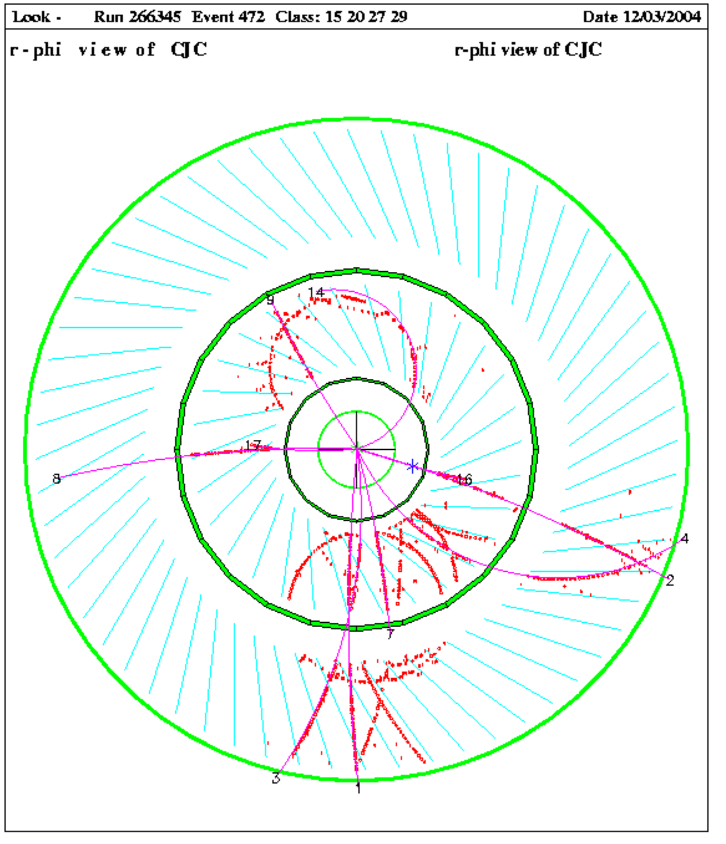
Evidence for a Narrow Exotic Anti-Charmed Baryon State

- Introduction.
- Identifying D and D^* mesons in H1.
- dE/dx measurements and proton identification.
- Studies of the D^*p mass spectrum.
- Summary



- H1 Collaboration, hep-ex/0403017, accepted by Physics Letters **B**.

Dedicated to our friend and colleague, Ralf Gerhards.

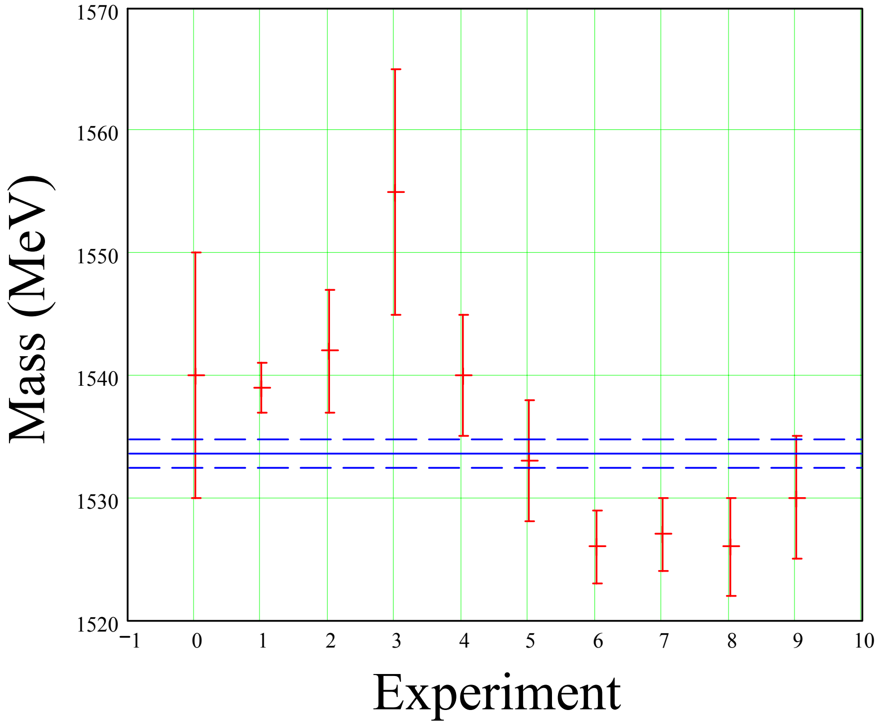
The strange pentaquark

- Experimental observations:

No.	Experiment	Channel	Mass (MeV)
0	LEPS	K^+n	1540 ± 10
1	DIANA	K^0p	1539 ± 2
2	CLAS	K^+n	1542 ± 5
3	CLAS	K^+n	1555 ± 10
4	SAPHIR	K^+n	1540 ± 5
5	ITEP	K^0p	1533 ± 5
6	HERMES	K^0p	1526 ± 3
7	ZEUS	K^0p	1527 ± 2
8	SVD	K^0p	1526 ± 4
9	COSY-TOF	K^0p	1530 ± 5

- Minimal quark content $uudd\bar{s}$

- Mass of Θ_s:



- Mean mass 1534 ± 1 MeV.
- Narrow resonance.

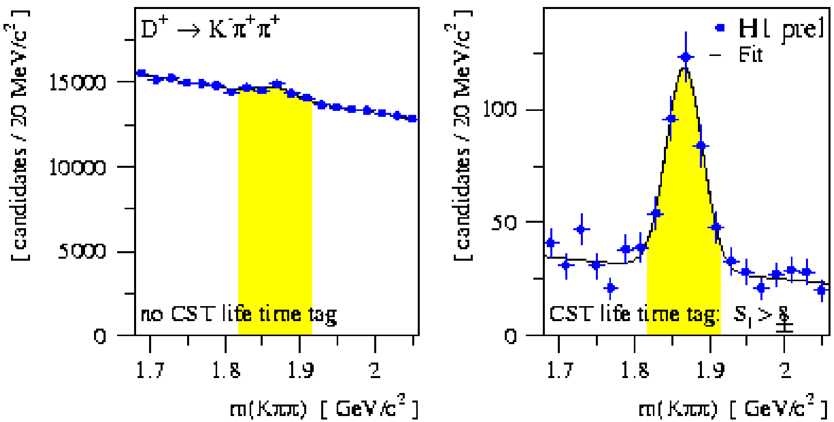
Is there a charmed pentaquark?

- A few predictions:
  - $m(\Theta_c^0) = 2710$ MeV (Jaffe, Wilczek, hep-ph/0307341).
  - $m(\Theta_c^0) = 2704$ MeV (Wu, Ma hep-ph/0402244).
- Such a Θ_c^0 would be too light to decay to D mesons, but could decay weakly to $\Theta_s^+\pi^-$.
  - $m(\Theta_c^0) = 2985 \pm 50$ MeV, $\Gamma(\Theta_c^0) = 21$MeV, Karliner, Lipkin (hep-ph/0307343).
  - $m(\Theta_c^0) = 2938...2997$ MeV, (Cheung, hep-ph/0308176).
- Such a Θ_c^0 could decay to D^-p.
- If $m(\Theta_c^0) > m(D^*)+m(p) = 2948$ MeV, Θ_c^0 can decay to D^*p.
- This decay mode can be dominant, (Karliner, Lipkin, hep-ph/0401072).

Experimental Considerations

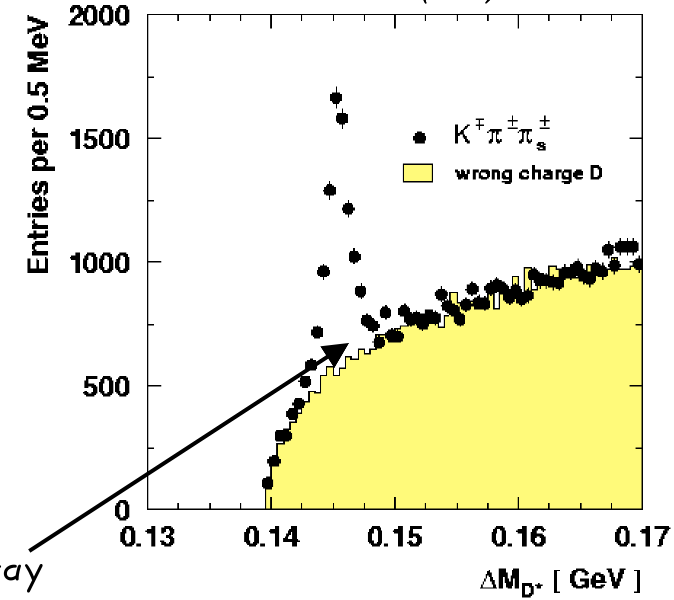
D^+ pseudoscalar meson

without *with lifetime tag*



D^* vector meson

$D^* \rightarrow D^0\pi \rightarrow (K\pi)\,\pi$



D^+: *huge background or low yield*

D^* *profits from small Q-value in* D^* *decay*

Mass difference technique $\Delta M(D^{*\pm}) = m(K^{\mp}\pi^{\pm}\pi) - m(K^{\mp}\pi^{\pm})$

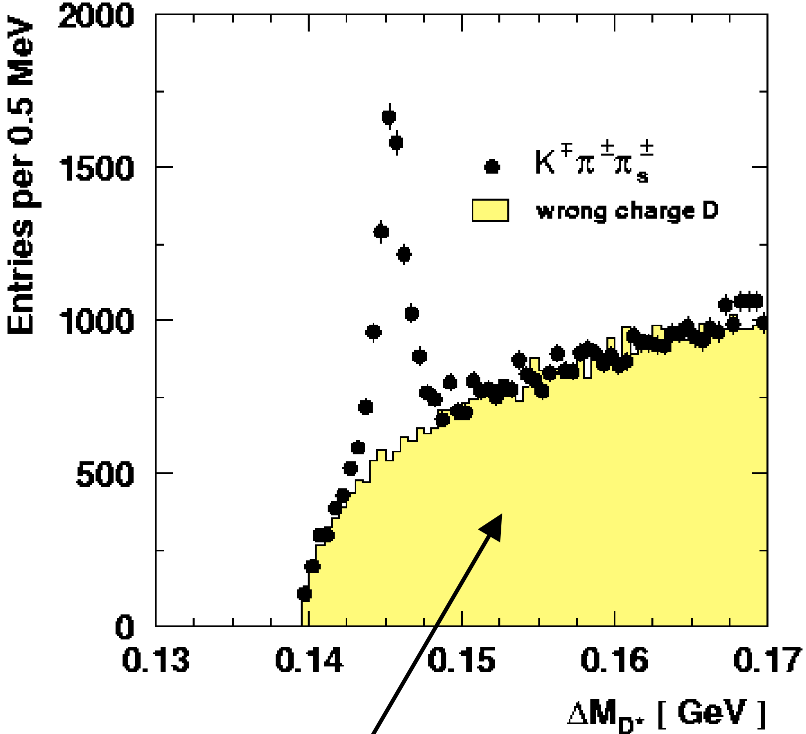
D^* *experimentally much easier*

Let's try it !

