Experimental study for D_s^+ leptonic decays at BESIII

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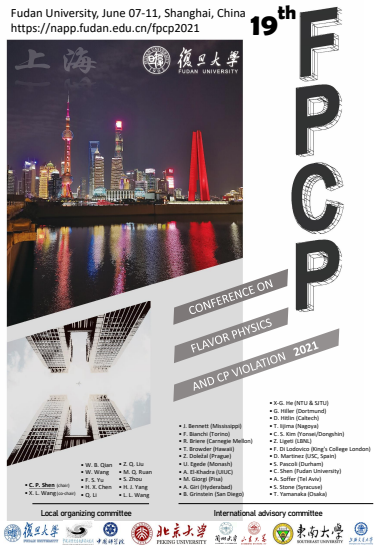
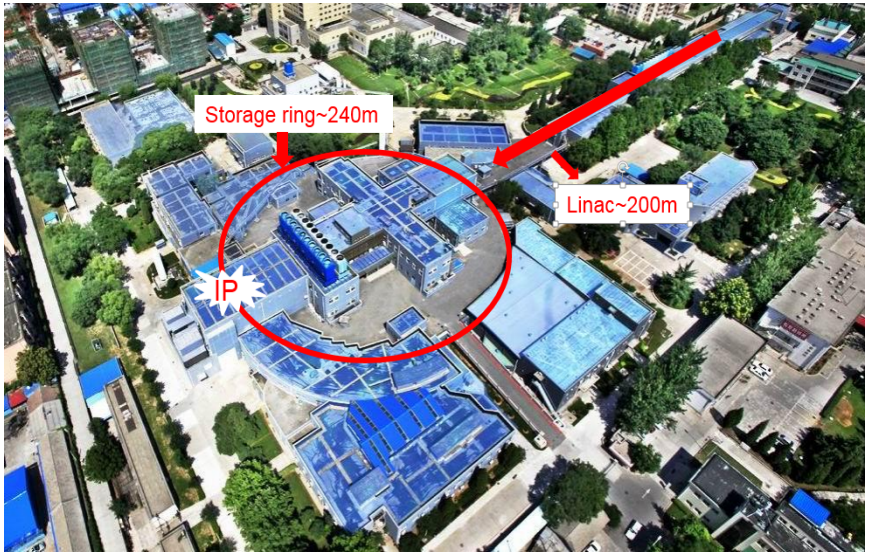
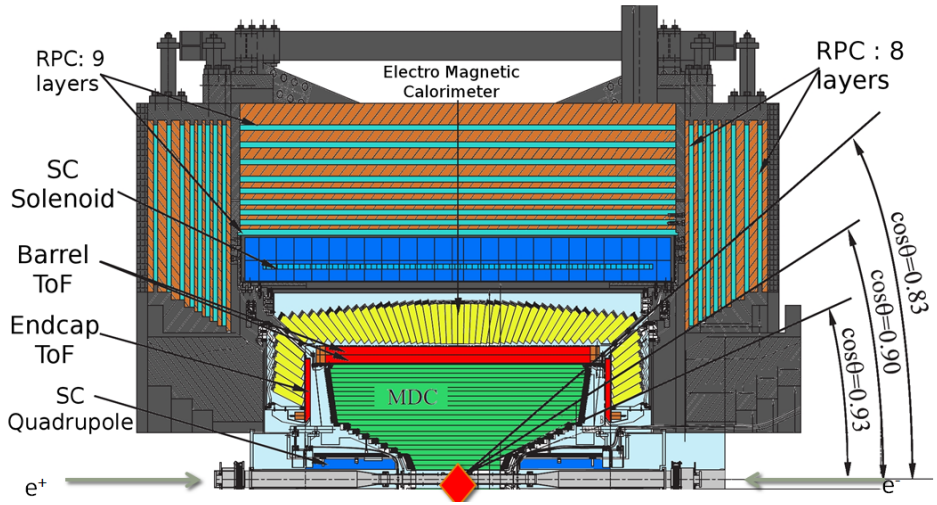
(on behalf of the BESIII collaboration)
Conference on flavor physics and CP violation 2021
07-11 June 2021



Outline

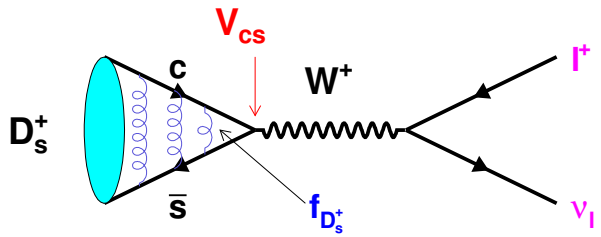
BESIII experiment





- $\sqrt{s} = (2.0 - 4.95)$ GeV
- MDC: $\sigma_P/P = 0.5\%$ @ 1 GeV; $\sigma_{dE/dx} = 6\%$
- TOF: $\sigma_T = 68(110)$ ps for barrel (endcap)
- EMC: σ_E/E =2.5%(5%) for barrel (endcap)

Introduction



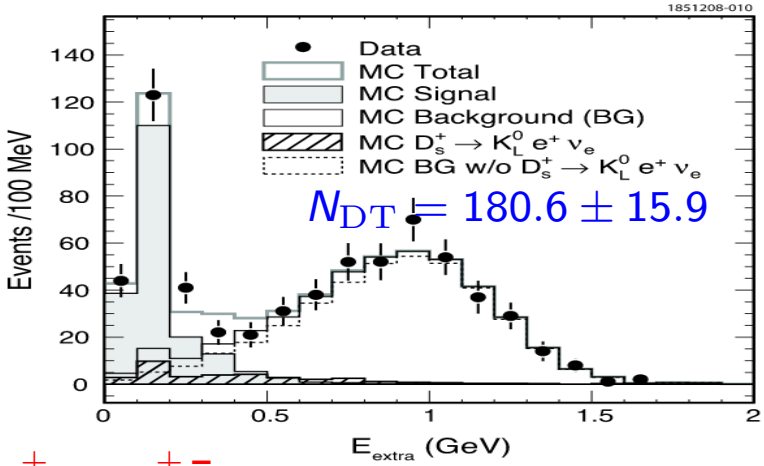
$$\Gamma_{D_s^+ \to \ell^+ \nu_\ell} = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s^+}{}^2 m_\ell^2 m_{D_s^+} \left(1 - \frac{m_\ell^2}{m_{D_s^+}^2}\right)^2$$

- Determined the decay constant f_{D_s} can test the theoretical calculation, especially LQCD.
- Precise measurement of CKM matrix element $|V_{cs}|$ can test the CKM matrix unitarity and search for NP beyond SM.
- Combine with the BF of leptonic decay $D_s^+ \to \mu^+ \nu_\mu$, the lepton flavor universality can be checked.
- BESIII and CLEO experiments have similar data sample of $e^+e^- \to D_s D_s^*$ near $\sqrt{s} = 4.170 - 4.180$ GeV, which offer a similar analysis environment.

