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# Strangeness production at HERA

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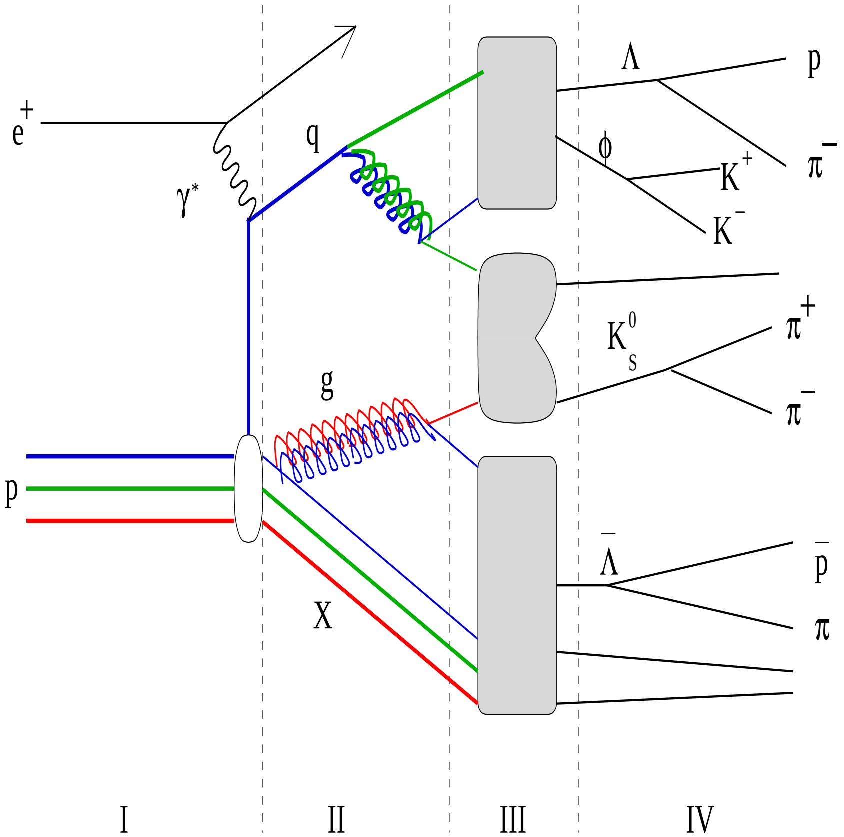
## Outline

- Motivation
- Color dynamics of strange quark production in ep scattering
- $K^0_S$, $\Lambda$, $\bar{\Lambda}$ and $\phi(1020)$ production in DIS at HERA
- Observation of $K^0_S K^0_S$ resonances in DIS
- Observation of the strange sea in the proton via $\phi(1020)$ production in DIS

# Motivation

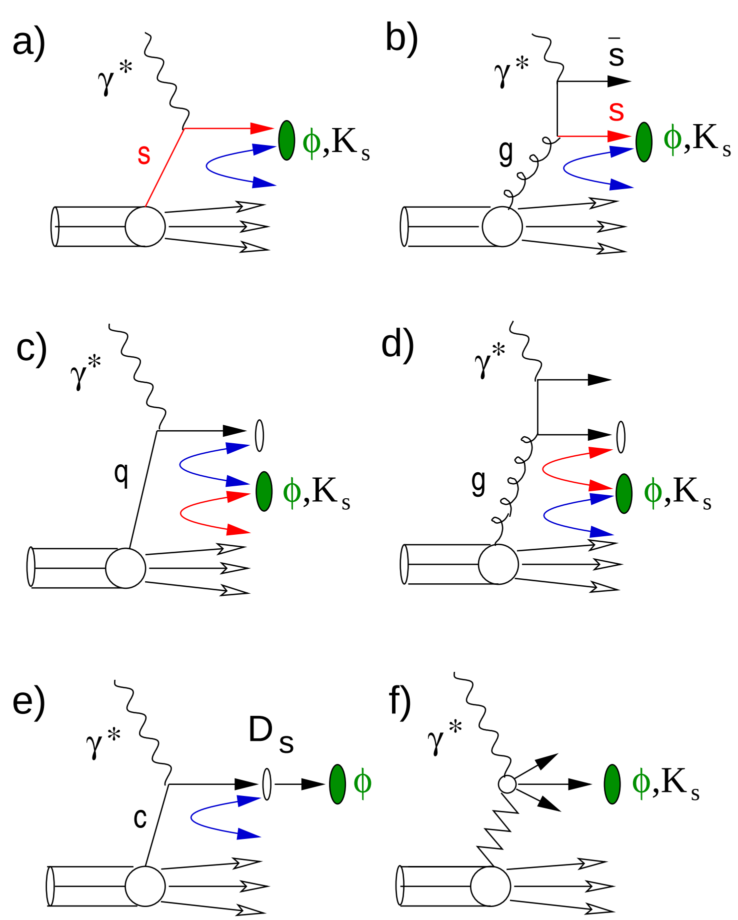



- DIS is viewed as few dynamically distinct phases:
  I - parton evolution, hard scattering;
  II - parton shower;
  III - strings/clusters formation, decays;
  IV - resonances decay

- A parton content of the proton:
  – DGLAP , PDF models , $F_2(x, Q^2)$
- $s\bar{s}$ production parametrised by the constant strangeness-suppression factor, $\lambda_s = P_s/P_{u,d}$
- $\lambda_s$ in $e^+e^-$ is larger them in $e^+p$ scattering.
- Strange hadron production is not know to be well described by MC models

- **How quantum systems like strings or clusters breakes into discrete mass species?**
- **Does the proton wave function contain a large strange component $|UUD\bar{s}sX\rangle$ ?**
- Fragmentation by $K^0_s, \Lambda$
  Proton content by $\phi$

