# Search for CP violation and rare decays in charm sector at Belle

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# Talk Outline

- First measurement of T-odd moments in the decay $D^0 \to K_s \pi^+ \pi^- \pi^0$ **PRD 95, 091101(R) (2017)**
- Observation of $D^0 \to \rho^0 \gamma$ and search for CP asymmetry in $D^0 \to \phi\gamma$, $D^0 \to K^{*0}\gamma$, $D^0 \to \rho^0\gamma$ decay **PRL 118, 051801 (2017)**
- Measurement of *Br* and CP asymmetry in $D^0 \to K^0_s K^0_s$ decay **arxiv:1705.05966**
- First search for $D^0$ decays to invisible final states. **(already covered by Youngjoon Kwon yesterday)** **PRD 95, 011102(R) (2017)**
- Data set used for all the above analysis: ~1000 $fb^{-1}$

# Motivation:

- Self conjugate final state, $D^0 \rightarrow K_s \pi^+ \pi^- \pi^0$ has large B.R. of 5.2%. This allows precise test of CP violation
- Previously the decay was studied by MARK III Collaboration with only 140 events using data sample of 9.56 $pb^{-1}$ Phys. Rev. D 45, 2196 (1992)
- Via CPT theorem, the T-asymmetry in this decays is sensitive to CP violation
- Measurement is performed via scalar triple product: $C_T = p_{KS} \cdot (p_{\pi+} \times p_{\pi-})$ for $D^0$ and $\bar{C}_T$ for $\bar{D}^0$
- The two asymmetry parameters for $D^0$ and $\bar{D}^0$:

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)},$$

$$\bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

and CP violation sensitive parameter:

$$a_{CP}^{T\text{-odd}} = \frac{1}{2}(A_T - \bar{A}_T)$$

# First measurement of T-odd moments in the decay $D^0 \to K_s \pi^+ \pi^- \pi^0$ PRD 95, 091101(R) (2017)

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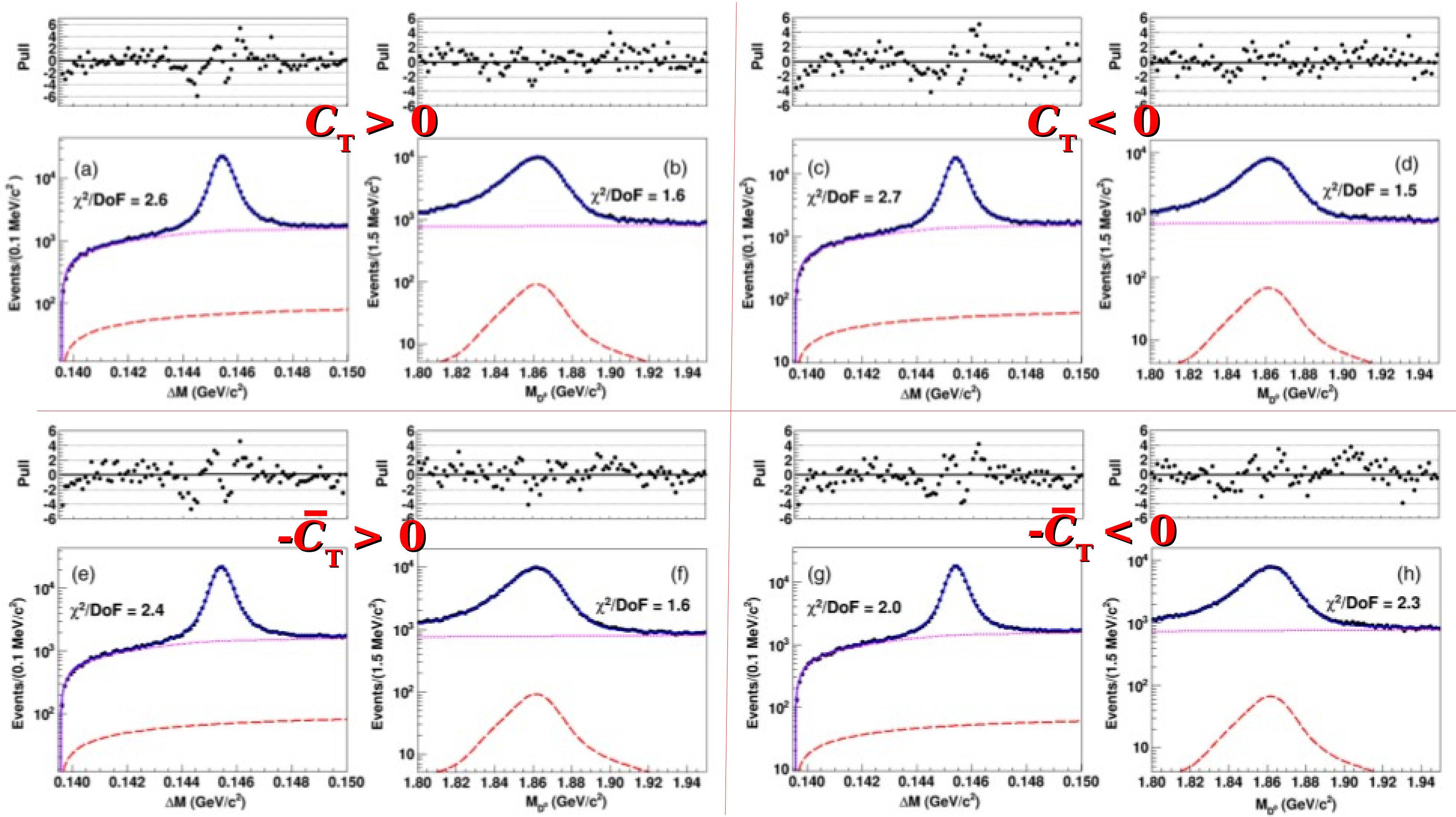
## Signal extraction($e^+e^- \to c\bar{c} \to XD^* \to \pi^+_{slow} D^0 \to K_s \pi^+\pi^-\pi^0$)

