Rare Charm Decays

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on behalf of LHCb

(including also results from BaBar, Belle, BESIII)

Beauty, Ljubljana, October 2019

- Why important & challenging?
- Charm samples
- Rare charm so far
- Recent news
- Summary & Outlook

Charm: unique, complementary but difficult

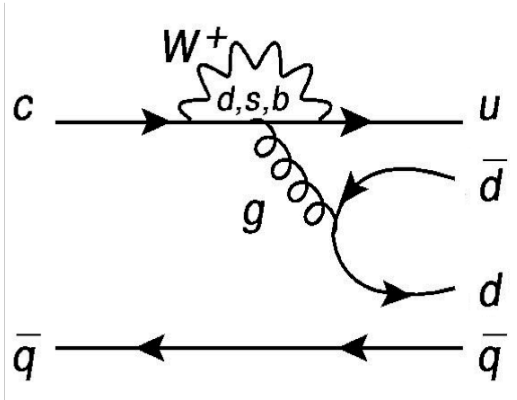
- **Complementary** to strange & beauty
  Down-type quarks in loops: different New Particles?
- **Unique** access to up-type quarks
  (Flavour physics with t-quark hopeless)

But...

- Loops very suppressed in charm
  ⇨ rare decays suppressed in SM
- QCD corrections are large (~$1/m_c$)
  ⇨ difficult to calculate

Needed:

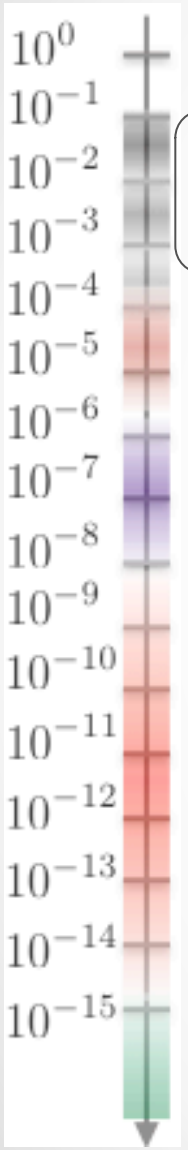
- Large & clean data samples
- Precise estimation of SM contribution
  (size of loop amplitude)



b loop CKM suppressed
$\sim V_{ub}V_{cb}(m_b/m_W)^2 \sim 10^{-6}$

s & d loops GIM suppressed
$\sim(m_s^2-m_d^2)/m_W^2$
Cancel in U-spin limit

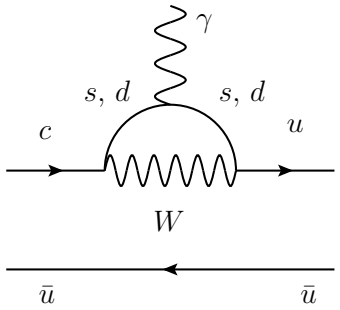
Spectrum of charm decays



Talk by Maxime Schubiger on mixing & CPV

Cabibbo Favoured

Cabibbo Suppressed

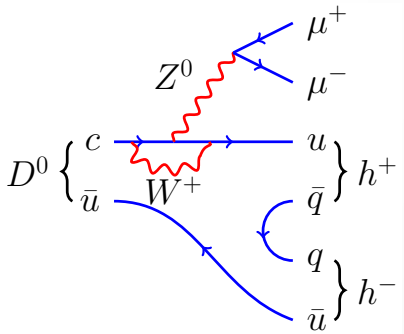


Radiative $D^0 \to \phi\gamma,\ \rho\gamma$

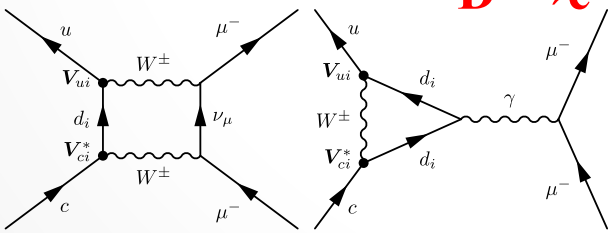
Vector-Meson Dominance $D^0 \to \pi^+\pi^- V(\to l^+l^-)$ $D^+ \to \pi^+ V(\to l^+l^-)$ $\Lambda_c \to p V(\to l^+l^-)$

$D^0 \to \gamma\gamma$

Flavour Changing Neutral Current $D^0 \to \pi^+\pi^- l^+l^-$ $D^+ \to \pi^+ l^+l^-$ $\Lambda_c \to p l^+l^-$



$D^0 \to e^+e^-$ $D^0 \to \mu^+\mu^-$



Lepton Number Violating $D^+ \to \pi^-\mu^+\mu^+$ $D^0 \to K^-\pi^-\mu^+\mu^+$

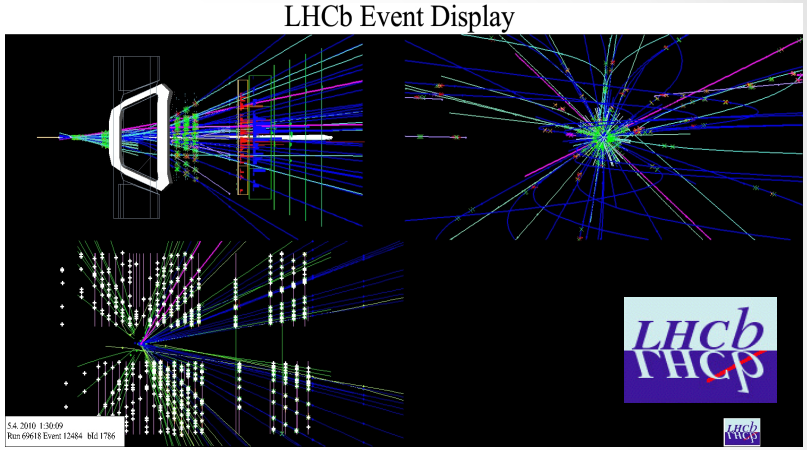
Lepton Flavour Violating $D^+ \to \pi^+e^+\mu^-$ $D^0 \to e^+\mu^-$ $D^0 \to K^-\pi^+e^+\mu^-$

Charm samples & their properties

LHCb

- $\sigma(pp \to c\bar{c}) \sim$ O(mb) ⇨ 12×10^{12} charm
- efficiencies < 0.1%
- busy environment, nontrivial triggers
- good tracking, identification & vertexing

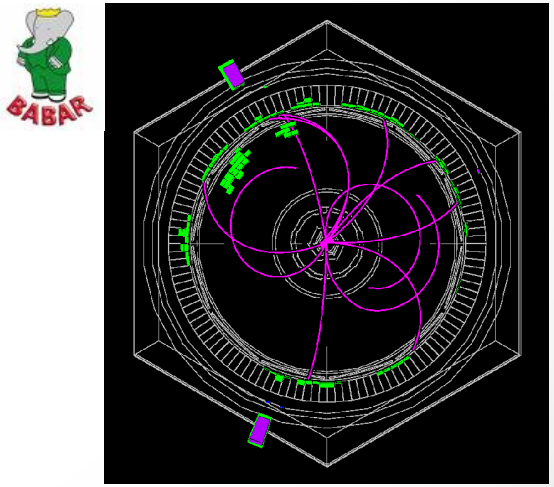
$D^0 \to \mu^+\mu^-$, $D^0 \to \pi\pi\mu^+\mu^-$, $\Lambda^+_c \to p\mu^+\mu^-$



Belle/BaBar

- $\sigma(e^+e^- \to \Upsilon(4S) \to c\bar{c}) \sim$ O(nb) ⇨ 2×10^9
- efficiencies ~ a few %
- clean environment, good calorimeter

$D^0 \to e^+e^-$, $D \to hhe^+e^-$, $D^0 \to hh\gamma$, $D^0 \to \gamma\gamma$



BESIII/Cleo-c

- $\sigma(e^+e^- \to \psi(3770) \to D\bar{D}) \sim$ O(nb) ⇨ 25×10^6
- efficiencies > 10%
- background-free charm

Precision down to $O(10^{-8})$
See signals!