D* Signal

- 1996 – 2000 Data $L_{\text{int}} = 75\,pb^{-1}$
- DIS: $1\ GeV^2 < Q^2 < 100\ GeV^2$
  $0.05 < y_e < 0.7$
- $p_t(\mathrm{D}^*) > 1.5\ GeV$, $|\eta(D^*)| < 1.5$
- S/B= 0.9

Only small signal expected
&
Tests of decay kinematics foreseen
↓
Try to improve S/B



n
o

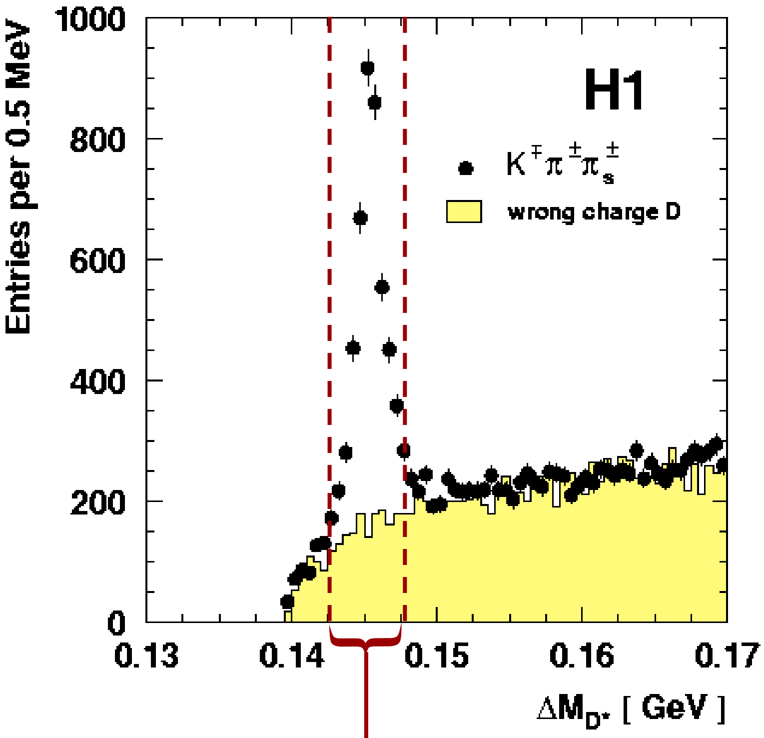
Non-charm induced background
-wrong charge D from $\mathrm{K}^{\pm}\pi^{\pm}$
Combinations in D^0 mass window

D* Signal Final Selection

- 1996 – 2000 Data $L_{\text{int}} = 75 pb^{-1}$
- DIS: 1 $GeV^2 < Q^2 < 100$ GeV^2
  $0.05 < y_e < 0.7$
- p_t (D*) > 1.5 GeV
- Modified & additional cuts:
- $-1.5<|\eta(D^*)| < 1.$
- p_t (K) + p_t (π) > 2 GeV.
- Inelasticity z(D*) > 0.2

S/B improves by 2.5

3400 D*'s in DIS to start with



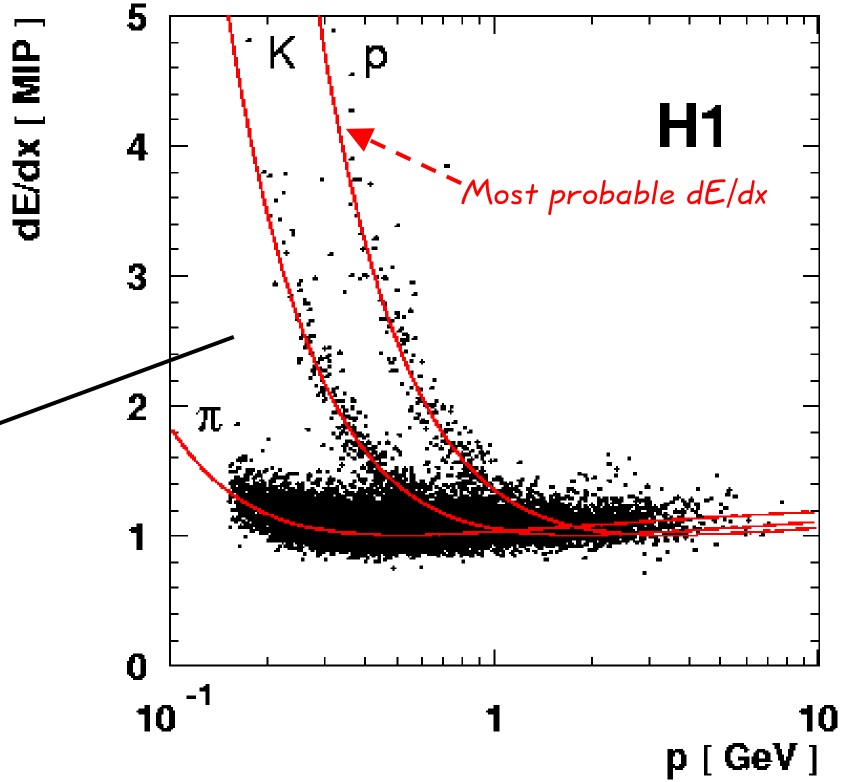
D* signal region subsequently used

dE/dx - Towards the Proton

- dE/dx calibrated for 1996 to 2000 data
- Parameterization accurate to 3-5%
- 8% average resolution

Normalized likelihood based on:
measured dE/dx & expectations
For π, K, p and resolution:
L(π)+L(K)+L(p) = 1

Final proton selection:
(L(p)>0.1&&p(p)>2).or.L(p)>0.3

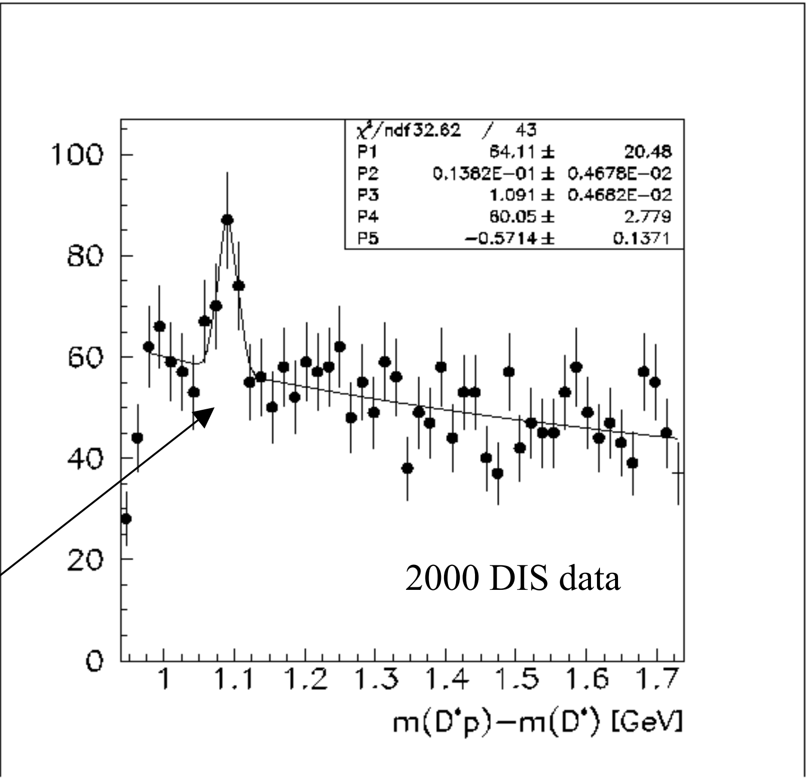


Well enough understood to be used for background suppression

The very first look at $D^{*-}p$

- Look for a *narrow state* near threshold
- Expected 4-particle mass resolution about 35 MeV ⟶ use mass difference: $m(D^*p)$-$m(D^*)$ [1)]
- Cut on the *normalized proton likelihood* $L(p)$ for pion suppression

Take a D^* candidate add a track consistent with a proton using m_p
D^* selection as used for F_c^2 96/97 analysis & $L(p)$> 5%



Narrow enhancement about 150 MeV above threshold: real or fake ?

$D^{*-}p$ + cc in DIS for 1996 - 2000

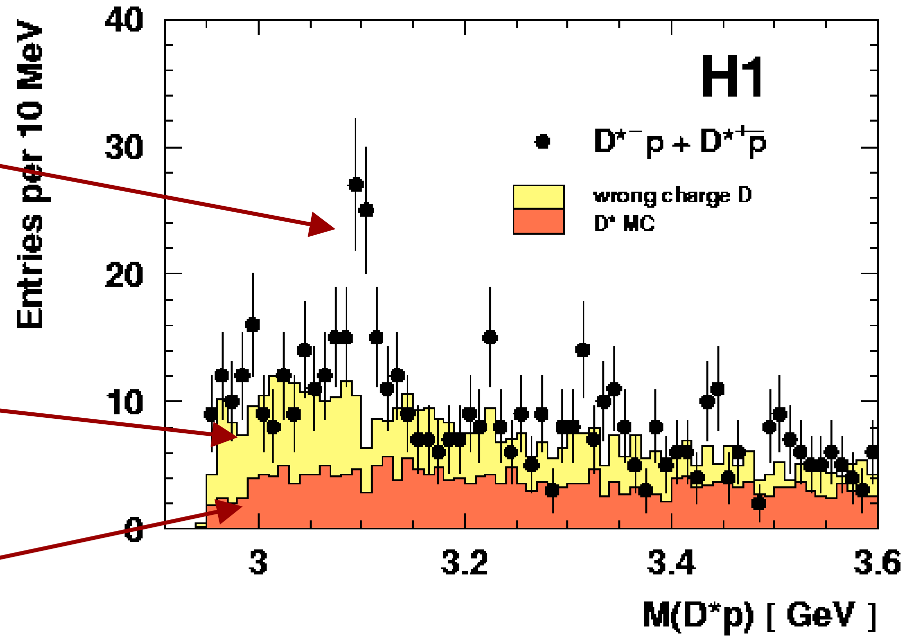
Cleanup of D* signal and proton candidates by cuts given before

Significant peak in opposite sign D*p

No enhancement in wrong charge D [1)]

No enhancement in D* MC (RAPGAP) [2)]

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$



Background well described by D* MC and wrong charge D from data

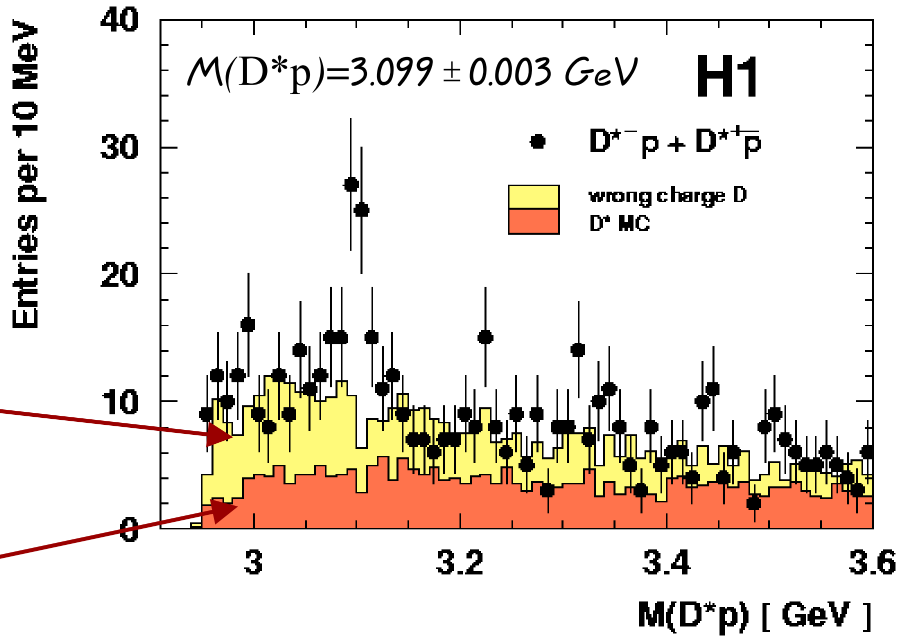
1) Mass of same sign $K^{\pm}\pi^{\pm}$ in $m(D^0)$ window
2) Also no peak from CASCADE or Beauty MC

Background significantly reduced – opposite sign D*p signal more pronounced

$D^{*-}p$ + cc in DIS for 1996 - 2000

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

Cleanup of D* signal and proton
Candidates given before



60-70% of background due to non-charm

No enhancement in D* MC (RAPGAP)[1)]

