Evidence for a Narrow Exotic Anti-Charmed Baryon State

Karin Daum

H1 Collaboration

Outline:

- The strange sector — A motivation
- The experimentalist's view — Where and how to search ?
- The D*p signal — Detailed investigation
- The D*p signal — Signal assessment
- Conclusion

Heidelberg, May 17

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

Particle Data Group 1986 reviewing evidence for *exotic baryons states*

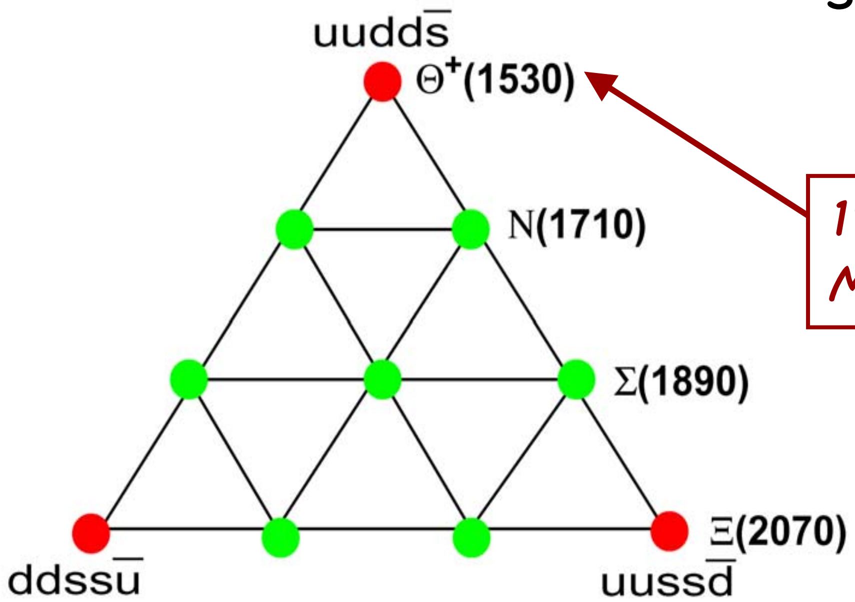
"…The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

Why should this be all ?

PDG dropped the discussion on exotic baryon searches after 1988.

Exotic baryons

Particles with B=1 and S=1 could not be made of 3 quarks !



Several theoretical predictions

Problem : $\Gamma \approx M$

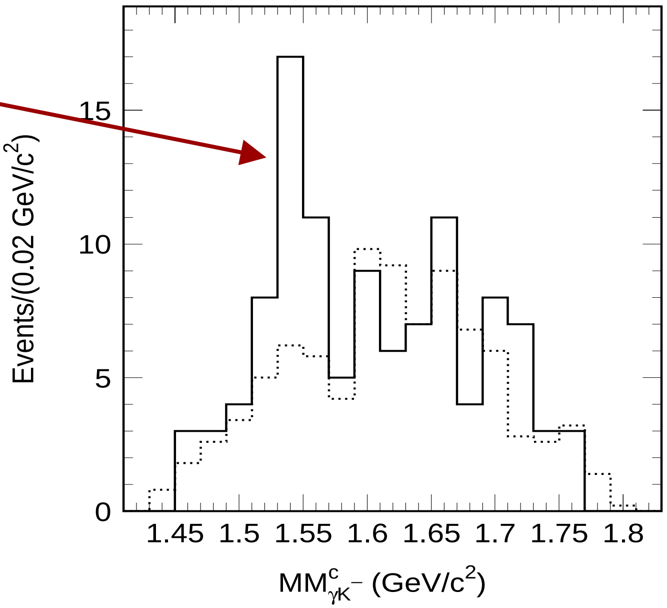
1997: DPP Soliton model

$M(\Theta^+) \approx 1530$ MeV, $\Gamma \approx 15$ MeV

PDG was right!

2003: LEPS at Spring-8
first evidence for Θ^+
M= 1540±10 MeV,
Γ< 25 MeV

Missing mass γK^-

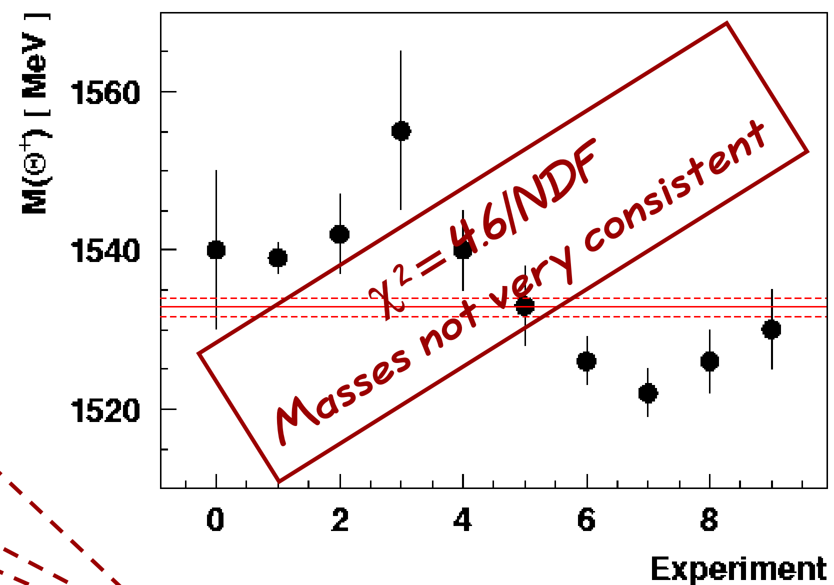


Restarting the quest
for exotic particles

It took more than 15 years

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



Sign of S not determined

$B=1$ & $S=1$

$\Downarrow$

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

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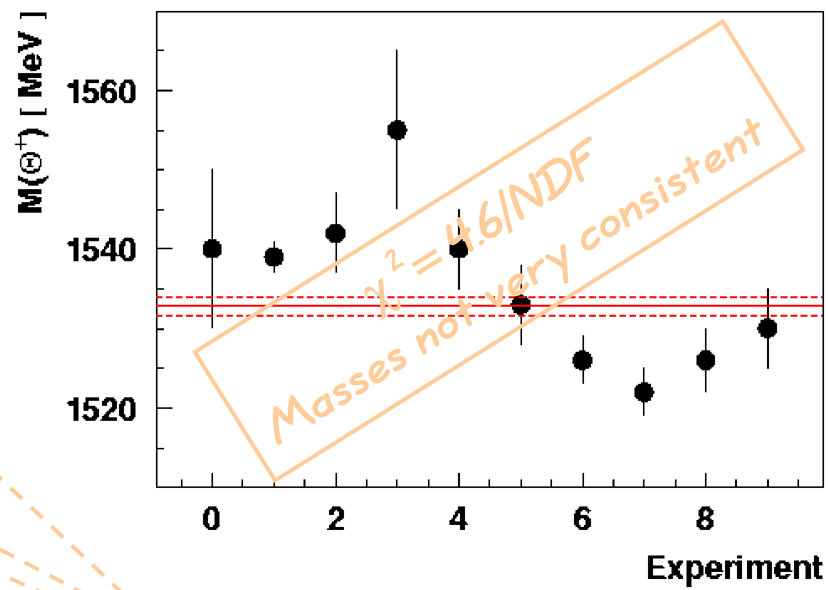


Sign of S not determined

B=1 & S=1

⇓

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

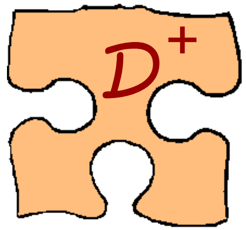
- $M(\Theta^+) - M(K) - M(n) = 100$ MeV
- Small natural width

Experimentalist's simple-minded picture of the strange pentaquark

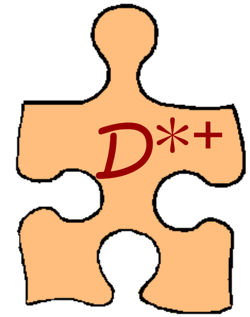
(Motivation for the search in the charm sector)

- Θ^+ produced by fragmentation from the vacuum
- It does not matter how the strange antiquark 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 ?

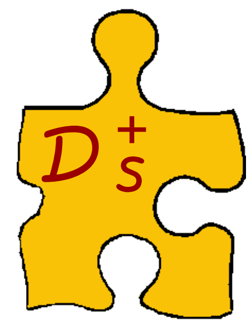


We need

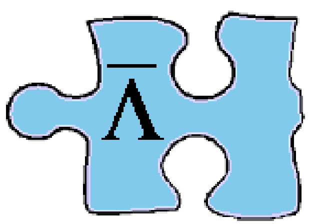


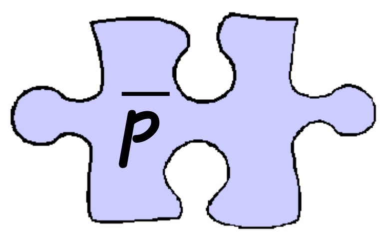
A charmed meson

+



An antibaryon





Where to look for the charmed pentaquark ?

Common belief:

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

(pseudo-scalar D meson)

Vector mesons not suppressed

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 ?

Common belief:

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

(pseudo-scalar D meson)

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

Vector mesons not suppressed

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

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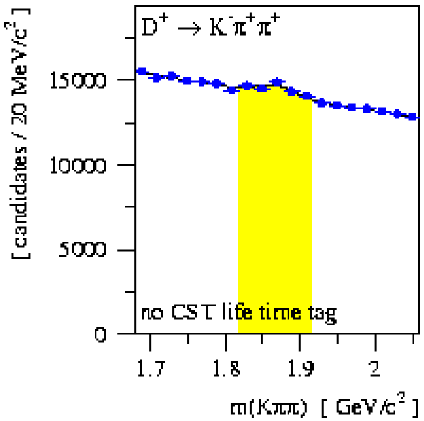
But what is experimentally feasible ?

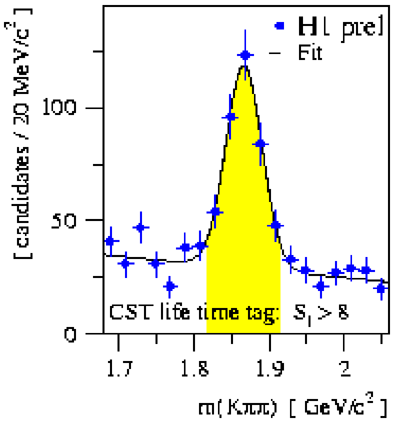
Experimental Considerations

D^+ *pseudoscalar meson*

without

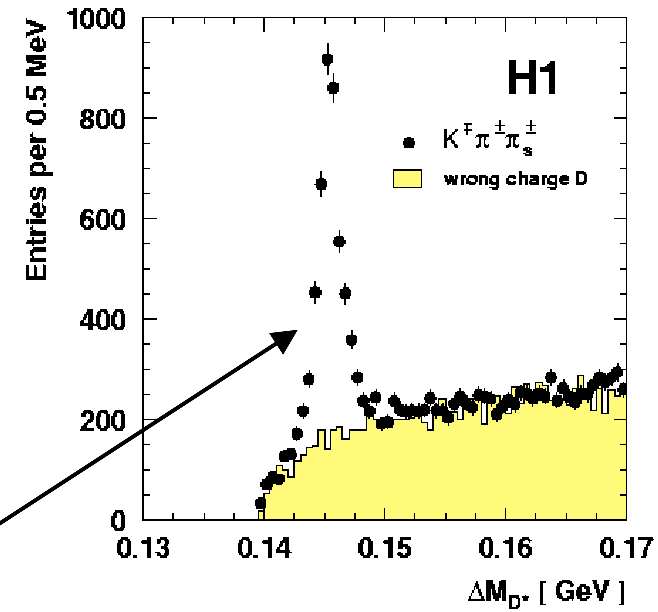


with lifetime tag



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*

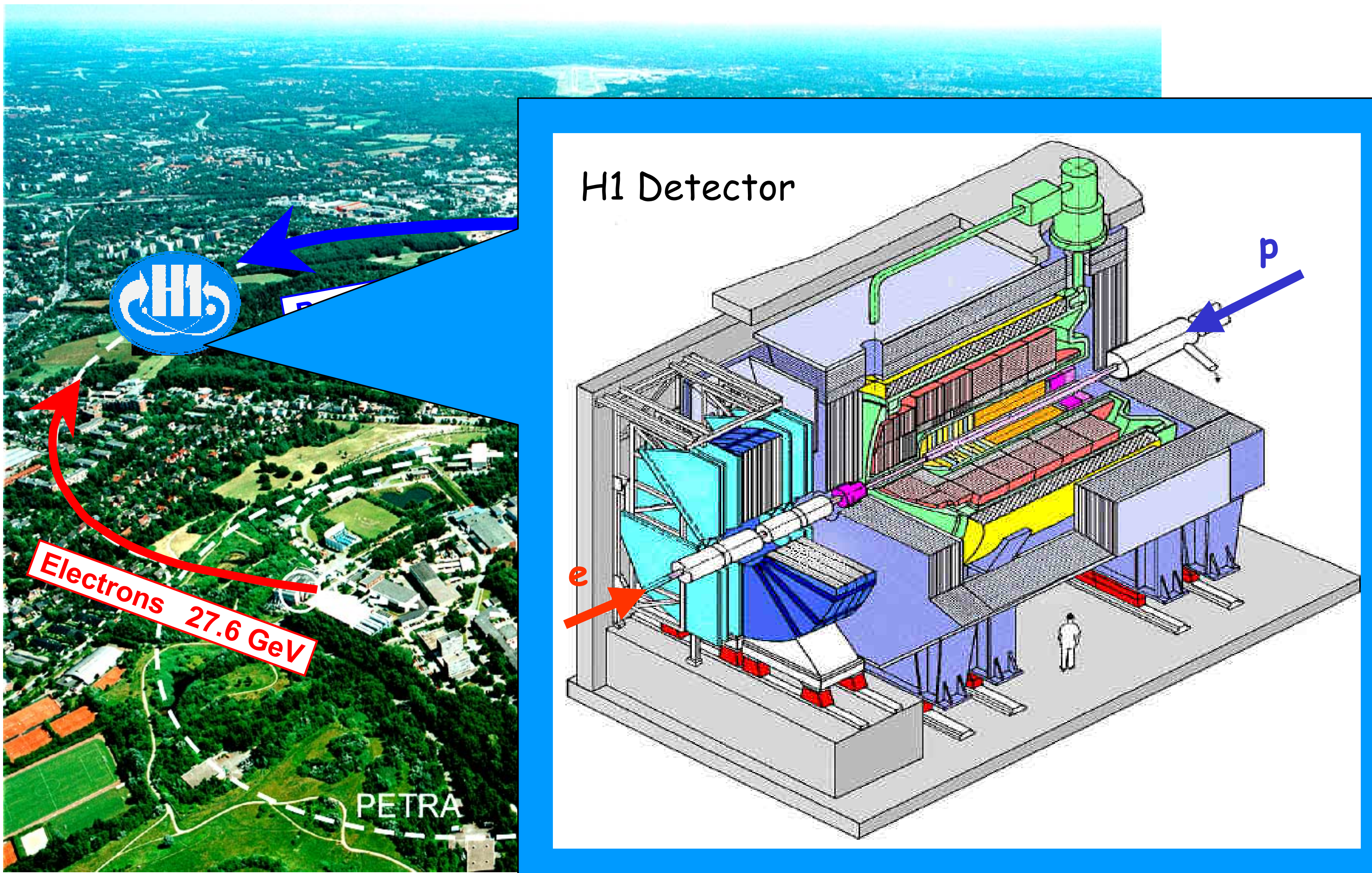
Mass difference technique $\Delta M(D^{*\pm}) = m(K^\mp\pi^\pm\pi) - m(K^\mp\pi^\pm)$

