

# $\tau \rightarrow \mu\mu\mu$ approval presentation

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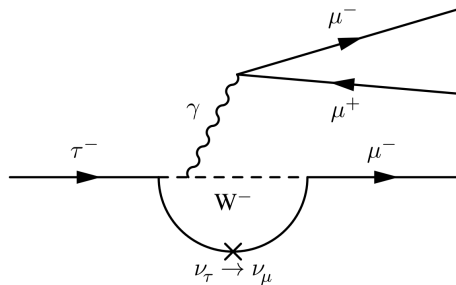
- 1 Introduction
- 2 Selection
- 3 Multivariate technique
- 4 Normalisation
- 5 Backgrounds
- 6 Expected limit
- 7 Model dependence
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- TWiki: [https://twiki.cern.ch/twiki/bin/viewauth/LHCbPhysics/Tau\\_LFV\\_3fb](https://twiki.cern.ch/twiki/bin/viewauth/LHCbPhysics/Tau_LFV_3fb).
- ANA note: LHCb-ANA-2014-005.
- Paper draft: LHCb-PAPER-2014-X.
- Target journal: JHEP.
- Conference: Tau 2014.



# Status of $\tau \rightarrow \mu\mu\mu$



- Charged Lepton Flavour Violation process.
- Possible as penguin with neutrino oscillation.
- SM prediction is beyond experimental reach  $O(10^{-40})$ .

## current limits (90% CL)

**BaBar**  $3.3 \times 10^{-8}$

**Belle**  $2.1 \times 10^{-8}$

**LHCb**  $8.0 \times 10^{-8}$

## BSM predictions

**var. SUSY**  $10^{-10}$

**non universal Z'**  $10^{-8}$

**mSUGRA+seesaw**  $10^{-9}$

**and many more...**

- Following same approach as other RD searches.
- Loose stripping selection.
- Multivariate classification in: mass, PID, “geometry/topology”.
- Binning optimisation.
- Relative normalisation ( $D_s \rightarrow \phi(\mu\mu)\pi$ ).
- Invariant mass fit for expected background in each likelihood bin: fit in  $|m - m_\tau| > 30$  MeV.
- “middle sidebands” for classifier evaluation and tests. ( $20 \text{ MeV} < |m - m_\tau| < 30 \text{ MeV}$ ).
- CLs for limit calculation.



- $\tau$ 's in LHCb come from five main sources:

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

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

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



- Data from Reco14Stripping20(r1).
  - Large MC samples:
    - 24M Inclusive background events ( $b\bar{b}$  and  $c\bar{c}$ ).
    - 10M Exclusive background events ( $D_s \rightarrow \eta(\mu\mu\gamma)\mu\nu_\mu$ ).
    - 2M Signal events (split over 5 production channels).
    - 12M  $D \rightarrow K\pi\pi$  (missID studies).
    - 10M  $D^* \rightarrow D(K\mu\nu_\mu)\pi$  (missID studies).
- ⇒ Generator level cuts for improved use of computing resources.
- $\sim 14$  times more signal statistics after stripping.
  - $\sim 2$  times more background statistics.
- Mix  $\tau$  production on ntuple level instead of reweighting.  
⇒ Ease up ntuple usage (no forgotten weighting, no double weighting, ...).



# Stripping and selection

	$\tau \rightarrow \mu\mu\mu$	$D_s \rightarrow \phi\pi$
$\mu^\pm, \pi^\pm$		
$p\tau$	> 300MeV	
Track $\chi^2/\text{ndf}$	< 3	
IP $\chi^2/\text{ndf}$	> 9	
track ghost probability	< 0.3	
$\mu$ pairs		
$m_{\mu^+\mu^-} - m_\phi$	> 20MeV	< 20MeV
$m_{\mu^+\mu^-}$	> 450MeV	-
$m_{\mu^+\mu^+}$	> 250MeV	-
$\tau^\pm$ and $D_s$		
$\Delta m$	< 400MeV	< 50MeV
Vertex $\chi^2$	< 15	
IP $\chi^2$	< 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	





	signal	normalisation
L0 <sup>1</sup>	L0Muon TOS	
Hlt1 <sup>1</sup>	Hlt1TrackMuon TOS	
Hlt2 2011	Hlt2CharmSemilepD2HMuMu TOS    Hlt2TriMuonTau TOS	Hlt2DiMuonDetached <sup>2</sup> TOS
Hlt2 2012	Hlt2TriMuonTau <sup>1</sup> TOS	Hlt2DiMuonDetached <sup>2</sup> TOS

## Triggers in 2012

- Cuts changed through 2012.  
→ emulated two different TCKs for 2012.  
→ Found negligible differences in ratio of signal/normalisation channels.
- Choice of triggers was optimised based on  $\frac{s}{\sqrt{b}}$  FOM.



