Evidence for a Narrow Exotic Anti-Charmed Baryon State

Karin Daum

H1 Collaboration

Paris, April 5

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Outline:

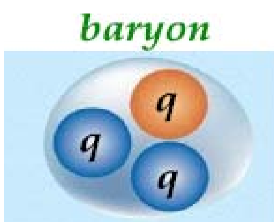
- *The strange sector — A motivation*
- *The experimentalist's view — Where and how to search ?*
- *The D^*p signal — Could it be real ?*
- *The D^*p signal — Could it be fake ?*
- *The D^*p signal — Signal assessment*
- *Conclusion*

Paris, April 5

The particle zoo

Hundreds of hadrons can be grouped into :

Made of quark-antiquark pairs



Made of three quarks

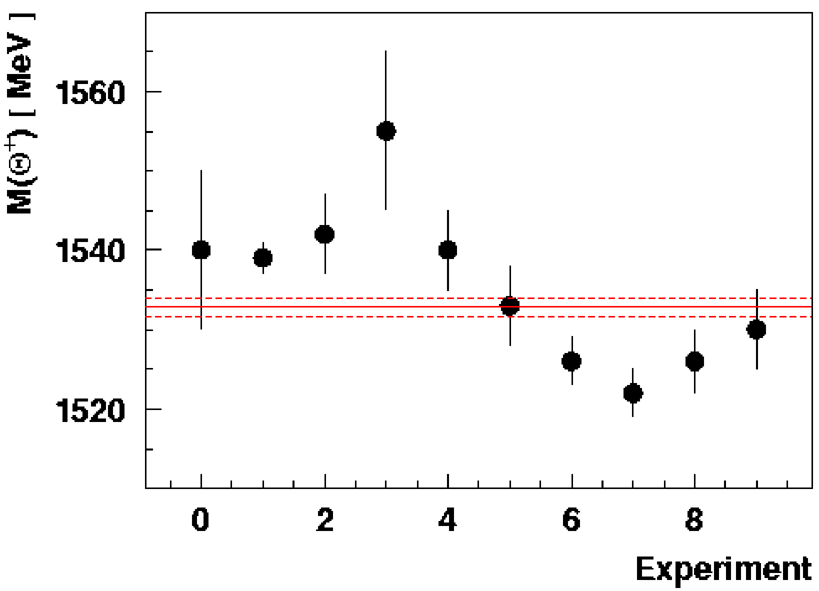
QCD does not forbid larger configurations

Why should this be all ?

More than 30 years of experimental searches fruitless until 2003

The case of the strange pentaquark Θ^+

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	1522 ± 3
8	SVD	K^0p	1526 ± 4
9	COSY-TOF	K^0p	1530 ± 5



B=1 & S=1

$\Downarrow$

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

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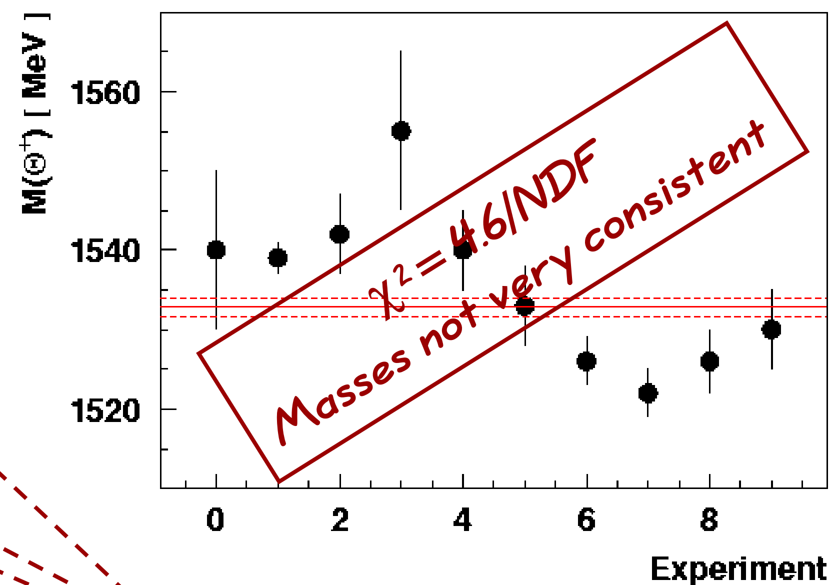

Sign of S not determined

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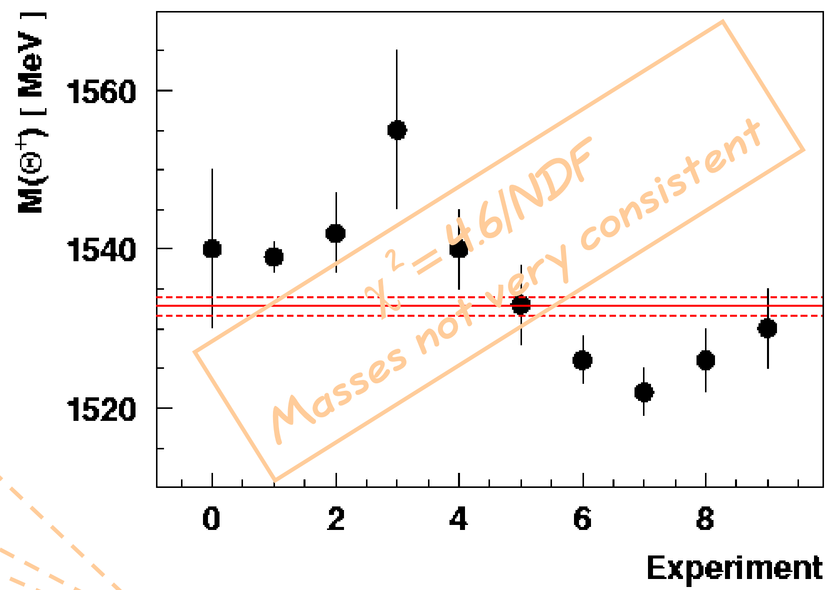

Sign of S not determined

B=1 & S=1

$\Downarrow$

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

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

Experimentalist's simple-minded picture of the strange pentaquark

(Motivation for the search in the charm sector)

- Θ^+ produced by fragmentation from the vacuum
- It does not matter how the strange quark of the Θ^+ has been produced
- Its properties (mass, lifetime) may possibly result from features of the QCD vacuum
- These features of the QCD vacuum are universal
  Since QCD is flavour blind, similar properties are expected for the charmed analogue of the Θ^+

Where to look for the charmed pentaquark ?

Common belief:

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

(pseudo-scalar D meson)

Charm fragmentation fractions

$f(c \to D^+)$	γp	$0.248 \pm 0.014^{+0.004}_{-0.008}$	Pseudo-scalar mesons
	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	$0.076 \pm 0.020^{+0.017}_{-0.001}$	Charmed baryon
	e^+e^-	0.076 ± 0.007	
$f(c \to D^{*+})$	γp	$0.233 \pm 0.009^{+0.003}_{-0.005}$	Vector meson
	DIS	$0.263 \pm 0.019^{+0.056+0.031}_{-0.042-0.022}$	
	e^+e^-	0.235 ± 0.007	

Where to look for the charmed pentaquark ?

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Vector mesons not suppressed

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(pseudo-scalar D meson)

Golden channel: $D^+ \rightarrow K^- \pi^+ \pi^+$

Vector mesons not suppressed

Golden channel: $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$

Charm fragmentation fractions

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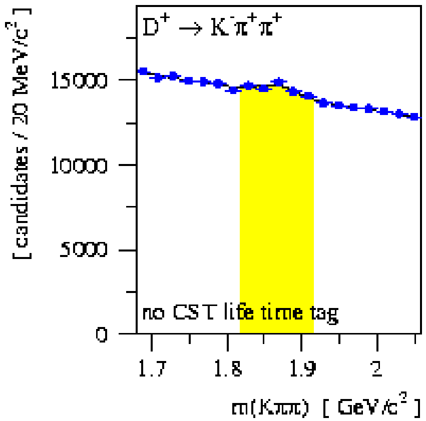
But what is experimentally feasible ?

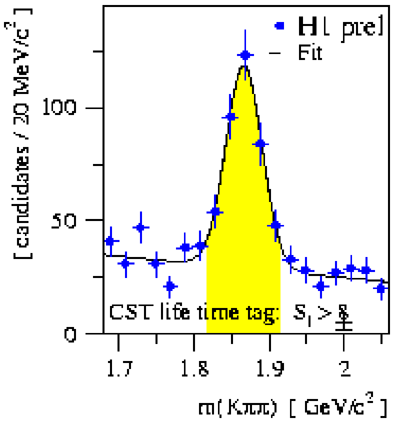
Experimental Considerations

D^+ pseudoscalar meson

without



with lifetime tag

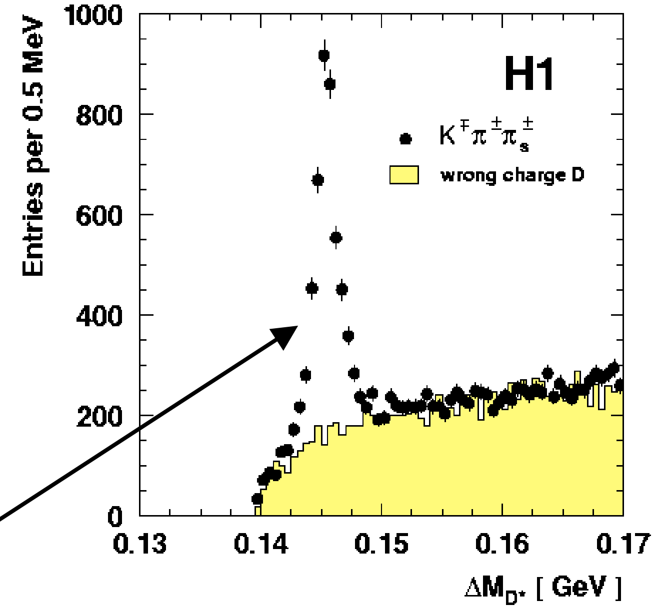


D^+ : *huge background or low yield*

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

D^* vector meson

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

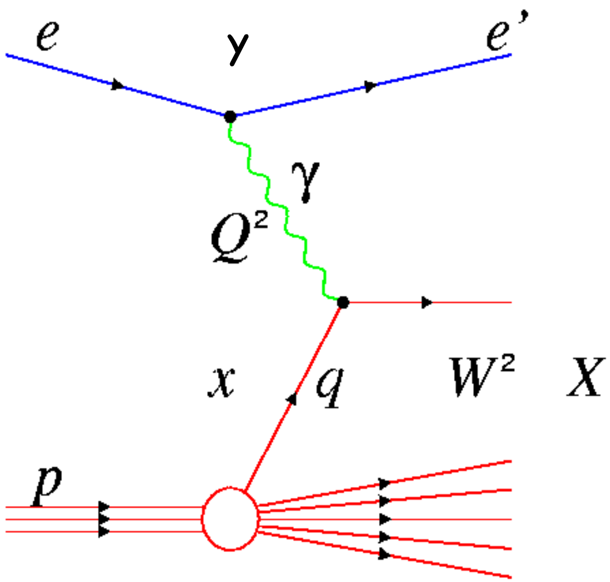


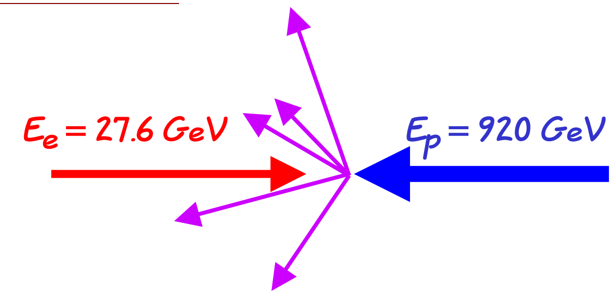
Mass difference technique $\Delta M(D^{*\pm}) = m(K^{\mp}\pi^{\pm}\pi) - m(K^{\mp}\pi^{\pm})$

D^* *experimentally much easier*

Let's try this !

HERA kinematics





Kinematic variables

Q^2: 4-momentum transfer squared

x : Bjorken x

y : Electron inelasticity

W : Mass of the hadronic system

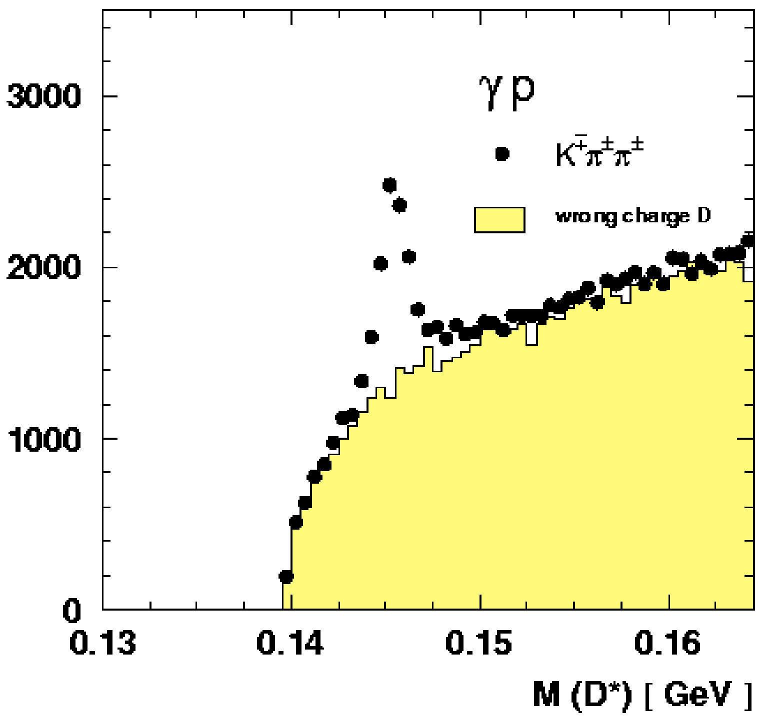
2 kinematic regimes :

$Q^2 \cong 0$ GeV^2 : Photoproduction

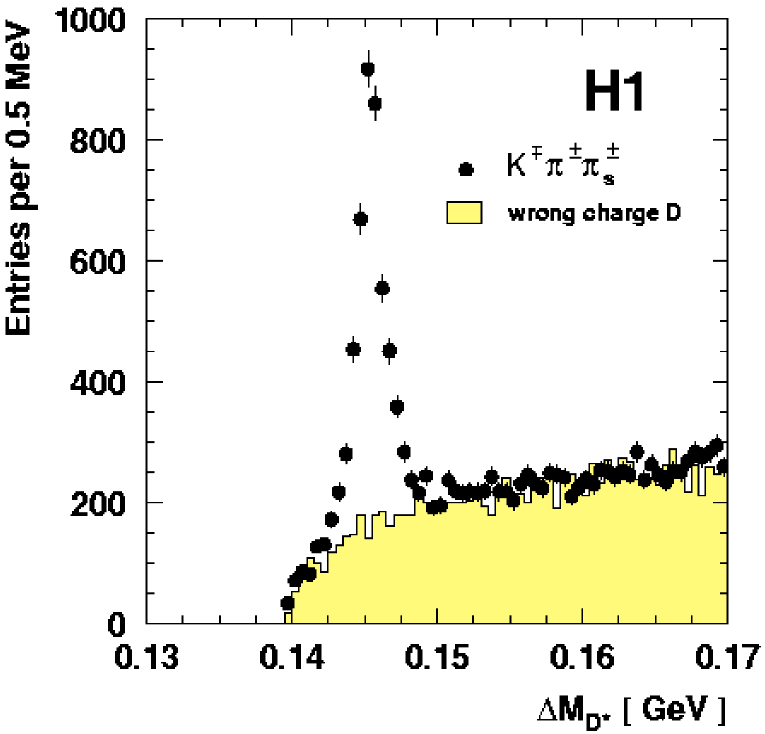
$Q^2 > 1$ GeV^2 : Electroproduction (DIS)

Both regimes equally well suited for the analysis ?

