10th International Workshop on Charm Physics – CHARM 2020

Radiative and rare charm decays @ BESIII

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On behalf of the BESIII Collaboration

CHARM2020
Virtual Conference

INFN
Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

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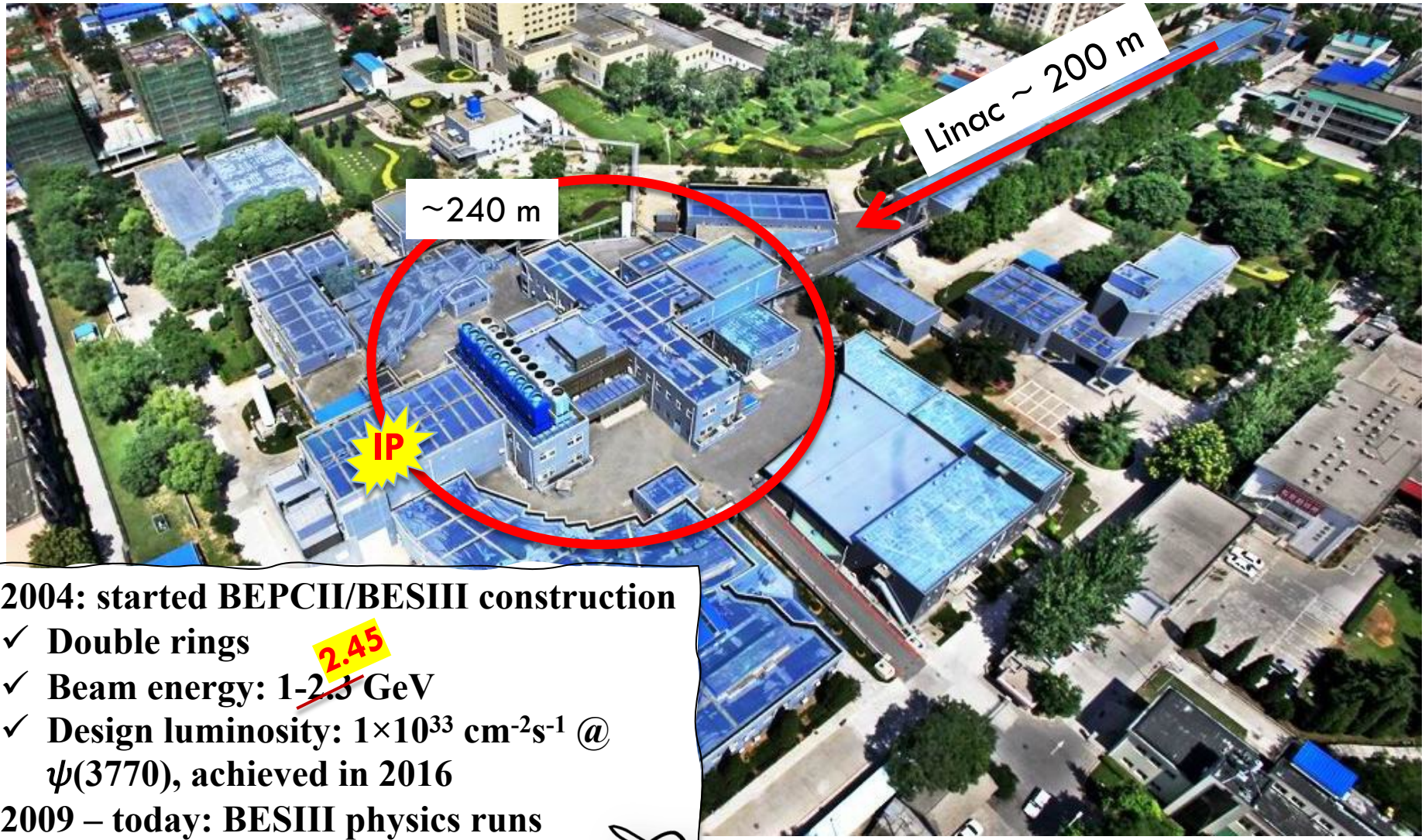
Mexico City, Mexico

BESIII

Beijing Electron Positron Collider II

http://english.ihep.cas.cn



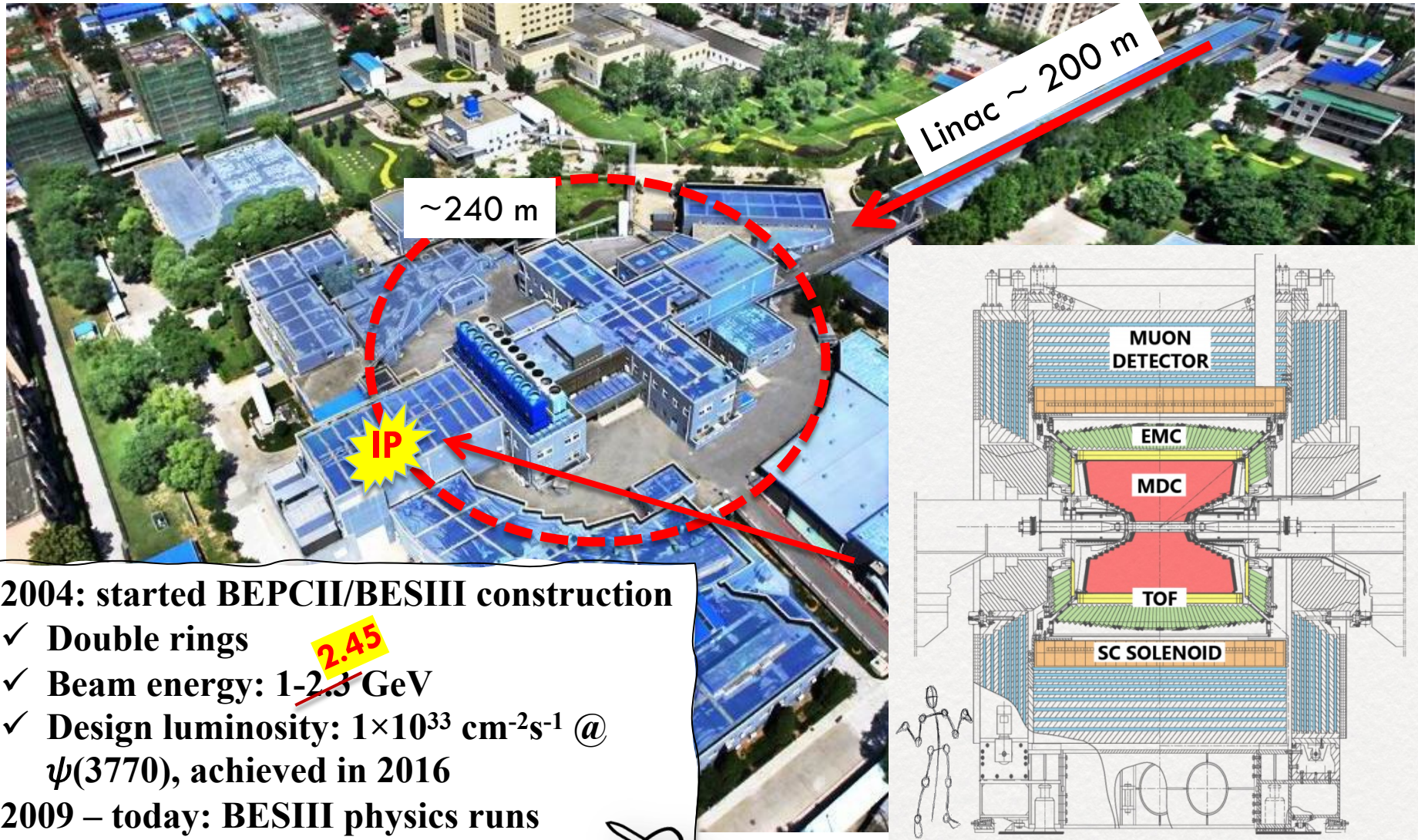
2004: started BEPCII/BESIII construction

- ✓ **Double rings**
- ✓ **Beam energy: 1-~~2.3~~ 2.45 GeV**
- ✓ **Design luminosity: 1×10^{33} $cm^{-2}s^{-1}$ @ $\psi(3770)$, achieved in 2016**

2009 – today: BESIII physics runs

Beijing Electron Positron Collider II

http://english.ihep.cas.cn



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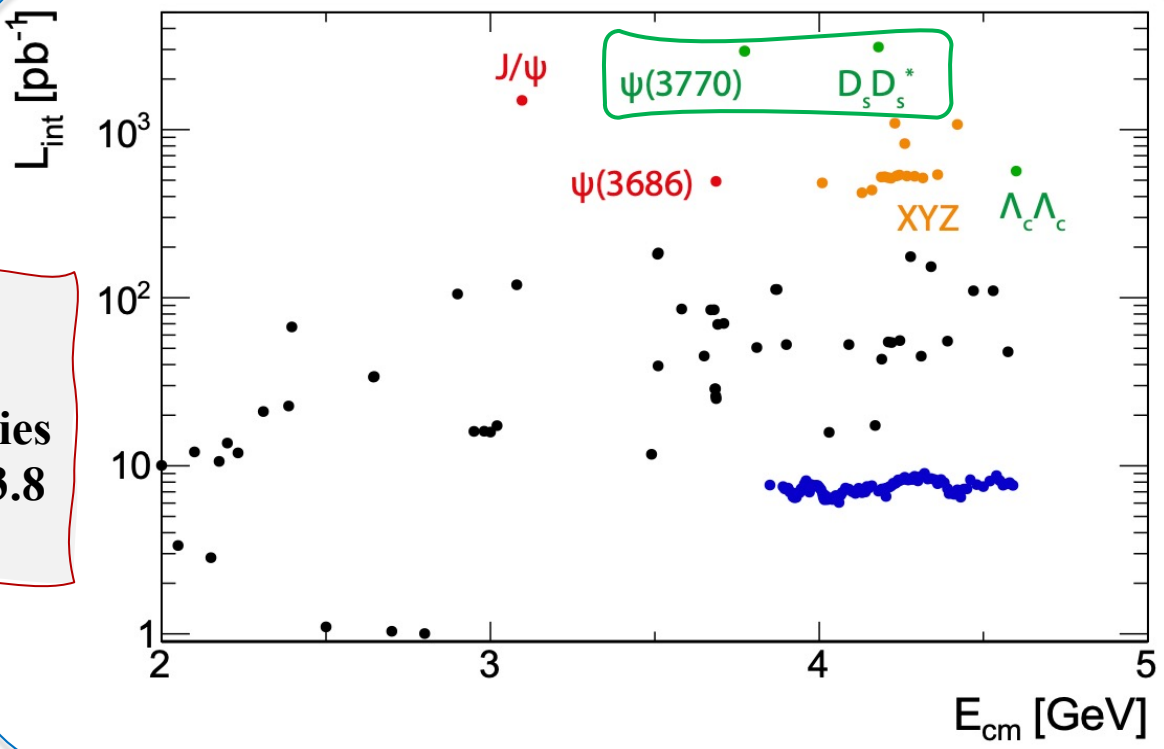
2009 – today: BESIII physics runs

Nucl. Instr. Meth. A614, 345 (2010)

BESIII Dataset

World largest J/ψ, ψ(2S) and ψ(3770) samples

- ✓ 10^{10} J/ψ event
- ✓ 448× 10^6 ψ(2S) event
- ✓ Large dataset for XYZ studies
- ✓ Scan data between 2.0 and 3.8 GeV, and above 3.735 GeV

