Search for the LFV Decay $\tau \to \mu\mu\bar{\mu}$ with the ATLAS Detector

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Outline

1. Introduction and Current Upper Limit
2. Sources of τ-Leptons at LHC and their Cross-Sections
3. How to Trigger on these Events?
4. Background to $\tau \rightarrow \mu\mu\mu$ from Heavy Mesons
5. Cut-Flow Analysis
6. Summary and Plans

$\tau \to \mu\mu\mu$ Decay

Possible Models and BR's

model, processes	**BR($\tau \to \mu\mu\mu$)**	**reference**
Neutral SUSY Higgs	10^{-7}	hep-ph/0304081
Non universal Z' (technicolor)	10^{-8}	PLB547(2002)252
mSUGRA + seesaw	10^{-9}	hep-ph/0206110
SUSY SO(10) + seesaw	10^{-10}	hep-ph/0405017
SM + heavy Majorana neutrino	10^{-10}	PRD66(2002)034008
Littlest Higgs with T-Parity	10^{-12}	hep-ph/0702136
SM+neutrino oscillations	10^{-14}	hep-ph/9819484

Experimental upper limit:
BaBar: $5.3 \cdot 10^{-8}$(in PDG)
Belle: $3.2 \cdot 10^{-8}$(in PDG[1]), $2.1 \cdot 10^{-8}$(Preliminary)

Which sensitivity can be reached with ATLAS ?

[1] Will be used to normalize the number of signal events

τ Production at LHC

Channel	$W \rightarrow \tau\bar{\nu}_\tau$	$Z \rightarrow \tau^+\tau^-$	$B^\pm/B^0/B^0_s$	$D^\pm_s$
Cross Section	17.2 nb	1.7 nb	$120 \cdot 10^3$ nb	$20 \cdot 10^3$ nb
exp. τ (10 fb^{-1})	$2 \cdot 10^8$	$3 \cdot 10^7$	$1 \cdot 10^{12}$	$2 \cdot 10^{11}$
max. $\tau \rightarrow 3\mu$	6	1	32000	6400

Cross-Section Calculation

- All cross-sections from `Pythia 6.420` for 14 TeV collisions.
- Special tuning for heavy meson production from ATLAS B-physics group (PythiaB).

Most τ's from B- and D-meson decays, but:

- High background from μ's from jets expected in meson channels
- Numbers are not too meaningful yet, as the detector acceptance has to be taken into account.

Signal Generation & Detector Acceptance

On Generator Level

- Code for $\tau \to \mu\mu\mu$ decay developed and included in ATLAS software.
  $\to$ Pure phase space decay
  $\to$ No spin correlations
- Determine detector acceptance ϵ_{acc} for the various production channels.
- Count events inside the geometrical and trigger acceptance of the detector for a better guess on the number of measurable events

Acceptance criteria (Considering a standard single or di-muon trigger without pre-scaling)

Three Muons
$p_T > 3$ GeV/c, $|\eta| < 2.7$

Two Muons
$p_T > 6$ GeV/c, $|\eta| < 2.4$,

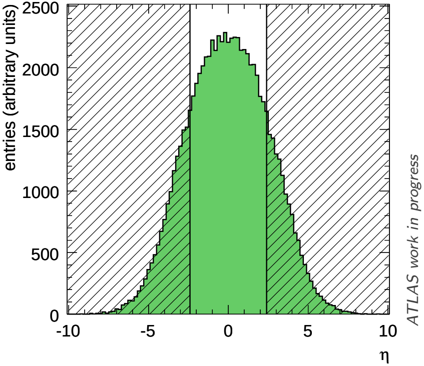
OR

One Muon
$p_T > 20$ GeV/c, $|\eta| < 2.4$

W/Z about 40× heavier then B/D-mesons.
⇒ Different kinematics of produced τ-leptons and muons.

