



南开大学
Nankai University



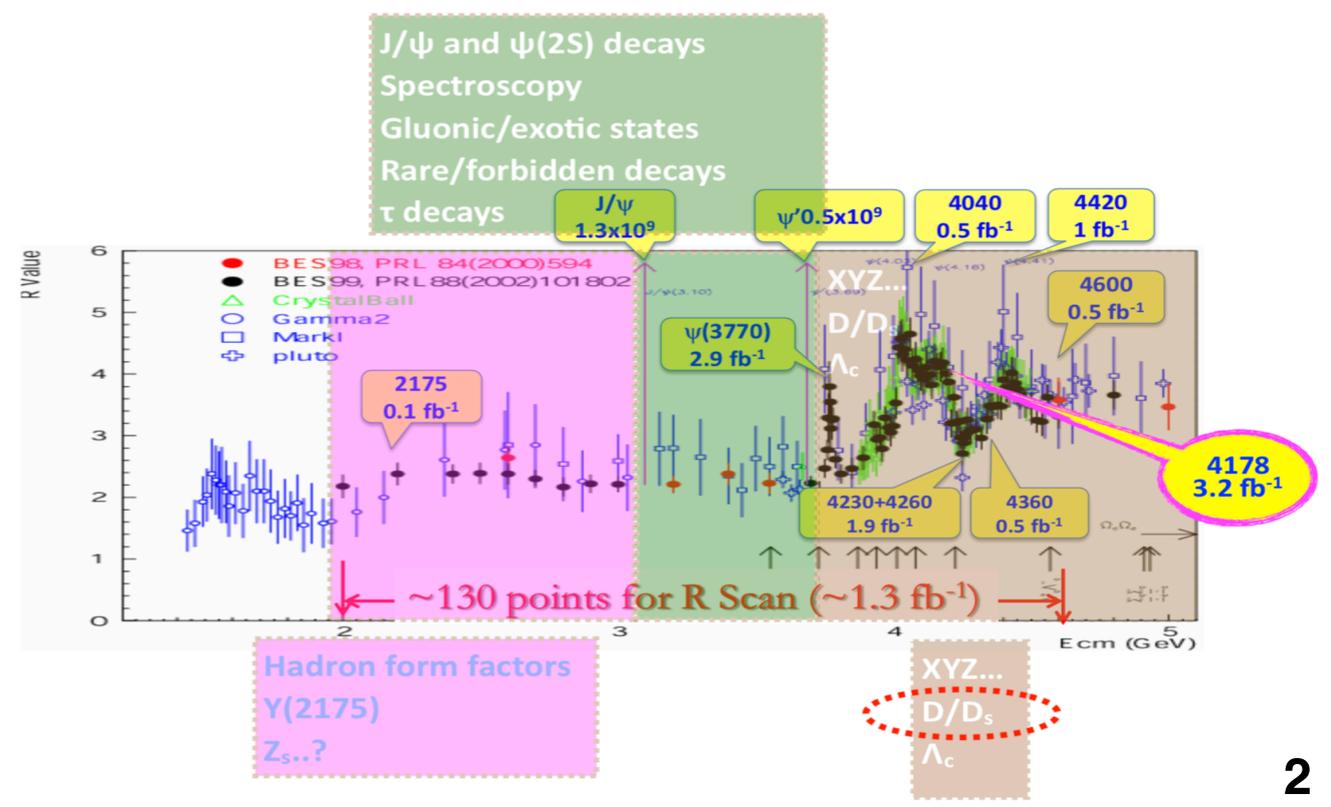
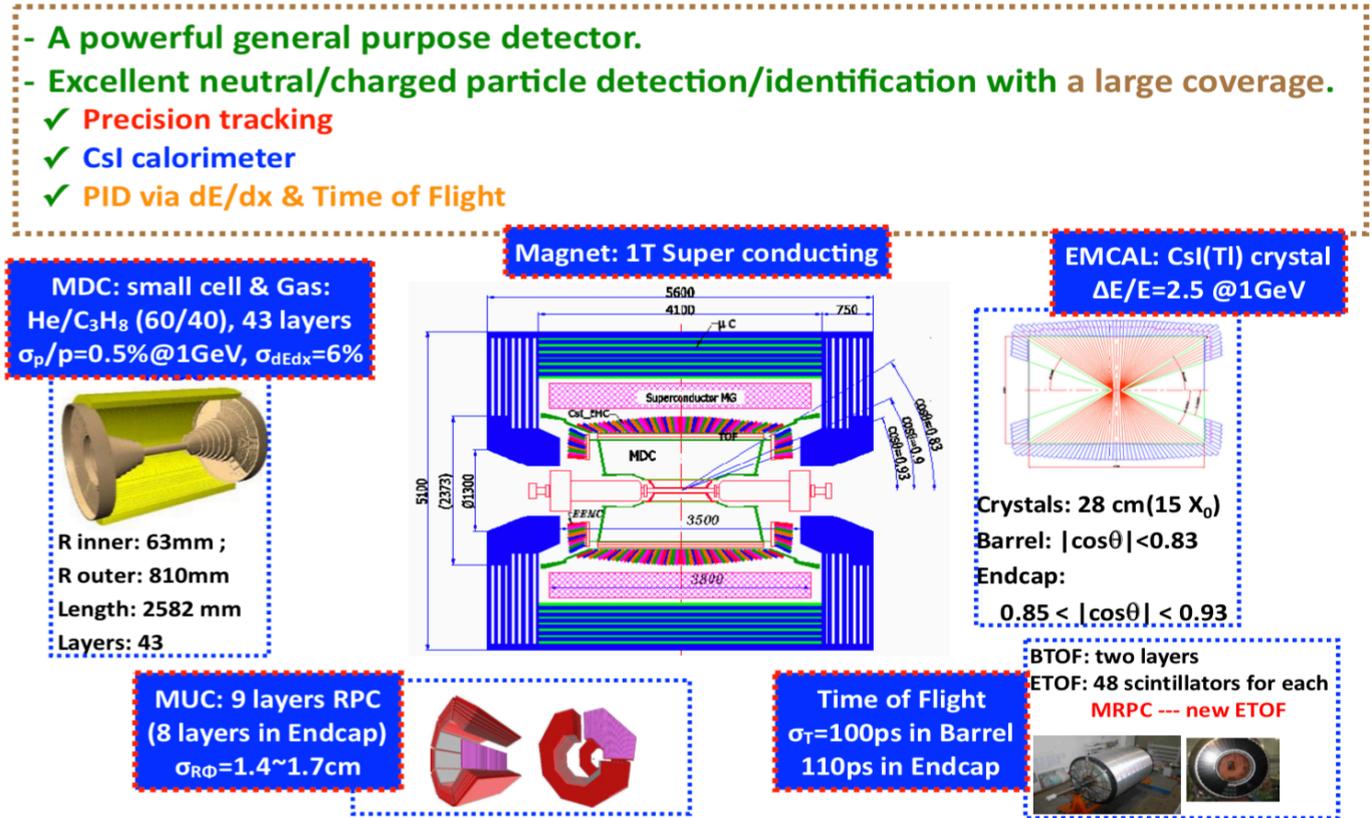
Leptonic and Semi-leptonic decays at BESIII

Minggang Zhao
(on behalf of the BESIII Collaboration)

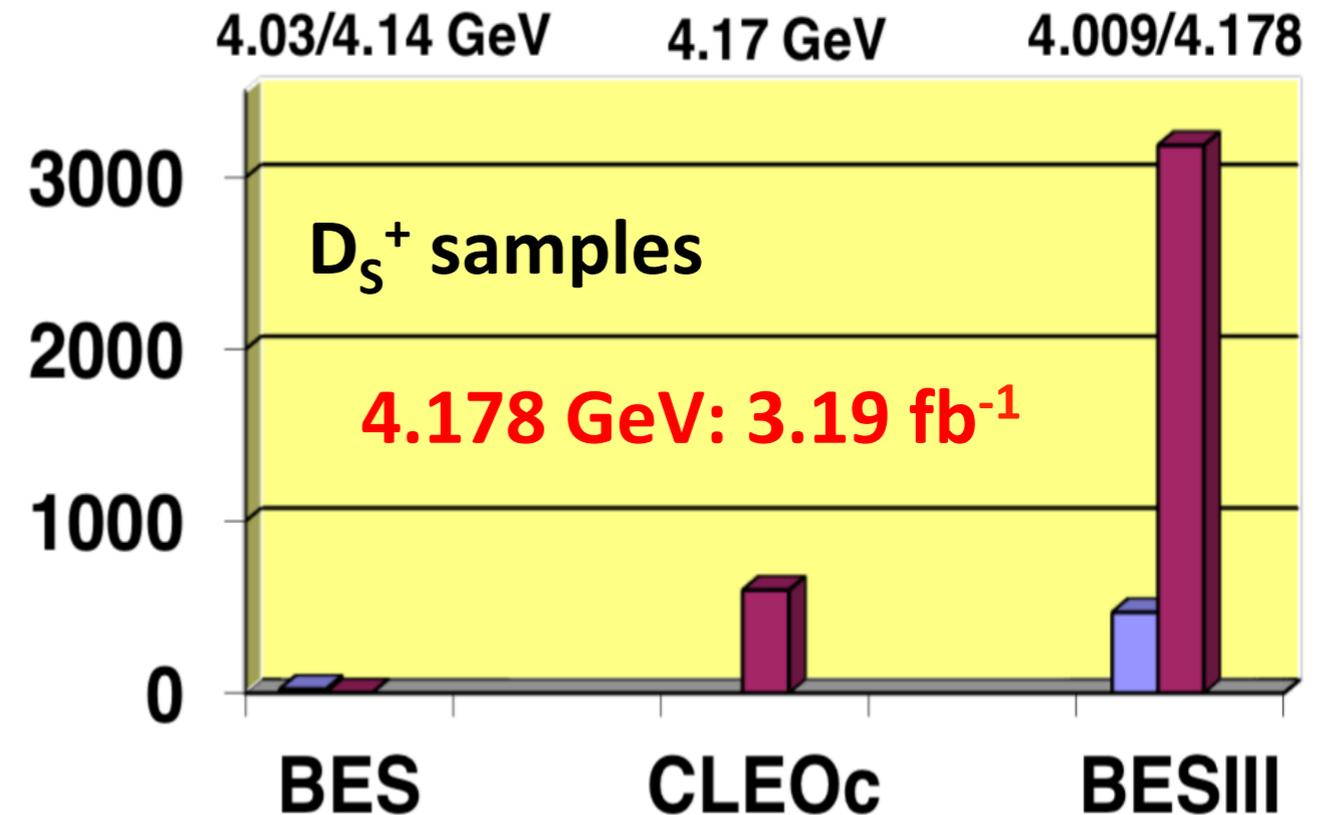
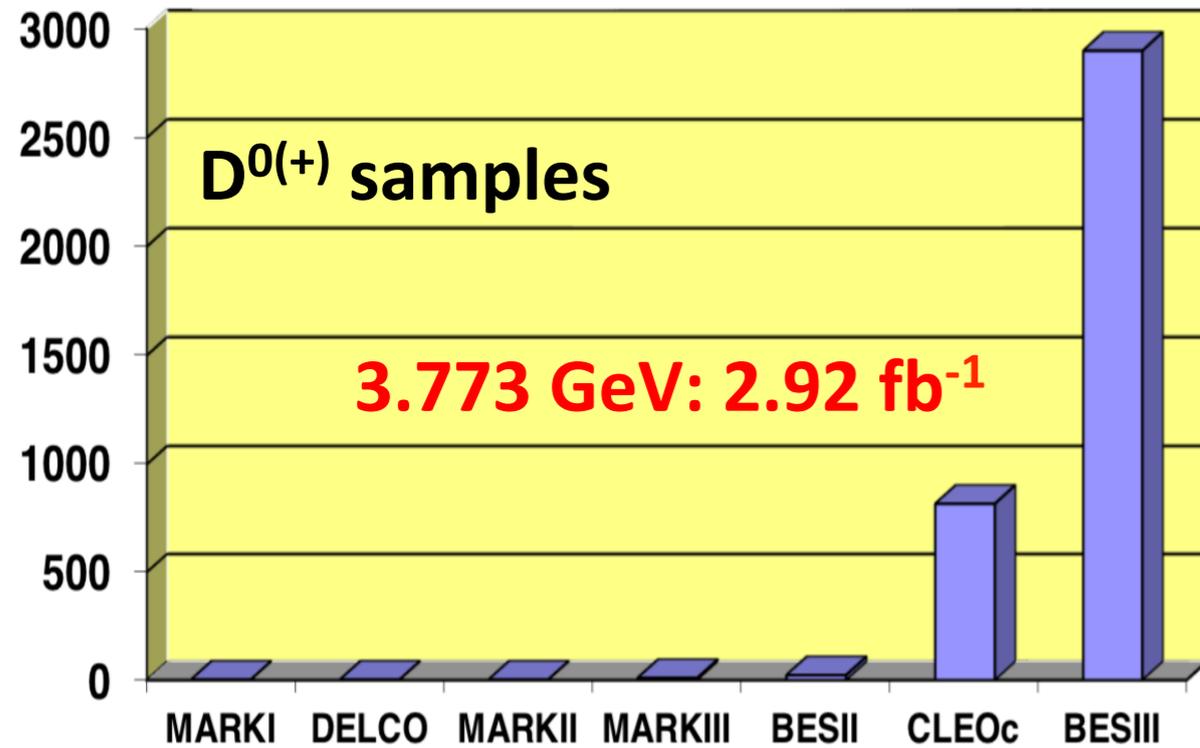
School of Physics, Nankai University, Tianjin, China

2019年理论与实验联合专题研讨会：粲物理
2019.11.22-24，暨南大学，广州

BESIII Experiment



Charm Datasets



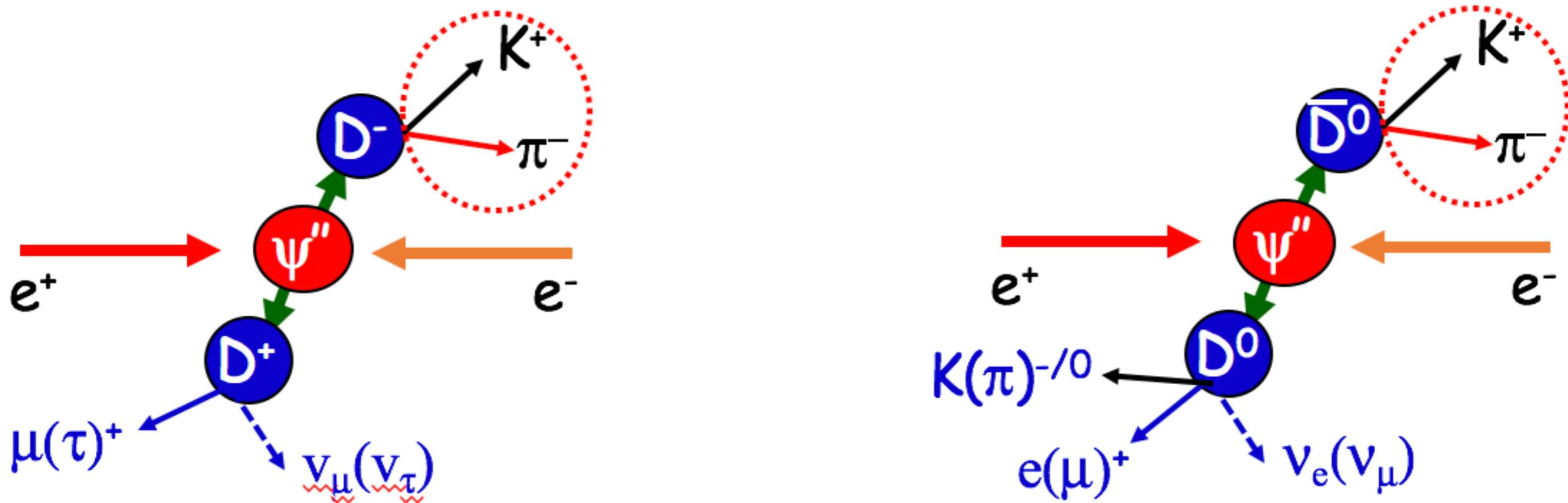
2010-2011: 2.92 fb⁻¹ @3.773 GeV

2011: 0.48 fb⁻¹ @4.009 GeV

2016: 3.19 fb⁻¹ @4.178 GeV

**Threshold data: charm meson produced in pair
-> double tag method**

Double Tag Method



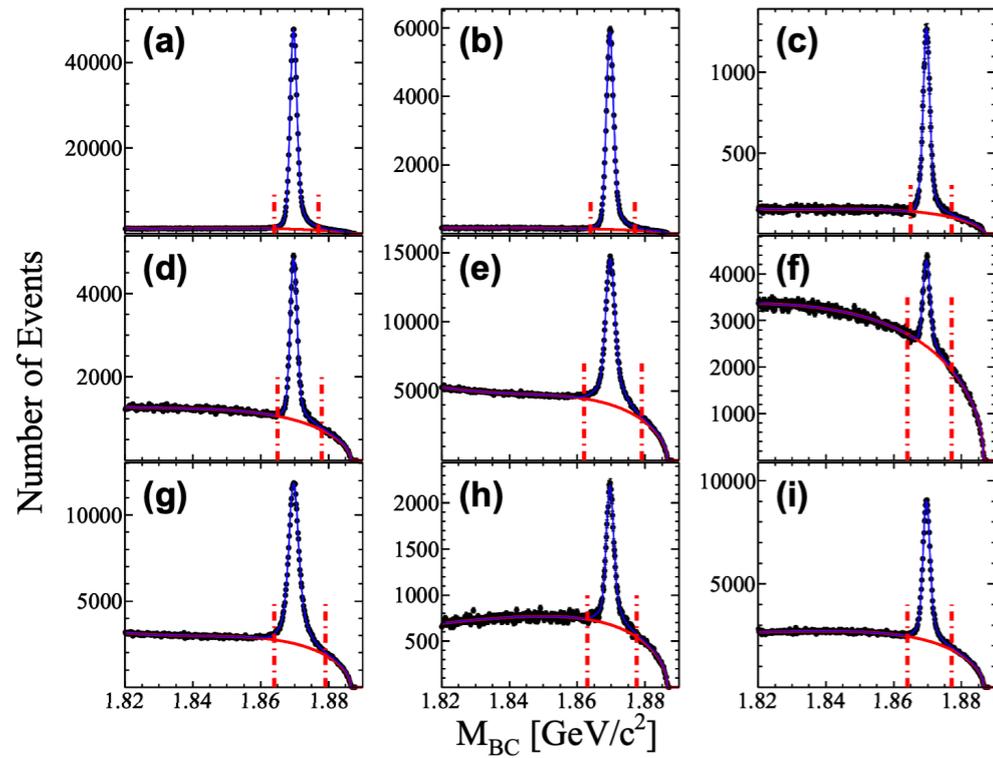
$$N_{ST}^i = 2 \times N_{D\bar{D}} \times B_{ST}^i \times \epsilon_{ST}^i$$

$$N_{DT}^i = 2 \times N_{D\bar{D}} \times B_{ST}^i \times B_{sig} \times \epsilon_{ST}^i \text{ vs sig}$$

$$B_{sig} = \frac{\sum N_{DT}^i}{\sum N_{ST}^i \times \bar{\epsilon}_{sig}} = \frac{N_{DT}^{tot}}{N_{ST}^{tot} \times \bar{\epsilon}_{sig}}$$

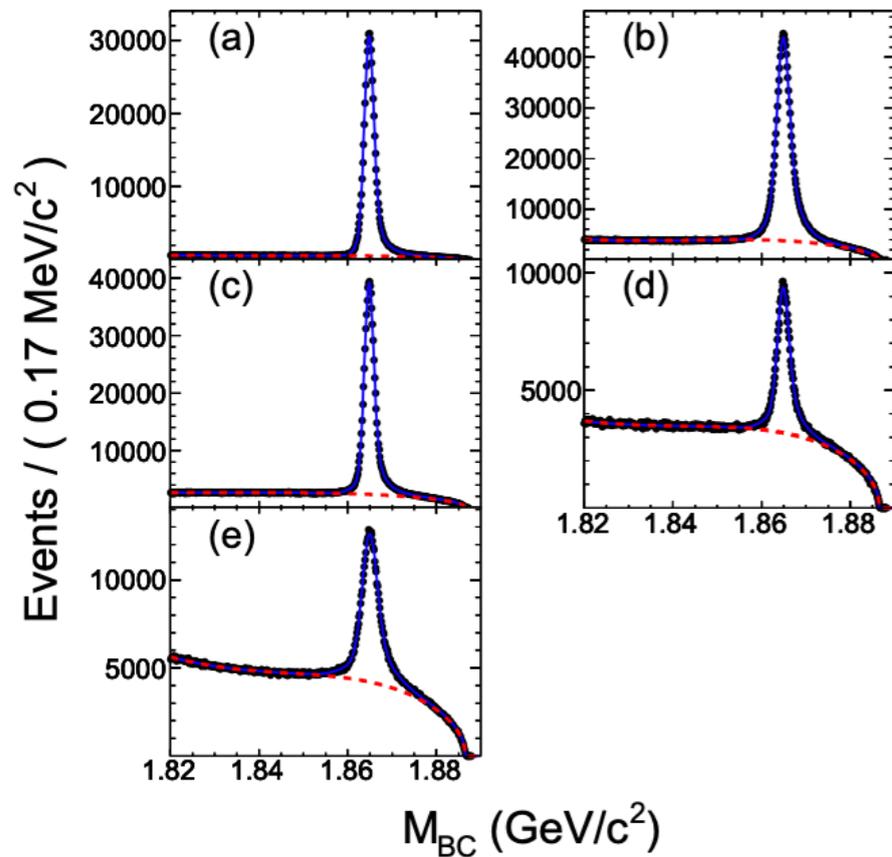
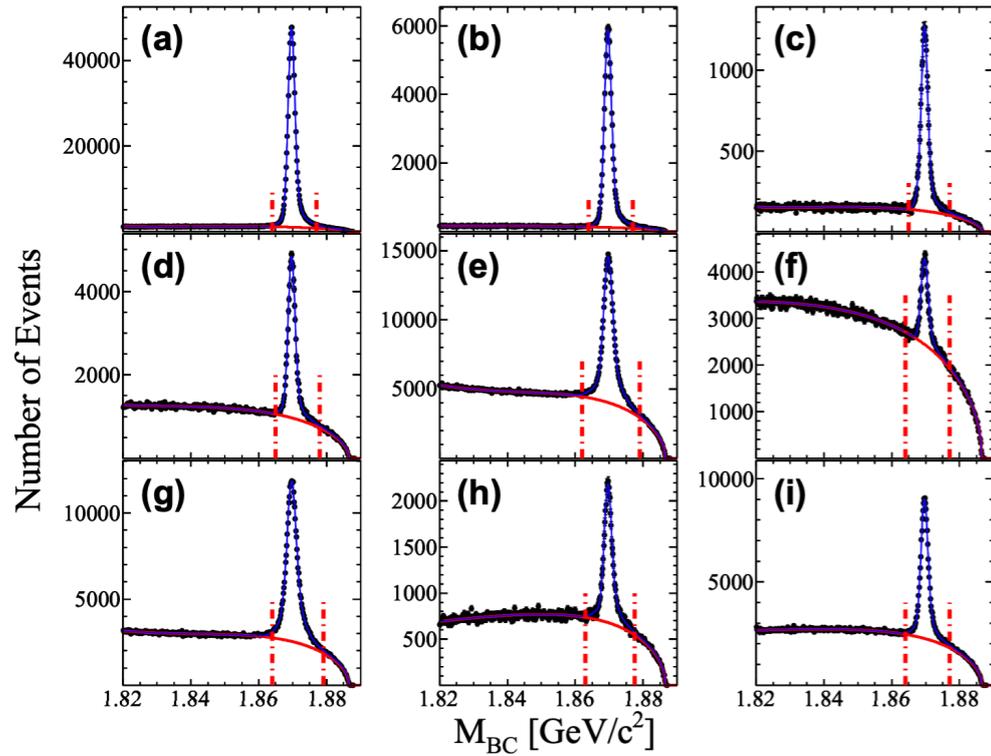
$$\bar{\epsilon}_{sig} = \sum (N_{ST}^i \times \epsilon_{ST}^i \text{ vs sig} / \epsilon_{ST}^i) / \sum N_{ST}^i$$

Single Tags



$$N_{D_{tag}^-} = (170.31 \pm 0.34) \times 10^4 \text{ [PRD89,051104(R)(2014)]}$$

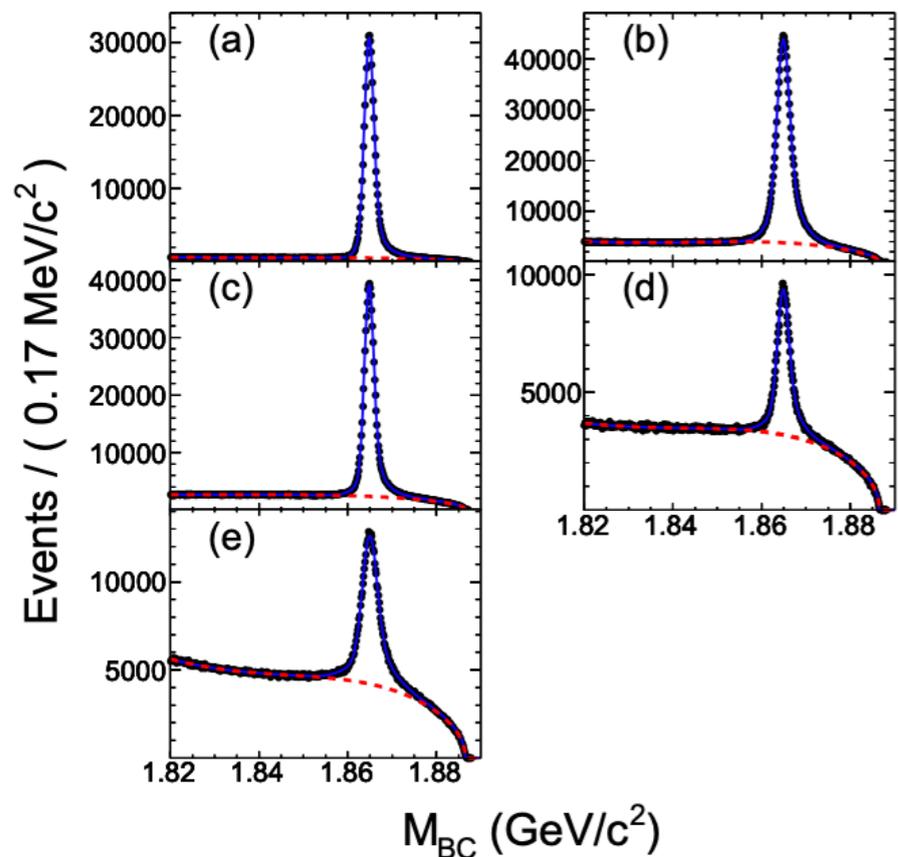
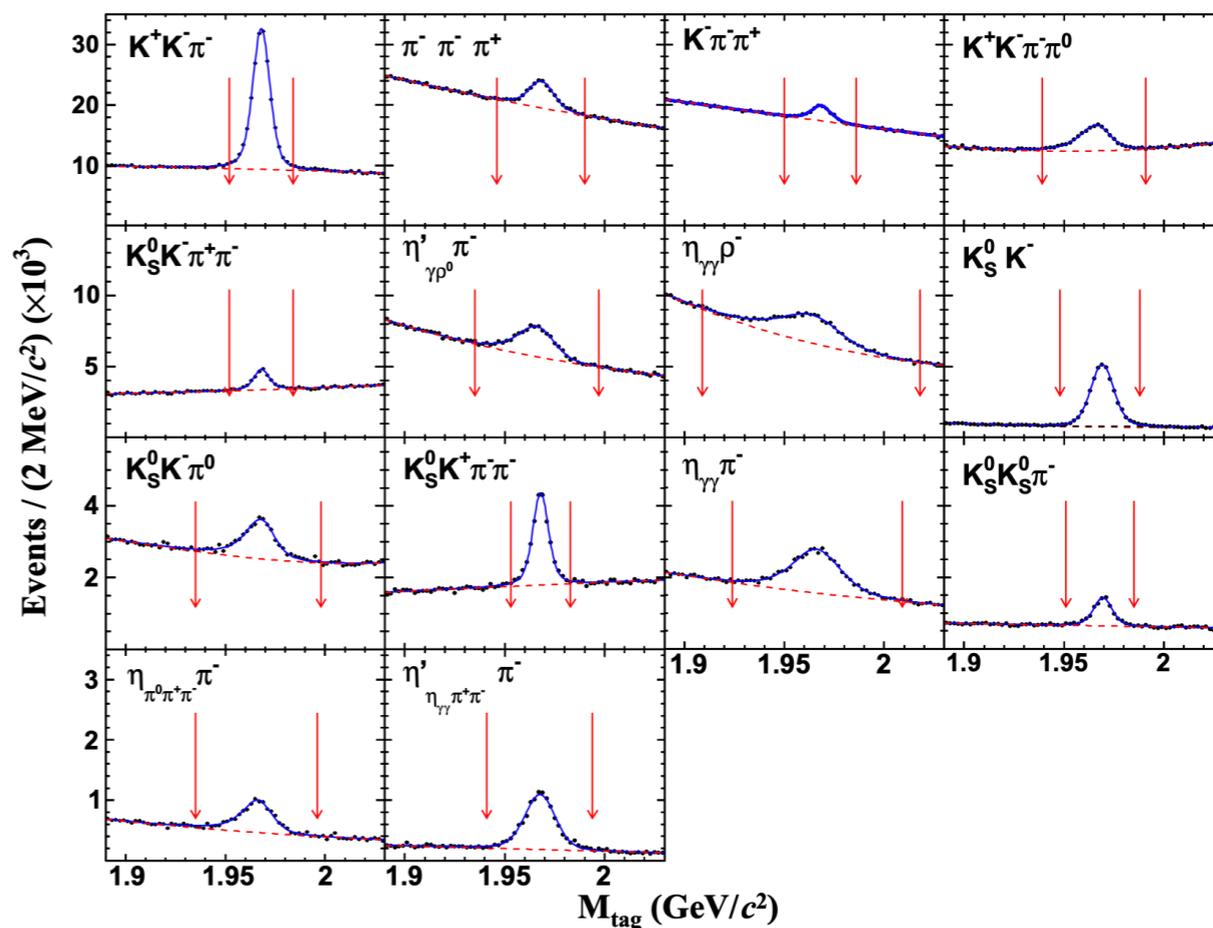
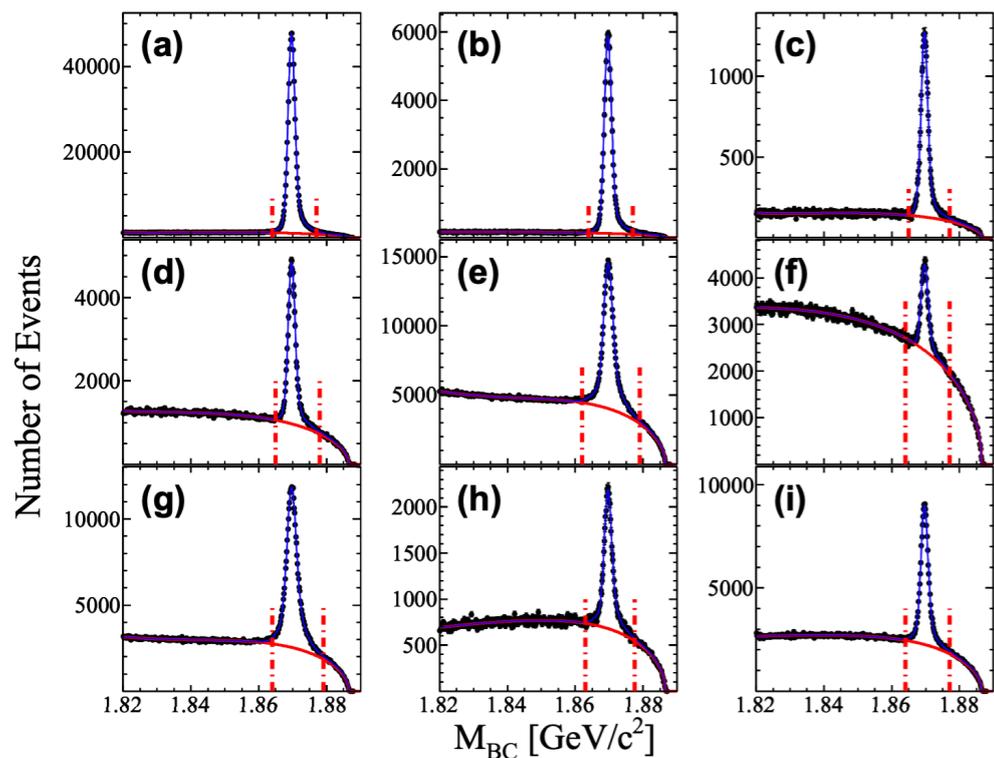
Single Tags



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$$N_{\bar{D}_{tag}^0} = (279.33 \pm 0.37) \times 10^4 \text{ [PRD92,072002(2015)]}$$

