Search for Rare decay at BESIII

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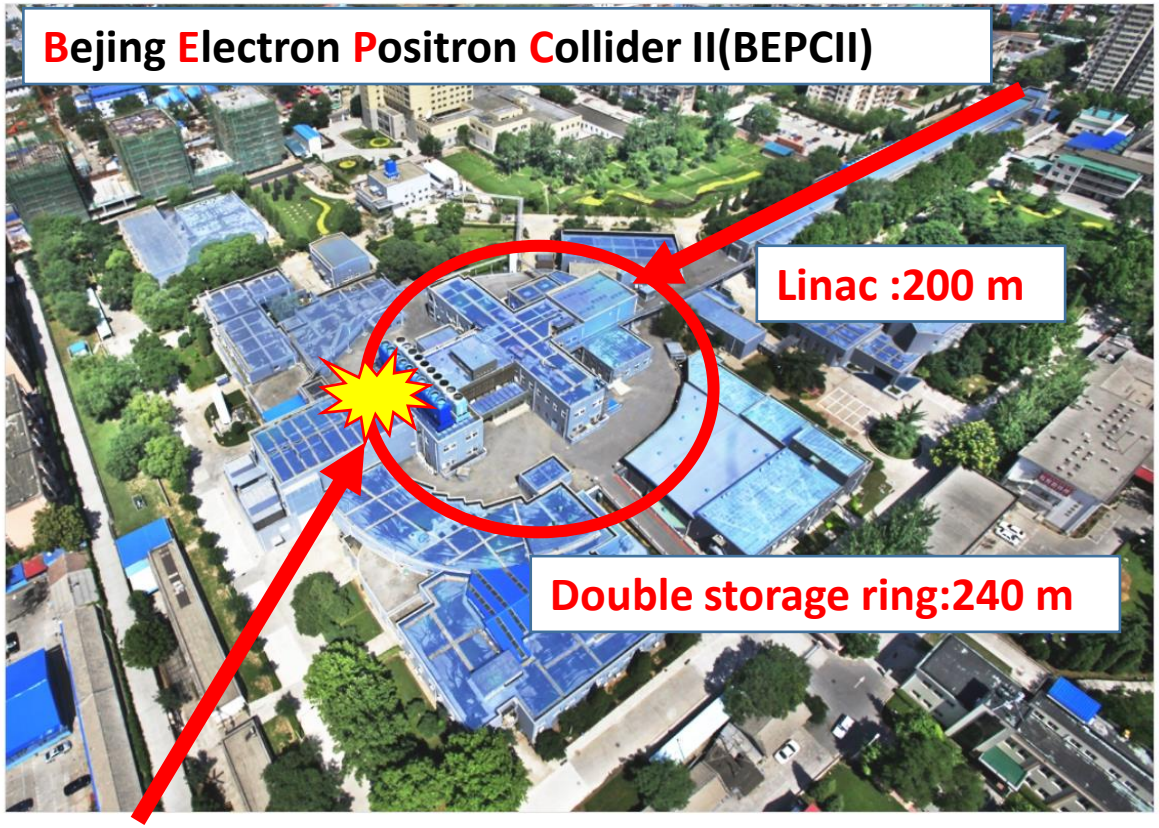
Outline

- BEPCII and BESIII experiment
- New Physics and benefit of BESIII
- Rare decays results at BESIII
- Ongoing Analyses
- Summary

