Rare & forbidden charm decays

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For STF informal workshop

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What’s the rare?

FCNC processes are very rare in SM being suppressed by absence of tree level diagrams and by GIM mechanism;

FCNC in Charm are even more suppressed due to absence of high mass down-type quark;

Many new physics scenarios can therefore contribute enhancing these processes with new particles running in the loops or even at tree level

Some models predict enhancements in the up sector only

Lepton flavour, lepton number and baryon number violating decays are essentially forbidden in the Standard Model

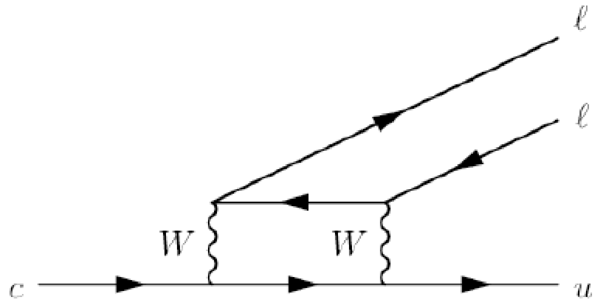
No theoretical uncertainties

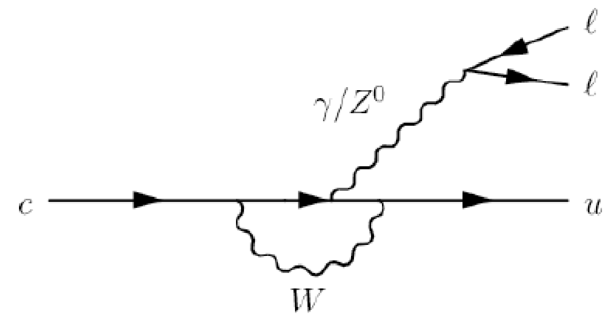
However in some new physics models they can be allowed at sizeable levels

If not seen can put strong constraints on NP parameters

FCNC in Charm

PRD66,(2002)014009





Standard Model:

- Short distance contributions heavily suppressed by GIM mechanism

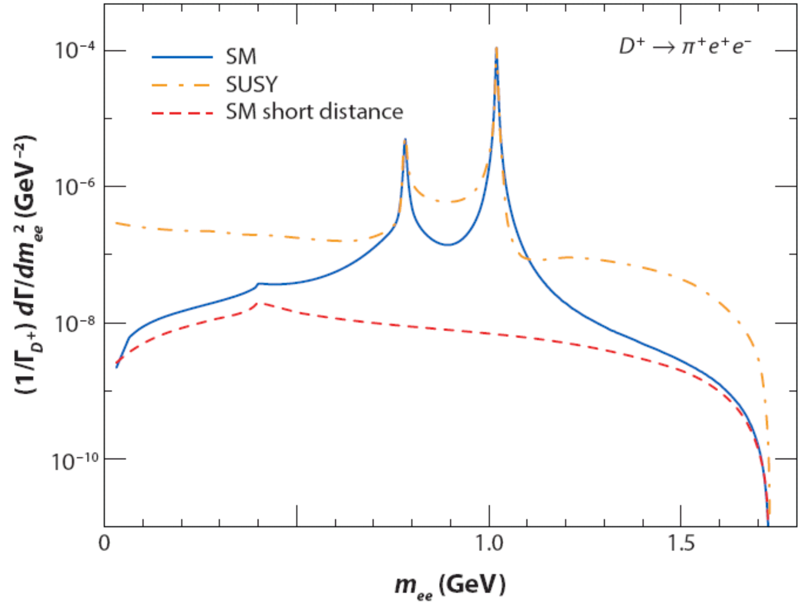
$$\mathcal{B}_{D^+\to X_u^+ e^+ e^-} \simeq 2\cdot 10^{-8} \qquad\qquad \mathcal{B}_{D^0\to X_u^0 e^+ e^-} \simeq 8\cdot 10^{-9}$$

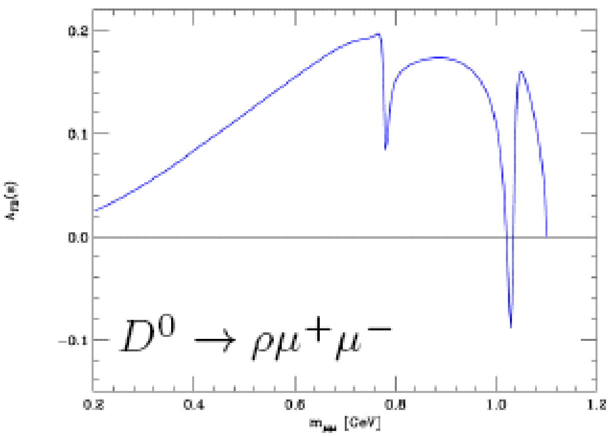
- SM rate dominated by long distance contribution due to $D \to XV \to X\ell^+\ell^-$ where $V = \phi, \rho, \omega$
- Long distance contribution are of non-perturbative nature giving large theoretical errors
- Branching fractions at 10^{-6}, but non-resonant part is at the level of 10^{-7}
- Outside of the resonances (both low and high q^2) there is still big room to discover new physics contributions

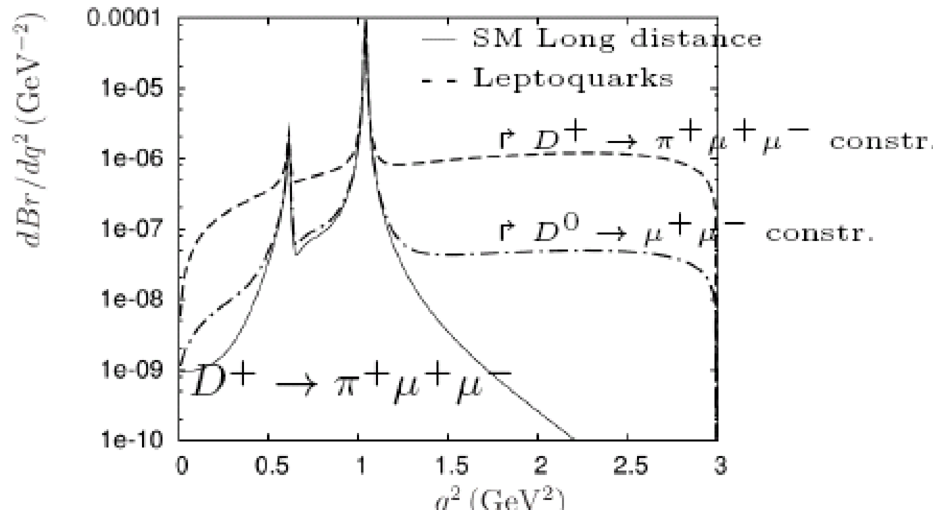
[Phys.Rev. D66 (2002) 014009]

