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# Search for Doubly Charmed Baryons at LHCb

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# State of Charmed Baryon Spectroscopy

- Many recently observed new states from BELLE and BABAR.
- First observations,  $J^P$ , BRs etc. of a variety of  $\Xi_c$ ,  $\Sigma_c$  and  $\Omega_c$  states.
- Still many rich avenues of physics to be investigated.

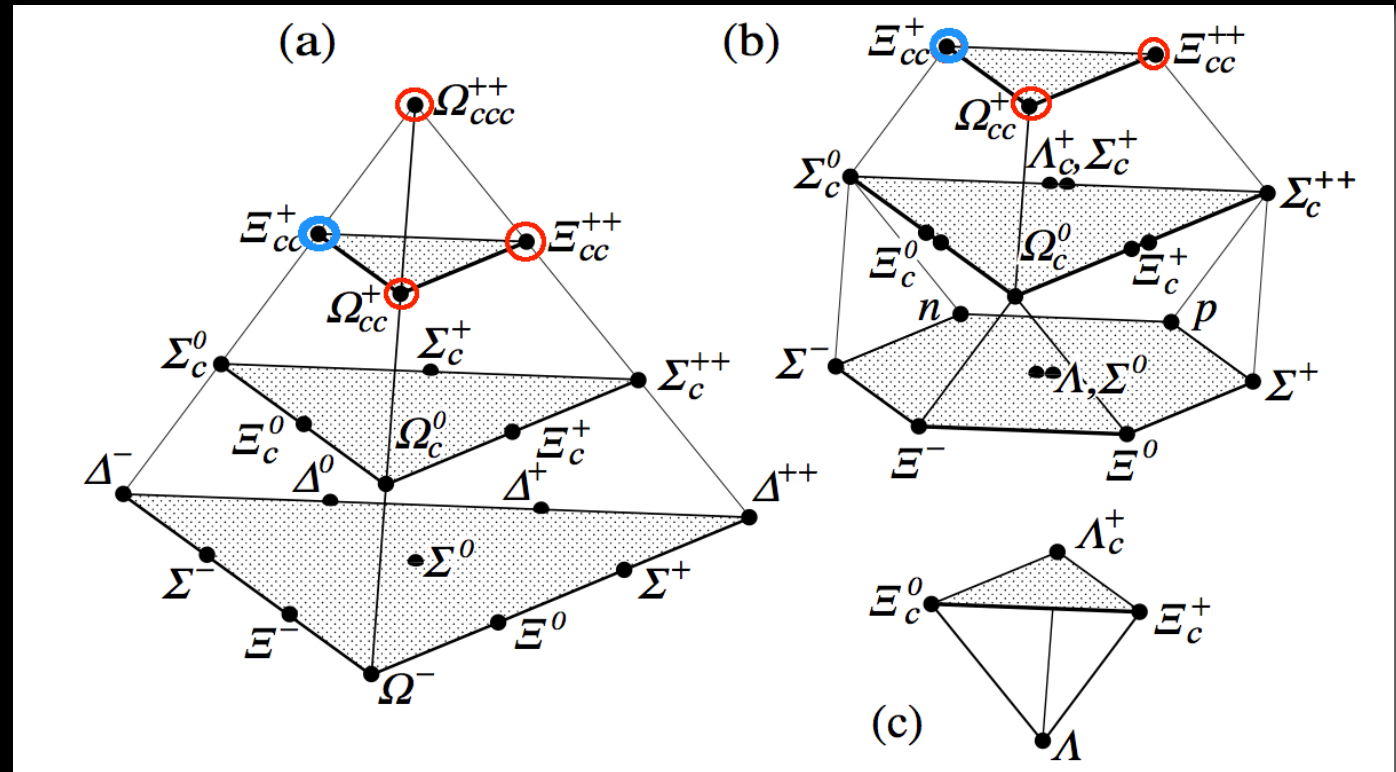


Figure 1: The SU(4) multiplets of baryons containing u,d,s,c quarks. Circled in blue is the  $\Xi_{cc}^{+}$ , which only SELEX has observed. Circled in red are completely unobserved states. From PDG.

