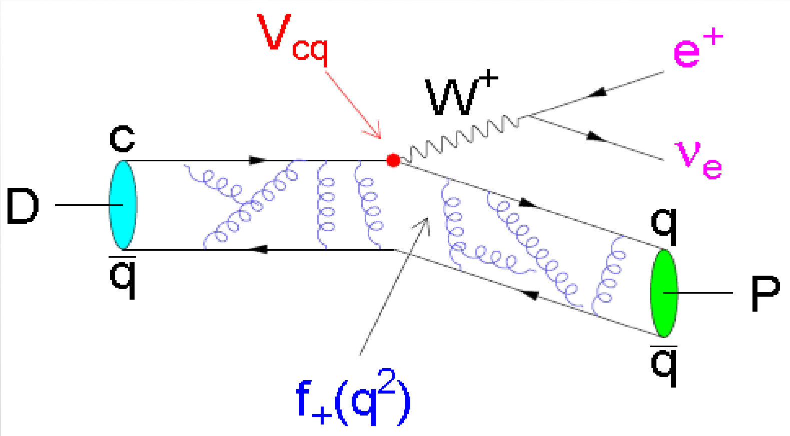
Charmed Meson Semi-leptonic Decays At BESIII



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CHEP2018, Shanghai

Outline

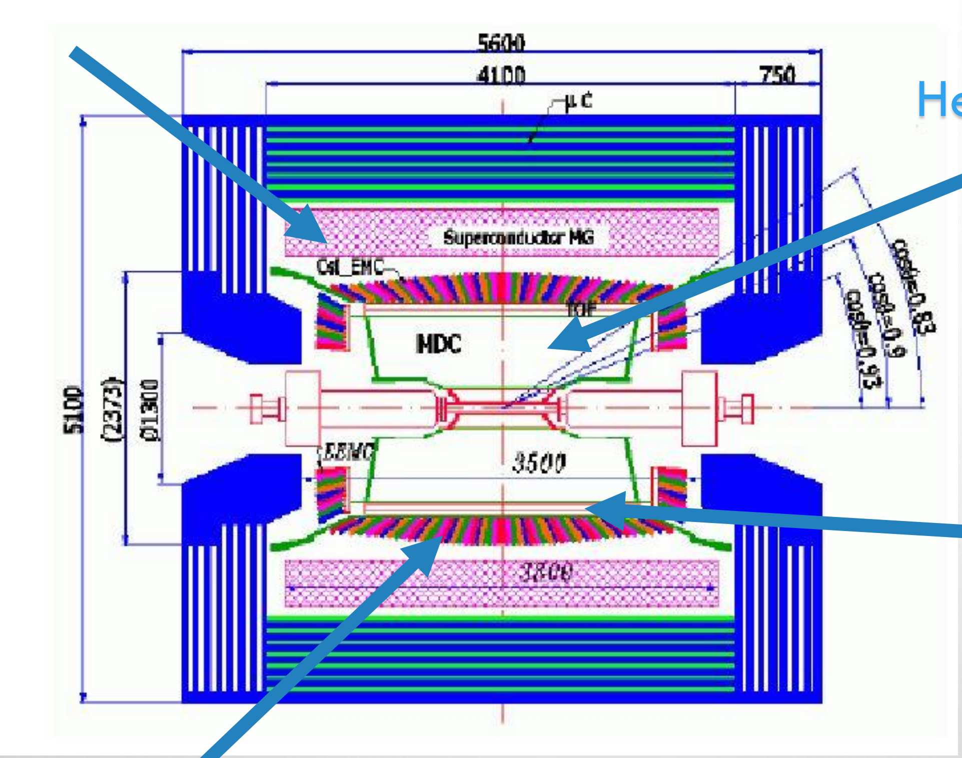
- BESIII detector
- Charm meson semileptonic decay
  - $D_s^+ \to \eta^{(\prime)} e^+\nu_e$ decays
  - Rare semileptonic decays of D
    - $D^+ \to D^0 e^+\nu_e$ decay
    - $D^+ \to \gamma e^+\nu_e$ decay
    - $D^{+(0)} \to a^0(980)^{0(-)} e^+\nu_e$ decays
- Summary

BEPCII


Satellite view of BEPCII /BESIII
LINAC
South
BESIII
detector

BESIII Detector

Magnet: 1T Super conducting

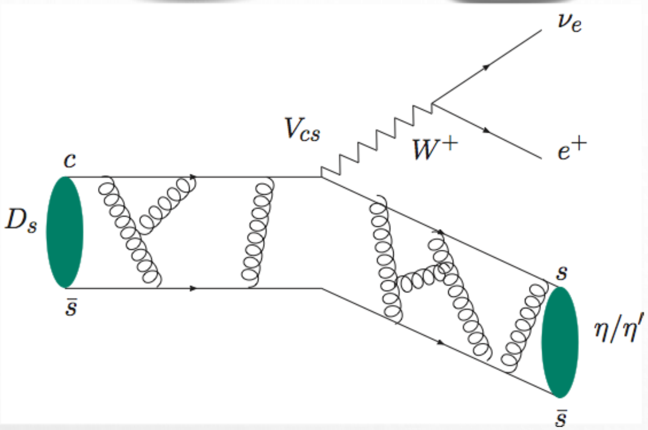


MDC: small cell & Gas:
$He/C_3H_8(60/40)$,43 layers
$\sigma_{xy} = 130\mu m$
σ_p/p=0.5%@1GeV
dE/dx=6%

TOF: σ_T <70ps

EMC: CsI crystal, 28 cm
ΔE/E=2.5% @ 1GeV
$\sigma_z = 0.6cm/\sqrt{E}$

$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$



- Differential partial widths

$$\Gamma(D_s^+ \to \eta^{(\prime)} e^+ \nu_e) = \frac{G_f^2}{24\pi^3} |V_{cs}|^2 |\vec{p}_{\eta^{(\prime)}}|^3 |f_+^{\eta^{(\prime)}}(q^2)|^2 dq^2$$

$\to f_+^{\eta^{(\prime)}}(0)|V_{cs}|$

Simple pole

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}}$$

Modified pole

$$f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M_{pole}^2})(1 - \alpha \frac{q^2}{M_{pole}^2})}$$

Series expansion

$$f_+(t) = \frac{1}{P(t)\Phi(t, t_0)} a_0(t_0)(1 + \sum_{i=1}^{\infty} r_k(t_0)[z(t, t_0)]^k)$$

