LFV&LNV@LHC:
Lepton Flavour Violation and Lepton Number Violation at the Large Hadron Collider

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UK HEP Forum, *Quarks and Leptons*
15th November 2013

Outline

- The Lepton Sector: Definitions of Lepton Flavour and Lepton Number Violation and (brief) motivations for searches
- Possibilities for LFV and LNV at the LHC
- A (biased) selection of some recent searches at the LHC
  - LFV in tau lepton decays at LHCb
  - LFV in B and D meson decays at LHCb
  - LNV in B and D meson decays at LHCb
  - Heavy Majorana neutrinos in CMS
  - Narrow heavy resonances decaying to two different-flavour leptons at CMS
  - LFV in the $e^{\pm}\mu^{\mp}$ continuum at ATLAS
- Conclusions

Some reminders (and to define nomenclature)

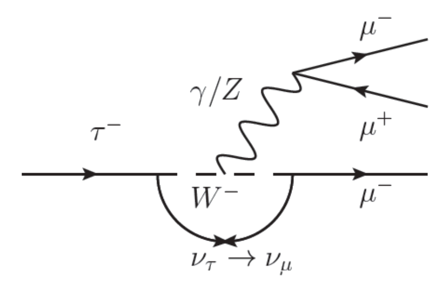
The Standard Model picture for leptons, adapted for neutrino oscillations

	Lepton Number, L	Lepton Flavour	Mass
e^-	+1	$L_e = +1$	0.511 MeV
ν_e	+1	$L_e = +1$	n/a
e^+	−1	$L_e = -1$	0.511 MeV
$\overline{\nu}_e$	−1	$L_e = -1$	n/a
μ^-	+1	$L_\mu = +1$	105.7 MeV
ν_μ	+1	$L_\mu = +1$	n/a
τ^-	+1	$L_\tau = +1$	1777 MeV
ν_τ	+1	$L_\tau = +1$	n/a

Antiparticles have lepton number L = −1 and corresponding lepton flavour −1

- Lepton Number Conservation: Total lepton number L is conserved
- Lepton Flavour Conservation: Total of each of L_e, L_μ, L_τ are separately conserved

In the Standard Model



- The neutrinos are massless
  - Neutrino flavour is conserved
- Lepton Flavour is conserved by construction
  - But LF is now known to be violated by neutrino oscillations
  - But suppressed by terms of order $(\Delta m_\nu^2/M_W^2)^2$
  - Charged LFV from neutrino oscillations is unobservable in any current or foreseeable experiment

- Charged LFV is expected in many New Physics (NP) extensions to the SM, with parameter spaces allowing rates up to current experimental limits

- Lepton Number is conserved by an "accidental" symmetry
  - LNV is needed for leptogenesis
  - May be violated along with baryon number (e.g. via sphalerons)
  - Would be violated if the neutrino is a Majorana particle (i.e. its own antiparticle)

- Note that LNV implies also LFV, but we can have LFV without LNV

A **sample** of various charged Lepton Flavour Violating reactions

Reaction	Current bound	Expected	Possible
$\mathcal{B}(\mu^+ \to e^+\gamma)$	$<1.2 \times 10^{-11}$	2×10^{-13}	2×10^{-14}
$\mathcal{B}(\mu^\pm \to e^\pm e^+ e^-)$	$<1.0 \times 10^{-12}$	–	10^{-14}
$\mathcal{B}(\mu^\pm \to e^\pm \gamma\gamma)$	$<7.2 \times 10^{-11}$	–	–
$R(\mu^- \mathrm{Au} \to e^- \mathrm{Au})$	$<7 \times 10^{-13}$	–	–
$R(\mu^- \mathrm{Al} \to e^- \mathrm{Al})$	–	10^{-16}	10^{-18}
$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)$	$<5.9 \times 10^{-8}$		$\mathcal{O}(10^{-9})$
$\mathcal{B}(\tau^\pm \to e^\pm \gamma)$	$<8.5 \times 10^{-8}$		$\mathcal{O}(10^{-9})$
$\mathcal{B}(\tau^\pm \to \mu^\pm \mu^+ \mu^-)$	$<2.0 \times 10^{-8}$		$\mathcal{O}(10^{-10})$
$\mathcal{B}(\tau^\pm \to e^\pm e^+ e^-)$	$<2.6 \times 10^{-8}$		$\mathcal{O}(10^{-10})$
$Z^0 \to e^\pm \mu^\mp$	$<1.7 \times 10^{-6}$		
$Z^0 \to e^\pm \tau^\mp$	$<9.8 \times 10^{-6}$		
$Z^0 \to \mu^\pm \tau^\mp$	$<1.2 \times 10^{-5}$		
$K_L^0 \to e^\pm \mu^\mp$	$<4.7 \times 10^{-12}$		10^{-13}
$D^0 \to e^\pm \mu^\mp$	$<8.1 \times 10^{-7}$		10^{-8}
$B^0 \to e^\pm \mu^\mp$	$<9.2 \times 10^{-8}$		10^{-9}

From Marciano, Mori and Roney, Ann. Rev. Nucl. Part. Sci. 2008. 58:315-41

The "most interesting" Lepton Flavour Violating reactions have

- Clean experimental signatures
- Good prospects for experimental sensitivity
- Relatively clean theoretical predictions

$\mu^- \rightarrow e^- \gamma$

$\mu^- \rightarrow e^+ e^- e^-$

MEG, Comet, PRISM

$\mu^- N \rightarrow e^- N$

Mu2e

$\tau^- \rightarrow \mu^- \gamma$

$\tau^- \rightarrow \mu^+ \mu^- \mu^-$

BaBar, Belle, **LHCb**, Belle II

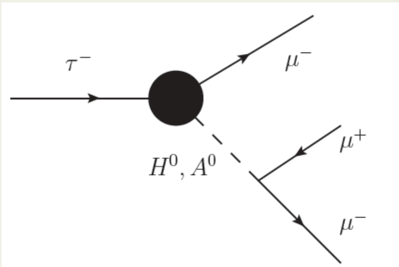
Heavy SUSY/exotic particles **ATLAS, CMS**

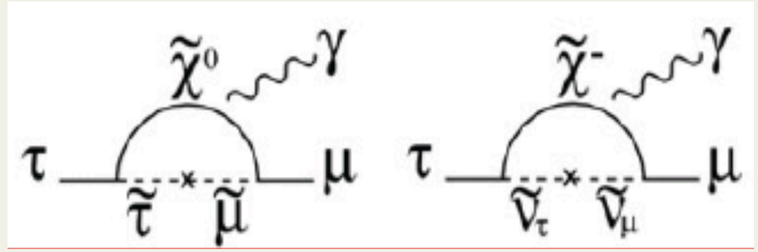
Majorana neutrinos BaBar, Belle, **LHCb**, **ATLAS**, **CMS**, Belle II, NDBD …

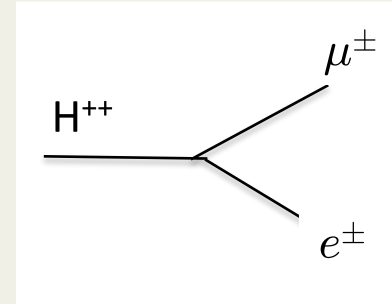
What can be done in LFV and LNV at the LHC?

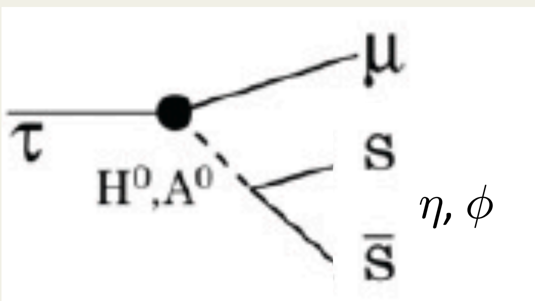
- Generic searches for new physics in final states with odd numbers of charged leptons
- Searches for new massive particles decaying into two different charged leptons
- Searches for doubly-charged Higgs bosons decaying to two same-sign leptons
- Direct searches for RPV+LFV SUSY particles
- Direct searches for LFV in tau lepton decays
- Direct searches for B and D meson decays containing two same-sign leptons (Majorana neutrinos)

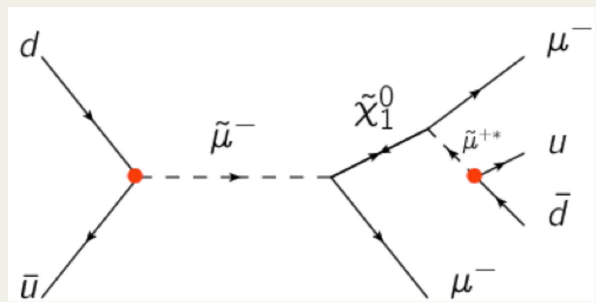
A miscellany possibilities for LFV&LNV@LHC

