Lepton Flavour Violation at τ decays

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FCC WG on experiments with the CERN injectors

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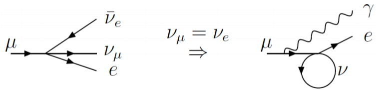
Outline

Lepton Flavour/Number Violation

Lepton Flavour Violation(LFV):
After μ^- was discovered (1936) it was natural to think of it as an excited e$^-$.



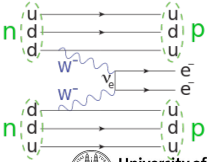
- Expected: $B(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another ν, in intermediate vector boson loop, cancels.

I.I.Rabi:

"Who ordered that?"

- Up to this day charged LFV is being searched for in various decay modes.
- LFV was already found in neutrino sector (oscillations).

Lepton Number Violation (LNV)

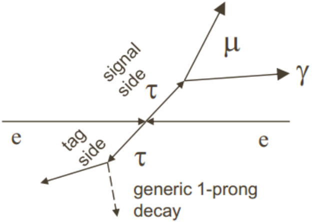


- Even with LFV, lepton number can be a conserved quantity.
- Many NP models predict it violation (Majorana neutrinos)
- Searched in so called Neutrinoless double β decays.

LFV at B-factories

$\sigma(e^-e^+ \to \tau^+\tau^-) = 0.919$ nb

- Clean environment.



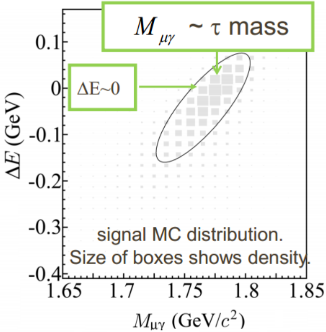
- High efficiency: $5 - 10\%$
- Background free.
- Efficient and simple tag.

Signal extraction:

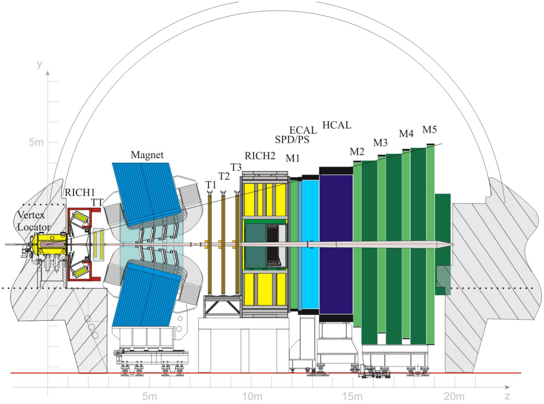
$$M_{\mu\gamma} = \sqrt{(E^{CM}_{sig})^2 - (p^{CM}_{sig})^2}$$

$$\Delta E = E^{CM}_{sig} - E^{CM}_{beam}$$

$$H_l = \sum_{ij} \frac{|\vec{p_j}||\vec{p_i}|P_l(\cos\Omega_{ij})}{s}$$



Hadron collider - LHCb



LHCb is a forward spectrometer:

- Excellent vertex resolution.
- Efficient trigger.
- High acceptance for τ and B.
- Great Particle ID

Analysis approach

B factories

1. Clean signal: $e^+e^- \rightarrow \tau^+\tau^-$
2. Calculate the thrust axis
3. "Partial tag" of the other τ
4. Small cross section $0.919nb$

LHCb, ($7-8TeV$, 2011-2012 data)

1. Inclusive τ cross section: ~ 80μb.
2. $\sim 10^{11}\tau$ produced.
3. Dominant contribution: $D_s \rightarrow \tau\nu_\tau$ (78%)
4. No tag possible.

Strategy

- Blind analysis.
- Loose selection.
- Multivariate classification in: mass, PID($\mathcal{M}_{PID}$), geometry($\mathcal{M}_{3body}$).
- Binning optimisation.
- Consider 2012(8 TeV) and 2011(7 TeV) data separately.
- Relative normalisation ($D_s \to \phi(\mu\mu)\pi$).
- 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 MeV $< |m - m_\tau| <$ 30 MeV).
- CLs for limit calculation.

τ production

- 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 $D^+ \to \tau$	$0.18 \pm 0.04\,\%$	$0.17 \pm 0.04\,\%$
$X_b \to \tau$	$15.5 \pm 2.7\,\%$	$14.7 \pm 2.3\,\%$

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

- 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[1]
- $\mathcal{O}(100)$ trigger lines.
- Lines change with data taking.
- Optimized choice of triggers based on $\frac{s}{\sqrt{b}}$ FOM.
- Evaluated different triggers used in 2012 data taking.
- Found negligible differences in trigger efficiencies.

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[1] arxiv 1211.3055

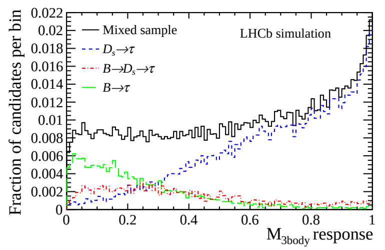
Geometric likelihood

- 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!

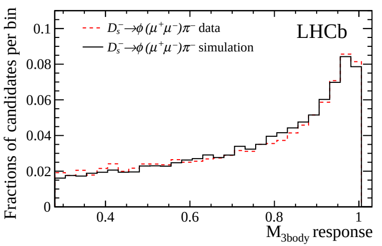
Performance of Blend classifier

- Classifier prefers τ's from prompt $\mathrm{D_s}$, the dominant channel.

MC response for different τ production channels



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



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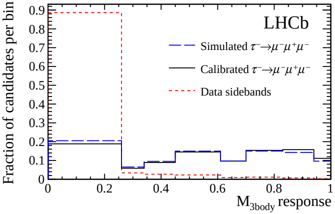
Calibration

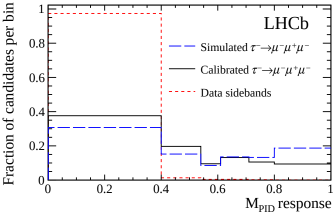
- Assume all differences between $\tau \to \mu\mu\mu$ and $\mathrm{D_s} \to \phi\pi$ come from kinematics (mass, resonance, decay time), which is correct in MC.
- Get correction $\mathrm{D_s} \rightsquigarrow \tau$ from MC.
- Apply corrections to $\mathrm{D_s} \to \phi\pi$ on data.



- $\mathrm{D_s} \to \phi\pi$ well modelled in MC.

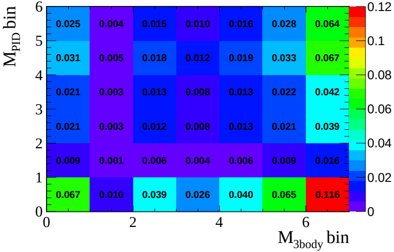
PID

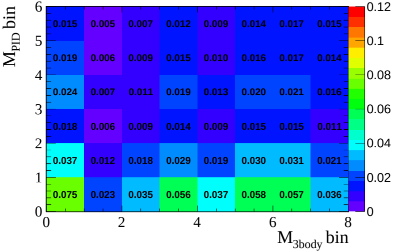
- Classifier trained on inclusive MC sample.
- Using information from: RICH, Calorimeters, Muon system and tracking.
- Correct for the MC efficiency using control channel: $D_s \to \phi(\mu\mu)\pi$ and $B \to J/\psi(\mu\mu)K$



Binning optimisation

- Events are distributed among $\mathcal{M}_{3body}, \mathcal{M}_{PID}$ plane.
- In 2D we group the events in groups(bins)
- Bins are optimised using CL_s method.
- The lowest bins are rejected, because they do not contribute to the limit sensitivity.
- In the remaining bins a fit to mass side-bands is performed in order to estimate number of expected background in signal window.

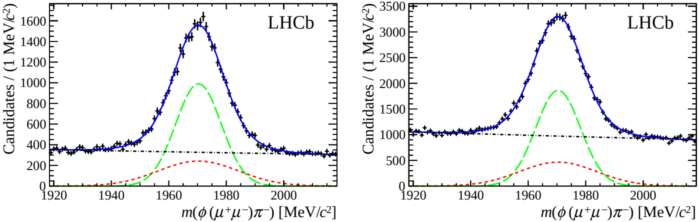

2011


2012

Mass shape

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

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

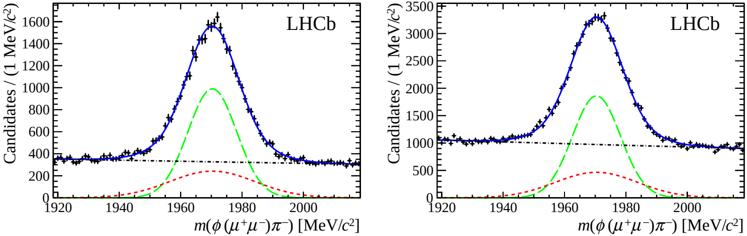


Calibrated τ Mass shape	7 TeV	8 TeV
Mean (MeV)	1779.1 ± 0.1	1779.0 ± 0.1
σ_1 (MeV)	7.7 ± 0.1	7.6 ± 0.1
σ_2 (MeV)	12.0 ± 0.8	11.5 ± 0.5

Relative normalisation

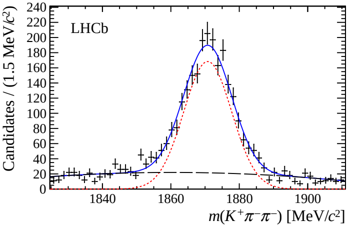
$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\mathcal{B}(\mathrm{D_s}\to\phi\pi)}{\mathcal{B}(\mathrm{D_s}\to\tau\nu_\tau)} \times f^{\tau}_{\mathrm{D_s}} \times \frac{\varepsilon_{\mathrm{norm}}}{\varepsilon_{\mathrm{sig}}} \times \frac{N_{\mathrm{sig}}}{N_{\mathrm{norm}}} = \alpha \times N_{\mathrm{sig}}$$

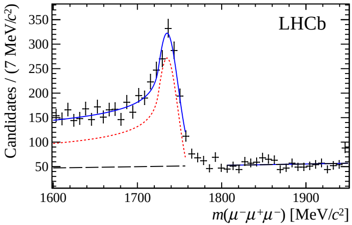
- where ε stands for trigger, reconstruction, selection efficiency.
- $f^{\tau}_{\mathrm{D_s}}$ is the fraction of τ coming from $\mathrm{D_s}$.
- norm = normalisation channel $\mathrm{D_s} \to \phi\pi$
  i.e. $(83 \pm 3)\,\%$ for 2012.

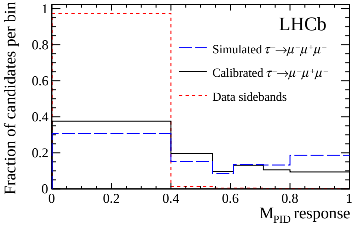


Misidentification

- 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.

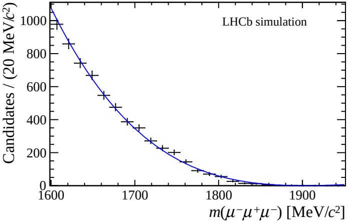


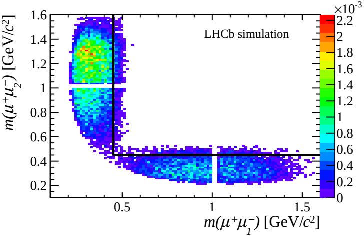




Dangerous backgrounds

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



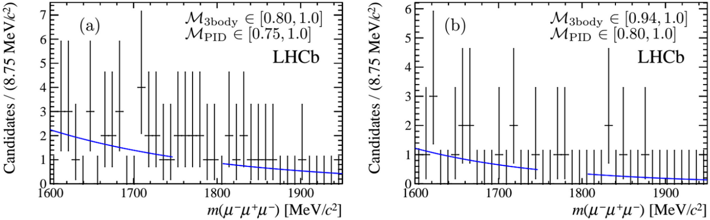


Remaining backgrounds

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

→ Compatible results blinding only ±20 MeV[2]

Example of most sensitive regions in 2011 and 2012



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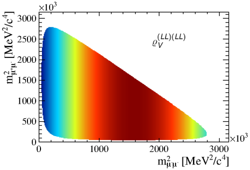
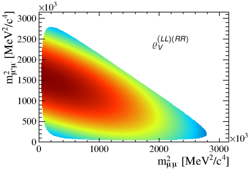
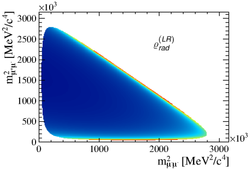
[2] partially used in classifier development

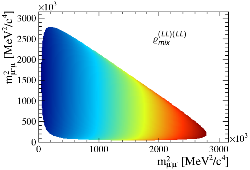
Model dependence

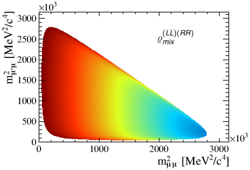
- η veto $\Rightarrow$ our limit not constraining to New Physics with small $m_{\mu^+\mu^-}$.
- Model description in arXiv:0707.0988 by S.Turczyk.
- 5 relevant Dalitz distributions: 2 four-point operators, 1 radiative operator, 2 interference terms.











Model dependence

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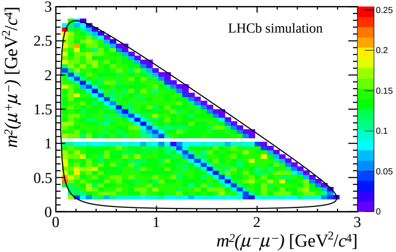
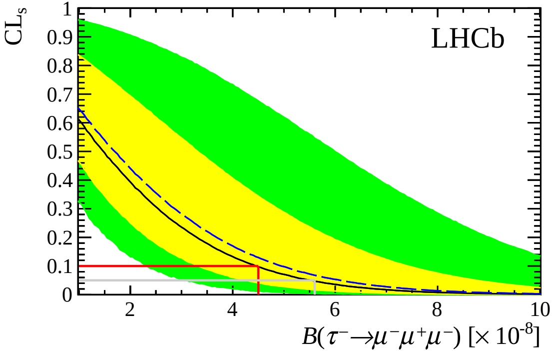
- Model description in `arXiv:0707.0988` by S.Turczyk.
- 5 relevant Dalitz distributions: 2 four-point operators, 1 radiative operator, 2 interference terms.

- With radiative distribution limit gets worse by a factor of 1.5 (dominantly from the η veto).
- The other four Dalitz distributions behave nicely (within 7 %).



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)

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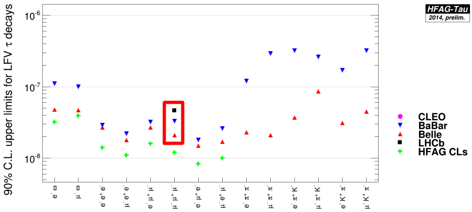
"The Rule of Three"

$\tau \to \mu\mu\mu$ 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}



From A.Lusiani talk

To conclude:

- LHCb updated $\tau \to \mu\mu\mu$ with full data set.
- We are getting close to B-factories.
- Thanks to 3 experiments we have a world limit: $\mathcal{B}(\tau \to \mu\mu\mu) < 1.2 \times 10^{-8}$ at 90% CL.

Future of $\tau \to 3\mu$ at hadron colliders.

More nasty background

D_s^+ decay	$\mathcal{B}_1^{(*)}$	Secondary decays	$\mathcal{B}_2$	$\mathcal{B}_{\text{tot}} = \mathcal{B}_1 \times \mathcal{B}_2$
$\eta\mu^+\nu_\mu$	2.67×10^{-2}	$\eta \to \mu^+\mu^-$	5.8×10^{-6}	1.5×10^{-7}
		$\eta \to \mu^+\mu^-\gamma$	3.1×10^{-4}	8.2×10^{-6}
		$\eta \to \pi^0\mu^+\mu^-\gamma$	$< 3 \times 10^{-6}$	$< 8.0 \times 10^{-8}$
$\eta'\mu^+\nu_\mu$	9.9×10^{-3}	$\eta' \to \mu^+\mu^-\gamma$	1.09×10^{-4}	1.1×10^{-6}
$\phi\mu^+\nu_\mu$	2.49×10^{-2}	$\phi \to \mu^+\mu^-$	2.87×10^{-4}	7.1×10^{-6}
		$\phi \to \mu^+\mu^-\gamma$	1.4×10^{-5}	3.5×10^{-7}
		$\phi \to \mu^+\mu^-\pi^0$	$1.12 \times 10^{-5}(\dagger)$	2.8×10^{-7}

(∗) : given branching ratios are from corresponding $e\nu_e$ decays

(†) : given branching ratio is from $\phi \to e^+e^-\pi^0$ decays

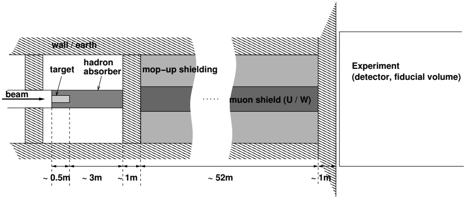
More nasty background

D^+ decay	$\mathcal{B}_1^{(*)}$	Secondary decays	$\mathcal{B}_2$	$\mathcal{B}_{\text{tot}} = \mathcal{B}_1 \times \mathcal{B}_2$
$\eta\mu^+\nu_\mu$	1.14×10^{-3}	$\eta \to \mu^+\mu^-$	5.8×10^{-6}	6.6×10^{-9}
		$\eta \to \mu^+\mu^-\gamma$	3.1×10^{-4}	3.5×10^{-7}
		$\eta \to \pi^0\mu^+\mu^-\gamma$	$< 3 \times 10^{-6}$	$< 3.4 \times 10^{-9}$
$\eta'\mu^+\nu_\mu$	2.2×10^{-4}	$\eta' \to \mu^+\mu^-\gamma$	1.09×10^{-4}	2.4×10^{-8}
$\omega\mu^+\nu_\mu$	1.6×10^{-3}	$\omega \to \mu^+\mu^-$	9.0×10^{-5}	1.4×10^{-7}
		$\omega \to \mu^+\mu^-\pi^0$	1.3×10^{-4}	2.1×10^{-7}
$\rho^0\mu^+\nu_\mu$	2.4×10^{-3}	$\rho^0 \to \mu^+\mu^-$	4.55×10^{-5}	1.1×10^{-7}
$\phi\mu^+\nu_\mu$	$< 9 \times 10^{-5}$	$\phi \to \mu^+\mu^-$	2.87×10^{-4}	2.6×10^{-8}

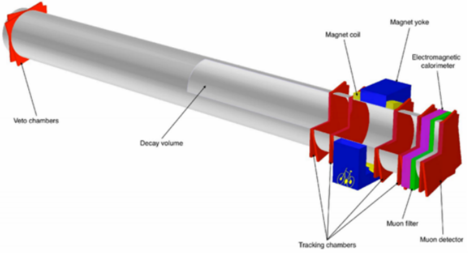
($*$) : given branching ratios are from corresponding $e\nu_e$ decays

(†) : given branching ratio is from $\phi \to e^+e^-\pi^0$ decays

LFV at SHIP experiment



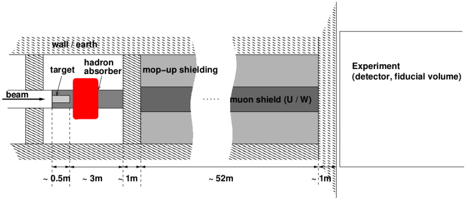
- Beam dump experiment from SPS.
- Designed to study long living particles e.g.. HNL.
- Main interest are particles coming from charm decays.
- Charm decays are also an excellent source of τ decays: $Br(\mathrm{D}_{\mathrm{s}}^{+} \to \tau^{+}\nu_{\tau}) = (5.6 \pm 0.4)\%$



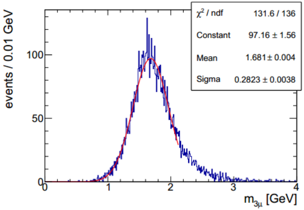
LFV at SHIP experiment: Idea 1

- Put a specific $\tau \to 3\mu$ detector just after the target.
- Huge number of τ produced: 1.2×10^{15}!
- The numbers are very encouraging!
- What is the mass resolution?