# $\phi, K_S, \Lambda, \bar{\Lambda}$ production mechanisms in ep

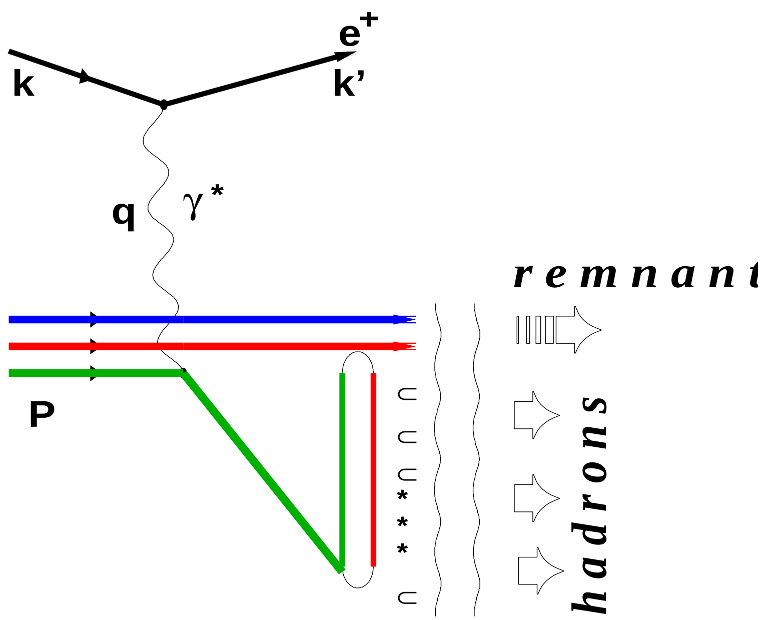



- a) Hadronisation of s from the proton sea in $\gamma^* s \longrightarrow s$ (QPM) or $\gamma^* s \longrightarrow sg$ (QCDC) process
- b) Rate of the boson-gluon fusion process (BGF), $\gamma^* g \longrightarrow s\bar{s}$, is related to the gluon density in the proton
- c)-d) Hadronisation process alone contributes to the strangeness production
- e) decay product of higher-mass states
- f) diffractive production

# DIS at HERA

- HERA collide

$e^{\pm}(27.6\,\mathrm{GeV}) + p(820/920\,\mathrm{GeV})$



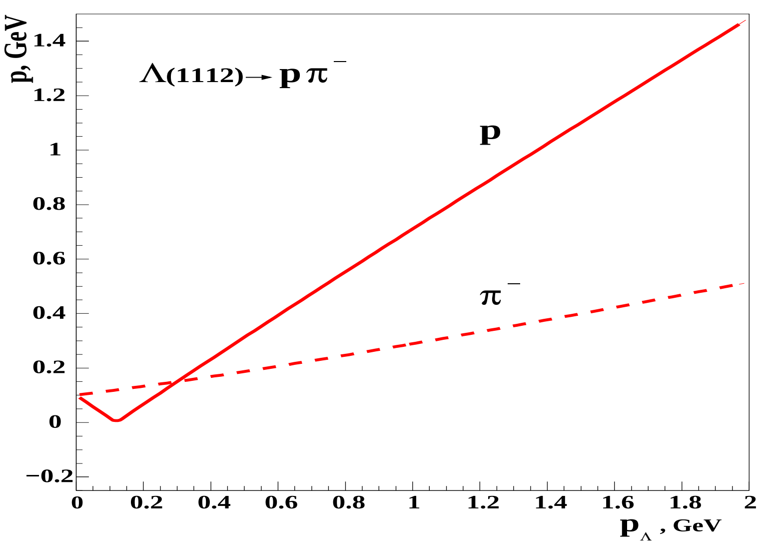

- $q = k - k'$  $Q^2 = -q^2$

$x = \frac{Q^2}{2p\cdot q}$  $y = \frac{p\cdot q}{p\cdot k}$

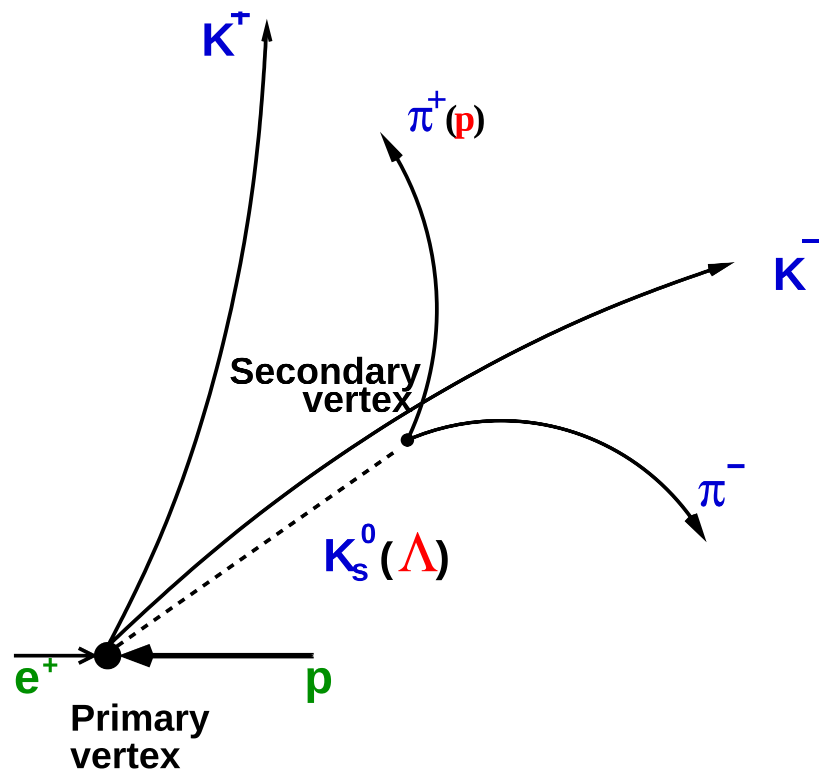
- Data samples (integrated luminosity)
  - $\phi(1020)$  45 pb$^{-1}$  '95-97
  - $K^0_s$, $\Lambda$, $\bar{\Lambda}$  60 pb$^{-1}$  '99-00
  - $K^0_s K^0_s$  121 pb$^{-1}$  '96-00

# $\phi, K_S, \Lambda, \bar{\Lambda}$ identification

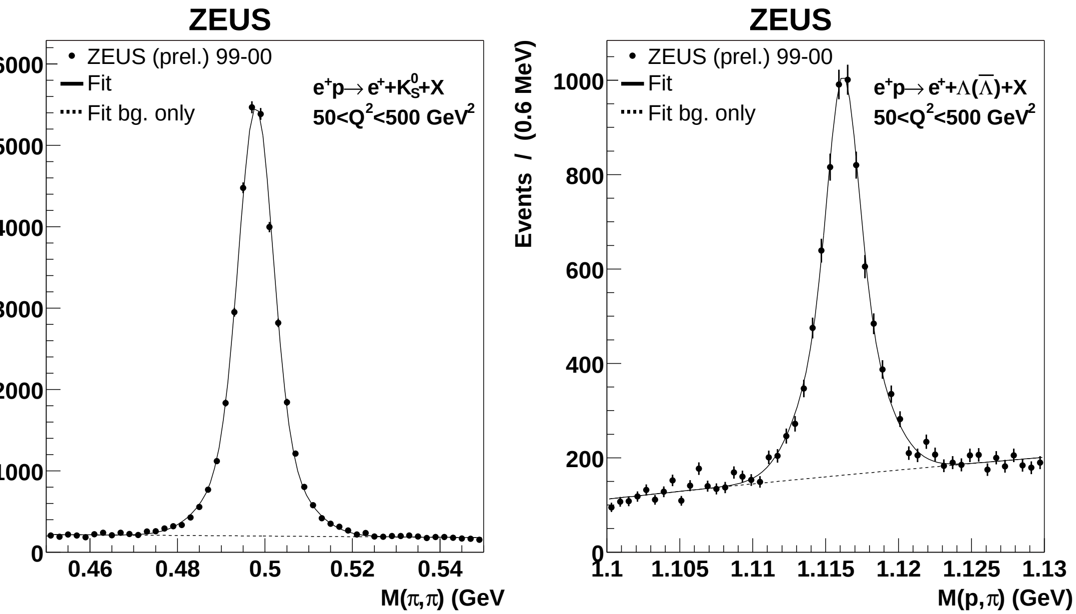
- $\phi$ identified through the decay $\phi \rightarrow K^+ K^-$
  - Pair of tracks with opposite charge from the primary vertex.
- $K^0_s, \Lambda, \bar{\Lambda}$ selection
  - Events with a well separated secondary vertex
  - Pair of tracks with opposite charge.
  - For $\Lambda/\bar{\Lambda}$ selection the highest momentum track is $p/\bar{p}$ assumed.

