university of groningen / faculty of mathematics and natural sciences / van swinderen institute for particle physics and gravity

Nikhef

LFV in B decay

– an overview –

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University of Groningen, the Netherlands

LHCb

"LFV/LFUV - Why and How?", Paris, France, 7-9 November 2016

Outline

Intro

LHCb Experiment

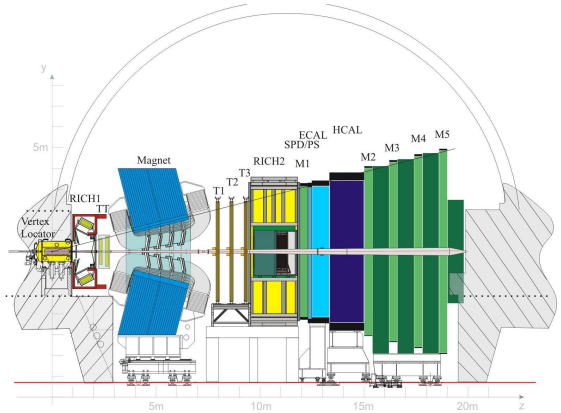
LFV with muons : $\tau \rightarrow \mu\mu\mu$

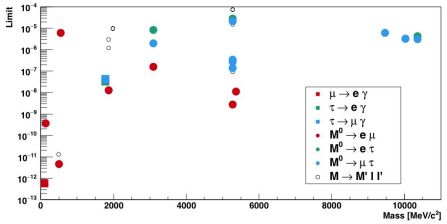
LFV with electrons : $D^0 \rightarrow e\mu$

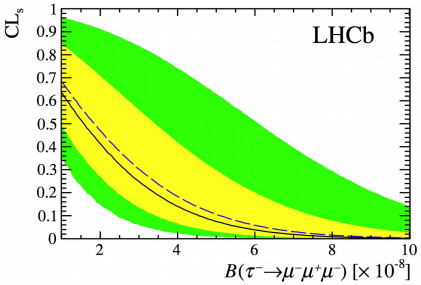
LFV with taus?

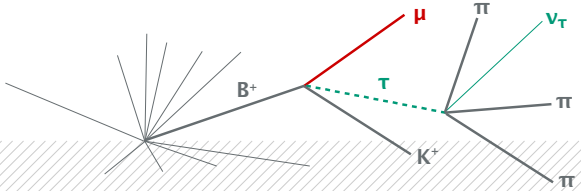
Insights

Conclusion





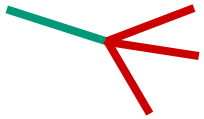


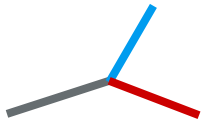


Intro

Towards studying (c)LFV

Decay	$\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\mu\mu$, $\tau \to \mu hh$, ...
Conversion	$\mu A \to eA$
Production	$B_s \to e\mu$, $B \to Ke\mu$, $h^0 \to \mu\tau$, ...
Oscillation	$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$, $M(\mu^+e^-) \leftrightarrow \overline{M}(\mu^-e^+)$
Number violation	$0\nu2\beta$, $B^- \to \pi^+\mu^-\mu^-$, ...
Non-Universality	$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ *vs* $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$, ...





Charges dropped, unless relevant

Tensions

$B^0 \to D^{(*)} \tau \bar{\nu}_\tau / l \bar{\nu}_l$ **3.9σ** : LHCb + BaBar + Belle

$B^+ \to K^+ \mu\mu$ / ee **2.6σ** : LHCb

Anomalies $b \to sll$, esp. P'_5 in $B \to K^* \mu\mu$ @ LHCb

$h^0 \to \mu\tau$ **2.4σ** : CMS

a_μ **2.7σ** : E821

Global fit favors large cLFV

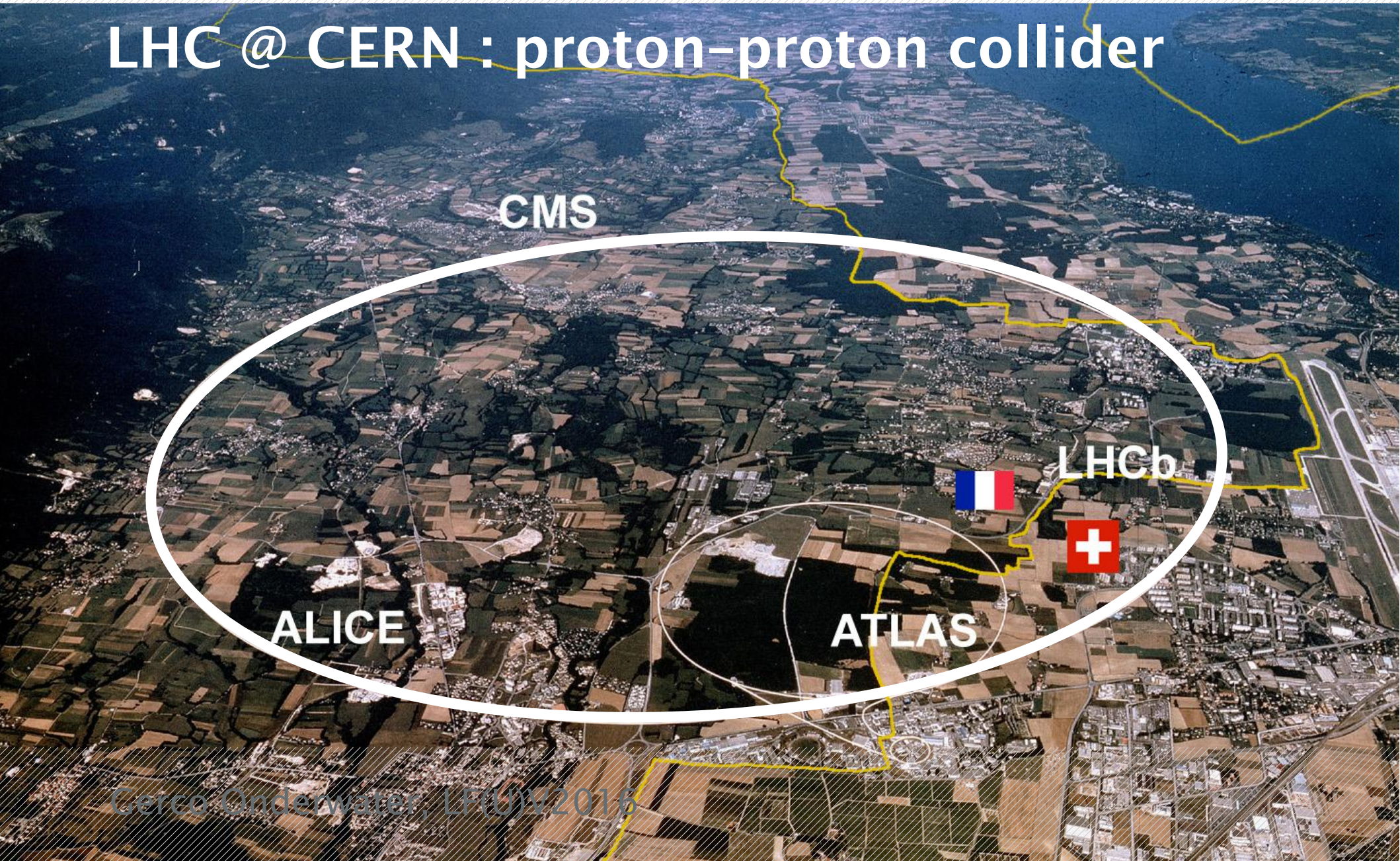
FERMILAB-PUB-16-131-T

Recent LHCb results

$D^0 \to e\mu$	PLB 754 (2016) 167	**LFV**
$\overline{B}^0 \to D^{*+} \tau \overline{\nu}_\tau$ / $\mu \overline{\nu}_\mu$	PRL 115, 111803 (2015)	LNU
$\tau \to \mu\mu\mu$	JHEP 02 (2015) 121	**LFV**
$B^+ \to K^+\mu\mu$ / ee	PRL 113, 151601 (2014)	LNU
$B^- \to \pi^+\mu^-\mu^-$	PRL 112, 131802 (2014)	*LNV*
$D^+_{(s)} \to \pi^-\mu^+\mu^+$	PLB 724 (2013) 203-212	*LNV*
$B^0_{(s)} \to e\mu$	PRL 111 (2013) 141801	**LFV**

LHCb

LHC @ CERN : proton-proton collider



LHCb detector

LHCb detector

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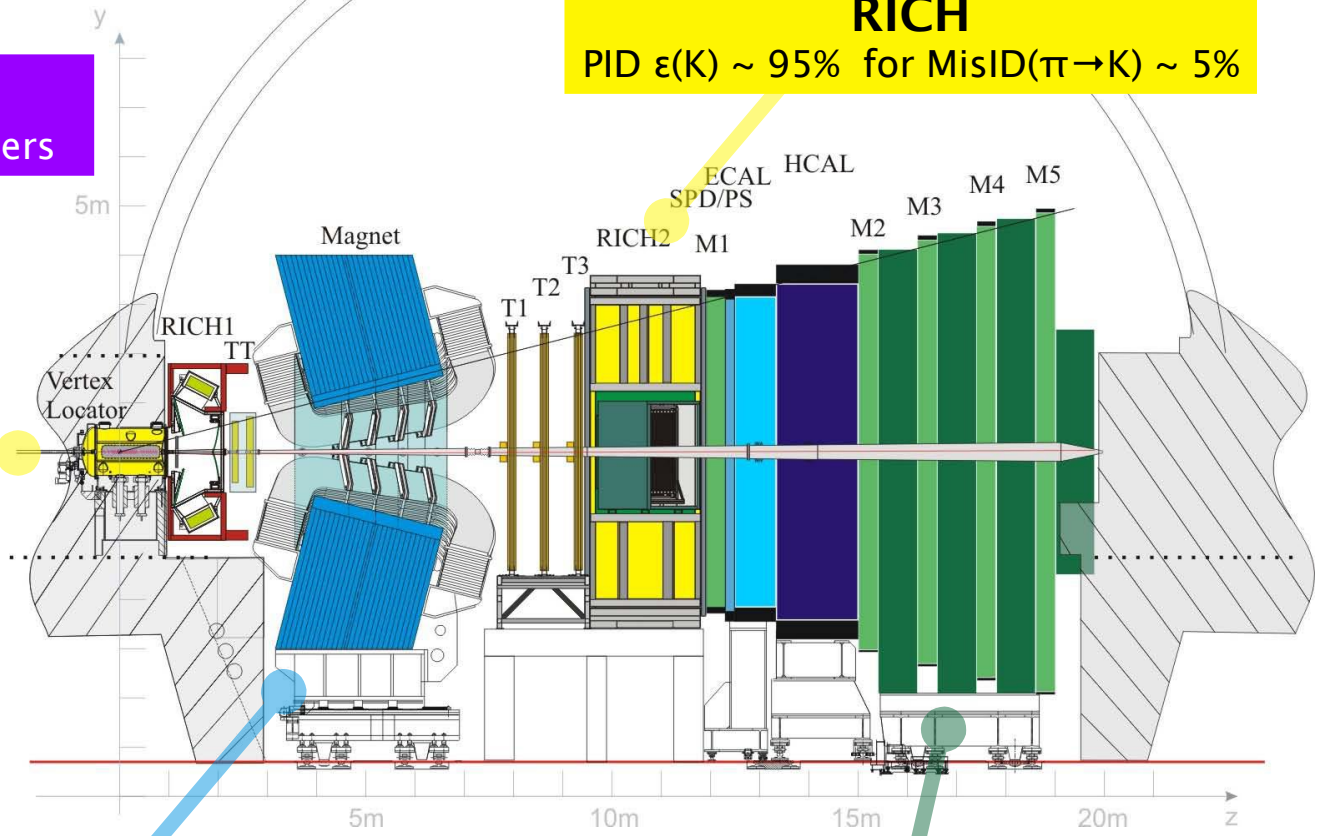
LHCb : precision measurement

