Rare and forbidden decays of heavy flavor mesons at the B-factories and LHC

Abi Soffer
Tel Aviv University

For the ATLAS, BABAR, Belle, CMS, LHCb Collaborations

Recent results covered in this talk

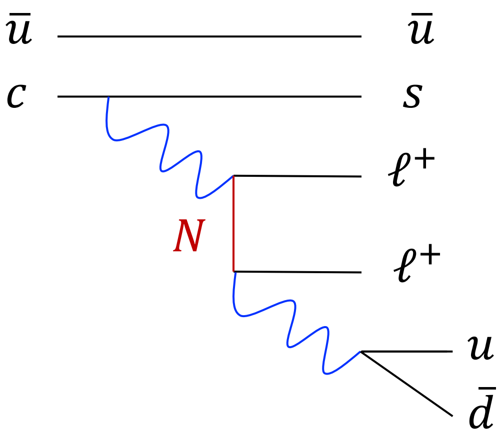
- LNV:
  - $D^0 \rightarrow h^{\mp} h'^{\mp} \ell^{\pm} \ell'^{\pm}$ BABAR
- LFV:
  - $D^0 \rightarrow h^{+} h'^{-} \ell^{+} \ell'^{-}$ BABAR — PRL 124 (2020) 071802
  - $D^0 \rightarrow X^0 e^{\pm} \mu^{\mp}$ BABAR — PRD 101 (2020) 112003
  - $B^+ \rightarrow K^+ \mu^- \tau^+$ LHCb — JHEP 2020 (2020) 129
- FCNC:
  - $B_{(s)} \rightarrow \mu^+ \mu^-$ ATLAS, CMS, LHCb — LHCb-CONF-2020-002, CMS PAS BPH-20-003, ATLAS-CONF-2020-049
  - $B^0 \rightarrow \text{invisible } (+\gamma)$ Belle — PRD 102 (2020) 012003

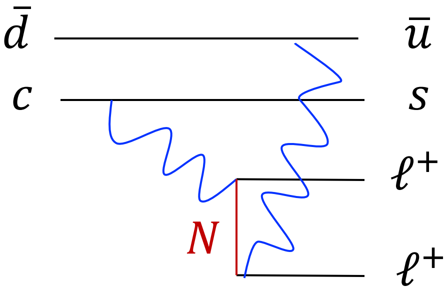
Lepton-number-violating decays

- Can be mediated by a Majorana neutrino that mixes with SM neutrino [1]:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{l=e}^{\tau} V_{lN}^* \overline{N^c} \gamma^\mu P_L l + \text{h.c.}$$

Mixing-matrix element





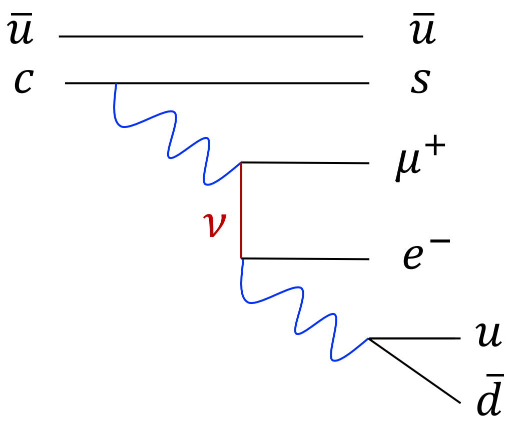
- 2nd-order, yet somewhat enhanced if N is on-shell, $m_N < m_{\text{hadron}}$
  - N can't be a SM neutrino (even if Majorana), since m_ν too small

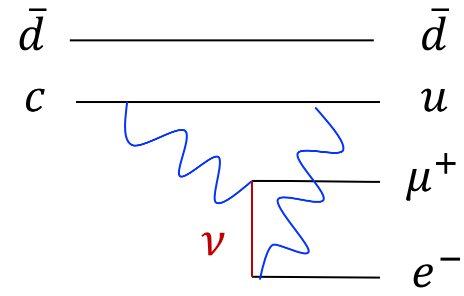
[1] e.g., Dong, Feng, Li, Chin. Phys. C 39 (2015) 013101

Lepton-flavor-violating decays

See talk by Avelino Vicente

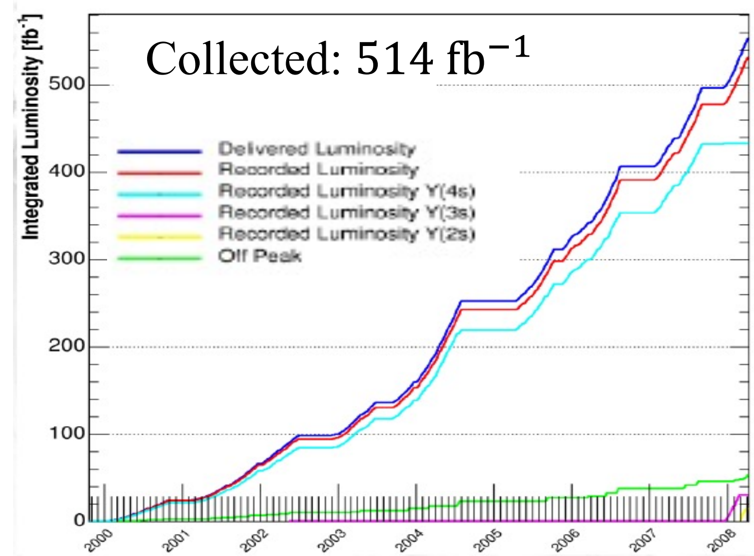
- In principle, possible due to neutrino flavor oscillations

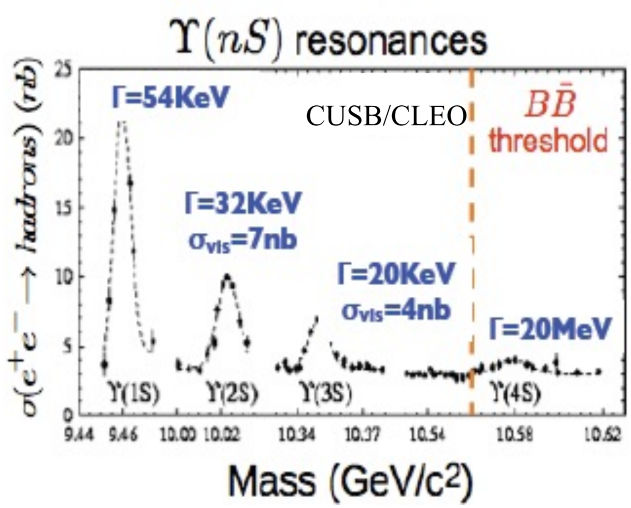




- But suppressed by slow neutrino oscillations & 2nd-order interaction
- Predicted LFV branching fractions $\ll 10^{-50}$
- → Any LFV observation requires BSM mediator that's highly LFV

The BABAR experiment





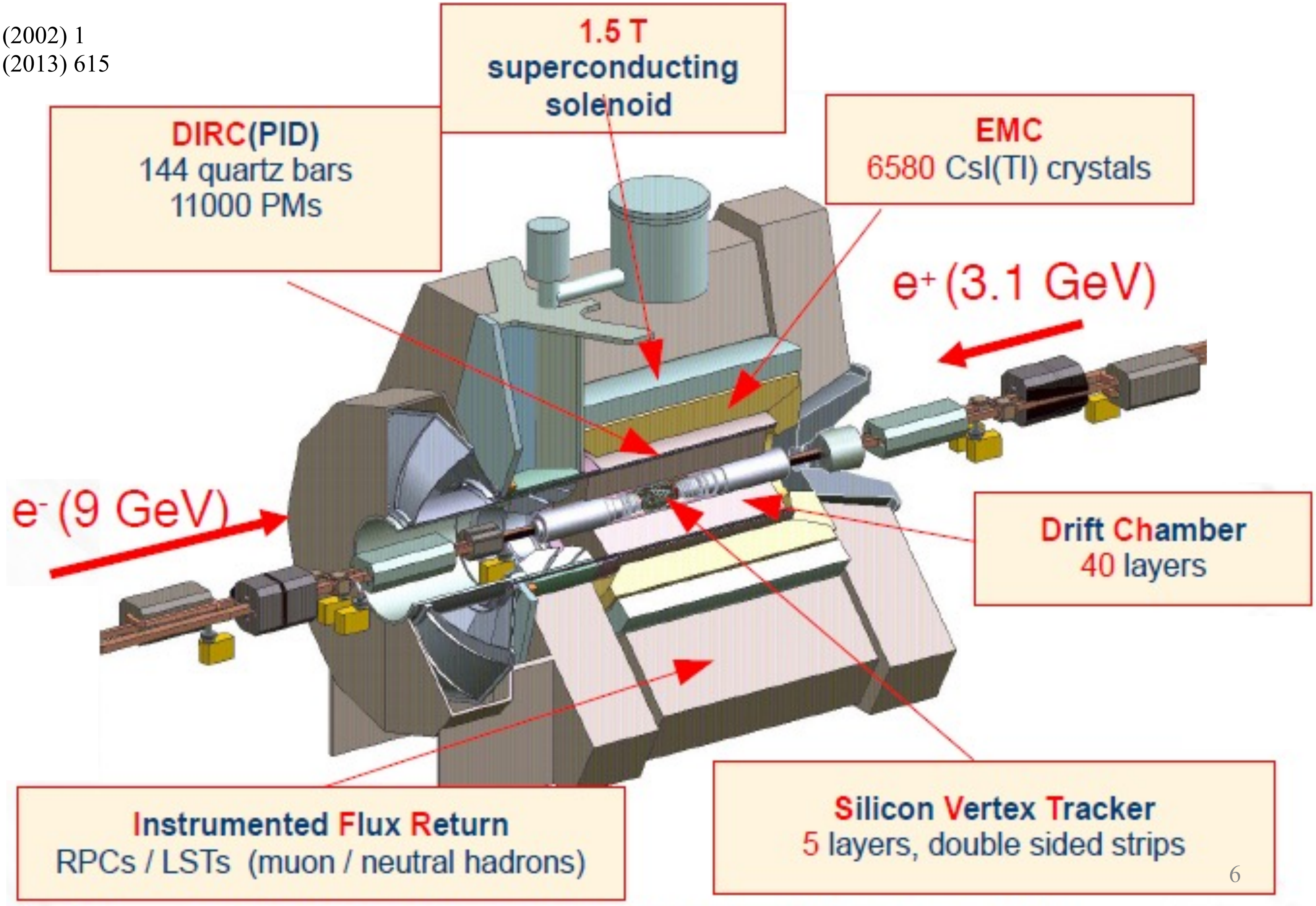
BABAR data

Resonance	L(fb^{-1})	#(10^6)
$\Upsilon(4S)$	424	471
$\Upsilon(3S)$	28	121
$\Upsilon(2S)$	14	99
Off-resonance	48	

40 fb^{-1} off-resonance in shown analysis

The BABAR Detector

NIM A479 (2002) 1
NIM A729 (2013) 615



$D^0 \to hh'\ell\ell'$ event selection

PRL 124 (2020) 071802

- Reconstruct $D^{*+} \to D^0\pi^+$ to reduce combinatorial background
- Select $D^0 \to$
  - LFV:

    $\pi^-\pi^+e^\pm\mu^\mp$, $K^-\pi^+e^\pm\mu^\mp$, $K^-K^+e^\pm\mu^\mp$
  - LNV:

    $\pi^-\pi^-e^+e^+$, $\pi^-\pi^-\mu^+\mu^+$, $\pi^-\pi^-e^+\mu^+$

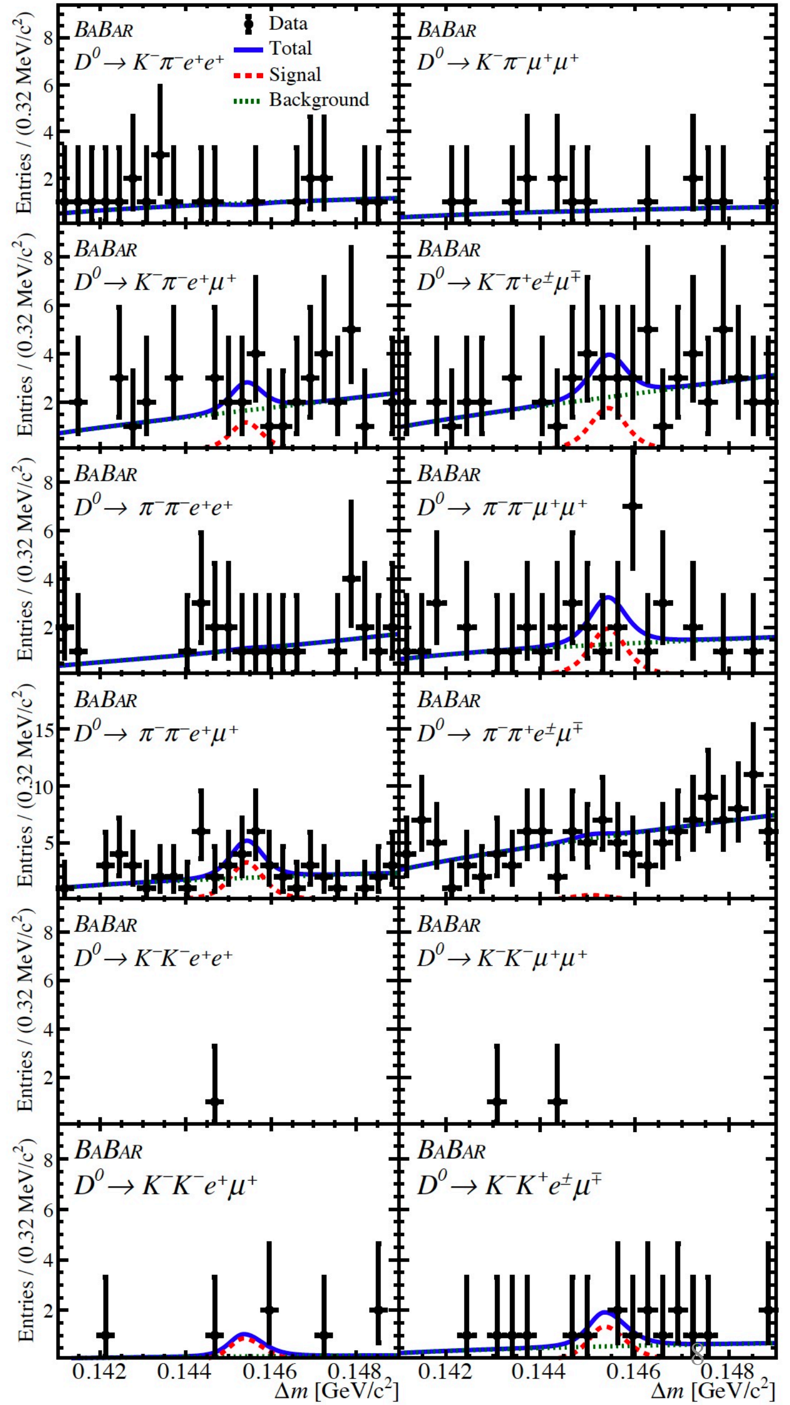
    $K^-\pi^-e^+e^+$, $K^-\pi^-\mu^+\mu^+$, $K^-\pi^-e^+\mu^+$

    $K^-K^-e^+e^+$, $K^-K^-\mu^+\mu^+$, $K^-Ke^+\mu^+$

- Hadronic-decays background (e.g., Cabibbo-favored $D^0 \to K^-\pi^+\pi^-\pi^+$) suppressed by requiring $m(K3\pi)$ to be inconsistent with M_{D^0}
- Backgrounds from leptons arising from semileptonic decays or charm decays with missing neutrals is suppressed with Fisher discriminant of 9 kinematic variables.

$D^0 \to hh'\ell\ell'$ yields

- Determined for each mode from fit to $\Delta m \equiv m(D^{*+}) - m(D^0)$ →



- Signal PDF = $e^{-(m-m_0)^2/[2\sigma^2_{L,R}+\alpha_{L,R}(m-m_0)^2]}$ (Cruijff function)

- Bgd PDF = $m \cdot \left[1-\left(\frac{m}{m_0}\right)^2\right]^p \cdot \exp\left[c \cdot \left(1-\left(\frac{m}{m_0}\right)^2\right)\right]$ (ARGUS function)

- No significant signal seen
- Signal Br and upper limits determined wrt. normalization mode $D^0 \to hh'\pi\pi$:

Decay mode	N_{norm} (candidates)	Systematic (%)
$D^0 \to K^-\pi^+\pi^+\pi^-$	$260\,870 \pm 520$	4.7
$D^0 \to K^-K^+\pi^+\pi^-$	8480 ± 110	6.6
$D^0 \to \pi^-\pi^+\pi^+\pi^-$	$28\,470 \pm 220$	6.8

$D^0 \to hh'\ell\ell'$ results

PRL 124 (2020) 071802

E791, PRL 86 (2001) 3969

Decay mode $D^0 \to$	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$)	Previous best limit ($\times 10^{-7}$)
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	4.38	$0.27 \pm 3.90 \pm 0.67$	9.1	1120
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	4.91	$7.40 \pm 5.40 \pm 0.91$	15.2	290
$\pi^-\pi^-e^+\mu^+$	$12.42 \pm 5.30 \pm 1.45$	4.38	$15.4 \pm 6.59 \pm 1.85$	30.6	790
$\pi^-\pi^+e^\pm\mu^\mp$	$1.37 \pm 6.15 \pm 1.28$	4.79	$1.55 \pm 6.97 \pm 1.45$	17.1	150
$K^-\pi^-e^+e^+$	$-0.23 \pm 0.97 \pm 1.28$	3.19	$-0.38 \pm 1.60 \pm 2.11$	5.0	2060
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	3.30	$-0.05 \pm 3.34 \pm 0.64$	5.3	3900
$K^-\pi^-e^+\mu^+$	$3.87 \pm 3.96 \pm 2.36$	3.48	$5.84 \pm 5.97 \pm 3.56$	21.0	2180
$K^-\pi^+e^\pm\mu^\mp$	$2.52 \pm 4.60 \pm 1.35$	3.65	$3.62 \pm 6.61 \pm 1.95$	19.0	5530
$K^-K^-e^+e^+$	$0.30 \pm 1.08 \pm 0.41$	3.25	$0.43 \pm 1.54 \pm 0.58$	3.4	1520
$K^-K^-\mu^+\mu^+$	$-1.09 \pm 1.29 \pm 0.42$	6.21	$-0.81 \pm 0.96 \pm 0.32$	1.0	950
$K^-K^-e^+\mu^+$	$1.93 \pm 1.92 \pm 0.83$	4.63	$1.93 \pm 1.93 \pm 0.84$	5.8	570
$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	4.83	$3.93 \pm 2.89 \pm 1.45$	10.0	1800

Implications for $V_{\ell N}$

- The authors of ref. [1] provide an expected limit plot for $|V_{N\ell}|^2$

- They comment that this is based on a MC study in an unpublished thesis, using 2.9 fb^{-1} collected at the $\psi(3770)$, leading to an expected Br limit $Br(D^0 \to K^-\pi^-e^+e^+) <\sim 10^{-9}$, too low given the cross section of 3.7 nb.

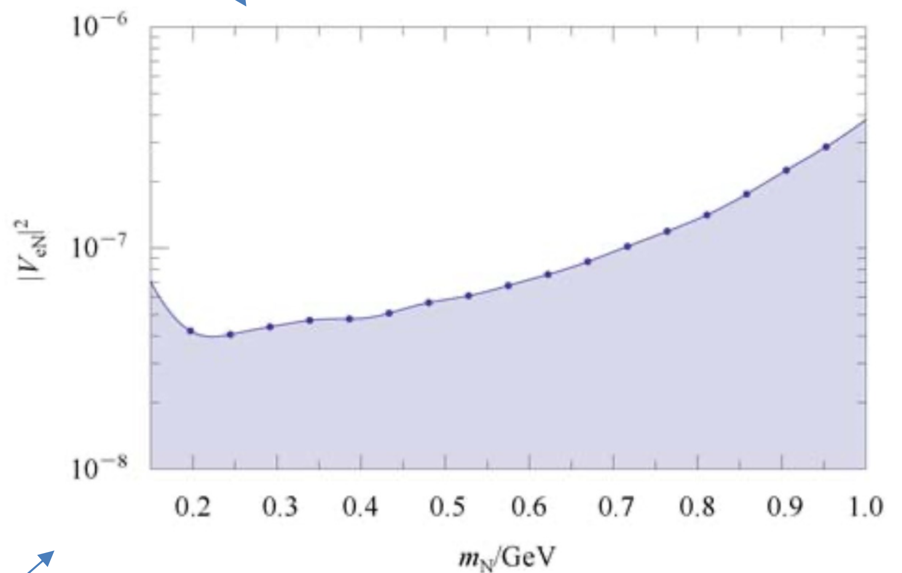


Fig. 3. Upper limits on $|V_{eN}|^2$ at 90% confidence level as a function of the Majorana neutrino mass from the $D^0 \to K^- e^+ e^+ \pi^-$ estimated from the MC study at BESIII.

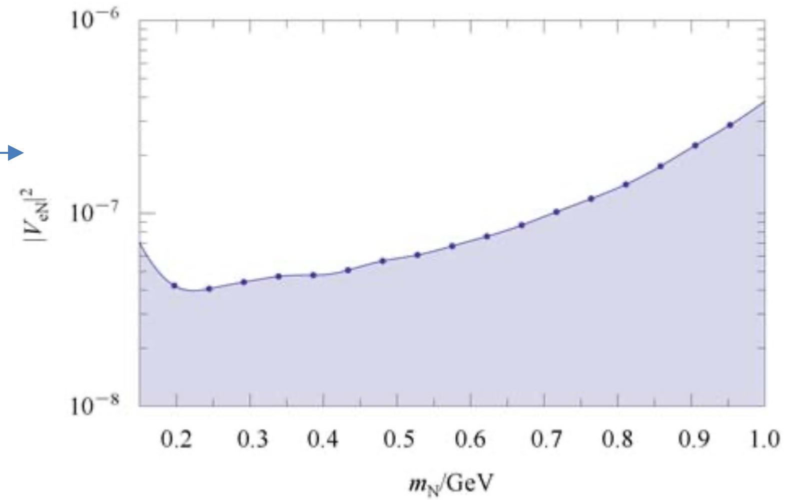
- Later, BESIII obtained a weaker limit [2], $Br(D^0 \to K^-\pi^-e^+e^+) < 2.8\times10^{-6}$ (cf. BABAR: 5.0×10^{-7})

- So this plot seems $O(300)$ too tight

[1] Dong, Feng, Li, Chin. Phys. C 39 (2015) 013101
[2] BESIII, PRD 99 (2019) 112002

Implications for $V_{\ell N}$

If so, the ~×300 projected limit for BESIII is similar to observed limits from searches for heavy neutral leptons
(summarized in Belle paper PRD 87 (2013) 071102, excluding newer measurements)



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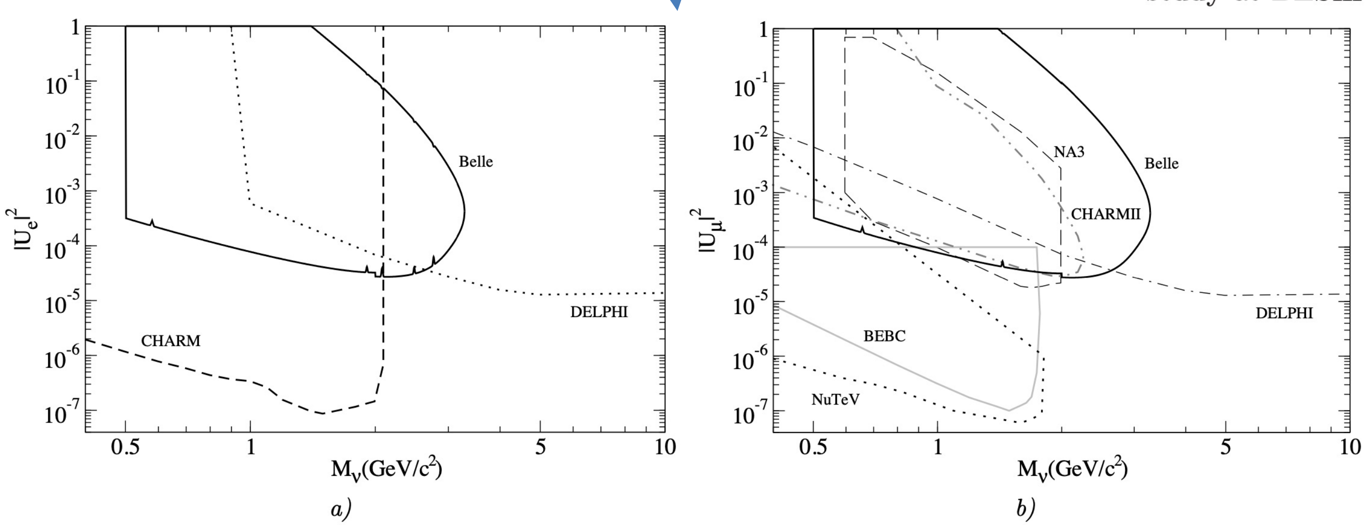
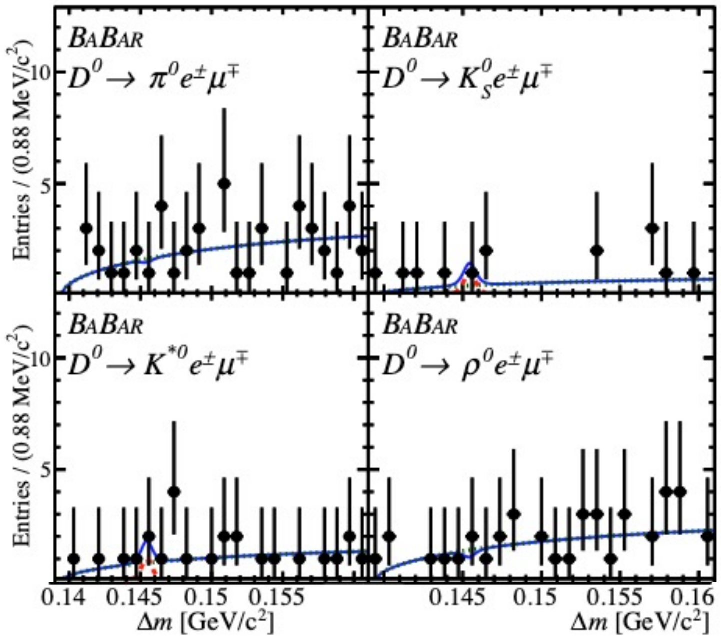
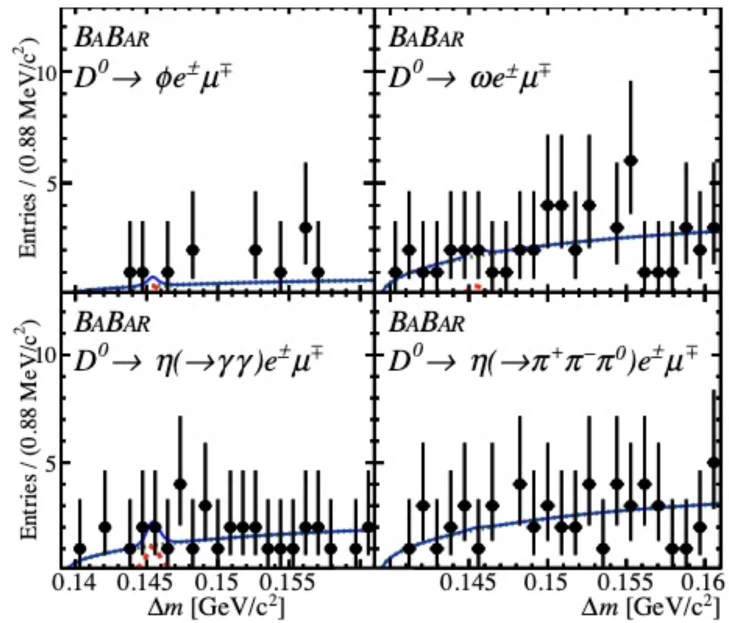


FIG. 2. Comparison of the obtained upper limits for $|U_e|^2$ *(a)* and $|U_\mu|^2$ *(b)* with existing experimental results from CHARM, CHARMII, DELPHI, NuTeV, BEBC and NA3.

$D^0 \to X^0 \ell\ell'$ results

PRD 101 (2020) 112003





Decay mode	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ $(\times 10^{-7})$	$\mathcal{B}$ 90% U.L. $(\times 10^{-7})$ BABAR	Previous
$D^0 \to \pi^0 e^\pm \mu^\mp$	$-0.3 \pm 2.0 \pm 0.9$	2.15 ± 0.03	$-0.6 \pm 4.8 \pm 2.3$	8.0	860
$D^0 \to K^0_S e^\pm \mu^\mp$	$0.7 \pm 1.7 \pm 0.7$	3.01 ± 0.04	$1.9 \pm 4.6 \pm 1.9$	8.6	500
$D^0 \to \overline{K}^{*0} e^\pm \mu^\mp$	$0.8 \pm 1.8 \pm 0.8$	2.31 ± 0.03	$2.8 \pm 6.1 \pm 2.6$	12.4	830
$D^0 \to \rho^0 e^\pm \mu^\mp$	$-0.7 \pm 1.7 \pm 0.4$	2.10 ± 0.03	$-1.8 \pm 4.4 \pm 1.0$	5.0	490
$D^0 \to \phi e^\pm \mu^\mp$	$0.0 \pm 1.4 \pm 0.3$	3.43 ± 0.04	$0.1 \pm 3.8 \pm 0.9$	5.1	340
$D^0 \to \omega e^\pm \mu^\mp$	$0.4 \pm 2.3 \pm 0.5$	1.46 ± 0.03	$1.8 \pm 9.5 \pm 1.9$	17.1	1200
$D^0 \to \eta e^\pm \mu^\mp$			$6.1 \pm 9.7 \pm 2.3$	22.5	1000
with $\eta \to \gamma\gamma$	$1.6 \pm 2.3 \pm 0.5$	2.96 ± 0.04	$7.0 \pm 10.5 \pm 2.4$	24.0	
with $\eta \to \pi^+\pi^-\pi^0$	$0.0 \pm 2.8 \pm 0.7$	2.46 ± 0.04	$0.4 \pm 25.8 \pm 6.0$	42.8	

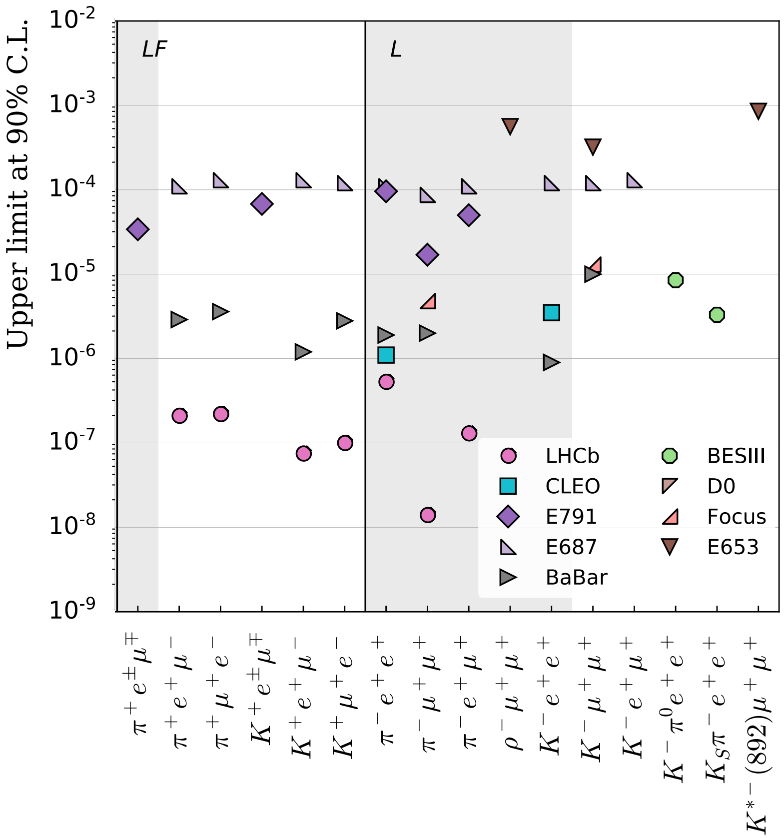
CLEO,
PRL 76 (1996) 3065.

E791,
PRL 86 (2001) 3969

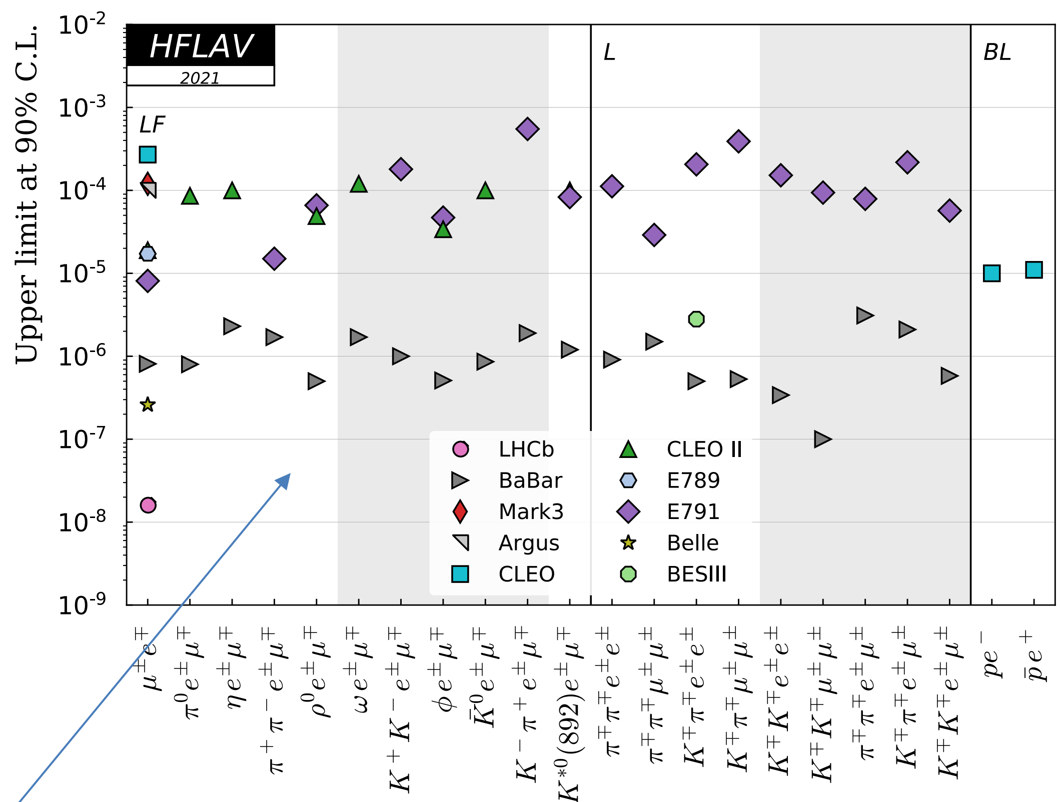
Summary of charm LNV/LFV

Heavy Flavor Averaging Group https://hflav.web.cern.ch

D^+



D^0

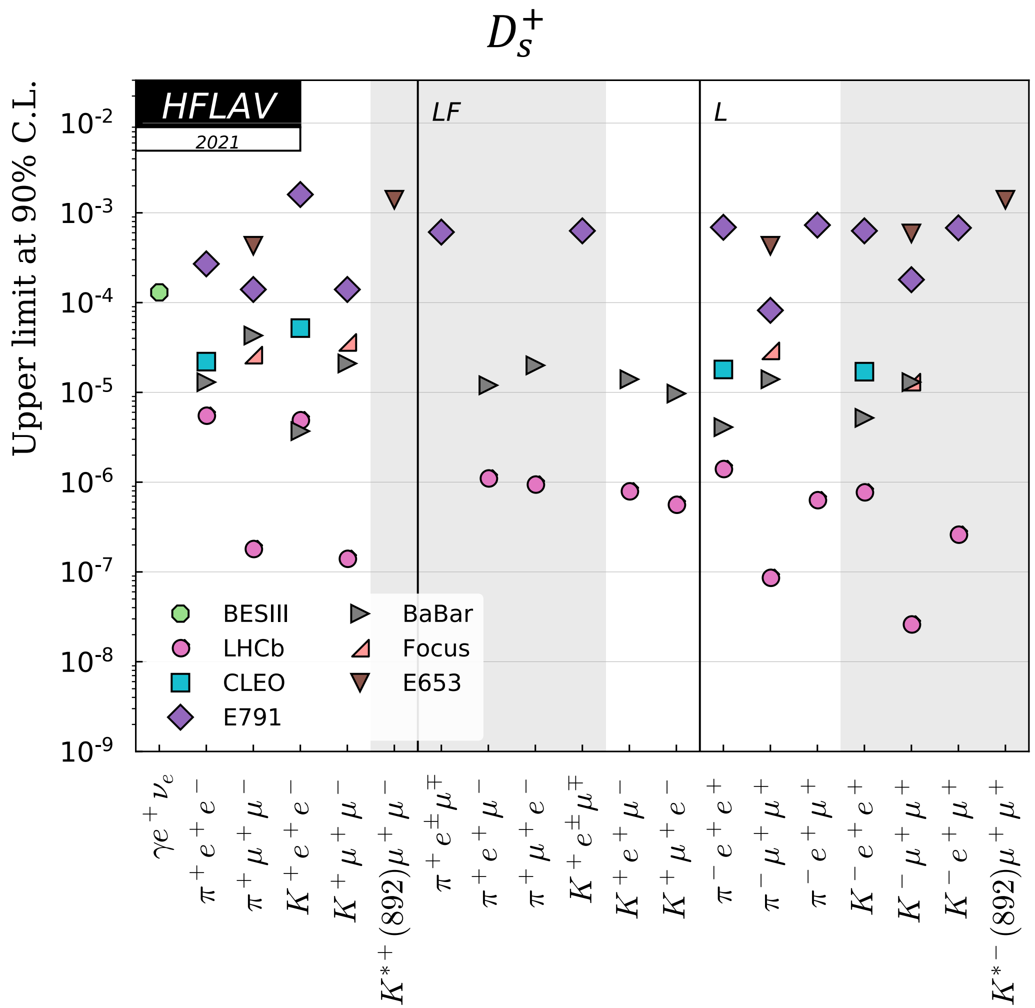


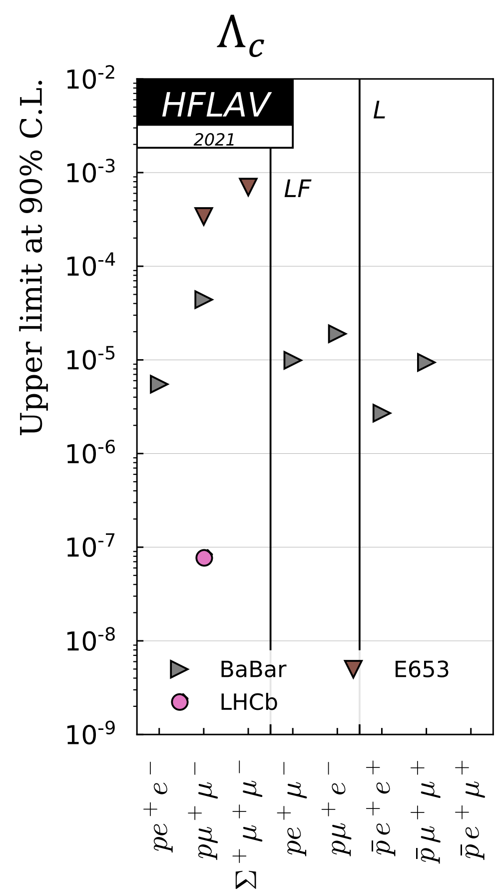
LHCb could greatly improve the D^0 modes

Some of these shown today

Summary of LNV/LFV

Heavy Flavor Averaging Group https://hflav.web.cern.ch

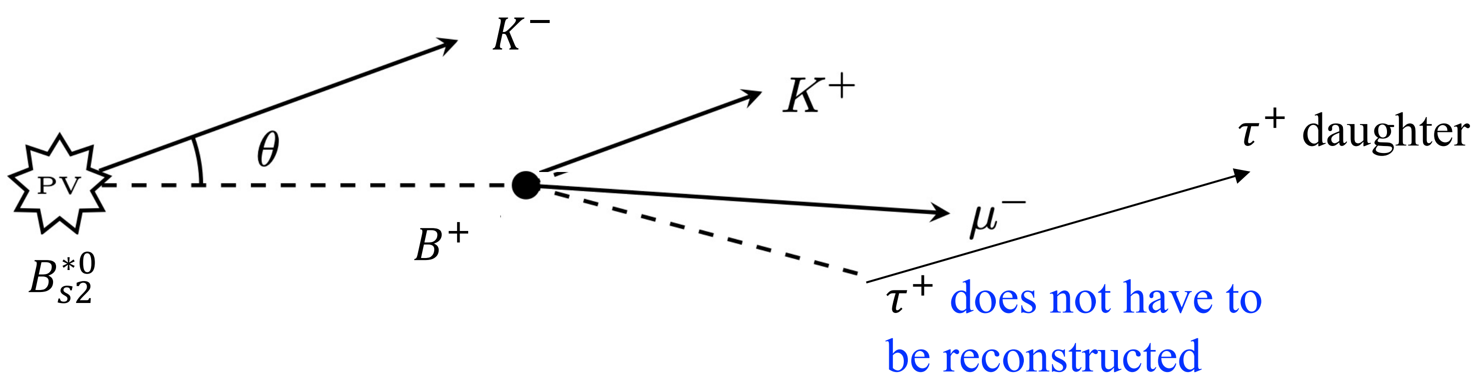




Search for $B^+ \to K^+\mu^-\tau^+$

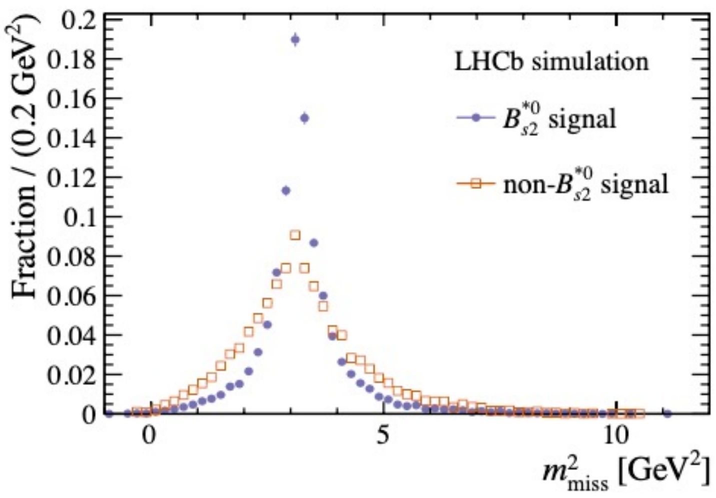
LHCb, JHEP 2020 (2020) 129   9 fb^{-1}

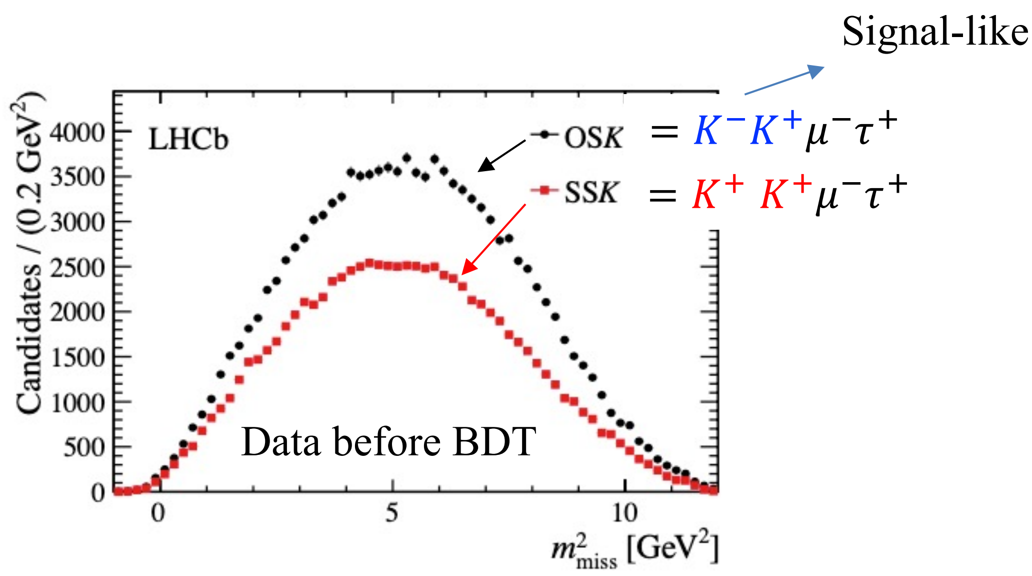
- This charge combination is cleaner than $B^+ \to K^+\mu^+\tau^-$, which has more background from $B \to \overline{D}X\mu^+\nu_\mu$ due to $\overline{D} \to K^+$
- Produce the B^+ in the decay $B_{s2}^{*0} \to B^+K^-$
- Obtain the τ^- 4-momentum up to a quadratic ambiguity by using the $K^+\mu^-$ vertex and the known masses.



– Previously used this technique for $B^+ \to \overline{D}^0X\mu^+\nu_\mu$ [PRD 99 (2019) 092009

Signal & background



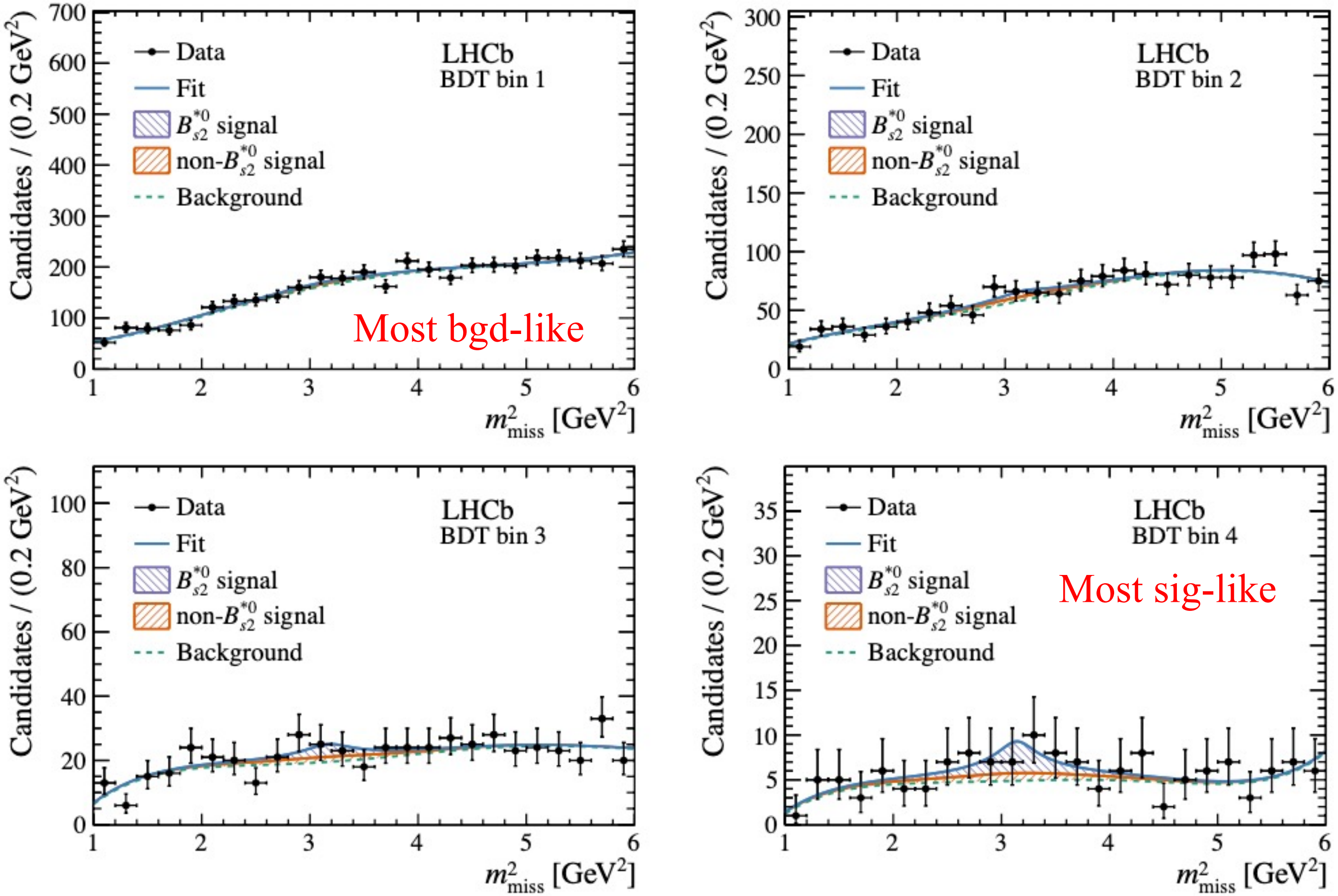


- Use the SSK sample to train a BDT to separate signal from background, e.g.,
  - $\bar{B} \to D(\to K^+X)Y\mu^-\bar{\nu}_\mu$ (SL b decays with wrong-sign charm decay)
  - $B \to \bar{D}(\to K^+\mu^-\bar{\nu}_\mu)Y$ (μ^- from charm decay)

- Although $M_D \sim M_\tau$, there is no SM background that peaks in $m^2_{\rm miss}$, e.g.,
  - $B^+ \to K^+\mu^-(\bar{\nu}_\mu)D^+$ not possible in the SM
  - $B^+ \to K^+\pi^-D^+$ is 2nd order (with π^- misidentified as μ^-)

Signal extraction

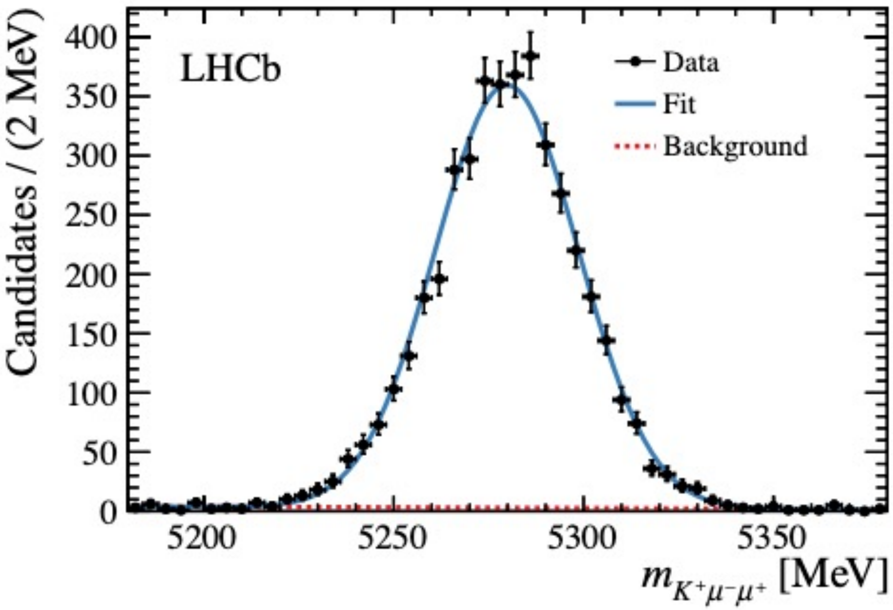
Fit m^2_{miss} distribution to signal peak + polynomial background in 4 BDT bins

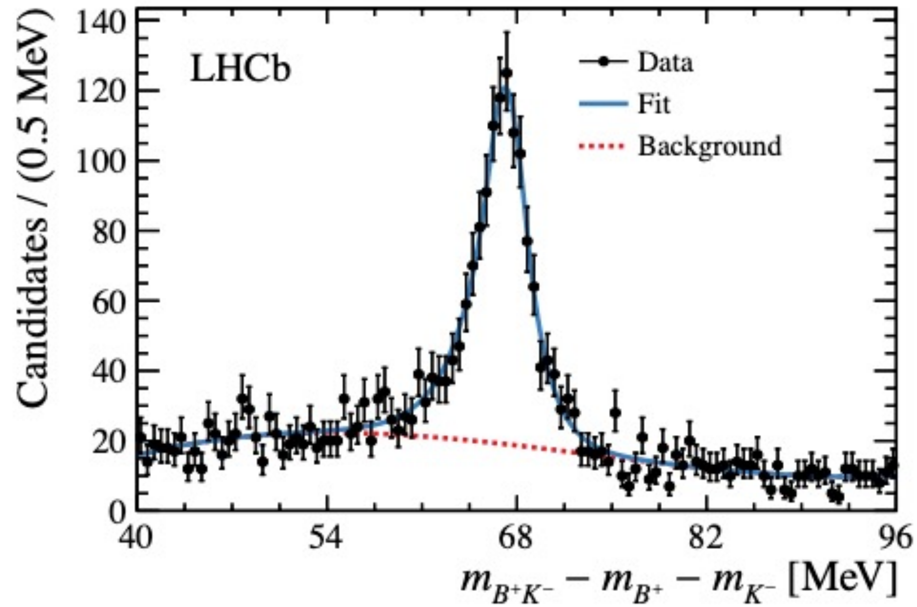


No significant signal

Normalization and results

Normalize the yield to $B^+ \to J/\psi\, K^+$





$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 3.9 \times 10^{-5} \text{ at } 90\% \text{ CL},$$
$$< 4.5 \times 10^{-5} \text{ at } 95\% \text{ CL}.$$

LNV & LFV
B decays summary

HFLAV https://hflav.web.cern.ch

Heavy FLavor AVeraging group (HFLAV) - April 2019

Compilation of B^+ Semi-leptonic LFV & LNV Branching Fractions ($\times 10^{-6}$) - UL at 90% CL

RPP#	Mode	PDG2017 Avg.	*BABAR*	BELLE	LHCb	Our Avg.
552	$\pi^+ e^\pm \mu^\mp$	< 0.17	< 0.17			< 0.17
553	$\pi^+ e^+ \tau^-$	< 74	< 74			< 74
554	$\pi^+ e^- \tau^+$	< 20	< 20			< 20
555	$\pi^+ e^\pm \tau^\mp$	< 75	< 75			< 75
556	$\pi^+ \mu^+ \tau^-$	< 62	< 62			< 62
557	$\pi^+ \mu^- \tau^+$	< 45	< 45			< 45
558	$\pi^+ \mu^\pm \tau^\mp$	< 72	< 72			< 72
559	$K^+ e^+ \mu^-$	< 0.091	< 0.091			< 0.091
560	$K^+ e^- \mu^+$	< 0.13	< 0.13			< 0.13
561	$K^+ e^\pm \mu^\mp$	< 0.091	< 0.091			< 0.091
562	$K^+ e^+ \tau^-$	< 43	< 43			< 43
563	$K^+ e^- \tau^+$	< 15	< 15			< 15
564	$K^+ e^\pm \tau^\mp$	< 30	< 30			< 30
565	$K^+ \mu^+ \tau^-$	< 45	< 45			< 45
566	$K^+ \mu^- \tau^+$	< 28	< 28		< 39	< 28
567	$K^+ \mu^\pm \tau^\mp$	< 48	< 48			< 48
568	$K^{*+} e^+ \mu^-$	< 1.3	< 1.3			< 1.3
569	$K^{*+} e^- \mu^+$	< 0.99	< 0.99			< 0.99
570	$K^{*+} e^\pm \mu^\mp$	< 1.4	< 1.4			< 1.4
571	$\pi^- e^+ e^+$	< 0.023	< 0.023			< 0.023
572	$\pi^- \mu^+ \mu^+$	< 0.013	< 0.107		$< 0.004^{\dagger}$	$< 0.004^{\dagger}$
573	$\pi^- e^+ \mu^+$	< 0.15	< 0.15			< 0.15
574	$\rho^- e^+ e^+$	< 0.17	< 0.17			< 0.17
575	$\rho^- \mu^+ \mu^+$	< 0.42	< 0.42			< 0.42
576	$\rho^- e^+ \mu^+$	< 0.47	< 0.47			< 0.47
577	$K^- e^+ e^+$	< 0.03	< 0.03			< 0.03
578	$K^- \mu^+ \mu^+$	< 0.041	< 0.067		< 0.041	< 0.041
579	$K^- e^+ \mu^+$	< 0.16	< 0.16			< 0.16
580	$K^{*-} e^+ e^+$	< 0.40	< 0.40			< 0.40
581	$K^{*-} \mu^+ \mu^+$	< 0.59	< 0.59			< 0.59
582	$K^{*-} e^+ \mu^+$	< 0.30	< 0.30			< 0.30
583	$D^- e^+ e^+$	< 2.6	< 2.6	< 2.6		< 2.6
584	$D^- e^+ \mu^+$	< 1.8	< 2.1	< 1.8		< 1.8
585	$D^- \mu^+ \mu^+$	< 0.69	< 1.7	< 1.1	< 0.69	< 0.69
586	$D_s^- \mu^+ \mu^+$	< 0.58			< 0.58	< 0.58
587	$\bar{D}^0 \pi^- \mu^+ \mu^+$	< 1.5			< 1.5	< 1.5
589	$\Lambda^0 \mu^+$	< 0.06	< 0.06			< 0.06
590	$\Lambda^0 e^+$	< 0.032	< 0.032			< 0.032
591	$\bar{\Lambda}^0 \mu^+$	< 0.06	< 0.06			< 0.06
592	$\bar{\Lambda}^0 e^+$	< 0.08	< 0.08			< 0.08

Chuck Norris observed LFV.
LNV too.

$B^0_{(s)} \to \mu^+\mu^-$ LHC combination

Same note:

LHCb-CONF-2020-002
CMS PAS BPH-20-003
ATLAS-CONF-2020-049

PRL 118 (2017) 191801, 1 fb^{-1} @ 7/8 TeV + 1.4 fb^{-1} @ 13 TeV
JHEP 04 (2020) 188, 25 fb^{-1} @ 7/8 TeV + 26.3 fb^{-1} @ 13 TeV
JHEP 04 (2019) 098, 25 fb^{-1} @ 7/8 TeV + 36.0 fb^{-1} @ 13 TeV

- FCNC decays, both loop- and helicity-suppressed
- Very rare in the SM and hence a good probe of NP
- Uncertainties in the SM BR calculation recently reduced thanks to advances in
  - Lattice QCD [e.g., Flavour Lattice Averaging Group, EPJC 80 (2020) 113]
  - EW effects at NLO [Bobeth, Gorbahn, Stamou, PRD 89 (2014) 034023]
  - QCD effects at NNLO [Hermann, Misiak, Steinhauser, JHEP 12 (2013) 097]
- SM expectations for the BRs:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

Effective lifetime for $B_s \to \mu^+\mu^-$

Time-dependent partial width for $B_s + \bar{B}_s$ (no flavor tag)

$$\tau_{B_s^0\to\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\langle\Gamma\left(B_s^0 \to \mu^+\mu^-\right)\rangle\,dt}{\int_0^\infty \langle\Gamma\left(B_s^0 \to \mu^+\mu^-\right)\rangle\,dt}$$

$$= \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2\mathcal{A}_{\Delta\Gamma}y_s+y_s^2}{1+\mathcal{A}_{\Delta\Gamma}y_s}\right]$$

Width diff. b/w mass eigenstates

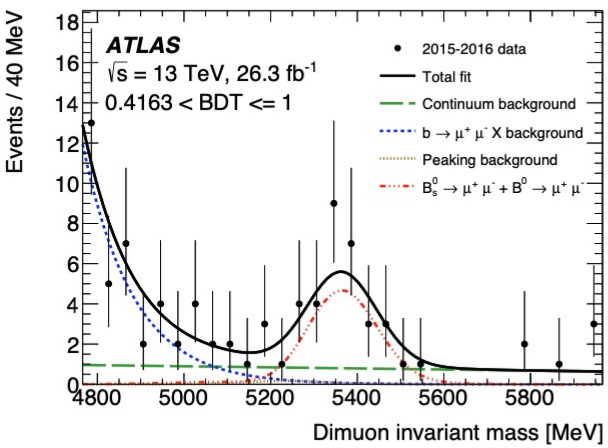
$$y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s}, \qquad \mathcal{A}_{\Delta\Gamma} \equiv \frac{R_H^{\mu^+\mu^-} - R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-} + R_L^{\mu^+\mu^-}}$$

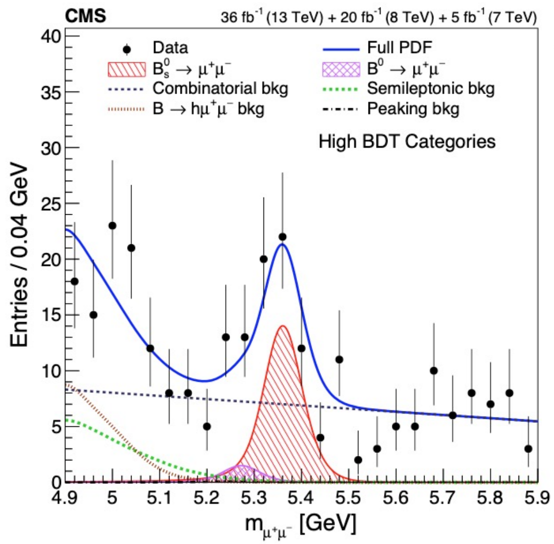
Average width of mass eigenstates, $1/\tau_{B_s}$

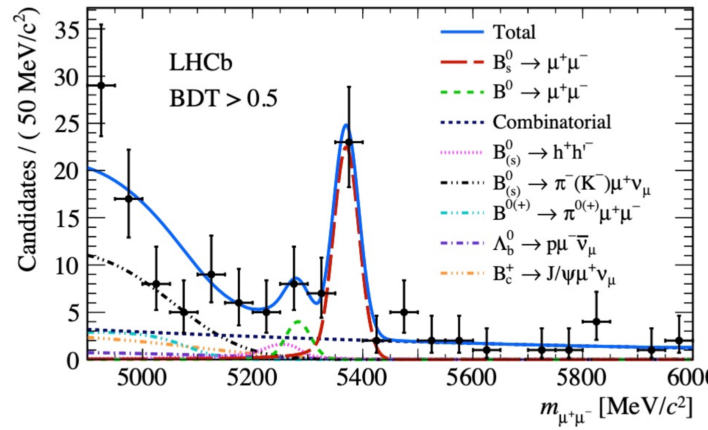
Heavy- and light-eigenstate contribution to the decay $\to \mu^+\mu^-$

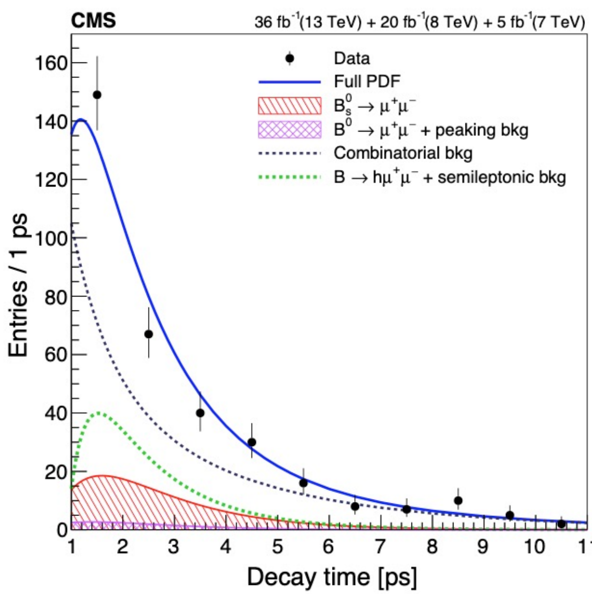
$\mu^+\mu^-$ is CP-odd, so $A_{\Delta\Gamma} = 1$ in the SM,
expect $\tau_{B_s\to\mu^+\mu^-} = \tau_{B_s^H}$=1.609 $\pm$ 0.010 ps. This could change in NP.

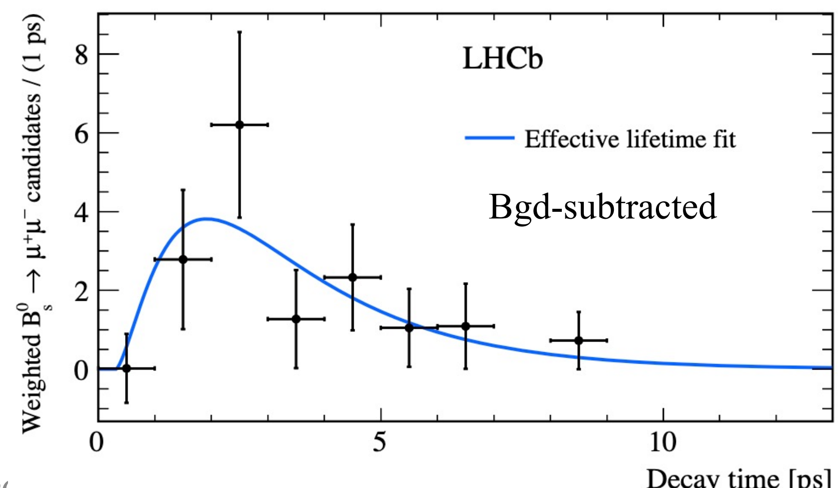
$m_{\mu^+\mu^-}$ & $t_{\mu^+\mu^-}$ distributions











ATLAS, CMS, LHCb results

- BR measured wrt. that of $B^+ \to J/\psi\, K^+$ (LHCb used also $B^0 \to K^+\pi^-$)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{f_d}{f_s} \frac{\varepsilon_{B^+\to J/\psi K^+}}{\varepsilon_{B_s^0\to\mu^+\mu^-}} \frac{N_{B_s^0\to\mu^+\mu^-}}{N_{B^+\to J/\psi K^+}} \mathcal{B}(B^+ \to J/\psi\, K^+)$$

$\frac{f_s}{f_d} = 0.259 \pm 0.015$ measured by LHCb @ 7 TeV

ATLAS

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8\,^{+0.8}_{-0.7}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (-1.9 \pm 1.6) \times 10^{-10},$$

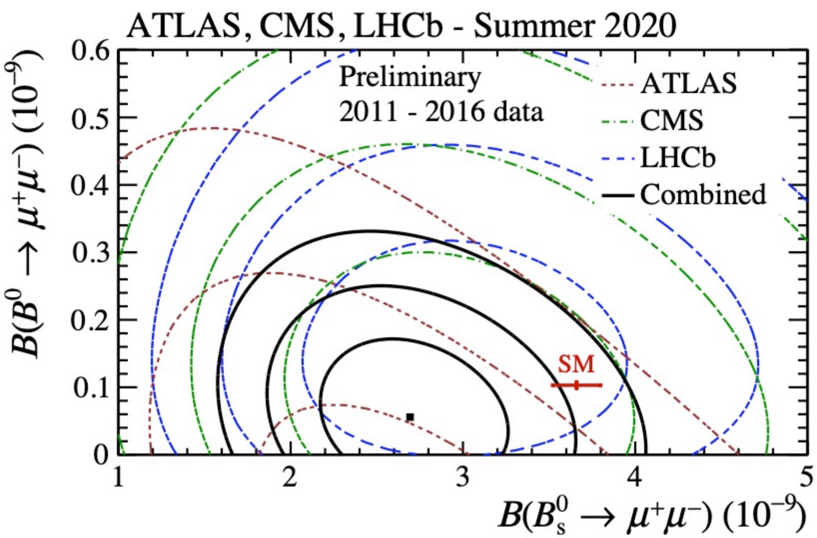
CMS

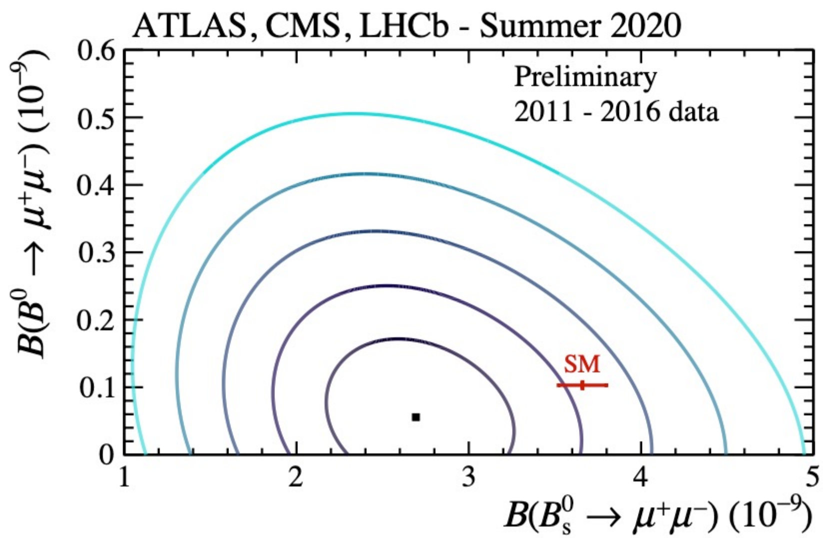
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[2.9\,^{+0.7}_{-0.6}(\text{exp}) \pm 0.2(\text{frag})\right] \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(0.8\,^{+1.4}_{-1.3}\right) \times 10^{-10},$$
$$\tau_{B_s^0\to\mu^+\mu^-} = 1.70^{+0.60}_{-0.43} \pm 0.09\,\text{ps}$$

LHCb

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.0 \pm 0.6\,^{+0.3}_{-0.2}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.5\,^{+1.2}_{-1.0}\,^{+0.2}_{-0.1}\right) \times 10^{-10},$$
$$\tau_{B_s^0\to\mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05\,\text{ps}$$

Combination of profile likelihoods



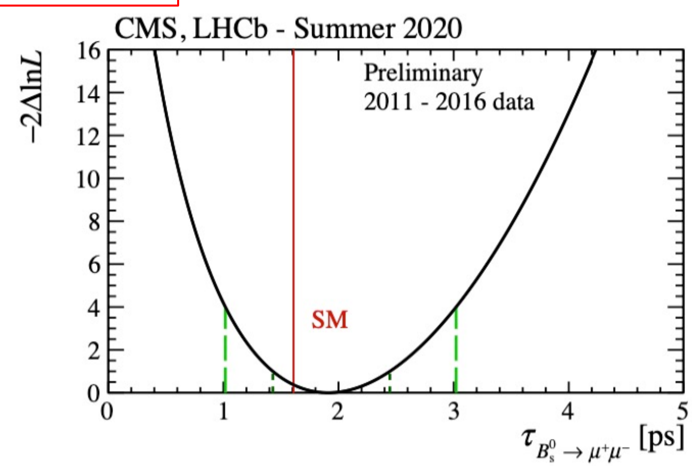


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.69\,^{+\,0.37}_{-\,0.35}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.6 \pm 0.7) \times 10^{-10} \quad < 1.9\times10^{-10}\ (95\%)$$

$$\mathcal{R} = 0.021^{+0.030}_{-0.025} \quad < 0.069\ (95\%)$$

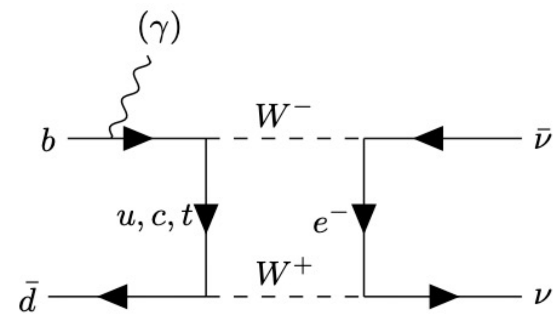
$$\tau_{B_s^0 \to \mu^+\mu^-} = 1.91^{+0.37}_{-0.35}\ \mathrm{ps}$$



Search for $B^0 \to$ invisible $(+\gamma)$

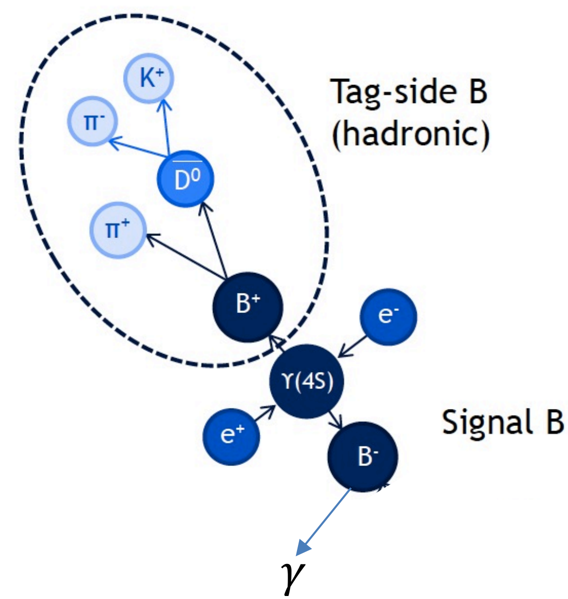
Belle, PRD 102 (2020) 012003 $711\ \mathrm{fb}^{-1}, 772\times10^6\ \mathrm{B\bar{B}}$

- FCNC, suppressed in the SM:
  - $\mathrm{BR}(B^0 \to \mathrm{invis.}) \sim 10^{-16}$ (for 4ν) [1]
  - $\mathrm{BR}(B^0 \to \nu\bar{\nu}\gamma) \sim 10^{-9}$ [2]



- Fully reconstruct the other (tag) B in O(10^3) hadronic modes
  - (The 2 B's are not separated by direction)

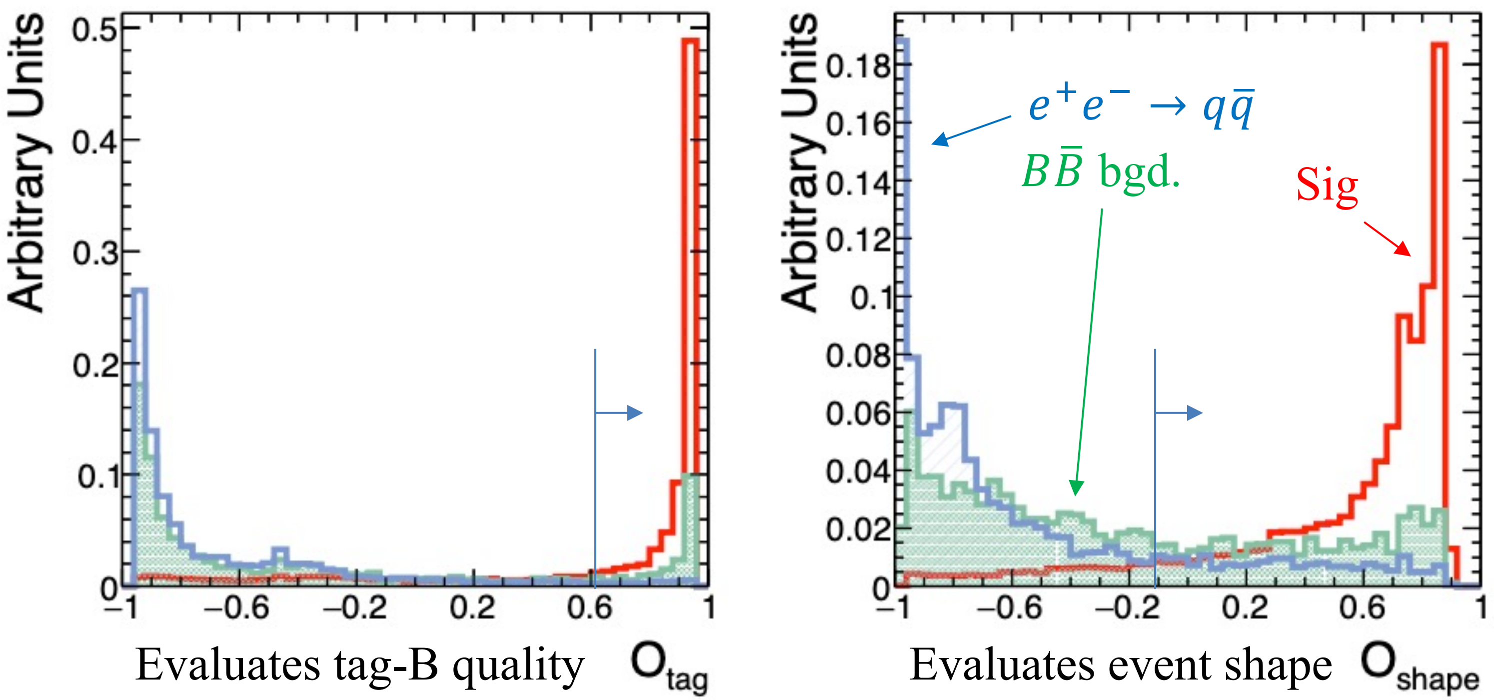
- Reject events with additional good tracks, π^0 or K_L



[1] Bhattacharya, Grant, Petrov, PRD 99 (2019) 093010
[2] Lu, Zhang, PLB 381 (1996) 348

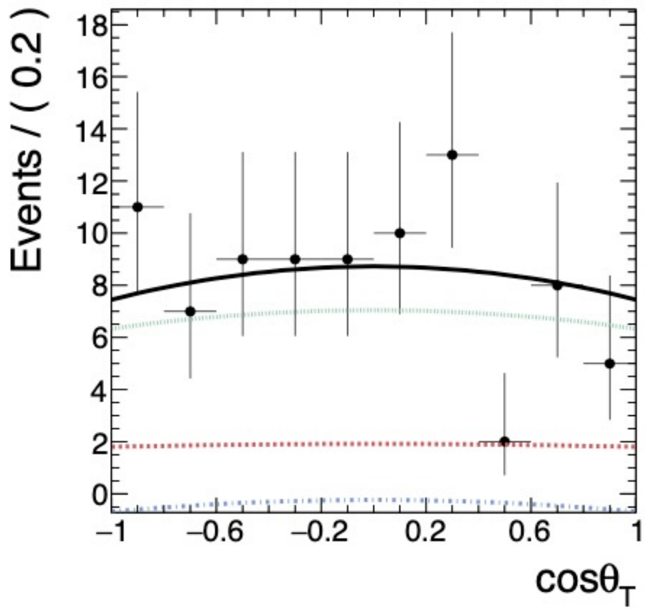
Signal and background

- Two neural networks used to suppress background
  - (plots for $B^0 \to \gamma +$ invis.   Those for $B^0 \to$ invis. are similar):

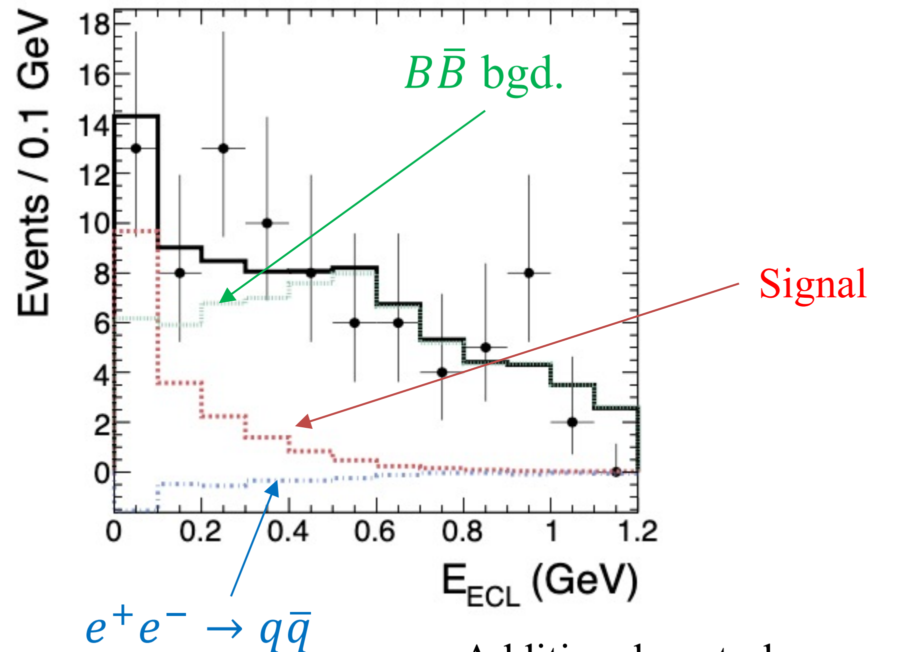


Signal extraction & results

- $B^0 \to$ invis.: Fit the data distributions in 2 variables (uncorrelated)



Cosine of angle b/w thrust axes of tag-B and remaining particles



Additional neutral energy in the EM calorimeter

- $B^0 \to$ invis. $+\gamma$: subtract bgd. estimated from O_{tag} sideband, and count

$$\mathcal{B}(B^0 \to \text{invisible}) < 7.8 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \text{invisible} + \gamma) < 1.6 \times 10^{-5}$$

90% CL

Conclusions

- LFV, LNV, and rare decays are an excellent probe for NP
- Continually exploited as experiments collect more data and develop new analysis techniques
- Summary of the recent numbers:

Decay mode $D^0 \to$	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ $(\times 10^{-7})$	$\mathcal{B}$ 90% U.L. $(\times 10^{-7})$
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	4.38	$0.27 \pm 3.90 \pm 0.67$	9.1
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	4.91	$7.40 \pm 5.40 \pm 0.91$	15.2
$\pi^-\pi^-e^+\mu^+$	$12.42 \pm 5.30 \pm 1.45$	4.38	$15.4 \pm 6.59 \pm 1.85$	30.6
$\pi^-\pi^+e^\pm\mu^\mp$	$1.37 \pm 6.15 \pm 1.28$	4.79	$1.55 \pm 6.97 \pm 1.45$	17.1
$K^-\pi^-e^+e^+$	$-0.23 \pm 0.97 \pm 1.28$	3.19	$-0.38 \pm 1.60 \pm 2.11$	5.0
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	3.30	$-0.05 \pm 3.34 \pm 0.64$	5.3
$K^-\pi^-e^+\mu^+$	$3.87 \pm 3.96 \pm 2.36$	3.48	$5.84 \pm 5.97 \pm 3.56$	21.0
$K^-\pi^+e^\pm\mu^\mp$	$2.52 \pm 4.60 \pm 1.35$	3.65	$3.62 \pm 6.61 \pm 1.95$	19.0
$K^-K^-e^+e^+$	$0.30 \pm 1.08 \pm 0.41$	3.25	$0.43 \pm 1.54 \pm 0.58$	3.4
$K^-K^-\mu^+\mu^+$	$-1.09 \pm 1.29 \pm 0.42$	6.21	$-0.81 \pm 0.96 \pm 0.32$	1.0
$K^-K^-e^+\mu^+$	$1.93 \pm 1.92 \pm 0.83$	4.63	$1.93 \pm 1.93 \pm 0.84$	5.8
$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	4.83	$3.93 \pm 2.89 \pm 1.45$	10.0

$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 3.9 \times 10^{-5} \text{ at } 90\% \text{ CL}, \quad < 4.5 \times 10^{-5} \text{ at } 95\% \text{ CL}.$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69\,^{+0.37}_{-0.35}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.6 \pm 0.7) \times 10^{-10} \quad < 1.9\times10^{-10}\ (95\%)$$

$$\mathcal{R} = 0.021^{+0.030}_{-0.025} \quad < 0.069\ (95\%)$$

$$\tau_{B_s^0\to\mu^+\mu^-} = 1.91^{+0.37}_{-0.35}\ \text{ps}$$

Decay mode	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ $(\times 10^{-7})$	$\mathcal{B}$ 90% U BABAR
$D^0 \to \pi^0 e^\pm\mu^\mp$	$-0.3 \pm 2.0 \pm 0.9$	2.15 ± 0.03	$-0.6 \pm 4.8 \pm 2.3$	8.0
$D^0 \to K_S^0 e^\pm\mu^\mp$	$0.7 \pm 1.7 \pm 0.7$	3.01 ± 0.04	$1.9 \pm 4.6 \pm 1.9$	8.6
$D^0 \to \overline{K}^{*0} e^\pm\mu^\mp$	$0.8 \pm 1.8 \pm 0.8$	2.31 ± 0.03	$2.8 \pm 6.1 \pm 2.6$	12.4
$D^0 \to \rho^0 e^\pm\mu^\mp$	$-0.7 \pm 1.7 \pm 0.4$	2.10 ± 0.03	$-1.8 \pm 4.4 \pm 1.0$	5.0
$D^0 \to \phi e^\pm\mu^\mp$	$0.0 \pm 1.4 \pm 0.3$	3.43 ± 0.04	$0.1 \pm 3.8 \pm 0.9$	5.1
$D^0 \to \omega e^\pm\mu^\mp$	$0.4 \pm 2.3 \pm 0.5$	1.46 ± 0.03	$1.8 \pm 9.5 \pm 1.9$	17.1
$D^0 \to \eta e^\pm\mu^\mp$			$6.1 \pm 9.7 \pm 2.3$	22.5
with $\eta \to \gamma\gamma$	$1.6 \pm 2.3 \pm 0.5$	2.96 ± 0.04	$7.0 \pm 10.5 \pm 2.4$	24.0
with $\eta \to \pi^+\pi^-\pi^0$	$0.0 \pm 2.8 \pm 0.7$	2.46 ± 0.04	$0.4 \pm 25.8 \pm 6.0$	42.8

$$\mathcal{B}(B^0 \to \text{invisible}) < 7.8 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \text{invisible} + \gamma) < 1.6 \times 10^{-5}$$

(90%)