$\eta-$Distributions of the 3 Muons

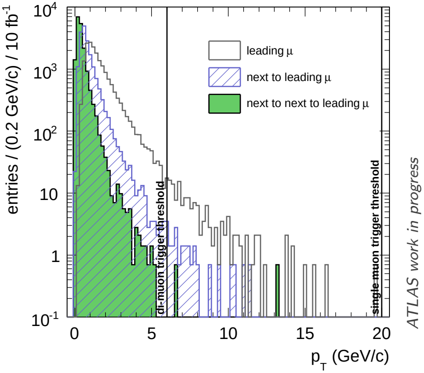
B^0-Source $\qquad$ $W^\pm-$Source



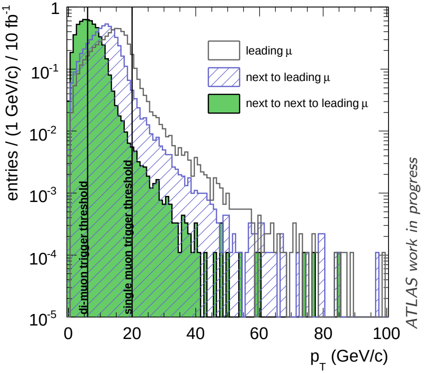
Note: Cut on $b-$quarks ($|\eta| < 4.5$) set in pythia

p_T–Distributions of the 3 Muons

B^0–Source



$W^{\pm}$–Source



(Normalized to 10 fb^{-1}, assuming Br($\tau \rightarrow \mu\mu\mu$)=$3.2 \cdot 10^{-8}$)

Expected Cross-Sections

τ-source	σ_{tot} [nb]	ϵ_{acc}	σ_{acc} [nb]	$N(\tau)/10\ \text{fb}^{-1}$	$N(3\mu)/10\ \text{fb}^{-1}$
$D_s^\pm$	$19.7 \cdot 10^3$	$8.9 \cdot 10^{-4}$	17.5	$17.5 \cdot 10^7$	6
B^0	$56.4 \cdot 10^3$	$7.4 \cdot 10^{-4}$	41.7	$41.7 \cdot 10^7$	13
$B^\pm$	$55.0 \cdot 10^3$	$6.8 \cdot 10^{-4}$	37.4	$37.4 \cdot 10^7$	12
B_s^0	$9.9 \cdot 10^3$	$7.2 \cdot 10^{-4}$	7.13	$7.13 \cdot 10^7$	2
Z^0	1.66	0.56	0.93	$2 \times 0.93 \cdot 10^7$	1
$W^\pm$	17.2	0.51	8.84	$8.84 \cdot 10^7$	3

$\sigma_{tot} = \sigma(pp \to \tau)$, $\sigma_{acc} = \sigma_{tot} \times \epsilon_{acc}$

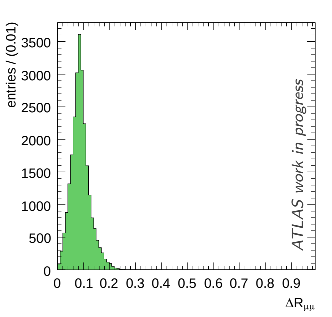
- Cross-sections for the $\tau-$production via meson-decays in the detector acceptance are $\sim 10\times$ larger then from gauge bosons.
- But: Much better background suppression for W/Z-decays expected:
  - Muons are isolated
  - τ's are boosted $\rightarrow$ muons are in a small cone (disadvantage for trigger)
  - W-source: $E_T^{miss}-$signature from ν_τ
  - Z-source: Mass constraint for Z, 'tag and probe'

$\Rightarrow$ Concentration on W-Channel

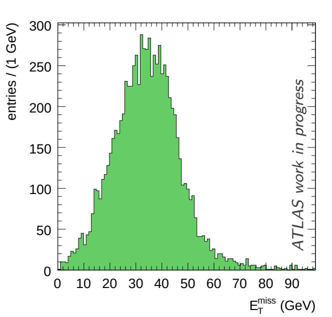
Signal Signature ($W \rightarrow \tau\bar{\nu}_\tau \rightarrow \mu\mu\bar{\mu}\bar{\nu}_\tau$)

- Three isolated μ's with total charge ± 1 and $M_{\mu\mu\mu} = M_\tau$
- τ's are boosted $\Rightarrow$ muons are in a small cone (< 0.2)
- ν_τ implies E_T^{miss}