Much work has been put into improving our geometric and kinematic classifier:

- Classify the displaced 3-body decay properties of a signal candidate.
- Revisit variable choice.
- Revisit classification technique.
- More toolkits tried: MatrixNet, NeuroBayes, TMVA.
- Retune input variables  
( $B_s^0 \rightarrow \mu\mu$  isolation  $\rightarrow$  BDT isolation:  
CERN-THESIS-2013-259).
- Apply Blending technique.



# Basic Setup - Step I

- Train 1/3 signal MC against 1/2 background MC.
- Input variables:
  - DOCA
  - Vertex  $\chi^2$
  - $\tau$  decay time
  - $\tau$  IP  $\chi^2$
  - min.  $\mu$  IP  $\chi^2$
  - $\tau$  pointing angle
  - $\tau$   $p_T$
  - max. track  $\chi^2$
  - $B_s^0 \rightarrow \mu\mu\mu$  track isolation
  - Cone isolation
  - BDT isolation
- Using these variables, train several classifiers ("Base") for each of the  $\tau$  source.



# Step II

- Train using second 1/3 signal MC against second 1/2 background MC.
- Introduce Blending technique.

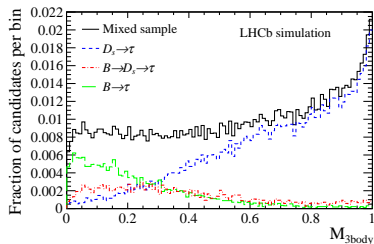
## Blending technique

- For each signal channel we train: one BDT, three Fisher classifier, four MLPs, one FDA, one LD classifier and MatrixNet classifier.
  - One final MatrixNet classifier using the 13 base variables and the base classifiers as input.
- 
- All evaluation is done on 3rd 1/3 signal sample and middle side-bands.
  - Splitting into independent samples makes the procedure insensitive to overtraining.

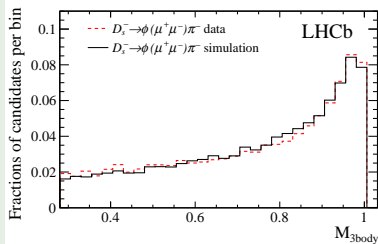
# Performance of Blend classifier

- Classifier prefers  $\tau$ 's from prompt  $D_S$ , the dominant channel.

## MC response for different $\tau$ production channels



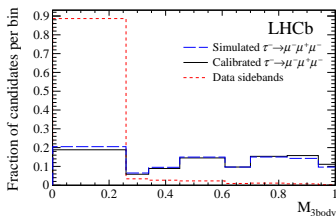
## Response for $D_S \rightarrow \phi\pi$ data and MC



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

## validation

- done for 2011 analysis, treating smeared MC as data



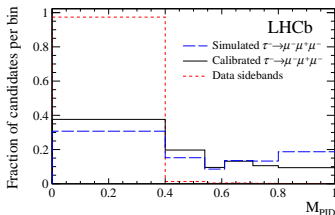
- $D_s \rightarrow \phi\pi$  well modelled in MC.

- We used ProbNNmu already in the previous round of the analysis.
- Now use MC12TuneV2.
- Two-fold reason:
  - Expect better performance than CombDLL variables.
  - “one variable for everything”:  
with CombDLL we needed both CombDLL( $\mu - \pi$ ) and CombDLL( $\mu - K$ ).
- We tested if PIDCalib samples ( $J/\psi$ ) are suited for us.
- $D_s \rightarrow \phi\pi$  better representing  $\tau \rightarrow 3\mu$  than  $J/\psi \rightarrow \mu\mu$ .
- Many thanks to Barbara Sciascia for help understanding the details: [LINK](#)



## Phenomenological treatment

- correlations are small in  $D_s \rightarrow \phi\pi$  data and MC:  
 $\varepsilon(\text{cut on one muon})^2 = \varepsilon(\text{cut on two muons})$
  - ⇒ use  $c^3 = (\varepsilon(\text{cut and fit})/\varepsilon(\text{PIDCalib}))^3$  as correction to PIDCalib for  $\tau \rightarrow \mu\mu\mu$
  - assign error of 0.02 for  $c$ .
- 
- Many cross-checks done.
  - Everything works fine.





