$B_s \rightarrow \mu^+\mu^-$ decay at LHC

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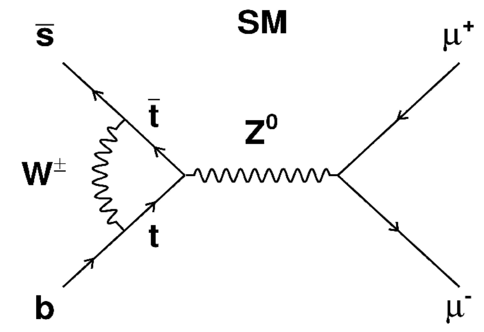
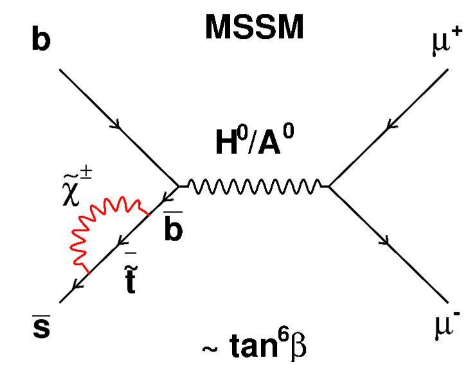
Motivation



Physics:

- $B^0_S \to \mu^+\mu^-$ is highly suppressed in SM (box, penguin diagr.)
  - $BR^{SM}(B_s \to \mu\mu) = (3.35 \pm 0.32) \times 10^{-9}$ (hep-ph/0604057)
  - Best exp. limit $BR^{CDF}(B_s \to \mu\mu) < 5.8 \times 10^{-8}$ (95%CL) (arXiv:0712.1708v2)
- Sensitive to New Physics (new particles in the loop)
  - MSSM $\sim \tan^6\beta$
  - BR in the range $10^{-9} \div 10^{-7}$ is favored by some models (i.e. CMSSM with constrains from g_μ-2 measurements)

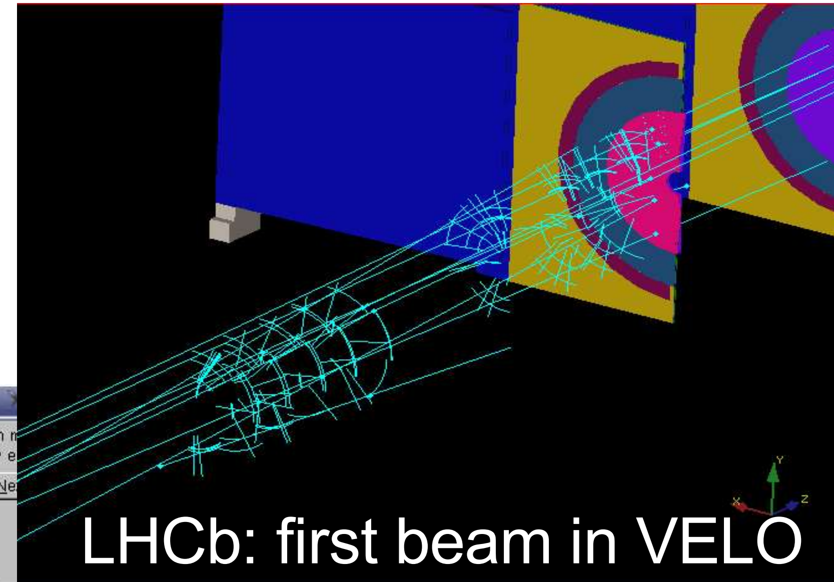


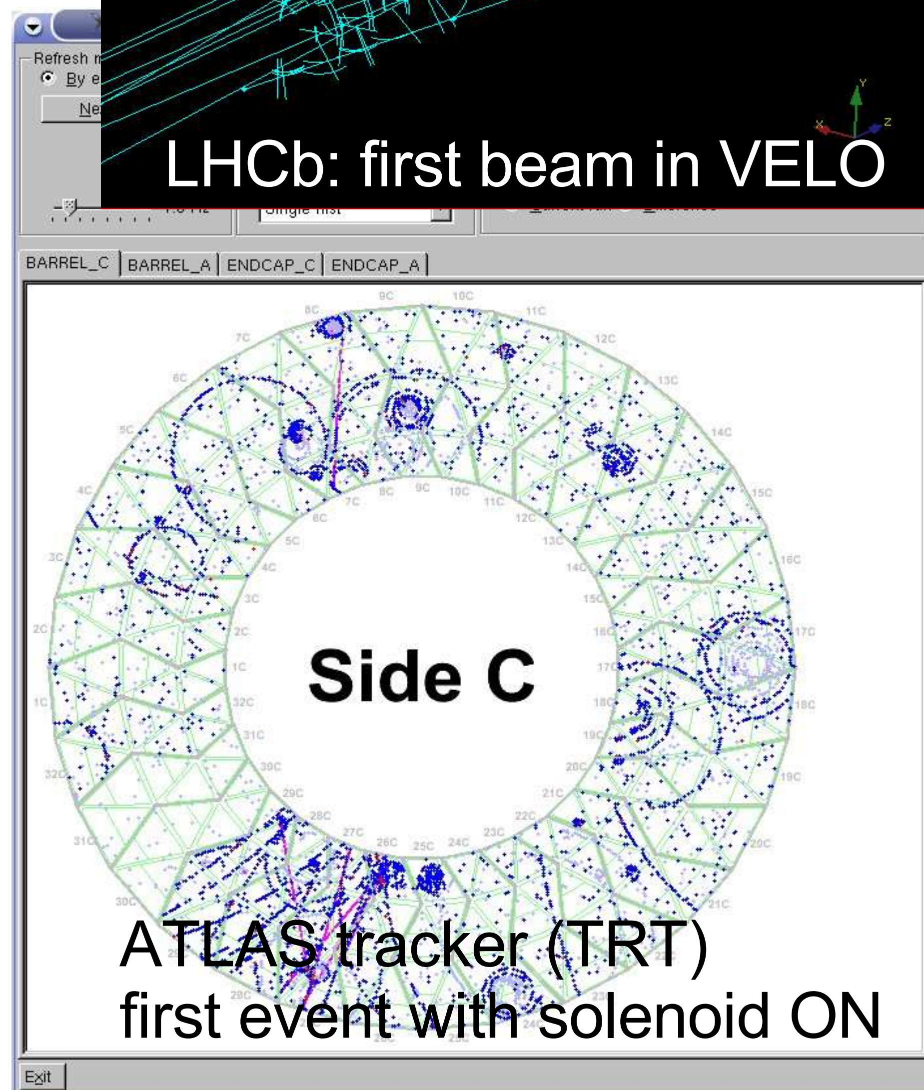
	Tevatron	LHC
$\sqrt{s}$	1.96 TeV	14 TeV
σ(bbbar)	150 μb	500 μb
σ_{inel}	60 mb	80 mb
Bunch cross. rate (Δt)	7.6 MHz (132 ns)	40 MHz (25 ns)
σ_{xy}	28(16) μm	16μm
σ_z	30 cm	7.5 cm
Luminosity	$2 \times 10^{32} cm^{-2}s^{-1}$	2×10^{32}-$10^{34} cm^{-2}s^{-1}$
events/crossing	1,6	2,0-25,0

- LHC machine:
  - ☹: hadron collider->heavy background conditions, extremely high luminosity
  - ☺: $\sim 10^5$ bb pairs/s @ $L = 10^{33} cm^{-2}s^{-1}$
  - ☺: several experiments with an excellent tracking detectors, complementary kinematic regions

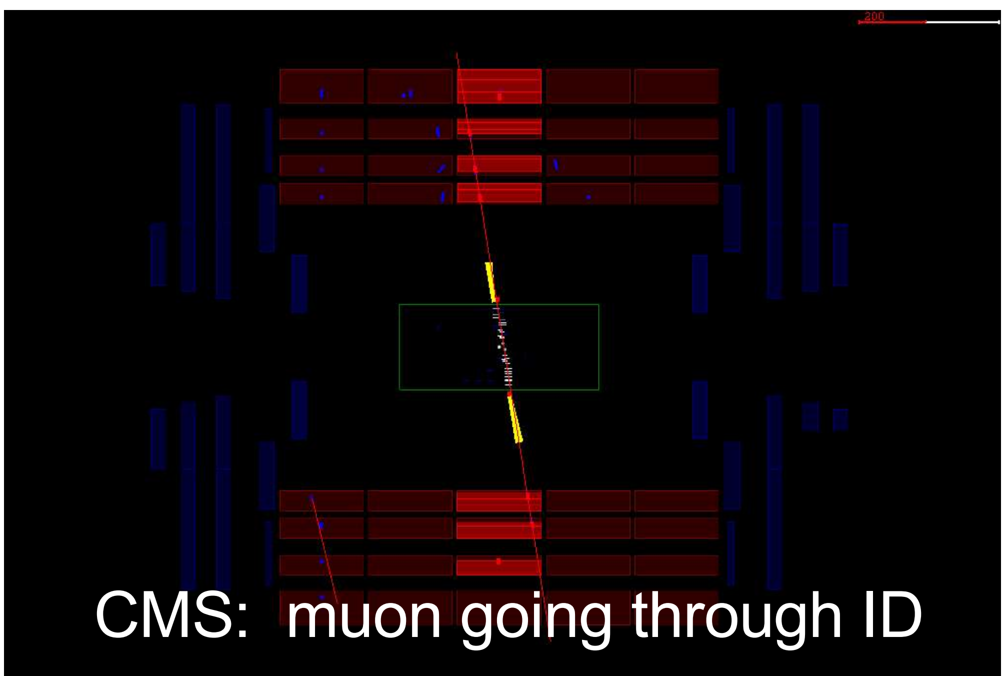
LHC status

- This year:
  - Energy: 5 TeV
  - 1, 12, 43, 156 bunches per beam
  - Luminosity 10^{27}->10^{32} $cm^{-2}s^{-1}$, events/crossing from ~0 to ~2
  - Integrated: first month – few pb^{-1}, another – 30-40 pb^{-1}
- 2009: 7 TeV, 10^{33} $cm^{-2}s^{-1}$, ~6 fb^{-1}


