Phys. Rev. D **89**, 091102(R) (2014)

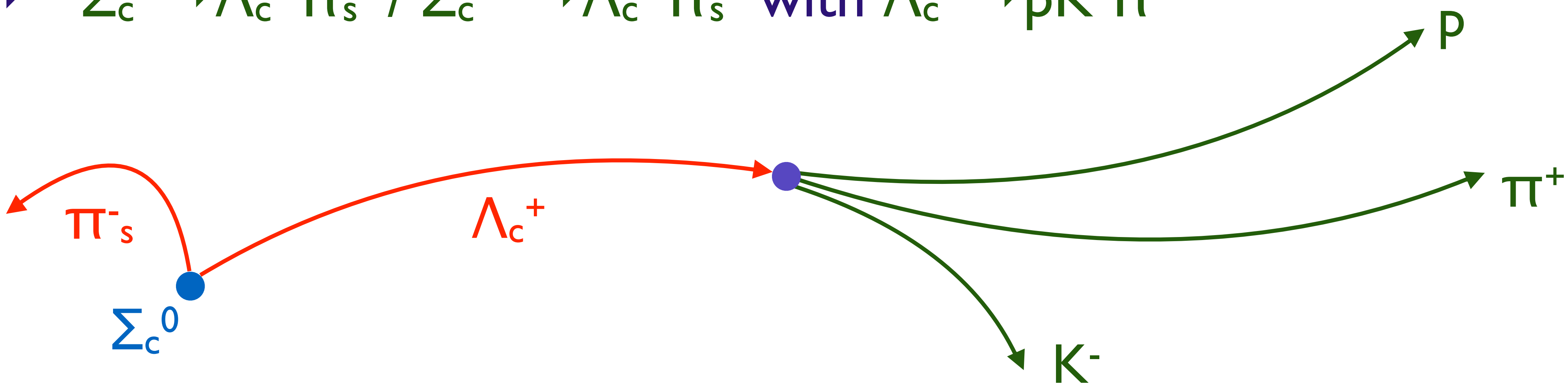
Measurement of masses and widths of Σ_c baryons at Belle

Lake Louise Winter Institute, Feb 19, 2015

Soohyung Lee
Center for Axion and Precision Physics Research / Institute for Basic Science
On behalf of the Belle Collaboration

Σ_c Baryons

- Σ_c baryons have very short lifetime → finite decay widths
  - Decays into $\Lambda_c^+\pi_s$ (~100%)
    - $\Sigma_c^0 \to \Lambda_c^+\pi_s^-$ / $\Sigma_c^{++} \to \Lambda_c^+\pi_s^+$ with $\Lambda_c^+ \to pK^-\pi^+$



- The uncertainties of the current world average values are a bit large
  - e.g. ~10% for widths

World average (MeV/c²)	$\Sigma_c(2455)^0$	$\Sigma_c(2455)^{++}$	$\Sigma_c(2520)^0$	$\Sigma_c(2520)^{++}$
Mass	2453.74 ± 0.16	2453.98 ± 0.16	2518.8 ± 0.6	2517.9 ± 0.6
Mass Difference	167.27 ± 0.08	167.52 ± 0.08	232.3 ± 0.5	231.4 ± 0.6
Decay Widths	**2.16 ± 0.26**	**2.26 ± 0.25**	**14.5 ± 1.5**	**14.9 ± 1.5**

* Large uncertainties

Σ_c Baryons

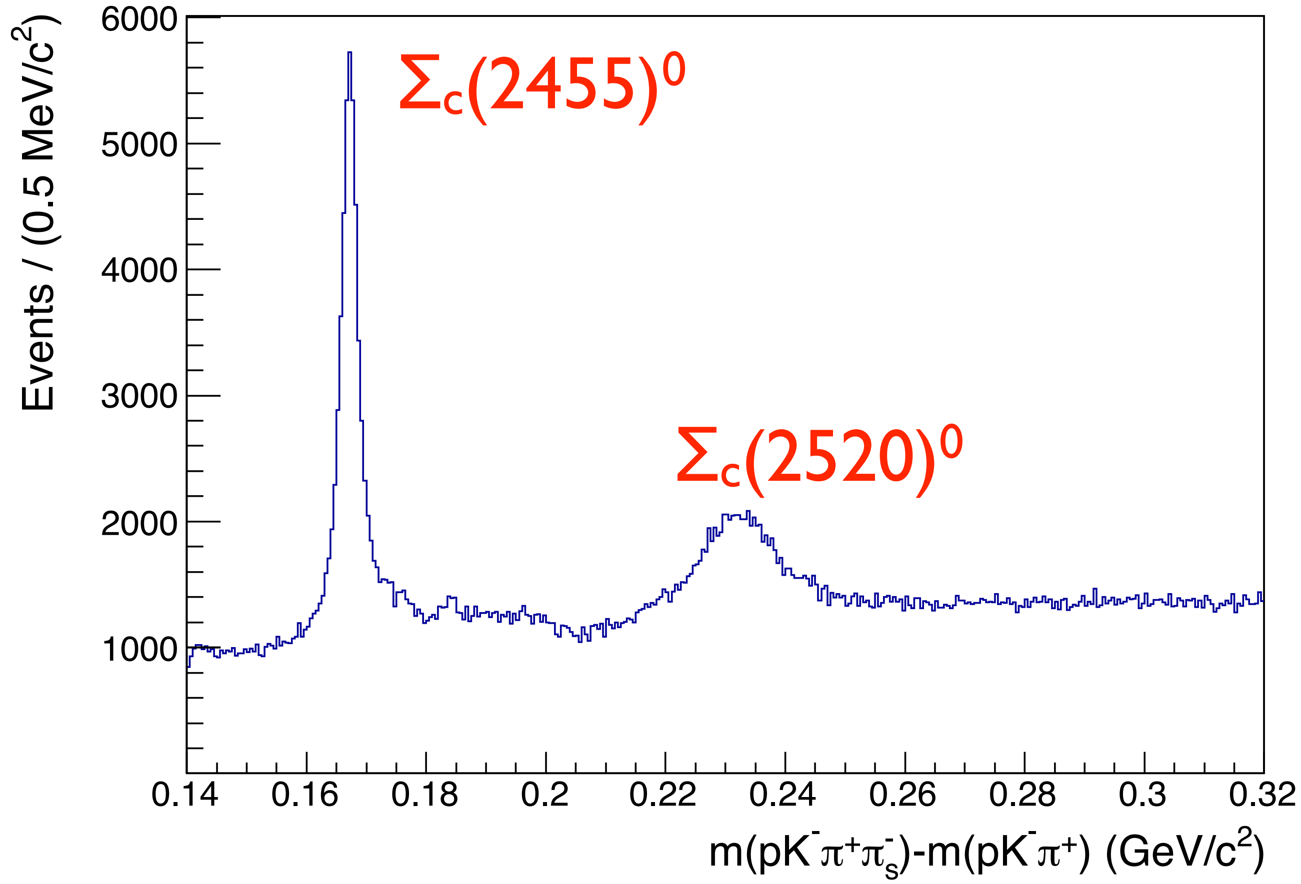
- Isospin mass splittings
  - Since u and d quarks have a bit different masses, their compositions may have different masses, therefore, one may expect that
    - $m(u) < m(d) \rightarrow m(\Sigma_c^{++})$ (uuc) $< m(\Sigma_c^{0})$ (ddc)
  - Experimental measurements show opposite results
    - $m(\Sigma_c(2455)^{++}) - m(\Sigma_c(2455)^{0}) = 0.24 \pm 0.09$ (PDG 2014)

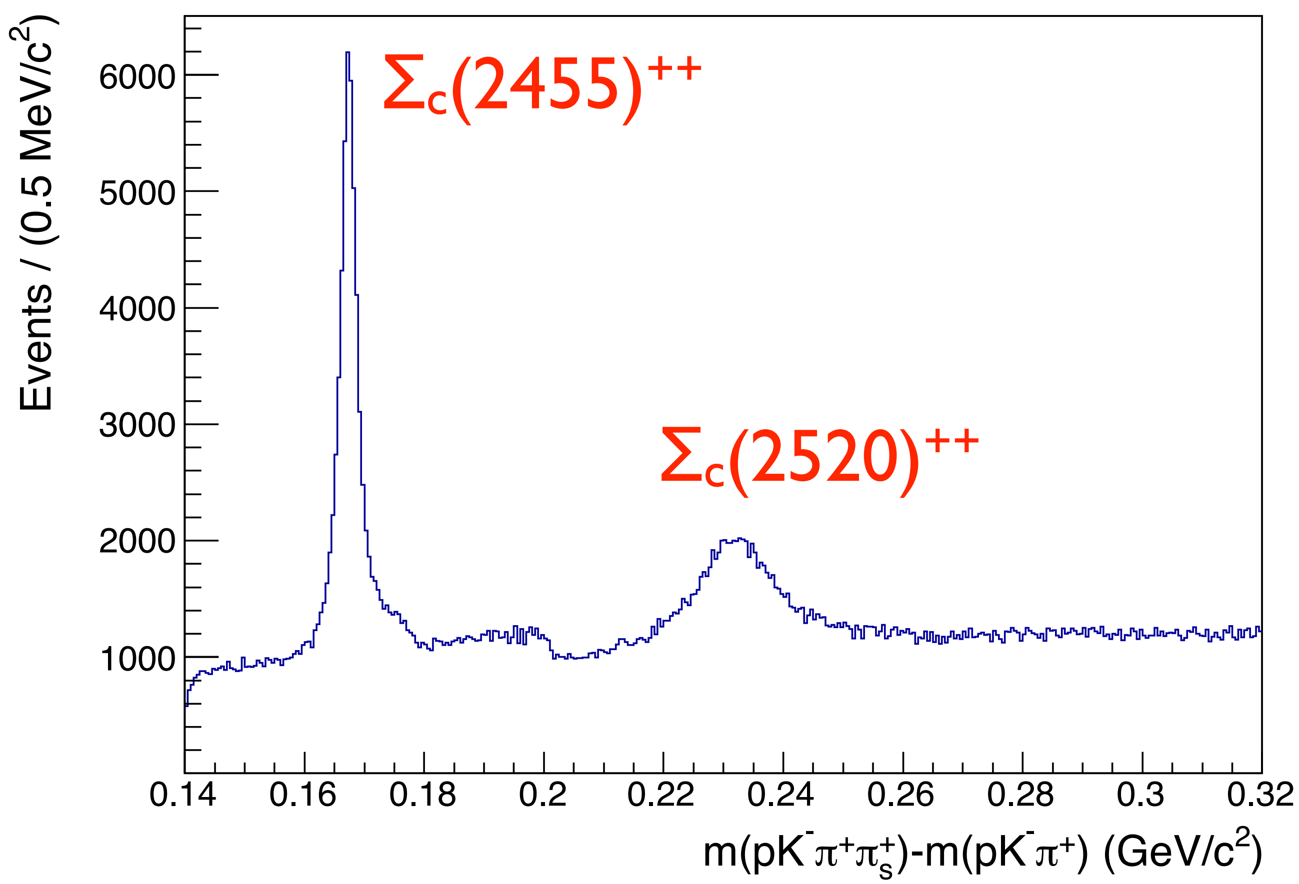
- Theoretical models calculate the mass splittings with considering various contributions
  - e.g. electromagnetic potential, hyperfine interaction, …
  - Precise measurements of the masses of Σ_c baryons will test the models

Theoretical Expectations	$m(\Sigma_c(2455)^{++}) - m(\Sigma_c(2455)^{0})$
Chan, *Phys. Rev. D* ***31****, 204* (1985)	0.18
Hwang and Lichtenberg, *Phys. Rev. D* ***35****, 3526* (1987)	3.0
Capstick, *Phys. Rev. D* ***36****, 2800* (1987)	1.4
Verma and Srivastava, *Phys. Rev. D* ***38****, 1623* (1988)	0.5
Cutkosky and Geiger, *Phys. Rev. D* ***48****, 1315* (1993)	0.84
Silvestre-Brac *et al.*, *J. Phys. G* ***29****, 2685* (2003)	0.27 ± 0.11
Guo *et al.*, *J. High Energy Phys.* ***09****, 136* (2008)	0.37

Data Samples and Backgrounds

- Belle data of 711 fb^{-1} taken at $\Upsilon(4S)$ used for the study
- Mass differences after event selections

