Status of rare charm decays

Rencontres du Vietnam 2016

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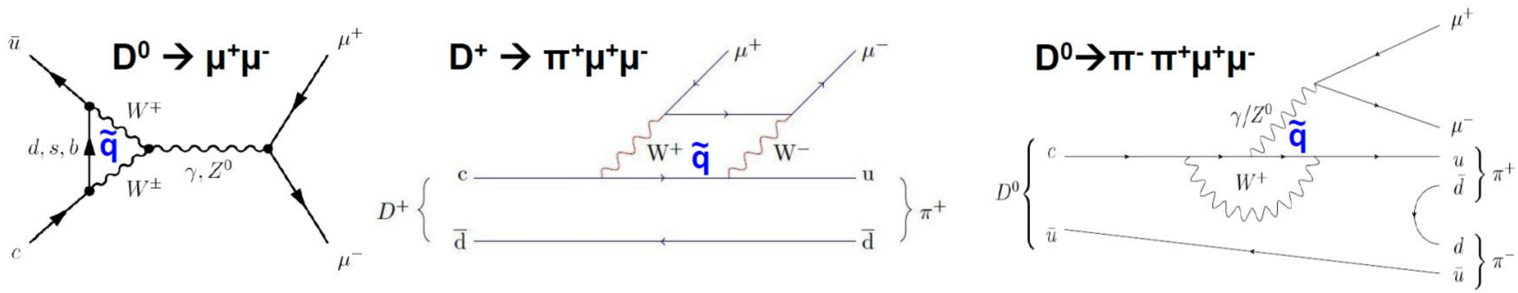
Rare decay

- Flavor Changing Neutral Currents (FCNC) are suppressed in the Standard Model (SM), only possible via loops. Like:

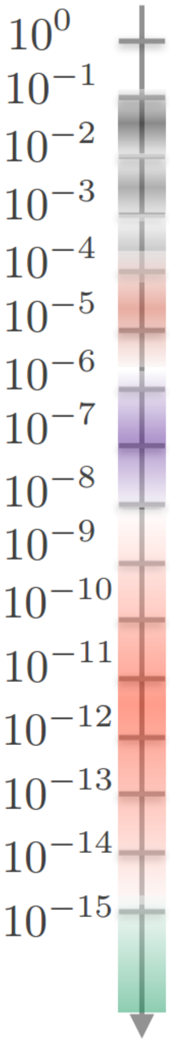


- However, there are many compelling reasons to believe SM can not be the full story.

- Rare decays can be used for indirect searches of NP since they are suppresses or forbidden in SM and highly sensitive to NP effects.

- Charm provides an interesting test bed for NP as SM footprints in this sector are tiny owing to large GIM/CKM suppression

Rare Charm decay



Cabibbo favored

Singly Cabibbo suppresed

Doubly Cabibbo suppresed

Radiative

$D^0 \to \overline{K}^{*0}\gamma,\ \phi\gamma,\ \omega\gamma,\ \rho^0\gamma$

Vector Meson Dominance

$D^0 \to \gamma\gamma$

$D^0 \to \rho V(\to \ell\ell),\ \pi^-\pi^+V(\to \ell\ell)$

$D^0 \to \phi V(\to \ell\ell),\ K^-K^+V(\to \ell\ell)$

$D^0 \to \overline{K}^{*0} V(\to \ell\ell),\ K^+\pi^-V(\to \ell\ell)$

Flavour Changing Neutral Current

$D^0 \to \mu^-\mu^+$

$D^0 \to e^-e^+$

$D \to h\ell^+\ell^-$

$D \to hh'\ell^-\ell^+$

$D \to V\ell^+\ell^-$

Lepton/Baryon Number Violating

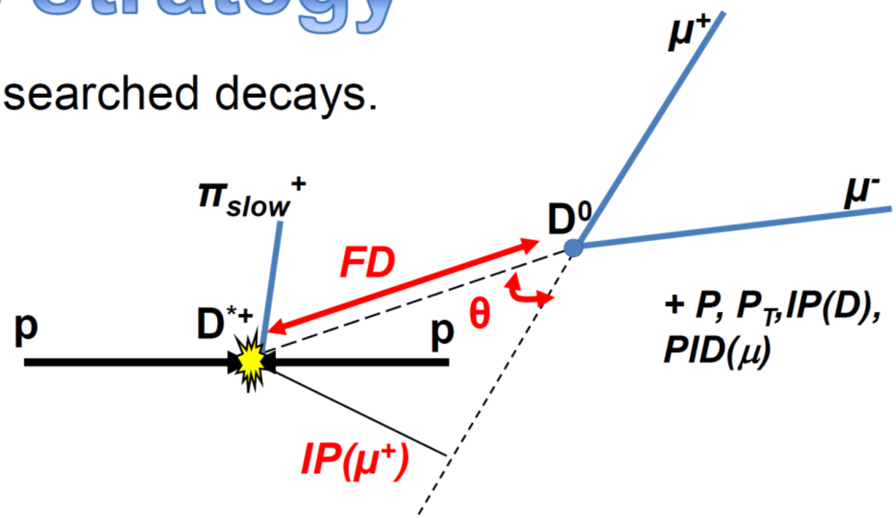
Lepton Flavor Violating

$D \to (h)e^-\mu^+$

$D \to (h)\ell^+\ell^+$

General analysis strategy

- Selection using the typical features for the searched decays.



- Very rare means very high relative combinatorial background
  → Use Multivariate Analysis

- Another difficulty with charm decays: very high peaking backgrounds (Ex: $D \to \pi\pi > 10^6 \times D \to \mu\mu$)
  → Use particle identification to fight against $\pi \to \mu$ misID

- Normalized Measurements to help controlling the systematics

$$BF_{(signal)} = BF_{(norm)} \frac{\varepsilon_{(norm)}}{\varepsilon_{(signal)}} \frac{N_{(signal)}}{N_{(norm)}}$$

Ex. : $D^+ \to \pi^+\mu^+\mu^-$
and $D^+ \to \pi^+ \varphi(\mu^+\mu^-)$

- Blind analyses, Upper limits from the CLs method *[A. Read, J. Phys. G28 (2002)]*

Looking for New Physics in rare SM processes $D^0 \to \gamma\gamma$

- FCNC: forbidden at tree level, loop: CKM and GIM suppressed
- Very rare process in SM: NP contribution could be substantial

Model	$\mathcal{B}r$	Reference
SM, VMD	$(3.5^{+4.0}_{-2.6}) \times 10^{-8}$	Burdman [PRD 66, 014009 (2002)]
SM, HQχPT	$(1.0 \pm 0.5) \times 10^{-8}$	Fajfer [PRD 64, 074008 (2001)]
MSSM	6×10^{-6}	Prelovšek [PLB 500, 304 (2001)]

Table: Theoretical calculations.