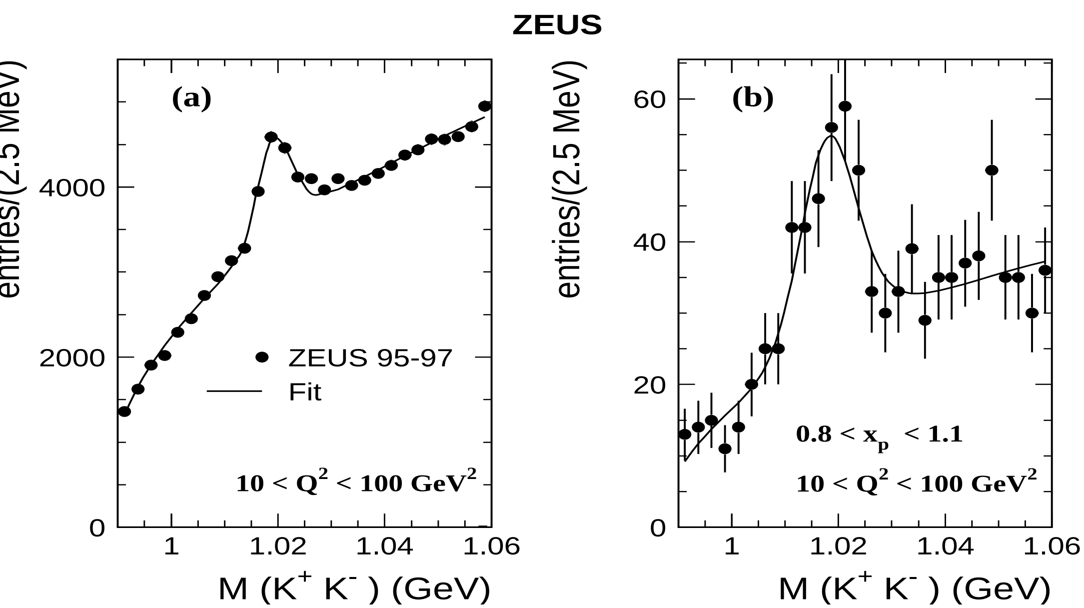



| Particle | Mass/ GeV | Decay length/ cm | $J^P$ | Main decay |
|---|---|---|---|---|
| $\phi$ | 1.019 | $\sim 0$ | $1^-$ | $K^+K^-$ |
| $K^0_s$ | 0.497 | 2.68 | $0^-$ | $\pi^+\pi^-$ |
| $\Lambda$ | 1.112 | 7.89 | $1/2^+$ | $p^+\pi^-$ |



# Strange particle signals in DIS




- Clear signals for $K^0_s$, $\Lambda$, $\bar{\Lambda}$ and $\phi$
- $K^0_s$
  Kinematic range: $50 < Q^2 < 500\,\mathrm{GeV}^2$, $3 \cdot 10^{-4} < x < 10^{-1}$, $0.5 < p_T < 5\,\mathrm{GeV}$, $|\eta| < 1.5$

  - Large statistics
  - Low background
- $\Lambda(\bar{\Lambda})$
  - Statistics lower than $K^0_s$, but low background
- $\phi(1020)$
  Kinematic range: $10 < Q^2 < 100\,\mathrm{GeV}^2$, $2 \cdot 10^{-4} < x < 10^{-2}$, $1.7 < p_T < 7\,\mathrm{GeV}$, $-1.7 < \eta < 1.6$

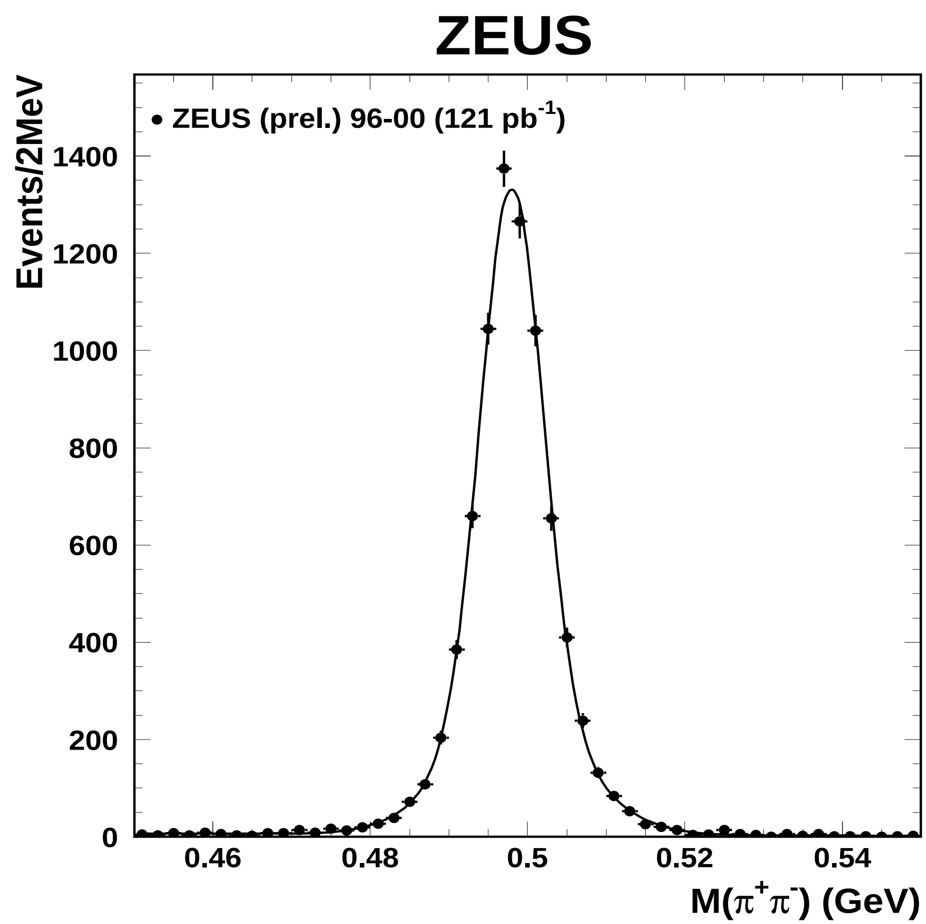
  - Statistics lower than $K^0_s$,$\Lambda$, high combinatoric background