Single Tags

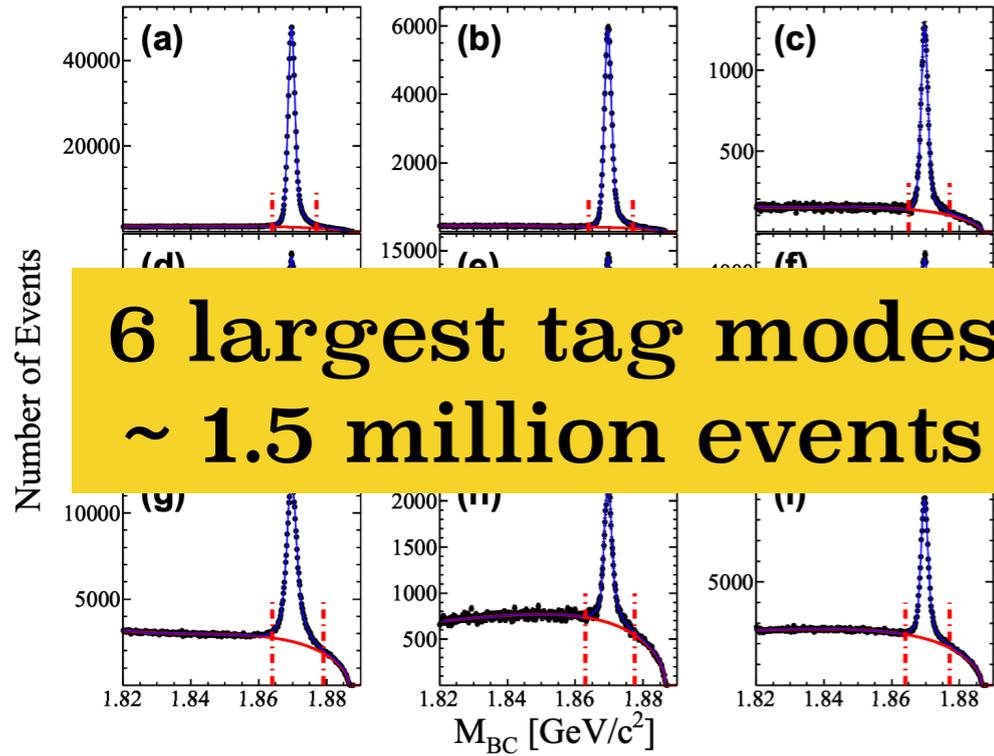


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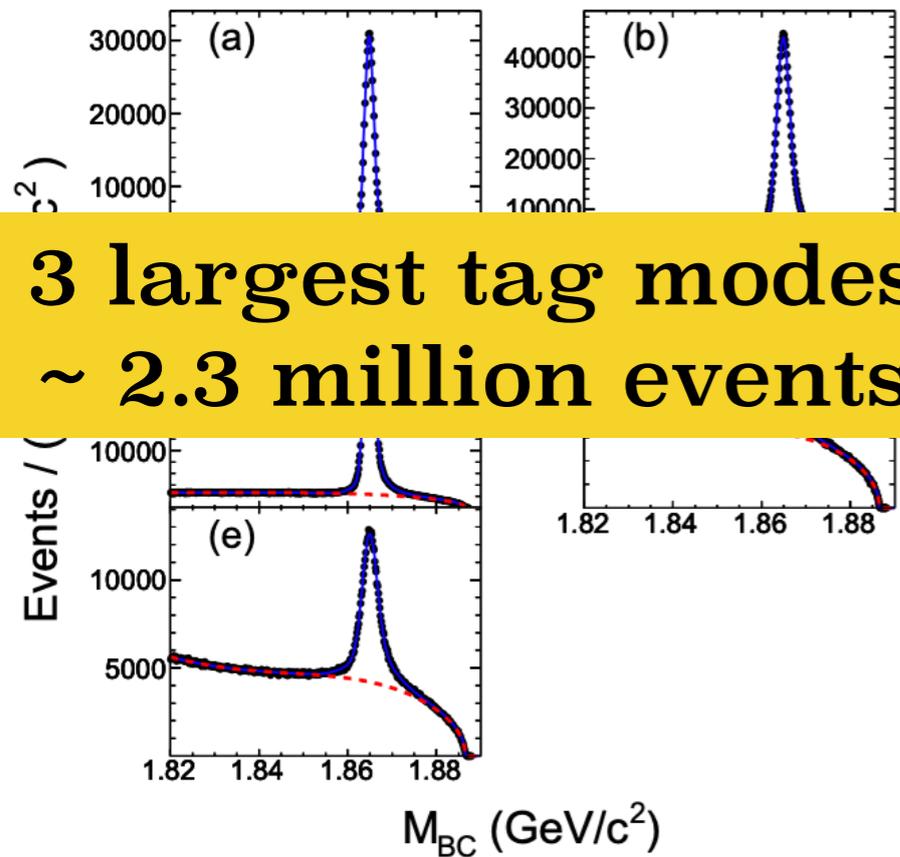
$$N_{\bar{D}_{tag}^0} = (279.33 \pm 0.37) \times 10^4 \text{ [PRD92,072002(2015)]}$$

$$N_{D_s^- tag} = (39.54 \pm 0.19) \times 10^4 \text{ [PRD92,072002(2015)]}$$

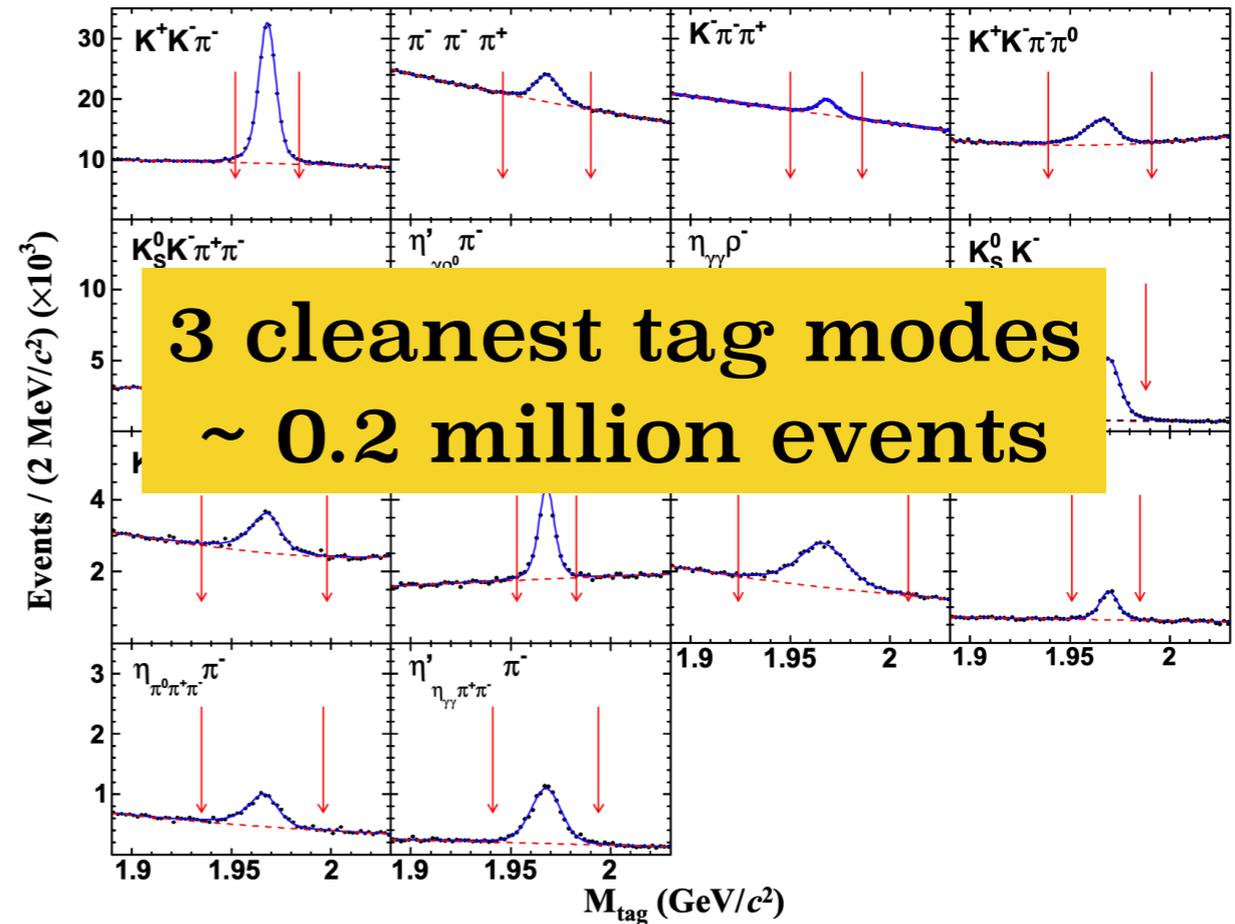
Single Tags



**6 largest tag modes
~ 1.5 million events**



**3 largest tag modes
~ 2.3 million events**



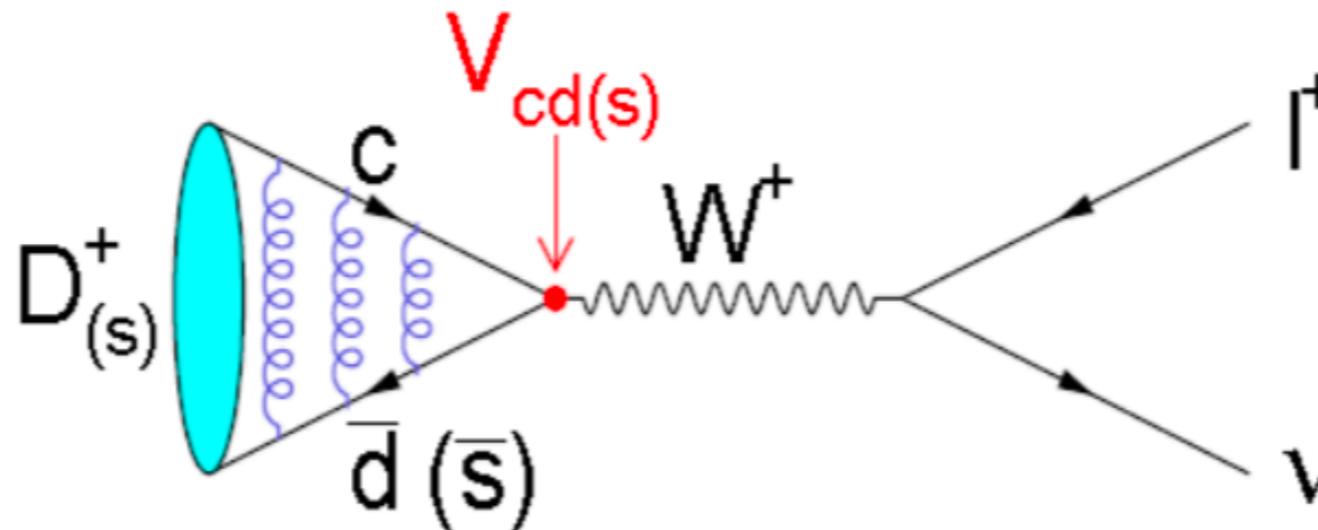
**3 cleanest tag modes
~ 0.2 million events**

$$N_{D_{tag}^-} = (170.31 \pm 0.34) \times 10^4 \text{ [PRD89,051104(R)(2014)]}$$

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$$N_{D_s^- \text{ tag}} = (39.54 \pm 0.19) \times 10^4 \text{ [PRD92,072002(2015)]}$$

CKM Matrix Element & Decay Constant



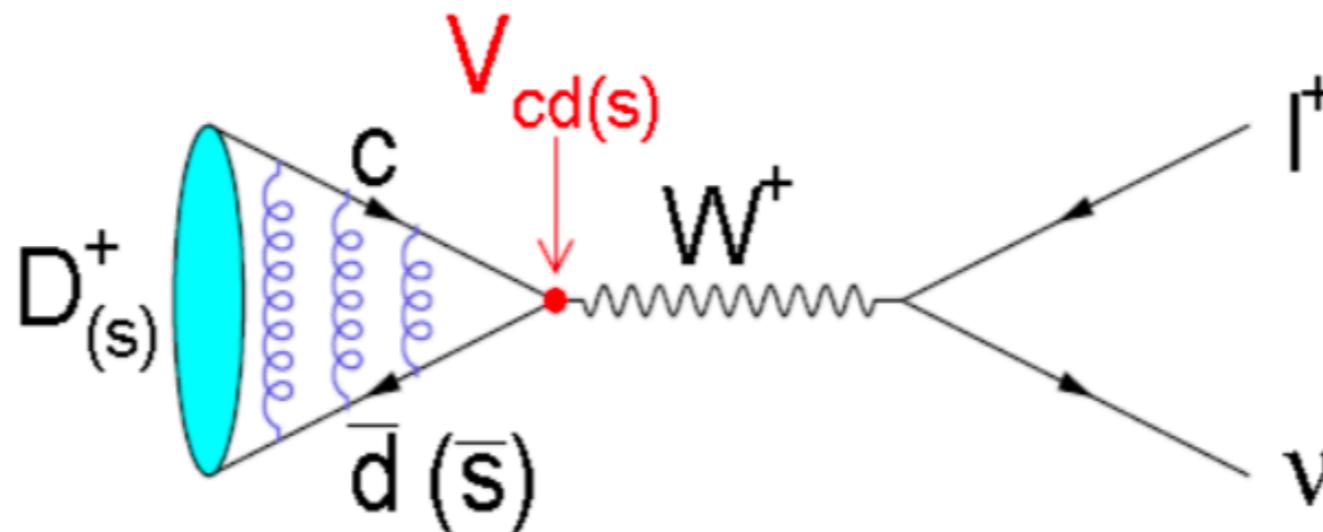
In the SM:

$$\Gamma(D_{(s)}^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$

Bridge to precisely measure

- Decay constant $f_{D(s)+}$ with input $|V_{cd(s)}|^{\text{CKMfitter}}$
- CKM matrix element $|V_{cd(s)}|$ with input $f_{D(s)+}^{\text{LQCD}}$

CKM Matrix Element & Decay Constant



In the SM:

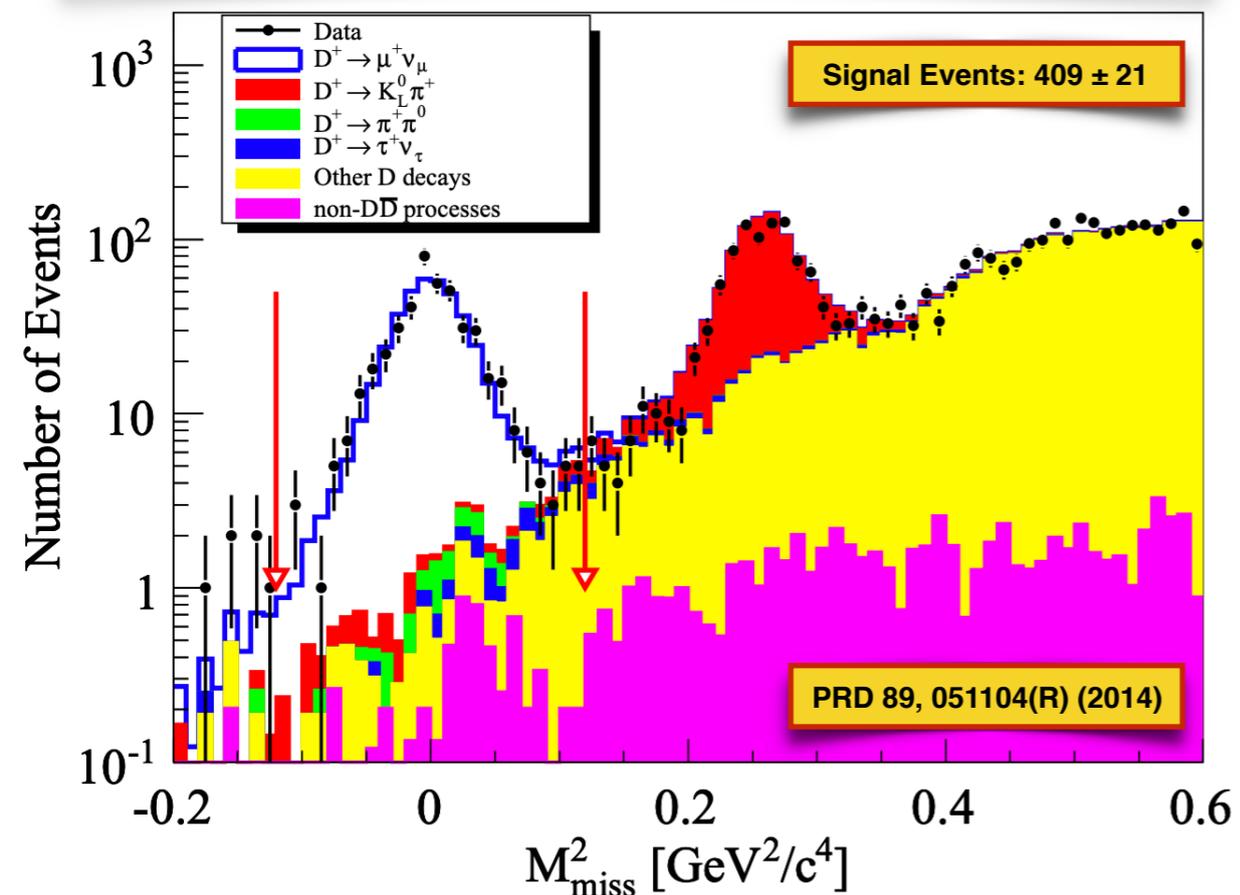
$$\Gamma(D_{(s)}^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 f_{D_{(s)}^+}^2 |V_{cd(s)}|^2 m_\ell^2 m_{D_{(s)}^+}}{8\pi} \left(1 - \frac{m_\ell^2}{m_{D_{(s)}^+}^2}\right)^2$$

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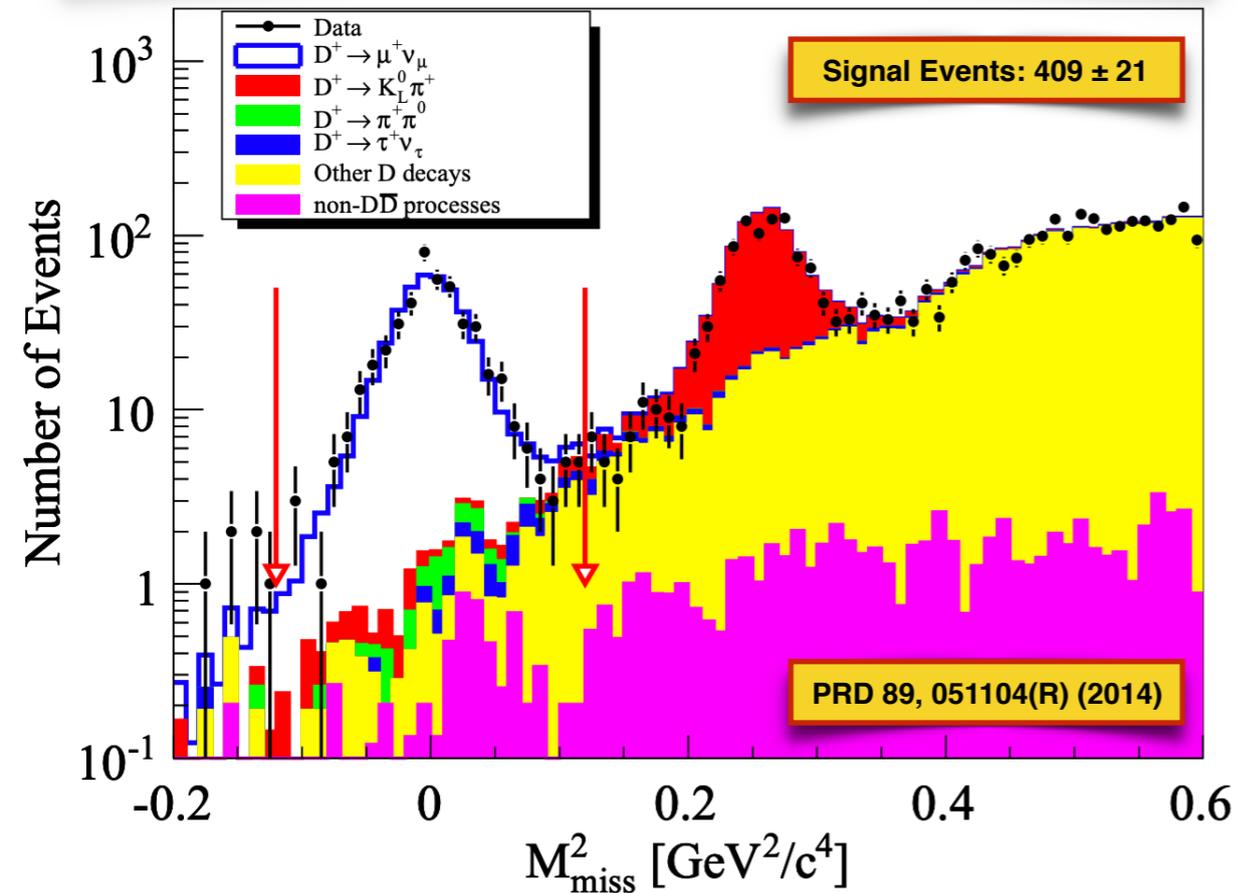
CKM Matrix Element & Decay Constant

$$\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$



CKM Matrix Element & Decay Constant

$$\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$



$$f_{D^+} |V_{cd}| = (45.75 \pm 1.20 \pm 0.39) \text{ MeV}$$

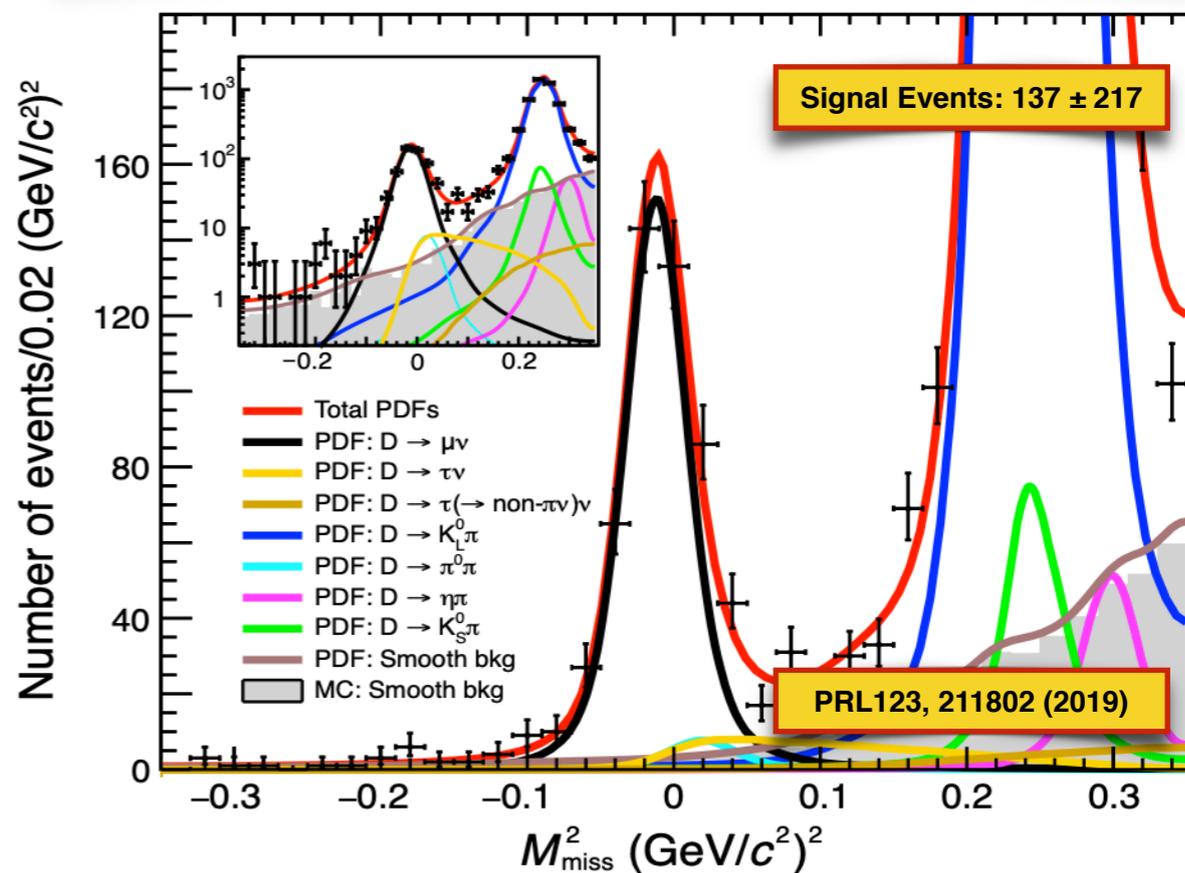
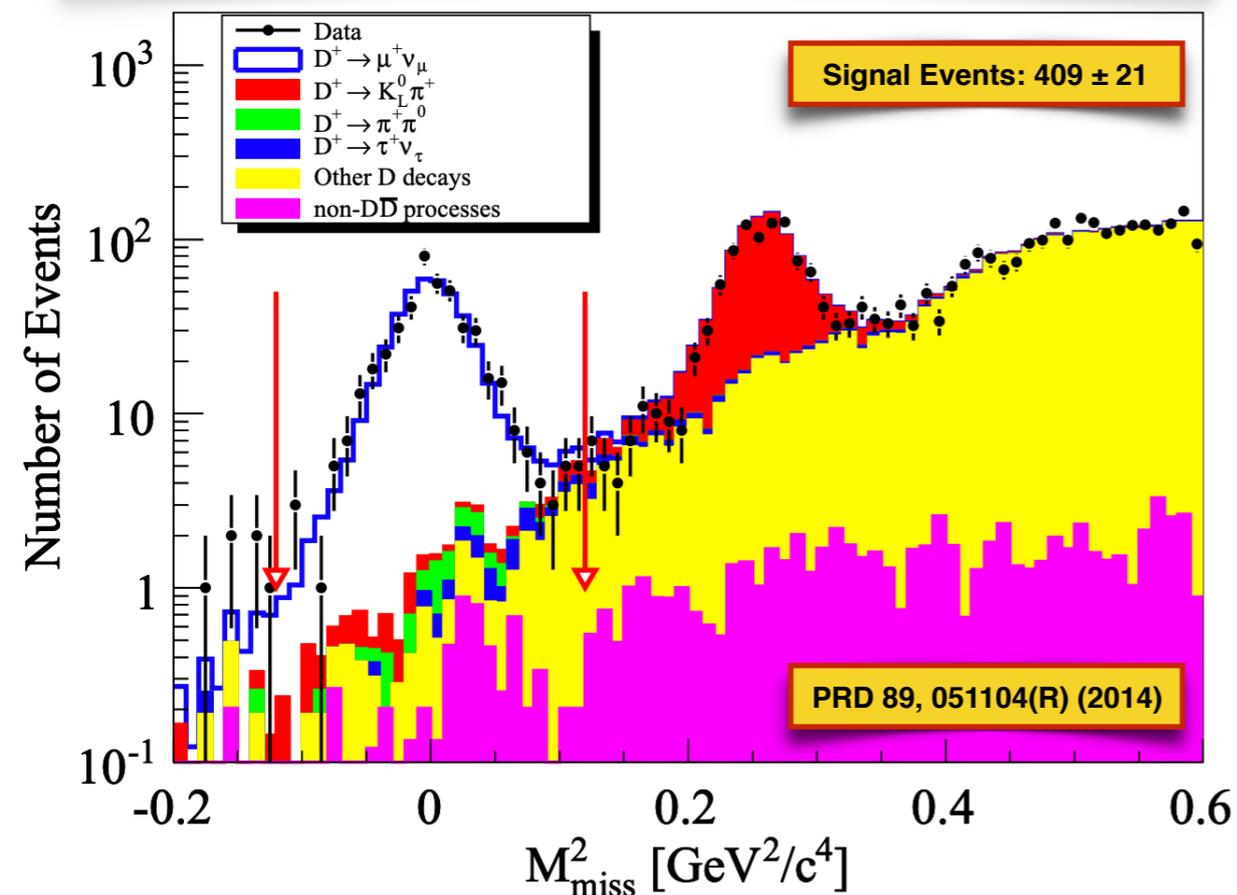
$$f_{D^+} = (203.2 \pm 5.3 \pm 1.8) \text{ MeV}$$

$$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$$

CKM Matrix Element & Decay Constant

$$\mathcal{B}(D^+ \rightarrow \mu^+ \nu_\mu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

$$\mathcal{B}(D^+ \rightarrow \tau^+ \nu_\tau) = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$



$$f_{D^+} |V_{cd}| = (45.75 \pm 1.20 \pm 0.39) \text{ MeV}$$

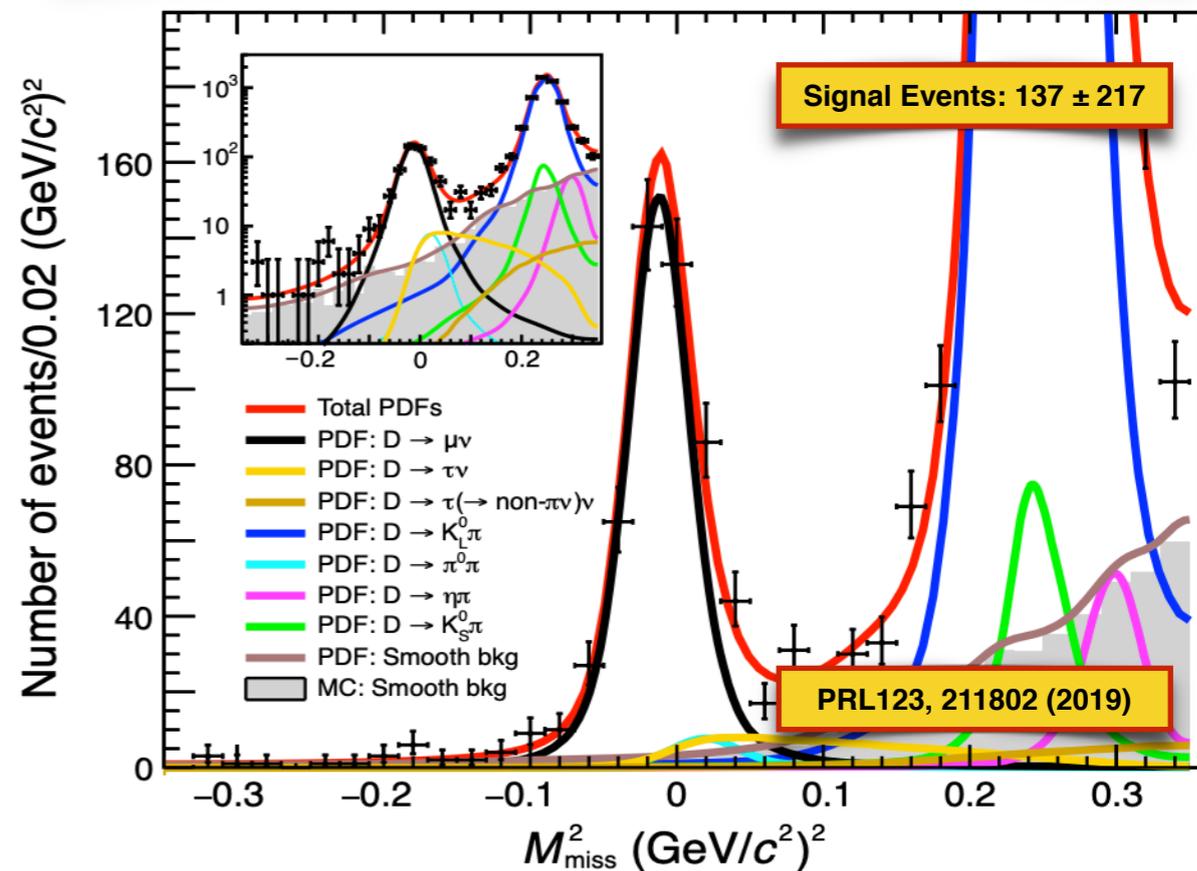
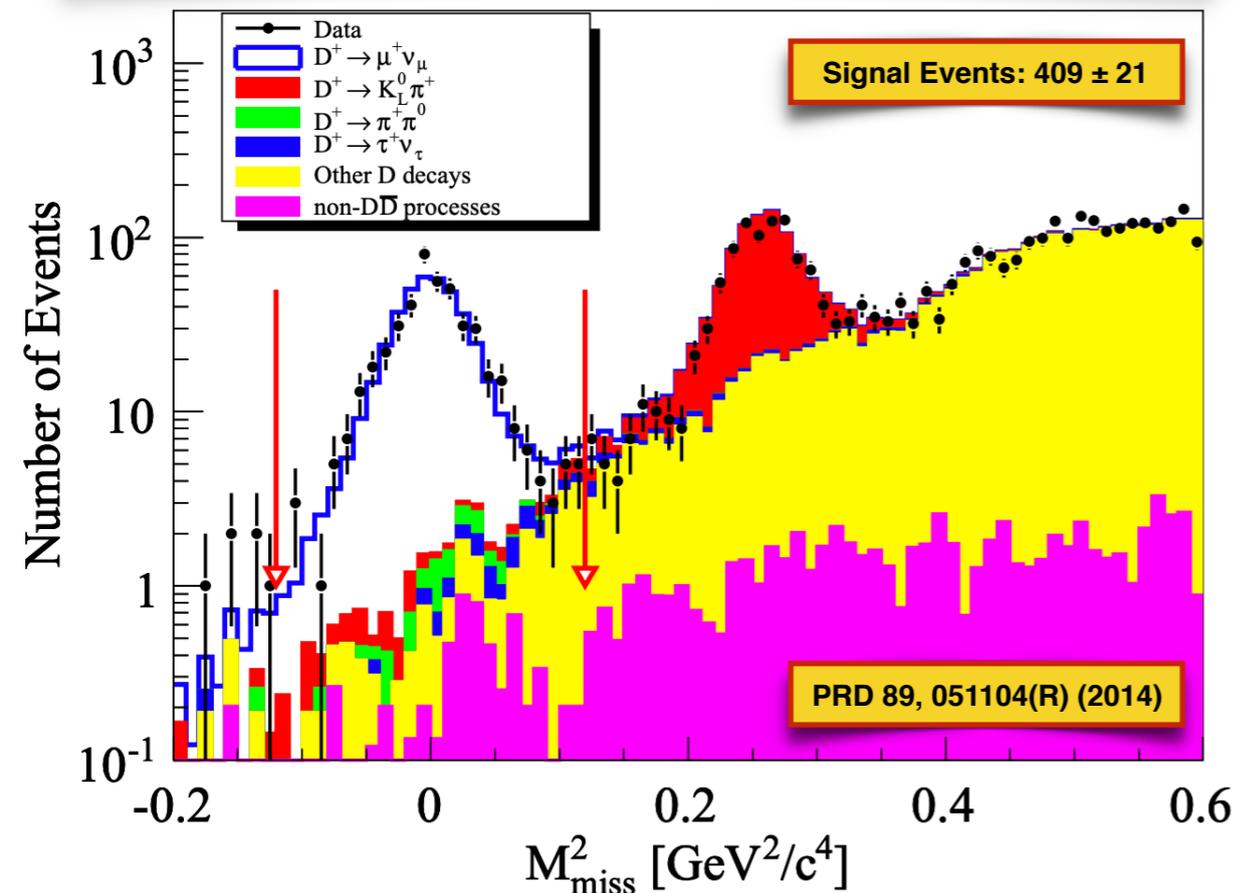
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$$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$$

$$f_{D^+} |V_{cd}| = (50.4 \pm 5.1 \pm 2.5) \text{ MeV}$$

$$f_{D^+} = (224.5 \pm 22.8 \pm 11.3 \pm 0.9_{V_{cd}}) \text{ MeV}$$

$$|V_{cd}| = 0.237 \pm 0.024 \pm 0.012 \pm 0.001_{LQCD}$$



CKM Matrix Element & Decay Constant

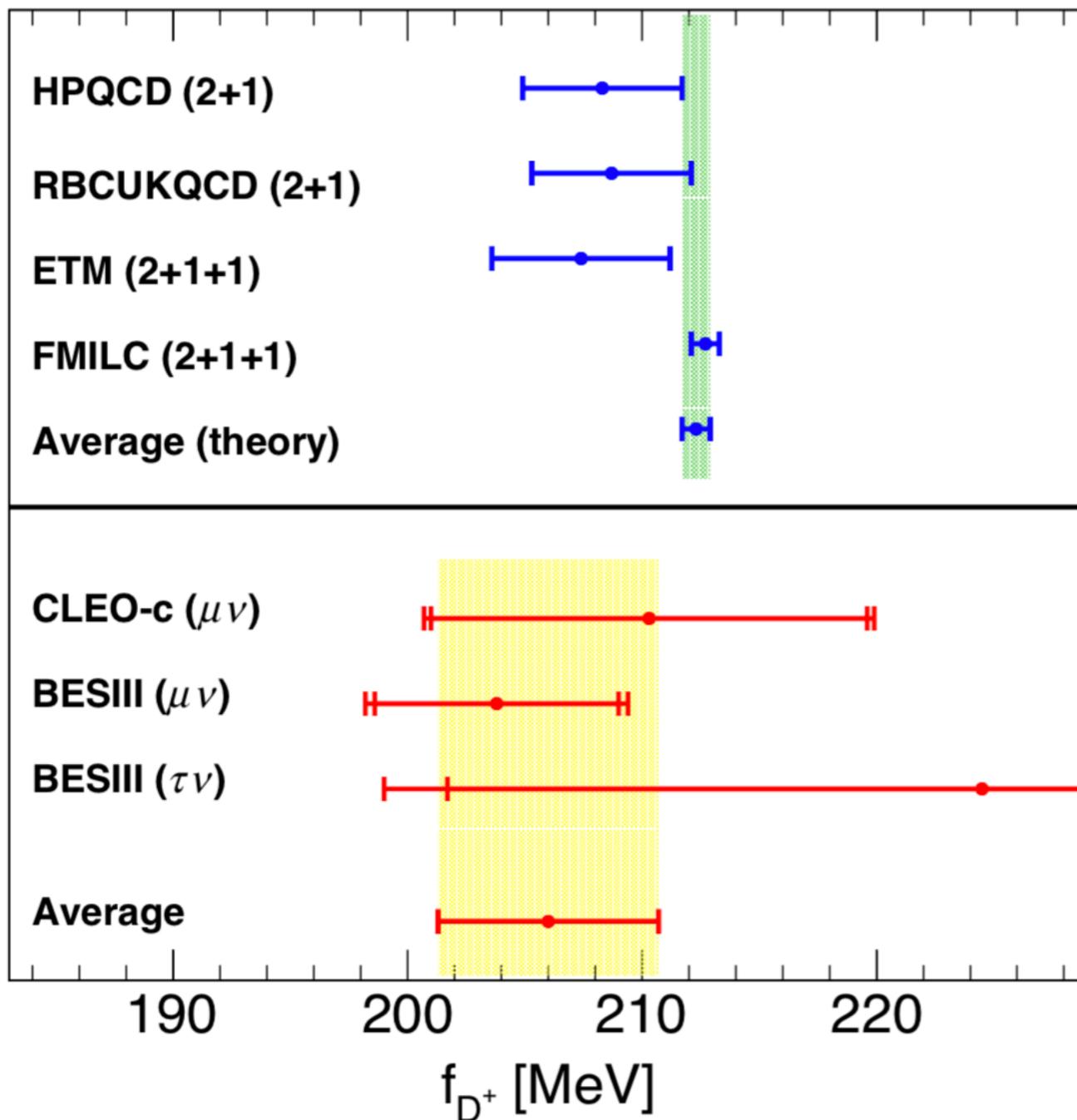
Input $|V_{cd}| = 0.22438 \pm 0.00044$

(PDG2018 from CKM unitarity)