D^* *experimentally much easier*

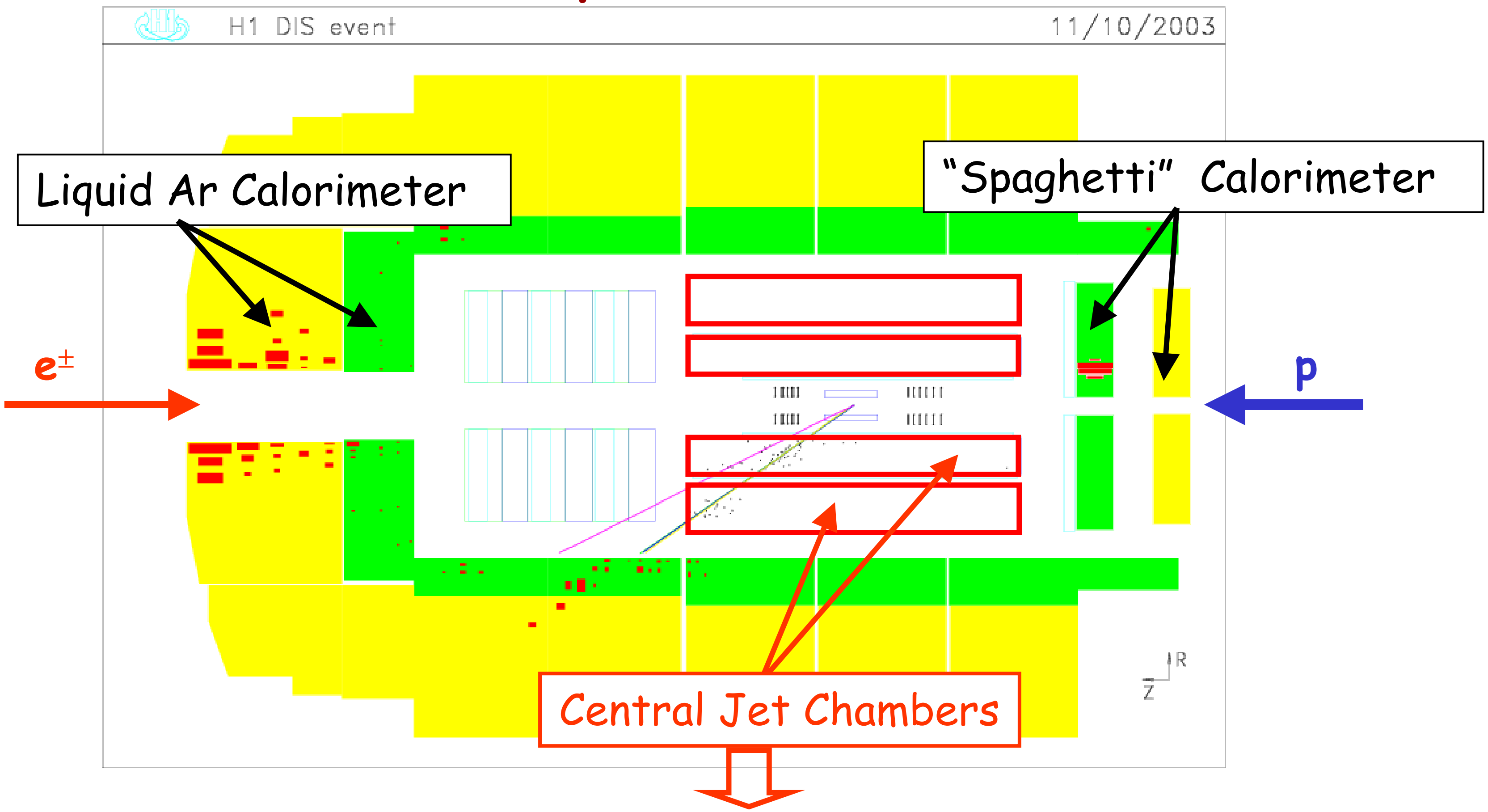
Let's try this !

H1 experiment at HERA

HERA storage ring at DESY



The H1 experiment at HERA



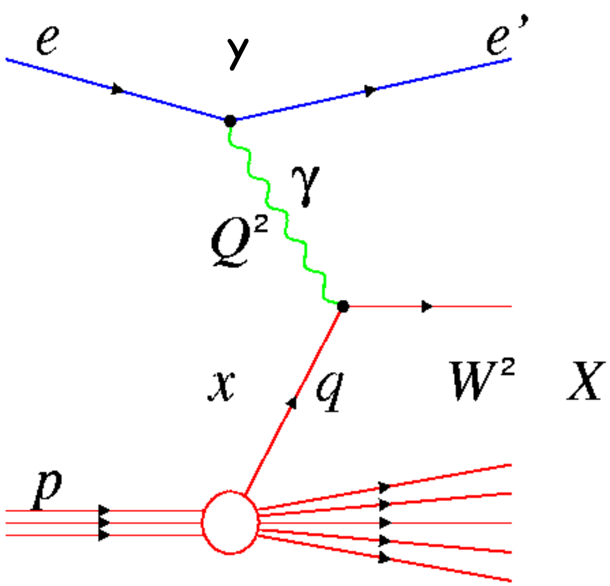
Drift chambers, acceptance: $15^0 < \theta < 165^0$

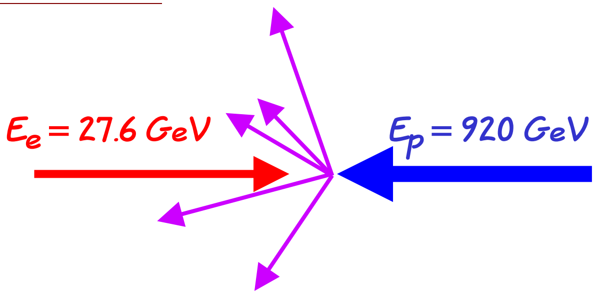
Yields simultaneously charge and timing information

$B = 1.15$ T $\rightarrow$ measure transverse momentum of charged particles

→ **Tracking , Particle ID via dE/dx**

HERA kinematics





Kinematic variables

Q^2: 4-momentum transfer squared

x : Bjorken x

y : Electron inelasticity

W : Mass of the hadronic system

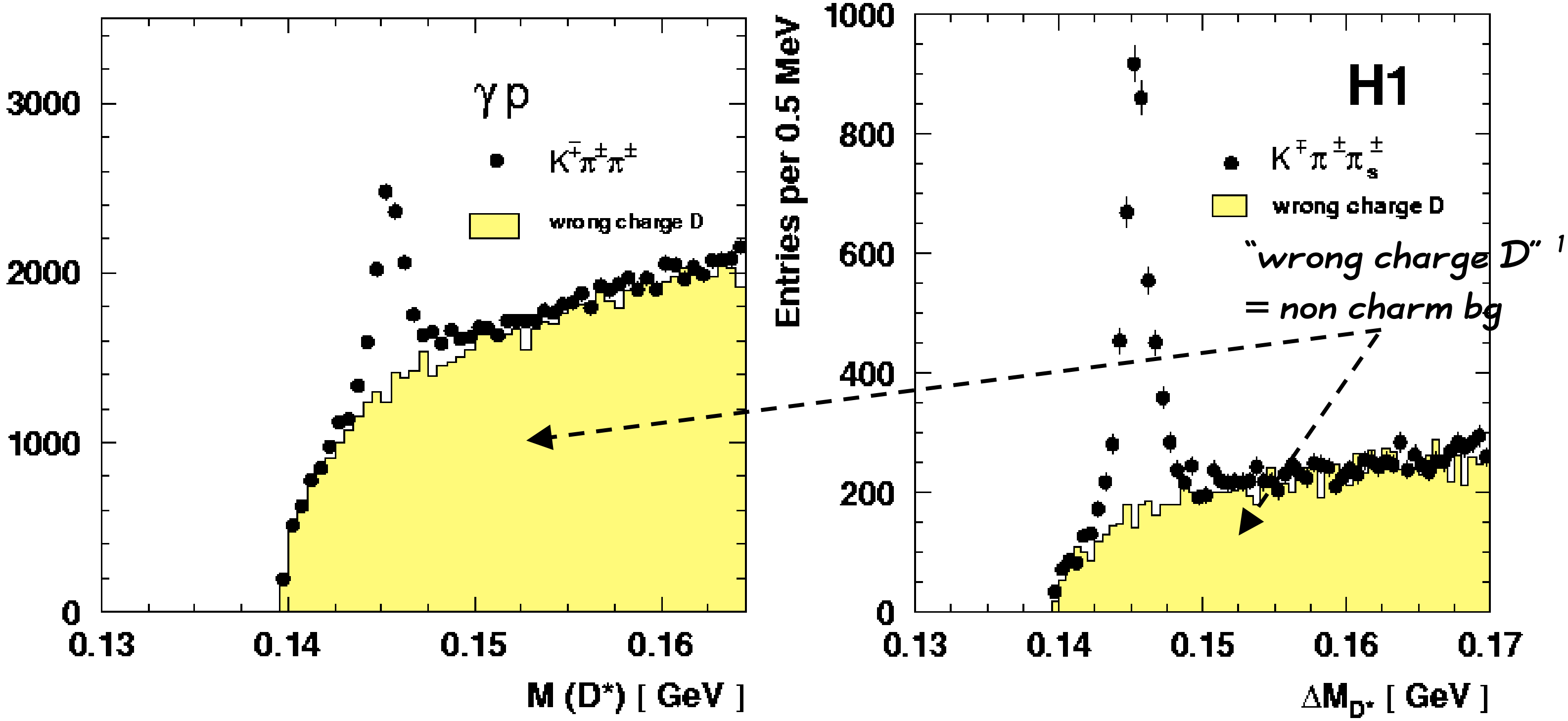
2 kinematic regimes :

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

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

Both regimes equally well suited for the analysis ?

Photoproduction (γp) DIS



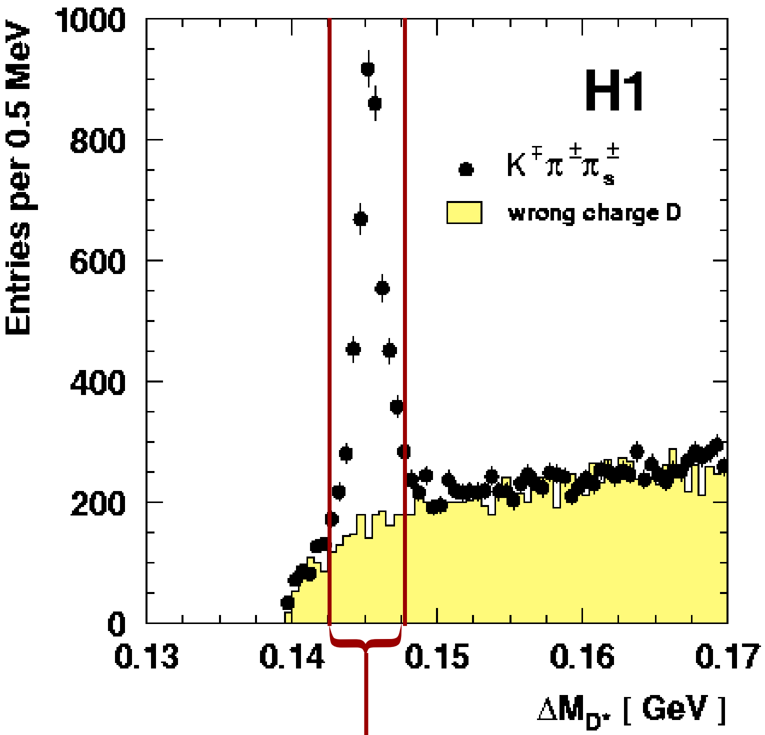
DIS much cleaner $\rightarrow$ base analysis on DIS

