Evidence for a Narrow Exotic Anti-Charmed Baryon State

H1 Collaboration

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Dedicated to our dear friend and colleague Ralf Gerhards

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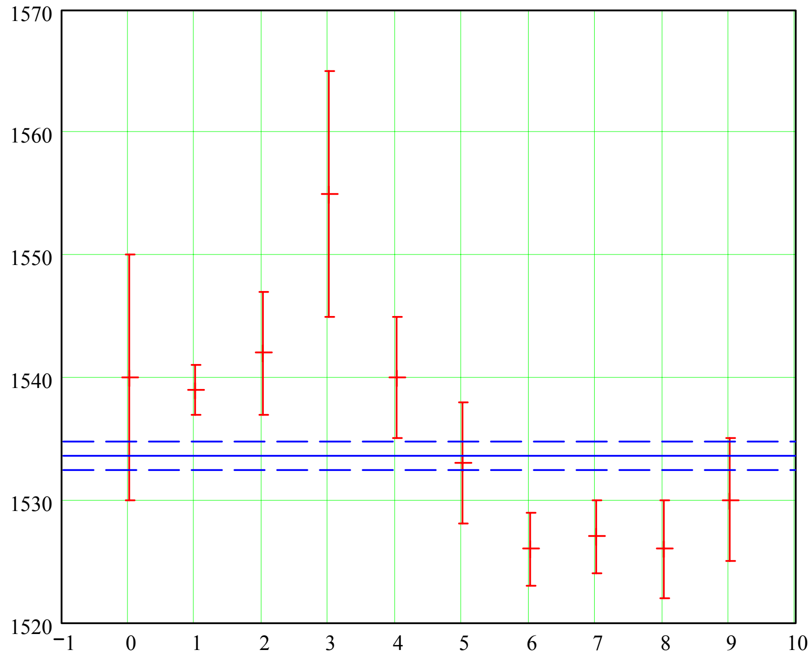
The Case of the Strange Pentaquark Θ^+

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

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



- $M(\Theta^+) - M(K) - M(p) = 100$ MeV
- Small natural width

If the strange pentaquark exists why shouldn't there also be a charmed pentaquark?

Let's have a look !

Possible Signature of the Charmed Pentaquark

Common belief:

$\Theta_c \rightarrow \overline{\mathrm{D}}\ \mathrm{p}$

(pseudo-scalar D meson)

Charm fragmentation fractions

$f(c \to D^+)$	γp	$0.248 \pm 0.014^{+0.004}_{-0.008}$
	DIS	$0.202 \pm 0.020^{+0.045+0.029}_{-0.033-0.021}$
	e^+e^-	0.232 ± 0.010
$f(c \to D^0)$	γp	$0.557 \pm 0.019^{+0.005}_{-0.013}$
	DIS	$0.658 \pm 0.054^{+0.117+0.086}_{-0.142-0.048}$
	e^+e^-	0.549 ± 0.023
$f(c \to D_s^+)$	γp	$0.107 \pm 0.009 \pm 0.005$
	DIS	$0.156 \pm 0.043^{+0.036+0.050}_{-0.035-0.046}$
	e^+e^-	0.101 ± 0.009
$f(c \to \Lambda_c^+)$	γp	$0.076 \pm 0.020^{+0.017}_{-0.001}$
	e^+e^-	0.076 ± 0.007
$f(c \to D^{*+})$	γp	$0.233 \pm 0.009^{+0.003}_{-0.005}$
	DIS	$0.263 \pm 0.019^{+0.056+0.031}_{-0.042-0.022}$
	e^+e^-	0.235 ± 0.007

Possible Signature of the Charmed Pentaquark

Common belief:

$\Theta_c \rightarrow \overline{\mathrm{D}}\,\mathrm{p}$

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Vector mesons not suppressed

Charm fragmentation fractions

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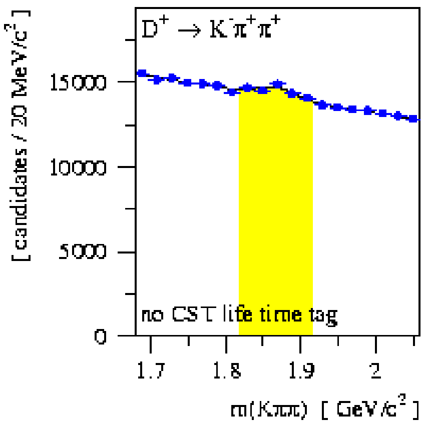
But what is experimentally feasible ?

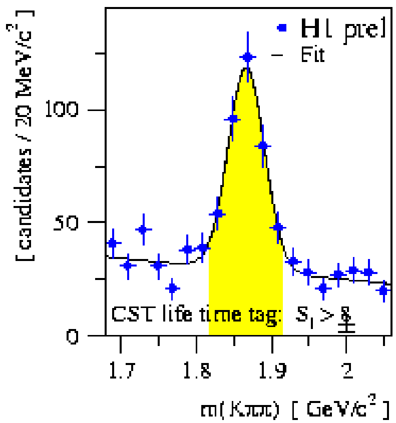
Experimental Considerations

D^+ *pseudoscalar meson*

without

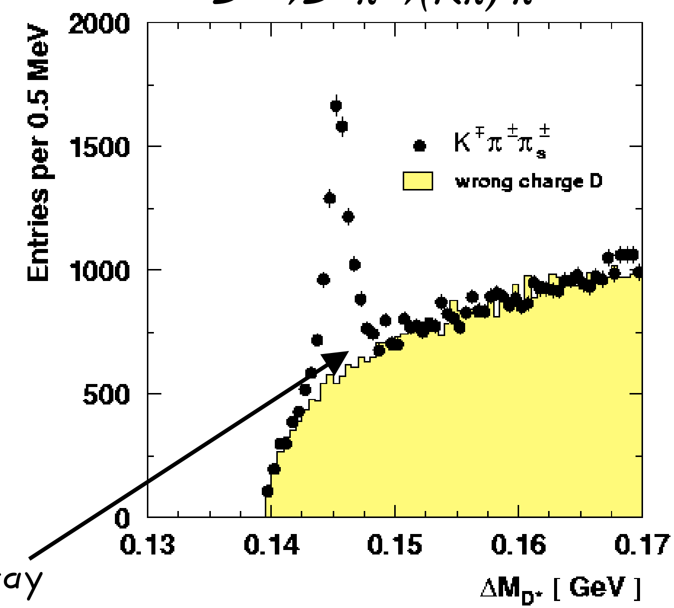


with lifetime tag



D^* *vector meson*

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



D^+: *huge background or low yield*

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

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

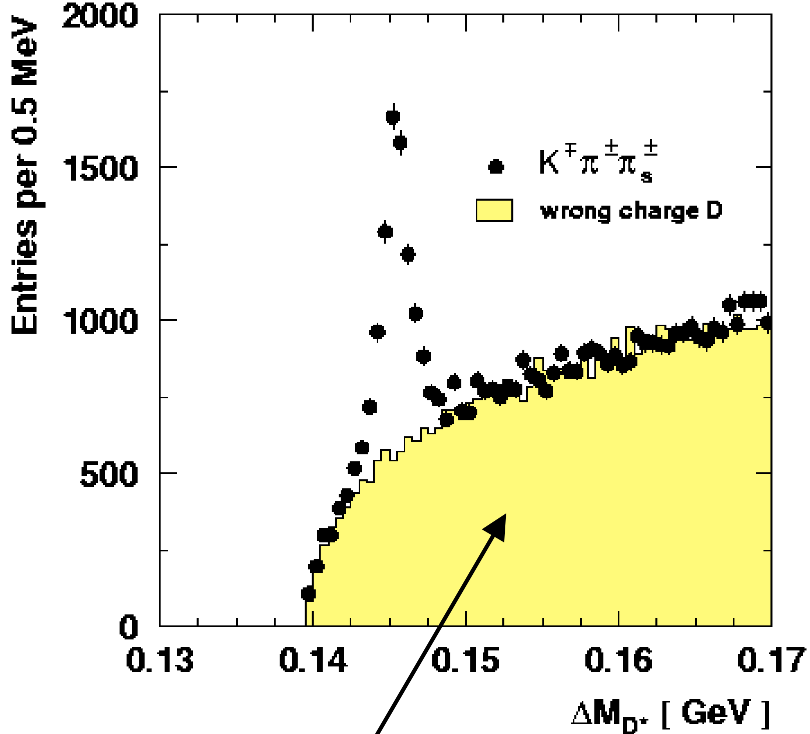
D^* *experimentally much easier*

Let's try it !

D* Signal

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

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



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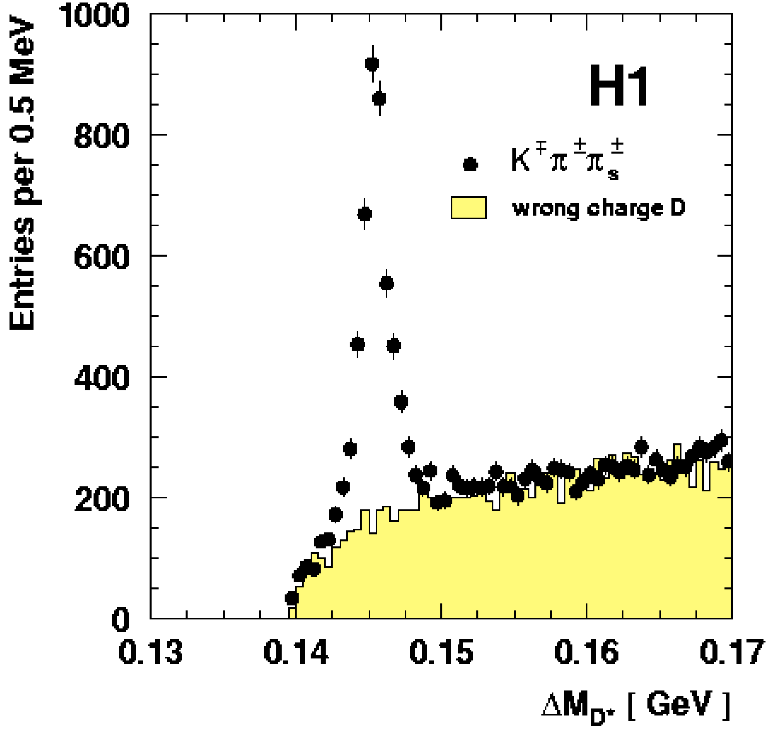
Non-charm induced background
-wrong charge $\mathbf{D}$ from $\mathbf{K}^{\pm}\pi^{\pm}$
Combinations in $\mathbf{D}^0$ mass window

$\mathbf{D^*}$ Signal Final Selection

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

S/B improves by 2.5

3400 D*'s in DIS to start with



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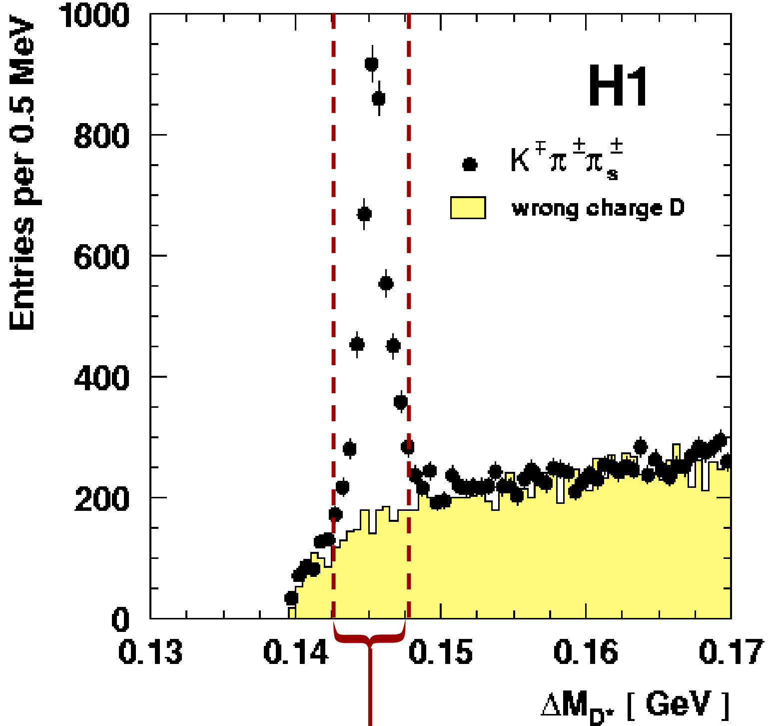


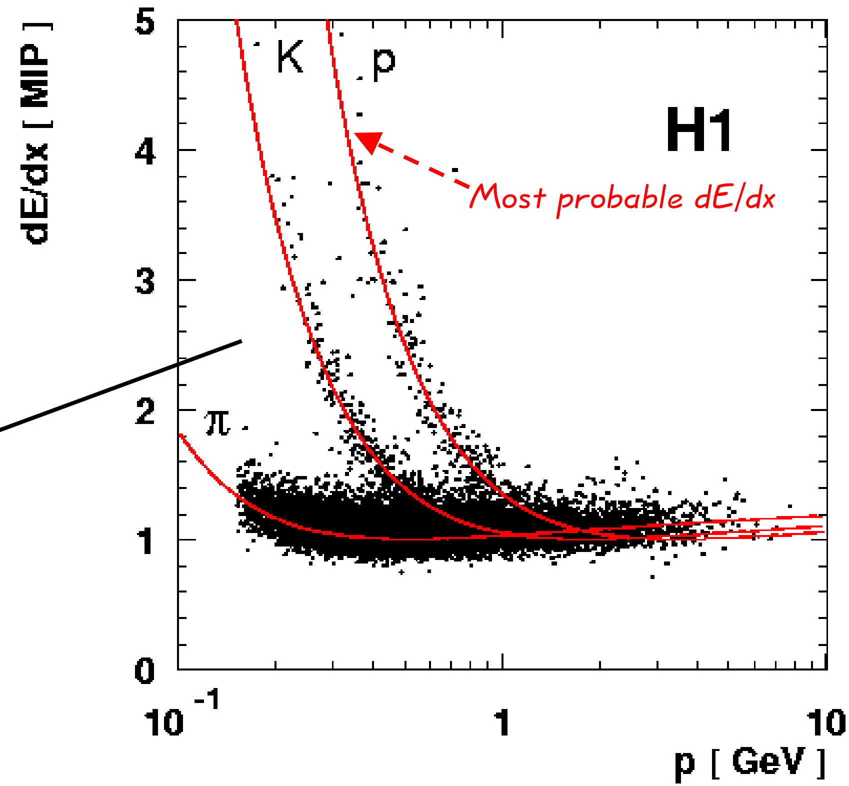
D* signal region subsequently used

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:
$L(\pi)+L(K)+L(p) = 1$

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



Well enough understood to be used for background suppression

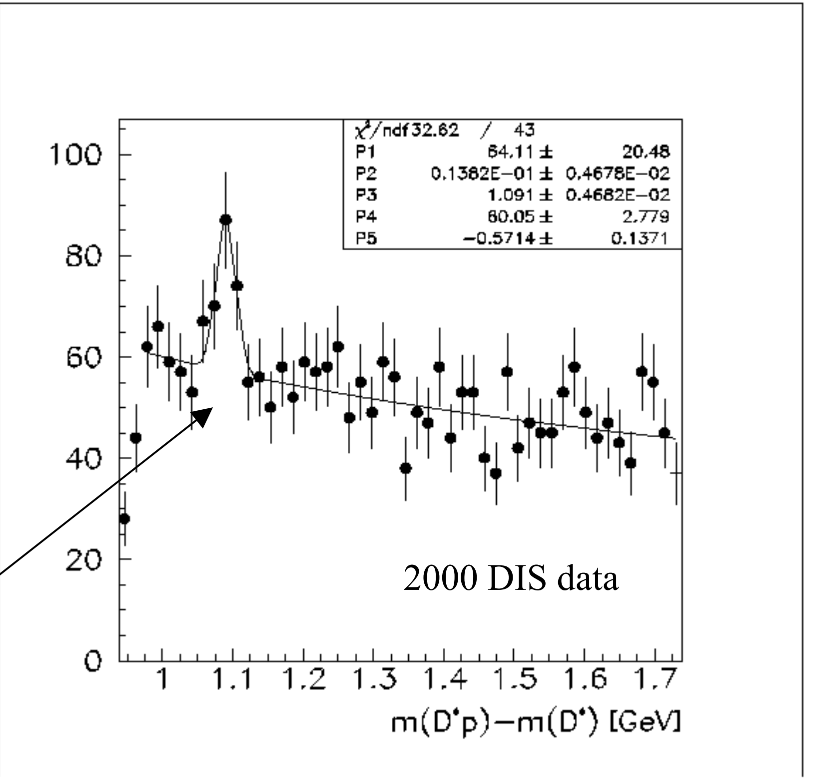
The very first look at $D^{*-}p$

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

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

- Look for a *narrow state* near threshold
- Expected 4-particle mass resolution about 35 MeV $\longrightarrow$ 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

