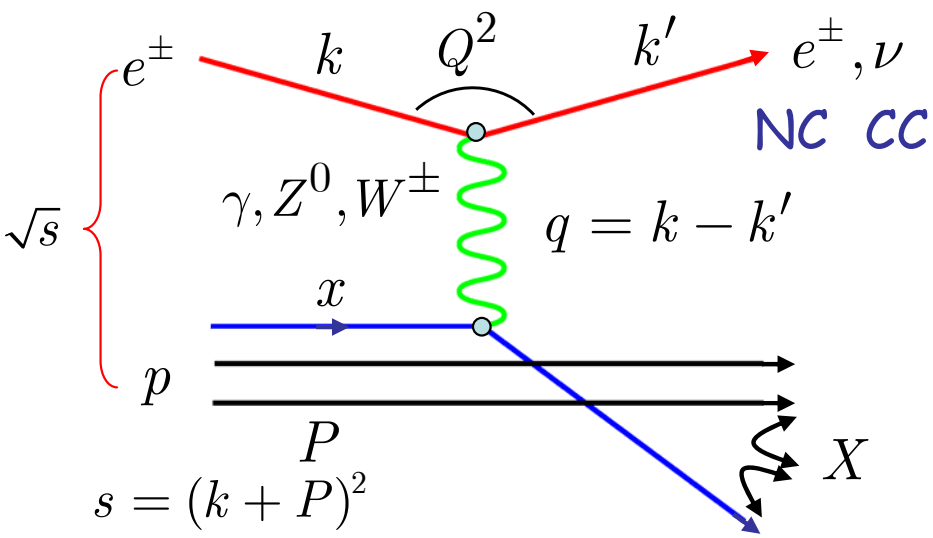




HERA – was the world's largest electron microscope (Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)



Deep Inelastic Scattering (DIS)



$$s = (k+P)^2$$

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

$$W^2 = M_X^2 = (q+P)^2$$

$$x = \frac{Q^2}{2\,P\cdot q}$$ fraction of the proton momentum carried by the charged parton

$$y = \frac{P\cdot q}{P\cdot k}$$ fraction of the electron energy carried by the virtual photon („inelasticity")

$$\boxed{Q^2 = sxy}$$ fixed s: 2 indep. variables

DIS :

electron scatters off a charged constituent (parton) of the proton (= elastic scattering)

$$\frac{d^2\sigma(e^{\pm}p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+ \underbrace{\left[F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3\right]}_{\text{"reduced cross section" } \sigma_r}$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

γ exchange only:

$$F_2(x) = \sum_{i=u,d} e_i^2 x q_i(x)$$

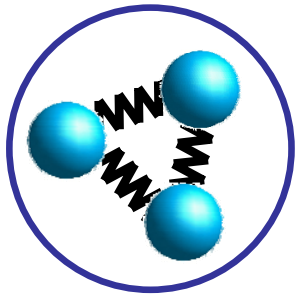
parton densities $xf_i(x)$ (pdf)

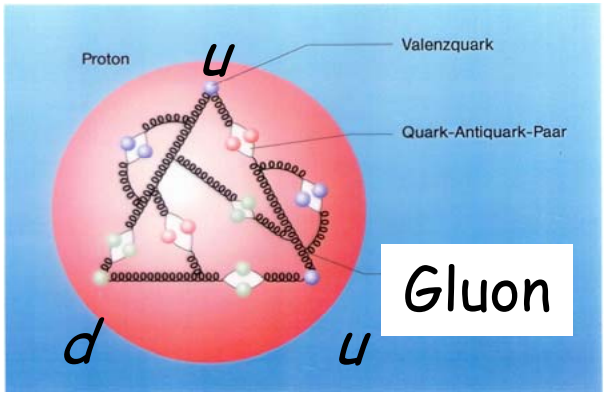
$W^{\pm}$ exchange only:

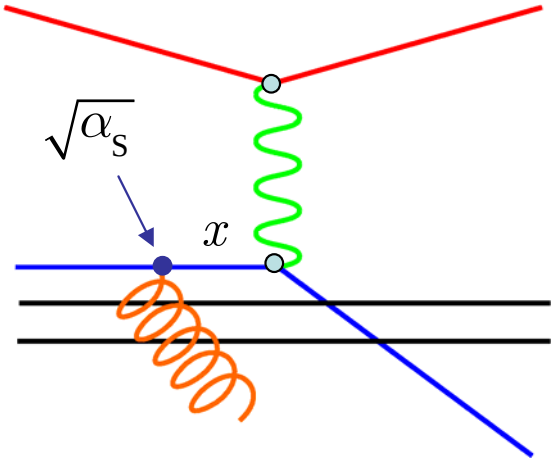
$$e^-p: \quad F_2(x) \sim xq_u(x)$$

$$e^+p: \quad F_2(x) \sim (1-y)^2 xq_d(x)$$

Quantum Chromodynamics (QCD)







Basic ingredients of QCD:

1. Asymptotic freedom :

$\alpha_S \to 0$ at short distances

→ perturbative QCD (pQCD)

„hard" scale Q^2

2. Factorization :

$$\sigma = \sum_i \sigma_{\gamma^* i}(Q^2) \otimes x f_i(x)$$

non-perturbative part

3. Evolution (calculable in pQCD) :

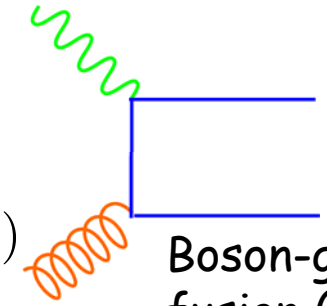
Parton densities become functions of Q^2

$xq_i(x) \to xq_i(x, Q^2)$ quarks

$x\overline{q}_i(x, Q^2)$ antiquarks

+ gluons

$g(x, Q^2)$



Boson-gluon fusion (BGF)

Kinematic Regime of HERA

- large reach in x
- large reach in Q^2

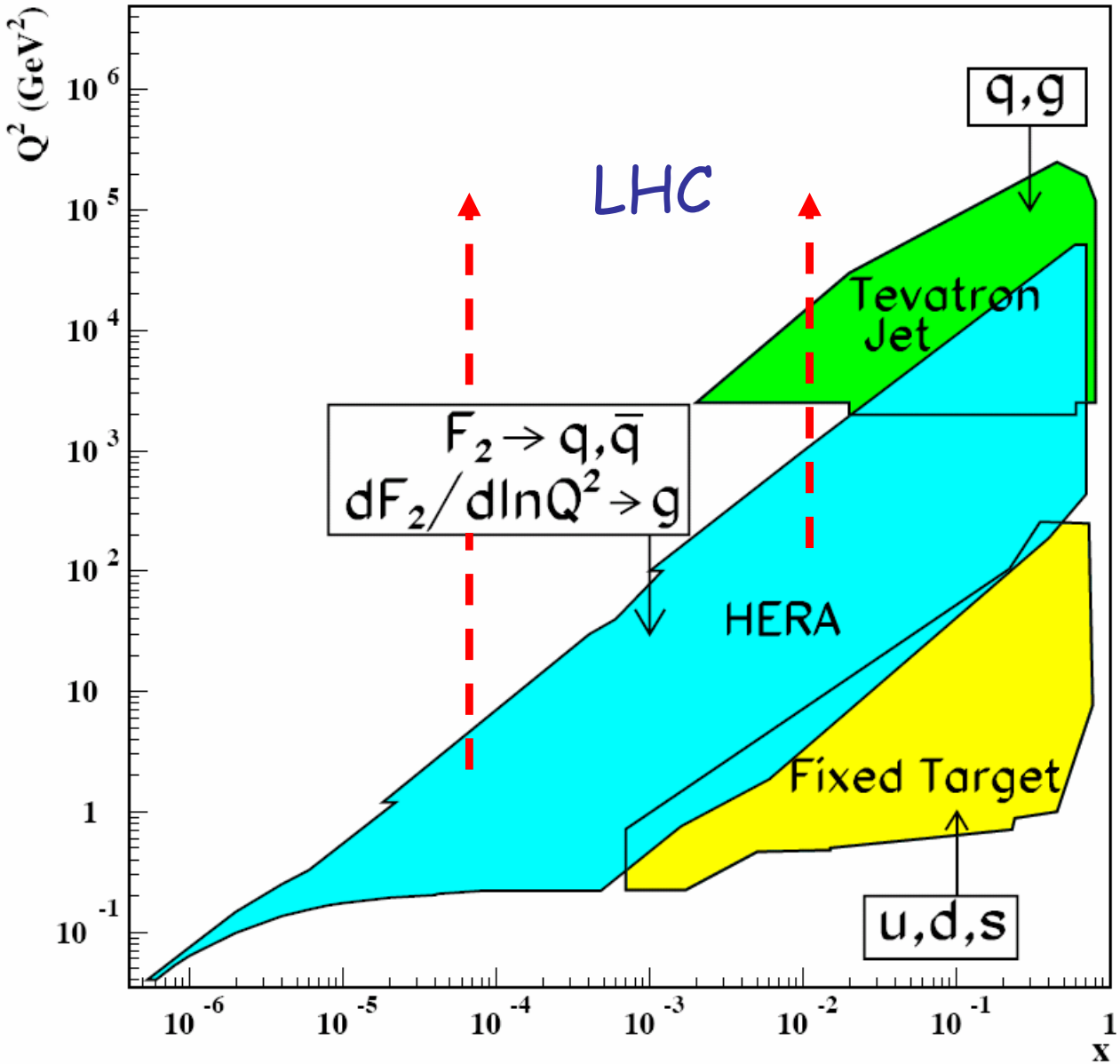
"Inclusive" scattering (integrate over all hadronic final states X)

→ pdf's of quarks from F_2

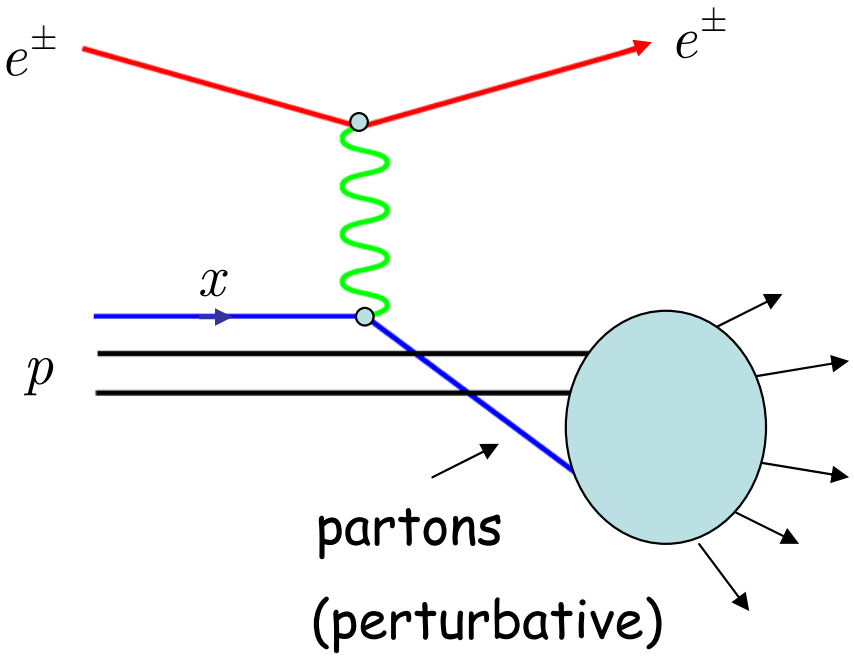
→ pdf of gluon from Q^2 variation of F_2 (e.g. DGLAP evolution)

Specific Hadronic Final States

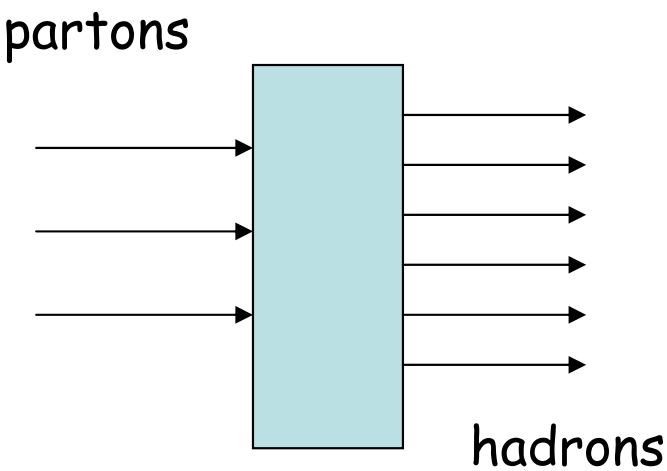
→ Details of the dynamics of QCD



General Properties of the Hadronic Final State



Models needed:
Lund string etc.

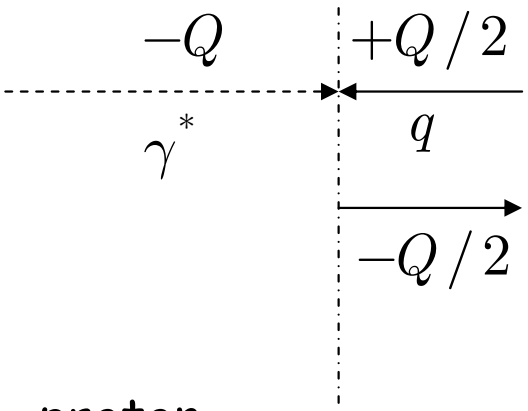


hadronisation = „universal" (?),

(independent of the initial state)

→ compare $ep, e^+e^-, pp, p\overline{p}, AA$

Charged Particle Spectra



Breit frame

proton remnant

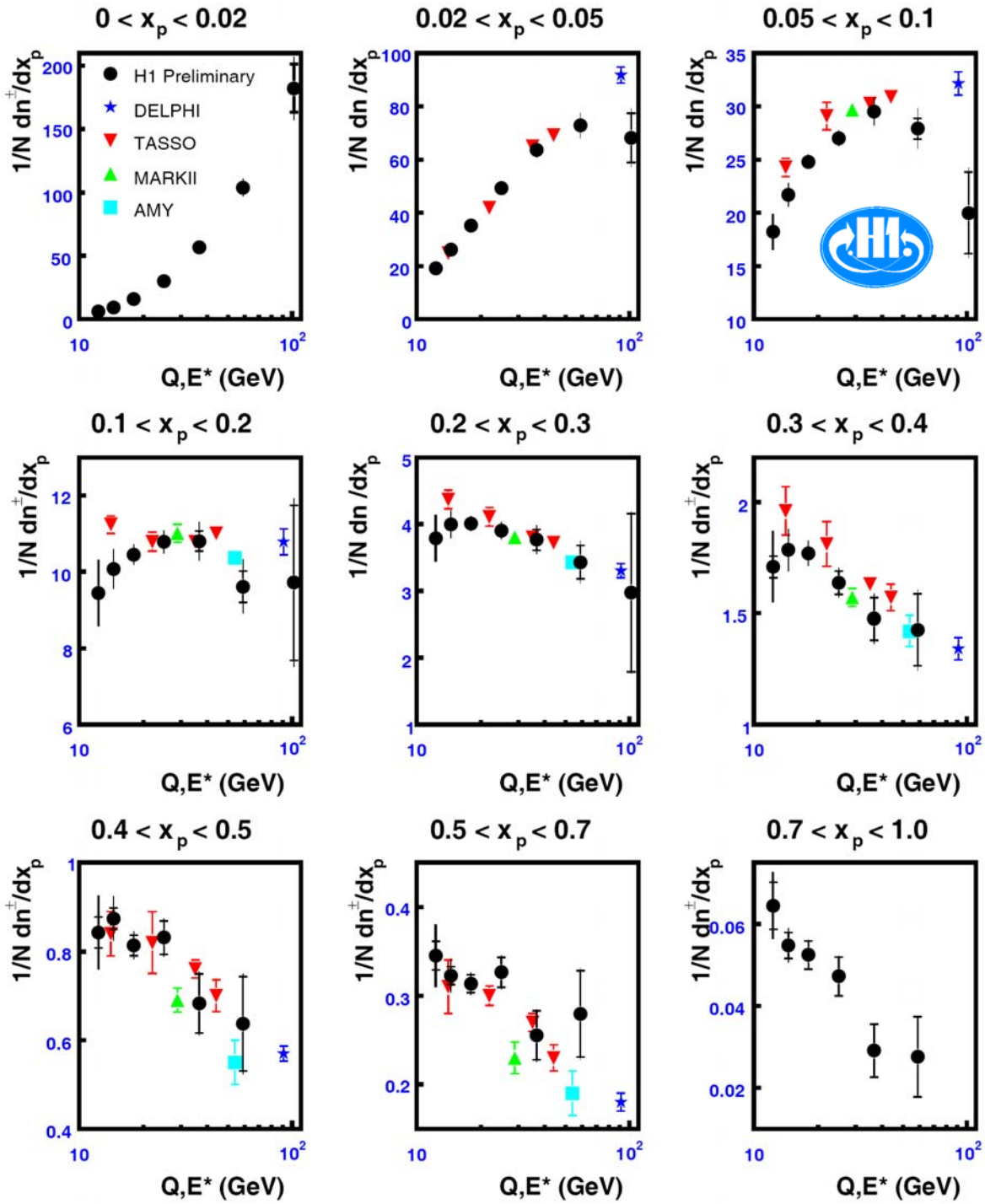
„current-region"

scaled particle momentum in current region:

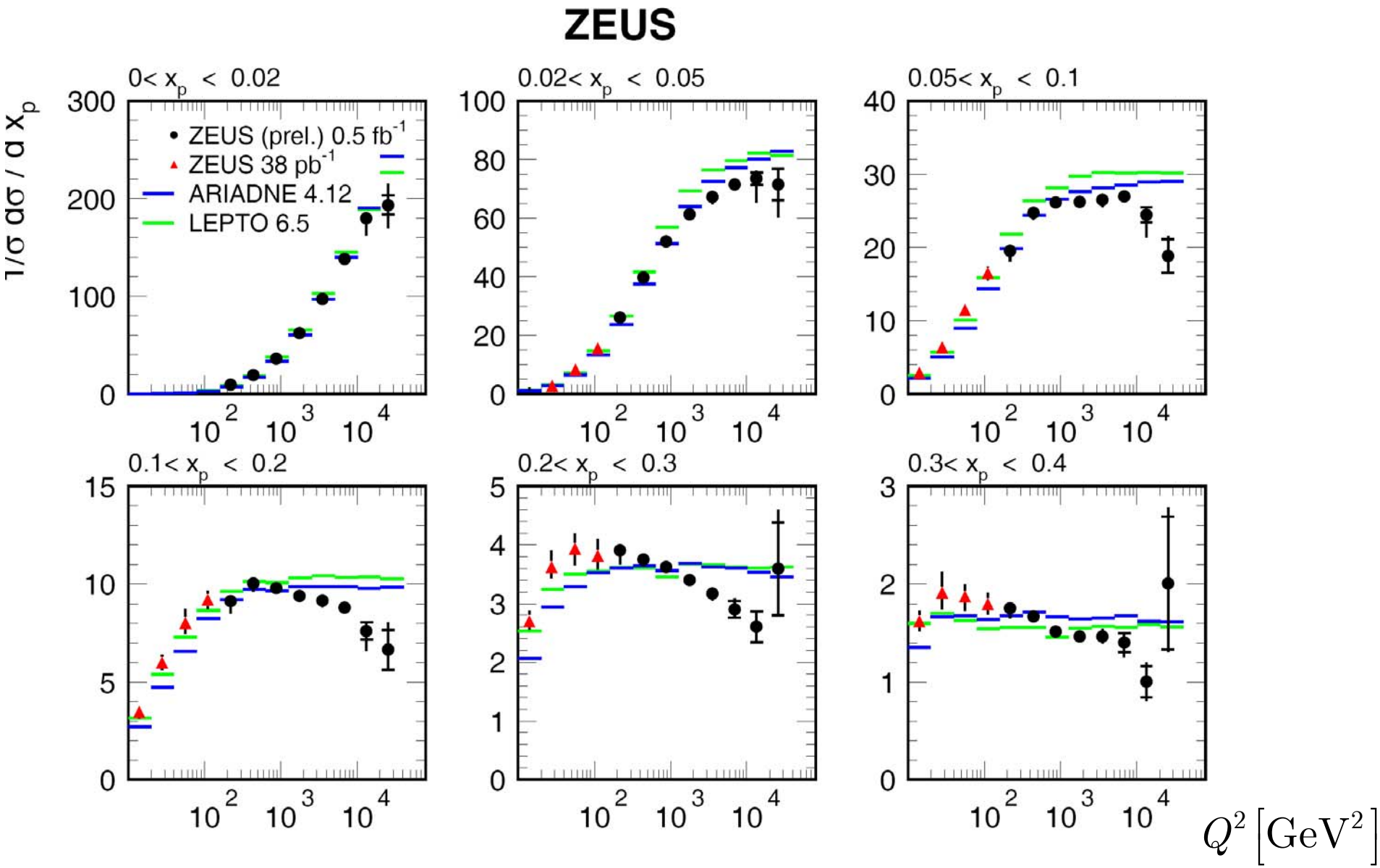
$$ep: \quad x_p = \frac{2p_{had}}{Q}$$

$$e^+e^-: \quad x_p = \frac{2p_{had}}{E^*}$$

→ overall agreement

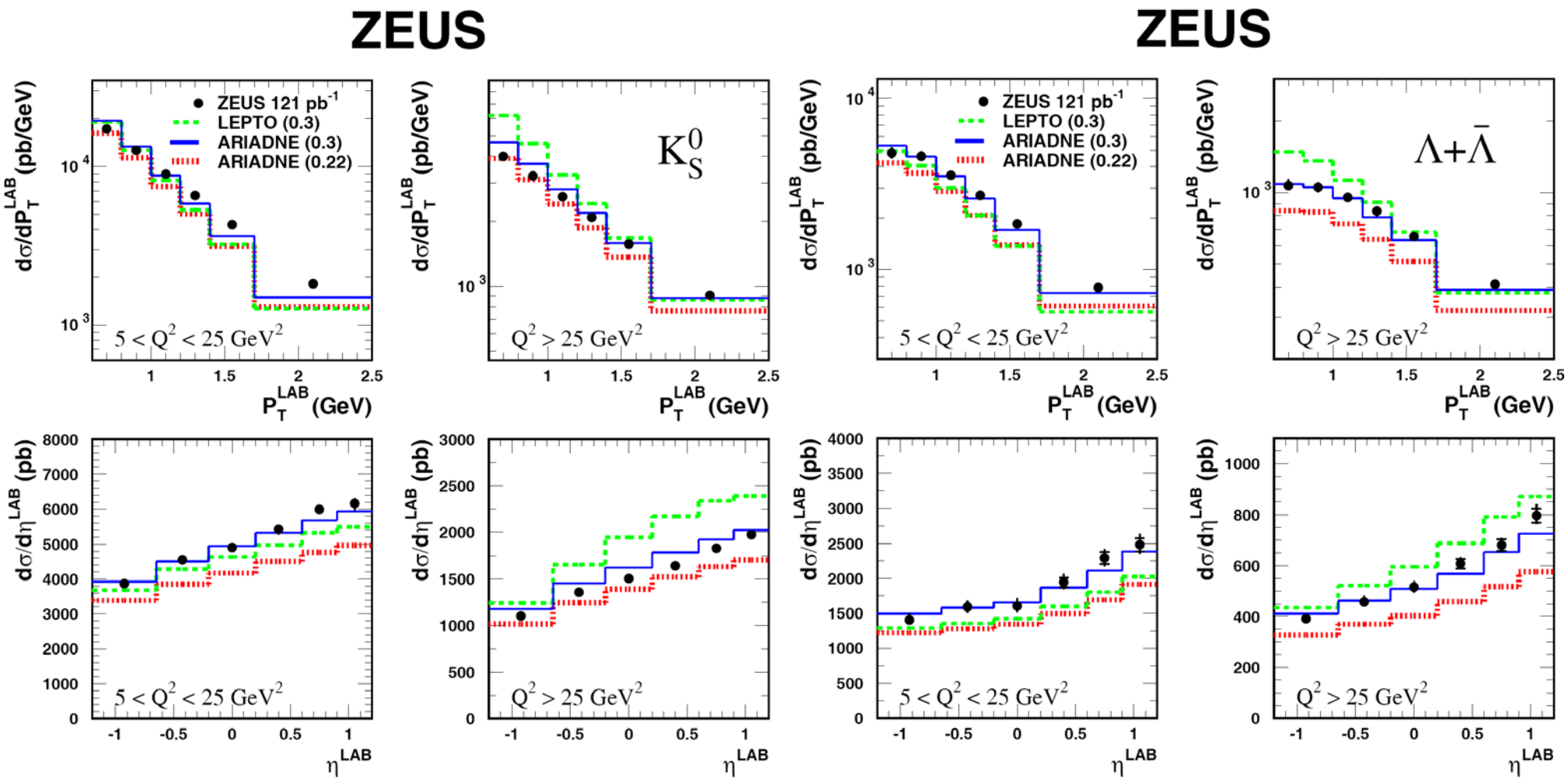


Charged Particle Spectra (cont.)



models reproduce the gross features, differences in details

Strange Particle production:

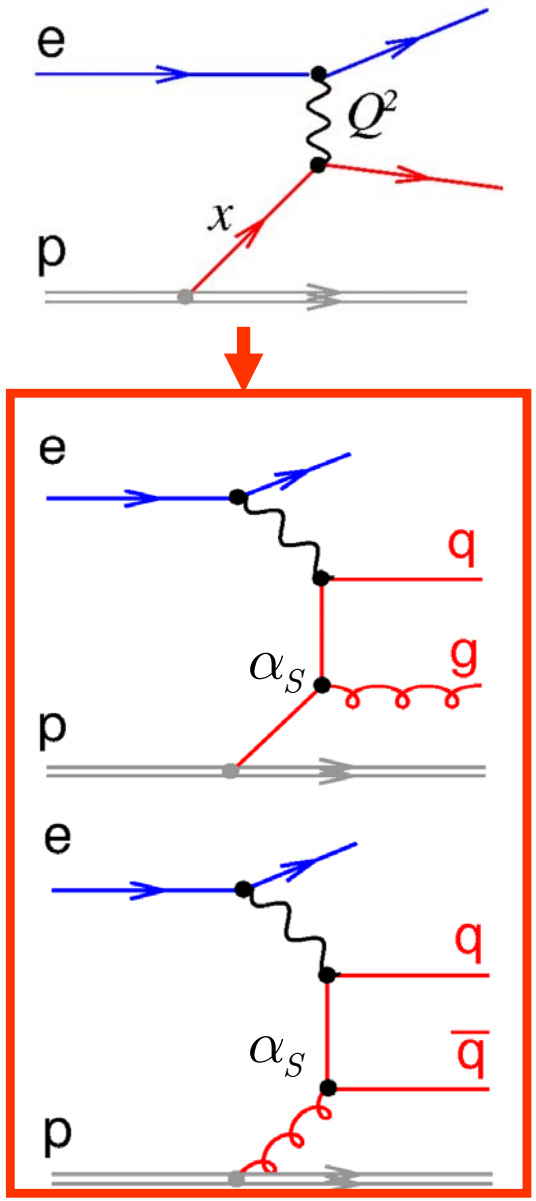


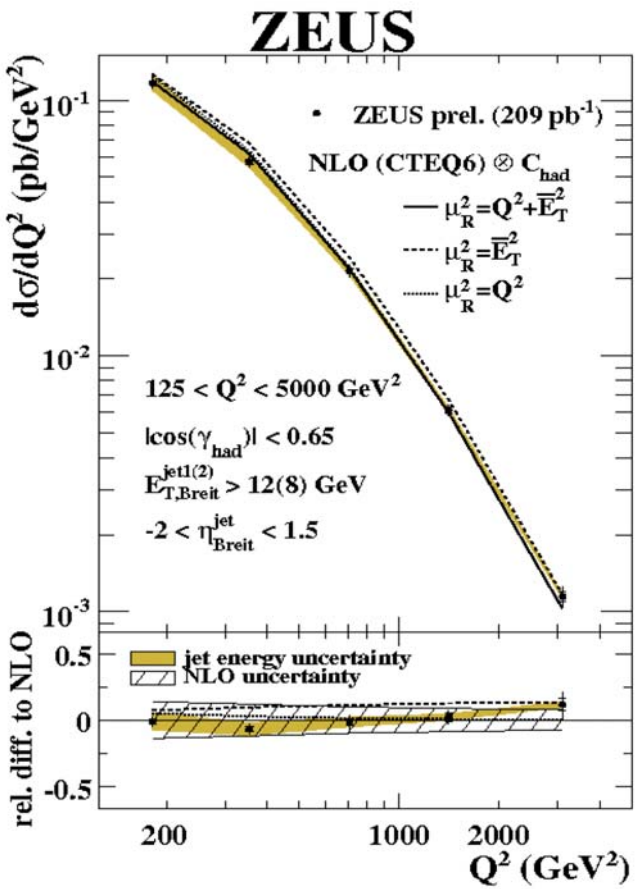
models reproduce the gross features, differences in details, CDM OK

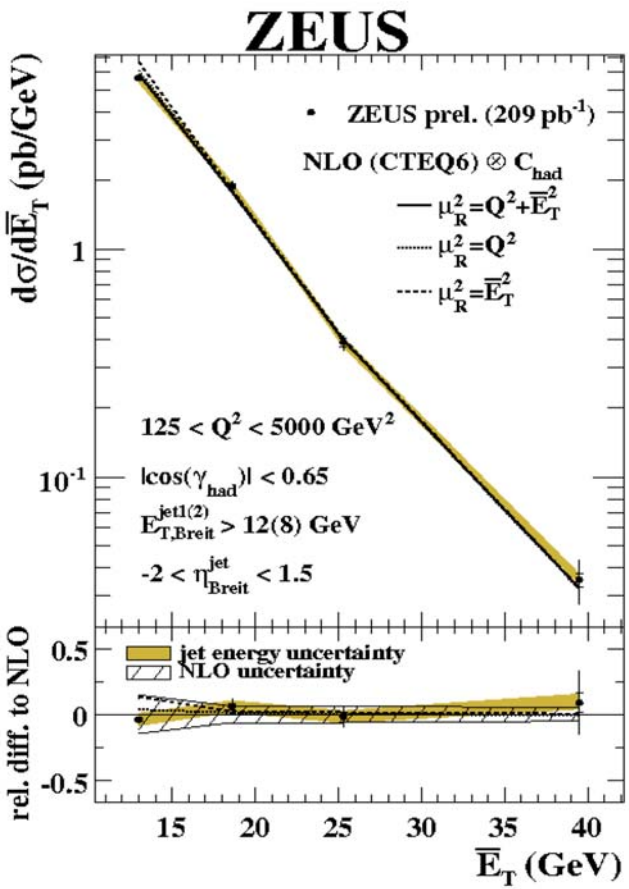
strangeness suppression factor as in e^+e^-

Jets at HERA

Dijets (and Multijets)



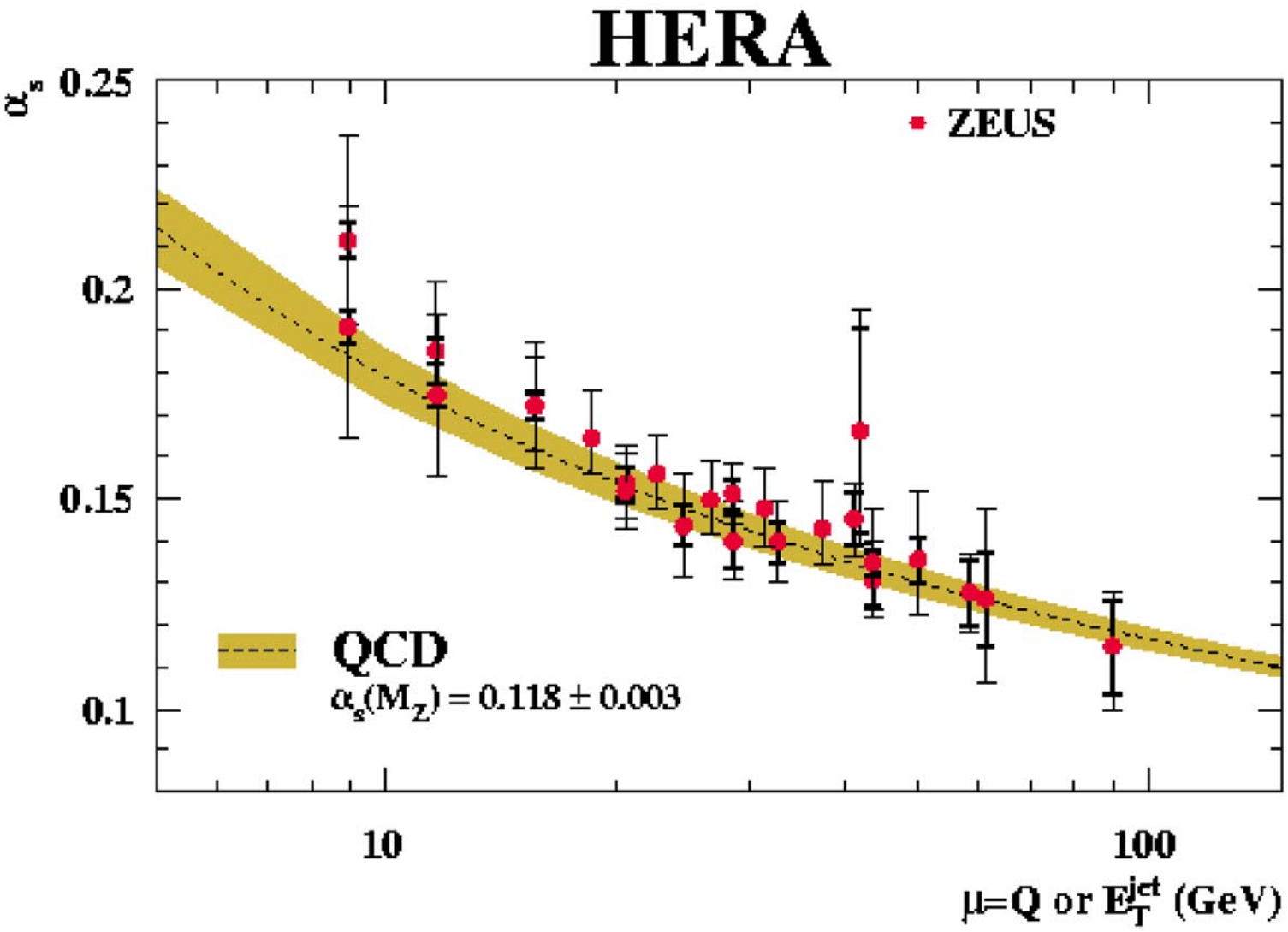




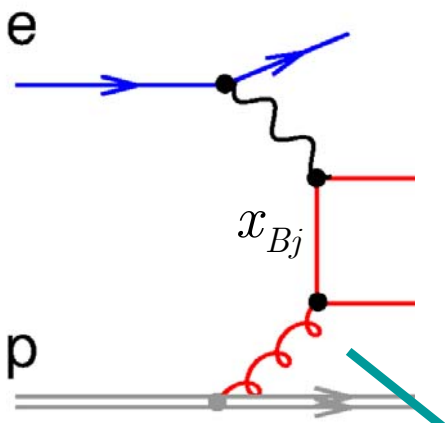
2 „hard scales": Q^2 and E_T(Jet)

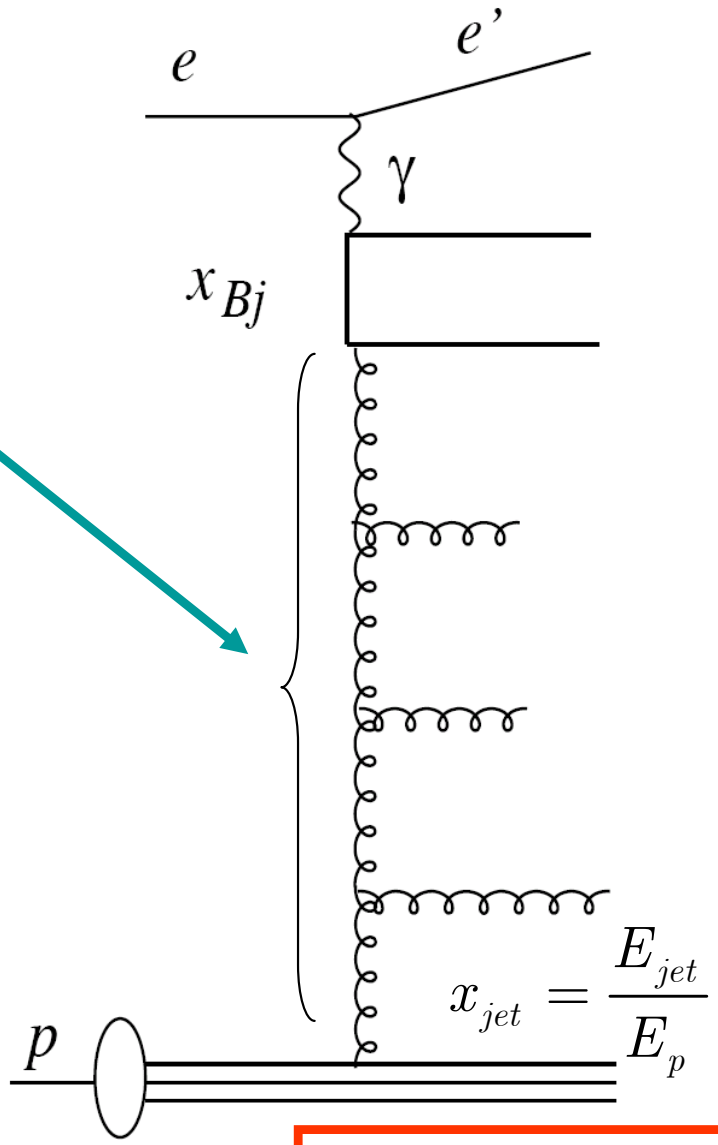
NLO prediction:
Corrections from parton to hadron level

Strong Coupling, from Jet Variables



Forward Jets





DGLAP evolution very successful

e.g. rise of F_2 at low x and Q^2 well described

But:

DGLAP evolution resums only leading log Q^2 terms

low x: leading log 1/x important

BFKL may describe data better

Low x = large phase space for QCD cascade

forward jets interesting to study QCD dynamics

Low x:

QCD cascade induced

DGLAP: jets ordered in kt, BFKL: no ordering in kt

Forward Jets (cont.)

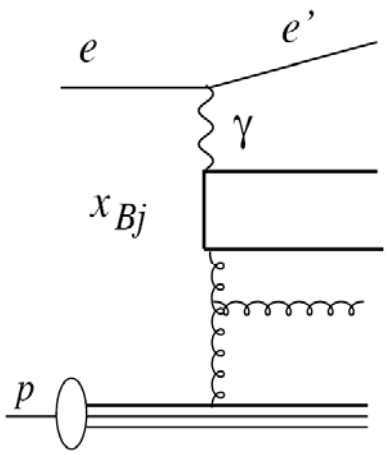
Selection of DIS events:

$$5 < Q^2 < 85 \text{ GeV}^2$$
$$0.0001 < x < 0.004$$

Selection of fwd jets:

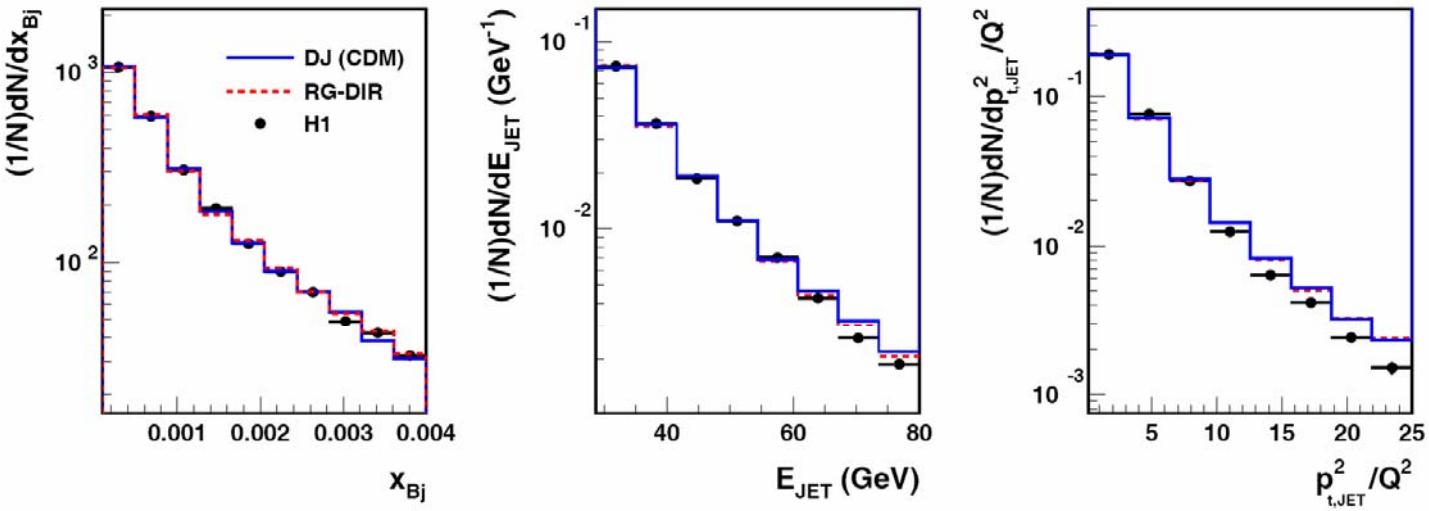
$$p_{t,jet} > 3.5 \text{ GeV}$$
$$7^\circ < \theta_{jet} < 20^\circ$$
$$x_{jet} > 0.035$$

Subsample: „2+fwd jet"