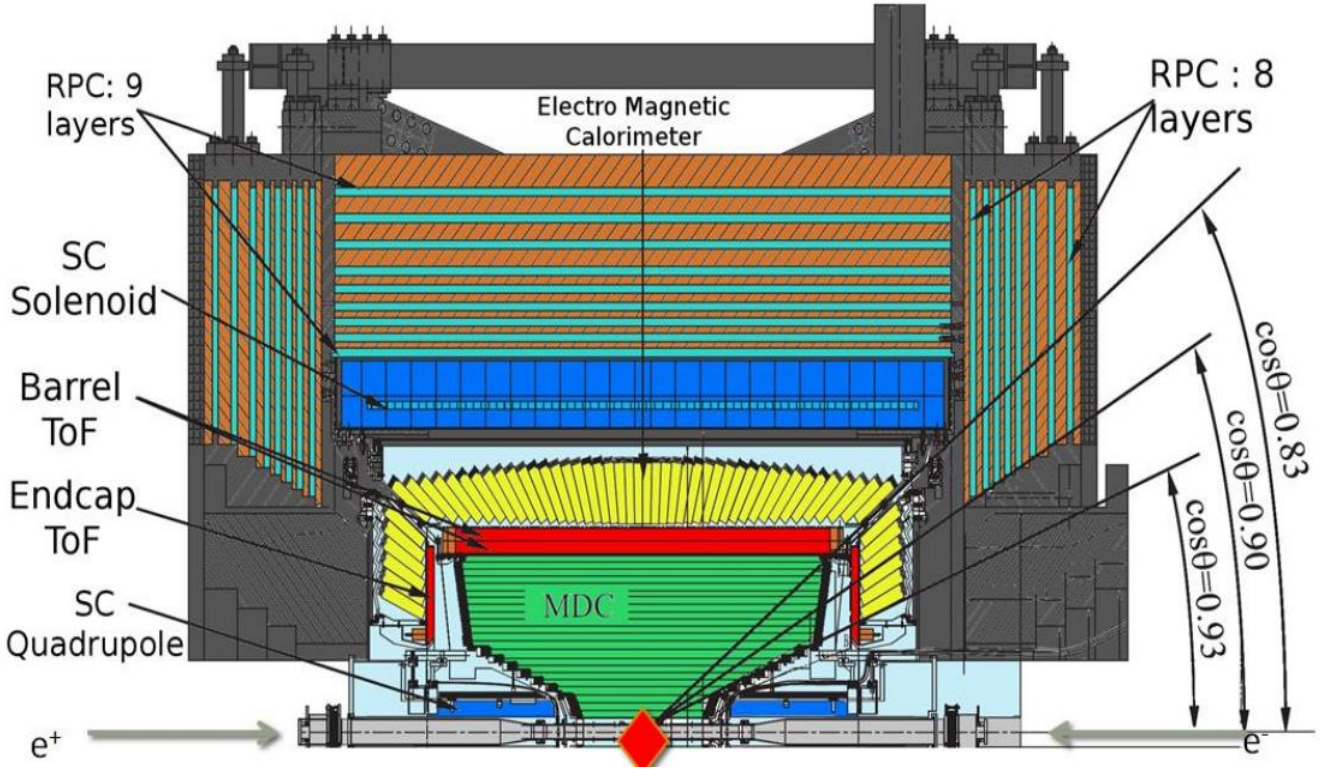
BEPCII and BESIII experiment

- Bird View of BEPCII/BESIII



BESIII detector

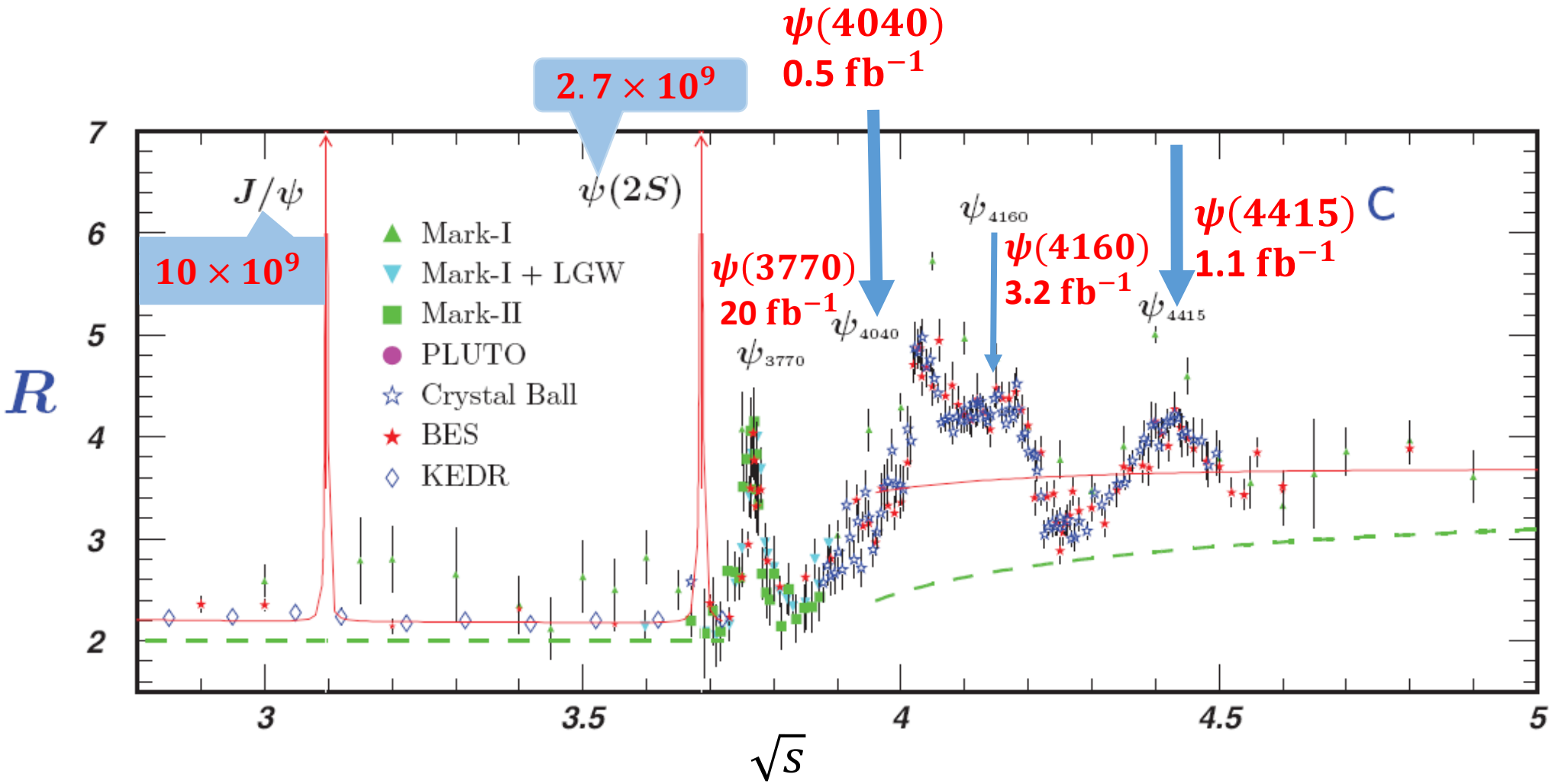
- CMS energy: 2 - 4.95 GeV
- Luminosity: $1 \times 10^{33}\ cm^{-2}s^{-1}$
- 2008:Test run
- 2009-now:$\tau - charm$ physics runs



- MDC: σ_p/p=0.5%@1 GeV, $\sigma_{dE/dx}$=6%;
- TOF: $\sigma_T = 68(110)$ ps for barrel(endcap); endcap TOF upgraded in 2015→ 60 ps;
- EMC: σ_E/E = 2.5% (5%) ps for barrel(endcap)

Data samples at BESIII

- Collected the world largest J/ψ, $\psi(2S)$ and $\psi(3770)$ data samples;
- BESIII has collected 20 fb^{-1} $\psi(3770)$, large D meson sample from $\psi \to D\bar{D}$.



New Physics and benefit of BESIII

- Standard Model (SM) is incredibly successful, it is well tested by many experiments.

- But it cannot explain:
  - Existence & mechanism of dark matter and dark energy;
  - Baryon asymmetry of the universe
  - Neutrino masses and oscillations, hierarchy

.....

Benefit

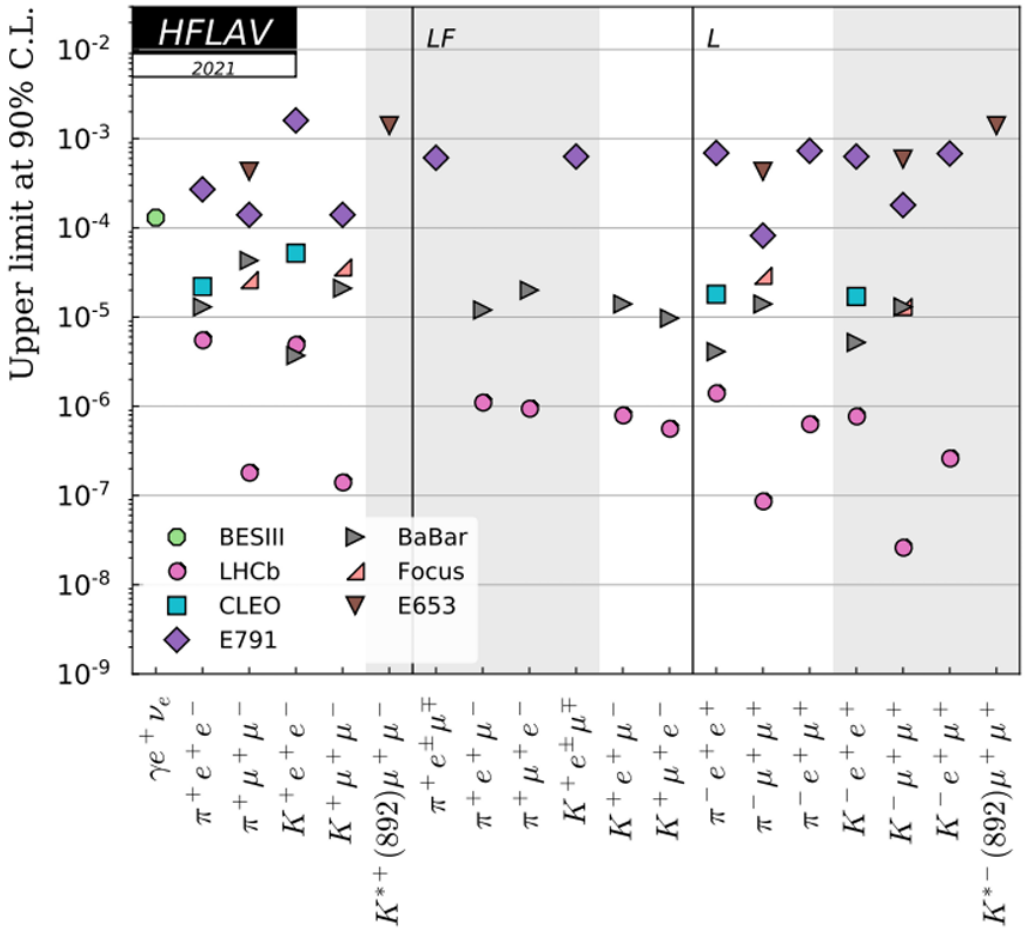
- **Huge data samples;**
- **Kinematic constraints:** deliver high purity for final states with invisible energy and photons;
- **Double-tag method:** allows almost background free studies, quantum coherence, high trigger efficiency, and easy detection of neutral particles
- **Semi-blind /full-blind strategy:** to avoid voluntary bias from analyst

Search for lepton number violating decays of $D_s^+ \to h^- h^0 e^+ e^+$

Motivation

JHEP01(2025)109

- Being forbidden in the SM, Lepton Number Violating (LNV) processes provide an approach to New Physics.
- The nature of neutrinos, whether neutrinos are Dirac or Majorana particles, is still an open question. LNV decays can be used to search for the Majorana neutrino.
- Experimentally, there are already many search results for $\Delta L = 2$ processes of D mesons. However, there are still no LNV results for four-body D_s decays.



- Upper limits at 90% C.L. for D_s^+ decays

Analysis method and data sets

JHEP01(2025)109

☐ Analysis method

- This work perform the search of six LNV processes: $D_s^+ \to (\pi^-\pi^0)/(K^-\pi^0)/(K_S^0\pi^-)/(K_S^0K^-)/(\phi\pi^-)/(\phi K^-)e^+e^+$
- Single-Tag (ST) method is used, in which an ST candidate has one of D_s and no additional requirement on the other
- The BF of $D_s^+ \to h^-h^0e^+e^+$ decays can be calculated by

$$\mathcal{B}(D_s^+ \to h^-h^0e^+e^+) = \frac{N_{\rm sig}}{2 \cdot N_{D_s^{*\pm}D_s^{\mp}} \cdot \epsilon \cdot \mathcal{B}_{\rm inter}},$$

☐ Data sets

- Data samples: ECM = 4.128~4.226 GeV; ~7.33 fb^{-1}
- MC samples:
  - x40 in-MC samples;
  - Events of signal MC samples are generated with PHSP generator

- D_s^- →anything
- $D_s^+ \to (\pi^-\pi^0)/(K^-\pi^0)/(K_S^0\pi^-)/(K_S^0K^-)/(\phi\pi^-)/(\phi K^-)e^+e^+$
- Charge-conjugate channels are implied automatically