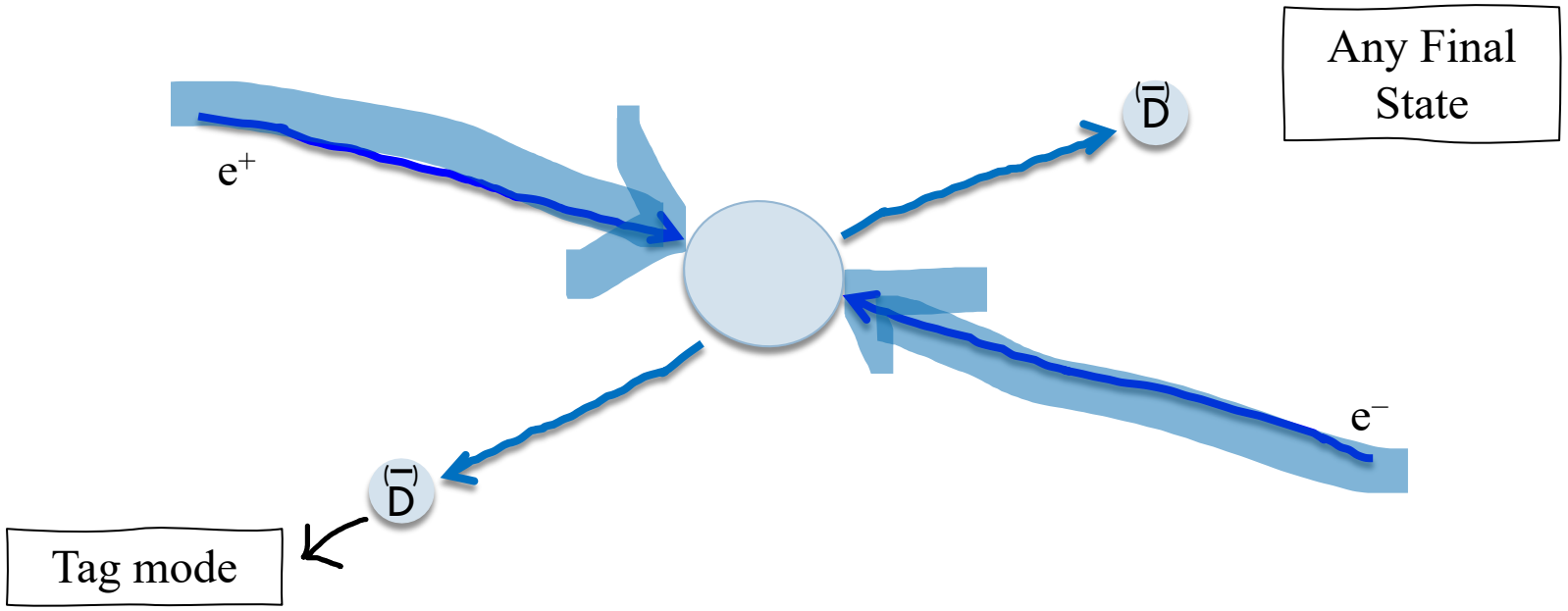


Unique dataset for open charm studies (used for the results in this talk):

√s (GeV)	L (fb^{-1})	
3.773	2.93	$D\bar{D}$
4.178	3.19	$D_sD_s^*$

→ quantum correlated state

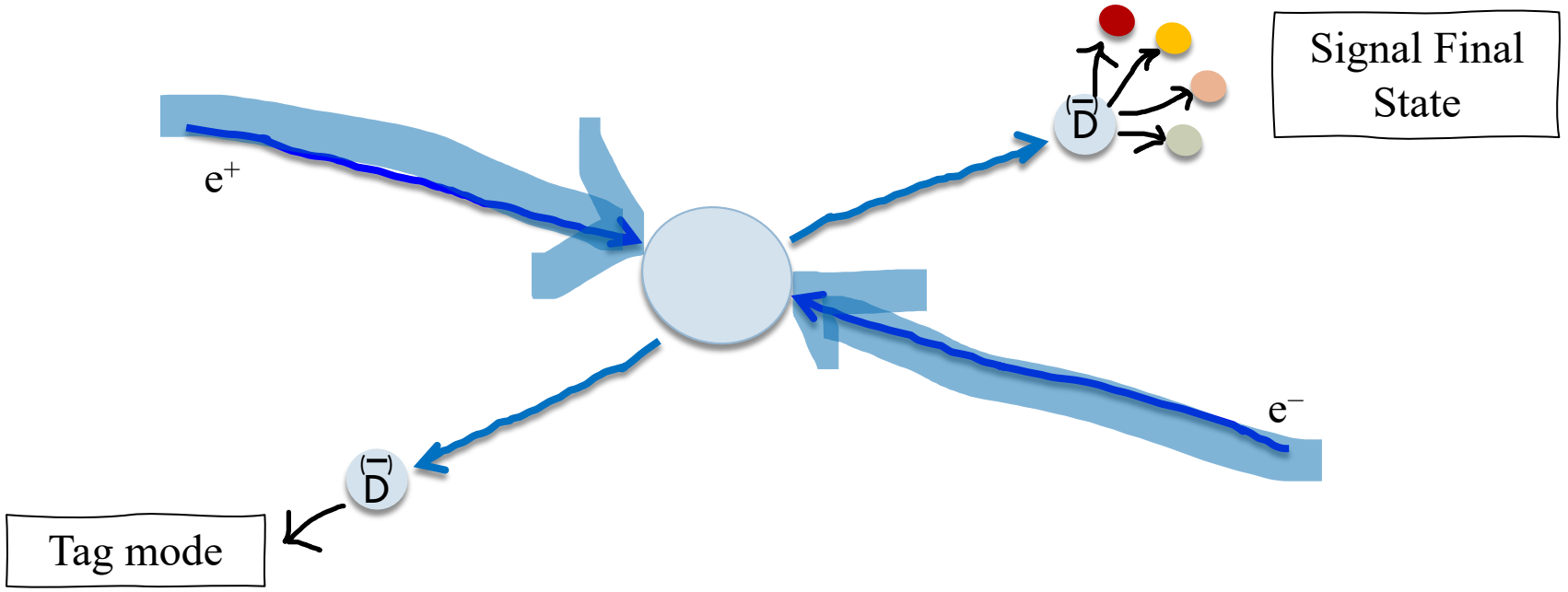
Single tag and Double tag method



Single tag: $\mathcal{B}(D \to f) = \dfrac{N_{sig}}{2 \cdot N_{D\bar{D}} \cdot \epsilon \cdot \mathcal{B}}$

Channels with low background, …

Single tag and Double tag method

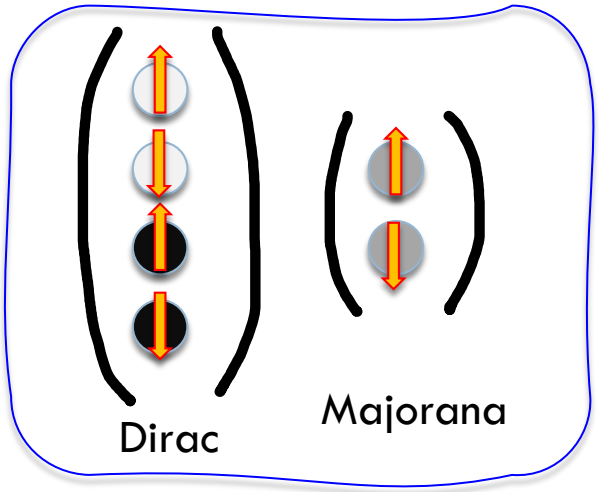


Single tag: $\mathcal{B}(D \to f) = \dfrac{N_{sig}}{2 \cdot N_{D\bar{D}} \cdot \epsilon \cdot \mathcal{B}}$ Channels with low background, …

Double tag: $\mathcal{B}(D \to f) = \dfrac{N_{sig,DT}}{N_{ST} \cdot \epsilon \cdot \mathcal{B}}$ Channels with high background, undetected particles, …

Search for LN Violation in D decays

- Lepton Number (LN) is conserved in Standard Model (SM)
  - ν massless LH particle
- Experimental evidence that $m_\nu \neq 0$
  - New Physics scenario
- ν nature: Dirac or Majorana particle?
- Majorana neutrino can be manifested through the processes violating LN by two units: $\Delta L = 2$



Search for LN Violation in D decays

PRD 99, 112002 (2019)

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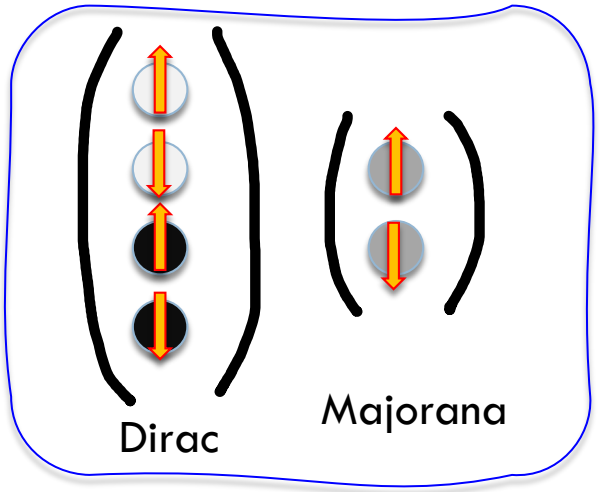
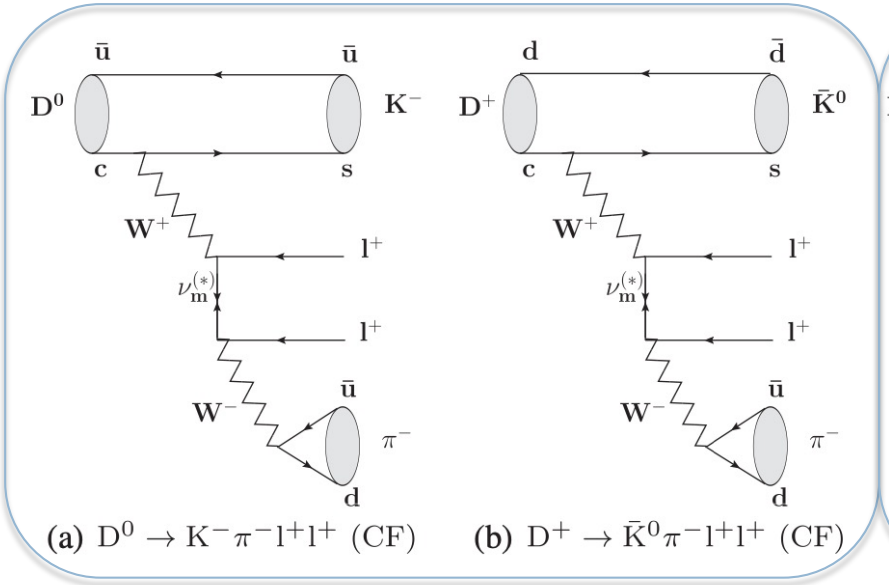
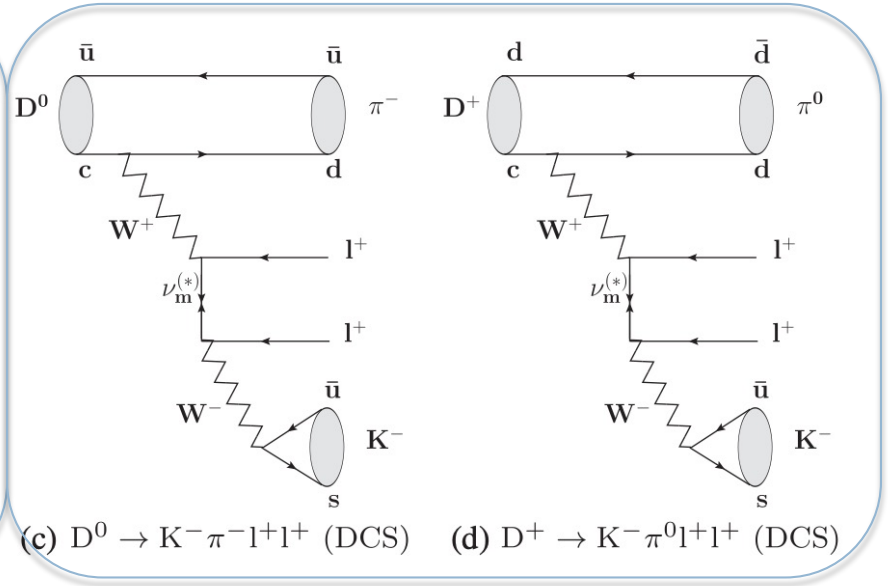


➢ **@ BESIII, using 2.93 fb^{-1} at $\sqrt{s}$=3.773 GeV:**



(a) $D^0 \to K^-\pi^-l^+l^+$ (CF) (b) $D^+ \to \bar{K}^0\pi^-l^+l^+$ (CF)