Group	$\sqrt{s}$	Data (fb^{-1})	$\mathcal{B}r$ UL @90%CL	Reference
CLEO	10.58 GeV	13.8	$< 2.9 \times 10^{-5}$	PRL 90, 101801 (2003)
BaBar	10.58 GeV	470.5	$< 2.2 \times 10^{-6}$	PRD 85, 091107
BESIII	3.77 GeV	2.92	$< 3.8 \times 10^{-6}$	PRD91, 112015 (2015)

Table: Previous measurements.

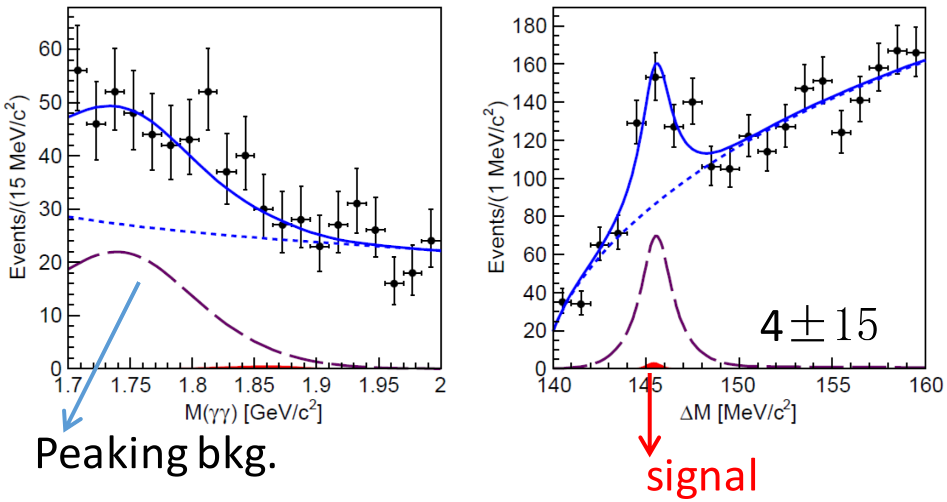
Determine $\mathcal{B}r$ via a **normalisation channel**: $D^0 \to K_S^0\pi^0$

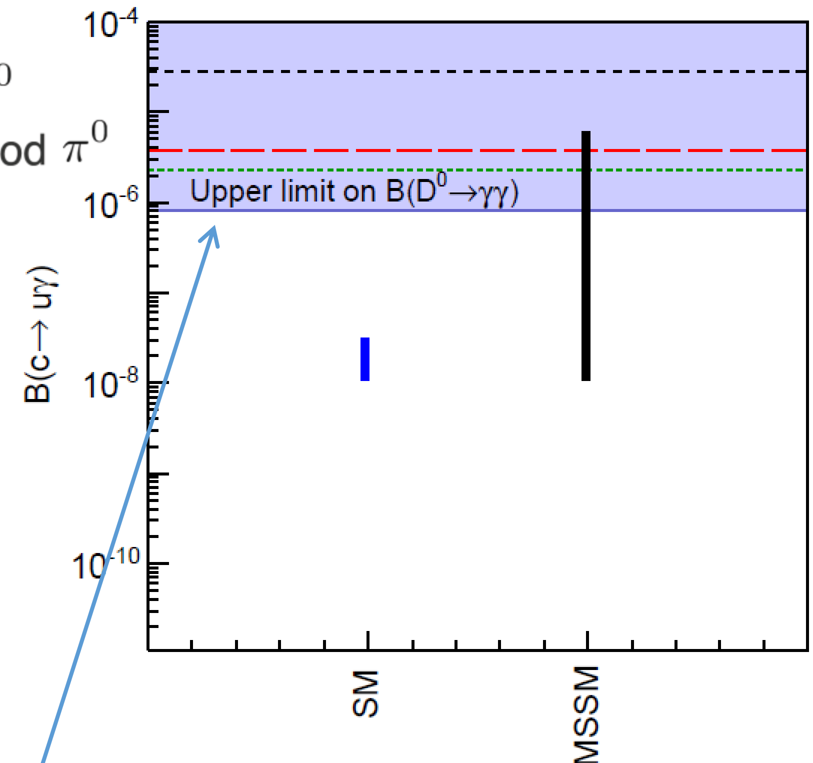
$$\mathcal{B}r(D^0 \to \gamma\gamma) = \frac{N(D^0 \to \gamma\gamma)}{N(D^0 \to K_S^0\pi^0)} \times \frac{\varepsilon_{K_S^0\pi^0}}{\varepsilon_{\gamma\gamma}} \times \mathcal{B}r(D^0 \to K_S^0\pi^0)$$

Signal yield extraction

PRD 93, 051102(R) (2016)

- Use a D* tag
- Normalisation to $D^0 \to K_S^0 \pi^0$
- Measure main background as well $D^0 \to \pi^0 \pi^0$
  - π^0 veto ➽ reject all γ's that can be used for a good π^0



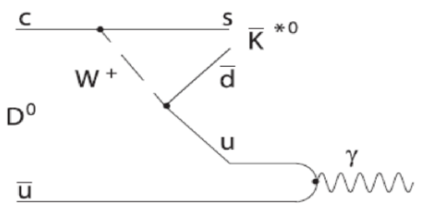


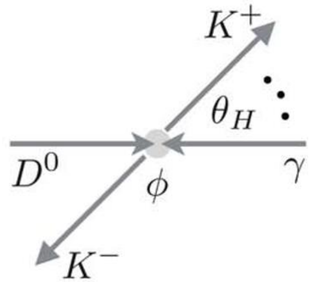
$$\mathcal{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$$

- Best result to date, however still only upper limit.
- Larger data samples needed in order to further improve the measurents.

