# Outlook for b and c physics at the LHC in ATLAS and CMS

Attila Krasznahorkay Jr.
for the ATLAS and CMS collaborations


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- Property measurements of heavy-flavoured mesons
- CP violation measurement possibilities
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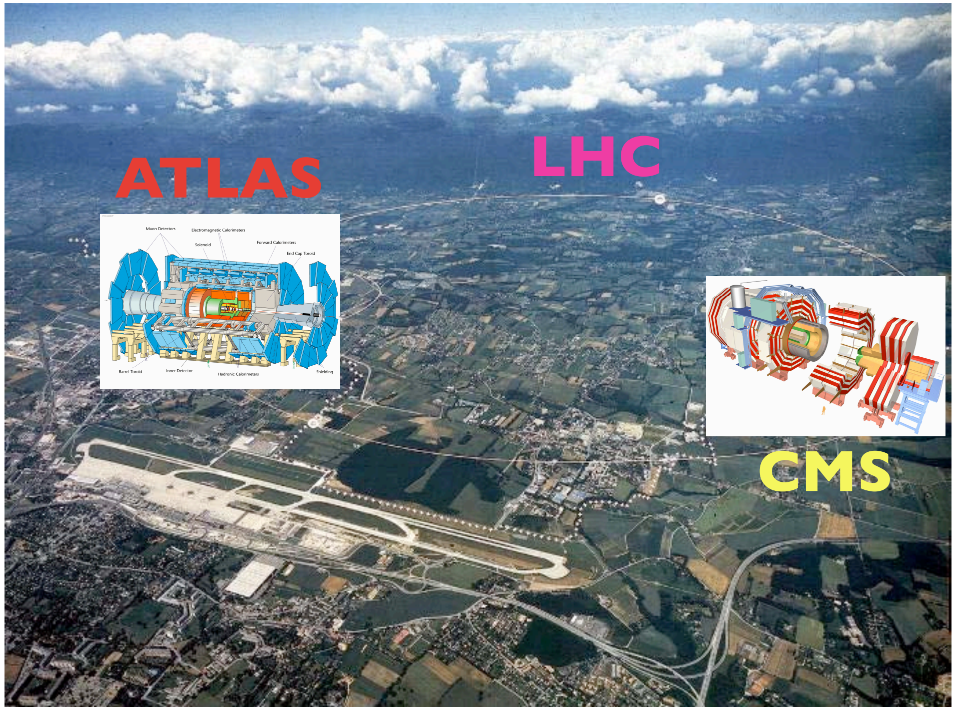
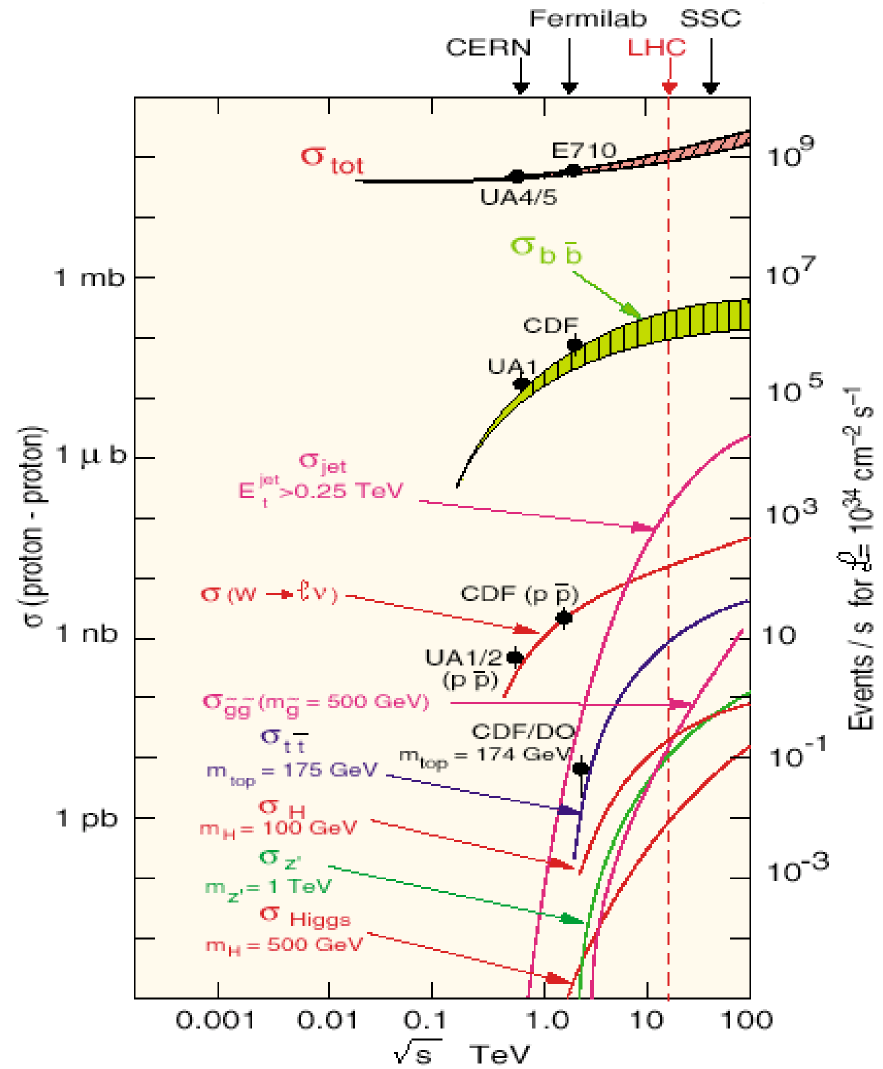
# The LHC