ΔR of all $\mu-$Pairs

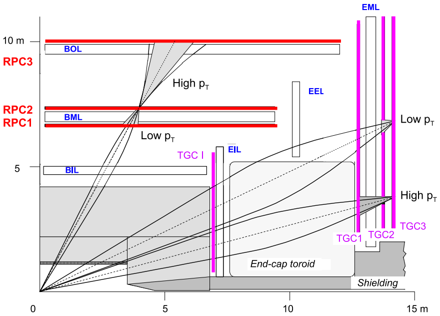


Missing E_T



The ATLAS Muon Trigger

- Level 1 (L1)
  → Hardware decision on muon p_T with fast trigger chambers (RPC, TGC).
  → Separate low- and high-p_T thresholds programmable.
- Level 2 (L2)
  → Fast event reconstruction on computing farm.
  → Also muon precision chambers and inner detector taken into account.
- Event Filter (EF)
  → Refine L2 by offline reconstruction.



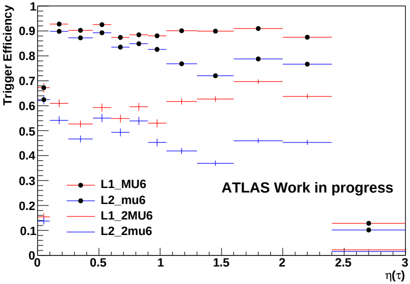
Challenges to Trigger $\tau \to \mu\mu\mu$

Signal muons have low p_T and decays are rare

- → Low-p_T threshold raised successively with increasing LHC lumi ($4 \to 9$ GeV).
- → Single muon trigger will be pre-scaled.
- → '2mu6' might be reasonable for first 10 fb^{-1}.

$\mathscr{L}$ [cm^{-2}s^{-1}]	10^{31}	10^{32}	10^{33}
single μ [GeV]	6	20	20
di-μ [GeV]	2x4	2x6	2x6(?)
tri-μ [GeV]	3x6	3x6	?

Trigger Efficiency vs. $\eta(\tau)$



- Trigger efficiencies calculated with respect to all signal events.
- 2mu6 about 30 % lower then single muon trigger.
- Not fully understood why L2-trigger efficiencies are going down in end-cap ($|\eta| > 1.1$).
- Comparative to $B_s \to \mu\mu$: $\epsilon(\texttt{2mu6}) = 51.6 \pm 0.2\,\%$.

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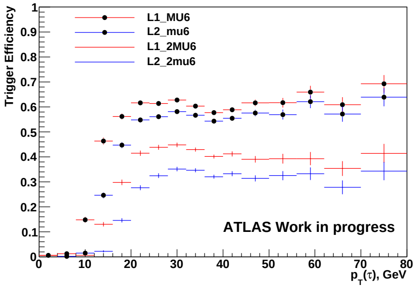
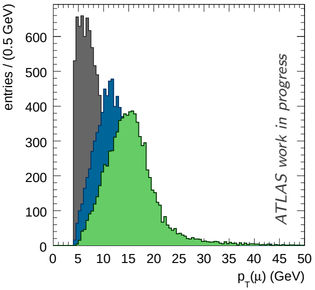
Trigger Efficiency vs. $p_T(\tau)$



Muon Momentum (> 4 GeV/c)



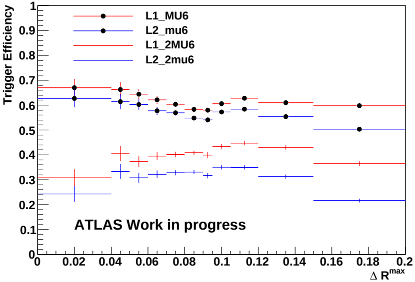
Challenges to Trigger $\tau \to \mu\mu\mu$

Di-muon trigger constrained by L1 resolution

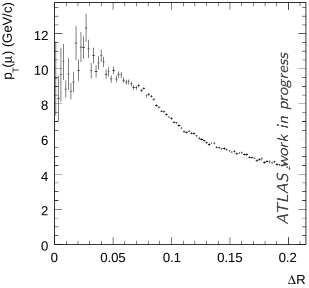
→ Barrel: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

→ End-Caps: $\Delta\eta \times \Delta\phi = 0.03 \times 0.03$

Trigger Efficiency vs. $\Delta R_{\mu\mu}^{max}$



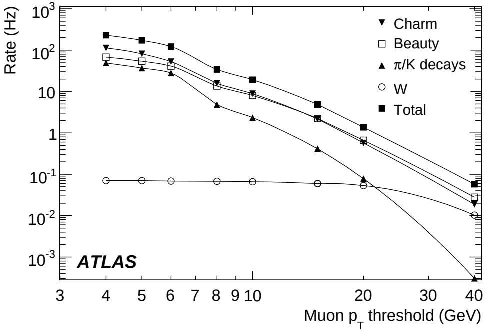
Muon Momentum vs. $\Delta R_{\mu\mu}^{max}$



- Single muon: Efficiency decreasing as ΔR correlated with p_T.
- Di-muon: Efficiency slightly increasing with ΔR.

