Particle Production and Spectroscopy at HERA

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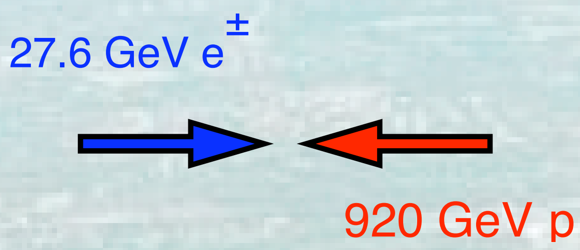
DESY, Hamburg

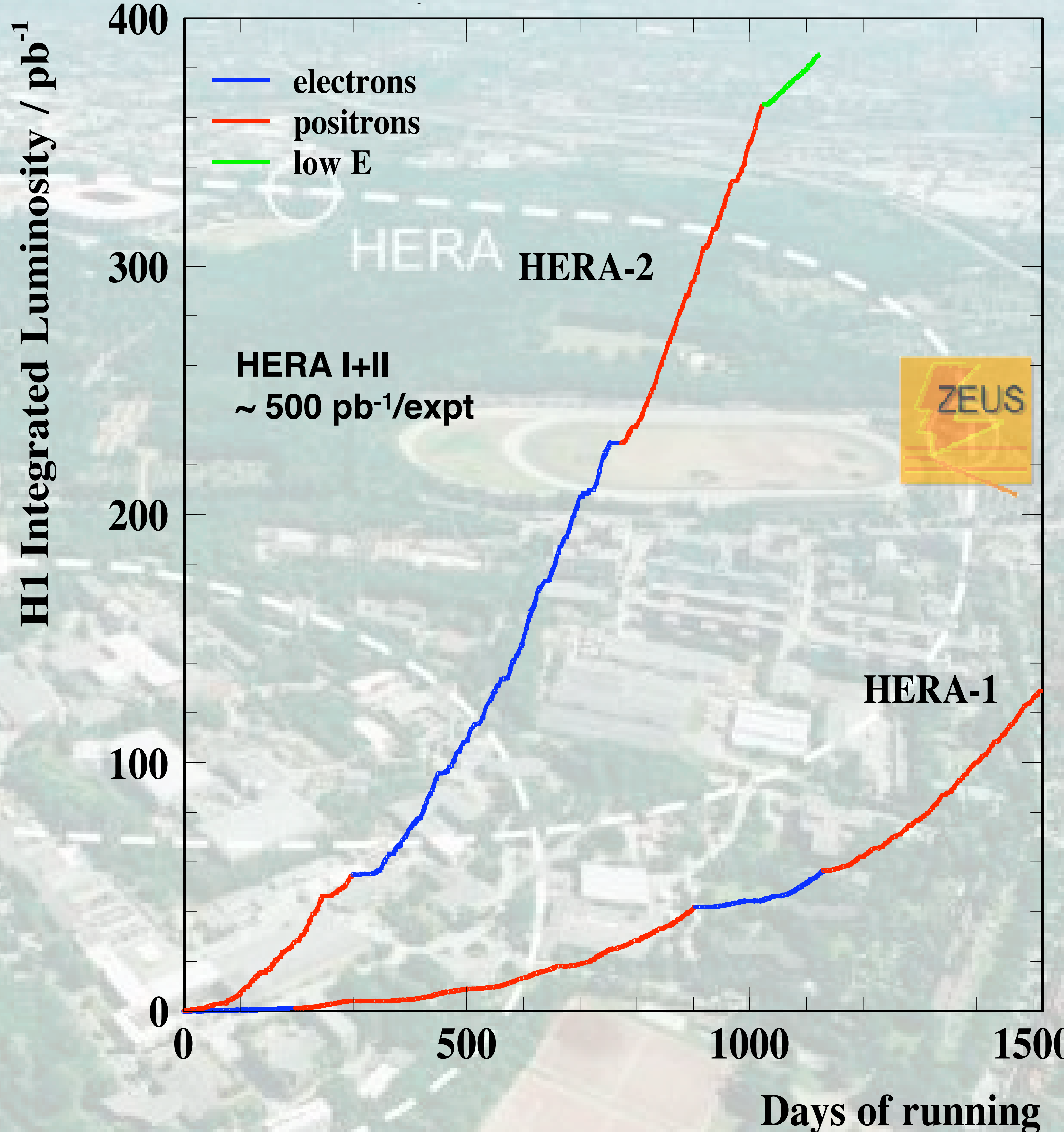
Low x Workshop, Kolimpari, Crete, Greece, July 6-10 2008

Outline



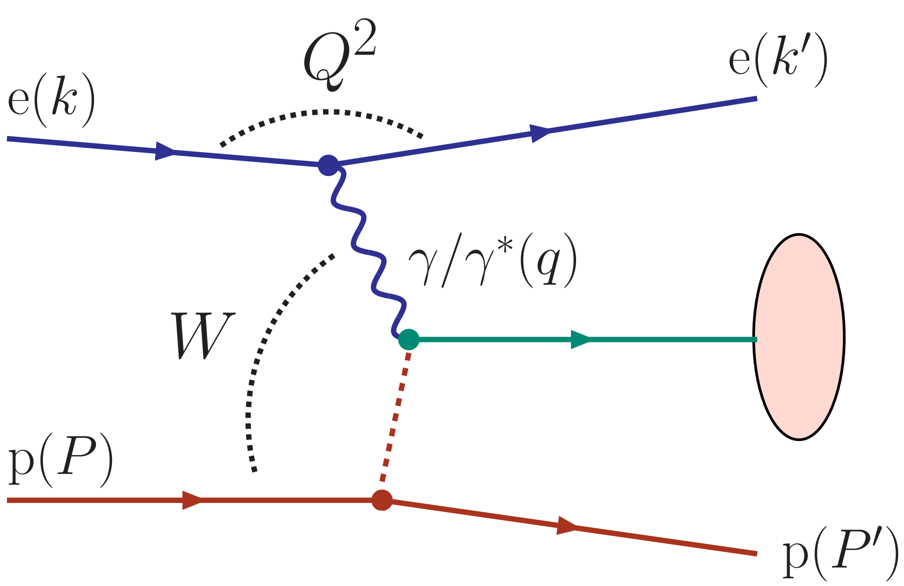
- **Fragmentation**
  - charged particle production
  - D* fragmentation
  - strangeness production

- **Spectroscopy**
  - excited charm mesons
  - search for glueballs
  - search for pentaquarks



Hadron Production at HERA

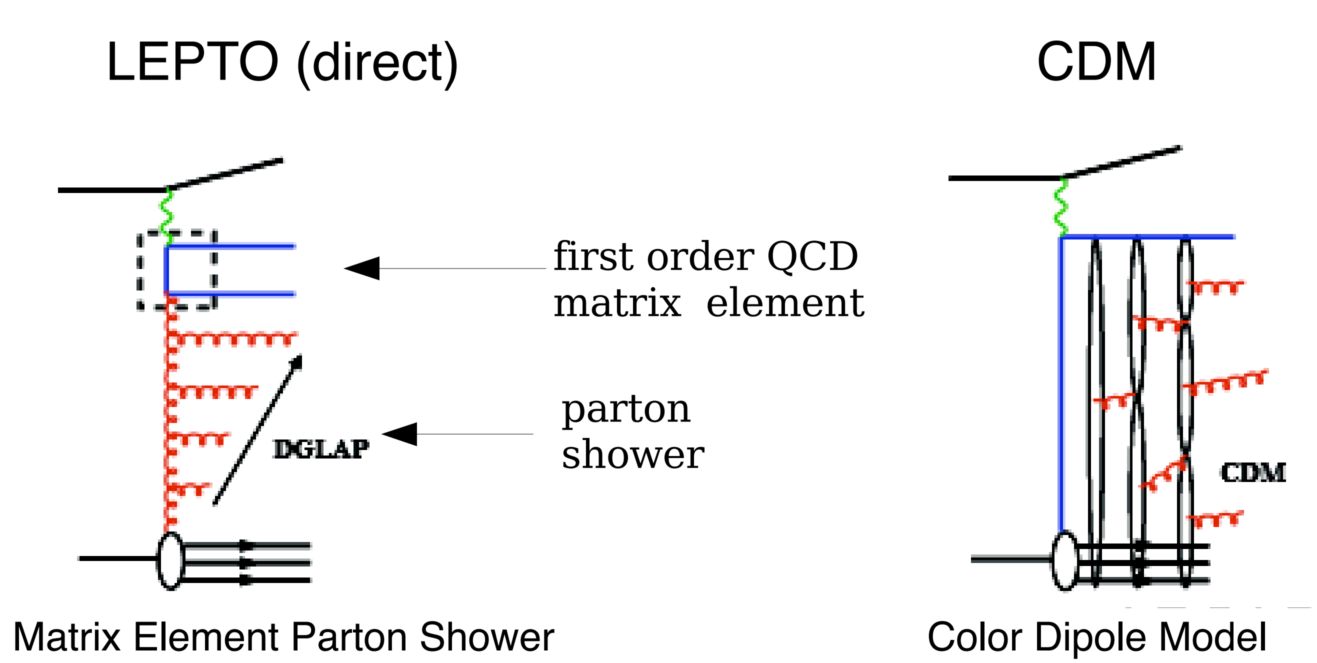
Born Level



ep Kinematics:

- Center of Mass Energy **$s = (P+k)^2$**
- Hadronic Energy (γ*p) **$W^2 = (P+q)^2$**
- Photon Virtuality **$Q^2 = -q^2 = -(k-k')^2 = xys$**
- Inelasticity **$y = P.q / P.k$**

QCD models



- Non-perturbative hadronisation process leading to hadronic final state
- Different QCD MC models have been developed
- Two regimes
  - $Q^2 \approx 0$ GeV^2 Photoproduction
  - $Q^2 > 1$ GeV^2 Electroproduction (DIS)

Charged Multiplicity

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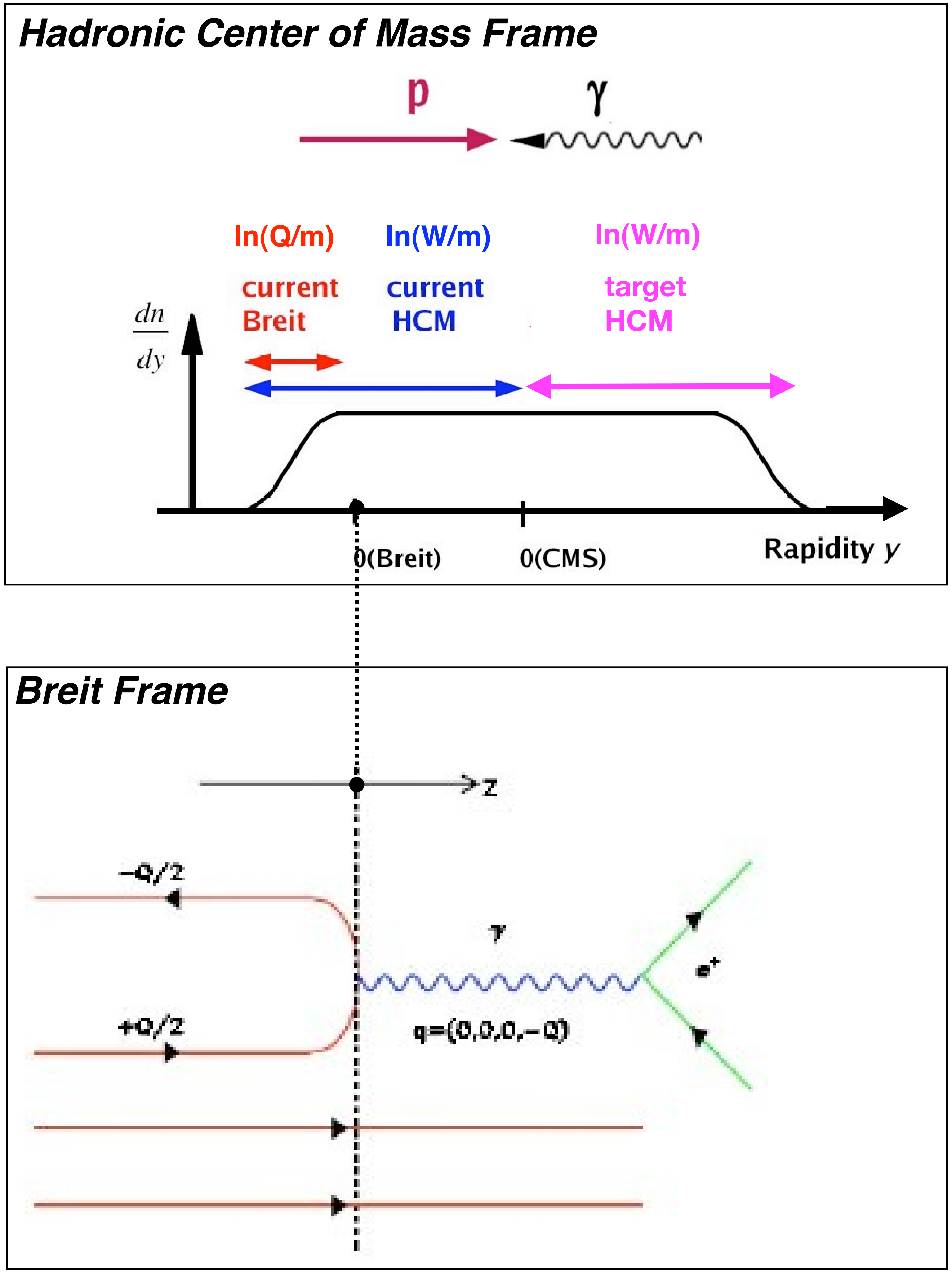
Global Event Characteristics

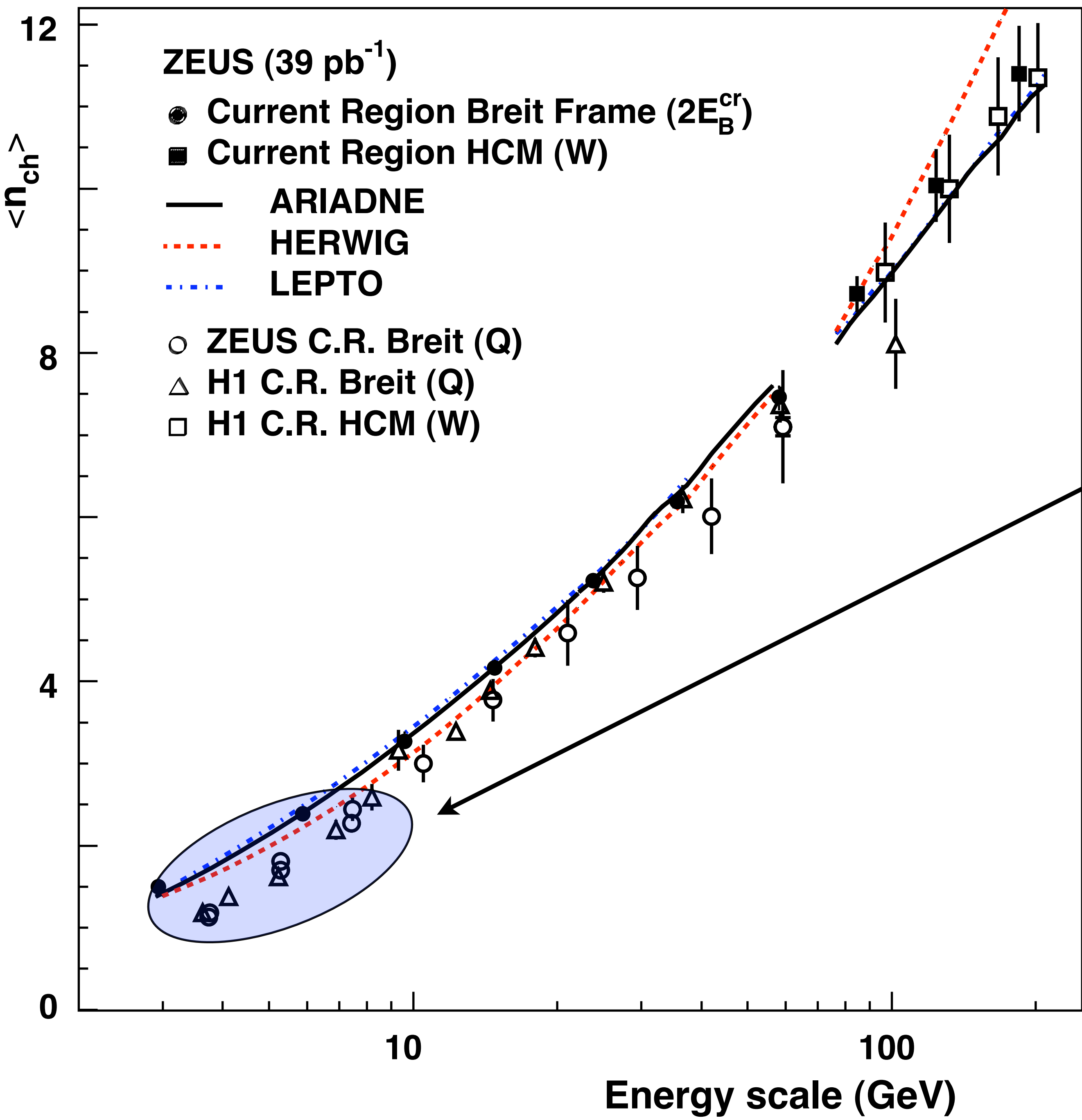


- For meaningful comparison of results obtained in different reactions have to chose appropriate frame of reference
  - hadronic center of mass
  - Breit frame
    - purely space like photon momentum
    - relatively clean separation from proton remnant

