Rare Charm Decays at BESIII

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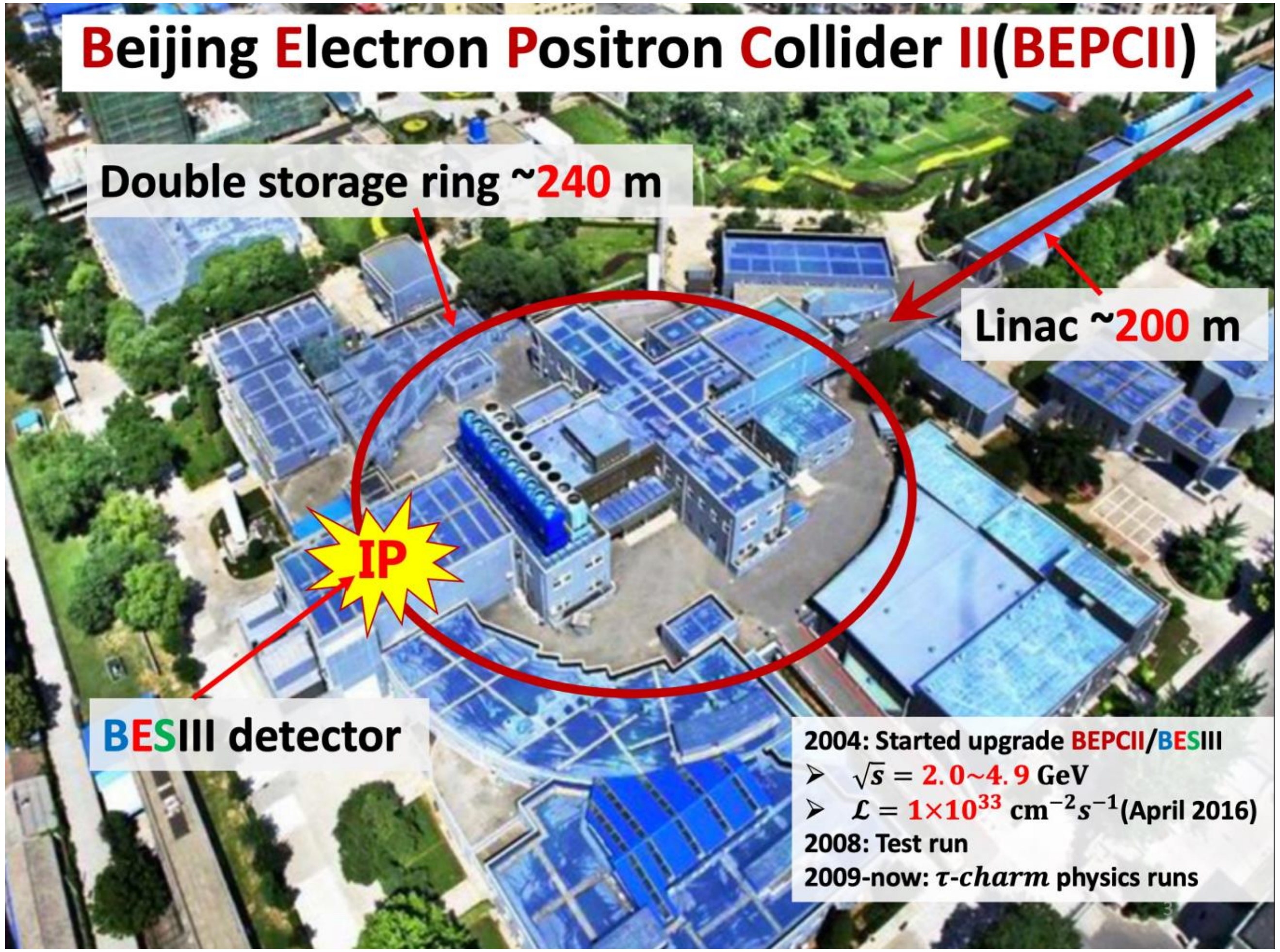
Outline

- BESIII experiment
- Charm datasets
- Included results (after CKM 2018):
  - Search for $D_s^+ \to \gamma e^+ \nu_e$ [PRD 99, 072002 (2019)]
  - Search for $D \to K\pi e^+ e^+$ [PRD 99, 112002 (2019)]
  - Search for $D^+ \to \Lambda(\Sigma^0)e$ [PRD 101, 031102 (2020)]
- Summary & outlook

BEPCII & BESIII



Electromagnetic CsI(Tl) Calorimeter (EMC)

σ_E/E < 2.5% @ 1 GeV (barrel)

σ_E/E < 5% @ 1 GeV (end-caps)

Time-of-Flight (TOF)

σ_t = 90 ps (barrel)

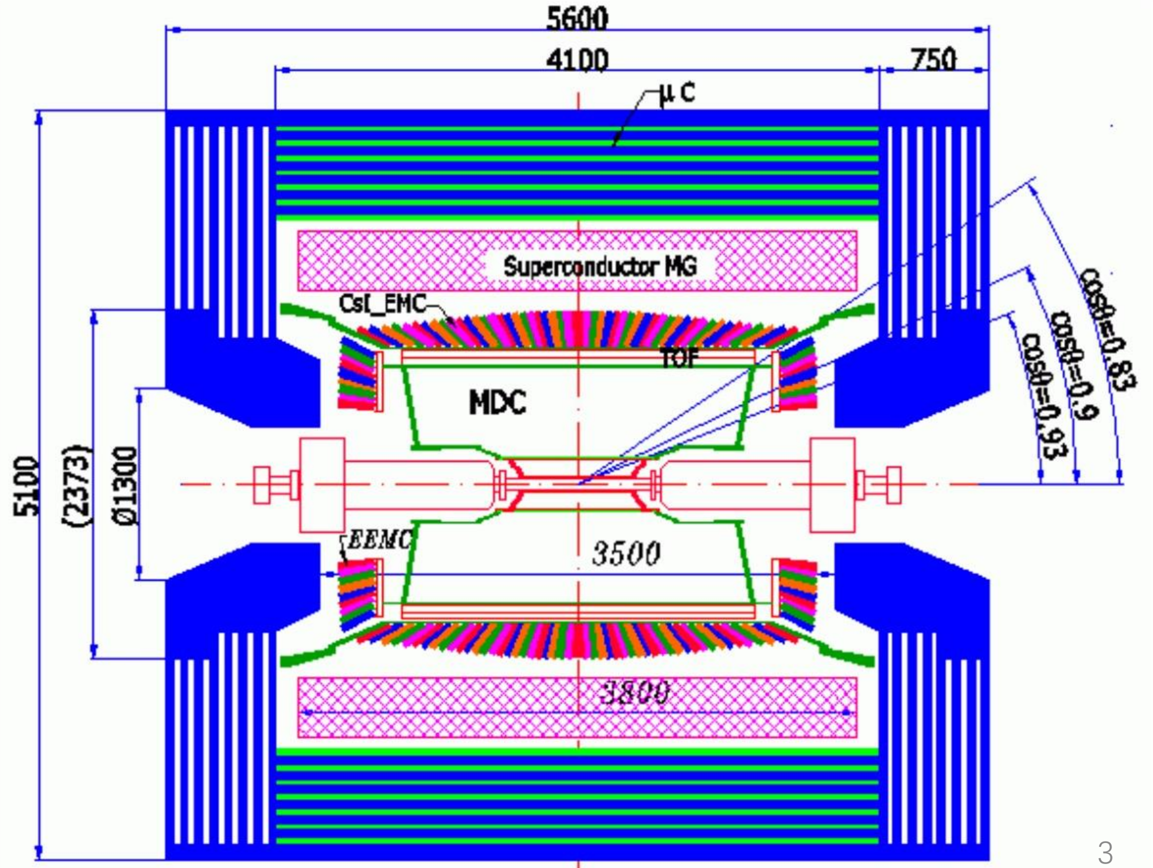
σ_t = 120 ps (end-caps)