$D \to V\gamma$ ($V = \phi, \bar{K}^{*0}, \rho^0$)

NEW





BABAR

PRD78,071101(2008)

$M_{V\gamma}$ and $\cos\theta_H$ 2-dimension fit:

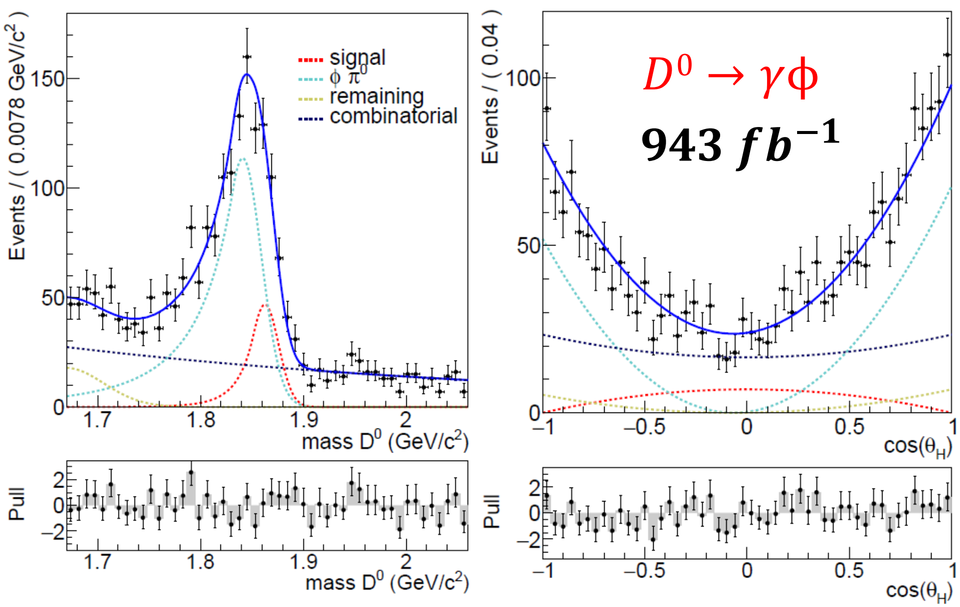
$$\mathcal{B}(D^0 \to \phi\gamma) = (2.78 \pm 0.30 \pm 0.27) \times 10^{-5}$$

only $M_{V\gamma}$ fit, and $\cos\theta_H$ consistency check:

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (3.28 \pm 0.20 \pm 0.27) \times 10^{-4}$$

(first observation)

- Dominated by long-range contibution
- Sensitive to New Physics via CP asymmetry
  Phys. Rev. Lett. 109, 171801
- $M_{V\gamma}$ and $\cos\theta_H$ 2-dimension fit



Belle results:

arxiv:1603.03257

$$\mathcal{B}(D^0 \to \phi\gamma) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}$$

(improved Belle result, $\simeq$ W.A)

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}$$

(3.3σ away from BABAR analysis)

$$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$$

(first observation, $\simeq$ theoretical predictions)

$$\mathcal{B}_{\rm sig} = \mathcal{B}_{\rm norm} \times \frac{N_{\rm sig}}{N_{\rm norm}} \times \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}$$

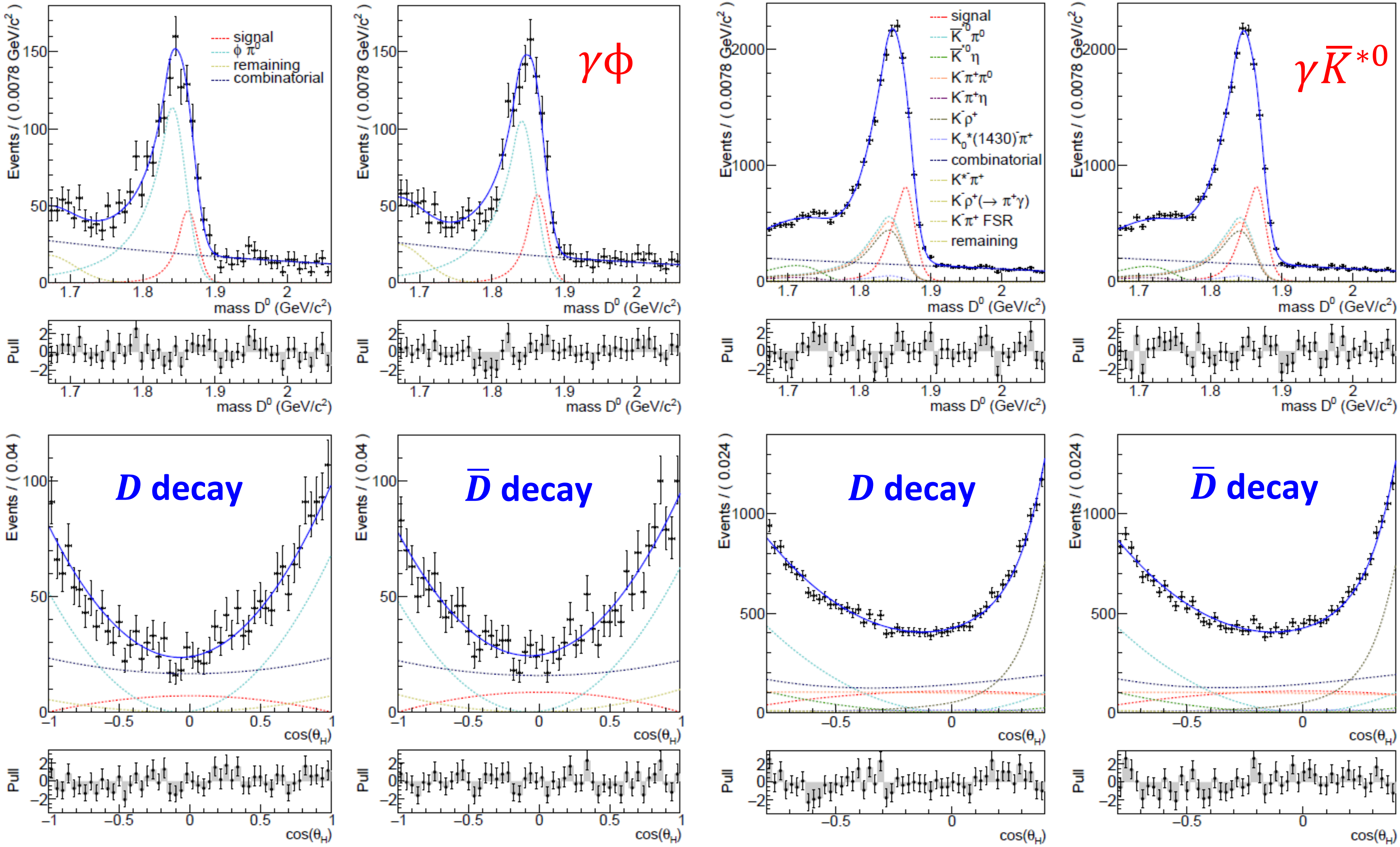
Normalized modes:

$D \to K^+K^-$ (ϕ mode); $K^-\pi^+$ (K^* mode)

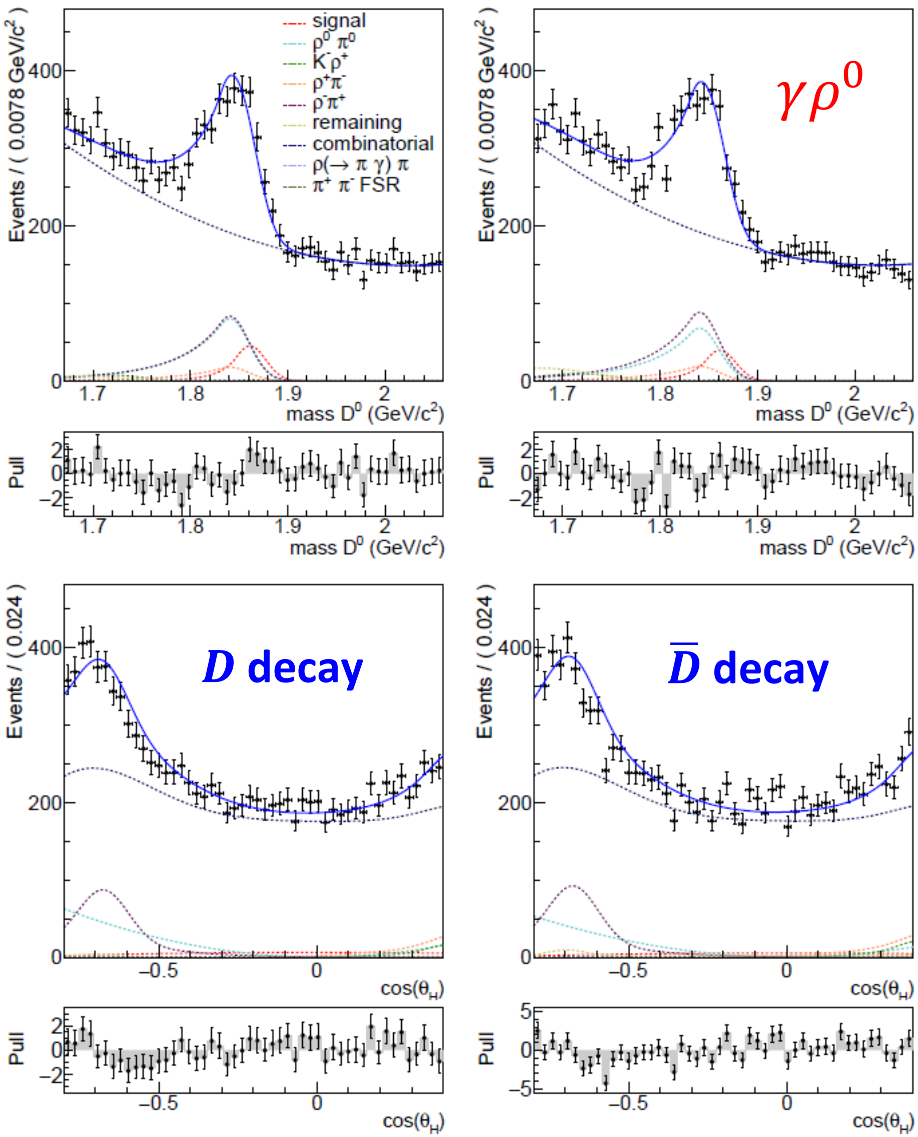
$\pi^+\pi^-$ (ρ^0 mode)

$D \to V\gamma$ (V = $\phi, \overline{K}^{*0}, \rho^0$)

arxiv:1603.03257



$D \to V\gamma$ (V = $\phi, \overline{K}^{*0}, \rho^0$)



- In radiative Charm decays: $\mathcal{A}_{CP}^{V\gamma}$ > 3% means signal for NP

(Phys. Rev. Lett. 109, 171801)

$$A_{\mathrm{raw}} = \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)}$$

$$\mathcal{A}_{CP}^{\mathrm{sig}} = A_{\mathrm{raw}}^{\mathrm{sig}} - A_{\mathrm{raw}}^{\mathrm{norm}} + \mathcal{A}_{CP}^{\mathrm{norm}}$$

arxiv:1603.03257

$$\mathcal{A}_{CP}(D^0 \to \phi\gamma) = -(0.094 \pm 0.066 \pm 0.001)$$

$$\mathcal{A}_{CP}(D^0 \to \overline{K}^{*0}\gamma) = -(0.003 \pm 0.020 \pm 0.000)$$

