Charm and Strange – Recent Results and Future Prospects

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tifr

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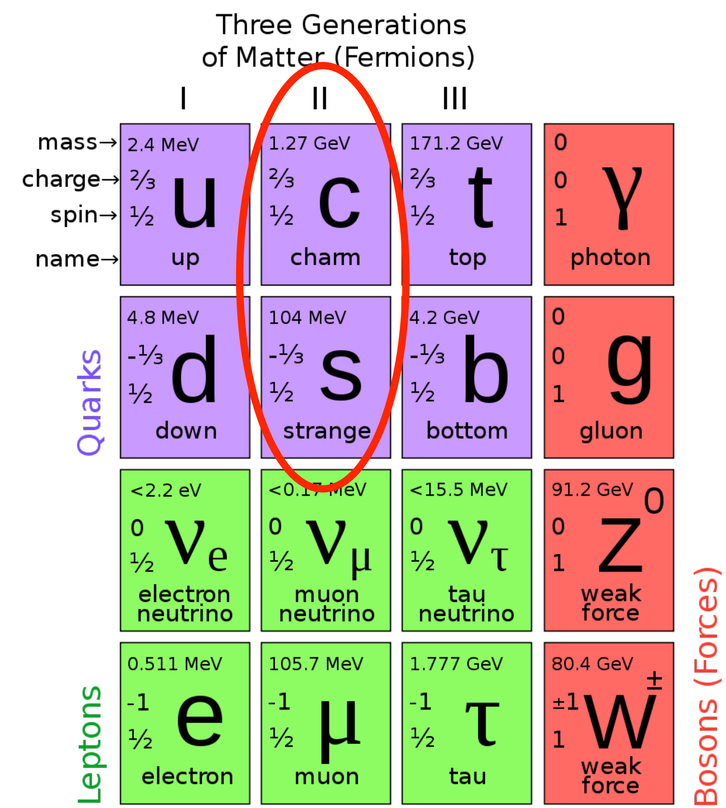
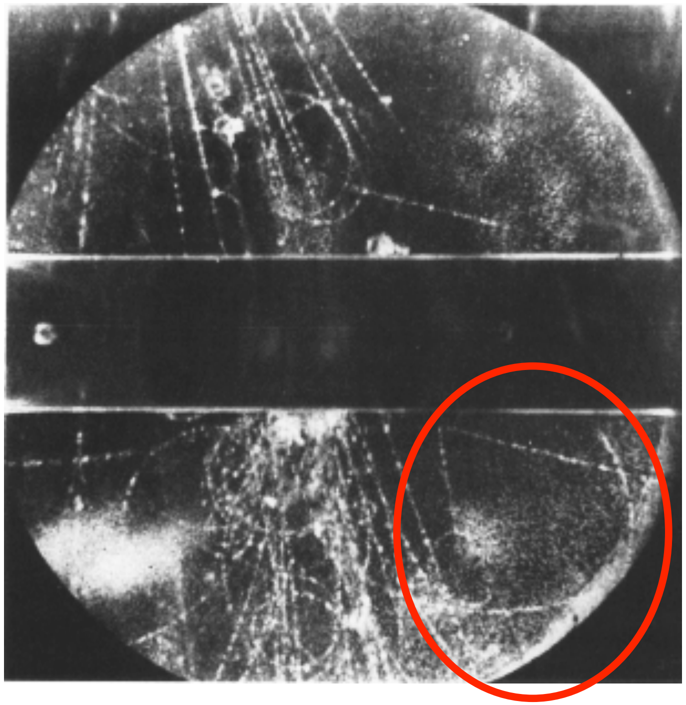
Prologue

- ❑ 123 years ago, a monk travelled from Mumbai to Chicago to speak about one of the oldest religions at the World Parliament of Religions

- ➢ Following almost the same trail, I am here to talk to you about two oldest members of the standard model (SM) of particle physics

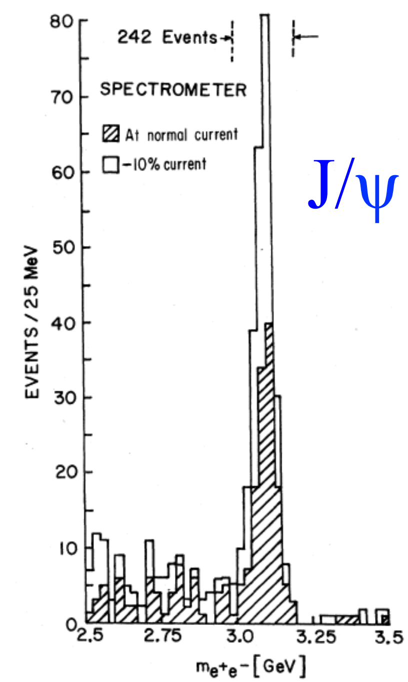


Glorious past to...



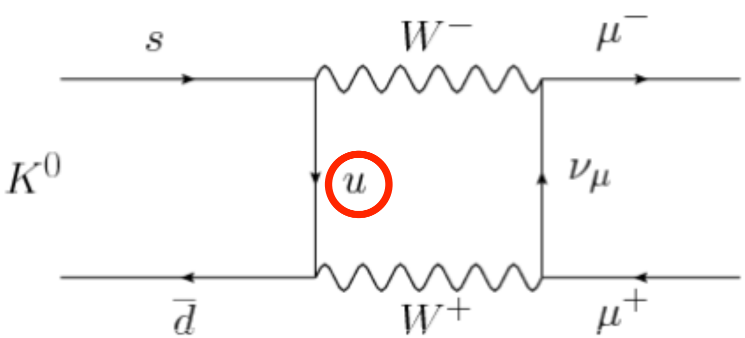
- First 'V' particle by Rochester & Butler (1946) ➔ strange
- Charm was discovered by two teams at SLAC and BNL, respectively led by Richter and Ting

PRL 33, 1404 (1974)



J/ψ

Almost non-existence of $K_L \to \mu^+\mu^-$ ➡ GIM mechanism ➡

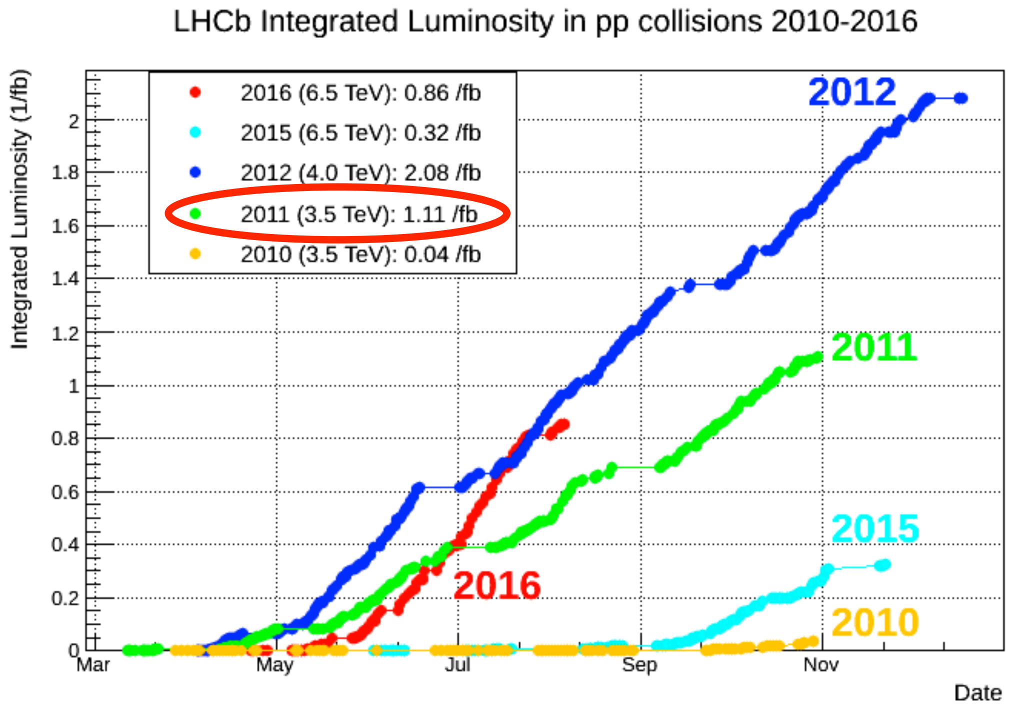


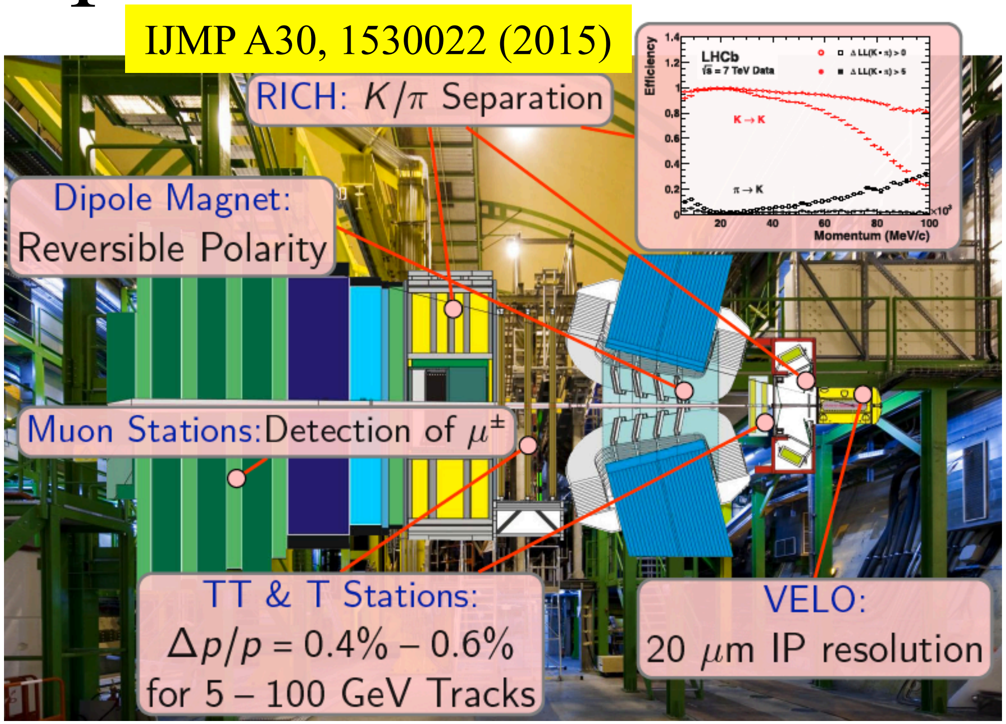
PRD 2, 1285 (1970)