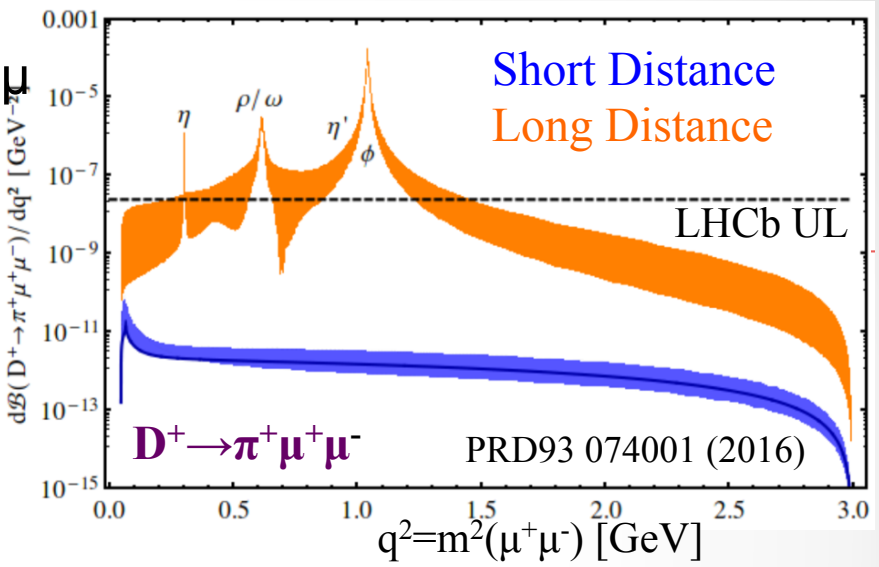
Hunting for rare charm signals

Decay	Note	SM	BF or best UL	Exp.
$D^0 \to \phi\gamma$	Radiative	$\sim 10^{-5}$	$(2.8 \pm 0.2 \pm 0.1) \times 10^{-5}$	Belle
$D^0 \to \rho\gamma$	" "	$\sim 10^{-6}$	$(1.8 \pm 0.3 \pm 0.1) \times 10^{-5}$	Belle
$D^0 \to \gamma\gamma$	" "	$\sim 10^{-8}$	$< 8.5 \times 10^{-7}$	Belle
$D_{(s)}^+ \to \pi^+\mu^+\mu^-$	FCNC, $\mu^+\mu^-$ non-resonant	$\sim 10^{-9}$	$< 8.3\ (48) \times 10^{-8}$	LHCb
$\Lambda_c^+ \to p\mu^+\mu^-$	" "	$\sim 10^{-9}$	$< 9.6 \times 10^{-8}$	LHCb
$D^+ \to \pi^+/K^+ e^+e^-$	FCNC, full e^+e^- spectrum	$10^{-8} \div 10^{-6}$	$< 0.3\ /\ 1.2 \times 10^{-6}$	BESIII
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	FCNC, low-mass $\mu^+\mu^-$	$\sim 10^{-9}$	$(7.8 \pm 1.9 \pm 0.5 \pm 0.8) \times 10^{-8}$	LHCb
$D^0 \to K^+K^-\mu^+\mu^-$	FCNC, low-mass $\mu^+\mu^-$	$\sim 10^{-9}$	$(2.6 \pm 1.2 \pm 0.2 \pm 0.3) \times 10^{-8}$	LHCb
$D^0 \to \mu^+\mu^-$	FCNC	$10^{-13} \div 10^{-12}$	$< 7.6 \times 10^{-9}$	LHCb
$D^0 \to e^+e^-$	FCNC	$10^{-13} \div 10^{-12}$	$< 7.9 \times 10^{-8}$	Belle
$D^0 \to \upsilon\bar{\upsilon}$	Helicity suppressed	$\sim 10^{-30}$	$< 8.8 \times 10^{-5}$	Belle
$D^0 \to e^+\mu^-$	Lepton Flavour Violating	0	$< 1.6 \times 10^{-8}$	LHCb
$D^+ \to \pi^-\mu^+\mu^+$	Lepton Number Violating	0	$< 2.5 \times 10^{-8}$	LHCb
$D_s^+ \to \pi^-\mu^+\mu^+$	" "	0	$< 1.4 \times 10^{-7}$	LHCb
$D^+ \to \pi^-/K^- e^+e^+$	" "	0	$< 1.2\ /\ 0.6 \times 10^{-6}$	BESIII

Decays with leptons: hot topic in beauty

Charm counterparts of $B \to K^{(*)}\mu\mu$

- No clean $m(\mu^+\mu^-)$ range in $D \to h(h)\mu^+\mu^-$
- Different angular observables useful in $D \to hh\mu^+\mu^-$



Lepton Flavour Universality Tests in charm?

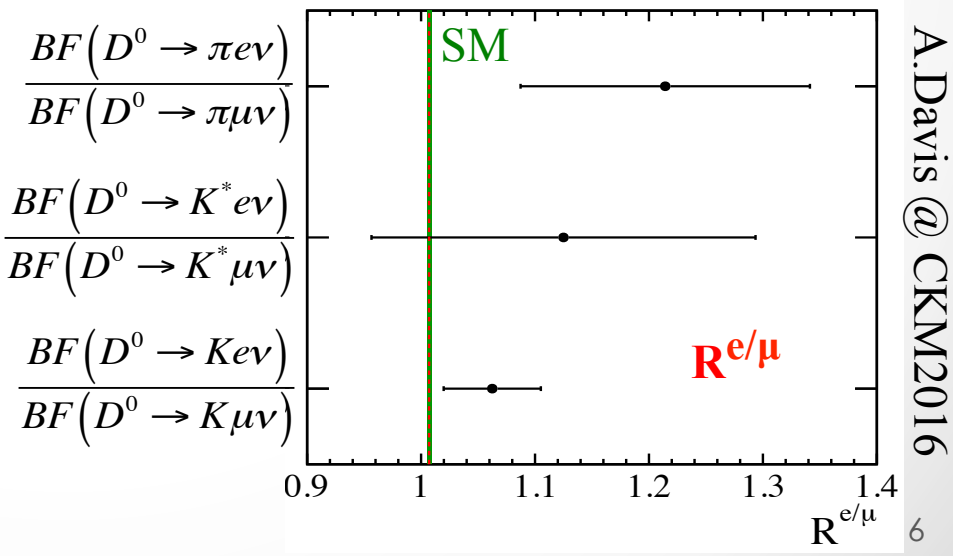
✓ $D \to h(h)e^+e^-$ and $D \to h(h)\mu^+\mu^-$ in resonance regions

✓ Leptonic decays, $R^{\tau/\mu}$

$$\frac{\mathcal{B}_{D_s^+ \to \tau^+\nu_\tau}}{\mathcal{B}_{D_s^+ \to \mu^+\nu_\mu}} = 9.98 \pm 0.52 \quad \text{SM: } 9.76$$

$$\frac{\mathcal{B}_{D^+ \to \tau^+\nu_\tau}}{\mathcal{B}_{D^+ \to \mu^+\nu_\mu}} = 3.21 \pm 0.64 \quad \text{SM: } 2.66$$

✓ Semileptonic decays, $R^{e/\mu}$



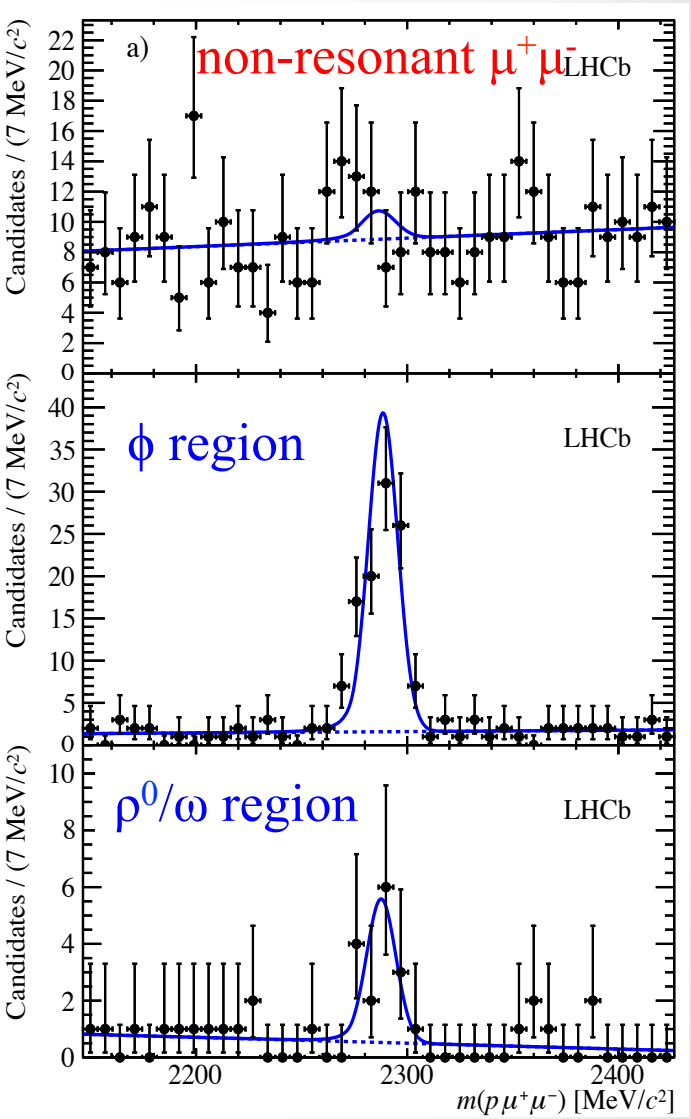
PRD97 091101 (2018) LHCb

Search for $\Lambda^+_c \to p\mu^+\mu^-$

- Rare decays overwhelmed with resonances: ρ^0/ω, $\phi \to \mu^+\mu^-$
- FCNC rates $\sim 10^{-9}$
  Resonances $\sim 10^{-6}$
- Look for signals in bins of $m(\mu^+\mu^-)$
- LHCb, 3 fb^{-1} of Run1 data
- Reference mode: $\Lambda^+_c \to p\phi(\to \mu^+\mu^-)$
- Non-resonant = ρ/ω, ϕ regions excluded

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

- 1000× better precision than BaBar for full $m(\mu^+\mu^-)$ PRD84 072006 (2011)