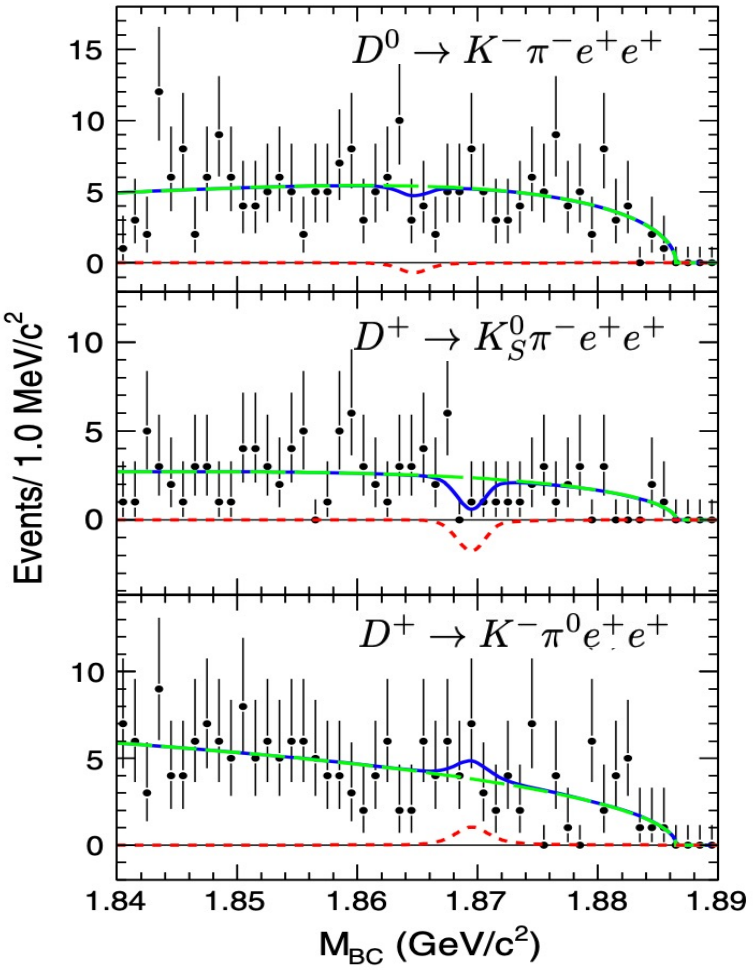


(c) $D^0 \to K^-\pi^-l^+l^+$ (DCS) (d) $D^+ \to K^-\pi^0l^+l^+$ (DCS)

Search for LN Violation in D decays

PRD 99, 112002 (2019)

- **Single tag method**



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

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

90% Confidence level

Channels	Upper limits
$D^0 \to K^-\pi^-e^+e^+$	$< 2.8 \times 10^{-6}$ (*)
$D^+ \to K^0_S\pi^-e^+e^+$	$< 3.3 \times 10^{-6}$
$D^+ \to K^-\pi^0e^+e^+$	$< 8.5 \times 10^{-6}$ (*)

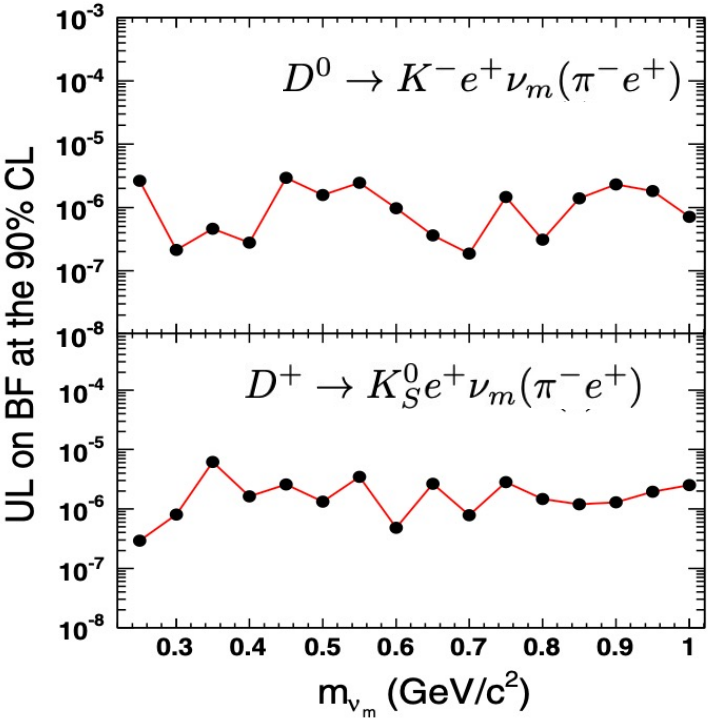
best limits on these channels up to now!!!

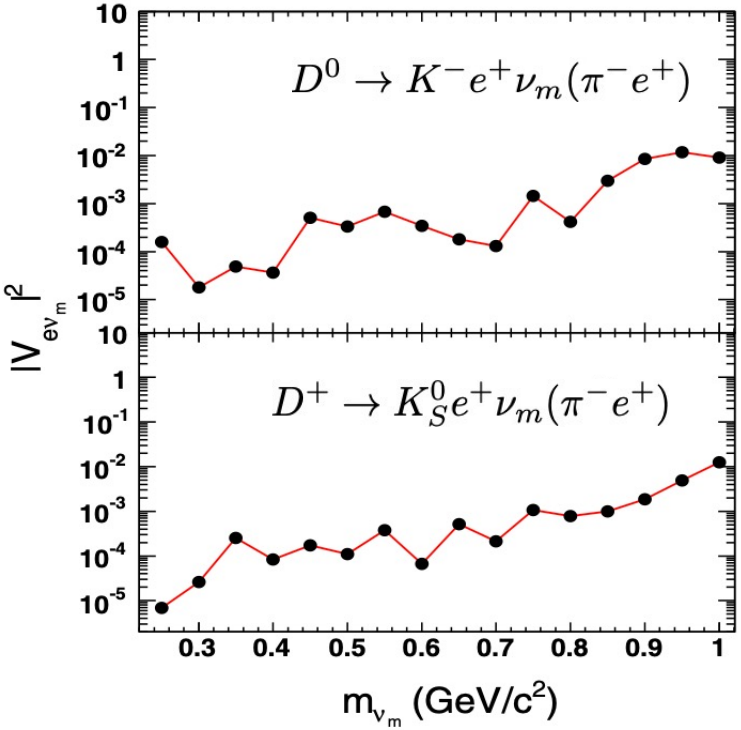
(*) from E791 Collaboration [PRL**86**, 3969 (2001) $BR^{UL} \sim 10^{-4}$ - 10^{-5}]

Search for LN Violation in D decays

PRD 99, 112002 (2019)

- **Single tag method**
- Search for Majorana neutrino in the decay chains $D^0 \to K^- e^+ \nu_m(\pi^- e^+)$, $D^+ \to K^0_S e^+ \nu_m(\pi^- e^+)$





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

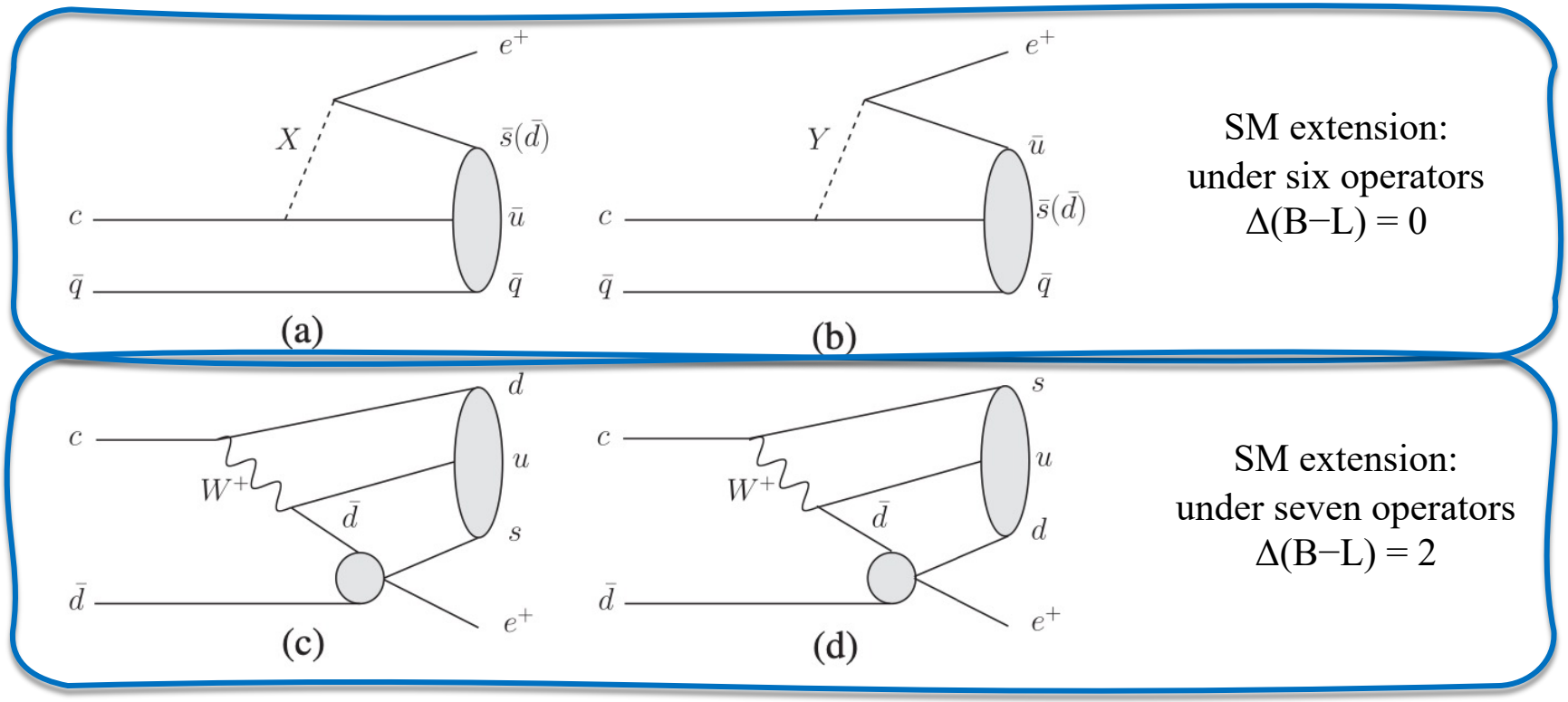
JHEP**05**,030
PRD**93**,094026
CP **C39**,013101

PRD**71**,077901

Search for BN Violation in D decays

- The excess of baryons over antibaryons in the Universe suggests the existence of baryon number violating (BNV) processes
- BNV described in SM extensions and GUTs
- Prediction of BR of $D^+ \to \bar{\Lambda} \ell^+$ no more than 10^{-29} (PRD **72**,095001)

Hint of NP

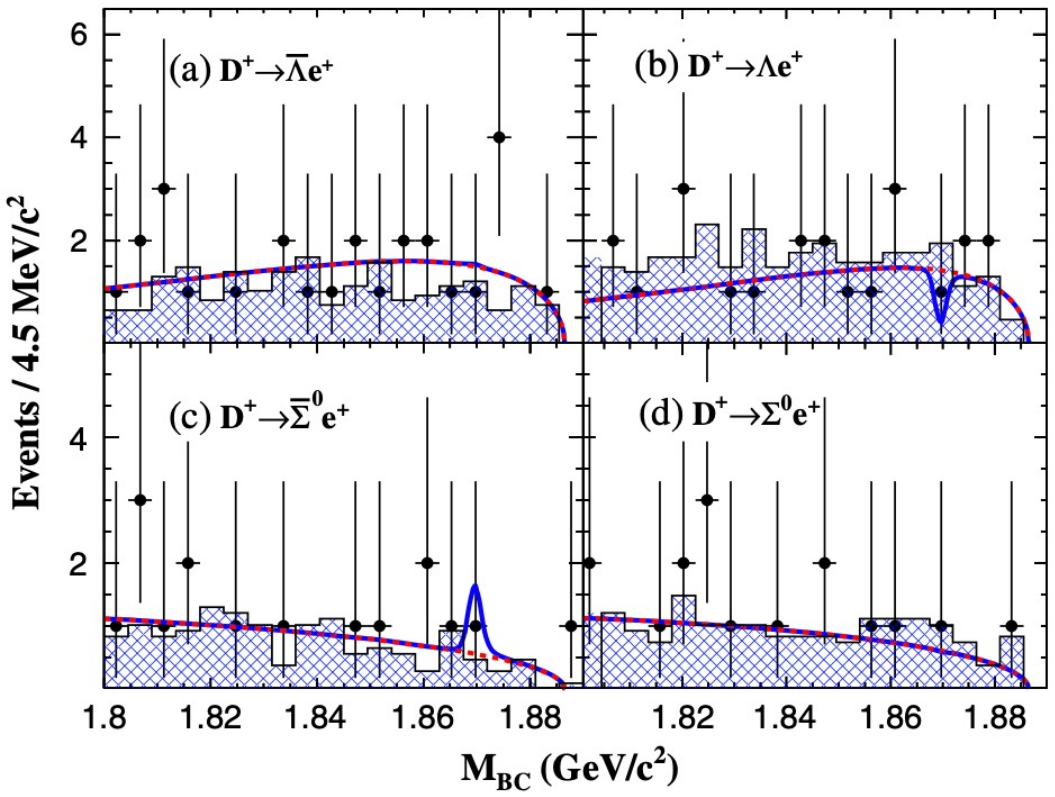


These decays amplitudes may be comparable (PRD **72**,095001)