Photoproduction (γp)



DIS



DIS much cleaner → base analysis on DIS

→ use γp as cross check

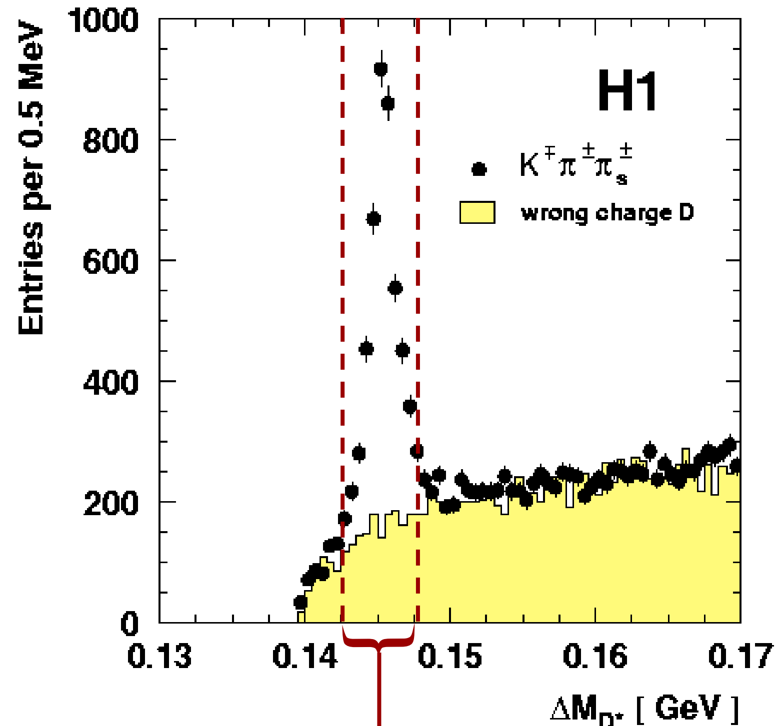
First ingredient - the D* meson

- 1996 – 2000 Data $L_{\text{int}} = 75\,pb^{-1}$
- DIS: $1\ GeV^2 < Q^2 < 100\ GeV^2$

  $0.05 < y_e < 0.7$
- $p_t(\mathbf{D}^*) > 1.5\ GeV$
- $-1.5 < |\eta(D^*)| < 1.$
- $p_t(\mathbf{K}) + p_t(\pi) > 2\ GeV.$
- Inelasticity $z(\mathbf{D}^*) > 0.2$

Good Signal/Background

3400 D*'s in DIS to start with



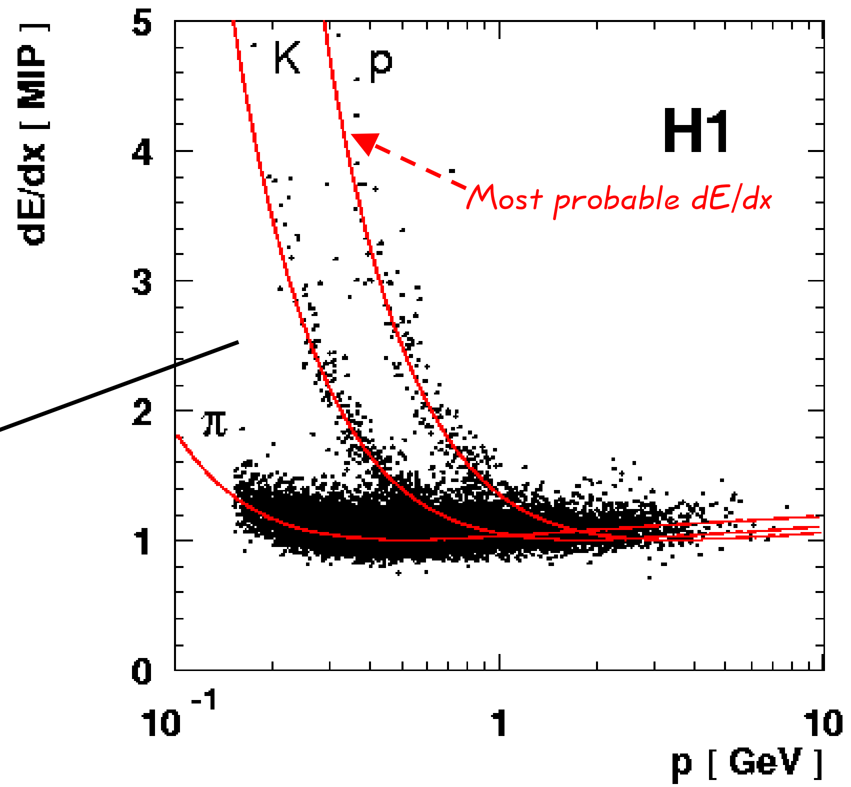
D* signal region subsequently used

Second ingredient - 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



Use dE/dx for background suppression

The recipe for the $D^{*-}p$ search

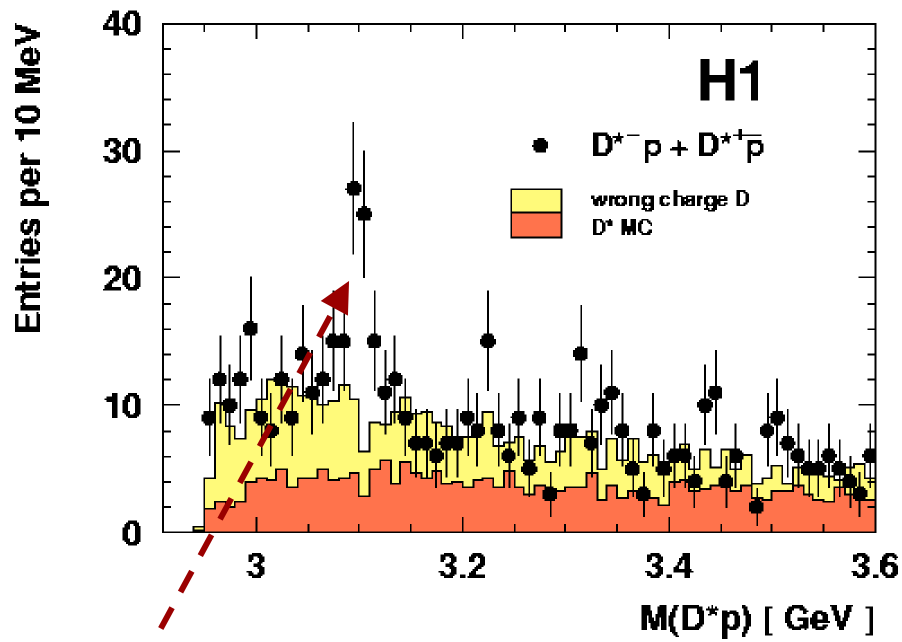
- Looking for a narrow state near threshold
- Expected 4-particle mass resolution about 35 MeV not favourable for a narrow state → use mass difference technique: $m(D^*p)-m(D^*)$
- Cut on the normalized proton likelihood $L(p)$ for pion suppression
- Take a D^* candidate add a track consistent with a proton using m_p

⇓

Look what you get !

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

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

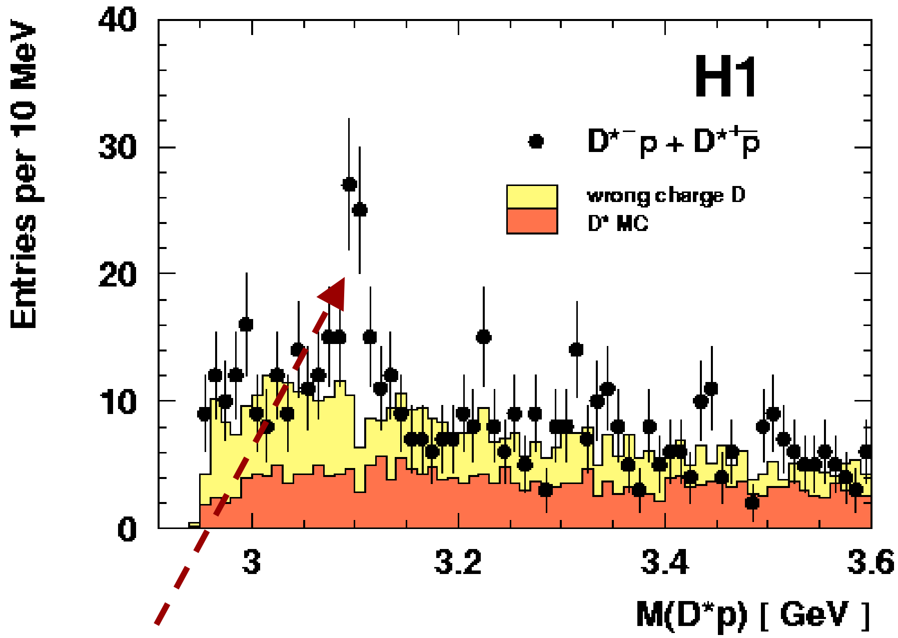


This is what we get !

D*⁻p + cc in DIS for 1996 - 2000

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

Could it be real ?
Or is it fake ?



This is what we get !

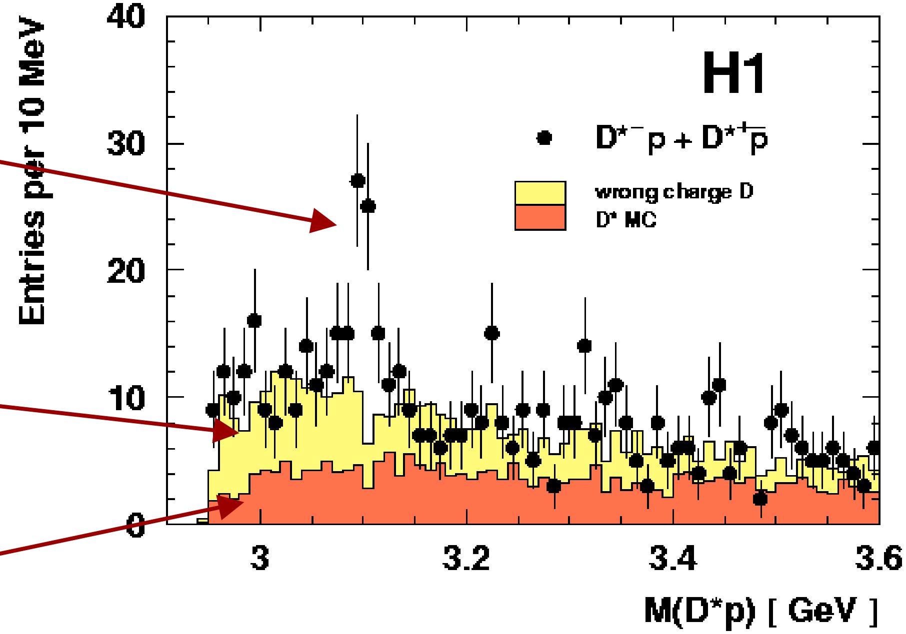
$D^{*-}p$ + cc in DIS for 1996 - 2000

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

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

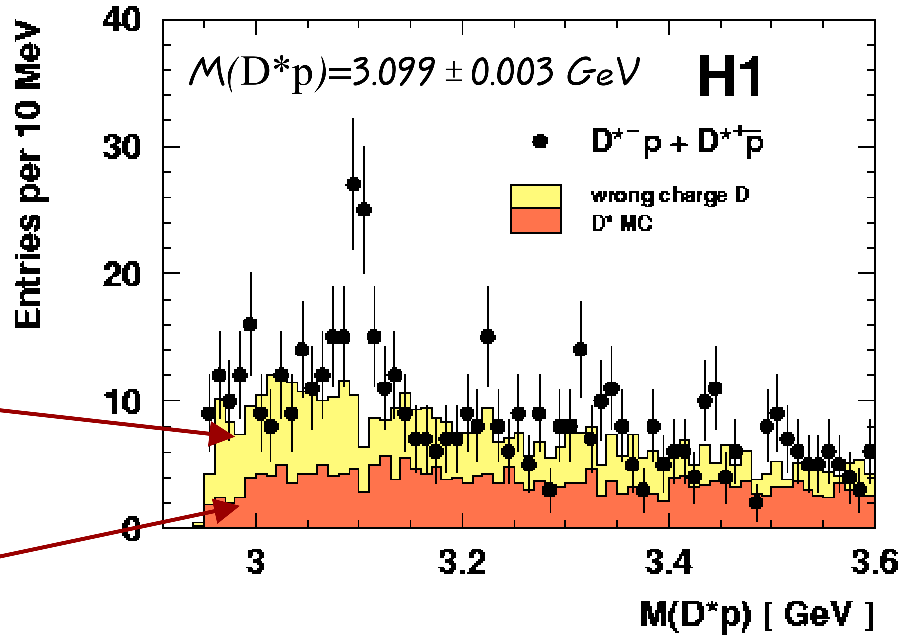
1) Mass of same sign $K^{\pm}\pi^{\pm}$ in $m(D^0)$ window

2) Also no peak from CASCADE or Beauty MC

Significant peak in opposite sign D^*p – is it real or is it fake ?

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

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



60-70% of background due to non-charm

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

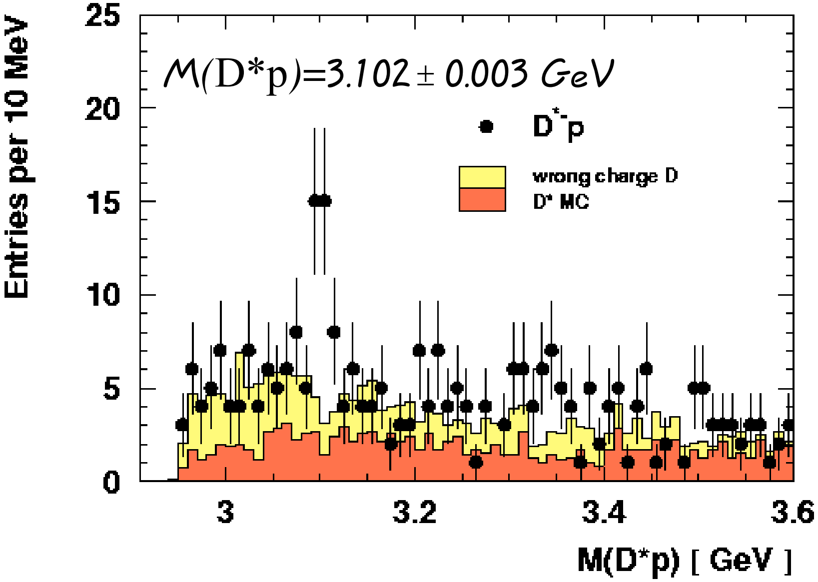
Background well described by D* MC and wrong charge D from data

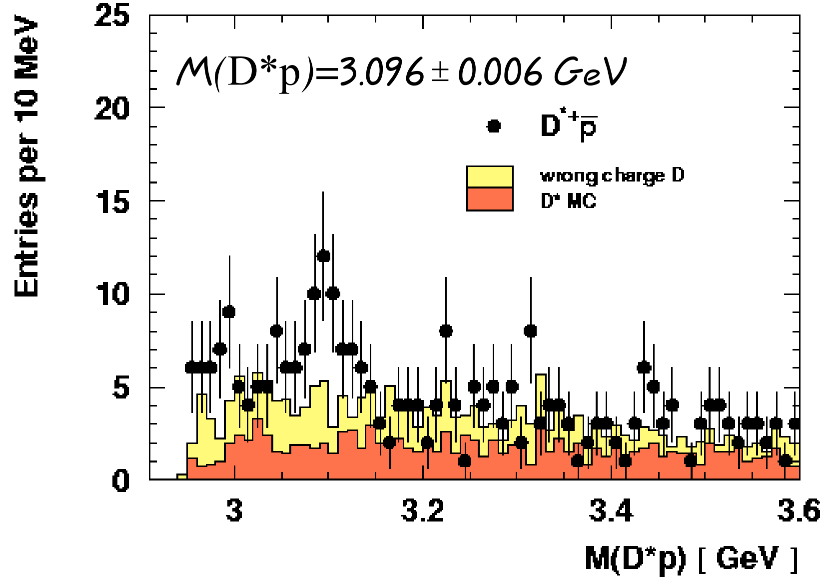
1) Also no peak from CASCADE or Beauty MC

Significant peak in opposite sign D*p – is it real or is it fake ?