# Binning optimisation

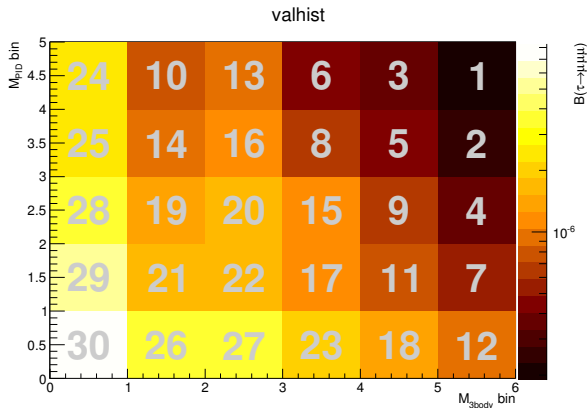
- How to optimise the binning in two classifiers?
- $1 \text{ fb}^{-1}$  CONF note: two one-dimensional optimisations as in  $B_s^0 \rightarrow \mu\mu$ .
- $1 \text{ fb}^{-1}$  PAPER: iterative loop of one-dimensional optimisations optimising one classifier on the sensitive range of the other classifier.
- Now: optimise two-dimensions (optimise bin boundaries in both dimensions simultaneously).
- Unchanged: don't use lowest likelihood bins (reflection backgrounds, no sensitivity gain).



# Impact of new binning optimisation

- Removal of tiny bins which contribute negligible sensitivity.
- Colour: limit obtained, using only this particular bin.
- Number: rank of that bin (1=best sensitivity bin).

Bin sensitivity (2011 data)



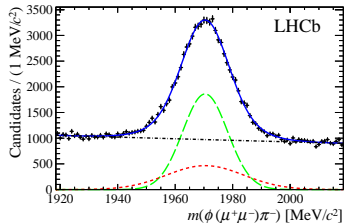
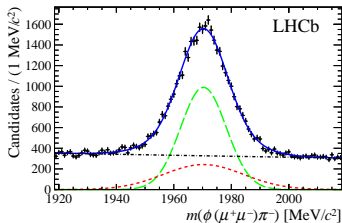
University of Zurich<sup>ZH</sup>



# Mass shape

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

$$\sigma_{data}^{\tau} = \frac{\sigma_{MC}^{\tau}}{\sigma_{MC}^{D_s}} \times \sigma_{data}^{D_s}$$



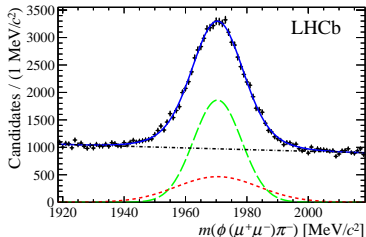
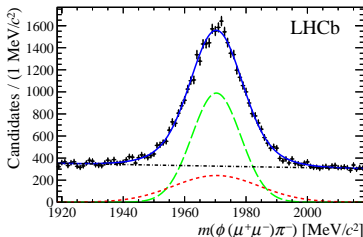
Calibrated $\tau$ Mass shape	7 TeV	8 TeV
Mean (MeV)	$1779.1 \pm 0.1$	$1779.0 \pm 0.1$
$\sigma_1$ (MeV)	$7.7 \pm 0.1$	$7.6 \pm 0.1$
$\sigma_2$ (MeV)	$12.0 \pm 0.8$	$11.5 \pm 0.5$



# Relative normalisation

$$\mathcal{B}(\tau \rightarrow \mu\mu\mu) = \frac{\mathcal{B}(D_s \rightarrow \phi\pi)}{\mathcal{B}(D_s \rightarrow \tau\nu_\tau)} \times f_{D_s}^\tau \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}} = \alpha \times N_{\text{sig}}$$

- where  $\varepsilon$  stands for trigger, reconstruction, selection,
- $f_{D_s}^\tau$  is the fraction of  $\tau$  coming from  $D_s$ ,
- norm = normalisation channel  $D_s \rightarrow \phi\pi$   
i.e.  $(83 \pm 3)\%$  for 2012.



# Normalisation in numbers I

	7 TeV	8 TeV
$\epsilon_{\text{sig}}^{\text{GEN}} (\%)$	$8.989 \pm 0.40$	$9.21 \pm 0.35$
$\epsilon_{\text{cal}}^{\text{GEN}} (\%)$	$11.19 \pm 0.34$	$11.53 \pm 0.32$
$\epsilon_{\text{sig}}^{\text{REC,isMuon,SEL}} (\%)$	$9.927 \pm 0.028$	$9.261 \pm 0.023$
$\epsilon_{\text{cal}}^{\text{REC,isMuon,SEL}} (\%)$	$7.187 \pm 0.022$	$6.690 \pm 0.022$
$\frac{c_{\text{cal}}^{\text{track}}}{c_{\text{sig}}^{\text{track}}}$	$0.997 \pm 0.009 \pm 0.026$	$0.996 \pm 0.009 \pm 0.026$
$\frac{c_{\text{cal}}^{\mu\text{ID}}}{c_{\text{sig}}^{\mu\text{ID}}}$	$0.9731 \pm 0.0031 \pm 0.0264$	$1.0071 \pm 0.0022 \pm 0.0204$
$c^{\phi}$	$0.98 \pm 0.01$	
$c^{\tau}$	$1.032 \pm 0.006$	$1.026 \pm 0.006$
$c^{\text{trash}}$	$1.89 \pm 0.12$	$1.96 \pm 0.12$
$\epsilon_{\text{sig}}^{\text{TRIG}} (\%)$	$35.52 \pm 0.14 \pm 0.14$	$39.3 \pm 1.7 \pm 2.0$
$\epsilon_{\text{cal}}^{\text{TRIG}} (\%)$	$23.42 \pm 0.14 \pm 0.09$	$20.62 \pm 0.76 \pm 1.07$



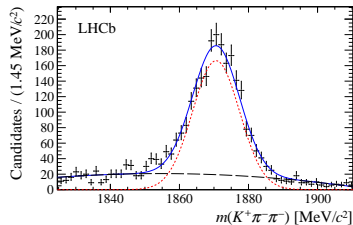
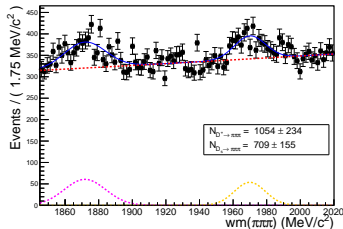
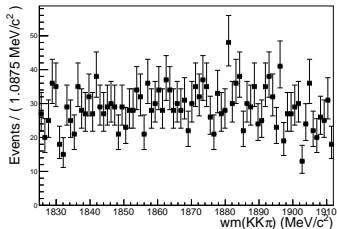
# Normalisation in numbers II

	7 TeV	8 TeV
$\mathcal{B}(D_s \rightarrow \phi\pi)$	$(1.317 \pm 0.099) \times 10^{-5}$	
$f_{D_s}^r$	$0.78 \pm 0.04$	$0.80 \pm 0.03$
$\mathcal{B}(D_s \rightarrow \tau\nu_\tau)$	$0.0561 \pm 0.0024$	
$\epsilon_{\text{cal}}^{\text{REC\&SEL}} / \epsilon_{\text{sig}}^{\text{REC\&SEL}}$	$0.898 \pm 0.060$	$0.912 \pm 0.054$
$\epsilon_{\text{cal}}^{\text{TRIG}} / \epsilon_{\text{sig}}^{\text{TRIG}}$	$0.6593 \pm 0.0058$	$0.525 \pm 0.040$
$N_{\text{cal}}$	$28,207 \pm 440$	$52,131 \pm 695$
$\alpha$	$(3.81 \pm 0.46) \times 10^{-9}$	$(1.72 \pm 0.23) \times 10^{-9}$
$\alpha^{\text{trash}}$	$(7.20 \pm 0.98) \times 10^{-9}$	$(3.37 \pm 0.50) \times 10^{-9}$



