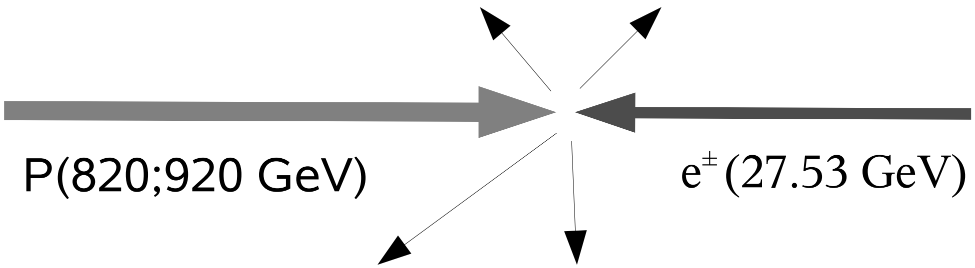
Particle production at HERA

Daniel Pitzl
DESY

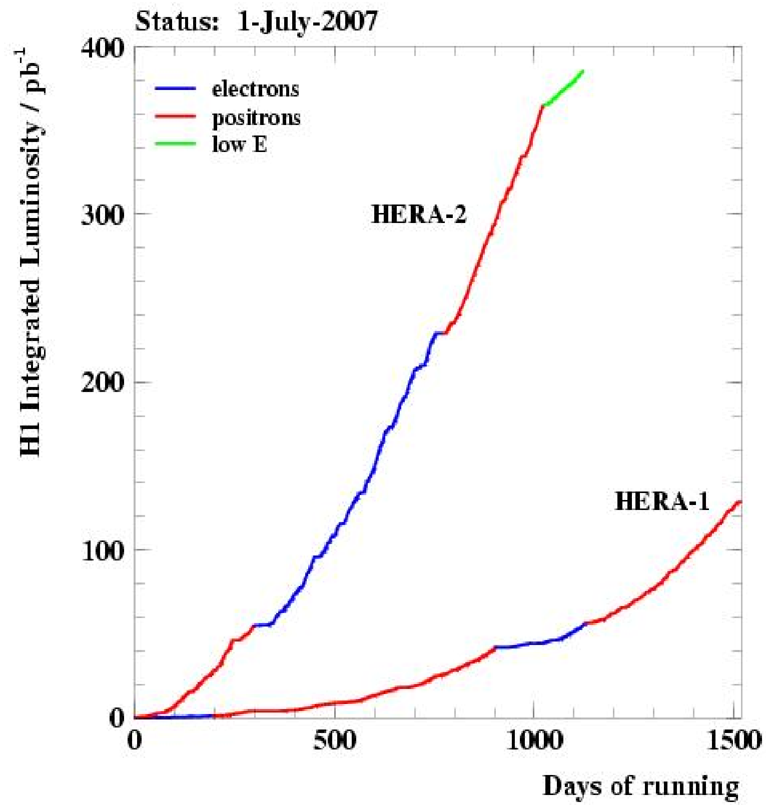
On behalf of the H1 and ZEUS Collaborations

Charged particle multiplicities
KNO scaling
Fragmentation
Strangeness production
Searches for multi-quark states

HERA



Data taking periods:
HERA I : 1992-2000
HERAII : 2002-2007



~0.5 fb^{-1} per experiment

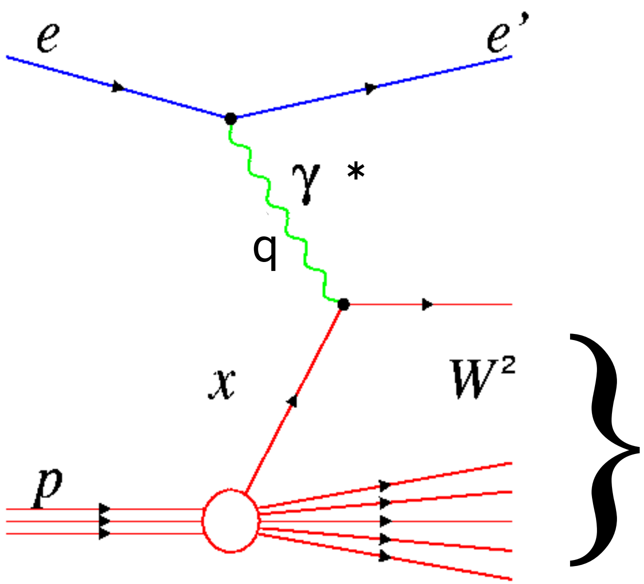
HERA ep kinematics

c.m. energy : $s^{1/2}$ = 301–319 GeV

hadronic energy : W = m(γ*p)

photon virtuality : $Q^2 = -q^2$

inelasticity : $y = Q^2/(x_{Bj}\ s)$



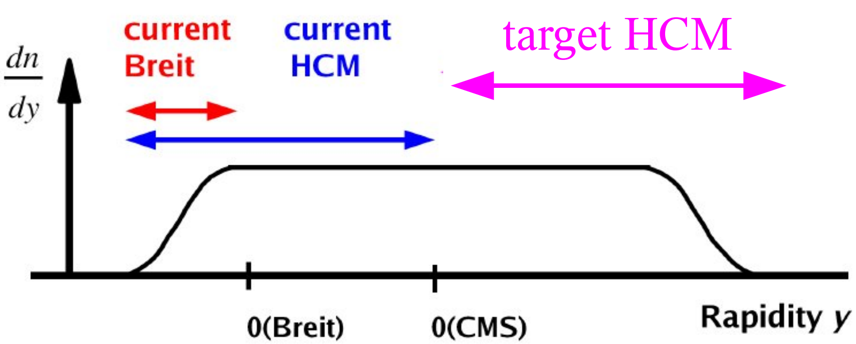
two regimes :

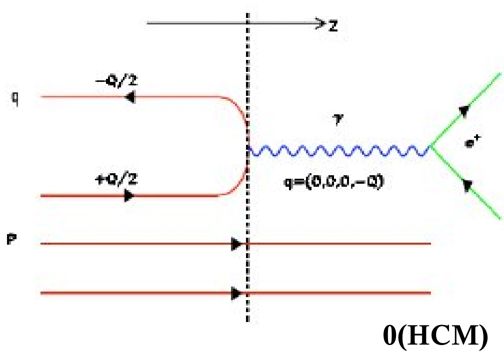
$Q^2 \approx 0\ GeV^2$: **Photoproduction**

$Q^2 > 2\ GeV^2$: **Electroproduction (DIS)**

Reference frames

HCM Frame
(hadronic centre-of-mass)





Breit Frame

Similarity expected between e^+e^- and ep in current regions of Breit or HCM frames.
Target region should look more like in pp collisions.

$$y = 0.5 \ln[(E+p_z)/(E-p_z)]$$

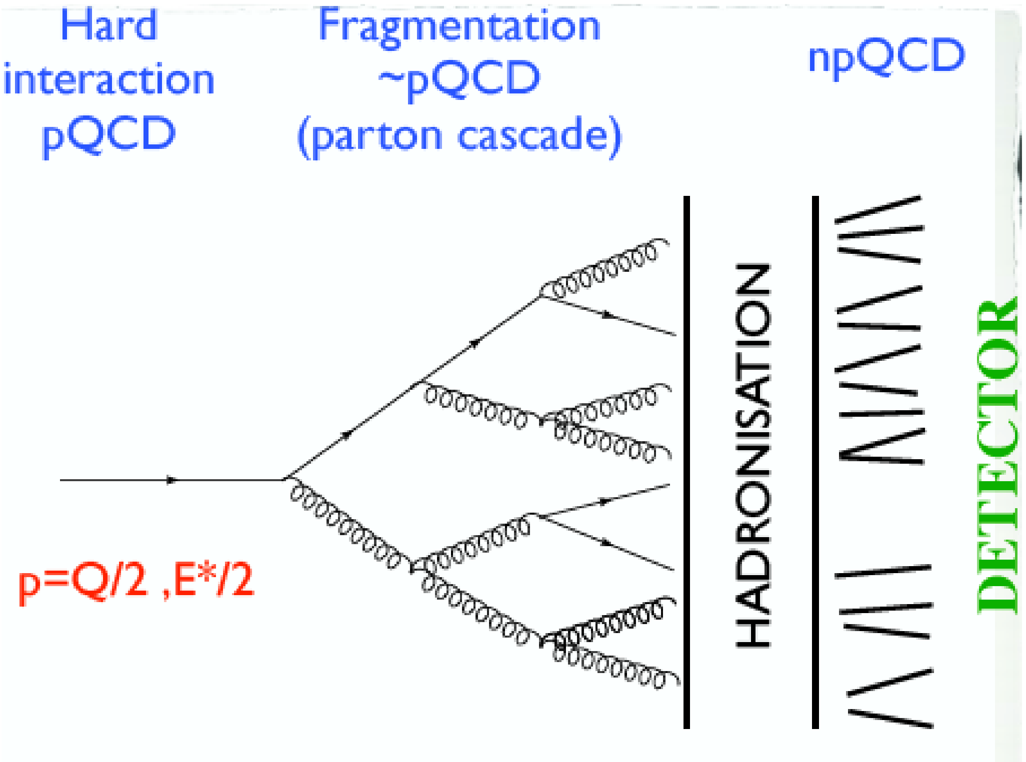
To see the similarity choose the proper variable:

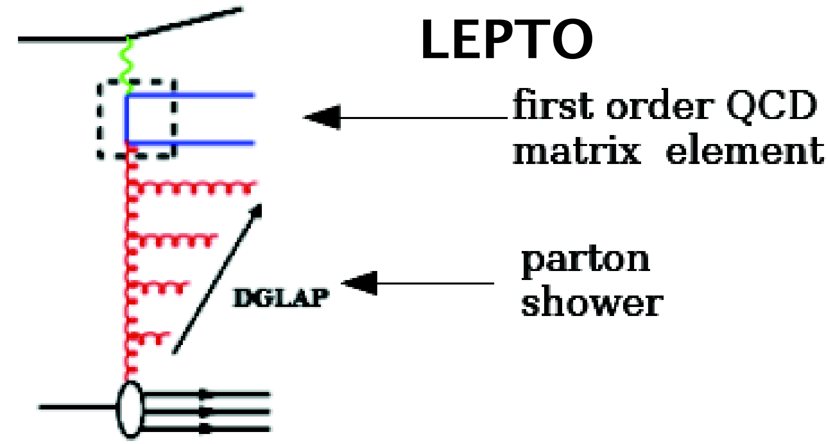
e^+e^- : $s^{1/2} = 2E_{beam}$.

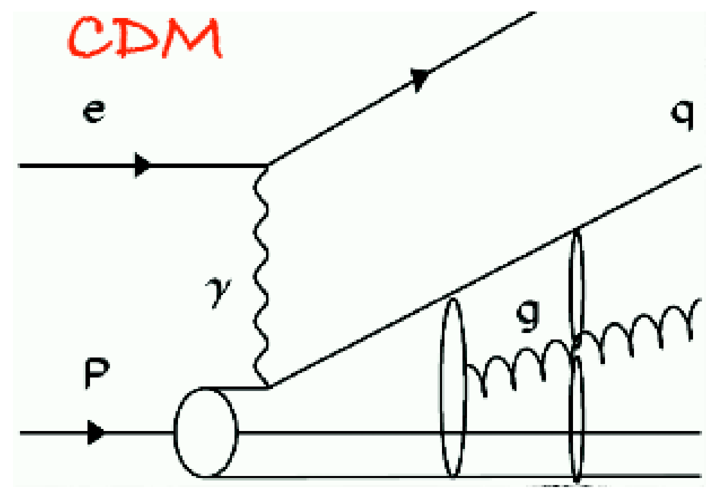
ep (HCM) : W.

ep (Breit Frame) : Q or E^{cr}_B (available energy in the current region of the Breit Frame).

Models







LEPTO, RAPGAP MEPS: PDF ⊗ PS(DGLAP) ⊗ ME(LO) ⊗ PS ⊗ String frag.

SCI: LEPTO + soft color interactions

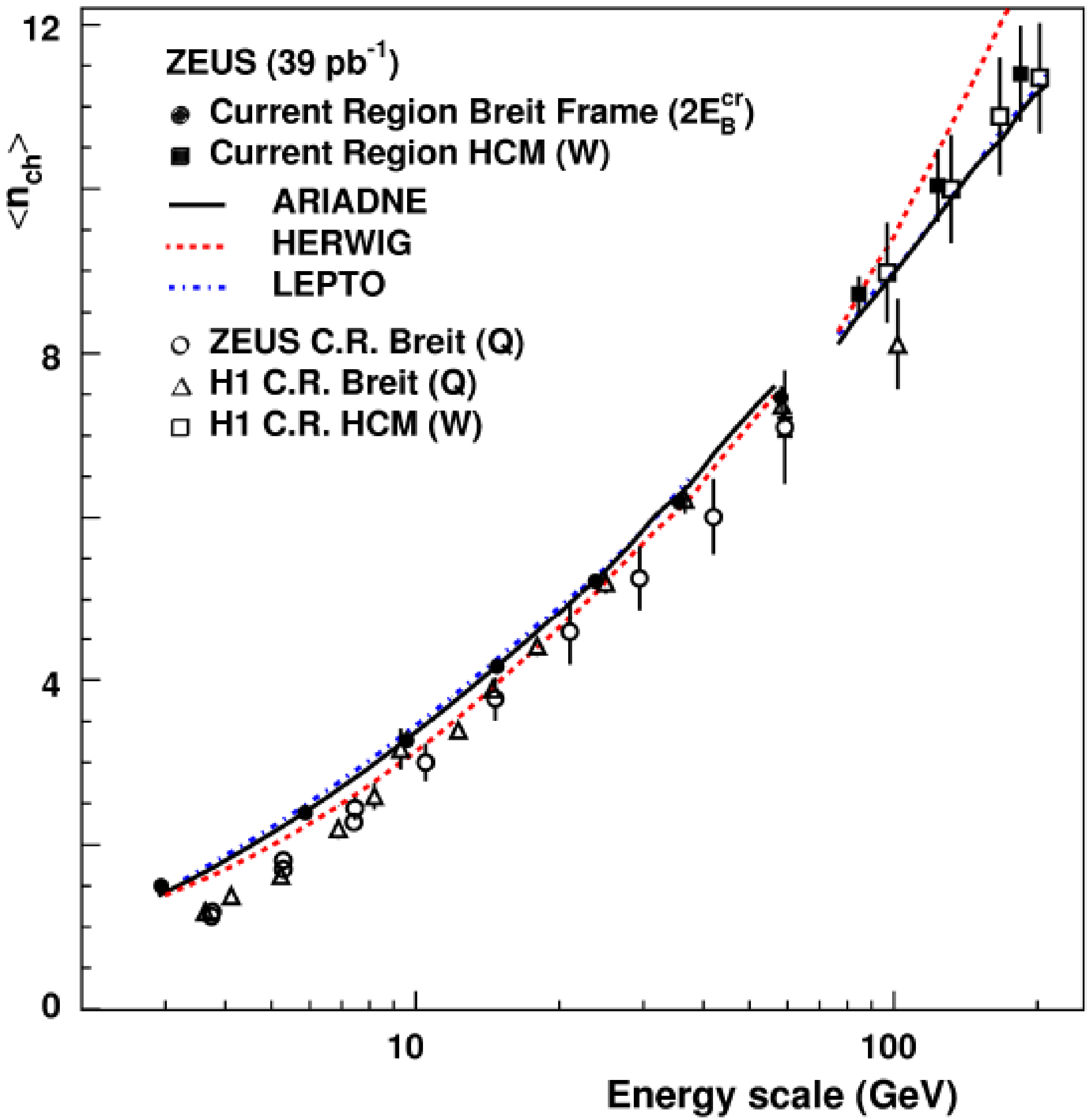
ARIADNE CDM: PDF ⊗ Dipole(BFKL) ⊗ ME(LO) ⊗ Dipole ⊗ String frag.

HERWIG: PDF ⊗ PS(DGLAP) ⊗ ME(LO) ⊗ PS ⊗ Cluster frag.

Cyclops: PDF ⊗ ME(NLO) ⊗ fragmentation function.

