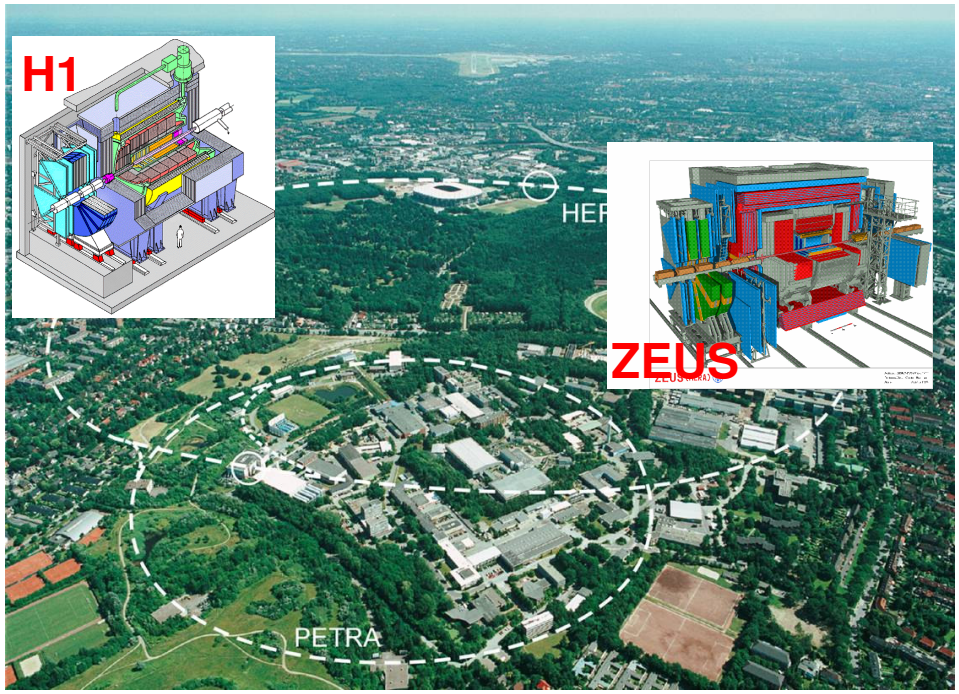
The 7th international conference on Hyperons, Charm and Beauty Hadrons, Lancaster, UK 2nd -8th July, 2006

Spectroscopy and pentaquark search in *ep* collisions at HERA

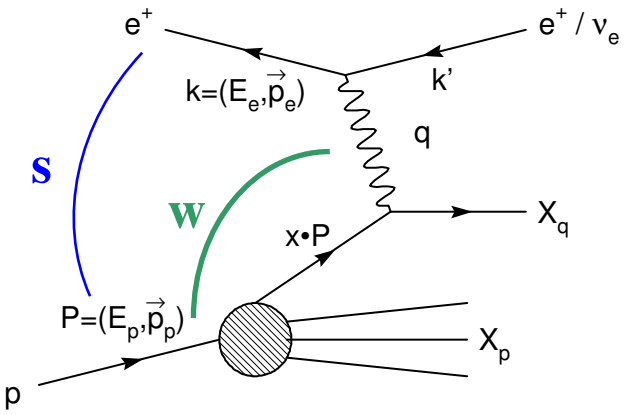
Chuanlei Liu (McGill University)
On behalf of H1 and ZEUS Collaborations

- **Introduction**
- **Hadron spectroscopy:** K^0_S, Λ, prod. , ratios, polarizations…
- **Charm fragmentation:** functions, fractions and ratios
- **Search for pentaquarks:** strange PQ, charm PQ.
- **Summary**

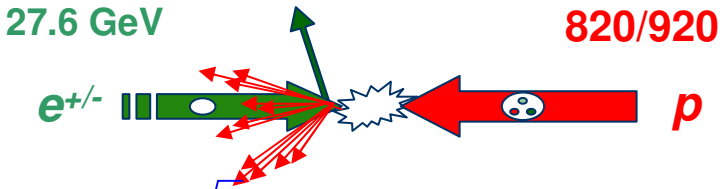
HERA experiments



Event Kinematics



- 4-momentum transfer squared
$$Q^2 = -(k-k')^2 = -q^2$$
- Bjorken scaling variable
$$x = \frac{Q^2}{2\,p\cdot q}$$
- Inelasticity parameter
$$y = \frac{p\cdot q}{p\cdot k}$$
- γ^*p c.m energy
$$w^2 = (p+q)^2$$



$$\sqrt{s} = 300 \sim 318 GeV$$

Two kinematic regimes

- **Deep Inelastic Scattering (DIS): Q^2>1 GeV^2**
- **Photoproduction (PHP): Q^2~0 GeV^2**

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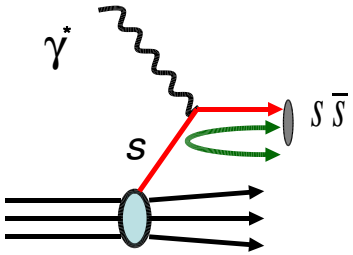
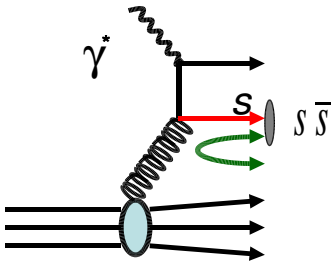
Strange production at HERA

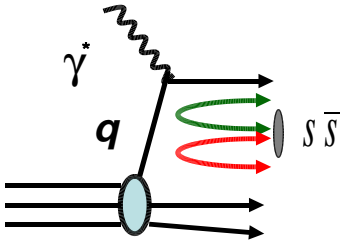
➢ **Copious strangeness produced at HERA provides a useful way to study the fragmentation process by investigating productions, relative yields, polarizations etc..**



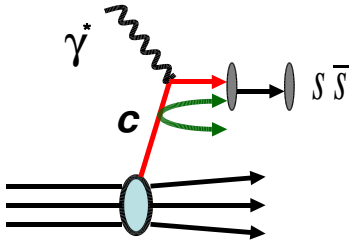
a) Hard scattering of *s* sea quark



b) Boson-gluon fusion (BGF)

