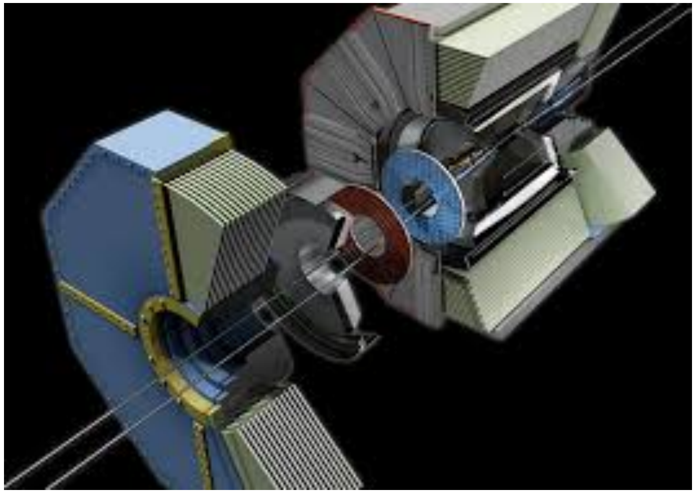


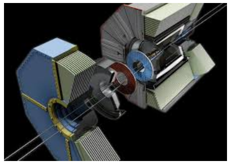
Semileptonic and leptonic D decays at Belle II

Alan Schwartz
University of Cincinnati, USA

10th International Workshop on the CKM Unitarity Triangle

Heidelberg
18 September 2018

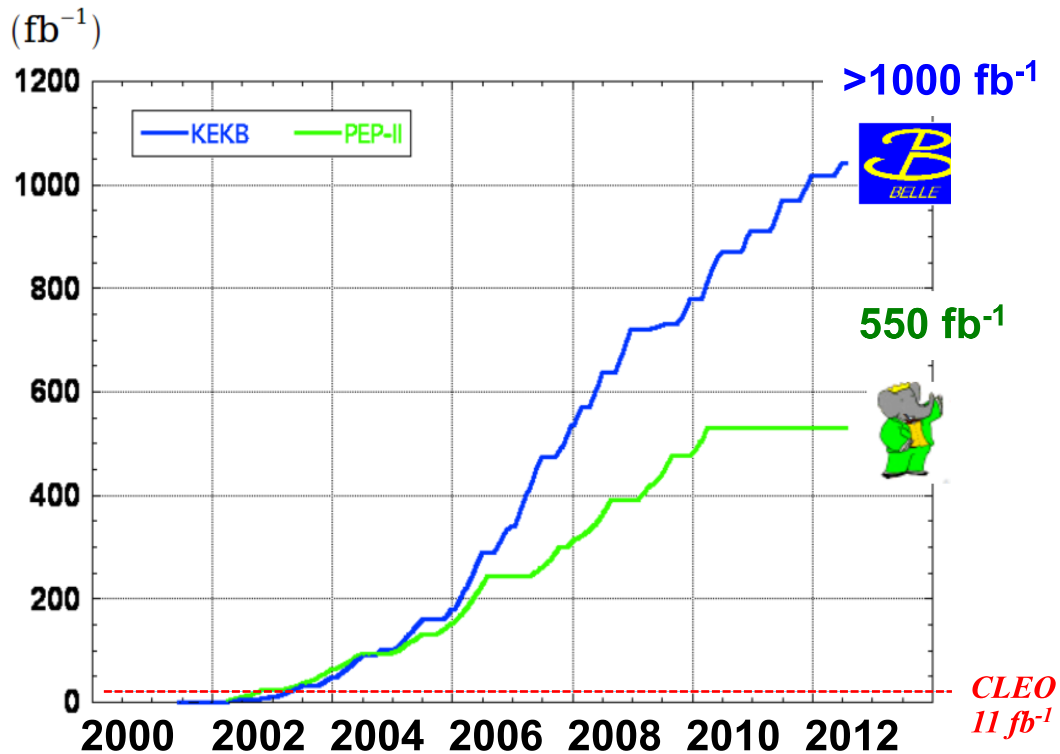
- *overview*
- *leptonic decays*
- *semileptonic decays*
- *searches for new physics*
- *status*



(Semi)leptonic decays at Belle II

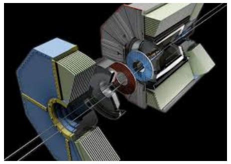
Semileptonic/leptonic decays are ideal for an e^+e^- machine:

- *Initial state is known, so signal decays can be identified via missing energy, missing "mass"*
- *Low backgrounds, high trigger efficiency, negligible trigger bias, excellent γ and π^0 reconstruction (and thus η, η', ρ+, etc. reconstruction efficiency)*
- *Good kinematic resolution, many control samples to study systematics*
- *Absolute (not only relative) branching fractions can be measured*



Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$:	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

Belle-II: *50 x present = 4 x 10^{10} BB pairs*
= 7.2 x 10^{10} DX events



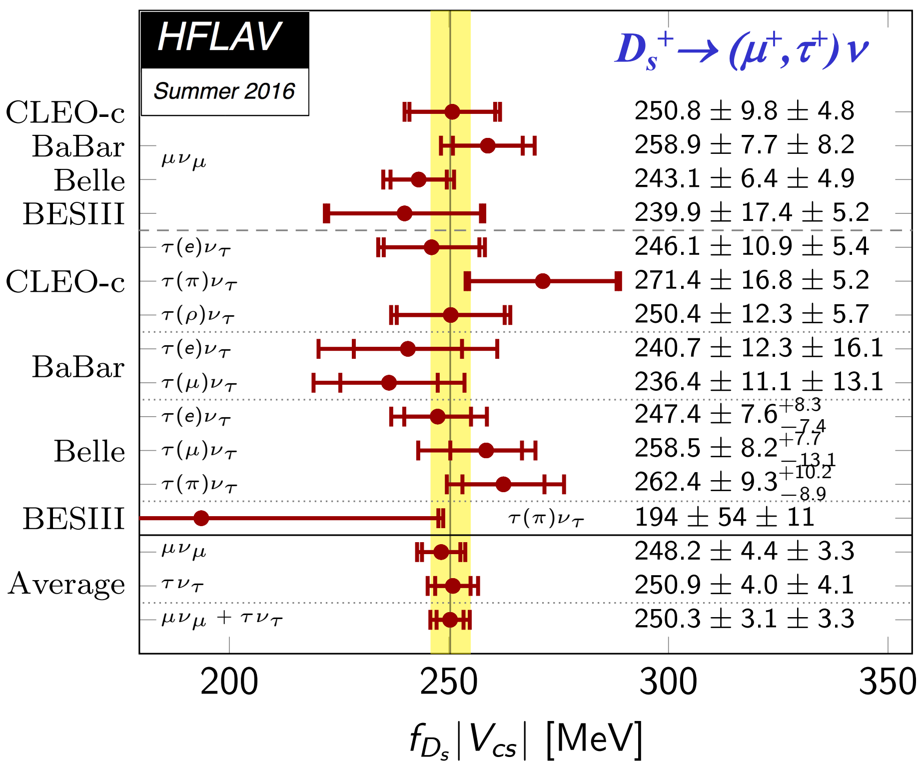
Leptonic decays $D_{(s)}^+ \to \ell^+ \nu$

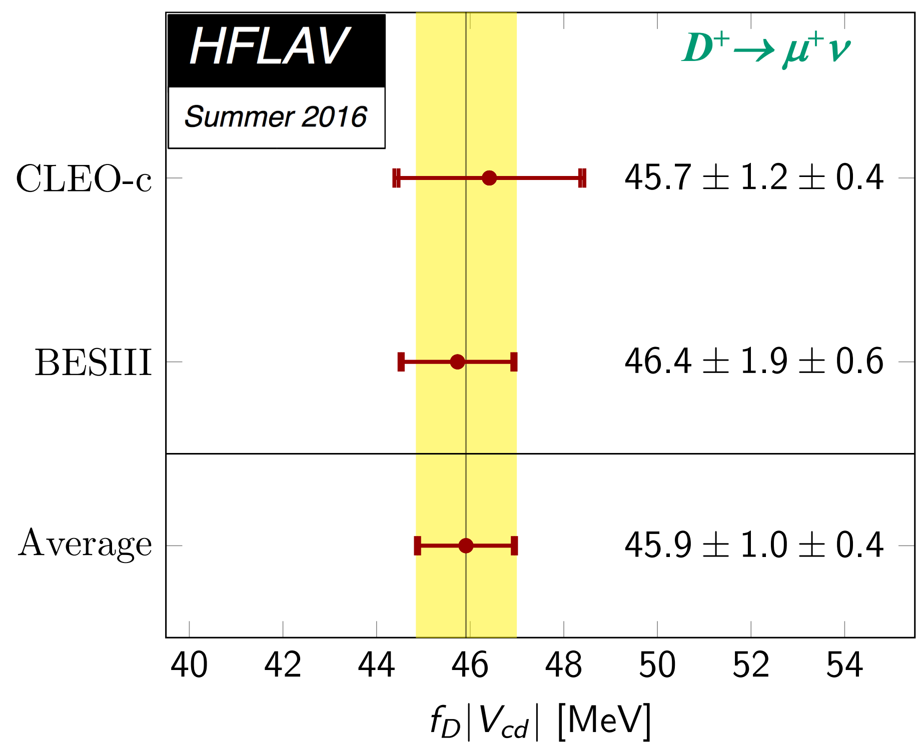
Amhis et al. (HFLAV), EPJC 77, 895 (2017)
https://hflav.web.cern.ch/

