Charmed Mesons in ep Scattering at HERA

NORDIC WINTER MEETING ON PHYSICS @ FAIR

Björkliden, Sweden, March 22-26, 2010

V. Aushev (DESY)

On behalf of the ZEUS collaboration

Outline

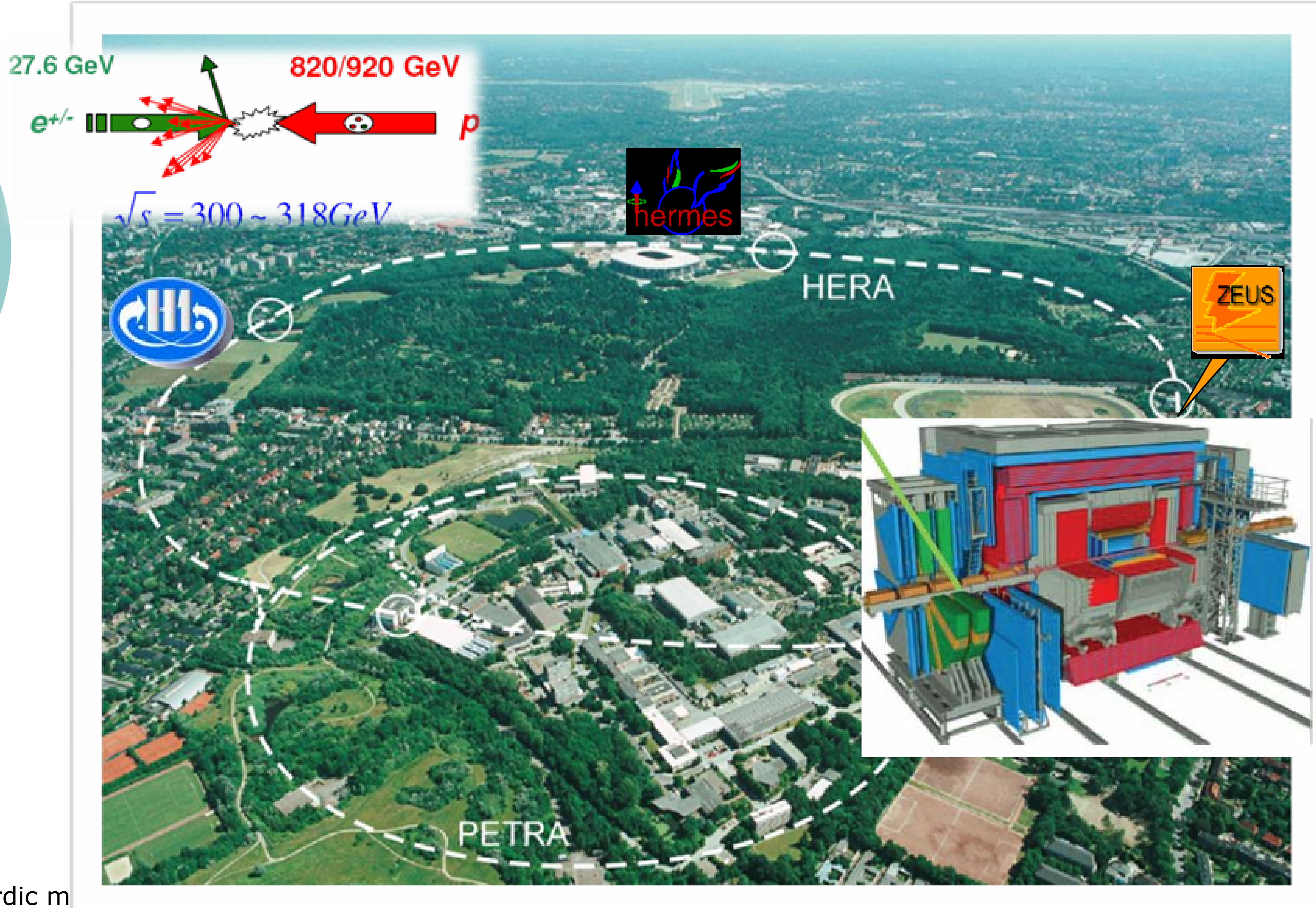
- ZEUS detector at the HERA;
- Tracking detector;
- D-meson decay reconstruction;
- Excited charm and charm-strange mesons;
- Summary;

Christian Forssén:

- “we would like to recommend that your presentation should aim for a target audience with diverse backgrounds. An introduction into the particular field for the general audience will also be appreciated by the fraction of PhD students in the audience.”

I’ll try to provide an overview of current achievements and challenges in this field of the ZEUS collaboration.

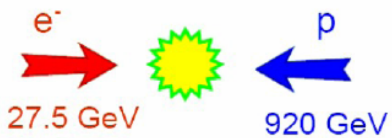
HERA



27.6 GeV
820/920 GeV
$e^{+/-}$
p
$\sqrt{s} = 300 \sim 318 GeV$
hermes
HERA
ZEUS
PETRA

The HERA Collider

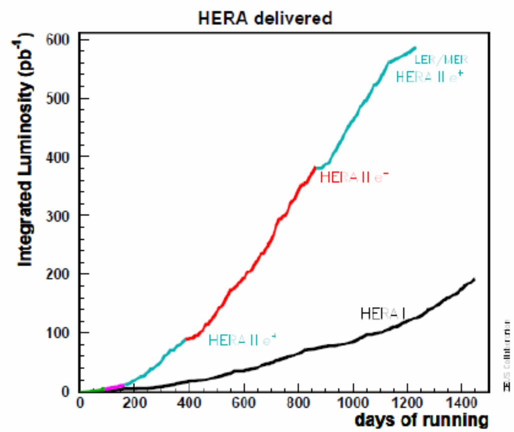
- World's only *ep collider*, located at DESY in Hamburg
- In operation from 1992-2007



Center of mass energy:

$\sqrt{s} = 318$ GeV

- Lepton beam longitudinally polarized in HERA-II running period (since 2002, P ≈ 30-40%)
- Two colliding experiments: H1 and ZEUS
- 0.5 fb^{-1} of data collected by each experiment



E_e=27.6 GeV

E_p	√s
820	301GeV
920	319GeV
460	225GeV
575	252GeV

Different √s allows *direct measurement* of the different structure functions contributions at a given point in phase space.

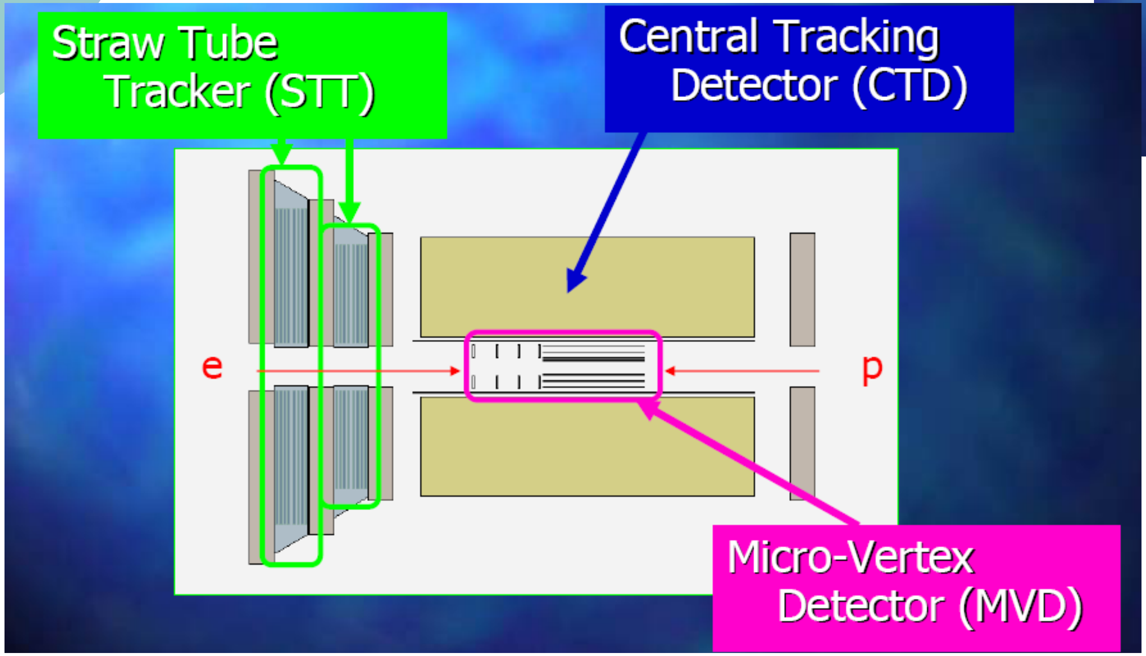
DATA sample:

- ZEUS data: $\mathcal{L} \approx 0.5$ fb^{-1}
- The data sample is dominated by 90% photoproduction, while 10% is Deep Inelastic Scattering

