Search for Charged Lepton Flavour Violation at LHCb experiment

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February 9, 2015

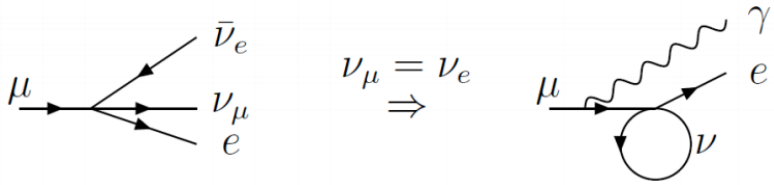
Outline

1. Lepton Flavour Violation phenomenon
2. LHCb detector
3. Selection
4. Multivariate technique
5. Normalisation
6. Backgrounds

Lepton Flavour/Number Violation

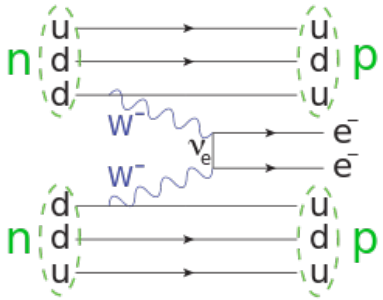
1. Lepton Flavour Violation (LFV) found in neutrino sector - the first phenomena outside the Standard Model.
2. The search for charged lepton flavour violation (CLFV) commenced with muon discovery (1936) and its identification as a separate particle.

- Expected: $B(\mu \to e\gamma) \approx 10^{-4}$
- Unless there is another ν.

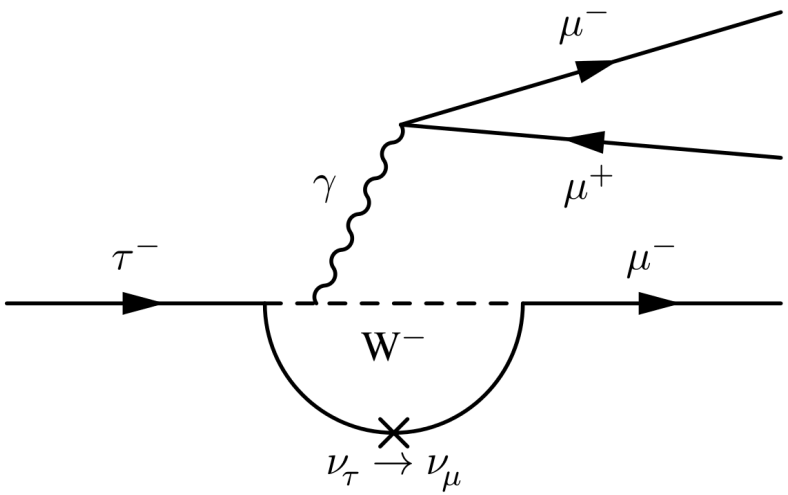


3. The observation of CLFV would be a clear signature of New Physics (NP) - paramount importance for flavour physics and the enigma of generations.
4. LFV vs LNV (Lepton Number Violation)

- Even with LFV, lepton number can be a conserved quantity.
- Many NP models predict LNV (Majorana neutrinos)
- LNV searched in so-called neutrinoless double β decays.



Status of searches for $\tau \longrightarrow \mu\mu\mu$



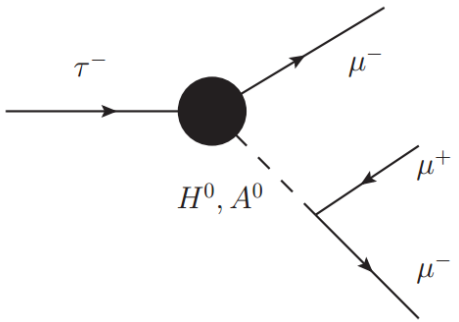
- Charged Lepton Flavour Violation process.
- The Standard Model contribution: penguin diagram with neutrino oscillation.
- Negligible SM branching fraction.
- Large enhacement from NP models like: SUSY, Little Higgs, Fourth generation, etc.

Predictions

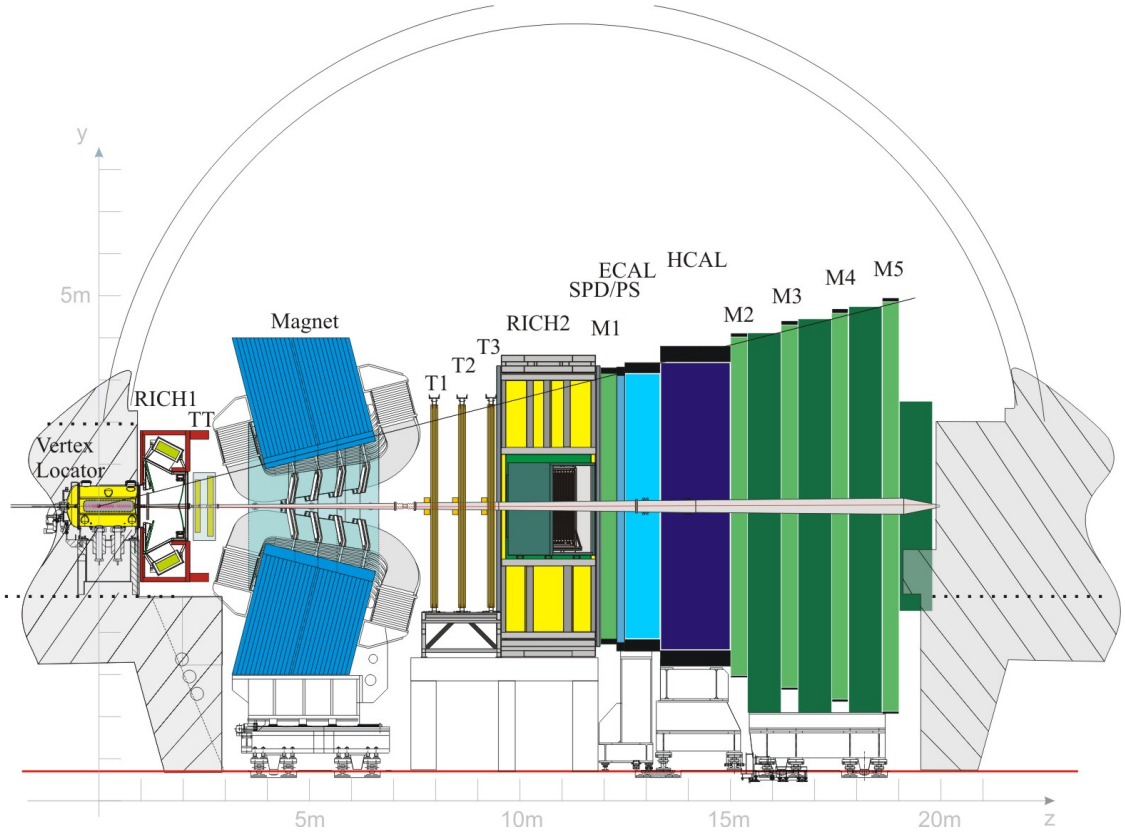
SM	$O(10^{-40})$
var. SUSY	10^{-10}
non universal Z'	10^{-8}
mSUGRA+seesaw	10^{-9}
and many more...	

Current limits (90 % CL)

BaBar	3.3×10^{-8}
Belle	2.1×10^{-8}



LHCb detector



LHCb is a forward spectrometer:

- Excellent vertex resolution.
- Efficient trigger.
- High acceptance for τ and B.
- Superb particle identification (PID).

Strategy

1. Data sample: 1fb^{-1} 7 TeV and 2fb^{-1} 8TeV.
2. Normalization (control) decay channel: $D_s \rightarrow \phi(\mu\mu)\pi$.
3. Blind analysis in the region of $|m_{\mu\mu\mu} - m_\tau| < 20$ MeV/c^2.
4. Event selection:
   - Preselection of three tracks that combine to give a mass close to m_τ, with displaced vertex.
   - Selection based on three classifiers:
     - Geometry and topology ($\mathcal{M}_{3body}$) - multivariate classifier
     - PID ($\mathcal{M}_{PID}$) - multivariate classifier
     - Three muon invariant mass ($m_{\mu\mu\mu}$)
5. Major background contributions:$D_s \rightarrow \eta(\mu\mu\gamma)\mu\nu$ and $D \rightarrow K\pi\pi$ decays.
6. Evaluation of the upper limit on $\mathcal{B}(\tau \rightarrow \mu\mu\mu)$ using CL_s method.

Stripping and selection

	$\tau \to \mu\mu\mu$	$D_s \to \phi\pi$
$\mu^{\pm}$, $\pi^{\pm}$		
p_T	> 300MeV	
Track χ^2/ndf	< 3	
IP χ^2/ndf	> 9	
track ghost probability	< 0.3	
μ pairs		
$m_{\mu^+\mu^-} - m_{\phi}$	> 20MeV	< 20MeV
$m_{\mu^+\mu^-}$	> 450MeV	-
$m_{\mu^+\mu^+}$	> 250MeV	-
$\tau^{\pm}$ and D_s		
Δm	< 400MeV	< 50MeV
Vertex χ^2	< 15	
IP χ^2	< 225	
$\cos\alpha$	> 0.99	
$c\tau$ (stripping)	$> 100\ \mu m$	
	no PV refitting	
decay time (offline)	> -0.01 ns & < 0.025 ns	
	PV refitting	

τ production at LHCb

- τ's in LHCb come from five main sources:

Mode	7 TeV	8 TeV
Prompt $D_s \to \tau$	$71.1 \pm 3.0\,\%$	$72.4 \pm 2.7\,\%$
Prompt $D^+ \to \tau$	$4.1 \pm 0.8\,\%$	$4.2 \pm 0.7\,\%$
Non-prompt $D_s \to \tau$	$9.0 \pm 2.0\,\%$	$8.5 \pm 1.7\,\%$
Non-prompt $D^+ \to \tau$	$0.18 \pm 0.04\,\%$	$0.17 \pm 0.04\,\%$
$X_b \to \tau$	$15.5 \pm 2.7\,\%$	$14.7 \pm 2.3\,\%$

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

- There is no measurement of $\mathcal{B}(D^+ \to \tau)$.
- One can calculate it from: $\mathcal{B}(D^+ \to \mu\nu_\mu)$ + helicity suppression + phase space.
- `hep-ex:0604043`.
- $\mathcal{B}(D^+ \to \tau\nu_\tau) = (1.0 \pm 0.1) \times 10^{-3}$.

Triggers at LHCb

- LHCb uses complex trigger, $\mathcal{O}(100)$ trigger lines.
- Lines change with data taking.
- Optimized choice of triggers based on $\frac{s}{\sqrt{b}}$ FOM,

$$\varepsilon(\beta)'_{\text{evt,line}} = \frac{N(\tau \text{ MC(BKG) events triggered line, but not by any better line})}{N(\tau \text{ MC(BKG) events triggered by any line})},$$

$$\text{CTFM} = \frac{\sqrt{\sum_{\text{trigger lines}} \beta'_{\text{evt,line}}}}{\sum_{\text{trigger lines}} \varepsilon'_{\text{evt,line}}}$$

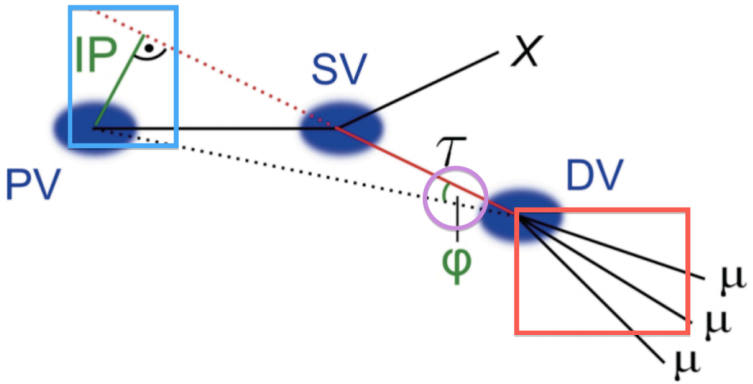
- Evaluated different triggers used in 2012 data taking.
- Found negligible differences in trigger efficiencies.

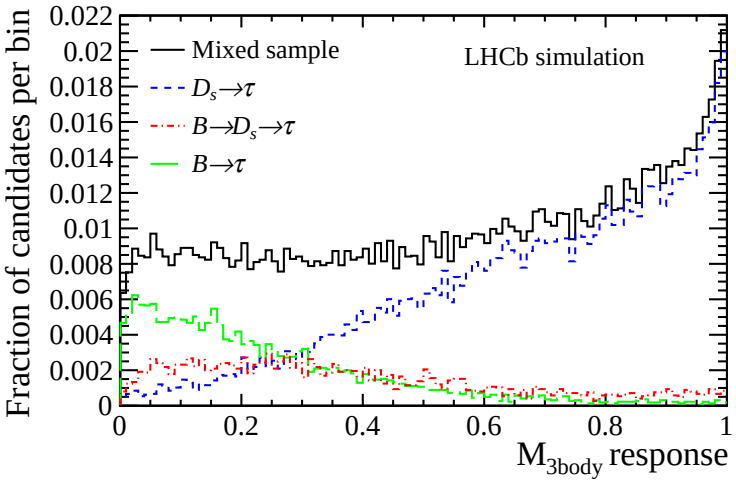
name	ε'	β'	CTFM
Hlt2TriMuonTauDecision	0.880708	0.736182	0.974228
Hlt2DiMuonDetachedDecision	0.0669841	0.173396	1.00636
Hlt2CharmSemilep3bodyD2KMuMuDecision	0.0206816	0.0182935	0.99472
Hlt2CharmHadD2HHHDecision	0.00554351	0.00666405	0.992604
Hlt2CharmSemilep3bodyD2KMuMuSSDecision	0.00195444	0.00470404	0.993106
Hlt2CharmSemilep3bodyD2PiMuMuDecision	0.00206105	0.00679472	0.994591
Hlt2TopoMu3BodyBBDTDecision	0.00394442	0.0121521	0.996937

Signal and background discrimination

- Two multivariate classifiers, $\mathcal{M}_{3body}$ and $\mathcal{M}_{\mathcal{PID}}$.

- $\mathcal{M}_{3body}$ trained using vertex and track fit quality, vertex displacement, vertex pointing, vertex isolation and τ p_T.
- Used Blending Technique (see the next slide).





- Trained on signal and background MC.
- Calibrated on $D_s \to \phi(\mu\mu)\pi$ sample.

Variables 1/2

The multi-variate classifiers were trained using the following variables:

- **DOCA:** the minimum of distances of the closest approach of two muons in each of three possible two muon pairings,
- $\boldsymbol{\tau}(\mathbf{D_s})$ **Vertex** χ^2**:** the quality of the vertex parametrized as the chi square of the τ secondary vertex fit (as defined in,
- $\mathbf{c}\tau$**:** The measured decay length of the τ lepton, assuming its production at the primary vertex. To smooth out the distribution, the decay time is transformed according to the formula $T = \exp(-1000 \cdot \tau)$,
- **IP** χ^2 **(**$\boldsymbol{\tau}$**):** τ lepton impact parameter χ^2/ndf,
- **Min. IP** χ^2 **(**$\boldsymbol{\mu}$**):** the minimum value of the three μ impact parameter (χ^2/ndf)s,
- **Track** χ^2**/ndf:** maximum of track's (χ^2)s of the three muons,

Variables 2/2

The multi-variate classifiers were trained using the following variables:

- **Pointing angle α:** the angle between the direction of τ momentum and a straight line from the τ decay vertex to the primary vertex,
- $\mathbf{p_T}$: the τ transverse momentum,
- **Track isolation:** the sum of three track isolations variables, each parametrising how far in space is an individual muon candidate w.r.t. the rest of event.
- **BDT (Boosted Decision Tree) isolation:** the response of multivariate analysis (MVA) working at the charged track level and aimed at discriminating between isolated and non-isolated tracks.
- **Cone isolation:** the fraction of the τ candidate transverse momentum among the sum of all transverse momenta within a certain cone around the τ candidate.

Isolations 1/2

The track isolation (TI) variable is constructed on the basis of the respective studies performed by the LHCb collaboration for the needs of $B_s^0 \to \mu^+\mu^-$ analysis. The TI is defined as the number of extra tracks (i.e. excluding tracks that are attributed to the $\tau \to \mu\mu\mu$ candidate) that can form a vertex with a muon track. The assignment to the above SV is based on the selection criteria imposed on the following variables:

- minimum distance between the **track** and the PV (**pvdist**),
- minimum distance between the **track** and the $\tau \to \mu\mu\mu$ vertex (**svdist**),
- the distance of the closest approach between the **muon** and the **track** (DOCA),
- IP χ^2,
- angle between the **muon** and the **track** (β),
- the quantity

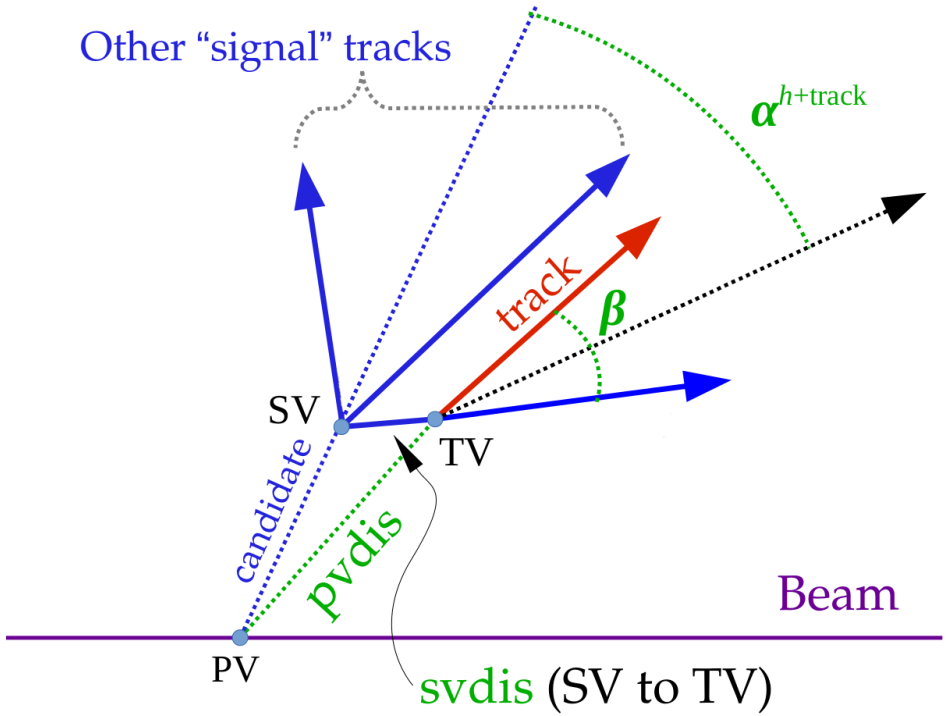
$$f_c = \frac{|\overrightarrow{p}_h + \overrightarrow{p}_{trk}|\alpha^{h+trk,PV}}{|\overrightarrow{p}_h + \overrightarrow{p}_{trk}|\alpha^{h+trk,PV} + p_{\mathrm{T},h} + p_{\mathrm{T},trk}}, \tag{1}$$

where $\alpha^{h+trk,PV}$ is the angle between the **muon** and the **track** candidate, $P_{\mathrm{T},h}$ and $P_{\mathrm{T},trk}$ are the transverse momentum with respect to the beam line.

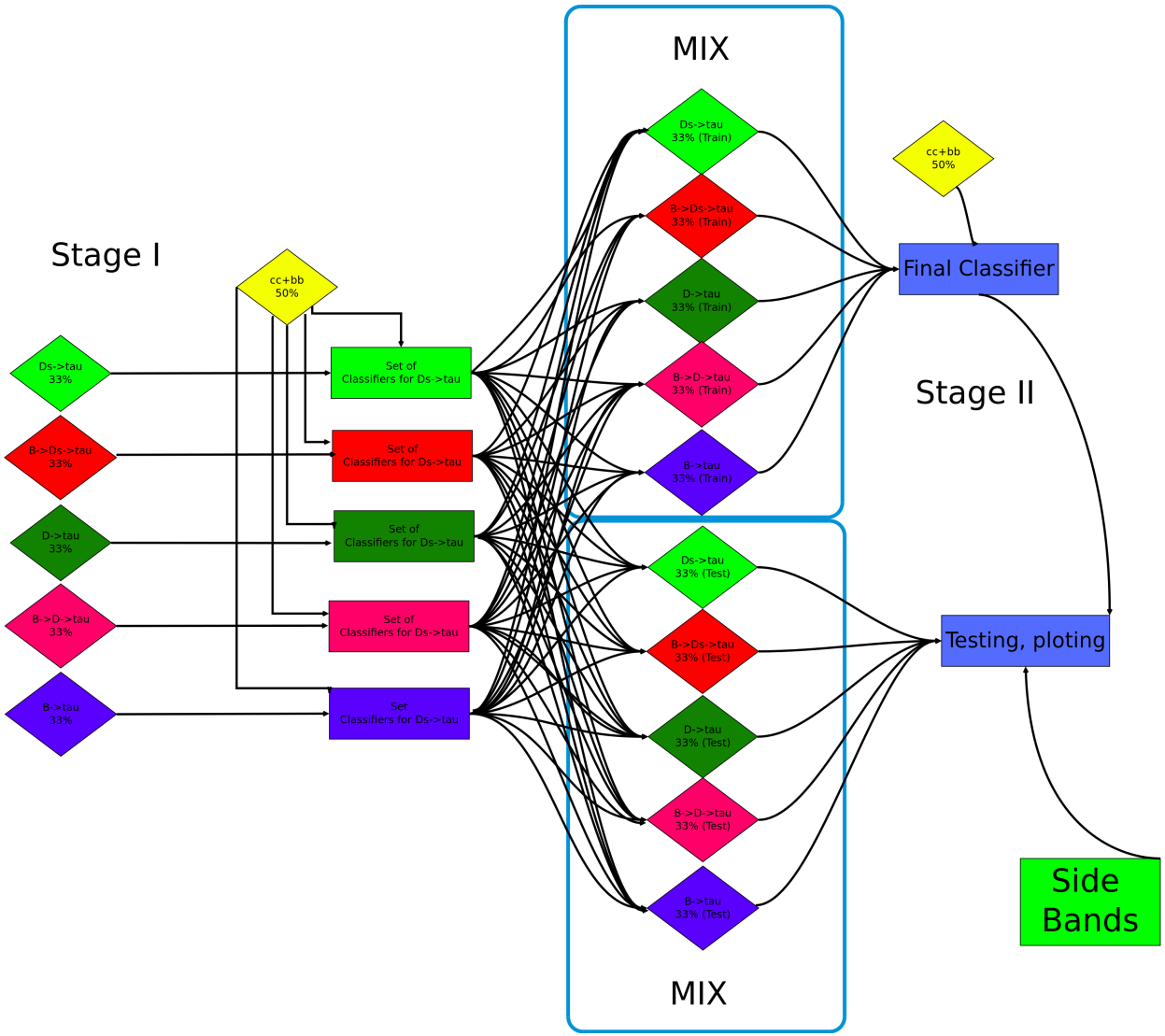
Isolations 2/2

The track is considered as "isolated" if it satisfies the following requirements (imposed on the above mentioned variables):

- pvdist $\in [0.5, 40]$ mm,
- svdist $\in [-0.15, 30]$ mm,
- DOCA < 0.13 mm,
- Track IP significance > 3,
- $\beta < 0.27$ rad,
- $f_c < 0.6$.



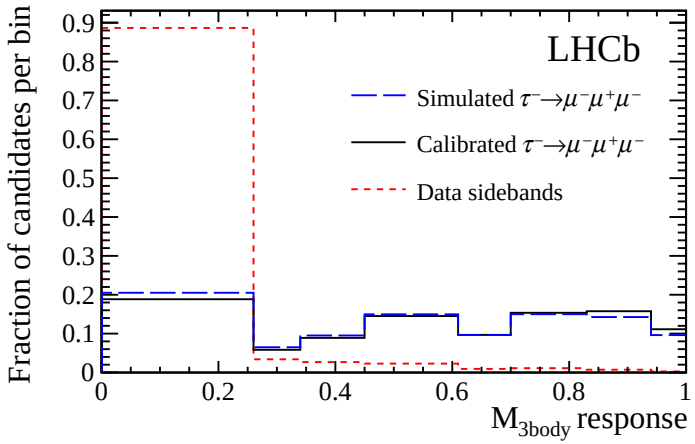
Blending technique



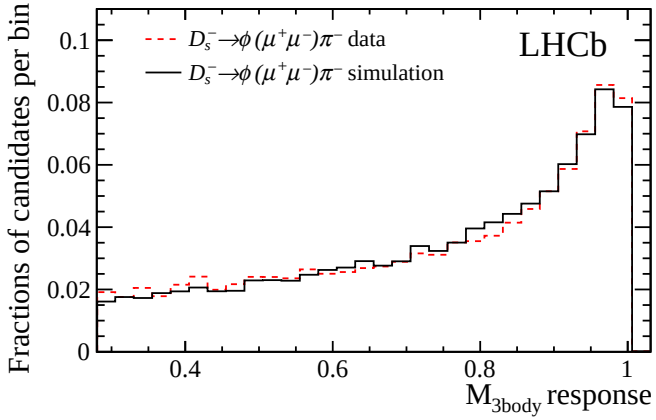
- Each of the τ lepton production channel have a different signature in terms of kinematic distributions.
- Signal blending technique improved the discriminating power by 6 %

Calibration

- Assume all differences between $\tau \longrightarrow \mu\mu\mu$ and $D_s \longrightarrow \phi\pi$ come from kinematics (mass, resonance, decay time), which is correct in MC.
- Get correction $D_s \Longrightarrow \tau$ from MC.
- Apply corrections to $D_s \longrightarrow \phi\pi$ on data.
- Publication in preparation.

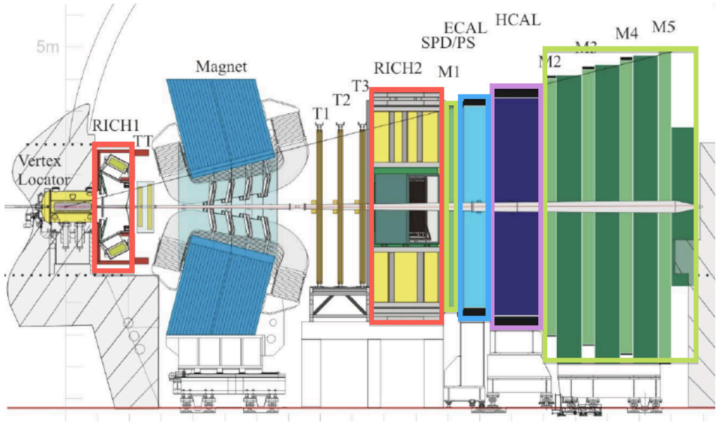


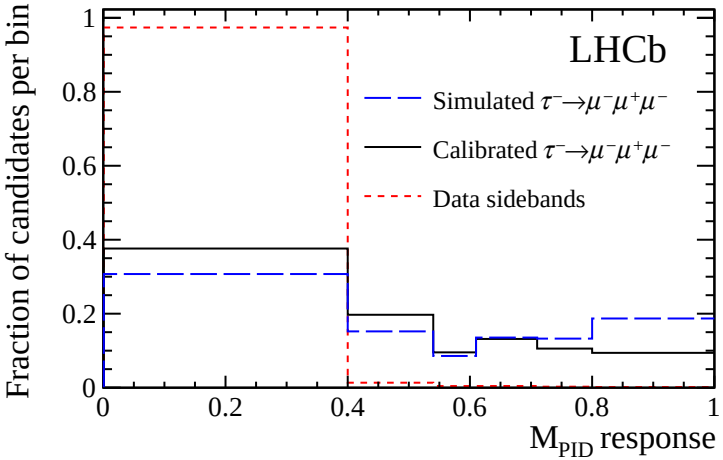
- $D_s \longrightarrow \phi\pi$ decay well modelled in MC.



Signal and background discrimination - $\mathcal{M}_{PID}$

- $\mathcal{M}_{PID}$ trained using RICH, ECAL and muon chambers.



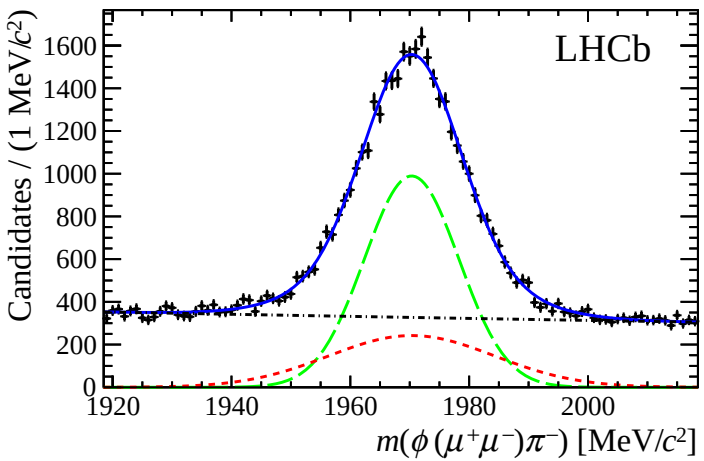


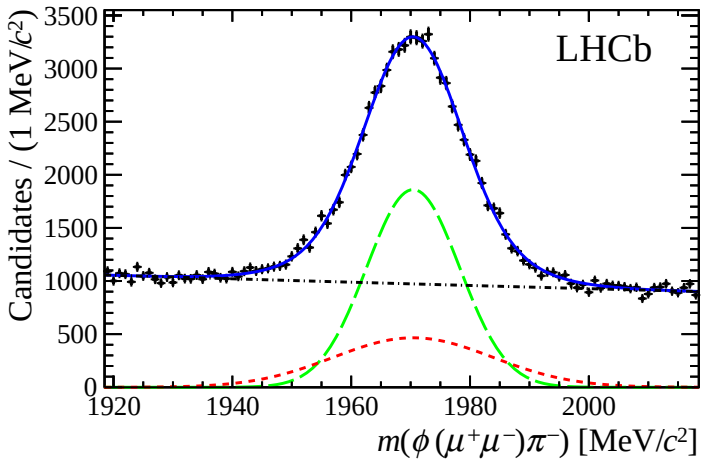
- Trained on signal and background MC.
- Calibrated on $B \to J/\psi K$ and $D_s \to \phi(\mu\mu)\pi$ decays.

Mass shape

- Double-Gaussian with fixed fraction (70 % inner Gaussian).
- Fix fraction to ease calibration.
- Correct mass by MC:

$$\sigma^{\tau}_{data} = \frac{\sigma^{\tau}_{MC}}{\sigma^{\mathrm{D_s}}_{MC}} \times \sigma^{\mathrm{D_s}}_{data}$$





Calibrated τ Mass shape	7 TeV	8 TeV
Mean (MeV)	1779.1 ± 0.1	1779.0 ± 0.1
σ_1 (MeV)	7.7 ± 0.1	7.6 ± 0.1
σ_2 (MeV)	12.0 ± 0.8	11.5 ± 0.5

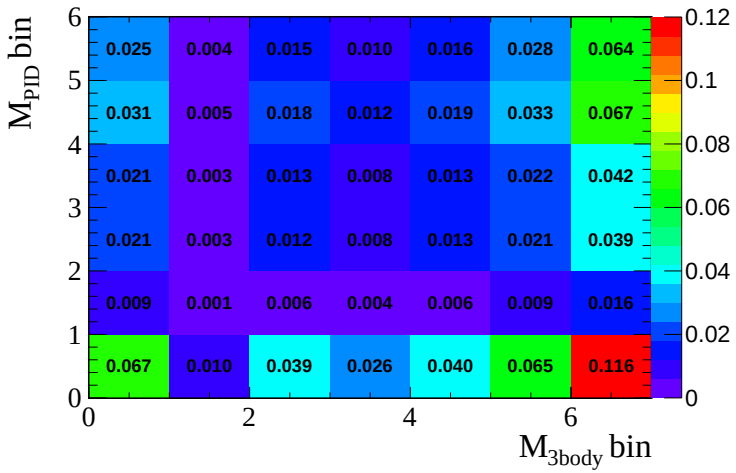
Binning optimisation

- Events are distributed among $\mathcal{M}_{3body}, \mathcal{M}_{PID}$ plane.
- In 2D we collect the events in groups(bins)
- Bins are optimised using CL_s method:

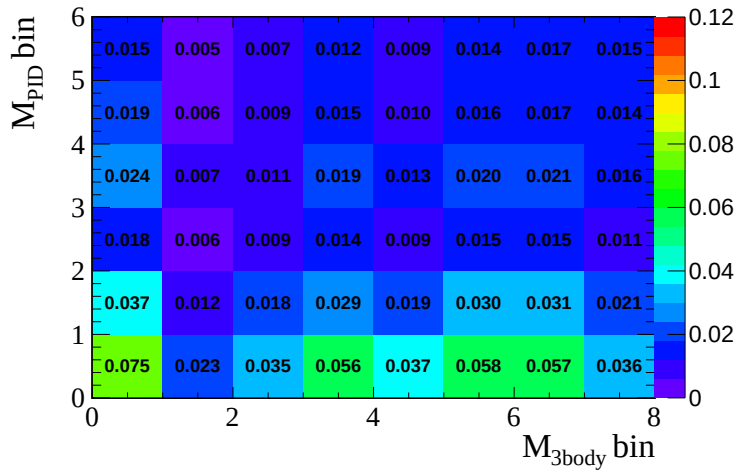
$$CL_s = \frac{\prod_{i=1}^{N_{\text{chan}}} \sum_{n=0}^{n_i} \frac{e^{-(s_i+b_i)}(s_i+b_i)^n}{n!}}{\prod_{i=1}^{n_{\text{chan}}} \sum_{n=0}^{n_i} \frac{e^{-b_i} b_i^n}{n!}},$$

- The lowest bins are rejected, because they do not contribute to the limit sensitivity.

2011



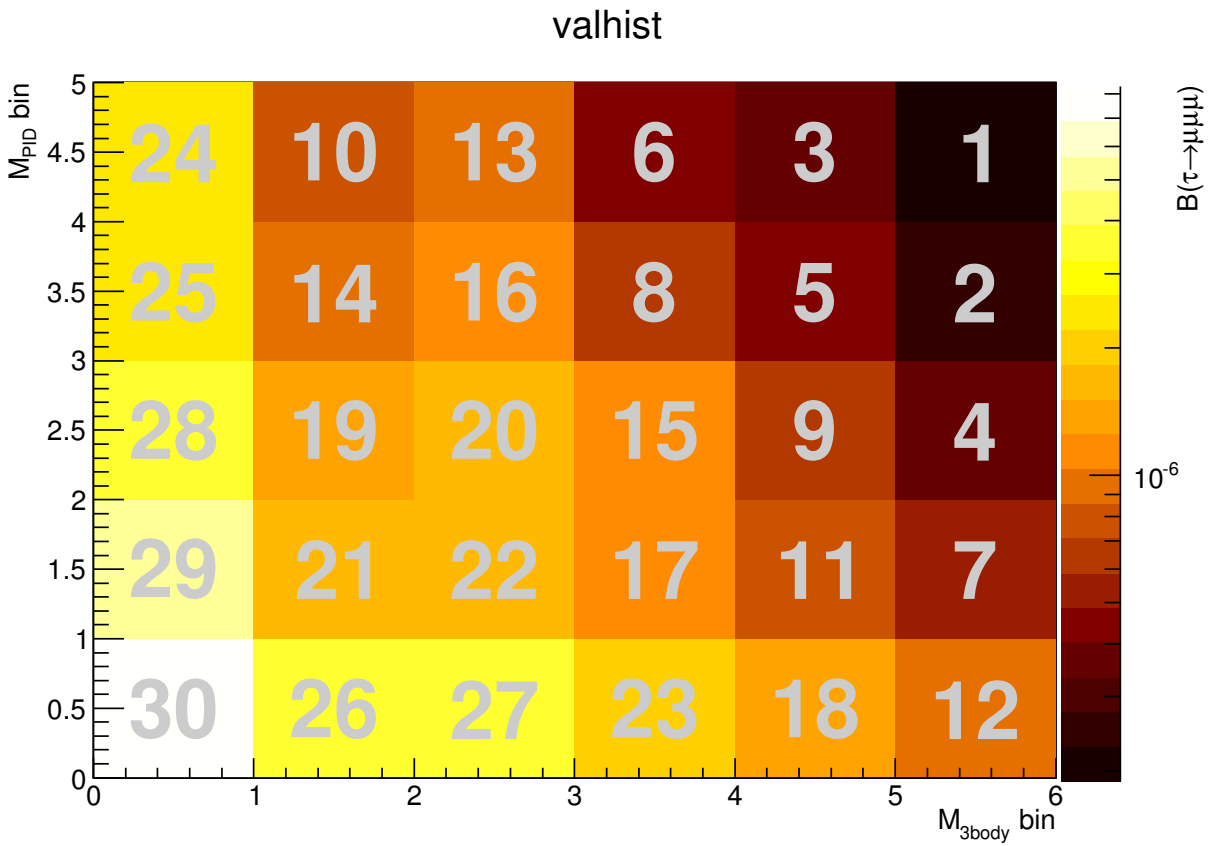
2012



Impact of 2D binning optimisation

- Colour: limit obtained, using only this particular bin.
- Number: rank of that bin (1=best sensitivity bin).

Bin sensitivity (2011 data)

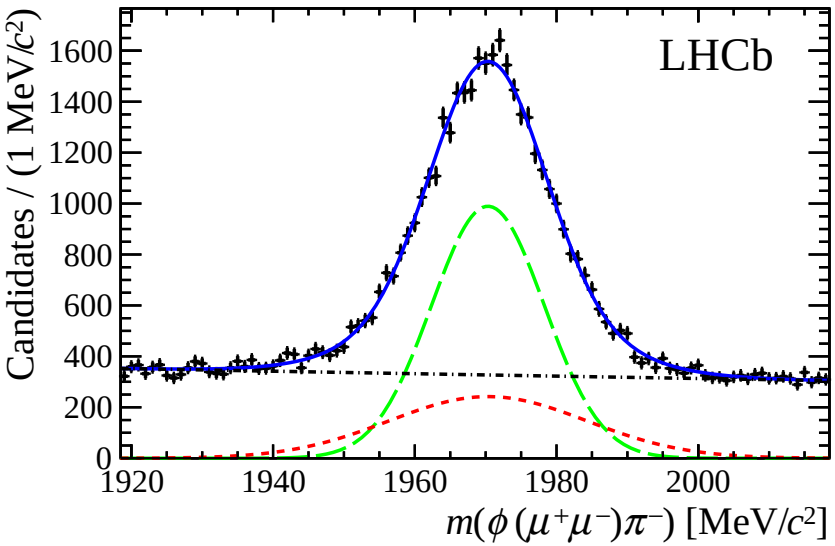


Relative normalisation

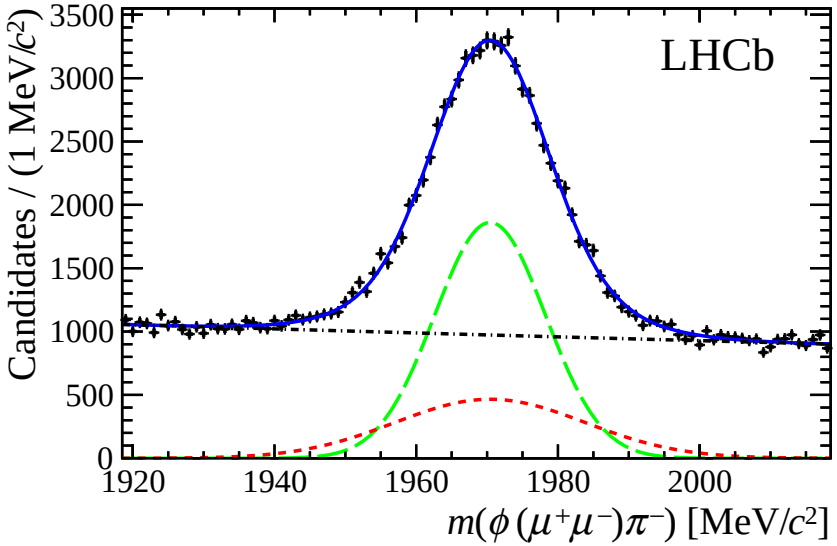
$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\mathcal{B}(\mathrm{D_s} \to \phi\pi)}{\mathcal{B}(\mathrm{D_s} \to \tau\nu_\tau)} \times f^{\tau}_{\mathrm{D_s}} \times \frac{\varepsilon_{\mathrm{norm}}}{\varepsilon_{\mathrm{sig}}} \times \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}} = \alpha \times N_{\mathrm{sig}}$$

- where ε stands for trigger, reconstruction, selection efficiency.
- $f^{\tau}_{\mathrm{D_s}}$ is the fraction of τ coming from $\mathrm{D_s}$.
- norm = normalisation channel $\mathrm{D_s} \to \phi\pi$ i.e. $(83 \pm 3)\,\%$ for 2012 data.

2011

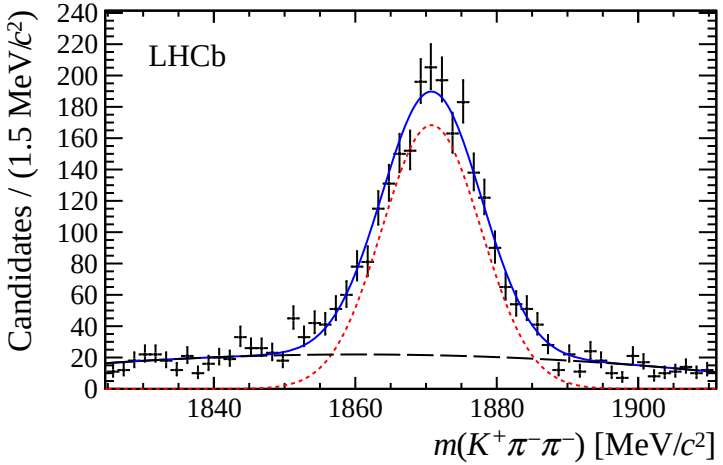


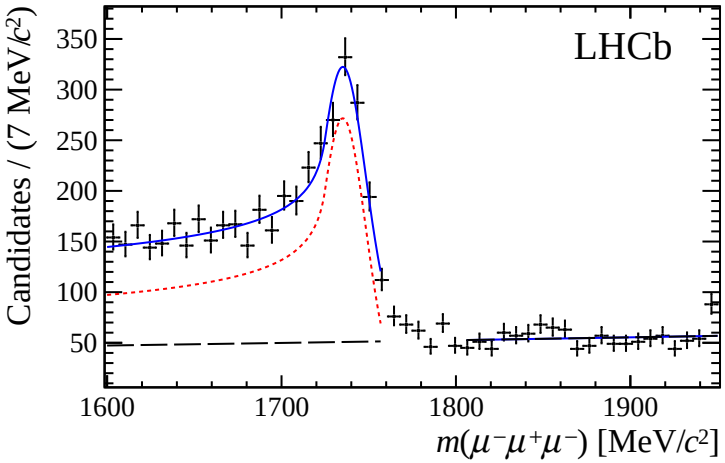
2012

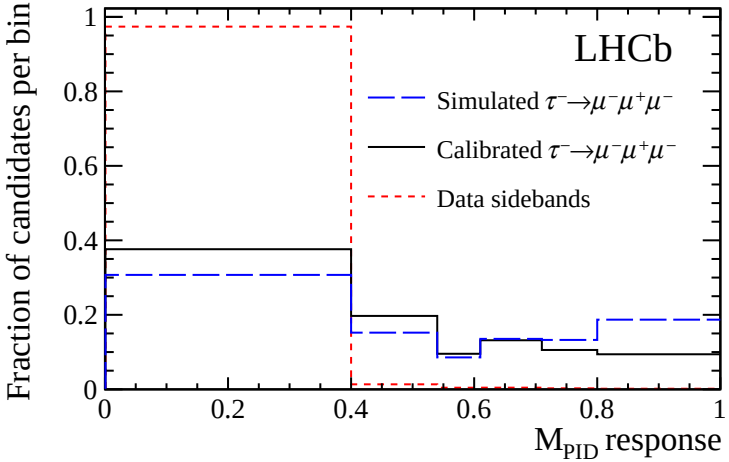


Misidentification (Peaking background) 1/2

- Dominant: $D^+ \to K\pi\pi$.
- Also seen $D^+ \to \pi\pi\pi$ and $D_s \to \pi\pi\pi$.
- All contained in the lowest $\mathcal{M}_{PID}$ bin.

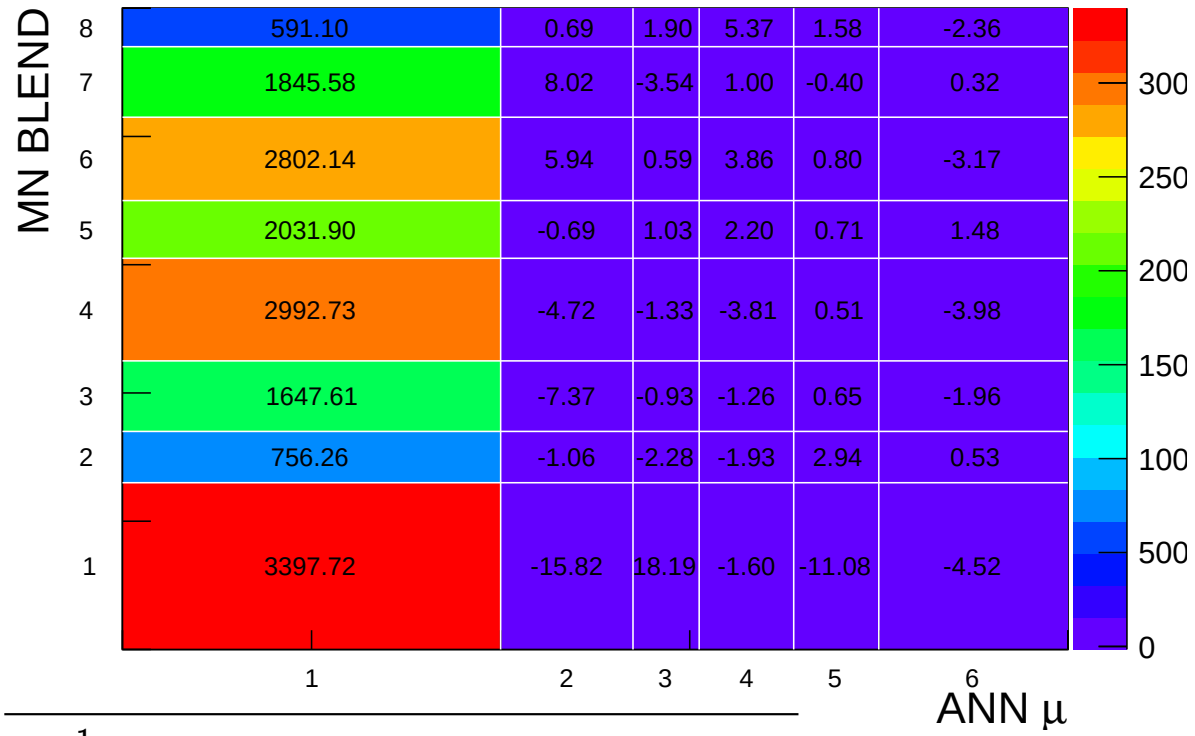






Misidentification (Peaking background) 2/2

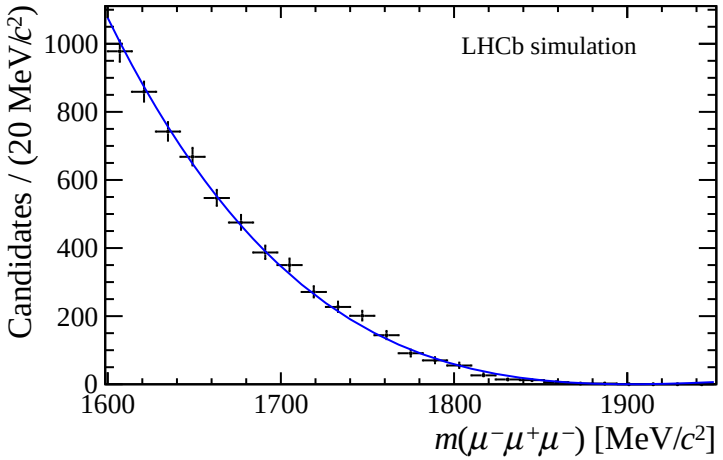
- Many tests were performed to be sure we are safe from $D_x \longrightarrow 3h$.
- Tested both on MC and data.
- Referees also suggest looking into semileptonic decays.
- Our background is safely contained in "trash"[1] bins.

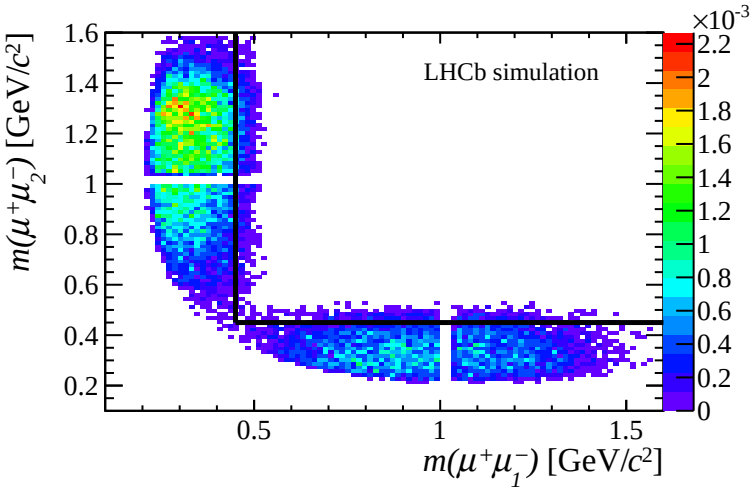


[1] Lowest *ProbNNmu* and M_{blend} bins, not taken for limit calculation.

Other backgrounds

- $\phi \longrightarrow \mu\mu + X$; narrow veto on dimuon mass.
- $D_s \longrightarrow \eta(\mu\mu\gamma)\mu\nu_\mu$; not so easy:
  - Model it
  - Remove it with dimuon mass cut:
    - Fits better understood.
    - Sensitivity unchanged when removing veto.
    - Smaller uncertainty on expected background.

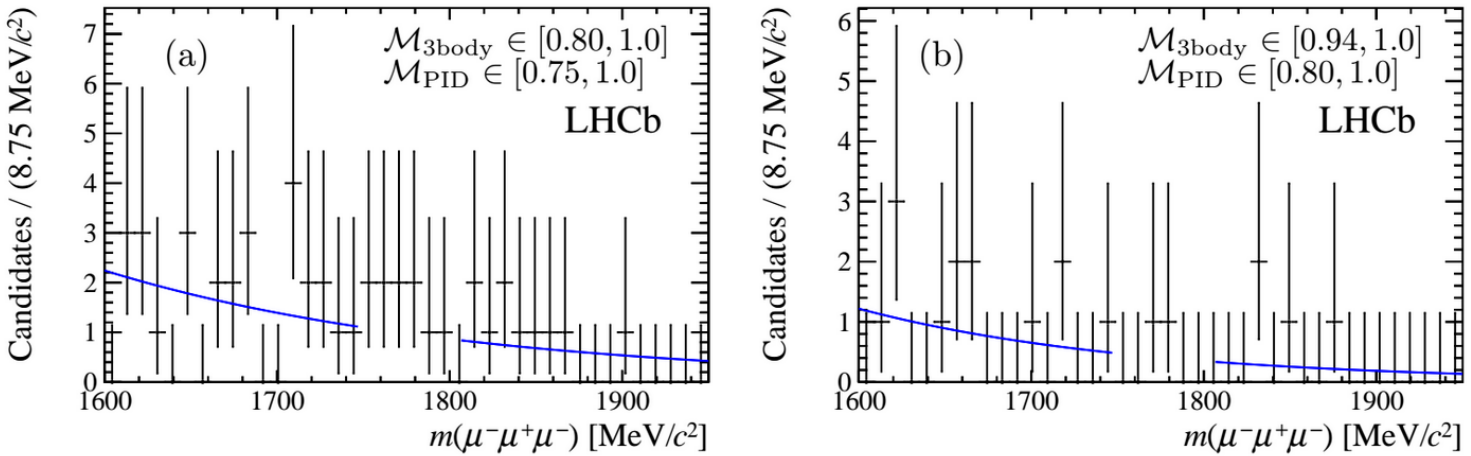




Remaining backgrounds

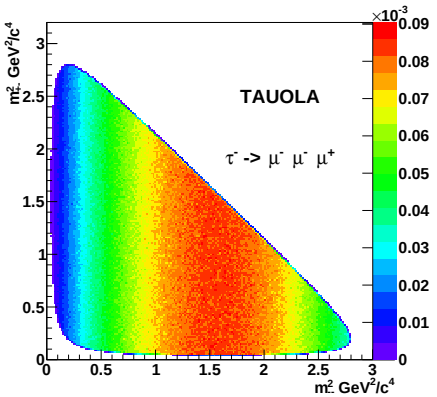
- Fit exponential to invariant mass spectrum in each likelihood bin.
- Don't use the ± 30 MeV region.

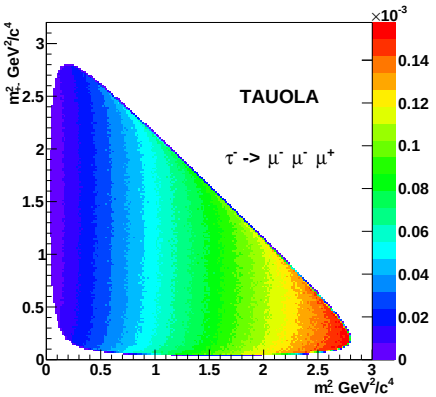
Example of most sensitive regions in 2011 and 2012

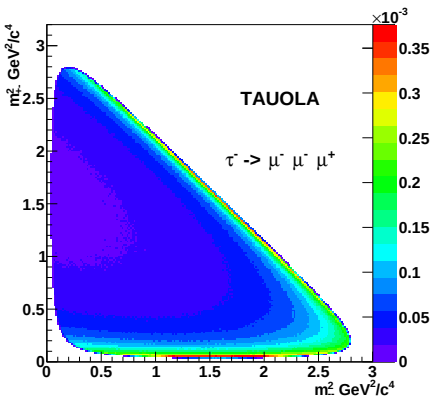


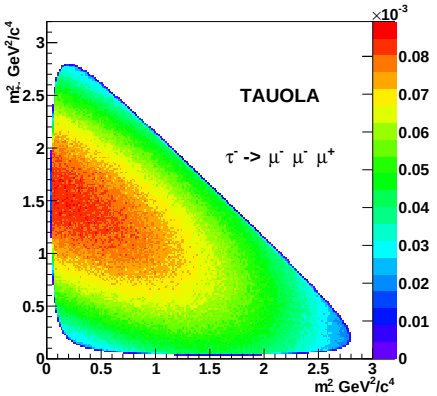
Model dependence

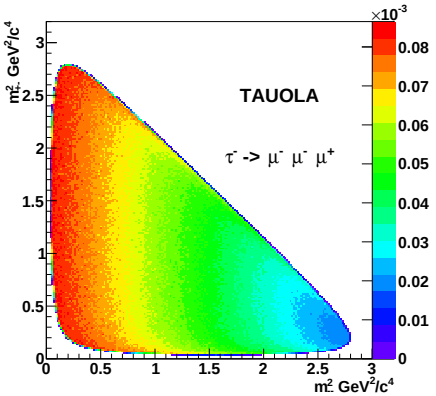
- η veto $\Rightarrow$ our limit not constraining to New Physics with small $m_{\mu^+\mu^-}$.
- Model description in arXiv:0707.0988 by S.Turczyk using Effective Field Theory approach.
- 5 relevant Dalitz distributions: 2 four-point operators, 1 radiative operator, 2 interference terms.







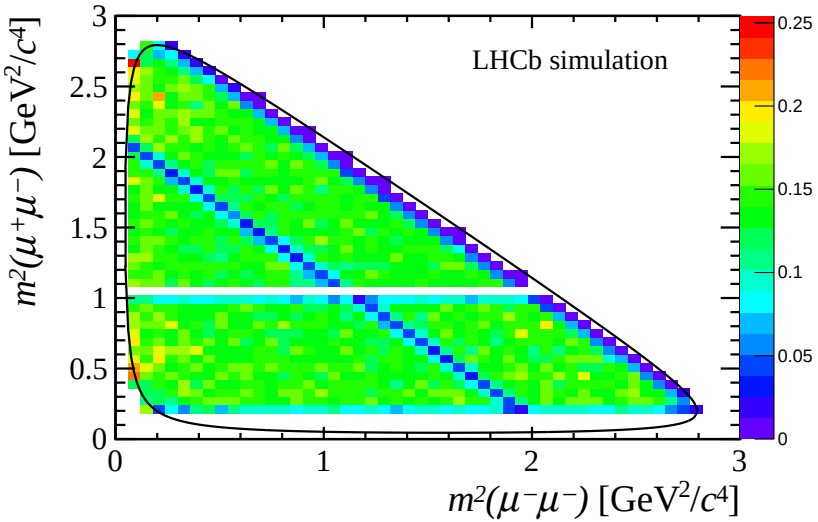




- All five cases implemented in TAUOLA.
- Publication in preparation.

Model dependence

- η veto $\Rightarrow$ our limit not constraining to New Physics with small $m_{\mu^+\mu^-}$.
- Model description in arXiv:0707.0988 by S.Turczyk using Effective Field Theory approach.
- 5 relevant Dalitz distributions: 2 four-point operators, 1 radiative operator, 2 interference terms.
- With radiative distribution limit gets worse by a factor of 1.5 (dominantly from the η veto).
- The other four Dalitz distributions remain stable (within 7 %).



Unblinding 1

" THERE came a day at summer's full
Entirely for us
I thought that such were for the saints,
Where revelations be. "[a]

[a] E.Dickinson

On Monday 4^{th} of August we were given the permission to unblind.

Unblinding 2

- Unfortunately no big "revelations" were there.
- 2011 numbers:

ProbNNmu	M_{blend}	Estimated	Observed
0.4, 0.45	0.28, 0.32	3.172 ± 0.661	4
0.4, 0.45	0.32, 0.46	9.242 ± 1.129	6
0.4, 0.45	0.46, 0.54	2.894 ± 0.632	6
0.4, 0.45	0.54, 0.65	3.173 ± 0.661	4
0.4, 0.45	0.65, 0.80	3.637 ± 0.716	2
0.4, 0.45	0.80, 1.0	3.787 ± 0.802	3
0.45, 0.54	0.28, 0.32	4.223 ± 0.779	6
0.45, 0.54	0.32, 0.46	8.345 ± 1.077	10
0.45, 0.54	0.46, 0.54	2.317 ± 0.568	4
0.45, 0.54	0.54, 0.65	2.828 ± 0.632	8
0.45, 0.54	0.65, 0.80	2.718 ± 0.688	5
0.45, 0.54	0.80, 1.00	4.825 ± 0.900	7

ProbNNmu	M_{blend}	Estimated	Observed
0.54, 0.63	0.28, 0.32	2.327 ± 0.584	6
0.54, 0.63	0.32, 0.46	8.324 ± 1.077	8
0.54, 0.63	0.46, 0.54	2.068 ± 0.534	1
0.54, 0.63	0.54, 0.65	3.291 ± 0.675	1
0.54, 0.63	0.65, 0.80	2.962 ± 0.646	4
0.54, 0.63	0.80, 1.00	3.114 ± 0.687	3
0.63, 0.75	0.28, 0.32	2.688 ± 0.616	1
0.63, 0.75	0.32, 0.46	7.541 ± 1.023	5
0.63, 0.75	0.46, 0.54	2.059 ± 0.534	3
0.63, 0.75	0.54, 0.65	1.996 ± 0.549	5
0.63, 0.75	0.65, 0.80	3.164 ± 0.661	2
0.63, 0.75	0.80, 1.00	4.674 ± 0.836	2
0.75, 1.0	0.28, 0.32	2.192 ± 0.551	2
0.75, 1.0	0.32, 0.46	3.384 ± 0.755	5
0.75, 1.0	0.46, 0.54	1.517 ± 0.457	3
0.75, 1.0	0.54, 0.65	1.280 ± 0.469	1
0.75, 1.0	0.65, 0.80	2.780 ± 0.645	1
0.75, 1.0	0.80, 1.00	4.421 ± 0.833	7

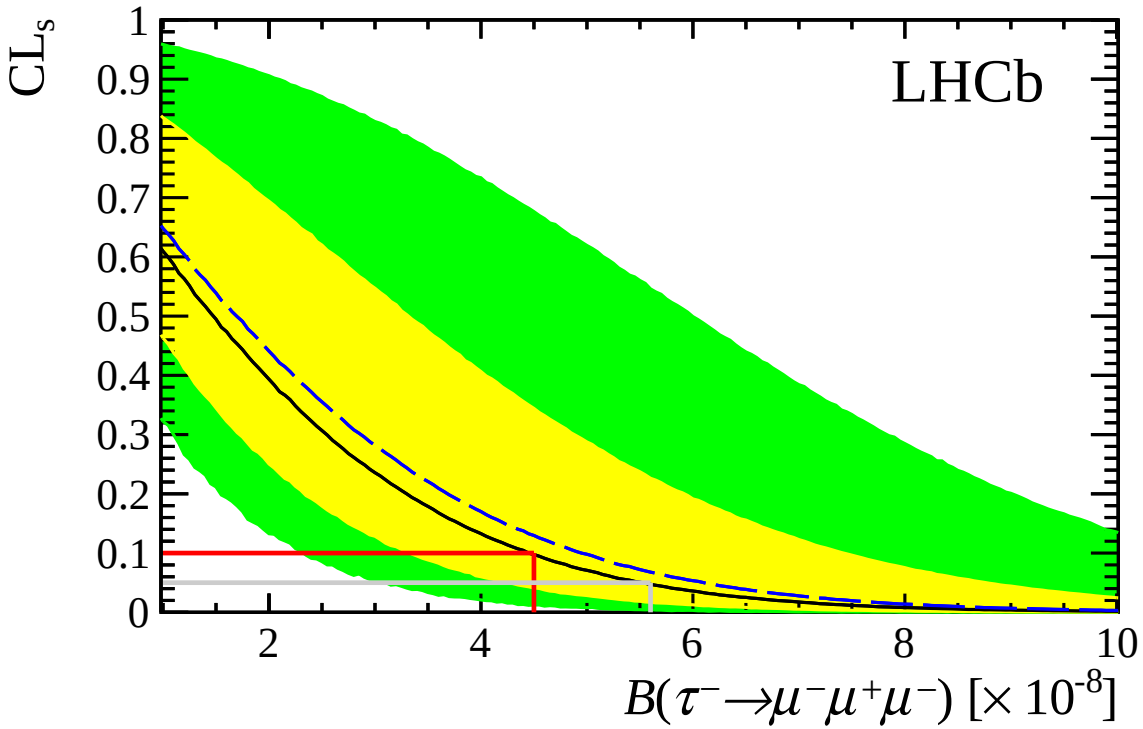
Unblinding 3

- Unfortunately no big "revelations" were either in 2012 data:

ProbNNmu	M_{blend}	Estimated	Observed
0.4, 0.54	0.26, 0.34	39.6 ± 2.3	39
0.4, 0.54	0.34, 0.45	32.2 ± 2.1	34
0.4, 0.54	0.45, 0.61	28.7 ± 2.0	28
0.4, 0.54	0.61, 0.7	9.72 ± 1.22	5
0.4, 0.54	0.7, 0.83	11.38 ± 1.26	7
0.4, 0.54	0.83, 0.94	7.34 ± 1.10	6
0.4, 0.54	0.94, 1.0001	5.98 ± 0.95	0
0.54, 0.61	0.26, 0.34	13.6 ± 1.37	8
0.54, 0.61	0.34, 0.45	12.1 ± 1.29	12
0.54, 0.61	0.45, 0.61	8.32 ± 1.086	13
0.54, 0.61	0.61, 0.7	2.595 ± 0.616	1
0.54, 0.61	0.7, 0.83	1.833 ± 0.601	5
0.54, 0.61	0.83, 0.94	2.929 ± 0.724	6
0.54, 0.61	0.94, 1.0001	2.693 ± 0.632	3

ProbNNmu	M_{blend}	Estimated	Observed
0.61, 0.71	0.26, 0.34	13.457 ± 1.366	7
0.61, 0.71	0.34, 0.45	10.852 ± 1.23	11
0.61, 0.71	0.45, 0.61	9.661 ± 1.18	12
0.61, 0.71	0.61, 0.7	3.346 ± 0.69	2
0.61, 0.71	0.7, 0.83	4.600 ± 0.888	5
0.61, 0.71	0.83, 0.94	4.091 ± 0.809	4
0.61, 0.71	0.94, 1.0001	2.780 ± 0.680	1
0.71, 0.8	0.26, 0.34	7.808 ± 1.067	6
0.71, 0.8	0.34, 0.45	7.001 ± 0.985	8
0.71, 0.8	0.45, 0.61	6.170 ± 0.945	6
0.71, 0.8	0.61, 0.7	1.570 ± 0.556	2
0.71, 0.8	0.7, 0.83	2.987 ± 0.717	0
0.71, 0.8	0.83, 0.94	3.929 ± 0.806	0
0.71, 0.8	0.94, 1.0001	3.222 ± 0.676	1
0.8, 1.0	0.26, 0.34	5.123 ± 0.861	3
0.8, 1.0	0.34, 0.45	4.435 ± 0.792	6
0.8, 1.0	0.45, 0.61	3.802 ± 0.784	5
0.8, 1.0	0.61, 0.7	2.649 ± 0.676	2
0.8, 1.0	0.7, 0.83	3.053 ± 0.674	2
0.8, 1.0	0.83, 0.94	1.740 ± 0.543	2
0.8, 1.0	0.94, 1.0001	3.361 ± 0.702	3

Results

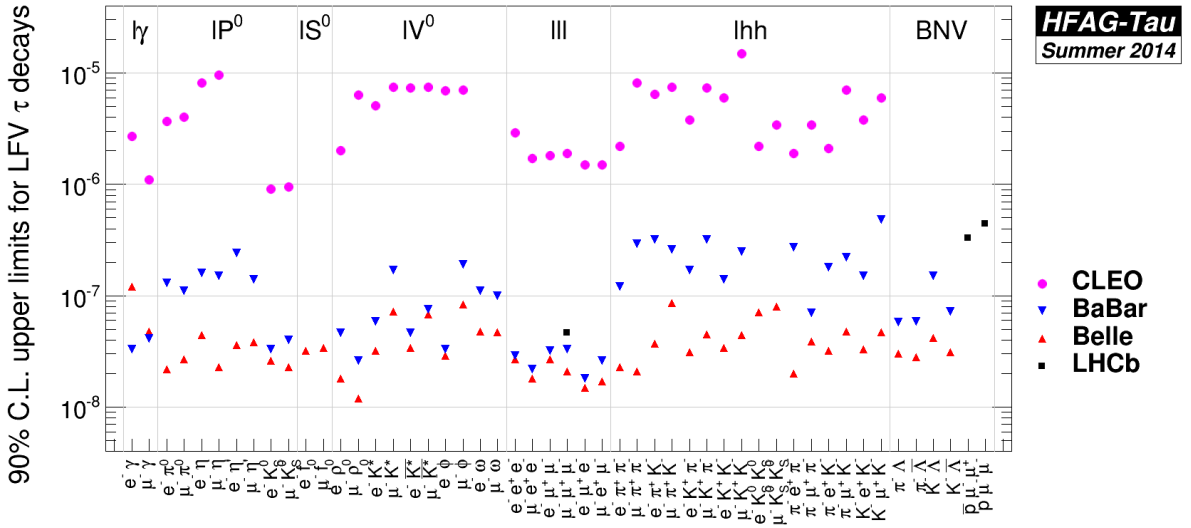


Limits(PHSP):
Observed(Expected)
4.6 (5.0) $\times 10^{-8}$ at 90% CL
5.6 (6.1) $\times 10^{-8}$ at 95% CL

Dalitz distribution	x10^{-8}
$\varrho_V^{(LL)(LL)}$	4.2 (4.7)
$\varrho_V^{(LL)(RR)}$	4.1 (4.6)
$\varrho_{rad}^{(LR)}$	6.8 (7.6)
$\varrho_{mix}^{(LL)(LL)}$	4.4 (5.1)
$\varrho_{mix}^{(LL)(RR)}$	4.6 (5.0)

Combination of LFV UL 1/2

- Searches for LFV in τ sector is a domain of B factories.
- Over last years both BaBar and Belle set very strong limits on branching fractions of several rare τ decays.



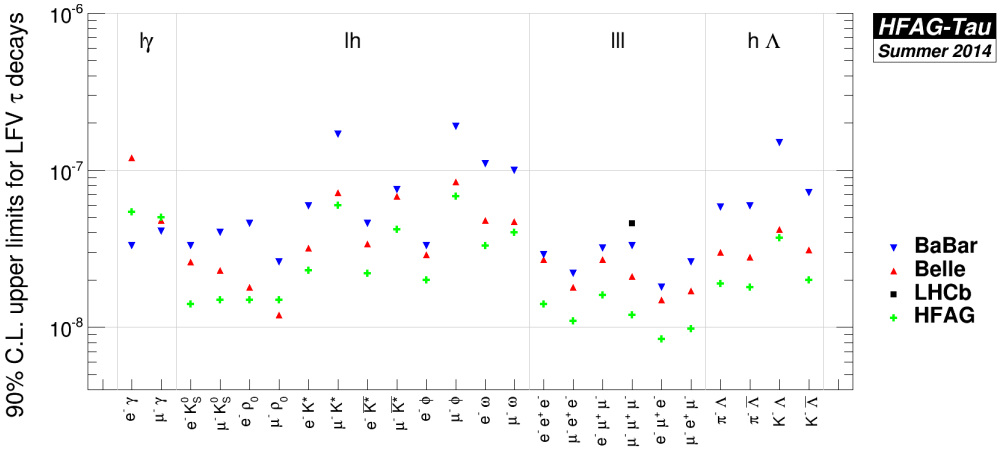
  - First result from hadron collider comparable with B factories.
  - Since those limits are used to constraint NP models, their "official" combination is of paramount importance.
  - Various methods of limit computation used in Belle and BaBar's studies.
  - The HFAG group recomputed consistently all estimates using the CL_s method and the the same approach was involved in the average evaluation.

Combination of LFV UL 2/2

- For each measurement take integrated luminosity ($\mathcal{L}$), cross section ($\sigma_{\tau\tau}$), efficiencies (ϵ), background expected(b) and all systematics.
- Calculate number of signal: $s = \mathcal{L}\sigma_{\tau\tau}\epsilon^{tot}\mathcal{B}(\tau \to LFV)$.
- Scan the CL_s wrt. $\mathcal{B}(\tau \to LFV)$:

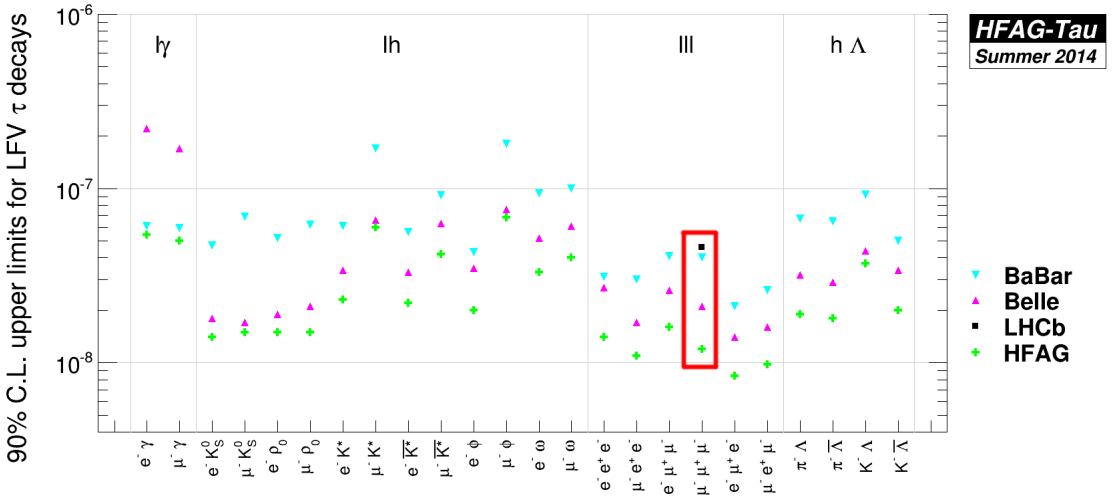
$$CL_s = \frac{\prod_{i=1}^{N_{\text{chan}}} \sum_{n=0}^{n_i} \frac{e^{-(s_i+b_i)}(s_i+b_i)^n}{n!}}{\prod_{i=1}^{n_{\text{chan}}} \sum_{n=0}^{n_i} \frac{e^{-b_i} b_i^n}{n!}}$$

$$\times \frac{\prod_{j=1}^{n} s_i S_i(x_{ij}) + b_i B_i(x_{ij})}{\prod_{j=1}^{n_i} B_i(x_{ij})} \,,$$



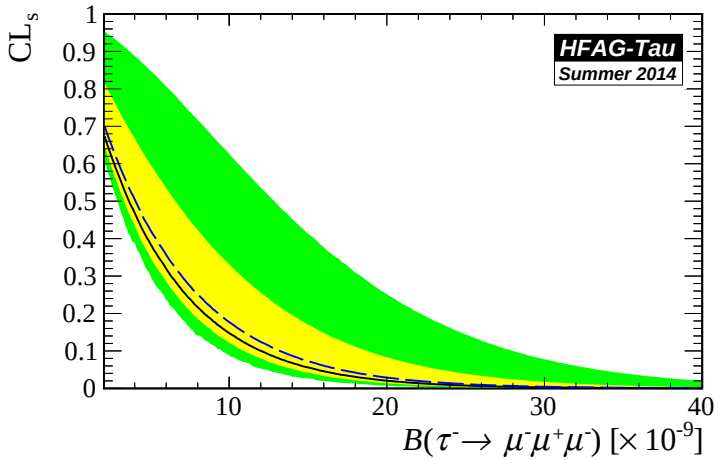
Summary

$\tau \to \mu\mu\mu$ limits (90 % CL)	
BaBar(FC)	3.3×10^{-8}
Belle(FC)	2.1×10^{-8}
LHCb(CLs)	4.6×10^{-8}
HFAG(CLs)	1.2×10^{-8}



To conclude:

- LHCb is reaching B-factories limits.
- Many new techniques developed to perform this analysis.
- Combination of UL within HFAG gave the best sensitivity for $\mathcal{B}(\tau \to \mu\mu\mu) < 1.2 \times 10^{-8}$ at 90% CL.
- Erratum to bibliography:
  - [120] HFAG report published:arXiv:1412.7515 (previous cited preliminary web report).
  - [76] accepted for publication in JHEP.



Backup

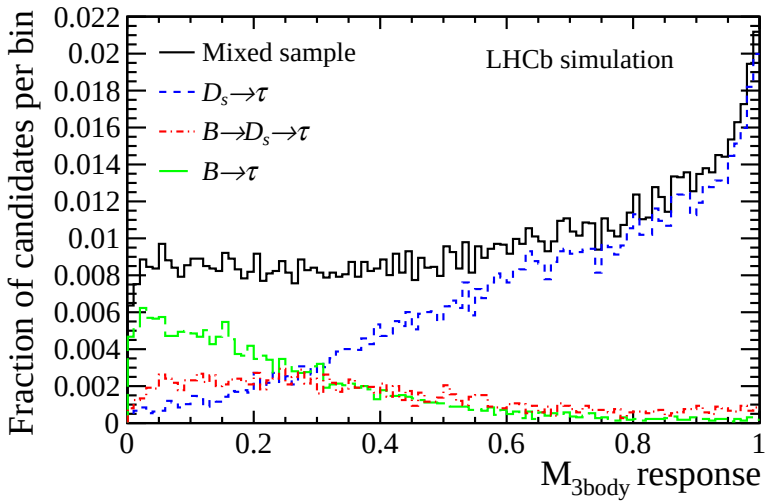
Geometric likelihood

- As mentioned in LHC we have different production sources of τ's.
- Each source has different detector response signature.
- To maximise our performance we trained classifiers for each of the τ sources using:
  - Kinematic properties of τ candidate.
  - Geometric properties of τ candidate, like pointing angle, DOCA, Vertex χ^2, flight distance.
  - Isolations, for vertex and individual tracks.
- After training the individual classifiers one that combines all this information in a single classifier on mixed sample of τ's.
- This technique is known as Blending or Ensemble learning.
- Using this approach we gain 6% sensitivity!

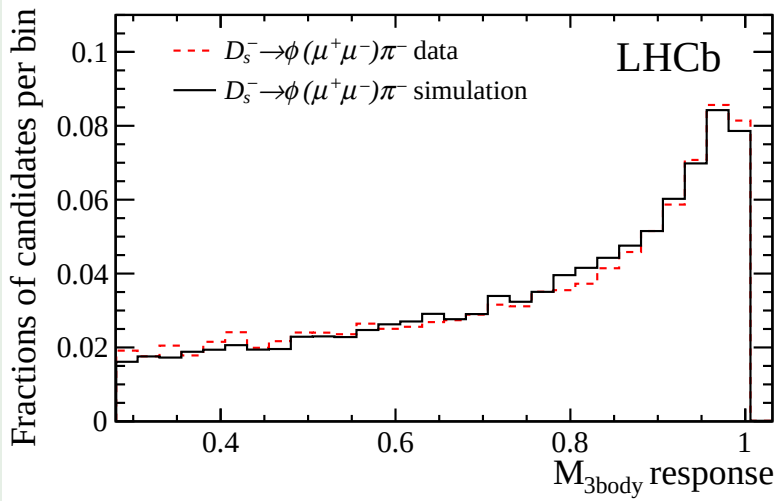
Performance of Blend classifier

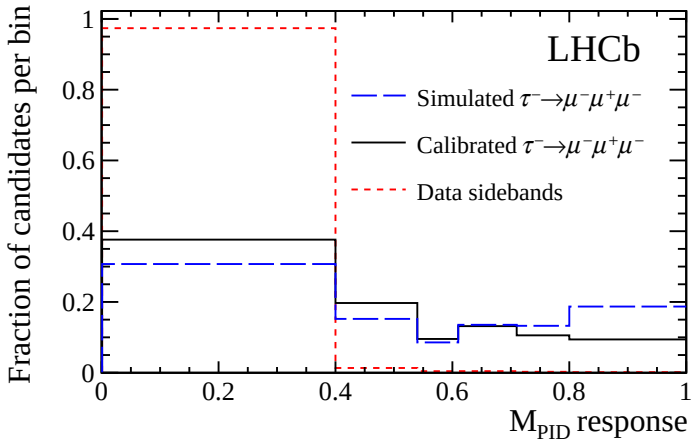
- Classifier prefers τ's from prompt D_s, the dominant channel.

MC response for different τ production channels



Response for $D_s \to \phi\pi$ data and MC



Particle Identification (PID)

- Classifier trained on inclusive MC sample.
- Using information from: RICH, Calorimeters, Muon system and tracking.
- Correct for the MC efficiency using control channel: $D_s \to \phi(\mu\mu)\pi$ and $B \to J/\psi(\mu\mu)K$