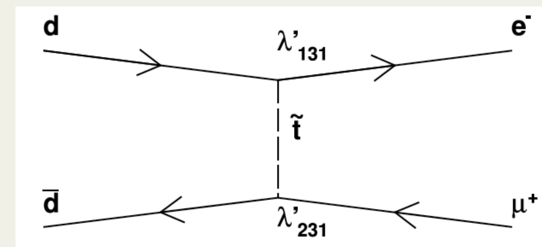


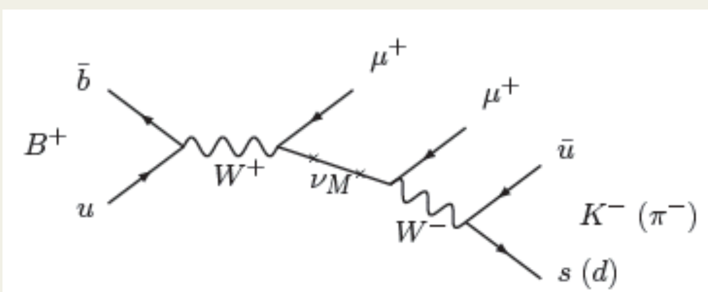


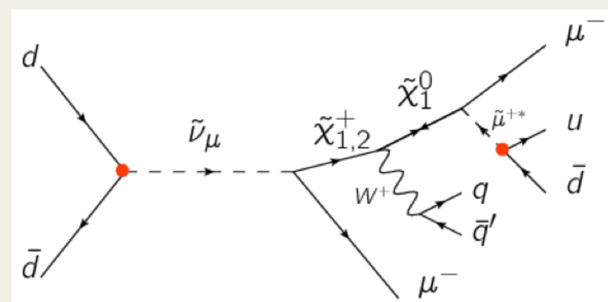










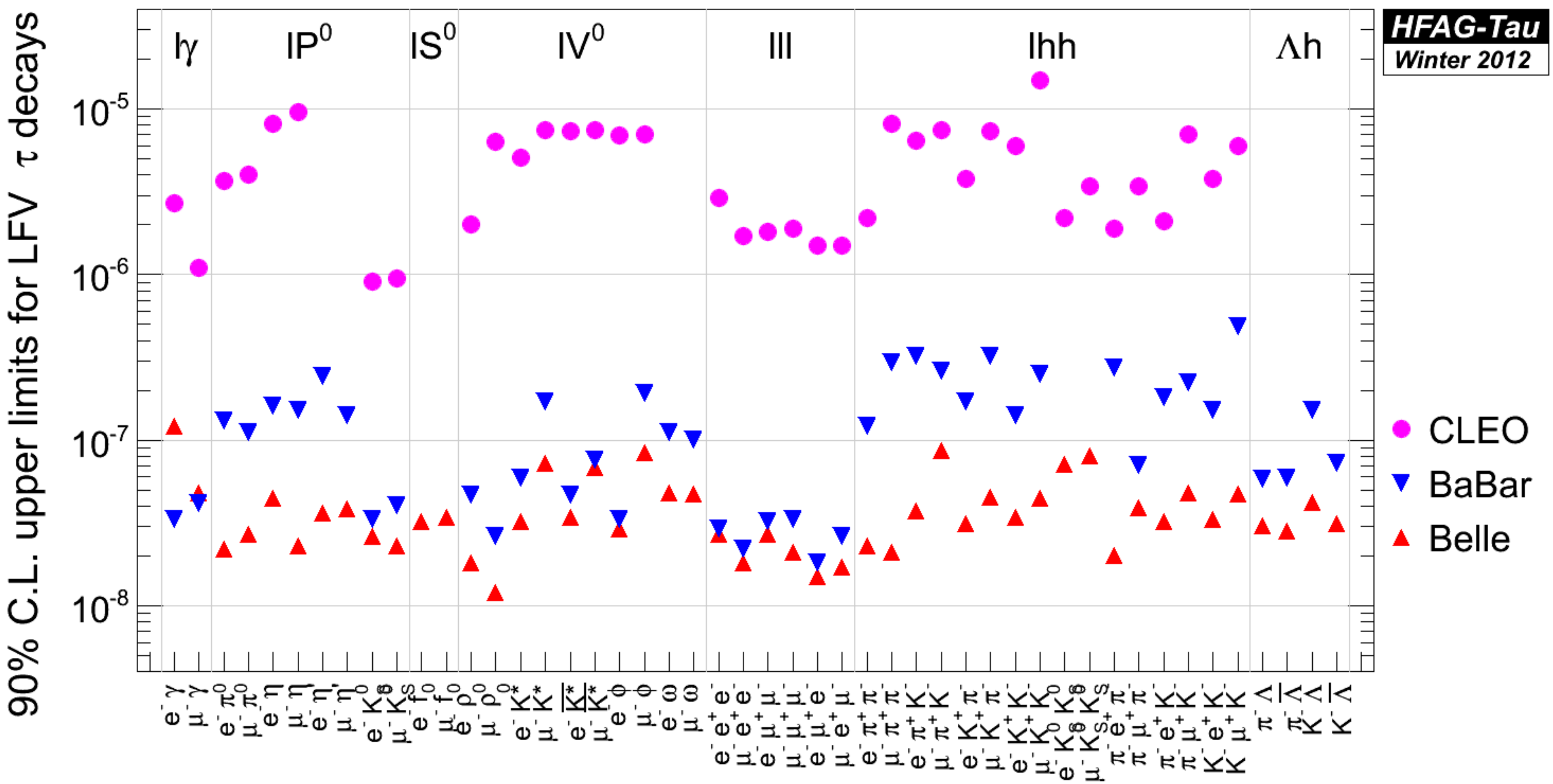


Direct searches for Lepton Flavour Violation in tau lepton decays at LHCb

Some (of many) New Physics predictions for LFV in tau decays

Model	References	Limits $\tau \to \mu\gamma$	$\tau \to 3\mu$
SM + ν mixing	Lee, Shrock, PRD 16,1444(1977) Cheng, Li, PRD 45,1908(1980)	10^{-40}	10^{-14}
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549,159(2002) Brignole, Rossi, PLB 566,517(2003)	10^{-10}	10^{-7}
SM + heavy Majorana ν	Cvetic, Dib, Kim, Kim, PRD 66,034008(2002)	10^{-9}	10^{-10}
Non-universal Z'	Yue, Zhang,Liu, PLB 547,252(2002)	10^{-9}	10^{-8}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649,189(2003) Fukuyama, Kikuchi, Okada, PRD 68,033012(2003)	10^{-8}	10^{-10}
MSUGRA + Seesaw	Ellis et al., EPJ C14, 319(2002) Ellis, Hisano, Raidal, Shimizu, PRD 66,115013(2002)	10^{-7}	10^{-9}

Compilation by **Heavy Flavor Averaging Group** of LFV limits for tau decays



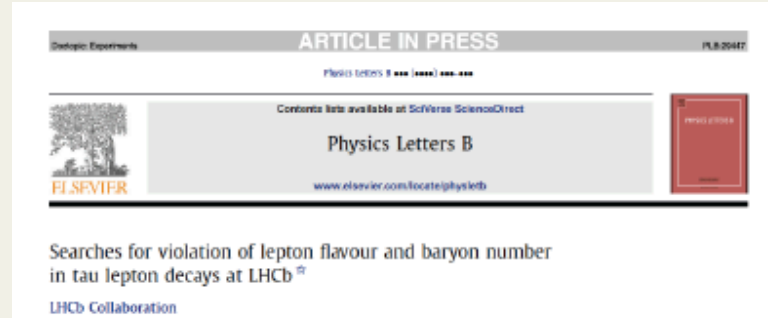
Tau production at the LHC

- Tau production at the LHC is mainly from D_s decays

Decay chain	Probability (%)
$D_s \to \tau$	78.3
$D_s \to \tau$	68.9
$B_x \to D_s \to \tau$	9.4
$D^+ \to \tau$	4.9
$D^+ \to \tau$	4.7
$B_x \to D^+ \to \tau$	0.2
$B_x \to \tau$	16.8

- LHCb, with forward geometry, low-p_T triggers, vertex locator and good mass resolution is well suited for these tau production channels
- But τ s are produced in high-multiplicity hadronic environments
- Situation is much cleaner in exclusive $e^+e^- \to \tau^+\tau^-$ at B factories

LHCb searches for $\tau \to 3\mu$ and $\tau \to p\mu\mu$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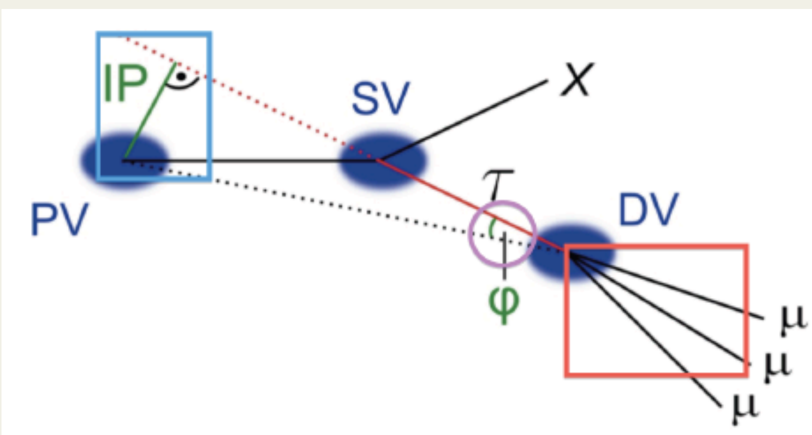
Searches for violation of lepton flavour and baryon number in tau lepton decays at LHCb

LHCb Collaboration

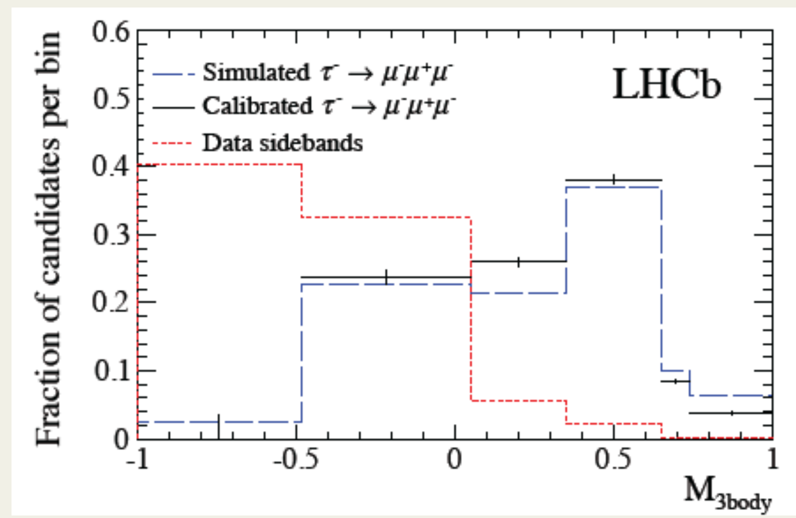
- Inclusive $\sigma(pp \to \tau + X)$ = 80$\pm$8 μb at 7 TeV in the LHCb acceptance
  - So 8 $\times$ 10^{10} produced τ in 1 fb^{-1} in 2011
  - c.f. total of 3 $\times$ 10^{9} τ produced in Belle+BaBar
- Search inclusively for 3μ and p$\mu\mu$ from displaced vertex consistent with τ decay
- Loose cut-based selection followed by event classification according to
  - Decay topology and kinematics
  - Particle ID
  - Invariant mass
- Event classifiers trained on simulated signals and background Monte Carlo, and calibrated on control channels
- Relative normalisation of rates to $D^-_s \to \phi(\mu^+\mu^-)\pi^-$
- Limits on BFs deduced using CL_s method

- Two multivariate classifiers:

- $\mathcal{M}_{\text{3body}}$ includes vertex and track fit qualities, vertex displacement, momentum direction (vertex pointing), vertex isolation, p_T of candidate
- Boosted decision tree with adaptive boosting, trained on MC for signal and background
- Response calibrated on $D^-_s \to \phi(\mu^+\mu^-)\pi^-$ in data to account for data-MC dirrerences

