Rare Charm Decays
Summary of experimental results

Anže Zupanc

BELLE

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Belle II

Institut "Jožef Stefan", Ljubljana, Slovenija

Theory of rare charm decays

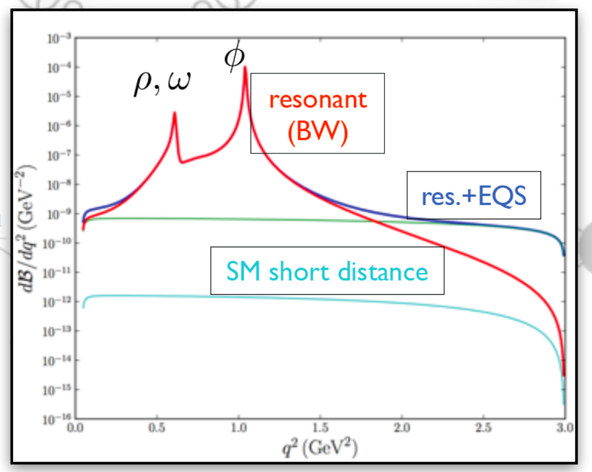
$$\mathcal{H}_{\text{eff}} = \lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s + \lambda_b \mathcal{H}^{\text{peng}}$$

$$\mathcal{H}^{q=d,s} = -\frac{4G_F}{\sqrt{2}}(C_1 \mathcal{O}_1^q + C_2 \mathcal{O}_2^q)$$

$$\mathcal{H}^{\text{peng}} = -\frac{4G_F}{\sqrt{2}} \sum_{i=3,\ldots,10} C_i \mathcal{O}_i$$

$$\mathcal{O}_1^q = (\bar{q}_L^\alpha \gamma^\mu c_L^\alpha)(\bar{u}_L^\beta \gamma_\mu q_L^\beta)$$
$$\mathcal{O}_2^q = (\bar{q}_L^\alpha \gamma^\mu c_L^\beta)(\bar{u}_L^\beta \gamma_\mu q_L^\alpha)$$

$$\mathcal{O}_7 = \frac{em_c}{(4\pi)^2}\,\bar{u}\sigma_{\mu\nu}P_R c\,F^{\mu\nu}\,,$$
$$\mathcal{O}_8 = \frac{gm_c}{(4\pi)^2}\,\bar{u}\sigma_{\mu\nu}P_R c\,G^{\mu\nu}\,,$$
$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}\,(\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \ell)\,,$$
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}\,(\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$



See S. Fajfer's theoretical review of rare charm decays earlier today.

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$$\mathcal{H}^{q=d,s} = -\frac{4G_F}{\sqrt{2}}\left(C_1 \mathcal{O}_1^q + C_2 \mathcal{O}_2^q\right) \qquad \mathcal{H}^{\text{peng}} = -\frac{4G_F}{\sqrt{2}} \sum_{i=3,\ldots,10} C_i \mathcal{O}_i$$

$$\mathcal{O}_1^q = (\bar{q}_L^\alpha \gamma^\mu c_L^\alpha)(\ldots)$$

$$\mathcal{O}_2^q = (\bar{q}_L^\alpha \gamma^\mu c_L^\beta)(\ldots)$$

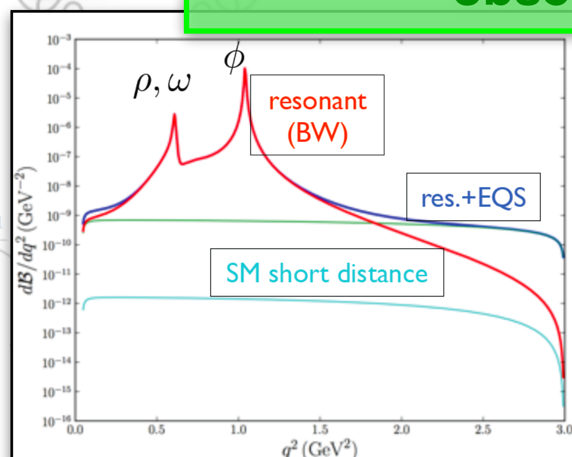
$$\mathcal{O}_7 = \frac{e m_c}{(4\pi)^2} \bar{u}\sigma_{\mu\nu} P_R c F^{\mu\nu},$$

$$\mathcal{O}_8 = \frac{g m_c}{(4\pi)^2} \bar{u}\sigma_{\mu\nu} P_R c G^{\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \ell),$$

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

Probing the beyond-Standard-Model Physics processes via measurements of branching fractions, CP asymmetries, and other observables.



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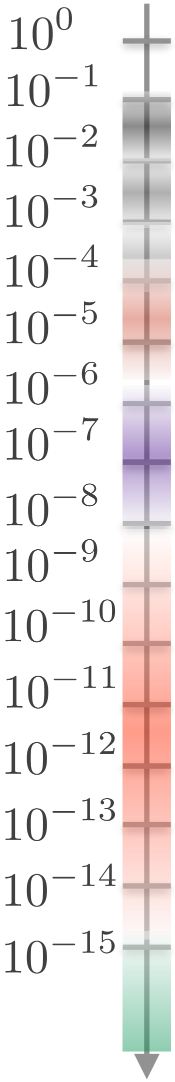
Outline



Overview of measurements of selected rare decays

Cabibbo favored

Singly Cabibbo suppresed

Doubly Cabibbo suppresed

Radiative

$D^0 \to \overline{K}^{*0}\gamma,\ \phi\gamma,\ \omega\gamma,\ \rho^0\gamma$

Vector Meson Dominance

$D^0 \to \rho V(\to \ell\ell),\ \pi^-\pi^+ V(\to \ell\ell)$

$D^0 \to \phi V(\to \ell\ell),\ K^-K^+ V(\to \ell\ell)$

$D^0 \to \gamma\gamma$

$D^0 \to \overline{K}^{*0} V(\to \ell\ell),\ K^+\pi^- V(\to \ell\ell)$

Flavour Changing Neutral Current

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

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

$D \to h\ell^+\ell^-$

$D \to hh'\ell^-\ell^+$

$D \to V\ell^+\ell^-$

Lepton/Baryon Number Violating

Lepton Flavor Violating

$D \to (h)e^-\mu^+$

$D \to (h)\ell^+\ell^+$

Experimental requirements

- Large samples of charm
- Good background rejection and high signal efficiency
  - excellent particle identification
  - large boost ➜ displaced vertex
  - excellent reconstruction of photons and neutral pions
  - hermeticity of detector

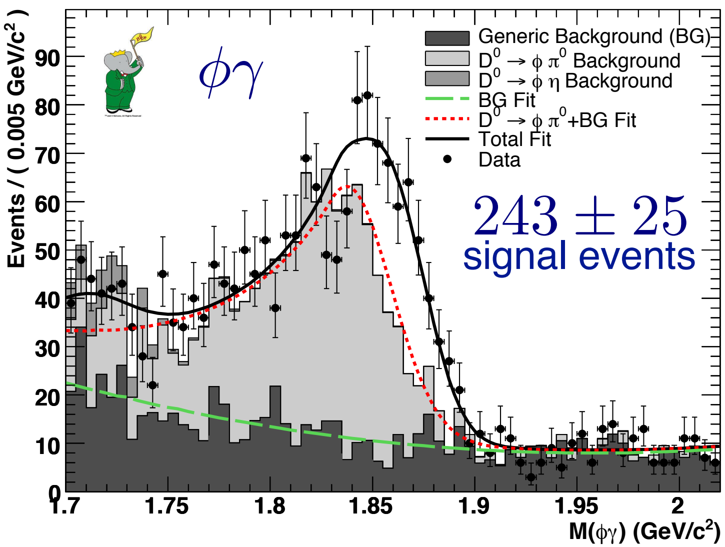
Available samples

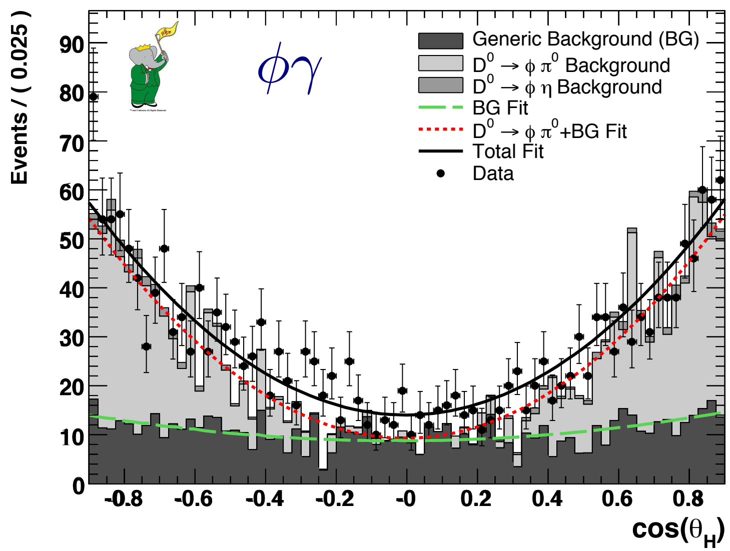
Experiment	Sample	N	efficiency
LHCb, CMS	pp @ 7 TeV	10^{12}	< 0.5%
DØ, CDF	$p\bar{p}$ @ 2 TeV	10^{11}	< 0.5%
BESIII, CLEO	e^+e^- @ 3.77 GeV e^+e^- @ 4.18 GeV	10^7	~10-30%
BaBar, BELLE	e^+e^- @ 10.6 GeV	10^9	~5-10%

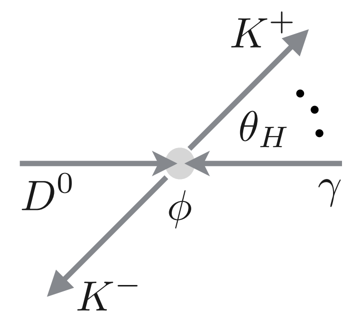
$D^0 \to V\gamma$

BaBar $387\ fb^{-1}$ @ $\Upsilon(4S)$
PRD78,071101(2008)

- Use a D* tag
- Large contamination from $D^0 \to V\pi^0,\ hh'\pi^0$
  - π^0 veto ➽ reject all γ's that can be used for a good π^0
  - extract signal from 2-dimensional fit to $m(V\gamma)$ and $\cos(\theta_H)$







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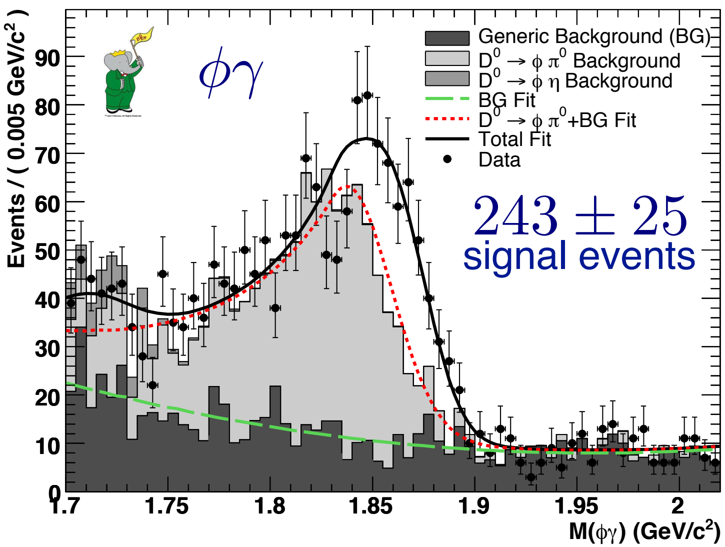

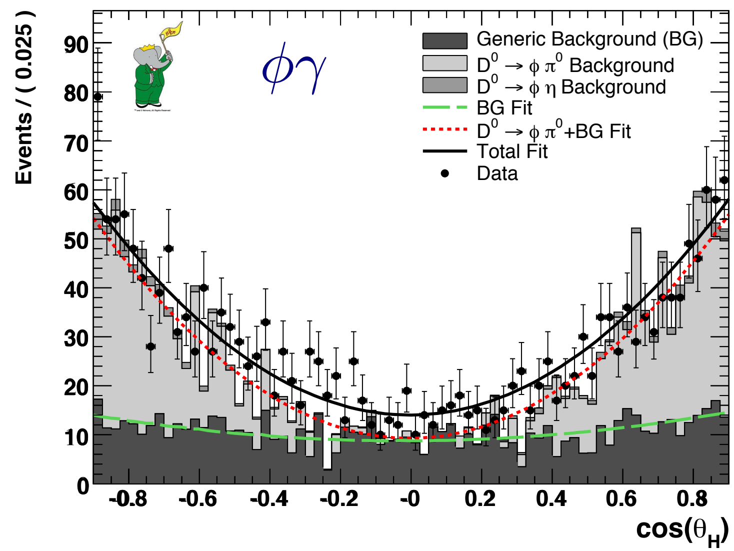

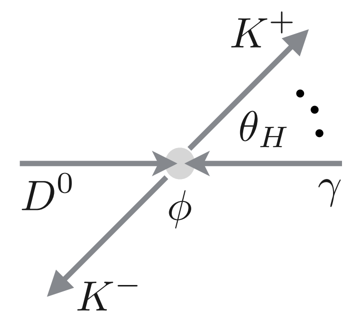

$$\begin{aligned}\mathcal{B}(D^0 \to \phi\gamma) &= (2.73 \pm 0.30 \pm 0.26) \times 10^{-5} \\ \mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) &= (3.22 \pm 0.20 \pm 0.27) \times 10^{-4}\end{aligned}$$

Dominated by Long Distance effects.

