

*Evidence for a Narrow Exotic Anti-Charmed
Baryon State*

H1 Collaboration

Karin Daum

Dedicated to our dear friend and colleague Ralf Gerhards

Submitted to Phys. Lett. B

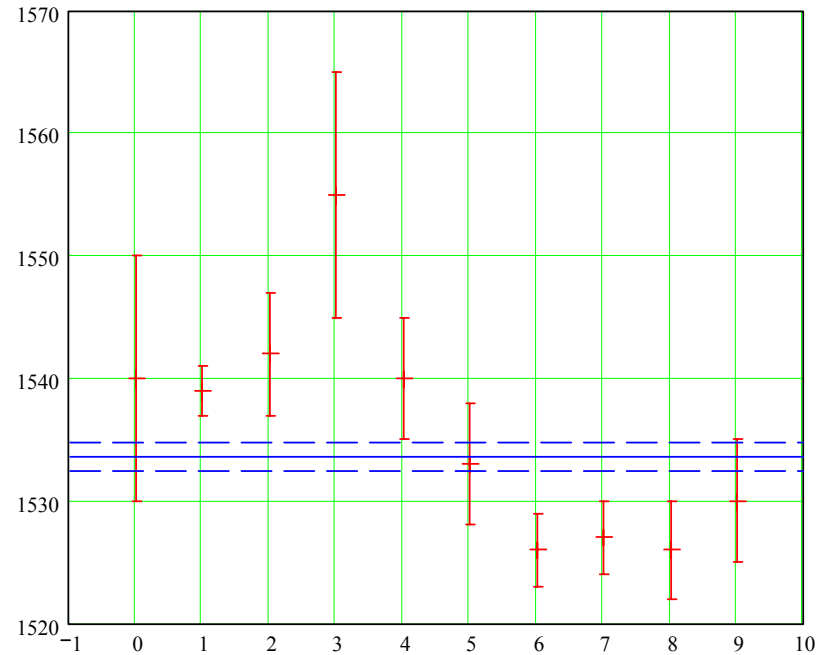
hep-ex/0403017

DESY 04-038

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



- $M(\Theta^+) - M(K) - M(p) = 100 \text{ MeV}$
- *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:

$$\Theta_c \rightarrow \bar{D} p$$

(pseudo-scalar D meson)

Charm fragmentation fractions

$f(c \rightarrow D^+)$	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
$f(c \rightarrow D^0)$	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
$f(c \rightarrow D_s^+)$	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
$f(c \rightarrow \Lambda_c^+)$	γp	$0.076 \pm 0.020^{+0.017}_{-0.001}$
	e^+e^-	0.076 ± 0.007
$f(c \rightarrow D^{*+})$	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

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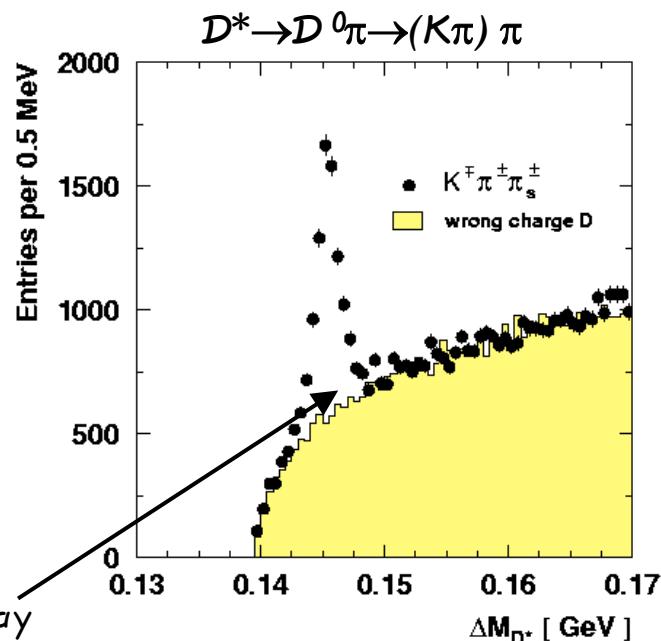
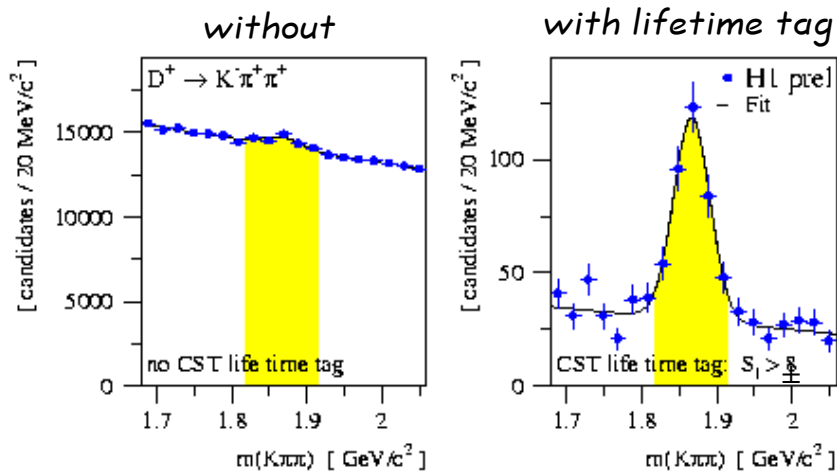
Vector mesons not suppressed

But what is experimentally feasible ?

Experimental Considerations

D^+ pseudoscalar meson

D^* vector meson



D^+ : huge background or low yield

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

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

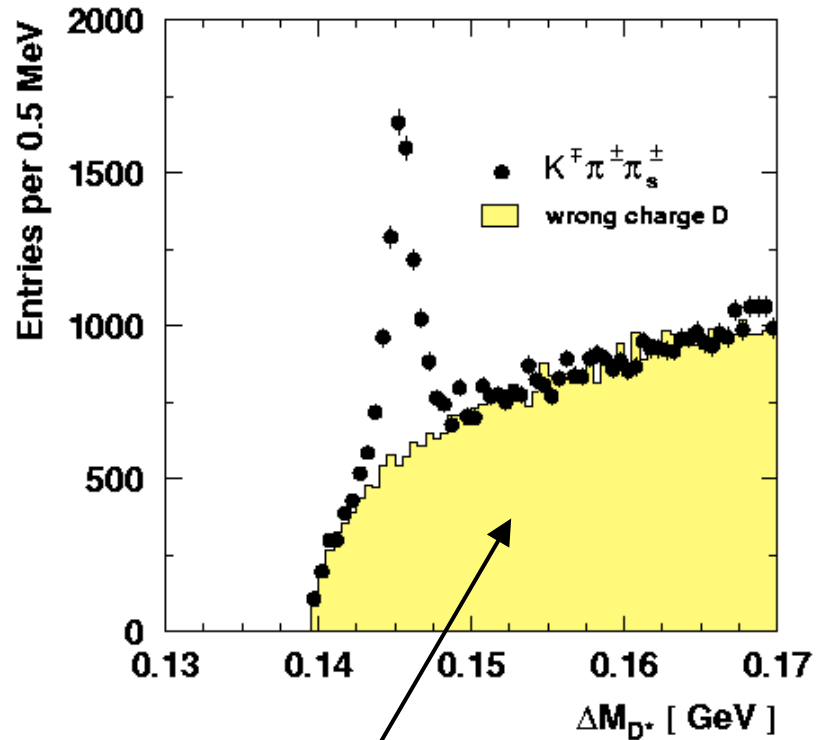
D^* experimentally much easier
Let's try it!

D* Signal

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

Only small signal expected
&
Tests of decay kinematics
foreseen

↓
Try to improve S/B



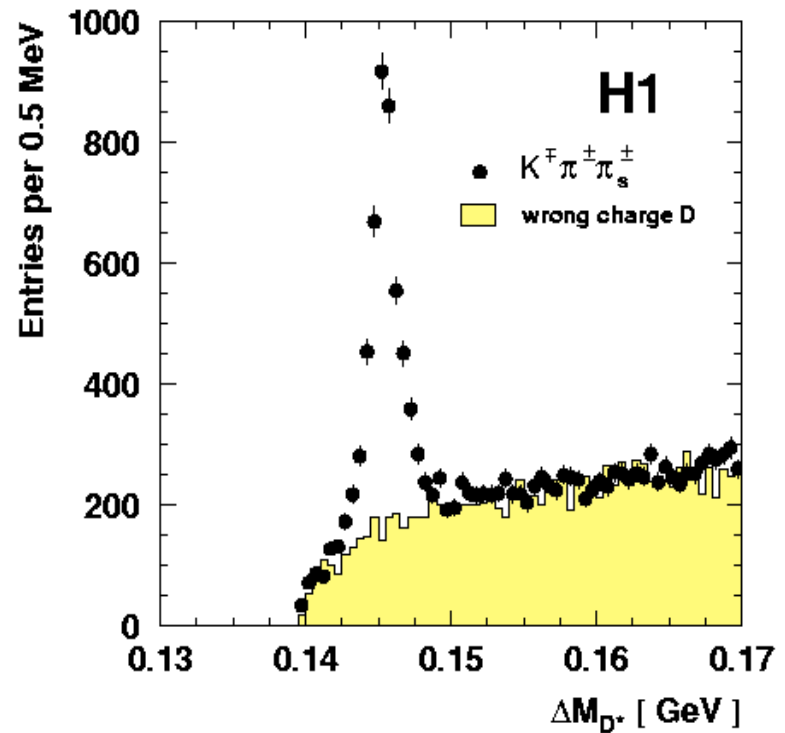
n
o
Non-charm induced background
-wrong charge D from $K^\pm \pi^\pm$
Combinations in D^0 mass window

D* Signal Final Selection

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

S/B improves by 2.5

3400 D's in DIS to start with*

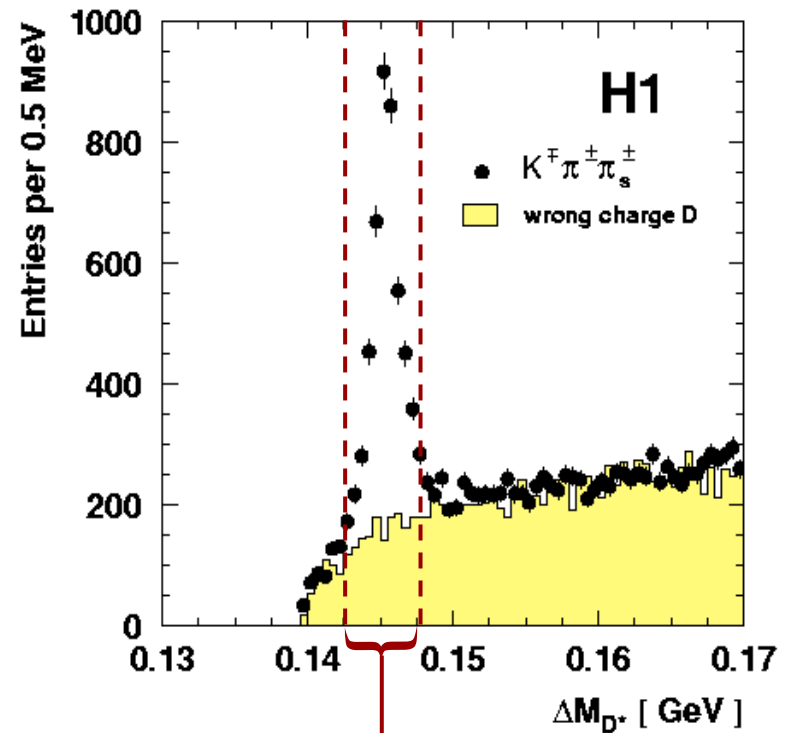


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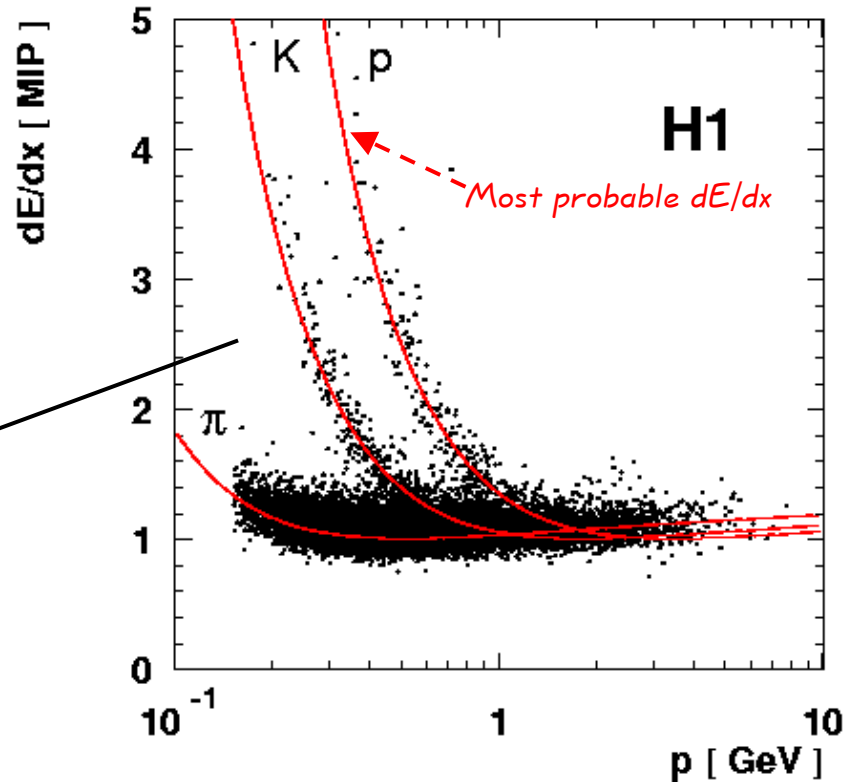
D signal region
subsequently used*

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:
 $(L(p) > 0.1 \& p(p) > 2) \text{ or } L(p) > 0.3$