Charged Particle Multiplicities

ZEUS, H1



Data are in good agreement with LEPTO and ARIADNE

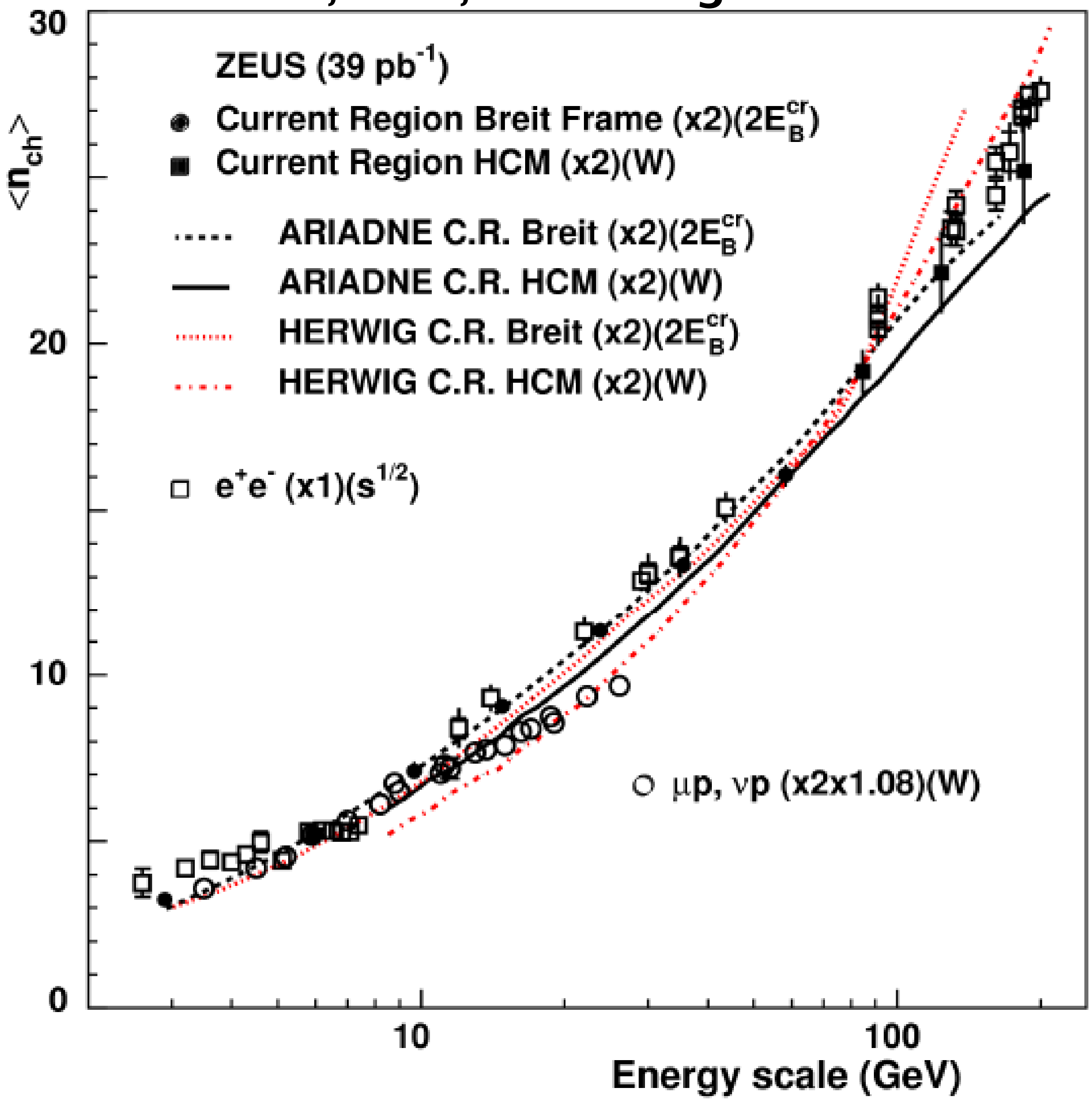
not with HERWIG

At low energy scales differences if $2E_B^{cr}$ or Q

At high scales good agreement

Charged Particle Multiplicities

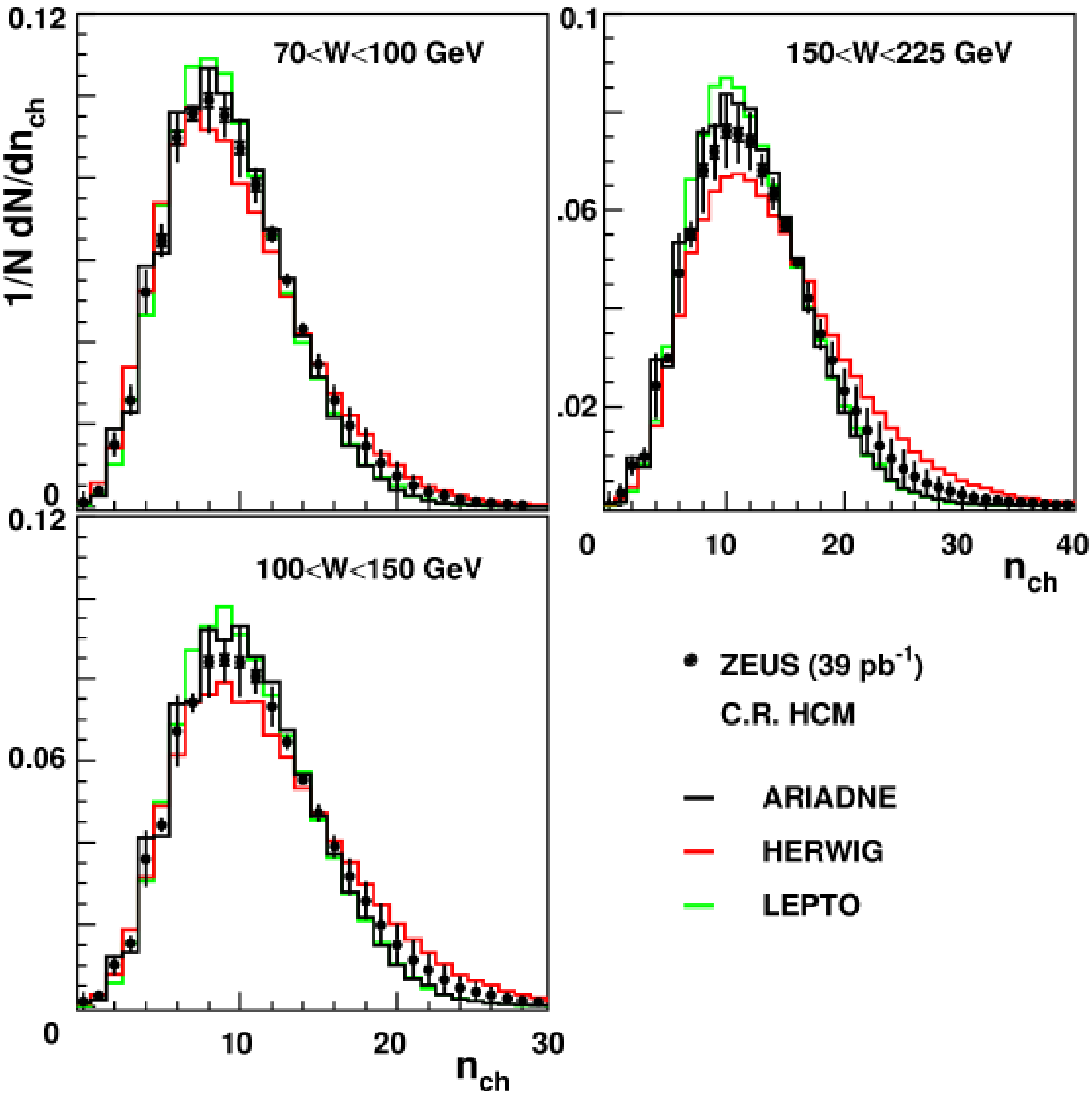
ZEUS, e^+e^-, fixed target



Breit Frame:
Good agreement between e^+e^- and ep data when $2 \cdot E^{cr}_B$ is used as energy scale.

HCM Frame:
overall good agreement with e^+e^- and ep experiments when W is used as energy scale. Fixed target DIS data deviate at W = 20–30 GeV.

Multiplicity distributions in hadronic CMS

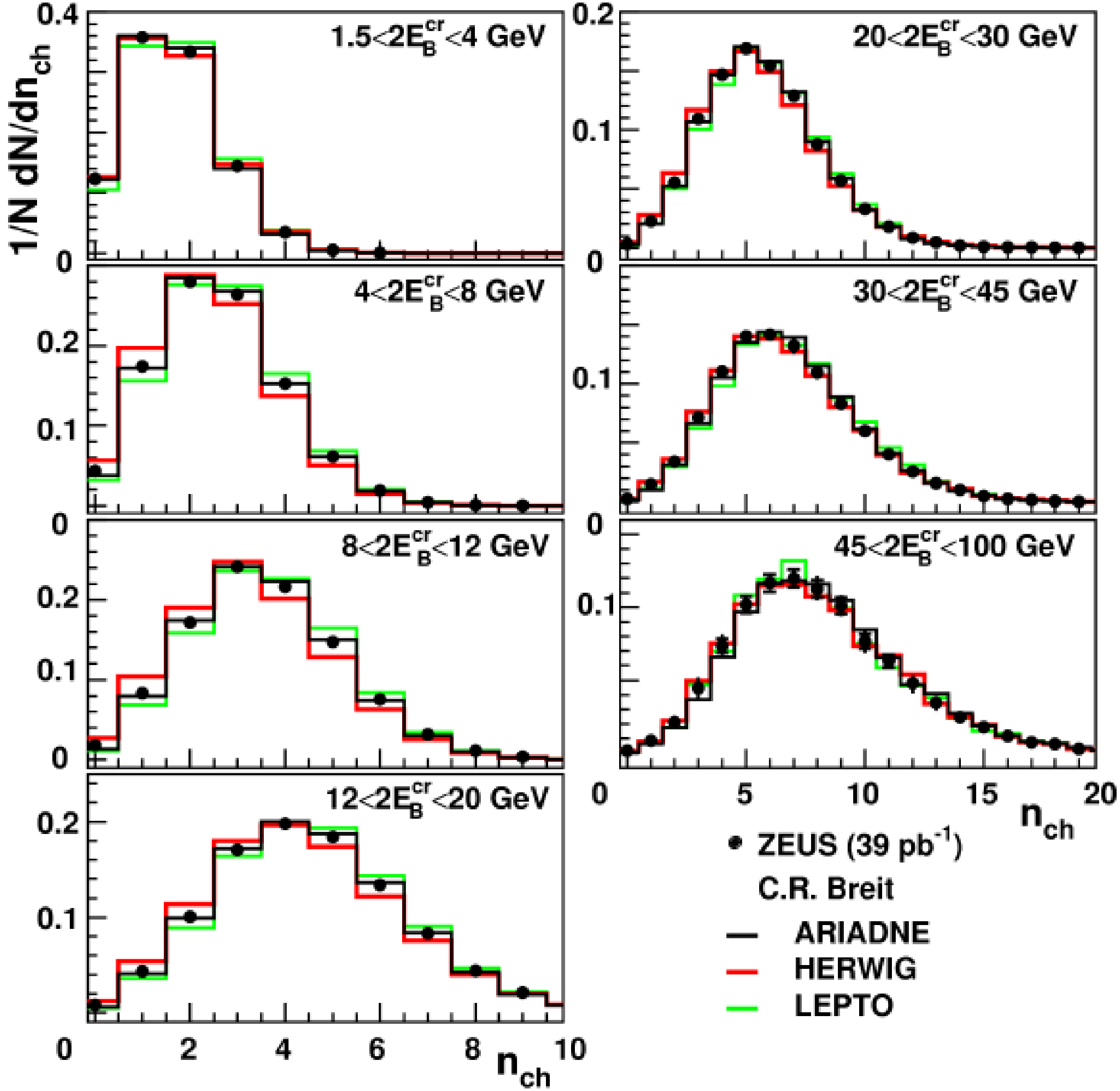


ARIADNE gives best description (not perfect)

LEPTO is too narrow

HERWIG has a too long tail.

Multiplicity distributions in the Breit frame

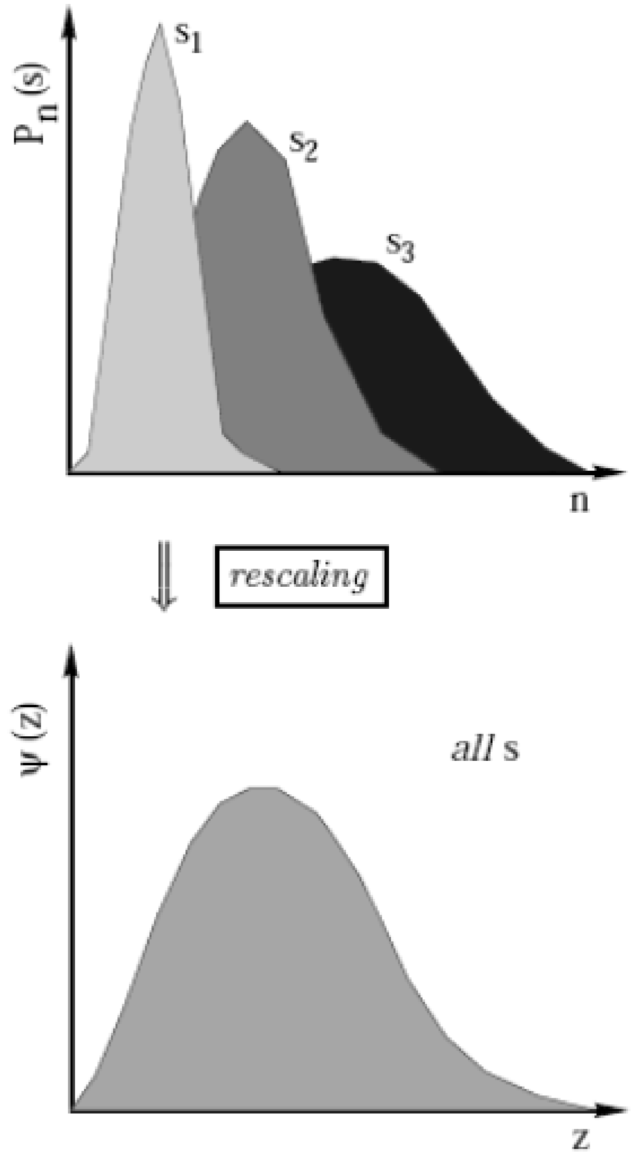


ARIADNE gives best description.

LEPTO is a little too high.

HERWIG is a little too low.

KNO scaling



$P(n_{ch})$ the probability distribution of multiplicity n_{ch}

$\langle n_{ch} \rangle$ the average multiplicity

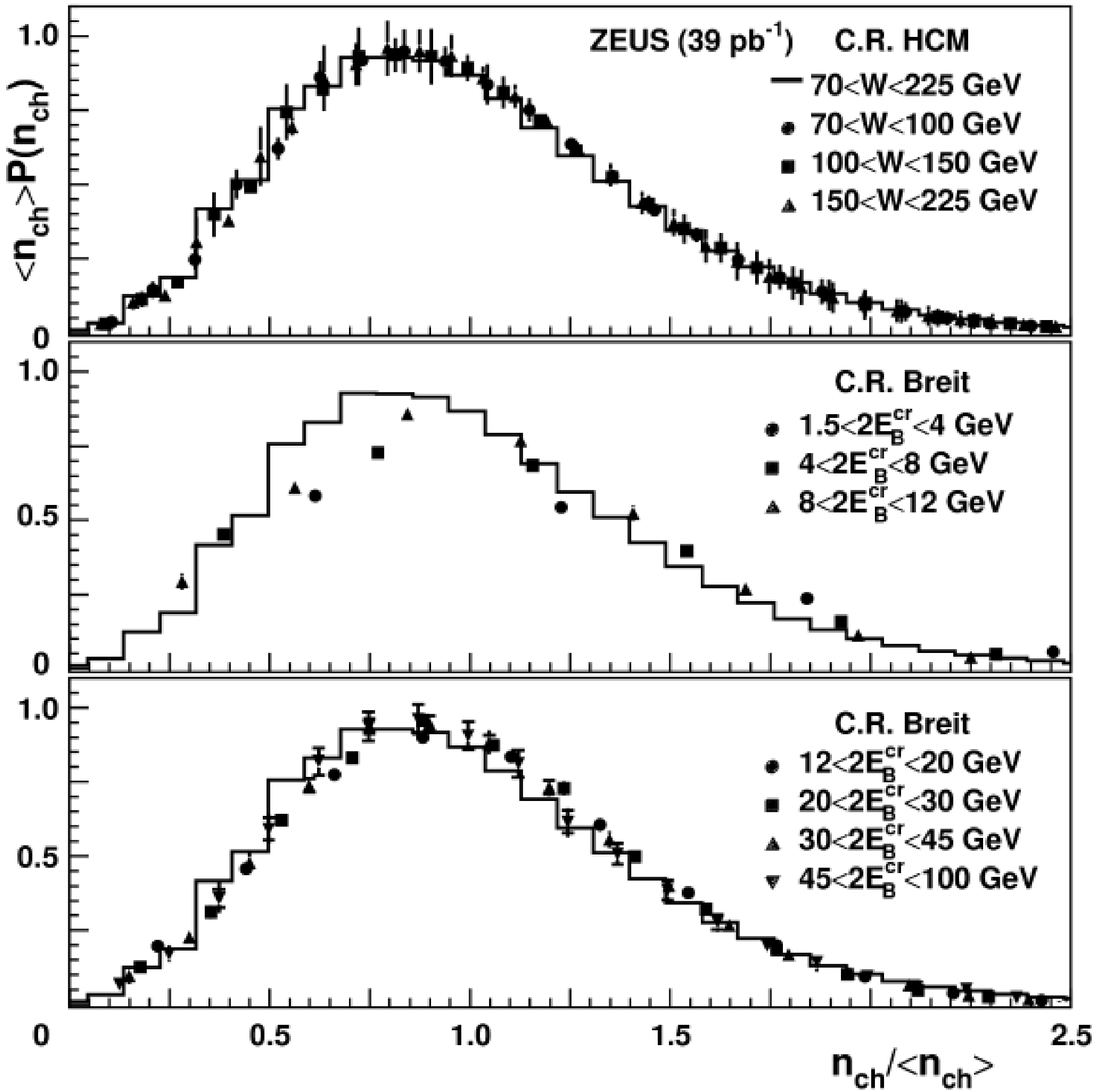
at high enough energies s
→ asymptotic behaviour

