First Observation of Doubly Cabibbo Suppressed Decay of a Charmed Baryon, $\Lambda_c^+ \to pK^+\pi^-$

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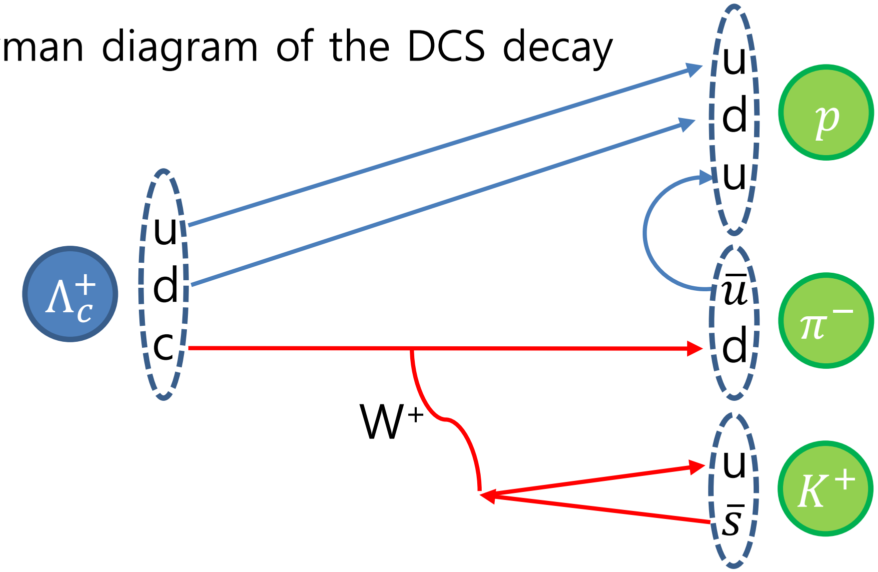
- Doubly Cabibbo-suppressed (DCS) decay, $\Lambda_c^+ \rightarrow pK^+\pi^-$

