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Expected LHCb physics with first 2 years of data

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on behalf of the LHCb collaboration

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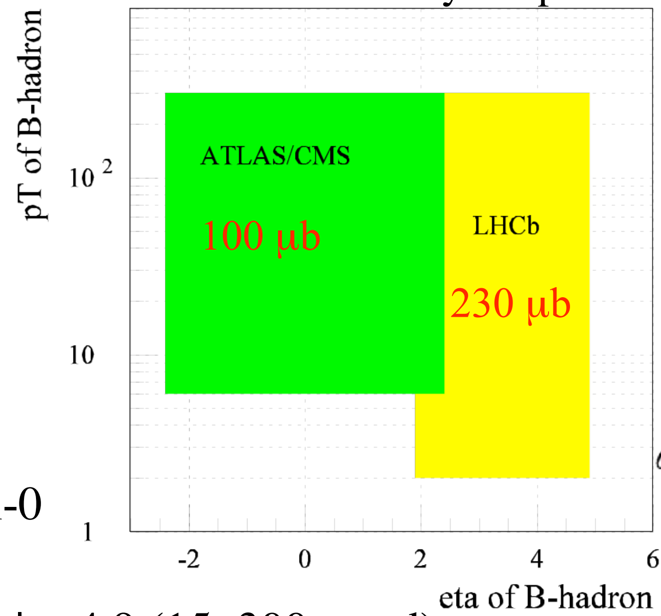
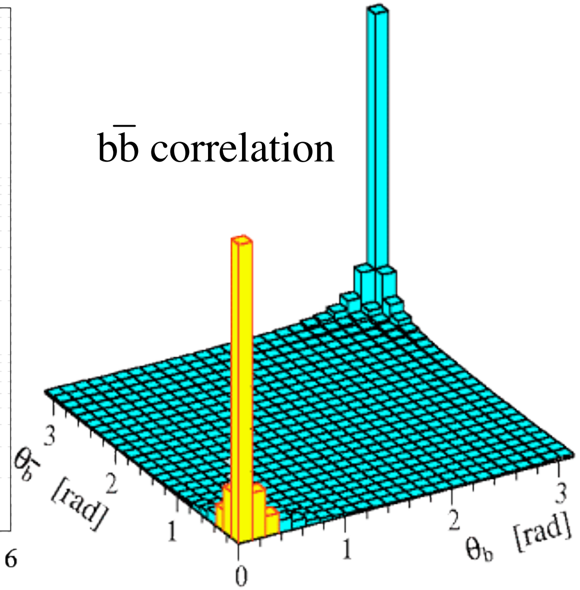
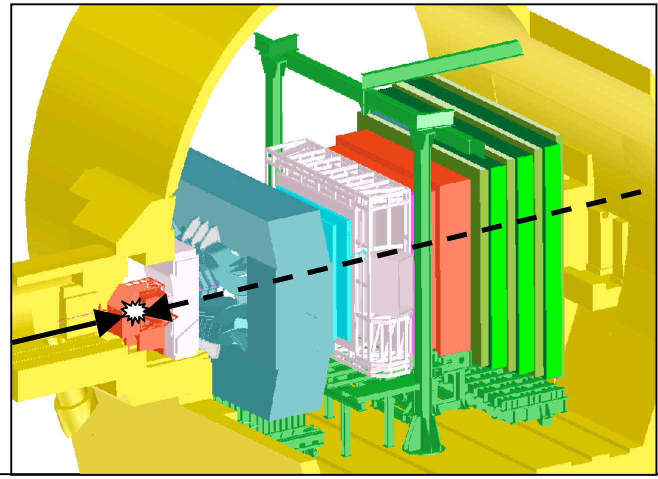
b production at LHC / LHCb

- LHCb's challenge
  - — Exploit the huge b production cross section at the LHC



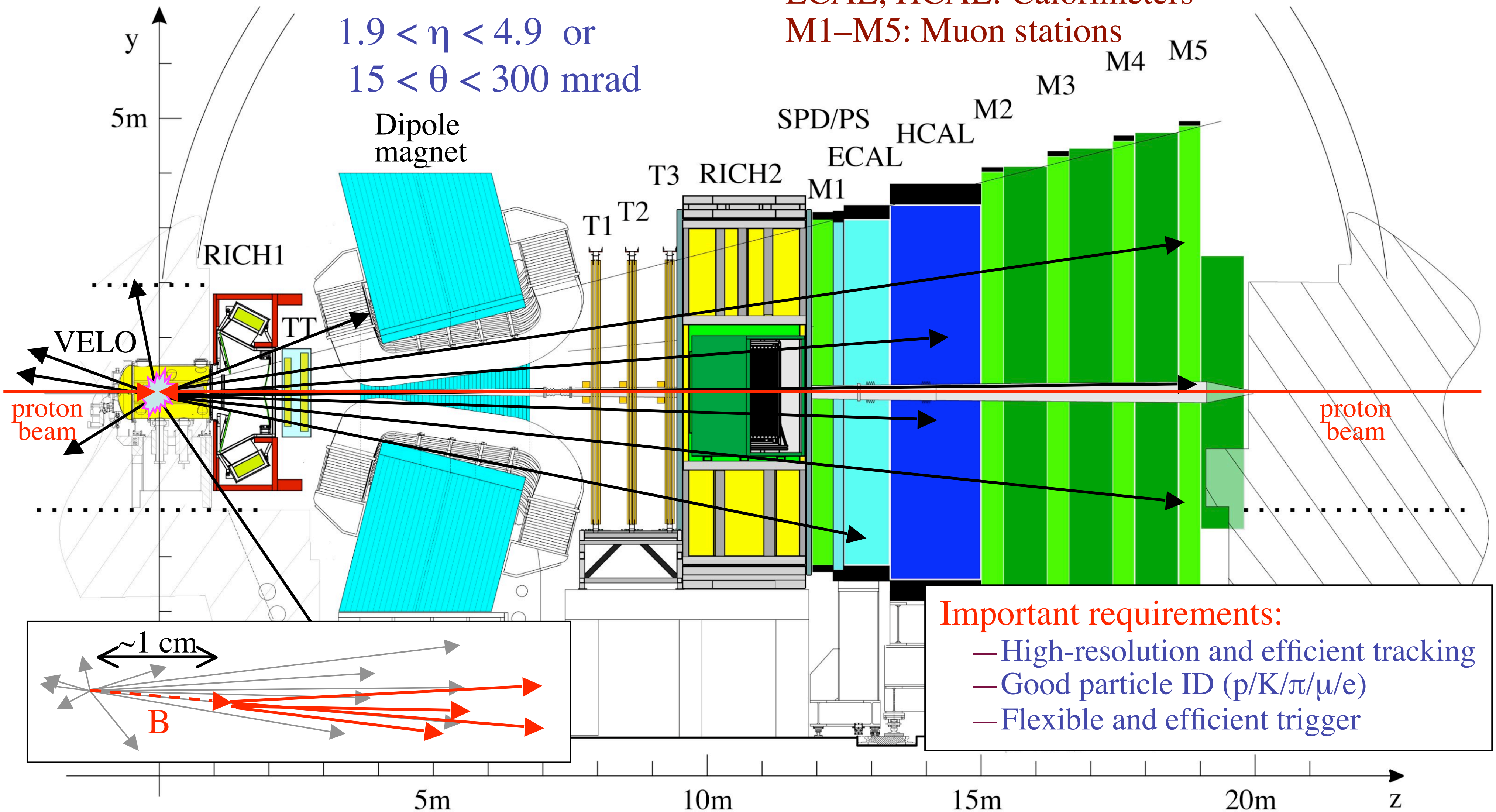


- Concept:
  - — maximize B acceptance
    - apply soft p_T triggers at Level-0 (lower than ATLAS/CMS)
    - forward spectrometer, $1.9 < |\eta| < 4.9$ (15–300 mrad), since more b hadrons produced at low angles
  - — only single arm (due to cost constraints)
    - OK since $b\bar{b}$ pairs produced correlated in space
  - — LHCb interaction point displaced by ~11m with respect to nominal position at center of cavern
    - OK for 25 ns (or 75 ns) bunch crossings, otherwise special "displaced" bunches are needed



LHCb spectrometer

VELO: Vertex Locator (around interaction point)
TT, T1, T2, T3: Tracking stations
RICH1–2: Ring Imaging Cherenkov detectors
ECAL, HCAL: Calorimeters
M1–M5: Muon stations



Important requirements:

- High-resolution and efficient tracking
- Good particle ID (p/K/π/μ/e)
- Flexible and efficient trigger

