Strangeness, Charm and Beauty Production at HERA

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on behalf of the ZEUS and H1 Collaborations

OUTLINE

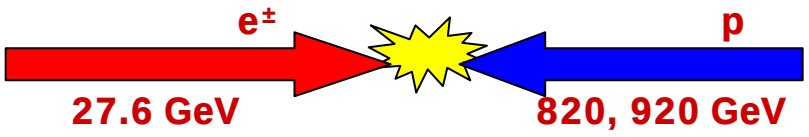
- Introduction
- Strangeness production
- Charm production
- Beauty production
- Summary

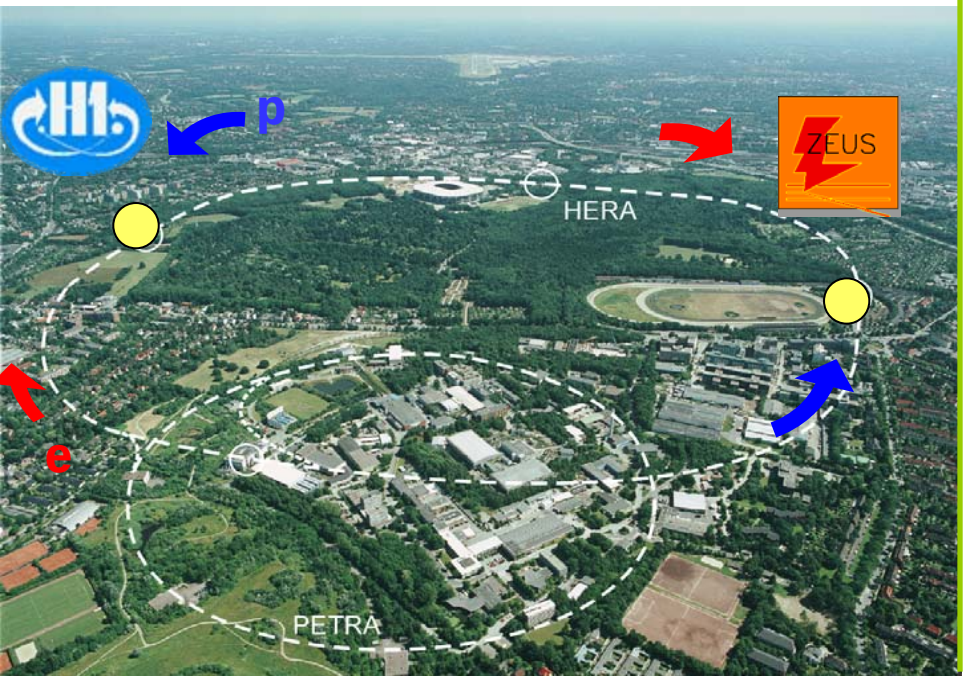
PHIPSI Workshop, Oct 13-17, Beijing, China

The HERA Collider

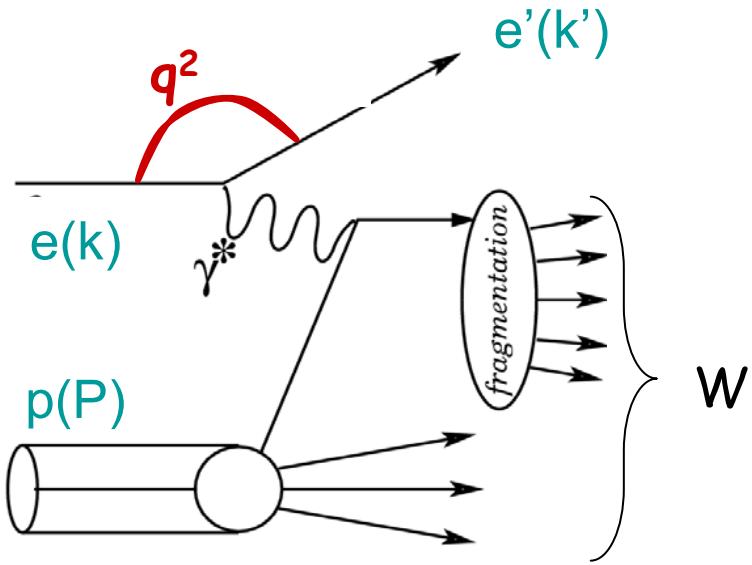
✓ two large multipurpose experiments: H1 and ZEUS

✓ running ended mid 2007 after about 2500 days of activity and ~500 pb^{-1} of integrated luminosity per experiment





The HERA Kinematics



ep c.m. energy: $s = (P+k)^2$

$\gamma^* p$ c.m. energy: $W = (P+q)^2$

exchanged momentum squared (photon virtuality) $Q^2 = -q^2 = -(k-k')^2$

$Q^2 \approx 0$ GeV^2 → photoproduction

$Q^2 > 1$ GeV^2 → electroproduction (DIS)

Strangeness Production at HERA

- K^0_S
- Λ, $\bar{\Lambda}$
- K*(892)
- ϕ
- Inclusive $K^0_S K^0_S$ resonance

K_S Production

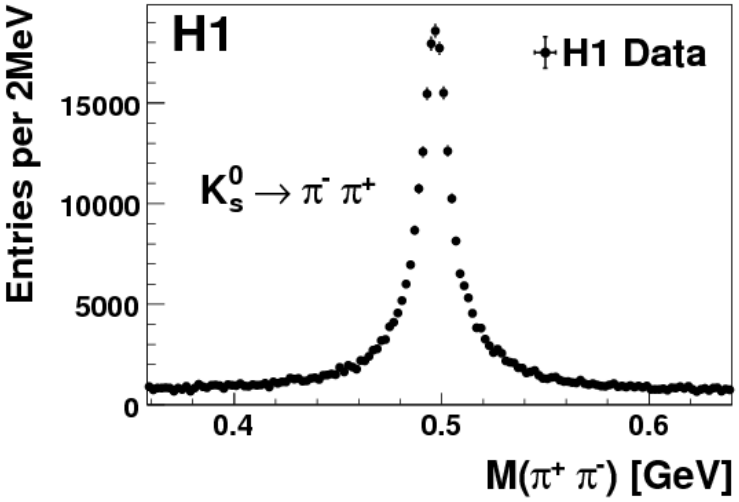
Eur. Phys. J. C61,185(2009)

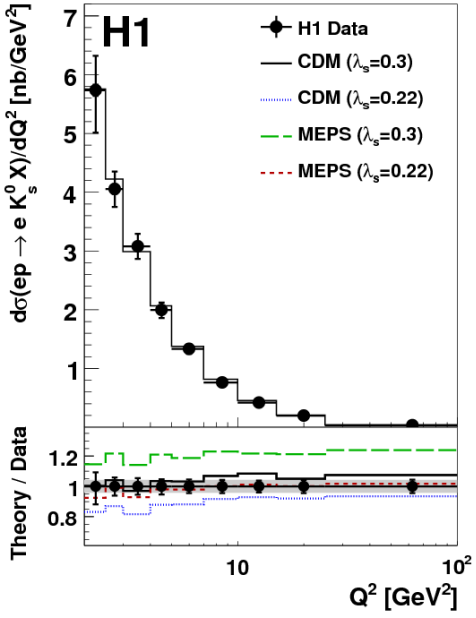
HERA I data:1999-2000, 50pb^{-1}

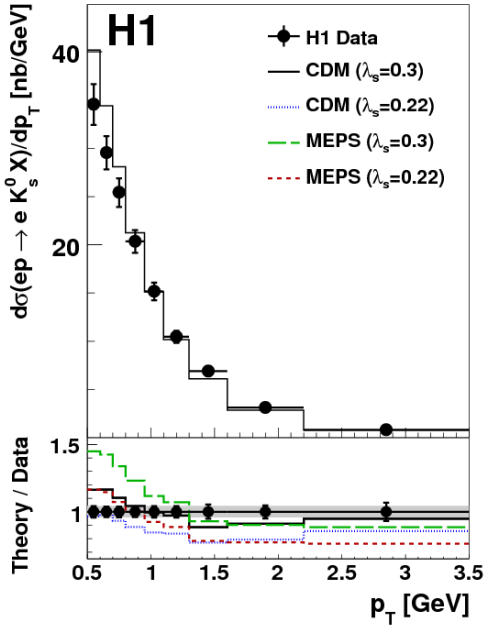
$2<Q^2<100$ GeV^2

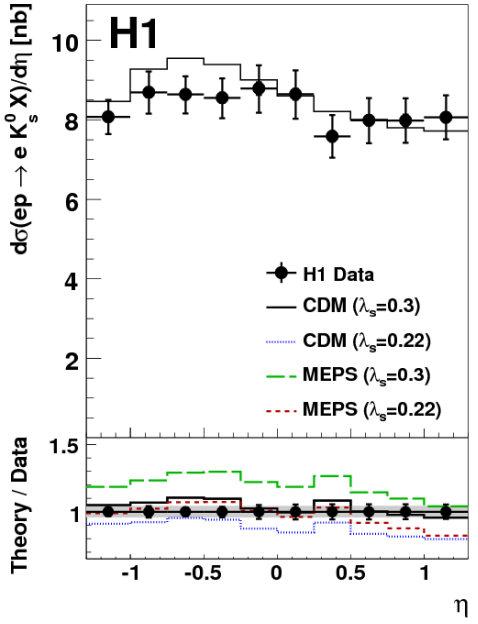
$0.1<y<0.6$

- $\sigma_{vis}(ep \rightarrow ek_sX)=21.18 \pm 0.09\ ^{+1.19}_{-1.23}$ nb
- CDM λ_s =0.3 for Q^2, η and p_T
- MEPS λ_s =0.2 for Q^2
- shape of η and low p_T show difficulties









K_S differential cross section in laboratory frame

Λ, $\bar{\Lambda}$ Production

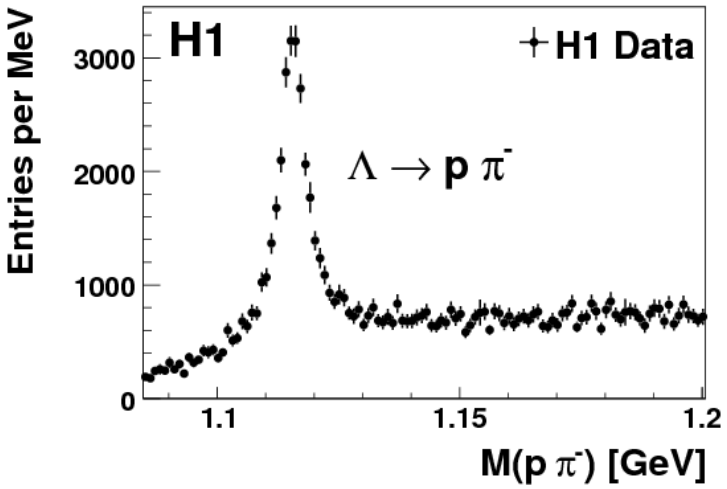
Eur. Phys. J. C61,185(2009)

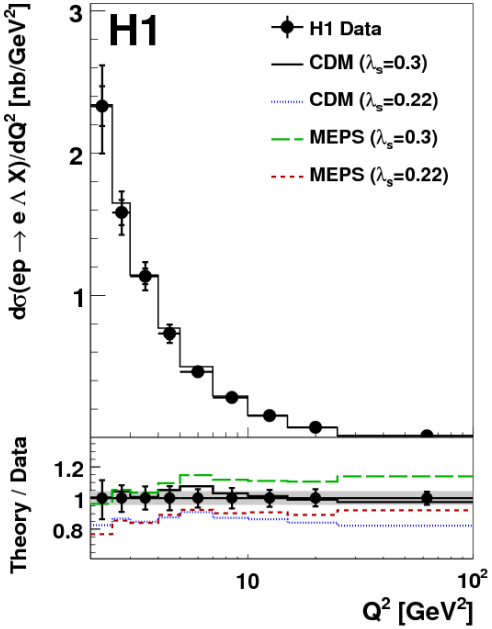
HERA I data:1999-2000, 50pb^{-1}

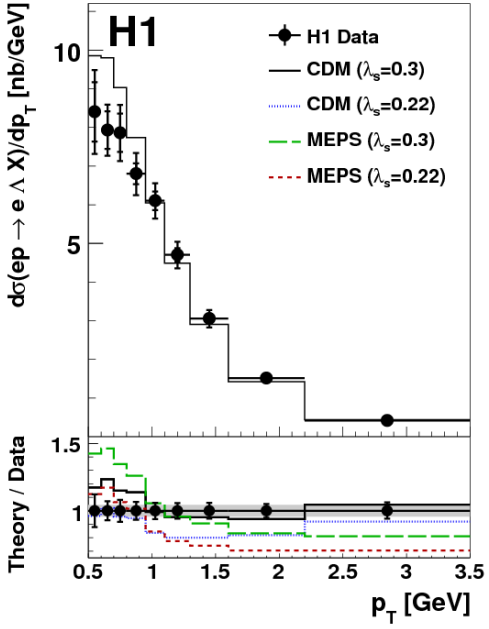
$2<Q^2<100$ GeV^2

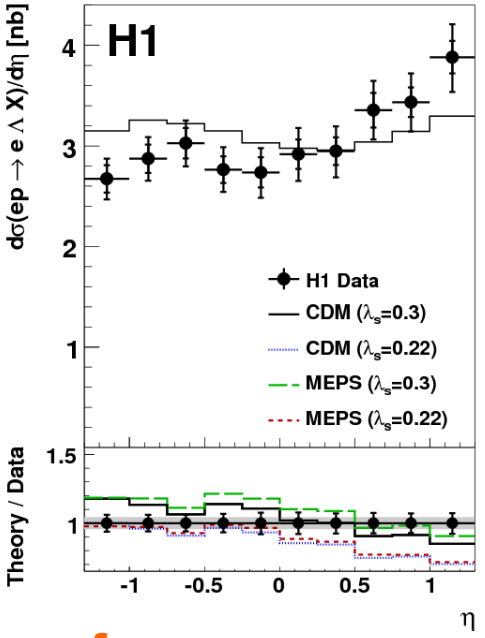
$0.1<y<0.6$

- $\sigma_{vis}(ep \rightarrow \Lambda X) = 3.96 \pm 0.06\ ^{+0.23}_{-0.24}$ nb
- $\sigma_{vis}(ep \rightarrow \bar{\Lambda} X) = 3.94 \pm 0.07\ ^{+0.23}_{-0.24}$ nb
- CDM $\lambda_s = 0.3$ for Q^2
- shape of η and low p_T show difficulties