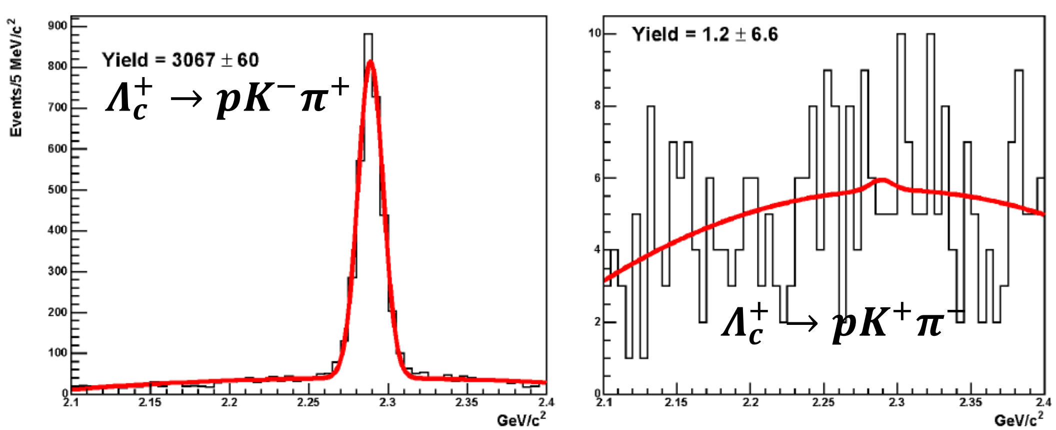
*Feyman diagram of the DCS decay



*Corresponding Cabibbo-favored (CF) decay, $\Lambda_c^+ \rightarrow pK^-\pi^+$

- Previous study → No positive results

*FOCUS group, PLB 624 (2005) 166-172



■ Naïve expectation of branching ratio,

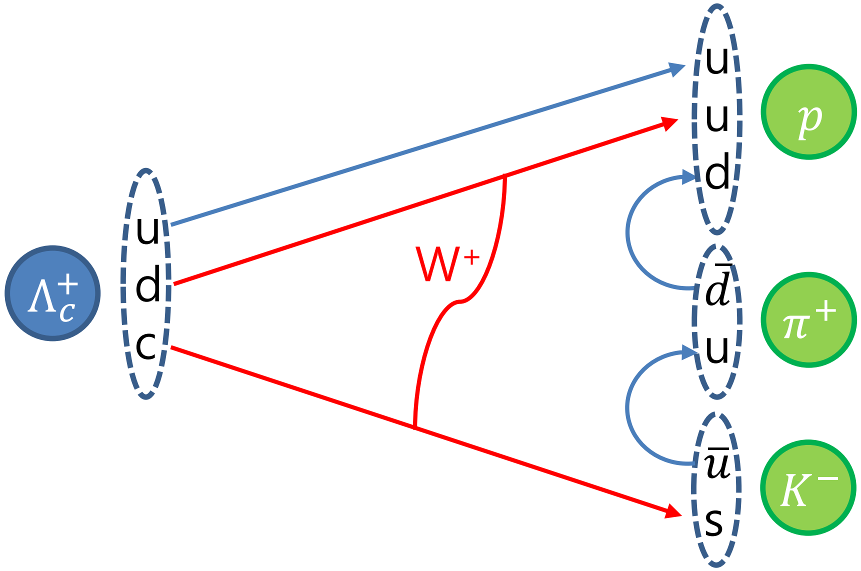
$$\frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)} \approx \tan^4\theta_C(= 0.00285),$$

where θ_C is a Cabibbo mixing angle.

■ Contribution of *W* exchange in Λ_c^+ decay

→ The *W* exchange is prohibited in DCS decay, but allowed in CF decay.

→ A contribution of *W* exchange can be estimated.



*Feyman diagram of *W* exchange of the CF decay.

■ Data sample

→ Full data sample of Belle, 980 fb^{-1}, at and near $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \Upsilon(4S)$, and $\Upsilon(5S)$ is used.

■ Analysis

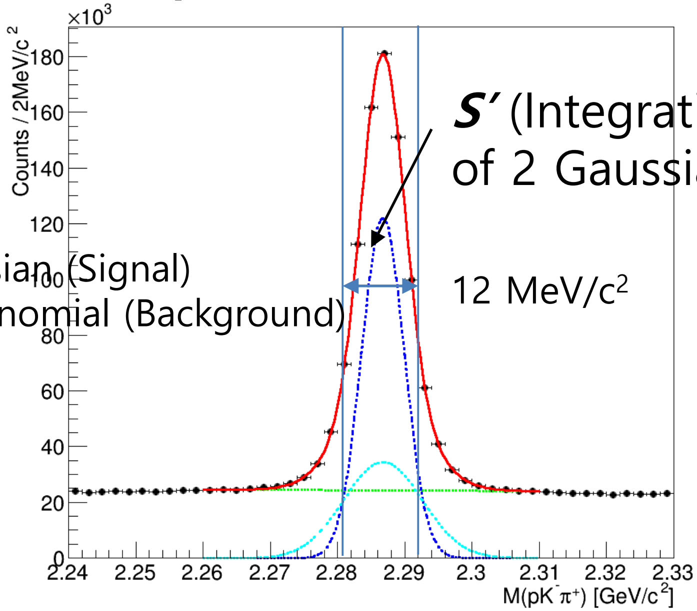
→ Optimization by using a control sample, $\Lambda_c^+ \rightarrow pK^-\pi^+$, to keep a blinded condition.

→ Reconstruction efficiency and backgrounds are estimated by MC samples.