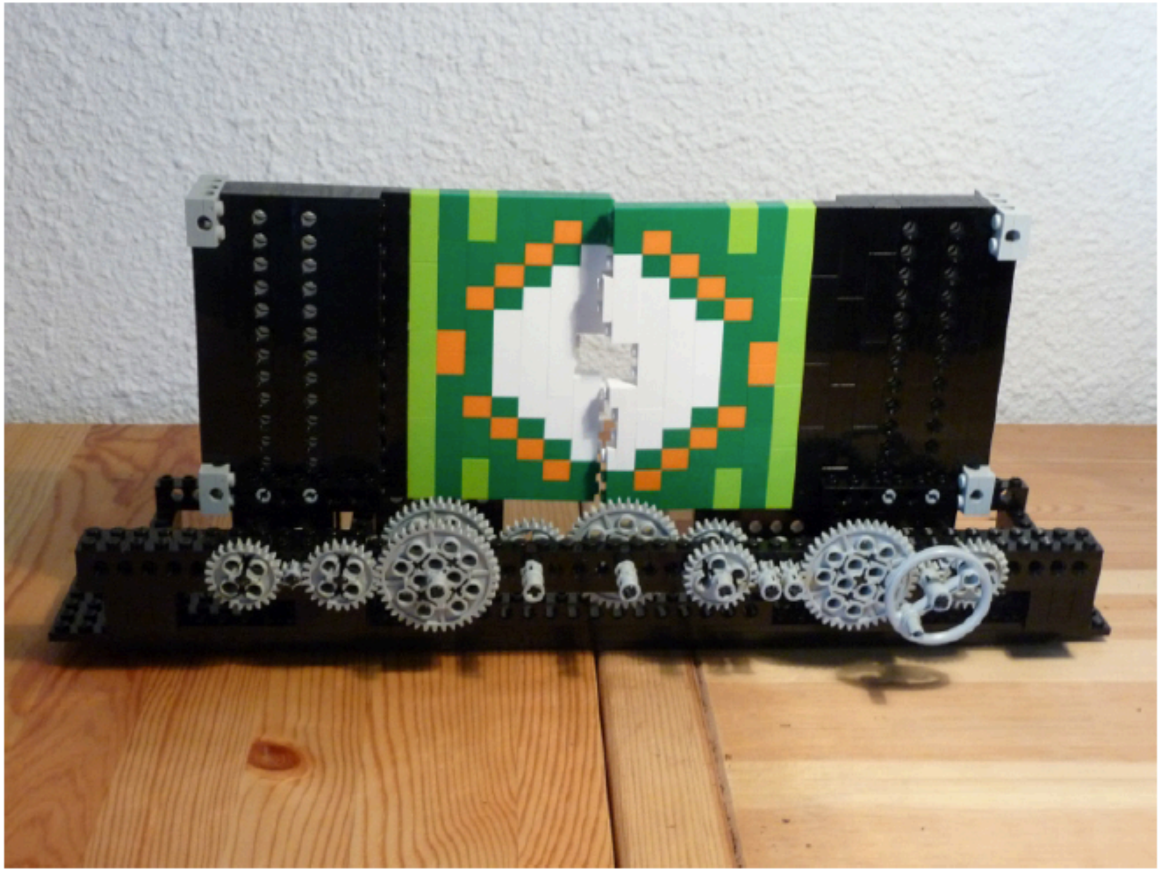


Vertex reconstruction relies on LHCb VELO

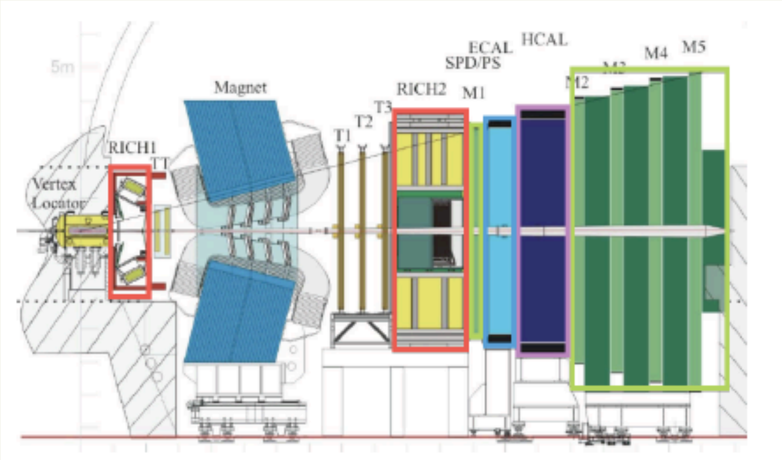


The VELO halves must be kept apart...

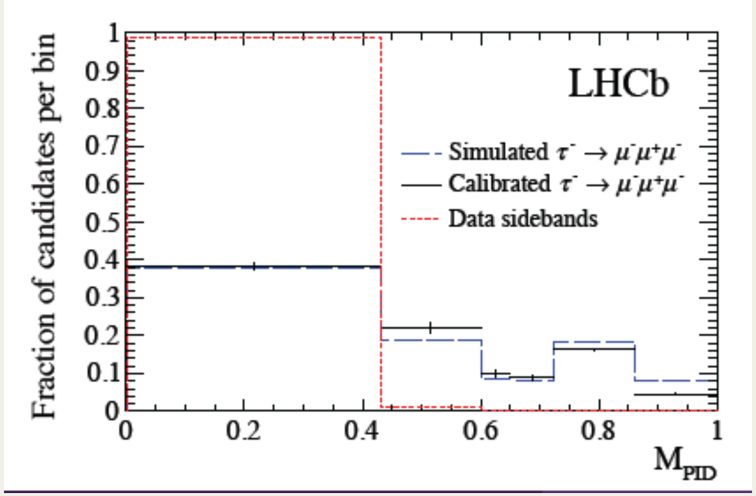
...until the LHC beam conditions stabilise:



- $\mathcal{M}_{\text{PID}}$ includes particle ID information from RICHs, ECAL, HCAL, MUON chambers

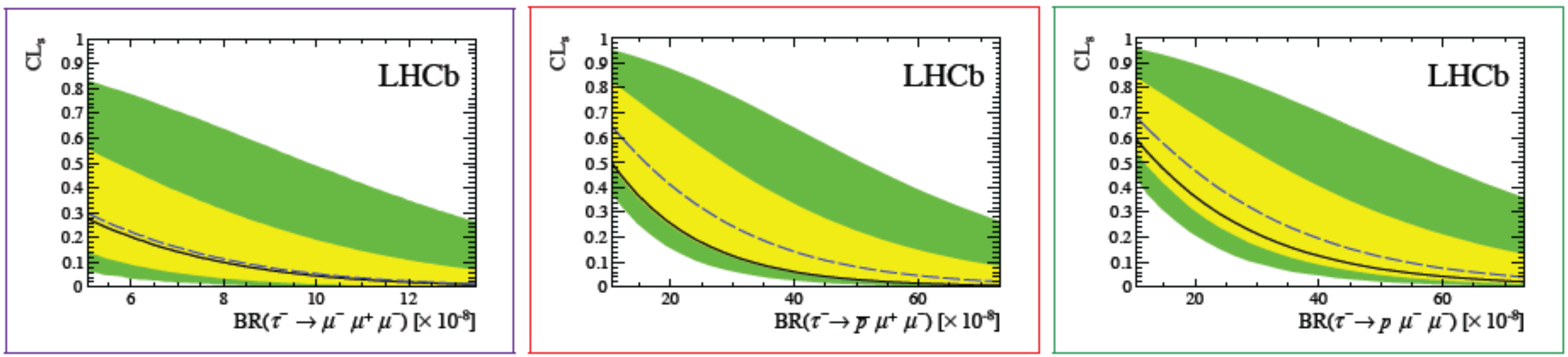


- Neural network trained on signal and background MC
- Calibrated on $J/\psi \to \mu\mu$ in data
- For $\tau \to p\mu\mu$ simple PID cuts applied, optimised on MC and data sidebands



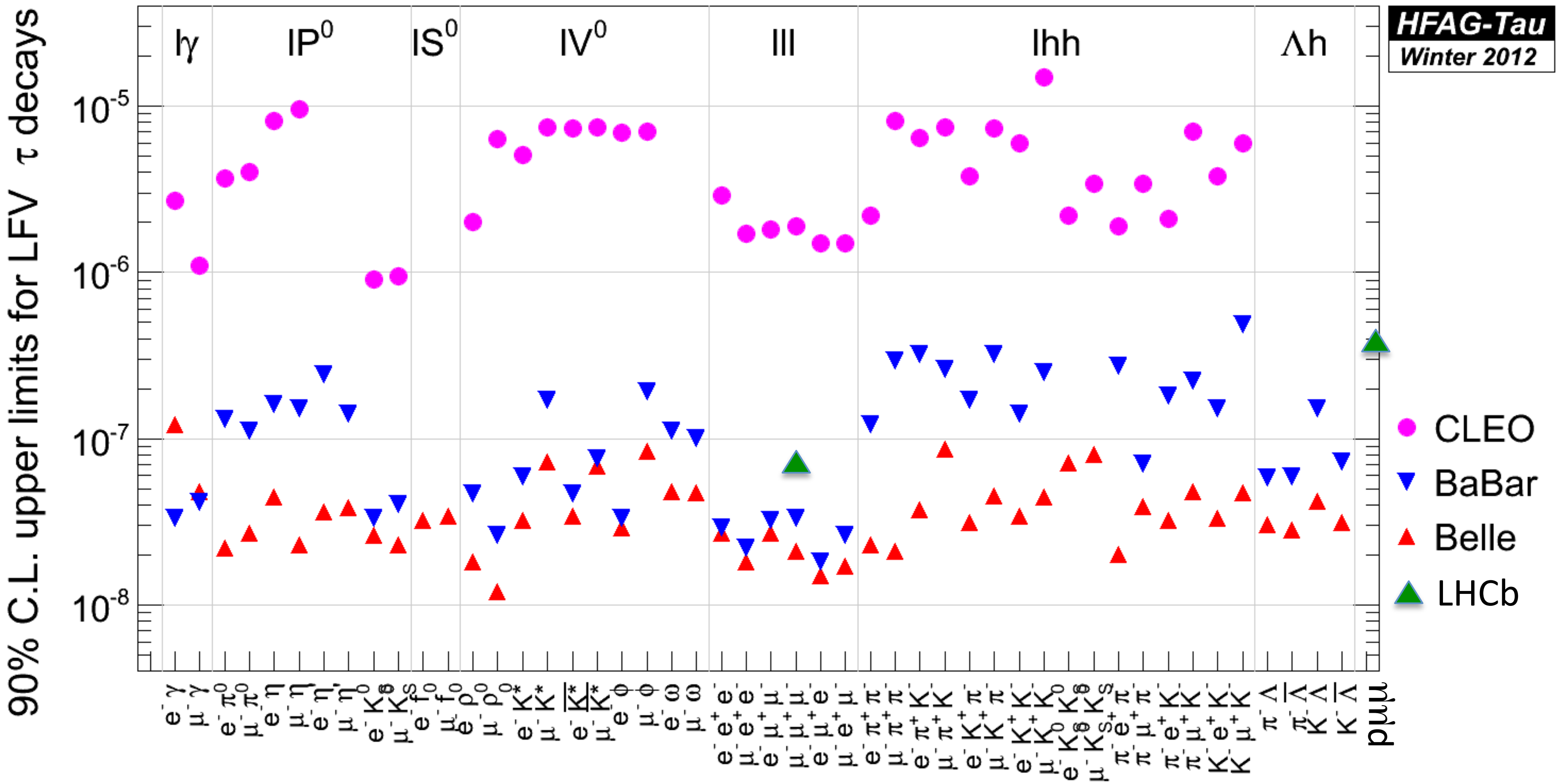
LHCb upper limits on BFs for $\tau \rightarrow 3\mu$ and $\tau \rightarrow p\mu\mu$

Channel	Expected (90% CL)	Observed (90% CL)
$\tau^- \to \mu^-\mu^+\mu^-$	8.3×10^{-8}	8.0×10^{-8}
$\tau^- \to \bar{p}\mu^+\mu^-$	4.6×10^{-7}	3.3×10^{-7}
$\tau^- \to p\mu^-\mu^-$	5.4×10^{-7}	4.4×10^{-7}



- LHCb limits on $\tau \rightarrow p\mu\mu$ modes
  - No previous limits existed for these mode, which violate both Lepton and Baryon Number with Δ(B-L)=0
  - But are we learning anything new here, or do limits on proton decay already rule this out (subject to CPT)?