Not a New Physics search.

$D^0 \to V\gamma$

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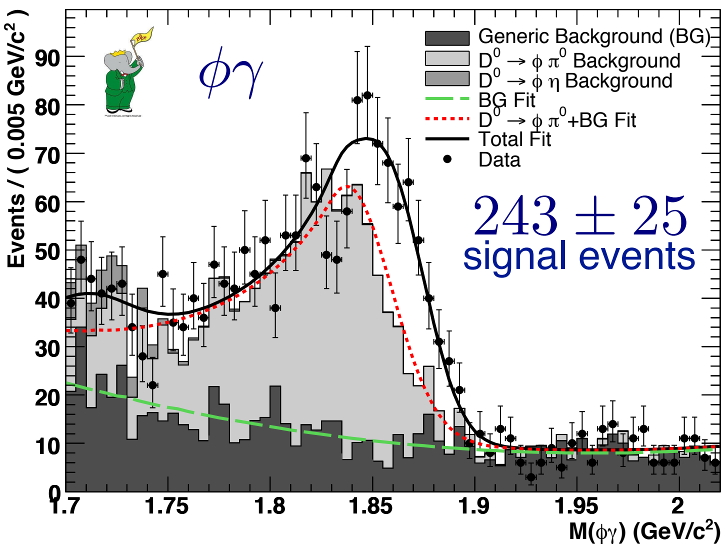

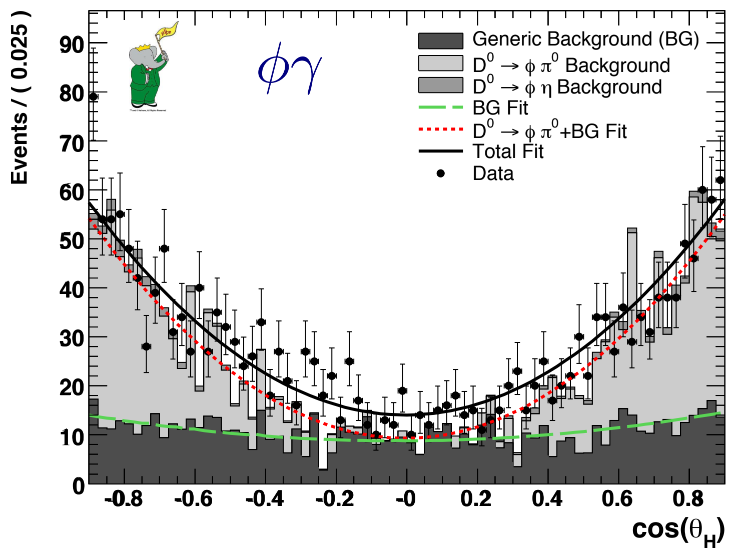

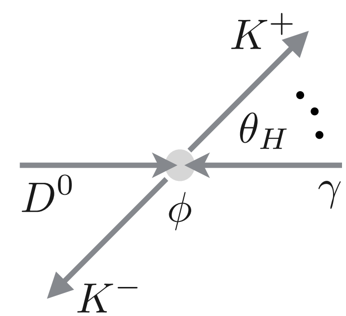

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Belle 78 fb^{-1} @ $\Upsilon(4S)$
PRL92,101803(2004)
$\mathcal{B}(D^0 \to \phi\gamma) = [2.60^{+0.70+0.15}_{-0.61-0.17}] \times 10^{-5}$

Cleo II 5 fb^{-1} @ $\Upsilon(4S)$
PRD58,92001(1998)
$\mathcal{B}(D^0 \to \omega(\rho^0)\gamma) < 2.4(2.4) \times 10^{-4}$@90% $C.L.$

$D^0 \to V\gamma$

BaBar 387 fb^{-1} @ $\Upsilon(4S)$

PRD78,071101(2008)

- Use a D* tag
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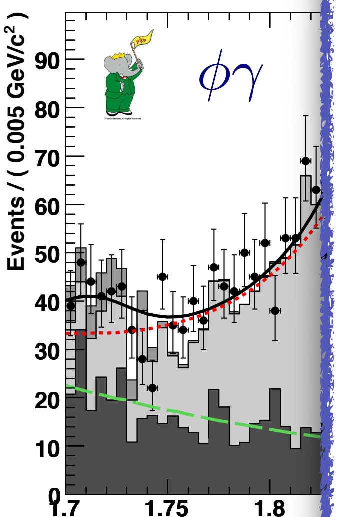
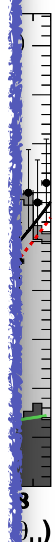
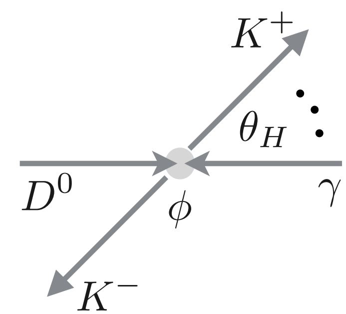
  - π^0 veto ➽ … 0
  - extract sig… os(θ_H)







In some SM extensions sizeable
CP asymmetry expected
in radiative charm decays:

$A_{CP}^{V\gamma} > 3\%$ ☛ signal of New Physics

PRL109,171801(2012); arXiv:1210.6546

see N. Košnik's talk later today (WG7@18:00)

$\mathcal{B}(D^0 \to \phi\gamma) = ($ …

$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = ($ …

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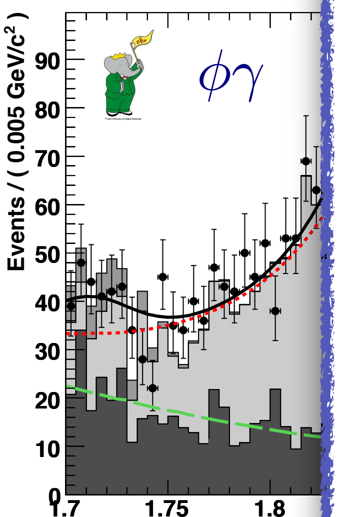
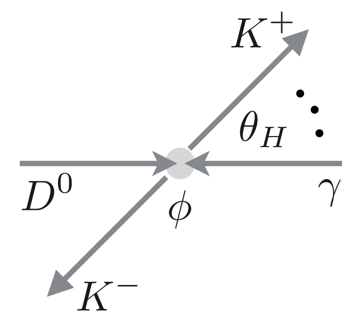
  - π^0 veto ➽ ... ^{0}
  - extract sig ... $\cos(\theta_H)$





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Belle II 50 ab^{-1} @ $\Upsilon(4S)$
estimating: $\sigma(A_{CP}^{\phi\gamma}) \sim 0.8\%$

Dominated by Long Distance effects.

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$D^0 \to \gamma\gamma$

BaBar $470 fb^{-1}$@$\Upsilon(4S)$
PRD85,091107(2012)

- Use a D* tag
- Normalisation to $D^0 \to K^0_S\pi^0$
- Measure main background as well $D^0 \to \pi^0\pi^0$
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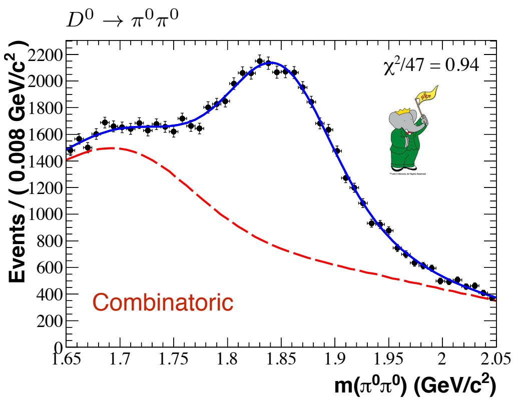

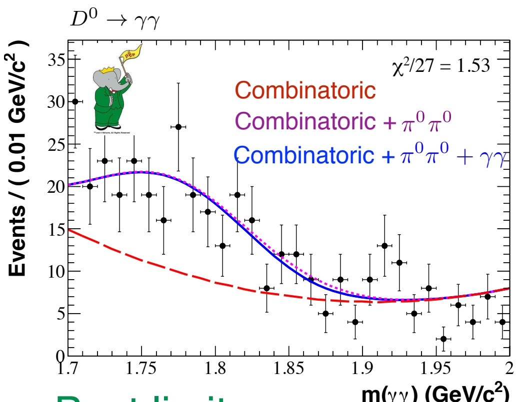

Best limit

$\mathcal{B}_{D^0\to\pi^0\pi^0} = (8.4 \pm 0.1 \pm 0.3)\cdot 10^{-4}$

$\mathcal{B}_{D^0\to\gamma\gamma} < 2.2\cdot 10^{-6}$ @ 90% $C.L.$

$D^0 \to \gamma\gamma$

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PRD85,091107(2012)

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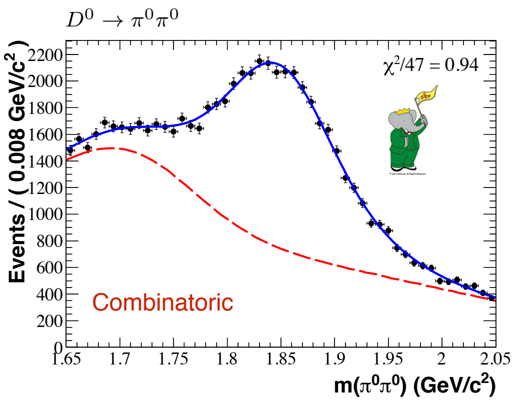

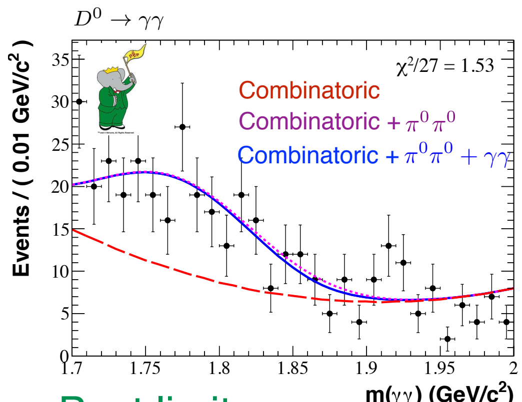

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BESIII $2.9\ fb^{-1}$ @ $\psi(3770)$

$\mathcal{B}_{D^0 \to \gamma\gamma} < 4.7 \cdot 10^{-6}$ @ 90% $C.L.$

arXiv:1208.4744

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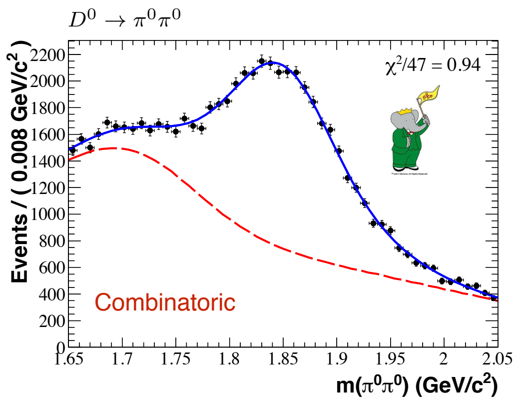