$\rightarrow$ use γp as cross check

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

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

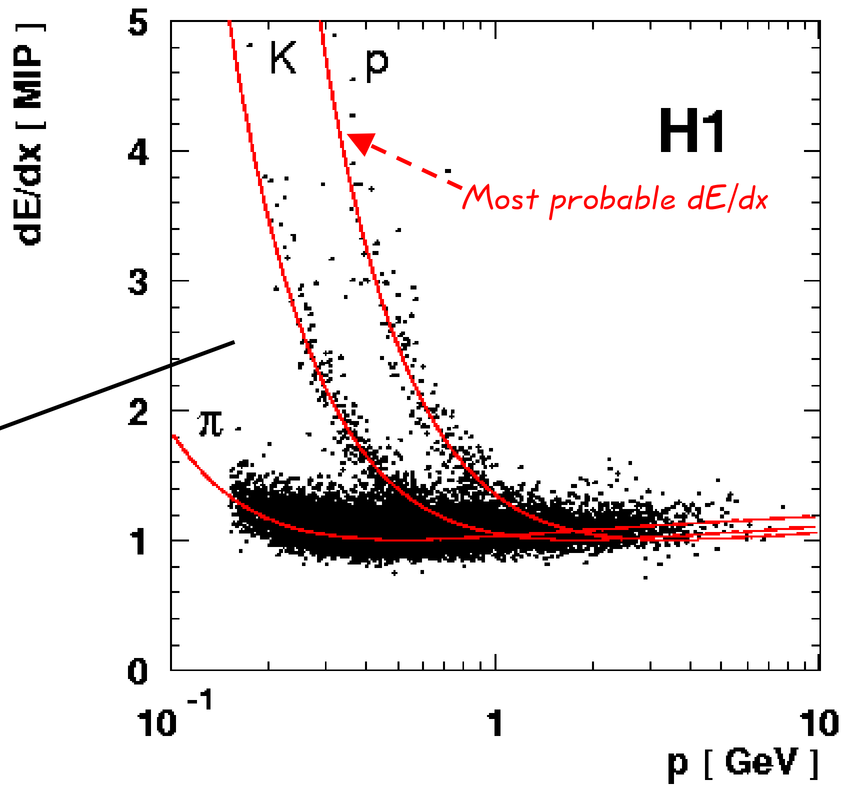
D* signal region subsequently used

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

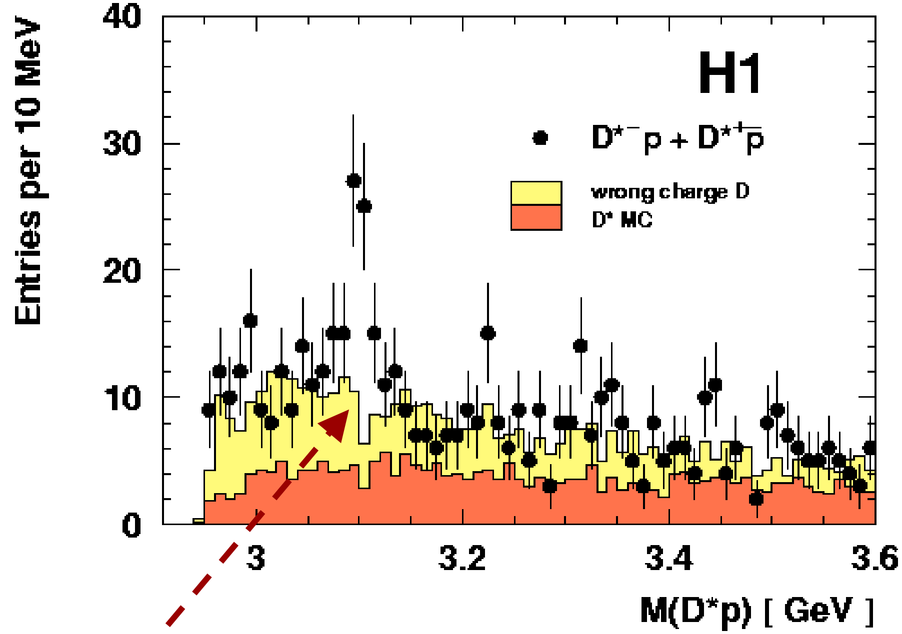
- Looking for a narrow state near threshold
- Expected 4-particle mass resolution about 35 MeV not favourable for a narrow state → use mass difference technique: $m(D^*p)$-$m(D^*)$
- Cut on the normalized proton likelihood $L(p)$ for pion suppression
- Take a D^* candidate add a track consistent with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

⇓

Look what you get !

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

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



This is what we get !

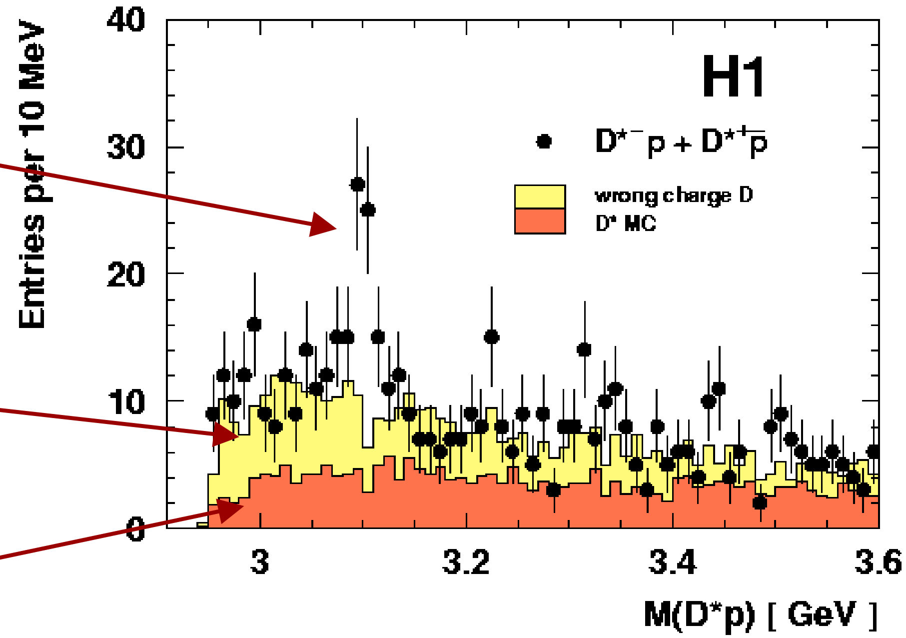
$D^{*-}p$ + cc in DIS for 1996 - 2000

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

Significant peak in opposite sign D^*p

No enhancement in wrong charge D [1)]

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

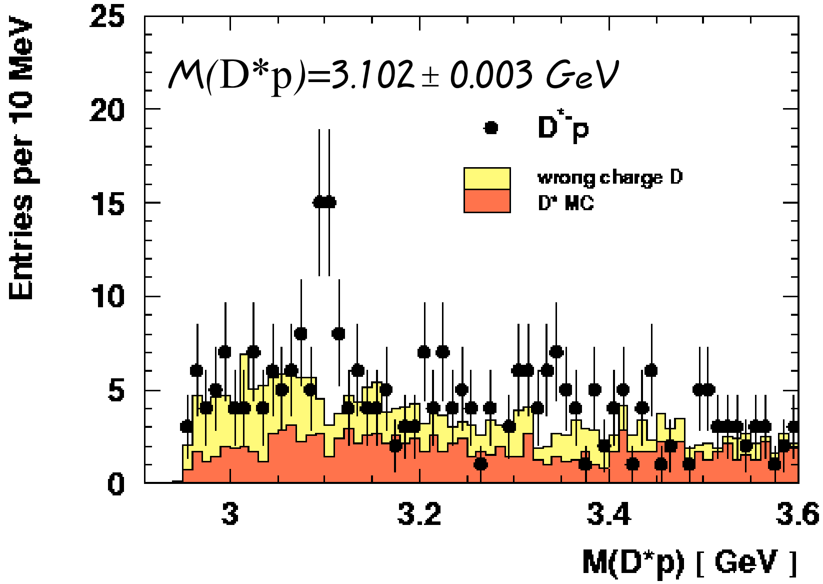


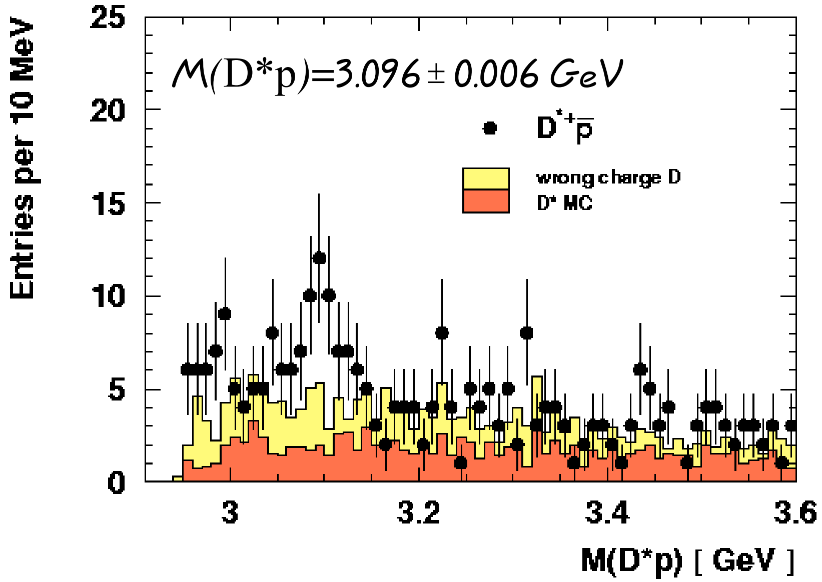
Background well described by D^* MC and wrong charge D from data

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

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

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



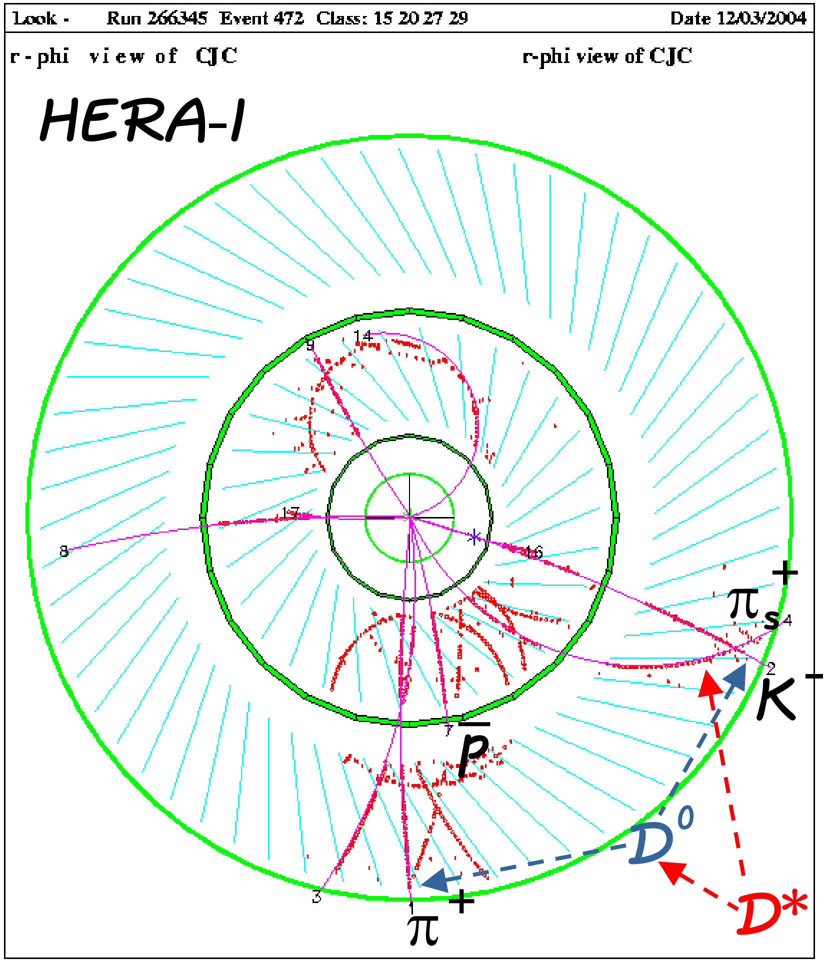


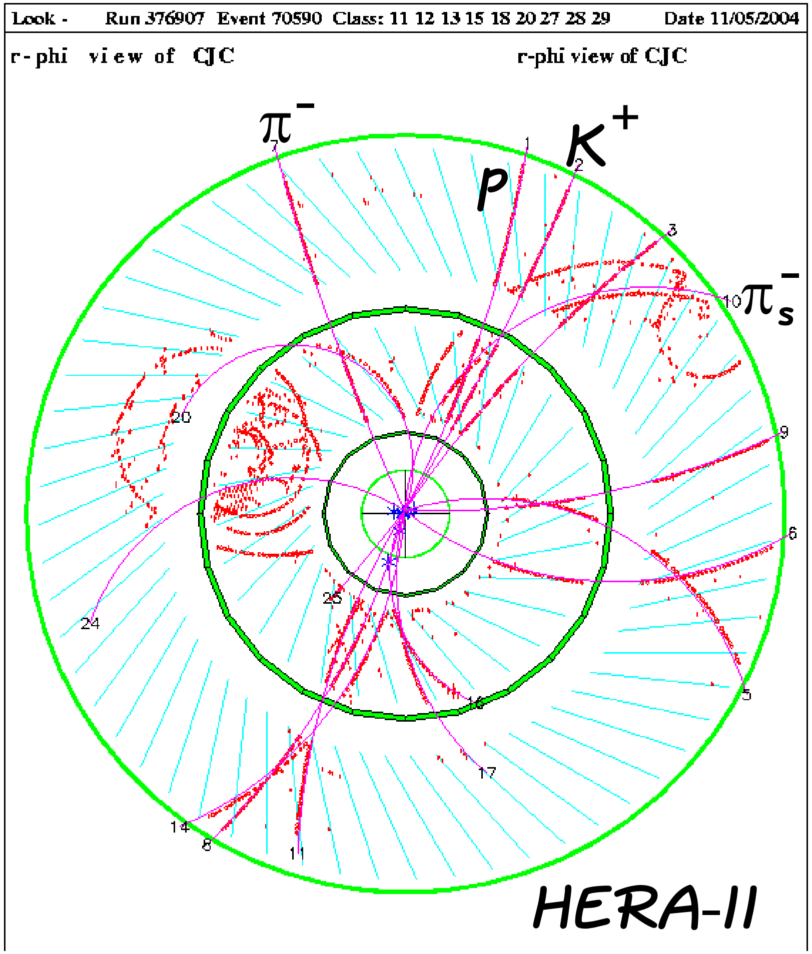
25.8 ± 7.1 *Events*

23.4 ± 8.6 *Events*

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

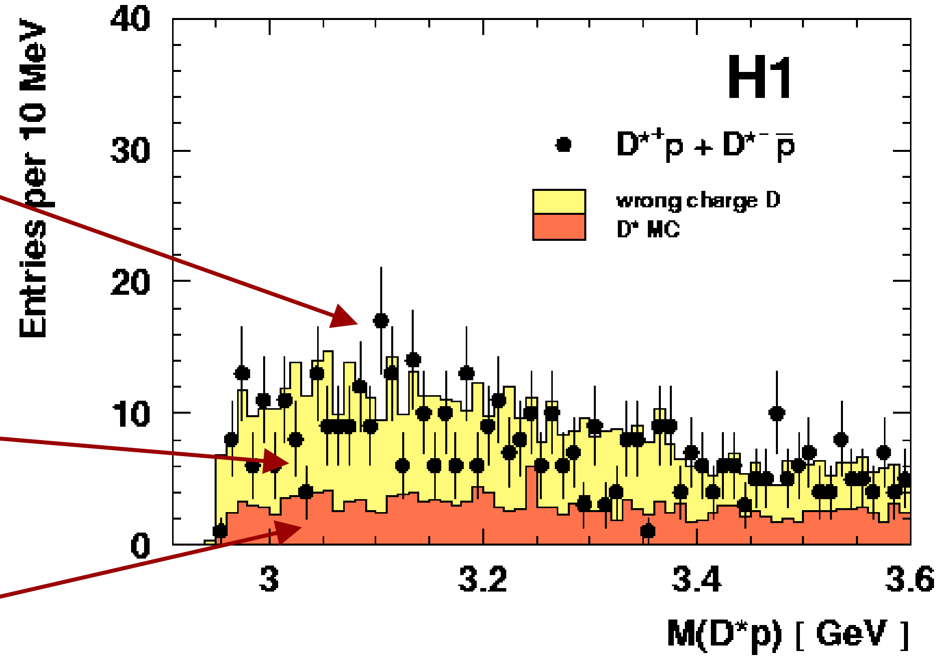
Typical Events





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]