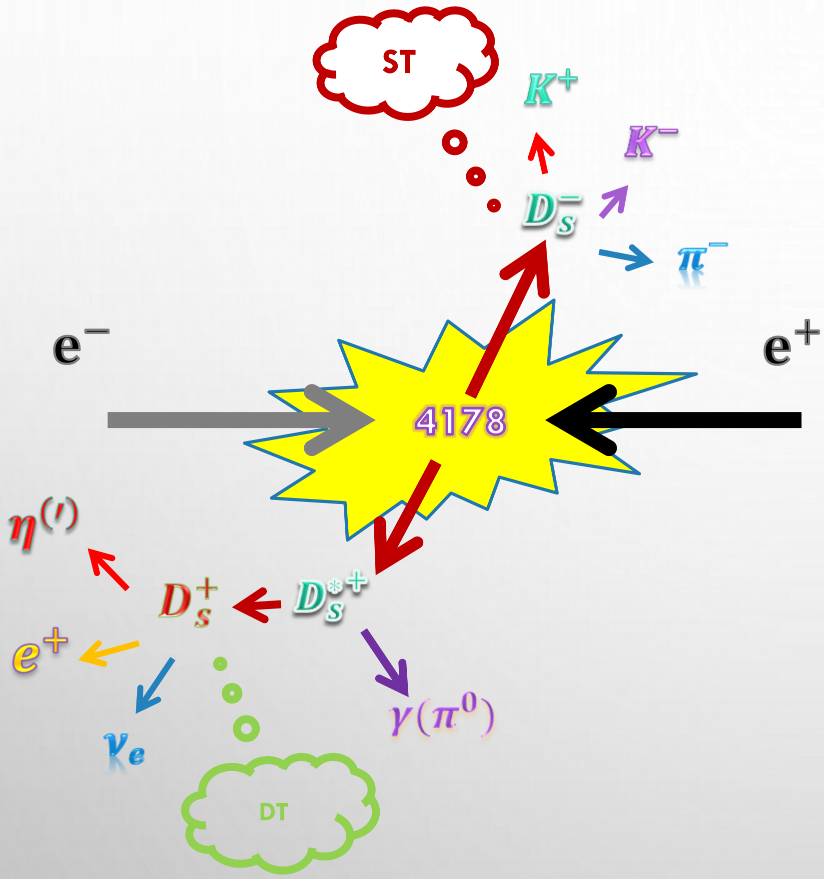
- η-η' mixing angle

$$\begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi_P & -\sin\phi_P \\ \sin\phi_P & \cos\phi_P \end{pmatrix} \begin{pmatrix} |\eta_q\rangle \\ |\eta_s\rangle \end{pmatrix}$$

$$\frac{\Gamma(D_s^+ \to \eta' e^+ \nu)/\Gamma(D_s^+ \to \eta e^+ \nu)}{\Gamma(D^+ \to \eta' e^+ \nu)/\Gamma(D^+ \to \eta e^+ \nu)} \simeq \cot^4\phi_P$$

- Measurements of $f_+^{D_s \to \eta^{(\prime)}}(0)$ will be crucial to calibrate the theoretical calculations
- Extraction of $|V_{cs}|$ provides complementary data to test the unitarity of the CKM matrix
- The ratio of B$[D_s^+ \to \eta e^+ \nu_e]$/B$[D_s^+ \to \eta' e^+ \nu_e]$ helps to determine $\eta - \eta'$ mixing angle (ϕ_P)

Analysis Technique



Single tag yield:

$$N_{\rm ST}^{i} = 2 \times N_{\rm D_s^{*+}D_s^-} \times B_{\rm ST}^{i} \times \epsilon_{\rm ST}^{i}$$

Double tag yield:

$$N_{\rm DT}^{i} = 2 \times N_{\rm D_s^{*+}D_s^-} \times B_{\rm ST}^{i} \times B_{\rm SL} \times \epsilon_{\rm ST vs.SL}^{i}$$

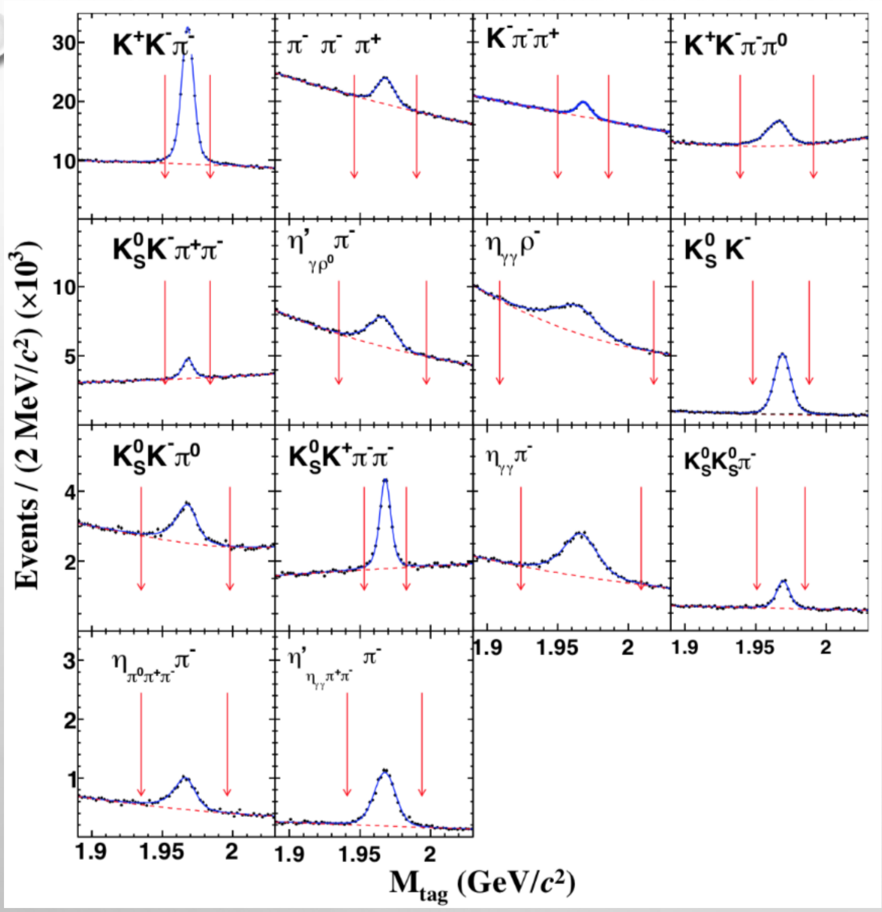
Branching fraction:

$$B_{\rm SL} = \frac{N_{\rm DT}}{N_{\rm ST}^{\rm tot} \times \bar{\epsilon}_{\rm SL}}, N_{\rm ST}^{\rm tot} = \sum_i N_{\rm ST}^{i}$$

Average efficiency:

$$\bar{\epsilon}_{\rm SL} = \sum_{i=1}^{N} (N_{\rm ST}^{i} \times \epsilon_{\rm ST vs.SL}^{i} / \epsilon_{\rm ST}^{i}) / \sum_{i=1}^{N} N_{\rm ST}^{i}$$