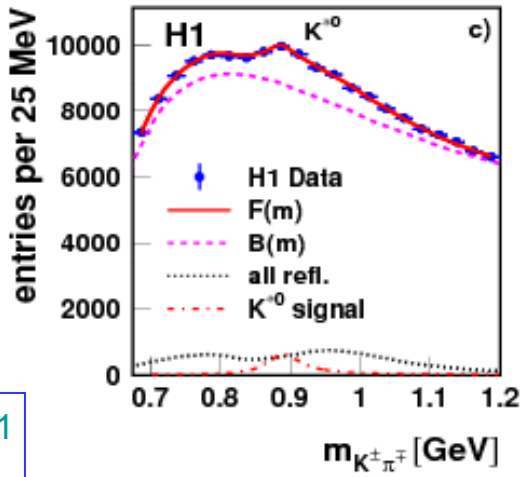


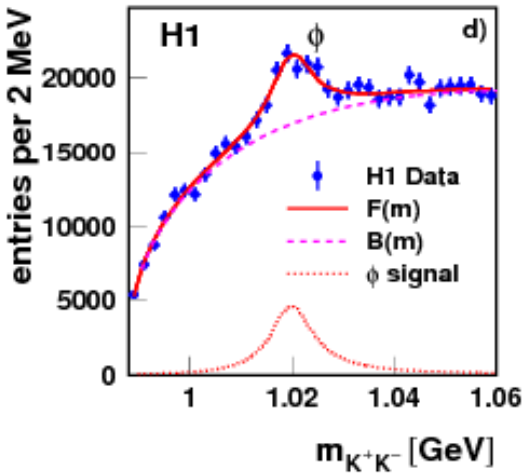
Λ differential cross section in laboratory frame

K^* and ϕ production

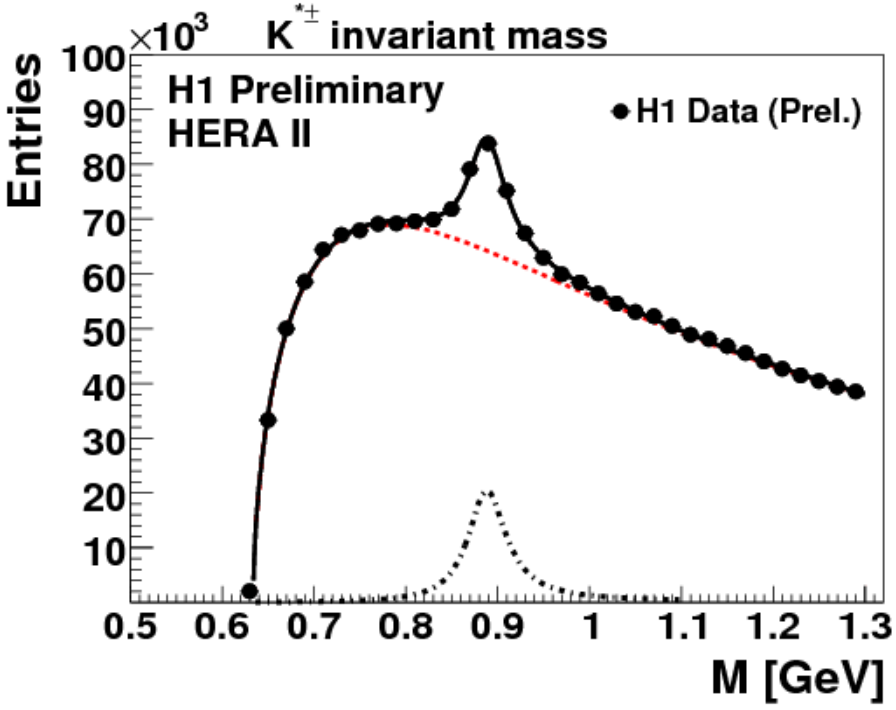
Phys. Lett. B73,119(2009), H1prelim-08-132

HERA I data:2000, 37pb^{-1}
$Q^2<0.01$ GeV^2
$0.5 < p_T(K^{*0},\phi) < 7$ GeV





HERA II data:2005-2007, 302pb^{-1}
$5<Q^2<100$ GeV^2
$0.1<y_{e\Sigma}<0.6$
$0.5 < p_T(K^{*\pm}) < 7$ GeV



Clear K^{*0},$K^{*\pm}$ and ϕ are observed

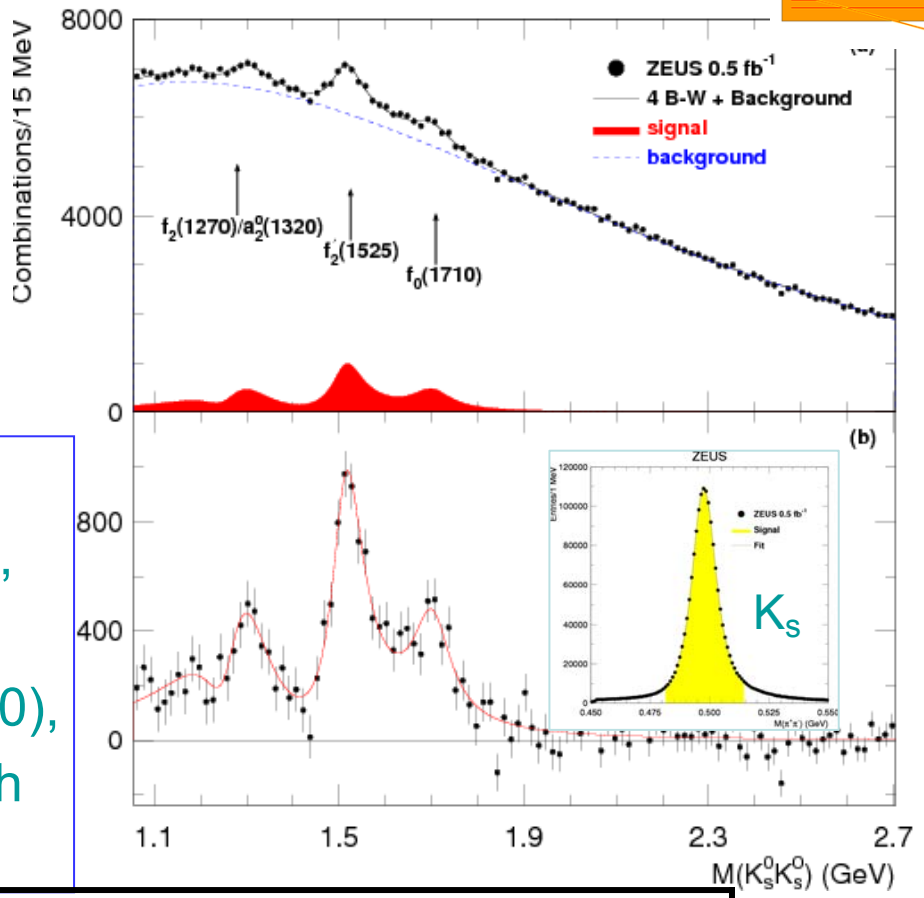
$\sigma_{vis}(ep \to K^{*0}X) = 6260 \pm 350 \pm 860$ nb
$\sigma_{vis}(ep \to \phi X) = 2400 \pm 180 \pm 340$ nb
$\sigma_{vis}(ep \to K^{*\pm}X) = 7.36 \pm 0.09 \pm 0.9$ nb

Inclusive K_SK_S resonance

Phys. Rev. Lett. 101,112003(2008)

ZEUS

- **HERA I + HERA II data: ~500pb^{-1}**
- dominated by photoproduction 90%, while 10% by DIS
- clear KS signal ~1260000
- signal region: 481 <M($\pi^+\pi^-$)<515 MeV



- Three clear enhancements, $f_2(1270)/a_2(1320)$, $f_2(1525)$ and $f_0(1710)$, were observed
- The mass and width of $f_2(1270)/a_2(1320)$, $f_2(1525)$ and $f_0(1710)$ are compatible with PDG value

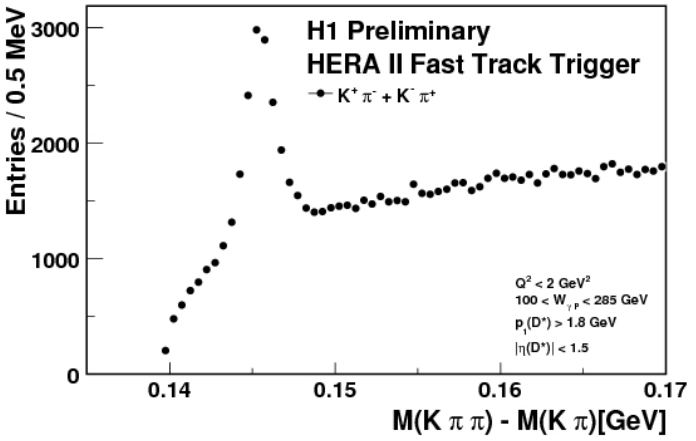
	Mass	Width	PDG08 Mass	Width
$f_2(1270)$	1268±10	176±17	1275.4±1.1	$185.2^{+3.1}_{-2.5}$
$a_2(1320)$	1257±9	114±14	1318.3±0.6	107±5
$f_2(1525)$	$1512\pm3^{+1.4}_{-1.5}$	$83\pm9^{+5}_{-4}$	1525±5	73^{+6}_{-5}
$f_0(1710)$	$1701\pm5^{+9}_{-2}$	$100\pm24^{+7}_{-22}$	1724±7	137±8

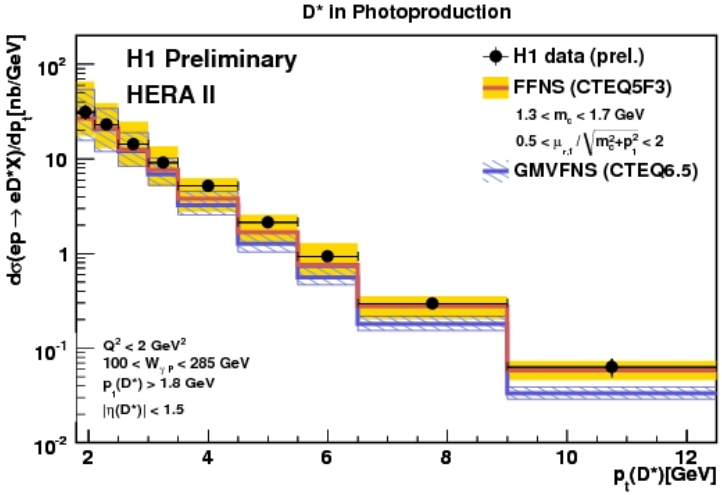
Charm Production at HERA

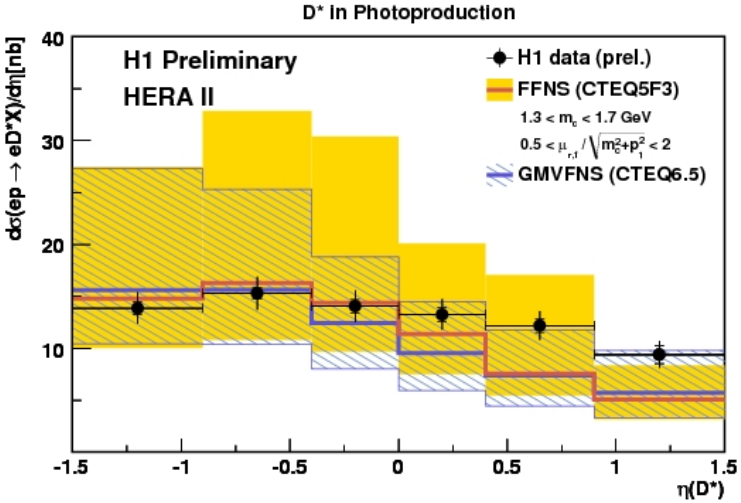
- **D* in photoproduction**
- **Excited charm and charm-strange production**

D* in Photoproduction

- HERA II data: 93pb^{-1}
- Kinematic range
  - Q^2<2 GeV^2
  - 100<W<285 GeV^2
  - p_t (D*)>1.8 GeV
  - |η(D*)|<1.5







Differential cross sections as functions of p_t (D*) and η(D*)

✓Data in reasonable agreement with NLO predictions (FMNR and GMVFNS)

✓ GMVFNS too steep in p_t, slightly different shape in η

Excited charm and charm-strange mesons production

the large charm production cross sections at HERA also offers a unique place to study excited charm and charm-strange mesons

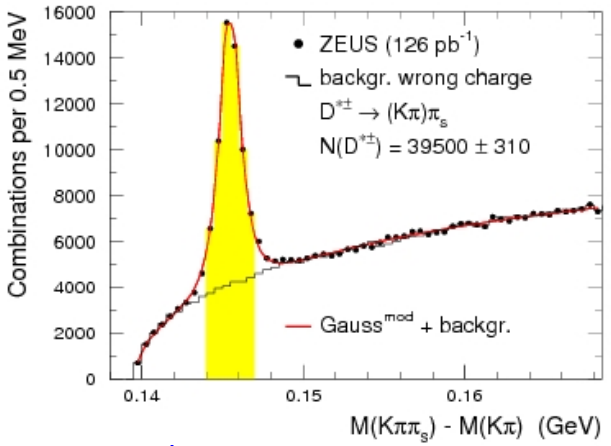
$D_1(2420)^0 \rightarrow D^{*+}\pi^-$ $J^P=1^+$

$D^*_2(2460)^0 \rightarrow D^{*+}\pi^-, D^+\pi^-$ $J^P=2^+$

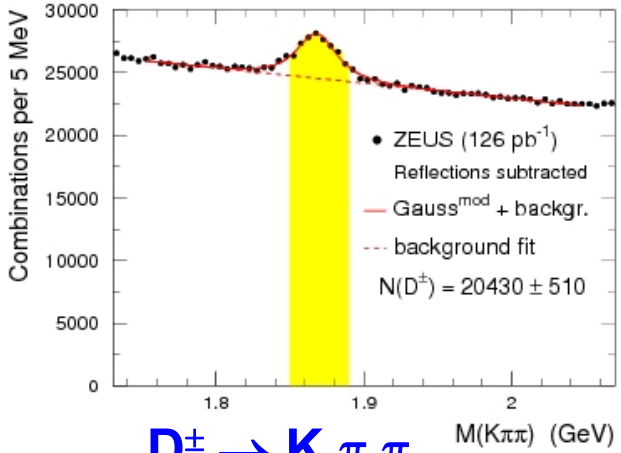
$D_{s1}(2536)^+ \rightarrow D^{*+}K_S, D^0K^+$ $J^P=1^+$