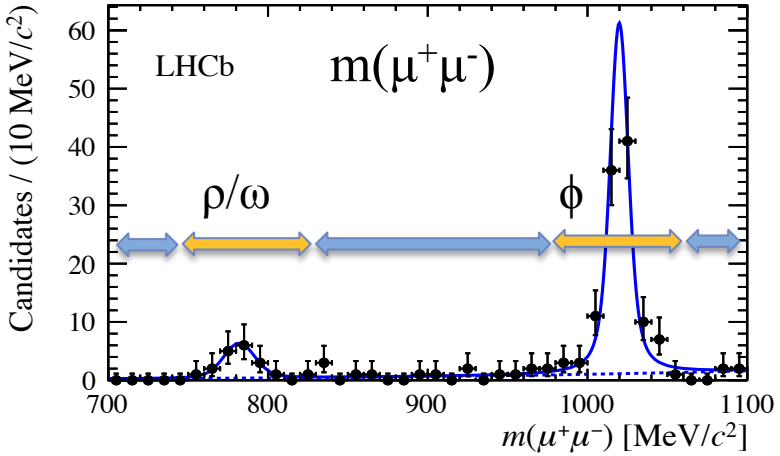


$m(p\mu^+\mu^-)$

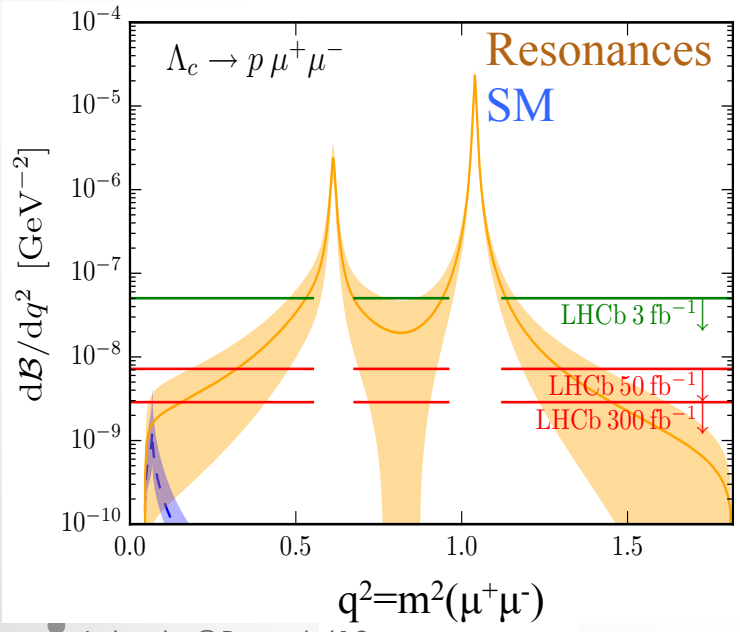
PRD97 091101 (2018) LHCb

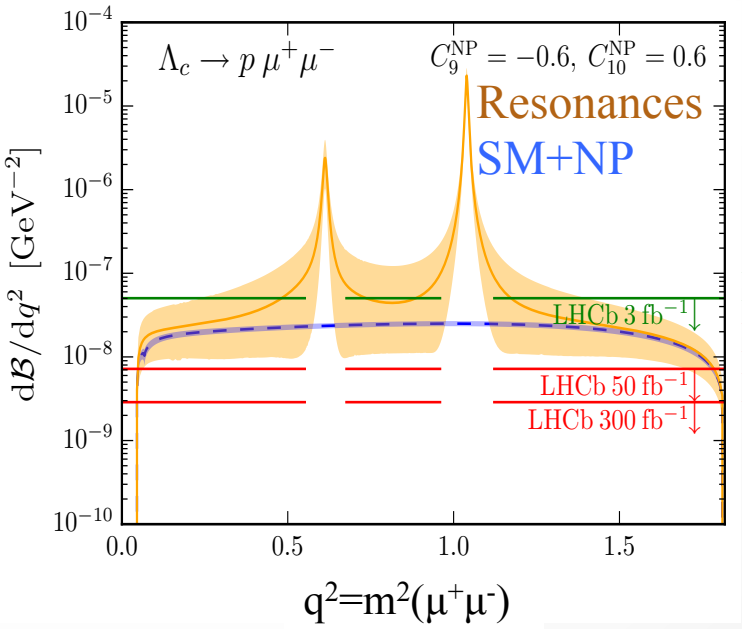
$\Lambda^+_c \to p\mu^+\mu^-$: issues & prospects

- $m(\mu^+\mu^-)$ for $\Lambda^+_c \to p\mu^+\mu^-$



- Resonance tails in non-resonant regions ⇨ BFs not clean observables





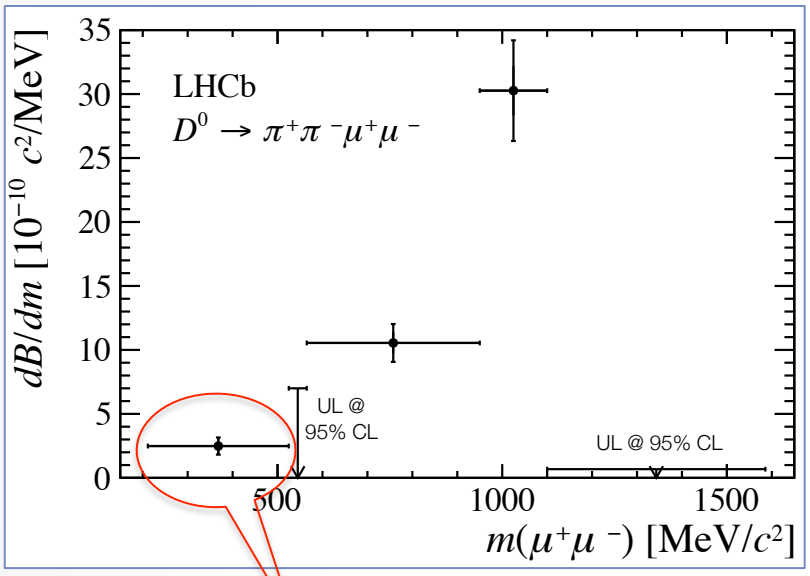
Meinel
PRD97 034511(2018)

LHCb Run1
LHCb Upgrade1
LHCb Upgrade2

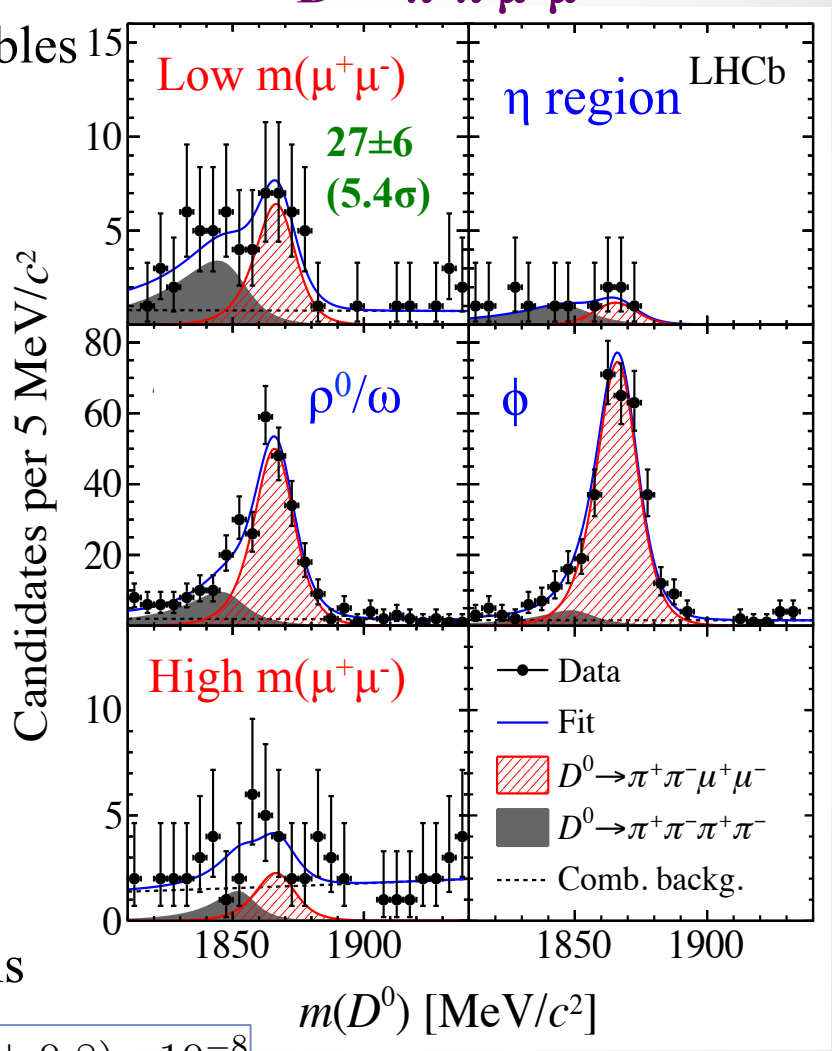
PRL119 181805 (2017) LHCb

$D^0 \to \pi^+\pi^-\mu^+\mu^-$, $K^+K^-\mu^+\mu^-$: first signal!