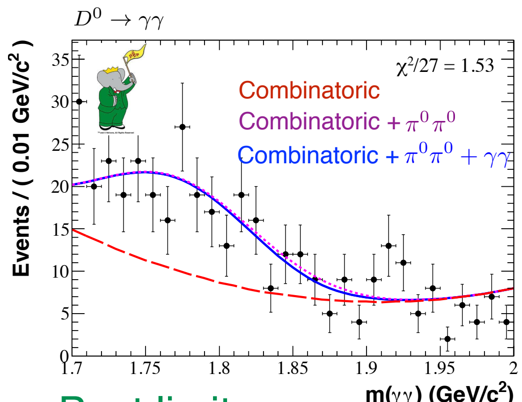

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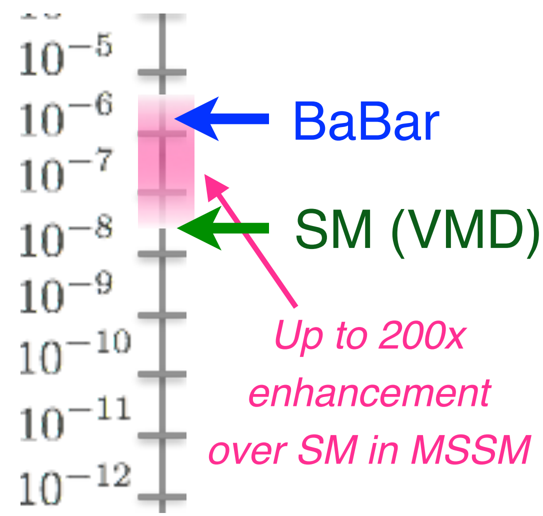

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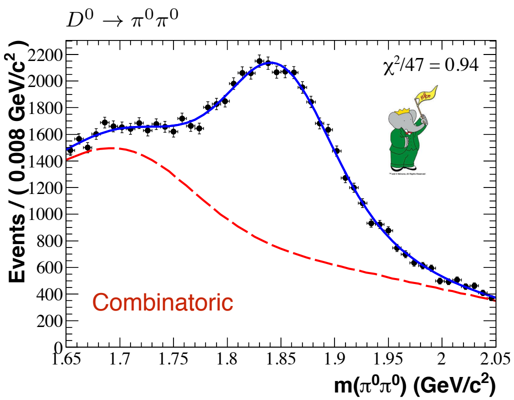

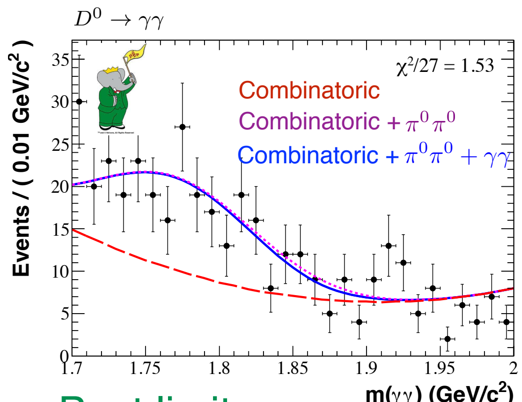

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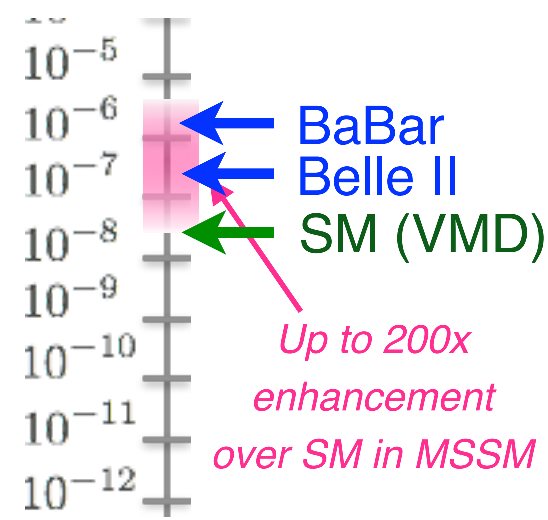
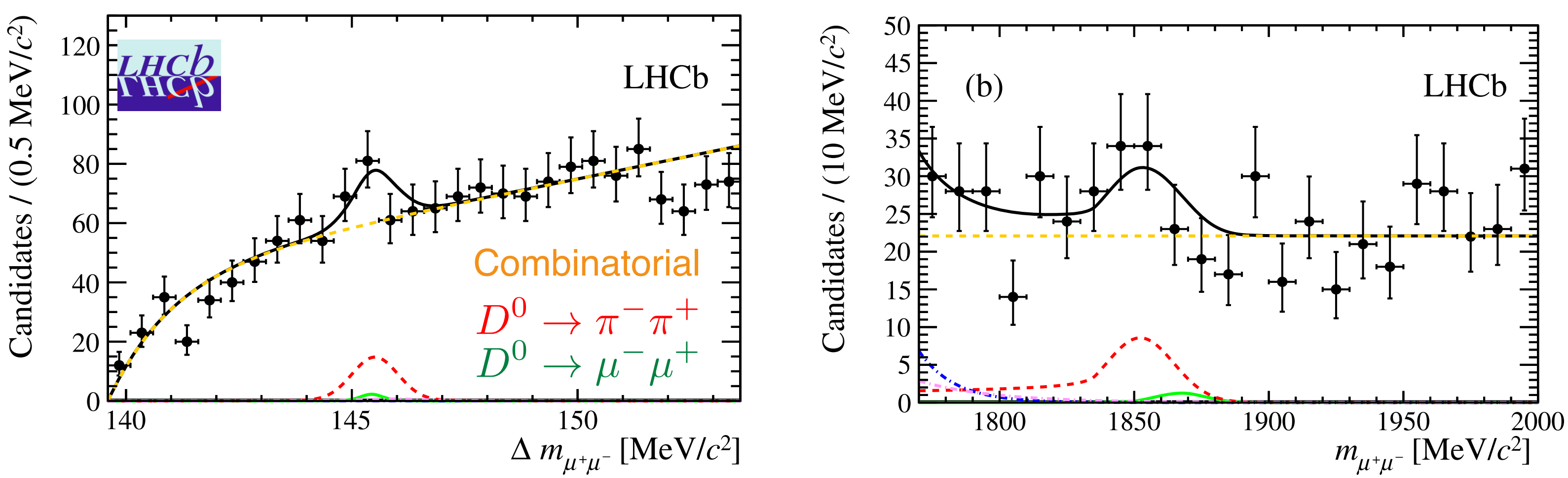


SM beyond the experimental reach, however NP parameter space is already being probed

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

LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB725,15(2013)

- Use a D* tag
- Normalization to $D^0 \to \pi^- \pi^+$
    - main physics background as well (double $\pi^\pm \to \mu^\pm$ mis-ID)
    - single $\pi^\pm \to \mu^\pm$ mis-ID probability estimated with $D^0 \to K^- \pi^+$
        - Double mis-ID $p(D^0 \to \pi^- \pi^+ \to \mu^- \mu^+) = (27.43 \pm 3.4 \pm 2.0) \times 10^{-6}$
    - Boosted-Decision-Tree trained to suppress combinatorial bkg.

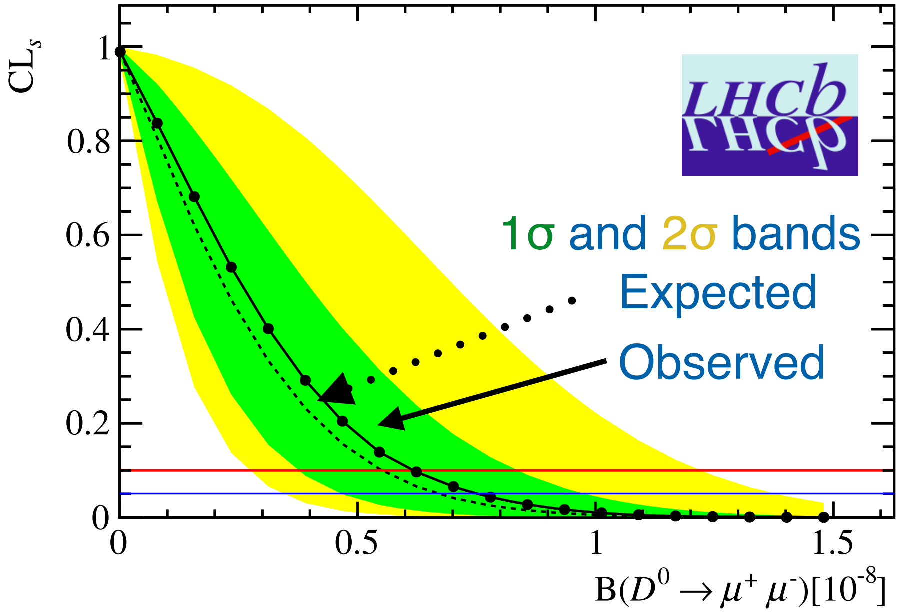


No significant signal is observed

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

LHCb 1 fb^{-1} @ 7 TeV
PLB725,15(2013)

U.L. set using CLs method



$\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2\ (7.6) \times 10^{-9}$ at 90% (95%) CL.

World's best

Upper Limits @ 90% C.L.

Belle PRD81,091102(2010)
$\mathcal{B}(D^0 \to \mu^-\mu^+) < 1.4 \times 10^{-7}$

CDF PRD82,091105(2010)
$\mathcal{B}(D^0 \to \mu^-\mu^+) < 2.1 \times 10^{-7}$

CMS PAS BPH-11-017
$\mathcal{B}(D^0 \to \mu^-\mu^+) < 5.4 \times 10^{-7}$

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

LHCb 1 fb^{-1} @ 7 TeV
PLB725,15(2013)

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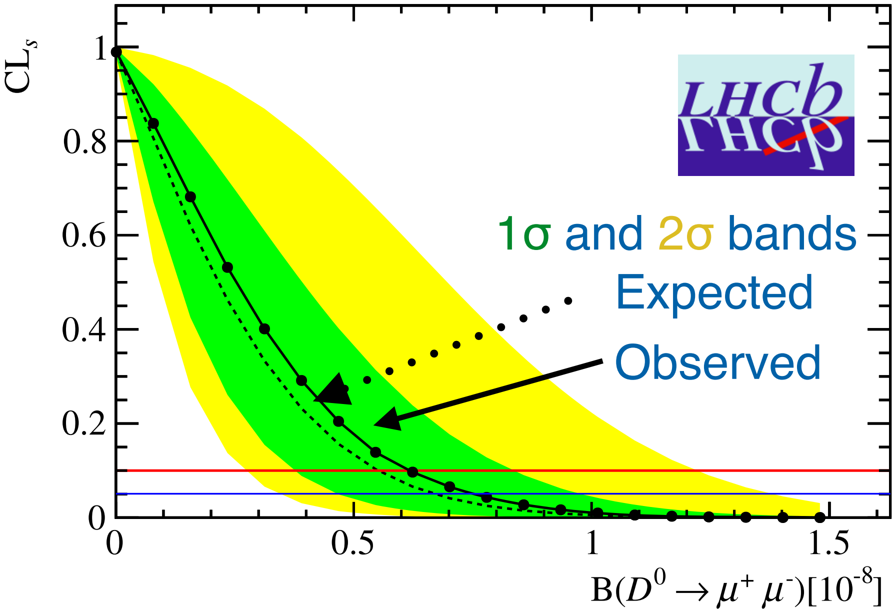

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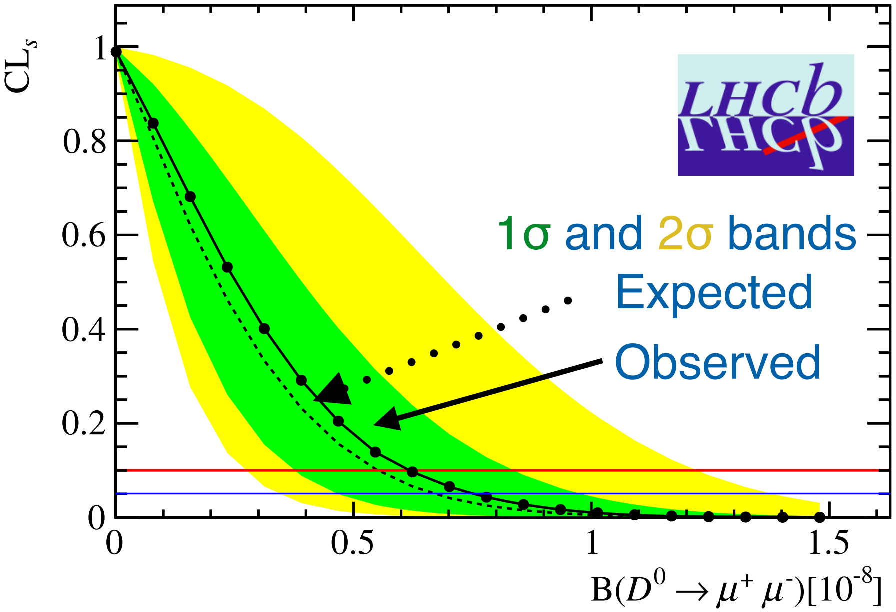
Experiments still ~100xSM
and ~10xNP predictions

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

LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB725,15(2013)

U.L. set using CLs method



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Upper Limits @ 90% C.L.