# $K^0_s K^0_s$ resonances in DIS

- **$K^0_s K^0_s$ is expacted to couple to $0^{++}$ and $2^{++}$ glueballs**

  **Lattice QCD predicts a glueball scalar state at 1.7$\pm$0.15GeV**

- Standard DIS cuts
- Events with at least two $K^0_s$ candidates
  - $p_T(K^0_s) \geq 200\mathrm{MeV}$
  - Decay length of $K^0_s \in$[2,30] cm
  - Collinearity angle $\theta_{XY} < 0.12$
  - Armenteros-Podolanski momentum $p_T^A > 110\mathrm{MeV}$
- $K^0_s$ purity better than $97\%$ after all selection cuts




$K^0_s K^0_s$ invariant-mass only for $K^0_s$ candidates in the region $\pm 10\mathrm{MeV}$:

# First observation of $J^{CP} = (even)^{++}$ in DIS

553 $\mathrm{K^0_s}$ pair candidates in the range
$995 < M(\mathrm{K^0_sK^0_s}) < 2.795\mathrm{GeV}$

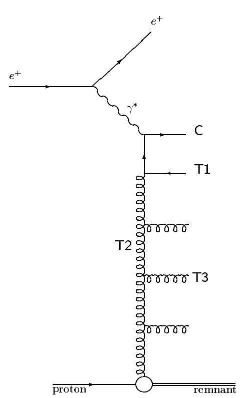
hreshold effects at $cos\theta_{\mathrm{K^0_sK^0_s}} > 0.92$:
E, $\mathrm{f_0(980)/a_0(980)}$

t with three modified relativistic
reit-Wigner + BG

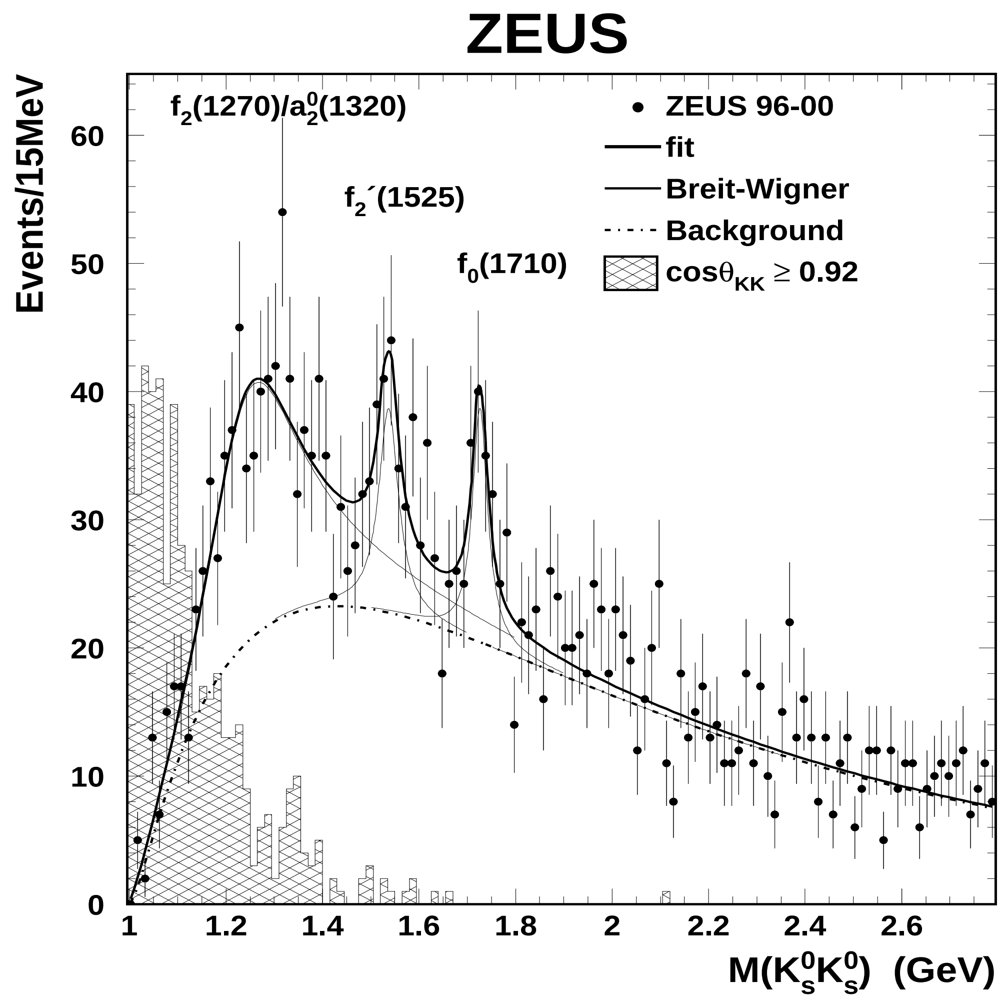
$(1276)$ consistent with:
$(1320)/f_2(1270)$ interference

$(1537)$ consistent with:
$(1525)$ 1-st obs-n in DIS

$(1726)$ consistent with:
$(1710)$ 1-st obs-n in DIS
lueball candidate)




