Open Charm Physics

International Workshop on e^+e^- collisions from Φ to Ψ

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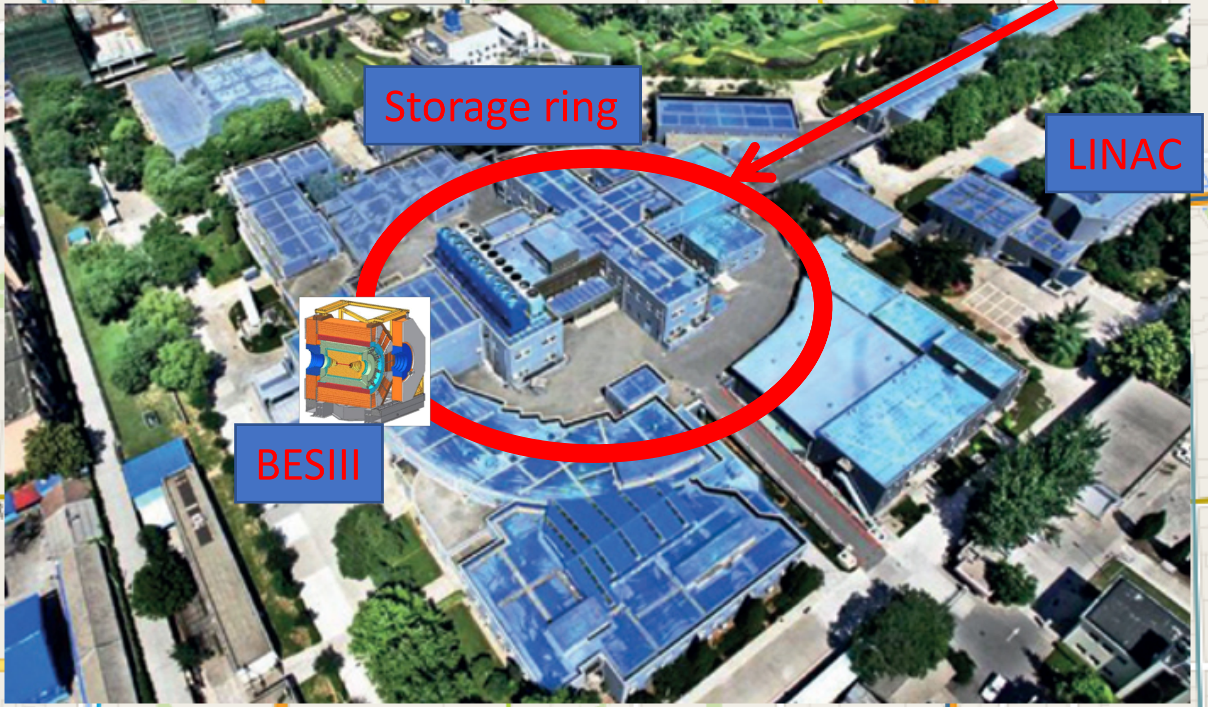
Dumplings

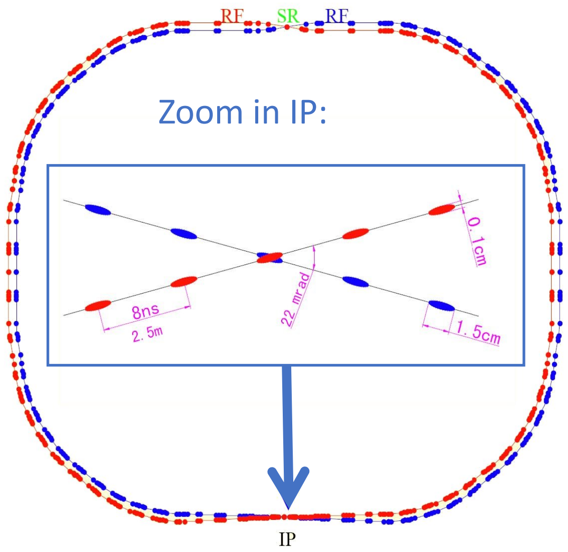


- Construction phase 2004-2008
  - Upgrade from BESII and BEPC
- First physics data taking 2009
- International collaboration
  - ~450 authors

The BESIII Experiment

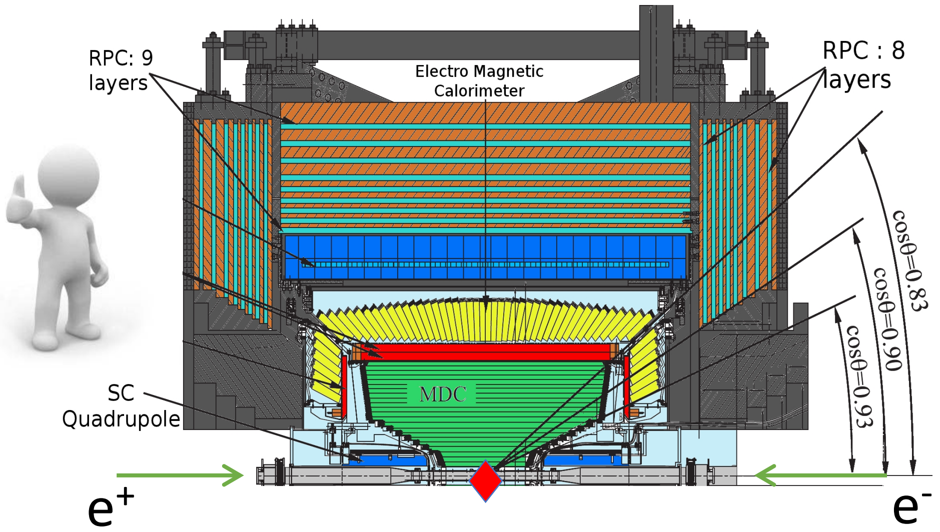
Beijing-Electron-Positron Collider II

- e^+e^- collisions with $\sqrt{s} = 2.0 - 4.6 GeV$
- Direct production of charmonia
- Luminosity $\mathcal{L} = 1\times10^{33} cm^{-2} s^{-1}$