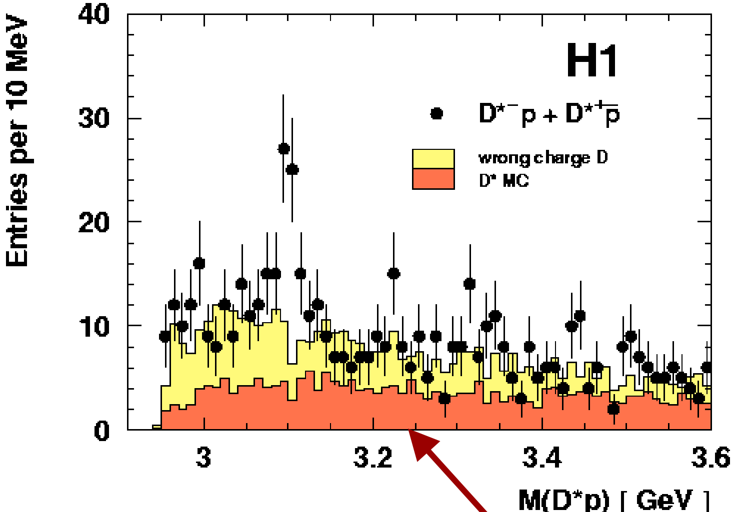
No enhancement in D^* MC (RAPGAP)[3]

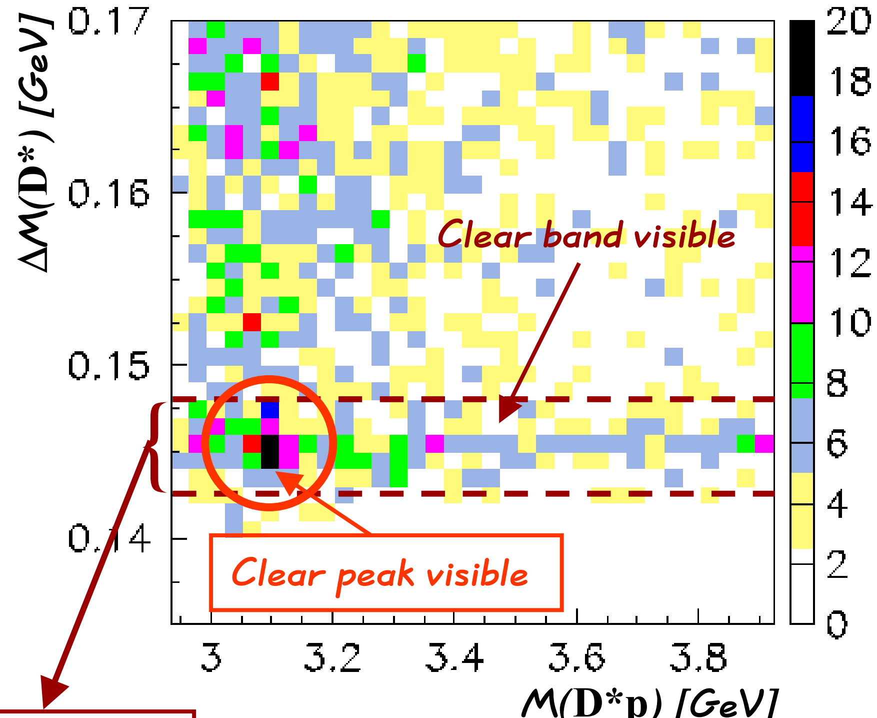
Reasonably described by D^* MC and wrong charge D from data

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

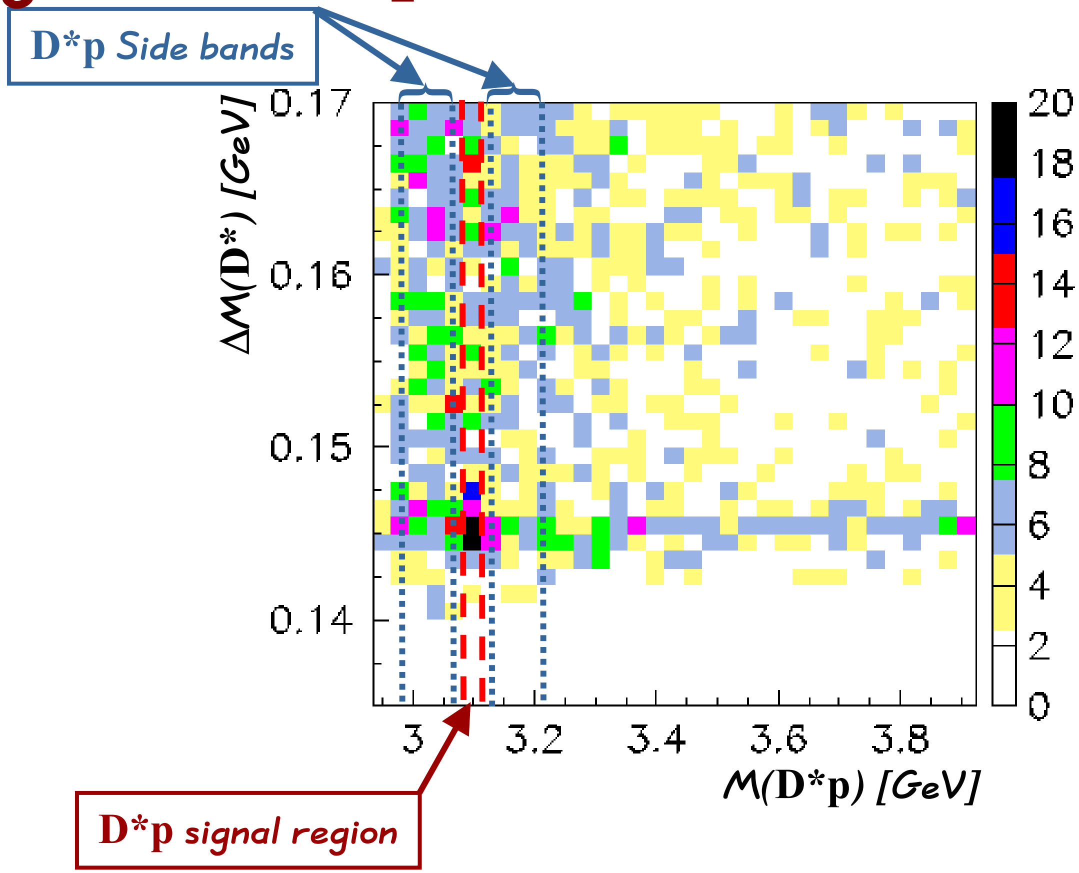




D* signal region

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

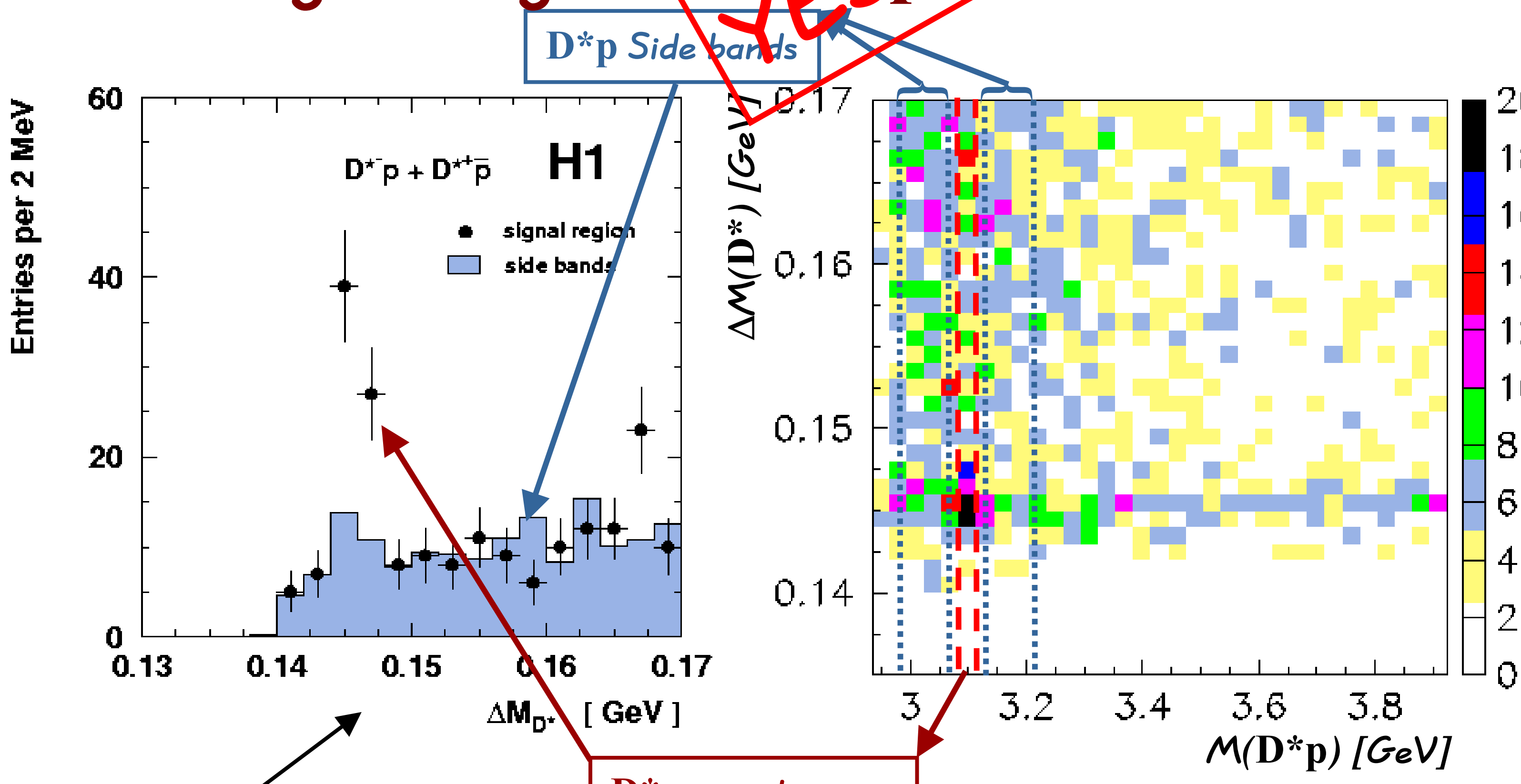
Signal region in $D^{*-}p$ [1] richer in D^{*-}?