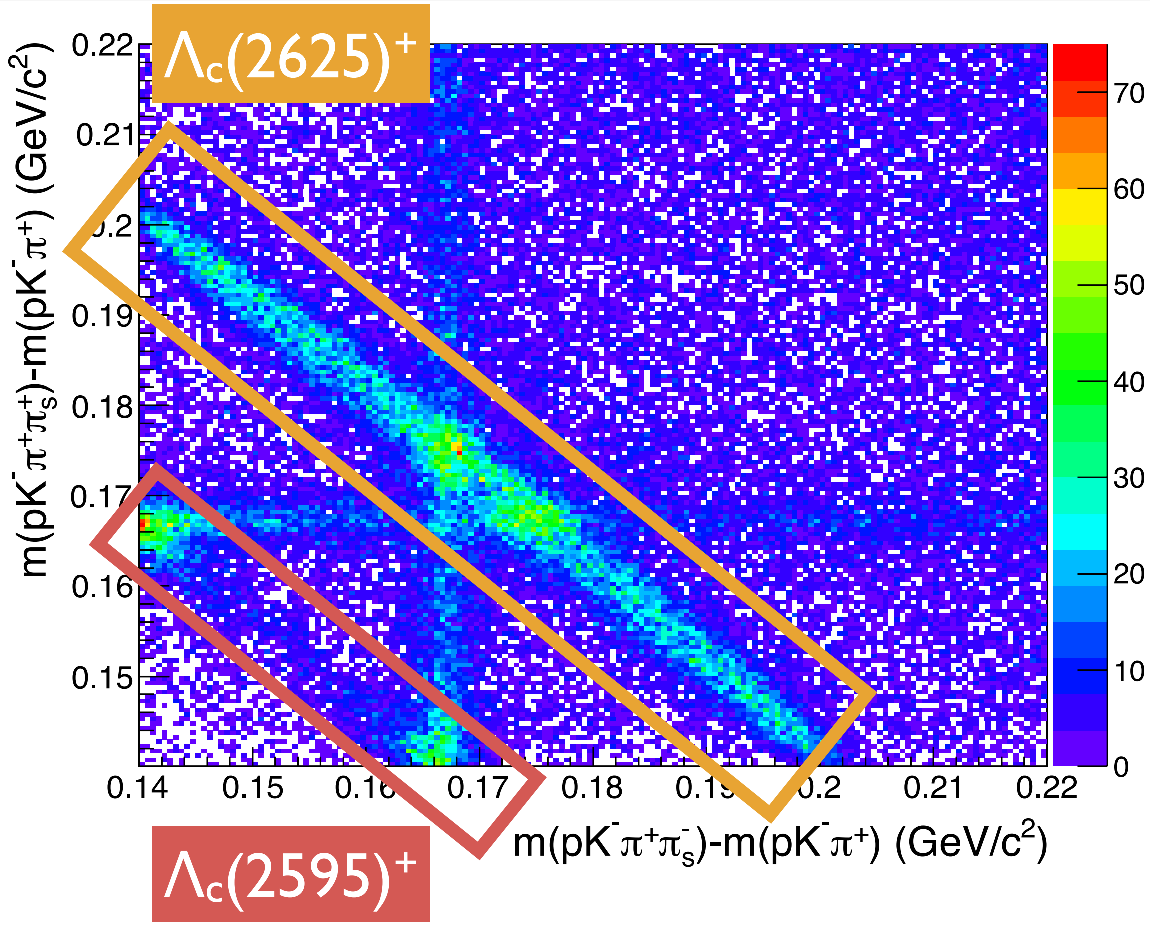


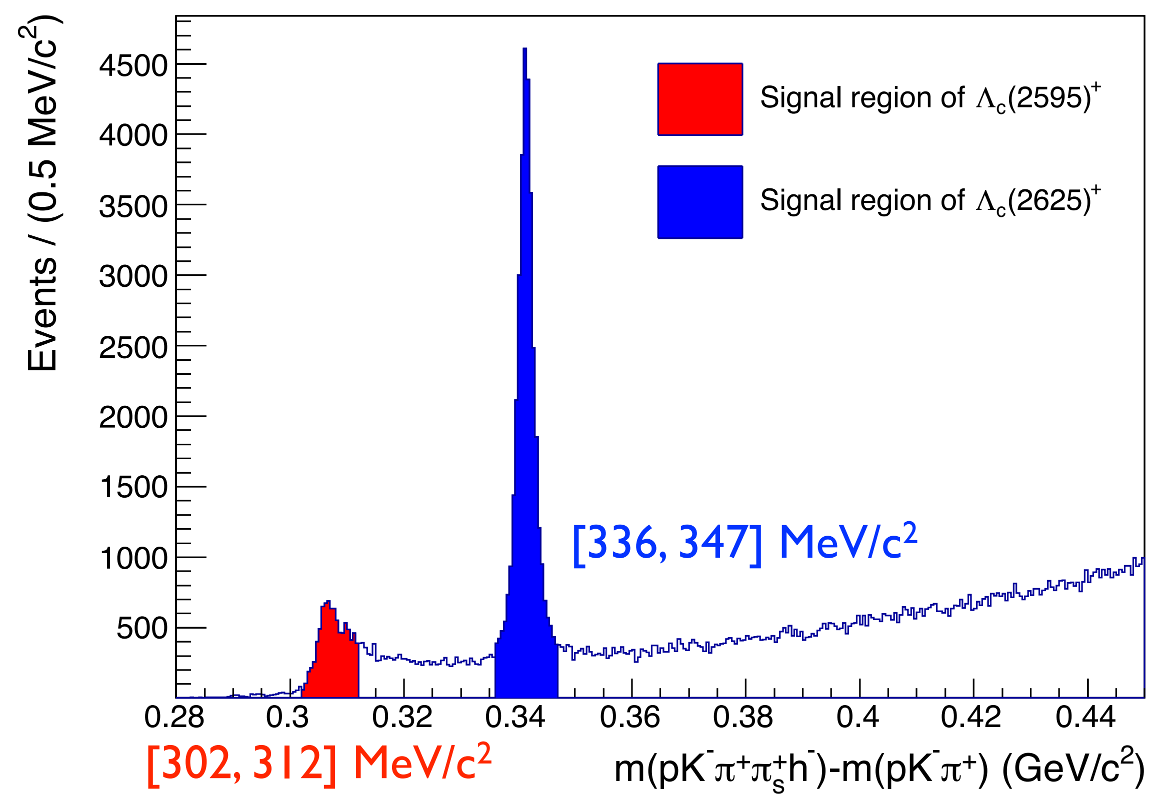


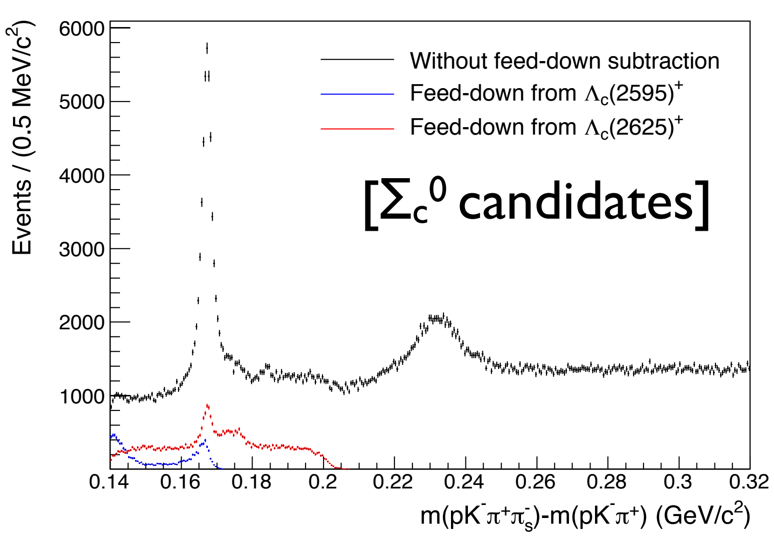
- Backgrounds are classified as:
  - Feed-down backgrounds from excited Λ_c^+ states
  - Reflection backgrounds from D^{*+} decays
  - Contribution from Ξ_c^0 decay
  - Random background due to wrong combinations

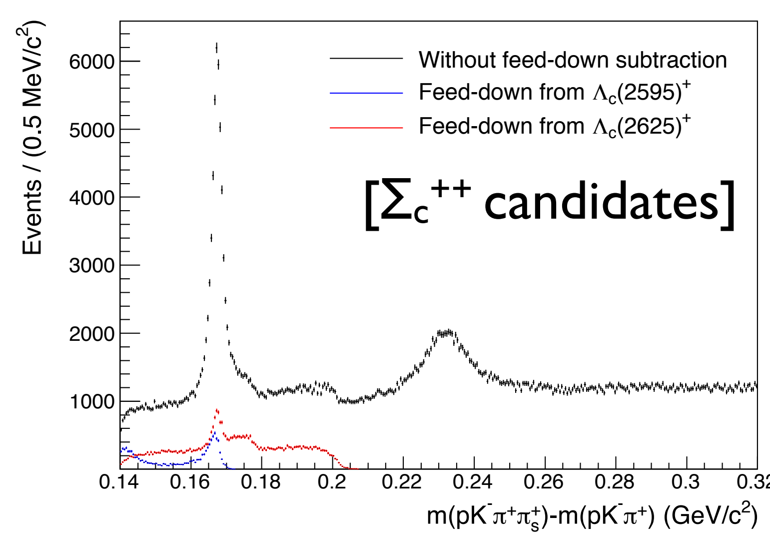
Feed-down Backgrounds from Λ_c^{*+} Decays

- Λ_c^{*+} decays can be either signal or background, e.g.:
  - $\Lambda_c^{*+} \to \Sigma_c^0 \pi^+$ is signal for Σ_c^0 measurement, but background for Σ_c^{++} measurement
- In order to extract the backgrounds, a tagging method is used
  - By appending an additional $h^{\pm}$, and test the mass with defined Λ_c^{*+} signal region, the candidates are tagged
- Obtained feed-down backgrounds are corrected with detection efficiency of the additional charged hadrons as a function of their momenta









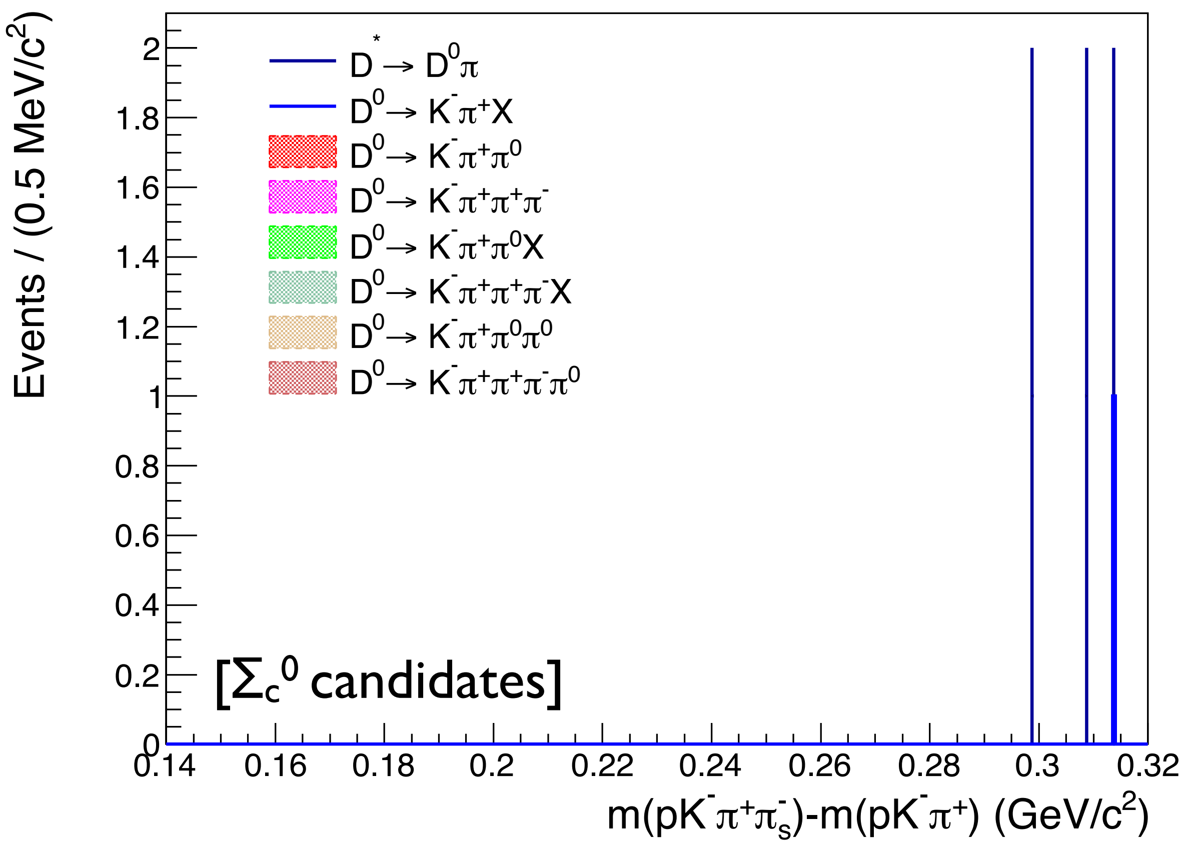
Reflection Backgrounds from D^{*+} Decays

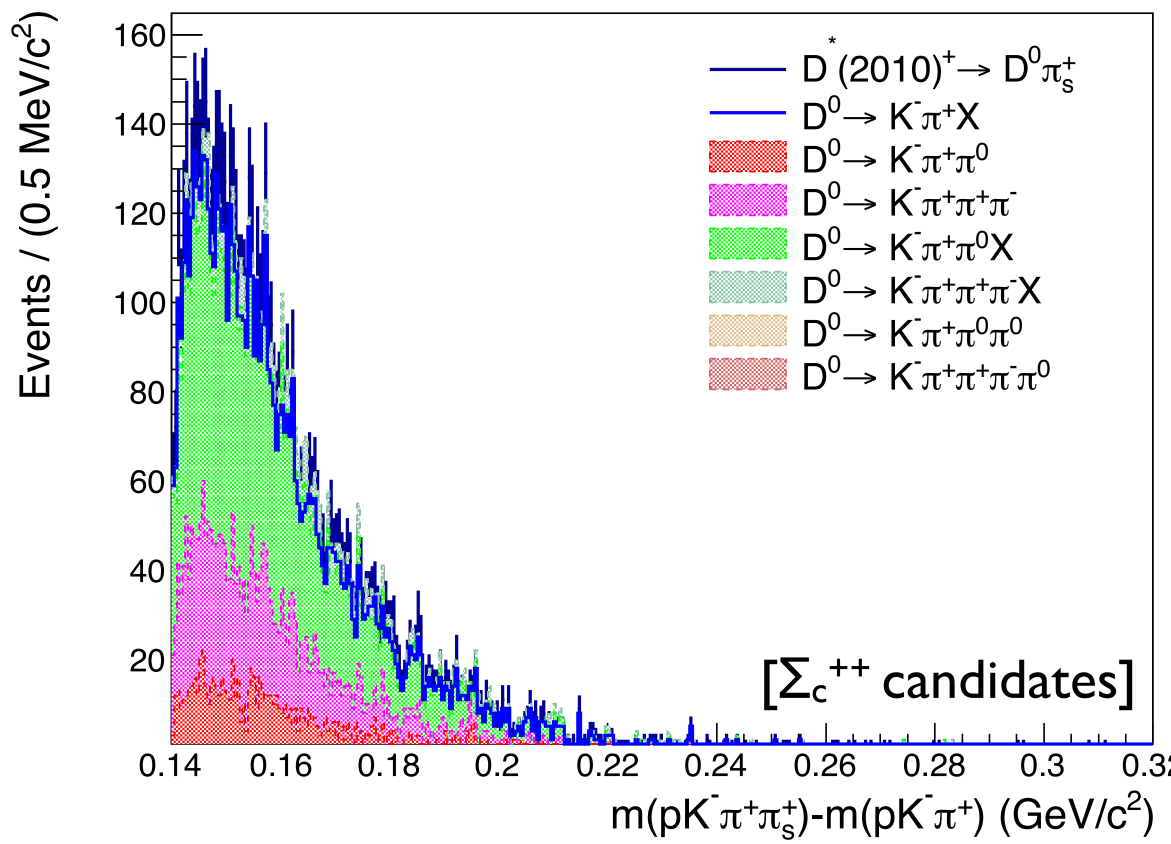
- D^{*+} decays may contribute as a background source
  - e.g. $D^{*+} \to D^0 \pi_s^+$ with $D^0 \to K^- \pi^+ \pi^+ \pi^-$

  Background contribution of $pK^-\pi^+\pi_s^+$ is possible

  random p

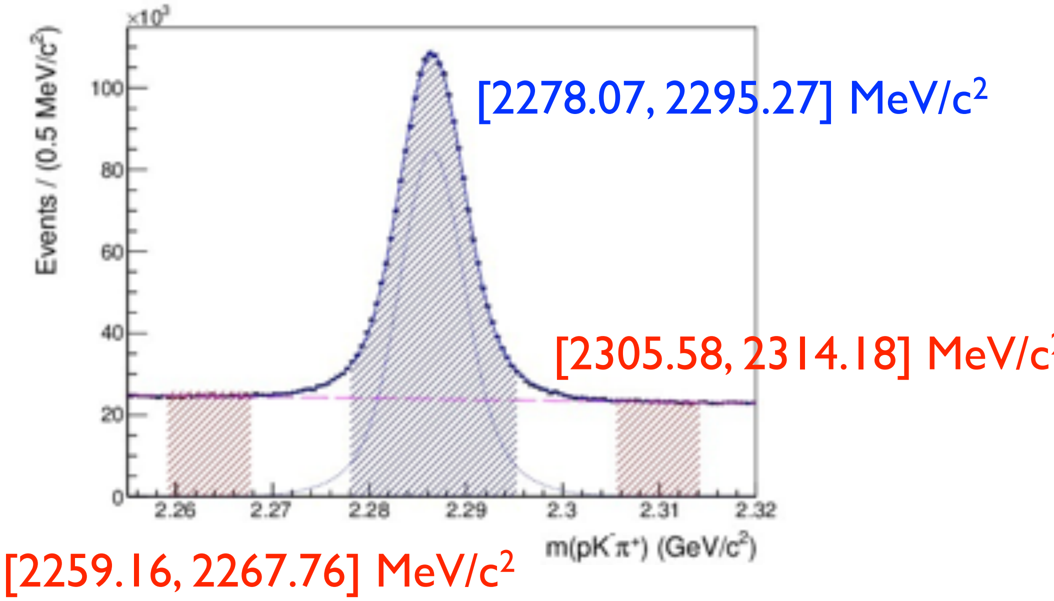
- The background contribution from D^{*+} decays are confirmed with MC
  - It appears only in $m(pK^-\pi^+\pi^+)-m(pK^-\pi^+)$