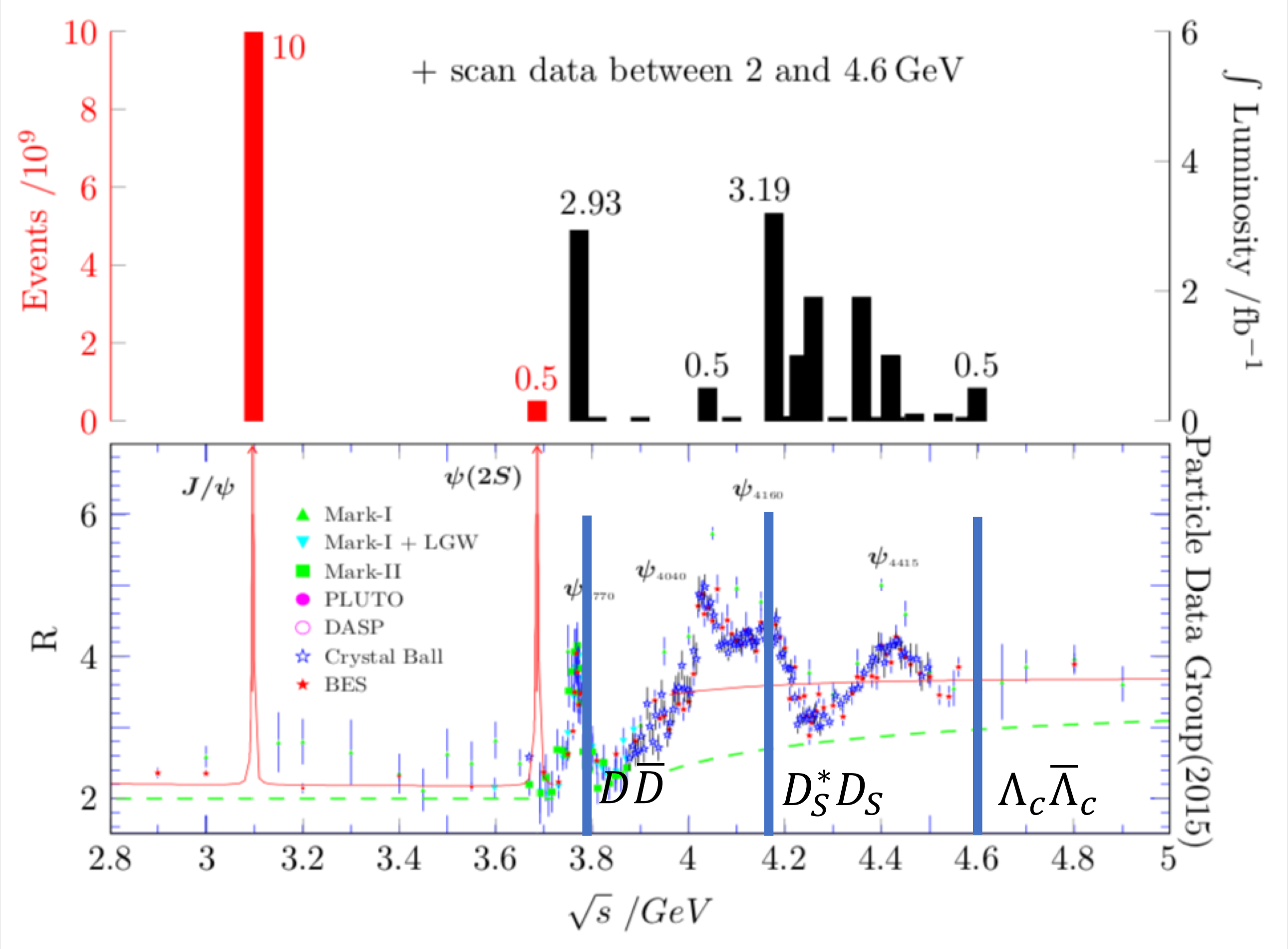


The detector

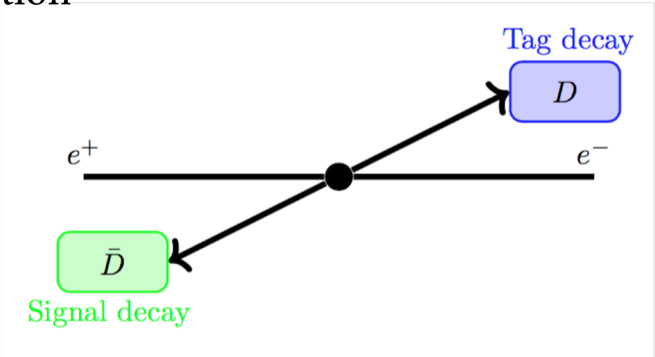
- 93% coverage of the full solid angle
- Main drift chamber $\sigma_p/p = 0.5\%@1GeV$
- Time-of-flight system $\sigma_T = 80ps$
- Elmg. Calorimeter $\Delta E/E = 2.5\%@1GeV$
- Superconducting $1T$ magnet
- Muon system (RPC)



Charm production @ threshold



- Large samples throughout the charmonium region
- Conservation laws hold for the combined decay amplitude
  - ‘Tag’ information of the signal decay
  - D^0 flavour, CP
  - Predict missing track
  - Normalization

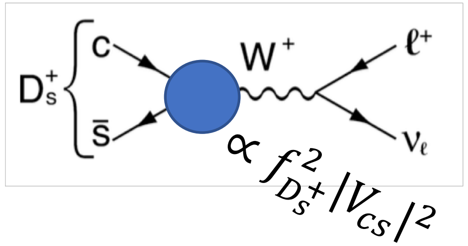


Charm physics @ BESIII

- Decay constants, form factors, CKM $V_{cd(s)}$
  - Dynamics of $D_S^+ \to \mu^+ \upsilon$
  - Dynamics of $D^0 \to K^-\mu^+\upsilon$
- Test of lepton number/flavour conservation laws
  - Search for $D \to K\pi e^+ e^+$
- Study of intermediate states
  - $D \to \pi\pi e^+ \upsilon_e$
  - Amplitude analysis $D^+ \to K_S\pi^+\pi^+\pi^-$
- Study of Λ_c baryons
  - Presented by Kai Zhu yesterday
- D^0 mixing and strong phases
  - Presented at CKM18 by Evelina Gersabeck