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

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





$25.8 \pm 7.1\ Events$

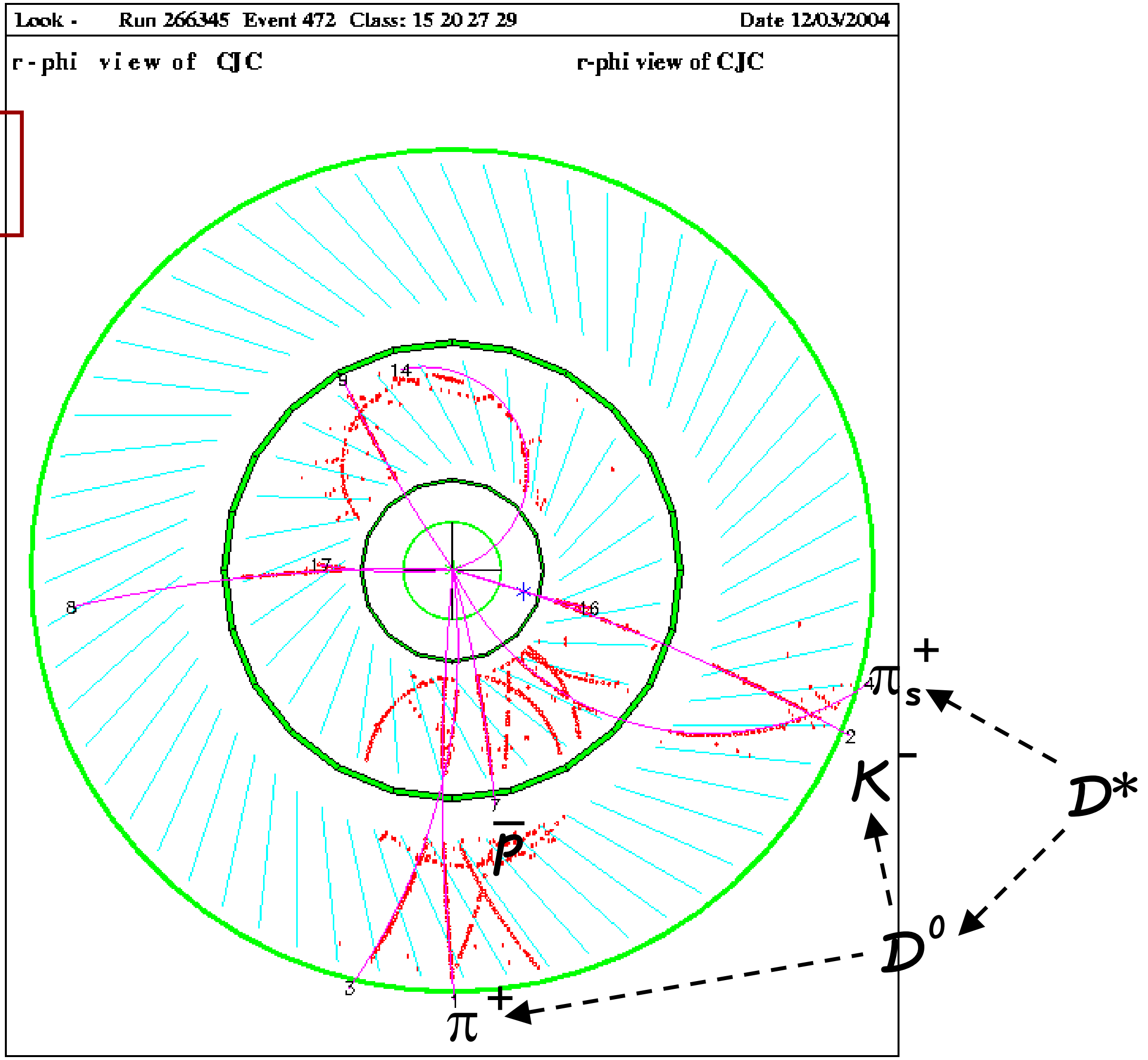
$23.4 \pm 8.6\ Events$

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

A typical Event

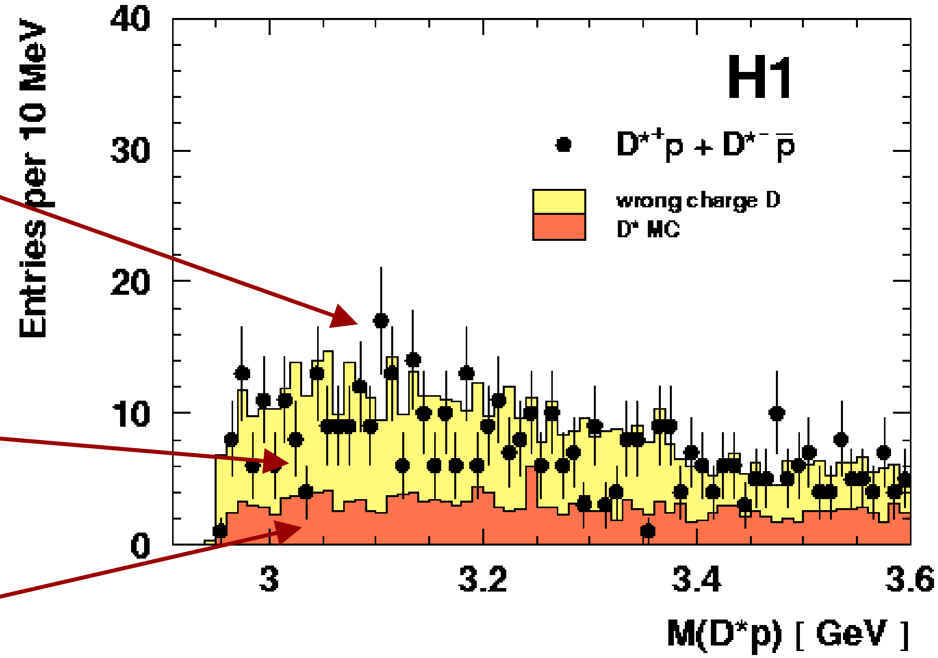
All events in the signal region have been scanned

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]

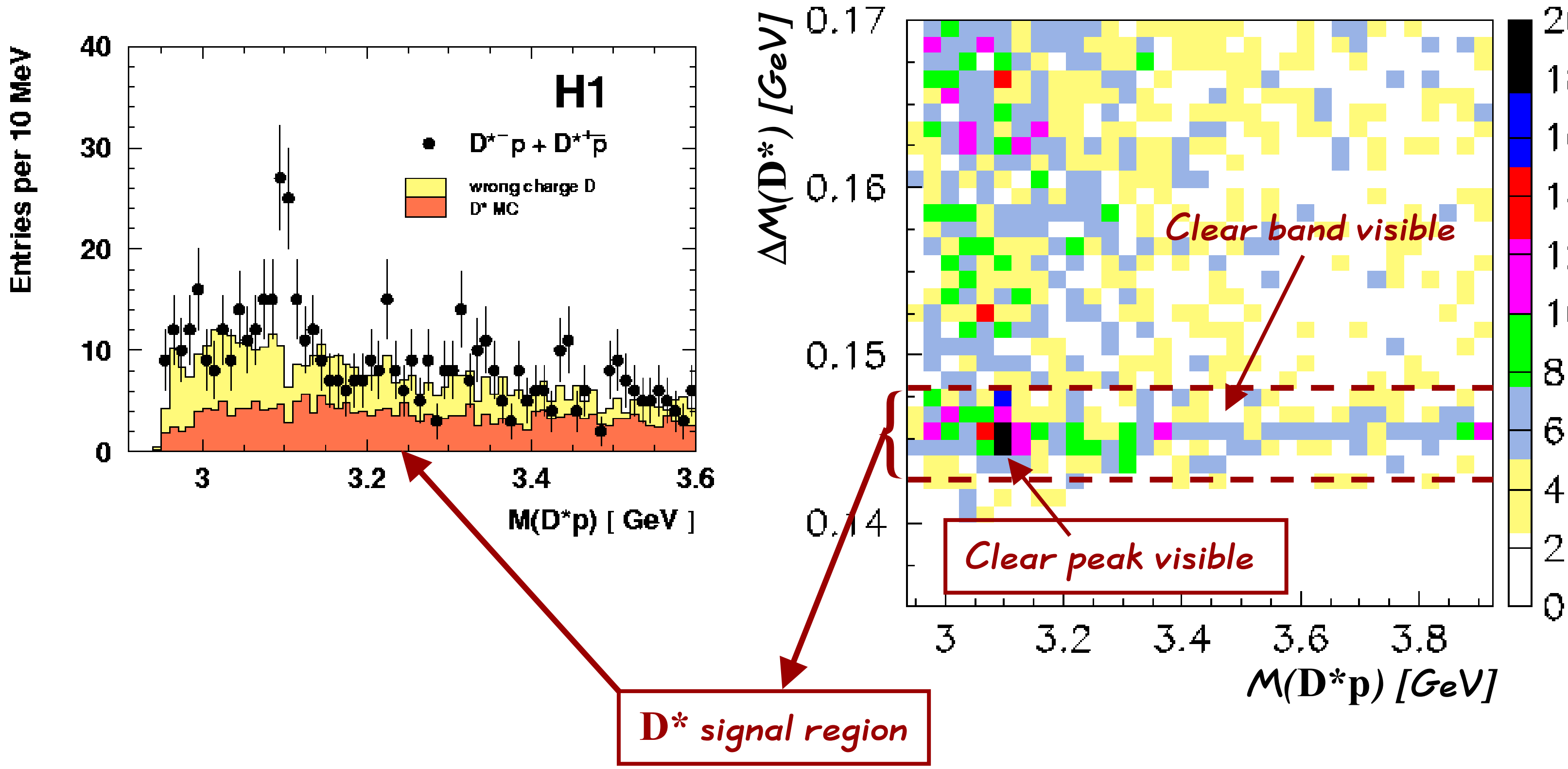
No enhancement in D^* MC (RAPGAP)[3]

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

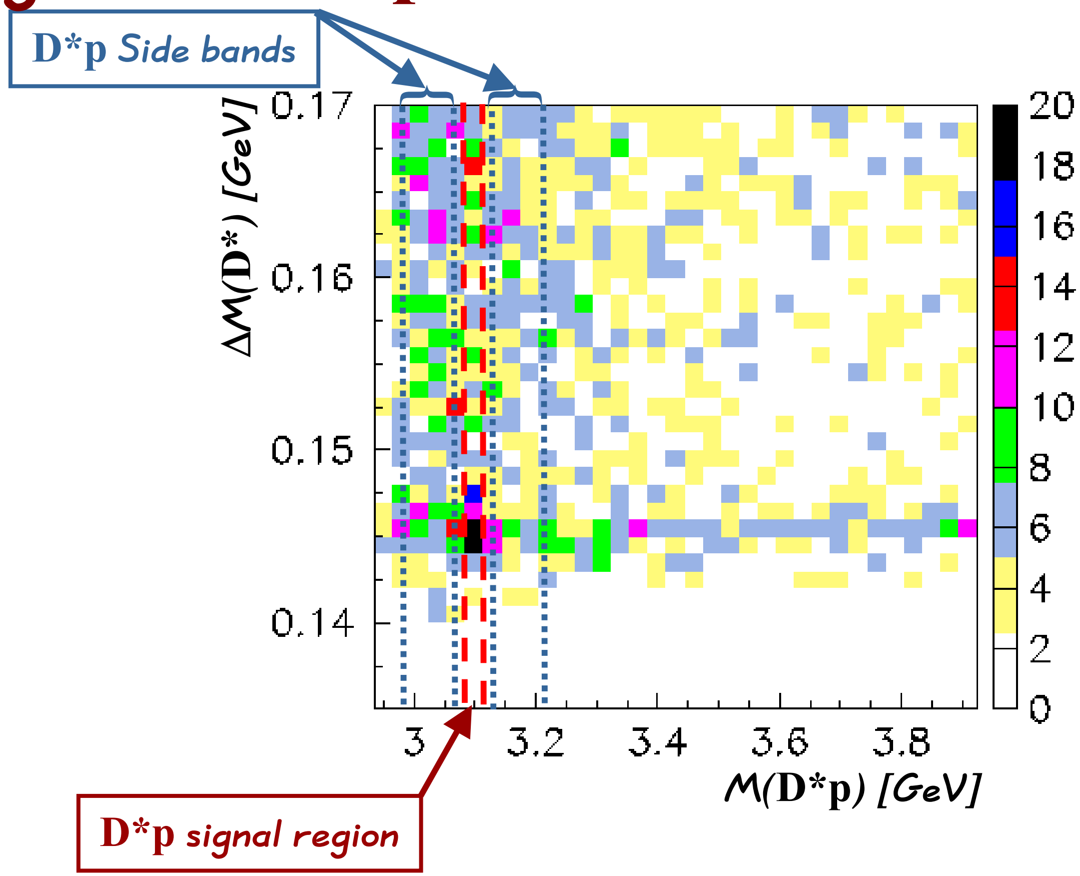
Signal region in $D^{*-}p$ [1] richer in D^{*-}?

1) Charge conjugate always implied



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

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



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

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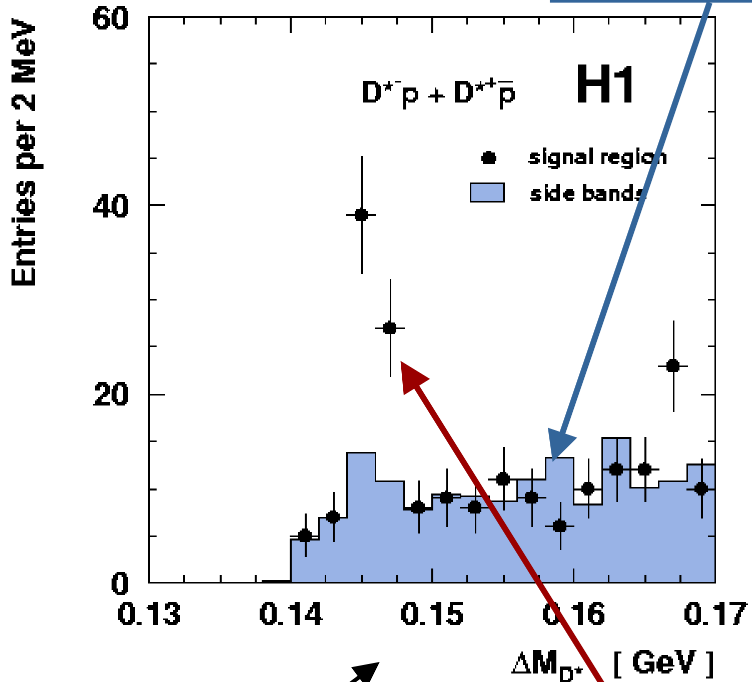
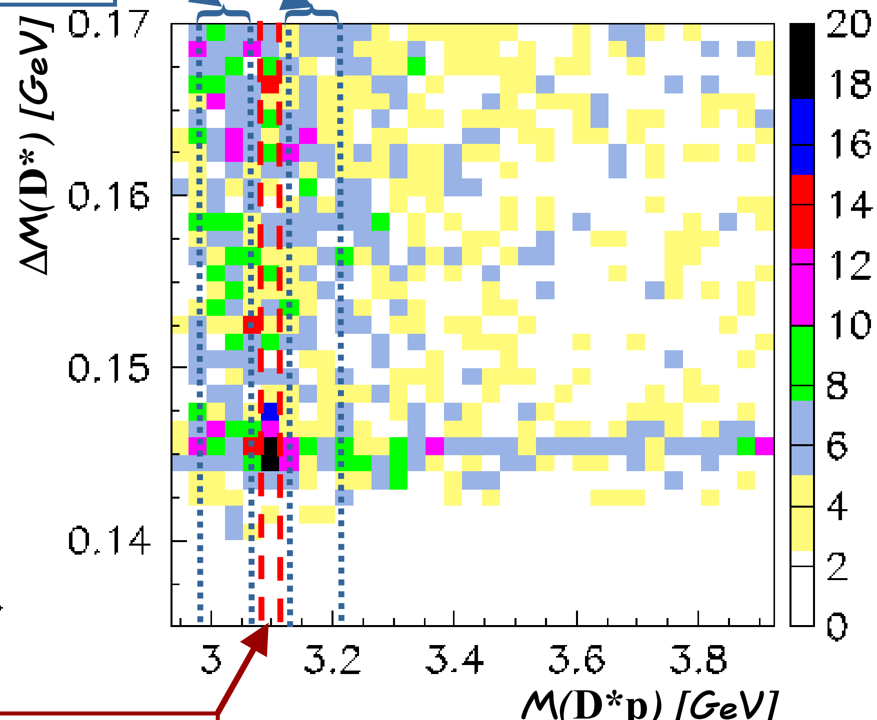
Signal region in $D^{*-}p$ [1] richer in D^{*-}?

D*p Side bands





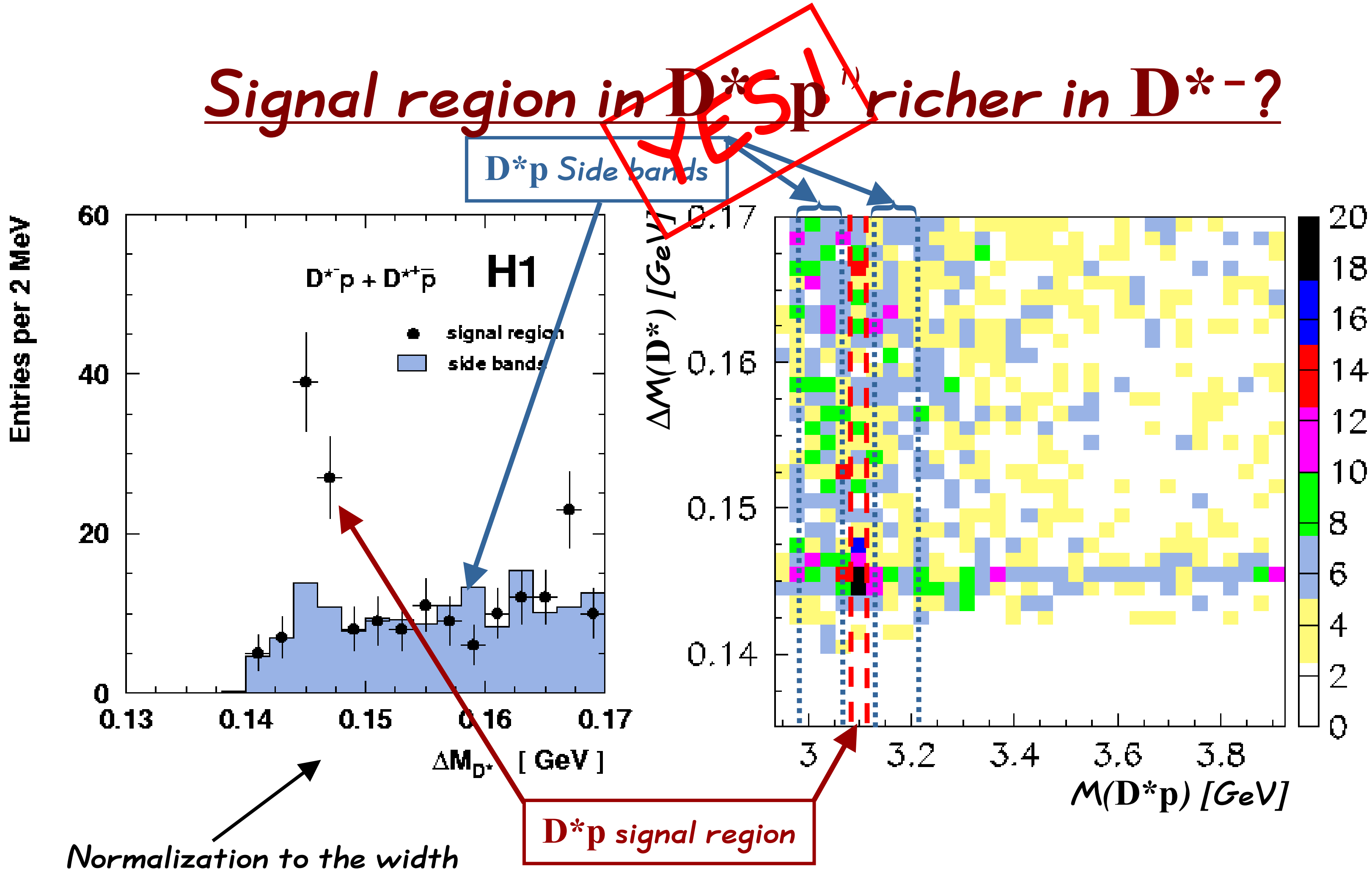
D*p signal region

*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^{*-}?