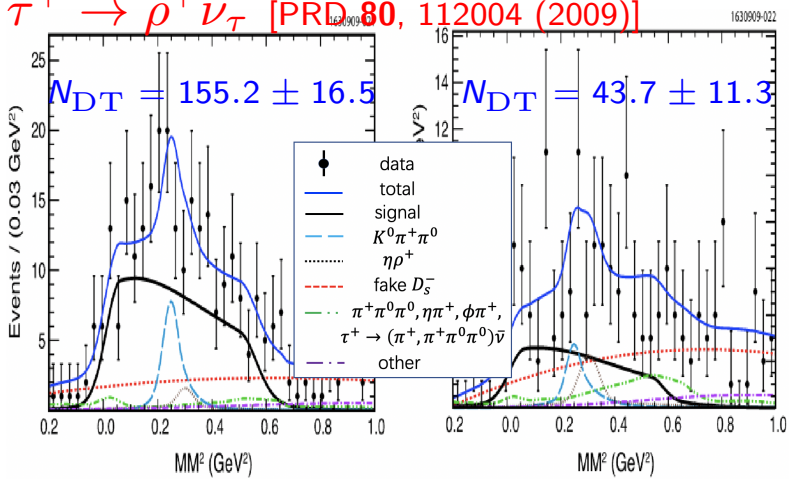
Overview I: $D_s^+ \to \mu^+\nu_\mu, \tau^+\nu_\tau$ (CLEO collaboration)

Data sample: 600 pb^{-1} @4.170 GeV

$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ [PRD **79**, 052002 (2009)]



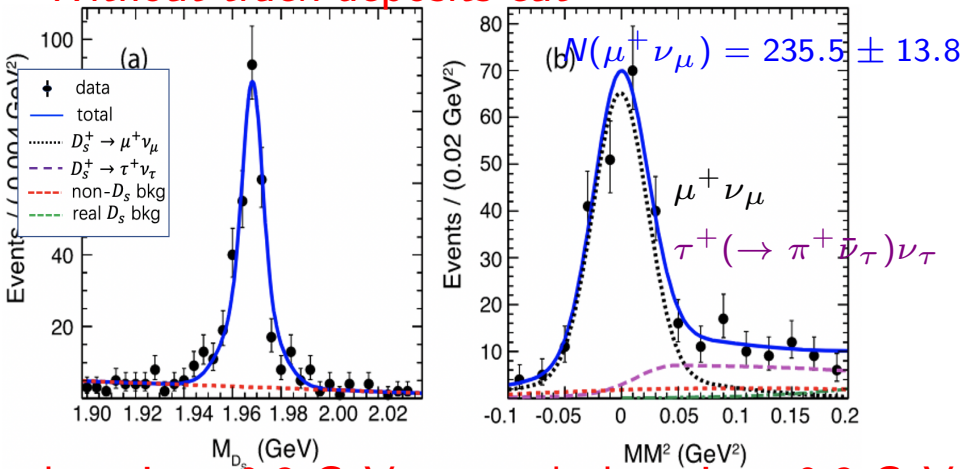
$\tau^+ \to \rho^+\bar{\nu}_\tau$ [PRD **80**, 112004 (2009)]



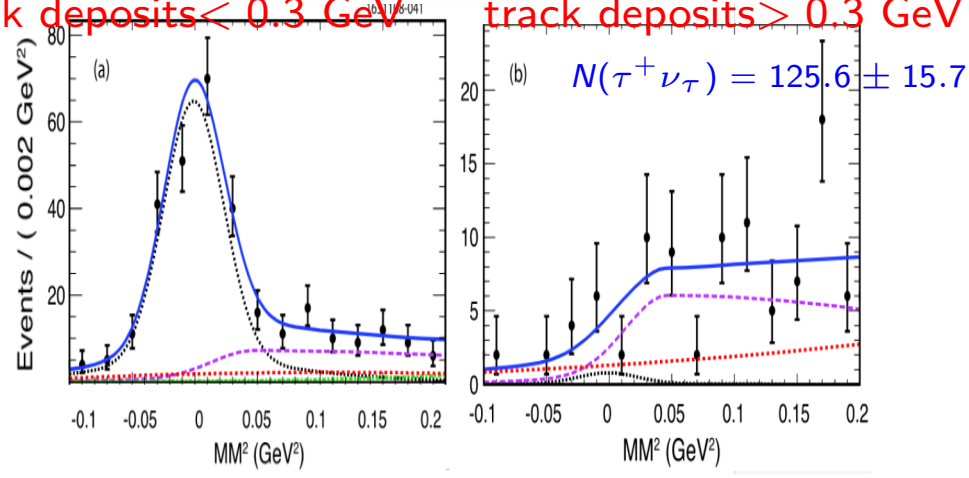
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)_{\rm ave} = (0.565 \pm 0.045 \pm 0.017)\%$

$\tau^+ \to \pi^+\bar{\nu}_\tau$ [PRD **79**, 052001 (2009)]

Without track deposits cut



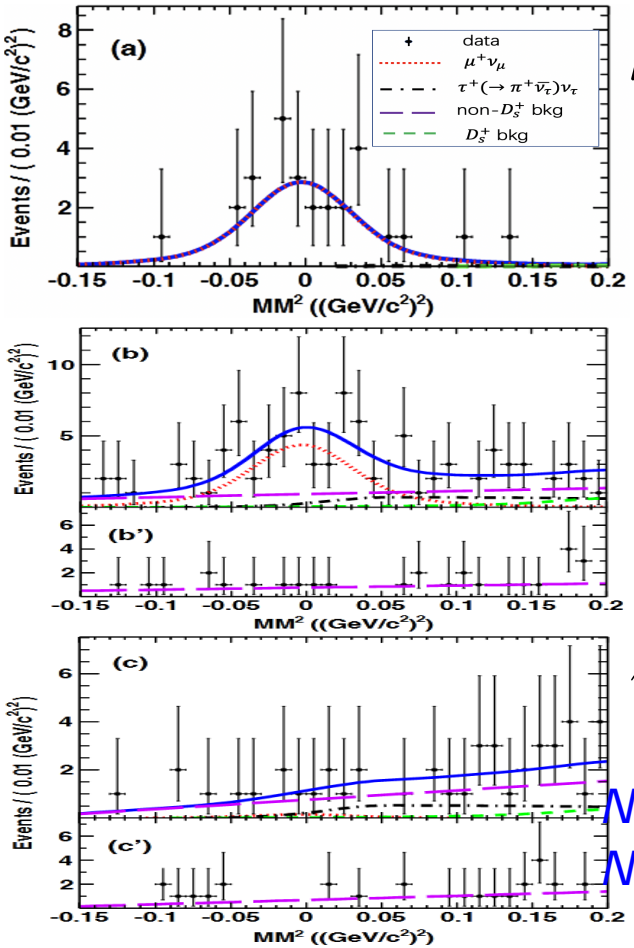
track deposits$<$ 0.3 GeV track deposits$>$ 0.3 GeV



$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)_{\rm ave} = (5.58 \pm 0.33 \pm 0.13)\%$

Overview II: $D_s^+ \to \mu^+\nu_\mu, \tau^+\nu_\tau$ (BESIII collaboration)

482 pb^{-1} @ 4.009 GeV [PRD **94**, 072004 (2016)]