Decay constants, form factors, CKM $V_{cd(s)}$

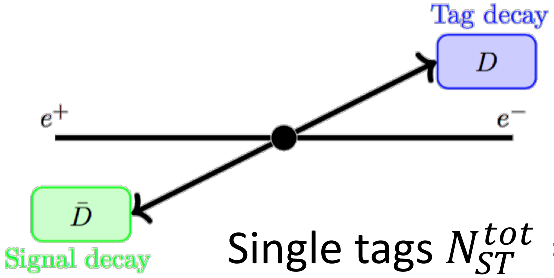
Dynamics of $D_S^+ \to \mu^+ \upsilon$



- $3.19 \mathrm{fb}^{-1}$ @ $\sqrt{s} = 4.178 GeV$ ($D_S^* D_S$ threshold)
- Decay rate

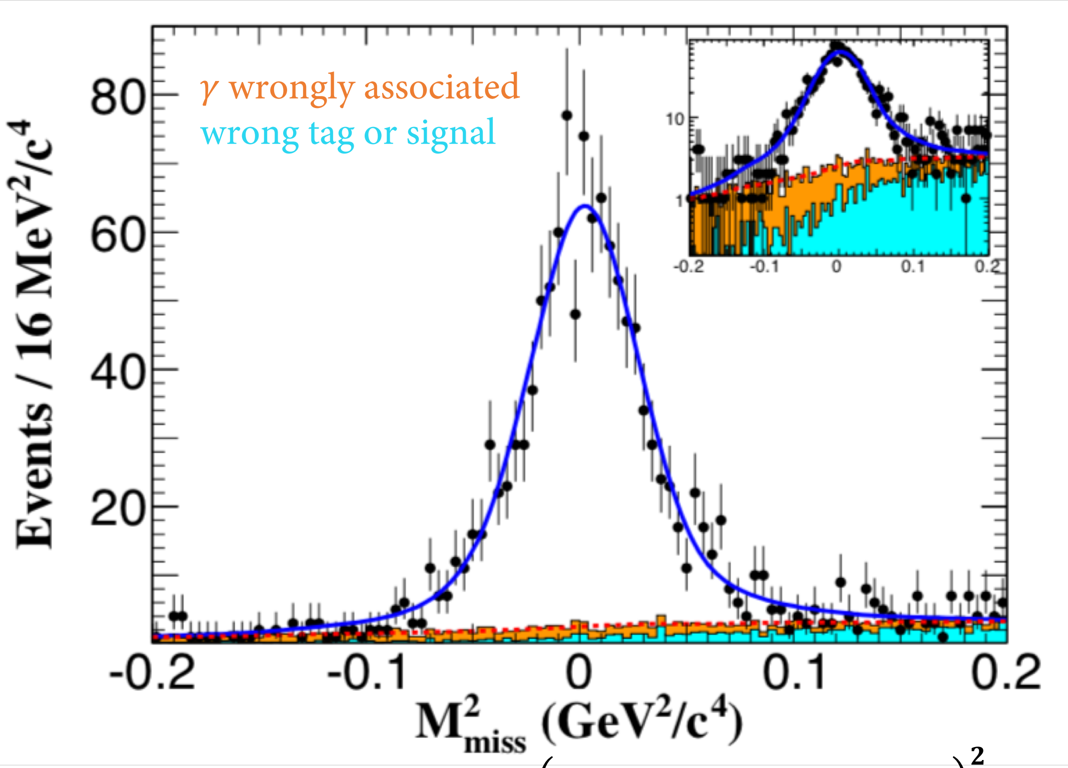
$$\Gamma_{D_s^+ \to \ell^+ \nu_\ell} = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s^+}^2 m_\ell^2 m_{D_s^+} \left(1 - \frac{m_\ell^2}{m_{D_s^+}^2}\right)^2$$

- Extract $f_{D_S^+}^2 \cdot |V_{cs}|^2$ from a measurement of the decay rate
- Analyse $D_S^{*+} \to D_S^+ \gamma(\pi^0)$



14 tag modes:
$K_S^+ K^-$
$K^+ K^- \pi^-$
$K_S^+ K^- \pi^0$
...

Single tags $N_{ST}^{tot} = 388660 \pm 2592$



$= \left(\mathbf{p}_{cm} - \mathbf{p}_{tag} - \mathbf{p}_{\gamma(\pi^0)} - \mathbf{p}_\mu\right)^2$

$$\mathcal{B}_{D_S^+ \to \mu^+ \upsilon} = (5.49 \pm \underset{(\text{stat.})}{0.16} \pm \underset{(\text{sys.})}{0.15}) \times 10^{-3}$$

Signal yield $N_{DT} = 1135.9 \pm 33.1$

PRL122(2019)071802

Dynamics of $D_s^+ \to \mu^+ \upsilon$

- Result:

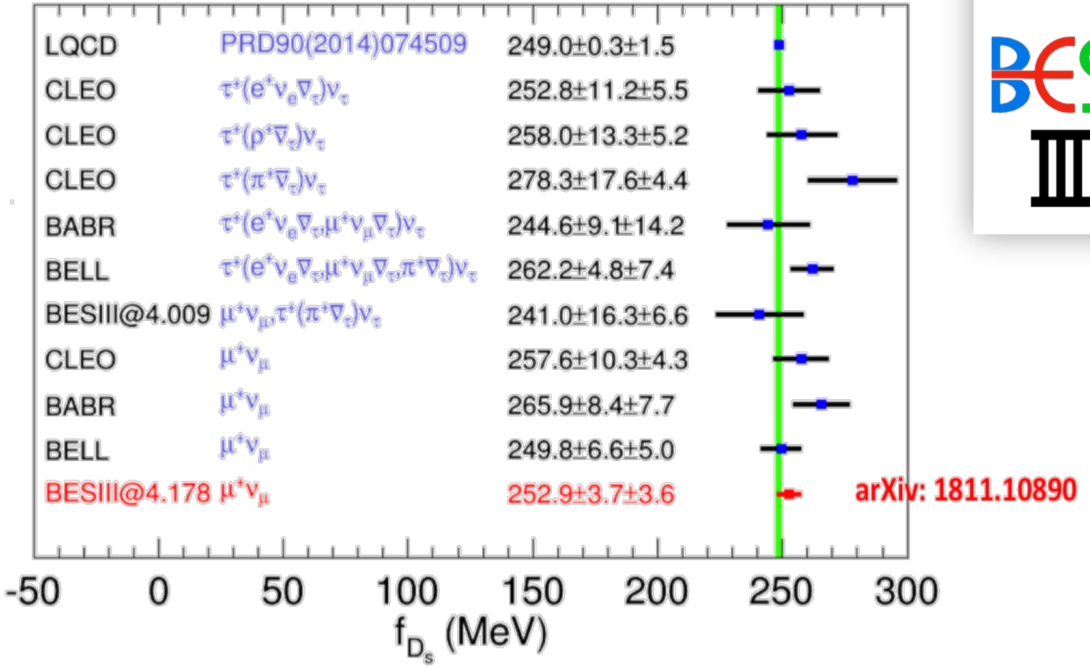
$$f_{D_s^+}|V_{cs}| = 246.2 \pm 3.6_{\mathrm{stat.}} \pm 3.5_{\mathrm{syst.}}\ \mathrm{MeV}$$