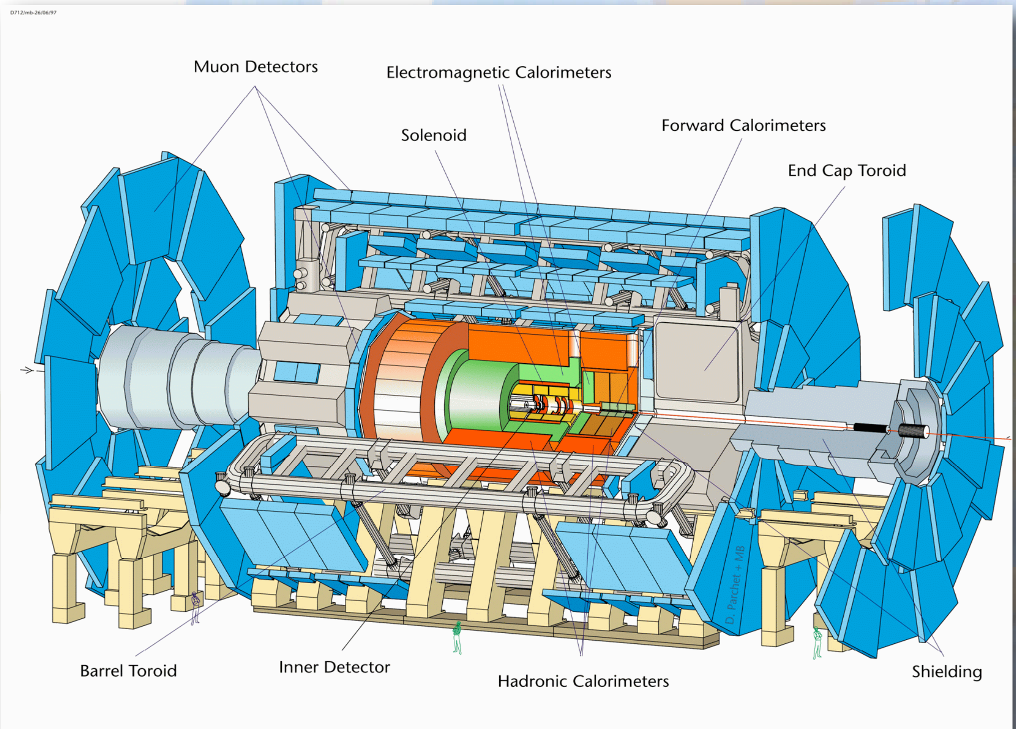

- 27 km in circumference, colliding protons at $\sqrt{s}$ = 14 TeV
- 4 experiments:
  - LHCb: dedicated to B-physics
  - ALICE: dedicated to heavy ion physics
  - **CMS, ATLAS**: general purpose experiments
- Operation plan:
  - Possibility of a 900 GeV commissioning run in 2007
  - From summer 2008: 14 TeV, low luminosity ($L=10^{33}$ $cm^{-2}s^{-1}$)
  - After 3 years of low luminosity, 14 TeV @ $L=10^{34}$ $cm^{-2}s^{-1}$

# B physics at the LHC

- p-p collisions at $\sqrt{s}$ = 14 TeV
- σ(bb) = 500 μb
  - $10^5$ bb pairs/s @ L=$10^{33}$ $cm^{-2}s^{-1}$
  - Huge statistics allows precision measurements despite the noisy environment.
- Heavy particle factory, as well as "new particle factory"
- Main B physics interests in ATLAS and CMS:
  - CP violation (e.g. B->J/ψ$K^0$)
  - Physics of the $B_s$ meson -> signatures beyond the SM (e.g. $B_s$->J/ψΦ)
  - Rare B decays (e.g. B->μμX)



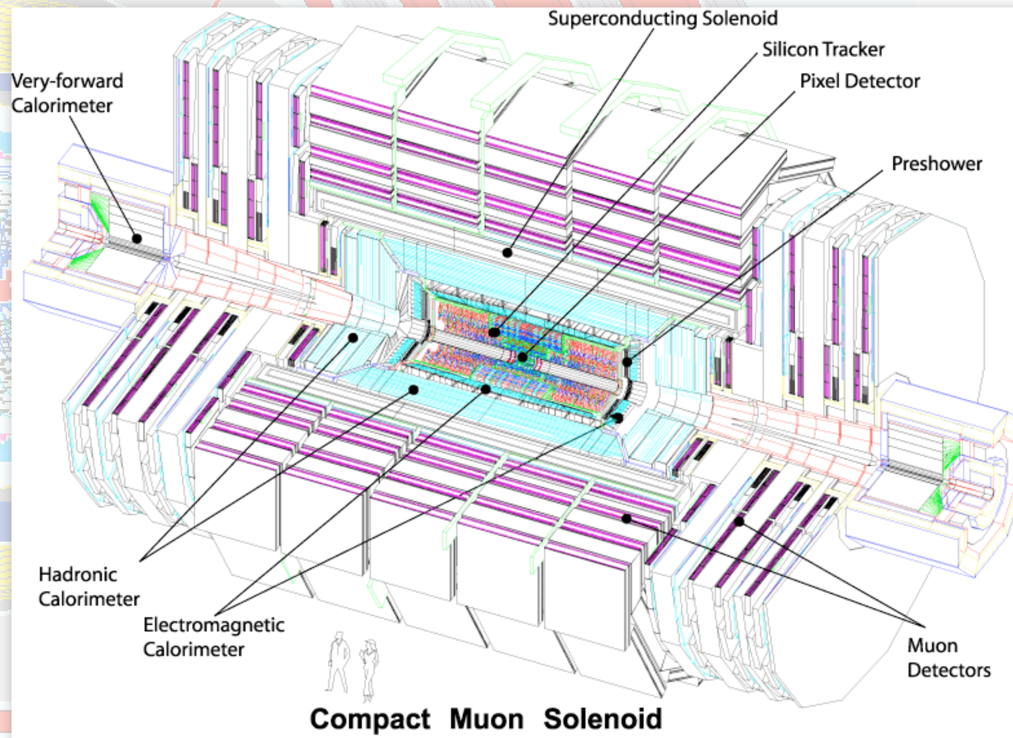
# The ATLAS detector




- Properties:
  - weight: ~7000 T
  - diameter: 22 m
  - length: 46 m
  - magnetic field: 2 Tesla (solenoid)
    0.5 Tesla (toroid)
- Good tracking, calorimetry & muon detection
- Dedicated and flexible B-physics trigger
- No K/π separation