μ-like

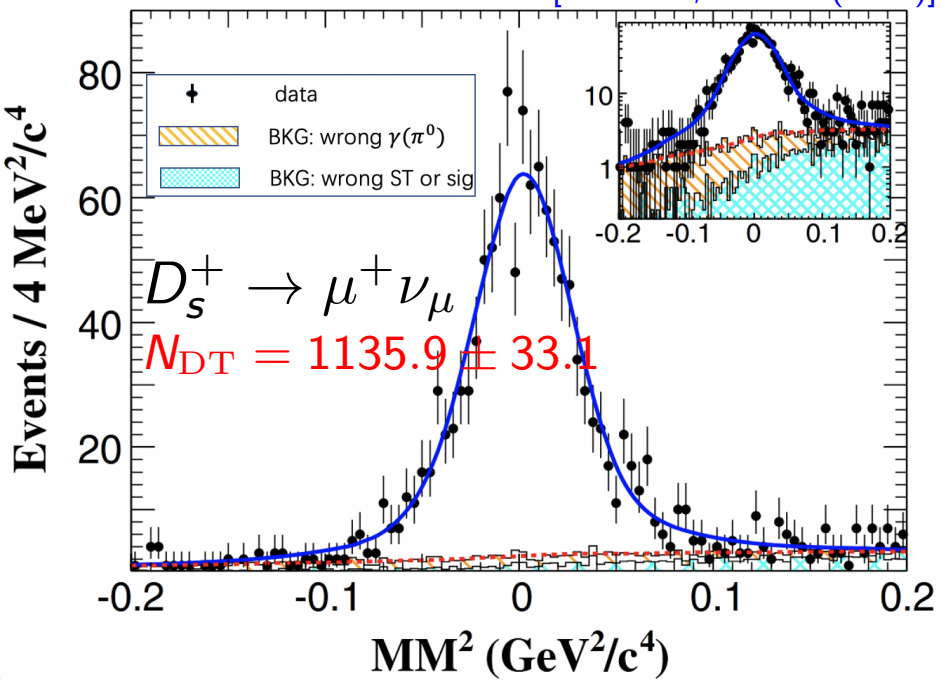
non-μ, π-like

π-like

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.517 \pm 0.075 \pm 0.021)\%$

$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (3.28 \pm 1.83 \pm 0.37)\%$

3.19 fb^{-1} @ 4.178 GeV [PRL **122**, 071802 (2019)]

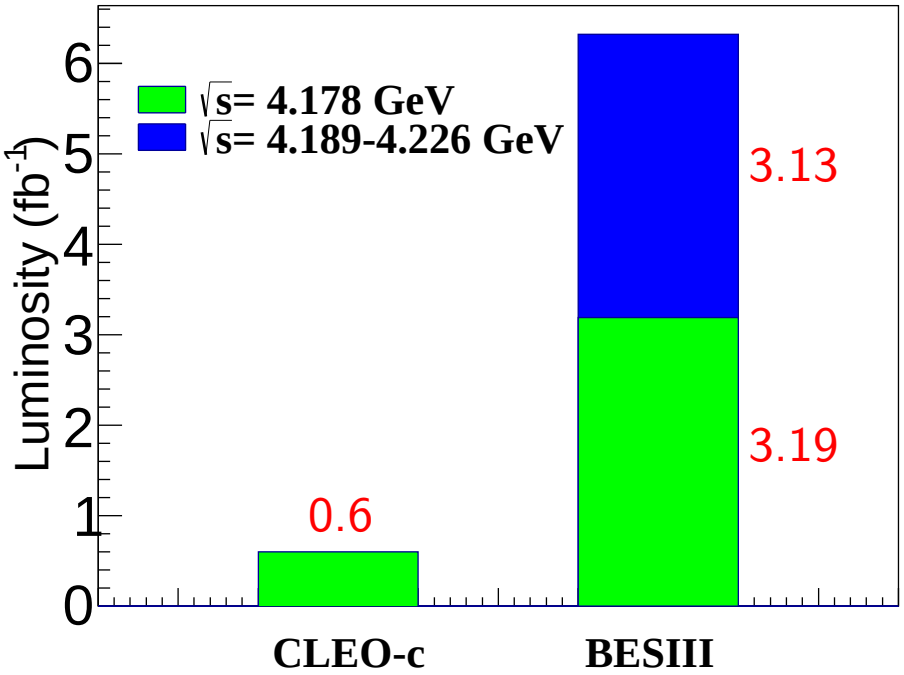


$N(\mu^+\nu_\mu) = 72.4 \pm 10.4$

$N(\tau^+\nu_\tau) = 22.1 \pm 12.3$

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.549 \pm 0.016 \pm 0.015)\%$

BESIII Data sample near $D_sD_s^*$ threshold



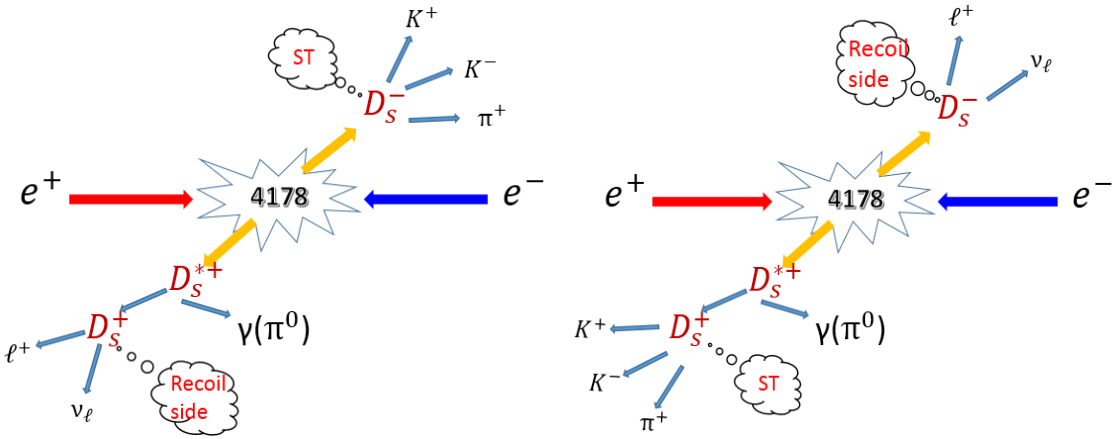
BESIII Data sample		
Year	$\sqrt{s}$ (GeV)	Luminosity (fb^{-1})
2016	4.178	3.19
2017	4.189	0.53
2017	4.199	0.53
2017	4.209	0.52
2017	4.219	0.51
2013	4.226	1.05
Sum		6.32

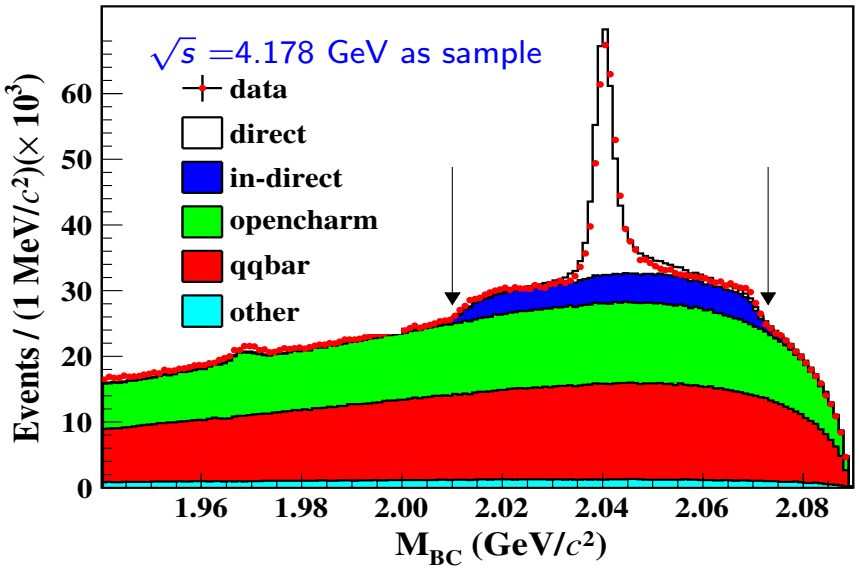
Precisions (Stat.&Syst.) (CLEO): $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$: 8.5% $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$: 6.4%

With ∼10×CLEO-c data, what precisions BESIII can reach???