Experiments still ~100xSM and ~10xNP predictions

LHCb Upgrade
$50\ fb^{-1}$ @ $14\ TeV\,(2 \times \sigma_{c\bar{c}})$
$\mathcal{B}(D^0 \to \mu^-\mu^+) < 5 \times 10^{-10}$

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

Belle $660\ fb^{-1}$ @ $\Upsilon(4S)$
PRD81,091102(2010)

- Use a D* tag
- Normalization to $D^0 \to \pi^- \pi^+$
  - main physics background as well
  - mis-ID probability estimated with $D^0 \to K^- \pi^+$

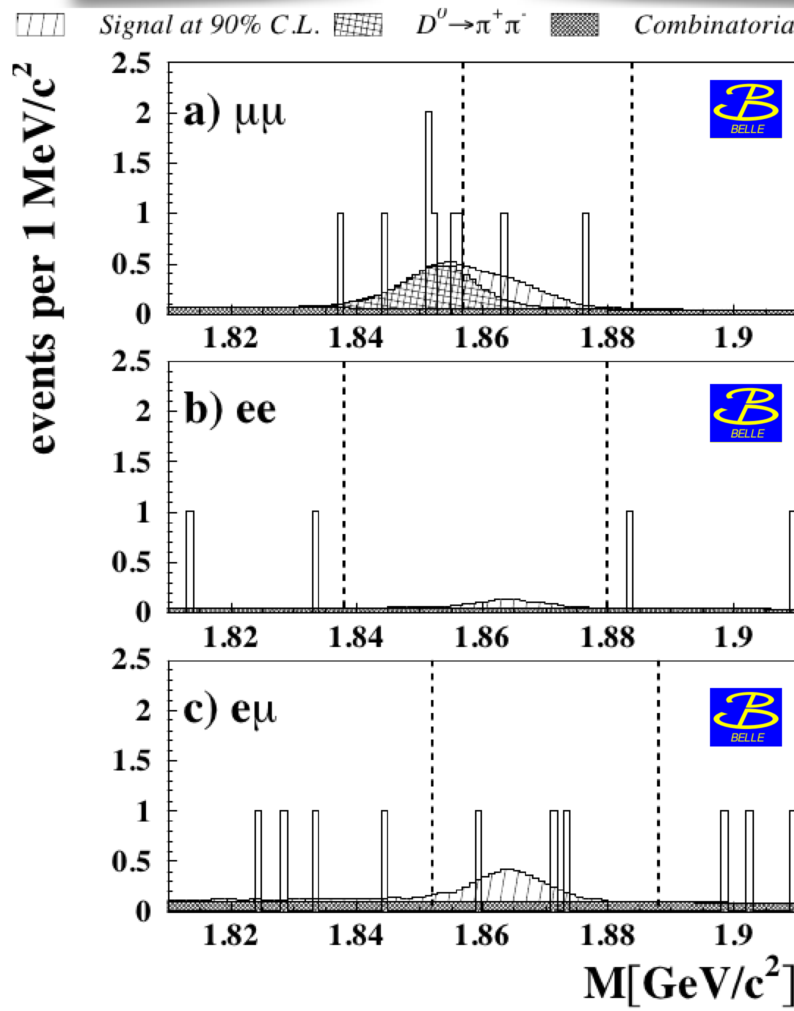
U.L. @ 90% C.L.

$$\mathcal{B}(D^0 \to \mu^+ \mu^-) < 1.4 \cdot 10^{-7}$$

$$\mathcal{B}(D^0 \to e^+ e^-) < 7.9 \cdot 10^{-8}$$

$$\mathcal{B}(D^0 \to e^\pm \mu^\mp) < 2.6 \cdot 10^{-7}$$

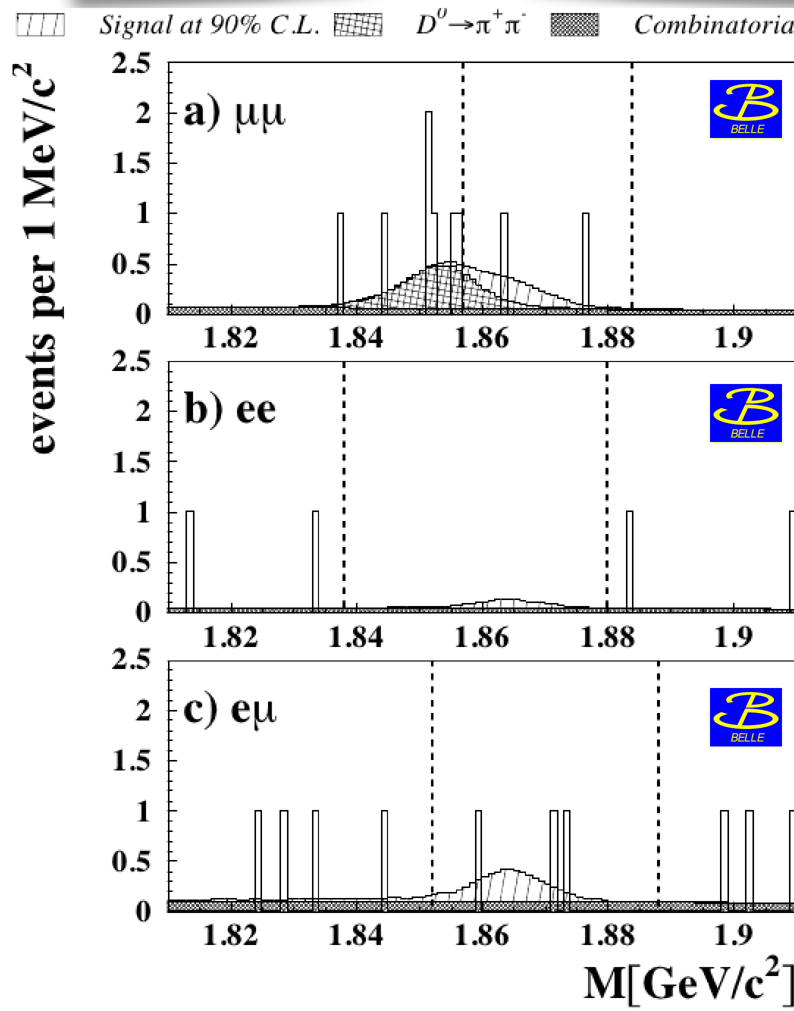
World's best



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

Belle $660\ fb^{-1}$ @ $\Upsilon(4S)$
PRD81,091102(2010)

- Use a D* tag
- Normalization to $D^0 \to \pi^- \pi^+$
  - main physics background as well
  - mis-ID probability estimated with $D^0 \to K^- \pi^+$



U.L. @ 90% C.L.

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \cdot 10^{-7}$$
$$\boxed{\begin{array}{c}\mathcal{B}(D^0 \to e^+e^-) < 7.9 \cdot 10^{-8} \\ \mathcal{B}(D^0 \to e^\pm\mu^\mp) < 2.6 \cdot 10^{-7}\end{array}}$$

World's best

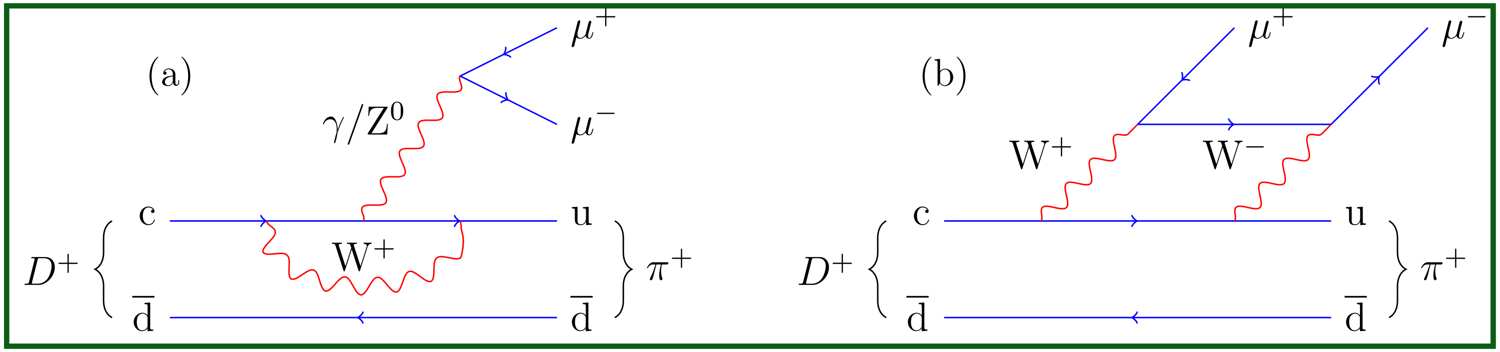
Belle II can improve these limits by an order of magnitude

$D_{(s)}^+ \to \pi^+\mu^-\mu^+$

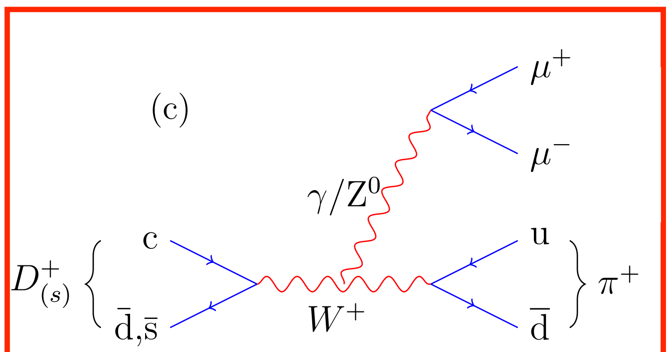
LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB724,203(2013)

- Include $D_s^+ \to \pi^+\mu^-\mu^+$ (not FCNC decay) to control (normalize) possible weak annihilation contributions in $D^+ \to \pi^+\mu^-\mu^+$ decays