Signal determination

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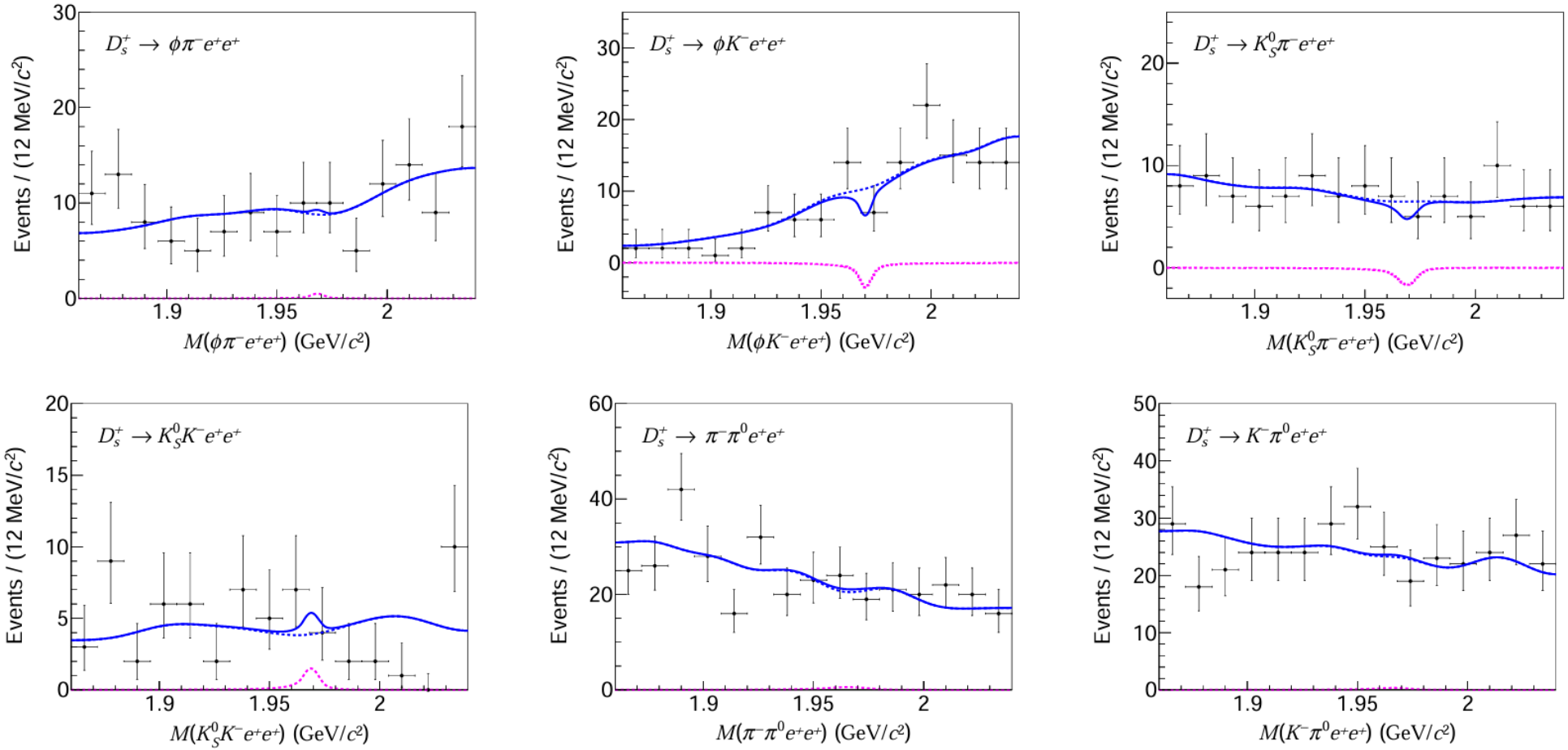
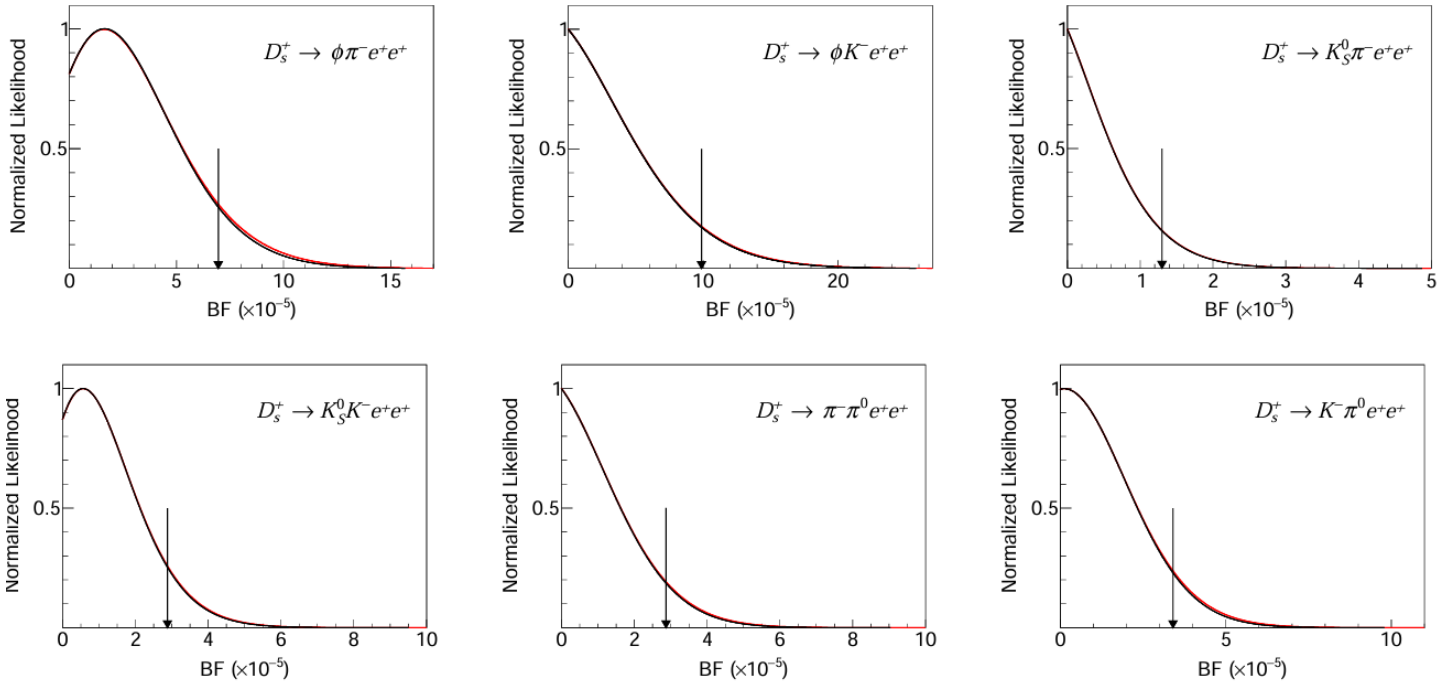


- The signal shape is modeled by the sum of adouble-sided Crystal Ball function and a bifurcated Gaussian function with asymmetric tails
- The background shape ismodeledby inclusiveMC samples using the RooKeysPdf

Result

Phys. Rev. D 107, 012002 (2023)



- @90% C.L.

- No significant signal observed in data
- The upper limit on the branching fraction is set using Bayesian method

Decay channel	ϵ (%)	$\mathcal{B}_{\rm UL}$ ($\mathcal{B}_{\rm UL}^{\rm expected}$)
$D_s^+ \to \phi\pi^- e^+e^+$	3.0 ± 0.1	$6.9\ (3.5) \times 10^{-5}$
$D_s^+ \to \phi K^- e^+e^+$	1.8 ± 0.1	$9.9\ (10.8) \times 10^{-5}$
$D_s^+ \to K_S^0\pi^- e^+e^+$	6.4 ± 0.1	$1.3\ (2.4) \times 10^{-5}$
$D_s^+ \to K_S^0 K^- e^+e^+$	4.0 ± 0.1	$2.9\ (2.3) \times 10^{-5}$
$D_s^+ \to \pi^-\pi^0 e^+e^+$	6.4 ± 0.1	$2.9\ (2.7) \times 10^{-5}$
$D_s^+ \to K^-\pi^0 e^+e^+$	5.1 ± 0.1	$3.4\ (3.9) \times 10^{-5}$

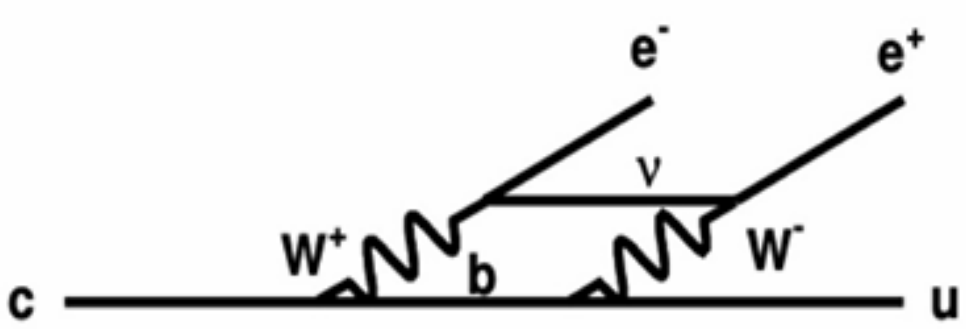
Search for Rare Decays of D_s^+ to Final States $\pi^+e^+e^-$, $\rho^+e^+e^-$, $\pi^+\pi^0e^+e^-$, $K^+\pi^0e^+e^-$ and $K_s^0\pi^+e^+e^-$