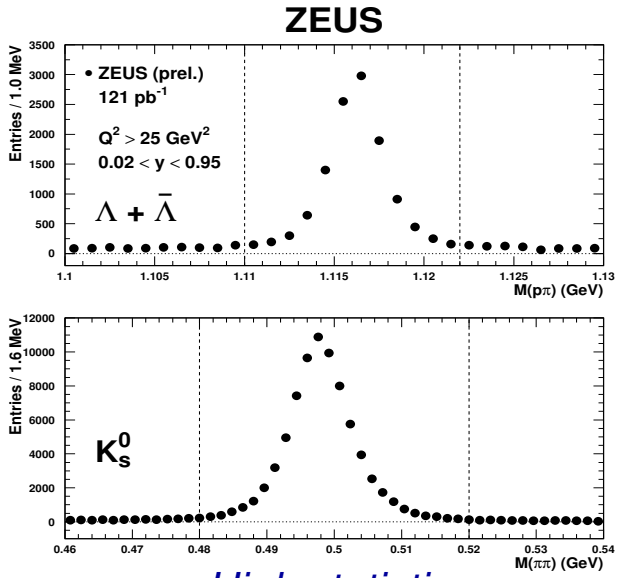


c) Parton pure fragmentation



d) Heavy quark decay

Production mechanism of strangeness



- *High statistic*
- *Small background*

➢ **Measurements in three different phase spaces**

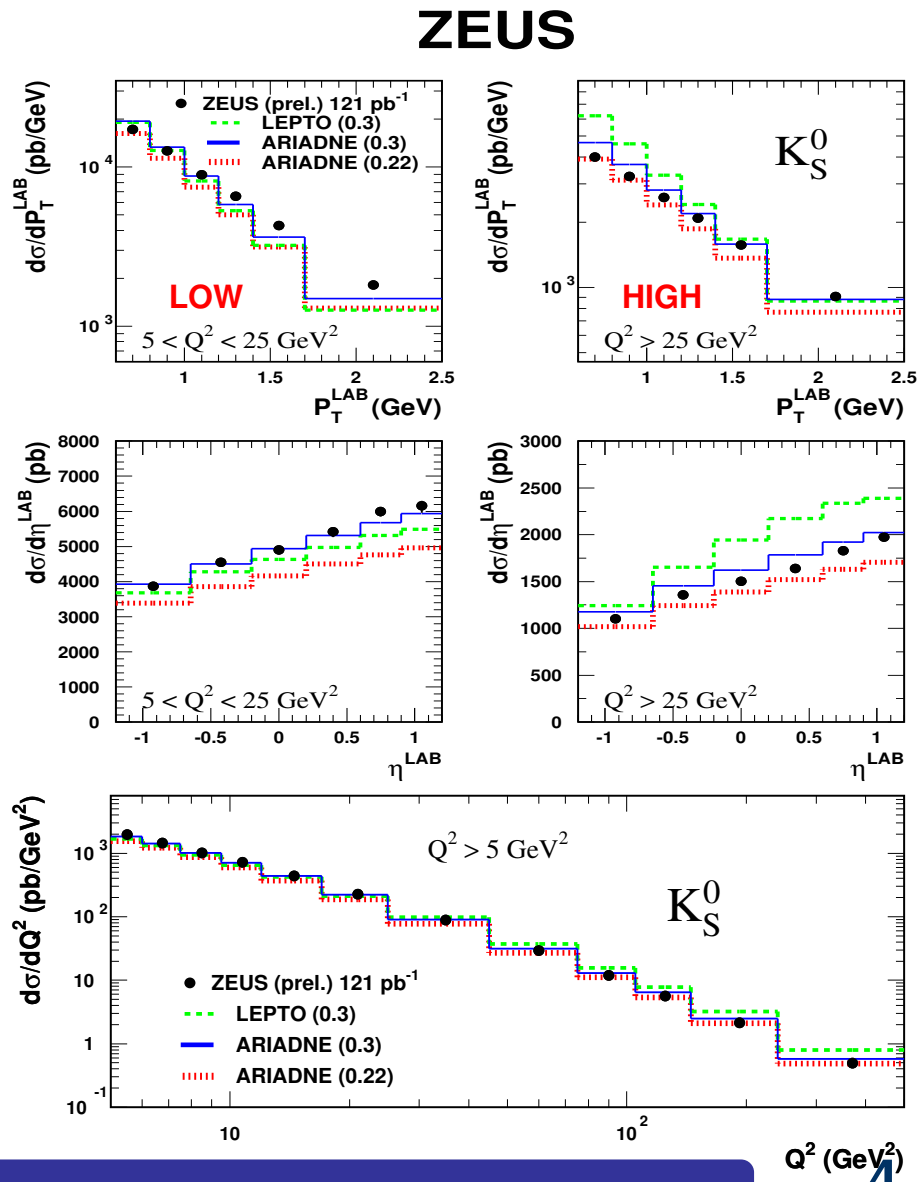
PHP: (Q^2 ~ 0 GeV^2) at least 2-jets

LOW: $5<Q^2<25$ GeV^2

HIGH: $Q^2>25$ GeV^2

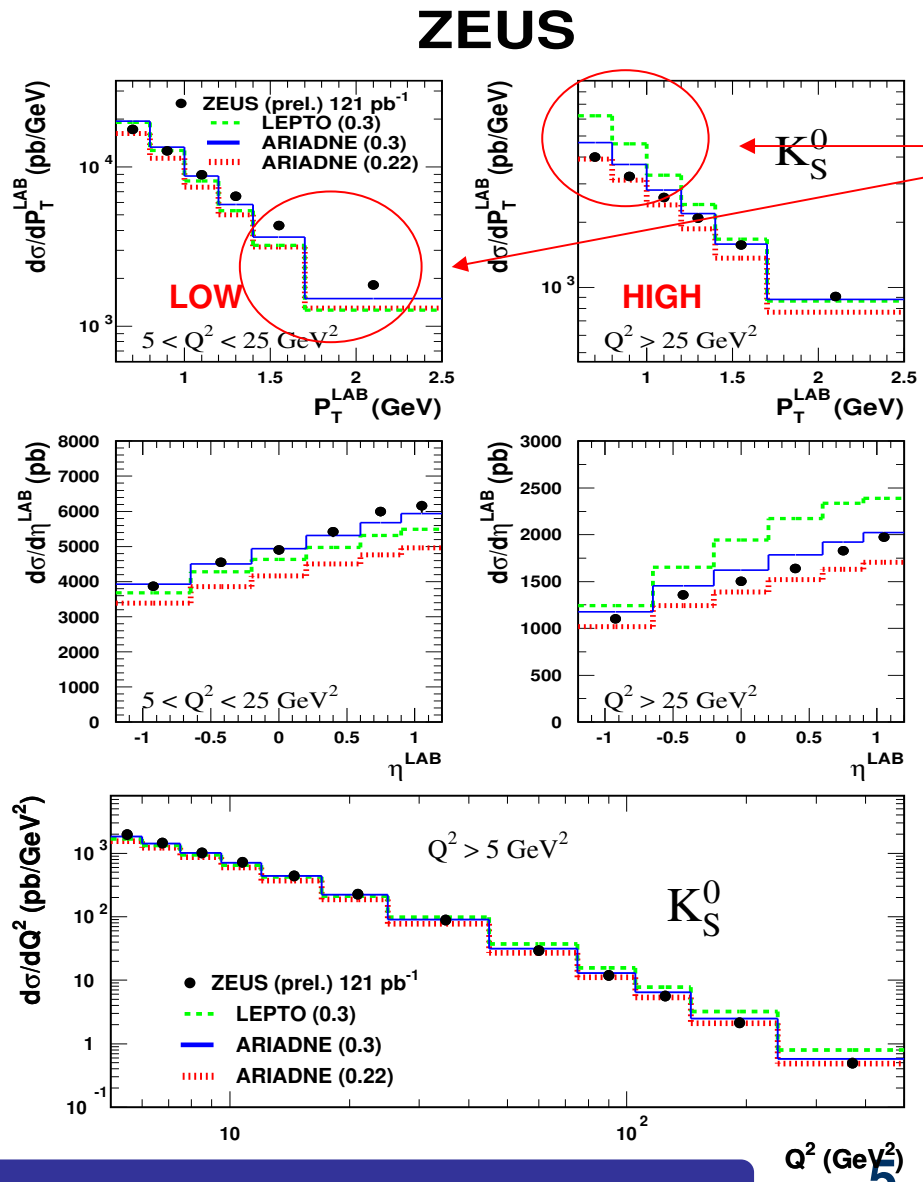
With $0.6<P_T<2.5$ GeV, $|\eta|<1.2$

K^0_S production in DIS



- **In general,** ARIADNE ($\lambda_s = 0.3$) reasonably describes the data.

K^0_S production in DIS



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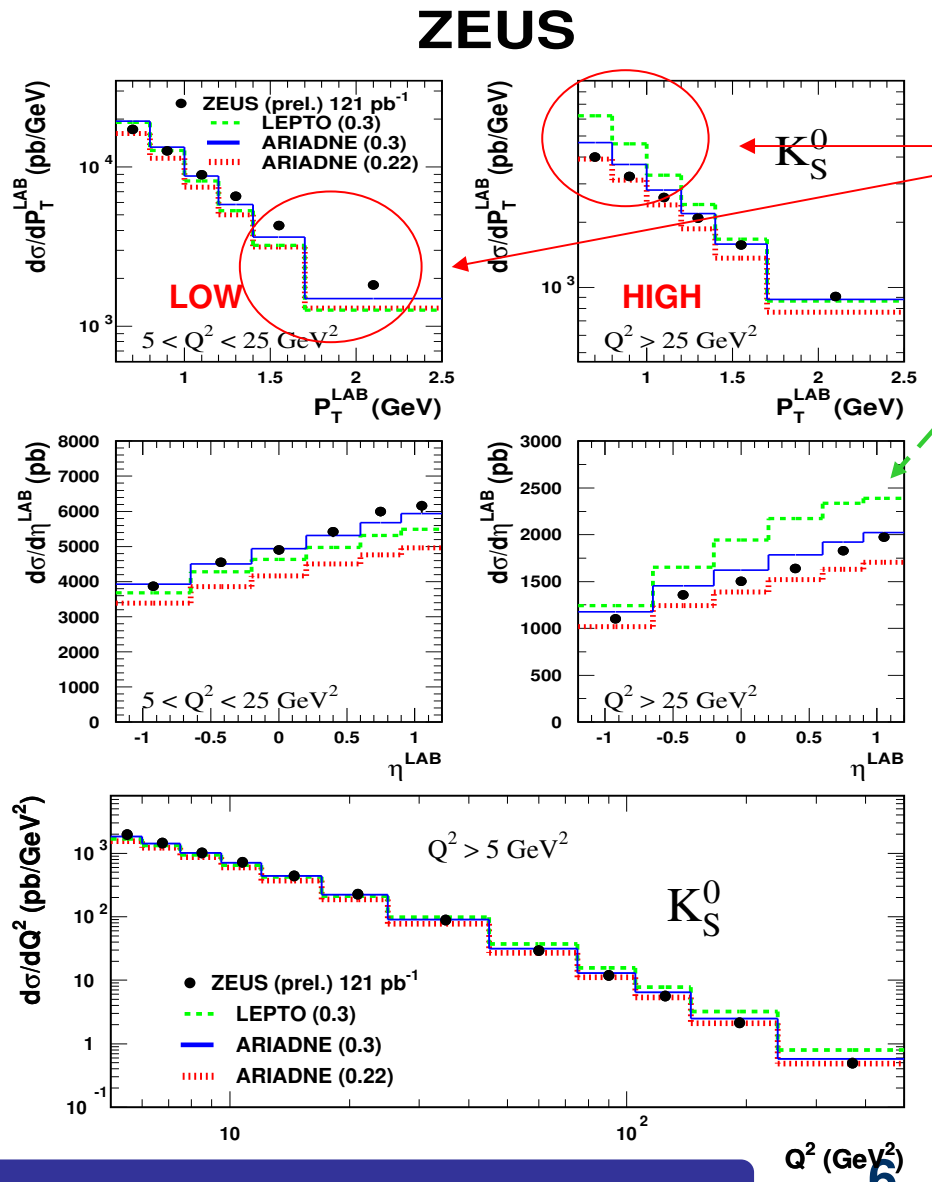
K^0_S production in DIS



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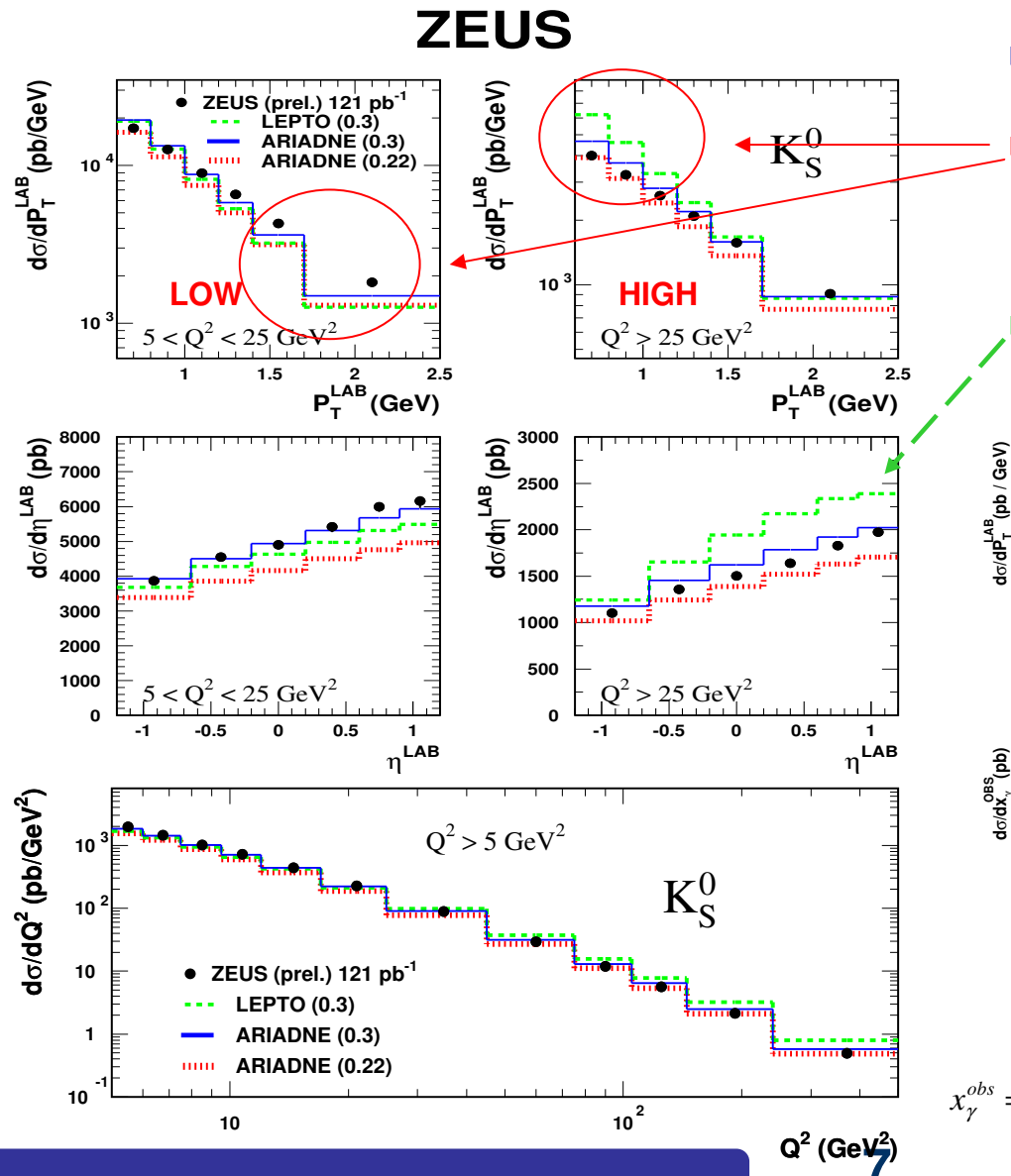
- **Lepto** fails to reproduce the K^0_S production.

K^0_S production



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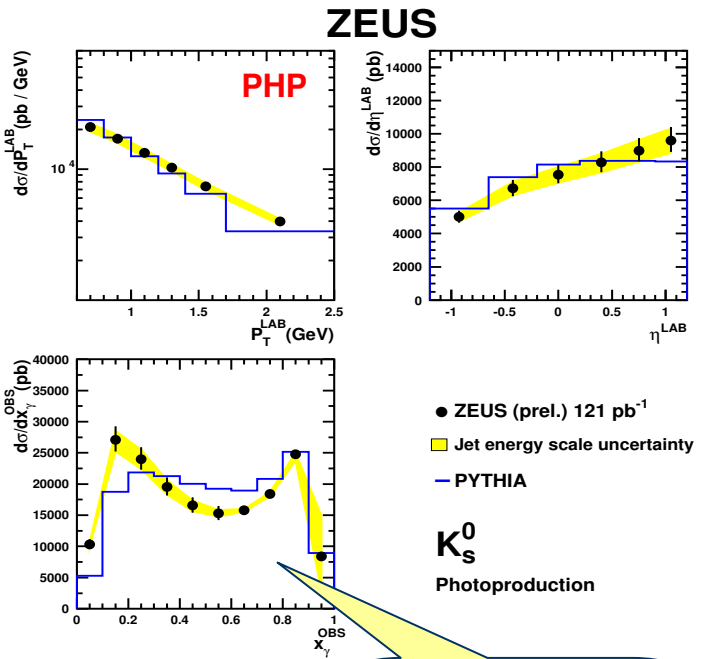
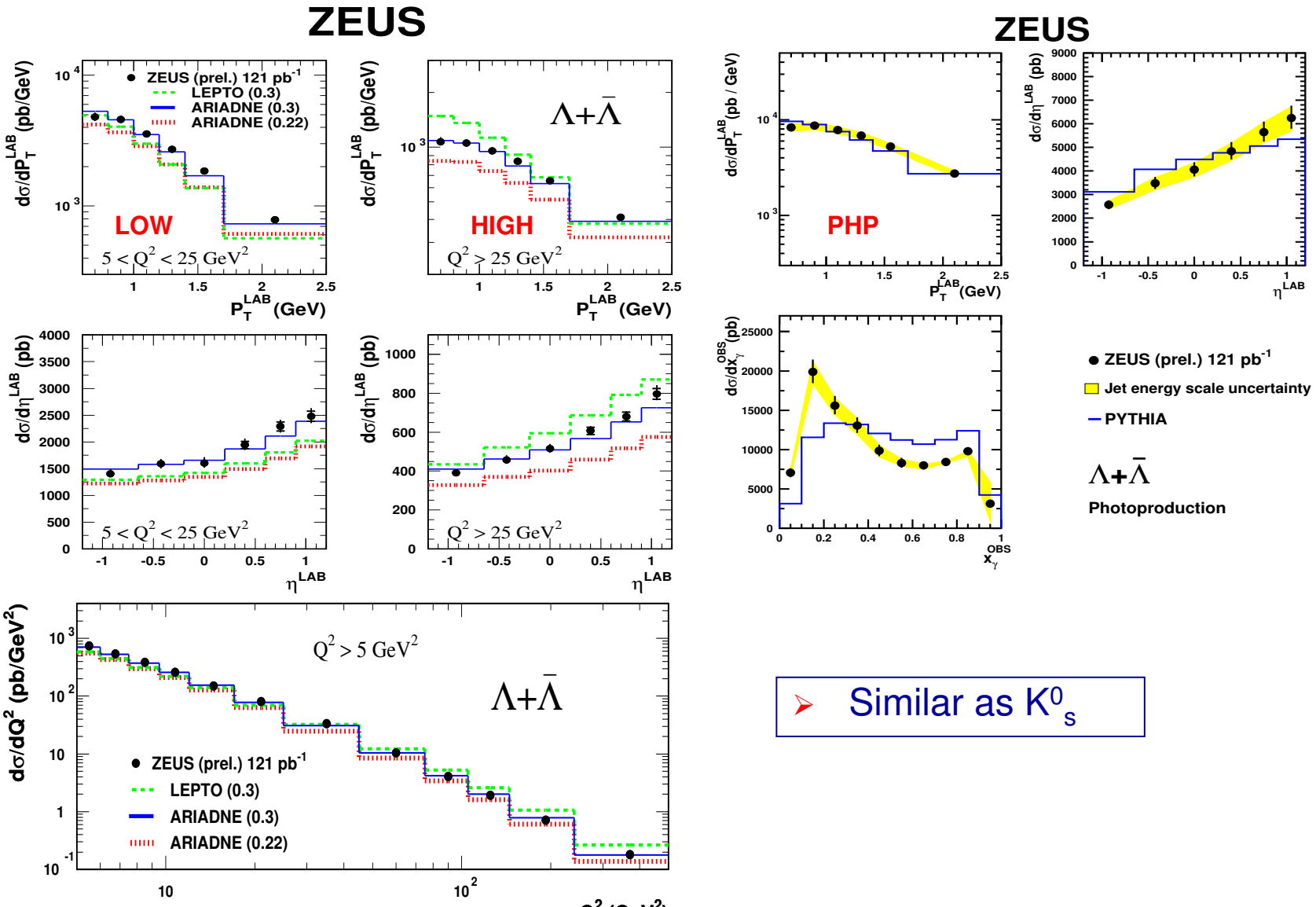