FCNC



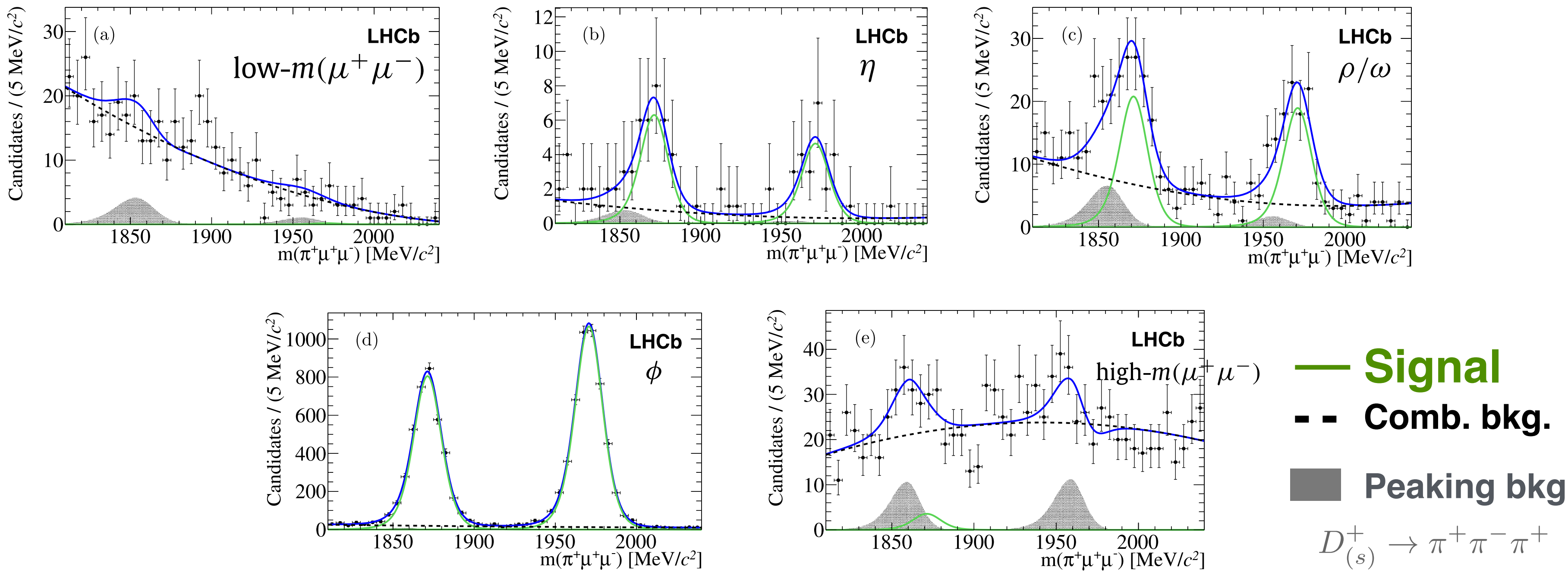
weak annihilation



$D^+_{(s)} \to \pi^+\mu^-\mu^+$

LHCb 1 fb^{-1} @ 7 TeV
PLB724,203(2013)

- Same approach used as for $D^0 \to \mu^-\mu^+$
- Use $D^+_{(s)} \to \pi^+\phi(\to \mu^-\mu^+)$ as a reference channel
  - serves as signal proxy to optimize the selection (BDT & muon ID)
- Extract signal in 5 $m(\mu^-\mu^+)$ bins



$D^+_{(s)} \to \pi^+\mu^-\mu^+$

LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB724,203(2013)

- Same approach used as for $D^0 \to \mu^-\mu^+$
- Use $D^+_{(s)} \to \pi^+\phi(\to \mu^-\mu^+)$ as a reference channel
  - serves as signal proxy to optimize the selection (BDT & muon ID)
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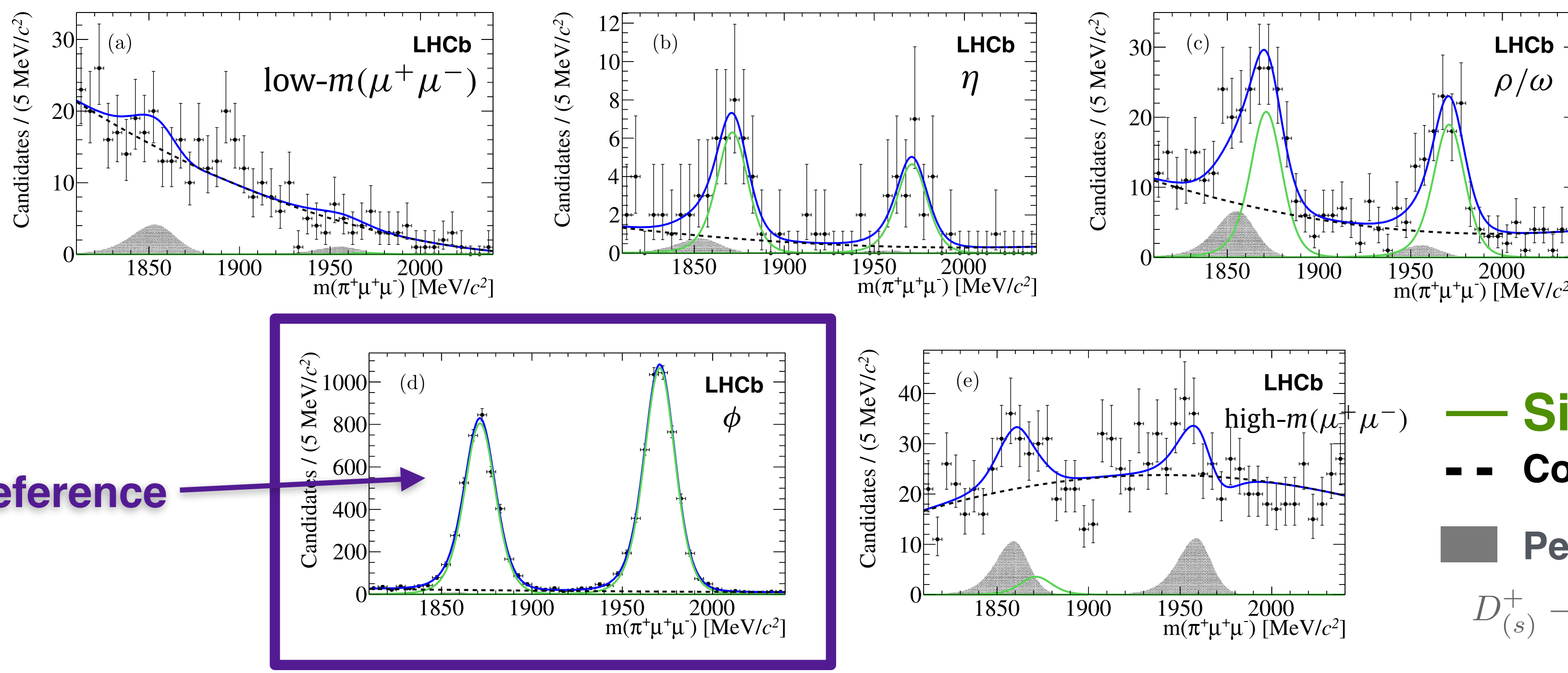


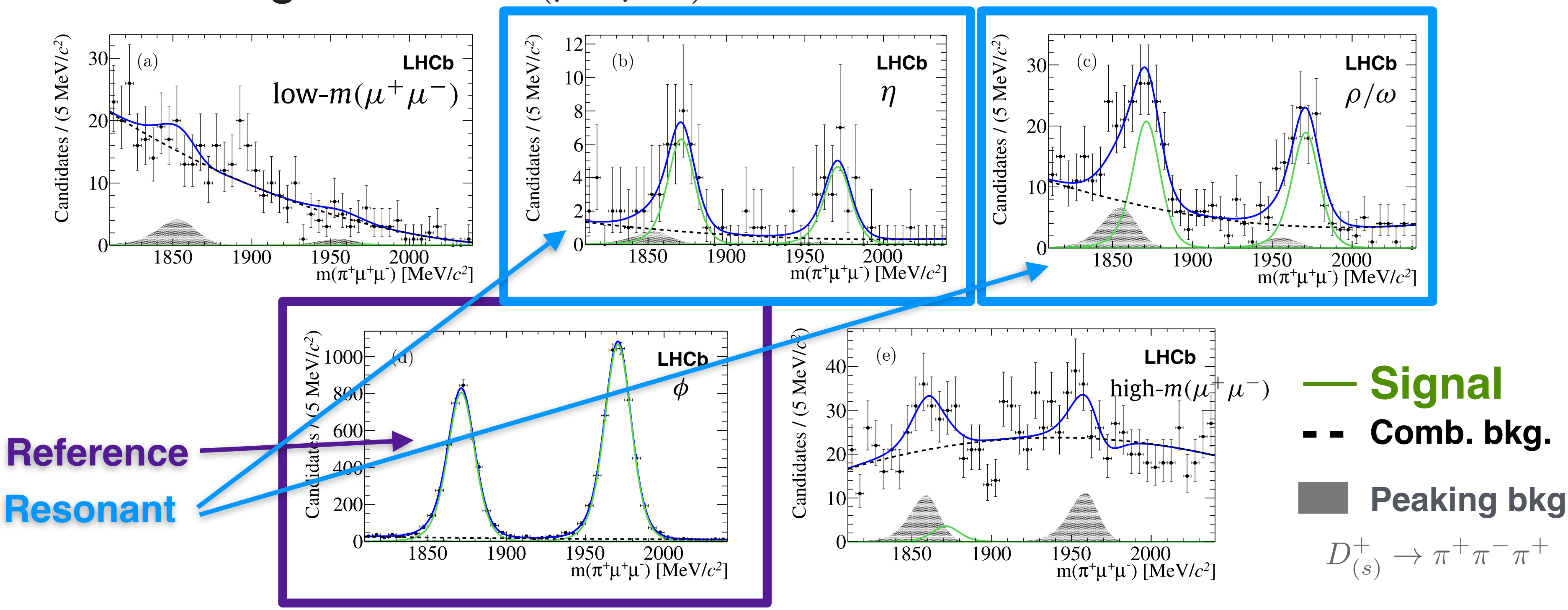
Reference

Signal
Comb. bkg.
Peaking bkg
$D^+_{(s)} \to \pi^+\pi^-\pi^+$

$D^+_{(s)} \to \pi^+\mu^-\mu^+$

LHCb 1 fb^{-1} @ 7 TeV
PLB724,203(2013)

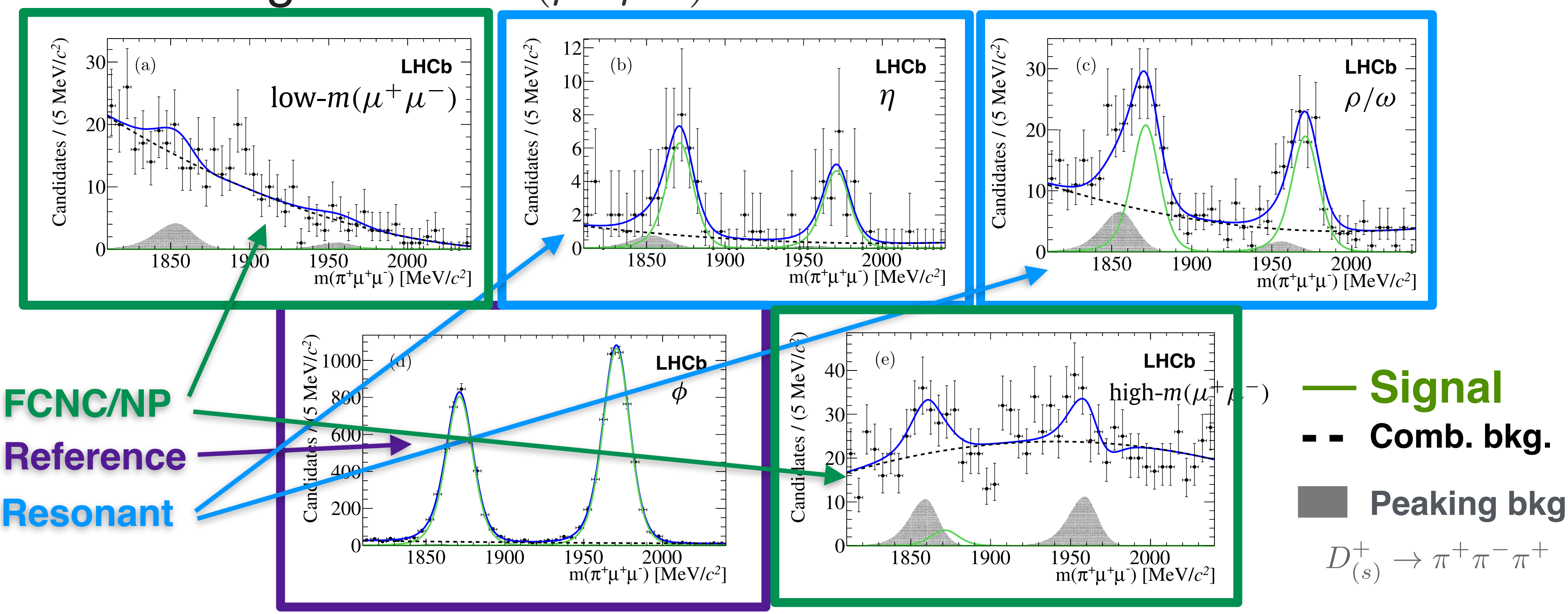
- Same approach used as for $D^0 \to \mu^-\mu^+$
- Use $D^+_{(s)} \to \pi^+\phi(\to \mu^-\mu^+)$ as a reference channel
  - serves as signal proxy to optimize the selection (BDT & muon ID)
- Extract signal in 5 $m(\mu^-\mu^+)$ bins