Double-tag method

direct: Tag D_s from e^+e^- in-direct: Tag D_s from D_s^*





Tag mode: $K^+K^-\pi^-$, ...

$$M_{\rm BC} = \sqrt{E^2_{\rm beam} - |\overrightarrow{p}_{tag}|^2},$$

suppress non-$D_sD_s^*$ background

$$N_{\rm ST} = 2N_{D_s^-D_s^+}\mathcal{B}_{\rm tag}\epsilon_{\rm tag}$$

$$N_{\rm DT} = 2N_{D_s^-D_s^+}\mathcal{B}_{\rm tag}\mathcal{B}_{\rm sig}\epsilon_{\rm tag,sig}$$

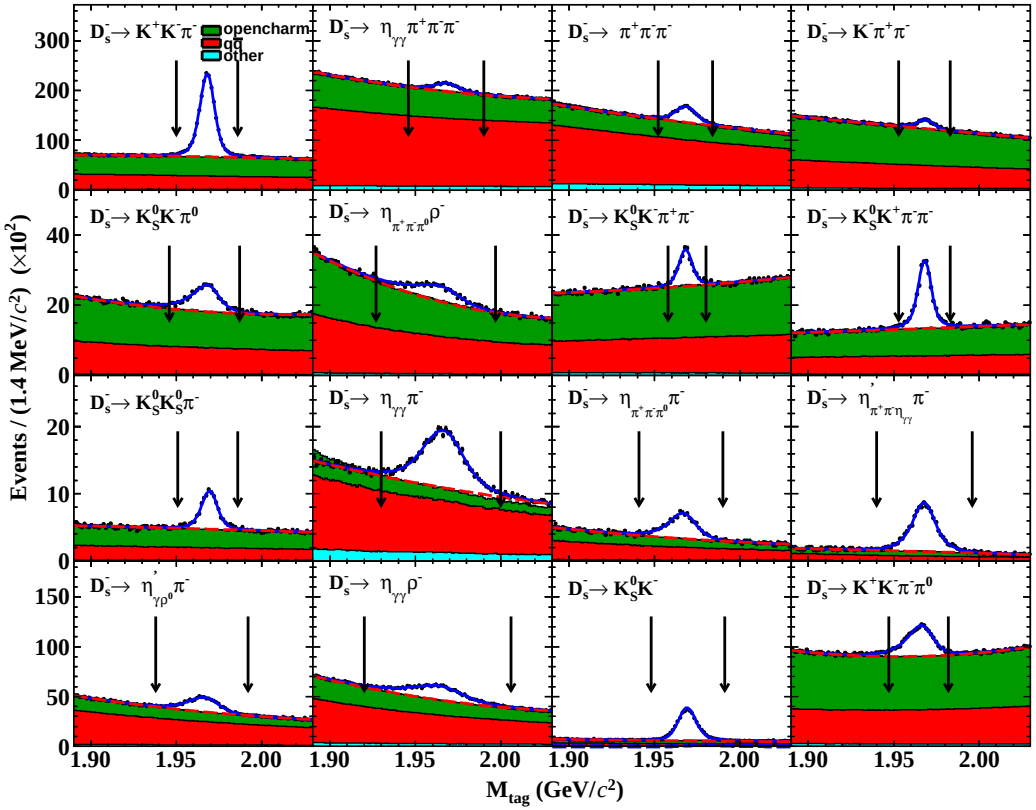
$$\mathcal{B}({\rm sig}) = \frac{N_{\rm DT}}{N_{\rm ST}\epsilon_{\rm DT}/\epsilon_{\rm ST}}$$

Double-tag method

16 possible single tags at BESIII

N_{ST}~0.78M with 16 tags @4.178-4.226 GeV

$\sqrt{s}$ =4.178 GeV as sample



signal side: X ($X = \pi, e, \mu$) is reconstructed, the missing neutrinos are determined by

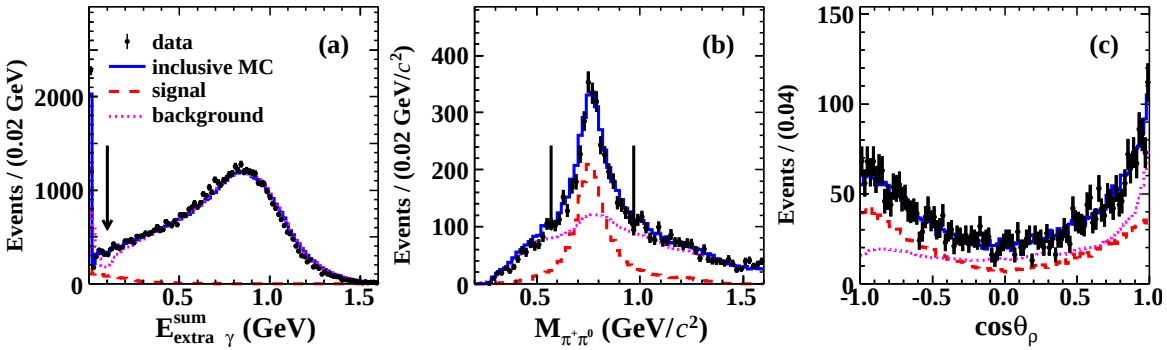
$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$$

$$E_{\rm miss} = E_{\rm cm} - \sqrt{|\vec{p}_{\rm tag}|^2 + m^2_{D_s}} - E_{\gamma(\pi^0)} - E_X$$

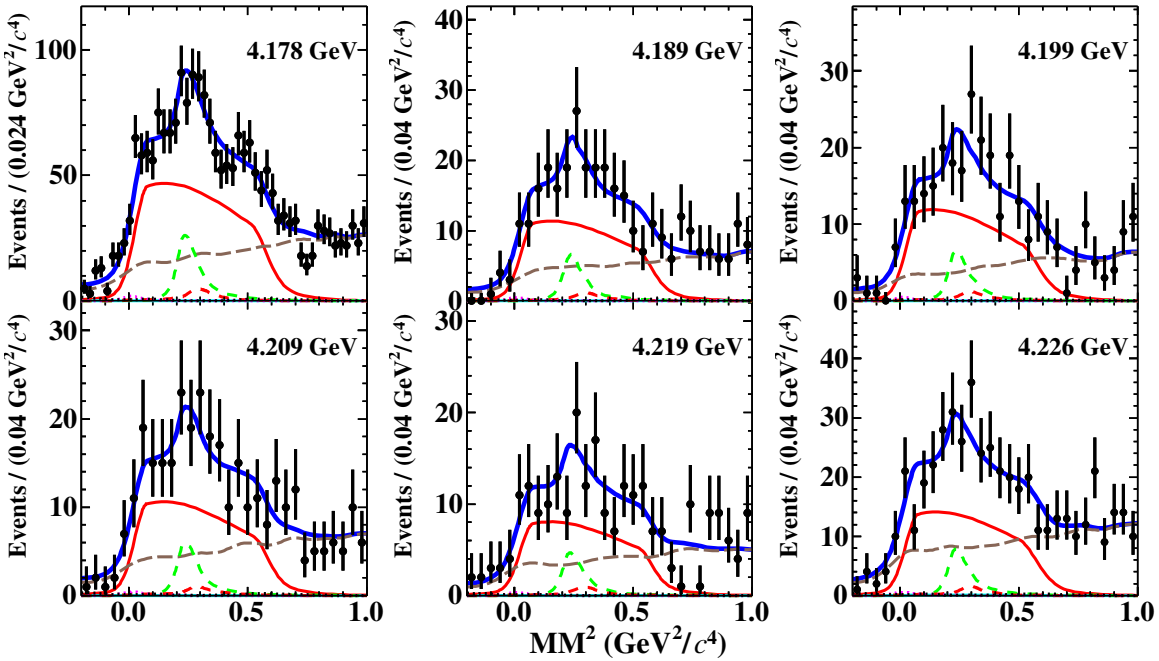
$$\vec{p}_{\rm miss} = -\vec{p}_{\rm tag} - \vec{p}_{\gamma(\pi^0)} - \vec{p}_X$$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$ [arXiv:2105.07178]