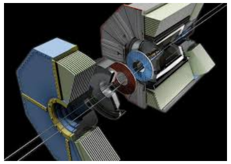
$$\Gamma(D_s^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s}^2 m_\ell^2 m_{D_s} \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

Two strategies:

- *Take $|V_{cs}|$ or $|V_{cd}|$ from CKM unitarity, extract $f_{D(s)}$, compare to lattice QCD calculation*
- *Take $f_{D(s)}$ from lattice QCD, extract $|V_{cs}|$ or $|V_{cd}|$, compare to CKM unitarity*







Leptonic decays $D_{(s)}^{+} \to \ell^{+} \nu$

Amhis et al. (HFLAV), EPJC 77, 895 (2017)
https://hflav.web.cern.ch/

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

- Take $|V_{cs}|$ or $|V_{cd}|$ from CKM unitarity, extract $f_{D(s)}$, compare to lattice QCD calculation
- Take $f_{D(s)}$ from lattice QCD, extract $|V_{cs}|$ or $|V_{cd}|$, compare to CKM unitarity

Using recent LQCD results:

f_{Ds} = (248.83 ± 1.27) MeV

f_{D} = (212.15 ± 1.45) MeV

Aoki et al. (Flavor Lattice Averaging Group), EPJC 77, 112 (2017) [arXiv:1607.00299]

FNAL/MILC, 1712.09262: f_{Ds} = (249.8 ± 0.4) MeV
f_D = (212.6 ± 0.5) MeV
RBC/UKQCD, .1701.02644: f_{Ds} = (246.4 ± 2.5) MeV
f_D = (208.7 ± 3.4) MeV

gives:

$|V_{cs}|$ = 1.006 ± 0.018 (exp) ± 0.005 (LQCD)

$|V_{cd}|$ = 0.2164 ± 0.0051 (exp) ± 0.0015 (LQCD)

Using CKM Unitarity:

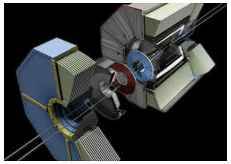
$|V_{cs}| = 0.973394^{+0.000074}_{-0.000096}$

$|V_{cd}| = 0.22537^{+0.00068}_{-0.00035}$

gives:

f_{Ds} = (257.1 ± 4.7) MeV

f_{D} = (203.7 ± 4.8) MeV



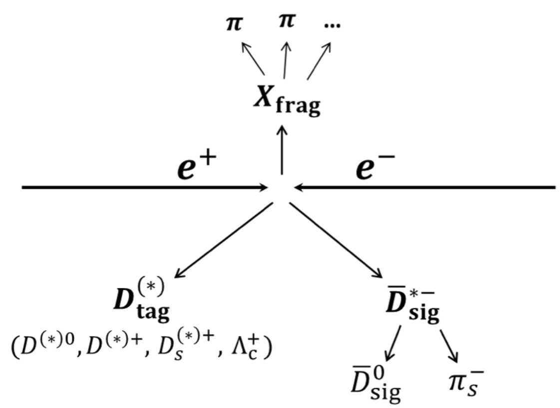
Leptonic Decay $D_s^+ \to \mu^+ \nu$

Zupanc et al., JHEP 09 (2013) 139

Method: *use energy/momentum conservation to search for rare $D^+ \to \ell^+ \nu$, $D^+ \to \nu\nu$, etc.*

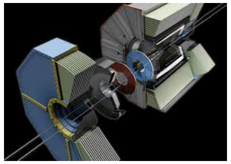
$e^+e^- \to D_{\rm tag}\, X_{\rm frag}\, D_{\rm signal}$

$X_{\rm frag} \to X\, K$ *(anti-p)*



Tag side:	D^0	D^+	Λ_c^+
Decay mode:	$K^-\pi^+$ $K^-\pi^+\pi^0$ $K^-\pi^+\pi^+\pi^-$ $K^-\pi^+\pi^+\pi^-\pi^0$ $K_S^0\pi^+\pi^-$ $K_S^0\pi^+\pi^-\pi^0$	$K^-\pi^+\pi^+$ $K^-\pi^+\pi^+\pi^0$ $K_S^0\pi^+$ $K_S^0\pi^+\pi^0$ $K_S^0\pi^+\pi^+\pi^-$ $K^+K^-\pi^+$	$pK^-\pi^+$ $pK^-\pi^+\pi^0$ pK_S^0 $\Lambda\pi^+$ $\Lambda\pi^+\pi^0$ $\Lambda\pi^+\pi^+\pi^-$
$X_{\rm frag}$:	$K_S^0\pi^+$ $K_S^0\pi^+\pi^0$ $K_S^0\pi^+\pi^+\pi^-$ K^+ $K^+\pi^0$ $K^+\pi^+\pi^-$ $K^+\pi^+\pi^-\pi^0$	K_S^0 $K_S^0\pi^0$ $K_S^0\pi^+\pi^-$ $K_S^0\pi^+\pi^-\pi^0$ $K^+\pi^-$ $K^+\pi^-\pi^0$ $K^+\pi^-\pi^+\pi^-$	same as for D^+ tag $+\ \bar{p}$

For $D_{\rm signal}$ require 1 lepton track ($D^+ \to \ell^+ \nu$)

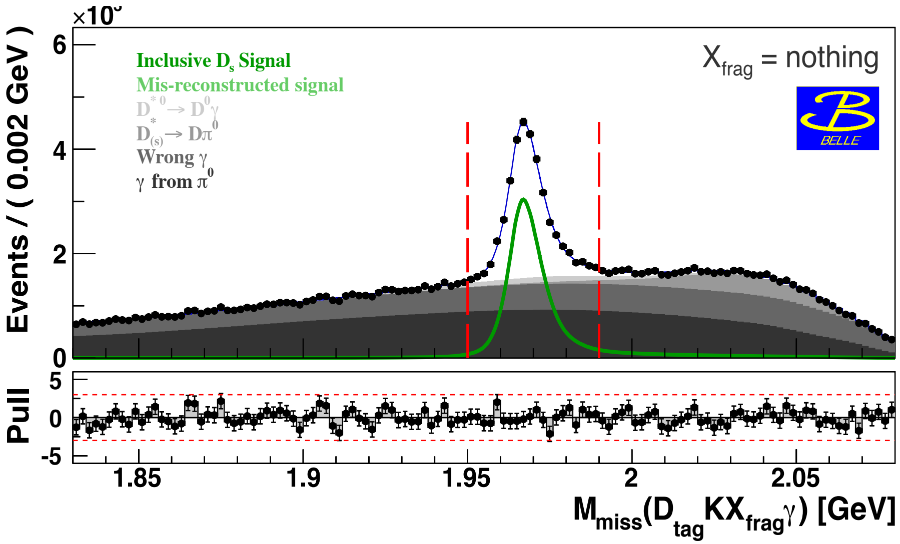


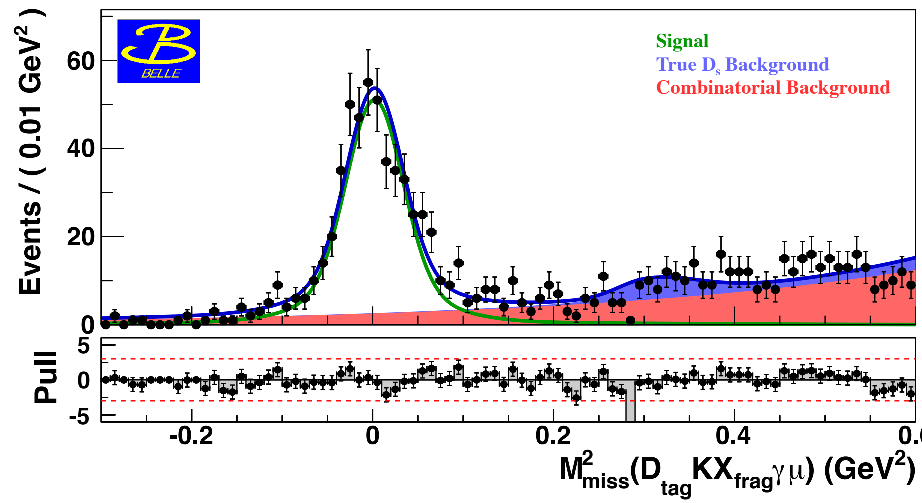
Leptonic Decay $D_s^+ \to \mu^+ \nu$

Zupanc et al., JHEP 09 (2013) 139

$$e^+e^- \to D_{tag}\, X_{frag}\, K\, D_s^{*+} \to D_s^+ \gamma$$
$$\hookrightarrow \mu^+ \nu$$