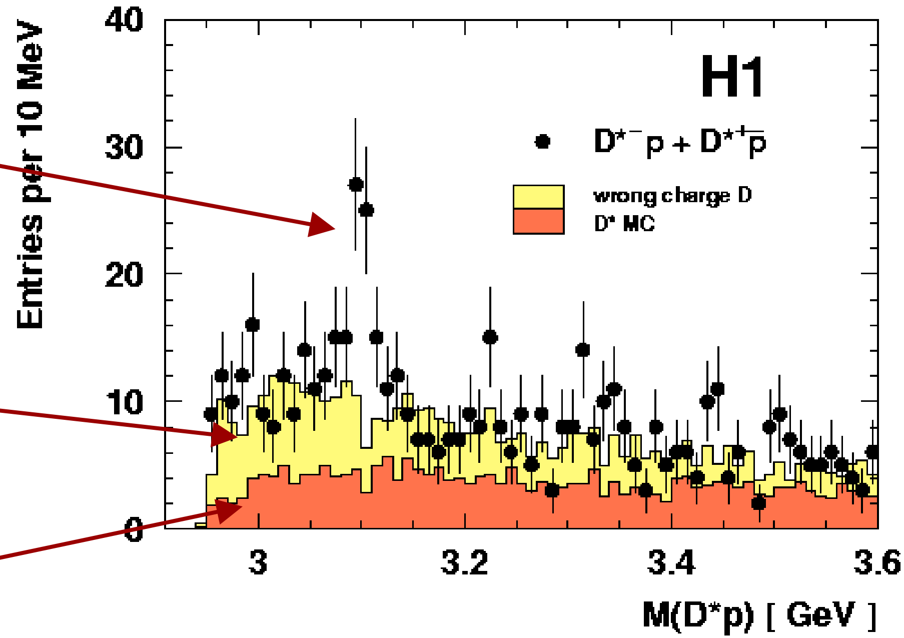
Cleanup of D signal and proton candidates by cuts given before*

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*

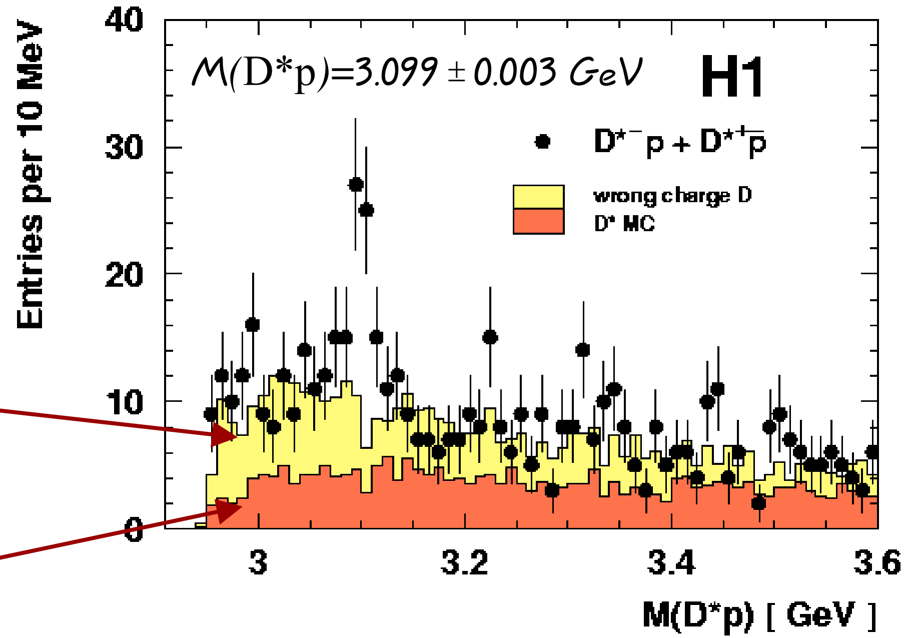
1) *Mass of same sign* $K^{\pm}\pi^{\pm}$ *in* $m(D^0)$ *window*
2) *Also no peak from CASCADE or Beauty MC*

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

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

Cleanup of D* signal and proton
Candidates given before

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



60-70% of background due to non-charm

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

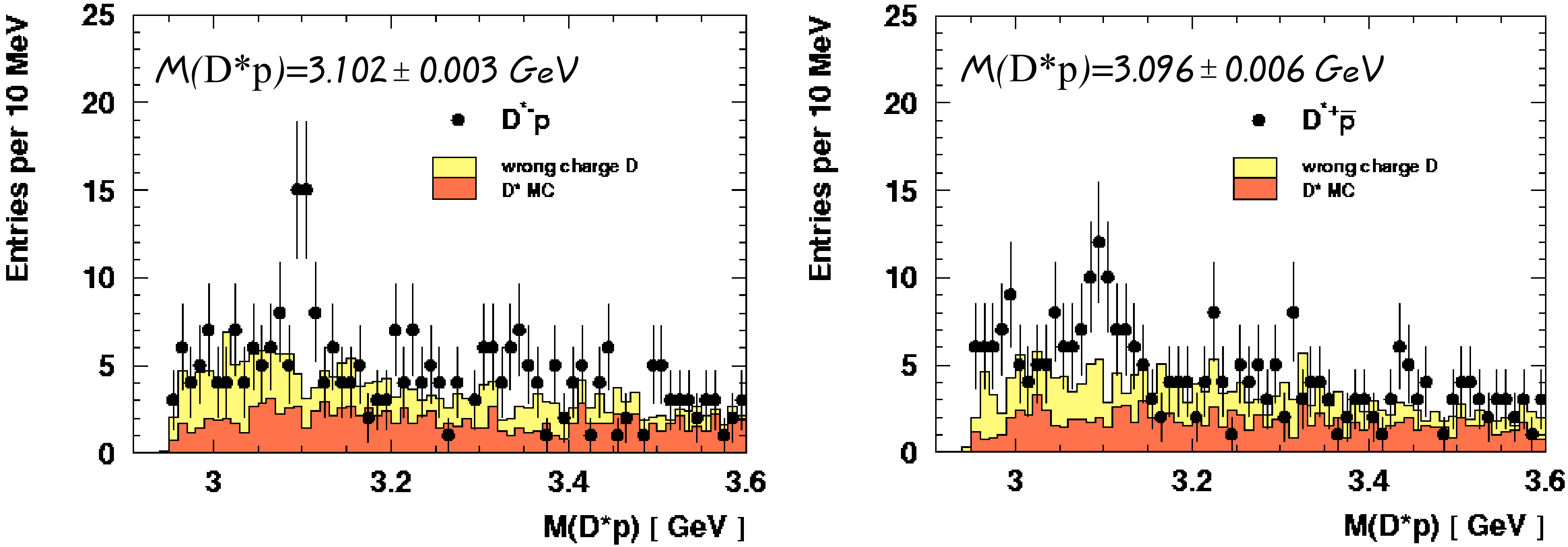
Background well described by D* MC and wrong charge D from data

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 $D^{*+}\bar{p}$

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



25.8 ± 7.1 *Events*

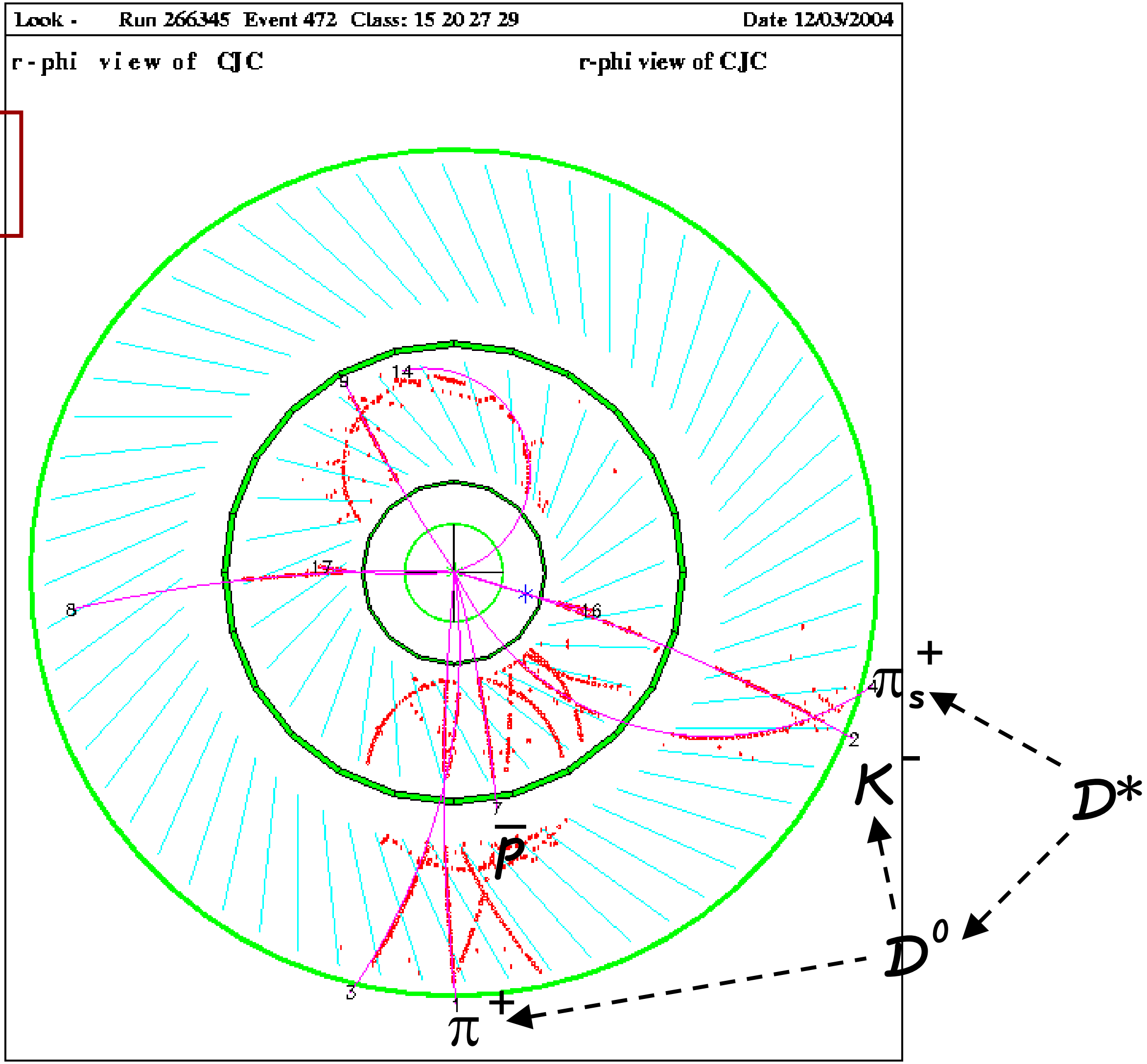
23.4 ± 8.6 *Events*

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

A typical Event

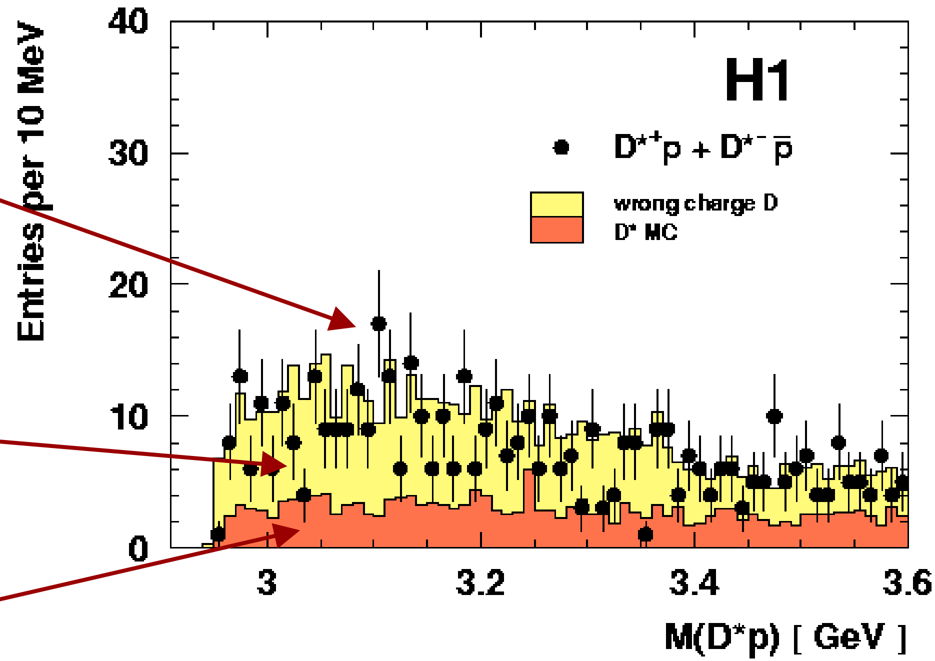
All events in the signal region have been scanned