Postulates existence of charm

➢ An example of intensity leading energy frontier

...Vibrant present

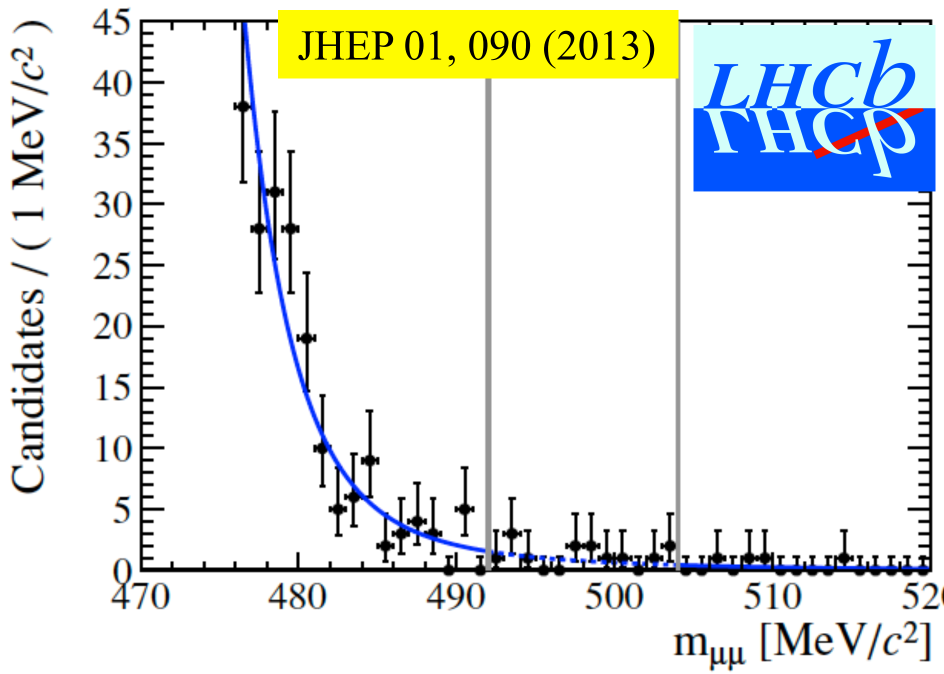




Search for the rare decay $K_S \to \mu^+\mu^-$

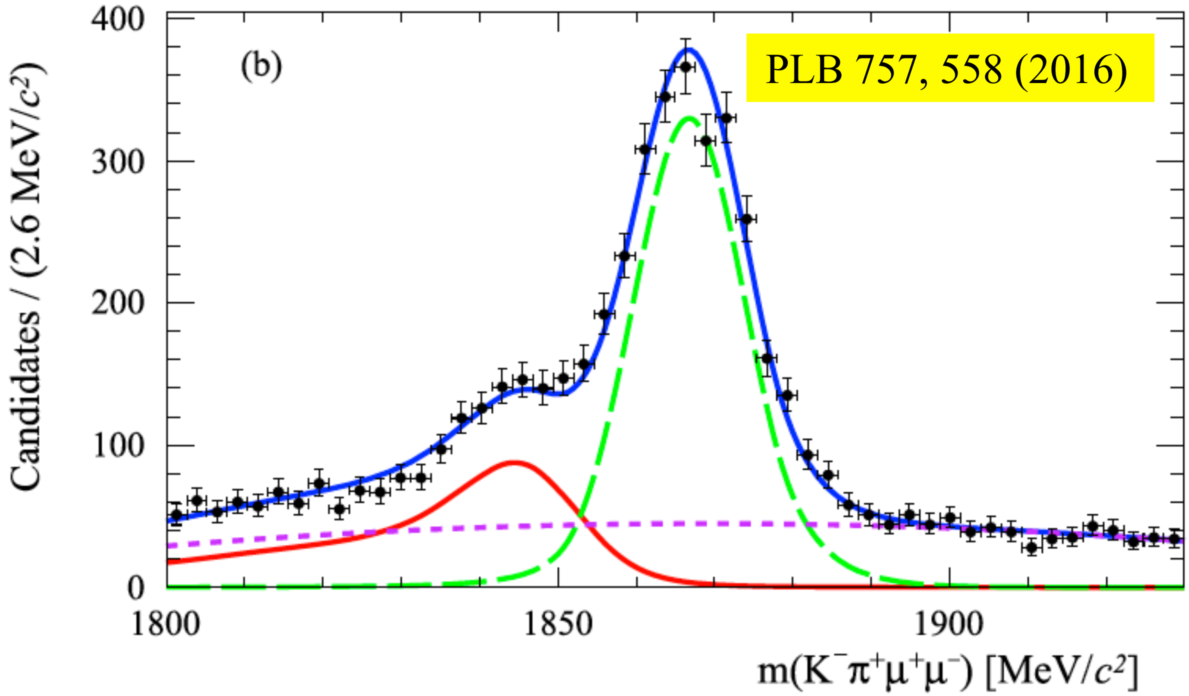
- 95 (90)% confidence-level upper limit on the branching fraction at at $11(9)\times10^{-9}$ ➔ factor 30 below the previous world's best limit

- Falls short by three orders of the SM prediction



Some recent rare decays from LHCb

A. Contu

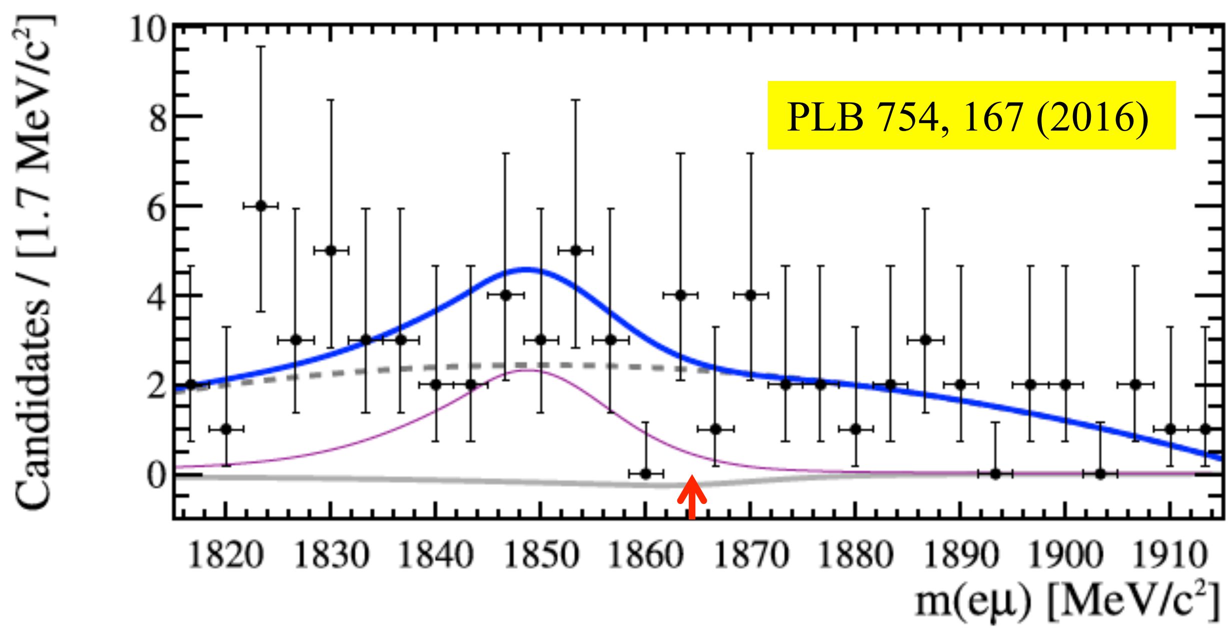


- Observation of $D^0 \to K^-\pi^+\mu^+\mu^-$ with the branching fraction

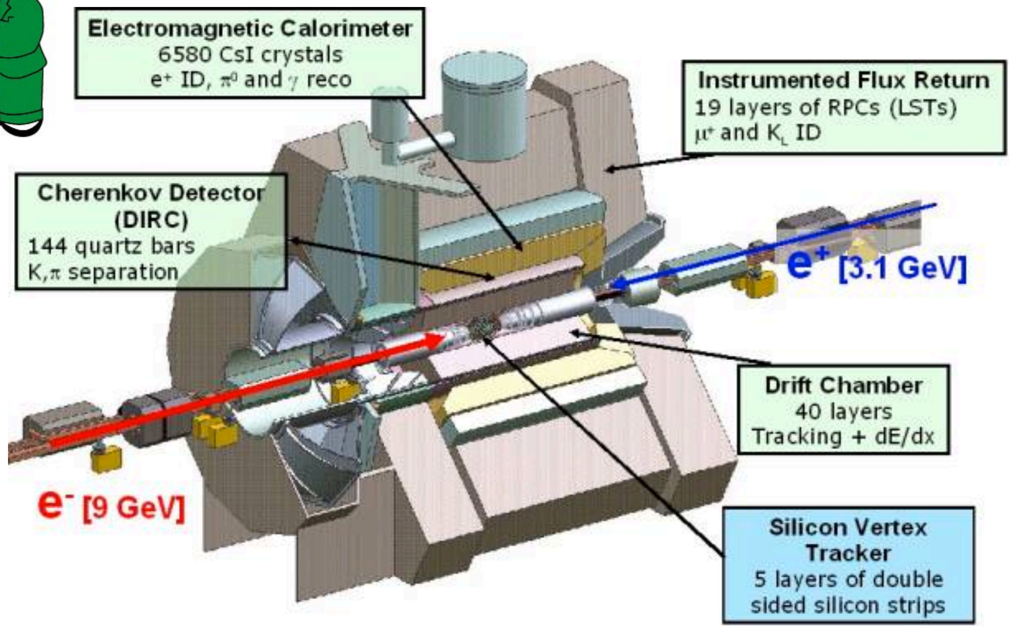
$$(4.17 \pm 0.12\,(\text{stat}) \pm 0.40\,(\text{syst})) \times 10^{-6}$$

- Consistent with SM prediction
- An amplitude analysis required to better understand decay dynamics

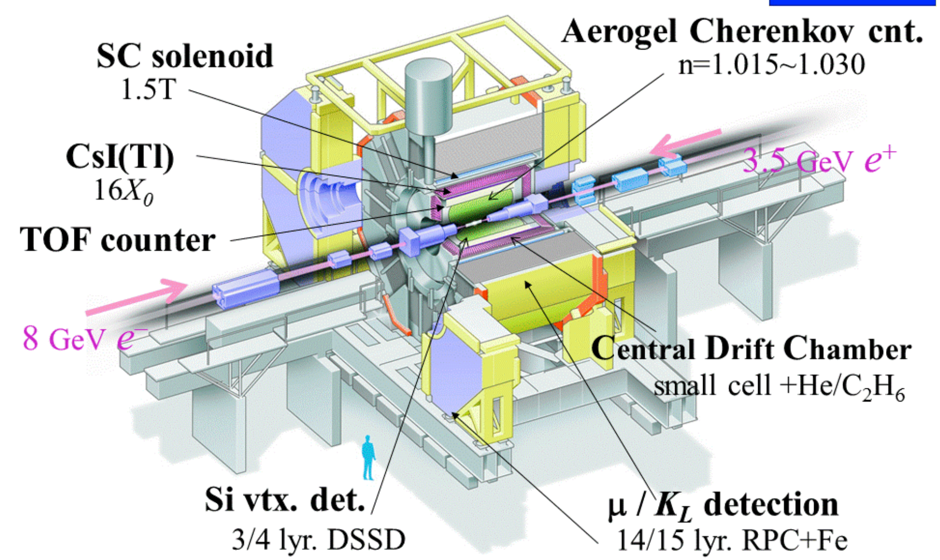
- Search for the lepton-flavor violating decay $D \to e^+\mu^-$ in the channel $D^* \to D^0\pi^+$
- No significant excess ➔ set 90% CL upper limit at 1.3×10^{-8}
- World's best limit & further helps in constraining some LQ and SUSY models