$$\mathcal{A}_{CP}(D^0 \to \rho^0\gamma) = 0.056 \pm 0.151 \pm 0.006$$

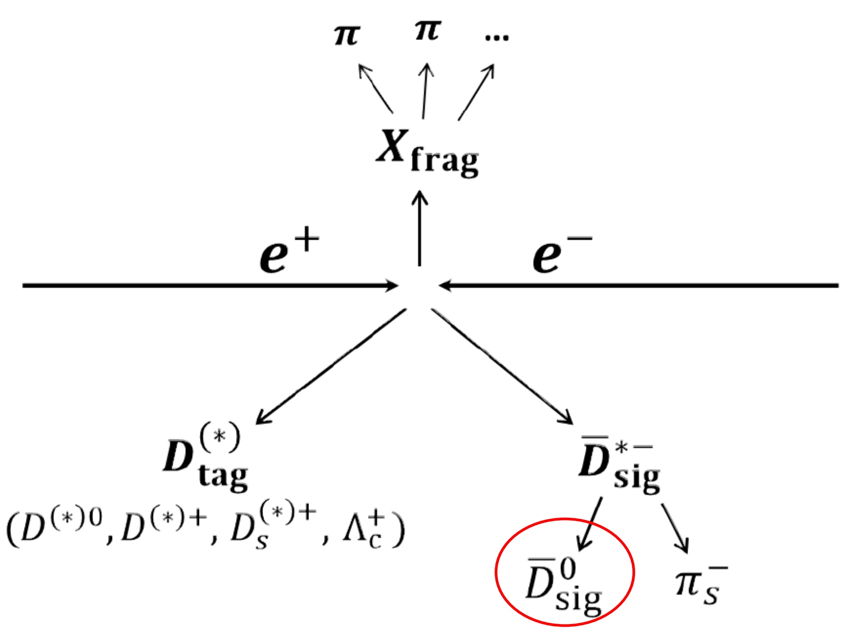
No observation of CP asymmetry

Higher precision needed

$D^0 \to$ invisible final states

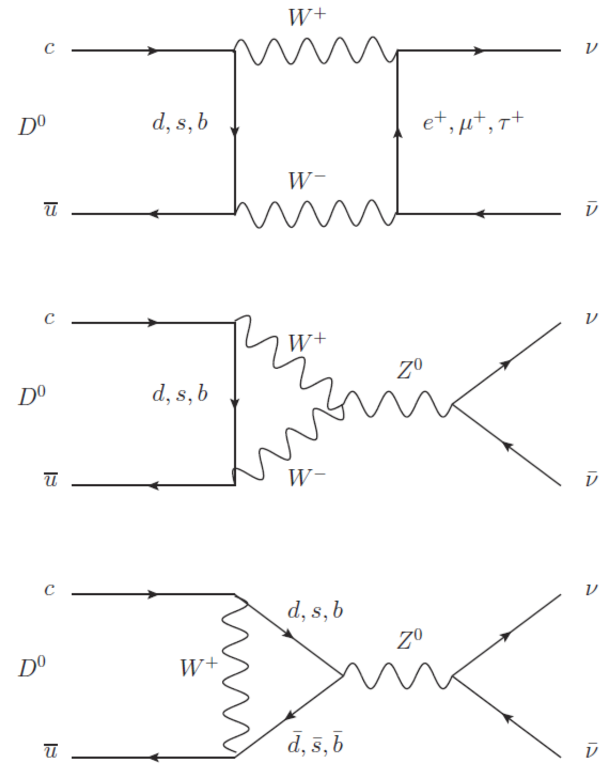
- D meson to $\nu\bar{\nu}$ is helicity suppressed in SM with Br~1.1×10^{-30}
- Under different DM models the Br can reach $O(10^{-15})$
  PLB651, 374(2007); Phys.Rept.117,75(1985)
- Use charm tagger method to select an inclusive D^0 sample which allows the identification of D^0 invisible decays

$$e^+e^- \to c\bar{c} \to D^{(*)}_{\rm tag} X_{\rm frag} \bar{D}^{*-}_{\rm sig}$$



An illustration of the charm tagger method.

$$M_{D^0} \equiv M_{\rm miss}(D^{(*)}_{\rm tag} X_{\rm frag} \pi_s^-)$$

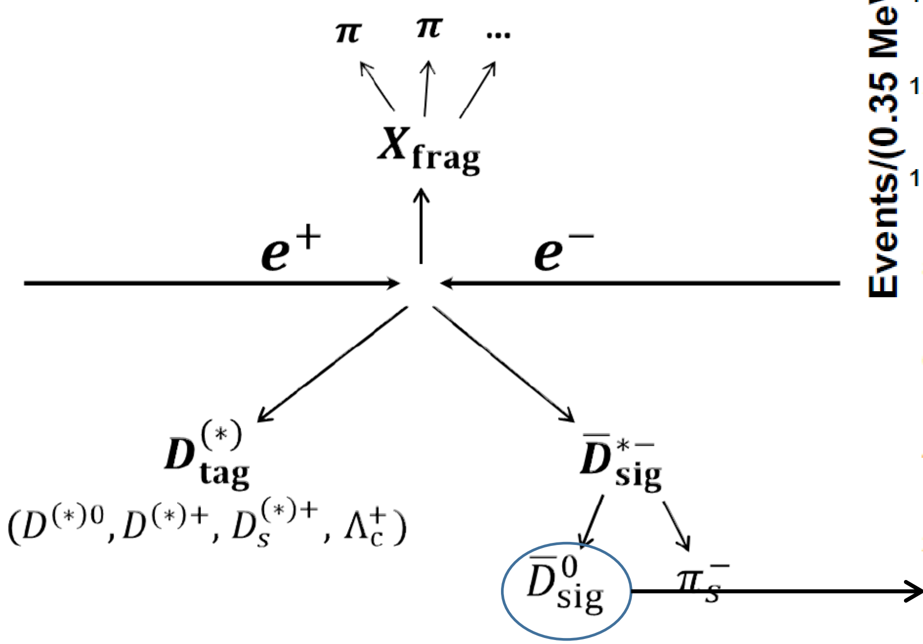


Decay diagrams of $D^0 \to \nu\bar{\nu}$.