Compilation by **Heavy Flavor Averaging Group** of LFV limits for tau decays (supplemented with **LHCb** results)

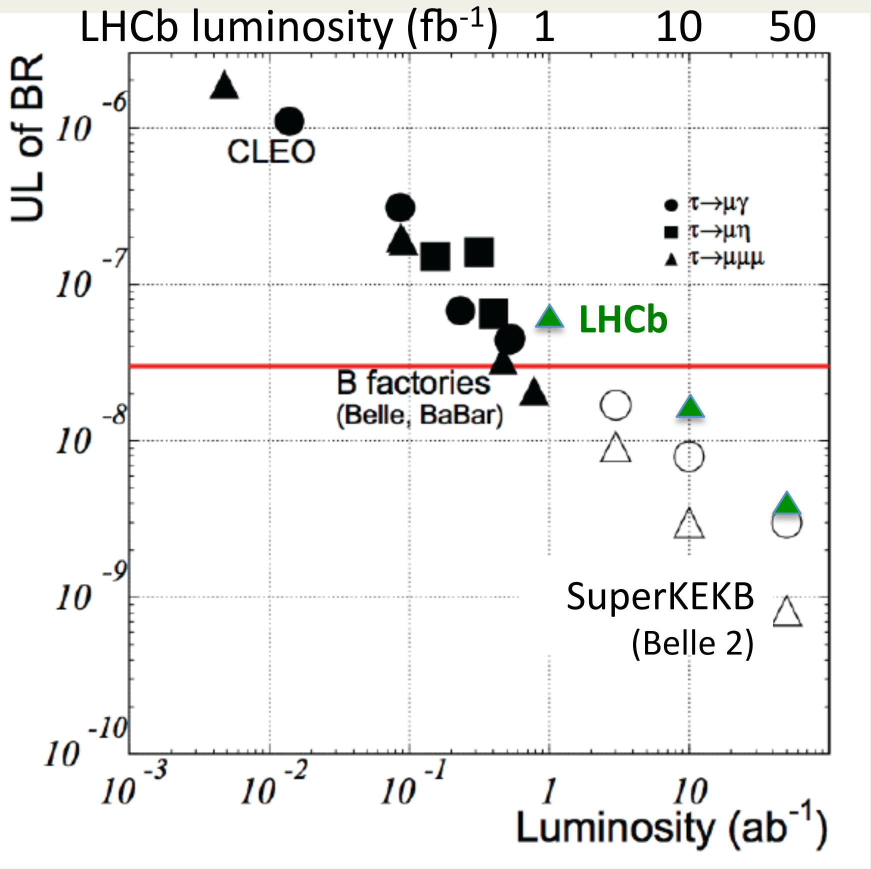


- Analysis now being updated using 3 fb^{-1} 2011+12 dataset
- Search started also for $\tau \rightarrow \phi\mu$

For $\tau \rightarrow 3\mu$ LHCb may overtake Belle but will eventually be overtaken by Belle 2

In terms of sensitivity for $\tau \rightarrow 3\mu$, a rule of thumb is:

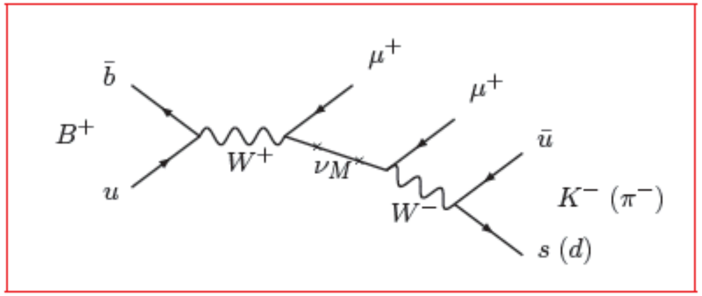
- 1 fb^{-1} at LHCb is equivalent to 1 ab^{-1} at an e^+e^- B/charm/tau factory



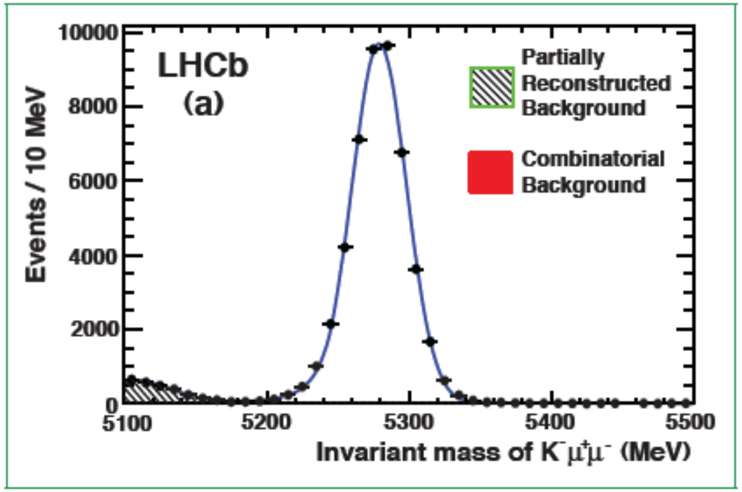
Direct searches for Lepton Number Violation in B and D meson decays at LHCb

LNV in B decays at LHCb – Majorana neutrinos

- A range of LFV B-decays are allowed in BSM models with a Majorana neutrino or a doubly charged Higgs boson
- Search for the decays $B^+ \to h^- \mu^+ \mu^+$, where h^- is a π^-, K^- or D^- meson
- Different final states probe a range of Majorana neutrino masses



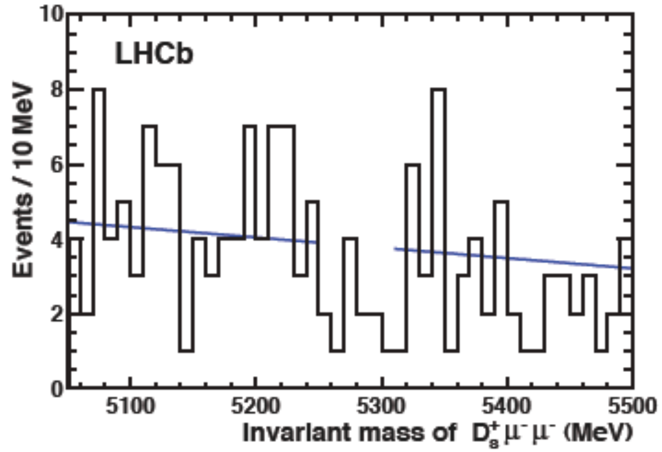
- Results obtained using 36 – 410 pb^{-1} of LHCb data from 2010 + 2011
- Normalisation channels: $B^+ \to J/\psi K^+$ (3-body) and $B^+ \to \psi(2S)K^+$ (5-body)

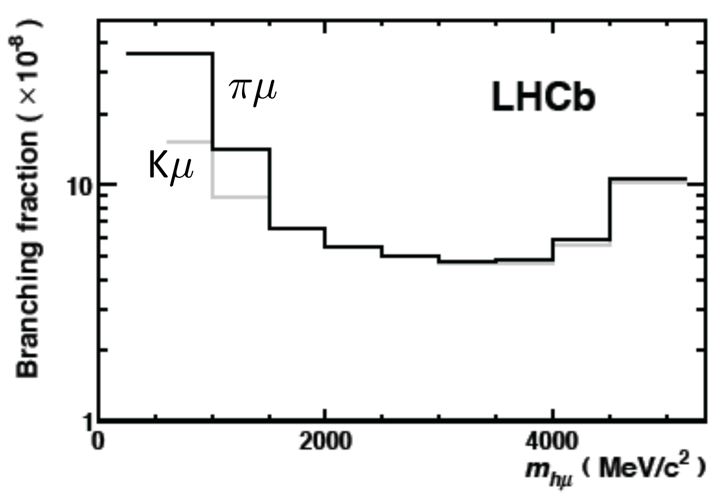


LHCb-PAPER-2011-038

LHCb searches for B$^-$ → $h^+\mu^-\mu^-$

- No significant signals are observed → Set limits as a function of the Majorana neutrino mass
- All limits are new world's bests → improved by as much as $\sim \times 100$

