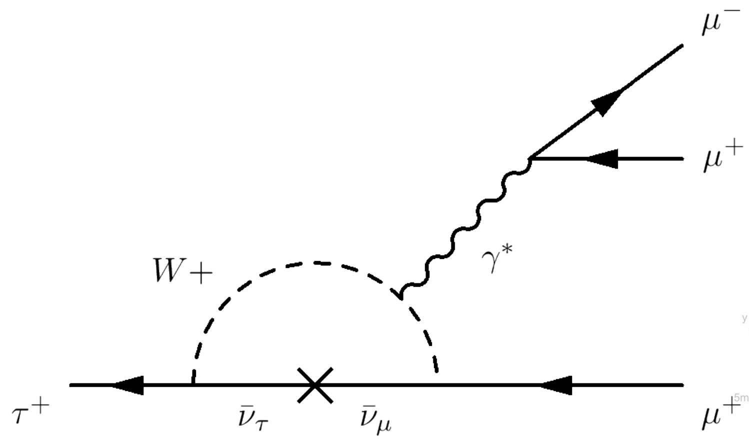
university of groningen
faculty of mathematics and natural sciences

Search for Lepton Flavor Violation in tau decays

Gerco Onderwater
on behalf of the LHCb collaboration

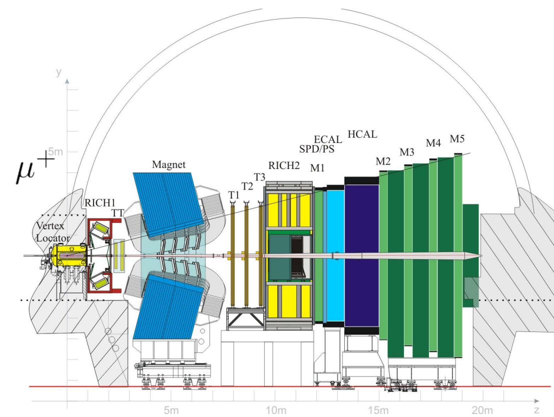
NUFACT2014, Glasgow, August 25, 2014

Outline



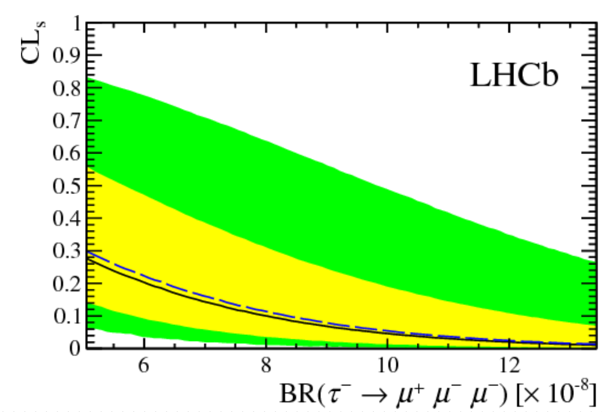
Context

LHCb Experiment



Results @ LHCb

Results and Prospects @ Belle & BaBar



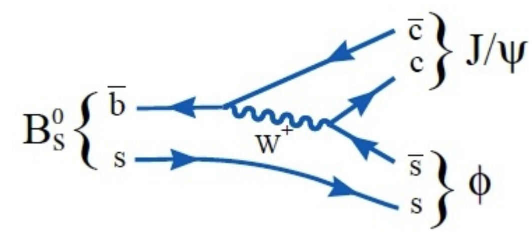
Conclusion

Standard Model

Remarkably successful, yet with unexplained features

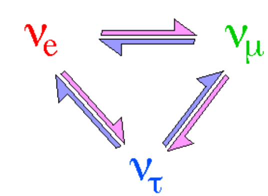
Puzzling : Existence of 3 generations quarks & leptons (flavor)

Rich phenomenology when weak interaction is involved



Flavor-Non-Conservation well established for quarks (CKM)

No FNC for <u>charged</u> leptons observed, only neutrino oscillations

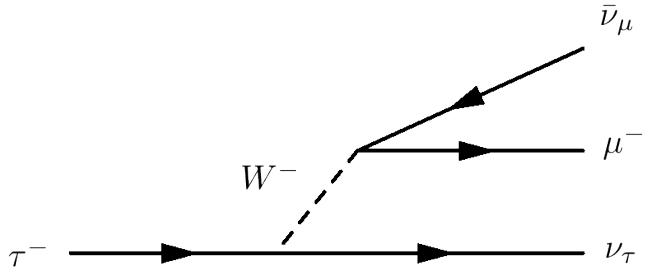


New physics cLFV amplitudes >>> immeasurably small SM ones

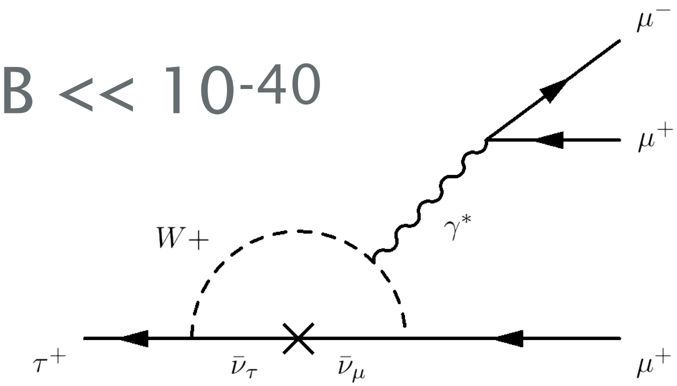
cLFV ideal test ground to search for new physics

Tau decay & cLFV

SM

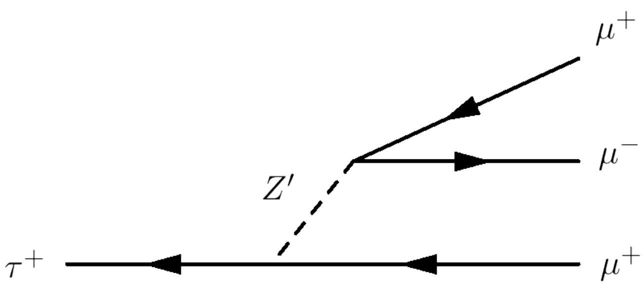


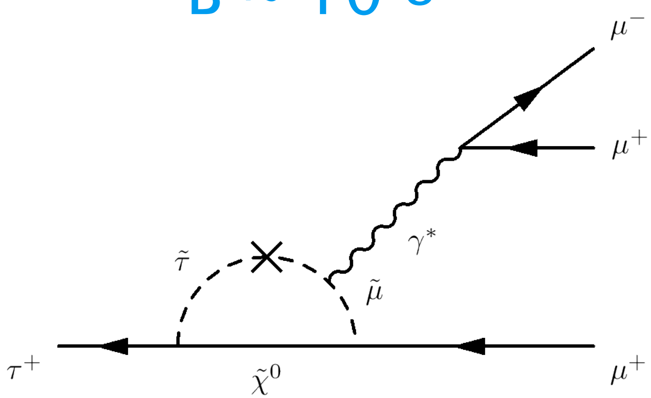
$B \ll 10^{-40}$

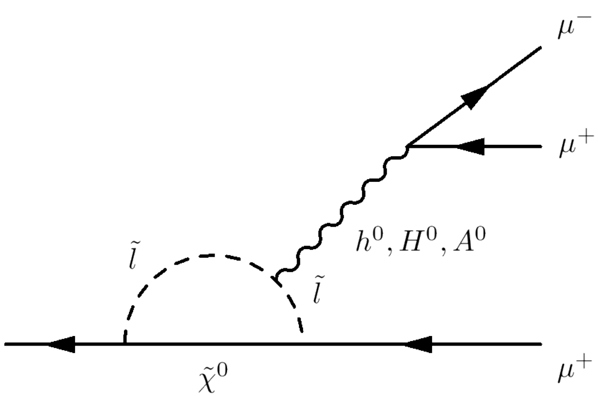


New physics

$B \overset{?}{\sim} 10^{-8}$







Large mass → many possible LFV final states
→ closer to high-mass new physics

Principle

Produce many tau's

Find signal

Fight backgrounds

Calculate branching fraction

Done!

Will mainly concentrate on $\tau \rightarrow 3\mu$ @ LHCb

Challenge : τ decays at hadron collider

B factory

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

LHC

- ✓ LHCb ~$8\text{x}10^{10}$ τ's in detector acceptance in 2011
- ✘ pp → τ + O(100) particles
- ✘ No "production traces" in $D_s \rightarrow \tau\nu_\tau$
- ✘ Charm decay with missing particles similar to τ signature

Challenge : τ decays at hadron collider

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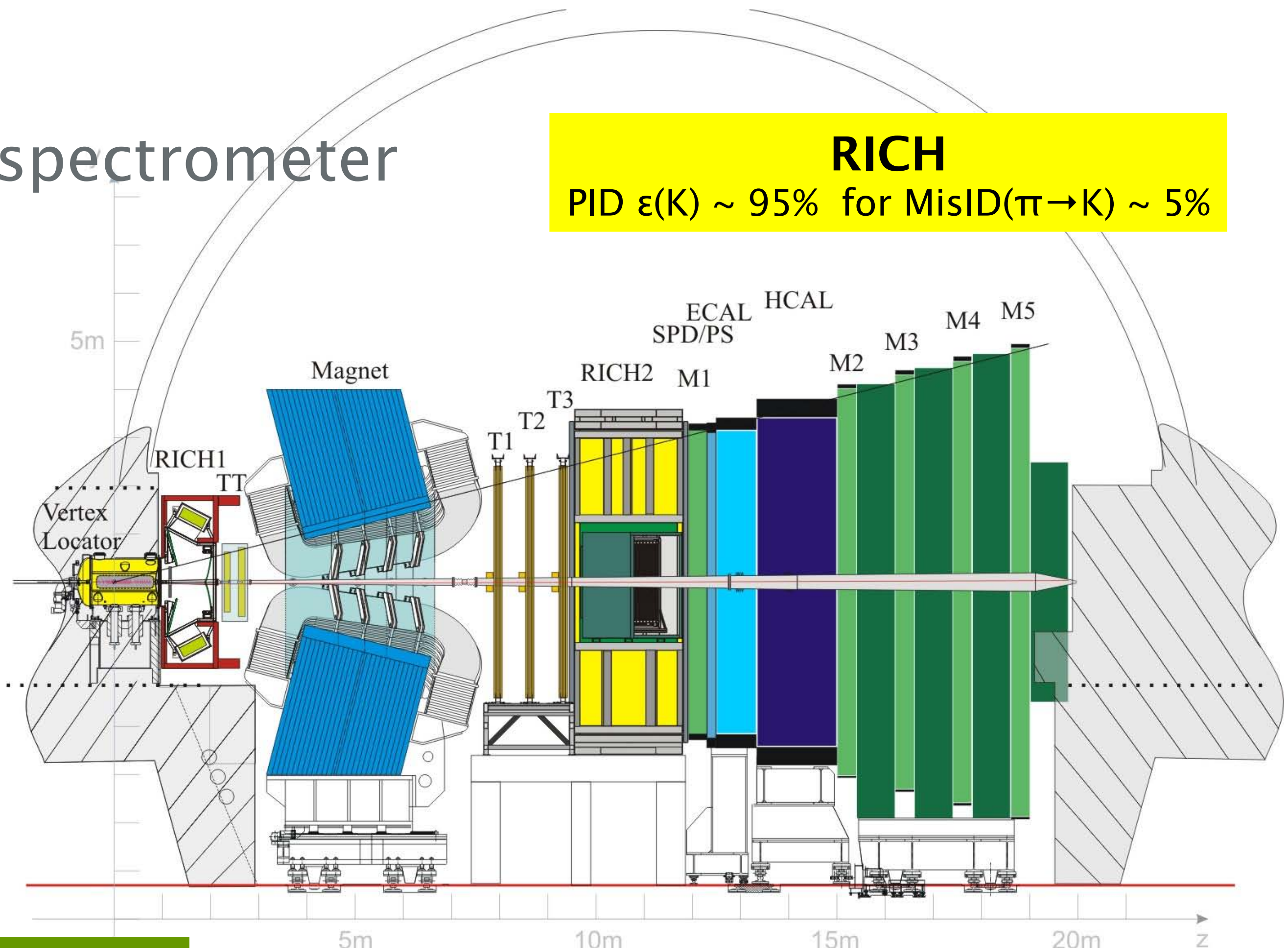
Remedies

- ➠ tight requirements to event selection
- ➠ develop strategies to suppress τ-less events
- ➠ understand τ production in detail

LHCb detector

JINST 3 (2008) S08005

Single arm forward spectrometer
($2 < \eta < 5$)



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

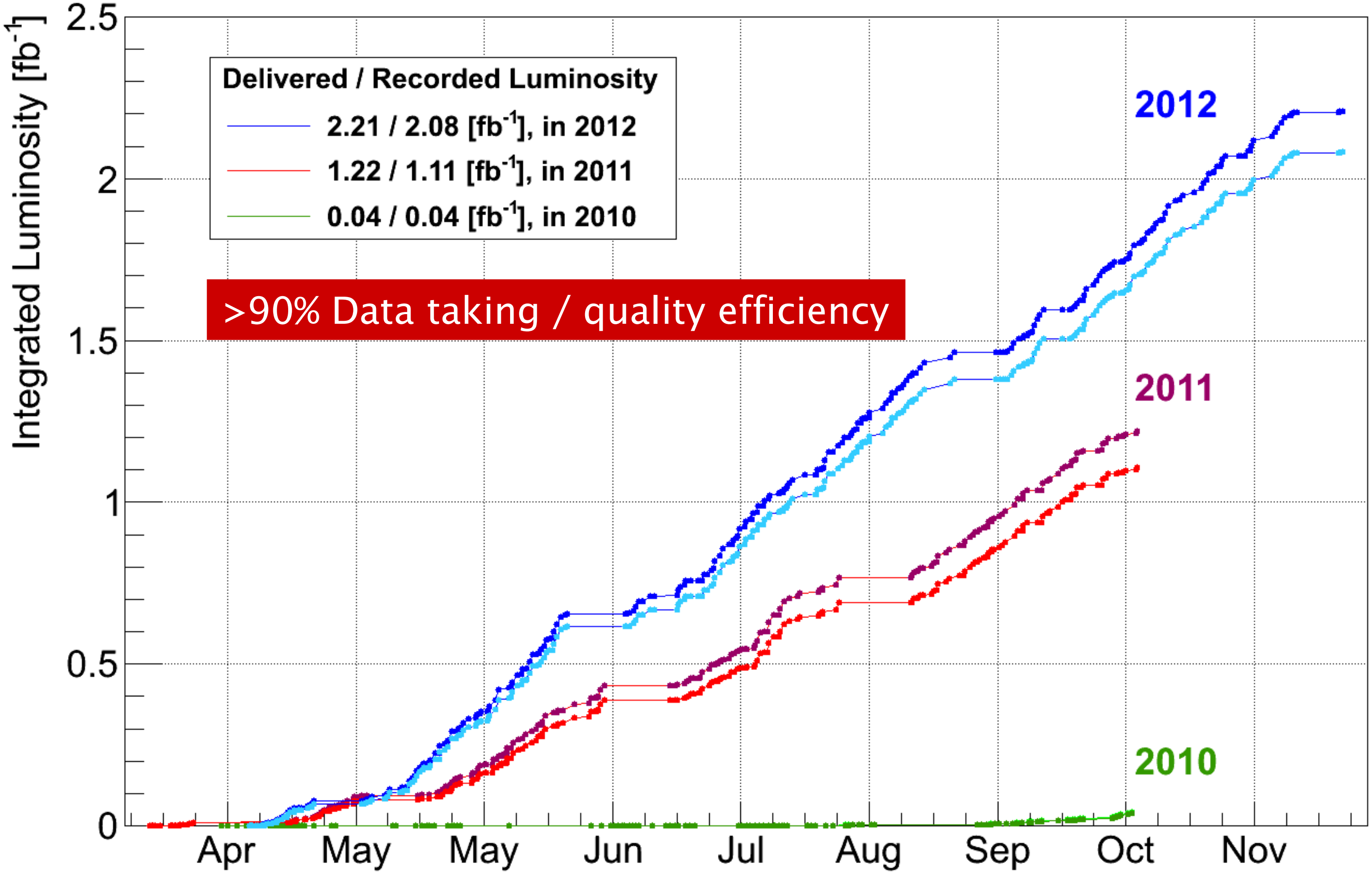
VELO
~20μm IP resolution for p_T > 2 GeV

Trigger
high efficiency for muon triggers

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

Muon ID
identification ε ~ 97% misID ~ 2%

LHCb data collection

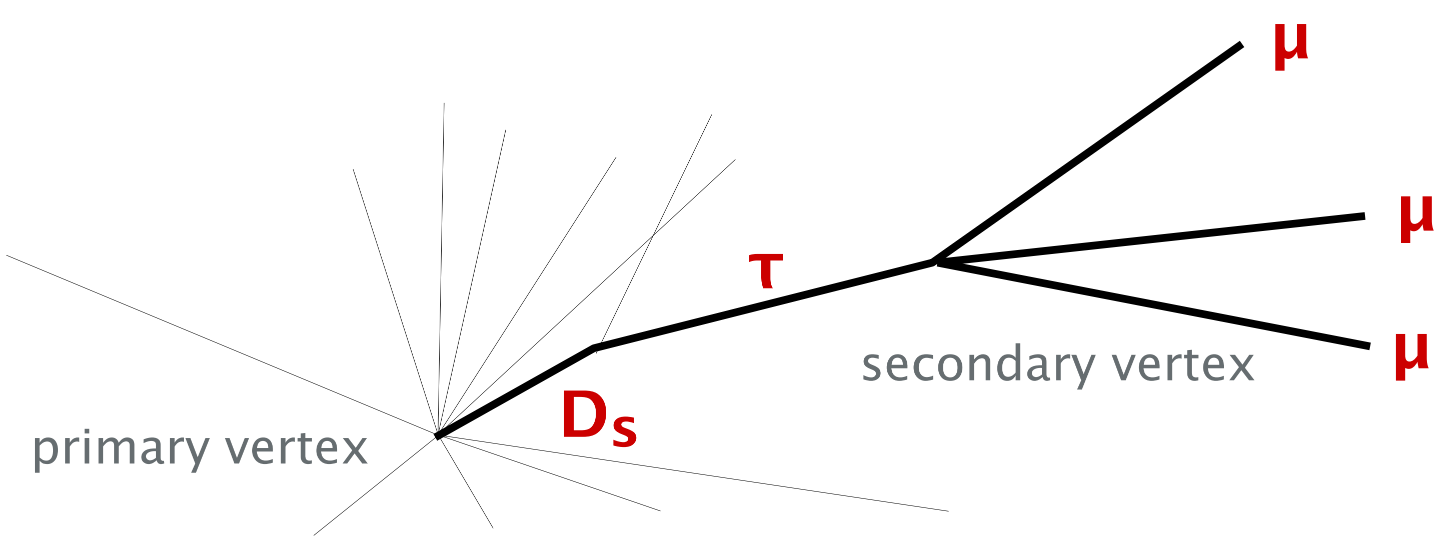


$\tau \rightarrow 3\mu$ @ LHCb

Main tau production via decay of D_s

Analysis strategy

- 1.0 fb^{-1} of data collected @ $\sqrt{s}$ = 7 TeV
- trigger on *muon* and *secondary vertex*
- *multivariate analysis* to discriminate signal and background
- *control sample* for normalization and calibration



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Signal candidate selection

Trigger

- Muons with $p_T > 1.48$ GeV/c (Hardware)
- Two-, three- or four-track secondary vertex
  High sum p_T and significant displacement from primary vertex
- ≥1 track with $p_T > 1.7$ GeV/c & IP w.r.t. PV $\chi^2 > 16$

Analysis

- All tracks: IP $\chi^2 > 9$
- Fitted 3-track vertex $\chi^2 < 15$
- Decay-time compatible with τ decay ($c\tau > 100$ μm)
- Reconstructed τ momentum must point back to PV

Background elimination

- $|M(\mu^+\mu^-) - M(\Phi)| < 20$ MeV/c^2
- $M(\mu^+\mu^-) < 450$ MeV/c^2 $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$
- $M(\mu^-\mu^-) < 250$ MeV/c^2 reconstructed from same particle

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Signal & background discrimination

Three likelihoods to give probability for candidate to be signal or background

I. M_{3body} discriminates signal from B/D decays

II. M_{PID} used to improve muon mis-identification

III. $M_{3\mu}$ shape from simulation

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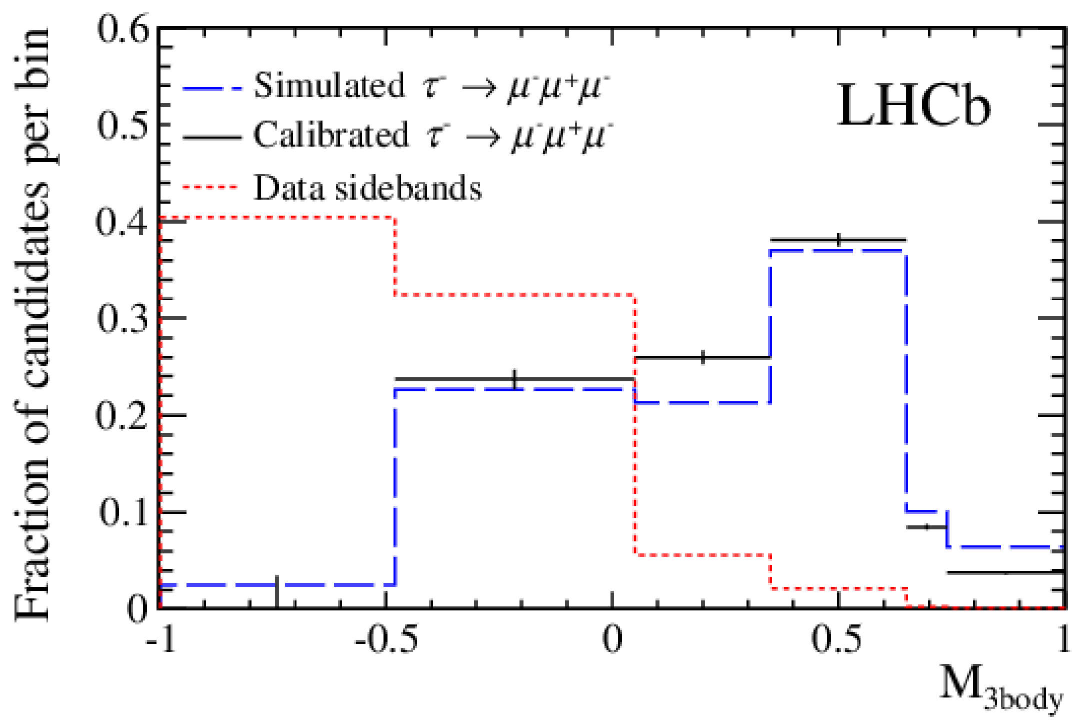
M_{3body} likelihood

3-body decay topology
- vertex quality
- displacement from primary vertex
- track quality
- isolation

boosted decision tree
- trained using simulated samples of signal and background
- calibrated with $D_s^- \to \Phi(\mu^+\mu^-)\pi^-$

minimal number of bins
maximize **S+B** vs **B-only** separation



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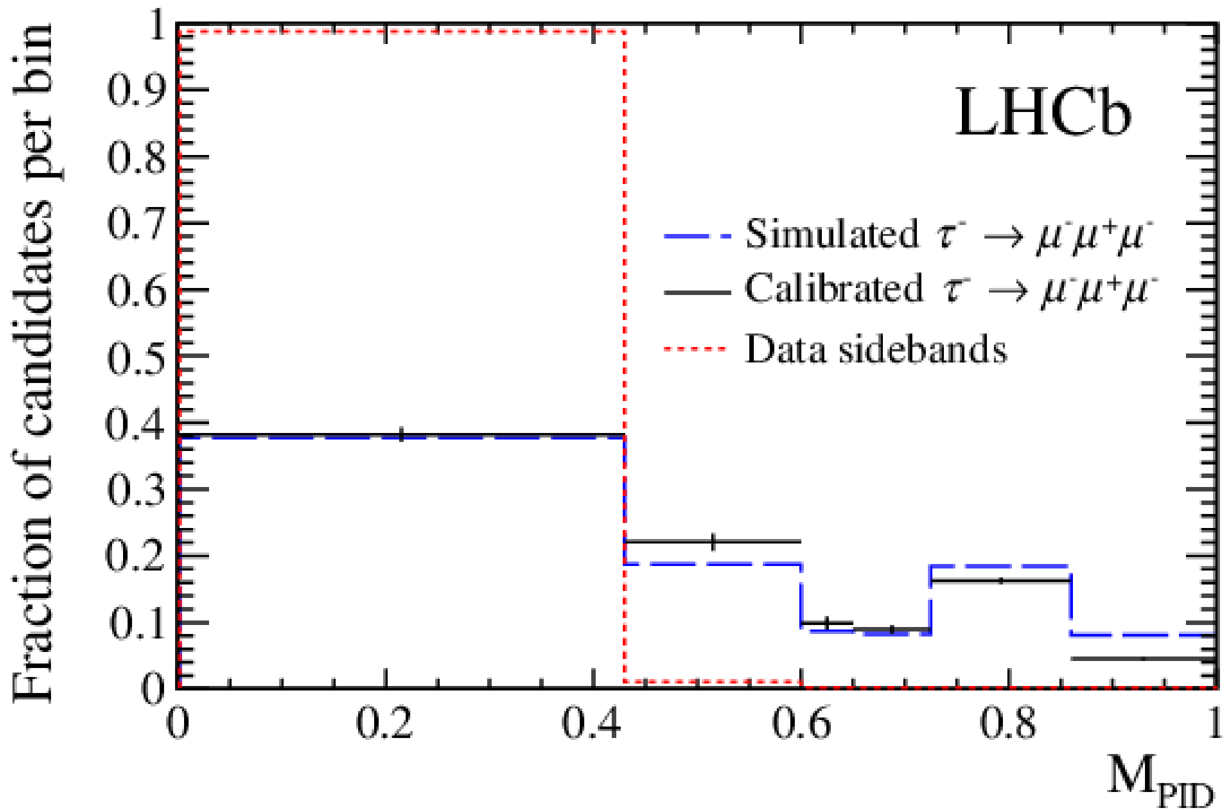
M_{PID} likelihood

Particle Identification

- hits in muon chambers
- energy in calorimeters compatible with MIP
- RICH information

Neural Network
trained on simulation

Calibration
$J/\psi \rightarrow \mu^+\mu^-$



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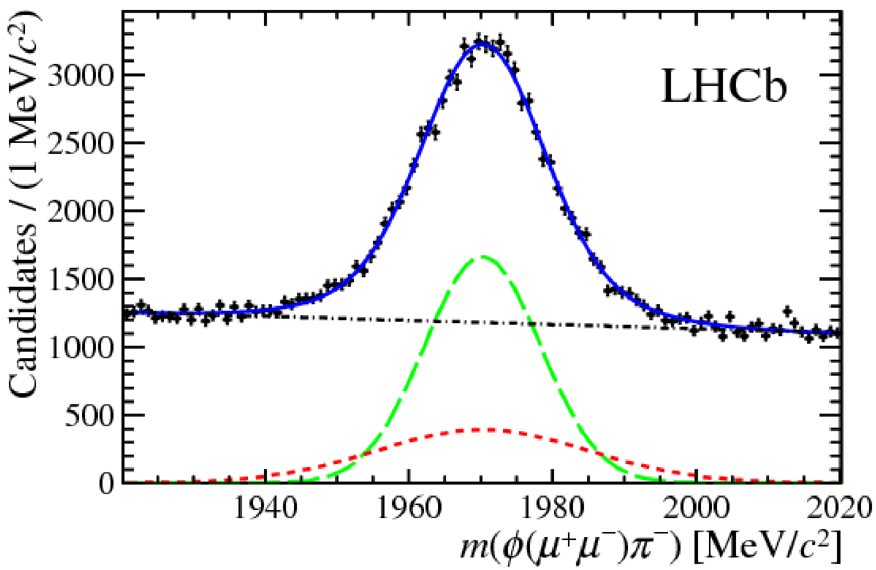
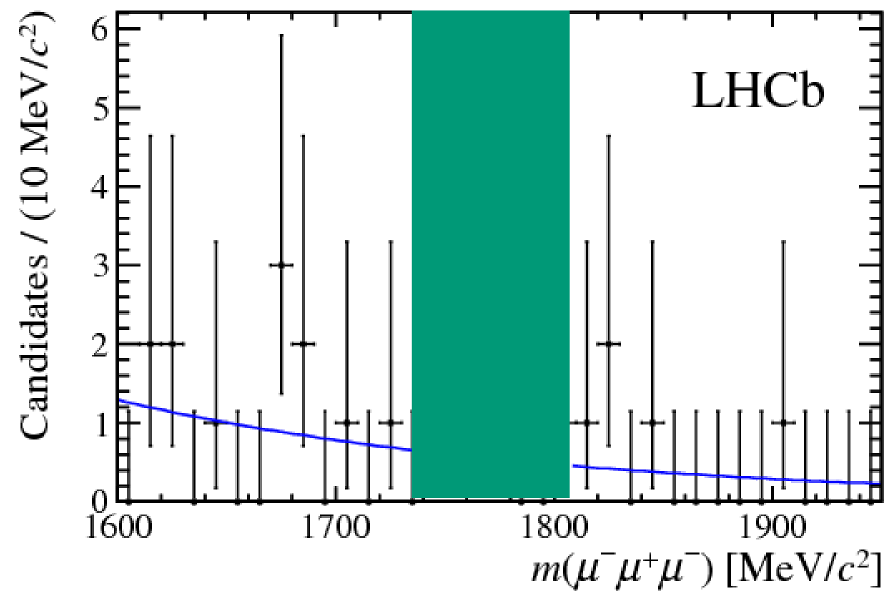
$M_{3\mu}$ distribution

- Shape modeled using $D_s^- \rightarrow \phi(\mu^+\mu^-)\pi^-$
- Analyze 5x5 best bins in M_{PID} and M_{3body}



Blind analysis



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

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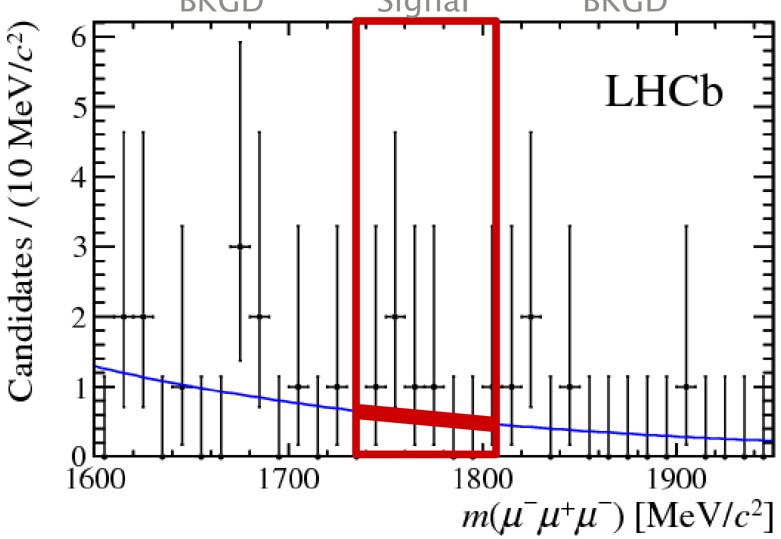
Counts

- Interpolate expected number of background events from sidebands to signal region
- Count number of events in signal region



$\mathcal{M}_{\mathrm{PID}}$	$\mathcal{M}_{\mathrm{3body}}$	Expected	Observed
0.43–0.6	−0.48–0.05	345.0 ± 6.7	409
	0.05–0.35	83.8 ± 3.3	68
	0.35–0.65	30.2 ± 2.0	35
	0.65–0.74	4.3 ± 0.8	2
	0.74–1.0	1.4 ± 0.4	1
0.6–0.65	−0.48–0.05	73.1 ± 3.1	64
	0.05–0.35	18.3 ± 1.5	15
	0.35–0.65	8.6 ± 1.1	7
	0.65–0.74	0.4 ± 0.1	0
	0.74–1.0	0.6 ± 0.2	2
0.65–0.725	−0.48–0.05	45.4 ± 2.4	51
	0.05–0.35	11.7 ± 1.2	6
	0.35–0.65	5.3 ± 0.8	3
	0.65–0.74	0.8 ± 0.2	1
	0.74–1.0	0.4 ± 0.1	0
0.725–0.86	−0.48–0.05	44.5 ± 2.4	62
	0.05–0.35	10.6 ± 1.2	13
	0.35–0.65	7.3 ± 1.0	7
	0.65–0.74	1.0 ± 0.2	2
	0.74–1.0	0.4 ± 0.1	0
0.86–1.0	−0.48–0.05	5.9 ± 0.9	7
	0.05–0.35	0.7 ± 0.2	1
	0.35–0.65	1.0 ± 0.2	1
	0.65–0.74	0.5 ± 0.0	0
	0.74–1.0	0.4 ± 0.1	0

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Normalization

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

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

$$N(\tau) \to 1/f_\tau^{D_s} N(D_s \to \tau \bar{\nu}_\tau)$$

calculated

$$N(D_s \to \tau \bar{\nu}_\tau) \to B(D_s \to \tau \bar{\nu}_\tau) N(D_s)$$

literature

$$N(D_s) \to N(D_s \to \phi(\mu\mu)\pi) / B(D_s \to \phi(\mu\mu)\pi)$$

literature

$$B(D_s \to \phi(\mu\mu)\pi) \to B(D_s \to \phi(KK)\pi) B(\phi \to \mu\mu) / B(\phi \to KK)$$

Must further include trigger, selection & reconstruction **efficiencies**

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Normalization

Branching fraction for τ⁻ → μ⁻μ⁺μ⁻ normalized to $D_s^- \to \Phi(\mu^+\mu^-)\pi^-$

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$$

$$= \mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-) \times \frac{f_\tau^{D_s}}{\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)}$$

$$\times \frac{\epsilon_{\text{cal}}^{\text{REC\&SEL}}}{\epsilon_{\text{sig}}^{\text{REC\&SEL}}} \times \frac{\epsilon_{\text{cal}}^{\text{TRIG}}}{\epsilon_{\text{sig}}^{\text{TRIG}}} \times \frac{N_{\text{sig}}}{N_{\text{cal}}}$$

$$= \alpha \times N_{\text{sig}}$$

$\mathcal{B}(D_s^- \to \phi(\mu^+\mu^-)\pi^-)$: (1.33±0.12)x10^{-5}

$f_\tau^{D_s}$: 0.78±0.05

$\mathcal{B}(D_s^- \to \tau^-\bar{\nu}_\tau)$: 0.0561±0.0024

REC&SEL efficiency ratio: 1.49±0.12

TRIG efficiency ratio: 0.753±0.037

N_{cal}: 48076 ± 840

α: (4.34±0.65)x10^{-9}

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Result

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

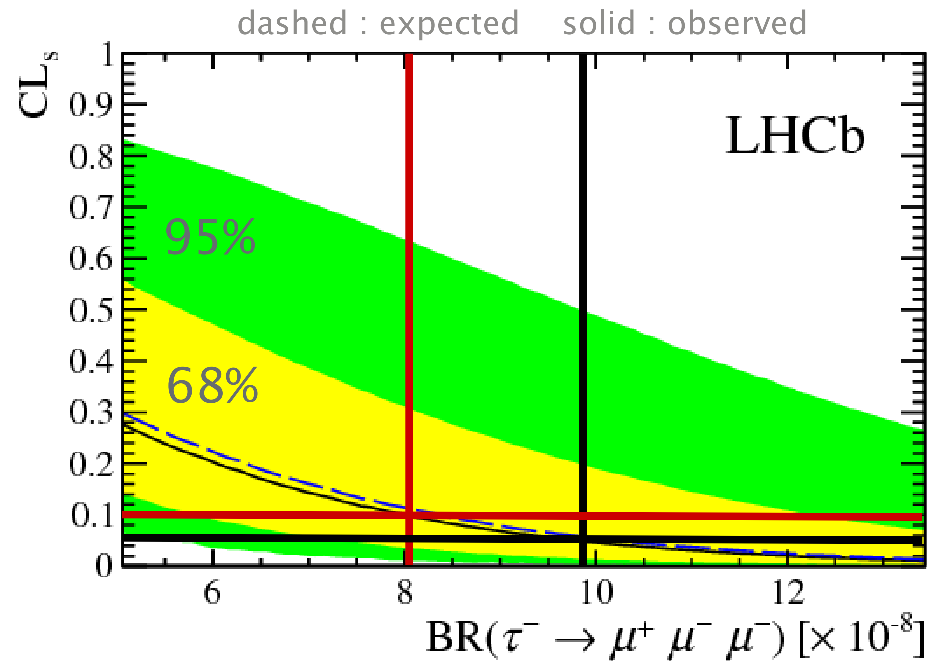
- No significant evidence for an excess of events
- CL_S method used to extract upper limit
  Likelihood ratio **signal+background** vs **background-only**

$B(\tau^- \to \mu^-\mu^+\mu^-) < 8.0\ (9.8) \times 10^{-8}$

@ 90% (95%) C.L

Belle 2.1×10^{-8} @ 90% C.L.
PLB 687, 139 (2010)

BaBar 3.3×10^{-8} @ 90% C.L.
PRD 81, 111101(R) (2010)



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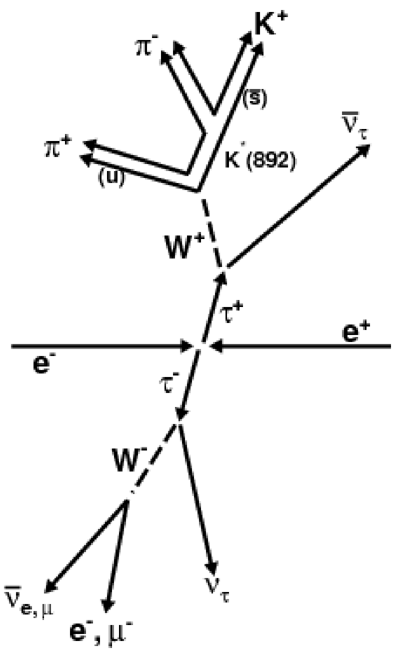
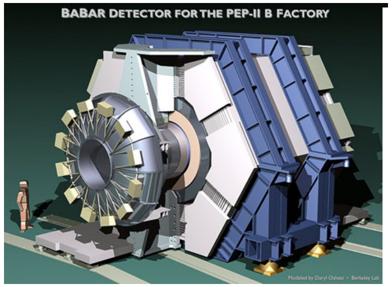
BaBar & Belle $\tau^- \rightarrow l^- l'^+ l''^-$

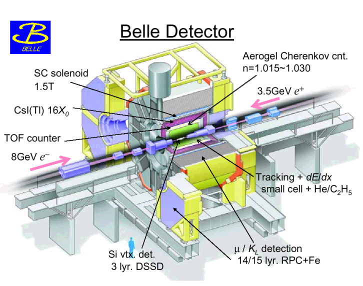
BaBar : PRD 81, 111101(R) (2010)
Belle : PLB 687, 139 (2010)



$10^8 \times UL_{90}$

Mode	BaBar	Belle
$e^-e^+e^-$	2.9	2.7
$\mu^-e^+e^-$	2.2	1.8
$\mu^+e^-e^-$	1.8	1.5
$e^+\mu^-\mu^-$	2.6	1.7
$e^-\mu^+\mu^-$	3.2	2.7
$\mu^-\mu^+\mu^-$	3.3	2.1





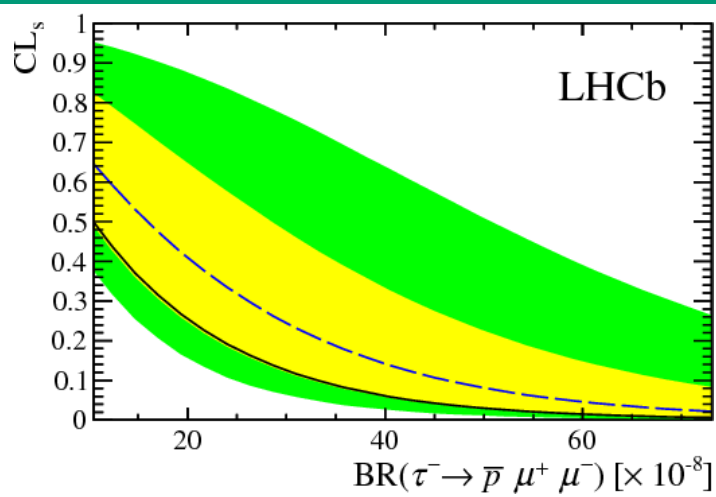
cLFV with LNV & BNV

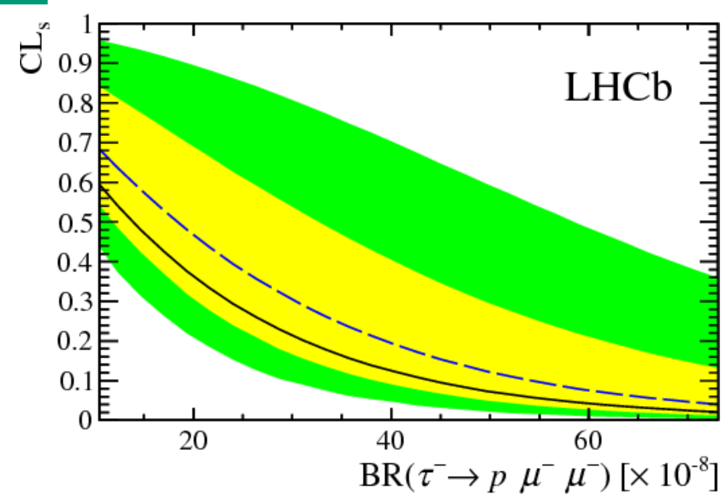
$\tau^- \to \bar{p}\mu^+\mu^-/p\mu^-\mu^-$ violate lepton and baryon number (thus lepton flavor)
First direct experiment limit @ LHCb with similar technique

$B(\tau^- \to \bar{p}\mu^+\mu^-) < 3.3\text{x}10^{-7}$

$B(\tau^- \to p\mu^-\mu^-) < 4.4\text{x}10^{-7}$

	$\tau^- \to \bar{p}\mu^+\mu^-$		$\tau^- \to p\mu^-\mu^-$	
$\mathcal{M}_{3\text{body}}$	Expected	Observed	Expected	Observed
−0.05–0.20	37.9 ± 0.8	43	41.0 ± 0.9	41
0.20–0.40	12.6 ± 0.5	8	11.0 ± 0.5	13
0.40–0.70	6.76 ± 0.37	6	7.64 ± 0.39	10
0.70–1.00	0.96 ± 0.14	0	0.49 ± 0.12	0





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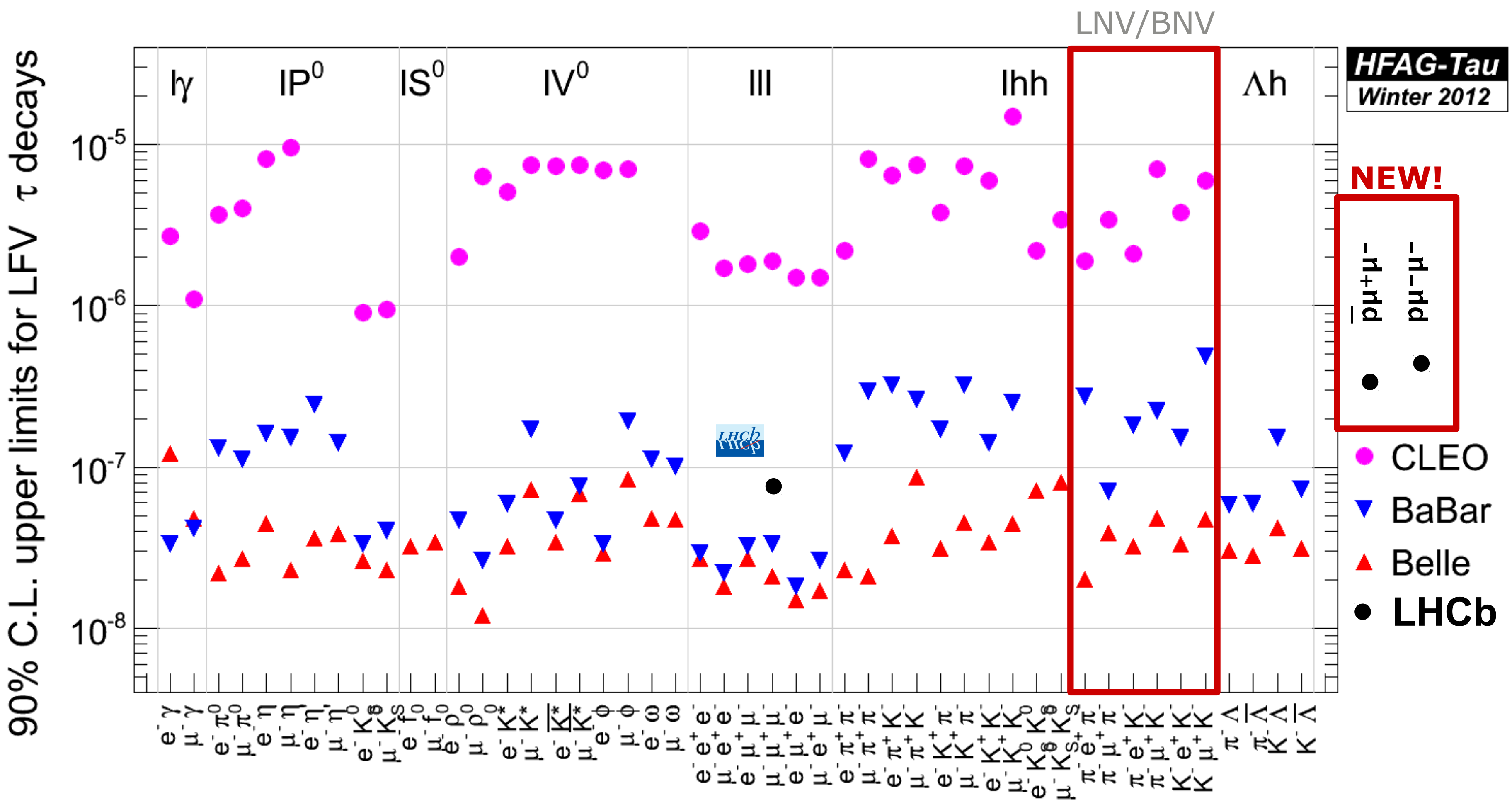
Overview

http://www.slac.stanford.edu/xorg/hfag/tau/winter-2012/



Prospects

BaBar

ended data taking 2008
analysis completed

Belle

ended data taking 2010
final analysis in progress

Belle-II

commissioning early 2015
expect to improve limits by O(10)

LHCb

2012 data being prepared for publication
energy upgrade underway, intensity upgrade planned

Conclusion

Some τ studies are possible at a hadron collider!

LHCb has set first $\tau \rightarrow \mu\mu\mu$ limit at a hadron collider

LHCb has set first $\tau \rightarrow p\mu\mu$ limits

More data available

Belle II : will come online soon …

LHCb : start taking more data after LHC energy upgrade

: LHC intensity upgrade planned ~2018

Stay tuned!

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Thank you for your attention!