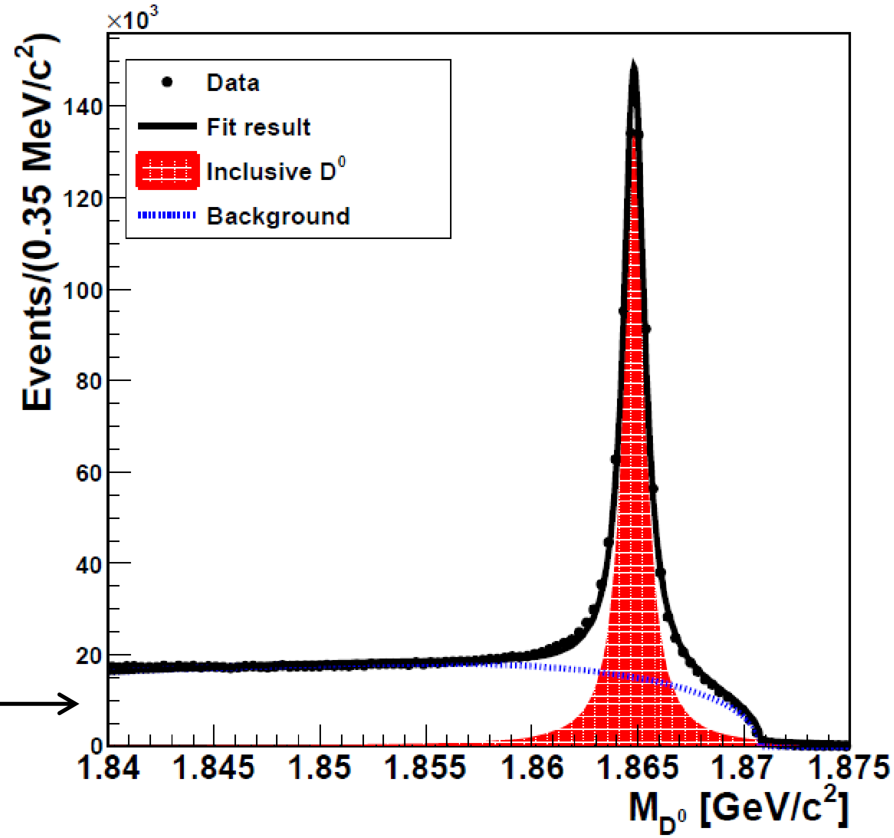
- $X_{\rm frag}$: a few unflavored mesons
- Four types of $D_{\rm tag}$ are reconstructed using 23 decay modes
- $D^*_{\rm tag}$ are reconstructed in five decay modes: $D^0\pi^+$, $D^+\pi^0$, $D^0\pi^0$, $D^0\gamma$, $D_s^+\gamma$

$D^0 \to$ invisible final states

$$e^+e^- \to c\bar{c} \to D^{(*)}_{\rm tag} X_{\rm frag} \bar{D}^{*-}_{\rm sig}$$



$$M_{D^0} \equiv M_{\rm miss}(D^{(*)}_{\rm tag} X_{\rm frag} \pi_s^-)$$

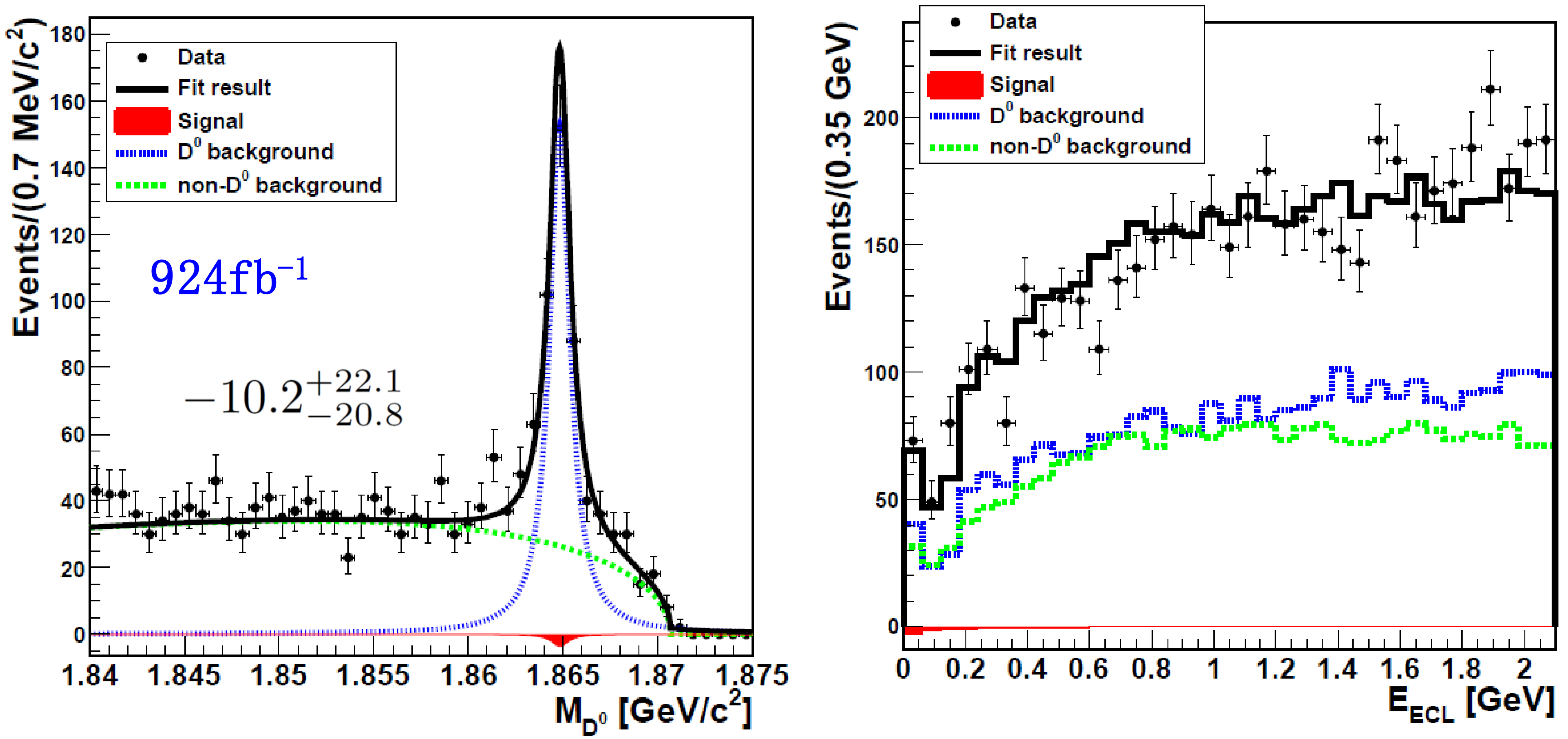


694505^{+1030}_{-1472} inclusive D^0 decays.