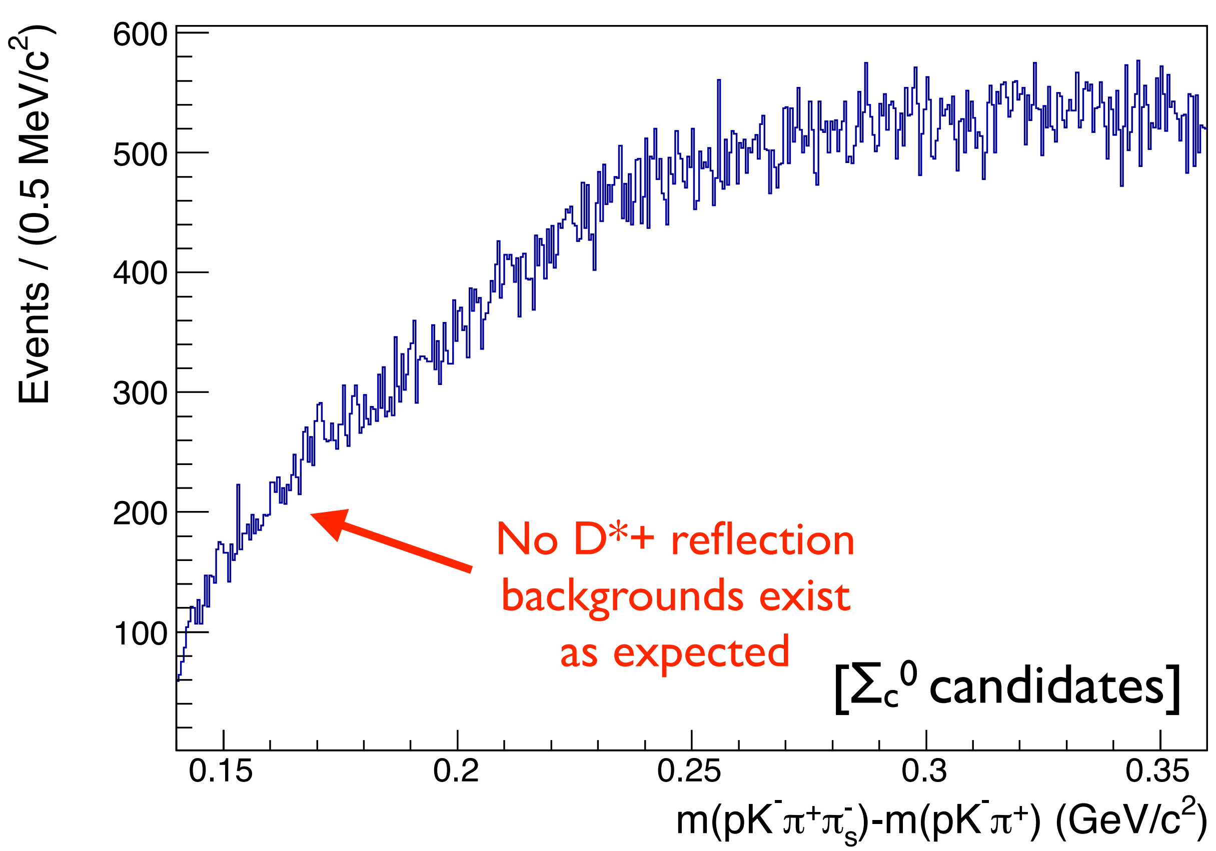


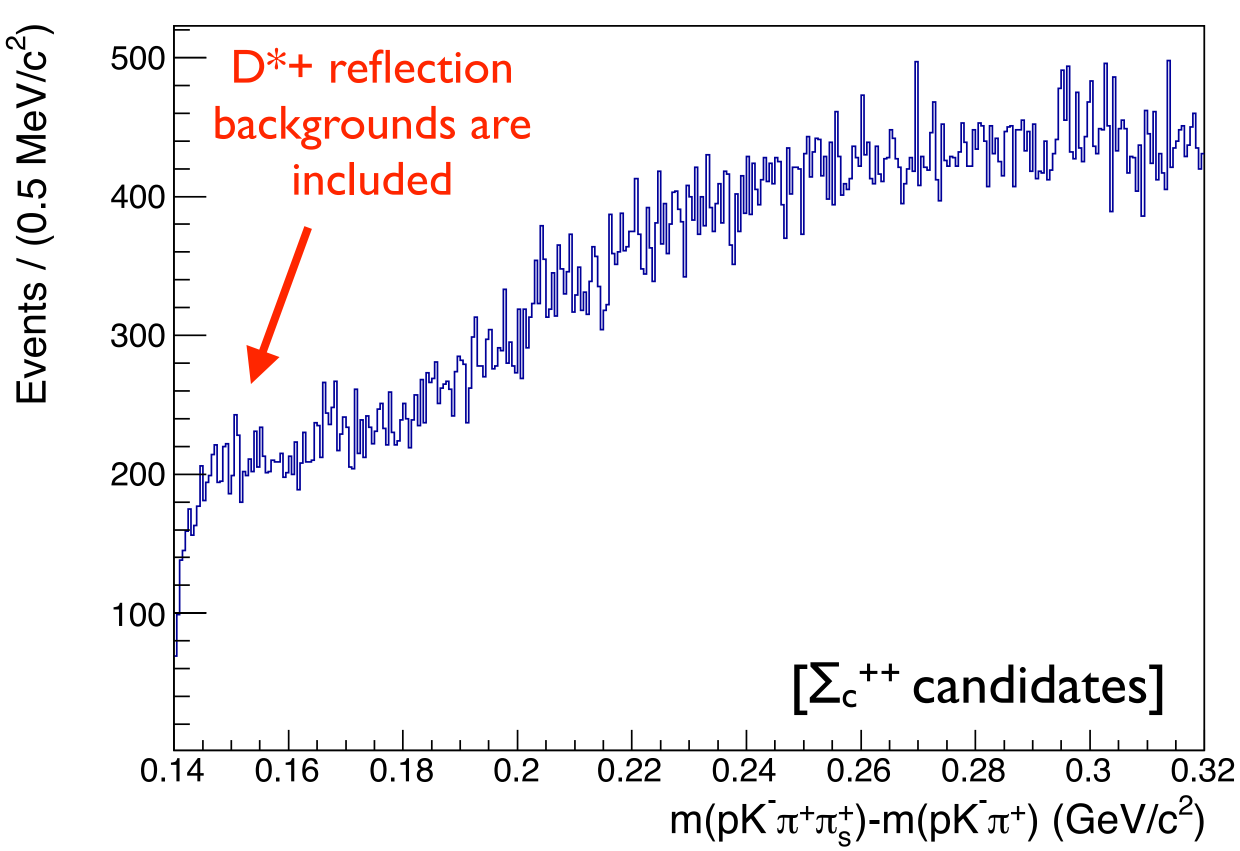


Random Backgrounds

- Random backgrounds are classified by true and fake Λ_c^+
  - Associated with fake Λ_c^+: Extractable by using Λ_c^+ sideband (sideband subtraction)
  - Since the reflection backgrounds from D^{*+} decays is also a random background associated with fake Λ_c^+, it appears here as well → no explicit description of the reflection background needed





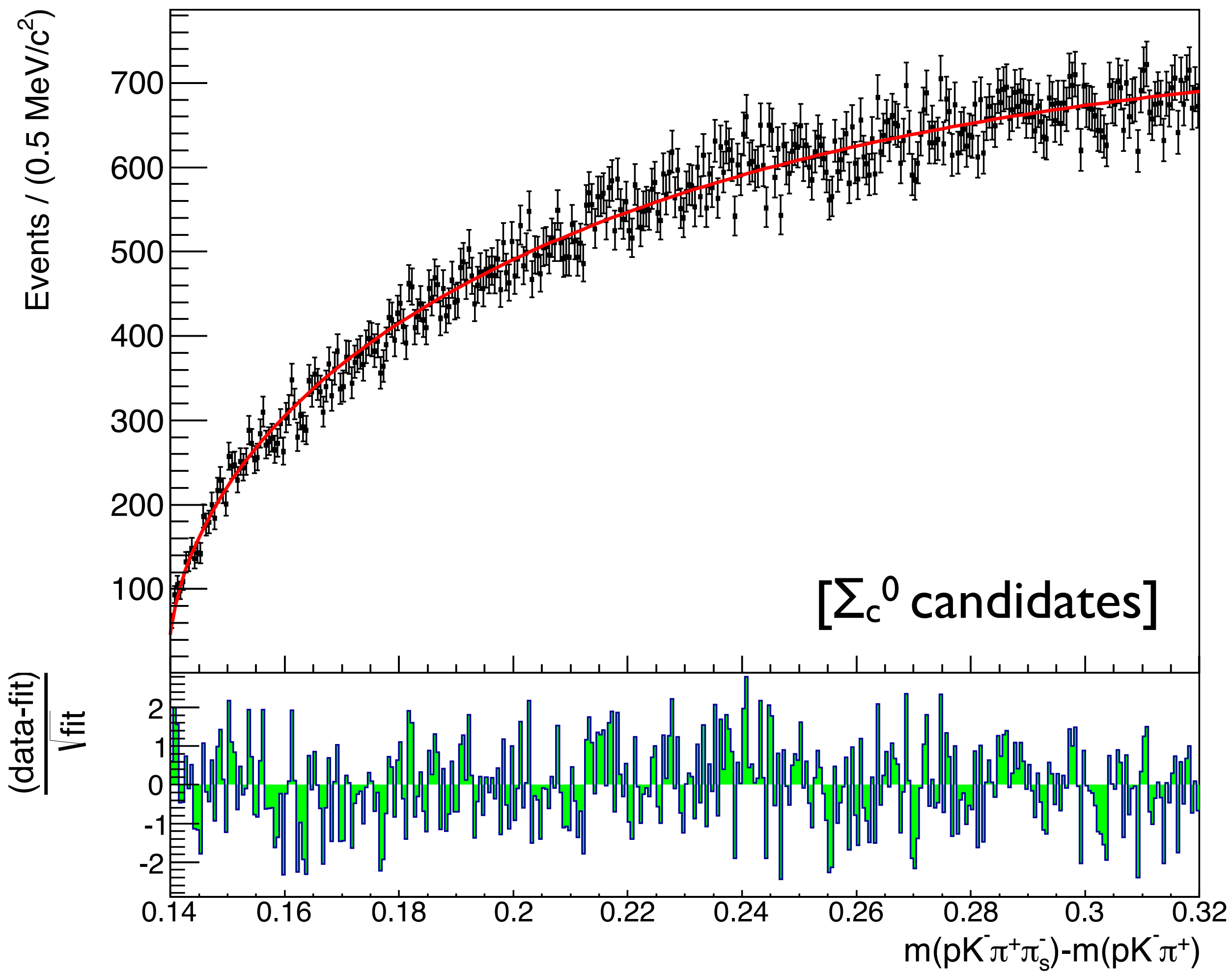


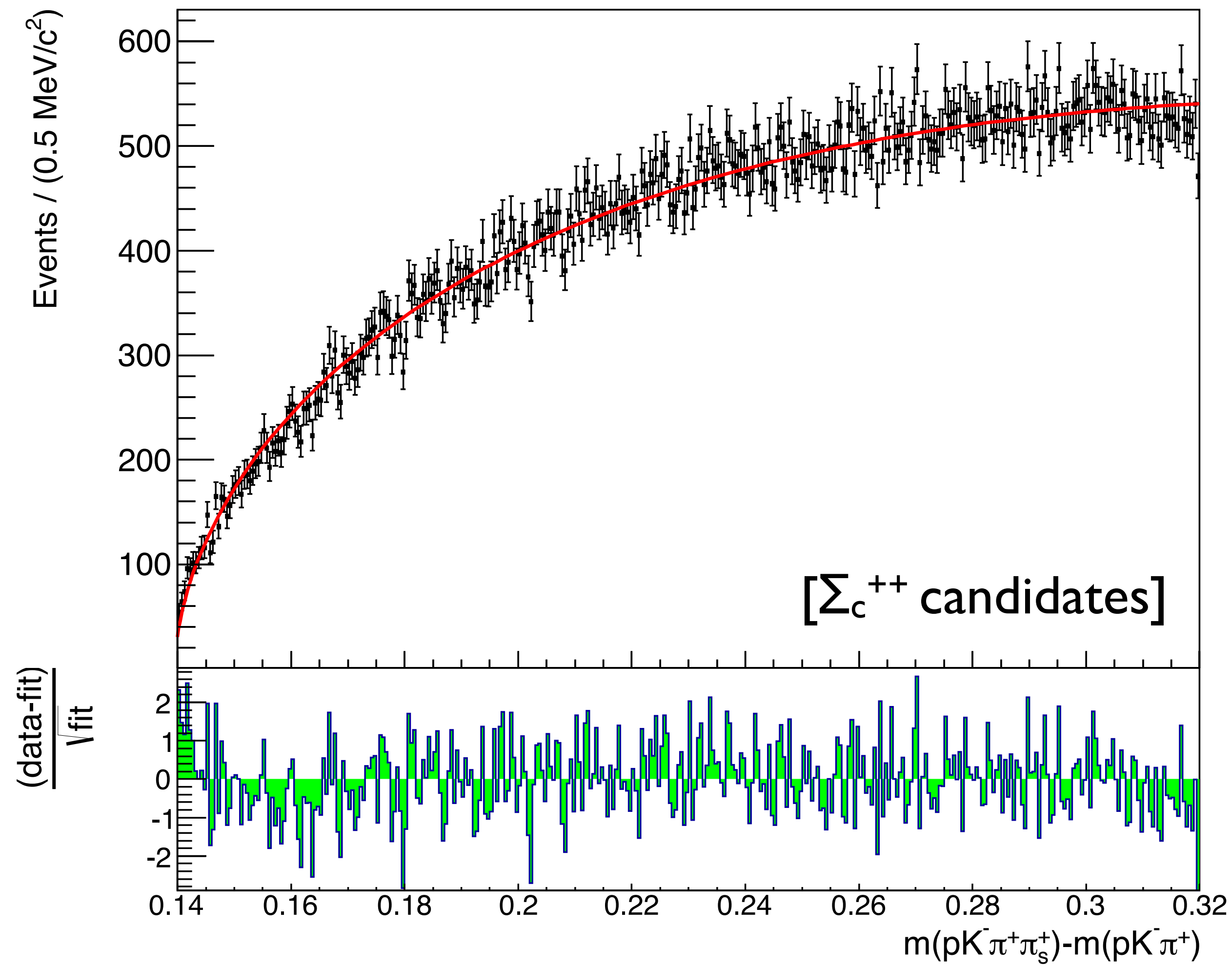
Random Backgrounds

- Random backgrounds are classified by true and fake Λ_c^+
  - Associated with true Λ_c^+: No way to extract from data
  - Modeled with:

$$(\Delta m - m_\pi)^{c_0} e^{-c_1(\Delta m - m_\pi)}$$

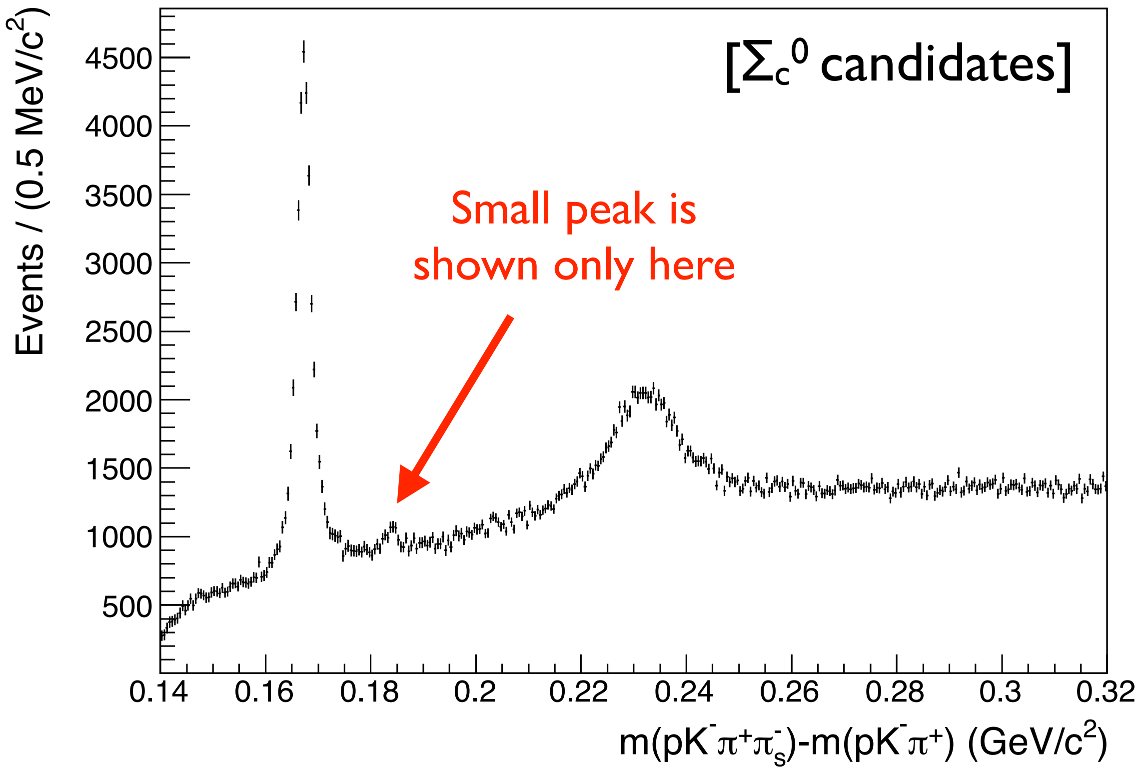
  - The modeling is confirmed by fitting to MC samples

