Physics at LHC

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ATLAS and CMS B-Physics Prospects

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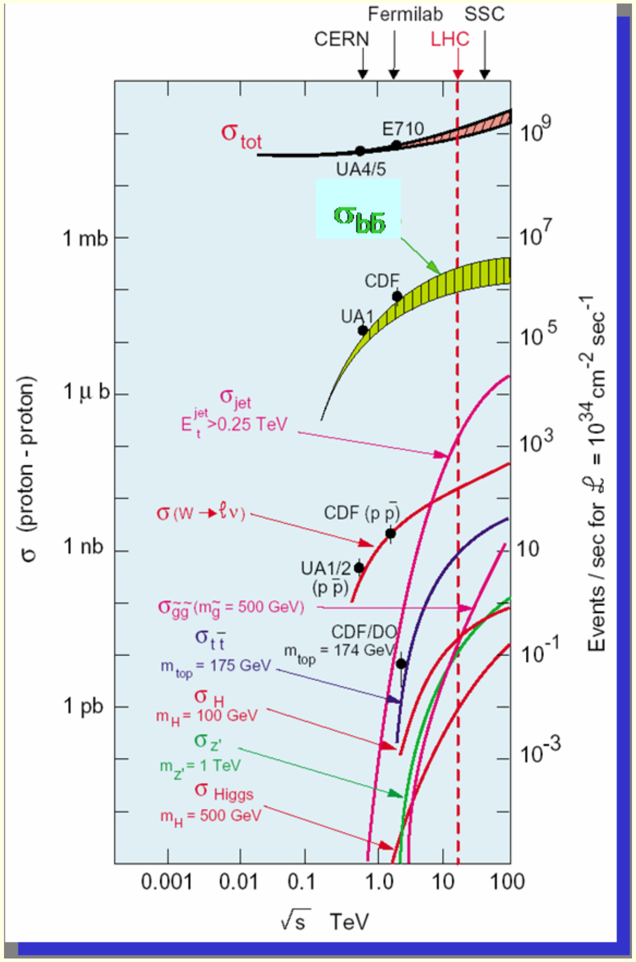
Introduction



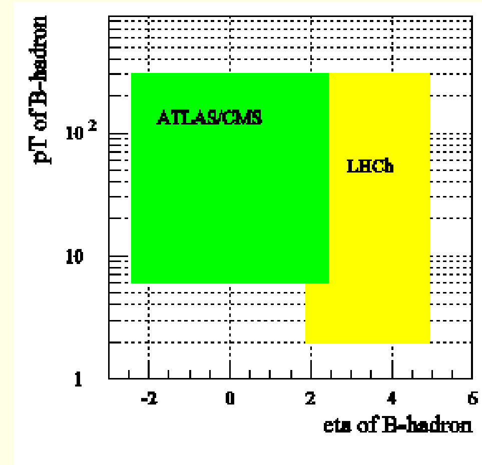
b production at LHC

$\sigma_{\rm total} = 100$ mb

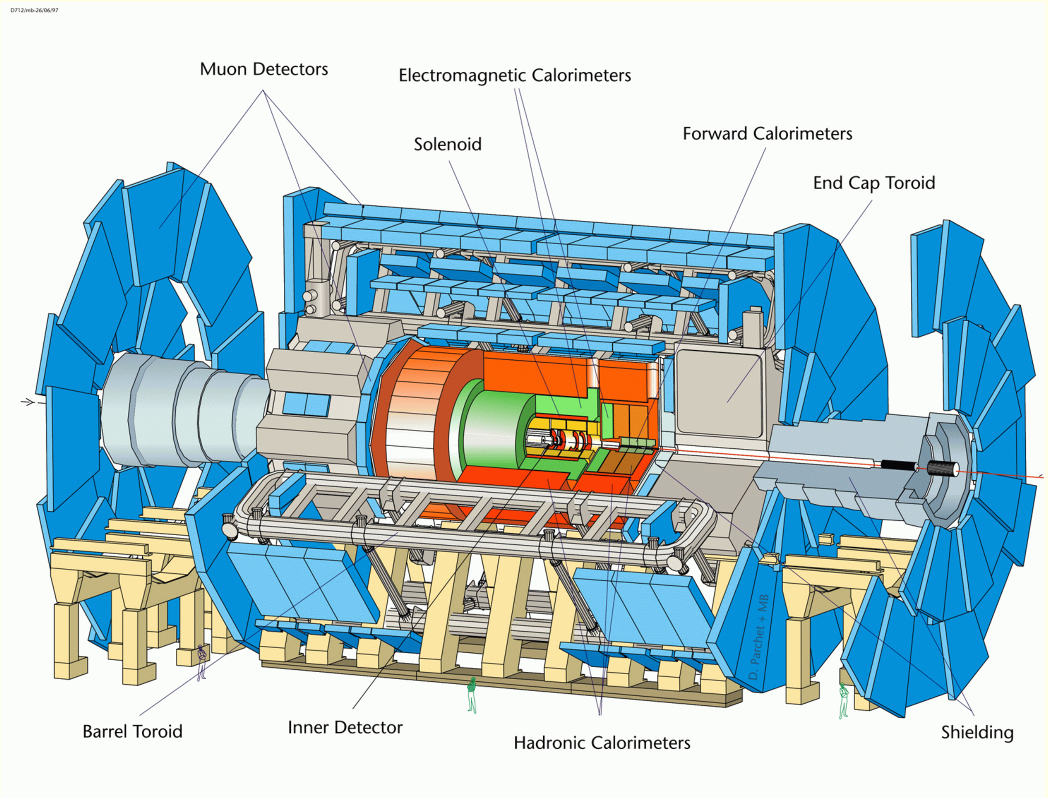
$\sigma_{\rm inelastic} = 80$ mb

$\sigma_{b\bar{b}} = 500\ \mu$b

- Copious production of b hadrons
- Access to B_s^0 and Λ_b^0 decays
- Higher statistics and better signal-to-noise ratio than at Tevatron
- ATLAS/CMS: complementary to LHCb