Single Tag D_s^-



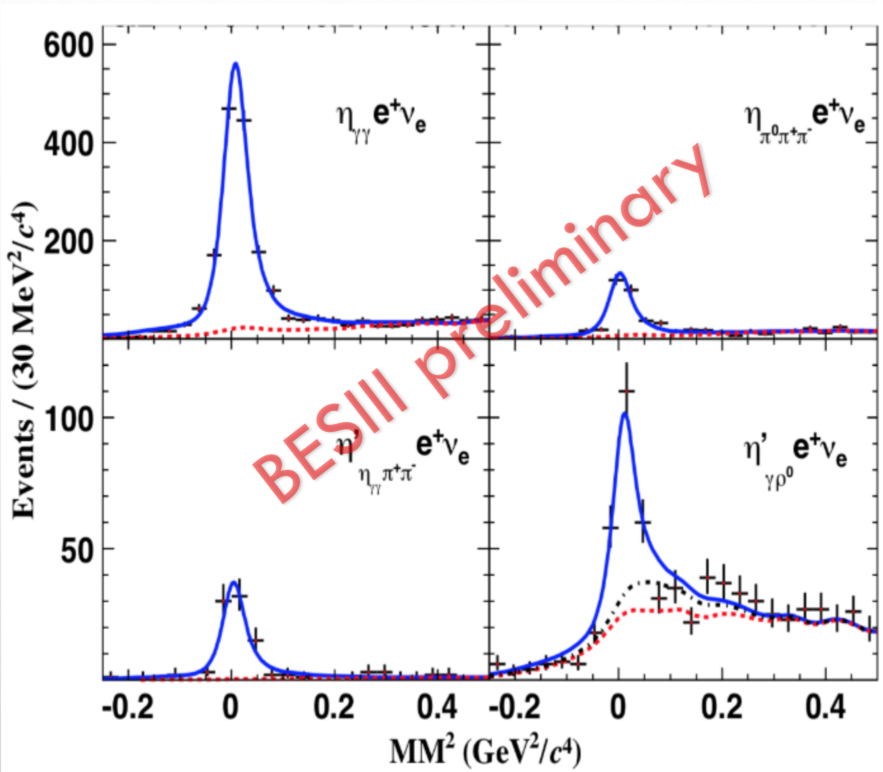
- **The blue curves are total fits: signal MC shape convoluted Gaussian + polynomial function**
- **The red dotted curves are the fitted combinatorial backgrounds: polynomial function**

$e^+e^- \to D_s^{*+}D_s^-, D_s^{*+} \to (\gamma/\pi^0)D_s^+$+c.c.