# Doubly Charmed Baryon Searches

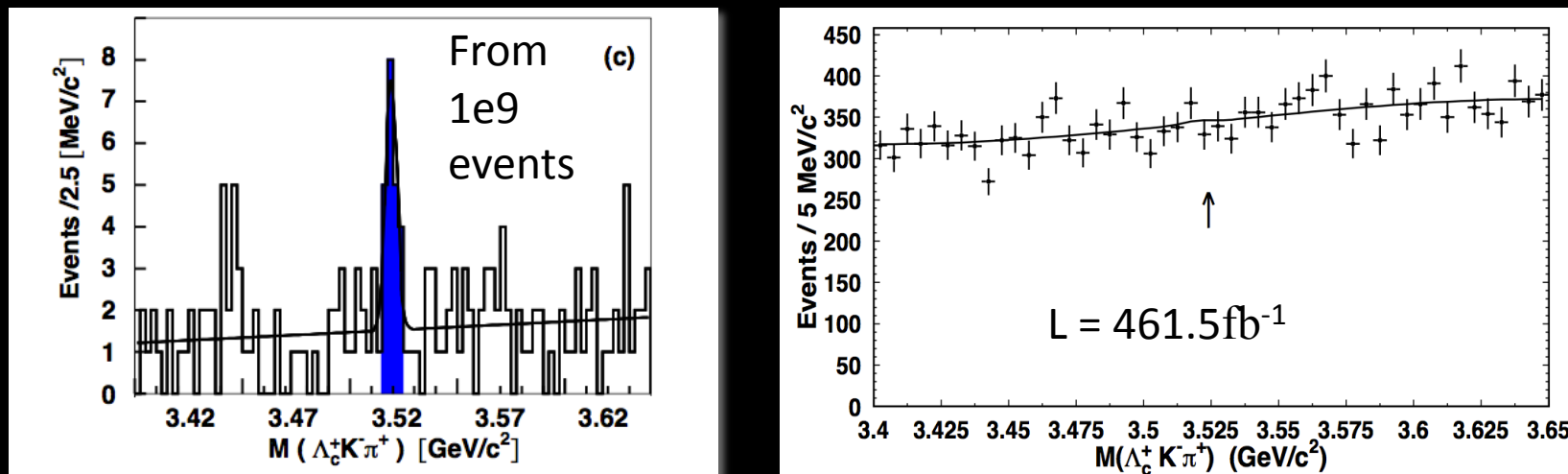


Figure 2: Searches for  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  at SELEX (left) and BELLE (right). Searches at BELLE, BABAR and FOCUS have failed to observe doubly charmed baryon production. From hep-ex/0208014 and hep-ex/0605075v1 respectively.

- In 2002 SELEX claimed observation of  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  ( $6.3\sigma$ ), subsequently claimed observation of  $\Xi_{cc}^+ \rightarrow D^+ p^+ K^-$  ( $4.8\sigma$ ).
- But no subsequent searches since then have found evidence of doubly charmed production.
- Production limits on  $\sigma(\Xi_{cc}^+) \times \text{BR}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ \rightarrow p^+ K^- \pi^+) / \sigma(\Lambda_c^+)$  :
  - BELLE:  $< 1.5 \times 10^{-4}$  at 90% CL.
  - BABAR:  $< 2.4 \times 10^{-4}$  at 95% CL.

# Doubly Charmed Baryon Searches

- There also exists a strong discrepancy between theory and SELEX results:
  - Theory  $M(\Xi_{cc}^+) = 3610 \text{ MeV}/c^2$
  - SELEX  $M(\Xi_{cc}^+) = 3518 \pm 1.7 \text{ MeV}/c^2$
  - Theory  $\tau(\Xi_{cc}^+) = 0.07 - 0.20 \text{ ps}$
  - SELEX  $\tau(\Xi_{cc}^+) < 0.033 \text{ ps}$  at 90% C.L.
  - Predicted that  $10^{-5}$  of SELEX  $\Lambda_c^+$ s should come from  $\Xi_{cc}^+$ s. They have measured 0.2 originate this way.
- To my knowledge, neither CDF or D0 published any production cross section limits for p-pbar environment.
- Hopefully we can resolve this tension between theory, SELEX and the non-observations on LHCb.