LHCb: first beam in VELO

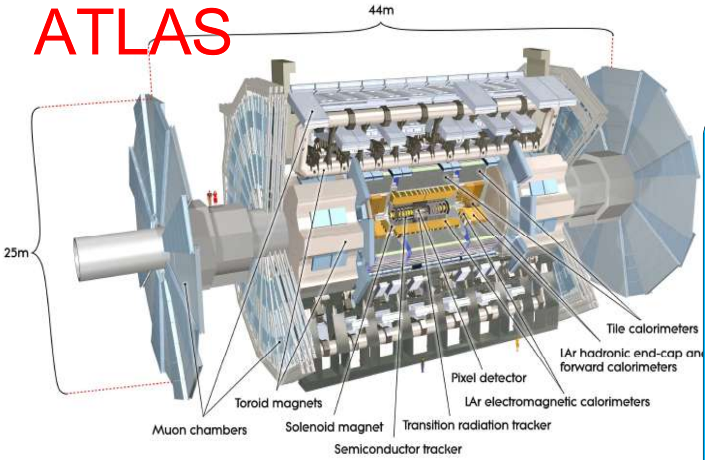


ATLAS tracker (TRT)
first event with solenoid ON


CMS: muon going through ID

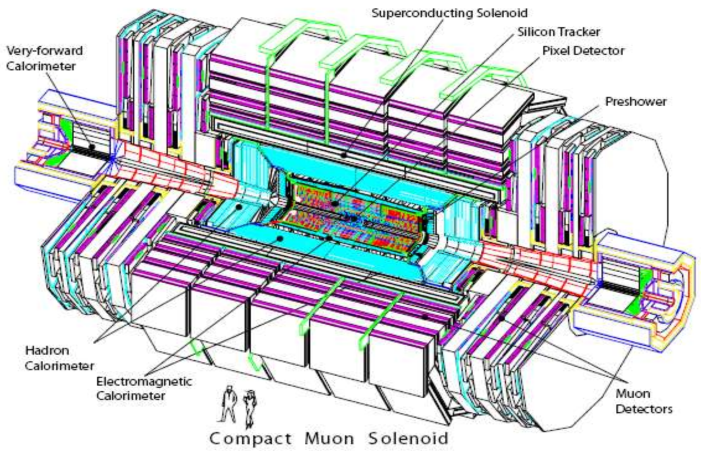
Detectors

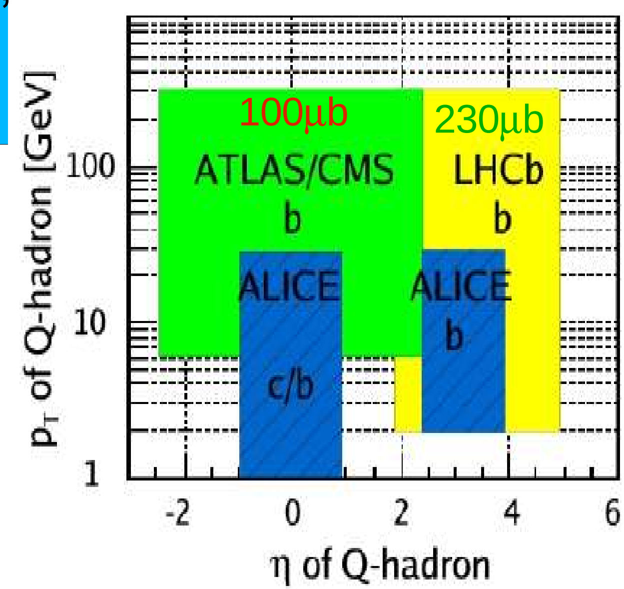
ATLAS



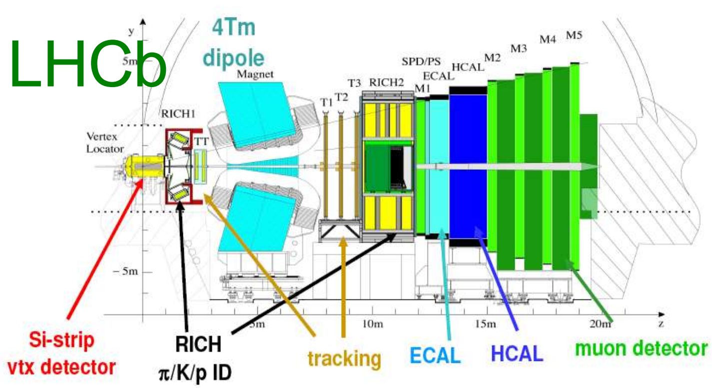
- ATLA S & CMS – general purpose detectors (with emphasis on high-p_T physics)
- very good tracking ($|\eta|<2.5$)
- precise vertexing (pixels, Si-strip, TRT (e/h-id, ATLAS), R>4-5cm)
- perfect muon system

CMS





LHCb

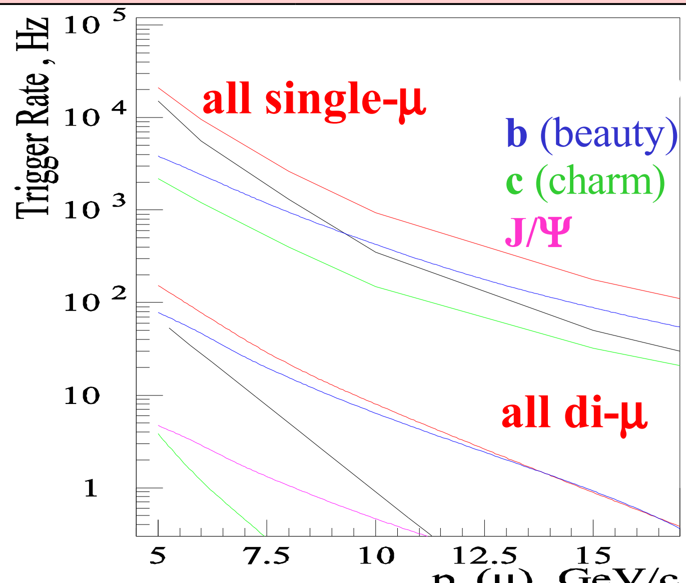


- LHCb – dedicated to B-physics (high η, low p_T)
- single-arm spectrometer, L~2x10^{32} $cm^{-2}s^{-1}$
- excellent vertexing (R>0.8 cm)
- K/π/p particle ID (RICH)

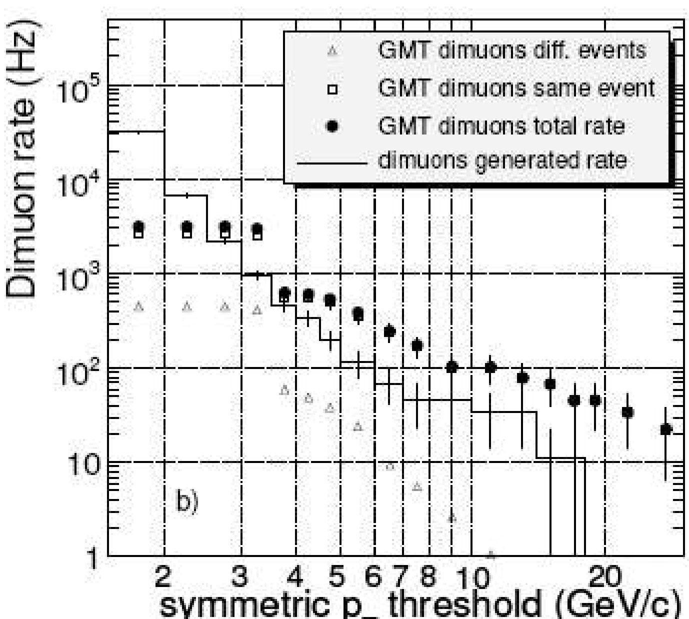
Trigger in ATLAS & CMS

- Efficient trigger – a key component in a heavy BG environment and a huge data streams volumes
- Both experiments utilize a trigger system with several levels to gradually reduce rate from 40 MHz (bunch crossing rate) to acceptable for permanent storage level of ~100 Hz
- An efficient di-muon trigger allow to continue B-physics study even at the design luminosity

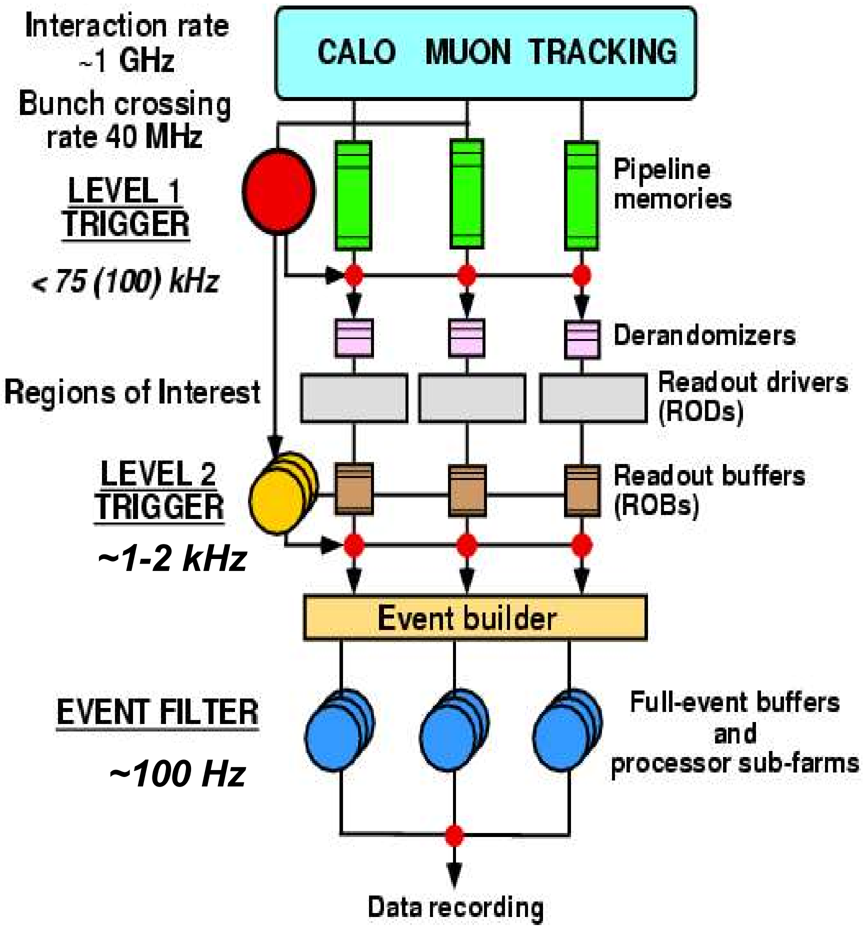
ATLAS μ–rates for 14 TeV and $10^{33}cm^{-2}s^{-1}$



CMS Global Muon Trigger rate @ L=$2x10^{32}$



ATLAS trigger (muons)



- Level 1 trigger – hardware based, info. from fast trigger chambers (TGC,RPC)
  - 2 muons p_T>6 GeV required
- High Level Trigger (HLT – Level 2 and Event Filter) software based
  - muons confirmed in precision chambers
  - combined with inner detector track
  - vertex fit, inv.mass cut
- p_T threshold can be lower in the startup period at lower luminosity, also single muon trigger at LVL1 can be used with a subsequent search of the second muon (with a lower threshold – up to 4 GeV)

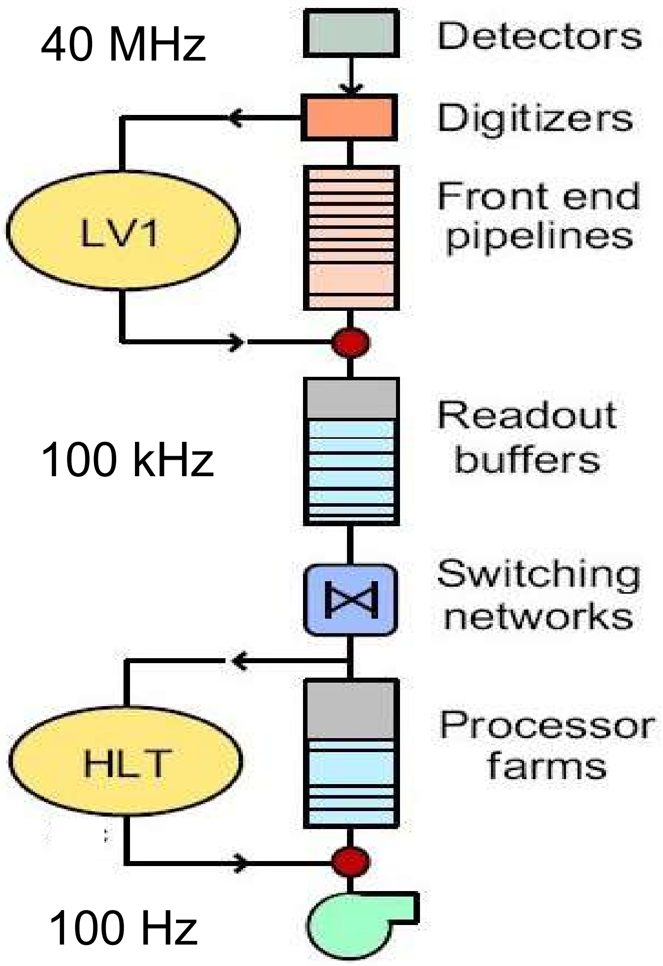
Estimated rates for L = $10^{31}cm^{-2}s^{-1}$

Object	L1 (Hz)	L2 (Hz)	EF (Hz)
Multi-muons	68.6	5.8	2.3
Single-muons	1730	204	21.8

for L = 2 x $10^{33}cm^{-2}s^{-1}$

2μ p_T > 6 : LVL2 - 200 Hz EF – 10 Hz

CMS trigger (muons)



- Level 1 Triggers

  - muons and calorimeters,

  Latency: 3.2 μs, 40 MHz -> 100 kHz
- High-level Triggers (HLT)

  fast (local) reconstruction, 100 kHz -> 100 Hz
- B-physics triggers
  - Level 1: single- or di-muon trigger

    1μ: p_T > 7(14) GeV/c,

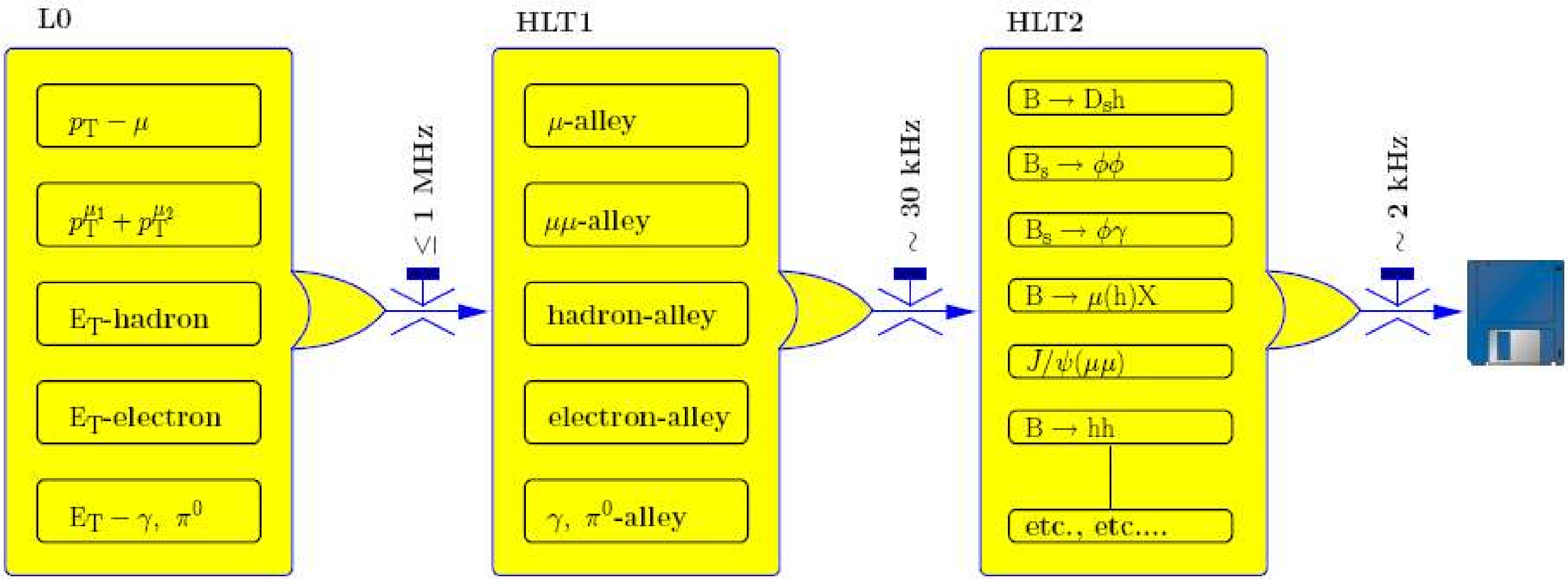
    2μ: p_T > 3(7) GeV/c
  - HLT: exclusive and inclusive b/c triggers at ~5Hz

    partial reconstruction,

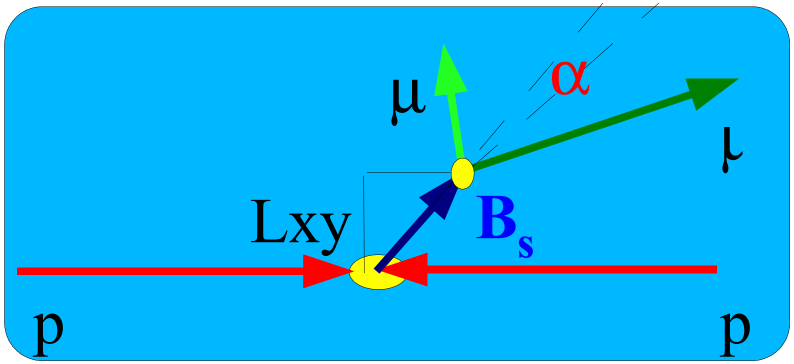
    displaced di-muons

LHCb trigger

- run at reduced L = 2 x 10^{32} cm^{-2} s^{-1}
- L0 trigger: $p^{\mu,\mu\mu}_T$ > ~1 GeV
- HLT1 : confirm L0 objects with tracker, VELO, optional IP cut
- selection for specific channels
- output ~1.5 kHz / small event size



Offline event selection



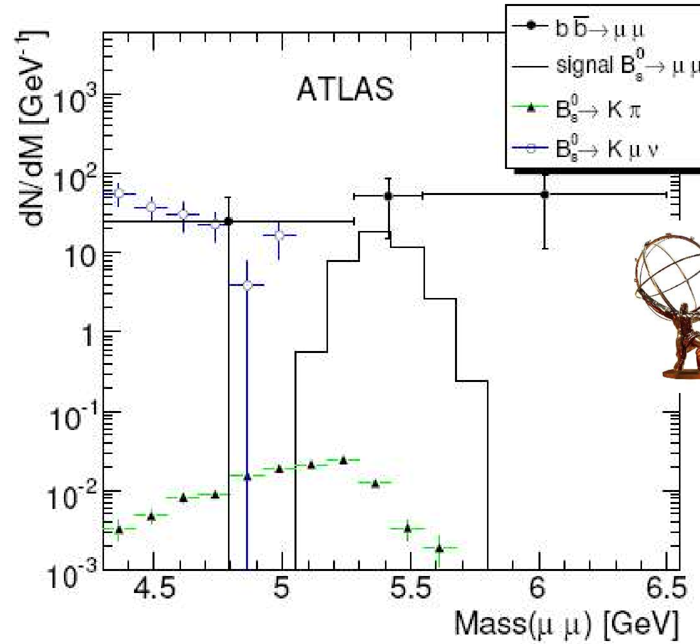
- $B^0_S \to \mu^+\mu^-$: clean experimental signature,

  but a main challenge is to controlling the background
- Similar approach in all experiments:
  - exploit precise tracking to reconstruct secondary vertex and separate signal candidate events from di-muon background
- ATLAS & CMS discriminating variables:
  - decay flight length (significance)
  - pointing angle between di-muon momentum and vector from primary vertex to di-muon vertex
  - B^0_S isolation (no or little hadronic activity around B^0_S flight direction)
  - mass cut
- LHCb – combined geometrical likelihood (***GL*** - lifetime, impact parameter (IP), distance of closest approach, B^0_S IP to primary vtx, Isolation)

Background

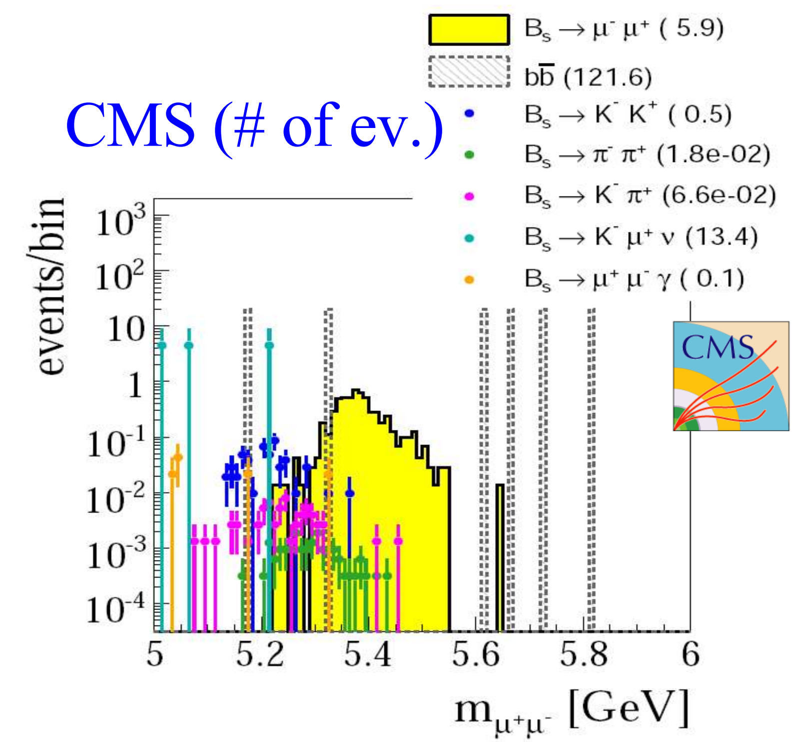
- Different sources considered:
  - combinatorial di-muon BG (dominated bbbar->μ μ X)
  - exclusive BG (2-3 body B_s,B_d,B_c decays*) (μ mis-id) - mostly insignificant
  - estimate BG in search region from sidebands

*) all processes calculated within SM

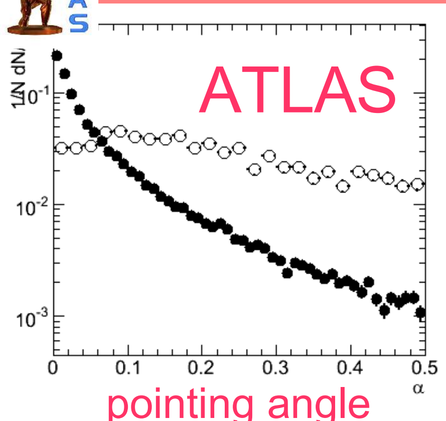


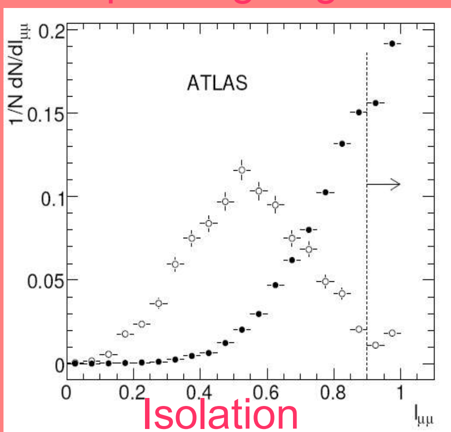
LHCb background in sensitive region

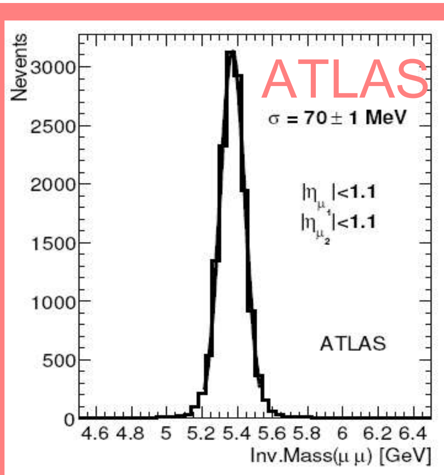
Source	Events in SR per nominal year
$B_s^0 \to \mu^+\mu^-$	22.8
$b\bar{b} \to \mu\mu X$	150; (< 324 at 90% C.L)
$B \to h^+h^-$	8; (<17.2 at 90% C.L)
$B_s^0 \to \mu^+\mu^-\gamma$	0; (<2.44 at 90% C.L)
$B_c^+ \to J/\Psi(\mu^+\mu^-)\mu^+\nu_\mu$	0; (< 20 at 90% C.L)



ATLAS analysis





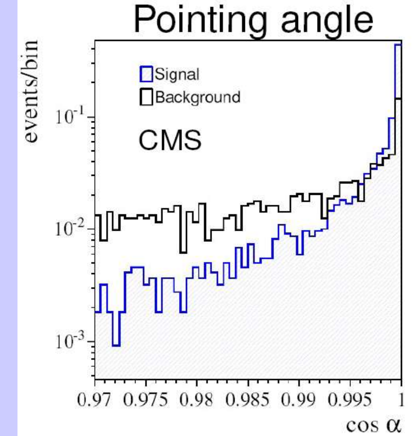


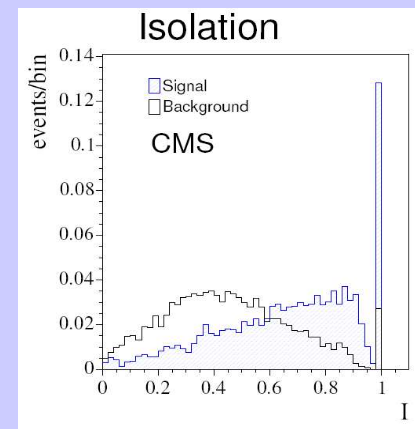
	$B_s \to \mu\mu$ efficiency	$bb \to \mu\mu X$ efficiency
Isolation>0.9	0.24	$(2.6\pm0.3)\times10^{-2}$
L_{xy} > 0.5 mm	0.26	$(1\pm0.3)\times10^{-3}$ *)
α < 0.017 rad	0.23	
$M=M_{Bs}{}^{+140}_{-70\,MeV}$	0.76	0.079
Events/10fb^{-1}	5,7	14^{+13}_{-10}

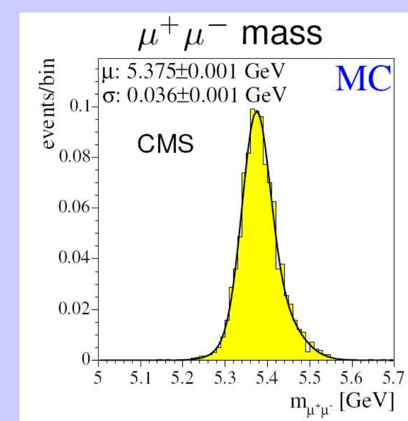
*) α & L_{xy} treated simultaneously to account for correlations

CMS analysis

	$B_s \to \mu\mu$ eff.	$bb \to \mu\mu X$ efficiency
Isolation > 0.85	0.29	0.023
L_{xy} / σ_{xy} > 18	0.37	0.024
α < 0.1 rad	0.63	0.06
$M=M_{Bs}{}^{+100}_{-100\,MeV}$	0.99	0.29
Events/10fb^{-1}	6,1	14^{+22}_{-14}

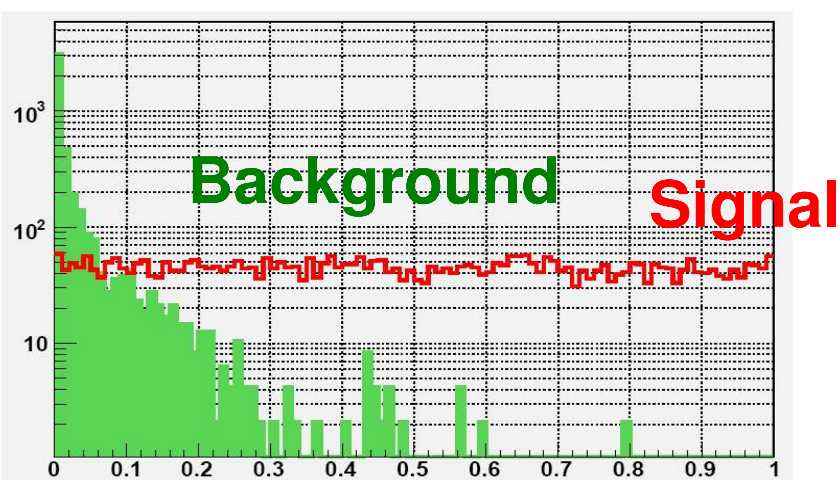






LHCb analysis

- The analysis is performed on events surviving a **common selection** (see LHCb 2008-18) for **signal and control channels** (i.e. $B_{(s)}$→hh and B^+→J/Psi K^+) with a selection efficiency for events fully reconstructed of: $\varepsilon(B_s \to \mu\mu) \cong \varepsilon(B_{(s)} \to hh) \cong \varepsilon(B^+ \to J/Psi\ K^+) \cong 60\%$
- The *GL*, Inv.mass and Muon ID likelihoods are used to discriminate S/B in 3D space
- In the most sensitive bin LHCb expects **~8 signal events** assuming the SM BR for **~12 bkg events with 2 fb^{-1}.**
- Control, normalisation:
  Signal (*GL*): $B_{(s)}$→hh (~200k @ 2 fb^{-1})
  background – from sidebands
  Normalisation - B^+→J/Psi K^+(2M @ 2 fb^{-1})



Geometric likelihood

	GL	
Mass	***0.5 – 0.65***	***0.65-1***
5406.6 - 5429.6	S = 0.23 $17^{+13}_{-8.1}$	S = 0.72 $9.5^{+12}_{-6.1}$
5384.1 - 5406.6	S = 1.0 $19^{+15}_{-9.0}$	S = 2.9 $9.5^{+12}_{-6.1}$
5353.4 - 5384.1	S = 3.3 26^{+20}_{-12}	S = 7.5 $12^{+16}_{-7.7}$
5331.5 – 5353.4	S = 1.4 $19^{+15}_{-9.0}$	S = 3.1 $9.5^{+12}_{-6.1}$
5309.6 – 5331.5	S = 0.42 $19^{+15}_{-9.0}$	S = 0.84 $9.5^{+12}_{-6.1}$

Sensitivity to $B^0_s \to \mu^+\mu^-$ (ATLAS/CMS)

- To convert number of observed events to BR the relative normalisation to the reference channel with a well-measured BR can be used.
  - The natural choice is $B^+ \to J/\psi(\mu\mu)K^+$
  - di-muon trigger and reconstruction efficiencies are essentially cancelled for *signal* and *calibration* channels

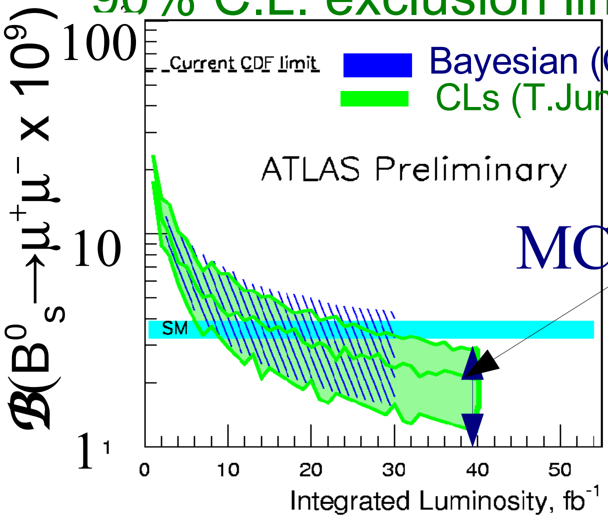
$$BR = \frac{BR_{cal} \cdot \varepsilon^{REC}_{cal} \varepsilon^{SEL/REC}_{cal} \varepsilon^{TRIG/SEL}_{cal}}{\varepsilon^{REC}_{sig} \varepsilon^{SEL/REC}_{sig} \varepsilon^{TRIG/SEL}_{sig}} \cdot \frac{f_{cal}}{f_{Bs}} \cdot \frac{N_{sig}}{N_{cal}}$$

- To set a limit on BR:
  - Bayesian approach (T.Hebekker, L3 Note 2633 (2001)

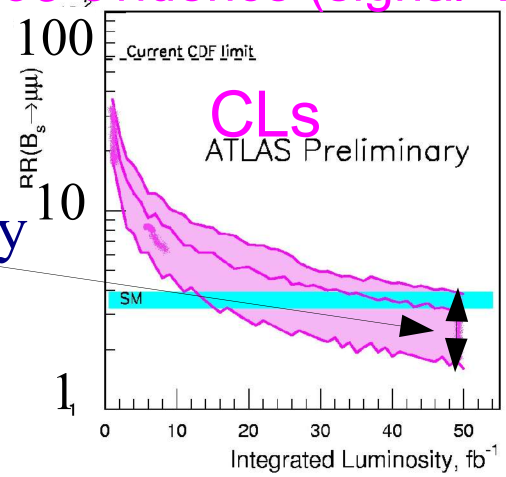
CMS ($10 fb^{-1}$): $\mathcal{B}(B^0_s \to \mu^+\mu^-) \leq \frac{N(n_{obs}, n_B, n_S)}{\varepsilon_{gen}\, \varepsilon_{total}\, N_{B_S}} \leq 1.4 \times 10^{-8}$ (90% C.L.)

ATLAS ($10 fb^{-1}$) $\mathcal{B}(B^0_s \to \mu^+\mu^-) \leq 1.2 \times 10^{-8}$ (90% C.L.)

90% C.L. exclusion limit

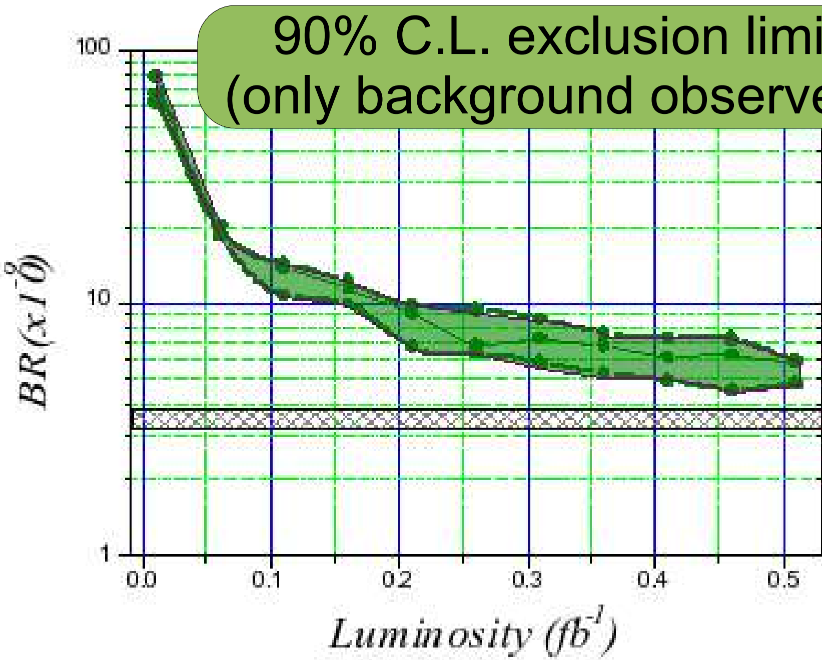


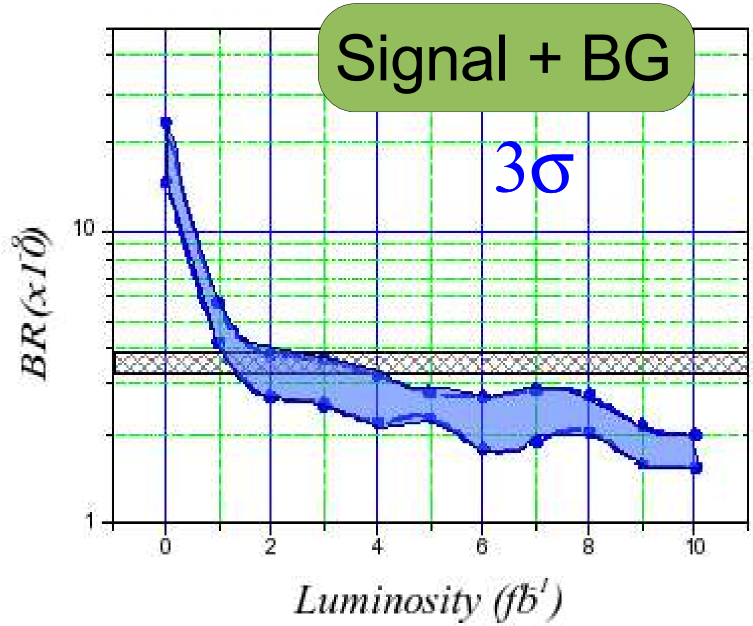
3σ evidence (signal+BG)



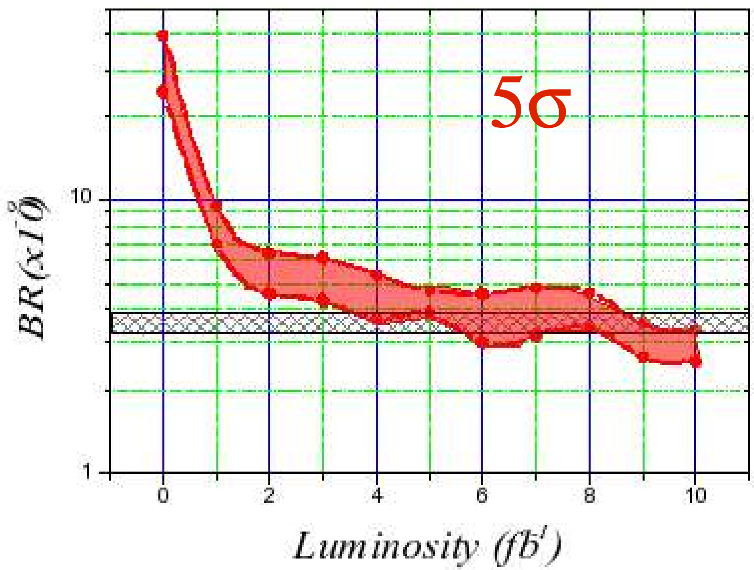
NB! there is the large uncertainty in n_B is due to poor MC statistic! The experimental uncertainty expected to be much less! suppose it of ~10%. Then the limit could be Br < 8×10^{-9} (90% C.L.10 fb^{-1})

LHCb sensitivity





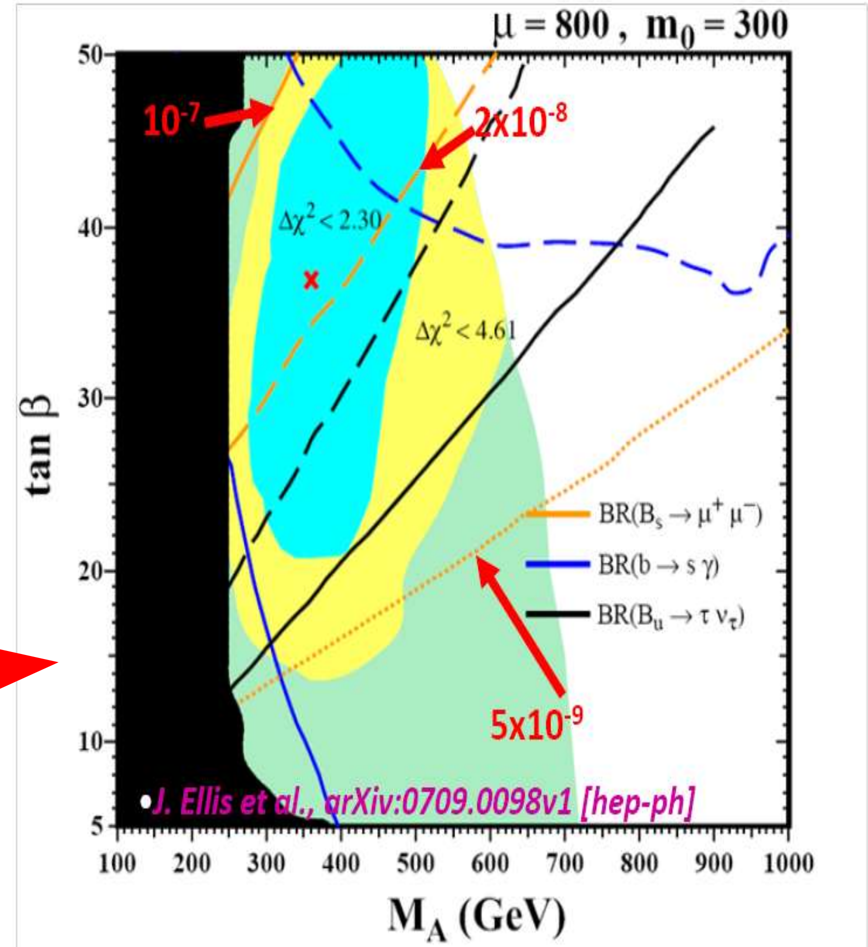
The shaded region correspond to the statistical uncertainty in the background simulation.

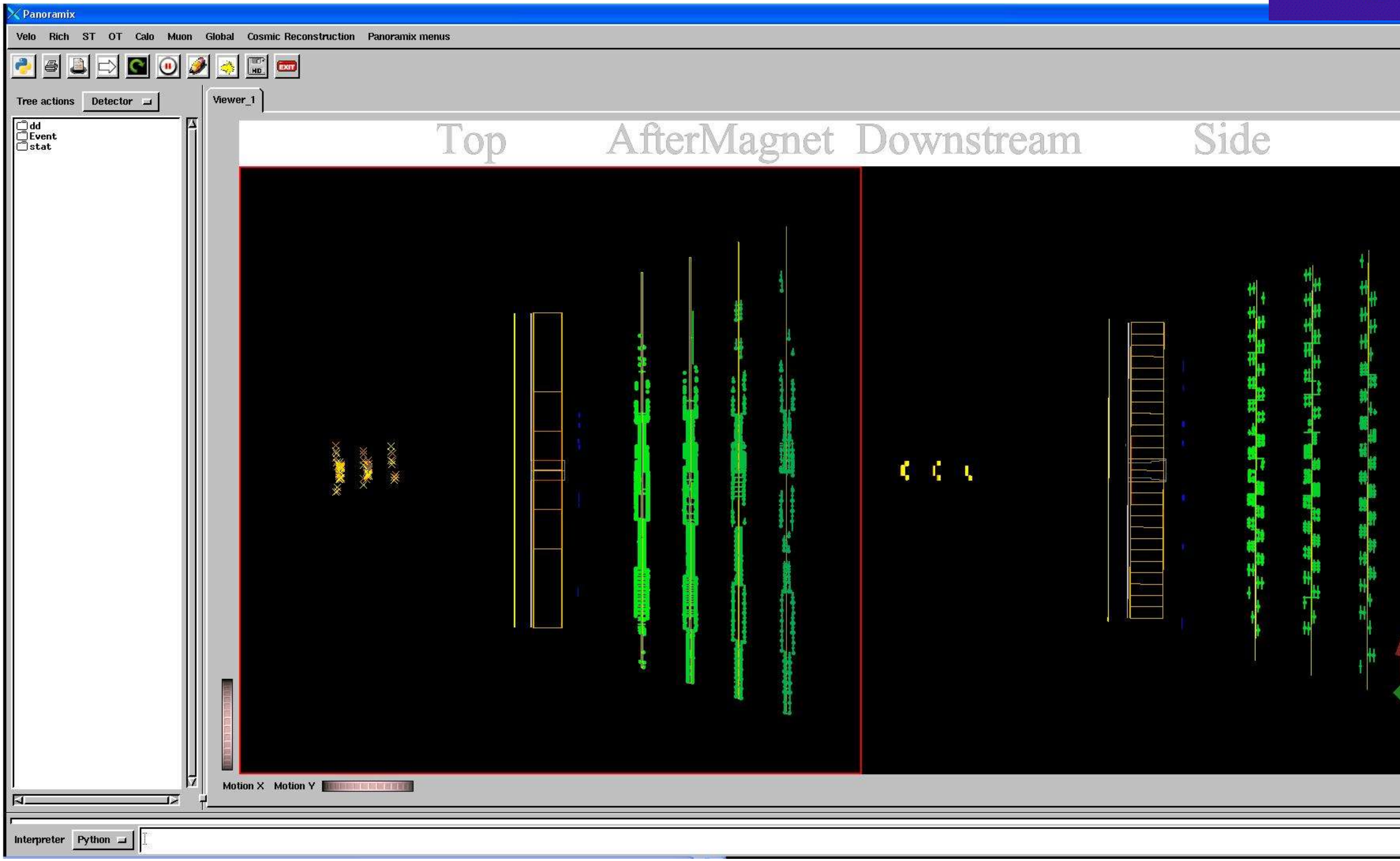


With SM Branching ratio
2 fb^{-1}(1Y)$\Rightarrow$ 3σ evidence
6 fb^{-1}(3Y)$\Rightarrow$ 5σ observation

Conclusions and Outlook

- All 3 experiments have a detailed program for B->μμ discovery and study
- LHCb has a potential for early discovery at low luminosity running (continuing with L = 2 x 10^{32} further)
- Already after several weeks of stable LHC operation considerable improvements of current limits are expected:
  - with only 0.1 fb^{-1} LHCb can observe at the 5σ level a BR~1.5x10^{-8} favored by some SUSY scenarios
- ATLAS and CMS will be competitive starting from L = 10^{33} and will continue at $10^{34}cm^{-2}s^{-1}$




Panoramix
Velo Rich ST OT Calo Muon Global Cosmic Reconstruction Panoramix menus
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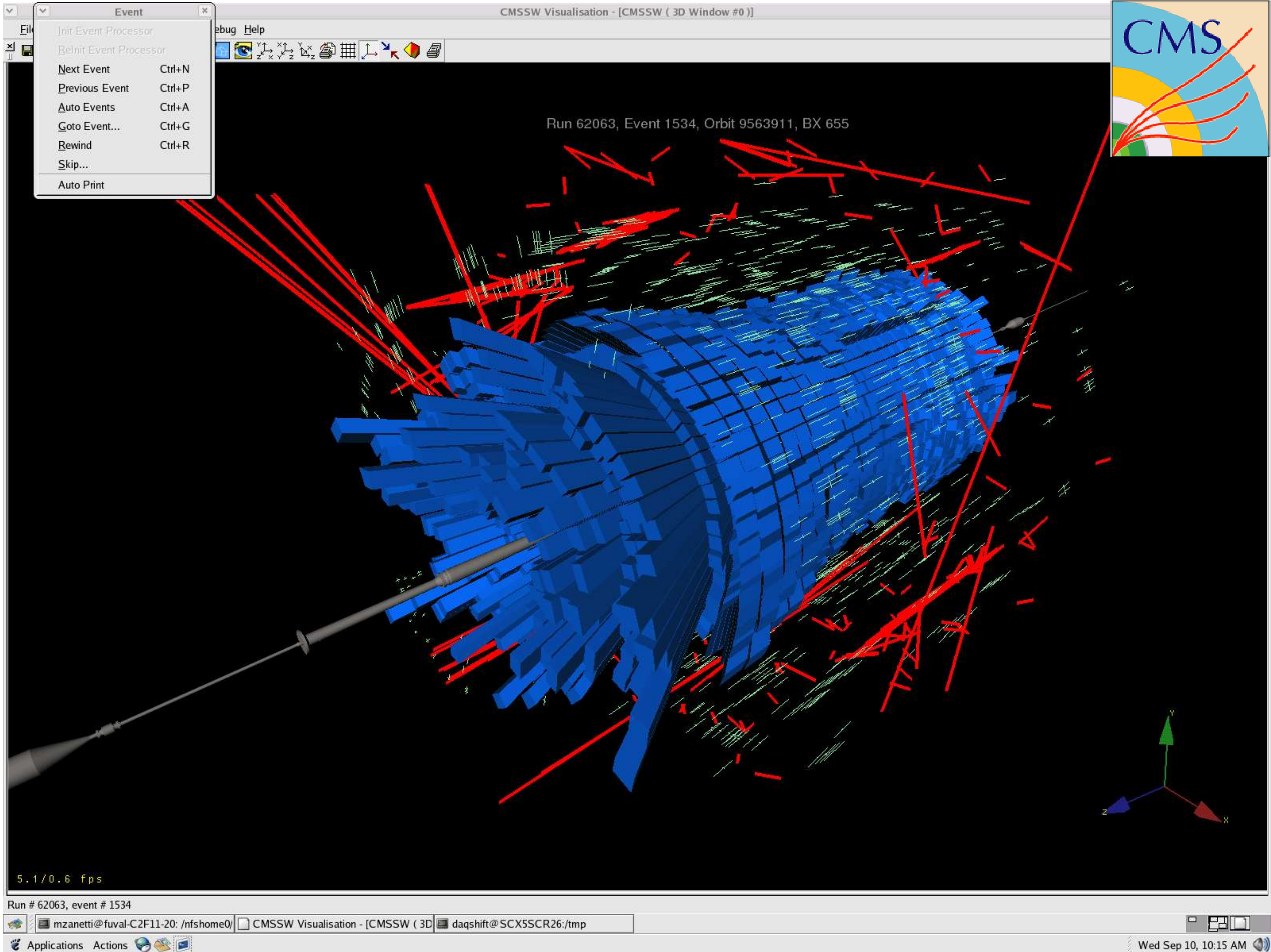

CMSSW Visualisation - [CMSSW (3D Window #0)]
Event
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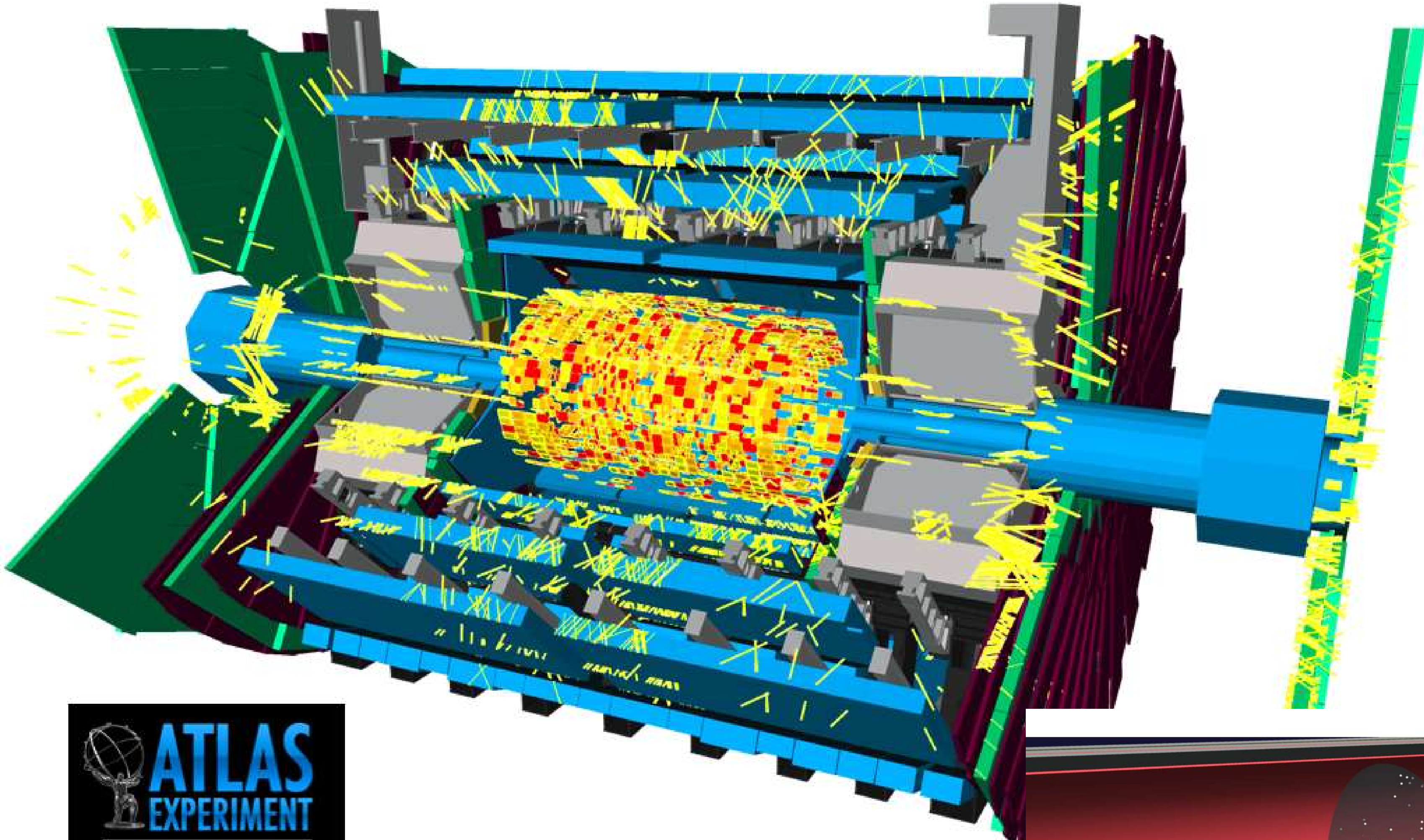
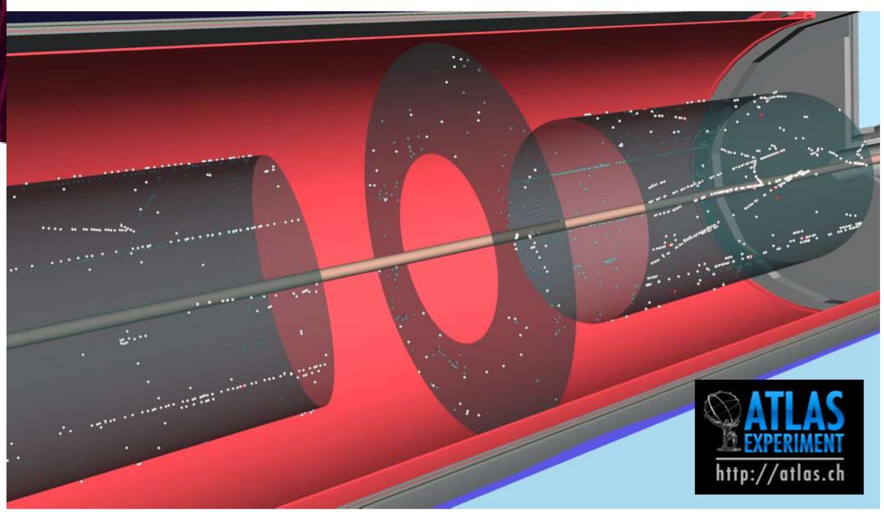


ATLAS EXPERIMENT
http://atlas.ch

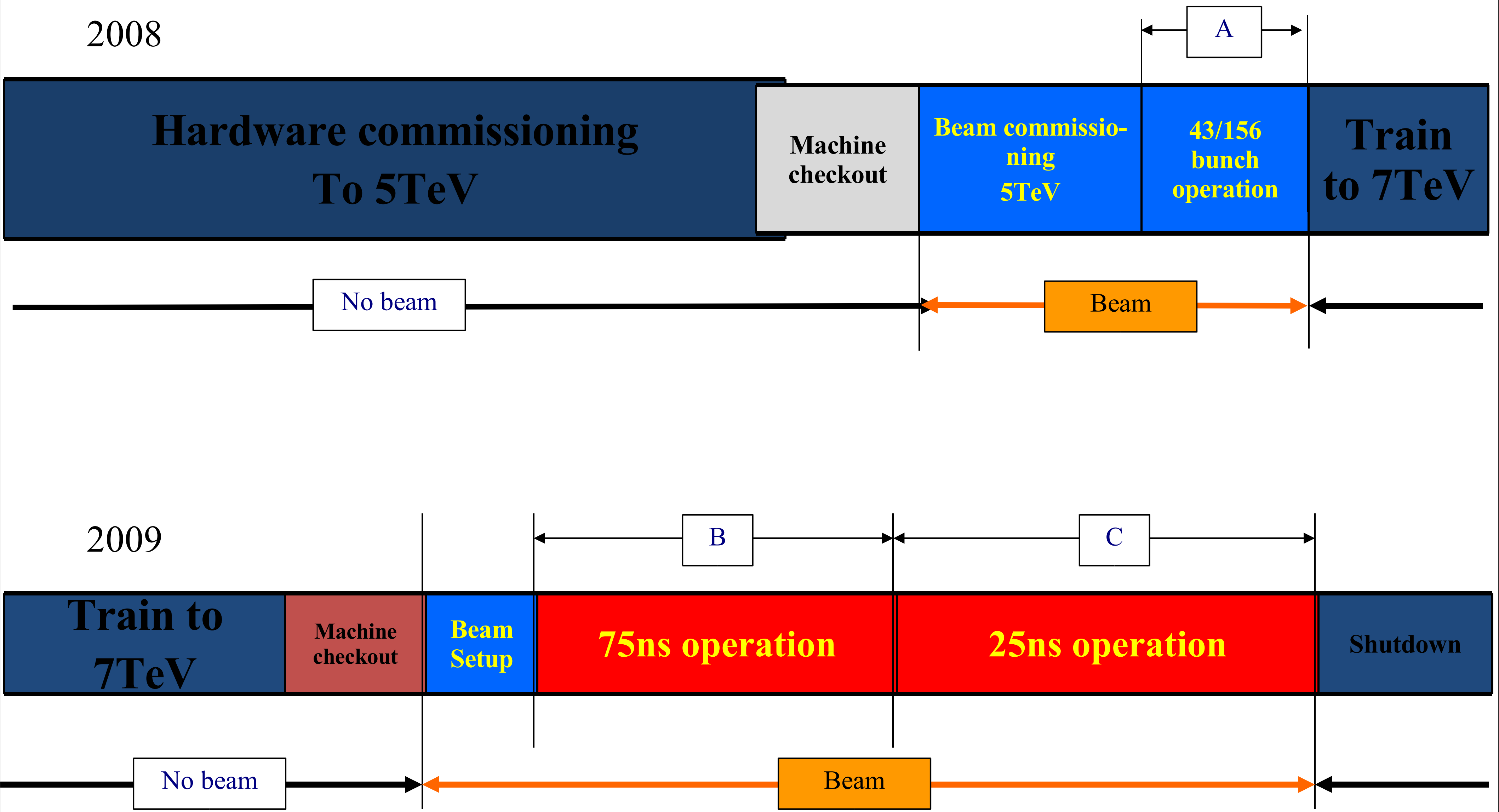
first beam event seen in ATLAS



beam halo event seen in ATLAS

Backup slides

Strategy for 2008 and 2009



Courtesy R. Bailey

Parameter evolution and rates

$$L = \frac{N^2 k_b f \gamma}{4 \pi \varepsilon_n \beta^{¿}} F$$

$$Eventrate / Cross = \frac{L \sigma_{TOT}}{k_b f}$$

All values for nominal emittance, 10m β* in points 2 and 8

All values for 936 or 2808 bunches colliding in 2 and 8 (not quite right)

	Parameters			Beam levels		Rates in 1 and 5		Rates in 2 and 8	
	k_b	N	β* 1,5 (m)	I_{beam} proton	E_{beam} (MJ)	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing	Luminosity ($cm^{-2}s^{-1}$)	Events/ crossing
5 TeV	43	4 10^{10}	11	1.7 10^{12}	1.4	8.0 10^{29}	<< 1	Depend on the configuration of collision pattern	
5 TeV	43	4 10^{10}	3	1.7 10^{12}	1.4	2.9 10^{30}	0.36		
5 TeV	156	4 10^{10}	3	6.2 10^{12}	5	1.0 10^{31}	0.36		
5 TeV	156	9 10^{10}	3	1.4 10^{13}	11	5.4 10^{31}	1.8		
7 TeV	936	4 10^{10}	11	3.7 10^{13}	42	2.4 10^{31}	<< 1	2.6 10^{31}	0.15
7 TeV	936	4 10^{10}	2	3.7 10^{13}	42	1.3 10^{32}	0.73	2.6 10^{31}	0.15
7 TeV	936	6 10^{10}	2	5.6 10^{13}	63	2.9 10^{32}	1.6	6.0 10^{31}	0.34
7 TeV	936	9 10^{10}	1	8.4 10^{13}	94	1.2 10^{33}	7	1.3 10^{32}	0.76
7 TeV	2808	4 10^{10}	11	1.1 10^{14}	126	7.2 10^{31}	<< 1	7.9 10^{31}	0.15
7 TeV	2808	4 10^{10}	2	1.1 10^{14}	126	3.8 10^{32}	0.72	7.9 10^{31}	0.15
7 TeV	2808	5 10^{10}	1	1.4 10^{14}	157	1.1 10^{33}	2.1	1.2 10^{32}	0.24
7 TeV	2808	5 10^{10}	0.55	1.4 10^{14}	157	1.9 10^{33}	3.6	1.2 10^{32}	0.24

R.Bailey, LHCMAC June 2008

(Shown by R Garoby at the LHCC meeting on 1st July)

Basic expectations

Year	Normal Ramp Peak Lumi ($x 10^{34}$)	Normal Ramp Annual Integrated (fb^{-1})	Normal Ramp Total Integrated (fb^{-1})	No phase II Peak Lumi ($x 10^{34}$)	No phase II Annual Integrated (fb^{-1})	No phase II Total Integrated (fb^{-1})
2009	0.1	6	6	0.1	6	6
2010	0.2	12	18	0.2	12	18
2011	0.5	30	48	0.5	30	48
2012	1	60	108	1	60	108
2013	1.5	90	198	1.5	90	198
2014	2	120	318	2	120	318
2015	2.5	150	468	2.5	150	468
2016	3	180	648	3	180	648
2017	3	0	648	3	0	648
2018	5	300	948	3	180	828
2019	8	420	1428	3	180	1008
2020	10	540	2028	3	180	1188
2021	10	600	2628	3	180	1368
2022	10	600	3228	3	180	1548
2023	10	600	3828	3	180	1728
2024	10	600	4428	3	180	1908
2025	10	600	5028	3	180	2088

Collimation phase 2 (2011)

Linac4 + IR upgrade phase 1 (2013)

New injectors + IR upgrade phase 2 (2018)

Radiation damage limit ??? (2022–2025)

ATLAS B-physics program

Measurements overview

CP Violation	$B_d \to J/\psi K_s^0(\pi\pi)$ $J/\psi \to \mu\mu/ee$ $B^+ \to J/\psi(\mu\mu)K^+$ $B_d^0 \to J/\psi(\mu\mu)K^{*0}(K^+\pi^-)$	$\sin(2\beta)$
	$B_s \to J/\psi(\mu\mu)\varphi(KK)$	$\Delta\Gamma_s = \Gamma_H - \Gamma_L$, Γ_s, the weak phase ϕ_s
Measurement of B_s oscillations:	$B_s \to D_s\pi$; $B_{s,d} \to D_s a_1$ $D_s^- \to \varphi\pi^-$; $\varphi \to K^+K^-$	$\Delta m_s = m_H - m_L$
Rare decays	$B_{s,d} \to \mu^+\mu^-$; $B_d^0 \to K^{*0}\mu\mu$ $\Lambda_b \to \Lambda\mu\mu$; $B_s^0 \to \varphi^0\mu\mu$	Precise measurements of the branching ratios and asymmetries
	radiative rare decays	
Λ_b polarization measurements	$\Lambda_b \to J/\psi(\mu\mu)\Lambda(p\pi)$	Asymmetry parameter α_b, P_b, life time measurements
B_c mesons	$B_c \to J/\psi\pi$; $B_c \to J/\psi\mu\nu$	Precise determination of B_c mass, B_c life time

LHCb Analysis Details

- Analysis:
  - Signal description: B→hh (~200k events/2fb^{-1})
  - Background estimation from mass sidebands
  - Normalisation: $B^+ \to J/\psi K^+$ (2M events/2fb^{-1})
  - Dominant uncertainty on BR from relative B_s, B^+ hadronisation fraction ~13%

$$BR = \frac{BR_{cal} \cdot \varepsilon_{cal}^{REC} \varepsilon_{cal}^{SEL/REC} \varepsilon_{cal}^{TRIG/SEL}}{\varepsilon_{sig}^{REC} \varepsilon_{sig}^{SEL/REC} \varepsilon_{sig}^{TRIG/SEL}} \cdot \frac{f_{cal}}{f_{Bs}} \cdot \frac{N_{sig}}{N_{cal}}$$

- Events classified according to geometrical likelihood, PID and B_s invariant mass:
  - Geometric likelihood:
    - B_s Lifetime
    - μ SIPS: Mu Impact Parameter Significance
    - DOCA: Distance of closest approach
    - B_s IP: B_s impact parameter to prim. vtx
    - Isolation: No. of good secondary vtx that can be made with μ candidates
  - PID:
    - Calibration muons (MIPs in calorimeter, J/ψ muons)
  - B_s Invariant Mass