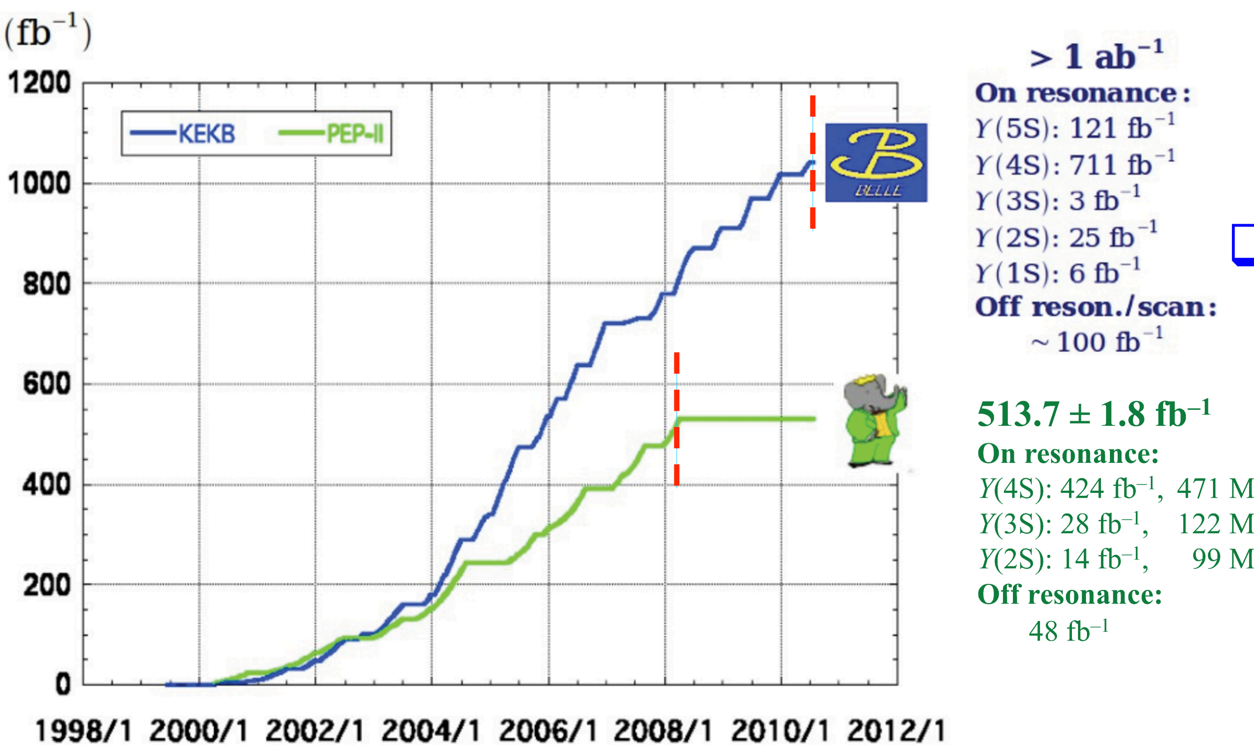


Asymmetric-energy flavor factories



Belle Detector





- Belle & BABAR have amassed close to 1.2×10^9 and 7×10^8 $c\bar{c}$ events

N. Dash

A poster-child search

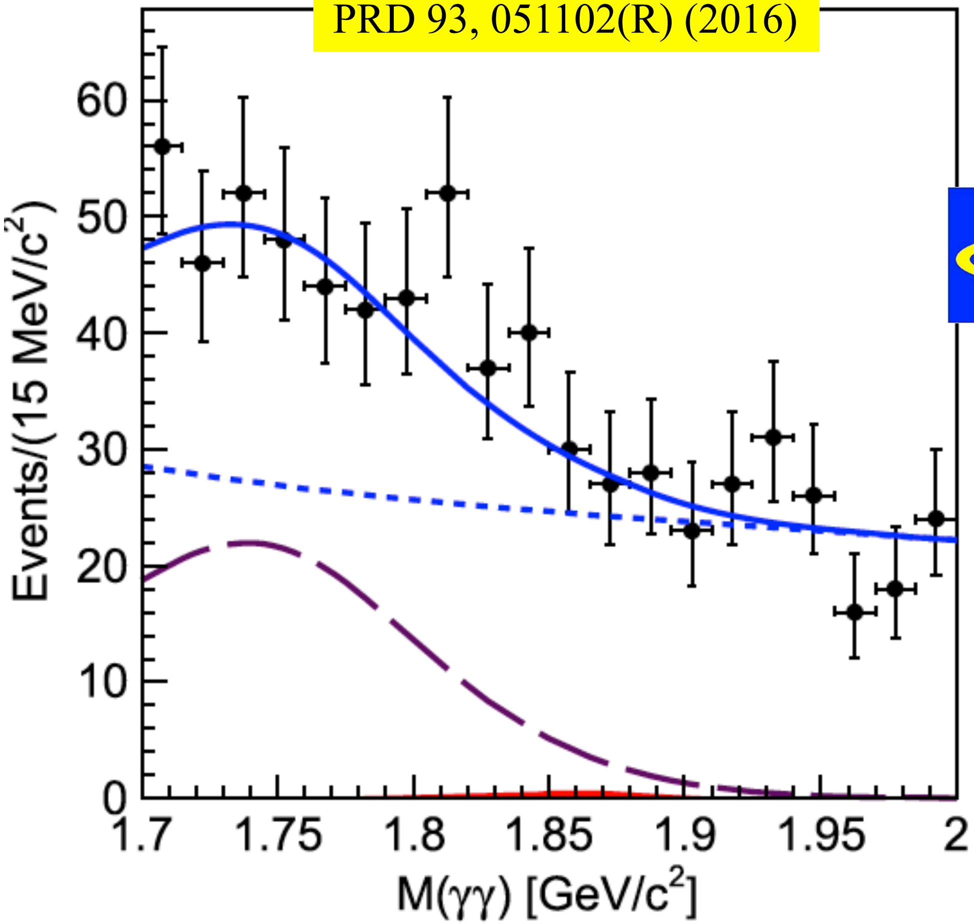
$D^0 \to \gamma\gamma$

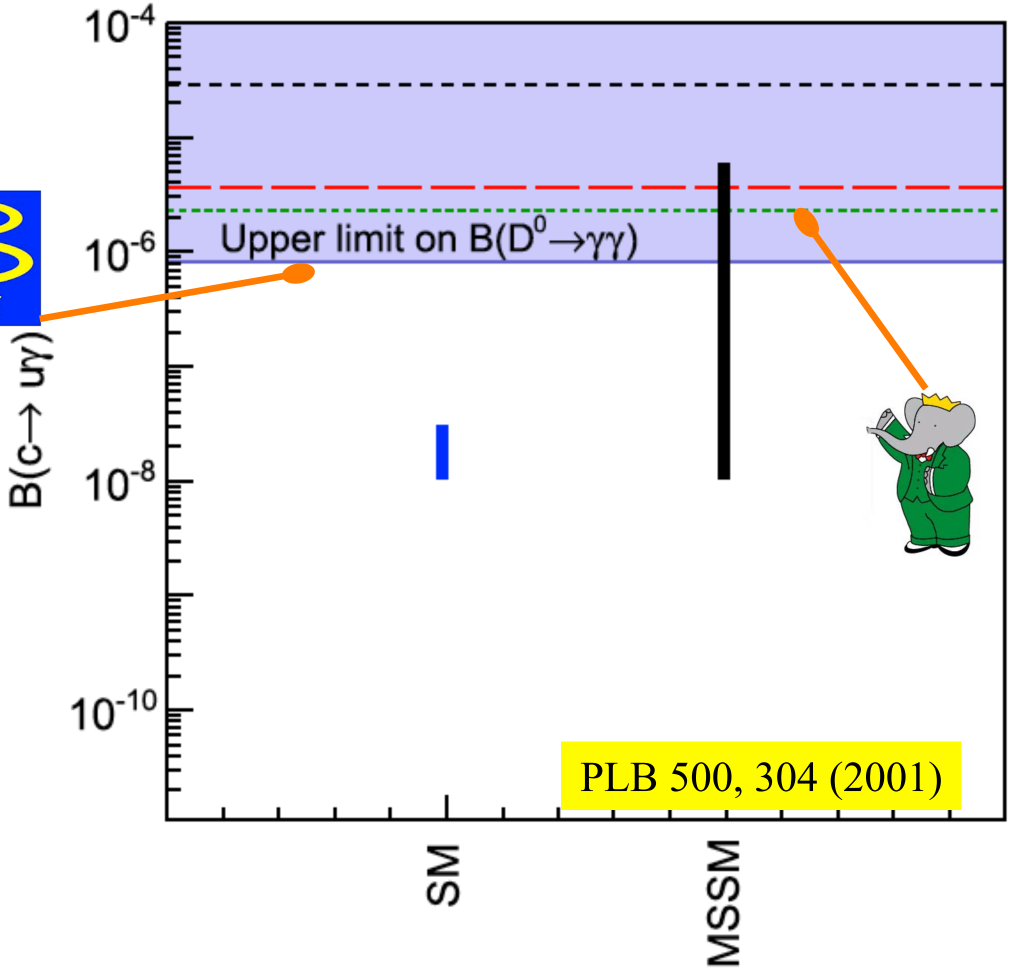
- ➢ Mediated by FCNC transition with small short-distance contribution
- ➢ Sizable long-distance contribution within the SM

PRD 64, 074008 (2001)

PRD 66, 014009 (2002)

PRD 93, 051102(R) (2016)

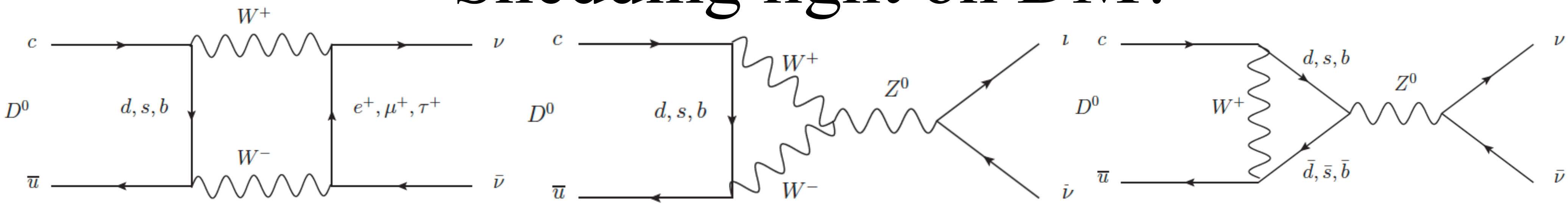




PLB 500, 304 (2001)

- ❑ Set world's best limit at 8.5×10^{-7} in absence of a signal
- ❑ Helps restrict new physics, viz. MSSM parameter space

Shedding light on DM?