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

1) Charge conjugate always implied

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

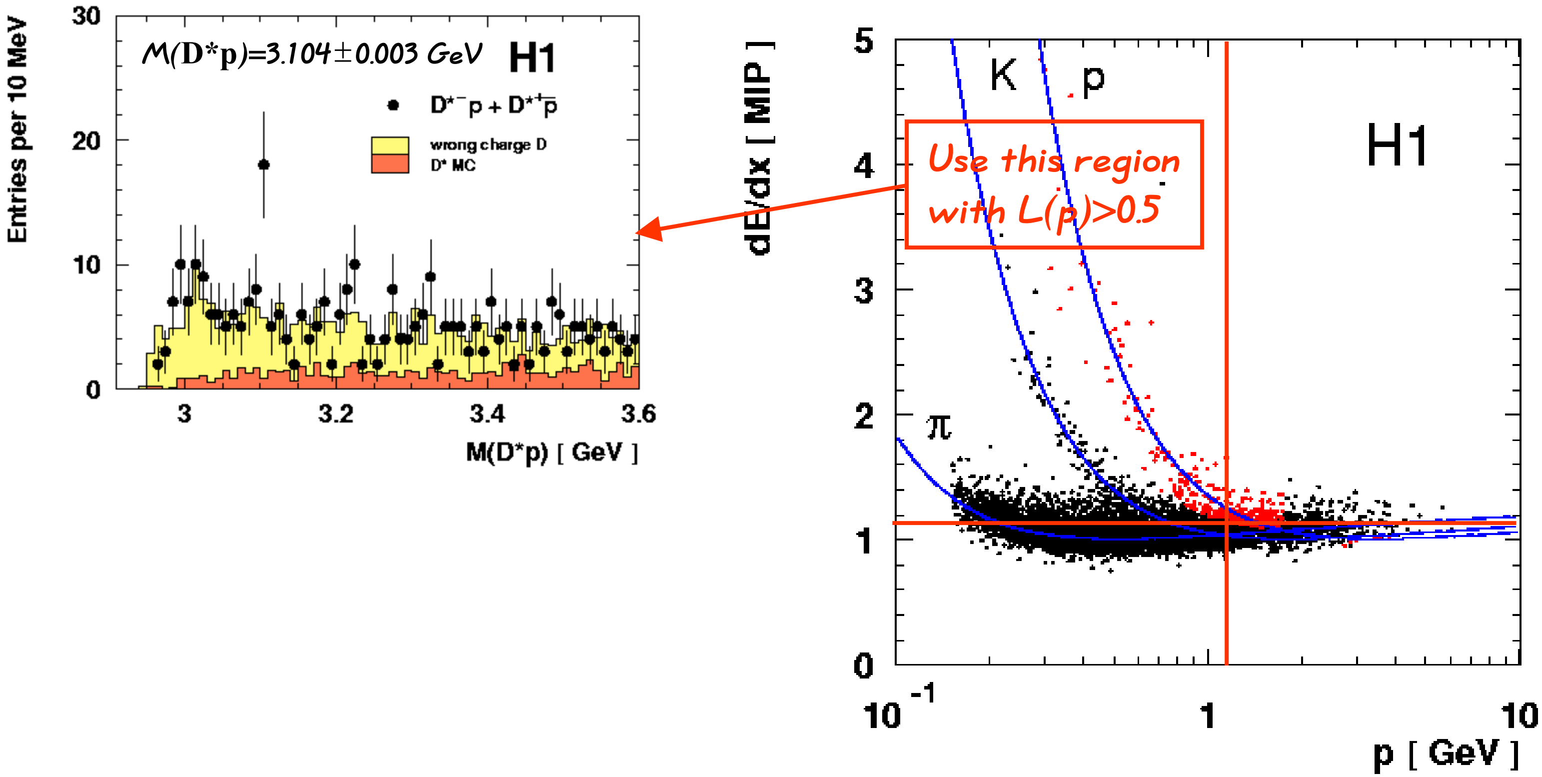


*Normalization to the width of the windows in M(D*p)*

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

1) Charge conjugate always implied

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



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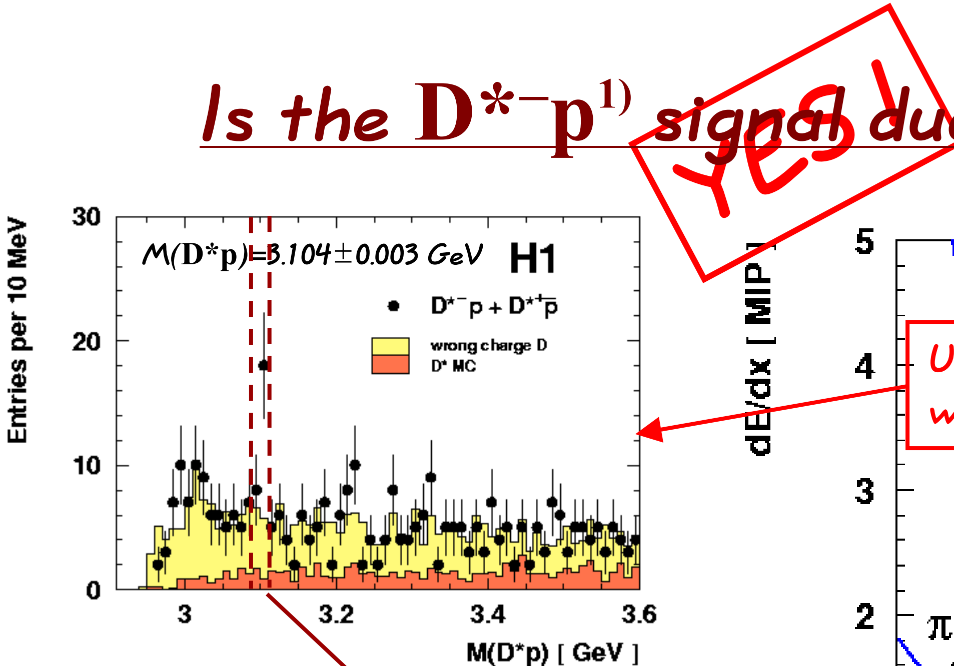
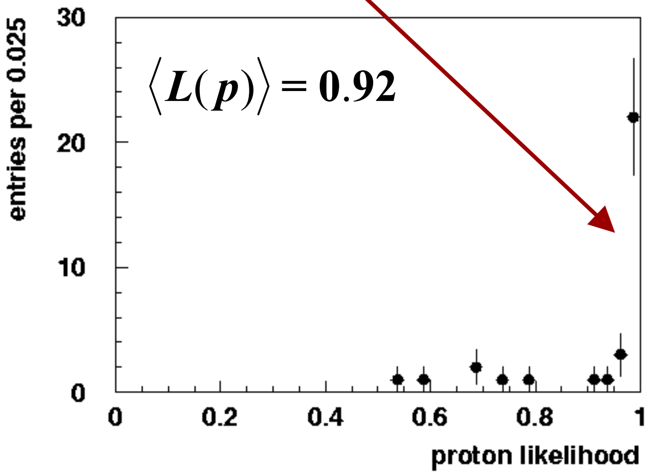
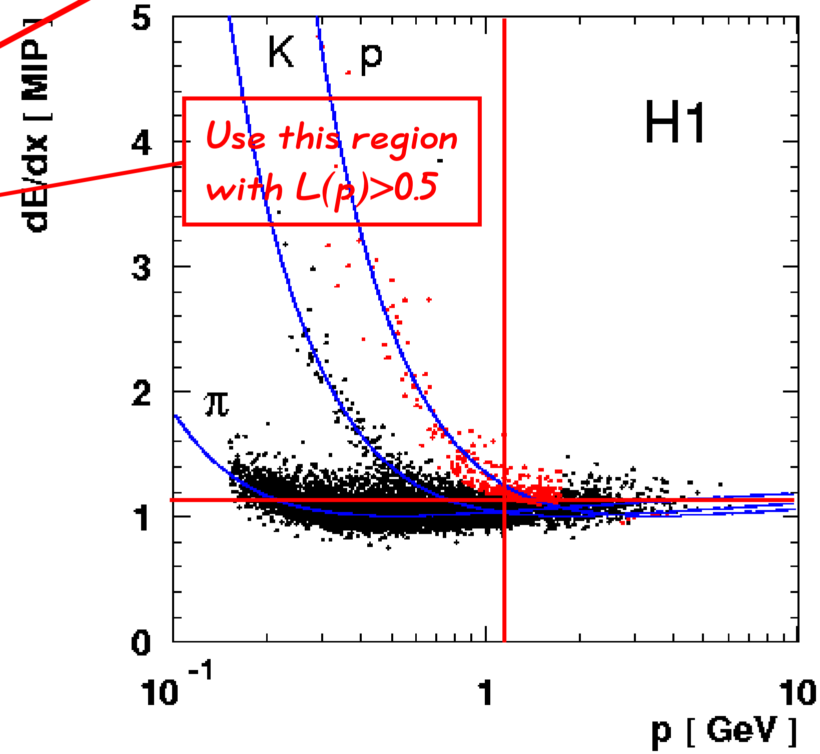






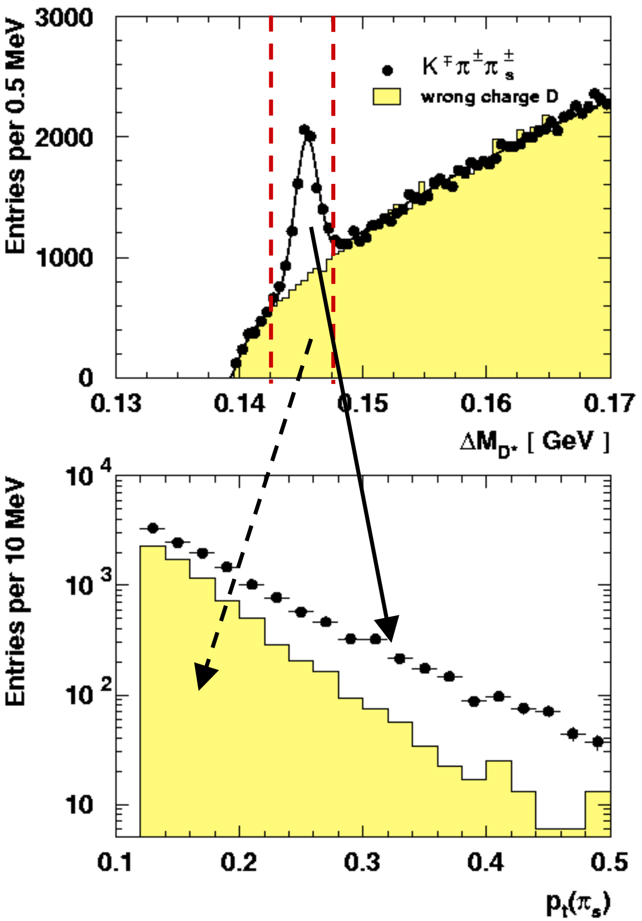
$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

1) Charge conjugate always implied

Is the physics different in the signal region?

• *Single particle momentum spectra are steeply falling*
→*This feature is preserved in the combinatorial background of invariant mass analyses*

• *In decays particles are also emitted in the direction of flight*
→ *Particles from a decay should have a harder spectrum than the combinatorial background*

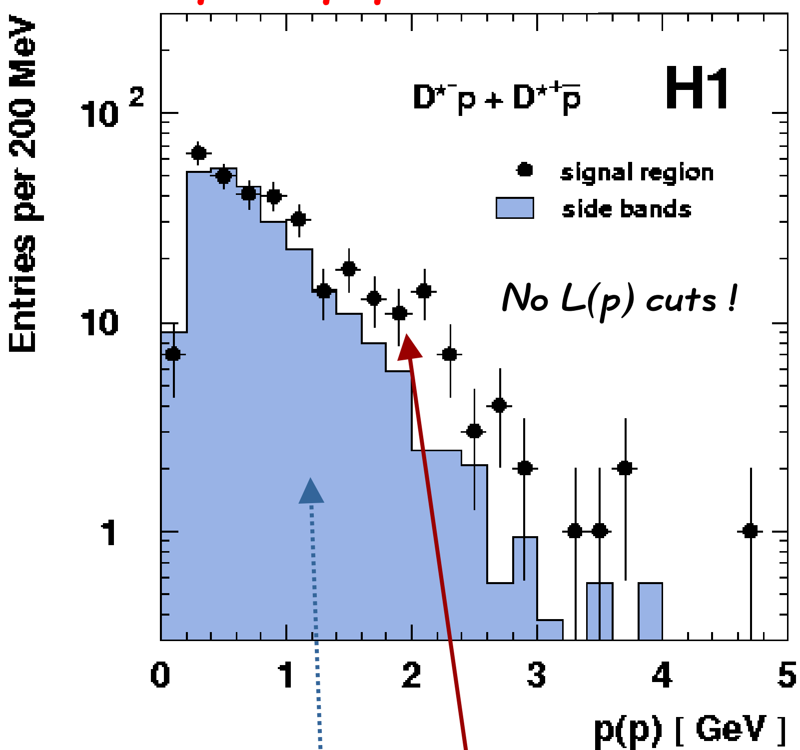


Check the proton momentum !

Is the physics different in the signal region?

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

Look at the momentum
of the proton candidate
in the signal region and
in the side bands
w/o dE/dx cuts

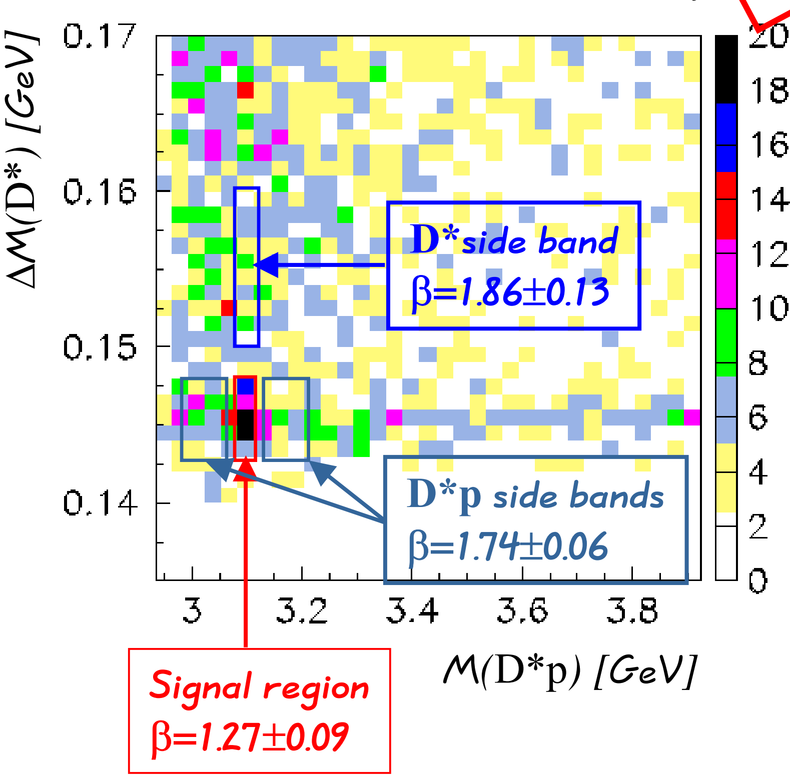


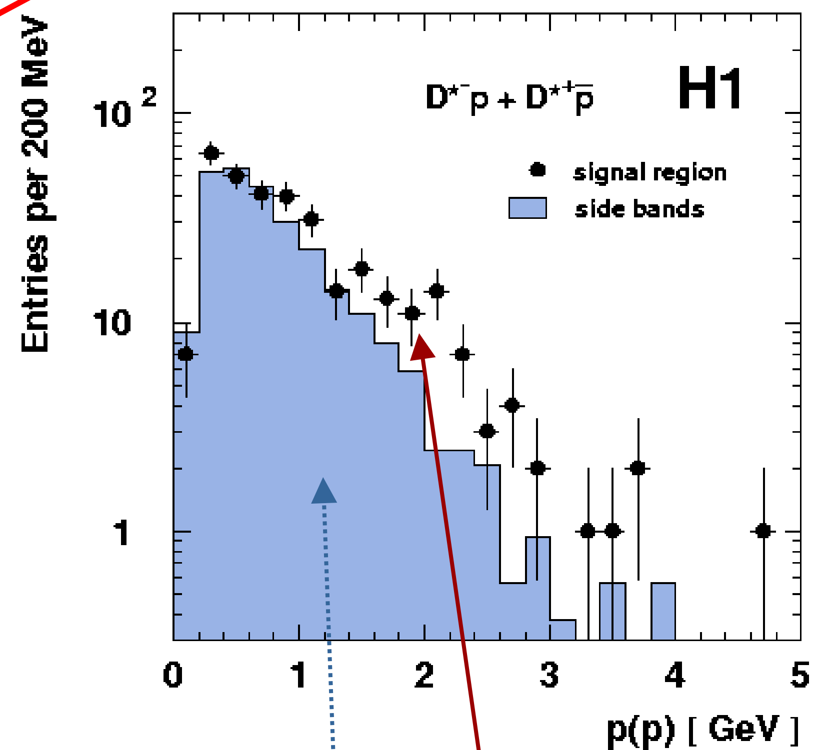
The momentum spectrum of the particles in the signal region is harder than in the M(D*p) side bands

Is the physics different in the signal region?