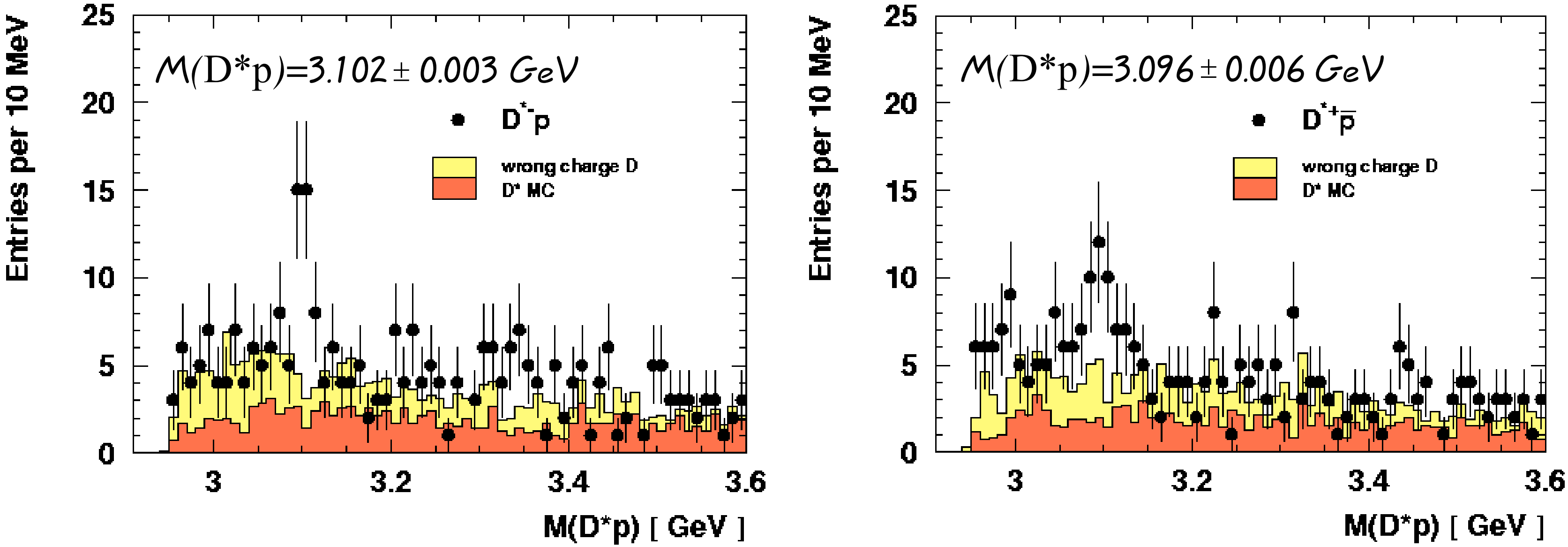
Background well described by D* MC and wrong charge D from data

1) Also no peak from CASCADE or Beauty MC

Background significantly reduced – opposite sign D*p signal more pronounced

Signal in both $D^{*-}p$ and in $D^{*+}\bar{p}$

$\mathcal{M}(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$



25.8 ± 7.1 *Events*

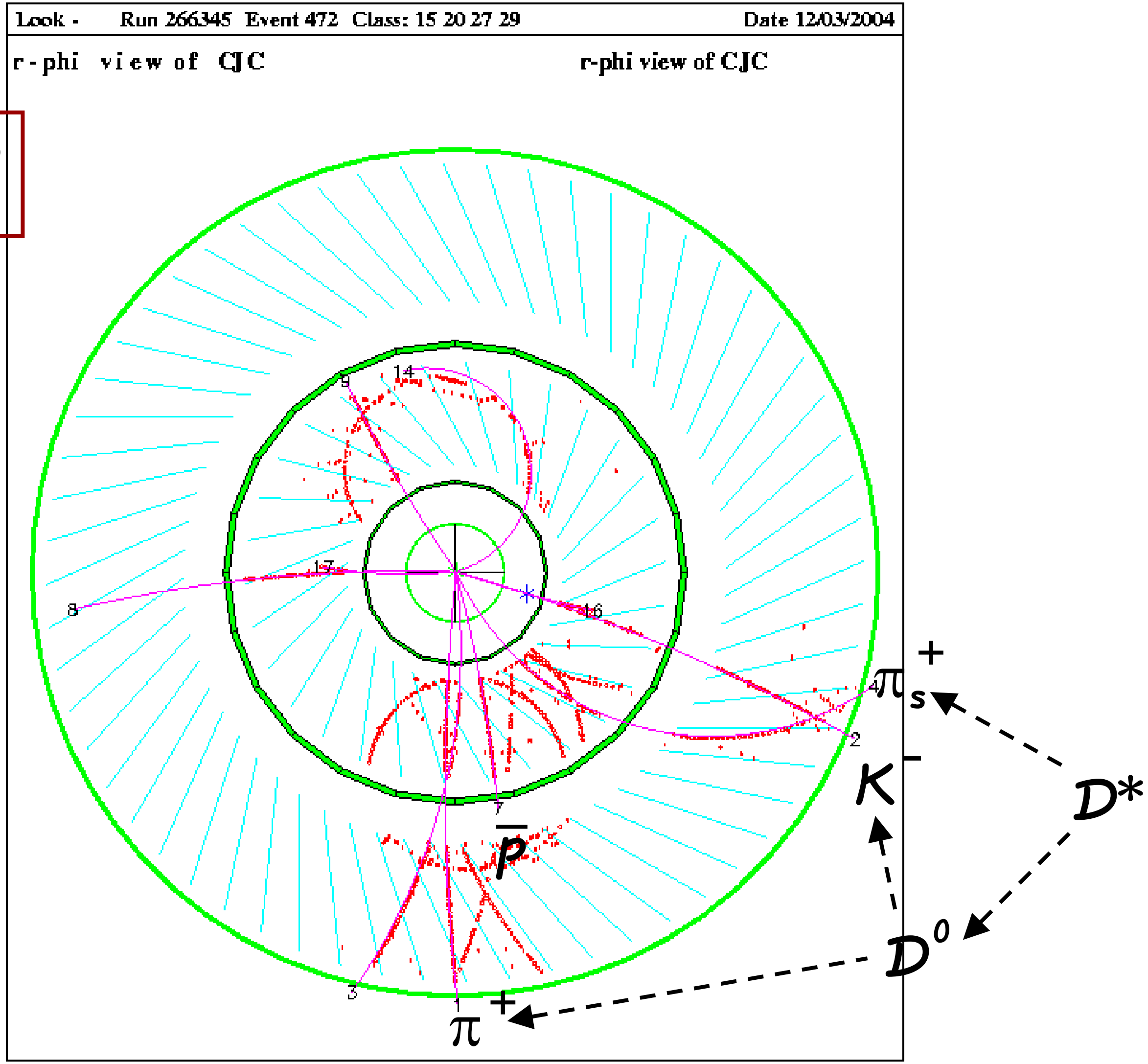
23.4 ± 8.6 *Events*

Signal of similar strength observed for both charge combinations at compatible $\mathcal{M}(D^*p)$

A typical Event

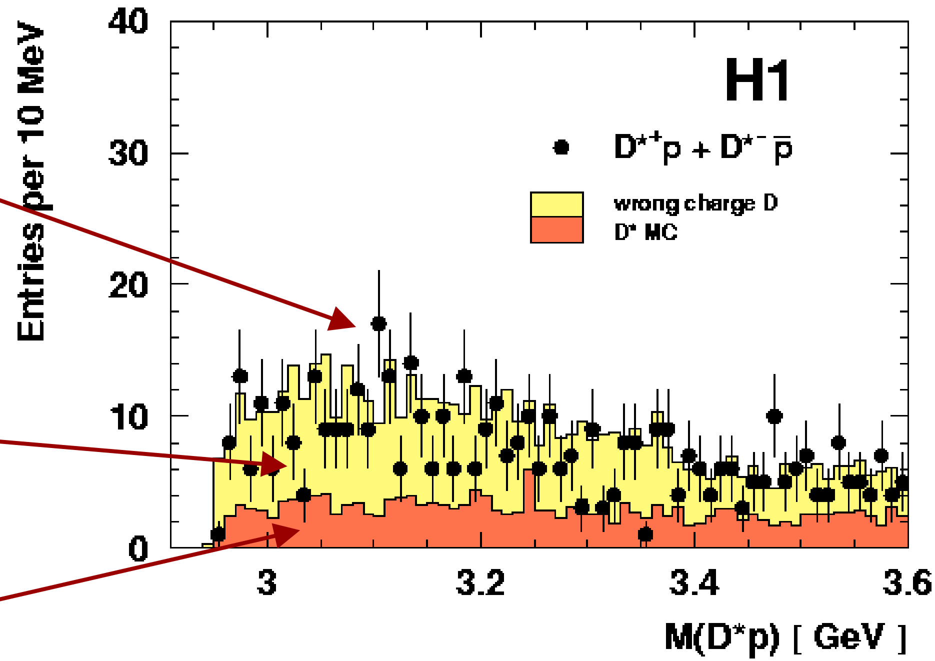
All events in the signal region have been scanned

NO anomalies observed e.g. split tracks, wrong reconstruction…



Signal in like sign $D^{*+}p$ [1]?

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$



No significant peak in like sign D^*p

No enhancement in wrong charge D [2]

No enhancement in D^* MC (RAPGAP) [3]

Reasonably described by D^* MC and wrong charge D from data

1) Charge conjugate always implied
2) Mass of same sign $K\pi$ in $m(D^0)$ window
3) Same results from CASCADE or Beauty MC

Possible Background: $D_1(2420)/D_2(2460) \rightarrow D^*\pi$?