Two-dimensional unbinned maximum likelihood fit to $\Delta M$ ($M_{D^{*+}}$ - $M_{D0}$) and $M_{D0}$

Fit includes a small correlation between the width of $\Delta M$ and $M_{D0}$




Signal enhanced logarthimic distribution

# First measurement of T-odd moments in the decay $D^0 \to K_s \pi^+ \pi^- \pi^0$ PRD 95, 091101(R) (2017)

## Result:

**Signal yield = 744509 ±1622**

**$A_T$ = (11.60 ± 0.19)%**

**$A_{CP}$(T-odd) = $(-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$**

Result consistent with no CP violation, also no evidence for CP violation in various bins of $K_s\pi^+\pi^-\pi^0$ phase space

| Bin | Resonance | Invariant mass requirement (MeV/$c^2$) | $A_T(\times 10^{-2})$ | $a_{CP}^{T\text{-odd}}(\times 10^{-3})$ |
|---|---|---|---|---|
| 1 | $K_S^0\omega$ | $762 < M_{\pi^+\pi^-\pi^0} < 802$ | $3.6 \pm 0.5 \pm 0.5$ | $-1.7 \pm 3.2 \pm 0.7$ |
| 2 | $K_S^0\eta$ | $M_{\pi^+\pi^-\pi^0} < 590$ | $0.2 \pm 1.3 \pm 0.4$ | $4.6 \pm 9.5 \pm 0.2$ |
| 3 | $K^{*-}\rho^+$ | $790 < M_{K_S^0\pi^-} < 994$<br>$610 < M_{\pi^+\pi^0} < 960$ | $6.9 \pm 0.3^{+0.6}_{-0.5}$ | $0.0 \pm 2.0^{+1.6}_{-1.4}$ |
| 4 | $K^{*+}\rho^-$ | $790 < M_{K_S^0\pi^+} < 994$<br>$610 < M_{\pi^-\pi^0} < 960$ | $22.0 \pm 0.6 \pm 0.6$ | $1.2 \pm 4.4^{+0.3}_{-0.4}$ |
| 5 | $K^{*-}\pi^+\pi^0$ | $790 < M_{K_S^0\pi^-} < 994$ | $25.5 \pm 0.7 \pm 0.5$ | $-7.1 \pm 5.2^{+1.2}_{-1.3}$ |
| 6 | $K^{*+}\pi^-\pi^0$ | $790 < M_{K_S^0\pi^+} < 994$ | $24.5 \pm 1.0^{+0.7}_{-0.6}$ | $-3.9 \pm 7.3^{+2.4}_{-1.2}$ |
| 7 | $K^{*0}\pi^+\pi^-$ | $790 < M_{K_S^0\pi^0} < 994$ | $19.7 \pm 0.8^{+0.4}_{-0.5}$ | $0.0 \pm 5.6^{+1.1}_{-0.9}$ |
| 8 | $K_S^0\rho^+\pi^-$ | $610 < M_{\pi^+\pi^0} < 960$ | $13.2 \pm 0.9 \pm 0.4$ | $7.6 \pm 6.1^{+0.2}_{-0.0}$ |
| 9 | Remainder | ... | $20.5 \pm 1.0^{+0.5}_{-0.6}$ | $1.8 \pm 7.4^{+2.1}_{-5.3}$ |