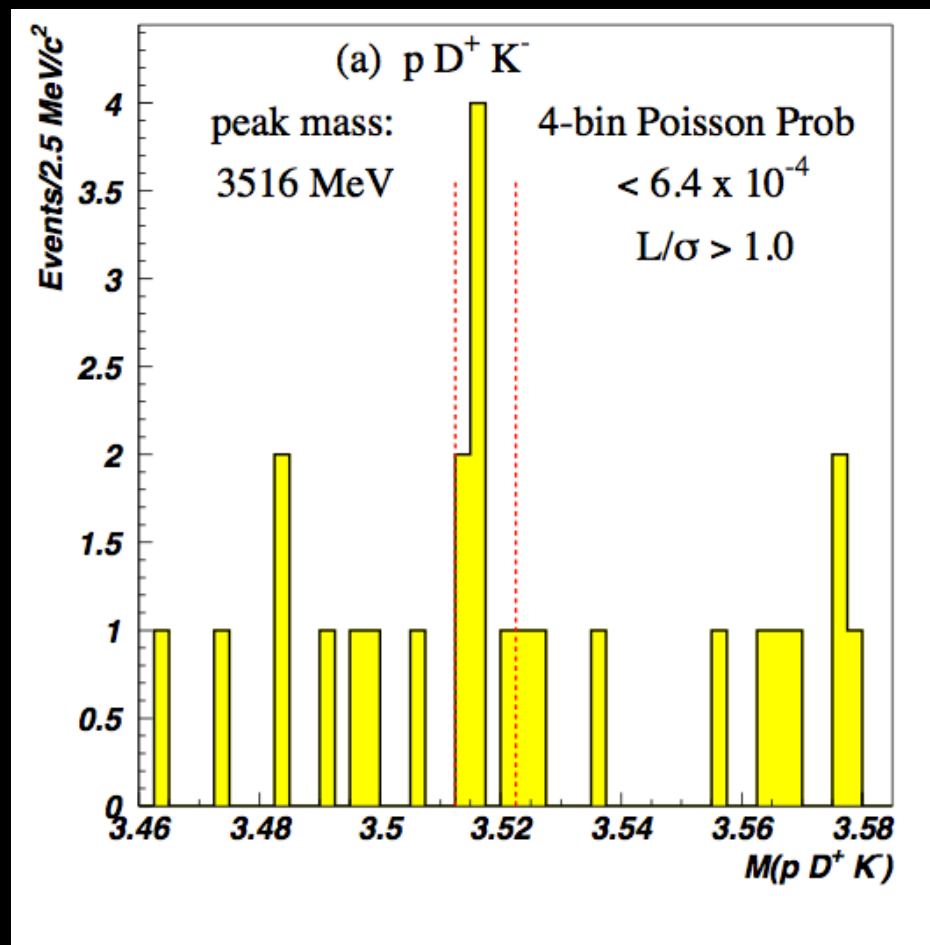
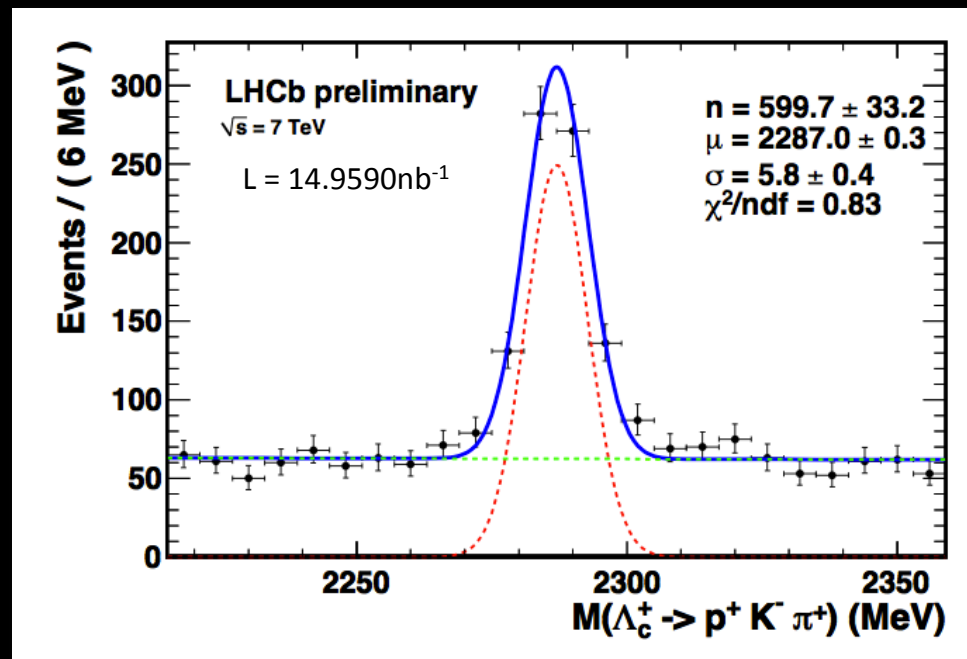


Figure 3: The SELEX observation of the decay mode  $\Xi_{cc}^+ \rightarrow p^+ D^+ K^-$ . From hep-ex/0406033.

# $\Lambda_c^+$ selection optimisation

- Daughter in dominant decay mode in doubly charmed baryons; important to optimise for a variety of analyses.
  - Doubly Cabibbo Suppressed mode  
 $\Lambda_c^+ \rightarrow p^+ K^+ \pi^-$  has not been observed (current BR constrained at  $< 2.4 \times 10^{-4}$ ).
  - Potential for CPV in heavy baryons.
- We have produced a first selection and are moving on to MVA to produce an improved trigger for 2012.



Shamelessly stolen from the prompt charm production internal note.

# Hybrid $\Lambda_c^+$ Optimisation

- Hybrid analysis undertaken by using  $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$  signal MC weighted against an inclusive charm background.
- Undertook a series of rectangular cuts to find a preliminary optimum selection.