HERA has a rich program on particle production, complementary to e^+e^- and pp

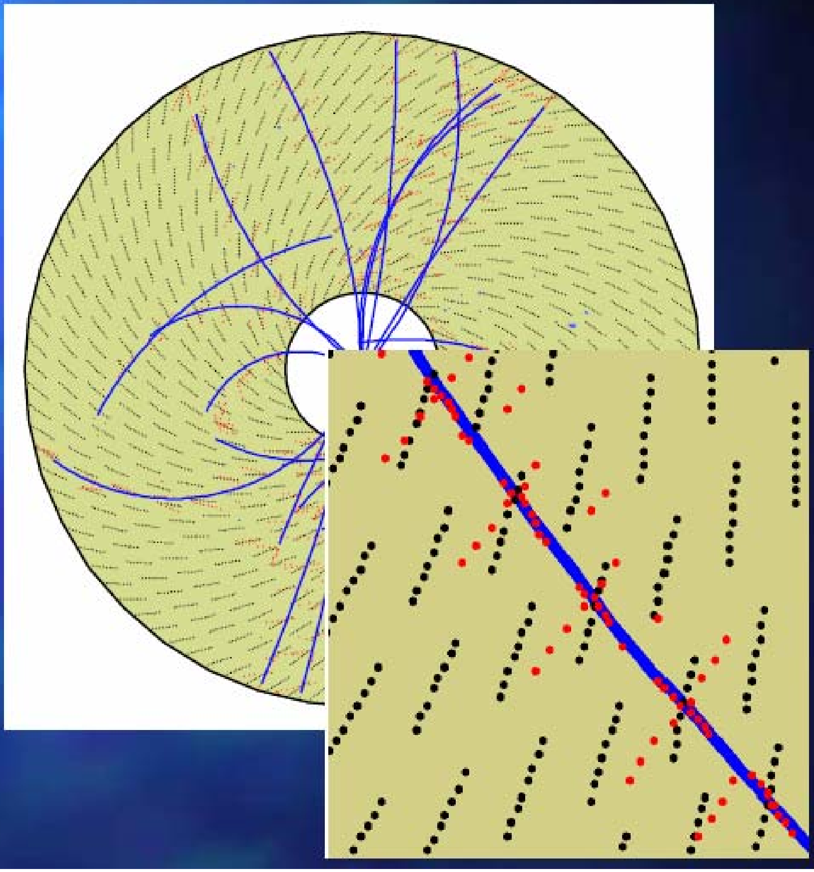
ZEUS Tracking System for HERAII

- Different kinds of analyses have very different ideas as to which information tracking should deliver
  - some analyses only test whether there is a "good" primary vertex
  - some analyses only need to know (roughly) the primary vertex position
  - a substantial set of analyses explicitly reconstruct more complex final states using track parameters
  - HERA-II state-of-the-art analyses use lifetime signatures → precision tracking (μm, not cm)



The Central Tracking Detector (CTD)

- Cylindrical drift chamber
- Nine superlayers (five axial + 4 stereo) with eight layers each
- drift cells tilted by 45° with respect to radial direction
- official coordinate resolution ~160 μm

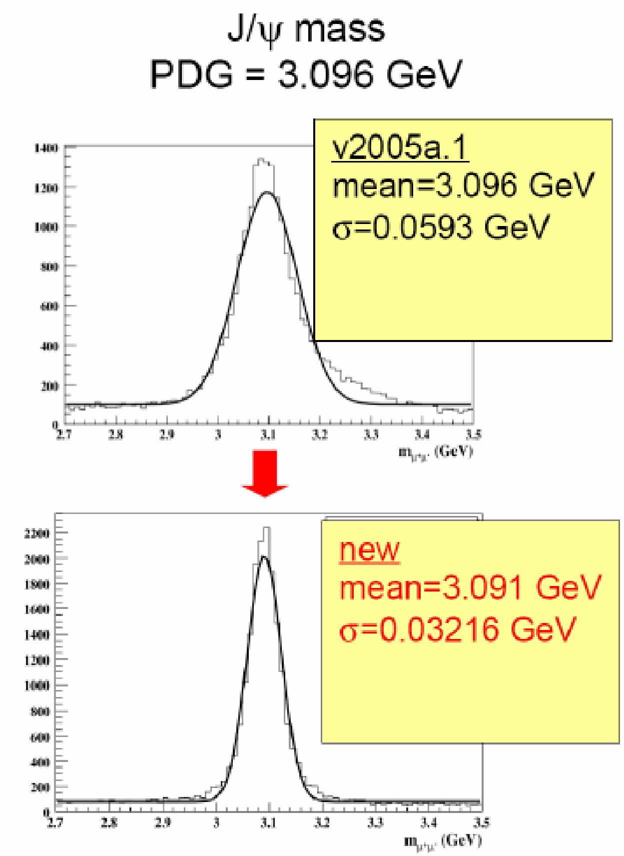


Track fit influences the quality of the our analysis.

improves mass resolution of

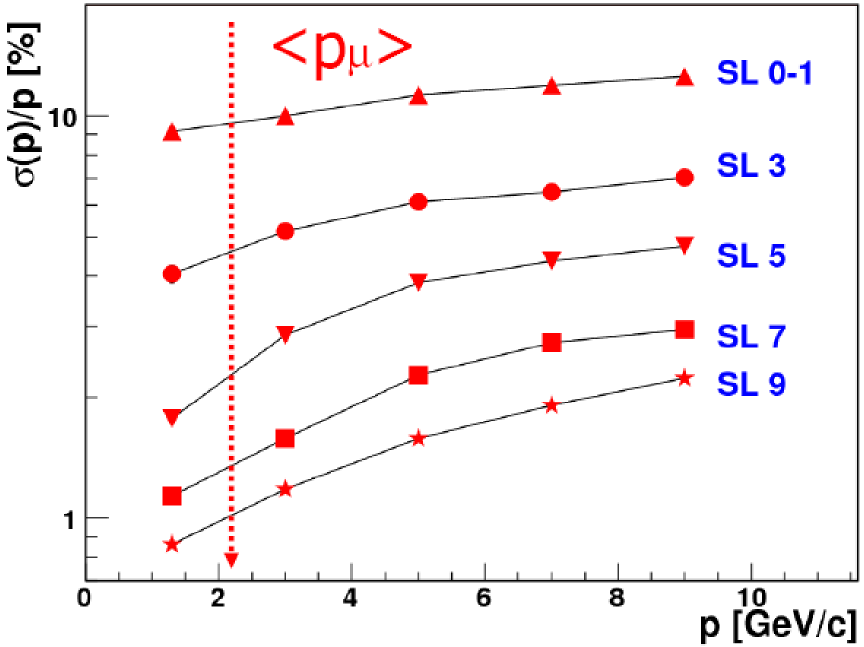
- K^0_S: by factor of 1.3
- J/ψ: by factor of 1.8

Huge gain on $S/\sqrt{B}$



Momentum Resolution

- Better for large SL due to bigger field integral
- J/ψ muon: $<p>=2.1$ GeV/c $\sigma(p)/p=1\%$ for SL=9
- Mass resolution 22 MeV for J/ψ if SL=9 for muons



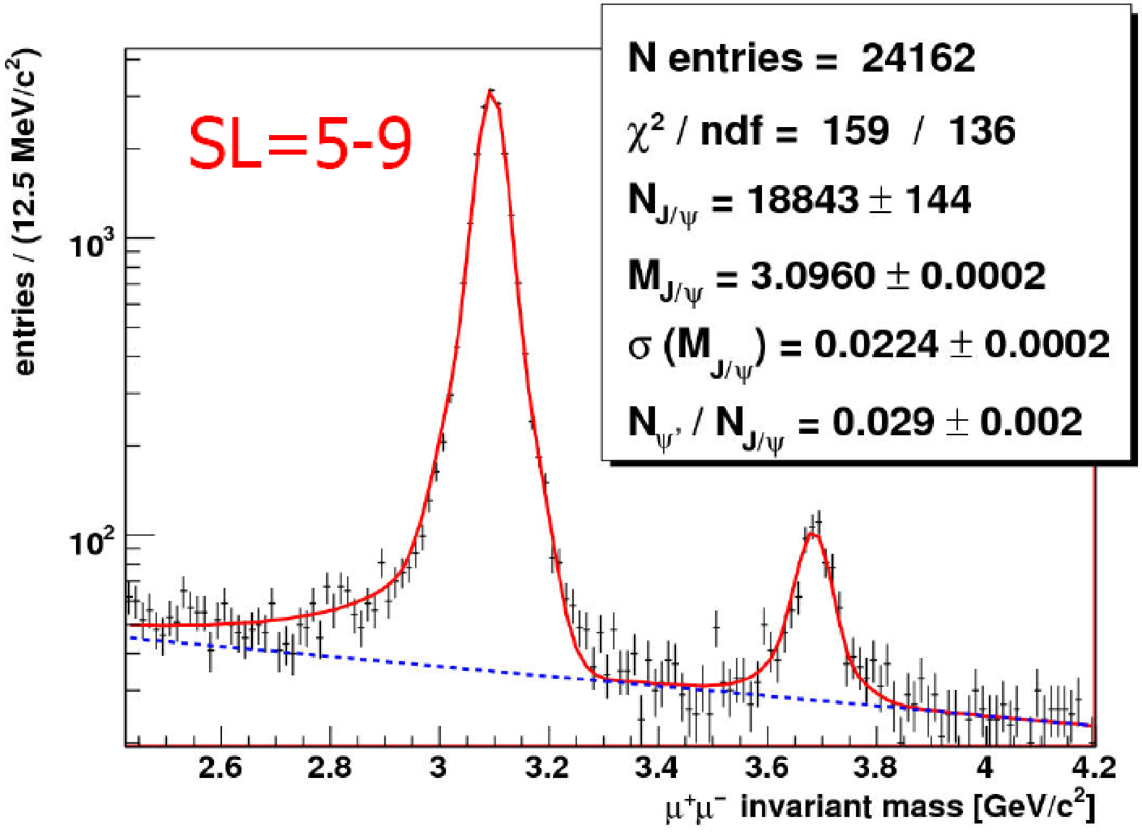
Mass resolution for different CTD SL

- Select smallest outer Super Layer for two tracks
- J/ψ and ψ' signals fitted by Gaussian + rad. tail