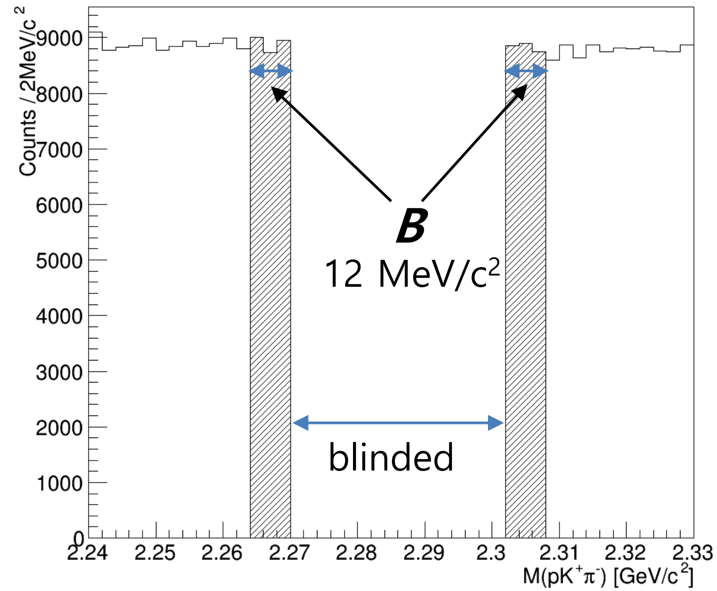
→ Most systematic sources (efficiency, phase space, etc.) for the branching fraction cancel out.

■ Figure-of-merit study for optimization

*$M(K^-\pi^+p)$ distribution, control sample



*$M(K^+\pi^-p)$ distribution, side band

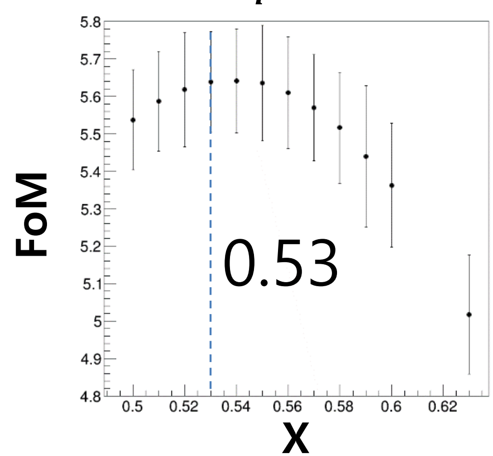


$$FoM = S/\sqrt{S+B}, \text{ where } S = 0.0025 \times S'$$

*example: scaled momentum, x_p

→ A condition with maximum FoM is selected.

* $x_p > \mathrm{X}$



■ Relative efficiency

→ $\epsilon(\Lambda_c^+,\ CF)/\epsilon(\Lambda_c^+,\ DCS)$ from MC study.

$$\epsilon = \frac{\sum_i \epsilon_i BR_i}{\sum_j BR_j},$$

where ϵ_i: efficiency of i^{th} sub-decay channel, BR_i: branch ratio of i^{th} sub-decay channel

→ Sub-decay channels

Sub Channel of CF decay, $\Lambda_c^+ \to pK^-\pi^+$	Branching Ratio *PDG2014
$p\bar{K}^*(892)^0$; $\bar{K}^*(892)^0 \to K^-\pi^+$	0.21±0.03
$\Delta(1232)^{++}K^-$; $\Delta(1232)^{++} \to p\pi^+$	0.17±0.04
$\Lambda(1520)\pi^+$; $\Lambda(1520) \to pK^-$	0.08±0.02
$pK^-\pi^+$ (non-resonant)	0.55±0.06

Sub Channel of DCS decay $\Lambda_c^+ \to pK^+\pi^-$	Branching Ratio
$pK^*(892)^0$; $K^*(892)^0 \to K^+\pi^-$	0.23
$\Delta(1232)^0K^+$; $\Delta(1232)^0 \to p\pi^-$	0.18
$pK^+\pi^-$ (non-resonant)	0.59

*They are just assumed branching ratios and sub-channels from CF decay.