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

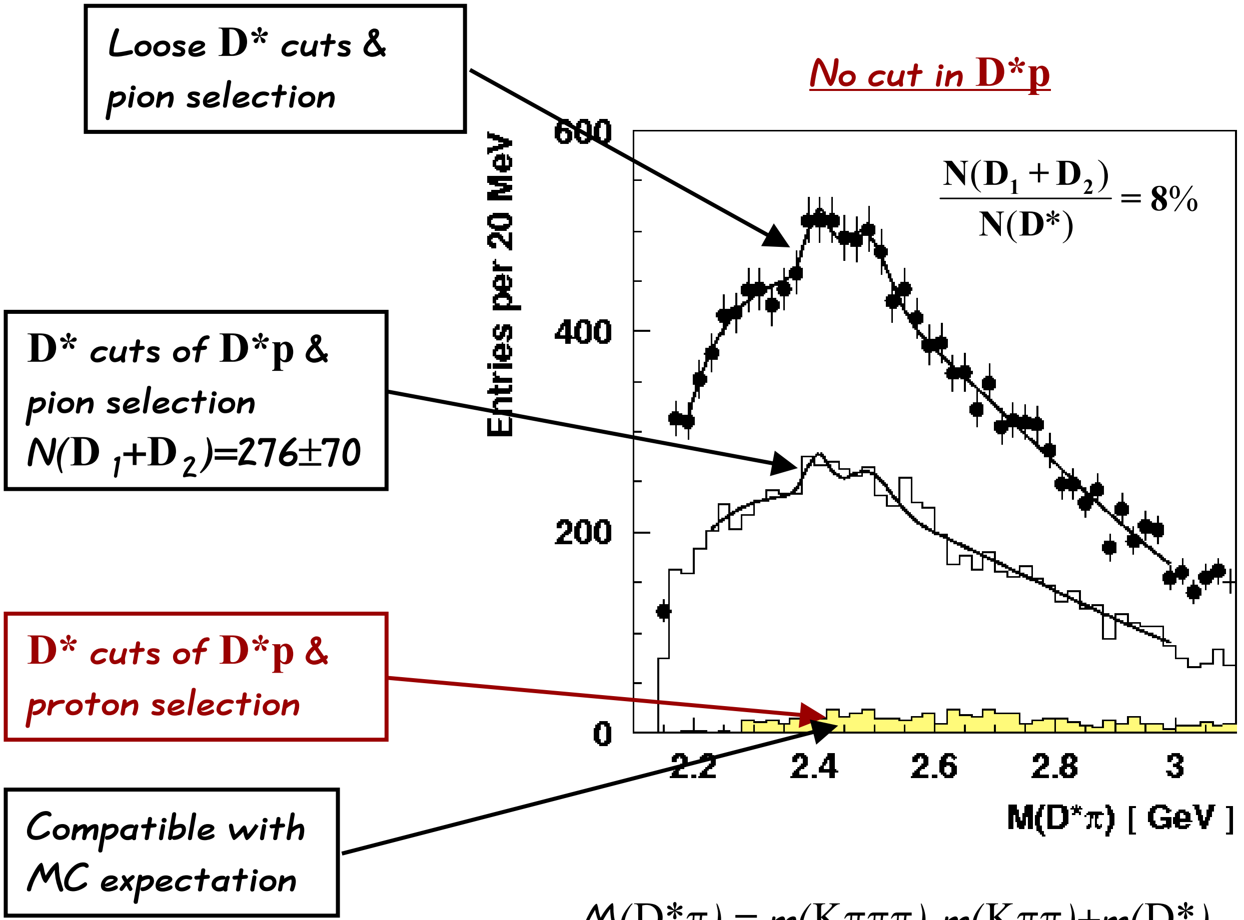
No enhancement in wrong charge D[2]

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



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

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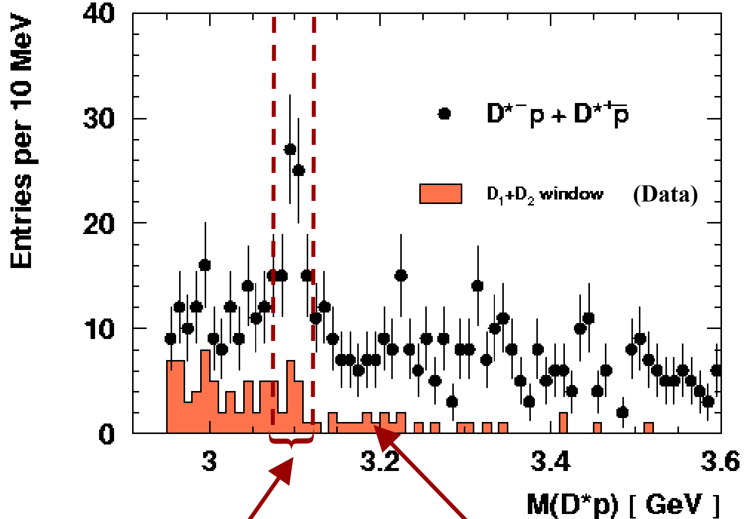
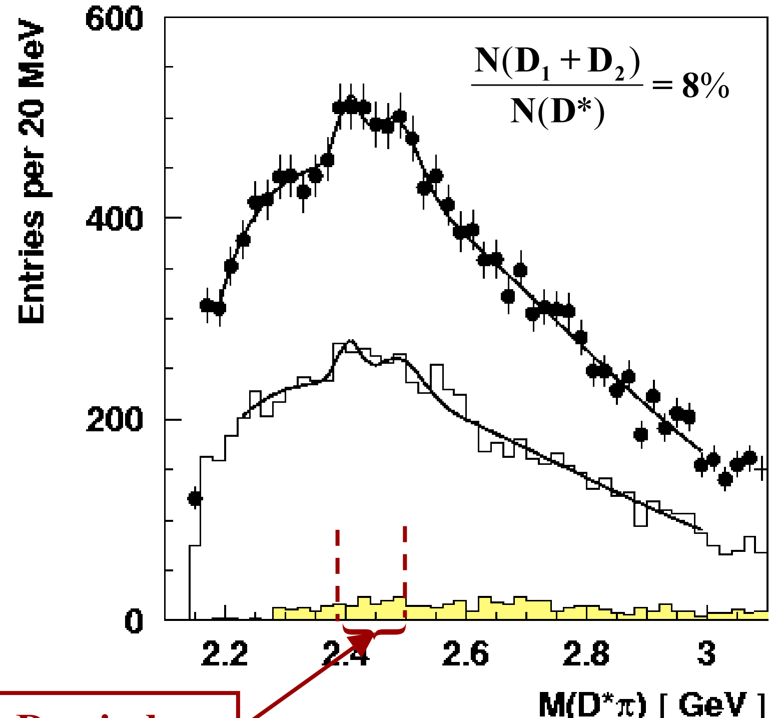


No cut in D^*p



Corrected for combinatorics,
Then expect 3.5 events from data

D_1, D_2 window

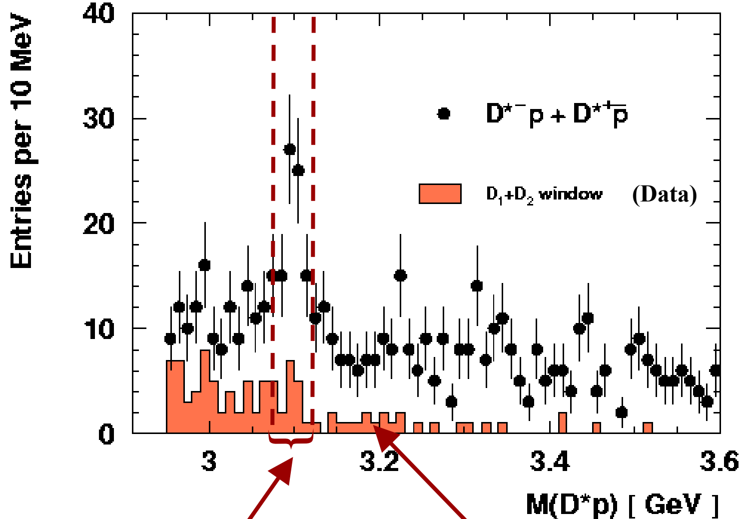
$N(D_1+D_2) = 3.5$ in the D^*p signal region from MC

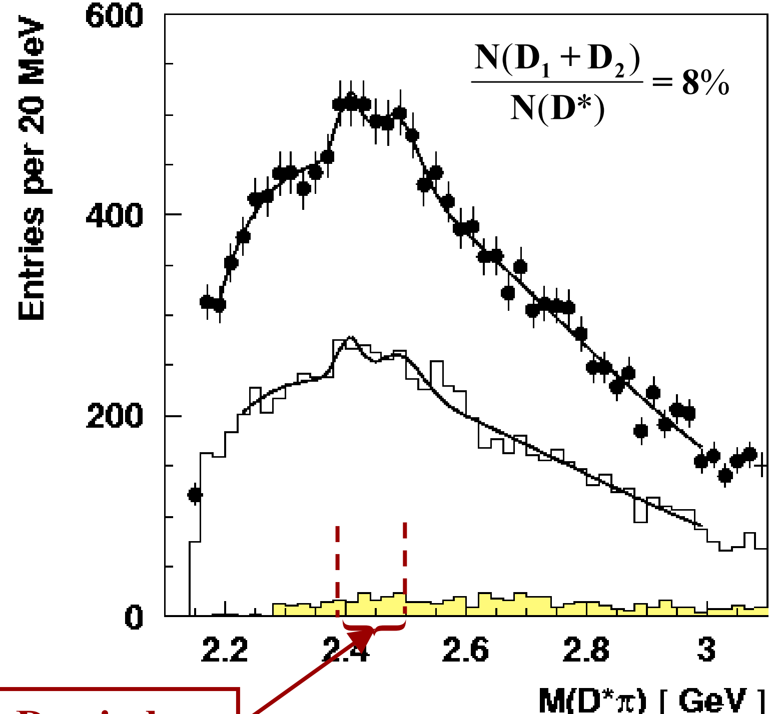
$M(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*)_{PDG}$

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

Small !

No cut in D^*p





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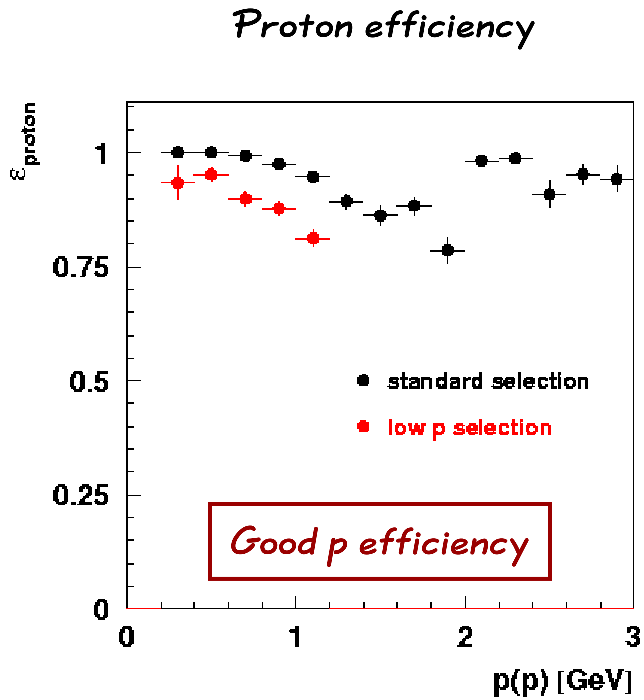
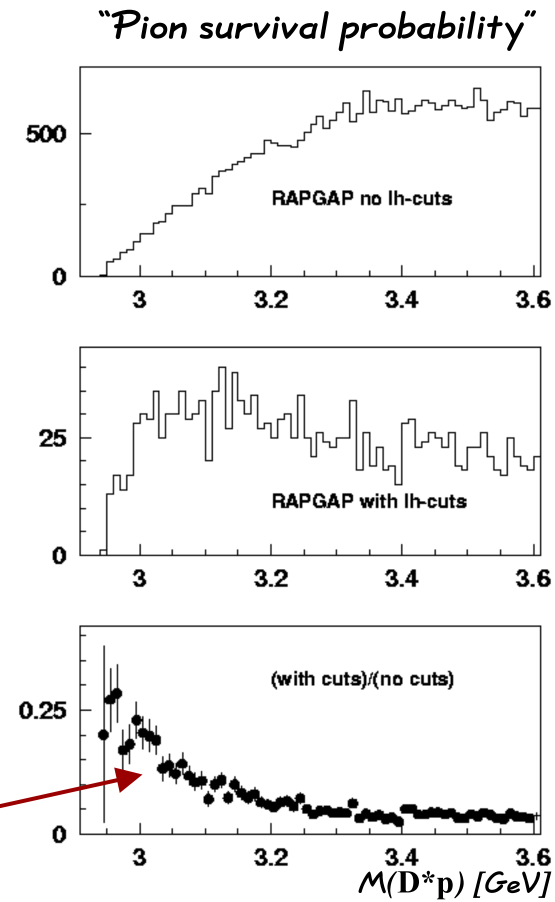
$N(D_1+D_2) = 3.5$ *in the*
D^*p *signal region from MC*

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

Does some acceptance effect fool us ?





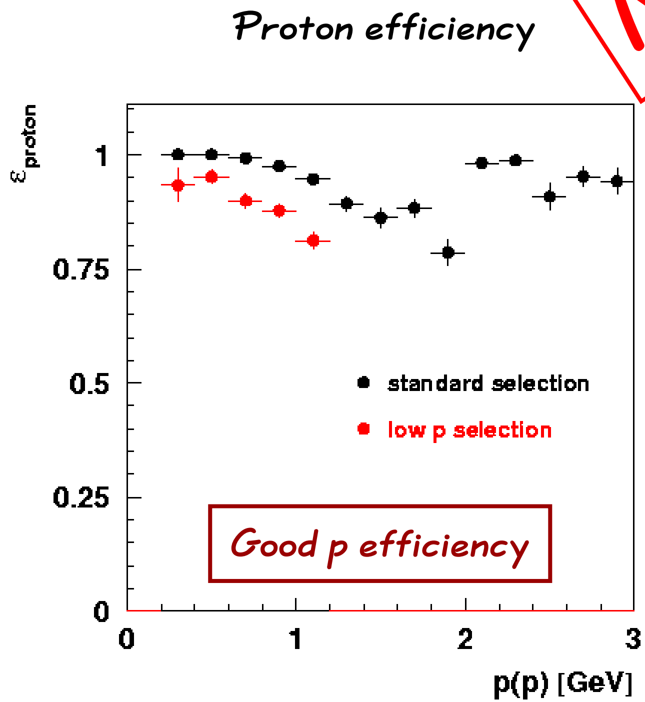
Smooth variation with $M(\mathrm{D^*p})$

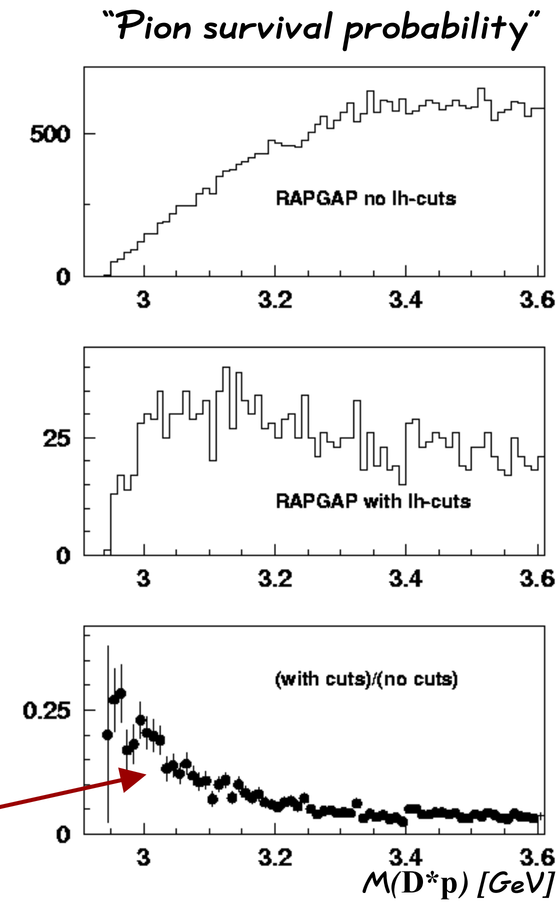
Shape reflects opening of phase space

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

Does some acceptance effect fool us ?

NO!