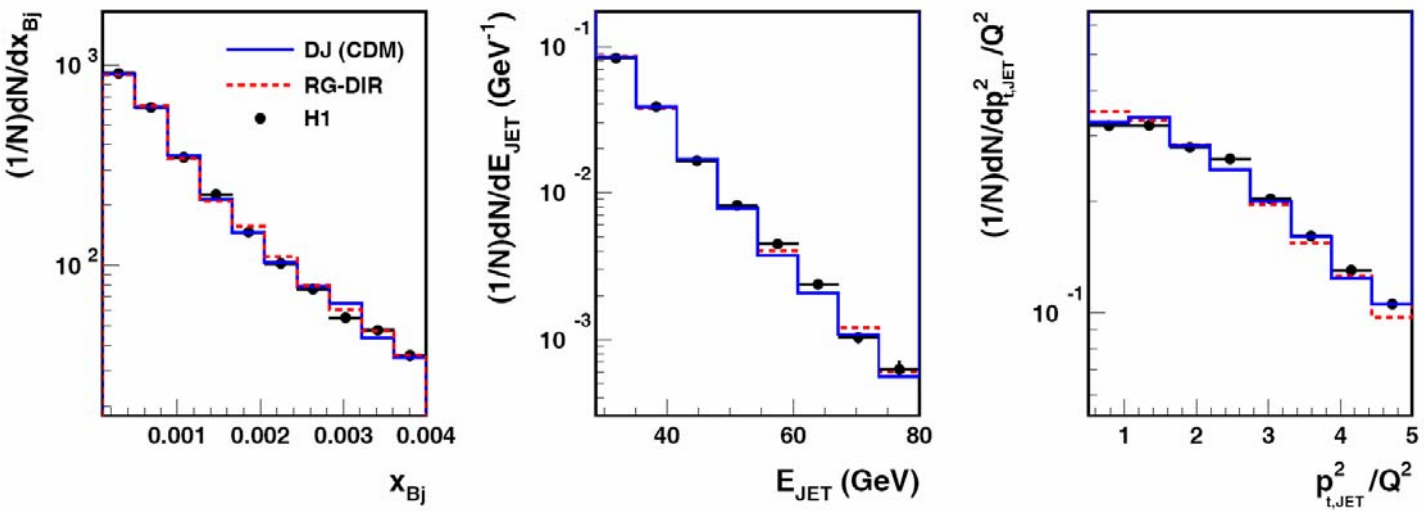
Forward jets

Control plots



Forward jets with $0.5 < p^2_{t,jet}/Q^2 < 5$

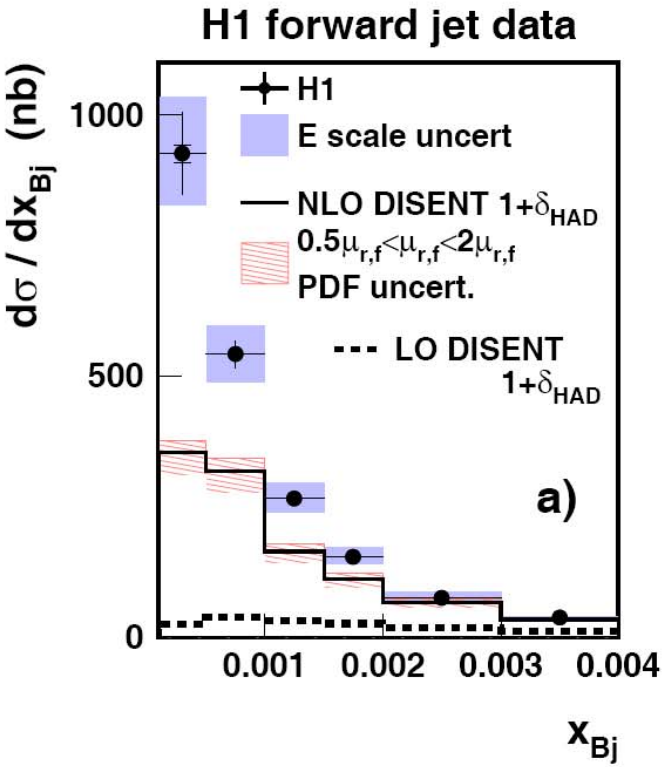
(for single diff. x sect.)

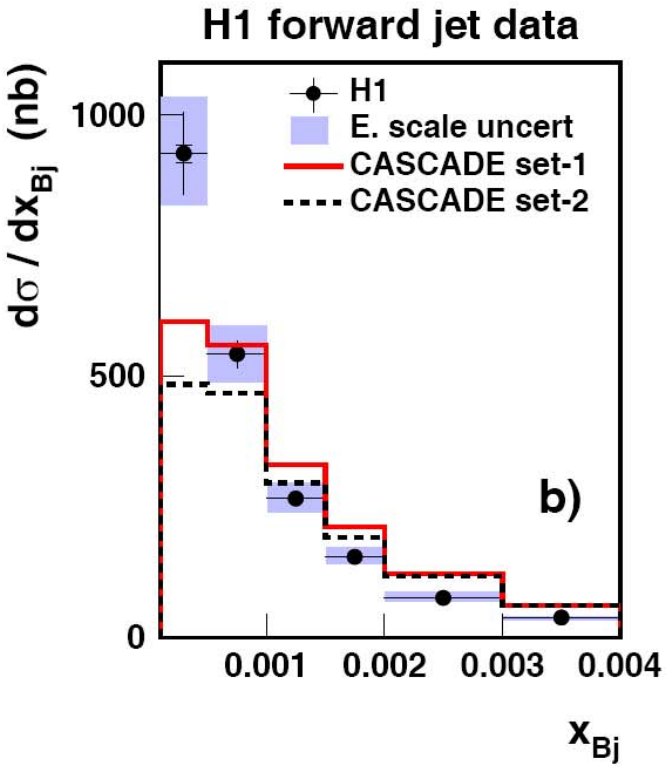


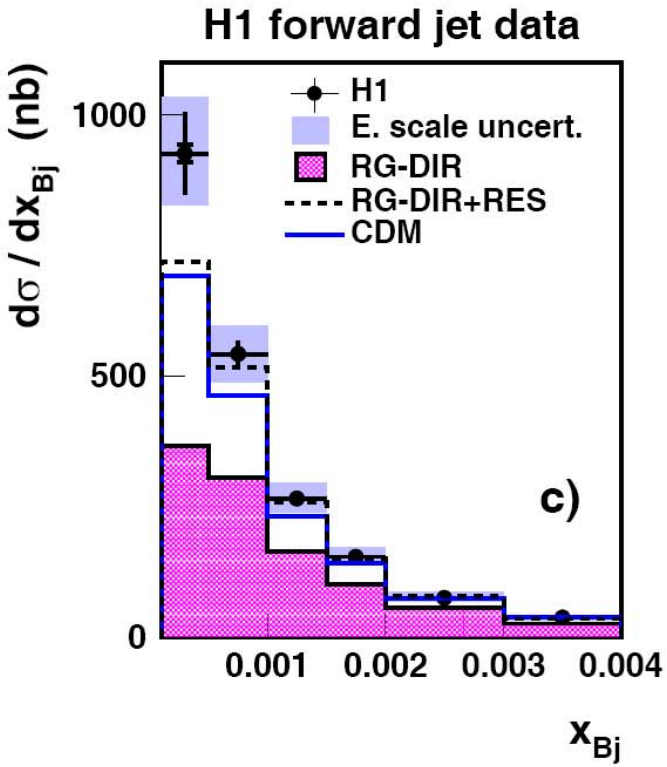
RG-DIR: LO with parton showers (DGLAP); DJ (CDM): Django + Ariadne

Forward Jets (cont.)

Single differential cross sections:





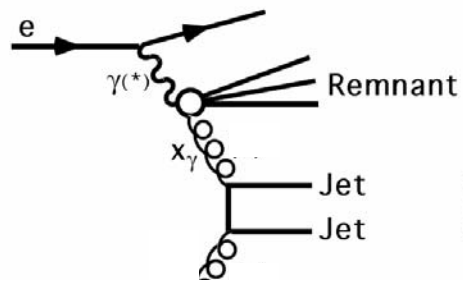


QCD calculations:

NLO (full), LO (dashed) from DISENT

Cascade: CCFM-model with 2 different sets of unintegrated pdfs

RG-DIR+RES:



→ DGLAP undershoots the data at low x !

Forward Jets (cont.)

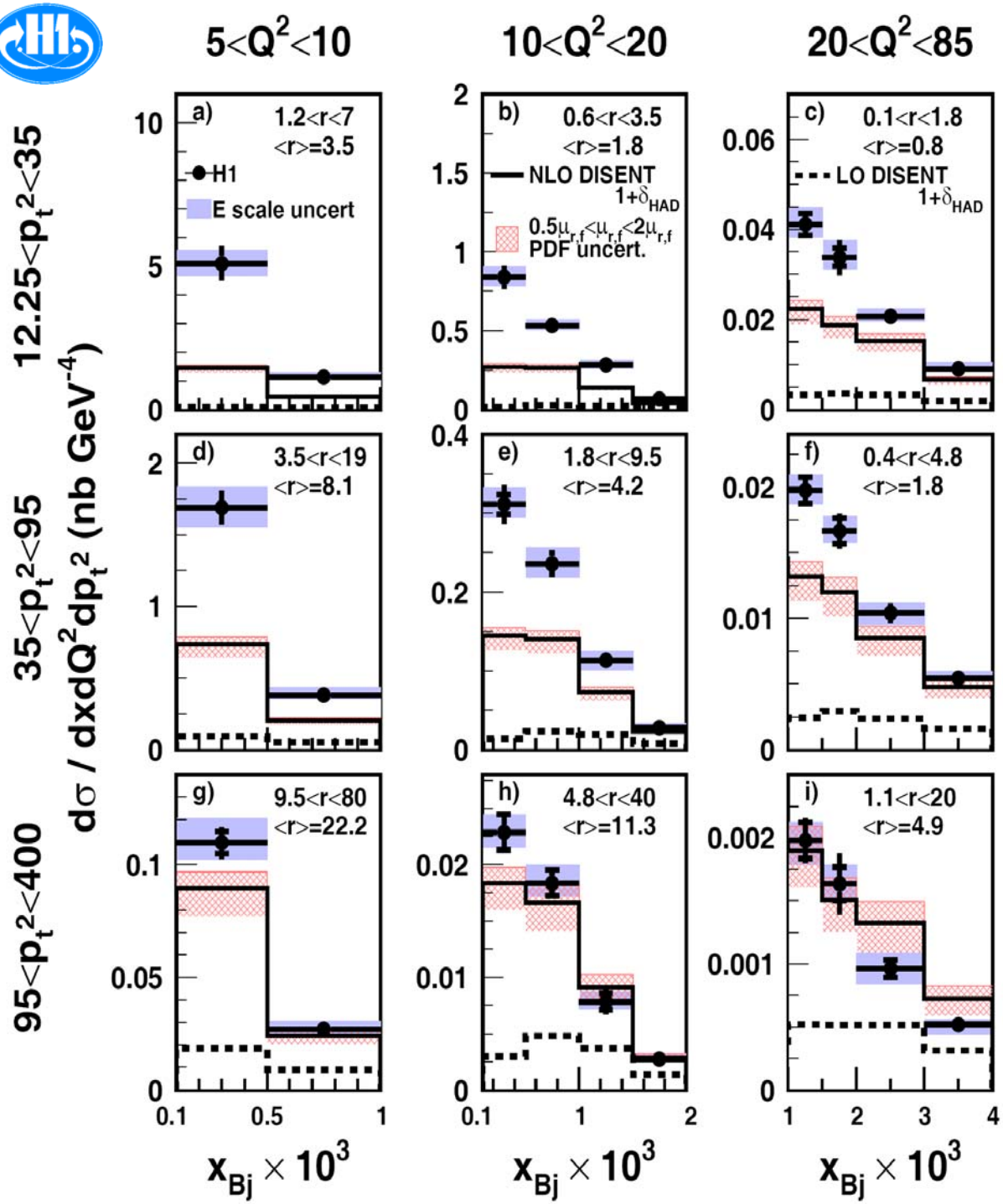
triple differential cross sections:

NLO-DGLAP (even with resolved photon) fails to describe the data

going up in pt:

NLO gets better

high pt jet limits phase space for additions emissions (parton ladder is shorter)
looks more like „NLO“



Forward Jets (cont.)

CDM and DGLAP (resolved) give similar predictions

3 regions:

- $p^2_{t,jet} < Q^2$ c)

  direct photon should dominate (but admixtures from larger pt)

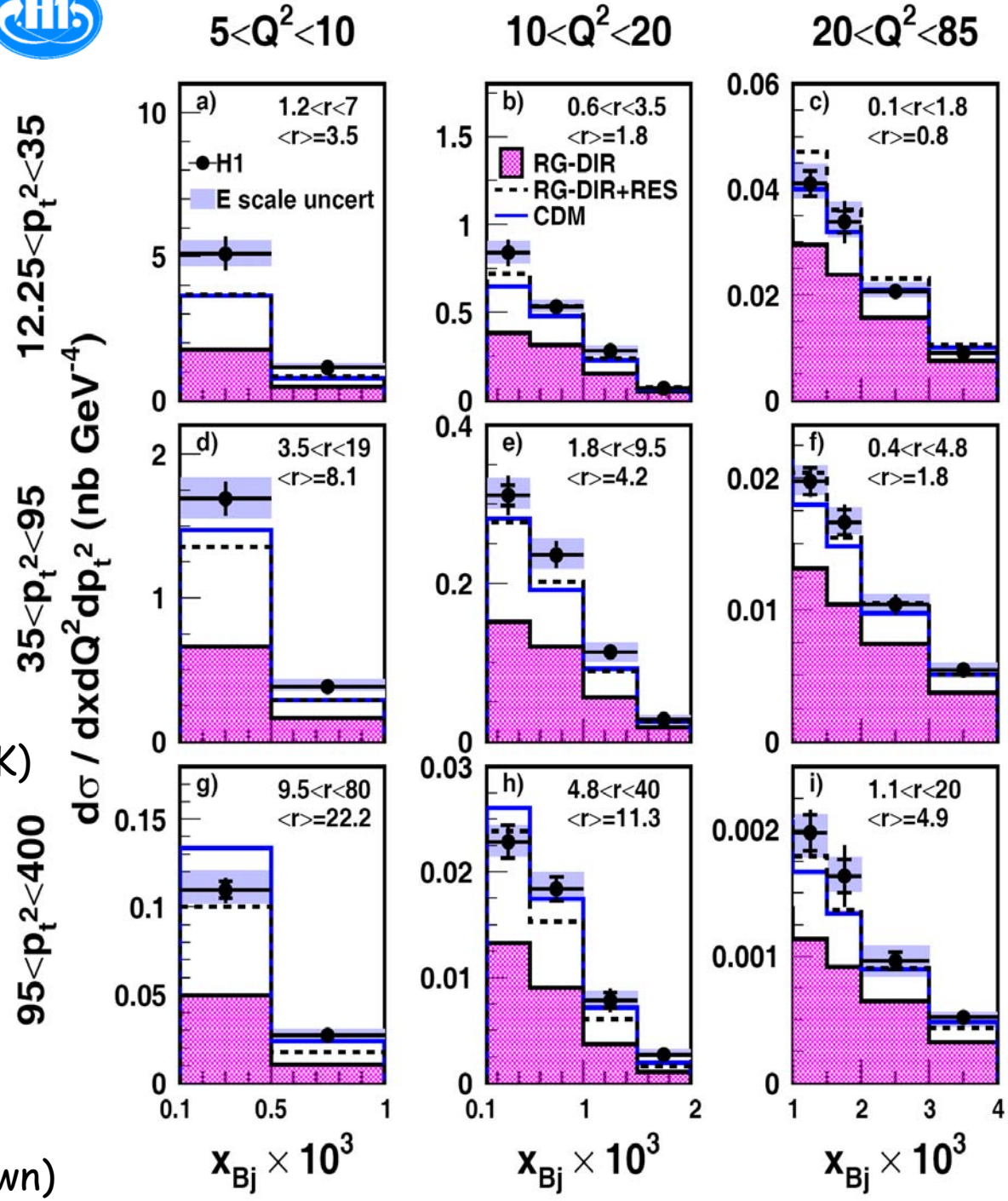
- $p^2_{t,jet} \sim Q^2$ b) and f)

  Parton dynamic beyond DGLAP should show up here (resolved: OK)

- $p^2_{t,jet} > Q^2$ d), g) and h)

  resolved photon should dominate (CDM overshoots the data at large pt and small x)

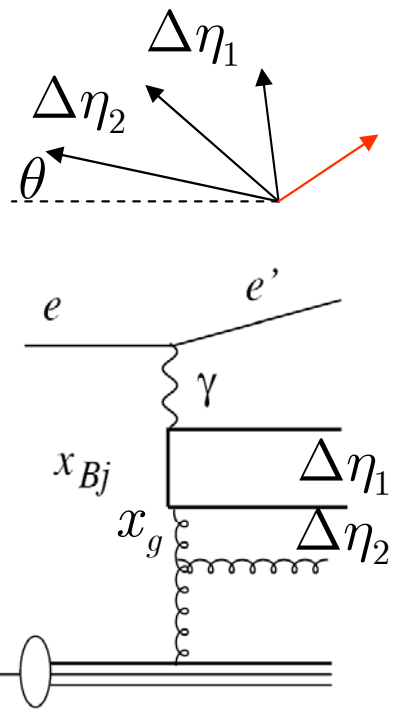
(CCFM: x spectrum too hard, bad description everywhere, not shown)

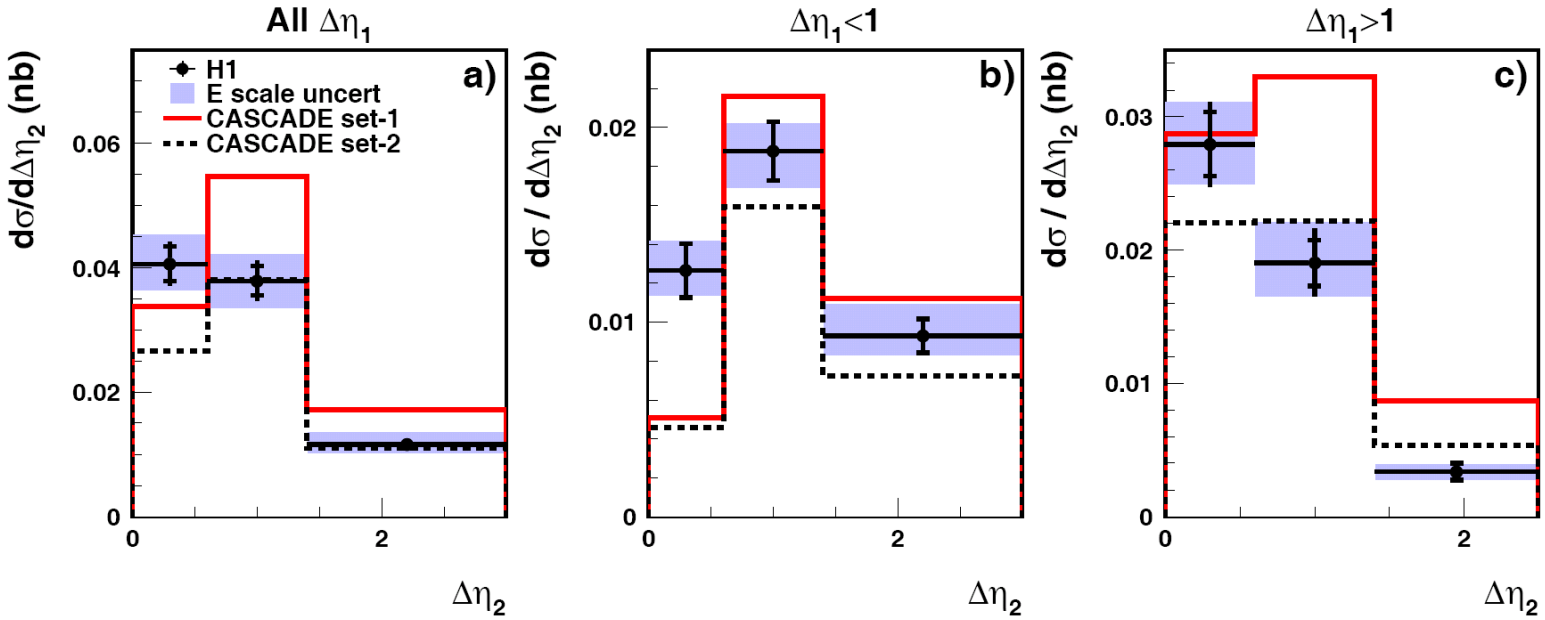


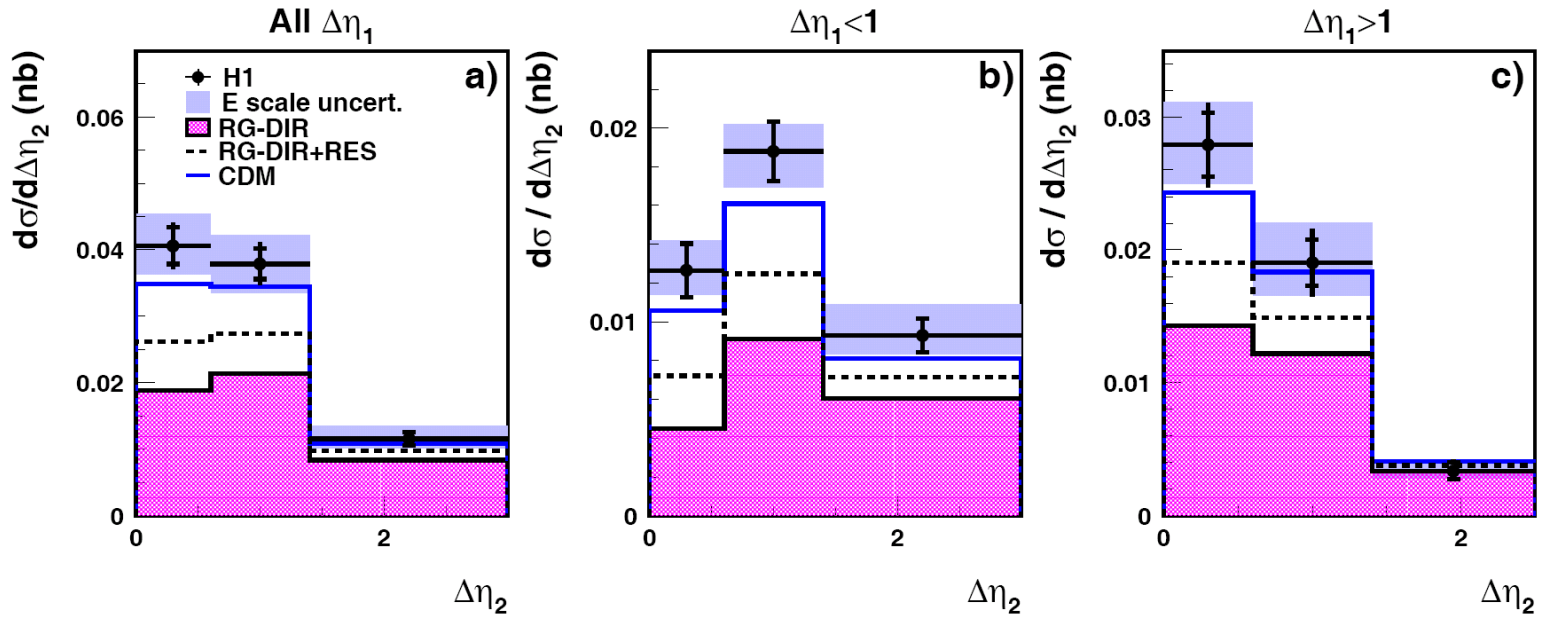
Events with additional dijets $p_{t,jet} > 6$ GeV

Can one discriminate CDM and DGLAP (+res)?

$$\eta = -\ln\tan(\theta/2)$$



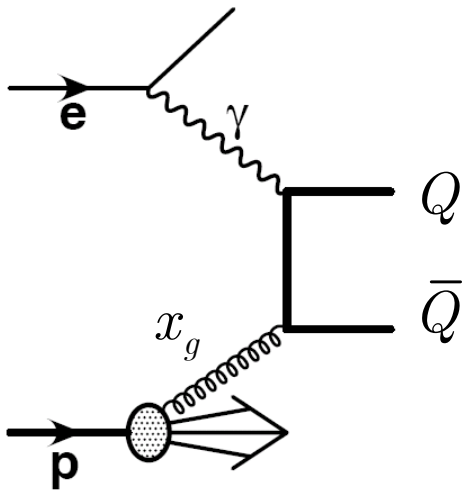




CDM (no kt ordering) describes the data.

DGLAP (+res) fails

Open Charm/Beauty Production

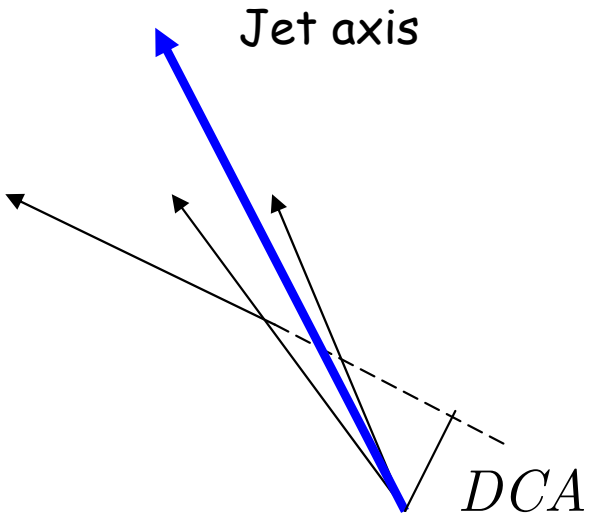


Motivation:
direct measure of the gluon content within the proton

Heavy Quarks (c and b):

- Explicit reconstruction of charm meson (e.g. D*) $\boxed{\text{c-Quark}}$
- Finite Lifetime → secondary (decay) vertex $\boxed{\text{c/b-Quark}}$

→ use of central Si-vertex detectors

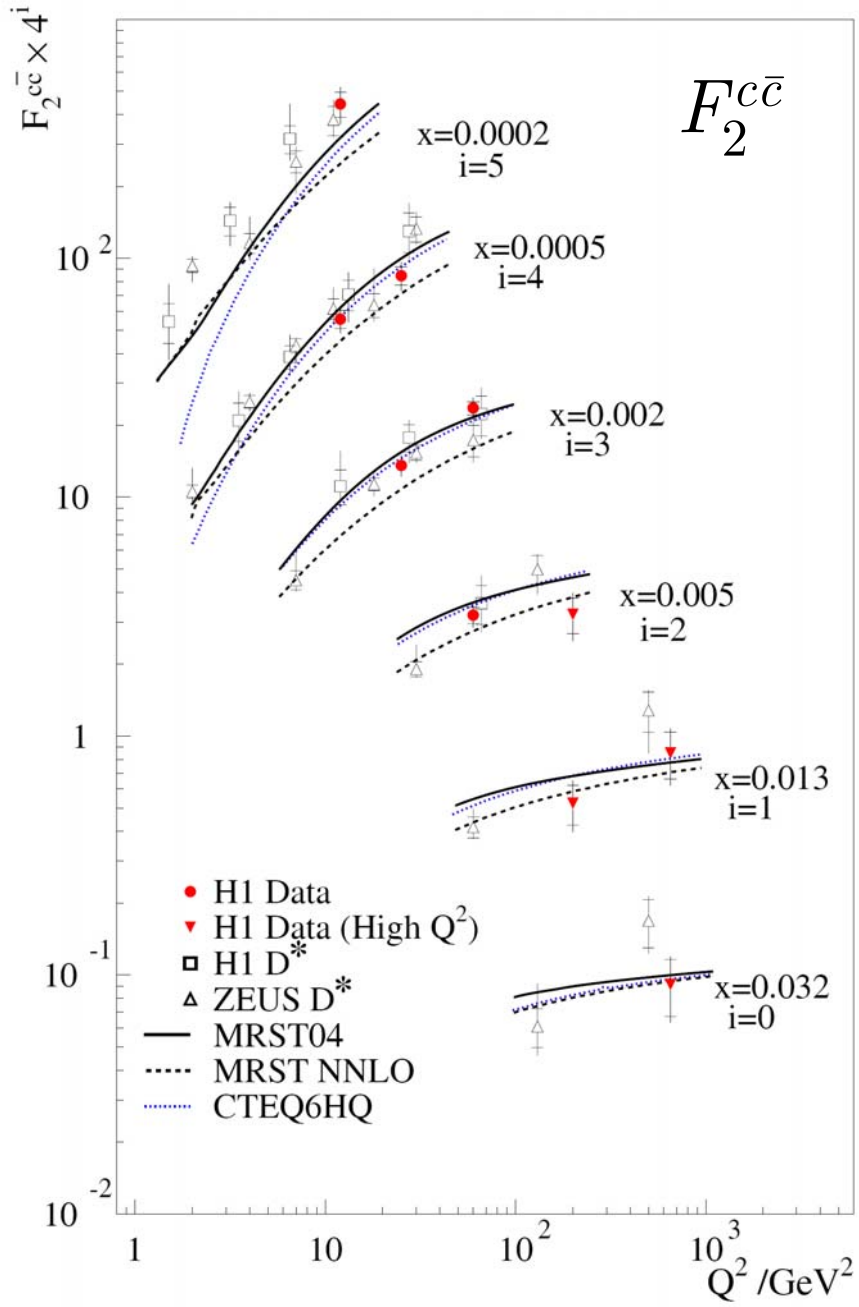


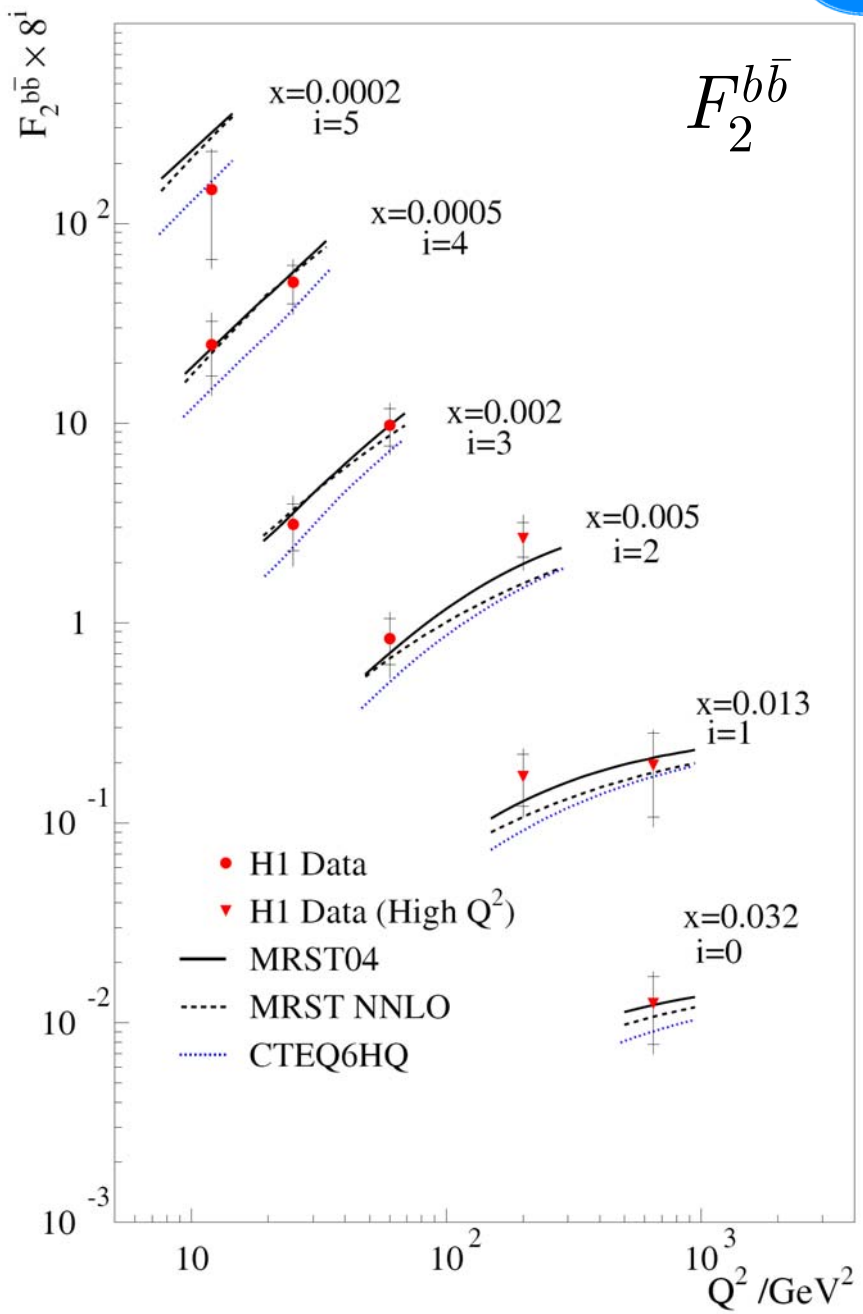
impact parameter method

(better statistics, higher background)

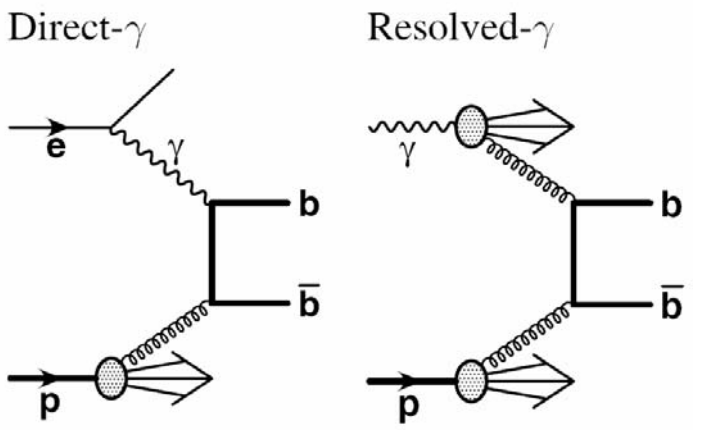
explicit reconstruction of secondary vertex

Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$





Open Beauty with Jets

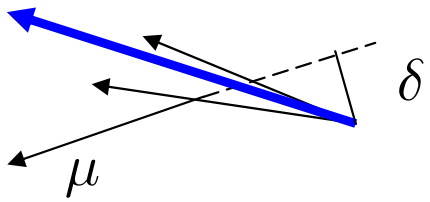


DIS Photoproduction

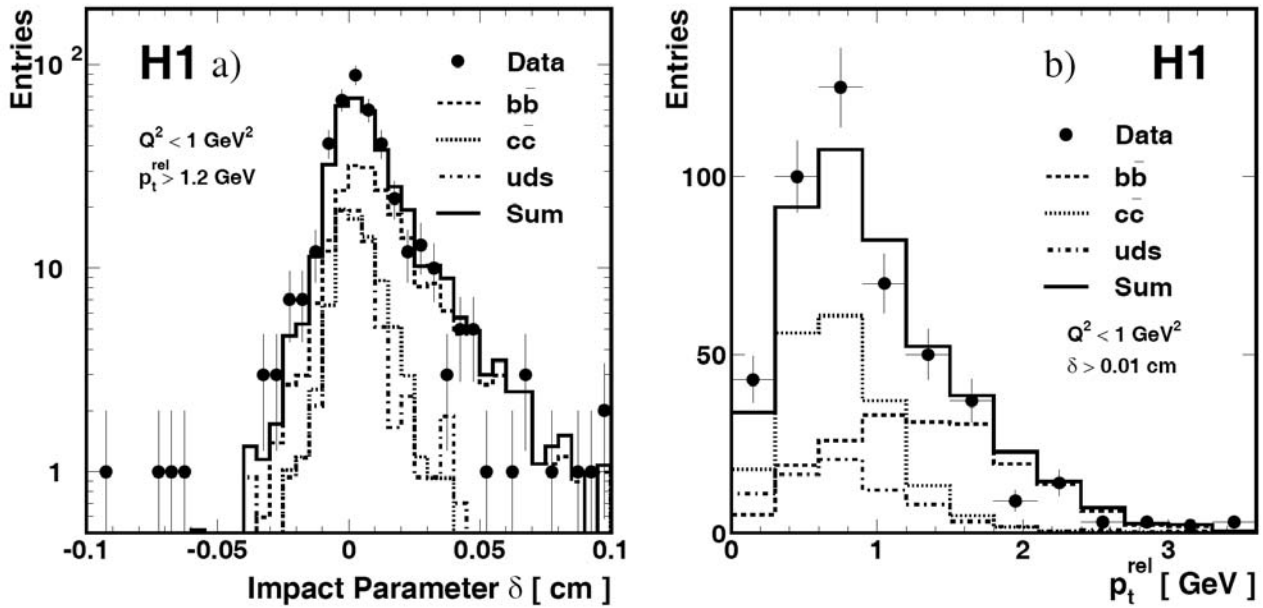
hard scales: m_b, Q^2, p_b^t

Signature for b-quark:

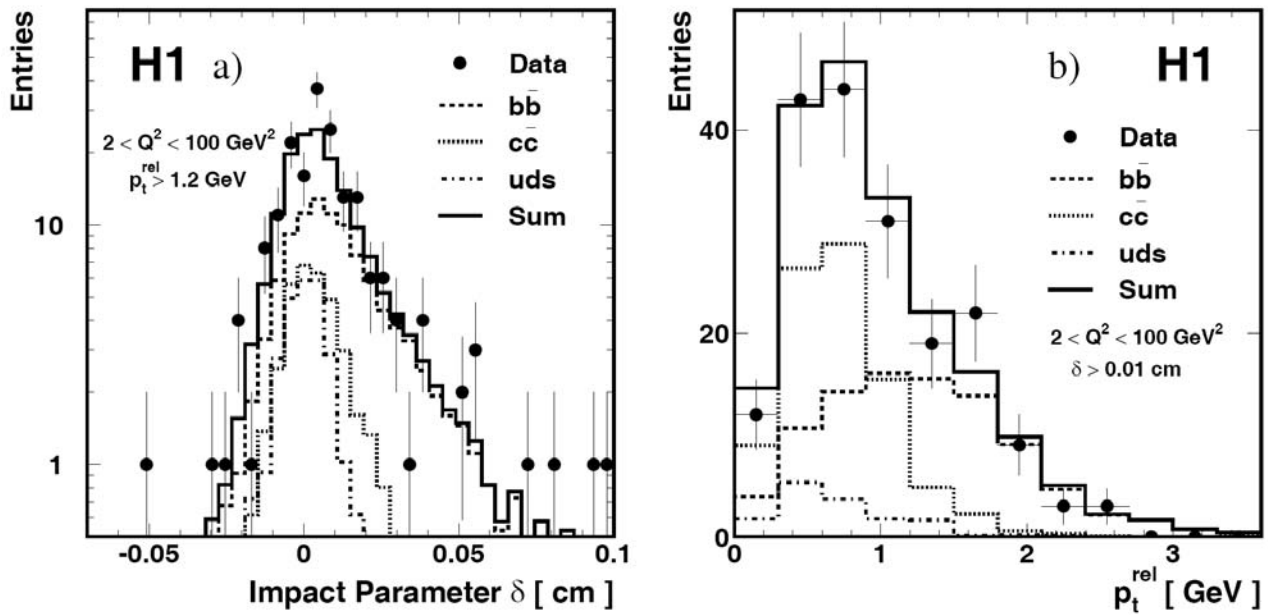
Identified muon at high pt (semileptonic decay)



Photoproduction

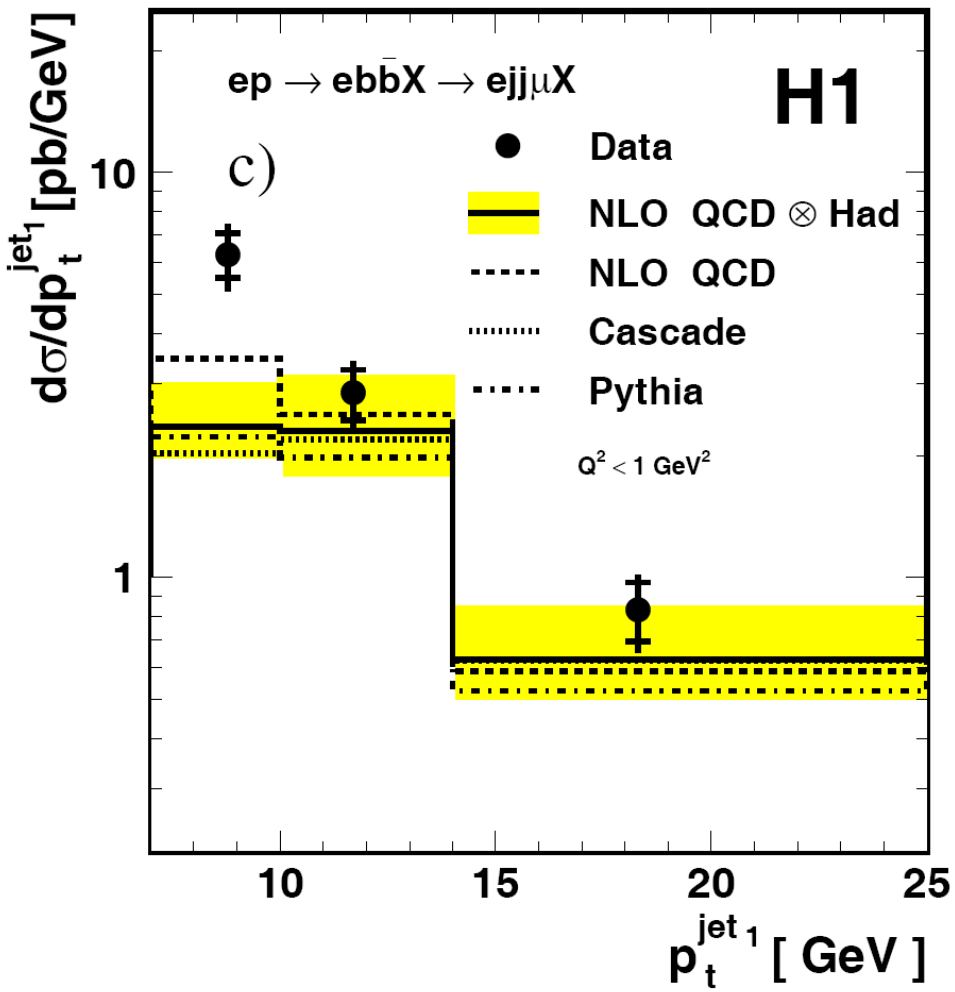


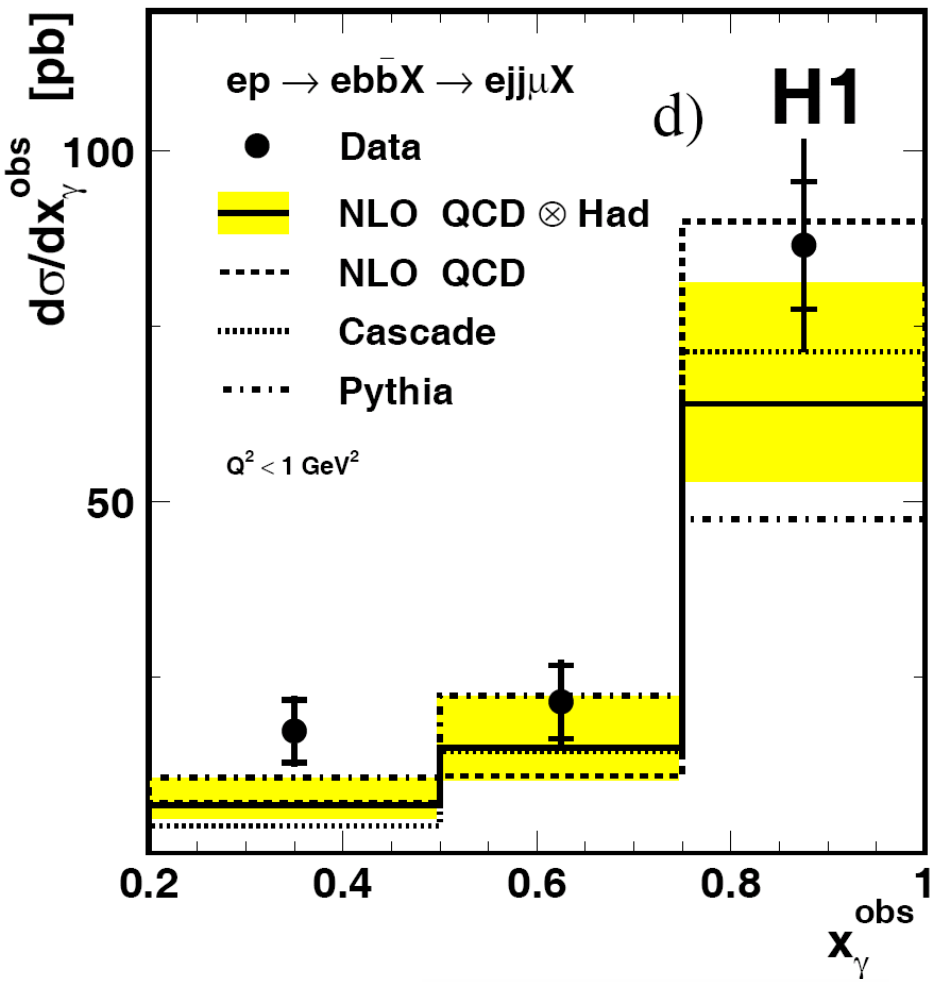
Electroproduction



Open Beauty with Jets (cont.)

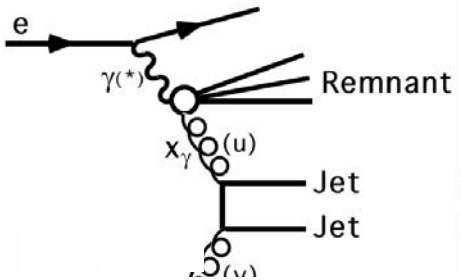
Photoproduction





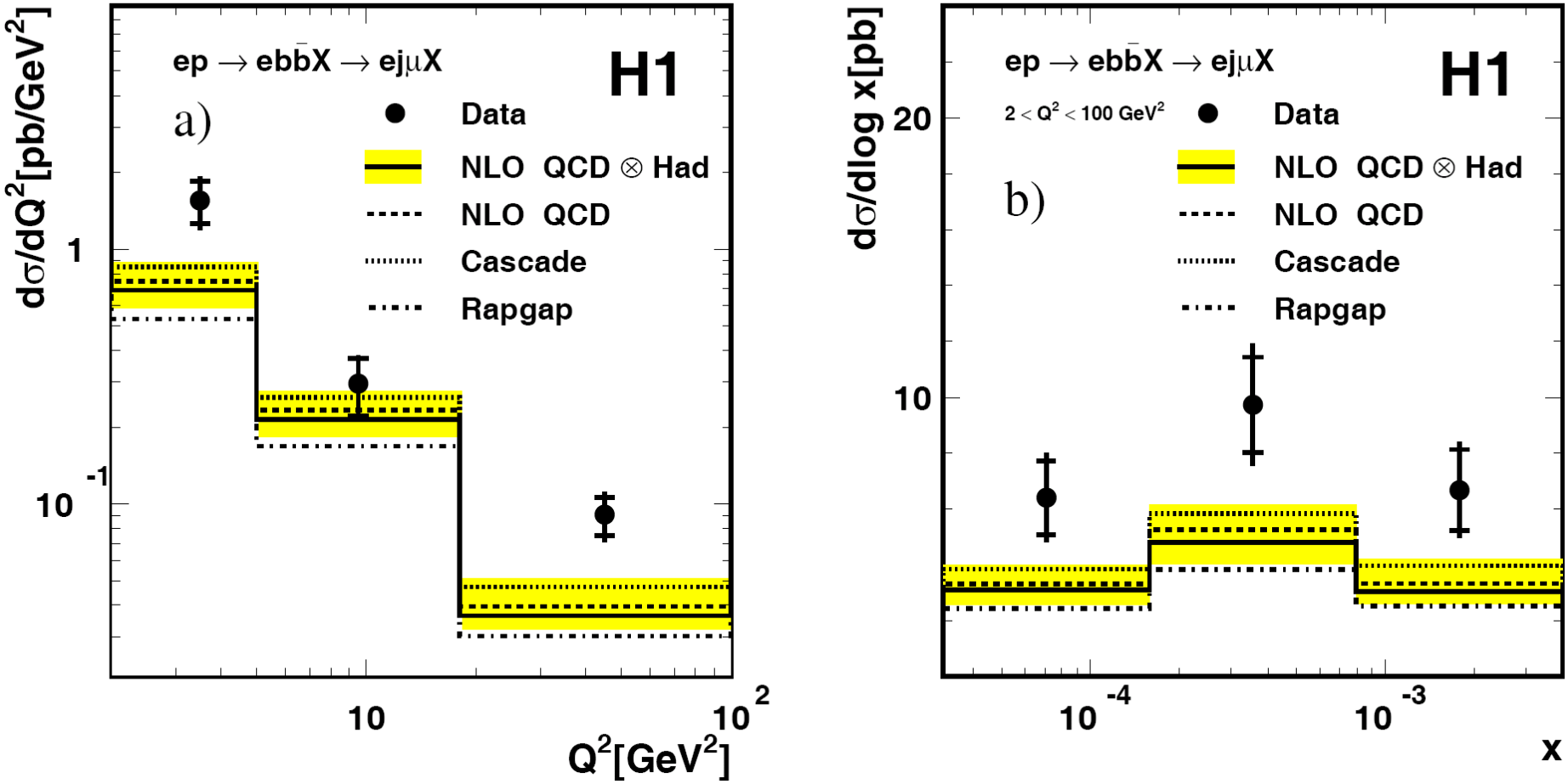
QCD predictions not steep enough towards low pt

yellow band: renormalisation/ factorisation scale uncertainties



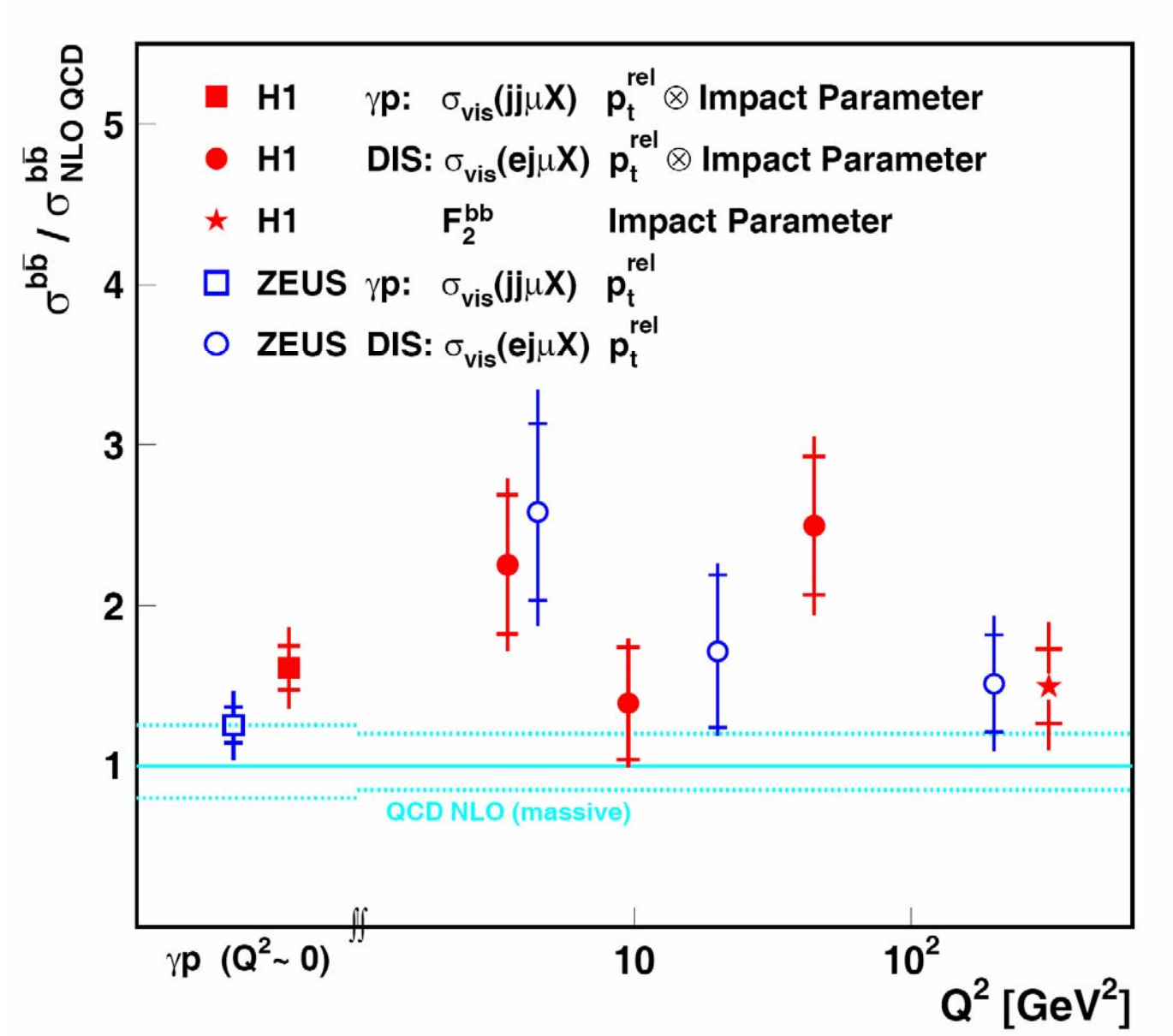
Open Beauty with Jets (cont.)

Electroproduction



Shapes reasonably well described by QCD, but undershoot the data

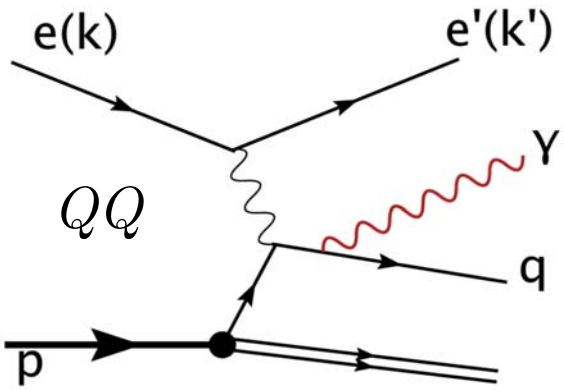
Open Beauty with Jets (cont.)

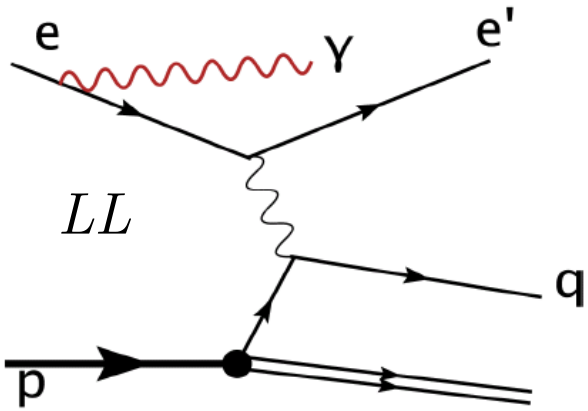


Good agreement between ZEUS and H1

Theory (massive scheme) does not predict the size of the cross section

Prompt Photons with Jets



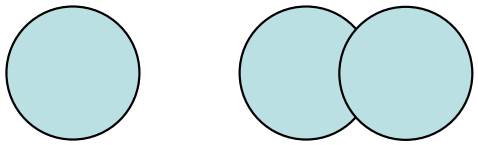


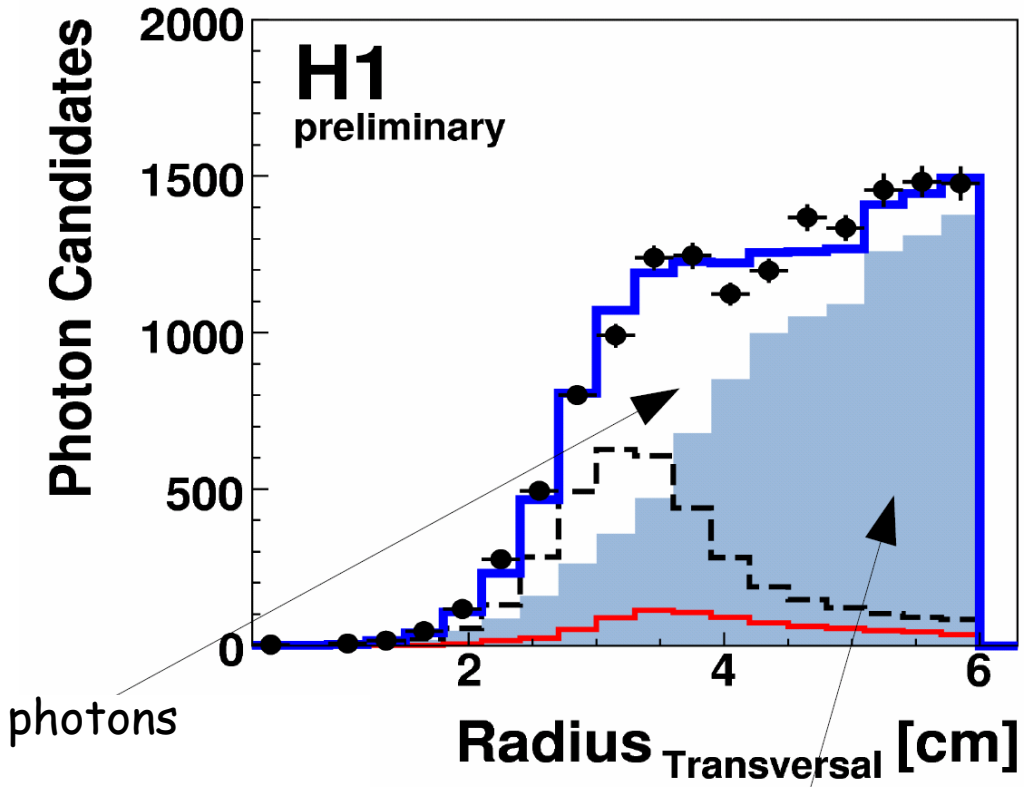
radiative corrections

+ No hadronisation corrections needed
no jet identification etc.

− Background (from π^0)

transverse
shower profile

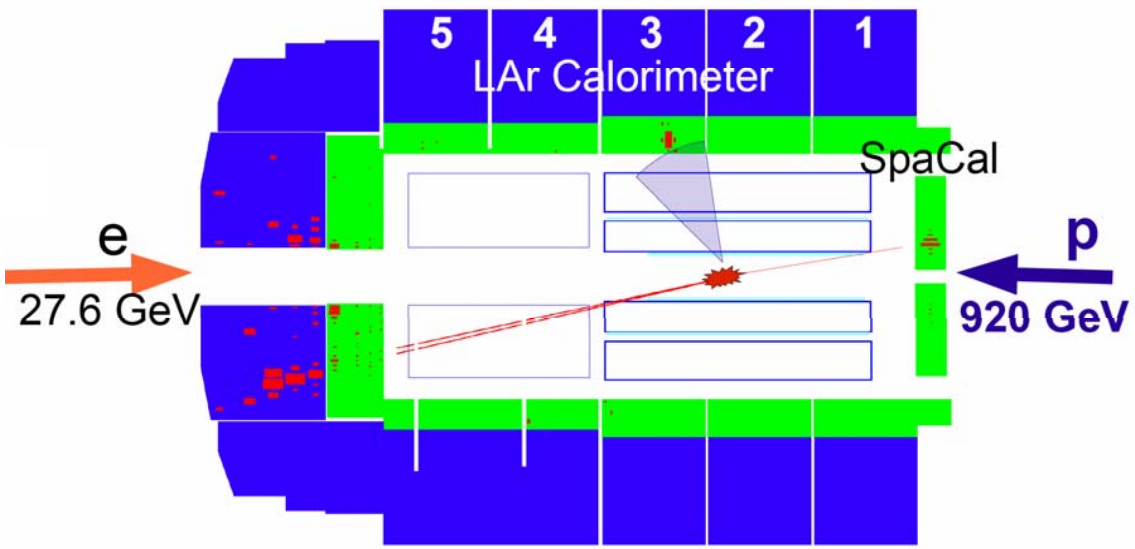




photons

neutral hadrons

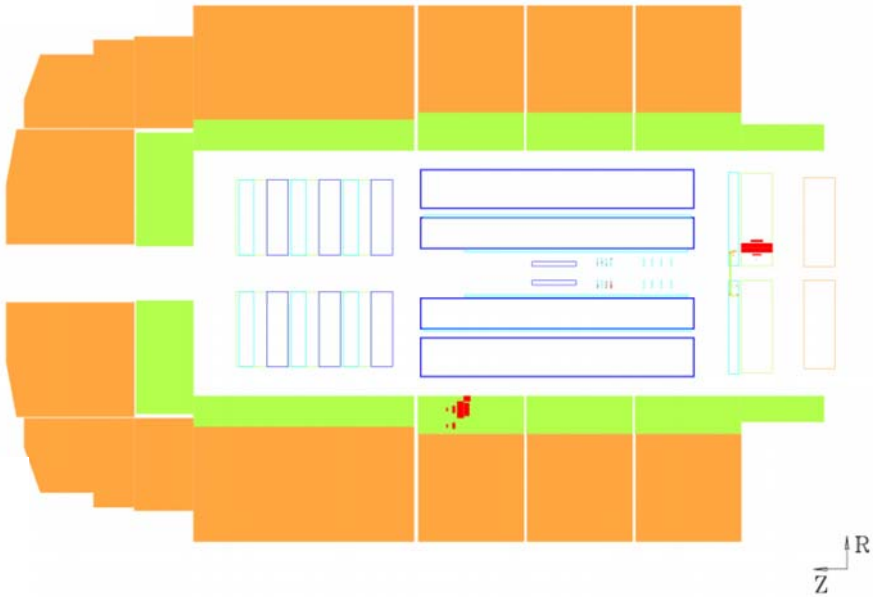
Prompt Photons with Jets (cont.)



prompt photon + jet
in the H1 detector

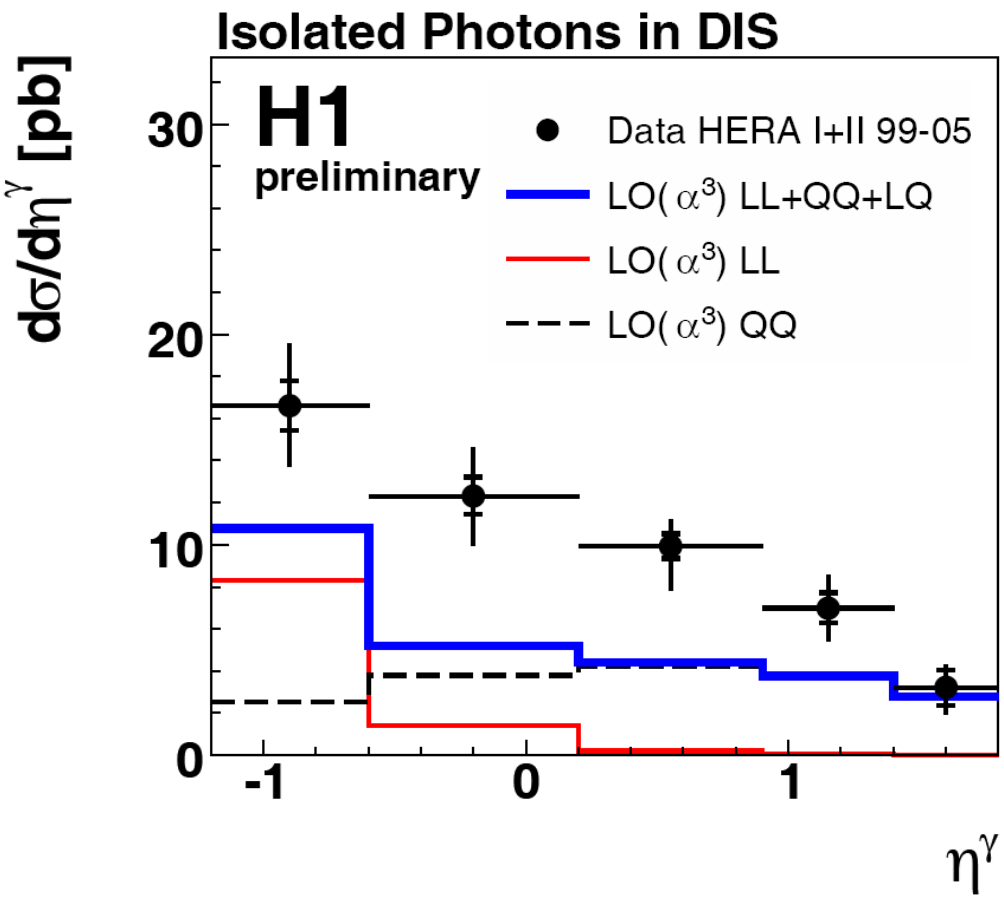
- selection of photon candidates via shower shapes
- control of efficiencies via Bethe-Heitler / DVCS processes

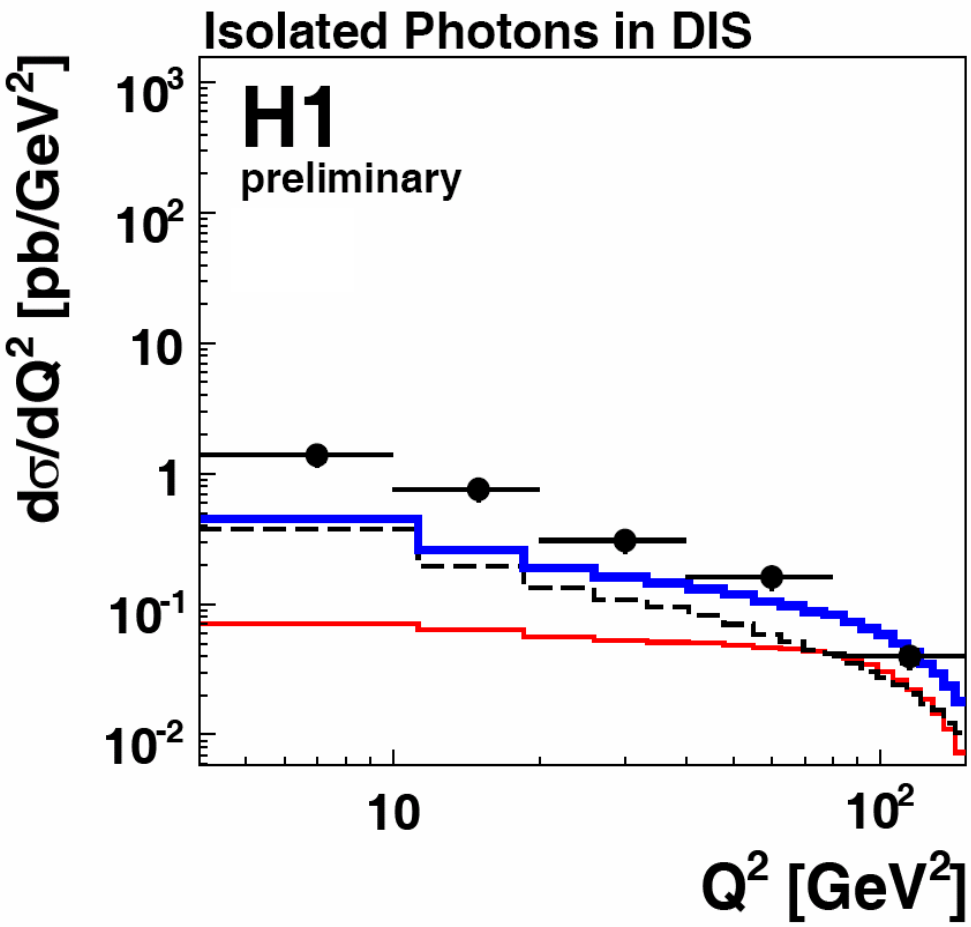
$$ep \rightarrow ep\gamma$$



Prompt Photons with Jets (cont.)

Cross Sections:

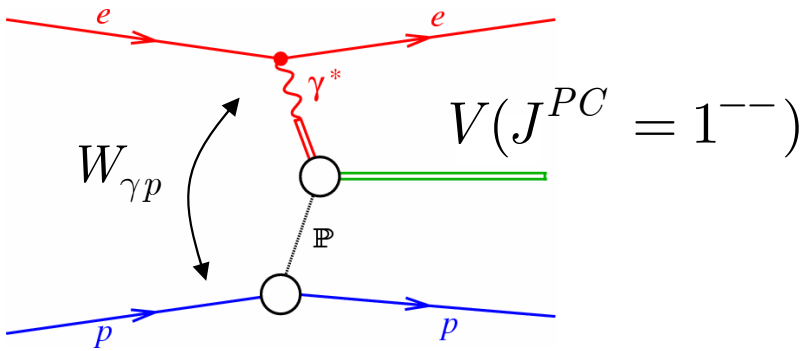




LO calculation (Gehrmann et al.) undershoots the data

Exclusive Final States: Vector Mesons

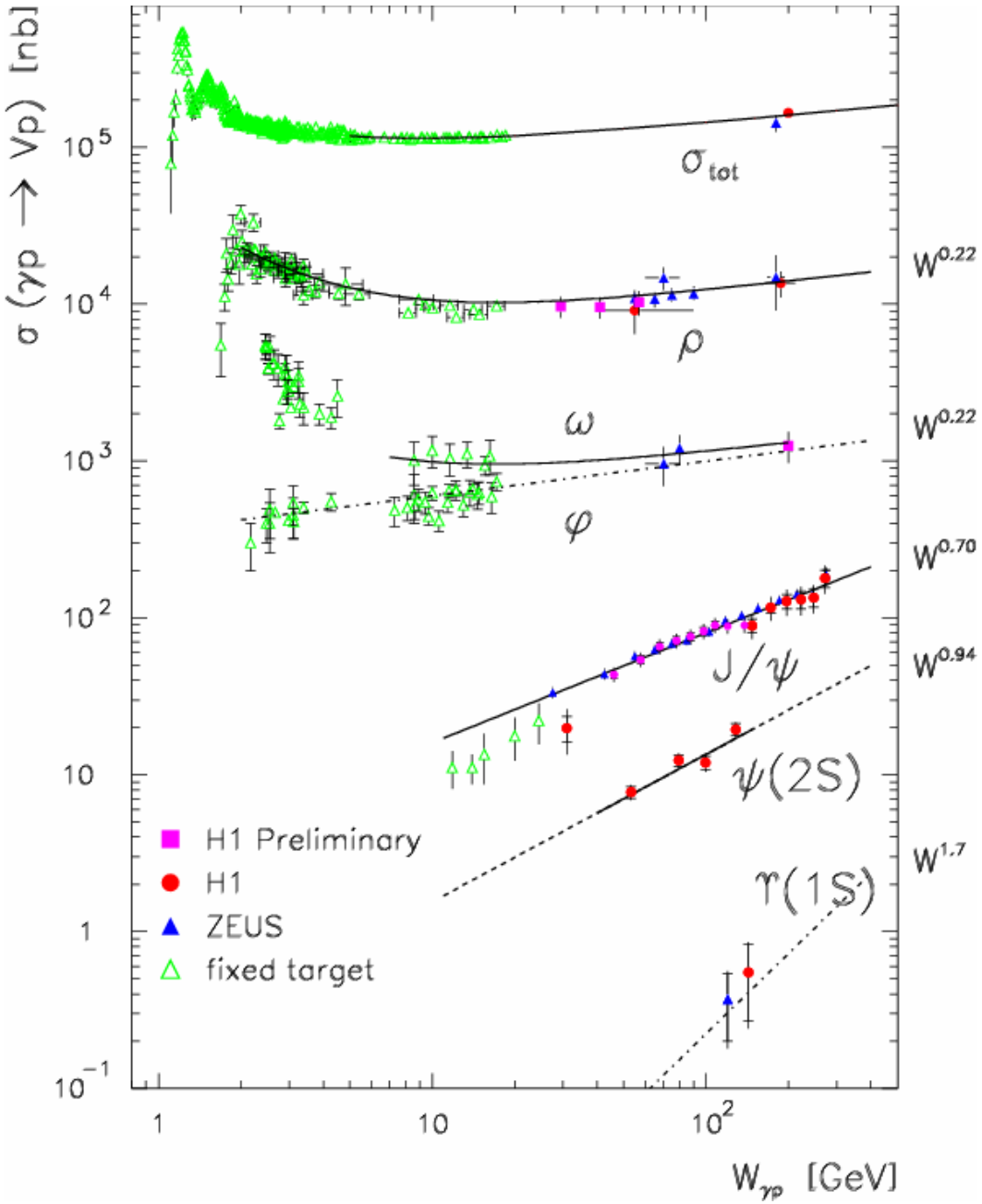
Regge picture



Total cross sections for photoproduction of vector mesons:

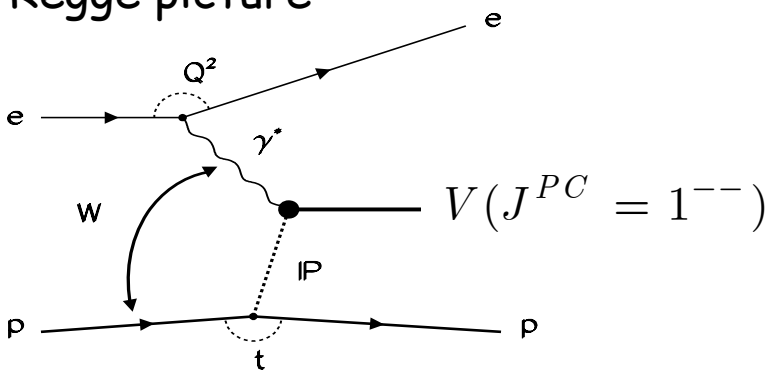
- ρ, ω, ϕ show Regge behaviour
  $\sigma(\gamma p \to Vp) \propto W^{0.22}$
- J/ψ not described by Regge, strong rise of cross section
  $\sigma(\gamma p \to J/\psi\, p) \propto W^{0.8}$

Break-down of Pomeron Universality

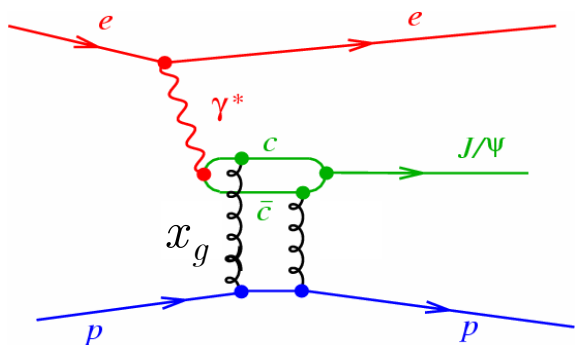


Theoretical Concepts of Exclusive VM Production

Regge picture



QCD picture



need hard scale:

Q^2

M_V^2

t

→ slow rise of total cross section with W

$$\sigma(W) \propto \frac{W^{4(\alpha_{\mathbf{P}}(0)-1)}}{b(W)} \sim W_{\gamma p}^{0.20}$$

steep rise of total cross section with W, in leading order:

$$\sigma(W) \propto \left(\alpha_S(\tilde{Q}^2) x_g g(x_g, \tilde{Q}^2)\right)^2 \qquad \tilde{Q}^2 \sim Q^2 + M_V^2$$

→ shrinkage of differential xsection

$$\frac{d\sigma}{dt} \propto e^{-b|t|} \ , \ b = b(W_0) + 2\alpha' \ln\left(\frac{W^2}{W_0^2}\right)$$

universal slope of t distribution, independent of flavor and energy W

some models: $\frac{d\sigma}{dt} \sim |t|^{-n}$

→ s-channel helicity conservation (SCHC)

violation of s-channel helicity conservation

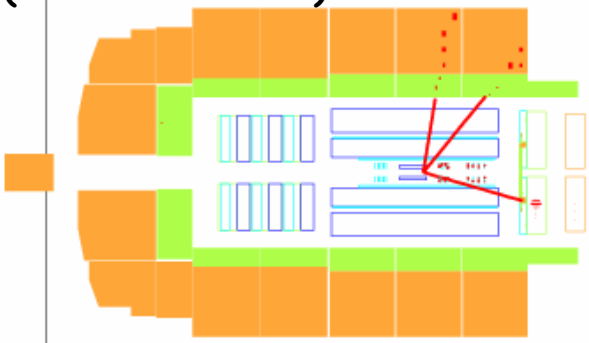
- access to Generalized Parton Distributions

Analysis Strategy

data from 1999/2000 (HERA I): 55 pb^{-1} central, 30 pb^{-1} backward

electroproduction (TT)

("track-track")

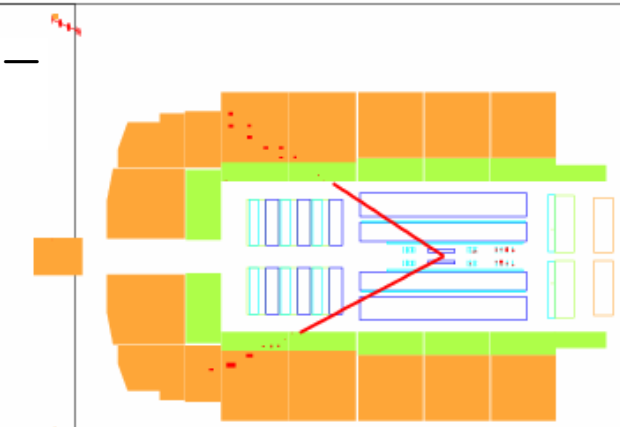


$40 < W_{\gamma p} < 160$ GeV

$J/\psi \rightarrow \mu^+\mu^-$

2 tracks
$\geq$ 1 muon
+ scatt.
electron

photoproduction (TT)



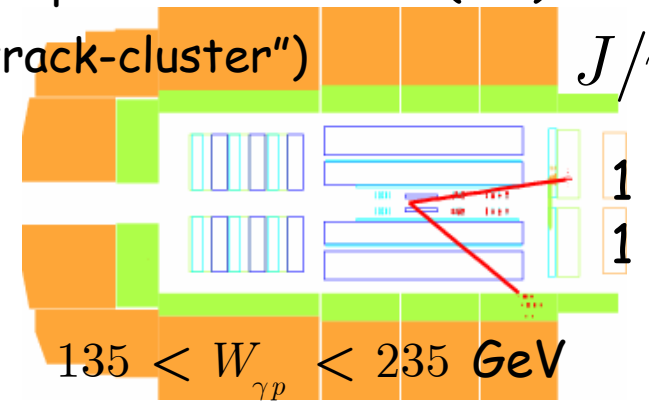
$40 < W_{\gamma p} < 160$ GeV

Muon analysis

2 tracks
$\geq$ 1 muon

photoproduction (TC)

("track-cluster")



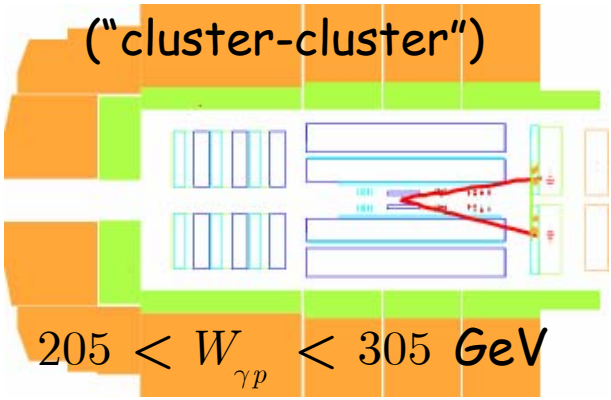
$135 < W_{\gamma p} < 235$ GeV

$J/\psi \rightarrow e^+e^-$

1 cluster
1 track

photoproduction (CC)

("cluster-cluster")

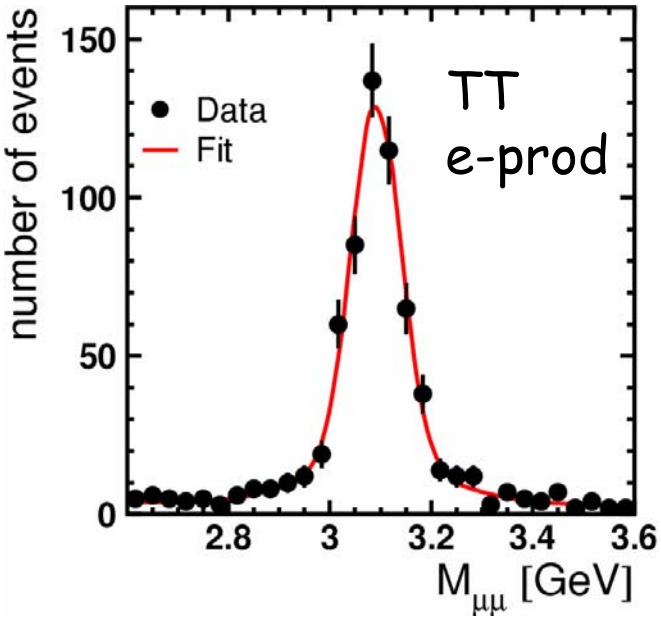


$205 < W_{\gamma p} < 305$ GeV

Electron analysis

2 clusters

Signal Extraction



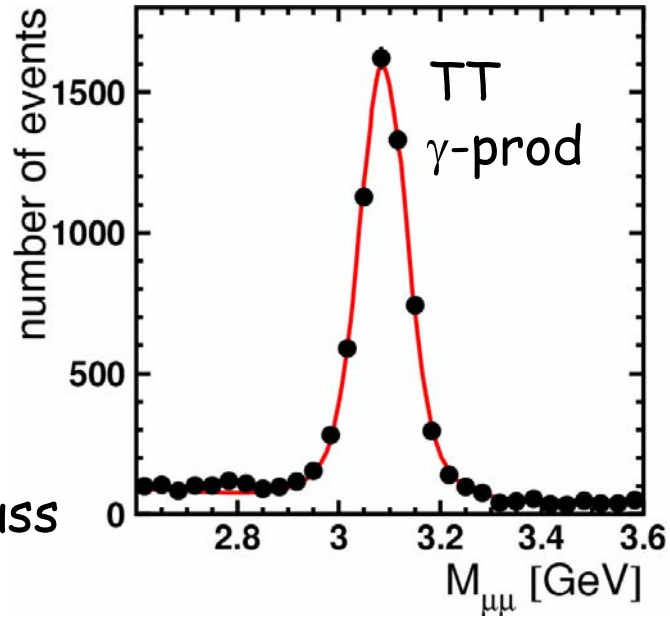
all data

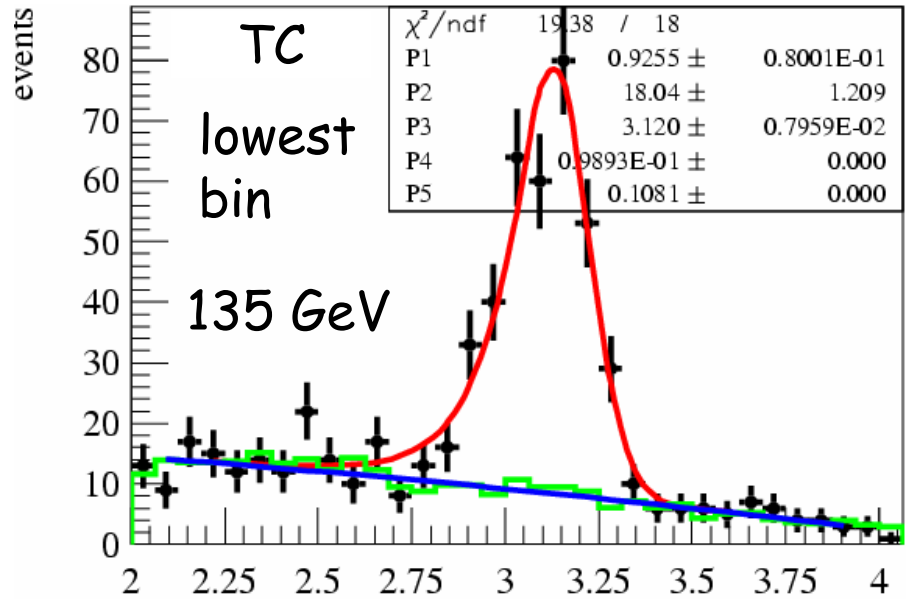
$$\langle W_{\gamma p} \rangle = 90 \text{ GeV}$$

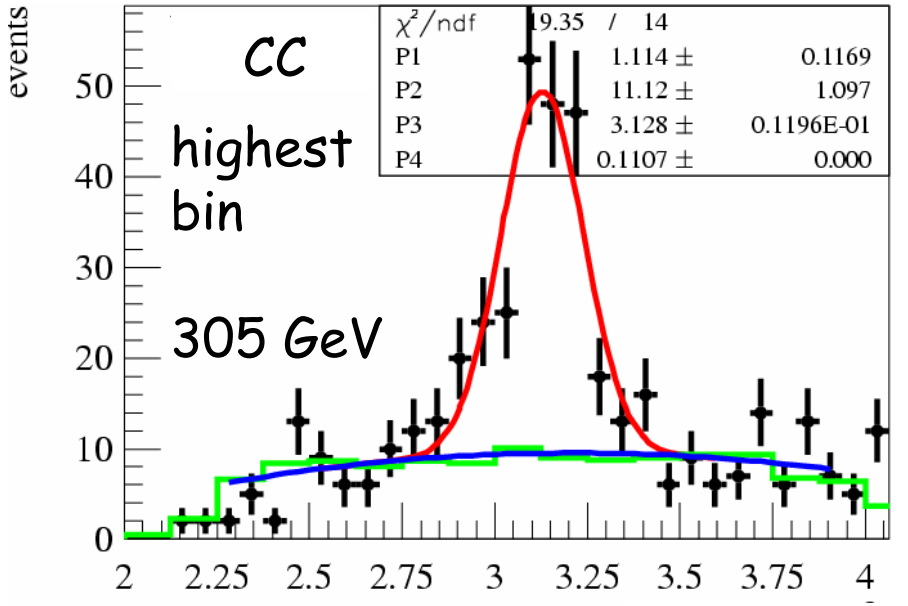
QED bg MC

Polynom fit to bg

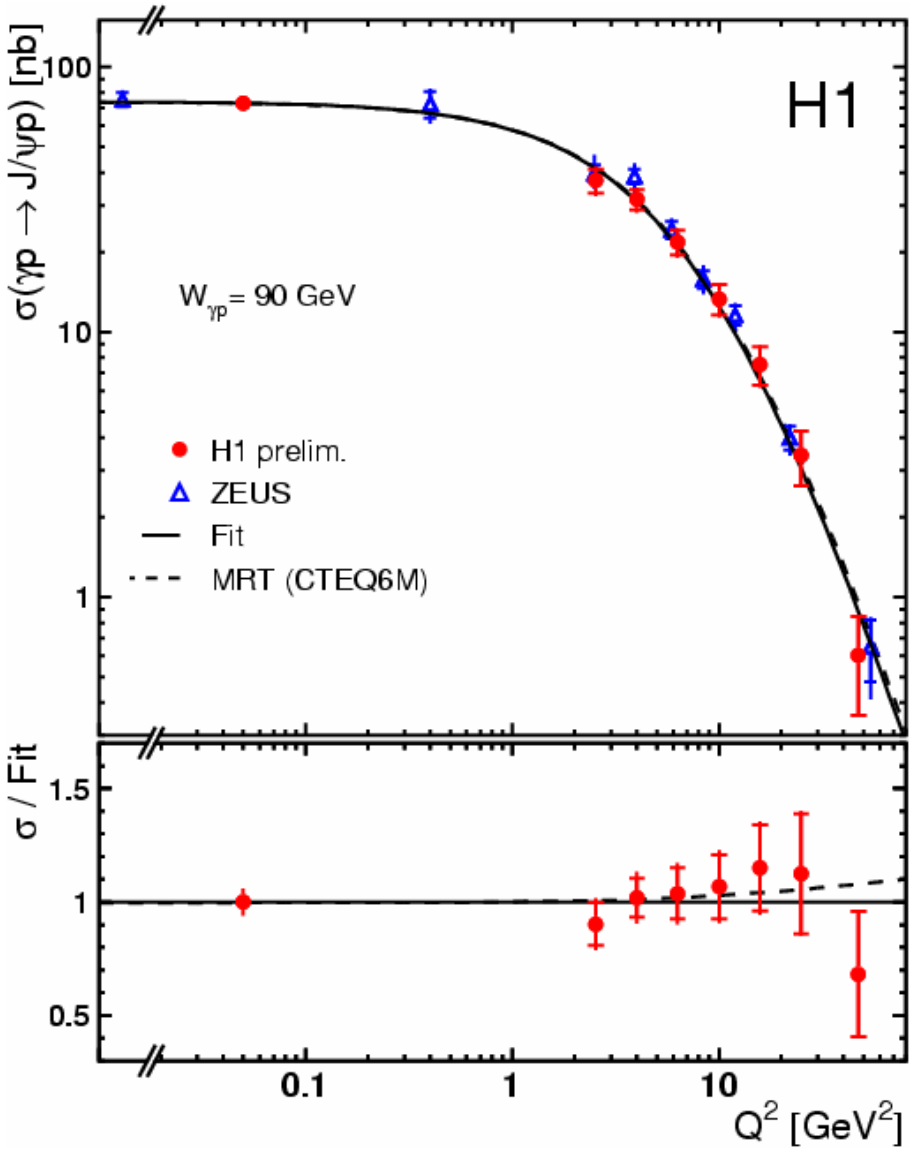
bg + (skewed) Gauss







Results: Q^2-Dependence



$$2 < Q^2 < 80 \text{ GeV}^2$$

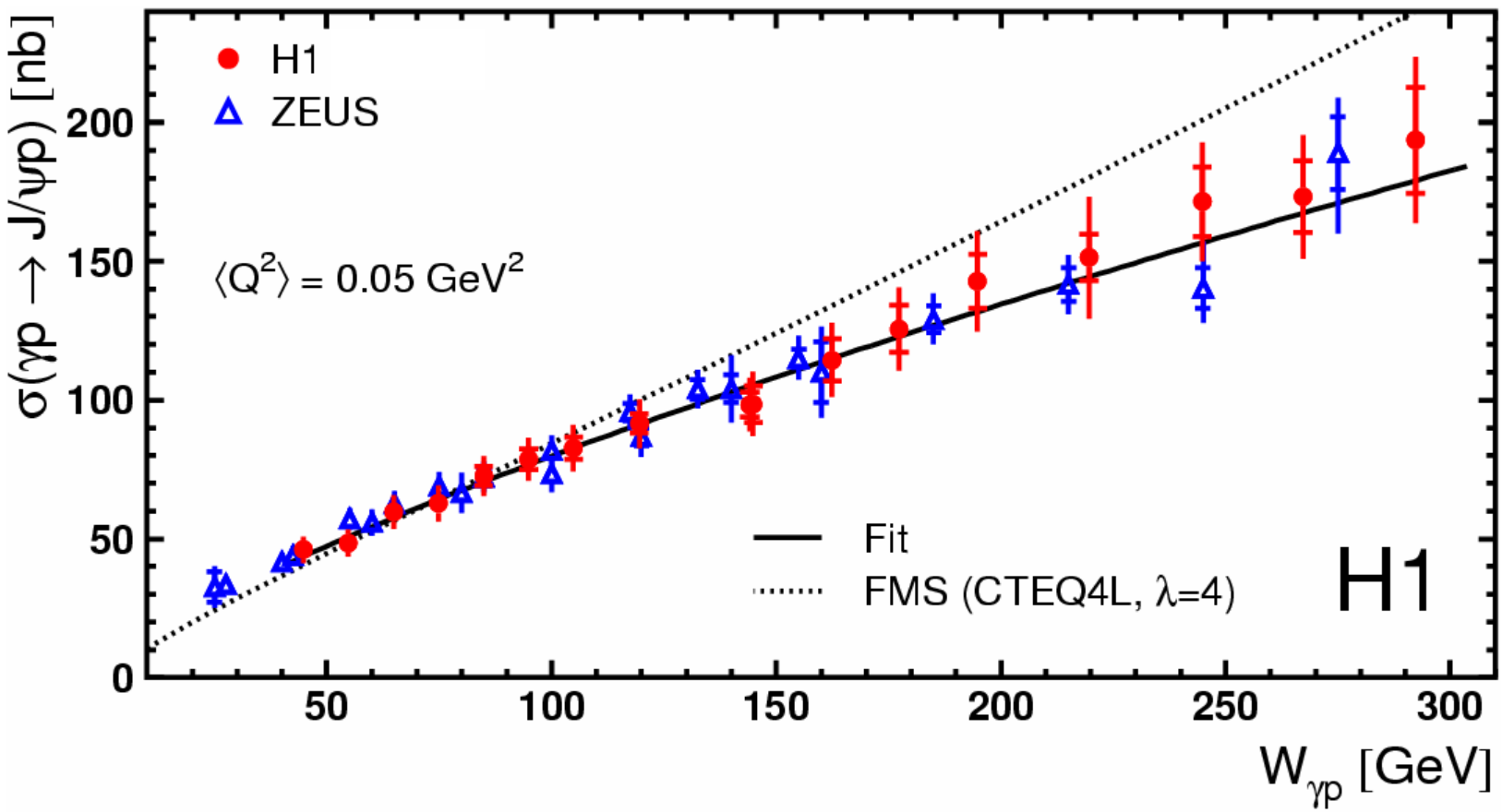
Fit: $\sigma \propto (Q^2 + M_V^2)^{-n}$

$$n = 2.486 \pm 0.080 \pm 0.068$$

(in agreement with ZEUS)

QCD-prediction (MRT) normalized to γ-prod point

W-Dependence (Photoproduction)



Fit: $\sigma \propto W^{\delta}$ $\delta = 0.740 \pm 0.034 \pm 0.034$ (from H1 alone)

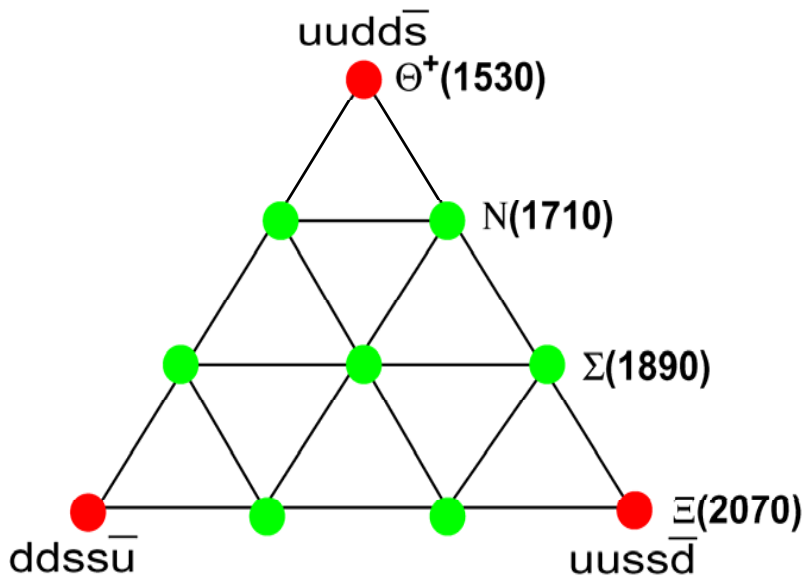
(soft Pomeron: $\delta \sim 0.22 - 0.32$)

slope very sensitive to the gluon pdf

Spectroscopy: Pentaquark Searches

„Baryons are made from 3 quarks"

???

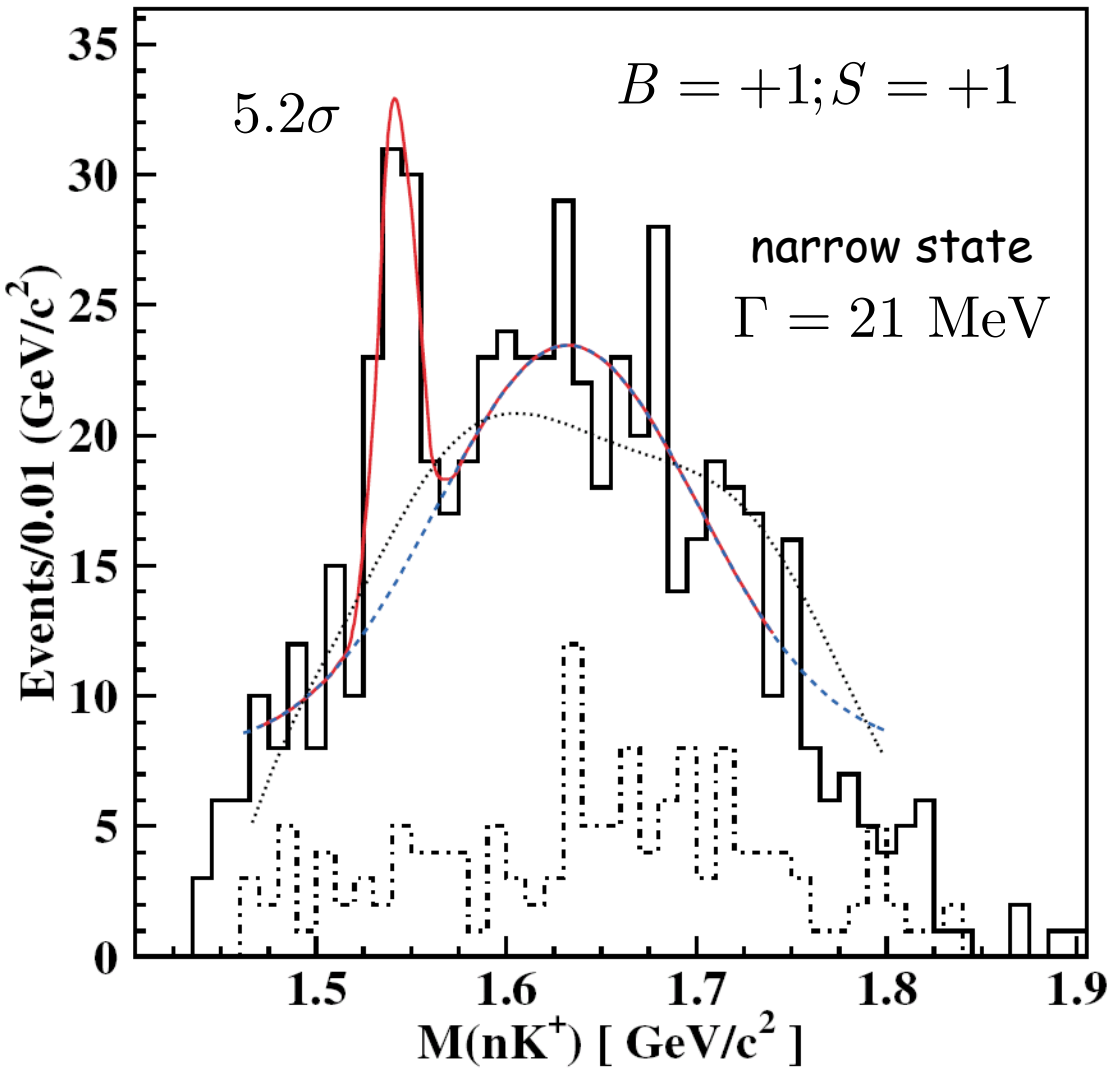


$$\theta^+(1530) \to nK^+$$

$$\to pK_S^0$$

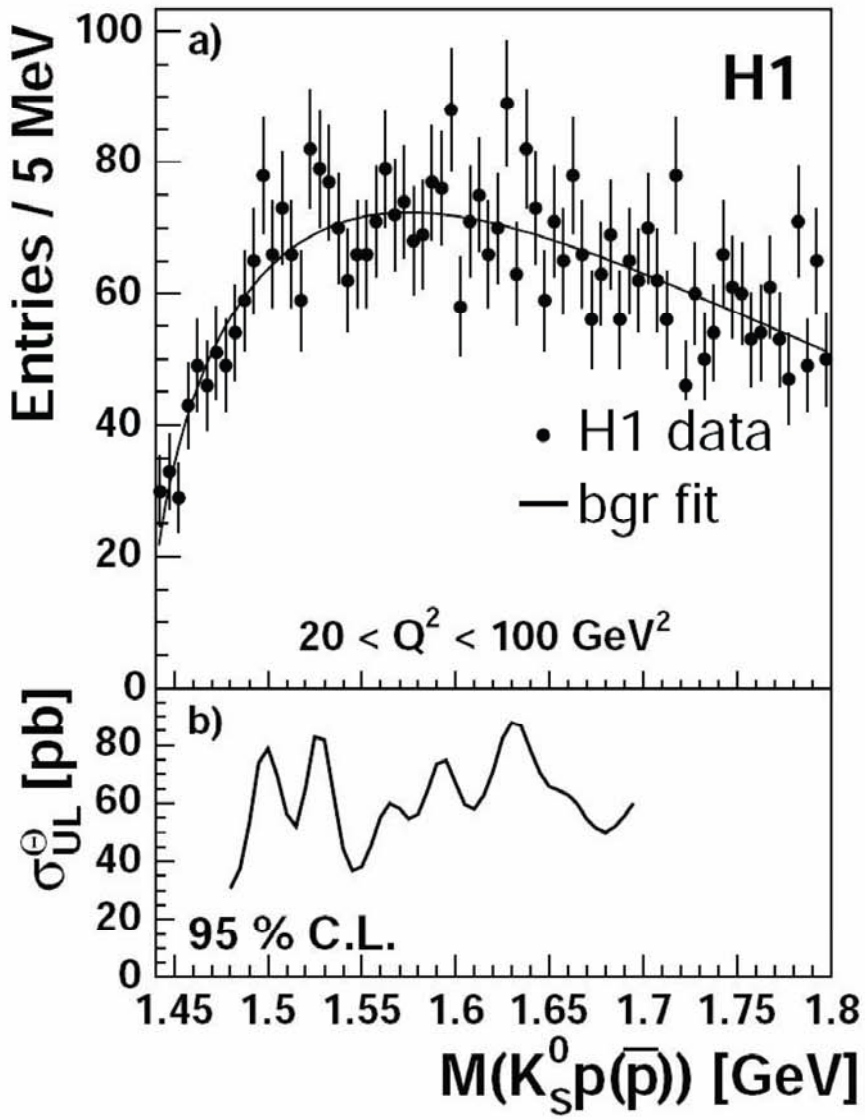
(originally 7 experiments, > 4 σ)

e.g. CLAS-Collaboration
(Phys. Rev. Lett. 91 (2003) 252001

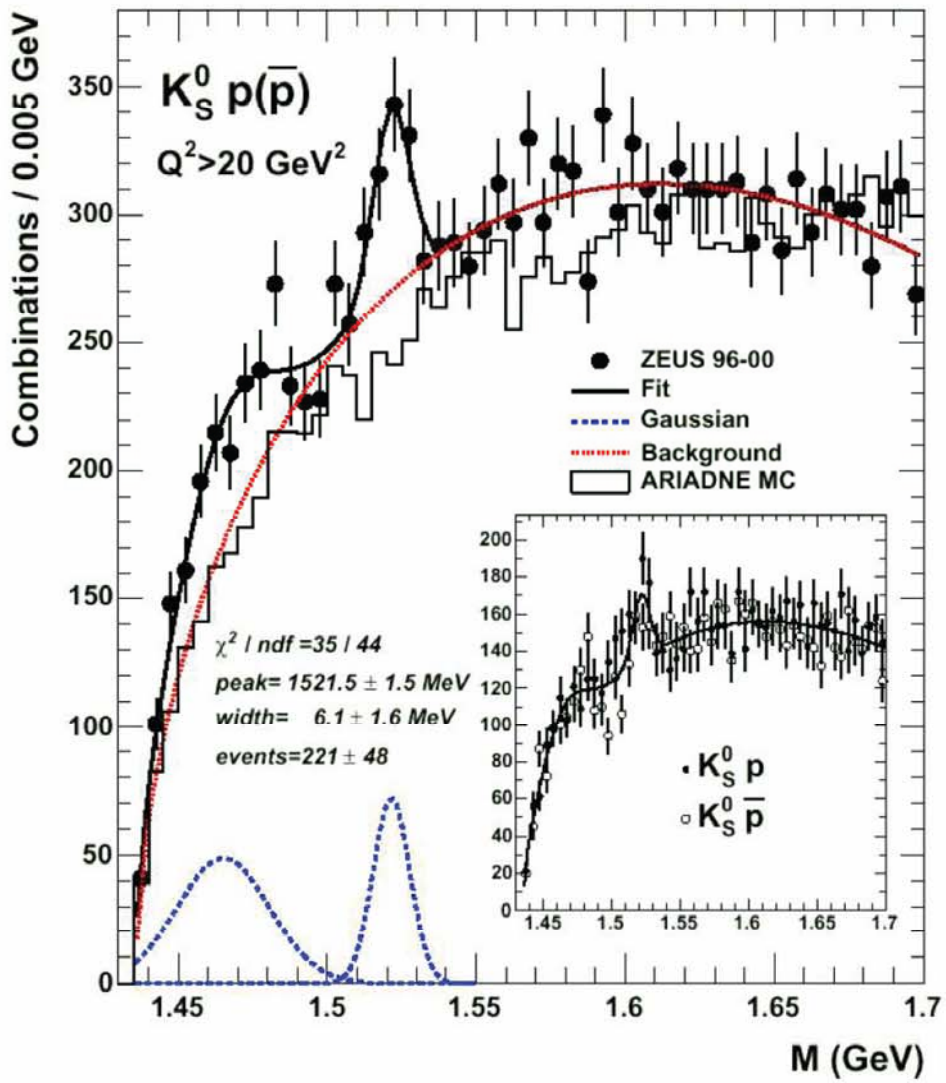


Pentaquark Searches (cont.)