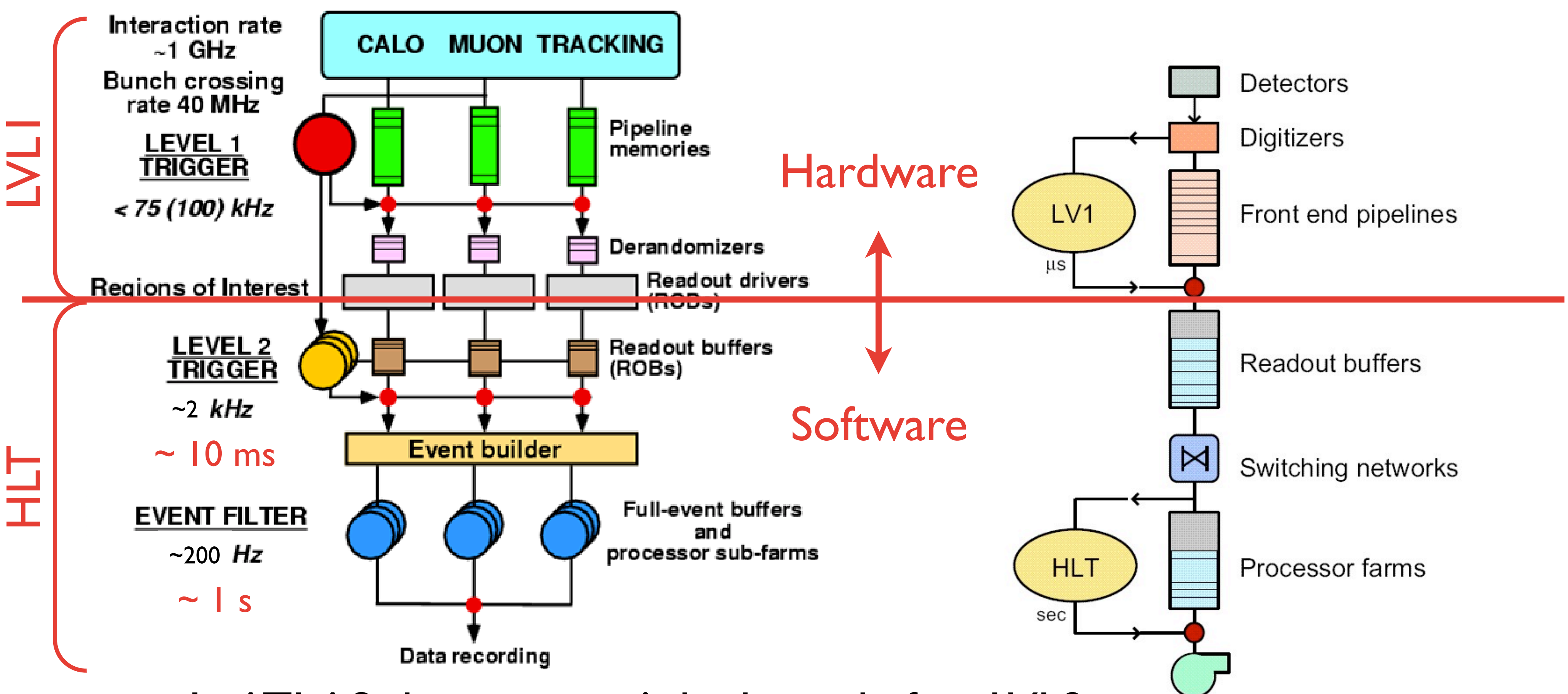
# The CMS detector

- Properties:
  - weight: ~12500 T
  - diameter: 15 m
  - length: 21.5 m
  - magnetic field: 4 Tesla
- Good tracking, excellent EM calorimetry, good muon detection
- Separate triggers for B-physics channels



# Trigger systems in ATLAS and CMS

## ATLAS                CMS




In ATLAS the event isn't built until after LVL2.
(LVL2 only sees data in Regions of Interest.)

# Selecting B-physics events

- Both experiments were designed for high-$p_T$ (discovery) physics.
- c and b events contain mostly low-$p_T$ particles. –> Triggering and selecting these events is a challenge.
- Many signatures contain one or more muon in their final state. These are of main interest. (Muons are easy to trigger/reconstruct in both experiments.)

# B-physics triggers in ATLAS

- At $L = 10^{33}$ $cm^{-2}s^{-1}$ (low luminosity): ATLAS uses single particle triggers at LVL1 and extends search for complex signatures in the HLT
  - Starting from LVL1 Jet RoI: hadronic final states, e.g. $B_s \rightarrow D_s(\Phi\pi)\pi$
  - Starting from LVL1 EM RoI: e/γ final states, e.g. $J/\psi \rightarrow ee$, $K^*\gamma$, $\Phi\gamma$
  - Starting from LVL1 Muon RoI: To recover di-muon final states in which the second muon was missed at LVL1.
- At $L = 10^{34}$ $cm^{-2}s^{-1}$ (high luminosity): Start from LVL1 di-muon trigger ($p_T > 6$ GeV)
  - $B \rightarrow J/\psi(\mu\mu)X$
  - double semi-leptonic decays
  - Rare decays, e.g. $B_s \rightarrow \mu\mu$

# B-physics triggers in CMS

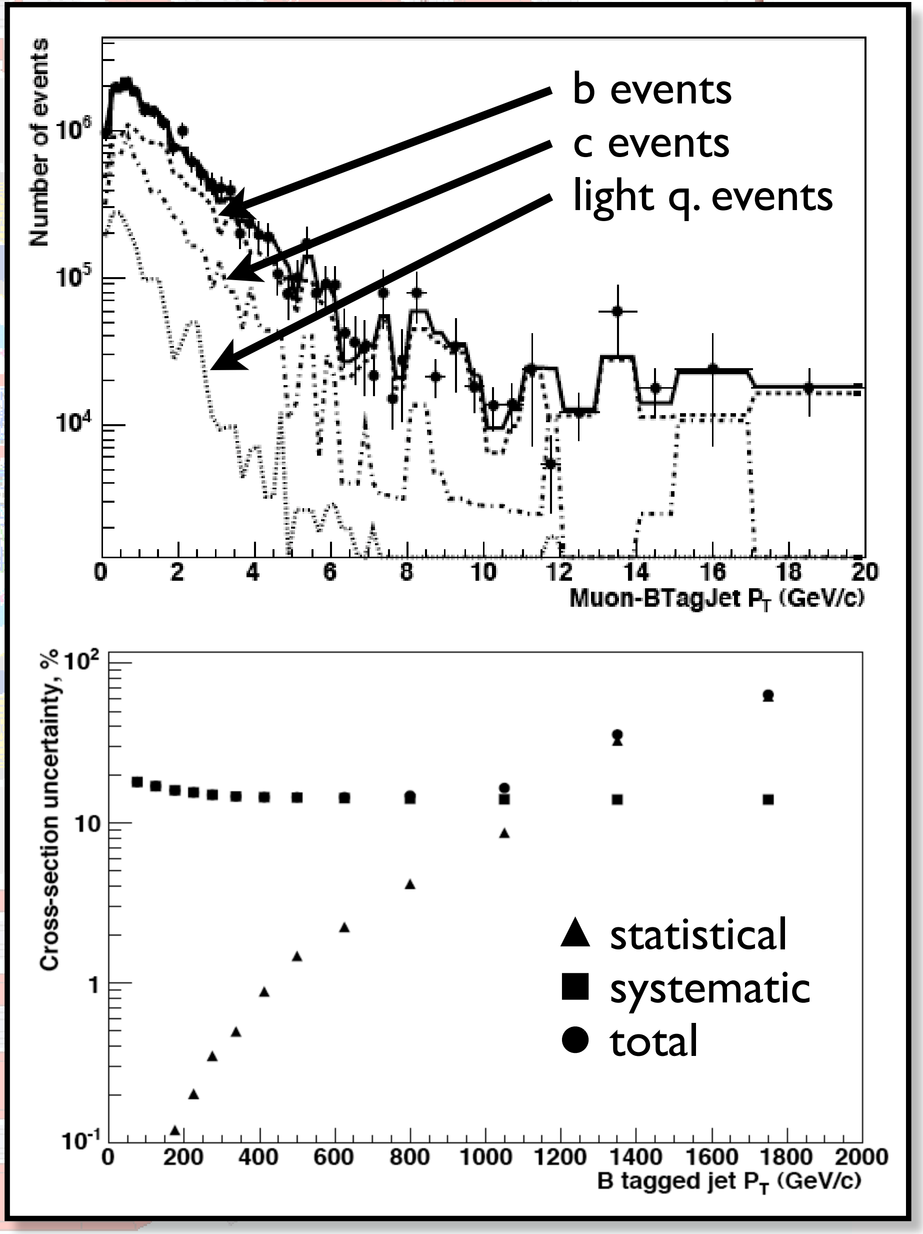
- CMS also uses LVL1 single- ($p_T$ > 14 GeV) and di-muon ($p_T$ > 3 GeV) triggers, 40 MHz -> 100 kHz accept rate
- The HLT provides fast (local) reconstruction, 100 kHz -> 100 Hz accept rate (~5 Hz for exclusive and inclusive b, c triggers)
  - Reconstruction of three most probable vertices with pixel detector
  - Regional track reconstruction around LVL1 muons
  - Search for (un)like charge track pairs in given mass windows
  - Decay length fit possible

# B hadron property measurements

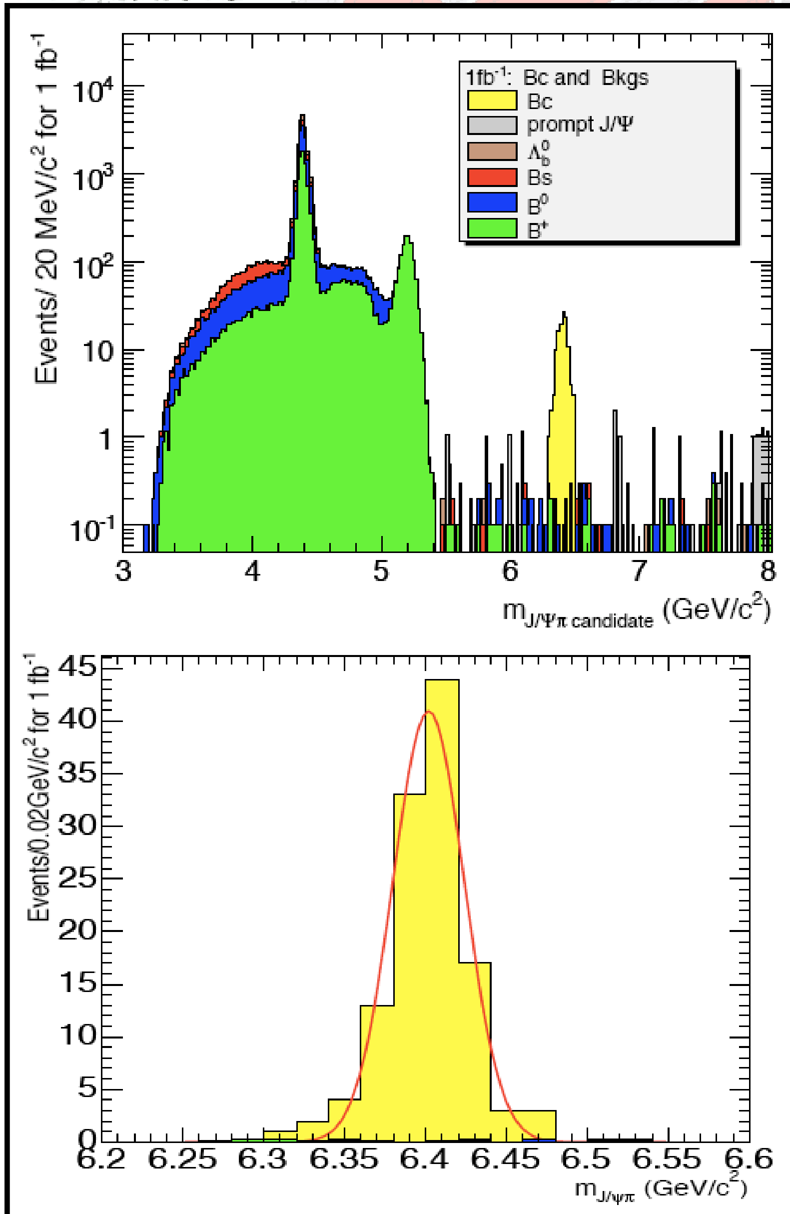
- Huge B hadron production statistics will allow precise measurements of their properties at LHC
- The theoretical description of heavy flavoured hadrons needs input at LHC energies
- Precision measurements can be achieved starting from 10 $fb^{-1}$ (one year at low luminosity) of data

# Inclusive b cross section

- Measured b production cross-sections at Tevatron/HERA/LEP are larger than the NLO QCD predictions.
- -> The improvement of the theoretical description requires experimental input from the LHC.
- CMS studied the feasibility to measure the inclusive b production cross section in events with jets and at least one muon.
- The spectrum of the muon $p_T$ with respect to the closest b-tagged jet is characteristic of the inclusive b events.
- It is possible to extract the cross section with a maximum likelihood fit.
- Measurement of $B^+ \to J/\psi K^+$ and inclusive $J/\psi$ x-section is also planned.



# $B_c$ meson properties




- Studying $B_c$ can help understanding heavy quark dynamics
- Different theoretical descriptions give $B_c$ properties with large uncertainties
- CMS studied the channel: $B_c \rightarrow J/\psi\pi$
- 120 such events are expected to be selected with 1 $fb^{-1}$ of data
- Expected resolutions:
  - mass: 22.0(stat.), 14.9(syst.) MeV/$c^2$
  - cτ: 13.1(stat.), 3.0(syst.) μm

# CP violation studies in ATLAS and CMS

- The full proper-time and angular analyses allow the investigation of several parameters of physics interest in $B^0_s$ decays.
- If the SM predictions are correct, the weak phase ($\Phi_s$) will not be measured with useful significance, but deviations from the SM could be detected.
- Heavy flavour hadron decays also allow the direct measurement of some CKM matrix elements.

# sin(2β) measurement

- ATLAS sensitivity to measure sin(2β) in the $B^0_d \to J/\psi K_s$ decay was estimated with a maximum likelihood fit.
- Combining all tags, a precision of 0.01 on sin(2β) could be achieved with 30 $fb^{-1}$ at low luminosity.

| | J/ψ(μ6μ5) | J/ψ(μ6μ3) | J/ψ(e1e1) |
|---|---|---|---|
| # of reconstructed events | 250k | 490k | 15k |
| Signal/background | 28 | 32 | 16 |
| $\delta\sin(2\beta)_{stat}$ lepton tag | 0.023 | 0.030 | 0.018 |
| $\delta\sin(2\beta)_{stat}$ jet-charge tag | 0.015 | 0.019 | - |
| $\delta\sin(2\beta)_{stat}$ combined tag | 0.0126 | 0.016 | 0.018 |

# $\Delta m_s$ measurement

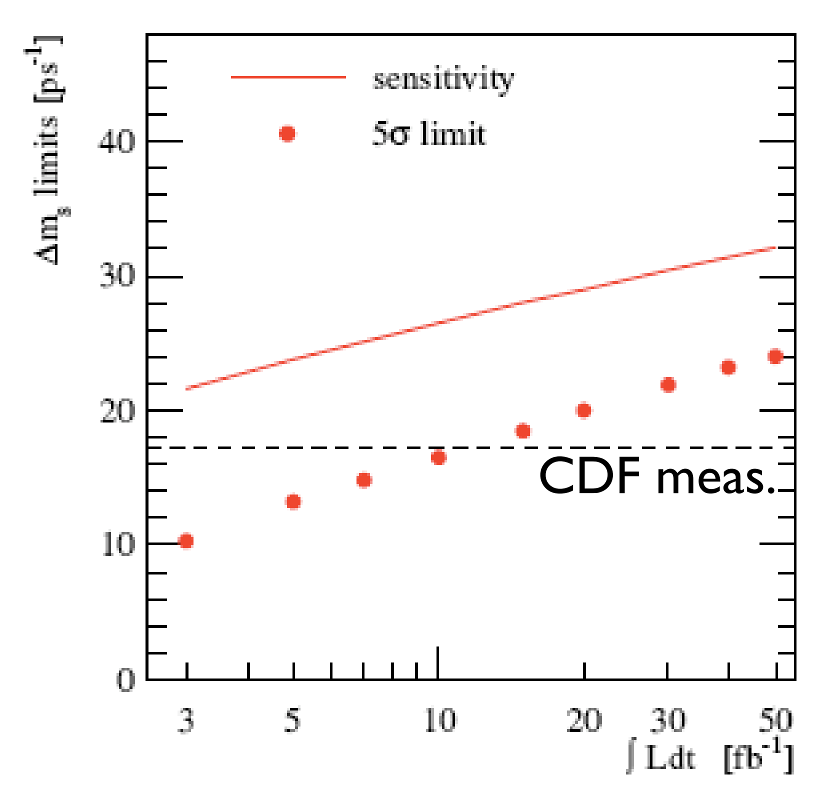
- In $B^0_s \to D_s\pi$, $B^0_s \to D_s a_1$ the probability to detect an initially pure $B^0_s$ as $B^0_s$ ($p_+$) or as $\bar{B}^0_s$ ($p_-$) is:

$$p_\pm(t) = e^{-\Gamma t}(\cosh\frac{\Delta\Gamma_s}{2}t \pm \cos\Delta m_s t)\frac{\Gamma^2-\Delta\Gamma_s^2}{2\Gamma}$$

- $\Delta m_s$ can be derived from:

$$\frac{p_+(t)-p_-(t)}{p_+(t)+p_-(t)} = \frac{\cos\Delta m_s t}{\cosh\frac{\Delta\Gamma_s}{2}t}$$

- The projection of ATLAS's sensitivity to $\Delta m_s$ can be seen on the right. A 5σ limit could be obtained for CDF's measurement already with 10 fb$^{-1}$



# ATLAS sensitivity in $B_s$ -> $J/\psi\Phi$

## For integrated luminosity 30 $fb^{-1}$

| | | |
|---|---|---|
| Signal events within kinematic cuts | | 810 000 |
| Signal events passing L1 & L2 di-muon triggers | | 623 700 |
| Signal events after offline reconstruction, vertex fit and signal selection cuts | | 270 700 |
| Bs mass resolution | | 16.5 MeV |
| Bs proper-life time resolution | | 83 fs |
| Tag efficiency / wrong tag fraction | jet charge | 63% / 38% |
| | electron | 1.2% / 27% |
| | muon | 2.5% / 24% |
| Background from $J/\psi K^{0*}$ & bb -> $J/\psi X$ | | 15% |

## Results

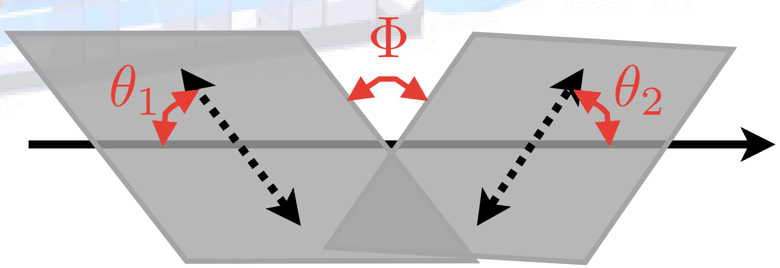
| | |
|---|---|
| $\sigma(\Phi_s)$ (for $\Delta m_s$ = 20 $ps^{-1}$) | 0.046 |
| $\sigma(\Delta\Gamma_s)/\Delta\Gamma_s$ supposing $\Delta\Gamma_s/\Gamma_s$ = 10% | 13% |
| $\sigma(\Gamma_s)/\Gamma_s$ | 1% |
| $\sigma(A_{\|})/A_{\|}$ | 0.9% |
| $\sigma(A_{\perp})/A_{\perp}$ | 3% |

7 parameters extracted in maximum likelihood

- 3 helicity amplitudes
  - 2 independent magnitudes and 2 phases: $|A_{\|}|\ |A_{\perp}|\ \delta_1\ \ \delta_2$
- 3 $B_s$ weak decay param.
  - $\Gamma_s$, $\Delta\Gamma_s$, $\Phi_s$

Fits done in phase-space of three angles:

- $\theta_1\ \theta_2\ \Phi$

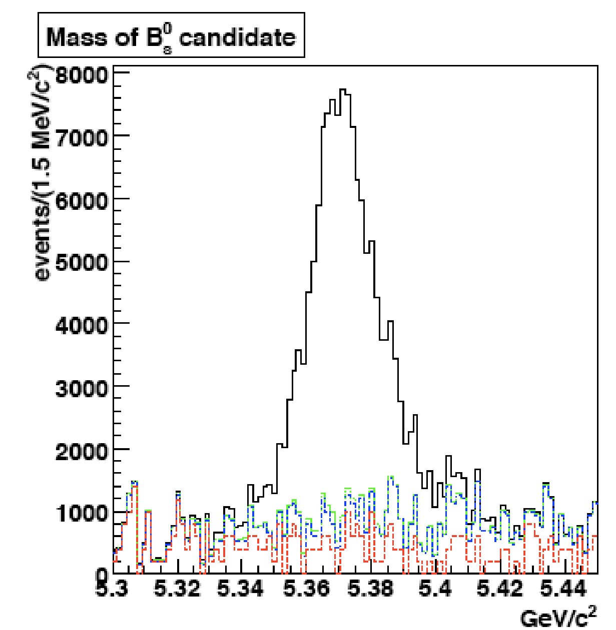


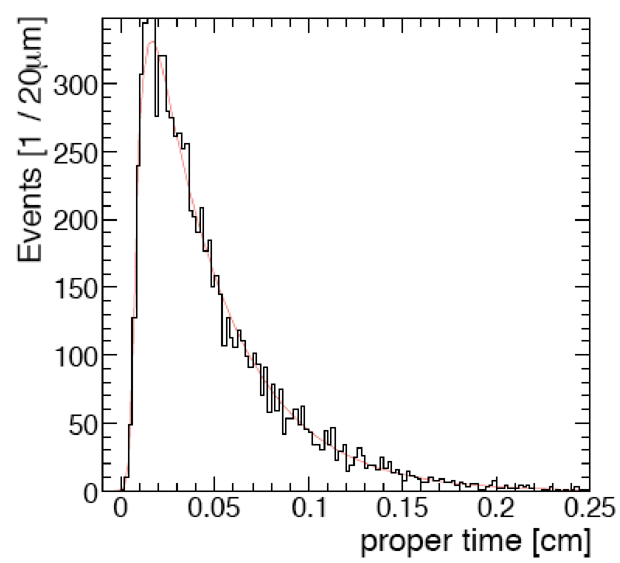
# $B^0_s$ -> $J/\psi\Phi$ -> $\mu^+\mu^-K^+K^-$

- CMS also studied this decay channel in a full angular analysis.
- After reconstructing the final state, a maximum likelihood fit could be used to extract all parameters of interest.

| Parameter | Input value | Result | Stat. error |
|---|---|---|---|
| $\|A_0(0)\|^2$ | 0.57 | 0.57398 | 0.00267 |
| $\|A_\parallel(0)\|^2$ | 0.217 | 0.21808 | 0.00473 |
| $\|A_\perp(0)\|^2$ | 0.213 | 0.20794 | 0.00396 |
| $\bar{\Gamma}_s$ | 0.712 ps$^{-1}$ | 0.712358 ps$^{-1}$ | 0.003506 ps$^{-1}$ |
| $\Delta\Gamma_s$ | 0.142 ps$^{-1}$ | 0.134645 ps$^{-1}$ | 0.010825 ps$^{-1}$ |
| $\Delta\Gamma_s/\bar{\Gamma}_s$ | 0.2 | 0.189013 | 0.0157993 |
| $\delta_1$ | π | 2.94405 | 0.632682 |
| $\delta_2$ | 0 | -0.109493 | 0.639713 |
| $\phi_s$ | -0.04 | -0.0297427 | 0.0758856 |

no sensitivity without flavour tagging for 10 fb$^{-1}$



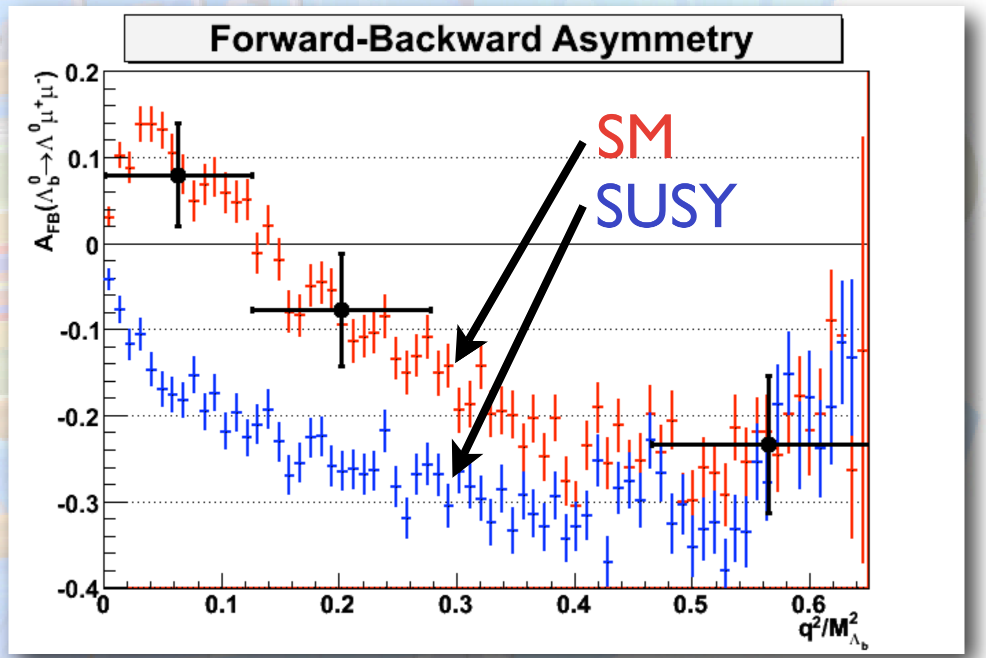



# Rare B-decays in ATLAS and CMS

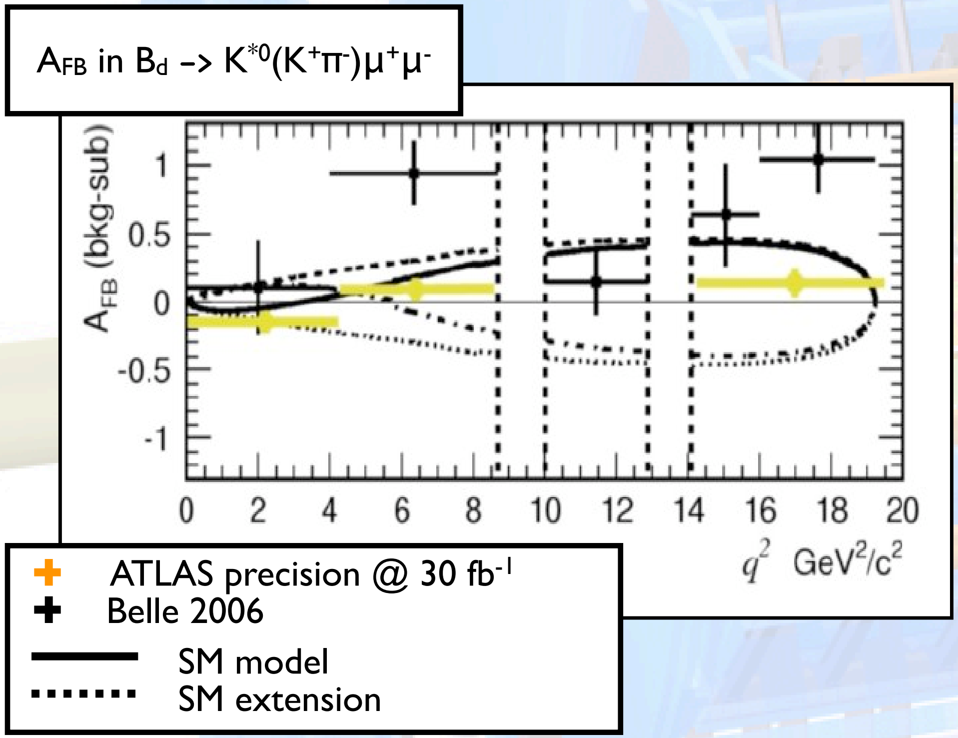
- Rare B-decays, produced by b -> d,s quark transitions, are forbidden at tree level in the SM.
- Their study gives opportunity to:
  - check SM predictions in a high perturbative order
  - search for new physics (SUSY, Extra Dimenstions, ...)
  - find the values of the $|V_{ts}|$ and $|V_{td}|$ CKM matrix elements
  - provide new information on long-distance QCD effects in matrix elements of the tensor currents

# $\Lambda_b \rightarrow \Lambda\mu\mu$

- In this process $A_{FB}$ is very sensitive to Supersymmetry both for small and large values of $\check{s}$, where $\check{s} = (p_{\mu^+} + p_{\mu^-})/M^2_{\Lambda_b} \equiv q^2/M^2_{\Lambda_b}$
- Muon triggers were proven not to change the shape of this distribution
- For 30 $fb^{-1}$ about 800 signal events are expected
- A clear separation will be possible between SM and some of its extensions



# $B^0_d \to K^* \mu^+\mu^-$ & $B^0_s \to \Phi\mu^+\mu^-$

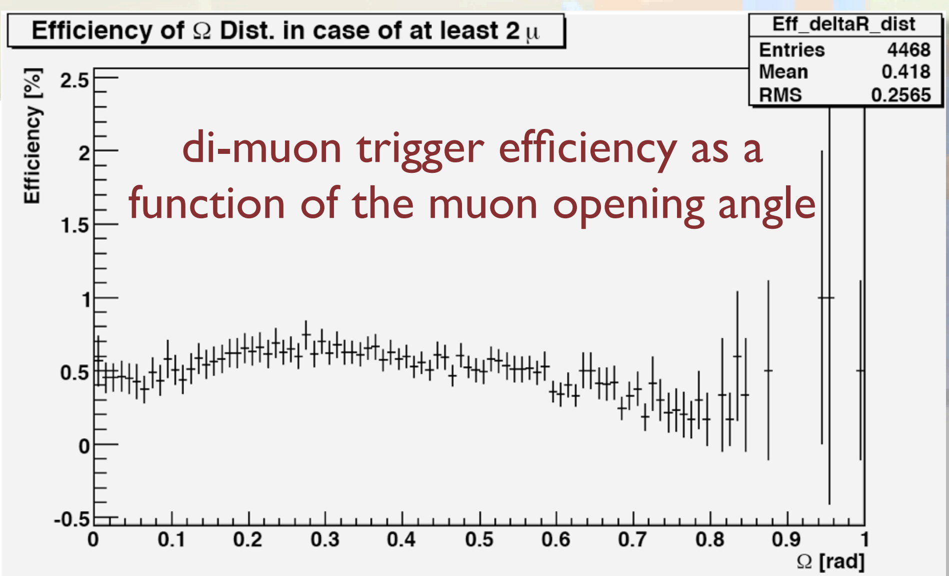



- Branching ratios and differential distributions of these processes are sensitive to SM extensions.
- After 3 years of data taking, we expect
  - 2500 signal and <12000 background events for $B^0_d \to K^* \mu^+\mu^-$
  - 900 signal and <10000 background events for $B^0_s \to \Phi\mu^+\mu^-$
- Also here it will be possible to set strong limits on SM extensions, or to undoubtfully detect beyond-SM physics.

# Expected rates for rare semi-muonic B-decays in ATLAS

| Channel | BR used in the MC | Statistics after trigger+offline reconstruction 3y @ $10^{33}$ $cm^{-2}s^{-1}$ | |
|---|---|---|---|
| | | Signal | Upper limit on background* |
| $B_d \to K^{0*}\mu\mu$ | $1.3\times10^{-6}$ | 2500 | <12000 |
| $B^+ \to K^+\mu\mu$ | $3.5\times10^{-7}$ | 4000 | <12000 |
| $B^+ \to K^{+*}\mu\mu$ | $6.4\times10^{-7}$ | 2300 | <12000 |
| $B_s \to \Phi\mu\mu$ | $1.0\times10^{-6}$ | 900 | <10000 |
| $\Lambda_b \to \Lambda\mu\mu$ | $2.0\times10^{-6}$ | 800 | <4000 |

*) Upper limit on background obtained with a sample of 250 000 bb -> μ6μ4X events. Additional 750 000 are in production.




## LVL1 di-muon trigger studies on semi-muonic rare decays

| L1 di-muon trigger rate @ $10^{33}$ $cm^{-2}s^{-1}$ using a suppression of false di-muon signals arising from single-muon (bb -> μ6X) events | |
|---|---|
| Fake L1 di-muon trigger rate (using fake suppression) | ~150 Hz |
| L1 trigger rate from real di-muons, dominated by beauty | ~200 Hz |

# $B^0_{d,s}$ -> $\mu^+\mu^-$

## BR is sensitive to SUSY and other possible SM extensions

| BR used in MC | | Luminosity | Signal | Background* |
|---|---|---|---|---|
| $B_s$ -> μμ 3.5x$10^{-9}$ | Final detector studies 2006-2007 | 3y@$10^{33}$cm$^{-2}$s$^{-1}$ (30fb$^{-1}$) | 21 | ~60 |
| | | | Upper limit 6.6x$10^{-9}$ | 90% CL |
| | Early detector studies 2000 | 1y@$10^{34}$cm$^{-2}$s$^{-1}$ (100 fb$^{-1}$) | 92 | ~900 |
| $B_d$ -> μμ 0.9x$10^{-10}$ | | | Upper limit 3x$10^{-10}$ | 95% CL |

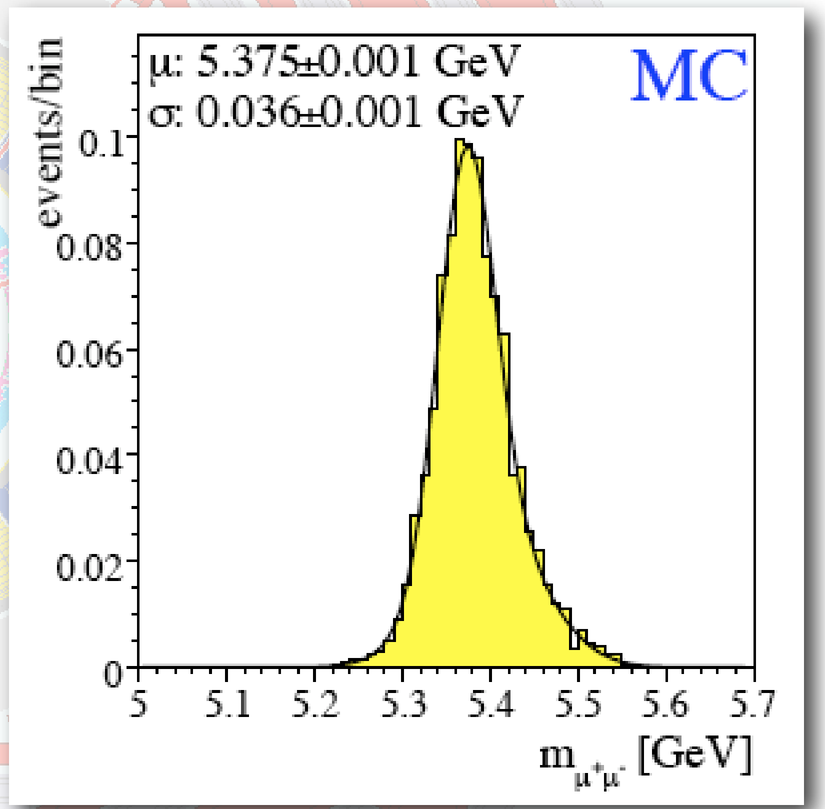
*) Upper limit on background obtained with a sample of 250 000 bb -> μ6μ4X events. Additional 750 000 are in production.

| Offline selection cuts | BG efficiency | SIG efficiency |
|---|---|---|
| isolation: $p^B_T/(p^B_T+\Sigma p_T(\Delta R<1.0)) > 0.85$ | 0.028 | 0.53 |
| angle between $p^B_T$ and direction to primary vertex < 1 degree | 0.024 | 0.52 |
| Transverse decay length significance $L_{xy}/\sigma_{xy} > 12$ | 0.06 | 0.49 |
| mass cut: m($B_s$) +140MeV -77MeV | 6x$10^{-2}$ | 0.77 |

Details of offline study done for L = $10^{33}$ cm$^{-2}$s$^{-1}$ with final detector layout

# $B_s \rightarrow \mu^+\mu^-$

- At low luminosity CMS expects a $\epsilon = 0.019 \pm 0.002$ signal selection and a $\eta = 2.6\times10^{-7}$ background rejection efficiency for this channel.
- For 10 $fb^{-1}$ (1 year at low luminosity) it gives
  $N_s = 6.1 \pm 0.6$ signal and
  $N_b = 13.8^{+22.0}_{-13.8}$ background events.
- This means a $B(B^0_s \rightarrow \mu^+\mu^-) < 1.4\times10^{-8}$ at 90% CL after one year of data taking.
- It should be possible to differentiate between $B_s \rightarrow \mu+\mu-$ and $B_d \rightarrow \mu+\mu-$ decays.
- Imperfect alignment is expected to give a mass resolution decrease of about 10%.



# Conclusions

- The LHC will provide experiments with unprecedented statistics of heavy flavour quark production.
- Physics program in both experiments is prepared for all luminosities of the LHC.
- Precision B studies will be useful as additional methods for new physics searches. (Complementing direct searches possible at LHC.)