Trigger
high efficiency *esp.* muon triggers

RICH
PID ε(K) ~ 95% for MisID(π→K) ~ 5%



VELO
~20μm IP resolution for p_T > 2 GeV

Tracking Δp/p
0.4% @ 5 GeV/*c* – 0.6% @ 100 GeV/*c*

Muon ID
identification ε ~ 97% misID ~ 2%

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Int. J. Mod. Phys. A 30, 1530022 (2015)

Results

Signal & background

Measure branching fraction **Br = N(signal)/N(total)**

Challenges to reach highest sensitivity:

Enormous **N(total)** = $\sigma \cdot \int \mathcal{L} dt$

Small **N(signal)**

Single-Event-Sensitivity: **S** = $\varepsilon \cdot Br \cdot N(total) \rightarrow Br < 1 / \varepsilon \cdot N(total)$

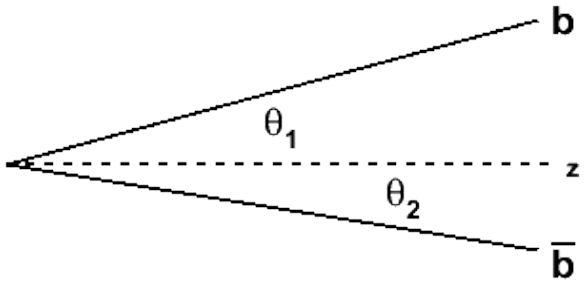
Background: **B** = $N(bkgd) = (1-\rho) \cdot \sigma_B \cdot \int \mathcal{L} dt \rightarrow Br < \sqrt{B} / \varepsilon \cdot N(total)$

$$\mathbf{Br = \sqrt{(1-\rho)/\varepsilon^2 \cdot \sigma_B/\sigma \cdot 1/\int \mathcal{L} dt}}$$

b-quark production

Acceptance

~25% for $b/\bar{b}$ or $b\bar{b}$ pairs



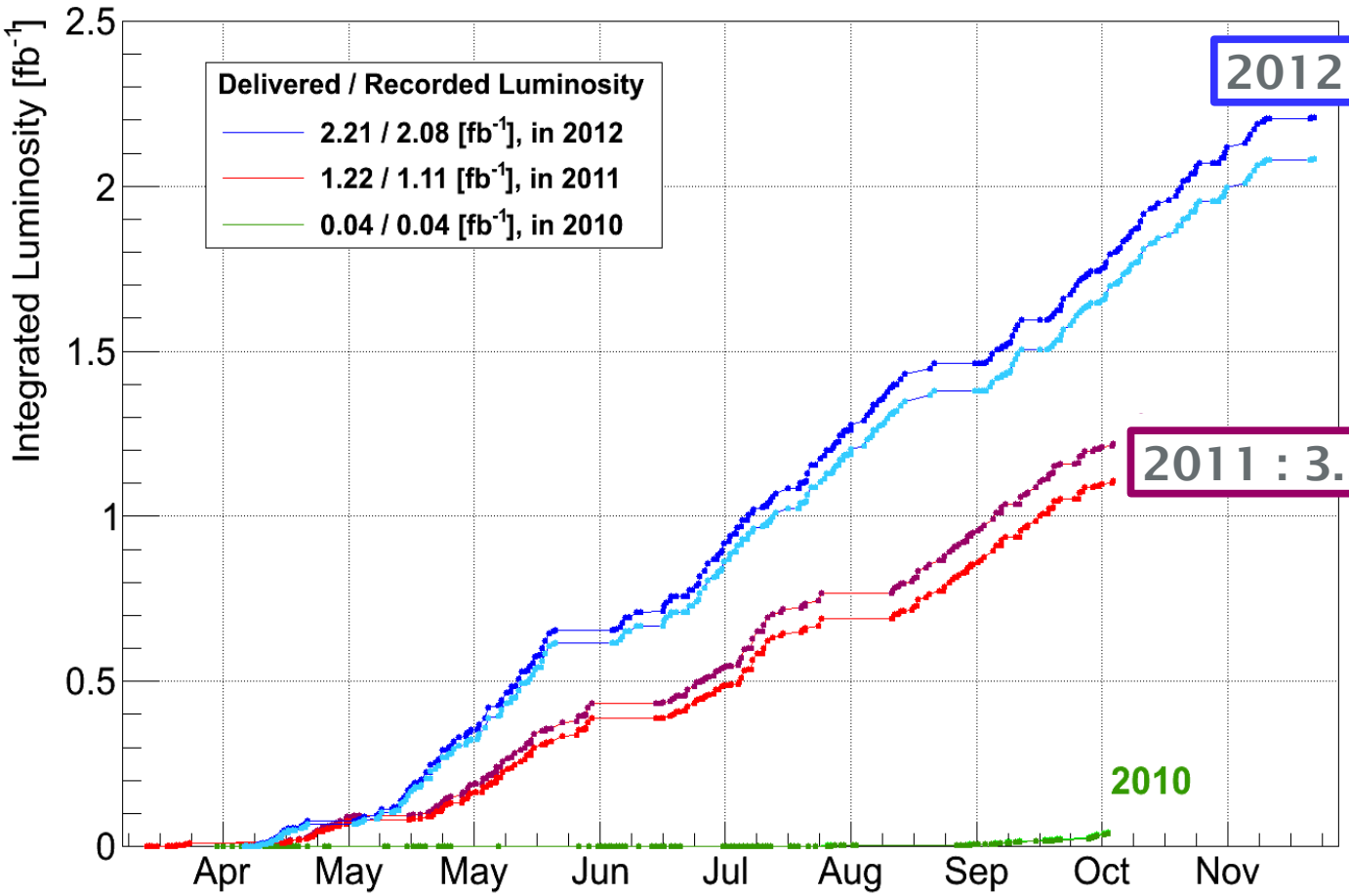
Total cross section

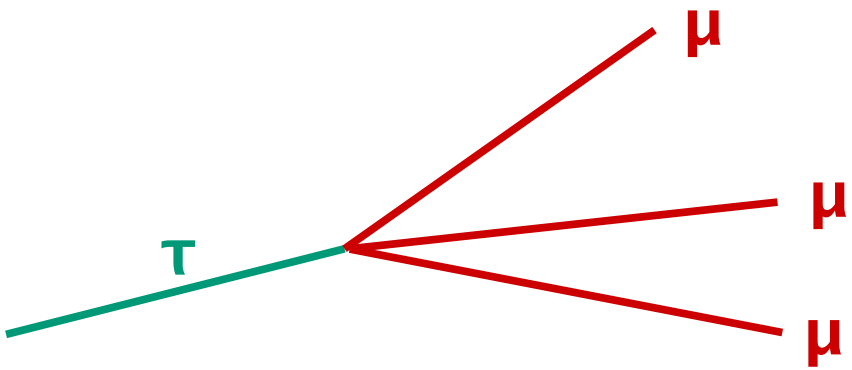
250μb – 500μb

10^5 $b\bar{b}$ / s

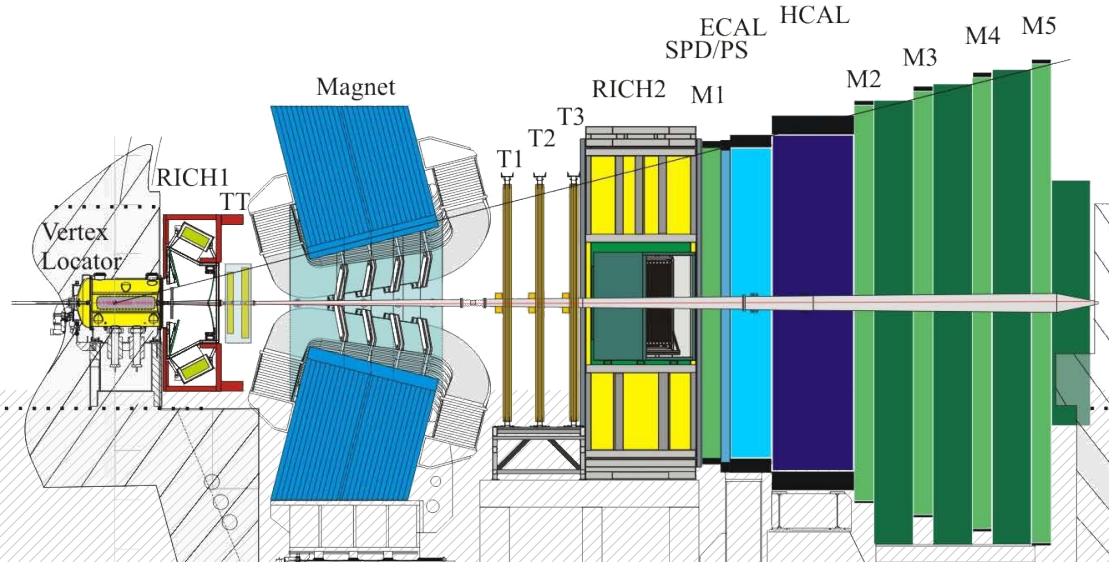
(10^4 x B-factories)

LHC run-I luminosity




τ
μ
μ
μ

μ detection


Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
ECAL
SPD/PS
HCAL
M2
M3
M4
M5

Challenge : τ decays at hadron collider

B factory

- ✘ Babar & Belle ~3×10^{9} τ−pairs
- ✓ $e^+e^- \rightarrow \tau^+\tau^-$ extremely clean
- ✓ tag with opposite τ possible

LHC

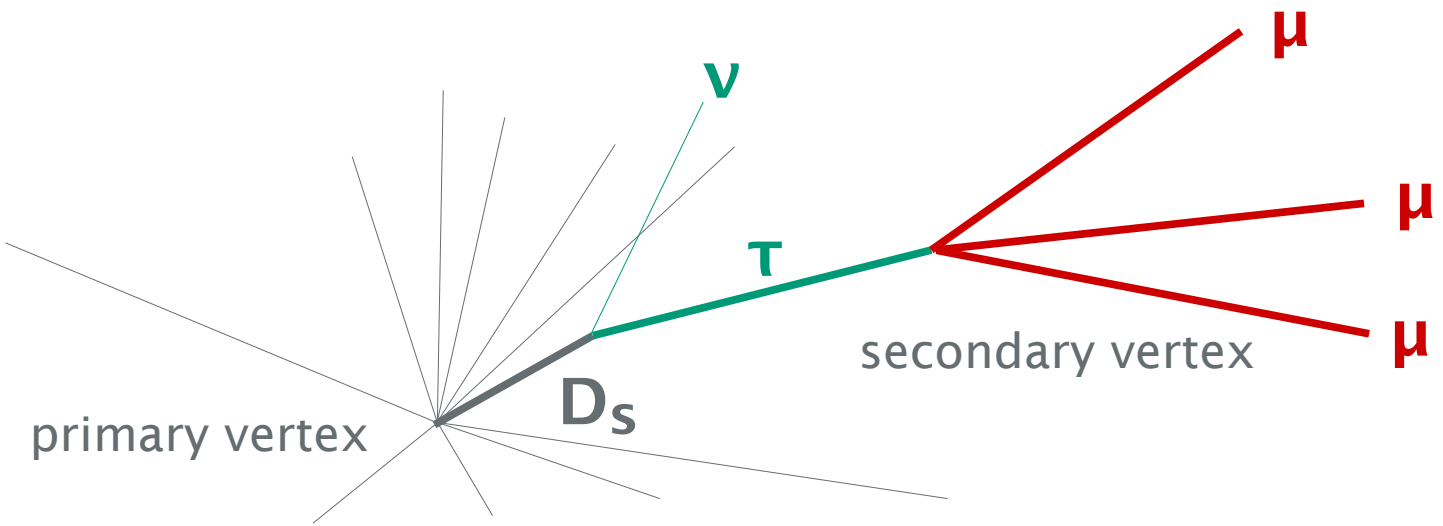
- ✓ LHCb ~3.5×10^{11} τ's in detector acceptance in 2011 & 2012
- ✘ pp → τ + O(100) particles
- ✘ No "production traces" in $D_s \rightarrow \tau\nu_\tau$
- ✘ Charm decay with missing particles similar to τ signature

τ → 3μ search

main tau production via decay of D_s

Approach:

- trigger on *muon* and *secondary vertex*
- *multivariate analysis* to discriminate signal and background
- *control sample* for normalization and calibration



JHEP 02 (2015) 121

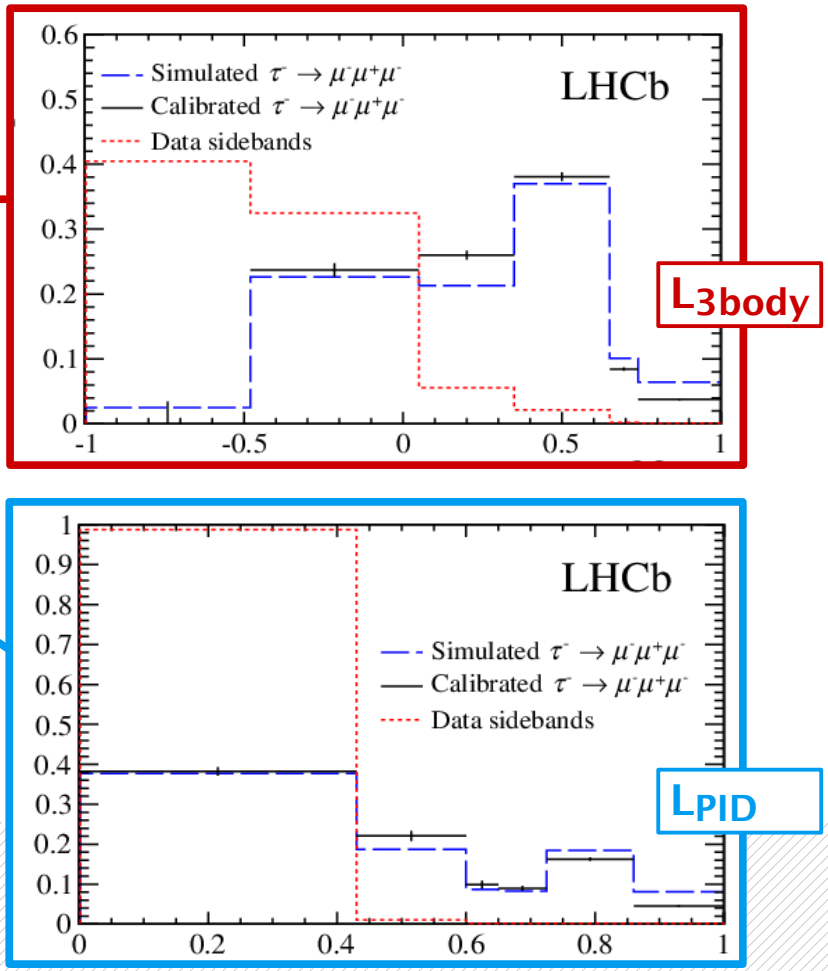
Signal & background discrimination

Three likelihoods to distinguish signal from background

I. L_{3body} : decay topology

II. L_{PID} : μ identification

III. $L_{3\mu}$: tau selection

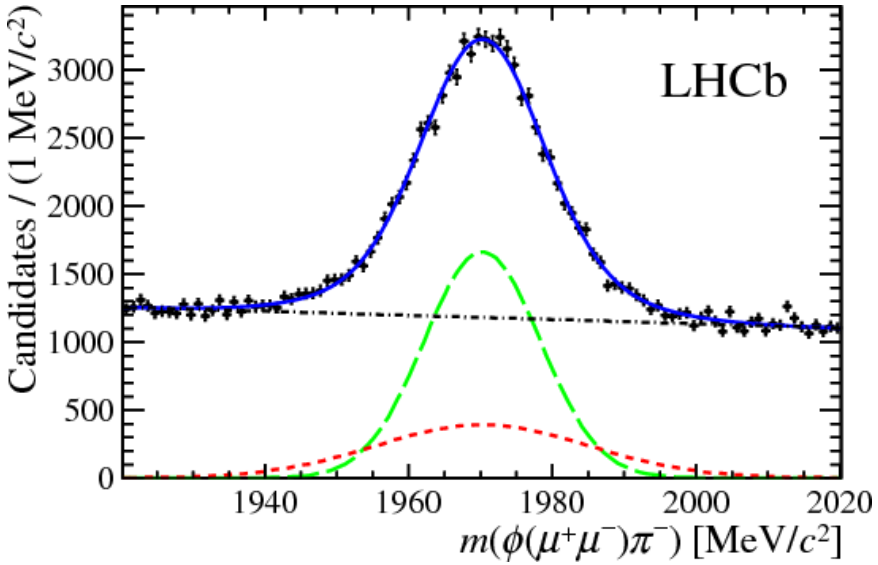


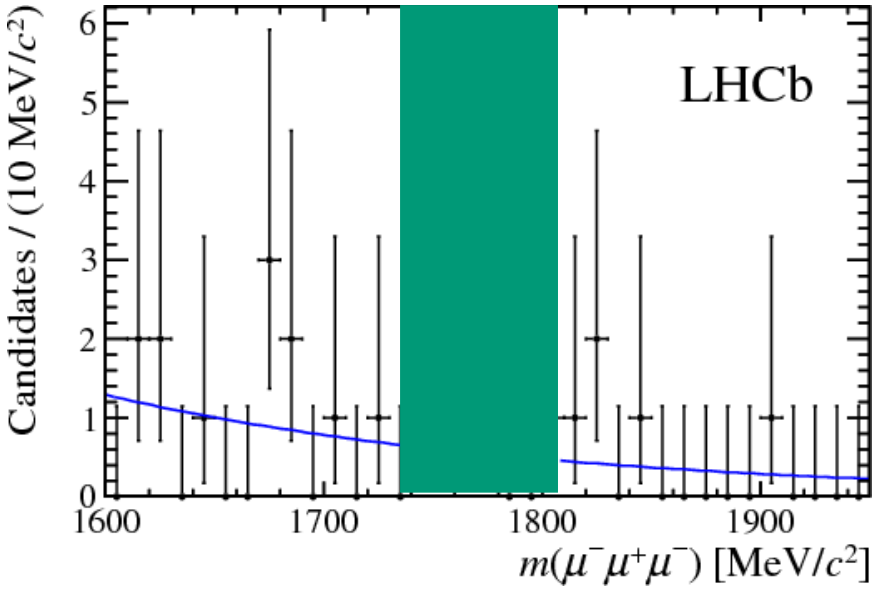
$M_{3\mu}$ distribution

- Shape determined using $D_s^- \to \Phi(\mu^+\mu^-)\pi^-$
- Analyze 5x5 best bins in L_{PID} and L_{3body}

Blind analysis

Bkgd Signal Bkgd



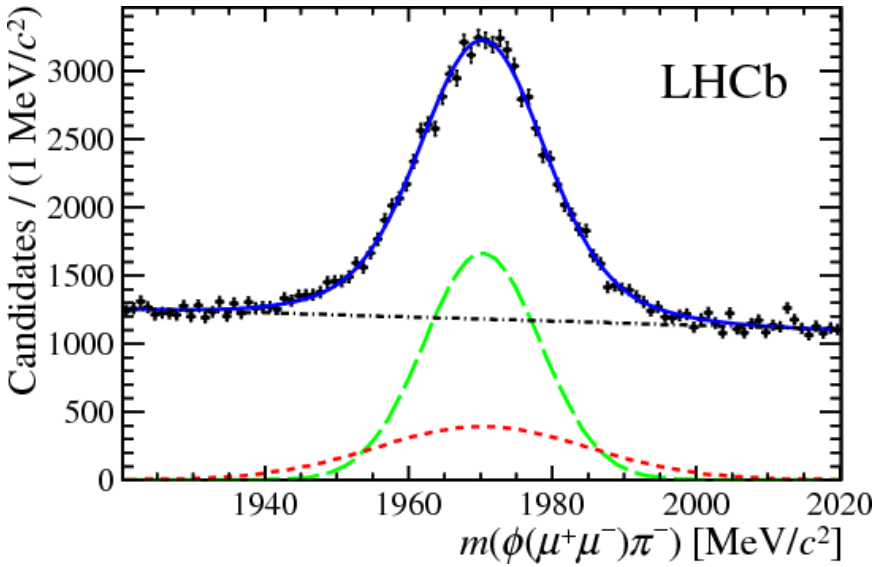


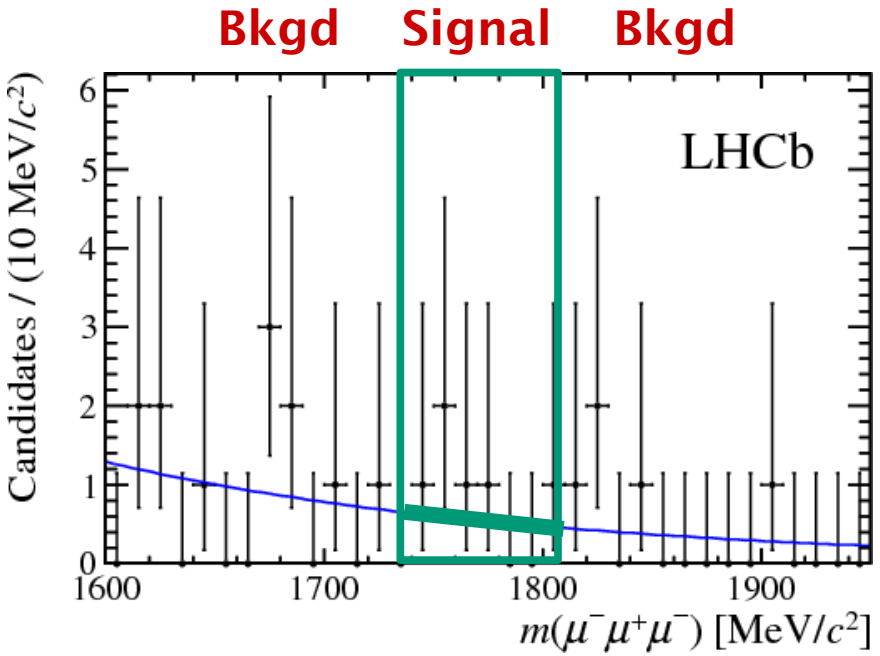
L_{PID} : [0.65, 1.0]
L_{3body} : [0.725, 1.0]

JHEP 02 (2015) 121

$M_{3\mu}$ distribution

- Shape determined using $D_s^- \to \Phi(\mu^+\mu^-)\pi^-$
- Analyze 5x5 best bins in L_{PID} and L_{3body}





L_{PID} : [0.65, 1.0]
L_{3body} : [0.725, 1.0]

JHEP 02 (2015) 121

Normalization

Branching fraction for $\tau^- \to \mu^-\mu^+\mu^-$ normalized to $D_s^- \to \Phi(\mu^+\mu^-)\pi^-$

$$B = \frac{N(\tau \to \mu\mu\mu)}{N(\tau)} = \alpha \times \frac{N_{sig}}{N_{cal}}$$

$$\alpha = \frac{N_{cal}}{N(\tau)}$$

	7 TeV	8 TeV
$\mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-)$	$(1.32 \pm 0.10) \times 10^{-5}$	
$\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)$	$(5.61 \pm 0.24) \times 10^{-2}$	
$f_\tau^{D_s}$	0.78 ± 0.04	0.80 ± 0.03
${\epsilon_{\rm cal}}^{\rm R}/{\epsilon_{\rm sig}}^{\rm R}$	0.898 ± 0.060	0.912 ± 0.054
${\epsilon_{\rm cal}}^{\rm T}/{\epsilon_{\rm sig}}^{\rm T}$	0.659 ± 0.006	0.525 ± 0.040
$N_{\rm cal}$	$28\,200 \pm 440$	$52\,130 \pm 700$
α	$(7.20 \pm 0.98) \times 10^{-9}$	$(3.37 \pm 0.50) \times 10^{-9}$

JHEP 02 (2015) 121

Result

$$\frac{\mathbb{P}(\theta_{up}(X) < \theta|\theta)}{\mathbb{P}(\theta_{up}(X) < \theta|0)} \leq \alpha' \text{ for all } \theta.$$

- Robust analysis method
- Statistics limited
- No significant evidence for excess of events

$B(\tau^- \to \mu^-\mu^+\mu^-) < 4.6 \times 10^{-8}$

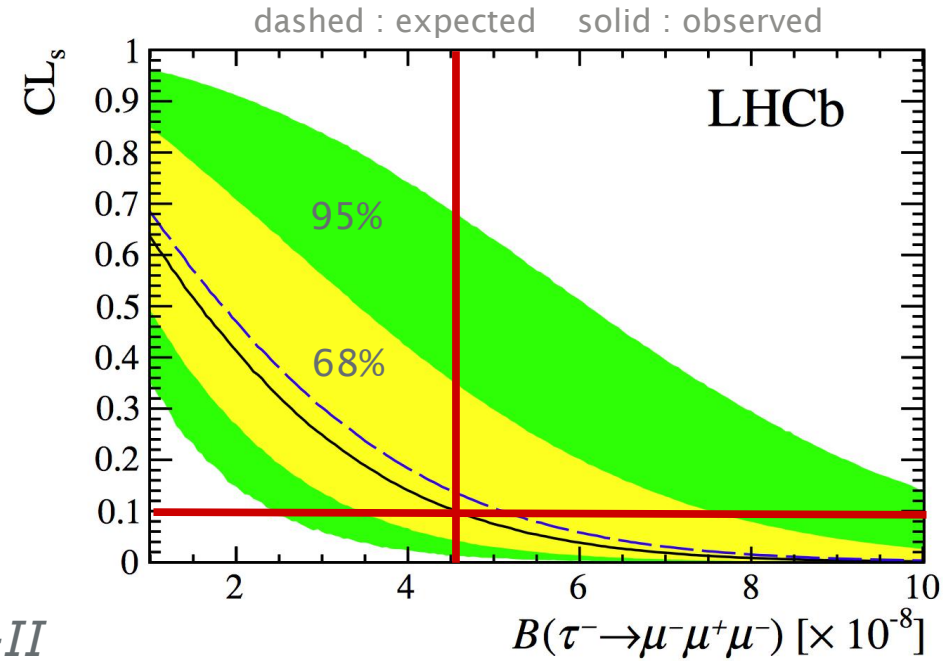
@ 90% C.L.

Belle 2.1 x 10^{-8} @ 90% C.L.

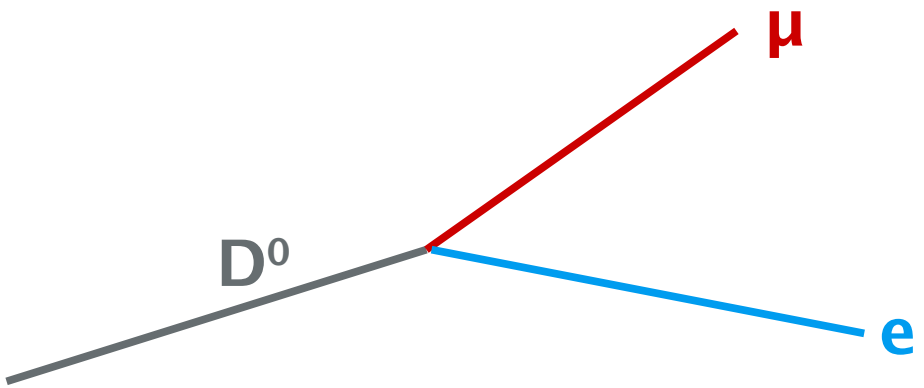
BaBar 3.3 x 10^{-8} @ 90% C.L.

@Run2: LHCb may overtake Belle

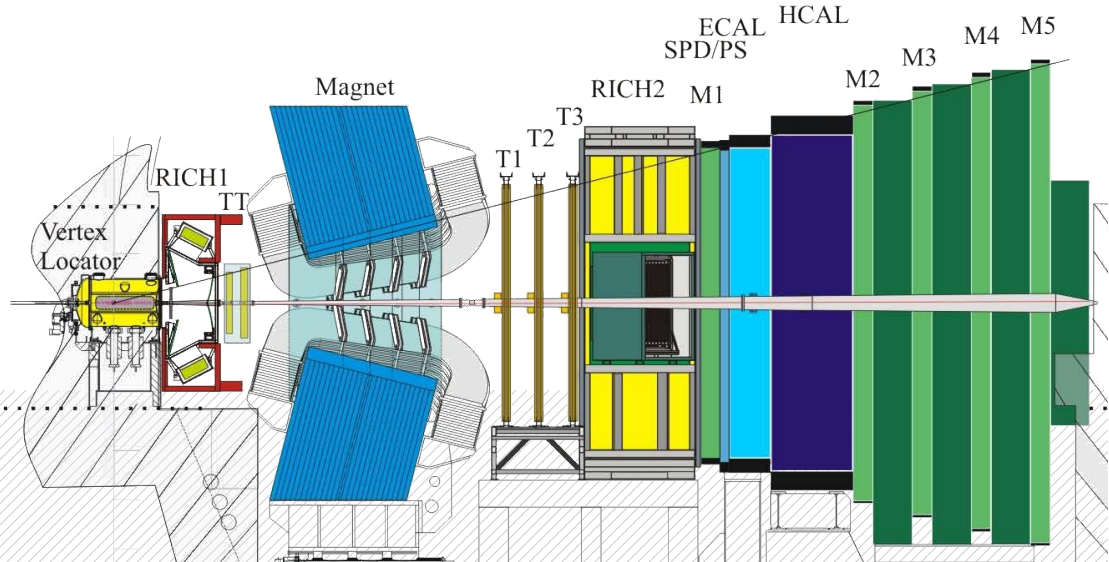
… which will then be overtaken by Belle-II



JHEP 02 (2015) 121


μ
D⁰
e

e detection


ECAL
HCAL
SPD/PS
M5
M4
M3
M2
M1
RICH2
Magnet
T3
T2
T1
RICH1
TT
Vertex
Locator

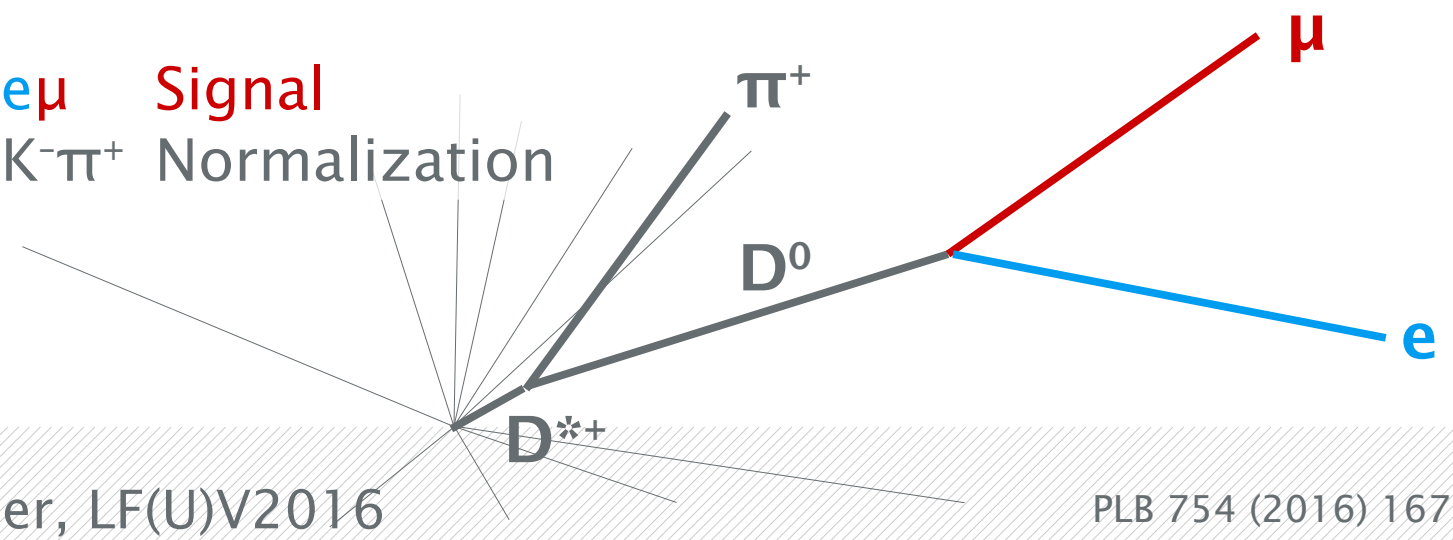
$D^0 \to e\mu$

Belle : $Br(D^0 \to e\mu) < 2.6 \times 10^{-7}$ (90% CL)

RPV SUSY : $\sim 10^{-7}$
Leptoquarks : 4×10^{-8}

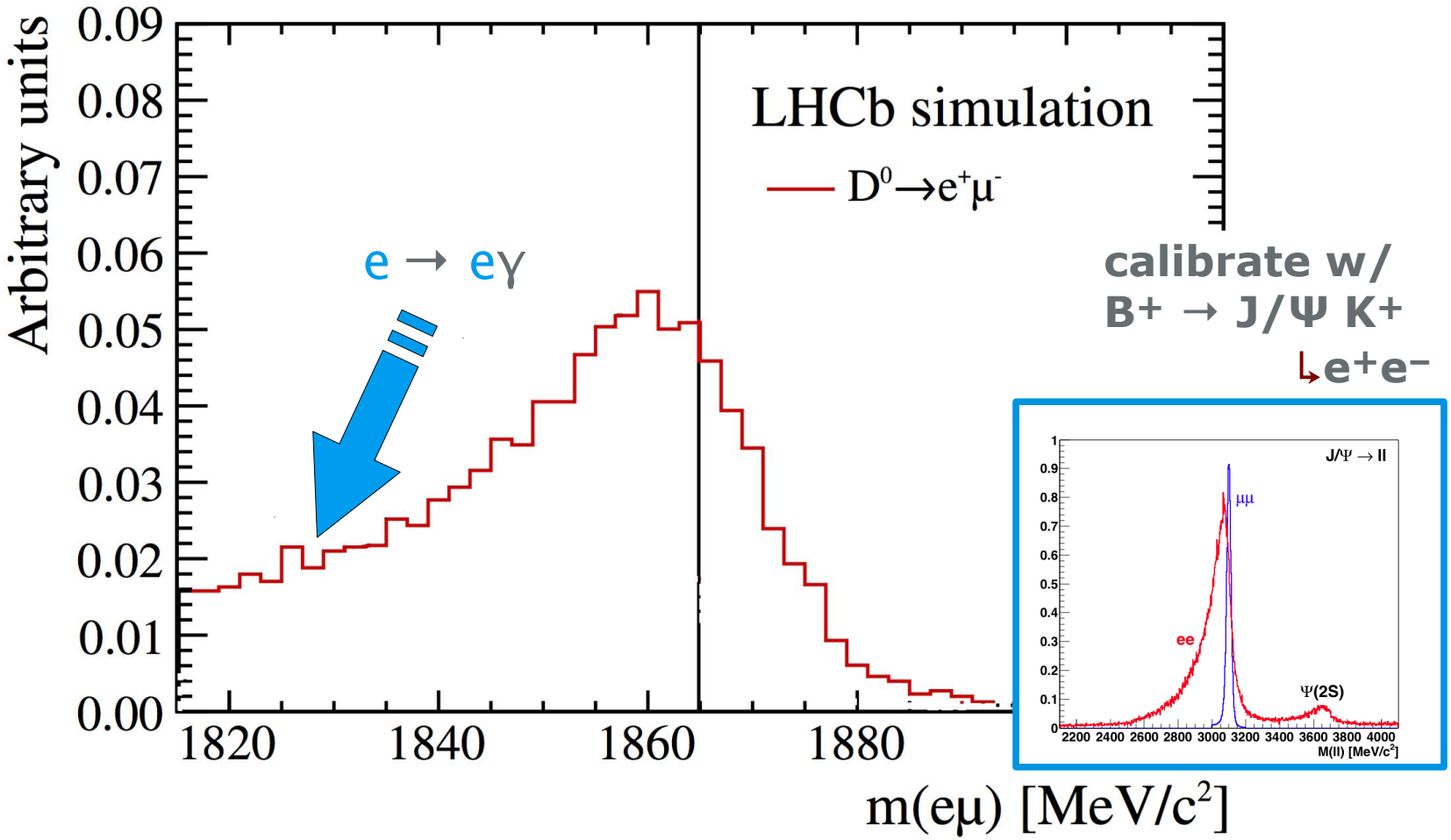
LHCb analysis based on 3 fb^{-1} collected @ $\sqrt{s}$ = 7 & 8 TeV

$D^{*+} \to D^0\pi^+$
↳ $D^0 \to e\mu$ Signal
↳ $D^0 \to K^-\pi^+$ Normalization



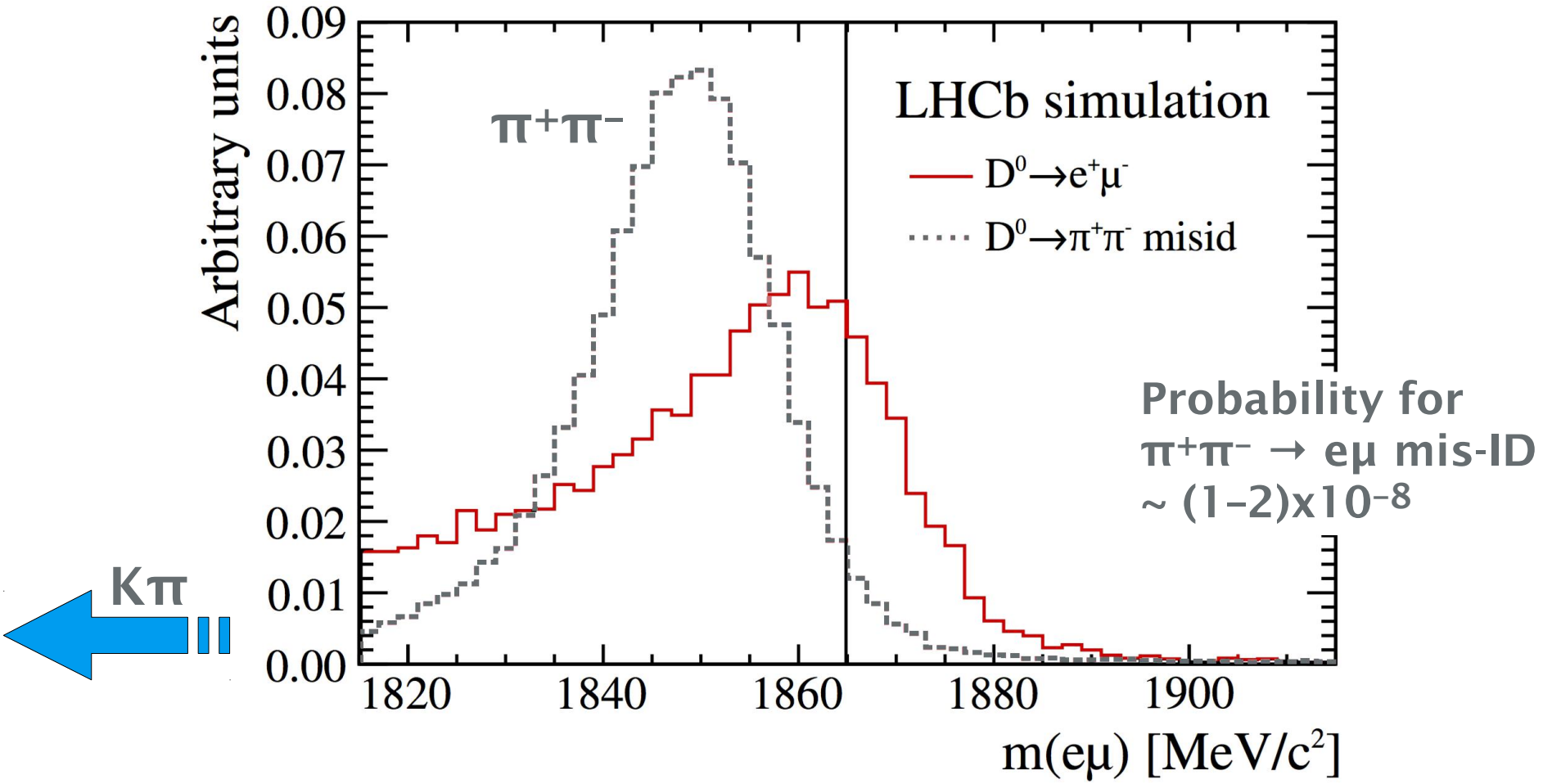
PLB 754 (2016) 167

Bremsstrahlung



PLB 754 (2016) 167

Mis-Identification



Probability for
$\pi^+\pi^- \rightarrow e\mu$ mis-ID
$\sim (1\text{–}2)\times 10^{-8}$

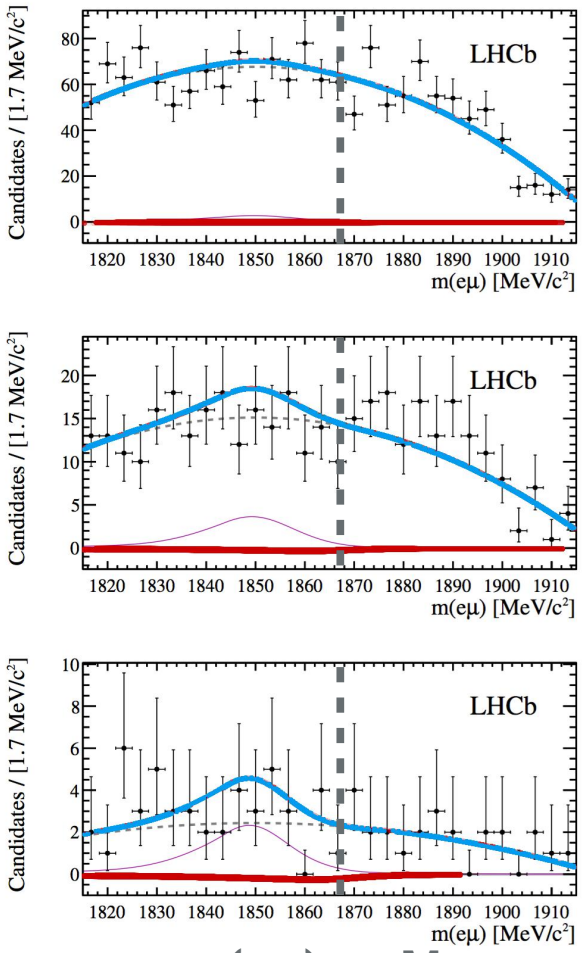
PLB 754 (2016) 167

Unbinned simultaneous fits

BKGD-like

intermediate

Signal-like



m(eμ) → M_D

Signal + bkgd

$D^0 \to e\mu$ (signal)

-7±15 events

PLB 754 (2016) 167

Result

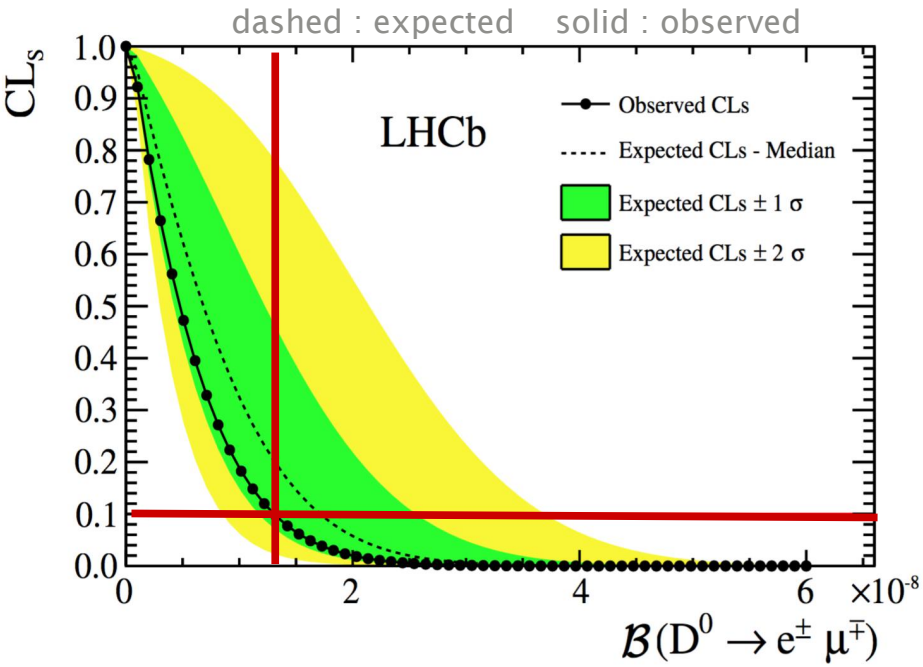
$$\frac{\mathbb{P}(\theta_{up}(X) < \theta|\theta)}{\mathbb{P}(\theta_{up}(X) < \theta|0)} \leq \alpha' \text{ for all } \theta.$$

- Robust analysis method
- Statistics limited
- No significant evidence for excess of events

$B(D^0 \to e\mu) < 1.3 \times 10^{-8}$

@ 90% C.L.

20x improvement over previous result
Effectively deal with backgrounds
Bremsstrahlung complicates analysis



PLB 754 (2016) 167

Other channels under investigation

$B_{(s)} \rightarrow e\mu$

$B^0 \rightarrow K^{*0}e\mu$

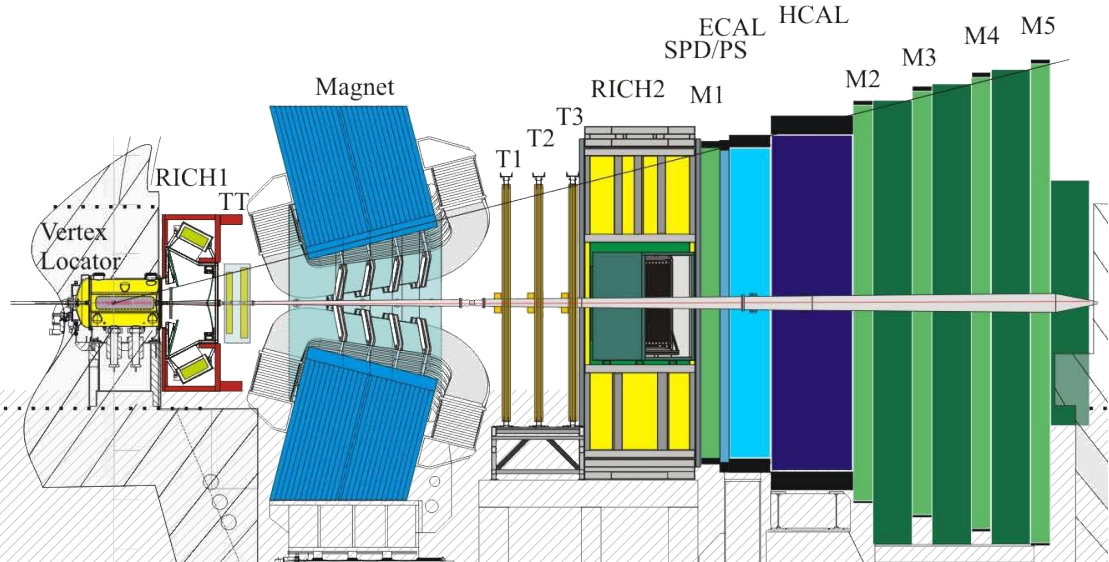
$B_s \rightarrow \Phi e\mu$

$B_{(s)} \rightarrow J/\Psi(\rightarrow e\mu)\, X$

$B^+ \rightarrow K^+e\mu$

Expect to improve existing limits

Opportunities for T detection



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Some existing limits

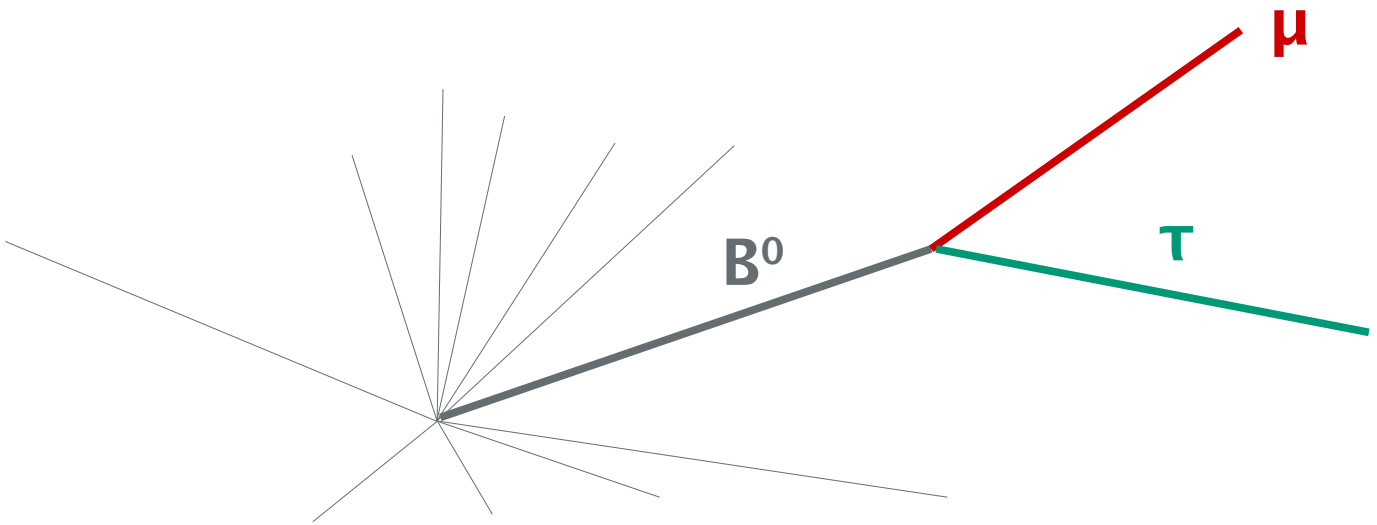
J/Ψ	→	$\mu\tau$	$< 2\times10^{-6}$
$\Upsilon(1S)$	→	$\mu\tau$	$< 6\times10^{-6}$
$\Upsilon(2S)$	→	$\mu\tau$	$< 3\times10^{-6}$
$\Upsilon(3S)$	→	$\mu\tau$	$< 3\times10^{-6}$
Z^0	→	$\mu\tau$	$< 1\times10^{-5}$
h^0	→	$\mu\tau$	$< 1.5\%$
J/Ψ	→	$e\tau$	$< 9\times10^{-6}$
Z^0	→	$e\tau$	$< 1\times10^{-6}$

O(few x 10^{-6})

@ 90-95% CL

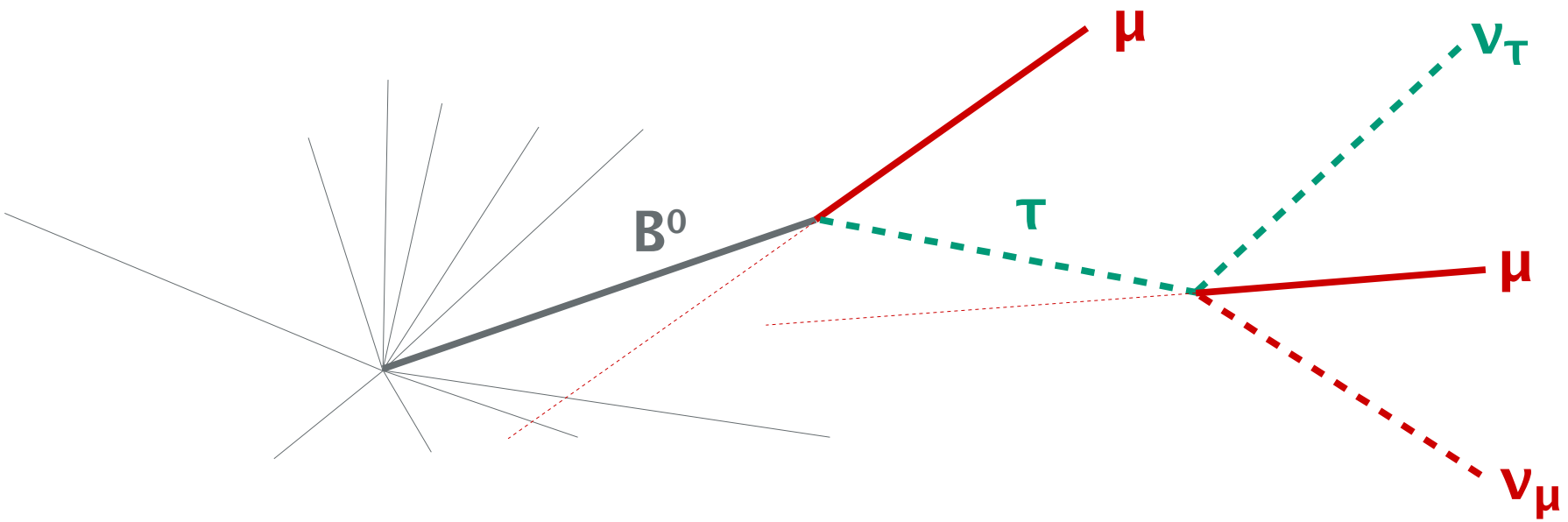
Reconstruction – I

Interesting possibility
Short lifetime prohibits direct detection



Reconstruction – II

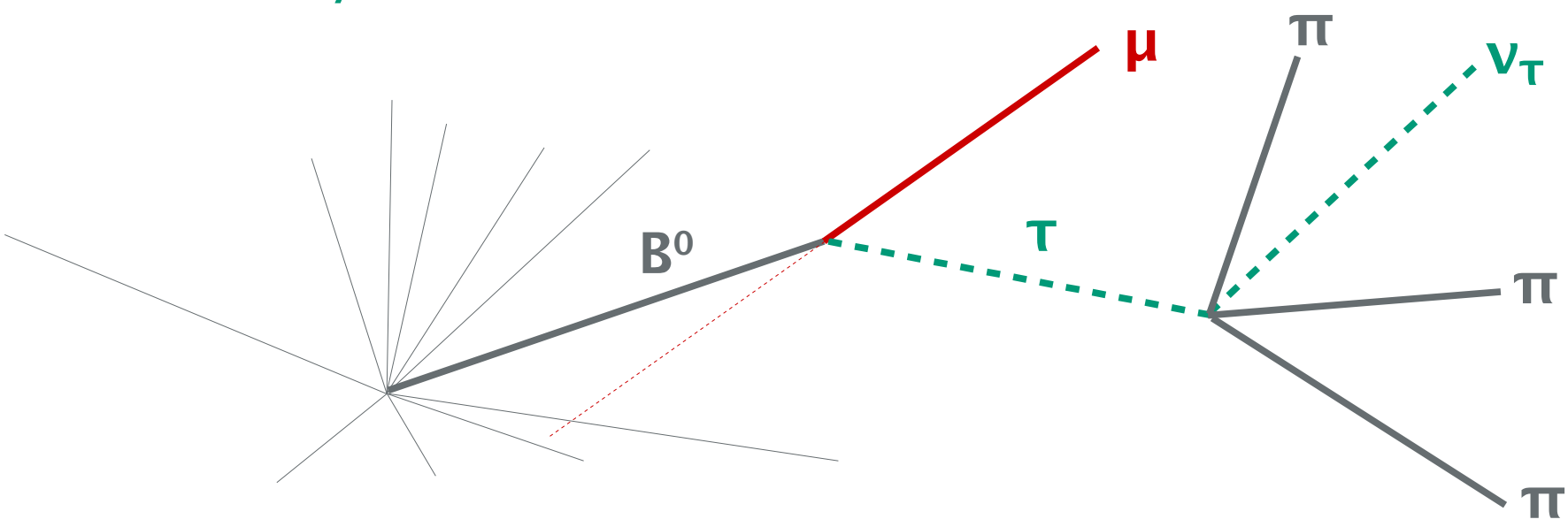
Interesting possibility
Short lifetime prohibits direct detection
Neutrinos remain undetected



Reconstruction – III

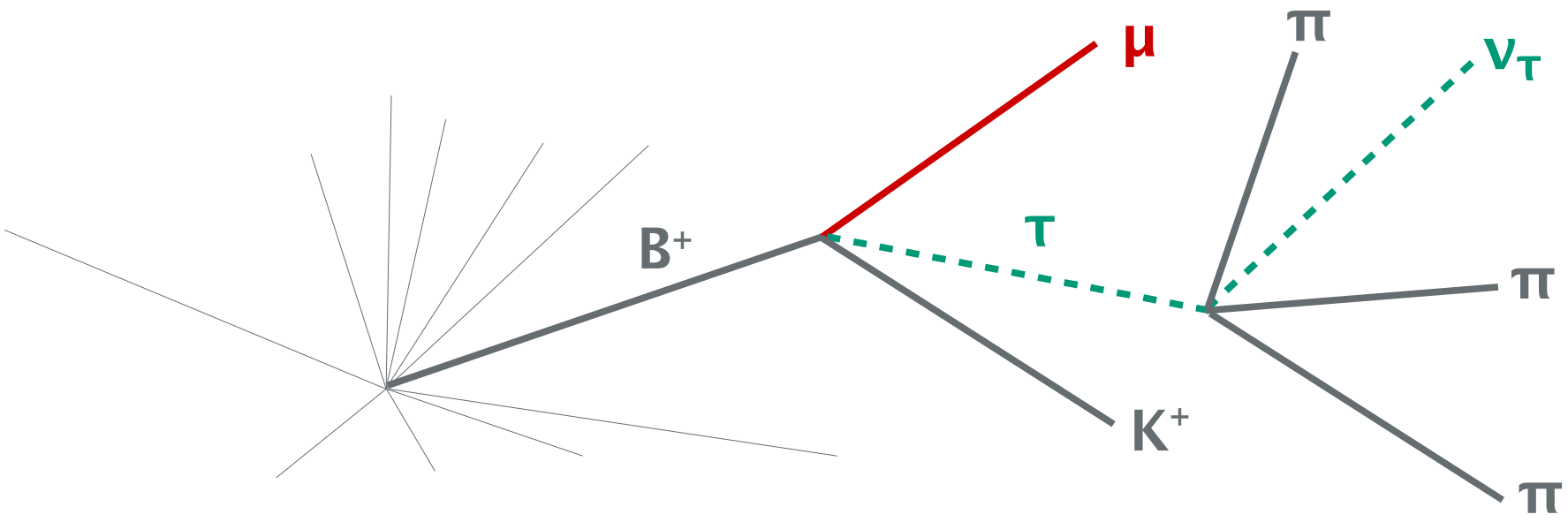
Interesting possibility
Short lifetime prohibits direct detection
Neutrino remains undetected
Known τ decay location

Br ~ 9%



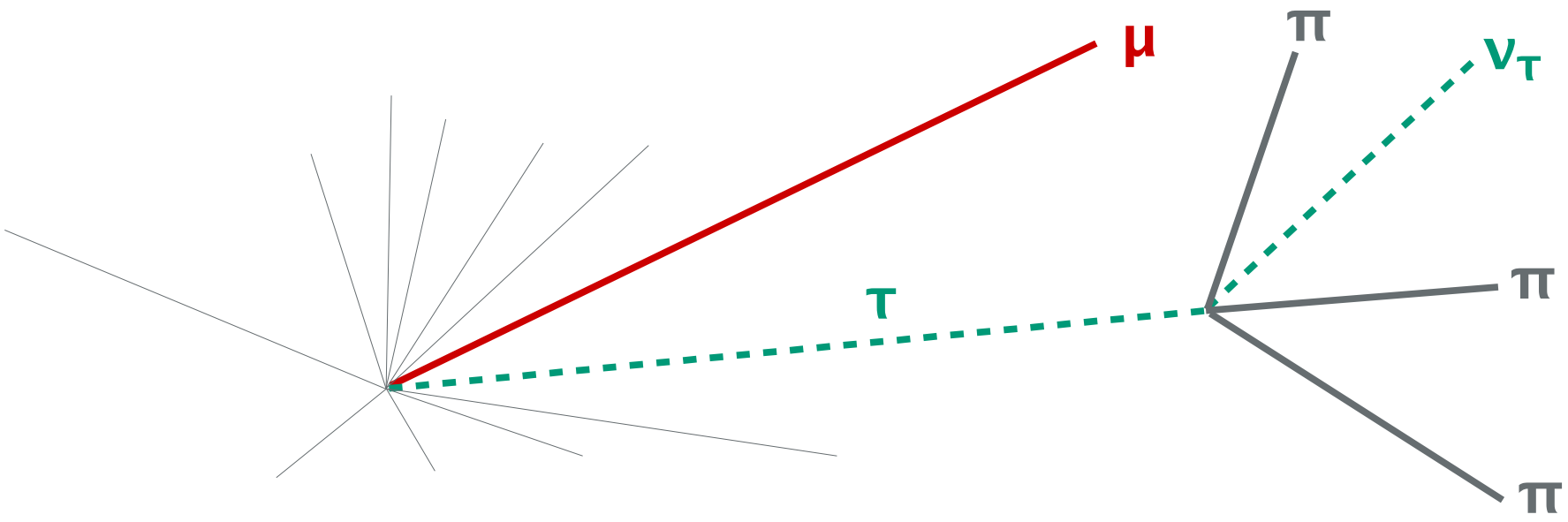
Reconstruction – IV

Interesting possibility
Short lifetime prohibits direct detection
Neutrino remains undetected
Known B & τ decay location

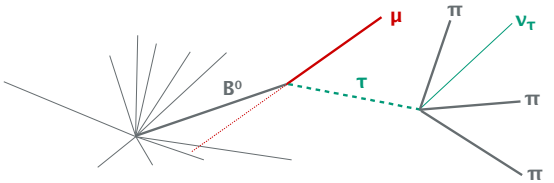


Reconstruction – V

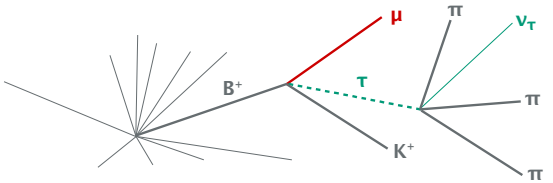
Interesting possibility
Short lifetime prohibits direct detection
Neutrino remains undetected



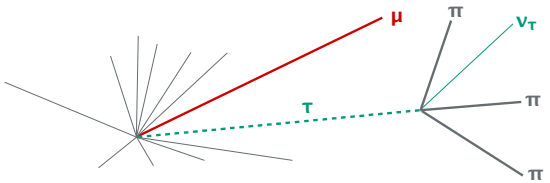
Possibly interesting channels



$B_{(s)} \rightarrow e/\mu\tau$



$B^+ \rightarrow K^+ e/\mu\tau$



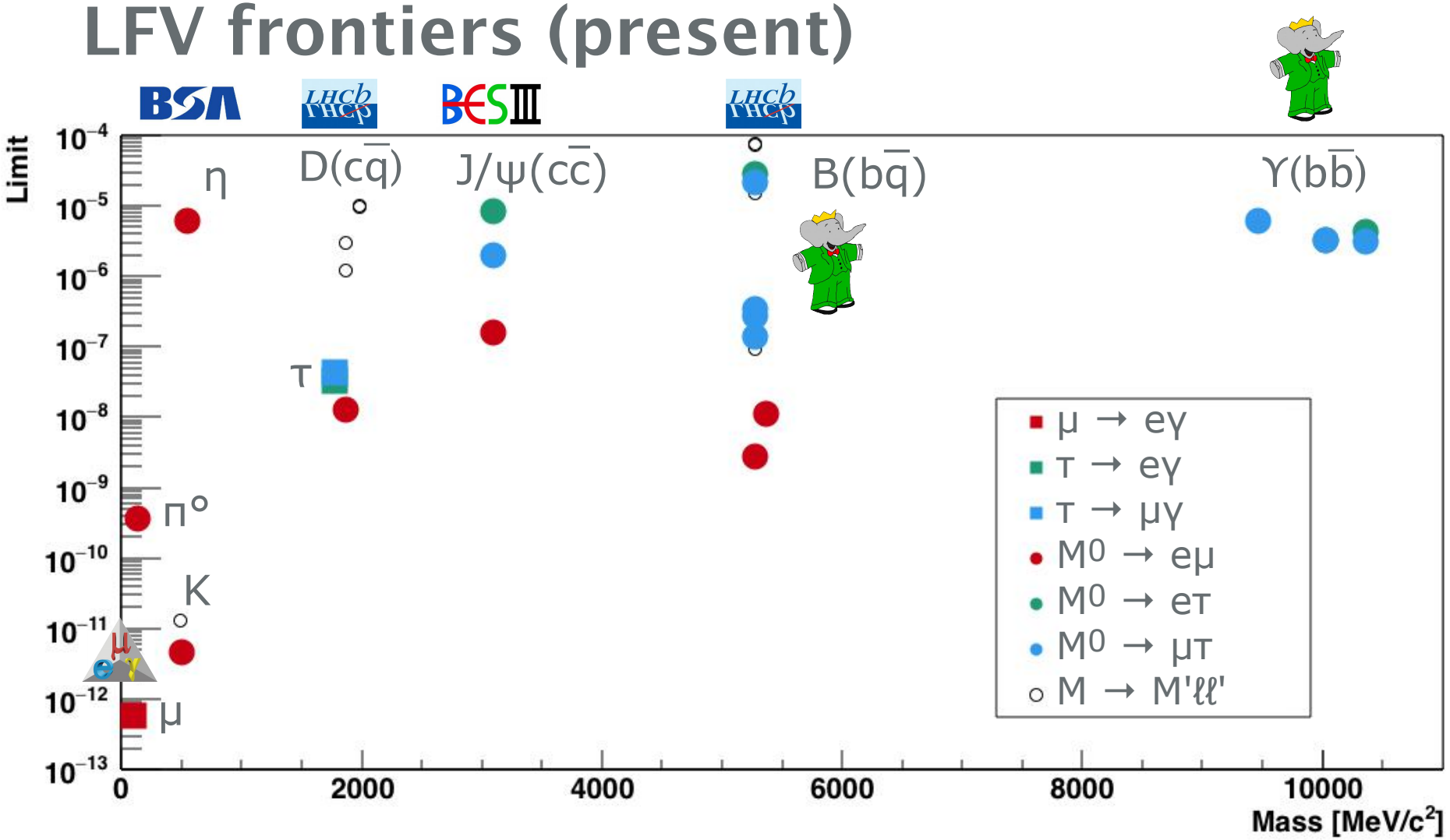
$\Upsilon(nS) \rightarrow e/\mu\tau$

Benefit from $\bar{B}^0 \rightarrow D^{*+}\tau\bar{\nu}_\tau$

Phys. Rev. Lett. 115, 111803 (2015)

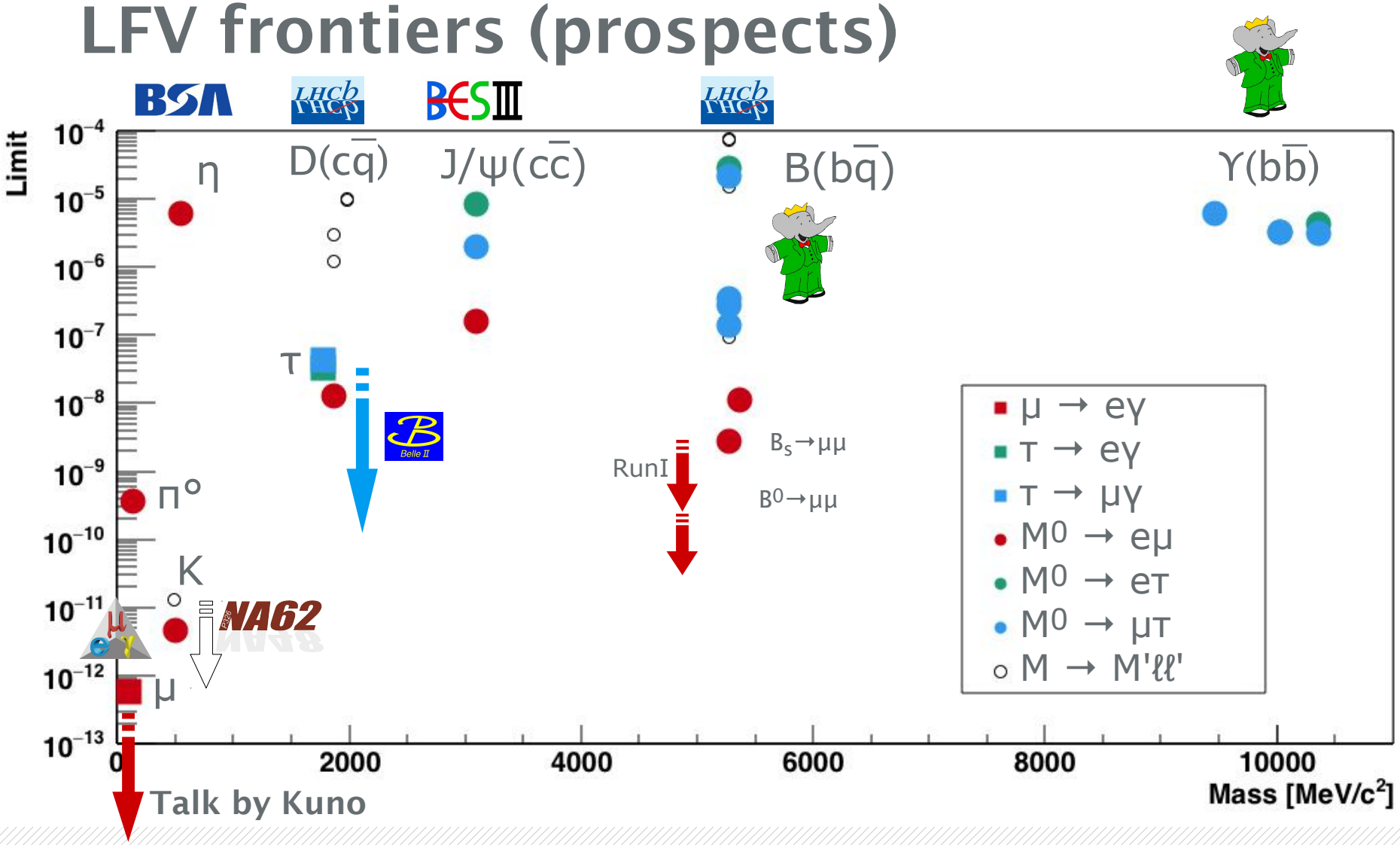
Insights

LFV frontiers (present)