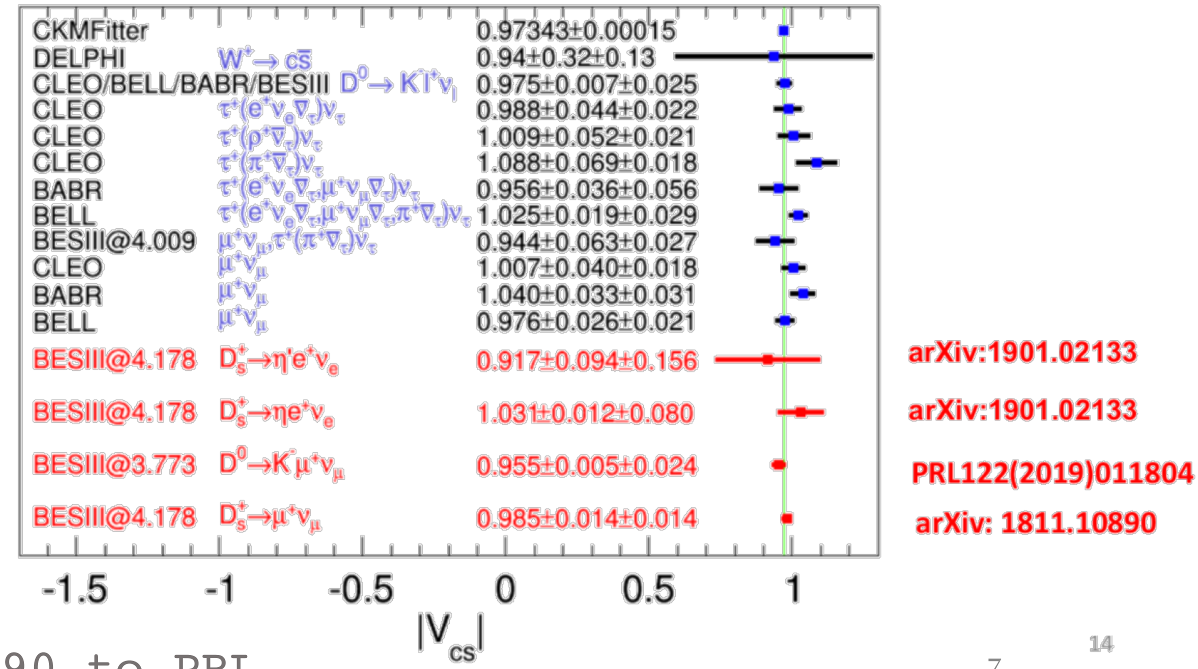
- External Input from LQCD Phys.Rev.D98, 074512 (2018) Phys.Rev.D91, 054507 (2015) and PDG (2018)

- Interfered results:

$$f_{D_s^+} = 252.9 \pm 3.7_{\mathrm{stat.}} \pm 3.6_{\mathrm{syst.}}\ \mathrm{MeV}$$

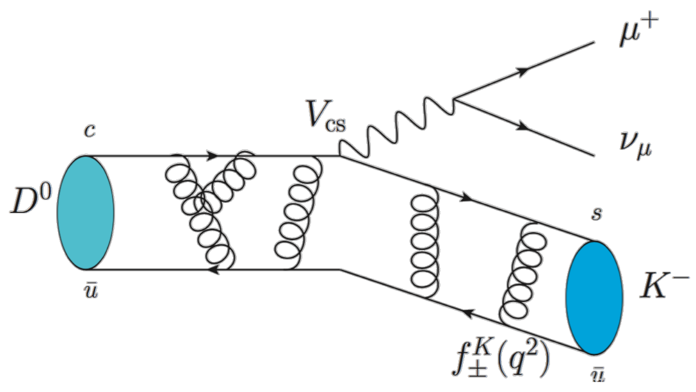
$$|V_{cs}| = 0.985 \pm 0.014_{\mathrm{stat.}} \pm 0.014_{\mathrm{syst.}}.$$





arXiv:1811.108090,to PRL

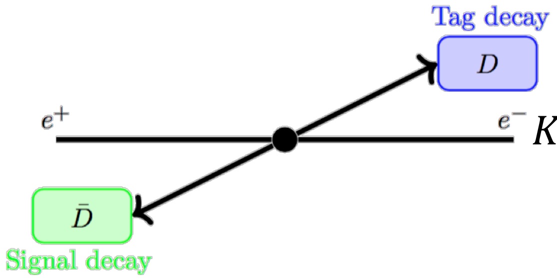
Dynamics of $D^0 \to K^- \mu^+ \upsilon$



- 2.93fb^{-1} @ $\sqrt{s} = 3.77GeV$ ($D\bar{D}$ threshold)
- Decay rate

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cs}|^2}{5\pi^3 m_D} |\vec{p}_K| \left|f_+^K(q^2)\right|^2 \left(\frac{W_0 - E_K}{F_0}\right)^2 H(q^2)$$

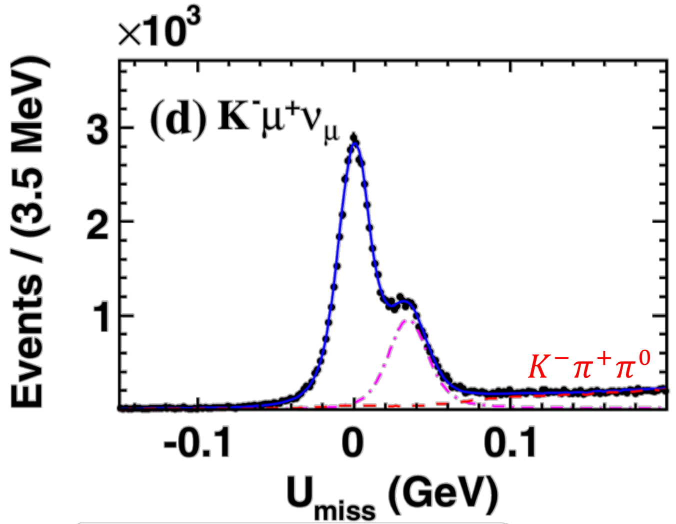
- Extract $|f_+^K(q^2)|^2 |V_{cs}|^2$ from a measurement of the decay rate in bins of q^2



3 tag modes:
$K^+\pi^-$
$K^+\pi^-\pi^0$
$K^+\pi^-\pi^-\pi^+$
...