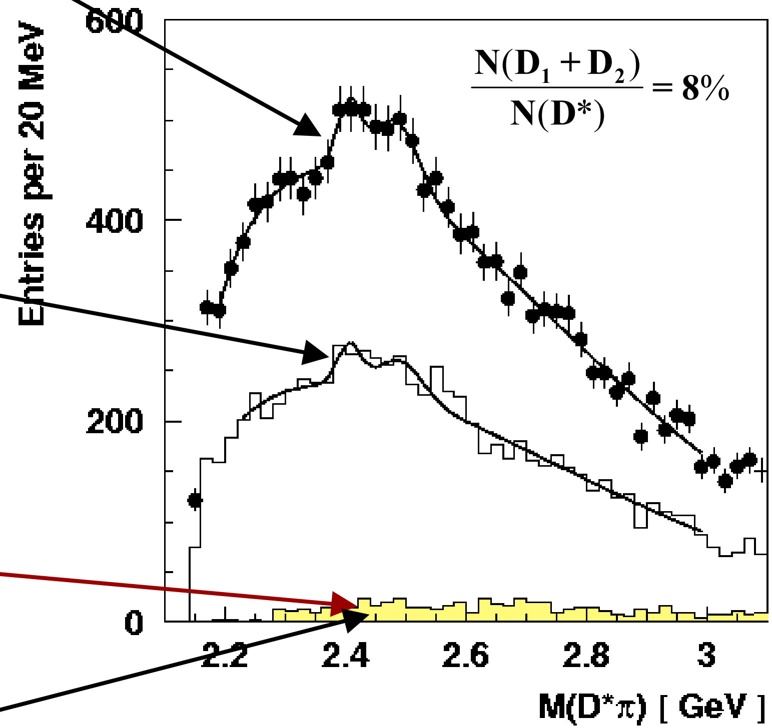
Loose D* cuts & pion selection

D* cuts of D*p & pion selection
$N(D_1+D_2)=276\pm70$

D* cuts of D*p & proton selection

Compatible with MC expectation

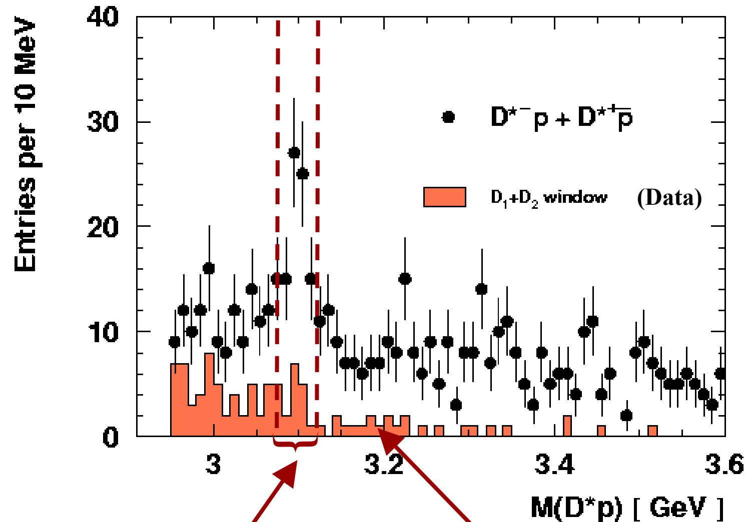
No cut in D*p

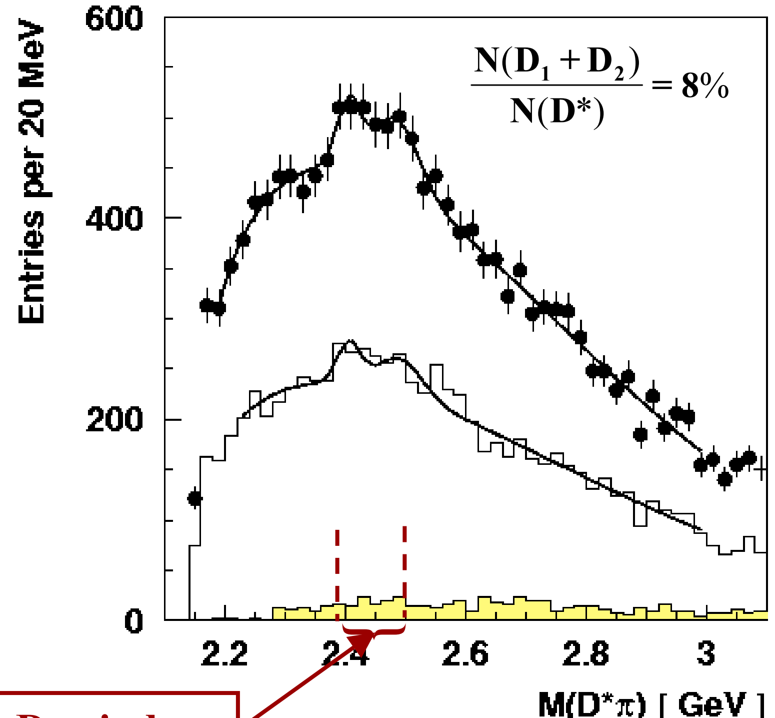


$M(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*)_{PDG}$

Possible Background: $D_1(2420)/D_2(2460) \rightarrow D^*\pi$?

No cut in D^*p





Corrected for combinatorics,
Then expect 3.5 events from data

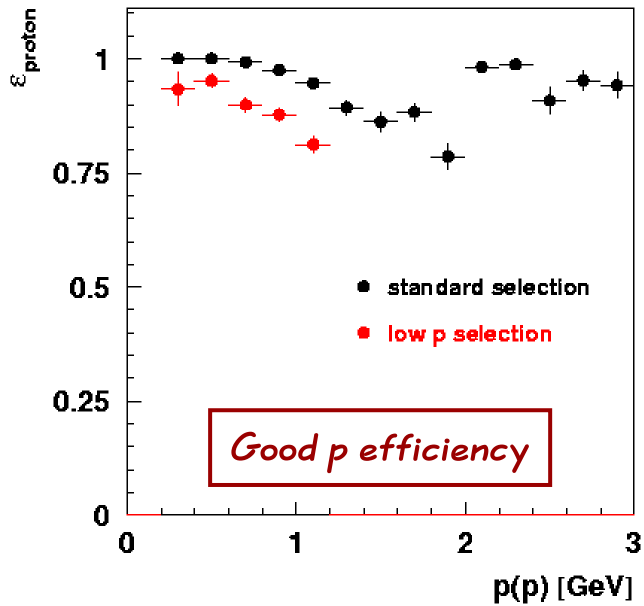
D_1, D_2 window

$N(D_1+D_2) = 3.5$ in the D^*p signal region from MC

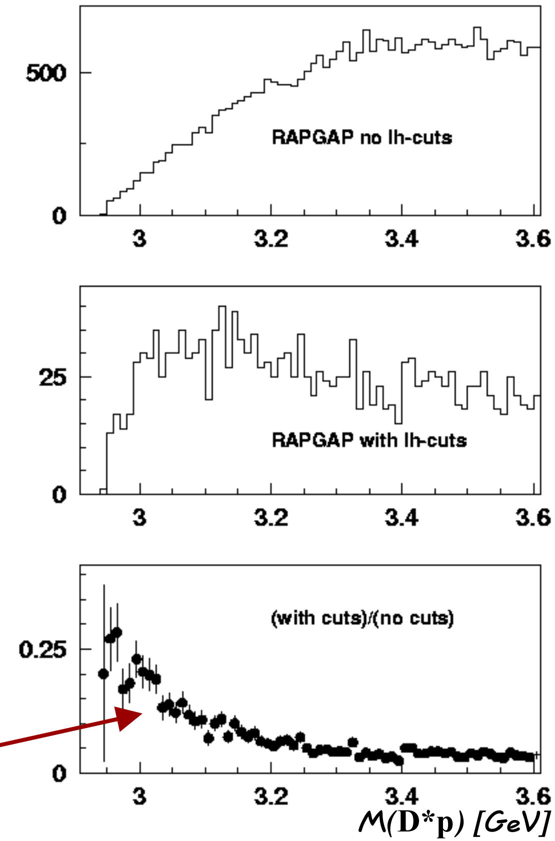
$M(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*)_{PDG}$

Does some acceptance effect fool us ?

Proton efficiency



"Pion survival probability"

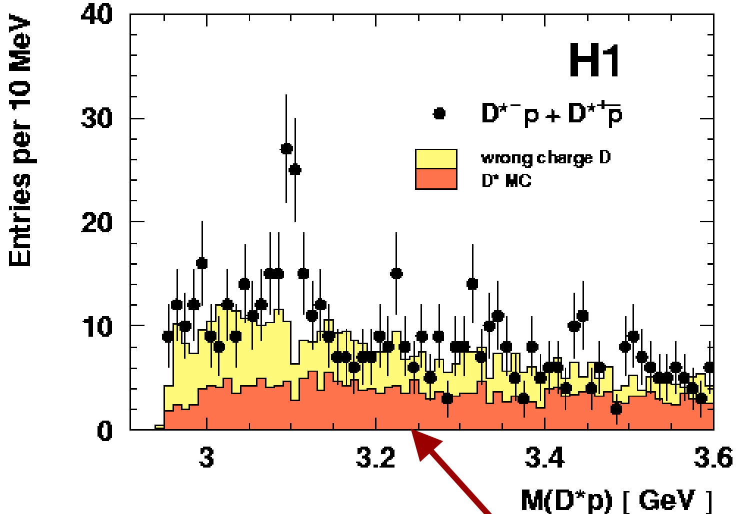


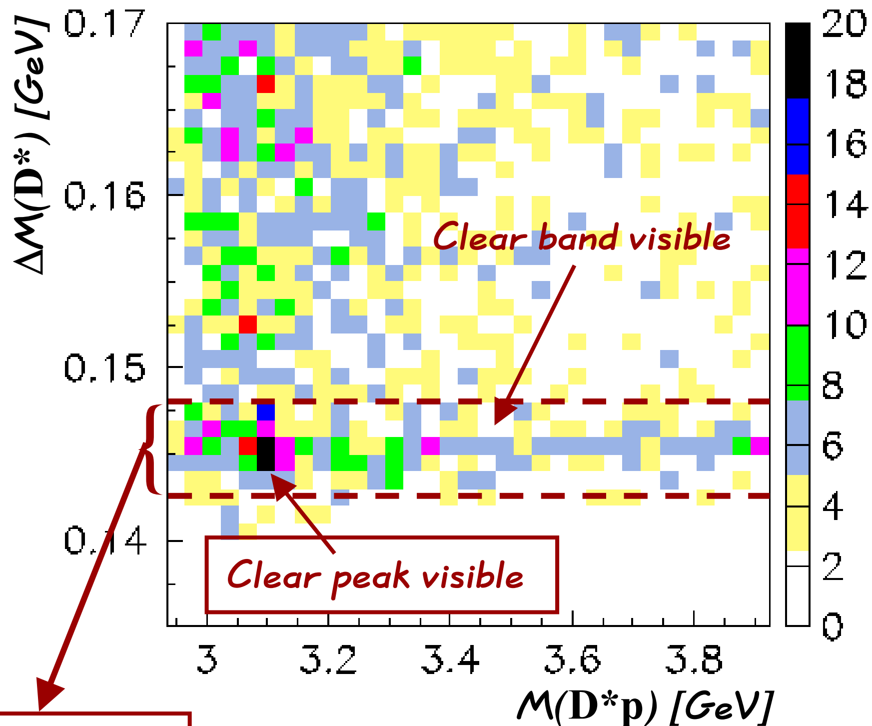
Smooth variation with M(D*p)
Shape reflects opening of phase space

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

Signal region in $D^{*-}p$[1] richer in D^{*-}?

1) Charge conjugate always implied

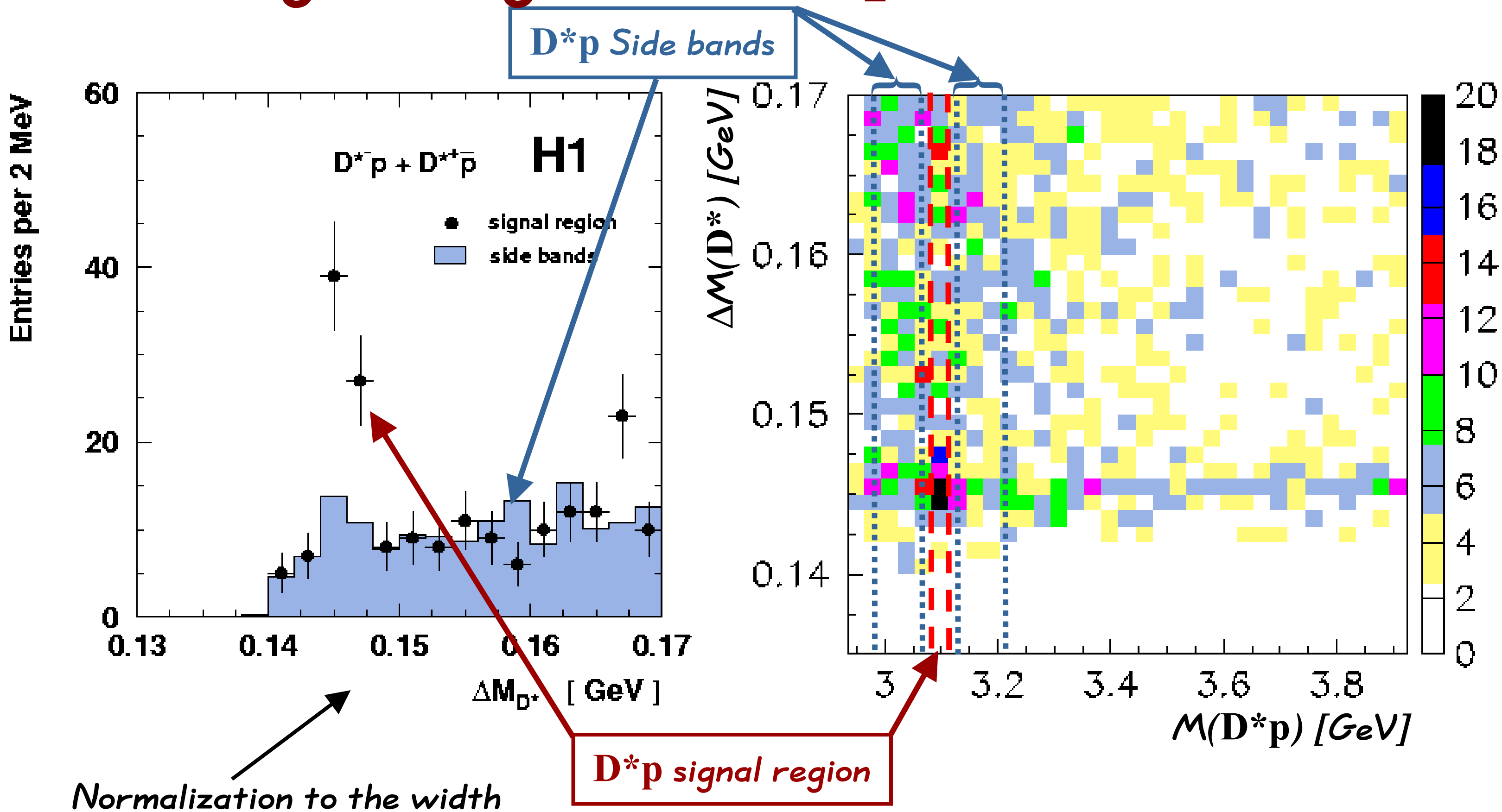




D* signal region

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

Signal region in $D^{*-}p$ [1] richer in D^{*-}?

