Heavy Quarks & Leptons

15 October 2010

Future and Prospects for Heavy Flavour Physics at LHC

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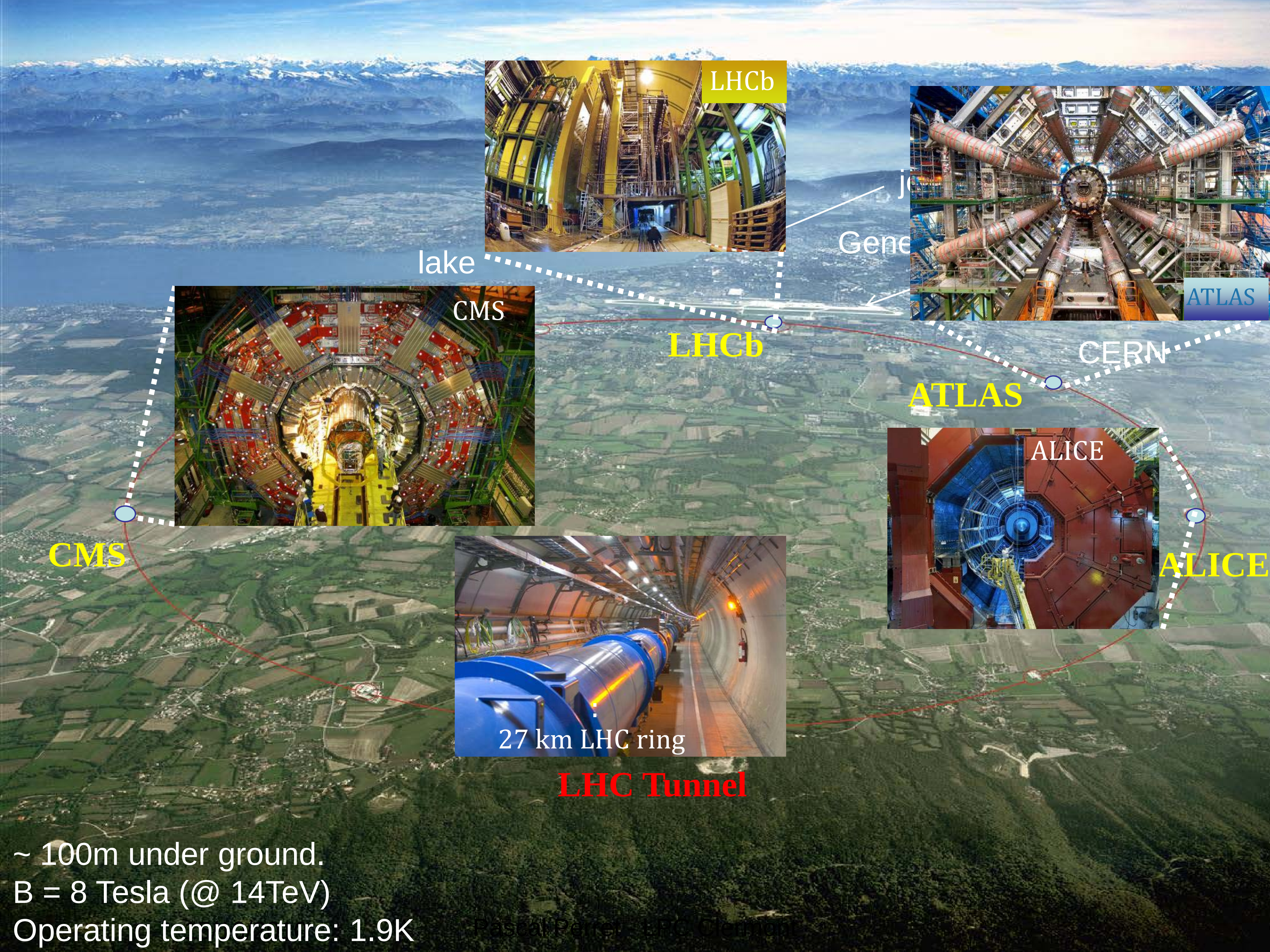
On behalf of the ATLAS, CMS & LHCb Collaboration

Content

- The present:
  - LHC & Detector performances highlight
  - First LHC Heavy Flavour Results
- The future (selected topics)
- Prospects: LHCb upgrade
- Conclusions

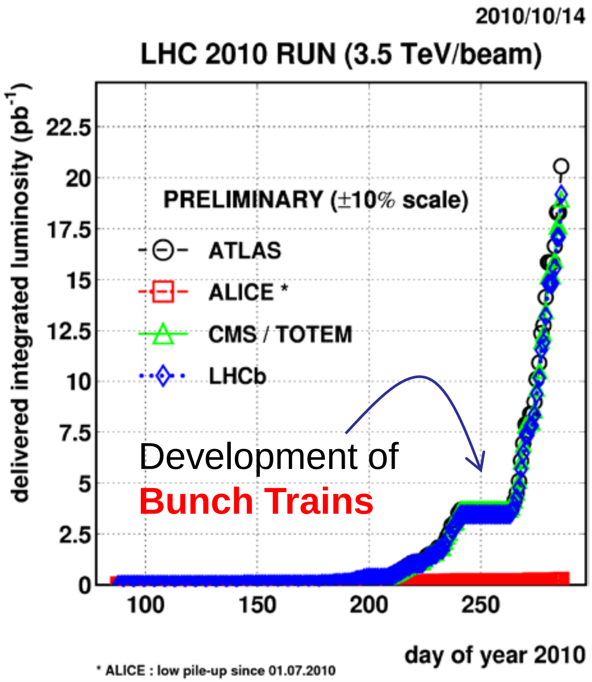
- Disclaimers:
  - Many topics not cover!
  - More details in other talks
    - LHC: ATLAS, CMS, LHCb
    - Tevatron: CDF, D0
    - Babar, Belle
    - …


LHCb
ATLAS
lake
CMS
LHCb
CERN
ATLAS
ALICE
CMS
ALICE
27 km LHC ring
LHC Tunnel
~ 100m under ground.
B = 8 Tesla (@ 14TeV)
Operating temperature: 1.9K

LHC Performance

- Current program
  - Data taking at 7 TeV since March 2010
  - Alternating periods of machine LHC commissioning and physics data taking
    - Initial collisions with 2×10^{10} p/bunch
    - Now: 10^{11} p/bunch
    - Last week:
      - N= 248 bunches in trains with 233 bunches colliding (nominal LHC 2808/beam)
      - 48bunches added in LHC beam each week!
    - **L^{peak}= 1.03×10^{32} cm^{-2}s^{-1} yesterday!**
- Future aims
  - ~~L=10^{32} cm^{-2}s^{-1}~~ by end 2010: **Achieved!**
    - We should collect ~30-50 pb^{-1}/experiment
  - 1 fb^{-1} by end 2011

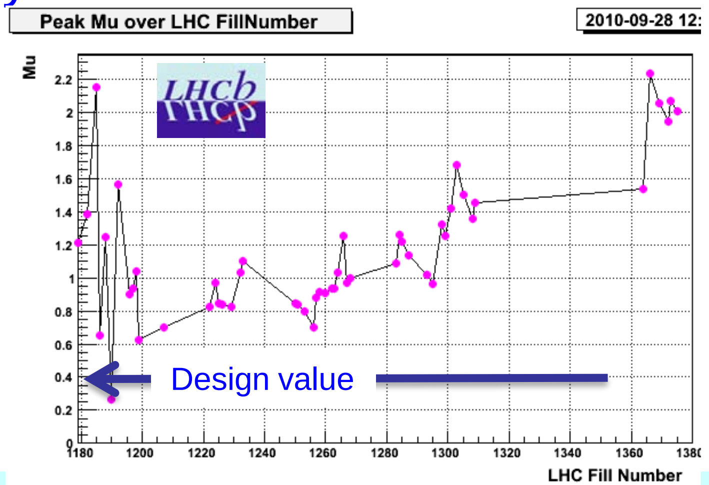
Excellent machine performances!



Delivered luminosity increasing exponentially!

LHC Performance

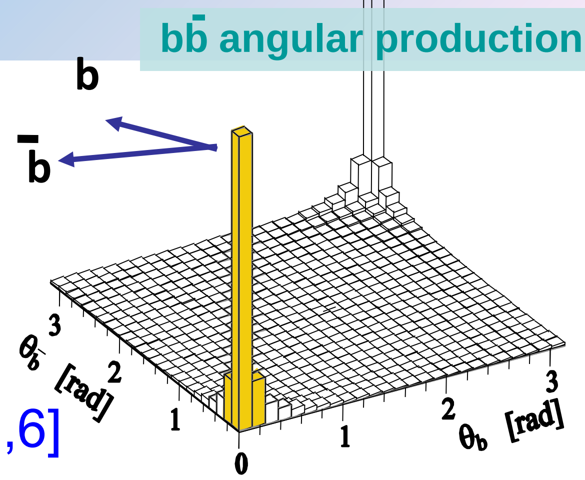
- LHC experiments will operate at different nominal luminosities:
  - ATLAS/CMS: $\mathcal{L}_{Nominal}=\mathcal{L}_{LHC}=10^{34}\ cm^{-2}s^{-1}$
  - LHCb: $\mathcal{L}_{LHCb}=2\times10^{32}\ cm^{-2}s^{-1}$
    - by focusing less than at ATLAS and CMS
      - with $\beta^* = 10$ m ~ 0.4 pp visible interactions per bunch crossing
- However, the present running conditions are different:
  - LHC is reaching $\mathcal{L}=10^{32}\ cm^{-2}s^{-1}$ soon
    - All experiments (but Alice) are running at the same luminosity
    - This is close to LHCb nominal luminosity
    - **But with fewer bunches and with β^* = 3.5 m $\Rightarrow$ ~ 2.0 pp visible interactions per crossing**
    - **LHCb use flexibility of trigger to adapt to actual conditions**



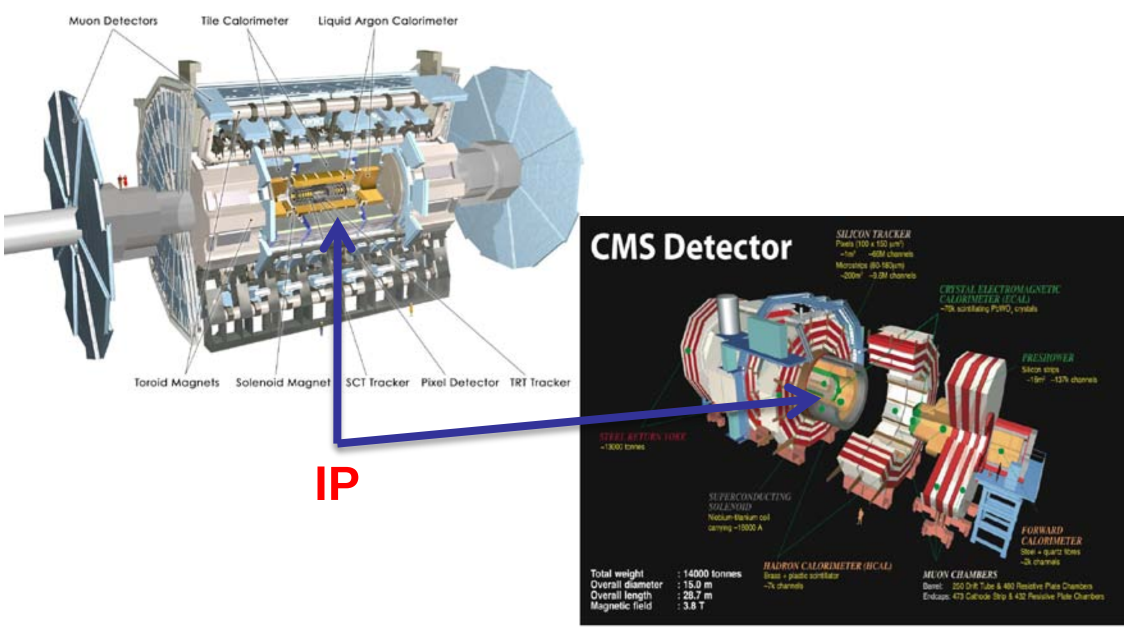
Heavy Flavours @ LHC

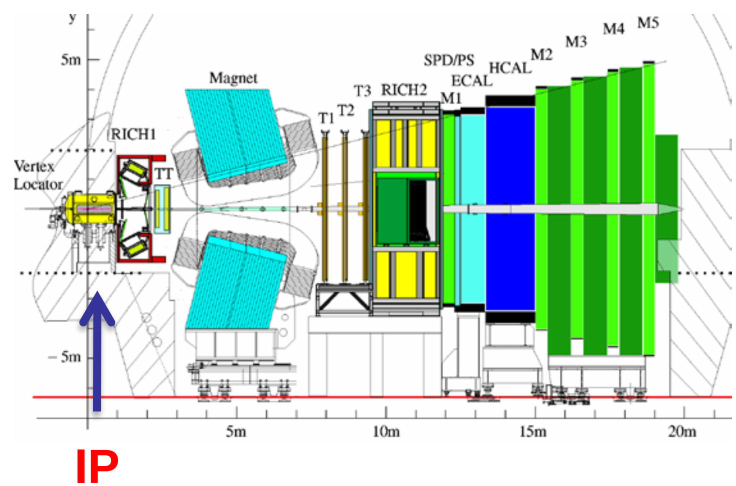
- LHC is a B- and D-mesons super factory:
  - Large $b\bar{b}$ cross section (~300 µb – 500 µb @ $\sqrt{s}$=7 – 14 TeV):
    - LHC @ 50 pb^{-1} [delivered per experiment]
      - ~ 1.5 x 10^{10} B mesons [all species produced, B^0,B^+,B_S,..]
      - ~ 2.5 x10^{11} D mesons
    - B factories @ Y(4S) full statistics [delivered, Babar+Belle]:
      - ~1.5 x10^9 B^+,B^0 mesons
      - ~2 x 10^9 D mesons
  - However, there are also challenges:
    - High multiplicity of tracks (~30 tracks per unit of rapidity)
    - High rate of background events ($\sigma_{vis.\ Inel.}$ ~ 60 mb at $\sqrt{s}$ =7 TeV)
      - 1/200 event contains a b quark, typical interesting BR < 10^{-3}