Single tags $N_{ST}^{tot} = 2341408 \pm 2056$

- Branching fraction measurement



$= E_{miss} - |\vec{p}_{miss}|$

Double tags $N_{DT} = 447100 \pm 259$

significant improvement w.r.t PDG

$$\mathcal{B}_{D^0 \to K^-\mu^+\upsilon} = (3.413 \underset{\text{(stat.)}}{\pm 0.019} \underset{\text{(sys.)}}{\pm 0.035})\%$$

PRL122(2019)011804

Dynamics of $D^0 \to K^- \mu^+ \upsilon$

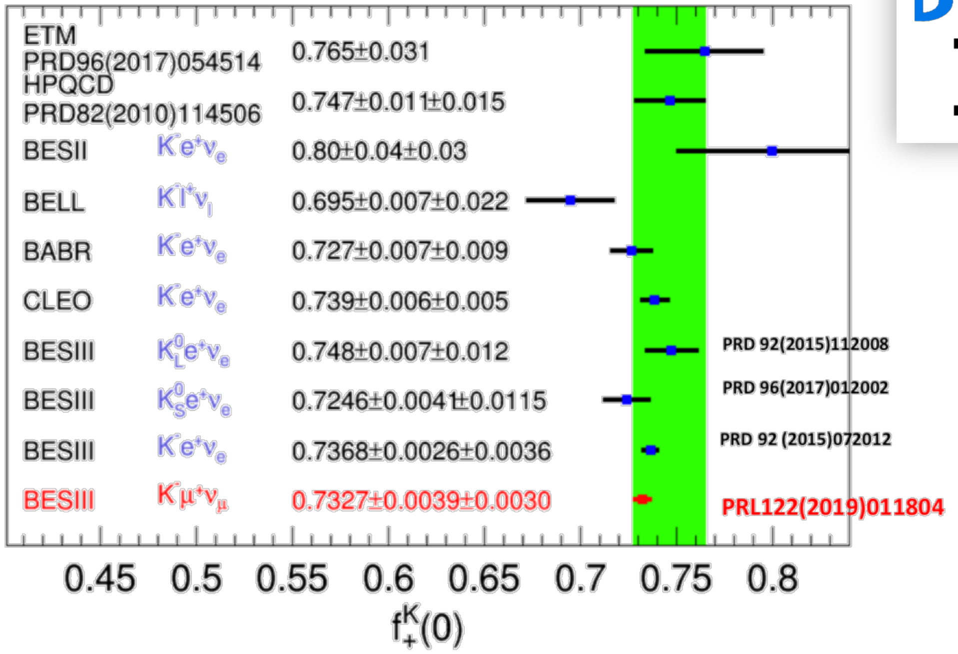
- Result extrapolated to $q = 0$:

$$f_+^K(0)|V_{cs}| = 0.7133 \underset{\text{(stat.)}}{\pm 0.0038} \underset{\text{(sys.)}}{\pm 0.0029}$$

- External Input from LQCD and PDG (2018)
  PRD82,114506(2010)
- Interfered results:

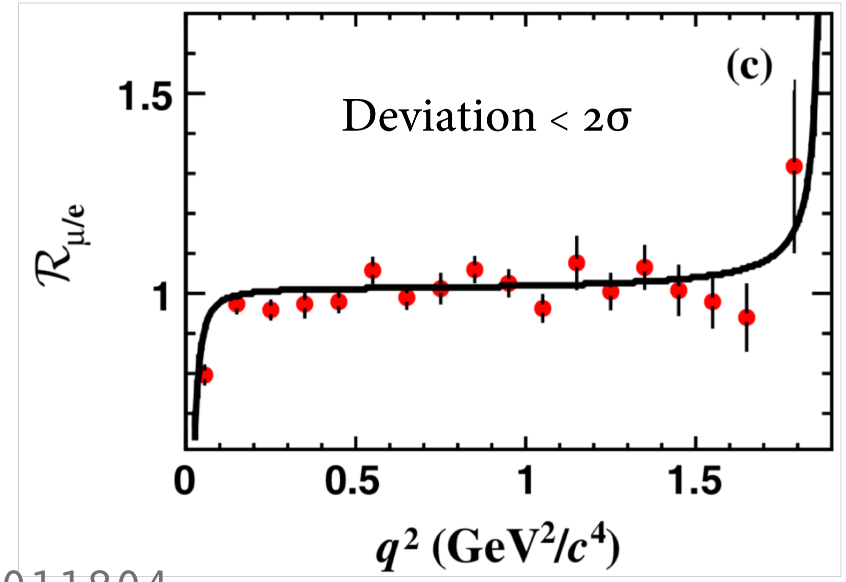
$$f_+^K(0) = 0.7327 \underset{\text{(stat.)}}{\pm 0.0039} \underset{\text{(sys.)}}{\pm 0.0030}$$

$$|V_{cs}| = 0.955 \underset{\text{(stat.)}}{\pm 0.005} \underset{\text{(sys.)}}{\pm 0.004} \underset{\text{(LQCD)}}{\pm 0.024}$$



- Test lepton flavour universality
  - Combine with $\Gamma_{D^0 \to K^- e^+ \nu_e}$

$$R_{\mu/e} = \frac{\Gamma(D^0 \to K^- \mu^+ \nu_\mu)}{\Gamma(D^0 \to K^- e^+ \nu_e)} = 0.974 \pm 0.007 \pm 0.012$$