SL	$N(J/\psi)$	$\sigma(M)$ [MeV]
9	8231+/-93	22.3+/-0.2
7	4384+/-68	27.8+/-0.4
5	5964+/-81	47.3+/-0.6
3	7704+/-109	122.4+/-1.8

Selection with SL 5-9

- Functions for J/ψ, ψ′ : 2 Gaussians + radiative tail
- Δ(M)/M =(-0.03+/-0.01) %



The Micro-Vertex Detector (MVD)

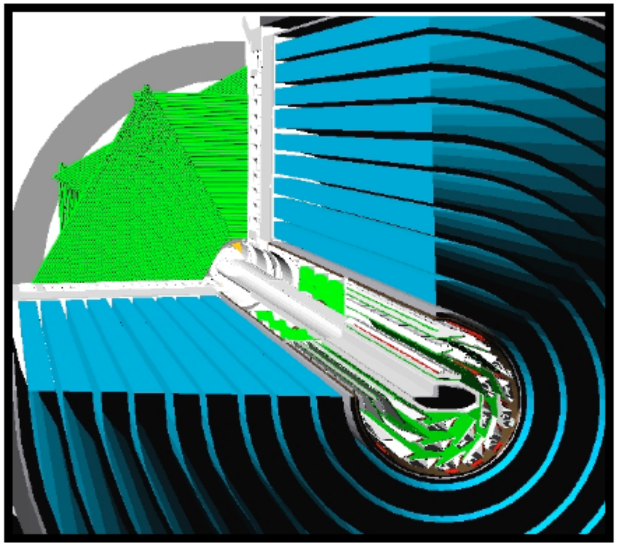
The forward section:
- 4 wheels
- each composed of 2 layers of 14 Si detectors
- in total 112 hybrids, 50k channels

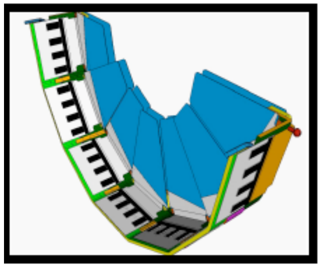
The barrel section:
- 30 ladders
- each composed of 5 modules of 4 Si detectors
- in total 300 hybrids, >150k channels

The rear section:
- Cooling pipes and manifolds
- Distribution of FE, slow control and alignment cables

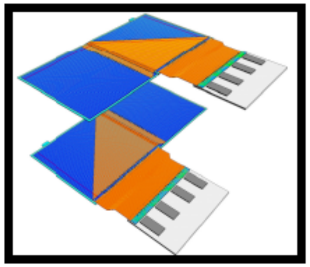
The ZEUS Micro Vertex Detector

ZEUS tracking





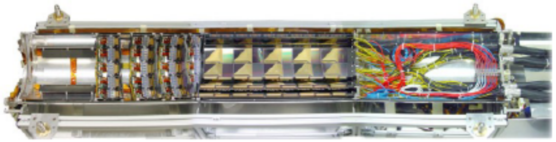
Half Wheel



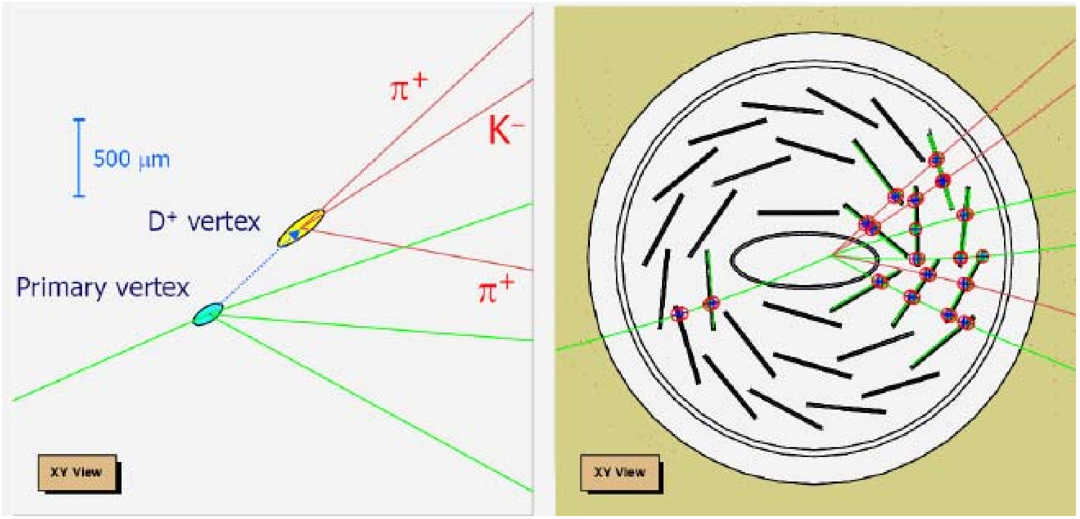
Barrel module

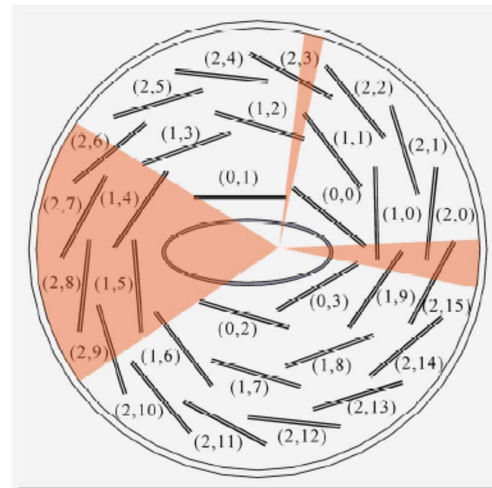
- For HERA II ZEUS was fitted with a silicon micro vertex detector (MVD).
- The MVD consists of forward and barrel regions.
- Barrel:
  - 30 ladders
  - 600 single sided silicon strip sensors
- Forward Wheels:
  - 4 wheels
  - 112 trapezoidal single sided silicon strip sensors
- Back to back sensors give information in (z, rϕ) for barrel tracks and (w, u) for forward tracks.

- Since HERA II both experiments equiped with Silicon Vertex Detectors
- Important for heavy flavour measurements



The Layout of the MVD Barrel



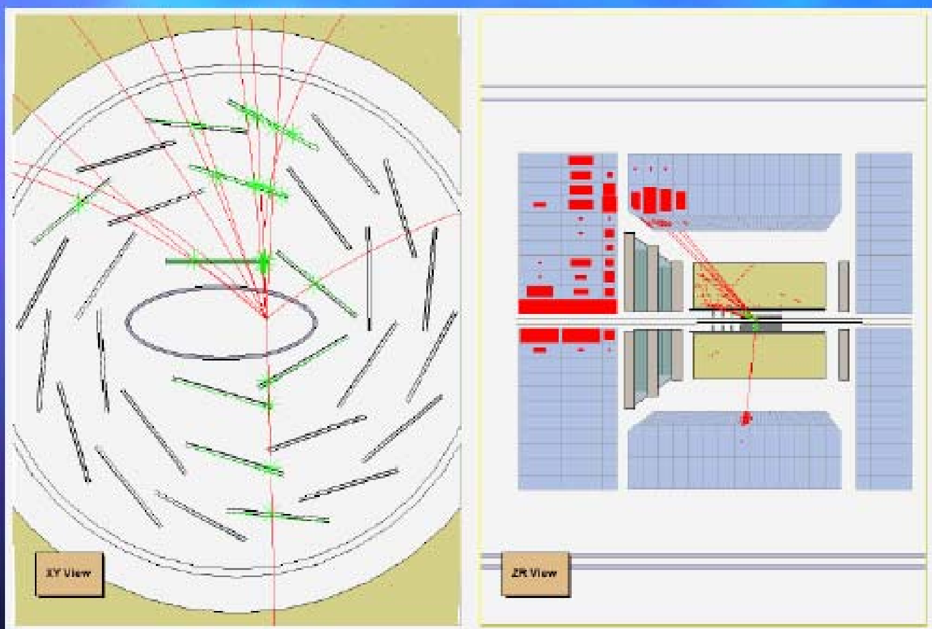


- Major part of azimuthal acceptance covered by three cylinders of ladders (→ six measurements per track)
- Optimal use of available space between beam pipe & CTD

Fig. 1: Layout of the MVD barrel. The orientation is such that the X axis points to the right and the Y axis points upwards. The logical numbering scheme according to cylinder and ladder number is also displayed. The shaded wedges indicate azimuthal regions that are not covered by the inner cylinder.