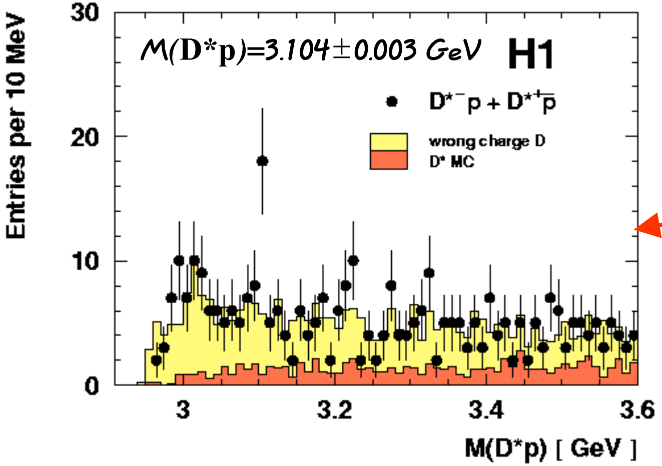


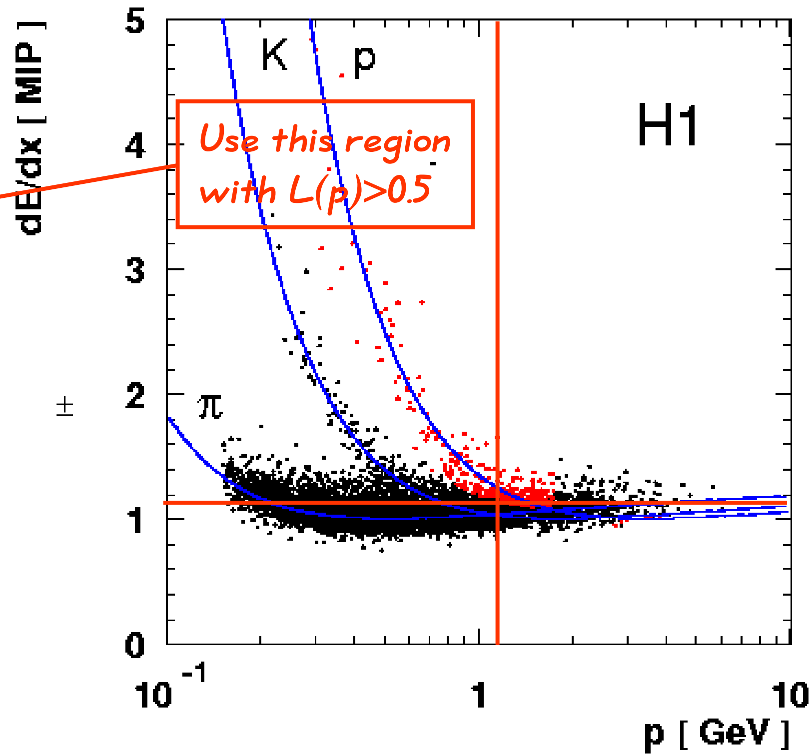
Normalization to the width of the windows in $M(D^*p)$

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

1) Charge conjugate always implied

Is the $D^{*-}p$[1)] signal due to protons?





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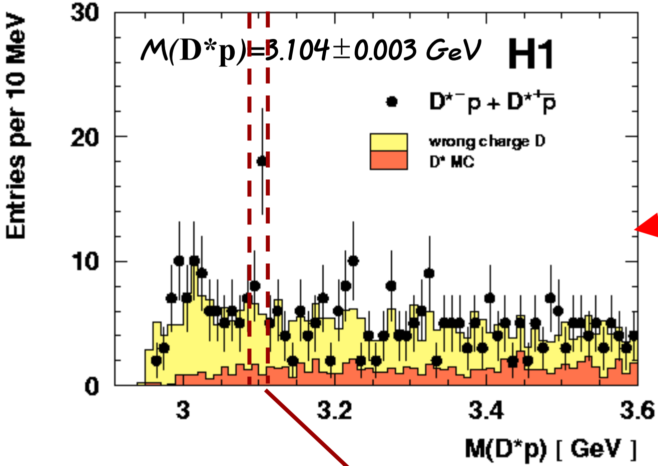
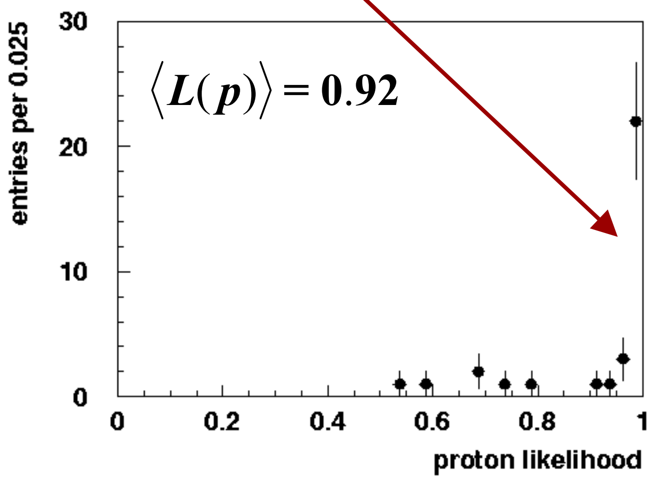
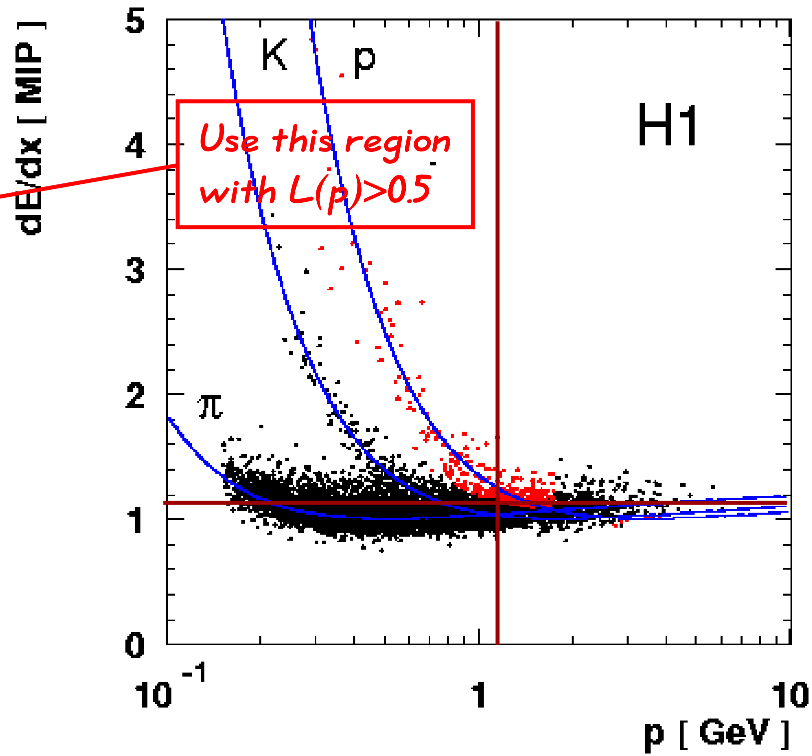






$$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$$

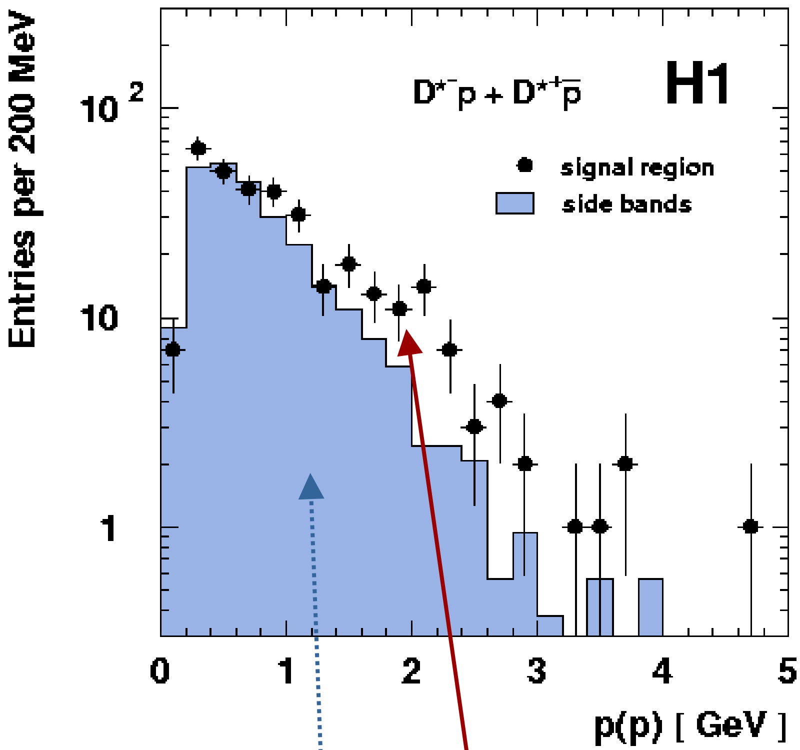
1) *Charge conjugate always implied*

Is the physics different in the signal region?

If a new particle is produced, the properties of its decay products is different from those of the back-ground

→ Look at the momentum of the proton candidate w/o dE/dx cuts

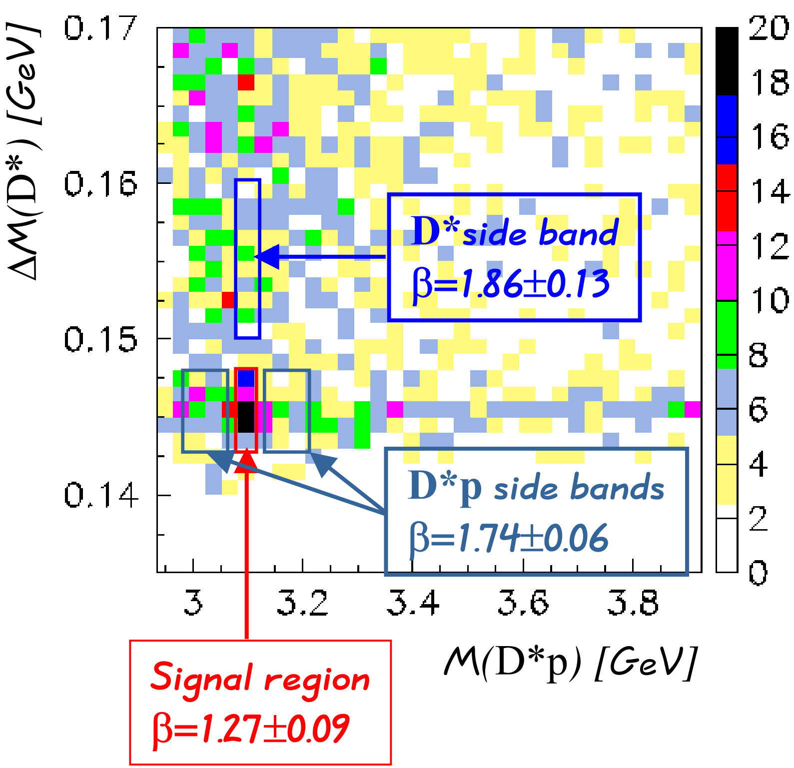
No L(p) cuts !