| | Fit, MeV | PDG, MeV |
|---|---|---|
| vidth | $38^{+20}_{-14}$ | 125±10 |

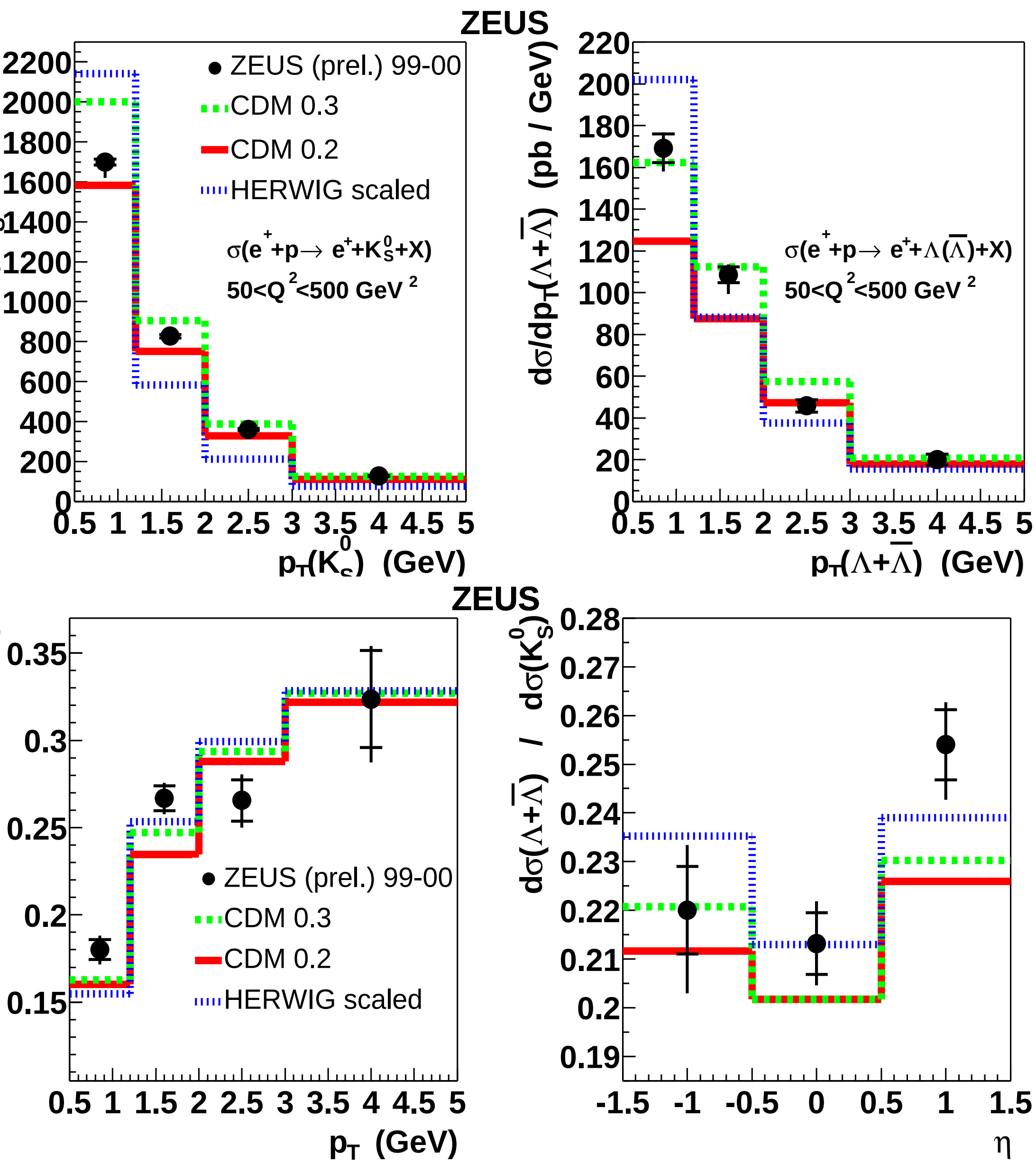



**93%** of the $\mathrm{K^0_sK^0_s}$ states are in the target region of BF: gluon-rich region

# Total $K_s$, $\Lambda$, $\phi$ cross sections in DIS

| | ZEUS (prel.) | CDM: $\lambda_s$=0.3 | CDM: $\lambda_s$=0.2 | HERWIG |
|---|---|---|---|---|
| $\sigma(K^0_s)$ [pb] | $2454 \pm 18^{+32}_{-102}$ | 2762 | 2257 | 1854 |
| $\sigma(\Lambda)$ [pb] | $292 \pm 9^{+7}_{-18}$ | 302 | 240 | 661 |
| $\sigma(\bar{\Lambda})$ [pb] | $279 \pm 9^{+12}_{-18}$ | 301 | 243 | 668 |
| $\sigma(\Lambda + \bar{\Lambda})/\sigma(K^0_s)$ | $0.231 \pm 0.005^{+0.005}_{-0.006}$ | 0.218 | 0.214 | 0.717 |
| $\sigma(\Lambda)/\sigma(\bar{\Lambda})$ | $1.05 \pm 0.05^{+0.05}_{-0.05}$ | 1.00 | 0.99 | 0.99 |
| $\sigma(\phi)$ [nb] | $0.507 \pm 0.022^{+0.010}_{-0.008}$ | 0.701 | $\lambda_s$=0.22<br>0.509 | 0.36 |

# $K^0_s$ and $\Lambda$ differential cross sections in Lab Frame




- Data cross sections are compared to MC models with the CTEQ5D parton densities.

- The HERWIG predictions are renormalised to the data cross sections.

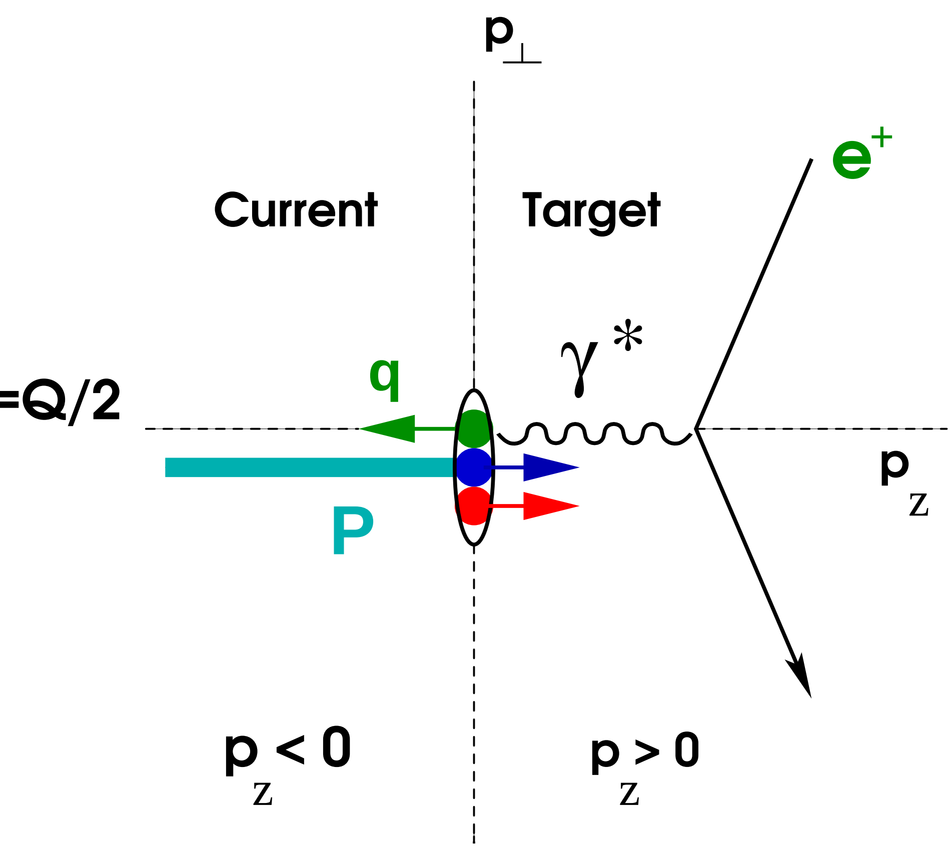
- HERWIG fails to reproduce shape of $K^0_s$ and $\Lambda$ cross sections in $p_T$; ARIADNE does better for $K^0_s$ with $\lambda_s$=0.2

  The effect of $\lambda_s$ variation is nonuniform.