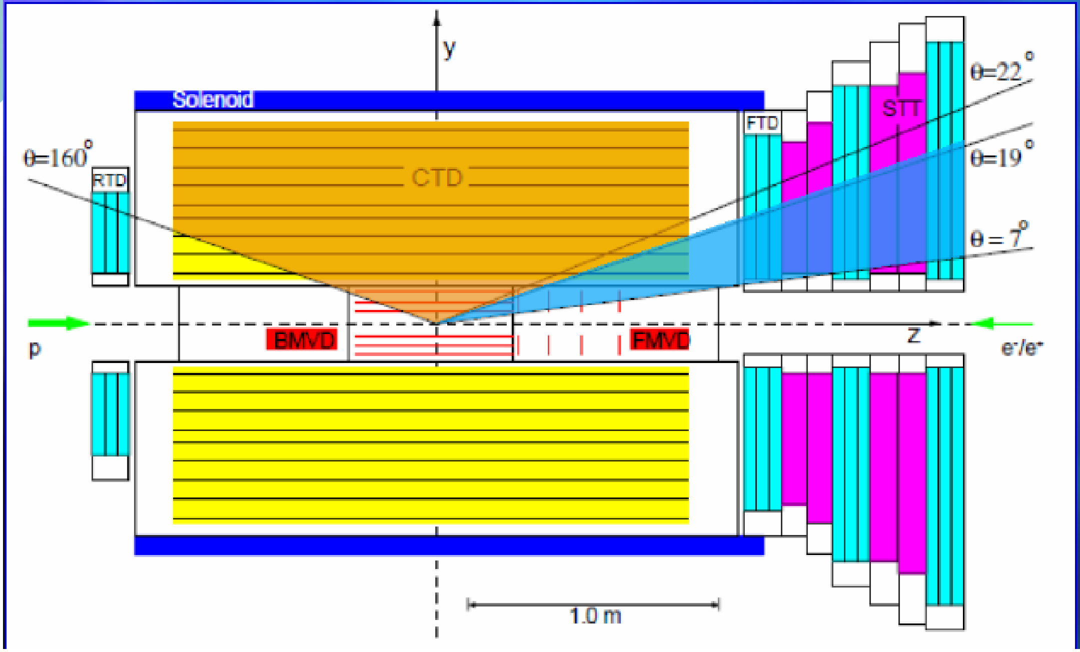
Micro Vertex Detector (MVD) allows detecting heavy flavor signatures!

The Track Reconstruction Chain



- Coordinate reconstruction
- Track pattern recognition
- Track fitting
- Vertex finding
- Vertex fitting
- Higher level analysis

- Traditionally, tracks are classified according to their outermost CTD superlayer (SL1...SL9)



- The typical analysis discards tracks below CTD SL3
- In future, the combined forward tracking (CTD+BMVD+FMVD+STT) will open up the range below θ~20°

→ Considerable increase

- We have plenty of new data, and a new level of precision & scope in tracking

↓

D-meson study

D+ production

$$D^{\pm} \rightarrow K^{\mp} + \pi^{\pm} + \pi^{\pm}$$

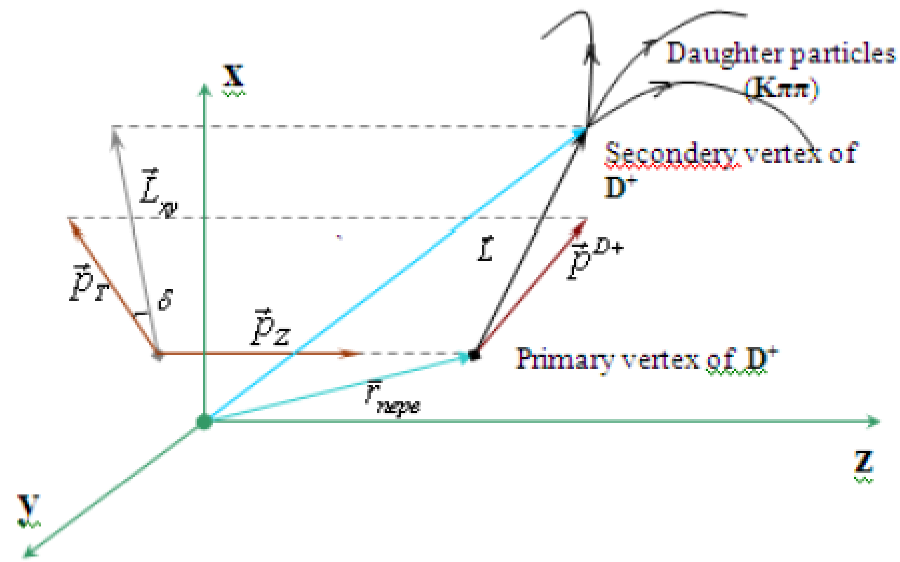
Pt(D+)>3GeV

|η(D+)|<1.6

$5Gev^2<Q^2<1000GeV^2$

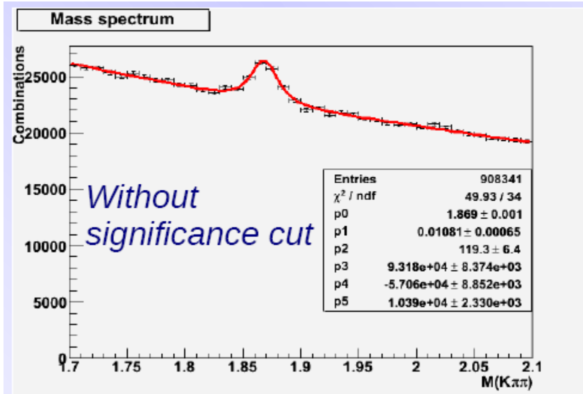
0.02<y<0.7

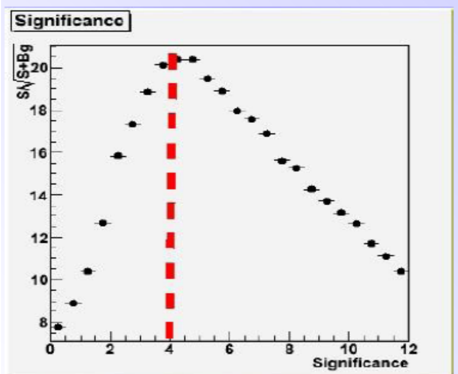
- Pt(K)>0.5
- Pt(π1,π2)>0.35
- |η(K,π1,π2)|<1.7
- $CTD_{OL}-CTD_{IL}$(K,π1,π2)>2
- nbr,nbz(K,π1,π2)>1
- χ2(sec.vtx.)/n.d.f.<10
- significance(2D, proj.)>4

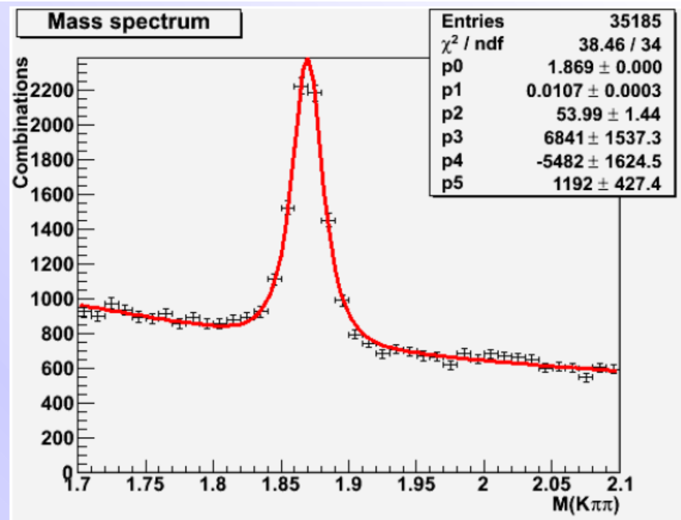


$$Significance\_2D = \frac{L_{XY\_Decay}}{\sigma_{XY\_Decaylenght}}$$

D+ with and without significance cut







- N(D+)=5340∓144
- Mass=1869.5∓0.3
- Width=10.7∓0.3
- S/Sqrt(S+Bg)=47

Optimal cut value:
Significance > 4

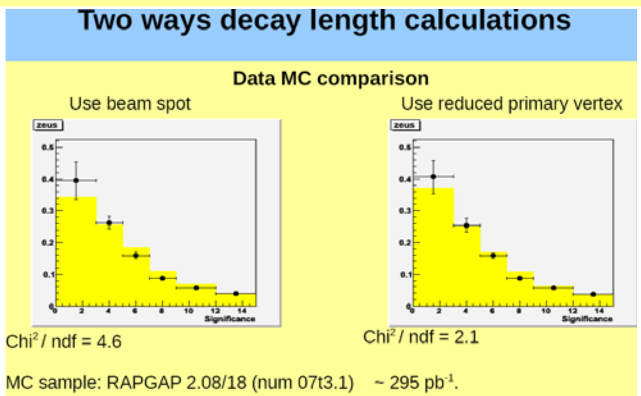
5

$$Sl(2\mathrm{D}, proj.) = \frac{l}{\sigma_l} \qquad l = \frac{\vec{r}\cdot\vec{p}}{|\vec{p}|} \qquad \vec{r} = \vec{r}^{\,sec.vtx.} - \vec{r}^{\,prim.vtx.}$$