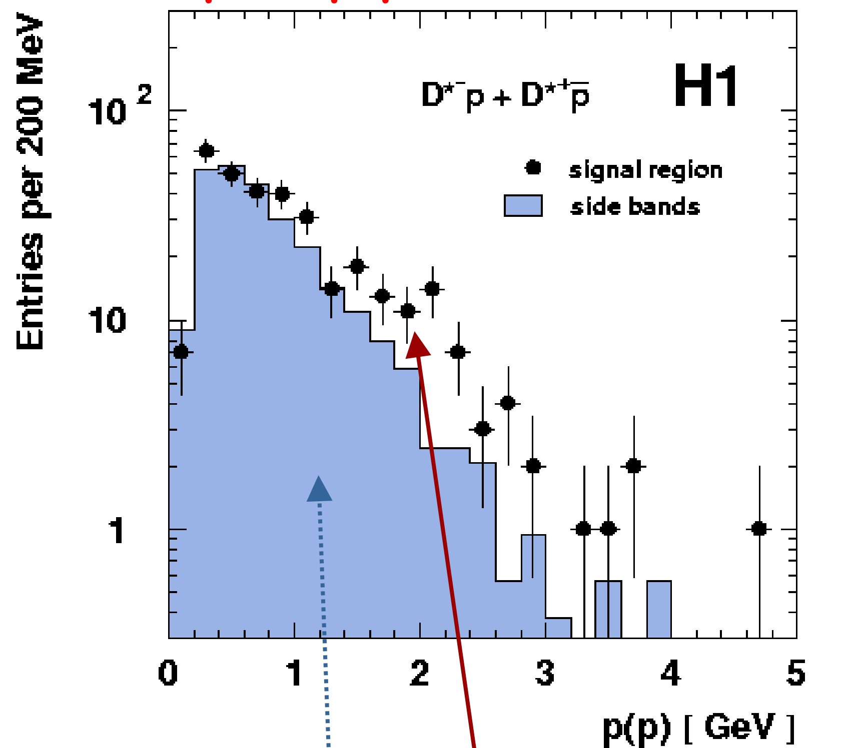


The momentum spectrum of the particles in the signal region is harder than in the M(D*p) side bands

Is the physics different in the signal region?

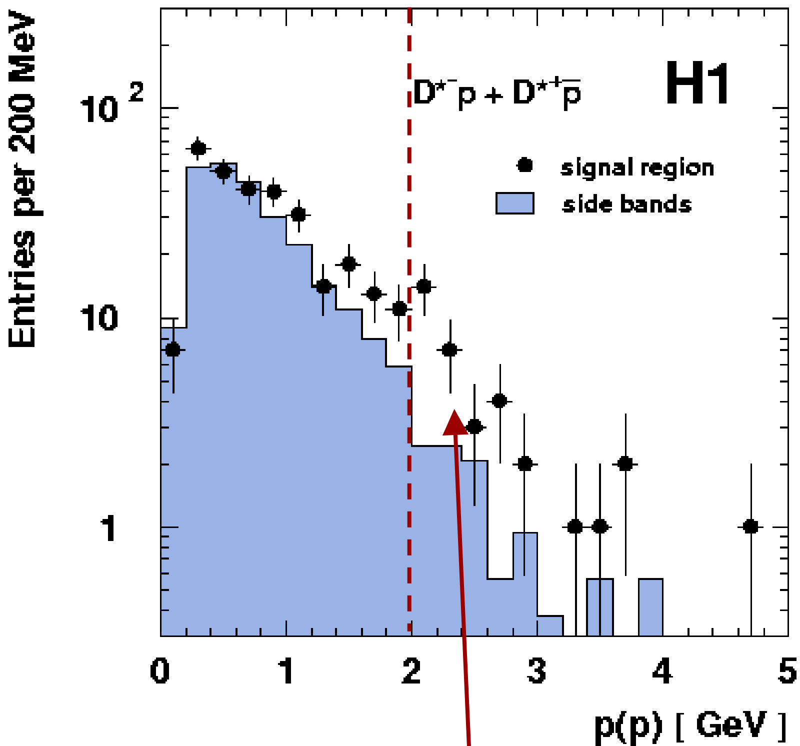
Fit slope with $\alpha \cdot exp\{-\beta p(p)\}$





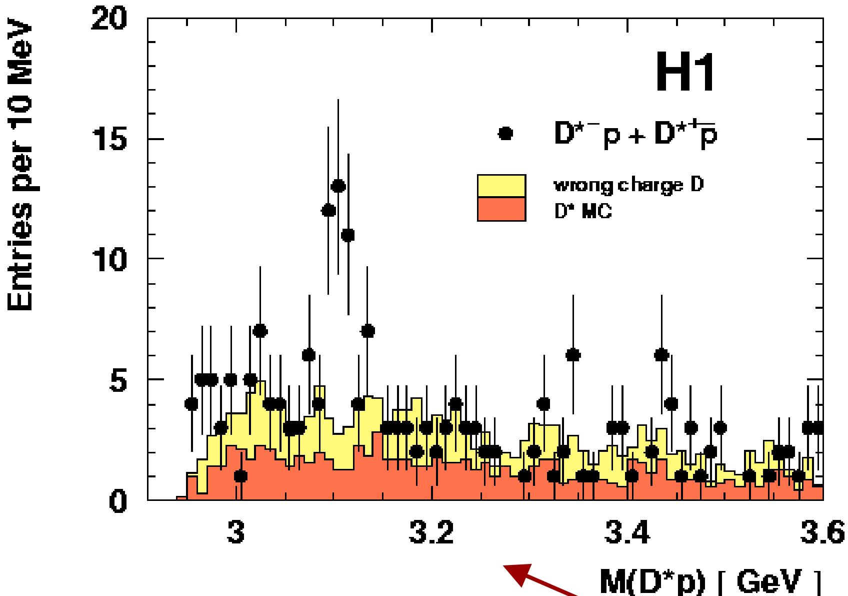
The momentum spectrum of the particles in the signal region is harder than in the M(D*p) side bands

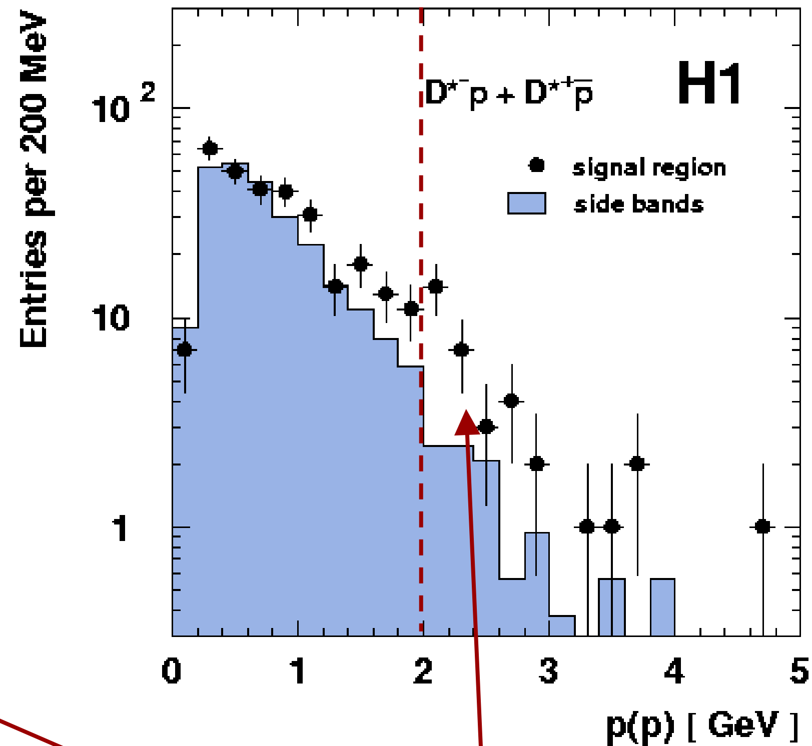
Signal at large p(p) more prominent ?



Signal to background improves at larger proton momentum → look at $M(D^*p)$

Signal at large p(p) more prominent ?





Signal to background improves at larger proton momentum → look at M(D*p)

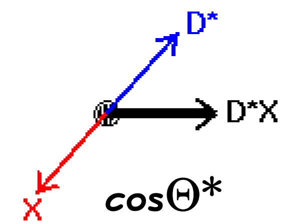
Basics of kinematic tests

2-Body Decay

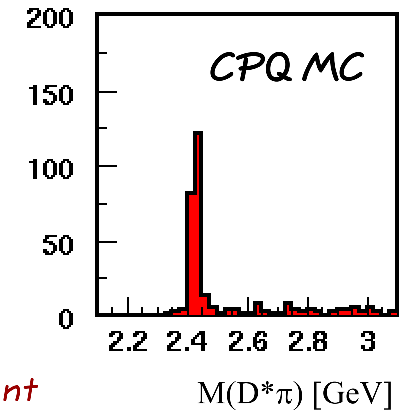
$$M^2 = (P_1 + P_2)^2$$
$$= (m_{D*}^2 + m_X^2 + 2E_{D*}E_X - 2\vec{p}_{D*}\vec{p}_X)$$

> M^2 independent of decay angle $\cos\Theta^*$ only for correct mass assignment

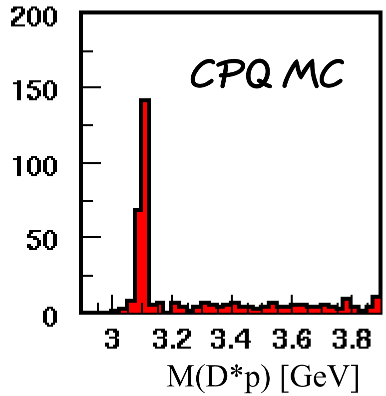
D*p rest frame

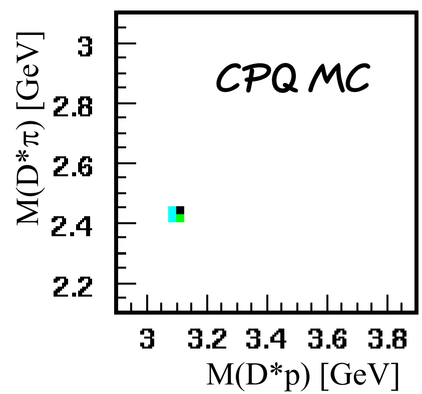


wrong mass assignment



correct mass assignment



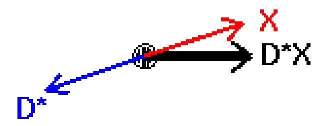


Kinematic tests

2-Body Decay

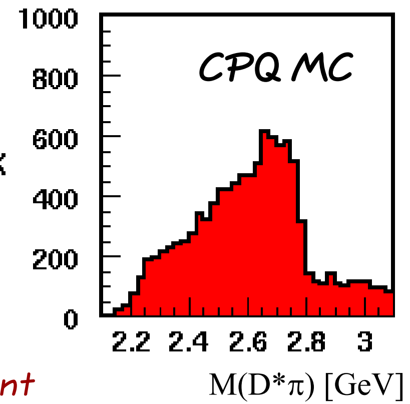
$$M^2 = (P_1 + P_2)^2$$
$$= (m_{D*}^2 + m_X^2 + 2E_{D*}E_X - 2\vec{p}_{D*}\vec{p}_X)$$