$$\langle n_{ch} \rangle P(n_{ch}) \sim n_{ch} / \langle n_{ch} \rangle$$

↑ $\psi(z)$ ↑ z

Z.Koba,H.B.Nielson,P.Olsen
N.P. B40(1972)317

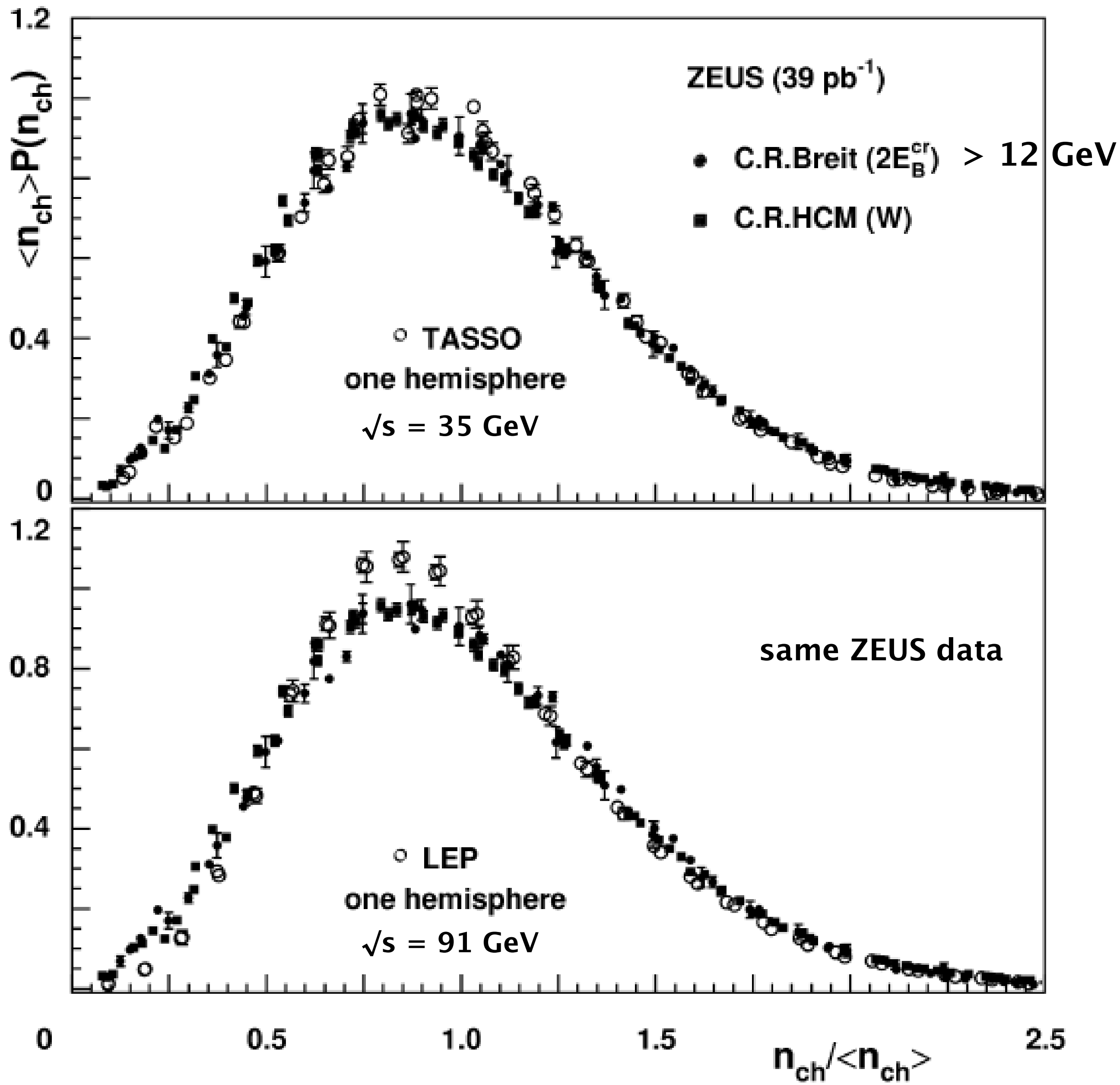
KNO scaling at HERA



— reference distribution
average distr. 70<W<225GeV

bins	agreement
$2\,E_B^{cr} < 12$ GeV	No
$2\,E_B^{cr} > 12$ GeV	OK

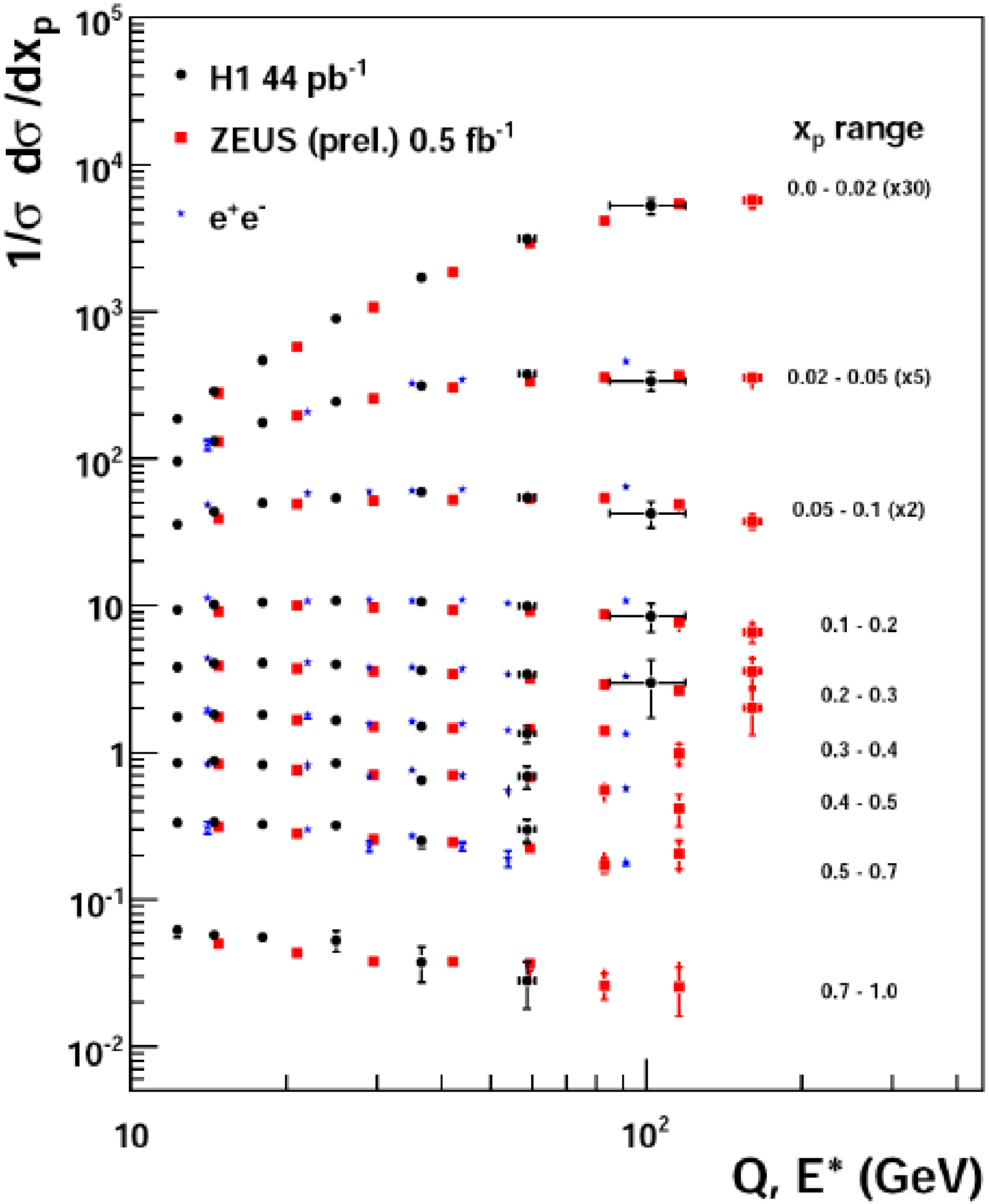
KNO scaling at HERA and in e^+e^-



Almost perfect universality between HERA and PETRA data.

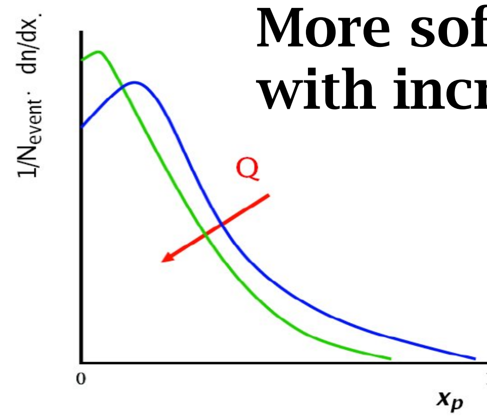
LEP data are a little more narrow than HERA data.

Scaled Momentum Distributions



$x_p = 2p_h/Q$ in ep

$= p_h/E_{beam}$ in e^+e^-.



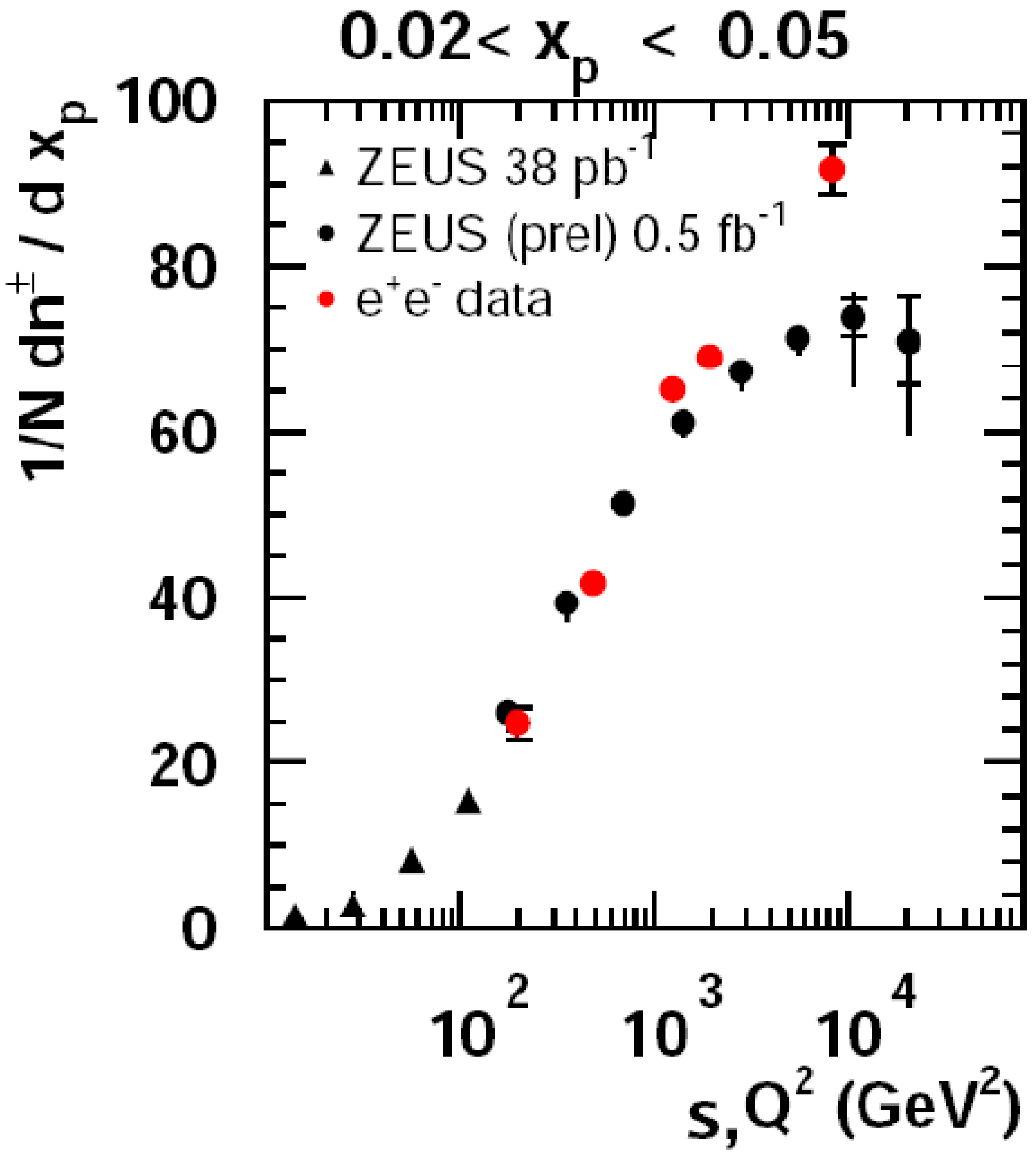
More softer particles with increasing energy

Scaling violation is observed

Agreement between e^+e^- and ep: support for universality of fragmentation.

ZEUS data (prel), 0.5 pb^{-1}, 1996-2007
H1 data, Phys.Lett. B654(2007)148
ee data from TASSO, MARK II, AMY, DELPHI PL,B311(1993)408
$E^* = 2 E_{beam}$

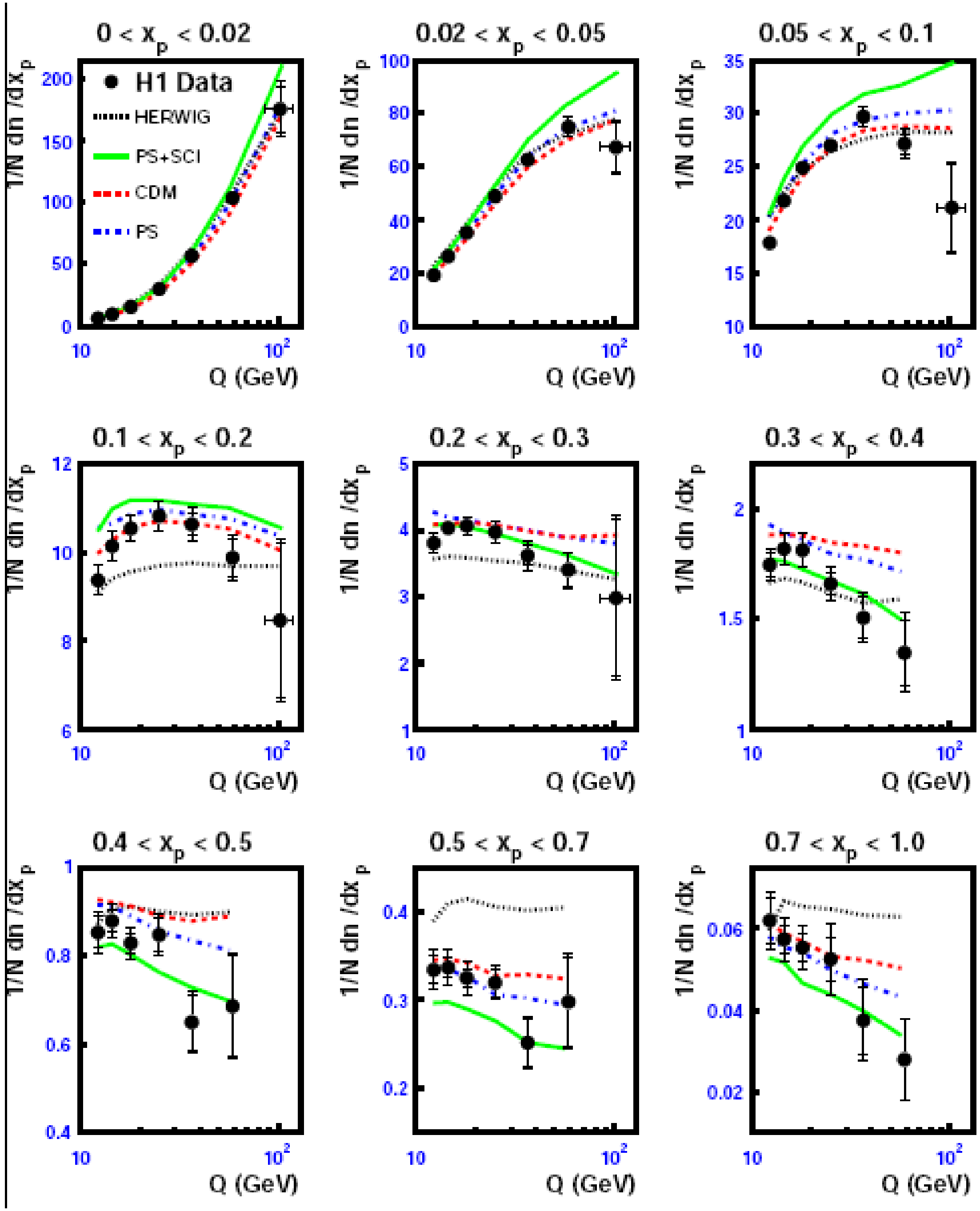
one x_p bin in detail



Strong scaling violation at this low x_p.

Deviation between e^+e^- and ep at highest s or Q^2.

Fragmentation vs models



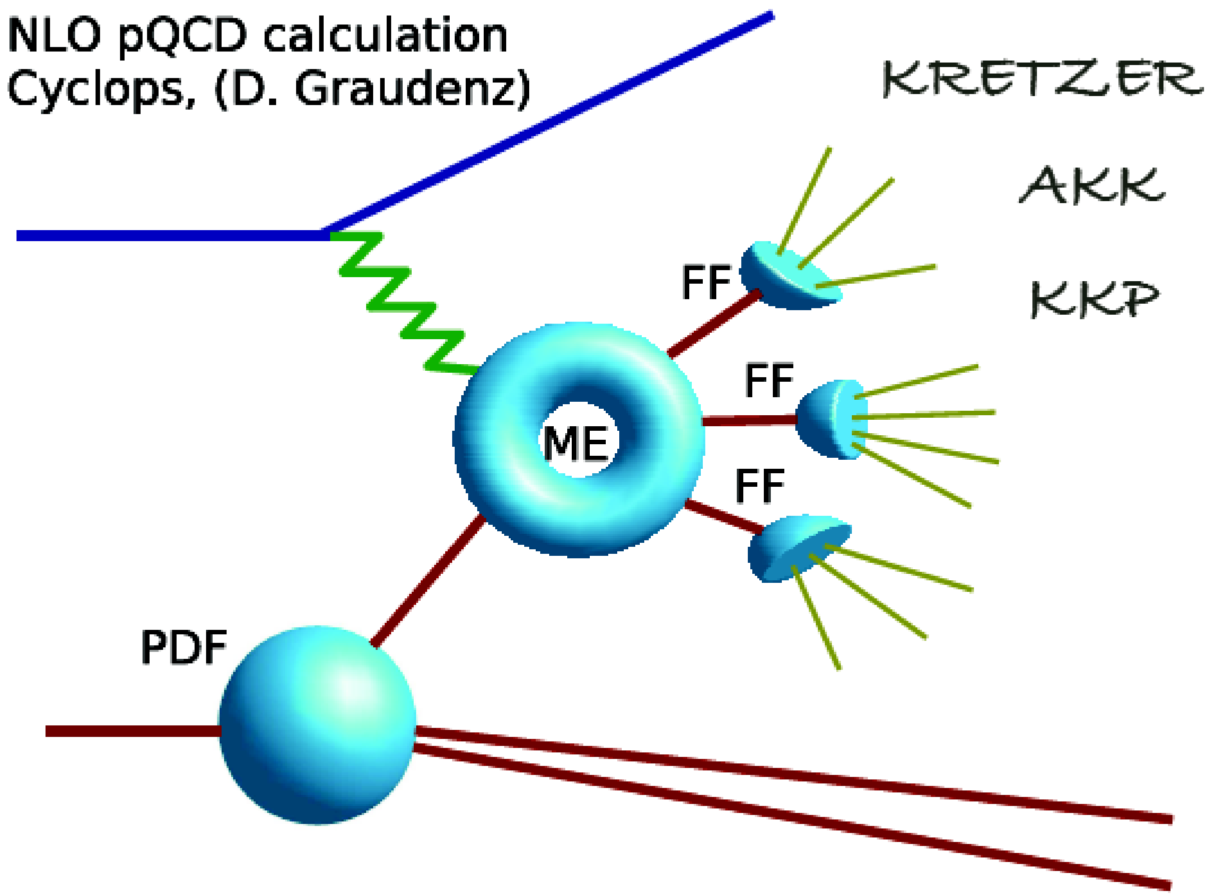
Color Dipole and **Parton Shower** models give fair description. Both overestimate the multiplicity at high Q.

Soft color interaction model fails: spectrum is too soft.

HERWIG cluster model fails at high x_p: spectrum is too hard.

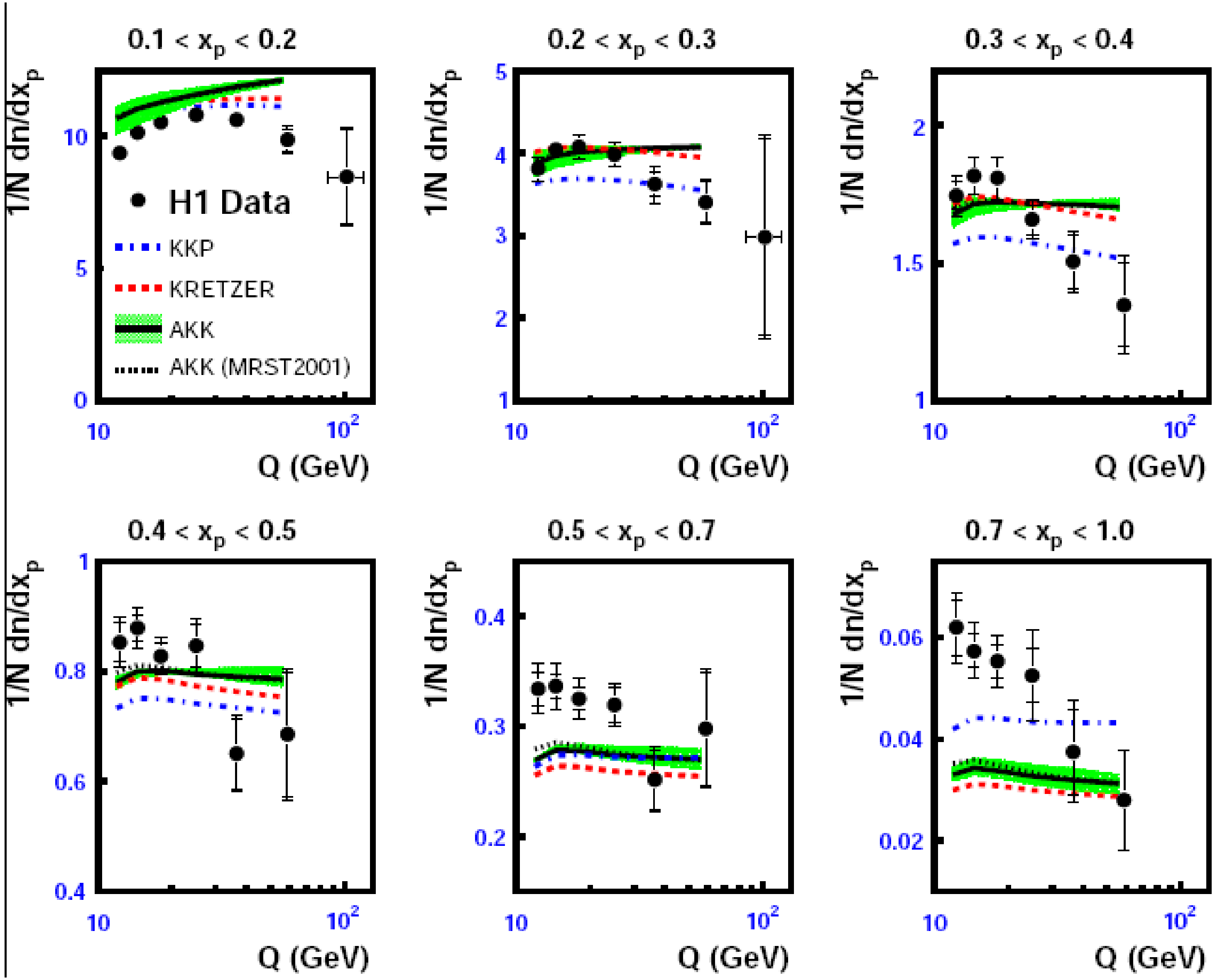
NLO

σ_h = PDF ⊗ M.E. ⊗ FF



Fragmentation functions
KKP, Kretzer, AKK from fits to e^+e^- data.

Fragmentation vs NLO



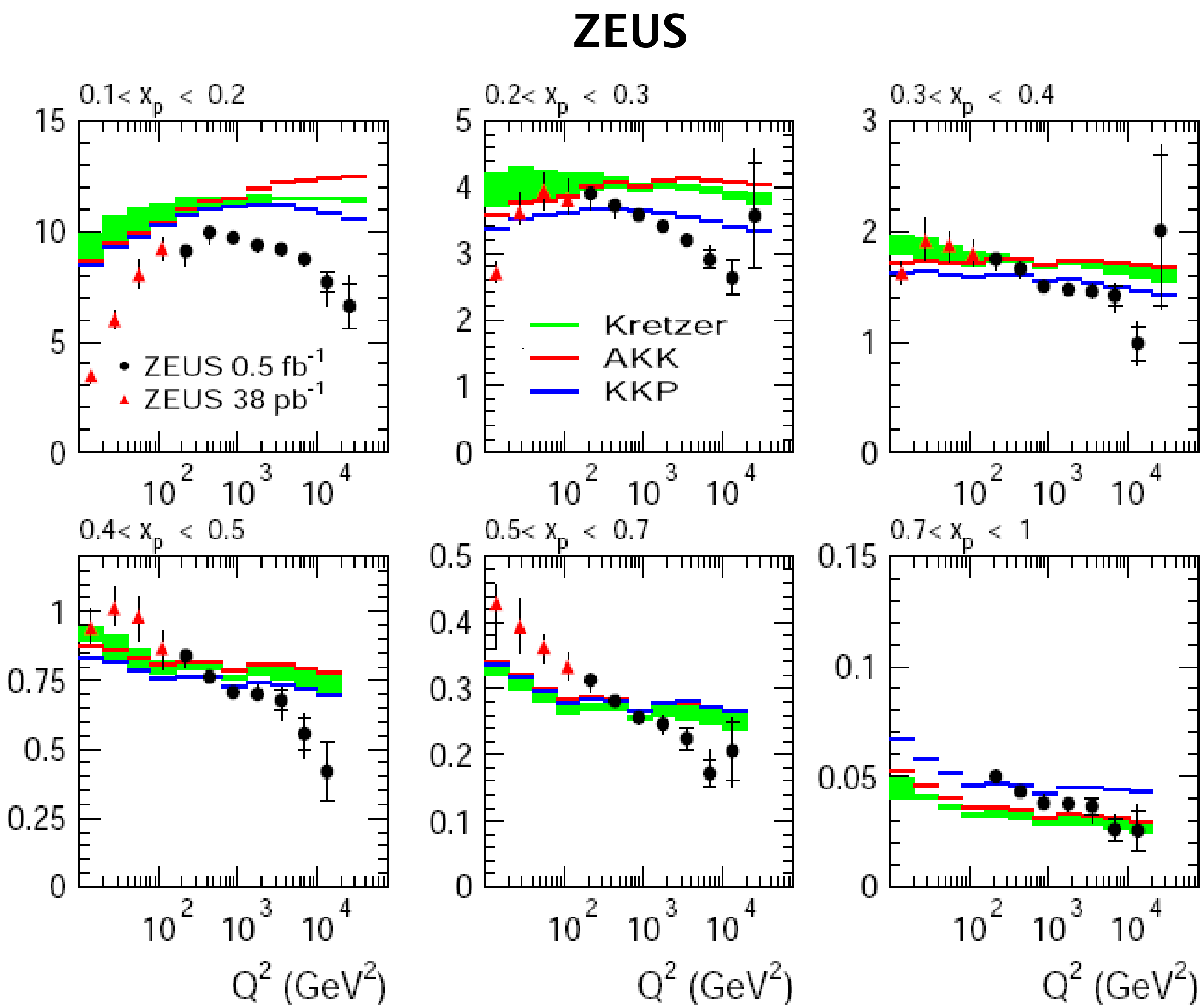
NLO does not describe the data.

Scale and PDF uncertainties are rather small.

Differences between FFs are significant.

Cannot use NLO to extract α_s from scaling violations in fragmentation.

Fragmentation vs NLO



NLO does not describe the data.

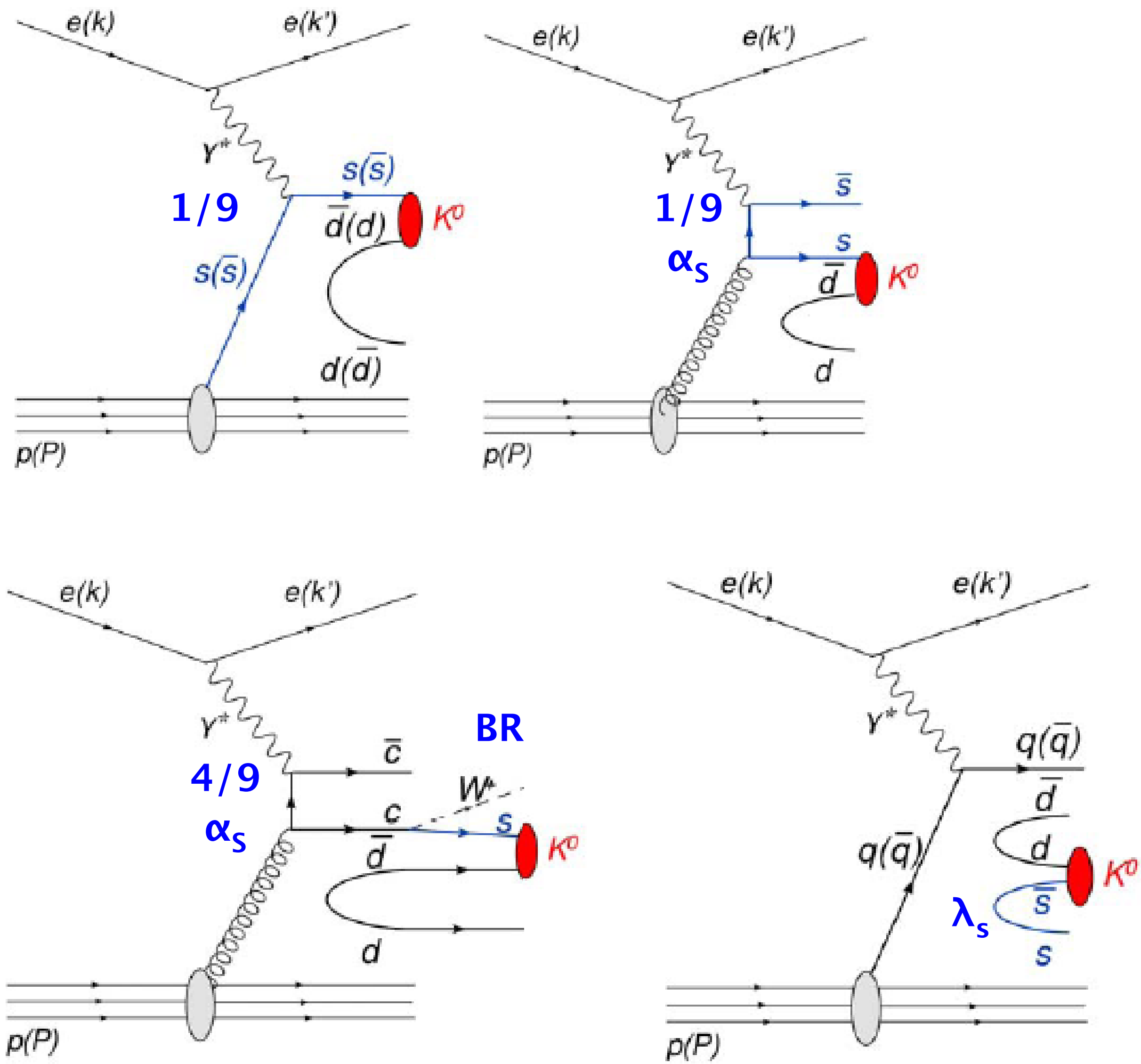
Scale and PDF uncertainties are rather small.

Differences between FFs are significant.

Desired: MC @ NLO = PDF ⊗ PS ⊗ ME(NLO) ⊗ PS ⊗ frag.

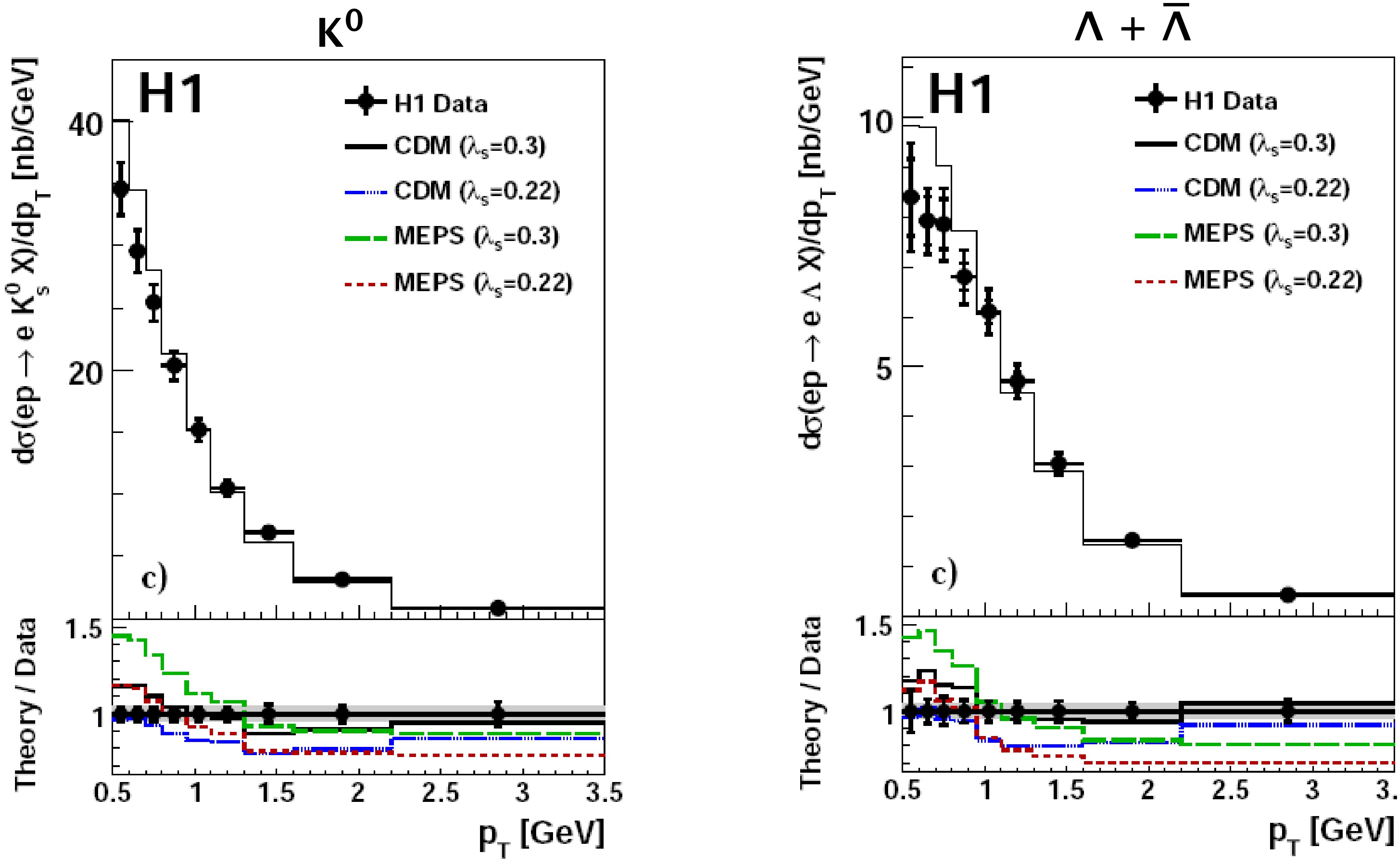
Strangeness production

Strangeness production



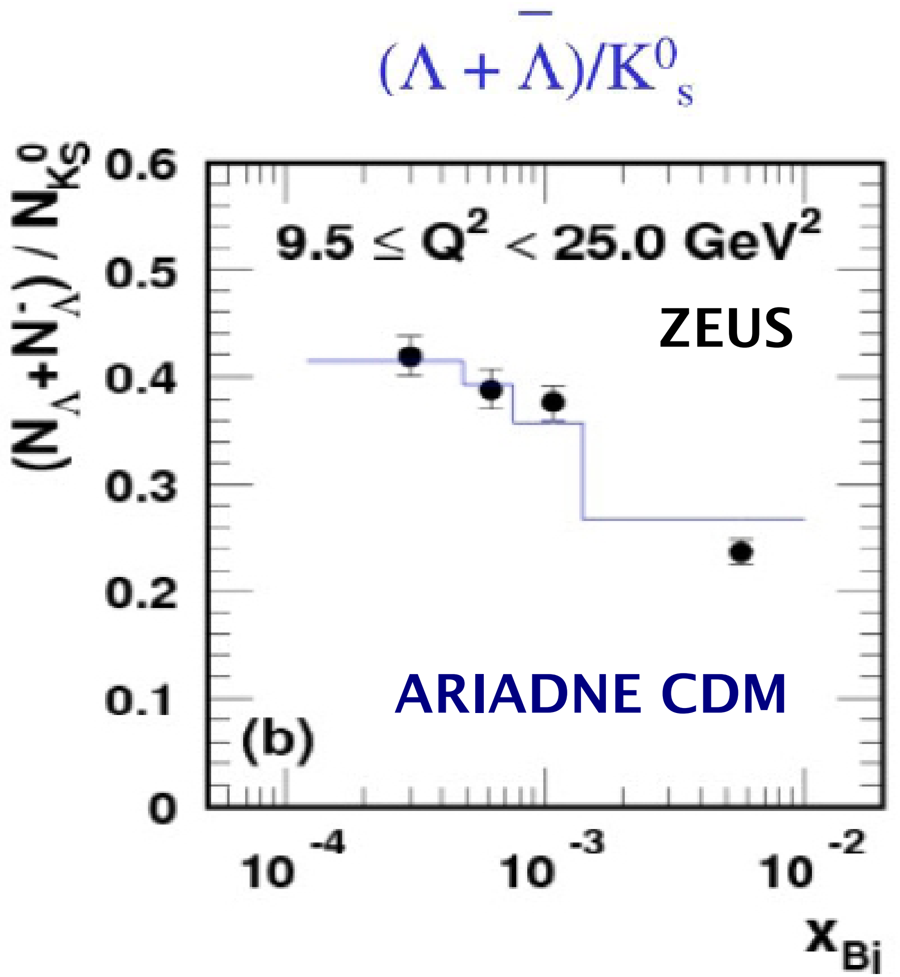
Strangeness production is always suppressed: $e_q{}^2$, branching fractions, fragmentation λ_s.

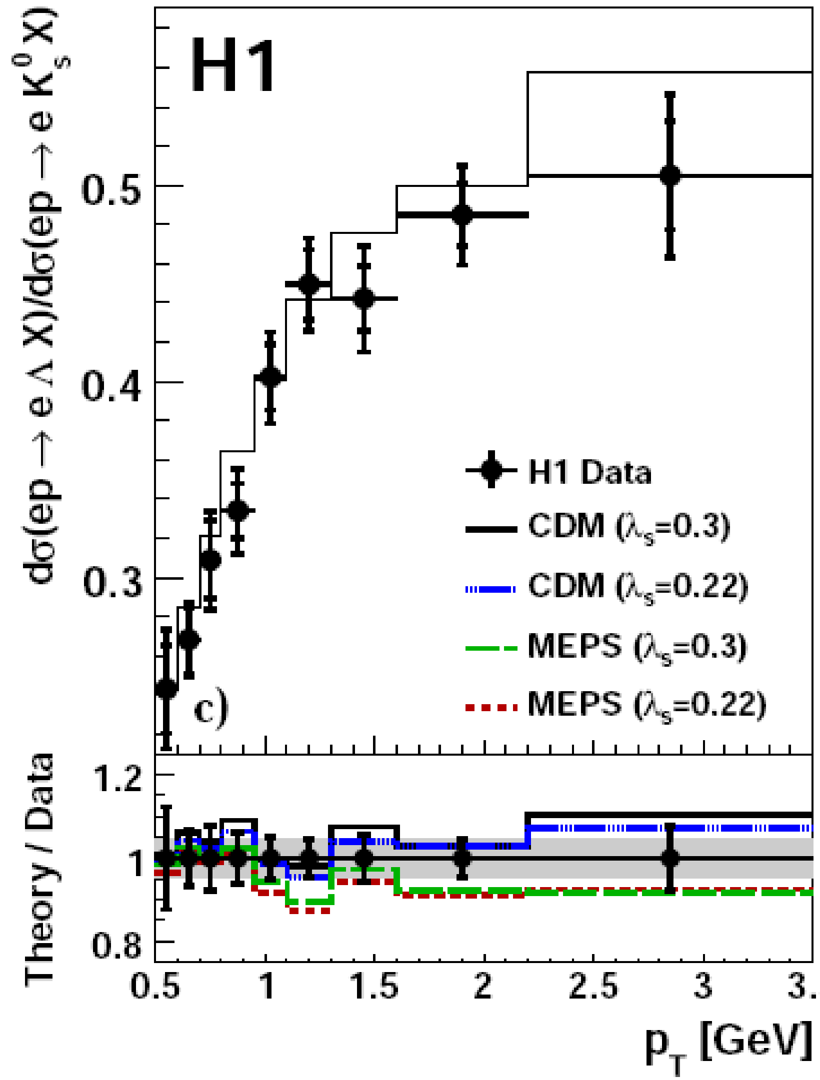
Strangeness production



Color dipole model with λ_s = 0.3 gives best description (not perfect).

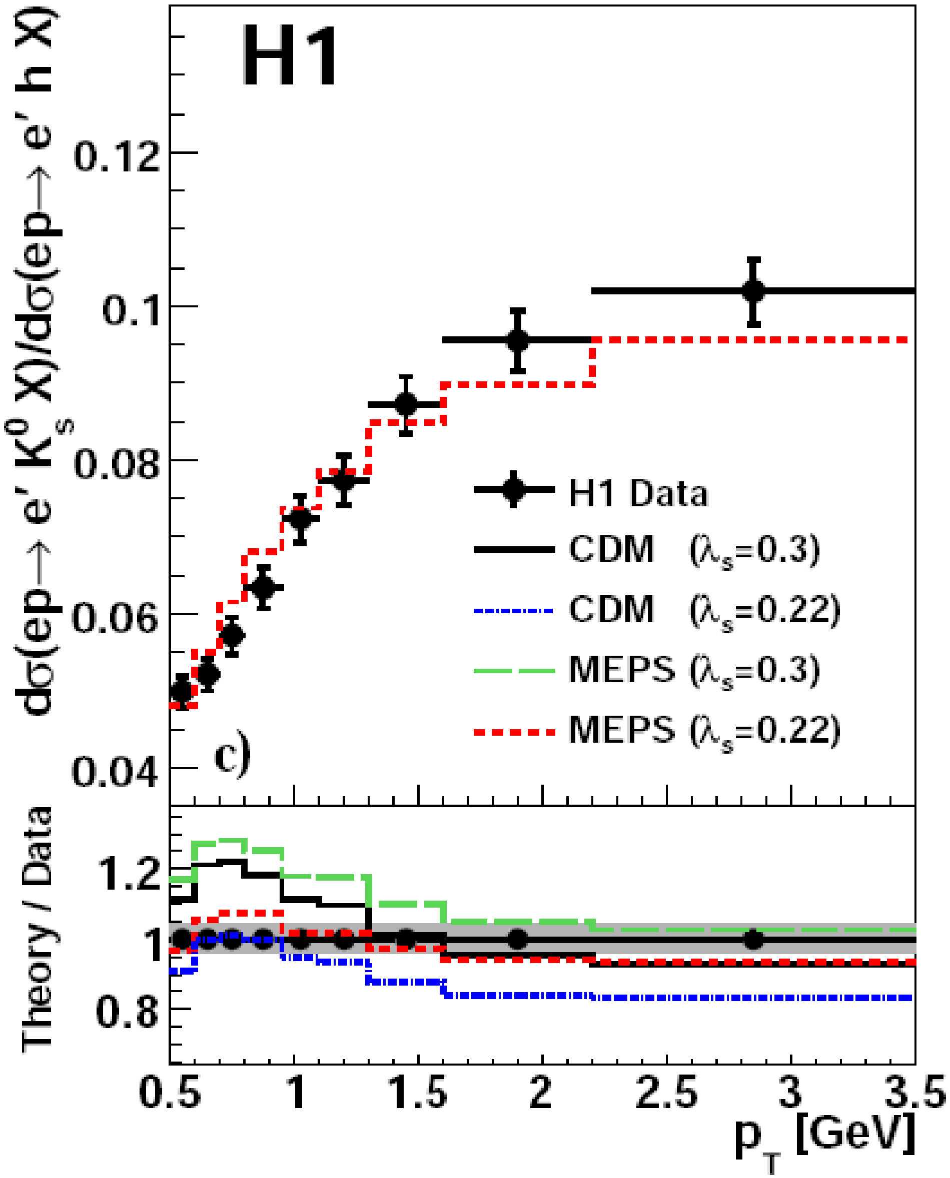
Strangeness production ratio





Color dipole model with λ_s = 0.3 gives best description (not perfect).

K^0 to charged hadron ratio



Ratio K^0/h has less sensitivity to PDFs and hard scattering process. Enhanced sensitivity to details of strangeness production.

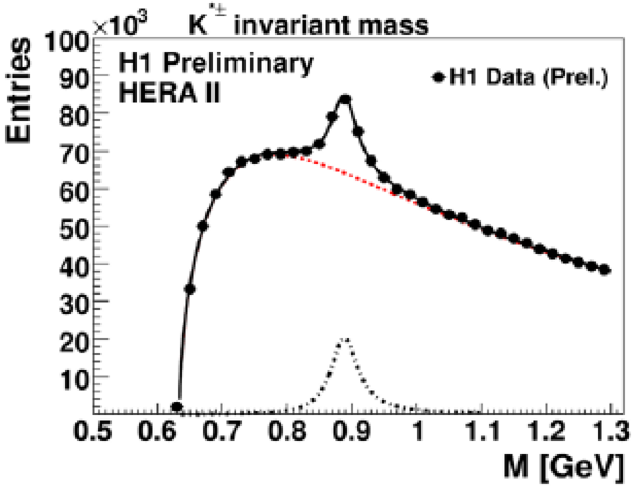
Ratio K/hadrons best described by MEPS with smaller λ_s = 0.22.

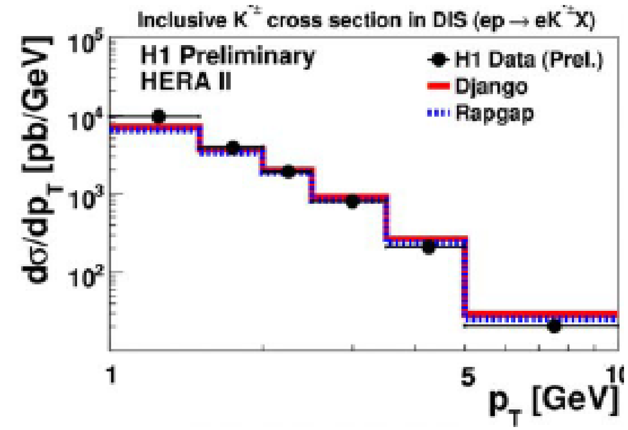
No single combination of model and λ_s describes all data.

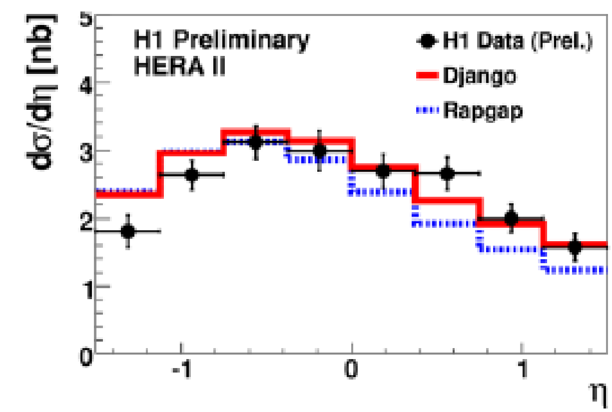
K*(892) production in DIS

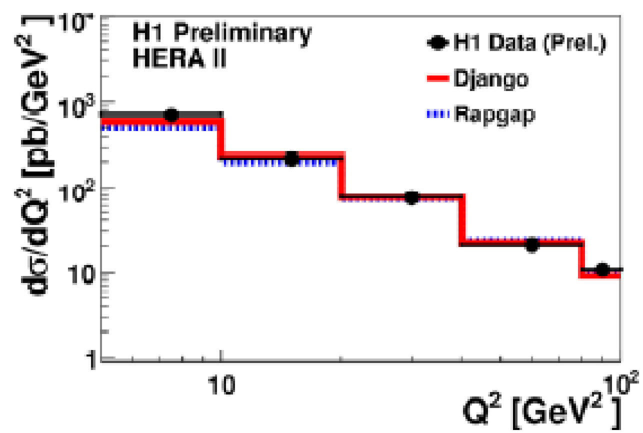
$K^{*\pm} \rightarrow K^0_S \pi^\pm$

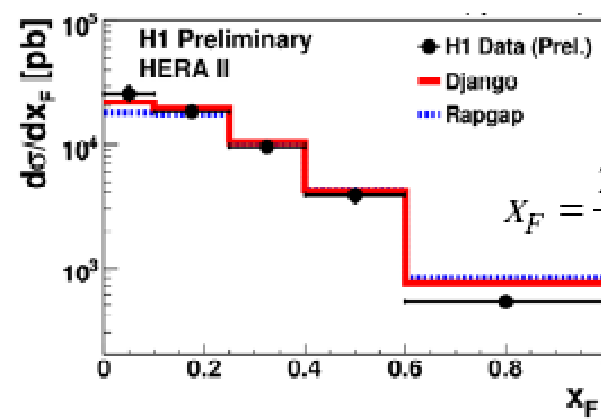
5<Q²<100 GeV², 301 pb⁻¹







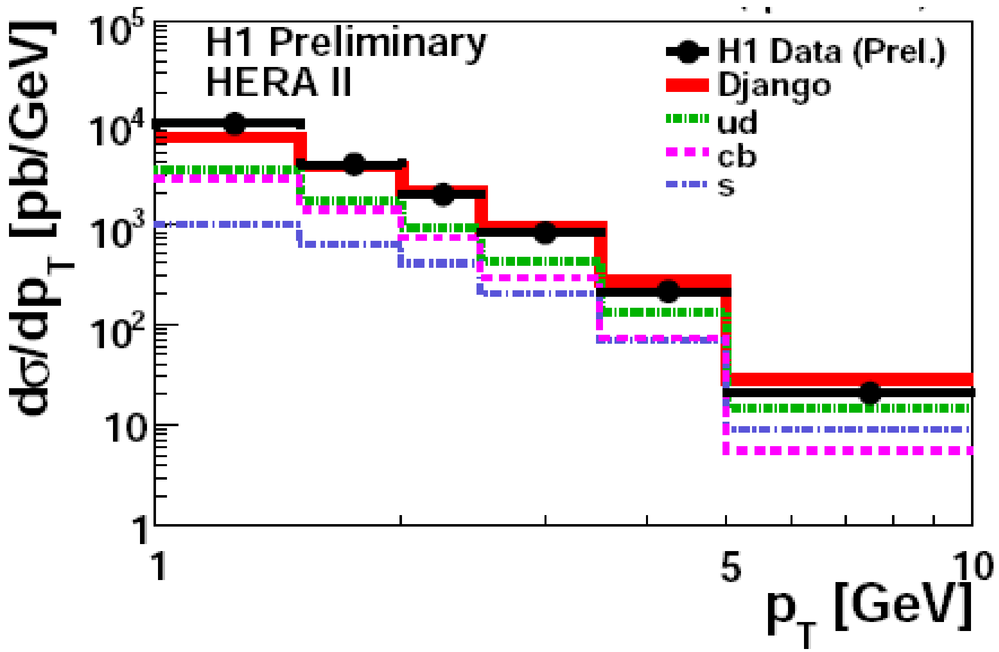


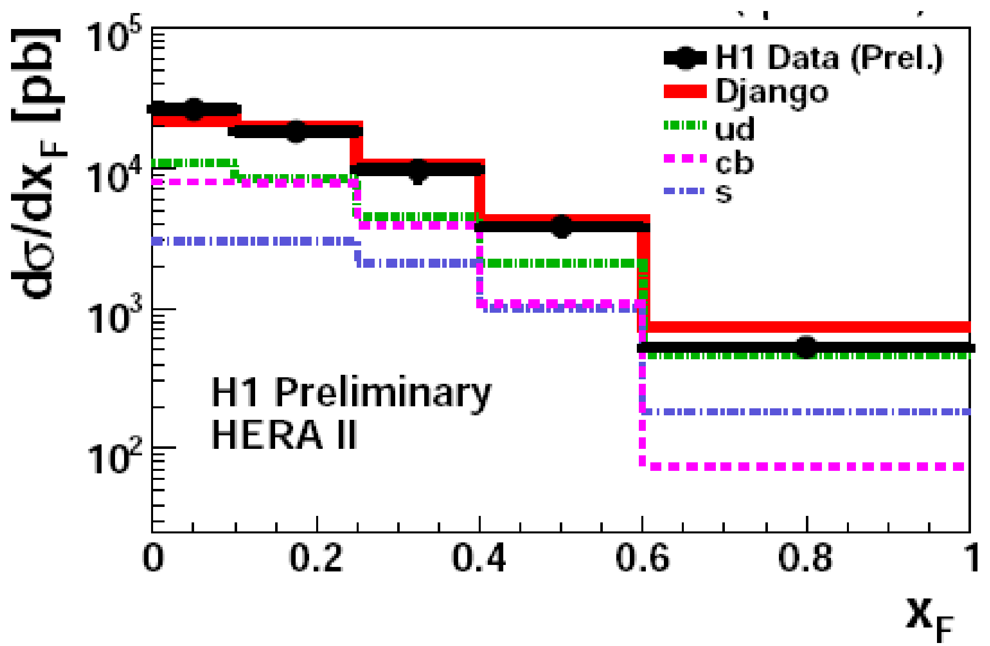


$$x_F = \frac{2P_L}{W}$$

K* cross sections measured first time at HERA : overall features described by Django (CDM) and RAPGAP (MEPS), details NOT (eg. eta shape)

K* production in DIS





Flavour decomposition:

Strangeness is never dominating.

Low sensitivity to strange pdf.

Bose-Einstein Correlations

BEC: enhanced production of pairs of identical bosons nearby in phase space.

Distance in phase space characterized by:

r = source size of particle emission

Q_{12} = distance in 4-momentum space

$$Q_{12} = \sqrt{-(p_1 - p_2)^2}$$

Correlation function $R(Q_{12})$, defined by two-particle density functions $P(Q_{12})$:

$$R(Q_{12}) = P(Q_{12}) \; / \; P_{noBEC}(Q_{12})$$

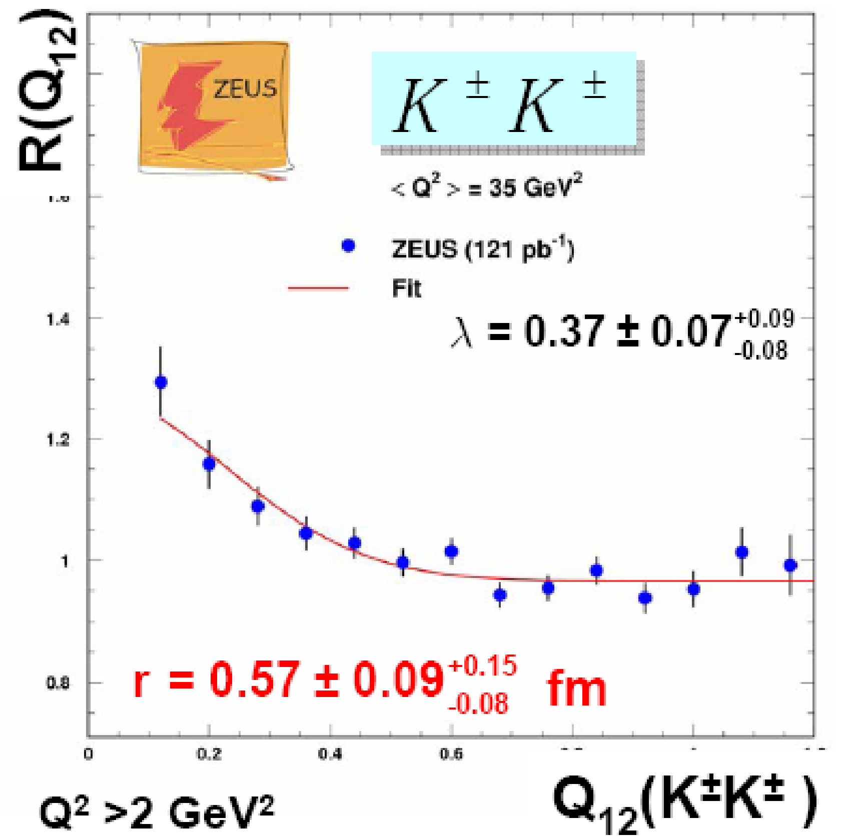
Static Gaussian source of strength λ:

$$R_{Gaus}(Q_{12}) = 1 + \lambda \exp(-r^2 Q^2{}_{12})$$

Reduce model sensitivity via double ratios R:

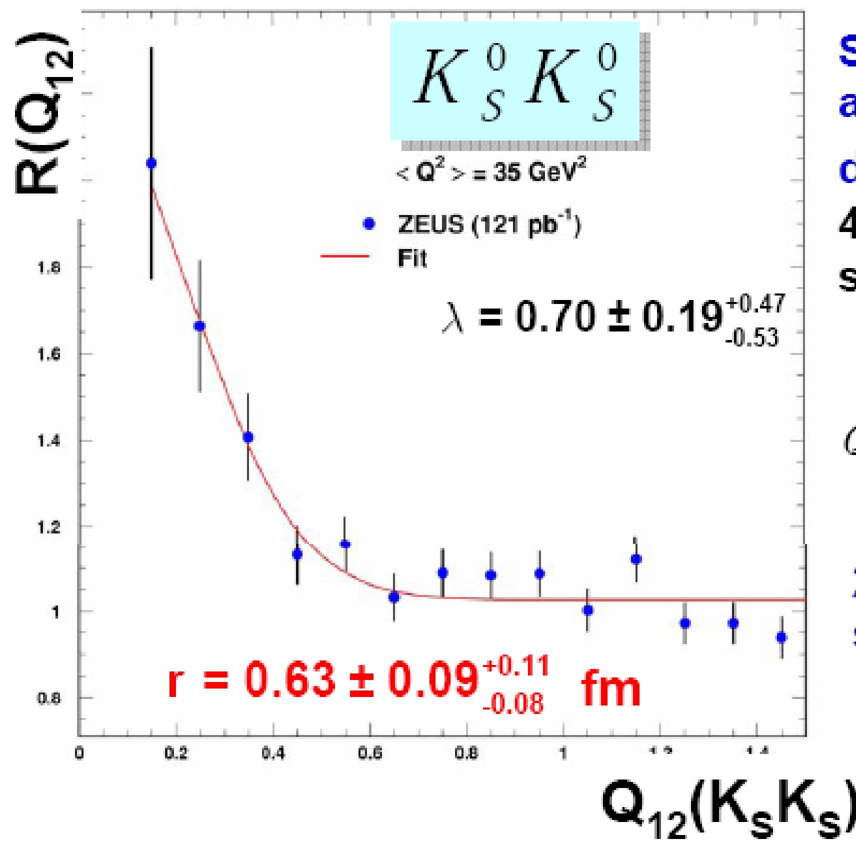
$$R(Q_{12}) = \frac{P(Q_{12})^{data}}{P_{mix}(Q_{12})^{data}} \; / \; \frac{P(Q_{12})^{MC,noBEC}}{P_{mix}(Q_{12})^{MC,noBEC}}$$

Bose–Einstein Correlation in the KK system



$Q^2 > 2$ GeV^2

121 pb^{-1}



Source size r and distance Q_{12} in 4-momentum space

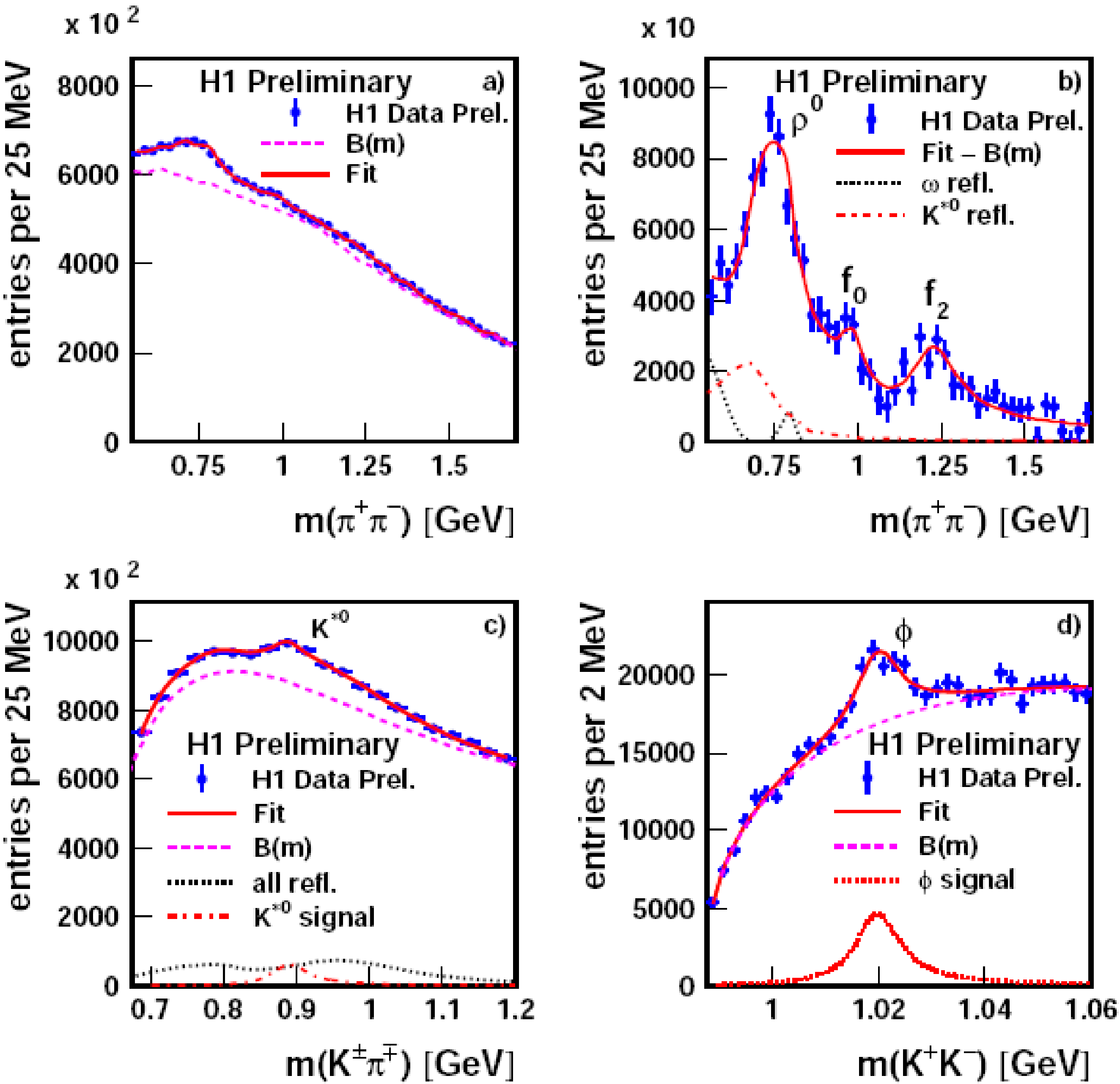
$$Q_{12} = \sqrt{-(p_1 - p_2)^2}$$

λ =source strength

ZEUS Collab., PL B 652 (2007) 181

Bose-Einstein correlations clearly established for $K^{\pm}K^{\pm}$ pairs
K_s K_s inconclusive, $f_0(980) \rightarrow K_s$ K_s background → large systematics
Source radius "r" found similar to LEP results

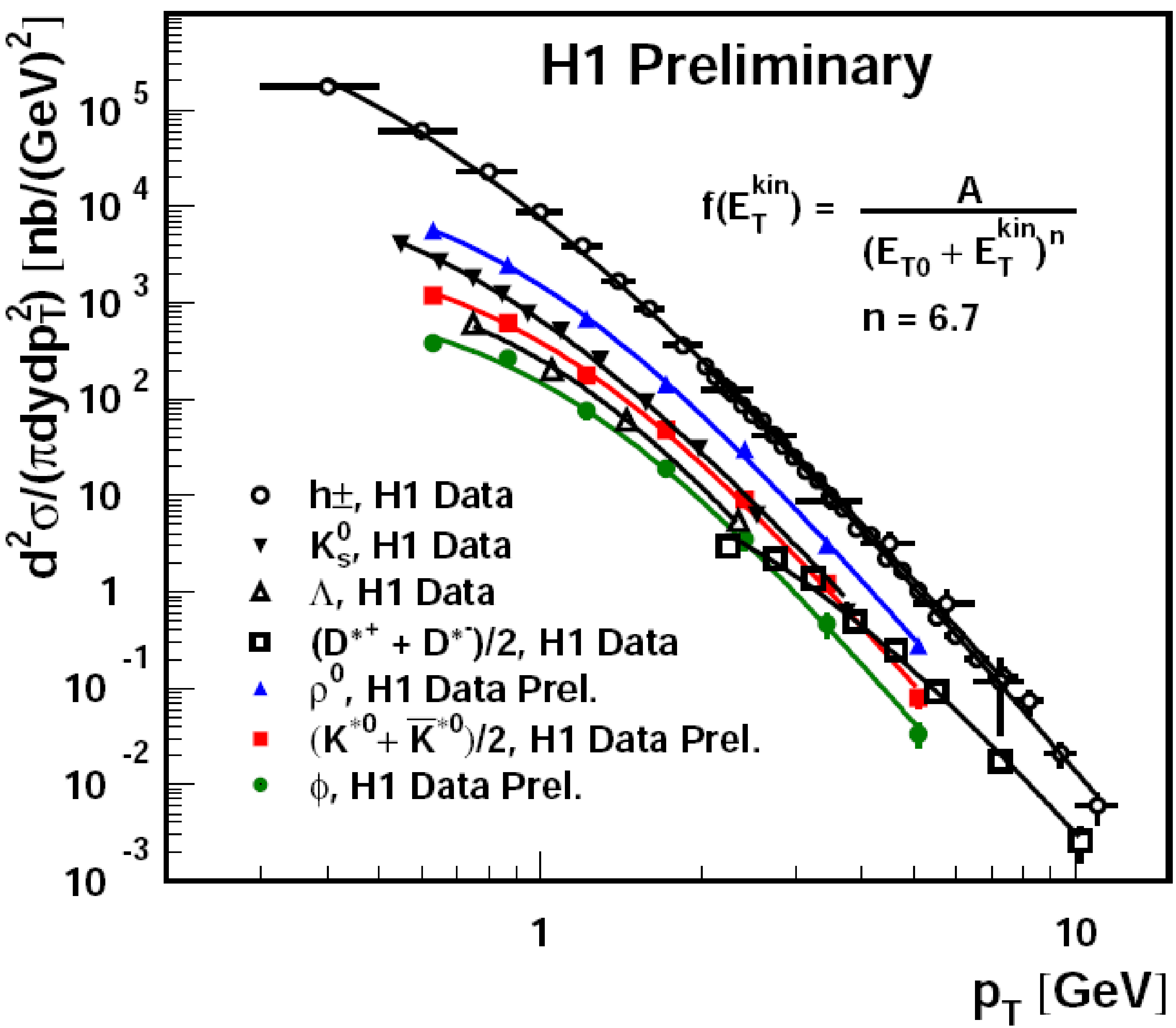
Inclusive photoproduction of ρ, K^*, and ϕ



Tagged photoproduction
<W> = 210 GeV.
36.5 pb^{-1}.

Fit:
modified relativistic
Breit–Wigner
+ reflections
+ combinatorial
background.

Particle spectra in photoproduction



Mass effects taken into account in E_T^{kin} = $(p_t^2 + m^2)^{1/2} - m$ and $E_{T0}(m)$.

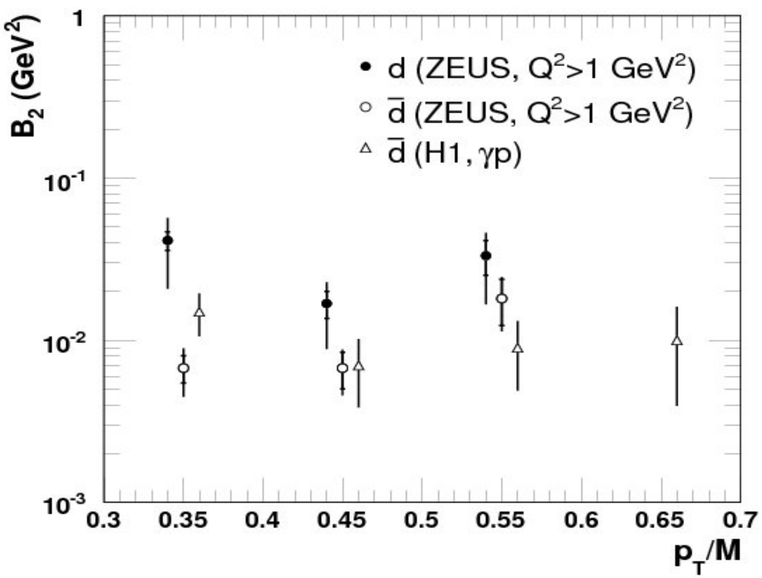
Universal power law with n = 6.7

Deuteron production

Coalescence model:

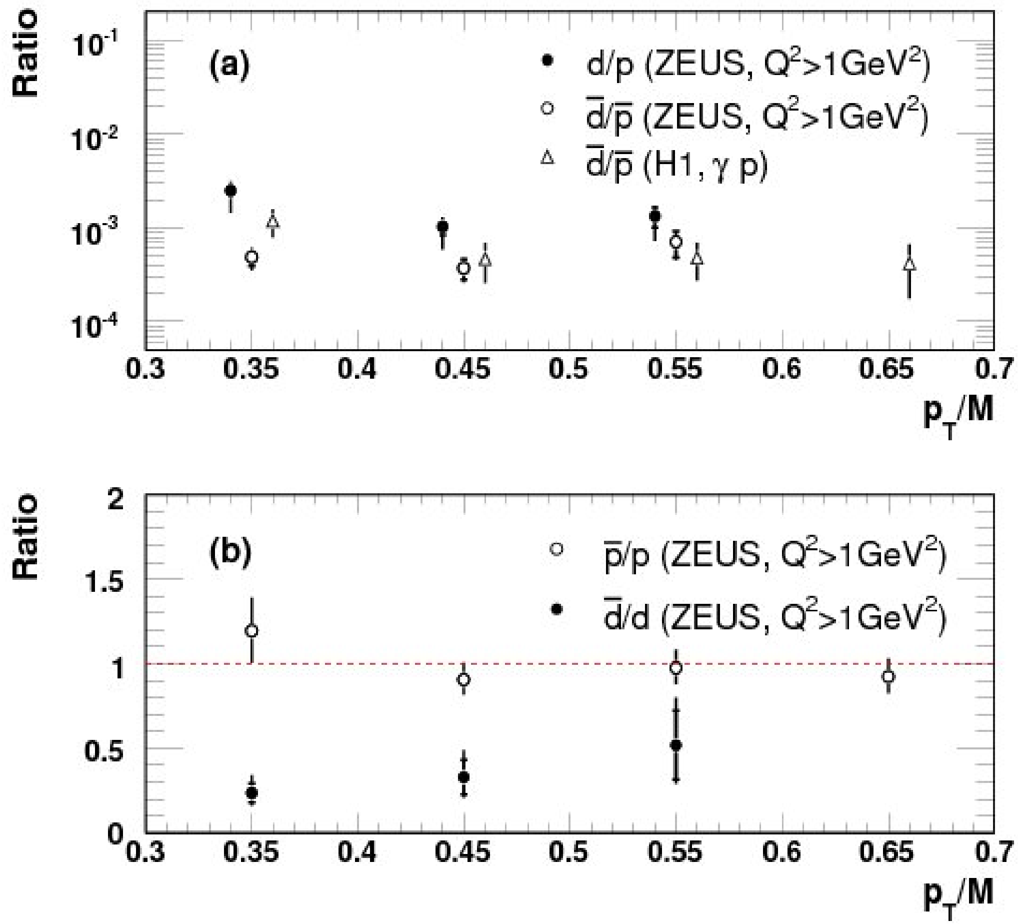
$$\frac{1}{\sigma}\frac{d^3\sigma(d)}{d^3p} = B_2\left(\frac{1}{\sigma}\frac{d^3\sigma(p)}{d^3p}\right)\left(\frac{1}{\sigma}\frac{d^3\sigma(n)}{d^3p}\right)$$

$B_2(d) = B_2(\bar{d})$ is expected



$$B_2(d) = 3.32 \pm 0.34^{+1.13}_{-1.55}$$

$$B_2(\bar{d}) = 0.89 \pm 0.14^{+0.19}_{-0.20}$$



Enhanced production of multi-quark states?

Spectroscopy

K^0K^0 - resonances

Since gluons carry both color and anti-color,
2 or 3 may form color singlet "glueballs"

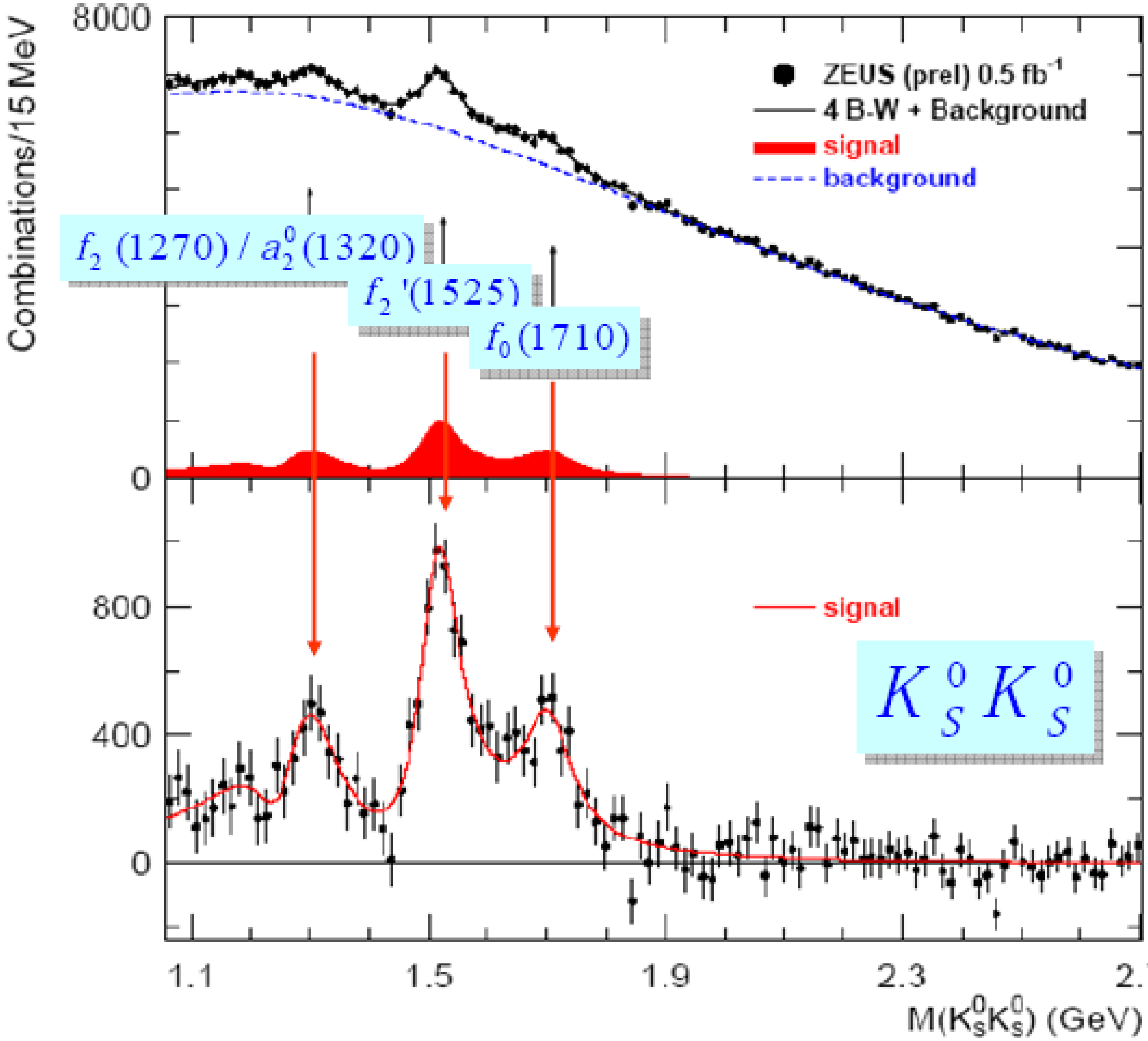
Lattice QCD calculations predict:

lightest glueball $J^{PC} = 0^{++}$ in mass range 1450-1750 MeV

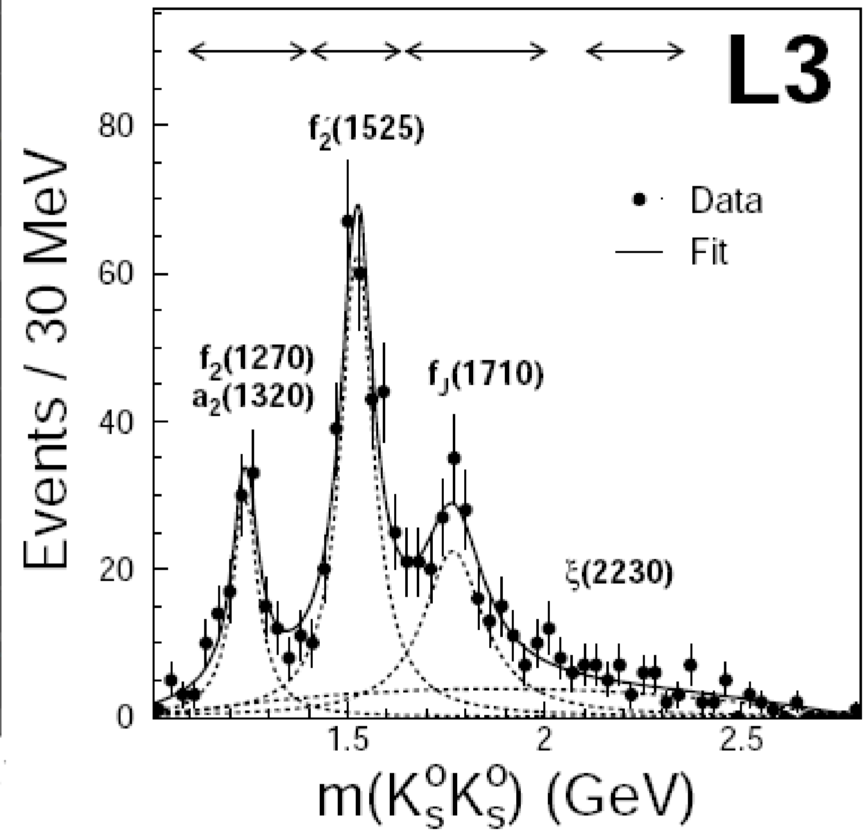
next: $J^{PC} = 2^{++}$ in mass range 2300-2600 MeV

$K_s^0K_s^0$ bound states: $J^{PC} = 0^{++}$ (scalar), 2^{++} (tensor), ..
hence may couple to glueballs