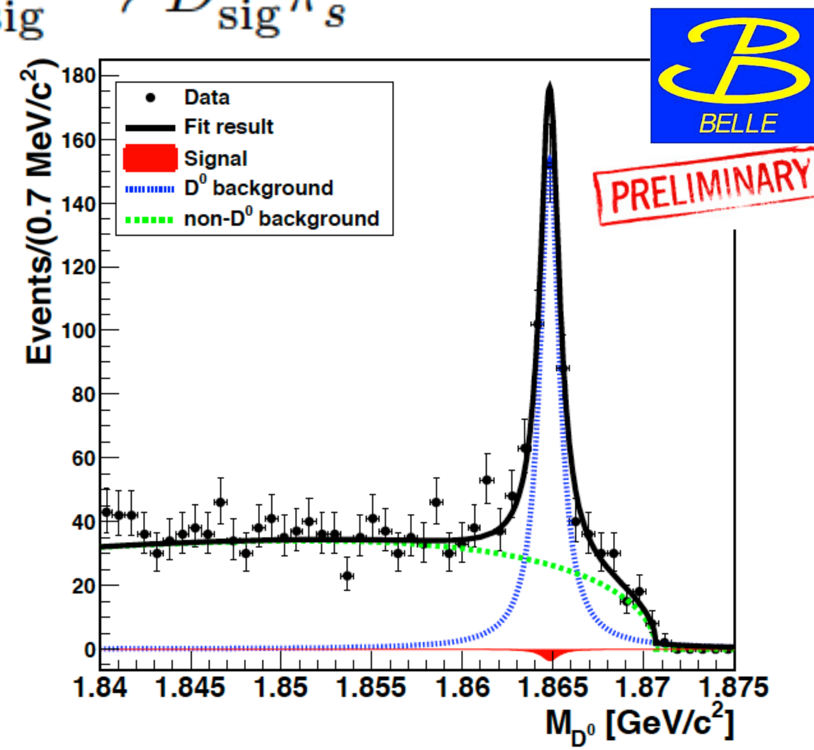


- ❑ Highly suppressed in SM with an expected BF of order 10^{-30} PRD 82, 034005 (2010)
- ❑ NP contributions such as scalar DM, right-handed neutrino or Majorana fermion could substantially enhance the value up to 10^{-15} PLB 651, 374 (2007) PR 117, 75 (1985)
  - ➢ Event reconstruction relies on an earlier technique by Belle JHEP 09, 139 (2013)

$$e^+e^- \to c\bar{c} \to D^{(*)}_{\rm tag} X_{\rm frag} \bar{D}^{*-}_{\rm sig} \;\; \text{with} \;\; \bar{D}^{*-}_{\rm sig} \to \bar{D}^0_{\rm sig}\pi^-_s$$

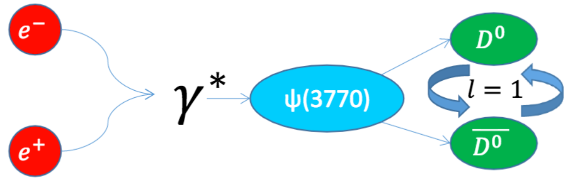
- ❑ Signal yield (−10 ± 22) is consistent with zero
- ❑ Set 90% CL upper limit at 8.8×10^{-5}

➢ Something BESIII can do, while Belle II will be able to substantially improve on



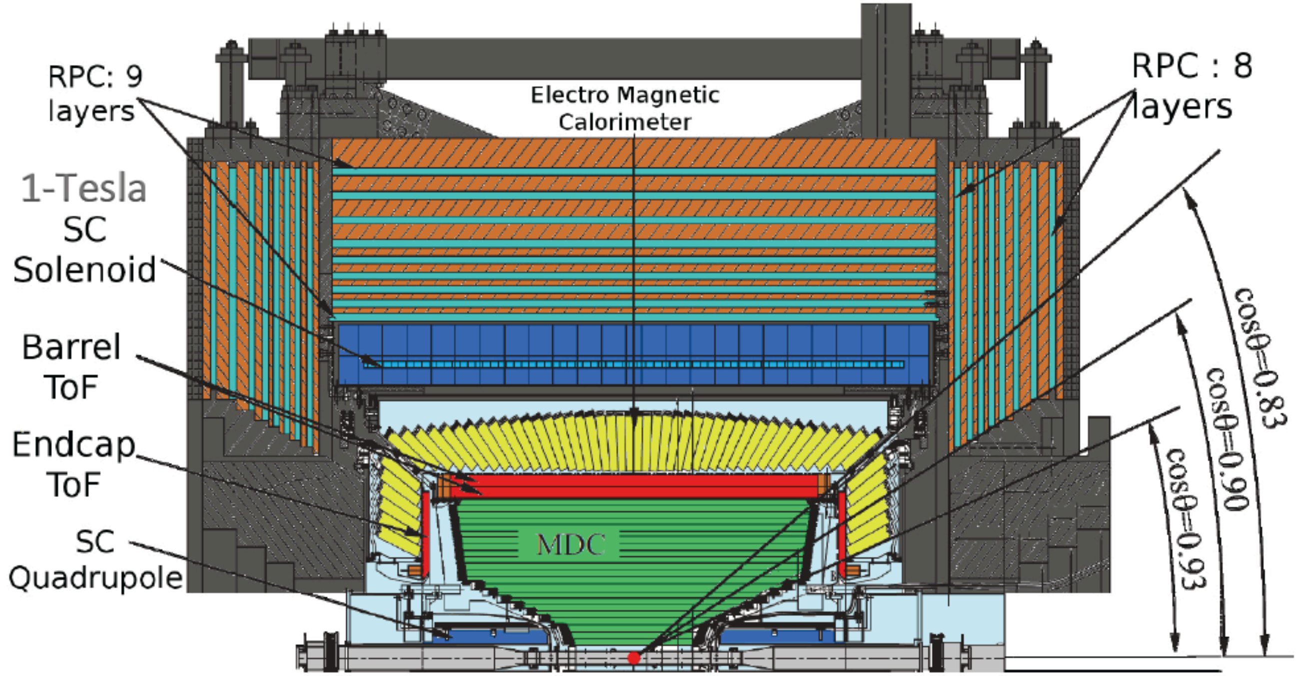
BESIII in the game

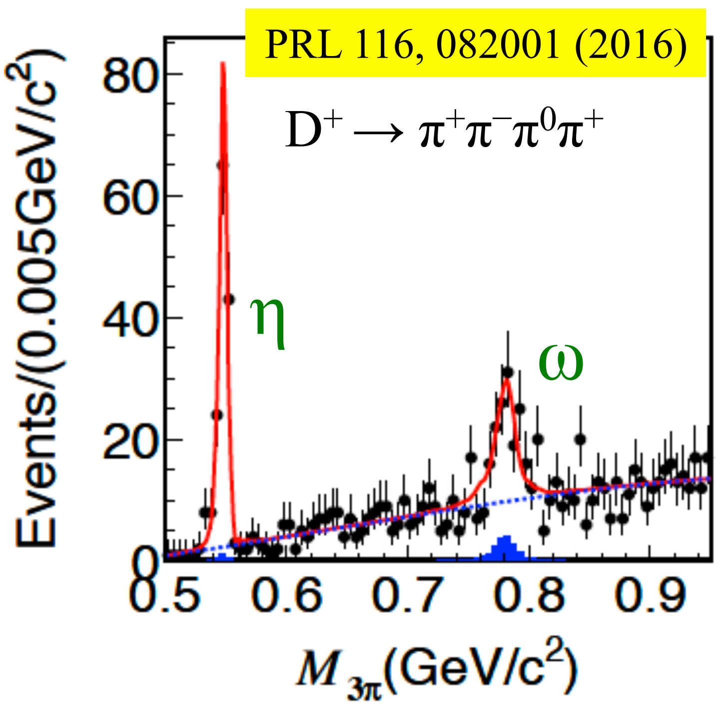
R. Poling
X.-R. Lyu



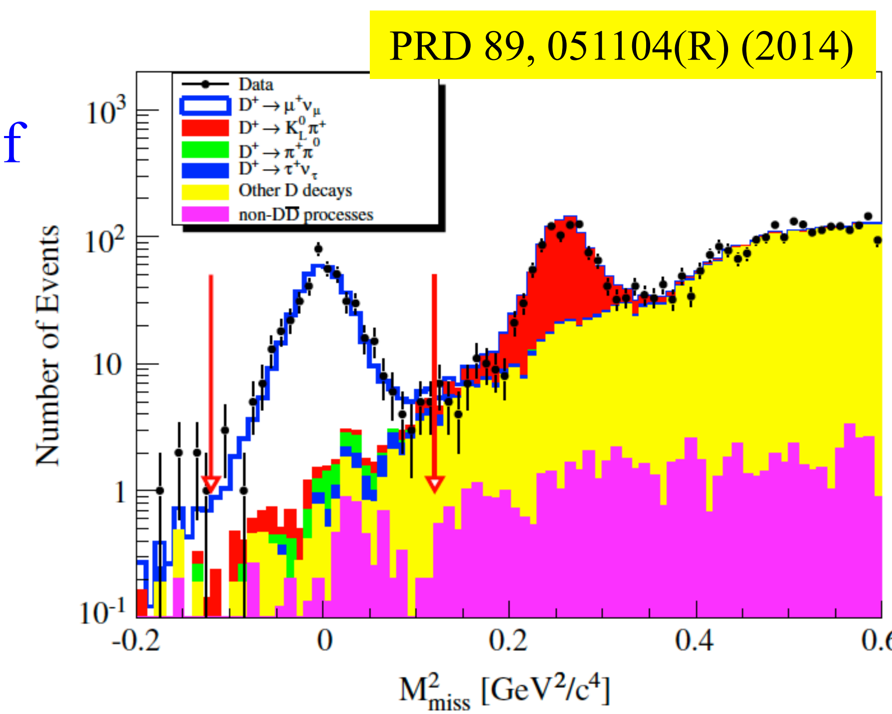
- Observation of the singly Cabibbo-suppressed (SCS) decay $D^+ \to \omega(\pi^+\pi^-\pi^0)\pi^+$
- Evidence for its neutral counterpart

$D^+ \to \omega\pi^+$	$(2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$
$D^0 \to \omega\pi^0$	$(1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$



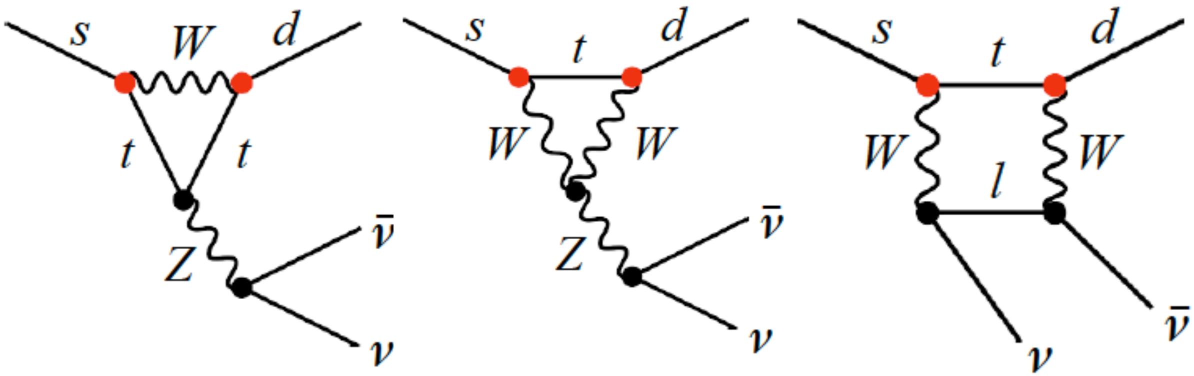


- Most precise measurement of BF($D^+ \to \mu^+\nu_\mu$)



M. Moulson
B. Beckford

Poster-child kaon decays



- ❑ Super-rare decays having precisely predicted BF values in the SM

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$ ★

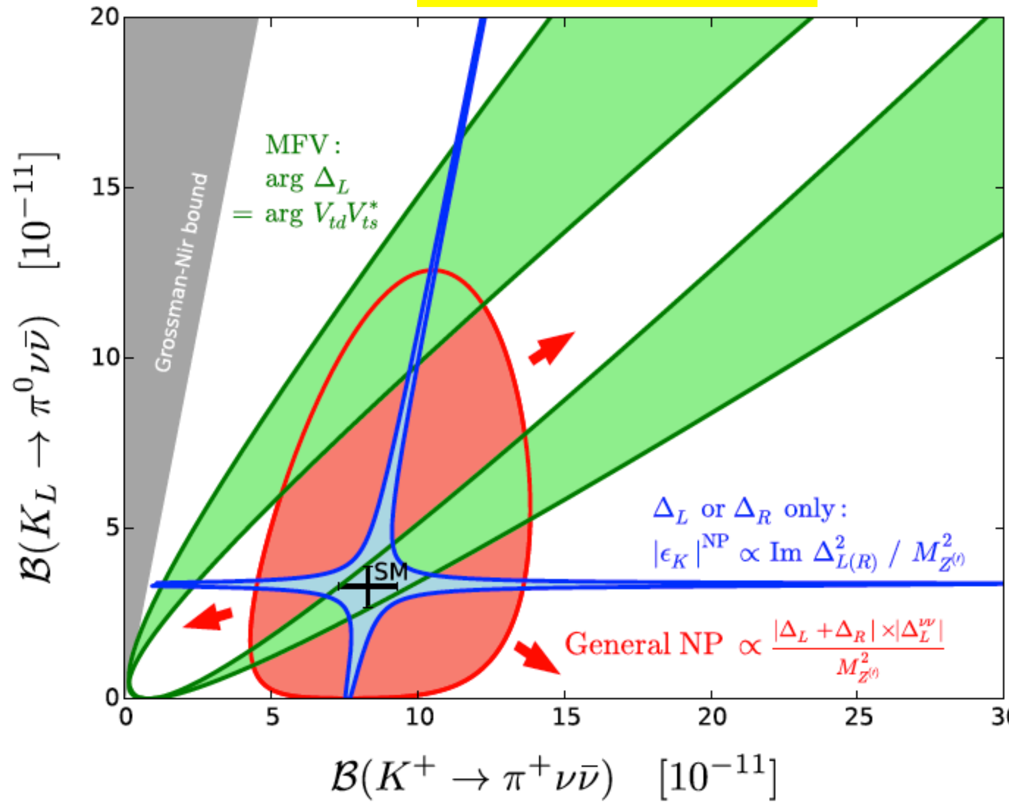
- ❑ An excellent hunting ground for new physics models:

① CKM-like flavor structure (MFV)

② Flavor-violating interactions in which either LH or RH currents dominate (Z-Z' or little Higgs with T parity)

③ Models without above constraints (Randall-Sundrum model)

JHEP 11, 166 (2015)



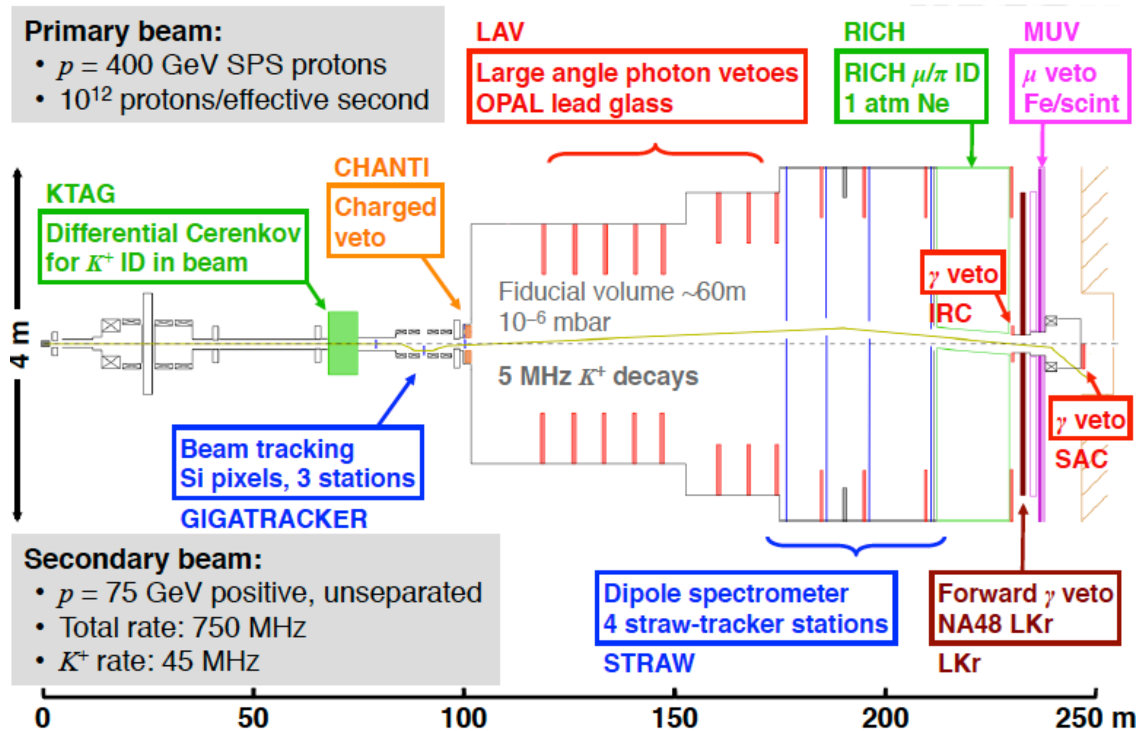
★ Tree-level determinations of CKM matrix elements

Experimentally, where do we stand?

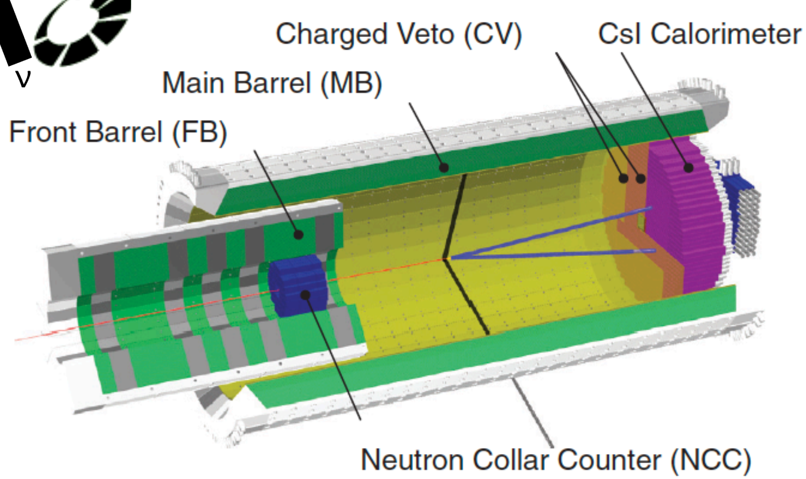
M. Moulson
B. Beckford

Earlier

- ➢ Charged: 7 events in BNL 787/949, BF = 17.3×10^{-11} with 70% error
- ➢ Neutral: 90% CL upper limit at 2.6×10^{-8} by KEK E391a



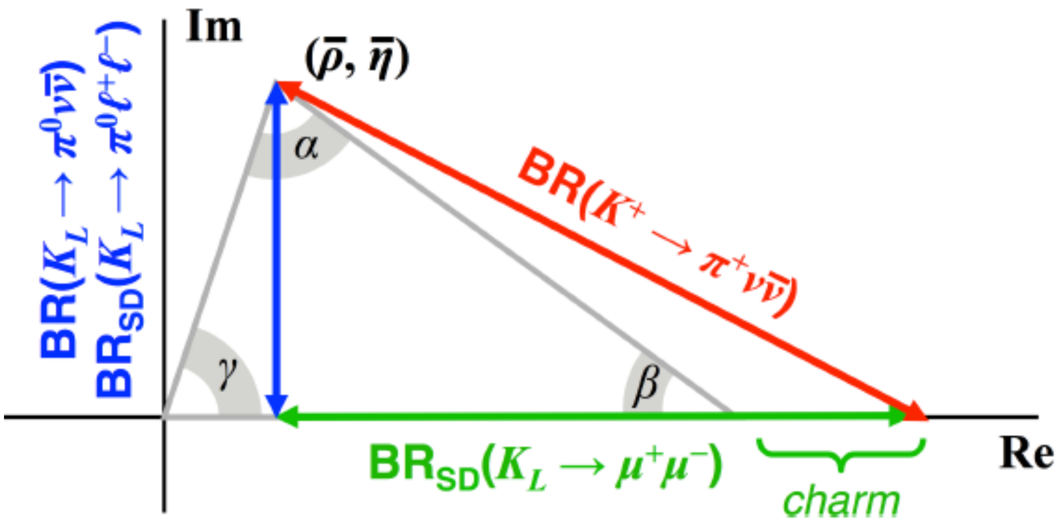
- ❑ First physics run during Jun-Nov 2015
- ❑ The 2016 run is in progress (Apr-Nov)
- ❑ Expect to take data through 2018 till LS2

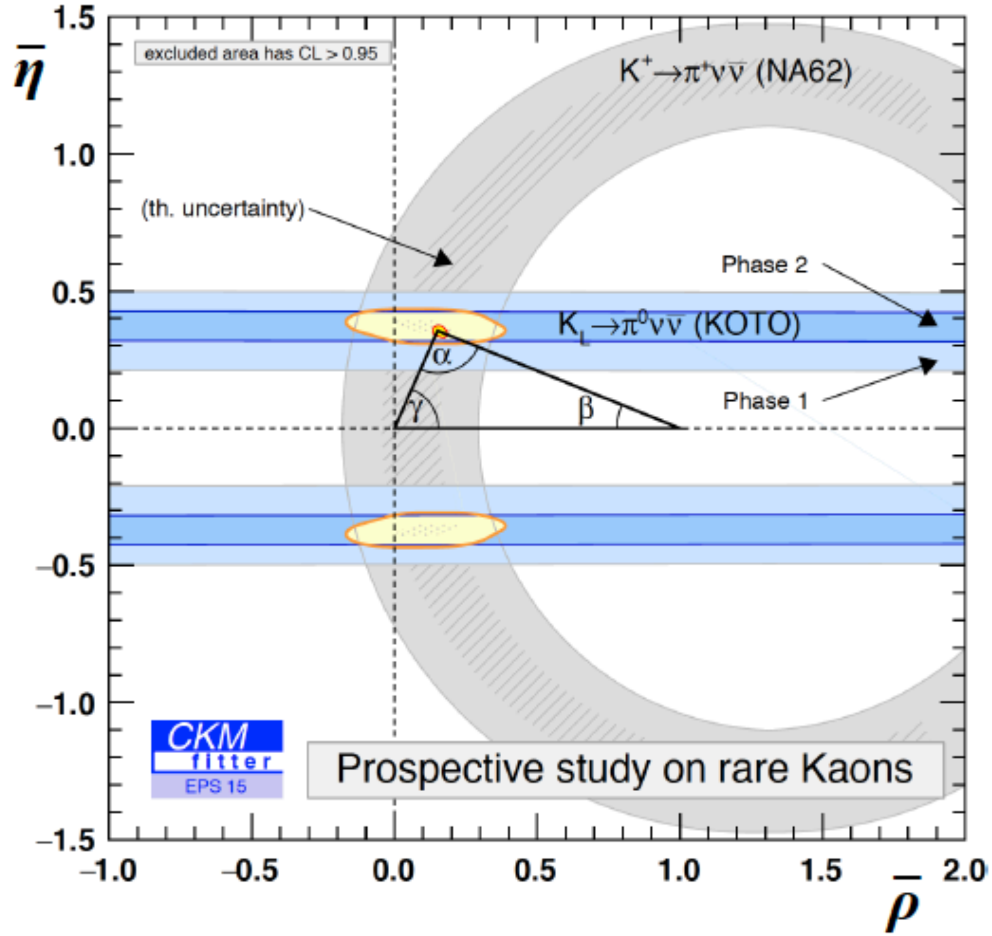


- ❑ 2013 data: 1 event observed against 0.36 ± 0.16 background predicted
- ❑ Resumed data taking since Apr 2015
- ❑ Plan to reach SM sensitivity by 2018