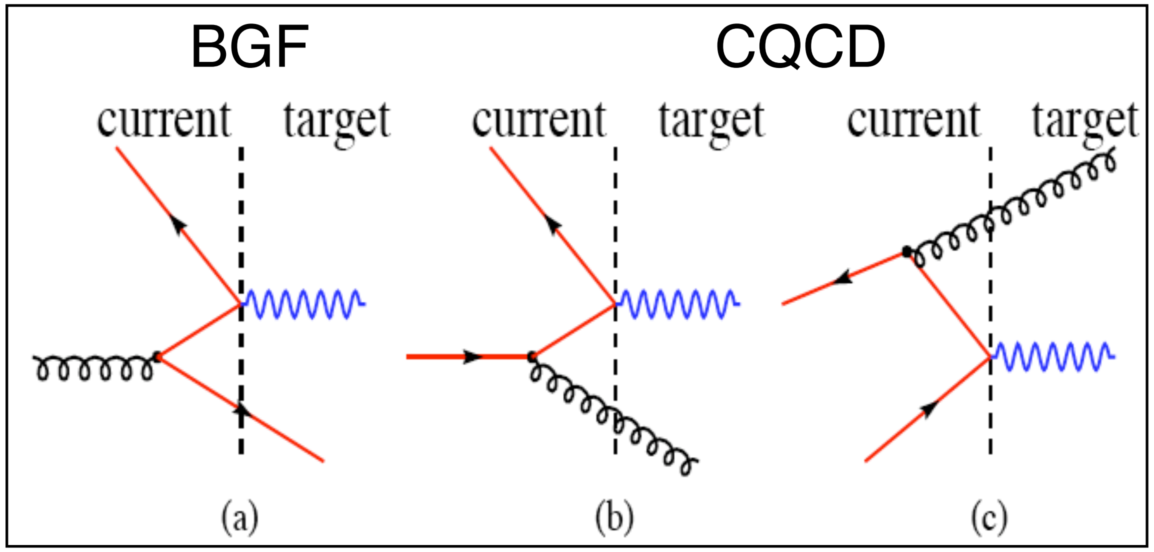
- Current region of ***ep*** expected to be similar to one hemisphere of e^+e^- annihilation if proper energy scale is chosen
  - e^+e^- $\sqrt{s}/2 = E_{beam}$
  - ep (HCM) **W**
  - ep (Breit) **Q** or E^{CR}_{B} (available energy)

- Variable for comparison: scaled momentum
  - $x_p = p_h / (Q/2)$
  - $x_p = p_h / E_{beam}$

Charged Particle Multiplicity

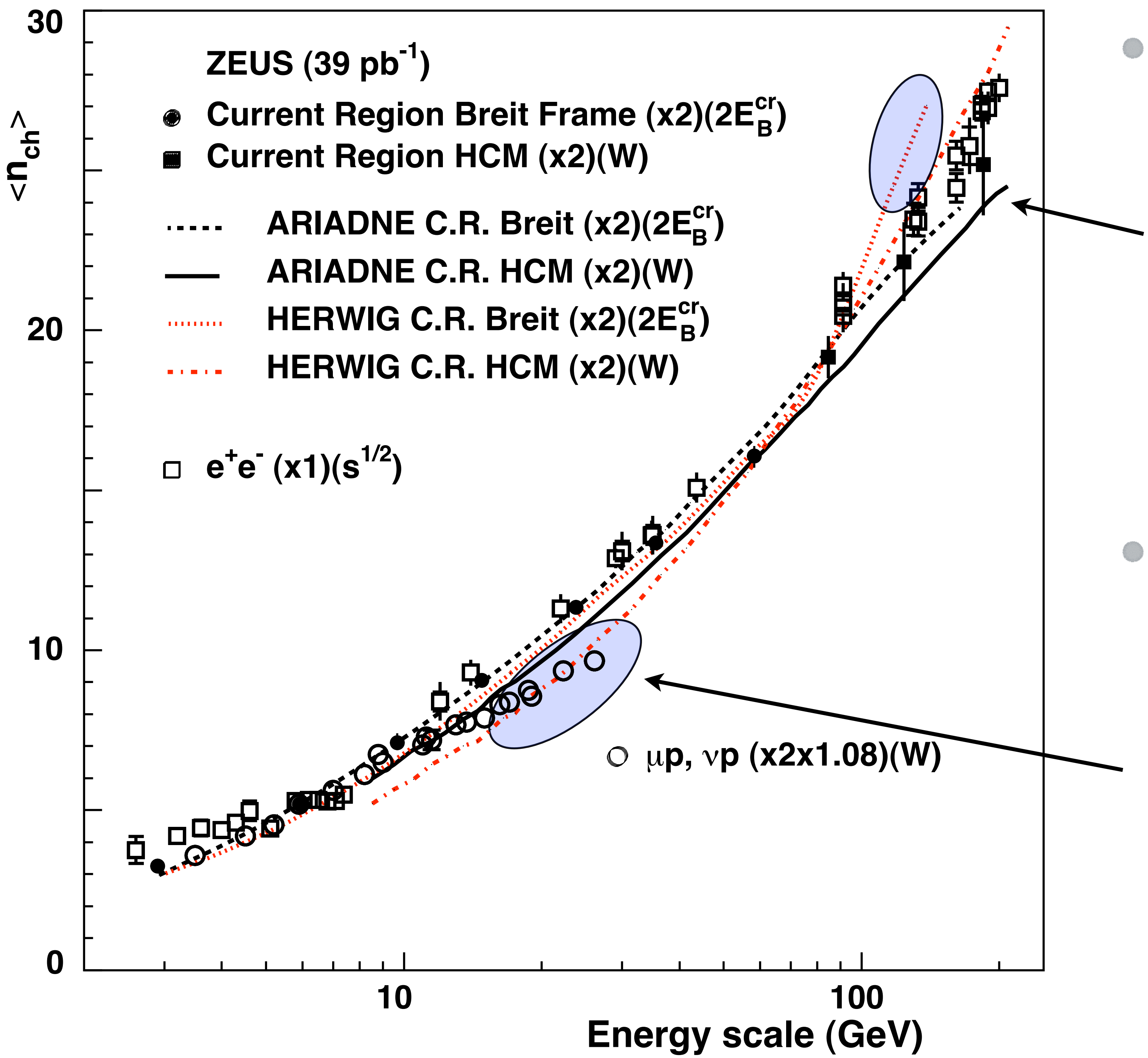


- Data enter the plot more than once
- Good agreement between ZEUS and H1
- Reasonable agreement with MC models which are tuned using e^+e^- data
  - exception at low scales, where additional DIS processes lead to depletion for ep



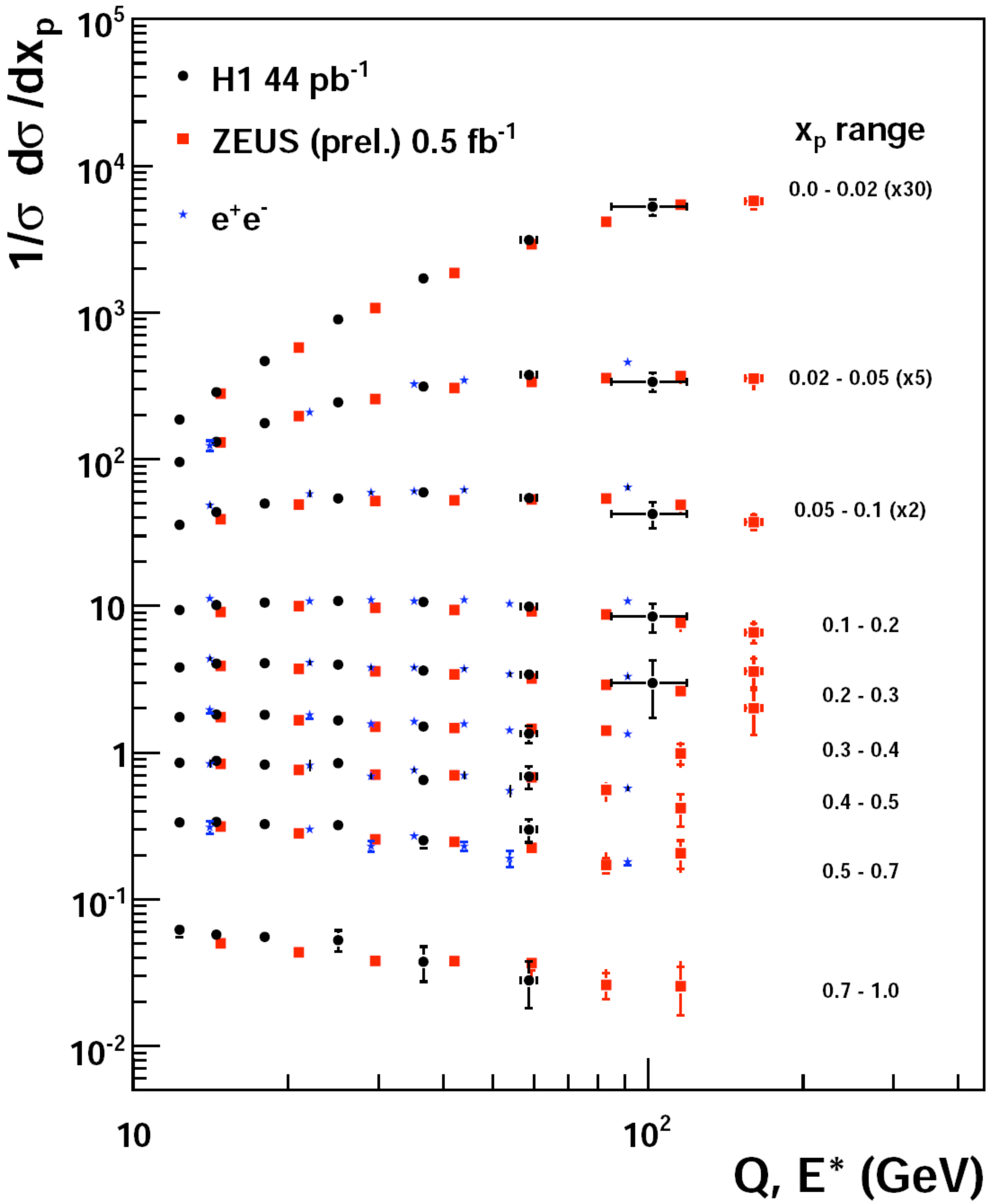
  - much better agreement at low scales if $2xE^{CR}_{B}$ is used instead of Q as energy scale

Charged Particle Multiplicity



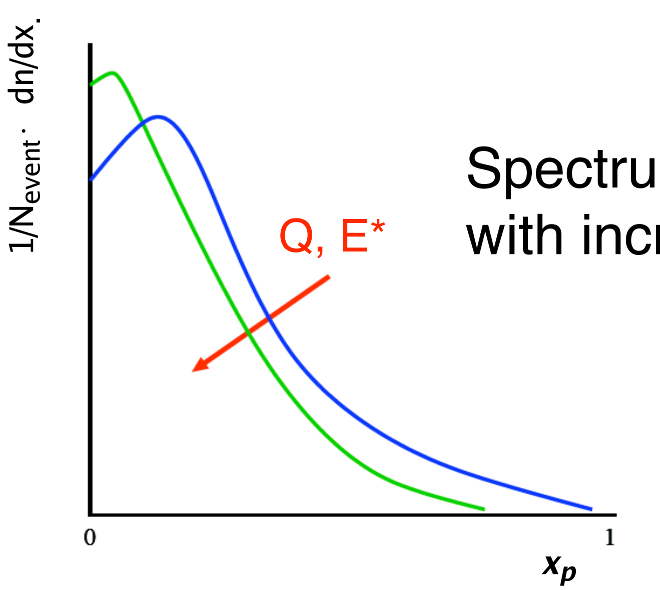
- Breit frame
  - good agreement between e^+e^- and ep when **$2xE^{CR}_B$** is used as energy scale
  - for large scales HERWIG is above the ep data
- HCM frame
  - overall good agreement with e^+e^- and fixed target data when **W** is used as energy scale
  - some discrepancy for fixed target data for scales above ~15 GeV

Scaled Momentum Distributions



- Variable for comparison: scaled momentum
  - $x_p = p_h / (Q/2)$ for ep
  - $x_p = p_h / (E^*/2)$ for e^+e^-

- Good agreement between e^+e^- and ep supports concept of quark fragmentation universality
- Scaling violation is clearly observed