395142±1923 tagged D_s mesons

with 3.2 fb^{-1} @4178 MeV

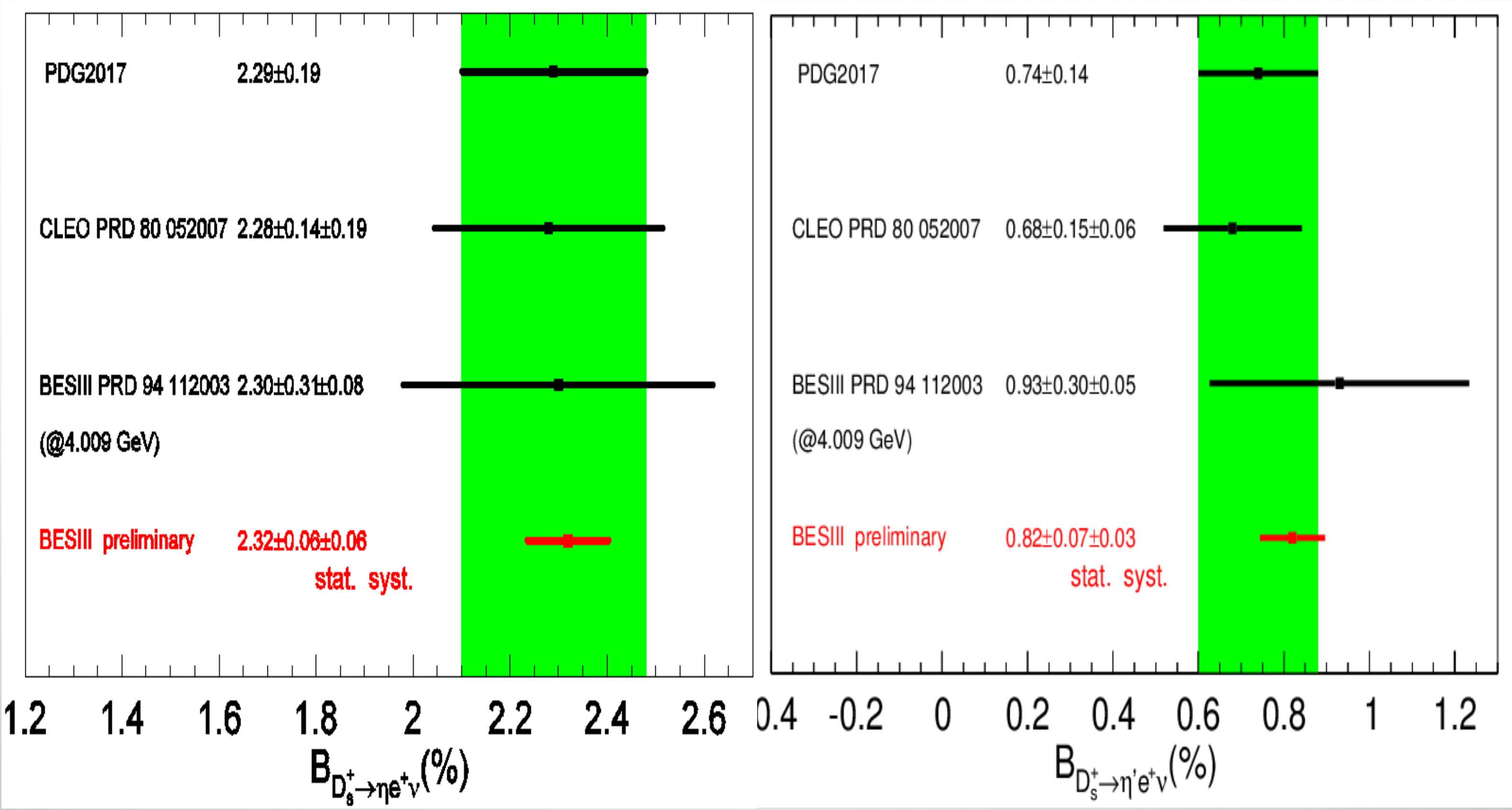
Fits To MM^2 of Semileptonic Candidates



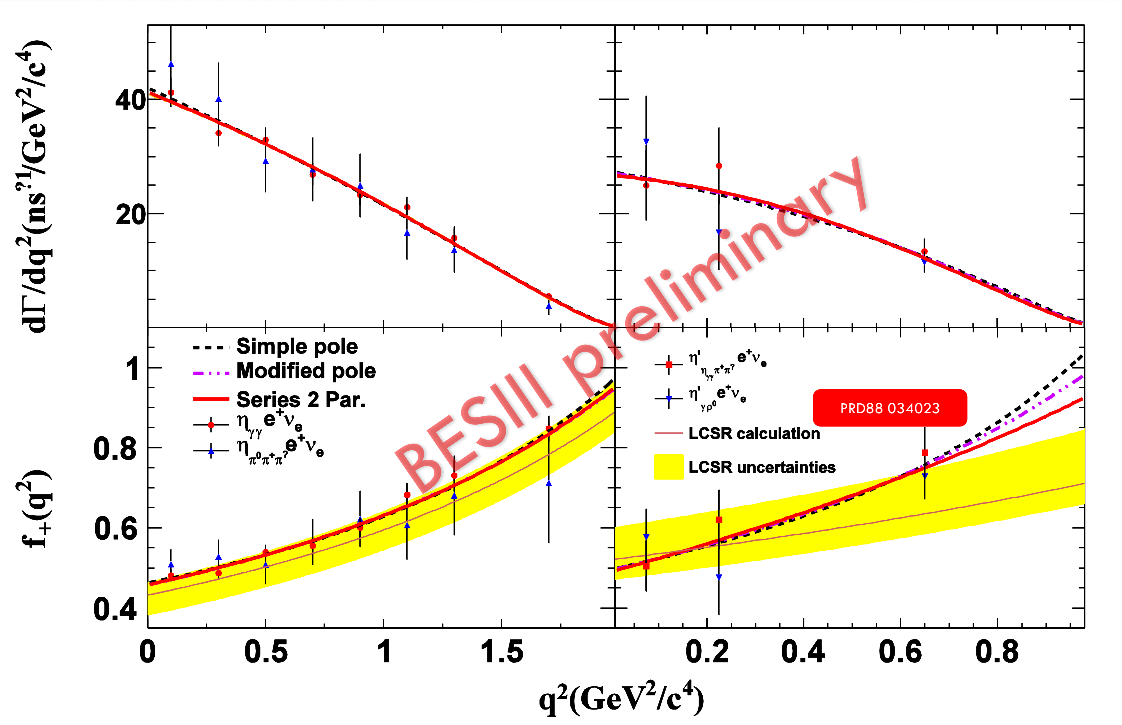
Decay	$\eta^{(\prime)}$ decay	$\epsilon_{\gamma(\pi^0)\mathrm{SL}}$ (%)	$N_{\mathrm{DT}}^{\mathrm{tot}}$	$\mathcal{B}_{\mathrm{SL}}$ (%)
$\eta e^+\nu_e$	$\gamma\gamma$	41.11±0.27	1834±47	2.32±0.06±0.06
	$\pi^0\pi^+\pi^-$	16.06±0.31		
$\eta' e^+\nu_e$	$\eta\pi^+\pi^-$	14.07±0.10	261±22	0.82±0.07±0.03
	$\gamma\rho^0$	18.98±0.10		

- **The blue curves are total fits:**
- **Signal shape: MC simulated shape convolved with Gaussian**
- **Black dotted-dashed curve is the fitted background from $D_s^+ \to \phi e^+\nu_e$: MC simulated shape**
- **Red dotted curve are fitted combinatorial background in signal side: MC simulated shape**
- **Constraint fit: The branching fractions of $D_s^+ \to \eta e^+\nu_e$ or $D_s^+ \to \eta' e^+\nu_e$ for two different $\eta^{(\prime)}$ subdecays are constrained to be same**

Comparisons Of Branching Fractions



Fits to partial decay rates and projections on form factors



- Partial decay rates are fitted simultaneously by two η/η' subdecays
- Based on the result extracted with the series 2 Parameters, we determine $|V_{cs}|$ and $f_+^{\eta^{(\prime)}}(0)$

Nominal result

Case	Simple pole			Modified pole			Series 2 Par.		
	$f_+^{\eta^{(\prime)}}(0)\|V_{cs}\|$	M_{pole}	$\chi^2/NDOF$	$f_+^{\eta^{(\prime)}}(0)\|V_{cs}\|$	α	$\chi^2/NDOF$	$f_+^{\eta^{(\prime)}}(0)\|V_{cs}\|$	r_1	$\chi^2/NDOF$
$\eta e^+\nu_e$	0.450(5)(3)	3.77(8)(5)	12.2/14	0.445(5)(3)	0.30(4)(3)	11.4/14	0.446(5)(4)	−2.2(2)(1)	11.5/14
$\eta' e^+\nu_e$	0.494(45)(10)	1.88(54)(5)	1.8/4	0.481(44)(10)	1.62(91)(11)	1.8/4	0.477(49)(11)	−13.1(76)(11)	1.9/4

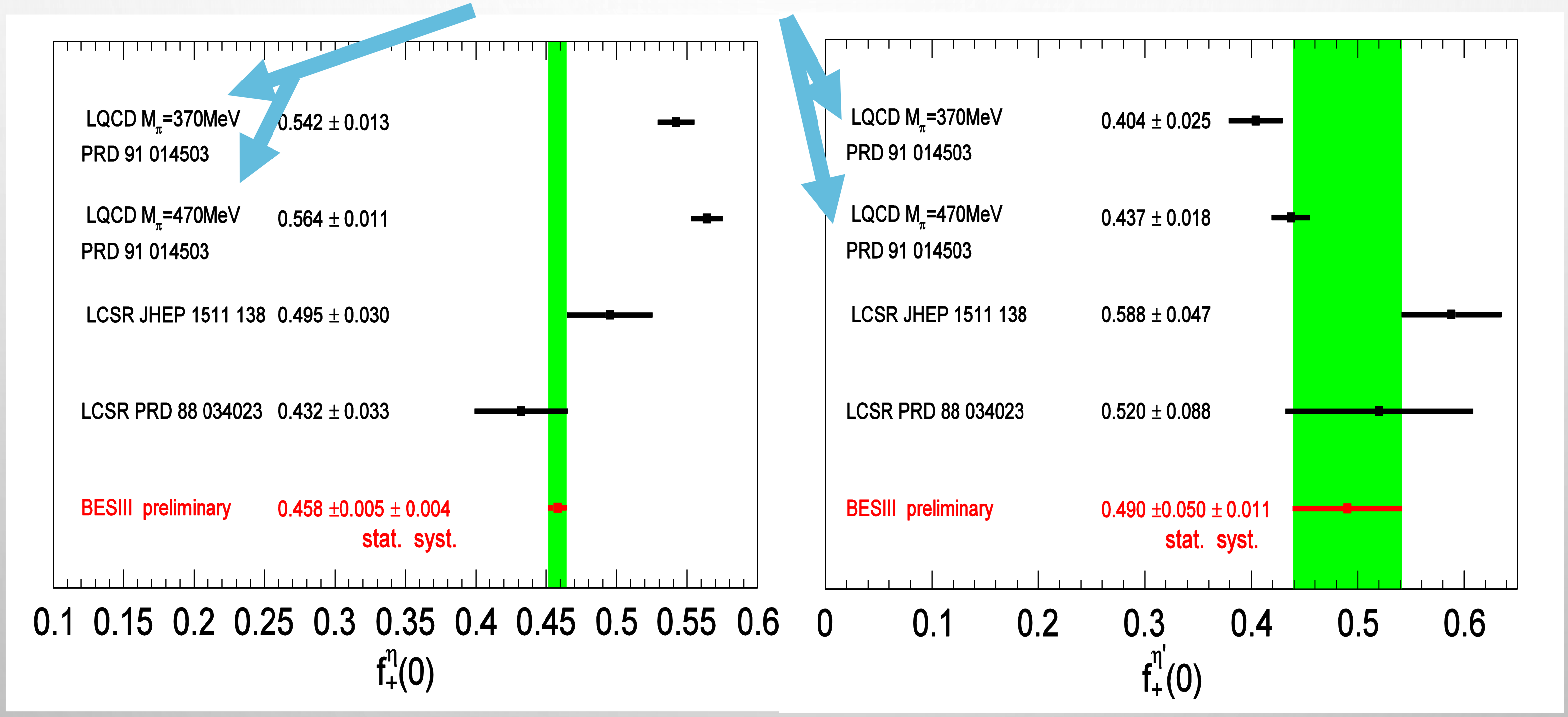
Uncertainties on the least significant digits are shown in parentheses, where the first (second) uncertainties are statistical (systematic)