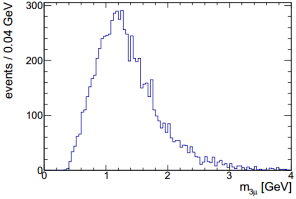
Based on SHIP $\tau \to 3\mu$ WG:
L.Shchutska, G.Mitselmakher, J.Harrison, C.Parkes, N.Serra, E. Rodrigues, B.Storaci, A.Golutvin ,M.Chrząszcz



Tungsten 50 cm

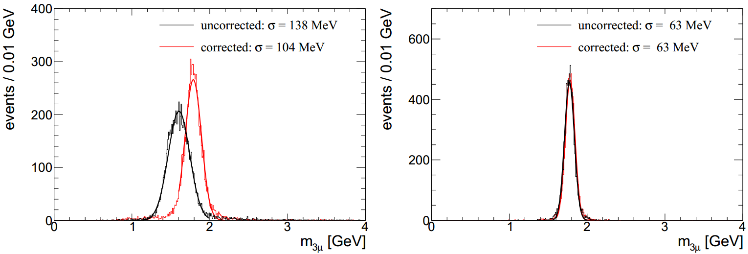


Carbon ($\sim 30\lambda_h$)



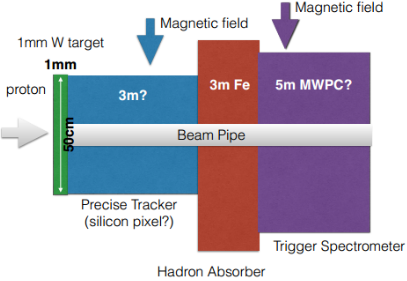
Momentum correction

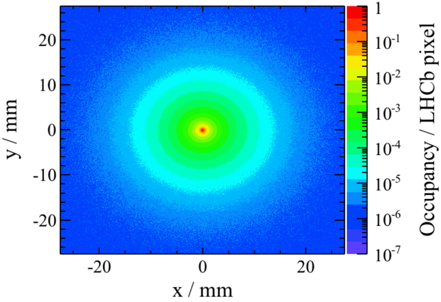
Carbon ($\sim 5\lambda_h$) **Tungsten 1cm**



- With correction of momentum after the target the resolution is better.
- However still not good enough to perform this measurement.
- Conclusions: momentum of the muons needs to be measured before absorber and on thin target.

LFV at SHIP experiment: Idea 2





- Multiple scattering is negligible.
- τ vertex outside the target.
- Reduce τ flux by a factor of 100.
- First estimate of sensor radius :$\sim$ 2.5 mm
- Evaluated acceptance: 33%
- Work ongoing.

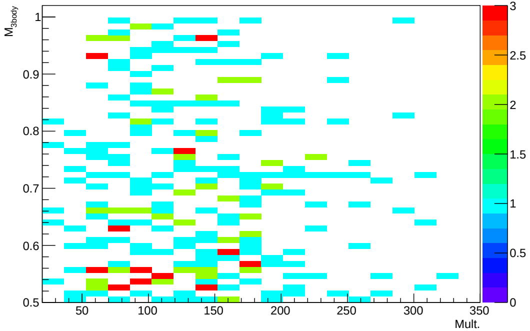
LFV at injectors for FCC

- First thought: Detector similar to LHCb.
- Lets try to make „zero approximation” using LHCb analysis.
- Ingredients:
  - Acceptance:$\sim$ 10 %.
  - Pre-Selection and tracking:$\sim$ 10 %.
  - Trigger:$\sim$ 40 %.
  - Selection(trash bins):$\sim$ 50 %.
  - In total: 0.2 %.
- Not bad so far!

Observation:

The total efficiency can be increased by factor $2-5$ if detector is optimised for τ's.