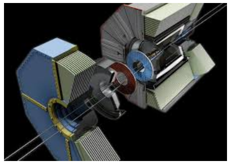
- $P_{miss} = P_{e+} + P_{e-} - P_{Dtag} - P_K - P_X - P_\gamma - P_\mu$
- $(M_{miss})^2 = (P_{miss})^2$
- Require 1 charged track passing μ ID and pointing to IP
- Fit to $(M_{miss})^2$ [$D_{tag}\, X_{frag}\, K\, \mu^+\, \gamma$ missing mass squared]





Belle yield (913 fb^{-1}):	94360 inclusive	492 ± 26 exclusive $D_s^+ \to \mu^+ \nu$
⇒ Belle II yield (50 ab^{-1}):	5.2 x 10^6 inclusive	26900 exclusive $D_s^+ \to \mu^+ \nu$

⇒ $\Delta|V_{cs}|$ = 0.003 (stat), below theory error (LQCD) of 0.005
Δf_{Ds} = 0.9 (stat), below theory error (FLAG16) error of 1.3



Leptonic Decay $D_s^+ \to \tau^+ \nu$

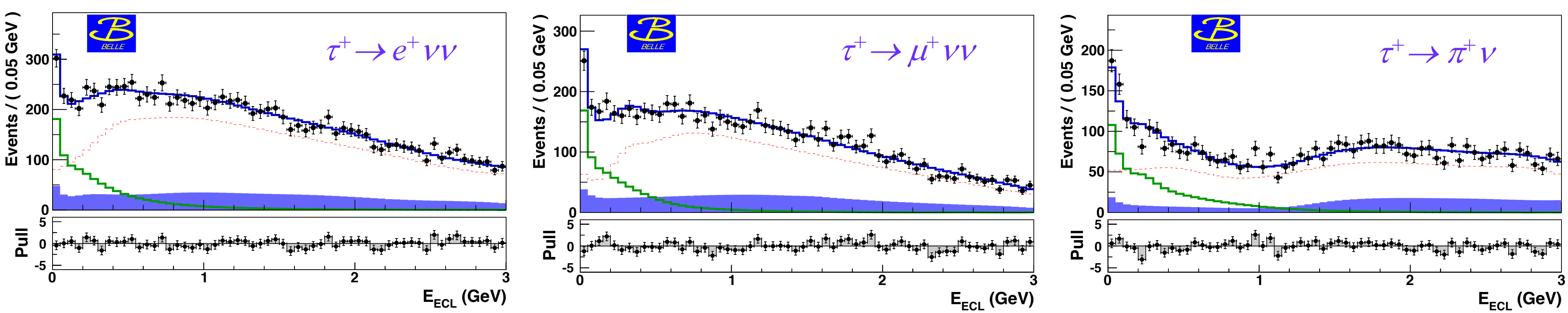
Zupanc et al., JHEP 09 (2013) 139

$e^+e^- \to D_{tag}\, X_{frag}\, K\, D_s^{*+} \to D_s^+ \gamma$

$D_s^+ \to \tau^+ \nu$

$\tau^+ \to e^+\nu\nu,\ \mu^+\nu\nu,\ \pi^+\nu$

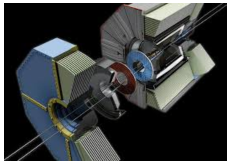
- $P_{miss} = P_{e+} + P_{e-} - P_{Dtag} - P_K - P_X - P_\gamma - P_{track}$
- $(M_{miss})^2 = (P_{miss})^2$
- Require $|p_{miss}| > 1.2$ GeV/c^2 in lab frame
- For π mode require $0 < (M_{miss})^2 < 0.6$ (GeV/c^2)^2
- For e/μ modes require $(M_{miss})^2 > 0.3$ (GeV/c^2)^2
- Obtain signal yield from fitting excess E_{ECL} distribution



Belle yield (913 fb^{-1}): 2217 ± 83 exclusive $D_s^+ \to \tau^+ \nu$

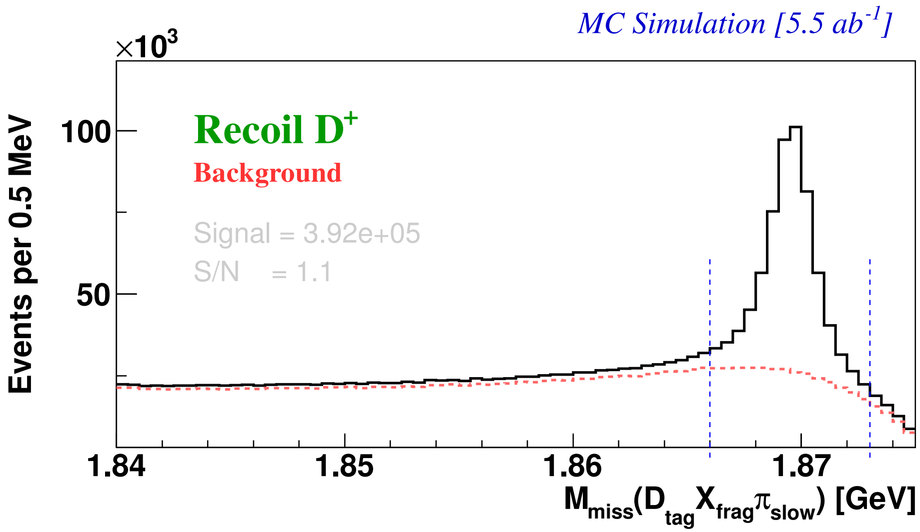
⇒ Belle II yield (50 ab^{-1}): 121400 exclusive $D_s^+ \to \tau^+ \nu$

⇒ $\Delta|V_{cs}|$ = 0.003 (stat), below theory error (LQCD) of 0.005
Δf_{Ds} = 0.6 (stat), well below theory error (FLAG16) error of 1.3

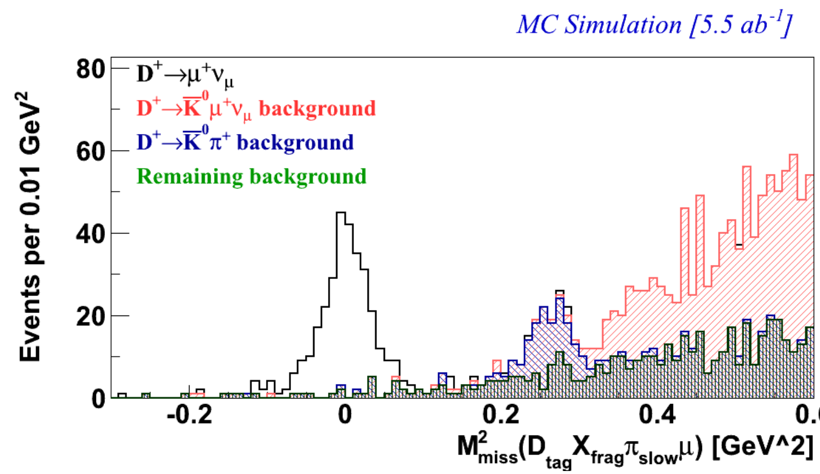


Leptonic Decay $D^+ \to \mu^+ \nu$ (Belle II MC)