$$x_\gamma^{obs} = \sum_{jet} E_T^{jet} e^{-\eta^{jet}} \Big/ 2yE_e$$

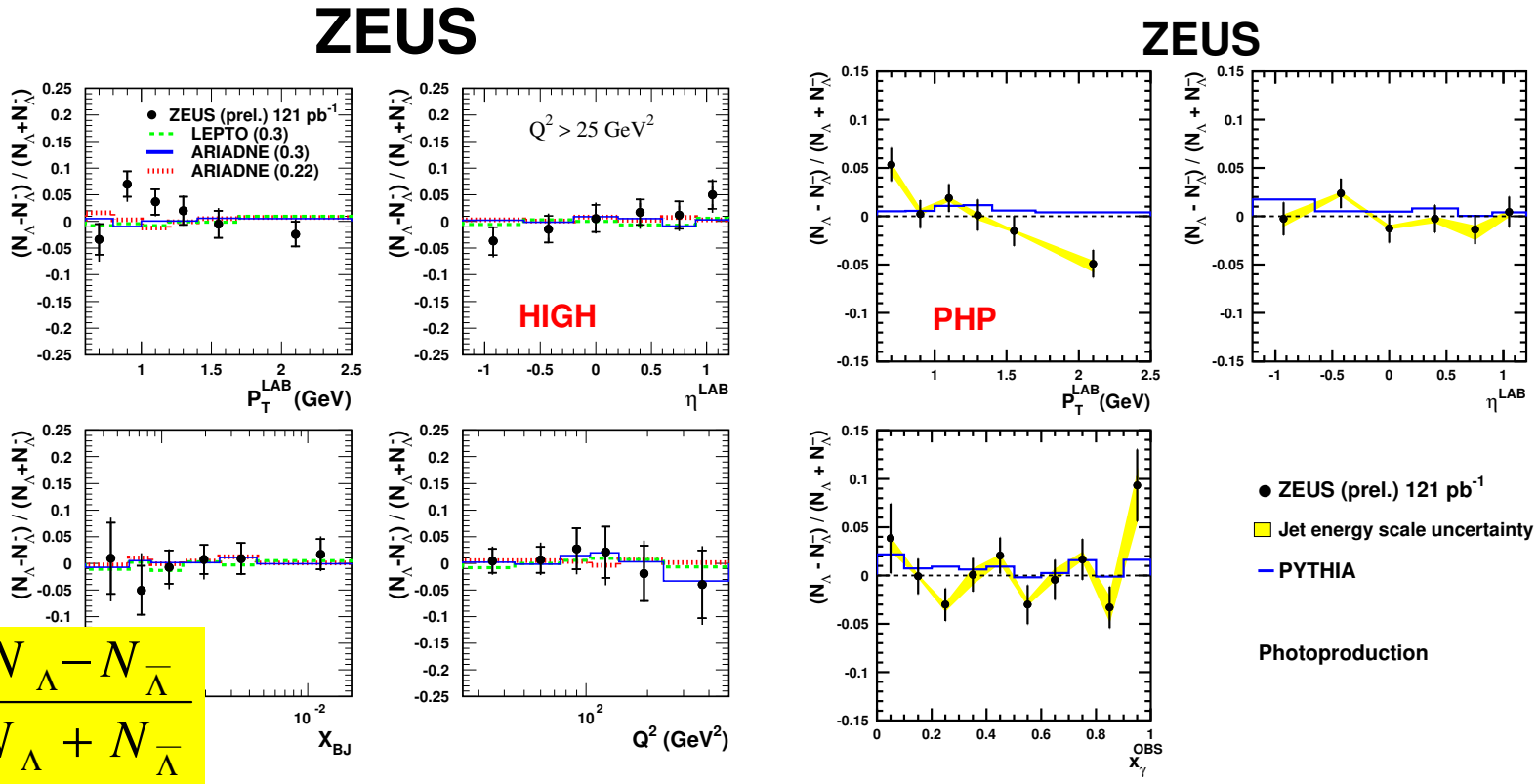
Poor agreement!

Λ and $\bar{\Lambda}$ production



- Similar as K^0_s

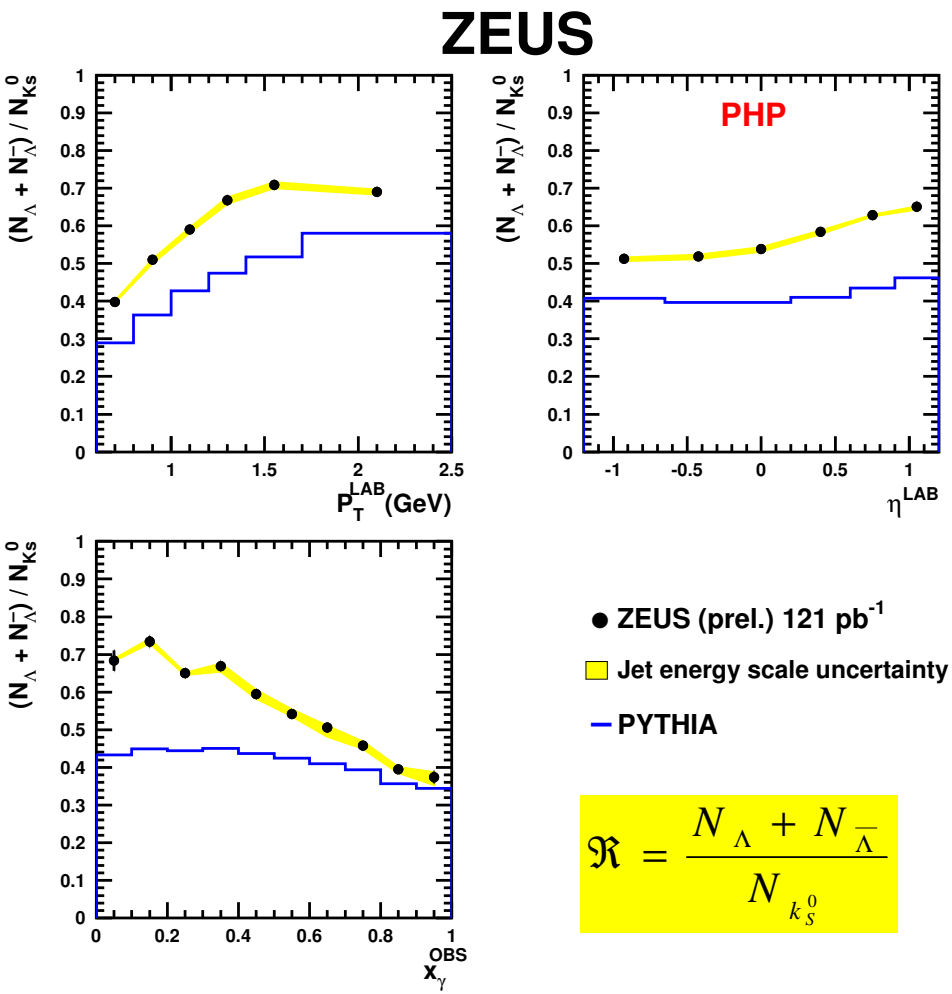
Λ - $\overline{\Lambda}$ asymmetry



$$A = \frac{N_\Lambda - N_{\overline{\Lambda}}}{N_\Lambda + N_{\overline{\Lambda}}}$$

- **No significant production asymmetry was observed.**
- **HIGH:** $A = +0.3 \pm 1.3^{+0.5}_{-0.8}\%$(Data), $A = +0.4 \pm 0.2\%$ (pred.)
- **PHP:** $A = -0.07 \pm 0.6 \pm 1.0\%$(Data), $A = +0.6 \pm 0.1\%$ (pred.)
  - Productions might be according to the same mechanism.
  - Influence of the initial proton is not observed in the central region of detector

Λ / K^0_S ratio in PHP



$$\Re = \frac{N_\Lambda + N_{\bar\Lambda}}{N_{k^0_S}}$$

- **PYTHIA underestimates $\mathcal{R}$ in photoproduction (Q^2~0 GeV^2).**

- **$\mathcal{R}$ as a function of x_γ**
  - PYTHIA fails to describe the shape of $\mathcal{R}$ as a function of x_γ
  - In smaller x_γ (resolved photoproduction dominated) → large $\mathcal{R}$ discrepancy

$$x_\gamma^{obs} = \sum_{jet} E_T^{jet} e^{-\eta^{jet}} \Big/ 2yE_e$$

X_γ is a measure of the fraction of the photon energy transferred to the highest E_T dijet system.

Further study is carried out to investigate the discrepancy.

Λ / K^0_s ratio in PHP

- **Two sub-samples with different topological features in photoproduction.**

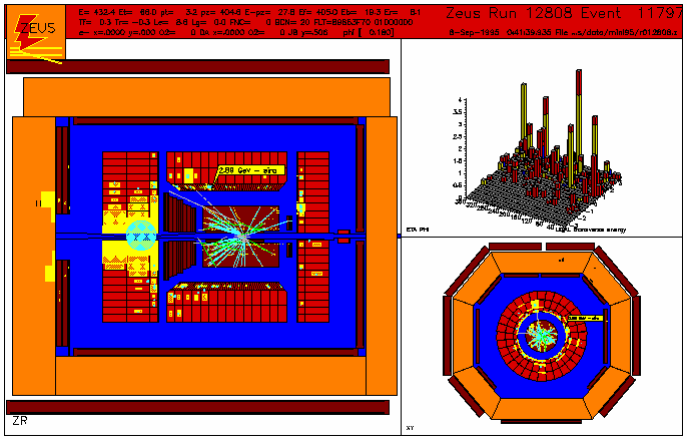
$$f = \frac{E_T^{jet}}{E_T^{total}}$$

E_T^{jet} ← from the highest E_T jet

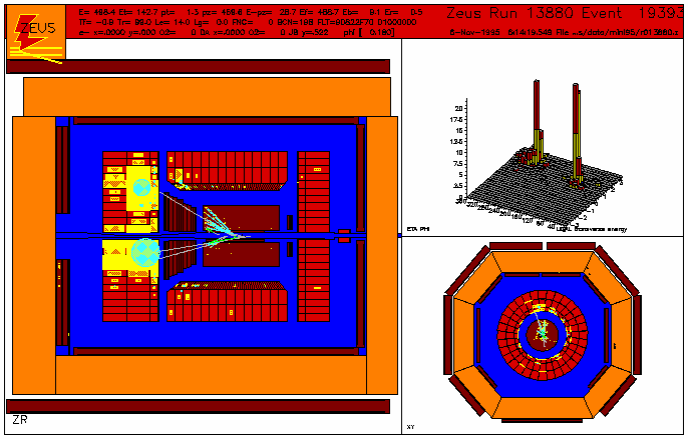
E_T^{total} ← the total E_T of the event