- 4-body decays: higher BFs, rich observables
- LHCb, 2 fb^{-1} Run1 data
- D^0 from $D^{*\pm} \to D^0\pi^\pm$ to suppress bkgd



- The rarest charm decay ever observed
- Agrees with SM. Contains resonance tails

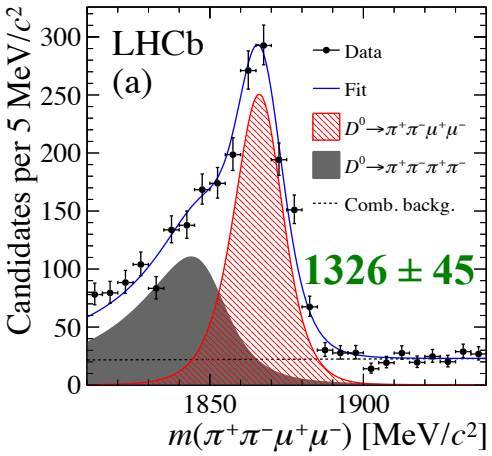


$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{\text{low } m(\mu^+\mu^-)} = (7.8 \pm 1.9 \pm 0.5 \pm 0.8) \times 10^{-8}$$

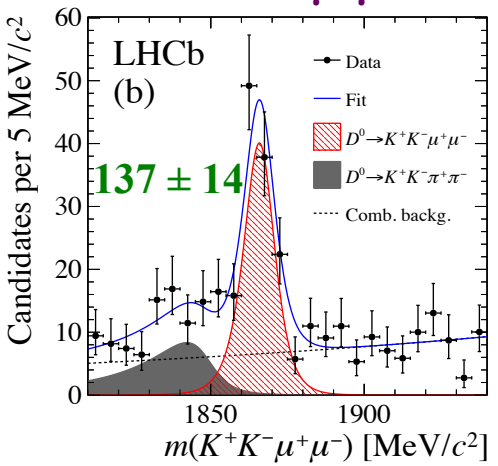
Asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-, K^+K^-\mu^+\mu^-$

- Exploit rich dynamics of 4-body
  ⇨ sensitive SM probes
- **A_{CP} A_{FB} A_φ** ~null in SM
  In NP ~O(%), also for resonances
  JHEP04 135 (2013) PRD98 035041 (2018)
- 2fb^{-1} Run1+ 3fb^{-1} Run2 data

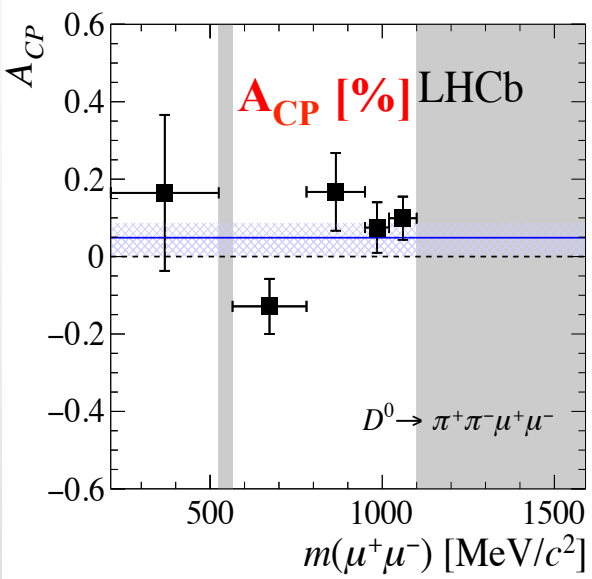
$D^0 \to \pi^+\pi^-\mu^+\mu^-$



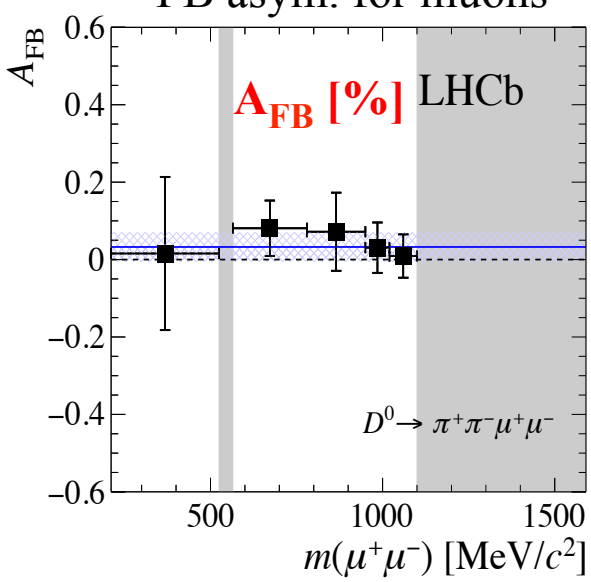
$D^0 \to K^+K^-\mu^+\mu^-$



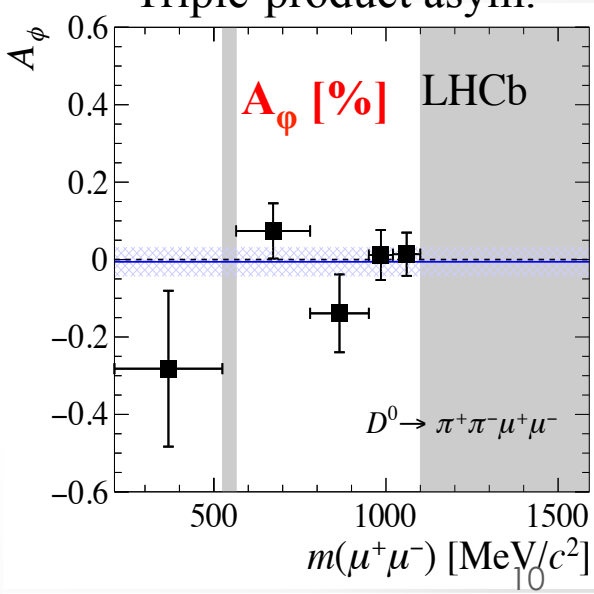
$D^0 \to \pi^+\pi^-\mu^+\mu^-$



FB asym. for muons



Triple-product asym.

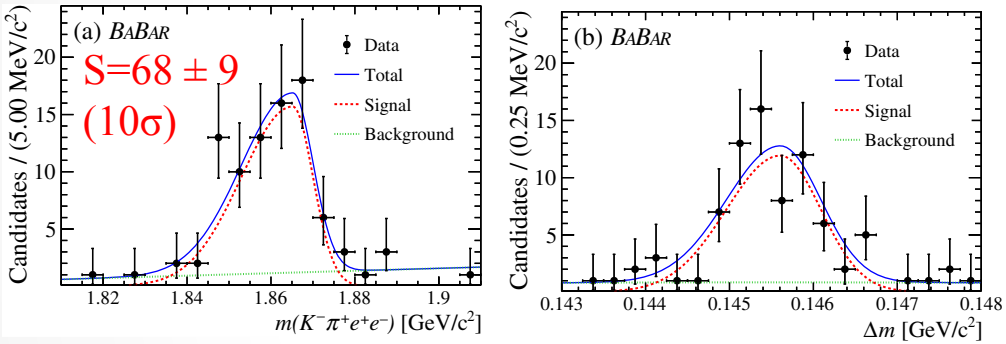


PRL 122 081802 (2019) BaBar

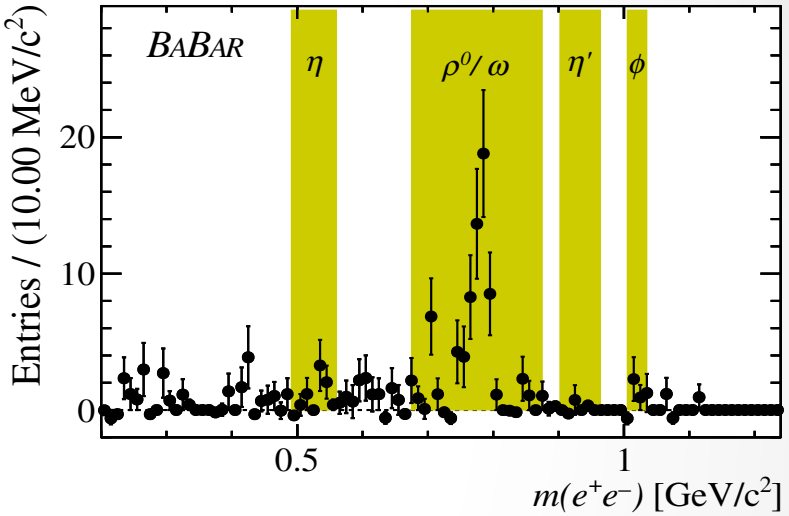
Observation of $D^0 \to K^-\pi^+e^+e^-$

- BaBar, full sample 468 fb^{-1}
- D^0 from $D^{*\pm} \to D^0\pi^\pm$ to suppress bkgd
- Fits to $m(D^0)$ and $\Delta m = m(D^*) - m(D^0)$

$m(D^0)$, Δm for $\rho/\omega \to e^+e^-$ region



Background-subtracted $m(e^+e^-)$



$$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)_{\rho/\omega} = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$$

- Consistent with SM and muon channel PLB 757 558 (2016) LHCb
- In non-resonant $m(e^+e^-)$: S =19 ± 7 (2.6 σ) (resonance tails subtracted)

$$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)_{NR} < 3.2 \times 10^{-6} \ @ \ 90\%\text{CL}$$