Spectrum softens with increasing scale

Fragmentation

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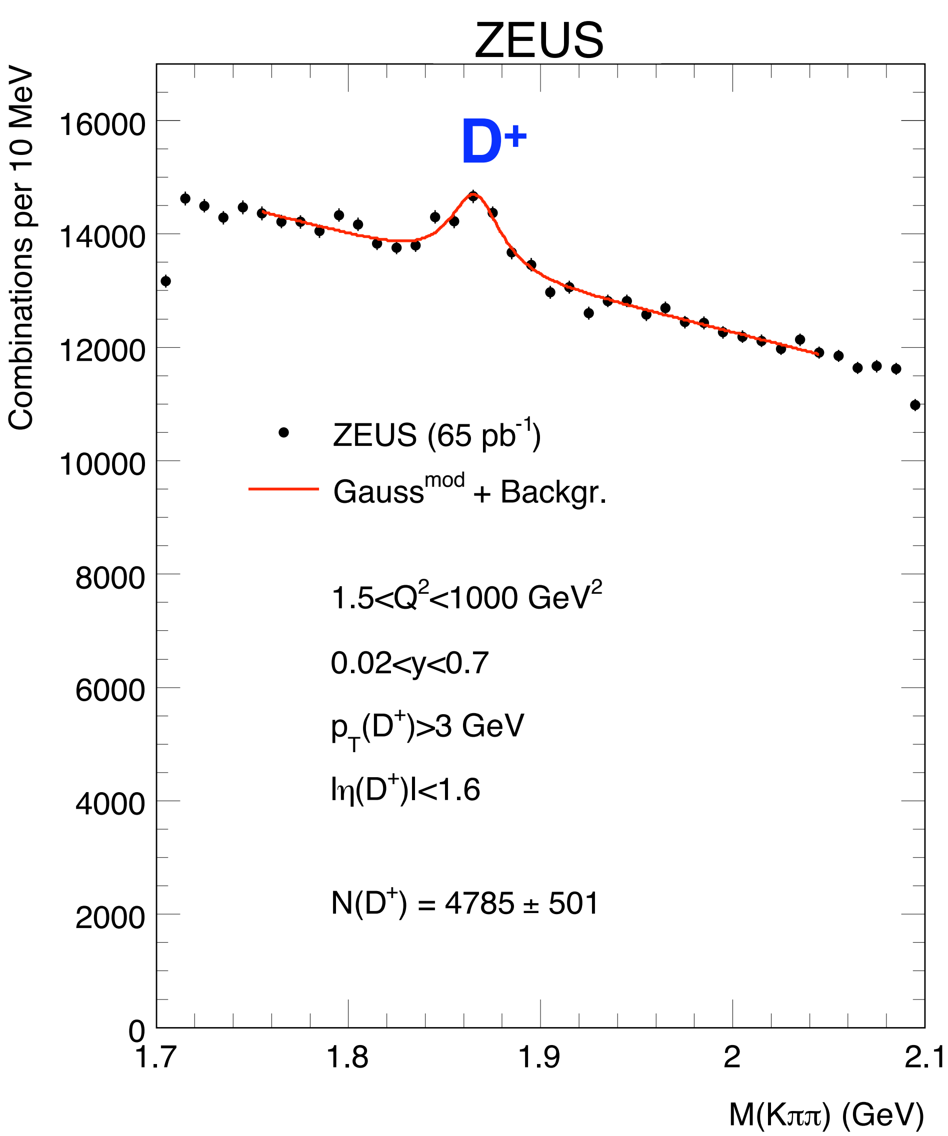
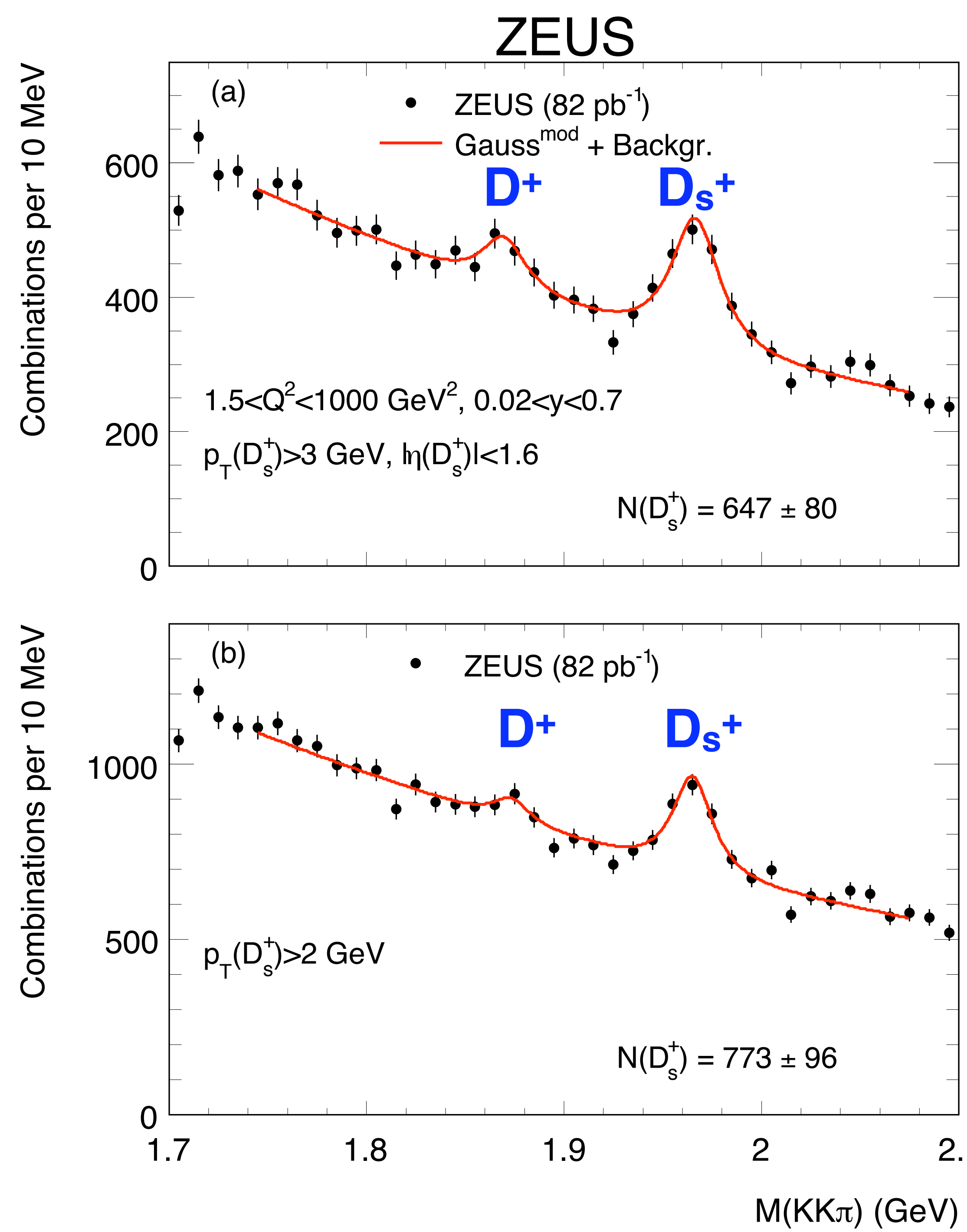
D^+ and D_s^+ Production at HERA

$D^0 \to K^-\pi^+$
$D^{*+} \to D^0\pi_s^+$
$D^+ \to K^-\pi^+\pi^+$
$D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$
$\Lambda_c^+ \to K^-p\pi^+$

- Sufficient statistics to study charm fragmentation ratios and fractions in some detail

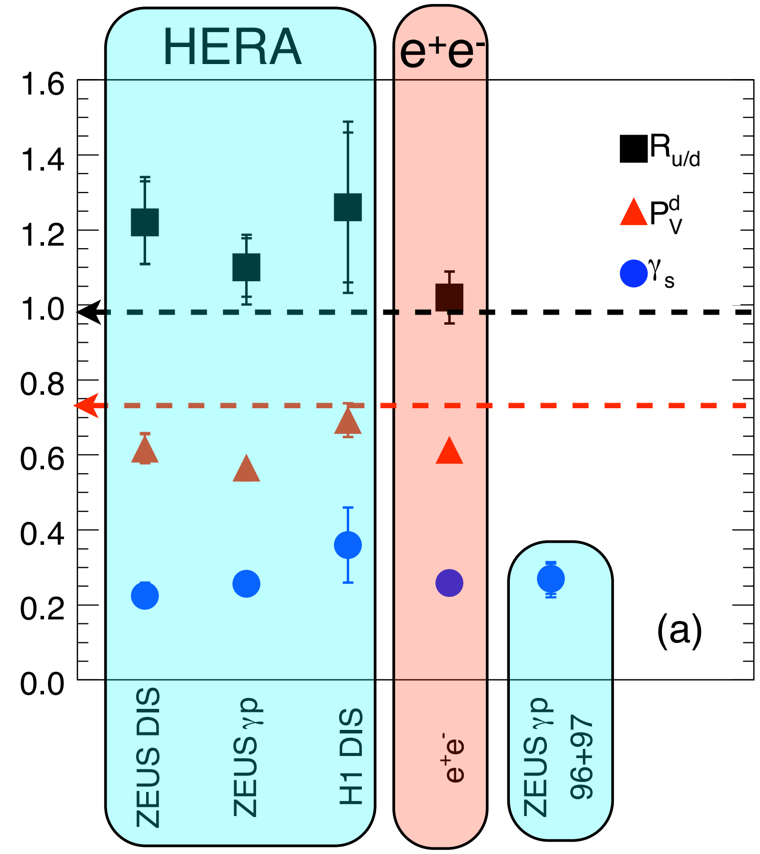
Signal examples





Charm Fragmentation

- Charm fragmentation ratios
  - u and d produced roughly equally in charm fragmentation
  - fraction of charged D's in vector state somewhat below naive expectation from spin counting (3/4)
  - strangeness suppression factor

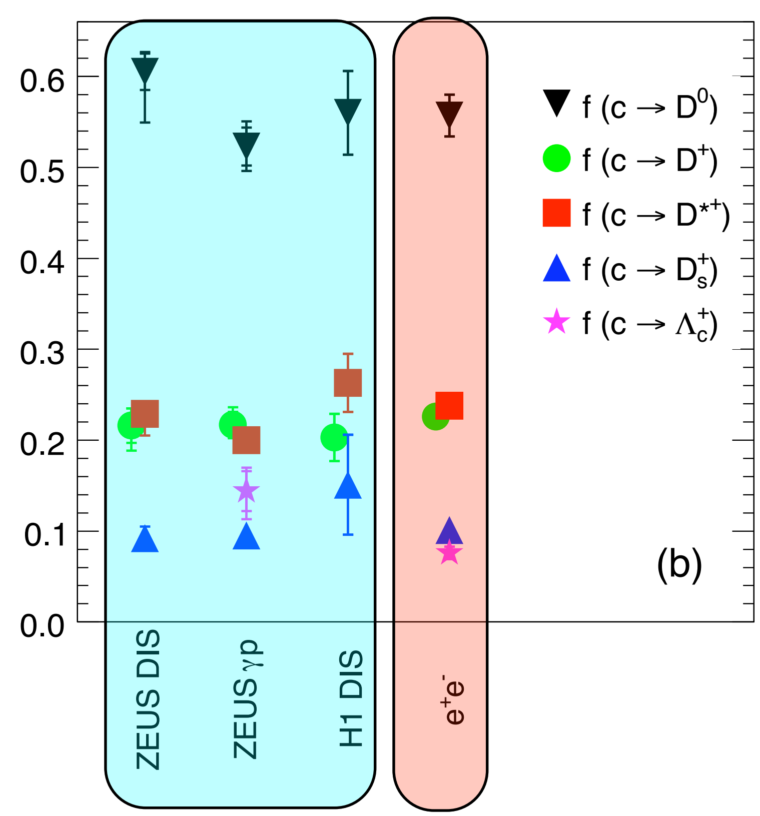


$$R_{u/d} = \frac{D_{neutral}}{D_{charged}} = \frac{c\bar{u}}{c\bar{d}}$$

$$P_V^d = \frac{V_D}{V_D + PS_D}$$

$$\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}}$$

- Charm fragmentation fractions
  - generally consistent with expectations

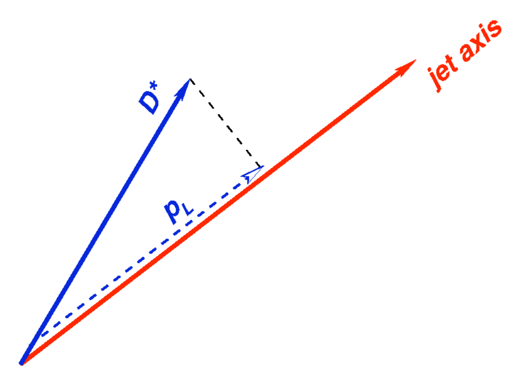


- Observe good agreement between
  - H1 and ZEUS (DIS)
  - γp and DIS
  - ep and e^+e^-
- Charm fragmentation ~ independent of the hard sub process

Variables to extract Fragmentation Functions

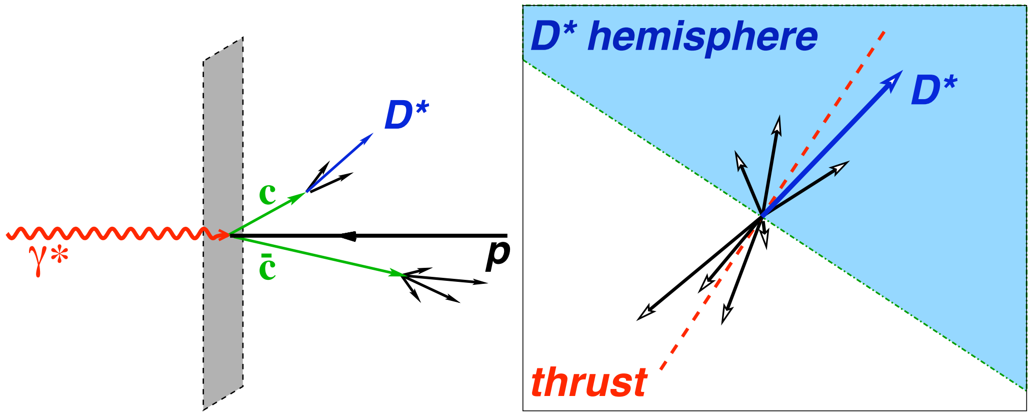
$$\sigma_H = \sum_i \sum_k f_{i/p}(x,\mu_f) \otimes \hat{\sigma}_{i\gamma \to kX}(\alpha_s(\mu_r),\mu_r,\mu_f) \otimes D_k^H(z,\mu_f)$$

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

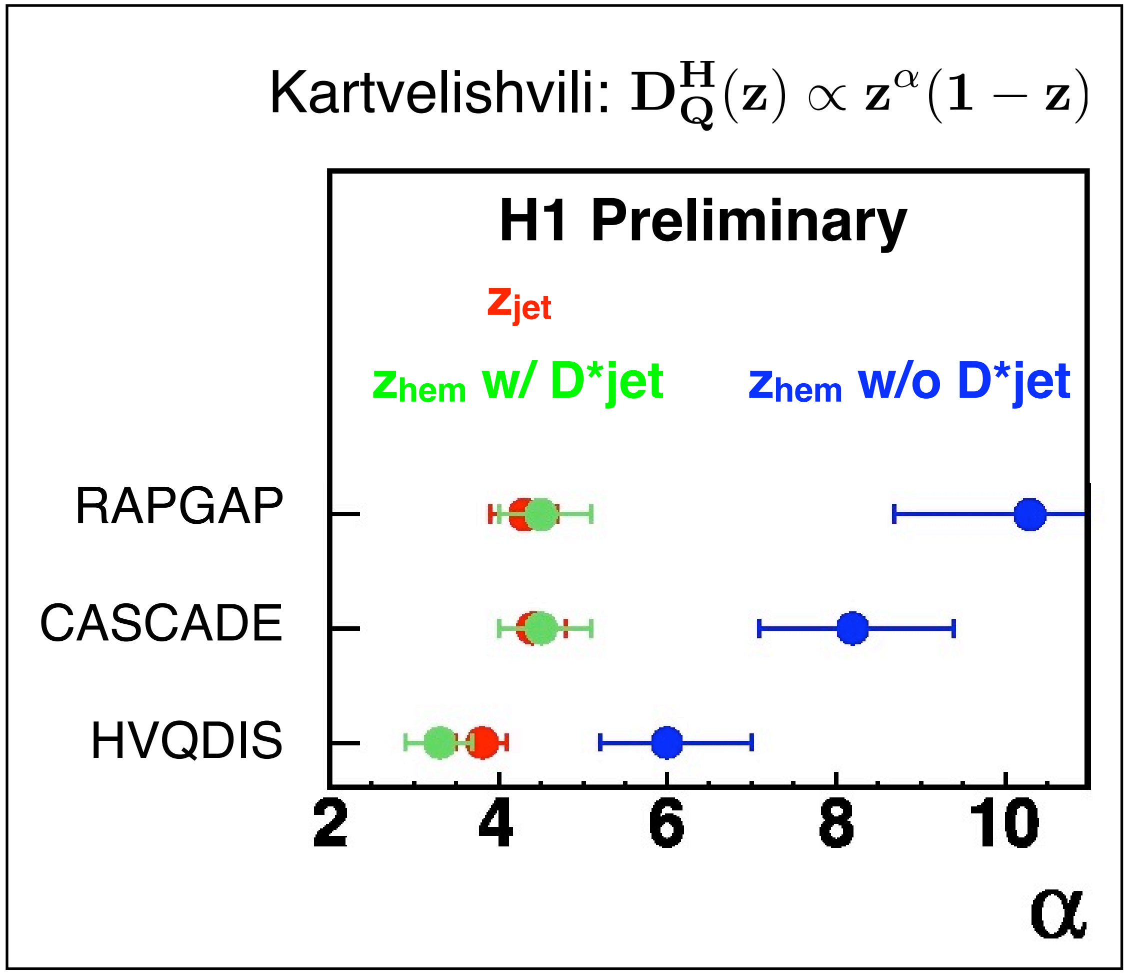


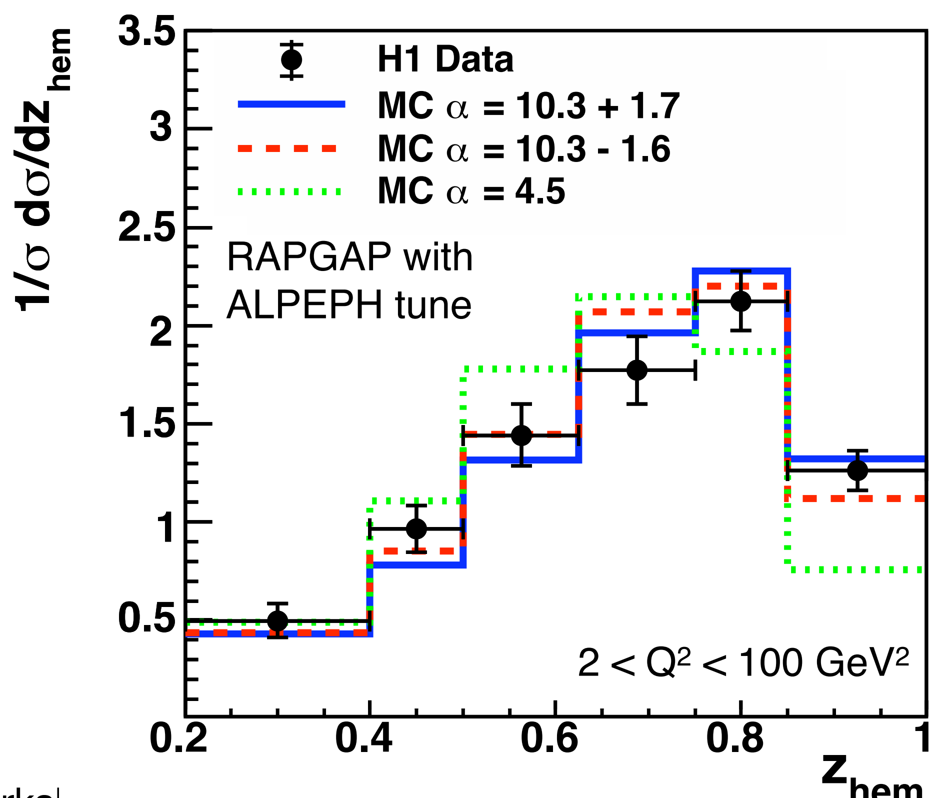
$$z_{hem} = \frac{(E+p_L)_{D^*}}{\sum_{hem}(E+p)_i}$$

