Precision measurements of charm decays

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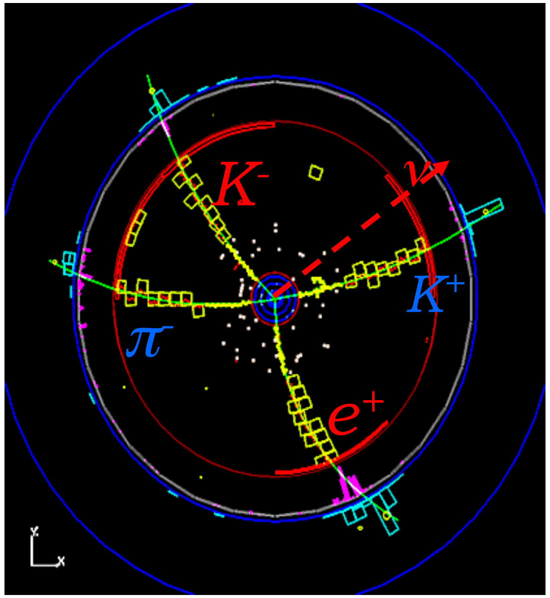
Outline

- **Introduction**
- **Data @ thresholds from e^+e^- collision: CLEO-c, BESIII**
- **Hadronic decays**
- **Rare and forbidden decays**
- **Lifetime of charmed baryons**
- **Future and summary**

Why still Charm?

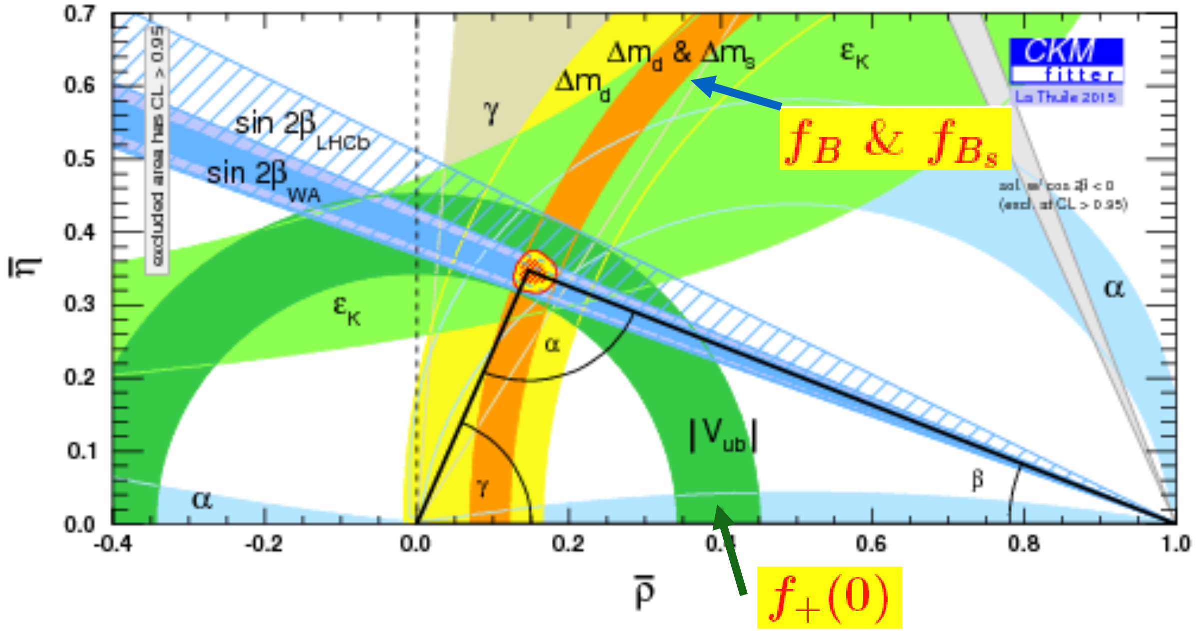
- **Why Charm is unique to test QCD in low energy?**
- **Why Charm allows us to overconstrain CKM in B decays?**
- **Why Charm can be used to probe New Physics beyond Standard Model?**



$$\psi(3770) \to D^0 \overline{D^0}$$

$$\overline{D^0} \to K^+\pi^-, D^0 \to K^- e^+ \nu$$

Precision theory + charm



Theoretical errors dominate width of bands

precision **QCD calculations tested with** ***precision*** **charm data at threshold**

→theory errors of a few % on B decay constants & semileptonic form factors

Charm Physics: the Context

Last Decade

Flavor physics was in the 'sin 2β era' akin to precision Z.
Over constrain CKM matrix with precision measurements
Discovery potential is limited by systematic errors
from non-perturbative QCD

This Decade

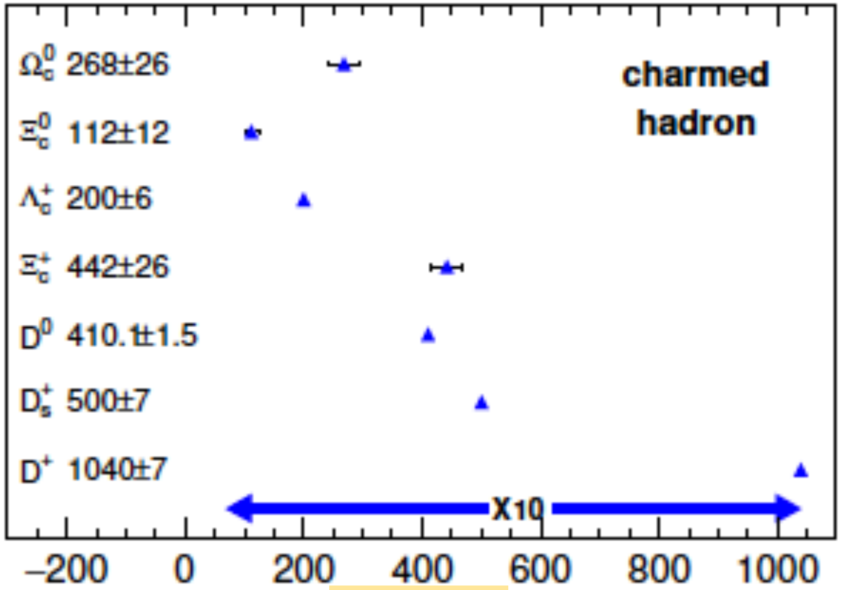
LHC found Higgs candidate and may uncover the physics beyond the Standard Model. An outstanding challenge to theory. Critical need: reliable theoretical techniques & detailed data to calibrate them

The Lattice

Complete definition of pert. and non-pert. QCD
Calculate B, D, Υ, ψ to a few % in a few years.

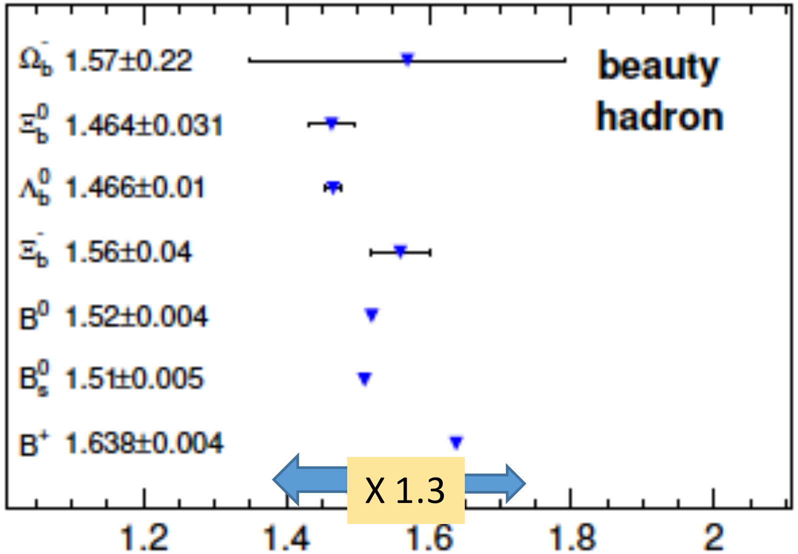
Charm can provide the data to test and calibrate non-pert. QCD techniques (especially true at charm threshold).

Charm Lifetimes



$\tau(fs)$

$\tau(D^+)$	$1040 \pm 7\ fs$
$\tau(D_S^+)$	$501 \pm 6\ fs$
$\tau(D^0)$	$410.3 \pm 1.5\ fs$
$\tau(\Xi^+{}_c)$	$442 \pm 26\ fs$
$\tau(\Lambda_c)$	$200 \pm 6\ fs$
$\tau(\Xi^0{}_c)$	$112^{+13}_{-10}\ fs$
$\tau(\Omega_c)$	$268 \pm 26\ fs$



$\tau(ps)$

D^+ 7 ‰, D^0 4 ‰, D_s 8 ‰,
Λ_c 3%, Ξ^0 10%, Ξ^+_c 6 %, Ω_c 10%
some lifetimes known as precisely as kaon lifetimes.

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.54 \pm 0.01 \quad \frac{\tau(B^+)}{\tau(B^0)} = 1.076 \pm 0.004$$

PDG2018

Charm quarks more influenced by hadronic environment than beauty quarks.

D Nonleptonic Decays

Nonleptonic decays dominate the total rate

$$D^+(c\bar{d}) : \tau_+ = 1042.7 \pm 6.9\ fs$$

$$D^0(c\bar{u}) : \tau_0 = 410.5 \pm 1.5\ fs$$

$$\frac{\tau(D^+)}{\tau(D^0)} = 2.54 \pm 0.01$$

Quarks or hadrons? ….in between

Compare to kaons and B-mesons:

$$K^+(\bar{s}u) : \tau_+ = 12390 \pm 20\ ps$$

$$K^0(\bar{s}d) : \tau_0 = 178.7 \pm 0.16\ ps$$

$$\tau_+ / \tau_0 \approx 70$$

Hadrons

$$B^+(\bar{b}u) : \tau_+ = 1643 \pm 10 \quad fs$$

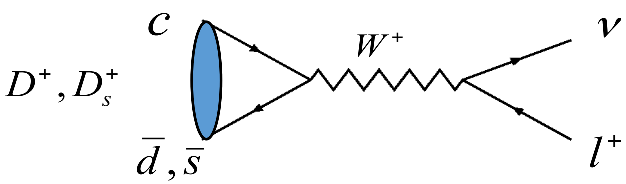
$$B^0(\bar{b}d) : \tau_0 = 1528 \pm 9 \quad fs$$

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.076 \pm 0.004$$

Like free quarks

D meson decays

a) Leptonic decay



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

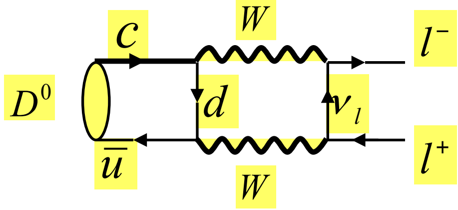
SM predicts : $(D^+ \to l^+ \nu) = 2.35\times10^{-5} : 1 : 2.65$ $(l = e : \mu : \tau)$

$D^+ \to e^+\nu_e,\ \mu^+\nu_\mu,\ \tau^+\nu_\tau$

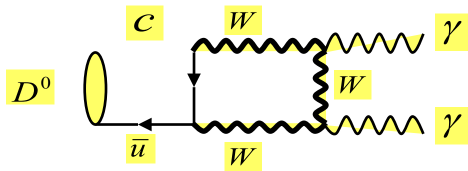
$D_s^+ \to e^+\nu_e,\ \mu^+\nu_\mu,\ \tau^+\nu_\tau$

$$f_{D^+} = \frac{1}{G_F |V_{cd}| m_l \left(1 - \frac{m_l^2}{m_{D^+}^2}\right)} \sqrt{\frac{8\pi \mathrm{B}(D^+ \to l^+\nu)}{m_{D^+}\tau_{D^+}}}$$

b) Rare decay



$D^0 \to l^+ l^-$

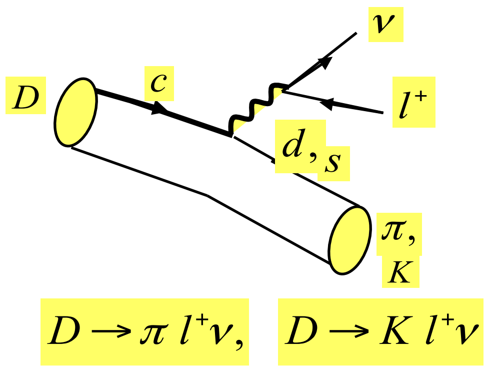


$\rightarrow$ $D^0 \to \gamma\gamma$

CKM & GIM suppressed [Short distance <10^{-9}]

D meson decays

c) Semi-leptonic decay

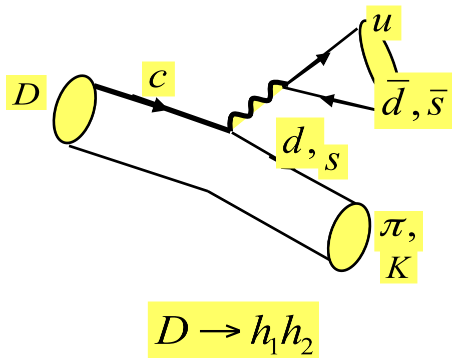


$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 \, p_X^3 \, |f_+(q^2)|^2$$

$$q^2 = (p_D - p_X)^2$$
$$= M_D^2 + M_X^2 - 2E_X M_D + 2\vec{p}_D \cdot \vec{p}_X$$

$V_{cx} = V_{cs}, V_{cd}$

d) Hadronic decay



Precision measurements of decay rates:

1) test SU(3)
2) access the relative strong phase
3) Improve the theoretical predictions of CPV and mixing
4) Light hadron spectroscopy in multi-body decays

The Landscape for open charm

- **B factories:**

  --BABAR, Belle

  -- Belle-II @Super-B factories

- **Hadronic Production:**

  --Fixed target

  --LHCb: on-going now! （finished two runs)

  --ATLAS and CMS

- **e^+e^- Colliders@threshold:**

  -- Precision results dominated by CLEO-c

  -- BESIII/BEPCII machine: higher luminosity: 10^{33} $cm^{-2}s^{-1}$

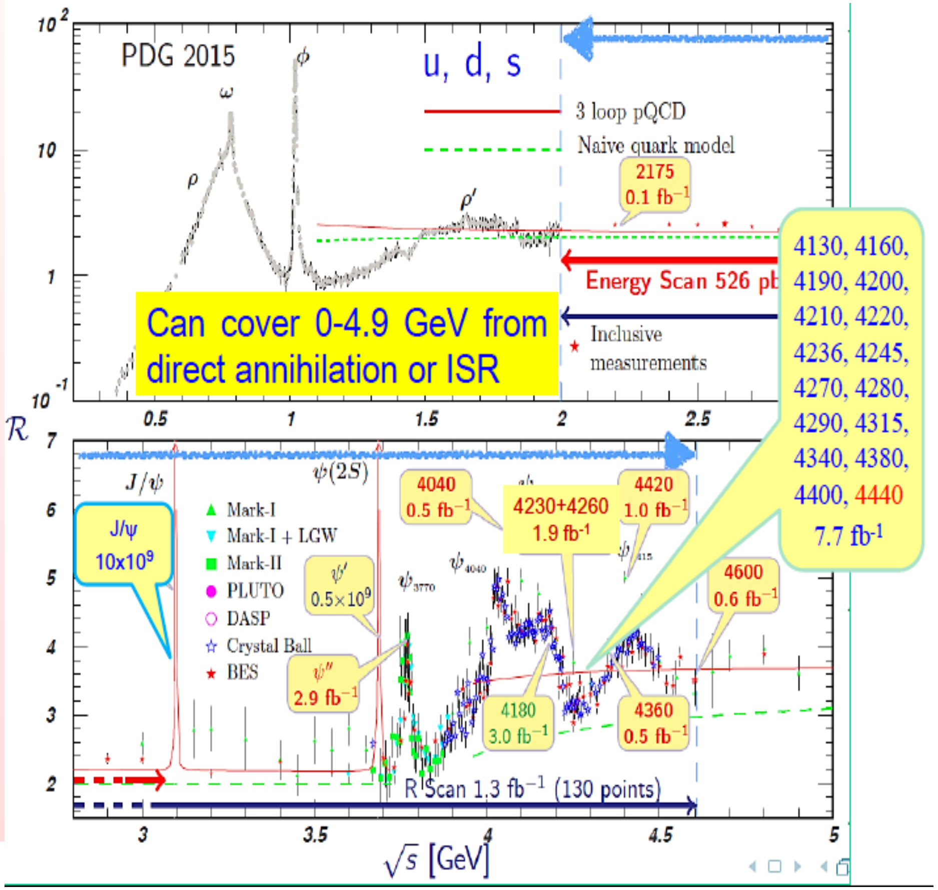
  -- Quantum correlations and CP-tagging are unique

Data set near threshold at BESIII

Leptonic & Semileptonic decays

Unique data sets at open charm thresholds @BESIII

- $D^{+(0)}$
  - @ $E_{cm} = 3.773$ GeV
  - Integrated luminosity of 2.93 fb^{-1}
  - $\sigma(e^+e^- \to D^0\overline{D^0}) \sim 3.6$ nb $\Rightarrow$ 21M D^0 produced
  - $\sigma(e^+e^- \to D^+D^-) \sim 2.9$ nb $\Rightarrow$ 17M D^+ produced
- D_s^+
  - @ $E_{cm} = 4.009$ GeV
    - Integrated luminosity of 0.482 fb^{-1}
    - $\sigma(e^+e^- \to D_s^+D_s^-) \sim 0.3$ nb $\Rightarrow$ 0.3M D_s produced
  - @ $E_{cm} = 4.178$ GeV
    - Integrated luminosity of 3.19 fb^{-1}
    - $\sigma(e^+e^- \to D_s^{*+}D_s^-) \sim 1$ nb $\Rightarrow$ 6M D_s produced
- Λ_c^+
  - @ $E_{cm} = 4.600$ GeV
  - Integrated luminosity of 0.567 fb^{-1}
  - $\sigma(e^+e^- \to \Lambda_c^+\Lambda_c^-) \sim 0.2$ nb $\Rightarrow$ 0.2M Λ_c produced

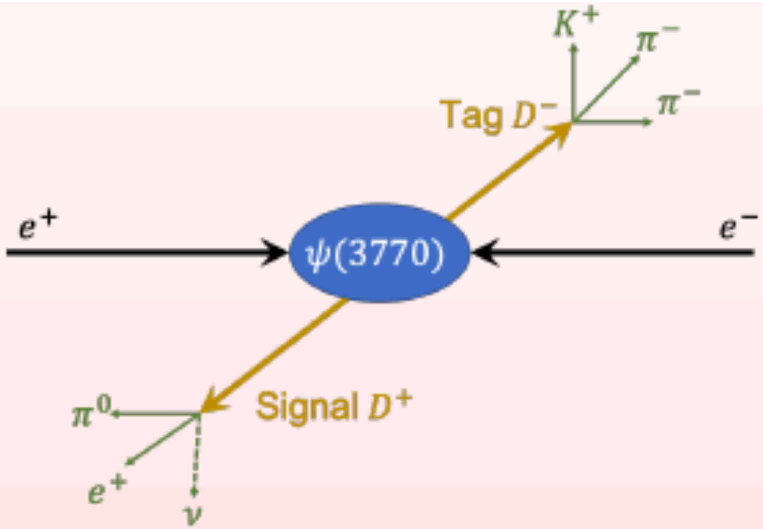


Double tag method

Alex Gilman

$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$

$$\Delta E = E_{beam} - E_D$$

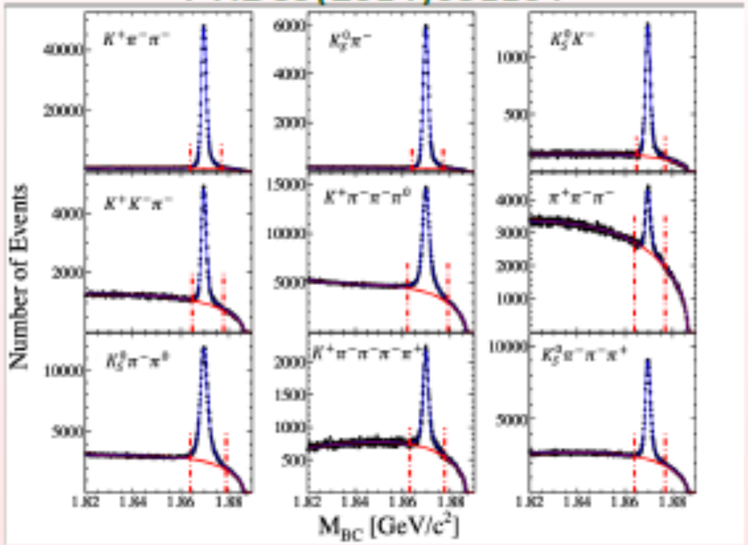


$$\mathcal{B}(D \to \text{signal}) = \frac{N_{\text{Signal}}/\epsilon_{\text{Tag \& Signal}}}{N_{\text{Tag}}/\epsilon_{\text{Tag}}}$$

- Reconstruct $\overline{D}$ meson through clean decay mode (the tag)
- Search for signal process of the D meson
- Advantages: Don't need to know $N_{D\overline{D}}$, can identify ν through missing mass, removes large component of backgrounds

$f_{D+}|V_{cd}|$ from $D^+ \rightarrow m^+ \nu_\mu$

PRD89(2014)051104



$$M_{BC} \equiv \sqrt{E^2_{beam} - |\vec{p}_{Tag}|^2}$$

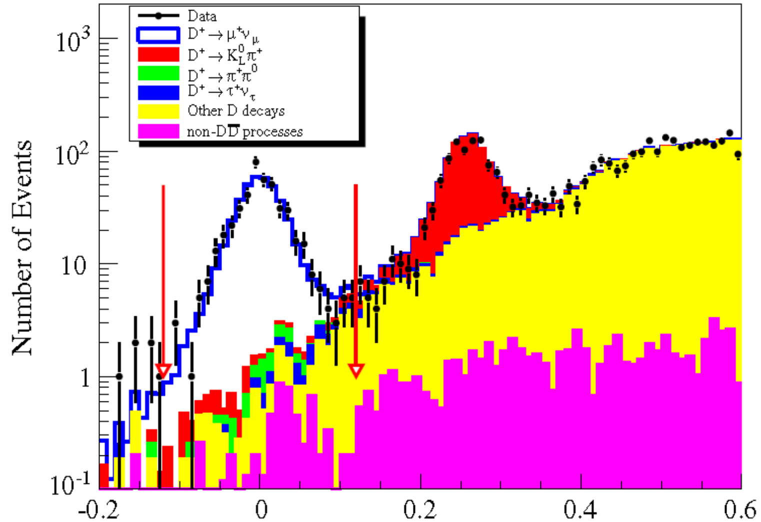
$$\mathcal{B}(D^+ \to \mu^+\nu) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

With PDG2018 Inputs

$$f_{D+}|V_{cd}| = 45.7 \pm 1.2 \pm 0.4 \text{ MeV}$$

Most precise measurement of $f_{D+}|V_{cd}|$ to date

- Using 2.93 fb^{-1} of data @ $E_{CM} = 3.773$ GeV

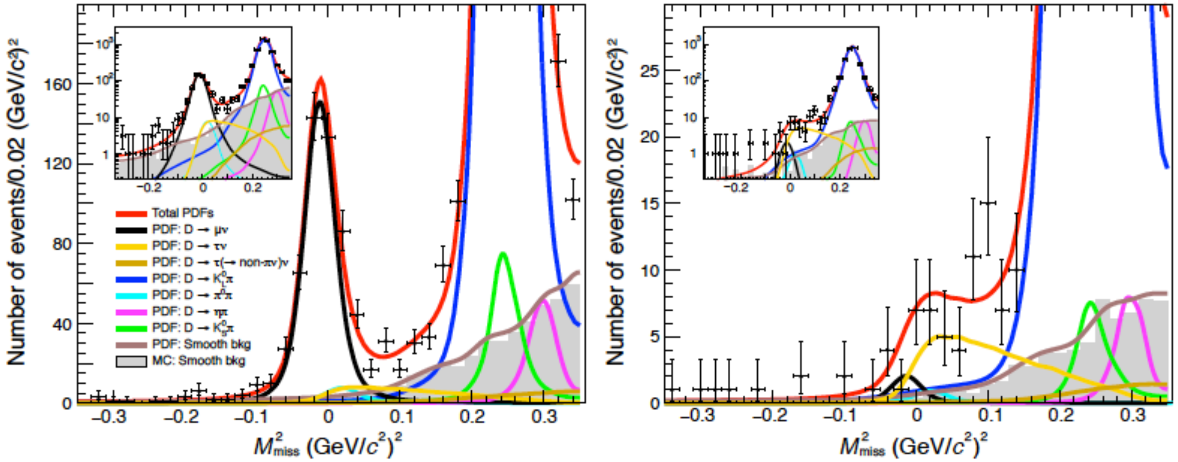


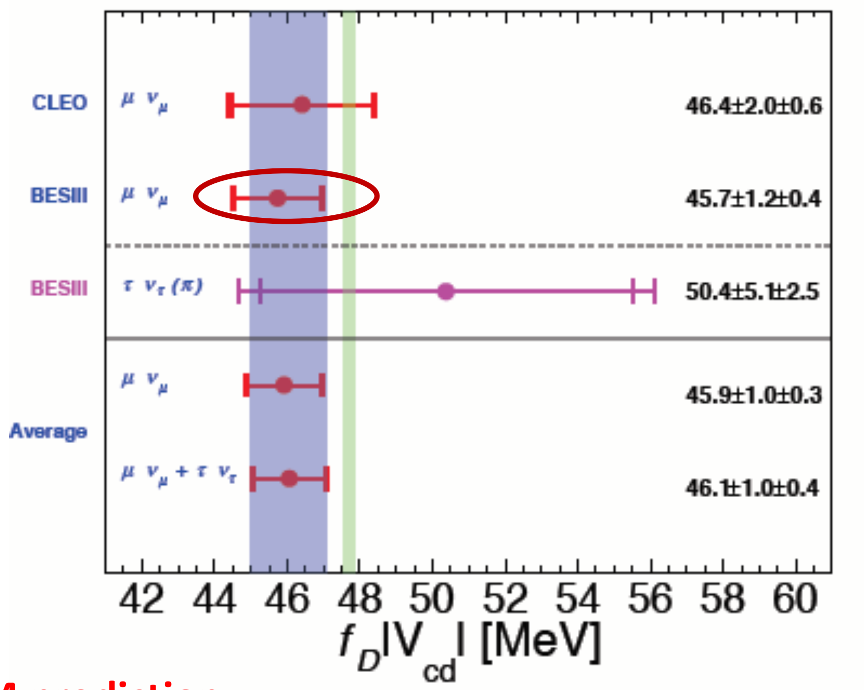
$$MM^2 = (E_{beam} - E_\mu)^2 - (-P_{Dtag^+} - P_\mu)^2$$