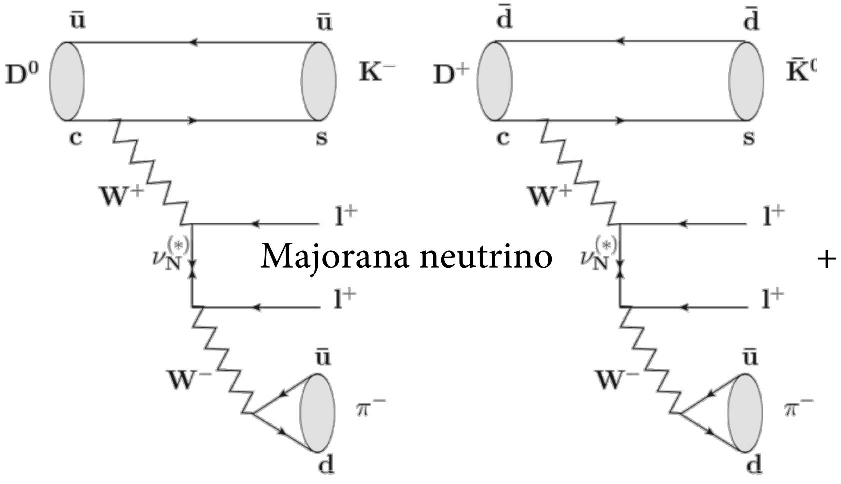


  - No evidence for lepton flavour universality violations

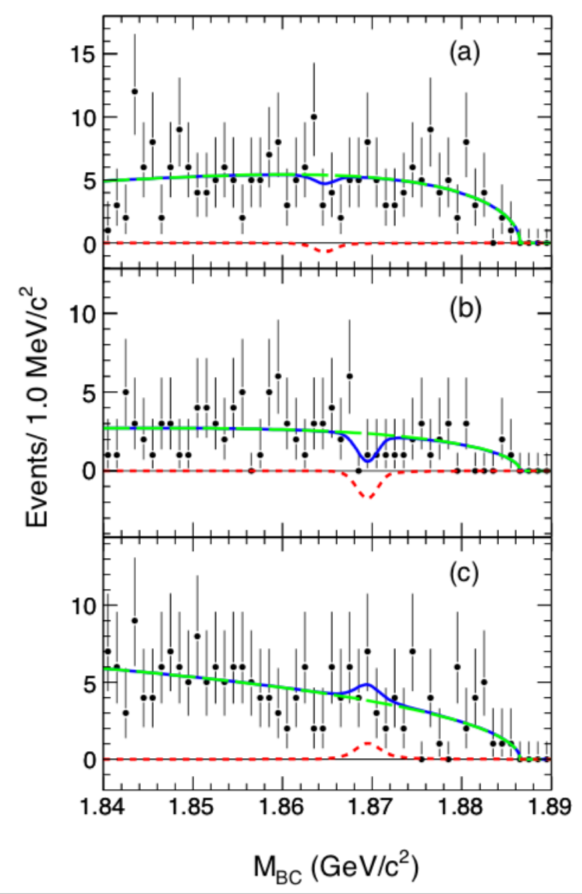
PRL122(2019)011804

Test of lepton number/flavour conservation laws

Search for $D \to K\pi e^+e^+$



+ DCS diagrams



$D^0 \to K^-\pi^-e^+e^+$
$\mathcal{B}_{sig}^{UL} < 2.7 \times 10^{-6}$

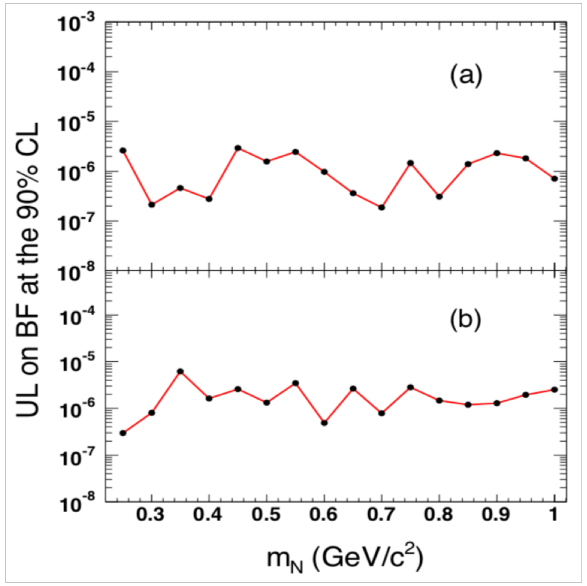
$D^+ \to K_S^0\pi^-e^+e^+$
$\mathcal{B}_{sig}^{UL} < 3.3 \times 10^{-6}$

$D^+ \to K^-\pi^0e^+e^+$
$\mathcal{B}_{sig}^{UL} < 8.5 \times 10^{-6}$

- Majorana neutrino $\to$ $\Delta L = 2$
- Data sample at $D\bar{D}$ threshold: 2.93fb^{-1} @ $\sqrt{s} = 3.773 GeV$
- Untagged measurement
  - Normalize to luminosity

$$\mathcal{B}_{D\to K\pi e^+e^+} = \frac{N_{\rm sig}}{2\cdot N^{\rm tot}_{\rm D\bar{D}}\cdot\epsilon\cdot\mathcal{B}},$$