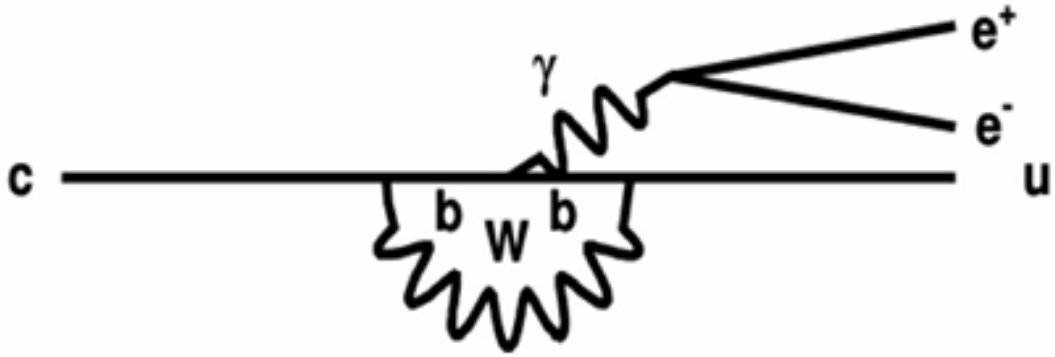
Motivation

PhysRevL 133, 121801 (2024)

- FCNC process ($c \to ull$) in $D_{(s)}$ decays highly suppressed with BF<O(10^{-12}) ; NP may greatly enhance the rates : the rates with a lepton-pair mass in the non-resonant regions could provide access to NP

- Long-distance contributions : $D_{(s)} \to hV(V \to ll)$decays, however, are more accessible experimentally with BF up to O(10^{-5}) ; BABAR / LHCbobserved decays in the M(ll) ranges of $\phi/\omega/\rho$: $D^0 \to h(h')ll$, $D_s \to hll$





Data sets and analysis Method

PhysRevL 133, 121801 (2024)

☐ Data sets

- Data samples: E =4.128-4.226 GeV; L=6.32 fb^{-1} (BOSS 7.0.3);
- MC samples:
  - 40 in-MC sample
  - signal MC samples -ConExc
    - $D_s^- \to$ anything
    - $D_s^+ \to \pi^+/(\pi^+\pi^0)/(K^+\pi^0)/(K_S^0\pi^+)e^+e^-$ LD / PHSP model.
- The charge conjugated channels are implied automatically

☐ Analysis method

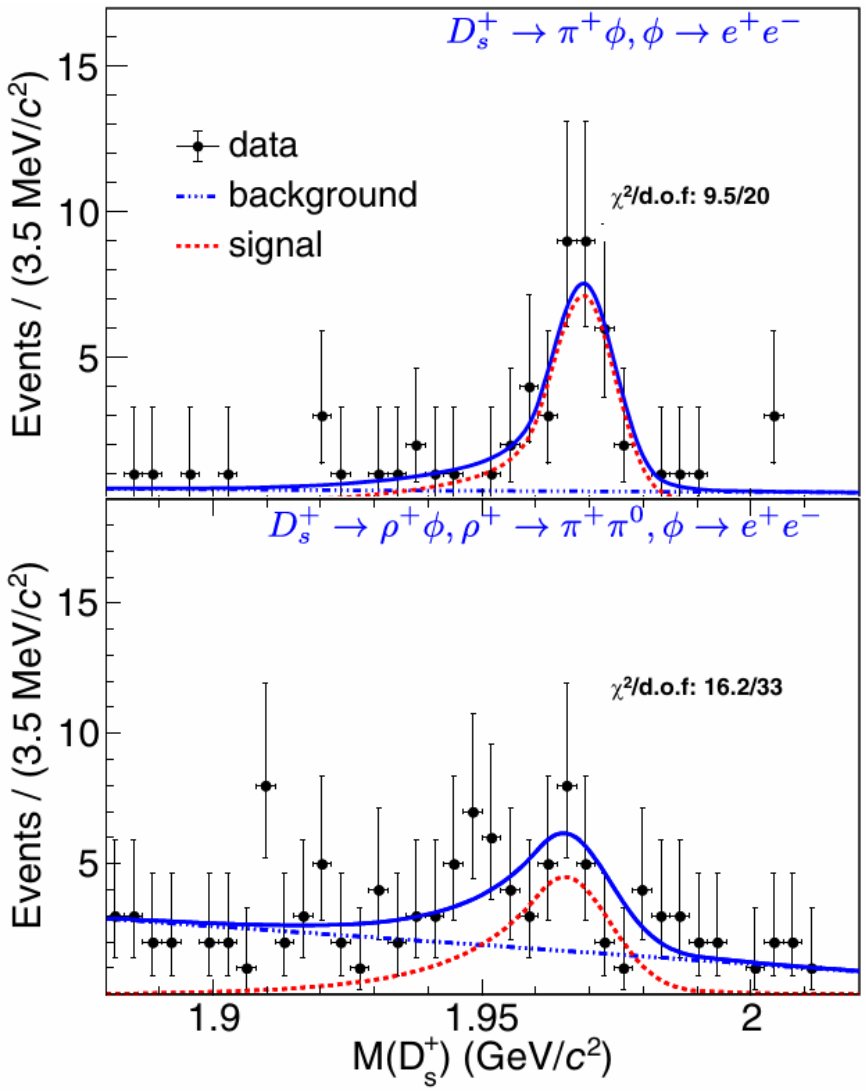
- Single-Tag (ST) method is used. The signal processes of $D_s \to h(h')e^+e^-$
- Using $D_s^+ \to \pi^+(\pi^0)K^+K^-/K_S^0K^-\pi^+\pi^-$ as normalization and calibration channels(NC)

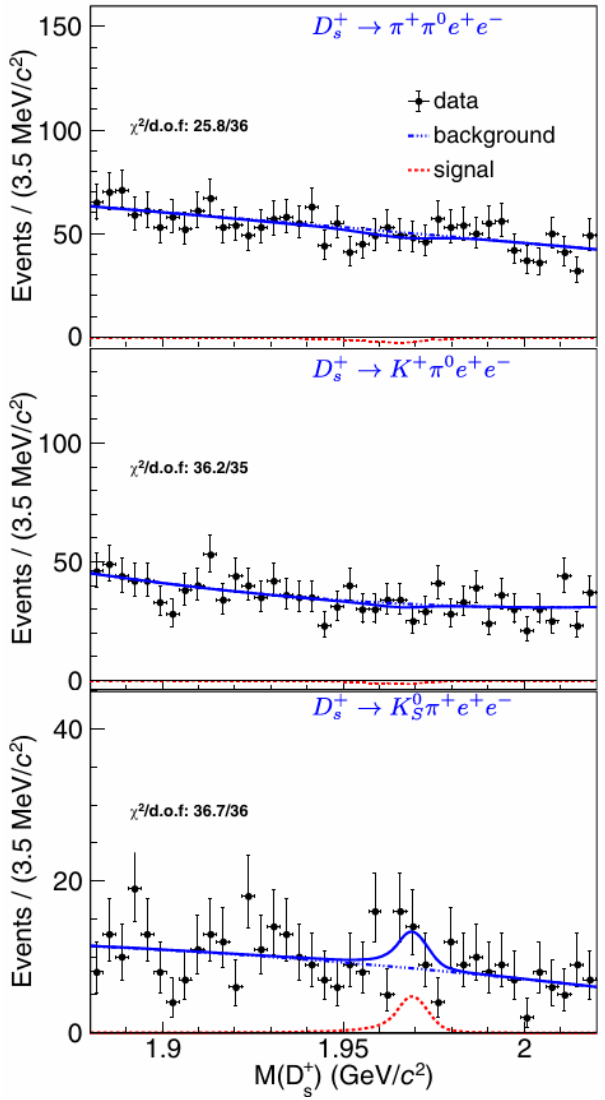
$$\mathcal{B}(D_s^+ \to h(h')e^+e^-) = \frac{N_{D_s^+\to h(h')e^+e^-}/\epsilon_{D_s^+\to h(h')e^+e^-}}{N_{NC}/\epsilon_{NC}} * \mathcal{B}_{NC}$$

Signal determination

PhysRevL 133, 121801 (2024)

- Fit in $M(D_s^+)$ to extract the signal yields





- The signalMC shape convolved with a Gaussian function
- The backgroundmodel are estimatedby repeating the fit with the background MC simulated shape

Result

PhysRevL 133, 121801 (2024)

Decay	$N_{\rm sig}$	ϵ (%)	$\mathcal{B}(\times 10^{-5})$
$D_s^+ \to \pi^+\phi,\ \phi \to e^+e^-$	$38.2^{+7.8}_{-6.8}$	25.1	$1.17^{+0.23}_{-0.21} \pm 0.03$
$D_s^+ \to \rho^+\phi,\ \phi \to e^+e^-$	$37.8^{+10.3}_{-9.6}$	12.1	$2.44^{+0.67}_{-0.62} \pm 0.16$
$D_s^+ \to \pi^+\pi^0 e^+e^-$	...	7.4	<7.0
$D_s^+ \to K^+\pi^0 e^+e^-$	...	5.3	<7.1
$D_s^+ \to K_S^0\pi^+ e^+e^-$	...	6.7	<8.1

- @90% C.L.