- Improves E791 upper limit of 4×10^{-4}

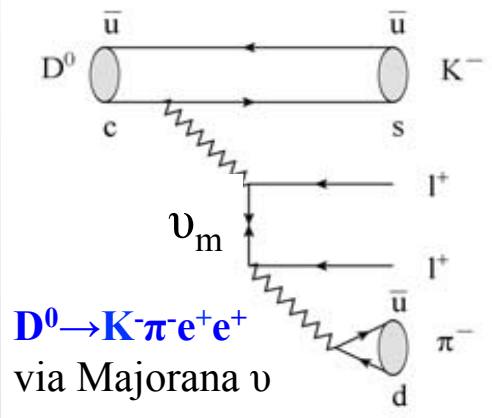
PRD 99 112002 (2019) BESIII

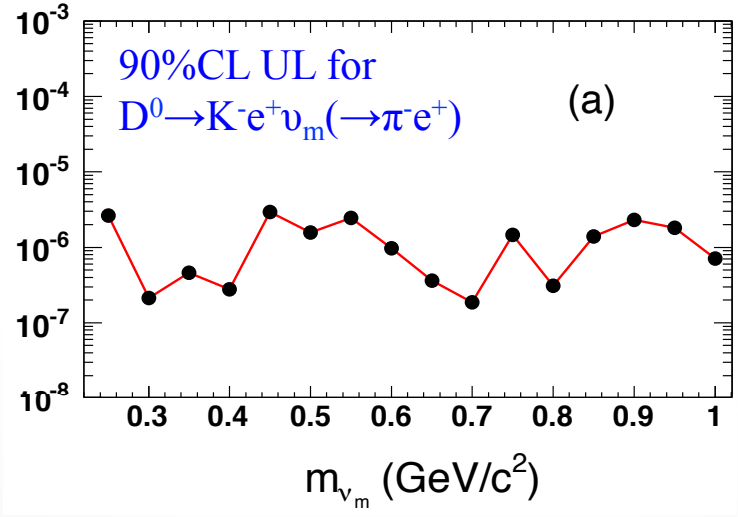
$D \to K\pi e^+e^+$ Lepton Number Violating decays

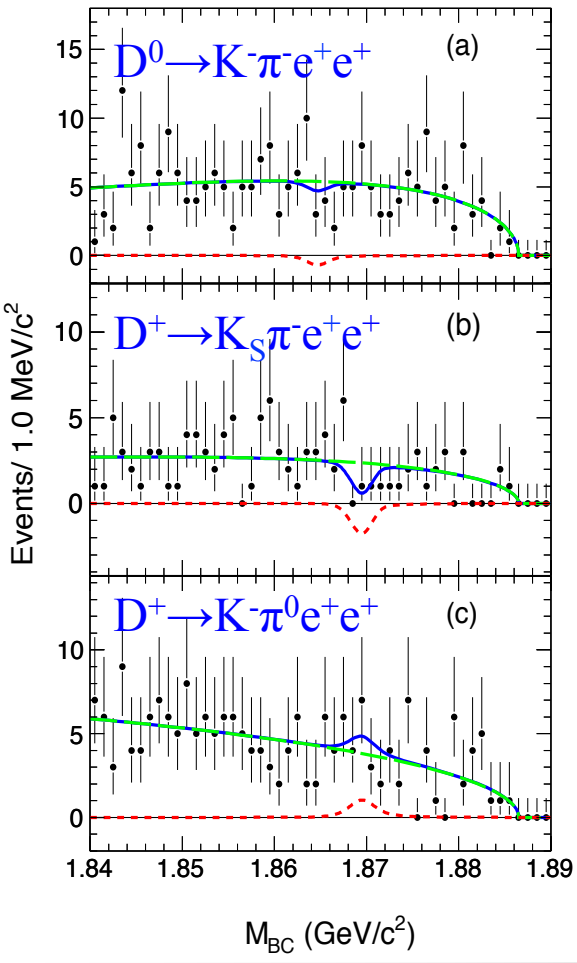
- Forbidden in SM ⇨ Signal = New Physics
- Rates with SUSY up to ~10^{-5}
- BESIII, 2.9 fb^{-1} @$D\bar{D}$ threshold

$$\mathcal{B}(D^0 \to K^-\pi^-e^+e^+) < 2.8 \times 10^{-6} \text{ @ } 90\%\text{CL}$$
$$\mathcal{B}(D^+ \to K_S\pi^-e^+e^+) < 3.3 \times 10^{-6} \text{ @ } 90\%\text{CL}$$
$$\mathcal{B}(D^+ \to K^-\pi^0e^+e^+) < 8.5 \times 10^{-6} \text{ @ } 90\%\text{CL}$$

- Search for Majorana neutrino $\upsilon_m \to \pi^-e^+$





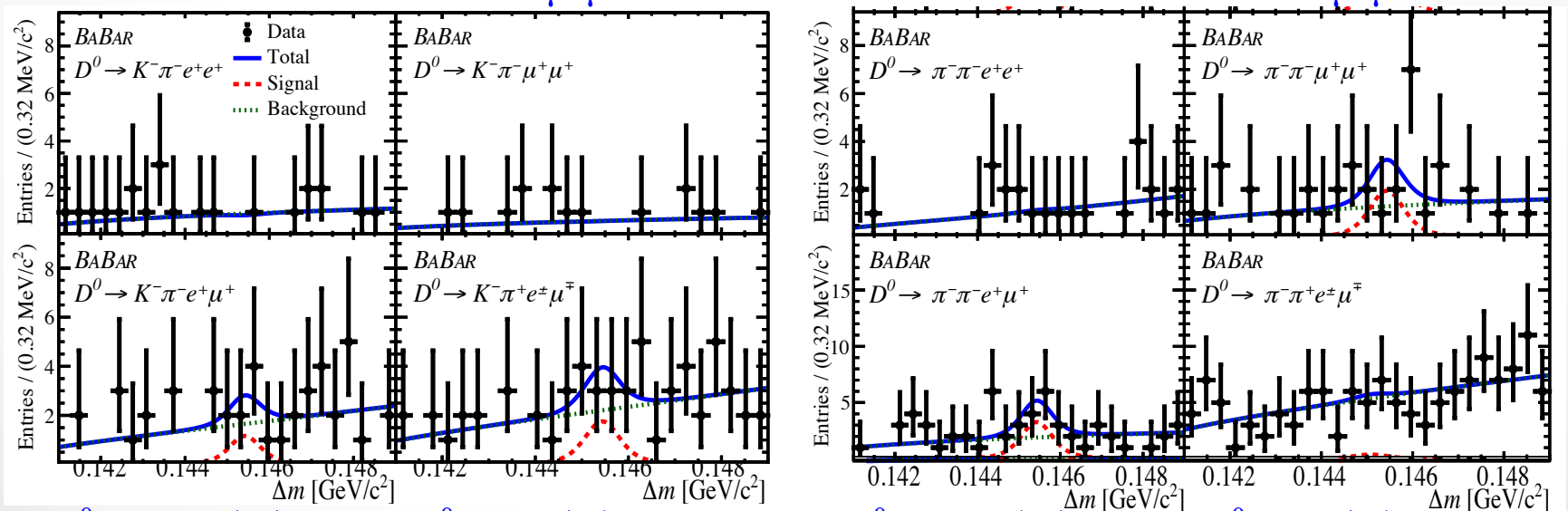


arXiv:1905.00608 BaBar

Lepton Number/Flavour Violating $D^0 \to hhll$

- **$D^0 \to hh\mu^+\mu^+$, hhe^+e^+, $hhe^+\mu^+$, $hhe^+\mu^-$** where h=K,π
- Forbidden in SM. Rates with SUSY up to ~10^{-5}
- BaBar, full sample 468 fb^{-1}
- D^0 from $D^{*\pm} \to D^0\pi^\pm$ to suppress bkgd
- Fits to $\Delta m = m(D^*) - m(D^0)$ for $m(D^0)$ signal region

$D^0 \to K^-\pi^-e^+e^+$ $D^0 \to K^-\pi^-\mu^+\mu^+$ $D^0 \to \pi^-\pi^-e^+e^+$ $D^0 \to \pi^-\pi^-\mu^+\mu^+$



$D^0 \to K^-\pi^-e^+\mu^+$ $D^0 \to K^-\pi^+e^+\mu^-$ $D^0 \to \pi^-\pi^-e^+\mu^+$ $D^0 \to \pi^-\pi^+e^+\mu^-$

arXiv:1905.00608 BaBar

Lepton Number/Flavour Violating $D^0 \to hhll$

- Normalisation channels: $D^0 \to 4\pi$, $K^-\pi^+\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$

Decay mode $D^0 \to$	N_{sig} (candidates)	$\mathcal{B}$ $(\times 10^{-7})$	$\mathcal{B}$ 90% U.L. $(\times 10^{-7})$
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	$0.27 \pm 3.90 \pm 0.67$	9.1
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	$7.40 \pm 5.40 \pm 0.91$	15.2
$\pi^-\pi^-e^+\mu^+$	$12.42 \pm 5.30 \pm 1.45$	$15.4 \pm 6.59 \pm 1.85$	30.6
$\pi^-\pi^+e^\pm\mu^\mp$	$1.37 \pm 6.15 \pm 1.28$	$1.55 \pm 6.97 \pm 1.45$	17.1
$K^-\pi^-e^+e^+$	$-0.23 \pm 0.97 \pm 1.28$	$-0.38 \pm 1.60 \pm 2.11$	5.0
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	$-0.05 \pm 3.34 \pm 0.64$	5.3
$K^-\pi^-e^+\mu^+$	$3.87 \pm 3.96 \pm 2.36$	$5.84 \pm 5.97 \pm 3.56$	21.0
$K^-\pi^+e^\pm\mu^\mp$	$2.52 \pm 4.60 \pm 1.35$	$3.62 \pm 6.61 \pm 1.95$	19.0
$K^-K^-e^+e^+$	$0.30 \pm 1.08 \pm 0.41$	$0.43 \pm 1.54 \pm 0.58$	3.4
$K^-K^-\mu^+\mu^+$	$-1.09 \pm 1.29 \pm 0.42$	$-0.81 \pm 0.96 \pm 0.32$	1.0
$K^-K^-e^+\mu^+$	$1.93 \pm 1.92 \pm 0.83$	$1.93 \pm 1.93 \pm 0.84$	5.8
$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	$3.93 \pm 2.89 \pm 1.45$	10.0