Main Drift Chamber (MDC)

$\sigma_{r\phi}$ = 130 μm (single wire)

σ_{p_t}/p_t = 0.5% @ 1 GeV

Superconducting solenoid (1 Tesla)



M. Ablikim *et al*. (BESIII Collaboration), Nucl. Instr. Meth. A614, 345 (2010)

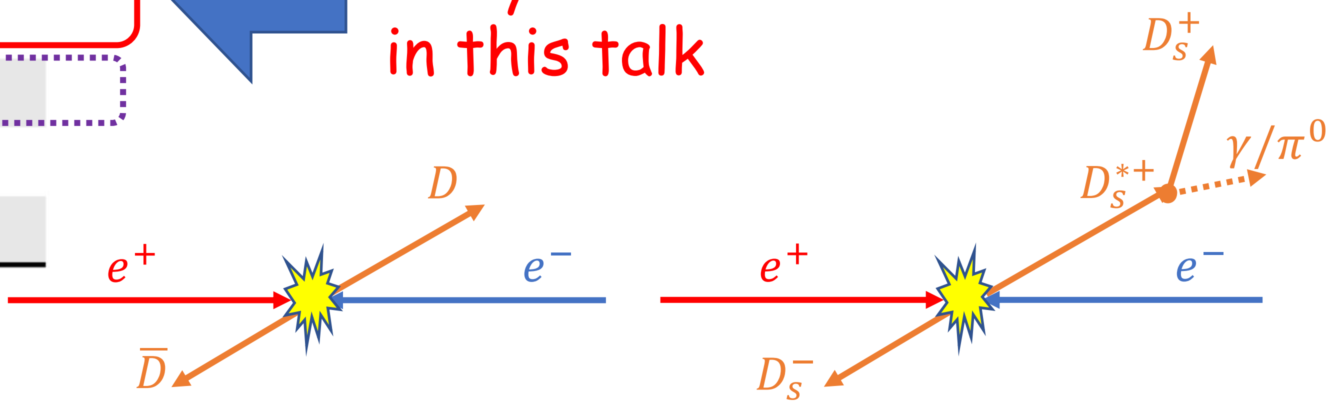
Charm datasets

- Pairs of $D_{(s)}$ produced near threshold w/o additional hadrons

Data samples	$\sqrt{s}$ (GeV)	Int. $\mathcal{L}$ (fb^{-1})
$D\bar{D}$	3.773	2.93
$D_s\bar{D}_s^*$	4.178	3.19
$D_s\bar{D}_s^*$	4.189 – 4.226	3.18
$\Lambda_c^+\bar{\Lambda}_c^-$	4.599	0.567
$\Lambda_c^+\bar{\Lambda}_c^-$	4.612 – 4.698	3.8

Used by the analyses covered in this talk

Already used in latest BESIII publications on D_s^+ decays



- Advantages:
  - Low background level
  - Full event info, neutrino kinematics can be inferred
  - Absolute branching fraction measurement possible with one $D_{(s)}$ tagged
  - Superb EMC performance on e / γ / π^0

Search for $D_s^+ \to \gamma e^+ \nu_e$ [PRD 99, 072002 (2019)]

Motivation

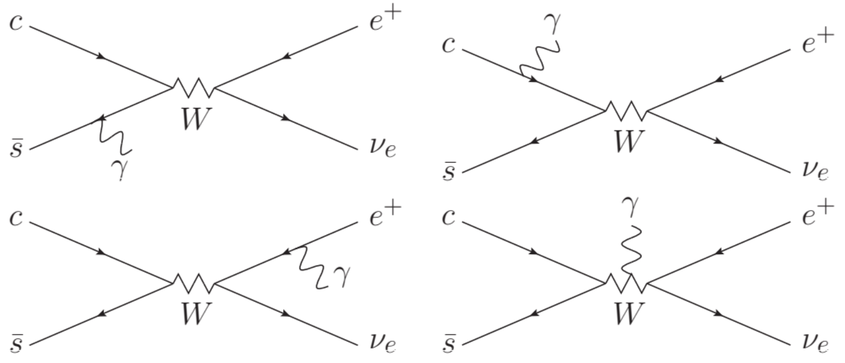
- Pure leptonic decays $P \to e^+\nu_e$ helicity suppressed by factor m_e^2
- Enhanced by emission of radiative photon, expected $\mathcal{B}(D_s^+ \to \gamma e^+\nu_e) \sim 10^{-5} - 10^{-3}$

Phys. Rev. D 51, 111 (1995)
Mod. Phys. Lett. A 15, 2087 (2000)
Phys. Lett. B 562, 75 (2003)
Mod. Phys. Lett. A 27, 1250120 (2012)
Phys. Rev. D 61, 114510 (2000)
Nucl. Phys. B650, 356 (2003)
…….

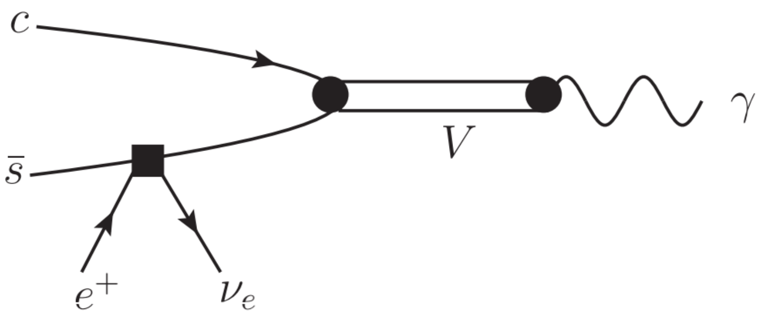
- BESIII reported in 2017

$$\mathcal{B}(D^+ \to \gamma e^+\nu_e) < 3.0 \times 10^{-5} \text{ @ 90\% CL}$$

[PRD 95 071102 (2017)]



Tree-level Feynman diagrams



Long-distance contributions

Double-tag method

- Fully reconstructed D_s^- at tag side (**ST**)
- Requiring one $\gamma_{\rm soft}(\pi^0_{\rm soft})$ from D_s^* and the signal decay at the other side (**DT**)

ST yields:

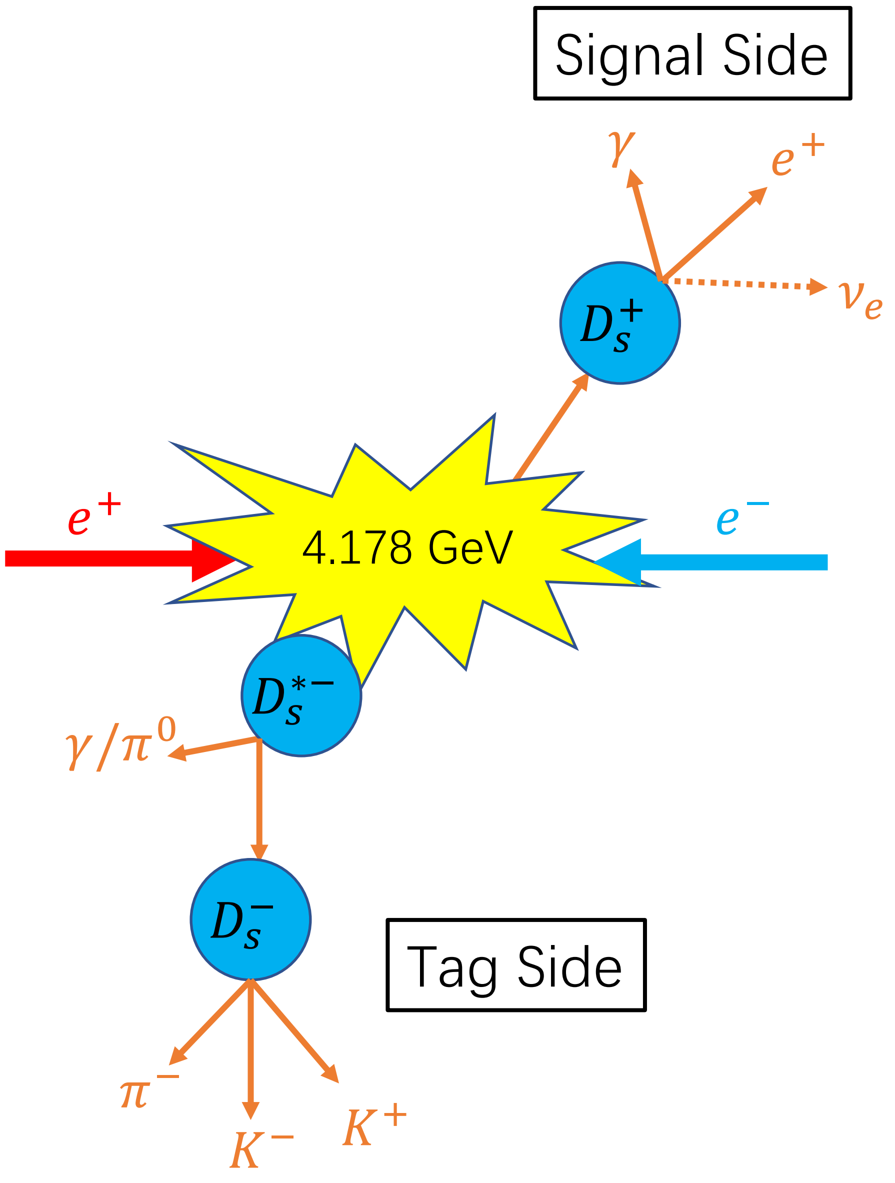
$$N^{\rm ST}_{D_{(s)}} = 2 \times N_{D\bar{D}} \times B_{ST} \times \varepsilon_{ST}$$

DT yield:

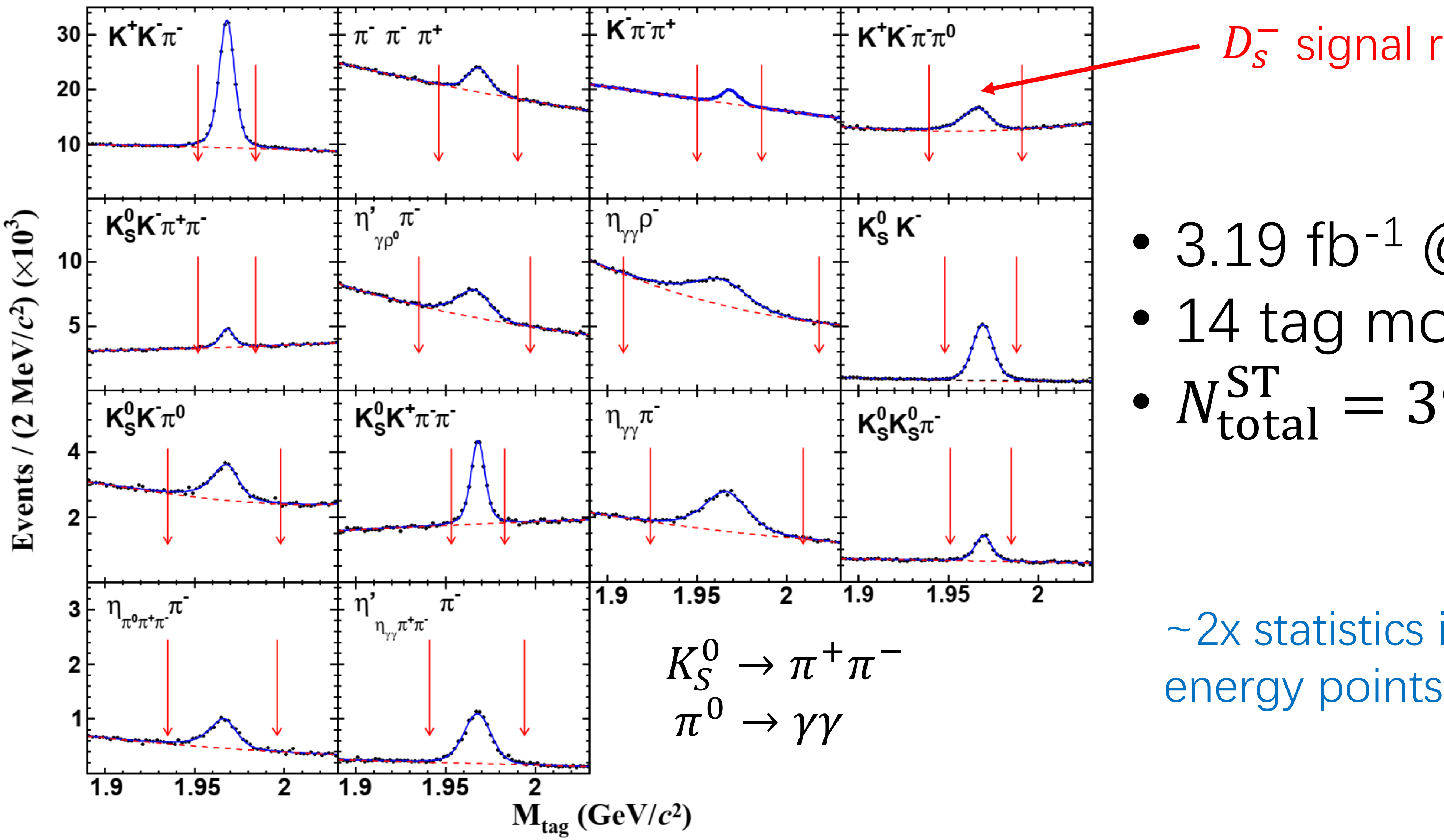
$$N^{\rm signal}_{\rm DT} = 2 \times N_{D\bar{D}} \times B_{ST} \times B_{sig} \times \varepsilon_{ST,sig}$$