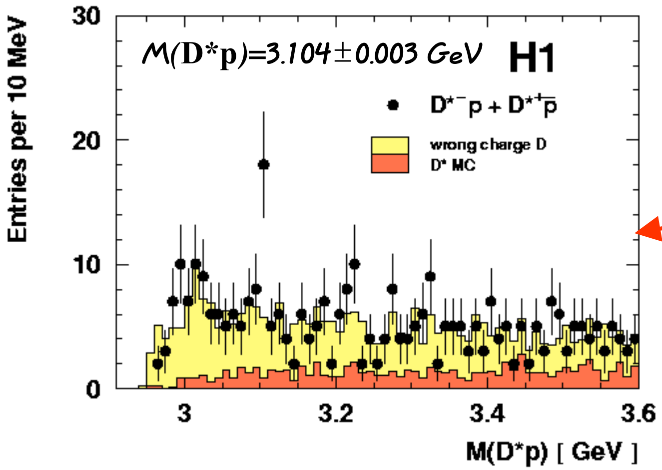


*Normalization to the width of the windows in M(D*p)*

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

1) Charge conjugate always implied

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



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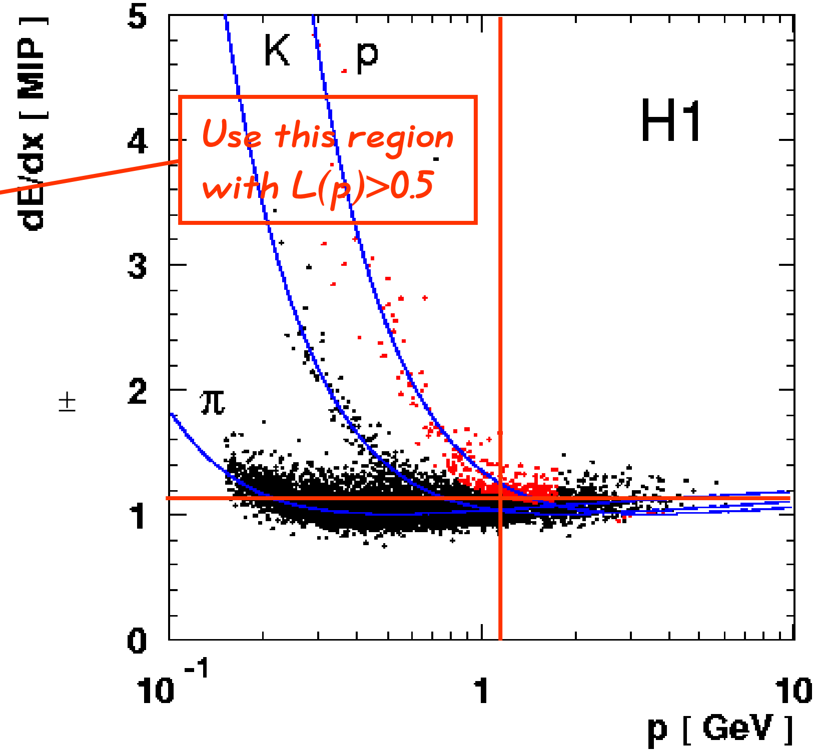

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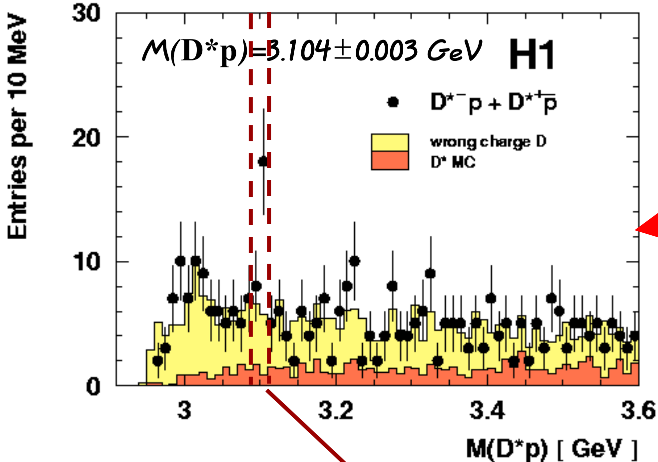

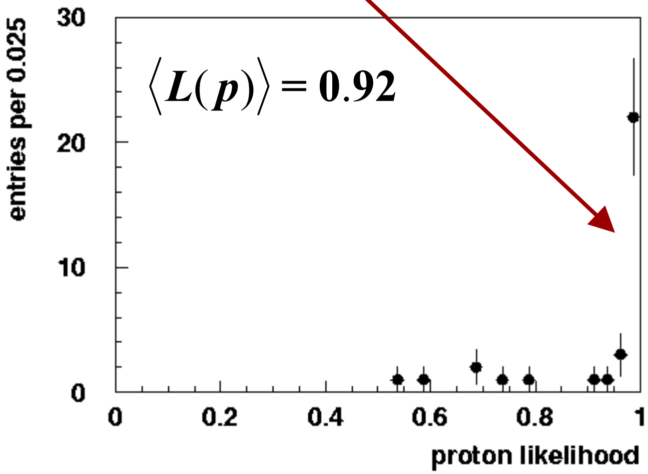

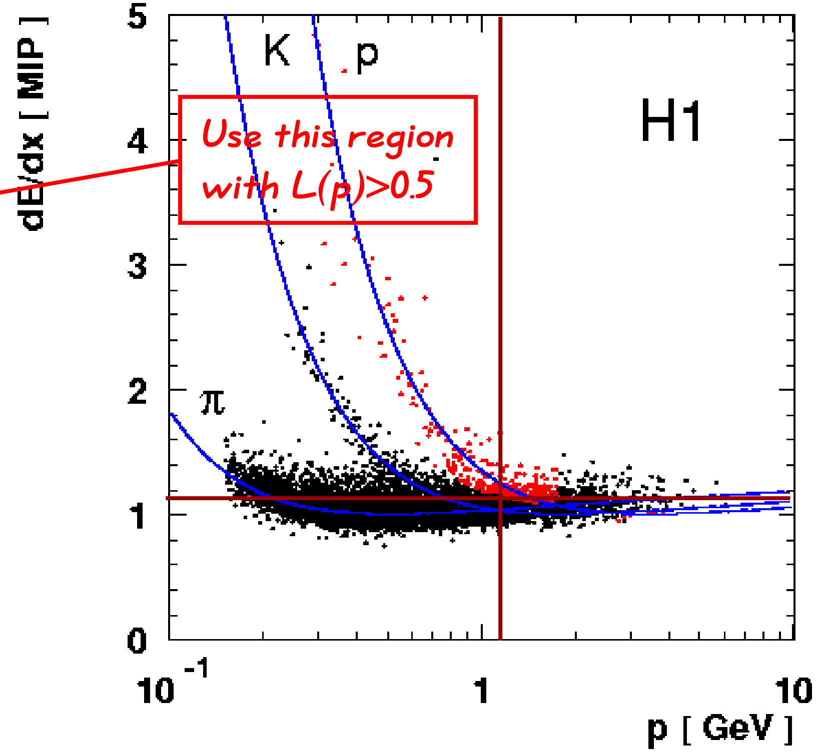

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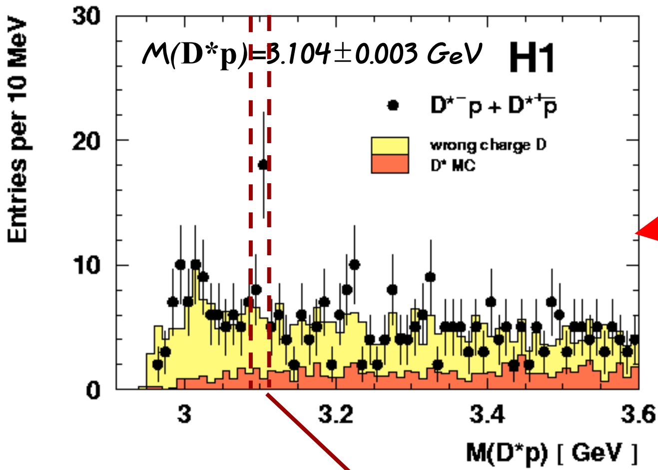
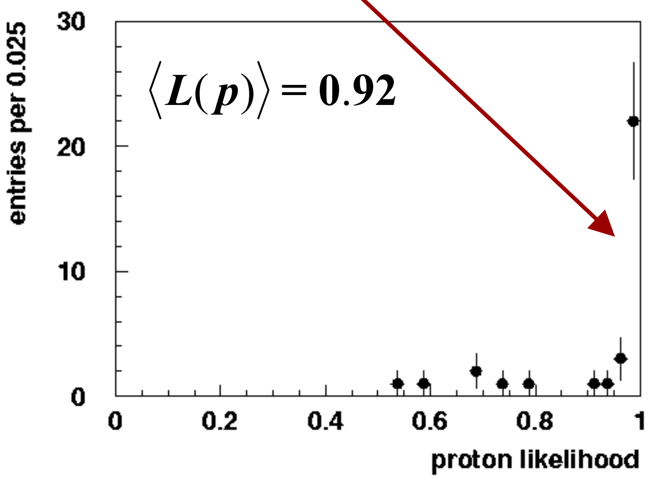
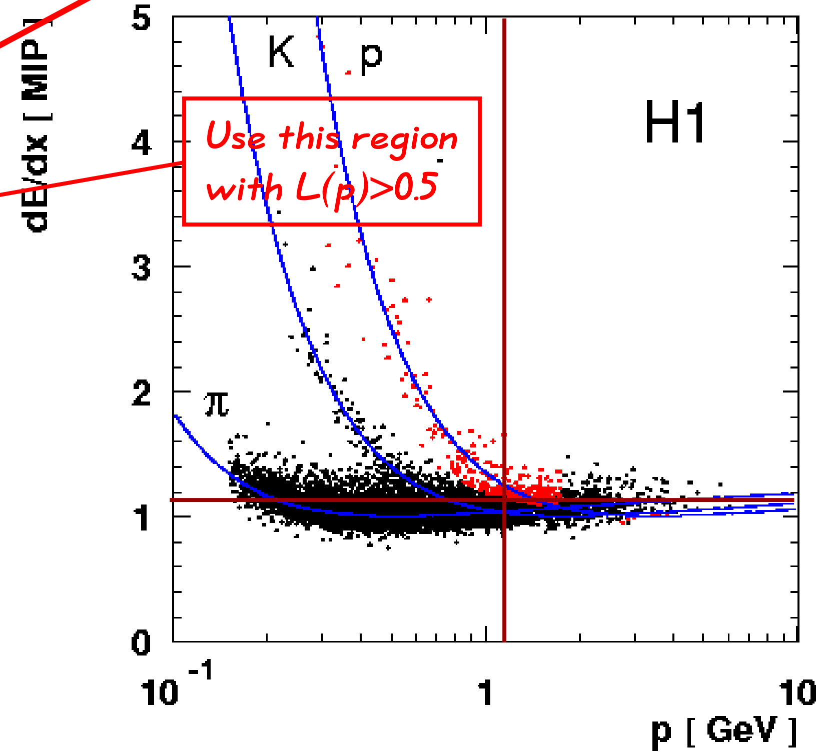
1) Charge conjugate always implied

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

YES!







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

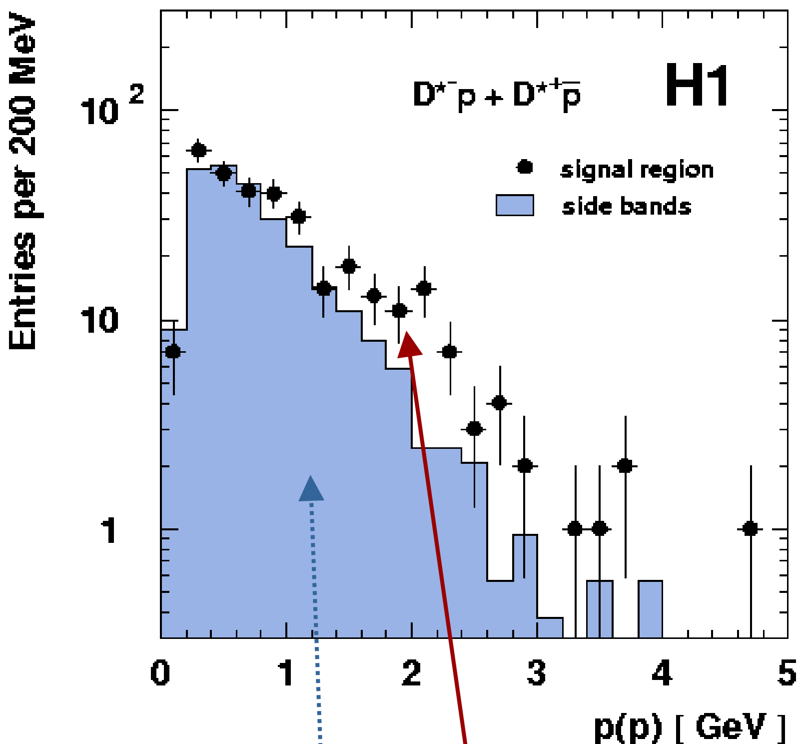
1) Charge conjugate always implied

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

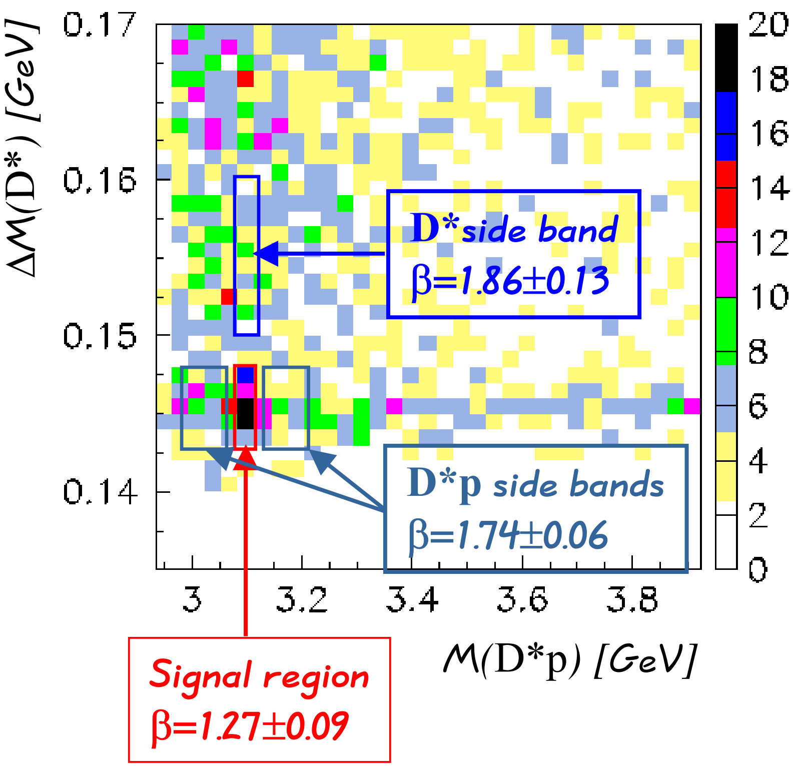
No L(p) cuts !