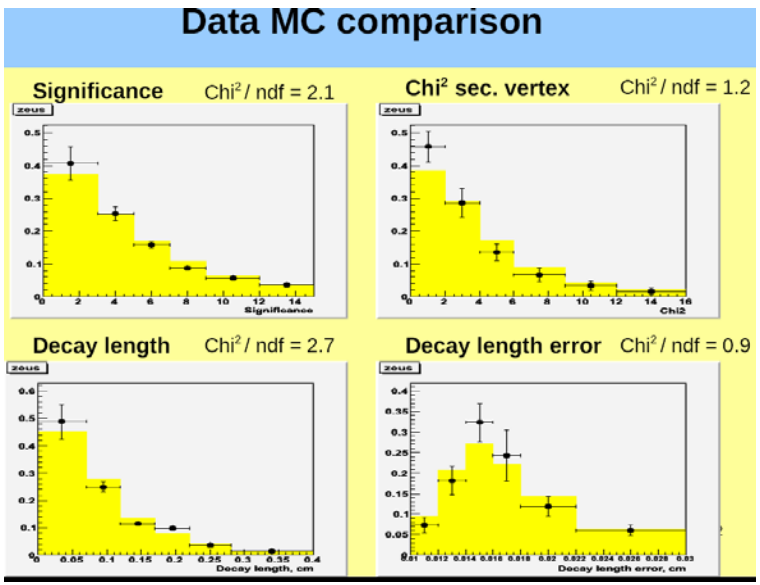
$$\sigma_l = \sqrt{(\sigma^{prim.vtx.}_{proj.})^2 + (\sigma^{sec.vtx.}_{proj.})^2}$$

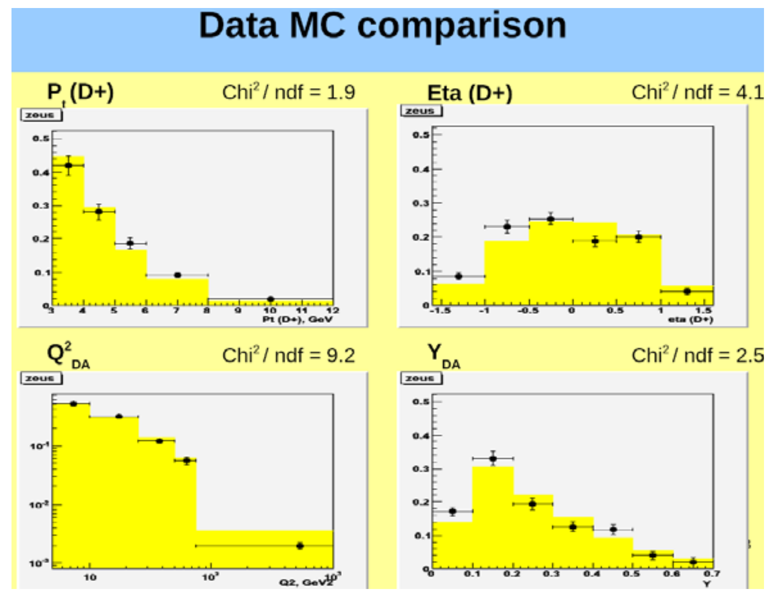
D+ life time measurements.

Period	Mass	Peak width	Peak sum	S/bg	Ctau
03p-04p	1868.8	10.8	844	0.36	318.3 +- 31.6
05e	1868.6	10.2	2853	0.41	315.8 +- 21.2
06e	1868.4	10.3	1402	0.41	296.8 +- 20.4
06p-07p	1869.8	11.2	3268	0.39	314.1 +- 13.9
all periods	**1869.0**	**10.6**	**8219**	**0.39**	**314.1 +- 11.8**



PDG 311.8 μm

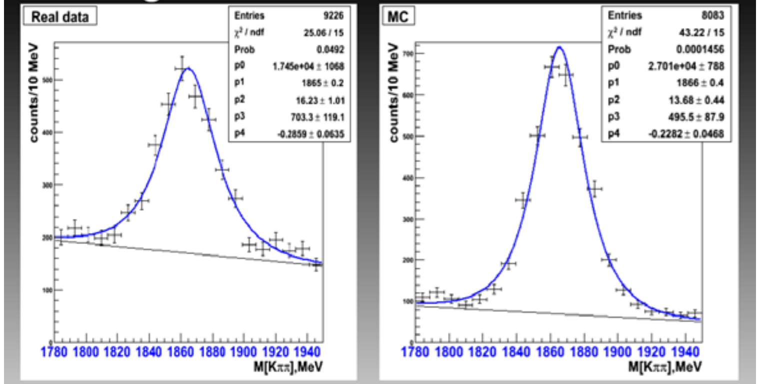

Data MC comparison
Significance
Chi²/ ndf = 2.1
Chi² sec. vertex
Chi²/ ndf = 1.2
Decay length
Chi²/ ndf = 2.7
Decay length error
Chi²/ ndf = 0.9
Decay length, cm
Decay length error, cm


Data MC comparison
P_t (D+)
Chi²/ ndf = 1.9
Eta (D+)
Chi²/ ndf = 4.1
Q²_DA
Chi²/ ndf = 9.2
Y_DA
Chi²/ ndf = 2.5

D0

$D0 \to K^- \pi^+$

Signal in Data and Monte Carlo



$$D^0\ mass = 1864.8 \pm 0.17\ MeV\ (PDG)$$

$$D^0\ mass = 1865.0 \pm 0.2\ MeV \qquad D^0\ mass = 1865.5 \pm 0.4\ MeV$$

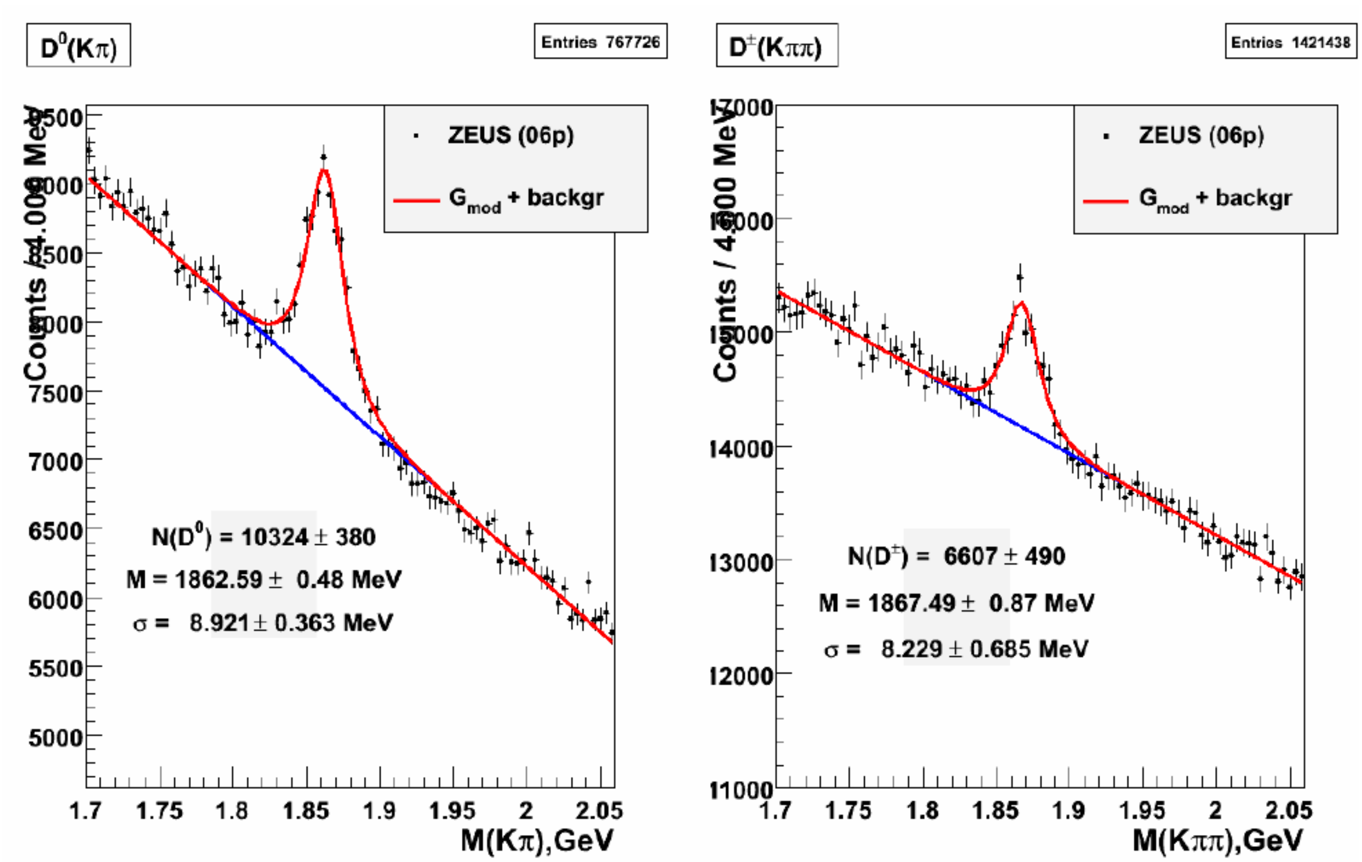
$$N(D^0) = 2053 \pm 126 \qquad N(D^0) = 3177 \pm 93$$

Data sample and cuts

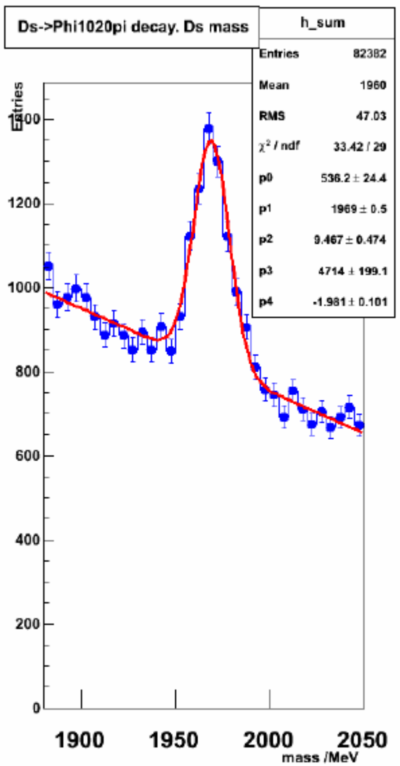
06/07p GR. Nevents ~ 93 millions
06/07p D mes. MC (v02e) Nevents ~ 7 millions