LFV at injectors for FCC - Pileup



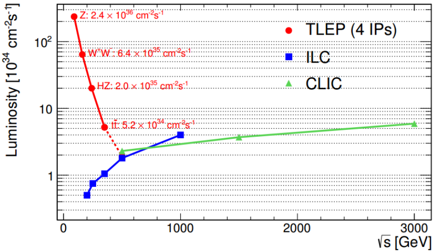
- Not clear correlation with multiplicity.
- Good for pile-up increase.

Observation:

Pile up in LHCb regime is not a problem.

LFV at injectors for FCC - Idea to shoot at

- Let's assume that FCC will be a $e^{-}e^{+}$ collider.
  LHC tunnel - $e^{-}e^{+}$ booster.
- We would collect 10^{12-13} Z decays.
- $Br(Z \to \tau^{-}\tau^{+}) = 3.370 \pm 0.008\%$.
- Number of τ: $6.7 \times 10^{10-11}$.



LFV at injectors for FCC - Idea to shoot at

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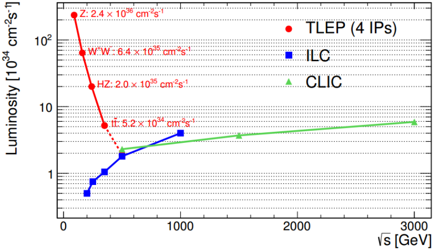
- $Br(Z \to \tau^- \tau^+) = 3.370 \pm 0.008\%$.
- Number of τ: $6.7 \times 10^{10-11}$.
- Belle2: $50 ab^{-1} \times 2 \times 0.919 nb = 9.2 \times 10^{10}$ τ's



Reminder:

- $\epsilon^{BaBar}_{\tau \to 3\mu} = 6.6 \pm 0.6\%$
- $\epsilon^{Belle}_{\tau \to 3\mu} = 7.6 \pm 0.6\%$
- $\epsilon^{ALEPH}_{\tau} = \sim 50\%$

- There is a factor of 8 to gain just in efficiency!

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LFV at injectors for FCC - Idea to shoot at

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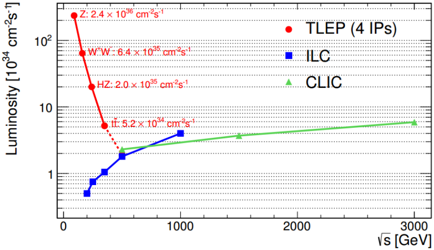
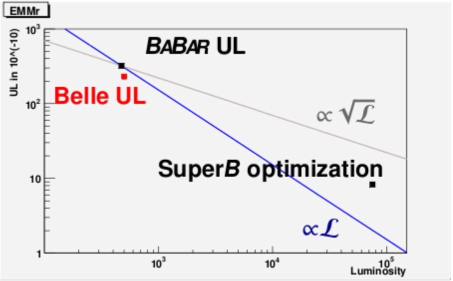




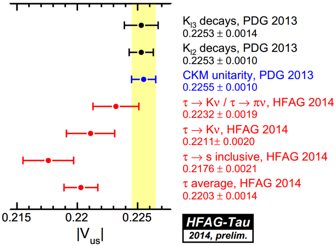
Reminder 2:

- In e^-e^+ machines in contrast to hadron colliders the limit doesn't necessary follow $\sqrt{\mathcal{L}}$.
- Another factor to gain.

Beyond LFV

τ's at hadron collider have limit use! At e^-e^+ we get for free:

- All LFV(at hadron colliders most decays are not possible).
- V_{us} from τ.
- Lepton universality tests (anomally from LEP):
  $$\frac{2BR(\mathrm{W}\to\tau\nu_\tau)}{BR(\mathrm{W}\to\mu\nu_\mu)+BR(\mathrm{W}\to e\nu_\mathrm{e})}=1.077(0.026).$$
- Hadronic spectral functions.
- etc.



Conclusions

- LFV is possible at hadron machines!
- LHCb already caught up with B-factories.
- In future there are many different possibilities for τ factories.
- Many studies ongoing.