→ $\epsilon(\Lambda_c^+,\ CF)/\epsilon(\Lambda_c^+,\ DCS)$ = 1.01

■ Peaking background from singly Cabibbo-suppressed (SCS) decay, $\Lambda_c^+ \to \Lambda K^+; \Lambda \to p\pi^-$

→ Yield of the SCS decay is estimated as follows,

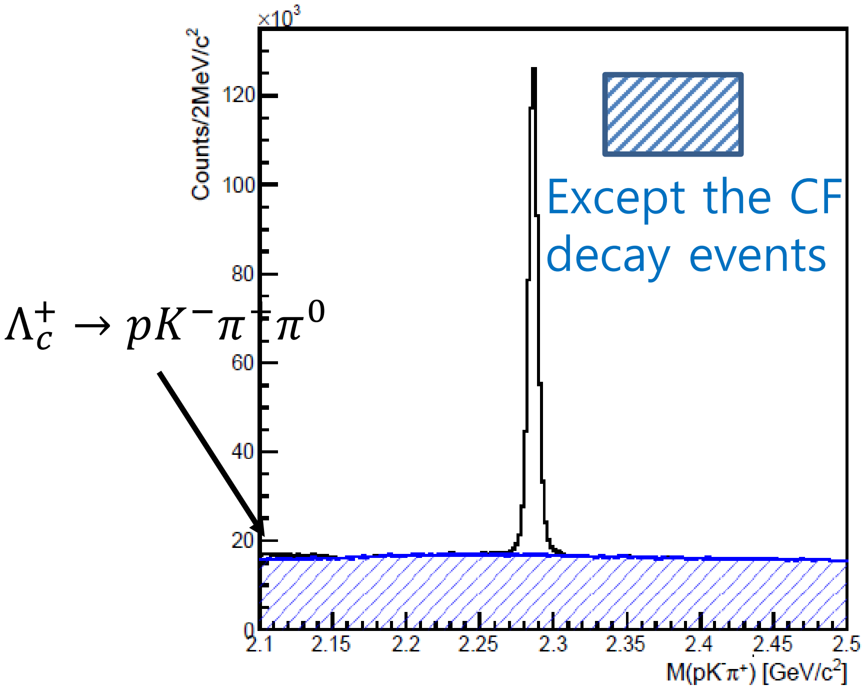
$$s(SCS) = \frac{BR(SCS)}{BR(CF)} \times \frac{\epsilon(SCS)}{\epsilon(CF)} \times s(CF),$$

where $\frac{BR(SCS)}{BR(CF)} = 0.61 \pm 0.13$ % (PDG2014), $\frac{\epsilon(SCS)}{\epsilon(CF)} = 0.023$, and $s(CF) = 1.452 \times 10^6$.

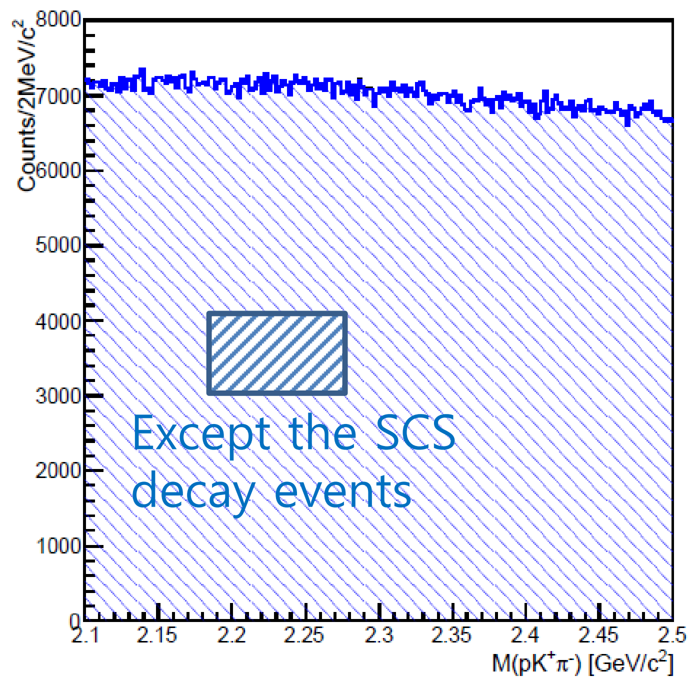
→ The estimated yield is 208 events.