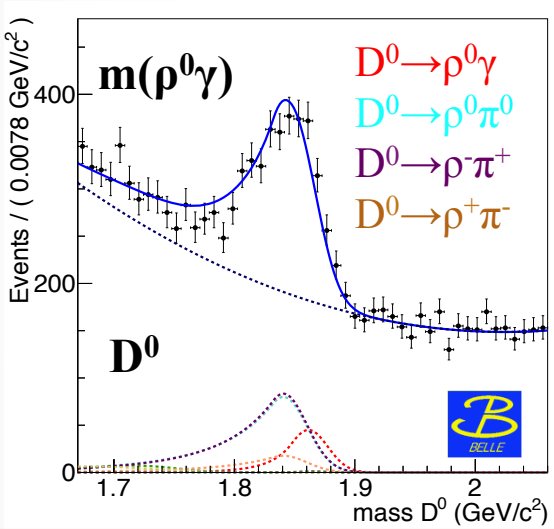
- No signal found. Upper limits of $(1 \div 30) \times 10^{-7}$
- $10 \div 10^3 \times$ more stringent limits than ones from E791 PRL86 3969 (2001)

PRL118 051801 (2017) Belle
PRD 93 051102 (2016) Belle

Decays with photons

- Theory problem: Long-distance rates ~ 10^3 × Short Distance
- Cleaner probes: CP asymmetry, γ polarisation
- Experimental problem: π^0 background

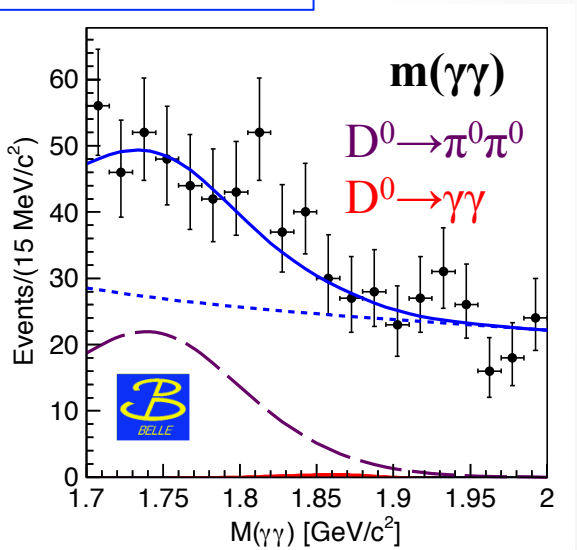
S. de Boer, G. Hiller
JHEP08, 101007 (2017)



$$\mathcal{B}(D^0 \to \rho^0\gamma) = (1.8 \pm 0.3 \pm 0.1) \times 10^{-5}$$

$$A_{CP}(D^0 \to \phi\gamma) = (-9.4 \pm 6.6 \pm 0.1)\%$$
$$A_{CP}(D^0 \to \rho^0\gamma) = (+5.6 \pm 15.1 \pm 0.6)\%$$

No CPV



$$\mathcal{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7} @\ 90\%\text{CL}$$

- LHCb competitive in $D^0 \to \rho\gamma$, $\varphi\gamma$
- Belle2 dominated: $D^0 \to \gamma\gamma$, $D^+ \to \rho^+\gamma$, $\Lambda_c \to p\gamma$
- LHCb Upgrade: improved calorimeter

Summary & Outlook

- Rare charm decays start entering the SM regime
- Probing rates down to 10^{-8}
- First signals!

  $BF(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{\text{low } m(\mu^+\mu^-)} = (7.8 \pm 1.9 \pm 0.5 \pm 0.8) \times 10^{-8}$
- First measurements for baryons:

  $BF(\Lambda^+_c \to p\mu^+\mu^-)|_{\text{non-resonant } \mu^+\mu^-} < 9.6 \times 10^{-8}$ @ 95% CL
- LFV/LNV decays $D^0 \to hhll$: UL~10^{-7}
- More than rates: A_{CP} A_{FB} A_φ for $D^0 \to h^+h^-\mu^+\mu^-$
- With more statistics charm will take "B-brother" path:

  angular analysis of $D^0 \to h^+h^-\mu^+\mu^-$, photon polarisation
- Ongoing with Run2 LHCb data:

  $D^0 \to \rho\gamma$, $\varphi\gamma$, $D_{(s)}^+ \to K/\pi\, l^+l^-$, $\Lambda^+_c \to p\mu^+\mu^-$, $D^0 \to l^+l^-$

  $D_{(s)}^+ \to K/\pi\, e^+\mu^-$

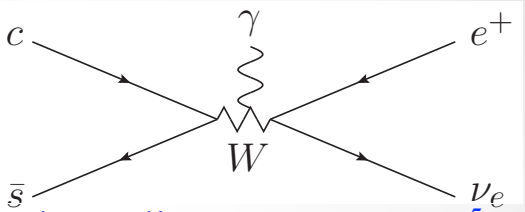
Backups

-

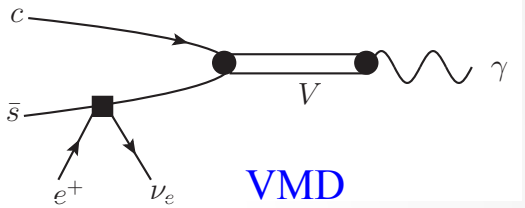
PRD 95 071102 (2017) BESIII
PRD 99 072202 (2019) BESIII

Search for $D_{(s)}^{+} \to \gamma e^{+} \upsilon$

- Unlike $D_{(s)} \to e^{+} \upsilon$, no helicity suppression
- BESIII, 2.9fb^{-1}@D$\bar{\text{D}}$ and 3.2fb^{-1}@$D_s D_s^{*}$ threshold
- Double Tag technique
- Photons with E_γ>10 MeV
- Signal identified with $U_{miss} = E_{miss} - |\vec{p}_{miss}|$

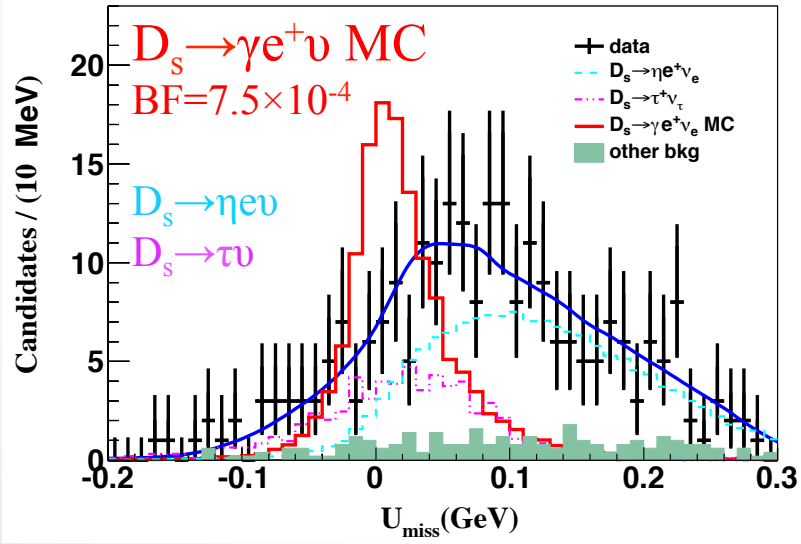


Short-distance rate ~10^{-5}

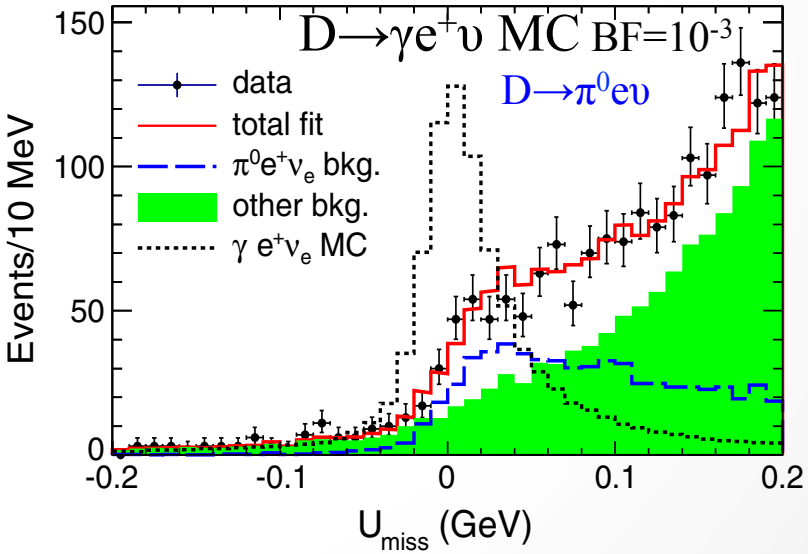


VMD

Long-distance ~$10^{-4} \div 10^{-3}$



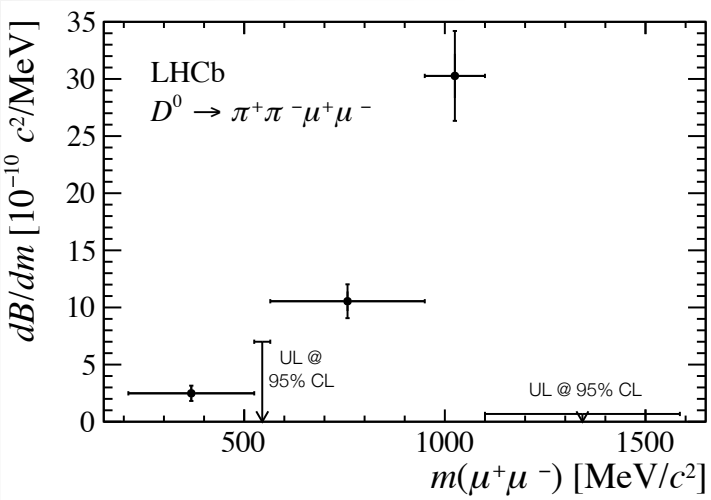
$\mathcal{B}(D_s^+ \to \gamma e^+ \nu) < 1.3 \times 10^{-4}$@ 90%CL