Background Processes

Muon Sources and Rates for $\mathscr{L} = 10^{31}$ cm^{-2}s^{-1}



Physical Background – Charm

Challenges

- No inclusive $c\bar{c} \to \mu\mu$ sample available in ATLAS.
- Inclusive $c\bar{c} \to \mu\mu\mu$ very time consuming to produce, as the cross-section is small.

⇒ Muon decays have to be forced in the event generation to get some statistics in a reasonable time.

⇒ Private production for 'most dangerous' channels

$c\bar{c}$–Processes

- Look for decay chains with 3 muons in final state:

$$D_s^- \to \phi\mu^-\bar{\nu}_\mu \to \mu^+\mu^-\mu^-\bar{\nu}_\mu$$
$$D_s^- \to \eta\mu^-\bar{\nu}_\mu \to \mu^+\mu^-\gamma\mu^-\bar{\nu}_\mu$$

- Branching ratios of these decay chains are $\sim 10^{-6}$

Physical Background – Beauty

For B-meson decays there are much more possibilities to get 3 muons, e.g.:

$$B_s \to D_s + X$$
$$\quad\quad \hookrightarrow \mu\mu\mu + Y$$

$$B_x \to D_x + \mu + X$$
$$\quad\quad \hookrightarrow \mu\mu + Y$$

$$B^- + B^+$$
$$\quad\quad \hookrightarrow \bar{D}^0 + \mu^+\nu_\mu$$
$$\quad\quad\quad\quad \hookrightarrow \mu^-\bar{\nu}_\mu + K^+$$
$$\hookrightarrow \mu^-\bar{\nu}_\mu + D^0$$

Forcing Decays

- Idea: Produce 6 separate samples, each forcing the muon decays of one meson.
- Neglecting contributions from in-flight K and π decays (decaying in `geant4`).

⇒ Small samples produced, but still to be understood and not presented here.

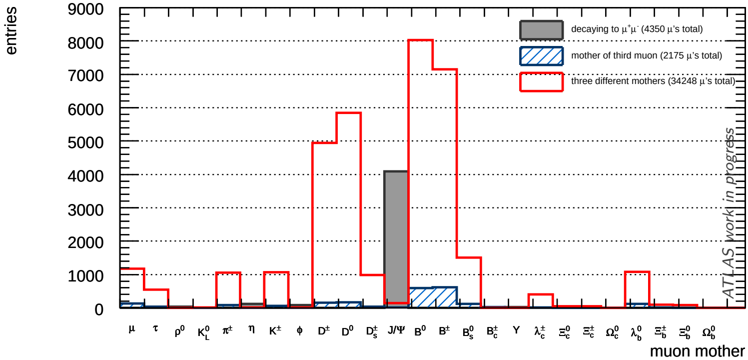
⇒ Inclusive $b\bar{b} \to \mu\mu$ existing and used to determine main backgrounds.

Background Sources

Search for Tri-Muon Processes in Inclusive $b\bar{b} \to \mu\mu$-Sample

- 1 mio. events from official ATLAS production (cross section: 64.5 nb).
- Leading muon: $p_T > 6$ GeV/c, NL muon: $p_T > 4$ GeV/c
- 1.4 % events with three muons > 4 GeV/c.

Muon Sources (corresponds to $\sim$ 20 pb^{-1})



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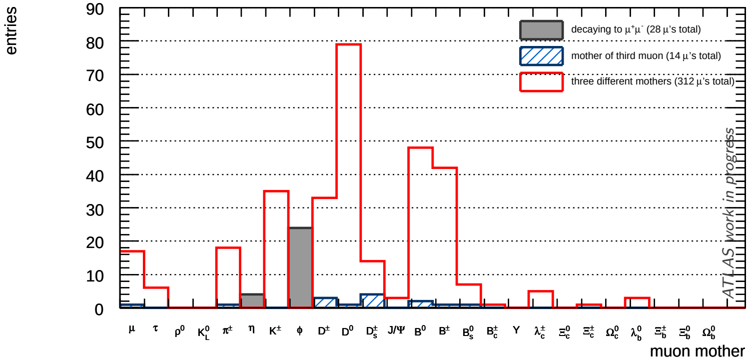
Muon Sources - Signal Region ($\sim$20 pb^{-1})

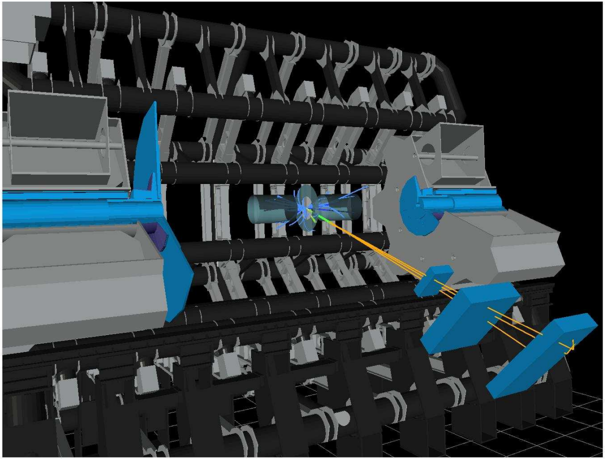


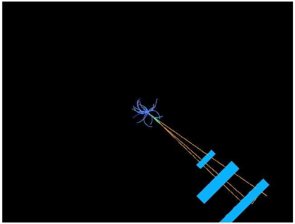
Datasets – Overview

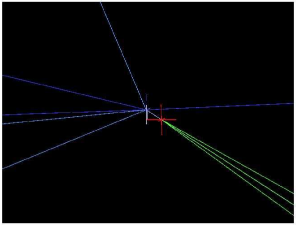
Process	Filter	Filter Eff.	XS[nb]	Events	$\mathscr{L}$ [fb^{-1}]
$b\bar{b} \to \mu\mu$	$\mu_1 > 6, \mu_2 > 4$	–	65.4	1M	0.002
$c\bar{c} \to Ds + X$ $\to \phi\mu\nu \to \mu\mu\mu\nu$	$\mu_{1,2} > 5, \lvert\eta_{1,2}\rvert < 2.5$ $\mu_3 > 3, \lvert\eta_3\rvert < 2.8$	0.02	$4.7 \cdot 10^{-3}$	47K	10
$c\bar{c} \to Ds + X$ $\to \eta\mu\nu \to \mu\mu\mu\nu\gamma$	$\mu_{1,2} > 5, \lvert\eta_{1,2}\rvert < 2.5$ $\mu_3 > 3, \lvert\eta_3\rvert < 2.8$	0.01	$8.1 \cdot 10^{-4}$	45K	55
$W \to \tau\nu_\tau \to \mu\mu\mu$	–	1	$< 5.5 \cdot 10^{-7}$	25K	–

⇒ All events fully simulated and reconstructed with recent software releases.

Analysis



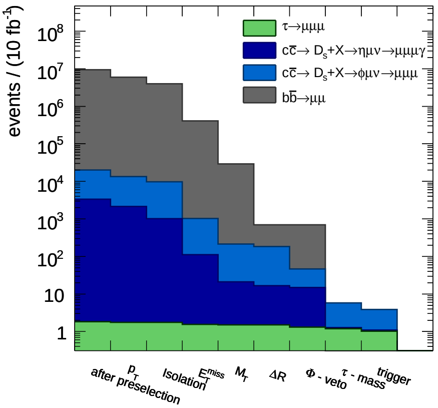




Cutflow

1. Event preselection
2. $2\ p_T^\mu > 6\,$GeV, $1\ p_T^\mu > 4\,$GeV
3. Muon isolation: E_T (cone 0.2) $< 10\,$GeV
4. $E_T^{miss} > 20\,$GeV
5. Transverse mass M_T $(3\mu + E_T^{miss}) > 40\,$GeV (constraint on W mass)
6. ΔR all possible pairs < 0.2
7. Veto on ϕ-mass (1σ window): $1020 \pm 20\,$MeV
8. 3μ invariant mass within 2σ window around $\tau-$mass: $1777 \pm 50\,$MeV
9. Trigger selection