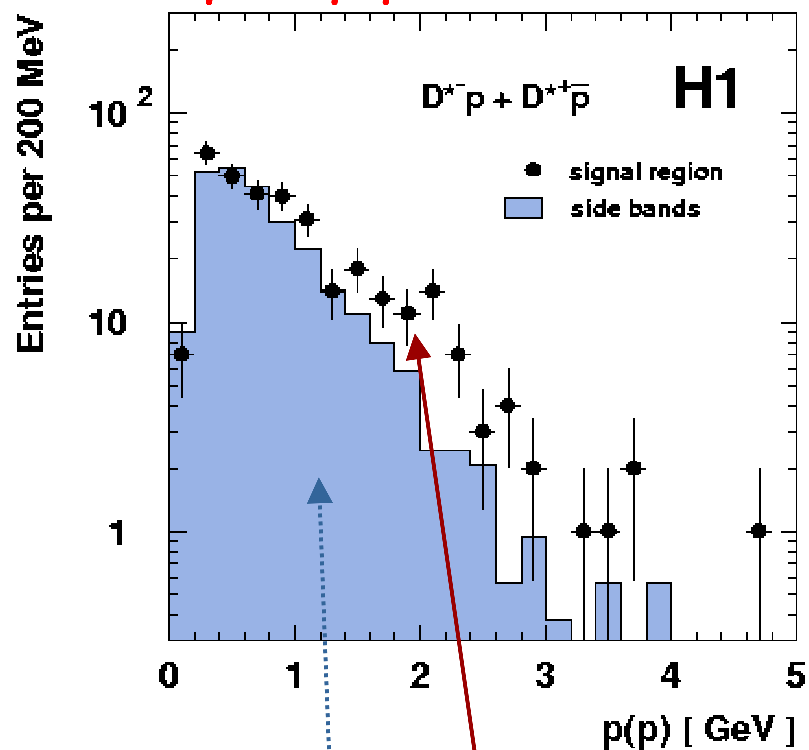


The momentum spectrum of the particles in the signal region is harder than in the M(D*p) side bands

Is the physics different in the signal region?

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



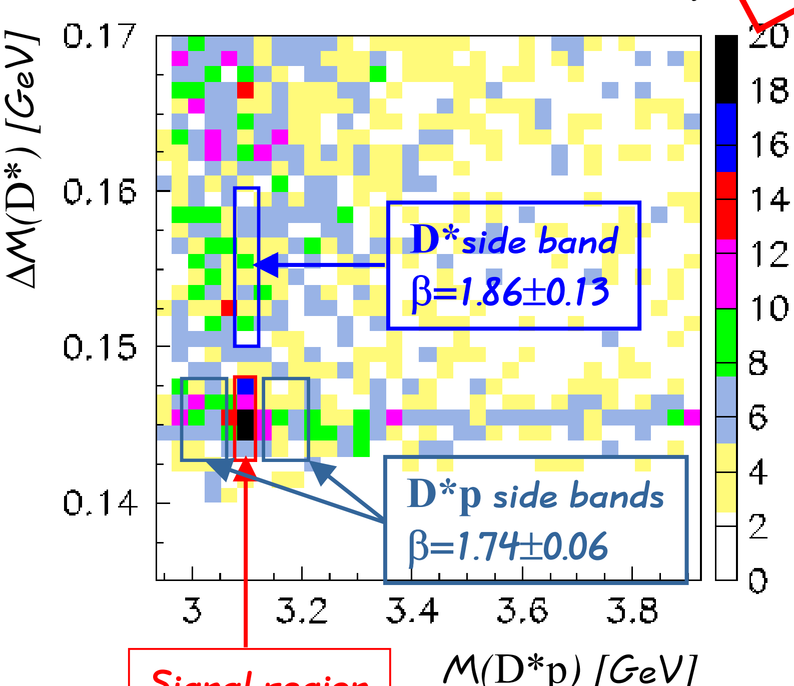


The momentum spectrum of the particles in the signal region is harder than in the M(D*p) side bands

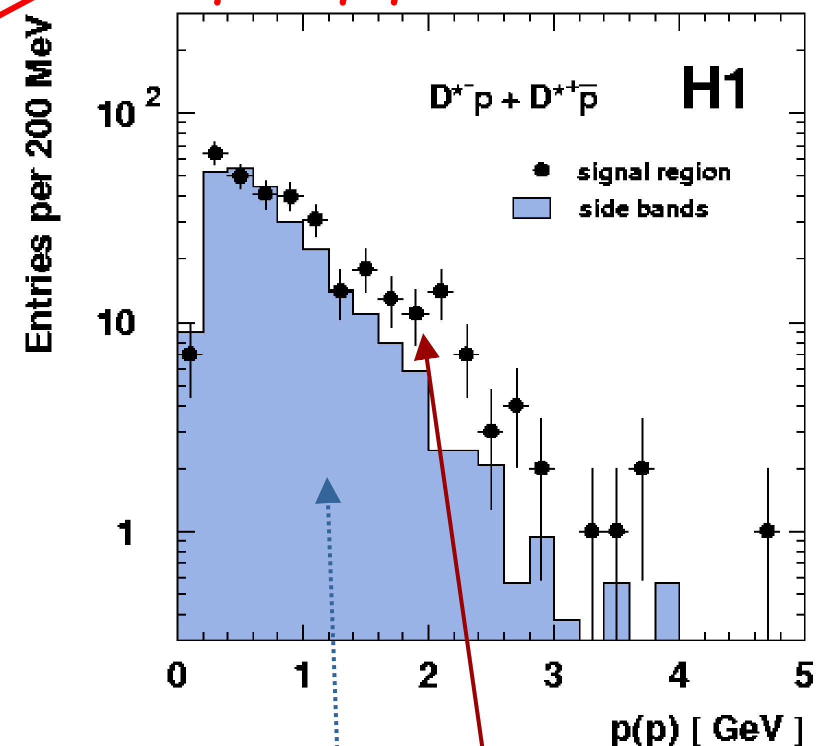
Is the physics different in the signal region?

YES!

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

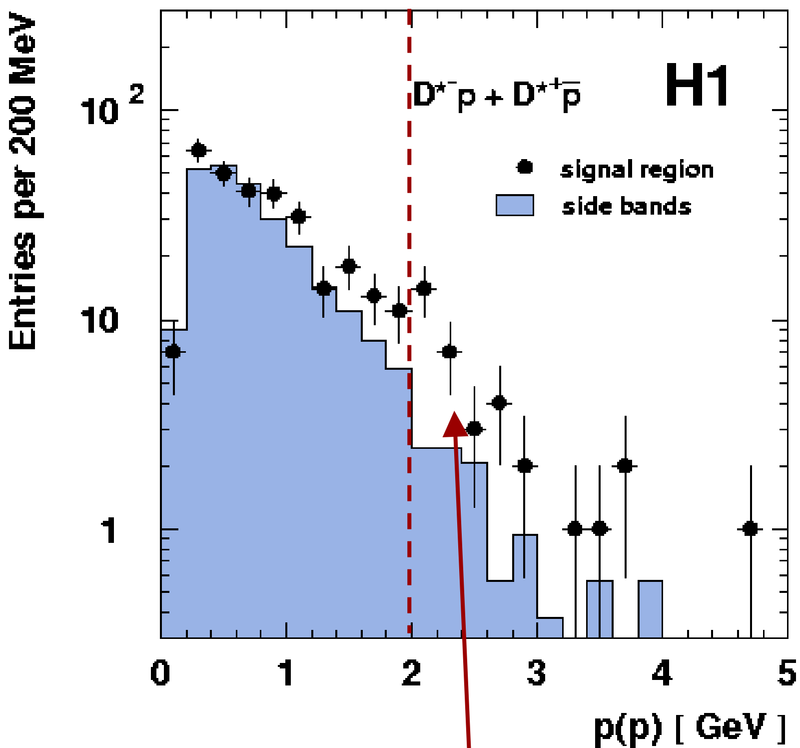


Signal region
β=1.27±0.09



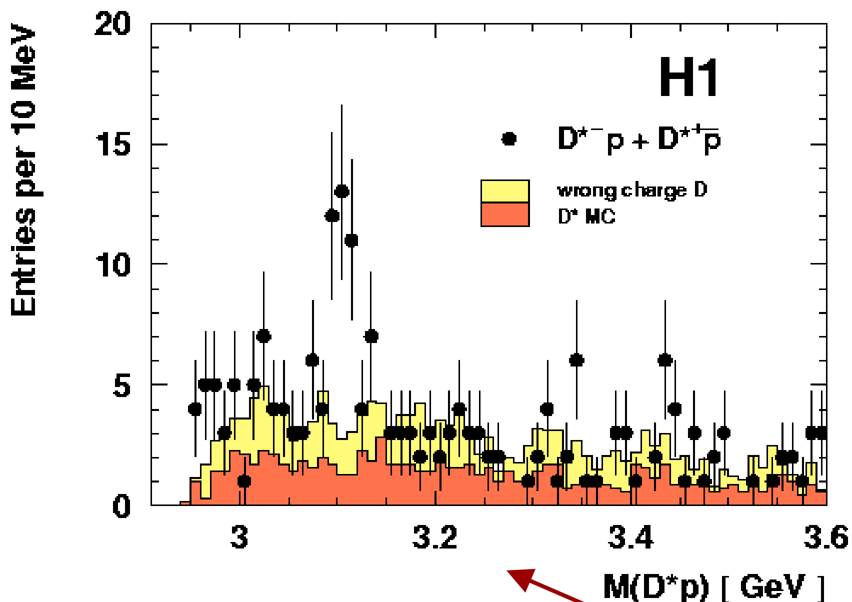
The momentum spectrum of the particles in the signal region is harder than in the M(D*p) side bands

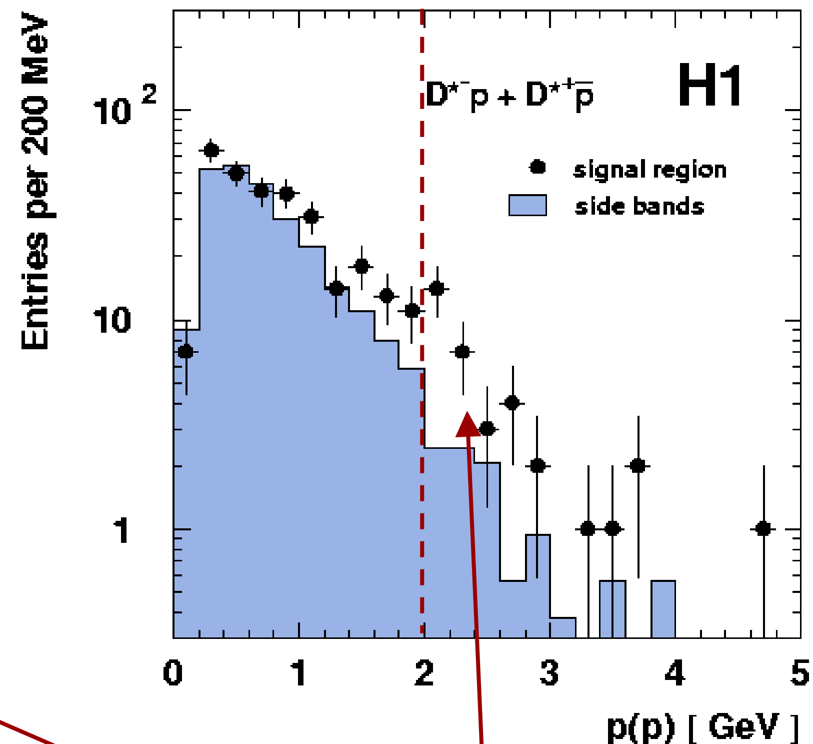
Signal at large p(p) more prominent ?



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

Signal at large p(p) more prominent ?





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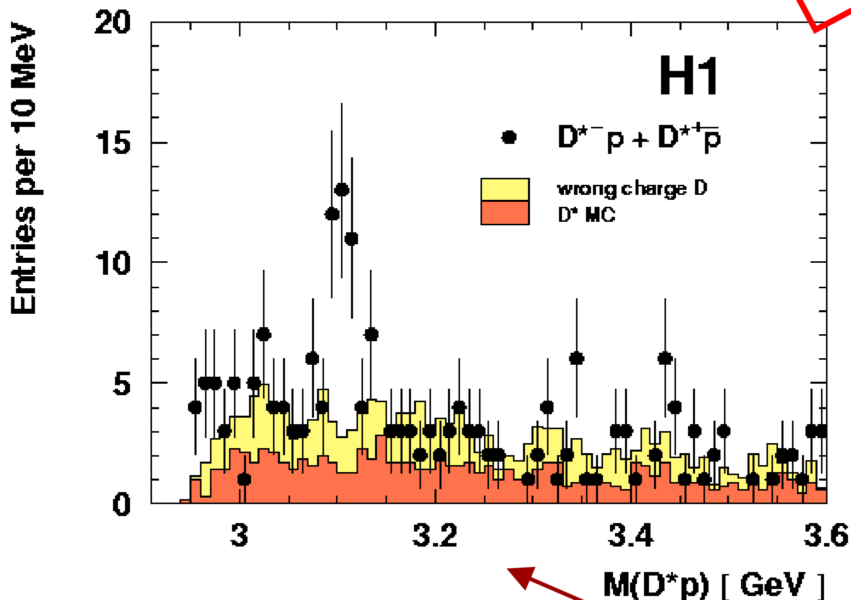
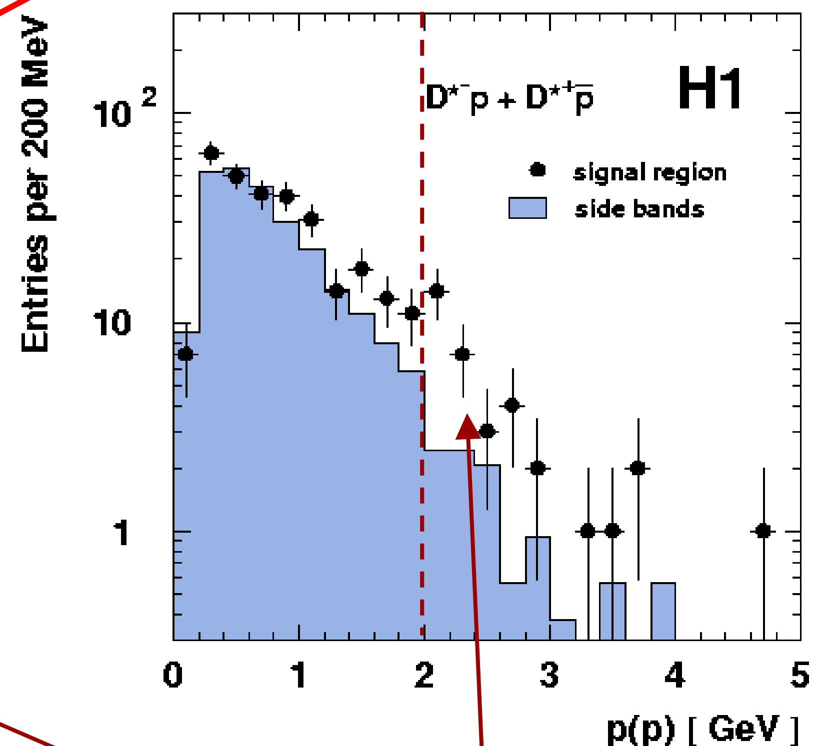
YES!