$e^+e^- \to D_{tag}\, X_{frag}\, D^{*+} \to D^+ \pi^0$

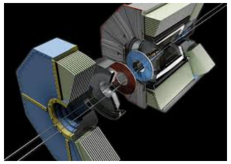


- *Require 1 charged track passing μ ID and pointing to IP*
- *Fit to $D_{tag}\, X_{frag}\, \mu^+ \pi^0$ missing mass*



⇒ *Belle II yield (50 ab^{-1}): 3.5 x 10^6 inclusive 1250 exclusive $D^+ \to \mu^+ \nu$*

⇒ *$\Delta f_D|V_{cd}|$ = 0.65 MeV (statistical error, which dominates), well below that of CLEOc (1.2) and BESIII (1.9)*



Semileptonic Decays

Amhis et al. (HFLAV), EPJC 77, 895 (2017)
https://hflav.web.cern.ch/

$D \to (K,\pi)\,\ell^+\nu$:

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

⇒ Take $f_+(q^2)$ form factor from theory, determine $|V_{cs}|$ or $|V_{cd}|$

Simple pole: $$f_+(q^2) = \frac{f_+(0)}{(1 - q^2/m^2_{\rm pole})}$$

Modified pole model: $$f_+(q^2) = \frac{f_+(0)}{(1 - q^2/m^2_{\rm pole})(1 - \alpha_p q^2/m^2_{\rm pole})}$$

z expansion: $$t_\pm = (m_D \pm m_P)^2 \qquad t_0 = t_+(1 - \sqrt{1 - t_-/t_+})$$

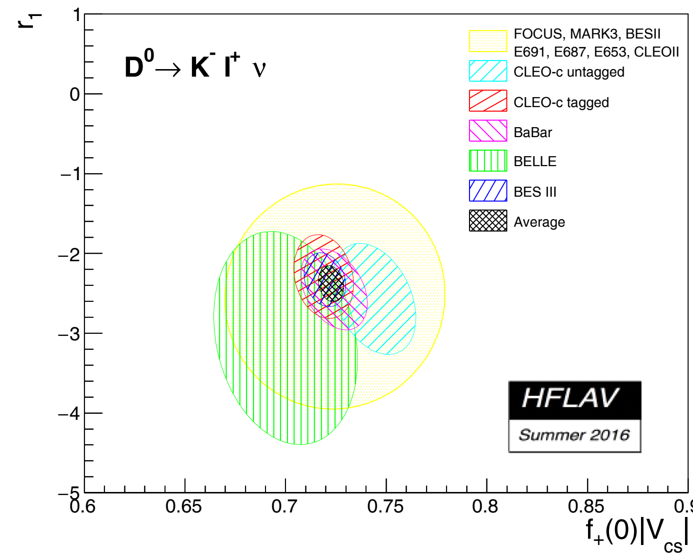
$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

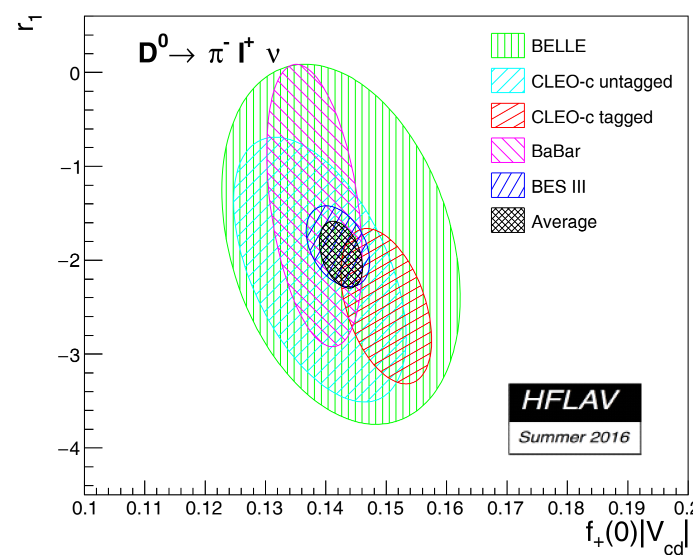
$$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2, t_0)} \sum_{k=0}^{\infty} a_k z^k$$

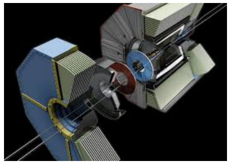
$$a_1/a_0 \equiv r_1 \qquad a_2/a_0 \equiv r_2$$

$f^K_+(0)|V_{cs}|$ = 0.7226 ± 0.0022 ± 0.0026

$f^\pi_+(0)|V_{cd}|$ = 0.1426 ± 0.0017 ± 0.0008







Semileptonic Decays

Amhis et al. (HFLAV), EPJC 77, 895 (2017)
https://hflav.web.cern.ch/

$D \to (K,\pi)\, \ell^+ \nu$:

$f^K_+(0)|V_{cs}|$ = 0.7226 ± 0.0022 ± 0.0026

$f^\pi_+(0)|V_{cd}|$ = 0.1426 ± 0.0017 ± 0.0008

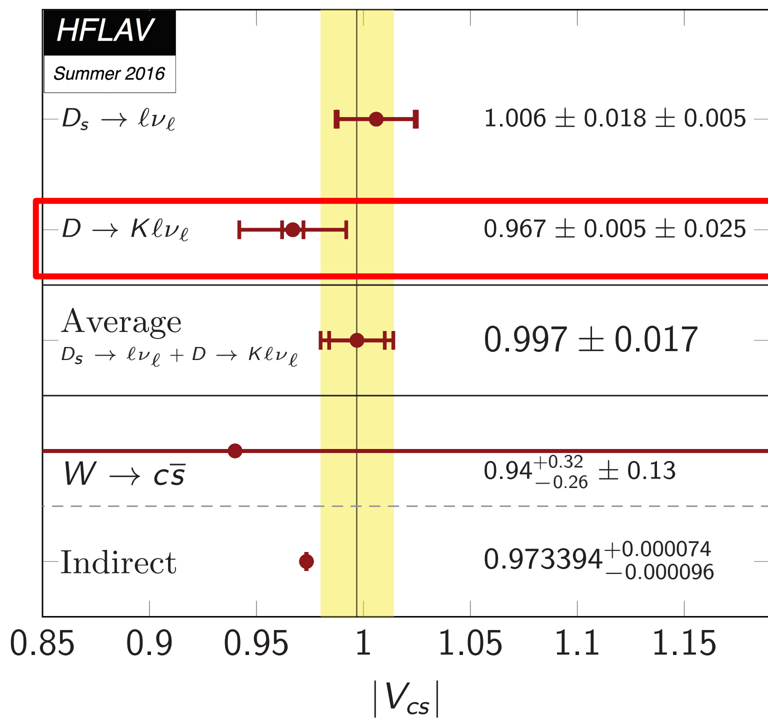
Using recent LQCD results:

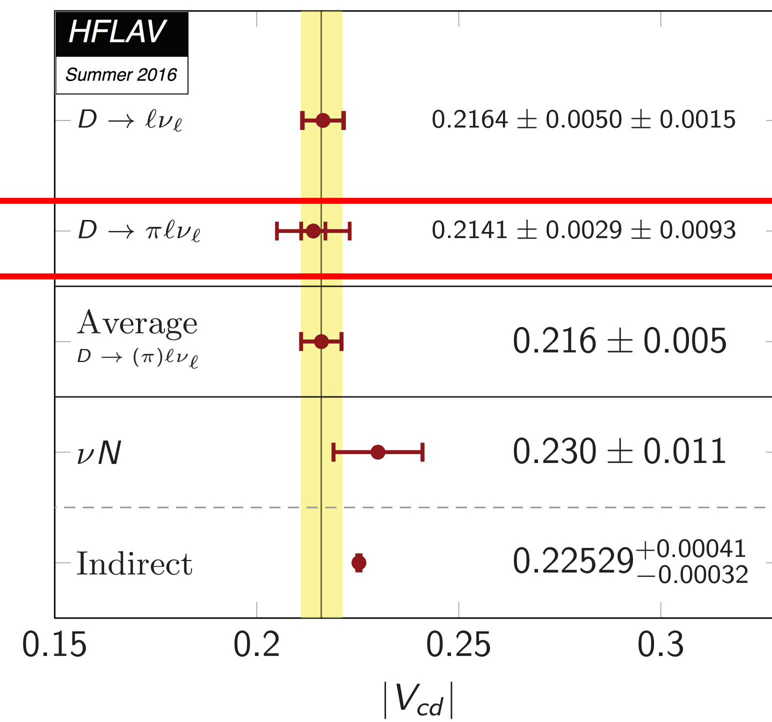
$f^K_+(0)$ = 0.747 ± 0.019

$f^\pi_+(0)$ = 0.666 ± 0.029

Aoki et al. (Flavor Lattice Averaging Group), EPJC 77, 112 (2017) [arXiv:1607.00299]