The signal branching fraction:

$$B_{\rm sig} = \frac{N^{\rm signal}_{\rm DT}}{N^{\rm ST}_{D_{(s)}} \times \varepsilon}$$



Extraction of ST signals



- 3.19 fb^{-1} @ 4.178 GeV
- 14 tag modes
- $N_{\text{total}}^{ST} = 395412 \pm 1931$

$K_S^0 \to \pi^+\pi^-$
$\pi^0 \to \gamma\gamma$

~2x statistics if data at higher energy points are also included

BF determination

- First search on this channel, the upper limit is set for $E_\gamma^* > 0.01$ GeV based on $\int_0^{\mathcal{B}_{\mathrm{UL}}} L(\mathcal{B})\mathrm{d}\mathcal{B} = 0.9$:

$\mathcal{B}(D_s^+ \to \gamma e^+ \nu_e) < 1.3 \times 10^{-4}$ @ 90% CL

All systematic effects included

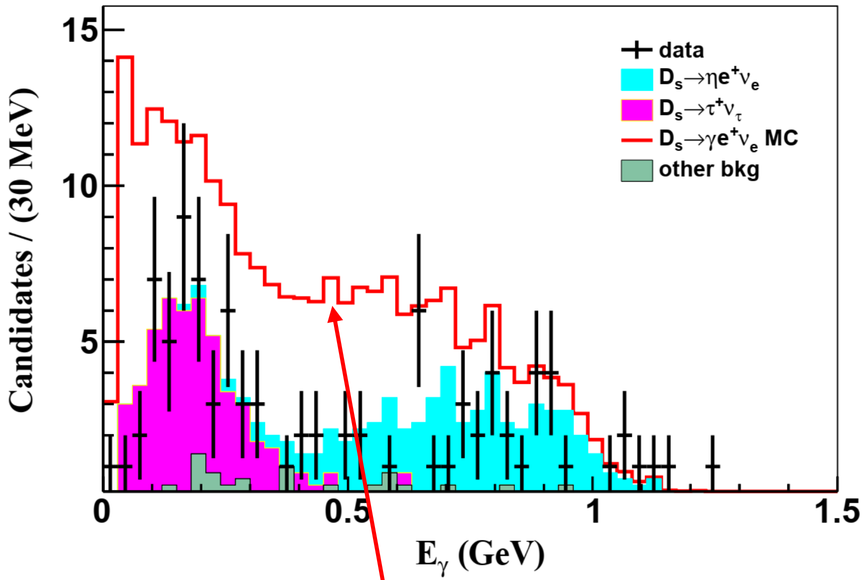
$$U_{\text{miss}} \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|,$$

where

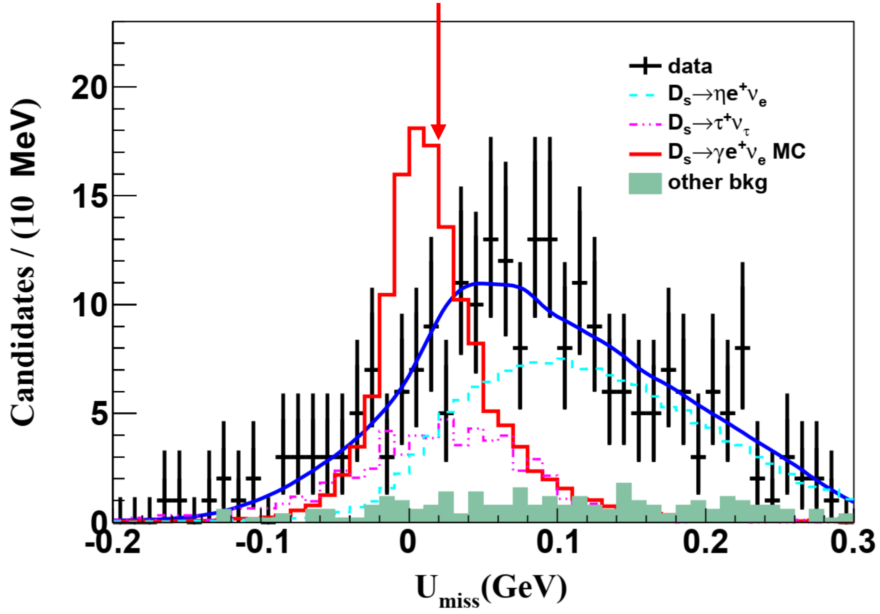
$$E_{\text{miss}} \equiv 2E_{\text{beam}} - E_\gamma - E_e - E_{\text{ST}} - E_{\gamma_{\text{soft}}(\pi^0_{\text{soft}})}$$

and

$$\vec{p}_{\text{miss}} \equiv -(\vec{p}_\gamma + \vec{p}_e + \vec{p}_{\text{ST}} + \vec{p}_{\gamma_{\text{soft}}(\pi^0_{\text{soft}})})$$



Assuming $\mathcal{B}(D_s^+ \to \gamma e^+ \nu_e) = 7.5 \times 10^{-4}$



[PRD 99. 072002 (2019)]

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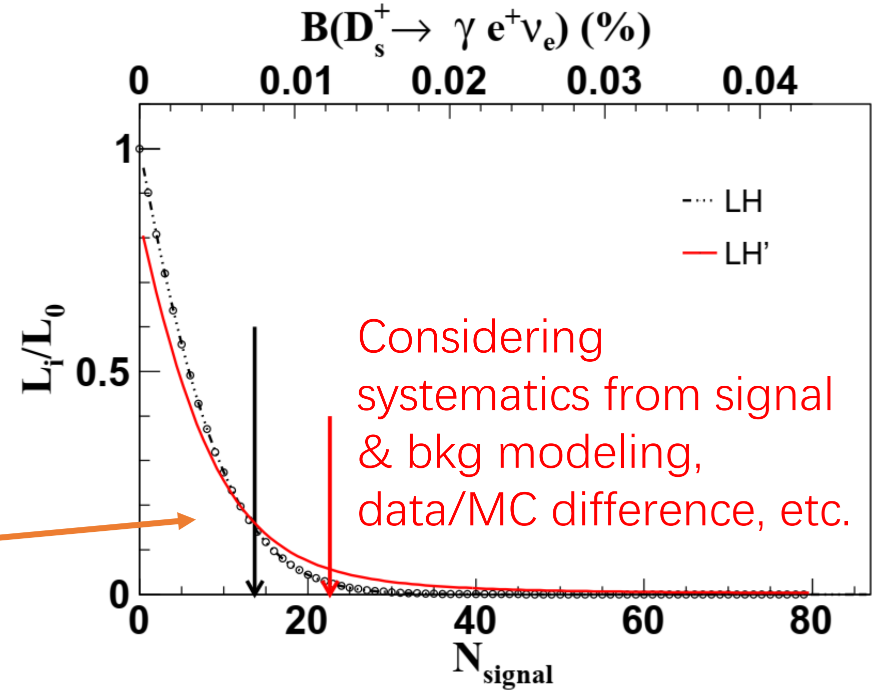

$$U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}|,$$

where

$$E_{\rm miss} \equiv 2E_{\rm beam} - E_\gamma - E_e - E_{\rm ST} - E_{\gamma_{\rm soft}(\pi^0_{\rm soft})}$$