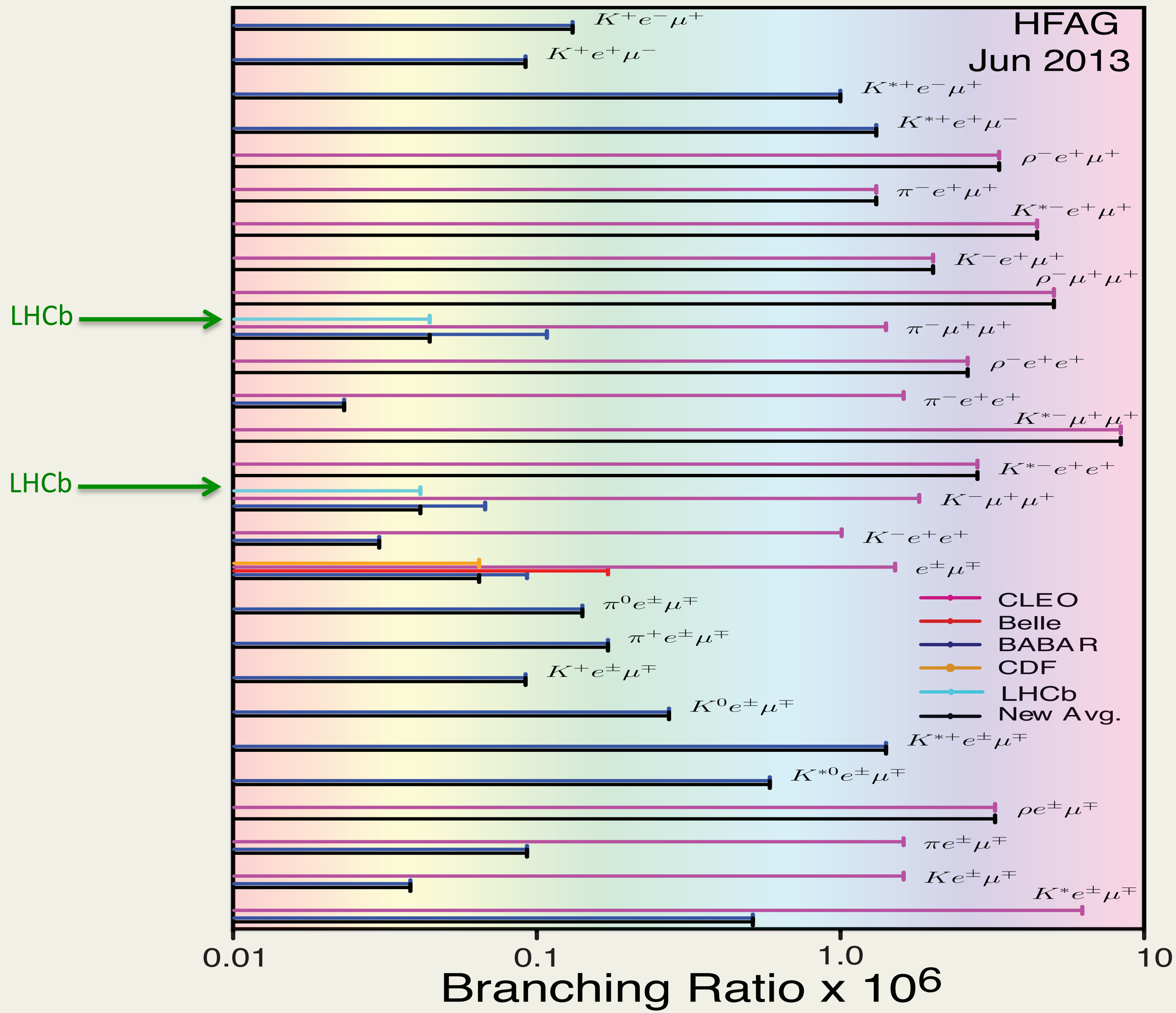




LHCb-PAPER-2011-009

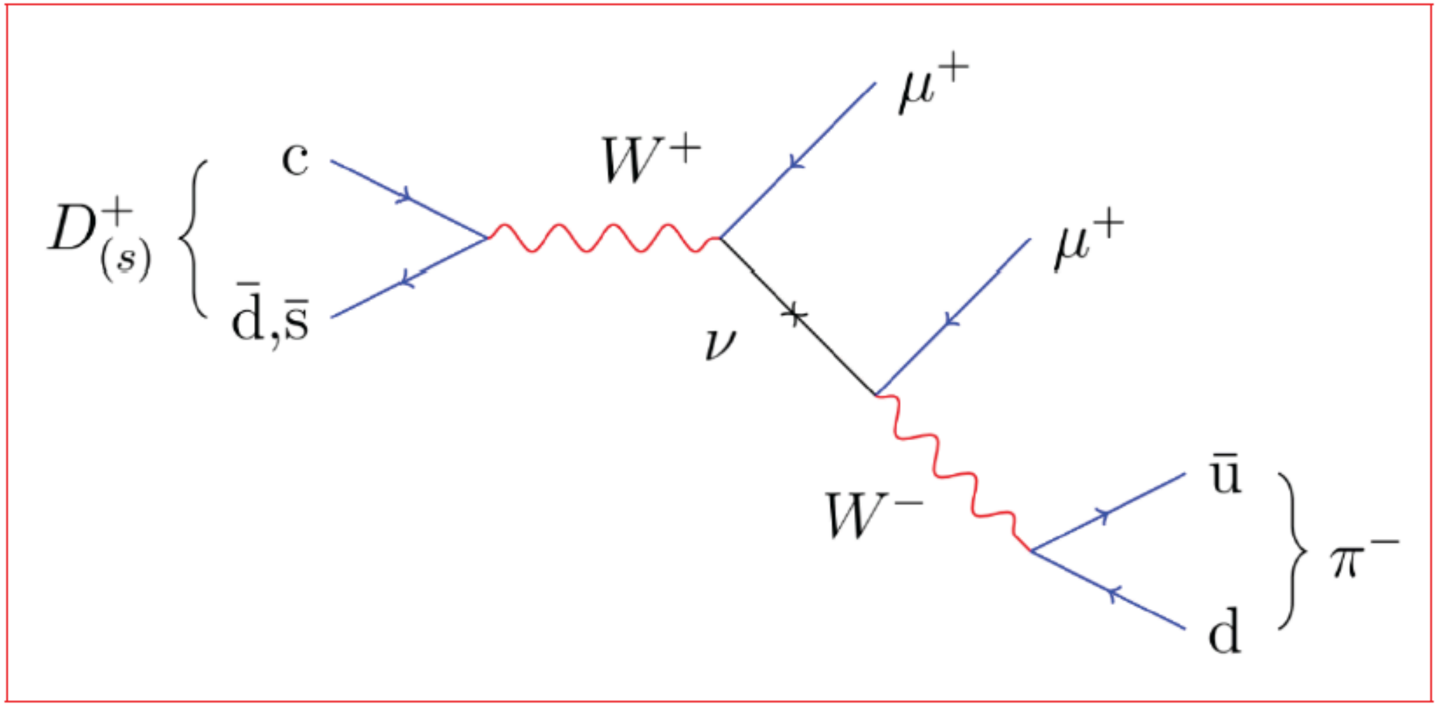
Channel	Observed 95% CL
$K^+\mu^-\mu^-$	5.4×10^{-8}
$D^+\mu^-\mu^-$	6.9×10^{-7}
$D^{*+}\mu^-\mu^-$	2.4×10^{-6}
$\pi^+\mu^-\mu^-$	1.3×10^{-8}
$D_s^+\mu^-\mu^-$	5.8×10^{-7}
$D^0\pi^+\mu^-\mu^-$	1.5×10^{-6}

Lepton Number Violating Charmless B Decays



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

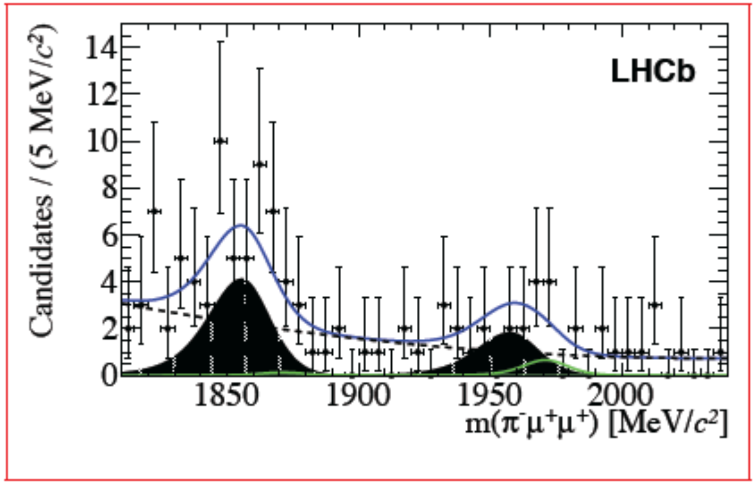
- $D^+_{(s)} \to \pi^- \mu^+ \mu^+$ decays can occur through leptonic mixing via a Majorana neutrino
- World's best experimental limits from BaBar of 2×10^{-6} and 1.4×10^{-5} for $D^+ \to \pi^- \mu^+ \mu^+$ and $D^+_s \to \pi^- \mu^+ \mu^+$ respectively



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

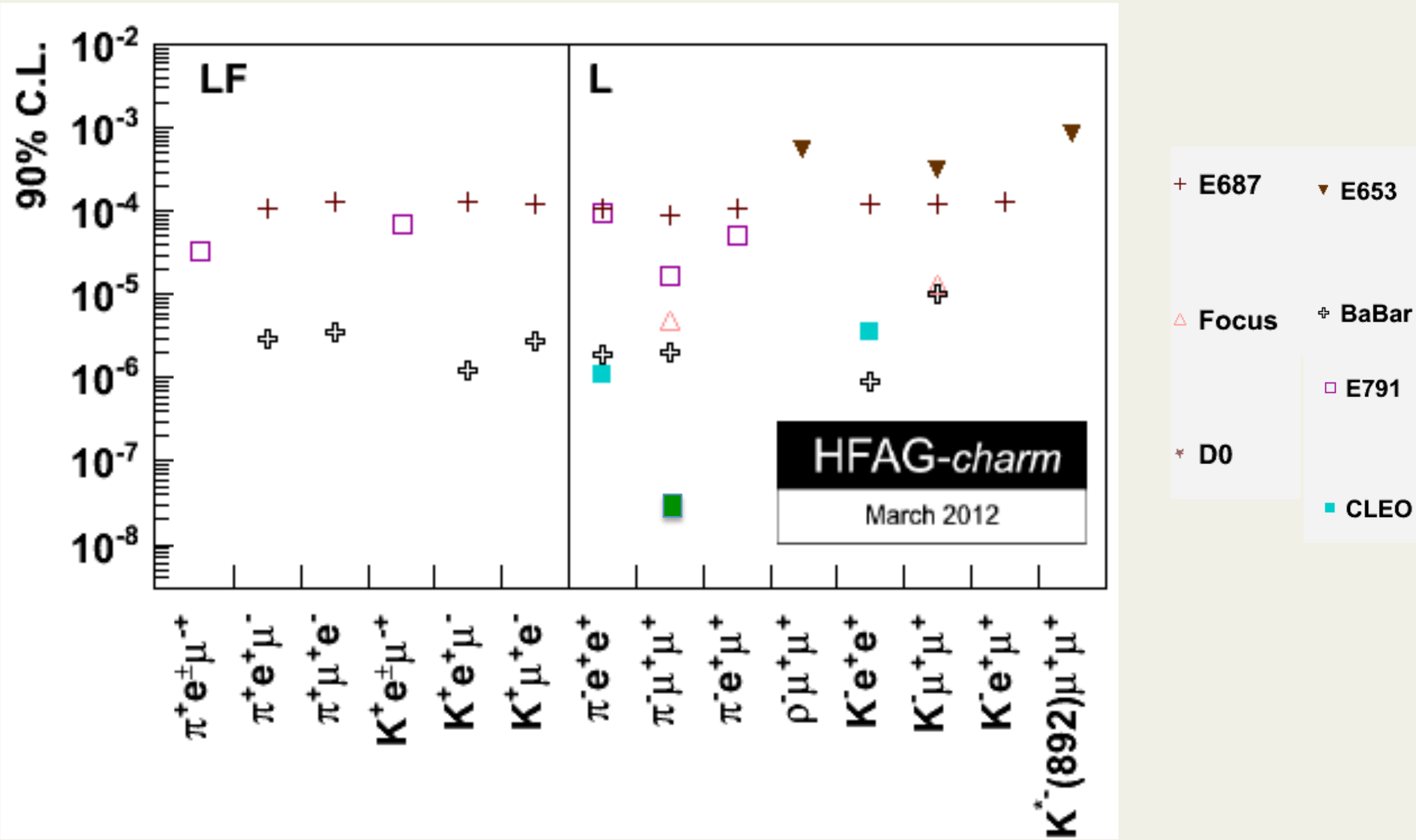
- Normalisation to $D^{+}_{(s)} \to \phi(\mu^{+}\mu^{-})\pi^{+}$
- Classification of signal and background from PID cuts and a BDT using kinematic and geometric variables, trained on 2010 data