$D^+_{(s)} \to \pi^+\mu^-\mu^+$

LHCb 1 fb^{-1} @ 7 TeV
PLB724,203(2013)

- Same approach used as for $D^0 \to \mu^-\mu^+$
- Use $D^+_{(s)} \to \pi^+\phi(\to \mu^-\mu^+)$ as a reference channel
  - serves as signal proxy to optimize the selection (BDT & muon ID)
- Extract signal in 5 $m(\mu^-\mu^+)$ bins

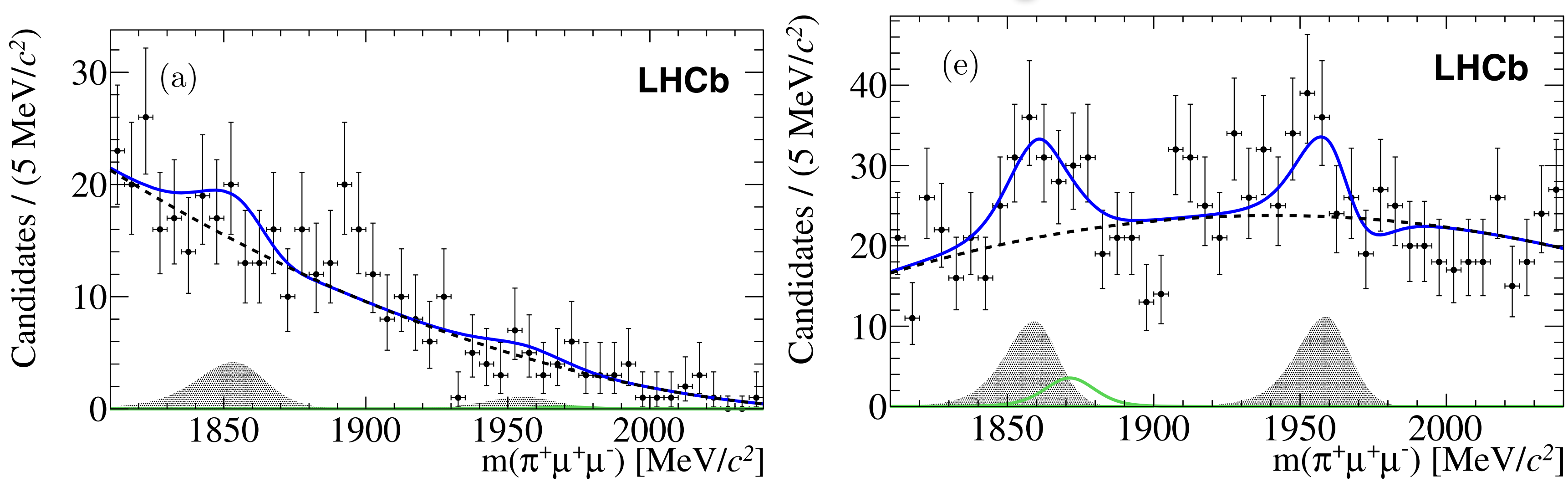


$D^+_{(s)} \to \pi^+\mu^-\mu^+$

LHCb 1 fb^{-1} @ 7 TeV
PLB724,203(2013)

- Same approach used as for $D^0 \to \mu^-\mu^+$
- Use $D^+_{(s)} \to \pi^+\phi(\to \mu^-\mu^+)$ as a reference channel
  - serves as signal proxy to optimize the selection (BDT & muon ID)
- Extract signal in 5 $m(\mu^-\mu^+)$ bins

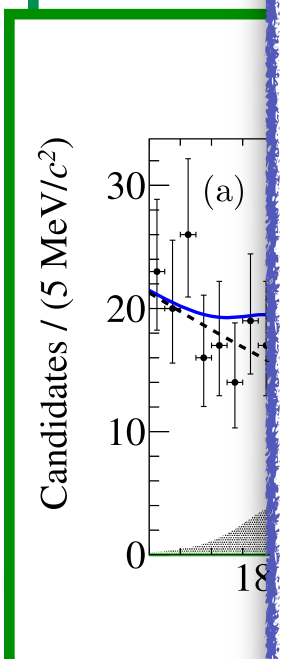
FCNC/NP di-muon mass regions

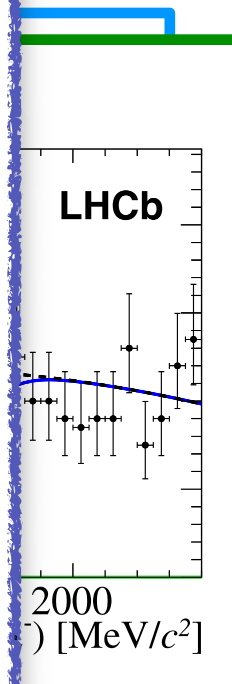


$D^+_{(s)} \to \pi^+\mu^-\mu^+$

LHCb 1 fb^{-1} @ 7 TeV
PLB724,203(2013)

- Same approach used as for $D^0 \to \mu^-\mu^+$
- Use $D^+_{(s)}$
  - serves … muon ID)
- Extract





bkg.
bkg
π^+

No signal observed
in the non-resonant regions

Decay	Bin	90% [$\times 10^{-8}$]
$D^+ \to \pi^+\mu^+\mu^-$	low-$m(\mu^+\mu^-)$	2.0
	high-$m(\mu^+\mu^-)$	2.6
	Total	7.3
$D_s^+ \to \pi^+\mu^+\mu^-$	low-$m(\mu^+\mu^-)$	6.9
	high-$m(\mu^+\mu^-)$	16.0
	Total	41.0

U.L. @ 90% C.L.

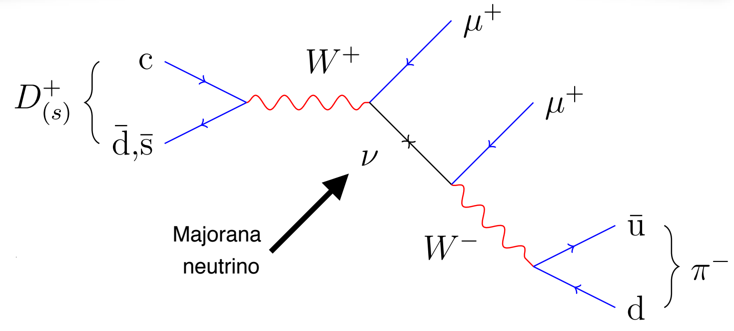
World's best, 50-100x better than BaBar and D0

Still above the highest NP predictions $\mathcal{O}(10^{-8})$

$D^+_{(s)} \to \pi^- \mu^+ \mu^+$

LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB724,203(2013)

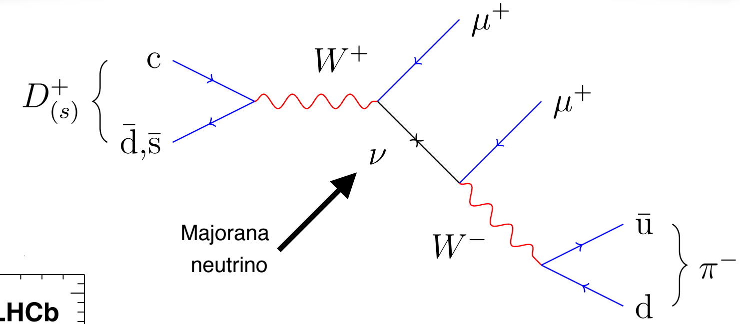
- Lepton Number Violating process
- extract signal in 4 bins of $m(\pi\mu)$
- same approach as $D^+_{(s)} \to \pi^+ \mu^- \mu^+$

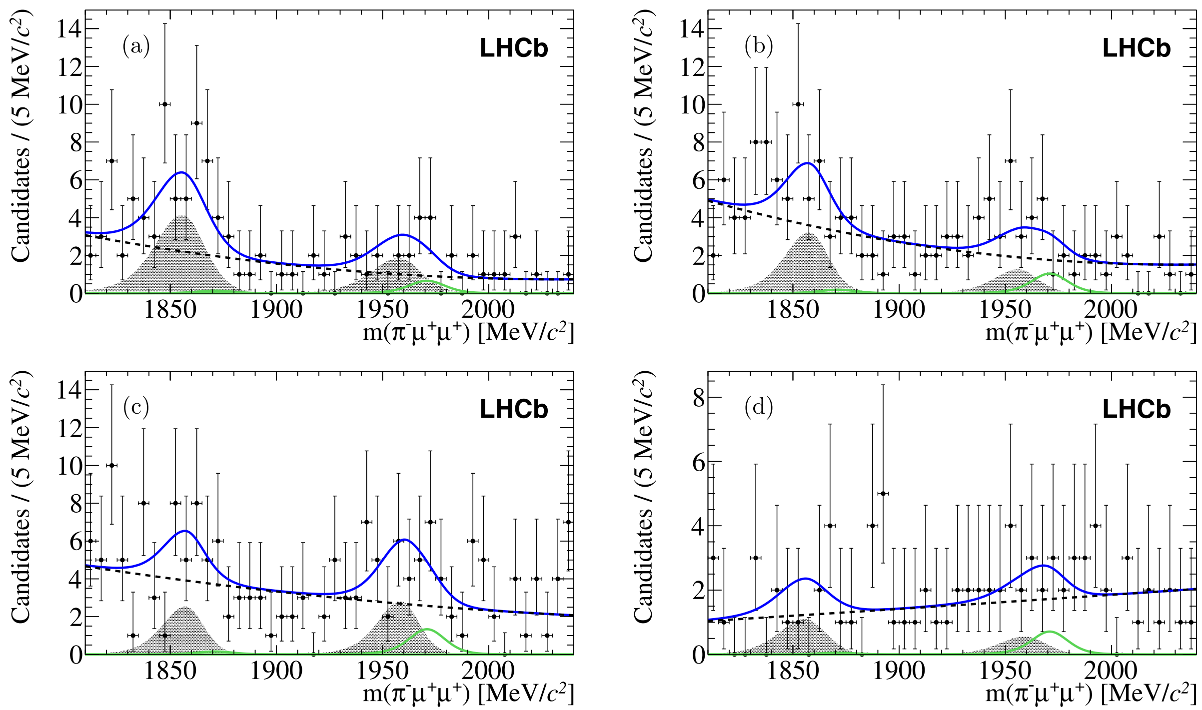


$D^+_{(s)} \to \pi^- \mu^+ \mu^+$

LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB724,203(2013)

- Lepton Number Violating process
- extract signal in 4 bins of $m(\pi\mu)$
- same approach as $D^+_{(s)} \to \pi^+ \mu^- \mu^+$





U.L. @ 90% C.L.

$$\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2.2 \times 10^{-8}$$
$$\mathcal{B}(D^+_s \to \pi^- \mu^+ \mu^+) < 12 \times 10^{-8}$$