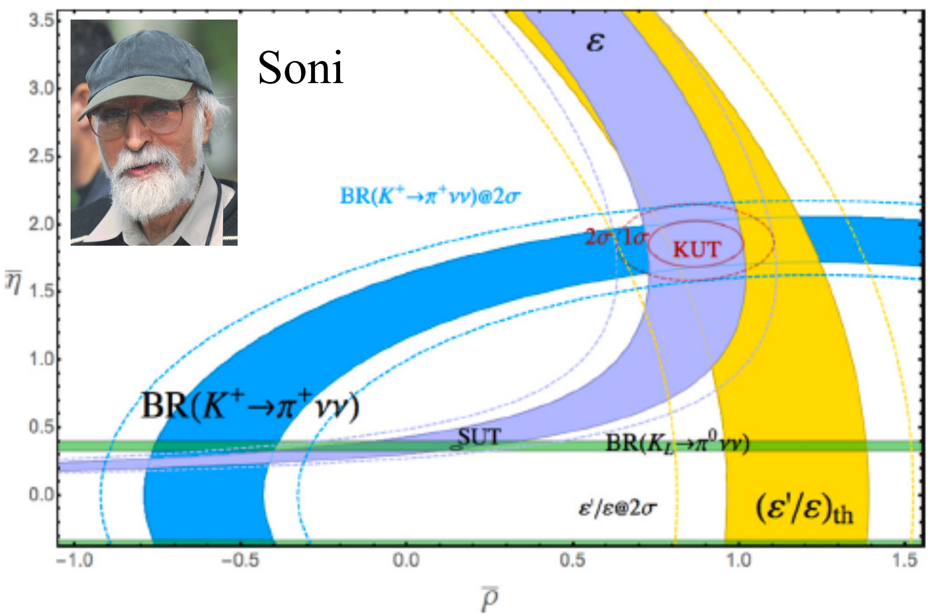
M. Moulson

Rare kaon decays & CKM metrology





- BF measurements alone overconstrain CKM matrix and may provide evidence for new physics



- While waiting for exp results e.g., from KOTO, improved lattice calculations on direct CP violation, ε'/ε can help us

PLB 759, 82 (2016)

Rare decays ➔ Mixing and CP violation

A theory premier

Meson-antimeson mixing

- Mass ≠ Flavor eigenstates
- Mass eigenstates:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

- Mixing parameters:

$$x = \frac{m_2 - m_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

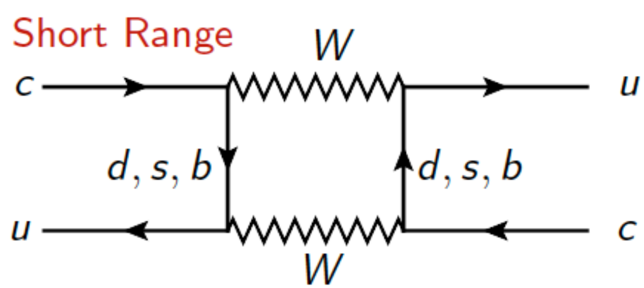
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

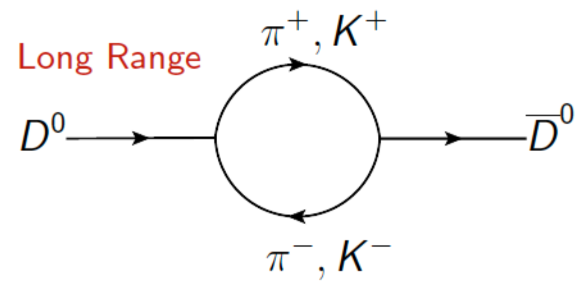
CP violation

① Direct CPV: $\left|\frac{\overline{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right| \neq 1$

② CPV in mixing: $\left|\frac{q}{p}\right| \neq 1$ $\boxed{\arg\left(\frac{q}{p}\right) \neq 0}$

③ CPV due to interference between mixing and decay: $\arg\left(\frac{q}{p}\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}\right) \neq 0$



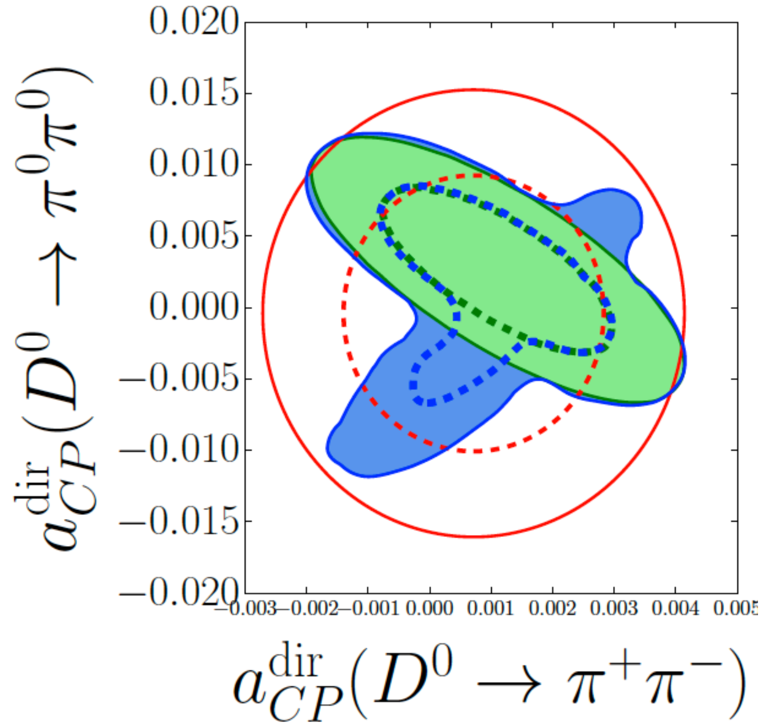


- ❑ Only up-type quark system with mixing
- ❑ Mixing enter at one-loop in the SM ➔ both GIM and CKM suppressed
- ❑ Long-range effects may dominate over short-range interactions
- ❑ In SM, x and y are of the order of 0.5% or less, while CPV of the order 10^{-3}
- ❑ Enhancements beyond these values could be NP signature

Where to look for CPV in charm?

Nierste

- Stress on SCS decays into two pseudoscalar mesons
- In the absence of loop suppression, suggest $D^0 \to K_S K_S$ as a good channel to probe CP violation



Red solid (dashed) curve: 2σ (1σ) current data

Blue solid (dashed) curve: 2σ (1σ) global fit

Light (dark) green region: 2σ (1σ) future projection assuming √50 more precise $A_{CP}(D^0 \to \pi^0\pi^0)$ than

PRL 112, 211601 (2014)

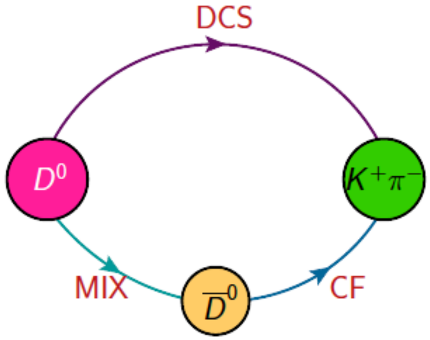
BELLE

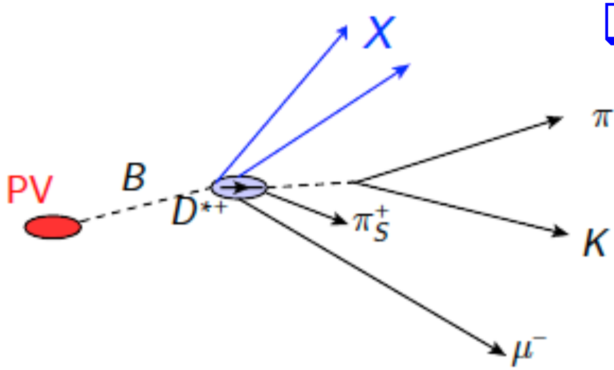
Bigi

➢ 3- & 4-body final states of charm & beauty hadrons *not* back-up for information from 2-body ones - the landscapes are very different !

A. Davis

Mixing and CPV in WS D→ Kπ





- Use a combined sample of
  - a) Doubly tagged (DT) events where muon and slow pion (π_s) tag D^0 flavor
  - b) Prompt events with only π_s tagging

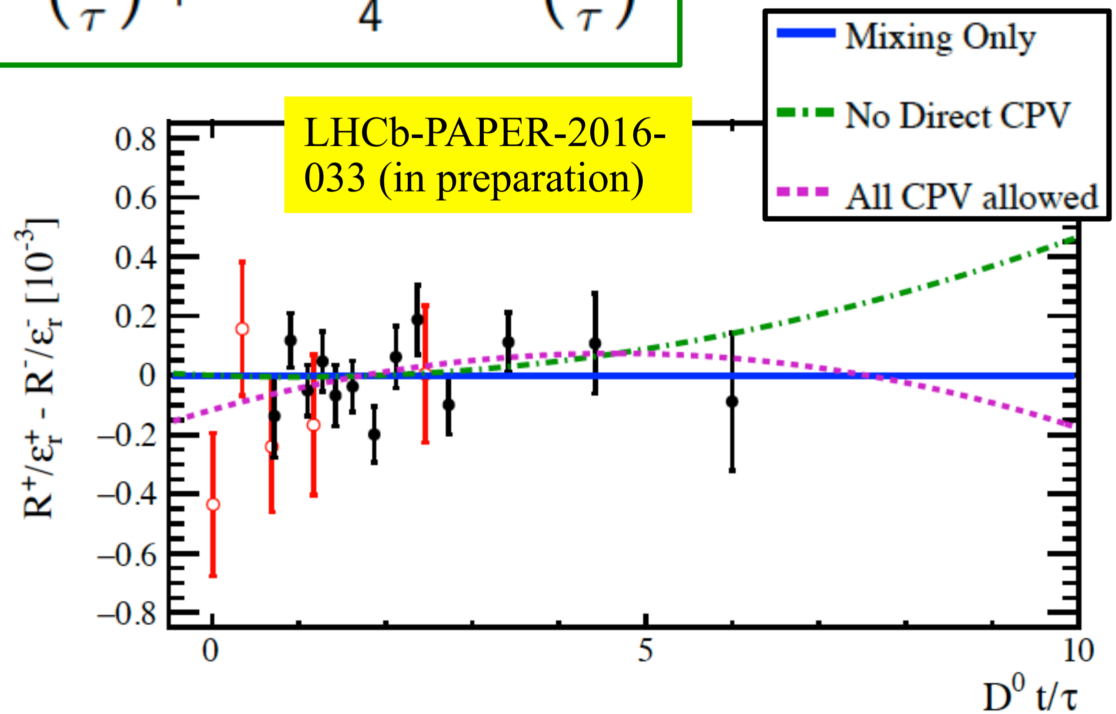
$$\boxed{R(t)^{\pm} = \left(\frac{WS(t)}{RS(t)}\right)^{\pm} = R_D^{\pm} + \sqrt{R_D^{\pm}}\,y'^{\pm}\left(\frac{t}{\tau}\right) + \frac{(x'^{\pm})^2+(y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2}$$