$D^{*\prime}(2640)^+ \rightarrow D^{*+}\pi^+\pi^-$ $J^P=?^?$

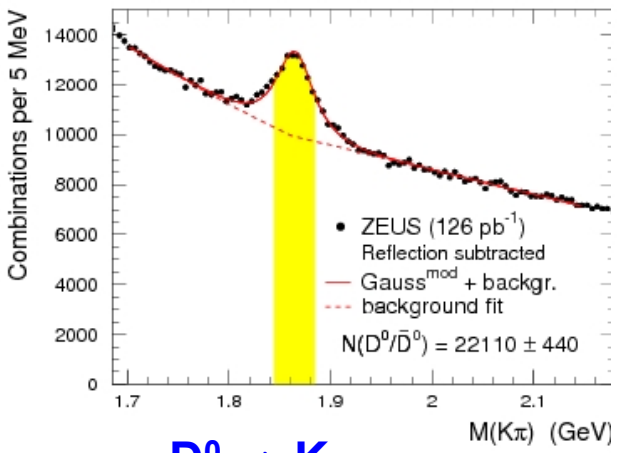
- HERA I data: 126 pb^{-1}
- DIS and photoproduction



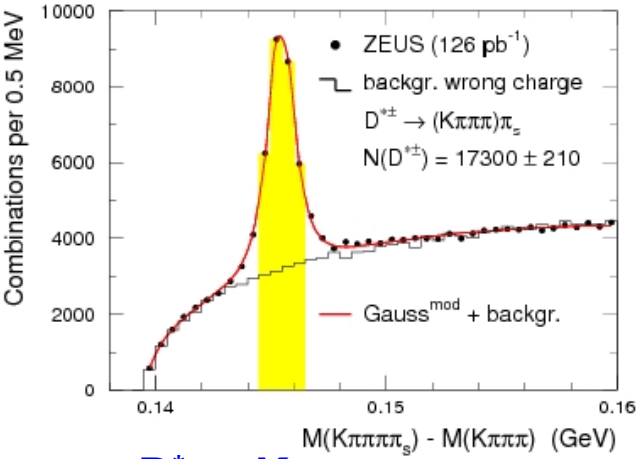
$D^* \rightarrow K\,\pi\,\pi_s$



$D^{\pm} \rightarrow K\,\pi\,\pi$



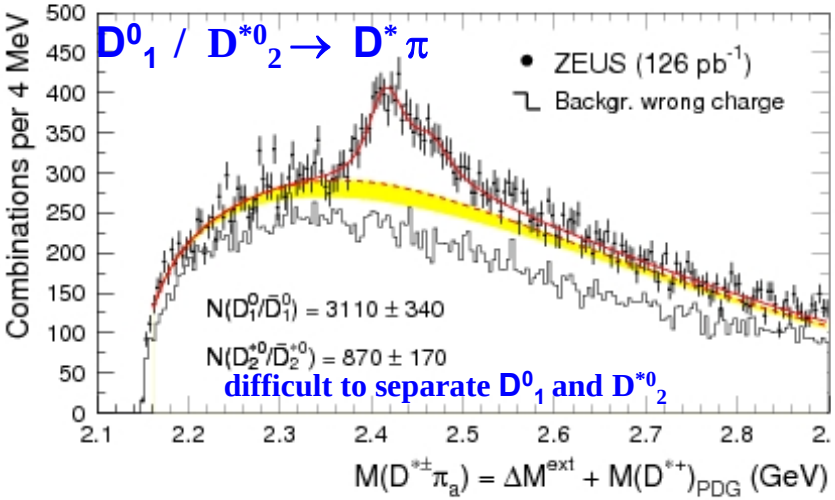
$D^0 \rightarrow K\,\pi$

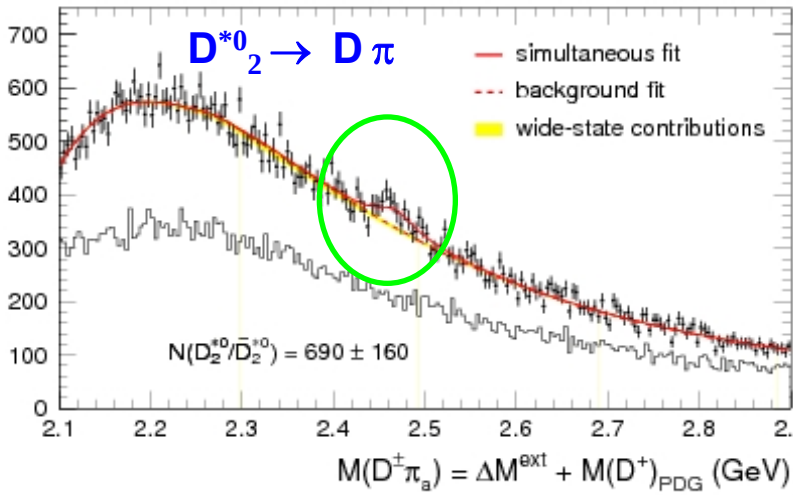


$D^* \rightarrow K\,\pi\pi\pi\pi_s$

Excited charm and charm-strange mesons production

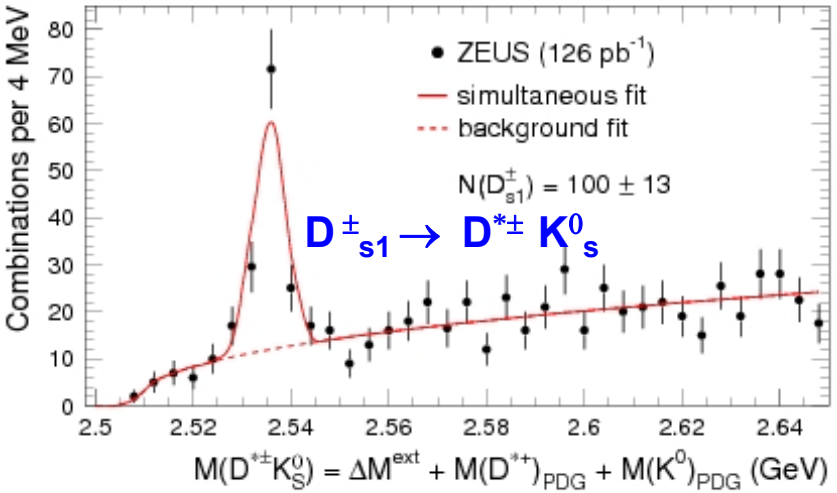
excited charm mesons

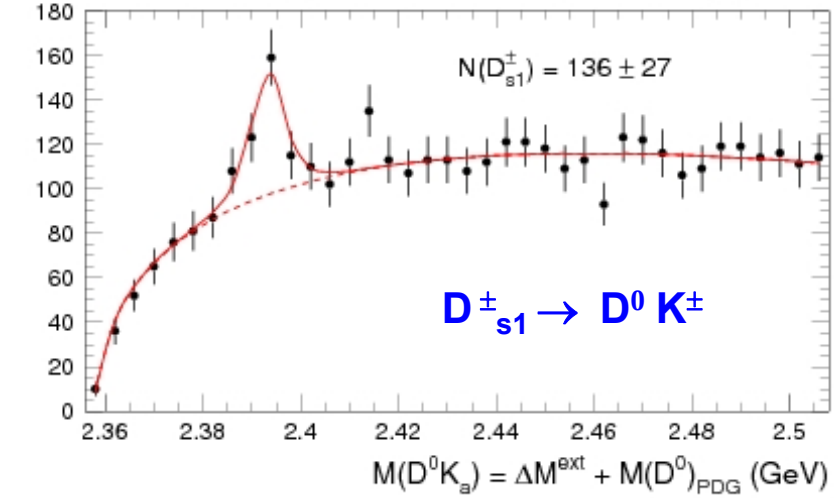




due to spin parity conservation D^0_1 can NOT decay in this mode

excited charm strange mesons



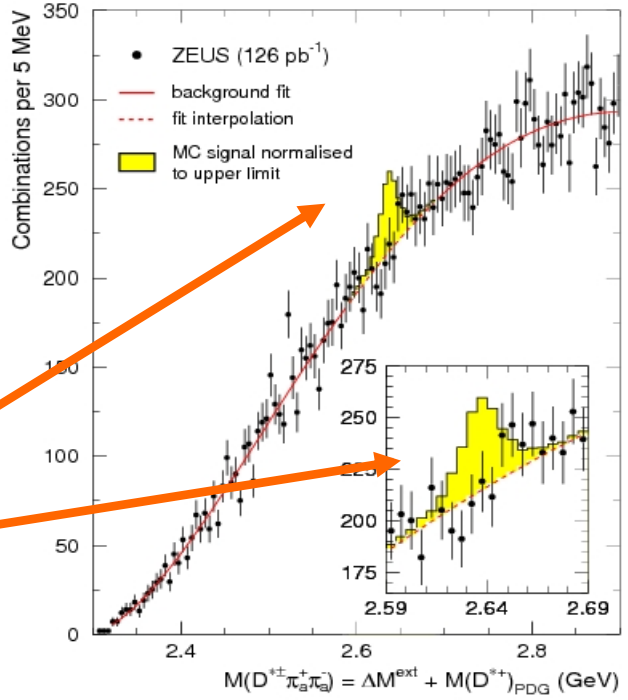


Excited charm and charm-strange mesons production

	$f(c\to D_1^0)(\%)$	$f(c\to D^*_2{}^0)(\%)$	$f(c\to D_{s1}^+)(\%)$
ZEUS	$3.5\pm0.4^{+0.4}_{-0.6}$	$3.8\pm0.7^{+0.5}_{-0.6}$	$1.11\pm0.16^{+0.08}_{-0.10}$
OPAL	2.1±0.7±0.3	5.2±2.2±1.3	1.6±0.4±0.3
ALEPH			0.94±0.22±0.07

•the HERA rates are in reasonable agreement with those measured in others (e^+e^-) experiments

- No radial excited $D^{*\prime}(2640)^+$ observed
- Upper limit:
  $f(c\to D^{*\prime})B(D^{*\prime}\to D^{*+}\pi^+\pi^-)<0.4\%$
- OPAL result : <0.9%
- MC signal normalized to the upper limit



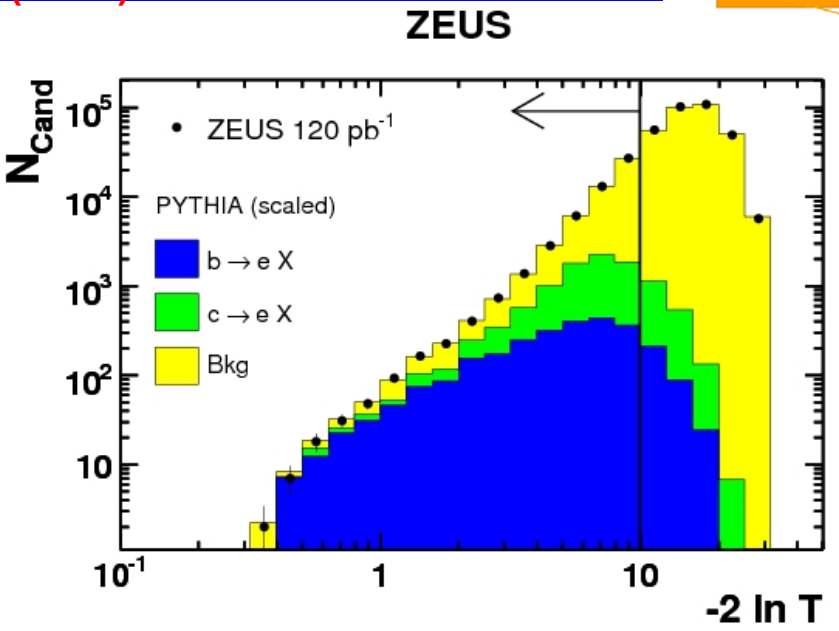
Beauty Production at HERA

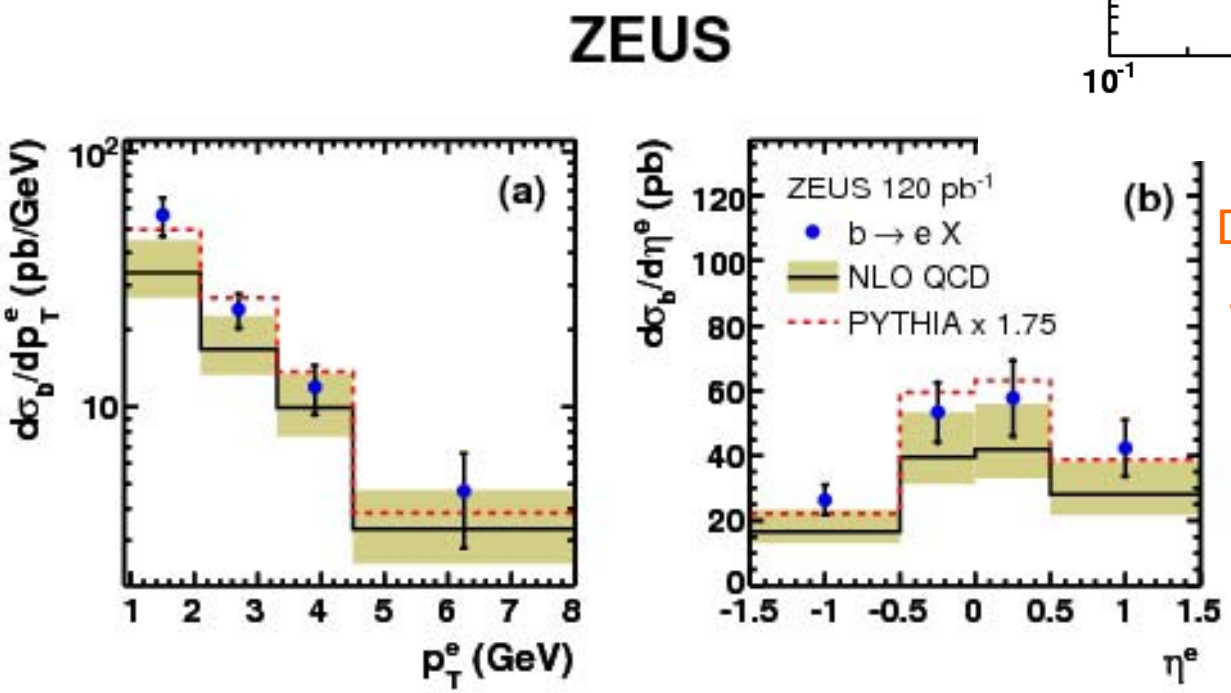
- **Beauty in Dijet PhP using electrons**
- **Beauty in Dijet PhP using muons**
- **Beauty in PhP using inclusive secondary vertexing**