"fireball-enriched" events: $f < 30\%$

"fireball-depleted" events: $f > 30\%$

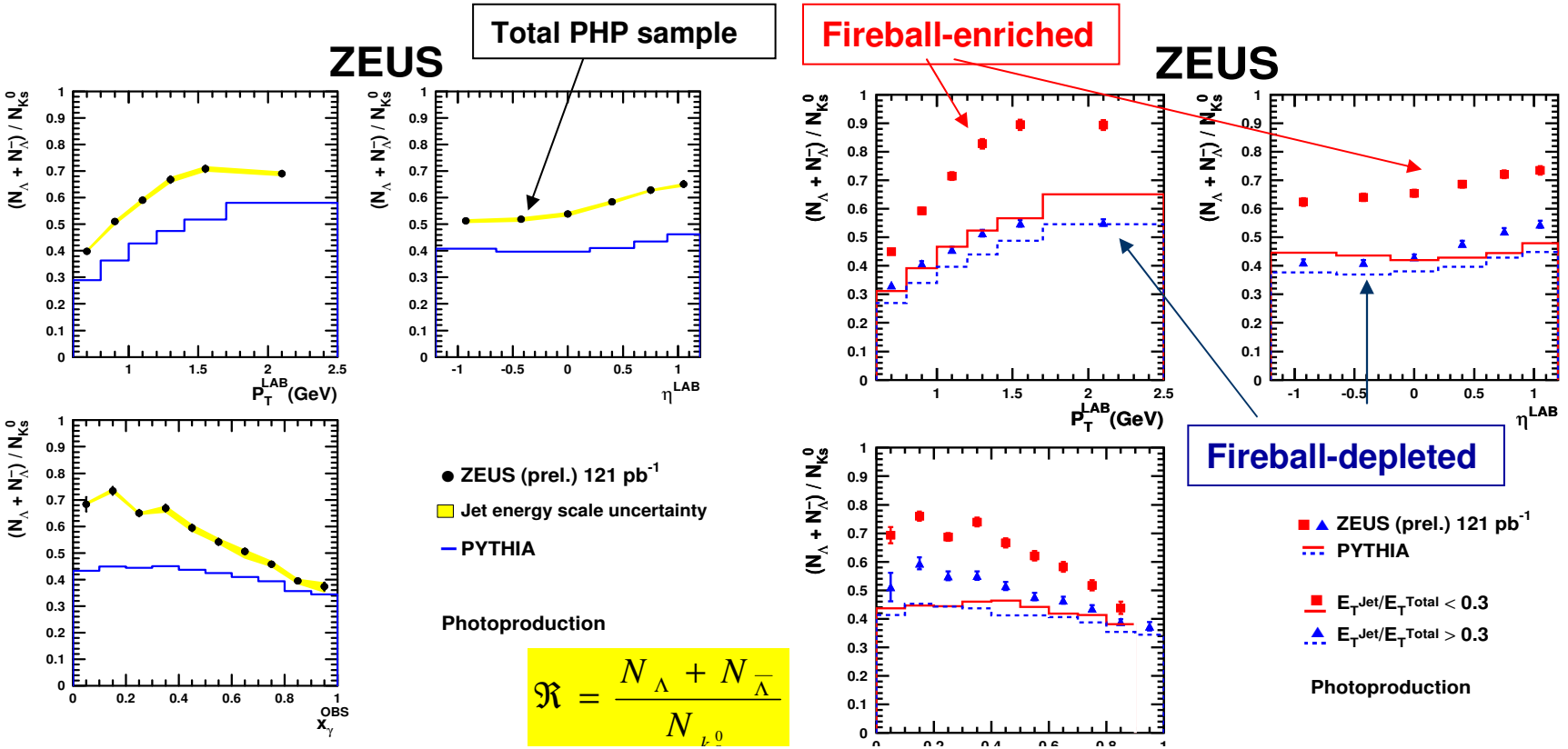


largely isotropic distribution (multiple jets production)



clear jet structure (dijet production)

Λ / K^0_S ratio in PHP



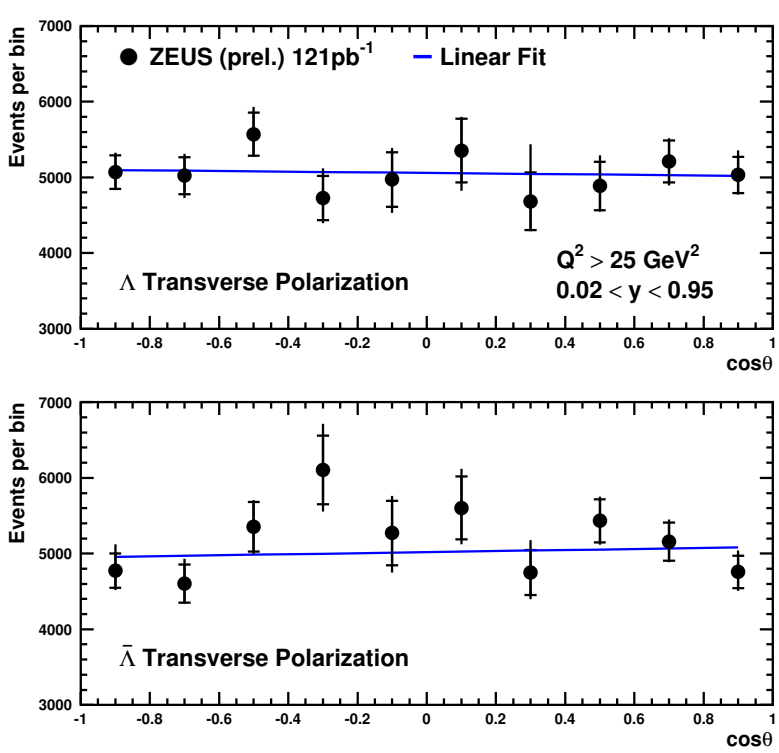
- **Large difference on $\mathcal{R}$ is observed**
  - for fireball-enriched events and
  - Especially in the lower x_γ region
- **Where 'multiple interaction' (MI) mechanism has most effect.**
  - Indicates inefficiency of MI in PYTHIA to describe $\mathcal{R}$

Λ and $\overline{\Lambda}$ polarization

- The transverse polarization of Λ, P^{Λ}, was measured via the angular distribution of proton (decay production of Λ) in the Λ rest frame.

$$\frac{dN}{d\cos\theta} \propto \frac{1}{4\pi}(1+\alpha \cdot P^{\Lambda} \cdot \cos\theta) \quad \alpha = 0.642$$

- The measured Λ polarization was consistent with zero.
- HERA II provides longitudinally polarized electron beam, could we see Λ polarization?



	$Q^2 > 25 GeV^2$	$5 < Q^2 < 25\ GeV^2$	PHP
P^{Λ} (%)	-1.3±4.3 (*stat.*) $^{+4.0}_{-0.8}$ (*syst.*)	-4.0±5.3 (*stat.*) $^{+4.7}_{-4.0}$ (*syst.*)	-2.4±2.2 (*stat.*)
$P^{\overline{\Lambda}}$ (%)	-2.2±4.2 (*stat.*) $^{+2.4}_{-1.3}$ (*syst.*)	-8.5±5.5 (*stat.*) $^{+4.7}_{-2.1}$ (*syst.*)	-5.8±2.2 (*stat.*)
$P^{K^0_S}$ (%)	-1.5±1.1(*stat.*)	-0.05±1.5 (*stat.*)	-0.5±0.2 (*stat.*)

Charm fragmentation

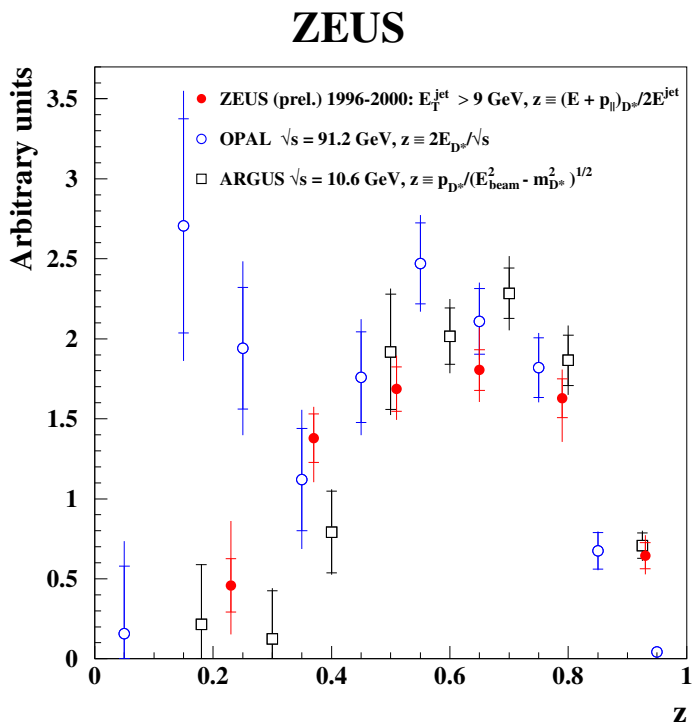
➢ To understand transition of charm quark to charmed mesons — non-perturbative aspect of the charm fragmentation.

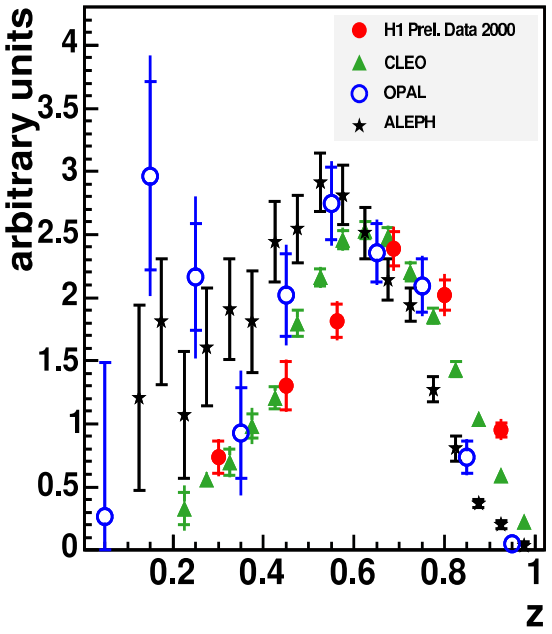
- **Fragmentation function:** proper parameterisation for the fractional transfer of *c* quark energy to a given D-meson *(z)*
- **Fragmentation fraction:** relative fragmentation fractions of charm hadrons.

  $f(c \rightarrow D) = \sigma(D) / \sigma(c)^{tot}$
- **Fragmentation ratio:**
  - $R_{u/d} = \frac{c\bar{u}}{c\bar{d}}$ Are *u* and *d* quarks produced equally?
  - $\gamma_s = \frac{2c\bar{s}}{c\bar{d} + c\bar{u}}$ *s*-quark production suppression
  - $P_v = \frac{v}{v + ps}$ Are Vector (D*) and pseudoscalar (D) mesons produced as what predicted by spin counting?

➢ To check the universality of the fragmentation: compared with predictions and results from e^+e^- annihilation.