Comparison of typical distributions between data/MC



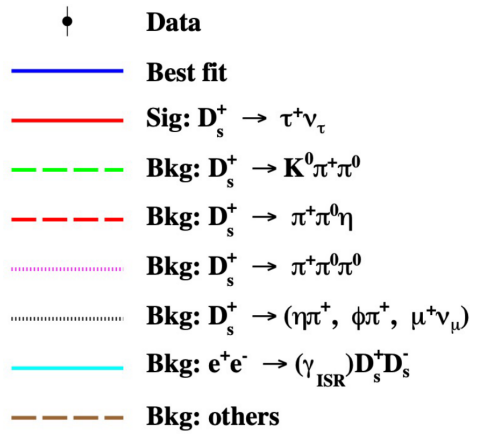
Simultaneous fit to $M^2_{\rm miss}$ @$\sqrt{s}$ =4.178-4.226 GeV



$$N_{\rm DT} = 1745 \pm 84$$

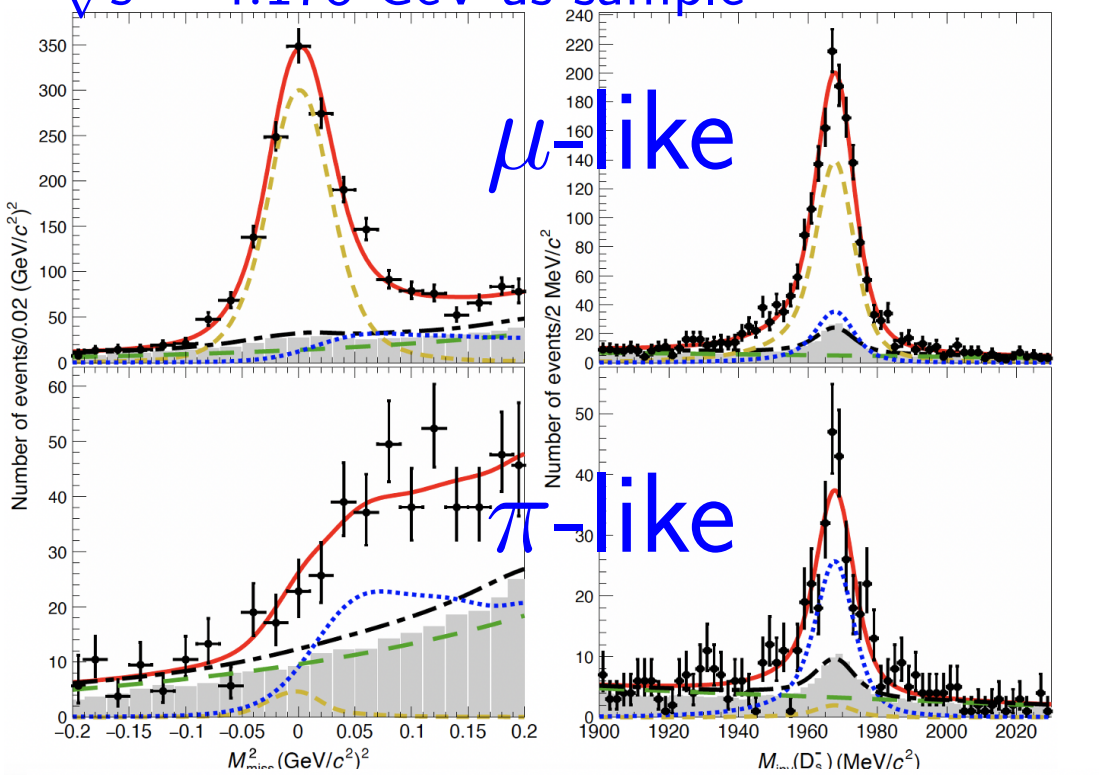
$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.29 \pm 0.25 \pm 0.20)\%$$

$$f_{D_s^+}|V_{cs}| = (244.8 \pm 5.8 \pm 4.8)\ \text{MeV}$$



$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to \pi^+\bar{\nu}_\tau$ [arXiv:2102.11734]

$\sqrt{s} = 4.178$ GeV as sample



Split data into two parts

- μ-like (upper): $E_{\rm EMC} \leq 300$ MeV, mixture of $D_s^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$ and $D_s^+ \to \mu^+\nu_\nu$
- π-like (lower): $E_{\rm EMC} > 300$ MeV, dominated of $D_s^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$