## Hybrid Optimisation Cuts

Mother Pt > 4.5 GeV

End Vertex  $\chi^2 < 3$

DIRA > 0.9996

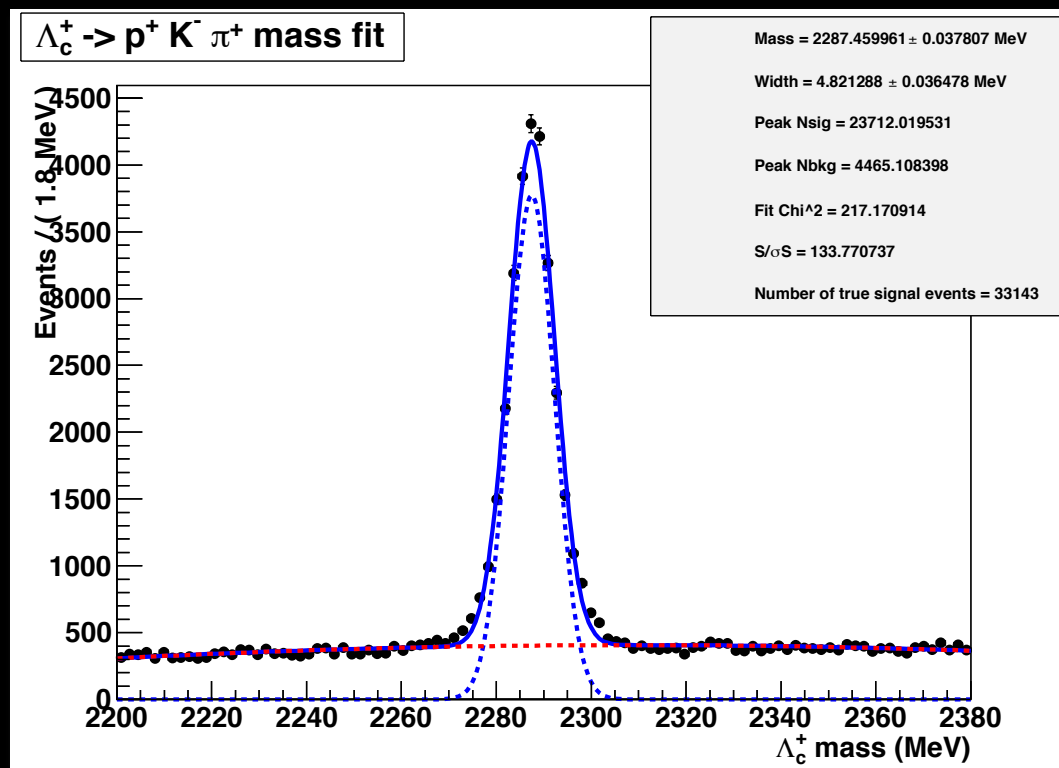
Combination DOCA < 0.75 mm

Proton PIDp – PIDpi > 5

Kaon PIDK – PIDpi > 5

All daughter track  $\chi^2 < 3$

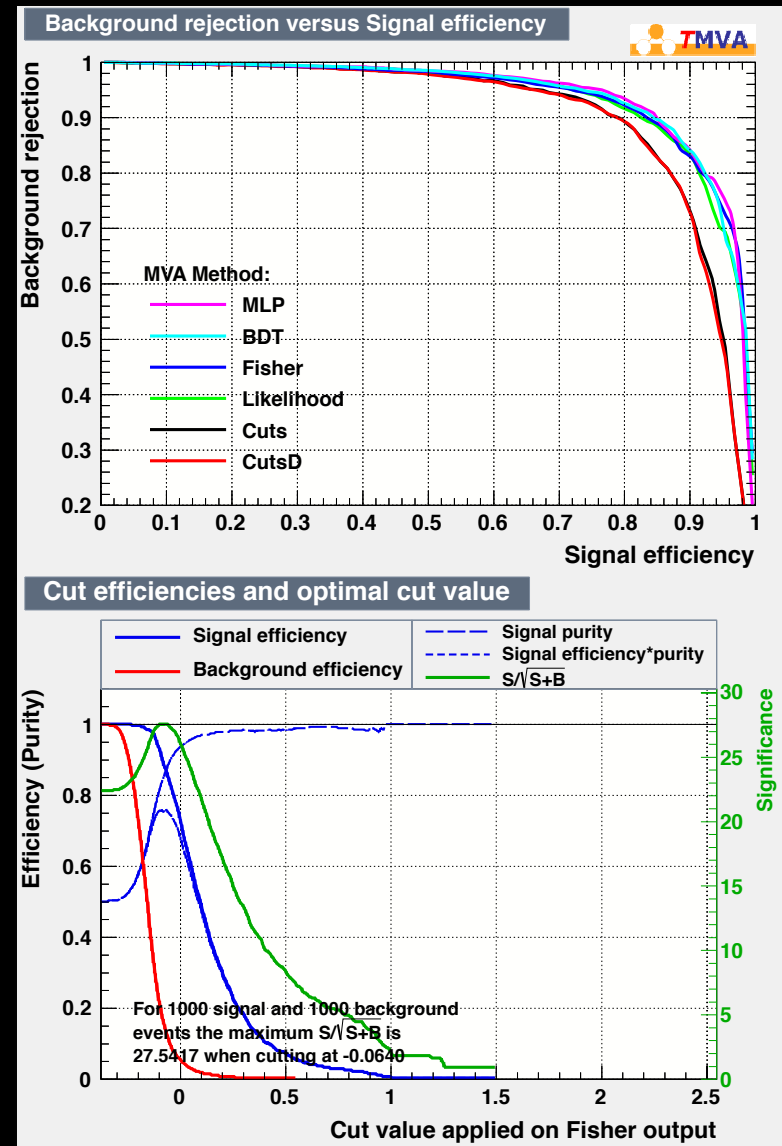
Daughter track Ghostprob < 0.5



Shown above: massfit from signal MC from 2.5M events. When weighted against an inclusive charm background and scaled up to full 2011 luminosity we expect a significance of around  $350\sigma$ .