- $D^0 \to$invisible decays are selected by requiring no remaining final states associated with $\overline{D^0}_{\rm tag}$
- The residual energy in the ECL, E_{ECL}, is used to extract signal events
- 2D fit: $M(D^0)$, E_{ECL}

$D^0 \rightarrow$ invisible final states

- 2D fit: $M(D^0)$, E_{ECL}

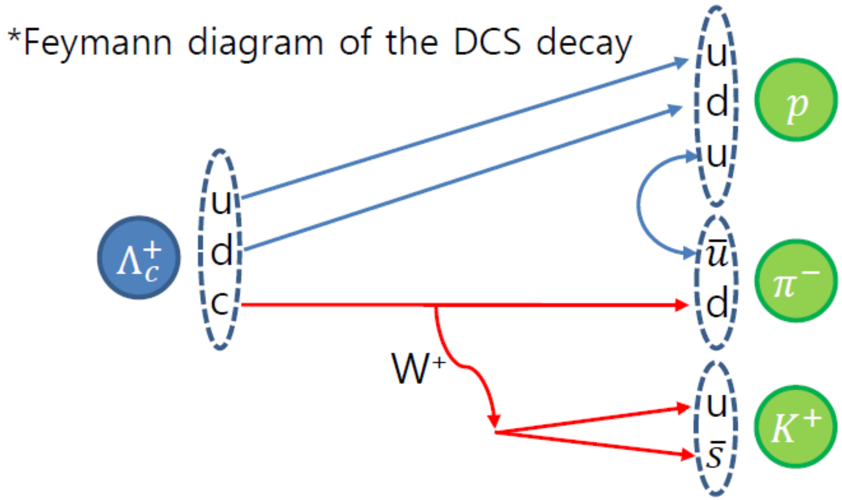


·No significant signal yield is found

·Br($D^0\rightarrow$invisible decays)<8.8×10^{-5} @ 90%C.L. with sys errors included

·Large data sample is needed to improve the UL.

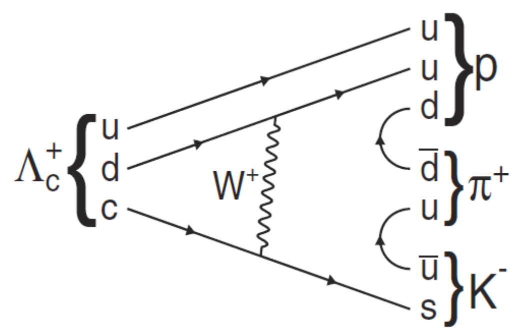
First Observation of DCS $\Lambda_c^+ \to p K^+ \pi^-$



- Naïve expectation

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

- Contribution of W exchange in Λ_c^+ decay can be estimated

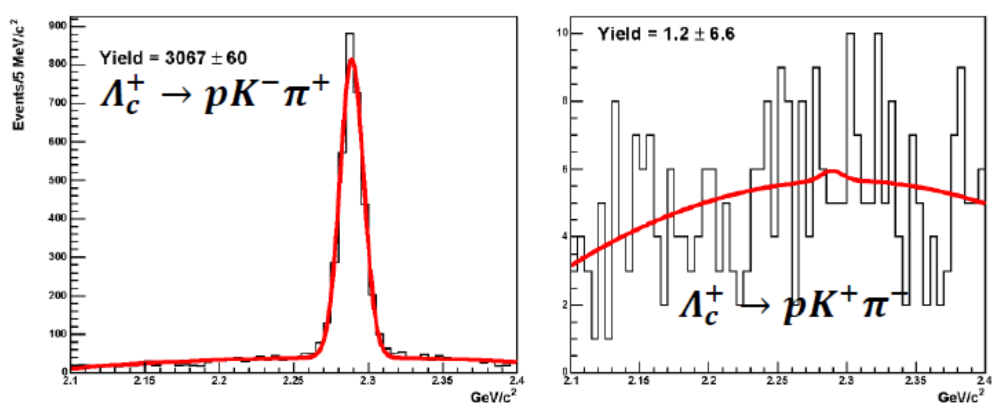


Only in CF, Prohibited in DCS

- Previous study

→FOCUS group reported a negative result.
It is the first observation of DCS decay of a charmed baryon.