Charm fragmentation function





H1 hemisphere method
$\langle\sqrt{\hat{s}}\rangle \approx 10$ GeV,
$z = \frac{(E+p_L)_{D^*}}{\sum_{hem}(E+p)}$

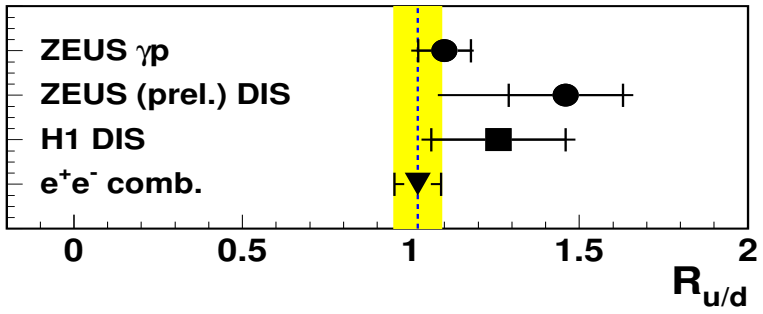
CLEO $\sqrt{s} \approx 10$ GeV,
$z = p_{D^*}/p_{max}$

OPAL $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D^*}/\sqrt{s}$

ALEPH $\sqrt{s} = 91.2$ GeV,
$z = 2E_{D^*}/\sqrt{s}$

- *z* (D*) is the fraction of the charm quark momentum carried by D*.
- *z* (D*) distribution from H1 and ZEUS, roughly comparable to the CLEO data at a similar center-of-mass energy.
- OPAL and ALEPH shows a large contribution from gluon splitting at small *z* due to large jet energy available at LEP.
- Measurements support universality of charm fragmentation function

Fragmentation ratios



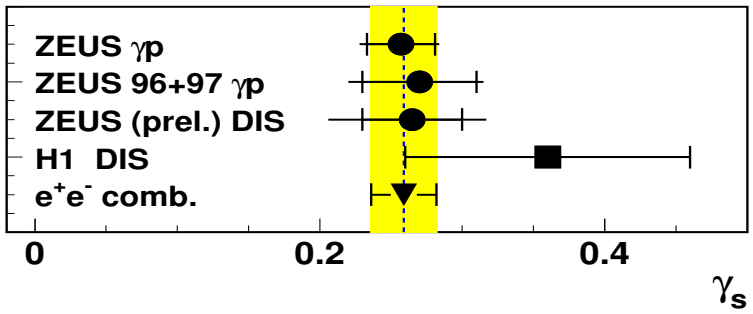
H1:

$$R_{u/d} = \frac{f(c \to D^0) - f(c \to D^{*+} \to D^0\pi)}{f(c \to D^+) + f(c \to D^{*+} \to D^0\pi)}$$

ZEUS:

$$R_{u/d} = \frac{\sigma^{dir}(D^{0,*0})}{\sigma^{dir}(D^{\pm,*\pm})} = \frac{\sigma^{untag}(D^0)}{\sigma(D^\pm) + \sigma^{tag}(D^0)}$$

- Consistent with isospin invariance



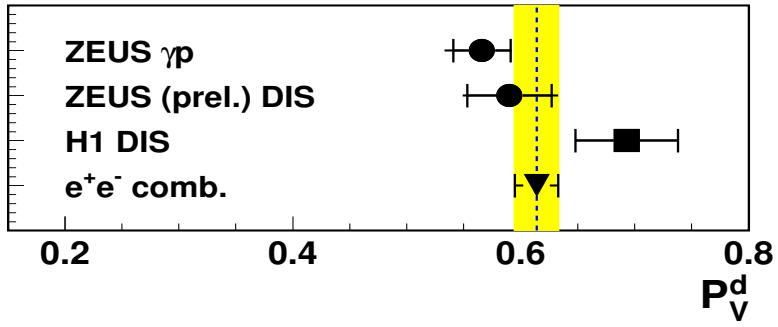
H1:

$$\gamma_s = \frac{2f(c \to D_S^+)}{f(c \to D^+) + f(c \to D^0)}$$

ZEUS:

$$\gamma_s = \frac{2\sigma(D_s^\pm)}{\sigma(D^\pm) + \sigma^{tag}(D^0) + \sigma^{untag}(D^0) + 2\sigma^{add}(D^{*\pm})}$$

- D_S production is suppressed by factor of ~3.9 in c-fragmentation



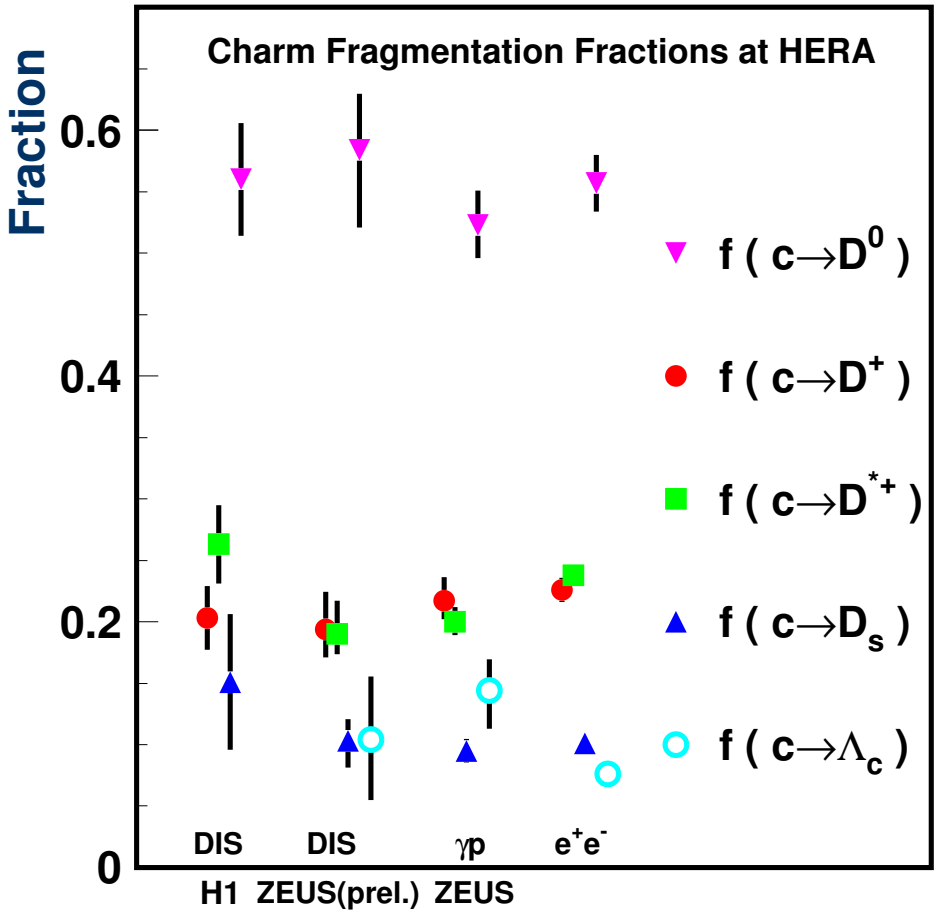
- Fraction of D mesons produced in vector state

$$P_V^d = \frac{V}{V + PS}$$

- Not consistent with Naïve spin counting which predicts $P^d_V \sim 3/4$

All ratios are in agreement with each other

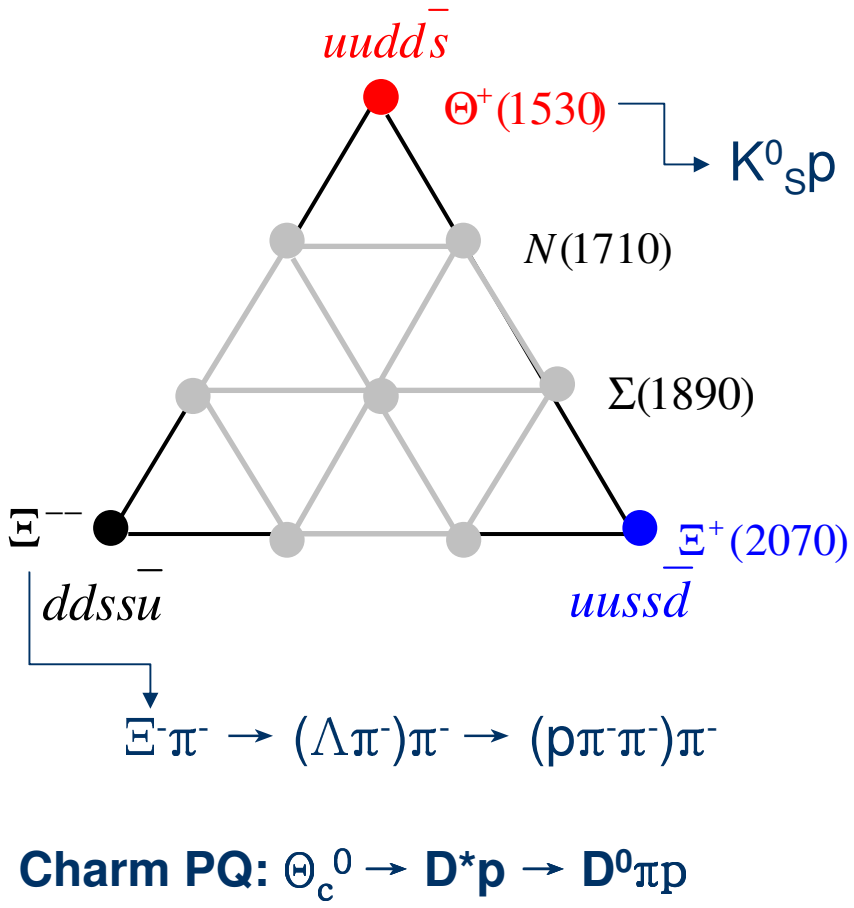
Fragmentation fractions



- Ratio of specific charmed hadron production to all charm ground states
- In agreement with world average, universality of charm fragmentation fractions.

Search for pentaquark

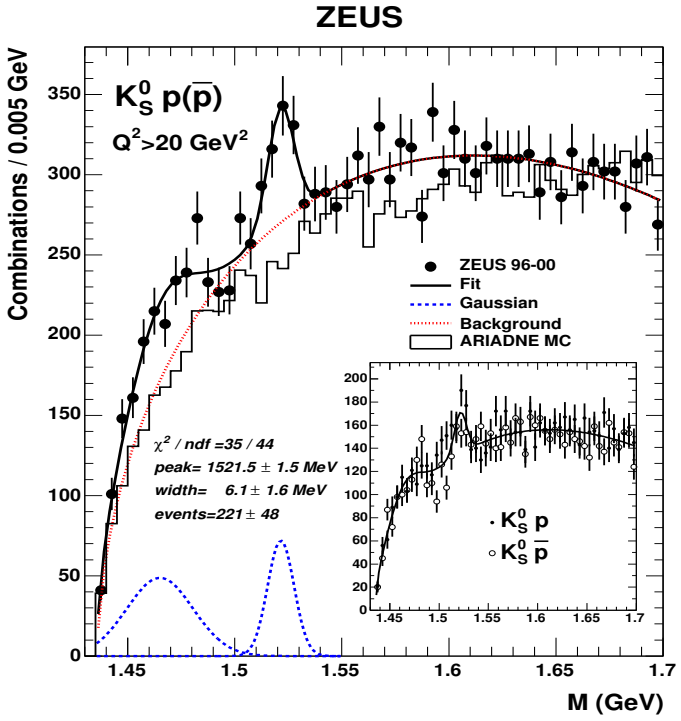
- At apex, baryons with exotic quantum numbers predicted, which are not explained and described with 3 quarks (D. Diakonov, V. Petrov and M. Polyakov). **hep-ph/9703373**
- Predicts a narrow exotic state Θ^+:
  $M_{\Theta+} \approx 1530$ MeV, $\Gamma_{\Theta+} < 15$ MeV
- Both positive and negative results are reported by many experiments.
- Searches for pentaquarks were preformed by H1 and ZEUS experiments in *ep* collisions.

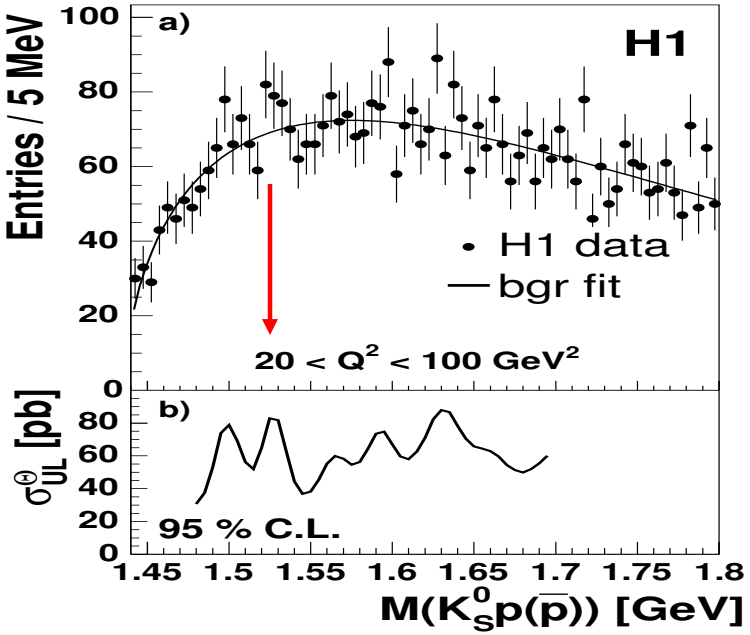


Charm PQ: $\Theta_c^0 \rightarrow D^*p \rightarrow D^0\pi p$

Search for $\Theta^+ \rightarrow K_S^0 p$

- **ZEUS** **PLB 591 (2004) 7**
  - Visible signal
  - $M(\Theta^+) = 1521.5 \pm 1.5^{+2.8}_{-1.7}$ MeV
  - Width = 6.1 ± 1.6 MeV
  - 221 ± 48 events ($4.6\,\sigma$)





- **H1**
  - No peak visible (same kinematic region as ZEUS, but less statistic)
  - H1 Upper limit on cross section (~100 pb) does NOT exclude ZEUS observation.