- $|P_t(D^0)|>3.6$
- $|P_t(D^*)|>1.8$
- $|Z_{vtx}|<50.0$ cm
- $|P_t(K,\pi)|>0.7$
- $|\eta(D^0,K,\pi)|<2.0$
- 130<W<280(ZUFOS)
- layouter(K) in CTD>3
- Significance2D>1
- $c\tau(D^0)>50$ μkm
- Trigger selection:
  - HFL01
  - HFM01,HFM04

$D^0 \to K_s^0\pi\pi$ decay channel



D± → Φπ±



- Mass **1969.1** ± 0.5

(PDG 1968.5 ± 0.34)

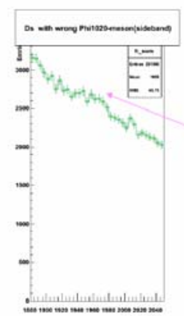
Width **9.5** ±0.5

- peak sum= **2455**
- sign/bg = 0.38

Cuts:

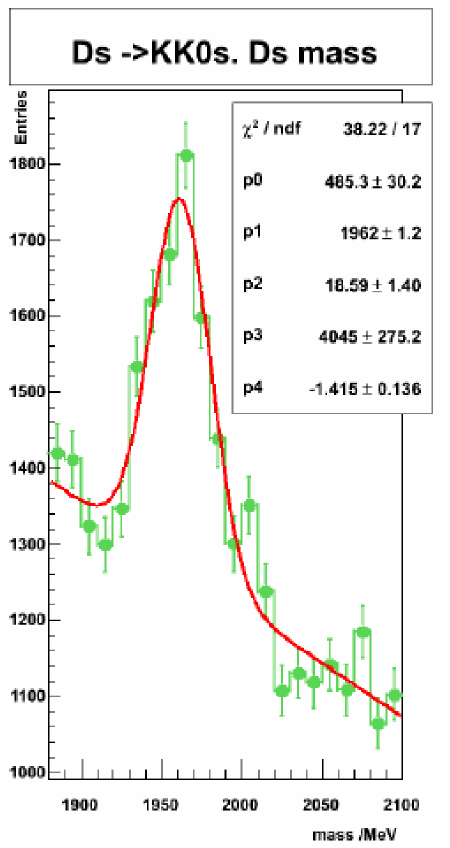
- Pt(Ds)>2.5;
- dl3_projection>80 micron;
- dl2>70 micron;
- 1017<mass(Φ)<1024;
- dl3>170 micron;
- P(π)>0.7;

Ds± mass spectrum with wrong Φ(1020)
(sideband around Φ-peak)



- 1.03 GeV< mass(Φ) or mass(Φ) < 1.01 GeV
- No peak!

$Ds\pm \rightarrow K\pm K0s$

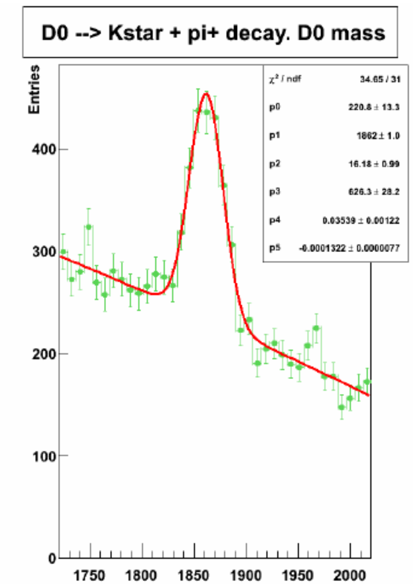


- Mass =**1961.8** ±1.2 MeV
- Width = **18.6** ±1.4 MeV
- peak sum= **2080** +-45

Cuts:

- 504 > K0s_mass > 487 MeV;
- Ds_theta > 0.9;
- Ds_Pt > 2.8;
- K0s_collin < 0.8° ;
- Kaon_layout > 5
- dE/dx>70;

D0 decay mode with K*(892)±

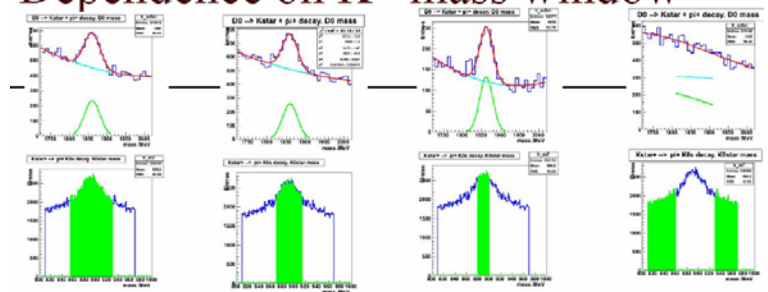


- D0 SUM = 1030;
- S/Bg = 0.6
- D0 mass = 1861.7 ;
- mass shift = -3.1;
- peak width= 16.2 +/-1.0

Cuts:

- Pt(D0)>3.0;
- Pt(pion2)>0.5;
- K0_collin2<2.5°;

Dependence on K* mass window



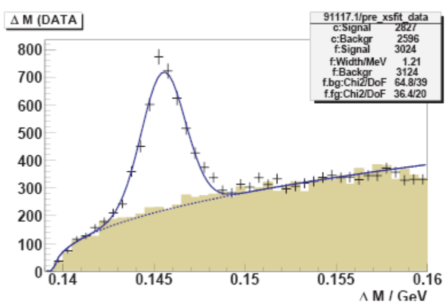
$$D^{*+} \to \pi_s^+ D^0 \to \pi_s^+ \pi^+ K^- \text{ and c.c.}$$

D^* Photoproduction

Reconstruction of D^* decays

- $3\,\text{GeV} < p_t^{D^*} < 15\,\text{GeV}$, $-1.5 < \eta^{D^*} < 1.5$
  - $p_t^K, p_t^\pi > 0.5\,\text{GeV}$, $p_t^{\pi_s} > 0.16\,\text{GeV}$, $SL > 3$
  - $m^{D^0} \approx 1.87\,\text{GeV}$

- Extract number of D* from background subtraction or fitting



$$
\begin{aligned}
f_b(\Delta M) &= B\sqrt{\Delta M - m^\pi} \\
f_s(\Delta M) &= \frac{A}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\xi^2\right] \\
\xi &\equiv \left(\Delta M - m^{\text{peak}}\right)/\sigma
\end{aligned}
$$

Motivation *for study excited charm and charm strange production*

Heavy-quark spectroscopy has recently undergone a renaissance with the discovery of several new states:

- Non-strange excited charm mesons $D_1(2420)^{0,\pm}$ and $D_2^*(2460)^{0,\pm}$
- Charm-strange excited mesons $D_{s1}(2536)^{\pm}$ and $D_{s2}(2573)^{\pm}$
- Recently, Supported Heavy Quark Effective Theory (HQET) predictions $D^{0*}(2400)^{0,\pm}$ and $D1(2430)^{0}$
- Recent discovery charm-strange $D_{s0}^*(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$
- *Predicted: broad non-strange charged excited charm meson with JP=1+ has not yet been observed.*
- *Predicted: radially excited charm $D' \to D\pi\pi$ and $D^{*\prime} \to D^*\pi\pi$, ~2.6 GeV. Narrow resonance at 2637 MeV with $D^{*\pm}\pi^+\pi^-$ reported by DELPHI, however OPAL – no evidence.*

The properties of these states challenge the theoretical description of heavy-quark resonances. Further measurement of excited charm and charm-strange mesons are important!

Excited charm and charm-strange mesons

- Large charm production cross sections at HERA allow to search for excited charm states

Look for orbitally excited states:

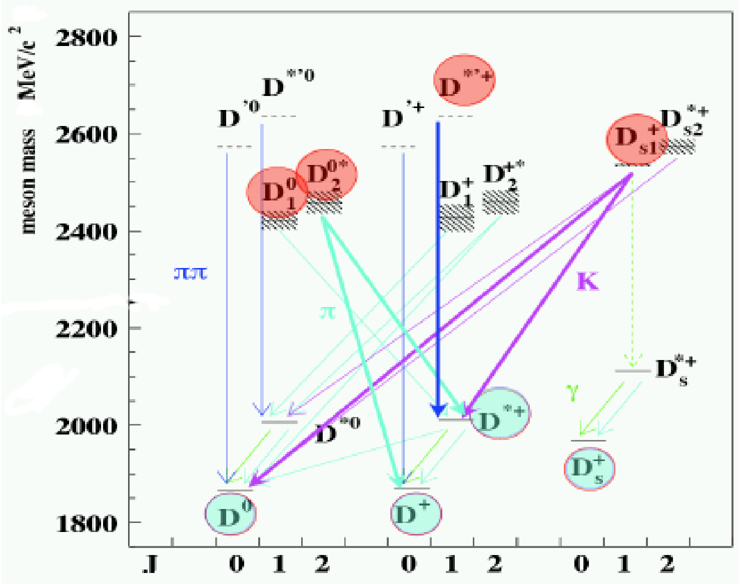
$D_1(2420)^0 \rightarrow D^{*\pm}\pi^{\mp}$ $\quad J^P = 1^+$

$D_2^*(2460)^0 \rightarrow D^{*\pm}\pi^{\mp}$ $\quad J^P = 2^{++}$

$D_2^*(2460)^0 \rightarrow D^{\pm}\pi^{\mp}$

$J^P = 1^+$ state cannot decay to $D\pi$

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



Search for radially excited states:

$D^{*\prime}(2640)^{\pm} \rightarrow D^{*\pm}\pi^+\pi^-$ (DELPHI) $\quad J^P = 1^-$?