- Ratios
  $p_T$ shape described by both MC models; $\eta$ is not.

  $\Lambda$ cross sections decreases with $p_T$ less steep if compared to $K^0_s$ cross sections
  The same is valid for the forward region.

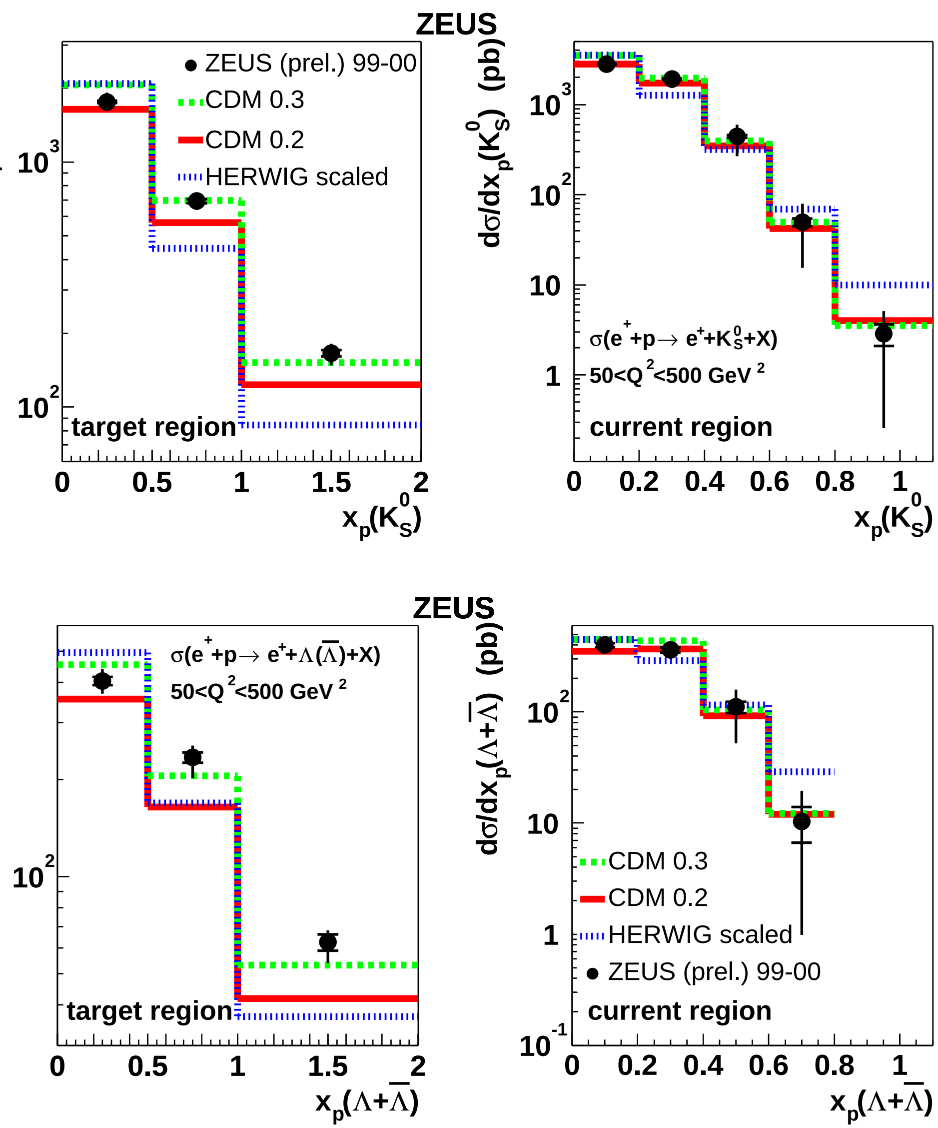
# Breit frame




- Breit frame is natural way to separete the radiation of struck quark and the proton remnant
- Scaled momentum
  $x_p = 2\,p/Q$
- Current region ($p_z < 0$)
  - Quark-parton model
    $x_p(s) = 2\,p(s)/Q \ = \ 1$
  - First and higher order QCD
    $x_p(s) \neq 1$
- Target region ($p_z > 0$)
  - Maximum remnant momentum
    $P_R \simeq Q(1 - x)/2x$

    $x_p^{max} \simeq (1 - x)/x >> \ 1$

# $K^0_S$ and $\Lambda$ cross sections in Breit frame




- Current region: weak sensitivity to $\lambda_s$
  - HERWIG does not fall steeply enough
  - ARIADNE describe the data with any $\lambda_s = 0.2 \div 0.3$

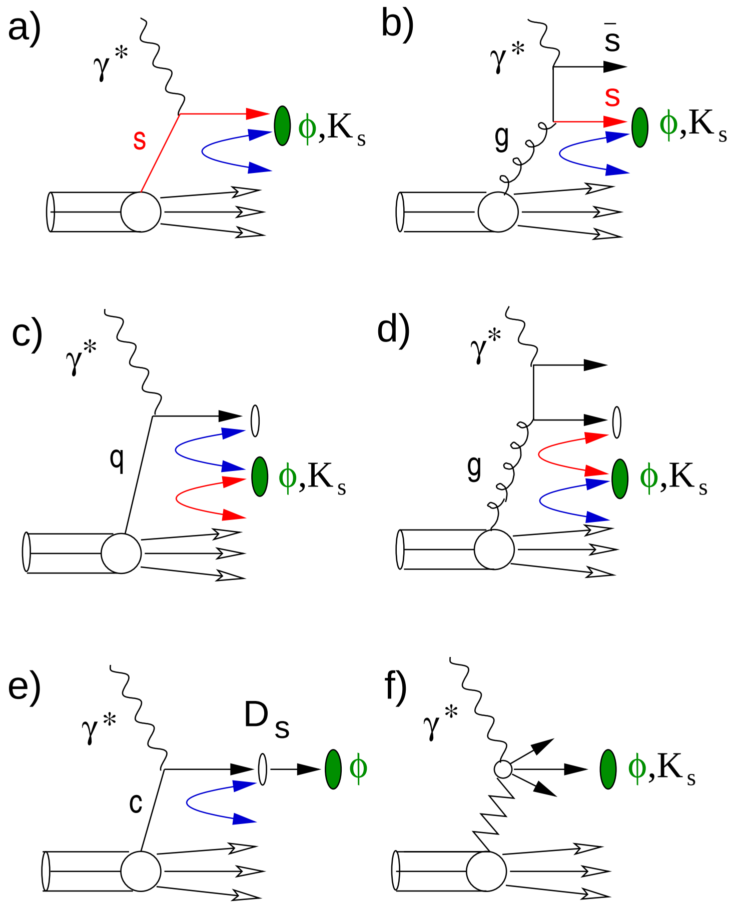
- Target region: $\frac{d\sigma}{dx_p} \sim e^{c\lambda_s}$ (cascade)