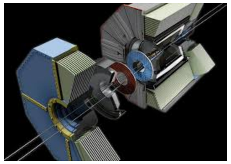
gives:





Recent LQCD:
Riggio et al., EPJC 78 (2018) 501 [1706.03657]:

$|V_{cs}|$ = 0.970 ± 0.033
$|V_{cd}|$ = 0.2341 ± 0.0074

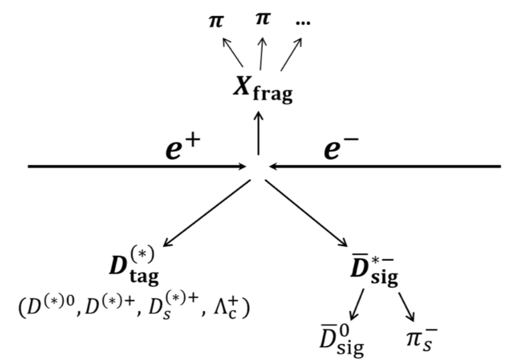


Semileptonic Decays

Widhalm et al., PRL 97, 061804 (2006)

$D \to (K,\pi)\, \ell^+ \nu$:

- To maximize q^2 resolution, fully reconstruct tag side, require a D , D^{*+}, D^{*0}
- define $P_{D^*} = P_{e+} + P_{e-} - P_{Dtag} - P_X$
- require $(P_{D^*})^2 = (M_{D^*})^2$
- require $(P_{D^*} - P_{\pi\,slow})^2 = (M_{D0})^2$
- Identify (K or π) and (μ or e), and require $|(P_{D^*} - P_{\pi\,slow} - P_{(K,\pi)} - P_{(\mu,e)})^2| < 0.05\ (\mathrm{GeV}/c^2)^2$



Belle yields
(282 fb^{-1}, 79% purity):

$D^0 \to K^+\mu^-\nu$: 1249
$D^0 \to K^+e^-\nu$: 1318
$D^0 \to \pi^+\mu^-\nu$: 106
$D^0 \to \pi^+e^-\nu$: 126

BaBar yields
(380 fb^{-1}, 53% purity):

$D^0 \to \pi^+e^-\nu$: 5303

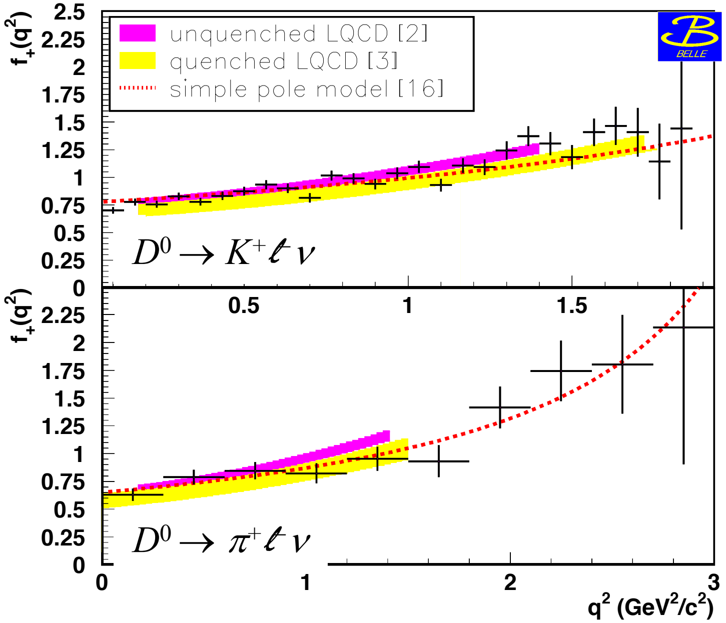
Belle II yields (50 ab^{-1}):

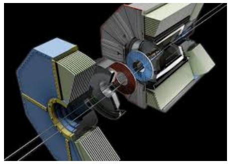
$D^0 \to K^+\ell\nu$: 455000
$D^0 \to \pi^+\ell\nu$: 41100

53% purity:

$D^0 \to \pi^+e^-\nu$: 698000

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\, p_h^3}{24\pi^3} \left|V_{cs,cd}\right|^2 \left|f_+(q^2)\right|^2$$





Semileptonic Decays (Belle II MC)

Kou et al. (Belle II Physics Book), arXiv:1808.10567, submitted to PTEP

$D \to (K,\pi)\,\ell^+\nu$:

Belle II yields (50 ab^{-1}):

$D^0 \to K^+\ell^-\nu$: 455000

$D^0 \to \pi^+\ell^-\nu$: 41100

53% purity:

$D^0 \to \pi^+ e^- \nu$: 698000

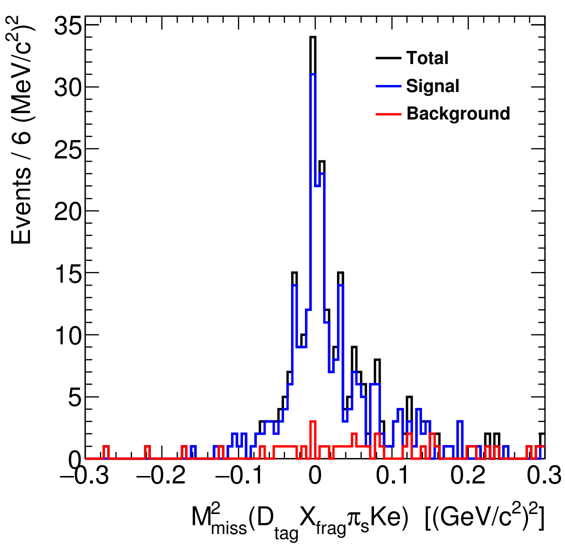
- *Fully reconstruct a* D^+, D^0 on tag side
- *Define* $P_{D^*} = P_{e+} + P_{e-} - P_{Dtag} - P_X$
- *require* $(P_{D^*})^2 = (M_{D^*})^2$
- *Identify* (K or π) and (μ or e)
- *calculate* $M_{miss}^2 = P_{miss}^2 = (P_{D^*} - P_{\pi\,slow} - P_{(K,\pi)} - P_{(\mu,e)})^2$

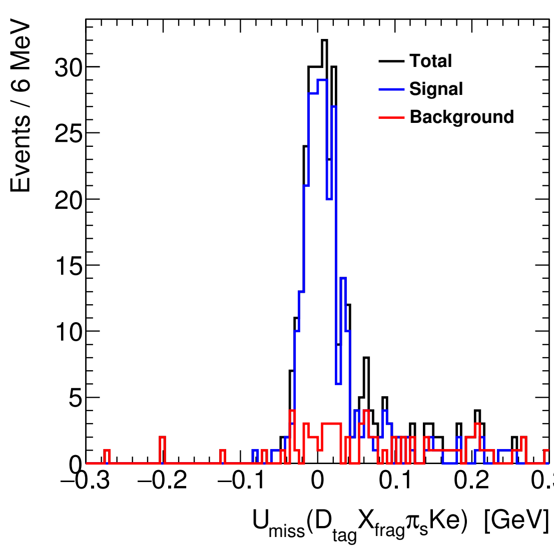
or

$$U_{miss} = E_{miss} - |\boldsymbol{p}_{miss}|$$

Tag side:	D^0	D^+
Final state:	$K^-\pi^+$	$K^-\pi^+\pi^+$
	$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$
	$K^-\pi^+\pi^+\pi^-$	$K^0_S\,\pi^+$
	$K^-\pi^+\pi^+\pi^-\pi^0$	$K^0_S\,\pi^+\pi^0$
	$K^0_S\,\pi^+\pi^-$	$K^0_S\,\pi^+\pi^+\pi^-$
	$K^0_S\,\pi^+\pi^-\pi^0$	$K^+K^-\pi^+$
X_{frag} :		none
	π^+	π^0
	$\pi^+\pi^0$	$\pi^+\pi^-$
	$\pi^+\pi^+\pi^-$	$\pi^+\pi^-\pi^0$