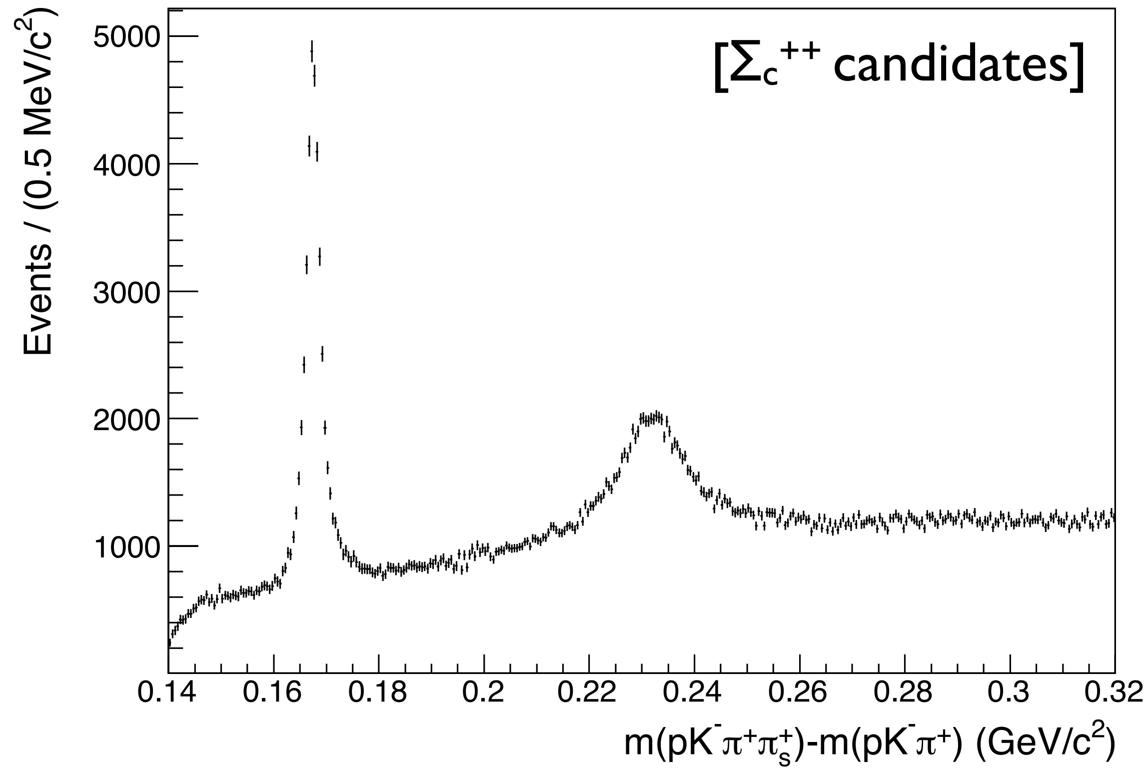




Contribution from Ξ_c^0 Decays

- Small peak is found in $m(pK^-\pi^+\pi^-)-m(pK^-\pi^+)$

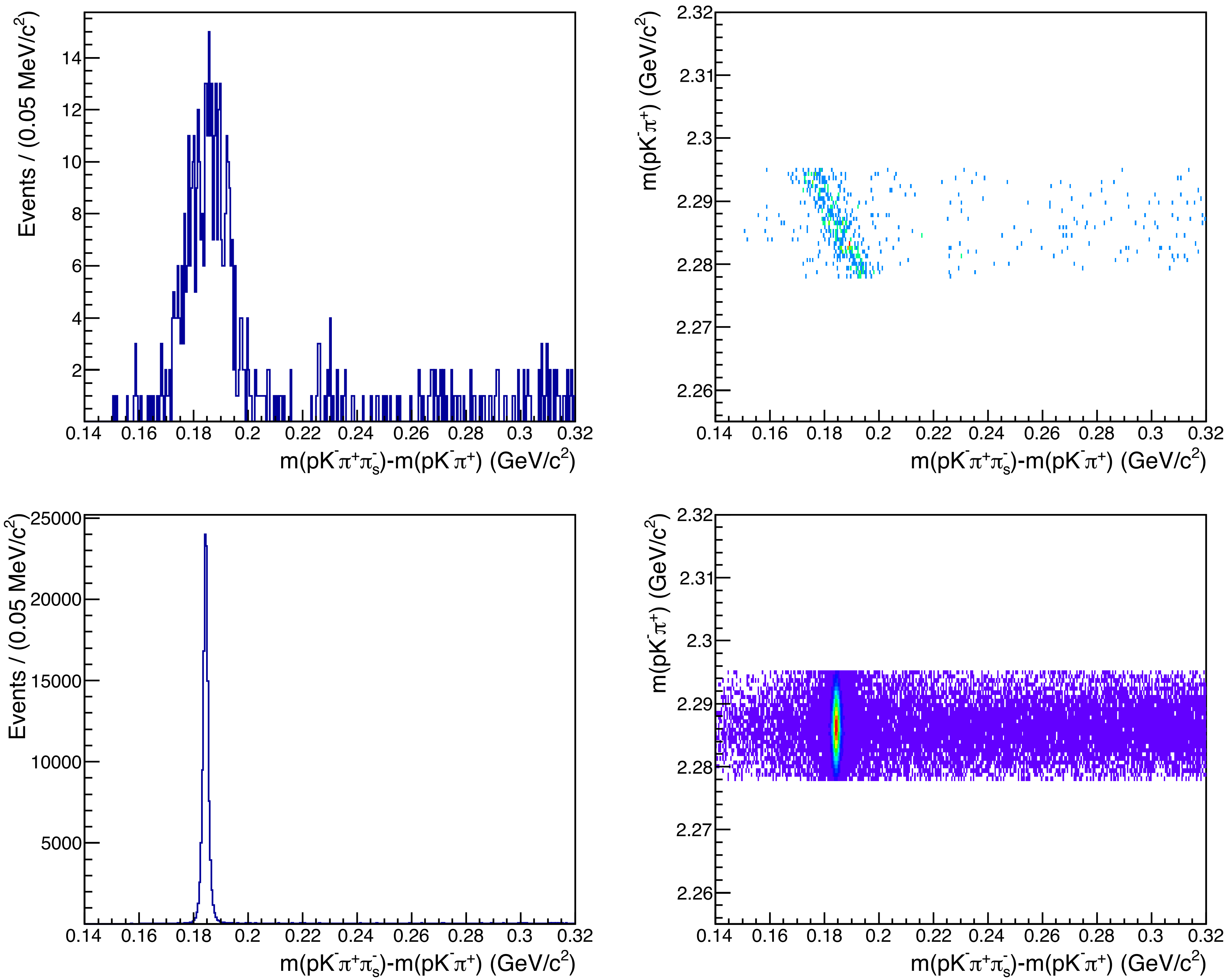




- The peak position is ~185 MeV/c^2
  - If a nominal mass of Λ_c^+ is added, it is compatible with Ξ_c^0 mass
    - m(peak) + m(Λ_c^+) = 185 + 2286.46 (PDG 2013) = 2471.46 MeV/c^2
    - m(Ξ_c^0) = 2470.88 (PDG 2013)
- Because of the charge conservation, it makes a sense that the peak only appears in the neutral mode (there is no Ξ_c^{++})

Contribution from Ξ_c^0 Decays

- From MC and data, this background contribution is confirmed
  - $\Xi_c^0 \to \Lambda_c^+ \pi^-$ is dominant, $\Xi_c^0 \to pK^-\pi^+\pi^-$ is negligible



$\Xi_c^0 \to pK^-\pi^+\pi^-$ MC simulation (1M events are generated)

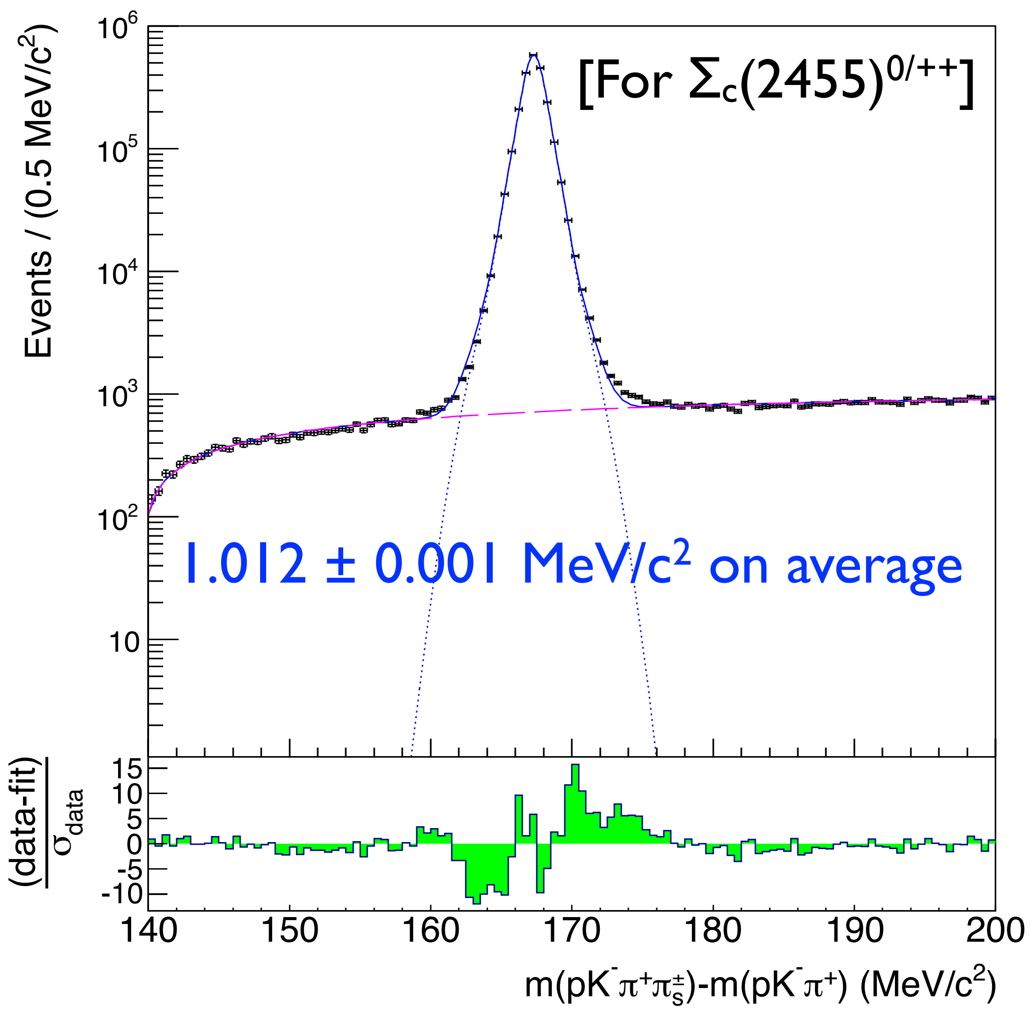
$\Xi_c^0 \to \Lambda_c^+\pi^-$ MC simulation (1M events are generated)

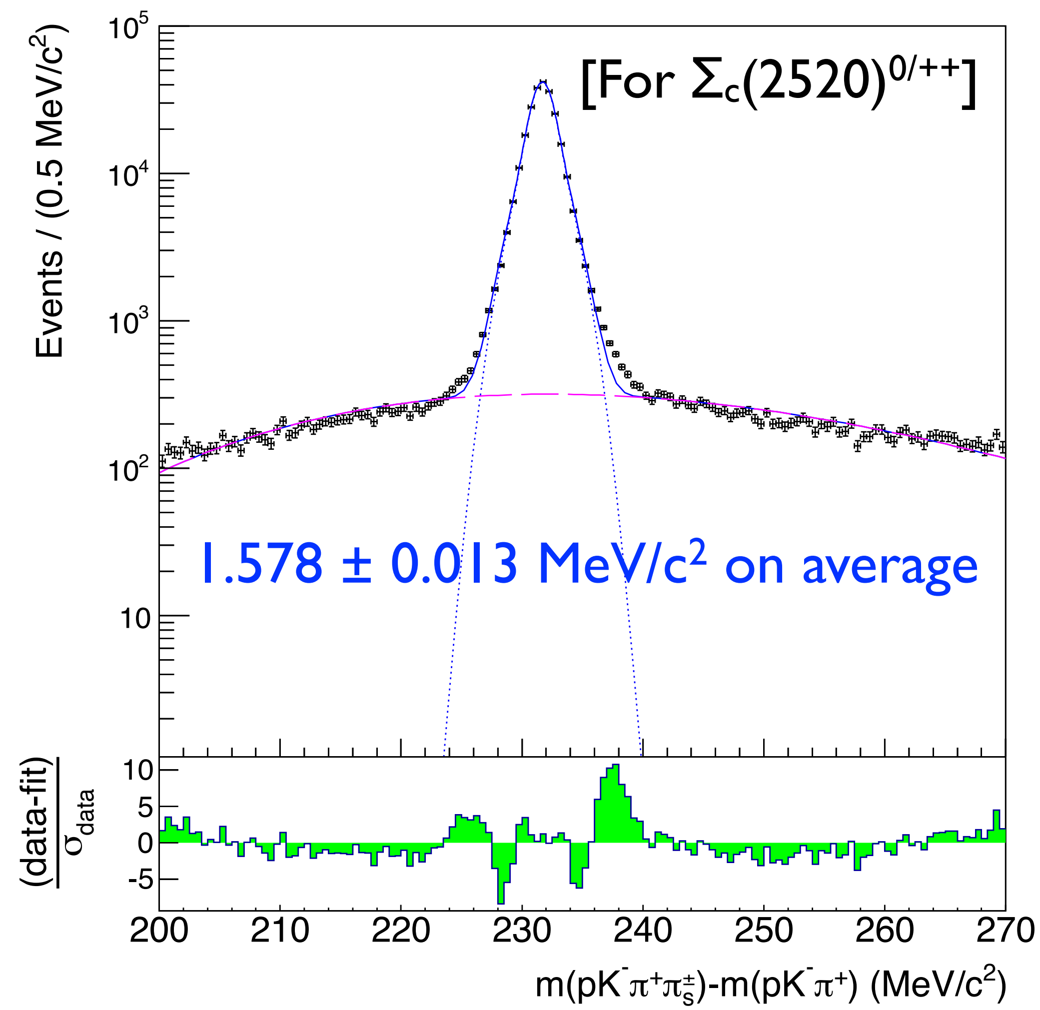
Fit Procedure

- Because of the finite decay width, it should be considered with a detector resolution simultaneously by the convolution theorem

$$M(m;m_0,\Gamma) = T(m;m_0,\Gamma) \otimes R(m)$$
$$= \int_{-\infty}^{+\infty} T(m;m_0,\Gamma)R(m-m')dm'$$

- Detector response functions are obtained from MC with no Σ_c widths

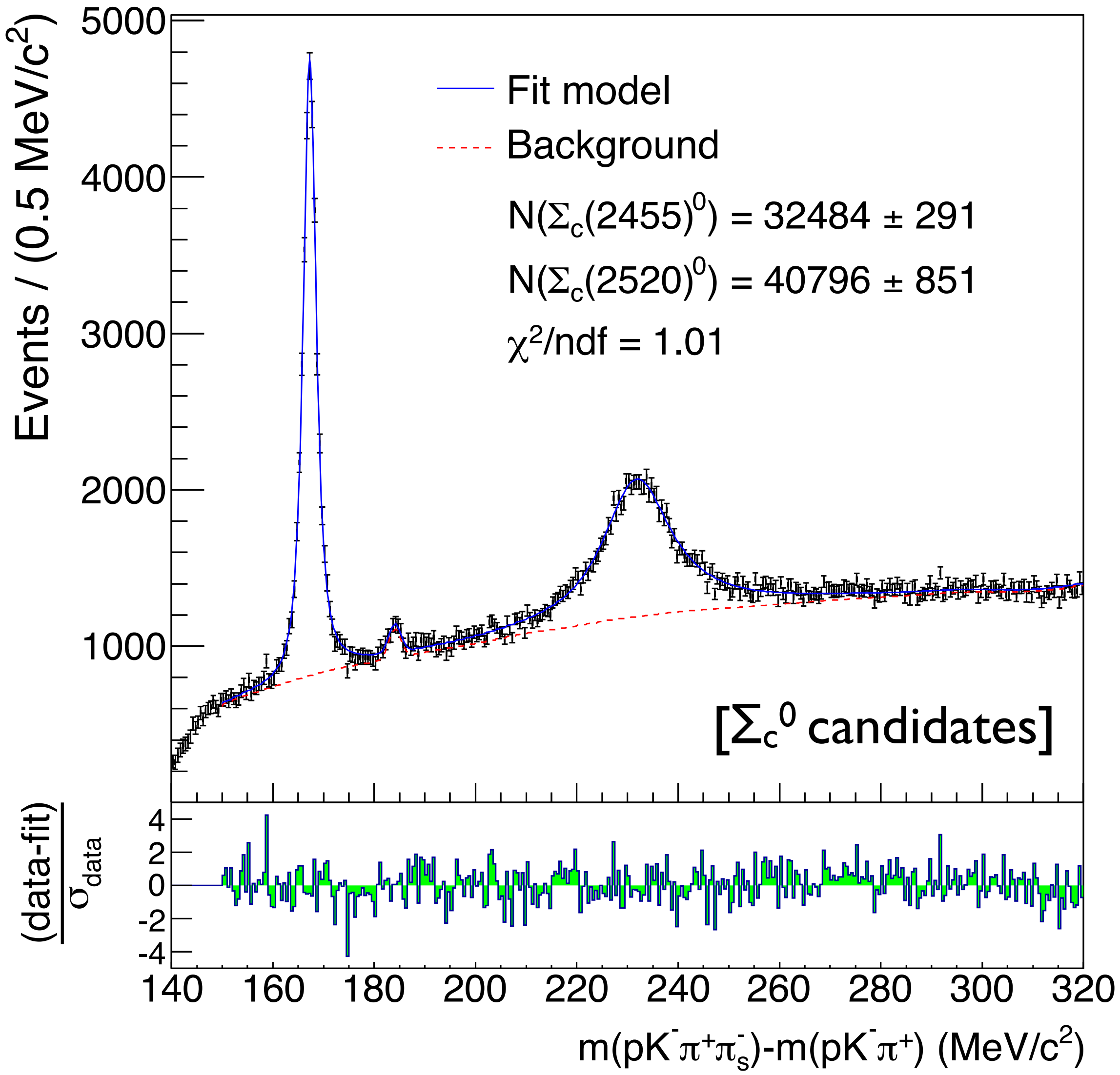


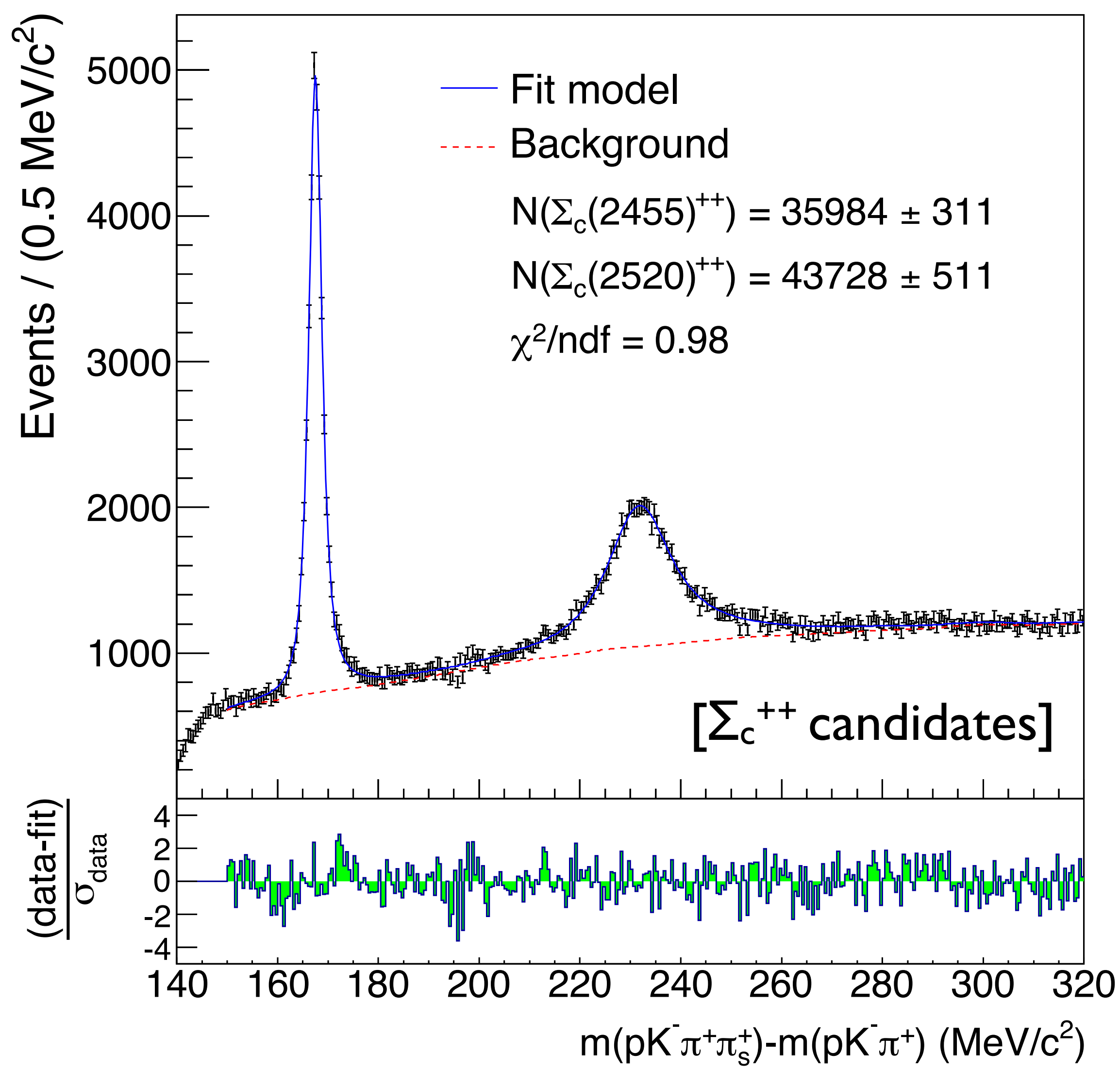


Results

- Binned ML fit done with necessary components

(Ξ_c^0 contribution is modeled by a Gaussian; mean=184.08 ± 0.15, width=1.21 ± 0.18 in MeV/c^2)