Flavour changing neutral currents: $c \to u\ell^+\ell^-$ new physics

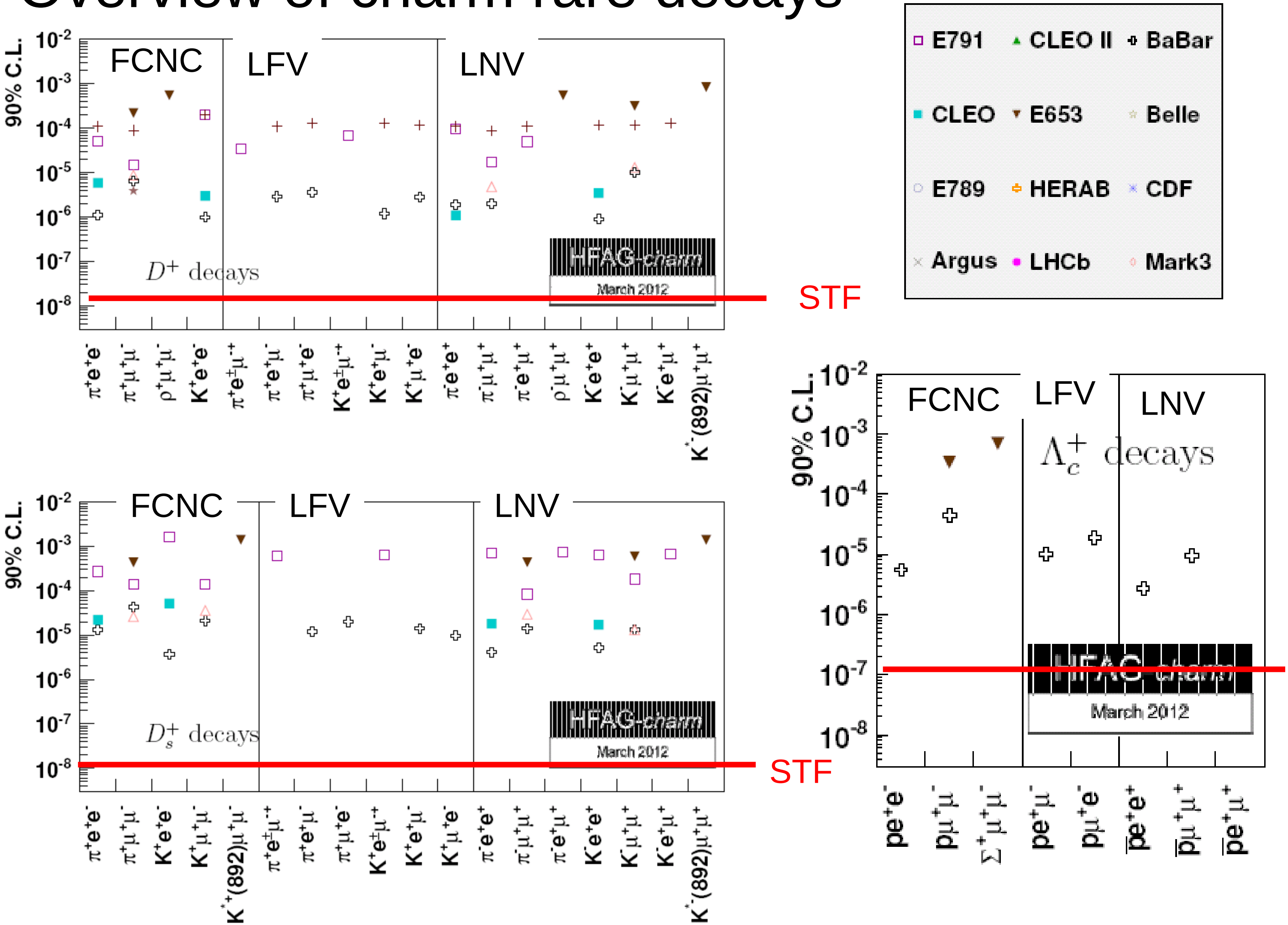
- Different new physics scenarios allow for enhancement of FCNC processes
- MSSM$\not{R}_p$ gives large contributions
  [Phys.Rev. D66 (2002) 014009]
- Leptoquarks can also contribute
  [Phys.Rev. D79 (2009) 017502]
- For $D^0 \to \rho^0\mu^+\mu^-$ also forward backward asymmetry





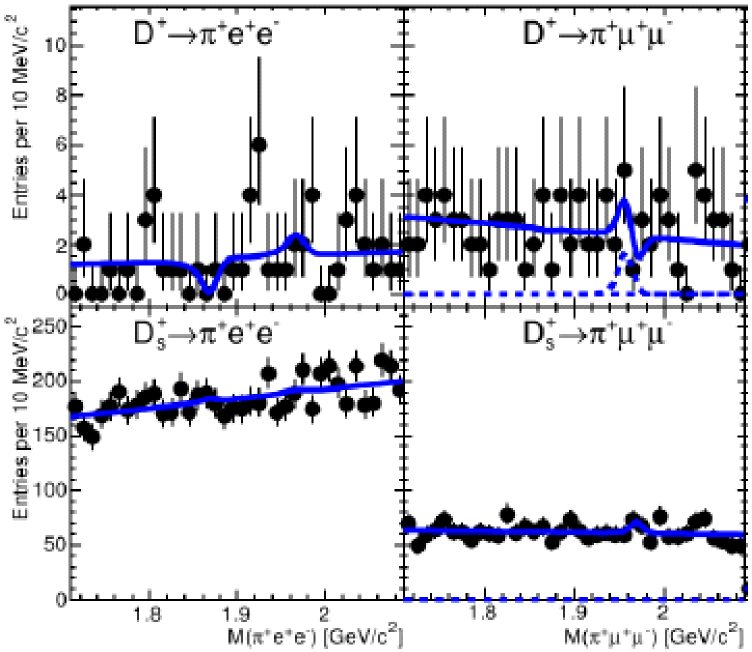


Overview of charm rare decays

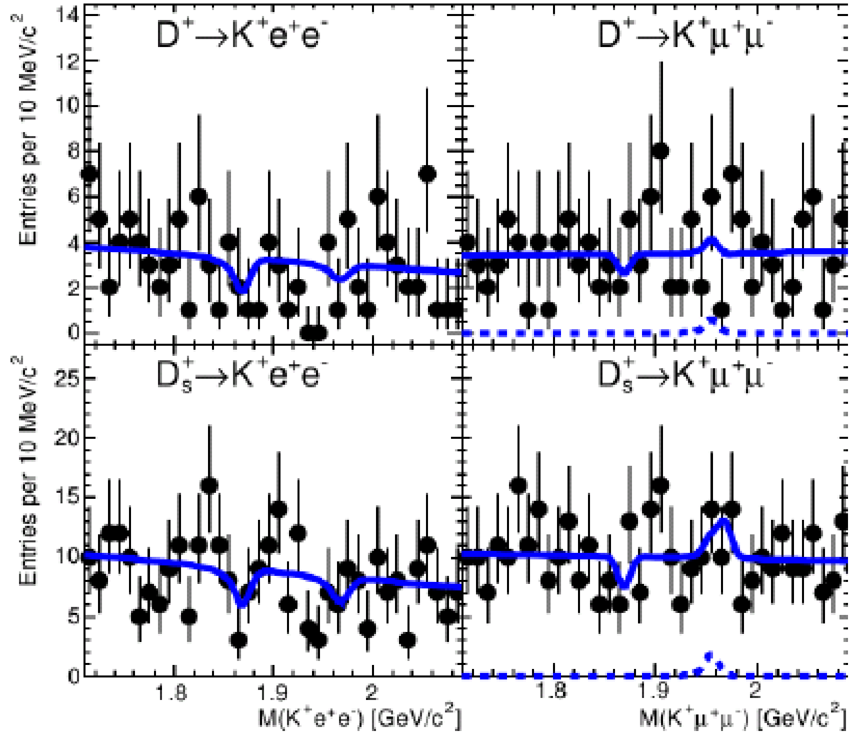


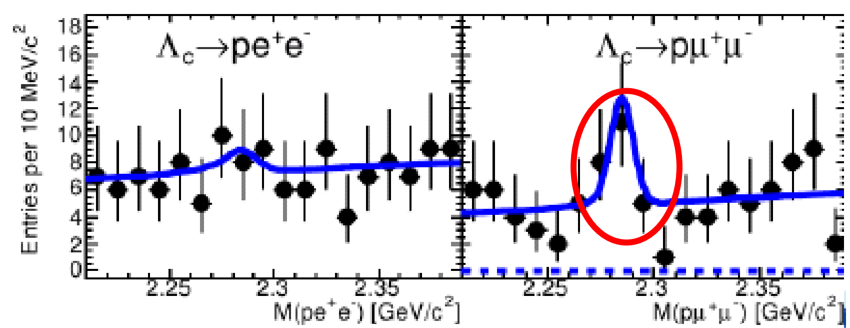
FCNC of charm from BABAR

[Phys.Rev. D84 (2011) 072006]



Decay	UL on $\mathcal{B}$ in 10^{-6} at 90% CL
$D^+ \to \pi^+ e^+ e^-$	1.1
$D^+ \to \pi^+ \mu^+ \mu^-$	6.5
$D_s^+ \to \pi^+ e^+ e^-$	13
$D_s^+ \to \pi^+ \mu^+ \mu^-$	43
$D^+ \to K^+ e^+ e^-$	1.0
$D^+ \to K^+ \mu^+ \mu^-$	4.3
$D_s^+ \to K^+ e^+ e^-$	21
$D_s^+ \to K^+ \mu^+ \mu^-$	14
$\Lambda_c^+ \to p e^+ e^-$	5.5
$\Lambda_c^+ \to p \mu^+ \mu^-$	44