Beauty in Dijet PhP using electrons

Phys. Rev. D78,072001(2008)

- HERA I data: 120pb^{-1}
- Kinematic range
  - Q^2<1 GeV^2
  - Dijet events with E_T>7(6) GeV
- likelihood analysis used to separate b→e from c→e and uds





Differential cross sections as functions of p_t (D*) and η(D*)

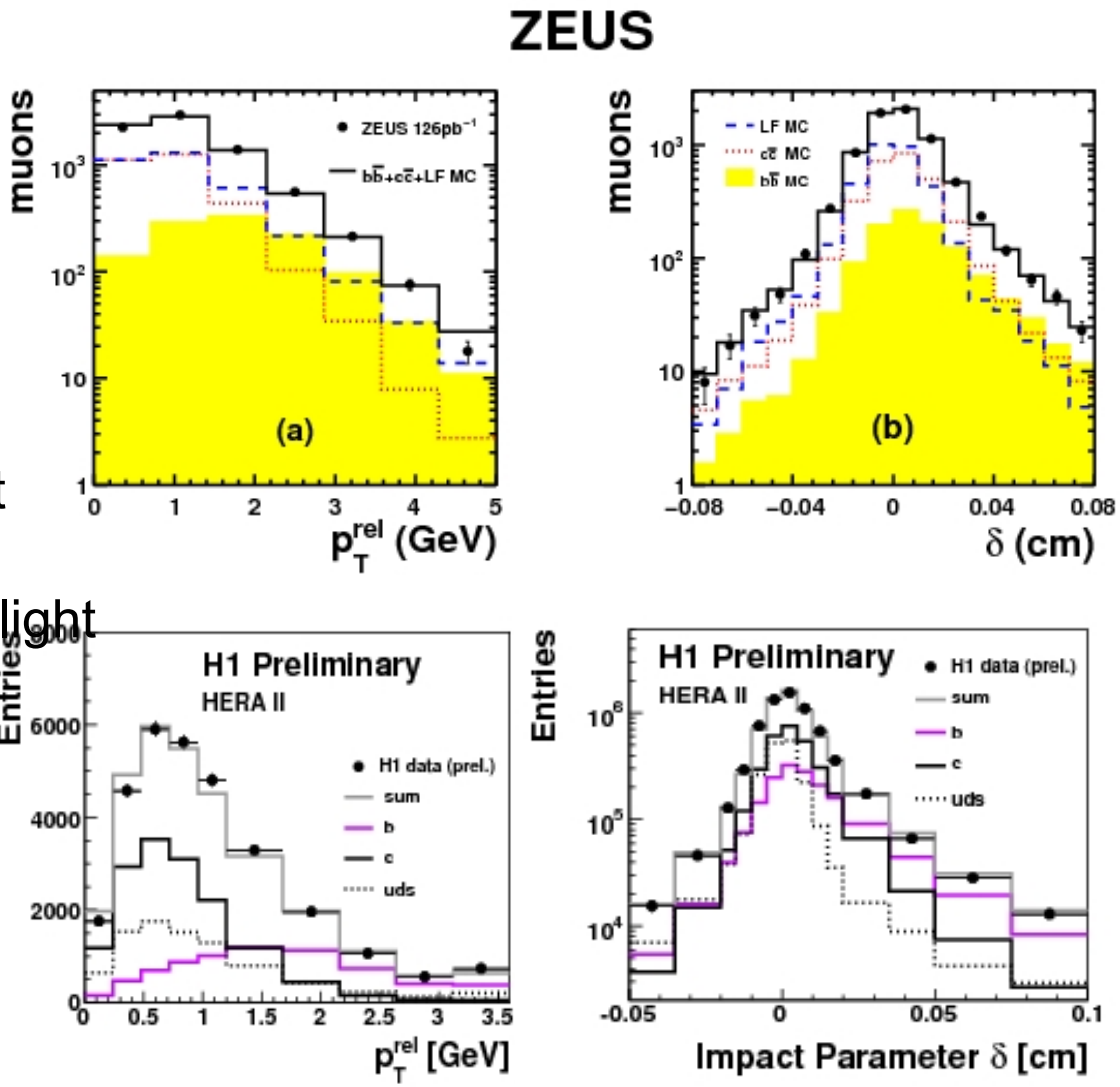
NLO QCD predication describes the shape well

Beauty in Dijet PhP using muons

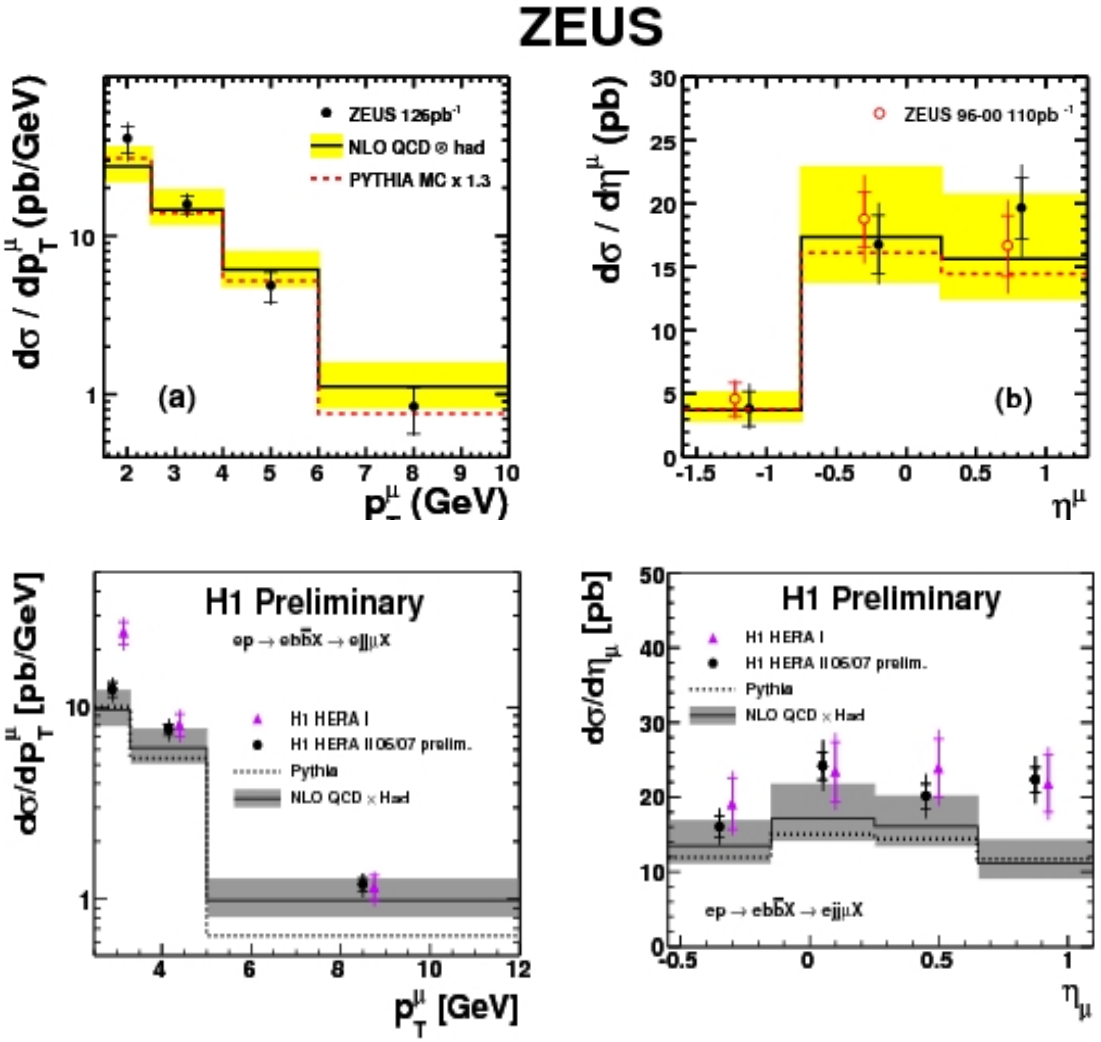
Phys. Rev. D78,072001(2008)

- HERA II data
- ZEUS: 124pb^{1}, H1: 171pb^{-1}
- Similar kinematic range
- $Q^2<1$ GeV^2
- Dijet events with $E_T>7(6)$ GeV

- Simultaneous fit of the impact parameter δ and p_t^{rel}
  → allows to separate b from c, light flavor background



Beauty in Dijet PhP using muons

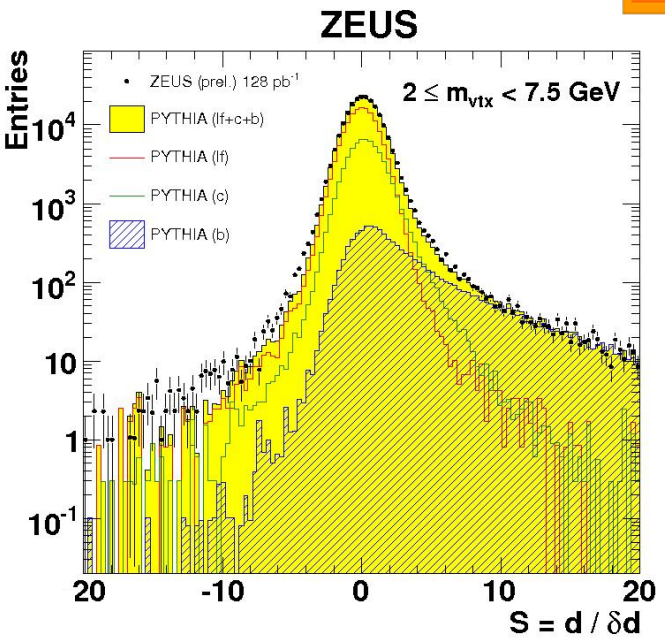


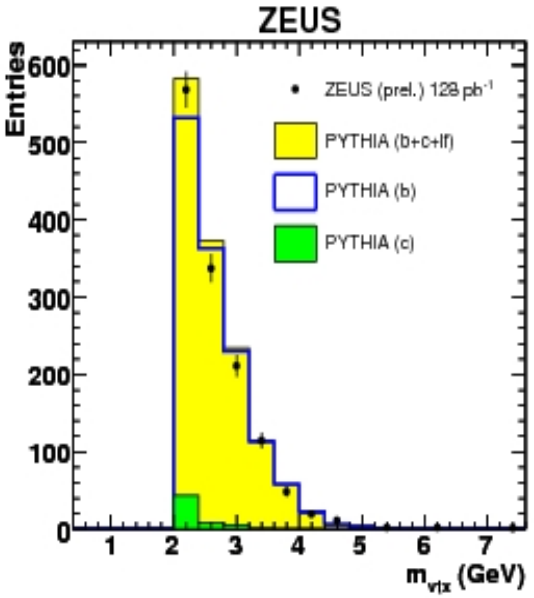
- Compatible with previous measurements
- NLO calculations provide reasonable good description of data

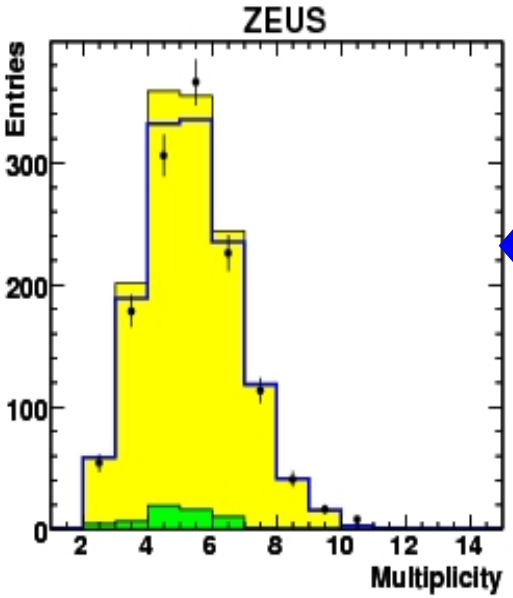
Beauty in PhP using inclusive secondary vertexing

- HERA II data : 128pb^{-1}
- Dijet events with p_T^{jet}>7(6) GeV
- Decay length significance S=d/δd
- For large m_{vtx} dominated by beauty