ATLAS/CMS Central detectors	LHCb Forward detector
$\lvert\eta\rvert < 2.5$, $p_{\rm T} > 10$ GeV $\sigma = 100\ \mu$b	$1.9 < \lvert\eta\rvert < 4.9$, $p_{\rm T} > 2$ GeV $\sigma = 230\ \mu$b
L $= 1 \div 2 \times 10^{33}$ cm^{-2}s^{-1} 10^{34} cm^{-2}s^{-1} rare decays	L $= 2 \times 10^{32}$ cm^{-2}s^{-1}
B-physics LVL1 trigger: lepton	lepton and hadronic trigger
Statistics: 1 y @ 10^{33} cm^{-2}s^{-1} 2.6×10^6 rec. 'physics' events dominated by $bb \to J/\psi$ $< 10^5$ hadronic	1 y @ 2×10^{32} cm^{-2}s^{-1} 3.4×10^6 'physics' events 1.7×10^6 $bb \to J/\psi$ 1.7×10^6 hadronic



Staged detector: $\Longrightarrow$ 'initial layout'

Initial/Complete	barrel	endcaps
InDet Pixel | SCT InDet TRT	2/3 | 4/4 axial tubes	2/3 | 9/9 C-Wheels: no/yes
Muon: endcaps	EEL/EES MDT and 1/2 of CSC	
HLT system	reduced computing resources	

Inner detector: (InDet)

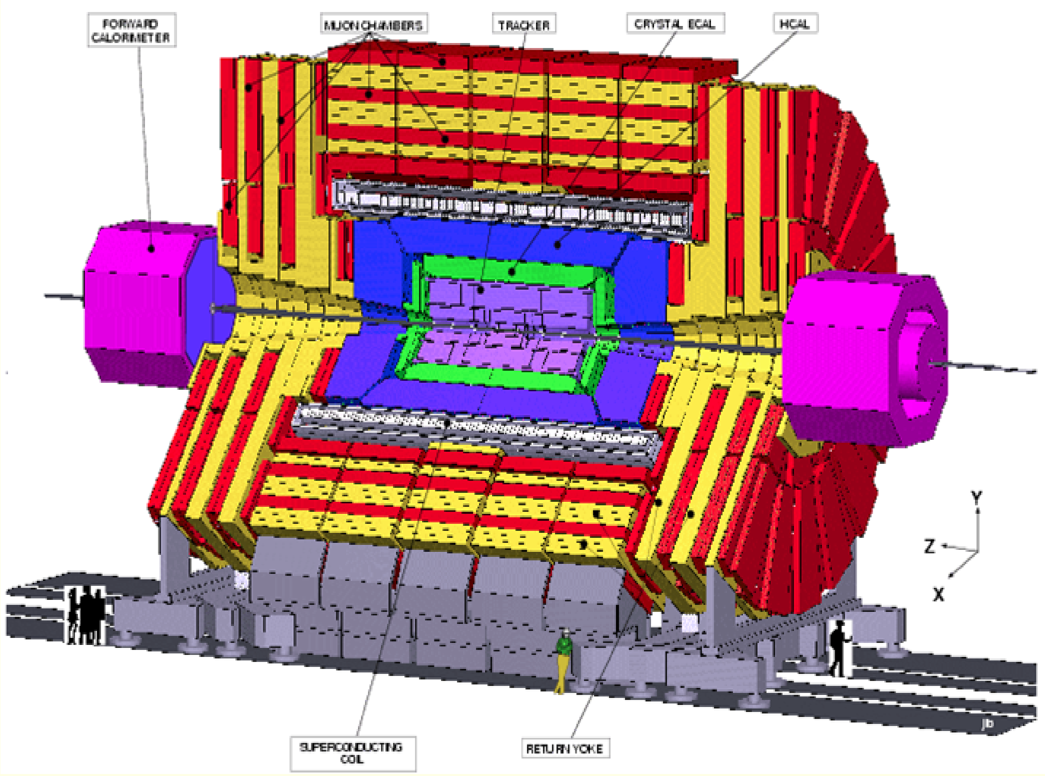
- discrete semiconductor pixel and strip detectors
- transition radiation tracker: straw-tubes interspersed with a radiator $\Longrightarrow$ e/π separation
- inside solenoid: 2 T magn. field

Calorimetry:

- highly granular LAr EM calorimeter: $|\eta| < 3.2$
- hadron calorimeter: $|\eta| < 4.9$ barrel: scintillator-tile, endcaps and forward: LAr

Muon spectrometer:

- air-core toroid system on average ~ 0.5 T.
- MDTs & CSCs; RPCs & TGCs



Staged (•) and descoped (⋆) items:

- muon endcap ME4, RE4, RE1÷3/1
- start with 50% HLT Farm: L1 rate $= 50$ kHz

⋆ HCAL: reduced no. of longitudinal samplings

⋆ ME1/1a (3 channels in one)

Tracker

- pixel detector: 3 barrel layers, 2 disks/E
- silicon strip detector:
  inner barrel TIB: 4 layers,
  inner endcaps TID: each 3 discs;
  outer barrel TOB: 6 layers;
  endcaps TEC: each 9 disks.
- inside the solenoid: 4 T magnetic field.