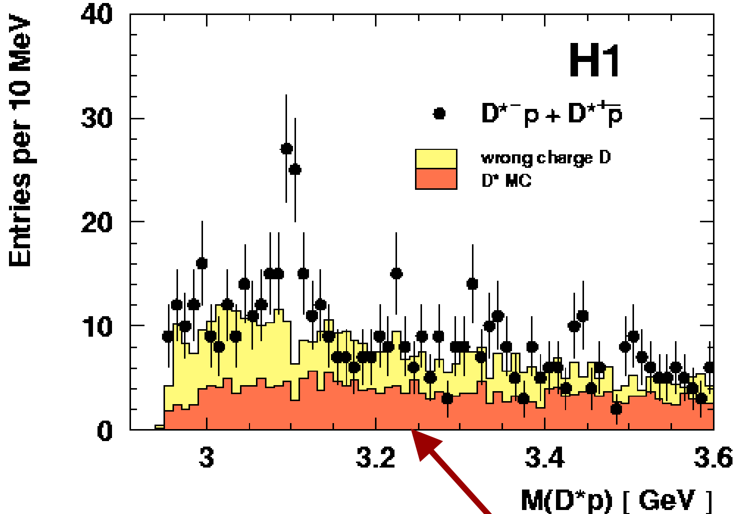


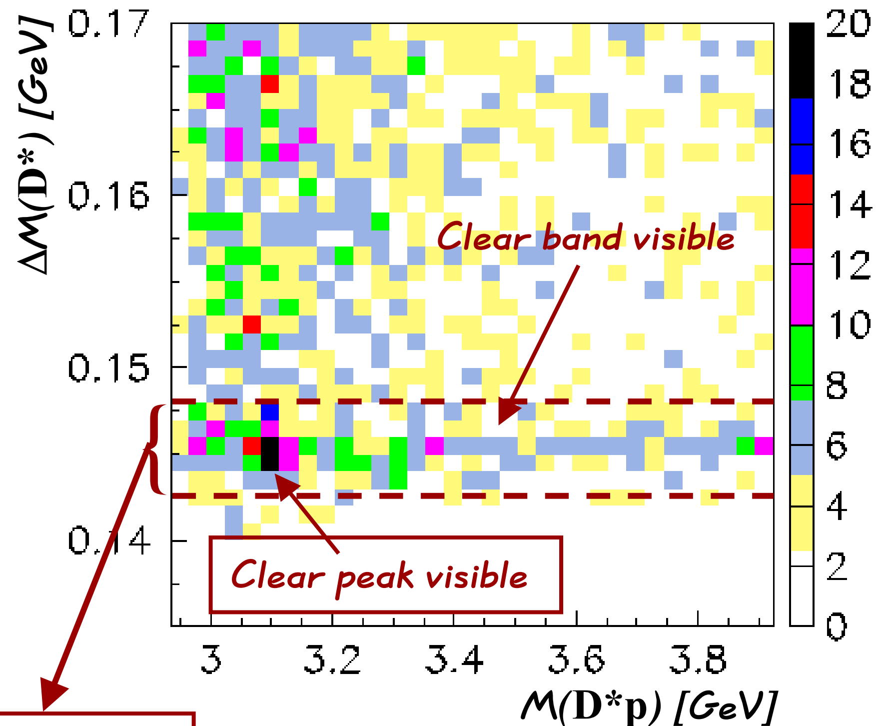
Smooth variation with M(D*p)
Shape reflects opening of phase space

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

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

1) Charge conjugate always implied





D* signal region

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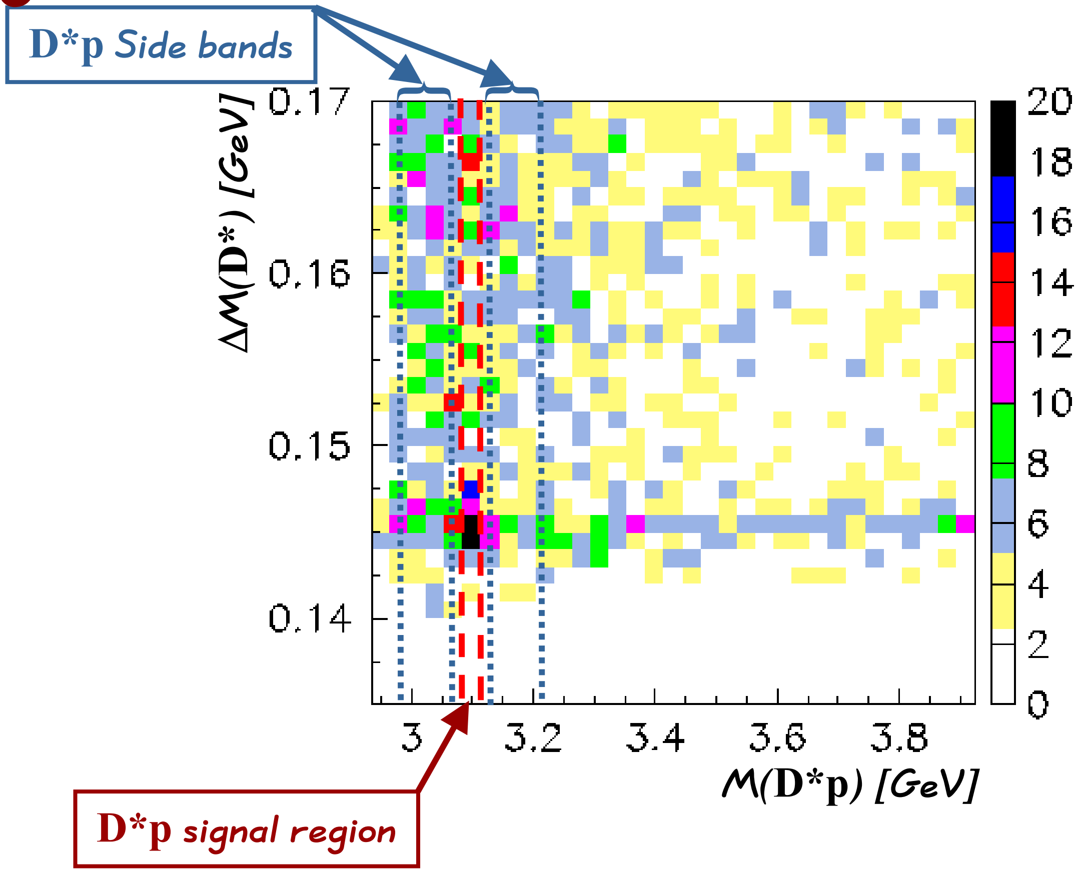

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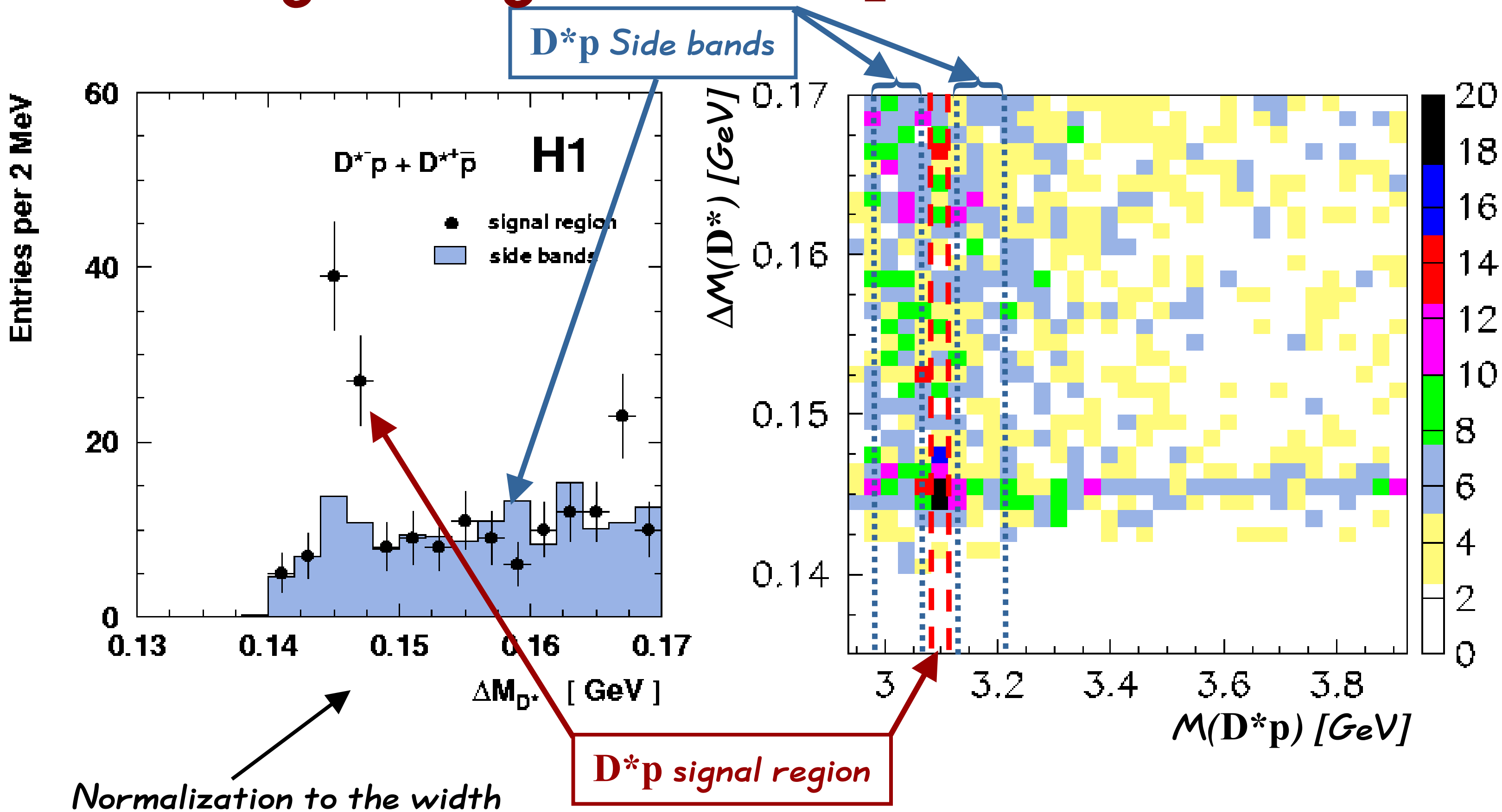


*Normalization to the width of the windows in M(D*p)*

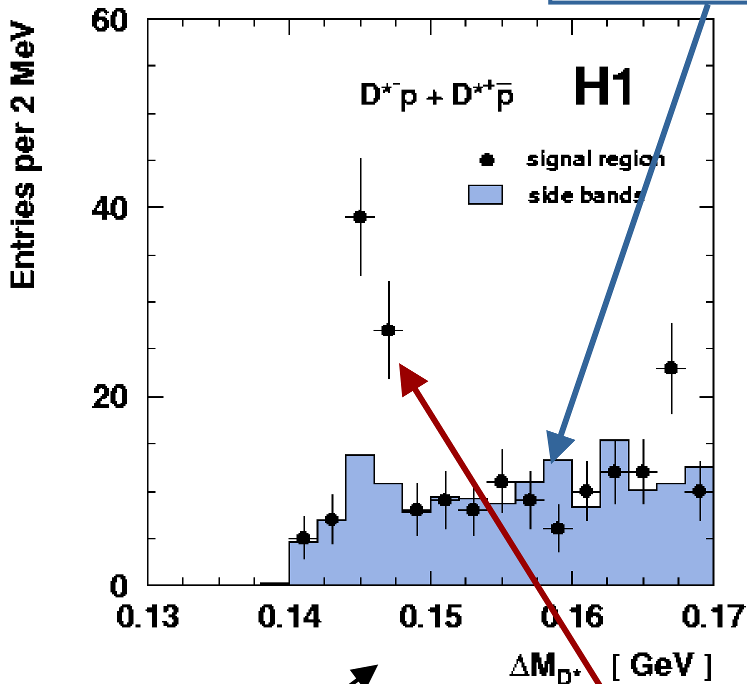
$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

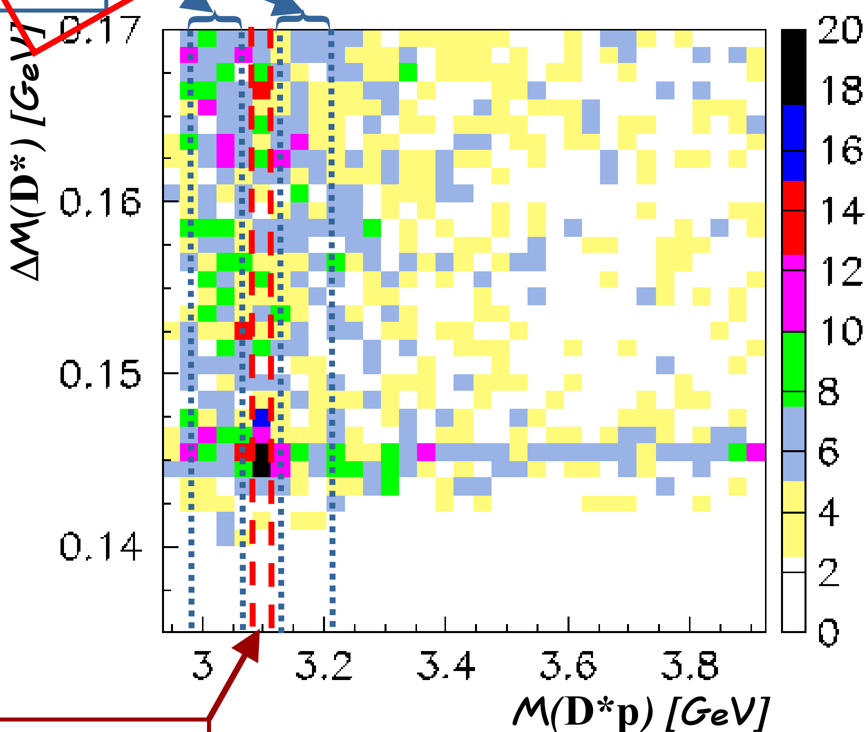
1) Charge conjugate always implied

Signal region in D*p [1] richer in D*⁻?

YES!