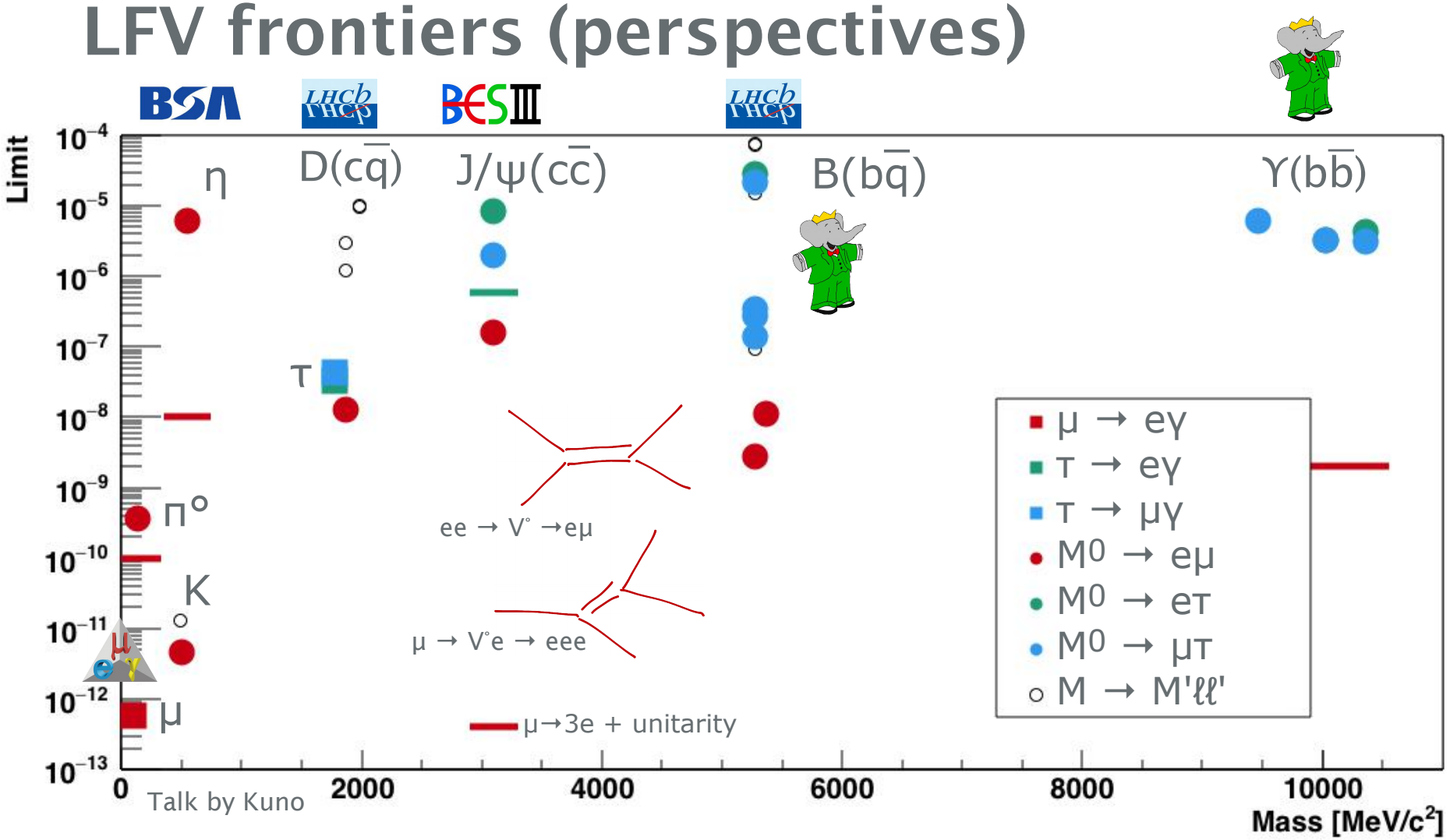
PDG, PRD63(2000)016003

LFV frontiers (prospects)



PDG, PRD63(2000)016003

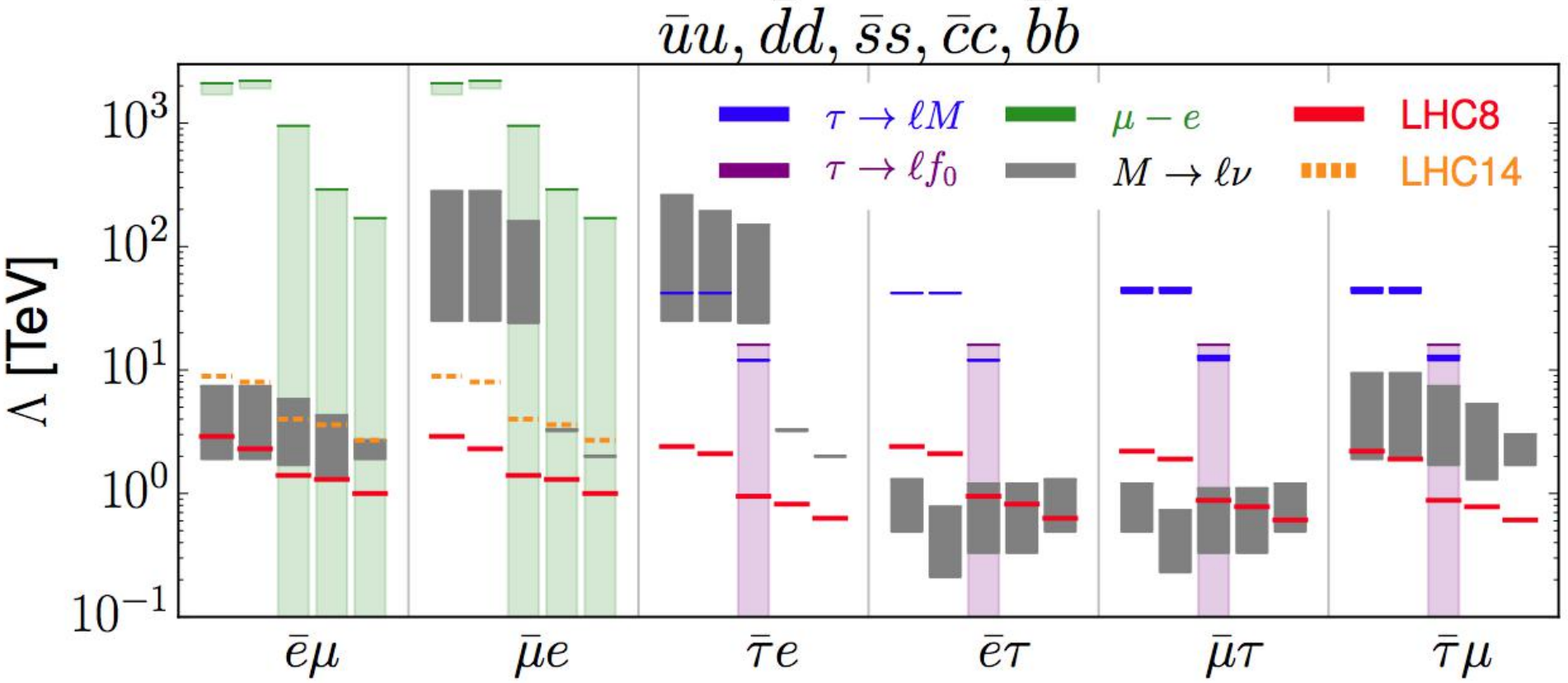
LFV frontiers (perspectives)



PDG, PRD63(2000)016003

Interpretation

"A Case Study of the Sensitivity to LFV Operators with Precision Measurements and the LHC"



Cai & Schmidt, JHEP02(2016)176

Insights & questions

Most stringent limits from μ & K → copious production

(π°, η, J/ψ, ϒ) lagging behind (+ strong limits from unitarity)

Strongest limits for eμ , weaker for eτ and μτ

$B_{(s)} \to e\mu$ most stringent of all meson decays

$M \to M'\ell\ell'$ less stringent, yet many channels available

How to relate various measurements? Complementarity?

→ many model-dependent attempts

Forecast (a personal view)

Lepton Number conservation assumed!

Leptonic decay

$B_{(s)} \to e\mu$ will improve 10–100 @ LHCb

$B_{(s)} \to \ell\tau$ via $\tau \to 3\pi\nu$ ~10–100 weaker than eμ

9% BR + lower detection efficiency + reduced signal definition

OR via B-tagging $\Upsilon(4S) \to B\bar{B}$ @ Belle-II

$\Upsilon \to e\mu$ can be done, but not worthwhile?

$B_{(s)} \to e\mu\gamma$ lifts helicity suppression, costs α, need E_γ threshold

Semi-Leptonic decay

$B_{(s)} \to K^{*0}(\to K^+\pi^-)\ell\ell'$ (eμ, eτ, μτ) ~10x below $B_{(s)} \to \ell\ell'$?

$B_{(c)}^+ \to K^+\ell\ell'$ "easier"; can do τ; $\sigma(B^+) \sim \sigma(B^0)$; gain from reduced background

$\text{฿} \to \text{฿}'\ell\ell'$ feasible & worthwhile?

Conclusion

Take away message

LHCb : diverse program studying flavor physics with all three quark & lepton generations

With LHC **Run-I** data **LHCb** sharpened limits for many LFV, LNV, and BNV channels

No significant deviations from **SM** seen

Demonstrated sensitive **BSM** searches @ hadron collider

Many more options around, lots of additional data expected in LHC **Run-II** & **Run-III**, Belle-II, NA-62, … : expect 10 – 100x improvement in years to come

Theory guidance & insights very welcome

Thank you for your attention!

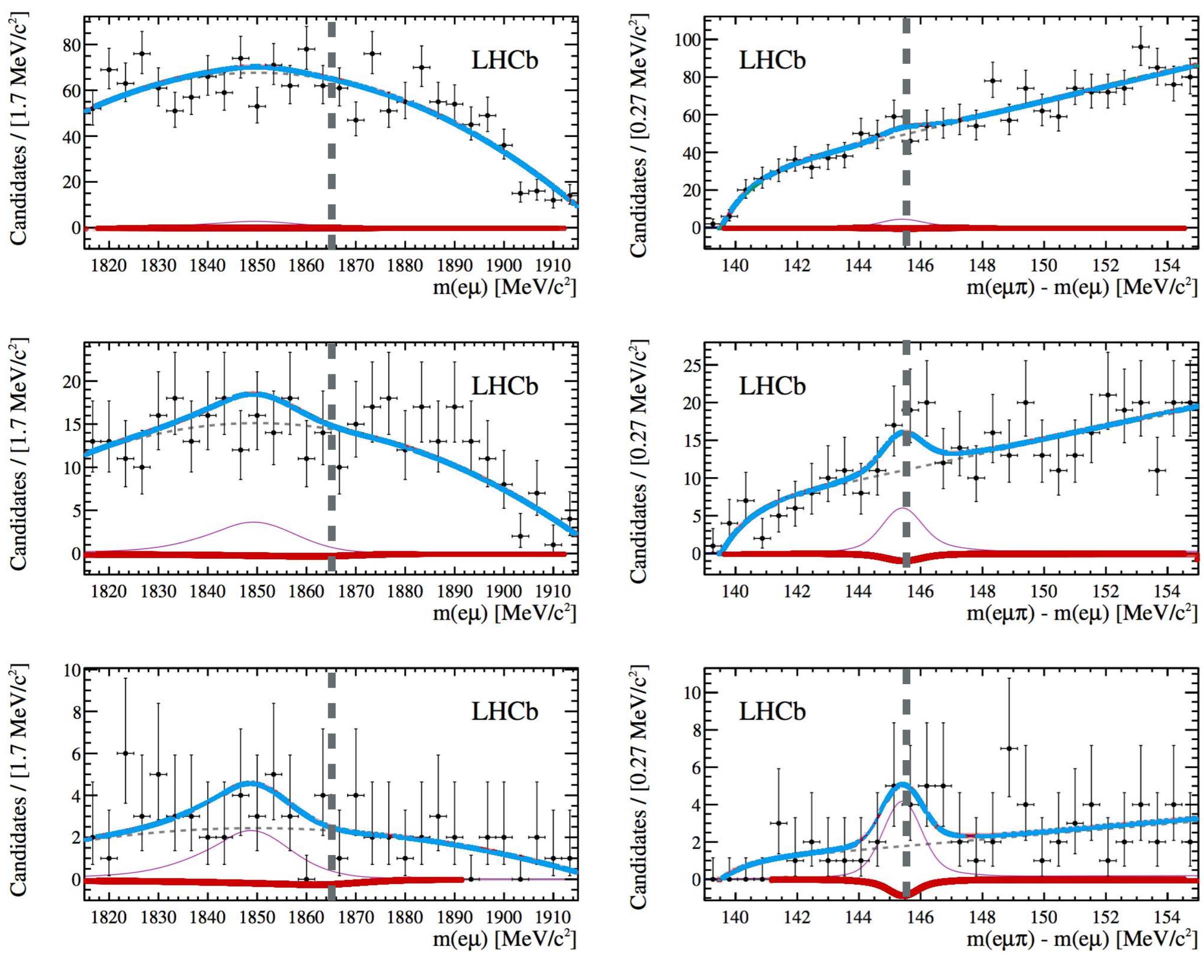
Gerco Onderwater, LF(U)V2016

Unbinned simultaneous fits

BKGD-like

intermediate

Signal-like



Signal + bkgd

$D^0 \to e\mu$ (signal)

-7±15 events

m(eμ) → M_D　　**m(eμπ)-m(eμ) → M_{D*}-M_D**

PLB 754 (2016) 167