■ Background distributions of the CF and the DCS decays
→MC sample (790 fb^{-1}) not including the DCS decay events.

$^{*}M(pK^-\pi^+)$ distribution



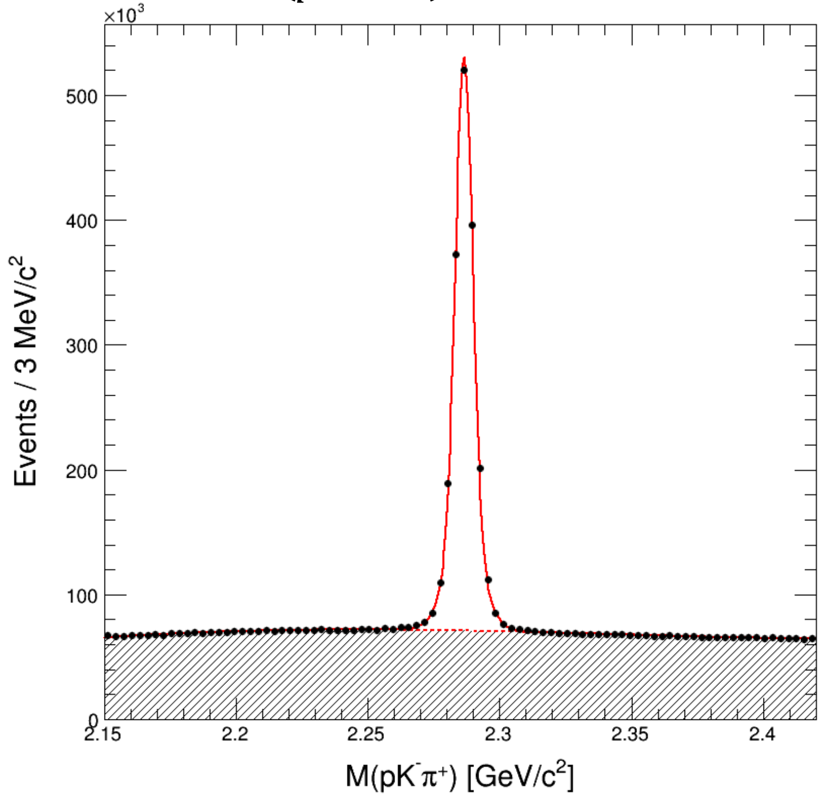
$^{*}M(pK^+\pi^-)$ distribution



→They are combinatorial or accidental backgrounds, and their distributions are flat.