$\sigma\,(ep \rightarrow e\Theta^+ X \rightarrow e\,k^0_S p\,X) = 125 \pm 27^{+36}_{-28}$ pb

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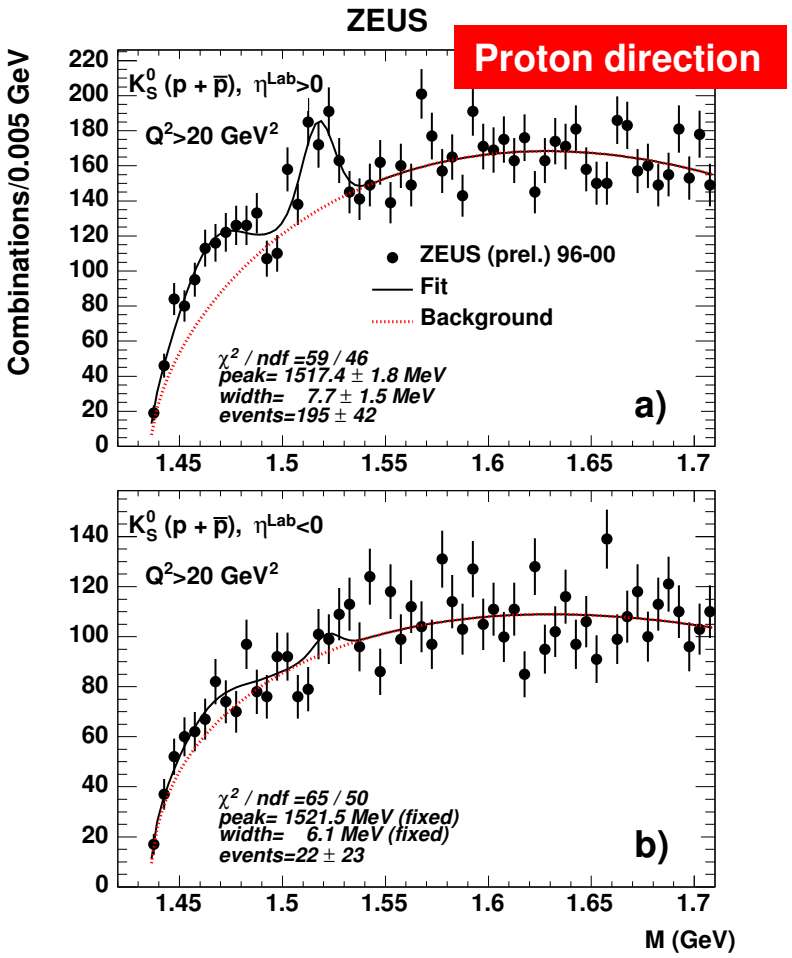
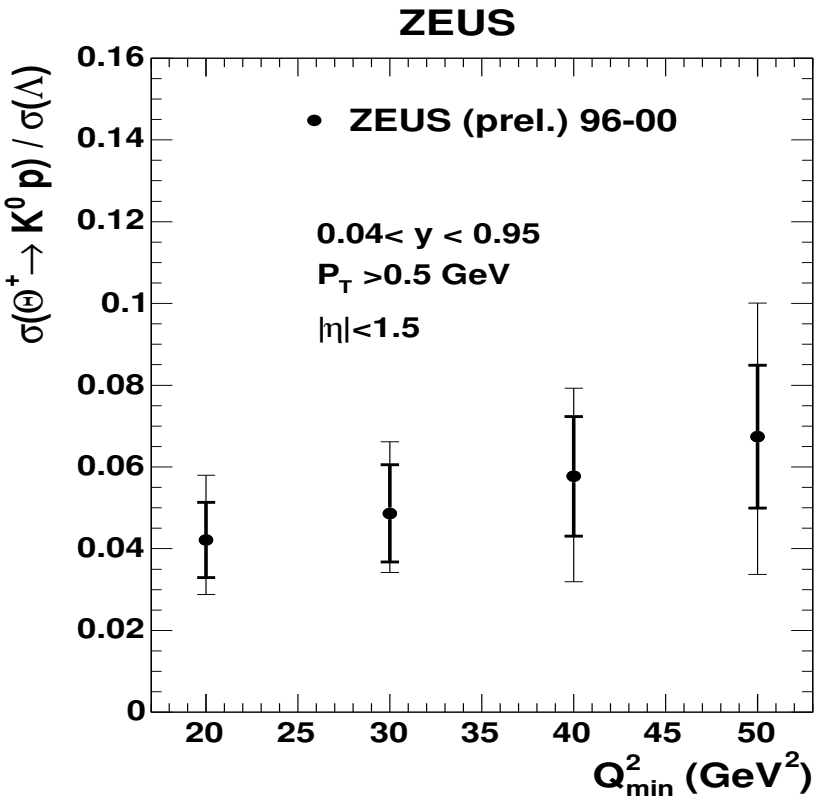
Θ^+ production property



- Θ^+ mostly in the forward region (proton direction)
- Indication of proton remnant related?

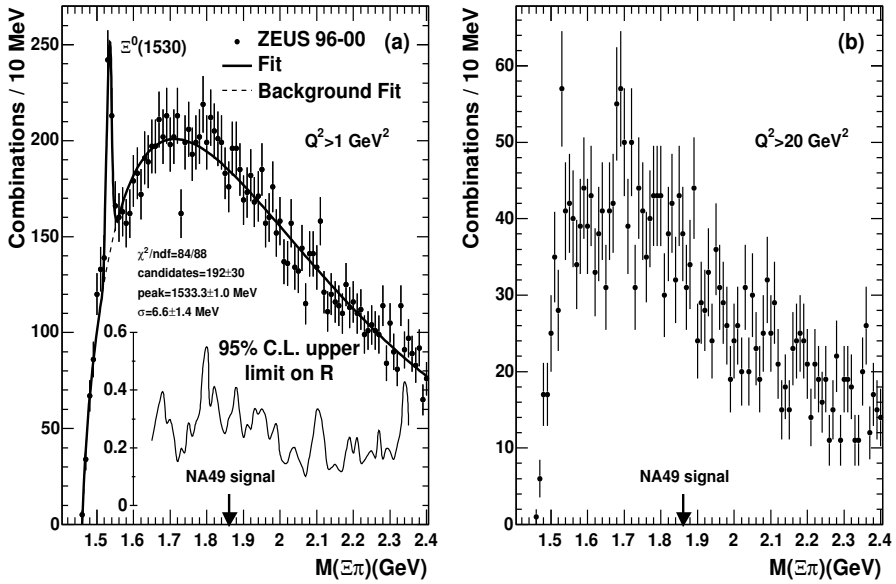


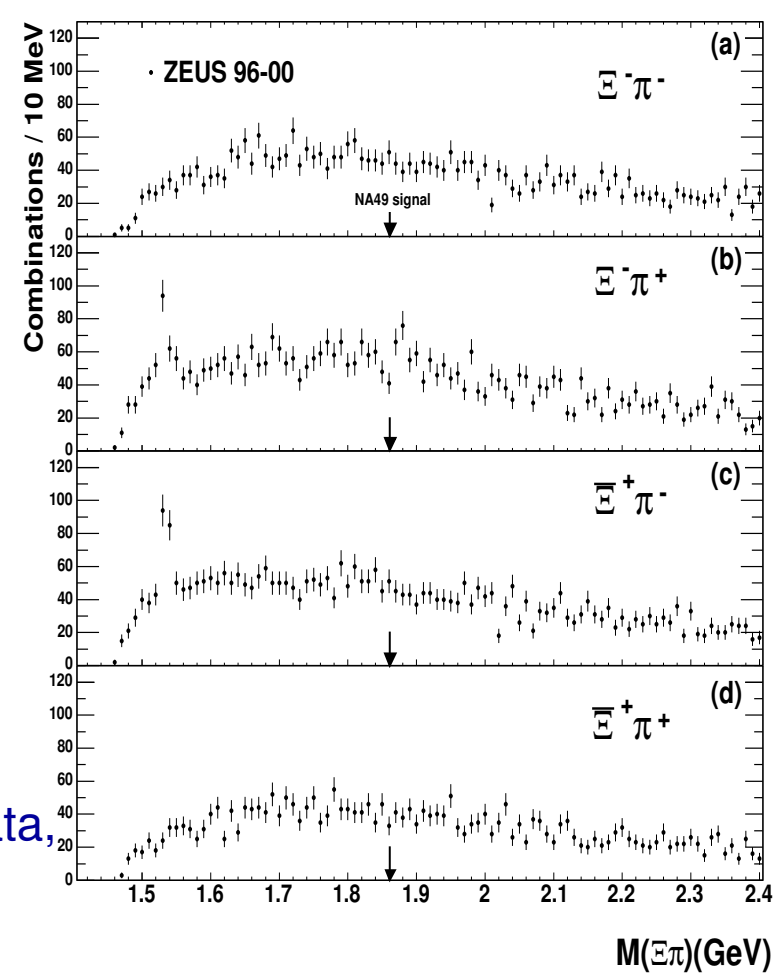
- Θ^+ / Λ production ratio
  - Θ^+ and Λ are reconstructed in the same kinematic region
  - $\sigma(\Theta^+) / \sigma(\Lambda) = 4.2 \pm 0.9\ ^{+1.2}_{-0.9}$ %

Search for $\Xi_{3/2}^{--} \rightarrow \Xi^{-}\pi^{-}$

ZEUS

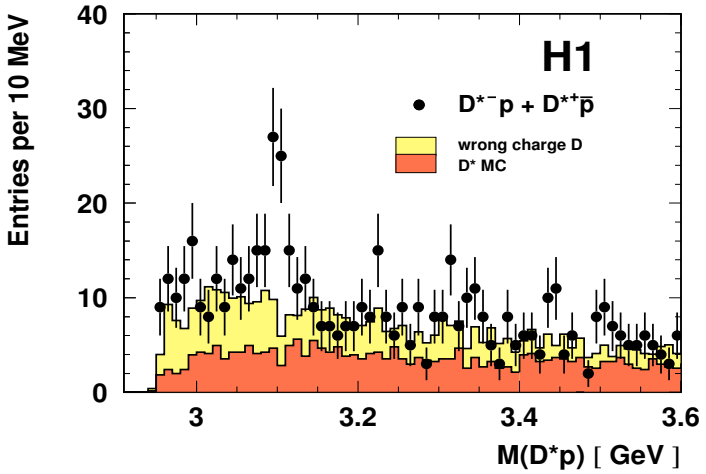
PLB 610 (2005) 212

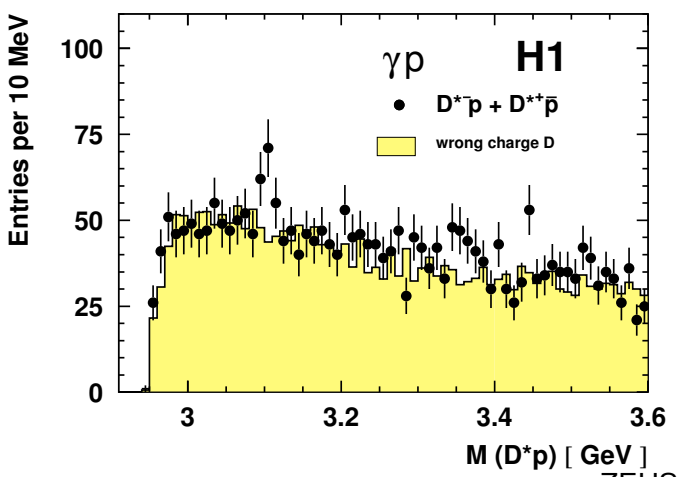




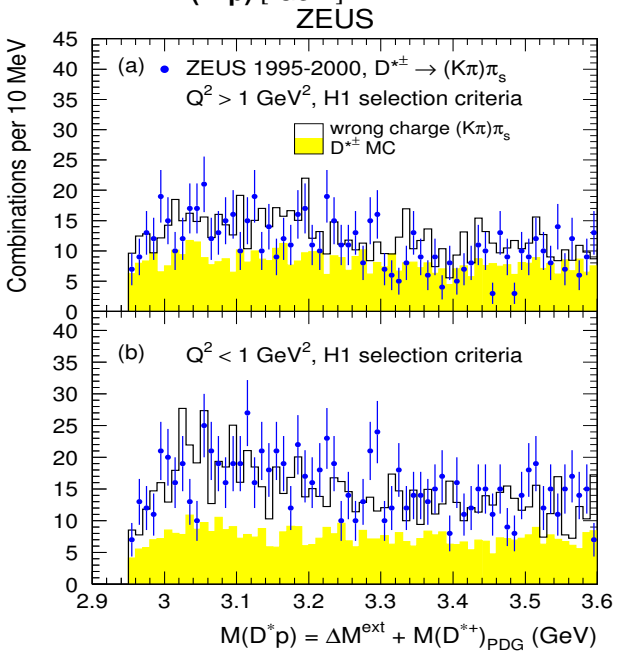
- **NA49:** narrow peak for all $\Xi\pi$ combinations observed, ($M \approx 1862$ MeV, width < 18 MeV)
- Similar analysis repeated in DIS with ZEUS data, no evidence for the existence of such state.
- Different phase space?