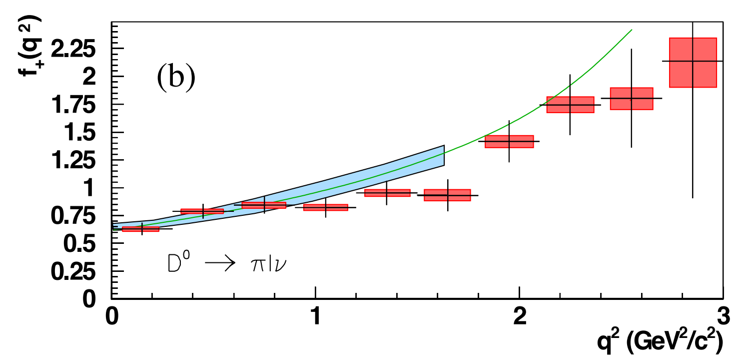
Belle II 1.0 ab^{-1}:

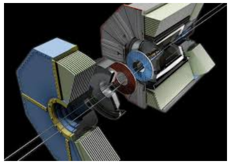




$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\,p_h^3}{24\pi^3}\,|V_{cs,cd}|^2\,|f_+(q^2)|^2$$

Belle II 5 ab^{-1}:





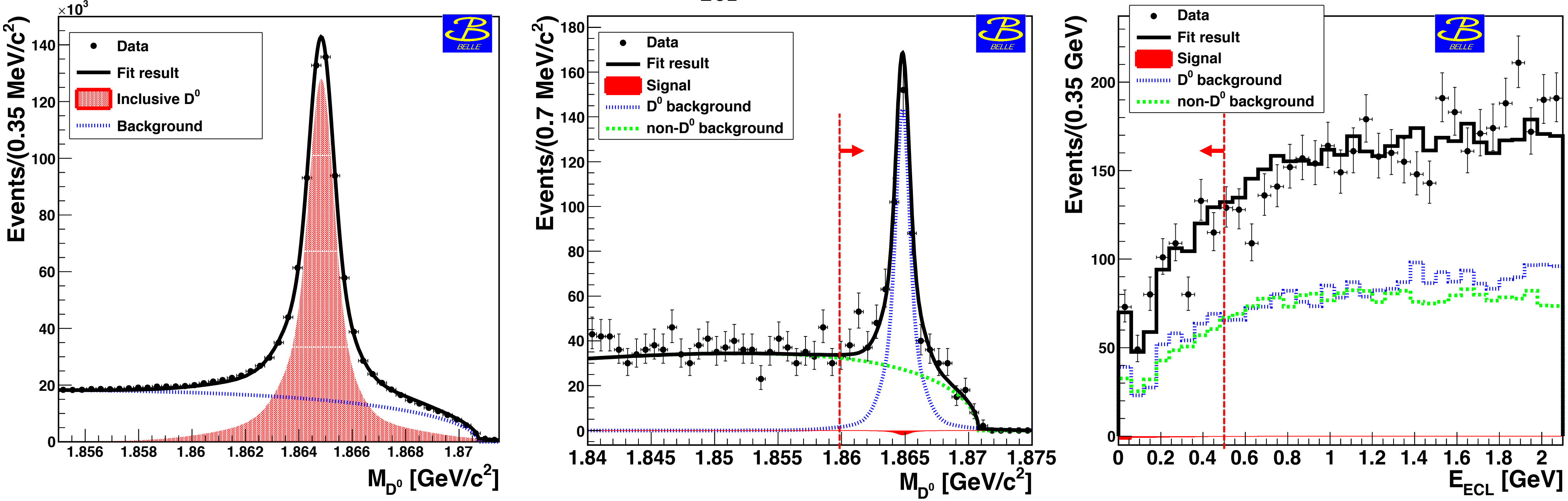
$D^0 \to \nu\nu$ (nothing)

Y.-T. Lai et al., PRD 95, 011102(R) (2017)

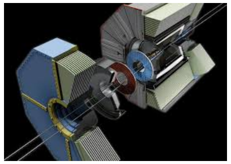
$e^+e^- \to D_{tag} X_{frag}$ $D^{*+} \to D^0 \pi_s^+$

- *Require no extra charged tracks, γ, π^0, etc.*
- *Fit to $D_{tag} X_{frag} \pi_s$ missing mass and ECL isolated energy distribution:*

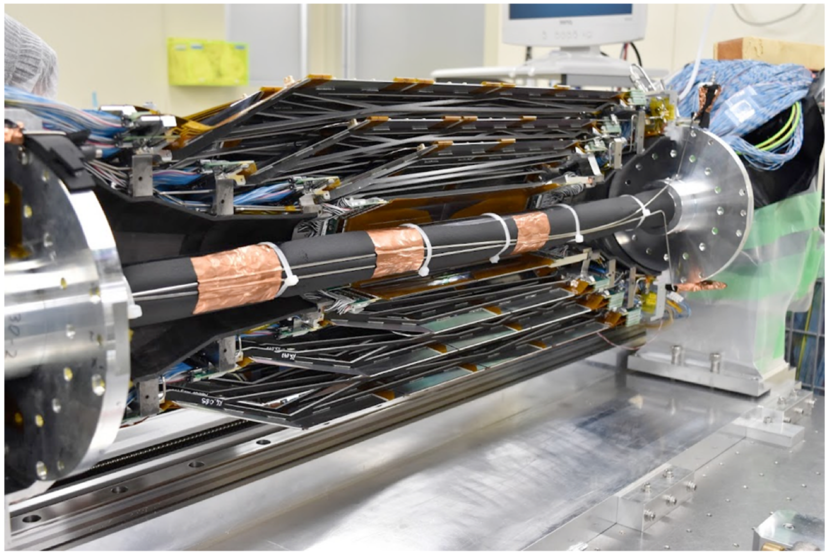
$E_{ECL} < 0.50$ GeV $\qquad\qquad$ $M_{D0} > 1.86$ GeV/c^2



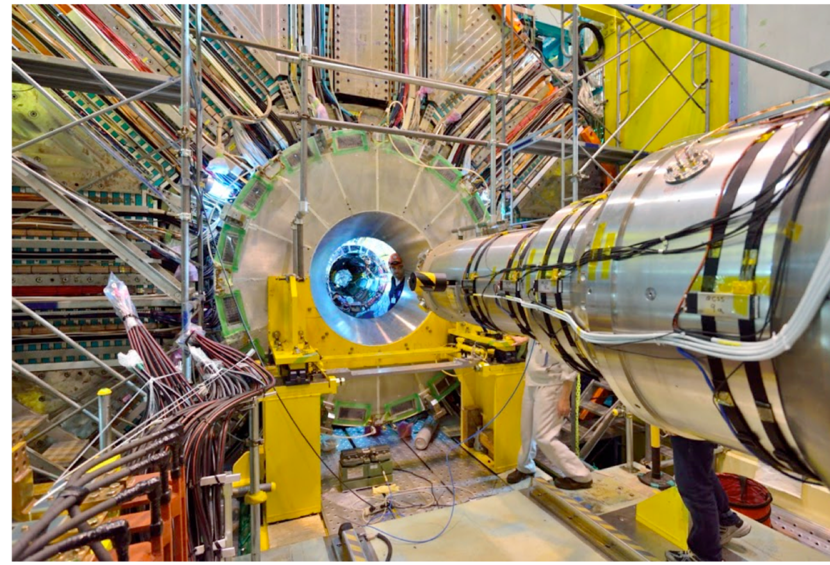
Belle yield (924 fb^{-1}):	*694700 inclusive*	*$-6.3\ ^{+23}_{-21}$ exclusive $D_s^+ \to \tau^+ \nu$*	*$\mathcal{B} < 9.4 \times 10^{-5}$ (90% CL)*
⇒ Belle II (50 ab^{-1}):	*37.6 x 10^6 inclusive*	*single-event sensitivity = (1-6) x 10^{-6}*	*[theory: 1.1 x 10^{-30}]*