- Mixing only:

$$\boxed{R_D^+ = R_D^-,\ x'^{+2} = x'^{-2},\ y'^+ = y'^-}$$

- No Direct CPV: $\boxed{R_D^+ = R_D^-}$

- All CPV allowed: $\boxed{\text{All +/- free}}$

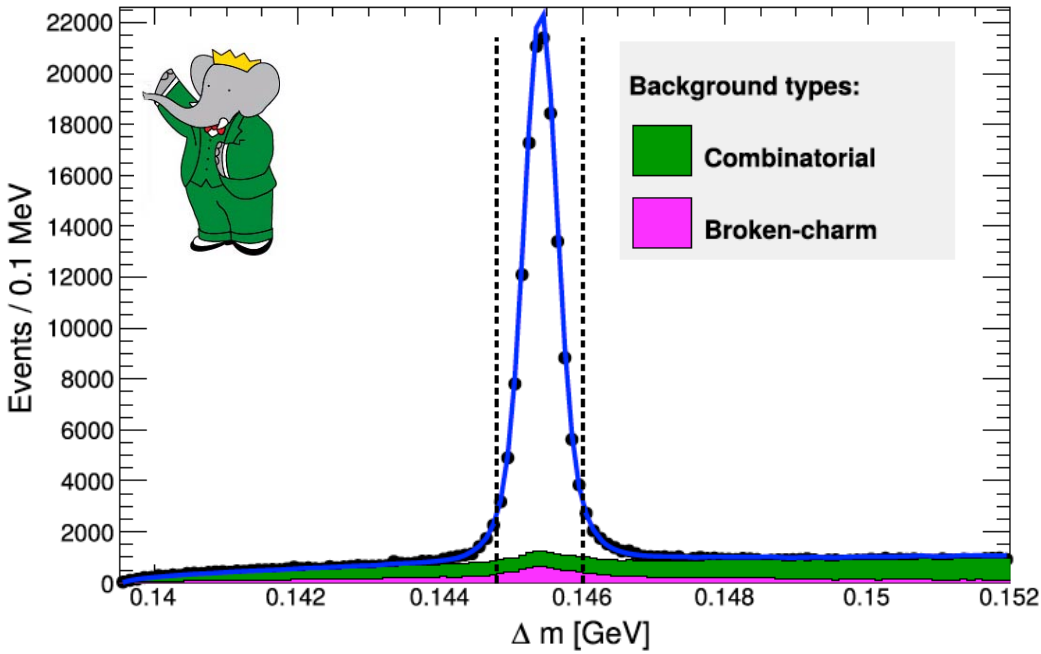


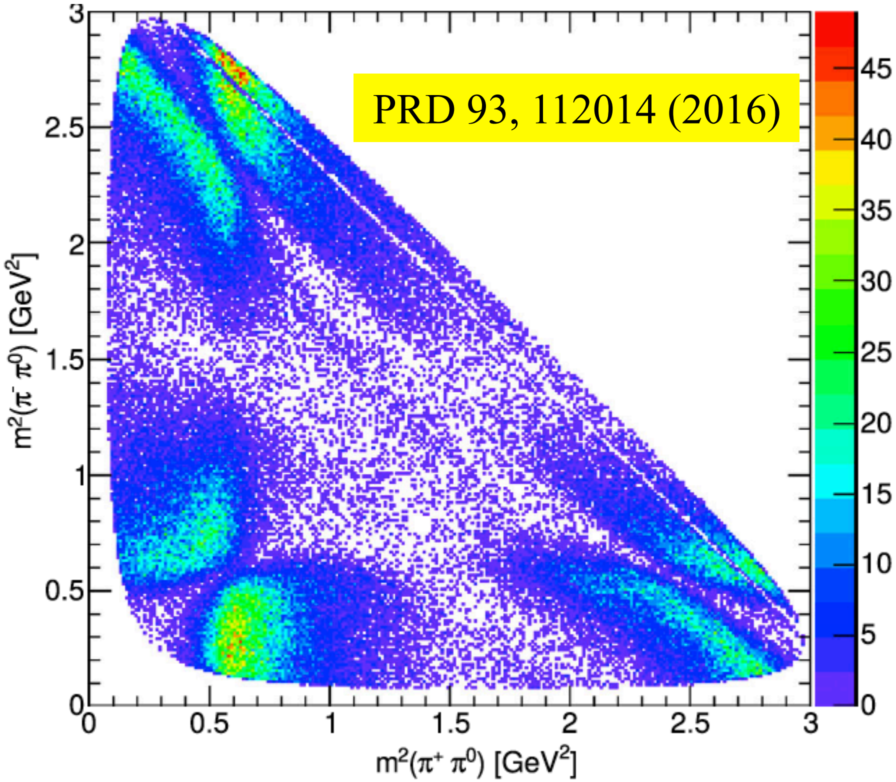
➢ Results in both DT and combined sample consistent with mixing only fit

Charm mixing results from BABAR

A. Pilloni

- First measurement of charm mixing parameters in the SCS decay channel $D^0 \rightarrow \pi^+\pi^-\pi^0$
- Time-dependent analysis of the Dalitz-plot distribution
  - Isobar model for signal
  - Decay-time distribution modeled as exponential convolved with detector resolution





$$x = (1.5 \pm 1.2 \pm 0.6)\%$$
$$y = (0.2 \pm 0.9 \pm 0.5)\%$$

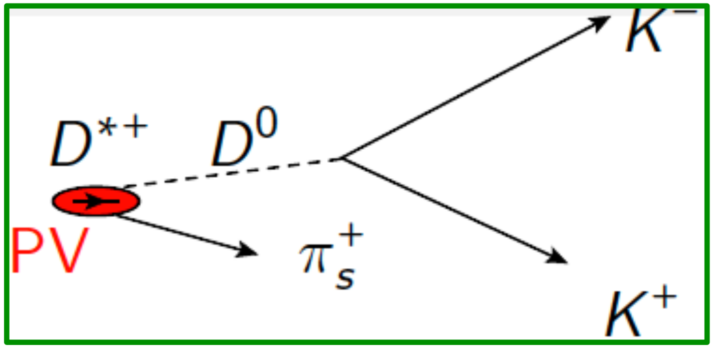
- Precision dominated by statistics
- Some of major systematic errors can be reduced with larger dataset
- Good for LHCb and Belle-II

Search for CP violation in $D \to K^+K^-$

A. Davis

- Use three control samples to eliminate all but for CP asymmetry:

$$A_{CP}(D^0 \to KK) = A_{raw}(D^0 \to KK) - A_{raw}(D^0 \to K^-\pi^+) + A_{raw}(D^+ \to K^-\pi^+\pi^+) - A_{raw}(D^+ \to \overline{K}^0\pi^+) + A_D(\overline{K}^0)$$



LHCb-PAPER-2016-035 (in preparation)

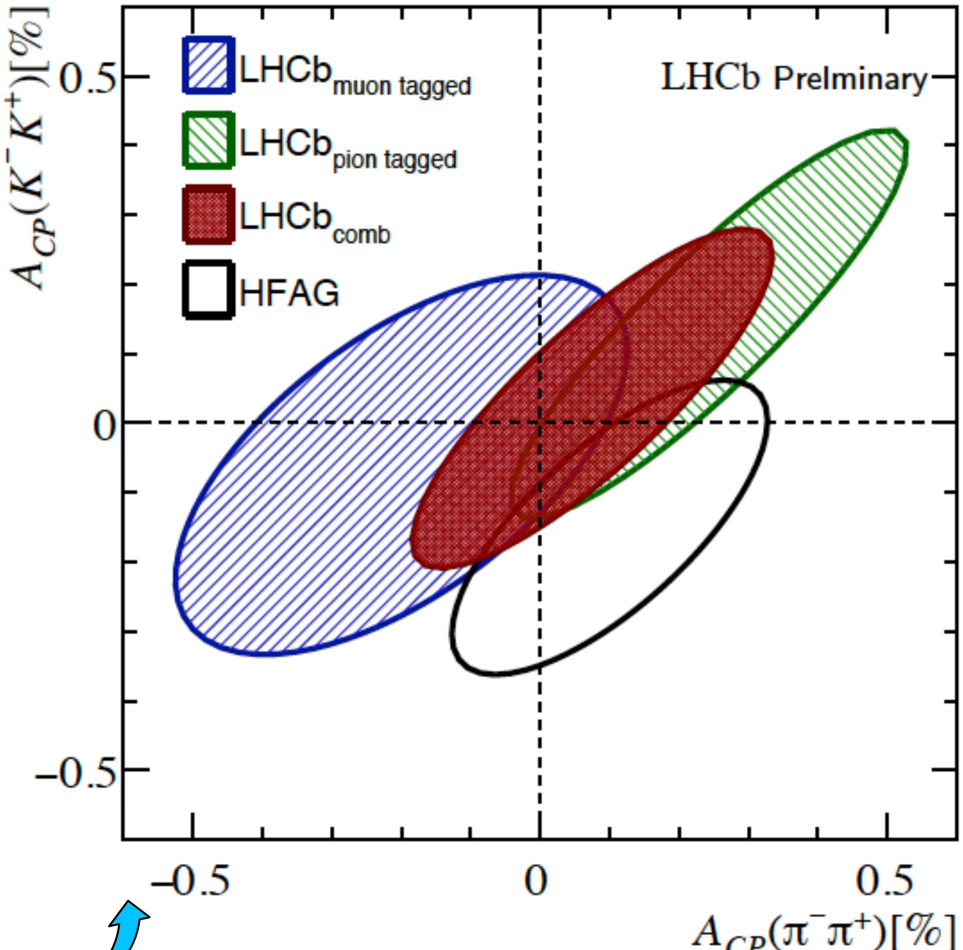
$$A_{CP}(KK) = (+0.14 \pm 0.15 \pm 0.10)\%$$

- Extract $A_{CP}(\pi^+\pi^-)$ using previous ΔA_{CP} from PRL 116, 191601 (2016)

$$A_{CP}(\pi\pi) = (0.24 \pm 0.15 \pm 0.11)\%$$

- Combine with the muon tagged results JHEP 07, 041 (2014)

✧ End result is shown in the right plot



➢ No evidence for CP violation

Search for CP violation in $D \to K_S K_S$

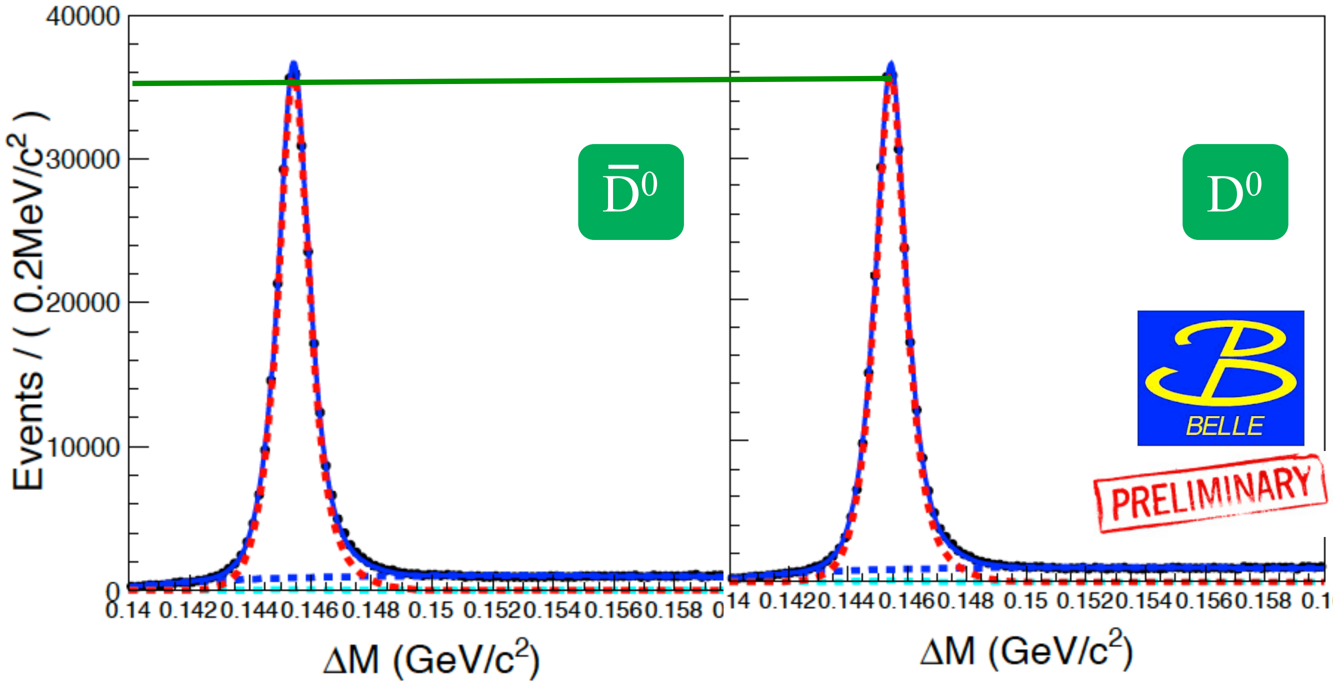
N. Dash

- SM expectation: 1.1% for direct CP violation

  PRD 92, 054036 (2015)