(MeV/c^2)	$\Sigma_c(2455)^0$	$\Sigma_c(2455)^{++}$	$\Sigma_c(2520)^0$	$\Sigma_c(2520)^{++}$
$m(\Sigma_c)-m(\Lambda_c^+)$	167.29 ± 0.01	167.51 ± 0.01	231.98 ± 0.11	231.99 ± 0.10
Decay Widths	1.76 ± 0.04	1.84 ± 0.04	15.41 ± 0.41	14.77 ± 0.25
$m(\Sigma_c)$*	2453.75 ± 0.01	2453.97 ± 0.01	2518.44 ± 0.11	2518.45 ± 0.10

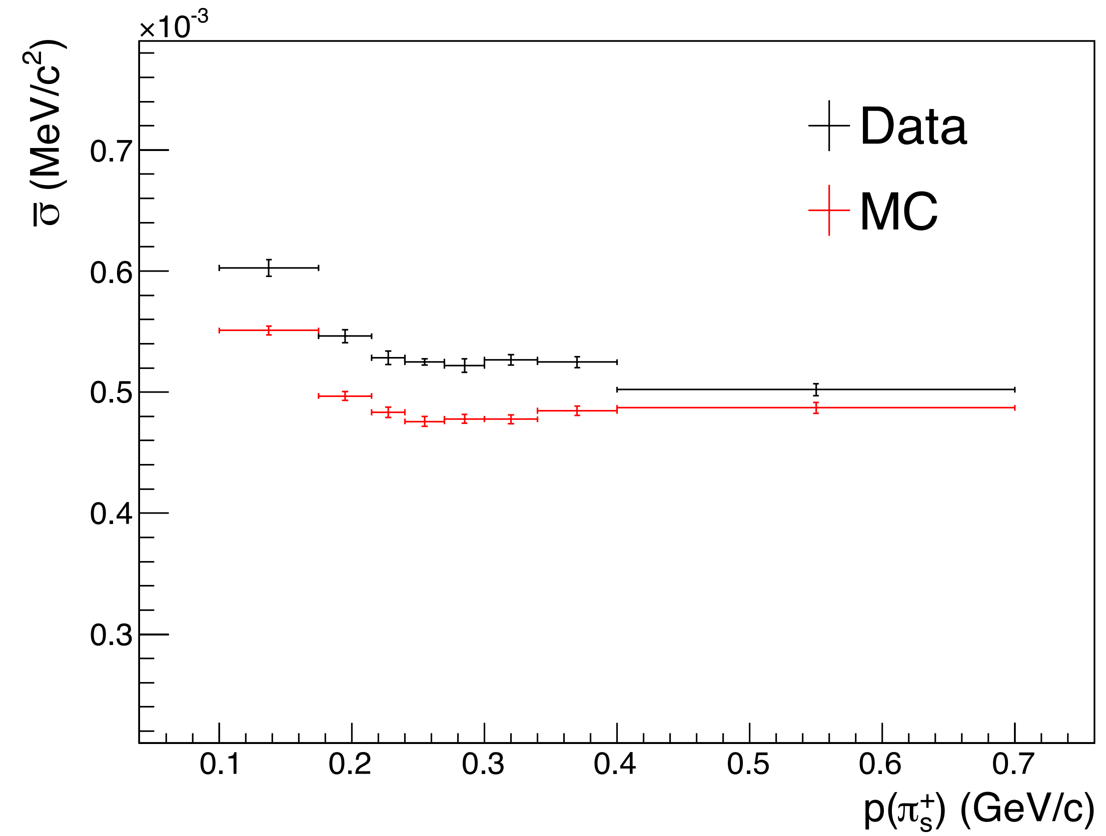
* Mass is calculated by adding a nominal Λ_c^+ mass to $m(\Sigma_c)-m(\Lambda_c^+)$

Systematic Uncertainties

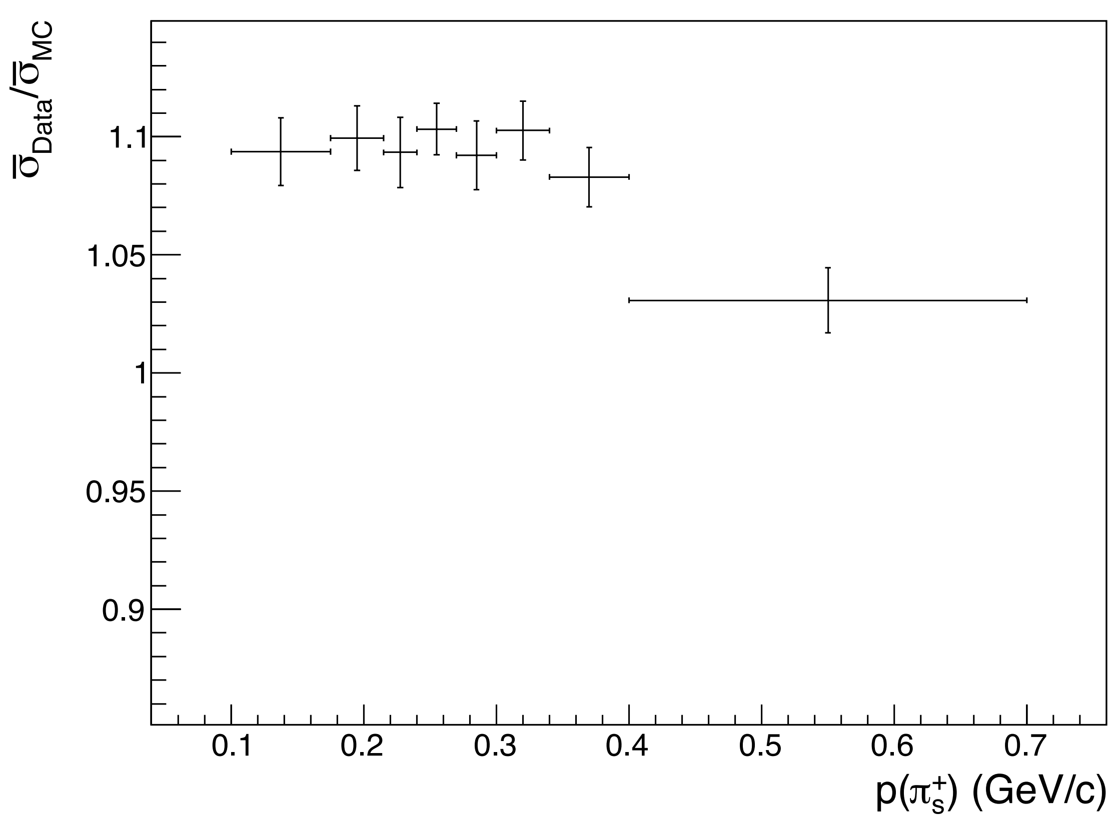
- Major contributions of the systematic uncertainties:
  - Resolution model
    - Discrepancy between data and MC
    - Statistical fluctuation of the resolution model
  - Momentum scale
  - Fit model
    - Bias by the fitter
    - Binning effect
    - Effect of the fit ranges
  - Background model
    - Feed-down correction
    - Statistical fluctuation of the random backgrounds with fake Λ_c^+
    - Various modeling of the random background with true Λ_c^+

Systematics: Resolution Model

- Discrepancy between data and MC
  - Studied by using a control sample, $D^{*+} \to D^0 \pi_s^+$
  - By comparing the resolution of $m(D^{*+})$-$m(D^0)$ between data and MC, a (single-sided) systematic uncertainties are assigned for the decay widths
    - -0.19 MeV/c^2 for $\Gamma(\Sigma_c(2455)^{0/++})$
    - -0.25 MeV/c^2 for $\Gamma(\Sigma_c(2520)^0)$
    - -0.24 MeV/c^2 for $\Gamma(\Sigma_c(2520)^{++})$

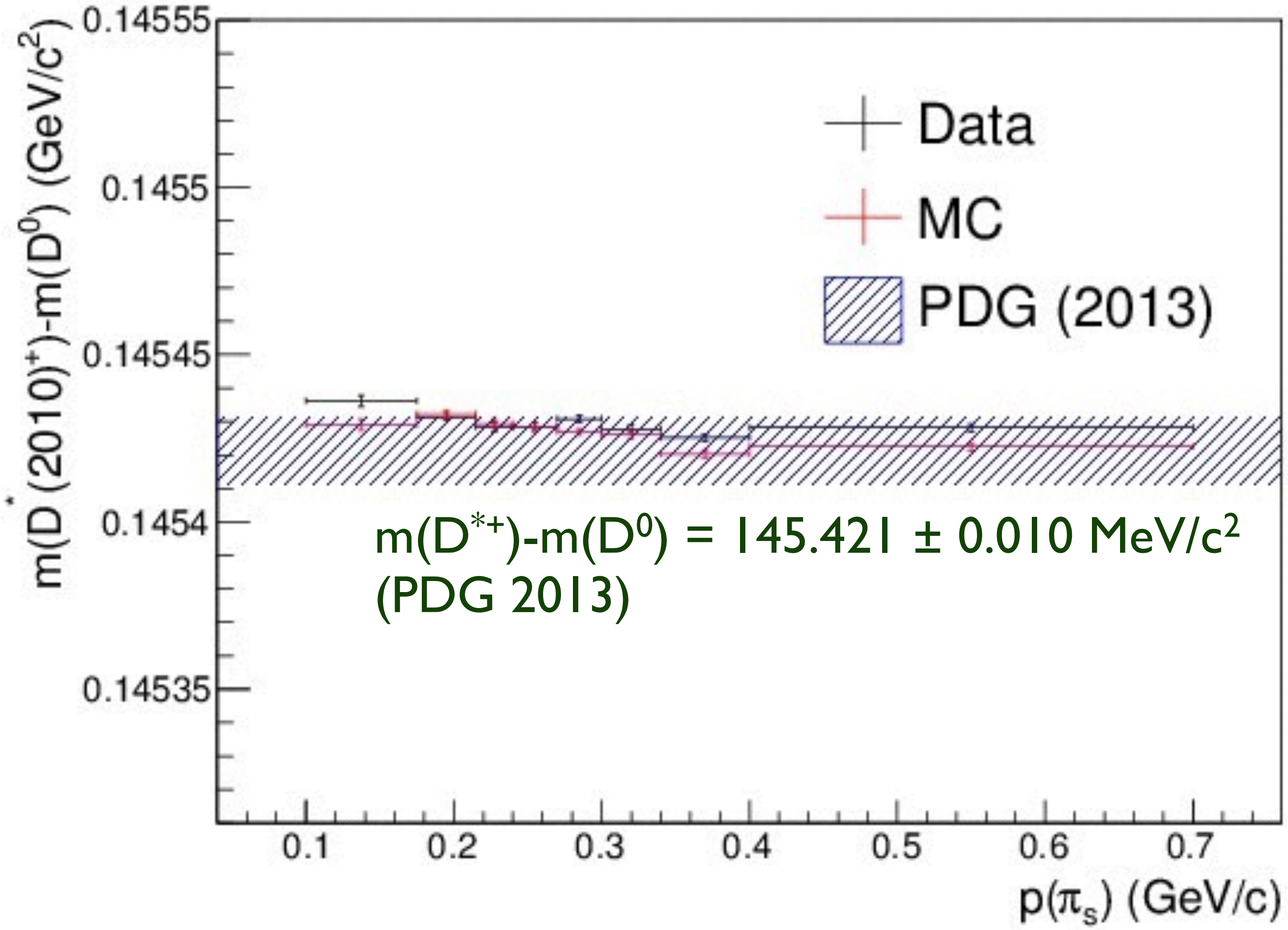


- Statistical fluctuation of the resolutions by ±1σ
  - Small uncertainties are found for the decay widths
    - 0.01 and 0.04 MeV/c^2 for $\Gamma(\Sigma_c(2455)^{0/++})$ and $\Gamma(\Sigma_c(2520)^{0/++})$, respectively



Systematics: Momentum Scale

- Possible bias in the measurements of charged particle momenta
  - Wrong momentum scale of the detector
  - The effect is studied with the control sample of D^{*+} decay
  - By comparing $m(D^{*+})$-$m(D^0)$ with the world average, the uncertainty is assigned to be 0.02 MeV/c^2 for the mass difference



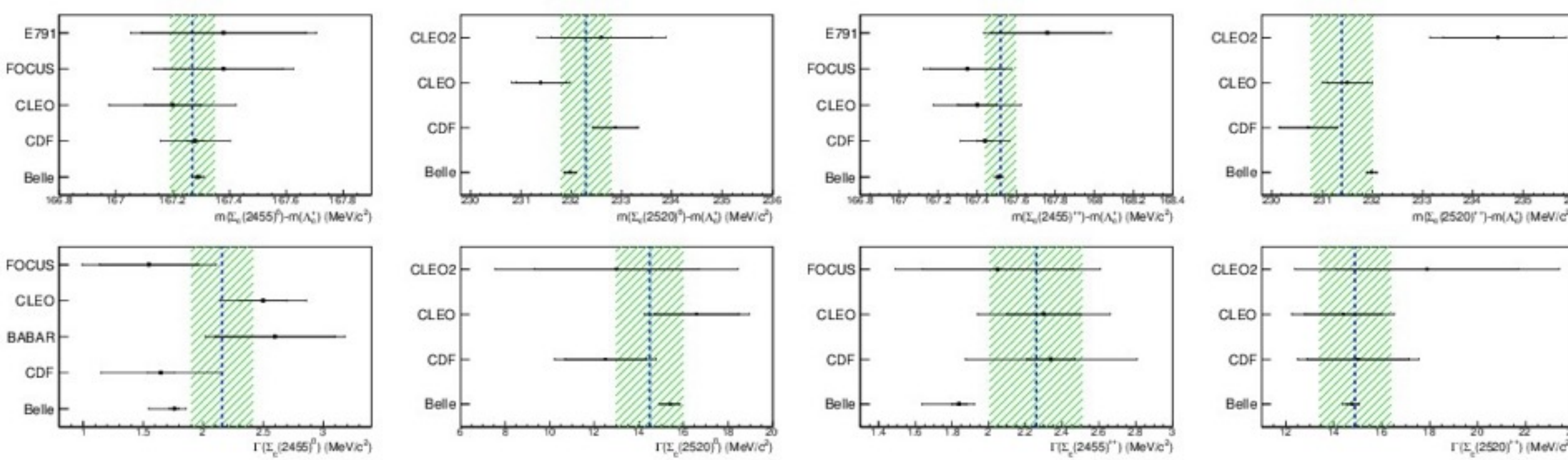
Systematic Uncertainties

- Major contributions of the systematic uncertainties:
  - Resolution model
    - Discrepancy between data and MC
    - Statistical fluctuation of the resolution model
  - Momentum scale
  - Fit model
    - Bias by the fitter
    - Binning effect
    - Effect of the fit ranges
  - ~~Background model~~ (all negligible)
    - ~~Feed-down correction~~
    - ~~Statistical fluctuation of the random backgrounds with fake Λ_c^+~~
    - ~~Various modeling of the random background with true Λ_c^+~~

(MeV/c^2)	$\Sigma_c(2455)^0$		$\Sigma_c(2455)^{++}$		$\Sigma_c(2520)^0$		$\Sigma_c(2520)^{++}$	
	Δm	Γ	Δm	Γ	Δm	Γ	Δm	Γ
Resolution model	—	$^{+0.01}_{-0.19}$	—	$^{+0.01}_{-0.19}$	—	$^{+0.01}_{-0.19}$	—	$^{+0.01}_{-0.19}$
Momentum scale	± 0.02	—	± 0.02	—	± 0.02	—	± 0.02	—
Fit model	± 0.01	± 0.09	± 0.03	± 0.20	± 0.01	± 0.07	± 0.01	± 0.18
Total	± 0.02	$^{+0.09}_{-0.21}$	± 0.04	$^{+0.20}_{-0.32}$	± 0.02	$^{+0.07}_{-0.20}$	± 0.02	$^{+0.18}_{-0.30}$

- The results are the most precise to date
  - $m(\Sigma_c)$'s are calculated by adding a nominal Λ_c^+ mass to the mass difference
    - The most systematic uncertainties cancels (e.g. momentum scale)