→ with cuts on S and m_{vtx} an almost pure beauty sample can be obtained



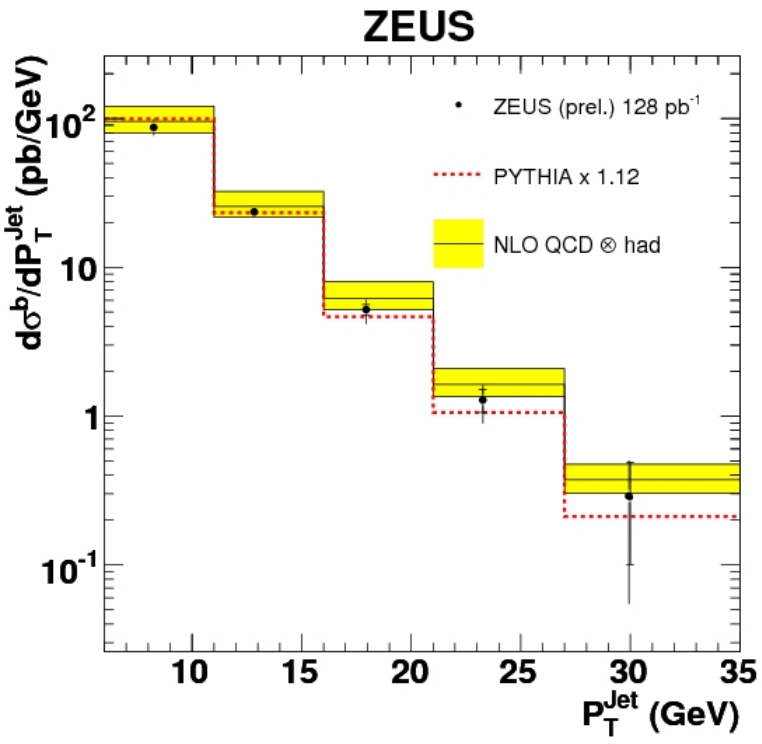


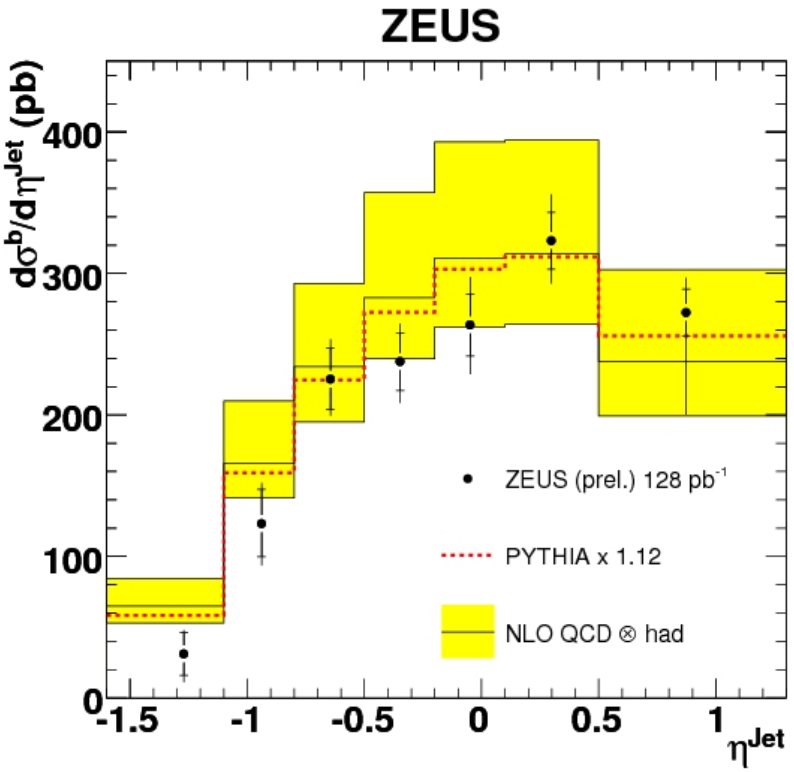


Good agreement between data and MC

Beauty-enriched m_{vtx} and multiplicity distributions

Beauty in PhP using inclusive secondary vertexing





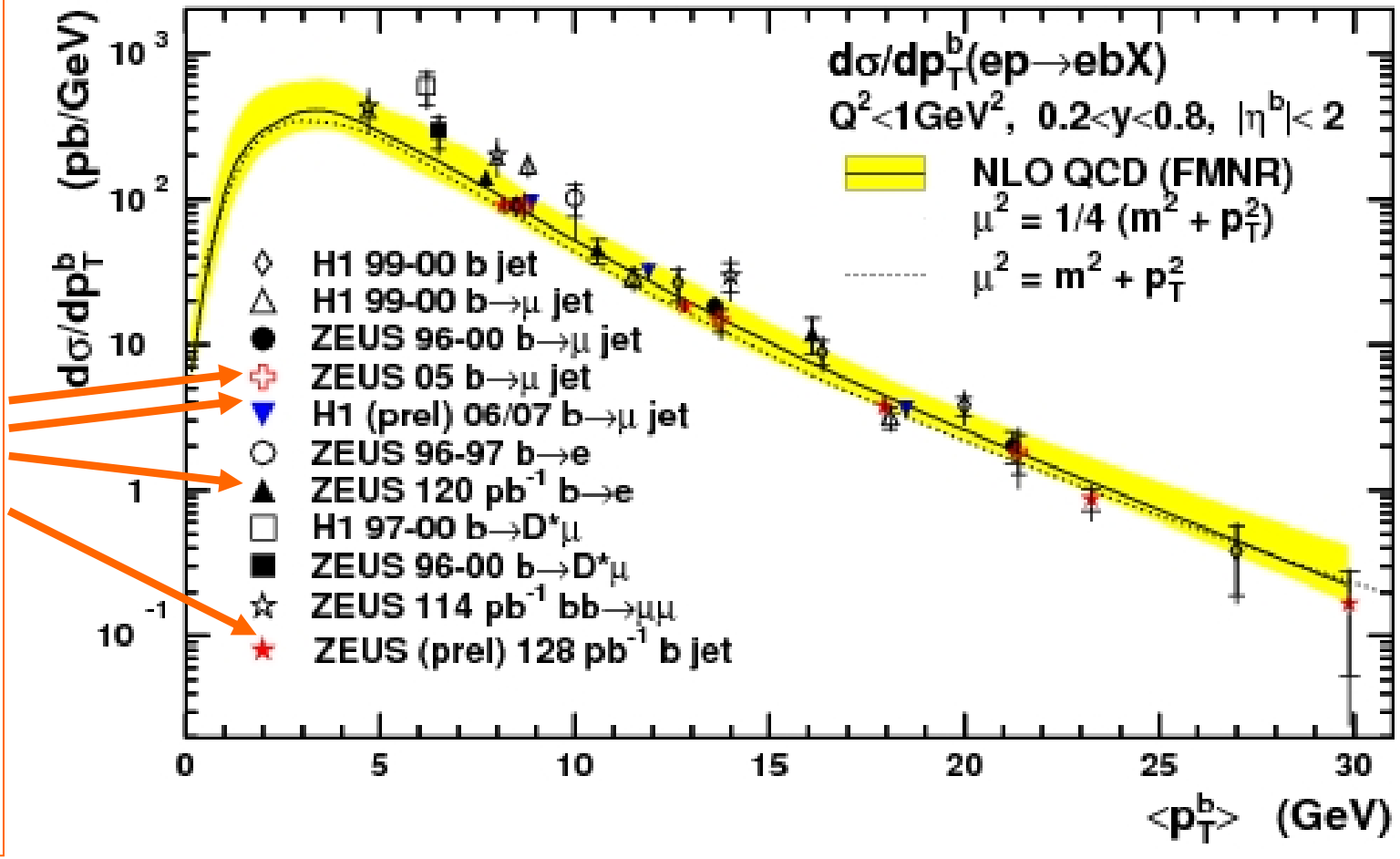
Differential cross-sections in P_T^{jet} and η^{Jet}

Good agreement between data and NLO QCD predications

beauty production

HERA

Beauty production presented in this talk



Cross sections for b production extrapolated using NLO calculations

- **The results are consistent with previous measurements**
- **General good agreement with NLO QCD predictions**

Summary

- Inclusive K_S,Λ,$K^*(892)$ and ϕ productions have been studied
- Three clear enhancements, $f_2(1270)/a_2(1320)$, $f_2(1525)$ and $f_0(1710)$, clearly observed in inclusive K_SK_S mass spectrum
- The masses and widths are compatible with PDG values

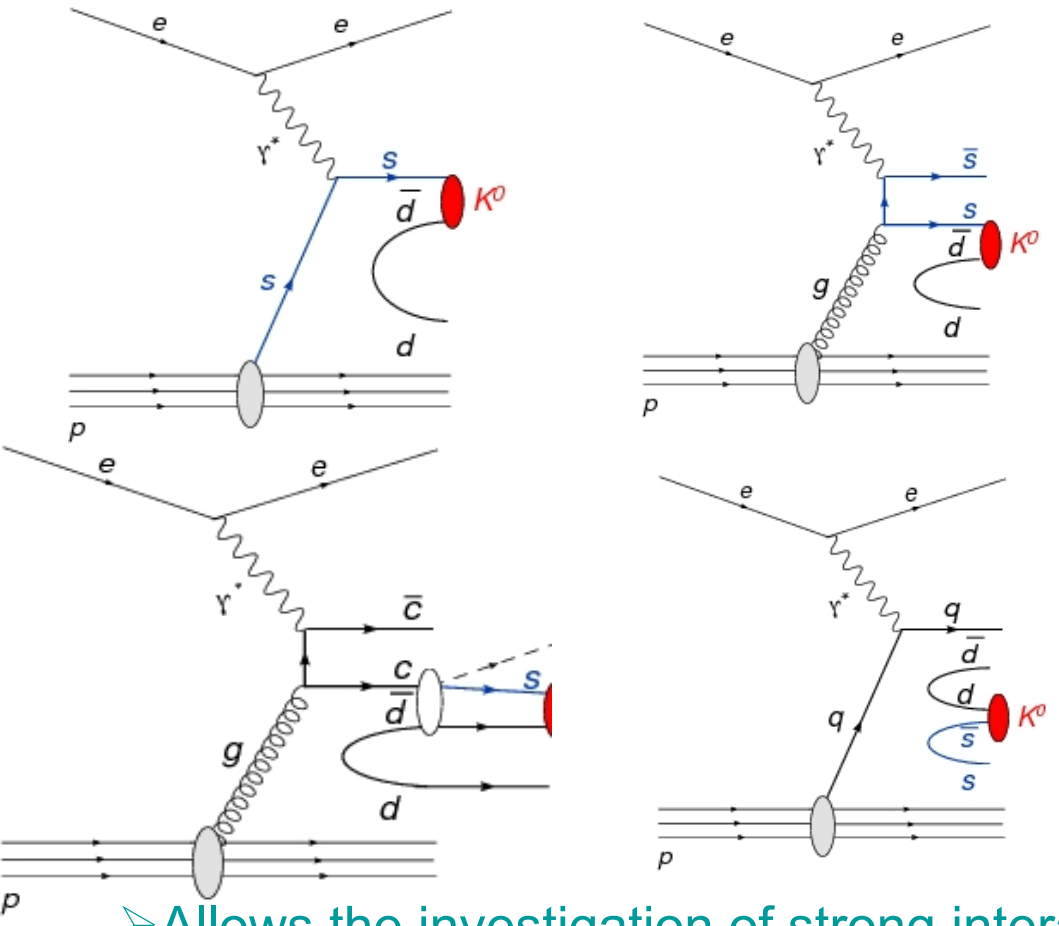
- D* production studied in photoproduction regime
- Excited charm and charm-strangeness mesons were observed in ep collision
- The fragmentation rates are compatible with those measured in other experiments
- No radial excited D*'(2460) meson was observed

- Beauty production measured using different experimental techniques
- Good description achieved with NLO calculations in all measurements

Many thanks for your attention!

K_S Production

Eur. Phys. J. C61,185(2009)



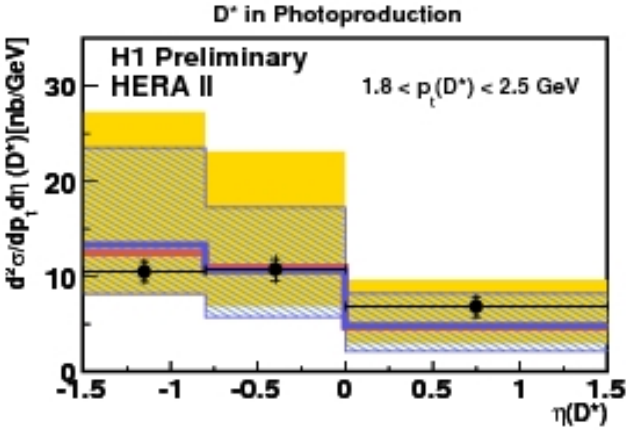
- Hadronization of s from the proton sea

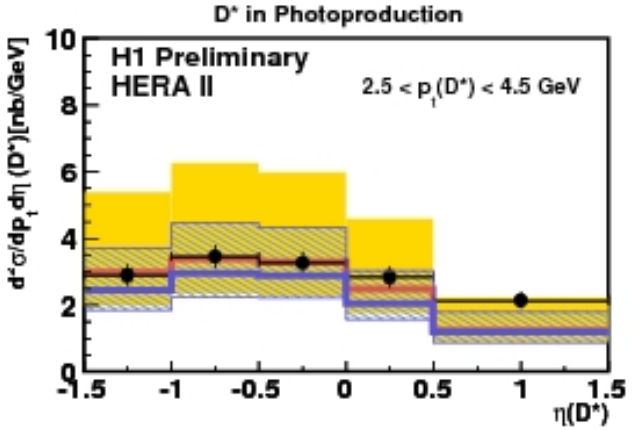
γ*s→s (QPM) or γ*s→sg process

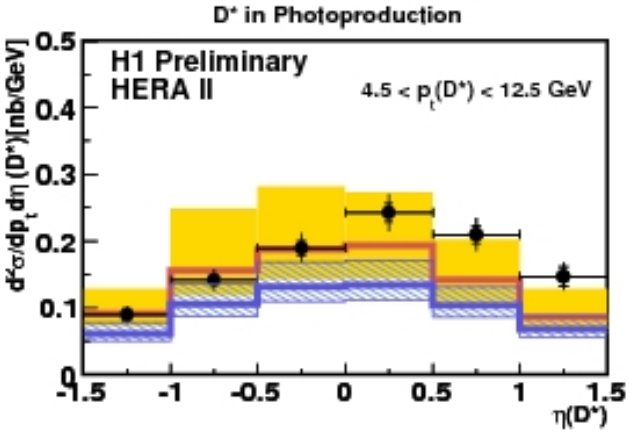
- rate of the boson-gluon fusion (BGF) γ*s→ssbar
- hadronization process alone contributes to the strangeness production

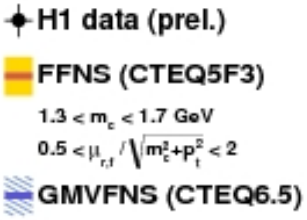
- Allows the investigation of strong interactions in the perturbative and non-perturbative process
- strange hadron production is not know to be well described by MC models
- ssbar production parameterized by the strangeness suppression factor