Search for $\Theta_C(3100) \rightarrow D^*p$





- **H1:** **PLB 588 (2004) 17**
  - Narrow resonance at 3.1 GeV was observed for both DIS and PHP.
  - In DIS, $M(\Theta_c) \approx 3099 \pm 3 \pm 5$ MeV, width $\approx 12 \pm 3$ MeV, No. of event $\approx 50.6 \pm 11.2$
- **ZEUS:** **Eur. Phys. J. C38 (2004) 29 610**
  - Select as close as possible kinematic to H1
  - No evidence for a signal around 3.1 GeV
- HERA II data is hopefully to provide further checks.

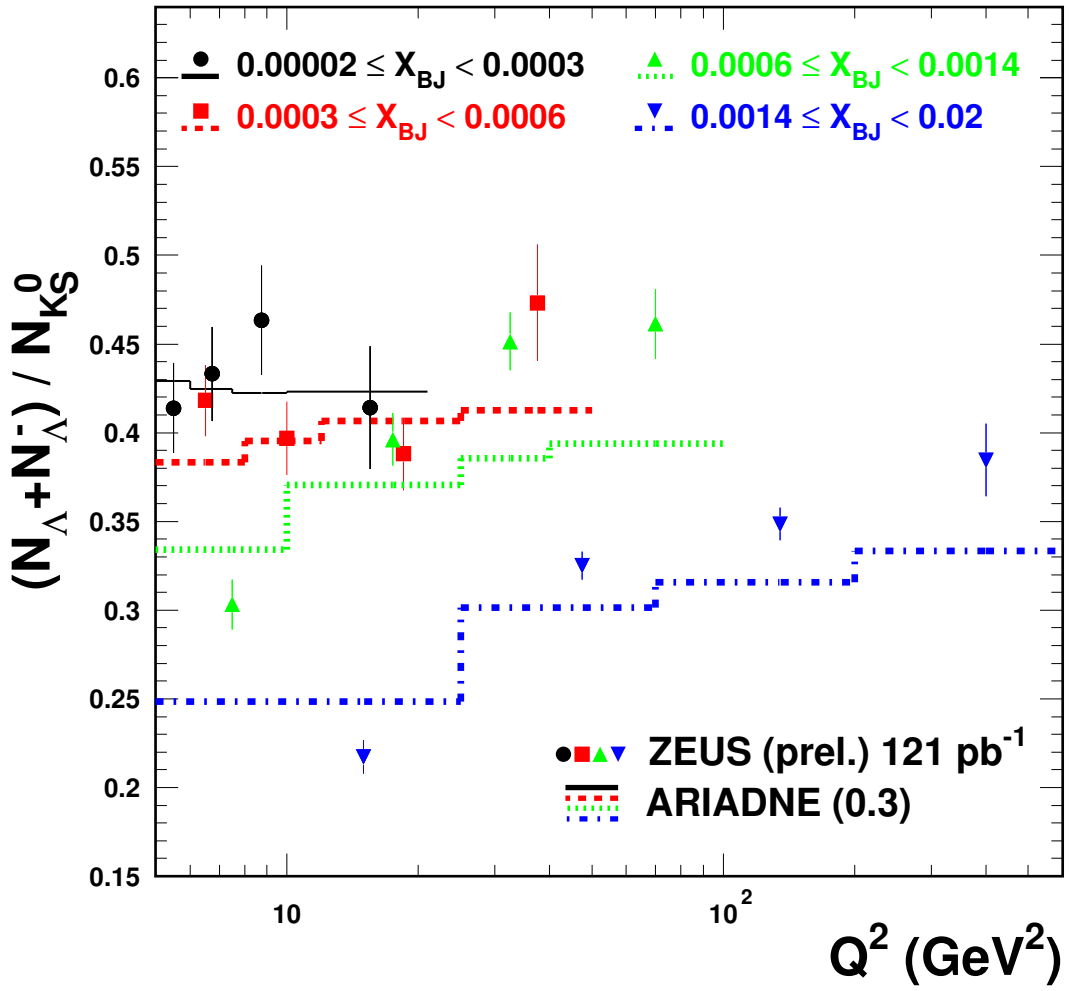


Summary

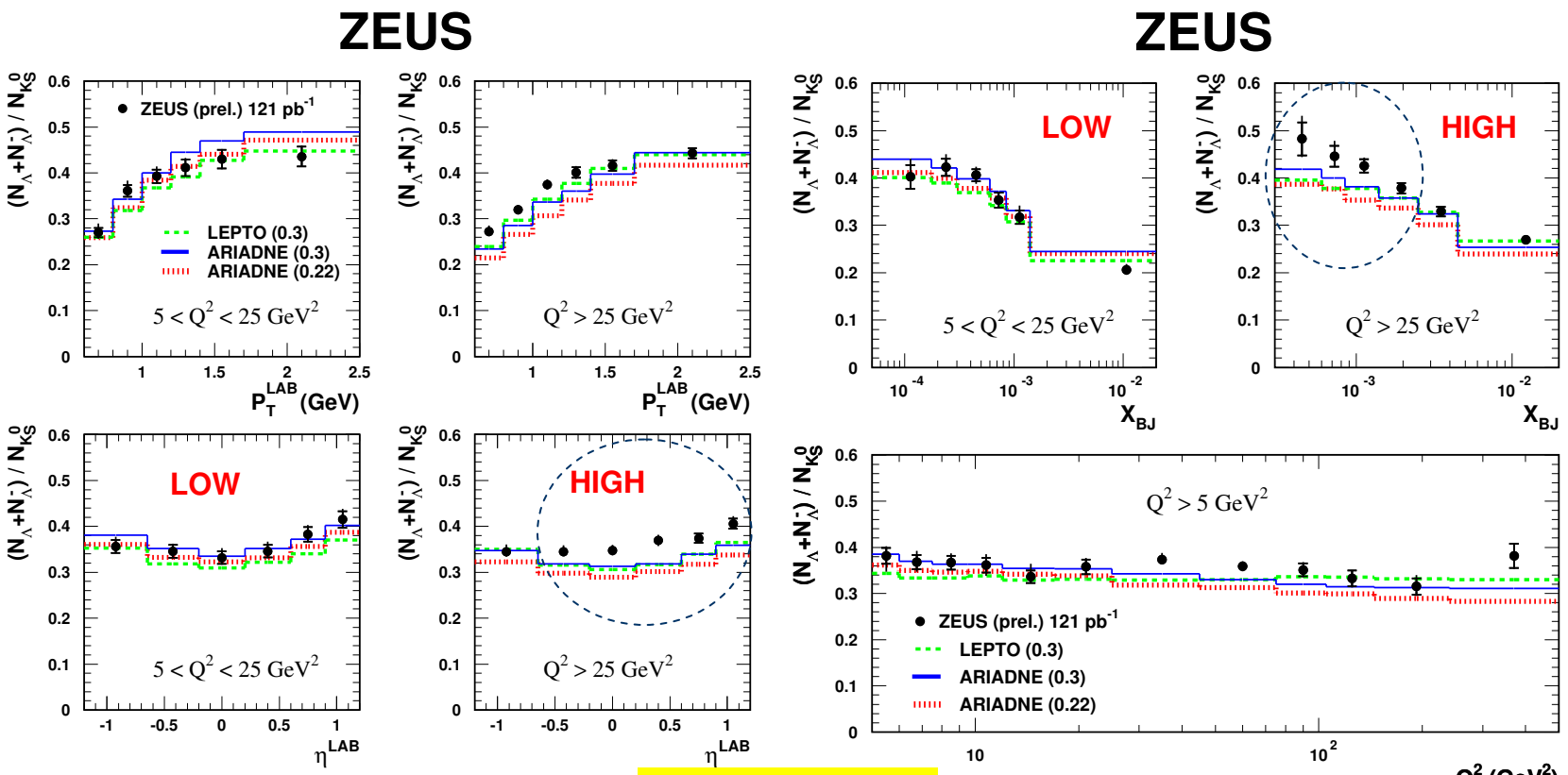
- Measurement of K^0_S, Λ and $\bar{\Lambda}$ production at HERA
  - Differential cross sections were measured in DIS and PHP, Ariadne describes data reasonably well.
  - No Λ to $\bar{\Lambda}$ production asymmetry was observed in the given phase space.
  - Λ to K^0_S production ratio were measured and enhancement of this ratio was observed for fireball-enriched sample in PHP. Pythia does not predict this excess.
  - The transverse polarization of Λ and $\bar{\Lambda}$ was consistent with zero.
- Charm fragmentation function, ratios and fractions are measured and the results are in agreement with e^+e^- data.
- Search for pentaquarks at HERA
  - Evidence for a narrow resonance Θ^+ decaying to $K^0_s p$ at 1521.5 MeV at ZEUS, no confirmation from H1, but H1 upper limit does not exclude ZEUS observation.
  - No evidence for $\Xi^{--}(1860)$ state decaying to $\Xi^-\pi^-$ at ZEUS.
  - Evidence for a narrow resonance Θ_c^0 which decays into D*p was observed at 3099 MeV in DIS and PHP at H1, but no confirmation from ZEUS.
  - The situation is not clear, HERA II data is expected to clarify the issue.

Backup slides

ZEUS



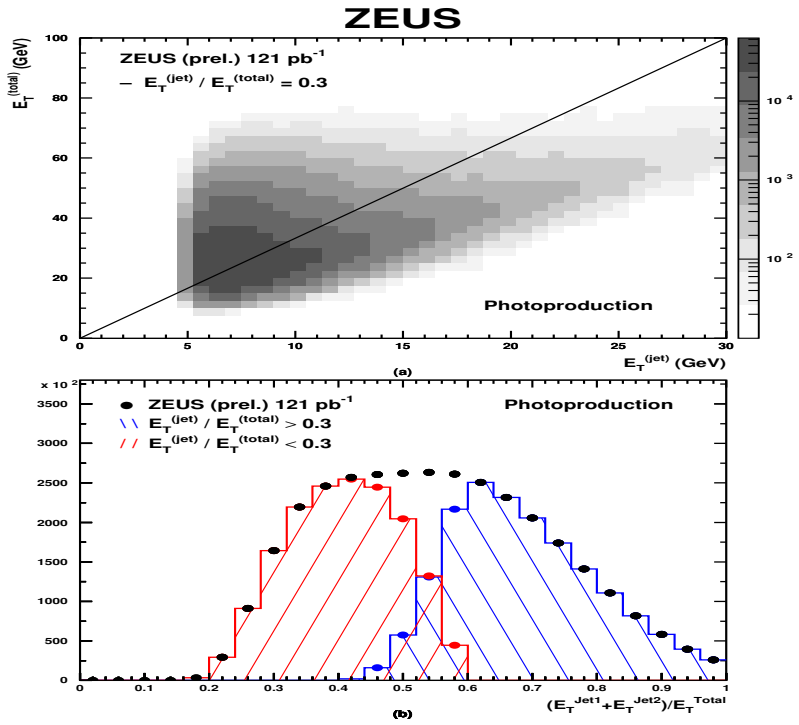
Λ / K^0_s ratio in DIS



$$\Re = \frac{N_{\Lambda} + N_{\bar{\Lambda}}}{N_{k^0_S}}$$

- **ARIADNE generally describes $\mathcal{R}$ in DIS**
  - ➢ but fails for lower x_{BJ} region and forward region for $Q^2 > 25\ GeV^2$

Backup slides



$$f = \frac{E_T^{jet}}{E_T^{total}}$$

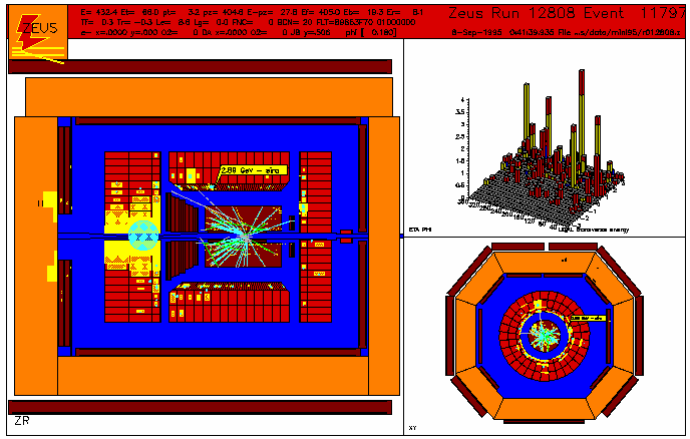
← from the highest E_T jet

← the total E_T of the event

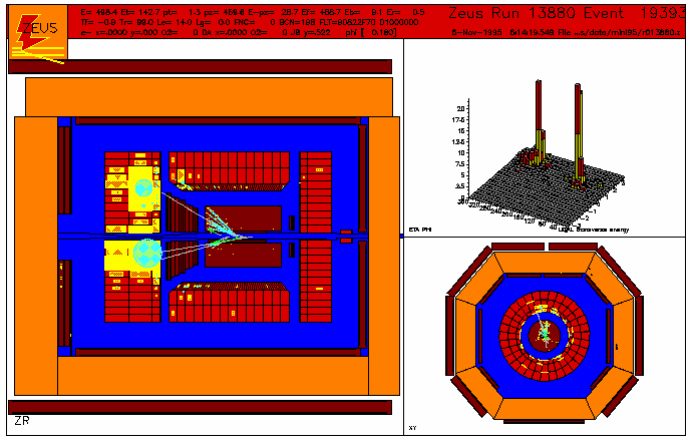
➢ **Two sub-samples with different topological features** .