■ Signal yield of the CF decay

*$M(pK^-\pi^+)$ distribution

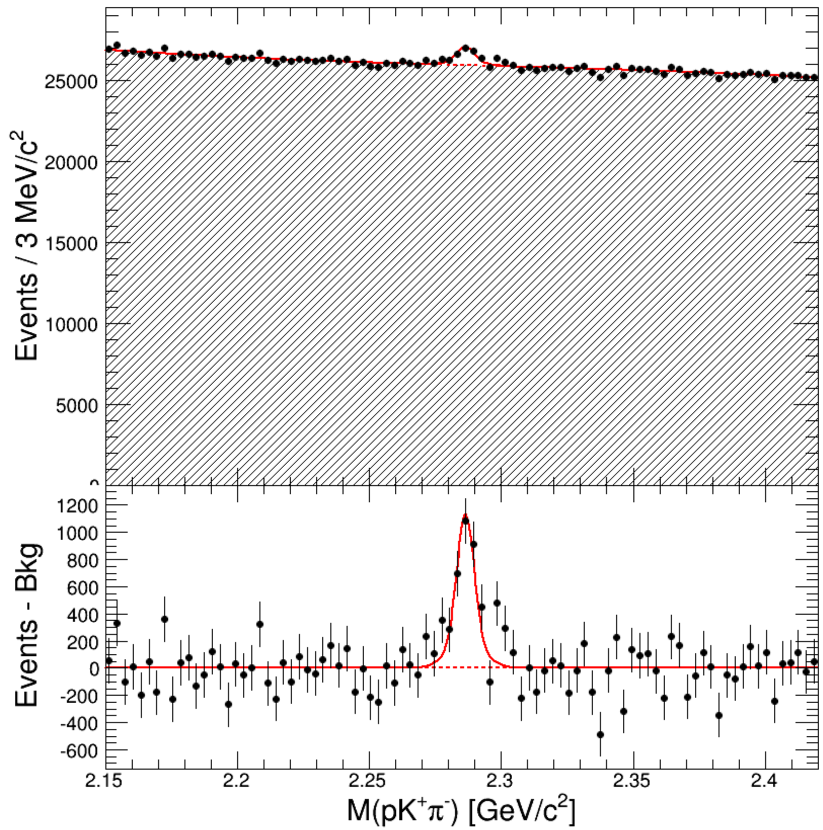


→ Fitting function: 2Gaussians with same mean (signal) + 5th Polynomials (background)

→ $(1.452 \pm 0.015(Stat.)) \times 10^6$ events

■ Signal yield of the DCS decay

*$M(pK^+\pi^-)$ distribution



→ Fitting function: 2Gaussians with fixed mean and width to be same as the CF decay (signal) + 3rd Polynomials (background)

→ $3587 \pm 380(Stat.)$ events including the SCS decay and 3379 events only for the DCS decay

→ Statistical significance (after subtracting the SCS decay): 9.4σ

■ Systematics of the branching ratio

Source	Uncertainty (%)
Background from SCS signal	±2.3
Intermediate state	±5.4
Binning and fit range (DCS)	±5.5
Binning and fit range (CF)	±0.6
PDF shape (DCS)	±2.6
PDF shape (CF)	±1.4
MC statistics	±0.4
PID	±2.2
Charge-conjugate mode	±1.8
Total	±9.0

■ Branching ratio between the DCS and CF decays

→ $$\frac{BR(DCS)}{BR(CF)} = (2.35 \pm 0.27(Stat.) \pm 0.21(Syst.)) \times 10^{-3}$$
$$= (0.82 \pm 0.12(total)) \times \tan^4\theta_\mathrm{C}$$

→ W exchange does not make a large contribution to Λ_c^+ decay.

→ $$BR(DCS) = (1.61 \pm 0.23(total)^{+0.07}_{-0.08}(CF)) \times 10^{-4}$$

* $BR(CF) = (6.84^{+0.32}_{-0.40}) \times 10^{-2}$ (PRL, 113, 042002(2014))

■ Summary

1. The $\Lambda_c^+ \to pK^+\pi^-$ is clearly observed, and it is the first observation of DCS decay of a charmed baryon.
2. The branching ratio between the DCS and CF decays is determined to be $(2.35 \pm 0.27(Stat.) \pm 0.21(Syst.)) \times 10^{-3}$, and it corresponds to $(0.82 \pm 0.12(total)) \times \tan^4\theta_\mathrm{C}$.
3. Naively, the result indicates the W exchange does not make a large contribution to Λ_c^+ decay.