$f_{D+}|V_{cd}|$ from $D^+ \rightarrow \tau^+ \nu_\tau$: first observation

BESIII: arXiv: 1908.08877 submitted to PRL

• Using 2.93 fb^{-1} of data @ $E_{CM} = 3.773$ GeV





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

$$R_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = 3.21 \pm\ 0.64 \pm 0.43$$

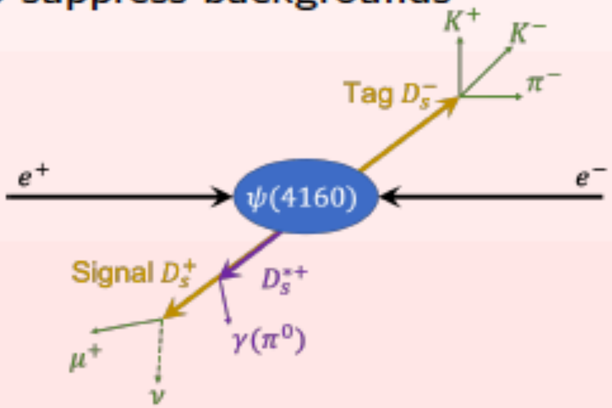
SM prediction:

$$R_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = \frac{m_\tau^2(1-\frac{m_\tau^2}{M_{D^+}^2})^2}{m_\mu^2(1-\frac{m_\mu^2}{M_{D^+}^2})^2} = 2.67,$$

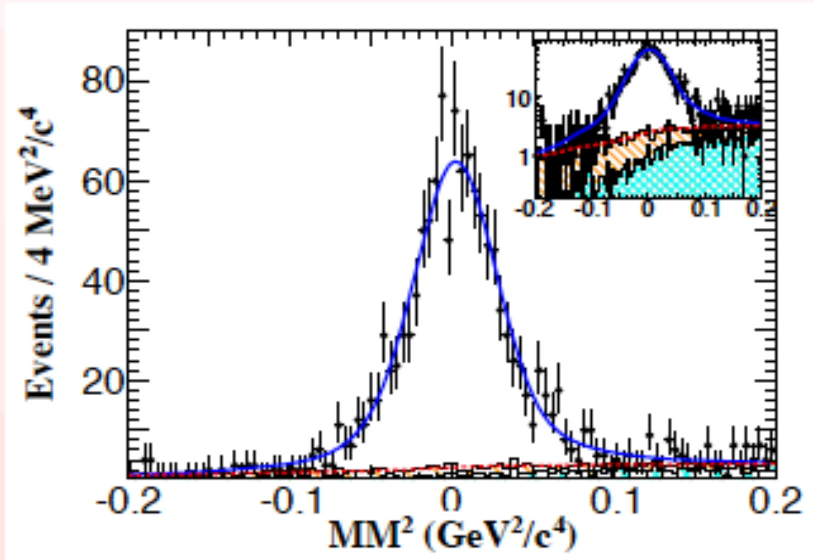
$D_s^+ \to \mu^+ \nu_\mu$

Alex Gilman

- Using 3.19 fb^{-1} of data @ $E_{CM} = 4.178$ GeV
- Double tag with 14 D_s^+ tag modes
- Utilize muon system to suppress backgrounds



PRL122(2019)071802



$$\mathcal{B}\left(D_s^+ \to \mu^+ \nu\right) = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

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

Most precise measurement of $f_{D_s^+} |V_{cs}|$ to date

$$\mathcal{B}_{\text{PDG}}\left(D_s^+ \to \tau^+ \nu\right) = (5.48 \pm 0.23)\,\%$$

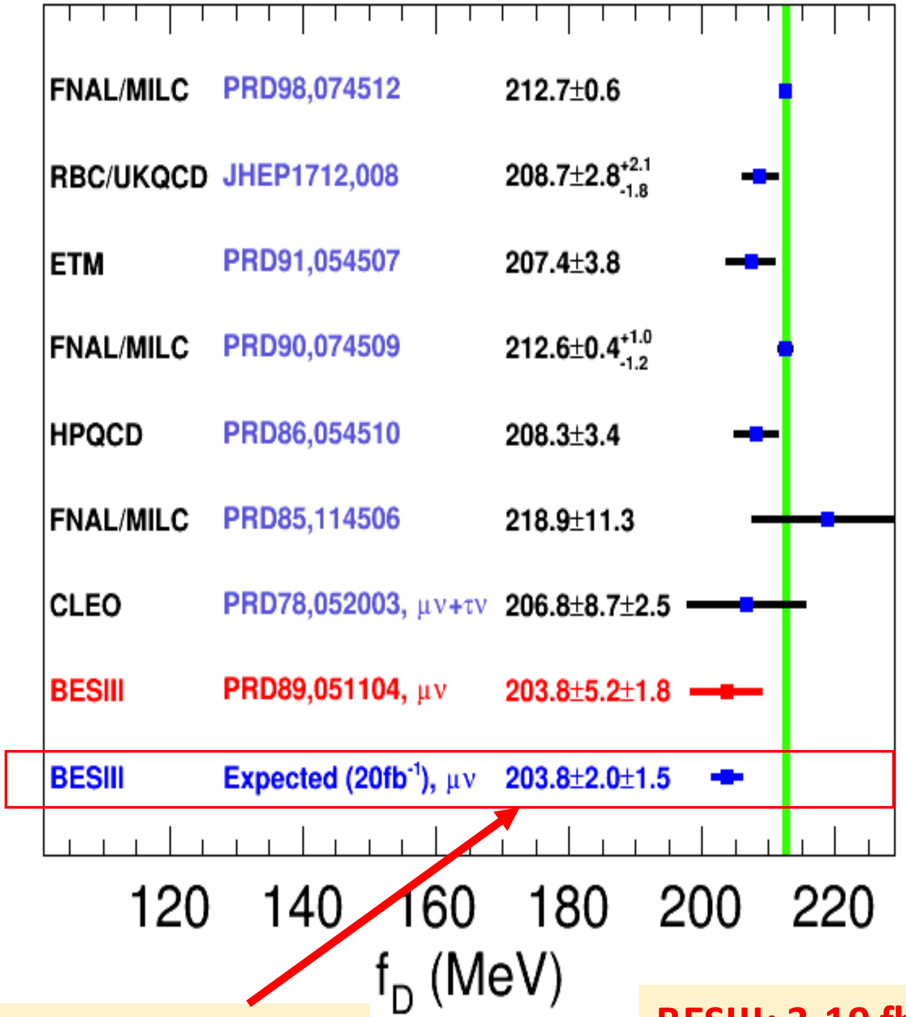
$$R_{D_s} \equiv \frac{\mathcal{B}\left(D_s^+ \to \tau^+ \nu\right)}{\mathcal{B}\left(D_s^+ \to \mu^+ \nu\right)} = 9.98 \pm 0.52$$

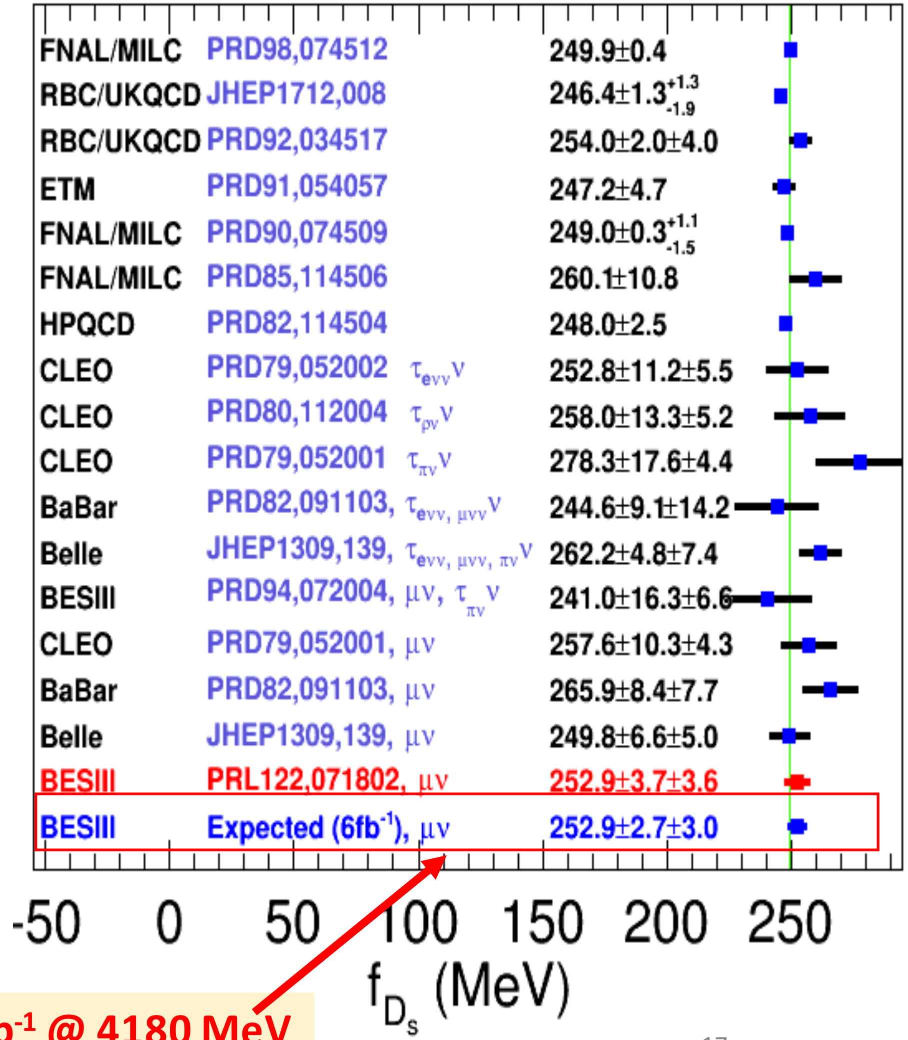
SM $R_{D_s} = 9.74$

f_{D^+} and $f_{D_s^+}$

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

Inputs:
$|V_{cd}| = 0.22438 \pm 0.00044$

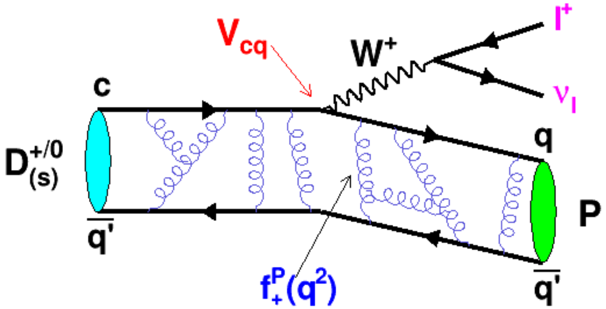




BESIII: 20 fb^{-1} @ 3770 MeV

BESIII: 3.19 fb^{-1} @ 4180 MeV

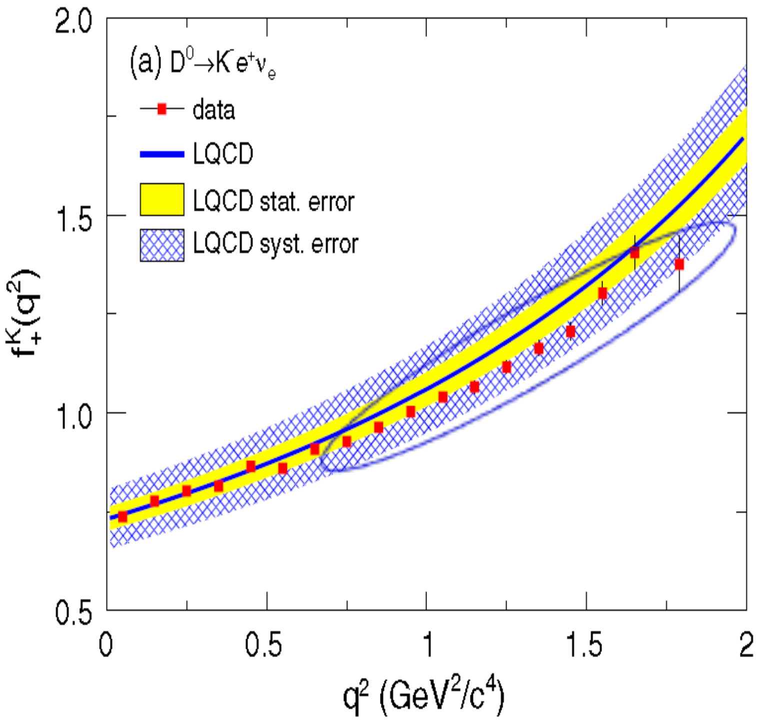
Form factors in $D^0 \to K^- e^+ \nu_e, \pi^- e^+ \nu_e$

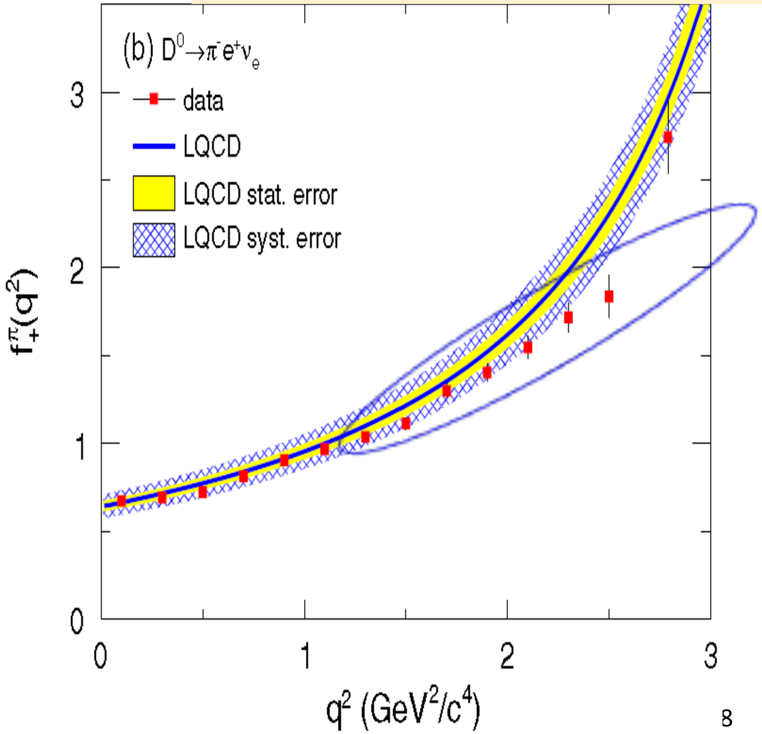


$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 \, p_X^3 \, |f_+(q^2)|^2$$

PRD92(2015)072012

BESIII: 2.93 fb^{-1} @ 3770 MeV





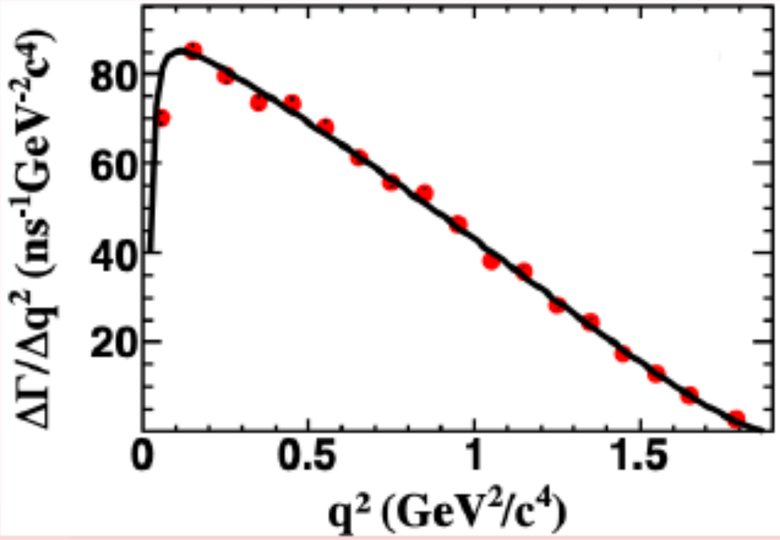
8

$D^0 \to K^- \mu^+ \nu_\mu$

Alex Gilman

- Using 2.93 fb^{-1} of data @ $E_{CM} = 3.773$ GeV
- Double tag with 3 D^0 tag modes
- $\frac{d\Gamma}{dq^2}$ from fits to U_{miss}
- Cut on $M_{\text{Inv}}(K^- \mu^+)$ to suppress $D^0 \to K^- \pi^+ (\pi^0)$

PRL122(2019)011804



$f_+^K(0)|V_{cs}| = 0.7148(38)(29)$

z series with $k_{\text{max}} = 1$ nominal

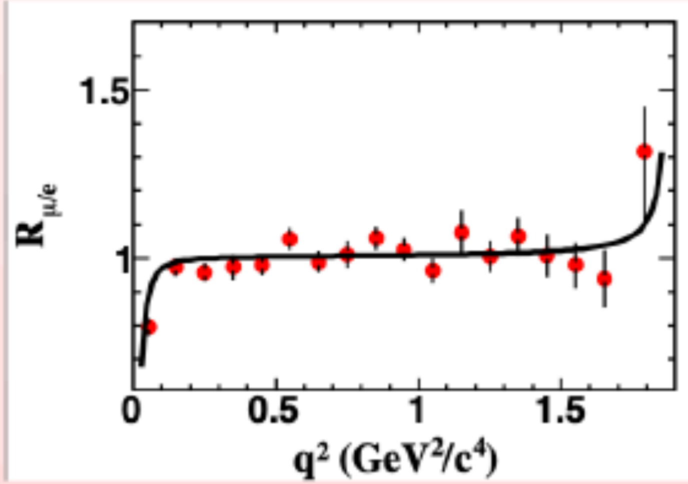
$\mathcal{B}(D^0 \to K^- \mu^+ \nu) = 3.413(19)(35)\%$

From PRD92(2015)072012:

$\mathcal{B}_{\text{BESIII}}(D^0 \to K^- e^+ \nu) = 3.505(14)(33)\%$

$$\frac{\mathcal{B}(D^0 \to K^- \mu^+ \nu)}{\mathcal{B}(D^0 \to K^- e^+ \nu)} = 0.974(07)(12)$$

SM Prediction : 0.97



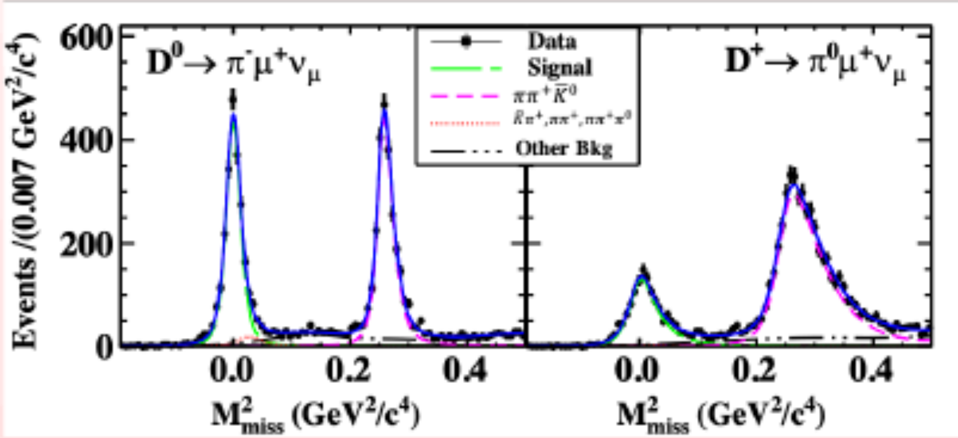
$R_{\mu/e} \equiv (\Delta\Gamma_\mu/\Delta q^2) / (\Delta\Gamma_e/\Delta q^2)$

$D^{0(+)} \to \pi^{-(0)}\mu^+\nu$

Alex Gilman

- Using 2.93 fb^{-1} of data @ $E_{CM} = 3.773$ GeV
- Double tag with 3 D^0(6 D^+) tag modes

PRL121(2018)171803



$\mathcal{B}(D^0 \to \pi^-\mu^+\nu) = 0.272(08)(06)\%$

$\mathcal{B}(D^+ \to \pi^0\mu^+\nu) = 0.350(11)(10)\%$

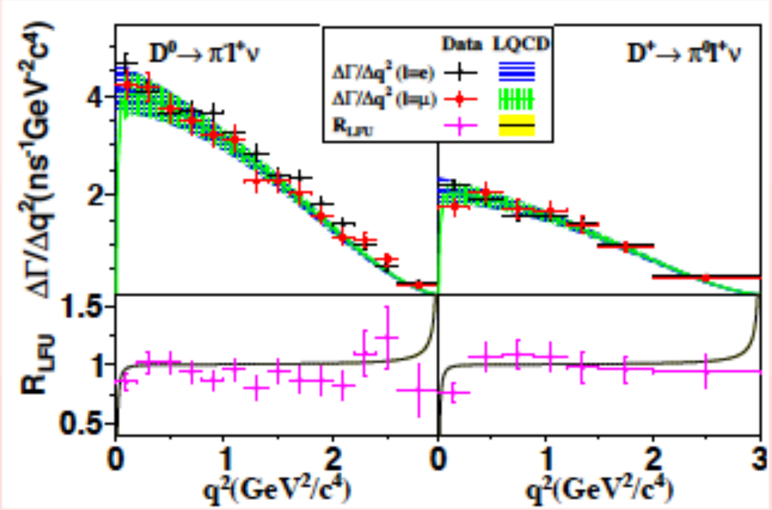
From PRD92(2015)072012:

$\mathcal{B}_{\text{BESIII}}(D^0 \to \pi^- e^+\nu) = 0.295(04)(03)\%$

$$\frac{\mathcal{B}(D^0 \to \pi^-\mu^+\nu)}{\mathcal{B}(D^0 \to \pi^- e^+\nu)} = 0.922(30)(22)$$

$$\frac{\mathcal{B}(D^+ \to \pi^0\mu^+\nu)}{\mathcal{B}(D^+ \to \pi^0 e^+\nu)} = 0.964(37)(26)$$