CKM Matrix Element & Decay Constant

Input $|V_{cd}| = 0.22438 \pm 0.00044$

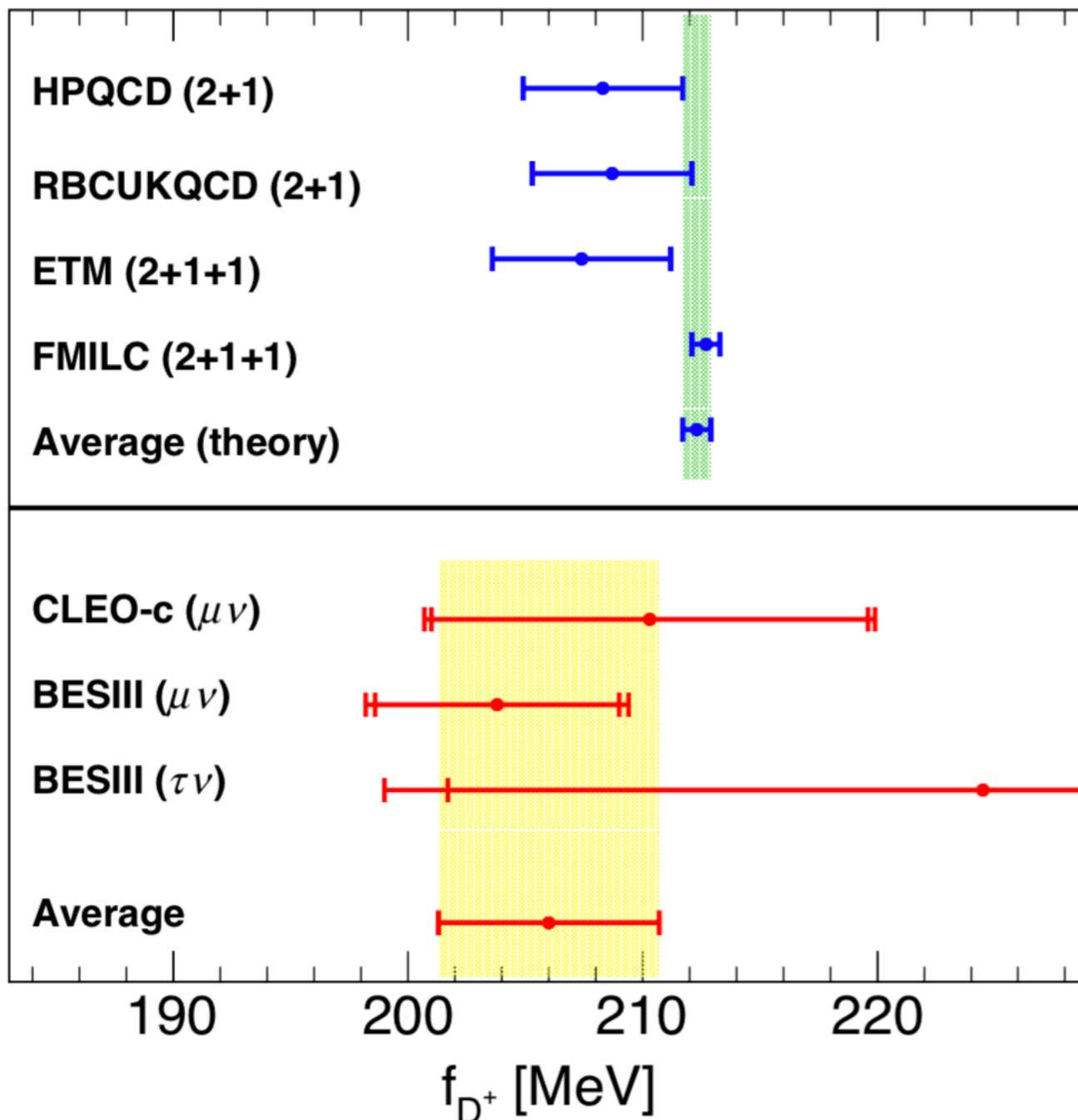
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CKM Matrix Element & Decay Constant

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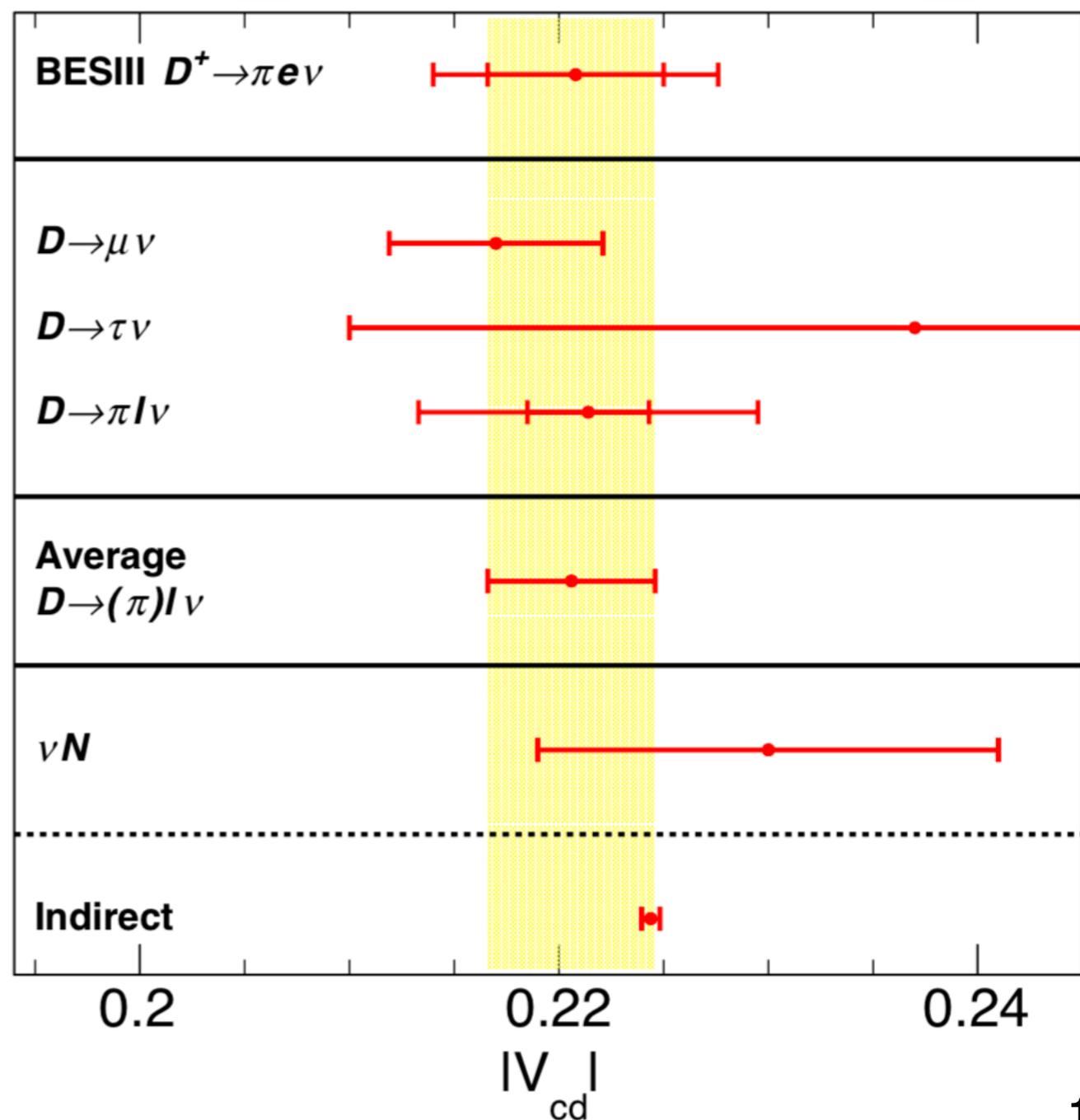
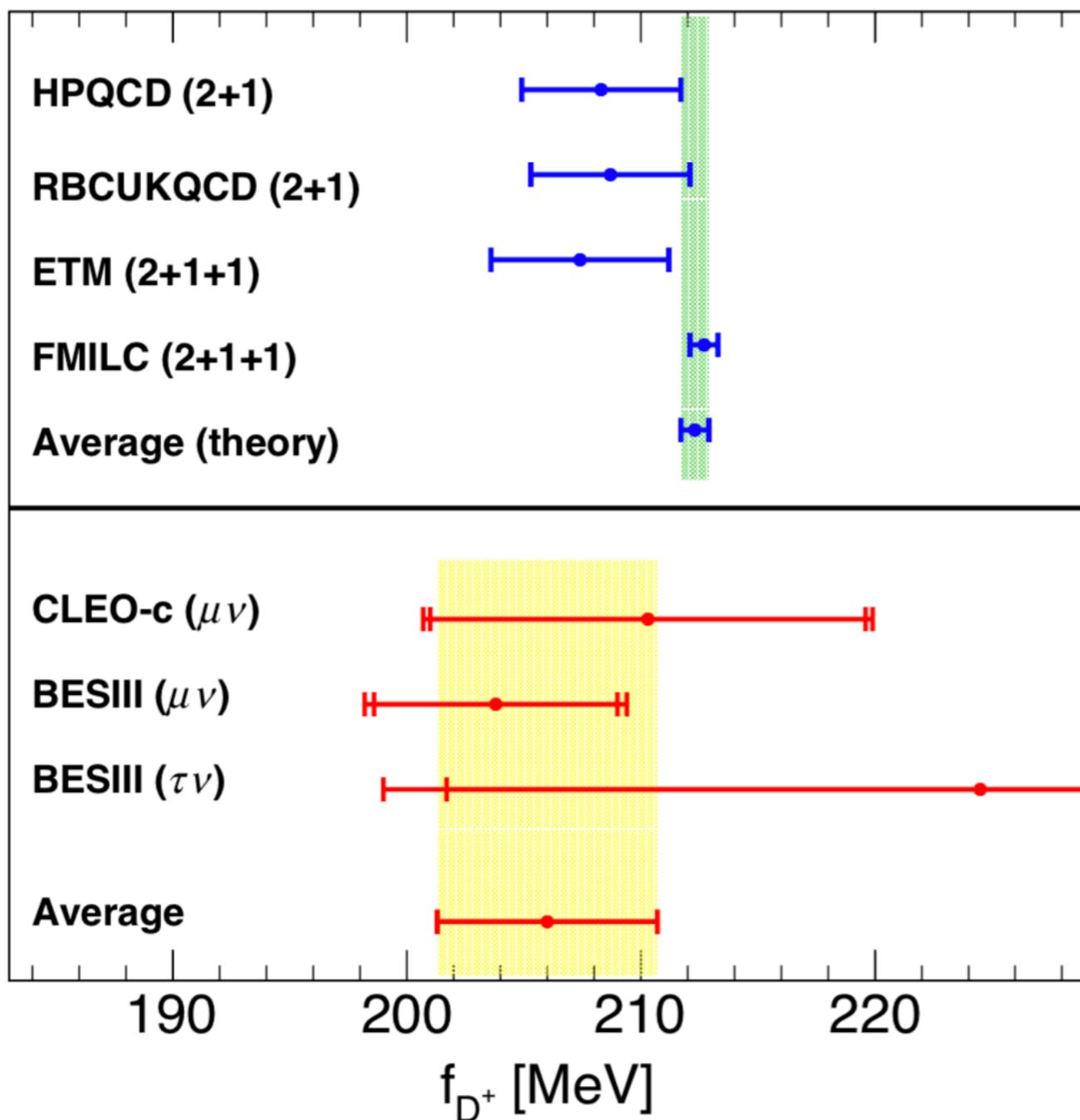
Input $f_{D^+}^{\text{LQCD}} = (212.3 \pm 0.6)\text{MeV}$
 or $f_+^{\pi}(0)^{\text{LQCD}} = 0.634 \pm 0.015$



CKM Matrix Element & Decay Constant

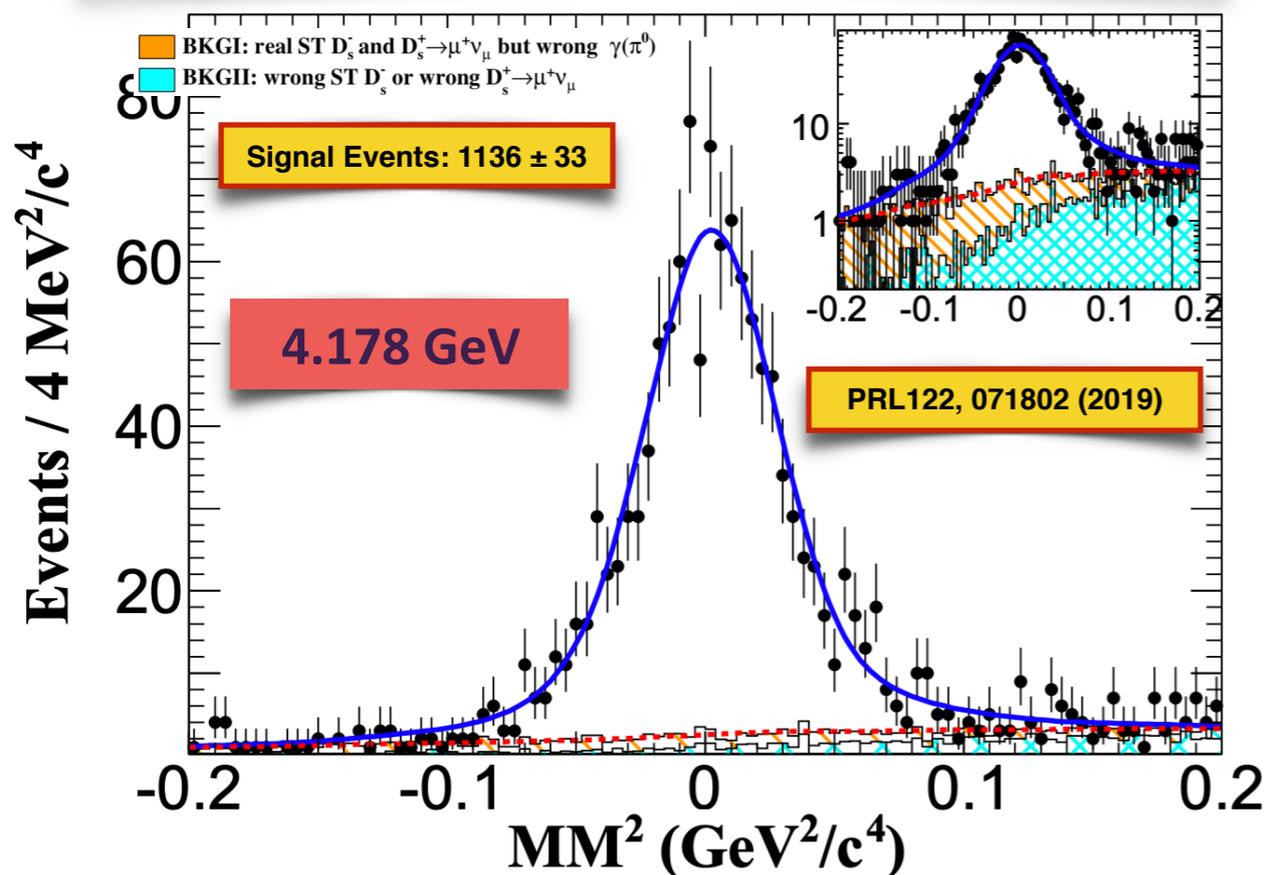
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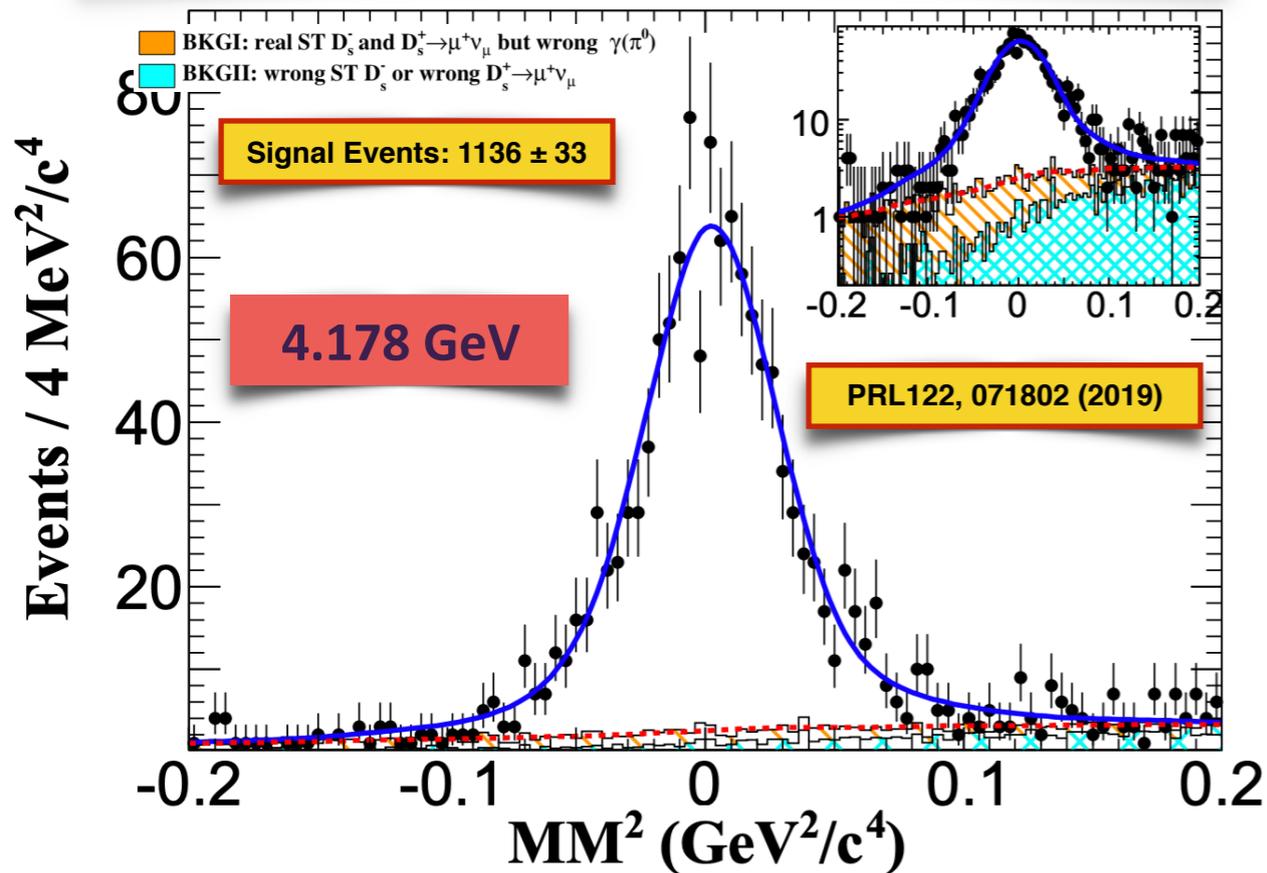
CKM Matrix Element & Decay Constant

$$\mathcal{B}(D_S^+ \rightarrow \mu^+ \nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$



CKM Matrix Element & Decay Constant

$$\mathcal{B}(D_S^+ \rightarrow \mu^+ \nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$



Most Precise!

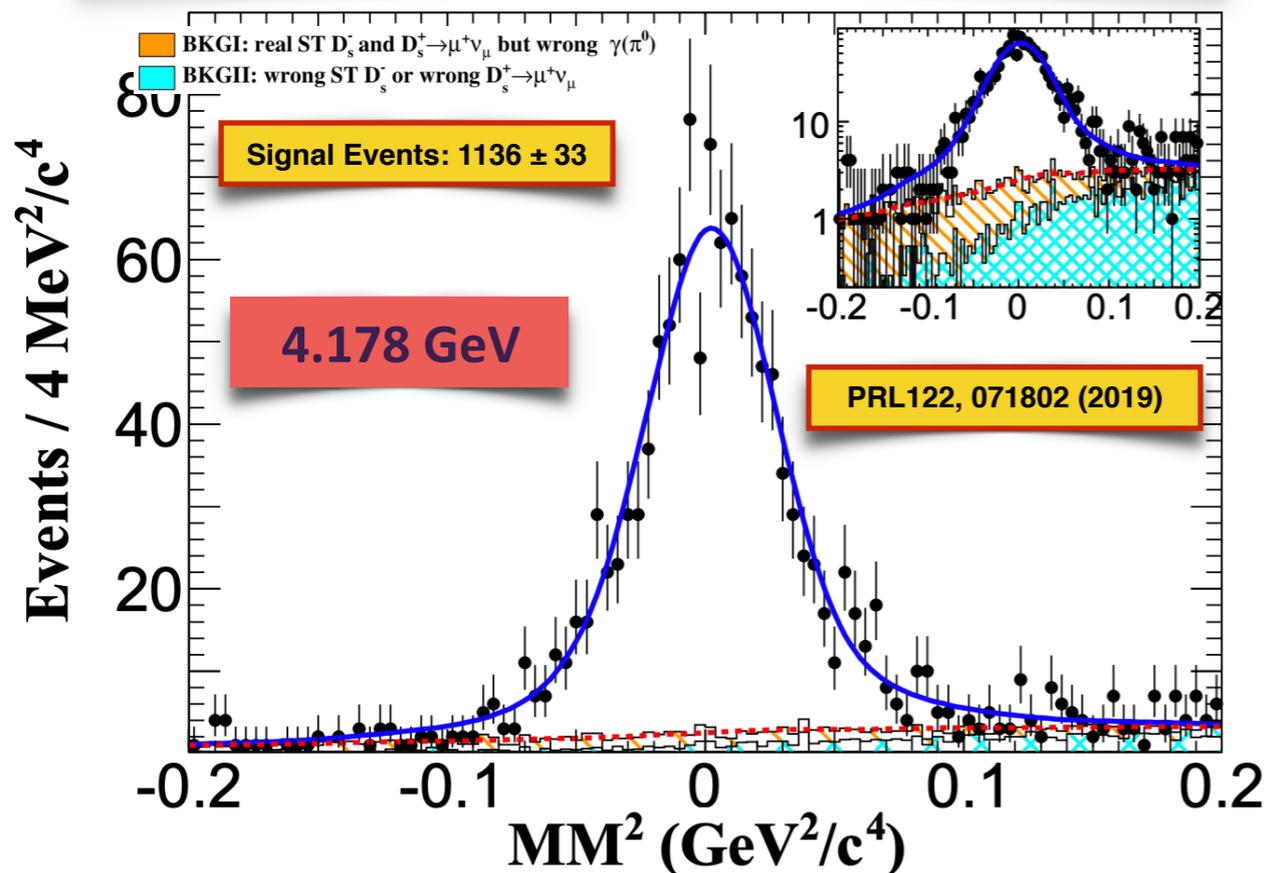
$$f_{D_S^+} |V_{cs}| = (246.2 \pm 3.6 \pm 3.5) \text{ MeV}$$

$$f_{D_S^+} = (252.9 \pm 3.7 \pm 3.6) \text{ MeV}$$

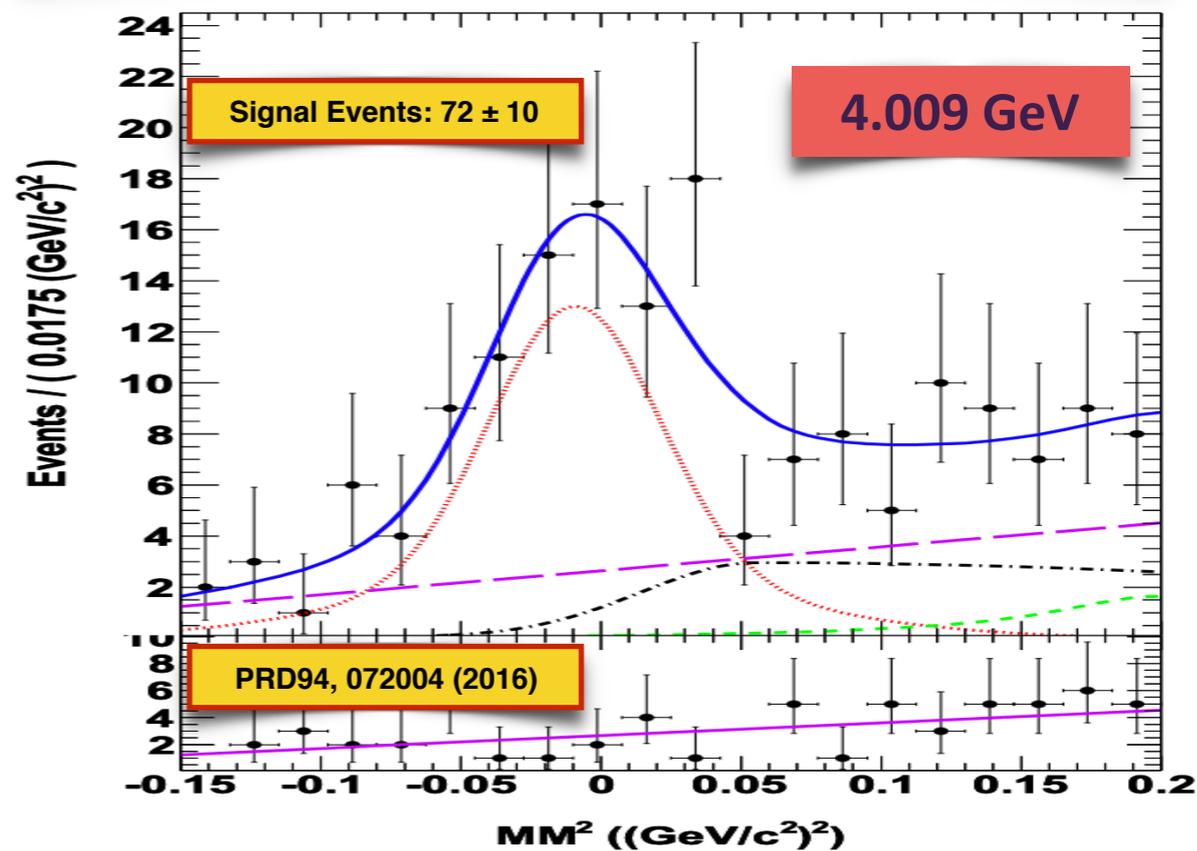
$$|V_{cs}| = 0.985 \pm 0.014 \pm 0.014$$

CKM Matrix Element & Decay Constant

$$\mathcal{B}(D_S^+ \rightarrow \mu^+ \nu_\mu) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$



$$\mathcal{B}(D_S^+ \rightarrow \mu^+ \nu_\mu) = (5.17 \pm 0.75 \pm 0.21) \times 10^{-3}$$



Most Precise!

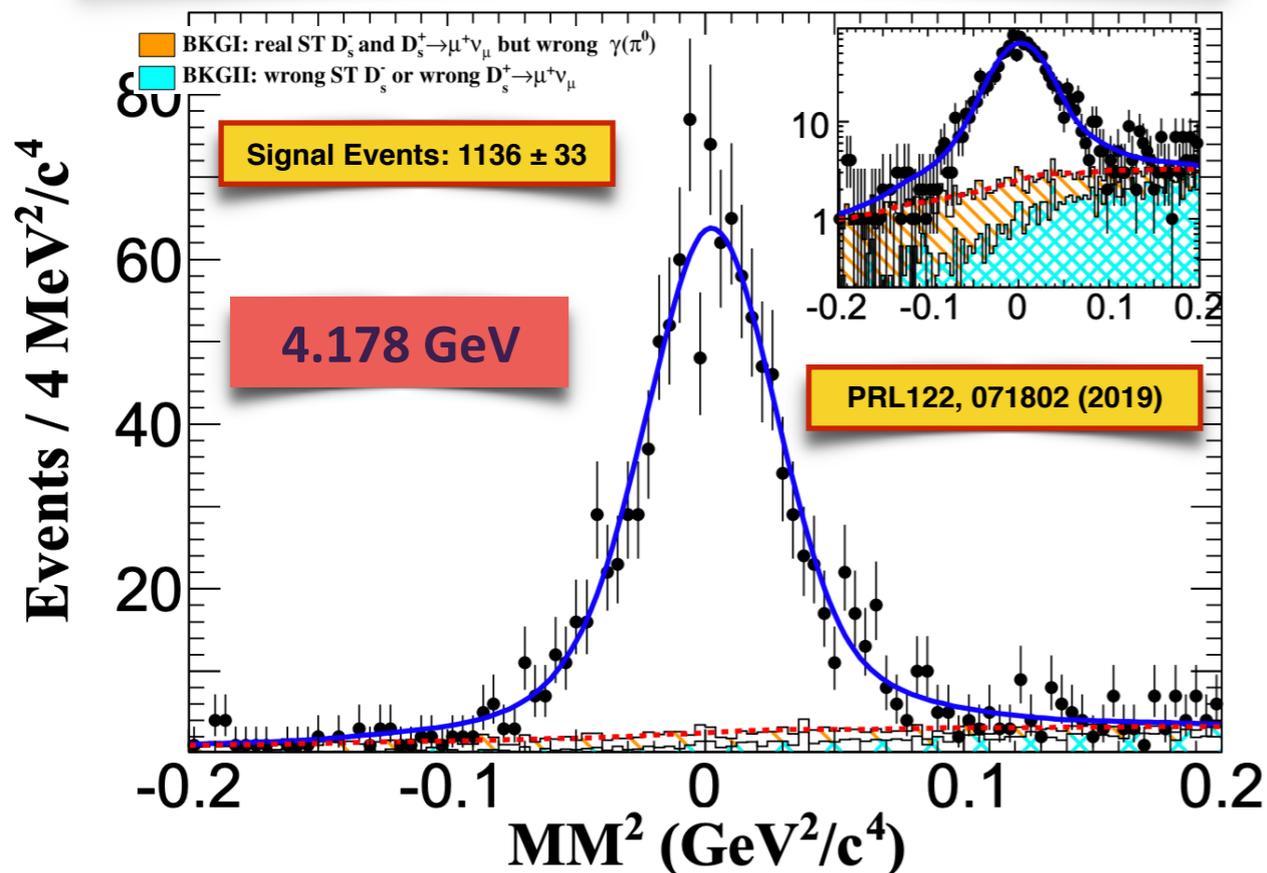
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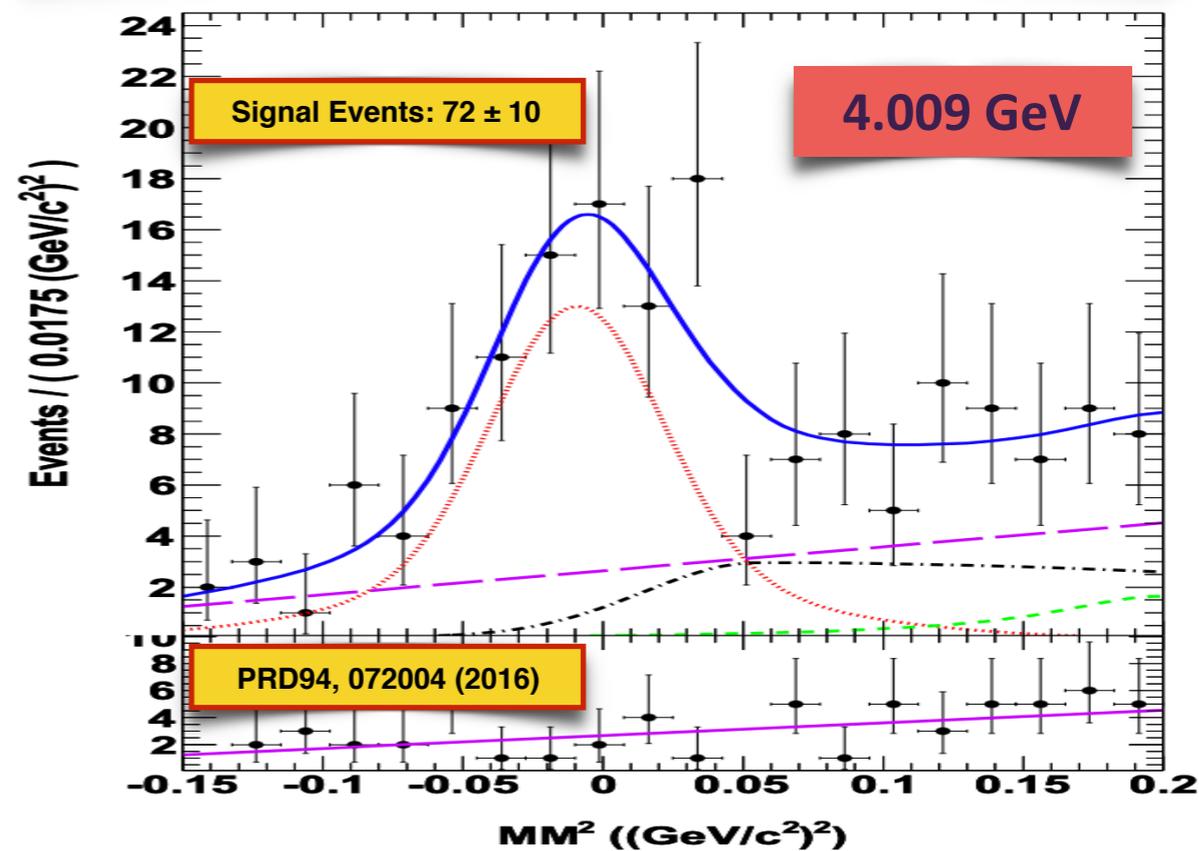
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$$f_{D_S^+} |V_{cs}| = (239 \pm 17 \pm 5) \text{ MeV}$$

$$f_{D_S^+} = (241.0 \pm 16.3 \pm 6.5) \text{ MeV}$$



CKM Matrix Element & Decay Constant

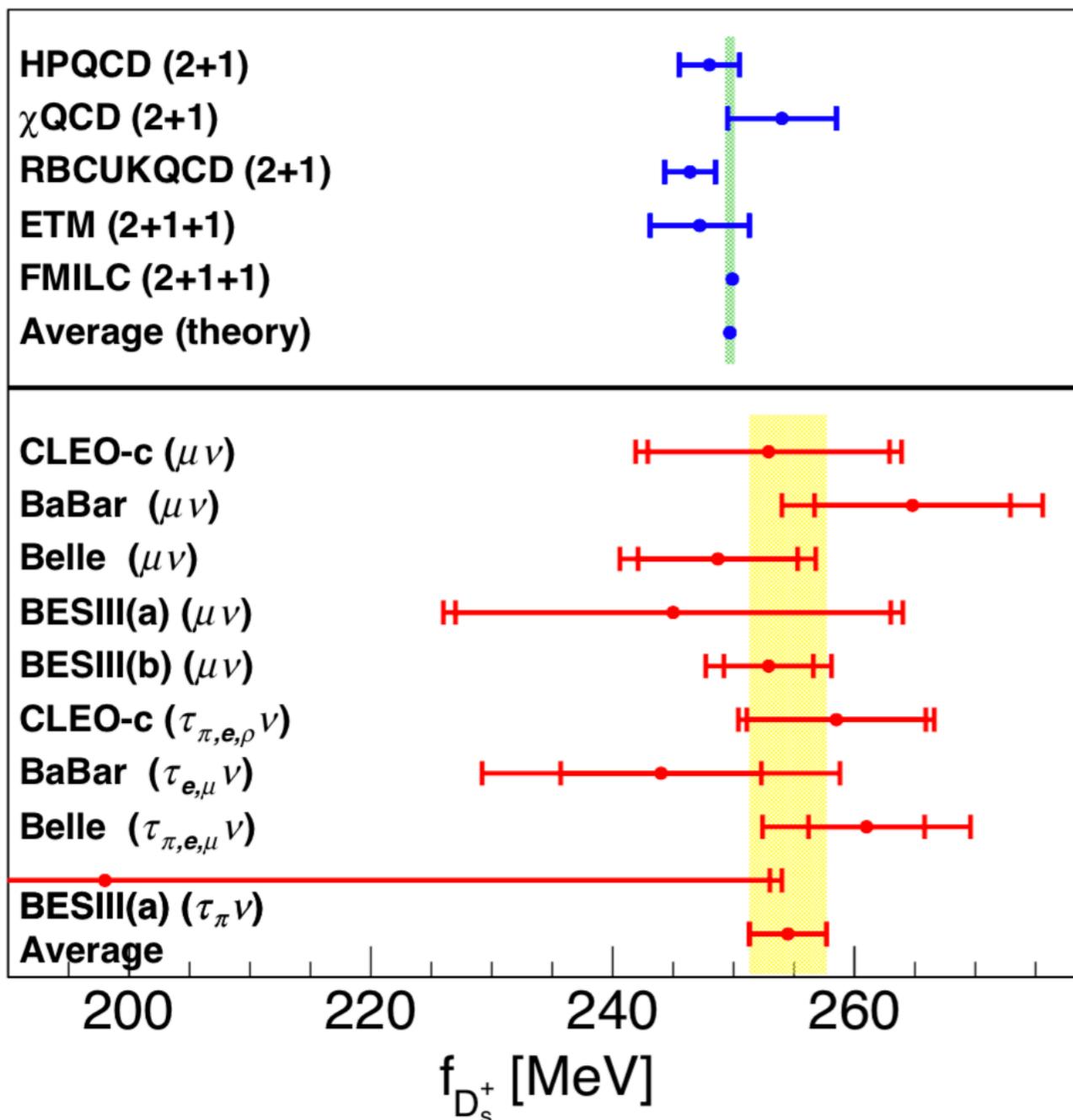
Input $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$

(PDG2018 from CKM unitarity)

CKM Matrix Element & Decay Constant

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(PDG2018 from CKM unitarity)