D*p Side bands





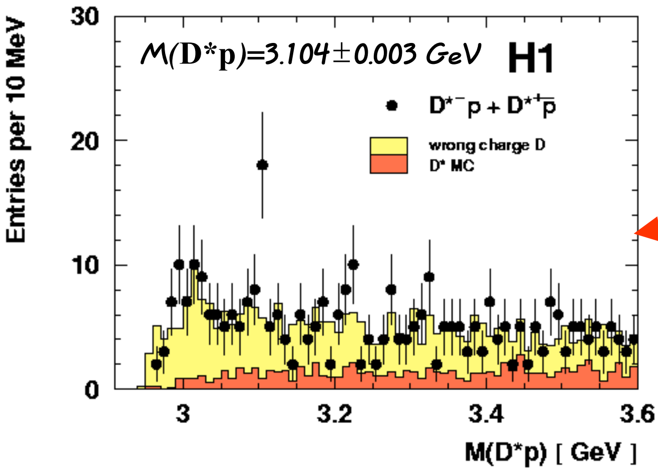
*Normalization to the width of the windows in M(D*p)*

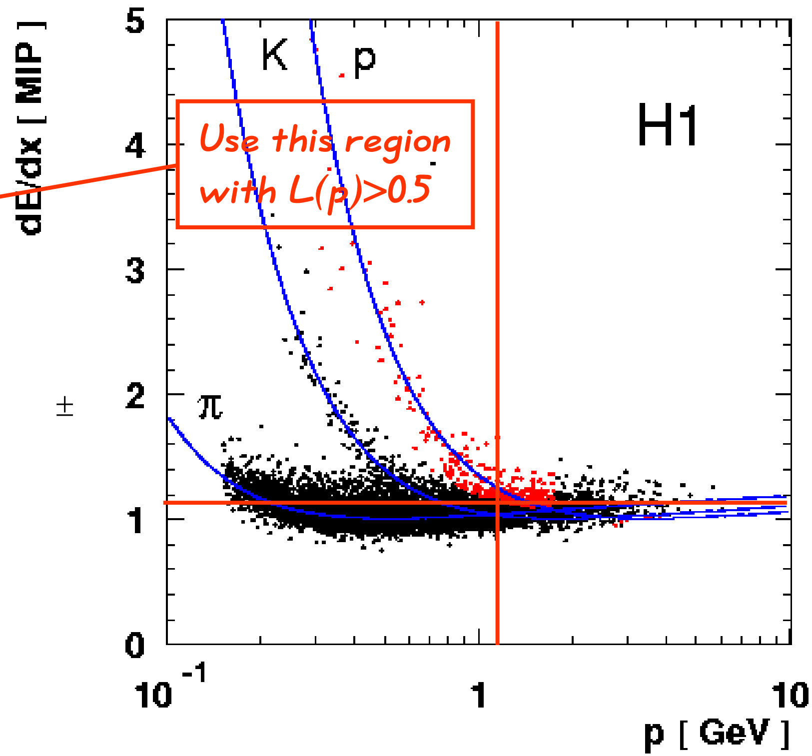
D*p signal region

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

1) *Charge conjugate always implied*

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





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

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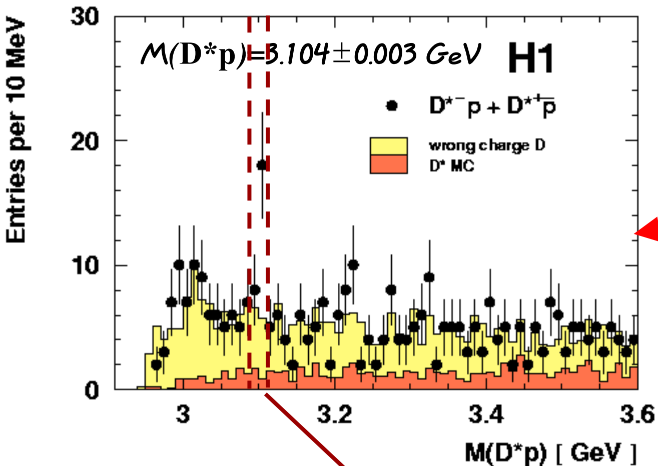

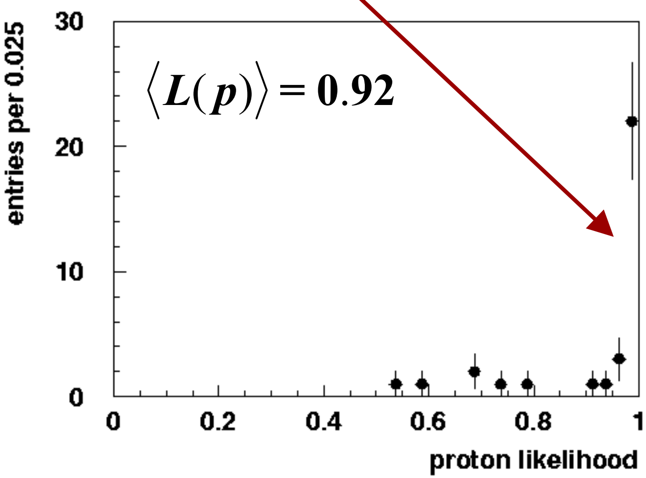

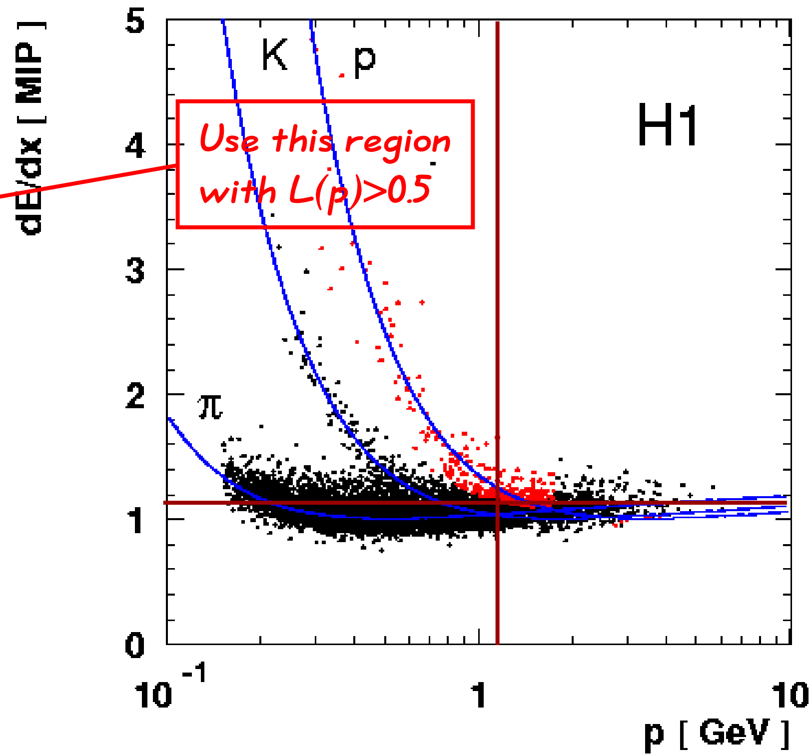

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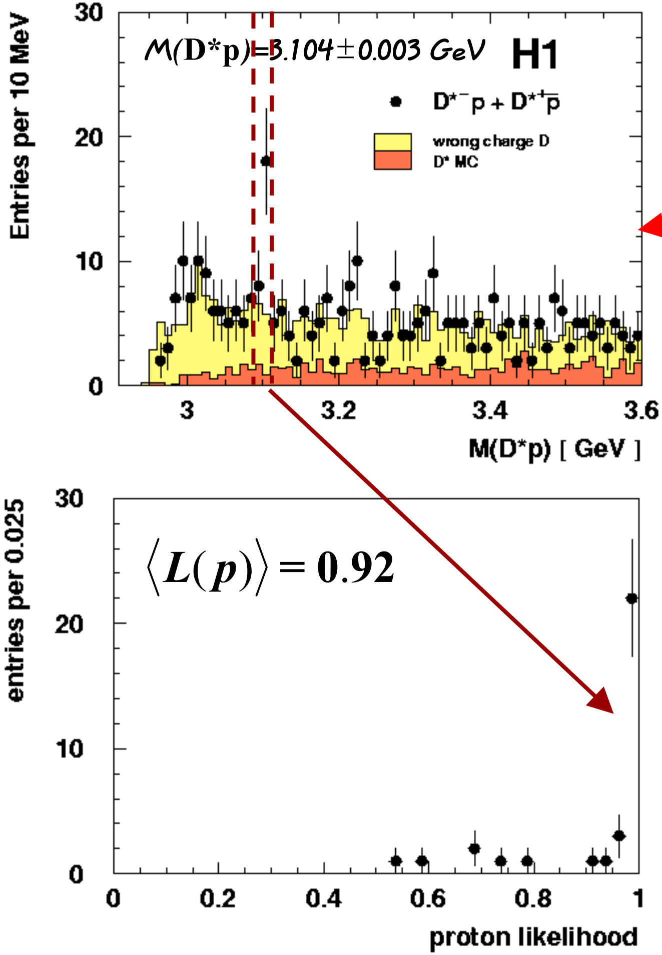
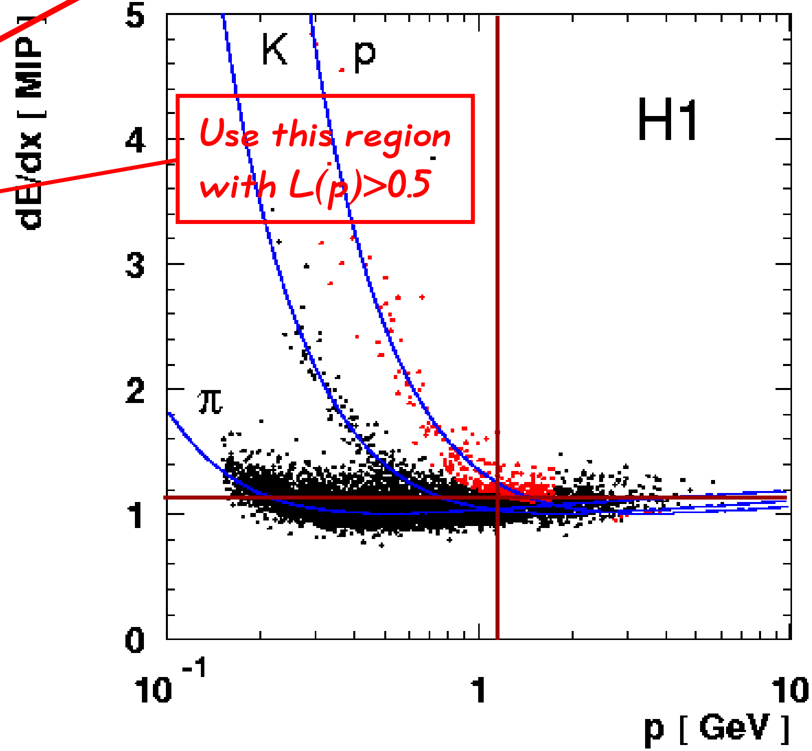
Is the $D^{*-}p$[1)] signal due to protons?

YES!





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

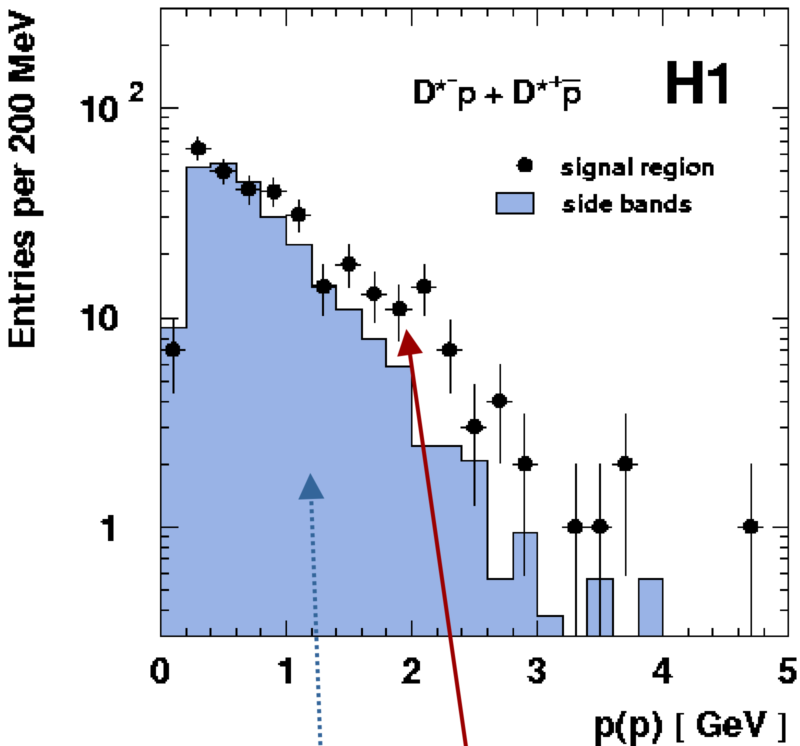
1) Charge conjugate always implied

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

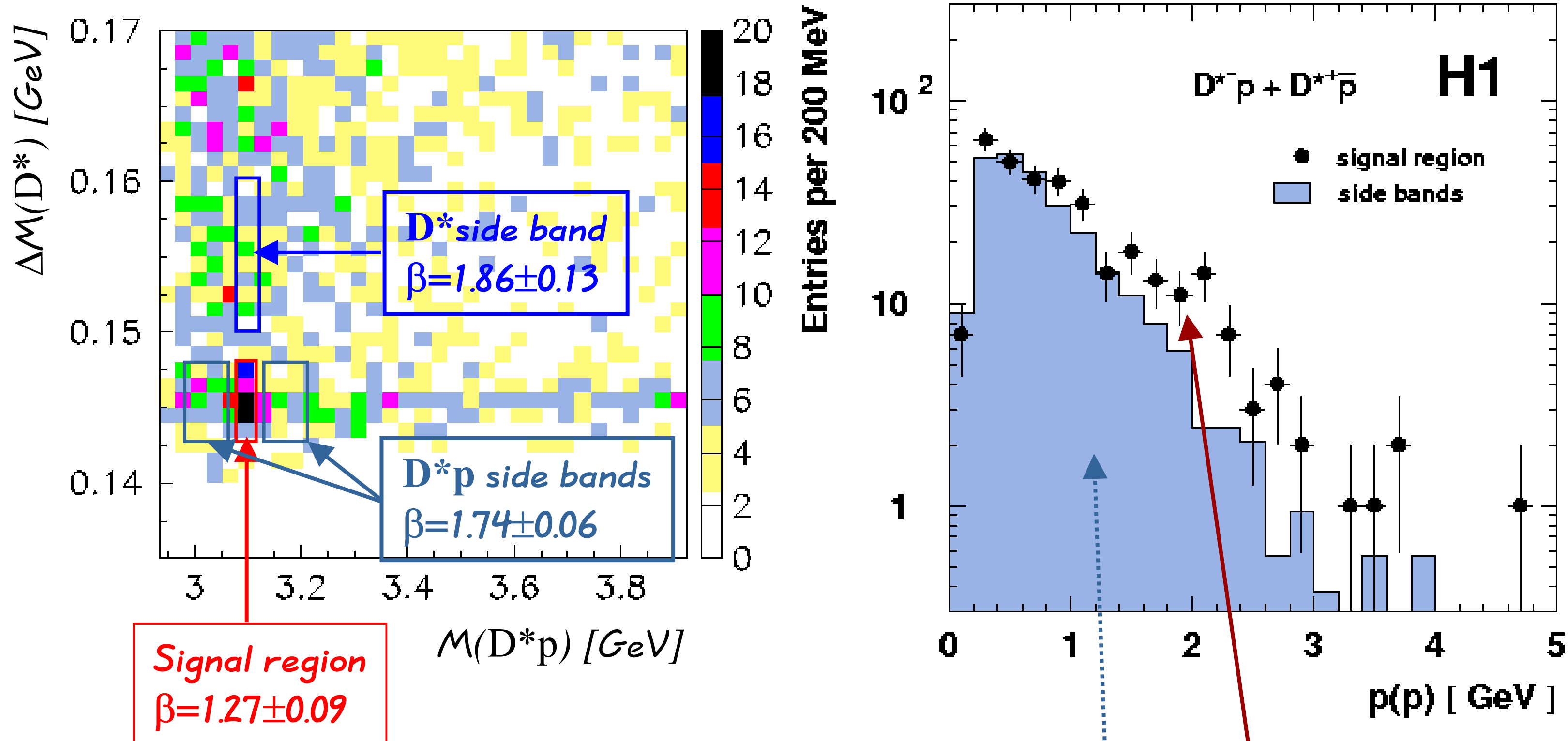
No L(p) cuts !