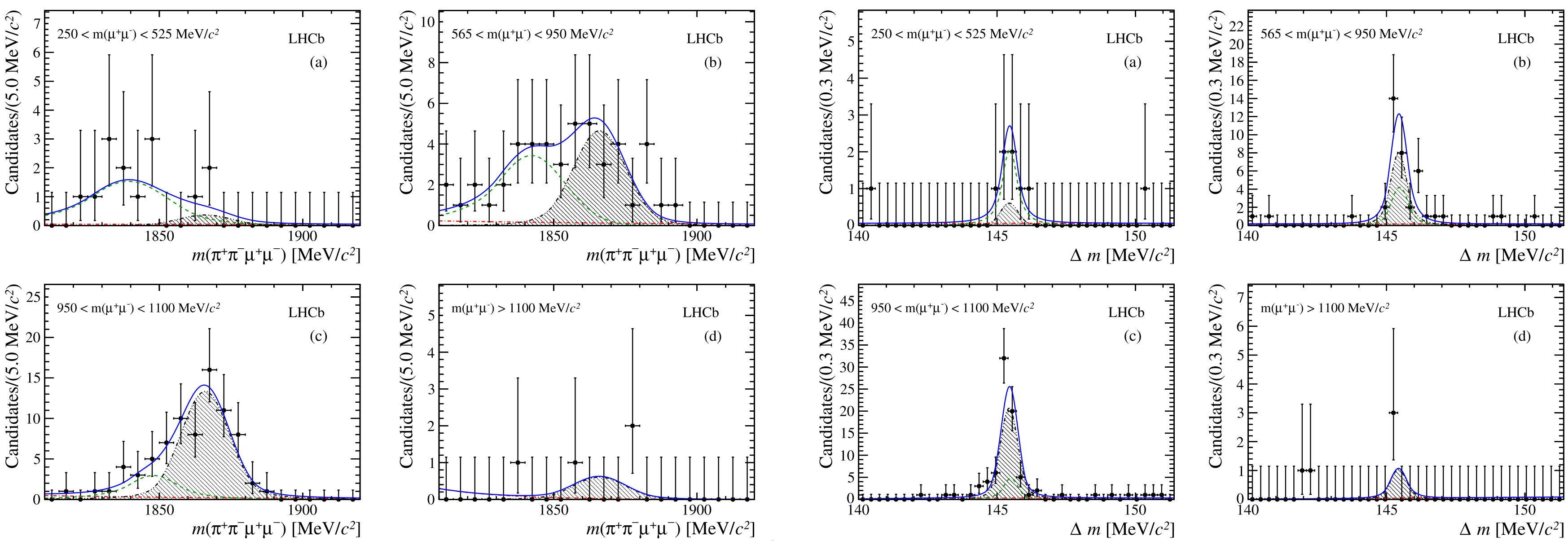
Two orders of magnitude below $h^- e^+ e^+$ modes studied bu BaBar and CLEO-c

Signal - - **Comb. bkg.** **Peaking bkg** $D^+_{(s)} \to \pi^+ \pi^- \pi^+$

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

LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB728,234(2014)

- Essentially the same approach as for $D^+_{(s)} \to \pi^+\mu^-\mu^+$
- Use a D* tag (cleans up the sample, but eff. x 1/10)
- Use $D^0 \to \pi^+\pi^-\phi(\to \mu^-\mu^+)$ as a reference channel
  - only 100 events expected (lower eff., $\mathcal{B} \sim 5 \times 10^{-7}$, D* x-section)
- Dominant background from $D^0 \to \pi^+\pi^-\pi^+\pi^-$

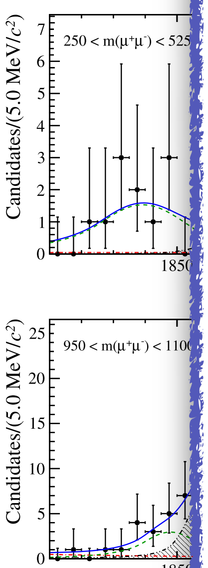


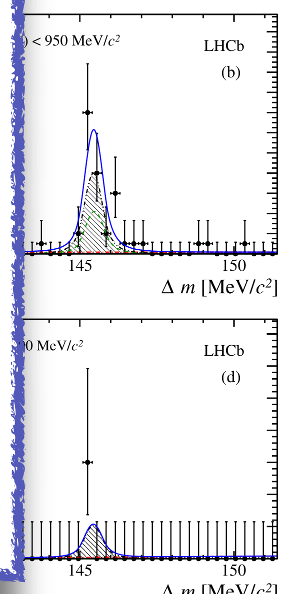
······ **Comb. bkg.** - - - - - **Peaking bkg.** $D^0 \to \pi^+\pi^-\pi^+\pi^-$ **Signal**

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

LHCb $1\ fb^{-1}$ @ $7\ TeV$
PLB728,234(2014)

- Essen... μ^+
- Use a...
- Use ... el
  - only ... * x-section)
- Domi...





No signal observed
in the non-resonant regions

Range description	$m(\mu^+\mu^-)$ [MeV/c^2]	$D^0 \to \pi^+\pi^-\mu^+\mu^-$ yield
low-$m(\mu^+\mu^-)$	250–525	2 ± 2
ρ/ω	565–950	23 ± 6
ϕ	950–1100	63 ± 10
high-$m(\mu^+\mu^-)$	> 1100	3 ± 2

Region	U.L. @ 90% [$\times 10^{-7}$]
low-$m(\mu^+\mu^-)$	2.3
high-$m(\mu^+\mu^-)$	1.0
Total	5.5

World's best

Still 1 or 2 order of magnitude above NP predictions

m(π⁺π⁻μ⁺μ⁻) [MeV/c²] m(π⁺π⁻μ⁺μ⁻) [MeV/c²] Δ m [MeV/c²]

Comb. bkg. *Peaking bkg.* $D^0 \to \pi^+\pi^-\pi^+\pi^-$ *Signal*

IJS

+ Many more

- references and limits of all rare decay searches can be found at the HFAG web-page: http://www.slac.stanford.edu/xorg/hfag/charm/April14/Rare/rare_charm.html

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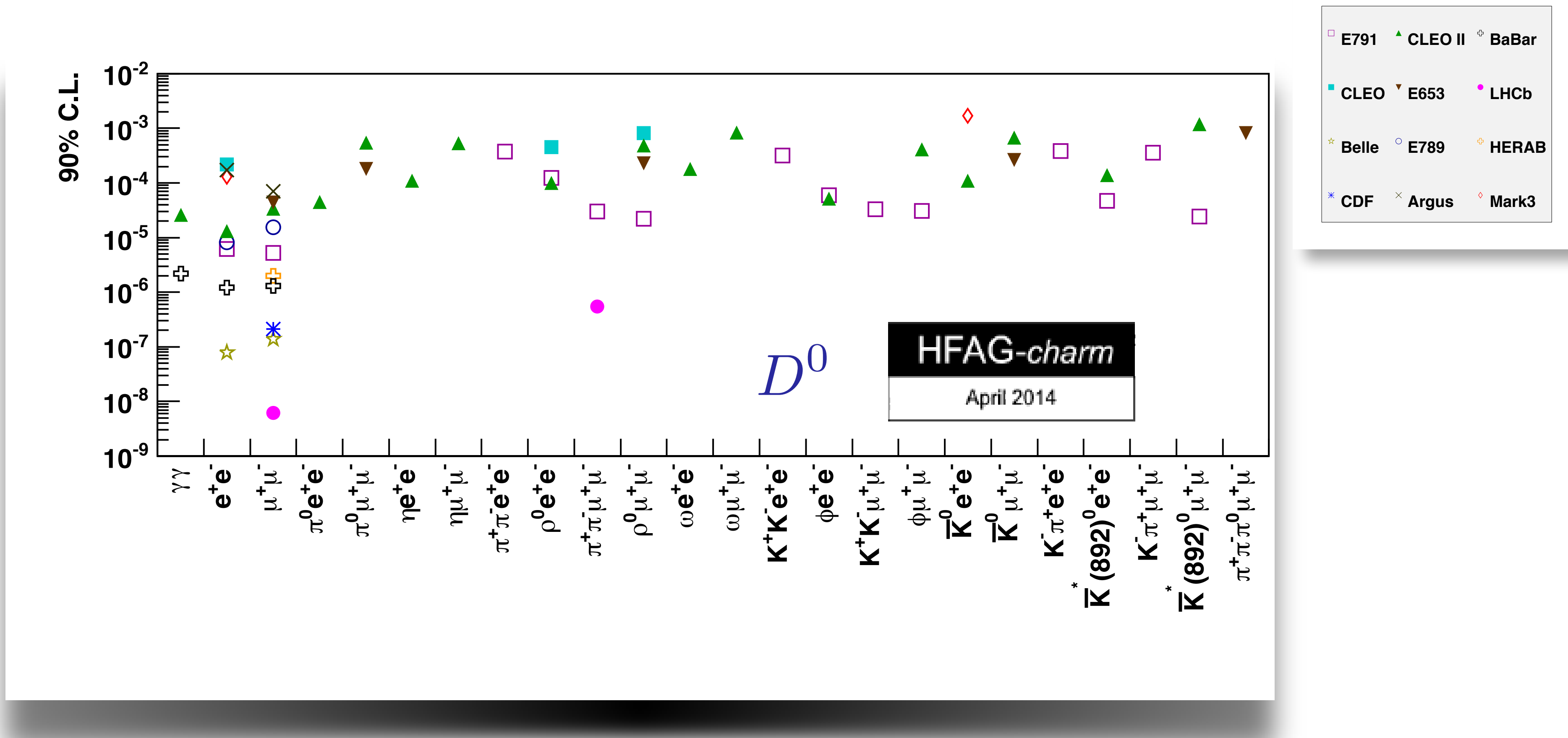

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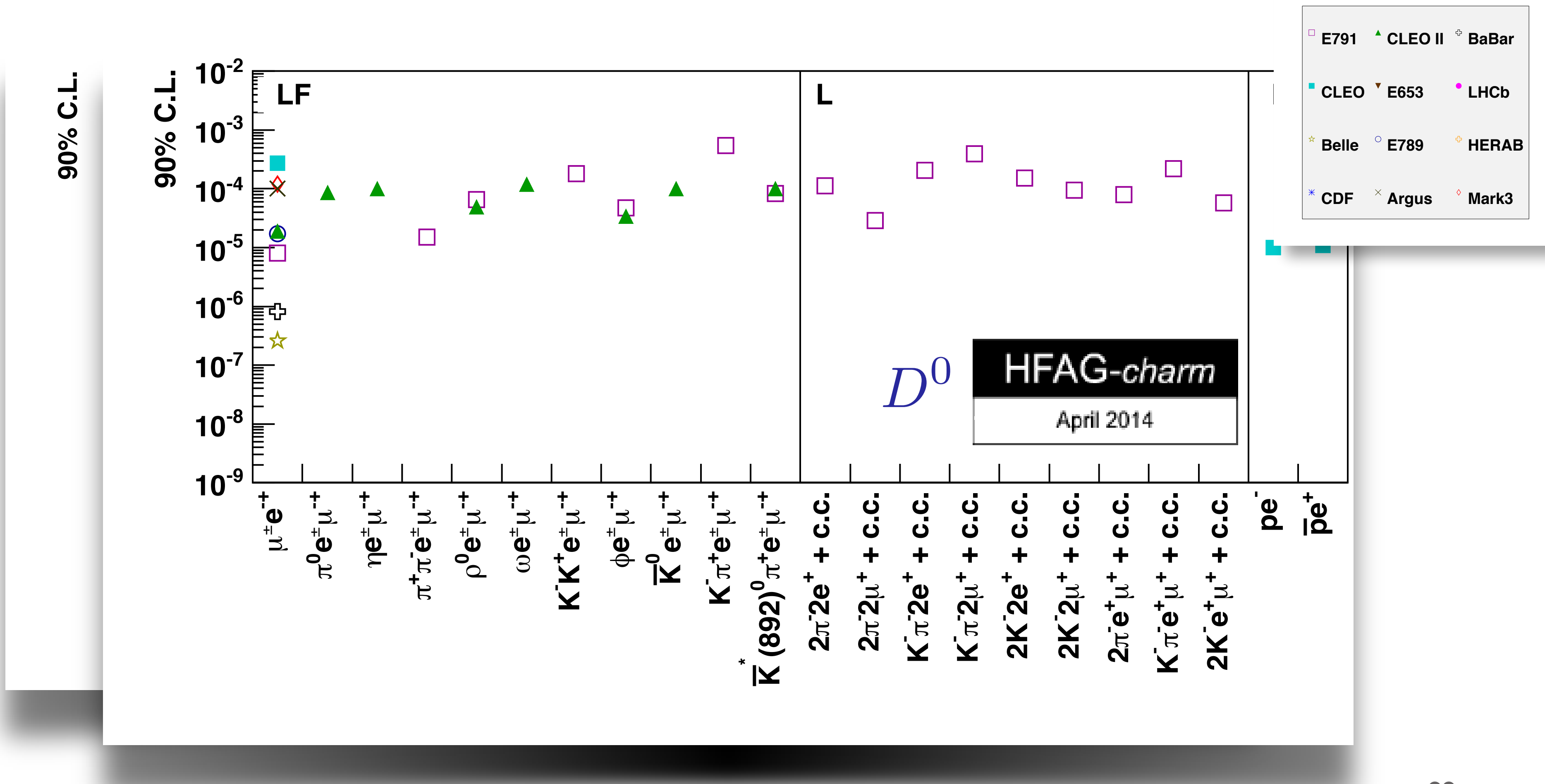