  $\lambda_s$ value is sensitive to the particle mass

  $$\lambda_s(m_\Lambda) > \lambda_s(m_{K^0_s})$$

  - ARIADNE: $\lambda_s \geq 0.3$ at $x_p > 0.5$ and $\lambda_s \sim 0.22 - 0.25$ at $x_p < 0.5$
  - HERWIG falls too steeply

# $\phi, K_S, \Lambda, \bar{\Lambda}$ production mechanisms in ep




- a) Hadronisation of s from the proton sea in $\gamma^* s \longrightarrow s$ (QPM) or $\gamma^* s \longrightarrow sg$ (QCDC) process
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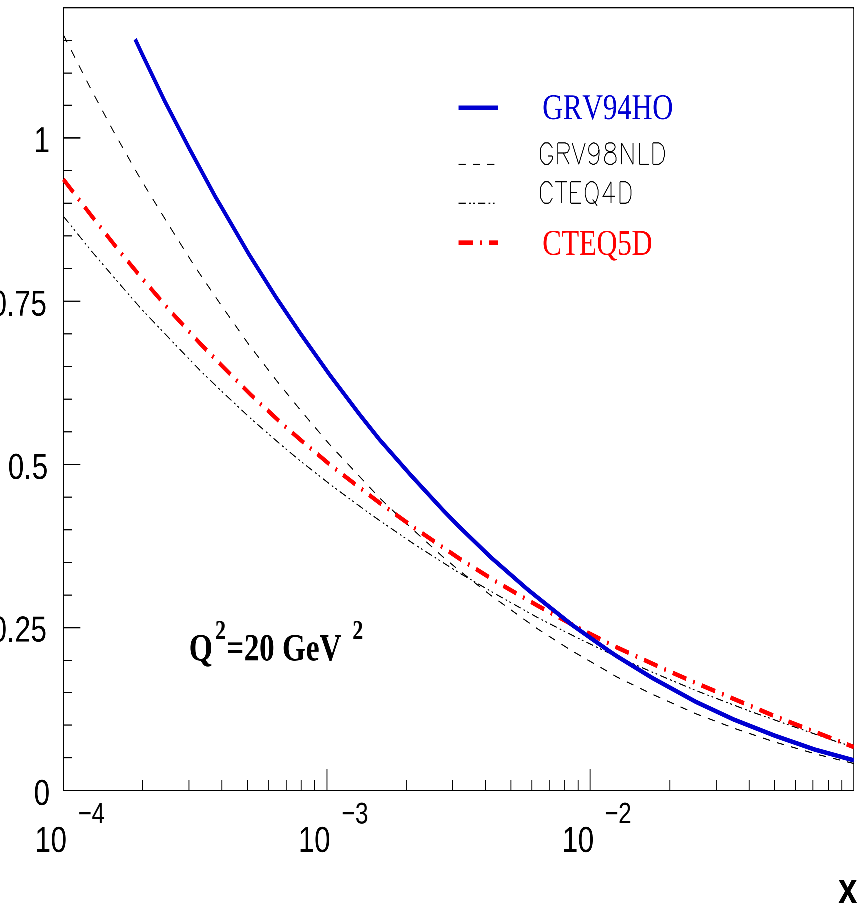
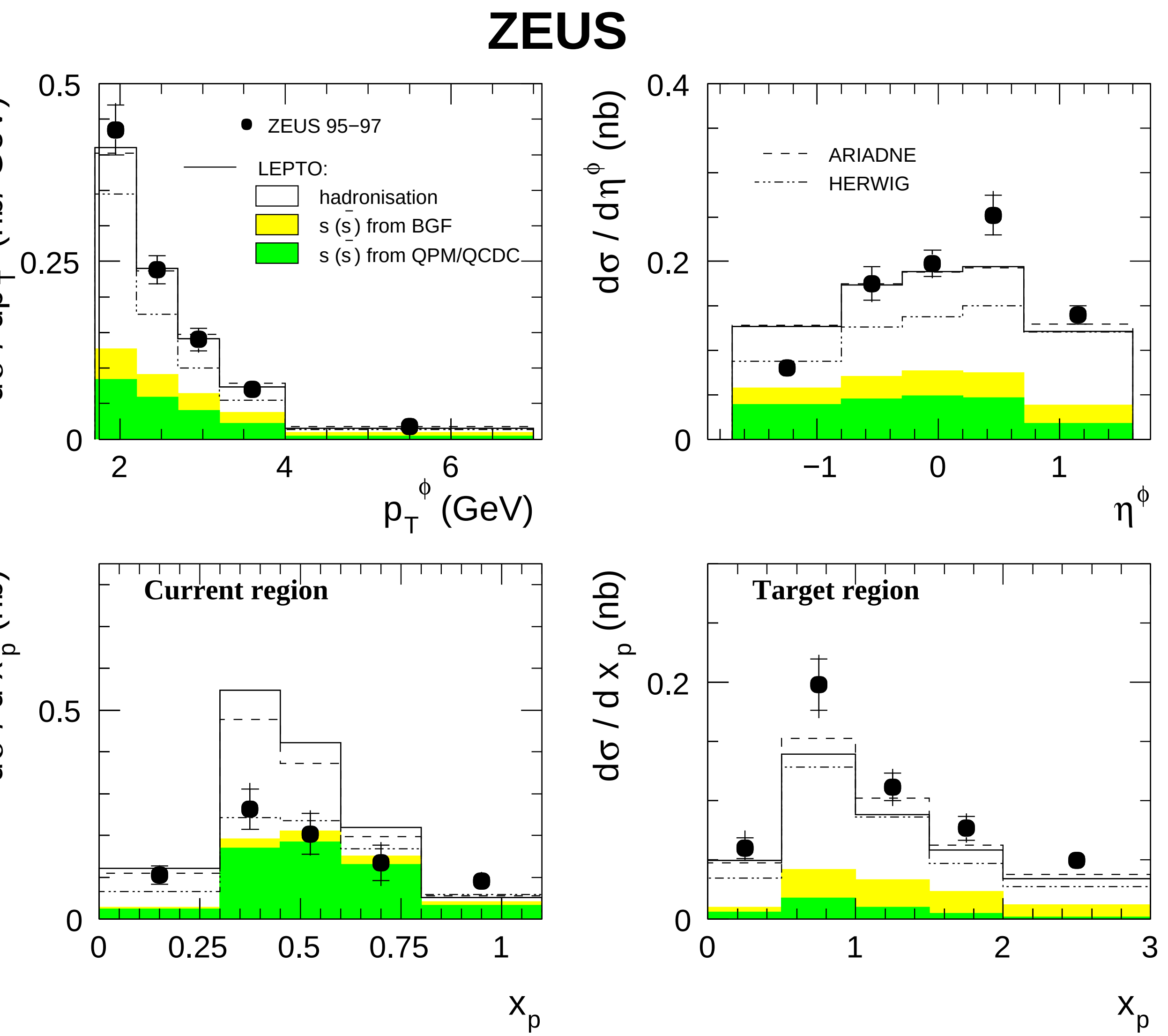
# Strange content of the proton