- Peaking background from $D^{+}_{(s)} \to \pi^{+}\pi^{+}\pi^{-}$ decays with shape (grey) measured from data
- Fit in bins of $m(\pi^{-}\mu^{+})$ to improve statistical significance
- Limit of 2.2×10^{-8} and 1.2×10^{-7} for D^{+} and D^{+}_{s} decays respectively are a factor of fifty improvement

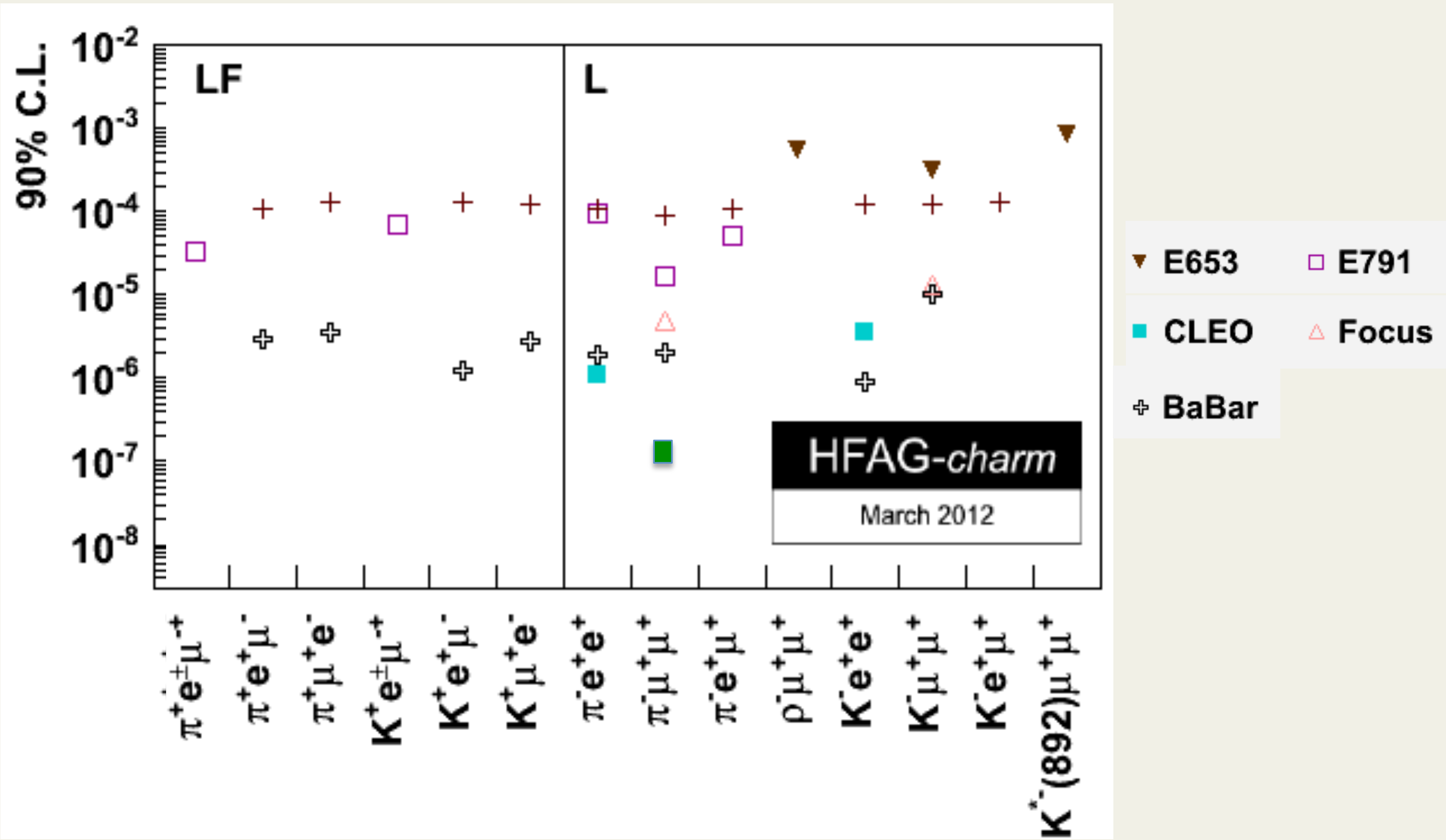


LHCb-PAPER-2012-051

Compilation by **Heavy Flavor Averaging Group** of LNV limits for D^+ decays (supplemented with **LHCb** result)



Compilation by **Heavy Flavor Averaging Group** of LNV limits for D_s^+ decays (supplemented with **LHCb** result)



Direct searches for Lepton Flavour Violation in B and D meson decays at LHCb

LHCb search for $B^0_{(s)} \to e^{\pm} \mu^{\mp}$

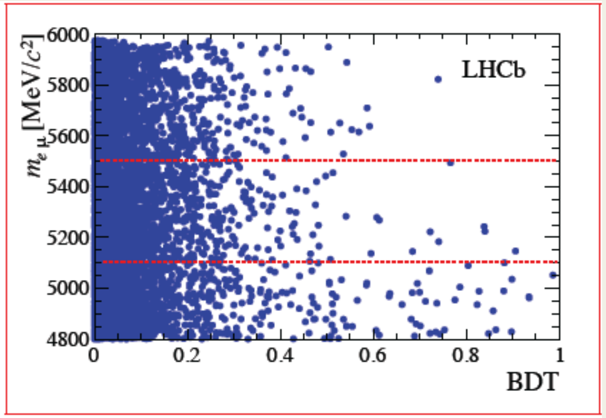
- These decays are allowed in several BSM models
  - Heavy singlet Dirac neutrinos
  - RPV and LNV SUSY models
  - Leptoquarks that couple leptons and quarks of different generations (Pati-Salam)

- Analysis uses 1 fb^{-1} of 7 TeV data (2011 sample)

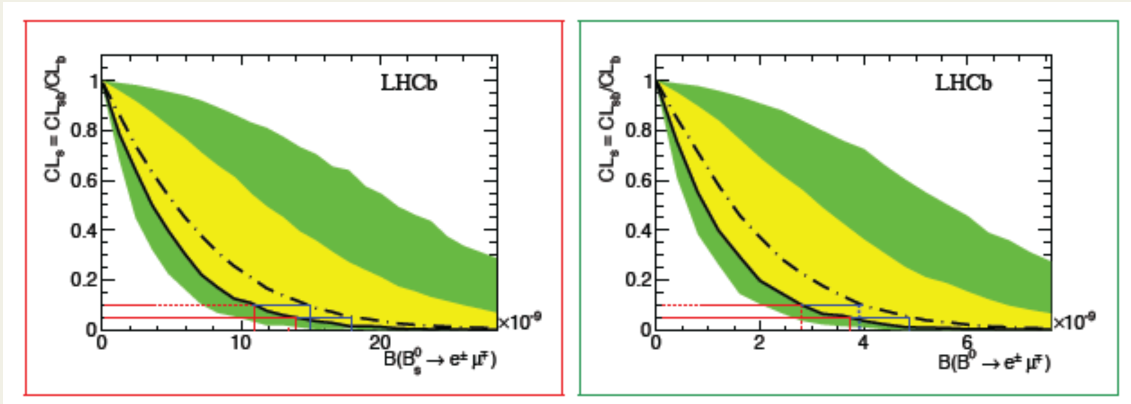
- Potential signal normalised to $B^0 \to K^+\pi^-$ with $B^0_{(s)} \to h^+h'^-$ as control channel

- Main backgrounds from semileptonic b decays: $b\bar{b} \to e^{\pm}\mu^{\mp} X$ and from particle misid

- Candidates classified by $e\mu$ mass and output of a geometrical BDT with 9 variables



LHCb search for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$

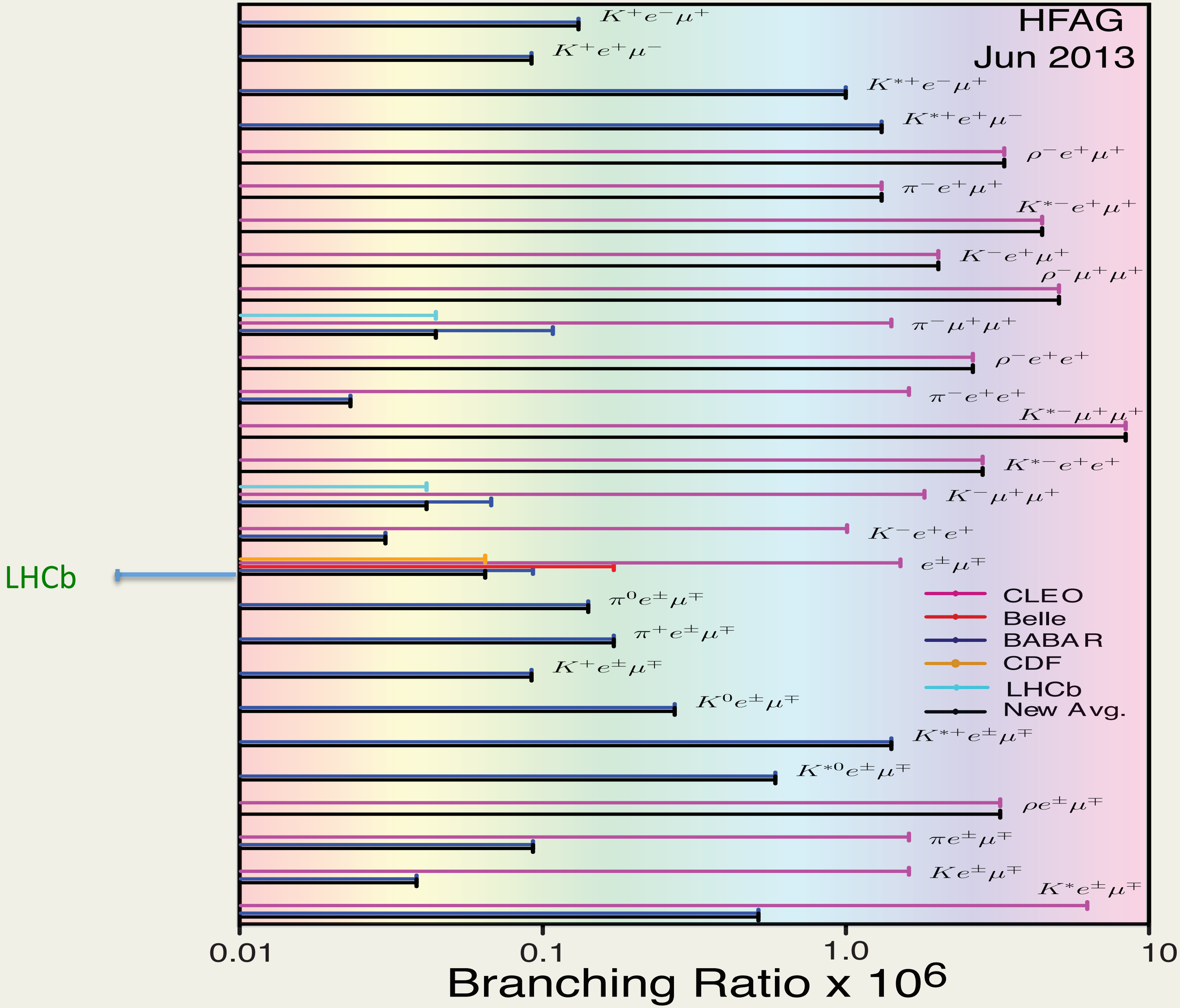


Channel	Observed (90% CL)	Observed (95% CL)
$B^0_s \to e^{\pm}\mu^{\mp}$	1.1×10^{-8}	1.4×10^{-8}
$B^0 \to e^{\pm}\mu^{\mp}$	2.8×10^{-9}	3.7×10^{-9}