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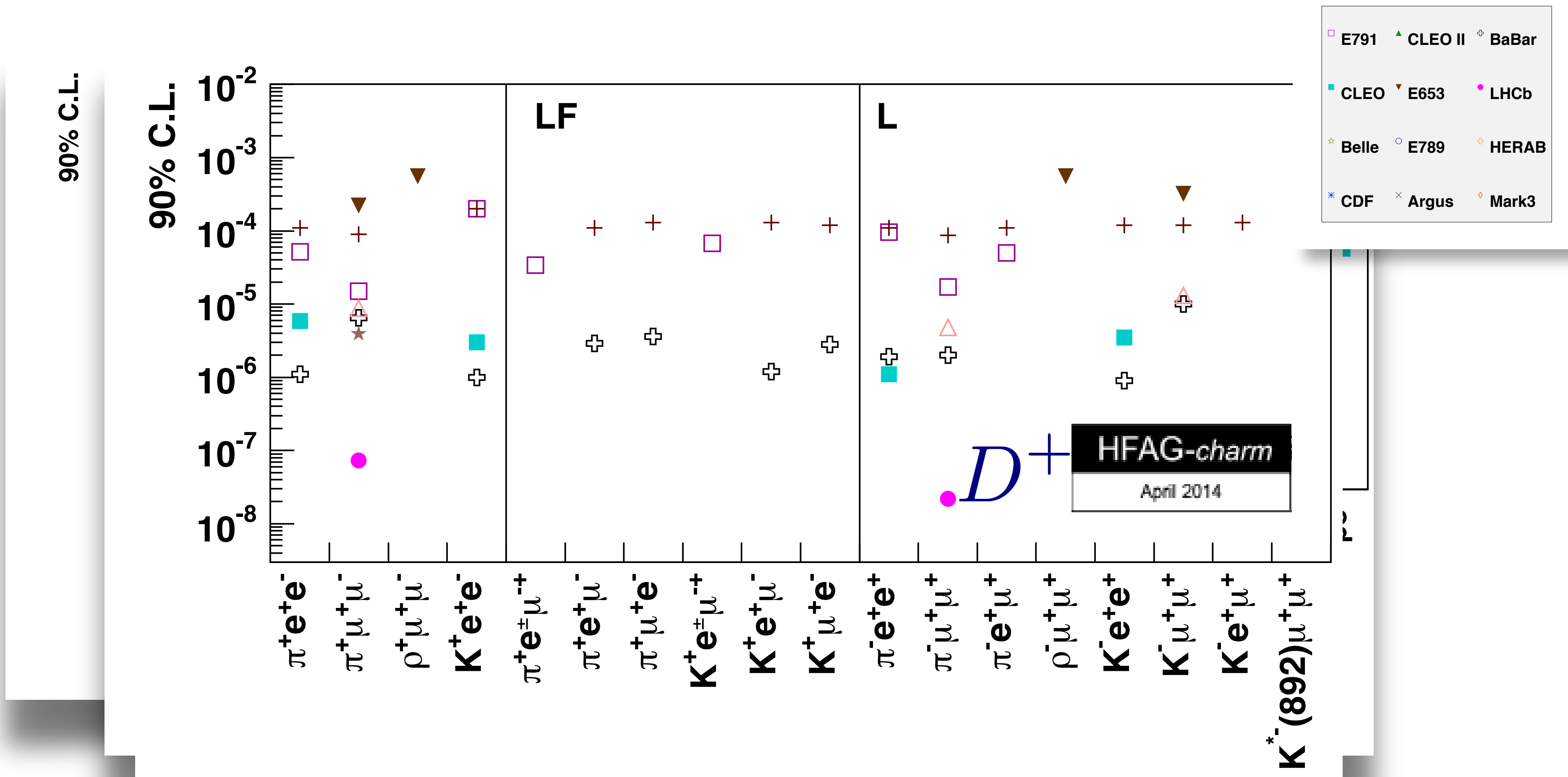

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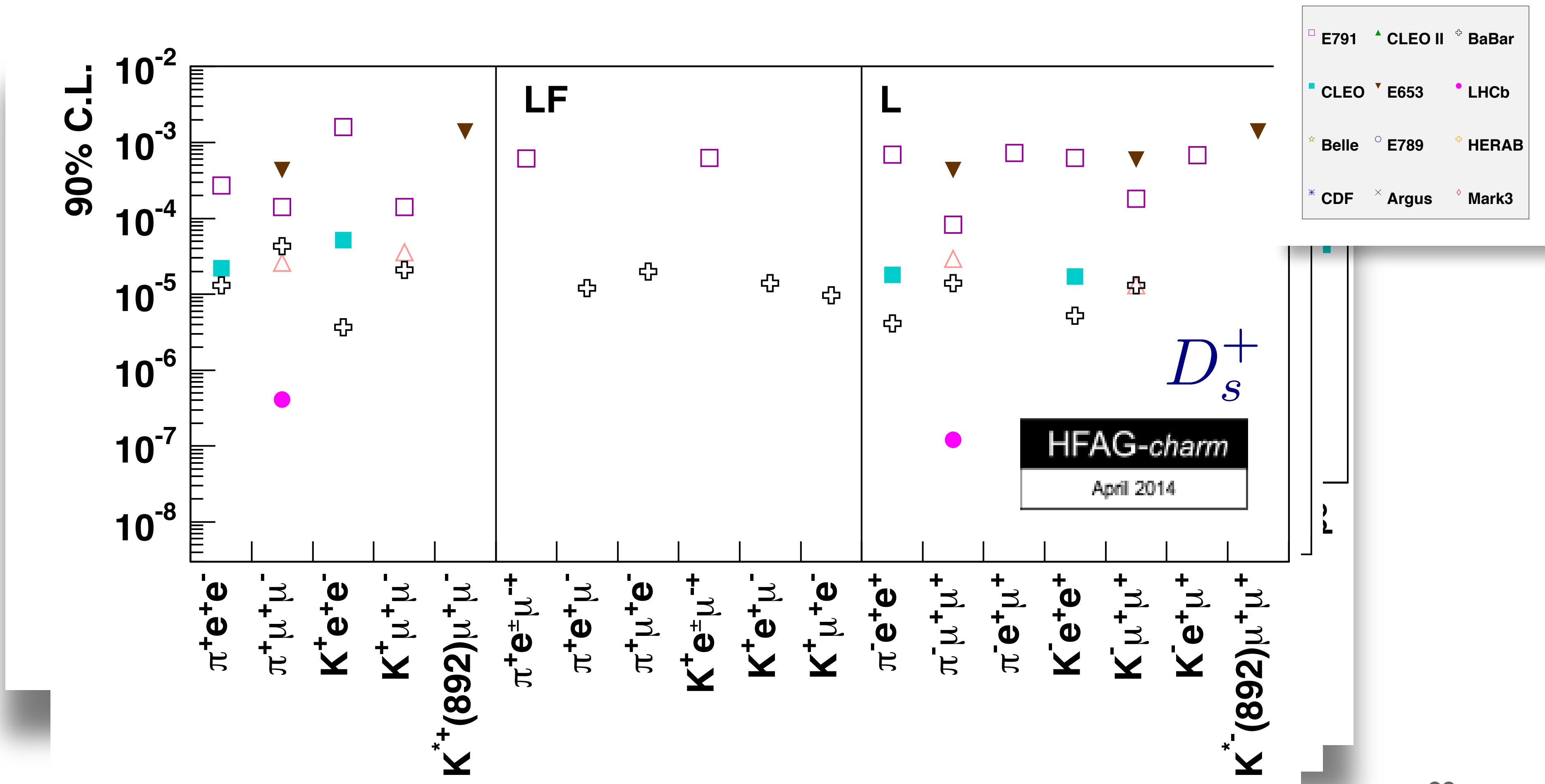

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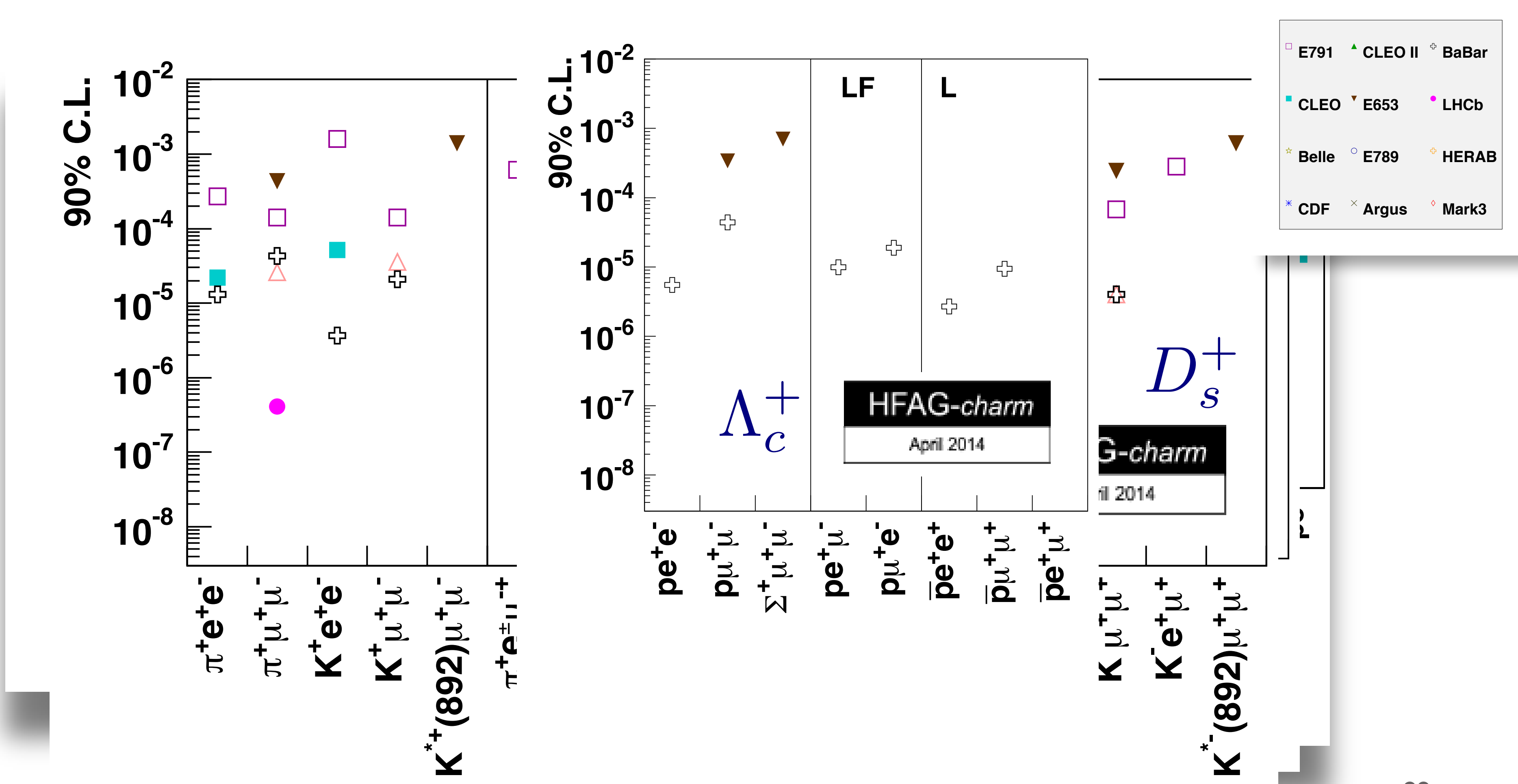

Conclusions

- Many rare charm decay modes searched for in last 15 years by CLEO, BESIII, E791, BaBar, Belle, D0, CMS, LHCb, …
- Starting to reach the level of the most optimistic New Physics predictions
- Order(s) of magnitude larger samples collected by LHCb, Belle II could improve the limits by order of magnitude
- Another opportunity are other observables (CP and angular asymmetries) in radiative and $D \to hh(\ell\ell)_V$ decays that might be sensitive to New Physics processes