Calorimetry: inside the solenoid

- high resolution lead-tungstate crystal EM calorimeter: $|\eta| < 3$
- endcap preshower: $\pi^0 - \gamma$ separation
- hadron calorimeter: $|\eta| < 5$

Muon spectrometer:

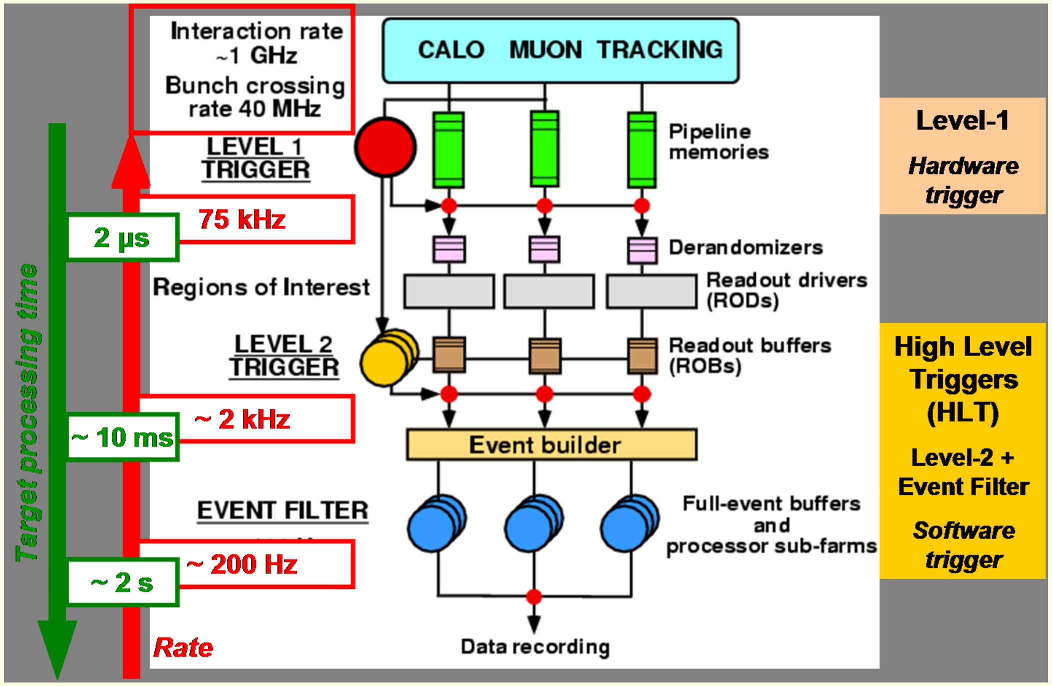
- superconducting solenoid, 4 T.
- barrel: DTs and RPCs
- endcaps: CSCs and RPCs.

Classical B-physics menu contains:

- CP violation studies:
  - $\sin 2\beta$: $B_d^0 \to J/\psi K_S^0$, with $J/\psi \to \mu^+\mu^-$ or $J/\psi \to e^+e^-$
  - α angle: $B_d^0 \to \pi\pi$
  - $\Delta\Gamma_s$, Γ_s, ϕ_s: $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi\eta$
- B_s^0 oscillation studies: $B_s^0 \to D_s\pi$, $B_s^0 \to D_s a_1$ with $D_s \to \phi\pi$
- Exclusive rare decays:
  - purely muonic decays: $B_{d,s} \to \mu^+\mu^-$
  - semi-muonic decays: $B_{d,s} \to \mu^+\mu^- X$ where $X = K^\star,\ \rho^0,\ \phi^0, \ldots$
  - radiative decays: $B_{d,s} \to X\gamma$ where $X = K^\star,\ \rho^0,\ \phi^0, \ldots$
- B_c studies
- B production, $b\bar{b}$ correlation
- b baryon physics, polarization

... but B-physics is and will remain for the next five years a very dynamic domain, both theoretically and experimentally (BaBar, Belle, CDF, D0,...), therefore new channels may become interesting.

Note: results presented here were obtained with different geometries, software releases and trigger conditions.



Trigger tasks:

- reduce the total event rate to ~ 200 Hz, most dedicated to high-p_{T} physics
- maximize coverage of discovery physics
- be open to new signatures
- use inclusive triggers as much as possible

Level-1 trigger (LVL1)

- selection: based on reduced-granularity information from calo and muon trigger chambers
- provides Region of Interest (η, ϕ of LVL1 signature, p_{T} and energy sum of candidate objects) to LVL2

Level-2 trigger (LVL2)

- has access to all event data, with full precision and granularity
- uses LVL1 RoIs to access selectively data, transfer minimum required data
- emphasis: fast rejection & algorithms

Event Filter (EF)

- refines LVL2 selection, using LVL2 RoIs and sophisticated algorithms
- can access detailed alignment and calibration data

B-physics trigger 'classical' scenario:

- LVL1: single muon, $p_{\mathrm{T}} > 6$ GeV, $|\eta| < 2.4$.
- LVL2: μ confirmation within LVL1 RoI, ID track 'full scan'

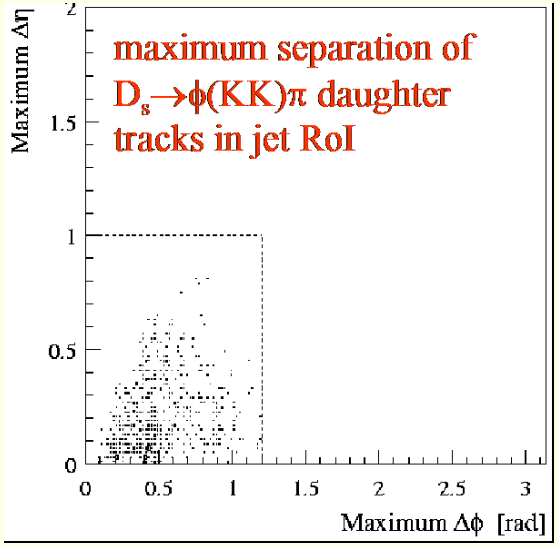
Revised strategy necessary due to:

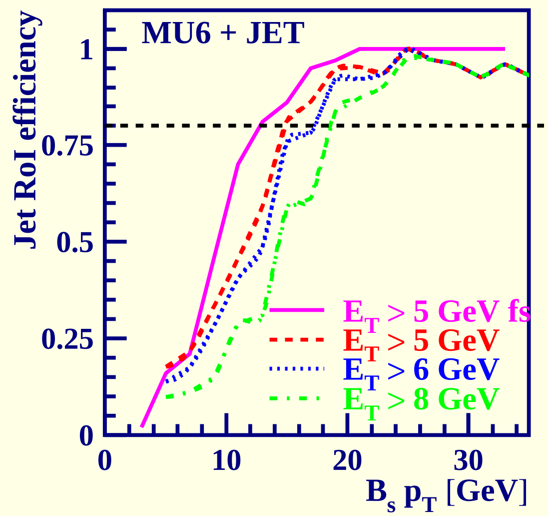
- tight funding constraints
- doubled luminosity target for LHC start-up (2×10^{33} cm^{-2}s^{-1})
- detector changes, staged detector items, significant HLT resource deferrals

B-physics trigger alternatives to reduce computing resources:

- require at LVL1, in addition to single μ trigger, a second muon, a JET or an EM RoI, reconstruct at LVL2/EF within RoI
- re-analyze thresholds and use a flexible trigger strategy, depending on luminosity.

LVL1 Jet, EM RoI: does it make sense?





LVL1 Jet RoI efficiency: reasonable.

Number of RoIs: not fully validated.

ATLAS B-Physics Trigger System (*contd.*)

Trigger types:

- di-muon trigger: LVL1 and LVL2
  - selection for $J/\psi(\mu^+\mu^-)$, $B \to \mu^+\mu^-(X)$, etc.
- hadronic final states triggers + single muon:
  - LVL1 single muon
  - RoI-guided reconstruction in ID at LVL2, RoI from LVL1 Jet trigger
  - alternative: full-scan in ID at LVL2
  - selection for hadronic channels: $B_d^0 \to \pi\pi$, $B_s^0 \to D_s\pi$, etc
- electron-muons final states triggers + single muon:
  - LVL1 single muon
  - RoI-guided reconstruction in TRT at LVL2, RoI from LVL1 EM trigger
  - alternative: full-scan in TRT at LVL2
  - selection for electrons, e.g. $J/\psi \to e^+e^-$

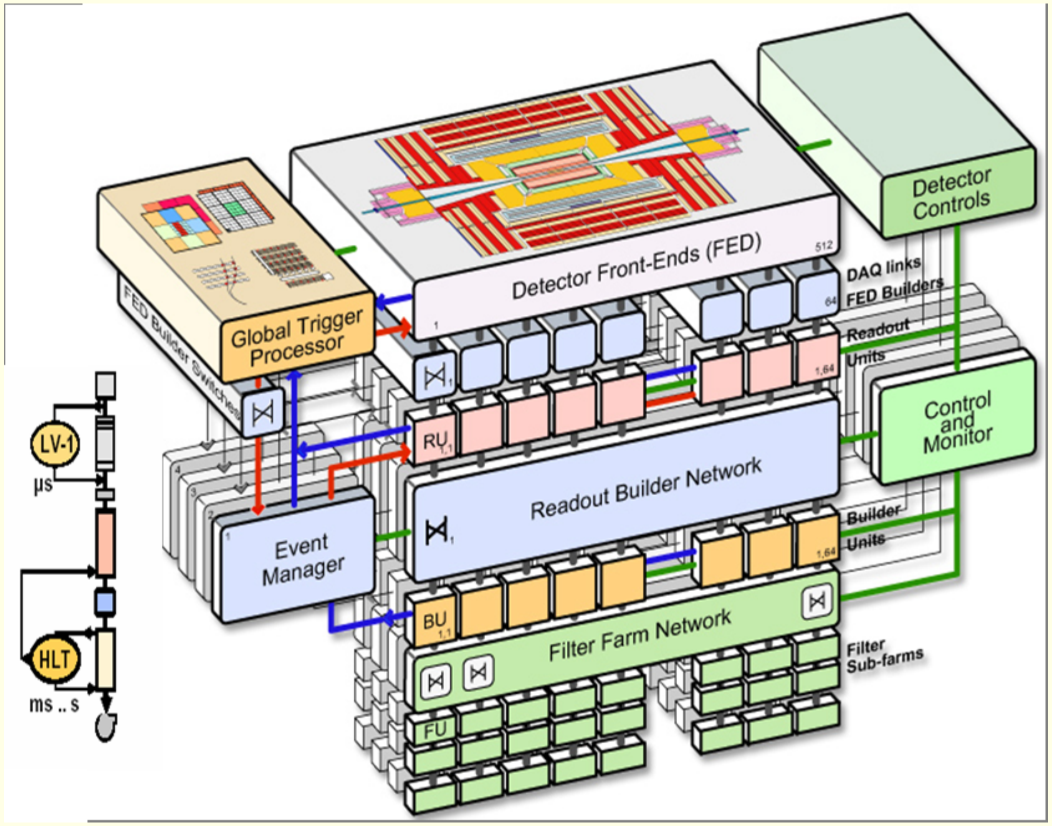
Flexible strategy adapted to limited bandwidth:

- Start with a di-muon trigger for higher luminosities LHC fills.
- Add further triggers (hadronic final states, final states with electrons and muons):
  - in the beam coast
  - for the low luminosity fills.
- Always fill the available bandwidth in the HLT system.