Our result constitutes one of the most precise tests of CP violation in the D meson system.

Statistically dominated, sensitivity can be improved by Belle II

# Observation of $D^0 \to \rho^0\gamma$ and search for CP asymmetry in $D^0 \to \varphi\gamma$, $D^0 \to \bar{K}^{*0}\gamma$, $D^0 \to \rho^0\gamma$ decay

PRL 118, 051801 (2017)

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## Motivation:

- Radiative charm decays dominated by long range non-perturbative processes which enhance the B.F. to $O(10^{-4})$ from $O(10^{-8})$, obtained from short range processes

- Measurement of Br can be used to test QCD based calculations of long distance dynamics

- Sensitive to New Physics in terms of $A_{CP}$ measurement:

  SM prediction: $O(10^{-3})$

  SM extensions with chromomagnetic dipole operators: up to several % for V = φ, ρ0

  [Phys. Rev. Lett. 109,171801 (2012)]

- Previous measurements:

  CLEO II : B.F.($D^0 \to \rho^0\gamma$) < 2.4 × 10 -4 (4.8 $fb^{-1}$ ) Phys. Rev. D 58, 092001 (1998)

  BELLE : $D^0 \to \varphi\gamma$ first observed (78.1 $fb^{-1}$ ) Phys. Rev. Lett. 92, 101803 (2004)

  BABAR : B.F.($D^0 \to \varphi\gamma$) = (2.78 ± 0.30 ± 0.27) x $10^{-5}$ (387.1 $fb^{-1}$)
  : B.F.($D^0 \to \bar{K}^{*0}\gamma$) = (2.78 ± 0.30 ± 0.27) x $10^{-5}$ (387.1 $fb^{-1}$) Phys. Rev. D 78, 071101(R) (2008)

- No $A_{cp}$ measurements yet in $D^0 \to V\gamma$

# Analysis overview:

- B.F. and $A_{CP}$ measured for modes: $D^0 \to \phi(K^+K^-)\gamma$, $\rho^0(\pi^+\pi^-)\gamma$ and $\bar{K}^{*0}(K^-\pi^+)\gamma$ w.r.t. their normalization modes: $D^0 \to K^+K-$, π+π-, and K- π+ respectively

- B.F. Measurement: $\mathcal{B}_{\rm sig} = \mathcal{B}_{\rm norm} \times \frac{N_{\rm sig}}{N_{\rm norm}} \times \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}$

- CP asymmetry: $A_{\rm raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to \bar{f})}{N(D^0 \to f) + N(\bar{D}^0 \to \bar{f})}$

$$A_{RAW} = A_{CP} + A_{FB} + A_{\varepsilon}^{\pm}$$

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

- For Flavor tag and combinatorial bkg suppression: $D^0$ from $D^{*+} \to D^0\pi^+$