Backup Pages

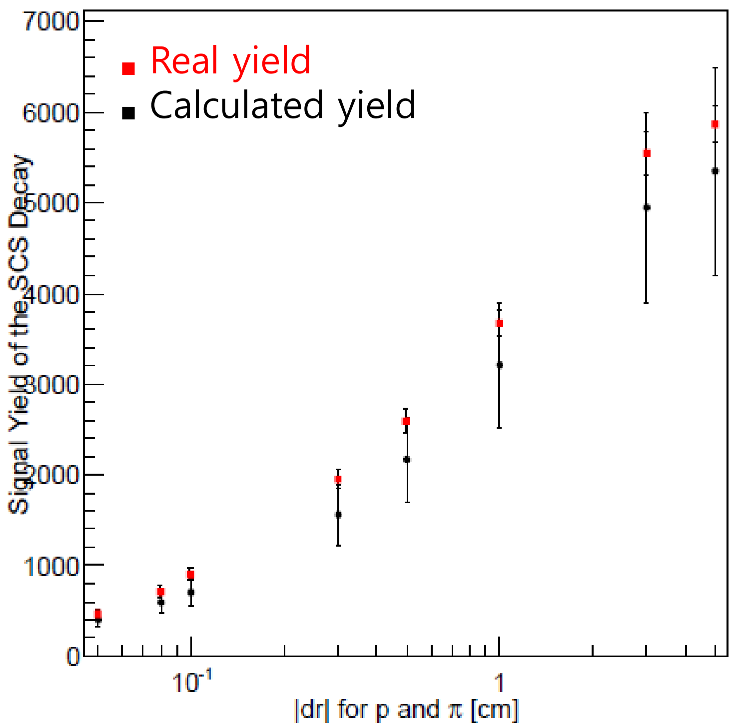
- Events selection criteria

→FoM study performed with typical condition

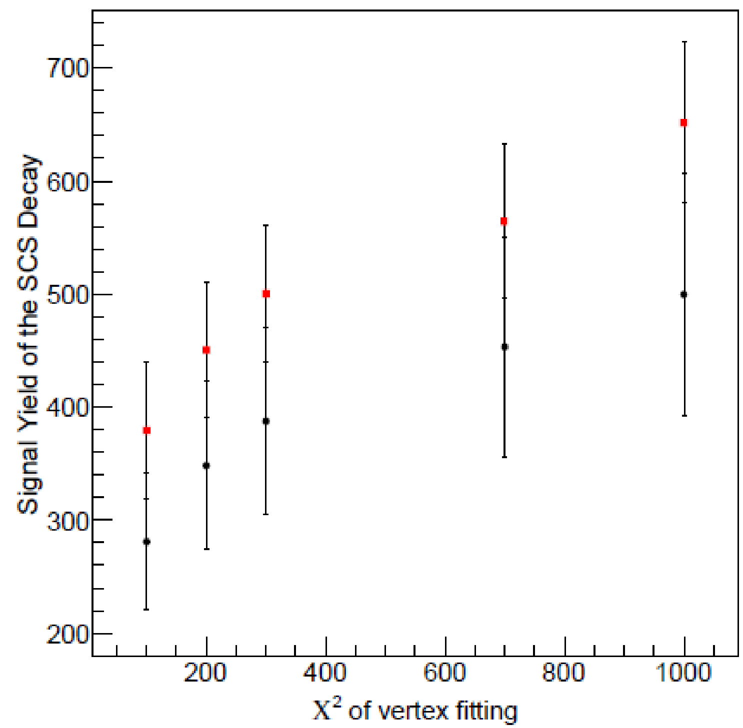
Selection Type	Quantity	Typical Condition	Selected Condition
Impact Parameter for all particles			
	$\lvert dr \rvert$	< 0.30 cm	< 0.10 cm
	$\lvert dz \rvert$	< 3.00 cm	< 2.00 cm
$PID(K)$			
	$\mathcal{R}(K\lvert\pi)$	> 0.60	> 0.90
	$\mathcal{R}(p\lvert K)$	< 0.40	< 0.60
$PID(p)$			
	$\mathcal{R}(p\lvert K)$	> 0.80	> 0.90
	$\mathcal{R}(p\lvert\pi)$	> 0.80	> 0.90
$PID(\pi)$			
	$\mathcal{R}(K\lvert\pi)$	< 0.40	< 0.60
	$\mathcal{R}(p\lvert\pi)$	< 0.40	< 0.60
Lepton PID			
	$\mathcal{R}(e)$	< 0.95	< 0.90
Number of SVD hits for all particles			
	$r\phi$-layer	≥ 1	≥ 1
	z-layer	≥ 1	≥ 1
scaled momentum			
	x_p	> 0.55	> 0.53
χ^2 *of vertex fitting*			
	χ^2	< 30	< 40