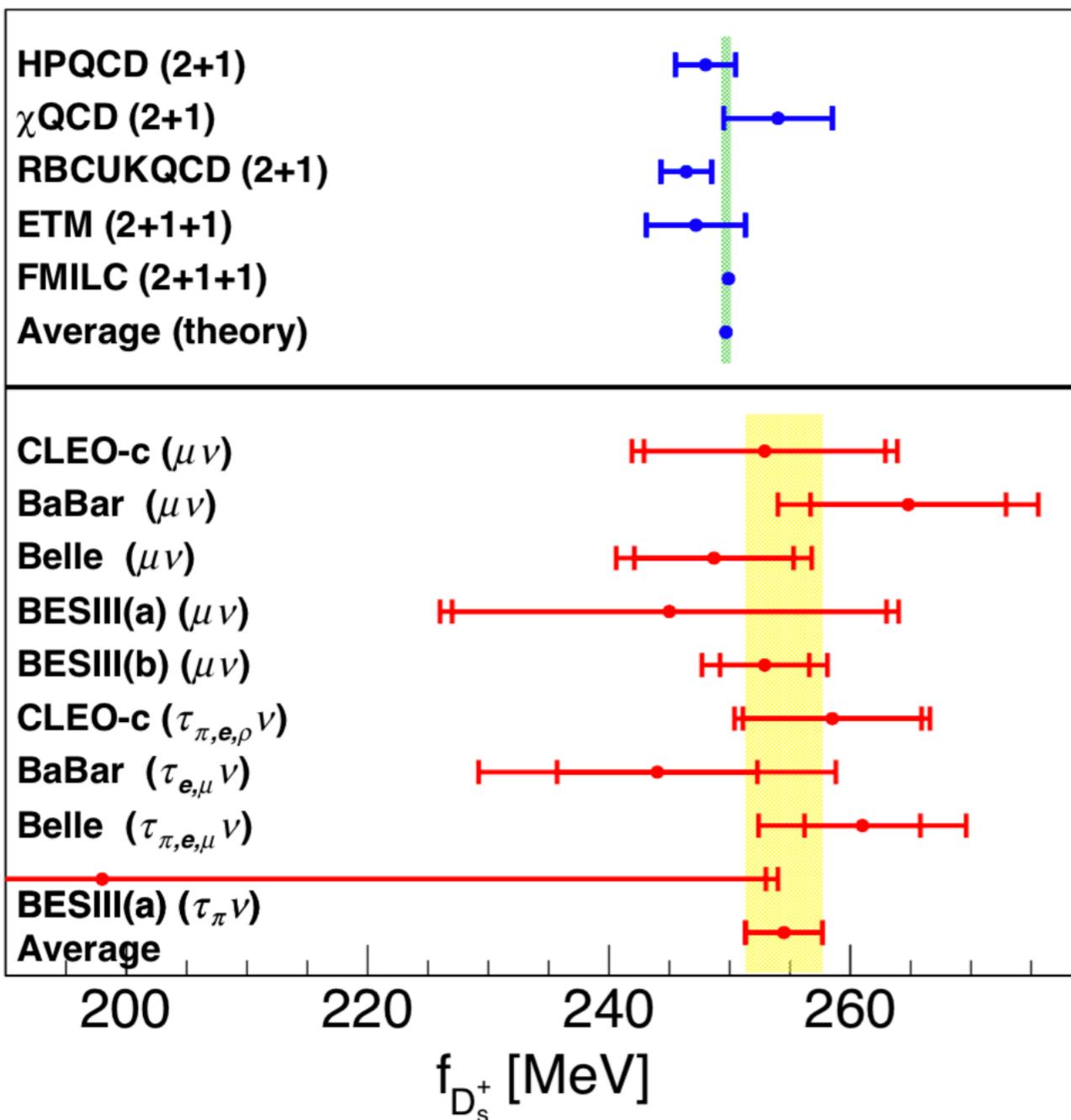
CKM Matrix Element & Decay Constant

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Input $f_{D_s^+}^{\text{LQCD}} = (249.7 \pm 0.4)\text{MeV}$

or $f_{+}^{\text{K}(0)\text{LQCD}} = 0.760 \pm 0.011$



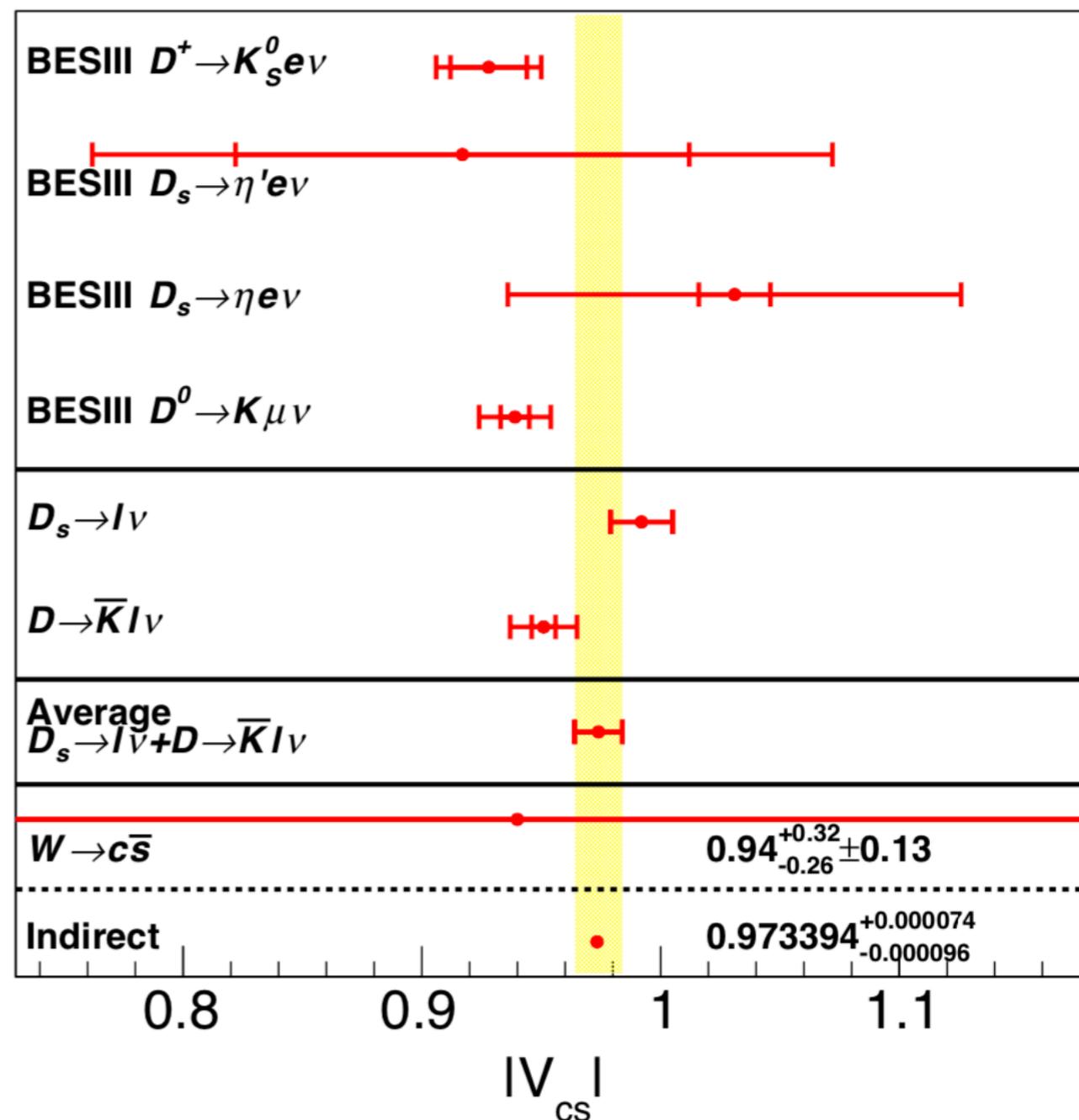
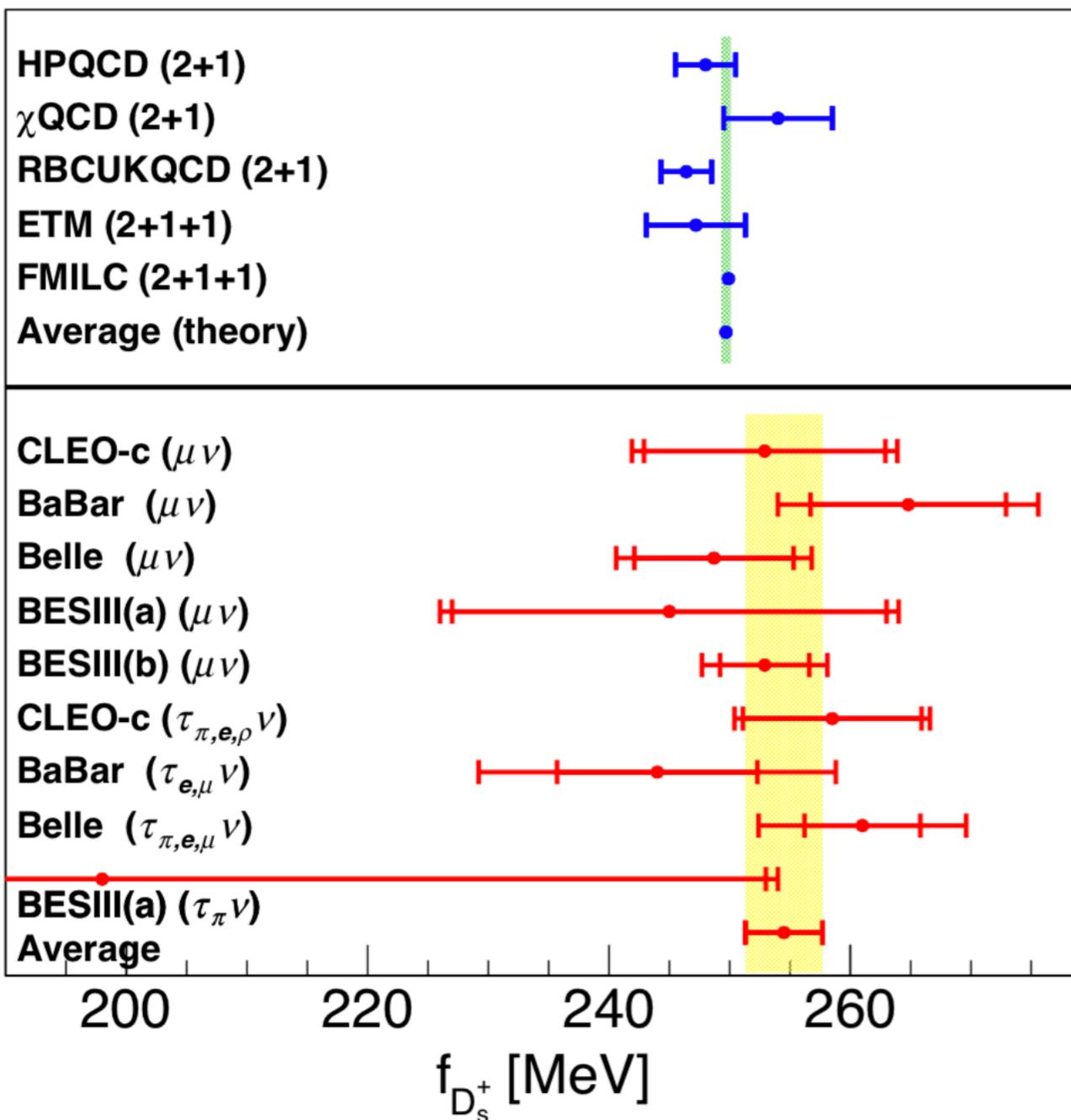
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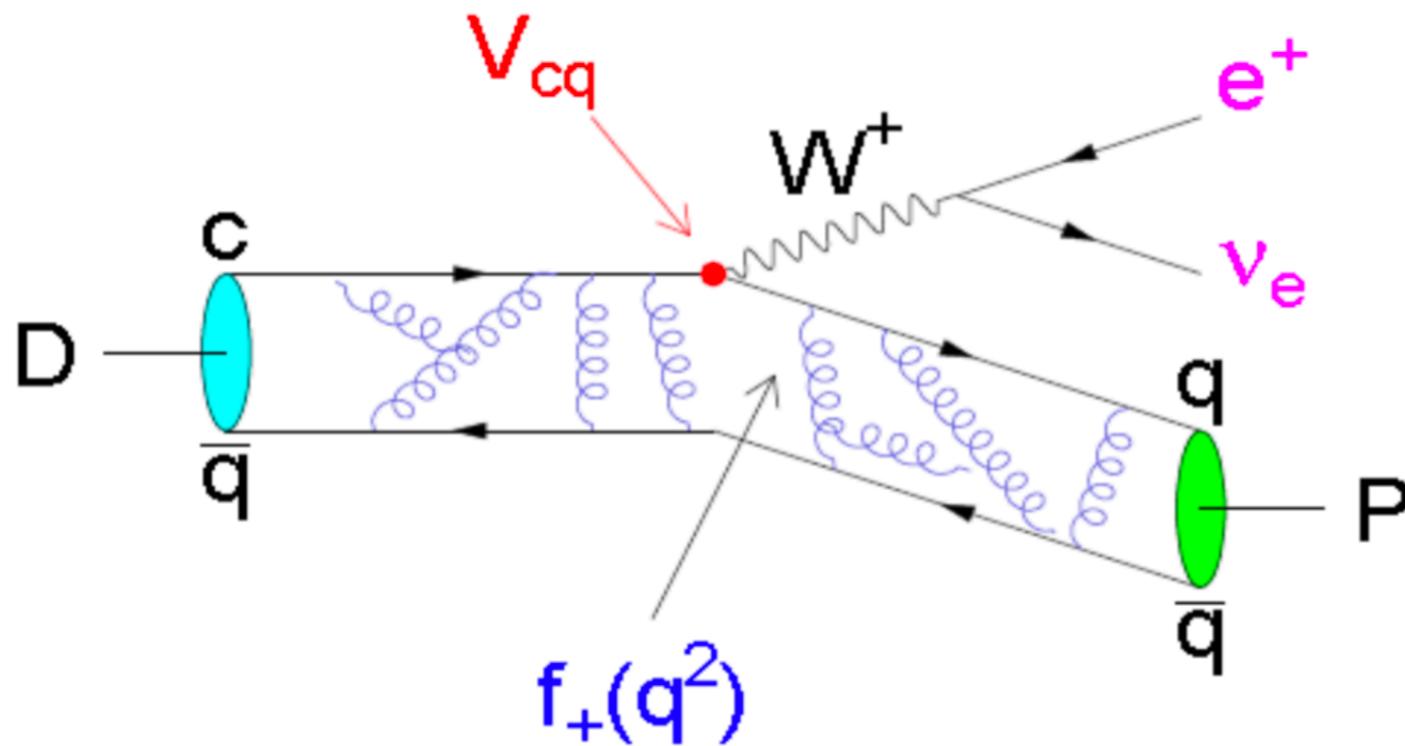
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CKM Matrix Element & Form Factor



– **Single pole form**

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

– **ISGW2 model**

$$f_+(q^2) = f_+(q_{\text{max}}^2) \left(1 + \frac{r_{\text{ISGW2}}^2}{12} (q_{\text{max}}^2 - q^2) \right)^{-2}$$

– **Modified pole model**

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

– **Series expansion model**

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

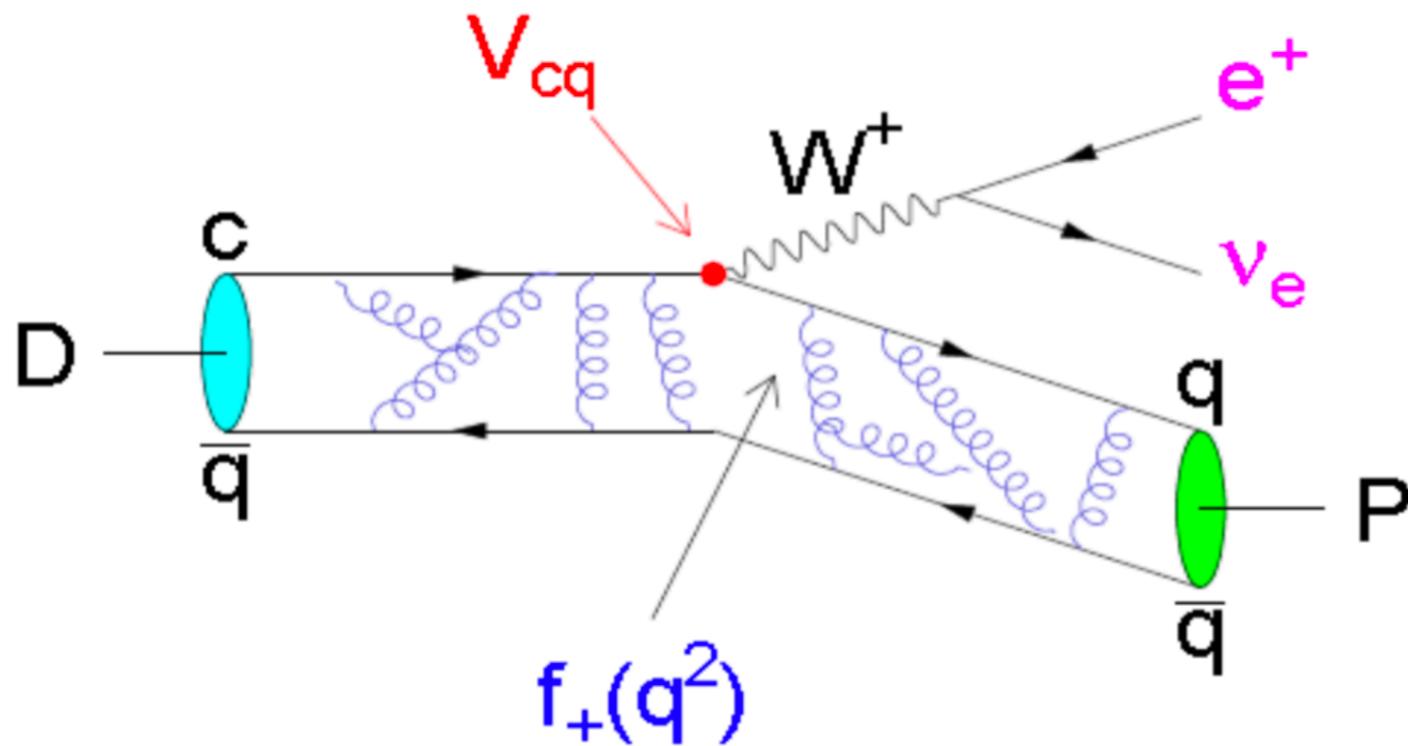
- partial decay width

$$\frac{d\Gamma_{P\ell^+\nu_\ell}}{dq^2} = \frac{G_F^2 |V_{cq}|^2}{8\pi^3 m_D} |\vec{p}_P| |f_+^P(q^2)|^2 \left(\frac{W_0 - E_P}{F_0} \right)^2 \times \left[\frac{1}{3} m_D |\vec{p}_P|^2 + \mathcal{O}(m_\ell^2) \right]$$

$$W_0 = (m_D^2 + m_P^2 - m_\ell^2)/2m_D, \quad F_0 = W_0 - E_P + m_\ell^2/2m_D$$

- measure $V_{cd(s)}$ to test the unitarity of CKM matrix
- measure the form factors $f_+^P(0)$ to calibrate the Lattice QCD calculation
- test lepton universality via $\mathcal{R} = \Gamma_\mu/\Gamma_e$

CKM Matrix Element & Form Factor



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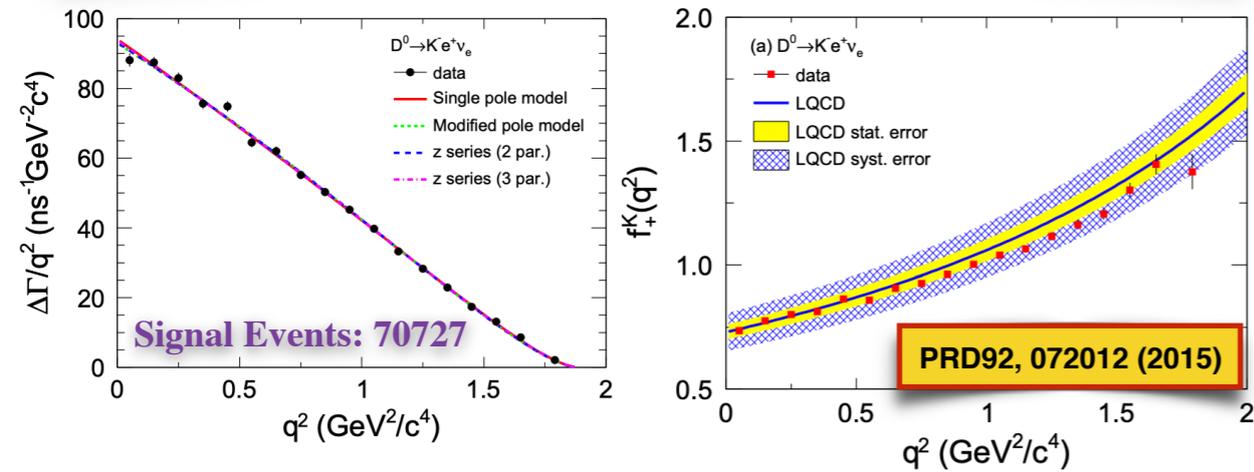
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CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033) \%$$





CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505$$

Most Precise!

$$f_+^K(0) |V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239_{LQCD}$$

q^2 (GeV²/c⁴)

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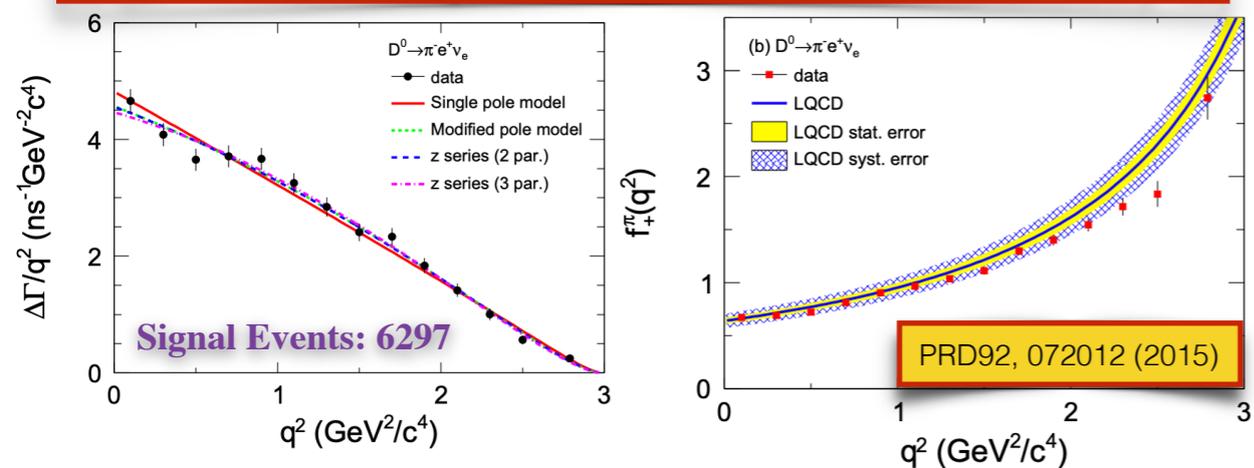
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$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003) \%$$





CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.010 \pm 0.010) \text{ Most Precise!}$$

$$f_+^K(0) |V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.005 \pm 0.005) \text{ Most Precise!}$$

$$f_+^\pi(0) |V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$

$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$

$$|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094_{LQCD}$$

q^2 (GeV²/c⁴)

CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.010 \pm 0.010) \% \quad \text{Most Precise!}$$

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q^2 (GeV²/c⁴)

$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.005 \pm 0.005) \% \quad \text{Most Precise!}$$

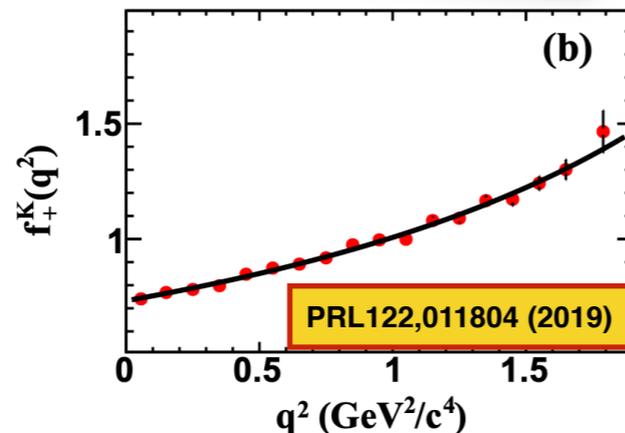
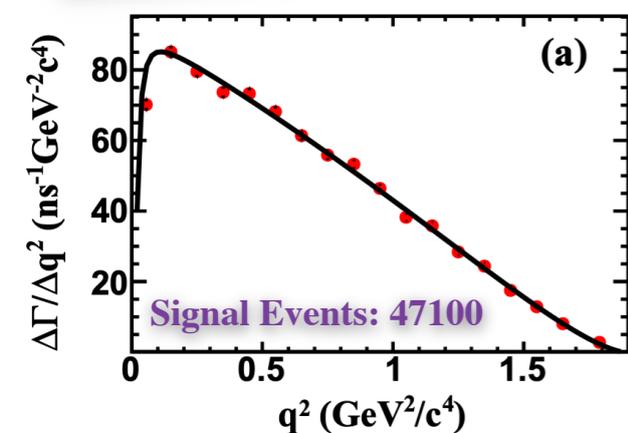
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$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$

$$|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_e) = (3.413 \pm 0.019 \pm 0.035) \%$$



CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.0025 \pm 0.0035) \% \quad \text{Most Precise!}$$

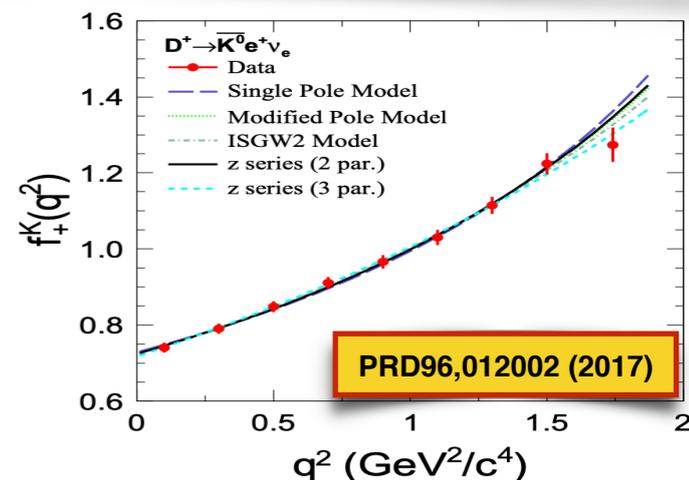
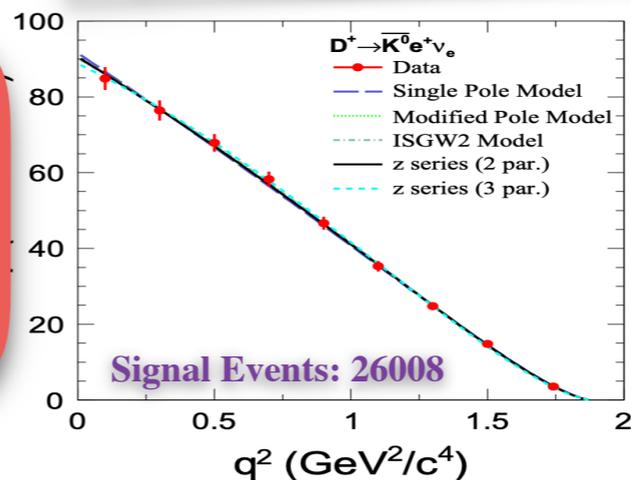
$$f_+^K(0) |V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow K^0 e^+ \nu_e) = (8.60 \pm 0.06 \pm 0.15) \% \quad (\text{via } K_S^0)$$



$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.0018 \pm 0.0009) \% \quad \text{Most Precise!}$$

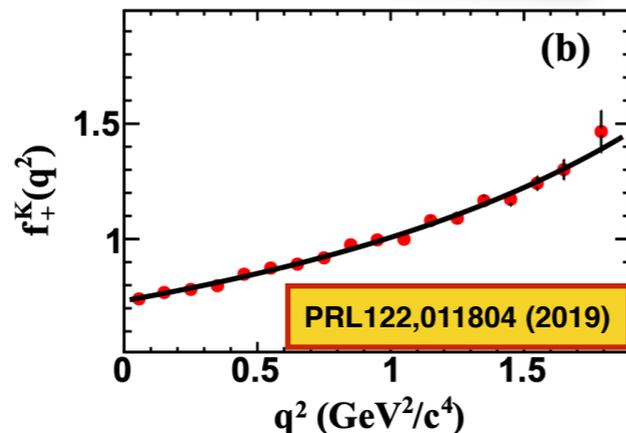
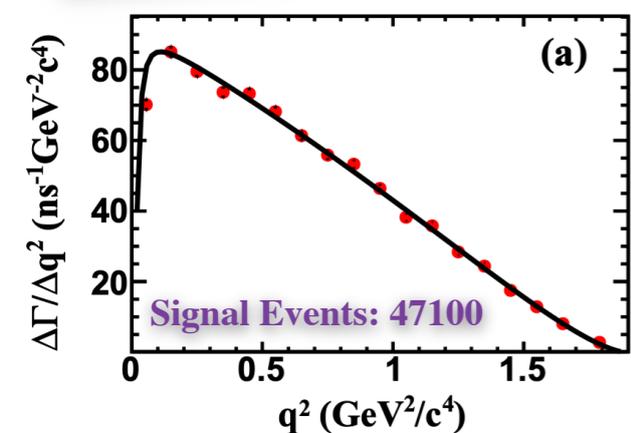
$$f_+^\pi(0) |V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$

$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$

$$|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_e) = (3.413 \pm 0.019 \pm 0.035) \%$$



CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.002 \pm 0.003) \% \quad \text{Most Precise!}$$

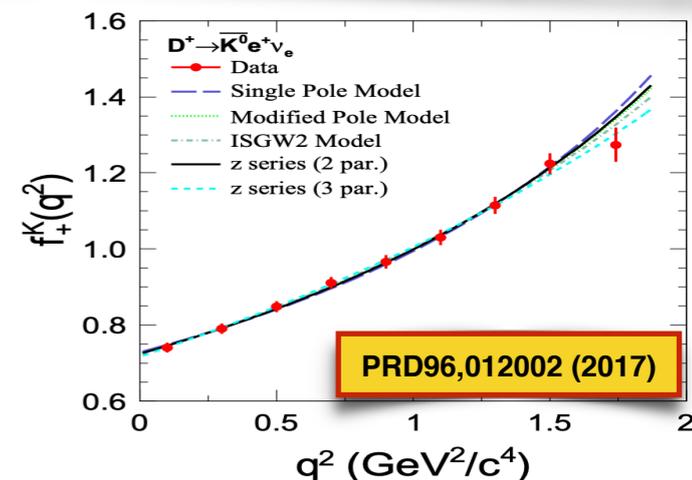
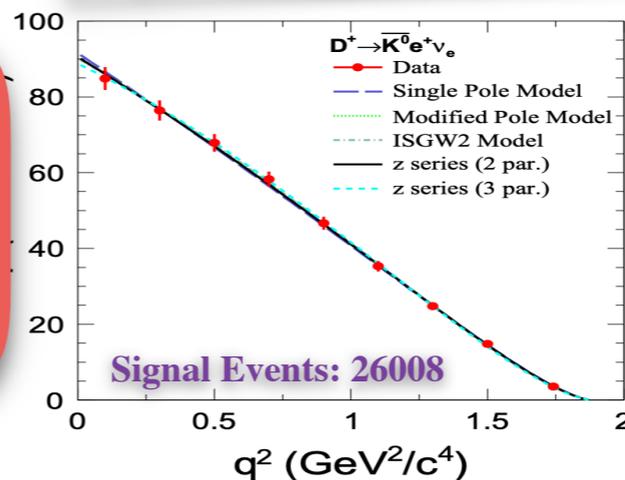
$$f_+^K(0) |V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow K^0 e^+ \nu_e) = (8.60 \pm 0.06 \pm 0.15) \% \quad (\text{via } K_S^0)$$



$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.002 \pm 0.003) \% \quad \text{Most Precise!}$$

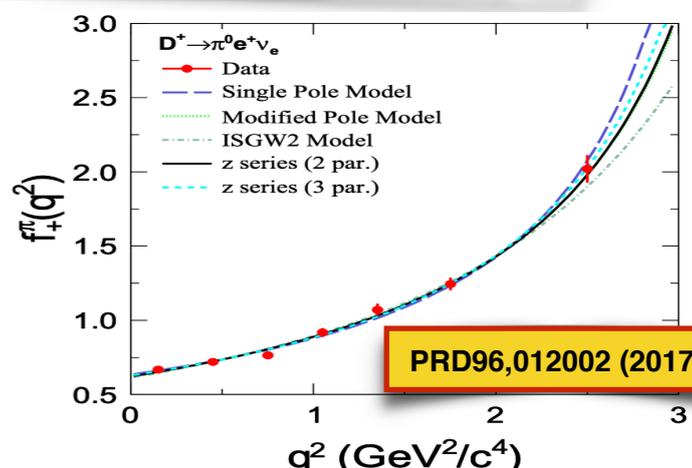
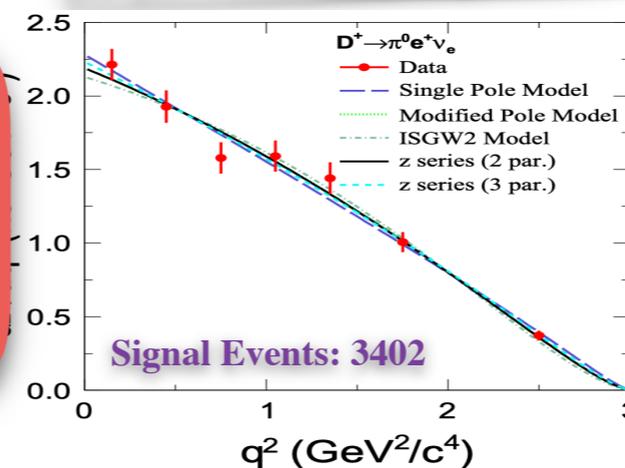
$$f_+^\pi(0) |V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$

$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$

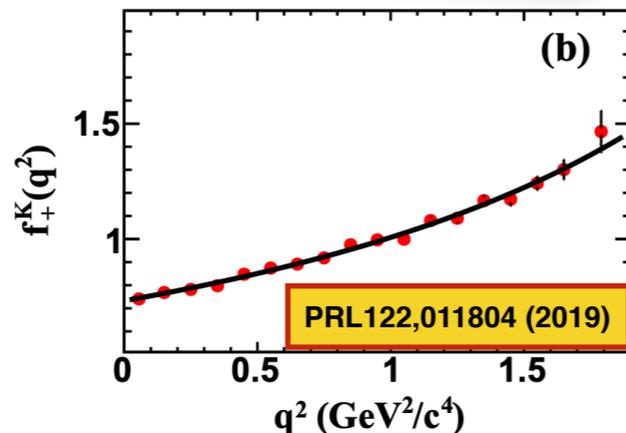
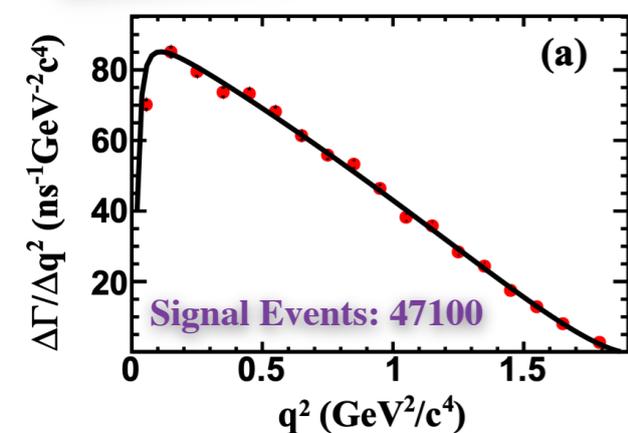
$$|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow \pi^0 e^+ \nu_e) = (0.363 \pm 0.008 \pm 0.005) \%$$



$$\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_e) = (3.413 \pm 0.019 \pm 0.035) \%$$



CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.005 \pm 0.005) \% \quad \text{Most Precise!}$$

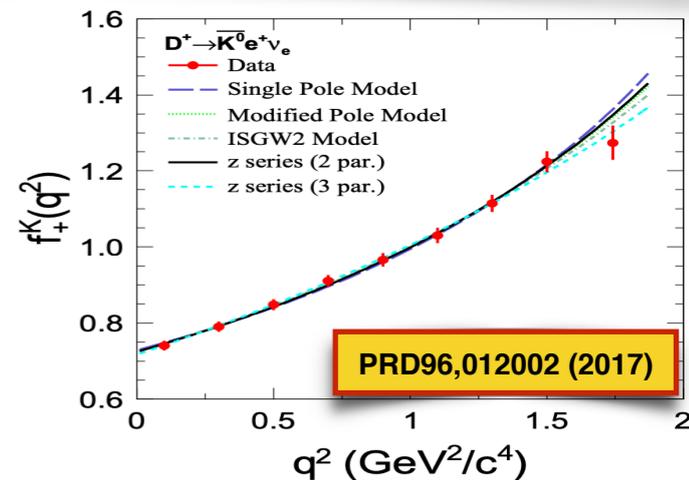
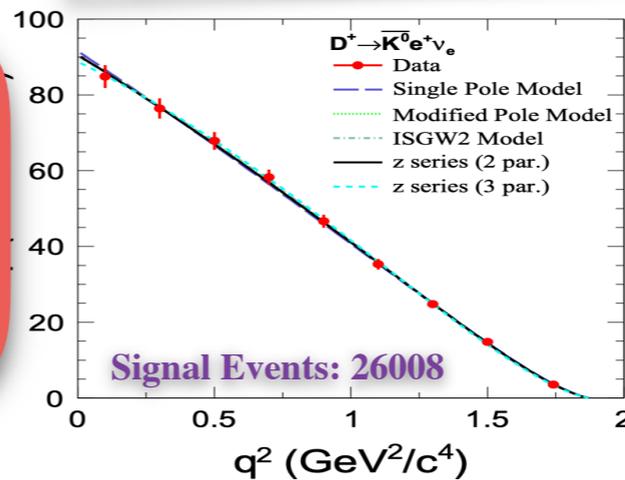
$$f_+^K(0) |V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239_{LQCD}$$