- Possible interference with NP amplitude could lead to a larger value

  PRD 87, 014024 (2013)



Method

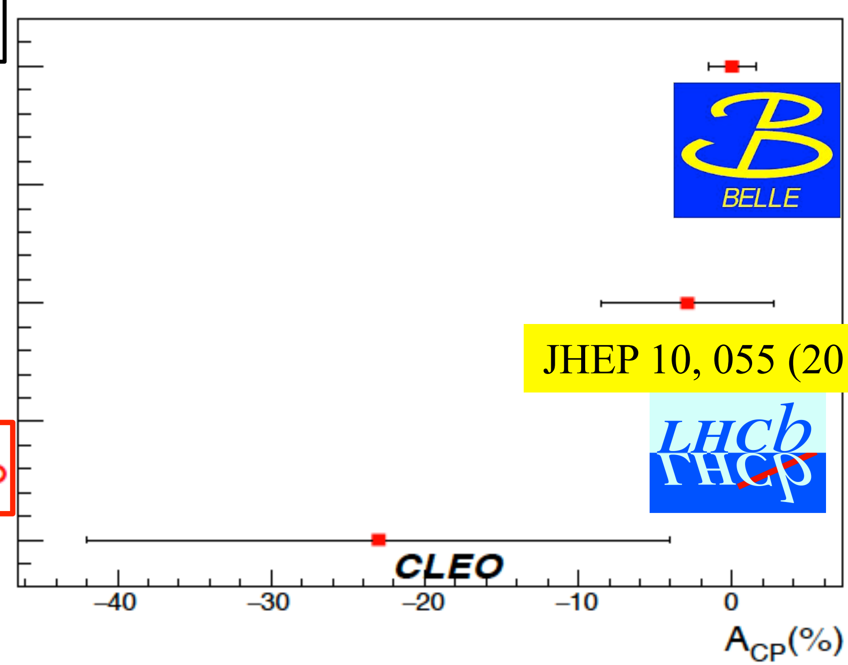
$$A_{CP}^{D^0\to K_S^0 K_S^0} = (A^{rec}_{D^0\to K_S^0 K_S^0} - A^{rec}_{D^0\to K_S^0 \pi^0}) + (A_{CP}^{D^0\to K_S^0\pi^0}) + A_\epsilon^{K^0/\bar{K}^0}$$

$\boxed{A_\epsilon^{K^0/\bar{K}^0}}$ Asymmetry originating from different interaction of K^0 and $\bar{K}^0$ with detector material

PRD 84, 111501 (2011) $(-0.11\pm0.01)\%$

$$\boxed{A_{CP}(D^0 \to K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.17)\%}$$

➢ Consistent with no CPV at a percent level



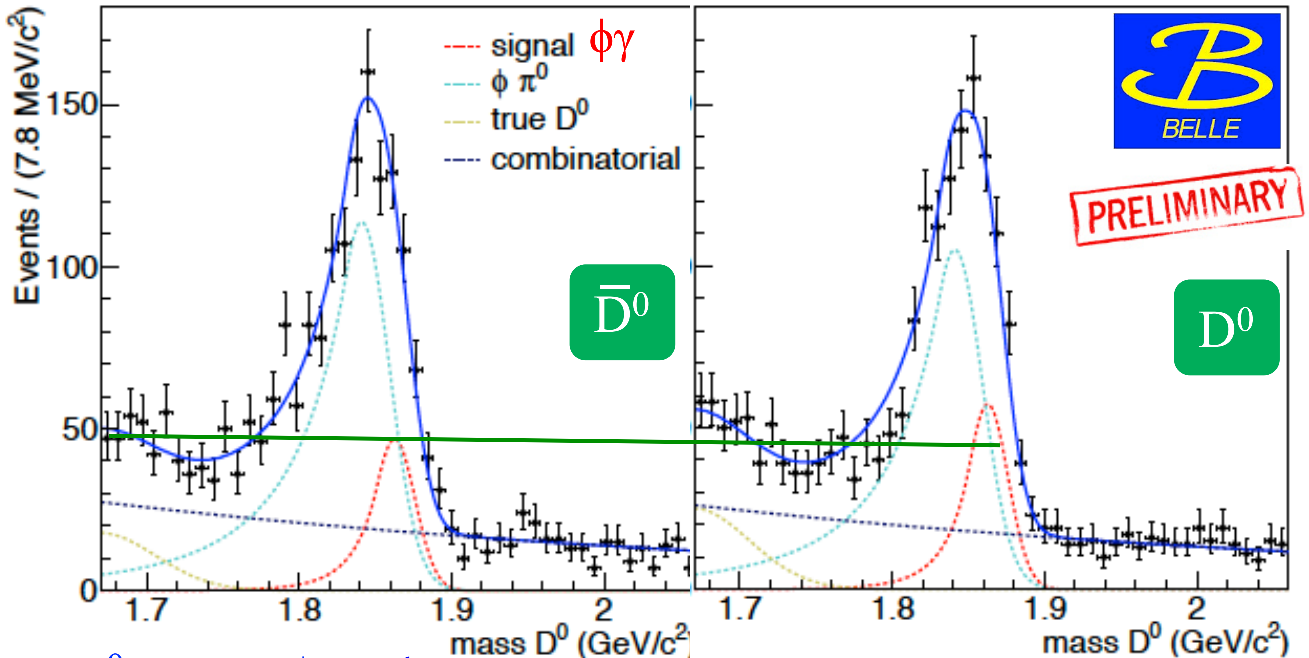
N. Dash

Results on radiative charm decays

- CP asymmetry in radiative decays provides a nice NP probe ➔ A_{CP} of the order of 3% would be a clear signal

PRL 109, 171801 (2012)

arXiv:1210.6546



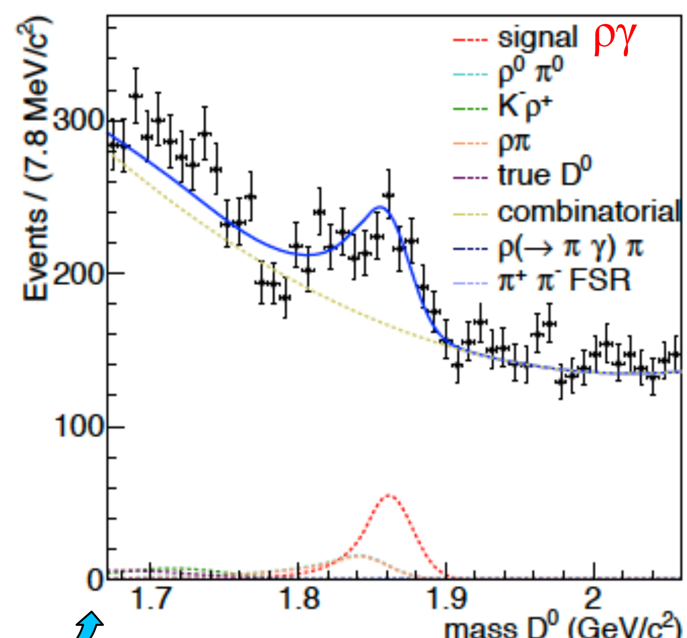
- $D^0 \to \rho\gamma$ is not yet seen ➔ SM prediction 10^{-3}

- Control channels: $D^0 \to K^+K^-$, $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$

$A_{CP}(D^0 \to \phi\gamma)$	$-0.094 \pm 0.066 \pm 0.001$
$A_{CP}(D^0 \to \bar{K}^{*0}\gamma)$	$-0.003 \pm 0.020 \pm 0.000$
$A_{CP}(D^0 \to \rho^0\gamma)$	$+0.056 \pm 0.151 \pm 0.006$

arXiv:1603.03257

$\mathcal{B}(D^0 \to \phi\gamma)$	$(2.76 \pm 0.20 \pm 0.08 \times 10^{-5}$
$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)$	$(4.66 \pm 0.21 \pm 0.18 \times 10^{-4}$
$\mathcal{B}(D^0 \to \rho^0\gamma)$	$(1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$



Epilogue

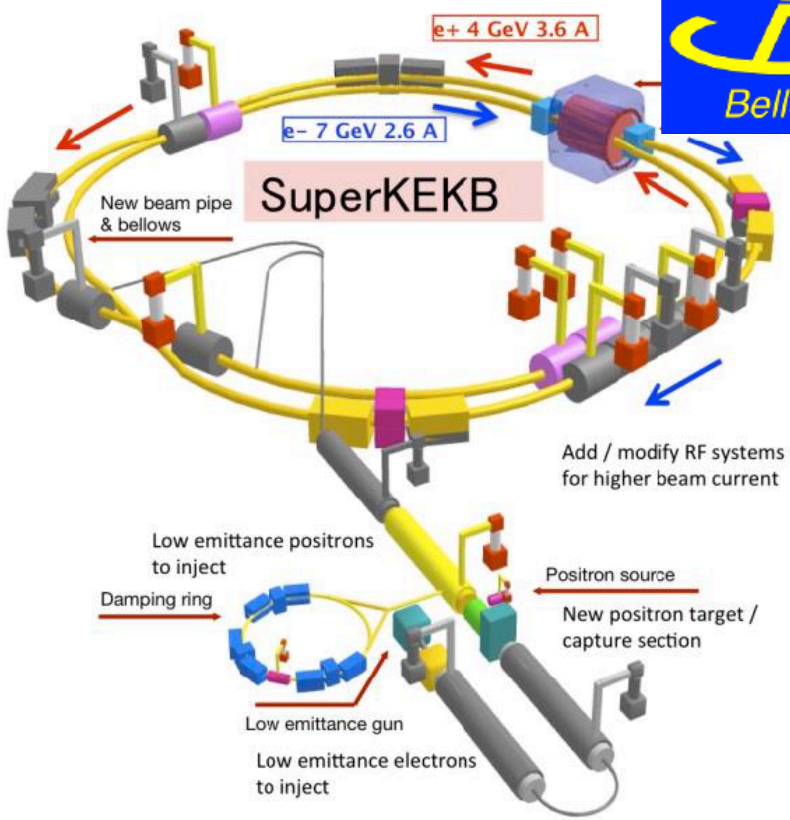
A. Contu

- Doing exceedingly well and prospect looks even brighter

CP asymmetry

Mode	Run II	Upgrade
$D^+ \to \pi^+\mu^+\mu^-$	0.6%(30K events)	0.2%(300K events)
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	3%(1500 events)	1%(15K events)
$D^0 \to K^-\pi^+\mu^+\mu^-$	1%(10K events)	0.3%(100K events)
$D^0 \to K^+\pi^-\mu^+\mu^-$	40%(30 events)	12%(300 events)
$D^0 \to K^+K^-\mu^+\mu^-$	11%(150 events)	4%(1500 events)

B. Fulsom



- Will be soon in running and produce lots of interesting results in the charm sector, especially the decays involving neutral and neutrino

- BESIII plans to run for 8-10 years and will continue to be productive

- Looking at distant future, possible super tau-charm factories at BINP, Russia and China (HIEPA) are exciting prospects

- On the strange sector, NA62 and KOTO will be the two major players


CKM2016
9th International Workshop on the CKM Unitarity Triangle
TIFR, Mumbai
Nov. 28 – Dec. 2, 2016
α/φ2
γ/φ3
β/φ1
Charm
Strange
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Image: https://en.wikipedia.org/wiki/Bandra-Worli_Sea_Link,Newscenter.phillips.com
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