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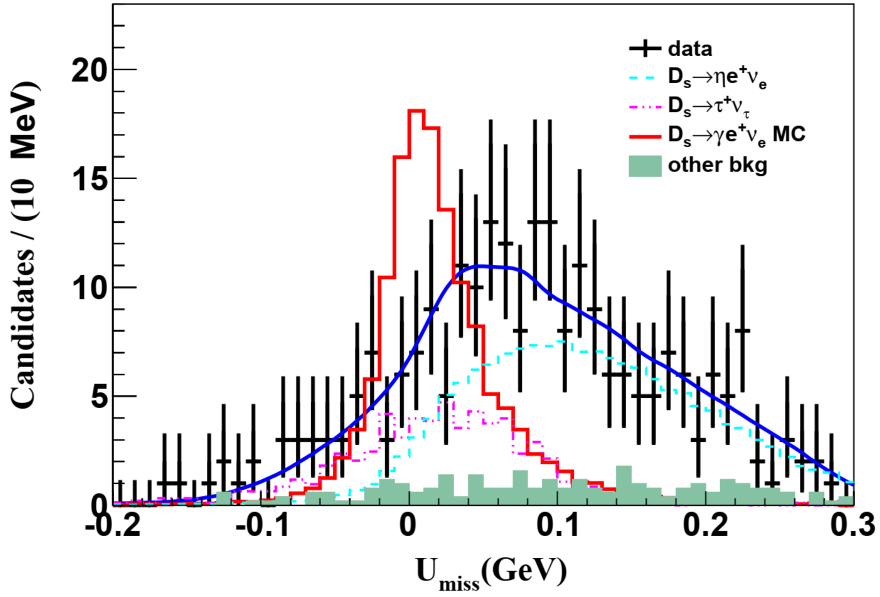
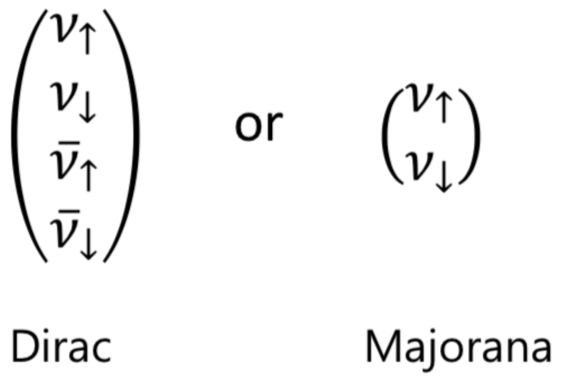
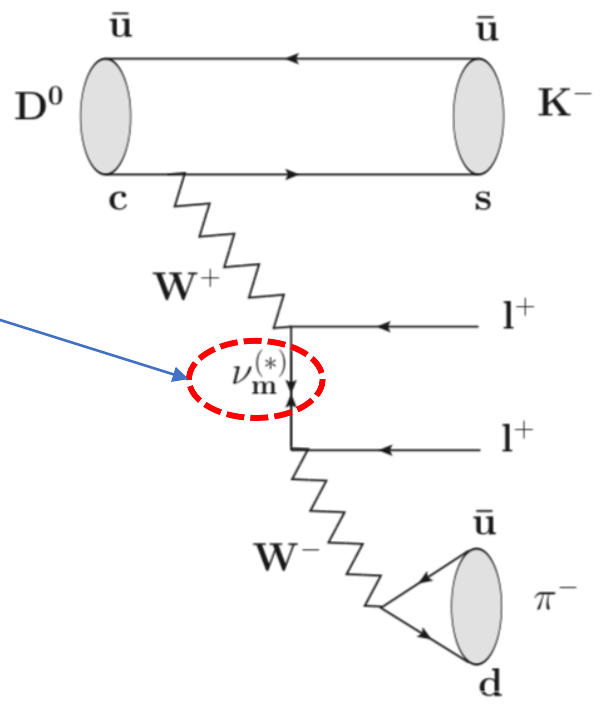


Search for $D \rightarrow K\pi e^{+}e^{+}$
[PRD 99, 112002 (2019)]

Motivation

- **L**epton **N**umber **V**iolation ($\Delta L \neq 0$) is forbidden in SM
- Neutrino oscillation $\rightarrow m_\nu \neq 0 \rightarrow$ New Physics needed to explain mass origin
- Nature of neutrino: Dirac or Majorana (ν_{m})?
- Majorana neutrino can lead to $\Delta L = 2$ LNV processes
- LNV is introduced in many NP models:
  - 4th quark generation, SO(10) SUSY GUT, exotic Higgs, etc.
- LNV processes have been widely searched for in τ, K, D, and B decays





[PRD 99, 112002 (2019)]

Analysis details

$$\Delta E = E_D - E_{\rm beam}$$

$$M_{\rm BC} = \sqrt{E^2_{\rm beam} - |\vec{p}_D|^2}$$

- Three channels studied
- Requirements on ΔE to suppress background
- BF determined using single-tag method:

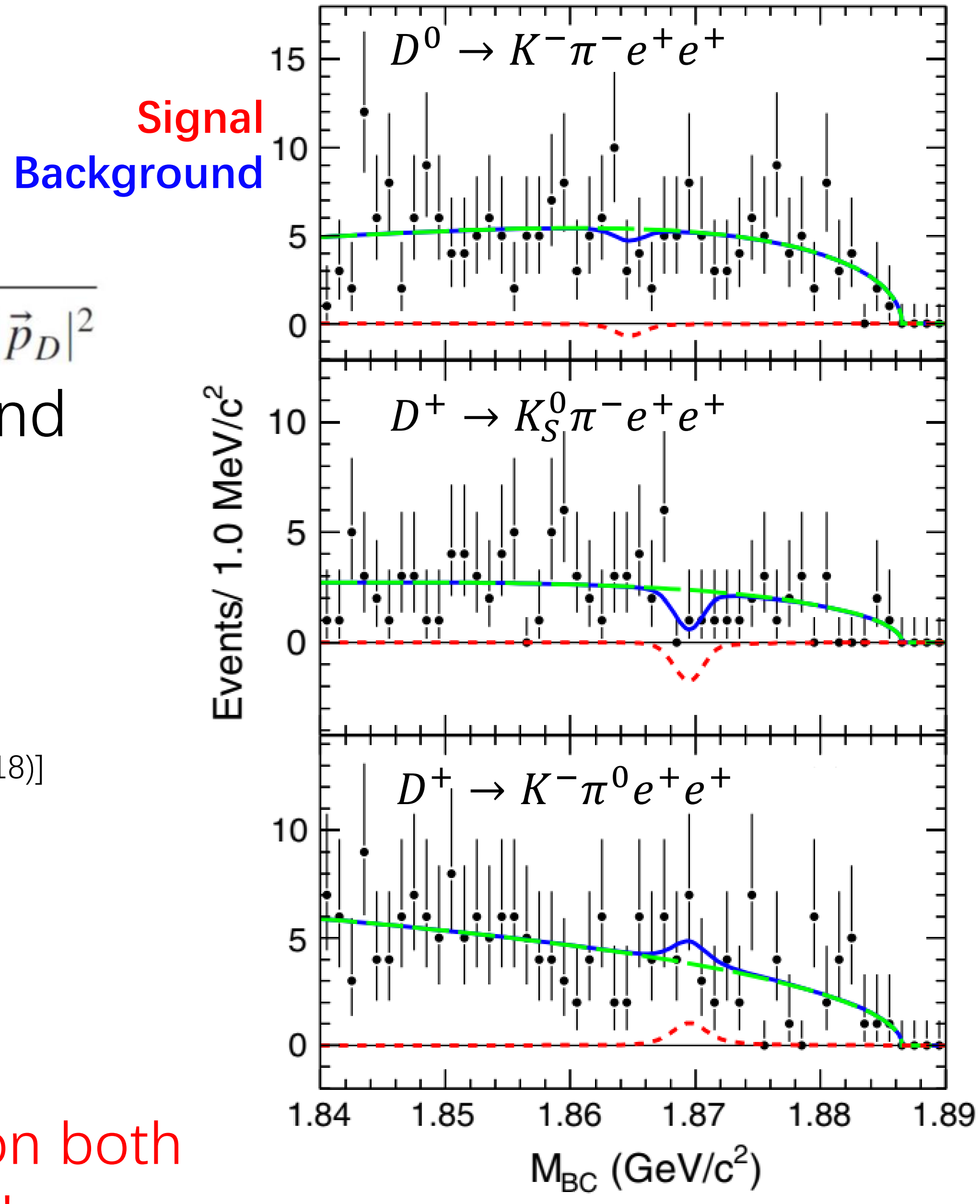
$$\mathcal{B}_{D\to K\pi e^+e^+} = \frac{N_{\rm sig}}{2\cdot N^{\rm tot}_{\rm D\bar{D}}\cdot\epsilon\cdot\mathcal{B}_{\rm sub}}$$

  - $N^{\rm tot}_{\rm D^+D^-}$~8.3 M, $N^{\rm tot}_{\rm D^0\bar{D}^0}$~10.6 M [Chin. Phys. C 42, 083001 (2018)]
- BF Upper limits @ 90% CL are determined:

$$\int_0^{\mathcal{B}_{\rm UL}} L(\mathcal{B})\mathrm{d}\mathcal{B} = 0.9$$

Channels	Upper Limit
$D^0 \to K^-\pi^-e^+e^+$	2.8×10^{-6}
$D^+ \to K^0_S\pi^-e^+e^+$	3.3×10^{-6}
$D^+ \to K^-\pi^0e^+e^+$	8.5×10^{-6}

First searches on both channels so far!

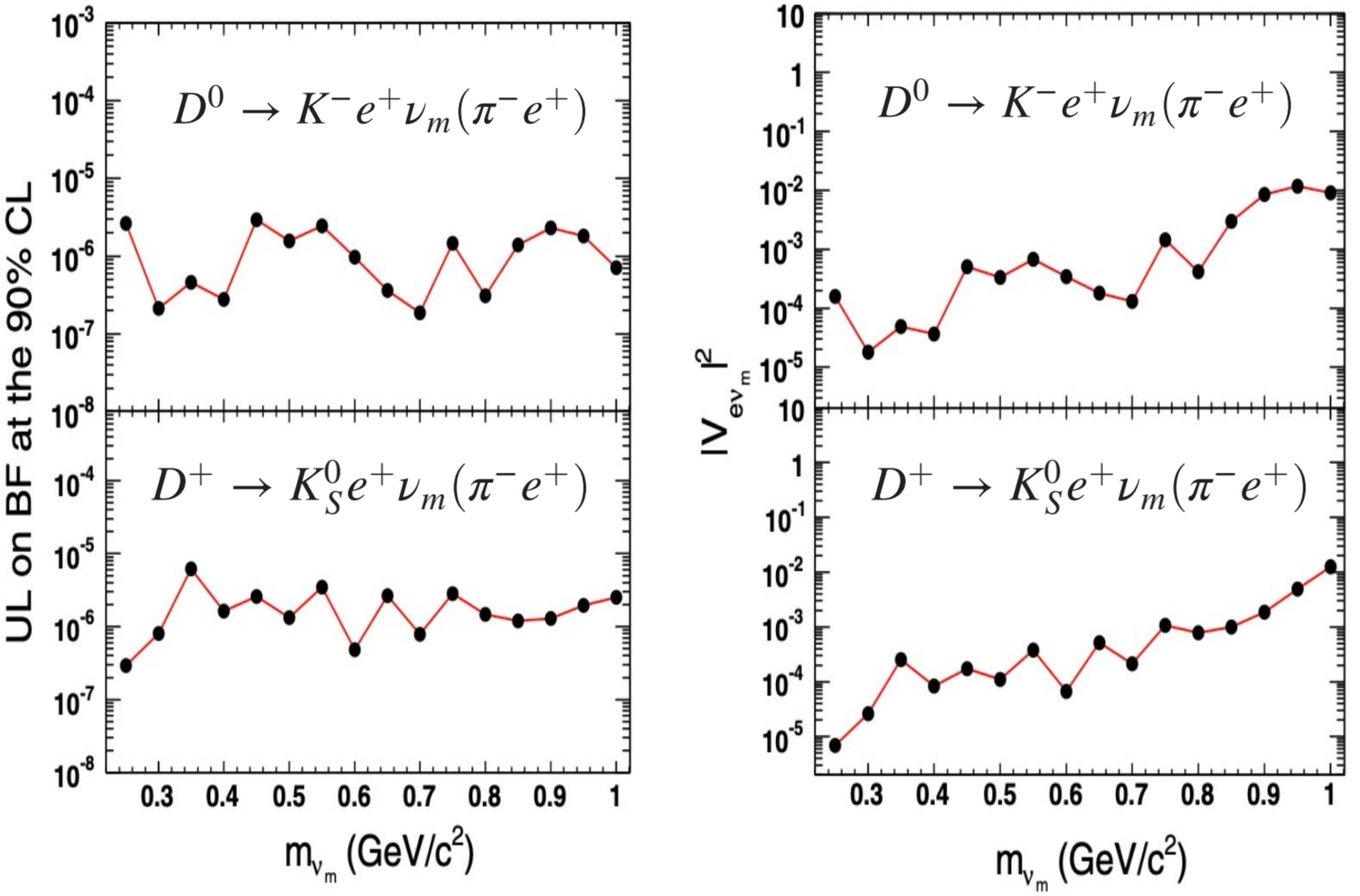


Searching for Majorana neutrino

- Different m_{ν_m} hypotheses tested between 0.25 and 1 GeV/c^2
- BFs are related to mixing matrix elements:

$$\frac{\Gamma(m_{\nu_m}, V_{e\nu_m}(m_{\nu_m}))}{\Gamma(m_{\nu_m}, V'_{e\nu_m}(m_{\nu_m}))} = \frac{|V_{e\nu_m}(m_{\nu_m})|^4}{|V'_{e\nu_m}(m_{\nu_m})|^4}$$