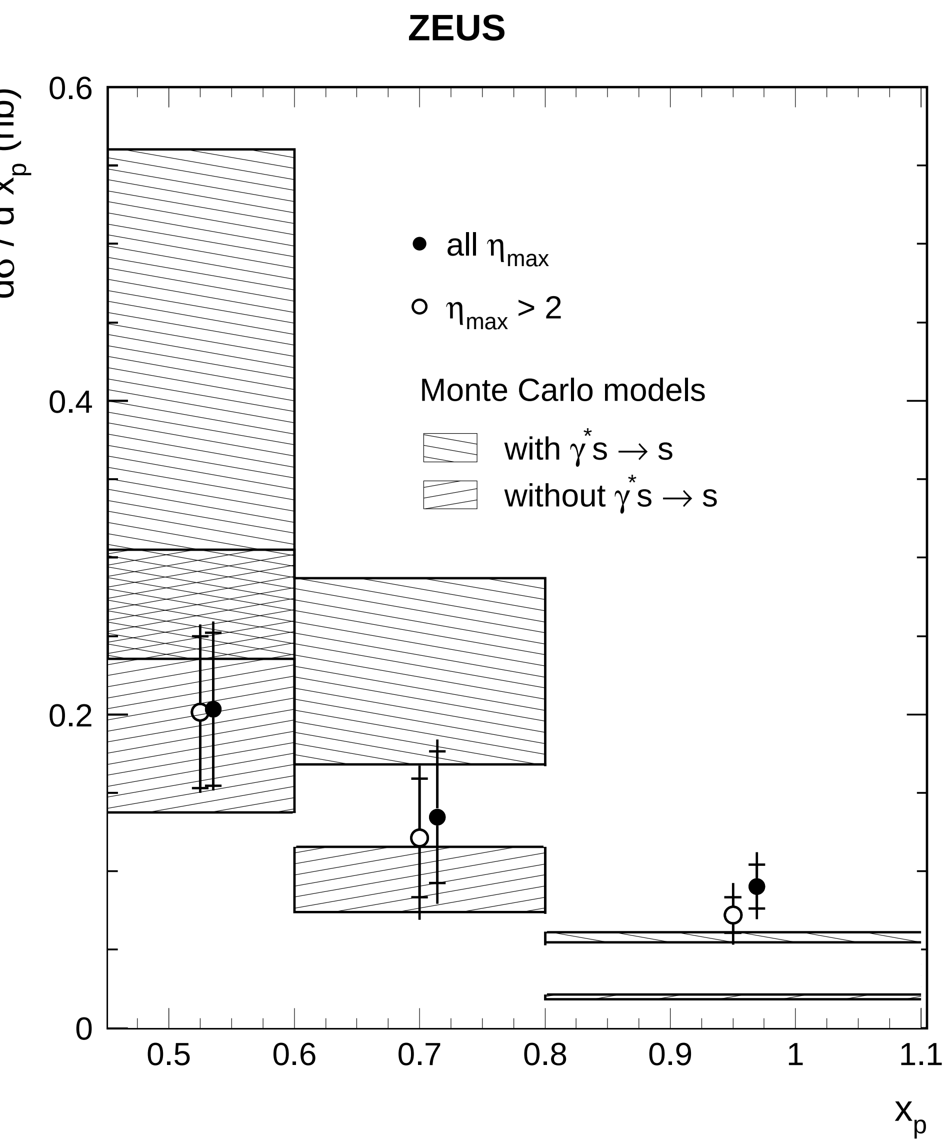

- s-quark distributions
  - CTEQ/MRS:
    $xs = Ax^{-\lambda}(1-x)^{\eta}P(x,s)$
    at $Q^2 = Q_0^2 \sim 1$ GeV$^2$
  - GRV:
    $xs = x\bar{s} = 0$ at $Q^2 = \mu^2 \sim 0.4$ GeV$^2$
- GRV model for $s(x, Q^2)$
  - $s(x, Q^2)$ generated radiatively
  - parameter free
  - lower bound for the strange sea
- GRV stronger rise as x decreases than CTEQ

# $\phi(1020)$ differential cross sections




- cross sections from MC models with $\lambda_s$=0.22 values and the CTEQ5D parton densities.
  - $s\bar{s}$ pairs from QPM and QCDC (green shaded band)
  - $s\bar{s}$ pairs from BGF (yellow shaded band)
- Current region of the Breit frame contains a significant fraction of events due to the hard scattering on the strange sea
- Relative contribution from hard QCD increases with $p_t(\phi)$

# Leading $\phi(1020)$ mesons in the current region




- Any additional gluon emissions are not important for $x_p$ >0.8 and the scattering is given by the well-understood process, $\gamma^* s \longrightarrow s$
- The hatched bands represents uncertainties in the simulation of the $\phi(1020)$ mesons production ($\lambda_s$=0.2-0.3) with the CTEQ5D parton density
- High-momentum $\phi$ mesons ($x_p$ >0.8 ) in the current region of the Breit frame give clear evidence for the strange sea in the proton.

# Conclusions

- Inclusive $\mathbf{K^0_s}, \phi, \Lambda, \bar{\Lambda}$ production in neutral current DIS $e^+p$ scattering has been studied with the ZEUS detector

- LEPTO/ARIADNE with CTEQ5D and $\lambda_s = 0.3$ overestimates the cross sections in the laboratory frame and in the current hemisphere of the Breit frame

  However, the hadron production in the target Breit-frame region, predominately determined by the fragmentaion process, is well described by MC models with $\lambda_s = 0.3$

  HERWIG is totally inconsistent with the ZEUS data on $\mathbf{K^0_s}, \phi, \Lambda$

- For all the $\lambda_s$ values studied, MC fail to describe $\eta(\phi)$ and the current-region $x_p(\phi)$ cross sections

- Detection of leading $\phi$-mesons in the current region of the Breit frame provides direct evidence for the strange sea in the proton

- Results indicate the need for an adjustment of $\lambda_s$ and $s(x, Q^2)$ in the proton

- First observation in DIS resonated $\mathbf{K^0_s K^0_s}$ systems at masses $\mathbf{1537^{+9}_{-8}MeV}$ and $\mathbf{1726 \pm 7MeV}$