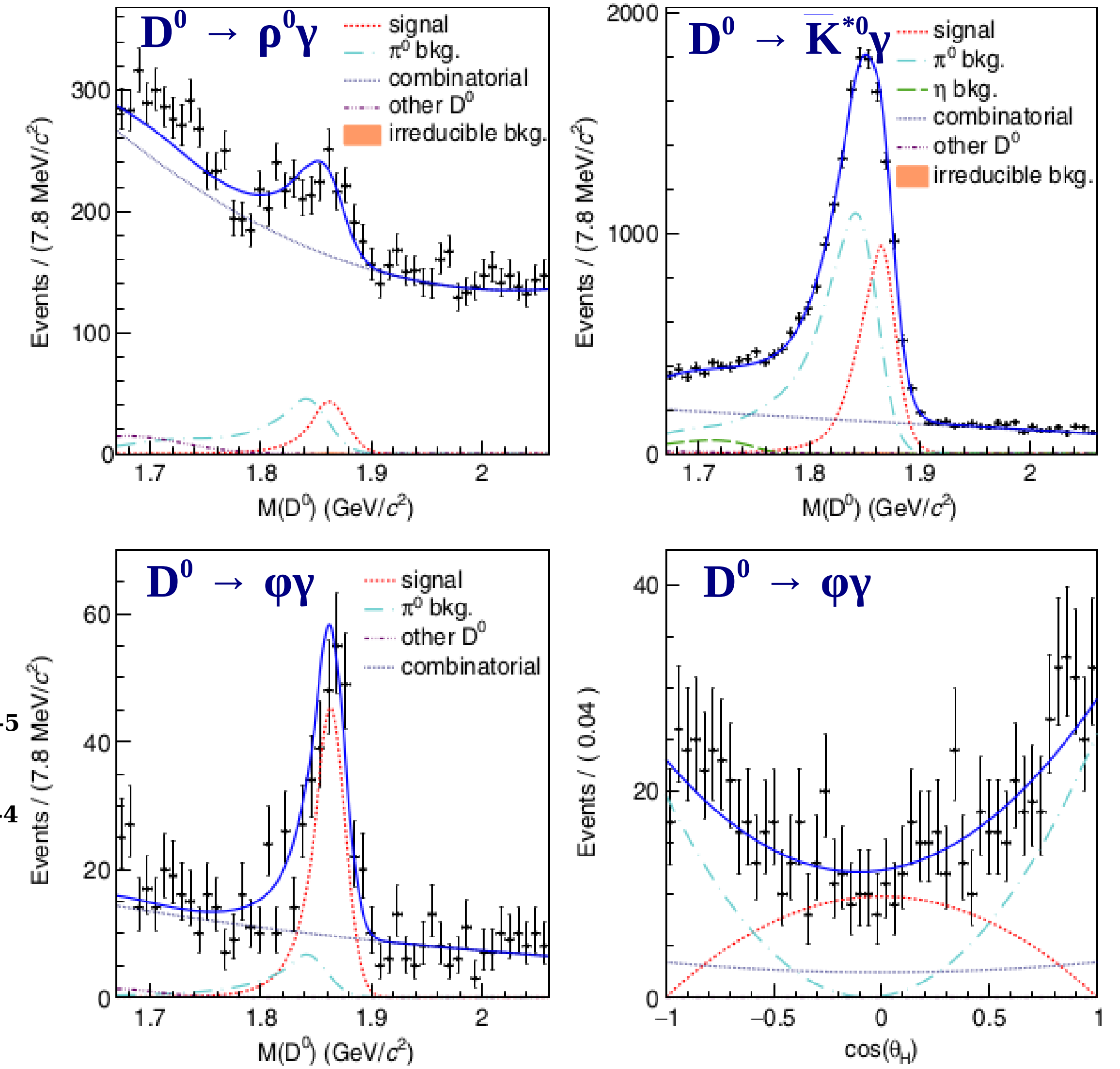
- Dedicated $\pi^0$ veto: using an artificial neural network;
→ The new veto rejects 13% more background than the previous veto at the same signal efficiency of 85%

# Observation of $D^0 \to \rho^0\gamma$ and search for CP asymmetry in $D^0 \to \varphi\gamma$, $D^0 \to \bar{K}^{*0}\gamma$, $D^0 \to \rho^0\gamma$ decay

PRL 118, 051801 (2017)

## Signal extraction:

Yield and CP asymmetry extracted from simultaneous unbinned ML fits to $M(D^0)$ and Helicity angle




## Results:

Branching fractions:

**B.F.($D^0 \to \rho^0\gamma$) = $(1.77 \pm 0.30 \pm 0.07) \times 10^{-5}$**
(first observation)

**B.F.($D^0 \to \varphi\gamma$) = $(2.76 \pm 0.19 \pm 0.10) \times 10^{-5}$**
(consistent with world average)

**B.F.($D^0 \to \bar{K}^{*0}\gamma$) = $(4.66 \pm 0.21 \pm 0.21) \times 10^{-4}$**
(3.3σ above the BABAR measurement)

CP asymmetry:

**$A_{CP}(D^0 \to \rho^0\gamma)$ = $+0.056 \pm 0.152 \pm 0.006$**

**$A_{CP}(D^0 \to \varphi\gamma)$ = $-0.094 \pm 0.066 \pm 0.001$**

**$A_{CP}(D^0 \to \bar{K}^{*0}\gamma)$ = $-0.003 \pm 0.020 \pm 0.000$**

First measurements! Results consistent with no CP violation, but statistically dominated, sensitivity can be greatly enhanced by Belle II

# Measurement of CP asymmetry in $D^0 \to K^0_s K^0_s$ decay

arxiv:1705.05966

- SCS decays (like $D^0 \to K^0_s K^0_s$) are of special interest: possibility of interference with NP amplitudes could lead to large nonzero CPV PRD 87 (2013) 014024
- SM UL of 1.1% for direct CPV in $D^0 \to K^0_s K^0_s$ PRD 92 (2015) 054036
- previous measurements:
  CLEO : $A_{CP}(D^0 \to K^0_s K^0_s) = (-23 \pm 19)\%$ (13.7 $fb^{-1}$) PRD 63 (2001), 071101(R)
  LHCb : $A_{CP}(D^0 \to K^0_s K^0_s) = (-2.9 \pm 5.2 \pm 2.2)\%$ (3 $fb^{-1}$) JHEP 10 (2015) 055
  BESIII: B.F.$(D^0 \to K^0_s K^0_s) = (1.67 \pm 0.11 \pm 0.11) \times 10^{-4}$ (2.93 $fb^{-1}$) Phys. Lett. B 765 (2017) 231
- Normalization mode $D^0 \to K^0_s \pi^0$

$$A_{\rm raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{CP} + A_{FB} + A_\epsilon^\pm + A_\epsilon^K$$

$$\begin{aligned} A_{CP}(D^0 \to K_S^0 K_S^0) \;=\; & A_{\rm raw}(D^0 \to K_S^0 K_S^0) - \\ & A_{\rm raw}(D^0 \to K_S^0 \pi^0) + \\ & A_{CP}(D^0 \to K_S^0 \pi^0) + A_\epsilon^K \end{aligned}$$

Asymmetry originating from different strong interaction of $K^0$ and $K^0$bar mesons with detector material, $A_\varepsilon^K = (-0.11 \pm 0.01)\%$ [PRD 84 (2011) 111501]

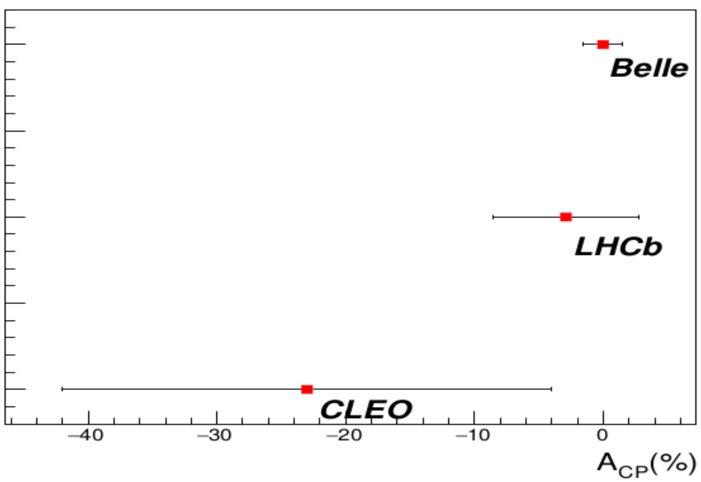
# Measurement of CP asymmetry in $D^0 \to K^0_s K^0_s$ decay