K^0K^0 - resonances

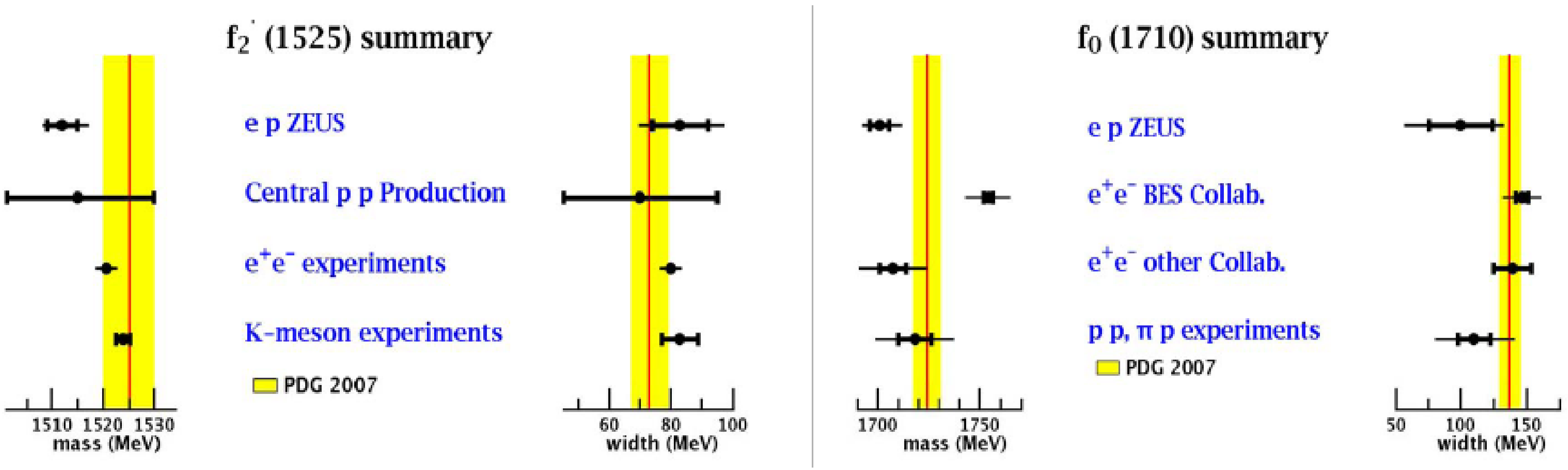


$\gamma\gamma \to K_S^0 K_S^0$



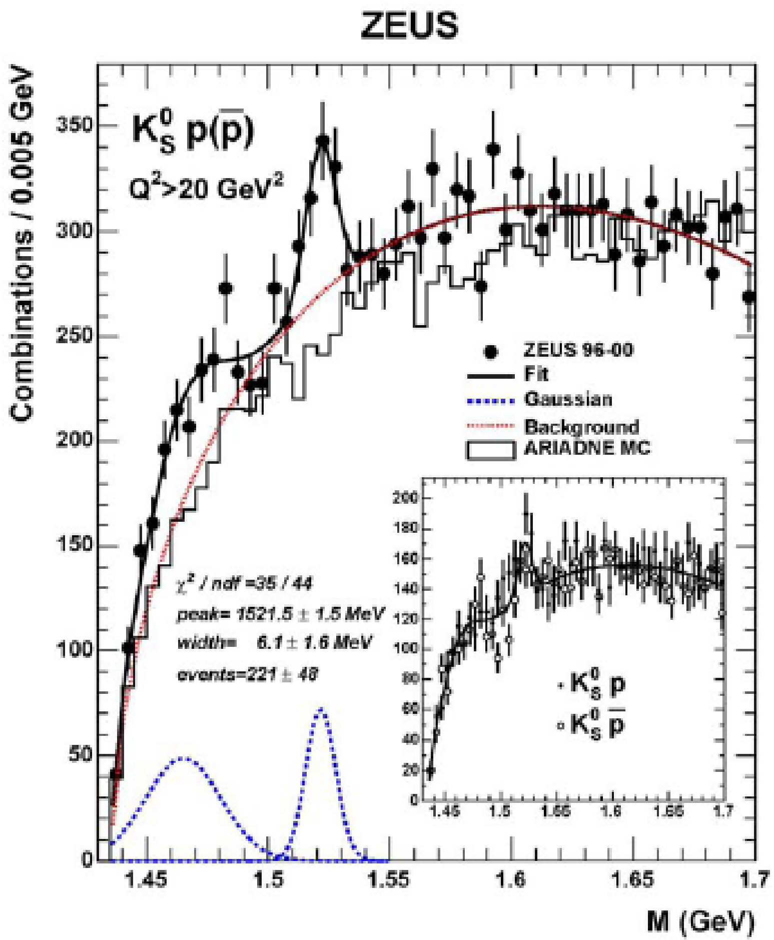
f_0(1710) cannot be a pure glueball, since it couples to γγ.

K^0K^0 - resonances



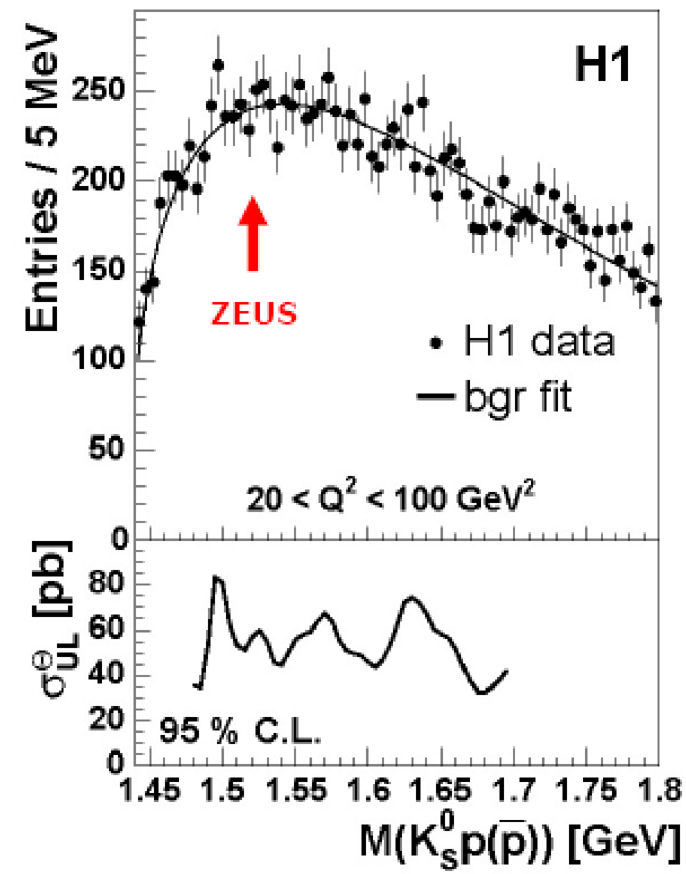
Strange Pentaquark Θ^+

Search for: $\Theta^+ \rightarrow K_s^0 p$ and $\overline{\Theta^+} \rightarrow K_s^0 \bar{p}$



ZEUS has a positive signal at 1522 MeV

HERA I data

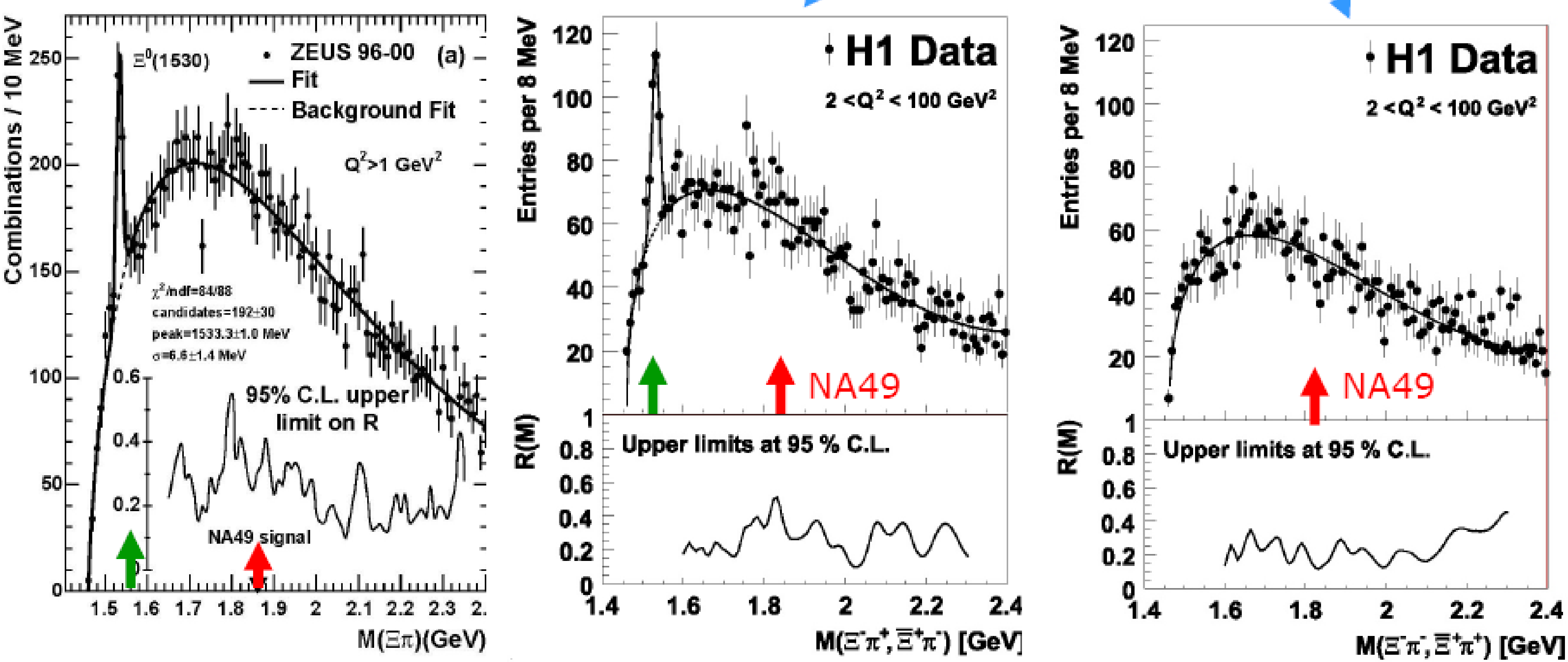


No signal observed in H1, upper limits set on cross sections.

Hyperons and double strange Pentaquarks Ξ_{5q}

Search for: Ξ_{5q}^{--} and Ξ_{5q}^{0}

$$\Xi^-\pi^- \rightarrow [\Lambda\pi^-]\pi^- \rightarrow [(p\pi^-)\pi^-]\pi^-$$
$$\Xi^-\pi^+ \rightarrow [\Lambda\pi^-]\pi^+ \rightarrow [(p\pi^-)\pi^-]\pi^+$$



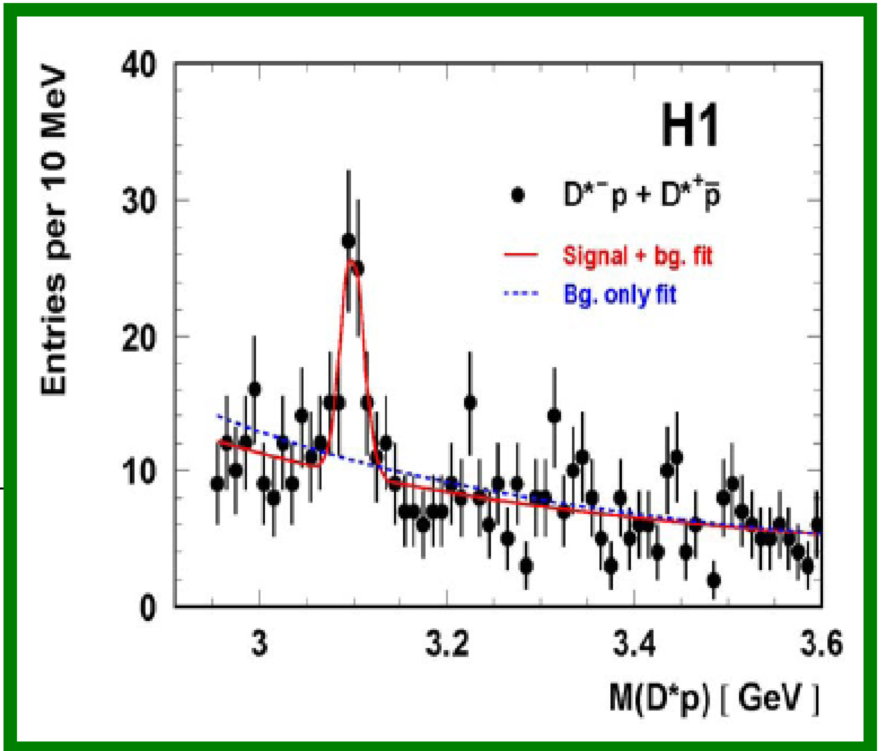
Known resonant state **$\Xi(1530\ \text{MeV})^0$**. No signal at 1862 MeV (**NA49**), cross section upper limits set relative to 1530 state.

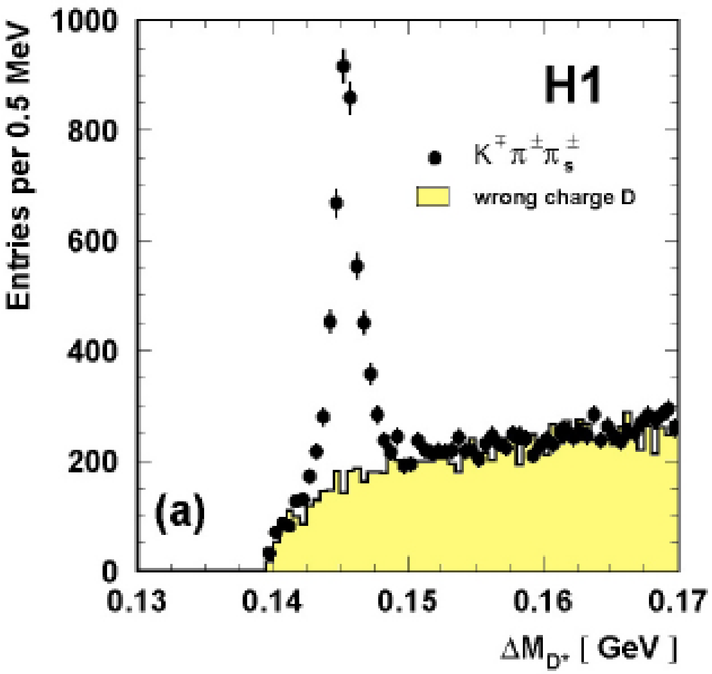
D*p resonance (charm PQ)

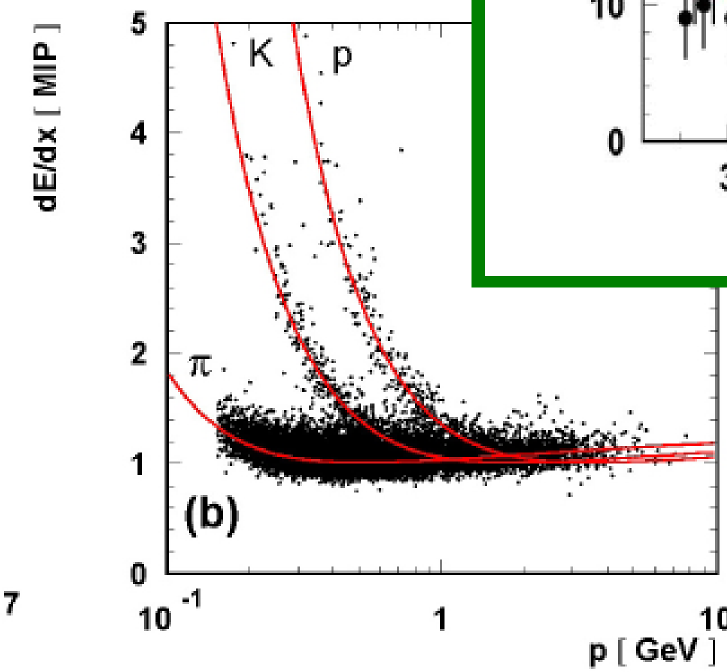
A resonance was observed by H1 with HERA I data (75 pb^{-1})

Invariant mass = 3099 ± 3 MeV

RMS = 12 ± 3 MeV







Minimum quark content:

$uudd\bar{c}$

anti-charm baryon.

pentaquark candidate?

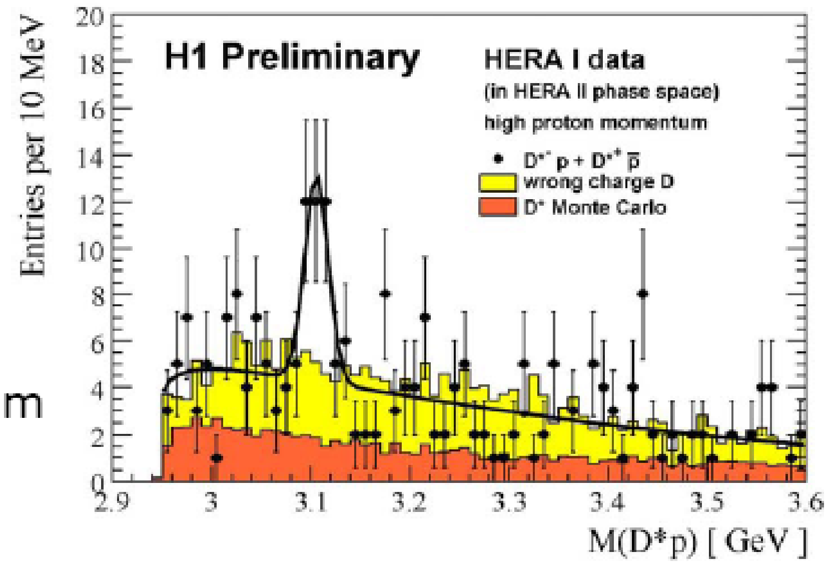
Not seen by ZEUS, FOCUS, BaBar, CDF, ALEPH.

D*p resonance

HERA I data

HERA II phase space

high proton momentum

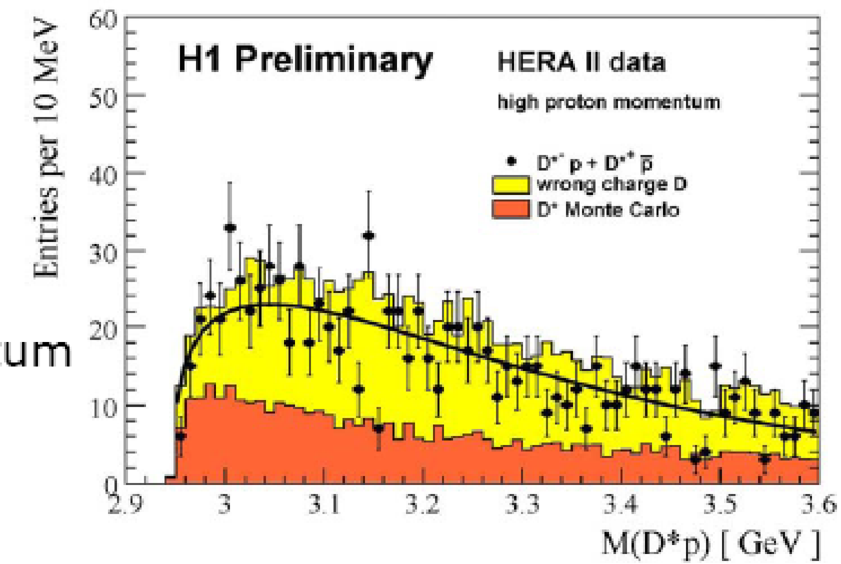


Signal observed in reduced phase space

ratio N(D*p)/N(D*) of 0.81±0.21%

HERA II data

high proton momentum



No peak, 95% CL limit of 16.3 events.

ratio limit: 0.10%

In both cases:
D* Background well described
(MC+wrong charge)

Summary

Precision measurements of particle production allow at detailed study of QCD dynamics in the perturbative and non-perturbative regimes.

Multiplicities and fragmentation functions broadly show similar behavior between ep and ee reactions, but some regions of phase space also show significant differences.

Models of particle production based on leading-order QCD matrix elements augmented by parton showers or dipole emission provide a decent description of the data, but no combination of model and parameters is perfect, especially for strangeness production.

Next-to-leading order QCD calculations augmented by fragmentation functions do not describe the data well.

Progress is expected with MC@NLO:

PDF ⊗ PS ⊗ ME(NLO) ⊗ PS ⊗ frag.