Comparisons of form factors

Taking $|V_{cs}|$ CKMfitter and $f_+^{\eta^{(\prime)}}(0)\,|V_{cs}|$ extracted with the series 2 Parameters as input, we obtain

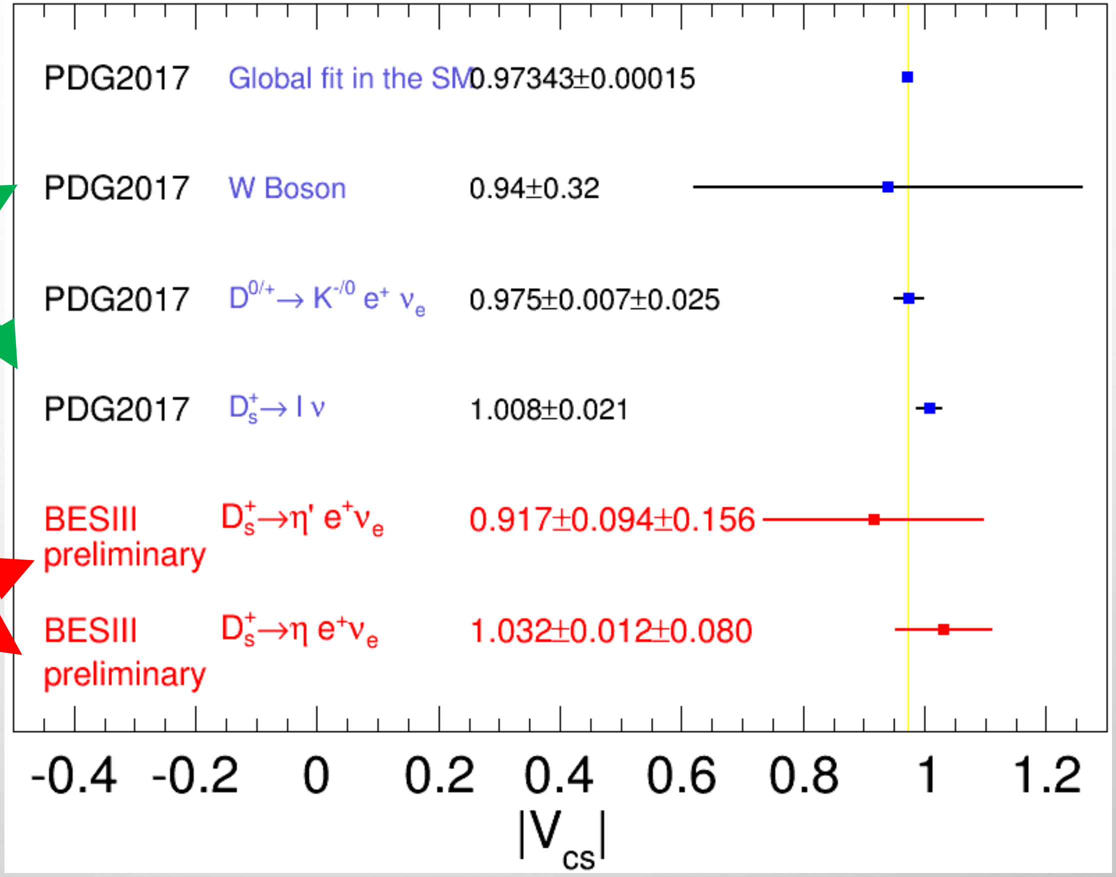
$$f_+^{\eta}(0) = 0.458 \pm 0.005_{stat} \pm 0.004_{syst} \quad f_+^{\eta'}(0) = 0.490 \pm 0.050_{stat} \pm 0.011_{syst}$$