- No significant signals for the three four-body decays of $D_s^+ \to \pi^+\pi^0 e^+e^-$,$D_s^+ \to K^+\pi^0 e^+e^-$, $D_s^+ \to K_S^0\pi^+ e^+e^-$ are observed

- For $D_s^+ \to \pi^+\pi^0 e^+e^-$ the ϕ mass region is vetoed to minimize the long-distance effects

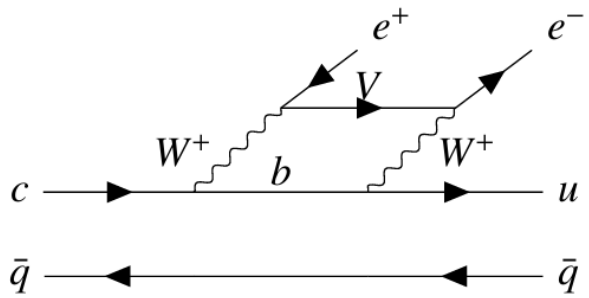
Search for Rare Decays of $D \to h(h')e^+e^-$

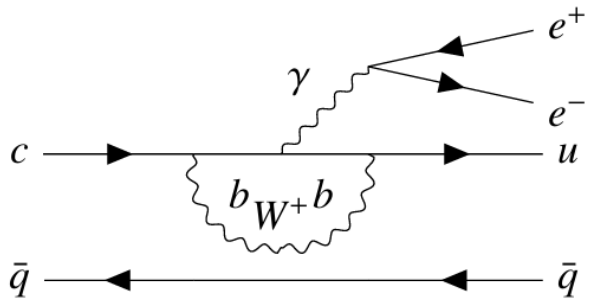
Motivation

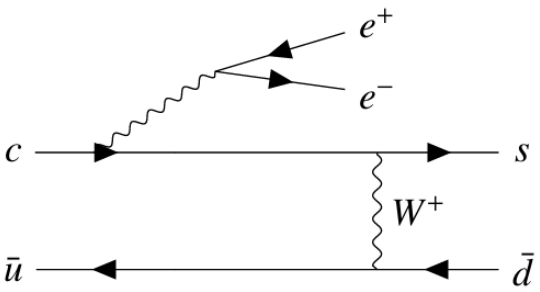
- In the SM model, the flavor changing neutral current (FCNC) is suppressed by GIM mechanism
  - It can not occur at tree level, it can occur at loop level
  - Possible NP can significantly increase the BFs (SD)
  - Long distance contributions from photon pole or vector meson

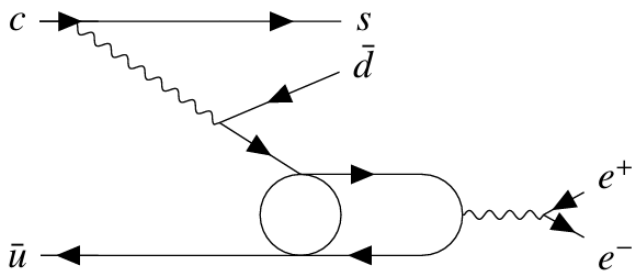
- The result published in 2018:
  - Integrated luminosity of 2.93 fb^{-1} [1] at $\sqrt{S}$ = 3.773GeV.The sensitive of the results are at the level of $10^{-5} \sim 10^{-6}$
  - No obvious LD contribution

[1]https://arxiv.org/pdf/1802.09752









Data sets

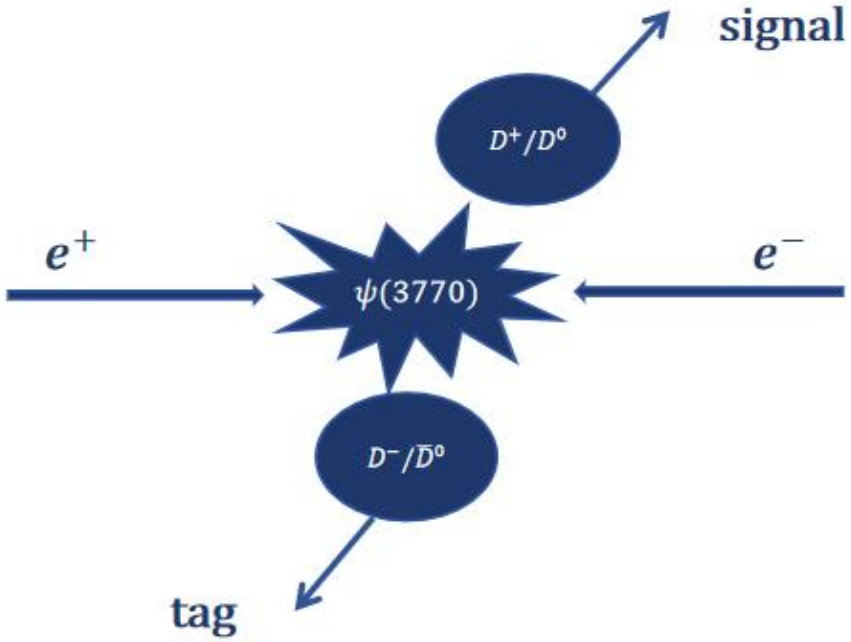
- @ $\sqrt{s}$ = 3.773 GeV
- Semi-blind Data: 2.03 fb^{-1}
- Fake Data: 20.3 fb^{-1}
- Inclusive MC: 40 times of data
- BOSS version: 7.1.2

- Signal MC mode: mixed ω model with bined PHSP model
  - ω model: $D \to hh'\omega$, $\omega \to e^+e^-$
  - Bined PHSP model: we divided the invariant mass interval of e^+e^- into several bins with each bin having a width of 0.1 GeV/c^2, the central masses locate at the middle of each e^+e^- bin

Analysis method

Ongoing BAM-1018

Process
$D^+ \to \pi^+\pi^0 e^+e^-$
$D^+ \to K^+\pi^0 e^+e^-$
$D^+ \to \pi^+ K_S^0 e^+e^-$
$D^+ \to K^+ K_S^0 e^+e^-$
$D^+ \to \rho^+ e^+e^-$
$D^+ \to K^{*+} e^+e^-$
$D^0 \to K^+K^- e^+e^-$
$D^0 \to \pi^+\pi^- e^+e^-$
$D^0 \to \pi^0 e^+e^-$
$D^0 \to \eta e^+e^-$
$D^0 \to \omega e^+e^-$
$D^0 \to K_S^0 e^+e^-$
$D^0 \to K_S^0 K_S^0 e^+e^-$
$D^0 \to \pi^0\pi^0 e^+e^-$
$D^0 \to \phi e^+e^-$
$D^0 \to \rho^0 e^+e^-$
$D^0 \to \eta' e^+e^-$



$$B_{sig} = \frac{N_{sig}\epsilon_{tag}}{N_{tag}\epsilon_{tag,sig}}$$

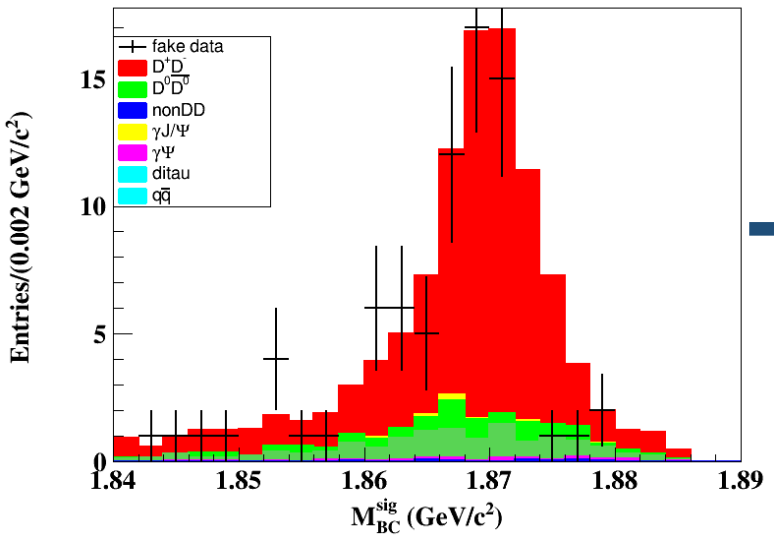
$$B_{sig} = \frac{N_{sig}}{\sum_\alpha N_{tag}^\alpha \epsilon_{tag,sig}^\alpha / \epsilon_{tag}^\alpha}$$