(MeV/c^2)	$m(\Sigma_c)-m(\Lambda_c^+)$	Decay widths (Γ)	$m(\Sigma_c)$
$\Sigma_c(2455)^0$	$167.29 \pm 0.01 \pm 0.02$	$1.76 \pm 0.04\ ^{+0.09}_{-0.21}$	$2453.75 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2455)^{++}$	$167.51 \pm 0.01 \pm 0.02$	$1.84 \pm 0.04\ ^{+0.07}_{-0.20}$	$2453.97 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2520)^0$	$231.98 \pm 0.11 \pm 0.04$	$15.41 \pm 0.41\ ^{+0.20}_{-0.32}$	$2518.44 \pm 0.11 \pm 0.04 \pm 0.14$
$\Sigma_c(2520)^{++}$	$231.99 \pm 0.10 \pm 0.02$	$14.77 \pm 0.25\ ^{+0.18}_{-0.30}$	$2518.45 \pm 0.10 \pm 0.02 \pm 0.14$



Summary

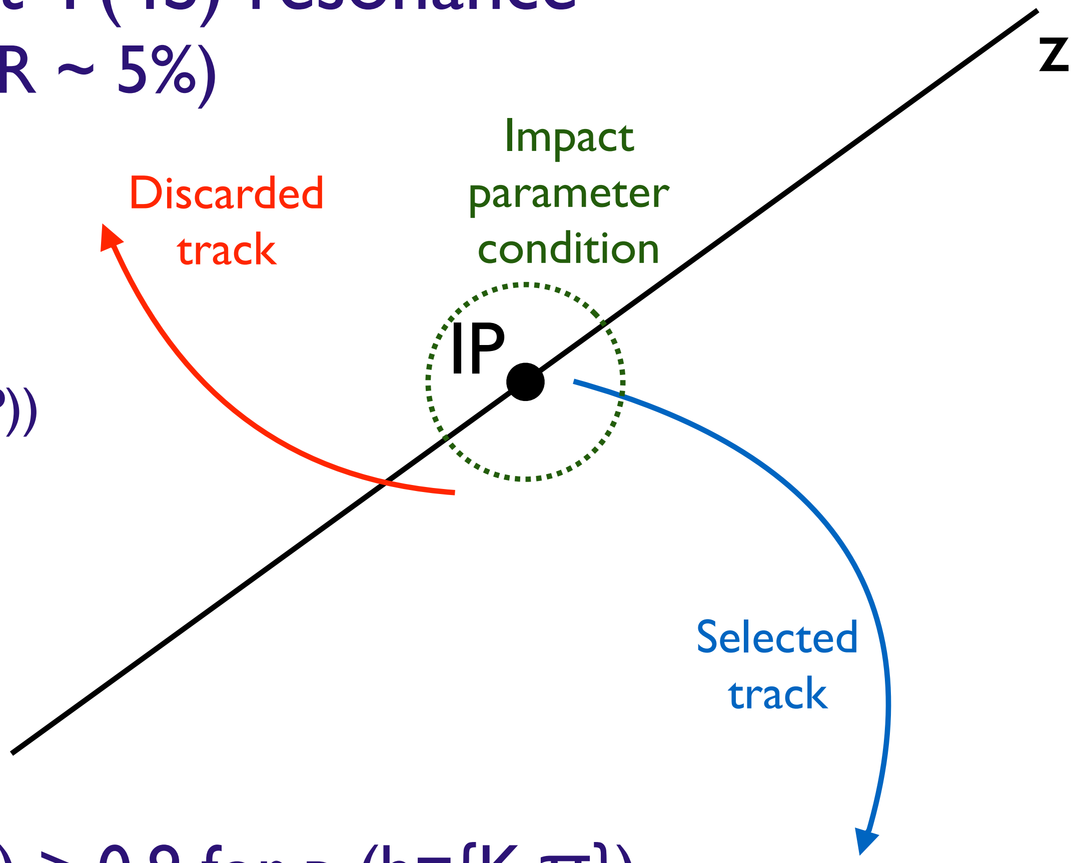
- Charmed baryons are an interesting testbed to test QCD models
  - Properties of Σ_c baryons are not well established
  - Isospin mass splitting contradicts a naive expectation
  - Precise measurements will be helpful to develop theoretical models

- Measurements of masses and decay widths of the $\Sigma_c(2455)^{0/++}$ and $\Sigma_c(2520)^{0/++}$ baryons have been performed at Belle
  - Various sources of the backgrounds are analyzed
  - Systematic uncertainties reduces significantly
  - The results are most precise to date

Backup Slides

Data Samples and Selection Criteria

- Integrated luminosity of 711 fb^{-1} collected at $\Upsilon(4S)$ resonance
  - Λ_c^+ decay chain is chosen to be $\Lambda_c^+ \to pK^-\pi^+$ (BR ~ 5%)



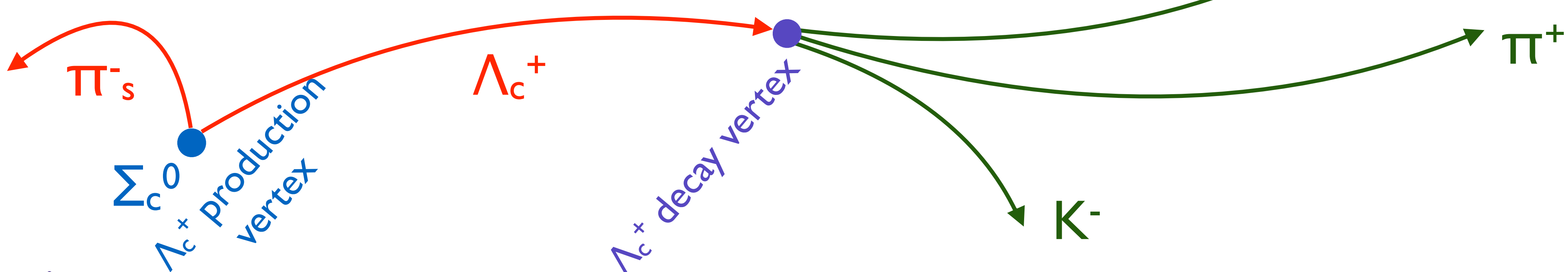
- Track selection for all charged tracks
  - Impact parameters
    - |dr| < 1 cm (radial position from the interaction point (IP))
    - |dz| < 3 cm (z-position from IP)
  - SVD hit requirements
    - > 1hits both r-φ and z direction

- Particle identification
  - $P(K:\pi) > 0.6$ for K / $P(\pi:K) > 0.6$ for π / $P(p:h) > 0.9$ for p (h={K,π})
  - PID efficiencies (ε: efficiency / f: fake rate)
    - $\varepsilon(K:\pi) = (90.58 \pm 0.53)\%$ $f(K:\pi) = (9.77 \pm 0.33)\%$
    - $\varepsilon(\pi:K) = (92.63 \pm 0.69)\%$ $f(\pi:K) = (7.84 \pm 0.33)\%$
    - $\varepsilon(\pi_s:K) = (99.18 \pm 0.89)\%$ $f(\pi_s:K) = (5.93 \pm 0.52)\%$

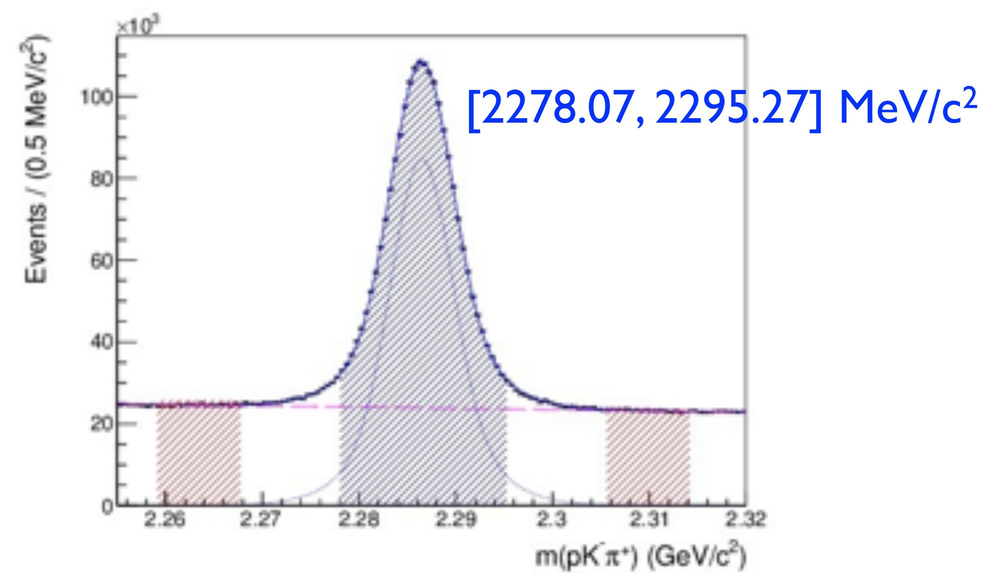
Data Samples and Selection Criteria

- Λ_c^+ reconstruction
  - Using p, K^-, π^+ tracks, Λ_c^+ candidates are reconstructed
  - Daughter tracks are refit to a common vertex (Λ_c^+ decay vertex)

- Σ_c reconstruction
  - Attaching π_s track to Λ_c^+ candidate, Σ_c candidates are reconstructed
  - Λ_c^+ production vertex is found by fitting Λ_c^+ trajectory to IP
  - π_s track is refit to the Λ_c^+ production vertex



- Σ_c selection
  - $m(\Lambda_c^+) \in [2278.07, 2295.79]$ MeV/c^2 ($\pm 2.1\sigma$ around $m(\Lambda_c^+)$)
  - $p(\Sigma_c) > 2.0$ GeV/c
  - (Confidence level of π_s vertex fit) > 0.1%



Feed-down Backgrounds from Λ_c^{*+} Decays

- Decays of the excited states of Λ_c^+ baryon can make contributions

	Mass (MeV/c^2)	Decay modes	Branching Fraction
$\Lambda_c(2595)^+$	2592.25 ± 0.28	$\Lambda_c^+\pi^+_s\pi^-_s$	~ 67%
		$\Sigma_c(2455)^{++}\pi^-_s$	$(24 \pm 7)\%$
		$\Sigma_c(2455)^0\pi^+_s$	$(24 \pm 7)\%$
		$\Lambda_c^+\pi^+_s\pi^-_s$ 3-body	$(18 \pm 10)\%$
$\Lambda_c(2625)^+$	2628.11 ± 0.19	$\Lambda_c^+\pi^+_s\pi^-_s$	~ 67%
		$\Sigma_c(2455)^{++}\pi^-_s$	< 5 @ 90% C.L.
		$\Sigma_c(2455)^0\pi^+_s$	< 5 @ 90% C.L.
		$\Lambda_c^+\pi^+_s\pi^-_s$ 3-body	Large
$\Lambda_c(2765)^+$	2766.6 ± 2.4	$\Lambda_c^+\pi^+_s\pi^-_s$ 3-body	seen
$\Lambda_c(2880)^+$	2881.53 ± 0.35	$\Lambda_c^+\pi^+_s\pi^-_s$	seen
		$\Sigma_c(2455)^{0/++}\pi^{+/-}_s$	seen
		$\Sigma_c(2520)^{0/++}\pi^{+/-}_s$	seen

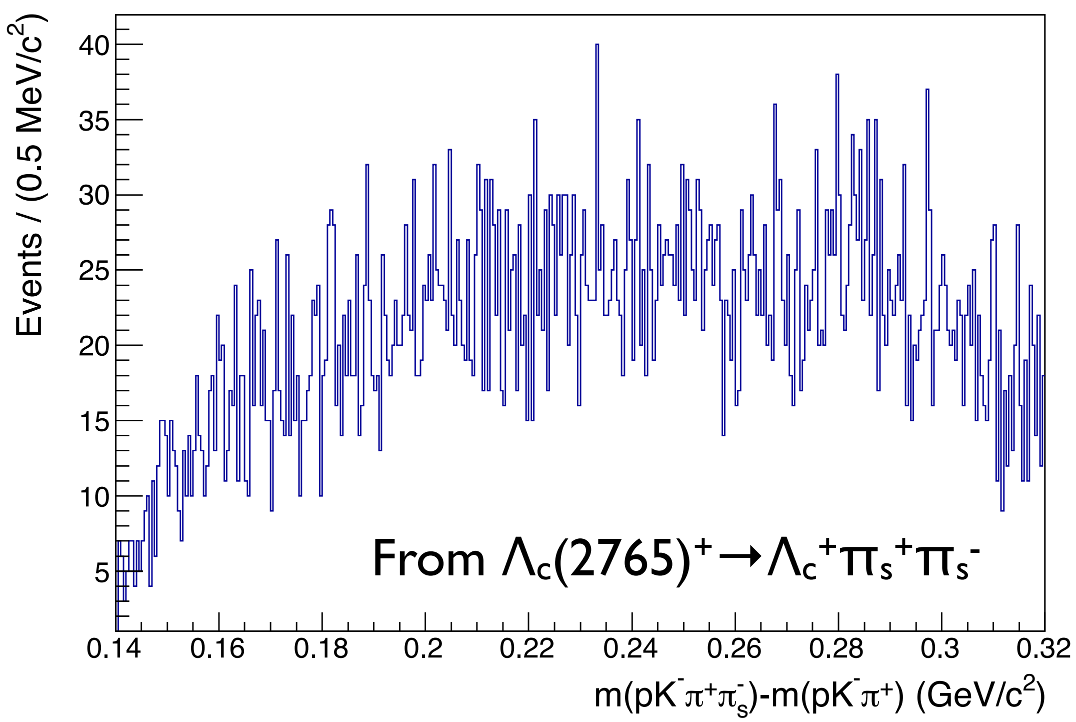
PDG 2013

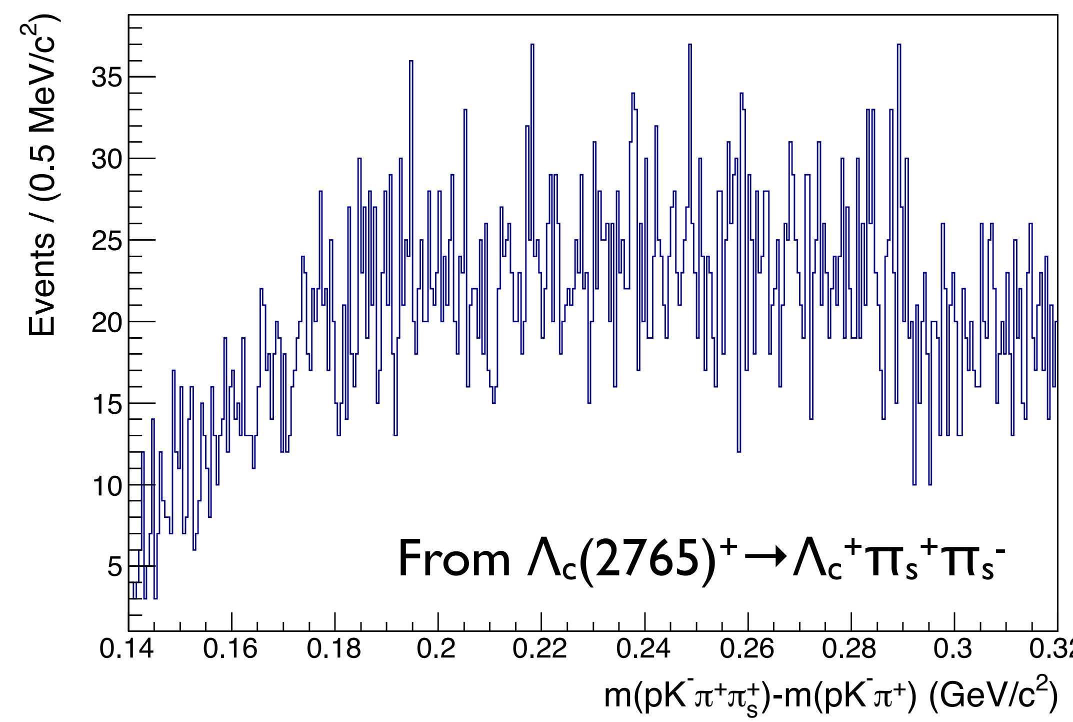
- Those contributions can be either signal or background events
  - $\Lambda_c(2625)^+\to\Sigma_c(2455)^0\pi^+$ (final state: $pK^-\pi^+\pi^-\pi^+$): Signal events for $\Sigma_c(2455)^0$ but background events for $\Sigma_c(2455)^{++}$
  - $\Lambda_c(2625)^+\to\Sigma_c(2455)^{++}\pi^-$: Background events for $\Sigma_c(2455)^0$ but signal events for $\Sigma_c(2455)^{++}$
  - $\Lambda_c(2625)^+\to\Lambda_c^+\pi^+\pi^-$: Background events for both