- Search for Majorana neutrino at different masses

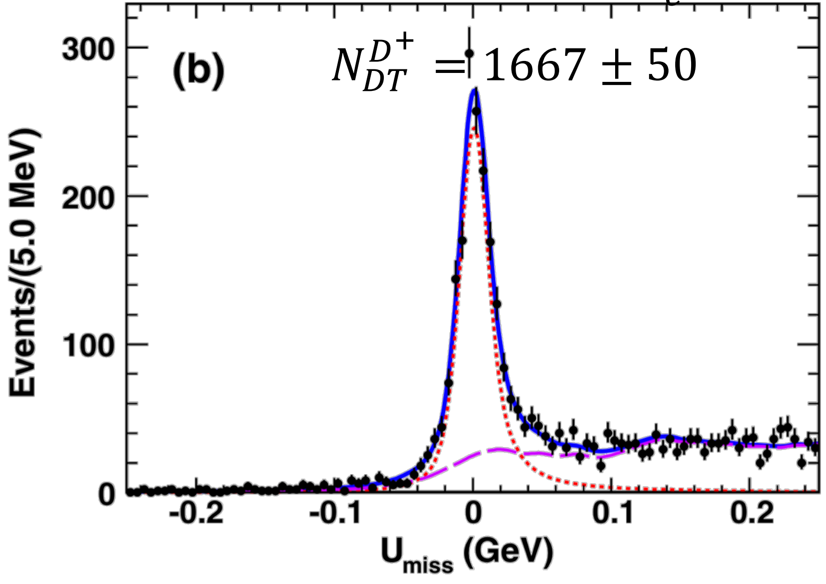


arXiv:1902.02450,to PRD

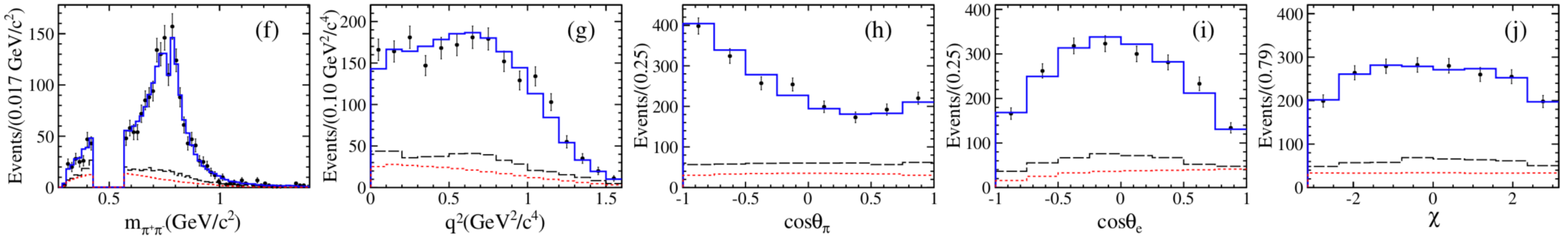
Study of intermediate states

Resonant states in $D \to \pi\pi e^+\nu_e$

- Nature of light scalar mesons $f_0(500)$, $f_0(980)$ and $a_0(980)$ still unclear
- Semi-leptonic D decays offer a clean production process
- 2.93fb^{-1} @ $\sqrt{s} = 3.77GeV$ ($D\bar{D}$ threshold)
- Partial-wave analysis
  - 5-dim phase space
  - dominant P-wave (ρ,ω), S-wave



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



PRL122(2019)062001

Resonant states in $D \to \pi\pi e^+ \nu_e$

PRD82(2010)034016

- Branching fractions from PWA

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

  - Simultaneous fit of neutral and charged modes
  - Upper limit on $f_0(980)$
  - Significance of $f_0(500) > 10\sigma$

- Test the nature of $f_0(500)$, $f_0(980)$ and $a_0(980)$ in a model independent way

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

  - R = 1.0 ± 0.3 → two-quark description
  - R = 3.0 ± 0.9 → SU(3) nonet tetraquark description.

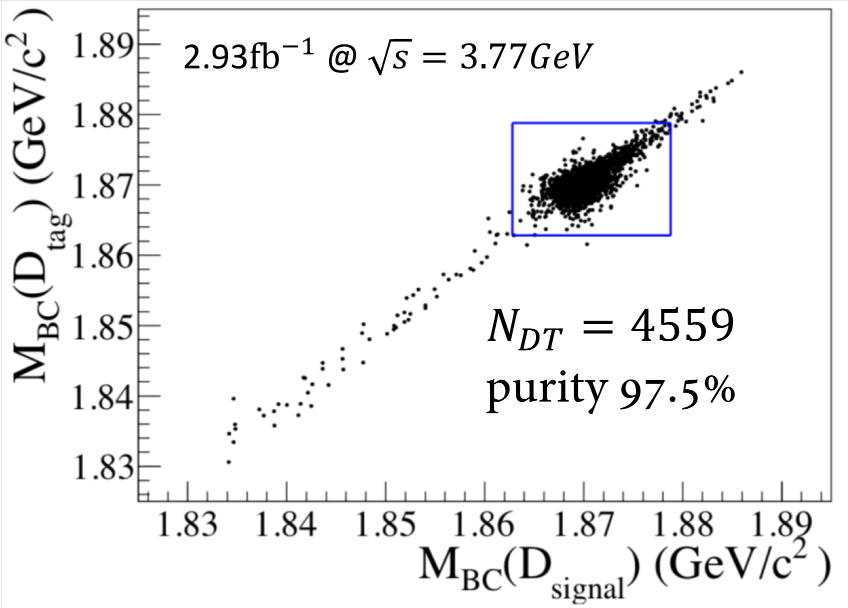
- Our result favors a tetraquark description