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow K^0 e^+ \nu_e) = (8.60 \pm 0.06 \pm 0.15) \% \quad (\text{via } K_S^0)$$



$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.003 \pm 0.003) \% \quad \text{Most Precise!}$$

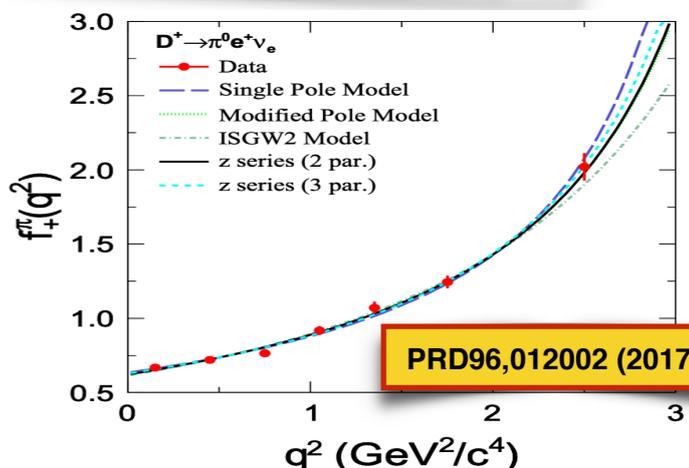
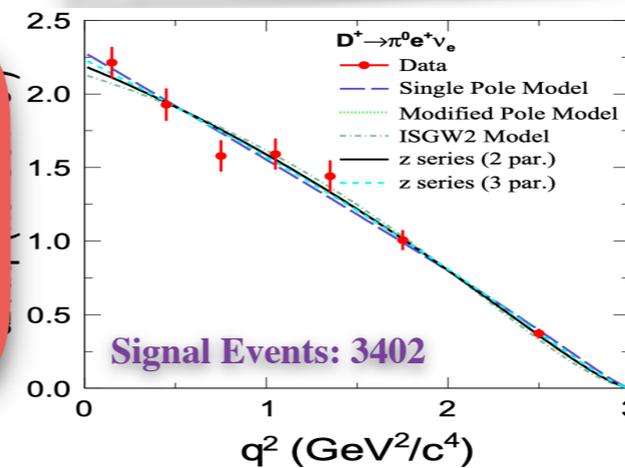
$$f_+^\pi(0) |V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$

$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$

$$|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094_{LQCD}$$

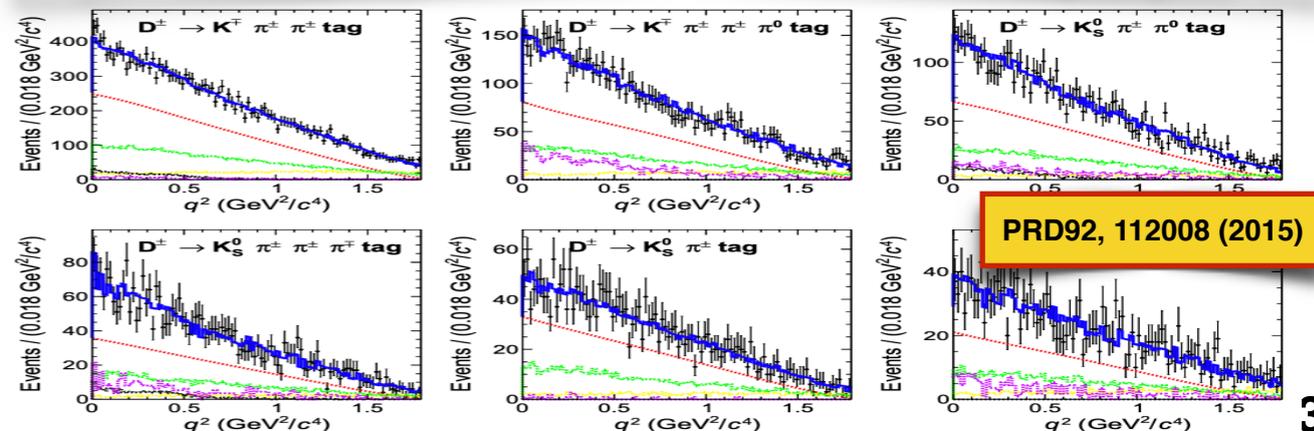
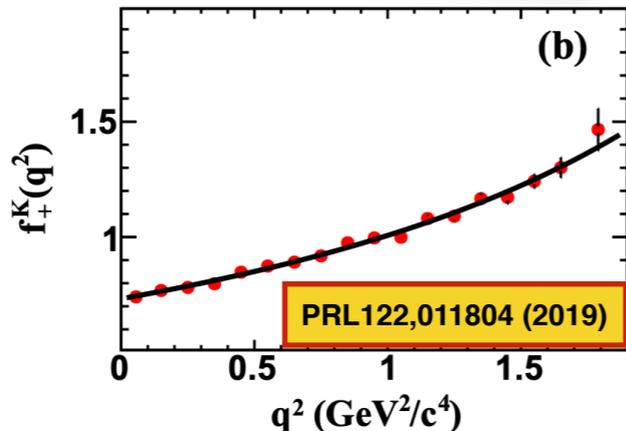
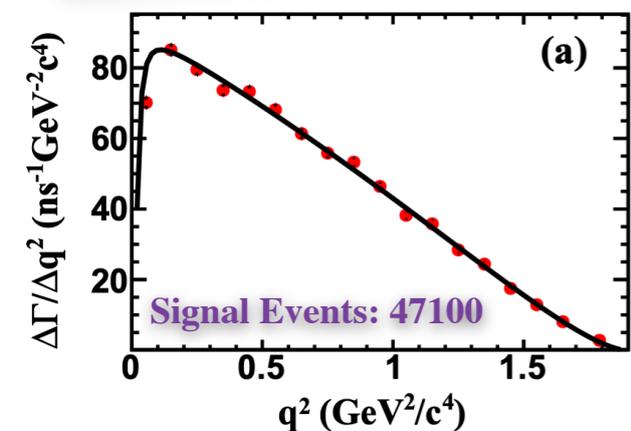
q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow \pi^0 e^+ \nu_e) = (0.363 \pm 0.008 \pm 0.005) \%$$



$$\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_e) = (3.413 \pm 0.019 \pm 0.035) \%$$

$$\mathcal{B}(D^+ \rightarrow K^0 e^+ \nu_e) = (8.962 \pm 0.054 \pm 0.206) \% \quad (\text{via } K_L^0)$$



CKM Matrix Element & Form Factor

$$\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.015 \pm 0.025) \% \quad \text{Most Precise!}$$

$$f_+^K(0) |V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cs}| = 0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239_{LQCD}$$

q^2 (GeV²/c⁴)

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.295 \pm 0.005 \pm 0.005) \% \quad \text{Most Precise!}$$

$$f_+^\pi(0) |V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$

$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$

$$|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094_{LQCD}$$

q^2 (GeV²/c⁴)

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^0 \rightarrow K^- \mu^+ \nu_e) = (3.413 \pm 0.019 \pm 0.035) \%$$

$$f_+^K(0) |V_{cs}| = 0.7133 \pm 0.0038 \pm 0.0029$$

$$f_+^K(0) = 0.7327 \pm 0.0039 \pm 0.0030$$

$$|V_{cs}| = 0.955 \pm 0.005 \pm 0.004 \pm 0.0024_{LQCD}$$

q^2 (GeV²/c⁴)

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow K^0 e^+ \nu_e) = (8.60 \pm 0.06 \pm 0.15) \% \quad (\text{via } K_S^0)$$

$$f_+^K(0) |V_{cs}| = 0.7053 \pm 0.0040 \pm 0.0112$$

$$f_+^K(0) = 0.725 \pm 0.004 \pm 0.012$$

$$|V_{cs}| = 0.944 \pm 0.005 \pm 0.015 \pm 0.024_{LQCD}$$

q^2 (GeV²/c⁴)

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow \pi^0 e^+ \nu_e) = (0.363 \pm 0.008 \pm 0.005) \%$$

$$f_+^\pi(0) |V_{cd}| = 0.1400 \pm 0.0026 \pm 0.0007$$

$$f_+^\pi(0) = 0.622 \pm 0.012 \pm 0.003$$

$$|V_{cd}| = 0.210 \pm 0.004 \pm 0.001 \pm 0.009_{LQCD}$$

q^2 (GeV²/c⁴)

q^2 (GeV²/c⁴)

$$\mathcal{B}(D^+ \rightarrow K^0 e^+ \nu_e) = (8.962 \pm 0.054 \pm 0.206) \% \quad (\text{via } K_L^0)$$

$$f_+^K(0) |V_{cs}| = 0.728 \pm 0.006 \pm 0.011$$

$$f_+^K(0) = 0.748 \pm 0.007 \pm 0.012$$

$$|V_{cs}| = 0.975 \pm 0.008 \pm 0.015 \pm 0.025_{LQCD}$$

q^2 (GeV²/c⁴)

q^2 (GeV²/c⁴)

q^2 (GeV²/c⁴)



CKM Matrix Element & Form Factor

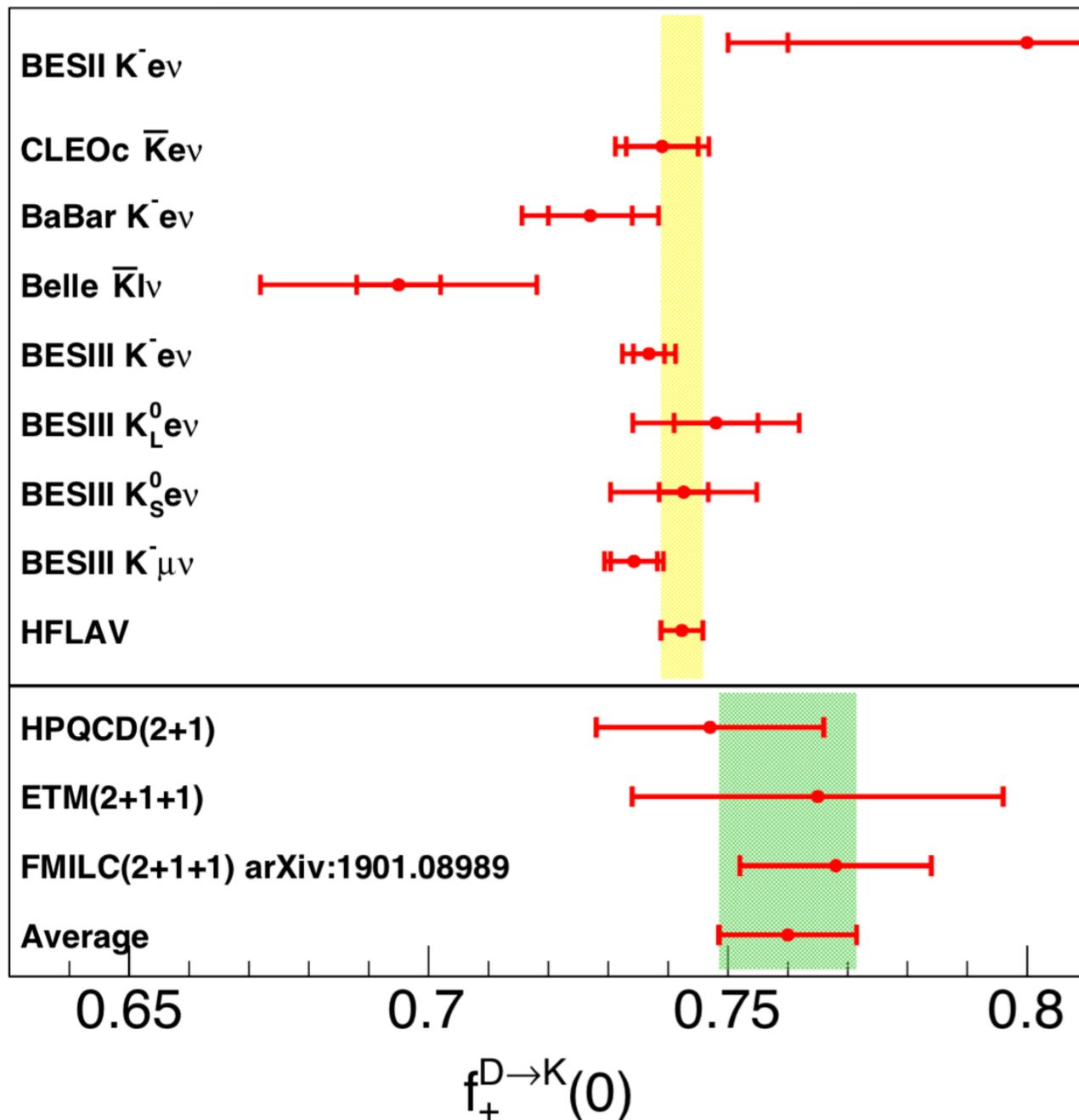
Input $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$

(PDG2018 from CKM unitarity)

CKM Matrix Element & Form Factor

Input $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$

(PDG2018 from CKM unitarity)



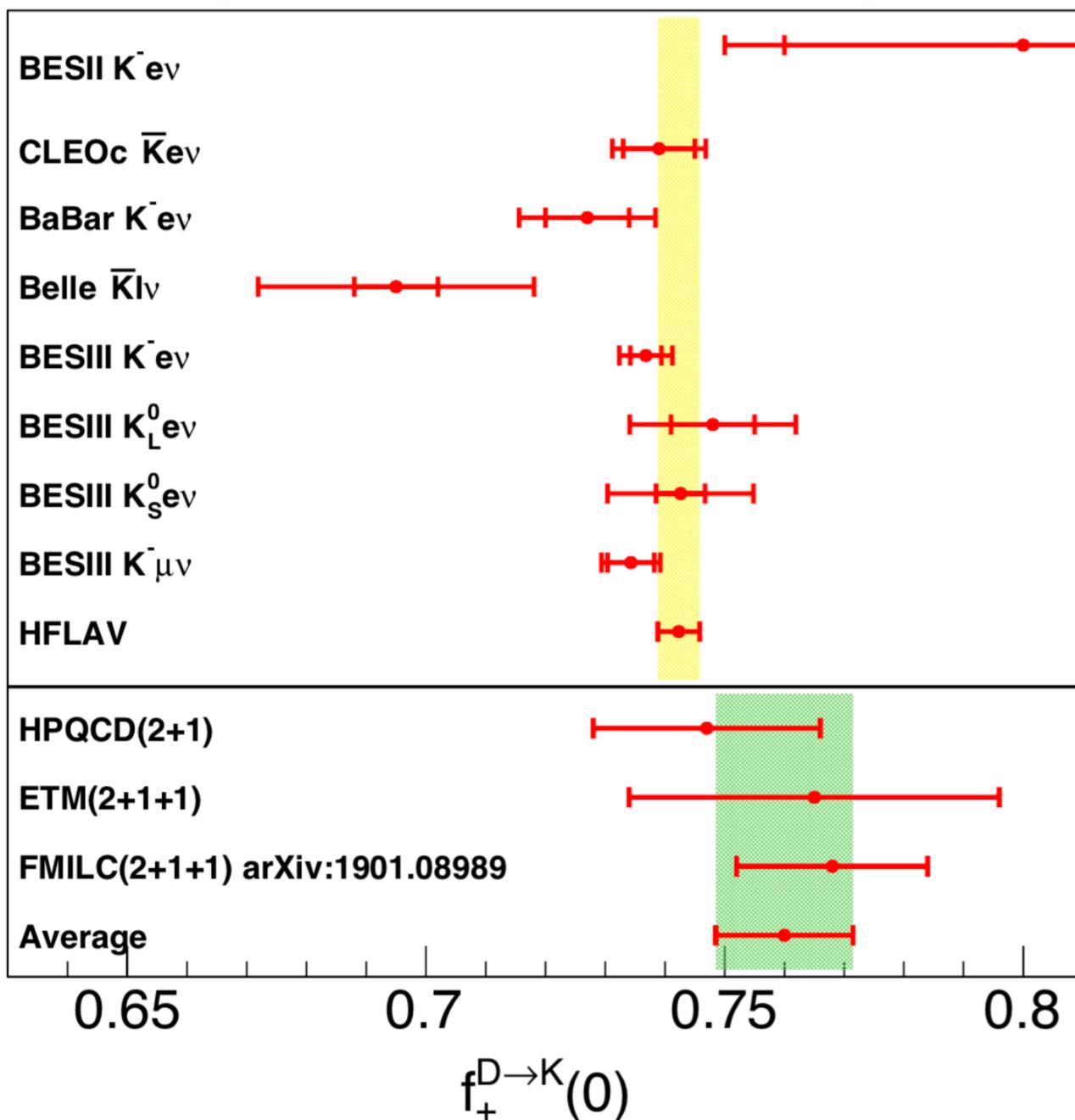
CKM Matrix Element & Form Factor

Input $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$

(PDG2018 from CKM unitarity)

Input $|V_{cd}| = 0.22438 \pm 0.00044$

(PDG2018 from CKM unitarity)



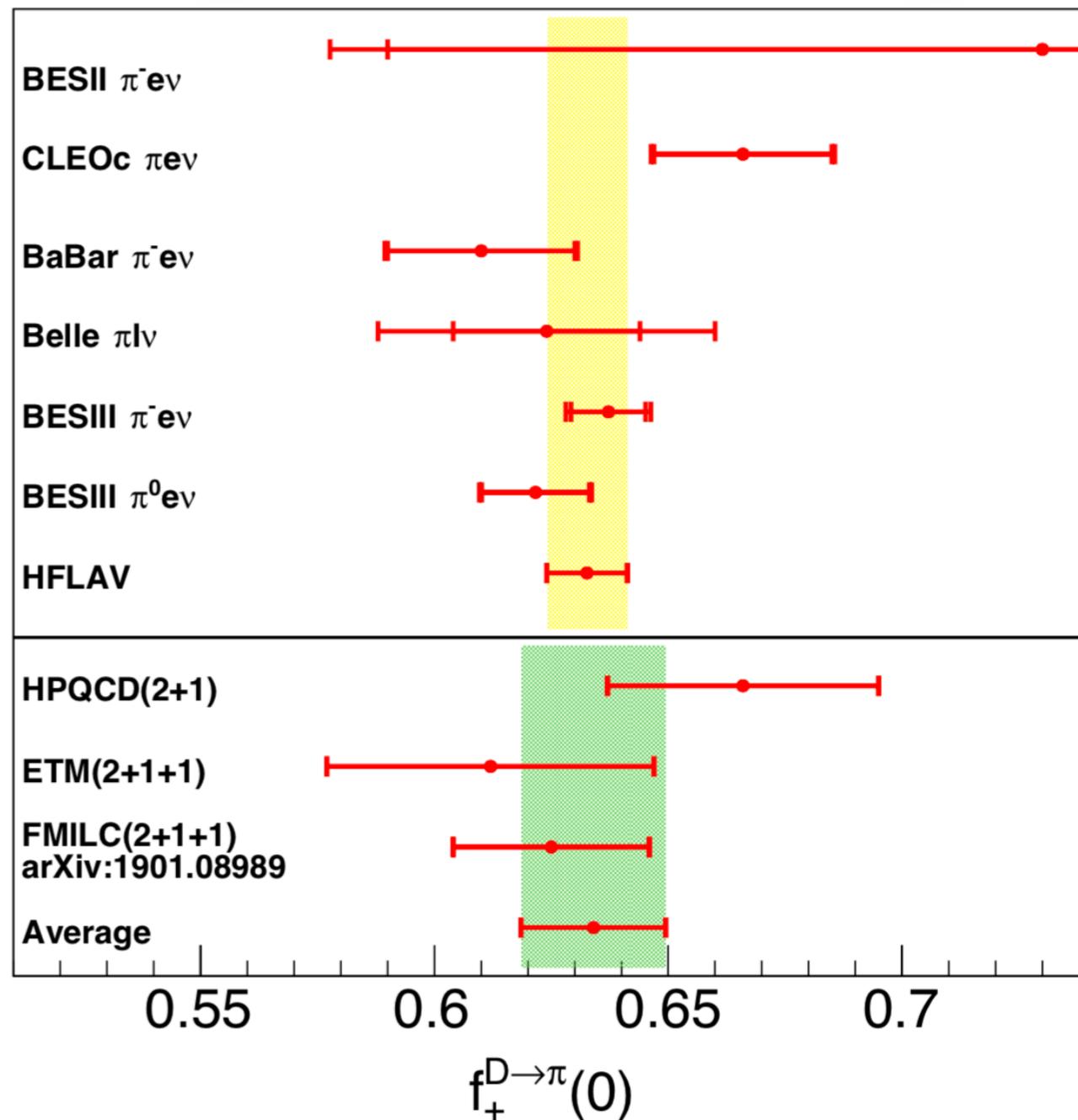
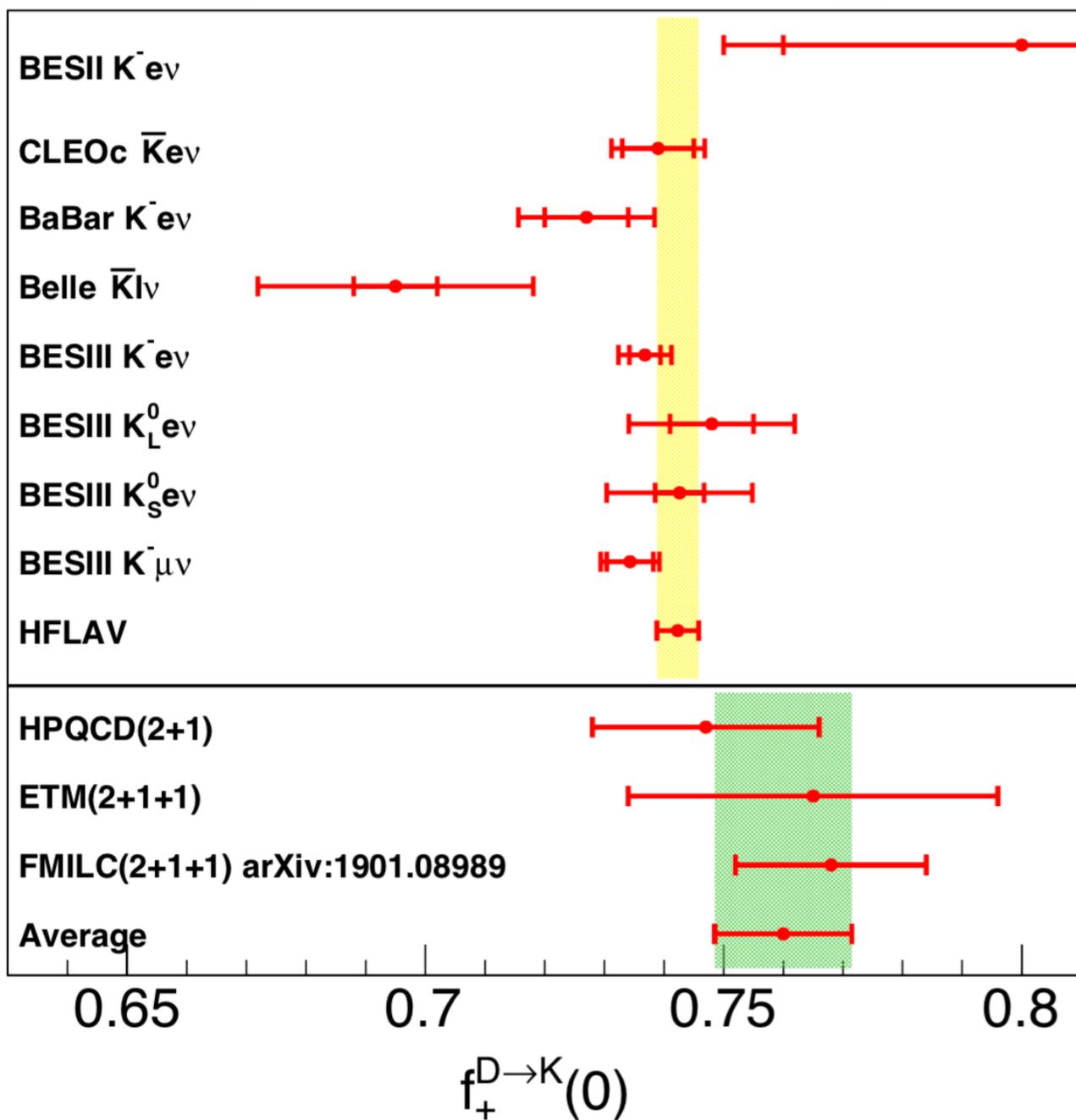
CKM Matrix Element & Form Factor

Input $|V_{cs}| = 0.97359^{+0.00010}_{-0.00011}$

(PDG2018 from CKM unitarity)

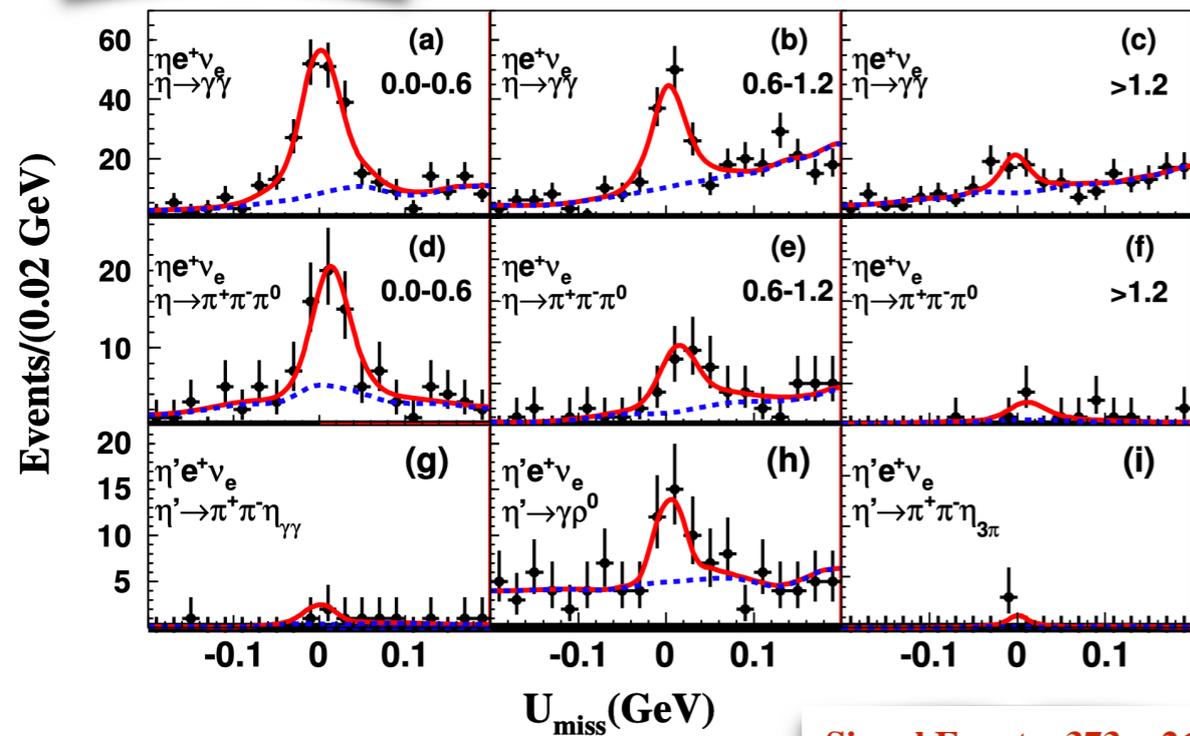
Input $|V_{cd}| = 0.22438 \pm 0.00044$

(PDG2018 from CKM unitarity)

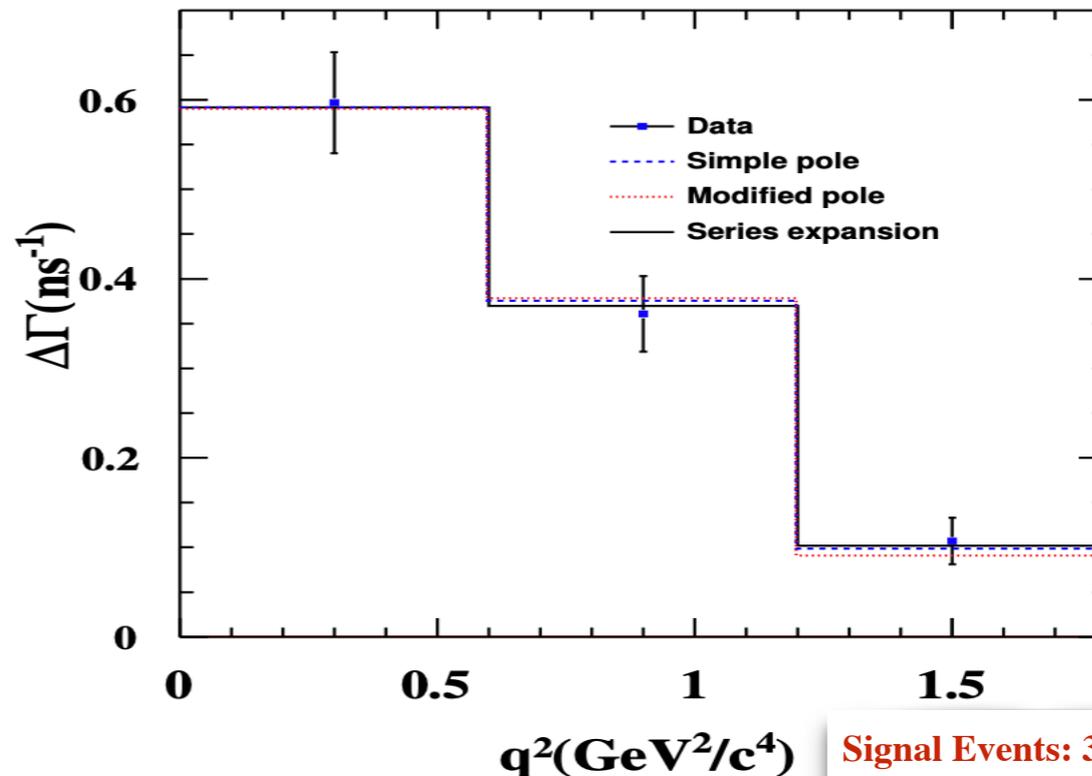


CKM Matrix Element & Form Factor

PRD97, 092009 (2018)



Signal Events: 373 ± 26



Signal Events: 31.6 ± 8.4

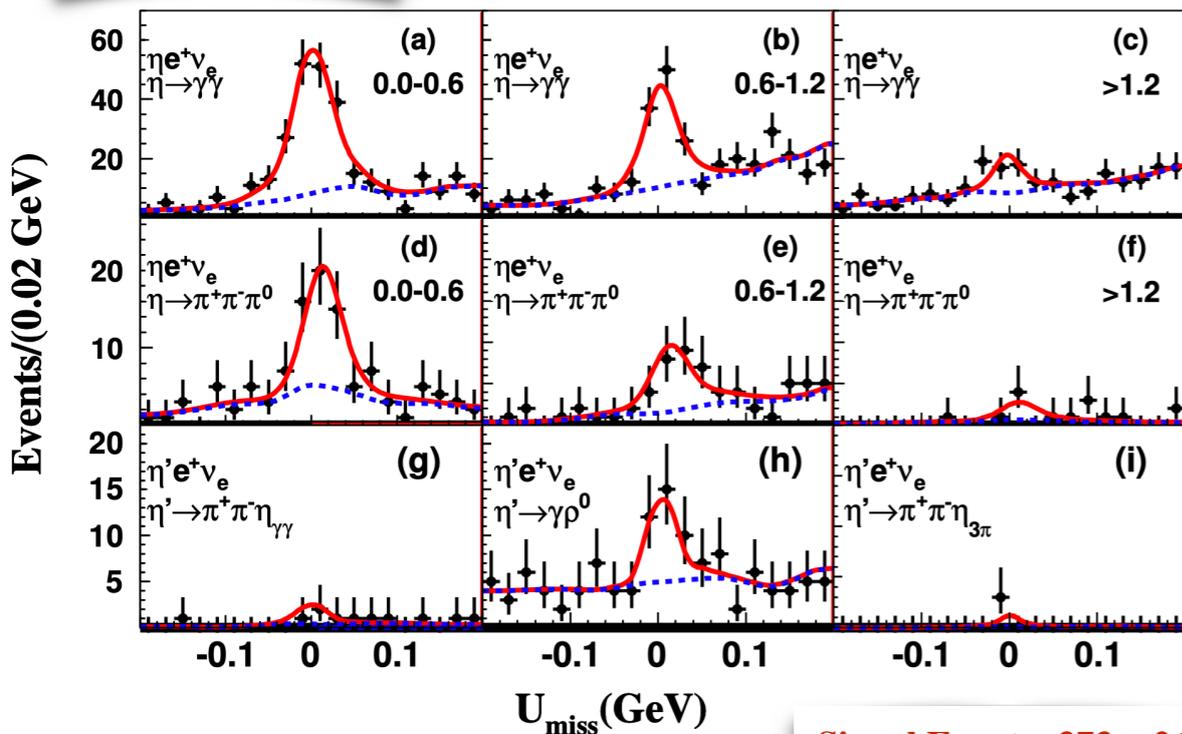
$$\mathcal{B}(D^+ \rightarrow \eta e^+ \nu_e) = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$$

$$\mathcal{B}(D^+ \rightarrow \eta' e^+ \nu_e) = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$$

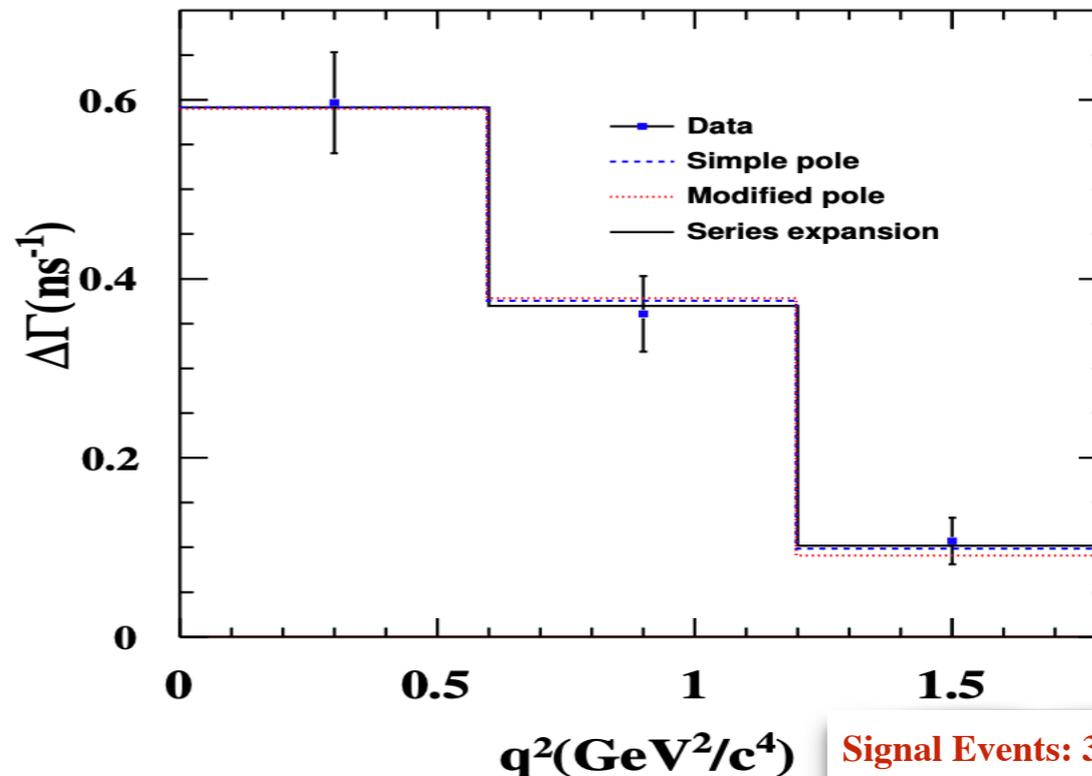
$$f_+^\eta(0) |V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$$

CKM Matrix Element & Form Factor

PRD97, 092009 (2018)



Signal Events: 373 ± 26

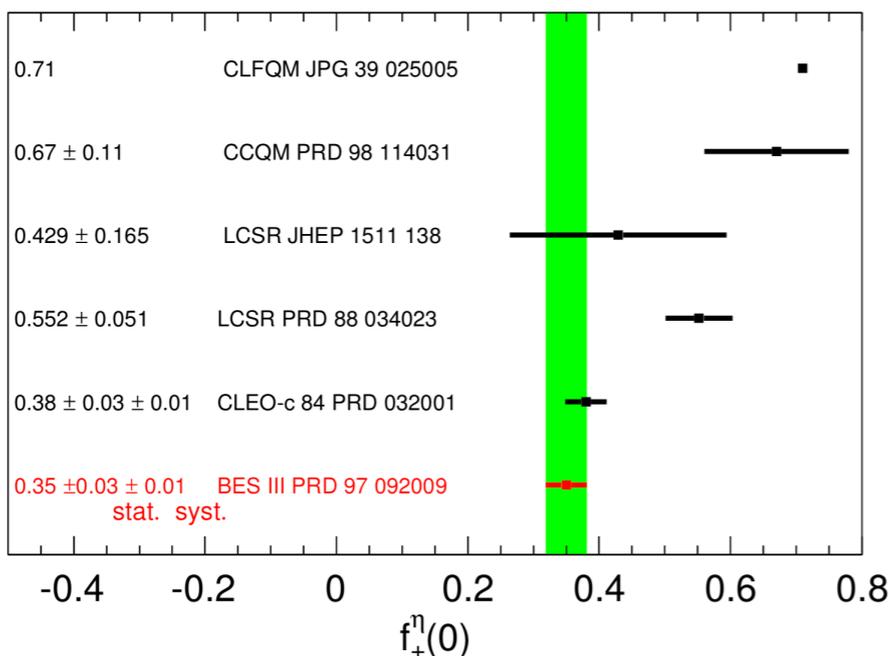


Signal Events: 31.6 ± 8.4

$$\mathcal{B}(D^+ \rightarrow \eta e^+ \nu_e) = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$$