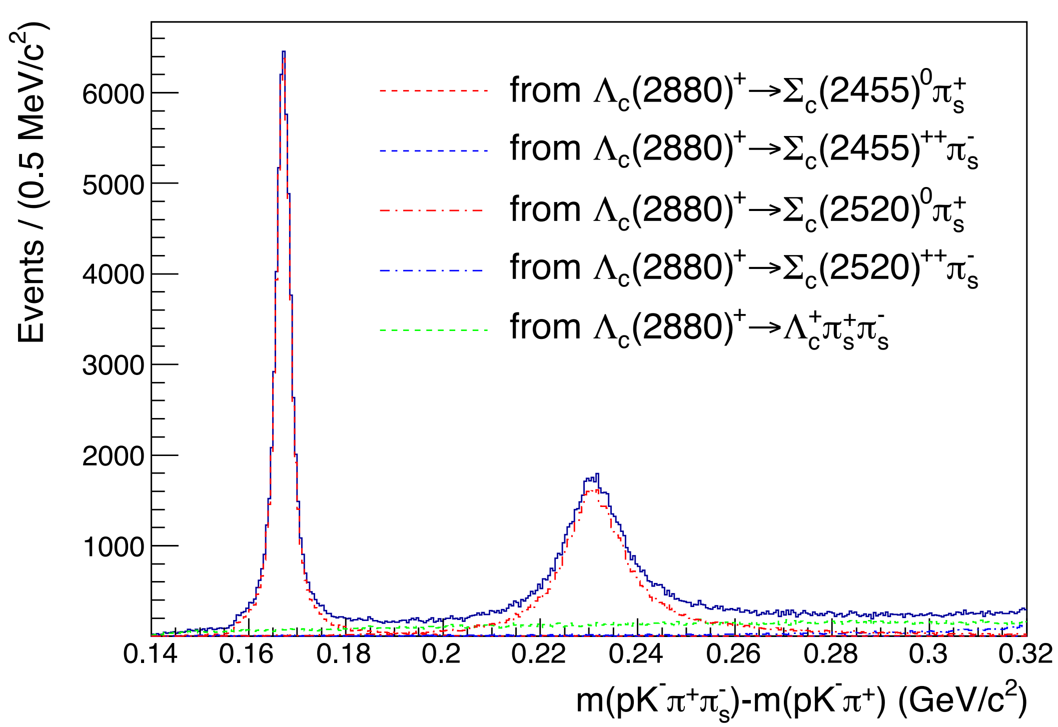
Feed-down Backgrounds from Λ_c^{*+} Decays

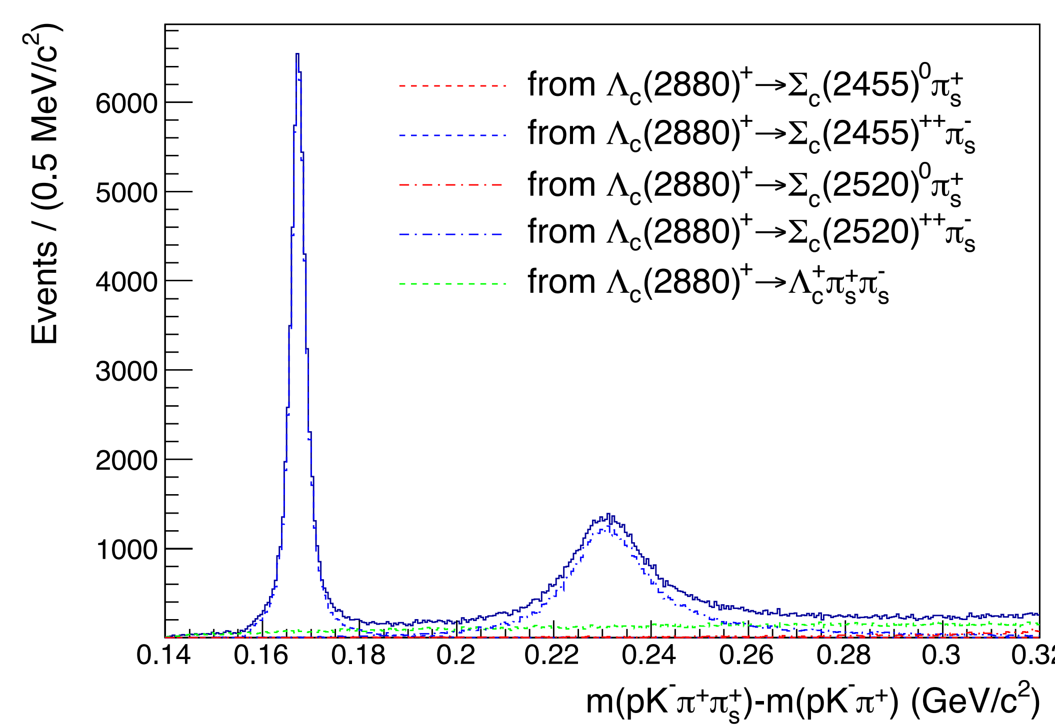
BELLE

- The contributions from $\Lambda_c(2765)^+$ and $\Lambda_c(2880)^+$ are kinematically negligible





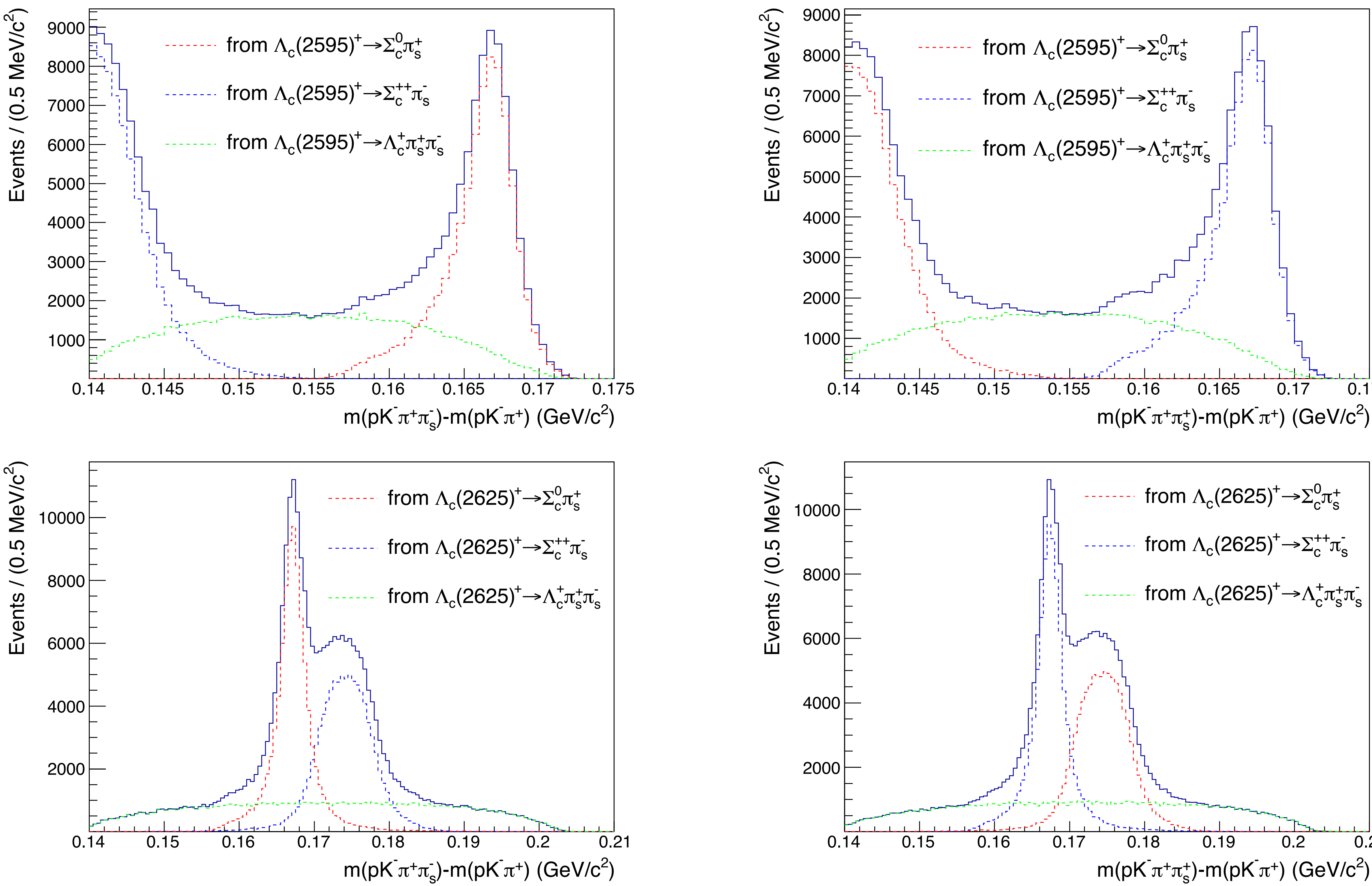




From MC simulations
(1M events generated for each channels)
* Branching fractions are not accounted

Feed-down Backgrounds from Λ_c^{*+} Decays

- The contributions from $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ are found to be dominant



From MC simulations
(1M events generated for each channels)
* Branching fractions are not accounted

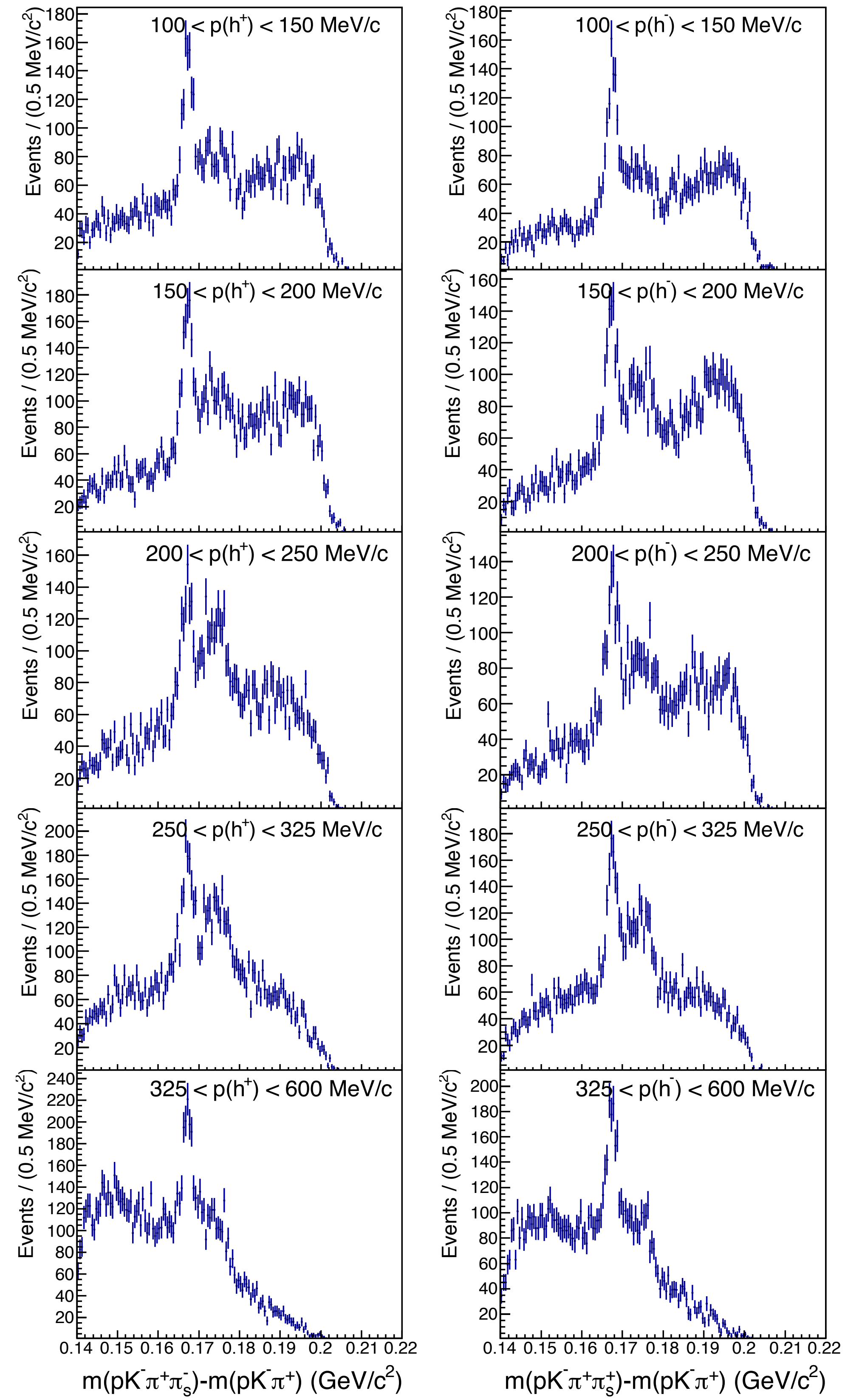
Feed-down Backgrounds from Λ_c^{*+} Decays

- Feed-down corrections
  - Partial reconstruction of $pK^-\pi^+\pi^+\pi^-$ events
    → no efficiency involves
  - Tagging by attaching an additional charged track
    → efficiency involves
  - Since the feed-down obtained by the tagging method reflects the detector efficiency, it should be corrected to get real feed-down normalization

$$\mathcal{N}_{\text{corrected}}(\text{Feed-down}) = \frac{\mathcal{N}_{\text{uncorrected}}(\text{Feed-down})}{\epsilon_{\text{tracking}}(h^{\pm}) \cdot \epsilon_{\text{acceptance}}(h^{\pm})}$$

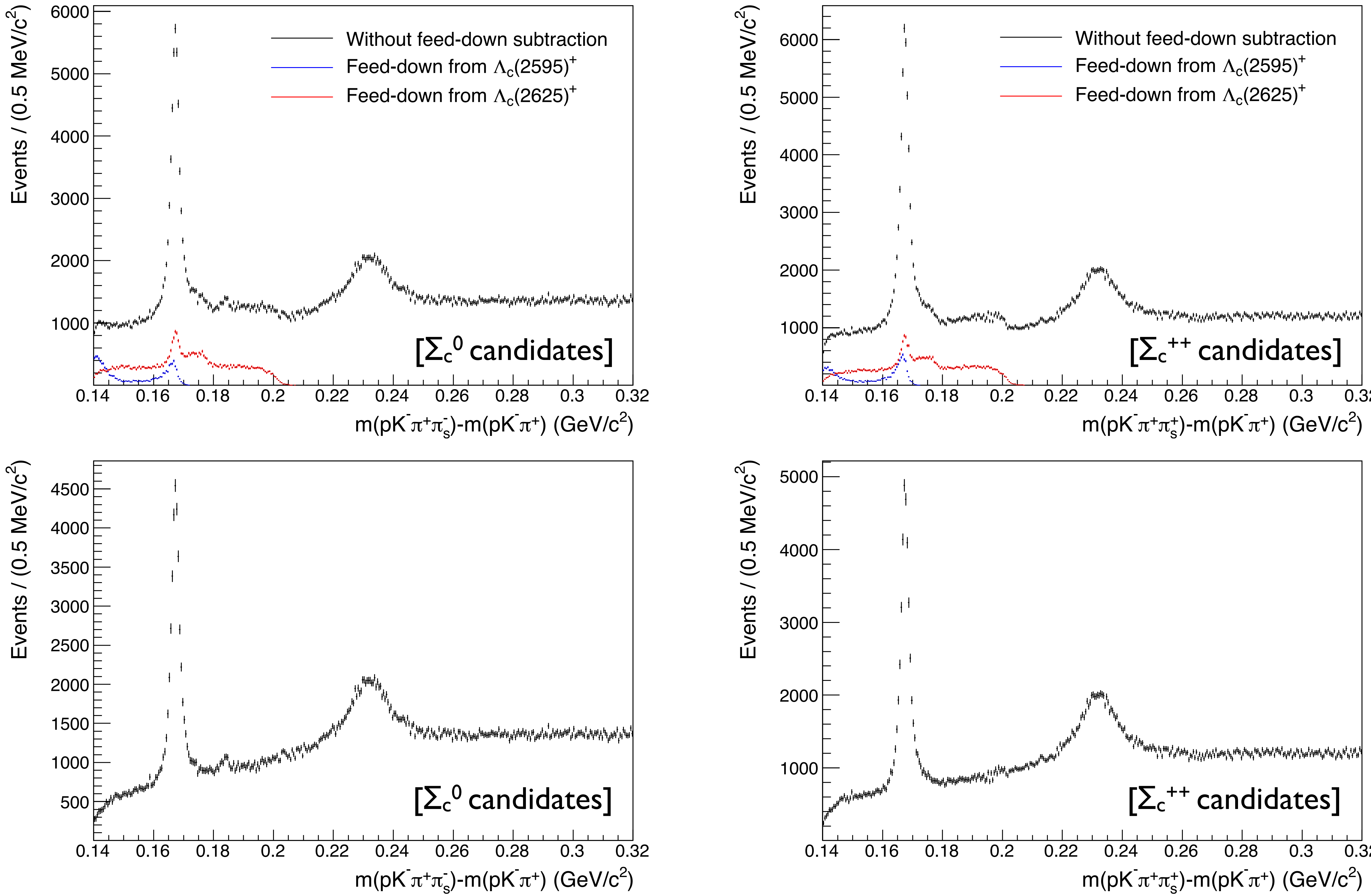
~74% on average

- The feed-down shape depends on charged track momentum
  - The efficiencies are obtained as a function of charged track momentum
  - The correction is applied as a function of charged track momentum