YES!

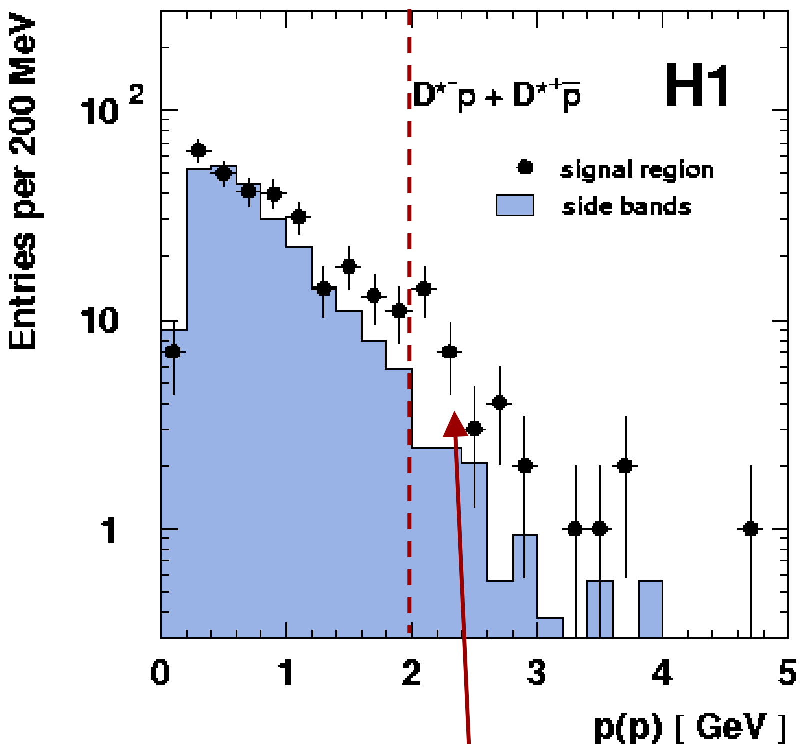
Fit slope with $\alpha \cdot exp\{-\beta p(p)\}$





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

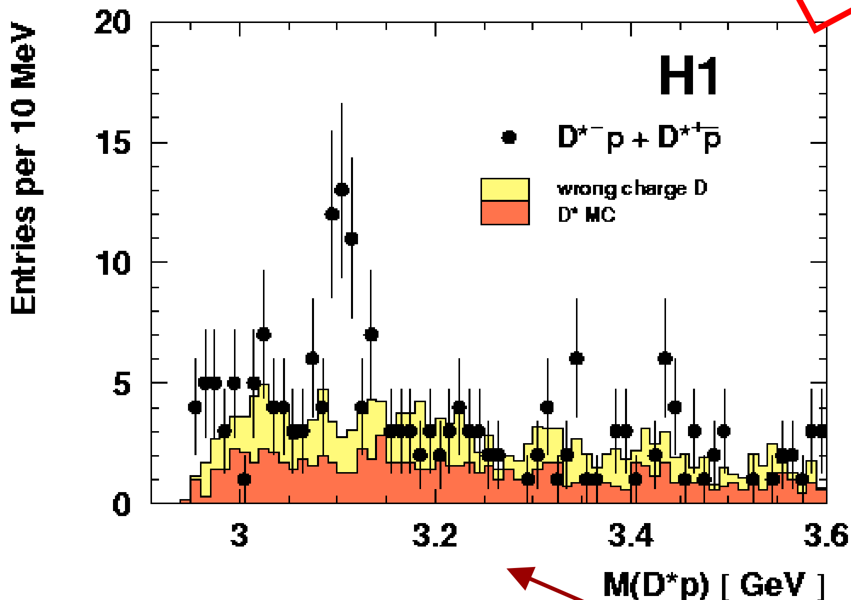
Signal at large p(p) more prominent ?

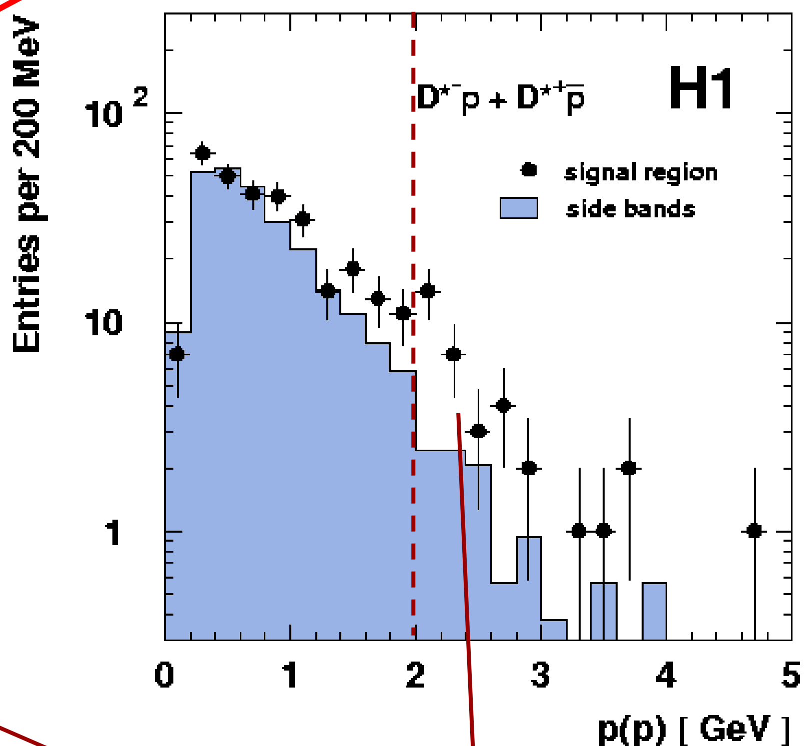


*Signal to background improves at larger proton momentum → look at M(D*p)*

Signal at large p(p) more prominent ?

YES!





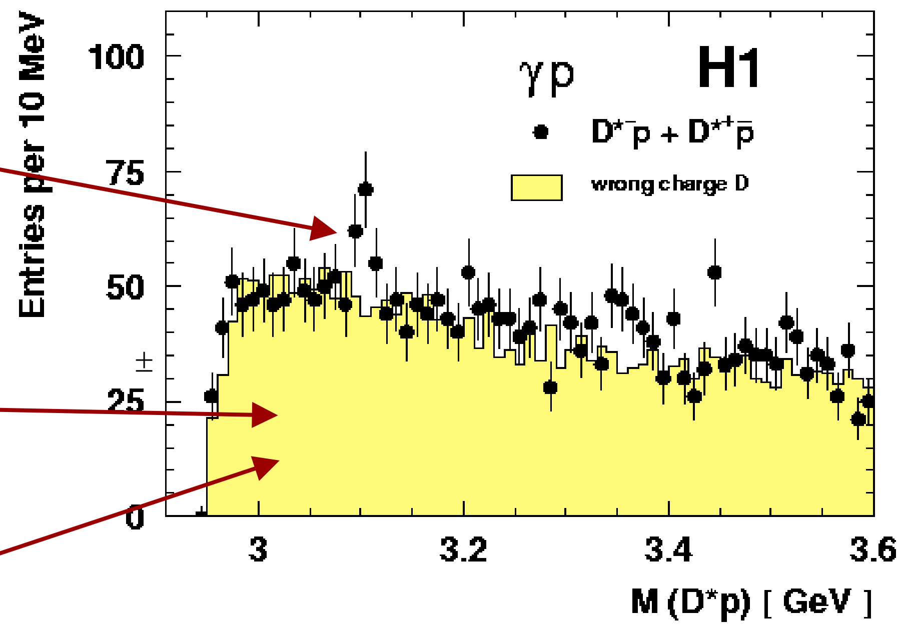
*Signal to background improves at larger proton momentum → look at M(D*p)*

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

4900 D*

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

1) Charge conjugate always implied

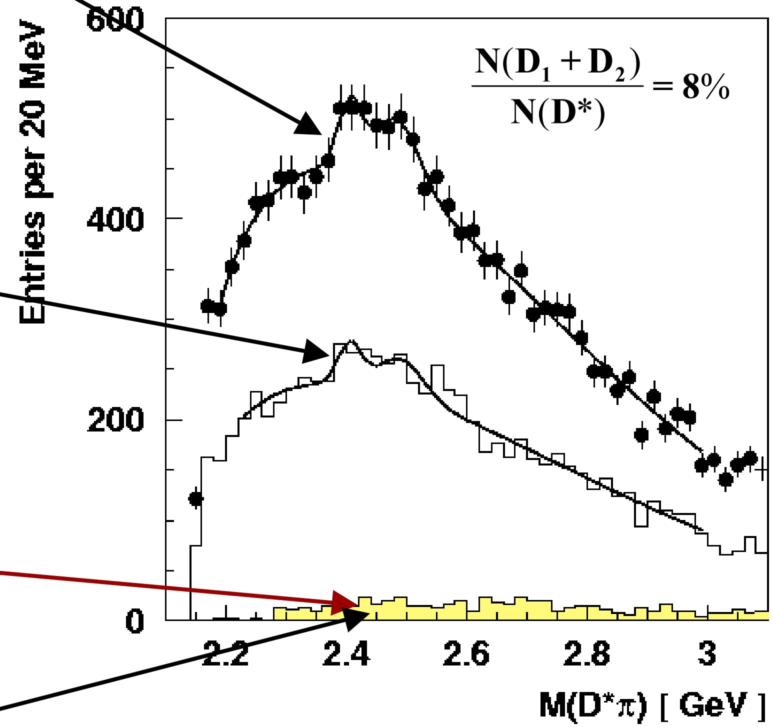
Photoproduction more difficult due to large non-charm background

→ independent confirmation of the signal

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

Loose D* cuts & pion selection

No cut in D*p



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

D* cuts of D*p & proton selection

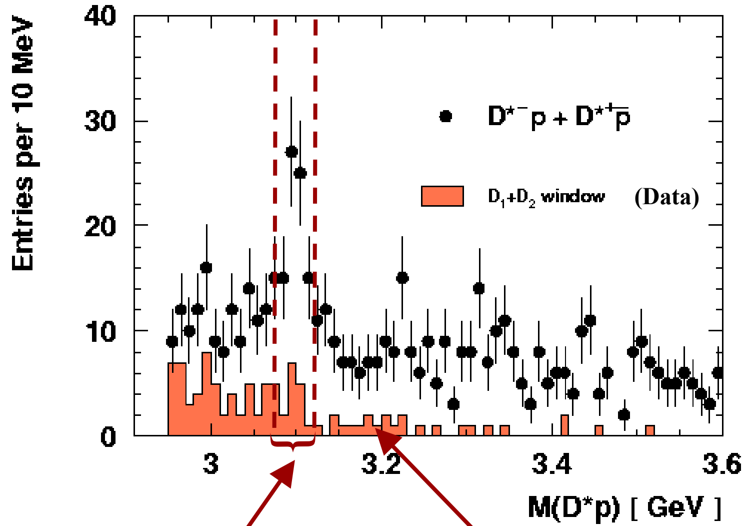
Compatible with MC expectation

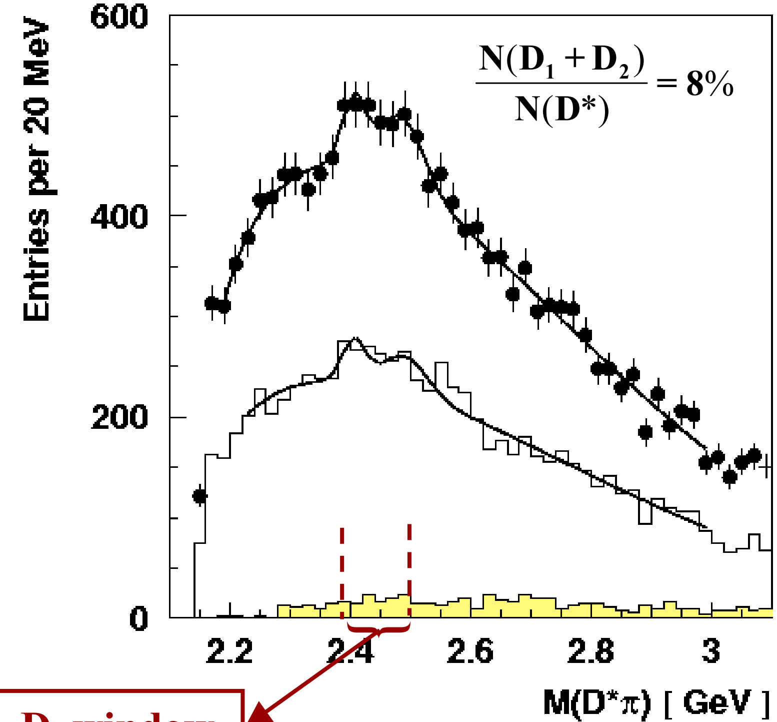
$M(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*)_{PDG}$

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

Small!