Estimated trigger rates: @ 2×10^{33}

Trigger	LVL1	EF
di-muon	200 Hz	10 Hz
		@ 1×10^{33}
di-muon	100 Hz	5 Hz
$D_s(\phi\pi)$	60 Hz	9 Hz
$B(\pi\pi)$	20 Hz	3 Hz

CMS Trigger System



Trigger tasks:

- reduce the event rate to $\mathcal{O}(100)$ Hz
- cover widest possible range of discovery physics

Main characteristics:

- LVL2, LVL3 merged in a single processor farm
- 8 slices, each slice allow 12.5 kHz

Level-1 trigger (LVL1)

- reduce event rate from 40 MHz to 100 kHz (complete) or 50 kHz (DAQ staged). Total processing time: 3 μs.
- selection: based on coarse information from calo and muon detector

High Level Trigger (HLT)

- output event rate: ~ 100 Hz
  total processing time up to 1 s.
- has access to all event data, with full precision and granularity
- can use the offline software
- to improve trigger performance, can also use HLT tracking algorithms
  - regional reconstruction: LVL1 seeded
  - partial reconstruction
  - conditional reconstruction

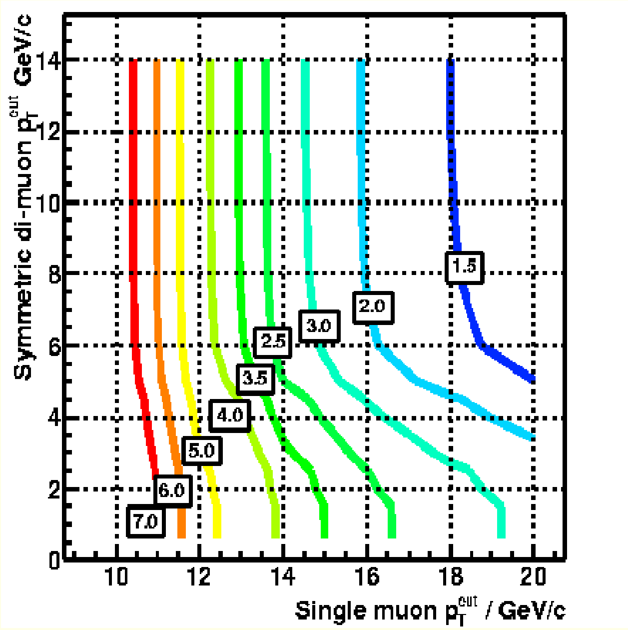
B-physics selection:

- LVL1: single muon, di-muon.
  Thresholds determined by allocated rate.
- HLT: single muon, di-muon.

Alternatives to reduce resources

- reconstruct at HLT some exclusive B decays around the muon(s).
  - use LVL1-seeded regional reconstruction for fast rejection
  - partial reconstruction, combined with p_T cuts (conditional reconstruction)
- possibly use at LVL1 low-p_T muon + low-E_T Jet for hadronic channels. Example:

Cumulative LVL1 $(1\mu, 2\mu)$ rate:



L$= 2 \times 10^{33}$ cm^{-2}s^{-1}, $|\eta^{\rm muon}| < 2.1$

Muon p_T (GeV/c)	$B_s^0 \to D_s\pi$ trigger rates in kHz: HLT(LVL1) $E_T > 0$ GeV	$E_T > 20$ GeV	$E_T > 30$ GeV
6	0.16 (26.0)	0.082(8.5)	0.055(3.6)
10	0.037(6.4)	0.021(2.5)	0.014(1.3)
14	0.017(3.2)	0.010(1.3)	0.008(0.7)

Measurement in the channel: $B_d^0 \to J/\psi K_S^0$.

Analysis: maximum likelihood fit with proper time resolution, tag probability, wrong tag fraction, background composition as input.

direct CP violation term $\sim \cos(\Delta m)$ neglected here, foreseen to be added.

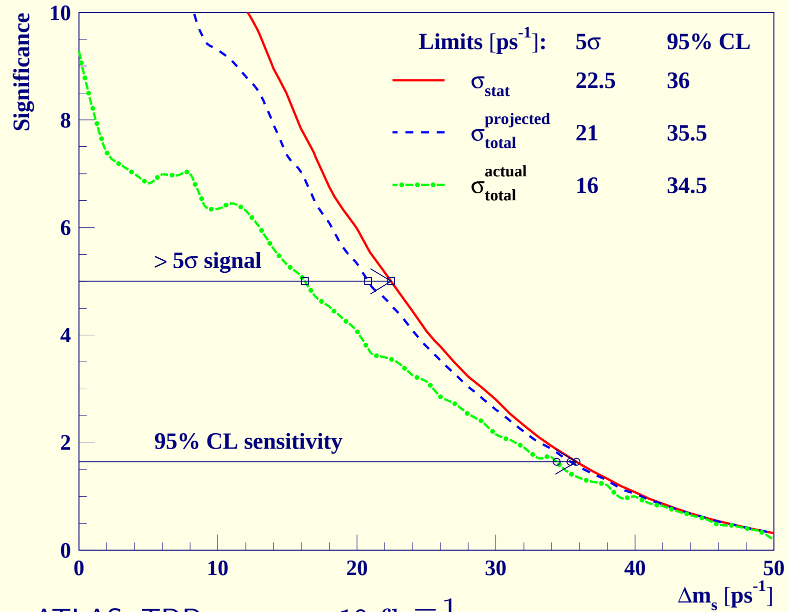
30 fb^{-1}	$J/\psi(\mu 6\,\mu 3)$	$J/\psi(\mu 6\,\mu 5)$	$J/\psi(e1e1)$
Reconstructed events	490k	250k	15k
Signal/Background	28	32	16
$\sigma_{\mathrm{stat}}(\sin 2\beta)$			
Lepton tag	0.023	0.030	0.018
Jet-charge tag	0.015	0.019	-
Combined tag	0.0126	0.016	0.018
$\sigma_{\mathrm{stat}}(\sin 2\beta)$ combined channels, combined tag			
$J/\psi(\mu 6\,\mu 3) + J/\psi(e1e1)$		0.010	
$J/\psi(\mu 6\,\mu 5) + J/\psi(e1e1)$		0.012	
$J/\psi(\mu 6\,\mu 5)$		0.016	
$\sigma_{\mathrm{syst}}(\sin 2\beta)$		0.005	

Numbers correspond to TDR geometry

Precision Measurements of B_s^0-$\bar{B}_s^0$ System Parameters

B_s^0 oscillations in channels $B_s^0 \to D_s\pi$, $B_s^0 \to D_s a_1$

- Performance: strongly dependent on allocated trigger rate (LVL1 muon threshold).
- ATLAS: sensitivity to Δm_s up to 36 ps^{-1} with 10 fb^{-1} and LVL1 muon threshold $p_\mathrm{T} = 6$ GeV.
- CMS: new evaluation, very restrictive trigger (1 kHz allocated at LVL1, 5 Hz @HLT, 1 year): sensitivity to Δm_s up to 20 ps^{-1}.
- SM allowed range $14.3 < \Delta m_s < 26\ \mathrm{ps}^{-1}$.