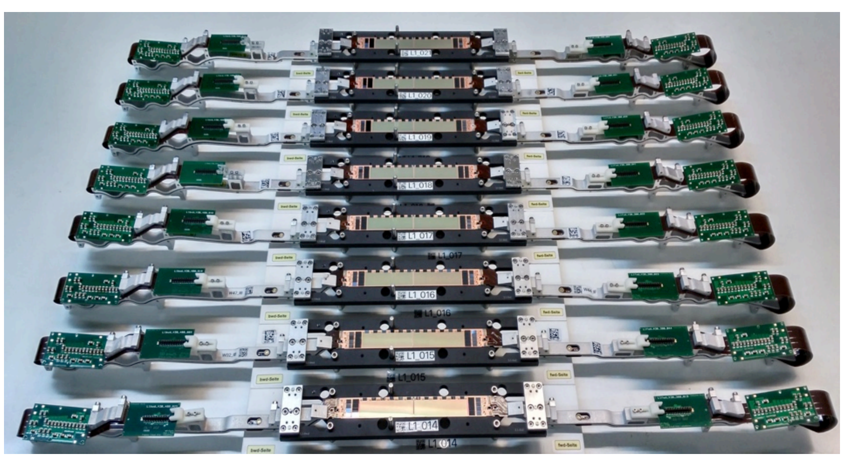
Detector is close (SVD, PXD to be installed this winter)



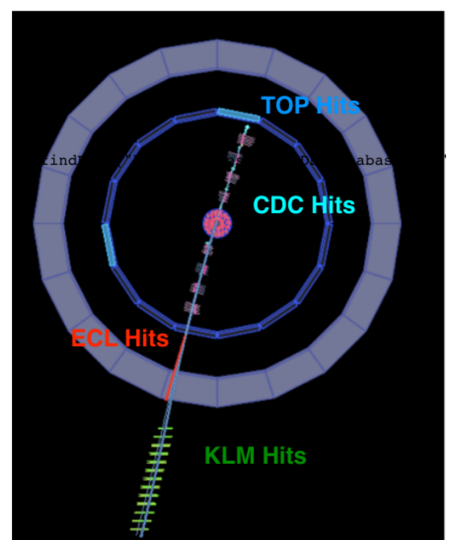
Completion of first SVD clam-shell (Jan 2018)



Final focus quadrupoles being prepared for insertion (Jan 2018)

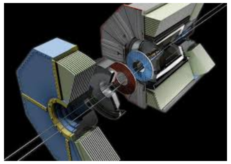


PXD L1 ladders ready for half-shell assembly

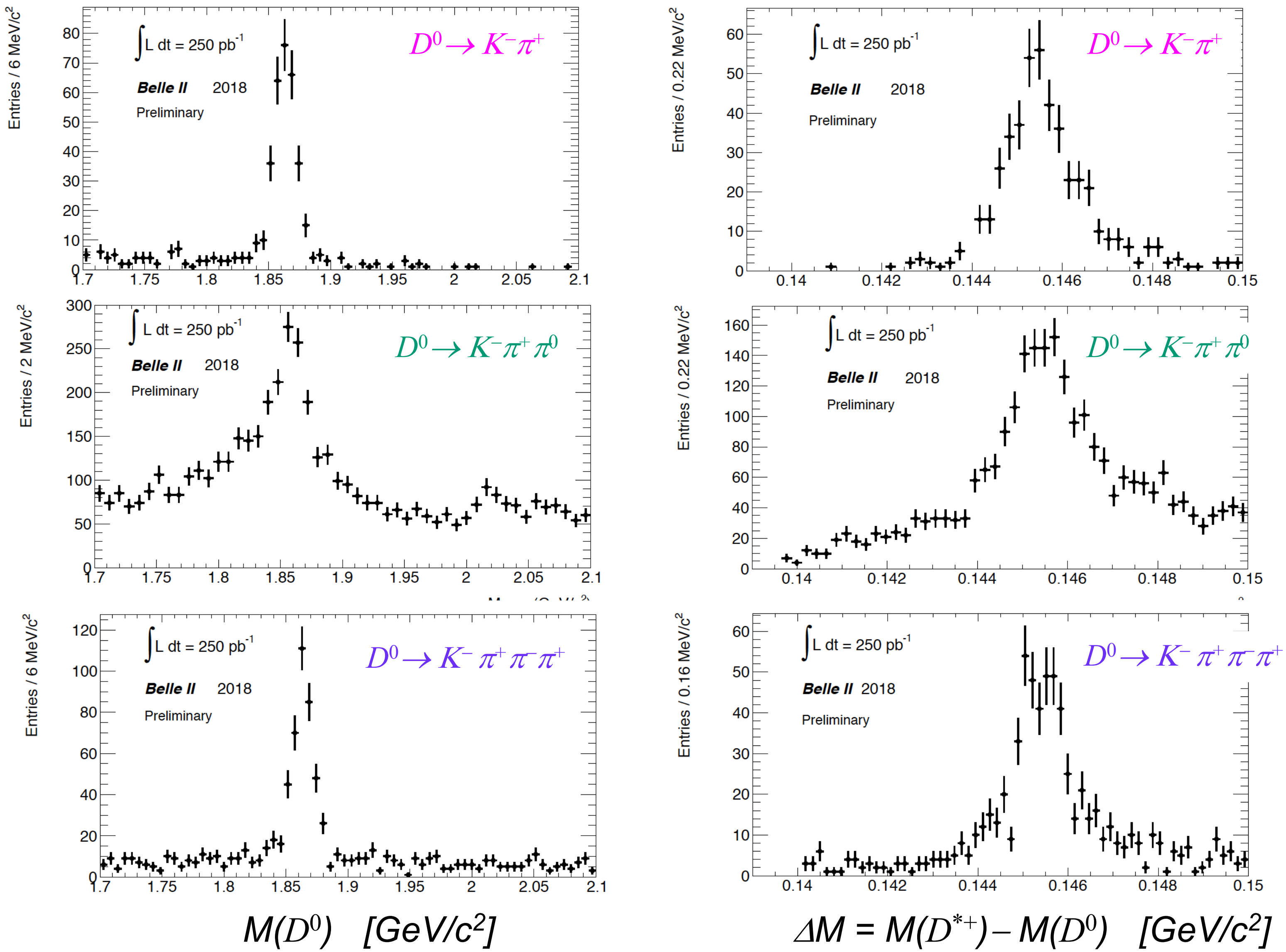


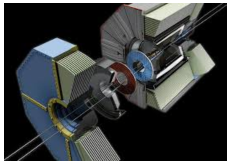
Event display, cosmic ray run

Detector is superior to Belle: better vertexing, better particle ID, full reconstruction (neural net) on tag side is greatly improved over Belle/BaBar.



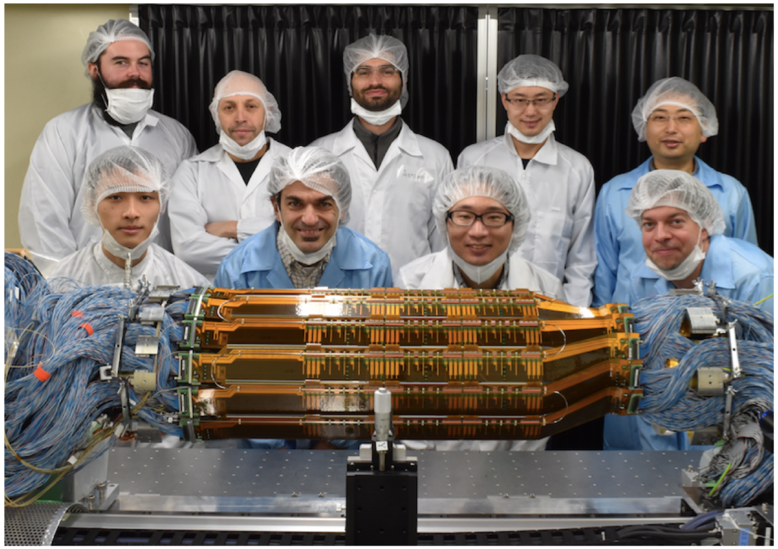
Belle II charm signals: 250 pb^{-1}, no VTX

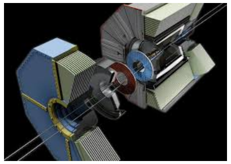




Summary

- Belle II is now (almost) fully constructed and installed. The entire detector except for the VTX is now undergoing commissioning (with beam from April - July)
- VTX detector (SVD + pixels) will be installed in the winter, physics run with full Belle II detector to begin in 2019
- Leptonic + semileptonic decays should be measured with ~50x larger statistics; as errors are dominated by statistics, precision on f_{Ds}, $|V_{cd}|$, $|V_{cs}|$ should improve by ~7. Will measure f_D and $|V_{cd}|$ with $D^+ \to \mu^+ \nu$ decays. Most measurements better/competitive with BESIII, precision similar to that of LQCD.