Well enough understood to be used for background suppression

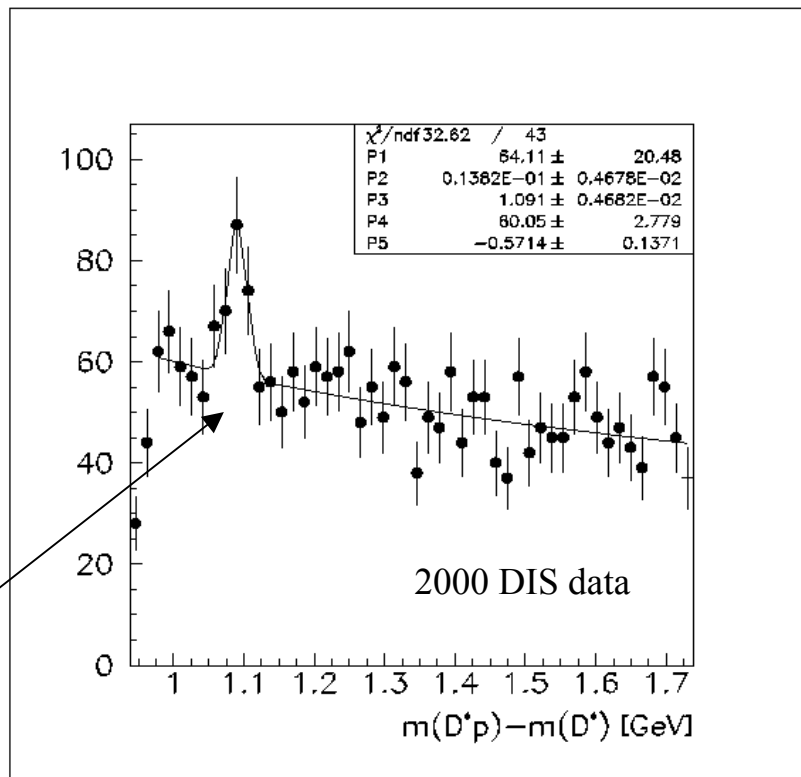
The very first look at $D^{*-}p$

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

$D^{*0}p + cc$ in DIS for 1996 - 2000

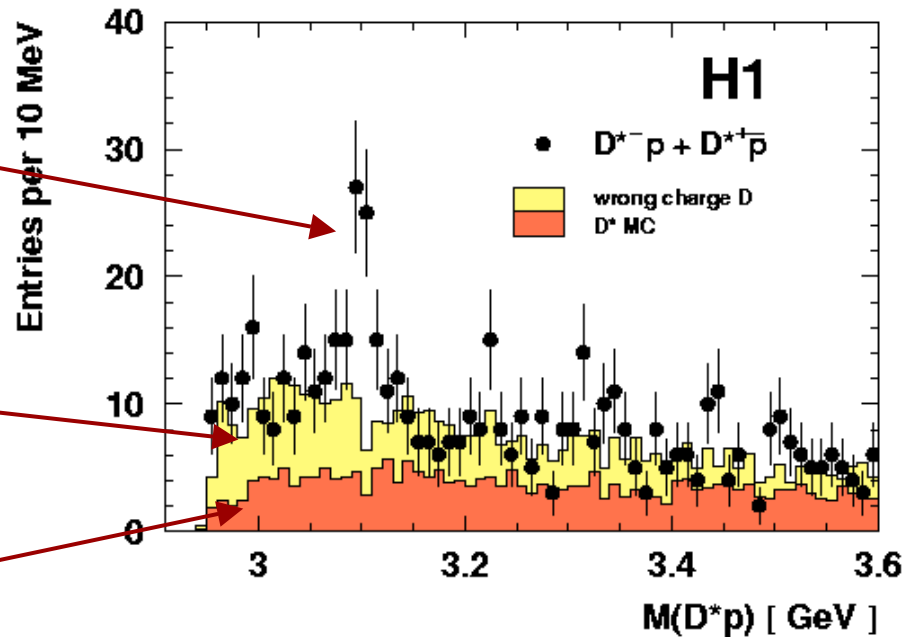
Cleanup of D^* signal and proton candidates by cuts given before

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

Significant peak in opposite sign D^*p

No enhancement in wrong charge D ¹⁾

No enhancement in D^* MC (RAPGAP) ²⁾



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

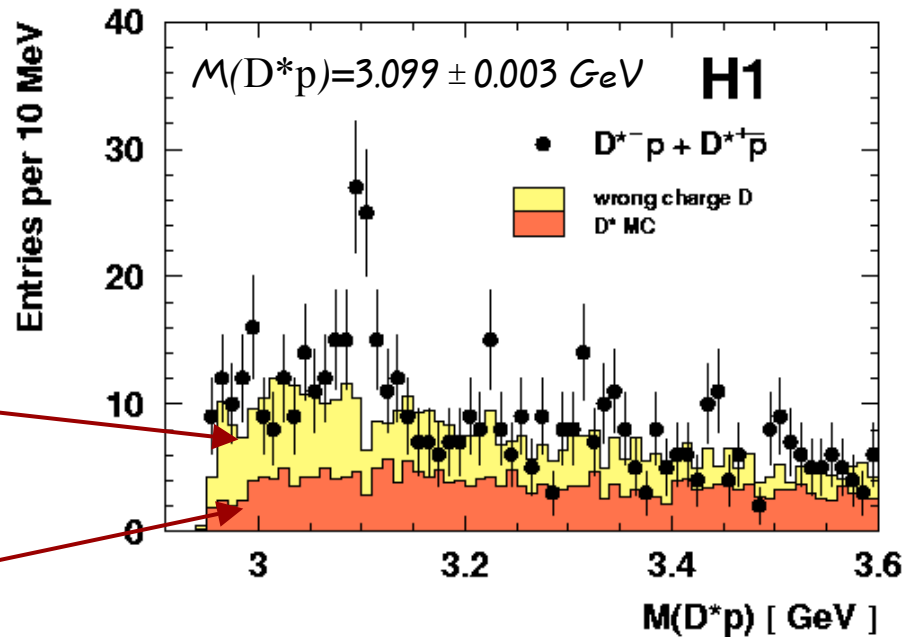
- 1) Mass of same sign $K^\pm \pi^\pm$ in $m(D^0)$ window
- 2) Also no peak from CASCADE or Beauty MC

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⁾

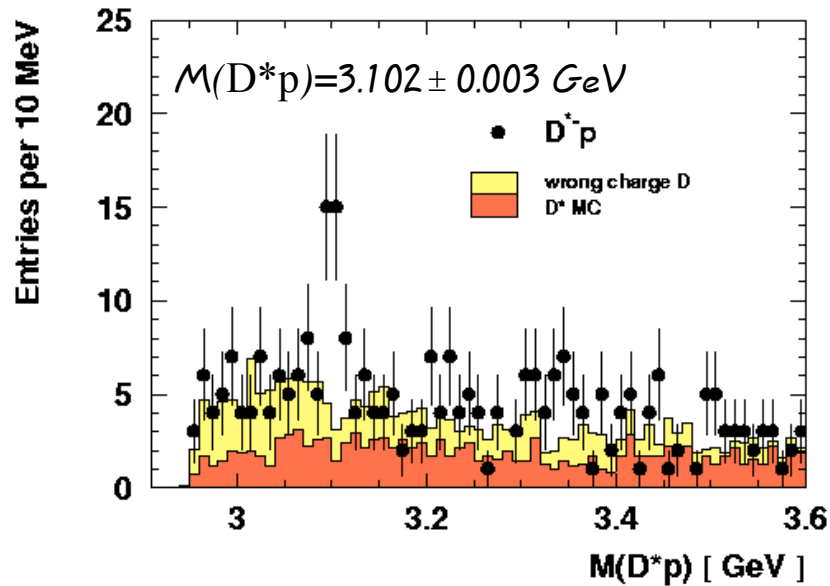
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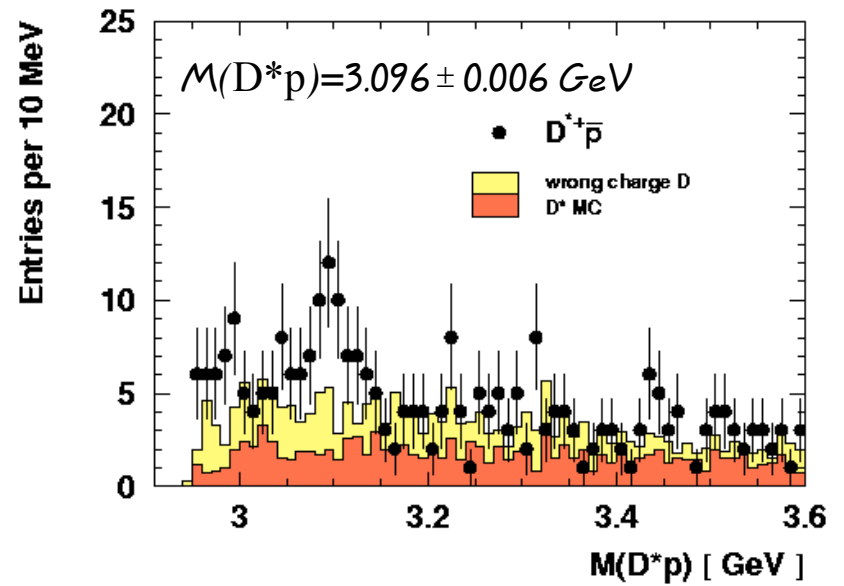
Background significantly reduced – opposite sign D^*p signal more pronounced

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

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



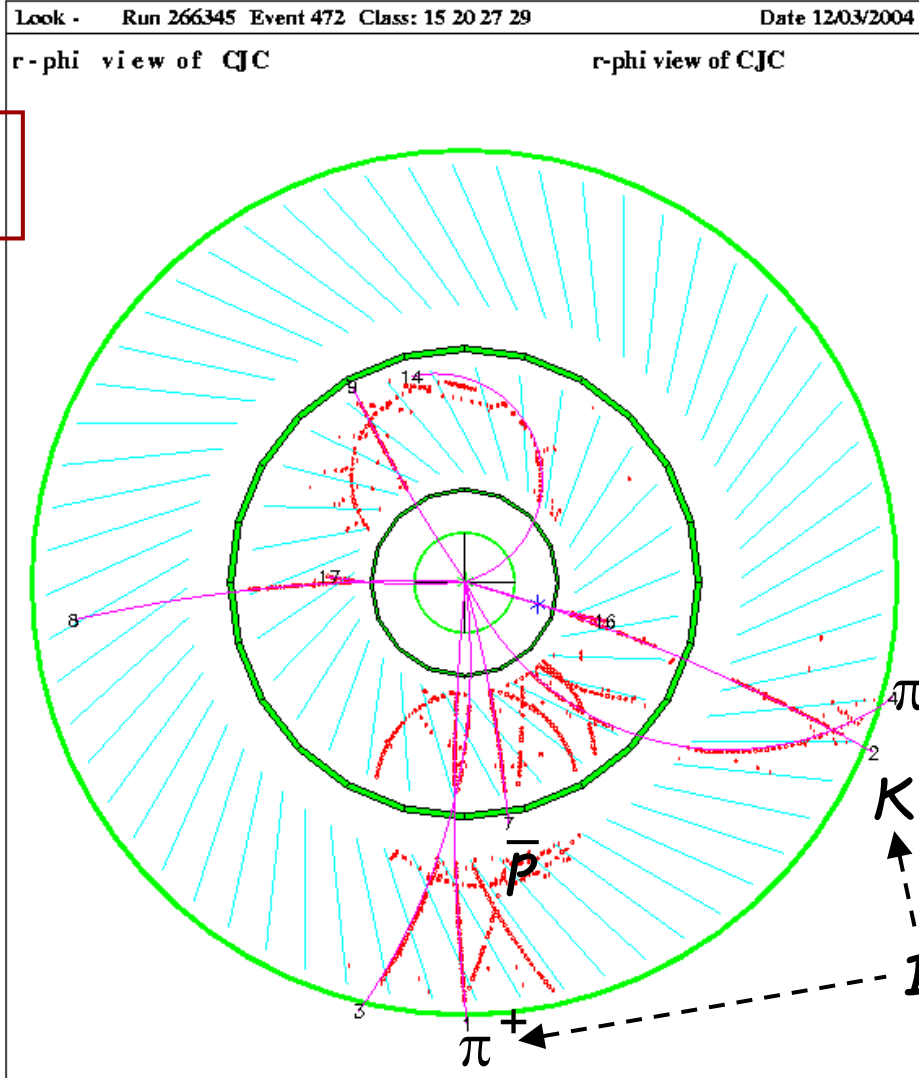
$25.8 \pm 7.1 \text{ Events}$



$23.4 \pm 8.6 \text{ Events}$

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

A typical Event

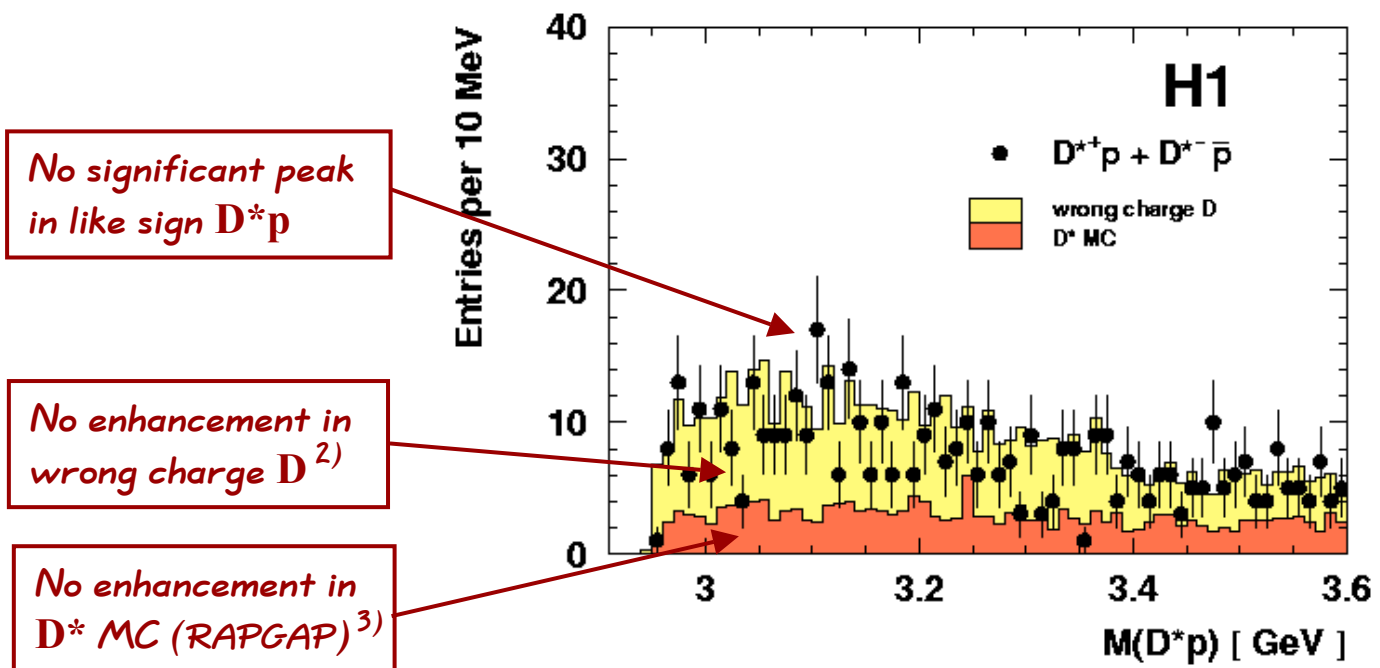


All events in the signal region have been scanned

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

Signal in like sign $D^{*+} p$ ¹⁾?

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



No significant peak in like sign $D^{*}p$

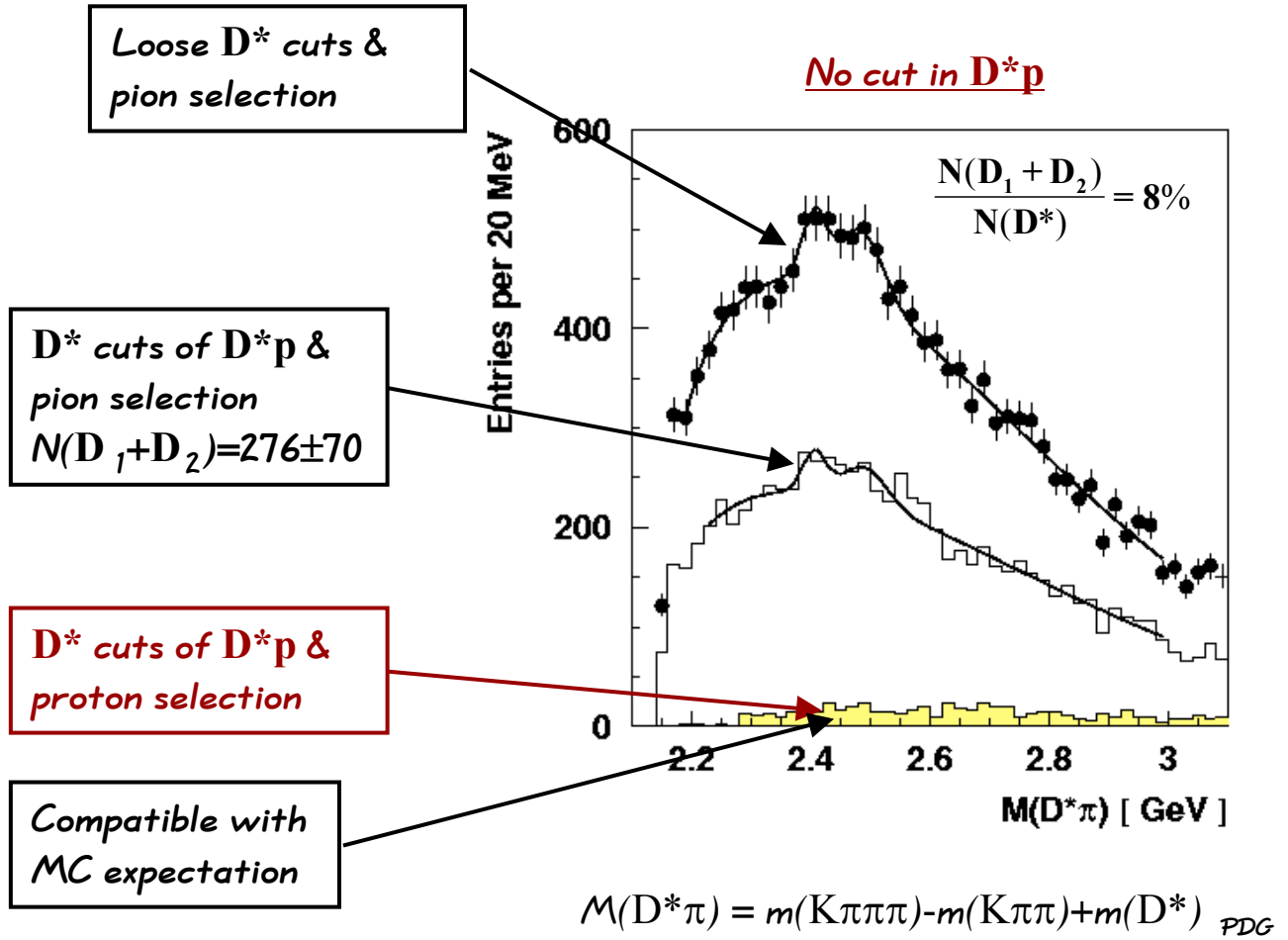
No enhancement in wrong charge D ²⁾

No enhancement in D^* MC (RAPGAP) ³⁾

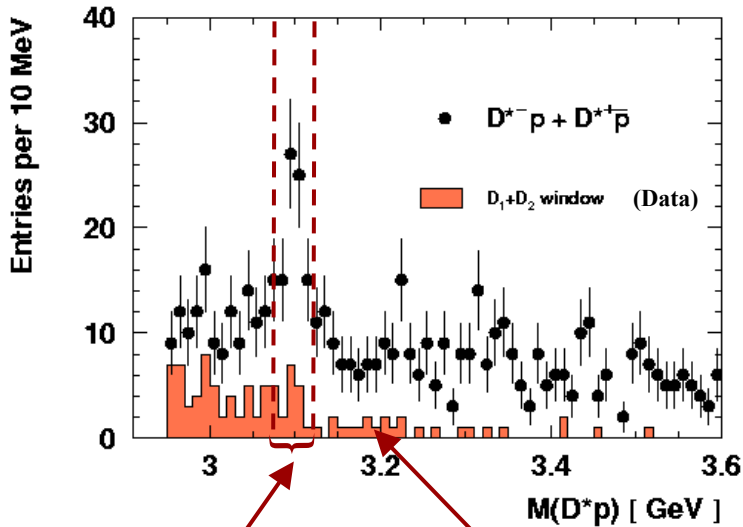
Reasonably described by D^* MC and wrong charge D from data

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



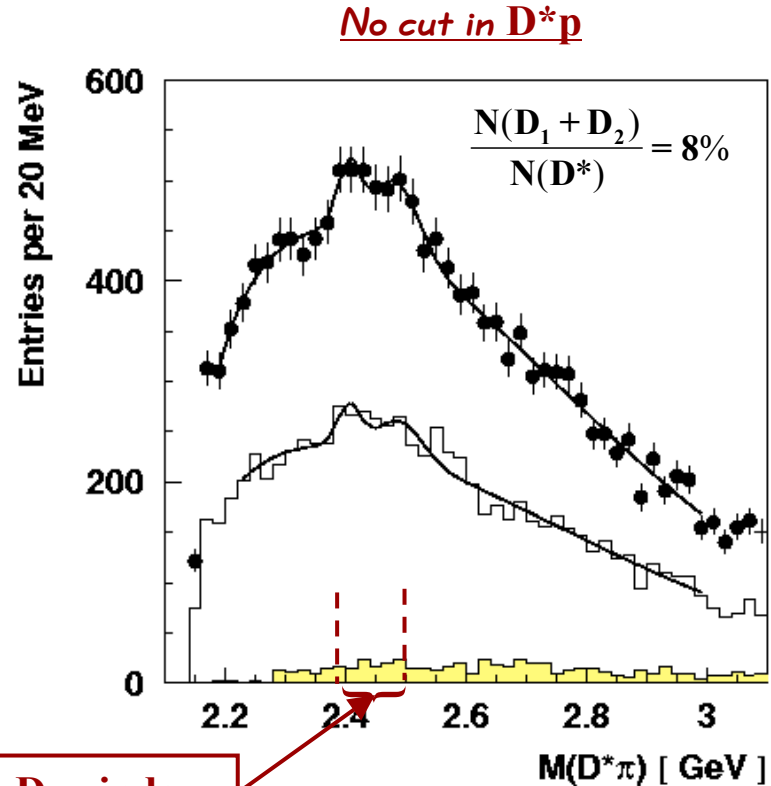
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Corrected for combinatorics,
Then expect 3.5 events from data

D_1, D_2 window

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

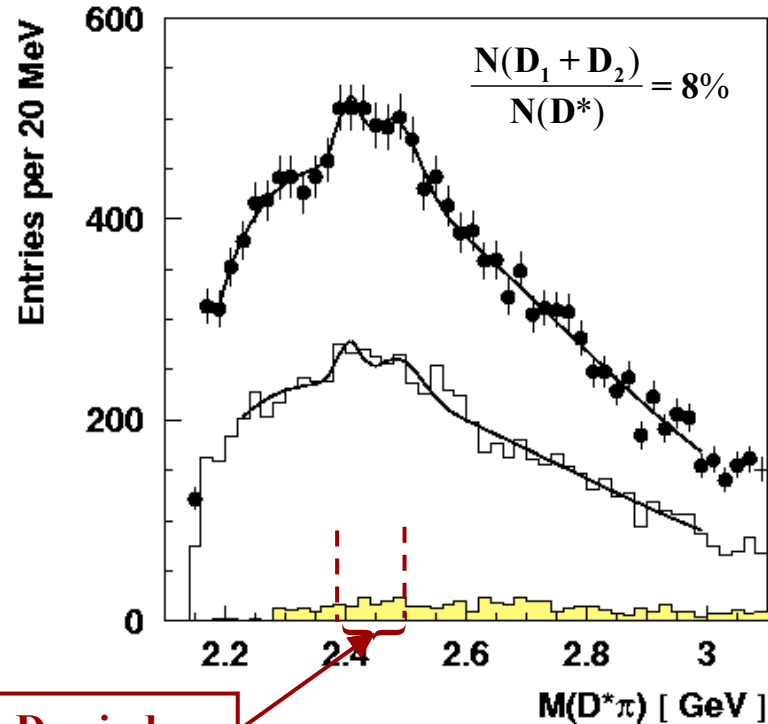
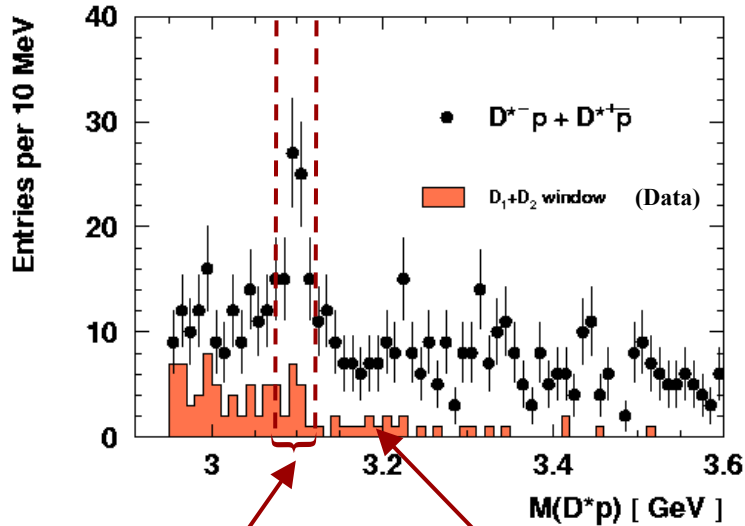


$$M(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*) \quad \text{PDG}$$

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

Small!

No cut in D^*p



*Corrected for combinatorics,
Then expect 3.5 events from data*

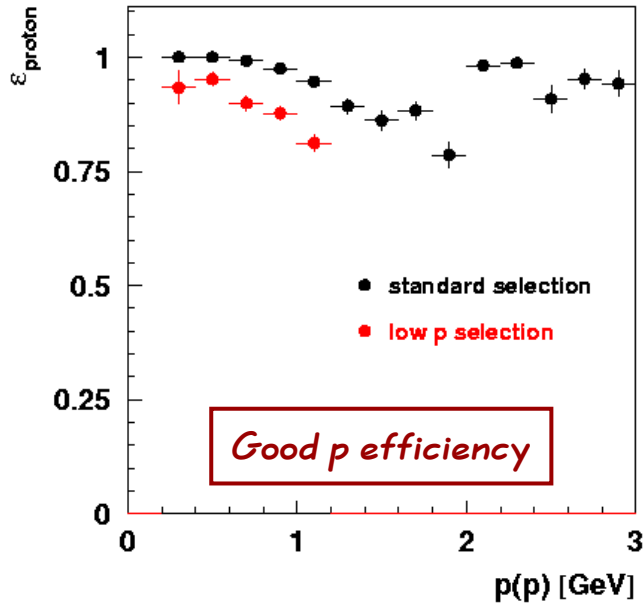
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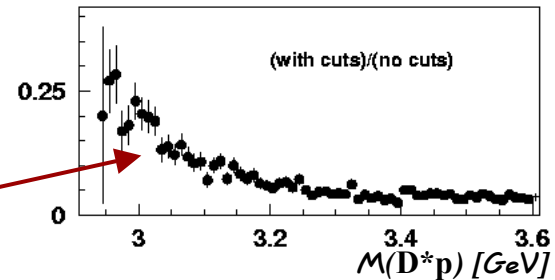
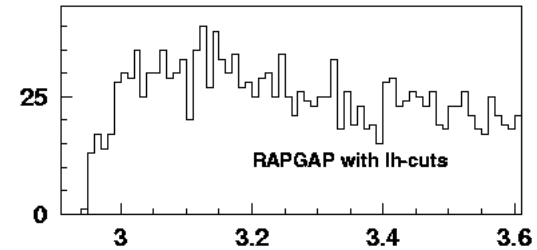
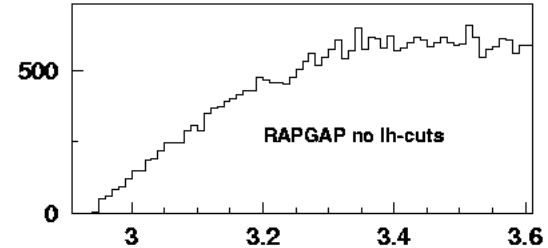
Does some acceptance effect fool us ?

Proton efficiency



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

"Pion survival probability"

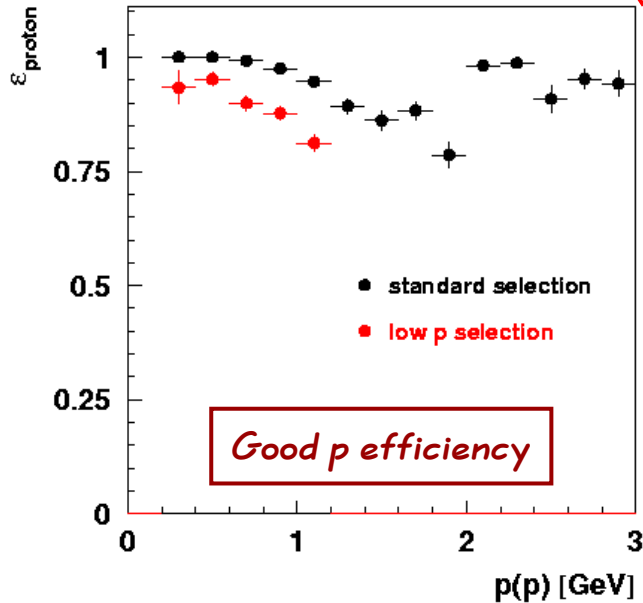


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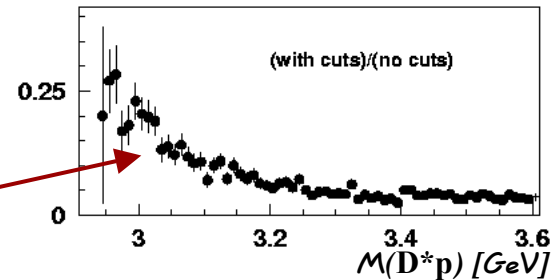
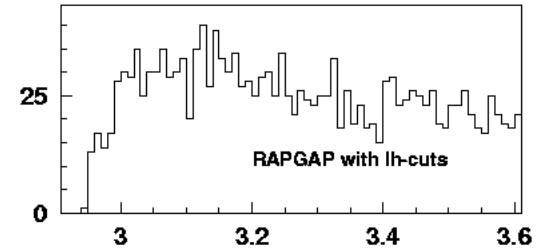
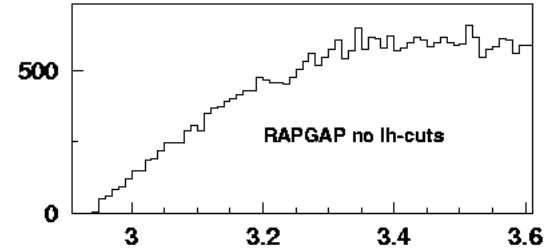
NO!

Proton efficiency



Smooth variation with $M(D^*p)$
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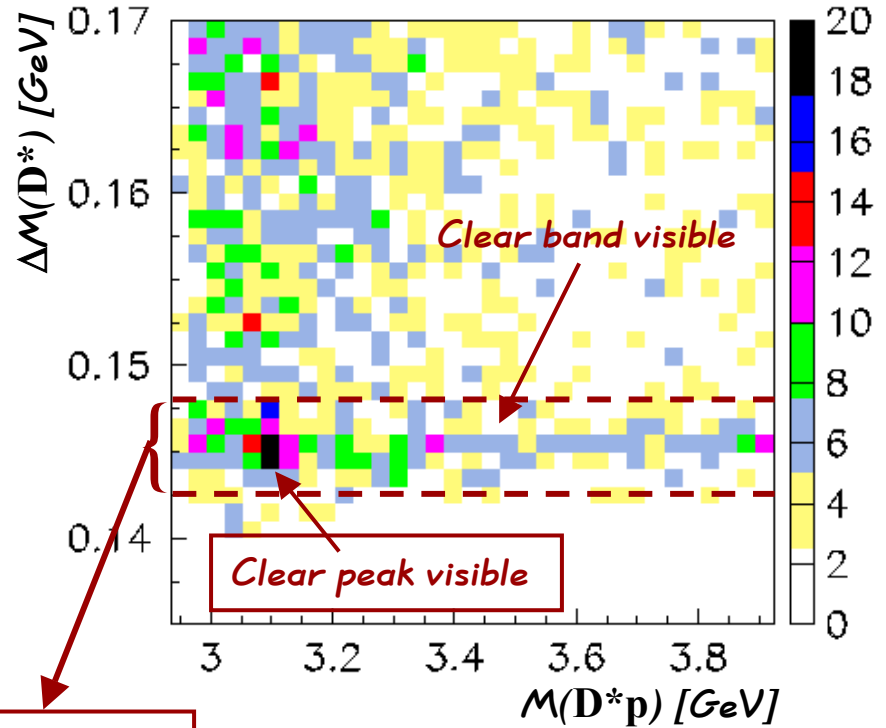
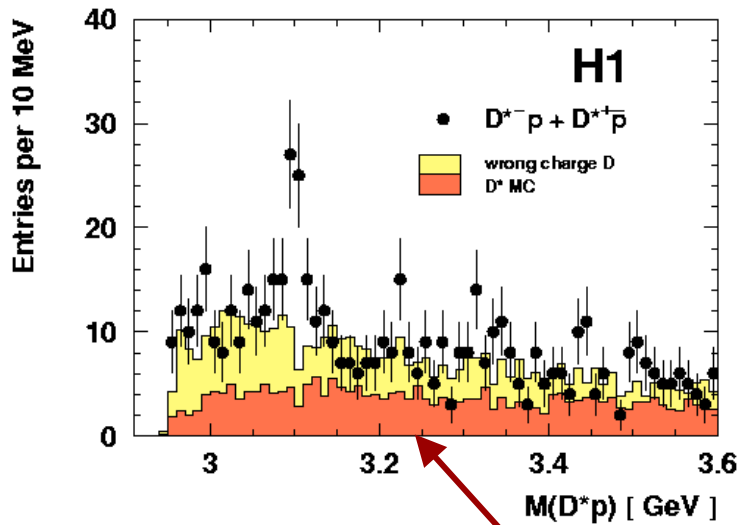
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Signal region in $D^{*-}p^1$ richer in D^{*-} ?

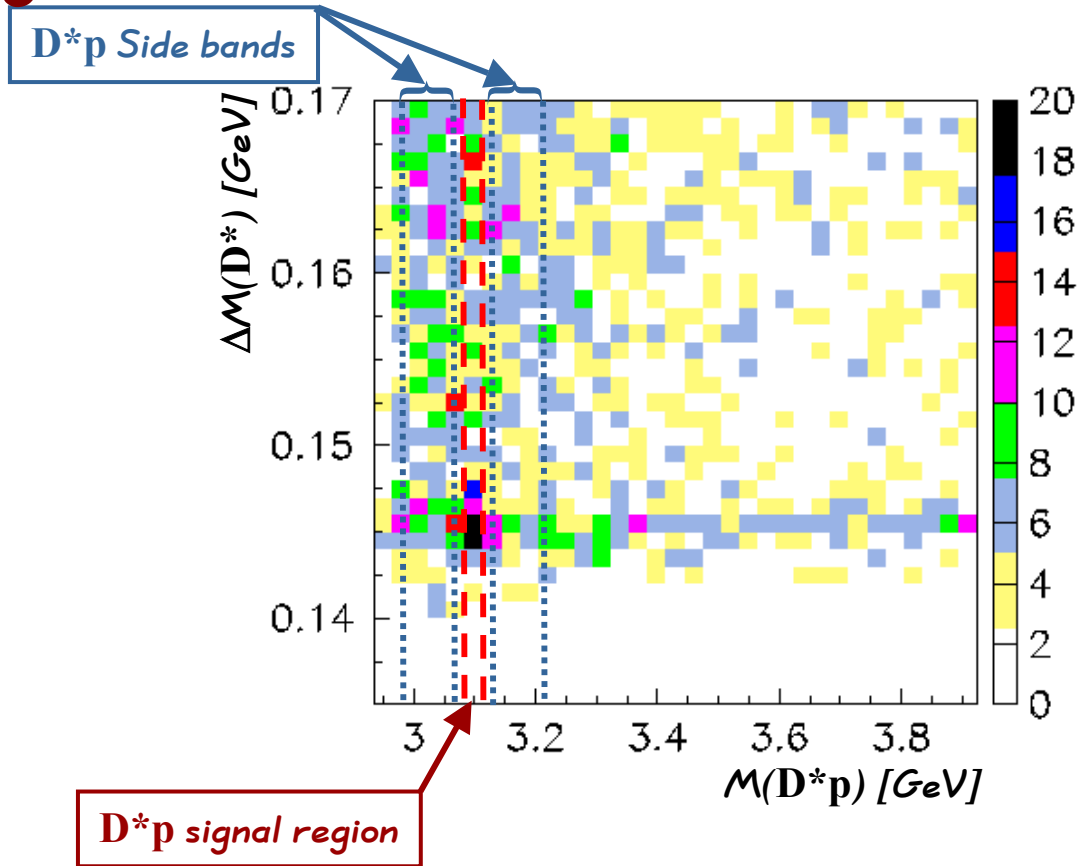
1) Charge conjugate always implied



D^* signal region

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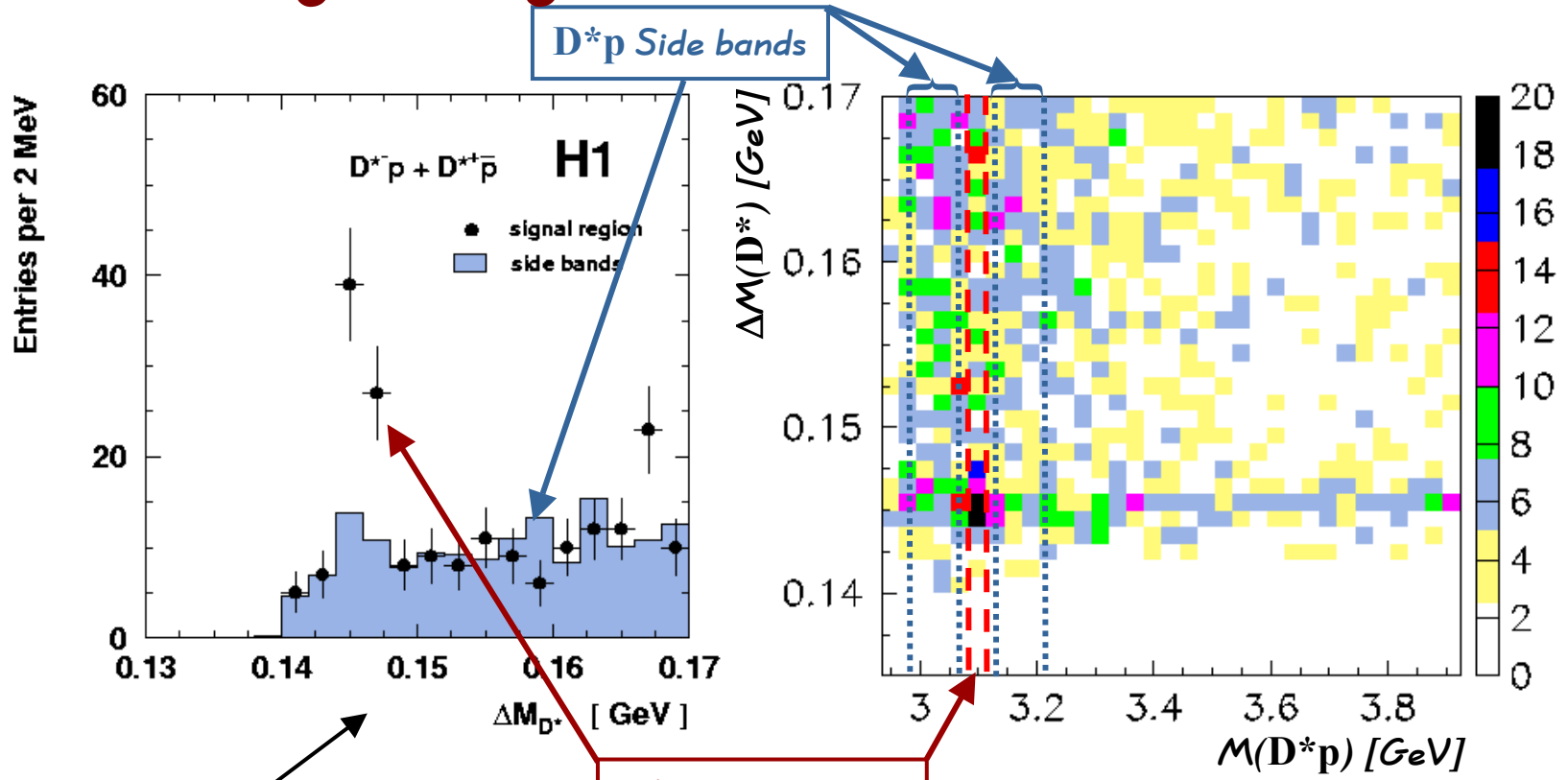
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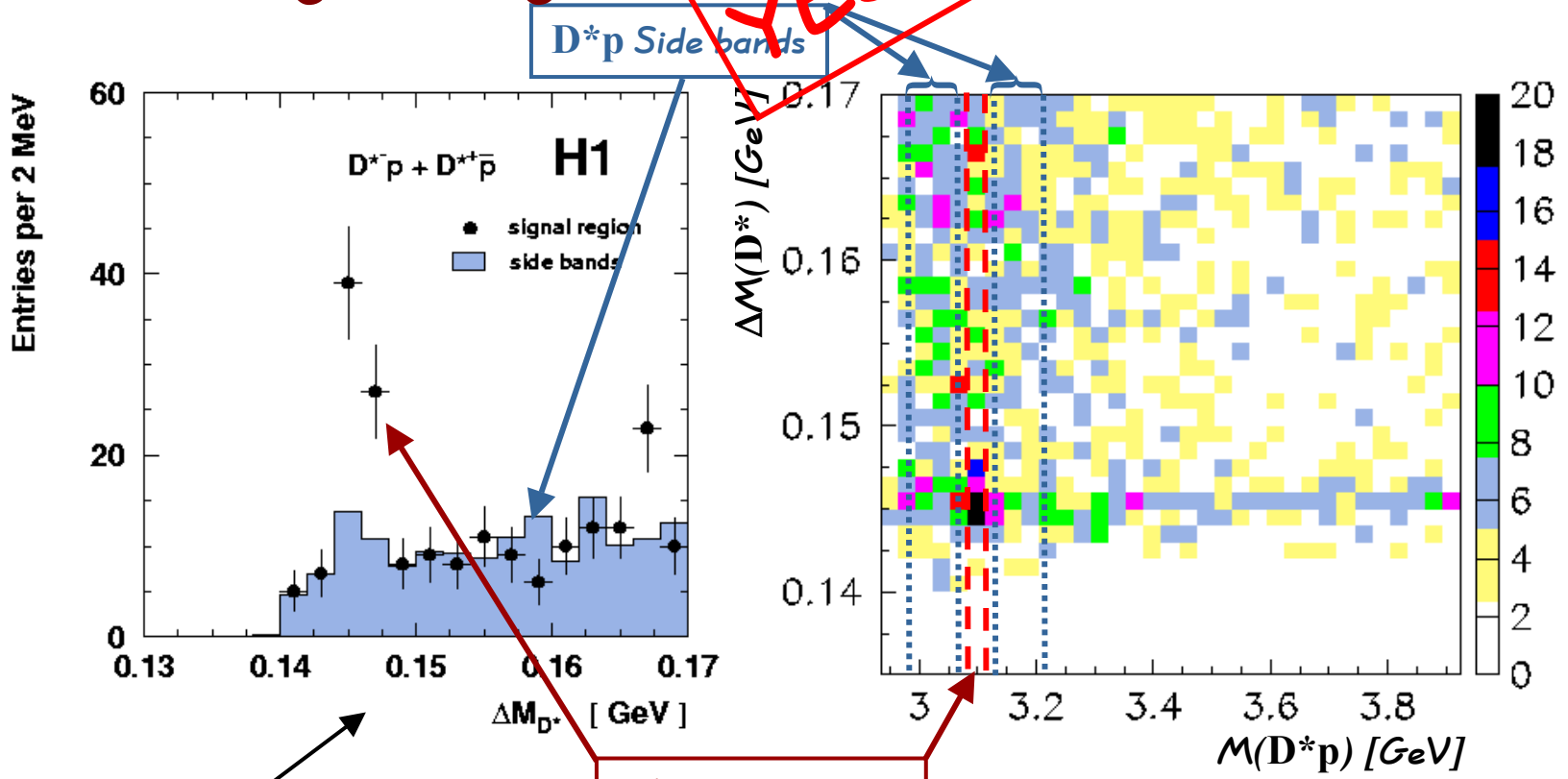
Normalization to the width of the windows in $M(D^*p)$

$D^{*+}p$ signal region

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

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Signal region in D^*p richer in D^{*-} ?



YES!

D^*p Side bands

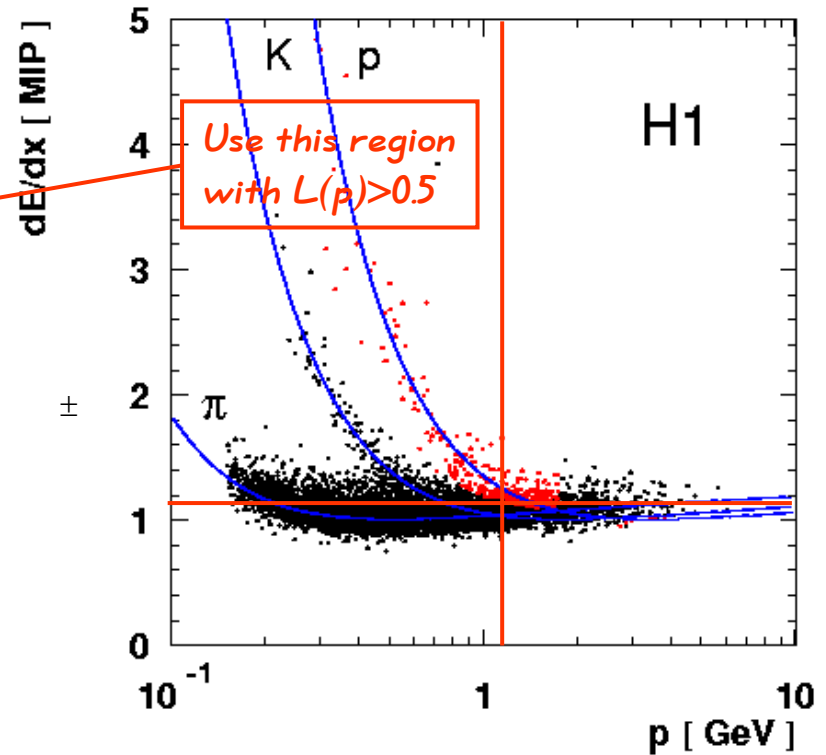
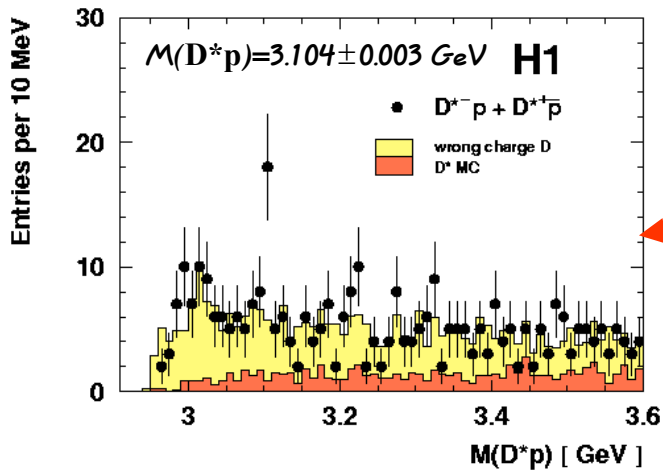
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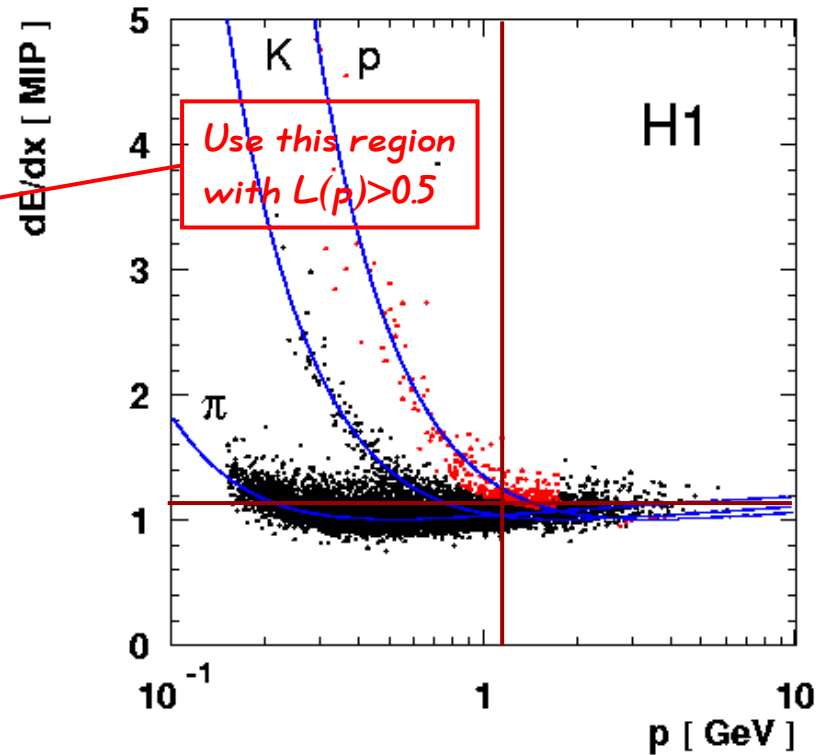
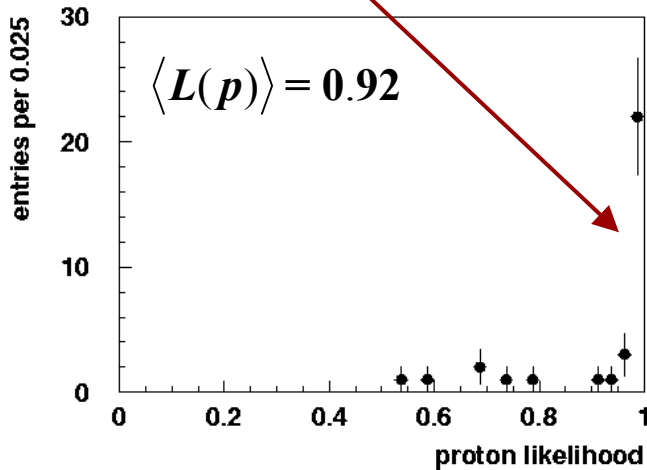
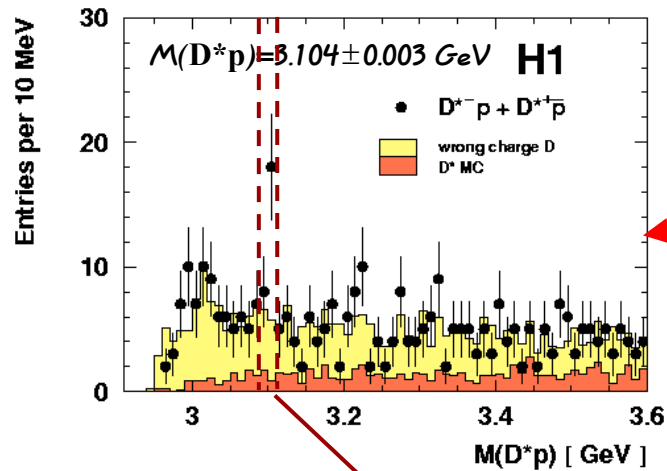
Is the $D^{*-}p^1$ signal due to protons?



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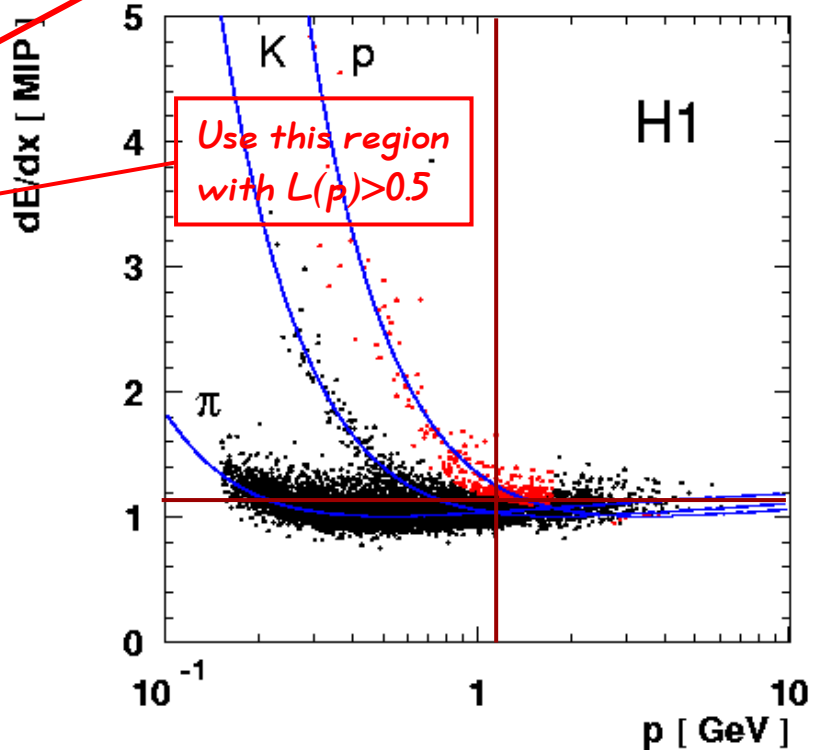
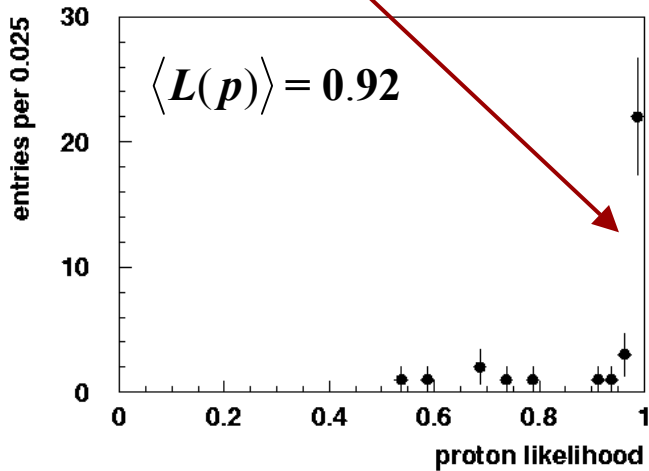
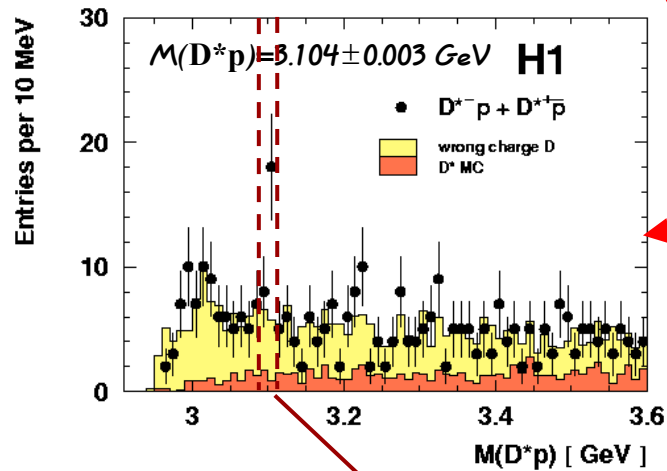


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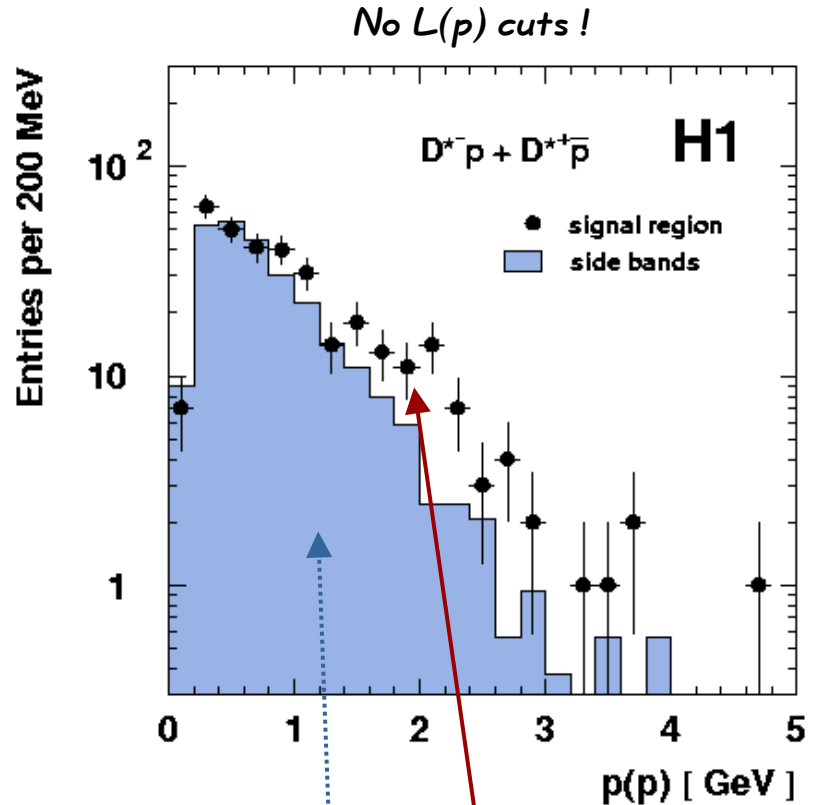
$$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$$

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 background

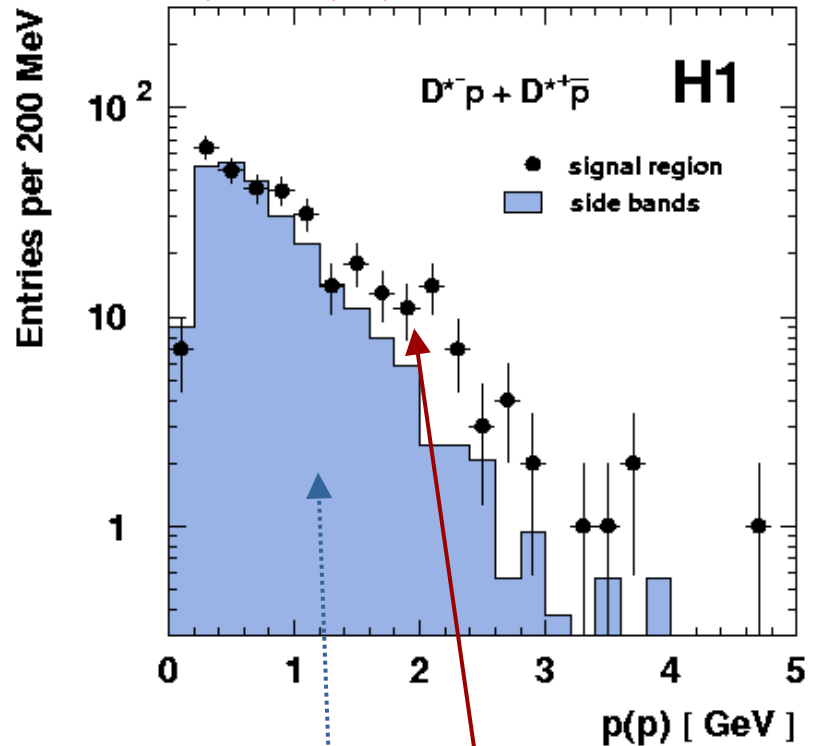
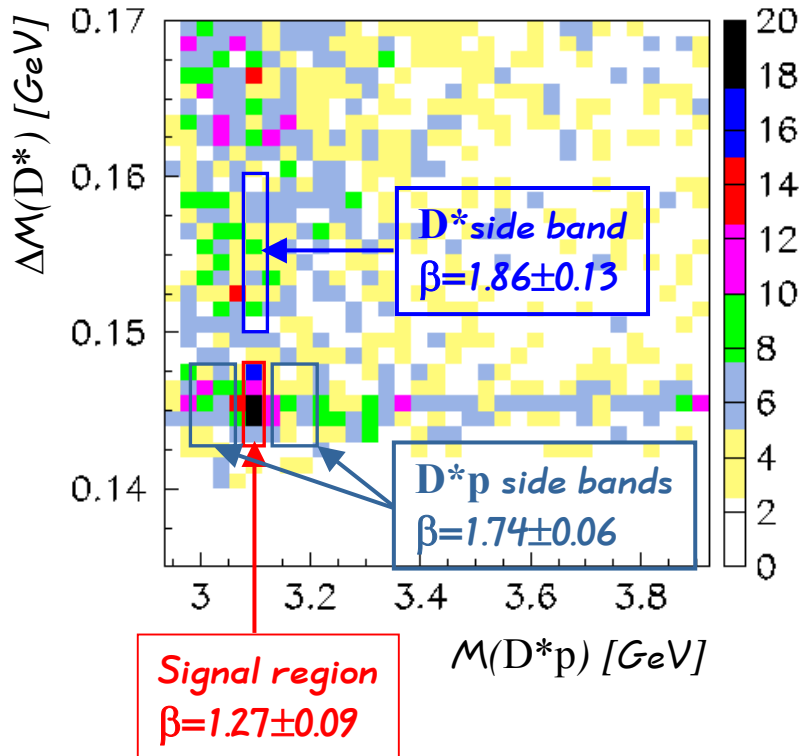
→ Look at the momentum of the proton candidate w/o dE/dx cuts



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

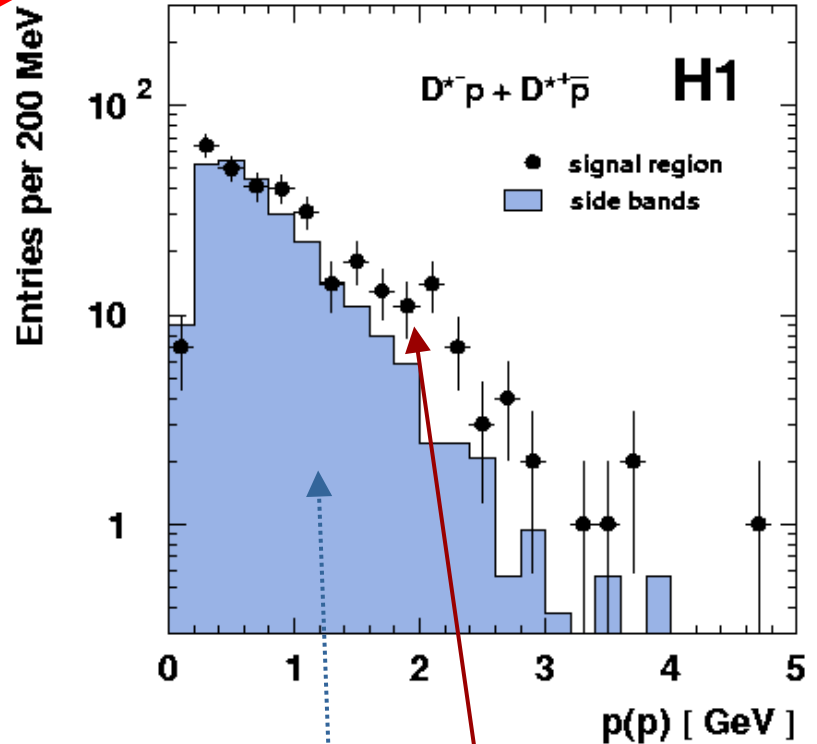
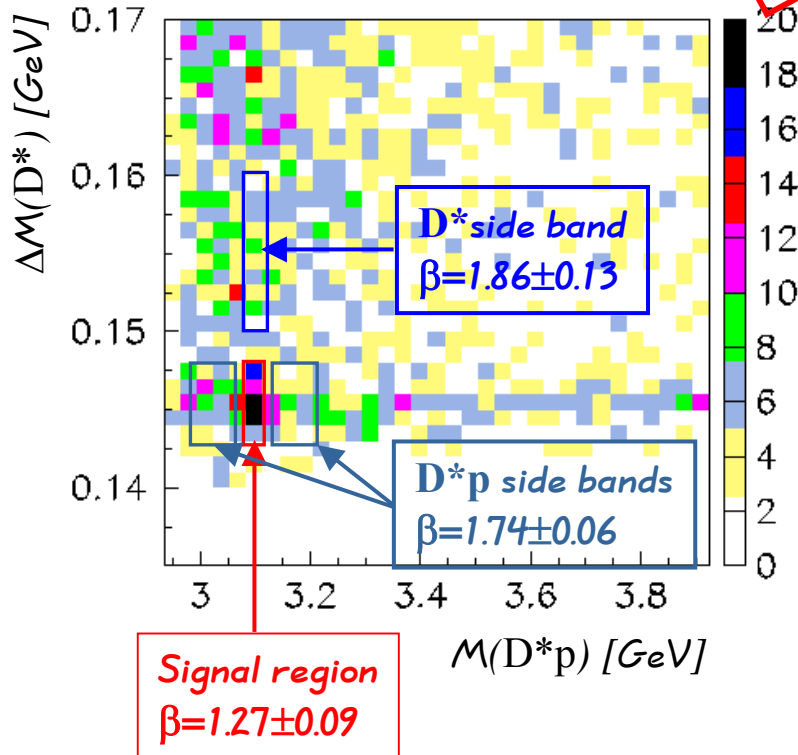


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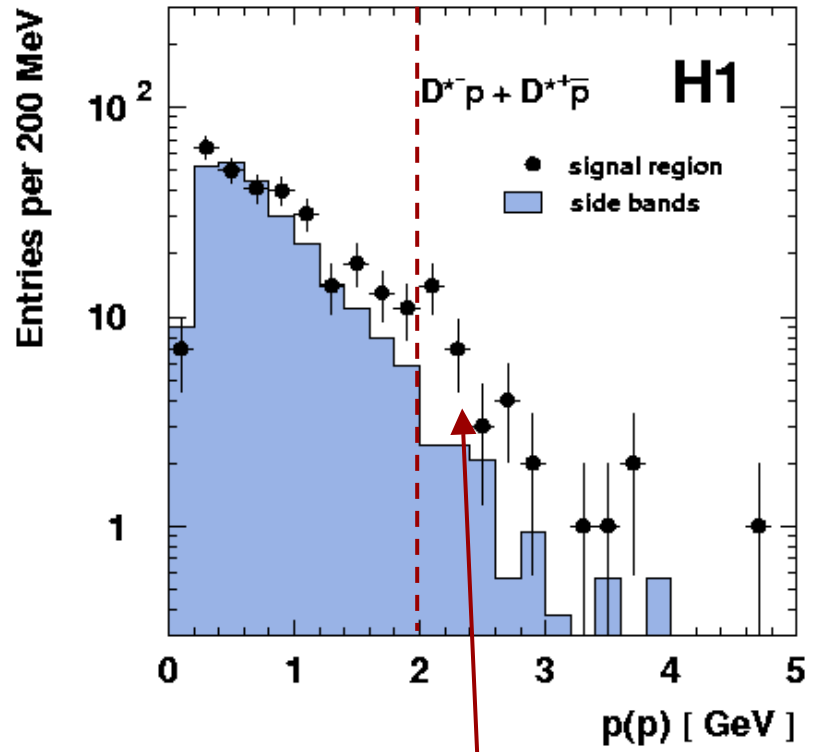
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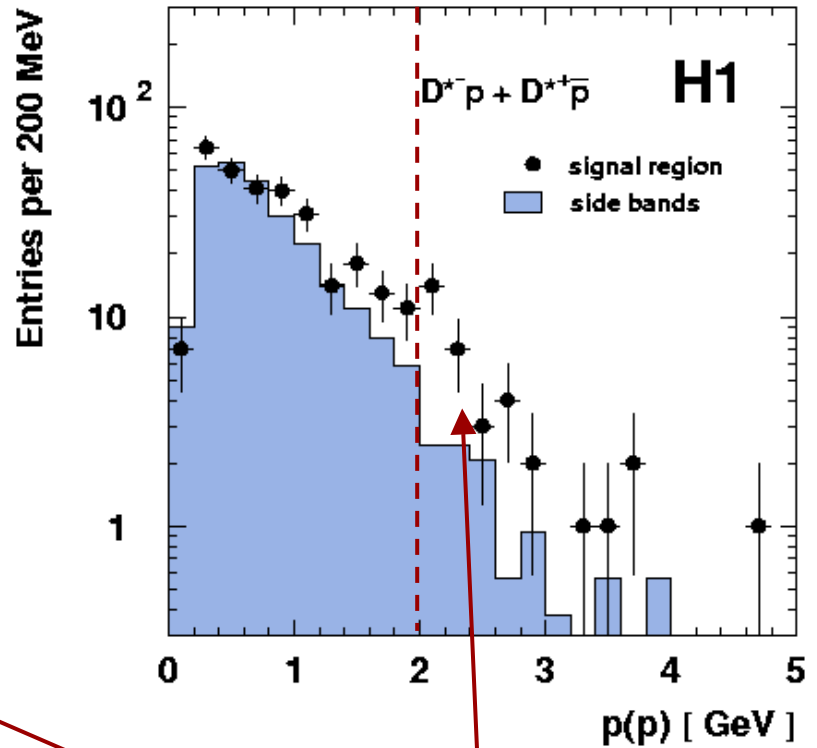
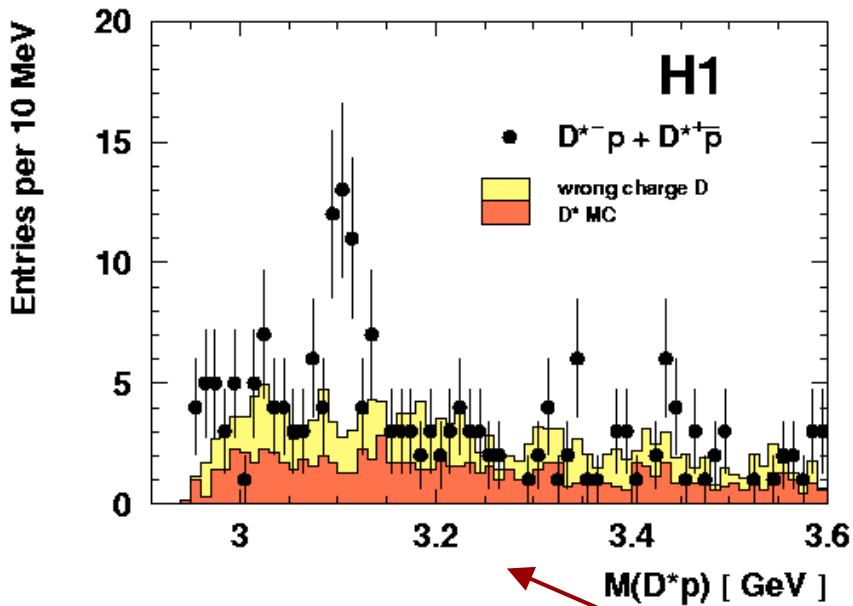
The momentum spectrum of the particles in the signal region is harder than in the $M(D^*p)$ side bands

Signal at large $p(p)$ more prominent ?



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

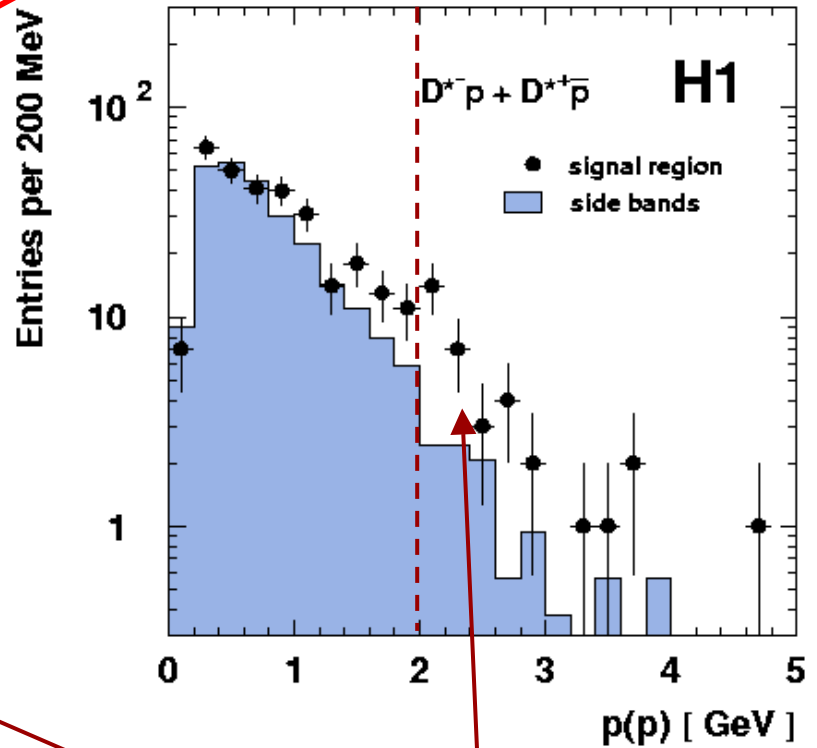
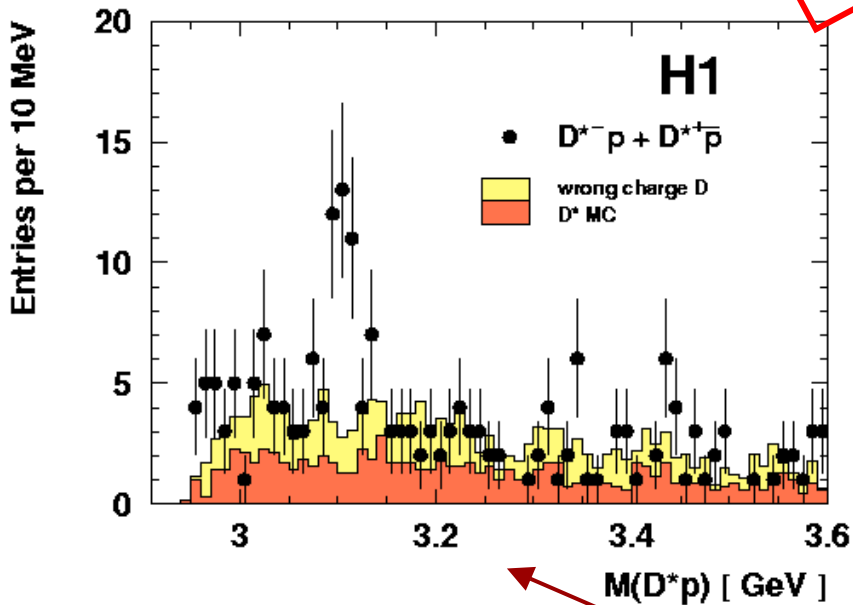
Signal at large $p(p)$ more prominent ?



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

Signal at large $p(p)$ more prominent ?

YES!



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

Basics of kinematic tests

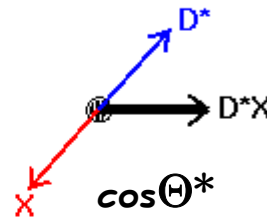
2-Body Decay

$$M^2 = (P_1 + P_2)^2$$

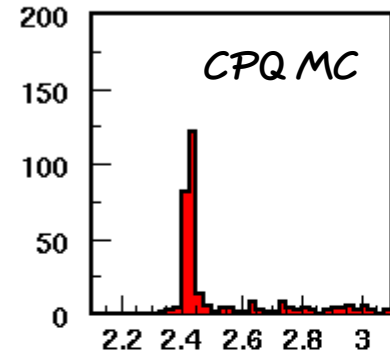
$$= (m_{D^*}^2 + m_X^2 + 2E_{D^*}E_X - 2\vec{p}_{D^*}\vec{p}_X)$$

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

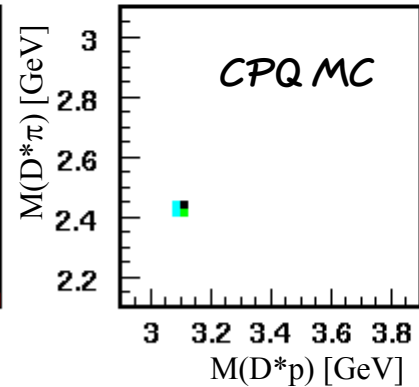
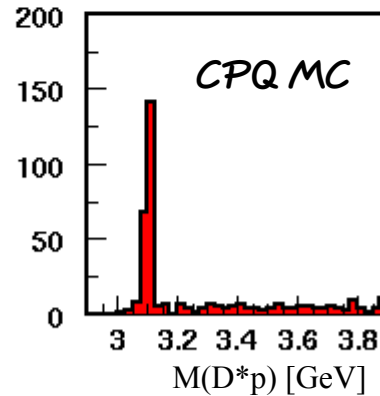
D^*p rest frame



wrong mass assignment



correct mass assignment



Basics of kinematic tests

2-Body Decay

$$M^2 = (P_1 + P_2)^2$$

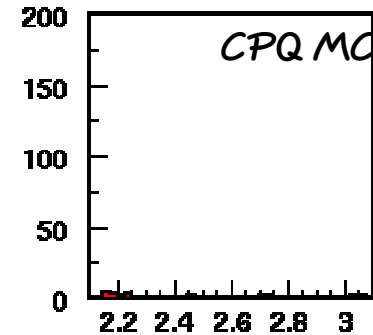
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M^2 independent of decay angle $\cos\Theta^*$ only for correct mass assignment

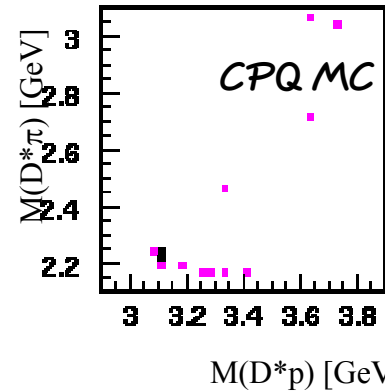
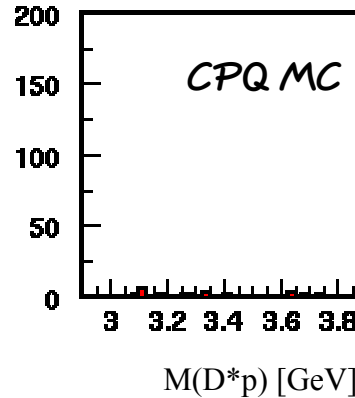
D^*p rest frame



wrong mass assignment



correct mass assignment



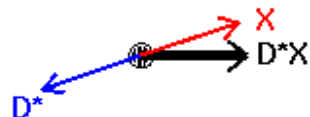
Kinematic tests

2-Body Decay

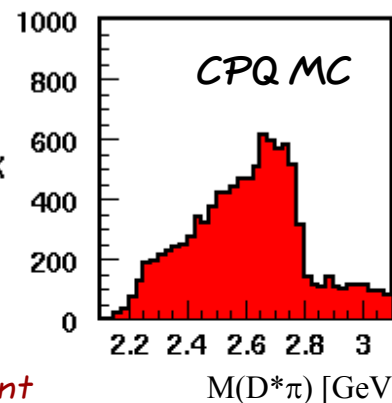
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D^*p rest frame

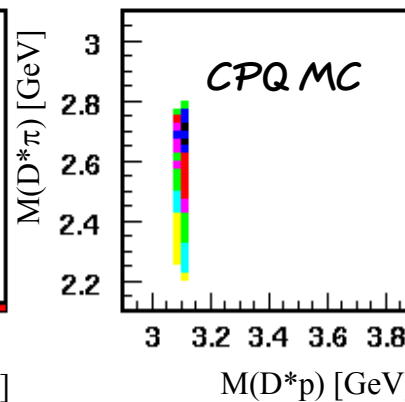
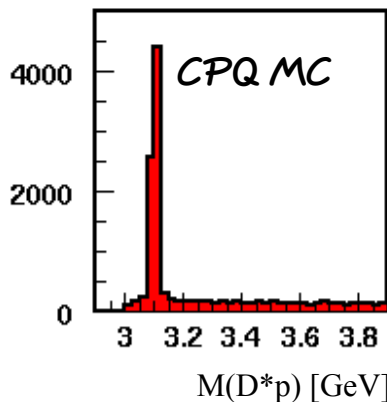


wrong mass assignment



Integrated in $\cos\Theta^*$

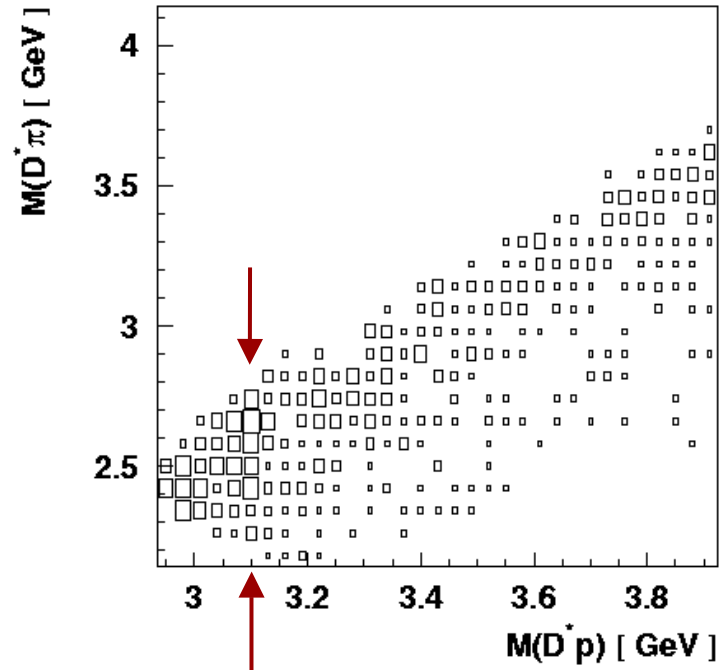
correct mass assignment



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

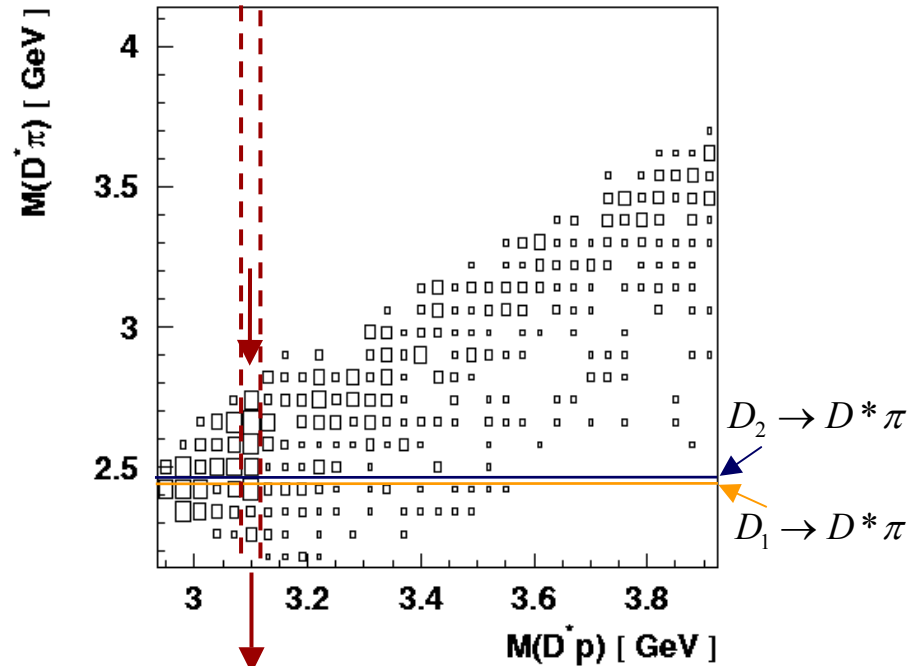
Signal due to $D^*\pi$?

Back to data !



Band in D^π clearly visible*

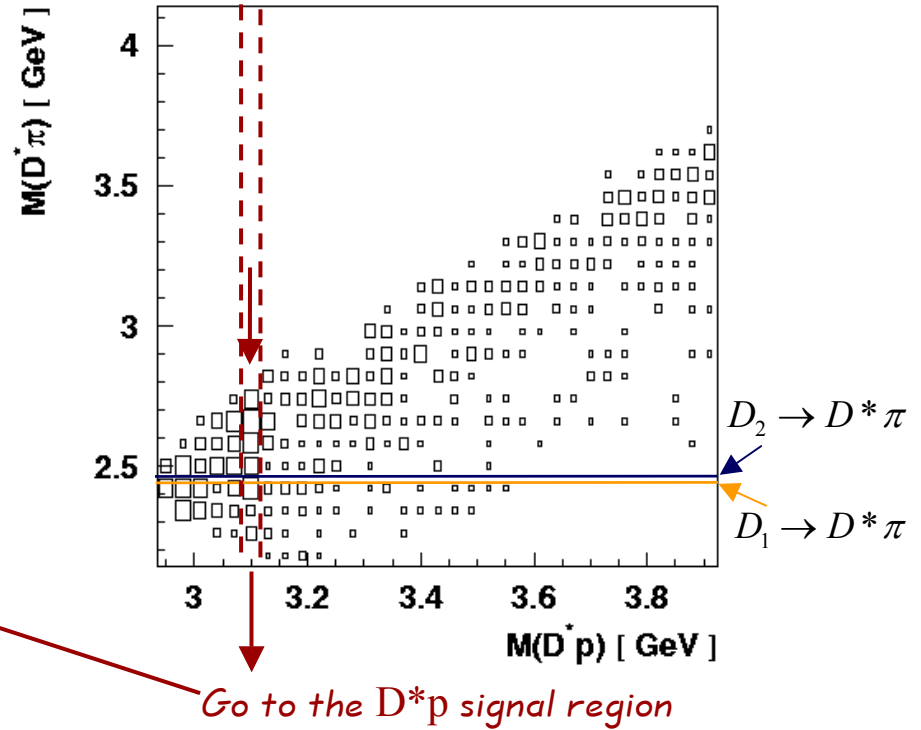
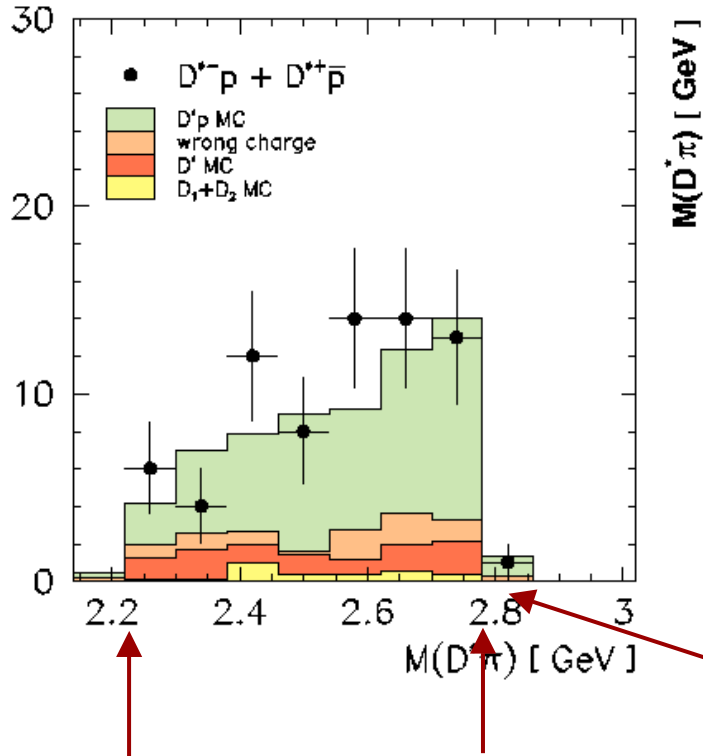
Signal due to $D^*\pi$?



*Go to the D^*p signal region*

*No indication for contributions
from D_1 and D_2*

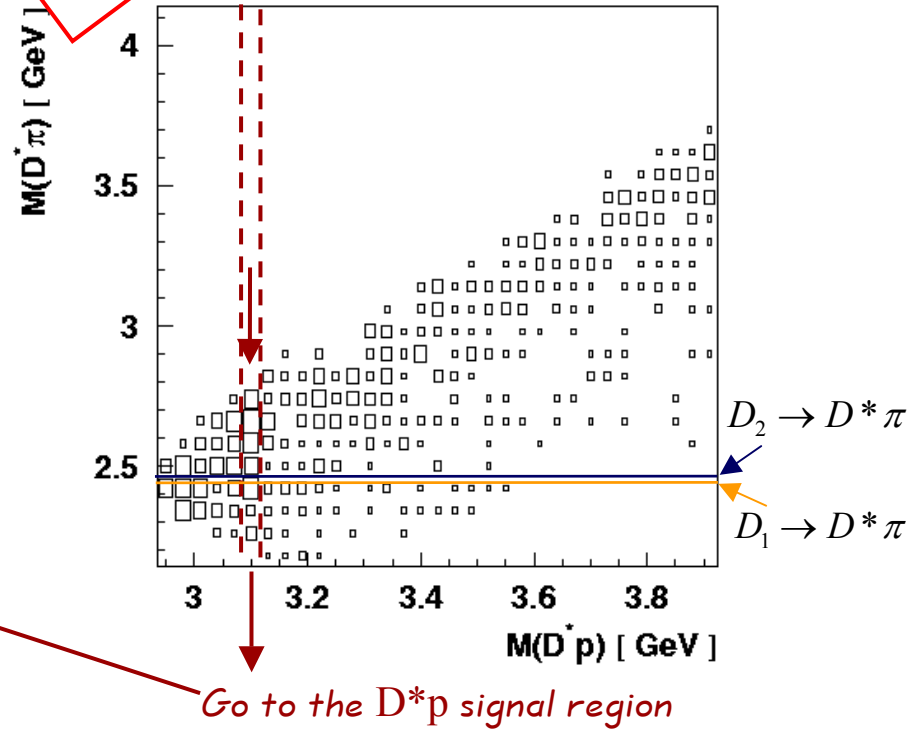
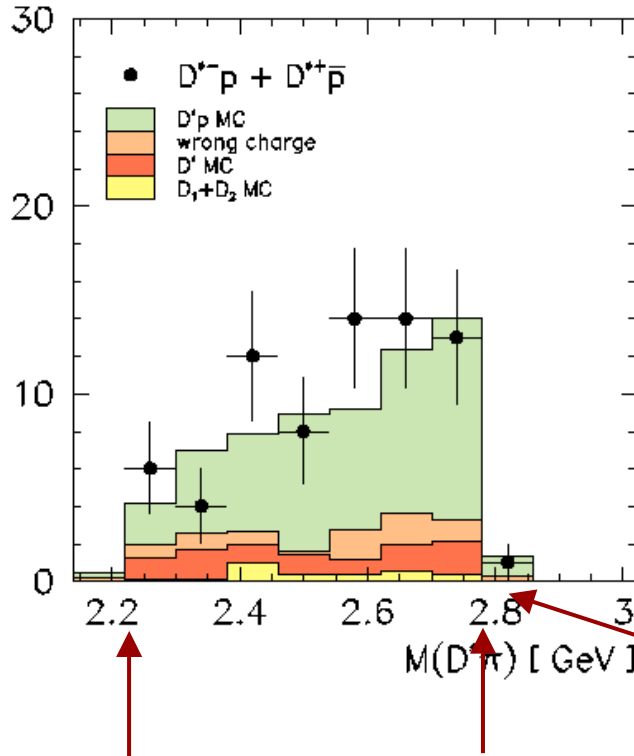
Signal due to $D^*\pi$?



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

Signal due to $D^*\pi$?

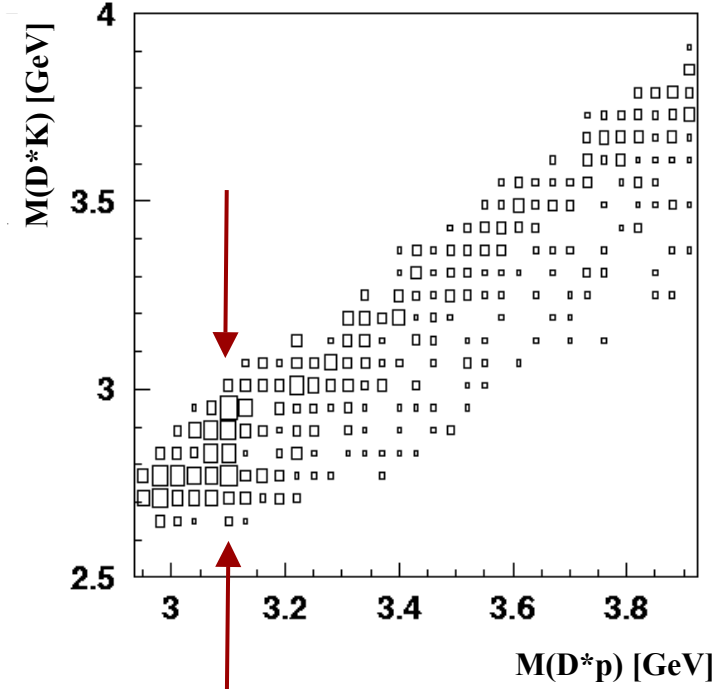
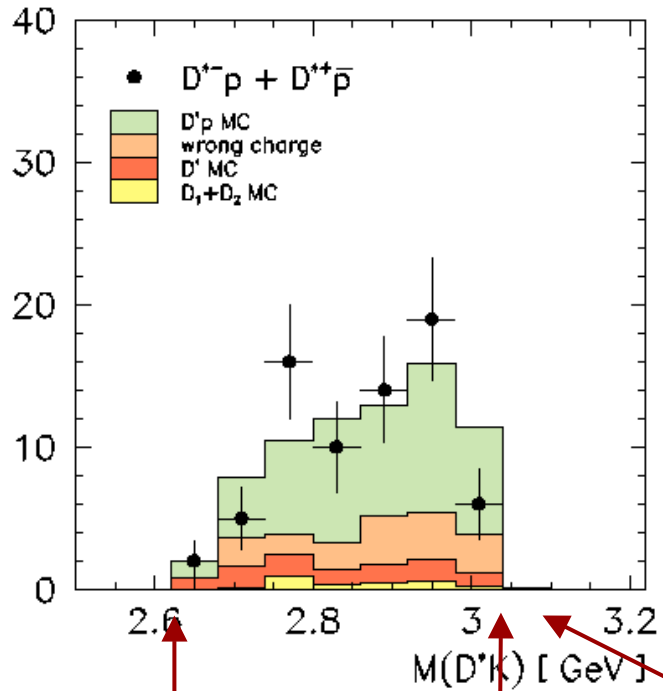
NO



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

Could it be due D^*K ?

This on its own would be worth a publication

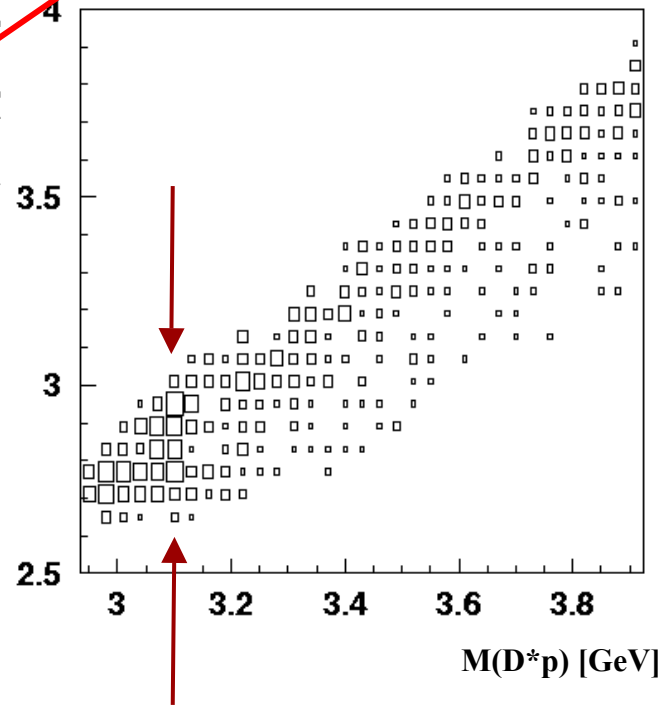
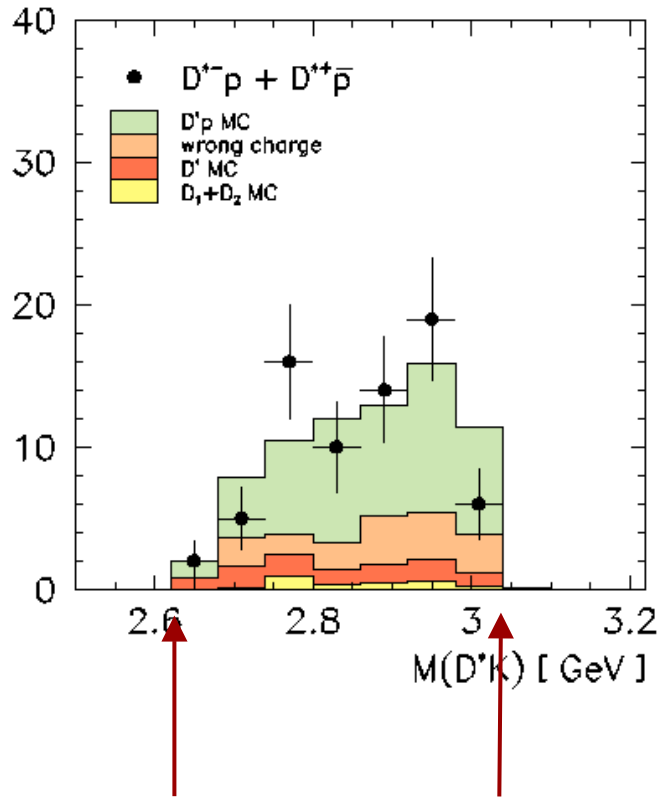


Sign for $X \rightarrow D^*p$: available phase space in D^*K completely used

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

Could it be due D^*K ?

NO

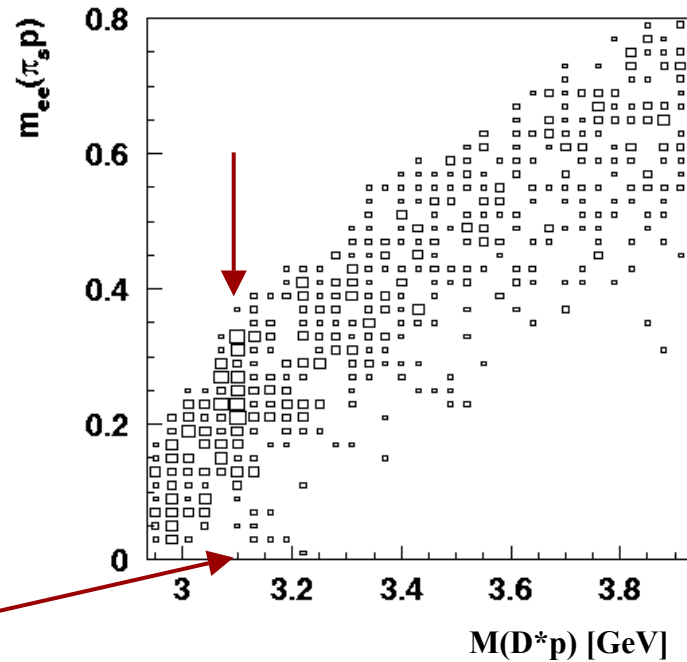


*Band in D^*K clearly visible*

*Sign for $X \rightarrow D^*p$: 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
→ may be misinterpreted
as π_s and proton
 $m_{ee}(\pi_s p)$ should peak at 0

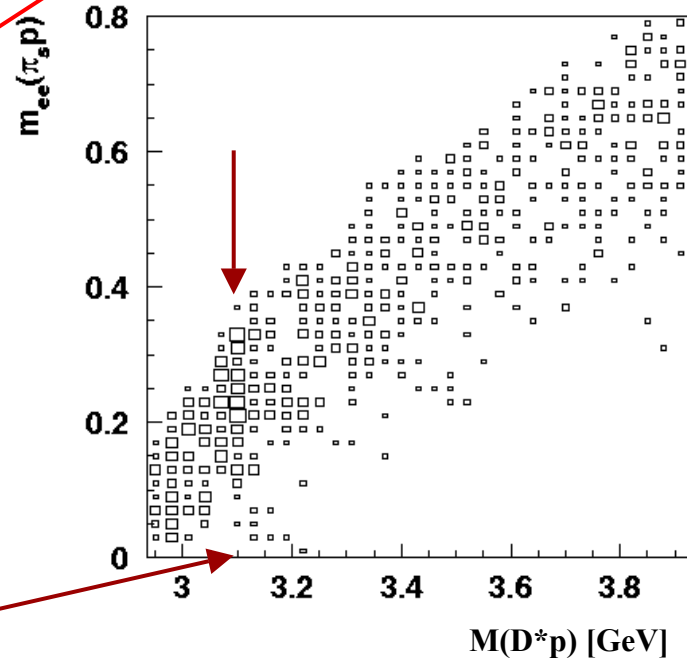


No accumulation at zero

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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 $\Lambda, \Delta^0, \Delta^{++} \dots$: **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 $K_S^0, \phi, f_2 \dots$: **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 $K_S^0, \phi, \Delta^0, \Delta^{++} \dots$: **no enhancements found**

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$D^{*-}p$ ¹⁾ in photoproduction

4900 D^*

$$M(D^*p) = 3.103 \pm 0.004 \text{ GeV}$$

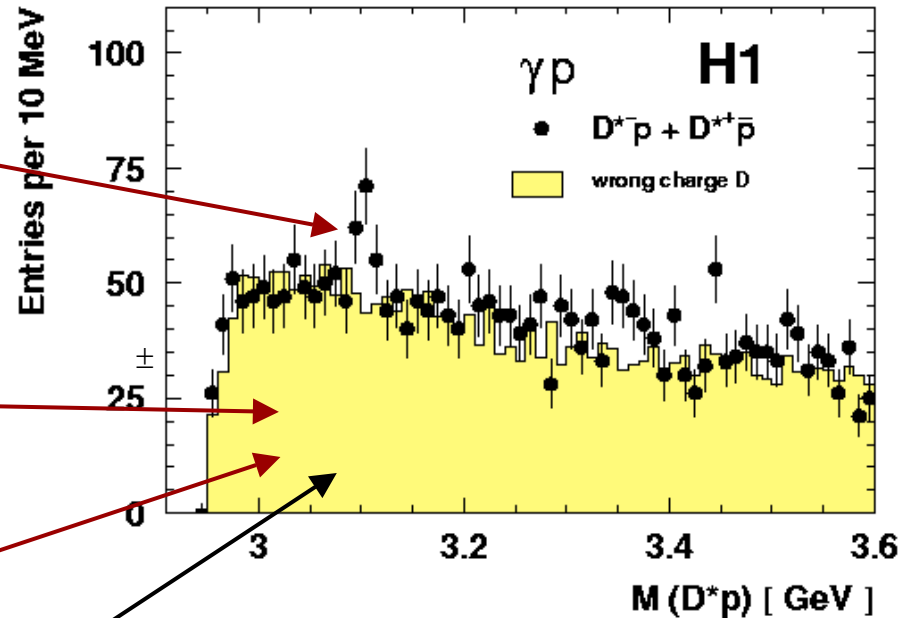
$$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$$

Peak also observed in photoproduction

>95% of background due to non-charm

No enhancement in non-charm background

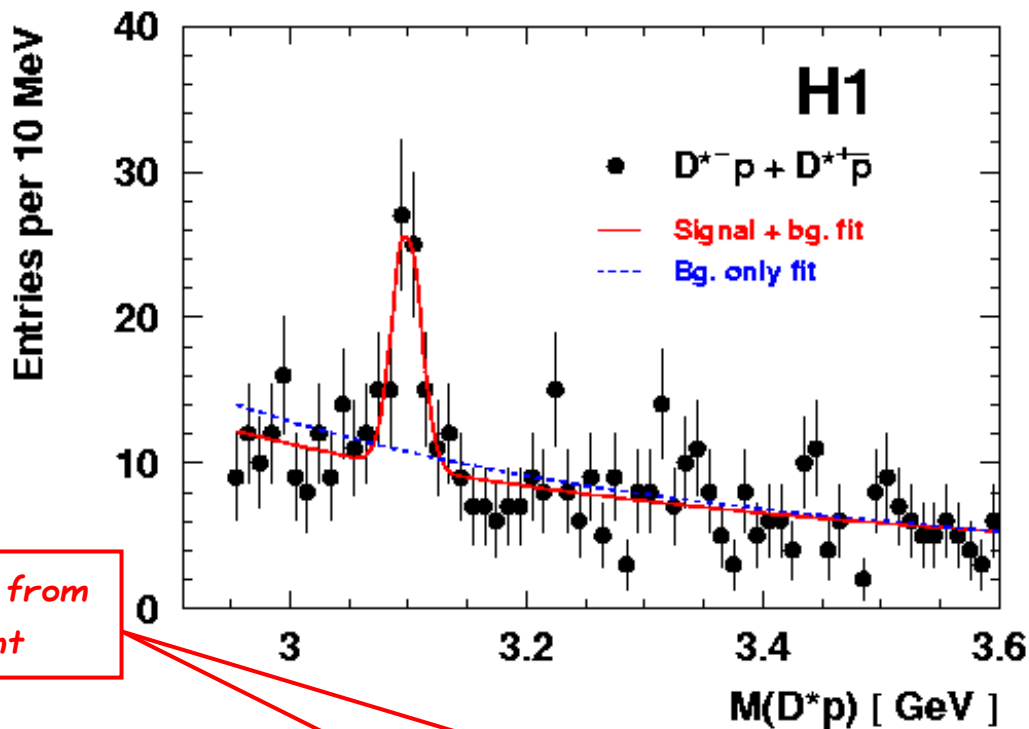
Background well described by wrong charge D from data



1) Charge conjugate always implied

Photoproduction more difficult due to large non-charm background

Signal assessment



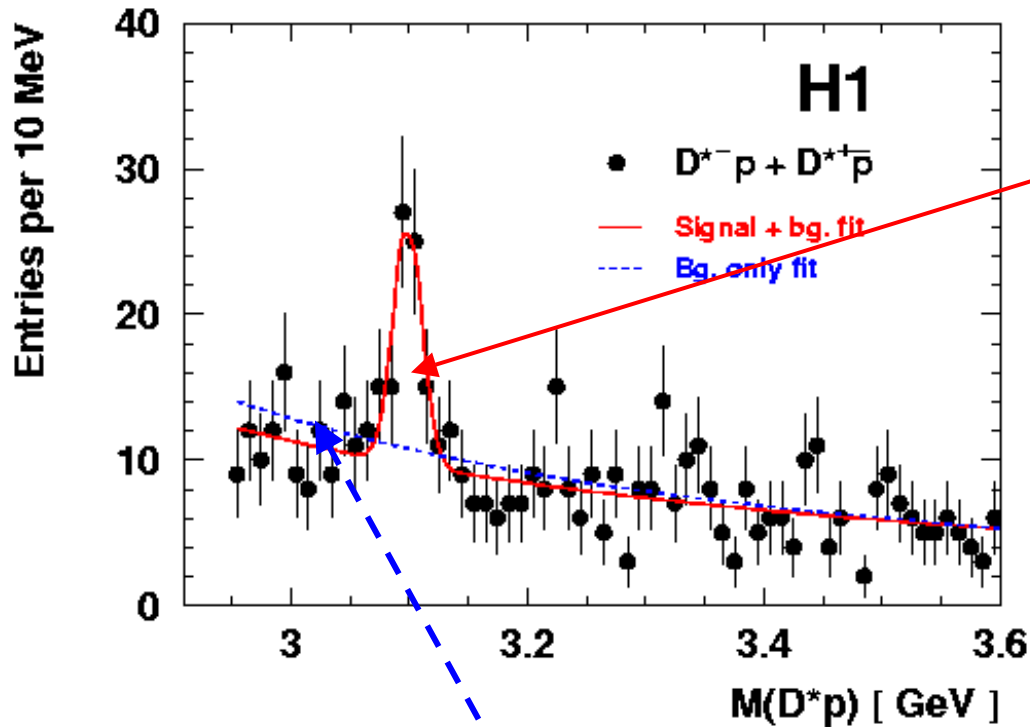
Stability of result against all sorts of variations checked

In total about 100 D^*p in $DIS+\gamma p$

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

$N_b = 45.0 \pm 2.8$ from
background + signal
Hypothesis (fit)

5.4σ

- Significance estimate based on the background only hypothesis $N_b = 51.7 \pm 2.7$
 - 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) $\equiv 5.4 \sigma$ (Gauss)
- Change in likelihood of fits: 6.2σ

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 $4 \cdot 10^{-8}$.*
- *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_S^0*
- *Bengt Wessling tried to kill the signal - but failed*
- *And many more...*