No systematic uncertainty is considered



Comparison of $|V_{cs}|$

Only reported one uncertainty, but include both statistical and systematic



Taking $f_+^{D_s \to \eta^{(\prime)}}(0)$

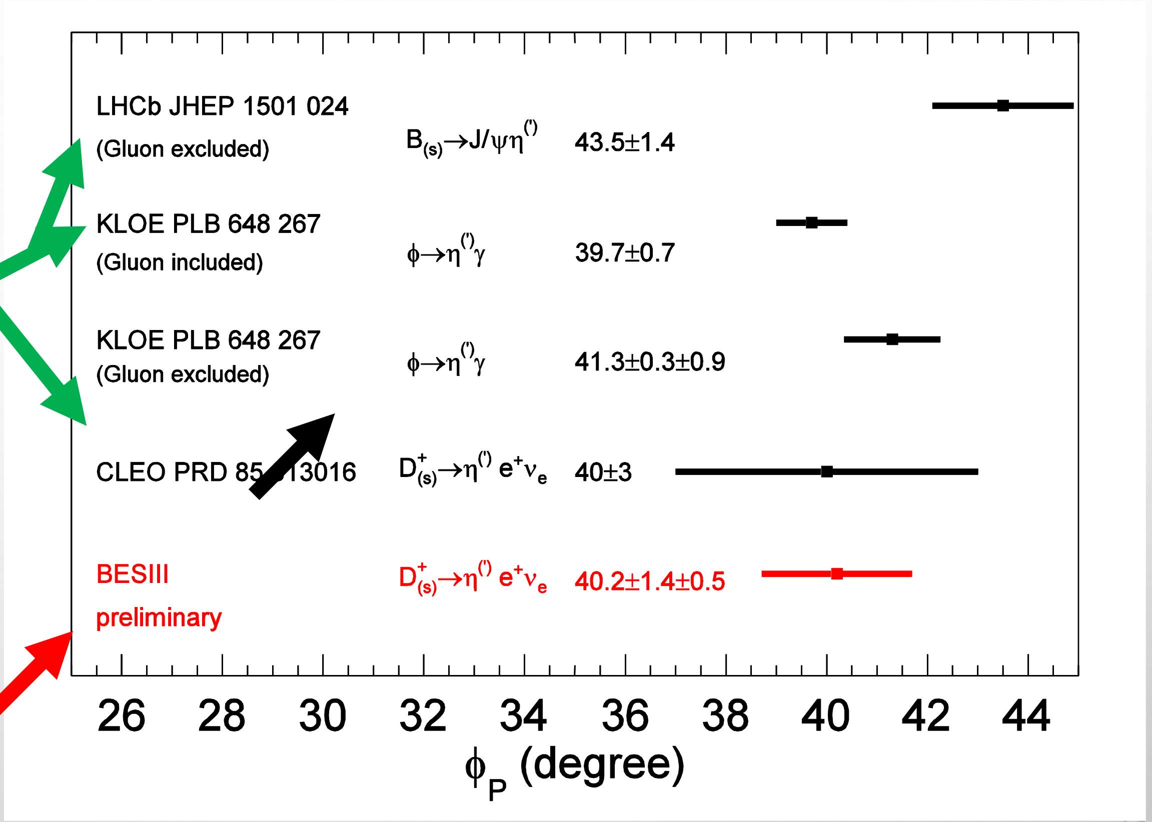
PRD88 034023 as input, we obtain

Comparison of mixing angle

Paper only reported one uncertainty, but include both statistical and systematic

Combining the branching fractions measured in this work and $B[D^+ \to \eta e^+ \nu_e] = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$, $B[D^+ \to \eta' e^+ \nu_e] = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$ (BESIII Phys. Rev. D 97, 092009 (2018)) into below equation, we obtain

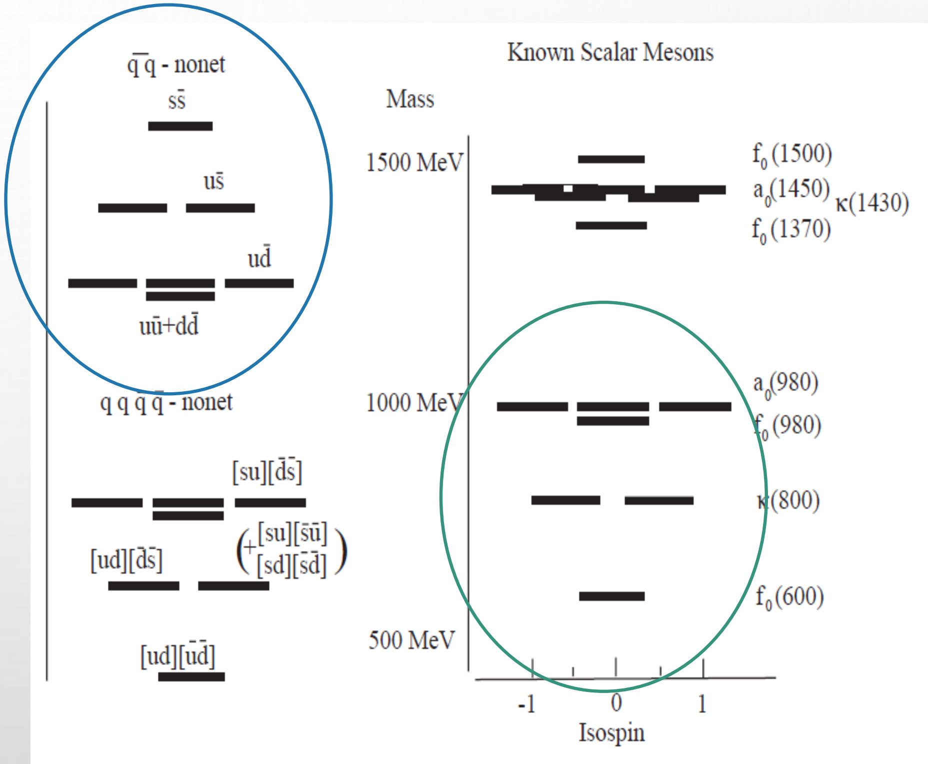
$$\frac{\Gamma(D_s^+ \to \eta' e^+ \nu)/\Gamma(D_s^+ \to \eta e^+ \nu)}{\Gamma(D^+ \to \eta' e^+ \nu)/\Gamma(D^+ \to \eta e^+ \nu)} \simeq \cot^4 \phi_P$$



Rare Semileptonic Decay of D

$D^{+(0)} \to a_0(980)^{0(-)} e^+ \nu_e$

- Study of the nature of light scalar $a_0(980)$ and $f_0(980)$ is one of the central problems of nonperturbative QCD
- This study are important for understanding the way that chiral symmetry is realized in the low-energy region and confinement physics
- Explore the nontrivial internal structure of light hadron mesons, traditional qq states, tetra quark system
- Improve understanding of classification of light scalar mesons
  - $R \equiv \frac{B(D^+ \to f_0 \ell^+ \nu) + B(D^+ \to \sigma \ell^+ \nu)}{B(D^+ \to a_0 \ell^+ \nu)}$