[Chin. Phys. C 39, 013101 (2015)]

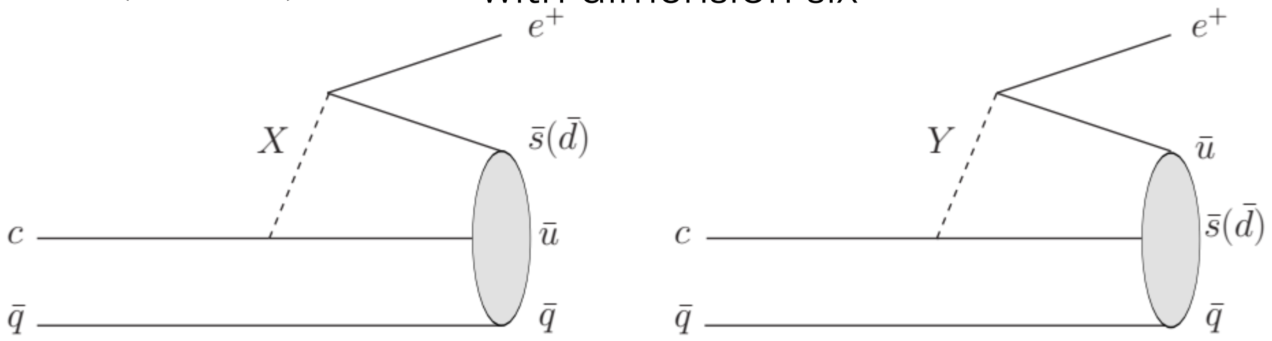


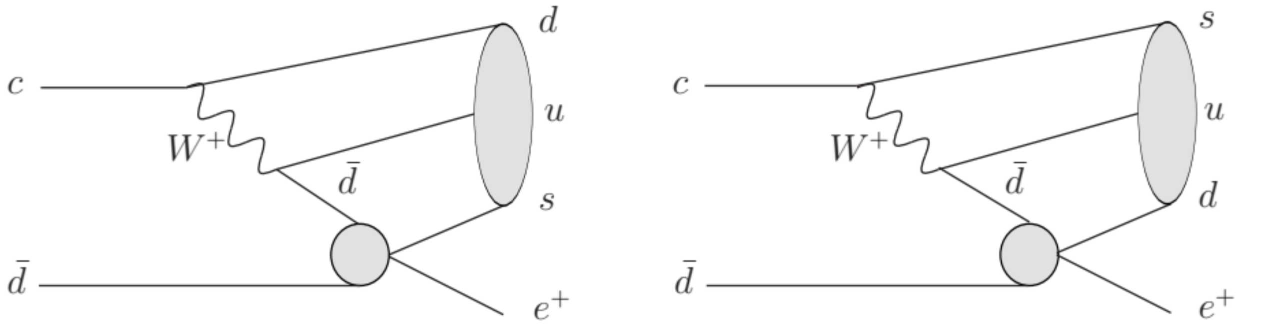
Search for $D^+ \to \Lambda(\Sigma^0)e$ [PRD 101, 031102 (2020)]

Motivation

- Excess of baryons over antibaryons in the Universe $\longrightarrow$ **B**aryon **N**umber **V**iolating processes exist
- BNV is allowed in GUTs and some SM extensions
- BFs of $D \to B\ell, B = \Lambda, \Sigma, \mathrm{p}$ expected to be no more than $\mathcal{O}(10^{-29})$ [PRD 72, 095001 (2005)]

$\Delta(B-L)=0$ Feynman diagrams under operators with dimension six





$\Delta(B-L)=2$ Feynman diagrams under operators with dimension seven

[PRD 101, 031102 (2020)]

Analysis details

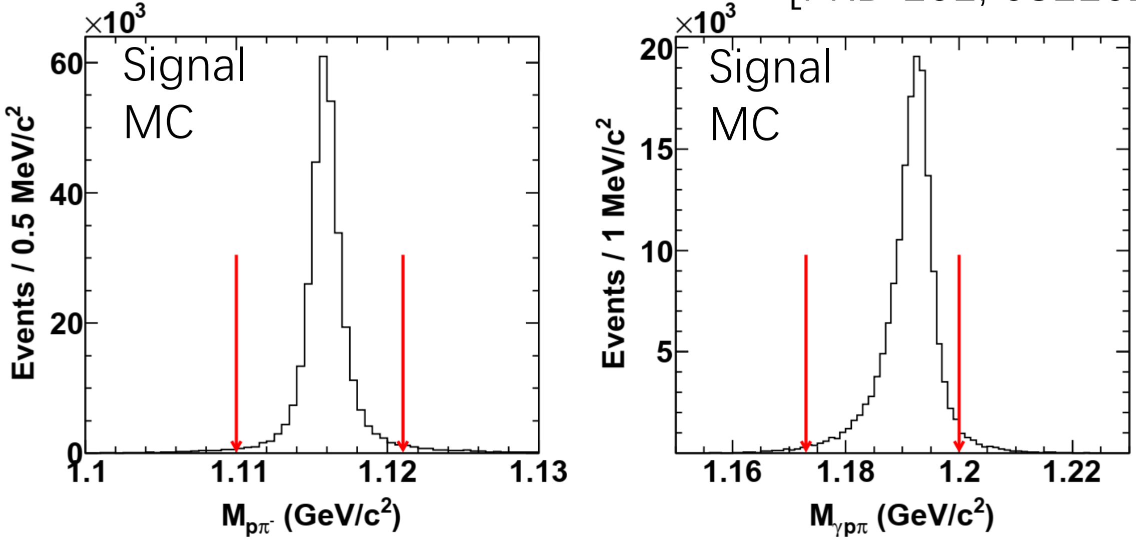
- Baryons reconstructed from $\Lambda \to p\pi^-$ and $\Sigma^0 \to \gamma\Lambda$
- Requirements on ΔE to suppress background
- BF determined using single-tag method:

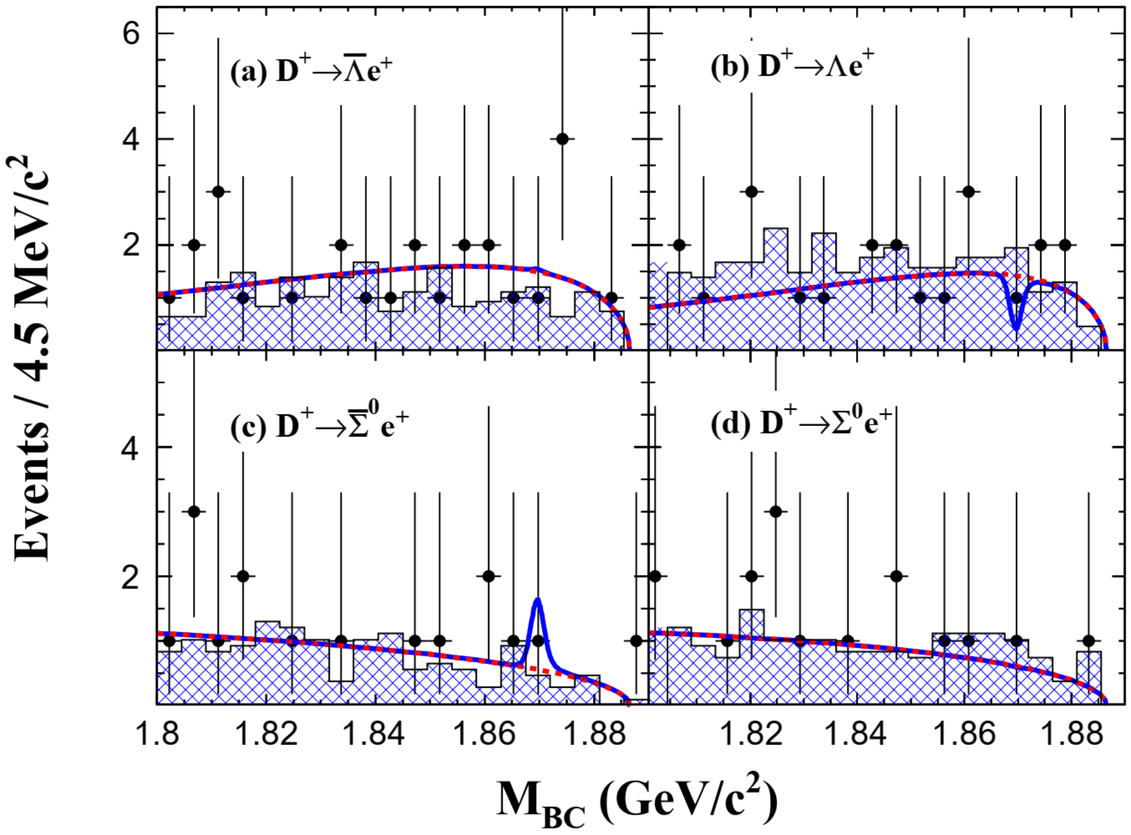
$$\mathcal{B}^{\mathrm{UL}} = N_{\mathrm{sig}}^{\mathrm{UL}} / (2 \times N_{D^+D^-}^{\mathrm{tot}} \times \varepsilon \times \mathcal{B}_{\Lambda,\Sigma^0})$$

  - $N_{\mathrm{D^+D^-}}^{\mathrm{tot}}$ ~8.3 M [Chin. Phys. C 42, 083001 (2018)]

$$\Delta E = E_D - E_{\mathrm{beam}}$$

$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_D|^2}$$





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$$\Delta E = E_D - E_{\mathrm{beam}}$$

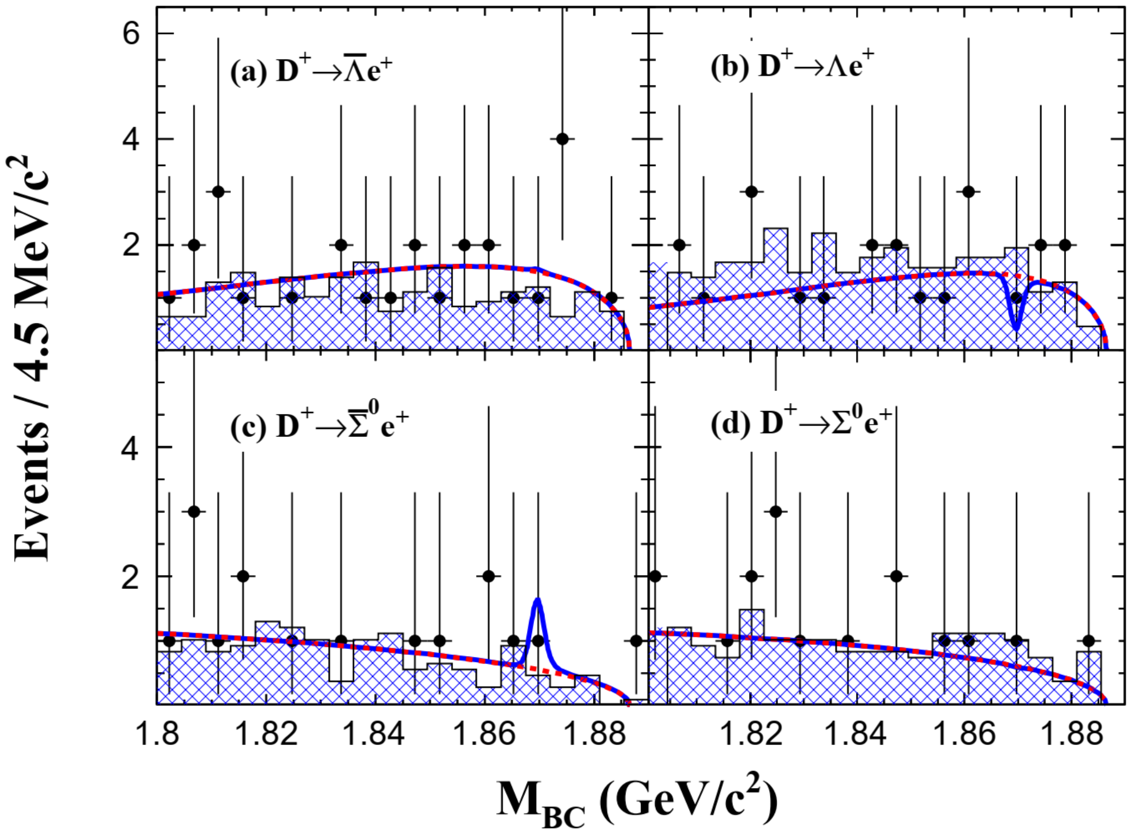
$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_D|^2}$$

BF Upper limits @ 90% CL are determined:

Channels	Upper Limit
$D^+ \to \Lambda\, e^+$	1.1×10^{-6}
$D^+ \to \bar{\Lambda}\, e^+$	6.5×10^{-7}
$D^+ \to \Sigma^0\, e^+$	1.7×10^{-6}
$D^+ \to \bar{\Sigma}^0\, e^+$	1.3×10^{-6}

$$\int_0^{\mathcal{B}_{\mathrm{UL}}} L(\mathcal{B}) d\mathcal{B} = 0.9$$

First searches



Summary & outlook

- BESIII provides large data samples near charm thresholds
- Recent searches on rare charm decays covered:
  - $D_s^+ \to \gamma e^+ \nu_e$
  - $D \to K\pi e^+ e^+$
  - $D^+ \to \Lambda(\Sigma^0) e$
  - Most are first searches
- More analyses on rare/forbidden decays are on the way:
  - A wide range of topics: invisible final states, LNV, BNV, FCNC, etc.
  - Still great potentials on D_s^+ and Λ_c^+ decays
- More $\psi(3770)$ data: $\int \mathcal{L} \sim$ 20 fb^{-1} in a few years [Chin. Phys. C 44, 040001 (2020)]