D* in photoproduction





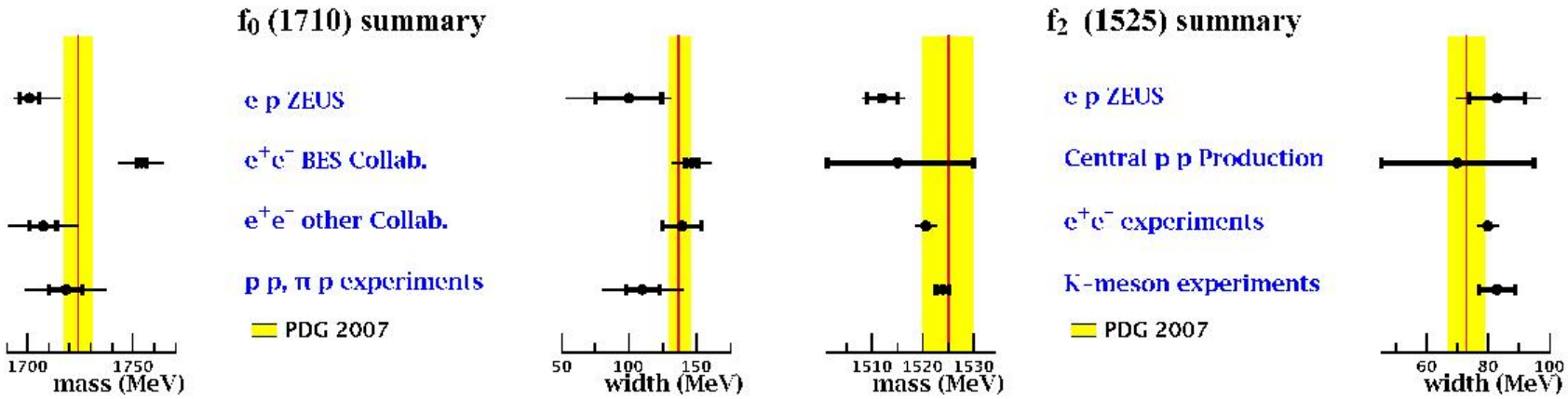




Double-differential cross sections

Good agreement between data and NLO predictions

Except for high pt, high η region


f0 (1710) summary
e p ZEUS
e+e− BES Collab.
e+e− other Collab.
p p, π p experiments
PDG 2007
1700
1750
mass (MeV)
50
100
150
width (MeV)
f2 (1525) summary
e p ZEUS
Central p p Production
e+e− experiments
K-meson experiments
PDG 2007
1510
1520
1530
mass (MeV)
60
80
100
width (MeV)

Inclusive K_SK_S resonance

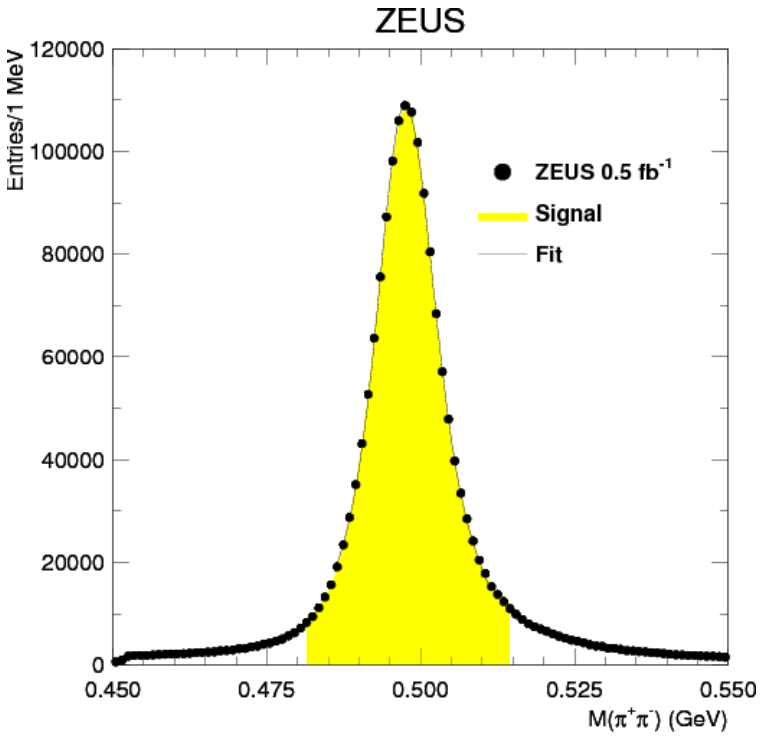
Phys. Rev. Lett. 101,112003(2008)

➢Motivations

- the Standard Model allows for the existence of color singlet glueball
- the KsKs system is expected to couple to scalar and tensor glueball
- Lattice QCD predicates that the lightest glueball has $J^{PC}=0^{++}$ and lies in the mass region 1550 -1750 MeV

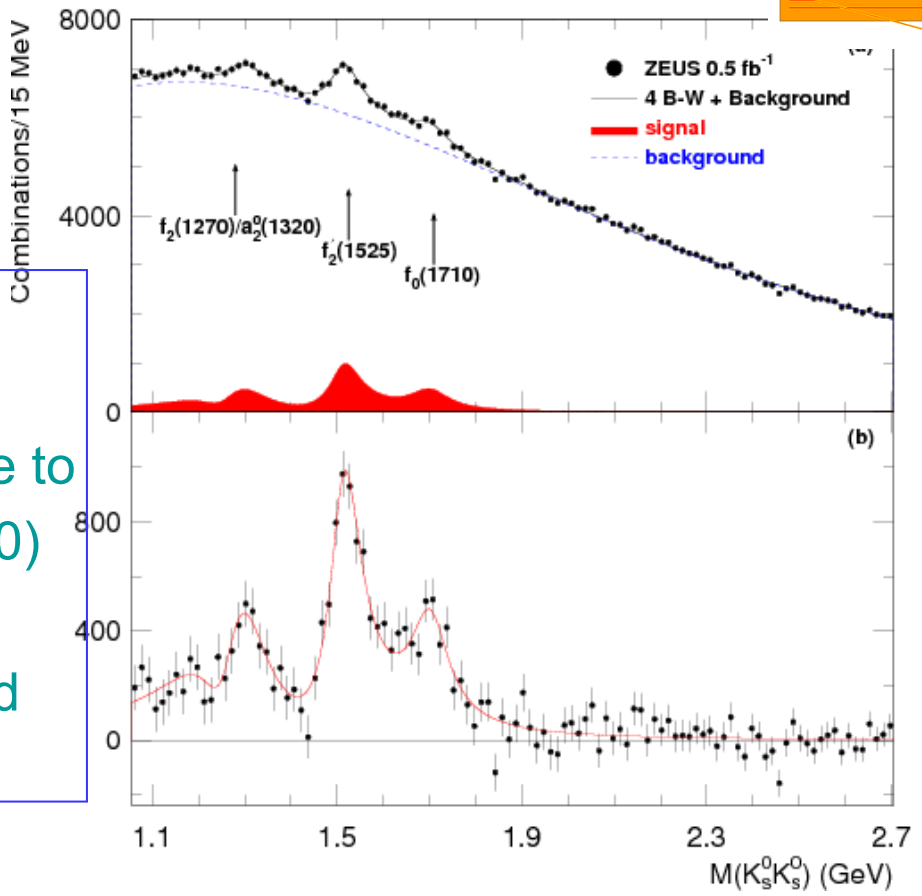
➢HERA I + HERA II data: ~500pb^{-1}

- dominated by photoproduction 90%, while 10% by DIS
- clear KS signal ~1260000
- signal region: 481 <M($\pi^+\pi^-$)<515 MeV



Inclusive $K_S K_S$ resonance

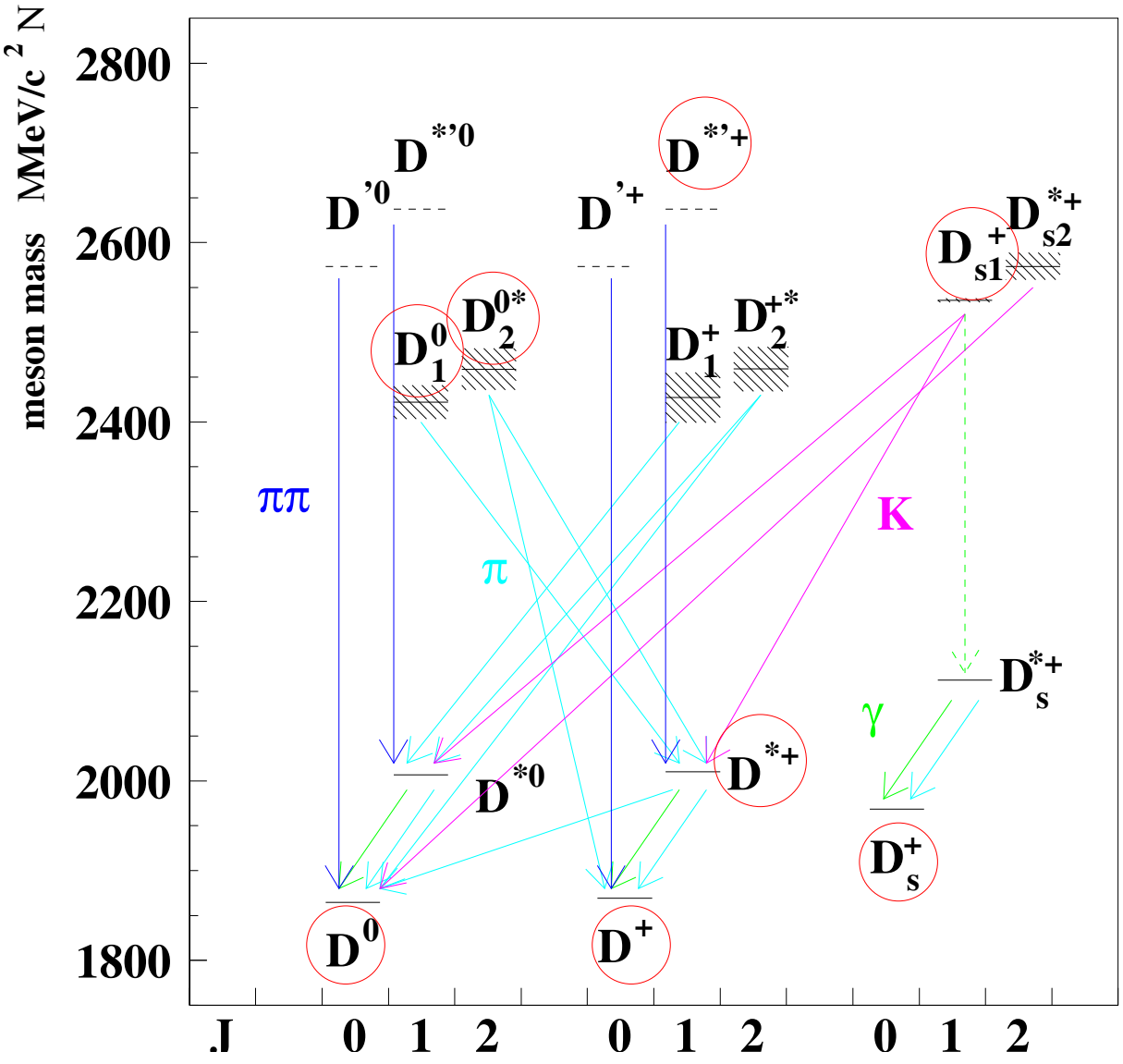
Phys. Rev. Lett. 101,112003(2008)



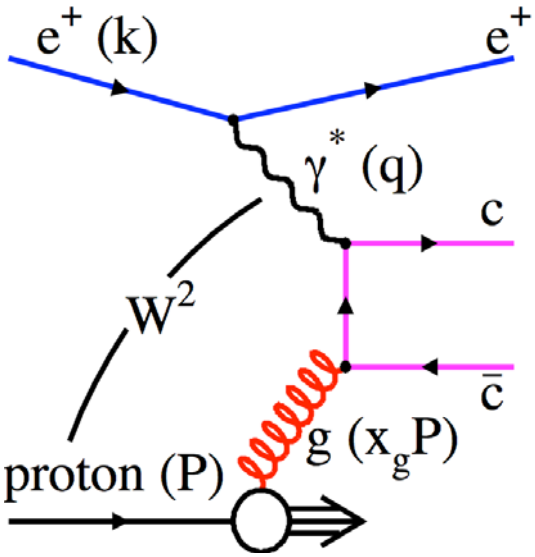
- No. of fitted $f_0(1710)$

4058±820 ~5σ significance

- peak around 1.3 GeV suppressed due to destructive interference between $f_2(1270)$ and $a_2(1320)$
- The dip between $f_2(1270)/a_2(1320)$ and $f_0(1500)$ is well reproduced


meson mass MMeV/c 2 N
2800
2600
2400
2200
2000
1800
J
0 1 2
0 1 2
0 1 2
D*'0
D'0
D*'+
D'+
D*+s2
D+s1
D0*2
D01
D+*2
D+1
ππ
π
K
γ
D*+s
D*0
D*+
D+s
D0
D+

Charm Production at HERA



main process:

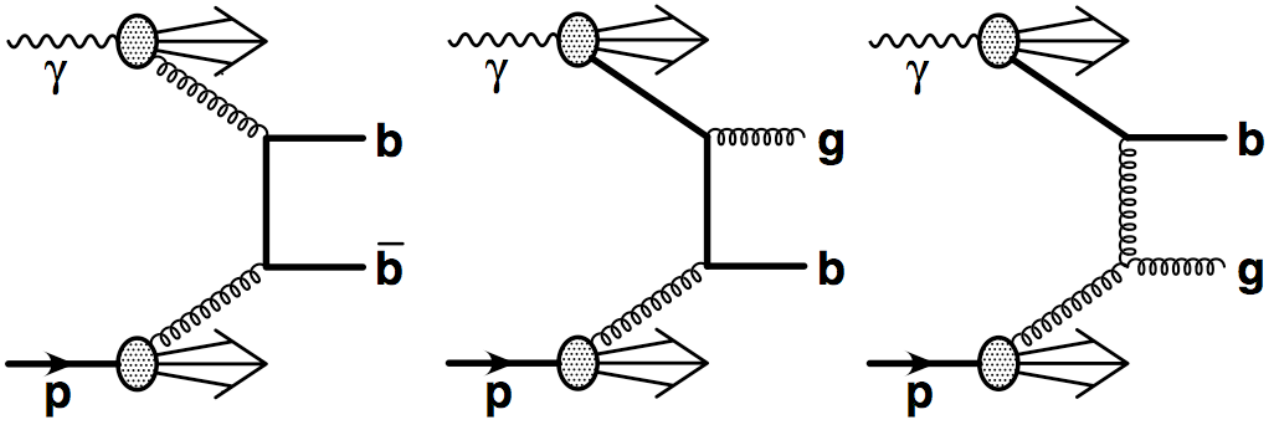
- direct γ
- boson gluon fusion
- $0.8 < x_\gamma^{obs} < 1$

key points:

- m_Q (or E_T^{jet} …) >> Λ_{QCD}

⇒ region of applicability of pQCD

- collinear vs. k_T parton dynamics



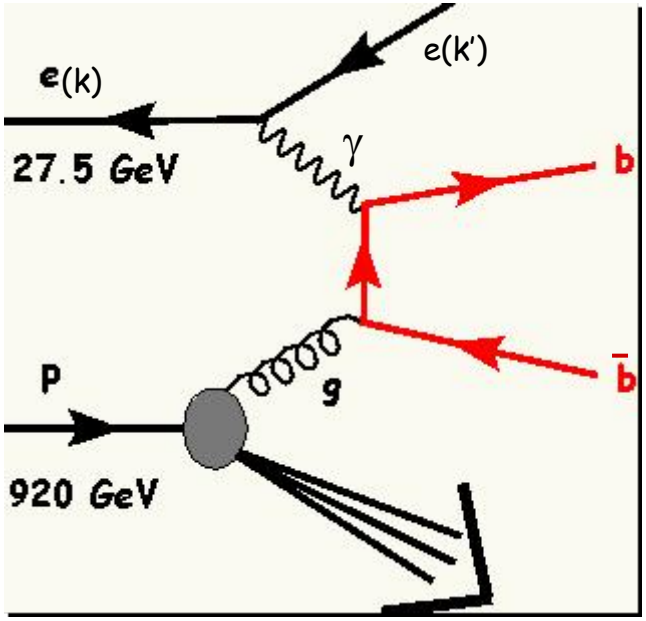
other processes:

- resolved γ processes
- $0 < x_\gamma^{obs} < 0.8$

- photoproduction (PHP) regime ⇔ scattered electron is undetected ⇔ $Q^2 < 1$ GeV^2

Heavy quark production at HERA

Dominant process: **boson-gluon fusion**



❑ Kinematic Variables:

$Q^2 = -q^2 = (k-k')^2$ — Neg. squared momentum transfer (virtuality of exchanged boson)

$s = (k+p)^2 \approx 4E_eE_p$ — CM Energy, at HERA $\sqrt{s}$ = 318 GeV

$x = Q^2/2p\bullet q$ — Bjorken scaling variable: momentum fraction of parton interacting with lepton in infinite momentum frame (QPM)

$y = p\bullet q/p\bullet k$ — Inelasticity: lepton momentum fraction transferred to boson in proton rest frame

❑ Kinematic Regimes:

- **Deep Inelastic Scattering (DIS):** $Q^2 > 1$ GeV^2
- **Photoproduction (PHP):** $Q^2<1$GeV^2 ($Q^2\sim10^{-3}$, quasi-real γ)

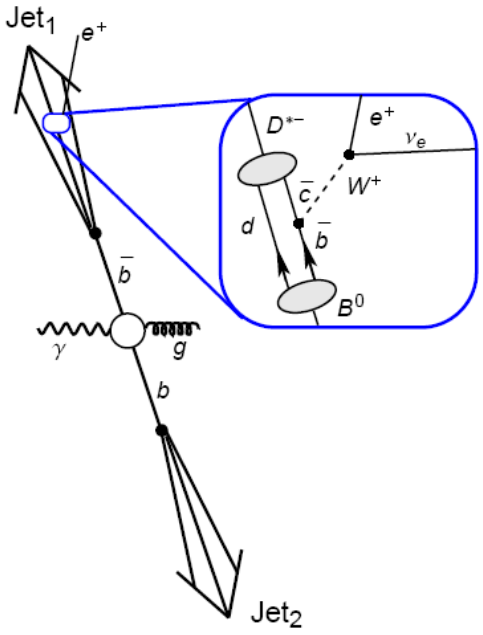
Why study heavy quark production at HERA?:

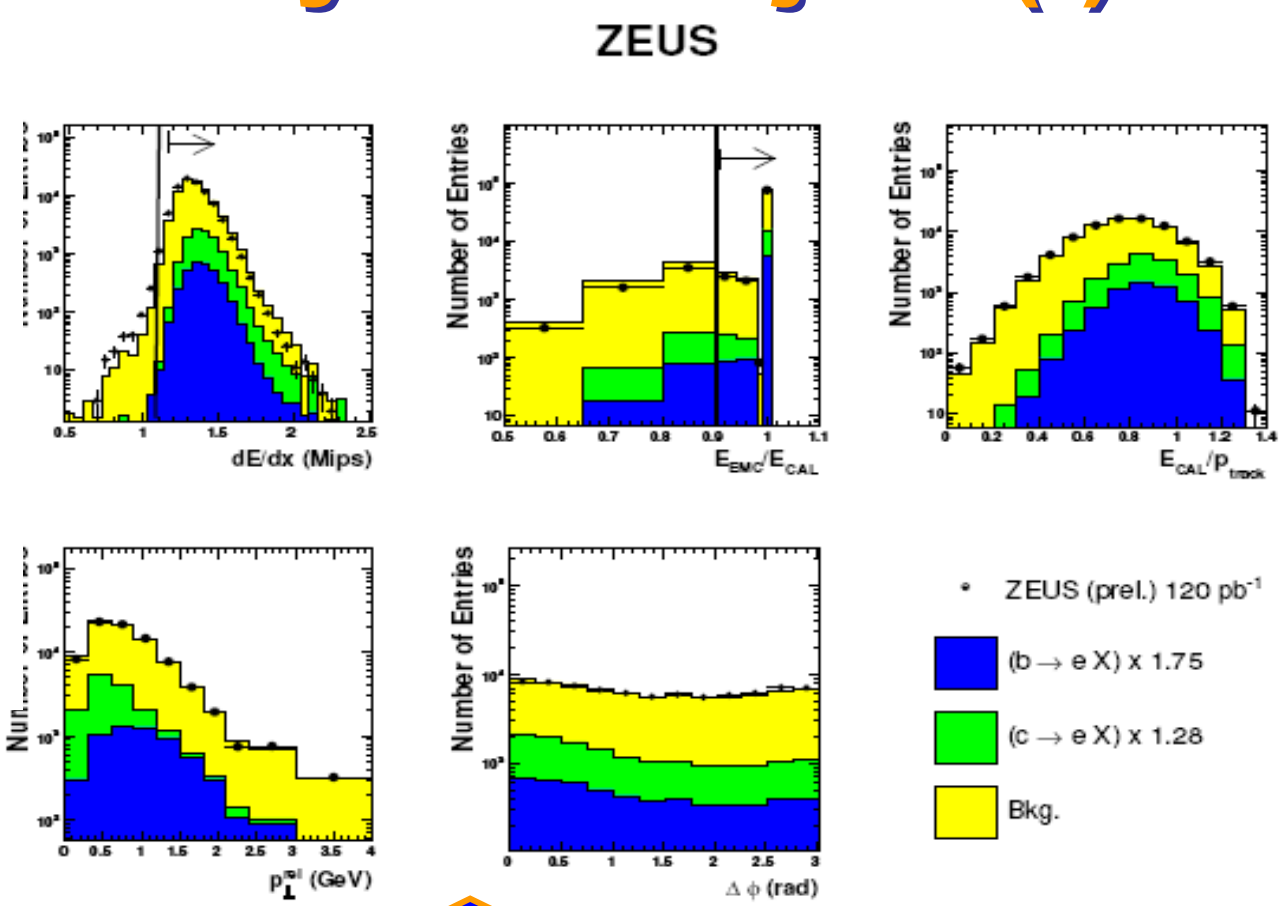
❖ **Test of perturbative QCD** due to the hard scale given by the heavy quark mass.

❖ **Study of multi-scale problem:** often mass scales compete with other hard scales (p_T,Q^2…) , additional theoretical uncertainties enter.

❖ **Better understanding of structure of the proton**

Tagging Beauty with e+jets (I)





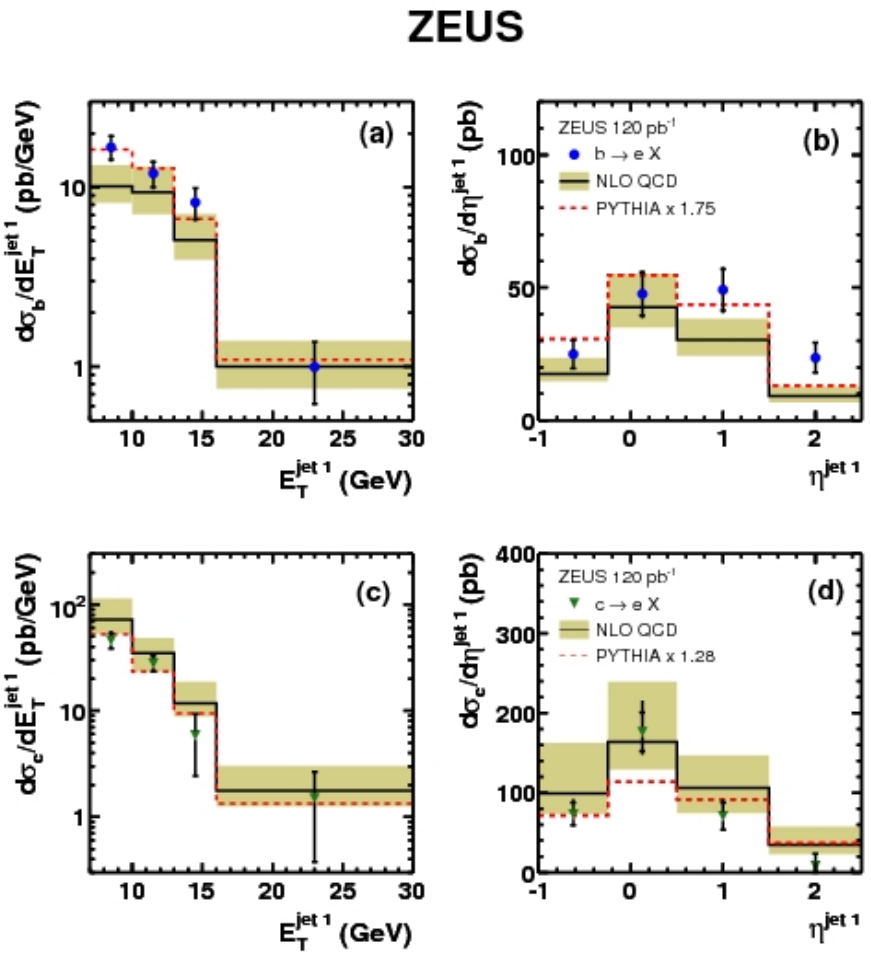
- **Semileptonic decay:**

  ep→e'bX→e'jj+eX

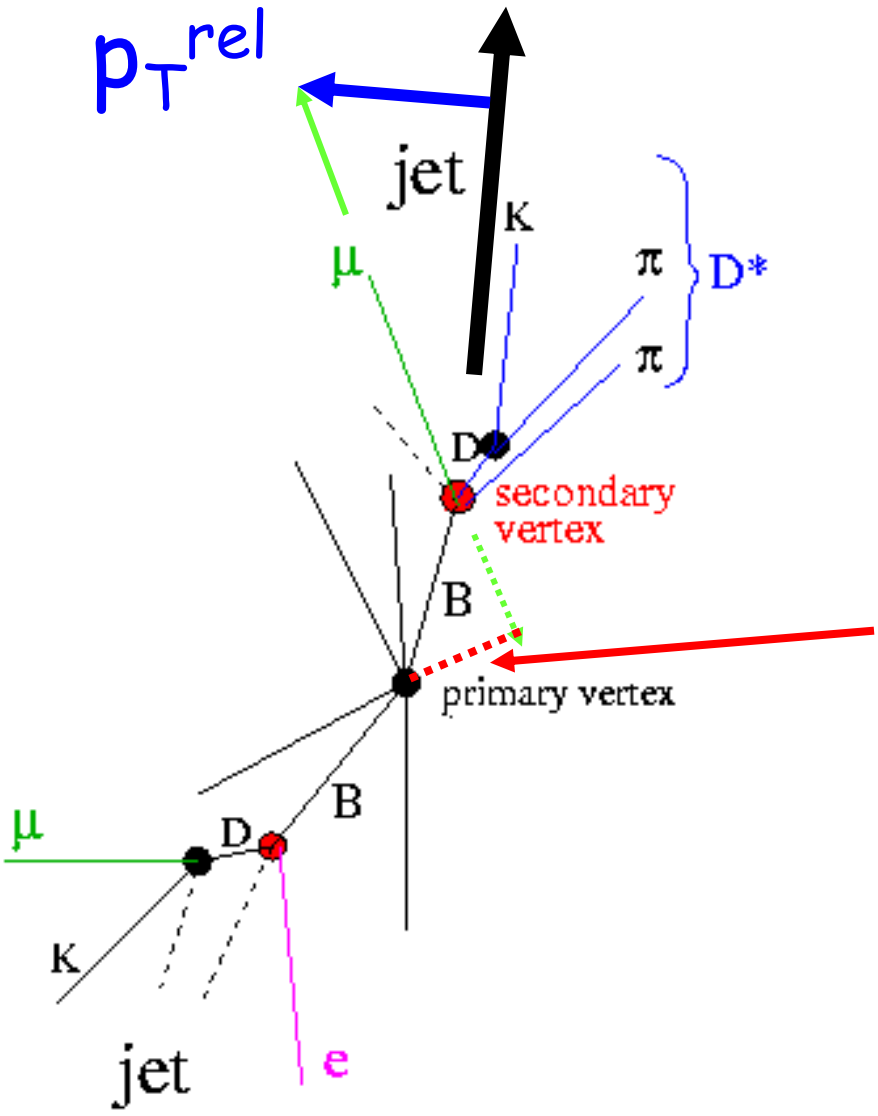
- b-fraction extracted from likelihood fit using variables sensitive to e⁻ identification and semileptonic decays

$$\text{Likelihood } \mathcal{L}_{i,j} = \alpha_i(p_T,\eta)\cdot\mathcal{P}(dE/dx)\cdot \mathcal{P}(E_{ECAL}/E_{tot})\cdot\mathcal{P}(E^{cal}/p_{trk})\cdot \alpha_j(p_T,\eta)\cdot\mathcal{P}(\sphericalangle(\not{p}_t,p_{trk}))\cdot\mathcal{P}(p_\perp^{rel})$$