$N(D_s^+ \to \mu^+\nu_\mu) = 2198 \pm 55$

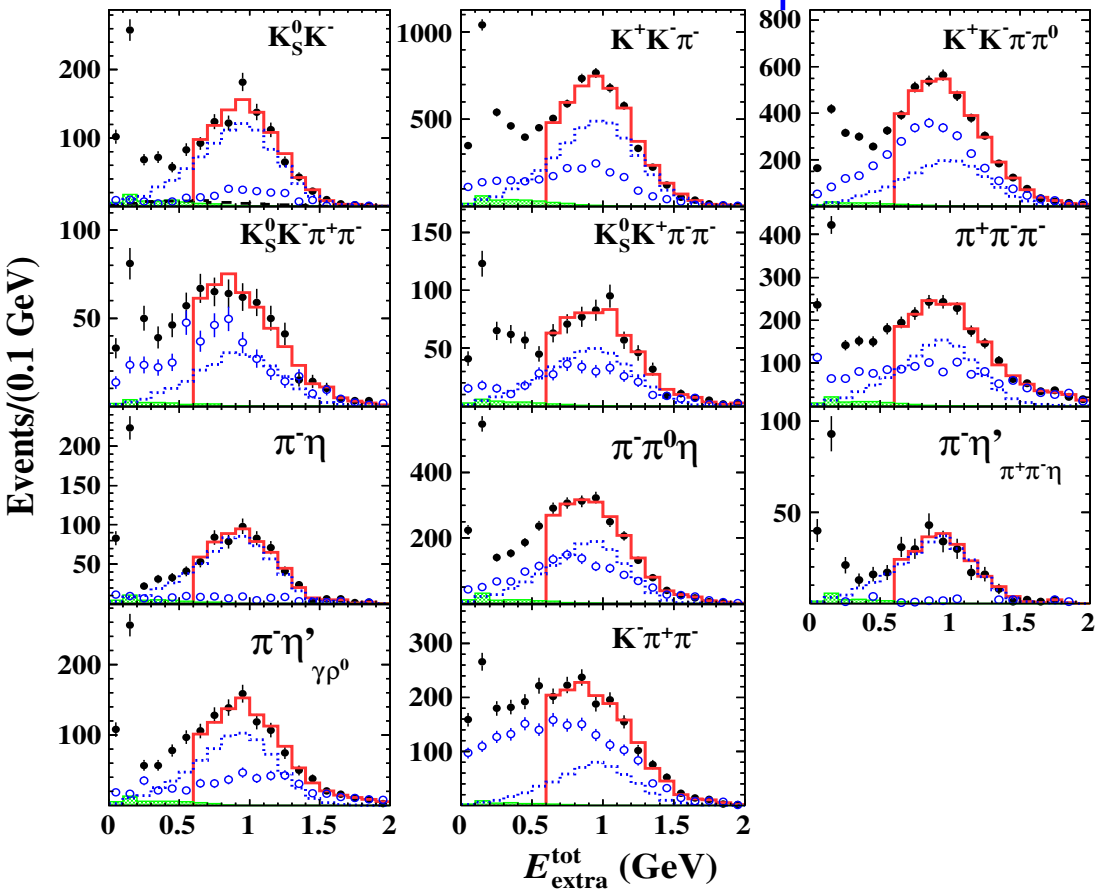
$N(D_s^+ \to \tau^+\nu_\tau) = 946^{+46}_{-45}$

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.535 \pm 0.013 \pm 0.016)\%$ $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25 \pm 0.17)\%$

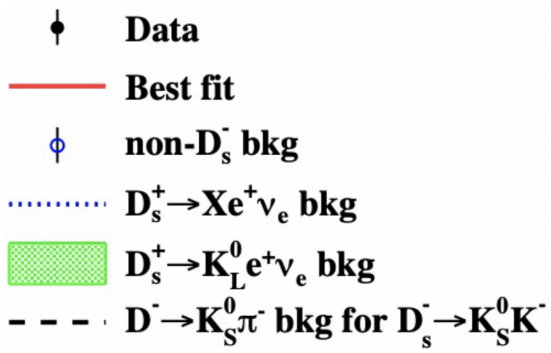
*Note: $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$ is an independent measurement and well consistent with BESIII previous result at 4.178 GeV. There exist anti-correlation between $D_s^+ \to \mu^+\nu_\mu$ and $\tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$

$D_s^+ \to \tau^+\nu_\tau$ via $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ [arXiv:2106.02218]

All data sample



- Signal peak at $E_{\rm extra}^{tot} < 0.4$ GeV
- BKG estimated with $E_{\rm extra}^{tot} > 0.6$ GeV, extrapolate to signal region



- $E_{\rm extra}^{\rm tot}$: the total energy of the good EMC showers, excluding FSR and those associated in ST
- $N_{\rm DT}^{\rm tot} = 4940 \pm 94$
- $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.27 \pm 0.10 \pm 0.12)\%$
- $f_{D_s^+}|V_{cs}| = (244.4 \pm 2.3 \pm 2.9)$ MeV

Averaged results

BESIII results	
Mode	$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$
$\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$	$(5.29 \pm 0.25 \pm 0.20)\%$
$\tau^+ \to \pi^+\bar{\nu}_\tau$	$(5.21 \pm 0.25 \pm 0.17)\%$
$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$	$(5.27 \pm 0.10 \pm 0.12)\%$
Average	$(5.26 \pm 0.09 \pm 0.09)\%$

(The correlated uncertainties of single-tag yields, tag bias, $\pi^\pm$ tracking/PID are considered)

Test LUV: $\mathcal{R}(\tau/\mu)_{\rm BESIII} = \dfrac{\mathcal{B}(D_s^+\to\tau^+\nu_\tau)^{4.178-4.226}/\tau_{D_s^+}}{\mathcal{B}(D_s^+\to\mu^+\nu_\mu)^{4.178}/\tau_{D_s^+}} = 9.58 \pm 0.44$

With the values of G_F, m_{D_s}, m_τ, and τ_{D_s} [PDG 2020],

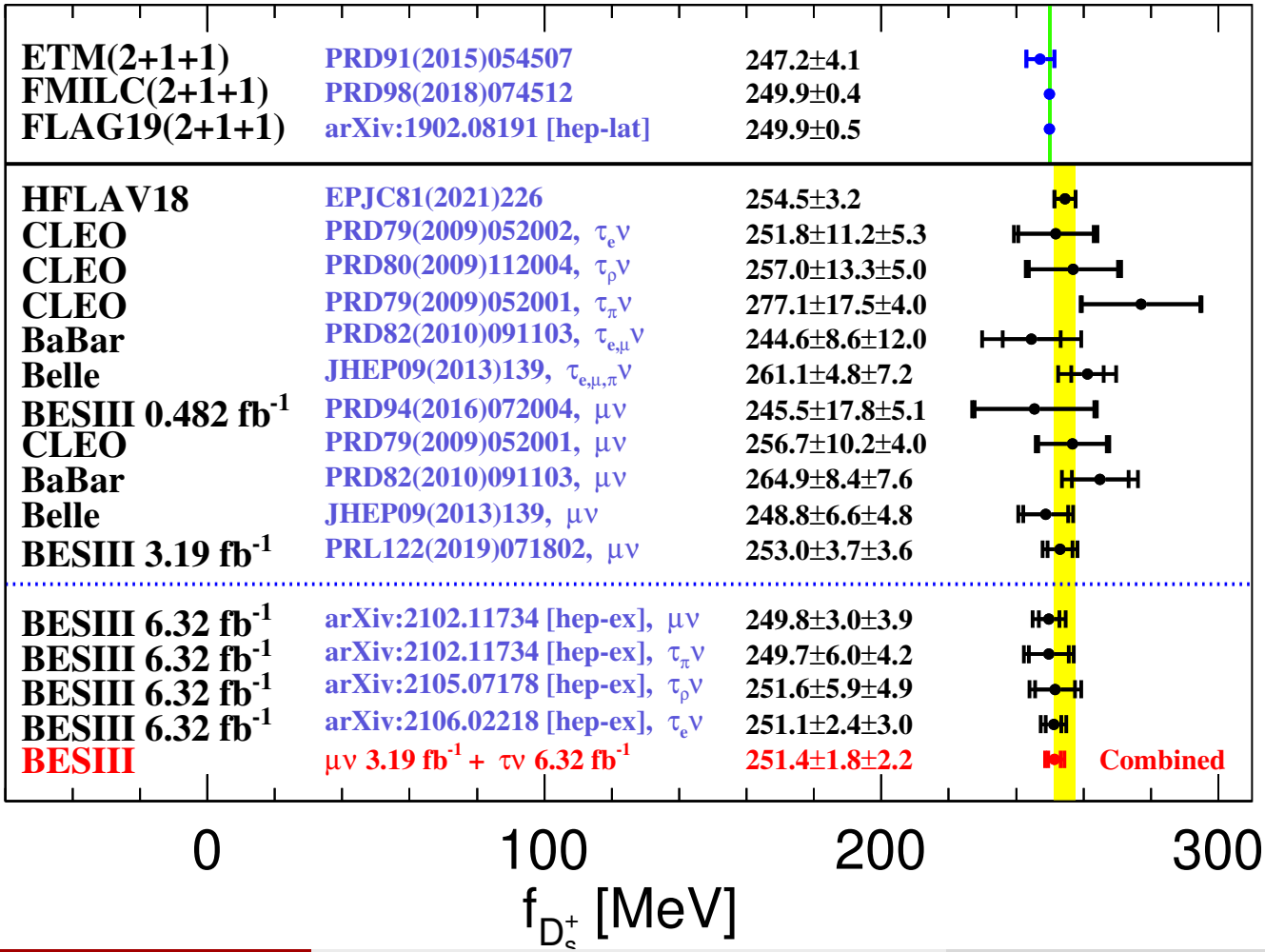
$f_{D_s^+}|V_{cs}|^{4.178-4.226}_{\tau^+\nu_\tau} = (244.1 \pm 2.1 \pm 2.3)$ MeV $f_{D_s^+}|V_{cs}|^{4.178}_{\mu^+\nu_\mu} = (246.2 \pm 3.6 \pm 3.5)$ MeV