# TMVA $\Lambda_c^+$ optimisation

- Will be tricky to observe the DCS  $\Lambda_c^+$  channel and the  $\Xi_{cc}^+$ , we are currently looking at MVA as an option for 2012.
- Again use  $\Lambda_c^+$  signal MC and incl. charm bkg.
- Initial results encouraging, MVA methods display greater discrimination than cuts -> definitely use MVA in offline selection.
- If the simpler MVA methods can easily translate to stripping/trigger may utilise a Fisher discriminant, shown bottom.



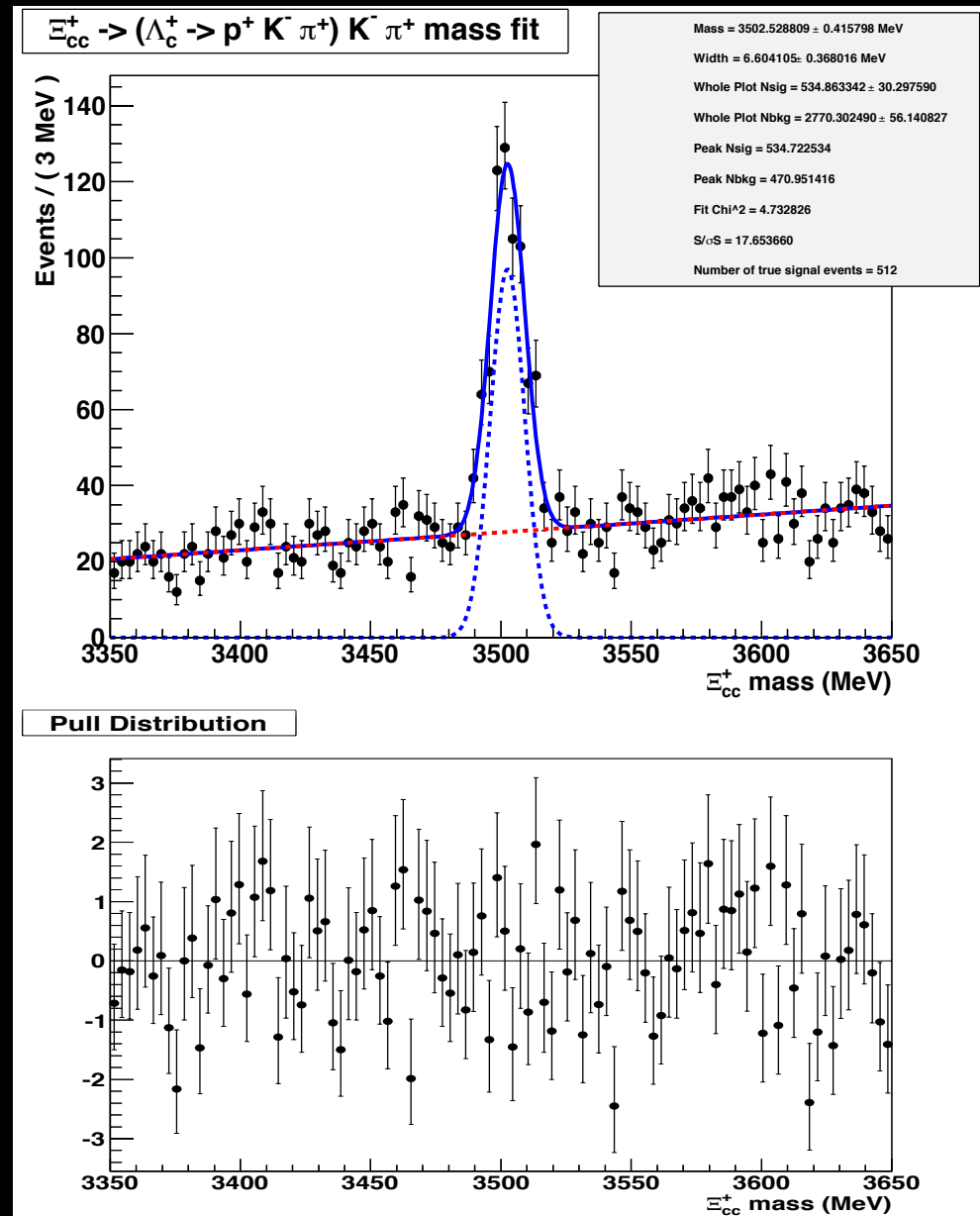


# $\Xi_{cc}^+$ signal MC

- Produced by Feng Zhang (Tsinghua) by interfacing genxicc2.0 to Gauss. Prior to this could not generate double heavy quark baryons.
- Still in early stages. We have:
  - 100k  $\Xi_{cc}^+ \rightarrow (\Lambda_c^+ \rightarrow p^+ K^- \pi^+) K^- \pi^+$  events.
    - BR  $\sim 0.05$ , dominant mode.
  - 30k  $\Xi_{cc}^+ \rightarrow (D^+ \rightarrow K^- \pi^+ \pi^+) p^+ K^-$  events.
  - 40k  $\Xi_{cc}^+ \rightarrow (D^0 \rightarrow K^- \pi^+) p^+ K^- \pi^+$  events.
- Caveat: following slides are an offline selection only, have not gone through trigger and stripping.
- A speculative line for  $\Xi_{cc}^+ \rightarrow (\Lambda_c^+ \rightarrow p^+ K^- \pi^+) K^- \pi^+$  has been operational since Stripping 13. Could we have anything in the 2011 data?

# $\Xi_{cc}^+ \rightarrow (\Lambda_c^+ \rightarrow p^+ K^- \pi^+) K^- \pi^+$ Signal MC (100k events)

- Apply very loose selection to estimate efficiencies.
- $\pm 15 \text{ MeV}/c^2$   $\Lambda_c^+$  mass window to suppress reflections.
- 1<sup>st</sup> order Polynomial background & Gaussian signal.
- Good agreement in MC truth Nsig & fitted Nsig.
- Approximately 0.51% offline reconstruction and selection efficiency.