Summary 2

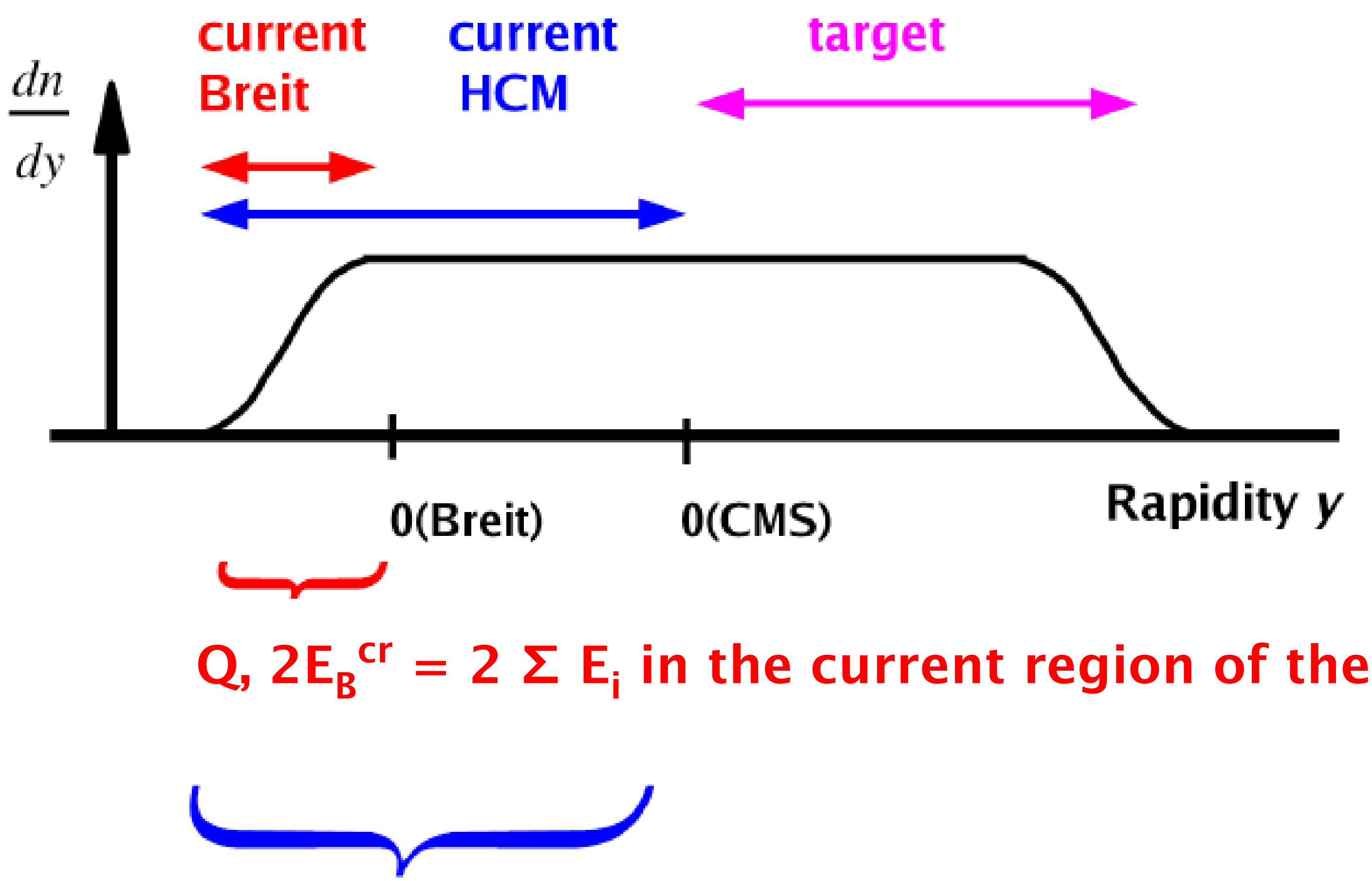
Strangeness production is dominated by u- and c-quark initiated processes: only low sensitivity to strange quark density.

Enhanced production of deuterons over anti-deuterons.

Pentaquarks:
- **Θ^+ seen by ZEUS (and Hermes) in HERA I data, not by H1.**
- **Ξ_{5q} not seen by ZEUS and H1.**
- **D*p (3099) seen by H1 in HERA I data, not by ZEUS. Not seen in H1 HERA II data.**

Backup

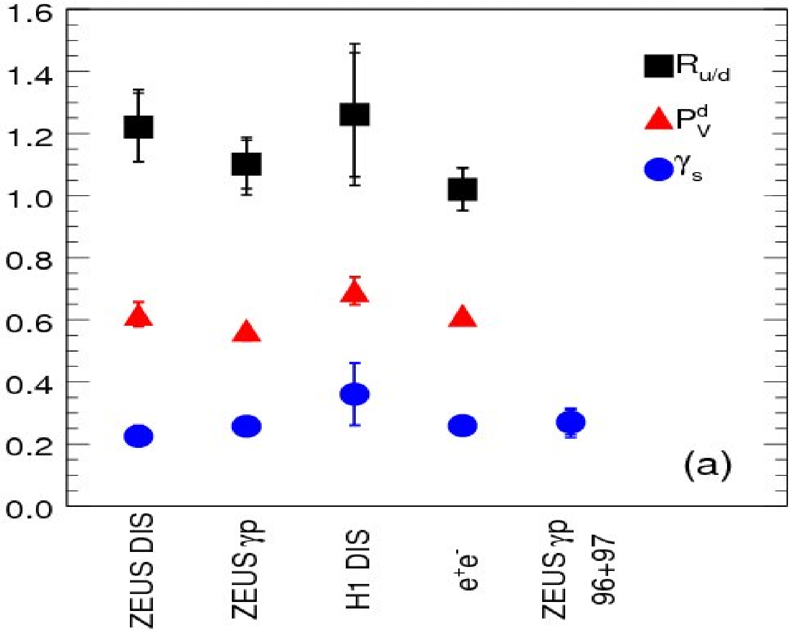
Energy scales

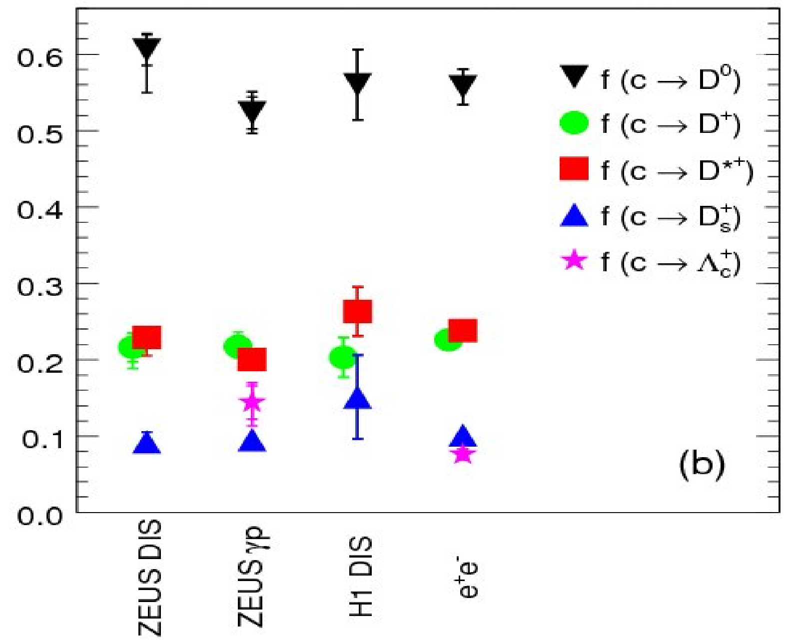


Q, $2E_B^{cr} = 2\,\Sigma\, E_i$ in the current region of the Breit frame

W in the hadronic center-of-mass system

Fragmentation of Charm Quarks   I





Fragmentation ratios:

$R_{u/d} = (c\bar{u})/(c\bar{d})$

$\gamma_s = (2c\bar{s})/(c\bar{d}+c\bar{u})$

$P_v = V/(V+PS)$

Fragmentation fraction

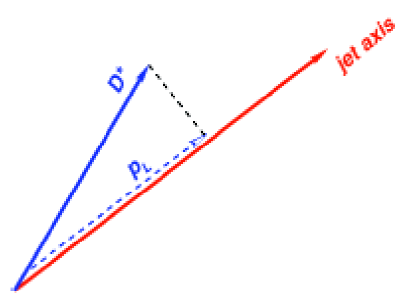
$f(c \to D) = \sigma(D)/\sigma(c)^{tot}$

Measurements support universality of charm fragmentation

Charm fragmentation

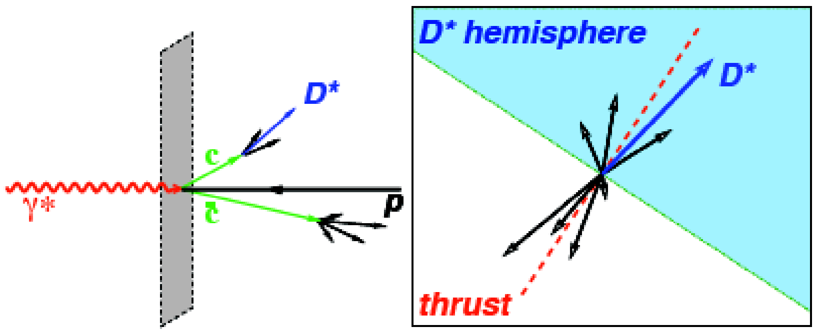
$$\sigma_H = \sum_i \sum_k f_{i/p}(x,\mu_f) \otimes \hat{\sigma}_{i\gamma\to kX}(\alpha_s(\mu_r),\mu_r,\mu_f) \otimes D_k^H(z,\mu_f)$$

Parton Density Function — **Hard Scattering (perturbative)** — **Fragmentation Function**



$$z_{jet} = \frac{(E+p_L)_{D^*}}{(E+p)_{jet}}$$

- Jet method
  - momentum of c-quark approximated by momentum of reconstructed D*-jet

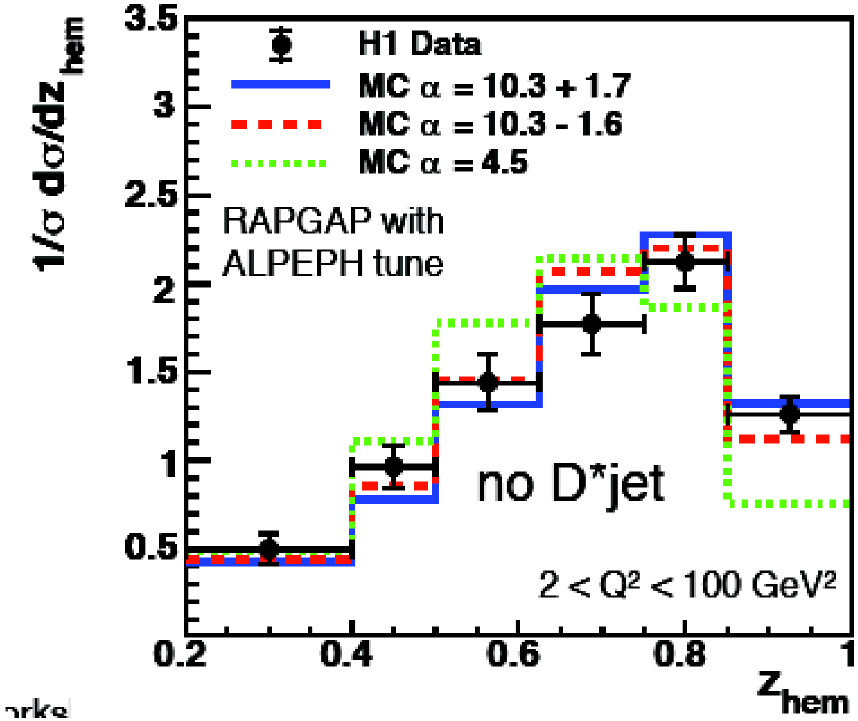


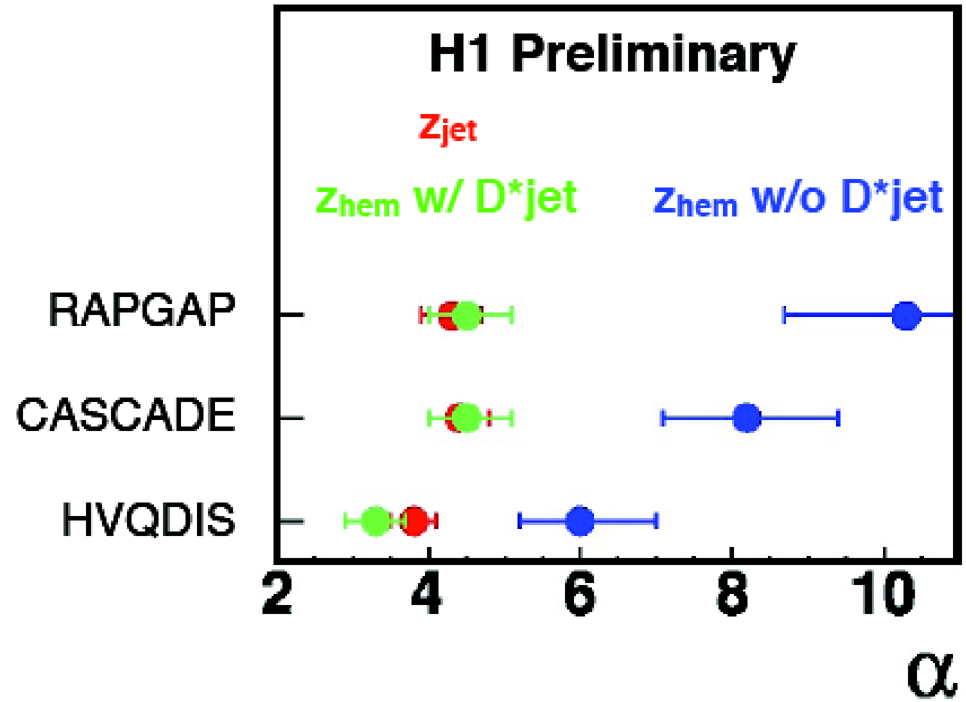
$$z_{hem} = \frac{(E+p_L)_{D^*}}{\sum_{hem}(E+p)_i}$$

- Hemisphere method
  - momentum of c-quark approximated by momentum of reconstructed D*-hemisphere

Charm fragmentation

Kartvelishvili: $D_Q^H(z) \propto z^\alpha(1-z)$





no D*jet

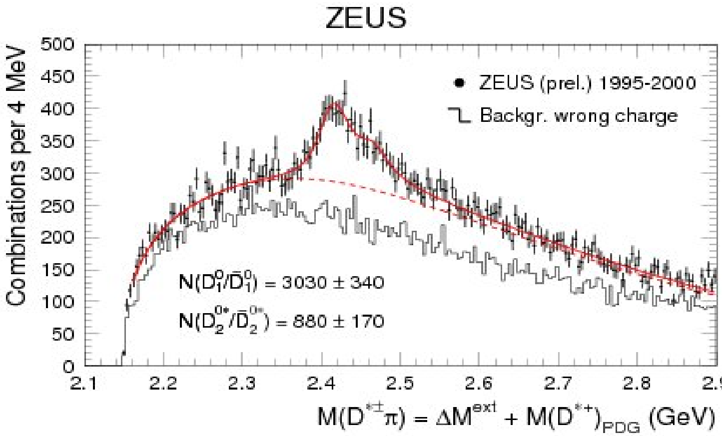
observed spectrum significantly harder

LO+PS MC models RAPGAP and CASCADE

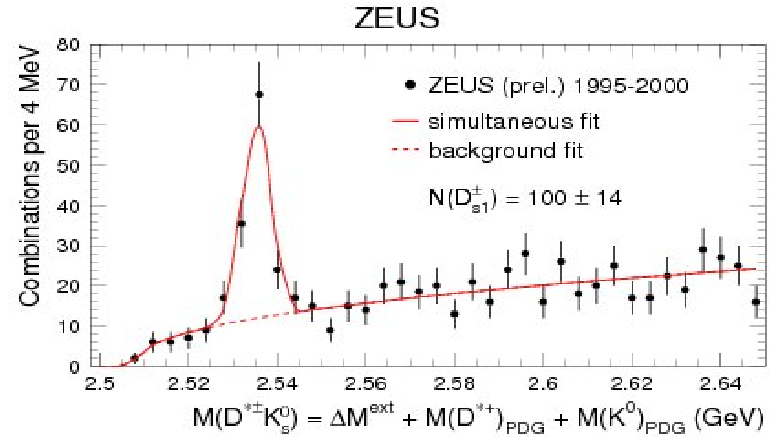
massive NLO calculation HVQDIS

Discrepancy due to improper description of underlying physics close to the charm production threshold in the models

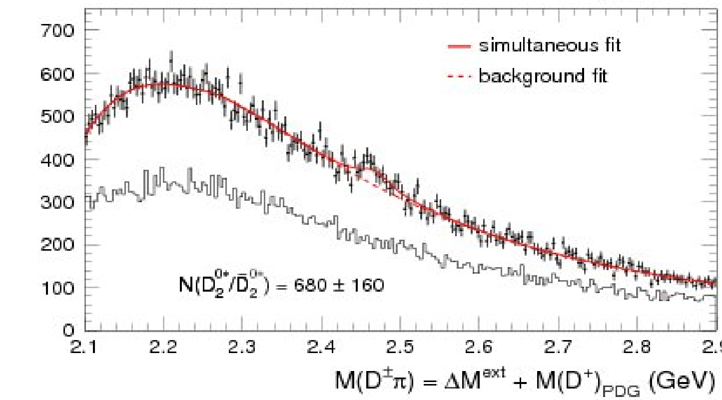
Excited charm and charm-strange mesons



$D_1(2420)^0$ and $D_2^*(2460)^0$ in $D^{*+}\pi^-$

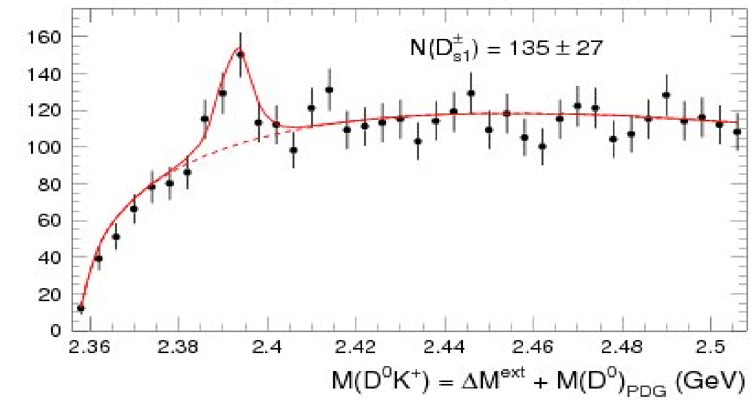


$D_{s1}(2536)^{\pm}$ in $D^{*\pm}K^0_s$



$D_2^*(2460)^0$ in $D^+\pi^-$

$D_{s1}(2536)^+$ in D^0K^+



$$f(c \to D_1^{\,0}) = 3.5 \pm 0.4^{+0.4}_{-0.6} \pm 0.2\,\%$$

$$f(c \to D_2^{\,*0}) = 3.8 \pm 0.7 \pm 0.6 \pm 0.2\,\%$$

$$f(c \to D_{s1}^{\,+}) = 1.1 \pm 0.2 \pm 0.1 \pm 0.1\,\%$$

Consistent with the e^+e^- measurements

Helicity measurements:

$$R(D_1^{\,0}) = 6.1 \pm 2.3^{+2.0}_{-0.8} \quad \text{HQET:} +3$$

$$R(D_{s1}^{\,+}) = -0.74^{+0.23+0.06}_{-0.17-0.05}$$

hardly consistent with 0 (CLEO conclusion)