- 3 tags to reconstruct D^0:
  - $D^0 \to K^-\pi^+$
  - $D^0 \to K^-\pi^+\pi^0$
  - $D^0 \to K^-\pi^+\pi^-\pi^+$
- 6 tags to reconstruct D^+:
  - $D^+ \to K^-K^+\pi^+$
  - $D^+ \to K^-\pi^+\pi^-$
  - $D^+ \to K^+\pi^+\pi^-\pi^0$
  - $D^+ \to K_S^0\pi^+$
  - $D^+ \to K_S^0\pi^+\pi^0$
  - $D^+ \to K_S^0\pi^+\pi^-\pi^+$

Background Analysis

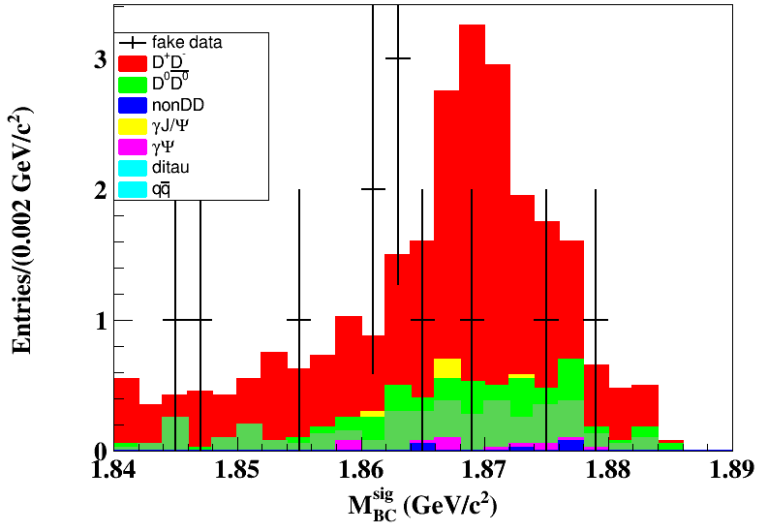
Ongoing BAM-1018

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



Veto $D \to h(h')\pi^0, \pi^0 \to \gamma\, e^+e^-$

Veto $D \to h(h')\eta, \eta \to \gamma\, e^+e^-$



- For background : $D \to h(h')\pi^0, \pi^0 \to \gamma\, e^+e^-$:
  - It can almost completely reject this type of background by $M_{e^+e^-} > 0.2$ GeV/c^2.
- For background : $D \to h(h')\eta, \eta \to \gamma\, e^+e^-$:
  - It reject nearly 60% of this background by $M_{e^+e^-\gamma} > 0.570$GeV/c^2 ,$M_{e^+e^-\gamma} < 0.505$ GeV/c^2

Branching fraction method

- $\mathcal{L} = P\,(N_{obs}, N_{ST}\cdot B\cdot \epsilon_{eff} + \hat{N}_{bkg1} + N_{bkg2})\cdot G\,(\hat{\epsilon}_{eff}, \epsilon_{eff}, \sigma_{\epsilon})\cdot P\,(N_{bkg1}, \hat{N}_{bkg1})\cdot G\,(\hat{N}_{bkg2}, N_{bkg2}, \sigma_{bkg2})$

- $\mathcal{L}_B = \max_{\text{with respect to } \hat{N}_{bkg1},\hat{N}_{bkg2},\hat{\epsilon}_{eff}} \mathcal{L}_{\hat{N}_{bkg1},\hat{N}_{bkg2},\hat{\epsilon}_{eff},B}$

  - N_{obs}: the observed events in data(Fake Data/semi-blind Data)
  - N_{bkg1} : flat backgrounds of misreconstructed tagged events
  - N_{bkg2} : peaking backgrounds of signal from data and MC
  - N_{ST}: the number of ST $D\bar{D}$ events
  - ϵ_{eff} : denotes the effective efficiencies
  - σ_{ϵ}: the standard deviation, including the systematics

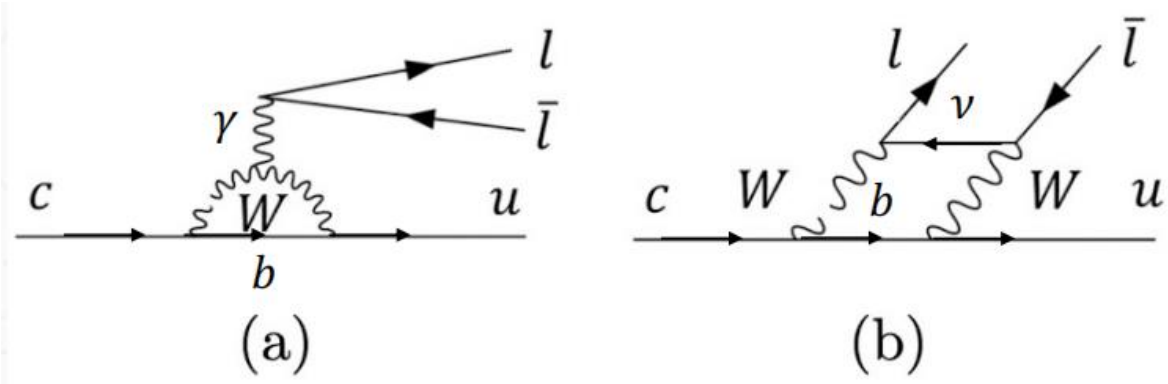
Expected results of B^{up}: $10^{-6}\sim10^{-7}$

Search for FCNC decay

$D^0 \to K^-\pi^+e^+e^-$ & $D^+ \to K_s^0\pi^+e^+e^-$

Motivation(1)

- In the SM model, the flavor changing neutral current (FCNC) is suppressed by GIM mechanism
  - It can not occur at tree level, it can occur at loop level
  - Possible NP can significantly increase the BFs (SD)
  - Long distance contributions from photon pole or vector meson



- The result published in 2018:
  - Integrated luminosity of 2.93 fb^{-1} [1] at $\sqrt{S}$ = 3.773GeV. The sensitive of the results are at the level of $10^{-5} \sim 10^{-6}$
  - No obvious LD contribution

[1]https://arxiv.org/pdf/1802.09752

Motivation(2)

- First observation of $D^0 \to K^-\pi^+e^+e^-$ in ρ/ω region in 2020 @ BABAR[2]
  - based on a data sample of 468 fb^{-1} and find 68 ± 9 signal events.
  - $B = (4.0 \pm 0.5) \times 10^{-6}$w/ the significance of the signal is > 9 standard deviations.
  - No significant signal in SD.
- Preliminary result for $D^0 \to K^-\pi^+e^+e^-$ in ρ/ω region in 2024 @ BELLEII
  - based on a data sample of 942 fb^{-1}
  - The result in omega region is compatible with Babar and with SM expectation
  - No signal observed in other channels and regions; upper limits is above 10−7 at 90% CL.
- The result of $R^+ = Br(D^+ \to K_s^0\pi^+e^+e^-)/Br(D^0 \to K^-\pi^+e^+e^-)$ has significant discrepancy between experiment and the SIM theory[3,4,5]