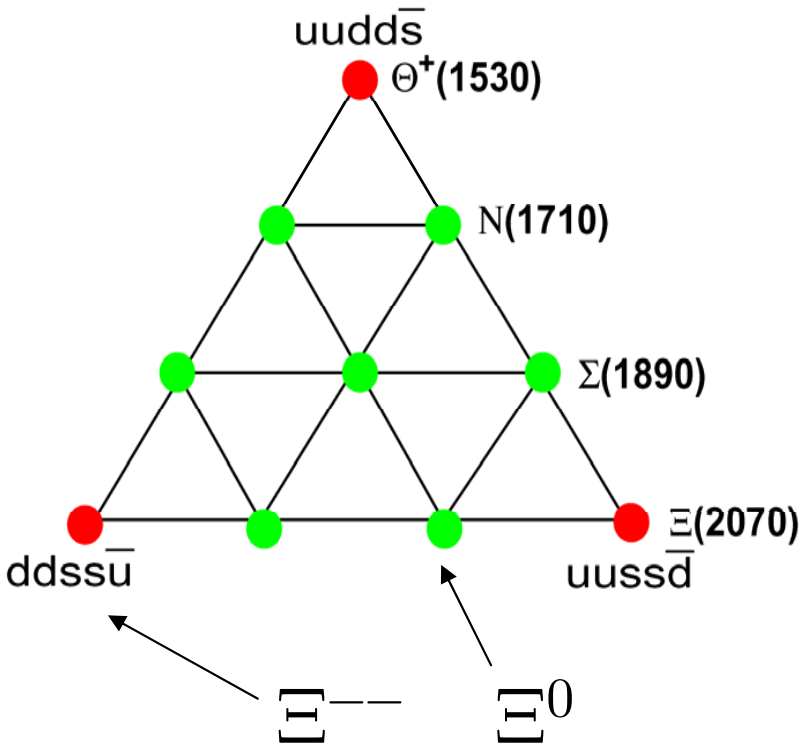
H1 (does not see it)

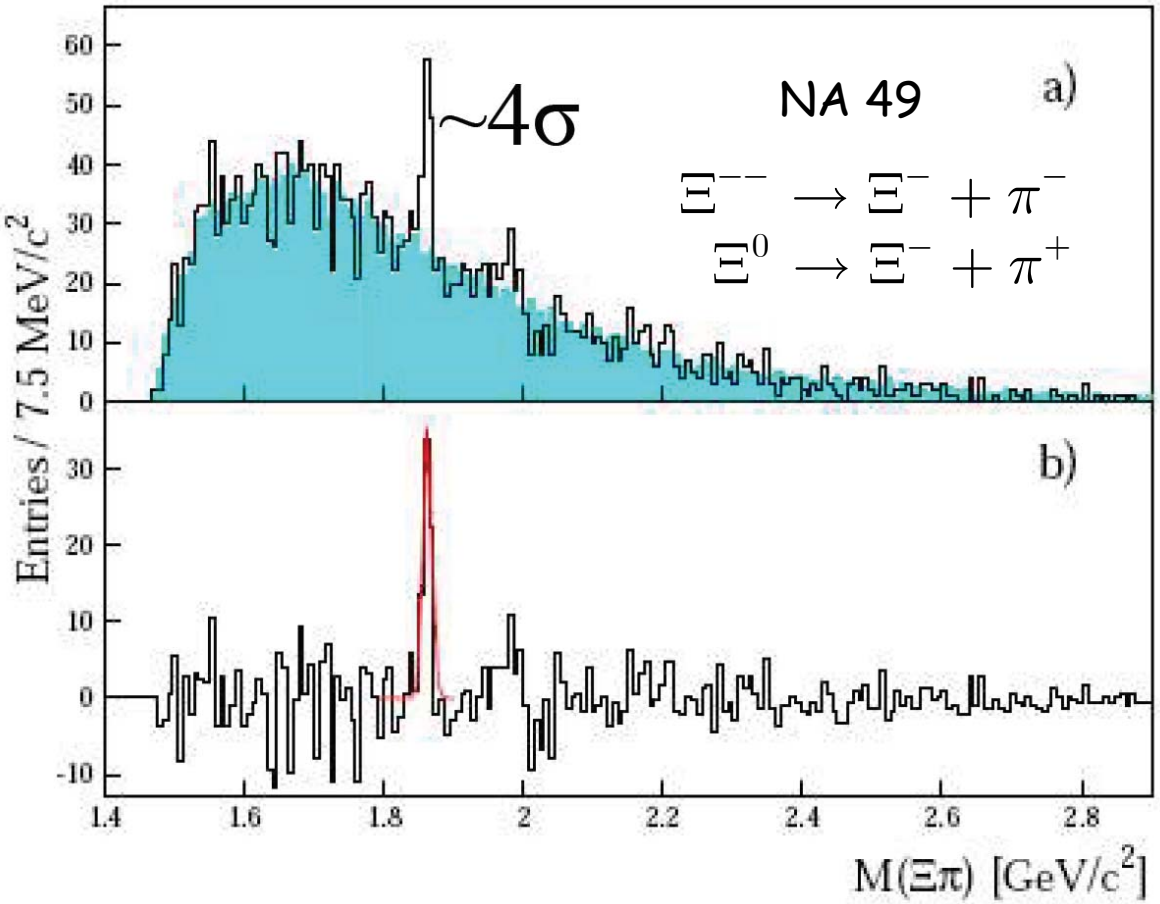


ZEUS (confirms)



Pentaquark Searches (cont.)

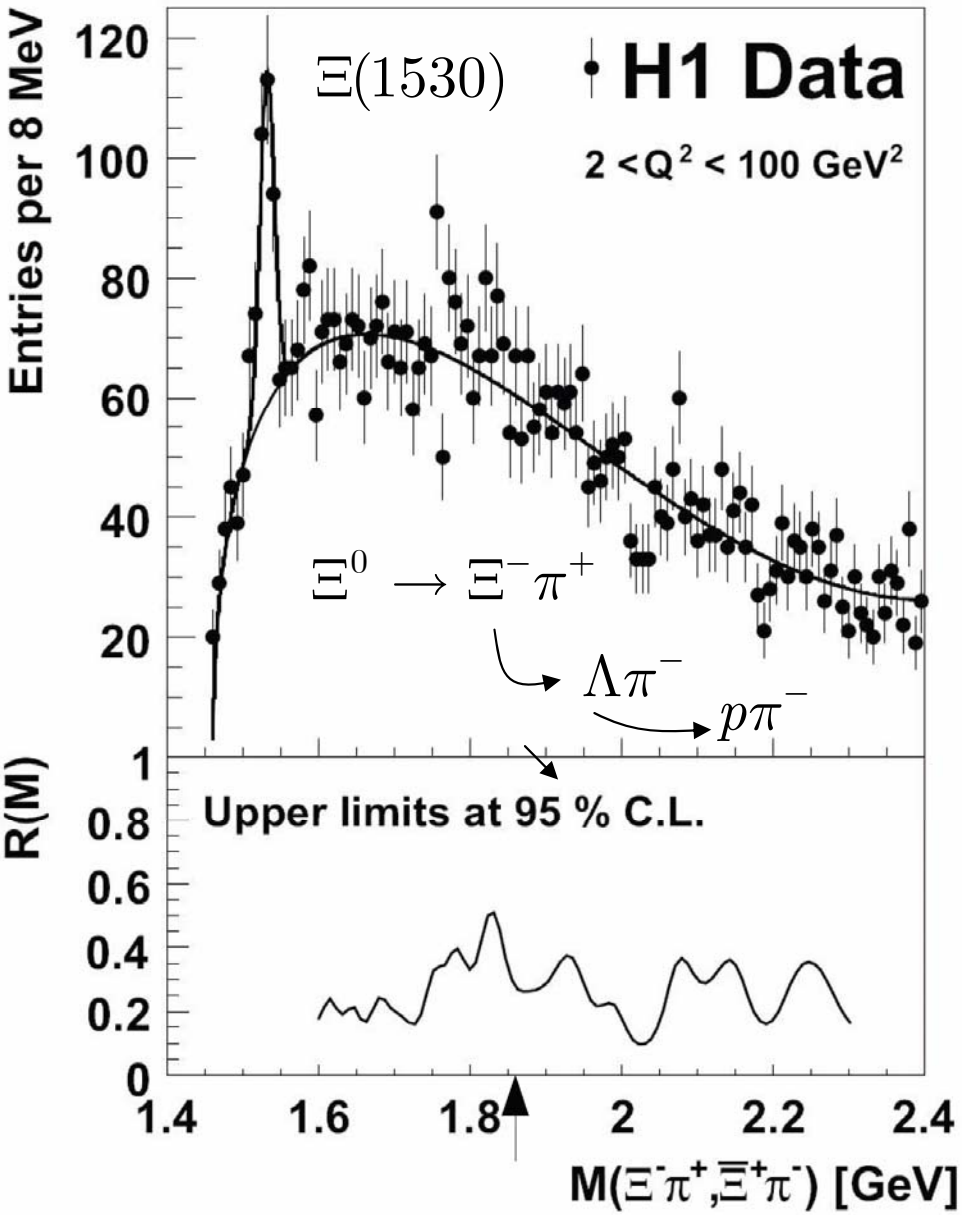


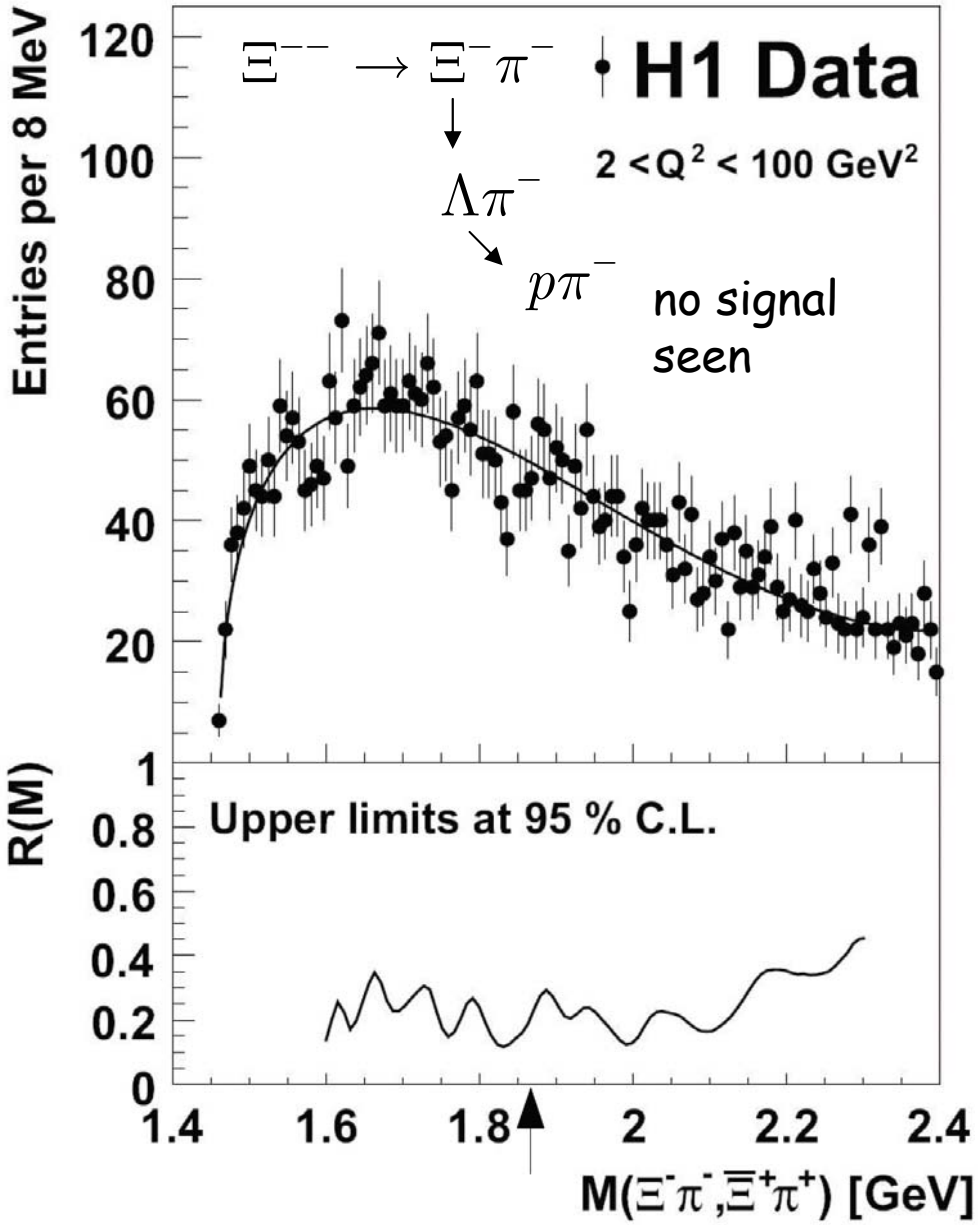


NA49: $m \approx 1860$ MeV

$\Gamma < 18$ MeV

Pentaquark Searches (cont.)

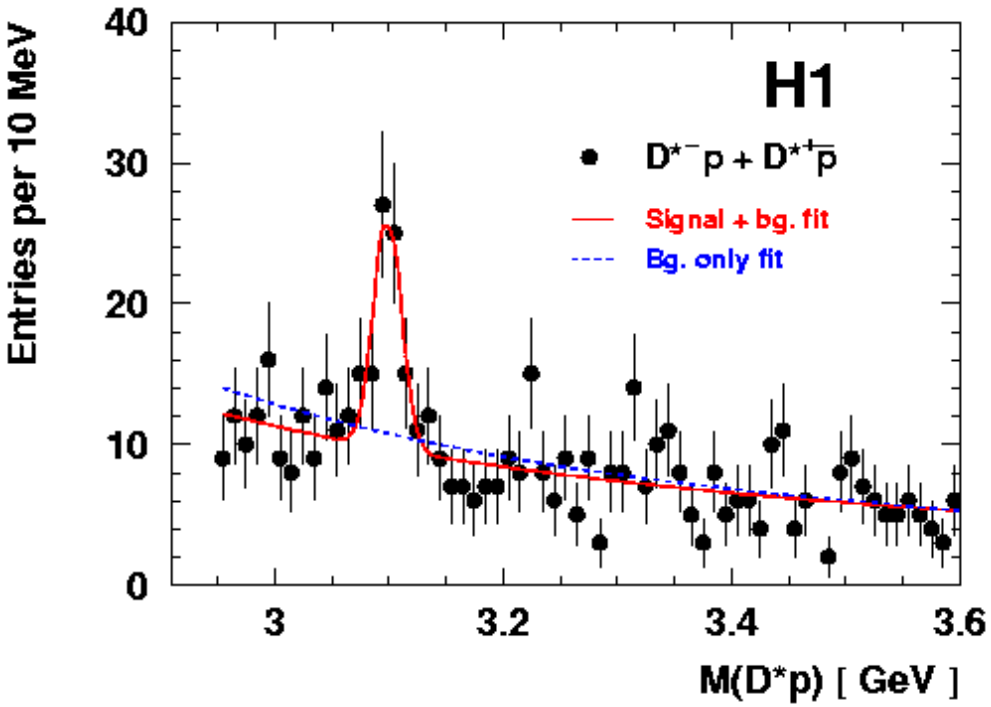


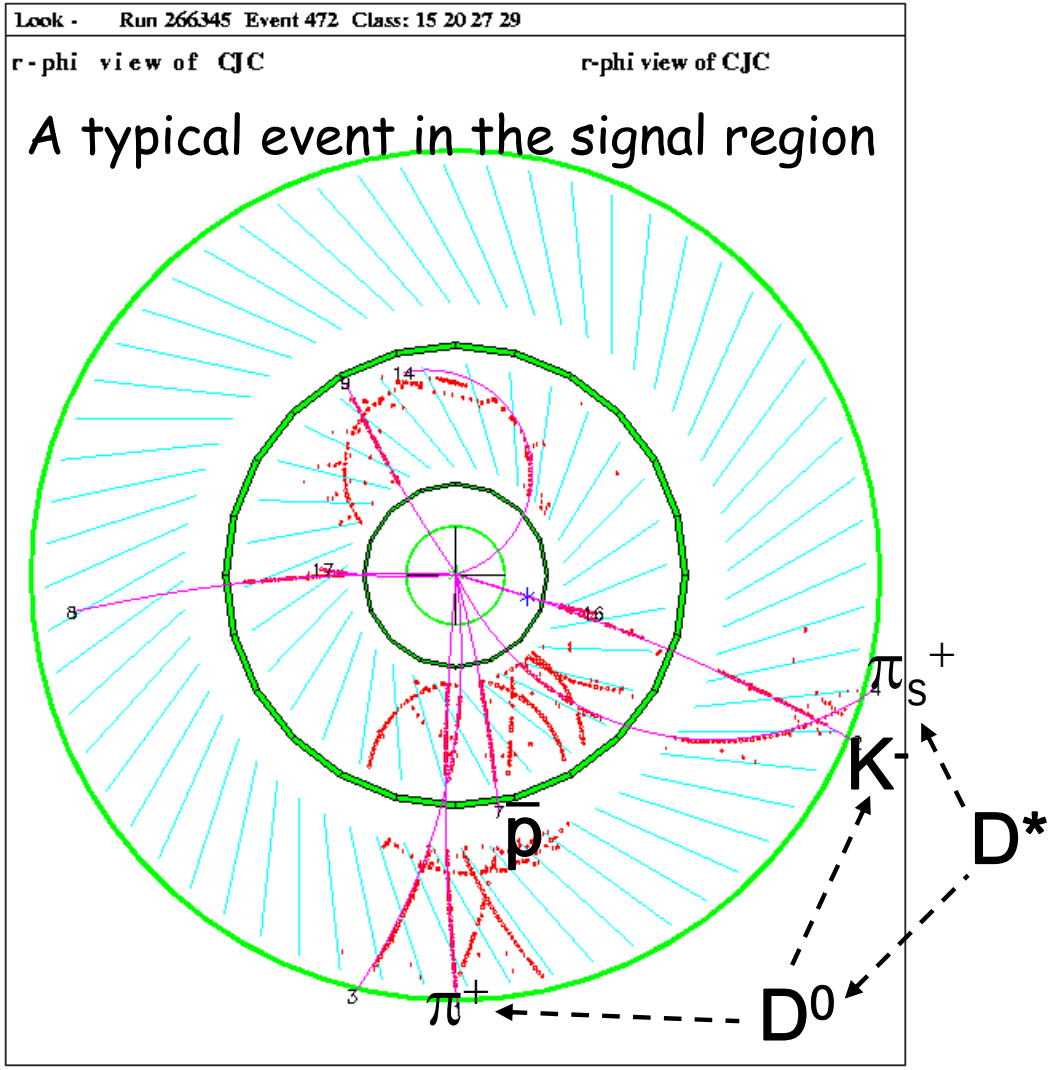


No signal also from ZEUS

Observation of an Anti-charm Pentaquark

New state seen in H1: a charmed pentaquark $\theta_C \to D^{*-}p(D^{*+}\bar{p})$ $uudd\bar{c}$





Mass: $3099 \pm 3(\text{stat.}) \pm 5(\text{syst.})$ MeV
Width: $12 \pm 3(\text{stat.})$ MeV

Background fluctuation prob. 4 x 10^{-8} $= 5.4\sigma$

→ nobody else sees it ...

Summary and Conclusions

- HERA has provided a wealth of new data in DIS
- One of the surprising results: strong rise of F_2,
  starting the era of low x physics
- Low x data for various final states have been presented
- Many of the data difficult to describe with present-day QCD calculations, usually higher order needed
- Some hints exist that DGLAP may not be sufficient at very low x (forward jets)
- (Semi)-exclusive final states challenging for QCD models
- Although closed down recently, lots of HERA data still to come
- [Beware of „large" signals in case of small statistics]