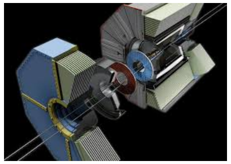


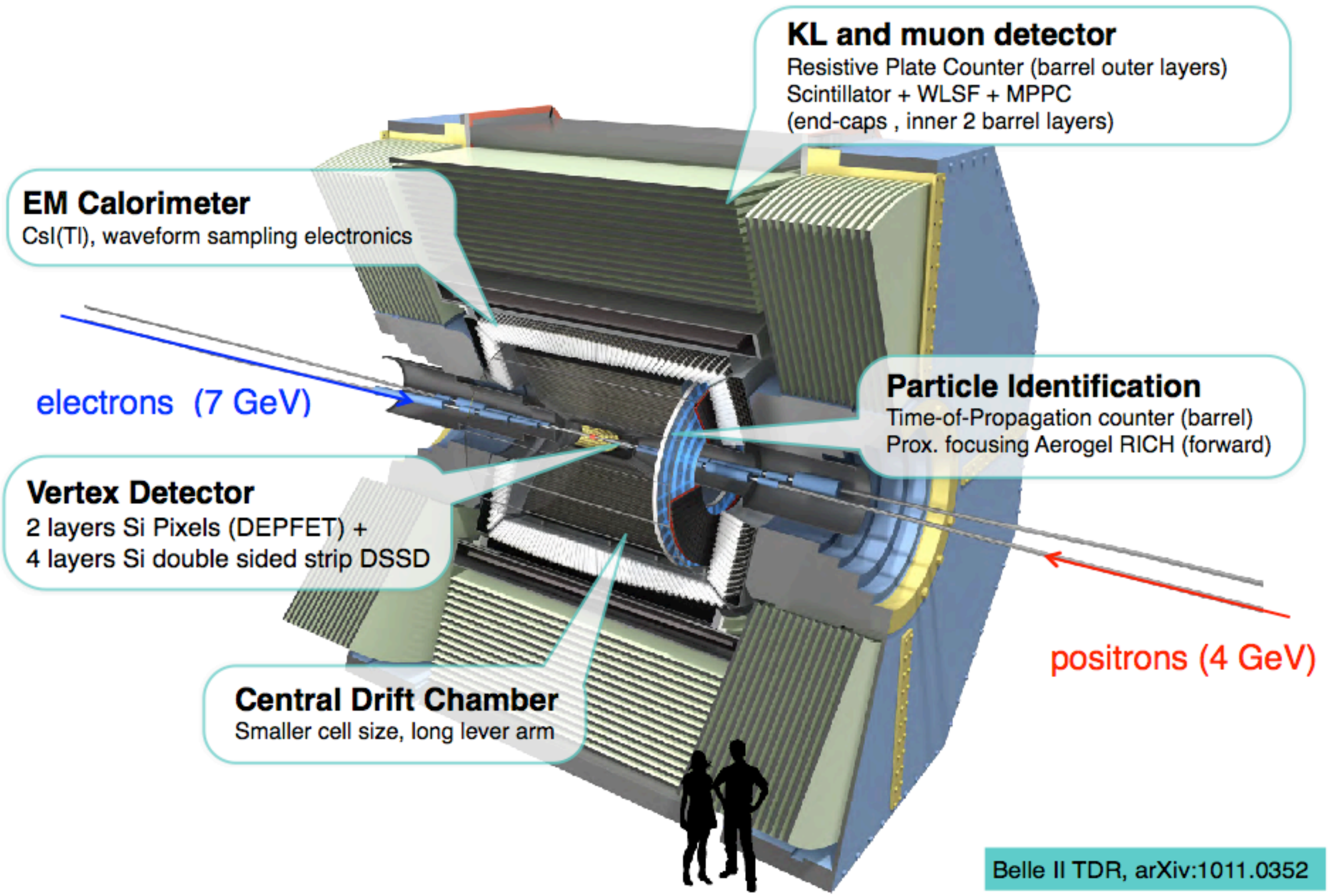


Extra

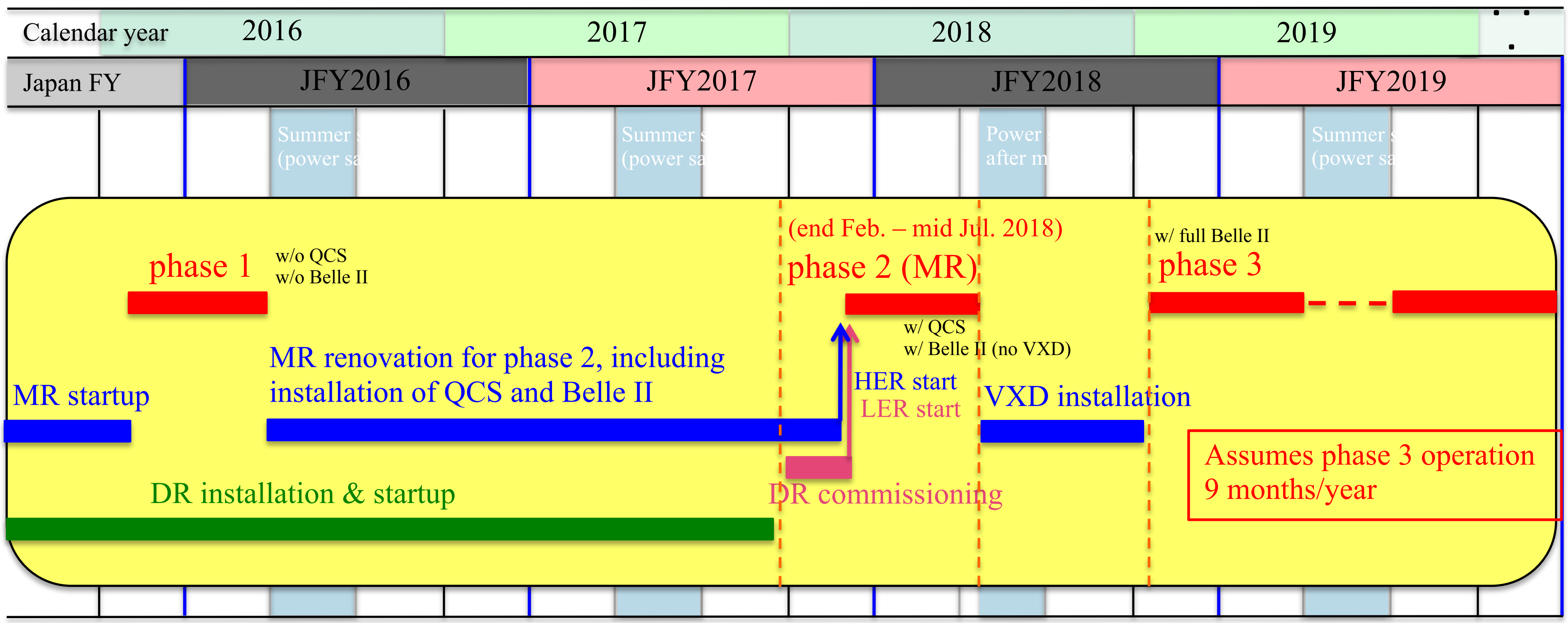
Extra Slides

The Belle II Detector

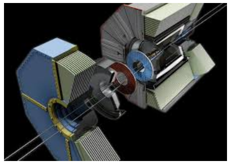




Schedule



Calendar year
2016
2017
2018
2019
Japan FY
JFY2016
JFY2017
JFY2018
JFY2019
Summer s
(power sa
Summer s
(power sa
Power
after m
Summer s
(power sa
(end Feb. – mid Jul. 2018)
phase 1
w/o QCS
w/o Belle II
phase 2 (MR)
w/ QCS
w/ Belle II (no VXD)
w/ full Belle II
phase 3
MR startup
MR renovation for phase 2, including
installation of QCS and Belle II
HER start
LER start
VXD installation
Assumes phase 3 operation
9 months/year
DR installation & startup
DR commissioning



Leptonic Decays $D_s^+ \to \ell^+ \nu$

S. Fajfer et al., PRD 91, 094009 (2015)

$$\mathcal{B}(D_s \to \ell\nu_\ell) = \tau_{Ds}\frac{m_{Ds}}{8\pi} f_{Ds}^2 \left(1 - \frac{m_\ell^2}{m_{Ds}^2}\right)^2 G_F^2 \times (1+\delta_{em}^{(\ell)})|V_{cs}|^2 m_\ell^2 \left|1 - c_P^{(\ell)} \frac{m_{Ds}^2}{(m_c+m_s)m_\ell}\right|^2$$

68% CL (dark) and 95% CL (light) allowed regions: