Rare Dimuon Decays at ATLAS

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for

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Workshop

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Introduction

Physics: $b \to d, s$ transitions (FCNC) are forbidden at the tree level in SM and occur at the lowest order through one-loop-diagrams “penguin” and “box”.

Main points for study:

a) The good test of SM and its possible extensions;

b) Information of the long-distance QCD effects;

c) Determination of the $|V_{td}|$ and $|V_{ts}|$;

d) Some of rare decays can produce the BG to other rare decays (for example: $B^+ \to \mu^+ \mu^- \ell^+ \nu_\ell$ as BG to $B^0_{d,s} \to \mu^+ \mu^-$).
Which new rare $B$-decays measurements can be performed by LHC in comparison with B-factories?

a) The rare decays of $B^0_s$ – meson ($B^0_s \rightarrow \phi \gamma$, $B^0_s \rightarrow \phi \mu^+ \mu^-$, and $B^0_s \rightarrow \mu^+ \mu^- (\gamma)$) and $\Lambda_b$ – baryon ($\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$, $\Lambda_b \rightarrow \Lambda \gamma$);

b) Differential distributions for rare semileptonic $B$-meson decays (dimuon mass spectra, forward-backward asymmetries) with sufficient accuracy for distinguishing SM and its extensions;

c) Branching fractions of extremely rare decays $B^0_{d,s} \rightarrow \mu^+ \mu^-$ and $B^0_{d,s} \rightarrow \mu^+ \mu^- \gamma$ decays have good sensitivity for some SM extensions.
ATLAS trigger strategy for di-muonic B-events

1) The study of two-muons rare decays $B^0_s \rightarrow \mu^+ \mu^-$, $B^0_{d,s} \rightarrow (K^*,\phi) \mu^+ \mu^-$ based on LVL1 di-muon trigger (can be continued at nominal $10^{34}$ cm$^{-2}$s$^{-1}$).

2) The study of rare decays: $B^0_d \rightarrow \pi^0 \mu^+ \mu^-$ and $B^0_s \rightarrow \mu^+ \mu^- \gamma$ based on LVL1 di-muon trigger and single muon LVL1 ($\mu 6$) with photons reconstruction in EM CALO.
$B^0_{d,s} \rightarrow \mu^+ \mu^-$ decays at ATLAS

$Br_{SM} \sim 10^{-9} - 10^{-10}$

All experimental limits are 100 times higher, than SM theoretical predictions.
Motivation for $B_{d,s}^0 \rightarrow \mu^+ \mu^-$ study

th) Clear theoretical picture for SM and it’s extensions for branching ratio predictions.

th’) Good potential sensitivity for the SUSY (for example: in MSSM $Br \sim \tan^6 \beta / M^2_H$).

ex) Only LHC can measure branching ratios of the rare muonic decays in SM.

ex’) ATLAS (and CMS) will have some advantages over LHCb studying rare muonic channels at nominal ($10^{34}$) luminosity.

ex’’) Simple signature for experimental search.
B_{0d,s} \rightarrow \mu^+\mu^- simulation at ATLAS

1) 1998-1999-years simulation TDR ATLAS Detector layout

Full detector simulation and reconstruction for initial and nominal LHC luminosity, signal + combinatorical background

After 3 year LHC at L=10^{33} cm^{-2}s^{-1} (30 fb^{-1})

B_{0d}^0 : 4 signal ev., B_{0s}^0 : 27 signal ev., 93 BG ev. common to both

After 1 year LHC at L=10^{34} cm^{-2}s^{-1} (100 fb^{-1})

B_{0d}^0 : 14 signal ev., B_{0s}^0 : 92 signal ev., 660 BG ev. common to both

B_{0d}^0 \rightarrow \mu^+\mu^- : 3 \times 10^{-10} upper limit at CL 95%

B_{0s}^0 \rightarrow \mu^+\mu^- : 2.8 \sigma at 3 year@10^{33} and combining with 1 year@10^{34} - 4.3 \sigma

“1999 Workshop on SM Physics (and more) at the LHC”, CERN Yellow Report, CERN-2000-004.

2) 2002-2005 simulations with Final ATLAS Detector layout and with new software

DC1: ATLAS B-Physics Group, ATL-PHYS-2005-002
DC2+ Rome Production: ATLAS Physics workshop (Rome),
http://agenda.cern.ch/fullAgenda.php?ida=a044738
**ATLAS sensitivity on $\text{Br}(B^0_s \rightarrow \mu^+\mu^-)$ with Final detector layout**

<table>
<thead>
<tr>
<th>Integral LHC Luminosity</th>
<th>$\text{BG ev. } p_T(\mu) &gt; 6 \text{ GeV, } \Delta R_{\mu\mu} &lt; 0.9$</th>
<th>SES</th>
<th>Expected Signal ev. after cuts</th>
<th>Expected BG ev. after cuts</th>
<th>ATLAS upper limit at 90% CL</th>
<th>CDF&amp;D0 best upper limit at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 pb$^{-1}$</td>
<td>$6.0 \times 10^4$</td>
<td>$2.7 \times 10^{-8}$</td>
<td>$\sim 0$</td>
<td>$\sim 0.2$</td>
<td>$6.4 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>10 fb$^{-1}$</td>
<td>$6.0 \times 10^6$</td>
<td>$2.7 \times 10^{-10}$</td>
<td>$\sim 7$</td>
<td>$\sim 20$</td>
<td>$7.0 \times 10^{-9}$</td>
<td>$1.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>30 fb$^{-1}$</td>
<td>$1.8 \times 10^7$</td>
<td>$0.9 \times 10^{-10}$</td>
<td>$\sim 21$</td>
<td>$\sim 60$</td>
<td>$6.6 \times 10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>

1) We get the cross section of $B^0_s$ multiplied by acceptance of $B^0_s \rightarrow \mu^+\mu^-$ decay with $p_T(\mu)>6 \text{ GeV and } |\eta(\mu)|<2.5$ from Rome PYTHIA samples: $\sigma(B_s)\times\alpha = 0.42 \mu\text{b};$

2) We get the background ($\bar{b}b \rightarrow \mu\mu X$) cross section $\sigma(\text{BG})$ with $p_T(\mu) > 6 \text{ GeV and } |\eta(\mu)|<2.5$ from Rome PYTHIA samples: $\sigma(\text{BG}) = 600 \text{ pb};$

3) SES - Single event sensitivity for $B^0_s \rightarrow \mu^+\mu^-$

$$\text{SES} = \left| (1 B_s \rightarrow \mu\mu 6 \text{ event})/(\text{total number of BG events}) \right| \times \frac{\sigma(\text{BG})}{(\sigma(B_s)\times\alpha) \times \varepsilon_{\mu^2}};$$

**BG for $B^0_{d,s} \to \mu^+\mu^-$ decays**

In order to find physics beyond SM in rare muonic decays, we need to know all possible SM BG.

1. In ATLAS conditions the largest BG is coming from $b\bar{b}(b\bar{b}b\bar{b}, b\bar{b}c\bar{c}) \to \mu\mu X$ processes, with muons originating mainly from **semileptonic** $b(c)$ decays.

2. Other **important BG** can be produced by **decays with small branching ratios** (rare decays!) or **exotic decays**, which are **NOT** included in standard MC-generators (PYTHIA, for example). These processes may be potentially dangerous as they **have signatures very similar** to $B \to \mu\mu$ signal in area of their phase space.
\( B^{0 \pm} \rightarrow \pi^{0 \pm} \mu^+\mu^- \) as BG for \( B^{0}_{d,s} \rightarrow \mu^+\mu^- \)

1. The branching ratios of \( B^{0 \pm} \rightarrow \pi^{0 \pm} \mu^+\mu^- \) decays approximately equal to \( 10^{-8} \) and are larger than branching ratios of rare leptonic decays \( B^{0}_{d,s} \rightarrow \mu^+\mu^- \).

2. The background would come from soft pions escaping the identification and leaving the invariant dimuon mass

\[
M_{\mu\mu} = M_B - M_\pi.
\]

within the limits of \( B \rightarrow \mu\mu \) mass resolution (\( \sigma \sim 80 \text{ MeV} \)).

3. Detailed detector simulation will allow to determine strategies to further reduce the contributions of these decays.

4. At first step (particle level study) there were revealed basic problems of \( B^{0 \pm} \rightarrow \pi^{0 \pm} \mu^+\mu^- \) as a background to \( B^{0}_{d,s} \rightarrow \mu^+\mu^- \) (see next slides).
$B^0_d \rightarrow \pi^0 \mu^+\mu^-$ as BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$

|$\eta(\mu)| < 2.5$, $p_T(\mu) > 6$ GeV, $\pi^0 \rightarrow \gamma \gamma$.

The particle level simulation of $B^0_d \rightarrow \pi^0 \mu^+\mu^-$ for SM (no cuts selecting $\mu\mu$-pairs pointing to primary vertex applied).
$B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ and $B_c \rightarrow \mu^+\mu^- \ell^+\nu_\ell$

as BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$

**Roughly:** the branching ratio of $B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ is

$$\text{Br}(B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell) \approx 5 \times 10^{-6},$$

the branching ratio of $B_c \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ is

$$\text{Br}(B_c \rightarrow \mu^+\mu^- \ell^+\nu_\ell) \approx 8 \times 10^{-5}.$$ 

Because of the fact, that $B_c$ – meson’s cross section is 400 times smaller than cross section of $B^+$ at LHC energy, this decay channels gives approximately equal BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$. **This BG seems to be very significant** comparing with BG from $B^0 \pm \rightarrow \pi^0 \pm \mu^+\mu^-$ decays (see particle level example for decays $B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ on the next slide).
$B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ as BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$

Number of events

For muons in $M_{\mu\mu}$: $|\eta(\mu)| < 2.5$, $p_T(\mu) > 5$ (or 6) GeV.

The particle level phase space simulation of $B^0_d \rightarrow \mu^+\mu^- \ell^+\nu_\ell$
(no cuts selecting $\mu\mu$-pairs pointing to primary vertex applied yet!).
Rare semileptonic b-decays at ATLAS

$\text{Br}_{\text{SM}} \sim 10^{-6} - 10^{-7}$
Motivation for study of $B^0_d(s) \rightarrow K^*(\phi)\mu^+\mu^-$

**th)** Good agreement between different nonperturbative theoretical models;

**th’)** Branching ratios and differential distributions (dimuon-mass spectra, $A_{FB}$) are sensitive to the SM extensions;

**ex)** It is possible to study the rare semileptonic decays at initial LHC luminosity;

**ex’)** ATLAS will have enough statistics at initial luminosity for precise measurement of differential distributions.
Expected ATLAS statistics at 30 fb$^{-1}$

<table>
<thead>
<tr>
<th>Decay Cannels</th>
<th>Reconstructed Signal events</th>
<th>BG after all cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_d \rightarrow K^* \mu^+ \mu^-$</td>
<td>3000</td>
<td>&lt; 3000</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi \mu^+ \mu^-$</td>
<td>900</td>
<td>&lt; 3000</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$</td>
<td>1500</td>
<td>in progress</td>
</tr>
</tbody>
</table>

Full detector simulation and reconstruction for **final ATLAS Detector layout with new software** at initial LHC luminosity: signal and **combinatorical background (in progress)**. Trigger efficiencies included.
$A_{FB}$ for $B^0_d \rightarrow K^*(892)\mu^+\mu^-$ decay

hep-ex/0410006
CONCLUSION

1. Already during the first year of LHC, with luminosity just 100 pb$^{-1}$ ATLAS can exceed best CDF and D0 current upper limit on branching ratios of $B^0_s \rightarrow \mu^+\mu^-$ decay.

2. After 30 fb$^{-1}$ (equivalent to 3 years at initial luminosity) ATLAS will be able to achieve sensitivity at level of SM predictions for $B^0_s \rightarrow \mu^+\mu^-$.

3. Under the same conditions ATLAS will have enough statistics for precise measurement of differential distributions of rare semileptonic decays.

4. Program of ATLAS rare muonic decays measurements can be continued at nominal LHC luminosity $10^{34}$ cm$^{-2}$ s$^{-1}$!
Appendix
The basic theoretical description

Effective Hamiltonian for $b \to d,s$ transition:

$$H_{\text{eff}}(b \to q) \sim G_F V_{tq}^* V_{tb} \sum C_i(\mu) O_i(\mu),$$

includes the lowest EW-contributions and perturbative QCD corrections for Wilson coefficients $C_i(\mu)$.

$\mu$ - scale parameter $\sim 5 \text{ GeV}$: separates SD (perturbative) and LD (nonperturbative) contributions of the strong interactions.

**SM NLO**: A.Buras, M.Munz, *PRD* 52, p.182, 1995

**SM NNLO**: C.Bobeth et al., *JHEP* 0404, 071, 2004

**MSSM NNLO**: C.Bobeth et al., *NPB* 713, p522, 2005
The basic theoretical description - II

$O_i(\mu)$ – set of the basic operators (specific for each model: SM, MSSM, LR and others);

**LD** (nonperturbative) contribution of the strong interactions are contained in the hadronic matrix elements:

$$\langle \text{final hadronic states} | O_i (\mu) | \text{initial hadronic states} \rangle$$

and are described in the terms of relativistic invariant function - **transition formfactors**.

Need the **nonperturbative methods** (SR, QM, Lat).
### SM Theoretical Branching Ratios Predictions

<table>
<thead>
<tr>
<th>Decay</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow \mu^+ \mu^-$</td>
<td>$\text{Br}(B^0_s \rightarrow \mu^+ \mu^-) = 3.5 \times 10^{-9}$ at $</td>
</tr>
<tr>
<td>$B^0_d \rightarrow \mu^+ \mu^-$</td>
<td>$\text{Br}(B^0_d \rightarrow \mu^+ \mu^-) = 0.9 \times 10^{-10}$ at $</td>
</tr>
<tr>
<td>$B^0_d \rightarrow K^* \mu^+ \mu^-$</td>
<td>$\text{Br}(B^0_d \rightarrow K^* \mu^+ \mu^-) = 1.3 \times 10^{-6}$ from PDG'04</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \varphi \mu^+ \mu^-$</td>
<td>$\text{Br}(B^0_s \rightarrow \varphi \mu^+ \mu^-) / \text{Br}(B^0_d \rightarrow K^* \mu^+ \mu^-) = 0.8$</td>
</tr>
<tr>
<td>$B^0_d \rightarrow \pi^0 \mu^+ \mu^-$</td>
<td>$\text{Br}(B^0_d \rightarrow \pi^0 \mu^+ \mu^-) = 2.0 \times 10^{-8}$ at $</td>
</tr>
<tr>
<td>$B^0_d \rightarrow \pi^\pm \mu^+ \mu^-$</td>
<td>$\text{Br}(B^0_d \rightarrow \pi^\pm \mu^+ \mu^-) = \text{Br}(B^0_d \rightarrow \pi^0 \mu^+ \mu^-)$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \mu^+ \mu^- \gamma$</td>
<td>$\text{Br}(B^0_s \rightarrow \mu^+ \mu^- \gamma) = 1.9 \times 10^{-8}$ at $</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$</td>
<td>$\text{Br}(\Lambda_b \rightarrow \Lambda \mu^+ \mu^-) = 2.0 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

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A.C. Chen, C.Q. Geng, PRD64, 074001, 2001  
T.M. Aliev et. al., NPB649, p. 168-188, 2003
“Rome production”: 2005 – Data Samples

Generation (with theoretical matrix elements), full simulation, digitization and reconstruction with 9.0.4 and 10.0.1 software releases, analysis of AOD in 10.0.1.

Signal channels:

\[ \text{B} \rightarrow \mu\bar{\mu}\mu \]  
Rome production. 5 kEv in analysis (AOD)

\[ \text{B} \rightarrow K^0\mu\bar{\mu}\mu \]  
Private (evgen-simul-digi-reco) 30 kEv (AOD)

\[ \text{B} \rightarrow \phi \mu\bar{\mu}\mu \]  
Private (evgen-simul-digi-reco) 12 kEv (AOD)

\[ \Lambda_b \rightarrow \Lambda \mu\bar{\mu}\mu\mu \]  
Private (evgen-simul-digi-reco) \sim 50 kEv (AOD)

Background samples:

\[ \text{bb} \rightarrow \mu\bar{\mu}\mu\bar{\mu}X \]  
\sim 50 kEv included cut on \( M(\mu\bar{\mu}) \sim M(B^0_s) \)

\[ \text{bb} \rightarrow \mu\bar{\mu}\mu\bar{\mu}X \]  
\sim 23 kEv for B-decays and \sim 31 kEv for \Lambda_b-decays
Upper limits for rare muonic decays

**CDF Run 2:**  $\text{Br}( B_s \rightarrow \mu\mu ) < 2.0 \times 10^{-7} @ 95\% \text{ CL}$

(hep-ex/0508036)

**D0 Run 2:**  $\text{Br}( B_s \rightarrow \mu\mu ) < 3.7 \times 10^{-7} @ 95\% \text{ CL}$

(D0-Note 4733-Conf, Preliminary)

**D0 Run 2:**  $\text{Br}( B_s \rightarrow \mu\mu ) < 5.0 \times 10^{-7} @ 95\% \text{ CL}$


**CDF Run 2:**  $\text{Br}( B_s \rightarrow \mu\mu ) < 7.5 \times 10^{-7} @ 95\% \text{ CL}$


**CDF Run 2:**  $\text{Br}( B_d \rightarrow \mu\mu ) < 3.9 \times 10^{-8} @ 90\% \text{ CL}$

(hep-ex/0508036)

**BaBar:**  $\text{Br}( B_d \rightarrow \mu\mu ) < 8.3 \times 10^{-8} @ 90\% \text{ CL}$

(hep-ex/0408096)

**CDF Run 2:**  $\text{Br}( B_d \rightarrow \mu\mu ) < 1.5 \times 10^{-7} @ 90\% \text{ CL}$


**Belle:**  $\text{Br}( B_d \rightarrow \mu\mu ) < 1.6 \times 10^{-7} @ 90\% \text{ CL}$

(Phys. Rev. D 68, 111101 (R) (2003))

All experimental limits are **100 times higher**, than SM theoretical predictions.
$B^0_s \rightarrow \mu^+\mu^-$ decays in ATLAS: Rome production at 2005 year

Signal, BG and efficiencies of selection cuts (10 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Cuts</th>
<th>BG: $b\bar{b} \rightarrow \mu\mu X$</th>
<th>$B^0_s$ - Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertexing procedure</td>
<td>CTMVFT</td>
<td>CTMVFT</td>
</tr>
<tr>
<td>$p_T(\mu) &gt; 6$ Gev, $\Delta R_{\mu\mu} &lt; 0.9$</td>
<td>$6.0 \times 10^6$ events</td>
<td>50 events</td>
</tr>
<tr>
<td>$M(\mu\mu) = M_B^{+140}_{-70}$ MeV</td>
<td>2×10$^{-2}$</td>
<td>0.77</td>
</tr>
<tr>
<td>Isolation cut: no ch.tracks</td>
<td>$5\times10^{-2}$</td>
<td>0.36</td>
</tr>
<tr>
<td>$p_T &gt; 0.8$ GeV in cone with $\theta &lt; 15^\circ$</td>
<td>$5\times10^{-2}$</td>
<td>0.36</td>
</tr>
<tr>
<td>$\sigma &lt; 90 \mu m$, $L_{xy}/\sigma &gt; 15$, $\alpha &lt; 1^\circ$</td>
<td>$2.8\times10^{-3}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$L_{xy}/\sigma &gt; 11$, $\chi^2 &lt; 15$</td>
<td>$&lt; 0.7\times10^{-4}$</td>
<td>0.4</td>
</tr>
<tr>
<td>Number of events after cuts</td>
<td>$15\pm10$</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>$20\pm20$</td>
<td>7</td>
</tr>
</tbody>
</table>
B-meson hadronic decays  
as BG for $B^0_{d,s} \rightarrow \mu^+ \mu^-$

Another important BG for $B^0_{d,s} \rightarrow \mu^+ \mu^-$ is **two-body hadronic decays** of B-mesons, when one (or both) final hadrons have short lifetime, and decayed inside ATLAS Inner Detector with high probability.

For example:

$$\text{Br}(B^0_d \rightarrow (D^+ \rightarrow \mu^+ X_s)(D^- \rightarrow \mu^- X_s) \text{ in ID}) \approx 10^{-6},$$

$$\text{Br}(B^0_d \rightarrow (D^+ \rightarrow \mu^+ X_d)(D^- \rightarrow \mu^- X_d) \text{ in ID}) \approx 10^{-8}.$$  

This decay and similar decays $B^0_d \rightarrow K^+ D^-$, $B^0_s \rightarrow K^+ D^-_s$ and $B^0_s \rightarrow D^{*+}_s D^{*-}_s$ are **not included in PYTHIA 6.x!**
The decays $B_{d,s}^0 \rightarrow \mu^+ \mu^- \gamma$ are not essential background for the decay $B_d^0 \rightarrow \mu^+ \mu^-$. 

| $|\eta(\mu)| < 2.5$, $p_T(\mu) > 6$ GeV |

**A9**
$B^0_d \rightarrow \pi^0 \mu^+ \mu^-$ as BG to $B^0_{d,s} \rightarrow \mu^+ \mu^- \gamma$

$|\eta(\mu)| < 2.5$, $p_T(\mu) > 6$ GeV, $\pi^0 \rightarrow \gamma \gamma$.

The particle level simulation $B^0_d \rightarrow \pi^0 \mu^+ \mu^-$ for SM (no cuts selecting $\mu\mu$-pairs pointing to primary vertex applied yet!).

A10
Impact of Trigger Cuts for $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

- expected number of triggered events for $30 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>$\Lambda_b$ - production</th>
<th>$\sigma_{bb} = 500 \mu b$, $\text{Br}(b \rightarrow \Lambda_b) = 0.071$</th>
<th>$1.1 \times 10^{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b$ rare decay</td>
<td>$\text{Br}(\Lambda_b \rightarrow \Lambda \mu \mu) = 2 \times 10^{-6}$, $\text{Br}(\Lambda \rightarrow p \pi) = 0.64$</td>
<td>$1.400.000$</td>
</tr>
<tr>
<td>Di-muon LVL1 cuts</td>
<td>$p_T &gt; 6/4 \text{ GeV},</td>
<td>\eta</td>
</tr>
<tr>
<td>Hadron cuts</td>
<td>$p_T &gt; 0.5 \text{ GeV},</td>
<td>\eta</td>
</tr>
</tbody>
</table>

- trigger cuts prefers higher di-muon invariant masses and slightly lowers absolute value of $A_{FB}$ in region of lower di-muon masses

P.Reznichek