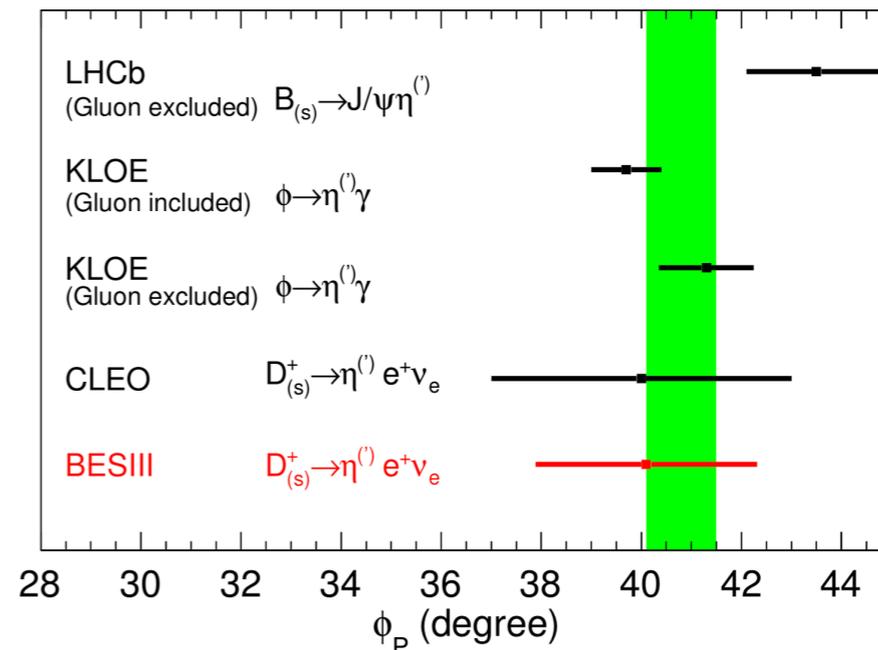
$$\mathcal{B}(D^+ \rightarrow \eta' e^+ \nu_e) = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$$

$$f_+^\eta(0) |V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$$



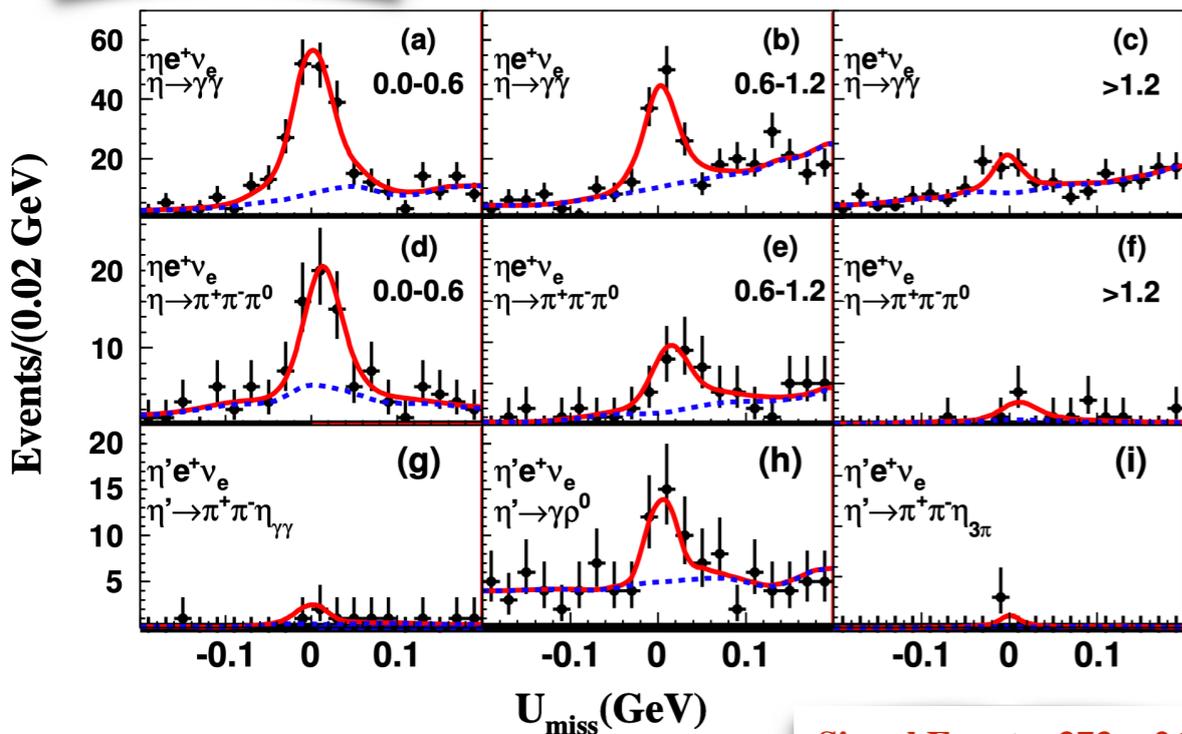
Model independent determination of $\eta - \eta'$ mixing angle.

$$\frac{\Gamma(D_s^+ \rightarrow \eta' e^+ \nu_e) / \Gamma(D_s^+ \rightarrow \eta e^+ \nu_e)}{\Gamma(D^+ \rightarrow \eta' e^+ \nu_e) / \Gamma(D^+ \rightarrow \eta e^+ \nu_e)} \simeq \cot^4 \Phi_P$$

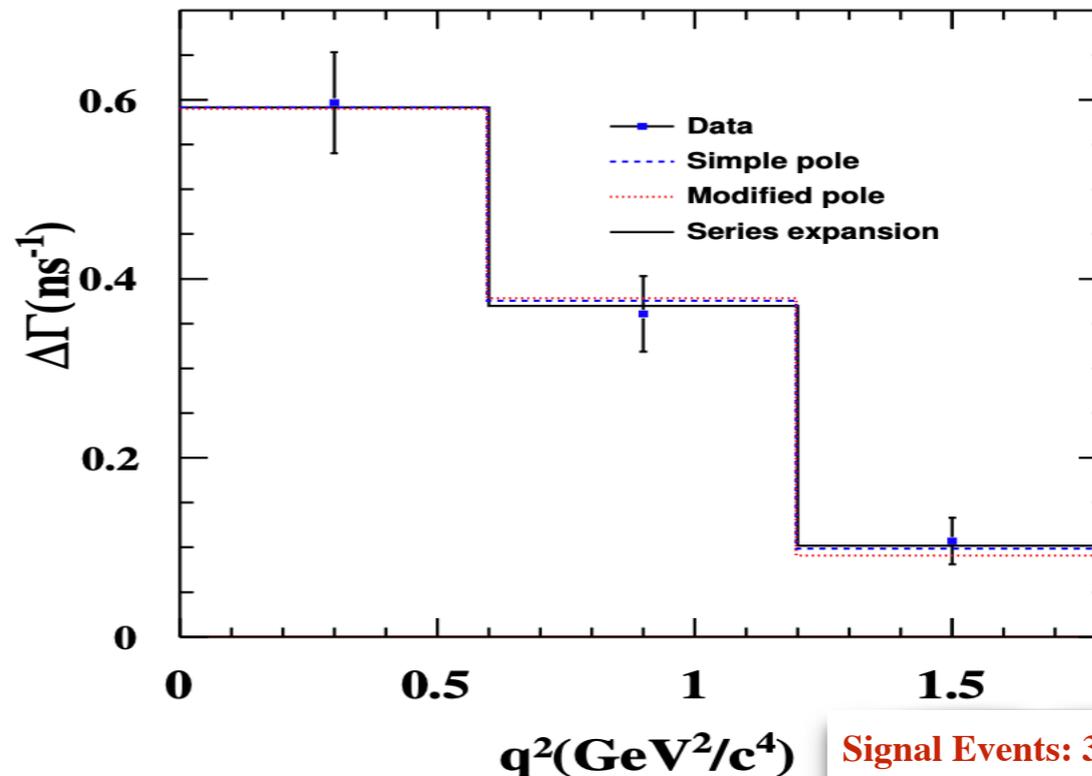


CKM Matrix Element & Form Factor

PRD97, 092009 (2018)



Signal Events: 373 ± 26

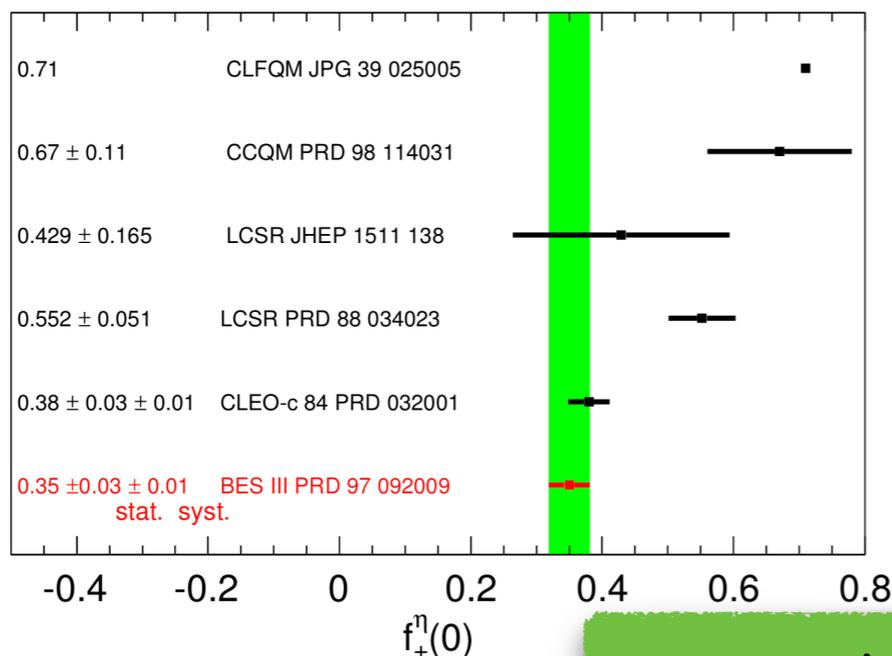


Signal Events: 31.6 ± 8.4

$$\mathcal{B}(D^+ \rightarrow \eta e^+ \nu_e) = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$$

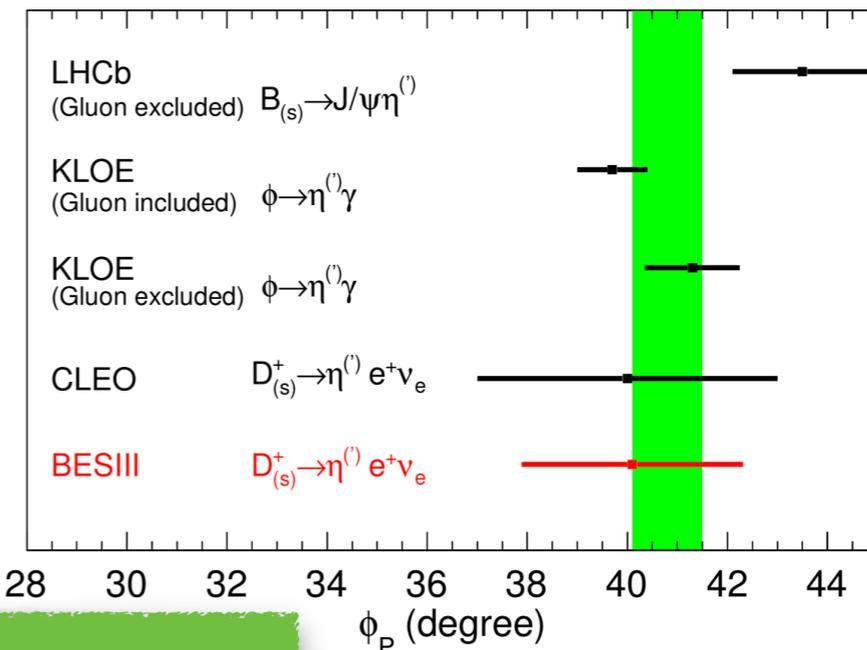
$$\mathcal{B}(D^+ \rightarrow \eta' e^+ \nu_e) = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$$

$$f_+^\eta(0) |V_{cd}| = (7.86 \pm 0.64 \pm 0.21) \times 10^{-2}$$



Model independent determination of $\eta - \eta'$ mixing angle.

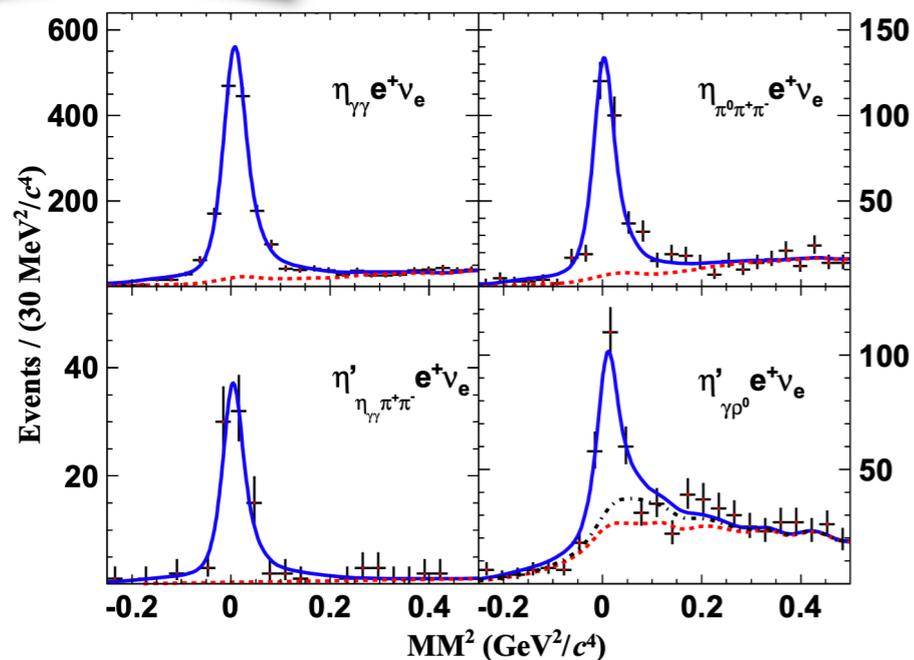
$$\frac{\Gamma(D_s^+ \rightarrow \eta' e^+ \nu_e) / \Gamma(D_s^+ \rightarrow \eta e^+ \nu_e)}{\Gamma(D^+ \rightarrow \eta' e^+ \nu_e) / \Gamma(D^+ \rightarrow \eta e^+ \nu_e)} \simeq \cot^4 \Phi_P$$



$\eta - \eta'$ mixing angle to be $\phi_P = (40 \pm 3 \pm 3)^\circ$

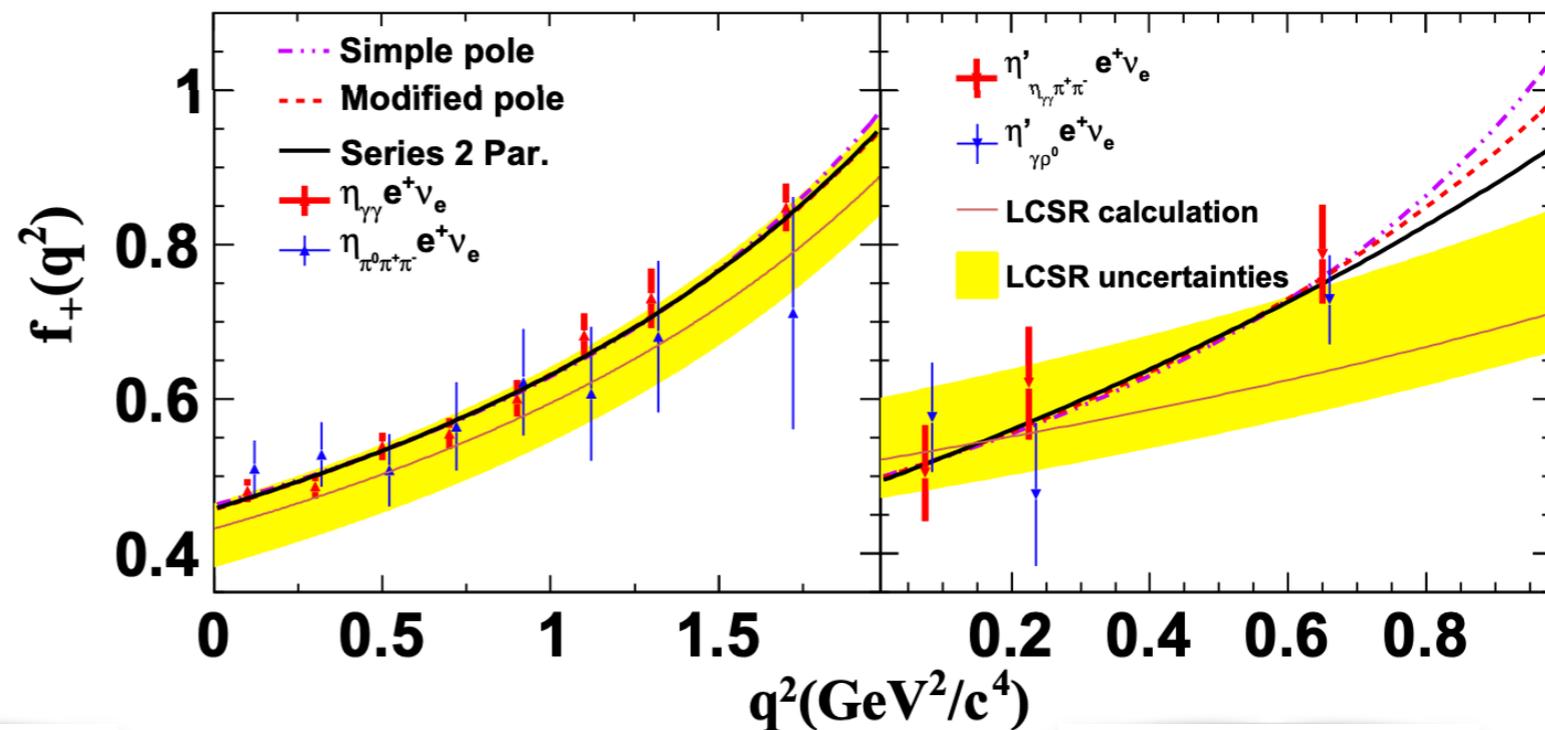
CKM Matrix Element & Form Factor

PRL122, 121801(2019)



Signal Events: 373 ± 26

$$\mathcal{B}(D_S^+ \rightarrow \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063) \%$$

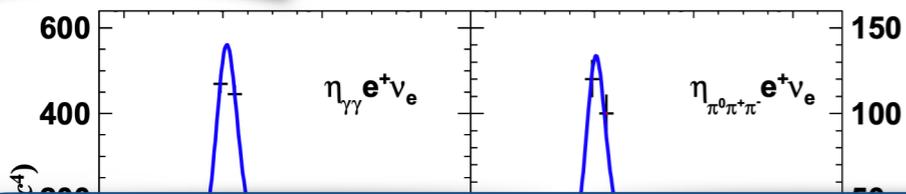


Signal Events: 31.6 ± 8.4

$$\mathcal{B}(D_S^+ \rightarrow \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027) \%$$

CKM Matrix Element & Form Factor

PRL122, 121801(2019)



$$f_+^\eta(0) |V_{cs}| = 0.4455 \pm 0.0053 \pm 0.0044$$

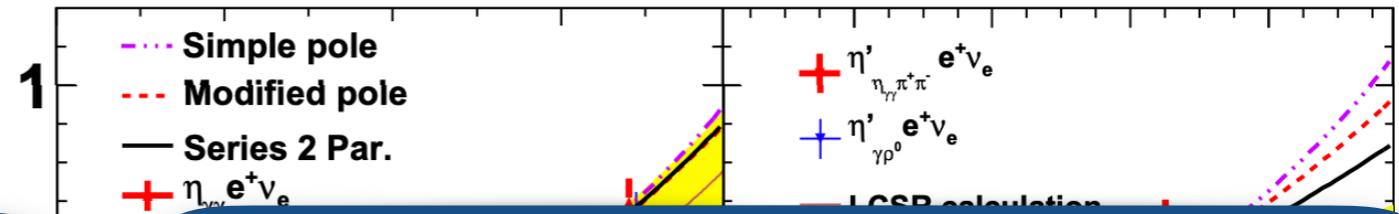
$$f_+^\eta(0) = 0.4576 \pm 0.0054 \pm 0.0045$$

$$|V_{cs}| = 1.031 \pm 0.012 \pm 0.009 \pm 0.079_{theory}$$

-0.2 0 0.2 0.4 -0.2 0 0.2 0.4
MM² (GeV²/c⁴)

Signal Events: 373 ± 26

$$\mathcal{B}(D_S^+ \rightarrow \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063) \%$$



$$f_+^{\eta'}(0) |V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

$$f_+^{\eta'}(0) = 0.490 \pm 0.050 \pm 0.011$$

$$|V_{cs}| = 0.917 \pm 0.094 \pm 0.021 \pm 0.155_{theory}$$

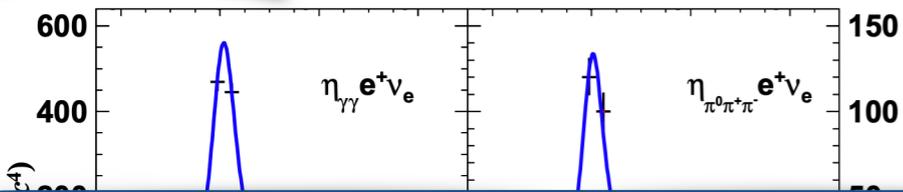
0 0.5 1 1.5 0.2 0.4 0.6 0.8
q² (GeV²/c⁴)

Signal Events: 31.6 ± 8.4

$$\mathcal{B}(D_S^+ \rightarrow \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027) \%$$

CKM Matrix Element & Form Factor

PRL122, 121801(2019)

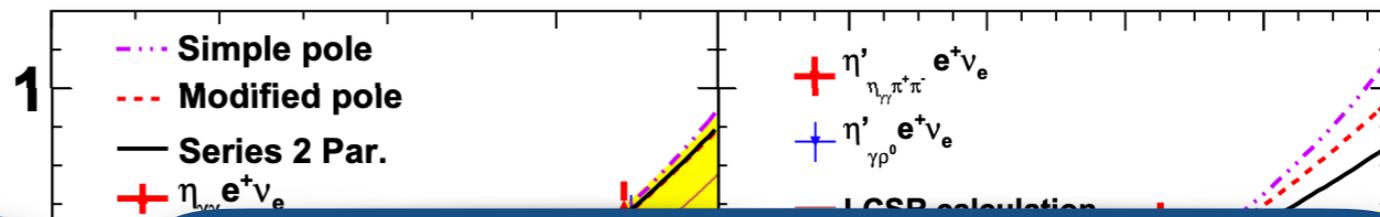


$$f_+^\eta(0) |V_{cs}| = 0.4455 \pm 0.0053 \pm 0.0044$$

$$f_+^\eta(0) = 0.4576 \pm 0.0054 \pm 0.0045$$

$$|V_{cs}| = 1.031 \pm 0.012 \pm 0.009 \pm 0.079_{theory}$$

-0.2 0 0.2 0.4 -0.2 0 0.2 0.4
MM² (GeV²/c⁴)



$$f_+^{\eta'}(0) |V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

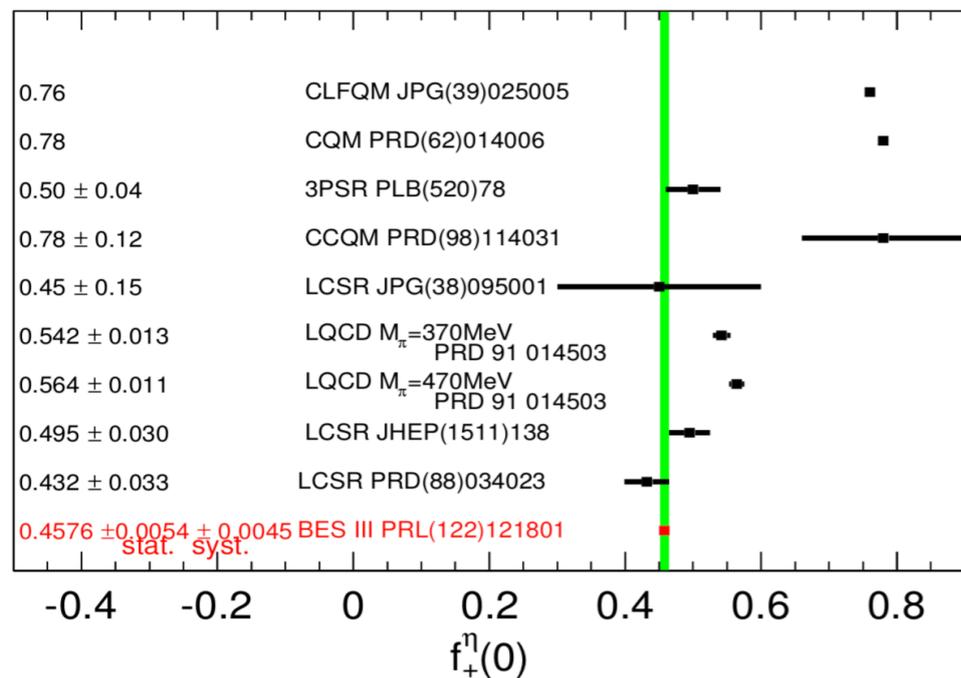
$$f_+^{\eta'}(0) = 0.490 \pm 0.050 \pm 0.011$$

$$|V_{cs}| = 0.917 \pm 0.094 \pm 0.021 \pm 0.155_{theory}$$

0 0.5 1 1.5 0.2 0.4 0.6 0.8
q² (GeV²/c⁴)

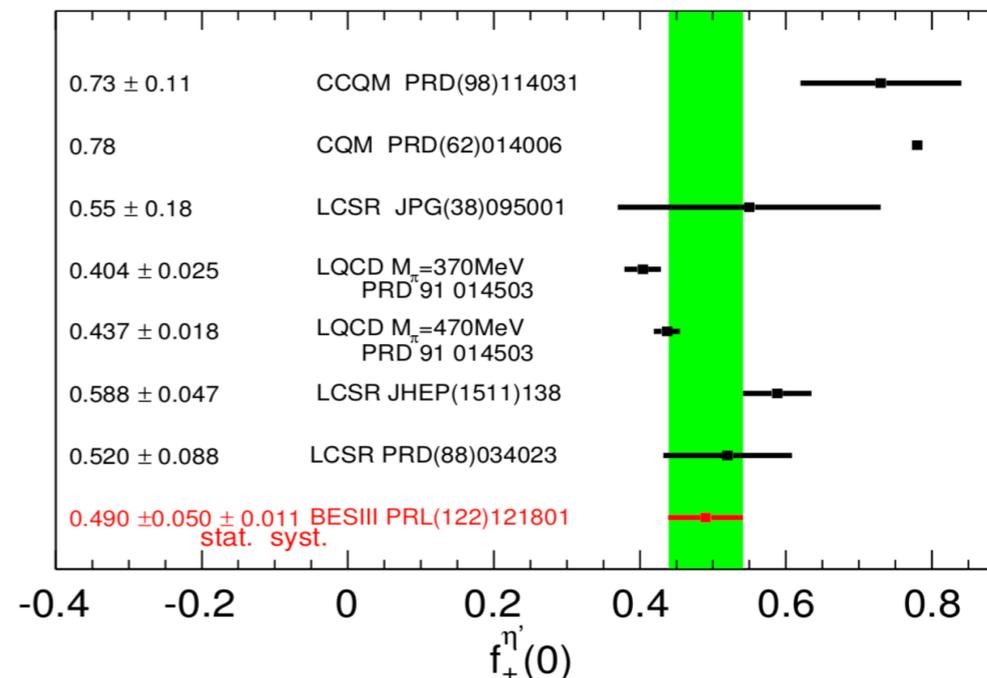
Signal Events: 373 ± 26

$$\mathcal{B}(D_S^+ \rightarrow \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063) \%$$



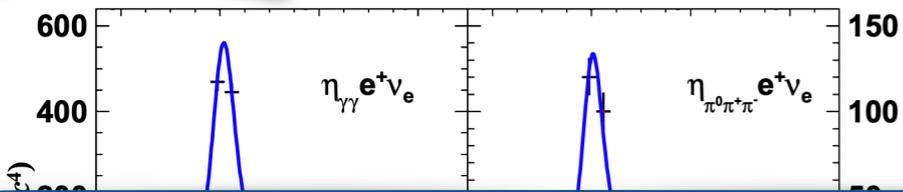
Signal Events: 31.6 ± 8.4

$$\mathcal{B}(D_S^+ \rightarrow \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027) \%$$



CKM Matrix Element & Form Factor

PRL122, 121801(2019)

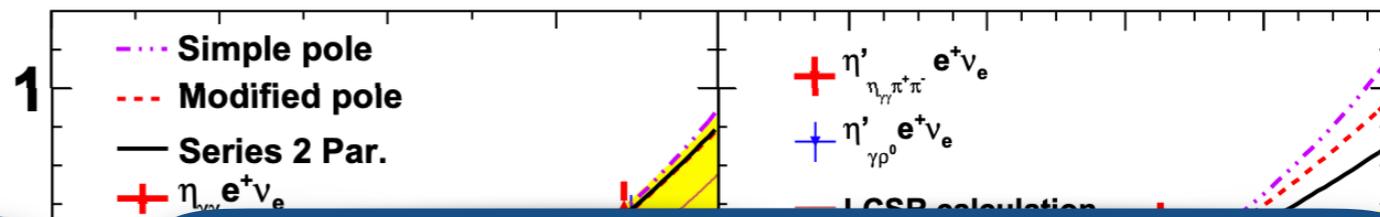


$$f_+^\eta(0) |V_{cs}| = 0.4455 \pm 0.0053 \pm 0.0044$$

$$f_+^\eta(0) = 0.4576 \pm 0.0054 \pm 0.0045$$

$$|V_{cs}| = 1.031 \pm 0.012 \pm 0.009 \pm 0.079_{theory}$$

-0.2 0 0.2 0.4 -0.2 0 0.2 0.4
MM² (GeV²/c⁴)



$$f_+^{\eta'}(0) |V_{cs}| = 0.477 \pm 0.049 \pm 0.011$$

$$f_+^{\eta'}(0) = 0.490 \pm 0.050 \pm 0.011$$

$$|V_{cs}| = 0.917 \pm 0.094 \pm 0.021 \pm 0.155_{theory}$$

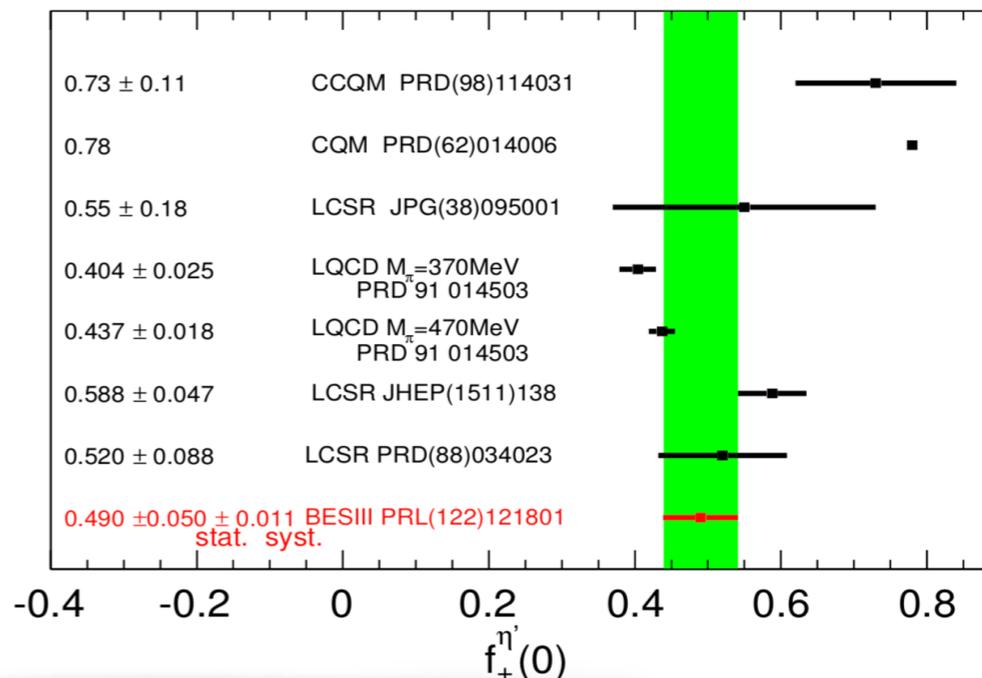
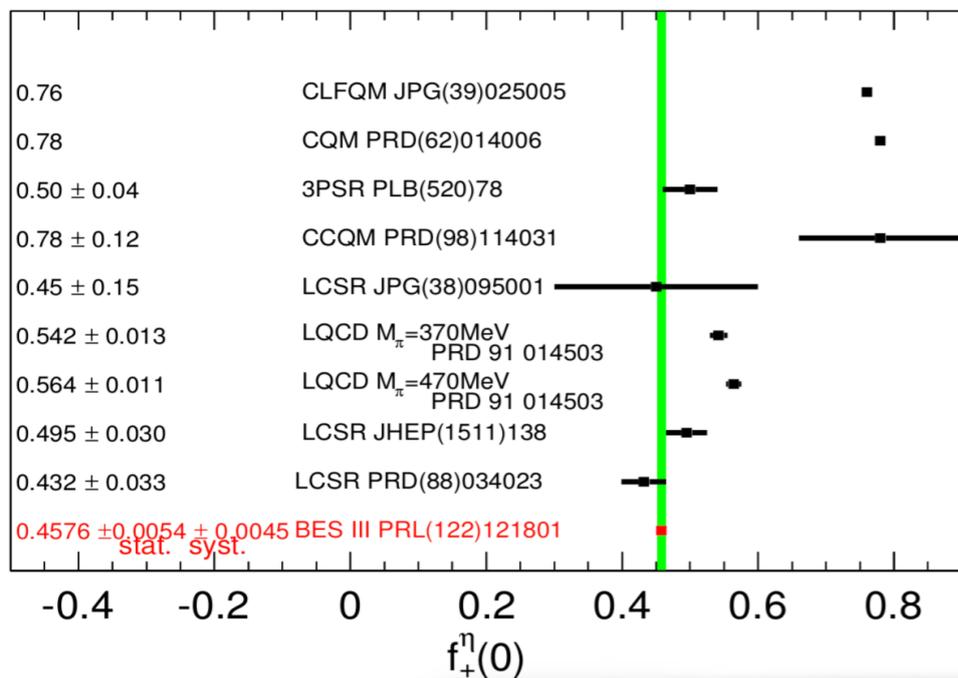
0 0.5 1 1.5 0.2 0.4 0.6 0.8
q² (GeV²/c⁴)

Signal Events: 373 ± 26

$$\mathcal{B}(D_S^+ \rightarrow \eta e^+ \nu_e) = (2.323 \pm 0.063 \pm 0.063) \%$$

Signal Events: 31.6 ± 8.4

$$\mathcal{B}(D_S^+ \rightarrow \eta' e^+ \nu_e) = (0.824 \pm 0.073 \pm 0.027) \%$$

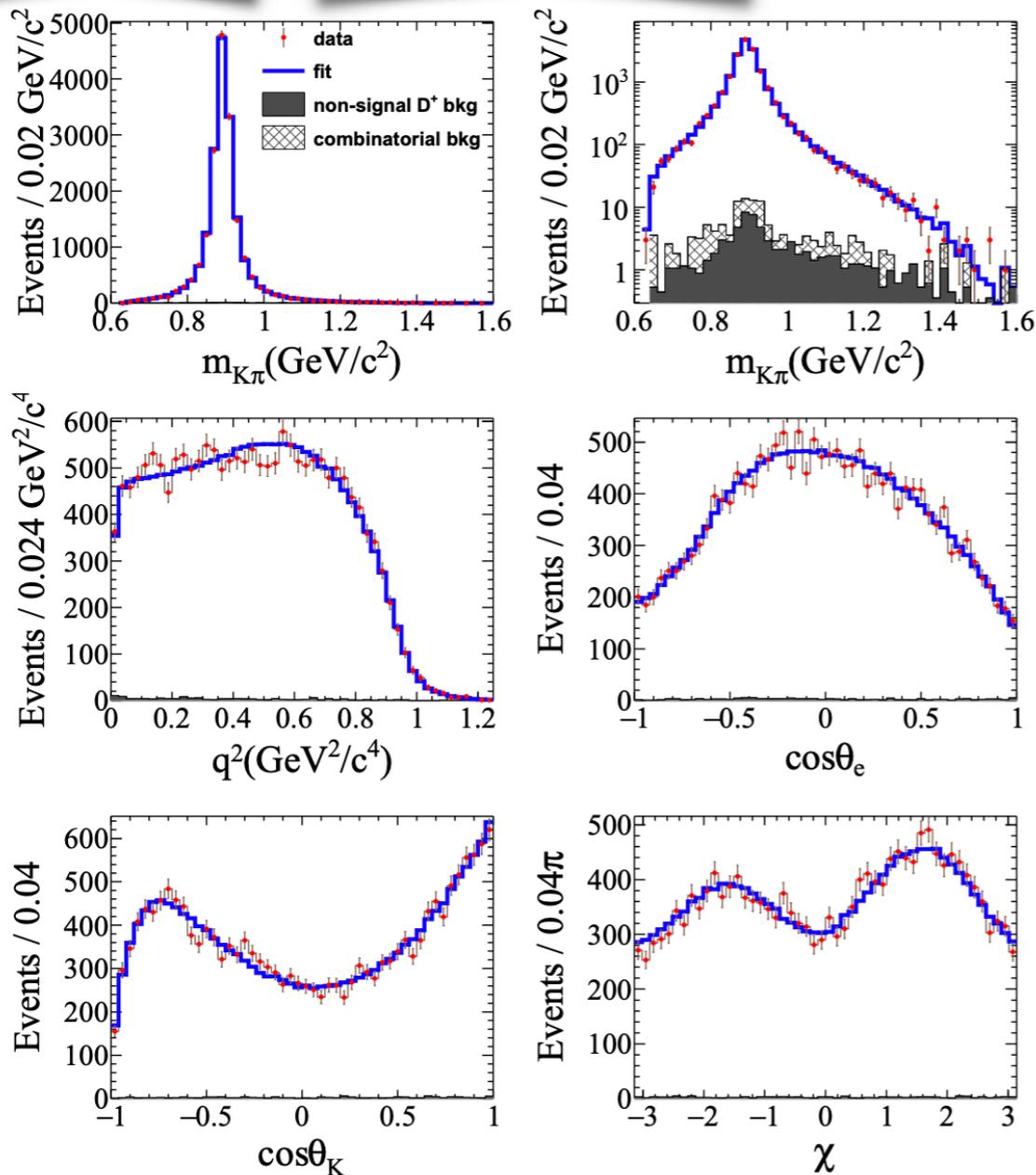


$$\eta - \eta' \text{ mixing angle to be } \phi_P = (40.1 \pm 2.1 \pm 0.7)^\circ$$

Form Factor of $D \rightarrow V e \nu_e$

PRD94, 032001(2016)

$D^+ \rightarrow K^- \pi^+ e^+ \nu_e$

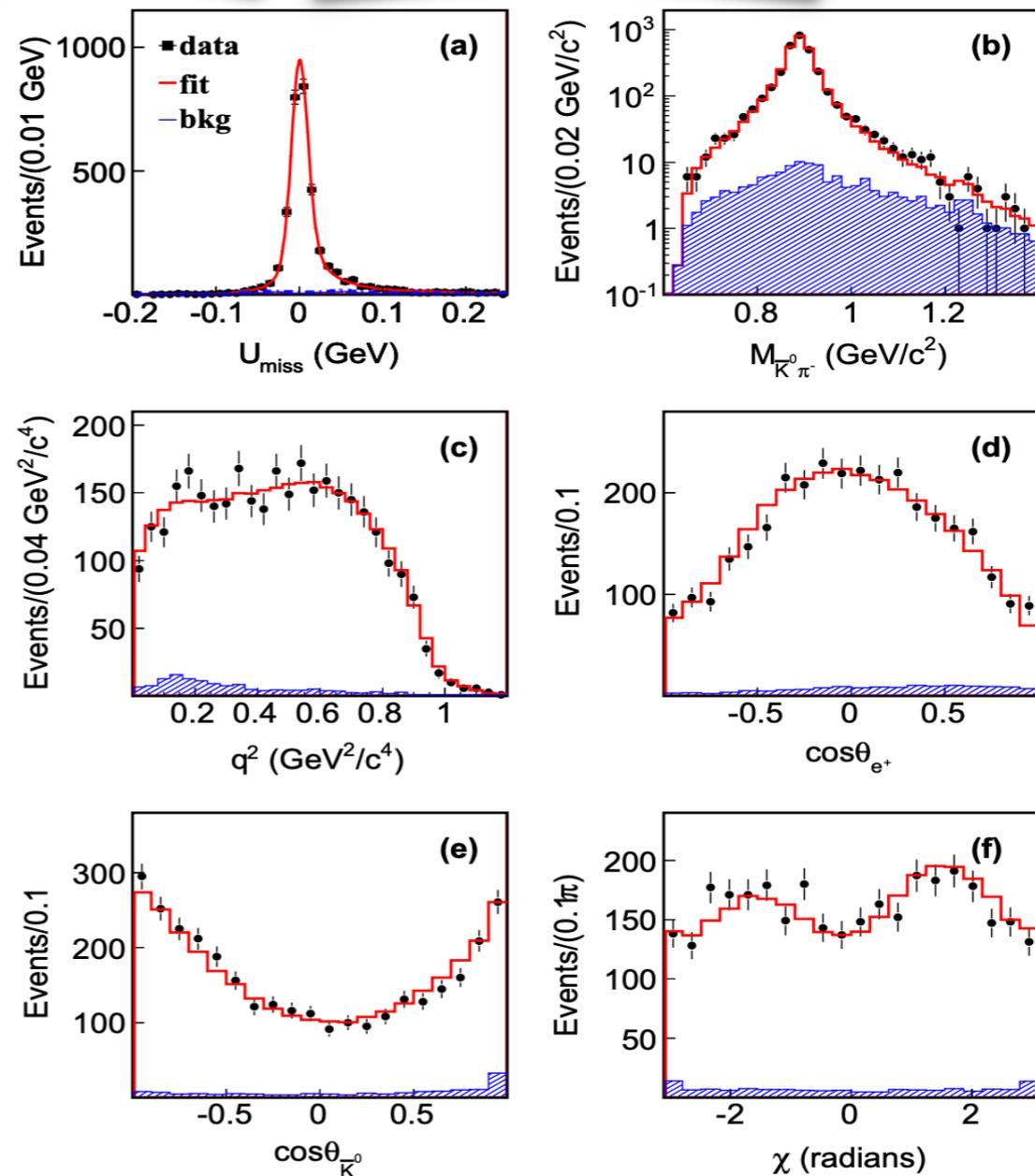


$$r_V = \frac{V(0)}{A_1(0)} = 1.411 \pm 0.058 \pm 0.007$$

$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.788 \pm 0.042 \pm 0.008$$

PRD99, 011103(2019)

$D^0 \rightarrow K^0 \bar{\pi}^- e^+ \nu_e$

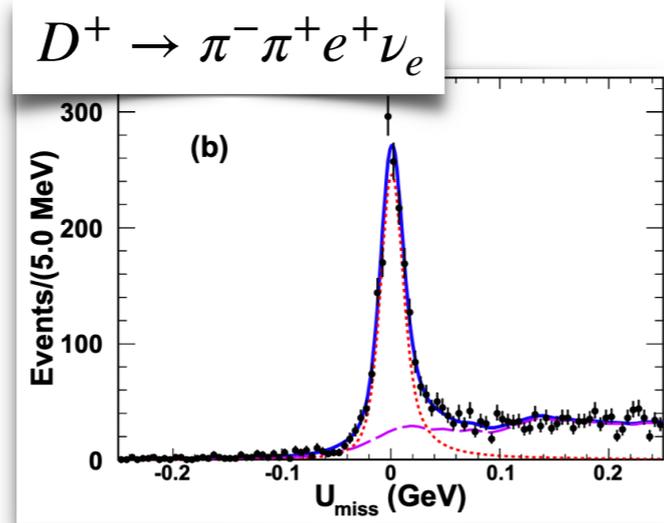
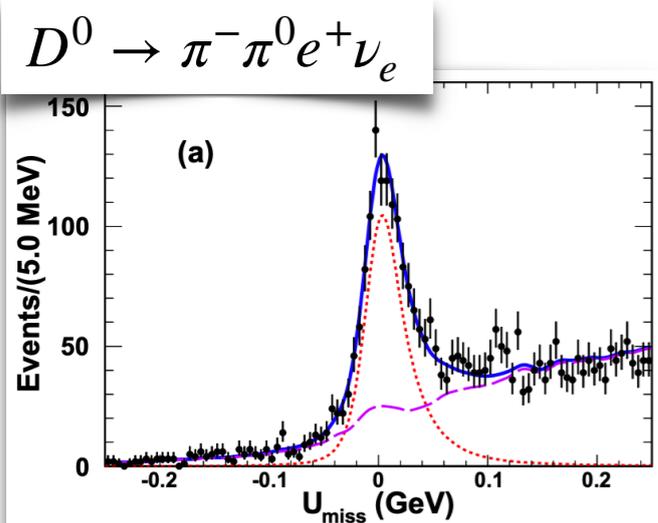


$$r_V = \frac{V(0)}{A_1(0)} = 1.46 \pm 0.07 \pm 0.02$$

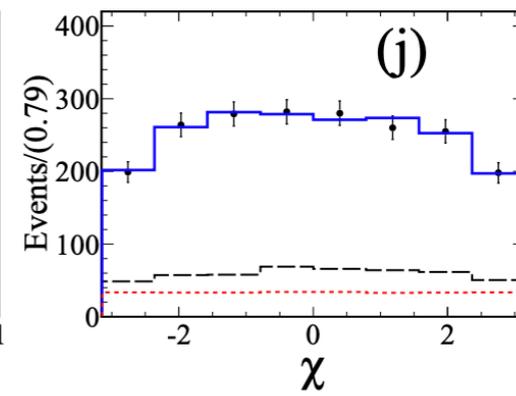
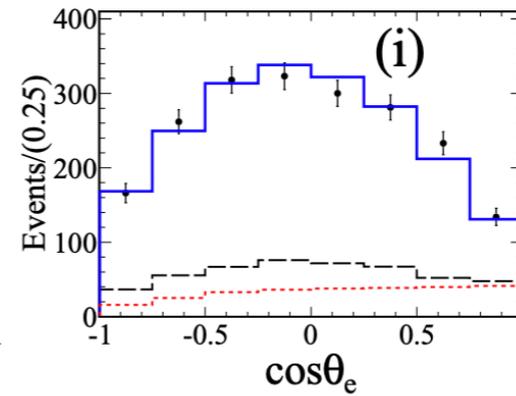
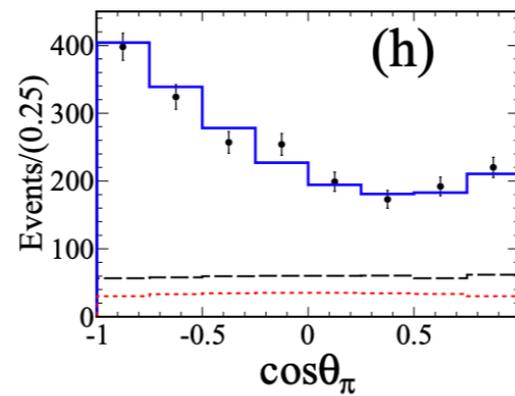
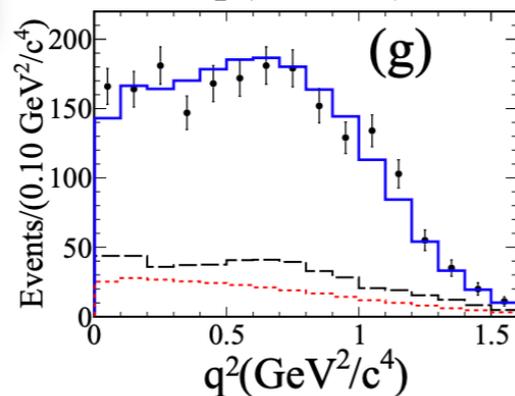
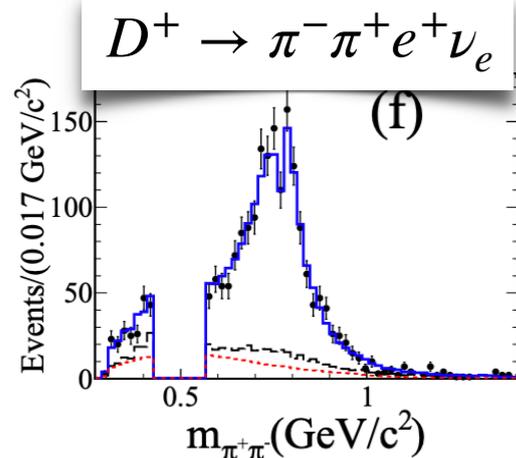
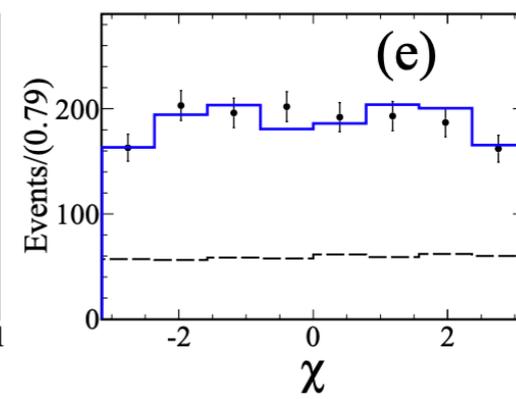
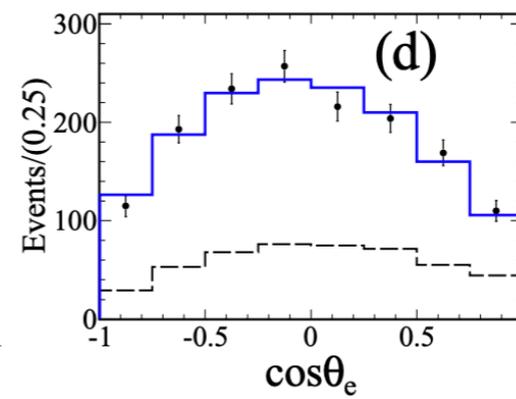
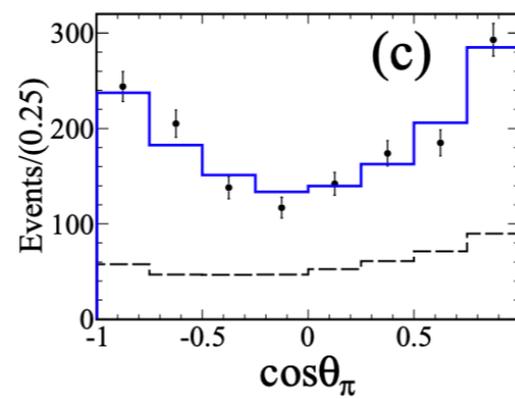
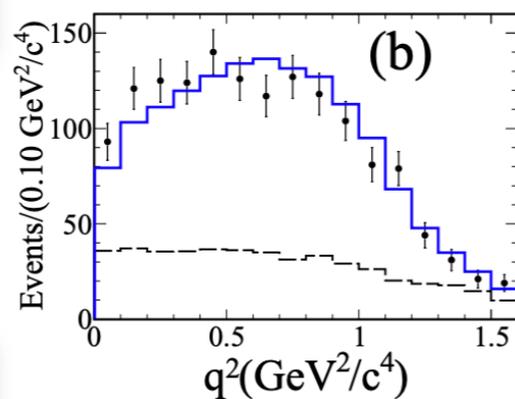
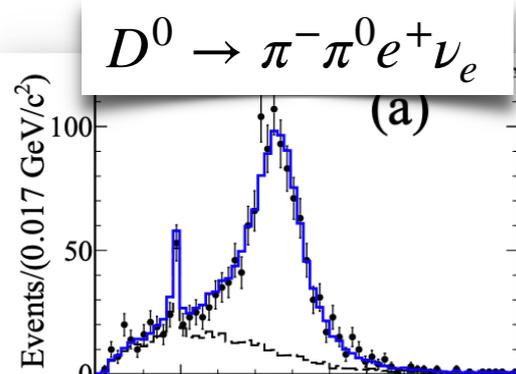
$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.67 \pm 0.06 \pm 0.01$$

Form Factor of $D \rightarrow V e \nu_e$

PRL122, 062001(2019)



Signal mode	this analysis ($\times 10^{-3}$)
$D^0 \rightarrow \pi^- \pi^0 e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^0 \rightarrow \rho^- e^+ \nu_e$	$1.445 \pm 0.058 \pm 0.039$
$D^+ \rightarrow \pi^- \pi^+ e^+ \nu_e$	$2.449 \pm 0.074 \pm 0.073$
$D^+ \rightarrow \rho^0 e^+ \nu_e$	$1.860 \pm 0.070 \pm 0.061$
$D^+ \rightarrow \omega e^+ \nu_e$	$2.05 \pm 0.66 \pm 0.30$
$D^+ \rightarrow f_0(500) e^+ \nu_e, f_0(500) \rightarrow \pi^+ \pi^-$	$0.630 \pm 0.043 \pm 0.032$
$D^+ \rightarrow f_0(980) e^+ \nu_e, f_0(980) \rightarrow \pi^+ \pi^-$	< 0.028

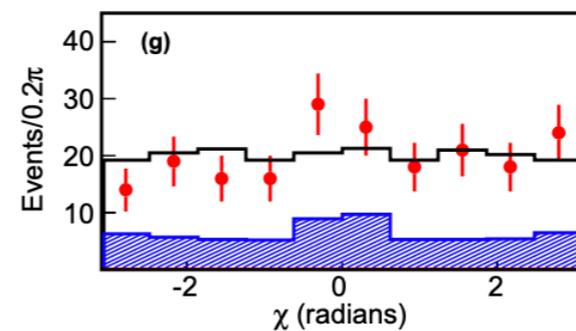
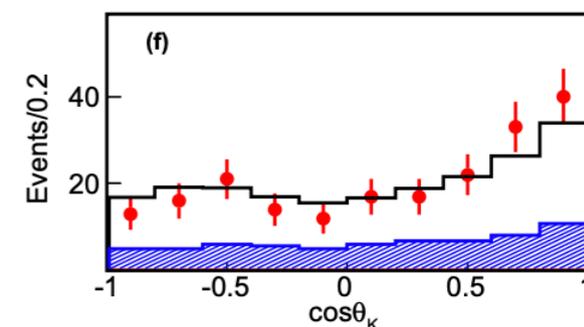
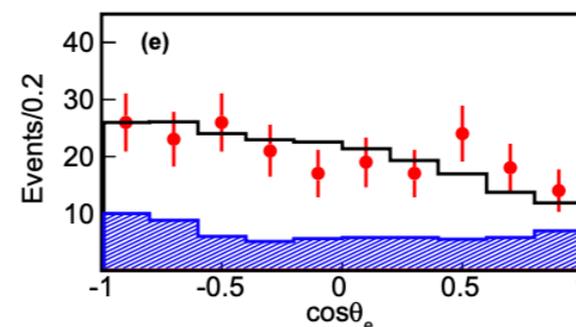
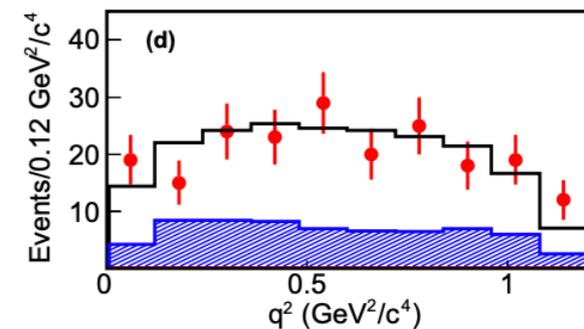
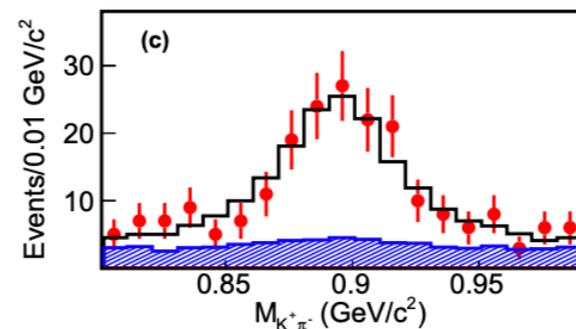
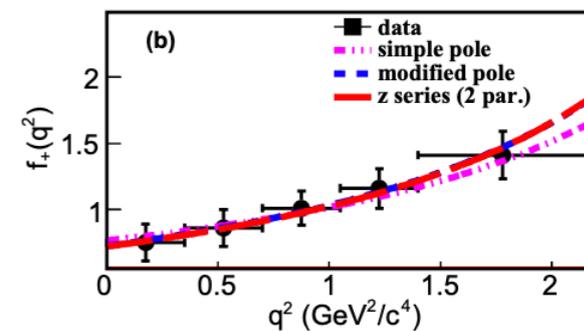
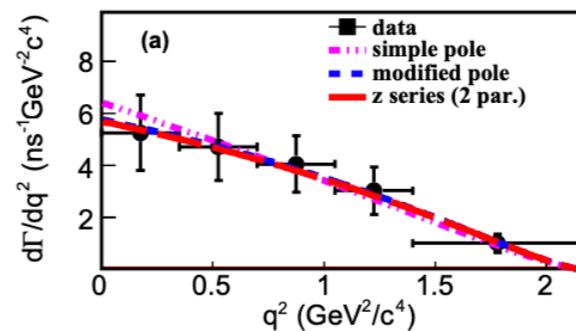
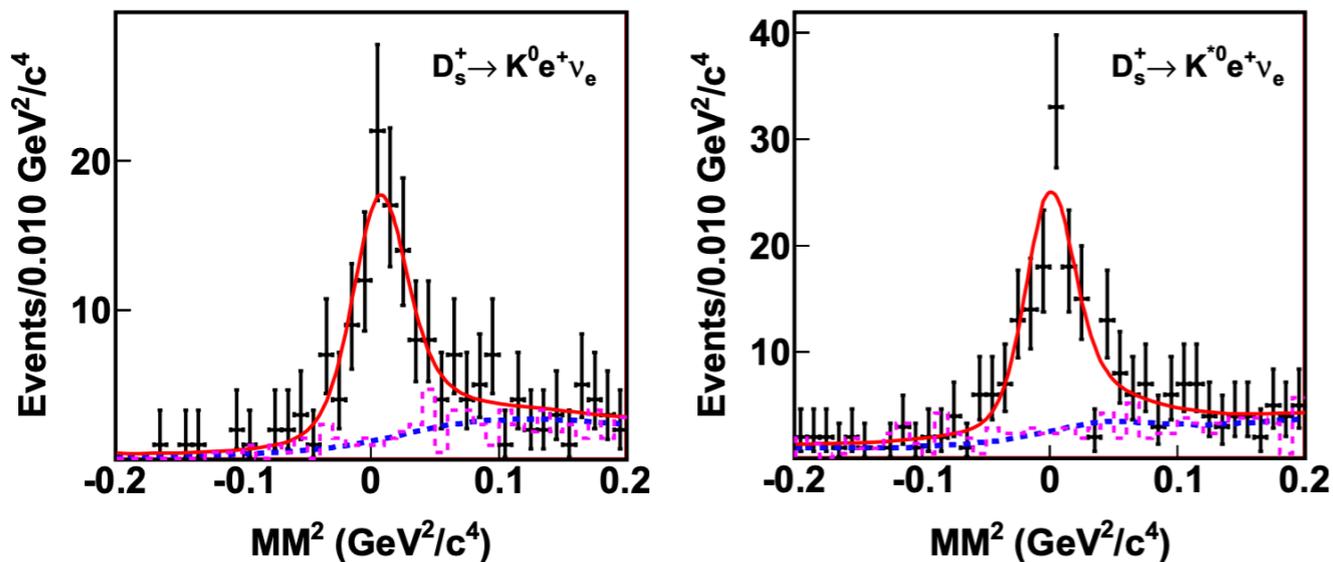


$$r_V = \frac{V(0)}{A_1(0)} = 1.695 \pm 0.083 \pm 0.051$$

$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.845 \pm 0.056 \pm 0.039$$

Form Factor of $D \rightarrow V e \nu_e$

PRL122, 061801(2019)



$$\mathcal{B}(D_S^+ \rightarrow K^0 e^+ \nu_e) = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$

$$f_+^{K^0}(0) |V_{cd}| = 0.162 \pm 0.019 \pm 0.003$$

$$\mathcal{B}(D_S^+ \rightarrow K^{*0} e^+ \nu_e) = (2.37 \pm 0.26 \pm 0.20) \times 10^{-3}$$

$$r_V = 1.67 \pm 0.34 \pm 0.16$$

$$r_2 = 0.77 \pm 0.28 \pm 0.07$$

$$f_+^{D_S^+ \rightarrow K^0}(0) / f_+^{D^+ \rightarrow \pi^0}(0) = 1.16 \pm 0.14 \pm 0.02$$

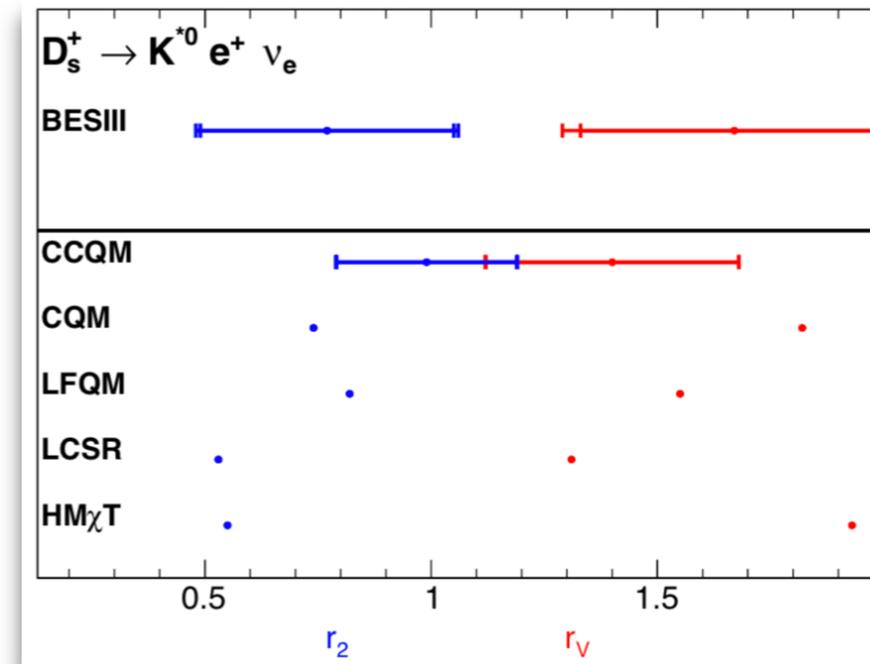
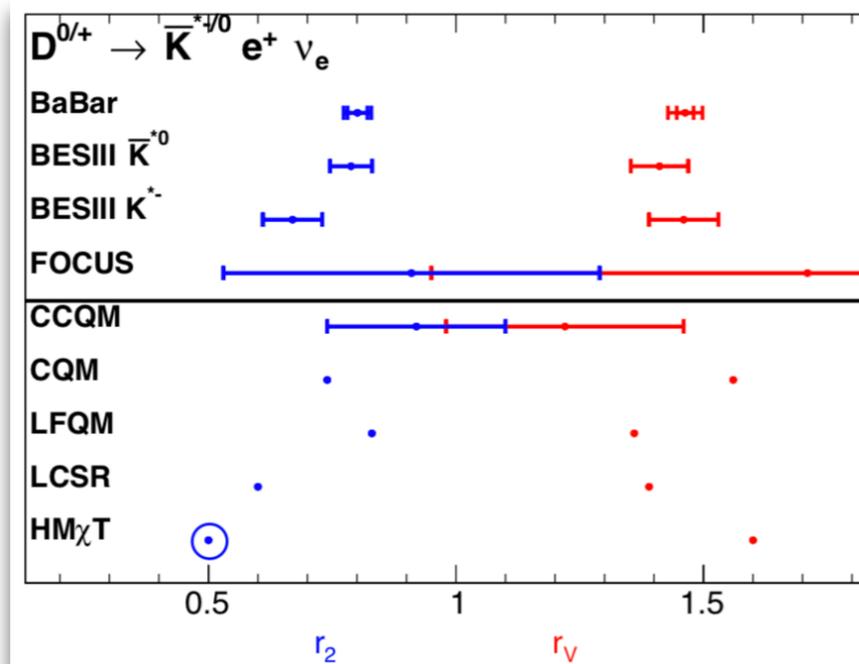
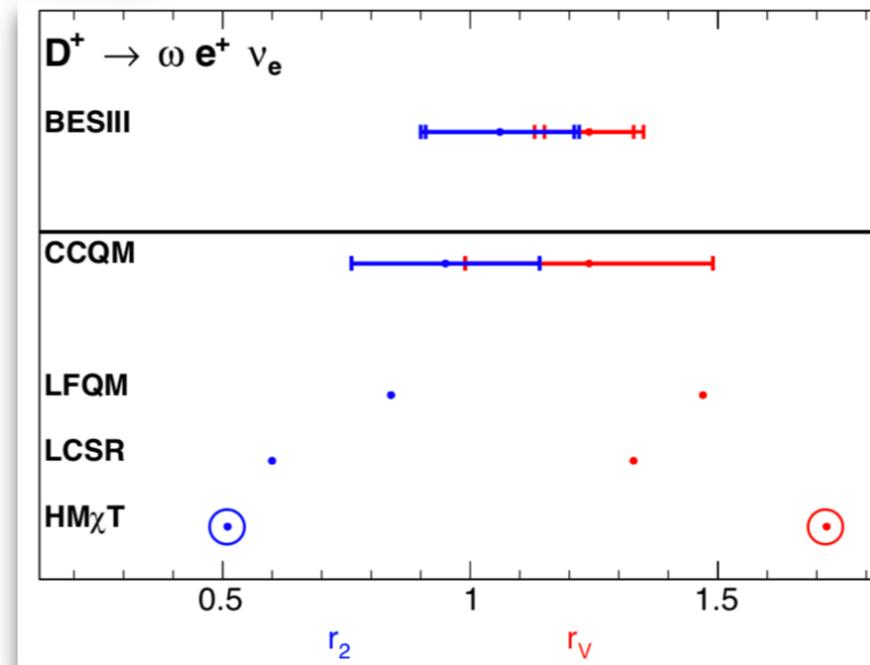
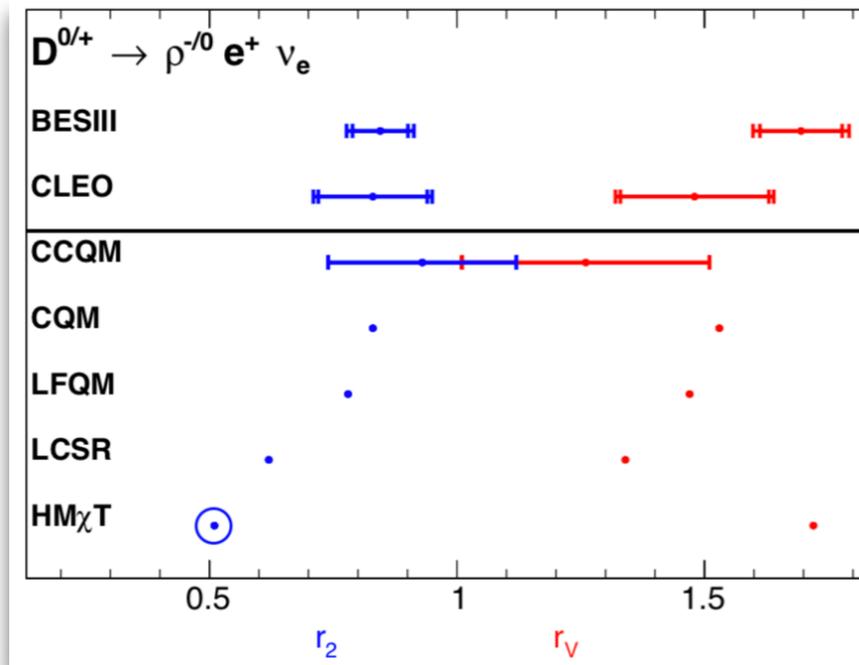
$$r_V^{D_S^+ \rightarrow K^{*0}} / r_V^{D^+ \rightarrow \rho^0} = 1.13 \pm 0.26 \pm 0.11$$

$$r_2^{D_S^+ \rightarrow K^{*0}} / r_2^{D^+ \rightarrow \rho^0} = 0.93 \pm 0.36 \pm 0.10$$

Agrees with U-spin ($d \leftrightarrow s$) symmetry.

Form Factor of $D \rightarrow V e \nu_e$

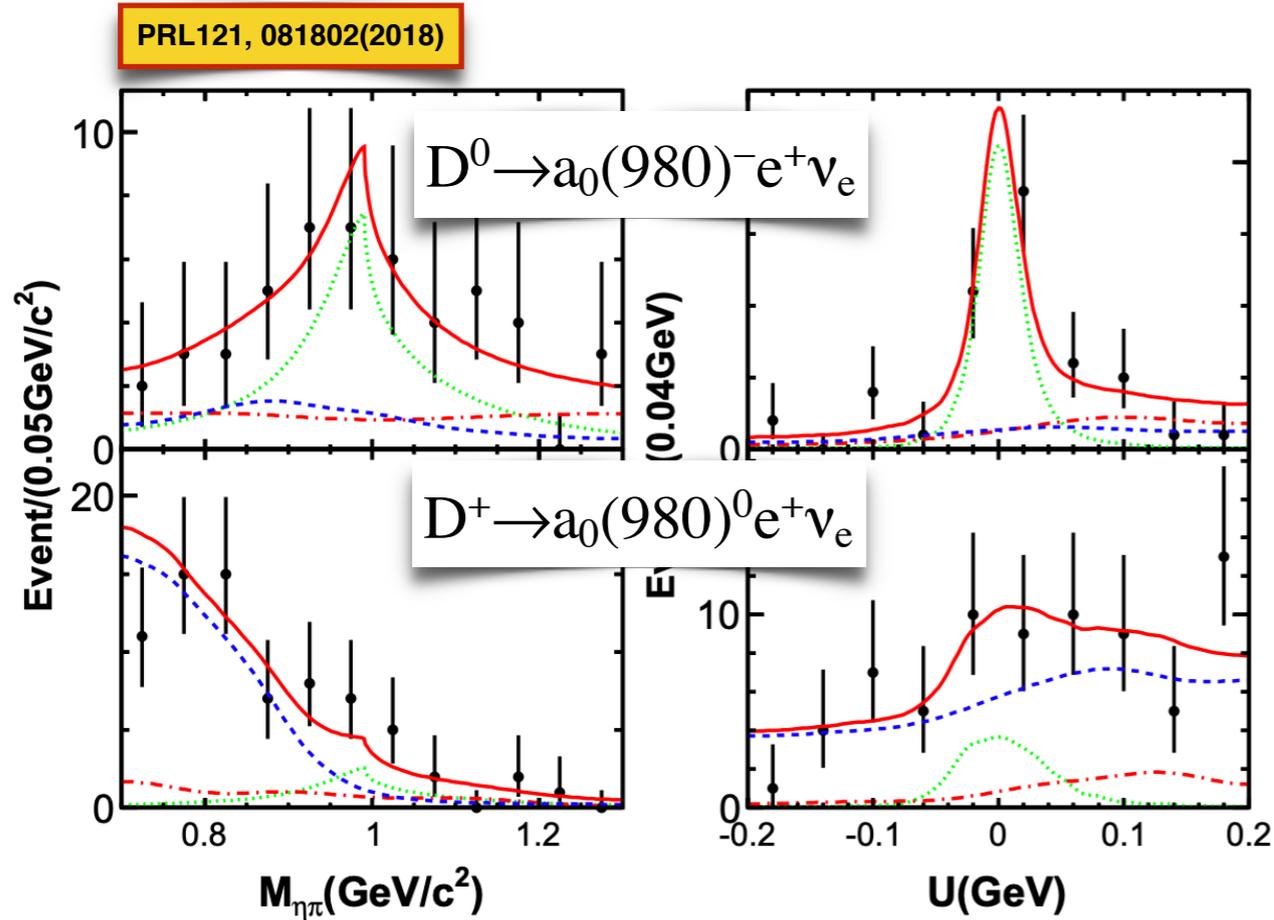
Comparison of r_V and r_2 with theoretical calculations



CCQM arXiv:1904.07740 CQM
 LFQM JPG39(2012)025005 LCSR
 HM χ T PRD72(2005)034029

PRD62(2000)014006
 Int. J. Mod. Phys. A 21(2006)6125

Observation of $D \rightarrow a_0(980)e\nu_e$



A model-independent way to study the nature of light scalar mesons proposed by PRD82(2016)034016

$$R = \frac{\mathcal{B}(D^+ \rightarrow f_0(980)e^+\nu_e) + \mathcal{B}(D^+ \rightarrow f_0(500)e^+\nu_e)}{\mathcal{B}(D^+ \rightarrow a_0(980)^0 e^+\nu_e)}$$

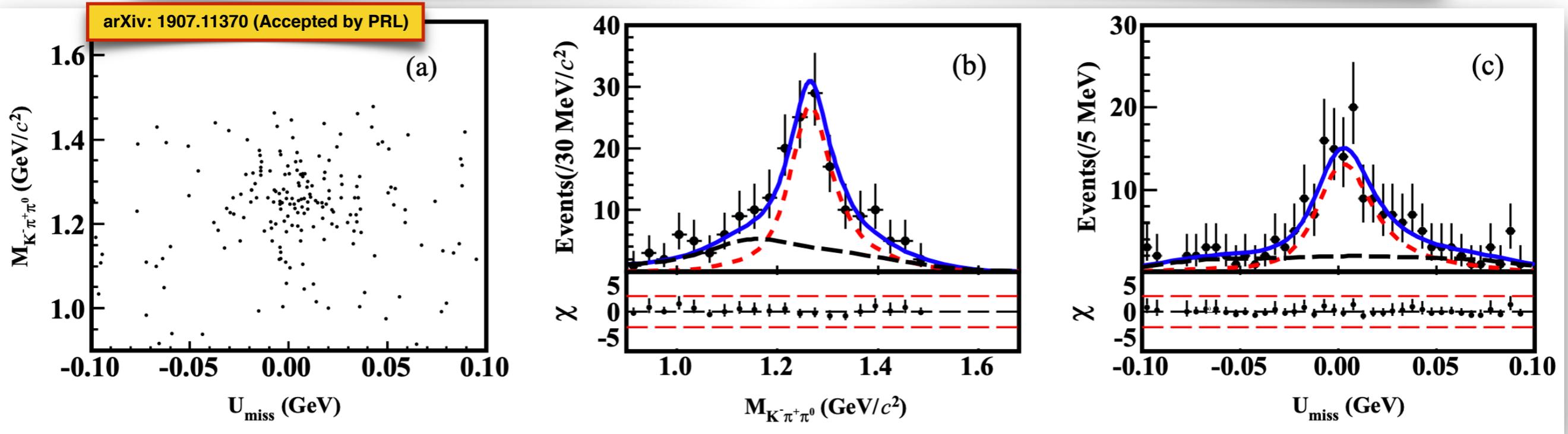
$R = 1.0 \pm 0.3$ for two-quark description;
 $R = 3.0 \pm 0.9$ for tetraquark description.