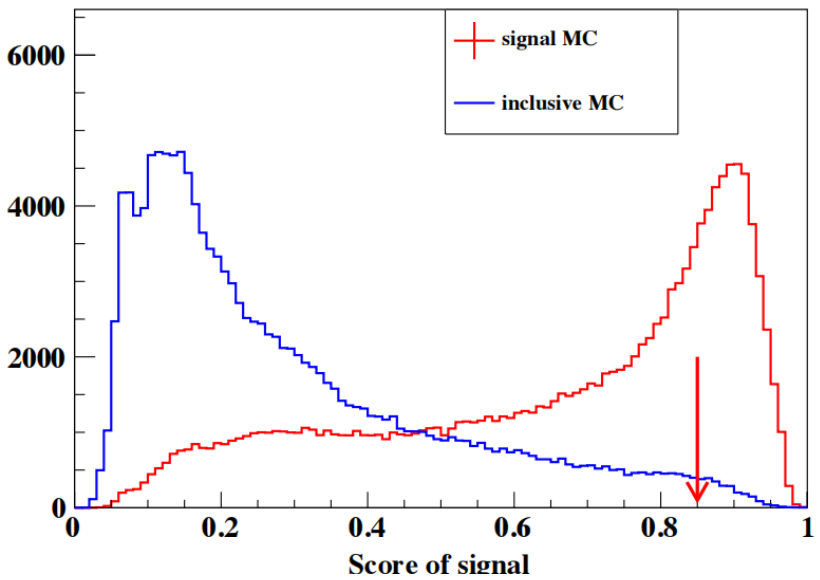
[2] EPJ Web Conf. 235, 04001 (2020)
[3] Nucl. Phys. B 122, 144 (1977)
[4] Phys. Rev. D 79 (2009) 074022
[5] Phys. Rev. D 105 (2022) 3, 032009

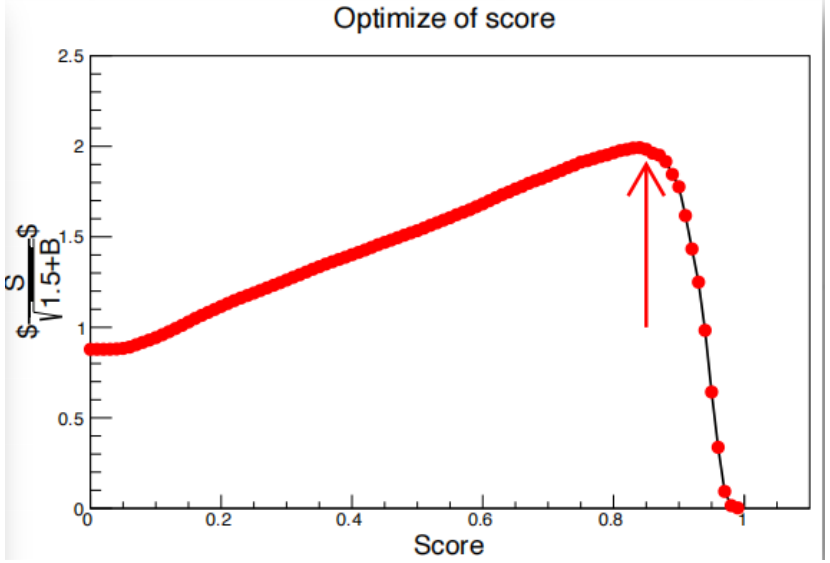
Data sets

- @ $\sqrt{s}$ = 3.773 GeV
- BOSS version: 7.1.2
- Total integrated luminosity = 20 fb^{-1}
- Inclusive MC: 40 times of data
- Signal MC
  - For low mee MC: a DIY Z0 with 10MeV mass and 0MeV width;
  - For vector meson: Kpi omega process & Ks0pi omega;
- Exclusive MC:
  - gamma K*, K*->Kpi

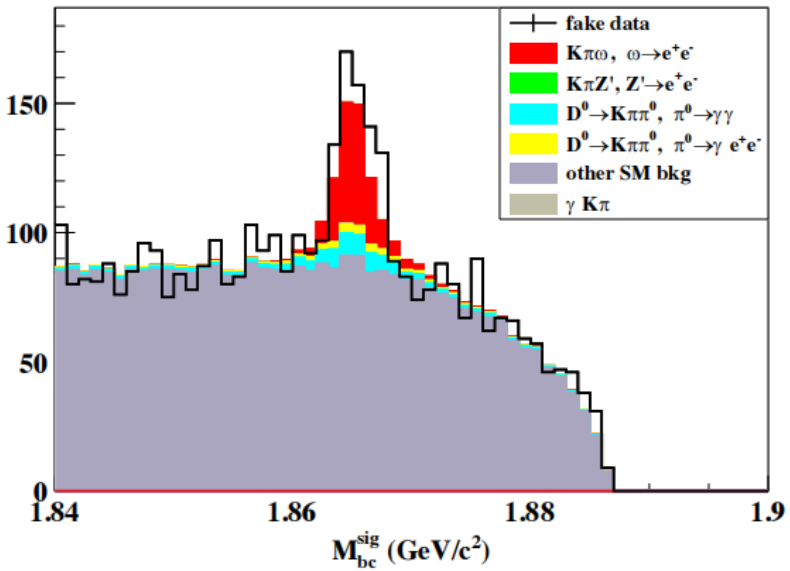
Processes	N_{gen} for each round	Branching fraction	Generator
$D^0 \to K\pi Z' \to K\pi e^+e^-$	400, 000	$1.0 \times 10^{-5} (\sim 10\%)$	PHSP + PHSP
$D^0 \to K\pi\omega \to K\pi e^+e^-$	400, 000	4×10^{-6}	D0toKpiomegaPlot + PHSP
$D^+ \to K^0_S\pi^+\omega \to K^0_S\pi^+e^+e^-$	400, 000	3.6×10^{-6}	DtoKSpiomegaPlot + PHSP
$D^0 \to K^*\gamma \to K\pi e^+e^-$	400, 000	2.73×10^{-4}	PHSP + VSS

DL based selection ($D^0 \to K^-\pi^+e^+e^-$)

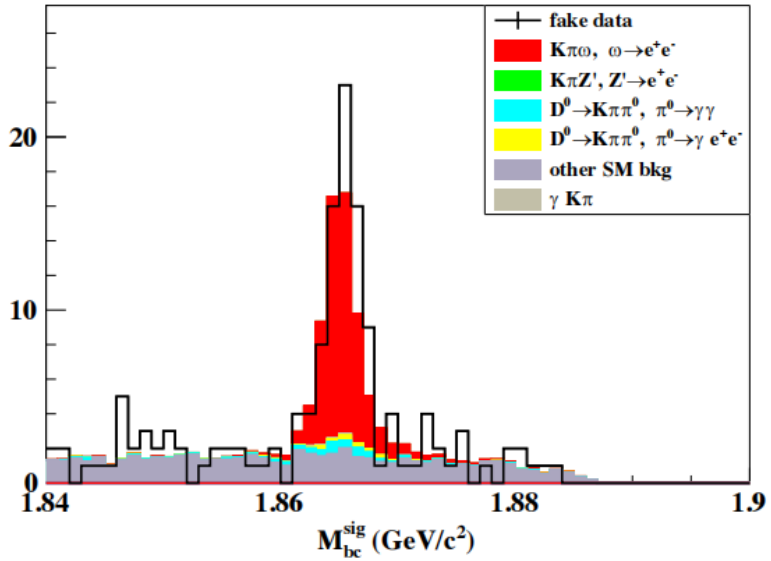




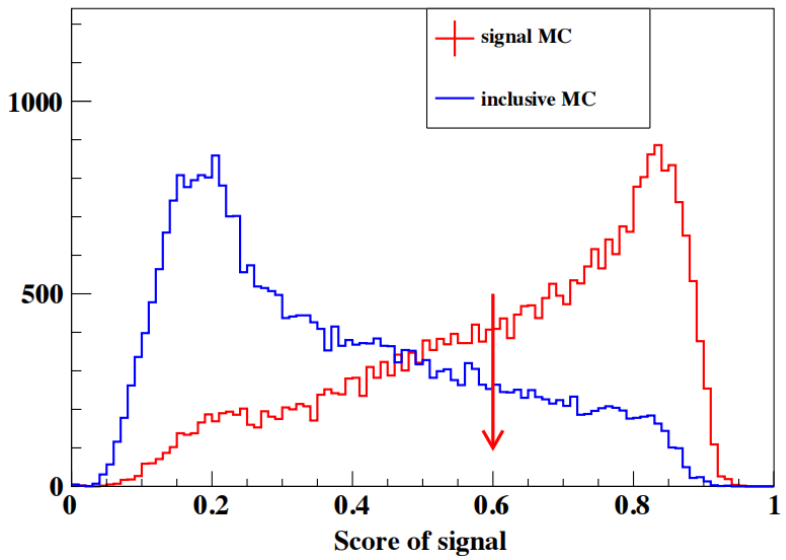
- To veto background score of signal larger than 0.85