ZEUS HERA I 1995 - 2000 (126 pb^{-1}) DIS + PHP

Eur.Phys.J C60,25(2009)

Study of the excited charm mesons

$D_1(2420)^o$, $D_2{}^*(2460)^o$

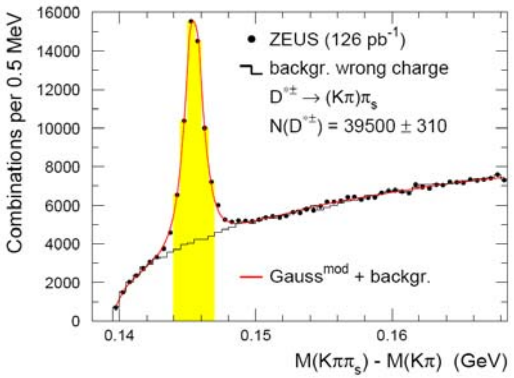
$$D_1(2420)^o \rightarrow D^{*+}\,\pi^-$$

$$D_2{}^*(2460)^o \rightarrow D^{*+}\,\pi^- \;,\; D^+\,\pi^-$$

combining each selected D^{*+} (or D^+) candidate with an additional track, assumed to be a pion, with a charge opposite to that of the D^{*+} (or D^+) candidate.

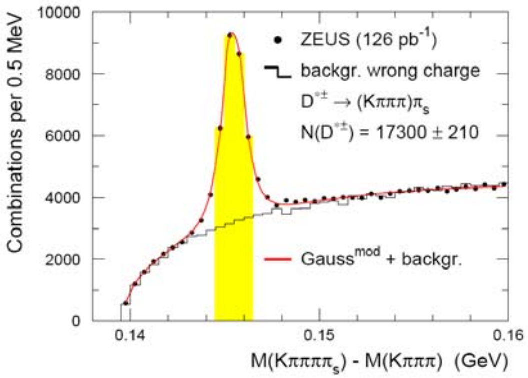
Reconstruction of lowest-mass charm mesons: *D*+*

D+* mesons were identified using the two decay channels:



$D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+)\pi_s^+$

$\Delta M = M(K\pi\pi) - M(K\pi)$, **Signal: 39500**



$D^{*+} \to D^0\pi_s^+ \to (K^-\pi^+\pi^+\pi^-)\pi_s^+$

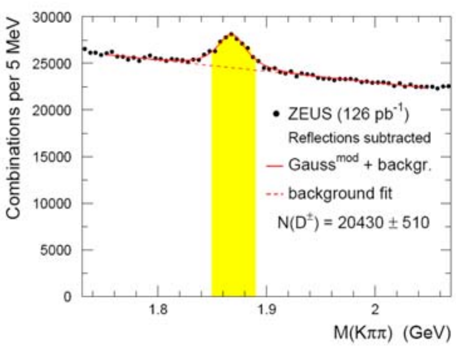
$\Delta M = M(K\pi\pi\pi\pi s) - M(K\pi\pi\pi)$, **Signal: 17300**

Background-wrong charge combination.

Yellow band - ranges used for excited charm mesons

Reconstruction of lowest-mass charm mesons: ***D+ and D0***

$$D^+ \to K^- \pi^+ \pi^+.$$



Width (D+)=12.9 MeV;

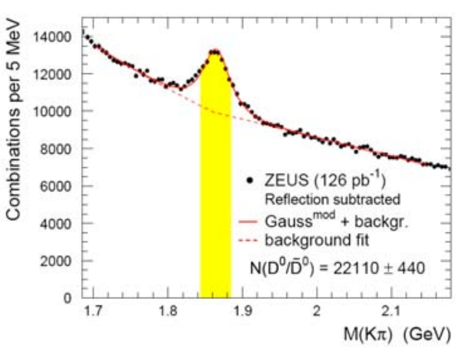
(detector resolution)

Guts:

p_T (D)>2.8 GeV

|η(D)|<1.6

Yellow band corresponds to ranges used for excited charm mesons



$$D^0 \to K^- \pi^+$$

Width (D0)=17.4 MeV;

Excited charm mesons: $D_1(2420)^o$ and $D_2{*}(2460)^o$

- *Decay channel* $\rightarrow D{*}{+}\ \pi{-}$

  A clear enhancement in the range where contributions from $D_1(2420)^o$ and $D_2{*}(2460)^o$ mesons are expected.

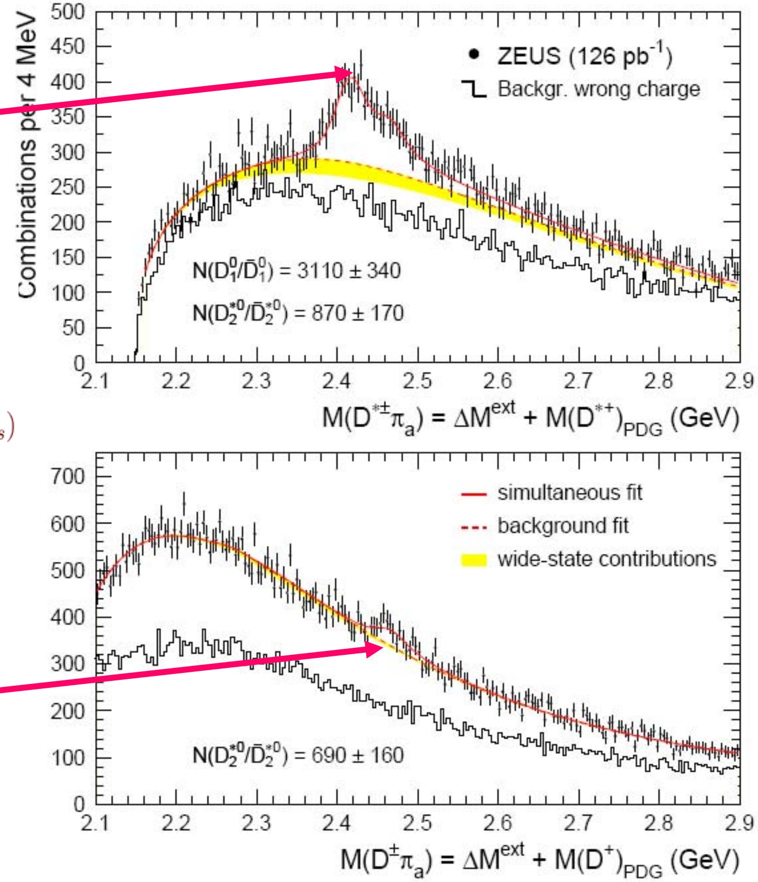
$\Delta M^{ext} + M(D^{*\pm})_{PDG}$ **(dots)**

$\Delta M^{ext} = M(K\pi\pi_s\pi_e) - M(K\pi\pi_s)$

$p_T(D^{*\pm}) > 1.35\ GeV,\ |\eta(D^{*\pm})| < 1.6$

$\Delta M^{ext} = M(K\pi\pi\pi\pi_s\pi_e) - M(K\pi\pi\pi\pi_s)$

$p_T(D^{*\pm}) > 2.80\ GeV,\ |\eta(D^{*\pm})| < 1.6$



- *Decay channel* $\rightarrow D{+}\ \pi{-}$

  A small excess around the nominal mass of the $D_2{*}^o$ meson.

D_1^o and $D_2{*}^o$ in four helicity bins

Used helicity angular distribution to extract
$D_1(2420)^o$ and $D_2{*}(2460)^o$ yields and properties

h -helicity parameter (h=3 for pure D-wave)

$$dN/d\cos\alpha \approx 1 + h\cos^2\alpha$$

Simultaneous fit including all contributions

final state	$D^{*+}\pi_a$	$D^{+}\pi_a$
Signal yields		
$N(D_1^0)$	3110 ± 340	
$N(D_2^{*0})$	870 ± 170	690 ± 160

$$M(D_1^0) = 2420.5 \pm 2.1(\mathrm{stat.}) \pm 0.9(\mathrm{syst.}) \pm 0.2(\mathrm{PDG})\ \mathrm{MeV},$$