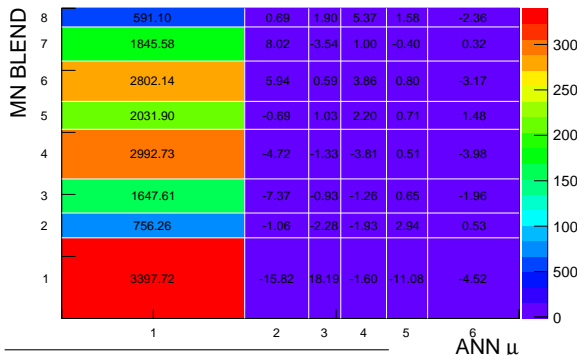
# Misidentification 1

- Most dominant:  $D^+ \rightarrow K\pi\pi$ .
- Also seen  $D^+ \rightarrow \pi\pi\pi$  and  $D_s \rightarrow \pi\pi\pi$ .
- Looked in all mass hypothesis combinations.



# Misidentification 2

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

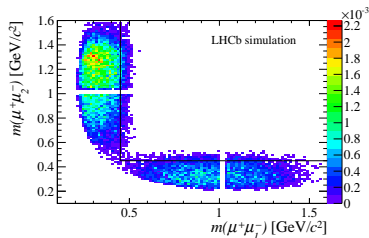
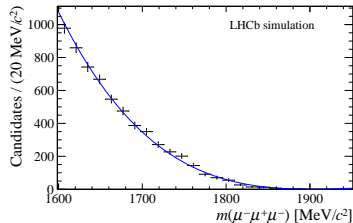


<sup>1</sup> Lowest  $ProbNN\mu$  and  $M_{blend}$  bins, not taken for limit calculation.



# Dangerous backgrounds

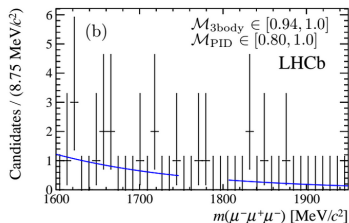
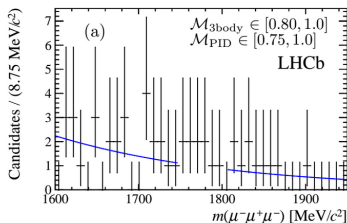
- $\phi \rightarrow \mu\mu + X$ : narrow veto on dimuon mass.
- $D_s \rightarrow \eta(\mu\mu\gamma)\mu\nu_\mu$ : not so easy:
  - Modelled in CONF note.
  - Optimised veto in PAPER.
  - Both versions in the ANA note.
- Baseline: veto  $m_{\mu^+\mu^-} < 450$  MeV:
  - Fits better understood.
  - Sensitivity unchanged when removing veto.
  - Smaller uncertainty on expected background.



# Remaining backgrounds

- Fit exponential to invariant mass spectrum in each likelihood bin.
  - Don't use blinded region ( $\pm 30$  MeV).
- Compatible results blinding only  $\pm 20$  MeV<sup>2</sup>

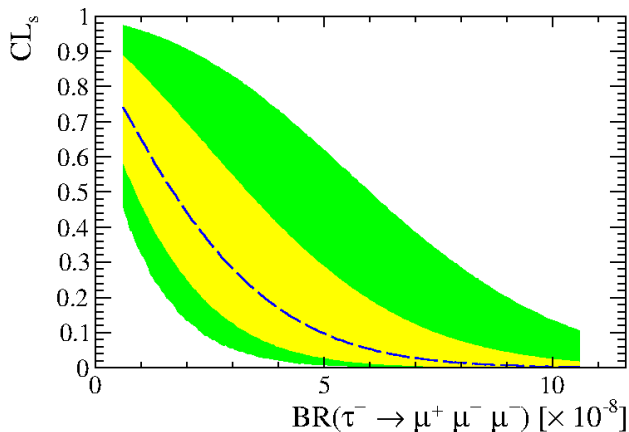
Example of most sensitive regions in 2011 and 2012