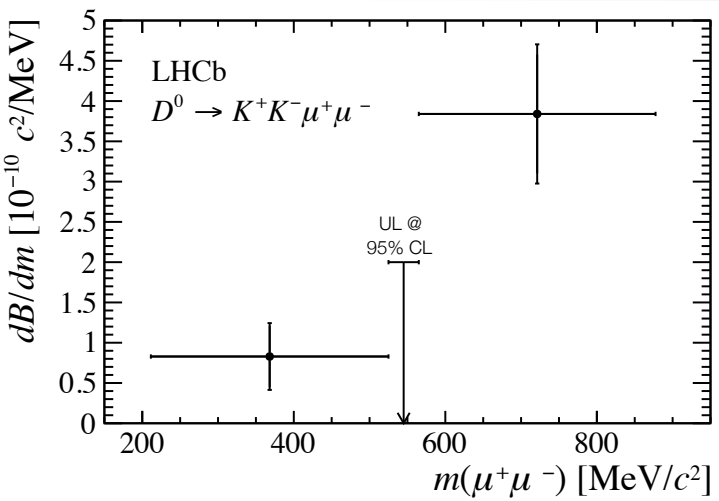


$\mathcal{B}(D^+ \to \gamma e^+ \nu) < 3.0 \times 10^{-5}$@ 90%CL

PRL 119 181805 (2017)

$D^0 \to \pi^+\pi^-\mu^+\mu^-, K^+K^-\mu^+\mu^-$

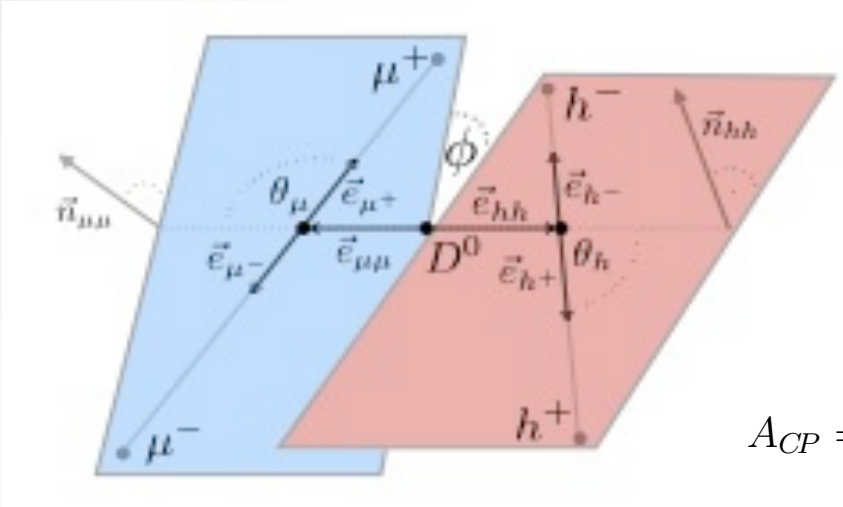




$D^0 \to \pi^+\pi^-\mu^+\mu^-$			
$m(\mu^+\mu^-)$ region	[MeV/c^2]	Yield	$\mathcal{S}$
Low mass	< 525	27 ± 6	5.4σ
η	525–565	5 ± 3	2.5σ
ρ^0/ω	565–950	208 ± 17	18σ
ϕ	950–1100	312 ± 20	23σ
High mass	> 1100	9 ± 6	1.6σ
$D^0 \to K^+K^-\mu^+\mu^-$			
$m(\mu^+\mu^-)$ region	[MeV/c^2]	Yield	$\mathcal{S}$
Low mass	< 525	5 ± 3	3.1σ
η	525–565	–	–
ρ^0/ω	> 565	29 ± 5	8.1σ

- Total BFs: $\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7}$,
  $\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}$.

Asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-, K^+K^-\mu^+\mu^-$

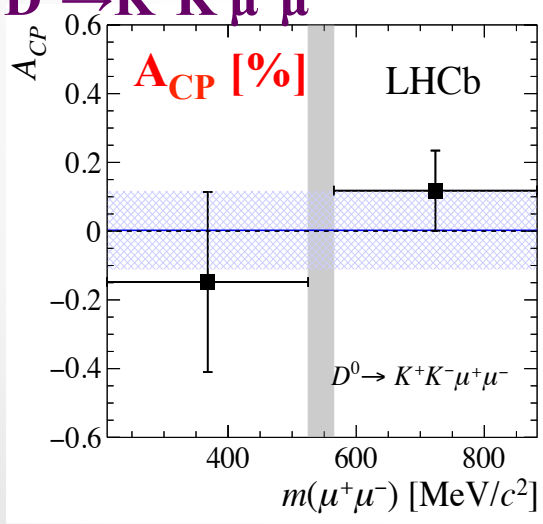


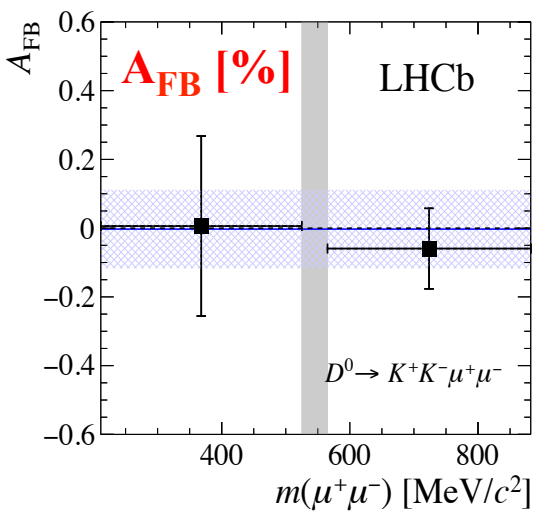
$$A_{\rm FB} = \frac{\Gamma(\cos\theta_\mu > 0) - \Gamma(\cos\theta_\mu < 0)}{\Gamma(\cos\theta_\mu > 0) + \Gamma(\cos\theta_\mu < 0)}$$

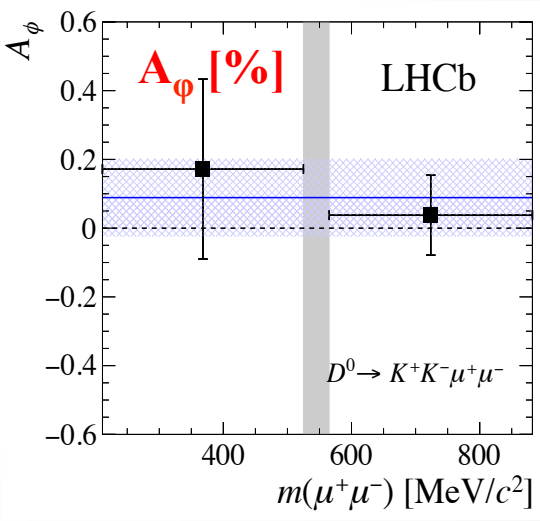
$$A_\phi = \frac{\Gamma(\sin 2\phi > 0) - \Gamma(\sin 2\phi < 0)}{\Gamma(\sin 2\phi > 0) + \Gamma(\sin 2\phi < 0)}$$