Luminosity at LHCb

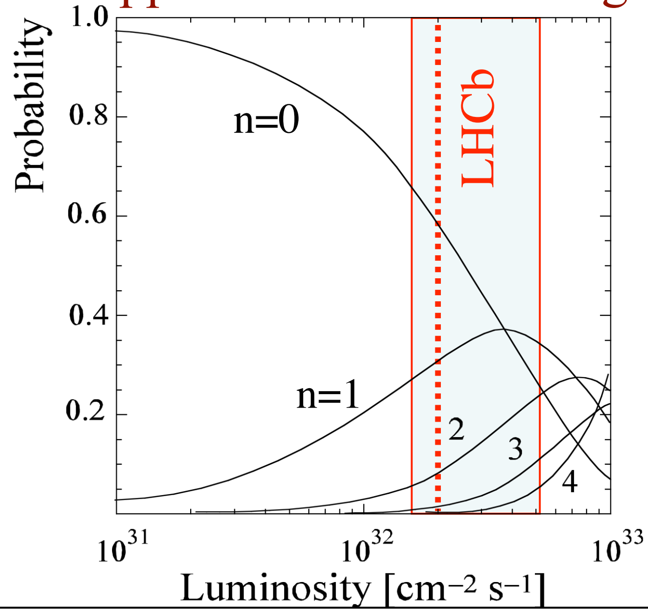
Instantaneous luminosity:

- L tuneable by adjusting final beam focusing
- Pileup is an issue:
  - n = number of inelastic pp interactions occurring in the same bunch crossing
  - Poisson distribution with mean $\langle n \rangle = L\sigma_{inel}/f$ where σ_{inel} = 80 mb and f = 30 MHz (non-empty BX rate)
- Choose to run at **$\langle L \rangle \sim 2\times10^{32}\ cm^{-2}s^{-1}$** (max. $5\times10^{32}\ cm^{-2}s^{-1}$)
  - Clean environment: $\langle n \rangle = 0.5$
  - Less radiation damage (VELO strips start at 8mm from beam)

Integrated luminosity scenario:

- 2008: **< 0.1 fb^{-1} ?** **(hope more of course)**
- 2009: **~ 0.5 fb^{-1}** – " –
- 2010–: **~ 2 fb^{-1}/year**
  - If the experiment can cope, push average luminosity from 2×10^{32} towards $5\times10^{32}\ cm^{-2}s^{-1}$