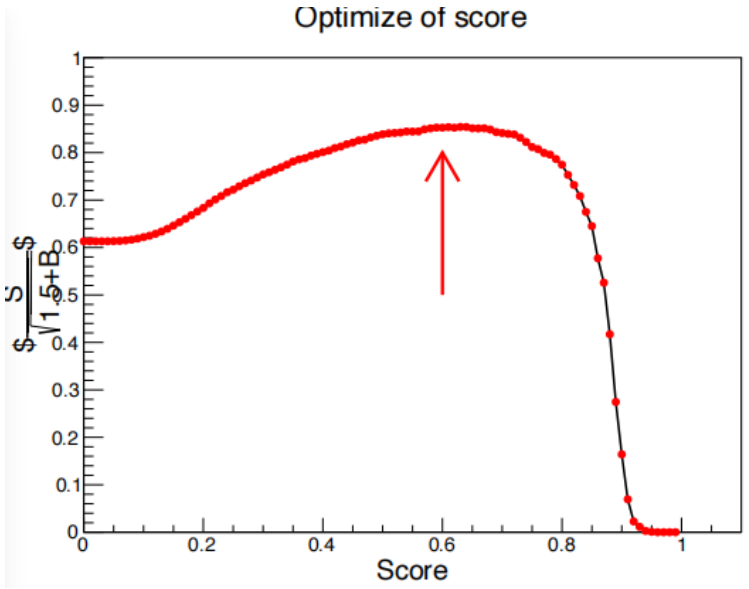


score>0.85

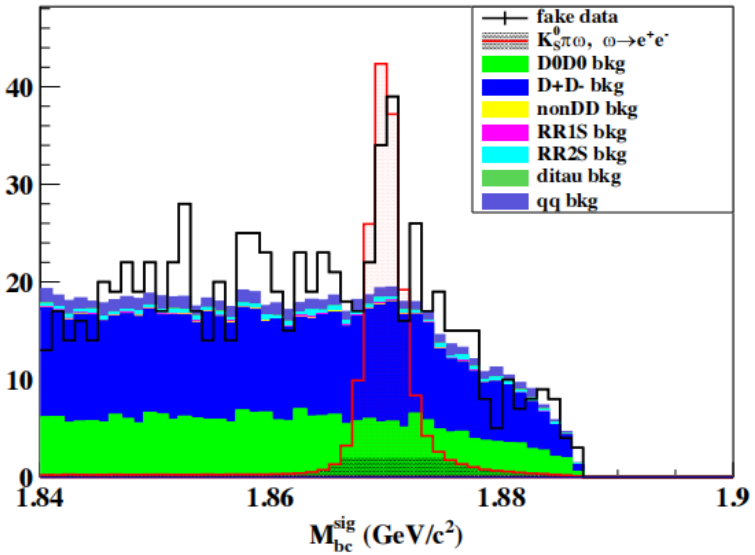


DL based selection ($D^+ \to K_s^0 \pi^+ e^+ e^-$)

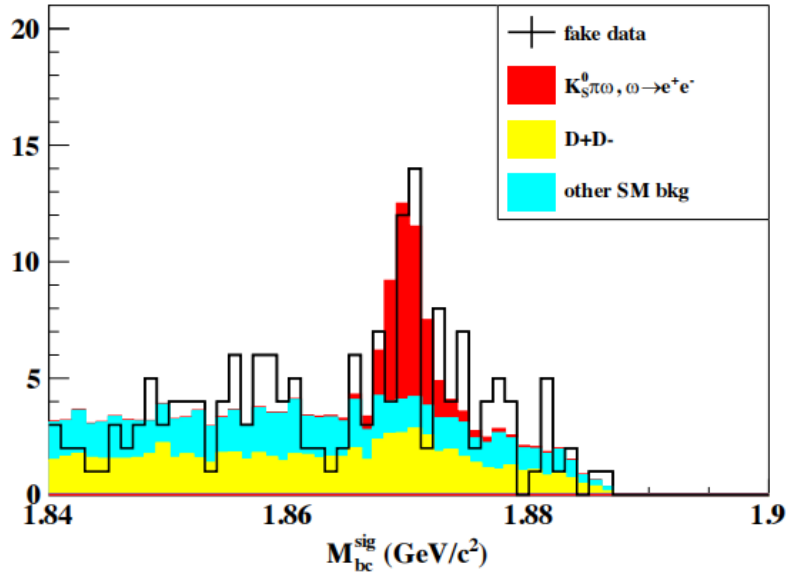




- To veto background score of signal larger than 0.6



score>0.6



Fit result

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

- Signal shape: KeysPdf from signal MC shape ⊗ Gaussian function (num floated)
- $D \to K\pi\pi^0$ bkg: KeysPdf from MC shape (num fixed)
- Non-peaking bkg: Argus function (num floated)

Expected results of B^{up}: 10^{-6}~10^{-7}

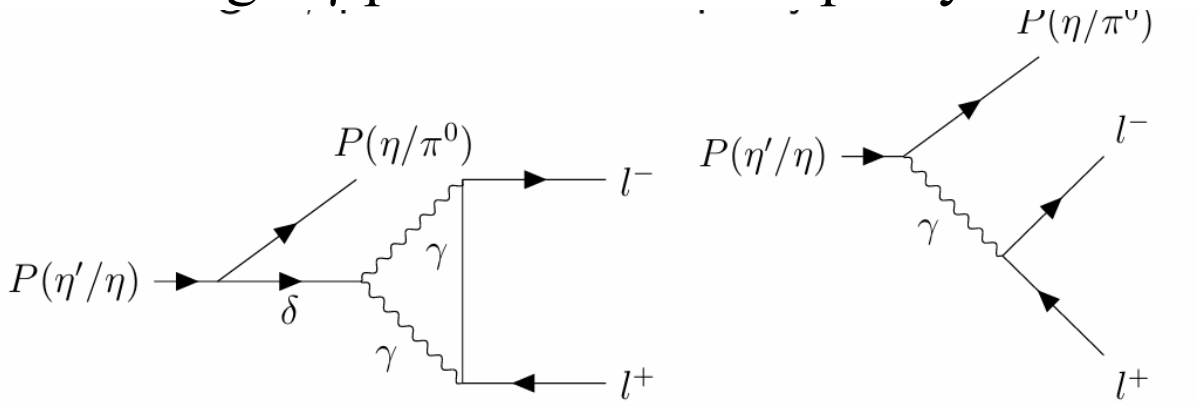
$D^+ \to K_S^0\pi^+e^+e^-$

- Signal shape: KeysPdf from signal MC shape ⊗ Gaussian function (num floated)
- Non-peaking bkg: Argus function (num floated)

Semi-blind Analysis on Searching for $\eta \to \pi^0 e^+ e^-$ and $\eta' \to \pi^0(\eta) e^+ e^-$

Motivation

- Single γ process violate C parity: $P \to Pl^+l^-$ could happen both through single γ and double γ process but single γ process violate C parity.



- Lower upper limit: Based on the J/ψ events taken on BESIII, there are three $P \to Pl^+l^-$ decay modes whose UL could be lower than the present results.

Decay	$\mathcal{B}$	Reference	CL
$\eta' \to \pi^0 e^+ e^-$	$< 1.4 \times 10^{-3}$	PDG2025	90%
$\eta' \to \eta e^+ e^-$	$< 1.0 \times 10^{-6}$(Sensitivity) $< 2.4 \times 10^{-3}$	Penglong Zhang PDG2025	
$\eta \to \pi^0 e^+ e^-$	$< 7.5 \times 10^{-6}$	PDG2025	

Data sets

- **Signal MC sample sets:**

$\eta \to \pi^0 e^+ e^- (0.8\ \mathrm{M})$

Decay	Model
$J/\psi \to \gamma\eta$	HELAMP 1,0,1,0
$\eta \to \pi^0 e^+ e^-$	DIY_eta2pi0ll
$\pi^0 \to \gamma\gamma$	PHSP

$\eta \to \pi^0 \pi^+ \pi^- (0.5\ \mathrm{M})$

Decay	Model
$J/\psi \to \gamma\eta$	HELAMP 1,0,1,0
$\eta \to \pi^0 \pi^+ \pi^-$	DIY_Eta23pi
$\pi^0 \to \gamma\gamma$	PHSP

- **Data**

	Year	Data	BOSS version
J/ψ	2009	30%	BOSS 7.0.8
	2012	10%	
	2018		
	2019		

Conclusions

- Estimation of misarrangement rate for photons had been accomplished.
- Bhabha analysis accomplished using ψ(3770),CMS(3650),CMS(3682) data under BOSS 7.0.8.
- We have checked the distribution of $\gamma\gamma e^+e^-$ mass spectrum using 30%×09+10%×12+10%×18+10%×19 data. No obvious signals were found.
- Reference channel branch fraction check using 09+12+18+19 data:

Summary

- The rare decays are important to probe New Physics beyond the Standard Model
- Ongoing analysis based on the data at @3.773 GeV, @4.128~4.226 GeV. BESIII has performed studies on rare decay and the upper limit of branching fractions (@90% C.L) are obtained
- BESIII has great potential, with high-statistics datasets and low backgrounds.

Thank you for your attention!