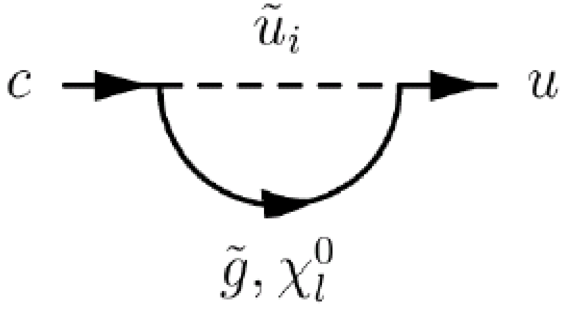
2.6 σ significance

$D^0 \to \gamma\gamma$

- SM short distance contribution at 3×10^{-11}
- Long distance contribution mainly due to Vector Meson Dominance, predicted to be [Phys.Rev. D66 (2002) 014009]

$$\mathcal{B}^{VMD}_{D^0\to\gamma\gamma} \simeq 3.5^{4.0}_{-2.6} \cdot 10^{-8}$$

- However $c \to u\gamma$ process can be enhanced up to $6 \cdot 10^{-6}$ (200 times the SM) level in MSSM [Phys.Lett. B500 (2001) 304-312]



$D^0 \to \gamma\gamma$ at BaBar

Fit procedure:

- Unbinned maximum likelihood fit to invariant mass
- $D^0 \to \gamma\gamma$ signal: crystal ball and bifurcated gaussian
- Combinatorial background: 2^{nd} order Chebychev polynomial
- $D^0 \to \pi^0\pi^0$ background Crystal Ball function

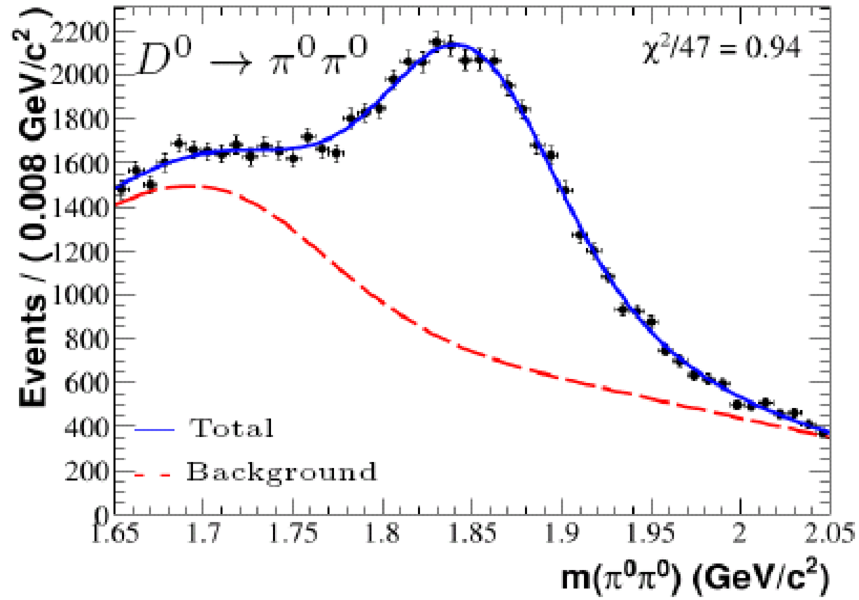
Results: [BaBar submitted to Physical Revew D]
Measured a $D^0 \to \pi^0\pi^0$ branching fraction:

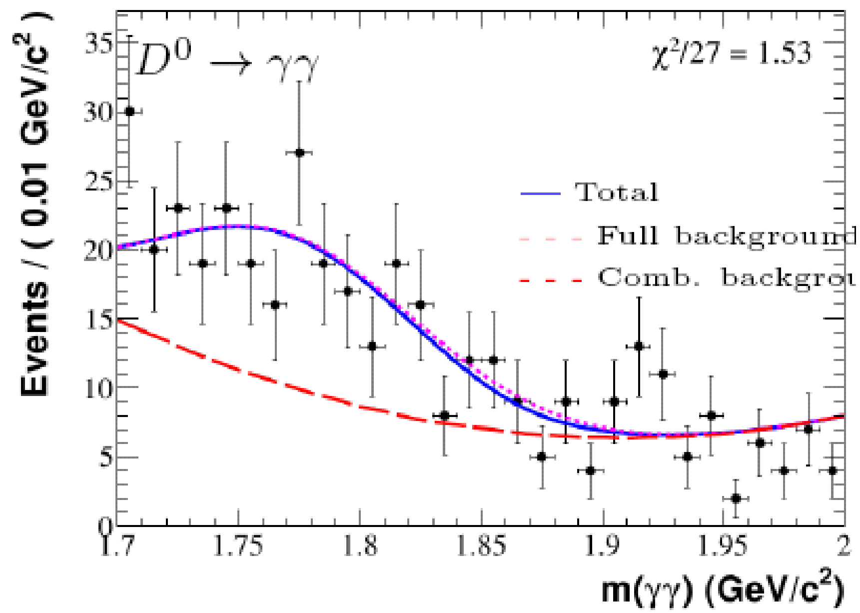
$$\mathcal{B}_{D^0 \to \pi^0\pi^0} = (8.4 \pm 0.1 \pm 0.3) \cdot 10^{-4}$$

For $D^0 \to \gamma\gamma$ found negative signal yield $N = -6 \pm 15$ events leading to an upper limit:

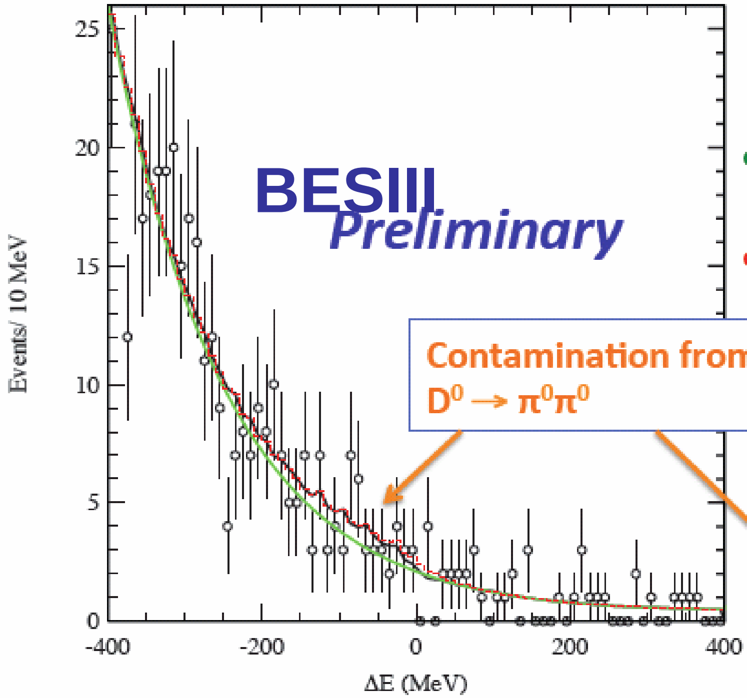
$$\mathcal{B}_{D^0 \to \gamma\gamma} < 2.2 \cdot 10^{-6} \quad \text{at} 90\% \text{CL}$$

which is constraints NP to at most 70 times the SM.



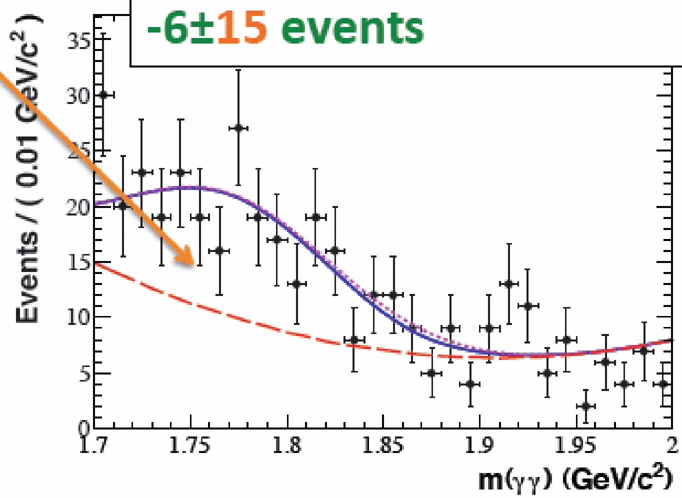


Comparison: BESIII vs. BABAR: $D^0 \to \gamma\gamma$



Fit to DATA

- Gives: -2.9 ± 7.1 events
- No significant signals.