<sup>2</sup>partially used in classifier development

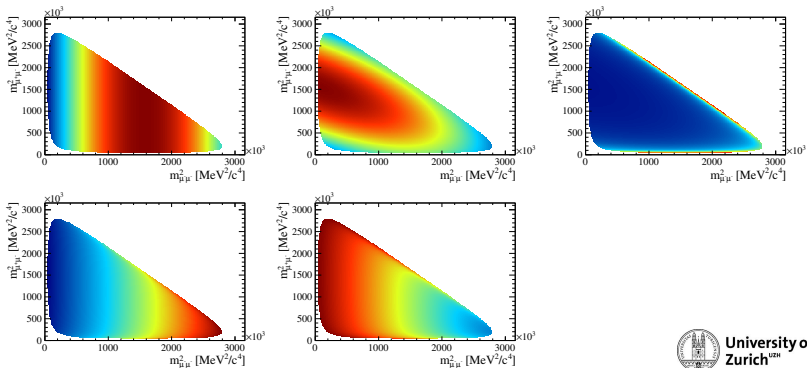
- Consider nuisance parameters from background fit, signal pdf calibration, normalisation.
- Nuisance parameters due to  $\tau$  production, normalization.
- Limit for combined 2011+2012 analysis.

$\mathcal{B}(\tau \rightarrow \mu\mu\mu) < 5.0 \times 10^{-8}$  at 90% CL



# Model dependence

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



# Model dependence

- $\eta$  veto  $\Rightarrow$  our limit not constraining to New Physics with small  $m_{\mu^+\mu^-}$ .
- Model description in [arXiv:0707.0988](https://arxiv.org/abs/0707.0988).
- 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  $\eta$  veto).
- The other four Dalitz distributions behave nicely (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. " <sup>a</sup>

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<sup>a</sup>E.Dickinson

On Monday 4<sup>th</sup> 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	$3.172 \pm 0.661$	4
0.4, 0.45	0.32, 0.46	$9.242 \pm 1.129$	6
0.4, 0.45	0.46, 0.54	$2.894 \pm 0.632$	6
0.4, 0.45	0.54, 0.65	$3.173 \pm 0.661$	4
0.4, 0.45	0.65, 0.80	$3.637 \pm 0.716$	2
0.4, 0.45	0.80, 1.0	$3.787 \pm 0.802$	3
0.45, 0.54	0.28, 0.32	$4.223 \pm 0.779$	6
0.45, 0.54	0.32, 0.46	$8.345 \pm 1.077$	10
0.45, 0.54	0.46, 0.54	$2.317 \pm 0.568$	4
0.45, 0.54	0.54, 0.65	$2.828 \pm 0.632$	8
0.45, 0.54	0.65, 0.80	$2.718 \pm 0.688$	5
0.45, 0.54	0.80, 1.00	$4.825 \pm 0.900$	7

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





# Unblinding 3

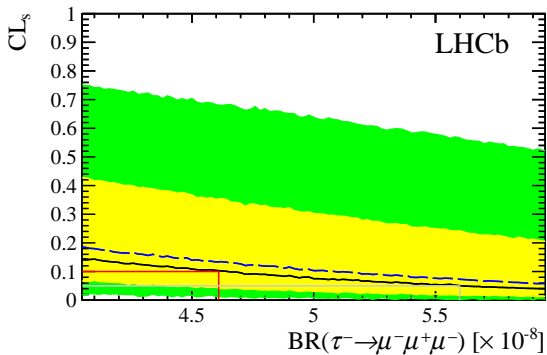
- Unfortunately no big "revelations" were either in 2012 data:

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

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



# Unblinding 4



Limits(PHSP):

Observed(Expected)

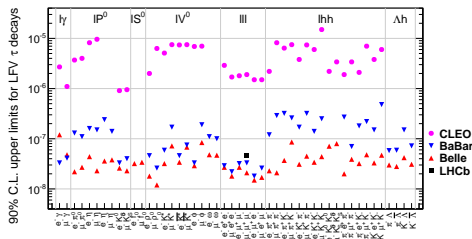
$4.6 (5.0) \times 10^{-8}$  at 90% CL

$5.6 (6.1) \times 10^{-8}$  at 95% CL

Dalitz distribution	$\times 10^{-8}$
$\rho_{V}^{(LL)(LL)}$	4.2 (4.7)
$\rho_{V}^{(LL)(RR)}$	4.1 (4.6)
$\rho_{V}^{(LR)}$	6.8 (7.6)
$\rho_{rad}^{(LL)(LL)}$	4.4 (5.1)
$\rho_{mix}^{(LL)(RR)}$	4.6 (5.0)
$\rho_{mix}$	

# Conclusions

- We didn't find NP (yet).
- Limits set with full LHCb dataset.
- We wait for the Run 2 dataset!



- We would like to thank our referees for very friendly, thorough and fruitful review.
- With this presentation we ask collaboration for approval.