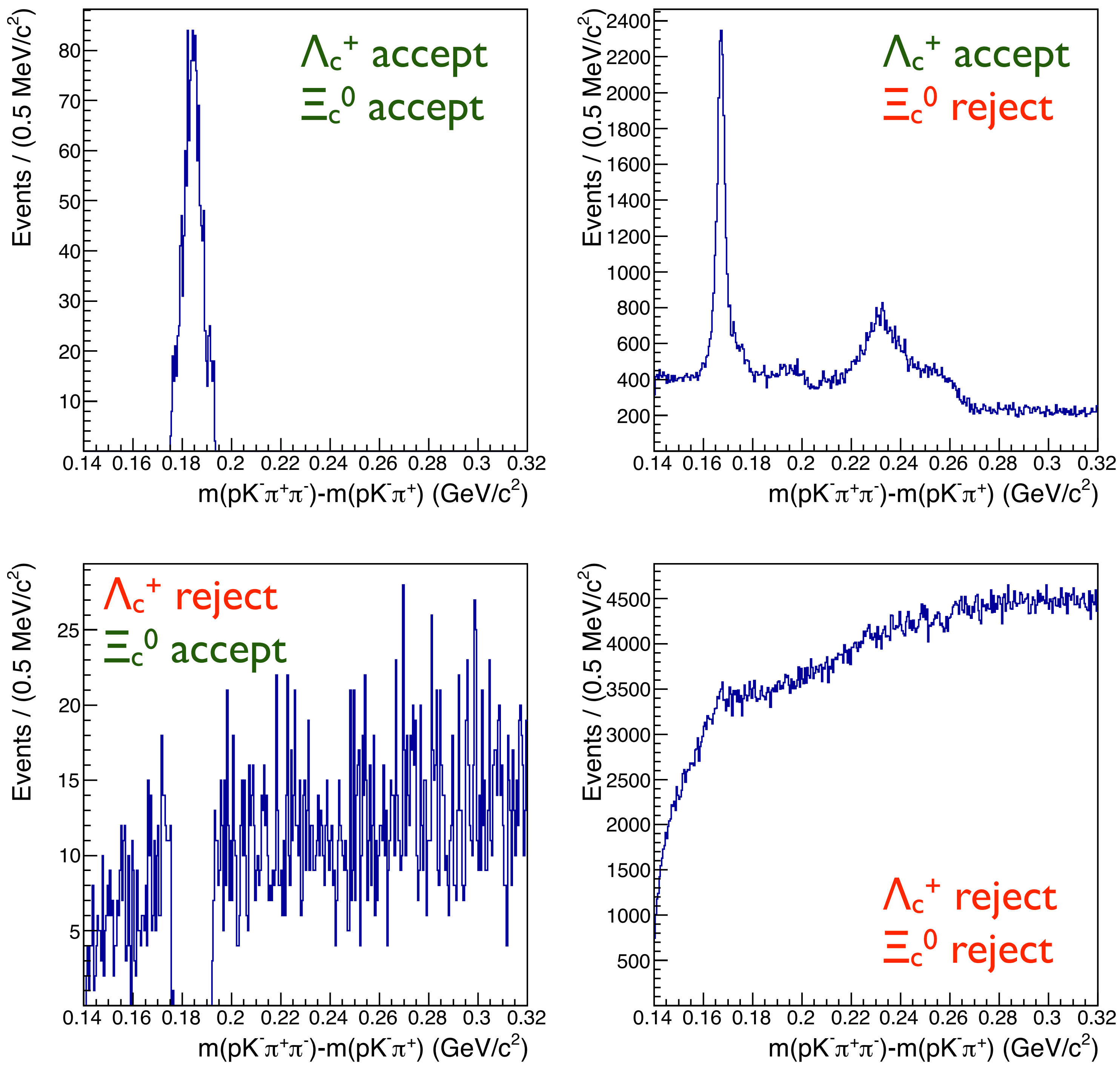
Feed-down Backgrounds from Λ_c^{*+} Decays

- Before and after the feed-down subtraction



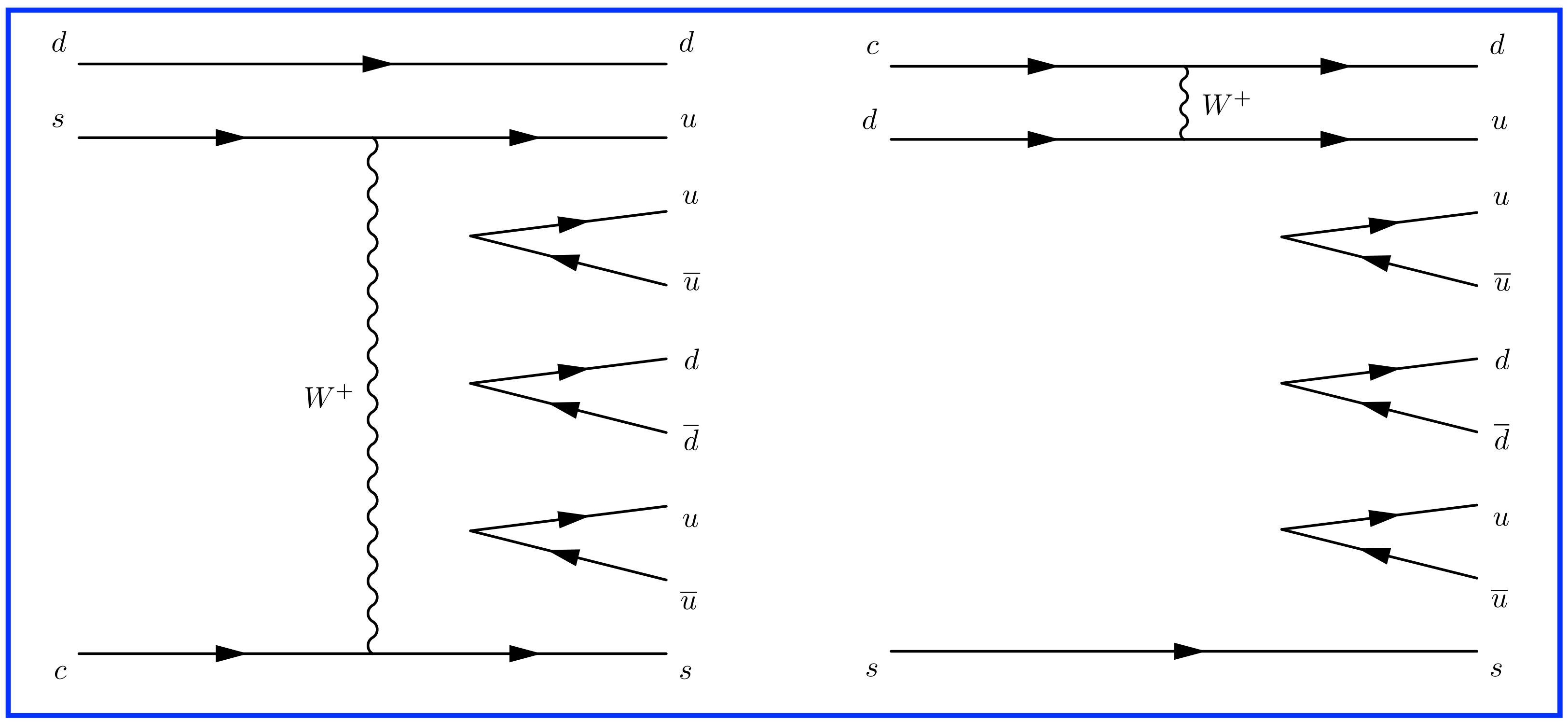
Backgrounds from Ξ_c^0 Decays

- From MC and data, this background contribution is confirmed
  - Data also shows that the peak is related to Λ_c^+ and Ξ_c^0 simultaneously

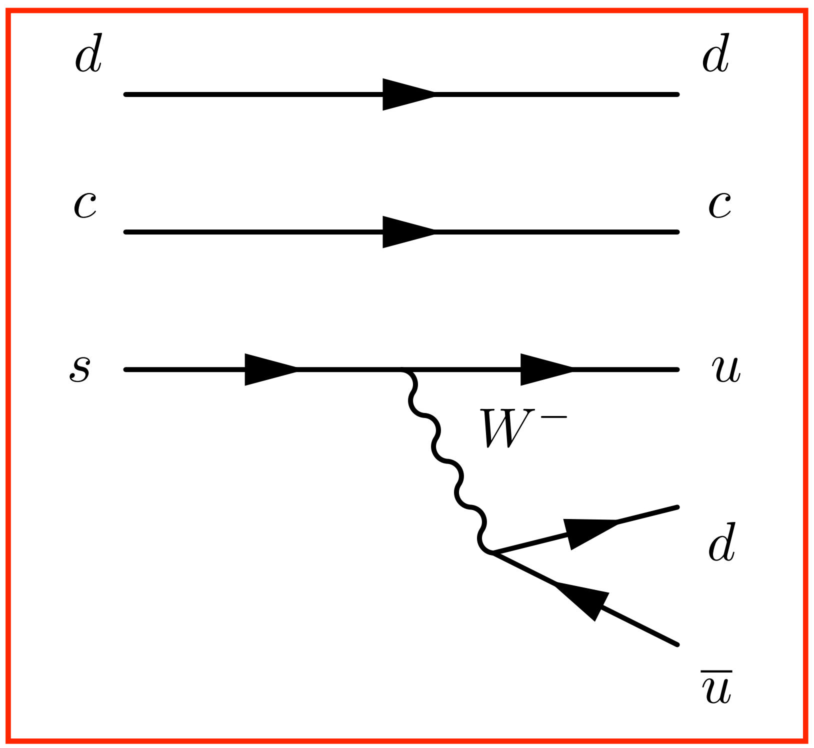


Backgrounds from Ξ_c^0 Decays

- However, there is no known decays of $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$ or $\Xi_c^0 \rightarrow pK^-\pi^+\pi^-$
  - Theoretically possible (Cabibbo-suppressed) but no experimental observation to date
  - No such an observation of which charmed baryon decays into charmed baryon through weak decay
  - The observation of this will be addressed in a separate study



$\Xi_c^0 \rightarrow pK^-\pi^+\pi^-$



$\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$

Fit Procedure

- Since the Σ_c baryons have finite decay widths, the decay widths and detector resolutions should be considered simultaneously in the modeling

$$M(\Delta m; \Delta m_0, \Gamma) = T(\Delta m; \Delta m_0, \Gamma) \otimes R(\Delta m)$$
$$= \int_{-\infty}^{+\infty} T(\Delta m; \Delta m_0, \Gamma) R(\Delta m - \Delta m') d(\Delta m')$$

- Relativistic Breit-Wigner function is employed for the theoretical model

$$\frac{dN}{dm} \propto \frac{m \cdot \Gamma(m)}{(m_0^2 - m^2)^2 + m_0^2 \cdot \Gamma^2(m)}$$

where

$$\Gamma(m) = \Gamma_0 \frac{m_0}{m} \left(\frac{q}{q_0} \right)^{2L+1} \frac{F(Rq)}{F(Rq_0)}$$

$$q = \frac{\sqrt{(m^2 - (m_{\Lambda_c^+} + m_\pi)^2)(m^2 - (m_{\Lambda_c^+} - m_\pi)^2)}}{2m}$$

- Since L=0 for the Σ_c baryons in SM, that is, the width reduces $\Gamma(m) = \Gamma_0 \frac{m_0}{m} \frac{q}{q_0}$ and Blatt-Weisskopf form factor F(Rq)=1, therefore,

$$\frac{dN}{dm} \propto \frac{m \cdot \left(\Gamma_0 \frac{m_0}{m} \frac{q}{q_0} \right)}{(m_0^2 - m^2)^2 + m_0^2 \cdot \left(\Gamma_0 \frac{m_0}{m} \frac{q}{q_0} \right)^2}$$

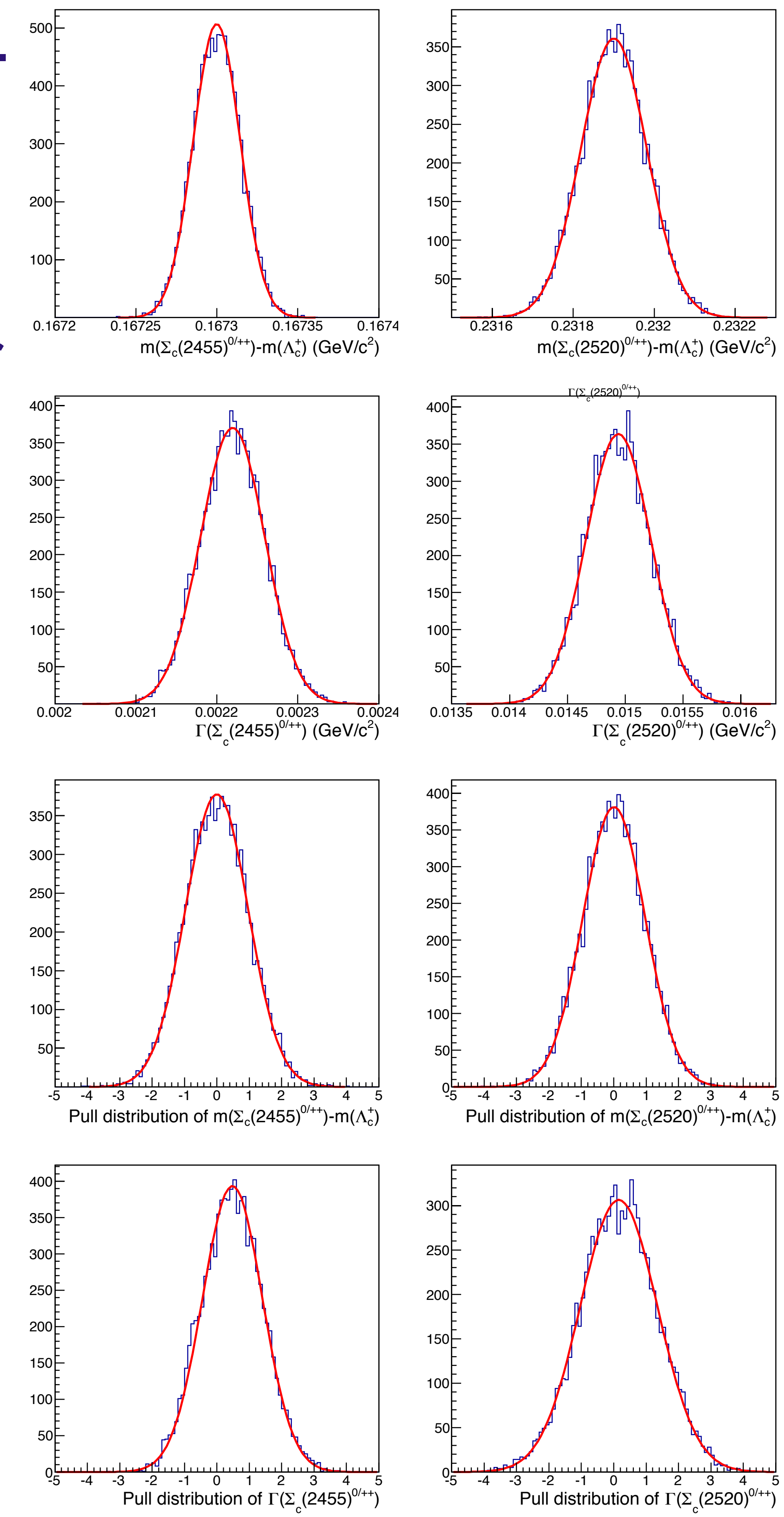
Systematics: Fit Model

BELLE

- Fit bias from the fitter is estimated with pseudo-experiments
  - Each pseudo-experiment has the same input values obtained from data
  - Only small uncertainties of 0.02 and 0.04 MeV/c^2 for $\Sigma_c(2455)^{0/++}$ and $\Sigma_c(2520)^{0/++}$ widths

- Binning effect
  - Fits are tested with various bin size from 0.1 to 1.0 MeV/c^2
  - Uncertainties:
    - For $m(\Sigma_c)-m(\Lambda_c^+)$: negligible
    - For $\Gamma(\Sigma_c)$: 0.09, 0.06, 0.04, and 0.05 MeV/c^2 for $\Sigma_c(2455)^0$, $\Sigma_c(2455)^{++}$, $\Sigma_c(2520)^0$, $\Sigma_c(2520)^{++}$, respectively

- Fit ranges
  - Fits are tested with various fit ranges
  - Uncertainties:
    - For $m(\Sigma_c)-m(\Lambda_c^+)$: 0.03 and 0.01 MeV/$c^2$ for $\Sigma_c(2520)^0$ and $\Sigma_c(2520)^{++}$
    - For $\Gamma(\Sigma_c)$: 0.19 and 0.17 MeV/c^2 for $\Sigma_c(2520)^0$ and $\Sigma_c(2520)^{++}$



10,000 pseudo-experiments are performed

Systematics: Background Model

- Feed-down correction

$$\frac{\delta\mathcal{N}_{\text{corrected}}(\text{Feed-down})}{\mathcal{N}_{\text{corrected}}(\text{Feed-down})} = \left[\left(\frac{\delta\mathcal{N}_{\text{uncorrected}}(\text{Feed-down})}{\mathcal{N}_{\text{uncorrected}}(\text{Feed-down})}\right)^2 + \left(\frac{\delta\epsilon_{\text{tracking}}(h^{\pm})}{\epsilon_{\text{tracking}}(h^{\pm})}\right)^2 + \left(\frac{\delta\epsilon_{\text{acceptance}}(h^{\pm})}{\epsilon_{\text{acceptance}}(h^{\pm})}\right)^2\right]^{1/2}$$

0.46 %   1.80%   0.17%

  - Total uncertainty is estimated to be 1.87% - negligible

- Statistical fluctuation of the random background with fake Λ_c^+
  - Normalizations of fake Λ_c^+ backgrounds by $\pm 1\sigma$
  - No uncertainties are found

- Various modeling of the random background with true Λ_c^+
  - e.g. $c_0(\Delta m - m_\pi)^{1/2} + c_1(\Delta m - m_\pi)^{3/2}$

    $c_0(\Delta m - m_\pi)^{1/2} + c_1(\Delta m - m_\pi)^{3/2} + c_2(\Delta m - m_\pi)^{5/2}$
  - No uncertainties are found