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

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

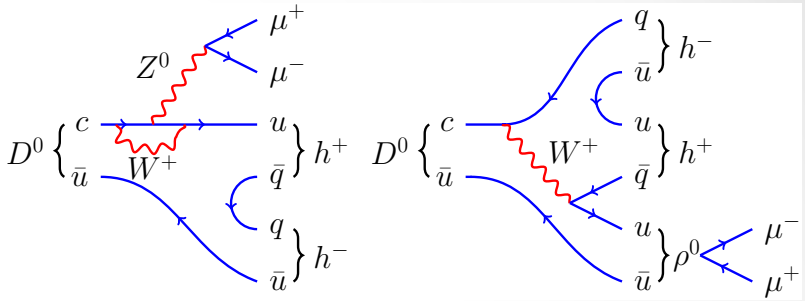






$D^0 \to \pi^+\pi^-\mu^+\mu^-, K^+K^-\mu^+\mu^-$

- 2/fb Run1+ 3/fb Run2



$m(\mu^+\mu^-)$ [MeV/c^2]	Efficiency-weighted yields			Signal asymmetries		
	Signal	Misid. back.	Comb. back.	A_{CP} [%]	$A_{\rm FB}$ [%]	A_ϕ [%]
			$D^0 \to \pi^+\pi^-\mu^+\mu^-$			
< 525	90 ± 17	233 ± 25	108 ± 22	$17 \pm 20 \pm 2$	$2 \pm 20 \pm 2$	$-28 \pm 20 \pm 2$
525–565	–	–	–	–	–	–
565–780	326 ± 23	253 ± 24	145 ± 21	$-12.9 \pm 7.1 \pm 0.7$	$8.1 \pm 7.1 \pm 0.7$	$7.4 \pm 7.1 \pm 0.7$
780–950	141 ± 14	159 ± 15	89 ± 14	$17 \pm 10 \pm 1$	$7 \pm 10 \pm 1$	$-14 \pm 10 \pm 1$
950–1020	244 ± 16	63 ± 13	43 ± 9	$7.5 \pm 6.5 \pm 0.7$	$3.1 \pm 6.5 \pm 0.6$	$1.2 \pm 6.4 \pm 0.5$
1020–1100	258 ± 14	33 ± 9	44 ± 9	$9.9 \pm 5.5 \pm 0.7$	$0.9 \pm 5.6 \pm 0.7$	$1.4 \pm 5.5 \pm 0.6$
> 1100	–	–	–	–	–	–
Full range	1083 ± 41	827 ± 42	579 ± 39	$4.9 \pm 3.8 \pm 0.7$	$3.3 \pm 3.7 \pm 0.6$	$-0.6 \pm 3.7 \pm 0.6$
			$D^0 \to K^+K^-\mu^+\mu^-$			
< 525	32 ± 8	5 ± 13	124 ± 20	$-33 \pm 26 \pm 4$	$13 \pm 26 \pm 4$	$9 \pm 26 \pm 3$
525–565	–	–	–	–	–	–
> 565	74 ± 9	39 ± 7	48 ± 8	$13 \pm 12 \pm 1$	$1 \pm 12 \pm 1$	$22 \pm 12 \pm 1$
Full range	110 ± 13	49 ± 12	181 ± 19	$0 \pm 11 \pm 2$	$0 \pm 11 \pm 2$	$9 \pm 11 \pm 1$

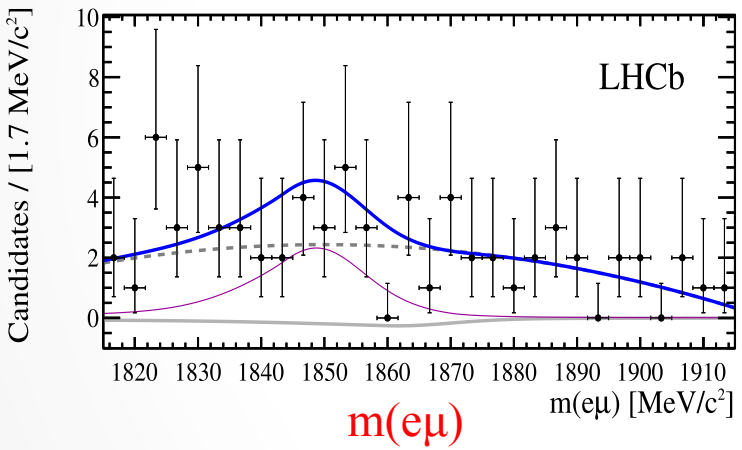
PLB 754 (2016) 167 LHCb

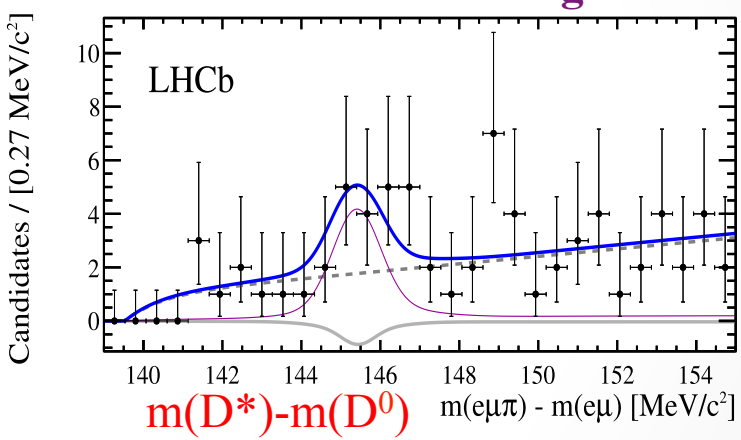
Search for LFV decays $D^0 \to e^+\mu^-$

- Forbidden in SM ⇨ Signal = New Physics
- With SUSY ~ 10^{-6}. With multiple Higgs doublets: < 7×10^{-10}
- 3 fb^{-1} of Run1 data
- D^0 from $D^{*\pm} \to D^0\pi^\pm$ to suppress bkgd

$D^0 \to e\mu$ signal

$D^0 \to \pi^+\pi^-$ background





$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3\ (1.6) \times 10^{-8}\ @90\ (95)\%\ \text{C.L.}$$

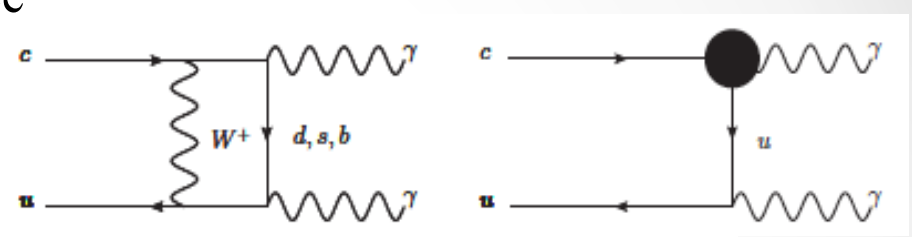
- 10× better precision than Belle PRD 81 091102 (2010)

PRD 93, 051102 (2016) Belle

$D^0 \to \gamma\gamma$

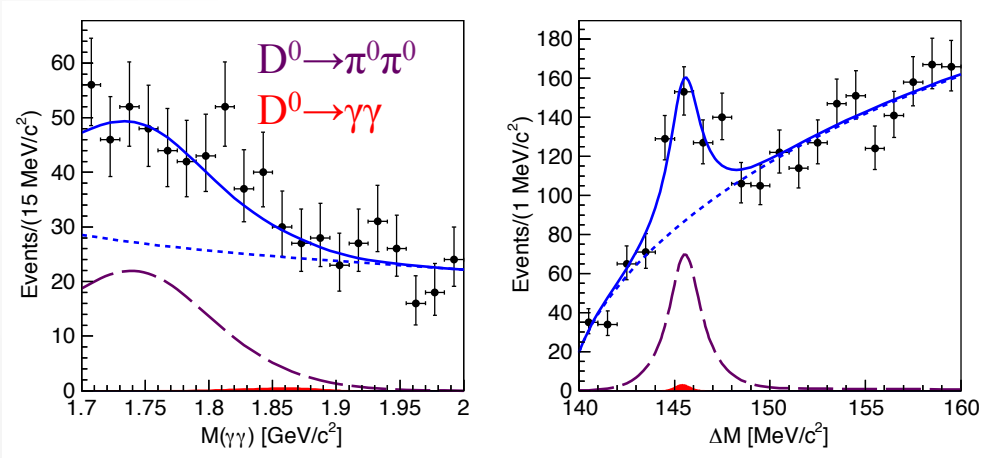
- Long Distance: vector meson dominance
- With SUSY: increased up to 6×10^{-6}

- Use tagged events: $D^{*\pm} \to D^0\pi^\pm$
- Reference mode: $D^0 \to K_s\pi^0$
- Background from $D^0 \to \pi^0\pi^0$ (BF~10^{-3})

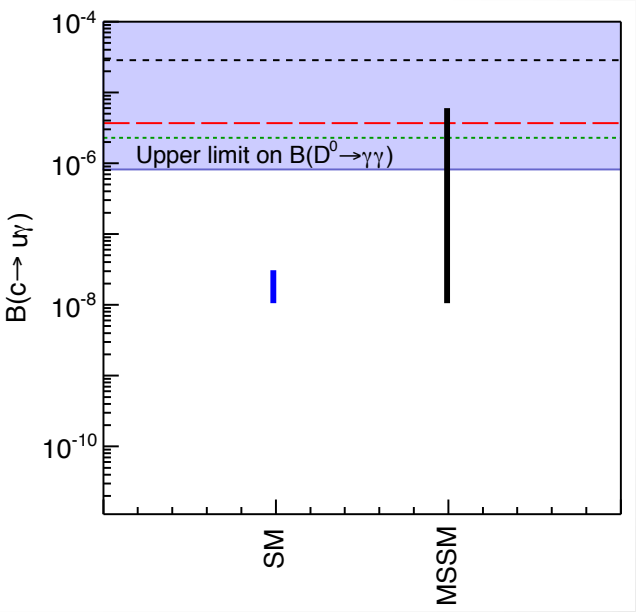


$$\mathrm{BR}_{\mathrm{SD}}^{\text{2-loop}}(D^0 \to \gamma\gamma) \simeq (3.6\text{–}8.1) \times 10^{-12}$$

$$\mathrm{BR}_{\mathrm{SM}}^{\mathrm{LD}}(D^0 \to \gamma\gamma) \sim (1\text{–}3) \times 10^{-8}$$



$$\mathcal{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$$



Plenty of charm produced

collider	Exp	√s	Lumi	σ(cc̄)	N(cc̄)
hadron	prompt charm				
	LHCb	7, 8 TeV	3/fb	1.4 mb	**4×10^{12}**
		13 TeV	6/fb	2.6 mb	**16×10^{12}**
	CDF	2 TeV	10/fb	0.1 mb	**2.3×10^{11}**
e^+e^-	B-Factories			continuum charm	
	Belle	10.6 GeV	1000/fb	1.3 nb	**1.3×10^{9}**
	BaBar		550/fb		**0.7×10^{9}**
	Charm Factories @DD̄ threshold				
	BESIII	3.7 GeV	3/fb	3 nb	**20×10^{6}**
	Cleo-c		0.8/fb		**5×10^{6}**