- Beauty with electron



Tagging semileptonic beauty decays



1) p_T^{rel} : p_T of μ with respect to jet axis

2) impact parameter of μ (or h) with respect to primary vertex

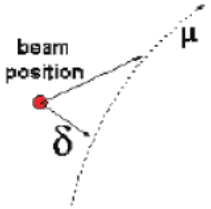
(H1: all, ZEUS: HERA II only)

3) D*μ and μμ correlations

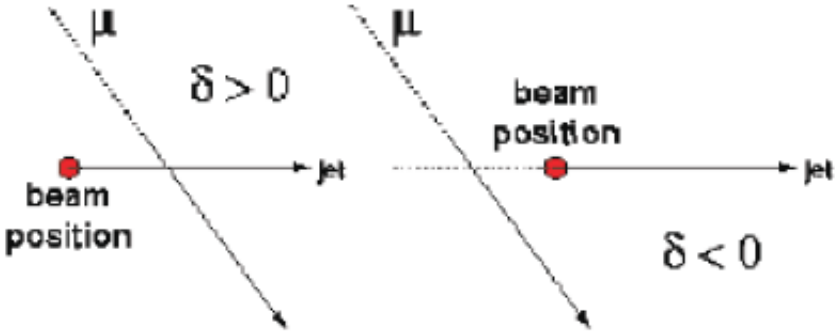
Tagging Beauty with μ+jets (I)

- **Semileptonic decay:**

  $ep \rightarrow e'bX \rightarrow \mu jjX$

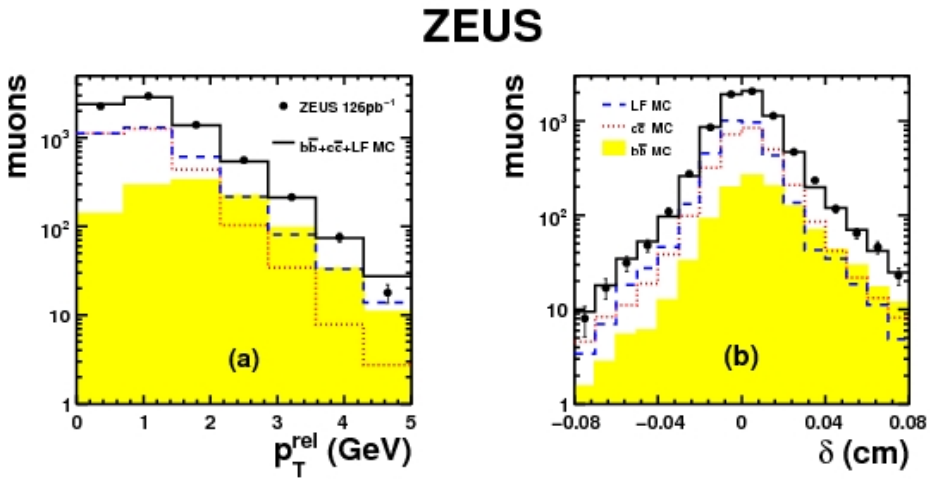


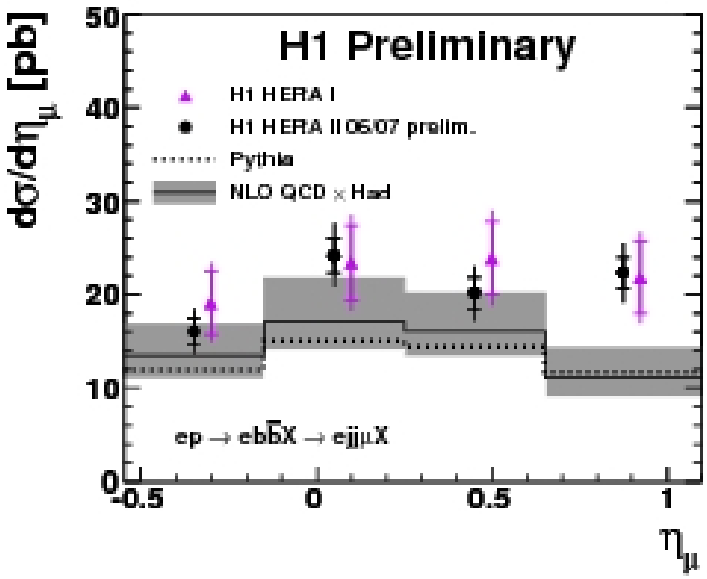
- **Separate b from c and uds:**

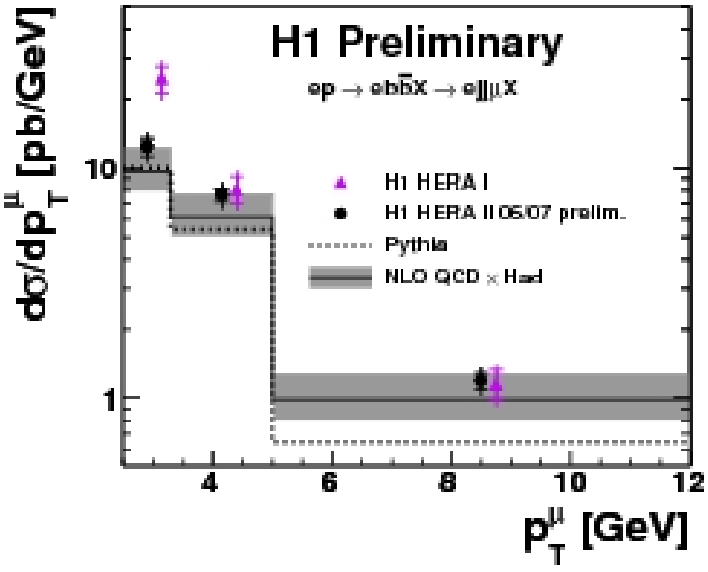


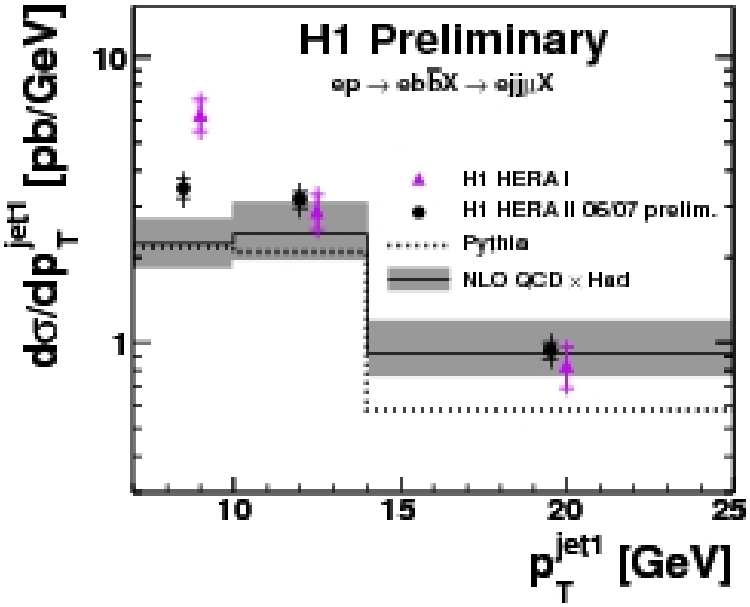
  - Large b mass → large muon P_T^{rel}
  - Large b lifetime → large muon impact param. δ

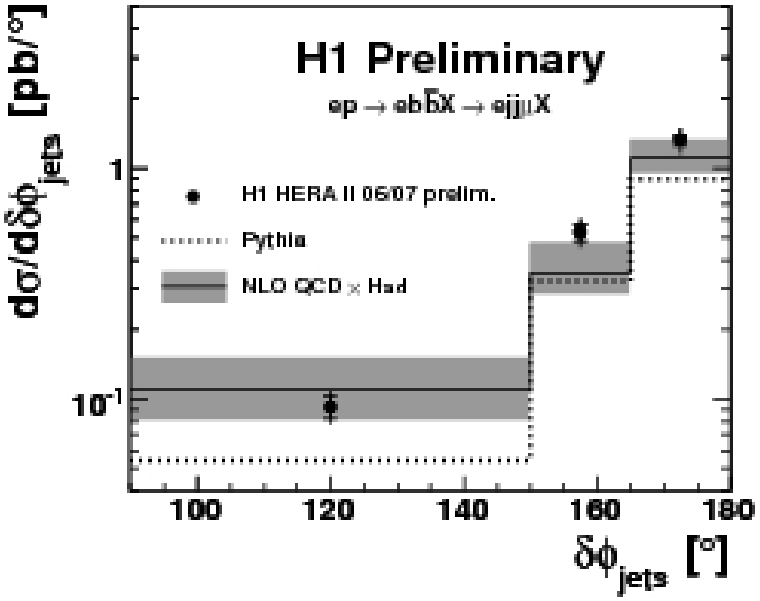
→ Simultaneous 2-dim P_T^{rel} and δ fit
(enhanced statistics
and reduced syst.errors)



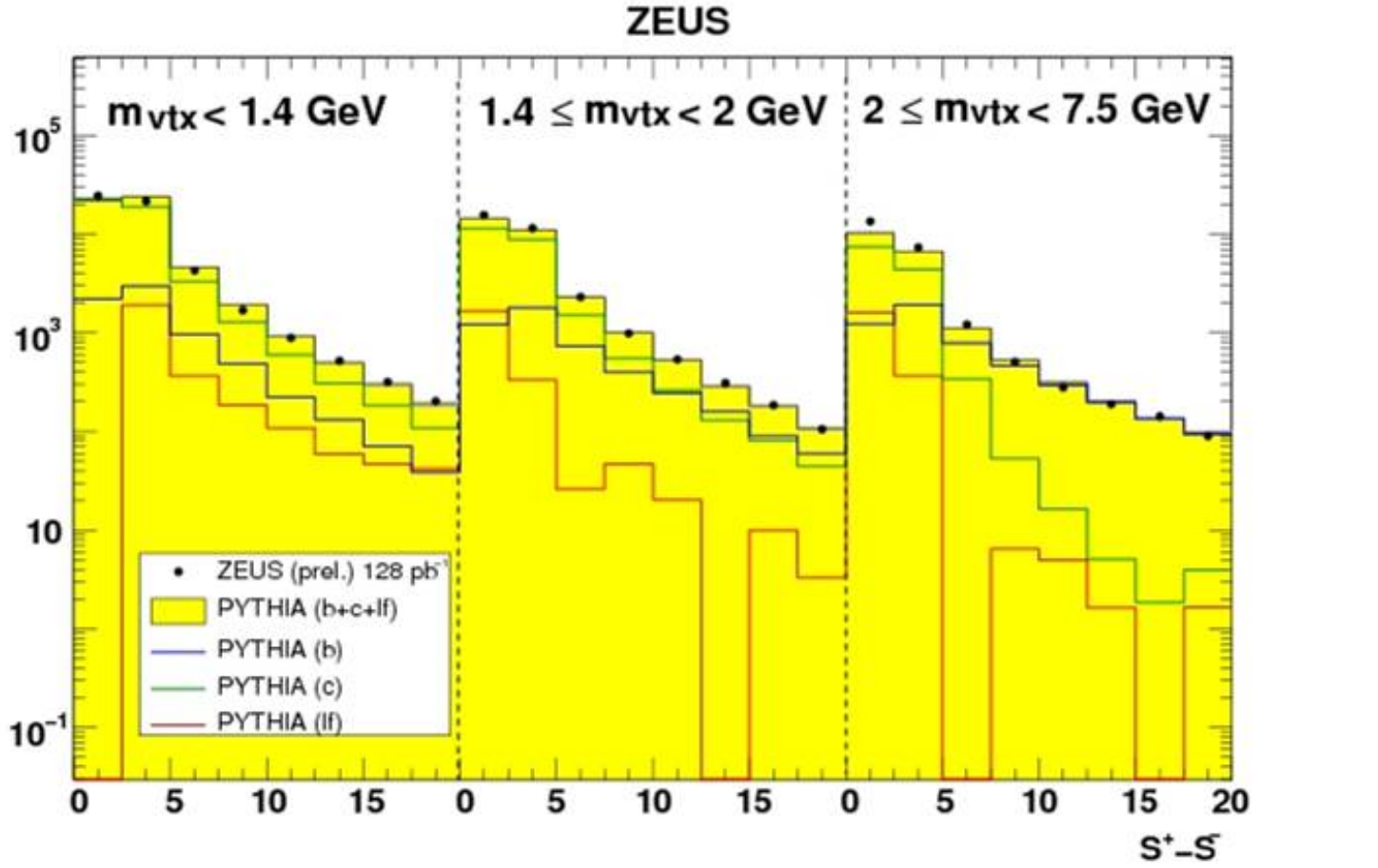

H1 Preliminary
H1 HERA I
H1 HERA II 06/07 prelim.
Pythia
NLO QCD × Had
ep → ebb̄X → ejjμX
dσ/dη_μ [pb]
η_μ


H1 Preliminary
ep → ebb̄X → ejjμX
H1 HERA I
H1 HERA II 06/07 prelim.
Pythia
NLO QCD × Had
dσ/dp_T^μ [pb/GeV]
p_T^μ [GeV]


H1 Preliminary
ep → ebb̄X → ejjμX
H1 HERA I
H1 HERA II 06/07 prelim.
Pythia
NLO QCD × Had
dσ/dp_T^jet1 [pb/GeV]
p_T^jet1 [GeV]


H1 Preliminary
ep → ebb̄X → ejjμX
H1 HERA II 06/07 prelim.
Pythia
NLO QCD × Had
dσ/dδφ_jets [pb/°]
δφ_jets [°]

Inclusive secondary vertexing



Fit mirrored and subtracted decay length significance (S^+-S^-) in bins of the secondary vertex mass