$R > 2.7$ @90%$C.L.$

PRL122(2019)062001

Amplitude analysis of $D^+ \to K_S\pi^+\pi^+\pi^-$

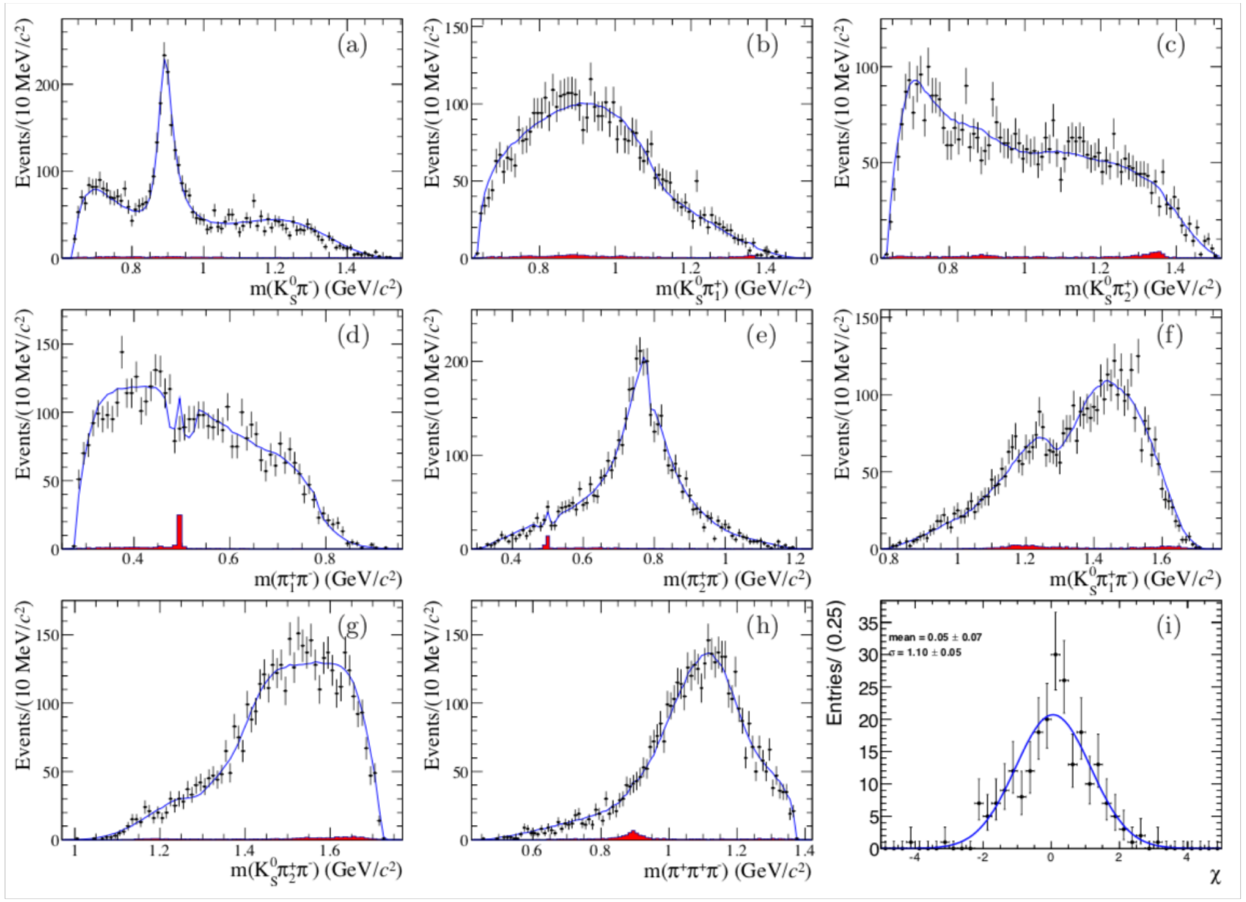
- Study dynamics of strong interaction at low energy + final state interaction effects
- Few results D→ *AP* decays
  - $D^+ \to K_S\pi^+\pi^+\pi^-$ @ MARKIII
    PRD45(1992)2196
- Compare to results of $D^0 \to K^-\pi^+\pi^+\pi^-$
  BESIII: PRD95(2017)072010
  LHCb: EPJC78(2018)443



- 5-dim phase space
- Covariant tensor formalism
- Parametrization:
  - $(K_S\pi)$ S-wave: effective range / LASS parametrization
    PRD78,034023(2008)
  - ϱ^0: Gounaris-Sakurai, inkl. $\varrho - \omega$ interference
  - Relativistic BW for other resonant states
- 13 significant amplitudes

 arXiv:1902.05936,to PRD

Amplitude analysis of $D^+ \to K_S \pi^+ \pi^+ \pi^-$



Component	Branching fraction (%)
$D^+ \to K^0_S a_1(1260)^+(\rho^0\pi^+)$	$1.197 \pm 0.062 \pm 0.086 \pm 0.044$
$D^+ \to K^0_S a_1(1260)^+(f_0(500)\pi^+)$	$0.163 \pm 0.021 \pm 0.005 \pm 0.006$
$D^+ \to \bar{K}_1(1400)^0(K^{*-}\pi^+)\pi^+$	$0.642 \pm 0.036 \pm 0.033 \pm 0.024$
$D^+ \to \bar{K}_1(1270)^0(K^0_S\rho^0)\pi^+$	$0.071 \pm 0.009 \pm 0.021 \pm 0.003$
$D^+ \to \bar{K}(1460)^0(K^{*-}\pi^+)\pi^+$	$0.202 \pm 0.018 \pm 0.006 \pm 0.007$
$D^+ \to \bar{K}(1460)^0(K^0_S\rho^0)\pi^+$	$0.024 \pm 0.006 \pm 0.015 \pm 0.009$
$D^+ \to \bar{K}_1(1650)^0(K^{*-}\pi^+)\pi^+$	$0.048 \pm 0.012 \pm 0.027 \pm 0.002$
$D^+ \to K^0_S\pi^+\rho^0$	$0.190 \pm 0.021 \pm 0.089 \pm 0.007$
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	$0.241 \pm 0.018 \pm 0.018 \pm 0.009$

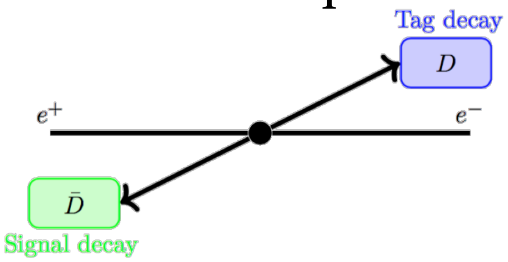
- Improved precision for sub decay modes
- Agreement with previous measurement
- Comparison with neural mode $D^0 \to K^-\pi^+\pi^+\pi^-$
  - $D^+ \to \bar{K}_1(1400)^0\pi^+$ larger

arXiv:1902.05936,to PRD

Summary

- BESIII provides large data samples close to charm related thresholds

- Correlated $D\overline{D}$ production offers unique opportunities
  - D^0 flavour and CP
  - Predict missing track
  - Normalization



- Long term perspective - large samples at charm thresholds
  - $D\overline{D}$ $2.93 fb^{-1} \rightarrow 20 fb^{-1}$
  - $D_S^* D_S$ $3.19 fb^{-1} \rightarrow 6 fb^{-1}$
  - $\Lambda_c \overline{\Lambda}_c$ $0.60 fb^{-1} \rightarrow 5 fb^{-1}$

- Decay constants, form factors, CKM $V_{cd(s)}$
  - Dynamics of $D_S^+ \rightarrow \mu^+ v$
  - Dynamics of $D^0 \rightarrow K^- \mu^+ v$

- Test of lepton number/flavour conservation laws
  - Search for $D \rightarrow K\pi e^+ e^+$

- Study of intermediate states
  - $D \rightarrow \pi\pi e^+ v_e$
  - Amplitude analysis $D^+ \rightarrow K_S \pi^+ \pi^+ \pi^-$

Thank you for your attention!