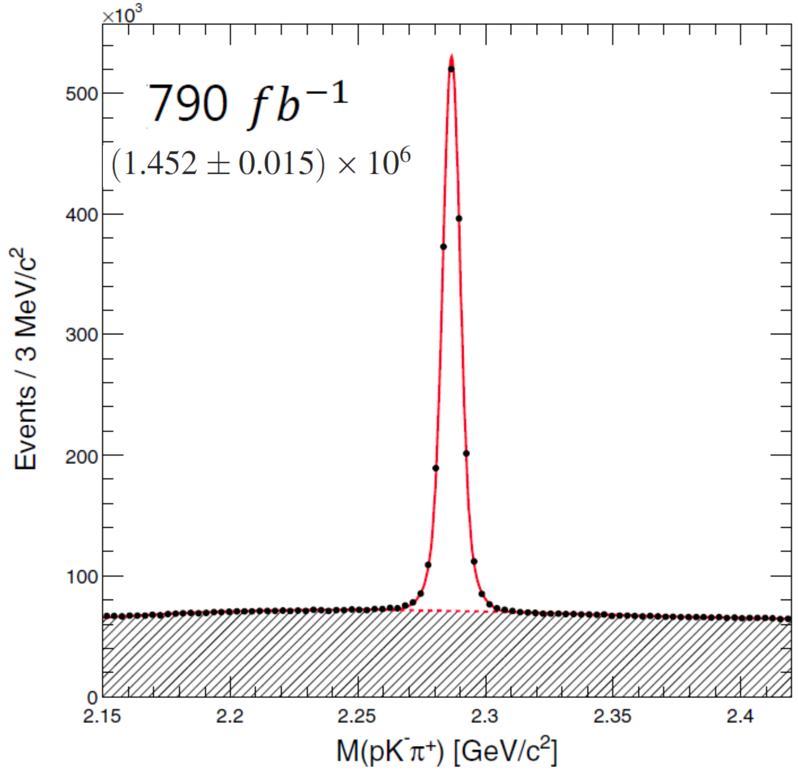
*FOCUS group, PLB 624 (2005) 166-172

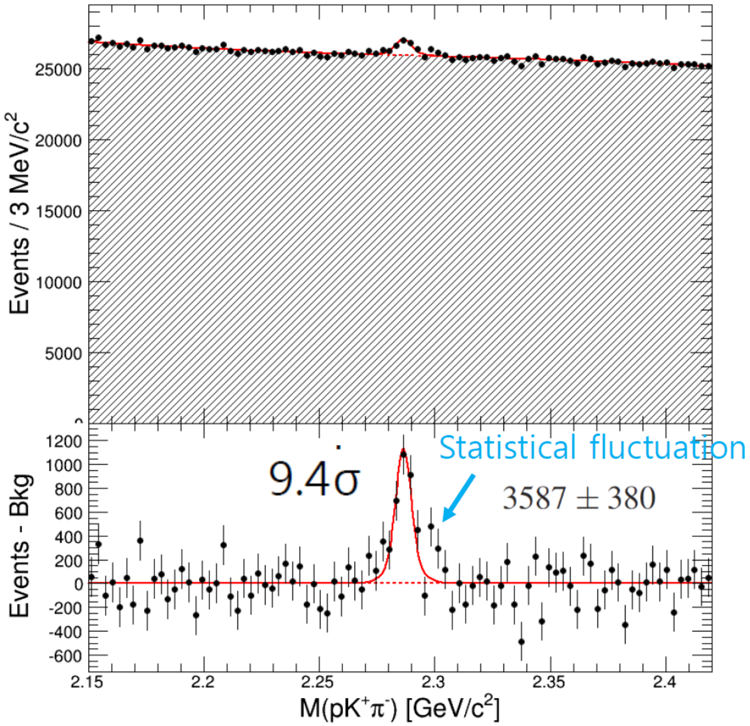


First Observation of DCS $\Lambda_c^+ \to p K^+ \pi^-$

- Fitting functions: 2 Gaussians (common mean) + a polynomial

PRL 117, 011801 (2016)





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

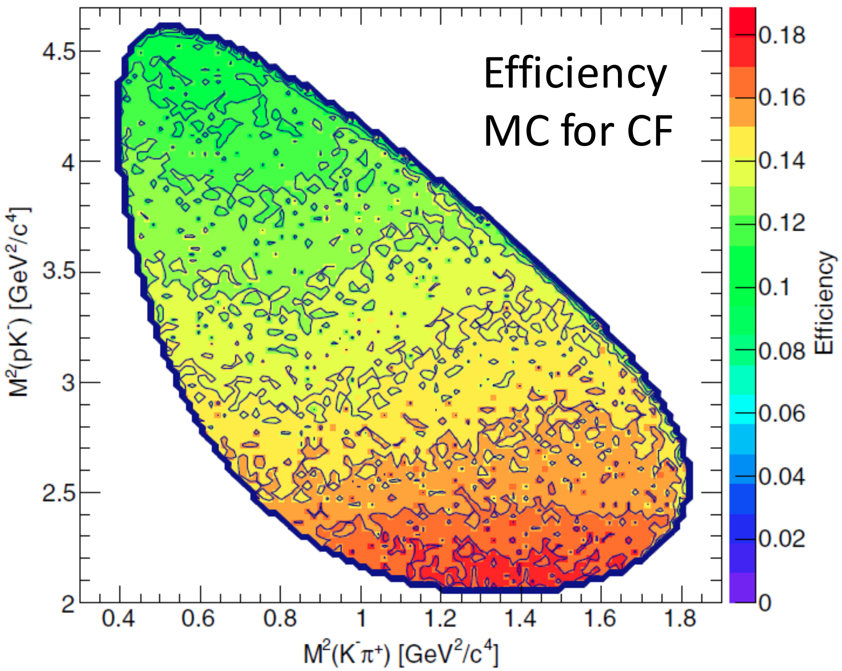
$$s(SCS) = \frac{BR(SCS)}{BR(CF)} \times \frac{\epsilon(SCS)}{\epsilon(CF)} \times s(CF),$$

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.

First Observation of DCS $\Lambda_c^+ \to p K^+ \pi^-$

PRL 117, 011801 (2016)



- Relative efficiency

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

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

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

$$\frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)}$$

$$= (2.35 \pm 0.27(Stat.) \pm 0.21(Syst.)) \times 10^{-3}$$

$$= (0.82 \pm 0.12(total)) \times \tan^4\theta_C$$

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

→ *W* exchange does not make a large contribution.

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

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

Summary

- The rare decay $D^0 \to \gamma\gamma$ using $832 fb^{-1}$ data is searched for, but no significant signal is seen and the most restrictive limit $B(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ @ 90% C.L. is set.
- Brs and Acp in $D^0 \to \gamma V$ ($V = \phi, \bar{K}^{*0}, \rho^0$) are measured. The $Br(D^0 \to \gamma\phi)$ is improved. The $Br(D^0 \to \gamma\bar{K}^{*0})$ is 3.3σ away from BaBar result. First observation of $D^0 \to \gamma\rho^0$. No observation of CP asymmetry in any of these three modes is observed.
- The first search for D^0 decays into invisible final states is performed. No significant signal is found and the upper limit on Br is 8.8×10^{-5} @ 90% C.L.
- The DCS $\Lambda_c^+ \to p K^+ \pi^-$ is clearly observed for the first time for a charmed baryon. The W-exchange contribution is small.
- BelleII construction is ongoing. The 50 ab^{-1} data is expected by 2024. Rare charm decays can be performed better especially for the modes with neutral tracks.

Thanks!

Experimental requirements

- Large samples of charm
- Good background rejection and high signal efficiency
  - excellent particle identification
  - large boost ➜ displaced vertex
  - excellent reconstruction of photons and neutral pions
  - hermeticity of detector