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

- The two methods may have different sensitivity to the hadronisation process =>
- Distributions expected to look differently, but extracted fragmentation functions should be the same

Details of Charm Fragmentation





- Non perturbative fragmentation function is only defined within a given model
  - LO+PS MC models RAPGAP and CASCADE
  - massive NLO calculation HVQDIS
- Results for events with jet [E_T(D*jet) > 3 GeV]
  - good agreement for extracted fragmentation parameters for jet and hemisphere methods
  - both QCD models lead to compatible results
  - good fit also obtained for comparison to HVQDIS at parton level
  - ep and e^+e^- parameters (Peterson, not shown) are consistent with each other => universal frag. function
- Investigation of threshold region using events which have no D*jet
  - can be studied using hemisphere method
  - observed spectrum significantly harder
  - extracted fragmentation parameters ≈4σ away from nominal ones

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

Strangeness

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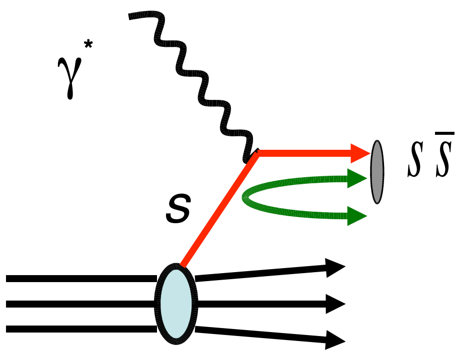
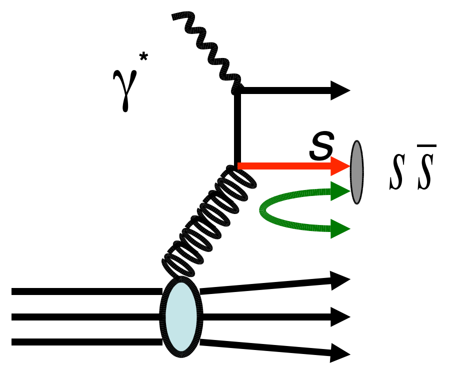
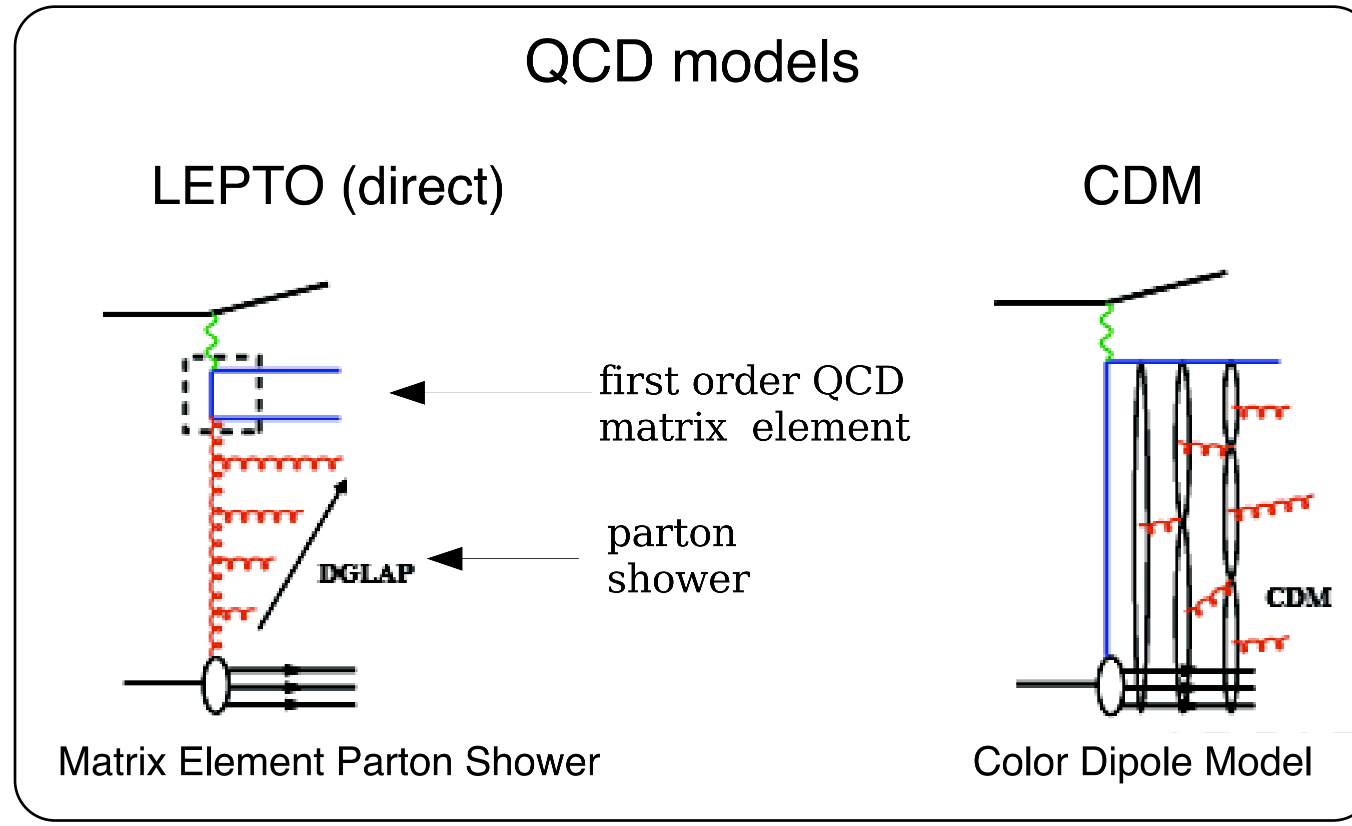
Strangeness Production at HERA

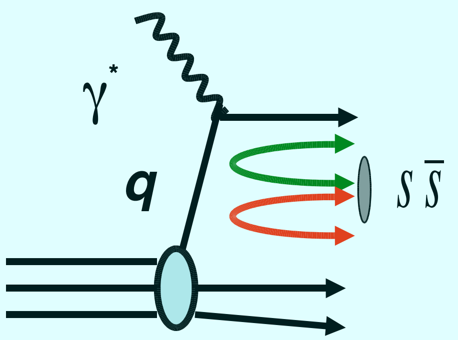


a) Hard scattering of *s* sea quark

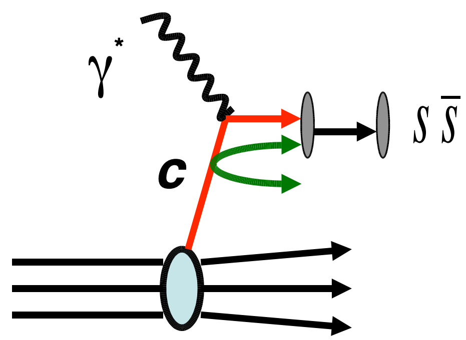


b) Boson-gluon fusion (BGF)

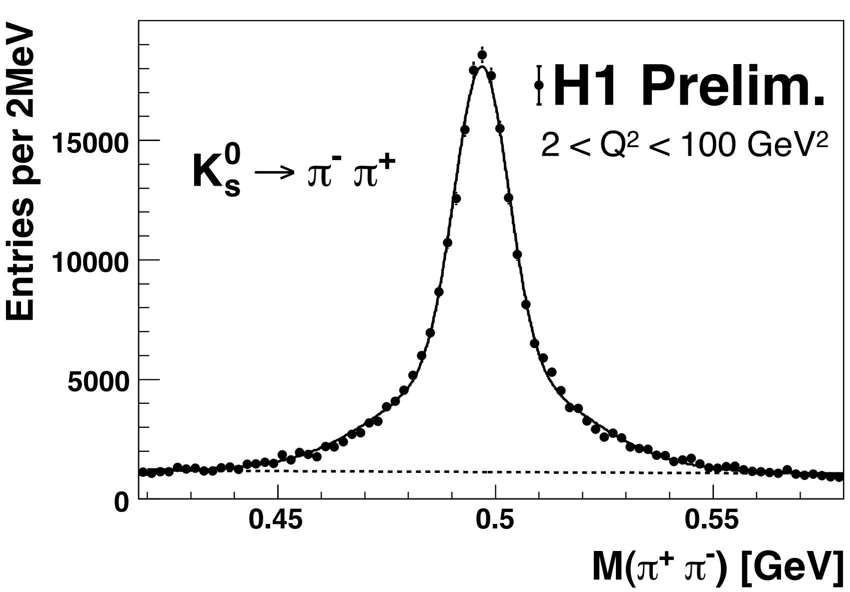


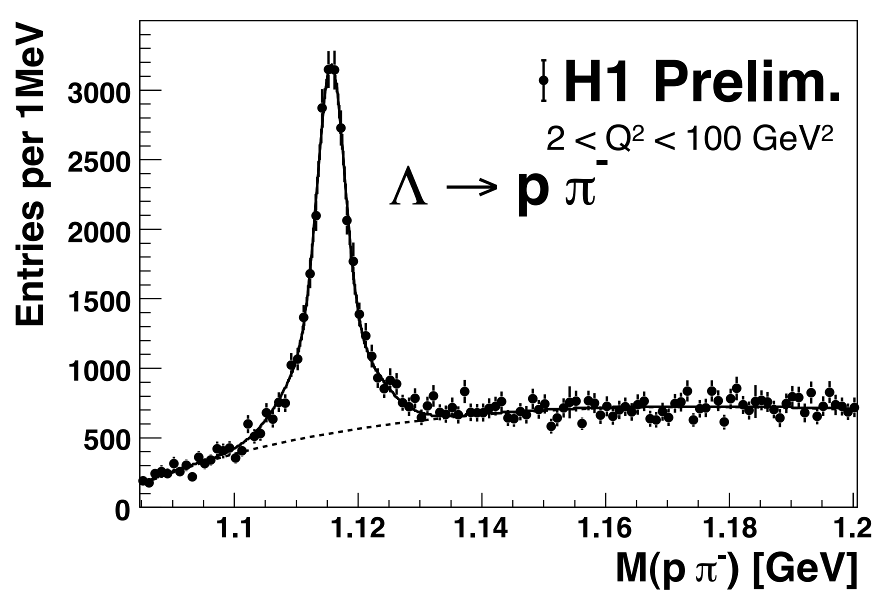


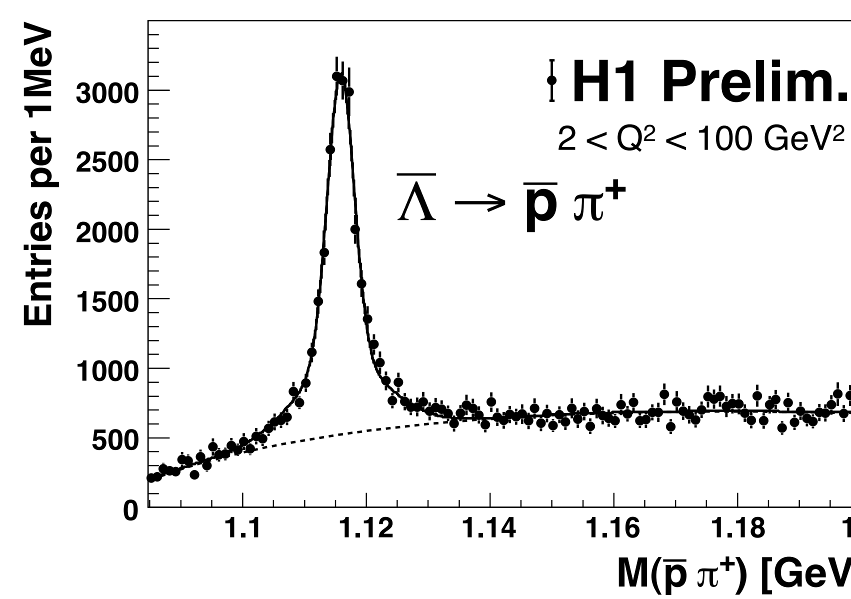
c) Parton pure fragmentation



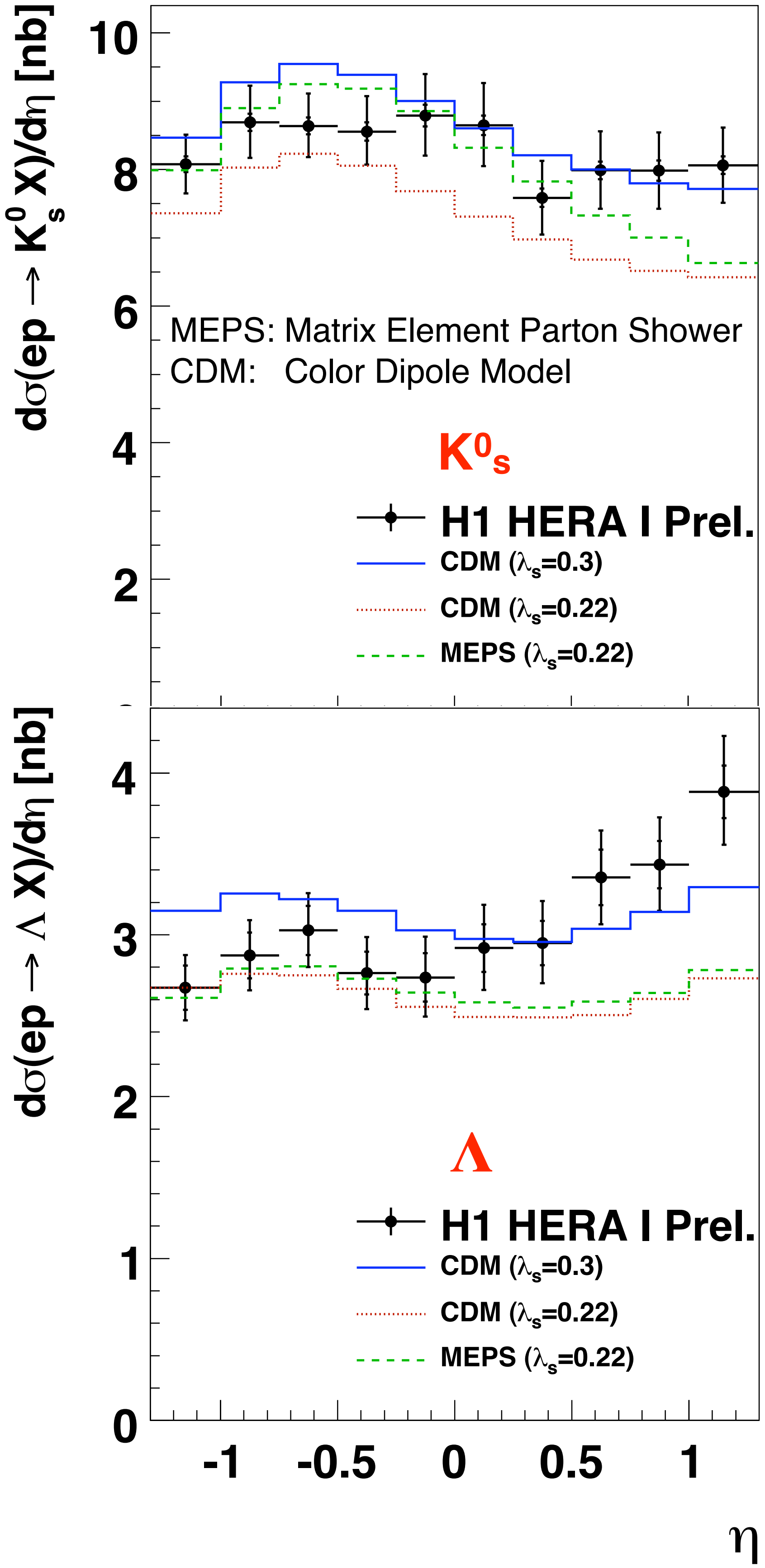
d) Heavy quark decay

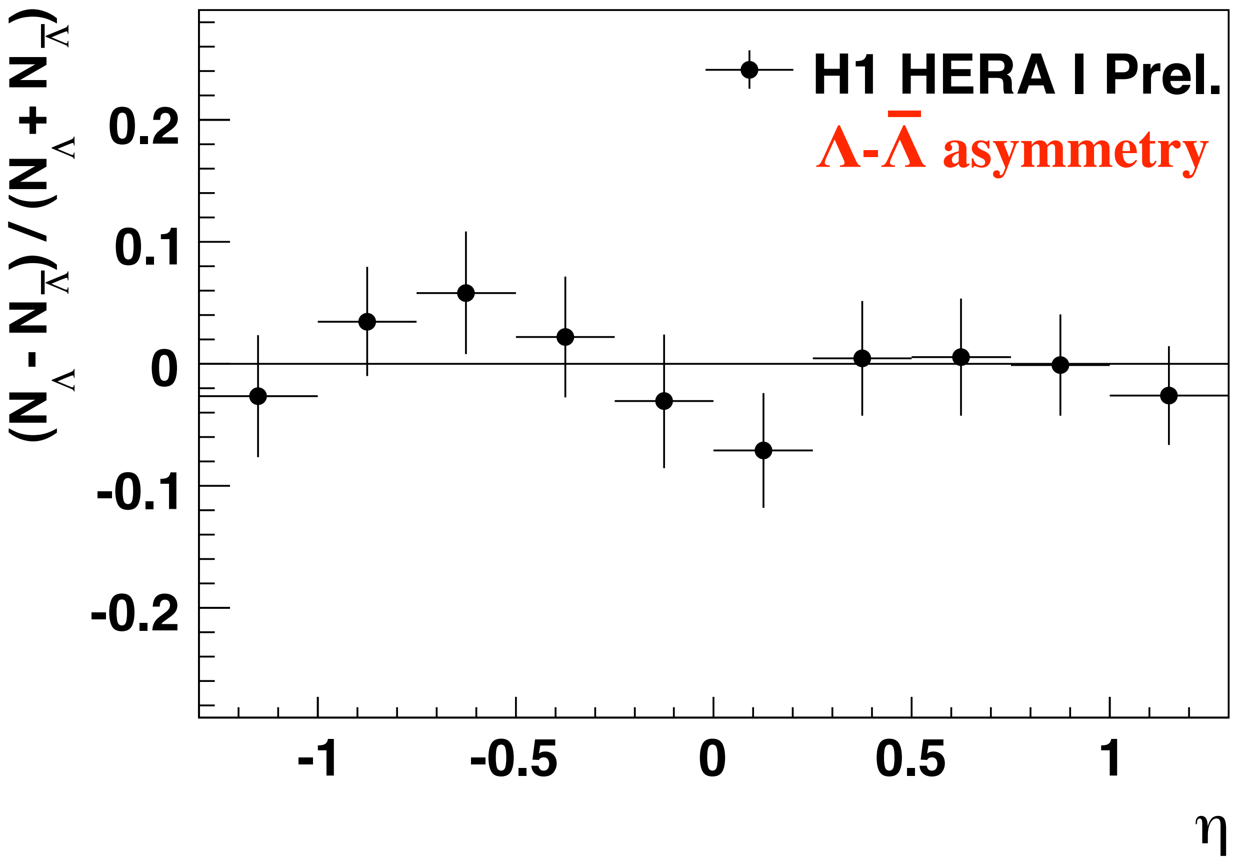






Details of Strangeness Production



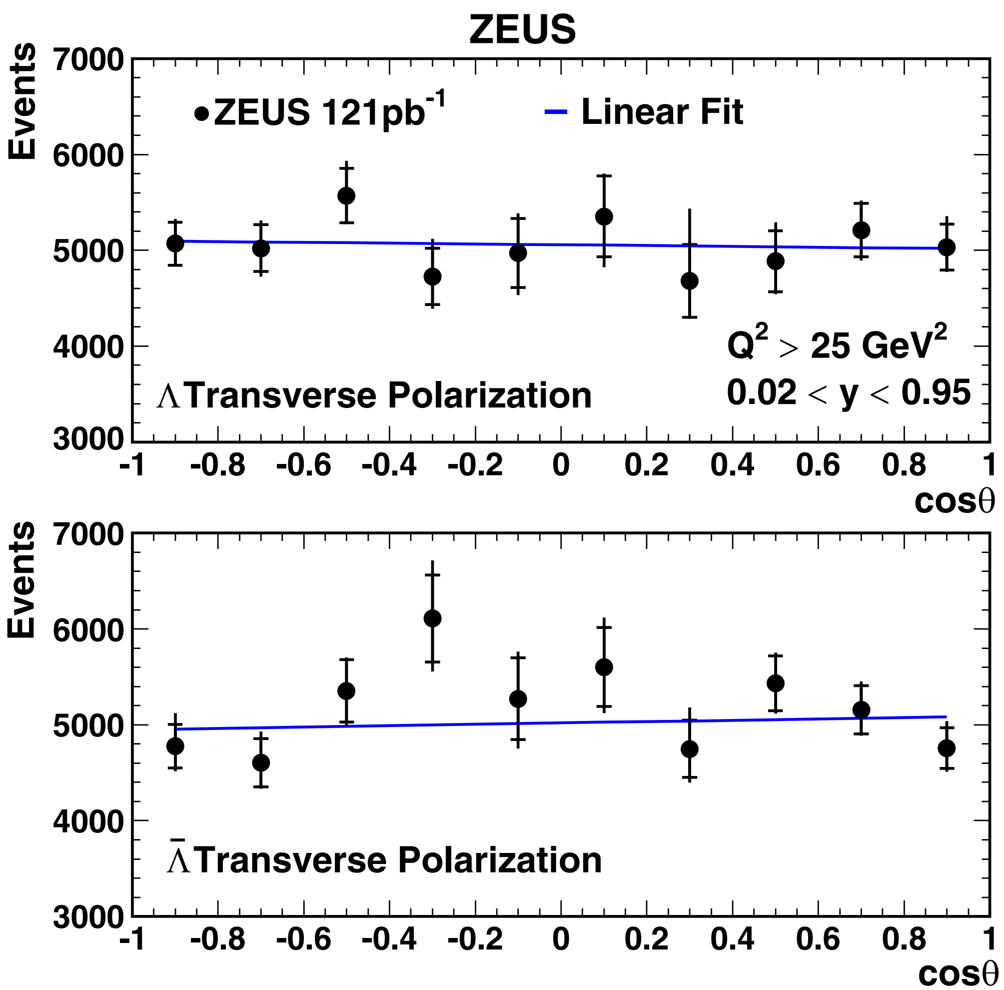


- Strangeness suppression factor **λ_S = P(s) / P(u)**
  - Neither MEPS nor CDM can describe all details of the data with a single value of λ_S parameter
- Asymmetry of Λ with respect to $\bar{\Lambda}$ production consistent with zero
  - no evidence of baryon number transport visible in data

Λ Polarisation

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{1}{2}[1+\alpha\mathcal{P}^{\Lambda}\cos\theta]$$
$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{1}{2}[1-\alpha\mathcal{P}^{\bar{\Lambda}}\cos\theta]$$

	Polarization (%) High-Q^2 DIS	Low-Q^2 DIS	Photoproduction
Λ	$-1.3\pm4.3(\text{stat.})^{+4.0}_{-0.8}(\text{syst.})$	$-4.0\pm5.3(\text{stat.})^{+4.7}_{-4.0}(\text{syst.})$	$-2.4\pm2.2(\text{stat.})$
$\bar{\Lambda}$	$-2.2\pm4.2(\text{stat.})^{+2.4}_{-1.3}(\text{syst.})$	$-8.5\pm5.5(\text{stat.})^{+4.7}_{-2.1}(\text{syst.})$	$-5.8\pm2.2(\text{stat.})$
K^0_S	$-1.5\pm1.1(\text{stat.})$	$-0.05\pm1.5(\text{stat.})$	$-0.5\pm0.2(\text{stat.})$



- Λ's are expected to inherit polarisation from the *s*-quark which get partially polarised due to elastic scattering in the colour field
  - decay asymmetry parameter $\alpha = 0.642 \pm 0.013$ (PDG)
  - θ is angle between the proton momentum boosted to the rest frame of the Λ and the polarisation axis
- All fitted values are compatible with zero

- No evidence for non-zero transverse polarisation in inclusive Λ or $\bar{\Lambda}$ production.

Spectroscopy

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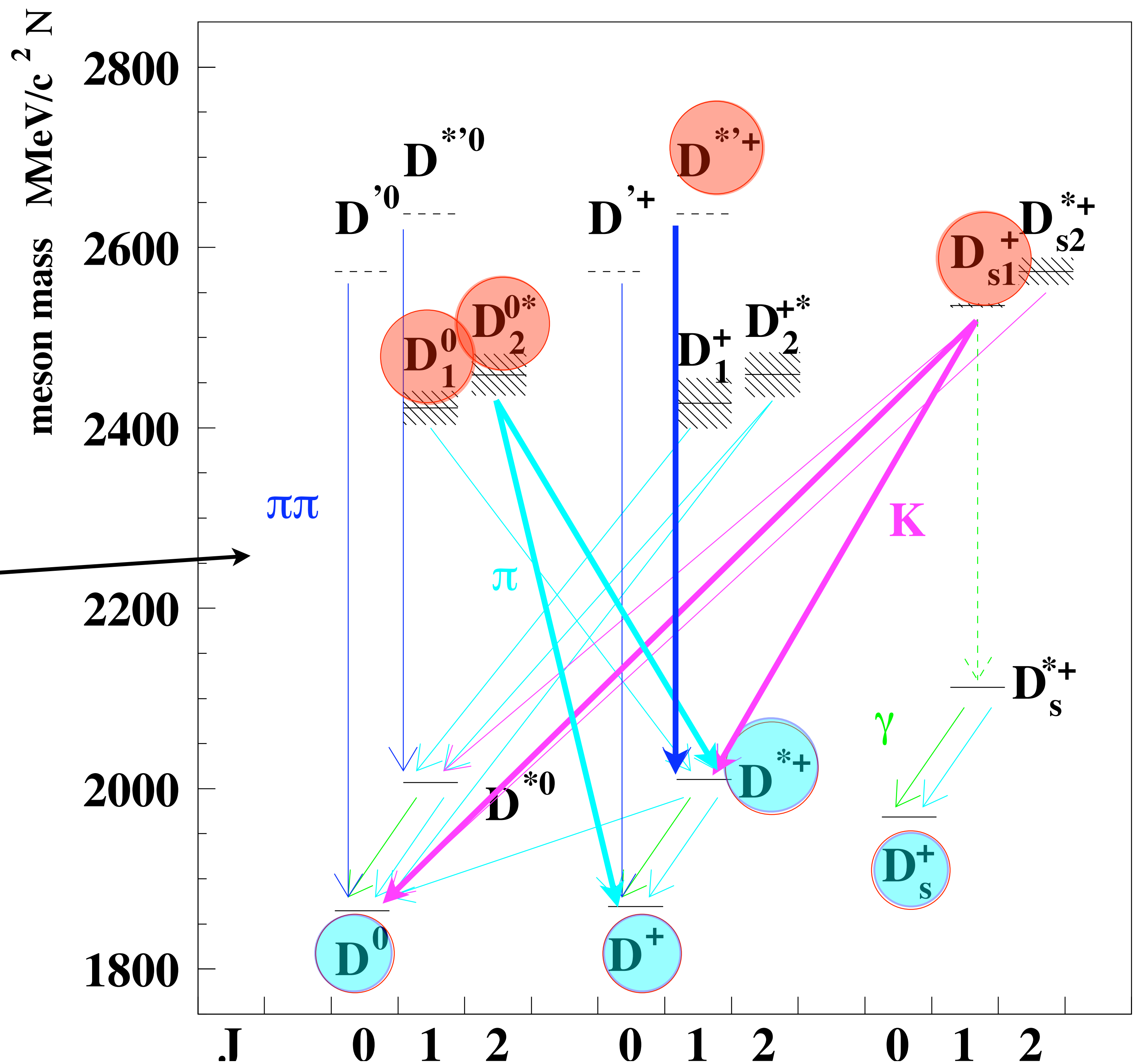
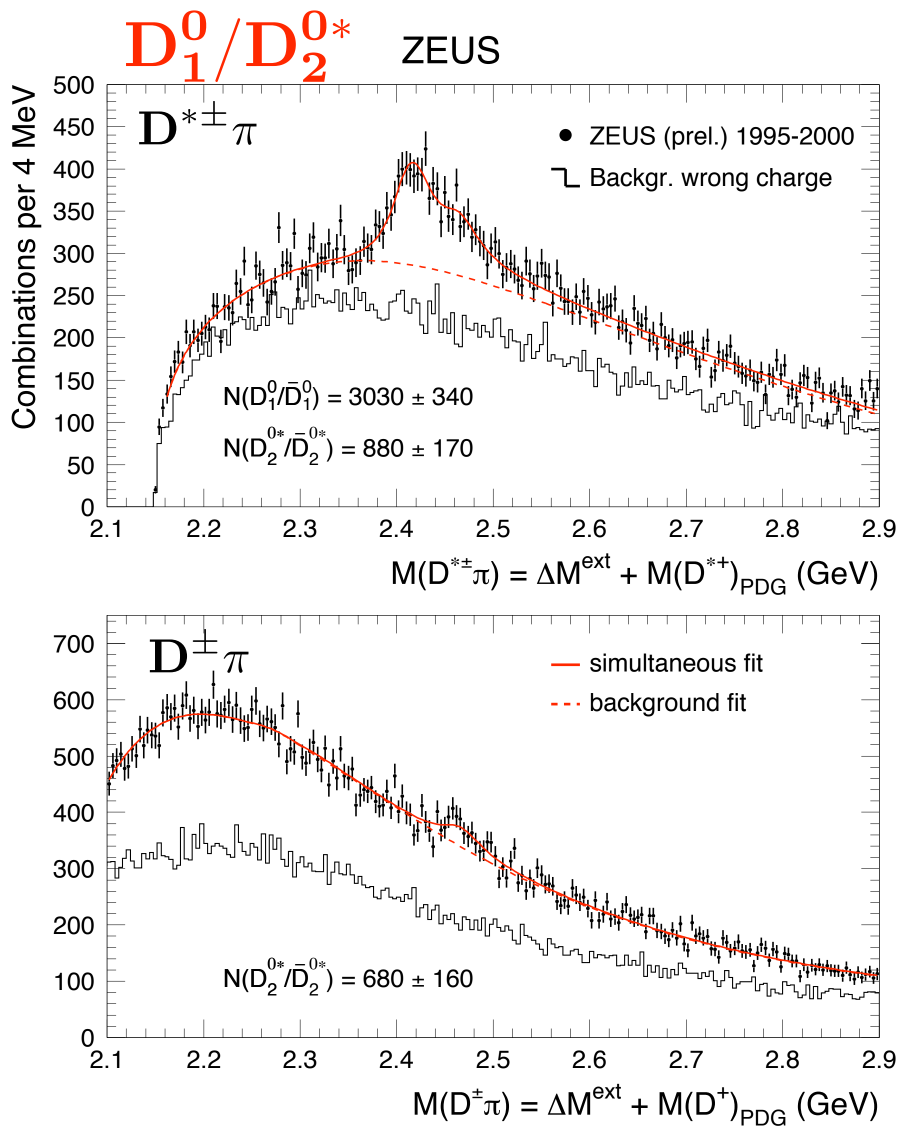
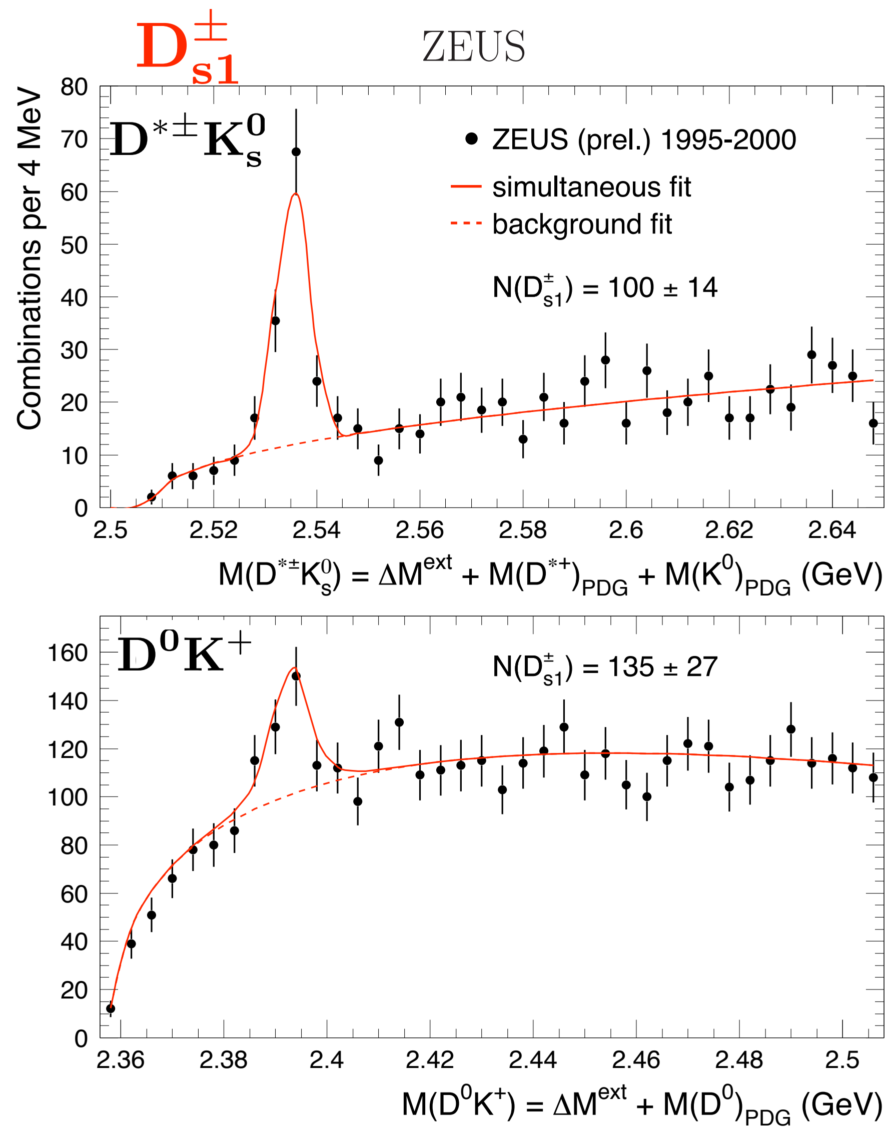
Excited Charm and Charm-Strange States

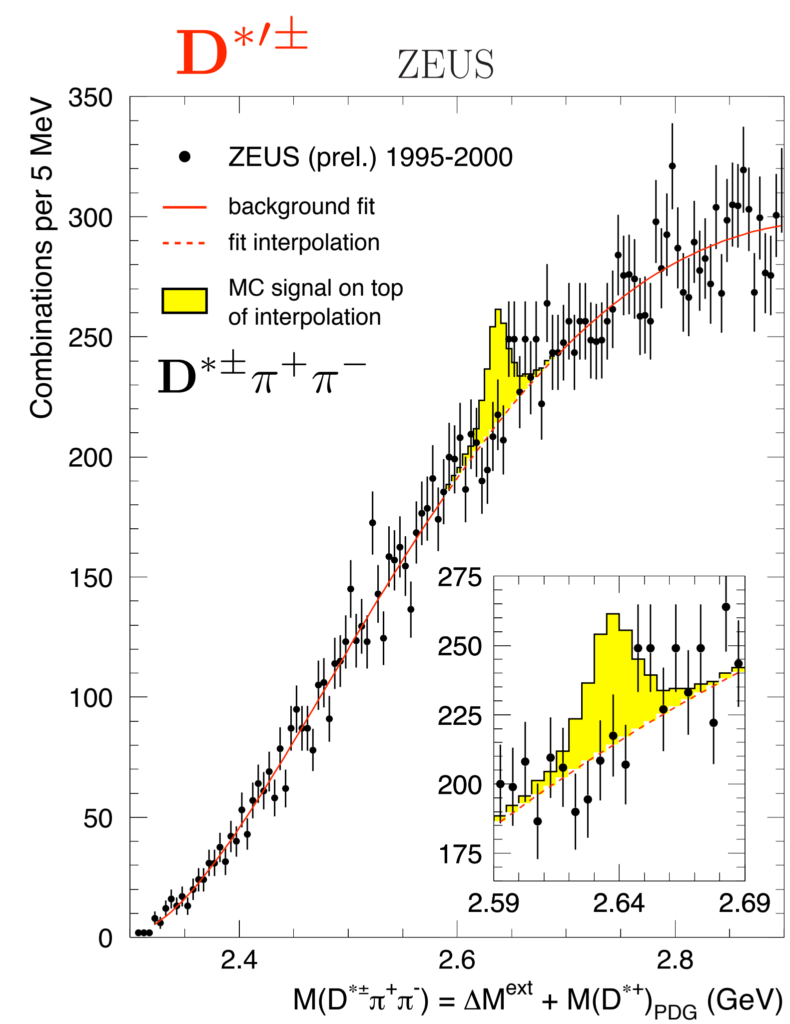
- Large charm production cross section at HERA allows to search for excited charm states
- Lowest-mass states with spin-0 (D) and spin-1 (D*) and L=0 are well established
- Look for these decay modes



Results on Excited Charm States







	$f(c \to D_1^0)$ [%]	$f(c \to D_2^{*0})$ [%]	$f(c \to D_{s1}^+)$ [%]
ZEUS (prel.)	$3.5 \pm 0.4^{+0.4}_{-0.6} \pm 0.2$	$3.8 \pm 0.7 \pm 0.6 \pm 0.2$	$1.1 \pm 0.2 \pm 0.1 \pm 0.1$
CLEO [17]	1.8 ± 0.3	1.9 ± 0.3	
OPAL [18]	$2.1 \pm 0.7 \pm 0.3$	$5.2 \pm 2.2 \pm 1.3$	$1.6 \pm 0.4 \pm 0.3$
ALEPH [19]			$0.94 \pm 0.22 \pm 0.07$

CLEO measured smaller resonance widths
OPAL used PDG values

- ep fragmentation fractions ~ consistent with those from e^+e^-
- No significant production of radially excited D*'± observed. 95% C.L. limit:

$$\mathbf{f(c \to D^{*\prime+}) \cdot BR_{D^{*\prime+} \to D^{*+}\pi^+\pi^-} < 0.45\%}$$

Exotica

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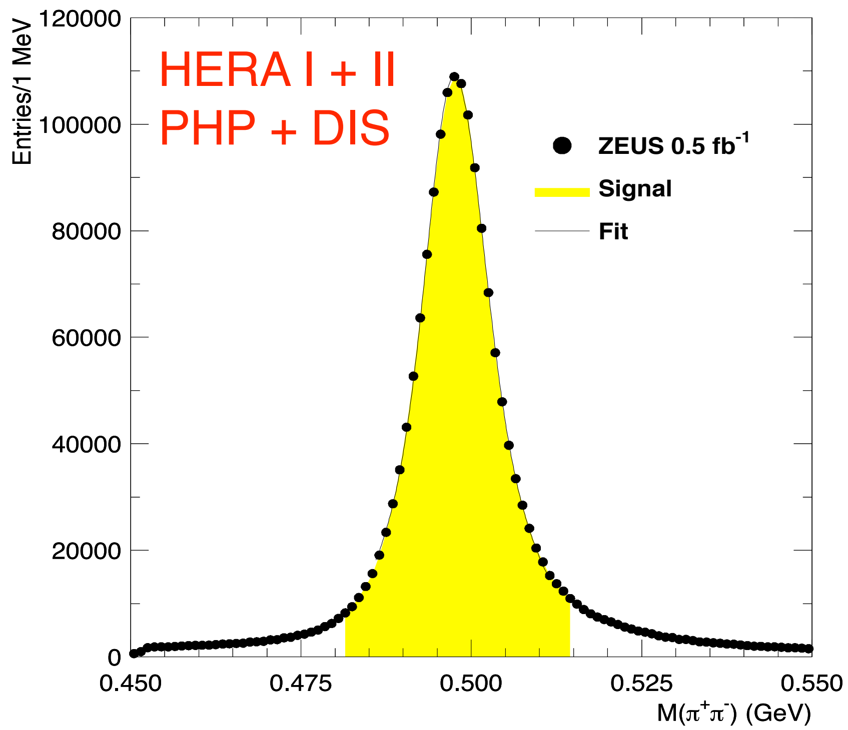
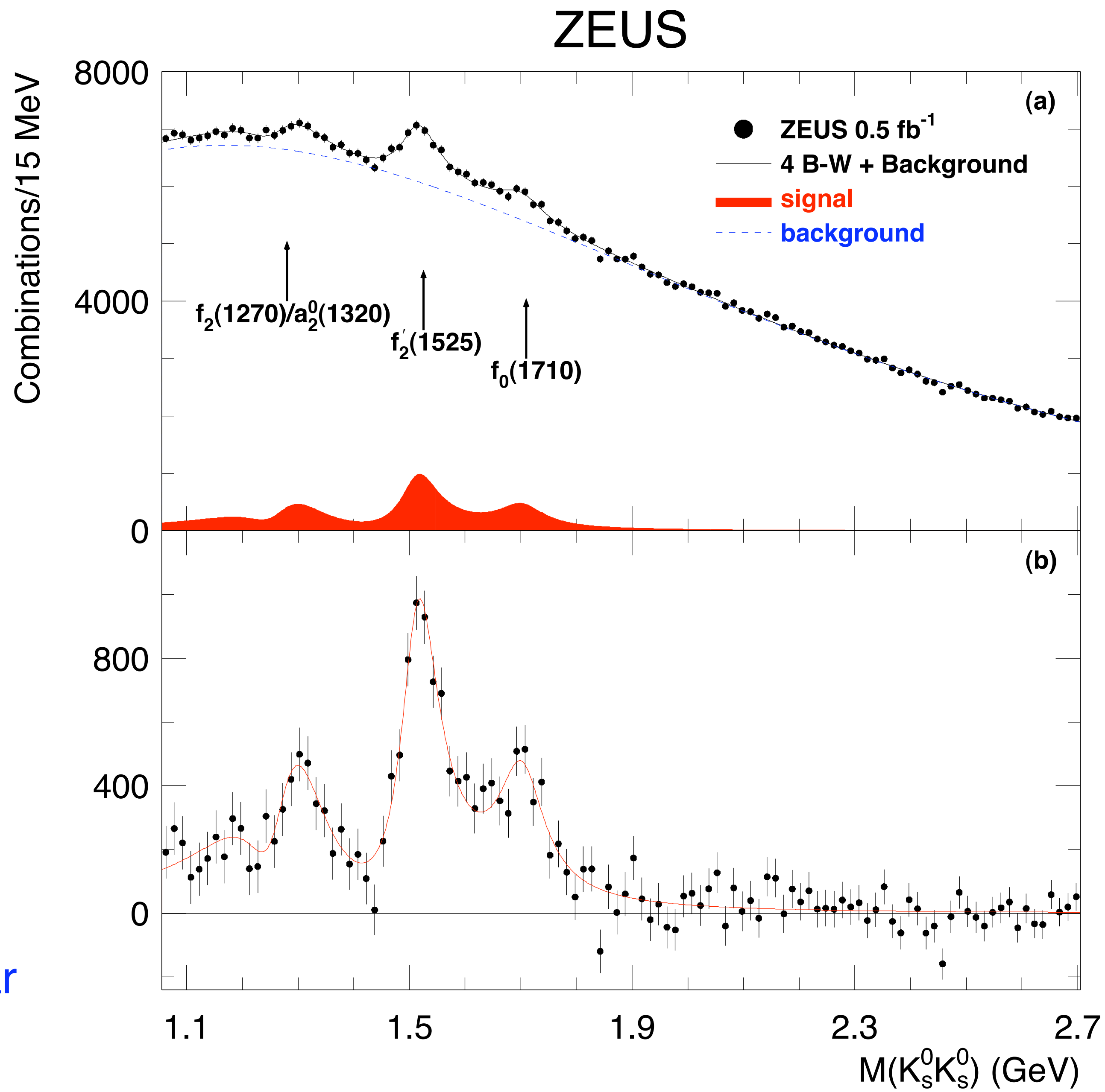
$K^0_s K^0_s$ Resonant States





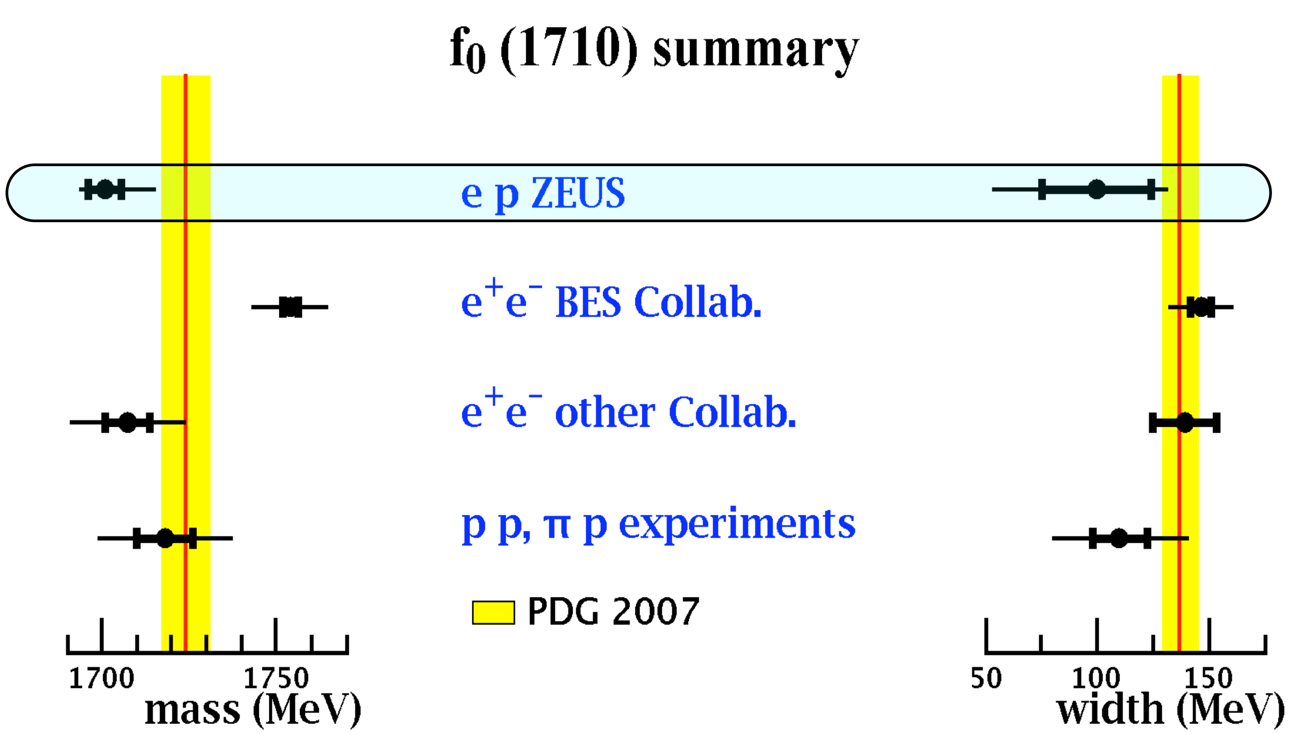
- Existence of glueballs is expected in QCD
- Lattice calculations predict
  - lightest one in mass range 1550-1750 MeV
  - quantum numbers $J^{PC} = 0^{++}$ => can mix with scalar mesons with $I = 0$
  - the well established $f_0(1710)$ is considered to be glueball candidate
- $K^0_s K^0_s$ system can couple to $J^P=0^+$(scalar) and 2^+ (tensor)
  - => good place to search for lowest lying 0^+ glueball

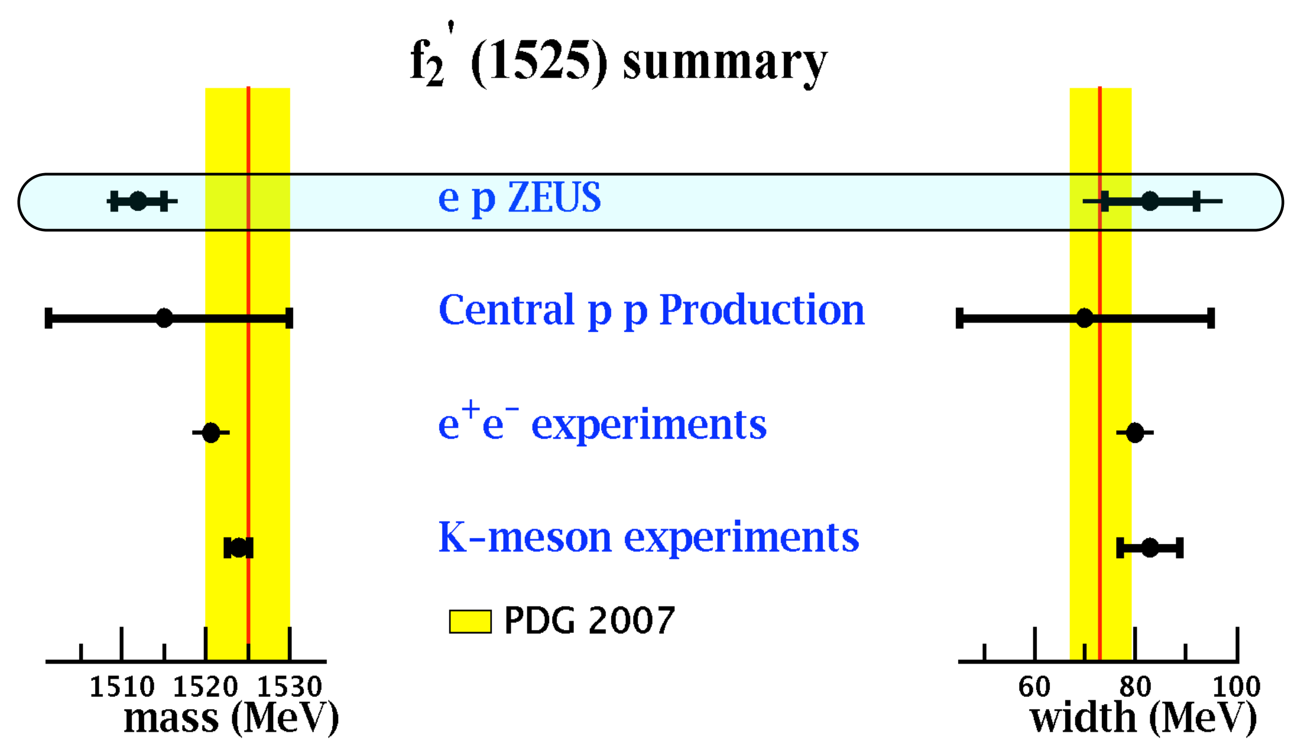
- SU(3) symmetry motivated fit function
  - Breit Wigner functions with interference terms included
  - 3 visible enhancements correspond to $f_2(1270)/a_2(1320)$, $f'_2(1525)$ and $f_0(1710)$

Summary of Fit Results

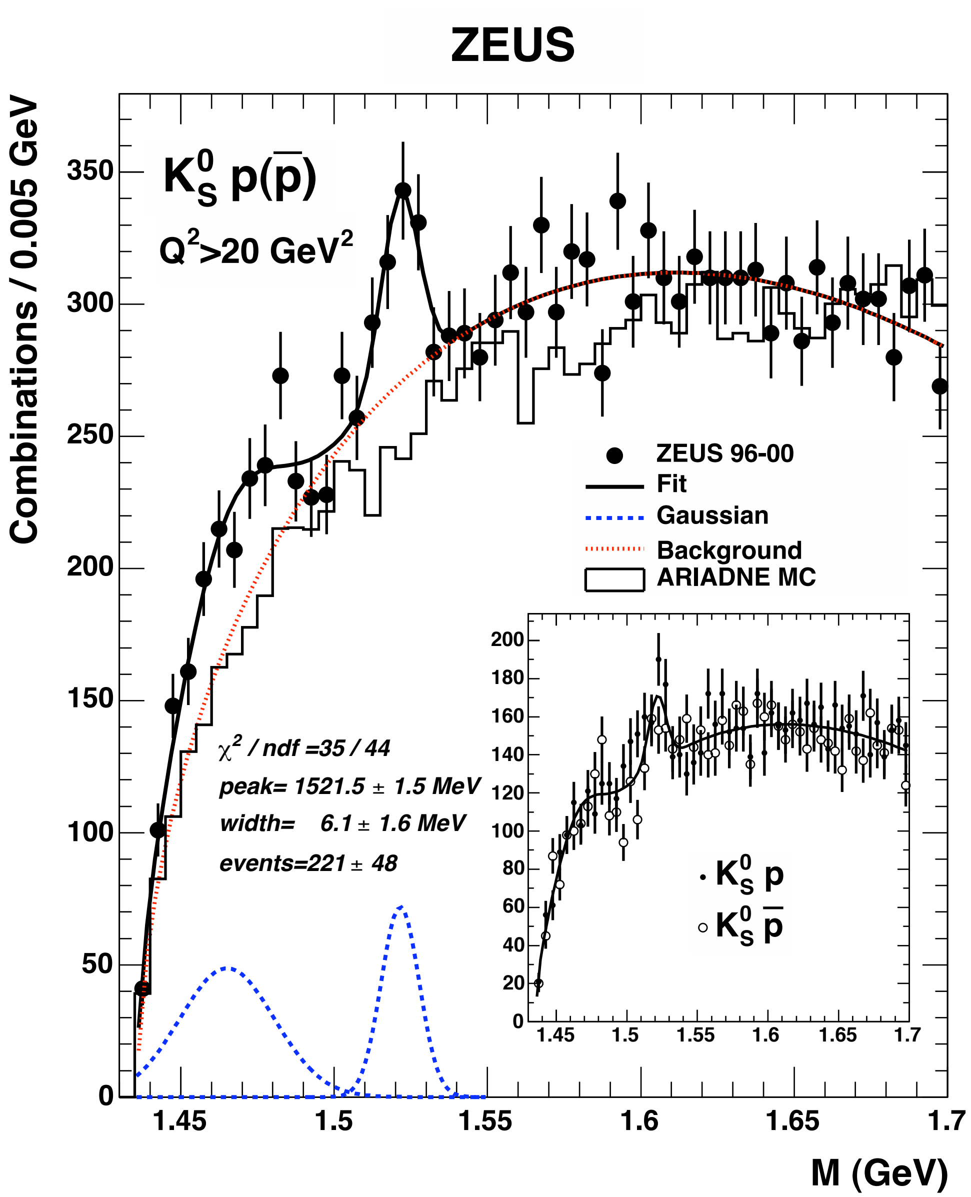
- State $f_0(1710)$
  - observed at 5σ significance
    - 4058 ± 820 events
  - fitted mass slightly below PDG value
  - consistent with $J^{PC}=0^{++}$
  - glueball candidate
    - if same state as seen in $\gamma\gamma \to K^0_s K^0_s$ then unlikely to be pure glueball state

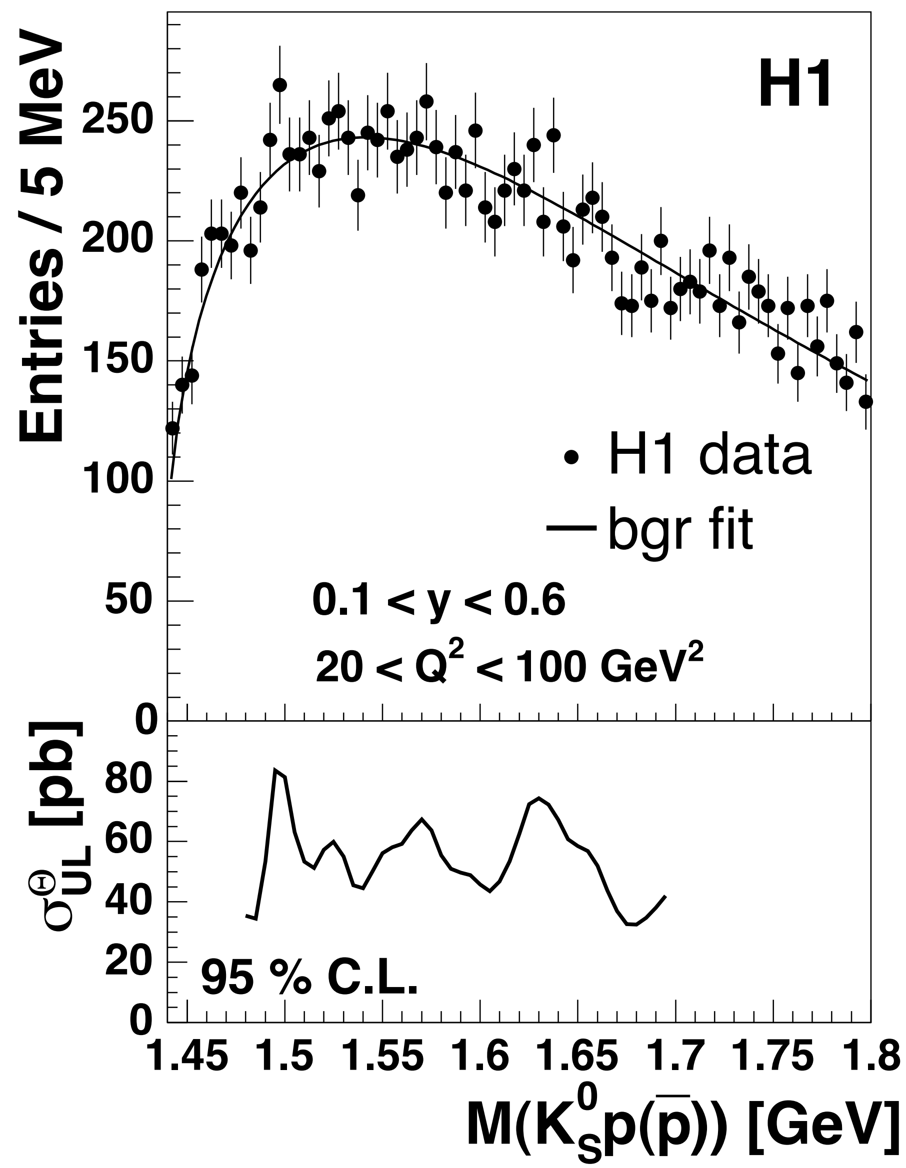
	Fit $\chi^2/ndf = 86/97$		PDG 2007 Values	
in MeV	Mass	Width	Mass	Width
$f_2(1270)$	1268 ± 10	176 ± 17	1275.4 ± 1.1	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$	1257 ± 9	114 ± 14	1318.3 ± 0.6	107 ± 5
$f_2'(1525)$	$1512 \pm 3^{+2}_{-0.6}$	$83 \pm 9^{+5}_{-4}$	1525 ± 5	73^{+6}_{-5}
$f_0(1710)$	$1701 \pm 5^{+5}_{-3}$	$100 \pm 24^{+8}_{-19}$	1724 ± 7	137 ± 8





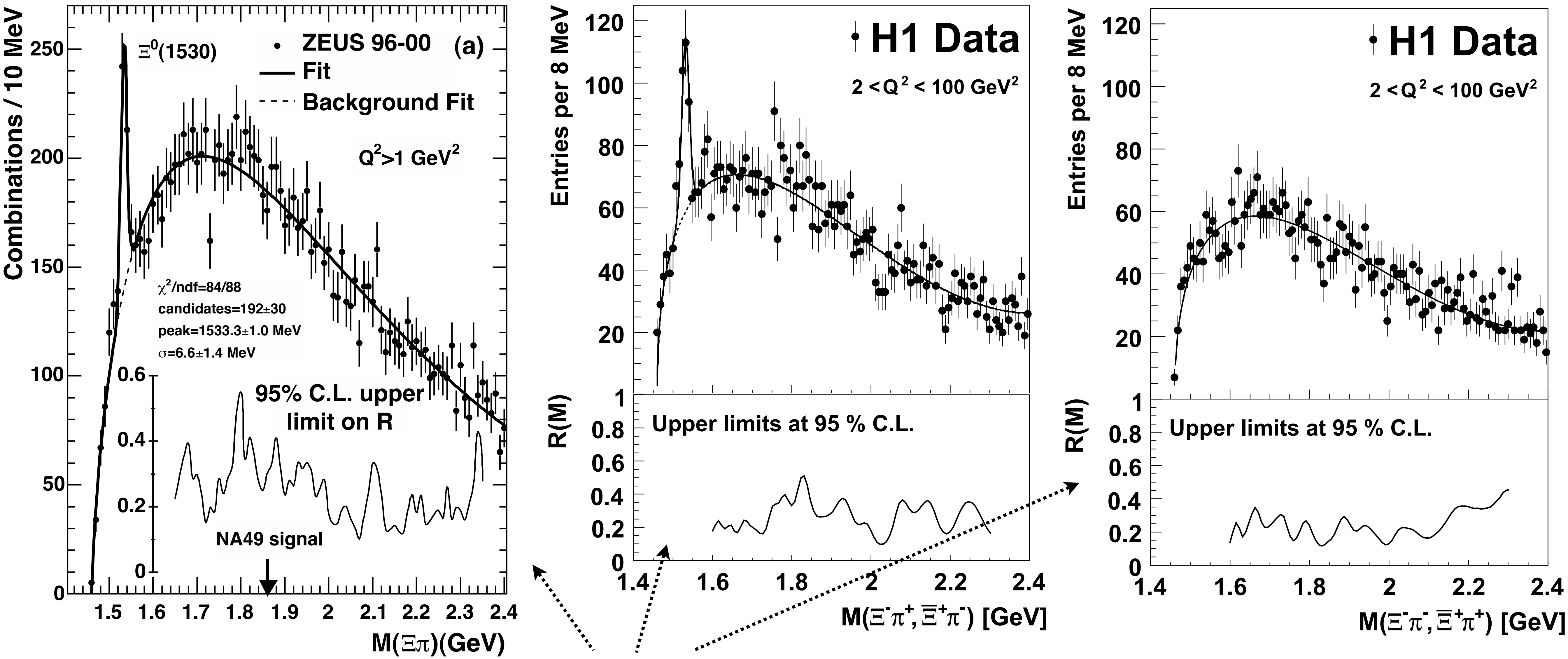
Strange Pentaquark Θ^+ in HERA I Data





- Evidence for signal at 1522 MeV found in ZEUS
  - $Q^2 > 20$ GeV^2, $0.04 < y < 0.95$: $\sigma(\mathbf{ep} \to \mathbf{e}\,\theta\mathbf{X} \to \mathbf{eK^0pX}) = \mathbf{125} \pm \mathbf{27^{+38}_{-28}}\ \mathrm{pb}$
- No signal seen in H1
  - upper limit [σ(M=1.52 GeV) < 100 pb (95%C.L.)] does not support ZEUS observation
- HERA II data should clarify

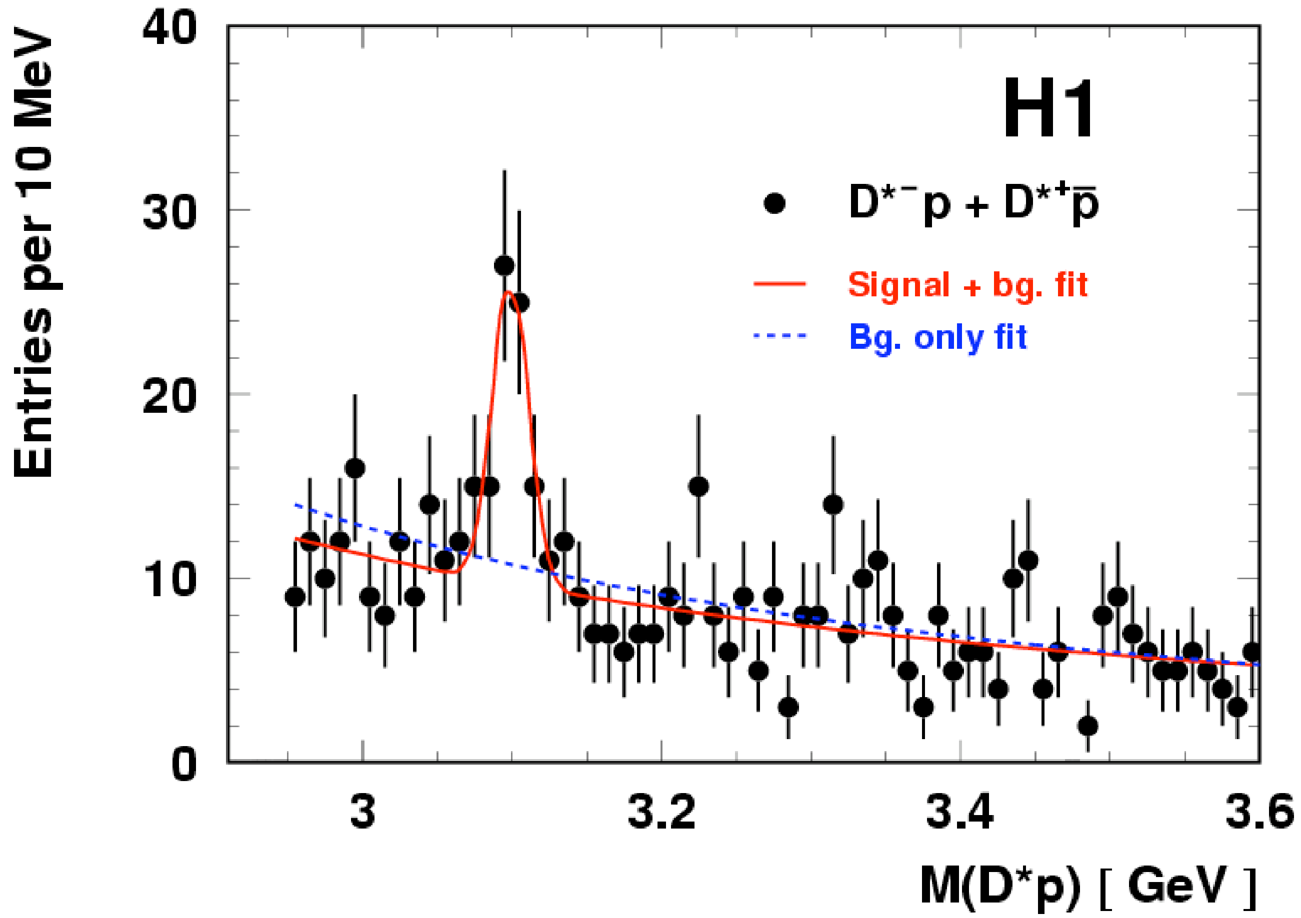
Search for Double Strange Pentaquark Ξ_{5q}

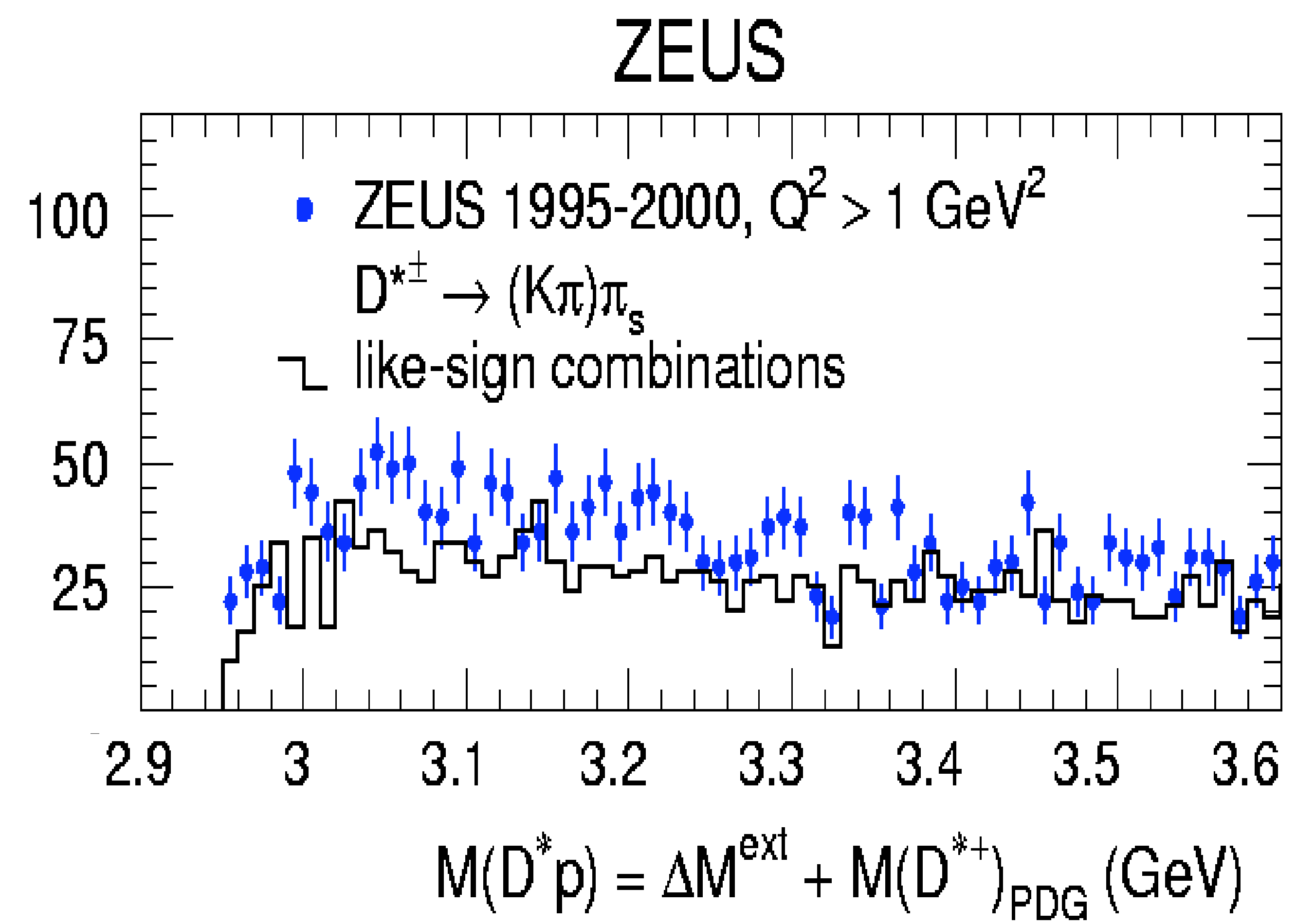


upper limit on ratio to Ξ^0(1530)

- Search motivated by evidence for two baryonic resonances reported by NA49 in 2004
- Established baryon state $\Xi^0(1530)$ clearly seen by ZEUS and H1
- No signal of new baryonic state found in the mass range 1600-2300 MeV
- NA49 observation not confirmed by HERA data

D*p Resonance - Charmed Pentaquark



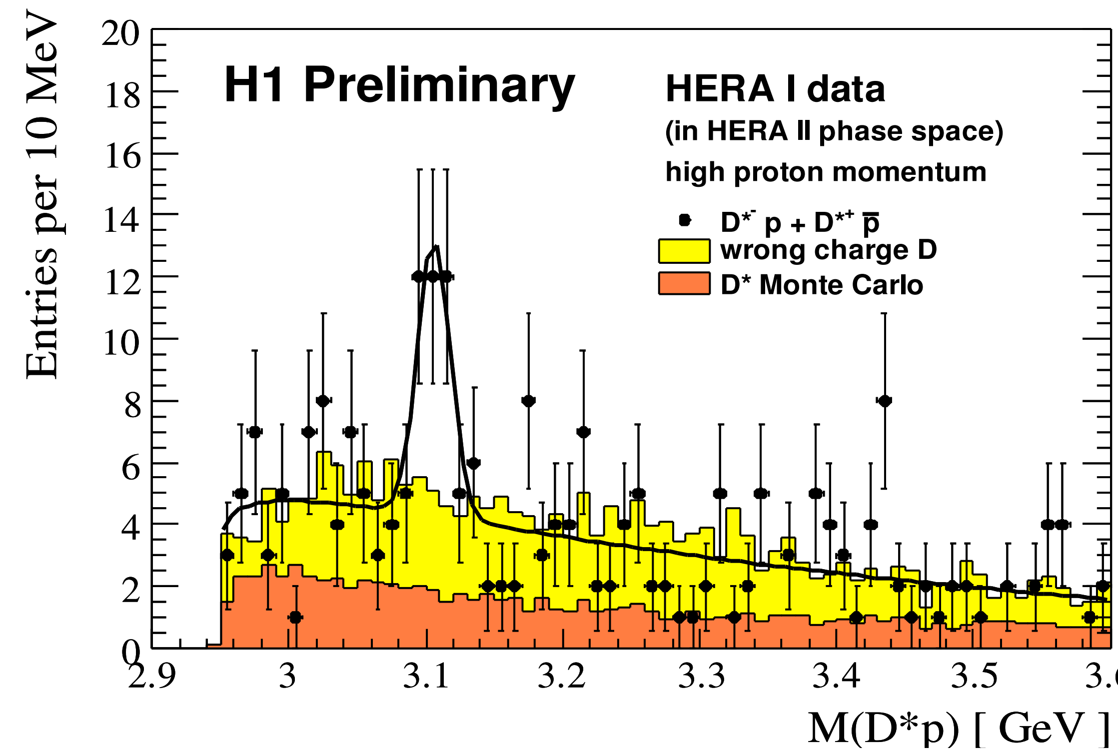


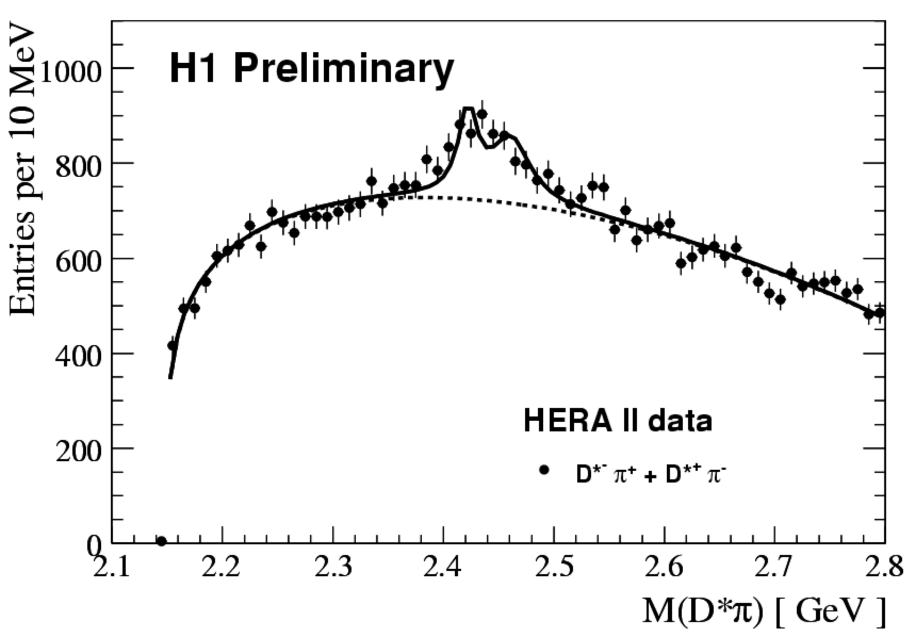
- H1 reported evidence for state at 3099 MeV in HERA I data (75 pb^{-1})
  - anti-charm baryon with minimum quark content *uuddc̄*
- No excess observed in other experiments
  - BaBar, CDF, ZEUS, ALPEPH, FOCUS

Search for D*p Resonance in HERA II Data

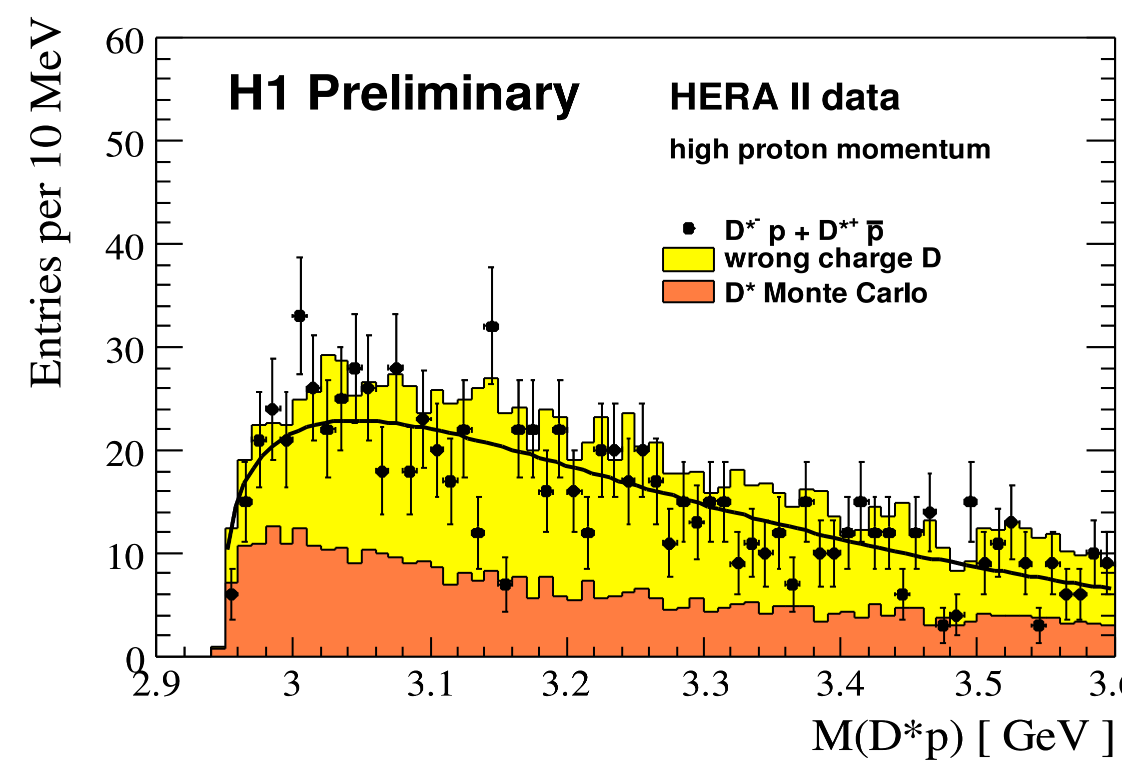
- Slightly reduced phase space after HERA II upgrade
- Compare data for high proton momentum selection (p_p > 2 GeV) without dE/dx cut
  - reanalysed HERA I data: signal clearly observed also in reduced phase space
    - **N(D*p) / N(D*) = 0.81 ± 0.21 %**
  - no excess observed in HERA II data
    - upper limit of 16.3 events (95% C.L.)
    - **N(D*p) / N(D*) < 0.10 % (95% C.L.)**
  - in both cases background well described by D* MC and wrong charge D

$L_{HERA\ II}$ = 384 pb^{-1}





Check for sensitivity by observing $D_1(2420)^0$ and $D_2^*(2460)^0 \rightarrow D^*\pi$: same D* selection and ΔM technique.



Summary

Fragmentation

- In general find good agreement of fragmentation properties between ep and e^+e^-
  - supports concept that fragmentation is independent of the hard sub-process

- But a number of issues need clarification
  - details of production of strangeness
  - charm fragmentation at kinematic threshold

Spectroscopy

- Several interesting (non)-observations
  - excited charm and charm-strange mesons observed
  - evidence for glueball candidate $f_0(1710)$
  - pentaquarks (not confirmed with HERA II data)

- Most results shown still based on HERA I data only
  - more results expected in near future from analyses of full data sets