■ Systematical uncertainty from SCS signal
→ By comparing real yield and calculated yield with loosened selection criteria for the vertex point.

*Changing |dr|

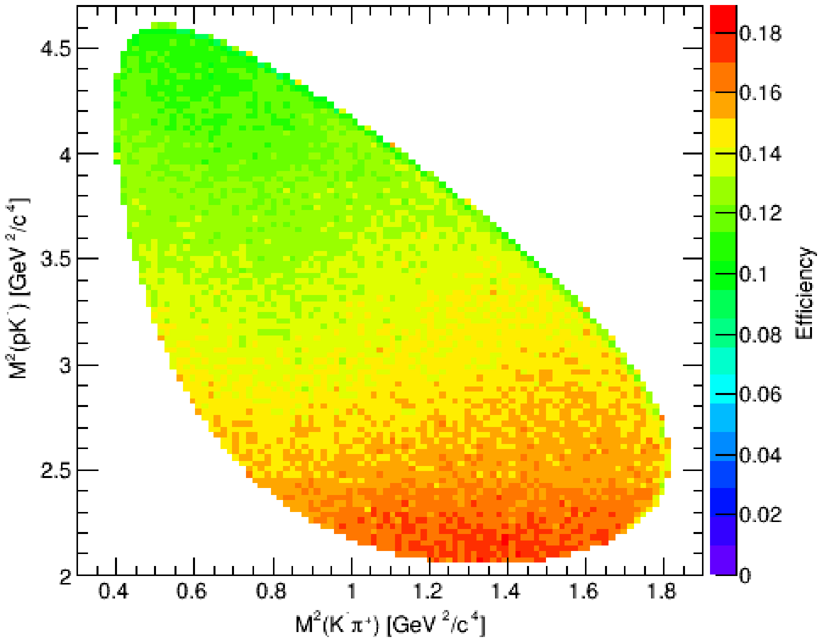


*Changing χ^2 of vertex fitting



→Maximum difference, 38 % of expected signal yield

■ Systematical uncertainty from intermediate states (CF)
→ Efficiency on Dalitz plot



→ Reconstruction efficiency can be estimated by weighting them by real data or MC sample.
Weighting by real data: 14.48 %
Weighting by MC sample: 14.04 %
→ The difference between them (0.44 %) is used for the systematic.

■ Systematical uncertainty from intermediate states (DCS)

→ $\epsilon\left(\frac{\sum_i \epsilon_i BR_i}{\sum_j BR_j}\right)$- ϵ(sub-channel)

The maximum difference between the overall reconstruction efficiency and efficiencies of the assumed sub-channels is used.

→ Overall: $\epsilon\left(\frac{\sum_i \epsilon_i BR_i}{\sum_j BR_j}\right) = 14.20 \pm 0.05\%$

Sub-channels:

$\epsilon(p\bar{K}^*(892)^0, \bar{K}^*(892)^0 \rightarrow K^-\pi^+) = 13.89 \pm 0.10\%$

$\epsilon(\Delta(1232)^0 K^+, \Delta(1232)^0 \rightarrow p\pi^-) = 13.56 \pm 0.10\%$

$\epsilon(non-resonant) = 14.55 \pm 0.08\%$

Maximum difference: 0.64%