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

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

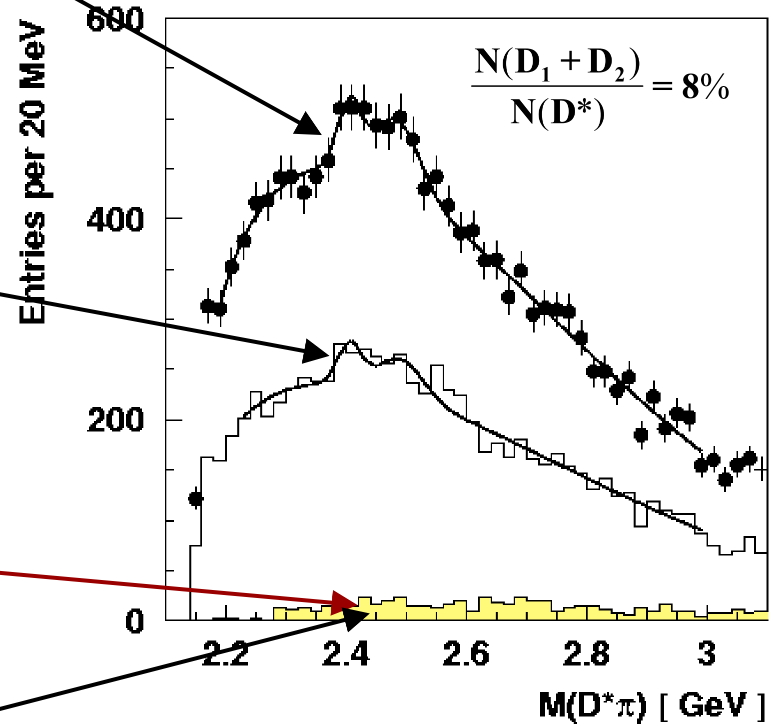
Loose D^* cuts & pion selection

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

D^* cuts of D^*p & proton selection

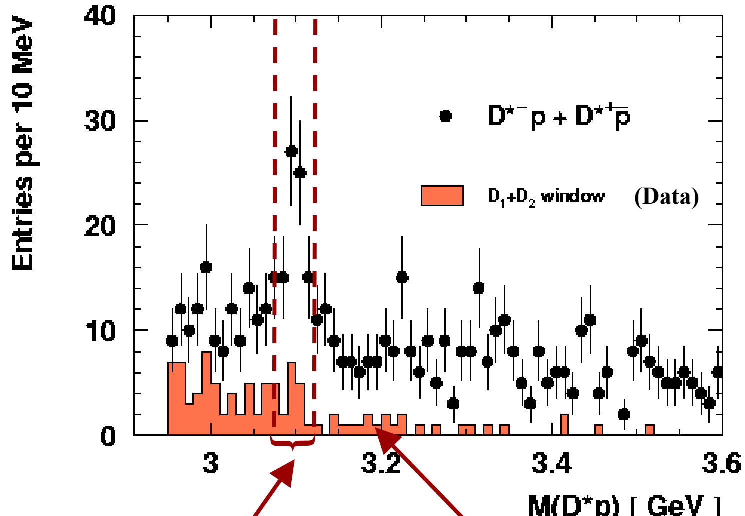
Compatible with MC expectation

No cut in D^*p

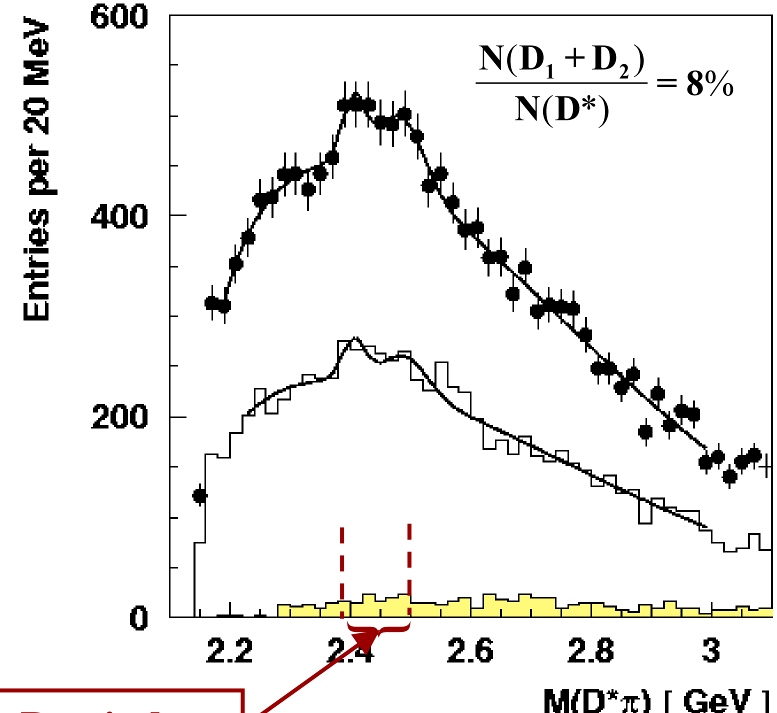


$M(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*)_{PDG}$

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

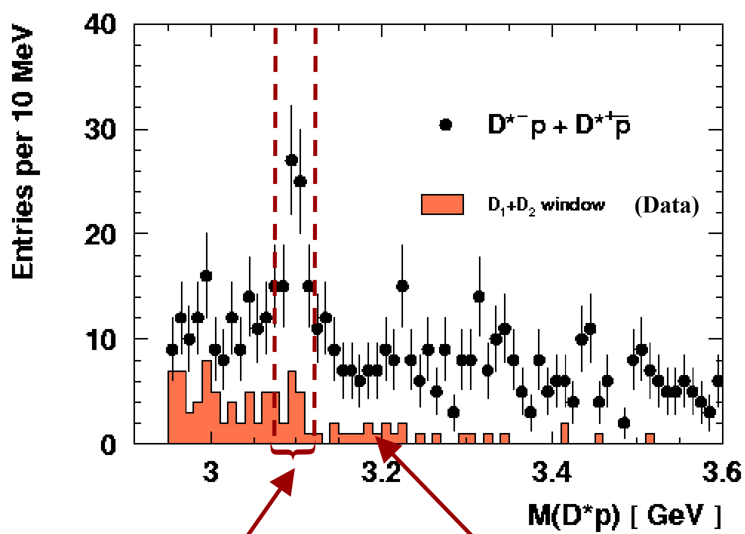
N(D_1+D_2) = *3.5 in the*
D*p *signal region from MC*

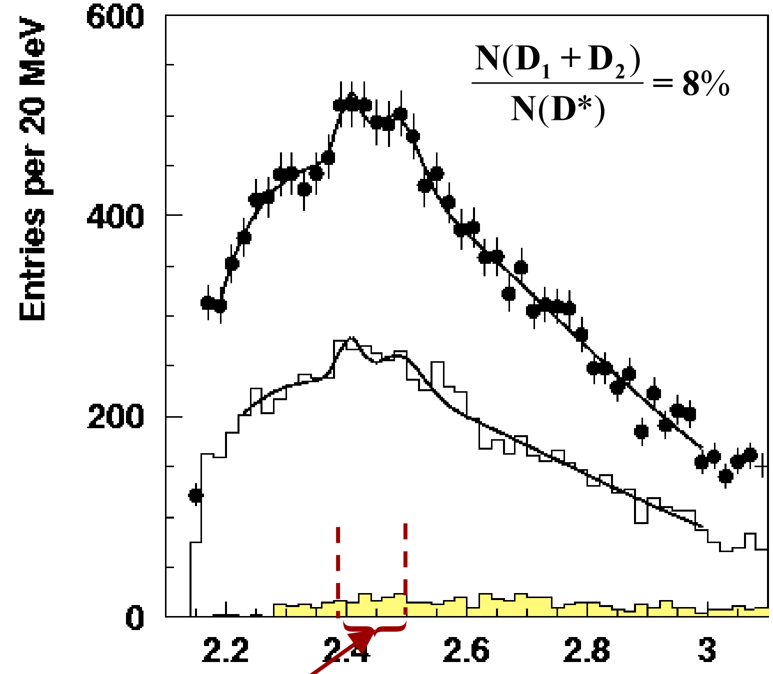
$M(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*)_{PDG}$

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

Small!

No cut in D^*p





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

Basics of kinematic tests

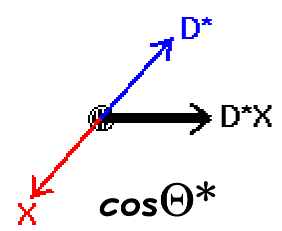
2-Body Decay

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

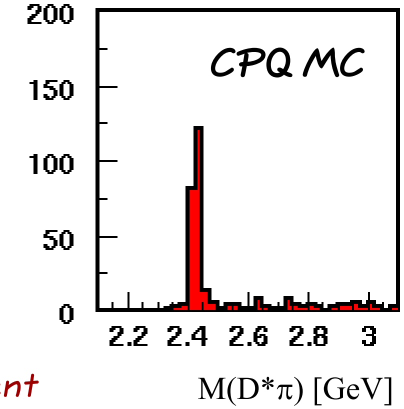
$$= (m_{D*}^2 + m_X^2 + 2E_{D*}E_X - 2\vec{p}_{D*}\vec{p}_X)$$

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

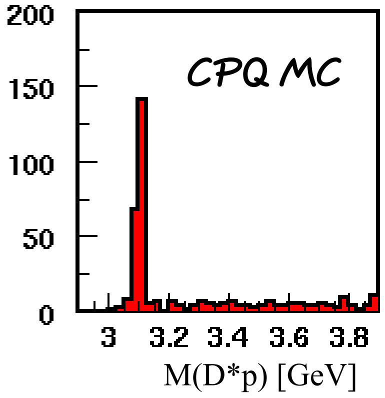
D*p rest frame

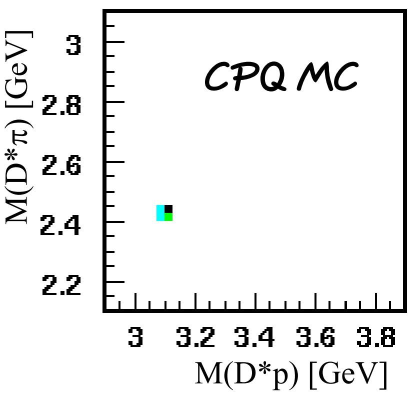


wrong mass assignment



correct mass assignment





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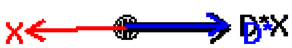
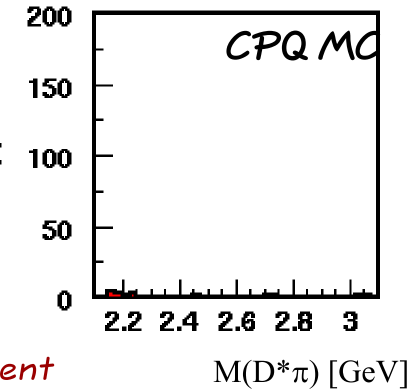
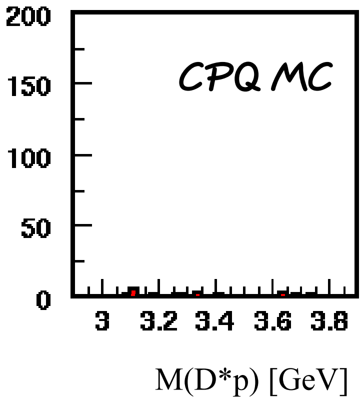
D*p *rest frame*

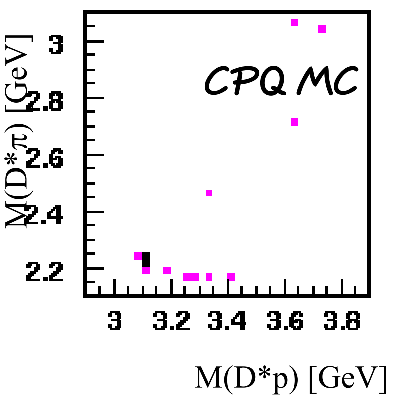


wrong mass assignment



correct mass assignment



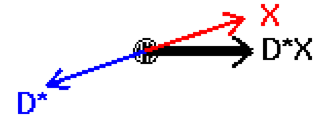


Kinematic tests

2-Body Decay

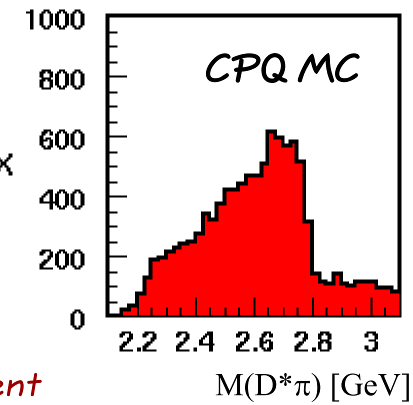
$$M^2 = (P_1 + P_2)^2$$
$$= (m_{D*}^2 + m_X^2 + 2E_{D*}E_X - 2\vec{p}_{D*}\vec{p}_X)$$

D*p *rest frame*

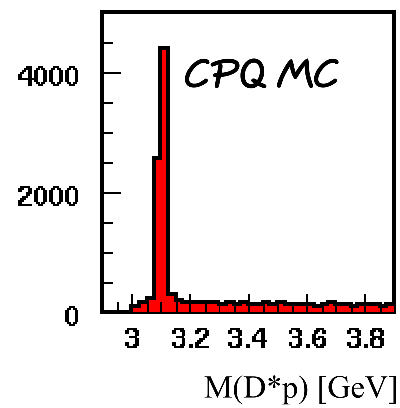


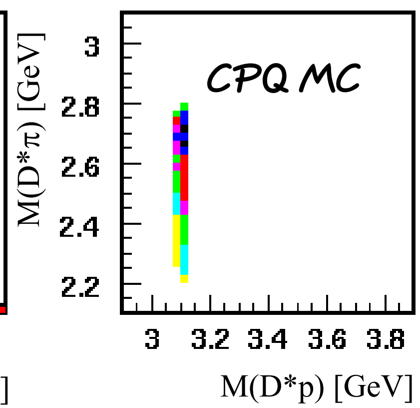
*Integrated in cosΘ**

wrong mass assignment



correct mass assignment

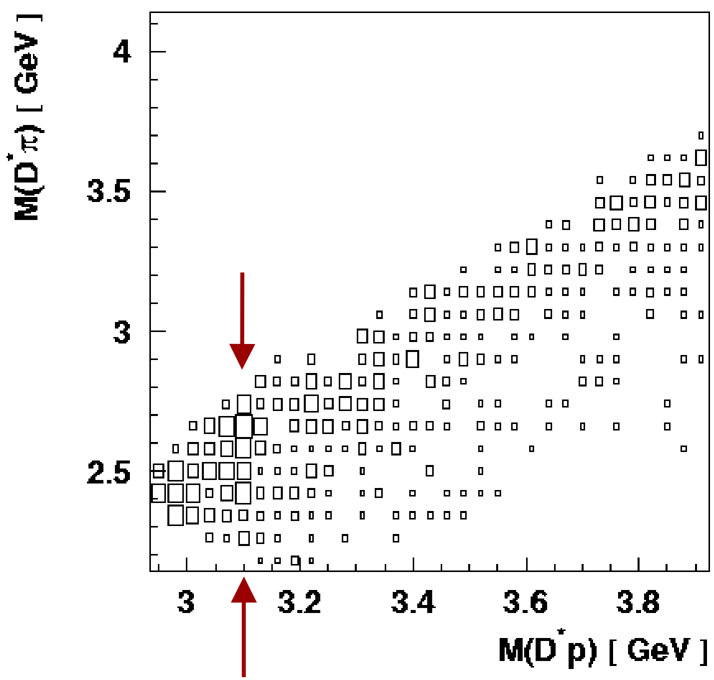




Do we see a band like structure in the M(D*p)-M(D*x) plane in data? → Let's have a look

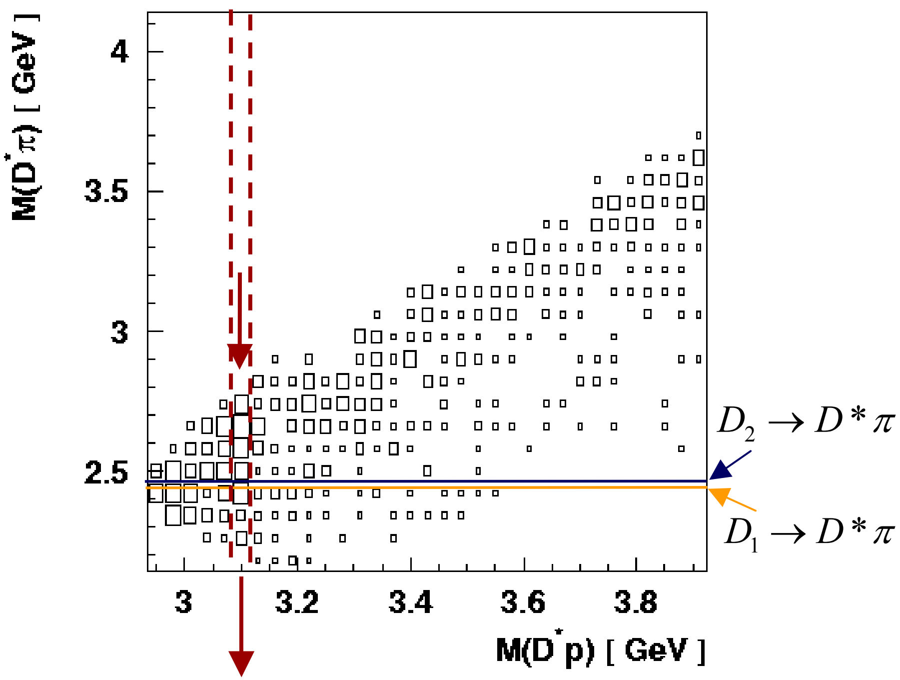
Signal due to $D^*\pi$?

Back to data !