SM Prediction : 0.985

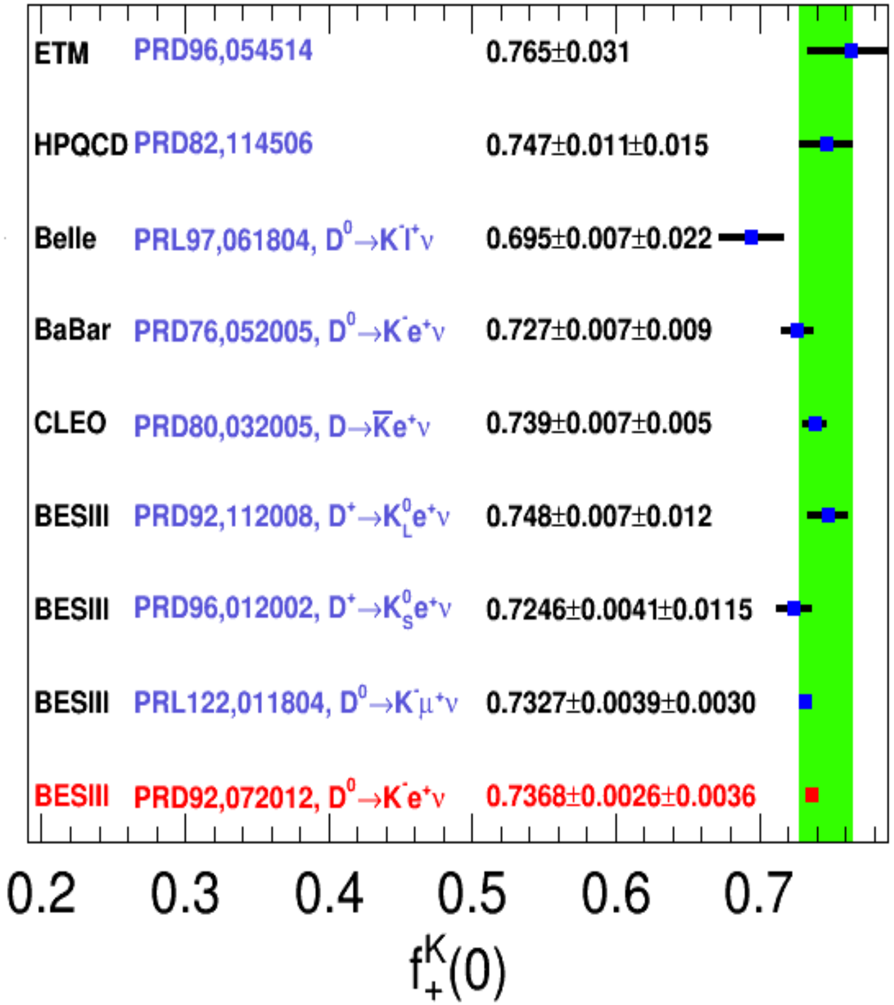


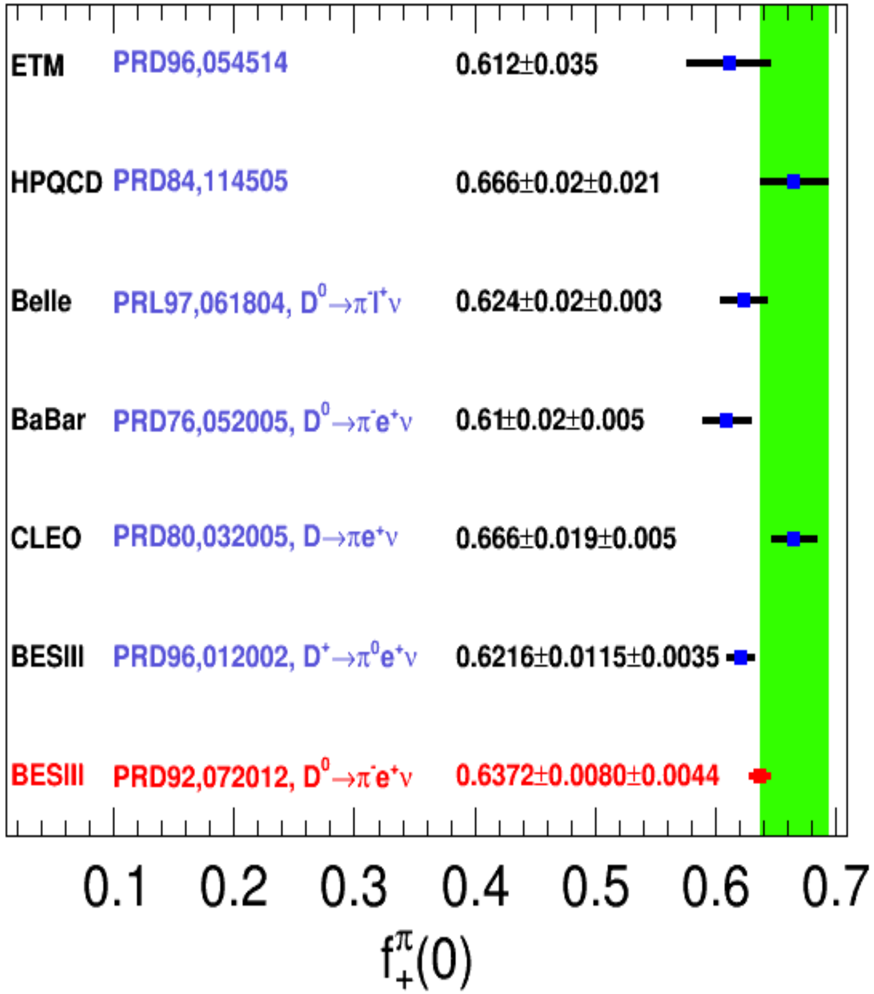
$f_+^{D\to K}(0)$ and $f_+^{D\to\pi}$

Inputs from 2018 PDG CKMFitter

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

Inputs:
$|V_{cd}| = 0.22438 \pm 0.00044$





$f_+^{D\to K}(0)$ and $f_+^{D\to\pi}$

Inputs from 2018 PDG CKMFitter

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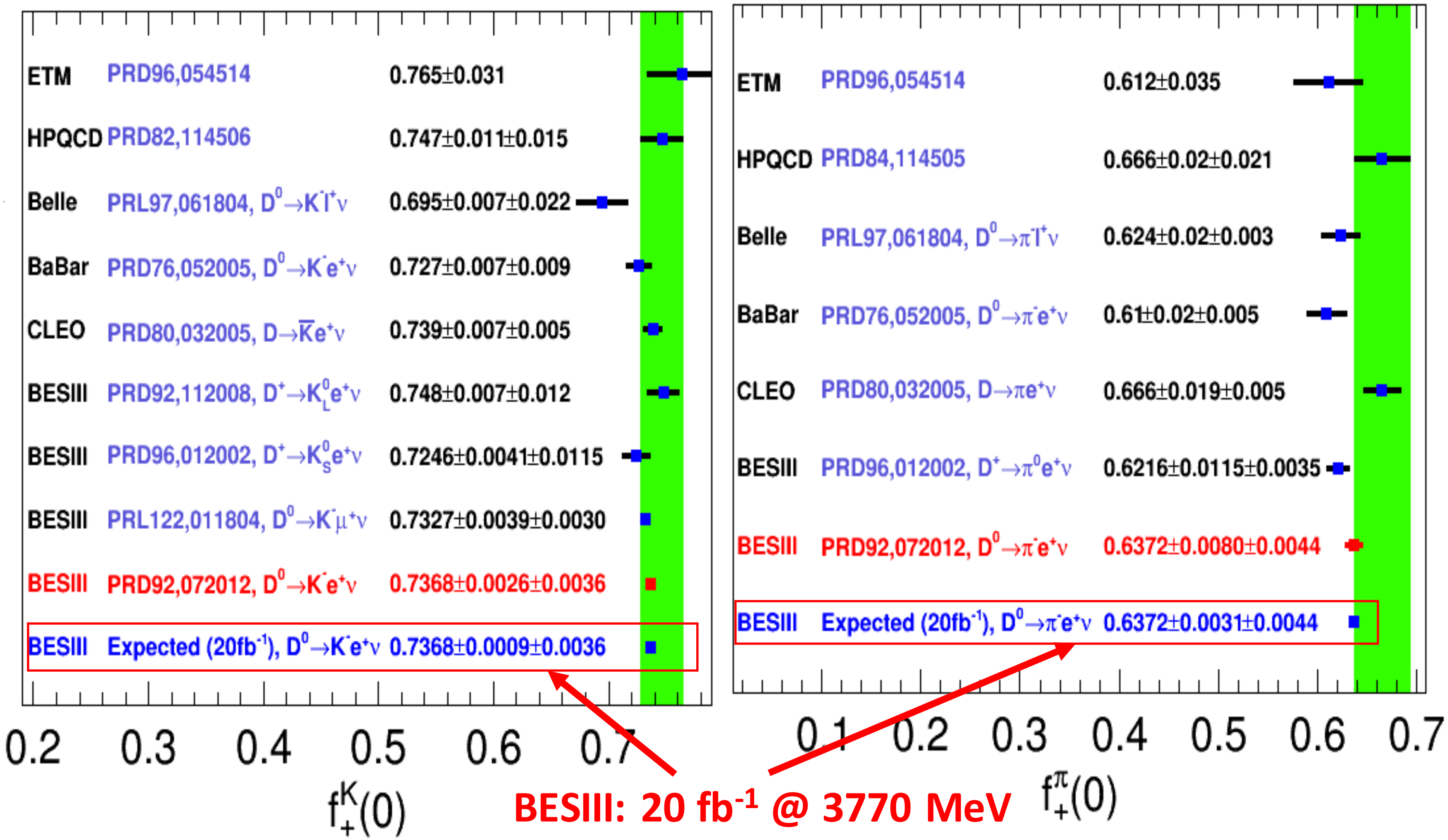
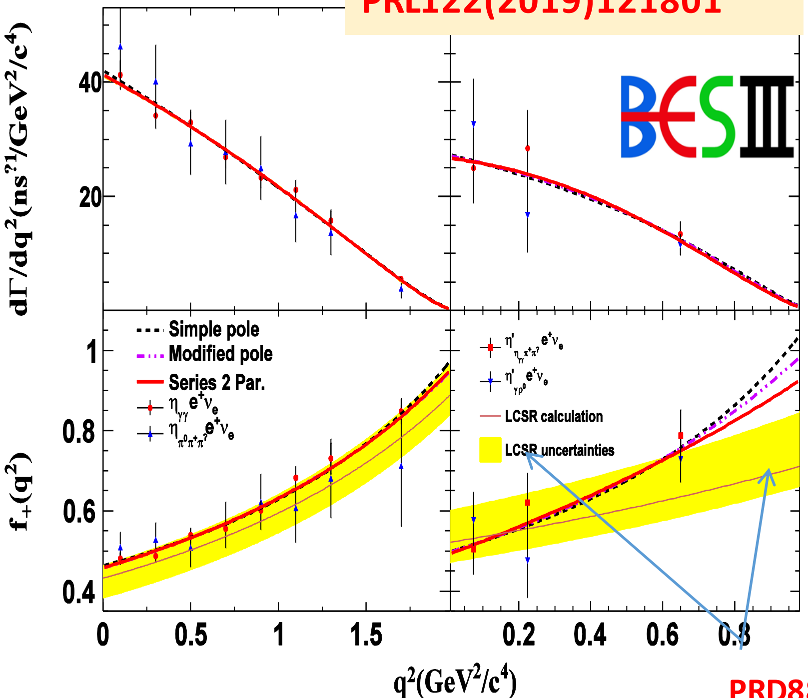


First extractions of FFs of $D_s^+ \to \eta^{(\prime)} e^+ \nu$

BESIII: 3.19 fb^{-1} @ 4180 MeV

PRL122(2019)121801

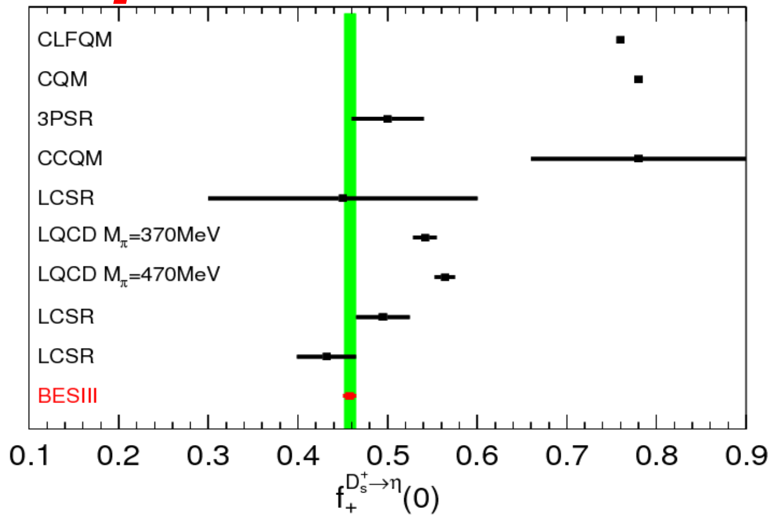


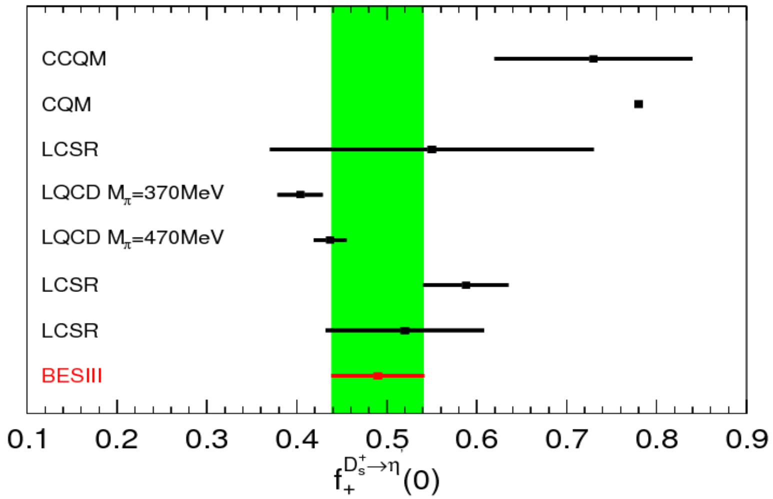
PRD88, 034023

$$f_+^{D_s \to \eta}(0) = 0.446 \pm 0.005 \pm 0.004$$

$$f_+^{D_s \to \eta'}(0) = 0.477 \pm 0.049 \pm 0.011$$

Statistical errors dominate





$D^0 \to \overline{K}^0 \pi^- e^+ \nu$

Alex Gilman

- Using 2.93 fb^{-1} of data @ $E_{CM} = 3.773$ GeV
- Double tag with 3 D^0 tag modes
- Partial Wave Analysis

$$\mathcal{B}\left(D^0 \to \overline{K}^0 \pi^- e^+ \nu\right) = (1.434 \pm 0.029 \pm 0.032)\,\%$$

$$\frac{\mathcal{B}\left(D^0 \to \left(\overline{K}^0 \pi^-\right)_{S-\text{wave}} e^+ \nu\right)}{\mathcal{B}\left(D^0 \to \overline{K}^0 \pi^- e^+ \nu\right)} = (5.51 \pm 0.97 \pm 0.62)\,\%$$

$$\mathcal{B}\left(D^0 \to \overline{K}^*(892)^- e^+ \nu\right) = (2.033 \pm 0.046 \pm 0.047)\,\%$$

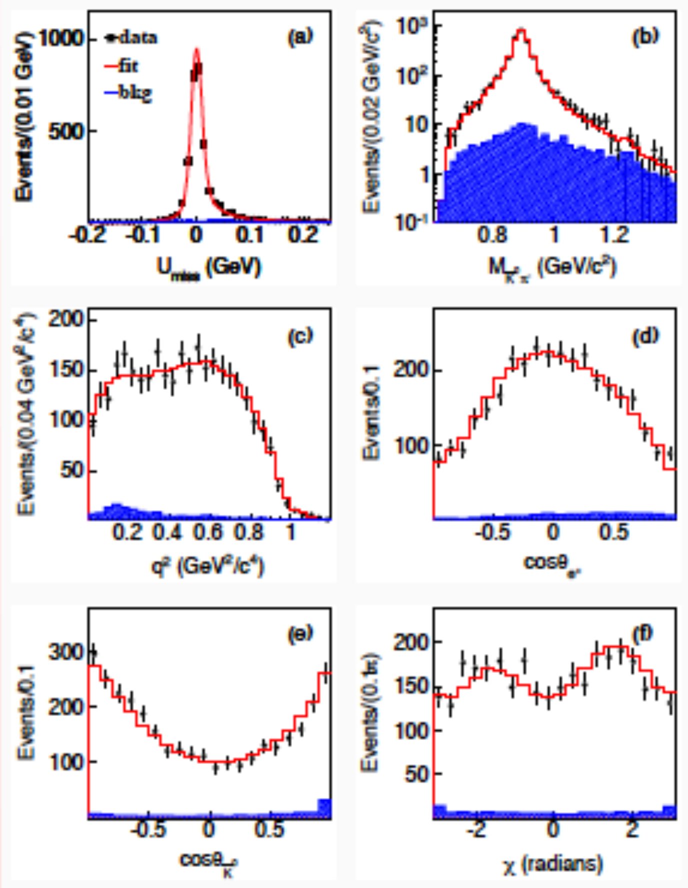
$$K^* \; d\Gamma/dq^2 \propto V(q^2), A_{1,2}(q^2)$$

$$r_V \equiv V(0)/A_1(0) = 1.46 \pm 0.07 \pm 0.02$$

$$r_2 \equiv A_2(0)/A_1(0) = 0.67 \pm 00.6 \pm 0.01$$

First FF Measurements

PRD99(2019)011103

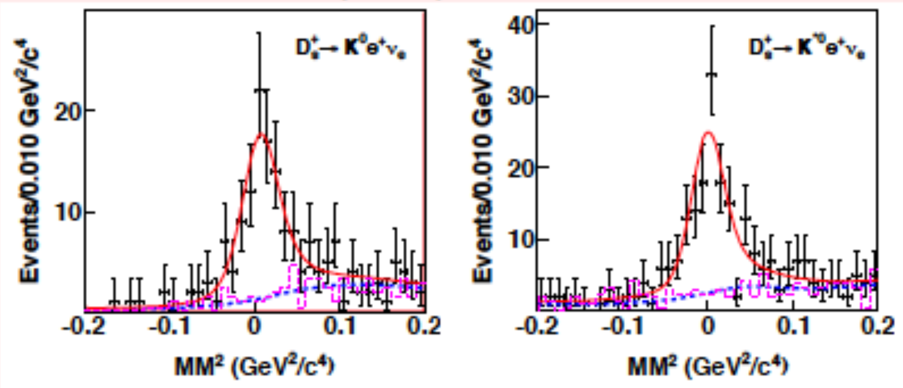


$D_s^+ \to K^{0(*)} e^+ \nu$

Alex Gilman

- Using 3.19 fb^{-1} of data @ $E_{CM} = 4.178$ GeV
- Double tag with 13 D_s^+ tag modes
- Identify through $K^0 \to K_S^0 \to \pi^+\pi^-$ and $K^{0*} \to K^+\pi^-$

PRL122(2019)061801

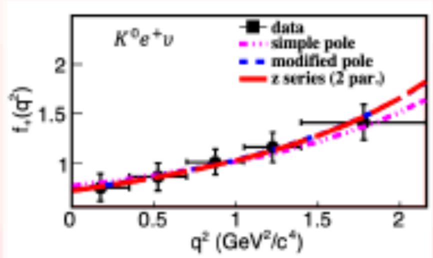


$$\mathcal{B}\left(D_s^+ \to K^0 e^+ \nu\right) = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$

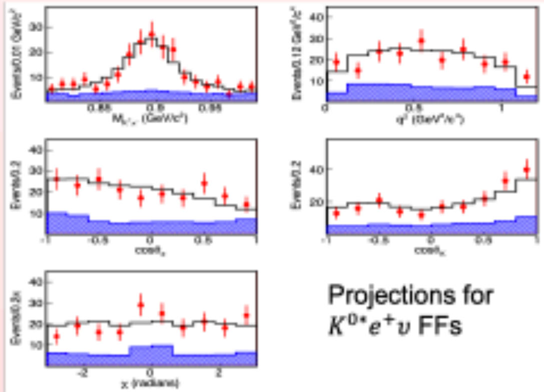
$$\mathcal{B}\left(D_s^+ \to K^{0*} e^+ \nu\right) = (2.37 \pm 0.26 \pm 0.20) \times 10^{-3}$$

Precision improved $\sim \times 2$ over PDG

With $|V_{cd}|$ from 2018 CKMFitter



$f_+^{K^0}(0) = 0.720(84)(13)$



K^{0*} $d\Gamma/dq^2 \propto V(q^2), A_{1,2}(q^2)$

$r_V \equiv V(0)/A_1(0) = 1.67(34)(16)$

$r_2 \equiv A_2(0)/A_1(0) = 0.77(28)(07)$

First FF measurements

$D \to S e^+ \nu$

Alex Gilman

From Wang and Lü PRD82(2010)034016

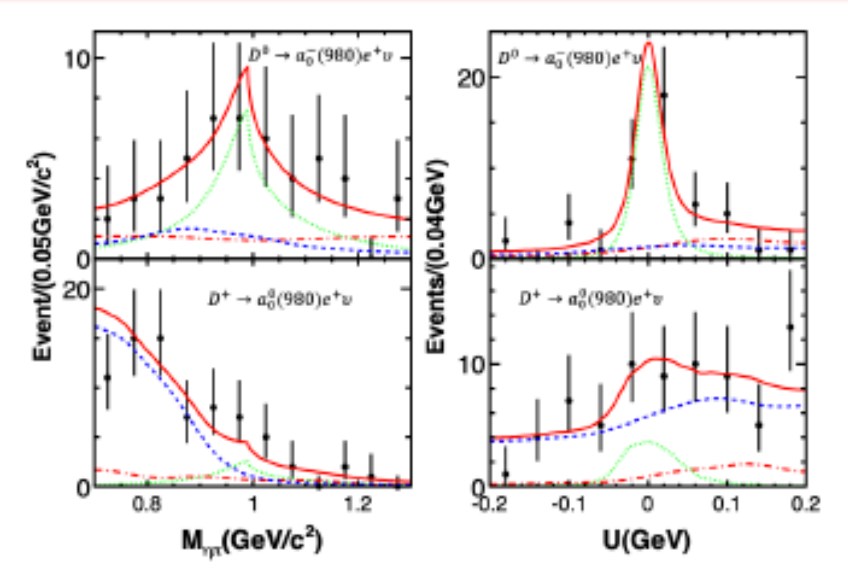
$D^+ \to S e^+ \nu$ can provide insight on the nature of light scalars

$$R \equiv \frac{\mathcal{B}\left(D^+ \to f_0(500) e^+ \nu\right) + \mathcal{B}\left(D^+ \to f_0(980) e^+ \nu\right)}{\mathcal{B}\left(D^+ \to a_0^0(980) e^+ \nu\right)}$$

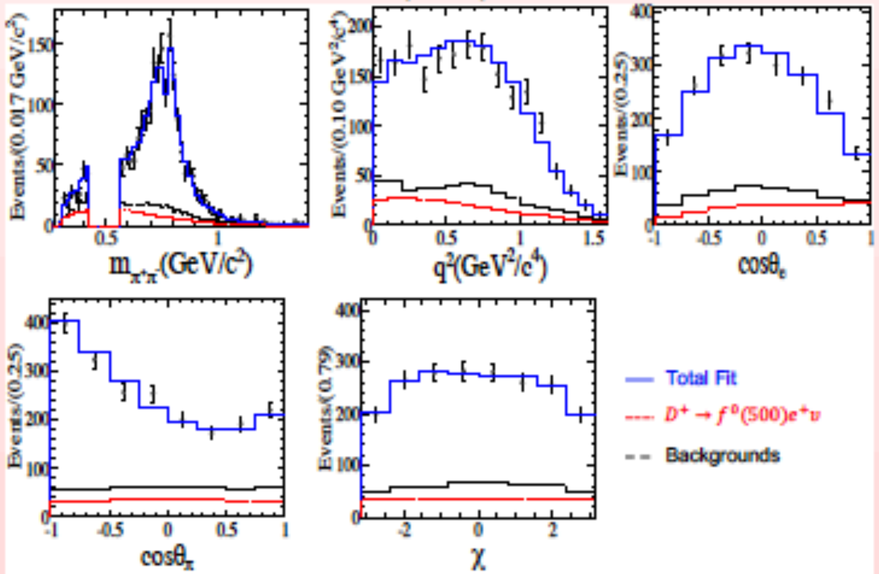
Two quark description $\Rightarrow R = 1.0 \pm 0.3$

Tetraquark description $\Rightarrow R = 3.0 \pm 0.9$

- $D \to a_0(980) e^+ \nu$
  PRL121(2018)081802



- $D^+ \to f_0 e^+ \nu$
  PRL122(2019)062001



$D \to S e^+ \nu$

Alex Gilman

$$\mathcal{B}\left(D^0 \to a_0^-(980) e^+ \nu\right) = \frac{\left(1.37^{+0.33}_{-0.29} \pm 0.09\right) \times 10^{-4}}{\mathcal{B}\left(a_0^-(980) \to \eta\pi^-\right)} \; (6.5\sigma)$$

$$\mathcal{B}\left(D^+ \to a_0^0(980) e^+ \nu\right) = \frac{\left(1.66^{+0.81}_{-0.66} \pm 0.11\right) \times 10^{-4}}{\mathcal{B}\left(a_0^0(980) \to \eta\pi^0\right)} \; (3.0\sigma)$$

First Observations

$$\mathcal{B}\left(D^+ \to f_0(500) e^+ \nu\right) = \frac{(6.30 \pm 0.43 \pm 0.32) \times 10^{-4}}{\mathcal{B}\left(f_0(500) \to \pi^+\pi^-\right)} \; (> 10\sigma)$$

$$\mathcal{B}\left(D^+ \to f_0(980) e^+ \nu\right) < \frac{2.8 \times 10^{-5}}{\mathcal{B}\left(f_0(980) \to \pi^+\pi^-\right)} \text{ @ 90\% C.L.}$$

Neglecting $f_0(980)$ contribution and assuming:

$$\mathcal{B}\left(f_0(500) \to \pi\pi\right) = 100\% \Rightarrow \mathcal{B}\left(f_0(500) \to \pi^+\pi^-\right) = 67\%$$

$$\Gamma\left(a_0(980)\right) = \Gamma\left(a_0(980) \to K\overline{K}\right) + \Gamma\left(a_0(980) \to \eta\pi^0\right)$$

$$\Rightarrow \mathcal{B}\left(a_0(980) \to \eta\pi^0\right) = (85 \pm 11)\,\% \text{ with PDG2018 avg. of } \frac{\Gamma\left(a_0(980) \to K\overline{K}\right)}{\Gamma\left(a_0(980) \to \eta\pi^0\right)}$$

$R > 2.7$ @ 90% C.L. $\Rightarrow$ Tetraquark favored

High precision charm physics @thresholds: D/Ds

Observables	Exp. measure	BESIII	Belle-II	LHCb
$B(D^+ \to l\nu)$	$f_D \lvert V_{cd} \rvert$	**1.1%**	1.4%	N/A
$B(D_S^+ \to l\nu)$	$f_{Ds} \lvert V_{cs} \rvert$	**1.0%**	1.0%	N/A
$\frac{B(D^+ \to l\nu)}{B(D_S^+ \to l\nu)}$	$\frac{f_D \lvert V_{cd} \rvert}{f_{Ds} \lvert V_{cs} \rvert}$	**1.0%**	1.4%	N/A
$d\Gamma(D \to \pi l\nu)/dq^2$	$f_{D\to\pi}(0) \lvert V_{cd} \rvert$	**0.6%**	1.0%	N/A
$d\Gamma(D \to Kl\nu)/dq^2$	$f_{D\to K}(0) \lvert V_{cs} \rvert$	**0.5%**	0.9%	N/A
$d\Gamma(D_S \to Kl\nu)/dq^2$	$f_{Ds\to K}(0) \lvert V_{cd} \rvert$	**1.3%**	N/A	N/A
$d\Gamma(D_S \to \phi l\nu)dq^2$	$f_{Ds\to\phi}(0) \lvert V_{cs} \rvert$	**1.0%**	N/A	N/A

BESIII: 20fb^{-1} @ 3770 MeV, 6fb^{-1} @ 4180 MeV, arXiv: 0809.1869 (BESIII physics book)

Belle-II: 50 ab^{-1} @ Y(4S) arXiv: 1808.10567 (Belle-II physics book)

LHCb: : **arXiv:1808.08865 for upgrade-II**

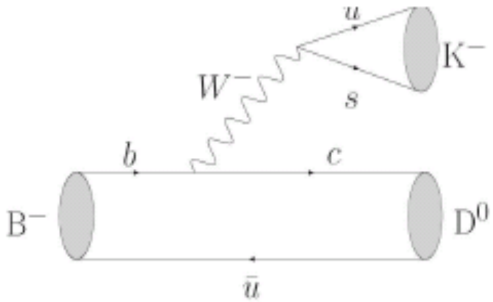
Hadronic decays

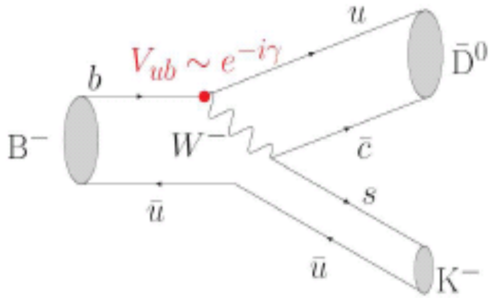
- Relative strong phase from Quantum Correlated data
- Light hadron spectroscopy from charm decays
- Multiple body decays (4-body)

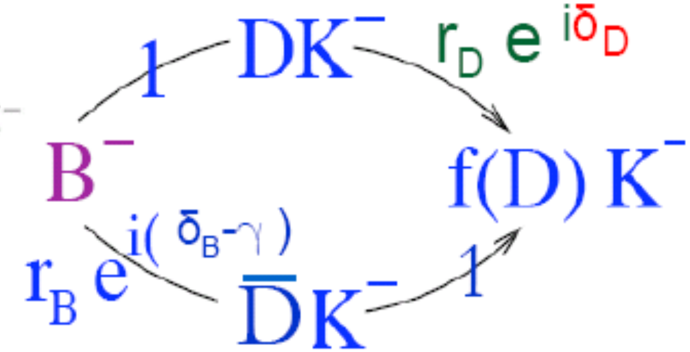
γ/ϕ_3 extraction

$B^- \longrightarrow D^0K^-$ $\quad$ $B^- \longrightarrow \overline{D}^0K^-$

$$\frac{< B^- \longrightarrow \overline{D}^0K^- >}{< B^- \longrightarrow D^0K^- >} = r_B e^{i(\delta_B - \gamma)}$$







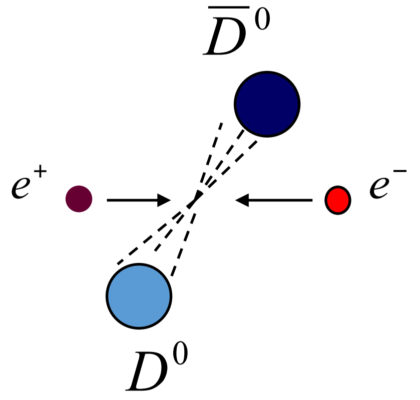
- Sensitivity through interference between $b \rightarrow u$ and $b \rightarrow c$ transitions
- Require D^0 and $\overline{D^0}$ decay to a common final state, f(D):

  $K^0_S hh$; $K\pi$; $K\pi\pi\pi$; $K\pi\pi^0$
- Comparison of B^- and B^+ rates allow γ to be extracted
- But other parameters to be considered
  - in particular δ_D – **accessed in quantum-correlated D-decays**

r_D & δ_D analogous to B-decay quantities. For multibody decays, these vary over Dalitz space

The correlated state

For a physical process producing $D^0 \overline{D}^0$ such as



$$e^+e^- \rightarrow \psi'' \rightarrow D^0\overline{D}^0$$

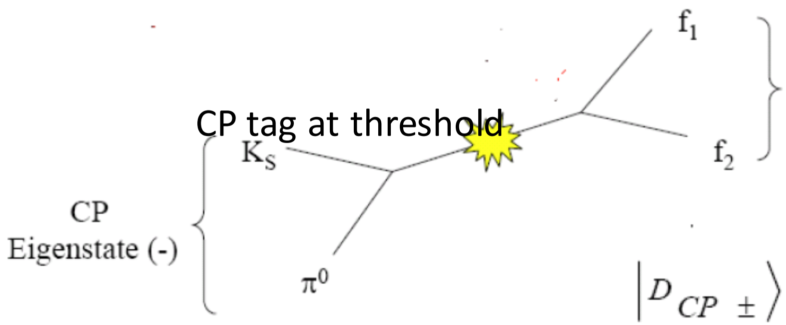
The $D^0 \overline{D}^0$ pair will be a quantum-correlated state

For a correlated state with $C = -$

$$\hat{C}\left|D^0\right\rangle = \left|\overline{D}^0\right\rangle$$

$$\hat{C}\left|\overline{D}^0\right\rangle = \left|D^0\right\rangle$$

$$\psi_- = \frac{1}{\sqrt{2}}\left(\left|D^0\right\rangle\left|\overline{D}^0\right\rangle - \left|\overline{D}^0\right\rangle\left|D^0\right\rangle\right)$$

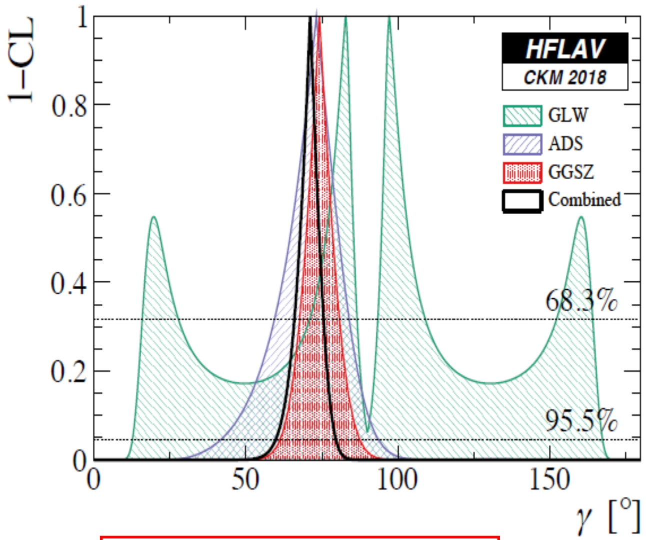


$$\left|D_{CP\pm}\right\rangle = \frac{1}{\sqrt{2}}\left[\left|D^0\right\rangle \pm \left|\overline{D}^0\right\rangle\right]$$

$$\frac{\left\langle K^-\pi^+\middle|\overline{D}^0\right\rangle^{DCS}}{\left\langle K^-\pi^+\middle|D^0\right\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$$

$$\sqrt{2}\,A\left(D_{CP\pm} \rightarrow K^-\pi^+\right) = A\left(D^0 \rightarrow K^-\pi^+\right) \pm A\left(\overline{D}^0 \rightarrow K^-\pi^+\right)$$

Uncertainties of γ/ϕ_3 measurement at LHCb



$$\gamma^{\mathrm{HFLAV}}_{\mathrm{CKM2018}} = (71.1^{+4.6}_{-5.3})^0$$

- **Dominated by LHCb**

- **Belle II: 1.5^0 with 50 ab^{-1} arXiv:1808.10567**
- **LHCb: arXiv:1808.08865v2**

Runs	Collected / Expected luminosity	Year attained	γ/ϕ_3 sensitivity
LHCb Run-1 [7, 8 TeV]	3 fb^{-1}	2012	8°
LHCb Run-2 [13 TeV]	5 fb^{-1}	2018	4°
Belle-II Run	50 ab^{-1}	2025	1.5°
LHCb phase-1 upgrade [14 TeV]	50 fb^{-1}	2030	$< 1°$
LHCb phase-2 upgrade [14 TeV]	300 fb^{-1}	(>)2035	$< 0.4°$

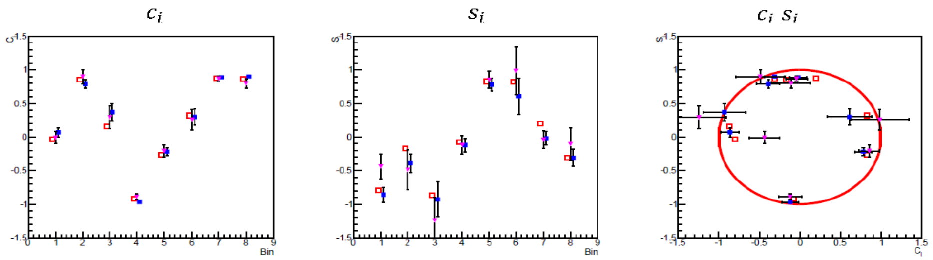
Strong-phase inputs from CLEO contribute an ~2^0 uncertainty to γ measurement, and will be comparable with experimental statistical uncertainty at LHCb RUN2.

Wishlist of Quantum Correlated measurements at BESIII

Decay mode	Quantity of interest	Comments
$D \to K_S^0 \pi^+ \pi^-$	c_i and s_i	Binning schemes as those used in the CLEO-c analysis. With 20 fb^{-1} of data at 3.773 GeV, it might be worthwhile to explore alternative binning.
$D \to K_S^0 K^+ K^-$	c_i and s_i	Binning schemes as those used in the CLEO-c analysis. With 20 fb^{-1} of data at 3.773 GeV, it might be worthwhile to explore alternative binning.
$D \to K^\pm \pi^\mp \pi^+ \pi^-$	R, δ	In bins guided by amplitude models, currently under development by LHCb.
$D \to K^+ K^- \pi^+ \pi^-$	c_i and s_i	Binning scheme guided by the CLEO-c model [69] or potentially an improved model in the future.
$D \to \pi^+ \pi^- \pi^+ \pi^-$	F_+ or c_i and s_i	Unbinned measurement of F_+. Measurements of F_+ in bins or c_i and s_i in bins could be explored.
$D \to K^\pm \pi^\mp \pi^0$	R, δ	Simple 2-3 bin scheme could be considered.
$D \to K_S^0 K^\pm \pi^\mp$	R, δ	Simple 2 bin scheme where one bin encloses the K^* resonance.
$D \to \pi^+ \pi^- \pi^0$	F_+	No binning required as $F_+ \sim 1$.
$D \to K_S^0 \pi^+ \pi^- \pi^0$	F_+ or c_i and s_i	Unbinned measurement of F_+ required. Additional measurements of F_+ or c_i and s_i in bins could be explored.
$D \to K^+ K^- \pi^0$	F_+	Unbinned measurement required. Extensions to binned measurements of either F_+ or c_i and s_i.
$D \to K^\pm \pi^\mp$	δ	Of low priority due to good precision available through charm-mixing analyses.

Quantum Correlated measurements with 2.93 fb^{-1} data

- Strong phase of $D \rightarrow K^- \pi^+$ PLB734(2014)227
- Strong phase of $D \rightarrow K_S \pi^+ \pi^-$, to be submitted this December

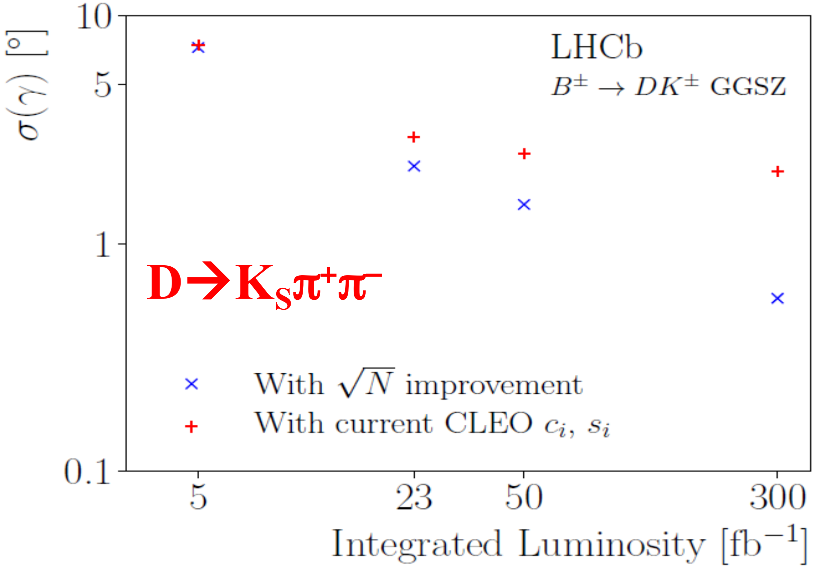


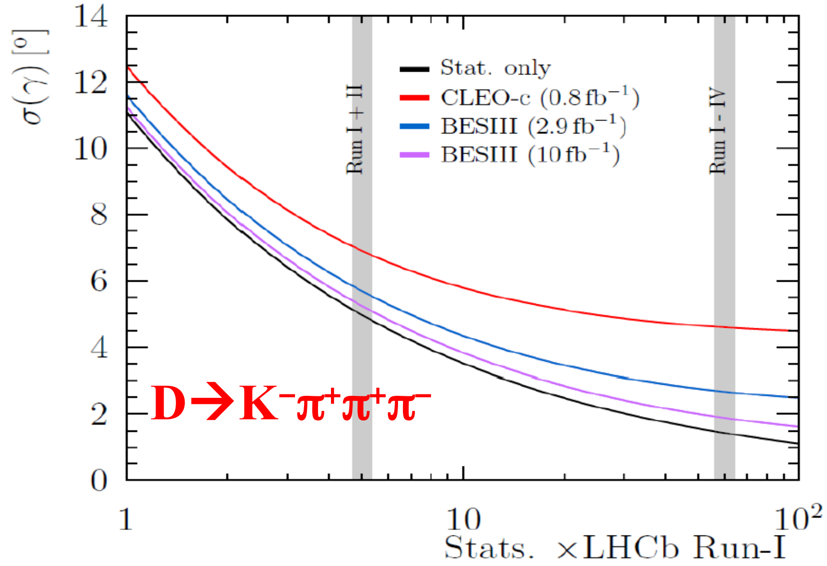
Preliminary

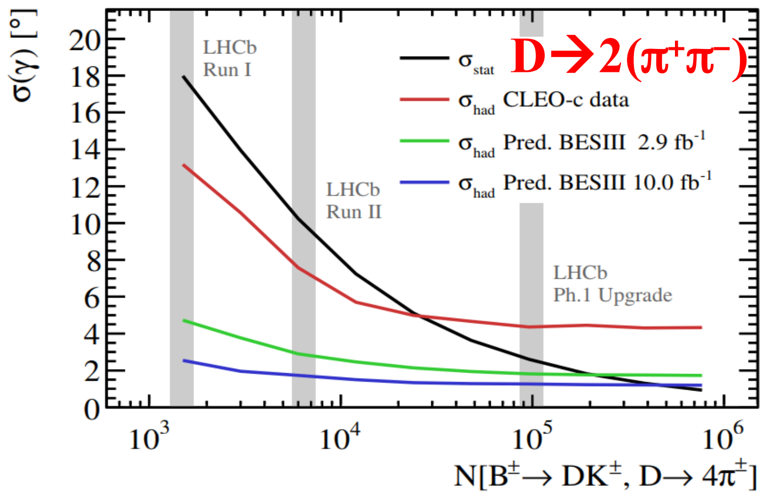
- CP+ fractions of $D \rightarrow \pi^+ \pi^- \pi^0$ and $K^+ K^- \pi^0$ Near to ready
- Strong phase of $D \rightarrow K_S K^+ K^-$ Ongoing
- Strong phase of $D \rightarrow K^- \pi^+ \pi^0$ and $K^- \pi^+ \pi^+ \pi^-$ Ongoing
- Analysis of $D \rightarrow 2(\pi^+ \pi^-)$ Ongoing
- Analysis of $D \rightarrow K_S \pi^+ \pi^- \pi^0$ Ongoing
- Analysis of $D \rightarrow K_S K^+ \pi^-$ and $K_S K^- \pi^+$ Ongoing

Constraint to γ/ϕ_3 measurement

LHCb, arXiv:1808.08865v2







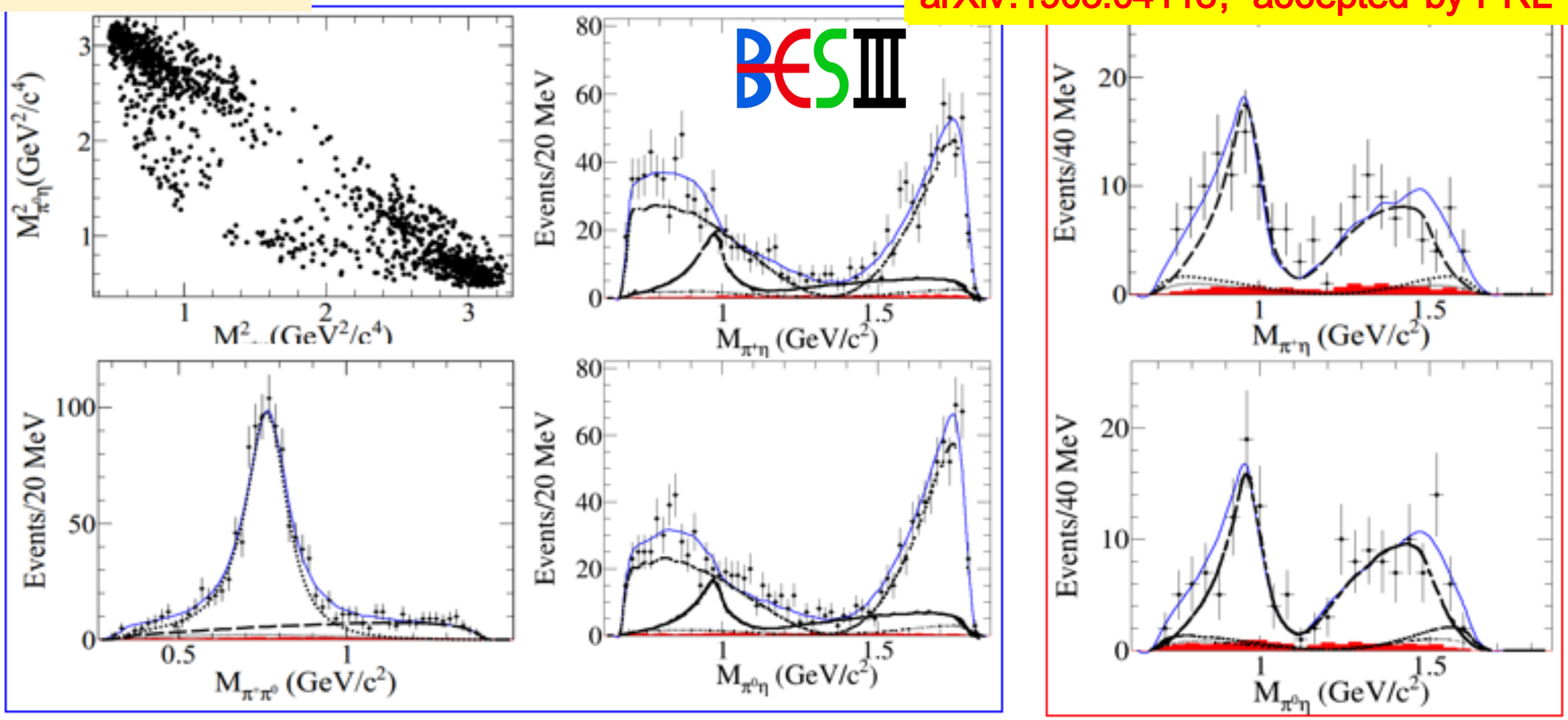
BESIII: 10 to 16 fb^{-1}

Strong phase from QC data at BESIII will be key to constrain the γ measurement at LHCb upgrade 1(2) to sub-degree level

Amplitude analysis of $D_s^+ \to \eta\pi^+\pi^0$

BESIII: 3.19 fb^{-1} @ 4180 MeV

arXiv:1903.04118, accepted by PRL



$$B_{D_s^+\to\pi^+\pi^0\eta} = (9.50 \pm 0.28 \pm 0.41)\%$$

$$B_{D_s^+\to\rho^+\eta} = (7.44 \pm 0.48 \pm 0.44)\%$$

$$B_{D_s^+\to a_0(980)\pi} = (2.20 \pm 0.22 \pm 0.34)\%$$

$$B^{\text{PDG18}}_{D_s^+\to\pi^+\pi^0\eta} = (9.2 \pm 1.2)\%$$

Branching fraction is one order higher than other known annihilation decays.

Y.K.Hsiao, Y. YU, B.C. Ke
arXiv:1909.07327

Rare decays and lifetime measurements from LHCb

Why Rare charm decays

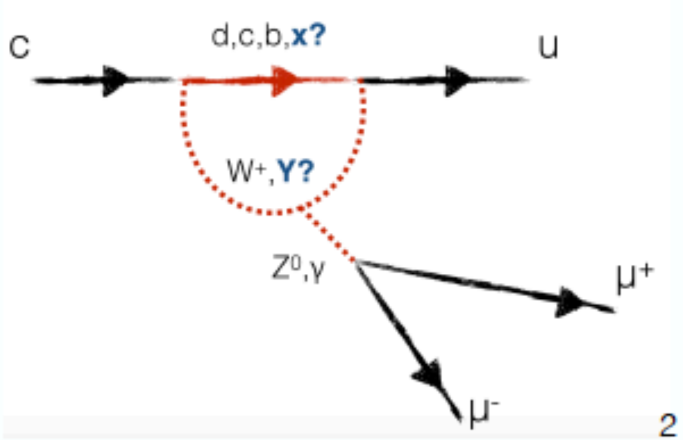
D. Mitzel

Promising to search for NP…

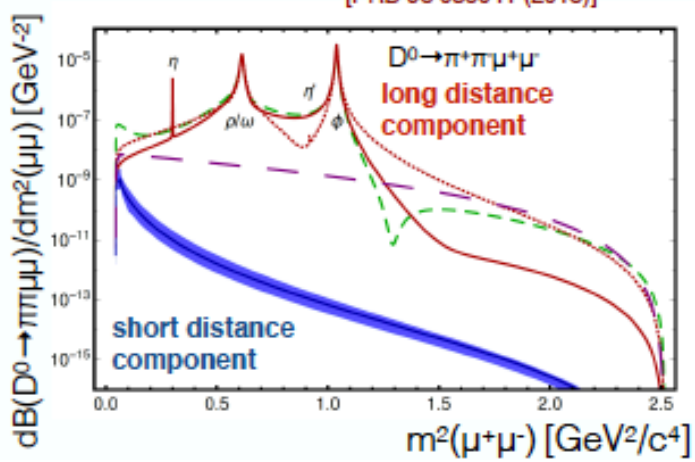
- rare charm decays involve FCNC $c \to u$ transitions at **short distances (SD)**
  - in SM only at loop level
- some NP models predict large enhancement in rates and asymmetries [PRD 83 114006 (2011)] [PRD 98 035041 (2018)]
- one of few occasions to investigate up-type quark FCNCs

…but also very challenging!