W.r.t. the BaBar's result:

- $BKG_{BESIII}/BKG_{BaBar} \sim 0.5$
- $\varepsilon_{BESIII}/\varepsilon_{BaBar} \sim 2$
- BUT, $N_{BESIII}(D^0)/N_{BaBar}(D^0) \sim 0.1$

BESIII: $B(D^0 \to \gamma\gamma) < 4.6 \times 10^{-6}$ @90% CL. $2.9\ fb^{-1}$

BaBar: $B(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ @90% CL. $470\ fb^{-1}$

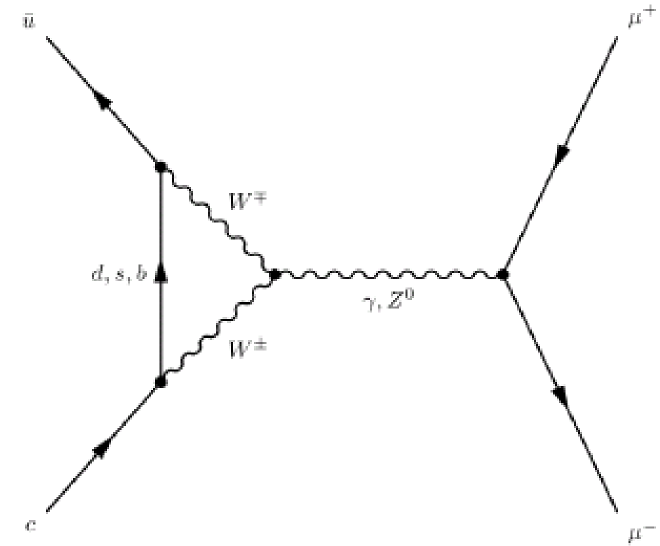
New method at BESIII: DT and ST simutaneous fits: 2.0×10^{-6}

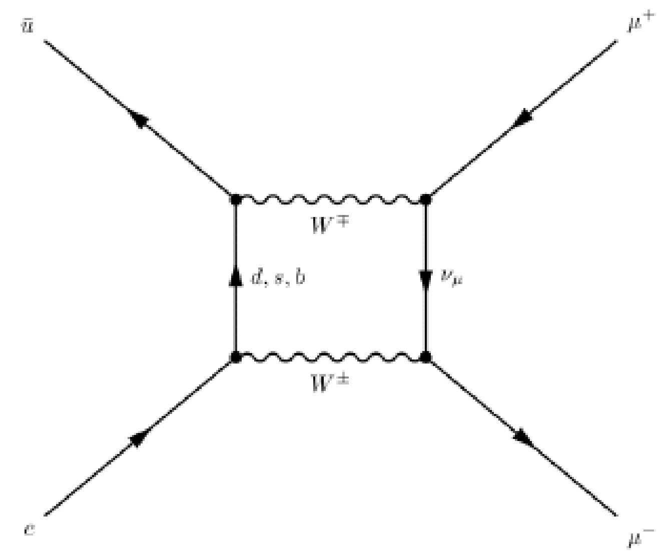
$D^0 \to \mu^+\mu^-$ decay: Standard Model

- Highly suppressed in the Standard Model. Short distance contribution $(D^0 \to \mu^+\mu^-) \simeq 10^{-18}$
- Dominated by long distance contribution in particular from $D^0 \to \gamma\gamma$: $\mathcal{B}(D^0 \to \mu^+\mu^-) \simeq 2.7 \times 10^{-5}\mathcal{B}(D^0 \to \gamma\gamma)$

  [Phys.Rev. D66 (2002) 014009]

  which gives an estimate: $\mathcal{B}(D^0 \to \mu^+\mu^-) \gtrsim 10^{-13}$
- Using BaBar upper limit: [BaBar 2011]: $\mathcal{B}(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ at 90% C.L. one could estimate an upper limit on this contribution of $\mathcal{B}(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-11}$
- $D^0 \to e^+e^-$ even more suppressed



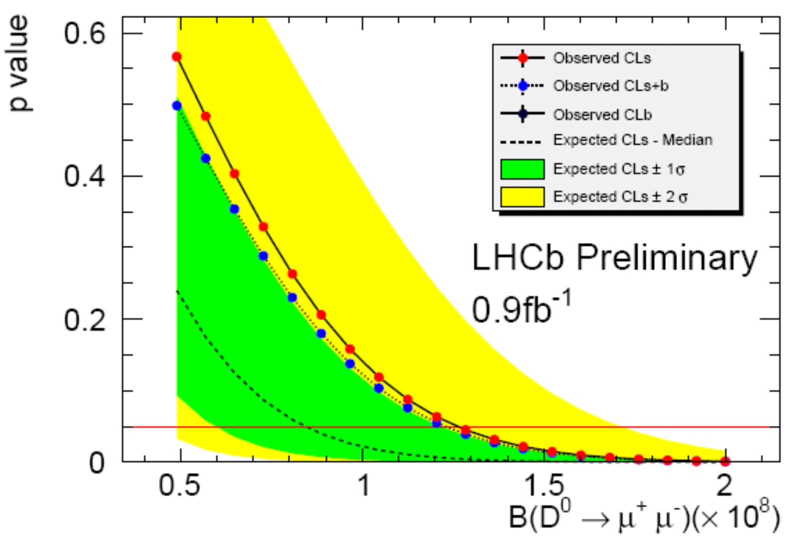


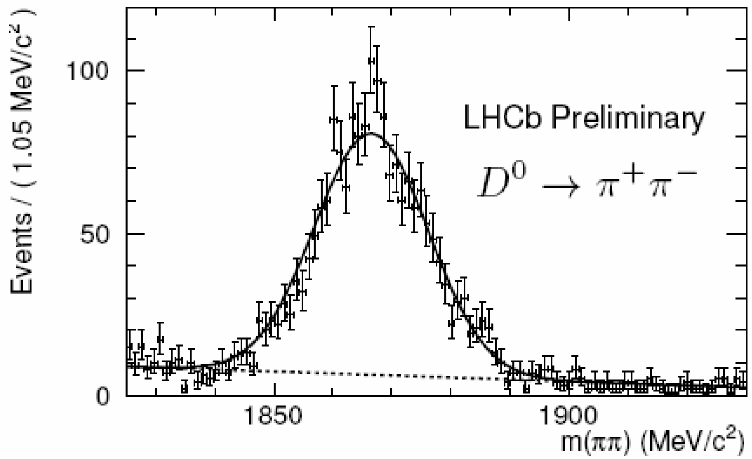
$D^0 \to \mu^+\mu^-$ at LHCb

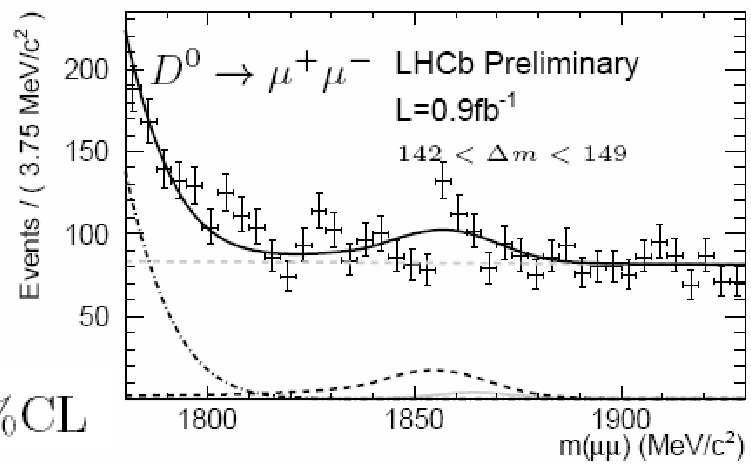
- $0.9\ \mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV were used
- An additional sample of $79\ \mathrm{pb}^{-1}$ for background studies
- Monte Carlo generated samples with full detector simulation

[LHCb-CONF-2012-005]

Normalization: $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$ yield extracted with an unbinned extended two-dimensional fit in mass and Δm







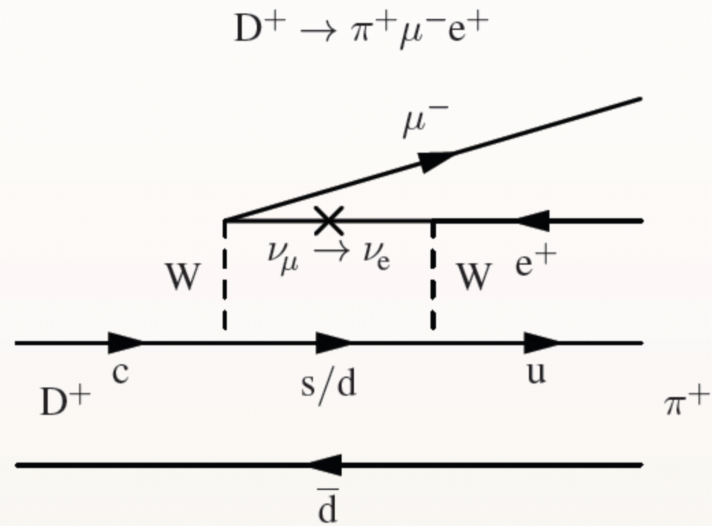
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3\ (1.1) \cdot 10^{-8} \quad \text{at } 95\ (90)\%\text{CL}$$

LFV in charm decay

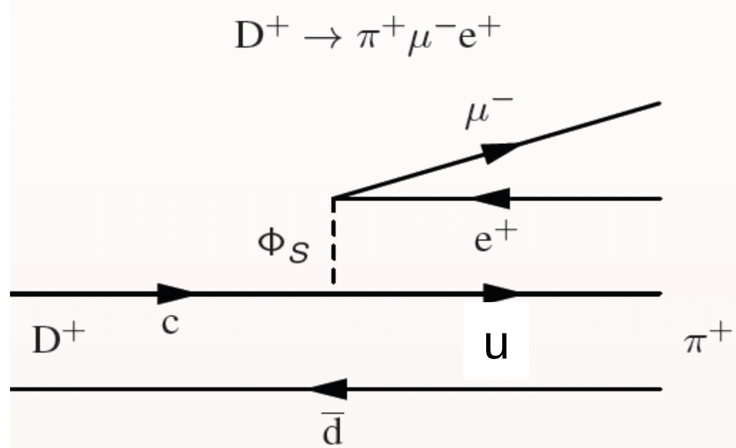
- established for neutrinos
- can enter charged sector in loops
- predicted rates unmeasurable small
- enhancement predicted in many New Physics models, e.g.
  - multi-Higgs extensions[1]
  - leptoquarks[2]
  - low scale seesaw models[3]

[1] Phys. Rev. D **44**, 1461
[2] Z. Phys. C **61**, 613
[3] Phys. Rev. D **73**, 074011

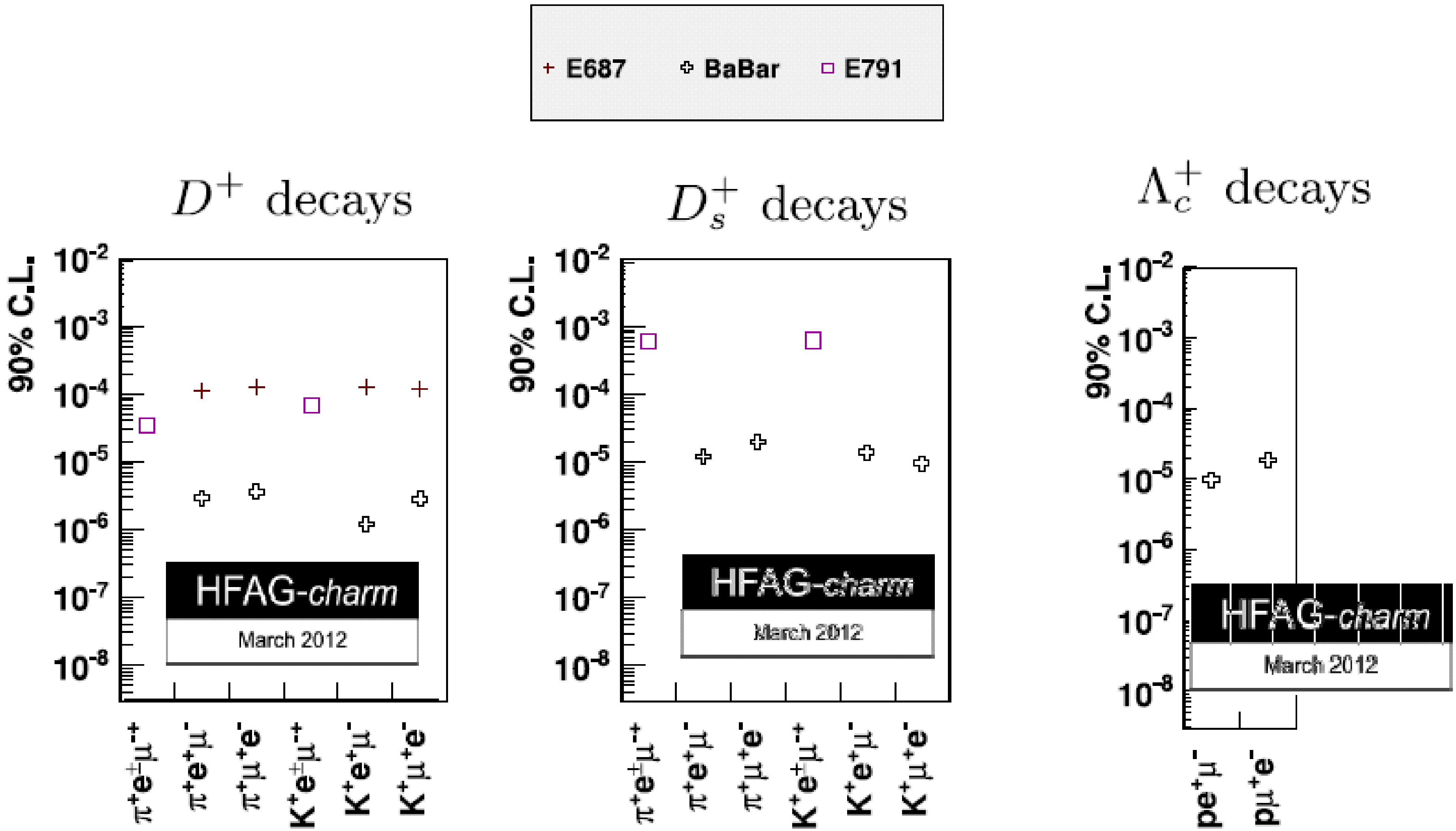
Standard Model + neutrino oscillation



extended Higgs

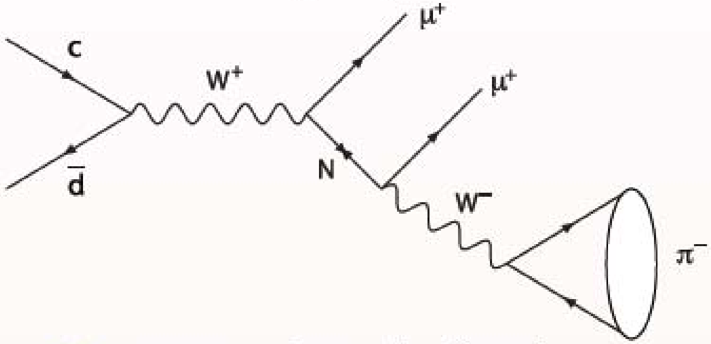


Overview of LFV in charm

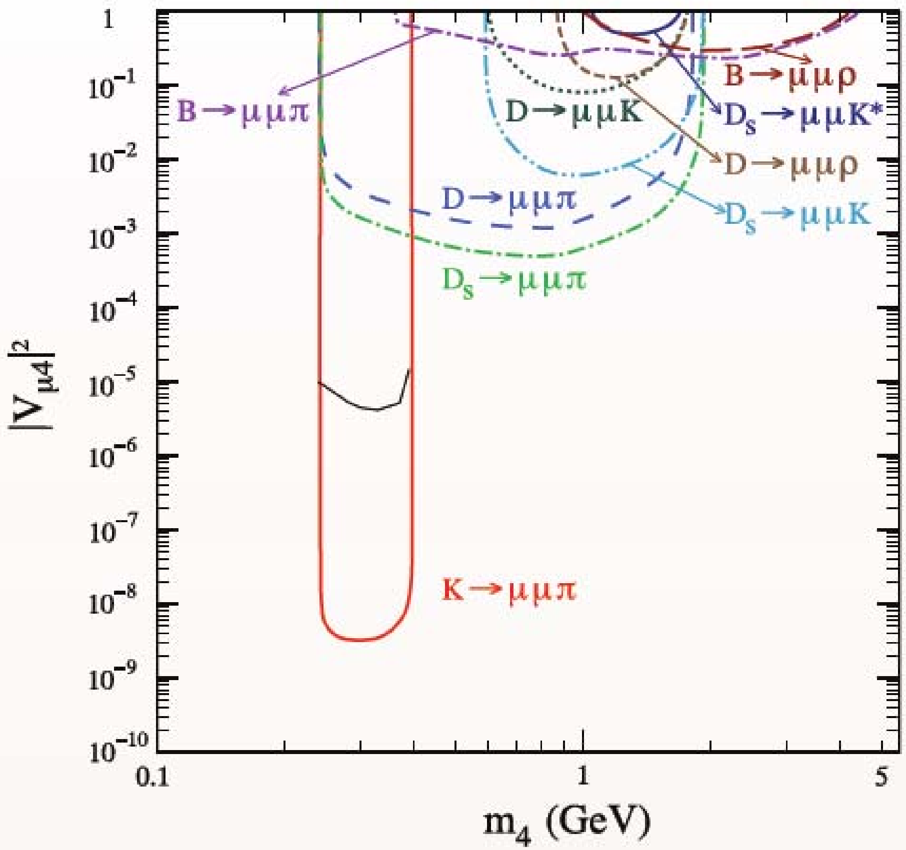


LNV in charm mesons

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



- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-,\pi^+}$



Status of 2009

arXiv:0901.3589

Limits on LNV in charm from BABAR

charm decays

- latest limits from BaBar
- includes Lepton Number and Flavour Violation
- comprehensive list of D^+, $\mathrm{D_s}^+$, and Λ_c^+ decays

Decay mode	Yield (events)	Eff. (%)	BR UL 90% CL (10^{-4})	BF UL 90% CL (10^{-6})
$D^+ \to \pi^- e^+ e^+$	$4.7 \pm 4.7 \pm 0.5$	3.16	6.8	1.9
$D^+ \to \pi^- \mu^+ \mu^+$	$-3.1 \pm 1.2 \pm 0.5$	0.70	7.5	2.0
$D^+ \to \pi^- \mu^+ e^+$	$-5.1 \pm 4.2 \pm 2.0$	1.72	7.4	2.0
$D_s^+ \to \pi^- e^+ e^+$	$-5.7 \pm 14. \pm 3.4$	6.84	1.8	4.1
$D_s^+ \to \pi^- \mu^+ \mu^+$	$0.6 \pm 5.1 \pm 2.7$	1.05	6.2	14
$D_s^+ \to \pi^- \mu^+ e^+$	$-0.2 \pm 7.9 \pm 0.6$	2.23	3.6	8.4
$D^+ \to K^- e^+ e^+$	$-2.8 \pm 2.4 \pm 0.2$	2.67	3.1	0.9
$D^+ \to K^- \mu^+ \mu^+$	$7.2 \pm 5.4 \pm 1.6$	0.80	37	10
$D^+ \to K^- \mu^+ e^+$	$-11.6 \pm 4.0 \pm 3.1$	1.52	6.8	1.9
$D_s^+ \to K^- e^+ e^+$	$2.3 \pm 7.9 \pm 3.3$	4.10	2.1	5.2
$D_s^+ \to K^- \mu^+ \mu^+$	$-2.3 \pm 5.0 \pm 2.8$	0.98	5.3	13
$D_s^+ \to K^- \mu^+ e^+$	$-14.0 \pm 8.4 \pm 2.0$	2.26	2.4	6.1
$\Lambda_c^+ \to \overline{p} e^+ e^+$	$-1.5 \pm 4.2 \pm 1.5$	5.14	0.4	2.7
$\Lambda_c^+ \to \overline{p} \mu^+ \mu^+$	$-0.0 \pm 2.1 \pm 0.6$	0.94	1.4	9.4
$\Lambda_c^+ \to \overline{p} \mu^+ e^+$	$10.1 \pm 5.8 \pm 3.5$	2.50	2.3	16

Phys. Rev. D **84**, 072006 (2011)

Sensitivities for rare charm decay at BESIII and super-B

- **$D \to X l^+ l^-$ can be reached at 10^{-6} at BESIII**

- **$D^0 \to l^+ l^-$ and $\gamma\gamma$ will be reached at 10^{-7}** at BESIII

BESIII may reach contribution from long distance

Sensitivities will be improved by order of two (10^{-8} -10^{-9}) at Super-B factories, and models can be tested.

Questions

- **Can we measure $D^0 \rightarrow \nu\bar{\nu}$, or $\gamma\nu\bar{\nu}$?**
- **Can we measure $D \rightarrow K/\pi\nu\bar{\nu}$?**

Radiative D decays-- Predictions

TABLE XI. Amplitudes (in GeV^{-1}) and branching fraction predictions.

Mode	$\mathcal{A}^{PC}$ P-I	$\mathcal{A}^{PC}$ P-II	$\mathcal{A}^{PC}$ VMD	$\mathcal{A}^{PV}$ VMD	$B_{D\to M_\gamma}(10^{-5})$
$D_s^+\rho^+\gamma$	8.2	-1.9	$\pm$ 3.2	± 2.8	6–38
$D^0\bar{K}^{*0}\gamma$	5.6	-5.9	± 3.8	$\pm(5.1–6.8)$	7–12
$D_s^+b_1^+\gamma$	7.2				~ 6.3
$D_s^+a_1^+\gamma$	1.2				~ 0.2
$D_s^+a_2^+\gamma$	2.1				~ 0.01
$D^+\rho^+\gamma$	1.3	-0.4	$\pm$ 1.6	± 1.9	2–6
$D^+b_1^+\gamma$	1.2				~ 3.5
$D^+a_1^+\gamma$	0.5				~ 0.04
$D^+a_2^+\gamma$	3.4				~ 0.03
$D_s^+K^{*+}\gamma$	2.8	-0.5	± 0.9	± 1.0	0.8–3
$D_s^+K_2^{*+}\gamma$	6.0				~ 0.2
$D^0\rho^0\gamma$	0.5	-0.5	$\pm(0.2–1.0)$	$\pm(0.6–1.0)$	0.1–0.5
$D^0\omega^0\gamma$	0.6	-0.7	± 0.6	± 0.7	$\simeq 0.2$
$D^0\phi^0\gamma$	0.7	-1.6	$\pm(0.6–3.5)$	$\pm(0.9–2.1)$	0.1–3.4
$D^+K^{*+}\gamma$	0.4	-0.1	± 0.4	± 0.4	0.1–0.3
$D^0K^{*0}\gamma$	0.2	-0.3	± 0.2	± 0.2	$\simeq 0.01$

PRD52, 6383

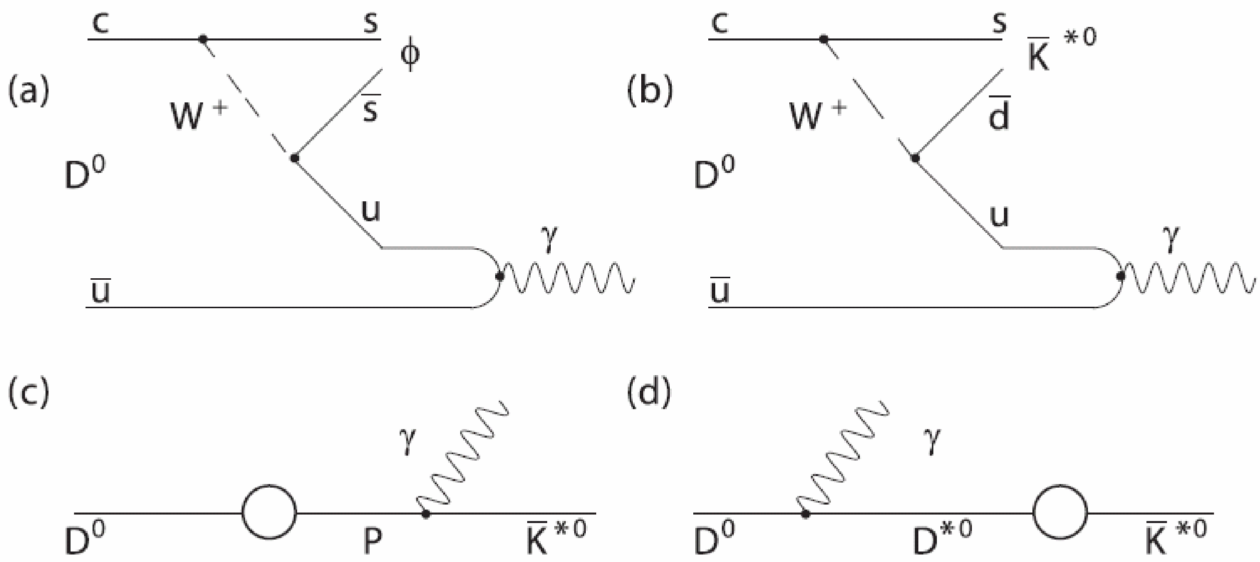
BABAR measurement:

$$\mathcal{B}(D^0 \to \phi\gamma) = (2.78 \pm 0.30 \pm 0.27) \times 10^{-5},$$

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (3.28 \pm 0.20 \pm 0.27) \times 10^{-4}.$$

$D^0 \rightarrow \phi\gamma$, $\bar{K}^{*0}\gamma$

Dominated short distance contribution (a) (b),
Long distance contribution: (c) and (d)

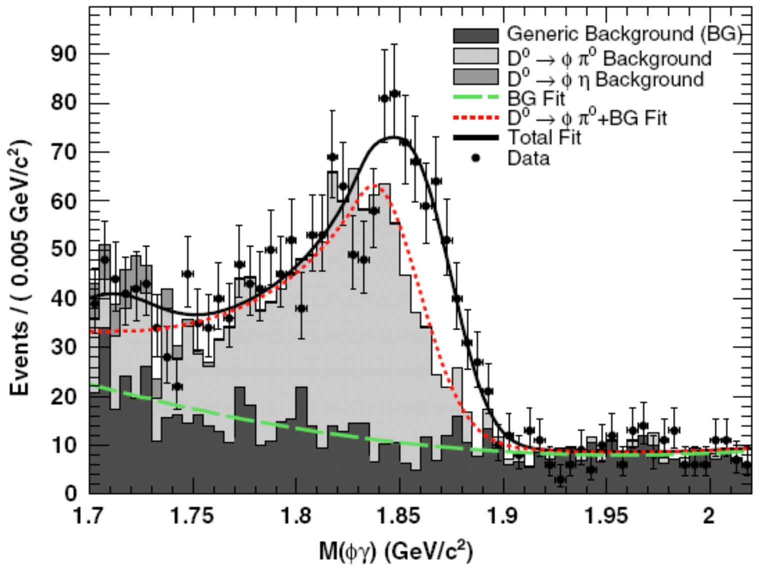


BABAR measurements:

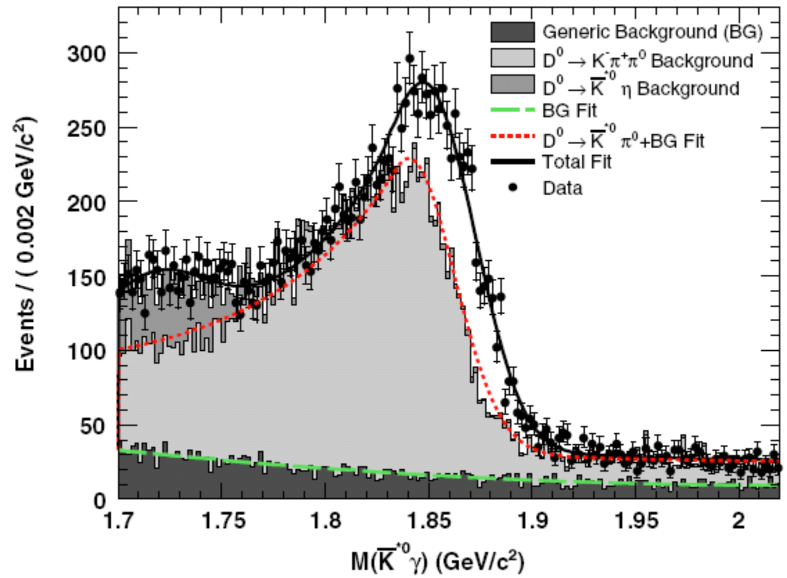
$$\mathcal{B}(D^0 \longrightarrow \phi\gamma) = (2.78 \pm 0.30 \pm 0.27) \times 10^{-5},$$

$$\mathcal{B}(D^0 \longrightarrow \bar{K}^{*0}\gamma) = (3.28 \pm 0.20 \pm 0.27) \times 10^{-4}.$$

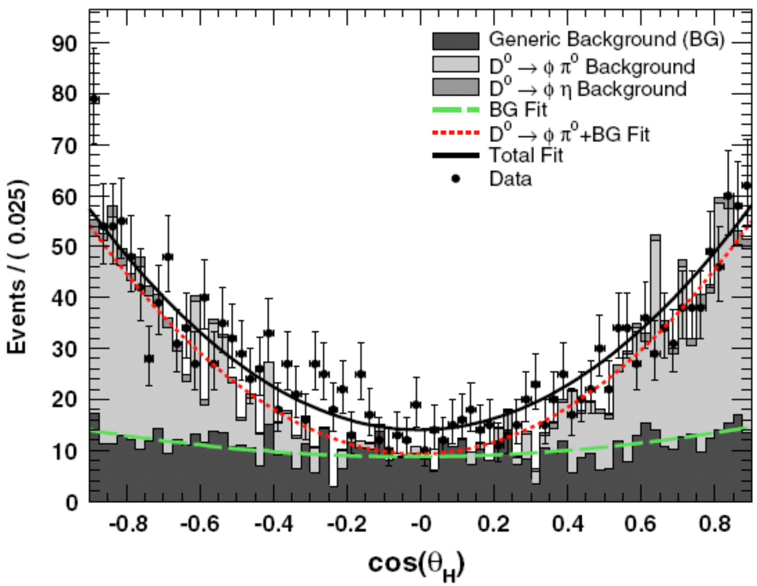
BABAR fit results

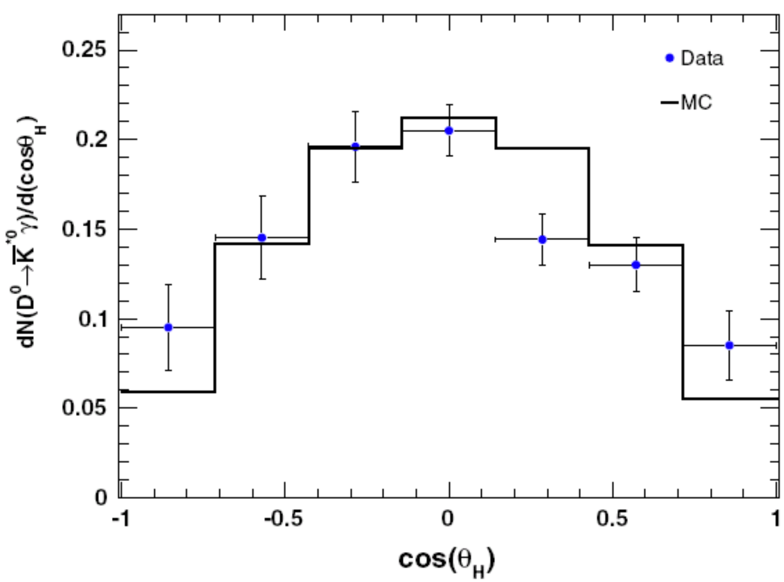


(a) The $\phi\gamma$ invariant mass distribution.



(c) The $\bar{K}^{*0}\gamma$ invariant mass distribution.