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



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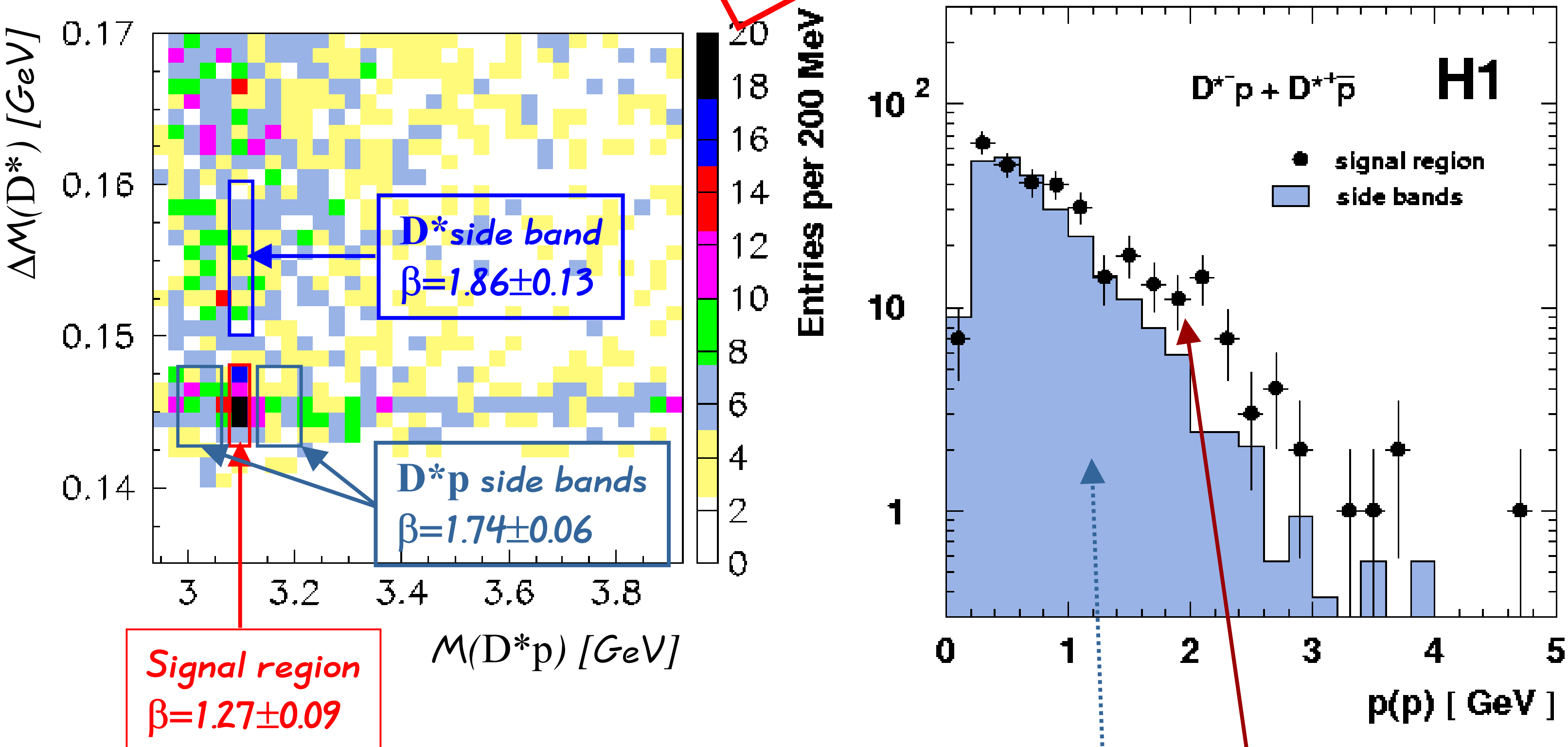
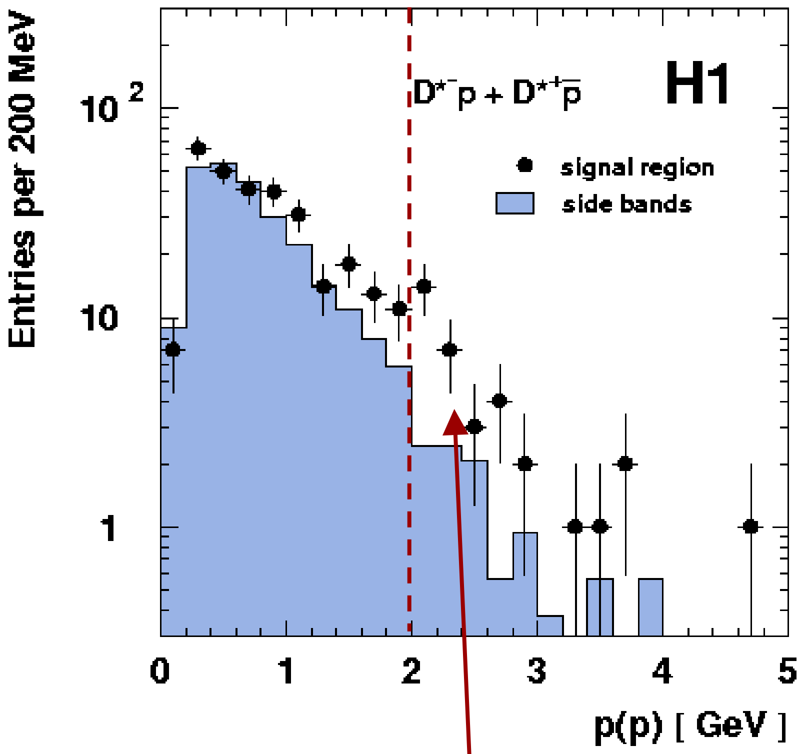


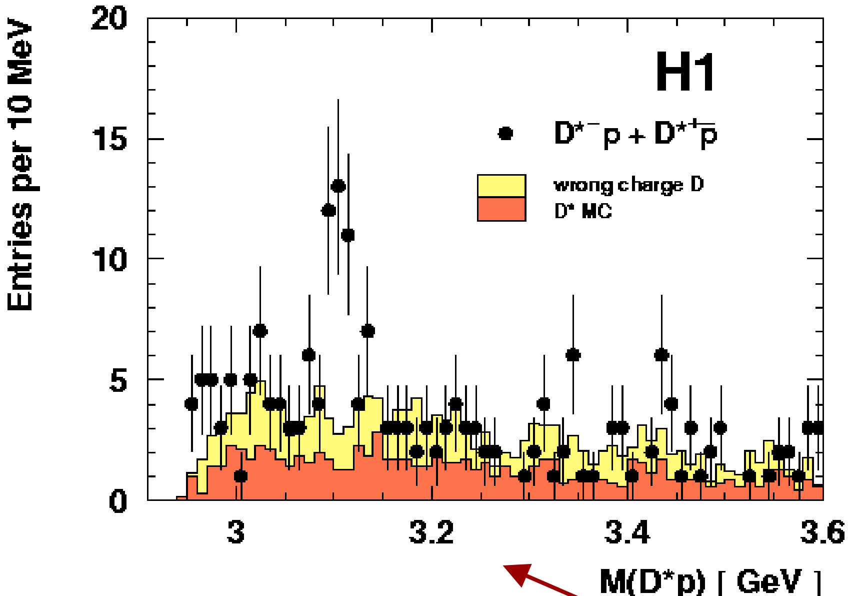
The momentum spectrum of the particles in the signal region is harder than in the M(D*p) side bands

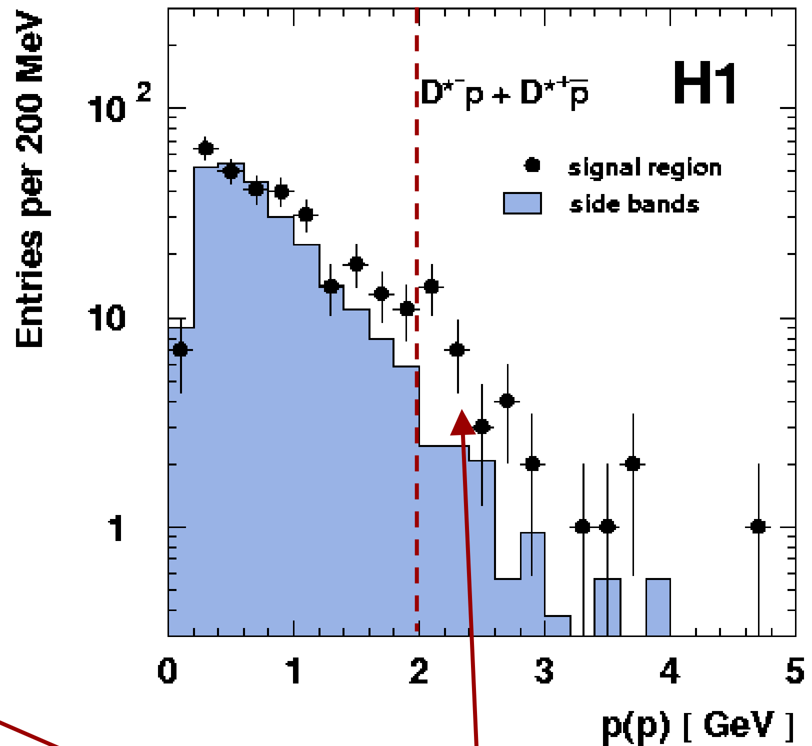
Signal at large p(p) more prominent ?



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

Signal at large p(p) more prominent ?

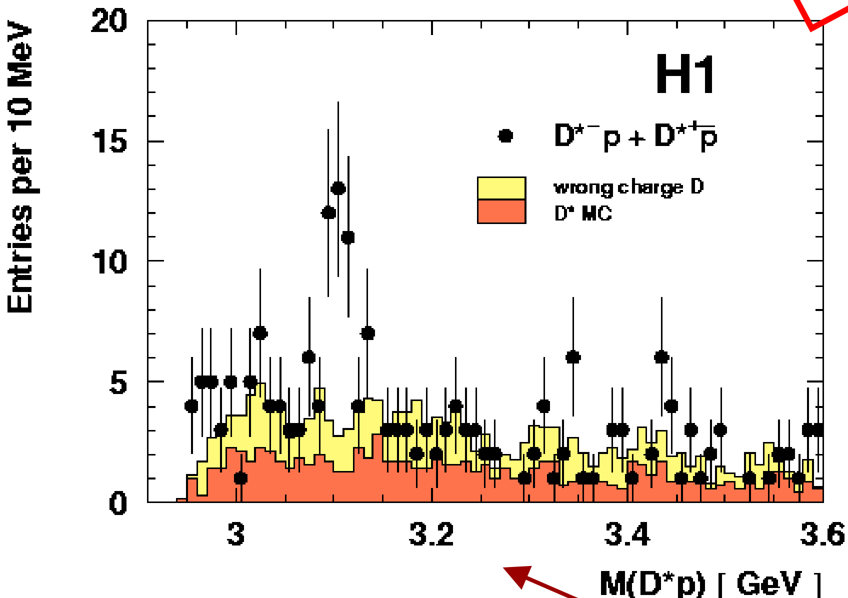


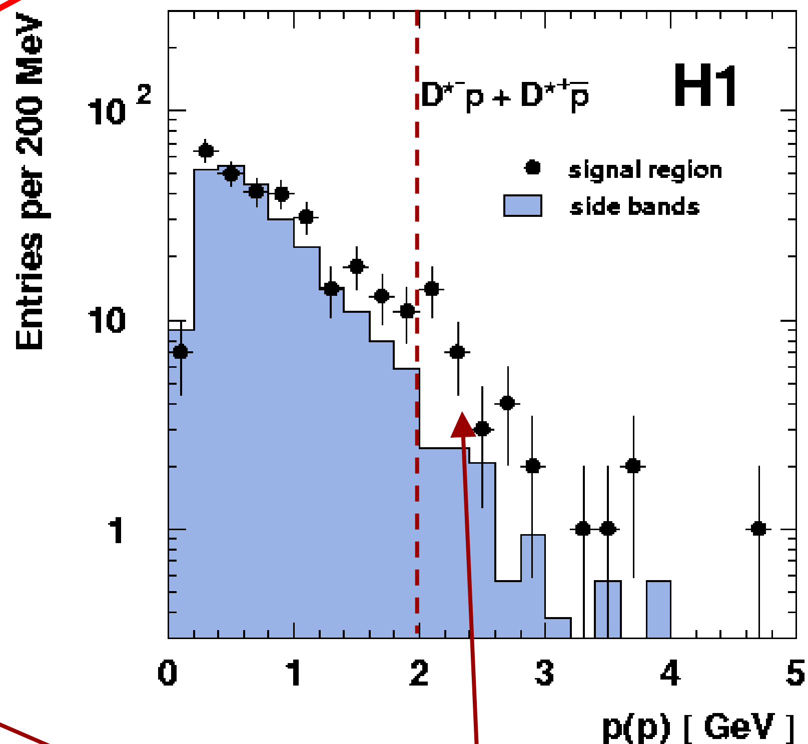


Signal to background improves at larger proton momentum → look at M(**D*p**)

Signal at large p(p) more prominent ?

YES!





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

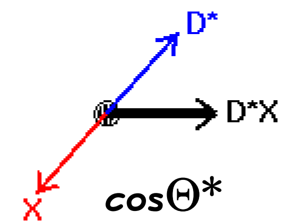
Basics of kinematic tests

2-Body Decay

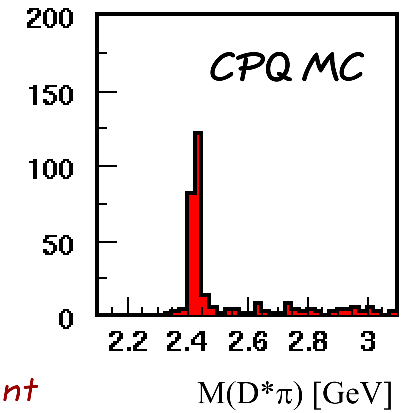
$$M^2 = (P_1 + P_2)^2$$
$$= (m_{D*}^2 + m_X^2 + 2E_{D*}E_X - 2\vec{p}_{D*}\vec{p}_X)$$