- SM short-distance contribution highly CKM & GIM suppressed
  - inclusive SM $D \to X\mu^+\mu^- \lesssim O(10^{-9})$
- processes dominated by **long distance (LD)** (tree-level) dynamics, shielding the FCNC processes
- theoretical description very hard



[PRD 98 035041 (2018)]

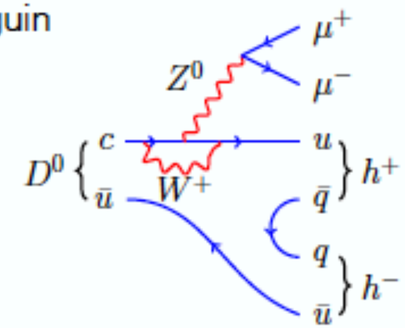


Observation of the $D^0 \to h^+h^-\mu^+\mu^-$

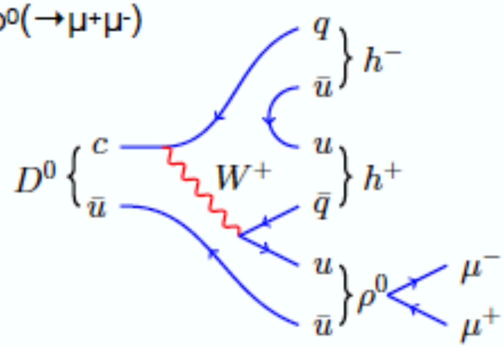
D. Mitzel

- overwhelming contribution from **LD** amplitudes proceeding through intermediate vector resonances screening the **SD** physics

example **short-distance** contribution
EW Penguin



example **long-distance** contribution
$D^0 \to h^+h^-\rho^0(\to\mu^+\mu^-)$



- **first step:** BF measurement (binned in dimuon mass and total BF)
  - (limited) sensitivity to **SD** contribution in regions away from resonances

5 fb^{-1} (2011-2016)

  - **total BF**:

$$\mathcal{B}(D^0 \to \pi^-\pi^+\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$$

$$\mathcal{B}(D^0 \to K^-K^+\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$$

[PRL 119 181805 (2017)]

- **second step:** measure asymmetries with sensitivity to **SD** in full range
  - O(few%) predictions for some NP models [JHEP 1304 135 (2013), PRD 87 054026 (2013)]

Asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

PRL, 121,091801 (2018)

- for the first time, measurements of angular and CP asymmetries in these decays
  - conceptual new and complementary to BF measurements

D. Mitzel

- asymmetries are sensitive to **SD** in full range due to **SD-LD** interference
  - observables are SM null tests
  - O(few%) predictions for some NP models

[JHEP 1304 135 (2013), PRD 87 054026 (2013), PRD 93, 074001 (2016), PRD 98, 035041 (2018)]

- angular asymmetries
  - forward backward asymmetry

$$A_{\mathrm{FB}} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

  - triple product asymmetry

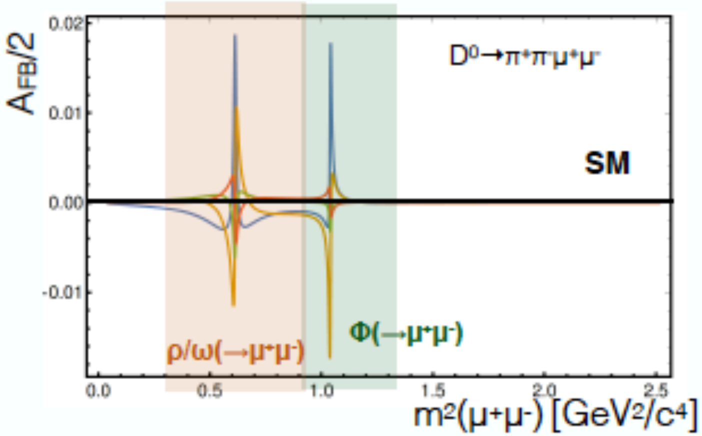
$$A_{2\phi} = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$

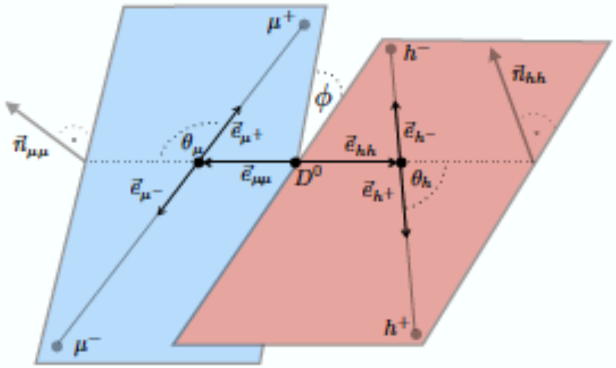
- CP asymmetry

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\overline{D}^0 \to h^+h^-\mu^+\mu^-)}$$

9

[PRD 98, 035041 (2018)]





Asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

PRL, 121,091801 (2018)

D. Mitzel

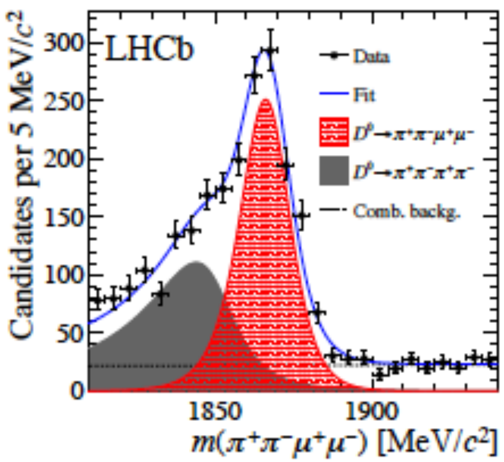
Measurement strategy

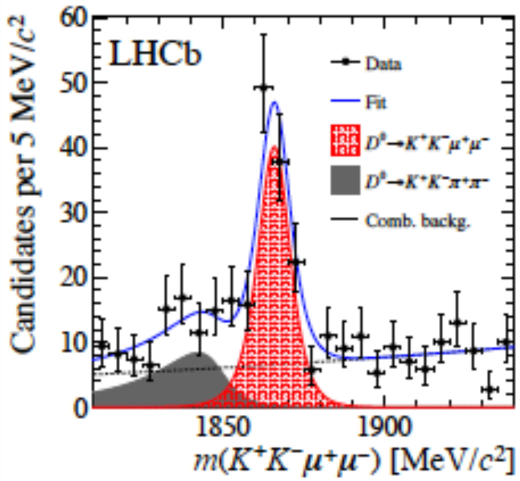
- measure A_{FB}, A_Φ and A_{CP} binned and integrated in dimuon mass
- select D^0 from flavour sepecific $D^{*+} \to D^0\pi^+$ decays
- 5/fb recorded 2011-2016

Decay mode	$m(\mu^+\mu^-)$ [MeV/c^2] low mass	η	ρ/ω		ϕ		high mass
$D^0 \to K^+K^-\mu^+\mu^-$	< 525	NS	> 565		NA		NA
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	< 525	NS	565-780	780-950	950-1020	1020-1100	NS

NA = not available
NS = no signal

- total yields
  - $D^0 \to \pi^+\pi^-\mu^+\mu^-$: 1.1k
  - $D^0 \to K^+K^-\mu^+\mu^-$: 110
- sensitivity on asymmetries of a few %





Asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$

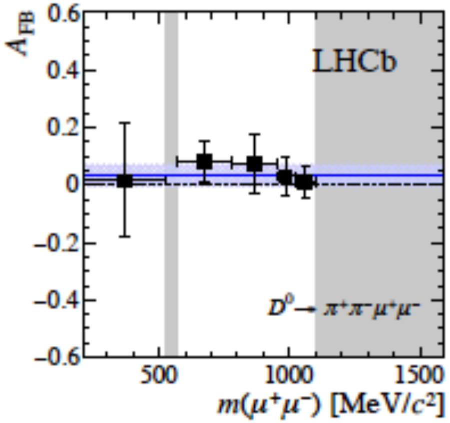
PRL, 121,091801 (2018)

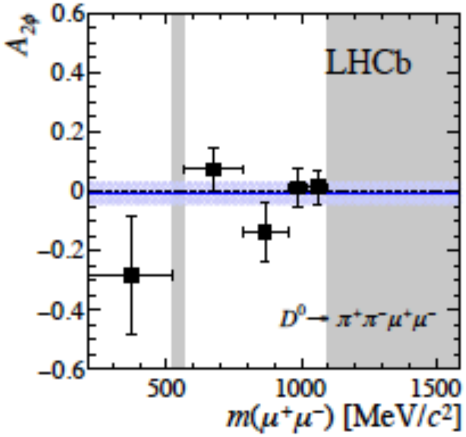
D. Mitzel

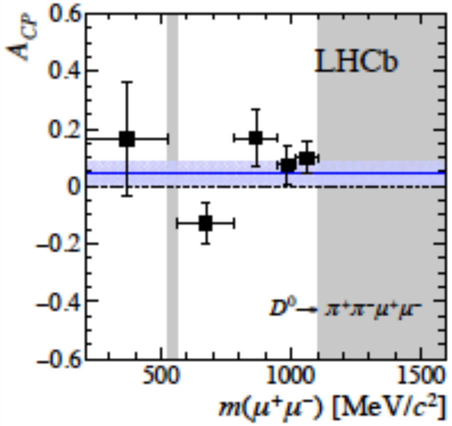
Total asymmetries

$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 4.9 \pm 3.8 \pm 0.7)\%,$$
$$A_{FB}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (\ \ 3.3 \pm 3.7 \pm 0.6)\%,$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 1)\%,$$
$$A_{FB}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\%$$

uncertainties are statistical and systematic





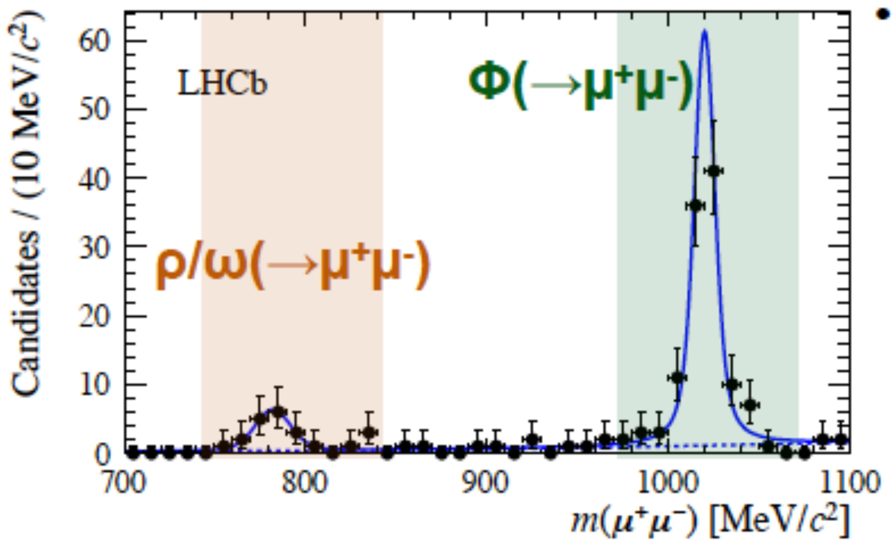


compatible with SM predictions
[JHEP 04 135 (2013), PRD 98, 035041(2018)]

- all asymmetries consistent with zero
- no dependency on dimuon mass observed (also true for $D^0 \to K^+K^-\mu^+\mu^-$)

Search for rare decay $\Lambda_c \rightarrow p\mu^+\mu^-$ LHCb: arXiv:1712.07938

D. Mitzel



- first measurement of rare decays of charmed baryons at LHCb
  - total BF dominated by resonant **LD** contributions:
    - $\Lambda_c^+ \rightarrow p\Phi(\rightarrow\mu^+\mu^-)$
    - $\Lambda_c^+ \rightarrow p\rho/\omega(\rightarrow\mu^+\mu^-)$
  - sensitivity to **SD** physics away from resonances in dimuon mass

LHCb analysis strategy

- define three dimuon mass regions: Φ,ρ/ω and non-resonant (NR)
  - measurement/limit of the BF in ρ/ω and NR region relative to $\Lambda_c^+ \rightarrow p\Phi(\rightarrow\mu^+\mu^-)$
- full Run 1 data (3/fb)

Search for rare decay $\Lambda_c \rightarrow p\mu^+\mu^-$

D. Mitzel

LHCb: arXiv:1712.07938

- upper limit on non-resonant component

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 9.6 \times 10^{-8} \text{ at } 95\% \text{ CL}$$

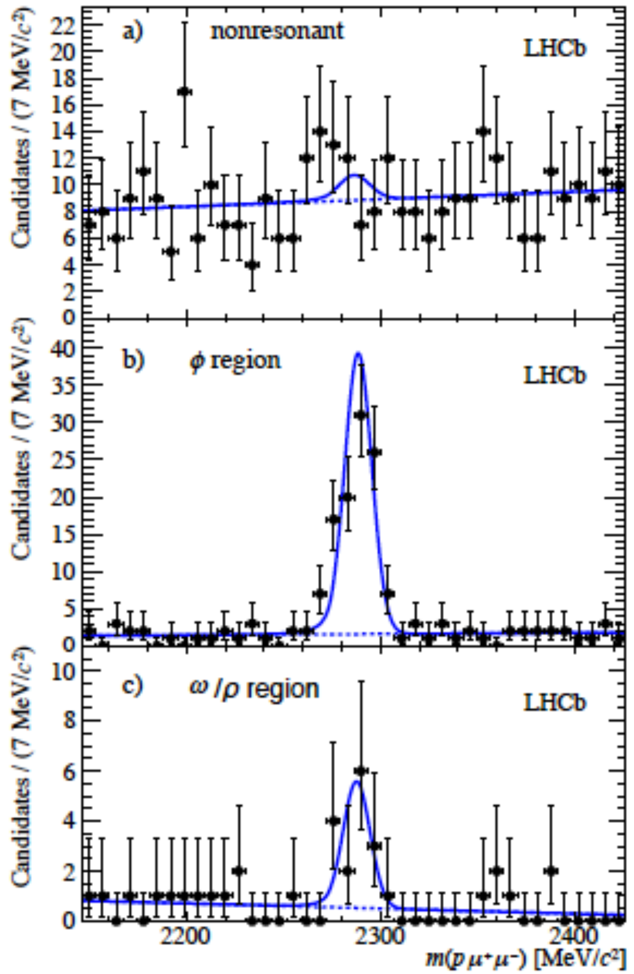
- ~1000x better than previous result from BaBar [PRD 84 072006 (2011)]

- first observation of $\Lambda_c^+ \rightarrow p\mu^+\mu^-$ in the ρ/ω region of the dimuon mass spectrum

$$\mathcal{B}(\Lambda_c^+ \to p[\mu^+\mu^-]_{\rho/\omega}) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-8}$$

- uncertainties are statistical, systematic and due to the BF of normalization mode

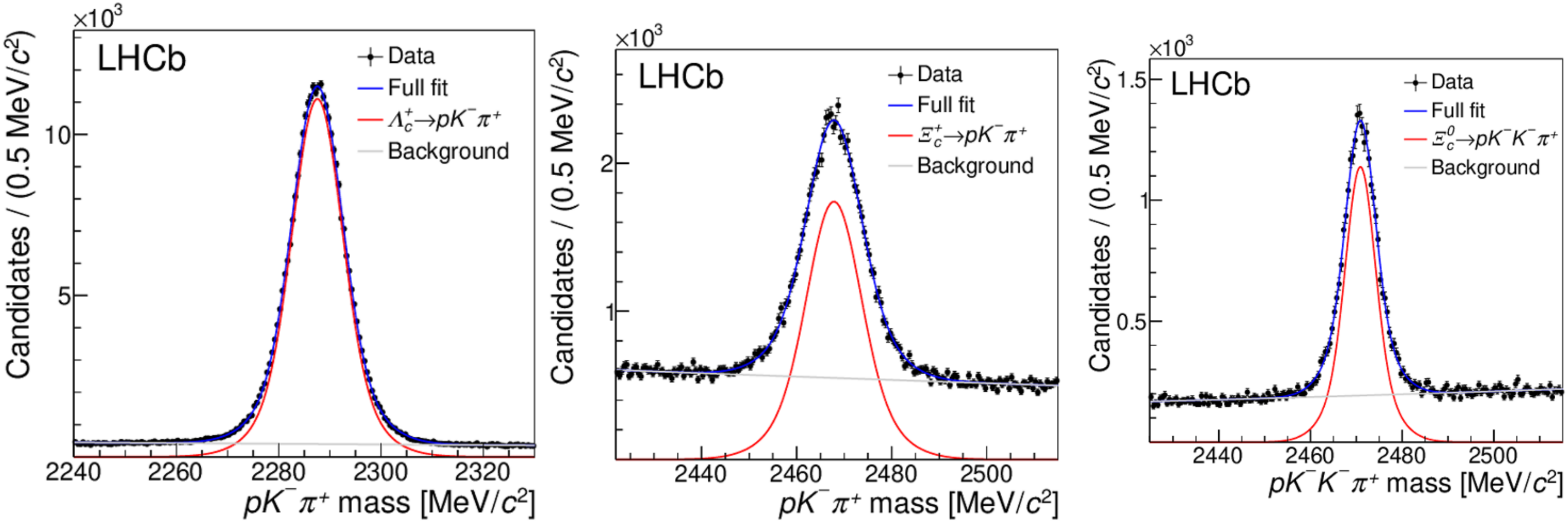
6



Precision lifetime measurements of charmed baryons

LHCb: arXiv:1906.08350

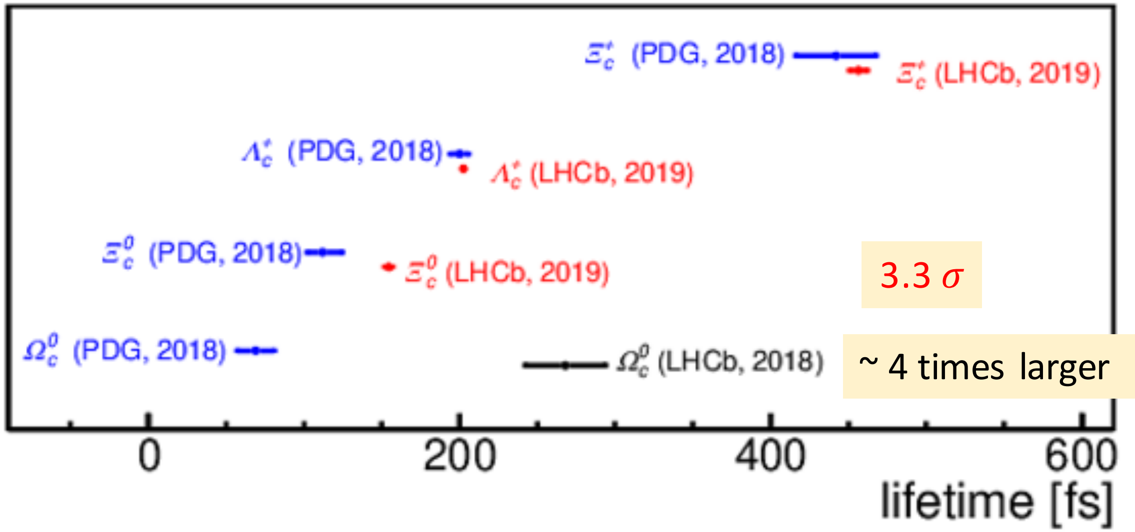
- Using run-I data: 3.0 fb^{-1}
- Decay channels: $\Lambda_c^+ \to pK^-\pi^+$, $\Xi_c^+ \to pK^-\pi^+$, $\Xi_c^0 \to pK^+K^-\pi^+$

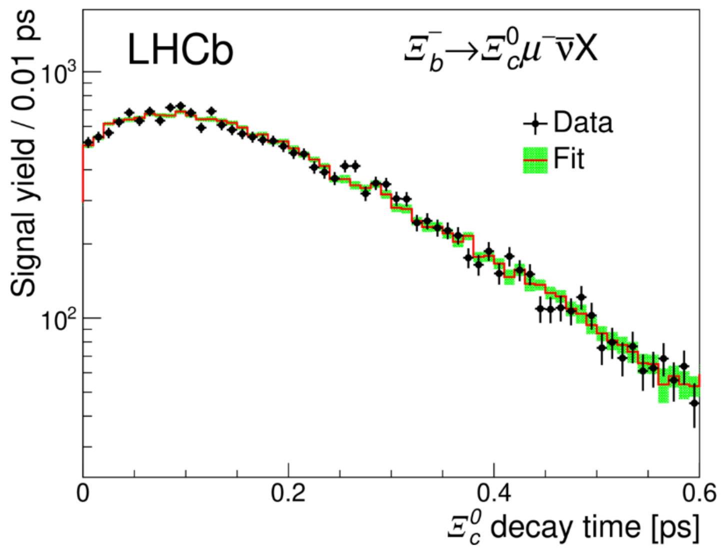


Precision lifetime measurements of charmed baryons

Fit decay time spectra to get lifetime information

LHCb: arXiv:1906.08350





$$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs},$$

$$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs},$$

$$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs},$$

The measurements are approximately 3–4 times more precise than the current world average values

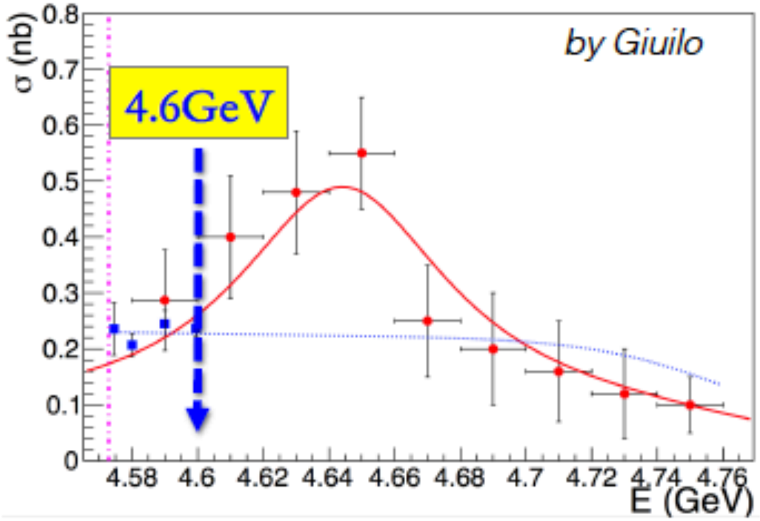
LHCb: arXiv:1807.02024

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \; fs$$

Near threshold data : $e^+e^- \rightarrow \Lambda_c^+\overline{\Lambda}_c^-$

	Energy(GeV)	lum.(1/pb)
	4.575	47.67
	4.580	8.54
	4.590	8.16
35 days data taking	4.600	566.93

Corresponds to 0.1M Λ_c pairs



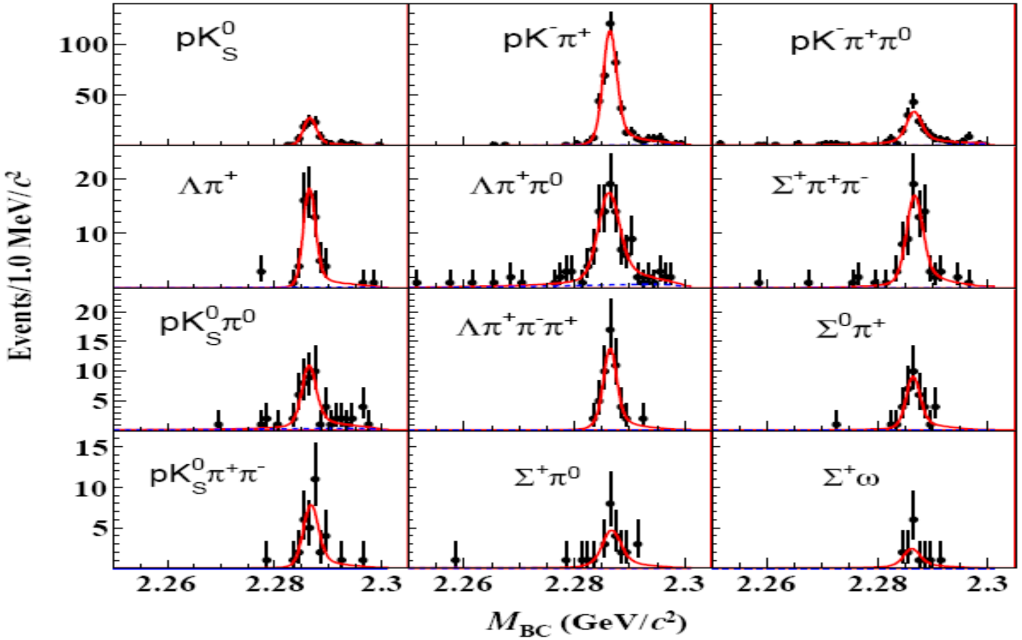
Measurement using the threshold pair-productions via e^+e^- annihilations is unique: *the most simple and straightforward*

First time to systematically study charmed baryon at threshold!