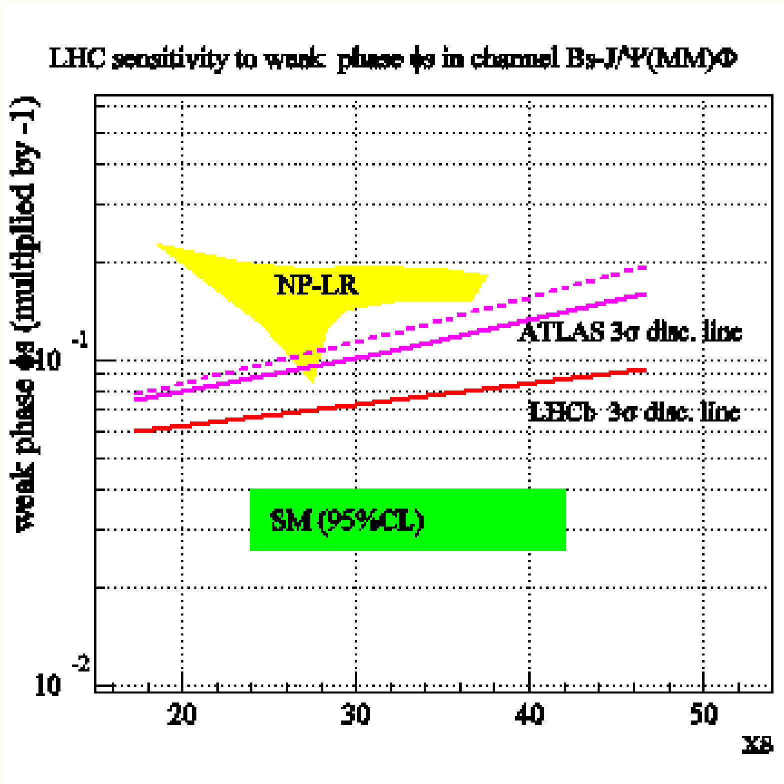
ATLAS, TDR geometry, 10 fb^{-1}

$\Delta\Gamma_s$, Γ_s, ϕ_s in channels: $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi\eta$

- Angular analyses of $B_s^0 \to J/\psi\phi$: determine $\Delta\Gamma_s$, Γ_s, ϕ_s simultaneously with $A_\parallel(t=0)$, $A_\perp(t=0)$, $A_0(t=0)$, δ_1, δ_2 from a maximum-likelihood fit.

30 fb^{-1}	$\sigma(\Delta\Gamma_s)/\Delta\Gamma_s$	$-\phi_s$	$\sigma(\phi_s)(x_s = 20 \div 40)$
ATLAS ($J/\psi\phi$)	12% (stat)	$0.08 \div 0.15$ ($x_s = 20 \div 40$)	$0.03 \div 0.05$
ATLAS ($J/\psi\eta$)		$0.27 \div 0.31$ ($x_s = 20 \div 30$)	
CMS ($J/\psi\phi$)	$8 \div 15$% (stat)	$0.04 \div 0.04$ ($x_s = 20 \div 40$)	$0.02 \div 0.04$

CP-Violation Weak Mixing Phase Φ_s and New Physics



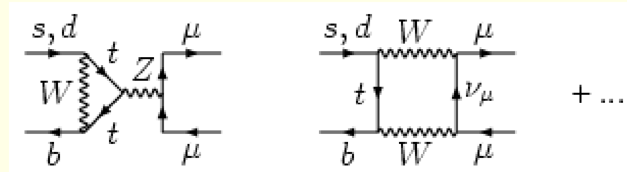
- Standard Model region (updated 2003)
- Left-Right Symmetric Models (NP-LR) (2000)
- LHCb (5 y, performance parameters 2000)
- ATLAS Initial Layout
- ATLAS Complete Layout

ATLAS sensitive to new physics, even with the Initial Layout.

- Physics potential of both ATLAS and CMS not yet fully investigated - studies underway for new tagging and trigger optimization.
- Theoretical model predictions also to be updated soon.

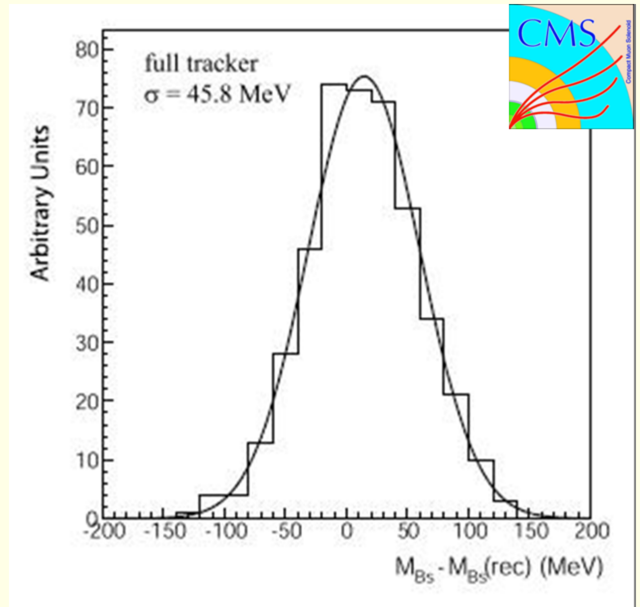
Rare decays:

- transitions at loop level in SM, FCNC B decays
  $\bar{b} \to \bar{s}$ or $\bar{b} \to \bar{d} \Longrightarrow$ small exclusive BRs $< 10^{-5}$
- sensitive probes for new physics



$B_{d,s} \to \mu^+\mu^-$

- theoretically clean channel: involves only f_{B_q}
  $\mathrm{BR} = 3.5 \times 10^{-9}$ (B^0_s), $1.5 \times 10^{-10}(B^0_d)$ in SM
- expect large contributions from new physics (SUSY)
- experimentally clean, but challenging
- triggered at low and high luminosity (di-muon trigger)

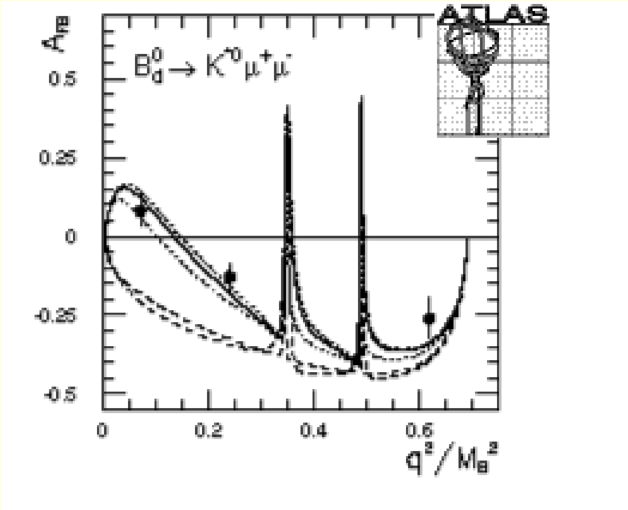


Expected number of events (SM BRs, 1y 10^{34} cm^{-2}s^{-1}, non-updated trigger)

100 fb^{-1}	Signal $B_s \to \mu^+\mu^-$	Signal $B_d \to \mu^+\mu^-$	Bkgd
ATLAS	92	14	660
CMS	26	4	< 6.4

Difference ATLAS/CMS for background rejection:
- no CAL muon isolation implemented yet in ATLAS
- ATLAS/CMS muon resolutions?
- ATLAS/CMS re-evaluation of background

- Theoretically difficult: involves hadron form factors and long-distance contributions.
- In SM: $B_d \to K^{\star 0}\mu^+\mu^-$ sensitive to $|V_{ts}|$ and N$(B_d \to \rho^0\mu^+\mu^-)$/N$(B_d \to K^{\star 0}\mu^+\mu^-) \sim |V_{td}|^2/|V_{ts}|^2$
- Shape of muon forward-backward asymmetry sensitive to new physics (MSSM) via non-standard values of Wilson coefficients.



——— SM
······ MSSM $C_{7_\gamma} > 0$
- - - - MSSM $C_{7_\gamma} < 0$
• mean A_{FB} in three experimental q^2/M_B^2 regions

Number of events (ATLAS, 30 fb^{-1}, TDR geometry)

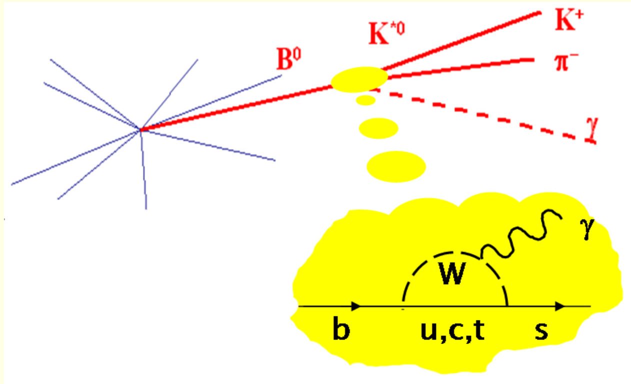
Channel	BR	Signal	Bkgd
$B_d \to K^{\star 0}\mu^+\mu^-$	1.5×10^{-6}	1995	290
$B_d \to \rho^0\mu^+\mu^-$	10^{-7}	222	950
$B_d \to \phi^0\mu^+\mu^-$	10^{-6}	411	140

$$A_{FB}(s) = \frac{1}{d\Gamma/ds}\int_0^1 \frac{d^2\Gamma}{ds\,d\cos\theta}d\cos\theta - \int_{-1}^0 \frac{d^2\Gamma}{ds\,d\cos(\theta)}d\cos\theta$$

θ: angle between μ^+ and B-meson direction in the dilepton rest frame

In the lowest mass region: sufficient accuracy to separate SM and MSSM if $C_{7_\gamma} < 0$.

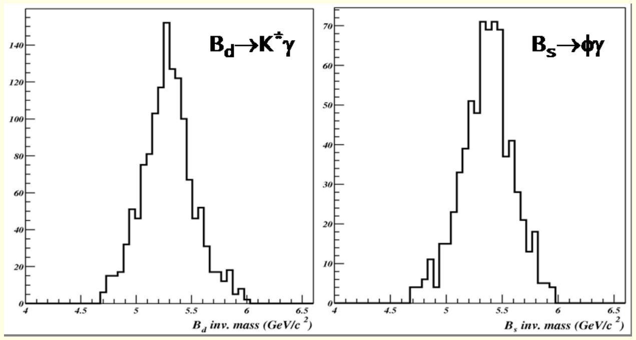
- Theoretically difficult: involves hadron form factors and long-distance contributions.
- Sensitive to new physics through BRs enhancements
- CP asymmetries in $B \to \rho\gamma$ decays
- Isospin violation in $B \to K^{\star 0}\gamma$ and $B \to \rho\gamma$ decays.



ATLAS studies: $B_d \to K^{\star 0}\gamma$, $B_s \to \phi\gamma$

Expected number of events:

20 fb^{-1}(1y 2×10^{33} cm^{-2}s^{-1}):
non-optimized offline cuts;
numbers depend also on trigger strategy, not validated



Channel	BR	Signal	S/B
$B_d \to K^{\star 0}\gamma$	4.3×10^{-5}	[4200, 8500]	> 0.01
$B_s \to \phi\gamma$	4.3×10^{-5}	[2500, 3200]	> 0.04

Inner Detector geometry evolution: most B-physics to be done with 'Initial Layout'

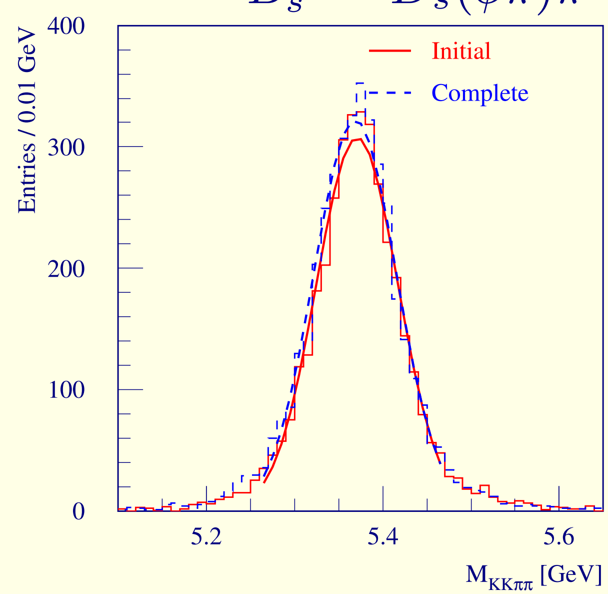
InDet Layout	Physics TDR	Initial	Complete
Radius of b-layer	4.3 cm	5.05 cm	5.05 cm
Radius of middle pixel layer	11.0 cm	staged	8.85 cm
Radius of last pixel layer	14.2 cm	12.25 cm	12.25 cm
Pitch Z in b-layer	300 μm	400μm	400 μm
Number of Pixel disks	4	2	3
Endcap TRT 'C' wheels	present	staged	present

B-physics performance with initial / complete layout

Mass resolution

Channel	Mass resolution, single Gaussian fit		
	TDR	Initial	Complete
$B_s^0 \to D_s(\phi\pi)\pi$	42 MeV	46 MeV	47 MeV
$B \to \mu^+\mu^-$	68 MeV	78 MeV	80 MeV
$B_d^0 \to J/\psi K_S^0$	19 MeV	21 MeV	22 MeV
$B_s^0 \to J/\psi\phi$	15 MeV	17 MeV	17 MeV

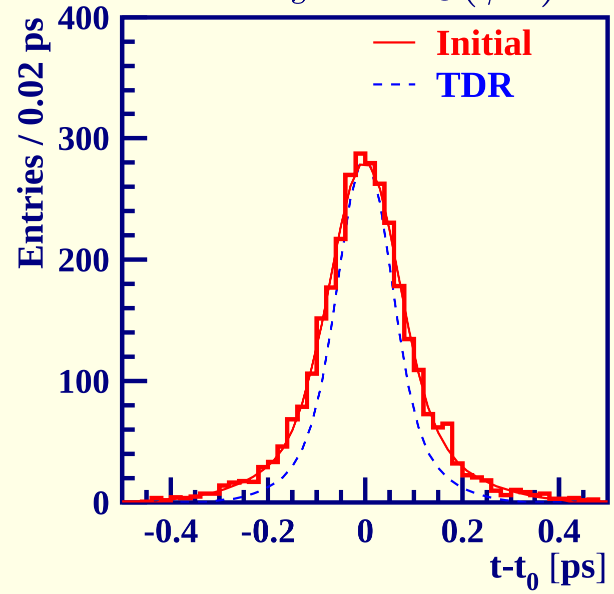
$B_s^0 \to D_s(\phi\pi)\pi$



B-physics performance with initial / complete layout: other quantities

- proper time resolution in B_s^0 decays:
  - initial and complete layouts have approx. the same resolution
  - core resolution: TDR layout ~ 52 fs, initial layout > 60 fs
  - cuts optimization: $\mathrm{N}_{\mathrm{events}}$ vs resolution
- number of reconstructed events:
  - $5 \div 10\%$ events lost for initial layout w.r.t. complete layout

$B_s^0 \to D_s(\phi\pi)\pi$



Preliminary conclusion: B-physics track-related performance

- The performance of the detector is not deteriorated significantly for the initial layout w.r.t. the complete layout.
- but . . . assuming no additional dead cells and mis-alignment in the InDet
- and . . . more elaborated track error calculation needed in the reconstruction.

HLT staging has the most significant effect on B-physics

Conclusions

- ATLAS and CMS are capable to pursue an extensive B-physics program:
  - main emphasis on underlaying mechanisms of CP-violation and evidence for new physics: precise measurement of β angle, new physics in $B_s^0 \to J/\psi\phi$.
  - precision measurements of B_s^0 properties: sensitivity on Δm_s beyond SM expectation, width difference $\Delta\Gamma_s$, width Γ_s.
  - rare decays measurements $B_s \to \mu^+\mu^-(X)$ extended to nominal LHC luminosity 10^{34} cm^{-2}s^{-1}; able to measure $B_s \to \mu^+\mu^-$ branching ratio of $\mathcal{O}(10^{-9})$ in SM.
  - precision measurements of B_c properties
  - QCD tests with measurements of b production and $b\bar{b}$ correlations
- B-physics performance will strongly dependent on:
  - allocated B-physics trigger rate: di-muon trigger safe, hadronic triggers mostly affected
  - LHC operating conditions: lower luminosity favors B-physics.
- Concentrated effort on B-physics trigger studies for both ATLAS and CMS. New strategies try to minimize effect of large resources deferrals in HLT systems.
- More details and better, more consistent prospect evaluation will be available in the next few years.