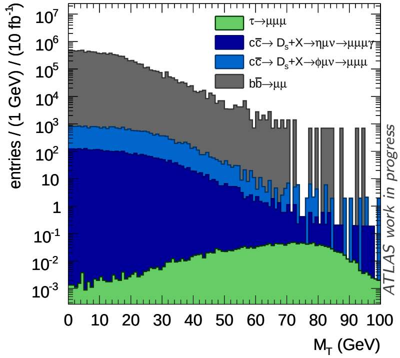
Cut Flow – Scaled to 10 fb^{-1}



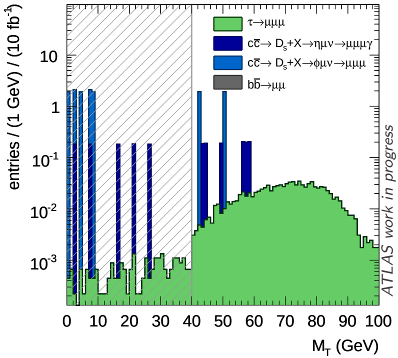
Cut-Variables – Transverse Mass M_T

$$M_T = \sqrt{2 p_T^{3\mu} E_T^{miss} \cdot (1 - \cos \Delta\phi)}$$

After Pre-Selection

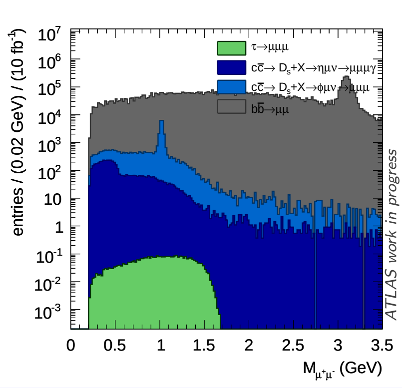


All Cuts Except M_T



Cut-Variables – $M_{\mu\mu}$

After Pre-Selection



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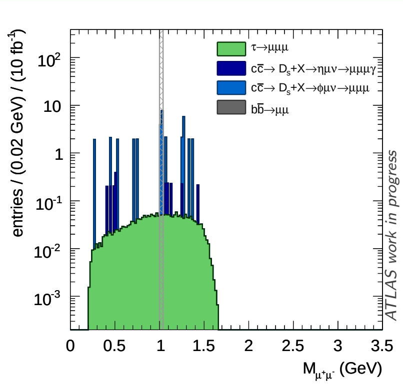

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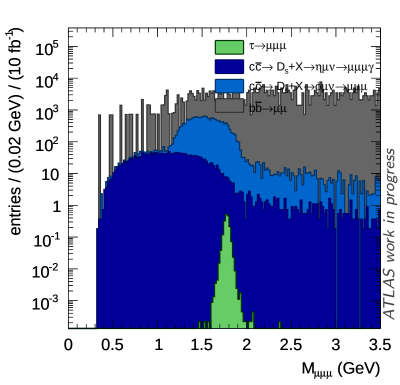

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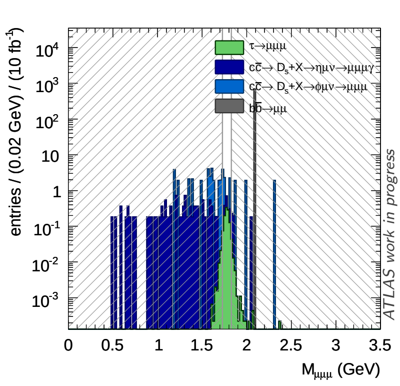

Results

- Total signal efficiency (including detector acceptance): $\epsilon_{sig} = 22\,\%$
- Trigger efficiency on signal after all cuts : $\epsilon_{trig} = 57\,\%$
- Total signal efficiency: $\epsilon_{sig} \times \epsilon_{trig} = 13\%$

$\Rightarrow$ Maximum only ~ 0.8 signal events for 10 fb^{-1}

- Background events surviving: 4.9

Estimation of Upper Limit – Very Preliminary!

- Take number of background events in signal region and calculate Poisson interval with method from Feldman-Cousins (90% CL).