Absolute BFs of Λ_c^+ hadronic decays

PRL 116, 052001 (2016)

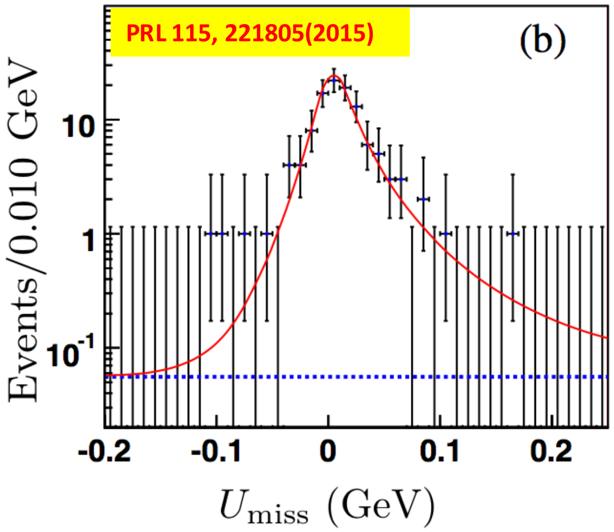
BESIII: 0.6 fb^{-1} @ 4600 MeV



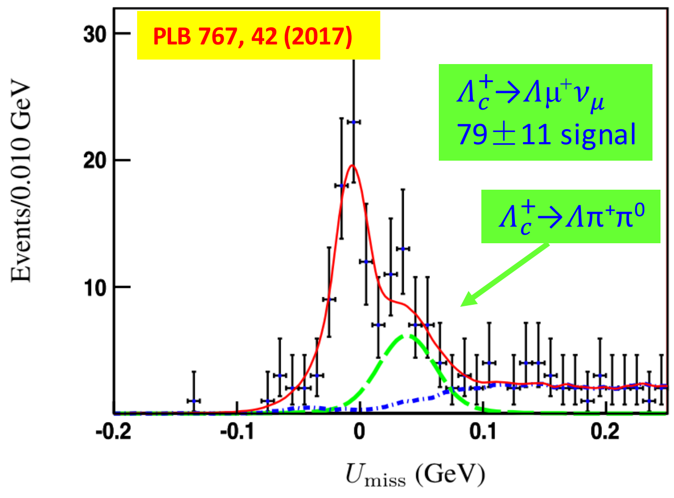
Mode	BESIII (%)	PDG (%)	BELLE $\mathcal{B}$
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30	
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3	$6.84 \pm 0.24^{+0.21}_{-0.27}$
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50	
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35	
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0	
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28	
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3	
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7	
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28	
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34	
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0	
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0	

Absolute BFs for $\Lambda_c^+ \to \Lambda l^+ \nu_l$

BESIII: 0.6 fb^{-1} @ 4600 MeV



B[$\Lambda_c^+ \to \Lambda e^+ \nu_e$]=(3.36±0.38±0.20)%



B[$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$]=(3.49±0.46±0.27)%

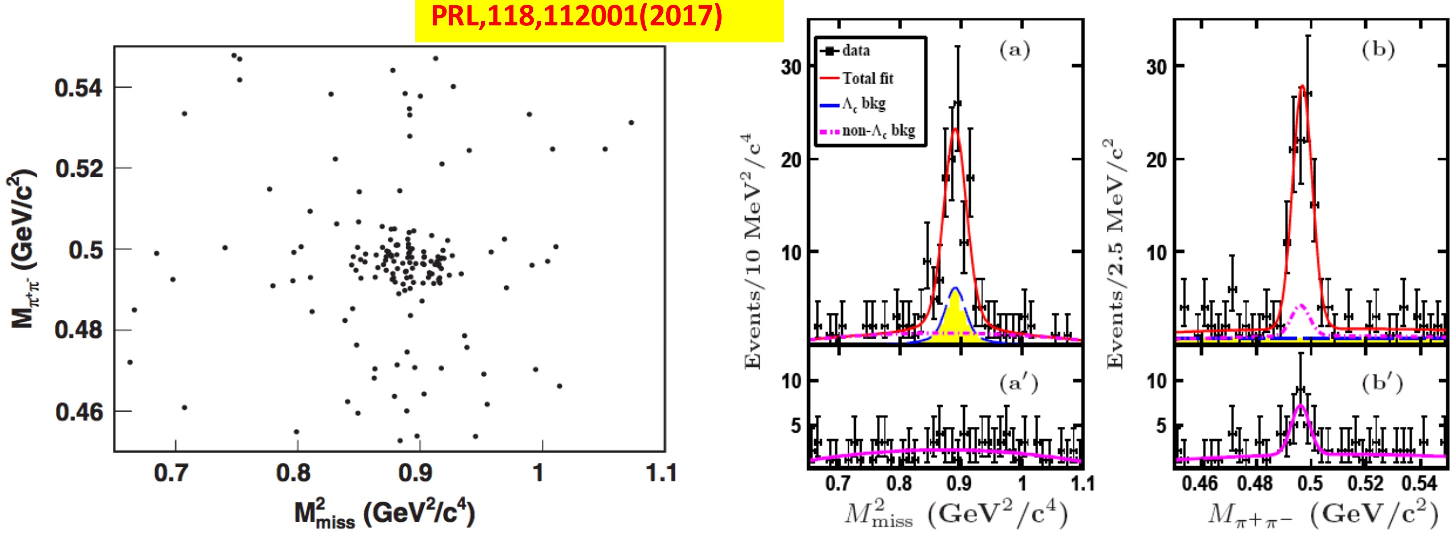
- First absolute measurement of the semi-leptonic decay (Statistics limited)
- Important input for implementing and calibrating the Lattice QCD calculations
- Best precision to date: twofold improvement
- $\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu]/\Gamma[\Lambda_c^+ \to \Lambda e^+ \nu_e] = 0.96 \pm 0.16 \pm 0.04$

Observation of $\Lambda_c^+ \to n K_S^0 \pi^+$

BESIII: 0.6 fb^{-1} @ 4600 MeV

- First direct measurement of Λ_c^+ decay involving the neutron in the final state.

PRL,118,112001(2017)

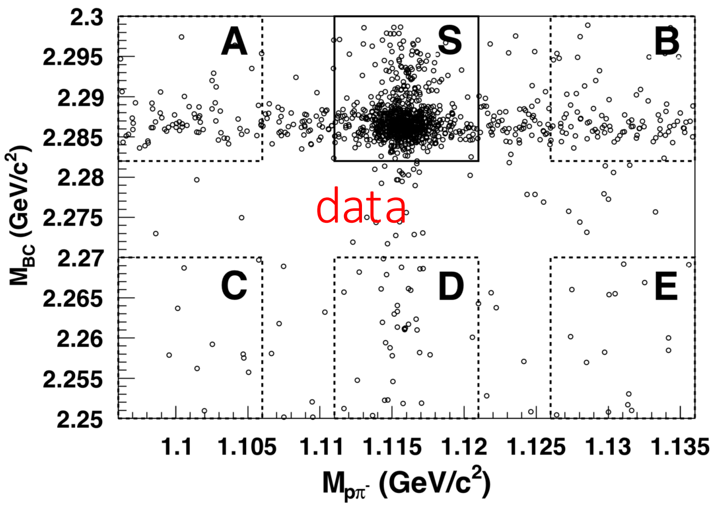


- 2-D fitting extract 83±11 net signals => B[$\Lambda_c^+ \to n K_S^0 \pi^+$]=(1.82±0.23±0.11)%
- B[$\Lambda_c^+ \to n K^0 \pi^+$]/B[$\Lambda_c^+ \to p K^- \pi^+$]=0.62±0.09; B[$\Lambda_c^+ \to n K^0 \pi^+$]/B[$\Lambda_c^+ \to p K^0 \pi^0$]=0.97±0.16
- A test of final state interactions and isospin symmetry in the charmed baryon sector. [PRD93, 056008 (2016)]

The inclusive channel $\Lambda_c^+ \to \Lambda$+X

BESIII: 0.6 fb^{-1} @ 4600 MeV

PRL 121, 062003(2018)



$$N^{\rm sig} = N^{\rm S} - \frac{N^{\rm A}+N^{\rm B}}{2} - f\cdot(N^{\rm D} - \frac{N^{\rm C}+N^{\rm E}}{2})$$

- **Comparison with K+X will shed light on the internal dynamics**

- In the ST modes of $\Lambda_c^+ \to pK^-p^+$ and pK_S^0, to measure the probability of find a Λ in the final states.
- Extract yields from 2D distributions in bins of $p-|cos\theta|$
- Data-driven 2D efficiency correction using several Λ control samples.
- $\mathcal{B}(\Lambda_C^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.9)\%$

  (excl. rate $(24.5 \pm 2.1)\%$ observed, indicates ~1/3 BFs are unknown)
- $A_{cp} = (2.1^{+7.0}_{-6.6} \pm 1.6)\%$

  (No CPV is observed.)

$\Lambda_c^+ \to e^+ \nu_e$+X

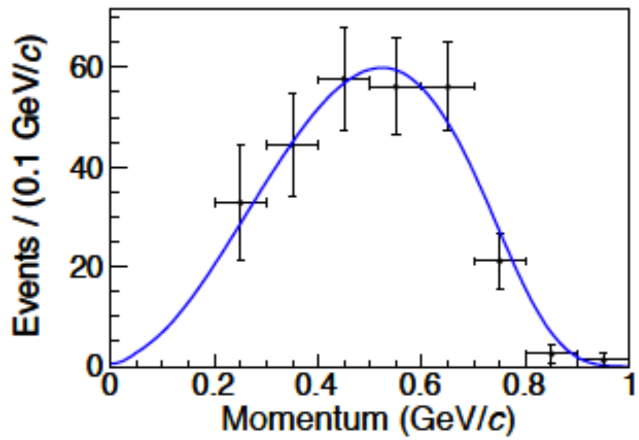
BESIII: 0.6 fb^{-1} @ 4600 MeV

PRL 121 251801(2018)

- Current PDG: BF($\Lambda_c^+ \to e$+X)=(4.5±1.7)%.
- Large rate, but also with large uncertainty
- Tagged with $\Lambda_c^+ \to pK^-\pi^+$ and pK_S^0

=> $\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$

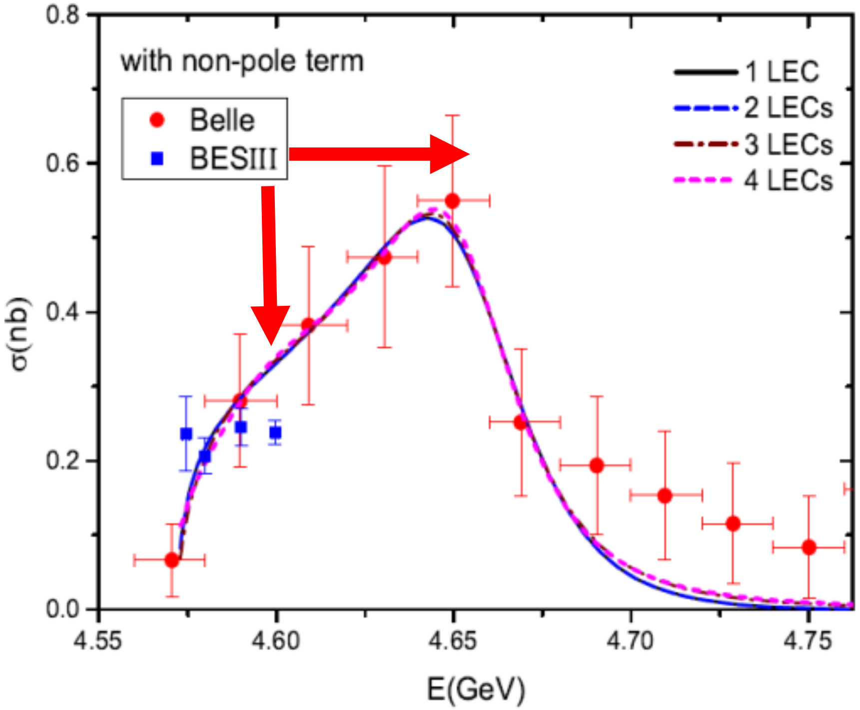
=> $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)}{\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e)} = (91.9 \pm 12.5 \pm 5.4)\%$



- The $\Lambda l^+ \nu_l$ dominate the l^++X =>$\mathcal{B}$ ($pKl^+\nu_l$)~10^{-3}.

Result	$\Lambda_c^+ \to Xe^+\nu_e$	$\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\Gamma(D \to Xe^+\nu_e)}$
BESIII	3.95 ± 0.35	1.26 ± 0.12
MARK II [7]	4.5 ± 1.7	1.44 ± 0.54
Effective-quark Method [9, 10]		1.67
Heavy-quark Expansion [11]		1.2

Lineshape of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$



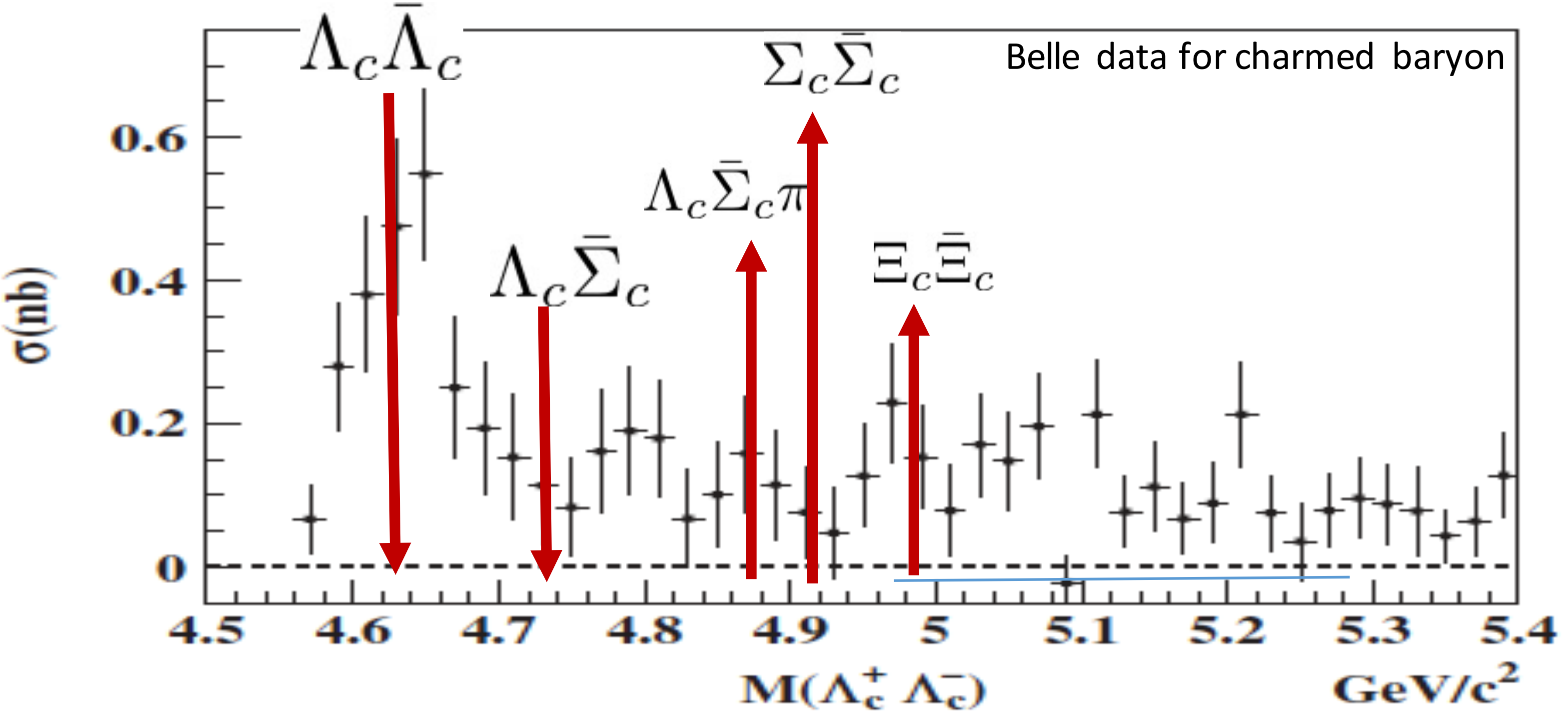
Belle: PRL101, 172001 (2008)
BESIII: PRL120,132001(2018)

Machine upgrades:

- ✓ **Energy upgrades**
- ✓ **Lumi improvement @ higher energy**
- ✓ **"Topup" injections**

Some tensions between Belle and BESIII data on $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

Access to the heavier charmed baryons



Energy thresholds

- ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c^-$ 4.74 GeV
- ✓ $e^+e^- \to \Lambda_c^+\bar{\Sigma}_c\ \pi$ 4.88 GeV
- ✓ $e^+e^- \to \Sigma_c\ \bar{\Sigma}_c$ 4.91 GeV (10MeV above current limit)
- ✓ $e^+e^- \to \Xi_c\ \bar{\Xi}_c$ 4.95 GeV (50 MeV above current limit)

Competition and complementary -future

- **Super-KEKB/Belle-II (50 ab^{-1} ccbar cross-secion = 1.0 nb@Υ(4S)) 50 billion**

  arXiv: 1808.10567 (Belle-II physics book)

- **Super-tau-charm factory (5 ab^{-1} ccbar cross-secion = 6.5 nb@ψ(3770)) 30 billion**
- **LHCb and its upgrades (50 fb^{-1} → 10^{11} reconstructed charm mesons)**

  arXiv:1808.08865 (LHCb upgrade-II)

- **proton-antiproton collisions (PANDA…)**
- **SHiP experiment at CERN: (10^{18} D mesons, 10^{16} τ, 10^{20} γ)**

arXiv:1504.04855 ; arXiv:1807.02746

Physics programmes for future data taking at BESIII

From the white paper

- **10-16 fb^{-1} on $\psi(3770)$**
- **6 fb^{-1} at 4.18 GeV → Ds meson**
- **5 fb^{-1} at 4.64 GeV for the charmed baryon**
- **Scan at the highest energy?**
- **Large Zc samples: 5 fb^{-1} each at 4.23, 4.42 GeV**
- **High-statistics data samples around 2.2, 2.4 GeV**
- **3 billion $\psi(3686)$**

…wishlist comprises about 40 fb^{-1}

BESIII has to run another 8 - 10 years to collect these data sets with current luminosity!

Summary

SM predictions

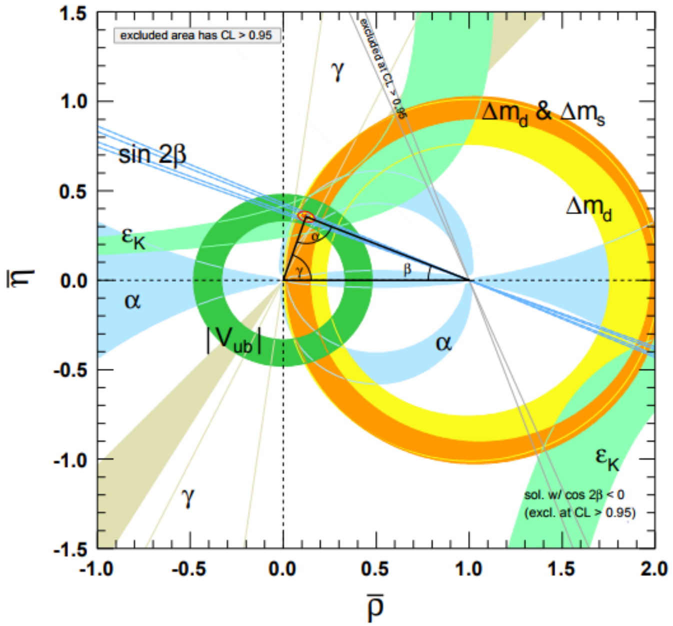
Experimental reaches

SM predictions	Decay class	Modes	Experimental reaches
10^{-0}			
10^{-1}	Cabibbo favored	$D^0 \to K^-\pi^+, /D^+ \to \overline{K}^0\pi^+/D^0 \to K^-l^+\nu/D_s^+ \to \tau^+\nu$	CLEO-c
10^{-2}			
10^{-3}	Singly Cabibbo suppressed	$D^0 \to \pi^-\pi^+, /D^+ \to \pi^0\pi^+/D^0 \to \pi^-l^+\nu/D^+ \to \mu\nu$	CLEO-c
10^{-4}	Doubly Cabibbo suppressed	$D^0 \to K^+\pi^-, /D^+ \to K^+\pi^0$	CLEO-c
10^{-5}	Radiative decays	$D^0 \to \overline{K}^{*0}\gamma / \phi\gamma / \rho\gamma / \omega\gamma$	**BESIII**
10^{-6}		$D^+ \to K^{*+}\gamma / \rho^+\gamma \quad D_S^+ \to K^{*+}\gamma / \rho^+\gamma$	**BESIII final/B factory**
10^{-7}	Long distance:		
10^{-8}	Vector Meson Dominance	$D^0 \to \gamma\gamma / VV'(\to ll) / hV(\to ll) / hh'V(\to ll)$	**LHCb**
10^{-9}			**Belle-II/Super-B**, **Super-τ-charm**
10^{-10}	**Short distance FCNC**	$D^0 / D^+ \to \gamma\gamma / Vl^+l^- / hl^+l^- / hh'l^+l^-$	
10^{-11}		$D^0 \to \mu^+\mu^-$	**LHCb upgrade 1 (50 fb^{-1})**
10^{-12}		$D^0 \to e^+e^-$	
10^{-13}			**LHCb upgrade 2 (300 fb^{-1})**
10^{-14}		$D \to (h)\mu^+e^-$	
10^{-15}	**Forbidden decays: LNV, LFV, BNV**	$D \to (hh)e^+e^+ / (hh)\mu^+\mu^+$	**SHiP experiment @CERN**

Thank you for your attentions!

Synergy with LHCb to measure γ/ϕ_3

- Has very small theory uncertainty $O(10^{-7})$ JHEP01,051(2014)
- Over-constrain the CKM triangle to probe for NP, which may cause a sizeable 4° effect. PRD92,033002(2015)



$$\alpha = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \equiv \phi_2,$$

$$\beta = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \equiv \phi_1,$$

$$\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \equiv \phi_3,$$

Accessed by the interference between b→cus and b→ucs

Decays: **B→DK,** B→D*K, B→Dπ, B→D*π, B→D$^{(*)}$Kπ, ...

Methods: **GGSZ, ADS, GLW: strong phase differences of neutral D**

10 years data taking at BESIII

Data sets collected so far include,

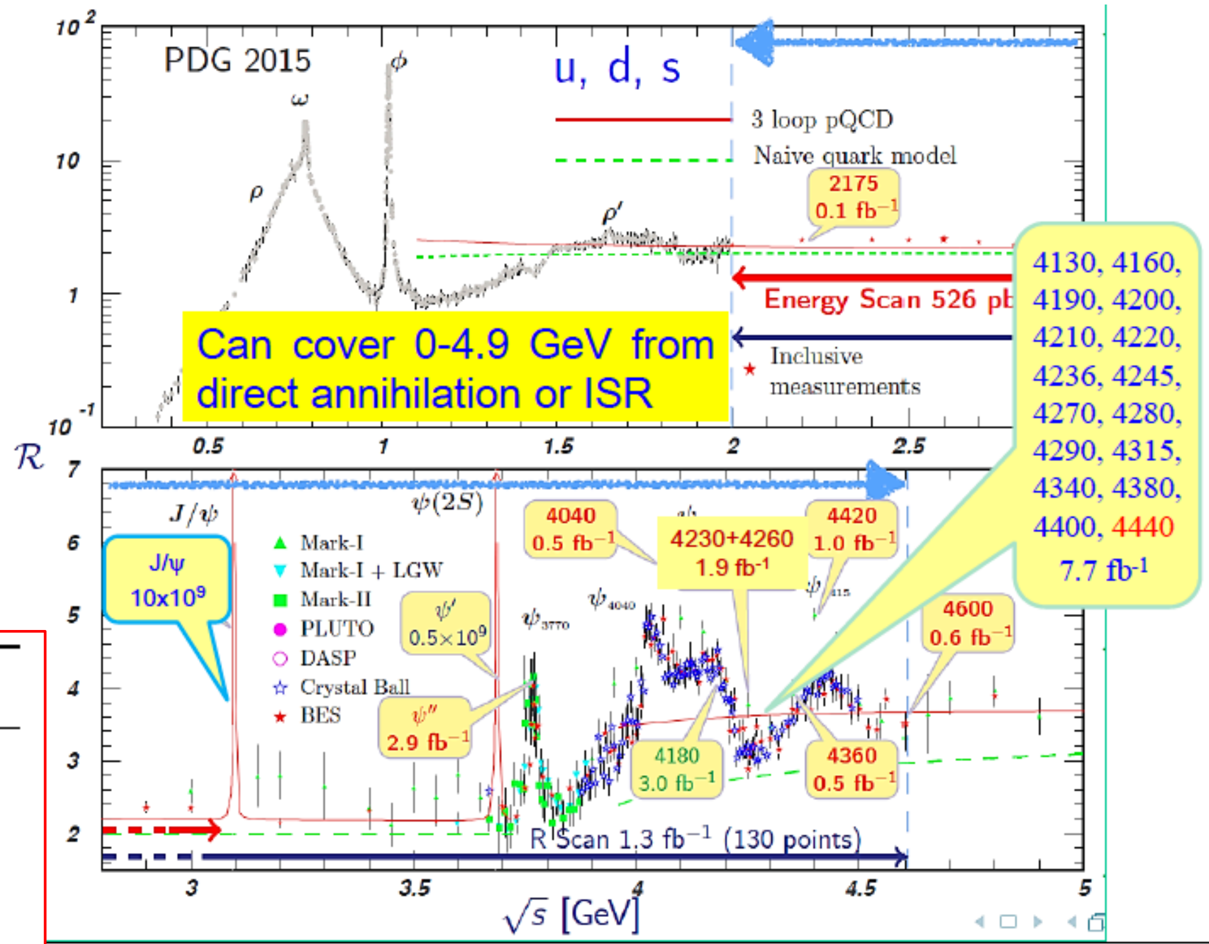
- **10×10^9 J/ψ events**
- 0.5×10^9 ψ' events
- Scan data [2.0, 3.08] GeV; [3.735, 4.600] GeV

  130 energy points, about 2.0 fb^{-1}
- Large data sets for XYZ study above 4.0 GeV