arxiv:1705.05966

## Result:

$A_{CP}(D^0 \to K^0_s K^0_s) = -0.02 \pm 1.53 \pm 0.02 \pm 0.17$

uncertainty on $A_{CP}(Br)$ of $D^0 \to K_S \pi^0$

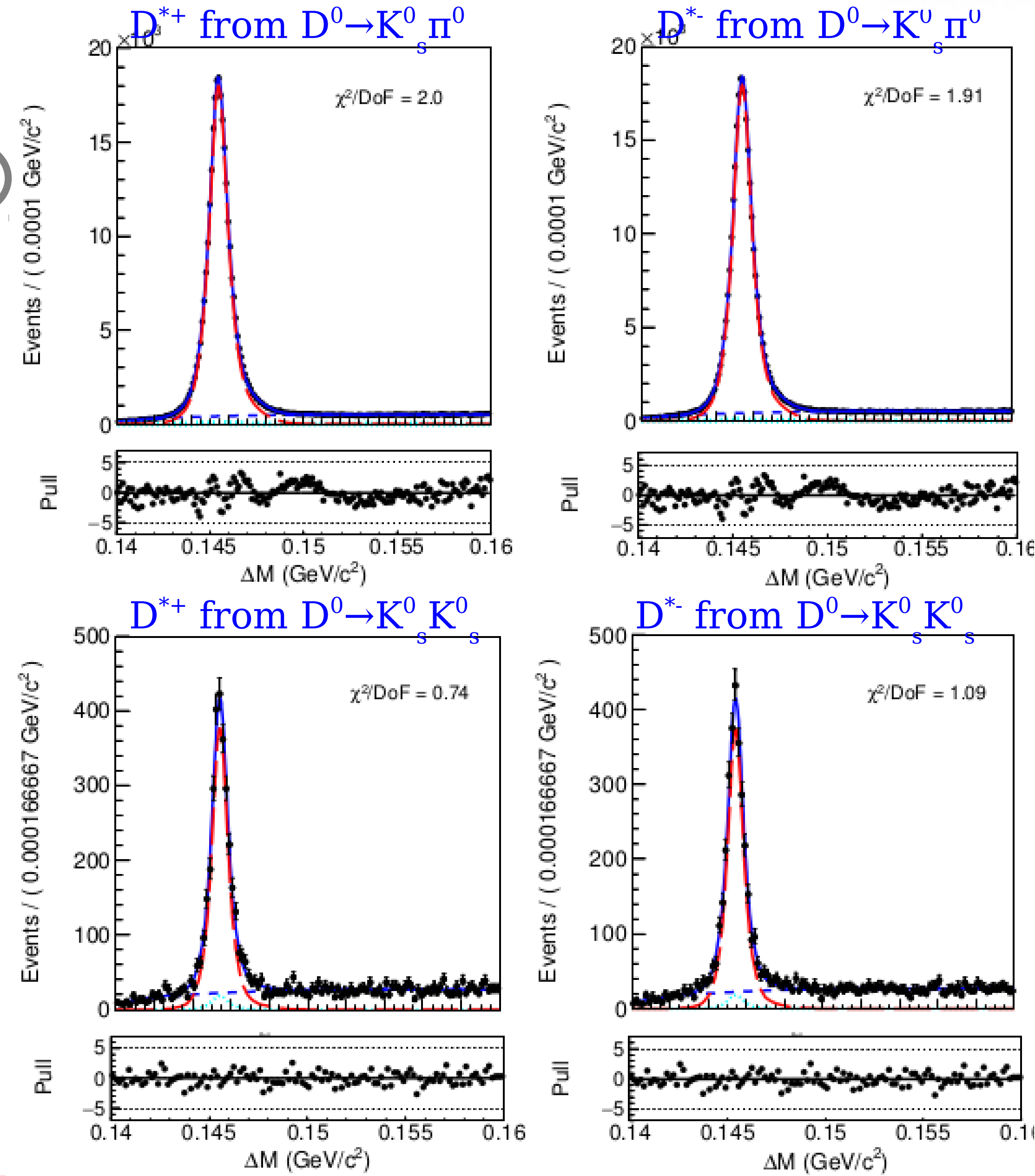



result consistent with no CPV, improved precision of previous best measurement by more than a factor 3 !!

$Br(D^0 \to K^0_s K^0_s)$

$= (1.32 \pm 0.02 \pm 0.04 \pm 0.04) \times 10^{-4}$

Result consistent with the world average.
2.3σ away from a recent BESIII measurement.






Both measurements are the most precise ones available for $D^0 \to K_S K_S$ mode.