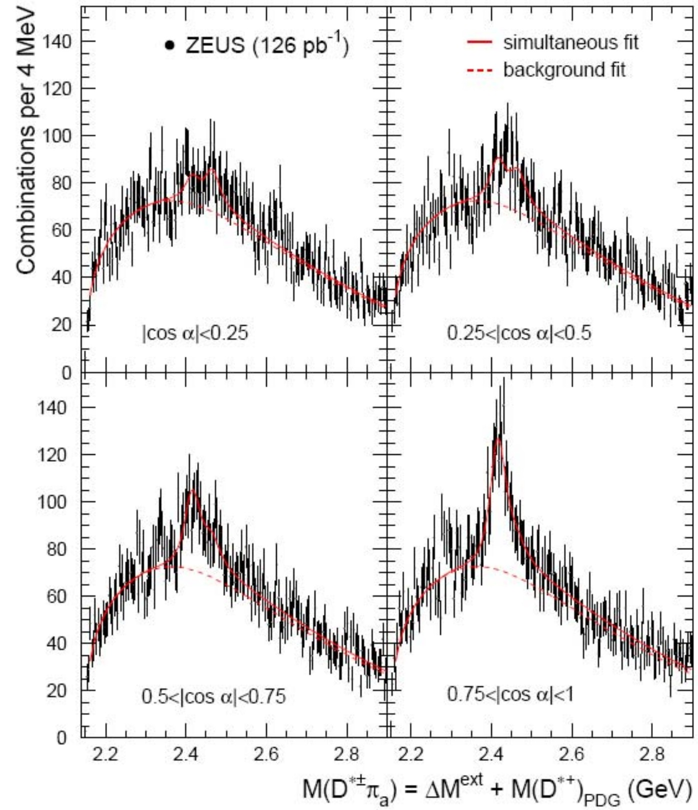
$$M(D_2^{*0}) = 2469.1 \pm 3.7(\mathrm{stat.})^{+1.2}_{-1.3}(\mathrm{syst.}) \pm 0.2(\mathrm{PDG})\ \mathrm{MeV}.$$

Fitted masses agree with PDG

$$\Gamma(D_1^0) = 53.2 \pm 7.2^{+3.3}_{-4.9}\, MeV\,(PDG : 20.4 \pm 1.7\, MeV)$$

$$h(D_1^0) = 5.9^{+3.0}_{-1.7}(stat.)^{+2.4}_{-1.0}(syst.) \quad (\textbf{CLEO:}\ 2.74^{+1.40}_{-0.93})$$

Roughly consistent with pure D-wave (h=3)

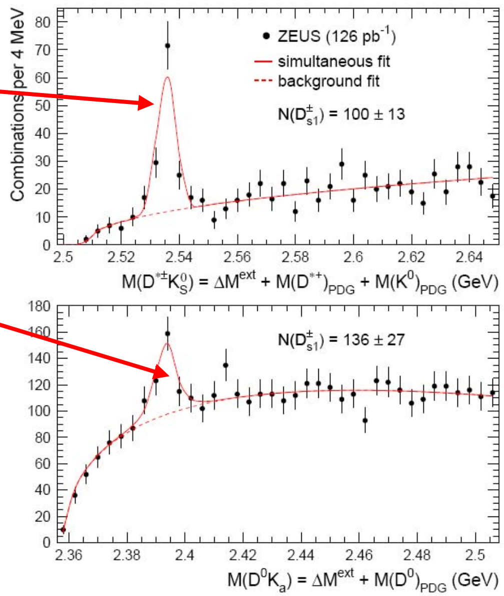


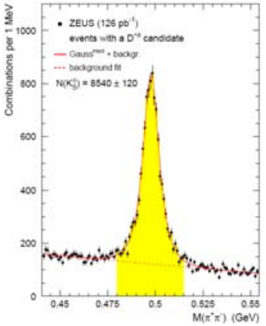
Excited charm mesons: *Ds1+*

- ***Ds1+*** –> ***D*+***(*both decay channels*) with ***K°s*** –> π+ π-
- ***Ds1+*** –> (***D*°*** with ***K±***)
- To extract ***Ds1+*** yields and properties: fit using simultaneously values of M(*D*° K±*) and M(*D*+ K°s*) in four helicity intervals
- *Clear Ds1(2536)+ signals! Measured Ds1+ mass in good agreement with the world average value!*

$$M(D_{s1}^{+}) = 2535.57^{+0.44}_{-0.41}(\text{stat.}) \pm 0.10(\text{syst.}) \pm 0.17(\text{PDG})\ \text{MeV}$$

final state	$D^{*+}K_S^0$	$D^0 K_a$
Signal yields		
$N(D_{s1}^{+})$	100 ± 13	136 ± 27





Fitted D_{s1} helicity parameter: $h(D_{s1}) = -0.74^{+0.23}_{-0.17}(stat.)^{+0.06}_{-0.05}(syst.)$

Inconsistent with pure 1^+ D-wave (h=3)

Barely consistent with pure 1^+ S-wave (h=0) → Significant S-D mixing

Branching ratios and fragmentation fractions

$$\frac{B_{D_2^{*0}\to D^+\pi^-}}{B_{D_2^{*0}\to D^{*+}\pi^-}} = 2.8 \pm 0.8(\mathrm{stat.})^{+0.5}_{-0.6}(\mathrm{syst.}) \qquad 2.3 \pm 0.6\ \mathbf{(PDG)}$$

$$\frac{B_{D_{s1}^+\to D^{*0}K^+}}{B_{D_{s1}^+\to D^{*+}K^0}} = 2.3 \pm 0.6(\mathrm{stat.}) \pm 0.3(\mathrm{syst.}) \qquad 1.27 \pm 0.21\ \mathbf{(PDG)}$$

Assuming I-spin conservation for D_1^0, D_2^{*0} and $B_{D_{s1}^+\to D^{*+}K^0} + B_{D_{s1}^+\to D^{*0}K^+} = 1$ yields

fragmentation functions and strangeness suppression of excited D mesons

$$f(c\to D_{s1}^+)/f(c\to D_1^0) = 0.31 \pm 0.06^{+0.05}_{-0.04}$$

	$f(c\to D_1^0)[\%]$	$f(c\to D_2^{*0})[\%]$	$f(c\to D_{s1}^+)[\%]$
ZEUS	$3.5 \pm 0.4^{+0.4}_{-0.6}$	$3.8 \pm 0.7^{+0.5}_{-0.6}$	$1.11 \pm 0.16^{+0.08}_{-0.10}$
OPAL	2.1 ± 0.8	5.2 ± 2.6	$1.6 \pm 0.4 \pm 0.3$
ALEPH			$0.94 \pm 0.22 \pm 0.07$

$\Rightarrow$ **Frag. fractions for excited D mesons in ep and e^+e^- consistent**

Search for radially excited charm meson $D^{*\prime}(2640)^{\pm}$

$$D^{*\prime +} \rightarrow D^{*+}\ \pi^+\ \pi^-$$

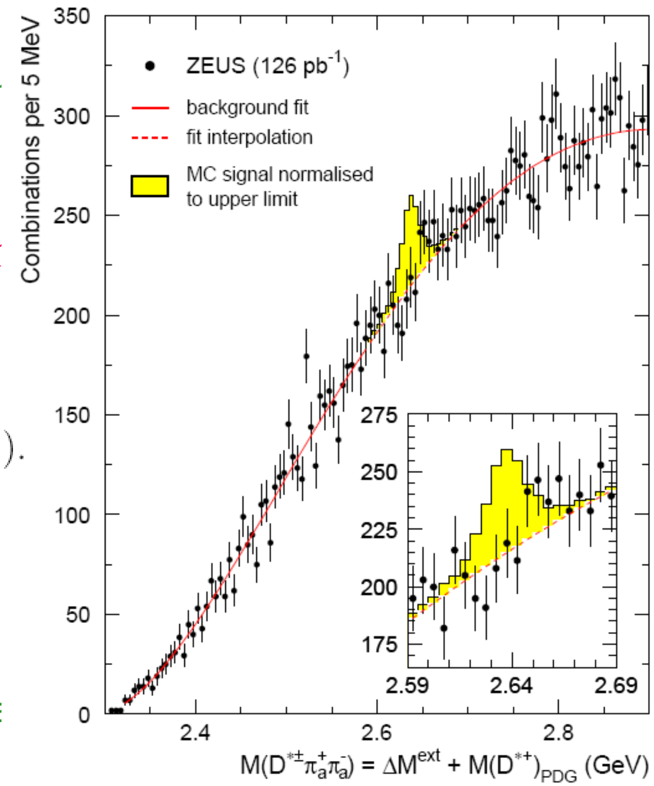
- combining each selected D^{*+} candida with two additional tracks with opposite charges.
- No radially excited $D^{*\prime}(2640)^{\pm}$ charn meson observed.

Upper limit:

$$f(c \rightarrow D^{*\prime +}) \cdot \mathcal{B}_{D^{*\prime +} \rightarrow D^{*+}\pi^+\pi^-} < 0.4\% \quad (95\% \ \text{C.L.}).$$

OPAL result: < 0.9%

$D^{*\prime}\pm$ signal window - theoretical predictions
solid curve - fit background ,
shaded histogram - Monte Carlo $D^{*\prime}\pm$ signa normalised to upper limit on top of the fit.



Summary

- Sizeable production of the charm, excited charm and charm-strange mesons was observed in *ep* interactions.
- Measured masses of the D_1^o, D_2^{*o} and D_{s1+} in reasonable agreement with the world average values. D_1^o width 53.2 MeV above PDG 20.4 MeV
- measured D_1^o helicity parameter h=5.9 consistent with prediction for pure *D*-wave.
- D_{s1+} helicity parameter $h = -0.74$, inconsistent with prediction for a pure *D*- or S- waves. Suggests significant contributions of both waves.
- Ratios of dominant branching fractions are in agreement with the world average values.
- Fraction of c quarks hadronising into D_1^o, D_2^{*o} or D_{s1+} are consistent with obtained in e+e-, agreement with charm fragmentation universality;
- No radially excited $D^{*\prime}(2640)^{\pm}$ meson was observed.