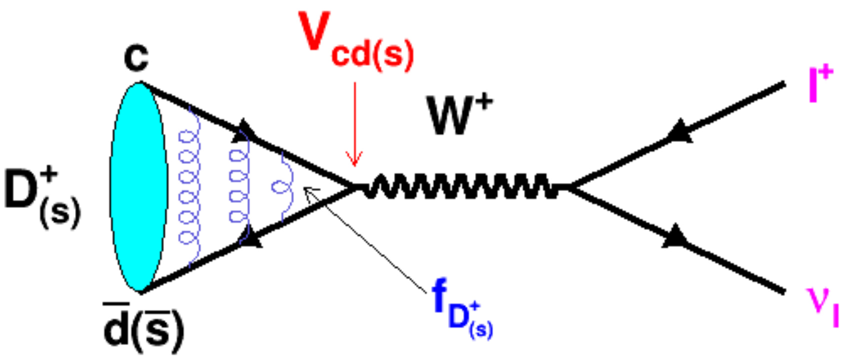
  about 12 fb^{-1}

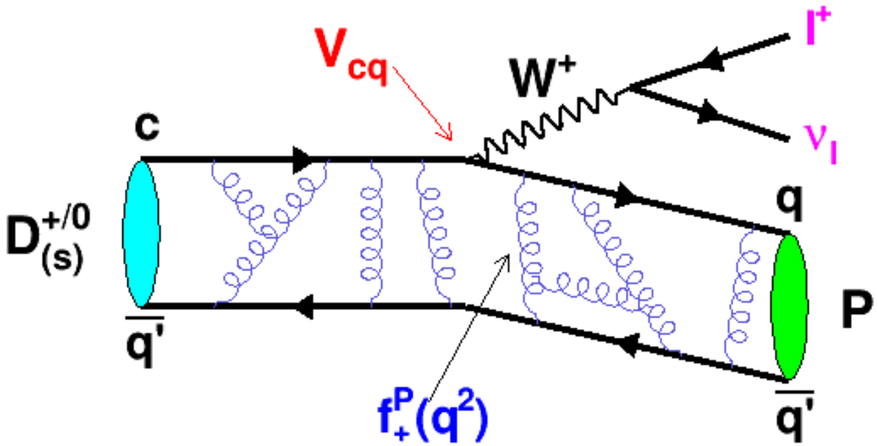
Unique data sets at open charm thresholds

$\sqrt{s}$ / GeV	$\mathcal{L}$ / fb^{-1}	
3.77	2.93	$D\bar{D}$
4.008	0.48	DD^*, $\psi(4040)$, $D_s^+D_s^-$
4.18	3.2	$D_sD_s^*$
4.6	0.59	$\Lambda_c^+\bar{\Lambda}_c^-$



Leptonic and semileptonic charm decays





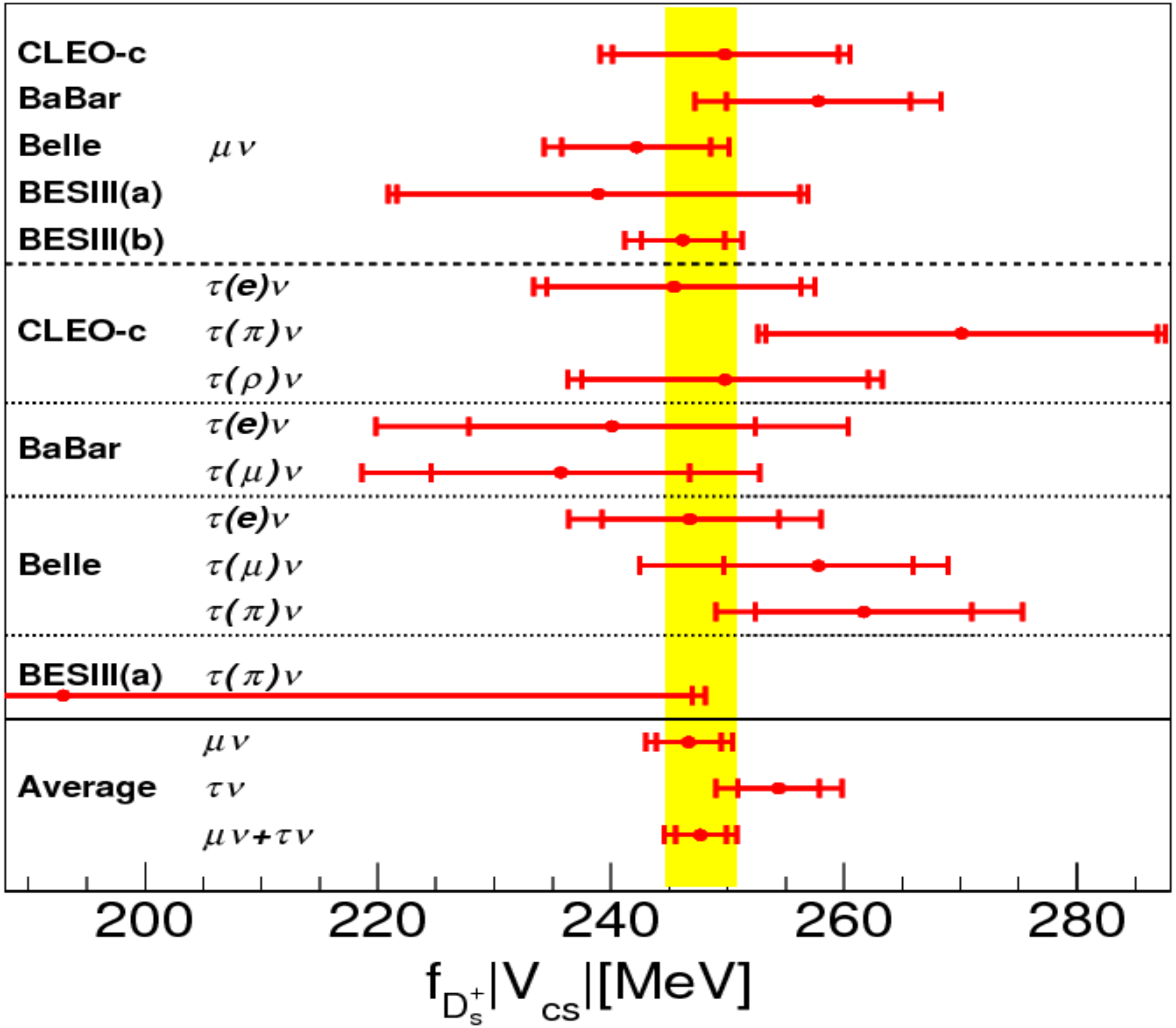
$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi}|V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}}\left(1-\frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2$$

1. $|V_{cs(d)}|$: test on CKM matrix unitarity
2. $f_{D(s)+}$, $f_+^{K(\pi)}(0)$: test LQCD calculations
3. Branching fractions allow for LFU tests

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$f_{D_s}^{+}|V_{cs}|$



CLEO-c
BaBar
Belle μν
BESIII(a)
BESIII(b)
τ(e)ν
CLEO-c τ(π)ν
τ(ρ)ν
τ(e)ν
BaBar
τ(μ)ν
τ(e)ν
Belle τ(μ)ν
τ(π)ν
BESIII(a) τ(π)ν
μν
Average τν
μν+τν
200
220
240
260
280
f_{D_s^+}|V_cs|[MeV]

$|V_{cs}|$ and $|V_{cd}|$

LQCD Inputs averaged from HPQCQ, ETM, and FMILC

Inputs:

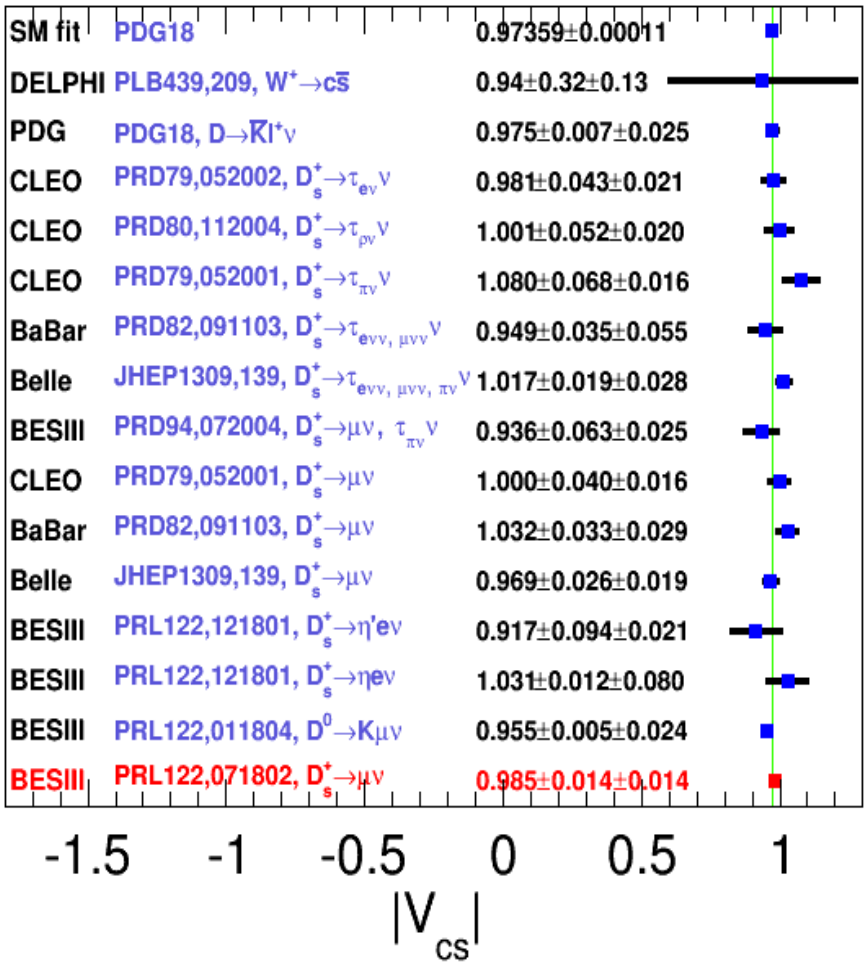
$$f_{D+}^{\text{LQCD}} = 212.3 \pm 0.6 \text{ MeV}$$

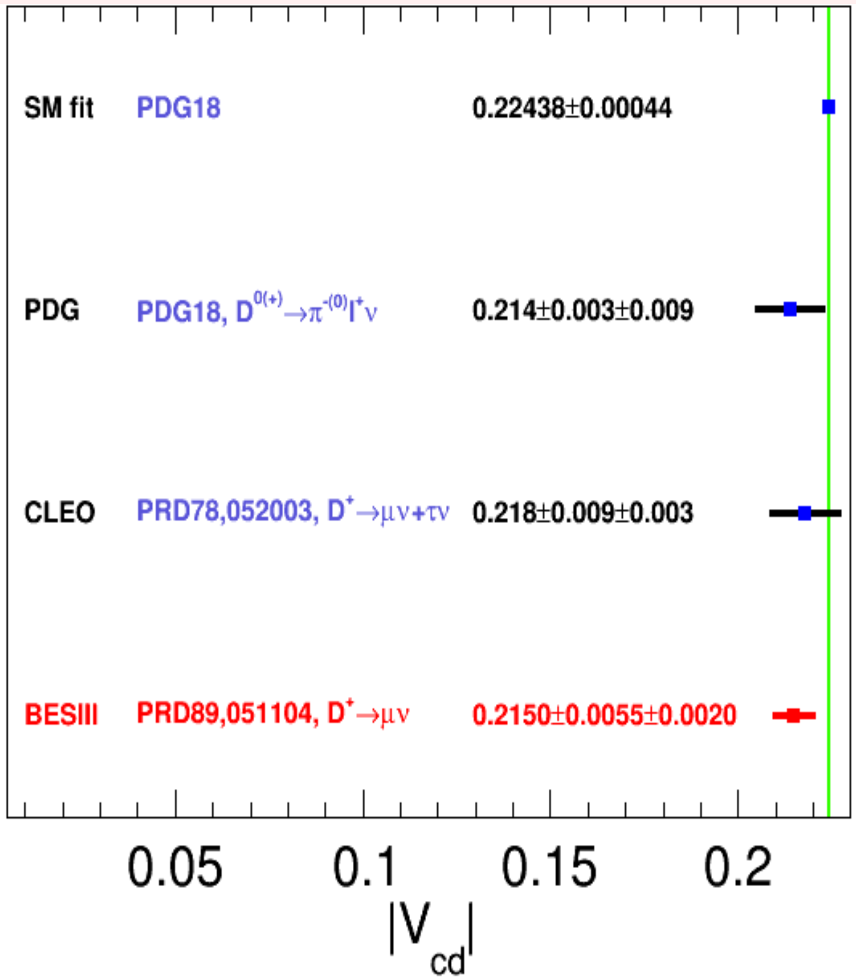
$$f_+^{D\to K}(0)^{\text{LQCD}} = 0.760 \pm 0.011$$

Inputs:

$$f_{D_s}^{\text{LQCD}} = 249.7 \pm 0.4 \text{ MeV}$$

$$f_+^{D\to \pi}(0)^{\text{LQCD}} = 0.634 \pm 0.015$$





$|V_{cs}|$ and $|V_{cd}|$

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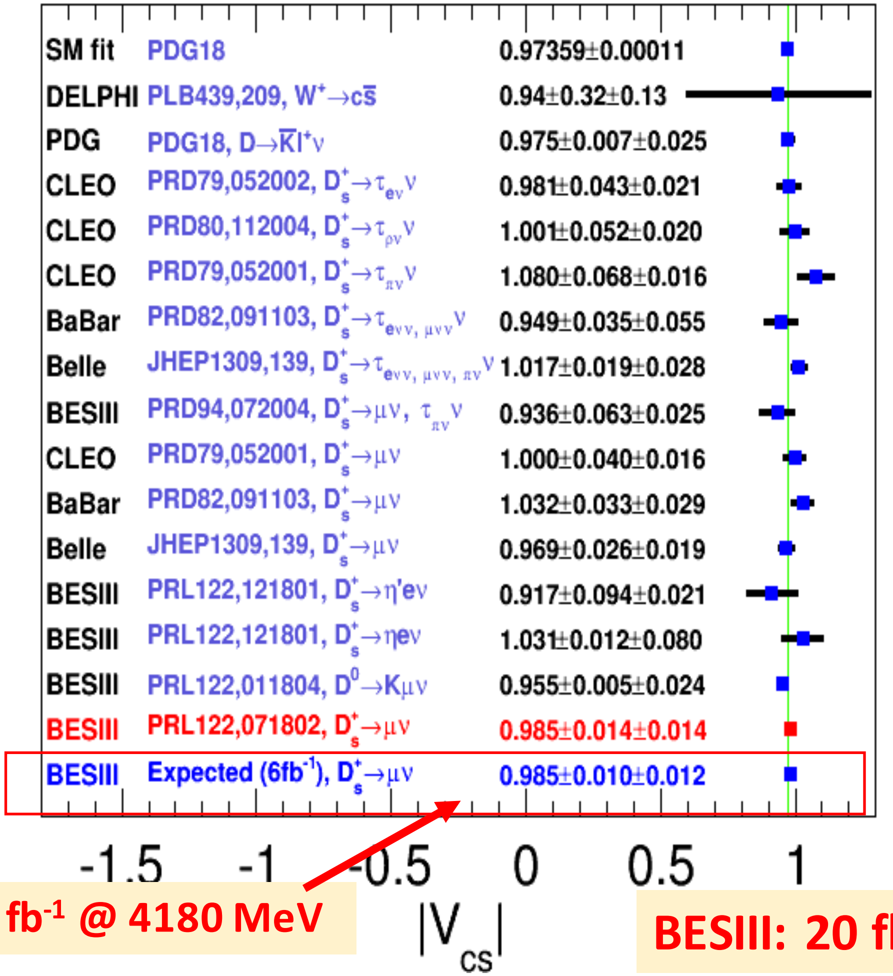
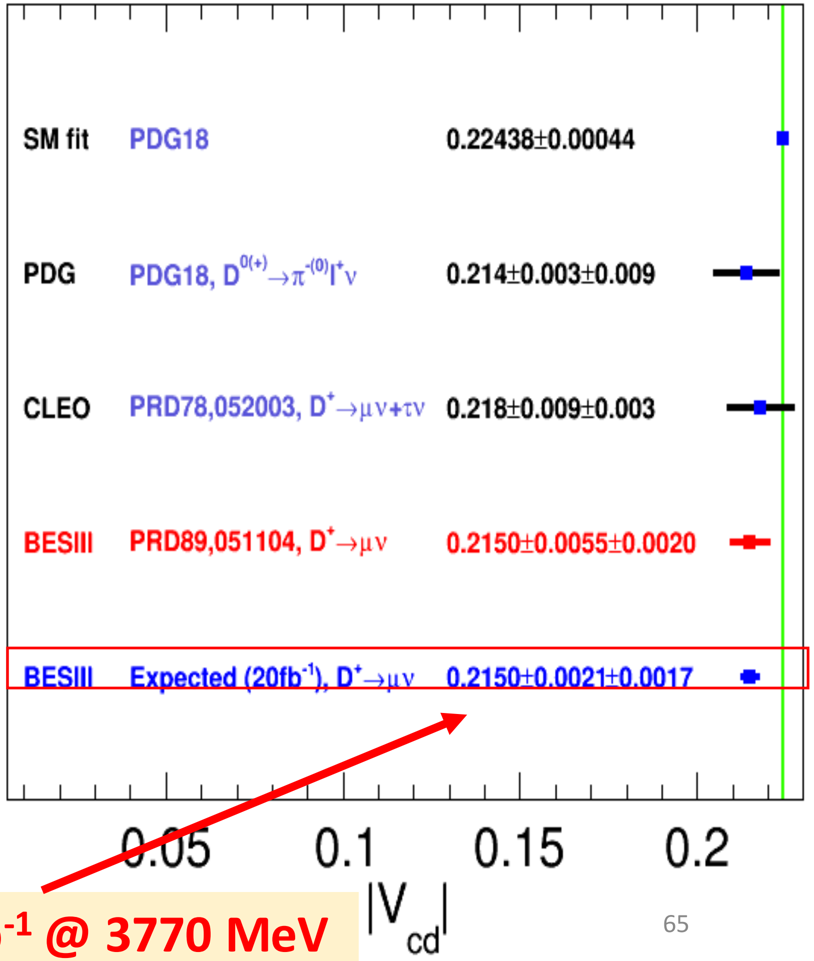


BESIII: 6 fb^{-1} @ 4180 MeV



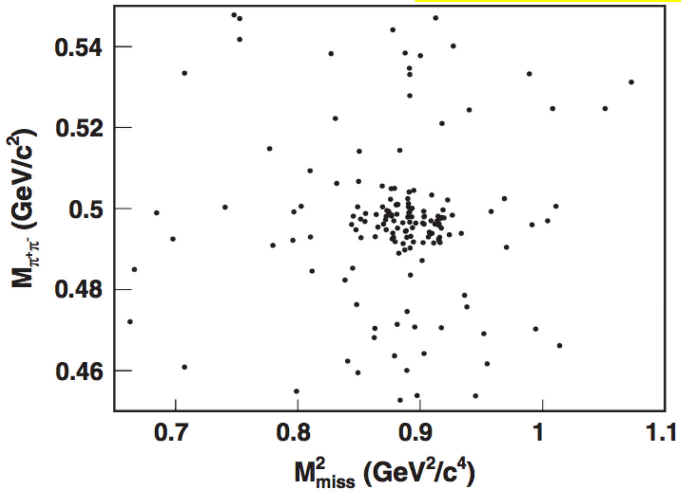
BESIII: 20 fb^{-1} @ 3770 MeV

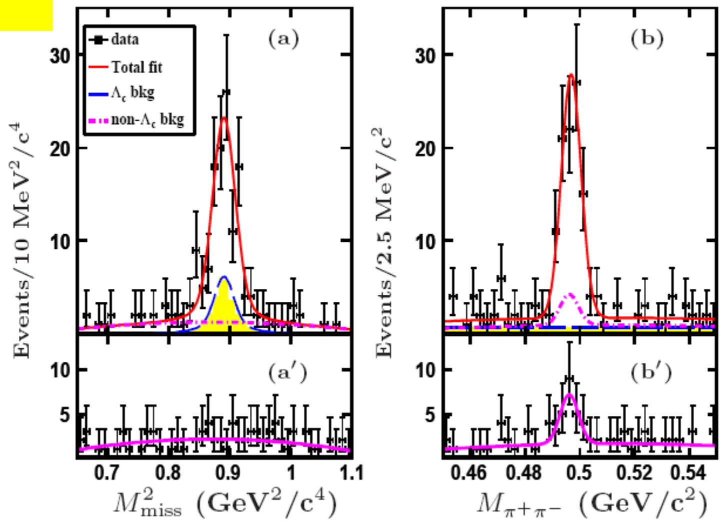
Observation of $\Lambda_c^+ \rightarrow nK_S^0\pi^+$

BESIII: 0.6 fb^{-1} @ 4600 MeV

- First direct measurement of Λ_c^+ decay involving the neutron in the final state.

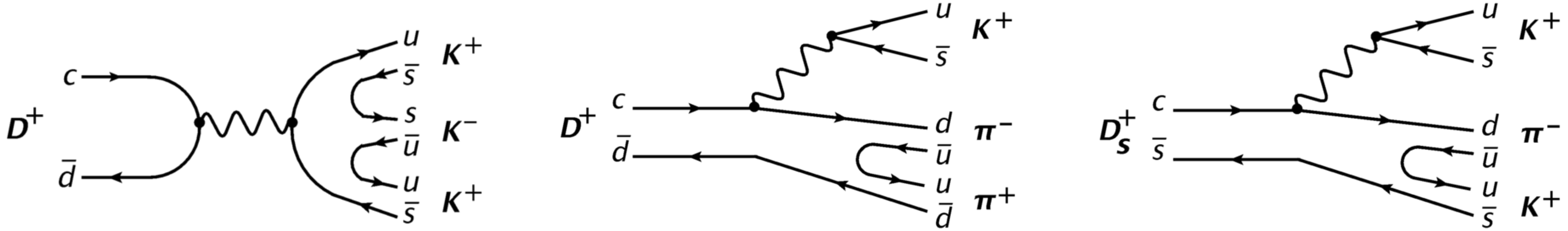
PRL,118,112001(2017)





- 2-D fitting extract 83±11 net signals => B[$\Lambda_c^+ \rightarrow nK_S^0\pi^+$]=(1.82±0.23±0.11)%
- B[$\Lambda_c^+ \rightarrow nK^0\pi^+$]/B[$\Lambda_c^+ \rightarrow pK^-\pi^+$]=0.62±0.09; B[$\Lambda_c^+ \rightarrow nK^0\pi^+$]/B[$\Lambda_c^+ \rightarrow pK^0\pi^0$]=0.97±0.16
- A test of final state interactions and isospin symmetry in the charmed baryon sector. [PRD93, 056008 (2016)]

Measurements of DCS decay D^+, D_s^+



LHCb: arXiv:1810.03138

Previous world average from PDG2018

Ratio	Value $[\times 10^{-3}]$
$\mathcal{B}(D^+ \to K^-K^+K^+)/\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	0.95 ± 0.22
$\mathcal{B}(D^+ \to \pi^-\pi^+K^+)/\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	5.77 ± 0.22
$\mathcal{B}(D_s^+ \to \pi^-K^+K^+)/\mathcal{B}(D_s^+ \to K^-K^+\pi^+)$	2.33 ± 0.23
$\mathcal{B}(D^+ \to K^-K^+\pi^+)/\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	105.9 ± 1.8

$$\frac{\mathcal{B}(D^+ \to K^-K^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (6.541 \pm 0.025 \pm 0.042) \times 10^{-4},$$

$$\frac{\mathcal{B}(D^+ \to \pi^-\pi^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (5.231 \pm 0.009 \pm 0.023) \times 10^{-3},$$

$$\frac{\mathcal{B}(D_s^+ \to \pi^-K^+K^+)}{\mathcal{B}(D_s^+ \to K^-K^+\pi^+)} = (2.372 \pm 0.024 \pm 0.025) \times 10^{-3},$$

$$\frac{\mathcal{B}(D^+ \to K^-K^+\pi^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (10.282 \pm 0.002 \pm 0.068) \times 10^{-2},$$

$$\mathcal{B}(D^+ \to K^-K^+K^+) = (5.87 \pm 0.02 \pm 0.04 \pm 0.18) \times 10^{-5},$$
$$\mathcal{B}(D^+ \to \pi^-\pi^+K^+) = (4.70 \pm 0.01 \pm 0.02 \pm 0.15) \times 10^{-4},$$
$$\mathcal{B}(D_s^+ \to \pi^-K^+K^+) = (1.293 \pm 0.013 \pm 0.014 \pm 0.040) \times 10^{-4},$$

$$\mathcal{B}(D^+ \to K^-K^+\pi^+) = (9.233 \pm 0.002 \pm 0.061 \pm 0.288) \times 10^{-3},$$

Upgrades to detectors: past and future

Detector has running smoothly, performance generally excellence.