"fireball-enriched" events: $f < 30\%$

"fireball-depleted" events: $f > 30\%$

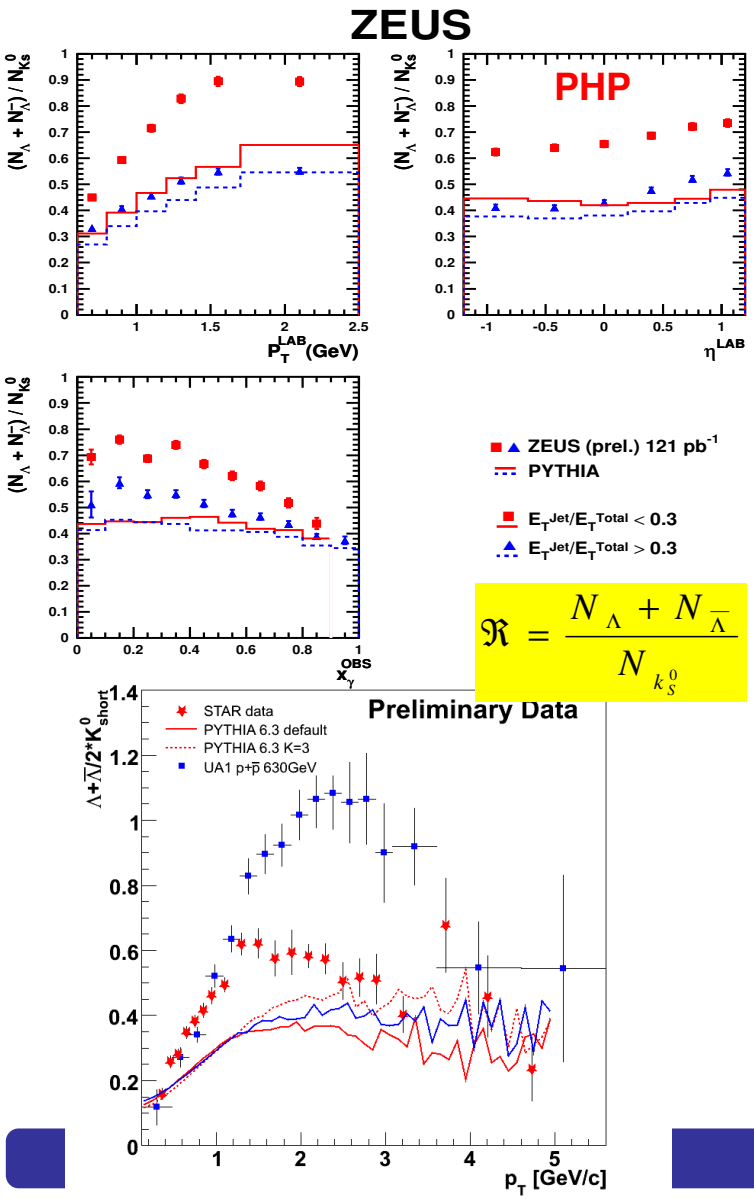


Fireball-enriched – largely isotropic distribution (Multiple jets production)



Fireball-depleted – clear jet structure (Dijet production)

Backup slides



$$\Re = \frac{N_{\Lambda} + N_{\bar{\Lambda}}}{N_{k^0_S}}$$

- **Data:** Excess was observed mainly in the fireball-enriched region.
- **RHIC** also observed large $\mathcal{R}$ ratios
  - Possible interpretation: High density, 3-dimensional distribution of produced partons. Large overlap of their wavefunctions provide larger phase space for baryon production(recombination?).
- **Pythia:**
  - Multiple interaction mechanism creates several 'independent and identical' jets.
  - Hadrons are created locally

Backup slides

- Strange pentaquark searches

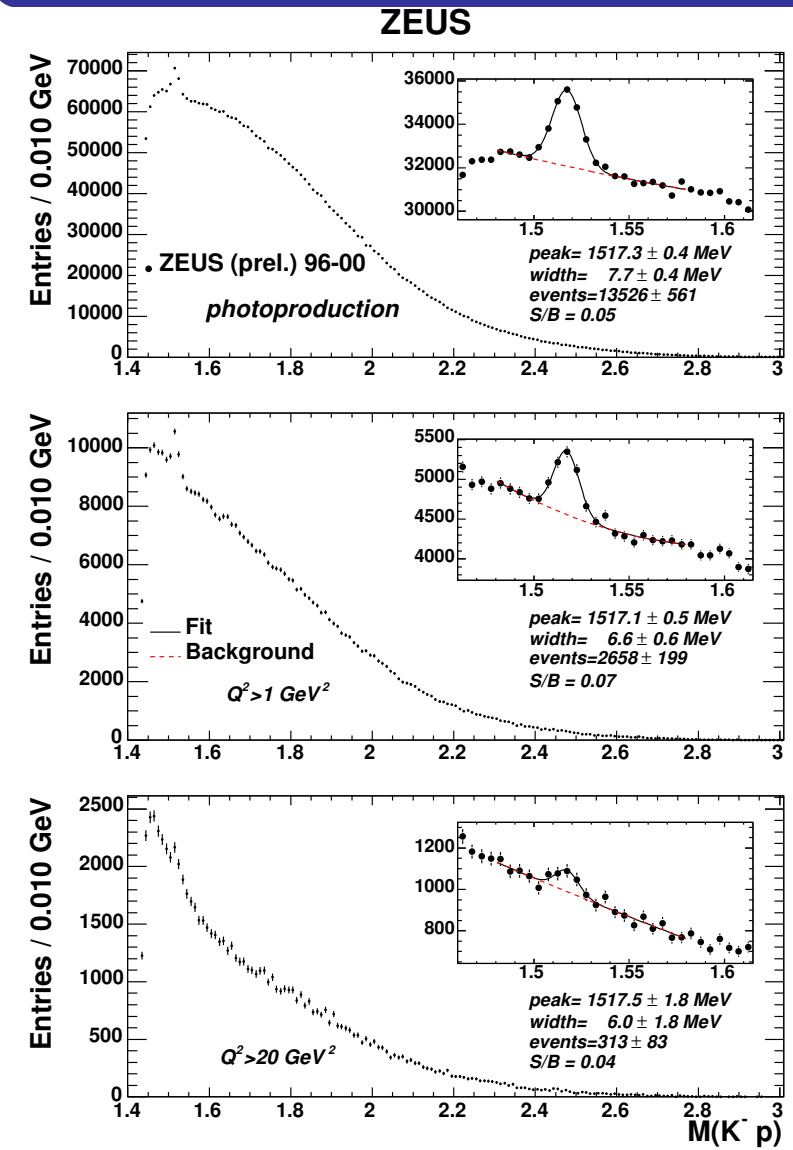
LEPS	$\gamma C \to K^+K^-X$	1540 ± 10	< 25	4.6
DIANA	$K^+Xe \to K^0pX$	1539 ± 2	< 9	4.4
CLAS	$\gamma d \to K^+K^-p(n)$	1542 ± 5	< 21	$5.2 \pm 0.6^\dagger$
SAPHIR	$\gamma d \to K^+K^0(n)$	1540 ± 6	< 25	4.8
ITEP	$\nu A \to K^0pX$	1533 ± 5	< 20	6.7
CLAS	$\gamma p \to \pi^+K^+K^-(n)$	1555 ± 10	< 26	7.8
HERMES	$e^+d \to K^0pX$	1526 ± 3	13 ± 9	~ 5
ZEUS	$e^+p \to e^+K^0pX$	1522 ± 3	8 ± 4	~ 5
COSY-TOF	$pp \to K^0p\Sigma^+$	1530 ± 5	< 18	4-6
SVD	$pA \to K^0pX$	1526 ± 5	< 24	5.6

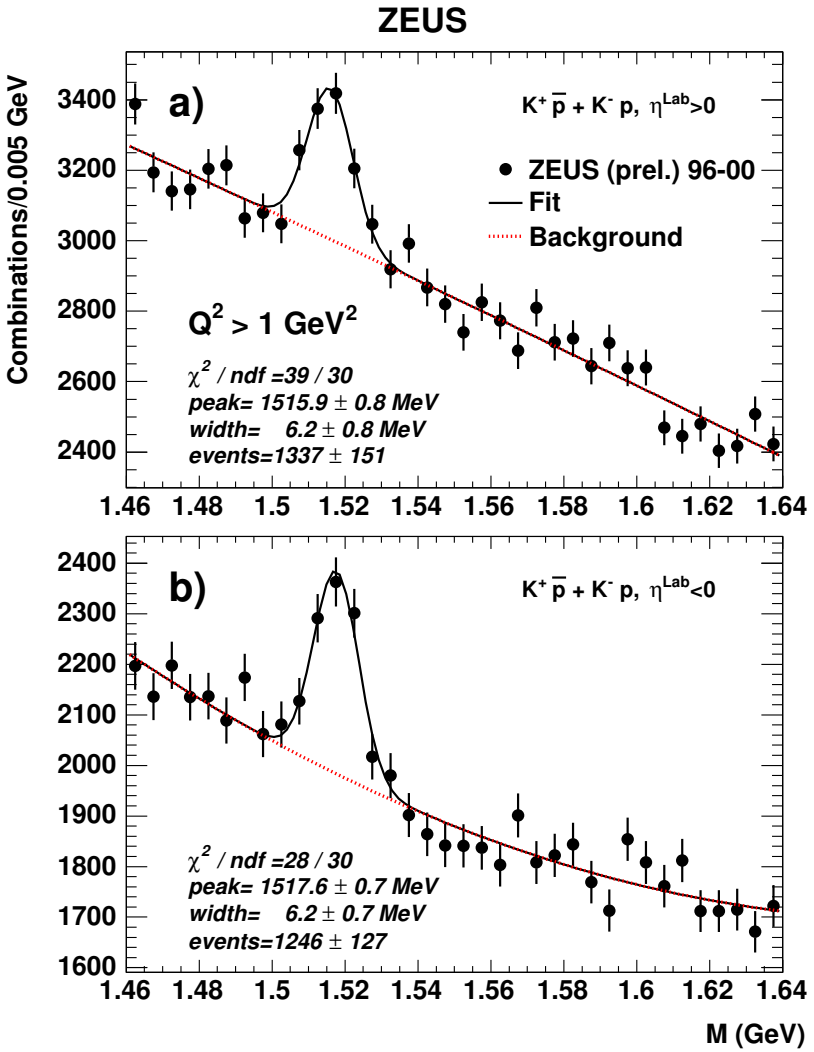
Positive results

BES	$e^+e^- \to J/\Psi \to \bar{\Theta}\Theta$	$< 1.1 \times 10^{-5}$ B.R.	No
Belle	$e^+e^- \to \bar{B}^0B^0 \to \bar{p}pK^0$	$< 2.3 \times 10^{-7}$ B.R.	Θ^{++}
BaBar	$e^+e^- \to \Upsilon(4S) \to pK^0X$	$< 1.0 \times 10^{-4}$ B.R.	??
HERA-B	$pA \to K^0pX$	$< 0.02 \times \Lambda^*$	No?
CDF	$p\bar{p} \to K^0pX$	$< 0.03 \times \Lambda^*$	No?
PHENIX	$Au + Au \to K^-\bar{n}X$	(not given)	??

Negative results

Backup slides





Acceptance corrected R_{cor}(D*p(3100) / D*)

- **H1 measurement:**
  - $1 < Q^2 < 100\ GeV^2$, $0.05 < y < 0.7$
  - $P_t(D^*p) > 1.5$ GeV, $-1.5 < \eta(D^*p) < 1.0$
  - $P_t(D^*) > 1.5$ GeV, $-1.5 < \eta(D^*) < 1.0$, $z(D^*) > 0.2$

  R_{cor}(D*p(3100) / D*) = 1.59 $\pm$0.33 $^{+0.33}_{-0.45}$ %

- **ZEUS:**
  - $Q^2 > 1\ GeV^2$, $y < 0.95$
  - $P_t(D^*) > 1.35$ GeV, $-1.6 < \eta(D^*) < 1.6$, $P_t(D^*) / E_T^{\Theta > 10} > 0.2$
  - 95% C.L. upper limit:

    R_{cor}(D*p(3100) / D*) < 0.51 %

  - 95% C.L. upper limit (full kinematic region: DIS + PHP):

    R_{cor}(D*p(3100) / D*) < 0.47 %