- LHCb results give an order of magnitude improvement over previous limits (CDF)
- Limits also set on masses of Pati-Salam leptoquarks

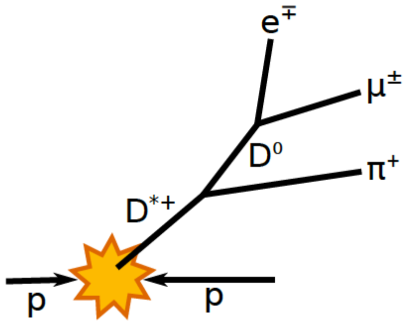
$$M_{LQ}(B^0_s \to e^{\pm}\mu^{\mp}) > 107\text{ TeV}$$
$$M_{LQ}(B^0 \to e^{\pm}\mu^{\mp}) > 135\text{ TeV}$$

Lepton Number Violating Charmless B Decays

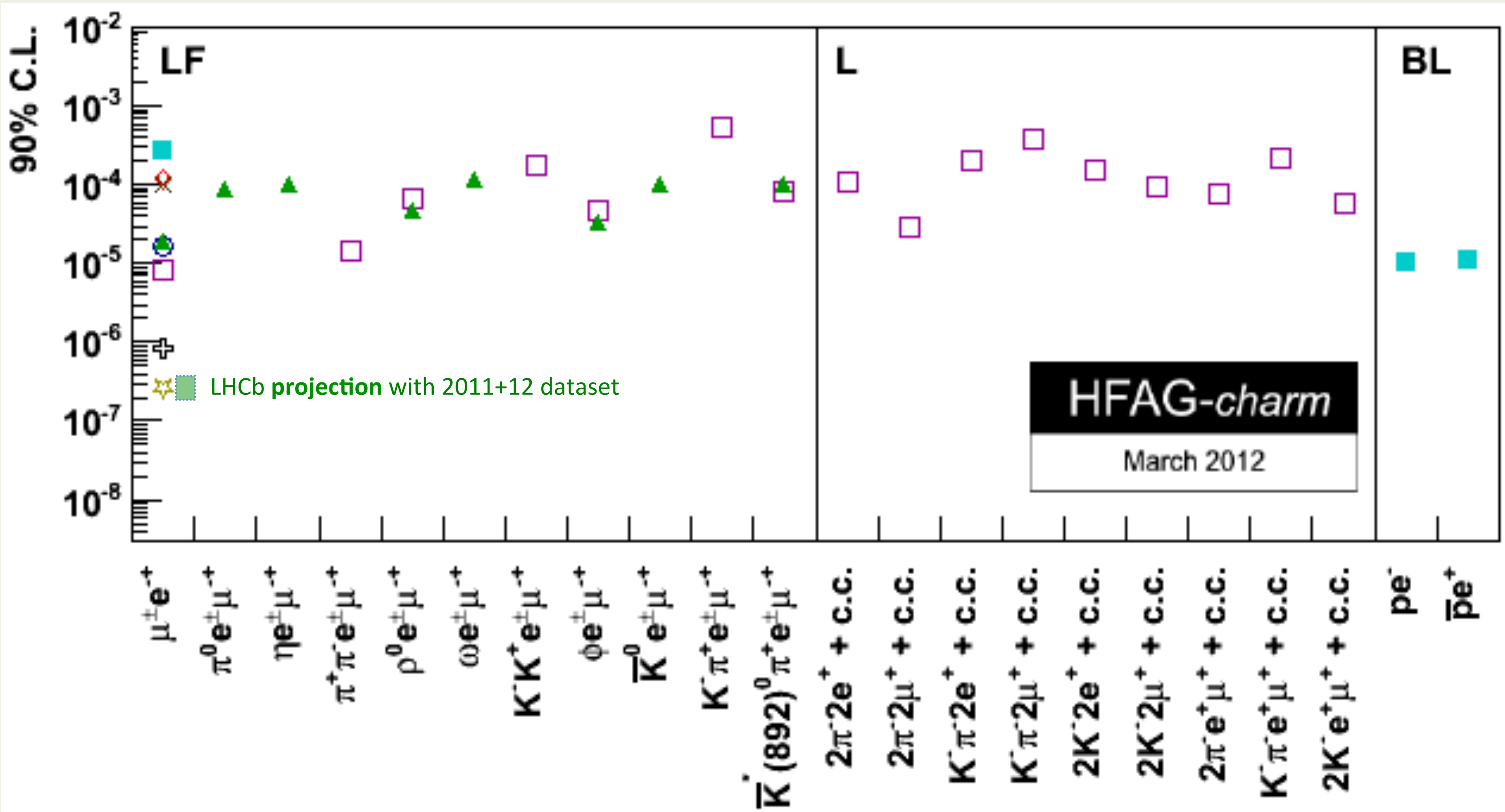


LHCb search for $D^0 \to e^{\pm} \mu^{\mp}$

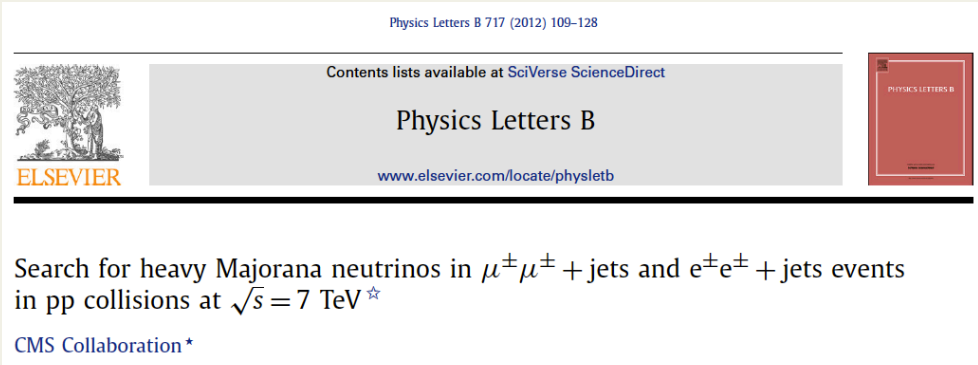
- LFV $D^0 \to e^{\pm} \mu^{\mp}$ decays would occur in R-parity violating SUSY, Higgs doublet models and models with extra fermions
- Current best limit is from Belle: $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 2.7 \times 10^{-7}$
- Analysis now started in LHCb
  - using D^0 tagged by $D^{*+} \to D^0\pi^-$ decays
  - normalising to $D^0 \to \pi^+\pi^-$ which has a large yield
- LHCb 3 fb^{-1} (2011+2012) data sample has potential to be competitive with the Belle result



Compilation by **Heavy Flavor Averaging Group** of LNV limits for D^0 decays



Search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$ + jets and $e^{+}e^{-}$ + jets at CMS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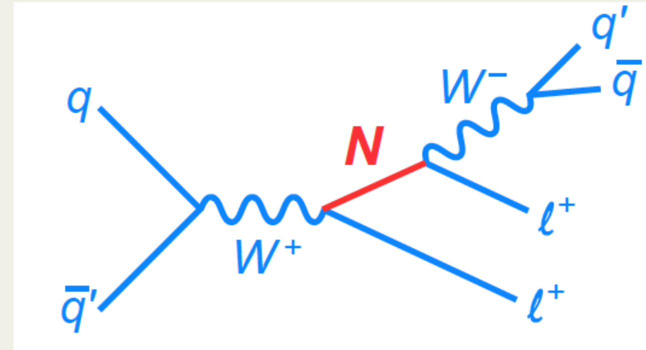
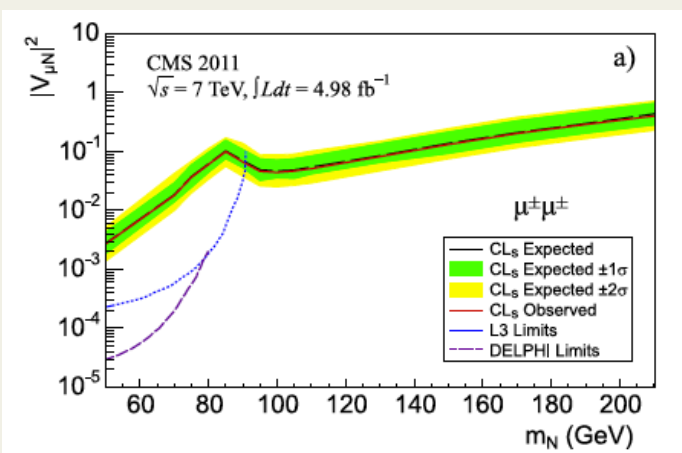
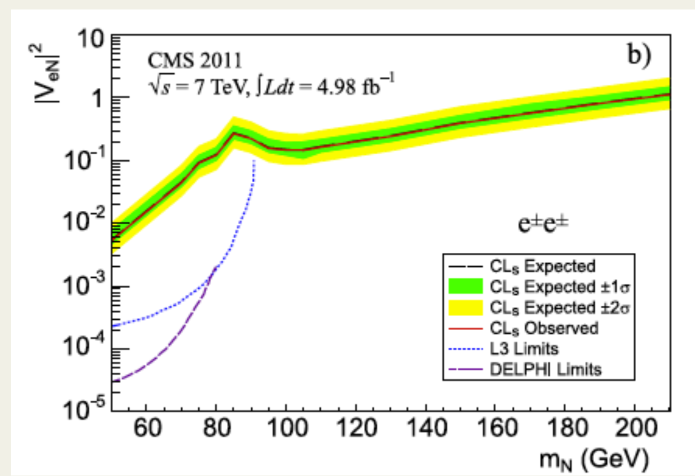
Search for heavy Majorana neutrinos in $\mu^{\pm}\mu^{\pm}$ + jets and $e^{\pm}e^{\pm}$ + jets events in pp collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *



- Analysis uses 4.98 fb^{-1} at $\sqrt{s}$ = 7 TeV
- N may decay to same-sign ($W^{-} l^{+}$)or opposite-sign ($W^{+} l^{-}$) lepton
- Same-sign events have no SM background – search for events with two isolated leptons of same sign and same flavour, plus at least two jet
- Free parameters are heavy neutrino mass m_N and mixing parameters $|V_{lN}|^2$ for l=e,μ

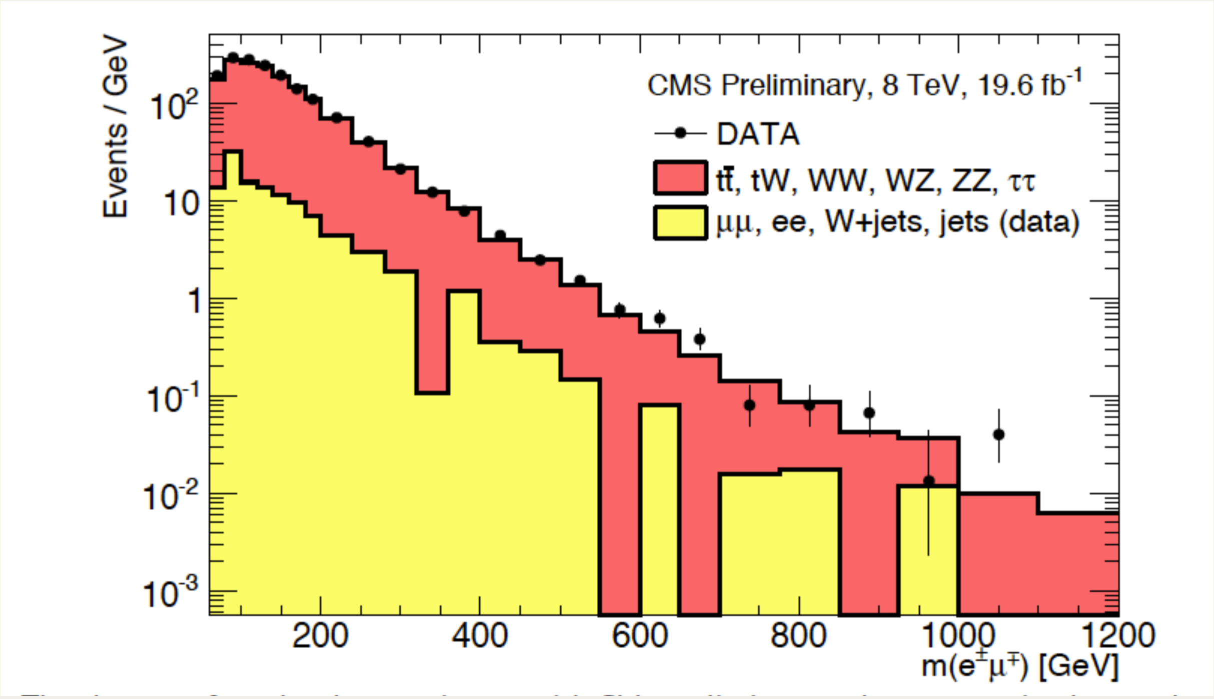




CMS search for narrow heavy resonances decaying into two leptons

- An easily identifiable cLFV signature: a pair of different flavour, opposite sign leptons with large p_T could arise from e.g.
  - A sneutrino decaying into $e^{\pm}\mu^{\mp}$ (in RPV+LFV SUSY)
  - A Z' boson with LFV couplings

- Analysis (CMS PAS EXO-12-061) used 20 fb^{-1} at 8 TeV
- Observed spectra consistent with SM



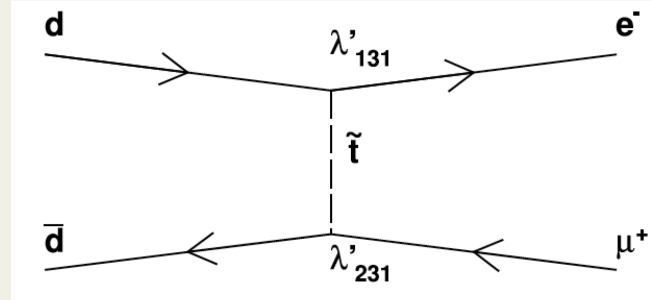
ATLAS search for LFV in the $e^{\pm}\mu^{\mp}$ continuum

Eur. Phys. J. C (2012) 72:2040
DOI 10.1140/epjc/s10052-012-2040-z

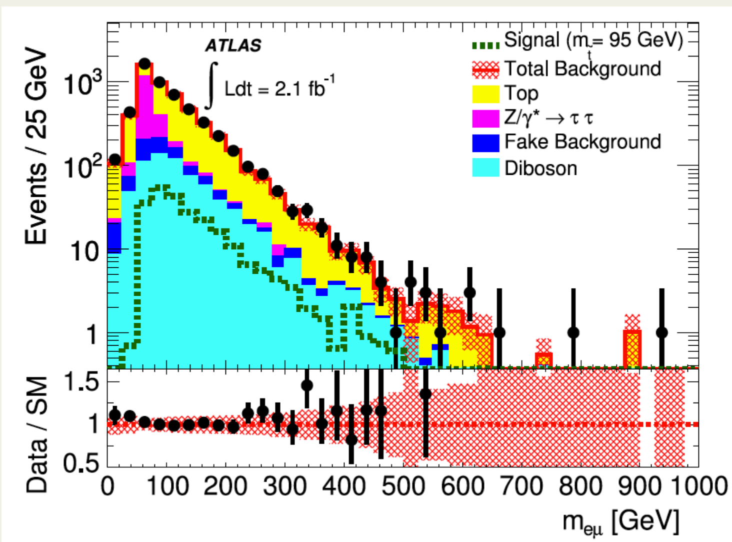
THE EUROPEAN PHYSICAL JOURNAL C

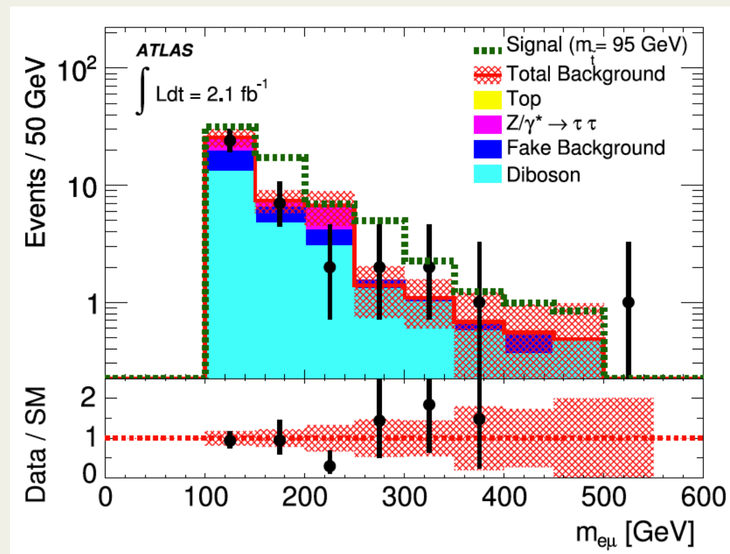
Regular Article - Experimental Physics

Search for lepton flavour violation in the $e\mu$ continuum with the ATLAS detector in $\sqrt{s} = 7$ TeV pp collisions at the LHC



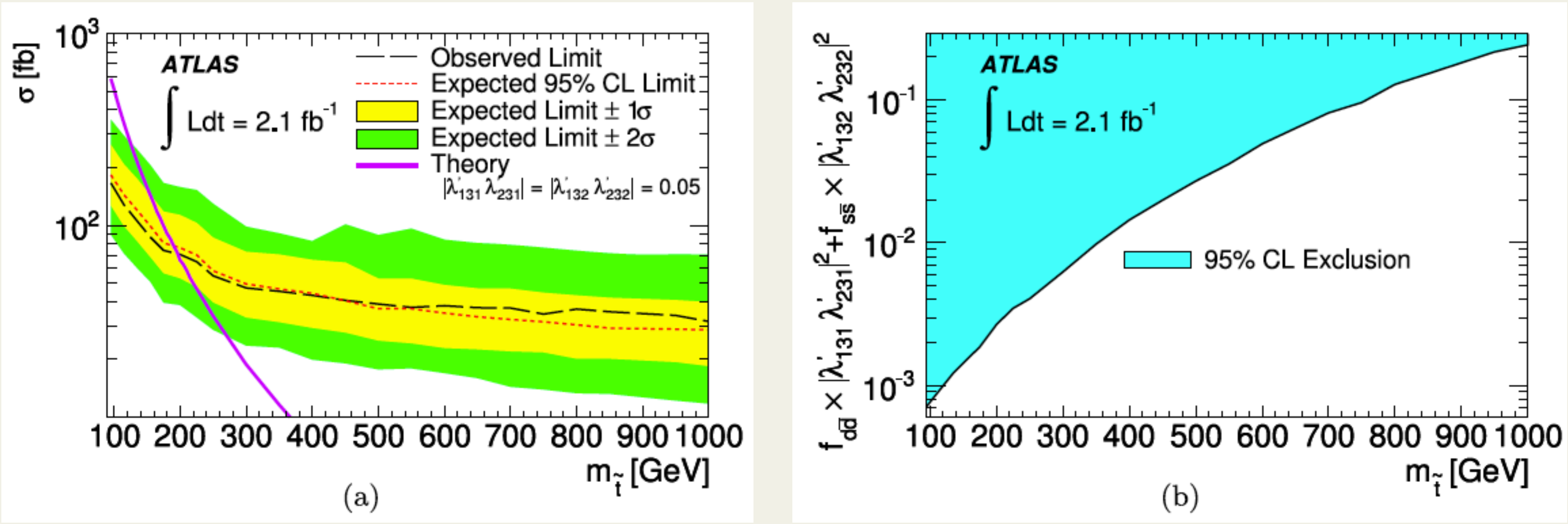
- Exemplified/interpreted via t-channel exchange of a stop in LFV SUSY
- Analysis uses 2.1 fb^{-1}
- Puts limits on RPV couplings as function of stop mass





ATLAS search for LFV in the $e^{\pm}\mu^{\mp}$ continuum

- Analysis puts limits on RPV couplings as function of stop mass



Conclusions

- Already LHC has improved on previous limits for a number of LFV and LNV channels
- No signals have been seen
- But new Physics is out there somewhere
- So we will keep pushing back the frontiers …