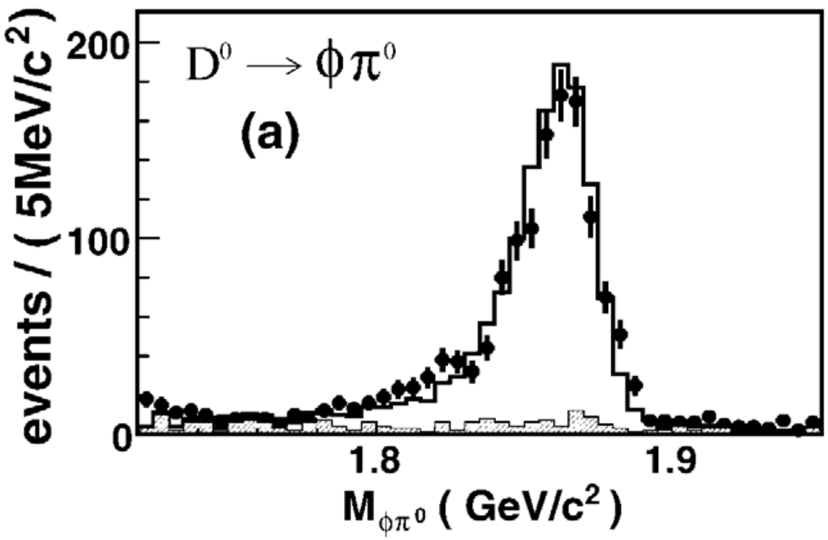


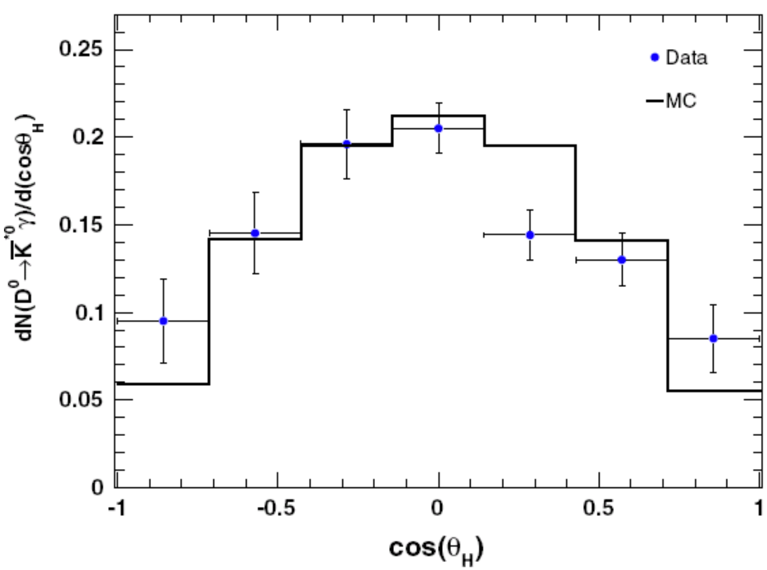


Dominant background $D^0 \rightarrow \phi\pi^0$

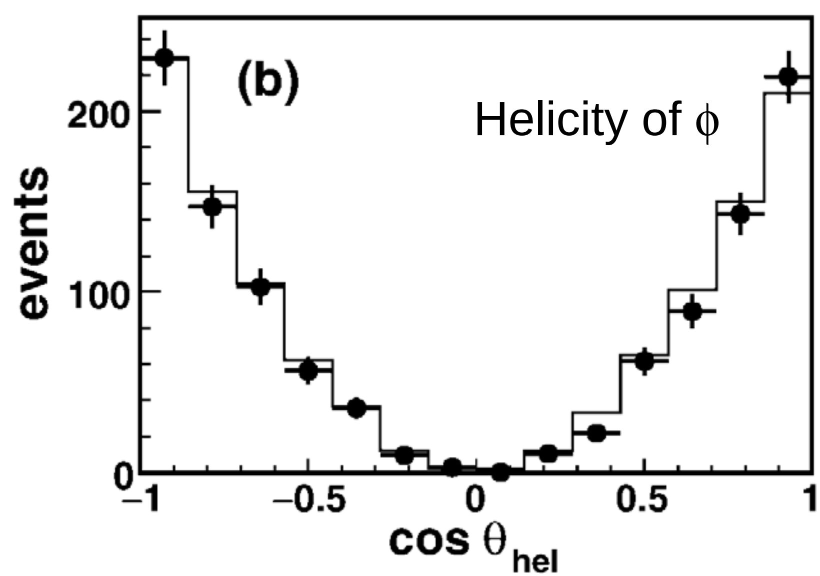
For background $D^0 \rightarrow \phi\,\pi^0$
the shape of $\cos(\theta_{hel})$ is $\cos(\theta)^2$

While for signal $D^0 \rightarrow \phi\,\gamma$
the shape of $\cos(\theta_{hel})$ is $1-\cos(\theta)^2$

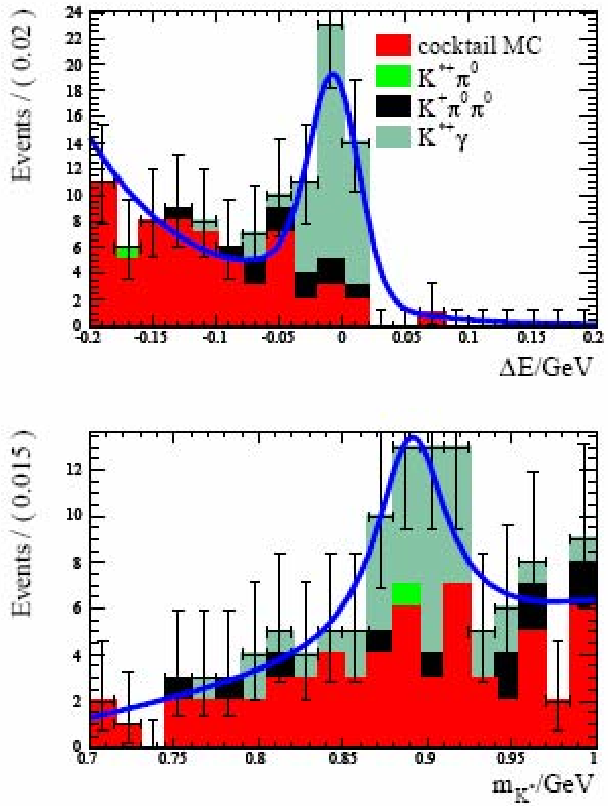




(d) The $D^0 \rightarrow \bar{K}^{*0}\gamma$ helicity angle distribution.



Study of $D^+ \rightarrow K^{*+} \gamma$ at BESIII



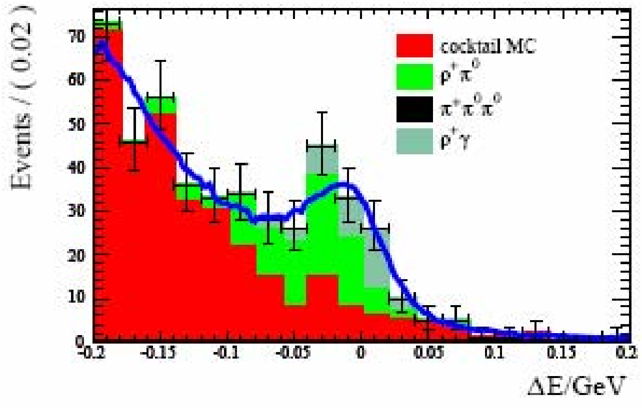
Expected peaking backgrounds:

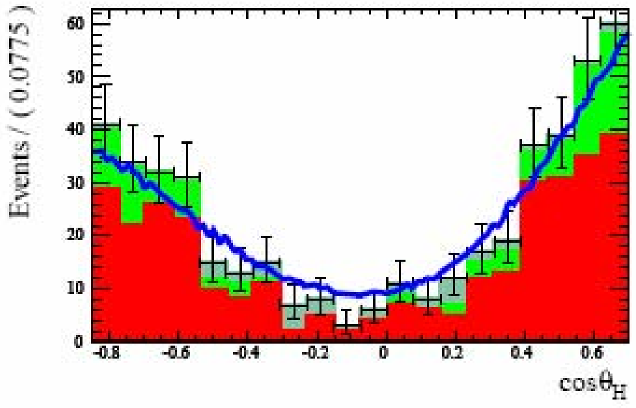
$D^+ \rightarrow K^{*+}\pi^0$: 1 events

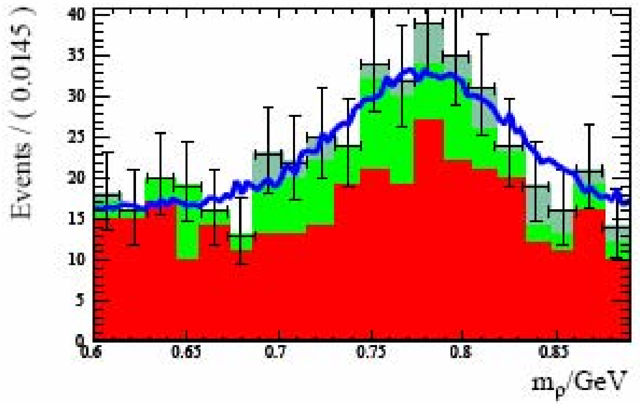
$D^+ \rightarrow K^+ \pi^0\pi^0$: 11 events

Figure 12: The fit results based on cocktail MC sample with 40 signal events inputed.

Study of $D^+ \rightarrow \rho^+ \gamma$ at BESIII







Expected peaking backgrounds:

$D^+ \rightarrow \rho^+\pi^0$: 101 events

$D^+ \rightarrow \pi^+ \pi^0\pi^0$: 0 events

Figure 20: The fit results based on cocktail MC sample with 40 signal events inputed

Highlights

- **$D \to Vl^+l^-$: A_{FB} asymmetry**
- **$D \to Pl^+l^-$: lineshape of lepton pair, interference effect between long-distance and FCNC weak amplitude (New physics amplitude);**
- **These variables are useful to discriminate NP from SM.**
- **Expected number of events: 1k – 10k at STF with 1ab $^{-1}$.**
- **We are looking at these decays at BESIII.**

谢谢！
预祝大家新年快乐！