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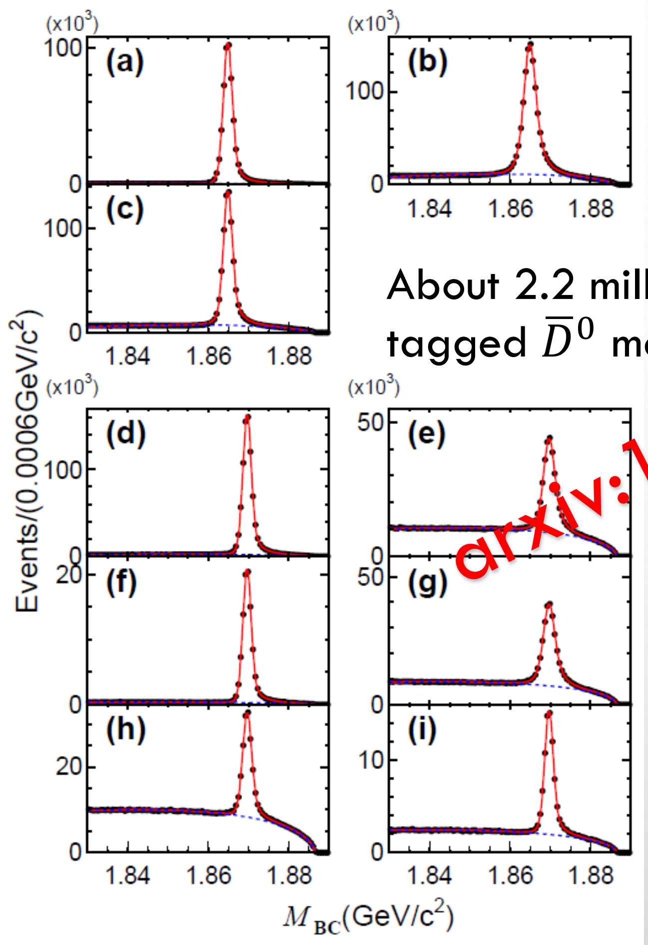
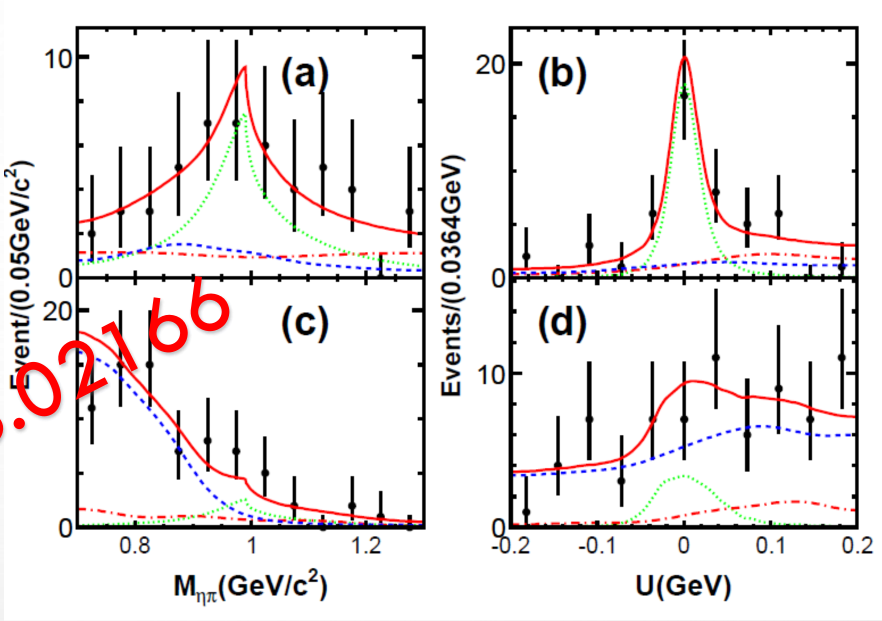
$D^{+(0)} \to a_0(980)^{0(-)} e^+ \nu_e$



About 2.2 million tagged $\overline{D}^0$ mesons

About 1.5 million tagged D^- mesons



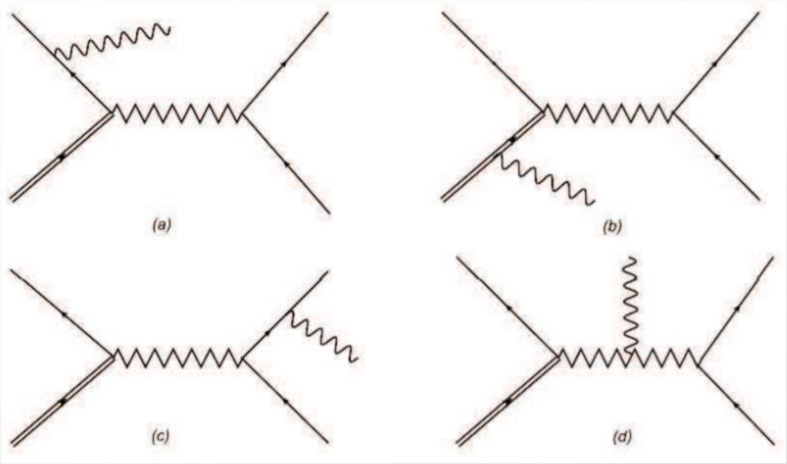
5.4 σ $B(D^0 \to a_0(980)^- e^+ \nu_e) \times B(a_0(980)^- \to \eta\pi^-)$
$=(1.33^{+0.33}_{-0.29} \pm 0.09) \times 10^{-4}$

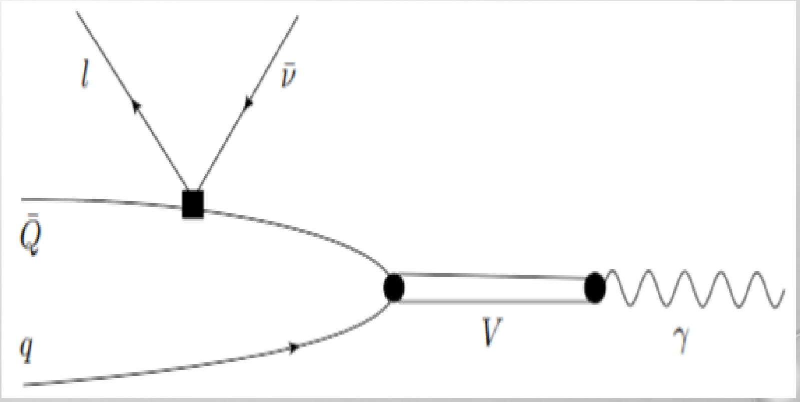
2.9 σ $B(D^+ \to a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \eta\pi^0)$
$=(1.66^{+0.81}_{-0.66} \pm 0.11) \times 10^{-4}$

$B(D^+ \to a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \eta\pi^0)$
$<3.0 \times 10^{-4}$

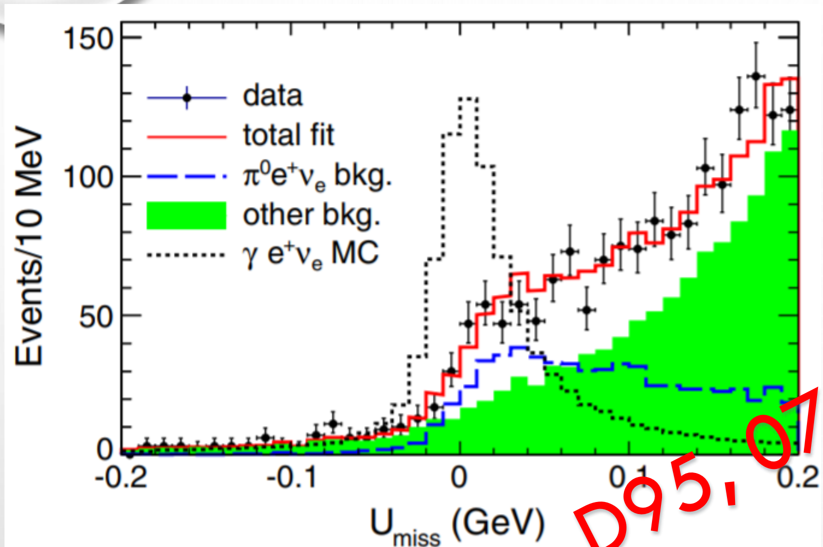
$D^+ \to \gamma e^+ \nu_e$

- Not subject to the helicity suppression rule due to the presence of a radiative photon.
- Nonperturbative strong interaction effects in theoretical calculations is relatively simple without final-state hadron
- Long-distance contribution is considered via the vector meson dominance model and the decay rate may be enhanced significantly