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

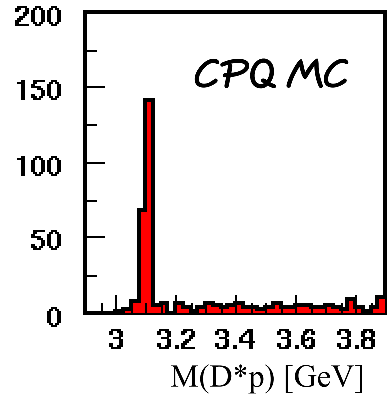
D*p rest frame

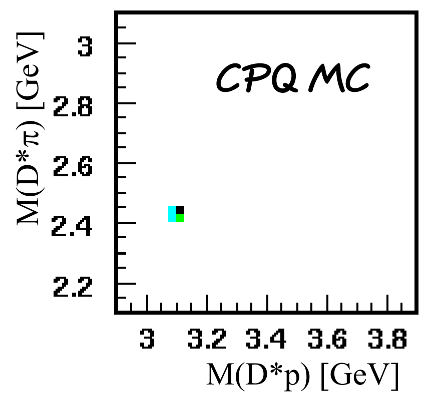


wrong mass assignment



correct mass assignment





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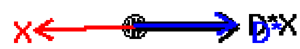
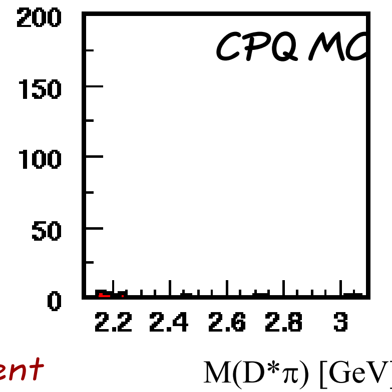
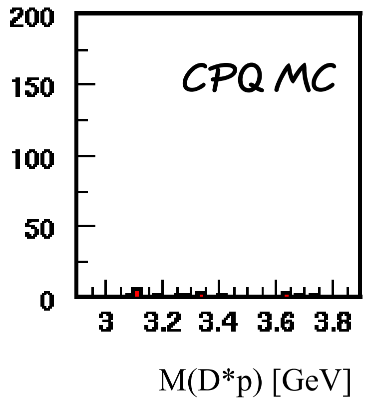
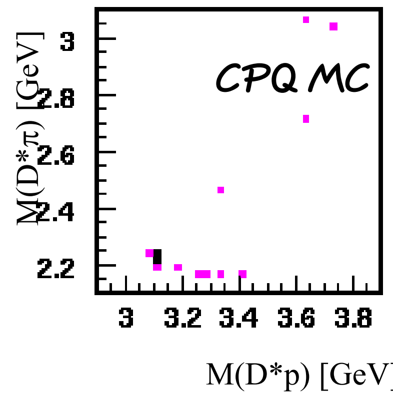


wrong mass assignment



correct mass assignment





Kinematic tests

2-Body Decay

$$M^2 = (P_1 + P_2)^2$$
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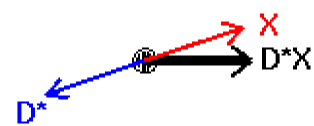
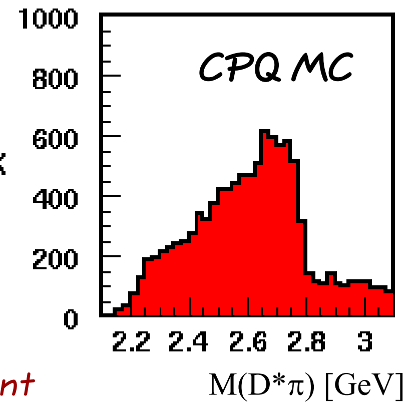
D*p *rest frame*

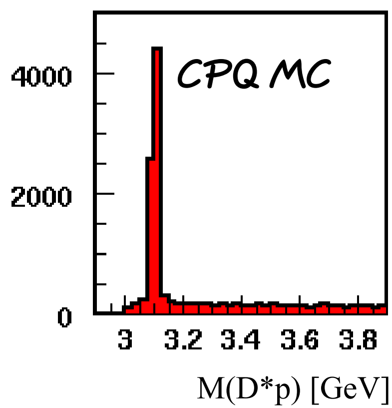


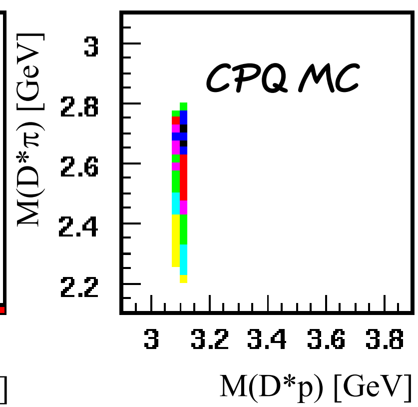
wrong mass assignment



*Integrated in cosΘ**

correct mass assignment

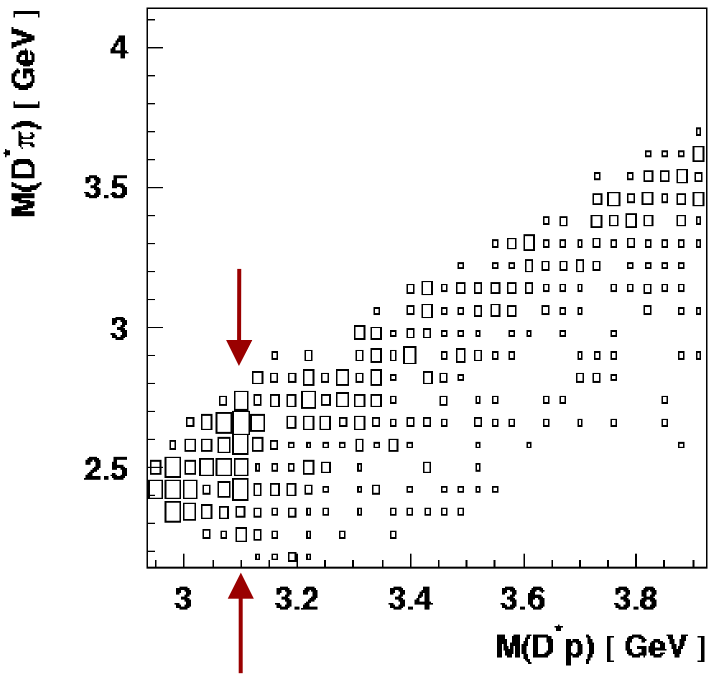




Do we see a band like structure in the M(D*p)-M(D*x) plane in data? → Let's have a look

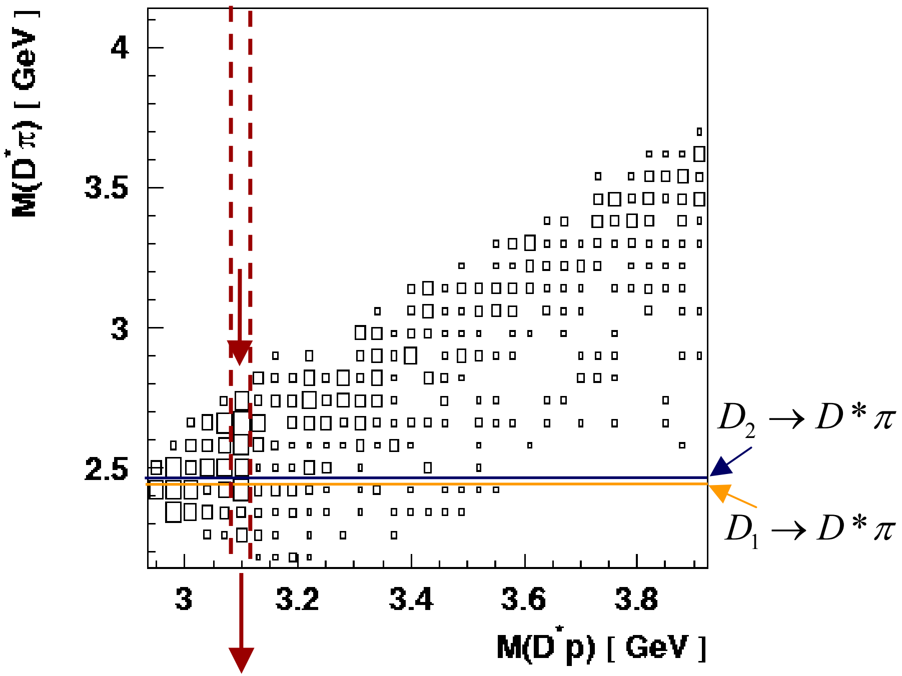
Signal due to $D^*\pi$?

Back to data !



Band in $D^*\pi$ clearly visible

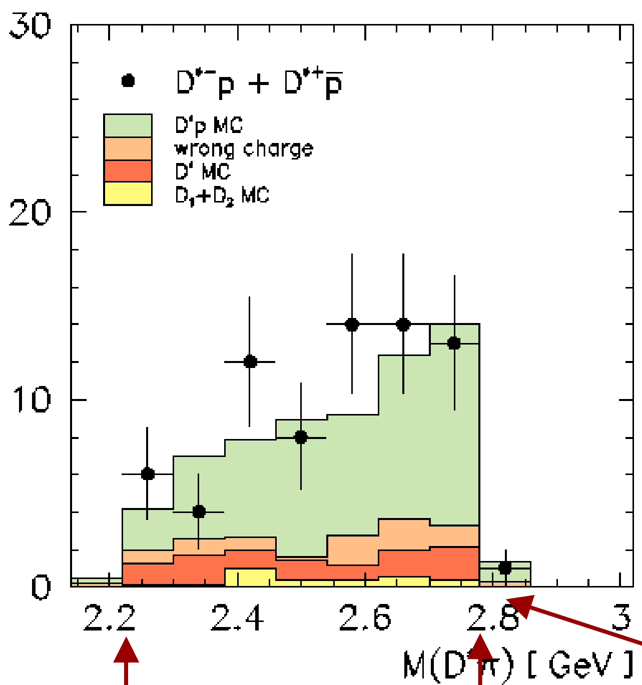
Signal due to $D^*\pi$?

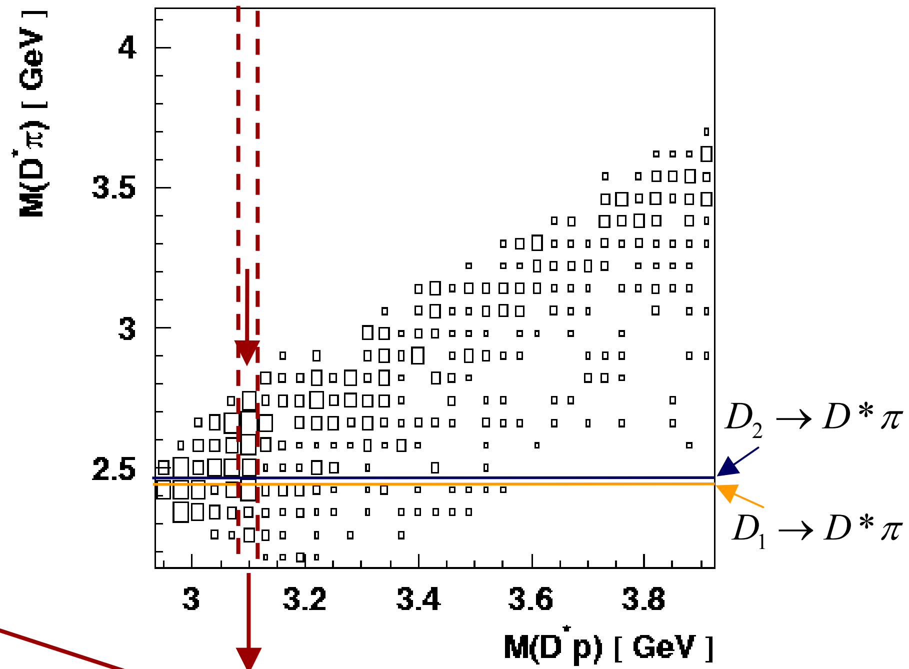


Go to the D^*p signal region

No indication for contributions from D_1 and D_2

Signal due to $D^*\pi$?



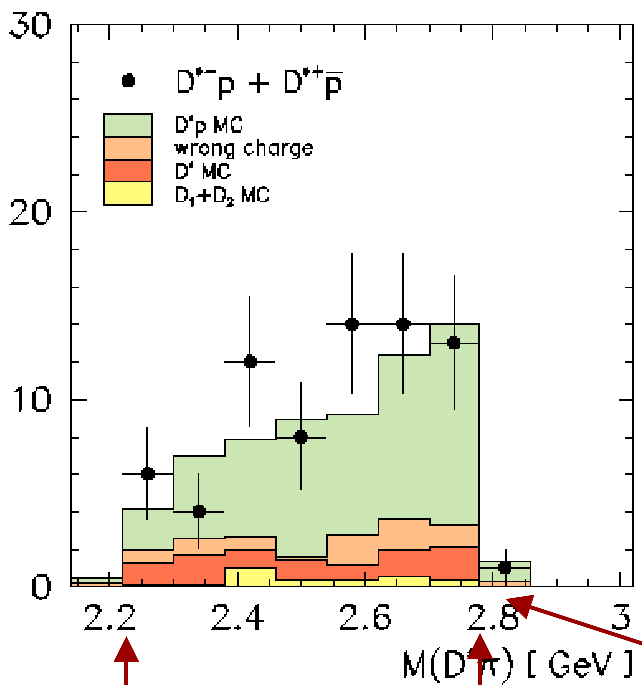


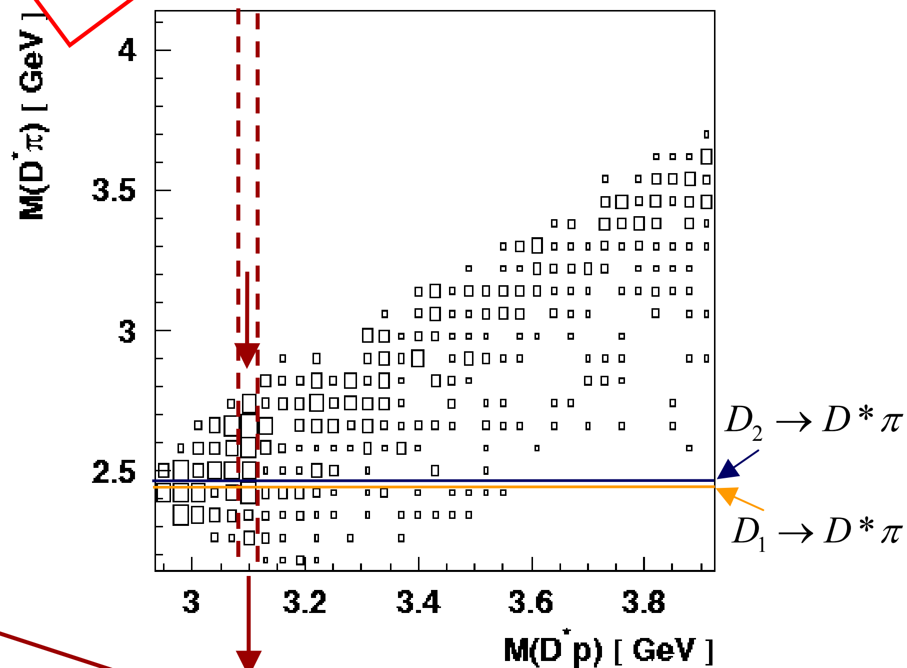
Go to the D^*p signal region

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

Signal due to $D^*\pi$?

NO!