D*p *rest frame*

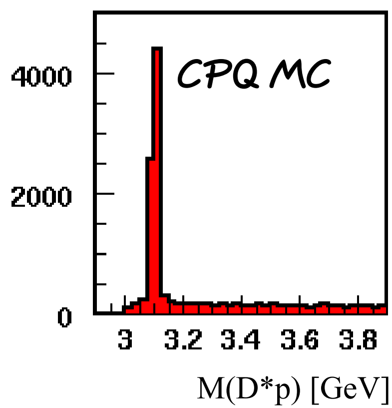


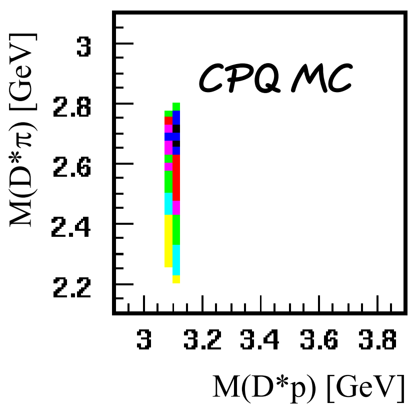
*Integrated in cosΘ**

wrong mass assignment



correct mass assignment

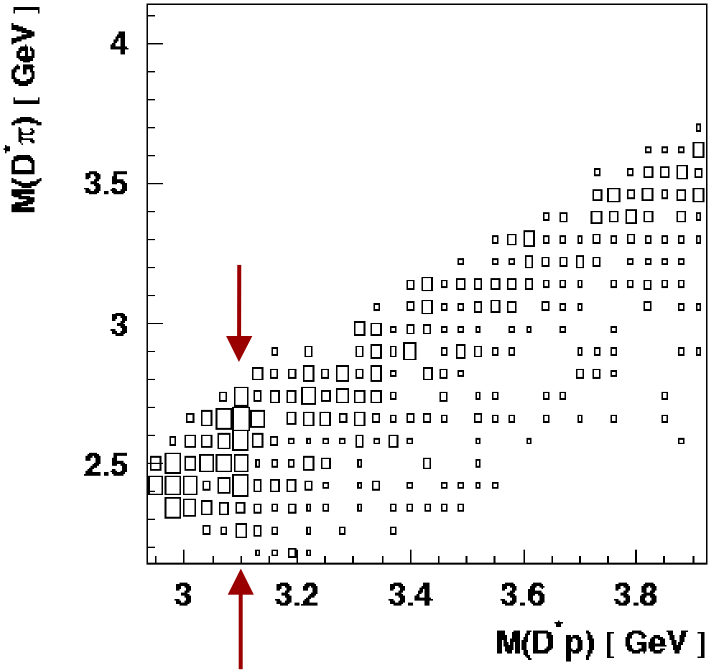




Do we see a band like structure in the M(D*p)-M(D*x) plane in data? → Let's have a look

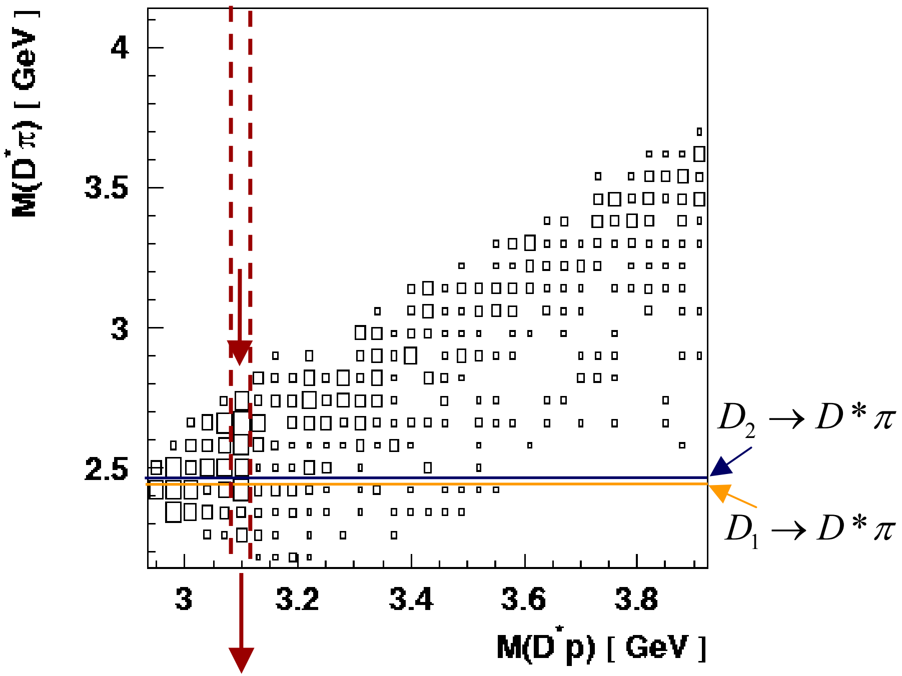
Signal due to $D^*\pi$?

Back to data !



Band in $D^*\pi$ clearly visible

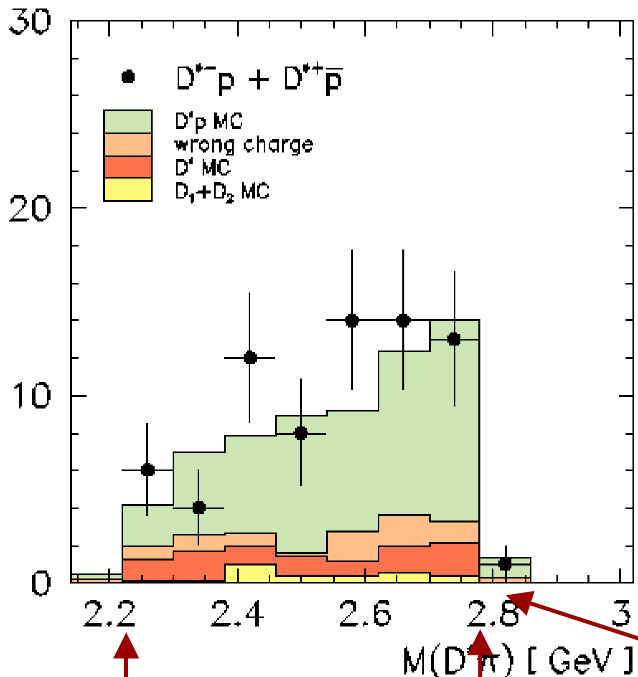
Signal due to $D^*\pi$?

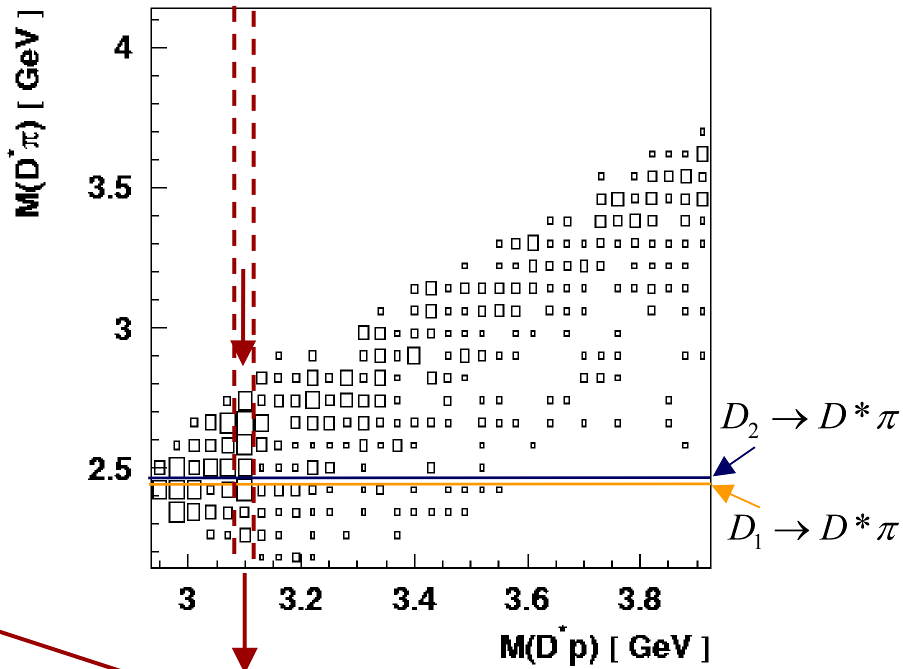


Go to the D^*p signal region

No indication for contributions from D_1 and D_2

Signal due to $D^*\pi$?



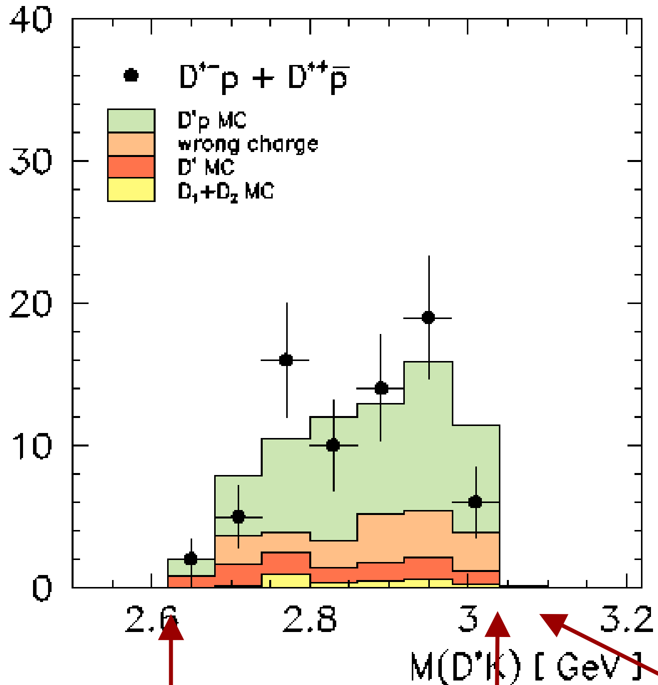


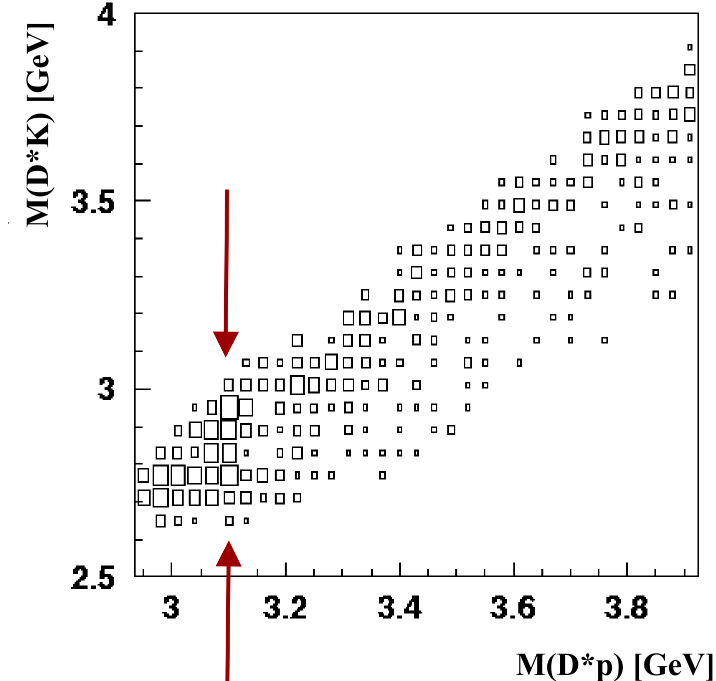
Go to the D^*p *signal region*

Sign for $X \longrightarrow D^*p$*: available phase space in* $D^*\pi$ *completely used*

Could it be due D*K ?