  $\Rightarrow Br(\tau \to \mu\mu\mu) = \frac{\text{UL from Poisson Intervall}}{\text{Number of produced}\tau's \times \epsilon_{sig} \times \epsilon_{trig}}$

- For 10 fb^{-1}:

$$\boxed{Br(\tau \to \mu\mu\mu) < 1.7 \cdot 10^{-7}}$$

- Compare to current UL from Belle: Br$(\tau \to \mu\mu\mu) < 3.2 \cdot 10^{-8}$.

$\Rightarrow$ About 100 fb^{-1} needed at ATLAS.

Summary & Plans

Summary

- Several BSM theories predict LFV τ-decays at accessible magnitudes.
- Triggering on $\tau \to \mu\mu\mu$ is tricky, especially for high LHC-luminosities a dedicated trigger menu seems be unavoidable.
- The code to simulate $\tau \to 3\mu$ decay at ATLAS is in place and working.
- Dedicated $c\bar{c}$-production for the background is done.
- Inclusive $b\bar{b} \to \mu\mu$-sample is very helpful to understand the background, but statistics is low.
- Dedicated $b\bar{b}$ background in preparation.
- No chance to quickly reach current UL from B-factories, at least 100 fb^{-1} will be needed.

Outlook & Plans

- Include systematic uncertainties in the analysis.
- Refit of the secondary vertex, especially to suppress $b\bar{b}-$background.
- Lancaster group recently started to look into the $Z \to \tau\tau$ channel: Promising method to add muon tracks from inner detector only.

B A C K U P

Preselection

- Select combined inner detector / muon spectrometer muons.
- In addition 'low-p_T' muons (inner detector + innermost MS layer)
- 3 muons with $p_T > 4\,$GeV/c and $|\eta| < 2.7$
- Total muon charge ± 1
- If more then one triplet, take the one closer to $\tau-$mass.

Efficiencies

Process	Events	After Selection	Efficiency
$b\bar{b} \to \mu\mu$	1 M	14 K	1.4 %
$c\bar{c} \to D_s\phi \to \mu\mu\mu$	47 K	20 K	43 %
$c\bar{c} \to D_s\eta \to \mu\mu\mu\gamma$	45 K	18 K	40 %
$\tau \to \mu\mu\mu$	25 K	8 K	32 %

Expected τ Cross-Sections at LHC

Meson-Sources

- 1 mio. $b\bar{b}$- and $c\bar{c}$-events generated with `PythiaB`, respectively.
- Used 'pysubs ckin 3 6', $p_T^c > 4$ GeV/c, $p_T^b > 5$ GeV/c, $|\eta| < 4.5$

τ-Source	$\boldsymbol{\sigma_{prod}}$	$\boldsymbol{Br_\tau}$	$\boldsymbol{\sigma_\tau}$	$\boldsymbol{N(\tau)/10\ \text{fb}^{-1}}$
$c\bar{c}$	$5.3 \cdot 10^6$ nb	$7 \cdot 10^{-3}$	$37 \cdot 10^3$ nb	$3.7 \cdot 10^{11}$
$b\bar{b}$	$1.2 \cdot 10^6$ nb	$8.7 \cdot 10^{-2}$	$104 \cdot 10^3$ nb	$1 \cdot 10^{12}$

$\sigma_{prod} = \sigma(pp \to M)$, $Br_\tau = Br(M \to \tau + X)$, $\sigma_\tau = \sigma_{prod} \cdot Br_\tau$

Boson-Sources

- Generated 50k events of $W \to \tau\nu_\tau$ and $Z \to \tau^+\tau^-$ with `Pythia`.
- Mass cut on 60 GeV for Z-source (standard), no cuts on W.

Boson (B)	$\boldsymbol{\sigma_{prod}}$	$\boldsymbol{Br_\tau}$	$\boldsymbol{\sigma_\tau}$	$\boldsymbol{N(\tau)/10\ \text{fb}^{-1}}$
Z^0	55 nb	0.03	1.66 nb	$1.7 \cdot 10^7$
$W^\pm$	156 nb	0.11	17.2 nb	$17.2 \cdot 10^7$

$\sigma_{prod} = \sigma(pp \to B)$, $Br_\tau = Br(B \to \tau + X)$, $\sigma_\tau = \sigma_{prod} \cdot Br_\tau$