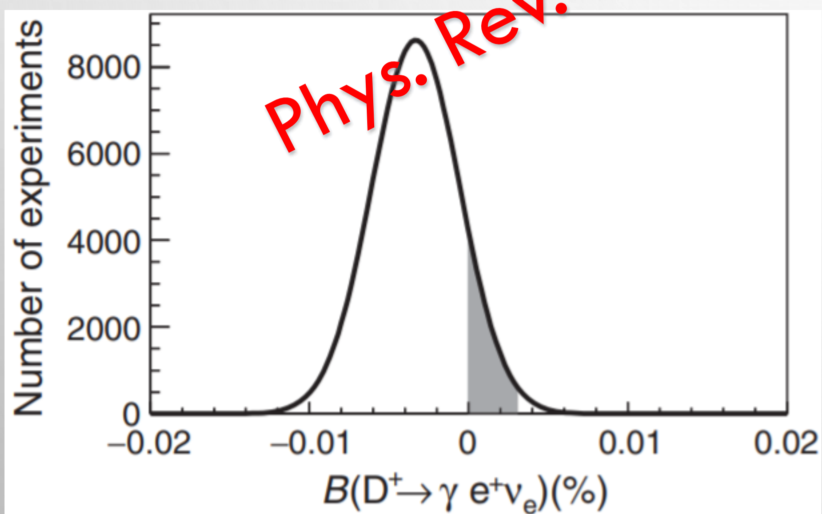


$D^+ \to \gamma e^+ \nu_e$



Source	Relative uncertainty (%)
Signal MC model	3.5
e^+ tracking	0.5
e^+ PID	0.5
γ reconstruction	1.0
Lateral moment	4.4
$\pi^0 e^+ \nu_e$ backgrounds	2.7[a]

Phys. Rev. D95, 071102(RC)

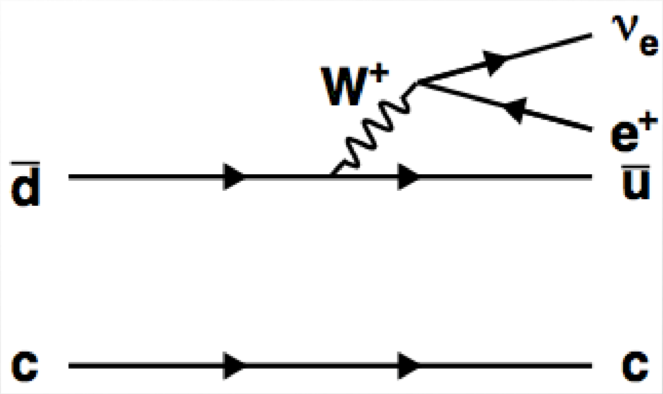


$B(D^+ \to \gamma e^+ \nu_e) < 3.0 \times 10^{-5}$ @ 90%C.L..

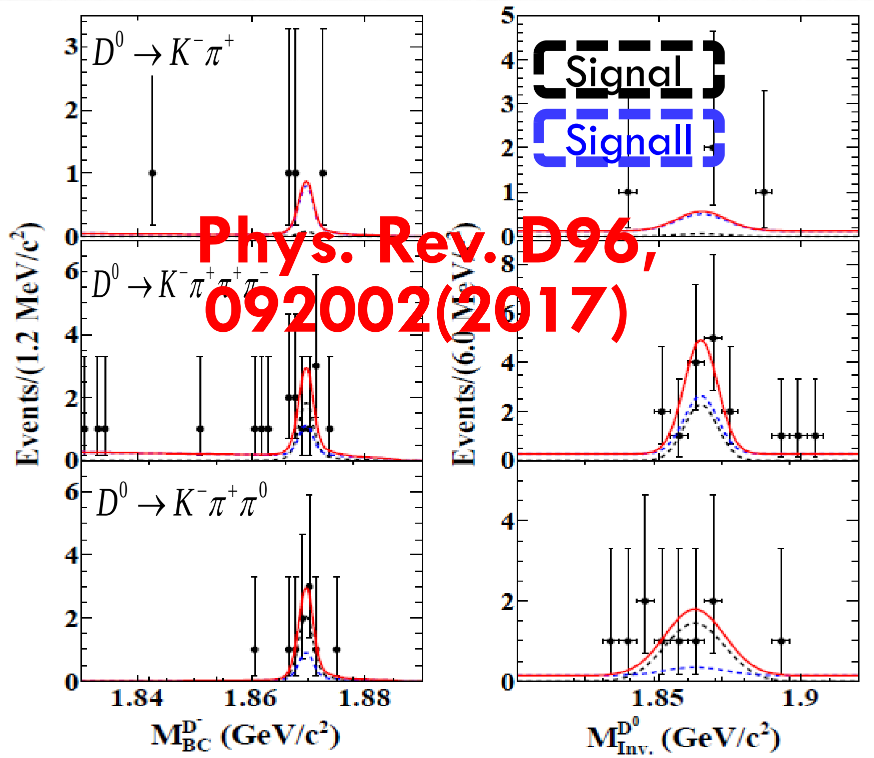
Approach to the factorization method prediction: 1.92×10^{-5}(Nucl. Phys. B914, 301 (2017).)

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

- In the rare decay processes of $D^+ \to D^0 e^+ \nu_e$, the heavy-quark flavors (c) remain unchanged, and the weak decays are managed by the light-quark sectors.
- Applying the SU(3) symmetry for the light quarks, this rare decay branching fraction can be predicted by theoretical calculation and its theoretical value is 2.78×10^{-13} [EPJC, 59:841-845(2009)].
- Measuring this decay may share light on testing the SM predictions for the rare semileptonic decays.



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



Phys. Rev. D96, 092002(2017)

Source	$D^0 \to K^-\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^0$
Tracking	2.0	4.0	2.0
PID	2.0	4.0	2.0
Quoted branching fraction	1.3	2.6	3.6
π^0 reconstruction	-	-	2.0
Summation of Signal side	3.1	6.2	5.0
Signal side		3.8	
Background estimation		11.5	
MC statistics		0.5	
M_{BC} fit (ST)		0.5	
Probability requirement		2.6	
2D fit		2.9	
Total		12.7	

Two dimensional fit

$B(D^+ \to D^0 e^+ \nu_e) < 1.0 \times 10^{-4}$ @ 90%C.L.

Summary

- With 2.93, 3.19 fb^{-1} data taken at 3.773, 4.178 GeV, BESIII have studied dynamics of $D_s^+ \to \eta^{(\prime)} e^+ \nu_e$, and search for $D^{+(0)} \to a^0(980)^{0(-)} e^+ \nu_e, \gamma e^+ \nu_e$ and $D^0 e^+ \nu_e$
- First measurement of form factor $f_+^{\eta^{(\prime)}}(0)$ helps to tune the LQCD calculation
- Determination of quark mixing matrix element $|V_{cs}|$ and $\eta - \eta'$ mixing angle ϕ_P provide complementary result
- First measurement of branching fraction B($D^{+(0)} \to a^0(980)^{0(-)} e^+ \nu_e$) opens one more interest page in investigation of the nature of puzzling $a^0(980)$ states.