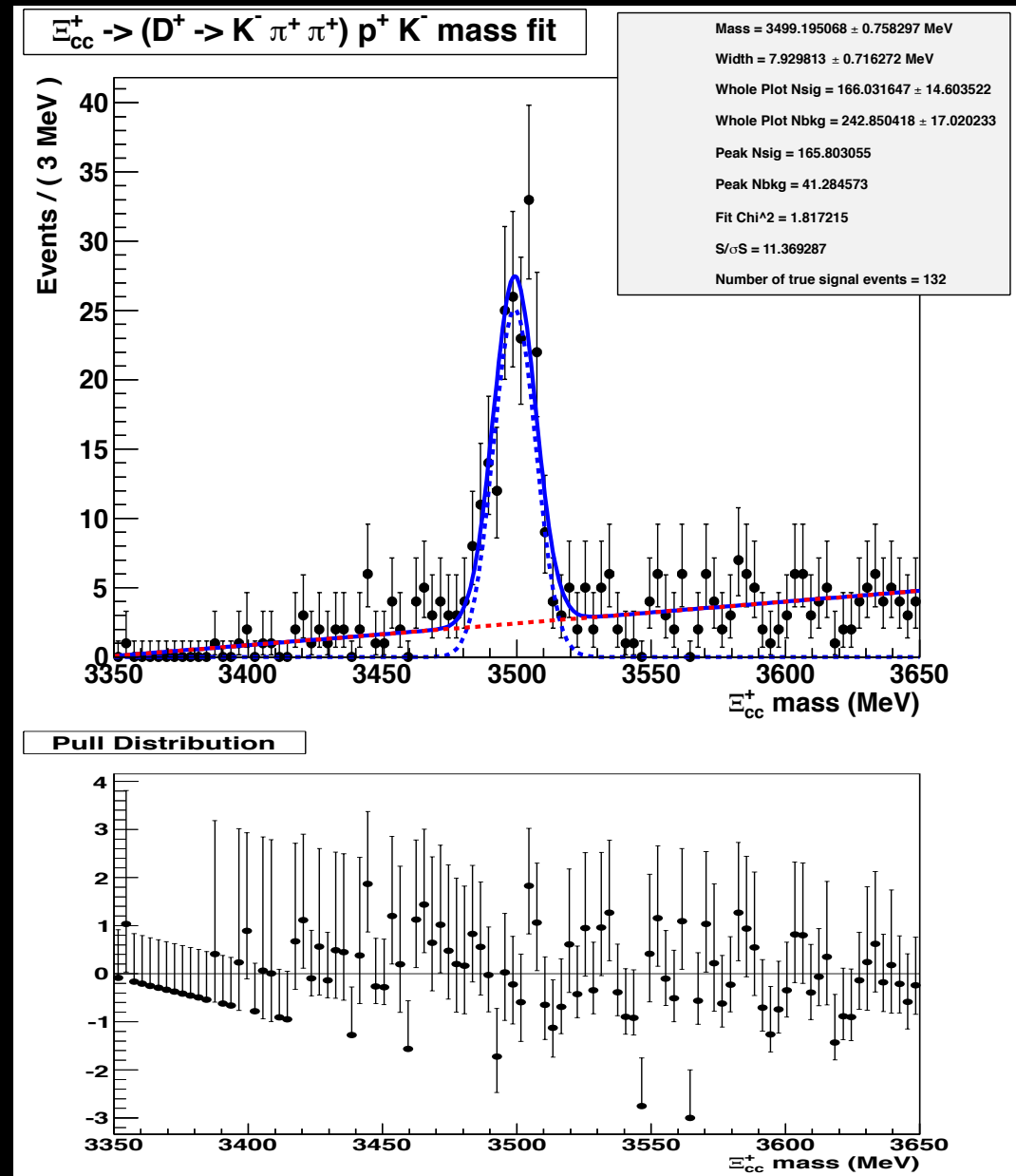


# $\Xi_{cc}^+ \rightarrow (D^+ \rightarrow K^- \pi^+ \pi^+) p^+ K^-$ signal MC (30k events)

- Widen  $D^+$  mass window to  $100 \text{ MeV}/c^2$ , same loose selection.
- Approximately 0.44% offline selection and reconstruction efficiency.
- SELEX reports relative BRs of

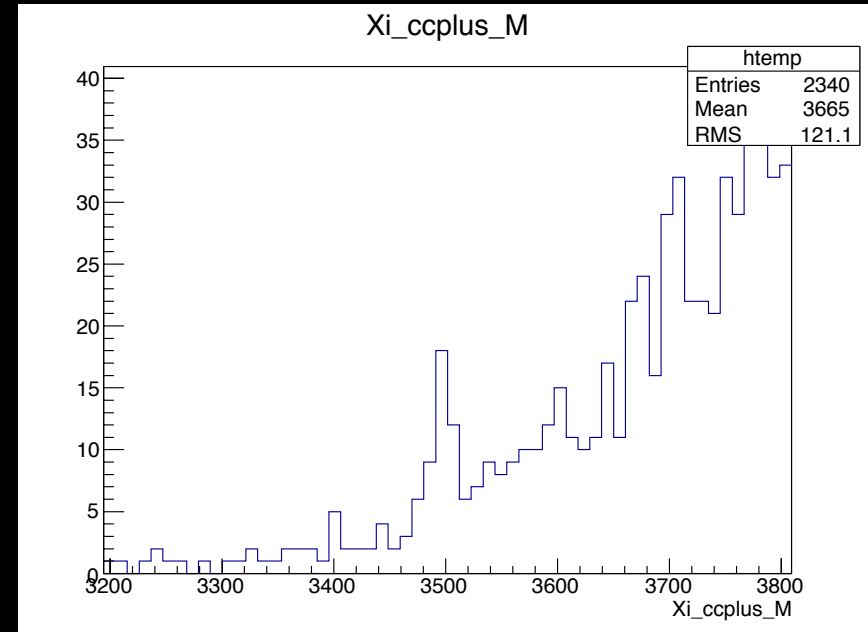
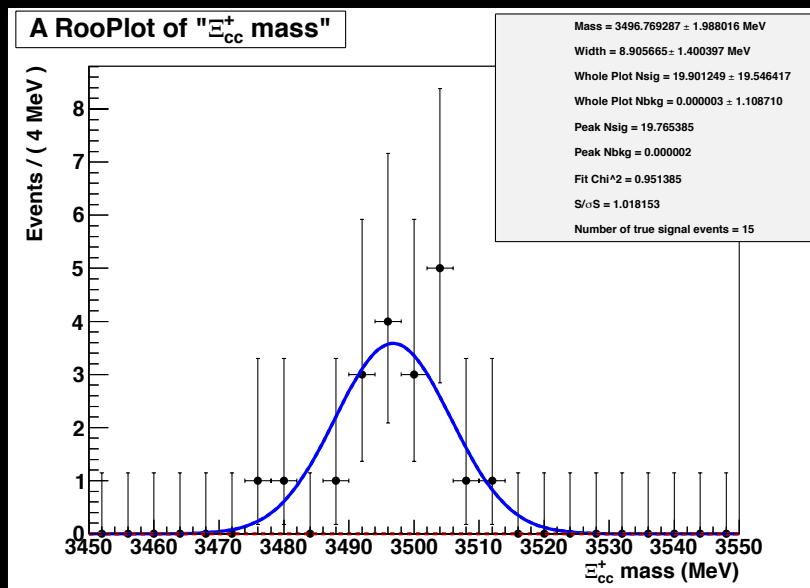
$$\frac{BR_{\Xi_{cc} \rightarrow \Lambda_c K \pi}}{BR_{\Xi_{cc} \rightarrow D p K}} = 0.36 \pm 0.21$$

- If accurate potentially an important mode in our DCB searches.



# $\Xi_{cc}^+ \rightarrow (D^0 \rightarrow K^- \pi^+) p^+ K^- \pi^+$ signal MC (40k events)

- Not so promising channel, approximate offline reconstruction and selection efficiency of 0.038%.
- However applying a  $\pm 50 \text{ MeV}/c^2$  window on the  $D^0$  mass results in a very pure signal.



A peak can be seen around  $3.5 \text{ GeV}/c^2$  but the statistics are too low to permit a decent fit.