This on its own would be worth a publication



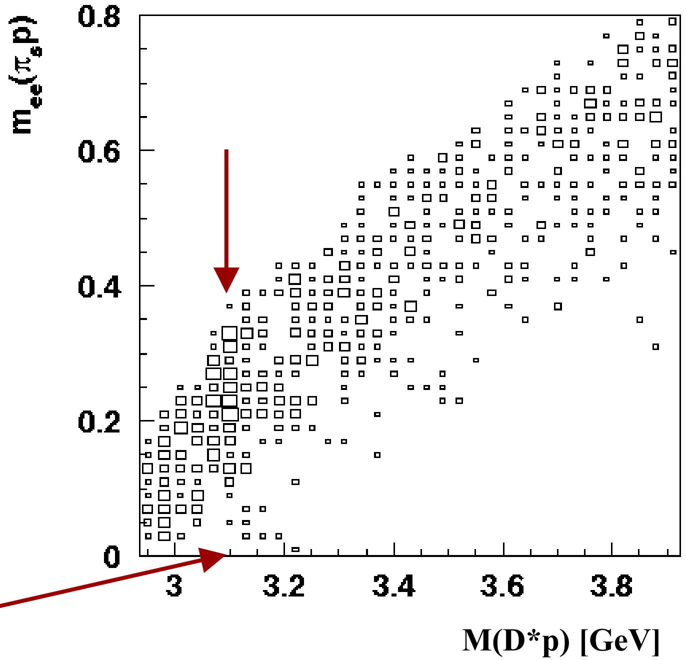


Band in D*K clearly visible
Go to the D*p signal region

Sign for X ⟶ D*p: available phase space in D*K completely used

Could it be due $D^{0*} \rightarrow D^0\gamma$?

$D^0\gamma$ may be dangerous
because of $\gamma \rightarrow e^+e^-$
γ-conversion asymmetric
in energy
$\rightarrow$may be misinterpreted
as π_s and proton
$m_{ee}(\pi_s\ p)$ should peak at 0



No accumulation at zero

Further investigation of mass correlations

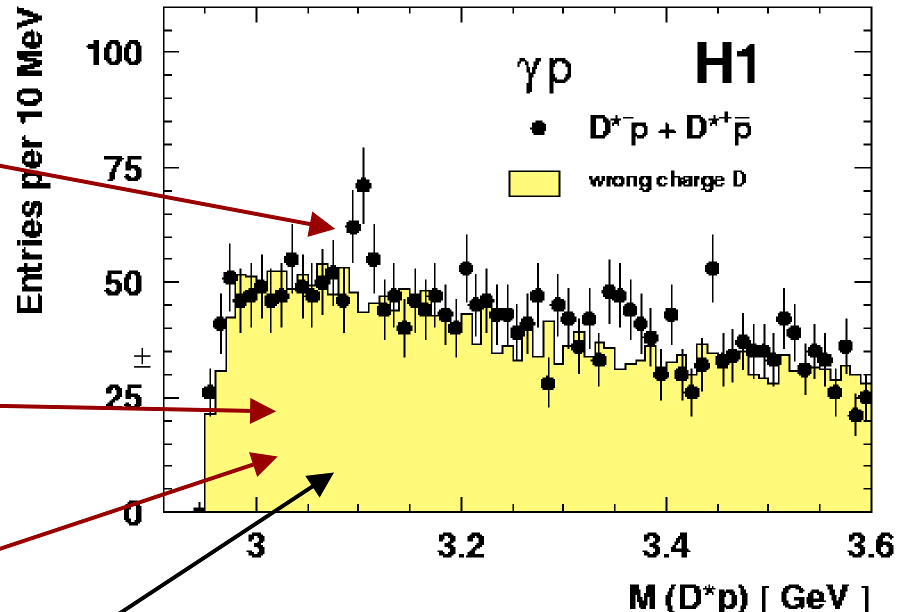
- Possible contributions from $D_{S1}/D_{S2} \rightarrow D^0 K$ have been ruled out
- All possible mass correlations among the particles making the D^* and the D^*p system have been investigated to search for real or fake peak structures, e.g Λ, Δ^0, Δ^{++}… : no enhancements found
- All possible mass hypotheses have been applied to the particles making the D^* and the D^*p system and the corresponding mass correlations have been studied to search for real or fake peak structures, e.g K^0_S, ϕ, f_2…: no enhancements found
- All possible mass correlations among the proton candidate the remaining charged particles of the event with all possible mass assignments have been looked at to search for real or fake peak structures, e.g K^0_S, ϕ, Δ^0, Δ^{++}…: no enhancements found

D*⁻p[1)] in photoproduction

4900 D*

$M(D^*p)=3.103\pm0.004$ GeV

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$



Peak also observed in photoproduction

>95% of background due to non-charm

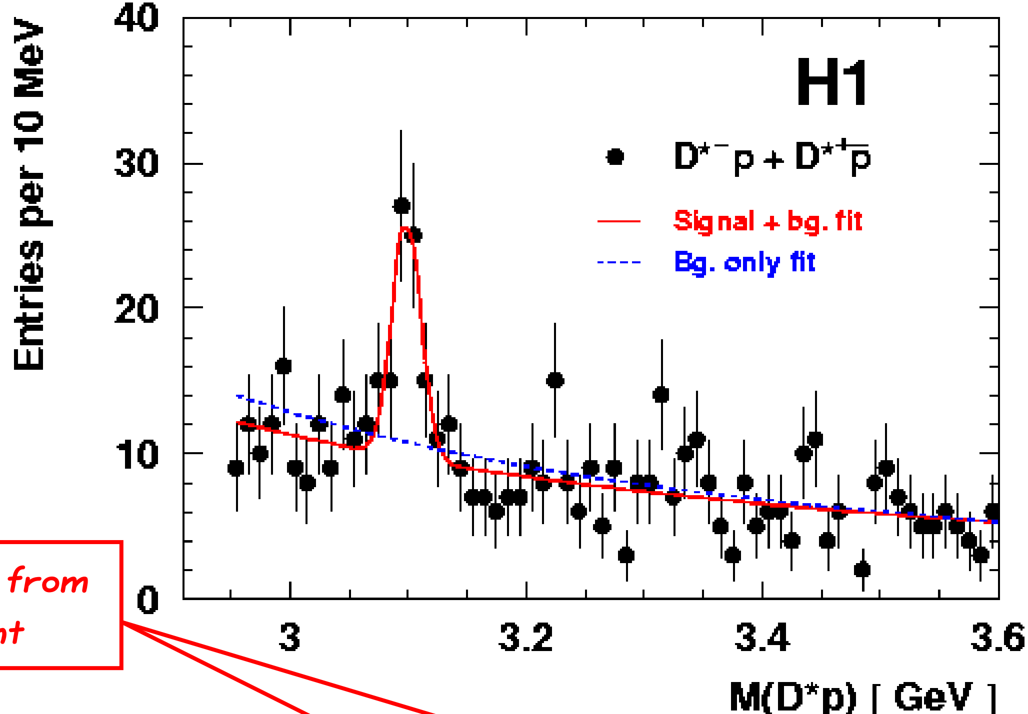
No enhancement in non-charm background

Background well described by wrong charge D from data

1) Charge conjugate always implied

Photoproduction more difficult due to large non-charm background

Signal assessment



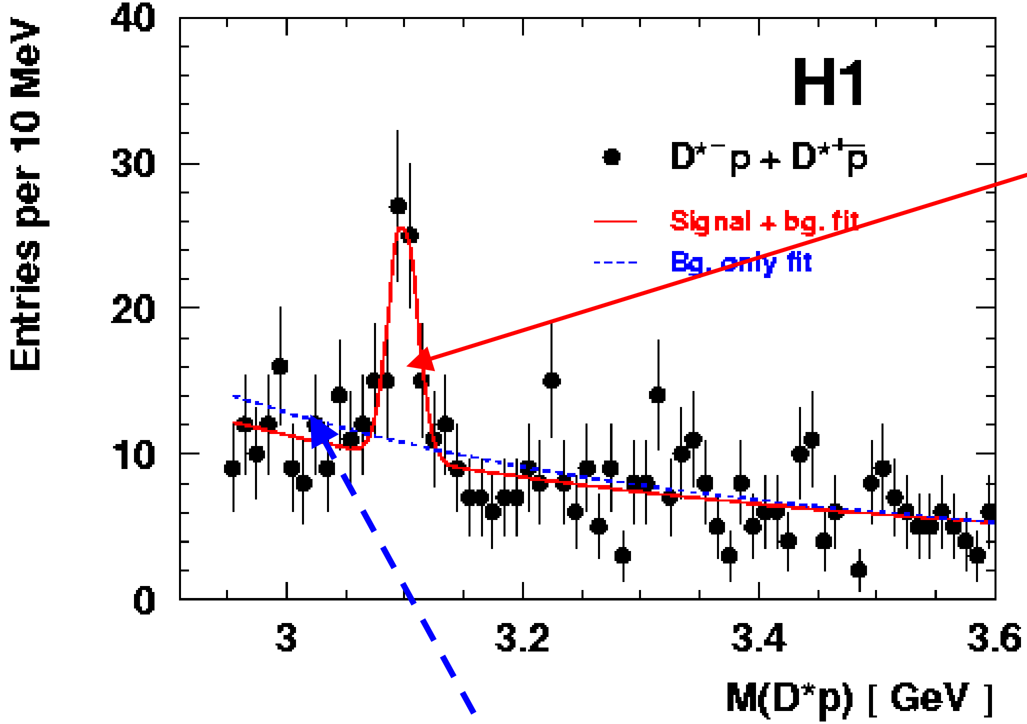
Stability of result against all sorts of variations checked

Masses & widths from fits are consistent

In total about 100 D^*p in DIS+γp

Sample	Mass [MeV]	Width [MeV]	N_s
$D^{*-}p + D^{*+}\bar{p}$ (DIS)	3099±3	12±3	50.6 ±11.2
$D^{*-}p$ (DIS)	3102 ±3	9 ±3	25.8 ±7.1
$D^{*+}\bar{p}$ (DIS)	3096 ±6	13 ±6	23.4 ±8.6
$D^{*-}p + D^{*+}\bar{p}$ (γp)	3103 ±4	7 ±3	43 ±14

Significance estimation



$N_s + N_b$=95 D*p cand. within 2σ

N_b=45.0±2.8 from background + signal Hypothesis (fit)

5.4 σ

- Significance estimate based on the background only hypothesis N_b= 51.7±2.7
- Use of different background functions as well as the background model from data and MC
- Significance determined in a binning free method

→Background fluctuation probability 4×10^{-8}(Poisson) ≡ 5.4 σ (Gauss)

Change in likelihood of fits: 6.2 σ

Conclusions

- A clear narrow resonance is observed for both $D^{*-}p$ and $D^{*+}\bar{p}$ with a mass of 3099 ± 3 (stat.) $\pm$ 5 (syst.) MeV in DIS
- The $M(D^{*}p)$ signal region have a richer yield of D^{*} mesons and show a harder momentum spectrum of the proton candidates
- The data have been subjected to many kinematical tests which are all found to be only consistent with the $D^{*}p$ hypothesis.
- The background fluctuation probability is smaller than $4*10^{-8}$.
- The measured RMS width of the resonance is 12 ± 3(stat.) MeV consistent with the experimental resolution
- The signal is also observed in an independent photoproduction sample
- The resonance is interpreted as an anti-charmed baryon decaying to $D^{*-}p$ and its charge conjugate.
- Its minimal quark content is $uudd\bar{c}$, therefore it is a candidate for a charmed pentaquark state.