# First search for $D^0$ decays to invisible final states.

PRD 95, 011102(R) (2017)

- Highly suppressed in SM with an expected Br of order $10^{-30}$ PRD 82, 034005 (2010)

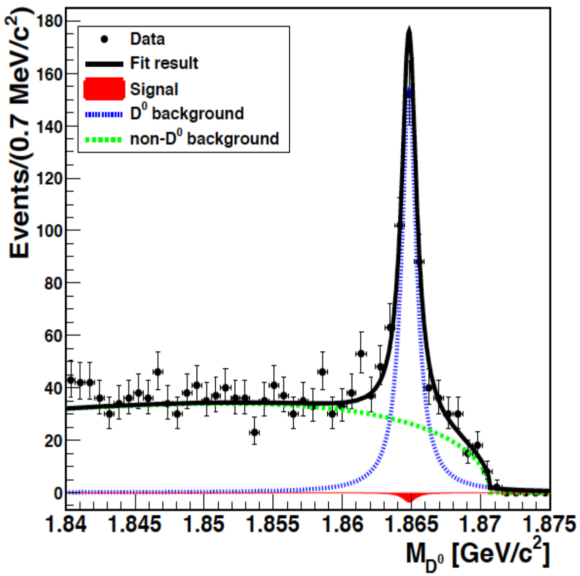
- Under different DM models the Br could reach up to to $10^{-15}$ PLB 651, 374 (2007) PR 117, 75 (1985)

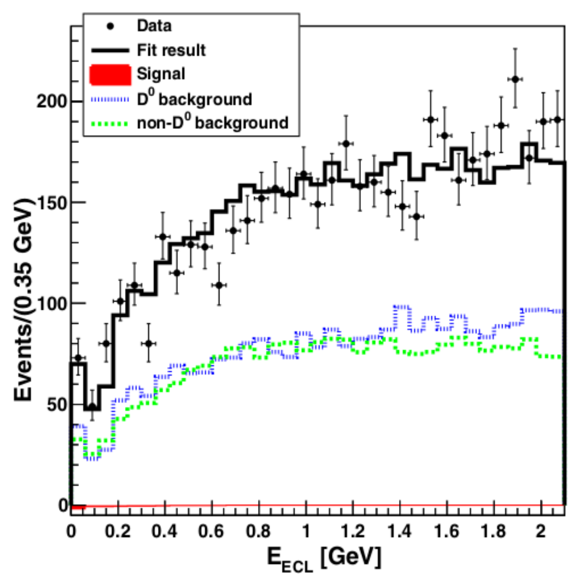
- Event reconstruction relies on an earlier technique by belle JHEP 09, 139 (2013)

Charm tagger method to select inclusive $D^0$ sample, which allows identification of $D^0$ decays to invisible particles

$$e^+e^- \to c\bar{c} \to D^{(*)}_{\rm tag} X_{\rm frag} \bar{D}^{*-}_{\rm sig} \text{ with } \bar{D}^{*-}_{\rm sig} \to \bar{D}^0_{\rm sig}\pi_s^-$$

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




- Signal extraction: 2D fit between $M(D^0)$ and $E_{ECL}$
- Signal yield = $-6.3^{+22.5}_{-21.0}$
- $Br(D^0 \to \text{invisible}) < 9.4 \times 10^{-5}$ @ 90% C.L.

First measurement!

# Summary:

- T-odd moments in the decay $D^0 \to K_s\pi^+\pi^-\pi^0$ :

  First measurement of T-odd moments in the decay $D^0 \to K_s\pi^+\pi^-\pi^0$. Result consistent with no CP violation, no evidence for CP violation in various bins of $K_s\pi^+\pi^-\pi^0$ phase space.

- $D^0 \to V\gamma$ decay:

  $Br(D^0 \to \rho^0\gamma)$ → first observation, $Br(D^0 \to \varphi\gamma)$ → consistent with world average, $Br(D^0 \to K^{*0}\gamma)$ → 3.3σ above the BABAR measurement. No observation of CP asymmetry in any of these three modes.

- $D^0 \to K^0_s K^0_s$ decay:

  CP asymmetry consistent with SM. significant improvement compared to the previous measurement of CLEO and LHCb Collaborations.
  Br consistent with the world average. 2.3σ away from a recent BESIII measurement.

- $D^0$ decays to invisible final states:

  The first search for $D^0$ decays into invisible final states is performed. No significant signal is found with Br < $9.4 \times 10^{-5}$ @ 90% C.L.

- BelleII expects 50 $ab^{-1}$ data by 2024. Rare charm decays with neutral tracks can be performed better .

Thank you!