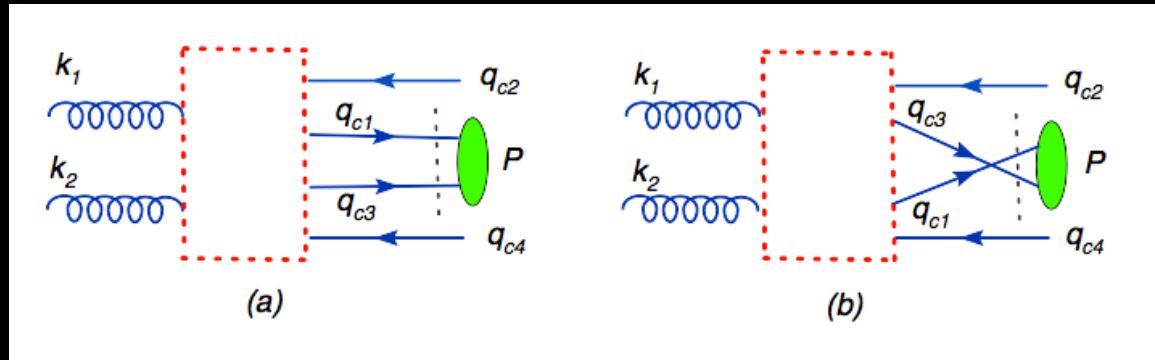
# $\Xi_{cc}^+ \rightarrow (\Lambda_c^+ \rightarrow p^+ K^- \pi^+) K^- \pi^+$ in 2011 data

- Speculative stripping code written pre-MC has been running since Stripping 13.
- How many  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  events can we expect to see in 2011 data?
- Apply trigger and stripping to MC to estimate yields.

Cut	Loose Value	Current Stripping
$\Xi_{cc}^+$ Pt	N/A	>2000MeV
$\Xi_{cc}^+$ Vertex $\chi^2$	<20	<30
$\Xi_{cc}^+$ Vertex Distance $\chi^2$	N/A	>16
$\Xi_{cc}^+$ DIRA	N/A	>0.999
$\Xi_{cc}^+$ Daughter K/ $\pi$ cuts	N/A	(P>2.0*GeV) & (TRCHI2DOF<4.0) & (PT>250.0*MeV) & (MIPCHI2DV(PRIMARY)>4.0)
$\Xi_{cc}^+$ Mass Window	3500 $\pm$ 500MeV	<4500MeV
All $\pi$ /K/p PID $\Delta$ LL	>-5 only for $\Lambda_c^+$	>-5
Child Vz – Parent Vz	N/A	>0.1mm
$\Lambda_c^+$ Daughter cuts	(P>2.0*GeV) & (TRCHI2DOF<4.0)	TRCHI2DOF<4
$\Lambda_c^+$ DIRA	>0.98	>0.95
$\Lambda_c^+$ Vertex Distance $\chi^2$	>9	>25
$\Lambda_c^+$ Pt	>1000MeV	N/A
$\Lambda_c^+$ DOCA	<0.5mm	N/A

# Outlook for 2011 data

- Plenty of theory papers on  $\Xi_{cc}^+$  production cross section at LHC.
- Should be of the order  $10^7 \Xi_{cc}^+$ s produced in LHCb acceptance in 2011.
- Trigger and selection efficiency studies underway to estimate how many will have made it to tape.



The dominant Feynman diagrams for hadronic  $\Xi_{cc}^+$  production at LHCb.  $k_{1,2}$  are gluon momenta,  $P$  is  $\Xi_{cc}^+$  momentum,  $q_{c2,c4}$  are  $c$ -bar momenta. From hep-ph/0601032v1.

-	Tevatron		LHC		LHCb	
-	$(cc)\bar{3}[^3S_1]$	$(cc)\bar{6}[^1S_0]$	$(cc)\bar{3}[^3S_1]$	$(cc)\bar{6}[^1S_0]$	$(cc)\bar{3}[^3S_1]$	$(cc)\bar{6}[^1S_0]$
$\sigma_{gg}$ (nb)	1.61	0.399	22.3	5.44	25.7	6.47
$\sigma_{gc}$ (nb)	2.31	0.361	22.1	3.42	20.6	3.00
$\sigma_{cc}$ (nb)	0.755	0.0435	8.75	0.478	3.18	0.169

Contributing subprocesses to cross sections for hadronic  $\Xi_{cc}^+$  production, incorporating detector acceptances. From hep-ph/0610205v3.

# Future work

- $\Lambda_c^+$  in 2012...
  - Finalise optimisations.
  - Improve on trigger and stripping for 2012.
  - Begin optimisation for DCS decay mode, search in 2011 data.
  - Opportunities for CPV searches.
- $\Xi_{cc}^{+/++}$  in 2012...
  - Full studies into existing trigger/stripping efficiencies.
  - Produce full signal MC samples for doubly charmed baryons.
  - Begin selection optimisations and improve stripping.
  - Almost certainly will use MVA.