Search for BN Violation in D decays

PRD 101, 031102 (2019)

- **2.93 fb^{-1} at $\sqrt{s}$=3.773 GeV**
- **Single tag**
- $D^+ \to \bar{\Lambda} e^+,\ D^+ \to \bar{\Sigma}^0 e^+ \quad (\Delta(B-L)=0) \qquad D^+ \to \Lambda e^+,\ D^+ \to \Sigma^0 e^+ \quad (\Delta(B-L)=2)$



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

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

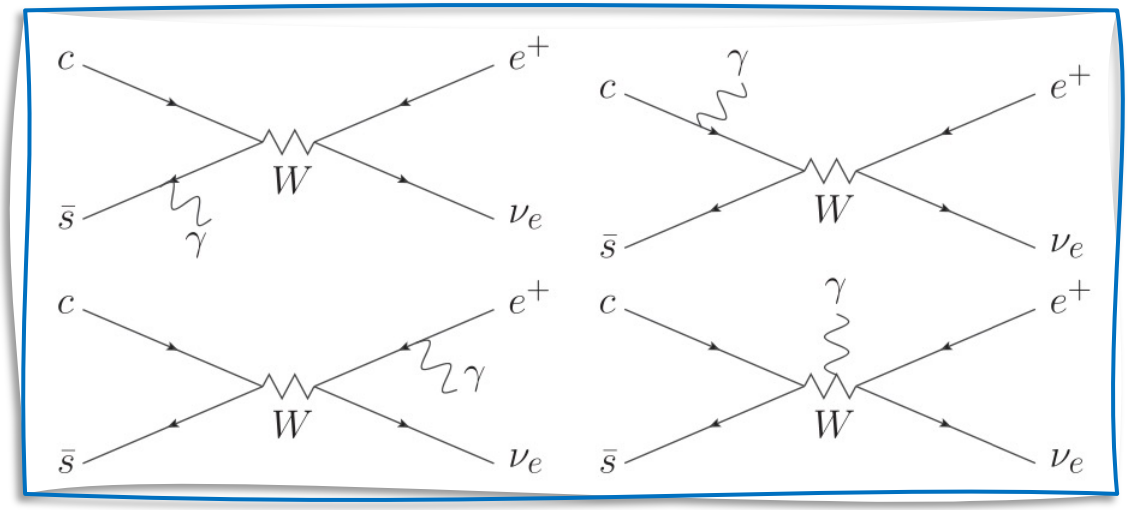
Decay mode	B^{UL} (90% CL)
Λe^+	1.1×10^{-6}
$\bar{\Lambda} e^+$	6.5×10^{-7}
$\Sigma^0 e^+$	1.7×10^{-6}
$\bar{\Sigma}^0 e^+$	1.3×10^{-6}

first time searches

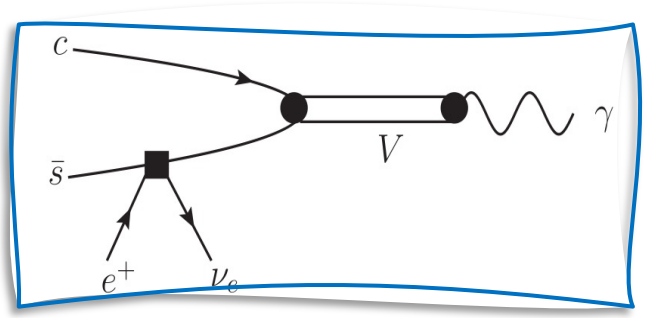
Search for $D_s^+ \to \gamma e^+ \nu_e$ radiative decays

PRD 99, 072002 (2019)

- P $\to l^+ \nu_l$ decays are helicity suppressed
- Radiative decays avoid helicity suppression
  - $B(D^+ \to \gamma e^+ \nu_e) < 3.0 \times 10^{-5}$ (Cabibbo suppressed): PRD **95**, 071102 (2017)
- $D_s^+ \to \gamma e^+ \nu_e$ is Cabibbo favored process
- BF is predicted to be of the order of 10^{-4} - 10^{-5} in the light front quark model (MPL A15, 2087, PLB 562, 75)



Tree-level Feynman diagrams contribution



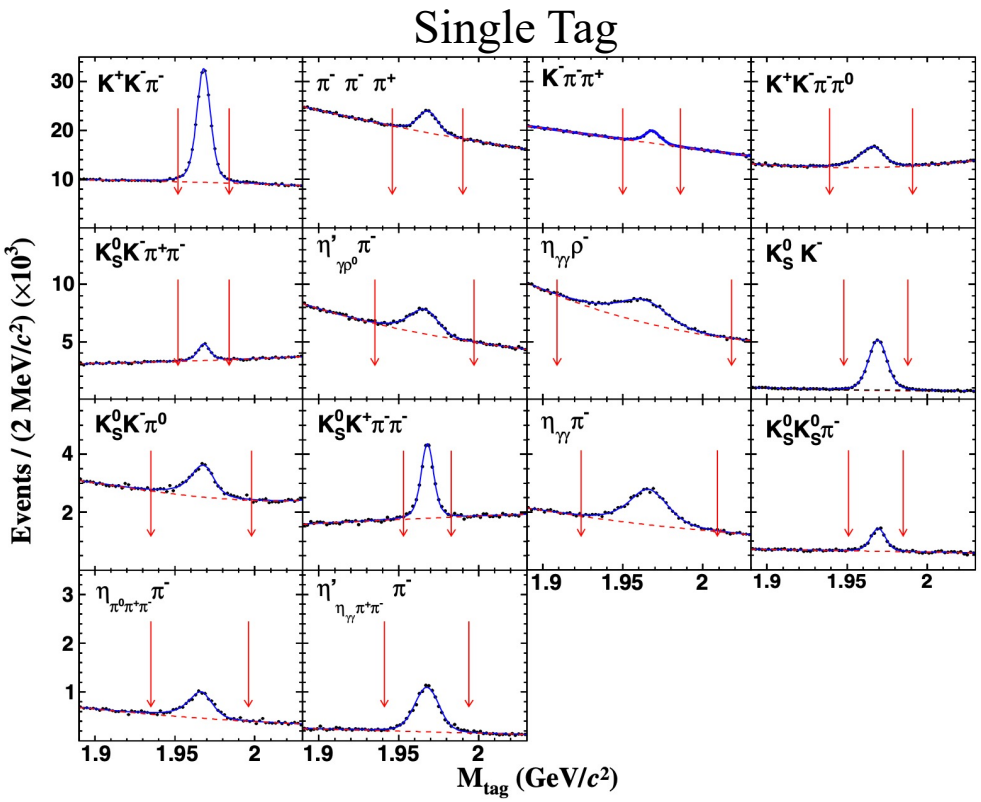
Long distance contribution described by the VDM model (MPL A27,1250120)

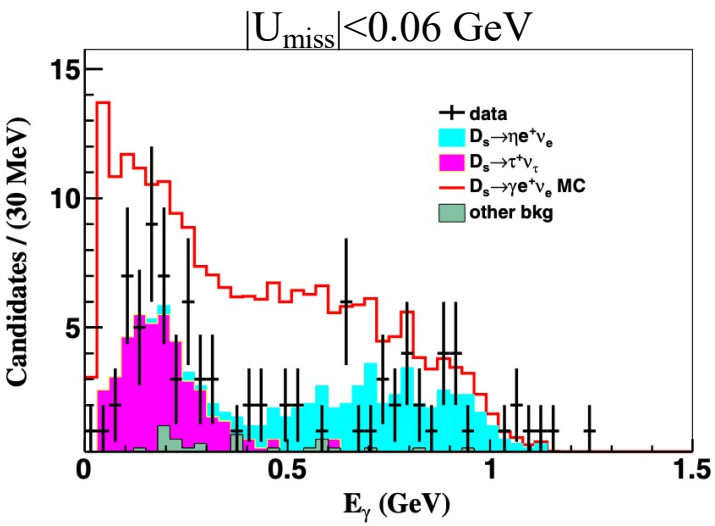
BF of the order of 10^{-3}

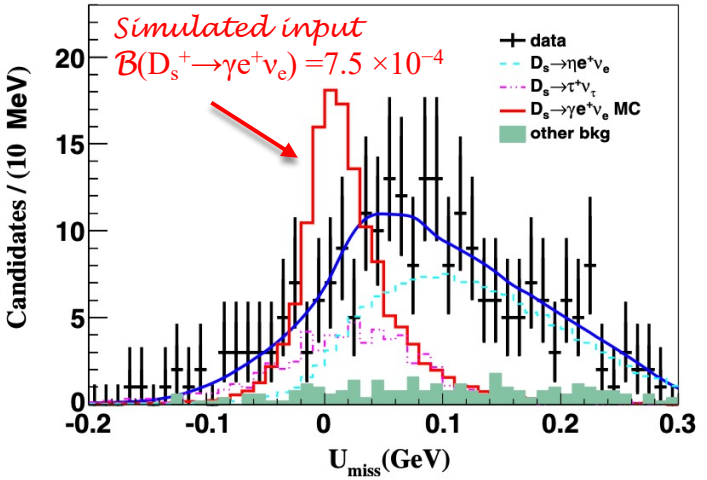
Search for $D_s^+ \to \gamma e^+ \nu_e$ radiative decays

PRD 99, 072002 (2019)

- **3.19 fb^{-1} at $\sqrt{s}$=4.178 GeV**
- **Double tag + Blind analysis**







$\mathcal{B}(D^+_s \to \gamma e^+\nu_e) < 1.3 \times 10^{-4}$ @ 90% C.L.

Singly CS decays $D \to \omega\pi\pi$

PRD 102, 052003 (2020)

- Multibody hadronic decays important to understand the decay dynamics of both strong and weak interaction
- Important input to the beauty sector for SM predictions
- **2.93 fb^{-1} at $\sqrt{s}$=3.773 GeV**
- **Double tag**

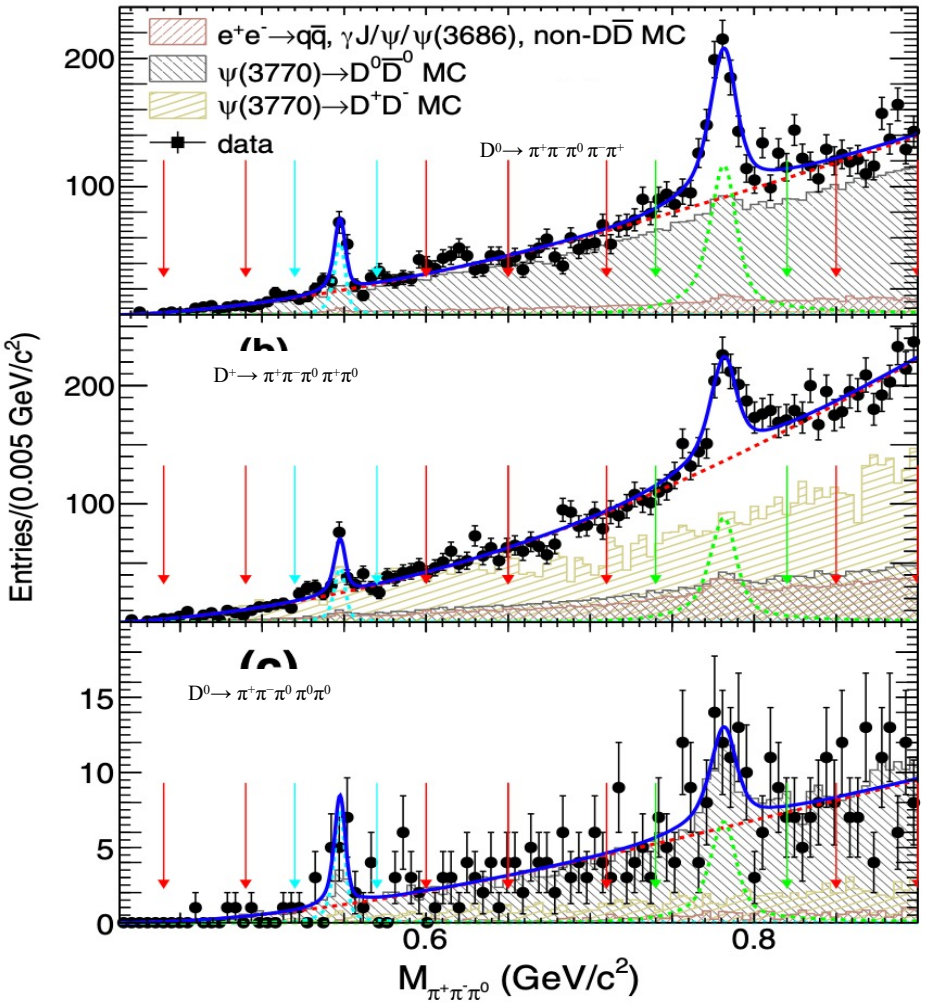
ST:

- $D^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$
- $D^- \to K^-\pi^+\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S\pi^-$, $K_S\pi^-\pi^0$, $K_S\pi^-\pi^-\pi^+$, $K^+\pi^-\pi^-$

DT:

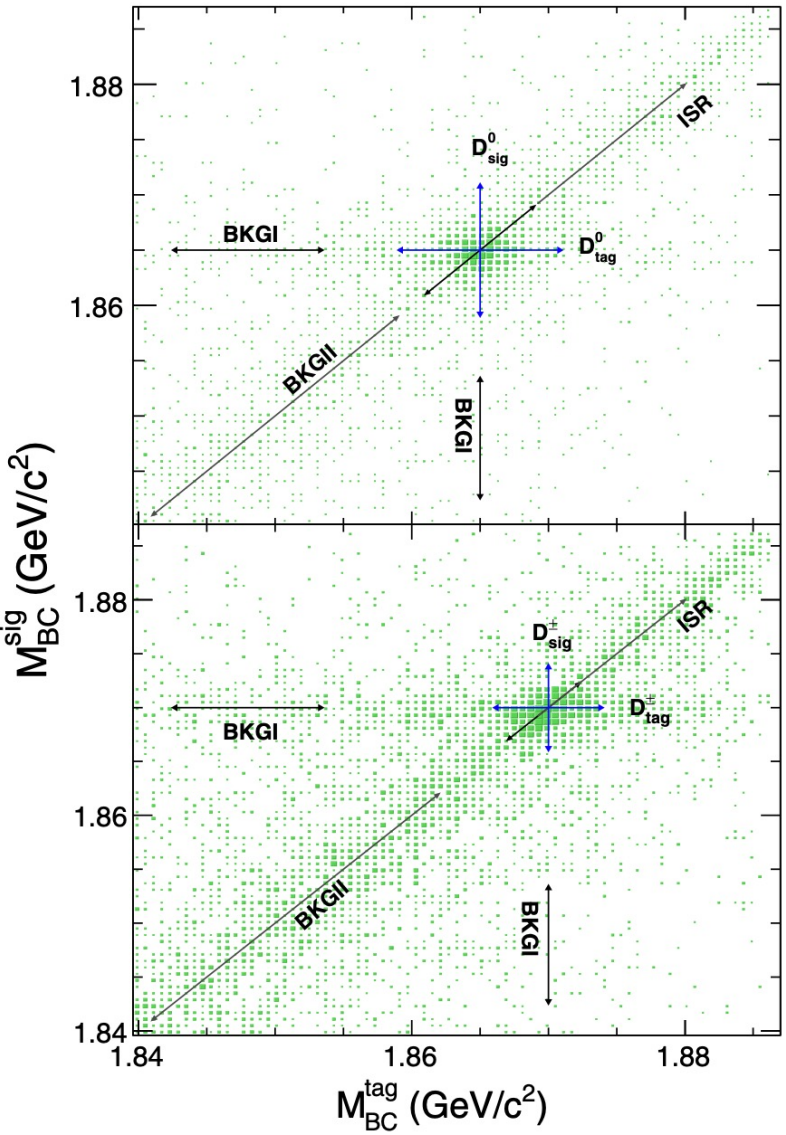
- $D^0 \to \pi^+\pi^-\pi^0\,\pi^-\pi^+$, $\pi^+\pi^-\pi^0\,\pi^0\pi^0$
- $D^+ \to \pi^+\pi^-\pi^0\,\pi^+\,\pi^0$

Clear ω and η signal



Singly CS decays $D \to \omega\pi\pi$

PRD 102, 052003 (2020)



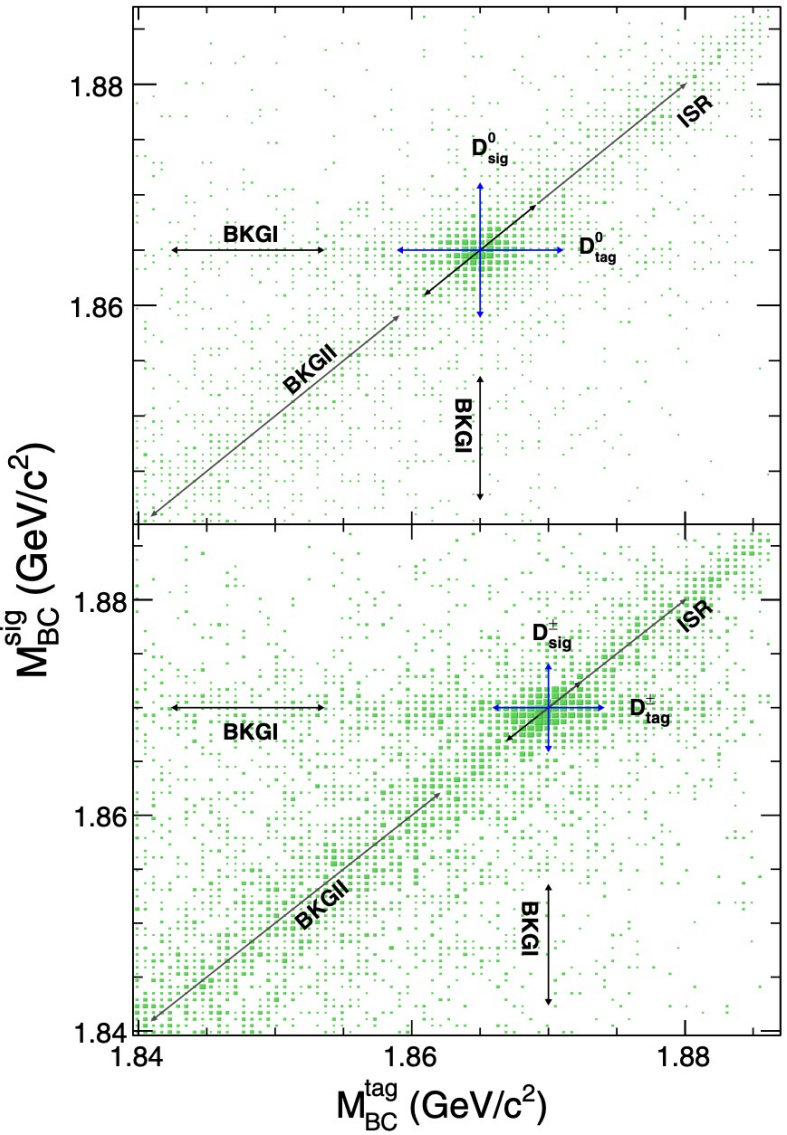
2D unbinned maximum likelihood fit is performed to M_{BC}^{sig} and M_{BC}^{tag} in the signal region

$$N_{DT}^{sig} = N_{SG}^{\omega/\eta} - f \cdot N_{SB}^{\omega/\eta} - N_{peak}^{BKGV}$$

- BKGI: only one of the two D mesons are incorrectly reconstructed
- BKGII: $e^+e^- \to$ qqbar
- BKGIII: PHSP

Singly CS decays $D \to \omega\pi\pi$

PRD 102, 052003 (2020)



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$$N_{DT}^{sig} = N_{SG}^{\omega/\eta} - f \cdot N_{SB}^{\omega/\eta} - N_{peak}^{BKGV}$$

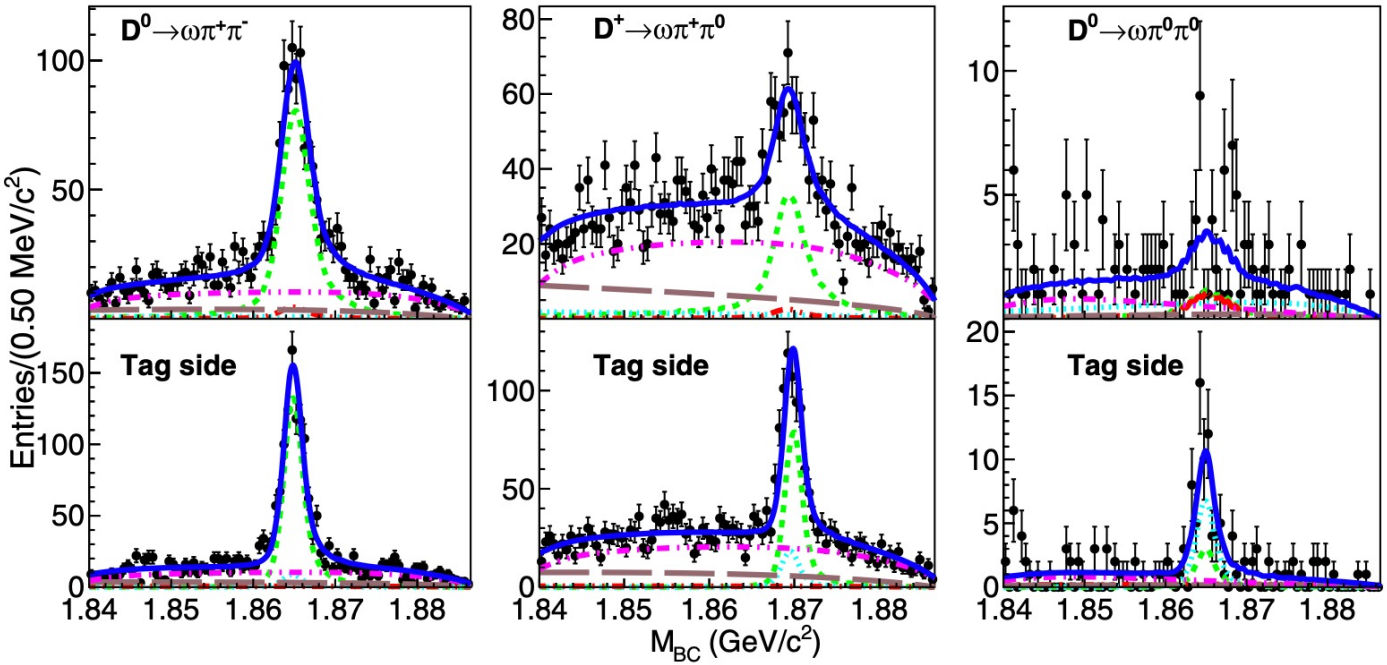
Bkg with same final states but without ω/η (from sidebands)

Small peaking bkg from CF processes $D^0 \to K^0_S\omega/\eta$ (from events surviving K^0_S mass veto)

- BKGI: only one of the two D mesons are incorrectly reconstructed
- BKGII: $e^+e^- \to$ qqbar
- BKGIII: PHSP

Singly CS decays $D \to \omega\pi\pi$

PRD 102, 052003 (2020)



Improved BF measurement

First measurement

No evidence is found

Consistent with previous results
(PRD101,052009; PLB781,368)

Decay mode	$\mathcal{B}^{\rm sig}(\times 10^{-3})$	$\mathcal{B}_{\rm PDG}(\times 10^{-3})$
$D^0 \to \omega\pi^+\pi^-$	$1.33 \pm 0.16 \pm 0.12$	1.6 ± 0.5
$D^+ \to \omega\pi^+\pi^0$	$3.87 \pm 0.83 \pm 0.25$	...
$D^0 \to \omega\pi^0\pi^0$	< 1.10	...
$D^0 \to \eta\pi^+\pi^-$	$1.06 \pm 0.18 \pm 0.07$	1.09 ± 0.16
$D^+ \to \eta\pi^+\pi^0$	$2.47 \pm 0.93 \pm 0.16$	1.38 ± 0.35
$D^0 \to \eta\pi^0\pi^0$	< 2.38	0.38 ± 0.13

Doubly CS decays $D^+ \to K^+\pi^+\pi^-\pi^0$

PRL 125, 141802 (2020)

- Doubly Cabibbo-Suppressed (DCS) decays of charmed hadrons relatively unexplored
- DCS/CF is of the order of $\tan^4\theta_C \sim 0.29\%$

*https://pdg.lbl.gov/2020/tables/rpp2020-sum-mesons.pdf

DCS decays	BF($\times 10^{-4}$)	CF decays	BF($\times 10^{-2}$)	Ratio($\times 10^{-3}$)
$D^0 \to K^+\pi^-$	1.50±0.07	$D^0 \to K^-\pi^+$	3.95±0.03	3.8±0.18
$D^0 \to K^+\pi^-\pi^0$	3.06±0.15	$D^0 \to K^-\pi^+\pi^0$	14.4±0.5	2.12±0.13
$D^0 \to K^+\pi^-\pi^-\pi^+$	2.65±0.06	$D^0 \to K^-\pi^+\pi^-\pi^+$	8.23±0.14	3.19±0.10
$D^+ \to K^+\pi^-\pi^+$	4.91±0.09	$D^+ \to K^-\pi^+\pi^+$	8.38±0.16	5.84±0.34

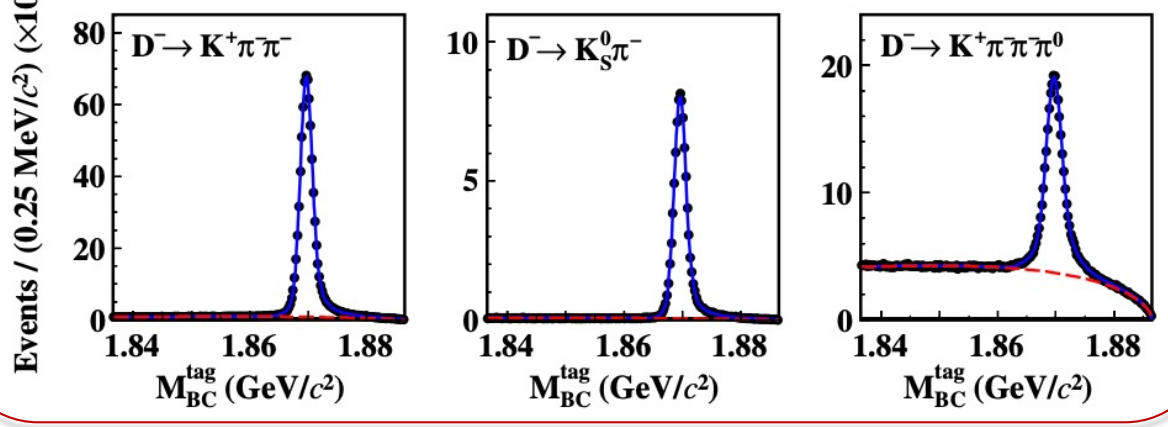
- Study of $D^+ \to K^+\pi^+\pi^-\pi^0$ offers unique opportunity to search for $D^+ \to K^+\omega$ and to determine its BR
- Search for CP violation in DCS decays: even if it is expected to be very tiny it offers complementary information about CP violation in the charm sector

- **2.93 fb^{-1} at $\sqrt{s}$=3.773 GeV**
- **Double tag**

Doubly CS decays $D^+ \to K^+\pi^+\pi^-\pi^0$

PRL 125, 141802 (2020)

Single TAG

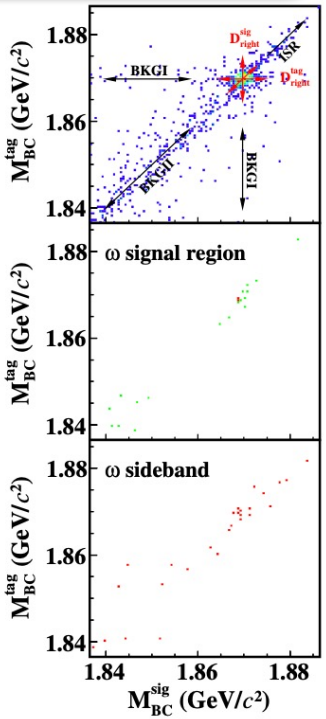


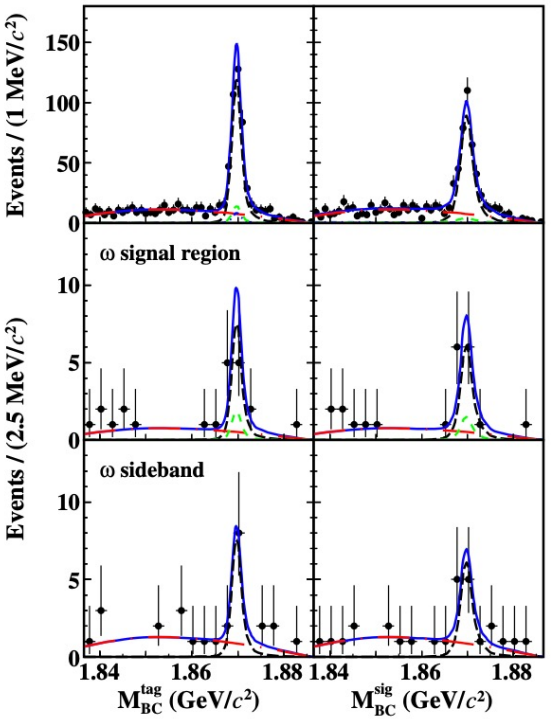
$$\Delta E = E_D - E_{beam}$$

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

Double TAG:

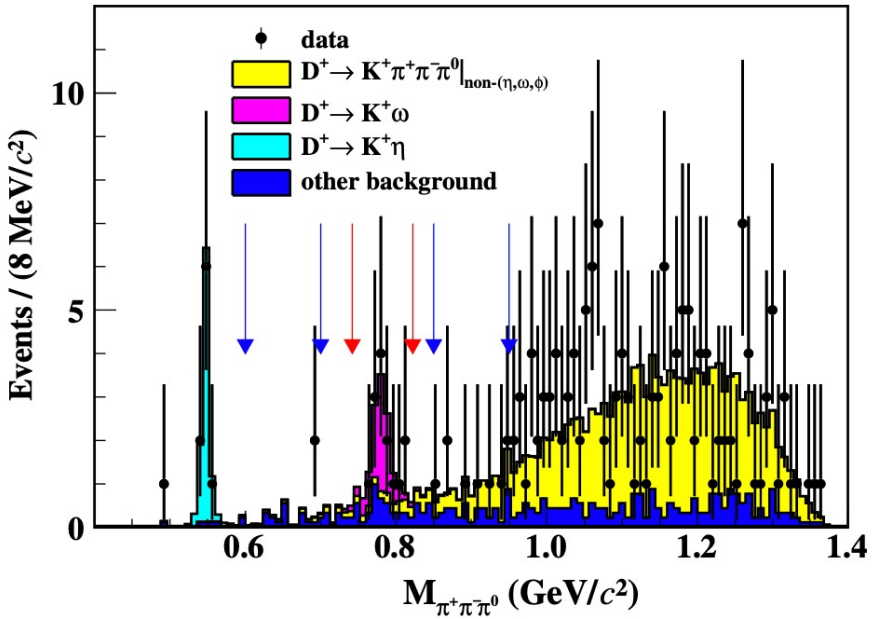
- D^- in the tag side and $D^+ \to K^+\pi^+\pi^-\pi^0$ in the signal side
- 2D unbinned maximum likelihood fit to M^{tag}_{BC} and M^{sig}_{BC}
- $D^+ \to K^+\omega$ 2D fit in the ω signal and sideband regions





Doubly CS decays $D^+ \to K^+\pi^+\pi^-\pi^0$

PRL 125, 141802 (2020)



Decay mode	$\mathcal{B}^*_{\rm sig}(\times 10^{-3})$
$D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0$	1.13 ± 0.08
$D^\pm \to K^\pm\omega$	$\cdots$
$D^+ \to K^+\pi^+\pi^-\pi^0$	1.17 ± 0.11
$D^- \to K^-\pi^-\pi^+\pi^0$	1.08 ± 0.11

* *without contributions from* $D^+ \to K^+\omega$, $K^+\eta$, $K^+\phi$

- **Evidence of $D^+ \to K^+\omega$**
  - **BF($D^+ \to K^+\omega$) = $(5.7^{+2.5}_{-2.1} \pm 0.2) \times 10^{-5}$ (3.3σ of statistical significance)**
- $\dfrac{\mathcal{B}(D^+ \to K^+\pi^-\pi^+\pi^0)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)} = (1.81 \pm 0.15)\% = (6.28 \pm 0.52)\tan^4\theta_c$ significantly larger than the values (0.21-0.58)% measured from the other DCS decays
  - Amplitude analysis with more data are needed
- No evidence for CP violation:

$$\mathcal{A}_{CP}^{D^\pm \to K^\pm\pi^\pm\pi^\mp\pi^0} = \frac{\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0) - \mathcal{B}(D^- \to K^-\pi^-\pi^+\pi^0)}{\mathcal{B}(D^+ \to K^+\pi^+\pi^-\pi^0) + \mathcal{B}(D^- \to K^-\pi^-\pi^+\pi^0)} = -0.04 \pm 0.06 \pm 0.01$$

Conclusions

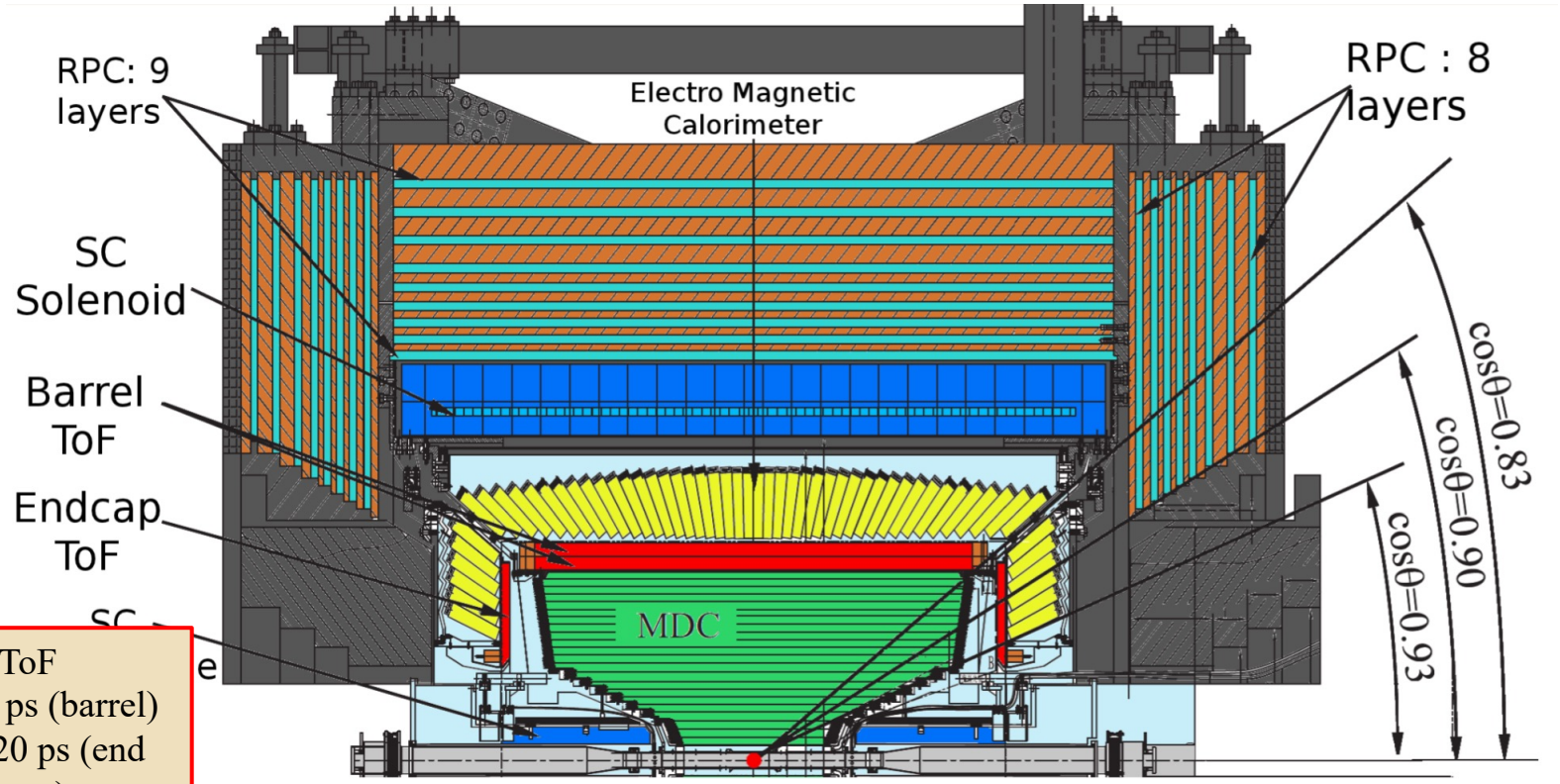
- The world largest datasets collected by the BESIII experiment provide unique opportunity to study and search for rare and radiative charm decays
  - ➢ Single Tag and Double Tag techniques
  - ➢ Low backgrounds
- Covered in this talk:
  - Search for LN violation in D decays PRD **99**, 112002 (2019)
  - Search for BN Violation in D decays PRD **101**, 031102(2019)
  - Search for $D_s^+ \to \gamma e^+ \nu_e$ radiative decays PRD **99**,072002 (2019)
  - $D \to \omega\pi\pi$ singly CS decay PRD **102**,052003 (2020)
  - $D^+ \to K^+\pi^+\pi^-\pi^0$ singly CS decay PRL **125**,141802 (2020)
  - …. many other results shown in this Conference …..

- New data @ $\psi(3770)$ (~20 fb^{-1}) will be available
  - New interesting results expected

Back-up slides

The BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)



ToF
$\sigma_t \sim 90$ ps (barrel)
$\sigma_t \sim 120$ ps (end caps)

Drift Chamber
$\sigma_{r\phi} \sim 130$ μm (single wire)
$\sigma_{pt}/p_t \sim 0.5$ % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\text{ mm})/E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi = 93\%$

BESIII physics programme

Light hadron physics

- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- two-photon physics
- Form factors

XYZ meson physics

- Y(4260), Y(4360) properties
- $Z_c(3900)^+$, …

QCD and τ

- Precision R measurement
- τ decay

Charm physics

- Semi-leptonic form factors
- Decay constants f_D and f_{Ds}
- CKM matrix: $|V_{cd}|$ and $|V_{cs}|$
- D^0-$\overline{D}^0$ mixing, CPV
- Strong phases

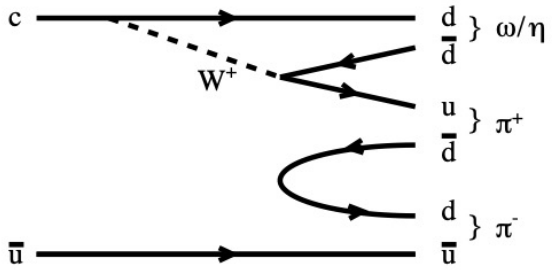
Charmonium physics

- Precision spectroscopy
- Transitions and decays

Precision mass measurements

- τ mass
- D, D^* mass

Single CS


c
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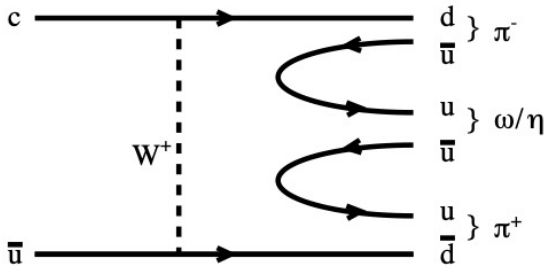
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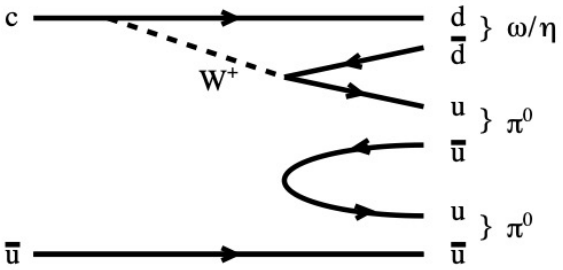
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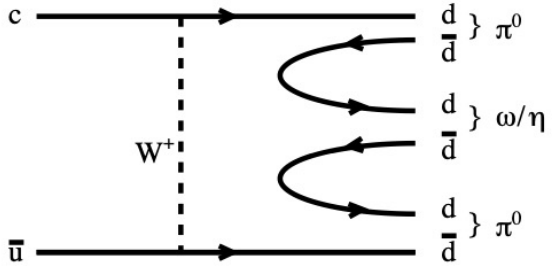
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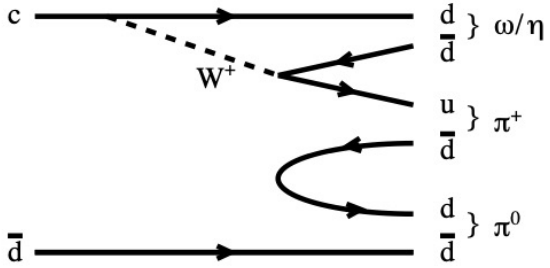
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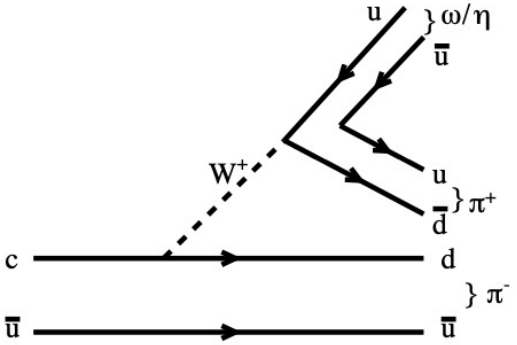
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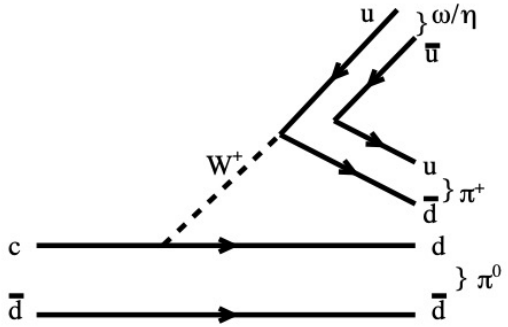
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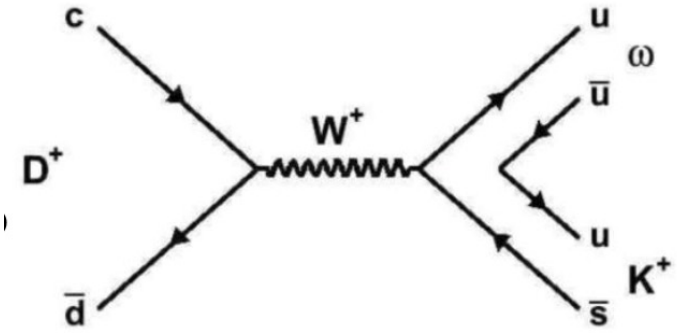
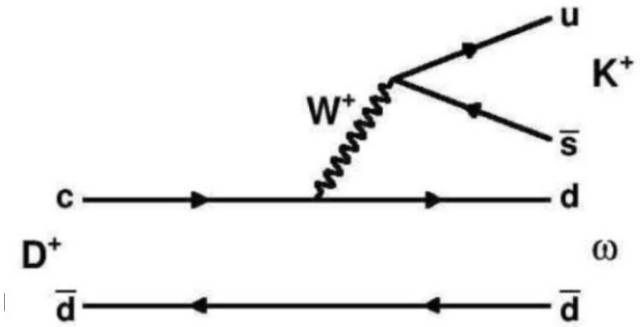
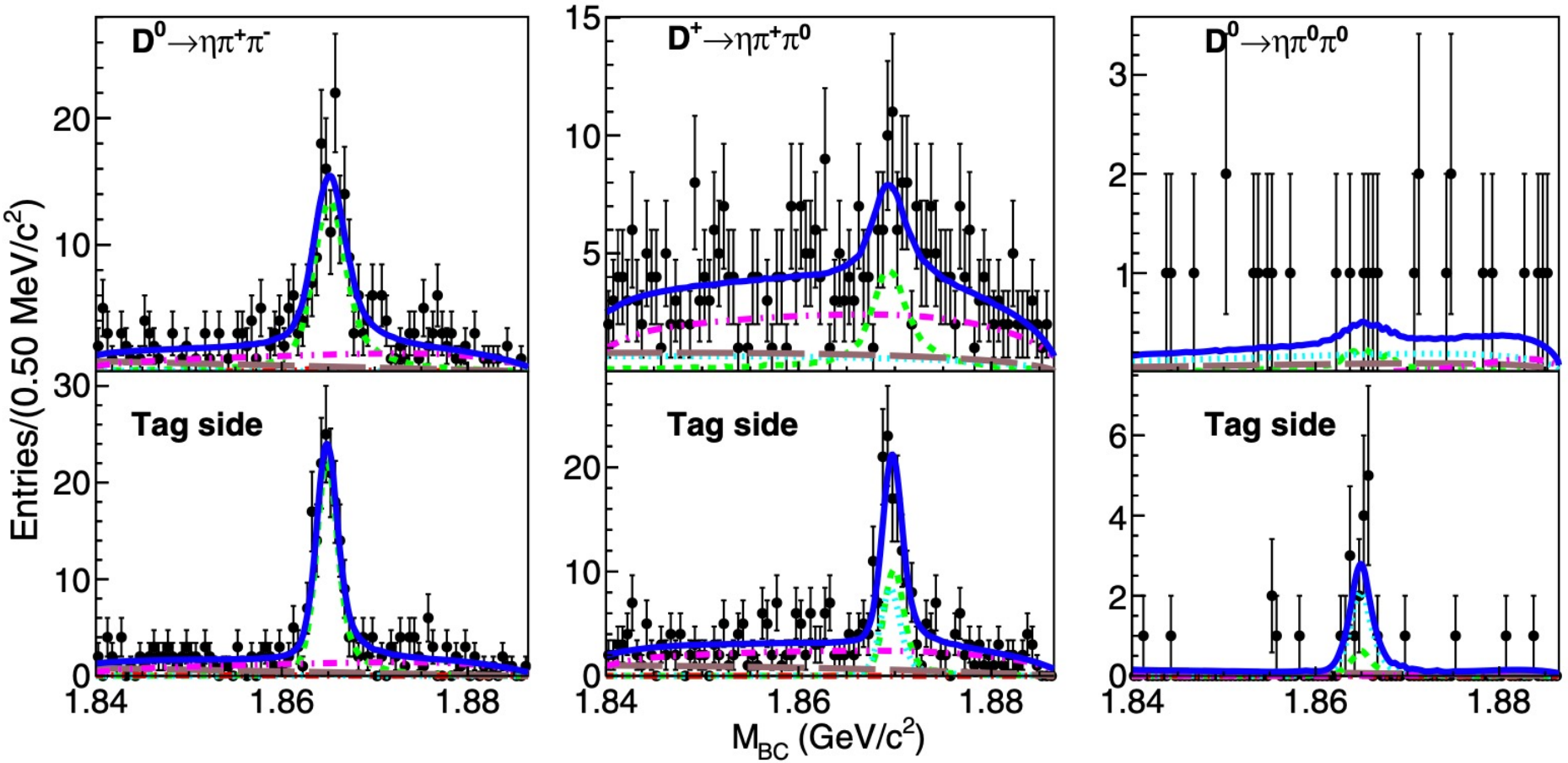
Double CS





Singly CS decays $D\to\eta\pi\pi$

PRD 102, 052003 (2020)

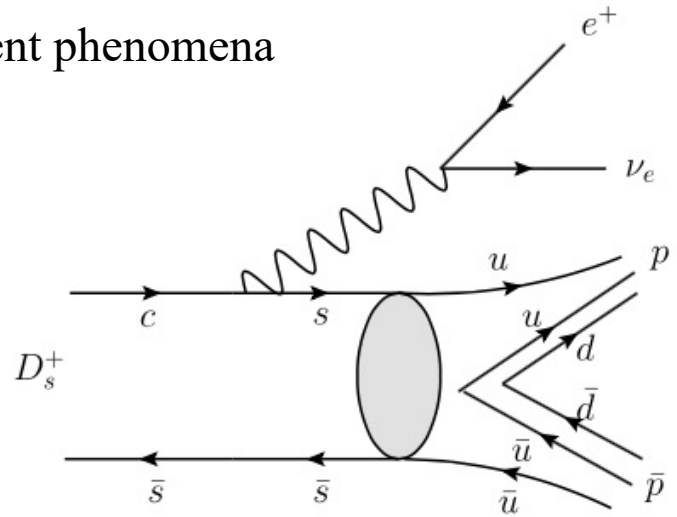


Rare semi-leptonic D decays

- Transition between charm meson and baryon pairs is still unexplored
- $D_s^+ \to p\bar{n}$ observed by CLEO (PRL **100**, 181802) and confirmed by BESIII (PRD **99**, 031101)
  - Observed BR of the order of 10^{-3},
  - Predicted to be of the order of 10^{-2} (PRL **45**, 1663)
- Promising candidate to study is $D_s^+ \to p\bar{p}e^+\nu_e$
  - BR prediction ~ 10^{-8}-10^{-9} (PLB **780**, 100)
  - Important to study the near-threshold enhancement phenomena

Differential rate:

$$\frac{d\Gamma(D_s^+ \to Xe^+\nu_e)}{dq^2} = \frac{G_F^2|V_{cs}|^2}{24\pi^3} p_X^3 |f_+(q^2)|^2$$

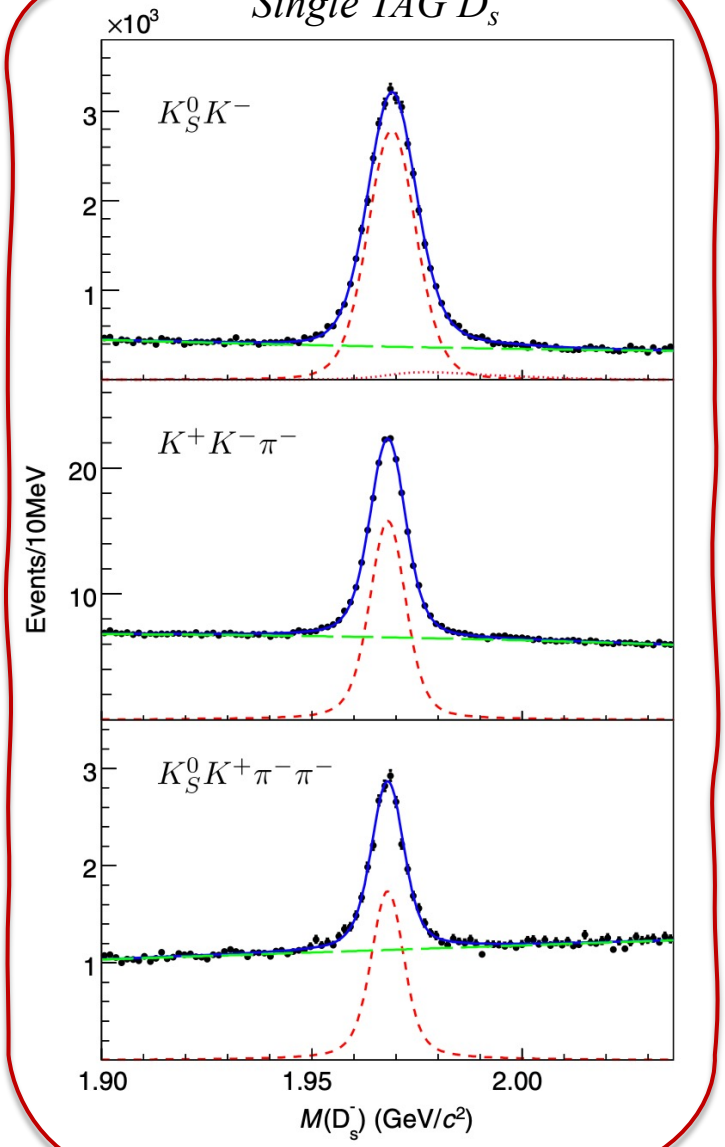


- **@ BESIII: 3.19 fb^{-1} at $\sqrt{s}$=4.178 GeV**
- **Double tag**

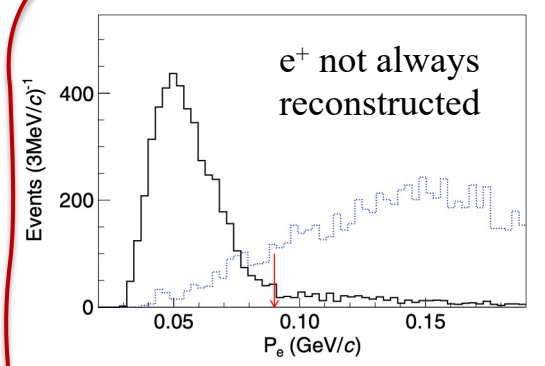
$D_s^+ \to p\bar{p}e^+\nu_e$

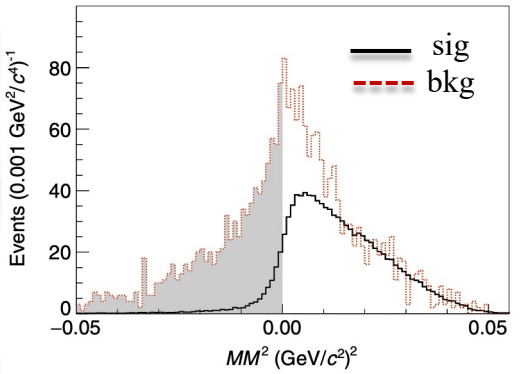
PRD 100, 112008 (2019)

Single TAG D_s

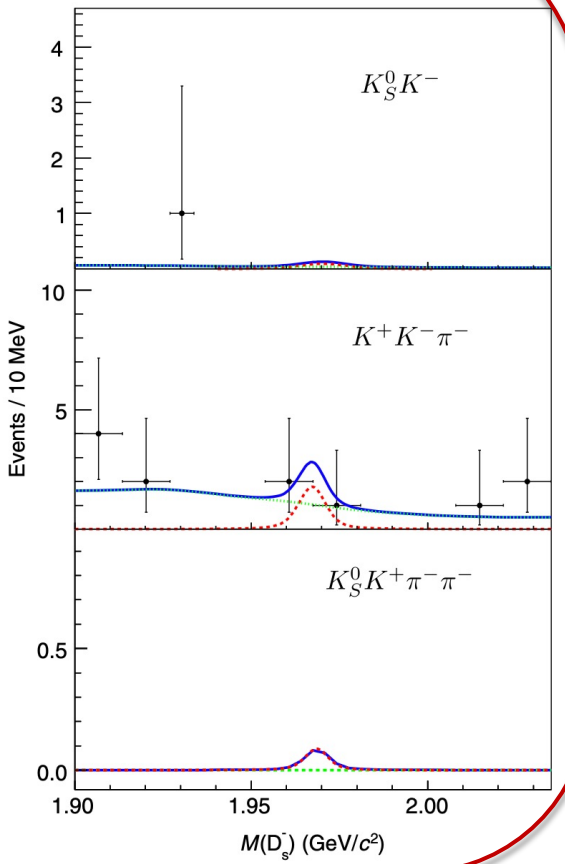


Double TAG





$$MM^2 = (\sqrt{s} - E_{tag} - E_{sig})^2 - (\vec{p}_{tag} - \vec{p}_{sig})^2$$



$$\mathcal{B}(D_s^+ \to p\bar{p}e^+\nu_e) < 2.0 \times 10^{-4}$$

Observation of $D^+ \to \omega \mu^+ \nu_\mu$

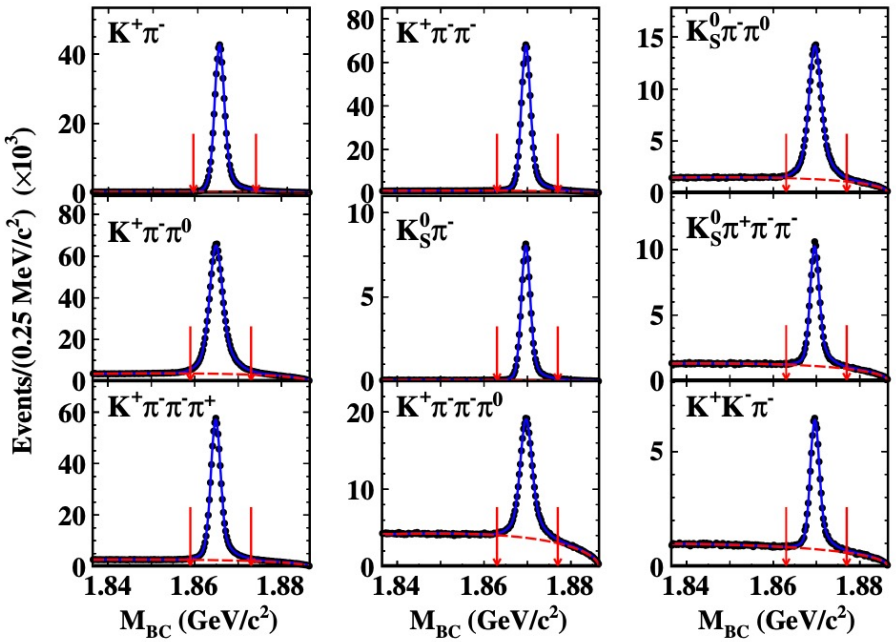
PRD 101, 072005 (2020)

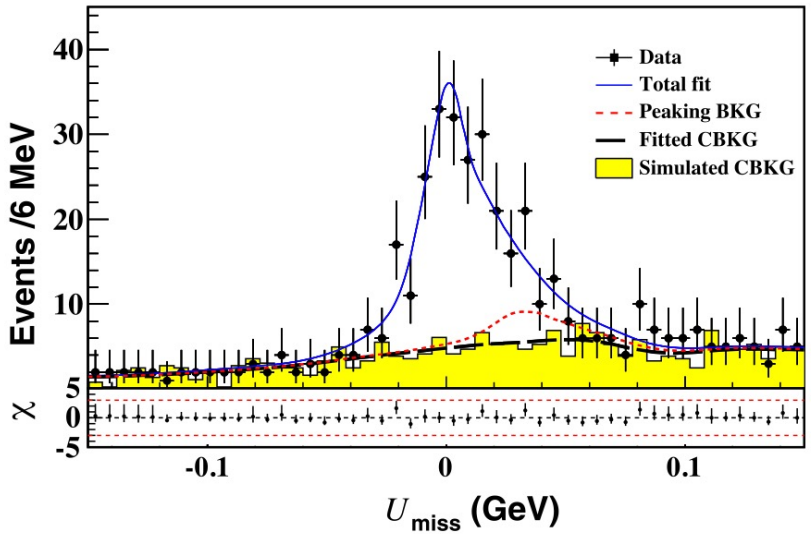
- Test for Lepton Flavor Universality
- $\mathcal{R}^+ \equiv \mathcal{B}_{D^+\to\pi^0\mu^+\nu_\mu}/\mathcal{B}_{D^+\to\pi^0 e^+\nu_e} = 0.964 \pm 0.037_{\rm stat} \pm 0.026_{\rm syst}$

  $\mathcal{R}^0 \equiv \mathcal{B}_{D^0\to\pi^-\mu^+\nu_\mu}/\mathcal{B}_{D^0\to\pi^- e^+\nu_e} = 0.922 \pm 0.030_{\rm stat} \pm 0.022_{\rm syst}$

  PRL 121, 171803 (BESIII Coll.)
  - 0.5σ and 1.7σ compatibility with expectations, respectively
- $D^+ \to \omega \mu^+ \nu_\mu$ ➔ **@ BESIII: 2.93 fb^{-1} at $\sqrt{s}$=3.773 GeV for the first time**

Single TAG





$$\mathcal{B}(D^+ \to \omega \mu^+ \nu_\mu) = (17.7 \pm 1.8 \pm 1.1) \times 10^{-4}$$

$$\frac{\mathcal{B}(D^+ \to \omega \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to \omega e^+ \nu_e)^{PDG}} = 1.05 \pm 0.14 \quad \text{(SM: 0.93-0.99)}$$