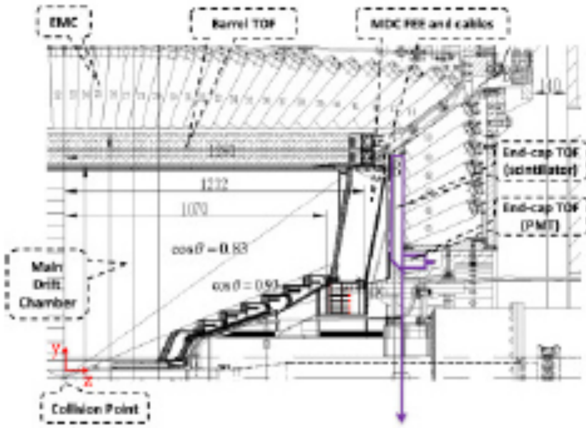
- ✓ **Endcap TOF upgrade （2015）**

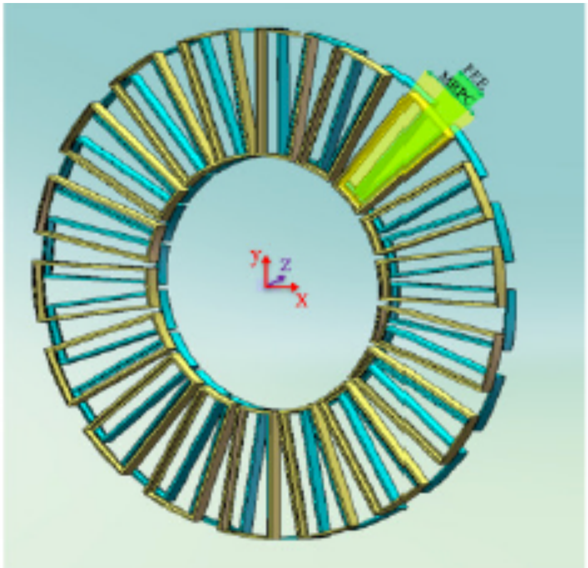
  single layer plastic scintillator

  was replaced with multi-gap RPC.

  Time resolution: 110 ps → 60 ps

  95% π/K separation up to 1.4 GeV





- ✓ **Inner most part of the drift chamber:**

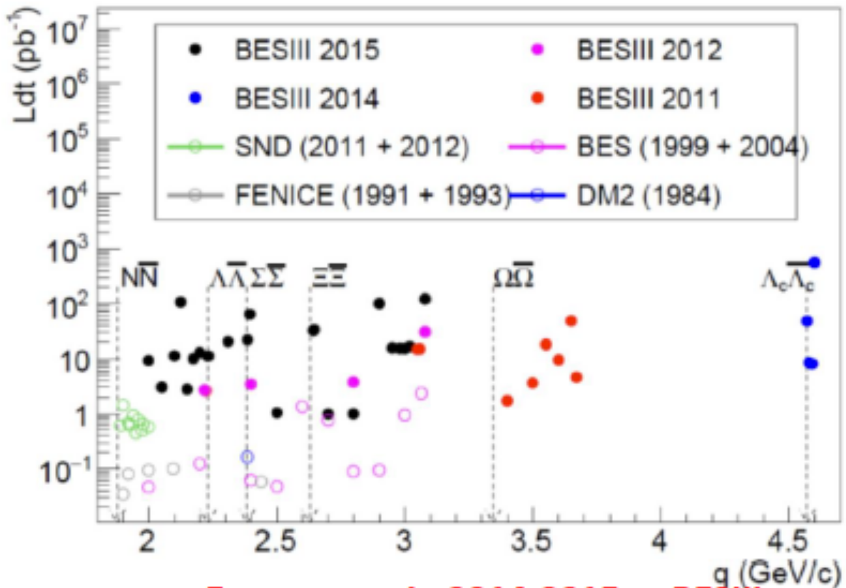
  1) New inner drift chamber is ready

  2) CGEM is in progress

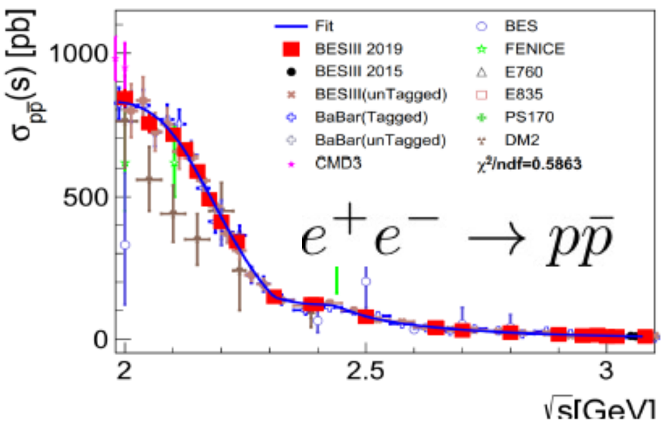
- ✓ **Super Conduct magnet : new valve box**

Advantage: unique data near to the thresholds

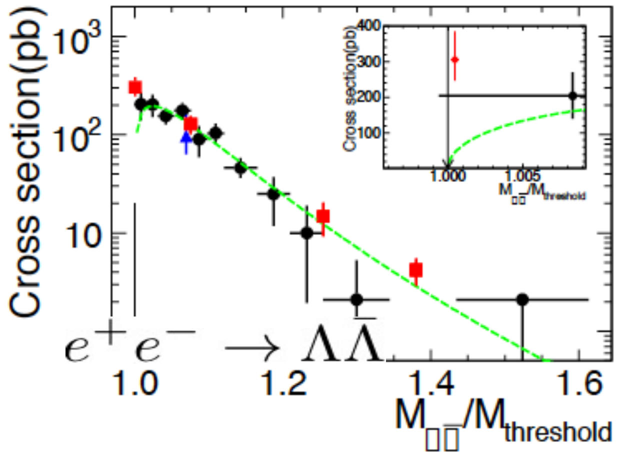
- **D/Ds/Λ_c hadrons near thresholds:**
  precision branching fractions, unique access to the relative phase, test of SM
- **Hyperon and charmed baryon Spin polarization in QC**
- **Form-factors in the time-like production**
- **CP violation with quantum-correlated pair productions of hyperons and charmed baryon**

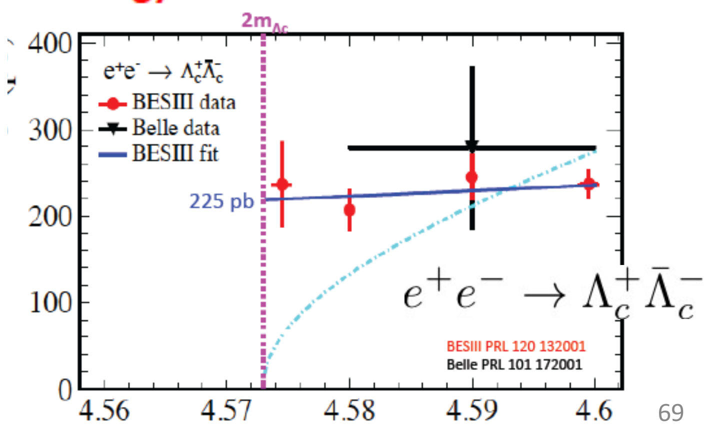


Energy scan in 2014-2015 at BESIII



Best precision on σ: 3% (systematic dominant)





Roadmap of CP violation in flavored hadrons

1980

2008

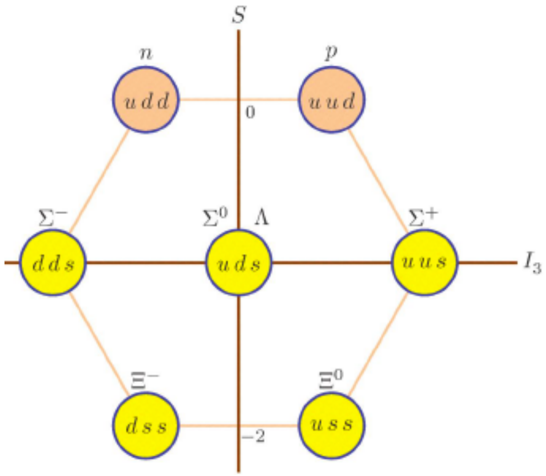
- **In 1964, the first CPV was discovered in Kaon ;**
- **In 2001, CPV in B was established by two B-factories;**
- **In 2019, CPV discovered in D meson: 10^{-4}, 10^{8} reconstructed D mesons (LHCb)**
- **All are consistent with CKM theory in the Standard model**
- **But no evidence was found in strange baryons?**

Baryon asymmetry of the Universe means that there must be non-SM CPV source.

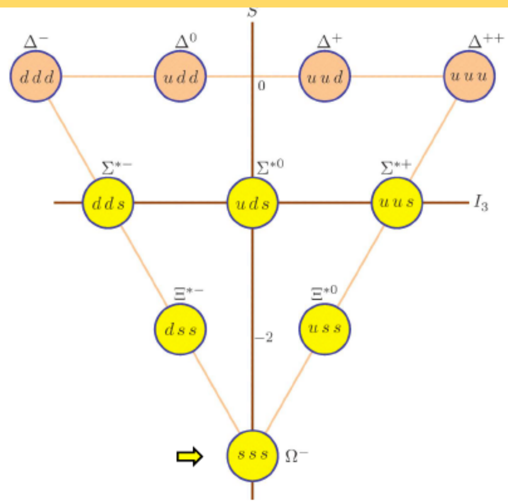
CPV in hyperon decays and New physics

CPV in SM is small :			# events	Experiments
B meson :	O(1)	discovered (2001)	10^3	B factory
K meson :	$O(10^{-3})$	discovered (1964)	10^6	Fix targets
D meson :	$O(10^{-4})$	discovered (2019)	10^8	LHCb
Hyperon :	$O(10^{-4})$	10^{-2}	$O(10^8)$	Fix targets
				→ BESIII ?

Flavor-SU(3) Octet of spin ½



Flavor-SU(3) Decuplet of spin 3/2



Why Hyperon physics at BESIII？

10 billion J/psi events collected

- **Large BRs in J/psi decays**
- **Quantum correlated pair productions**
- **Easy to reconstruct**
- **Background free**

Decay mode	$\mathcal{B}(\times 10^{-3})$	N_B $(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 0.5
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.10 ± 0.12	11.0 ± 1.2
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03

Hai-Bo Li, arXiv:1612.01775
A. Adlarson, A. Kupsc, arXiv:1908.03102

The number of reconstructed hyperon-anti-hyperon pairs will be a few millions.

Advantage at e^+e^- machine

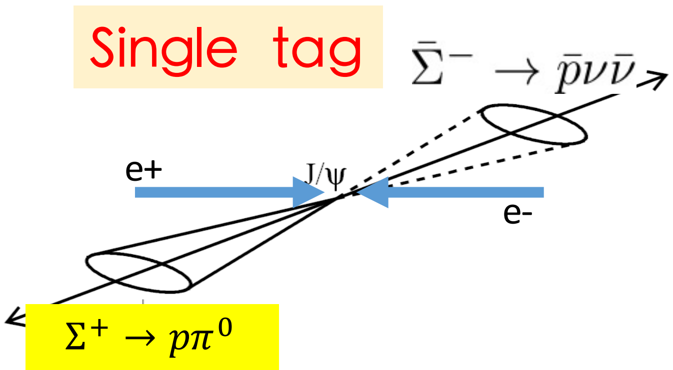
Known initial 4-momentum

Strongly boosted

Substantial polarization

Decay with neutron & π^0

Decay with invisibles



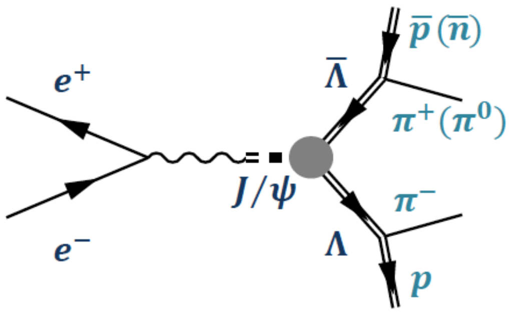
$$|\Lambda\bar{\Lambda}\rangle^{C=-1} = \chi_1 \frac{1}{\sqrt{2}}[|\Lambda\rangle|\bar{\Lambda}\rangle - |\bar{\Lambda}\rangle|\Lambda\rangle],$$

$$\alpha(\Lambda \to p\pi^-) = \alpha_-$$

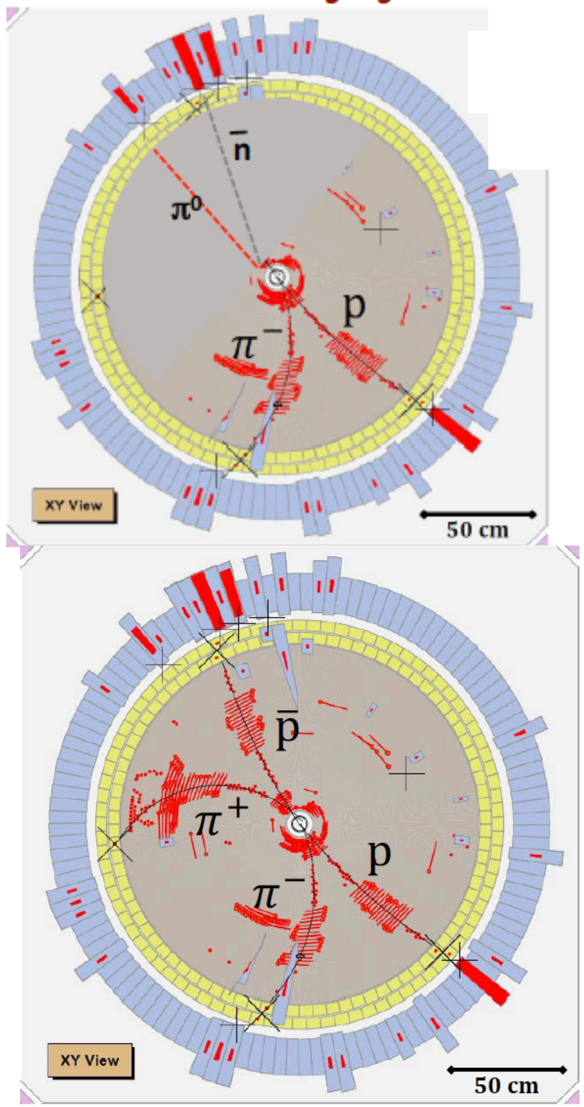
$$\alpha(\bar{\Lambda} \to \bar{p}\pi^+) = \alpha_+$$

$$\alpha(\bar{\Lambda} \to \bar{n}\pi^0) = \bar{\alpha}_0$$

$$\alpha(\Lambda \to n\pi^0) = \alpha_0$$

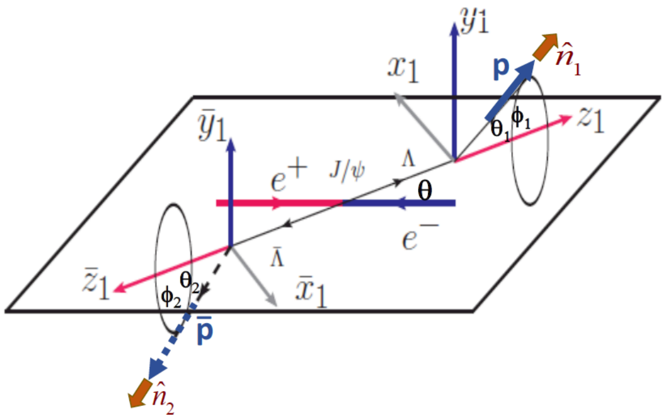


use machine-learning algorithms?



Correlated 5-dim. angular distribution

$$\mathcal{W}(\xi;\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+) = 1+\alpha_\psi\cos^2\theta_\Lambda$$



$$+\alpha_-\alpha_+\left[\sin^2\theta_\Lambda\left(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y}\right)+\left(\cos^2\theta_\Lambda+\alpha_\psi\right)n_{1,z}n_{2,z}\right]$$

$$+\alpha_-\alpha_+\sqrt{1-\alpha_\psi{}^2}\cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(n_{1,x}n_{2,z}+n_{1,z}n_{2,x}\right)$$

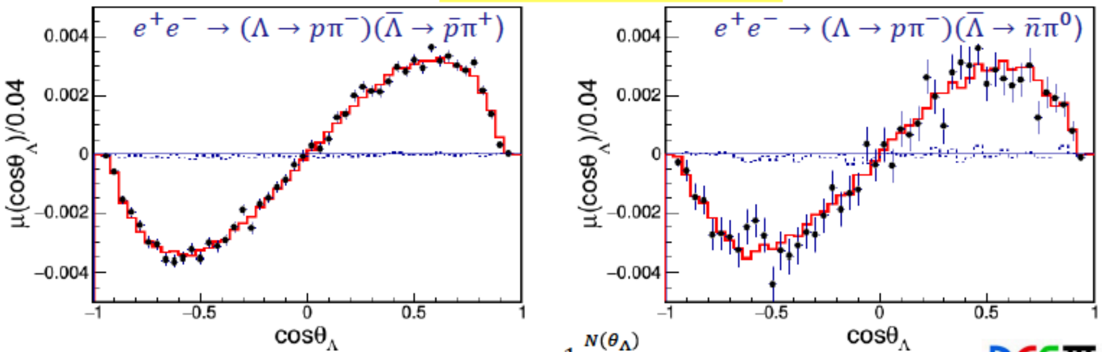
$$+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda\left(\alpha_- n_{1,y}+\alpha_+ n_{2,y}\right),$$

If Λ is polarized, both a$_-$ and a$_+$ can be measured simultaneously, which allow us to search for CPV

$$P_y(\cos\theta_\Lambda)=\frac{\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}$$

Fit results

ΔΦ=42.3°±0.6°±0.5°



moment: $\mu(\cos\theta_\Lambda)=\frac{1}{N}\sum_{i=1}^{N(\theta_\Lambda)}\left(n_{1,y}^{(i)}-n_{2,y}^{(i)}\right)$

(uncorrected for acceptance)

BESIII

BESIII results with 1.3 billion J/ψ

Nature Physics May 2019
arXiv:1808.08917

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [14]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [16]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [16]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [16]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

comments on these 3 items:

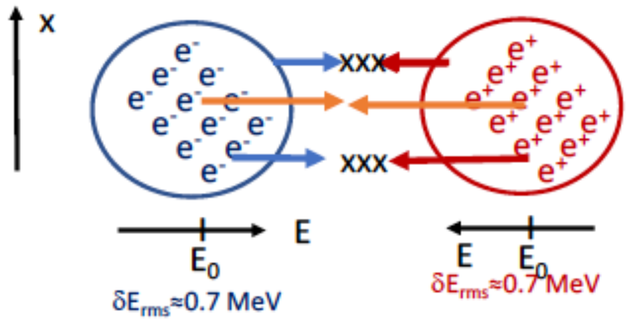
← 1) 3x precision improvement
-same data sample-

← 2) ~7σ upward shift from all previous measurements

← 3) ~3σ difference from 1. Is this reasonable?

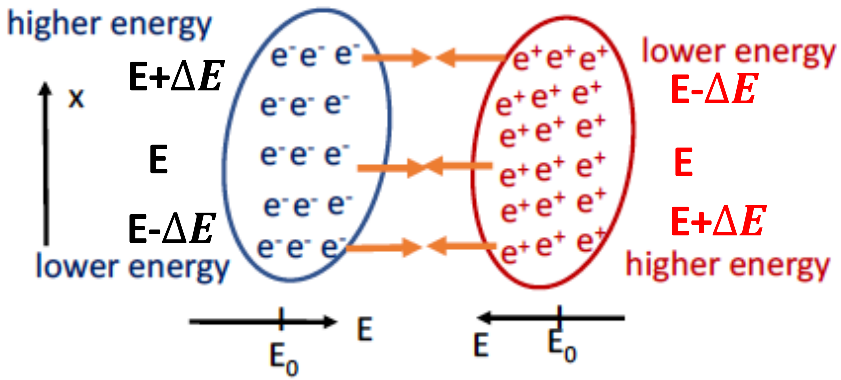
$|\Delta I| = ½$ rule in Kaon decay

Monochromatic collision: factor of 10 from reduction of e^+e^- CM spread



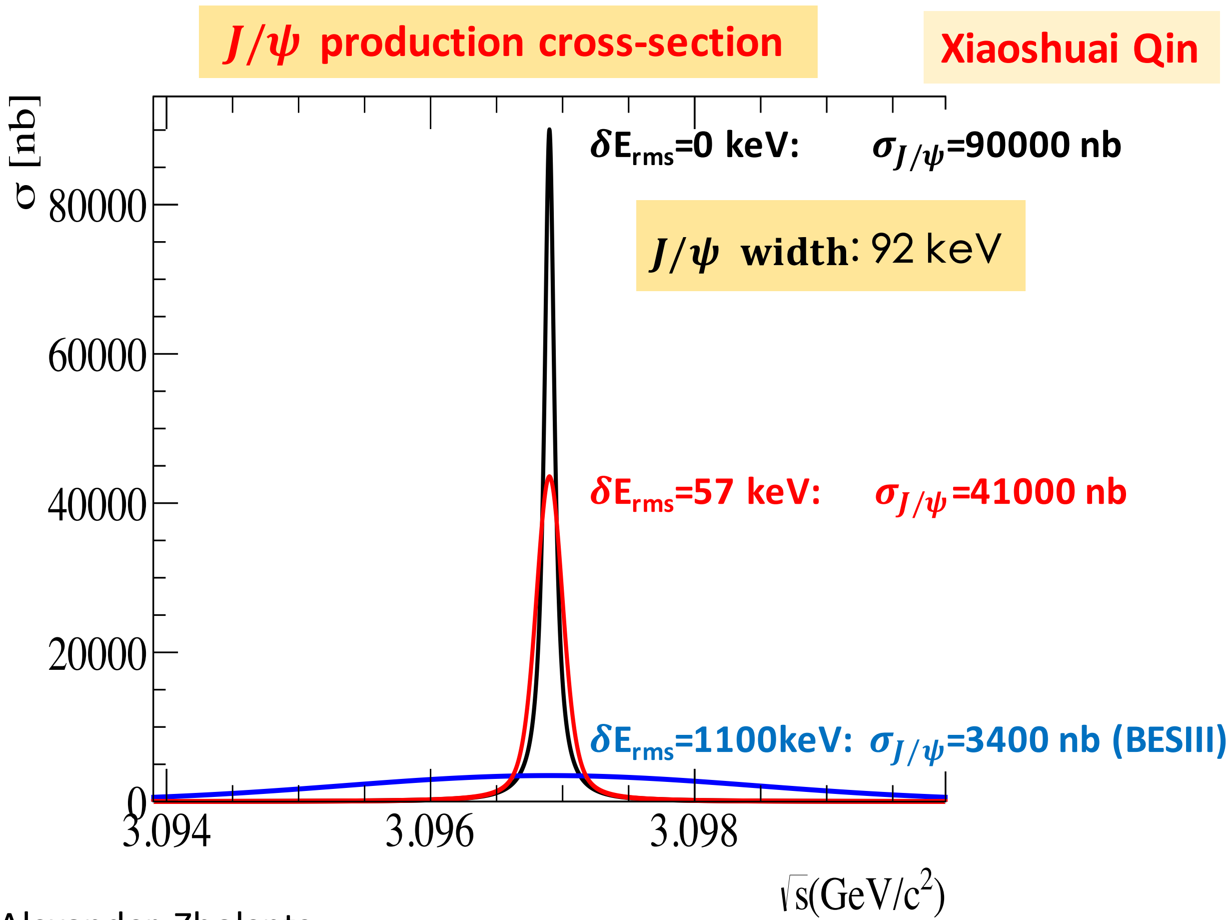
only e^+e^- pairs with E_{cm}=3096 ± 0.14 MeV
can produce a J/ψ, ~1/30th of the total

introduce dispersion



more e^+e^- pairs with E_{cm}=3096 ± 0.14 MeV

Xiaoshuai Qin



Alexander Zholents
CERN SL/92-27/AP

BESIII may get trillion J/ψ per year!

CP violation with 10 billion J/ψ, plus monochromator

1.3 billion J/ψ

CP test: $A_\Lambda = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$

A_Λ = -0.006 ± 0.012± 0.007

BESIII

$J/\psi \to \Lambda\bar{\Lambda}$

Previous result:

A_Λ = 0.013 ± 0.021
PS185 PRC54(96)1877

From A. Kupcs
Adlarson and Kupsc,
arXiv:1908.03102
I.I. Bigi, X.W. Kang, HBL
arXiv:1704.04708

$J/\psi \to \Xi^-\bar{\Xi}^+(\Xi \to \Lambda\pi)$

	Events	Error A_Λ	
BESIII(2018)	**4.2 ·10^5**	**1.2· 10^{-2}**	**1.31 10^9 J/ψ**
BESIII	3 ·10^6	5 ·10^{-3}	10^{10} J/ψ L=0.47· 10^{33} $\Delta E = 0.9$ MeV
SuperTauCharm	6 · 10^8	3 ·10^{-4}	L=10^{35} cm^{-2}s^{-1} 2· 10^{12} J/ψ $\Delta E = 0.9$ MeV
SuperTauCharm + reduced ΔE	3 · 10^9	1.4· 10^{-4}	L=10^{35} cm^{-2}s^{-1} 10^{13} J/ψ $\Delta E < 0.9$ MeV??

2×10^{-3}

1×10^{-5}

$-3 \times 10^{-5} \le A_\Lambda \le 4 \times 10^{-5}$
$-2 \times 10^{-5} \le A_\Xi \le 1 \times 10^{-5}$
$-5 \times 10^{-5} \le A_{\Xi\Lambda} \le 5 \times 10^{-5}$

CKM

Tandean, Valencia PRD67, 056001