Band in $D^*\pi$ clearly visible

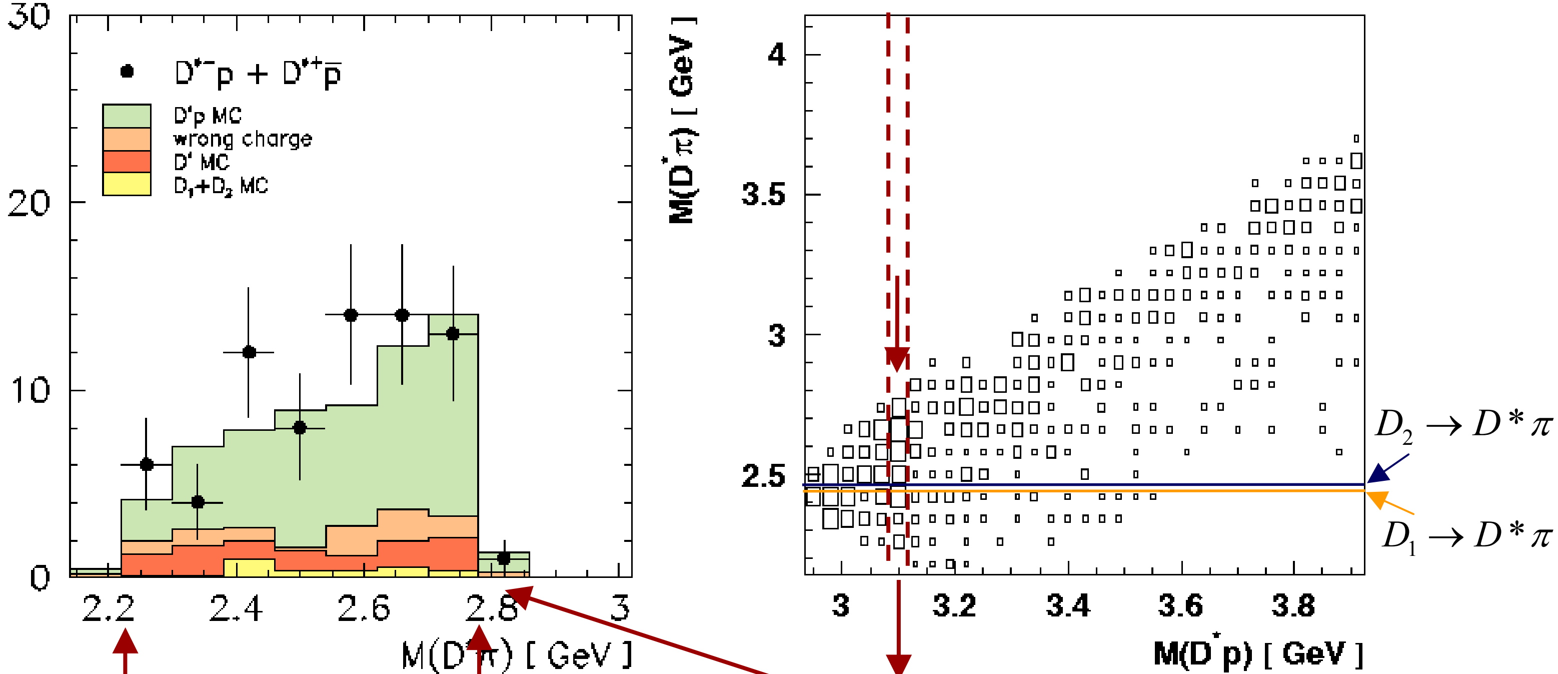
Signal due to $\mathbf{D^*\pi}$?



Go to the $\mathrm{D^*p}$ *signal region*

No indication for contributions from $\mathbf{D}_1$ *and* $\mathbf{D}_2$

Signal due to D*π ?

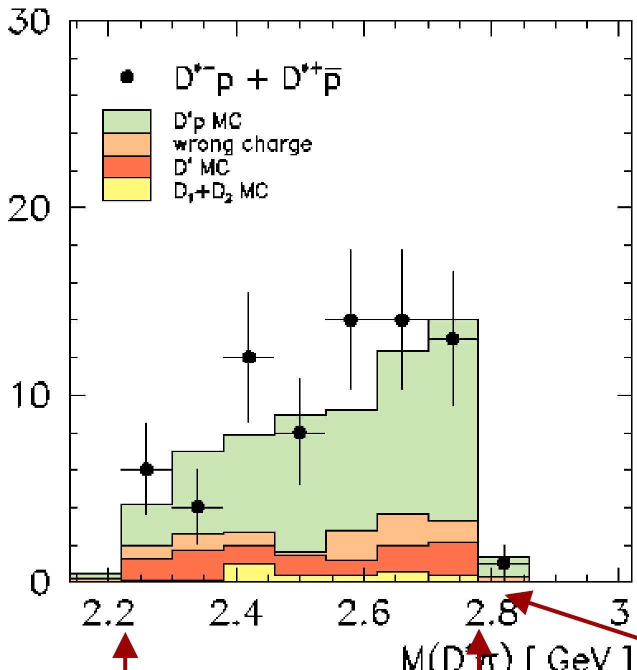


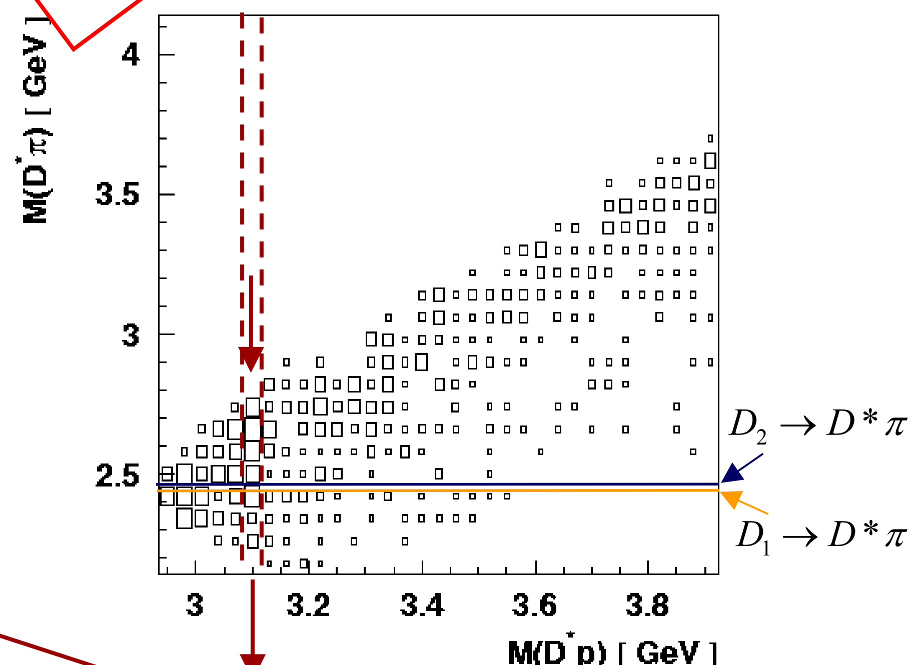
Go to the D*p *signal region*

Sign for X ⟶ D*p*: available phase space in* D*π *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*

Lots of further kinematic test

- Reflections from a possible signal in D^*K mass distribution:
- Possible contributions from $D^{*0} \to D^0\gamma$ with γ-conversion:
- Possible contributions from $D_{S1}/D_{S2} \to D^0K$:
- Possible peak structures in all possible mass correlations with all possible mass hypotheses of the particles making the D^* and the D^*p system to search for real or fake resonances, e.g Λ, Δ^0, Δ^{++}, K_S^0, ϕ, f_2

- Possible peak structures in all possible mass correlations among the proton candidate the remaining charged particles of the event with all possible mass assignments to search for real or fake peaks,

Lots of further kinematic test

- Reflections from a possible signal in D^*K mass distribution: ruled out
- Possible contributions from $D^{*0} \to D^0\gamma$ with γ-conversion: ruled out
- Possible contributions from $D_{S1}/D_{S2} \to D^0K$: ruled out
- Possible peak structures in all possible mass correlations with all possible mass hypotheses of the particles making the D^* and the D^*p system to search for real or fake resonances, e.g Λ, Δ^0, Δ^{++}, K^0_S, ϕ, f_2
  no enhancements found
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  no enhancements found

- Possible peak structures in all possible mass correlations among the proton candidate the remaining charged particles of the event with all possible mass assignments to search for real or fake peaks,

  no enhancements found

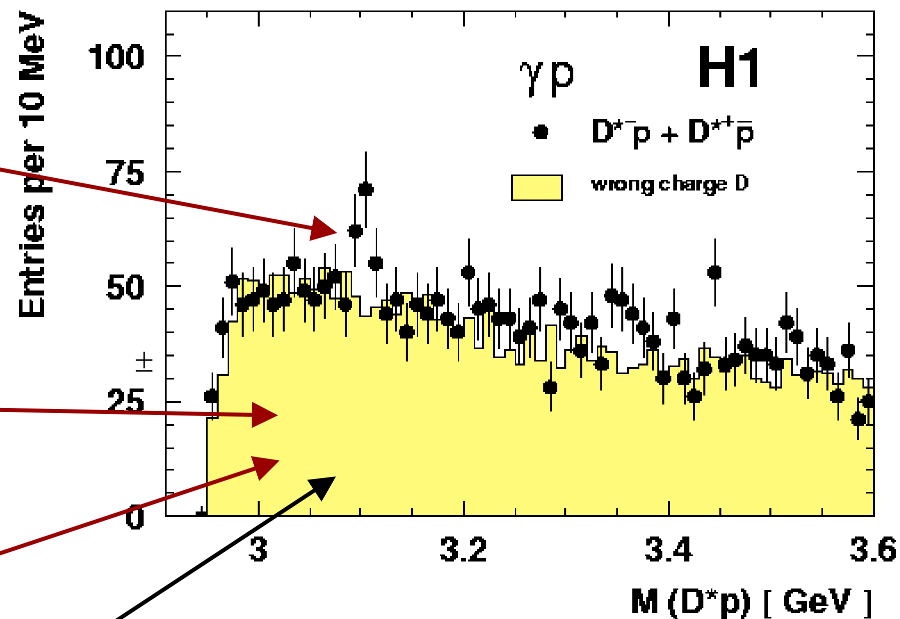
PASSED!

$D^{*-}p$[1)] in photoproduction

4900 D*

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

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



Peak also observed in photoproduction

>95% of background due to non-charm

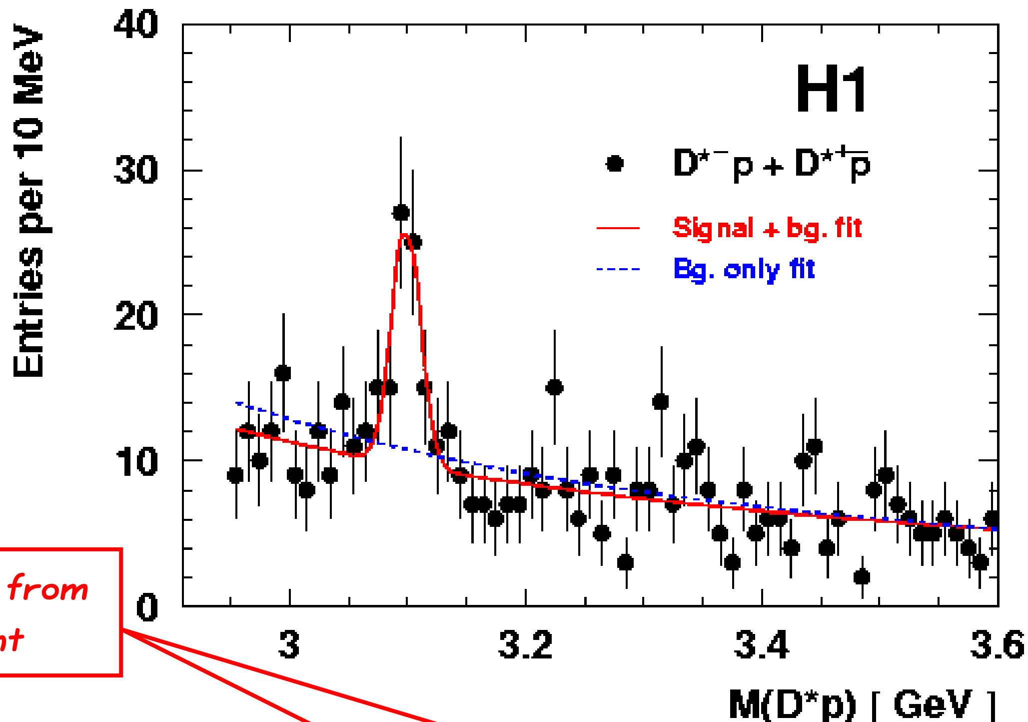
No enhancement in non-charm background

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



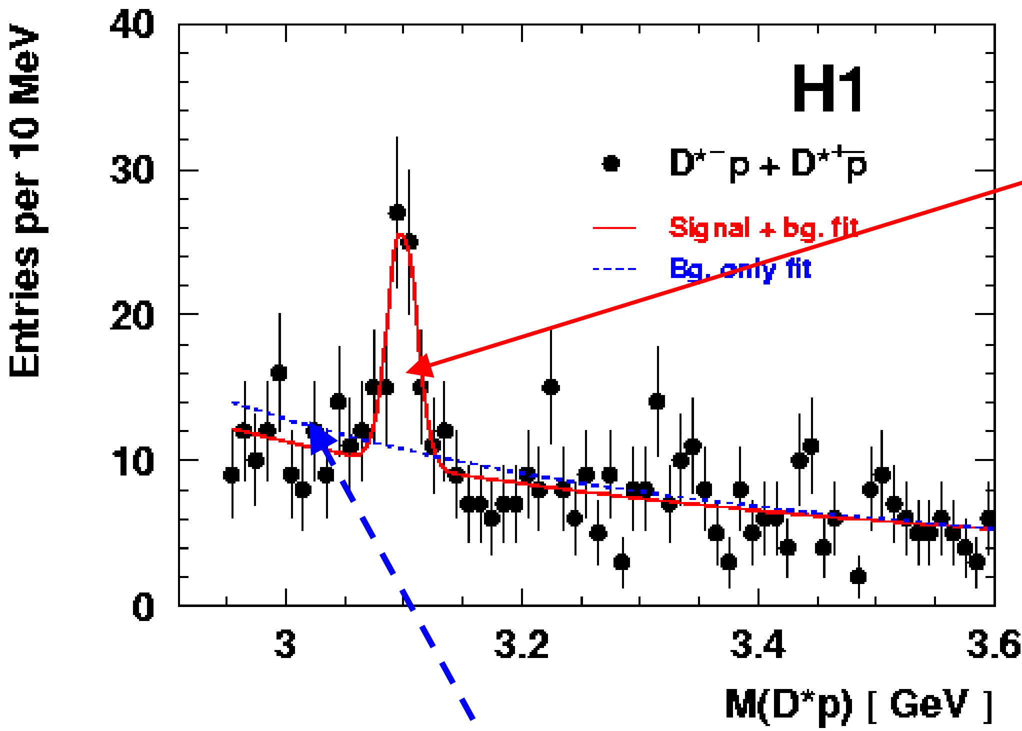
Stability of result against all sorts of variations checked

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

Conclusions

- H1 has observed a narrow resonance in both $D^{*-}p$ and $D^{*+}\bar{p}$ with

$$M(D^*p) = 3099 \pm 3\ (stat.) \pm 5\ (syst.)\ MeV$$

$$\sigma = 12 \pm 3 (stat.)\ MeV$$

- The background fluctuation probability is smaller than $4*10^{-8}$.
- The signal is also observed in an independent photoproduction sample
- The signal region is richer in D^* mesons and show a harder momentum spectrum of the proton candidates
- No simple explanation for this resonance could be found.
  $\Rightarrow$ It is interpreted as an anti-charmed baryon decaying to $D^{*-}p$ and its charge conjugate.
- Its quantum numbers are C=-1 and B=1. The minimal quark content is $uudd\bar{c}$, It is a candidate for a charmed pentaquark state.