The averaged $f_{D_s^+}|V_{cs}|_{\rm BESIII} = (244.7 \pm 1.8 \pm 2.1)$ MeV

Note: $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$ quoted from BESIII result @4.178 GeV

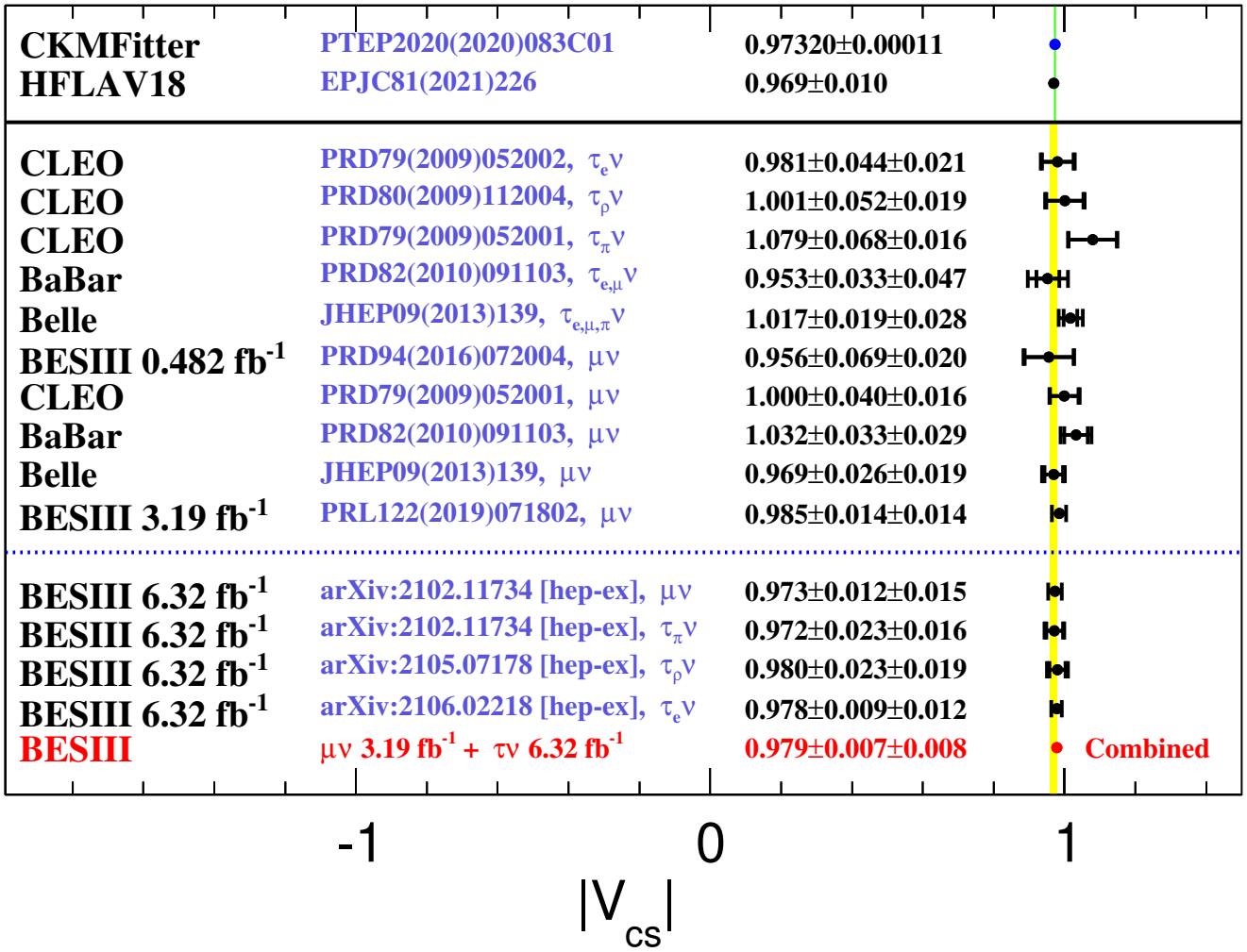
Comparison of $f_{D_s^+}$

With the values of G_F, m_{D_s}, m_τ, and τ_{D_s} [PDG 2020].
Input $|V_{cs}|_{\mathrm{CKMFitter}} = 0.97320 \pm 0.00011$



Comparison of $|V_{cs}|$

With the value of G_F, m_{D_s}, m_τ, and τ_{D_s} [PDG 2020].
Input $f_{D_s^+\,LQCD} = (249.9 \pm 0.5)$ MeV



Summary

Precise measurements of $D_s^+ \to \tau^+\nu_\tau$ and $D_s^+ \to \mu^+\nu_\mu$ using 6.32 fb^{-1} data at $\sqrt{s}$ =4.178-4.226 GeV have been reported by BESIII

- The precision (Stat.&Syst.) of $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$ has greatly improvement $(2.7\times)$ compared with the averaged CLEO result. $(6.4\% \to 2.4\%)$
- Independent measurement of $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$ is reported and consistent with BESIII previous result at 4.178 GeV.
- The precisions of f_{D_s} and $|V_{cs}|$ (BESIII) have reached $\sim 1\%$
- $\mathcal{R}(\tau/\mu)_{\rm BESIII} = 9.58 \pm 0.44$, consistent with SM prediction (9.75 ± 0.01)

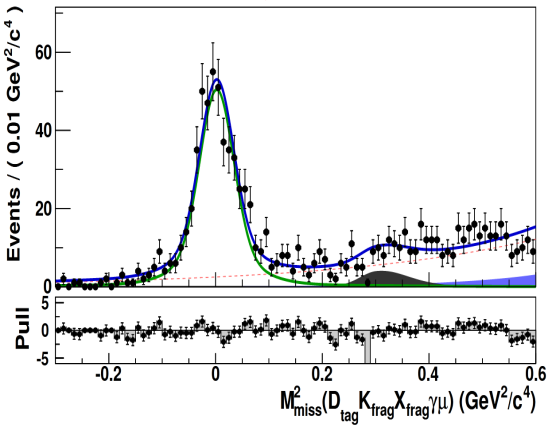
Thanks for your attention!