No cut in D^*p





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*

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

Basics of kinematic tests

2-Body Decay

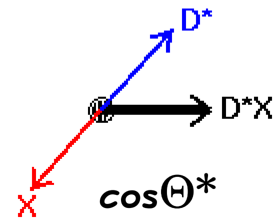
$$M^2 = (P_1 + P_2)^2$$

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

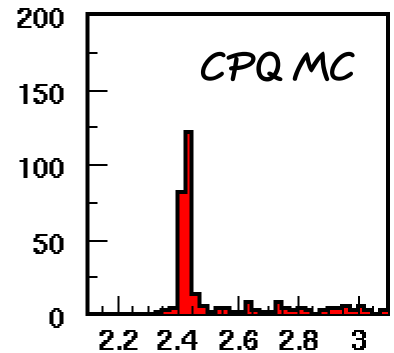
M^2 independent of decay angle $\cos\Theta^*$ only for correct mass assignment

Monte Carlo !

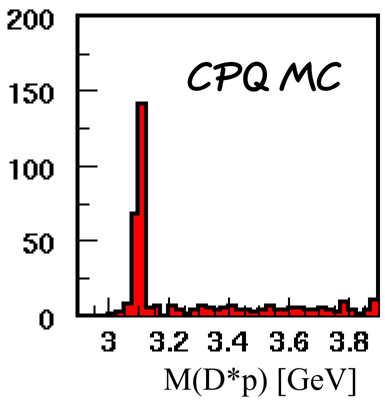
D*p *rest frame*

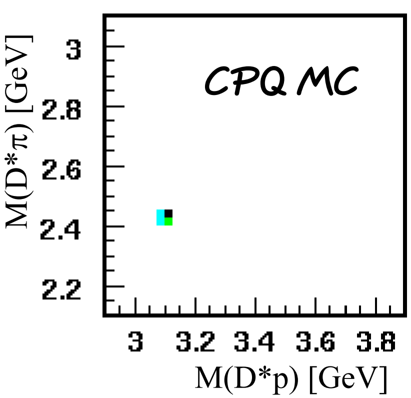


wrong mass assignment



correct mass assignment





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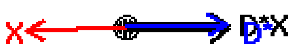
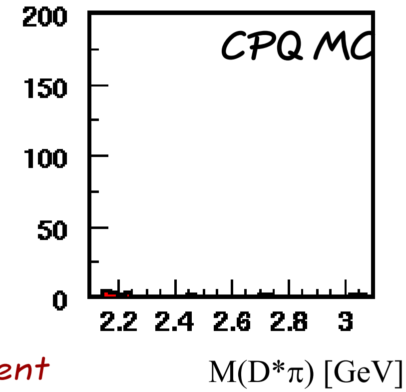
> M^2 independent of decay angle $\cos\Theta^*$ only for correct mass assignment

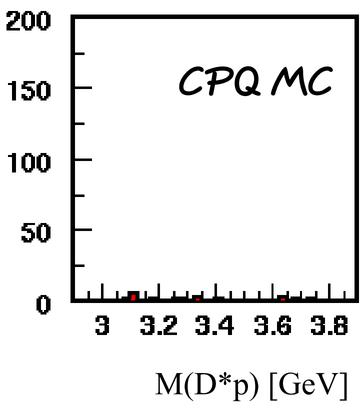
D*p *rest frame*

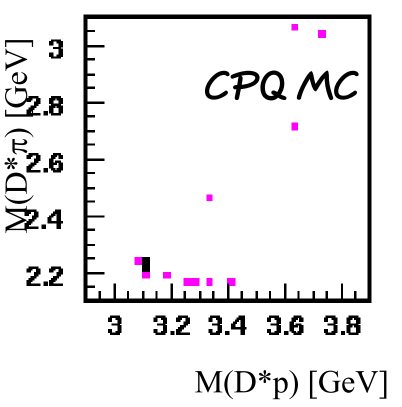


wrong mass assignment



correct mass assignment





Basics of kinematic tests

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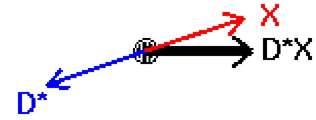
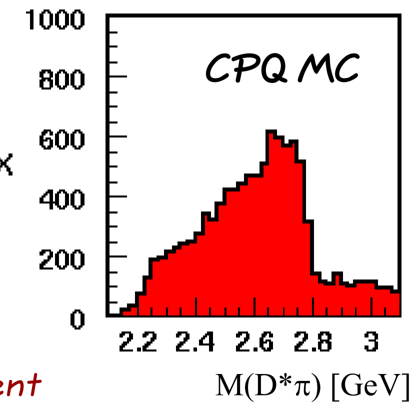
$$M^2 = (P_1 + P_2)^2$$
$$= (m_{D*}^2 + m_X^2 + 2E_{D*}E_X - 2\vec{p}_{D*}\vec{p}_X)$$

D*p rest frame

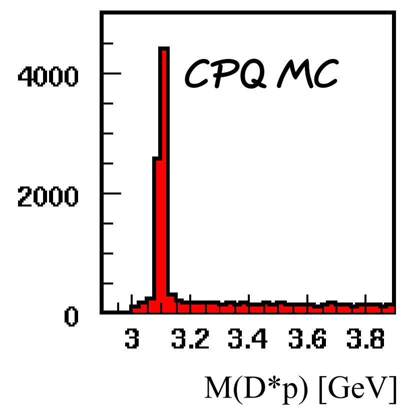


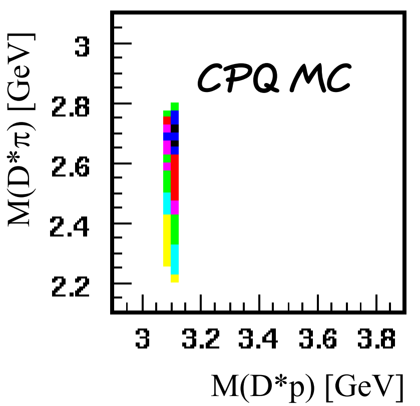
Integrated in cosΘ*

wrong mass assignment



correct mass assignment

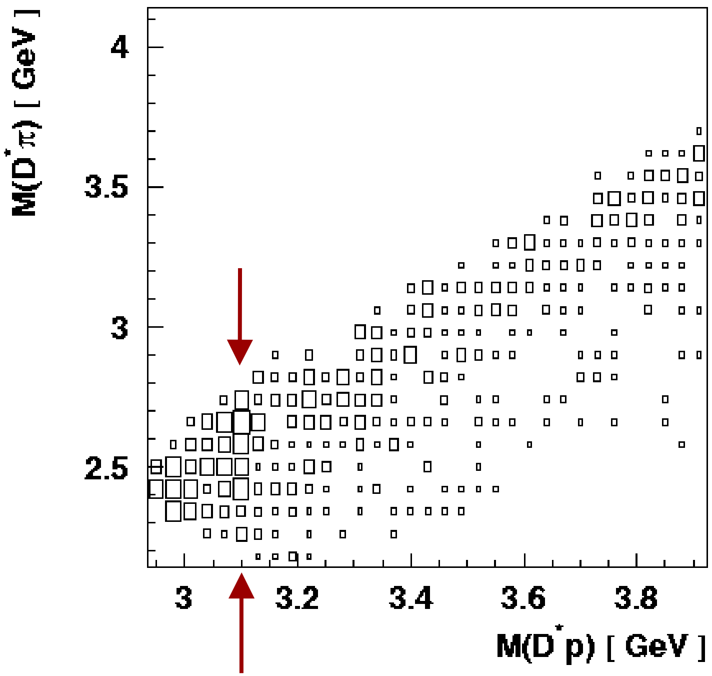




Do we see a band like structure in the M(D*p)-M(D*x) plane in data? → Let's have a look

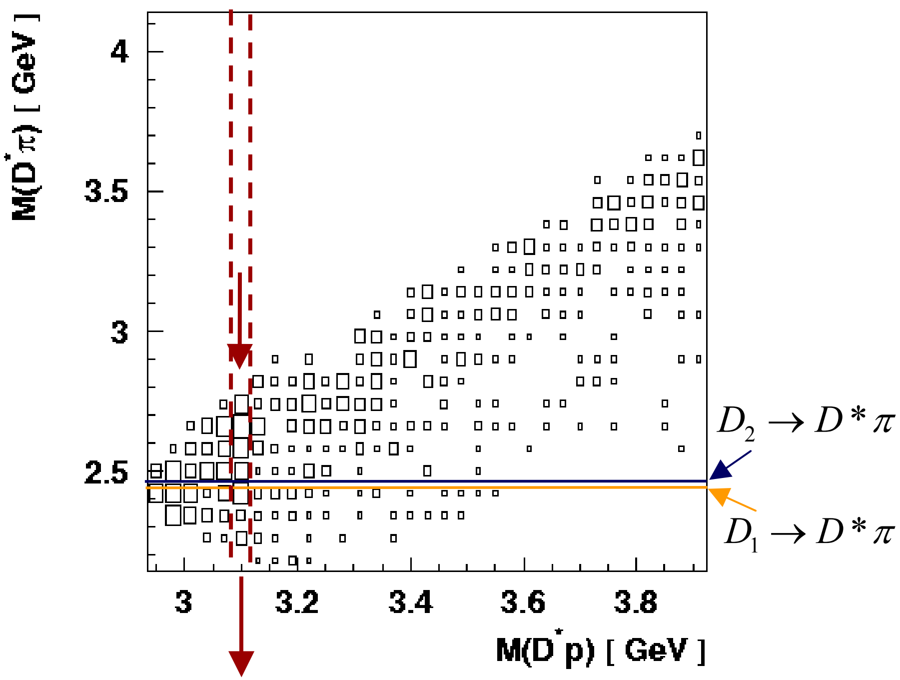
Signal due to D*π ?

Back to data !



Band in D*π clearly visible

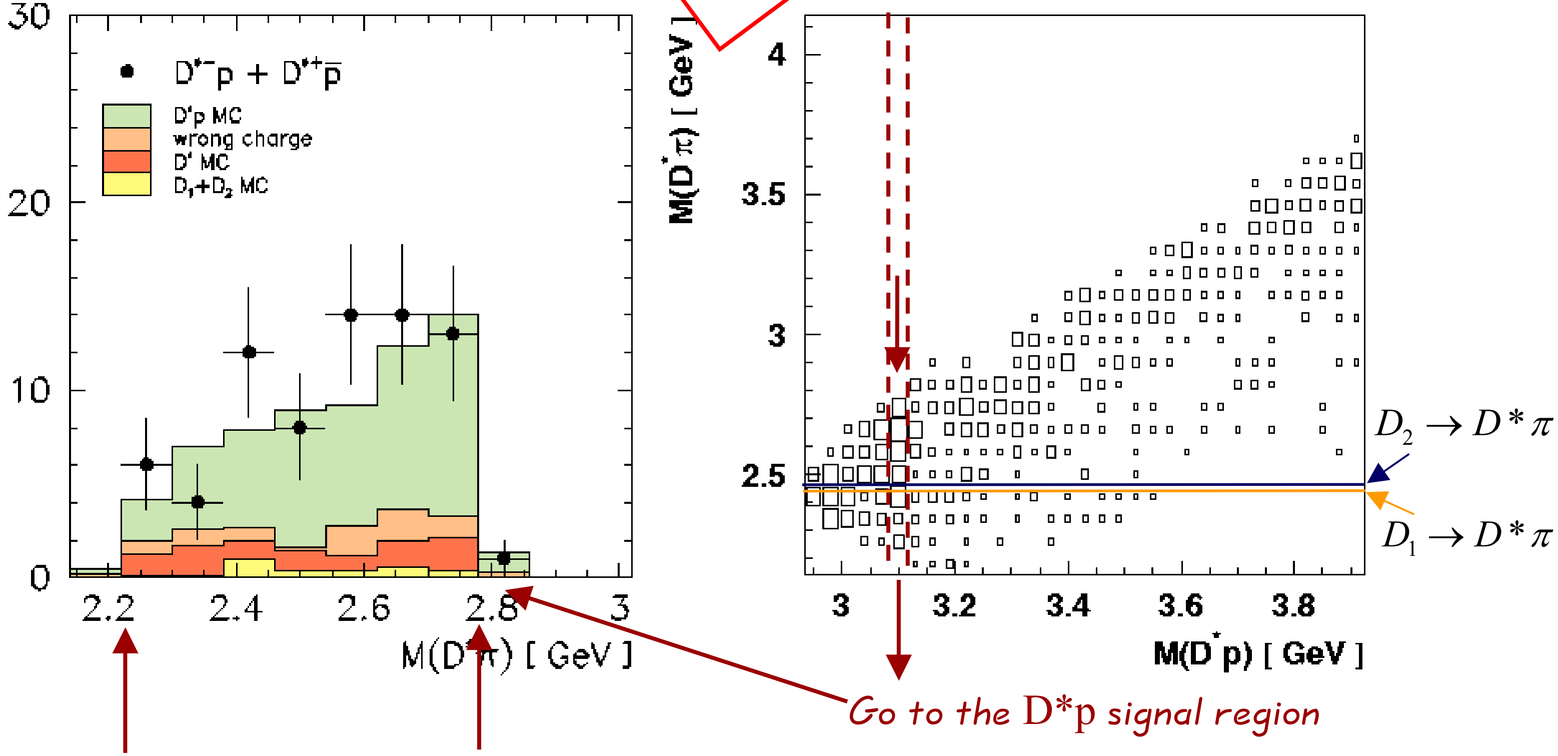
Signal due to D*π ?



Go to the D*p signal region

No indication for contributions from D_1 and D_2

Signal due to $D^*\pi$? NO!