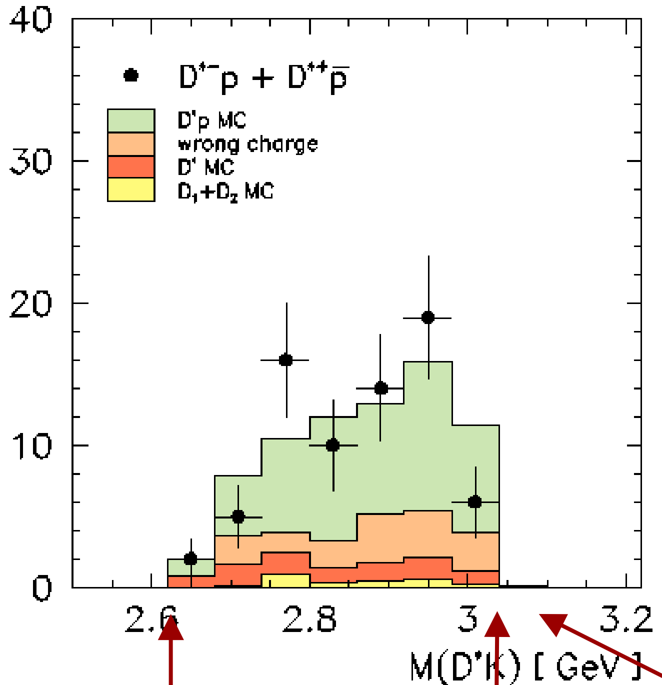


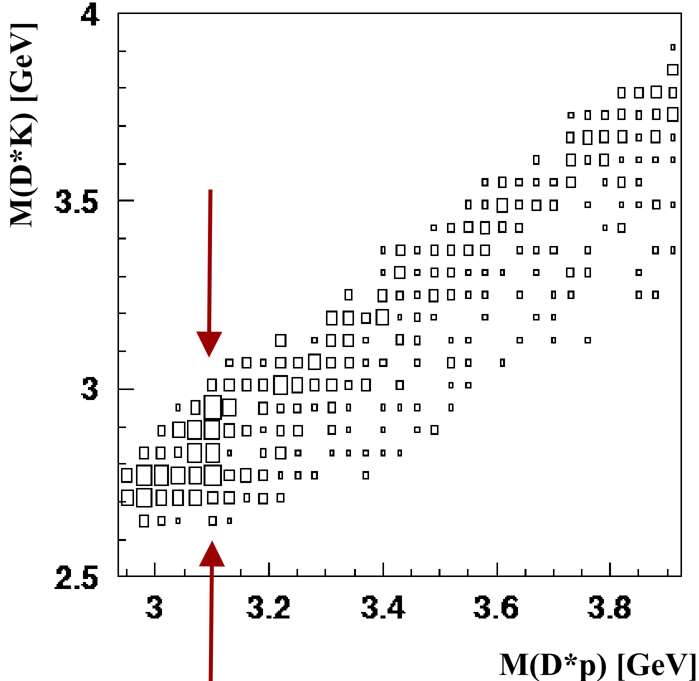
Go to the D^*p signal region

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



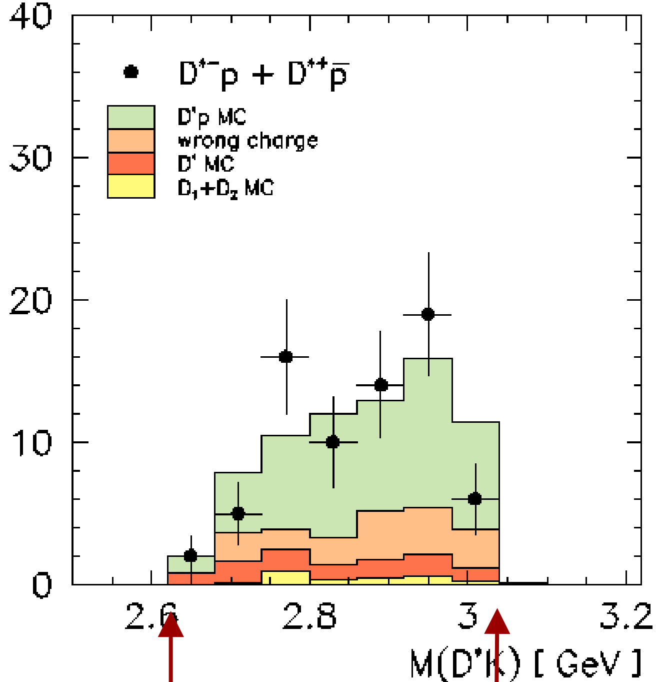


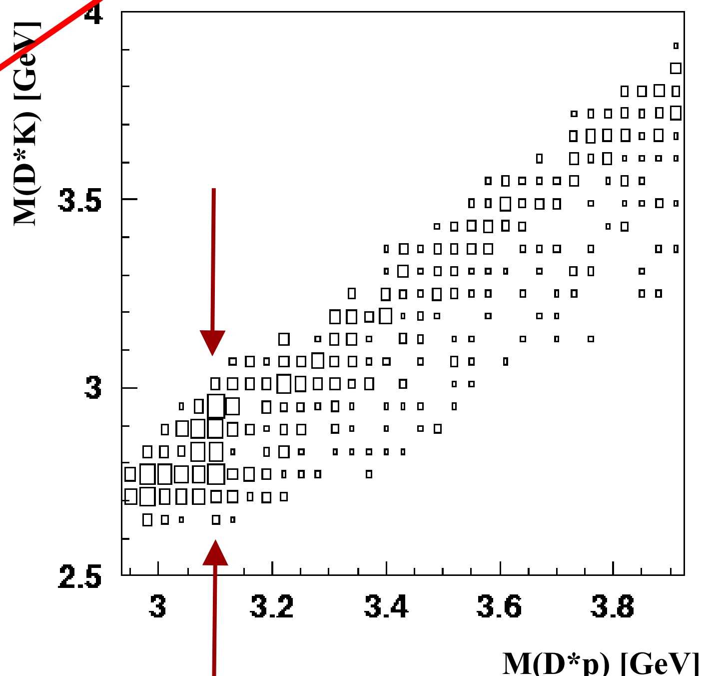
Band in D*K clearly visible
Go to the D*p signal region

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

Could it be due D*K ?

NO!



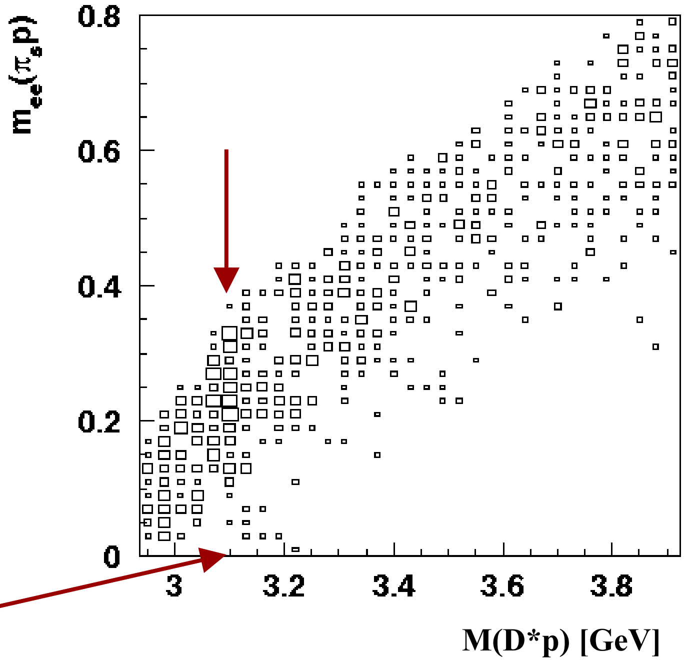


Band in D*K clearly visible

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

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

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



No accumulation at zero

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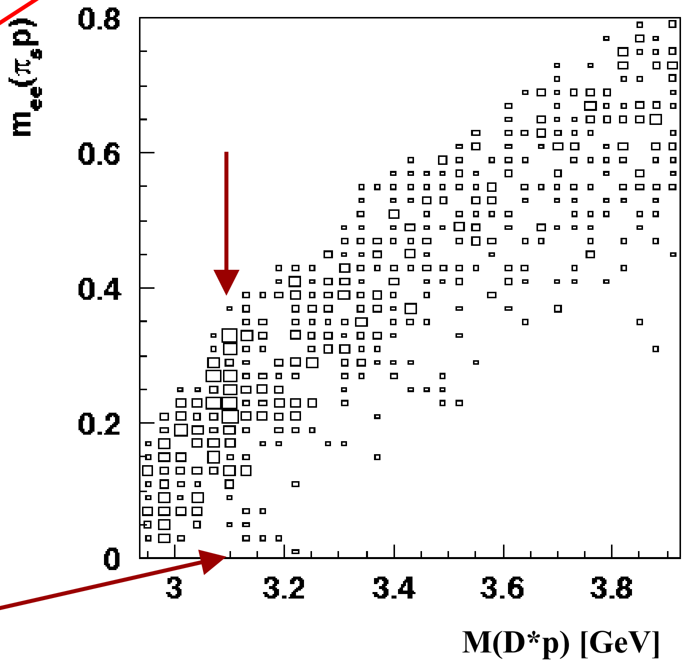

No accumulation at zero

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

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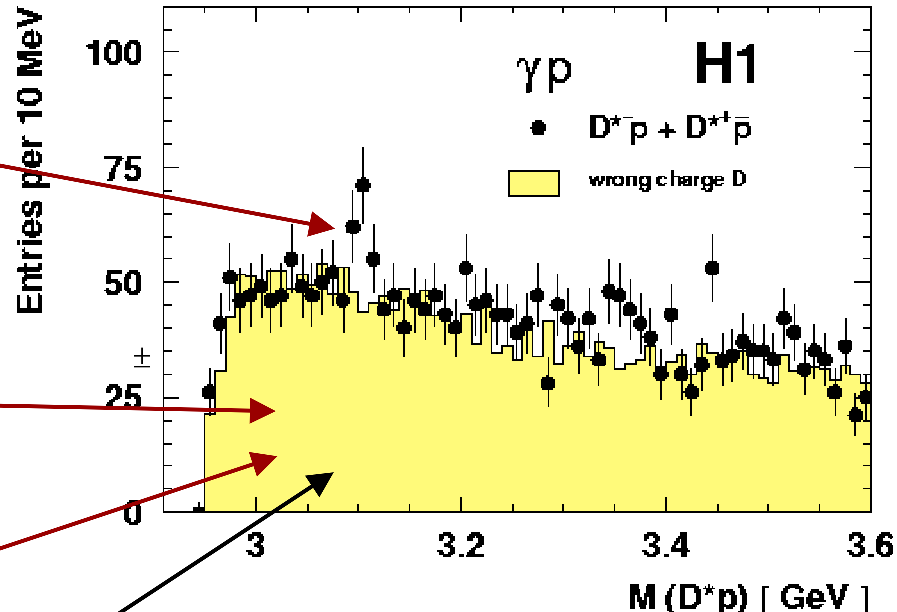
PASSED!

$D^{*-}p$[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

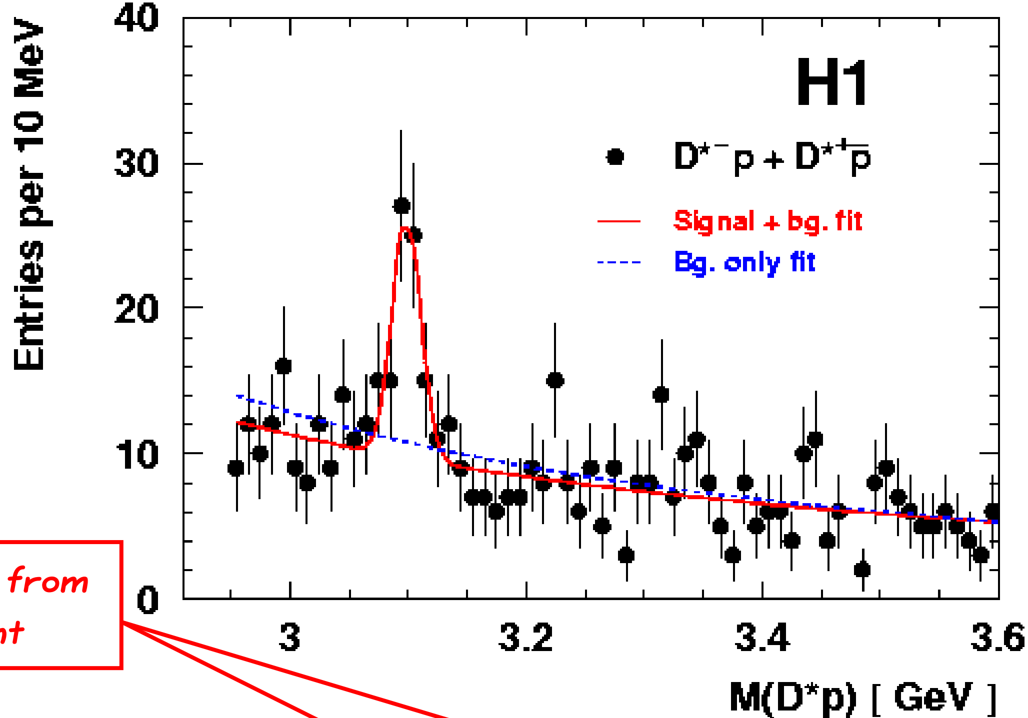
No enhancement in non-charm background

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



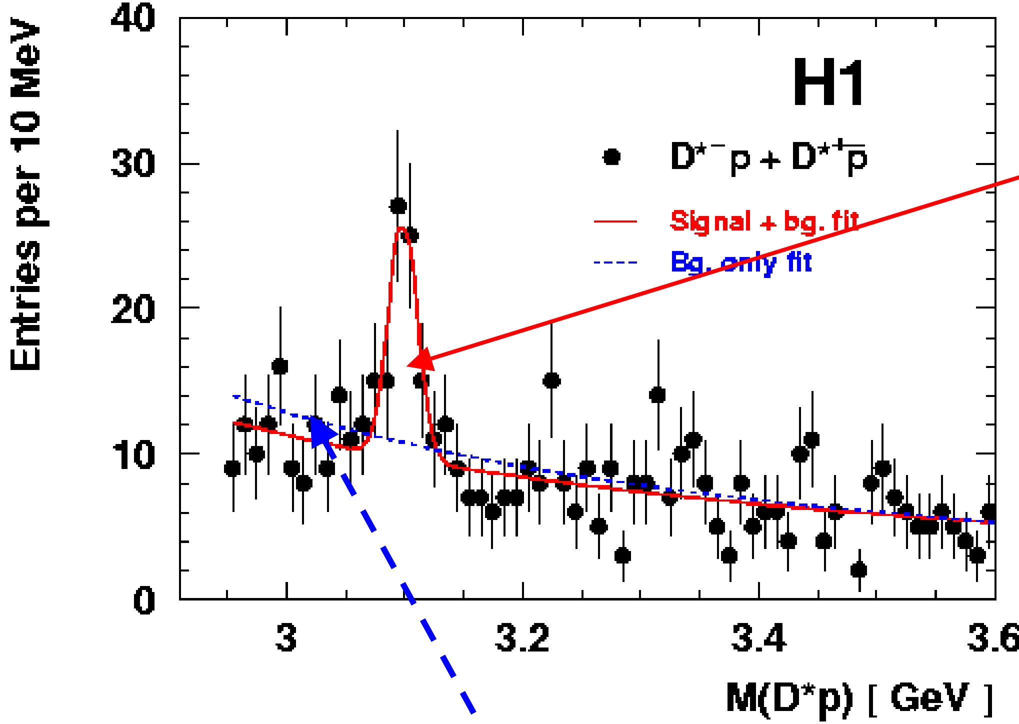
Stability of result against all sorts of variations checked

In total about 100 D^*p in DIS+γp

Masses & widths from fits are consistent

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

Checks

- Meanwhile 4 independent analyses

  (whoever looks for it, verifies it)
- Using 4 independent codes for the central analyses

  (final D^* selection and proton selection)
- Based on 3 independent D^* pre-selections
- With 2 different methods (mass difference technique / constrained fit)
- Signal observed in DIS and photoproduction
- In independent running periods
- All events in the signal region scanned independently

Conclusions

- A clear narrow resonance is observed for both $D^{*-}p$ and $D^{*+}\bar{p}$ with a mass of 3099 ± 3 (stat.) ± 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.

It was a real collaboration

- Many H1 members have contributed actively to this analysis. About 20 people have been more or less intensively involved.
- I would like to name especially the younger scientists explicitly:
- Katerina Lipka did the second full analysis focusing on γp in the end
- Sebastian Schmidt took the responsibility to provide the n-tuples and made checks
- Olaf Behnke immediately jumped on the CPQ MC, did everything needed on generator level, did many checks on stability and especially on significance…
- Andreas Meyer immediately took care of the first simulation, RAW data retrieval, did many cross checks…
- Christiane Risler, Dimitrij Ozerov, helped checking dE/dx from Λ and K^0_S.
- Bengt Wessling tried to kill the signal - but failed
- And many more…