Heavy Flavours @ LHC



- LHC is a B- and D-mesons super factory:
  - $b\bar{b}$ produced mostly forward/backward
  - Detectors have different acceptance:
    - ATLAS/CMS $|\eta|<2.5$
    - LHCb forward spectrometer covering $\eta=[2,6]$
      - ~30% in LHCb acceptance

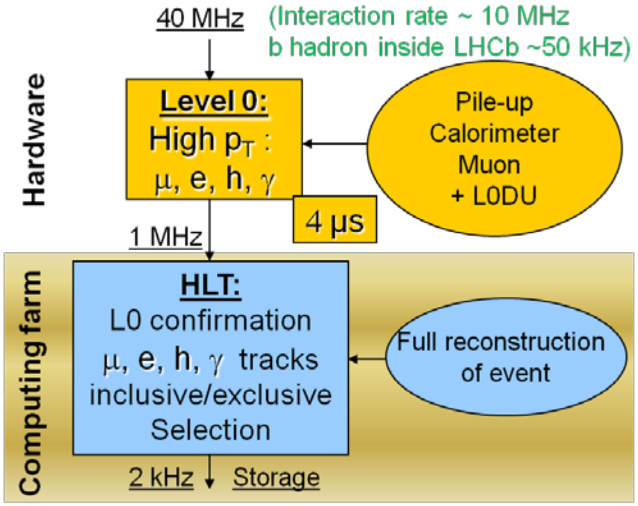




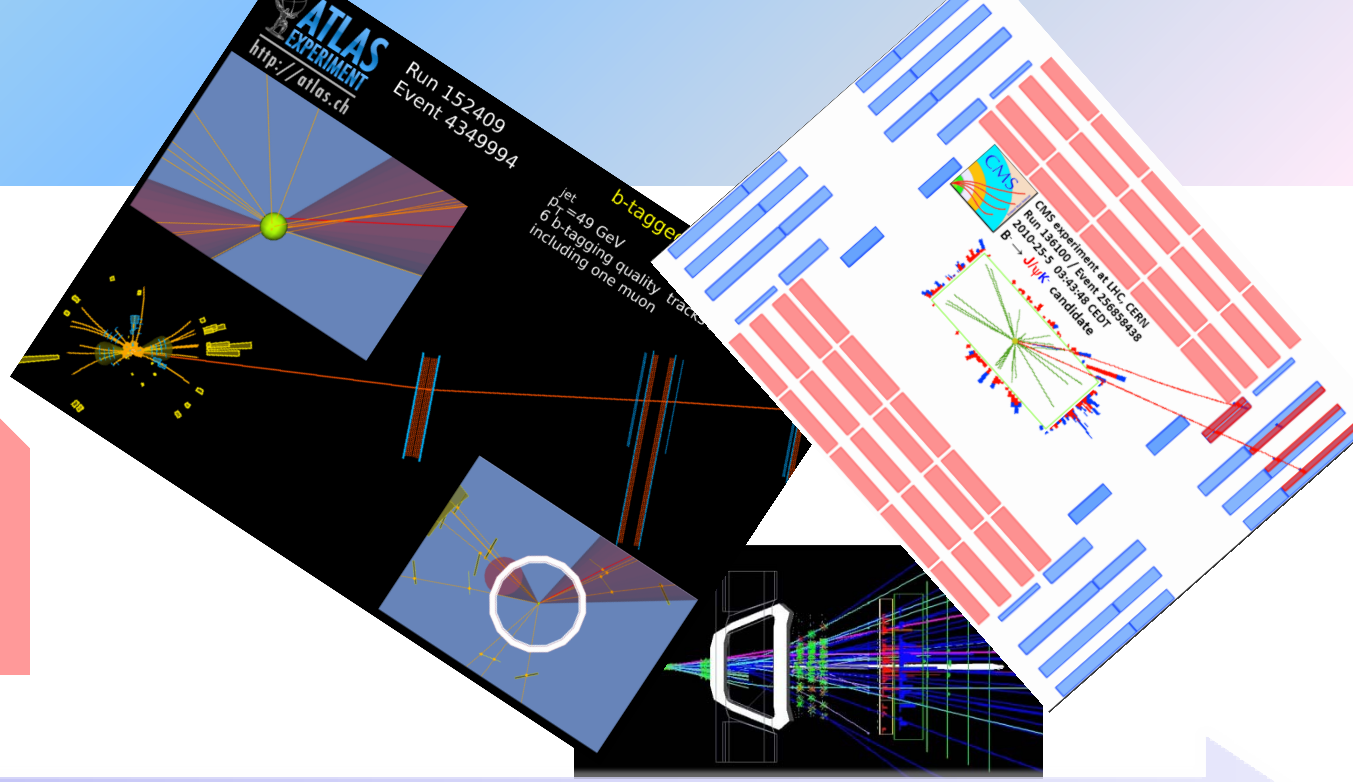
- **An efficient trigger is essential**

Trigger

- ATLAS/CMS
  - Search for new physics
    - High p_T/E_T trigger or E_{Miss}
      - Try to keep a "low" p_T muon trigger for b-physics: single or dimuon
      - B-Physics is accounted for 5÷10% of total trigger resources
      - *Event storage @ 200Hz*
- LHCb
  - Dedicated to b-physics!
    - Moderate p_T signals in calorimeter & muon systems
      - Highest $p_T^{\mu} \sim 1$ GeV
    - *Event storage @ 2kHz (small event size)*



- **Triggers are highly configurable:**
  - **evolve to match LHC luminosity & physics requirements**



- Detector and trigger understanding and Calibration
- Early measurements: cross sections, …

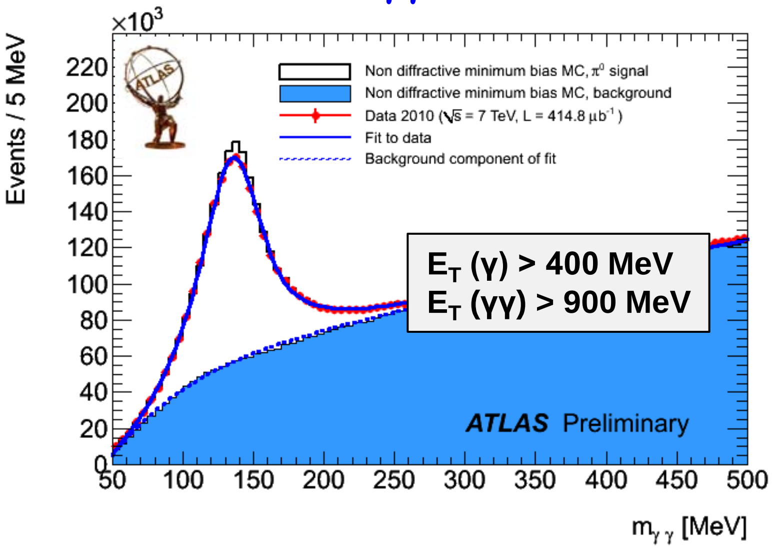
2010 — Start-up

Now — O(10 pb^{-1})

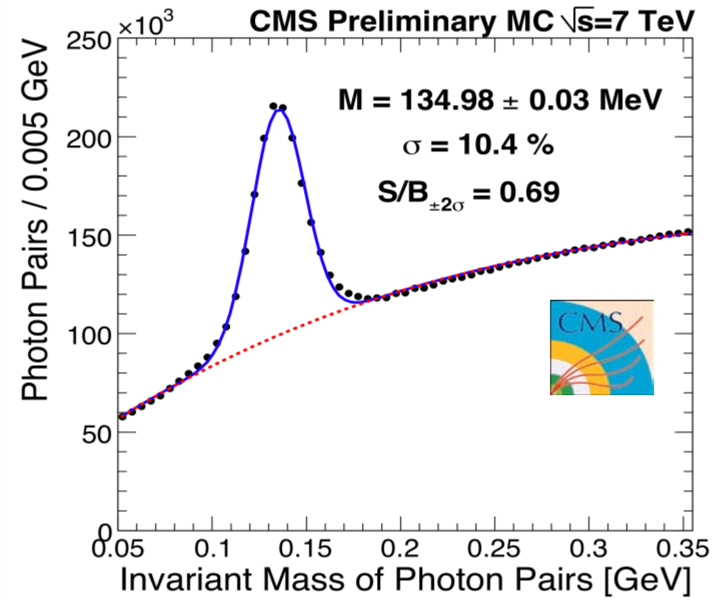
DETECTOR PERFORMANCE HIGHLIGHT & FIRST LHC HEAVY FLAVOUR RESULTS

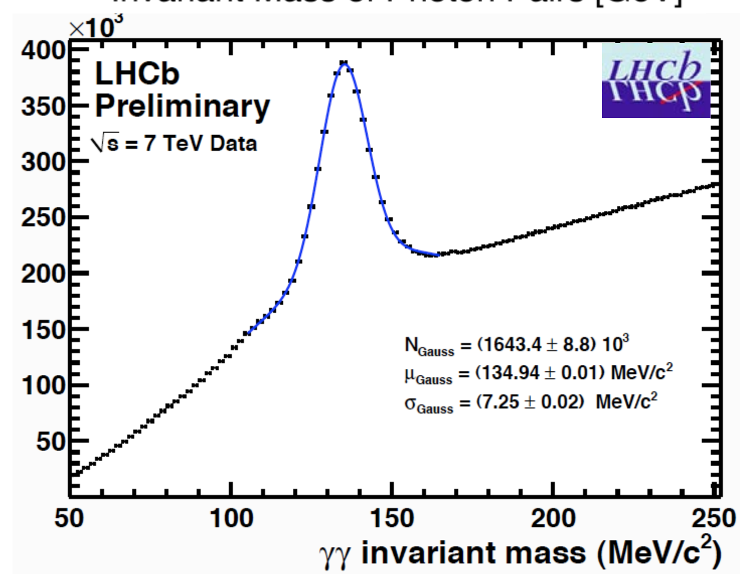
Detector performances

- Electromagnetic calorimeters:
  - First detectors to be calibrated
  - The $\pi^0 \rightarrow \gamma\gamma$ candle:



	ATLAS	CMS	LHCb
$\sigma(M\pi^0)$	20 MeV	14 MeV	7.2 MeV

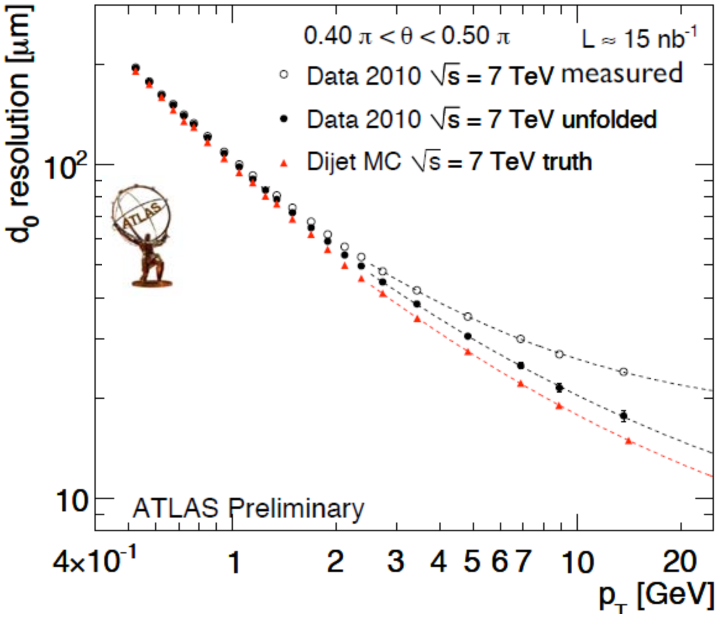


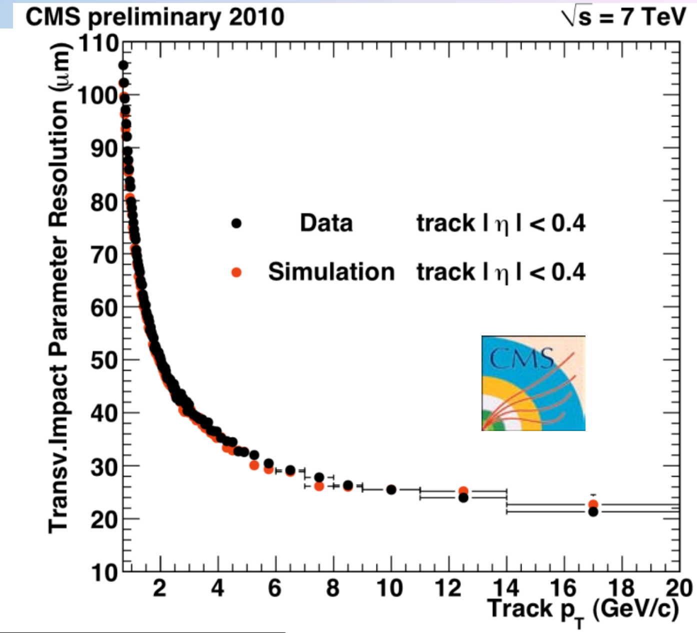


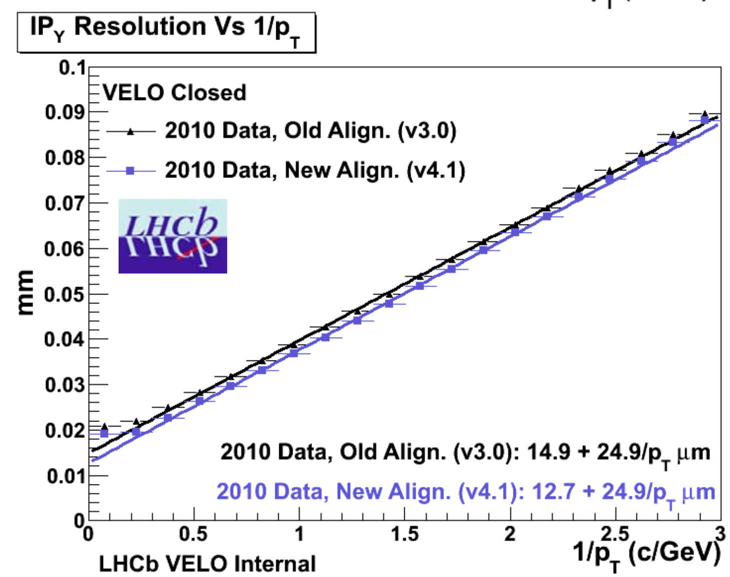
- ECAL calibrated to 1- 2% level
  - π^0 resolution close to expectation
    - Even better for LHCb!

Detector performances (cont')

- Tracking performances







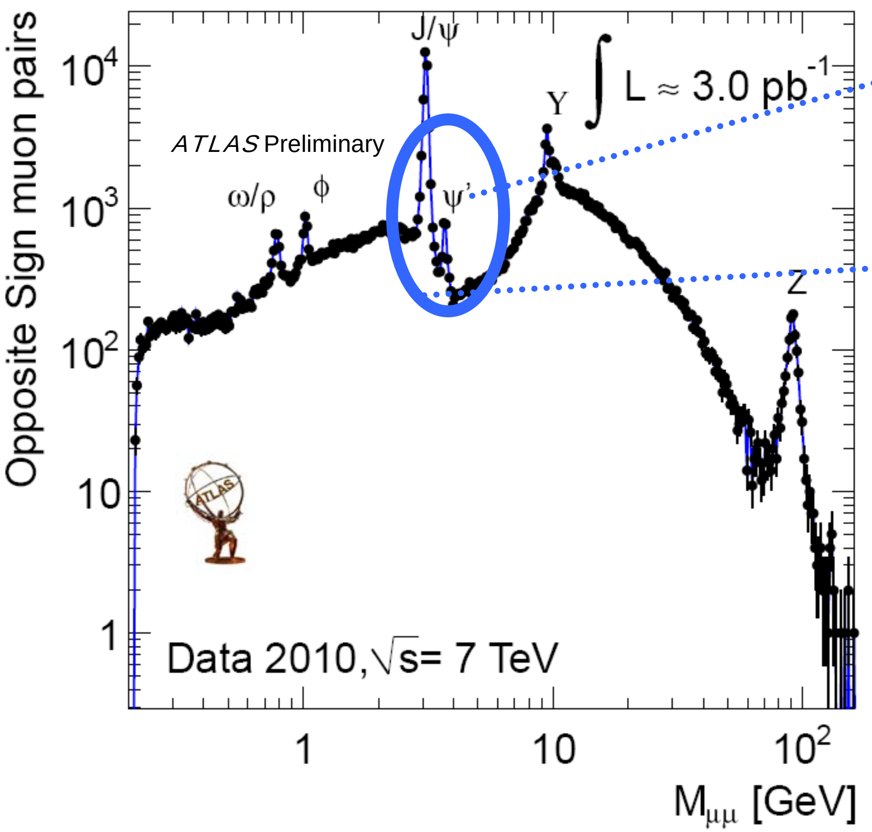
@2GeV	ATLAS	CMS	LHCb
σ (IP)	60 μm	50 μm	25 μm *

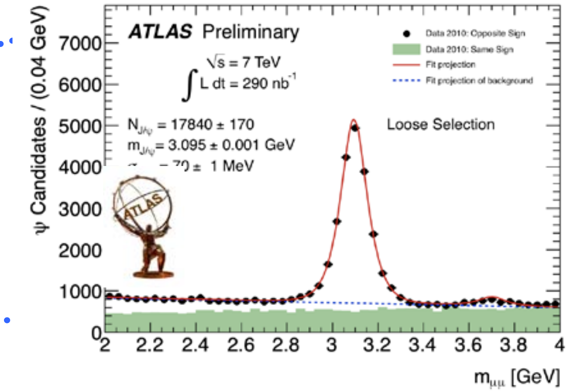
- Better performance expected:
  - Alignment on-going

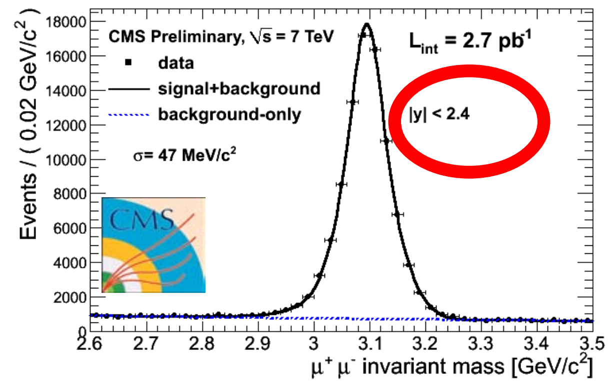
* single hit resolution 4μm!

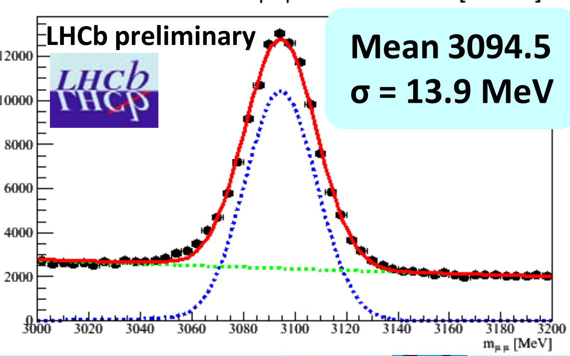
Detector performances (cont')

- Di-muon spectrum (J/ψ → $\mu^+\mu^-$ candle)





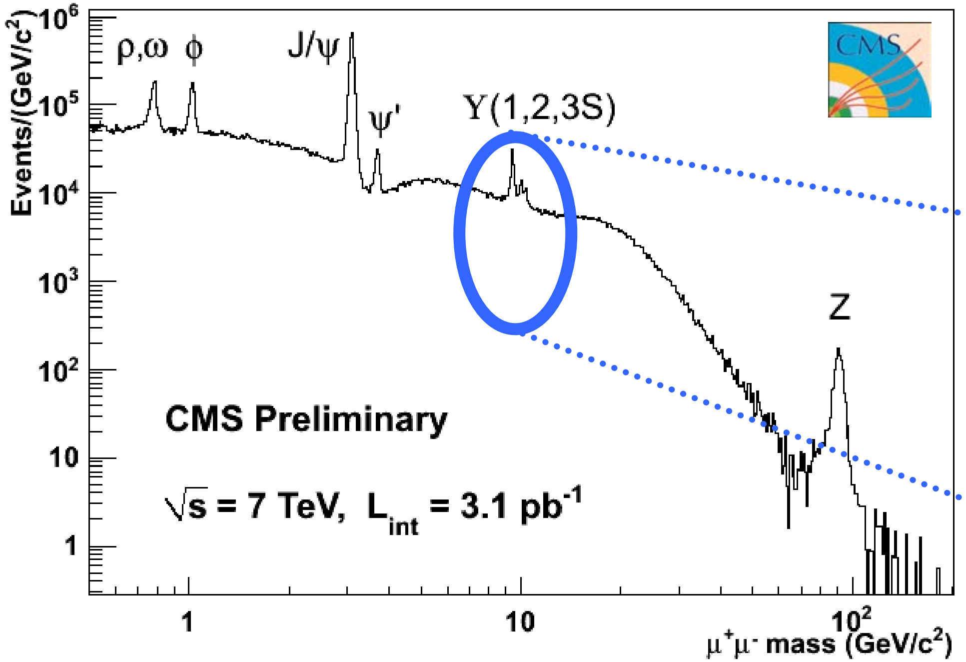


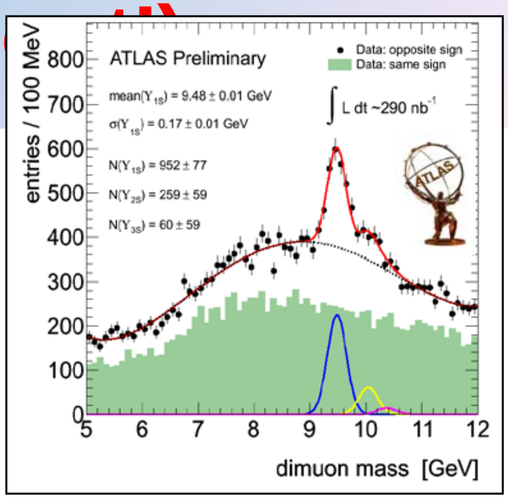


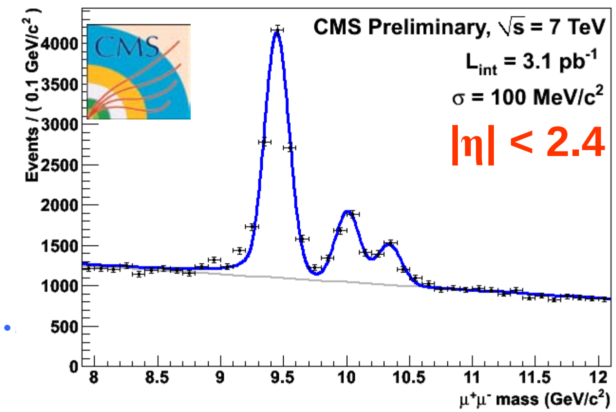
	ATLAS	CMS	LHCb
σ (MJ/ψ)	70 MeV	47 MeV	14 MeV

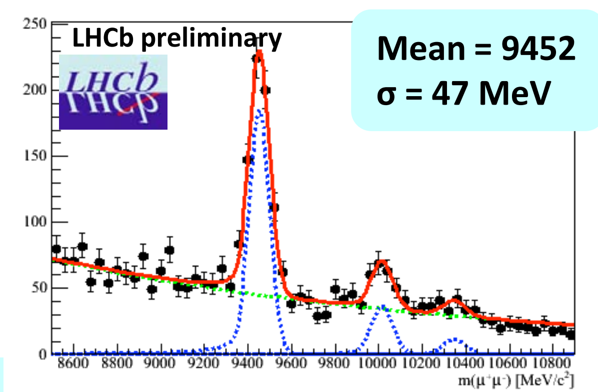
Detector performances (c

- Di-muon spectrum









	ATLAS	CMS	LHCb
$\sigma(M_\Upsilon)$	170 MeV	100 MeV	47 MeV

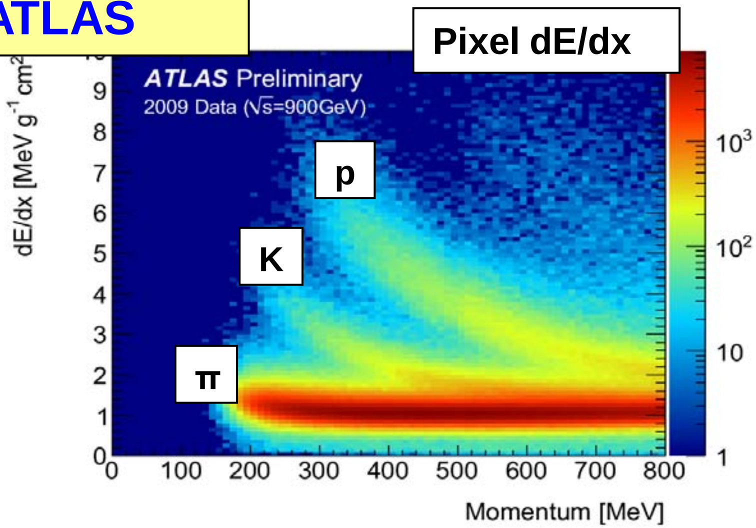
- Mass resolution approaching MC expectation

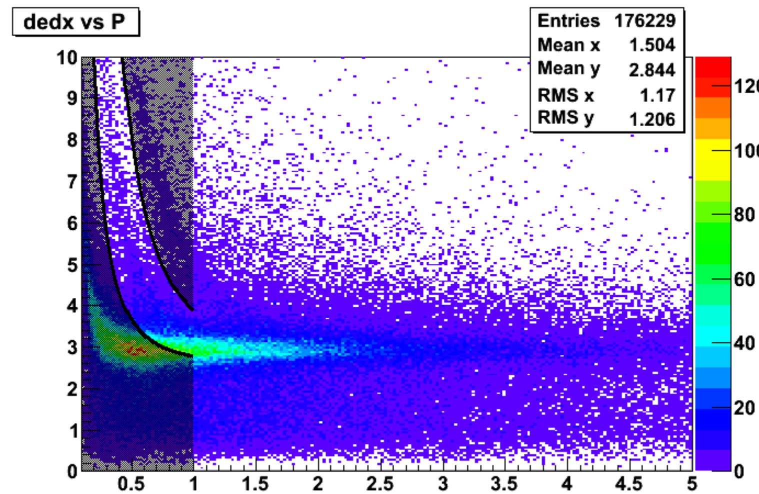
Detector performances (cont')

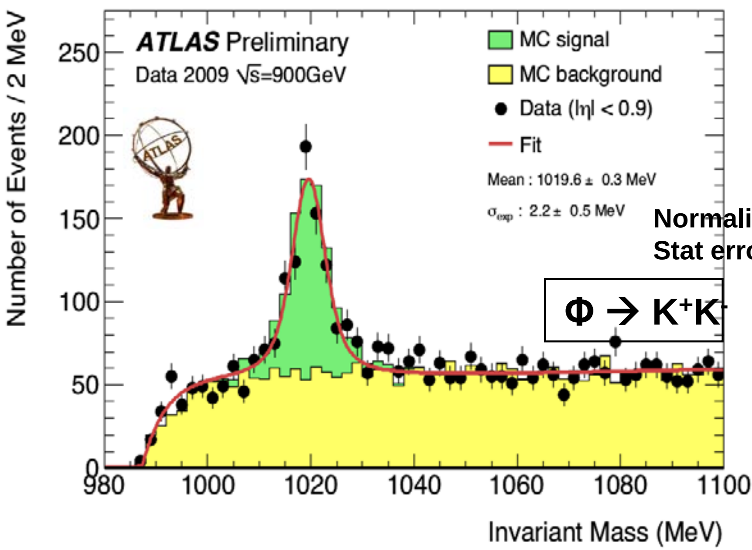
◆ Particle Identification: $\Phi \rightarrow K^+ K^-$ using dE/dx

ATLAS

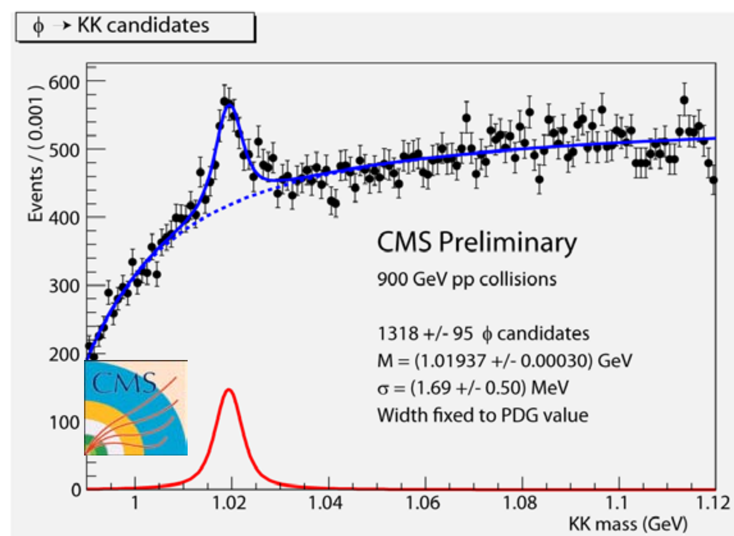
CMS







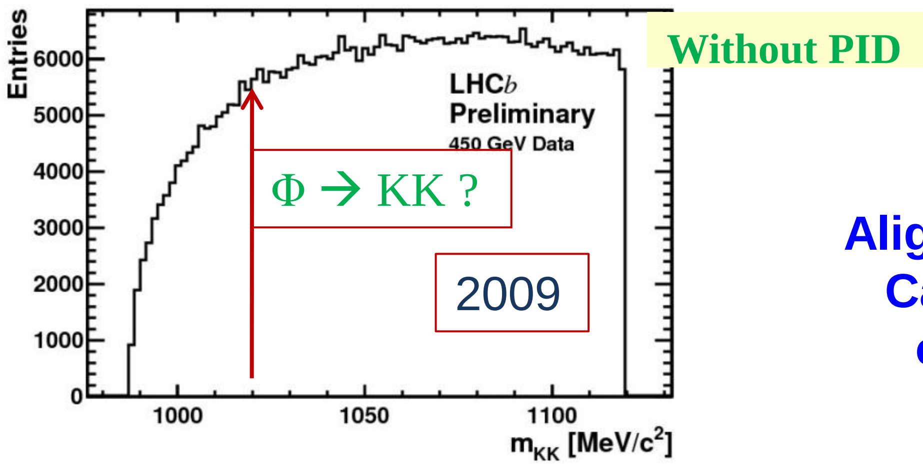
Normalized to data
Stat errors only

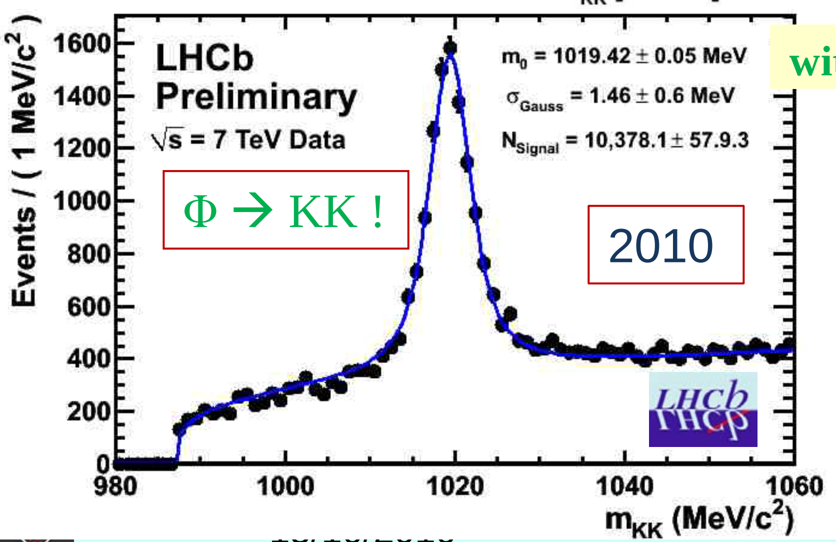


Detector performances (cont')

- Particle Identification
  - Performance still improving, getting close to MC

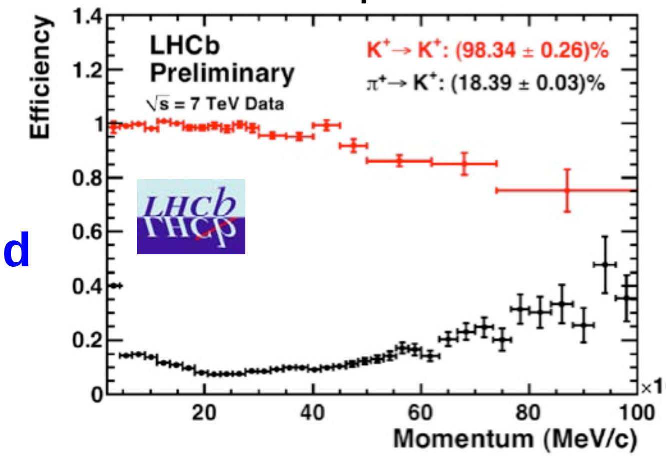
LHCb:
$\phi \rightarrow K^+ K^-$ using RICH detectors



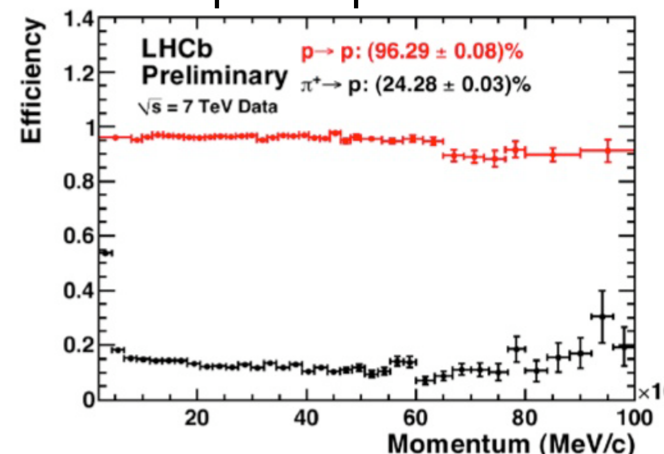


Alignment and Calibration ongoing

K-π separation



p-π separation

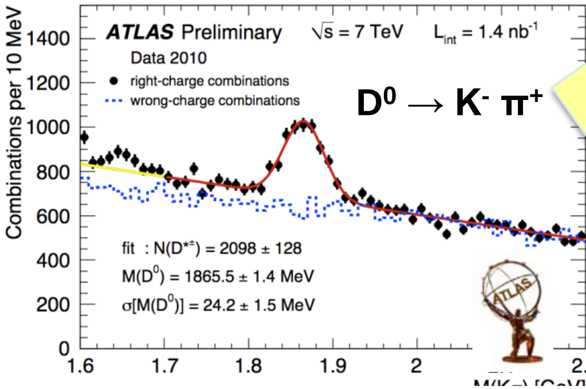


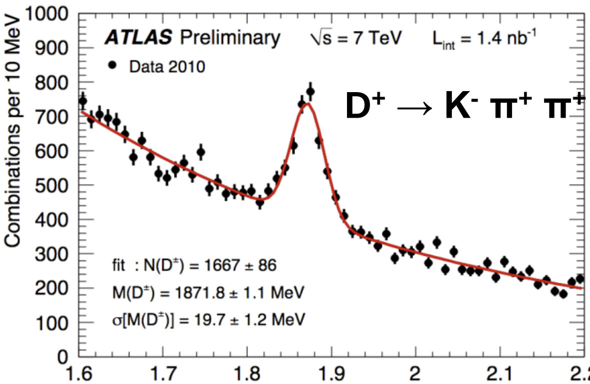
First LHC Heavy Flavour Results

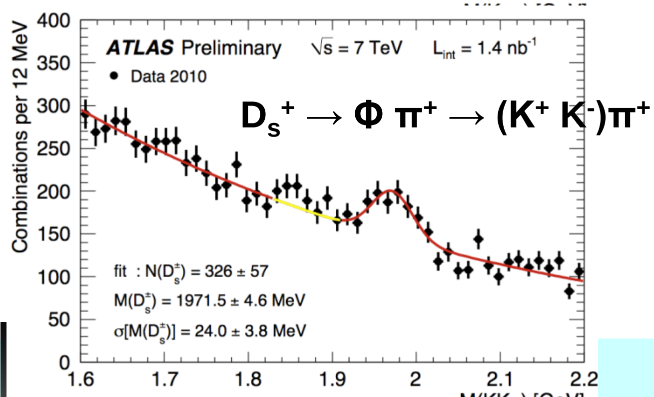
- Charm physics: Huge charm production!

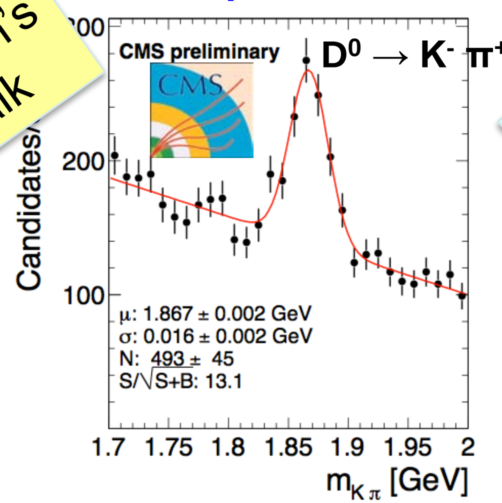
Adrian's talk

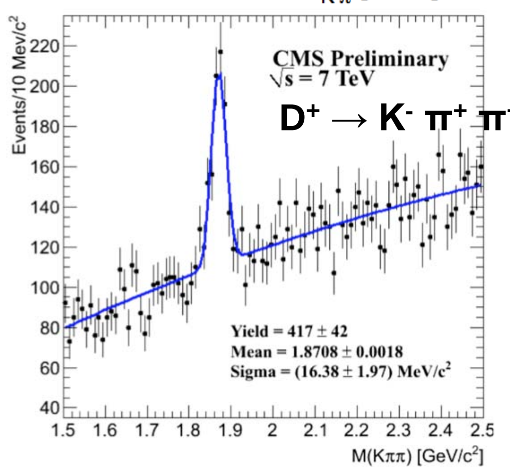
Johan's talk

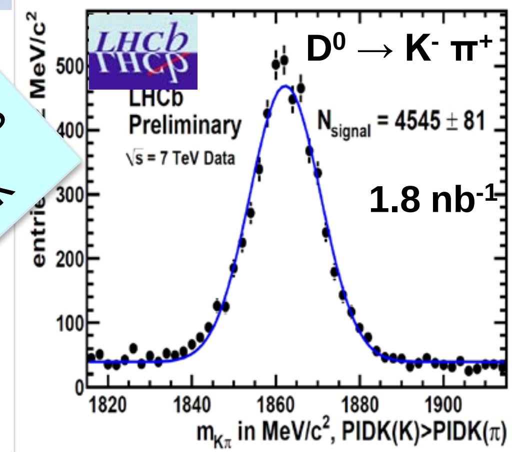


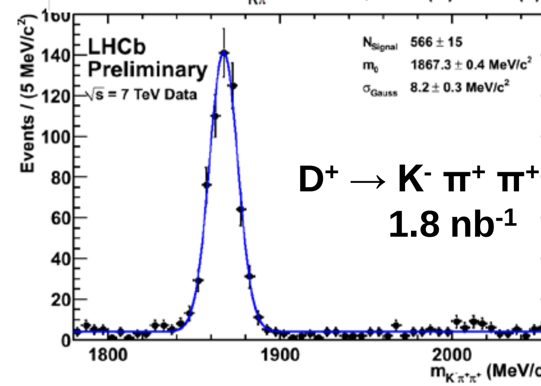


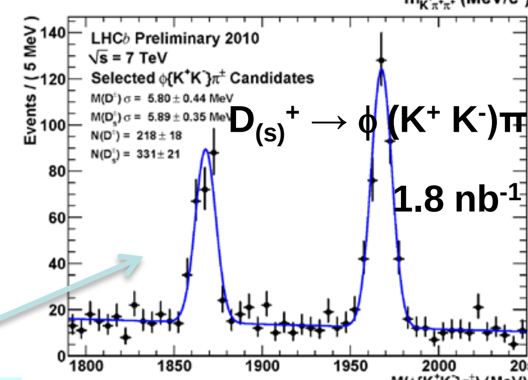












Clear selection of Cabibbo-suppressed decay

First LHC Heavy Flavour Results (cont')

- Charm physics: Huge charm production!
  - From plots to cross-sections: LHCb
    - Open charm production cross-sections are being studied vs y and p_T in forward region ($2 < y < 5$) for D^*, D^0, D^+ and D_s by LHCb :
      - Used small sub-sample of collected data :~ 2 nb^{-1} with unbiased trigger
    - Measurement of $\sigma(pp \to D^+X) / \sigma(pp \to D_sX) = 2.32 \pm 0.27 \pm 0.26$
      - many systematics drop out in the ratio: in agreement with PDG: 3.1 ± 0.7
  - $J/\psi \to \mu^+\mu^-$ production: ATLAS/CMS/LHCb
    - Measurement of the differential (p_T) inclusive cross-section (prompt + from b) and the overall fraction of J/ψ from b
  - b production cross-section from $b \to D^0\mu\nu X$ events: LHCb
    - Measure cross-section in four bins of η (**admitted to PLB**)
      - $\sigma(pp \to H_bX) = (75.3 \pm 5.4 \pm 13.0)\mu b$ for $2<\eta<6$, any p_T $\sqrt{s}=7$ TeV

      Use MC and Pythia to extrapolate to 4π and averaging with prel. Result from $b \to J/\psi$:
      - **$\sigma(pp \to b\bar{b}X) = (292 \pm 15 \pm 43)\mu b$**

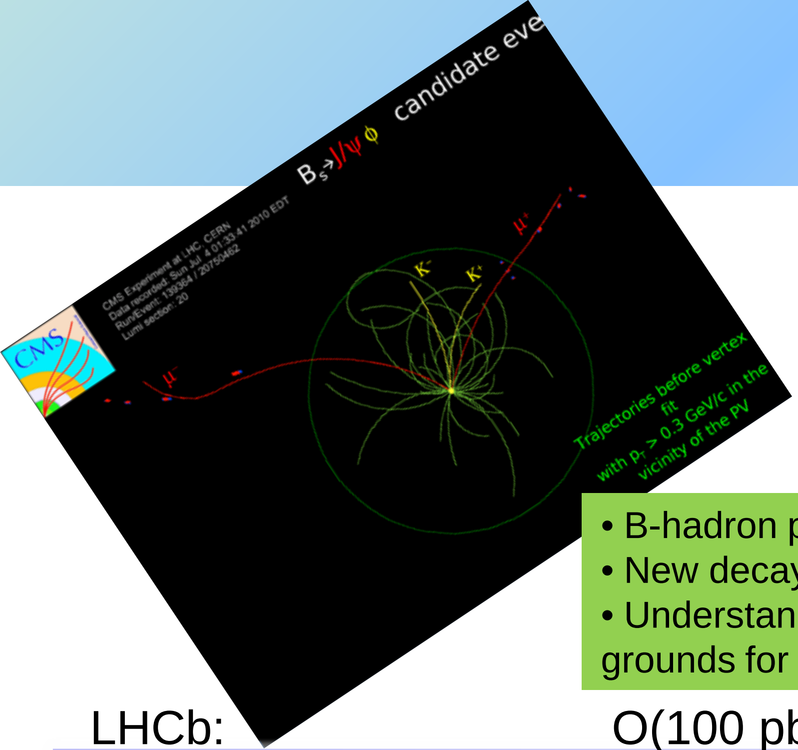
Theory:
MCFM 332 μb,
NFMR 254 μb

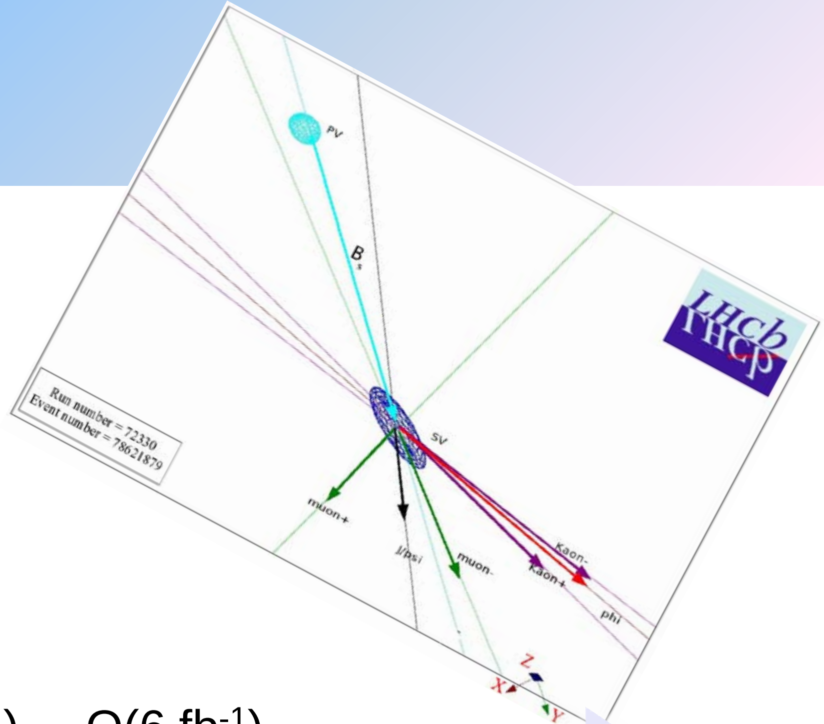
LHCb assumed in MC ~ 250 μb

Conor's talk

Roberto's talk

Conor & Rob's talk





- B-hadron properties
- New decay limits
- Understand back-grounds for rare decays

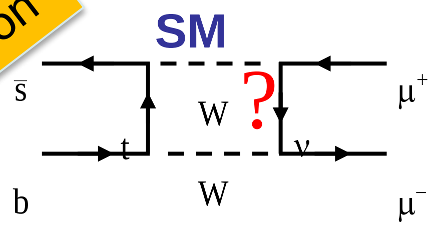
LHCb:	O(100 pb^{-1})	O(1 fb^{-1})	O(6 fb^{-1})
Start-up	End 2010	2011	2015
ATLAS: CMS	O(100 pb^{-1})	O(1 fb^{-1})	O(30 fb^{-1})

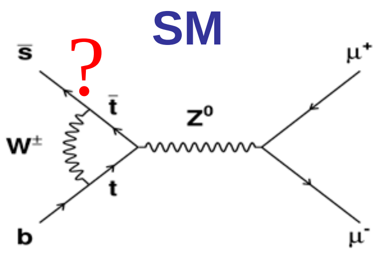
FUTURE

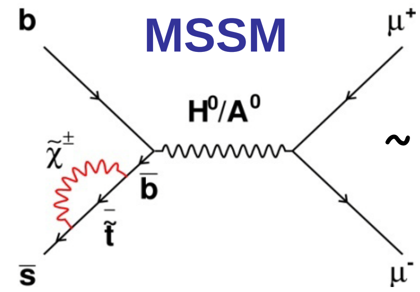
- Rare decay searches
- Searches for CP violation in weak decays of B mesons

New Physics in $B_s \to \mu^+\mu^-$

Morning session







$\sim \tan^6\beta/M_H^2$

A.Buras, EPS09, arXiv:0910.1032

- Helicity suppressed and in SM: $BR(B_s \to \mu^+\mu^-)=(3.6\quad 0.3)\times10^{-9}$
  - sensitive to New Physics; could be strongly enhanced in SUSY
  - Current best limit from CDF: $BR(B_s \to \mu^+\mu^-) < 3.6 \times10^{-8}$ @90%CL
    - $BR(B_s \to \mu^+\mu^-) < 4.2 \times10^{-8}$ from D0 @90%CL
- Event selection
  - Main issue is background rejection:
    - dominated by $B \to \mu^+X$, $B \to \mu^- X$ decays
  - good mass resolution, vertex resolution and PID are essential

$B_s \rightarrow \mu^+\mu^-$: ATLAS/CMS

- « Easy » for the trigger: hight p_T (di-)muons
- ATLAS/CMS have similar discriminating variables
  - They perform cut based analysis to separate signal from background, using:
    - isolation of the muon pair
    - decay length significance
    - angle between di-muon momentum and direction to PV
    - mass window around $m(B_s)$

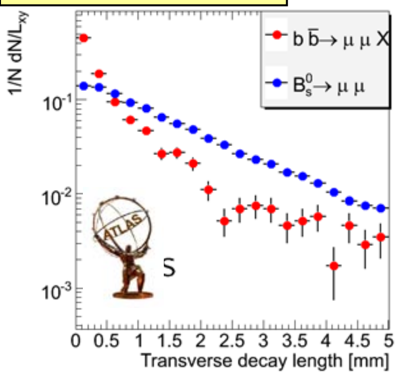
Valentin's talk

Luca's talk

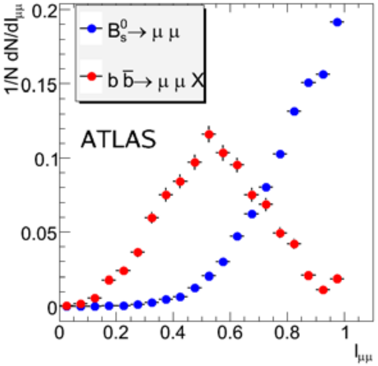
ATLAS

MC

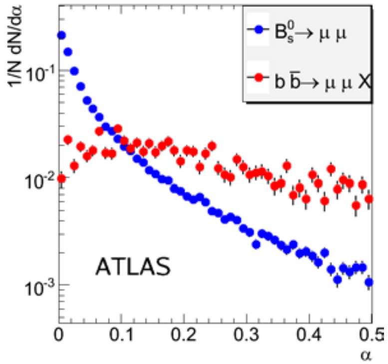
CMS



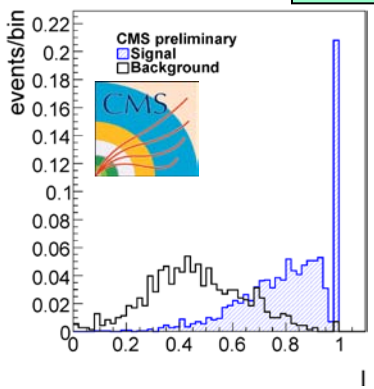
Trans. decay length



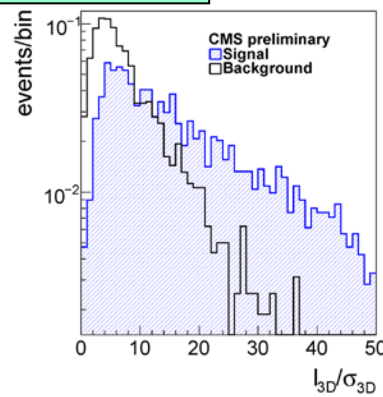
Isolation



Pointing angle



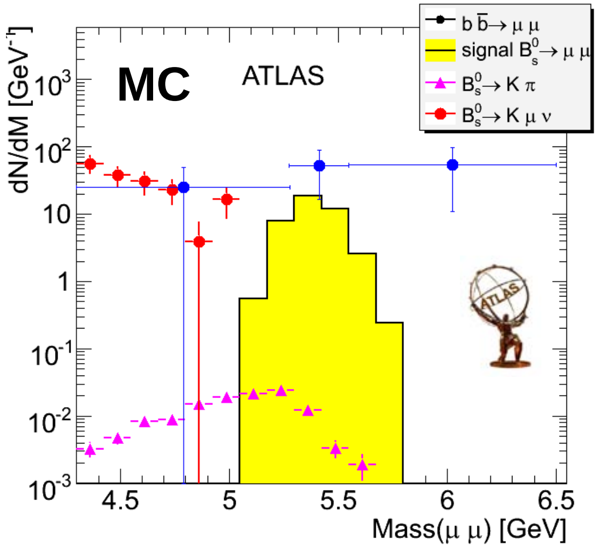
Isolation



Flight-length sig.

$B_s \to \mu^+\mu^-$: ATLAS/CMS

◆ Expected results *(assuming σ(pp → $b\bar{b}$X) = 500 μb) @14TeV*:

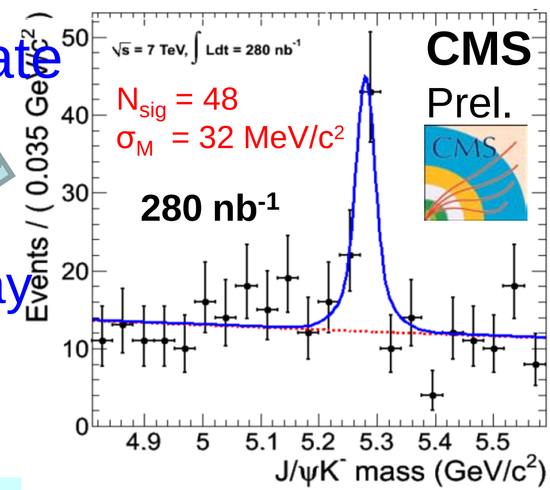


	N sig	N bkg	90% CL
ATLAS (10 fb^{-1})	5.6	14	---
CMS (1 fb^{-1})	2.4	6.5	<1.6 10^{-8}

2.1 10^{-8} *

- with 10 – 20 fb^{-1} SM prediction region
- 3σ evidence after 3 years@10^{33}
- 5σ observation after 1 years@10^{34}

- Uncertainty coming from limited amount of MC
- B → J/ψ K is used for normalization to translate the signal cross section to a BR
  - Well measure BR
  - Only 1 additional track compare to signal decay

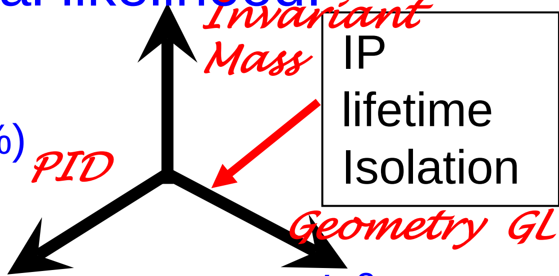


* Scaling quoted result by ratio of LHCb measured x-sec at √s = 7 TeV to 14 TeV value assumed in MC study.

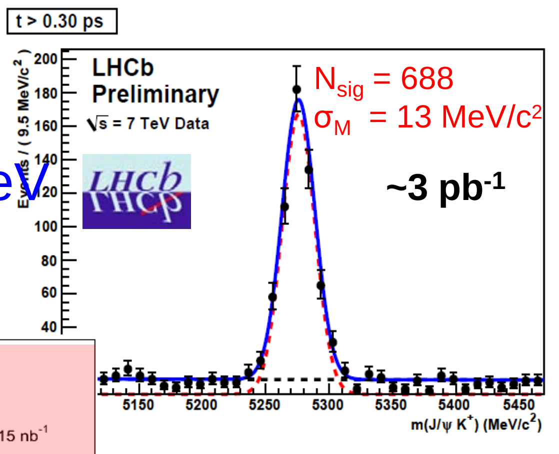
Niels' talk

$B_s \to \mu^+\mu^-$: LHCb

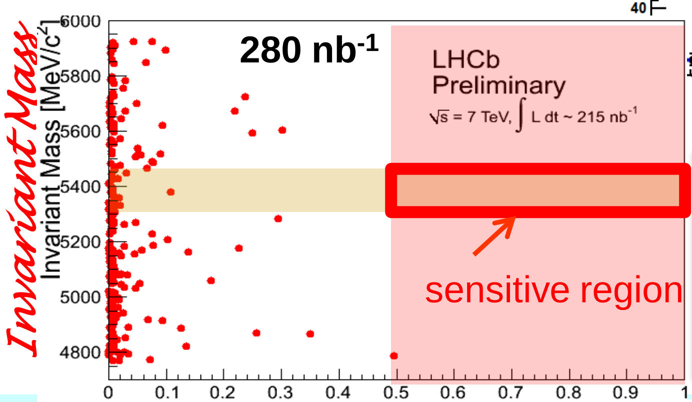
- LHCb approach is philosophically similar to Tevatron's:
  - loose selection and then construction of global likelihood:
    - Analysis in 3 Parameter Space
      - production fraction is the larger systematic (13%)



  - **Prospects from Data**:
    - Mass resolution measured on $B \to \pi\pi, \pi K, \ldots$ now 24 MeV/c^2
      - Getting closer to MC expectation (22 MeV/c^2)
      - Nice $B^+ \to J/\psi K^+$ signal



    - IP resolution in agreement to MC for $p_T > 2$ GeV
    - Background at the expected level
      - no events in sensitive region and general properties of background as expected



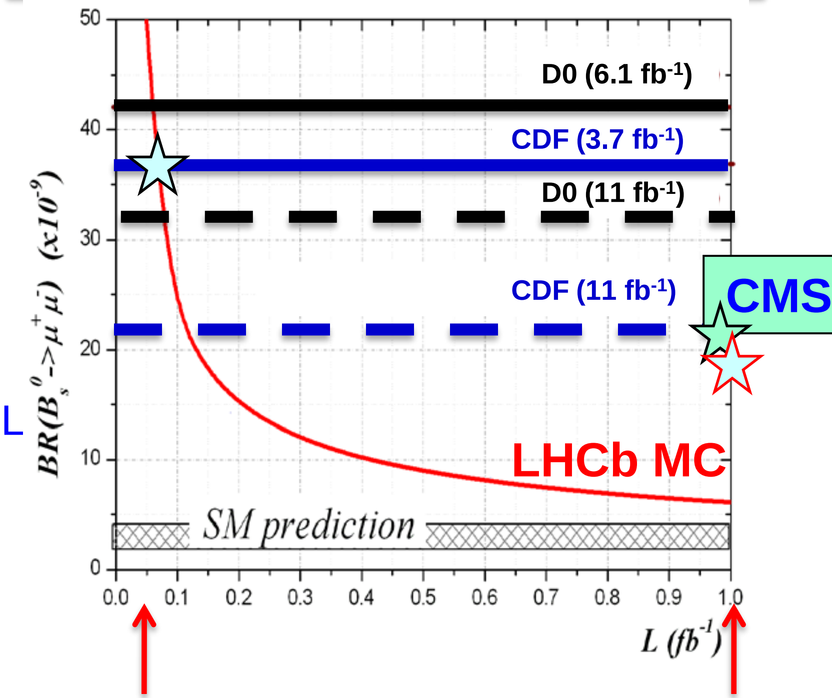
expected ~ 6 signal events and ~ 30 background events for 1 fb^{-1}

Geometry Likelihood

$B_s \to \mu^+\mu^-$

- ATLAS/CMS & LHCb should be complementary for such a measurement
  - Very soon LHC should be able to approach or surpass world best sensitivity
    - With 50 pb^{-1} possible already to approach new limit:
    - LHCb alone:
      - $BR(B_s \to \mu^+\mu^-) < 3.4 \times 10^{-8}$ @90%CL
      - 5σ observation down to BR = 5 x SM with 1 fb^{-1} ($BR(B_s \to \mu^+\mu^-) > 1.7 \times 10^{-8}$)
  - For a 5σ measurement at SM value a combination of all LHC observations will help!

Exclusion limit at 90% CL at √s=7TeV



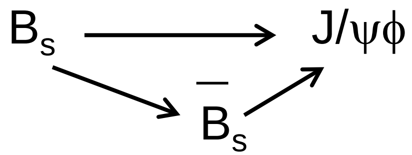
Close to CDF limit possible already end of the year

2011

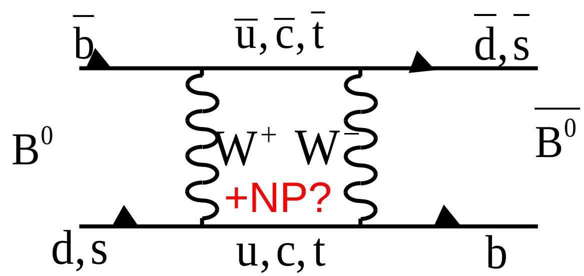
Wednesday session

β_s measurements from $B_s \to J/\psi\ \phi$

◆ The interference between B_s decay to $J/\psi\phi$ with or without mixing gives rise to a CP violating phase Φ.



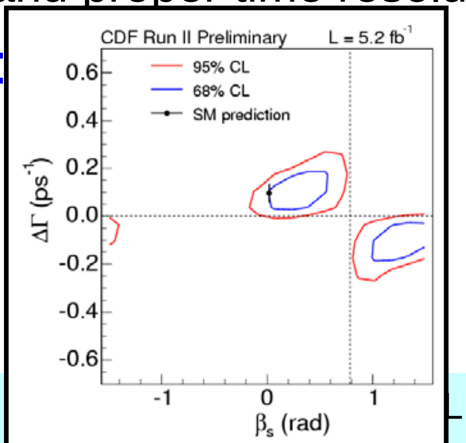
- It is a sensitive probe of New Physics:
  - It is well predicted in the SM: $\Phi=-2\beta_s=-0.0368\pm0.0017$
  - New particles can contribute to the B_s-$\bar{B}_s$ box diagrams and significantly modify the SM prediction

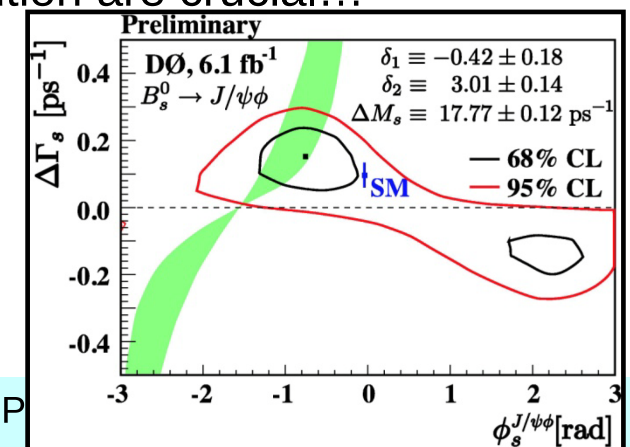


- It is not a pure CP eigenstate (VV decay)
  - 2 CP even, 1 CP odd amplitude
    - Initial states must be tagged
    - Final states need to be statistically separated through angular analysis
    - Mistag and proper time resolution are crucial…
- TEVATRON:

CDF and D0 set confidence level bounds on

$\Delta\Gamma s$ - ϕs



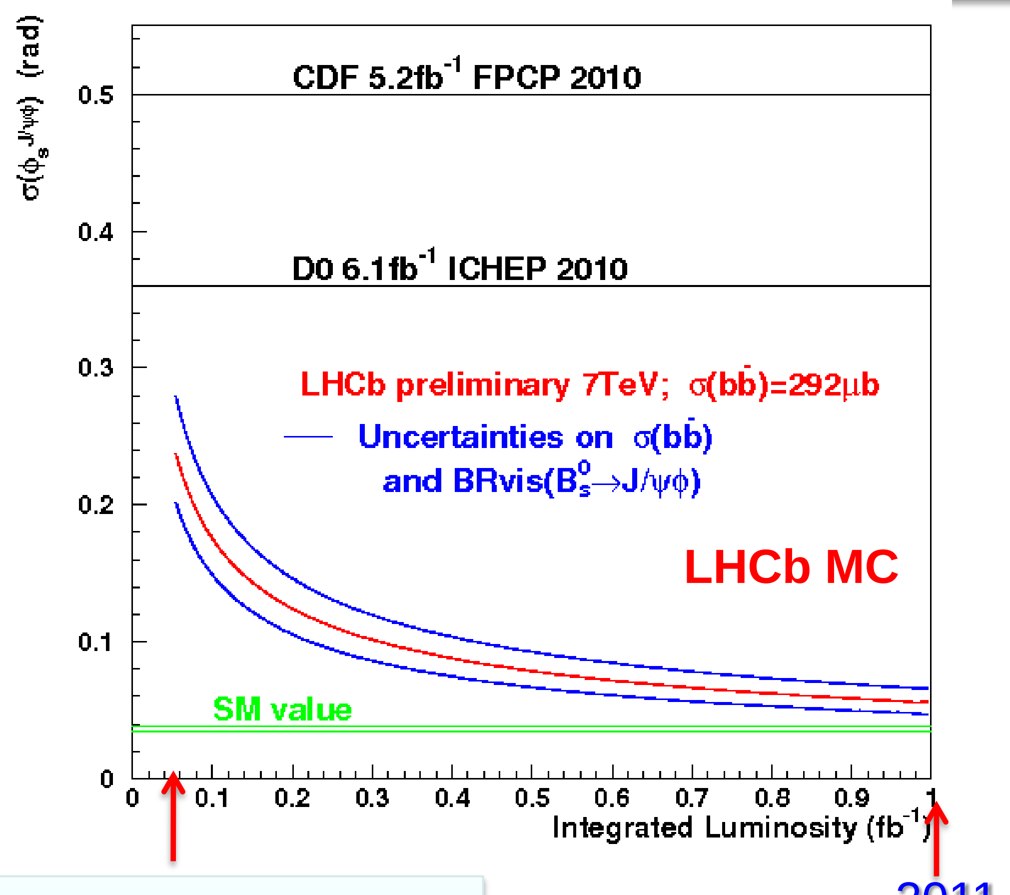


SM at ~1σ

β_s measurements from $B_s \to J/\psi\ \phi$

- ATLAS/CMS:
  - use Bs lifetime cuts
    - main background is long-lived
    - main systematics: control of acceptance
- LHCb:
  - Does NOT use Bs lifetime cuts
    - main background is prompt
    - Main systematics are mistag and proper-time resolution

Expected LHCb sensitivity
10TeV - $\sigma(pp \to b\bar{b}X) = 292\ \mu b$



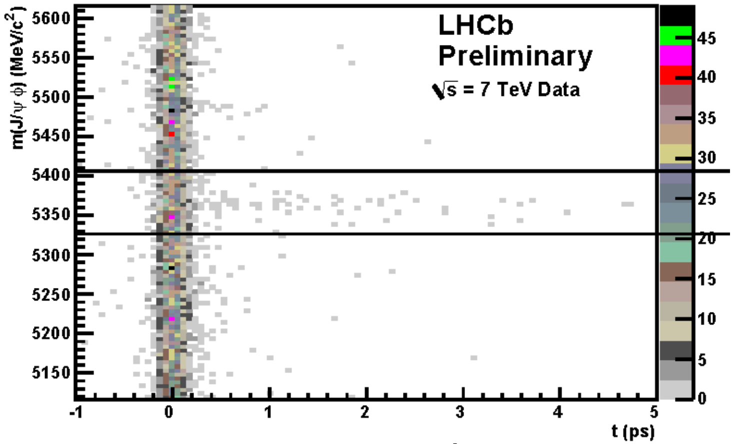
First result possible already with 50 pb^{-1} data

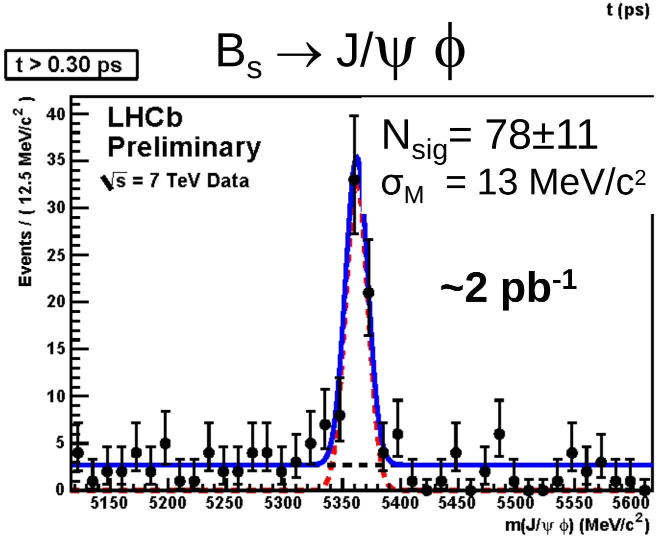
LHCb: yield for 0.2 fb^{-1}: ~ 7 k comparable to CDF @ 5.2 fb^{-1}

β_s measurements from $B_s \to J/\psi\ \phi$

Johan's talk

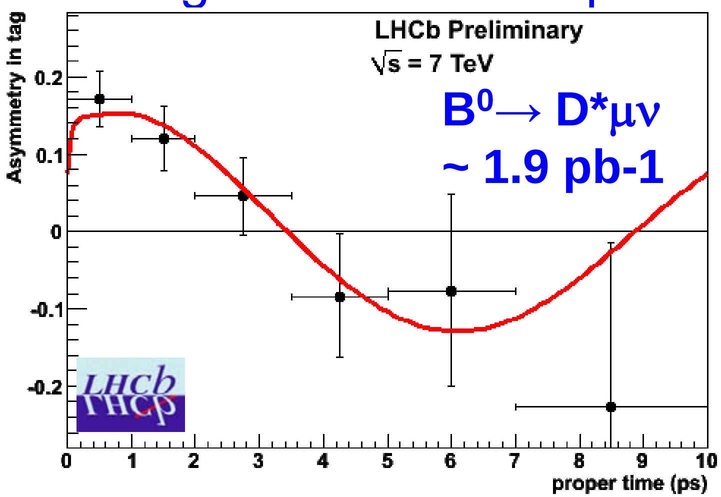
- Prospects at LHCb from Data:





Signal starts to show up

- yield in ≈ agreement with expectation



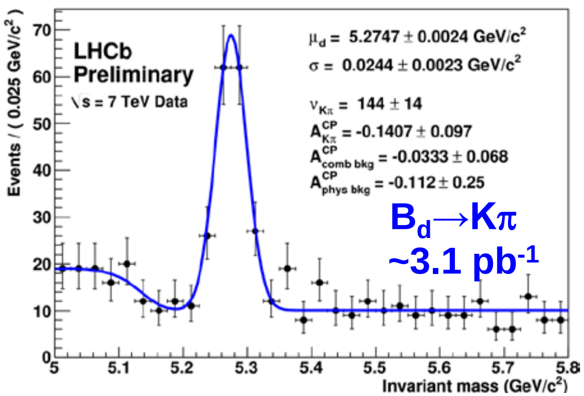
First signal of flavour oscillation from $B^0_d \to D^{*-}(D^0\ \pi^-)\mu^+\nu$ events.
"Out of the box" un-calibrated tagging performance already at 60% of expected performance.

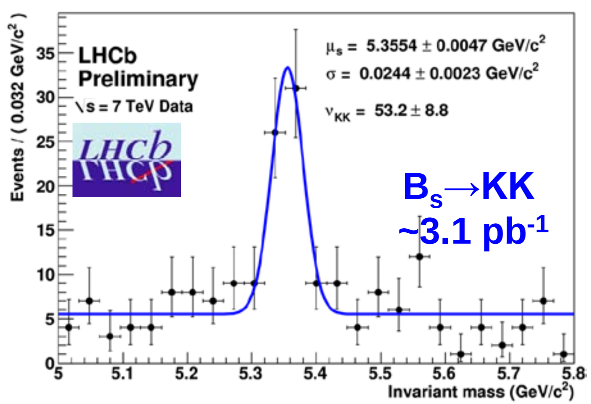
Propertime resolution not yet as in MC :~50-60 fs. Still very good for B_s physics (would give a ~20% decrease in sensitivity). Work on-going on alignment …

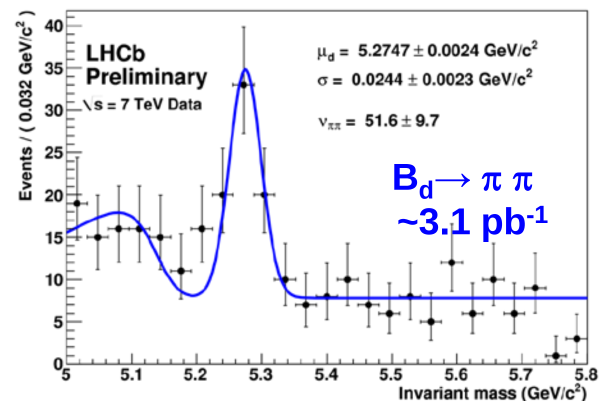
γ Measurements

Denis' talk

- $B_{(s)} \rightarrow K\pi, KK, \pi\pi\ldots$
  - Two body charmless B decays are core to LHCb programme: γ angle, loop effects etc.
    - Penguin amplitudes:
      - Interference of $b \rightarrow u$ tree & $b \rightarrow d(s)$ penguin diagrams
      - CP time-dependent measurements from $B_d \rightarrow \pi\pi$ and $B_s \rightarrow KK$ allow to extract γ relying on U-Spin.
  - Crucial use of PID from RICH and very good mass resolution



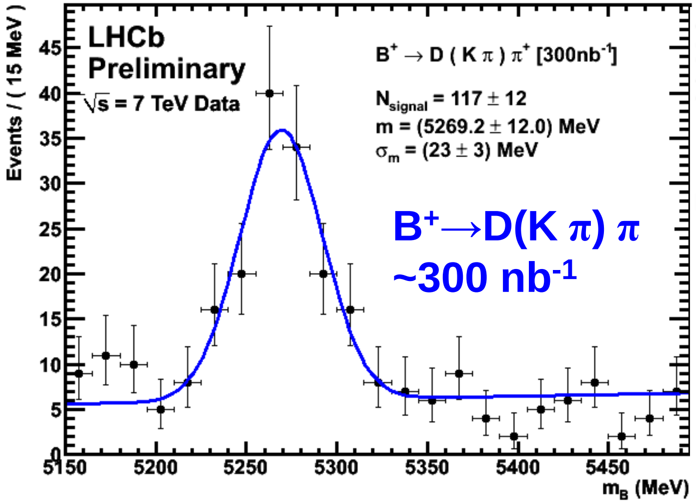


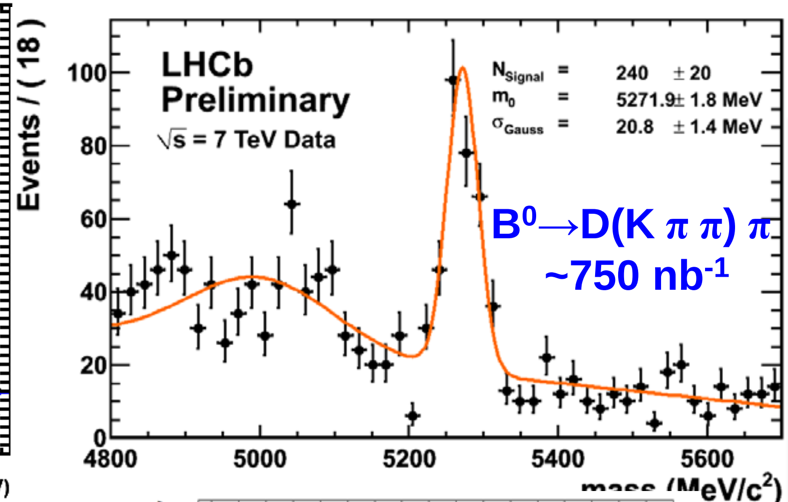


  - Yields so far ~match expectations. *In 2011 running LHCb will get largest world samples both in B^0 and B_s.*

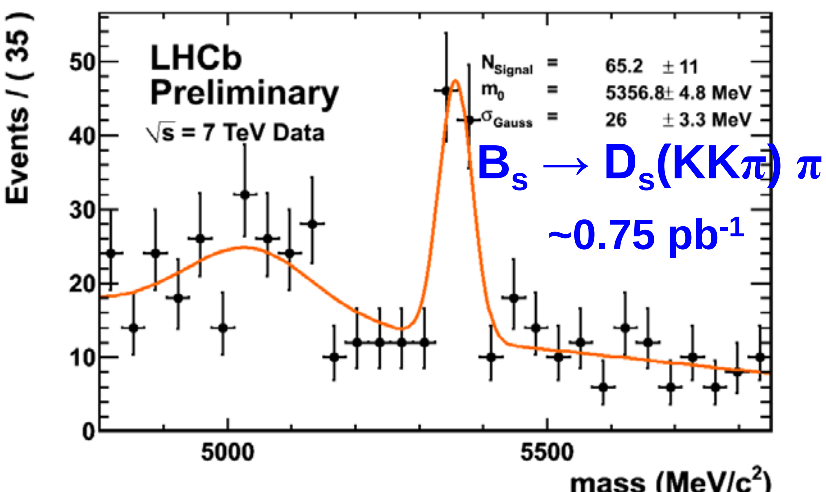
γ Measurements

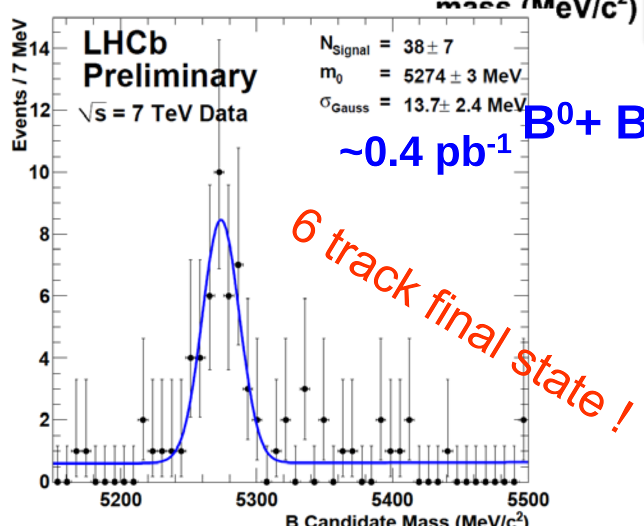
- Multibody hadronic final states: First look @ LHCb





Clean samples with high S/B at ~ expected rate





B^0+ $B^+ \to D(K\pi, K\pi\pi)\, \pi\pi\pi$

2011:
$1fb^{-1}$ @ 7 TeV
$\sigma(\gamma) < 10°$?

Many channels and strategies will give a complete picture for

- Very rare decays
- CP violation
- NP studies

LHCb:	$O(6\ fb^{-1})$	$O(100\ fb^{-1})$
	2015	2022
ATLAS: CMS	$O(30\ fb^{-1})$	$O(500\ fb^{-1})$

PROSPECTS: LHCB UPGRADE

LHCb Upgrade

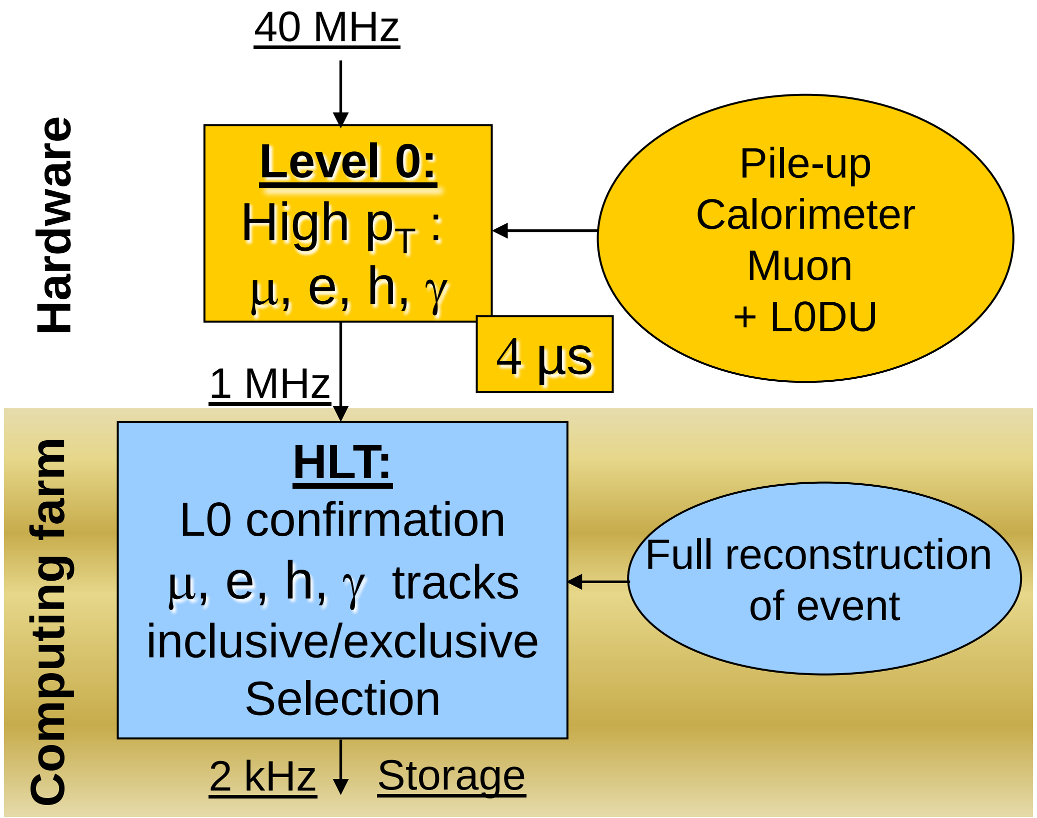
- LHC physics in ~2015
  - New Physics (NP) will hopefully be discovered by ATLAS/CMS and LHCb
  - New Physics will very likely show up in Flavour observables: LHCb should see it!

LHCb Sensitivities (2 fb^{-1} @14TeV)		
Observable	Sensitivity	SM
$CPV(B_s \to J/\psi\phi)$ $(2\beta_s)$	0.03	0.04
γ tree	5^o	67.2°
$\mathcal{B}(B_s \to \mu^+\mu^-)$	Observed at 3σ	3.6×10^{-9}
$A_{FB}(B \to K^*\mu^+\mu^-)$	0.5 GeV^2	4.36 GeV^2
$CPV(B_s \to \phi\gamma)$	0.22	0.10

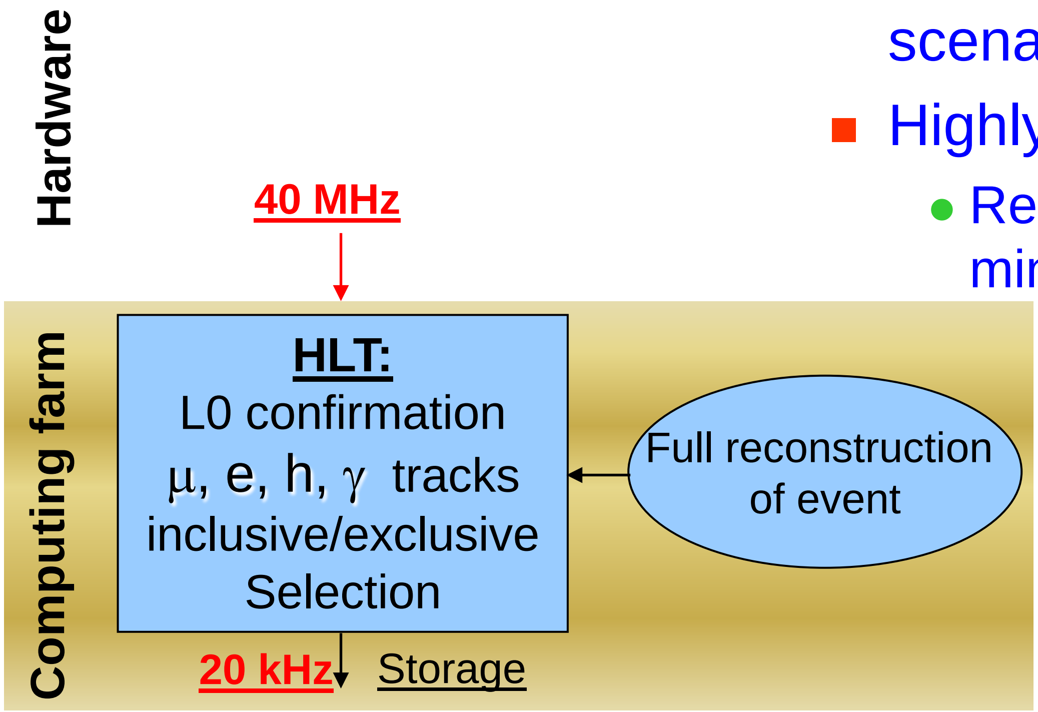
LHCb Upgrade

- Better Flavour Physics will be required to elucidate the NP flavour structure or probe NP at higher mass scale
  - LHC is a Super Flavour factory: 10^6 Hz of b-quarks produced
    - LHCb exploits only a small fraction of LHC:
      - $\mathcal{L}_{LHCb}=2x10^{32}$ $cm^{-2}s^{-1}$ / $\mathcal{L}_{LHC}=10^{34}$ $cm^{-2}s^{-1}$
    - **LHCb Upgrade will be complementary to Super B(Belle) factory!**
- LHCb Upgrade Strategy
  - Running at 10 times design luminosity, i.e. at ~ $2x10^{33}$ $cm^{-2}s^{-1}$
    - Upgrade planned in 2 phases matching LHC schedule :
      - Phase 1: ~ 2016 $\mathcal{L} = 10^{33}$ $cm^{-2}s^{-1}$: **R&D has started**
      - Phase 2: $\mathcal{L} = 2x10^{33}$ $cm^{-2}s^{-1}$
    - *read out full experiment at 40 MHz, currently at 1 MHz*
      - *Gain a factor 2 in the trigger efficiency for hadronic channels*
    - *vertex and photon detector needs to be replaced*

LHCb Trigger



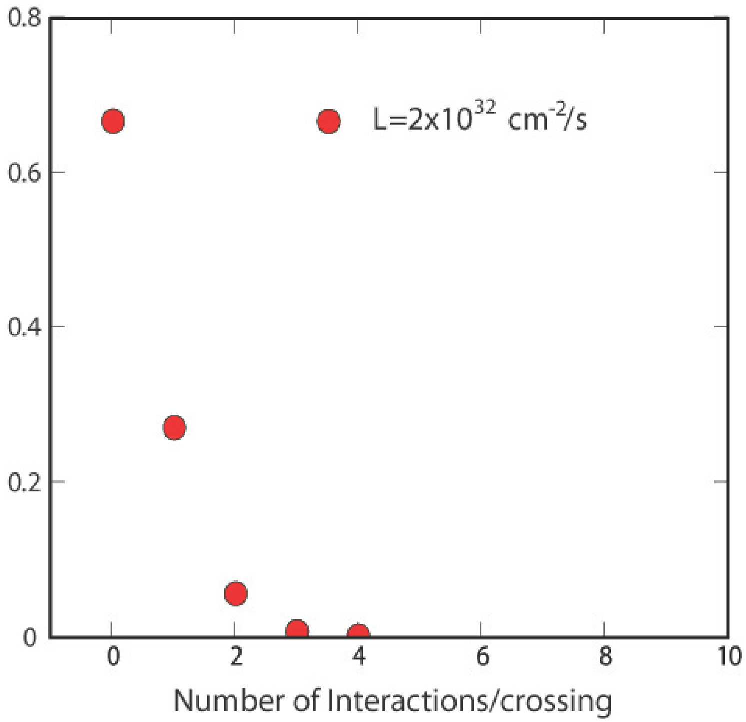
LHCb Trigger: new scheme



- Very flexible software trigger
  - Can be adapted to any kind of scenarii
  - Highly selective for b-mesons:
    - Reduction factor of 10^5 on minimum bias
- Readout the detector at 40 MHz
  - Replace all front-end electronics
  - Replace all very front-end ASIC with a readout speed limited to 1 MHz

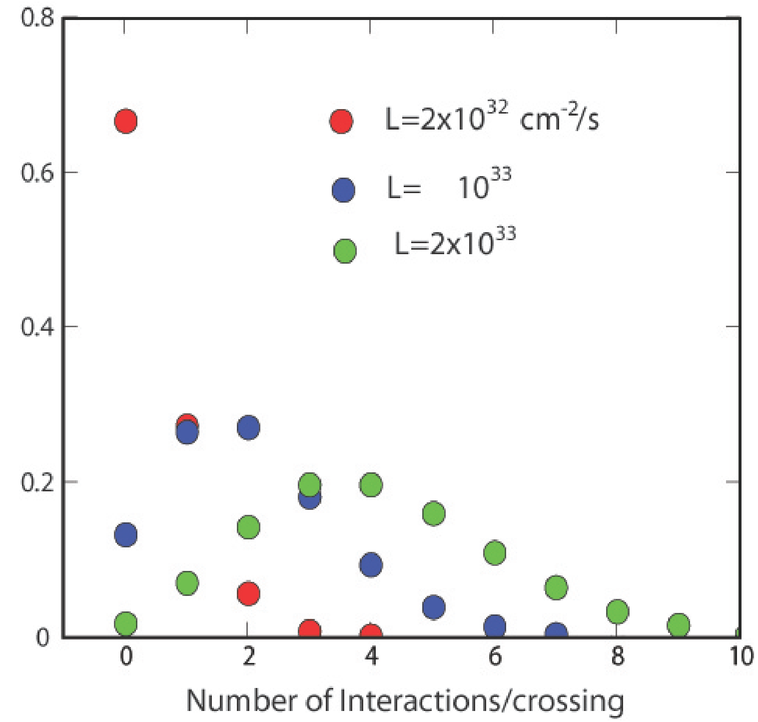
The high luminosity challenge

- $\mathcal{L} = 10^{32}\ cm^{-2}s^{-1}$
  - Average number of interactions per crossing: **0.4**
    - Most crossings don't have an interaction



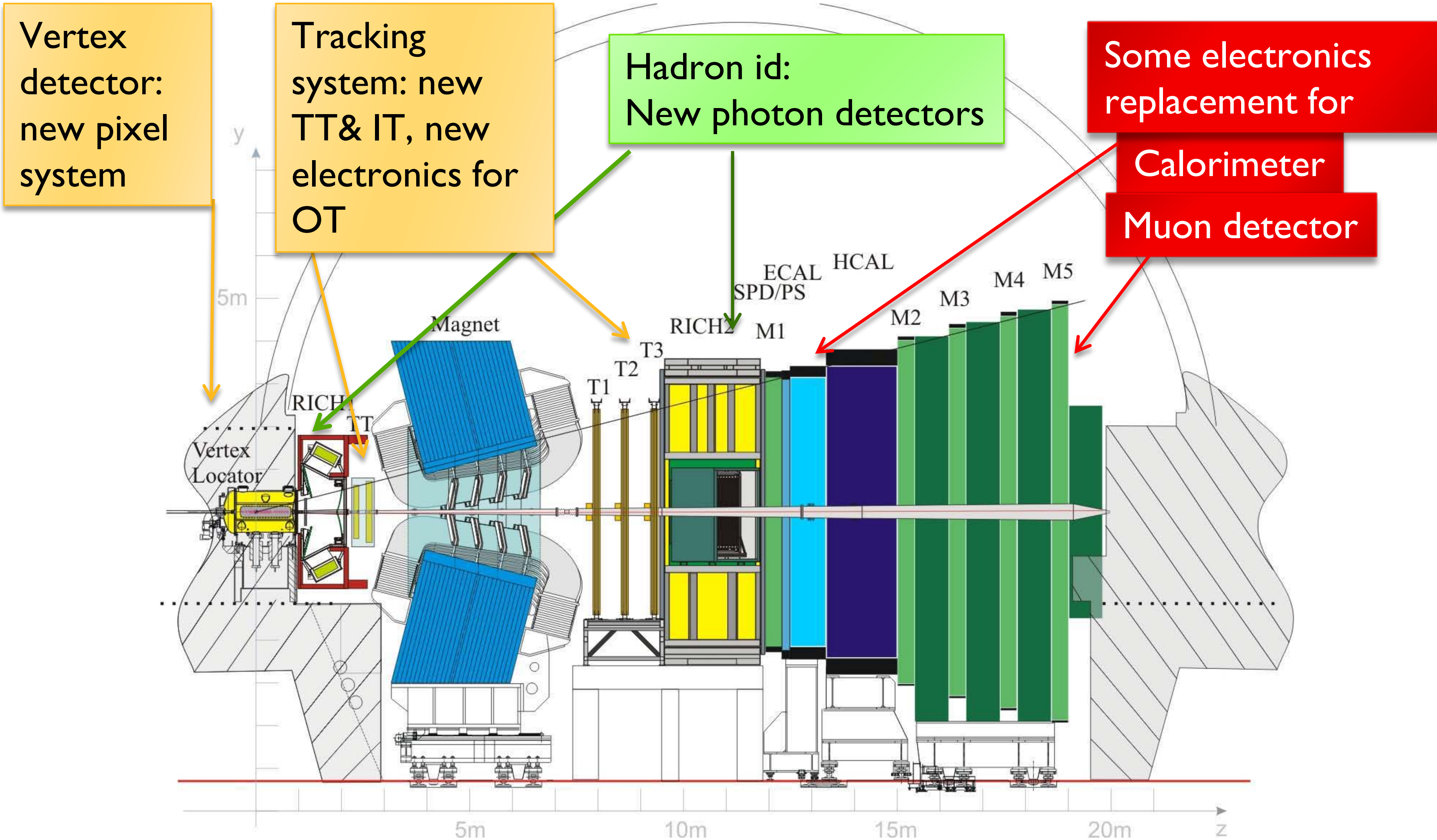
The high luminosity challenge

- $\mathcal{L} = 10^{32}\ cm^{-2}s^{-1}$
  - Average number of interactions per crossing: **0.4**
    - Most crossings don't have an interaction
- $\mathcal{L} = 10^{33}\ cm^{-2}s^{-1}$
  - Average number of interactions per crossing: **2.3**
    - With 15% of empty crossings
- $\mathcal{L} = 2x10^{33}\ cm^{-2}s^{-1}$
  - Average number of interactions per crossing: **4.6**
    - With all crossings with at least one interaction



- Handle higher occupancy and radiation dose
  - *Redesign the inner part of the tracking system (VELO, TT, IT)*

LHCb detector evolution in Phase I



- Replace all the front-end electronics + DAQ network

LHCb sensitivities

- With 100 fb^{-1} error in $2\beta_s$ decreases to ±0.003 (only L improvement), useful to distinguish among Supersymmetry (or other) models, where the differences are on the order of ~0.02

LHCb Sensitivities (100 fb^{-1} @14TeV)		
Observable	Sensitivity	SM
CPV($B_s \to J/\psi\phi$) ($2\beta_s$)	0.003	0.04
γ tree	1°	67.2°
$\mathcal{B}(B_s \to \mu^+\mu^-)$	5-10% of SM	3.6×10^{-9}
$A_{FB}(B \to K^*\mu^+\mu^-)$	0.07 GeV^2	4.36 GeV^2
CPV($B_s \to \phi\gamma$)	0.02	0.10

  - + many more observables:
    - ϕ_s in $B_s \to \phi\phi$, γ mediated by loops, cos 2β in $B_d \to J/\psi K_S$, …
- **The upgrade strategy is SLHC independent**
  - **Letter of Intent → end 2010**

CONCLUSIONS

Conclusions

- **Excellent LHC & detectors start-up**
    - Progressing very well to design performances
  - LHCb is dedicated to b-physics and designed for it!
    - It has the best performances in terms of: Momentum and mass resolution, PID (π/K separation), Proper time resolution, Trigger
  - ATLAS/CMS:
    - will complement the b-physics program of LHCb
      - Fully profit from muon trigger capabilities at high luminosity
  - **LHC is entering into the game!**
    - First data collected are very promising
    - Many significant measurements will be achieved in the b and c-quark sectors in a near future
- *LHCb is preparing a challenging upgrade aiming at an integrated luminosity of 100 fb^{-1} complementary to a Super B factory*
- **We are poised for a long and exciting physics program !!!**

TANK YOU!