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

Lots of further kinematic test

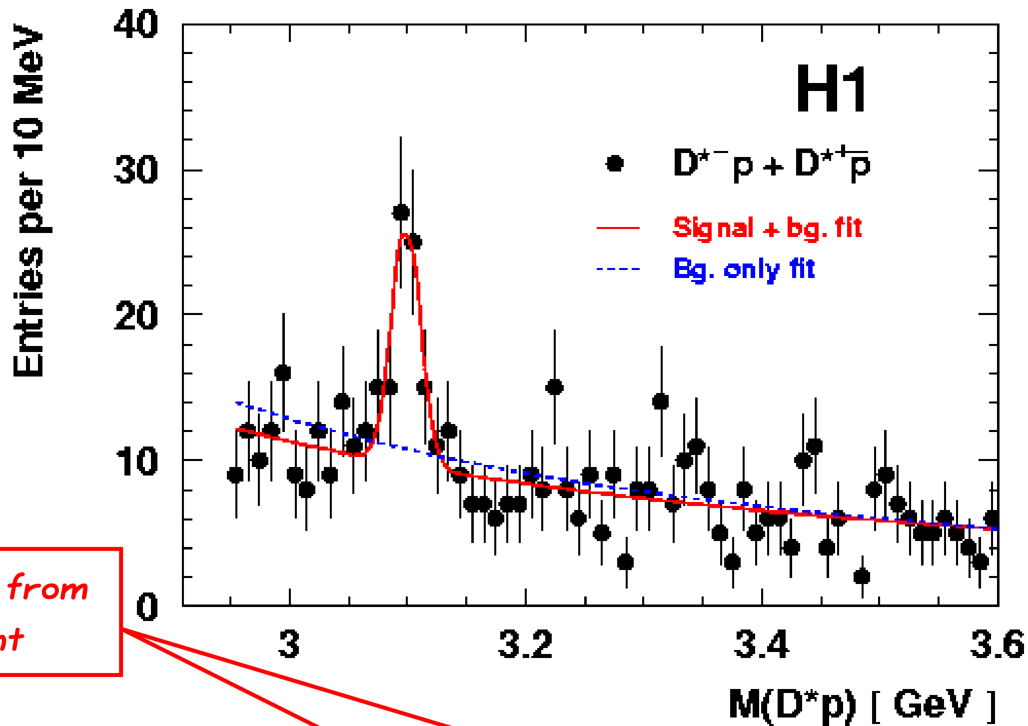
- Reflections from a possible signal in D^*K mass distribution: ruled out
- Possible contributions from $D^{*0} \to D^0 \gamma$ with γ-conversion: ruled out
- Possible contributions from $D_{S1}/D_{S2} \to D^0 K$: ruled out
- Possible peak structures in all possible mass correlations with all possible 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

- 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

Signal assessment



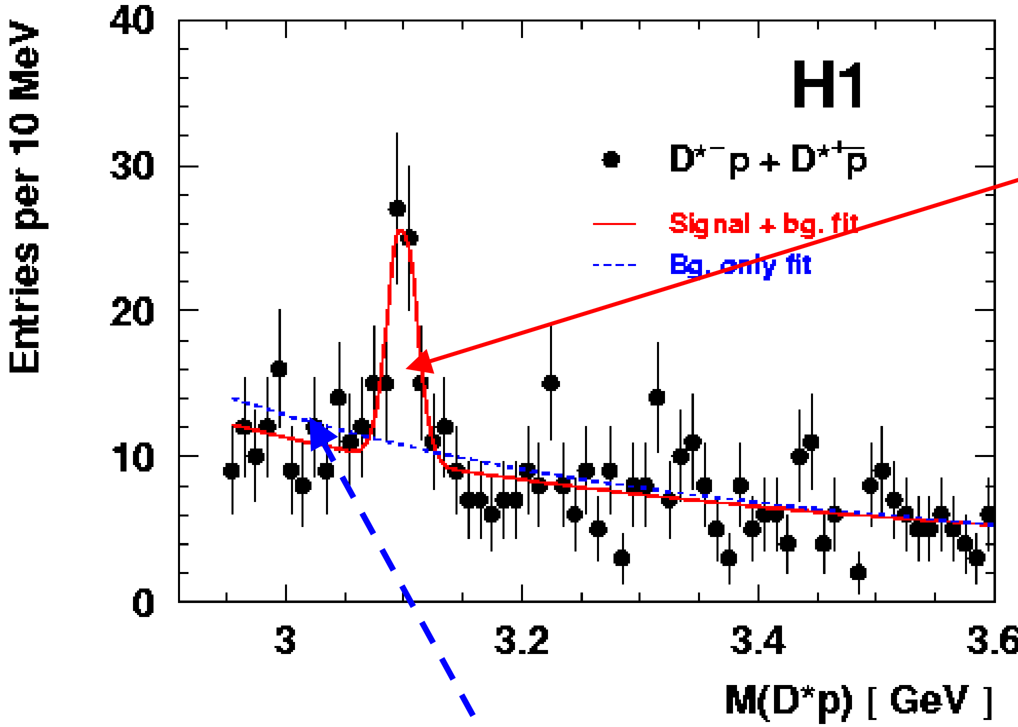
Stability of result against all sorts of variations checked

In total about 90 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

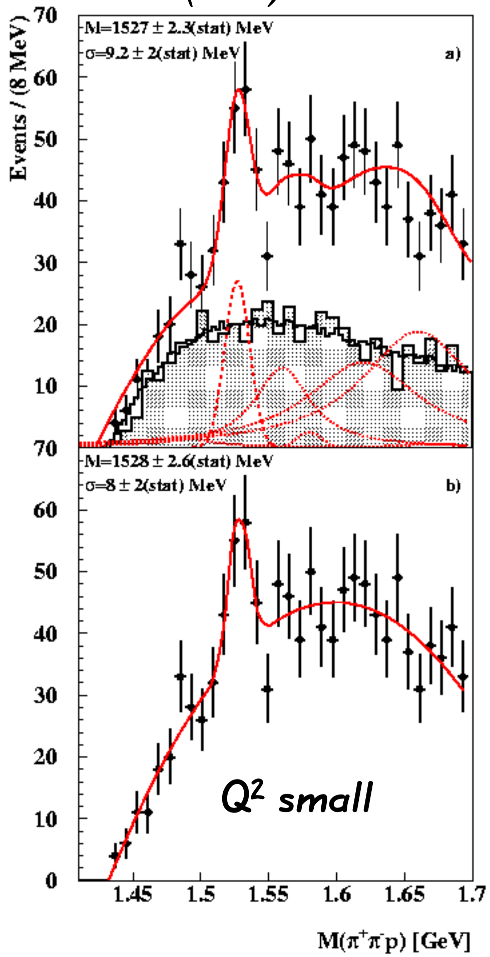
$$M(D^{*}p) = 3099 \pm 3\ (stat.) \pm 5\ (syst.)\ MeV$$

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

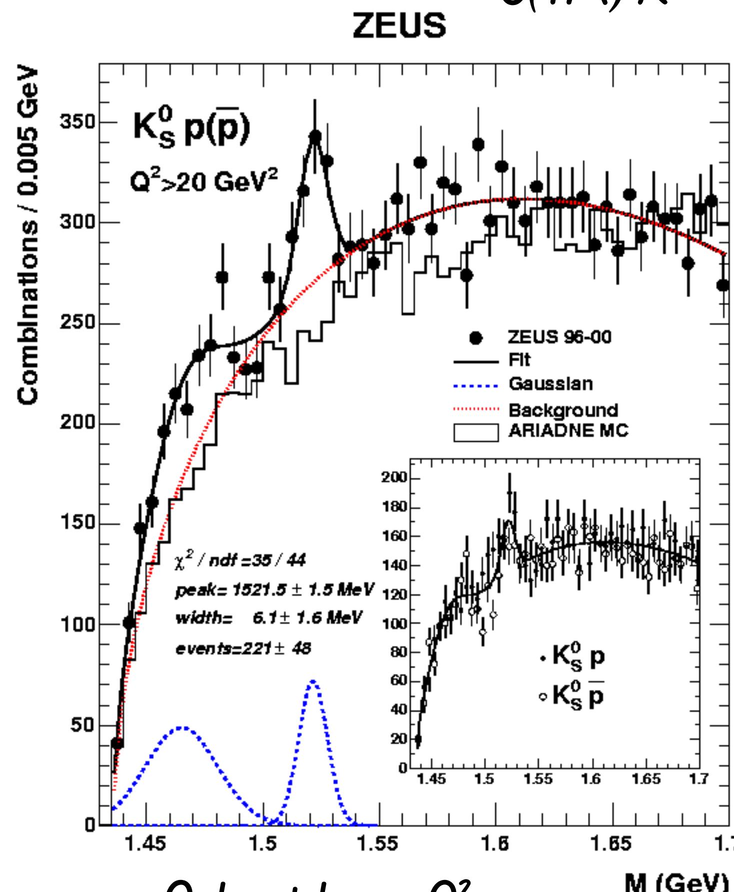
- The background fluctuation probability is smaller than $4*10^{-8}$.
- The signal is also observed in an independent photoproduction sample
- The signal region is richer in D^{*} mesons and show a harder momentum spectrum of the proton candidates
- No simple explanation for this resonance could be found.
  $\Rightarrow$ 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.

The strange pentaquark Θ^+

O(10k) K°



O(1M) K°



Only at large Q^2

Checks

- Meanwhile 4 independent analyses

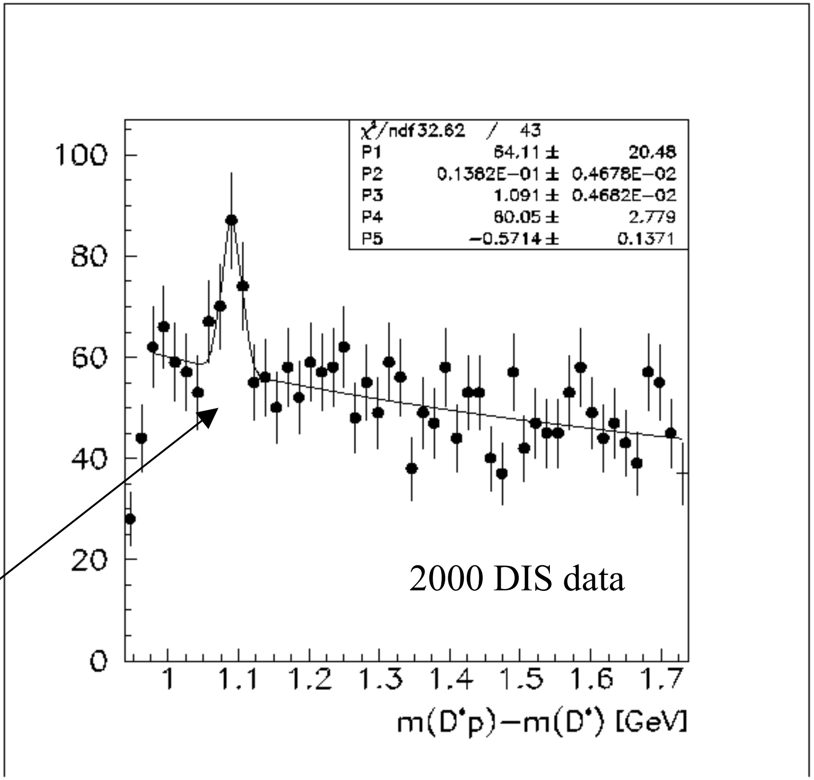
  (whoever looks for it, verifies it)
- Using 4 independent codes for the central analyses

  (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

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*

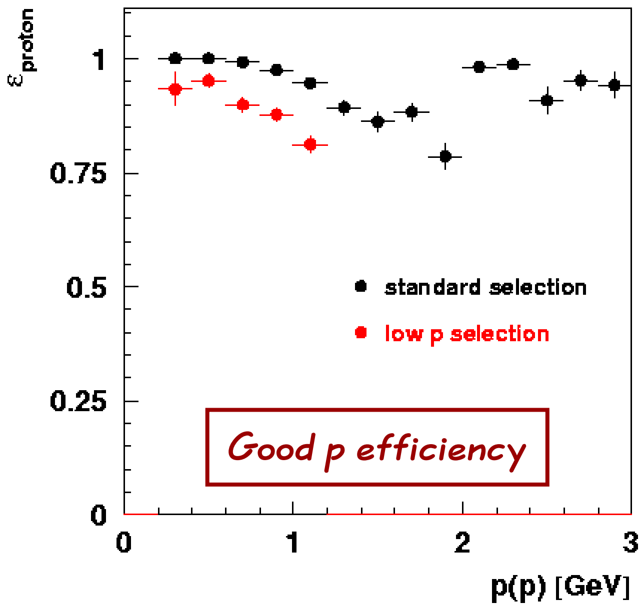
> *Take a D* candidate add a track consistent with a proton using m_p*
> *D* selection as used for F_c^2 96/97 analysis & L(p)> 5%*



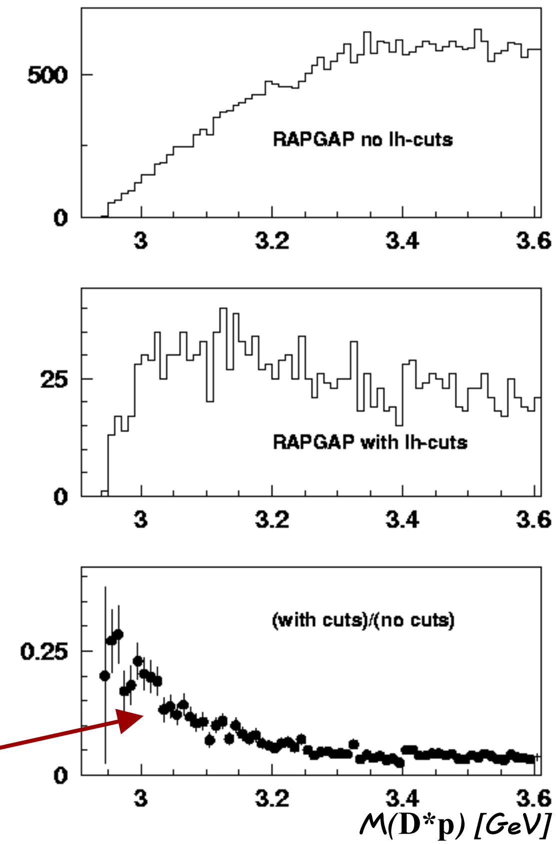
Narrow enhancement about 150 MeV above threshold: real or fake ?

Does some acceptance effect fool us ?

Proton efficiency



"Pion survival probability"



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

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

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- Possible contributions from $D^{*0} \rightarrow D^0\gamma$ with γ-conversion:
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  no enhancements found
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  no enhancements found

PASSED !