Backup

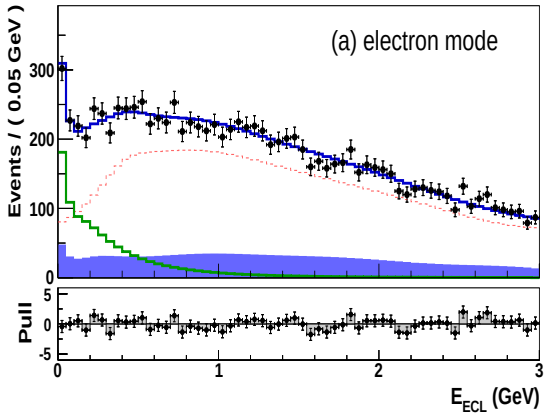
Overview: $D_s^+ \to \mu^+\nu_\mu, \tau^+\nu_\tau$ (Belle collaboration)

Data sample: 913 fb^{-1} near $\Upsilon(4S)$ and $\Upsilon(5S)$ [JHEP **09** (2013) 139]
$(e^+e^- \to c\bar{c} \to D_{\rm tag} K_{frag} X_{frag} D_s^{*-},\ D_s^{*-} \to D_s^-\gamma)$

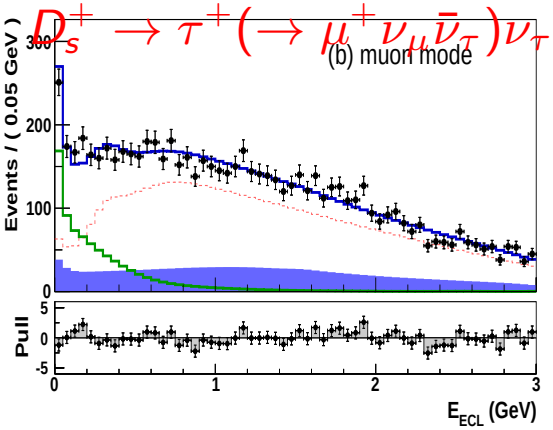
$D_s^+ \to \mu^+\nu_\mu$



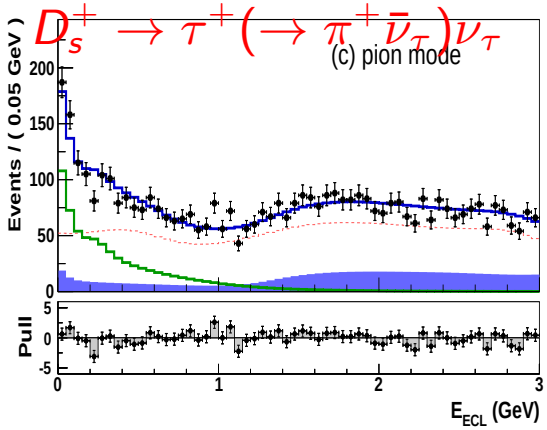
$D_s^+ \to \tau^+(\to e^+\nu_e\bar{\nu}_\tau)\nu_\tau$



$D_s^+ \to \tau^+(\to \mu^+\nu_\mu\bar{\nu}_\tau)\nu_\tau$



$D_s^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\nu_\tau$



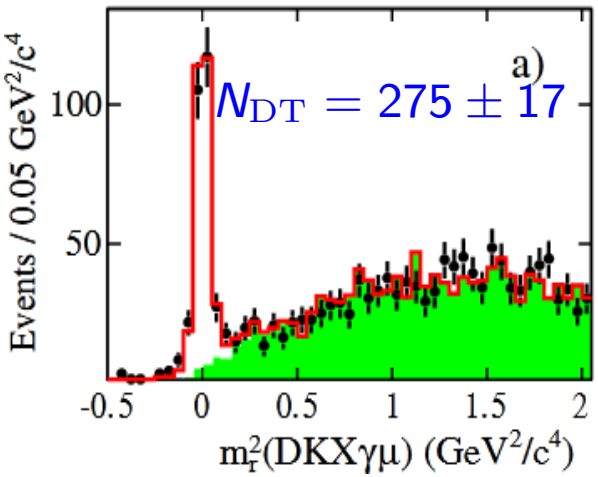
$N(D_s^+ \to \mu^+\nu_\mu) = 492 \pm 36$
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) =$
$(0.531 \pm 0.028 \pm 0.020)\%$

$N(D_s^+ \to \tau^+\nu_\tau) =$
2217 ± 83
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)_{\rm ave} =$
$(5.70 \pm 0.21^{+0.31}_{-0.30})\%$

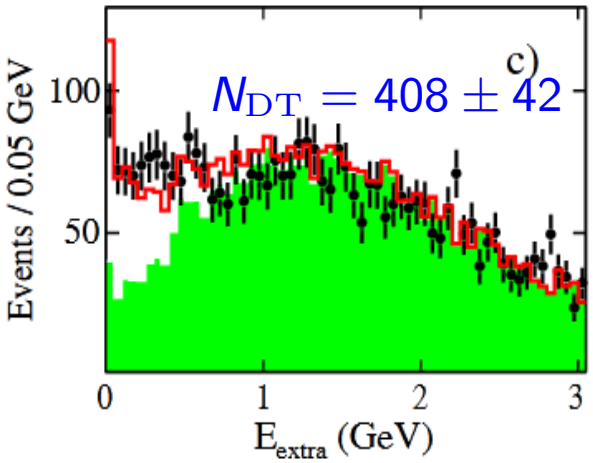
Overview: $D_s^+ \to \mu^+\nu_\mu, \tau^+\nu_\tau$ (BABAR collaboration)

Data sample: 521 fb^{-1} @ 10.58 GeV [PRD **82**, 091103(R) (2010)]
($e^+e^- \to c\bar{c} \to DKXD_s^{*-}$, $D_s^{*-} \to D_s^-\gamma$)

$D_s^+ \to \mu^+\nu_\mu$

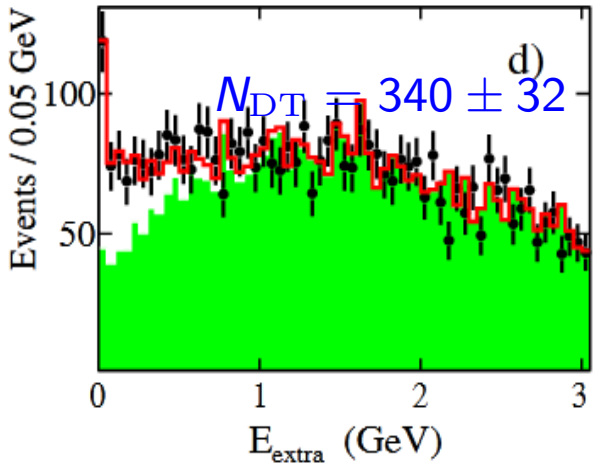


$D_s^+ \to \tau^+(\to e^+\nu_e\bar{\nu}_\tau)\nu_\tau$



$\mathcal{B} = (5.07 \pm 0.52 \pm 0.68)\%$

$D_s^+ \to \tau^+(\to \mu^+\nu_\mu\bar{\nu}_\tau)\nu_\tau$



$\mathcal{B} = (4.91 \pm 0.47 \pm 0.54)\%$

$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.602 \pm 0.038 \pm 0.034)\%$

$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)_{\rm ave} = (4.96 \pm 0.37 \pm 0.57)\%$