We have $R > 2.7$ @90% C.L. at BESIII
 Which favors the tetraquark description.

Decay	BF ($\times 10^{-4}$)	Significance
$D^0 \rightarrow a_0(980)^- e^+ \nu_e, a_0(980)^- \rightarrow \eta \pi^-$	$1.33^{+0.33}_{-0.29} \pm 0.09$	6.4σ
$D^+ \rightarrow a_0(980)^0 e^+ \nu_e, a_0(980)^0 \rightarrow \eta \pi^0$	$1.66^{+0.81}_{-0.66} \pm 0.11$ < 3.0 (90% C.L.)	2.9σ

Observation of $D \rightarrow \bar{K}_1(1270)^0 e \nu_e$

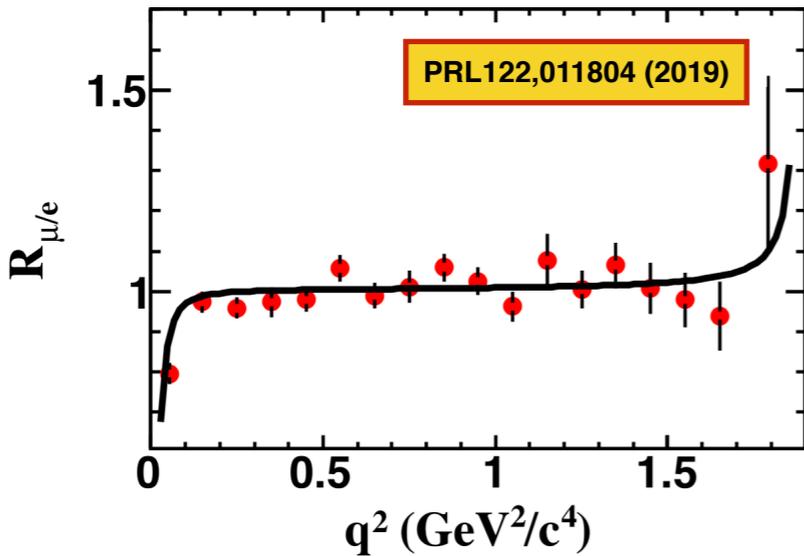
- First observation of D meson semileptonic decay into axial-vector mesons
- Provide insight into the mixing angle of 1P_1 and 3P_1 states θ_{K_1}
- Test various theoretical calculations
- Provide important input to study the photon polarisation in $B \rightarrow K_1 \gamma$ by measuring the ration of up-down asymmetries of θ_K and θ_l (more statistics needed)



$$B(D^+ \rightarrow K_1(1270)^0 e^+ \nu_e) = (2.30 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-3}$$

The BF agrees with CLFQM and LCSR predictions when $\theta_{K_1} \sim 33^\circ$ or 57° and rules out negative θ_{K_1} case.

Lepton Flavor Universality



$$R_{\mu/e}^{D^+} = \frac{\Gamma(D^+ \rightarrow \tau^+ \nu_\tau) [\text{PRL123, 211802(2019)}]}{\Gamma(D^+ \rightarrow \mu^+ \nu_\mu) [\text{PRD89, 051104(2014)}]} = 3.21 \pm 0.64 \pm 0.43$$

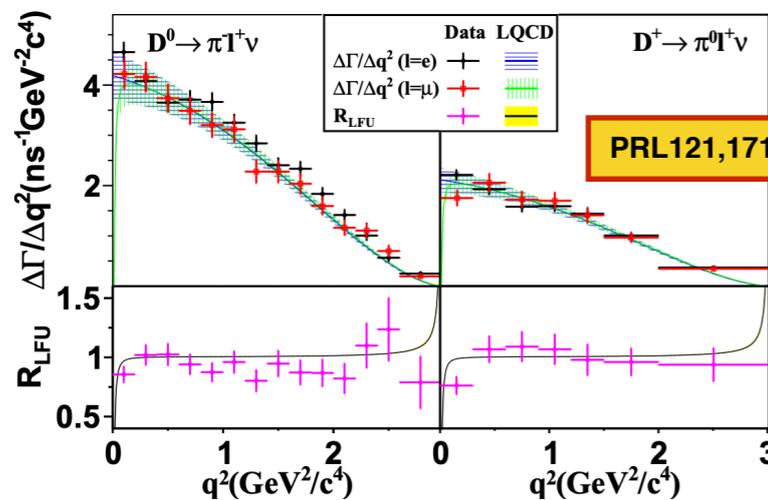
$$R_{\mu/e}^{D_s^+} = \frac{\Gamma(D_s^+ \rightarrow \tau^+ \nu_\tau) [\text{PDG2018}]}{\Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu) [\text{PRL122, 071802(2019) + PDG2018}]} = 10.19 \pm 0.52$$

$$R_{\mu/e}^K = \frac{\Gamma(D^0 \rightarrow K^- \mu^+ \nu_\mu) [\text{PRL122, 011804(2019)}]}{\Gamma(D^0 \rightarrow K^- e^+ \nu_e) [\text{PRD92, 072012(2017)}]} = 0.974 \pm 0.007 \pm 0.012$$

$$R_{\mu/e}^{K^0} = \frac{\Gamma(D^+ \rightarrow K^0 \mu^+ \nu_\mu) [\text{EPJC76, 369(2016)}]}{\Gamma(D^+ \rightarrow K^0 e^+ \nu_e) [\text{PRD96, 012002(2017)}]} = 1.013 \pm 0.011 \pm 0.027$$

$$R_{\mu/e}^\pi = \frac{\Gamma(D^0 \rightarrow \pi^- \mu^+ \nu_\mu) [\text{PRL121, 171803(2018)}]}{\Gamma(D^0 \rightarrow \pi^- e^+ \nu_e) [\text{PRD92, 072012(2017)}]} = 0.922 \pm 0.030 \pm 0.022$$

$$R_{\mu/e}^{\pi^0} = \frac{\Gamma(D^+ \rightarrow \pi^0 \mu^+ \nu_\mu) [\text{PRL121, 171803(2018)}]}{\Gamma(D^+ \rightarrow \pi^0 e^+ \nu_e) [\text{PRD96, 012002(2017)}]} = 0.964 \pm 0.037 \pm 0.026$$



	$R(D_s^+)$	$R(D^+)$	$R(K^-)$	$R(\bar{K}^0)$	$R(\pi^-)$	$R(\pi^0)$
SM	9.74(1)	2.66(1)	0.975(1)	0.975(1)	0.985(2)	0.985(2)
BESIII	10.19(52)	3.21(64)	0.974(14)	1.013(29)	0.922(37)	0.964(45)

Rare Decay

Theoretical Prediction: $10^{-5} \sim 10^{-3}$ level

- [2] C. Q. Geng, C. C. Lih and W. M. Zhang, *Mod. Phys. Lett. A* **15**, 2087 (2000).
- [3] G. P. Korchemsky, D. Pirjol and T. M. Yan, *Phys. Rev. D* **61**, 114510 (2000).
- [4] C. D. Lu and G. L. Song, *Phys. Lett. B* **562**, 75 (2003).
- [5] J. C. Yang and M. Z. Yang, *Mod. Phys. Lett. A* **27**, 1250120 (2012).
- [6] J. C. Yang and M. Z. Yang, *Nucl. Phys. B* **889**, 778 (2014).
- [7] D. Atwood, G. Eilam and A. Soni, *Mod. Phys. Lett. A* **11**, 1061 (1996).
- [8] G. Burdman, T. Goldman and D. Wyler, *Phys. Rev. D* **51**, 111 (1995).

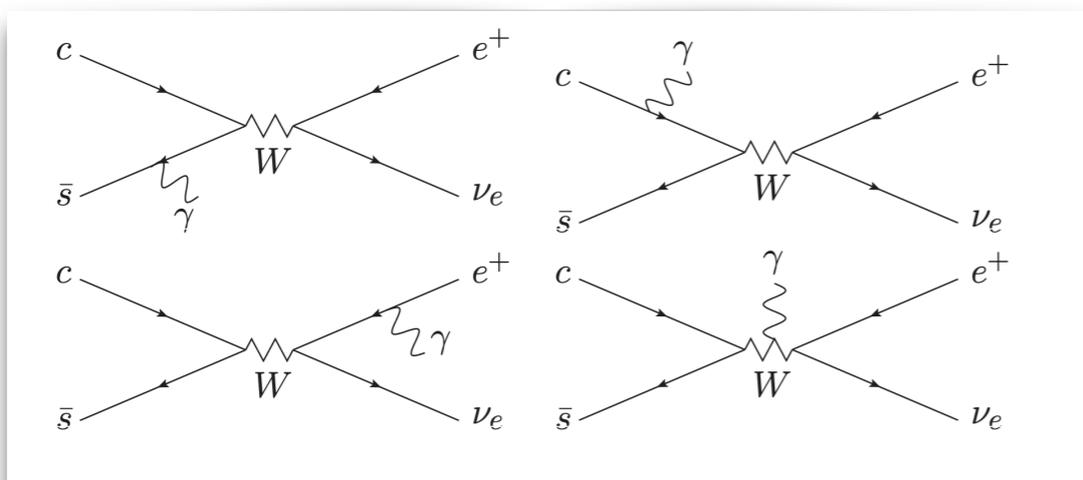


FIG. 1. Tree-level Feynman diagrams contributing to $D_s^+ \rightarrow \gamma e^+ \nu_e$.

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

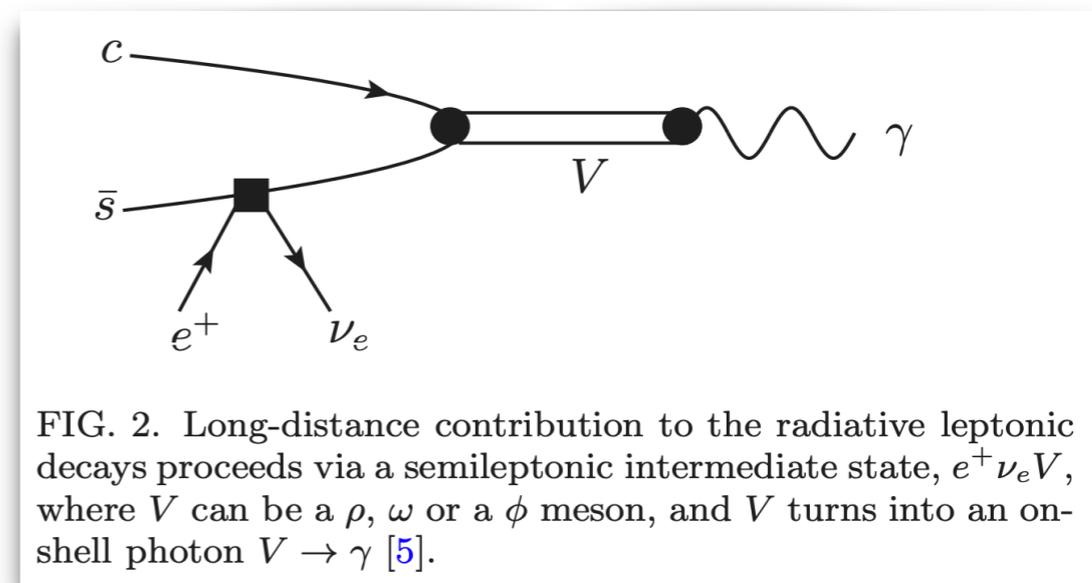
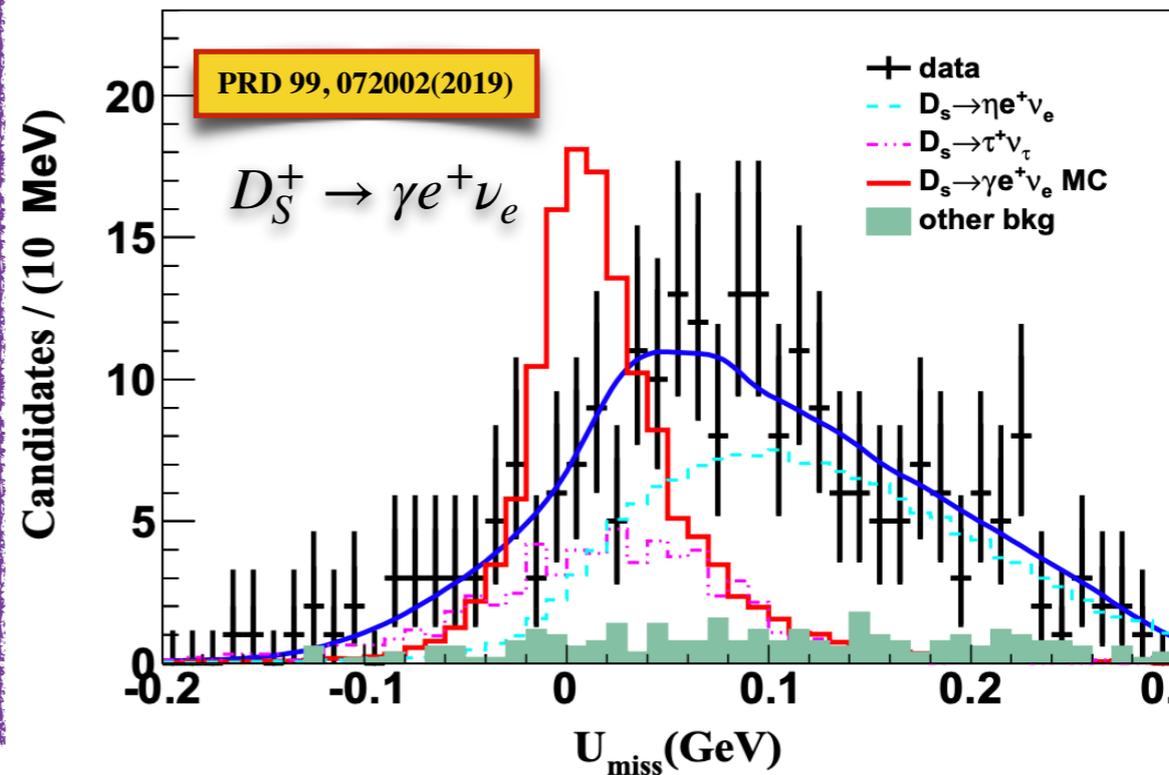
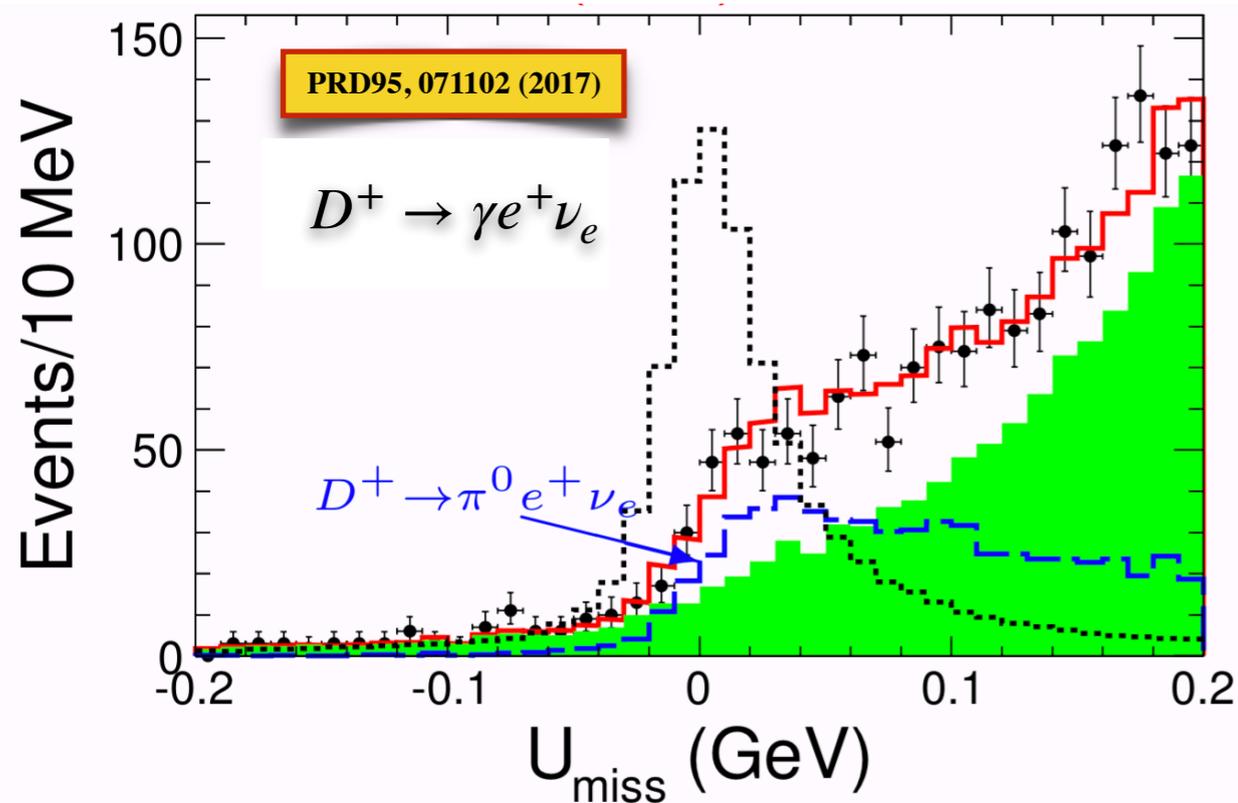


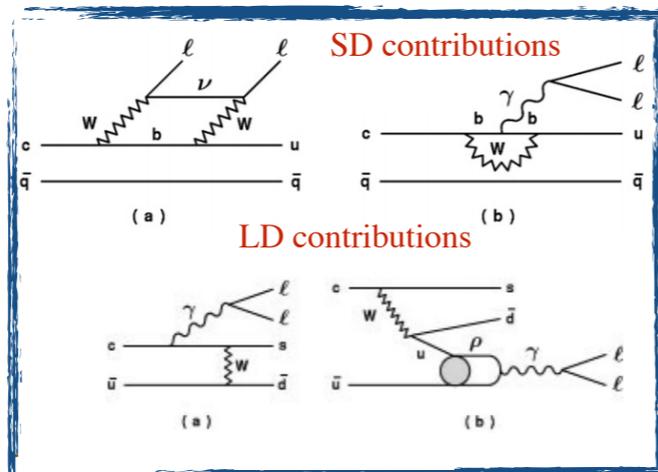
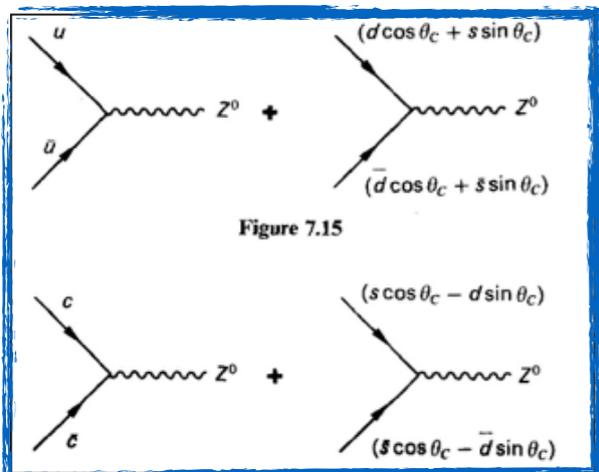
FIG. 2. Long-distance contribution to the radiative leptonic decays proceeds via a semileptonic intermediate state, $e^+ \nu_e V$, where V can be a ρ , ω or a ϕ meson, and V turns into an on-shell photon $V \rightarrow \gamma$ [5].

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



Rare Decay

Flavor Changing Neutral Current

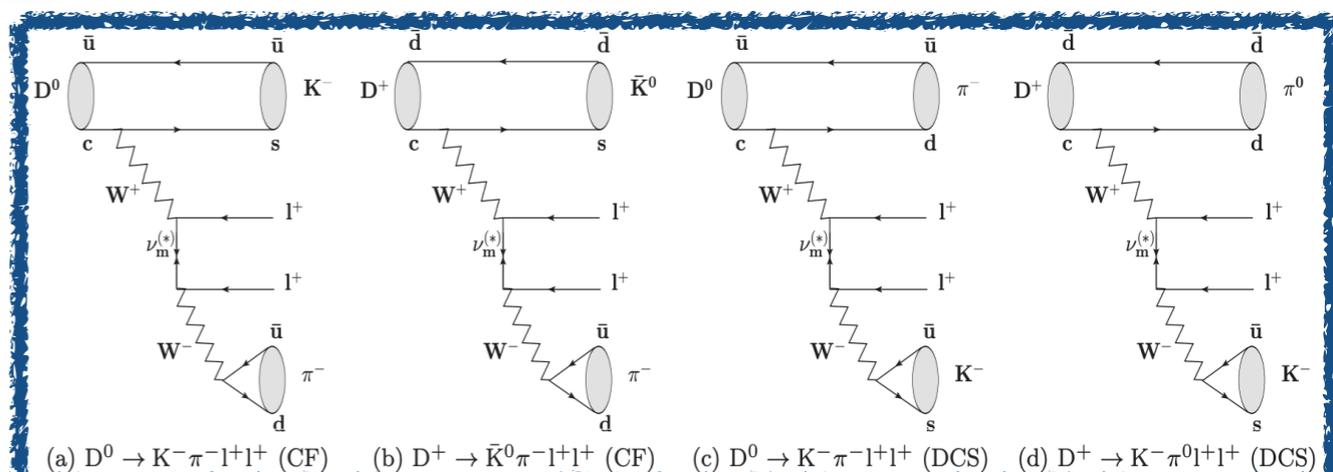


Lepton Number Violation

$$\mathcal{B}(D^0 \rightarrow K^- \pi^- e^+ e^+) < 2.8 \times 10^{-6} \text{ @90\% C.L.}$$

$$\mathcal{B}(D^+ \rightarrow K_S^0 \pi^- e^+ e^+) < 3.3 \times 10^{-6} \text{ @90\% C.L.}$$

$$\mathcal{B}(D^+ \rightarrow K^- \pi^0 e^+ e^+) < 8.5 \times 10^{-6} \text{ @90\% C.L.}$$



PRD97, 072015(2018)

Signal decays $\mathcal{B} (\times 10^{-5})$ PDG [9] ($\times 10^{-5}$)

$D^+ \rightarrow \pi^+ \pi^0 e^+ e^-$	<1.4	...
$D^+ \rightarrow K^+ \pi^0 e^+ e^-$	<1.5	...
$D^+ \rightarrow K_S^0 \pi^+ e^+ e^-$	<2.6	...
$D^+ \rightarrow K_S^0 K^+ e^+ e^-$	<1.1	...
$D^0 \rightarrow K^- K^+ e^+ e^-$	<1.1	<31.5
$D^0 \rightarrow \pi^+ \pi^- e^+ e^-$	<0.7	<37.3
$D^0 \rightarrow K^- \pi^+ e^+ e^-^\dagger$	<4.1	<38.5
$D^0 \rightarrow \pi^0 e^+ e^-$	<0.4	<4.5
$D^0 \rightarrow \eta e^+ e^-$	<0.3	<11
$D^0 \rightarrow \omega e^+ e^-$	<0.6	<18
$D^0 \rightarrow K_S^0 e^+ e^-$	<1.2	<11

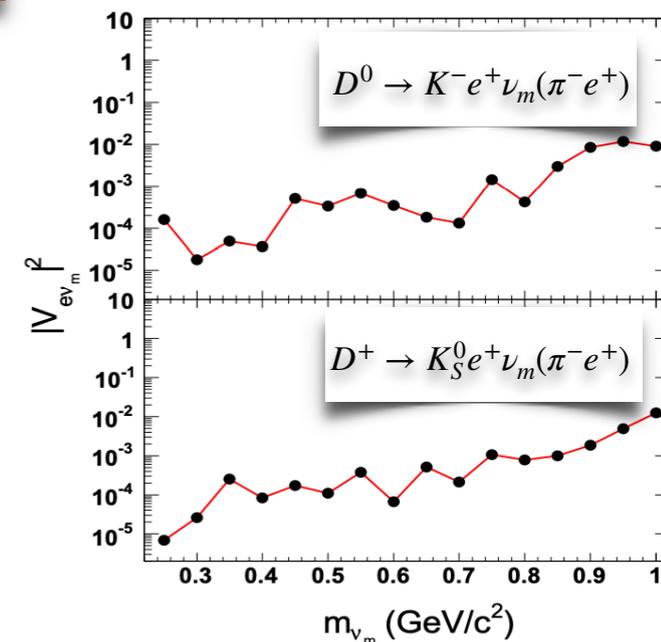
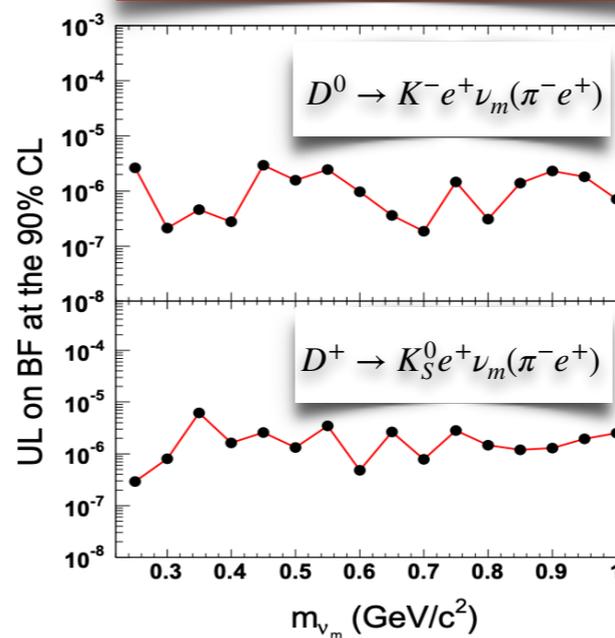
† in $M_{e^+e^-}$ regions:

$[0.00, 0.20) \text{ GeV}/c^2$	<3.0 ($1.5^{+1.0}_{-0.9}$)	...
$[0.20, 0.65) \text{ GeV}/c^2$	<0.7	...

- UL for D^+ are obtained for the first time.
- UL for D^0 are greatly improved.
- Divide the M_{ee} distribution of $K\pi^+e^+e^-$ into 3 regions to help separate LD

Theoretical [JHEP, 04, 135 (2014)]

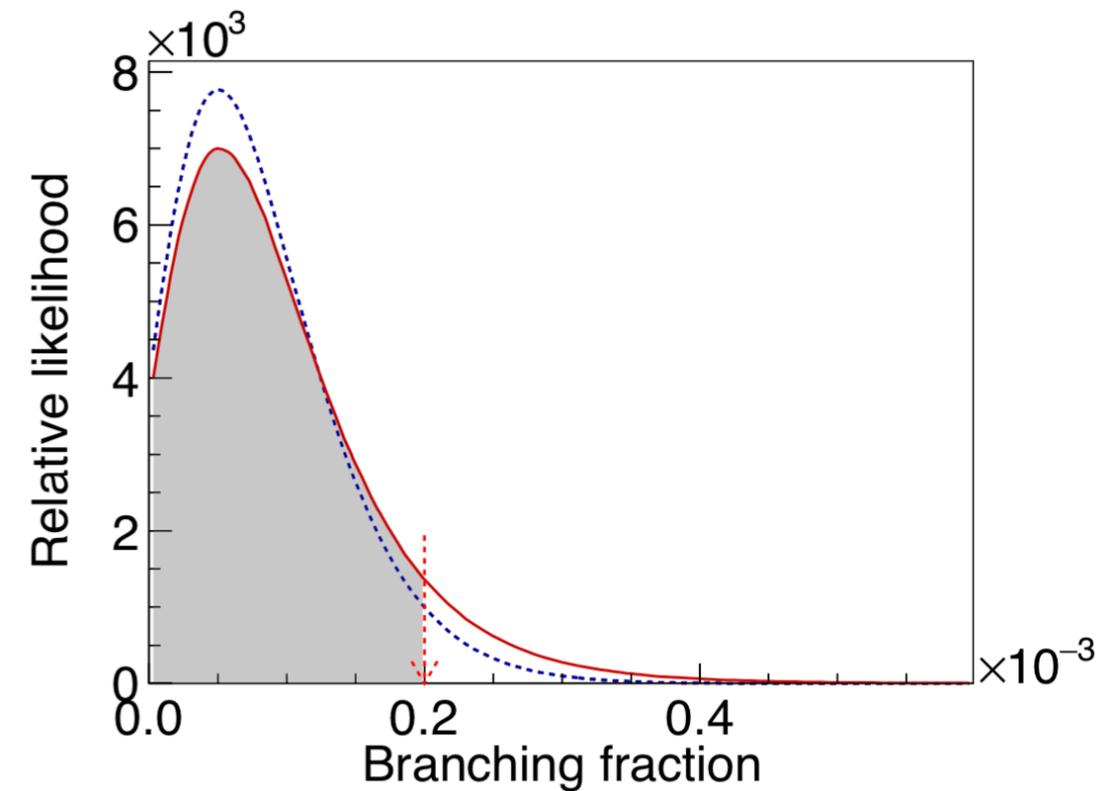
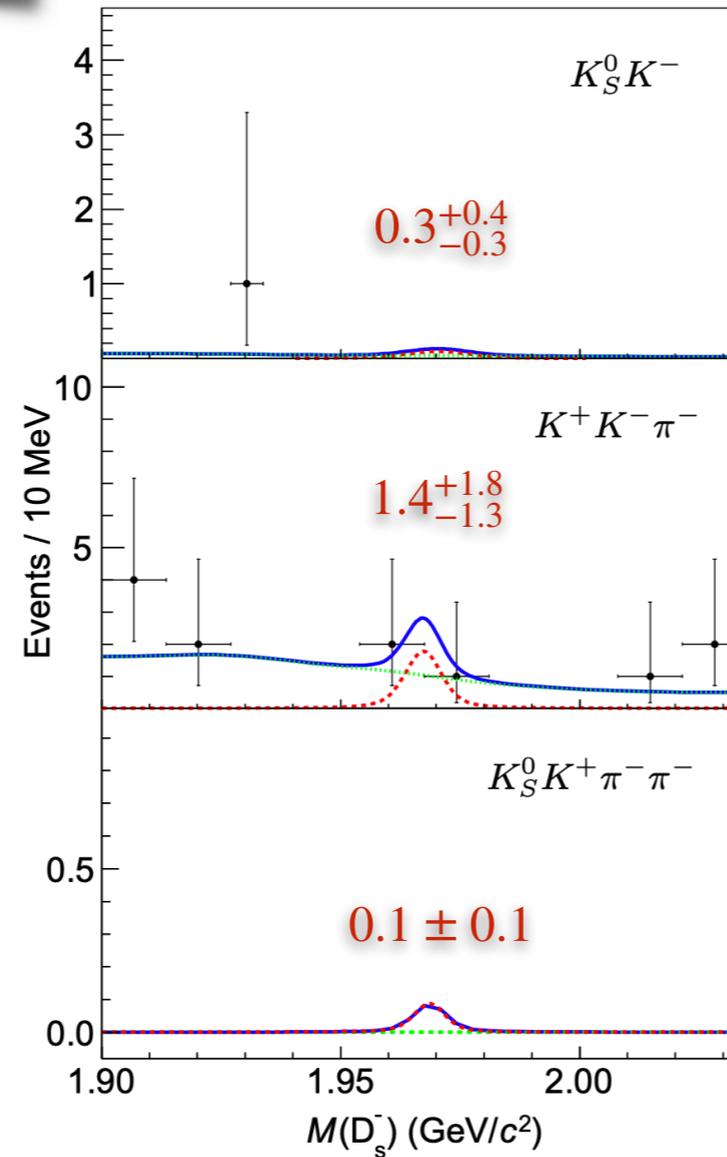
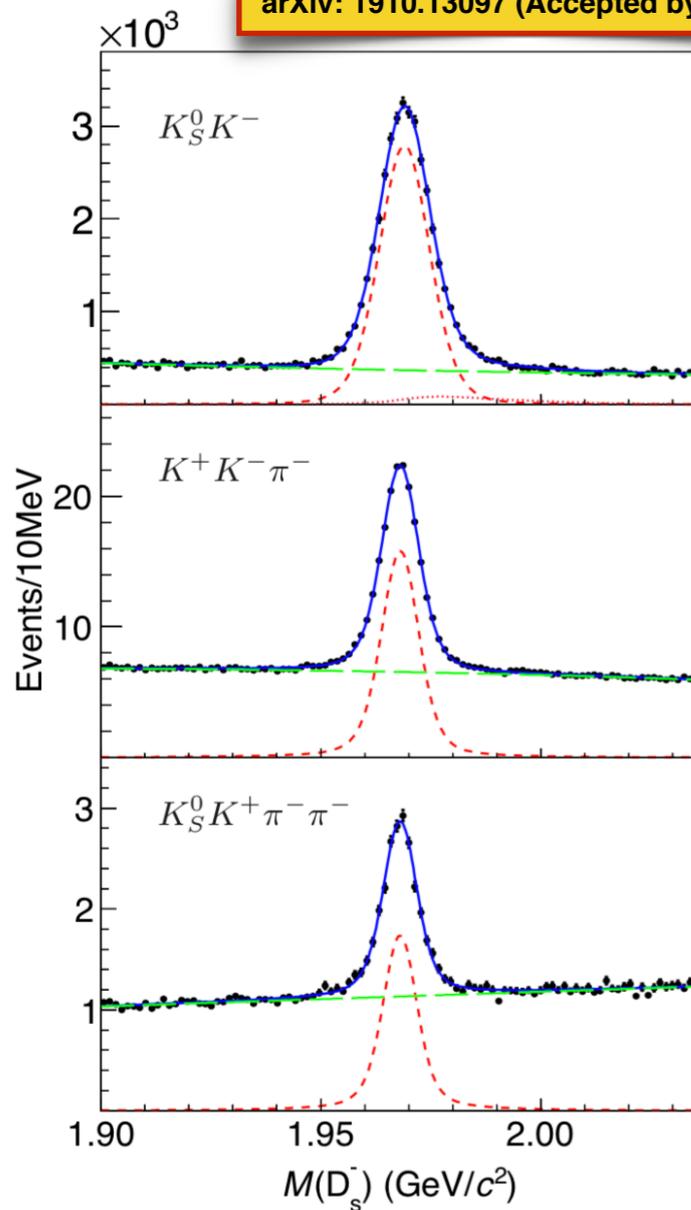
arXiv: 1910.13097 (PRD accepted)



Rare Decay

Transition between charm meson and baryon Paris

arXiv: 1910.13097 (Accepted by PRD)



H. Y. Cheng and X. W. Kang, PLB780, 100 (2018)

Predict: $\sim 10^{-8}$

$$\mathcal{B}(D_S^+ \rightarrow p\bar{p}e^+\nu_e) = (0.50_{-0.44}^{+0.63}) \times 10^{-4} \quad @1.2\sigma$$

$$\mathcal{B}(D_S^+ \rightarrow p\bar{p}e^+\nu_e) < 2.0 \times 10^{-4} \quad @90\% C.L.$$



南开大学建校100周年
NANKAI UNIVERSITY
100th Anniversary

广告时间

2020.4.中上旬 (2天) @南开大学

BESIII New Physics Workshop

理论 - 实验 - 交流

交通方便 (跑跳皆宜)

饮食多样 (可盐可甜)

娱乐丰富 (大鼓相声)



Summary

1. 与Belle或LHCb等B工厂相比，BESIII在统计量很小，所有单纯拼统计量的工作都没有优势；
2. BESIII数据的优势，在于可用近阈双标记方法，本底最干净，系统误差最好；
3. 2015年以来，BESIII的粲物理研究在CKM矩阵元、粲介子衰变常量、半轻形状因子、轻子普适性、稀有衰变等方面取得了一系列重要进展；
- 4.

Thanks for your attention!