Checks

- Meanwhile <u>4 independent analyses</u>

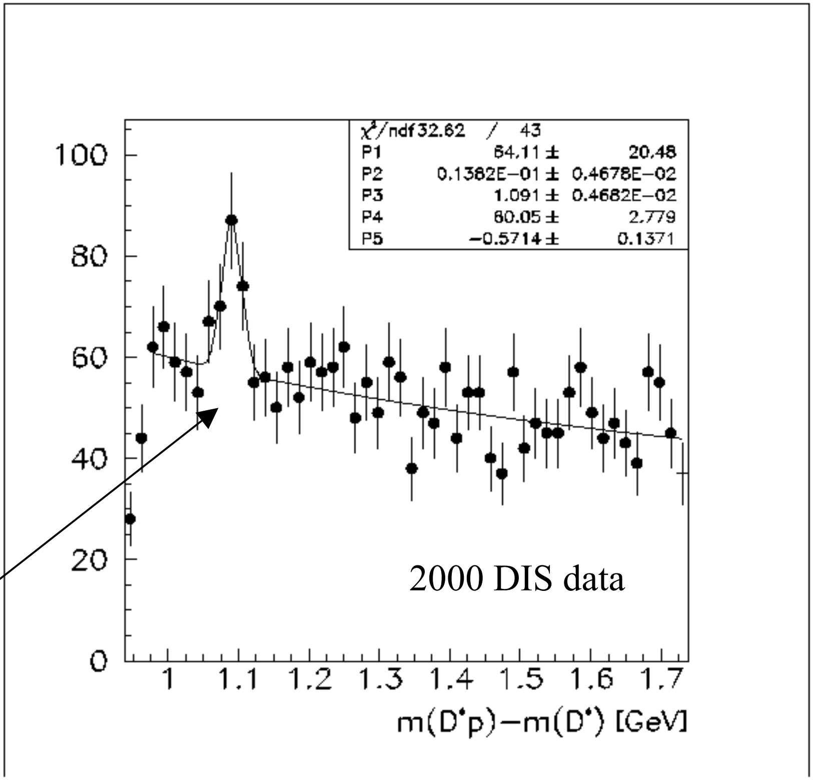
  (whoever looks for it, verifies it)
- Using <u>4 independent codes</u> for the central analyses

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

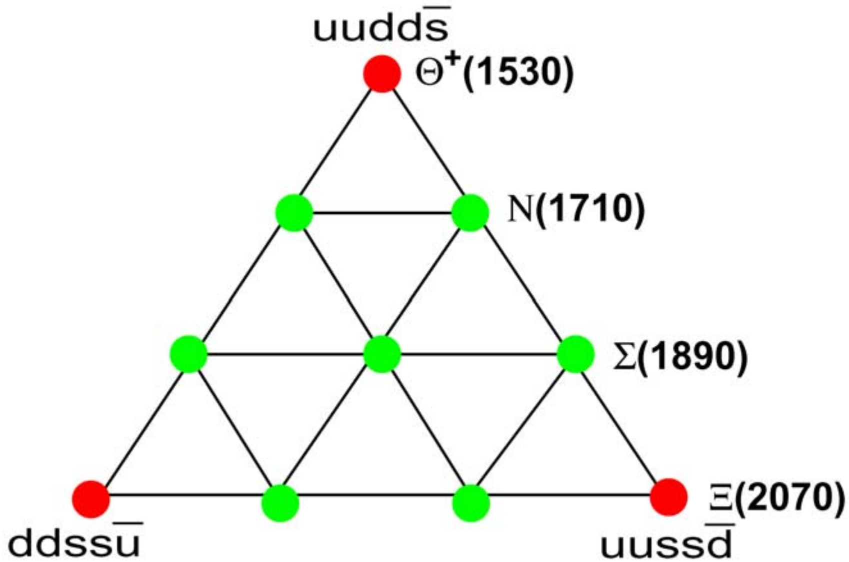
The very first look at $D^{*-}p$

- 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%



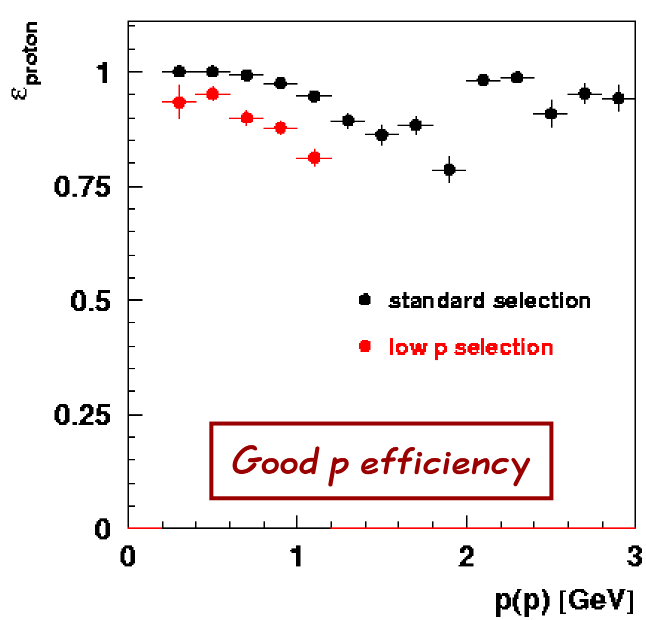
Narrow enhancement about 150 MeV above threshold: real or fake ?



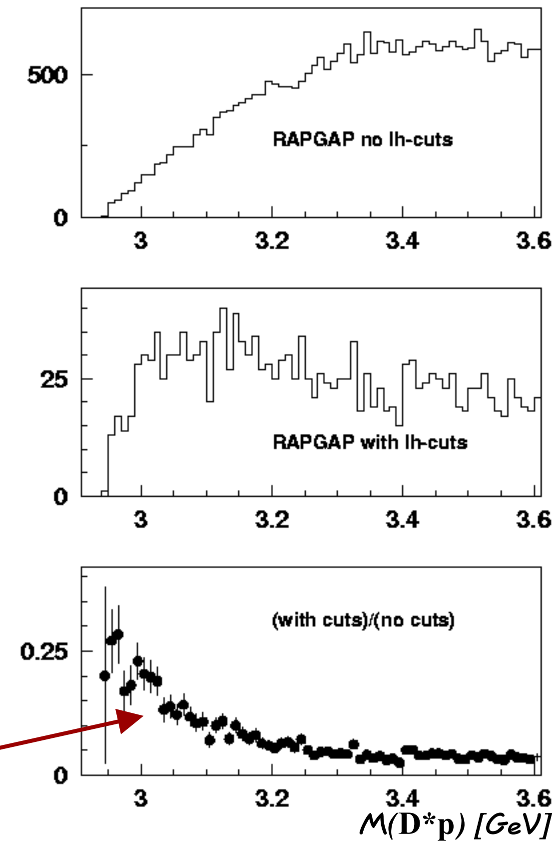
uudd$\bar{s}$
Θ^+(1530)
N(1710)
Σ(1890)
Ξ(2070)
dds$s\bar{u}$
uuss$\bar{d}$

Does some acceptance effect fool us ?

Proton efficiency



"Pion survival probability"



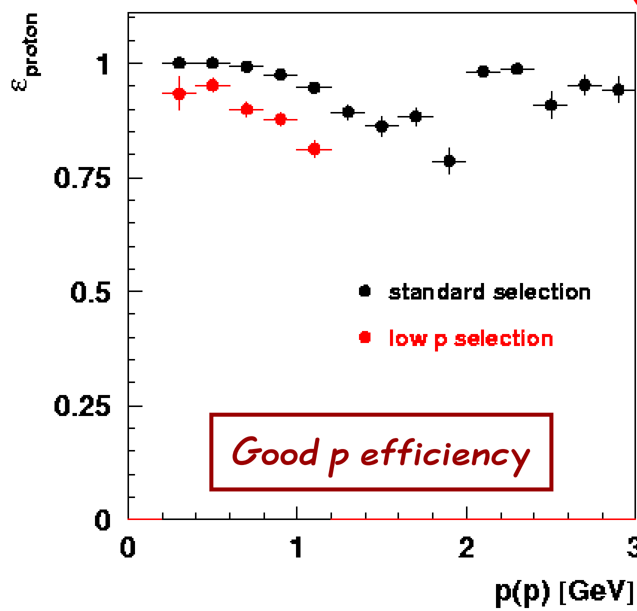
Smooth variation with $M(D^*p)$
Shape reflects opening of phase space

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

Does some acceptance effect fool us ?

NO!

Proton efficiency



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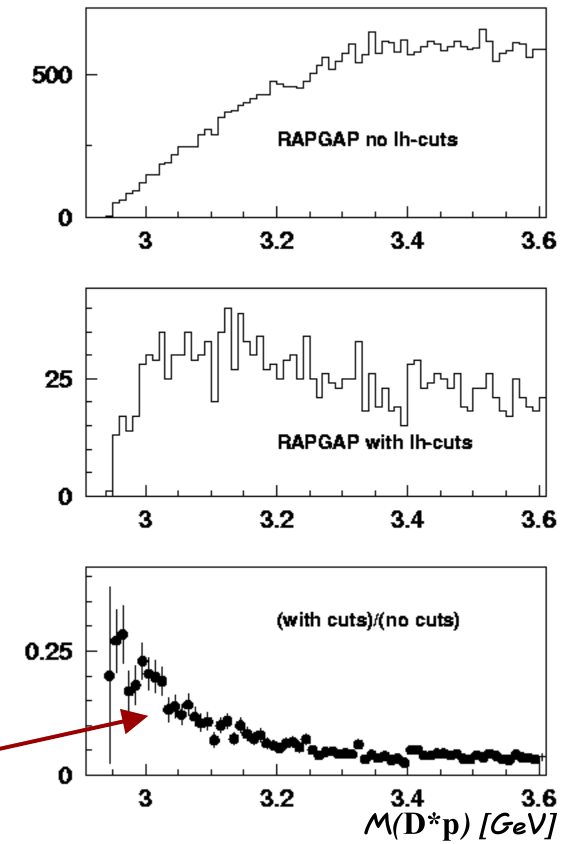
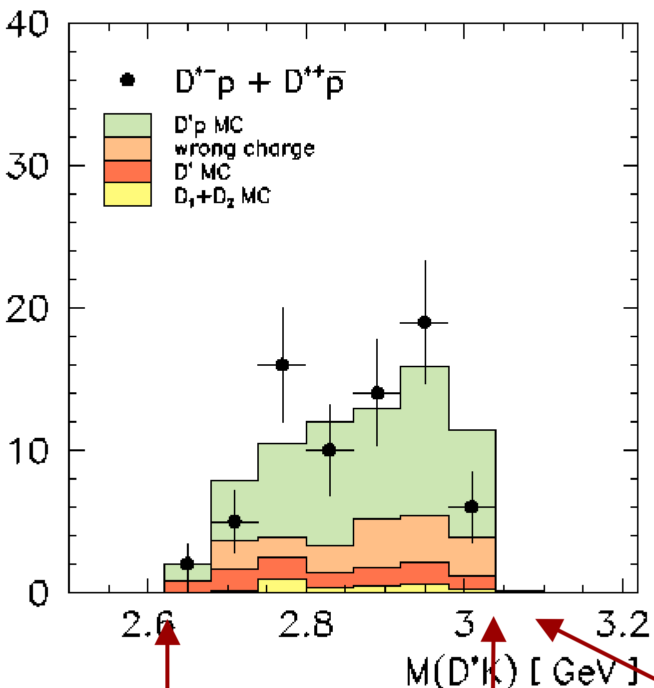


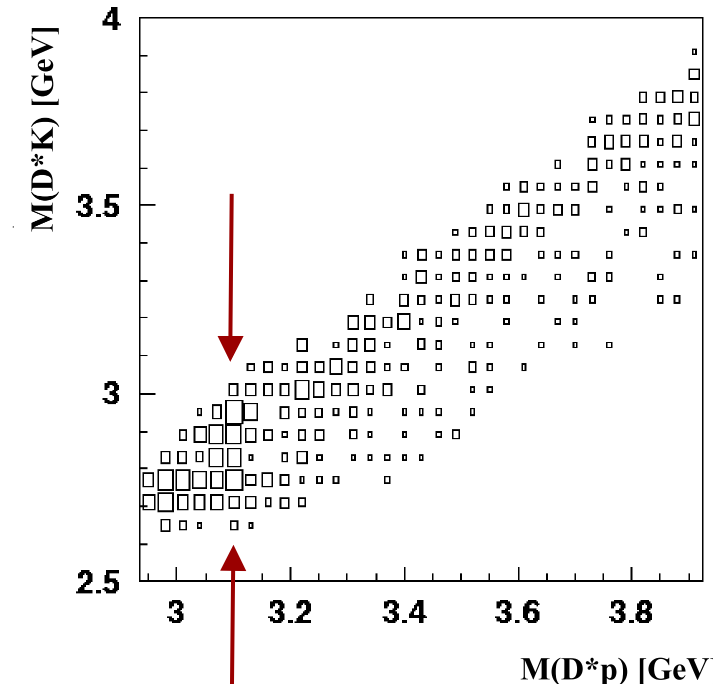
*Smooth variation with M(D*p)*
Shape reflects opening of phase space

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

Could it be due D*K ?

This on its own would be worth a publication



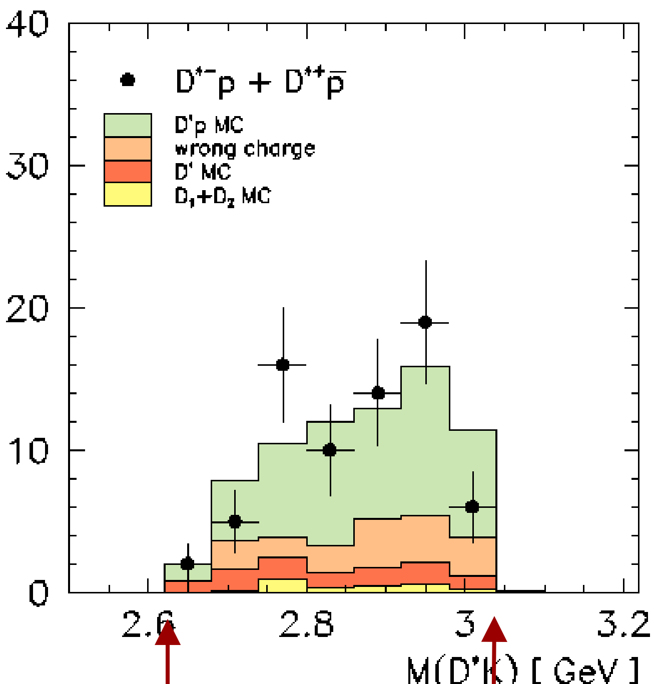


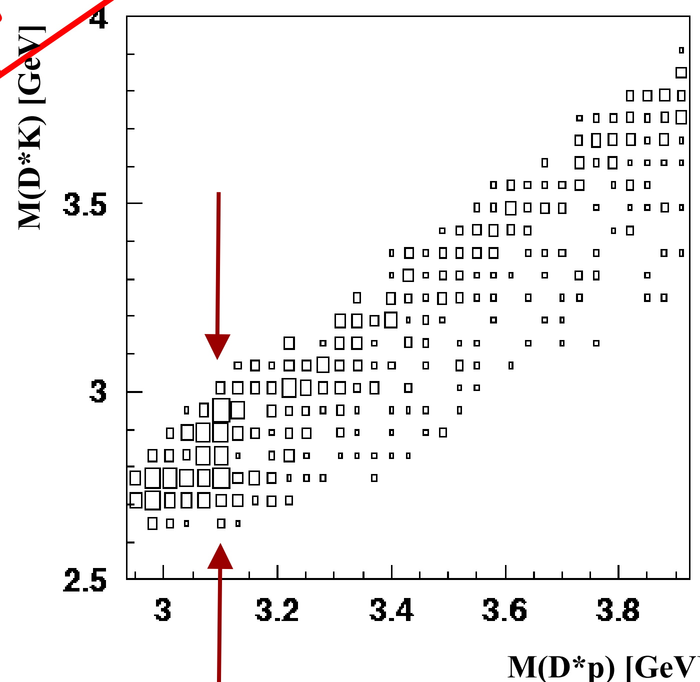
Band in D*K clearly visible
Go to the D*p signal region

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

Could it be due D*K ?

NO!



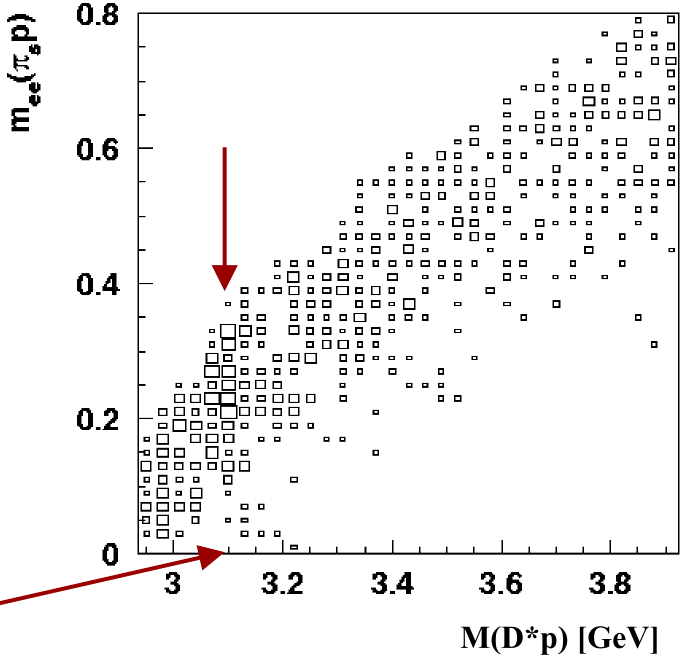


Band in D*K *clearly visible*

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

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

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



No accumulation at zero

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

NO !

$D^0\gamma$ may be dangerous
because of $\gamma \to e^+e^-$
γ-conversion asymmetric
in energy
$\to$may be misinterpreted
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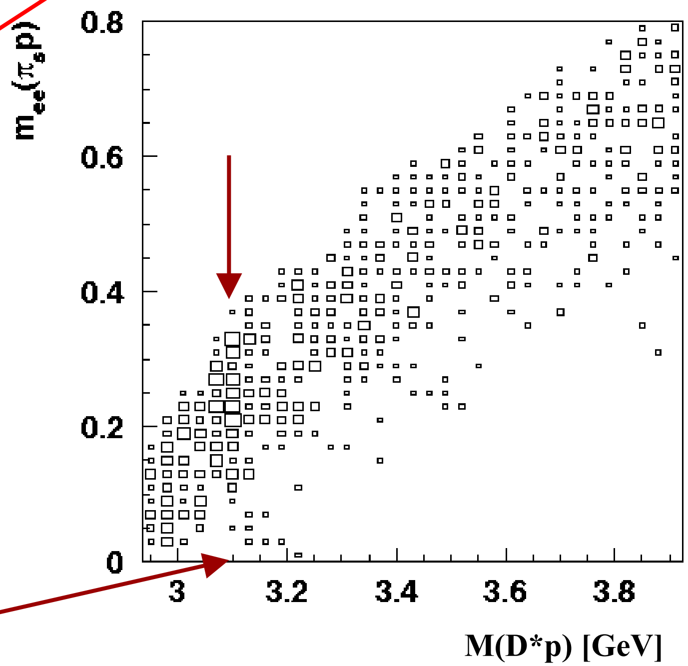

No accumulation at zero