pp interactions/crossing



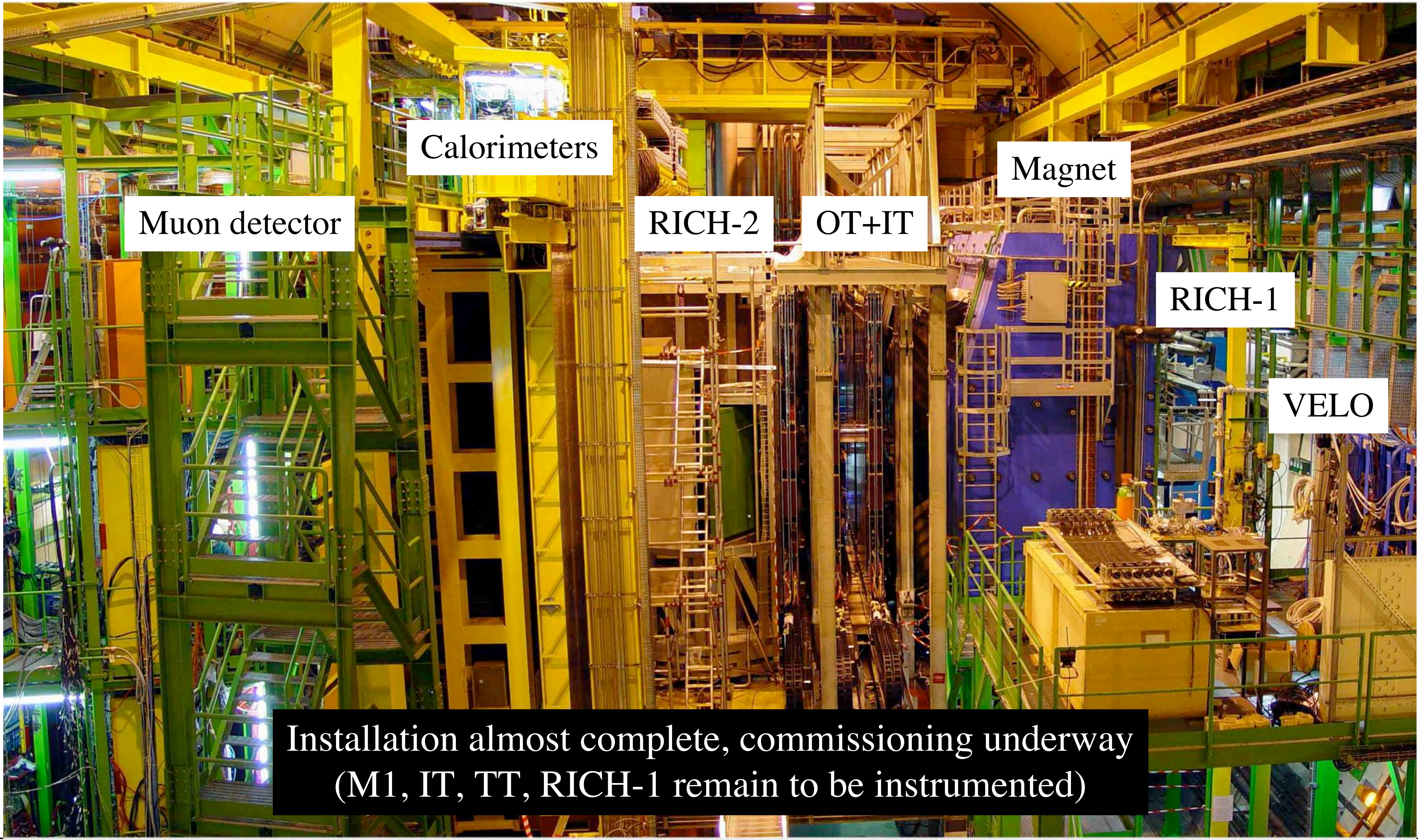
LHCb flavour physics program

- Precision CP violation, rare B decays, and more …
  - **Indirect search for New Physics (NP) in loop-induced decays**
    - Measurement of $B_s \to \mu\mu$ decay
    - B mixing parameters, incl. B_s mixing phase
    - CPV in exclusive $b \to sss$ hadronic penguin decays
    - CPV in B decay amplitudes
    - Measurements of exclusive $b \to sl^+l^-$ and $b \to s\gamma$ (i.e. chiral structure)
  - **Determination of weak phase difference between V_{ub} and V_{cb} (angle γ) using $B \to DK$ tree decays**
  - **Search for LFV in leptonic B decays**
  - **NP search in charm sector (D mixing, CPV, rare decays)**
  - **b-hadron spectroscopy, heavy quarkonia, …**

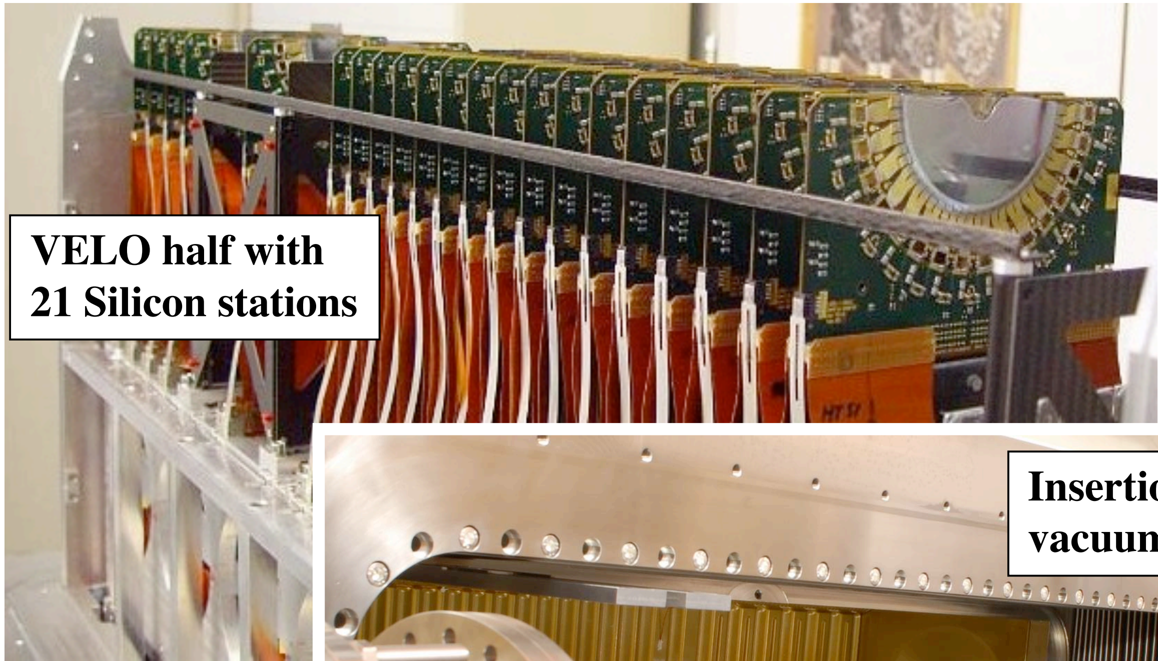
- If NP found by ATLAS/CMS, LHCb **provides complementary information** by probing NP flavour structure
- Otherwise, **explore much higher scales** than those reached by the direct search

See http://www.cern.ch/lhcb-phys/DC04_physics_performance/ for expected sensitivities and documentation on some of the key LHCb measurements

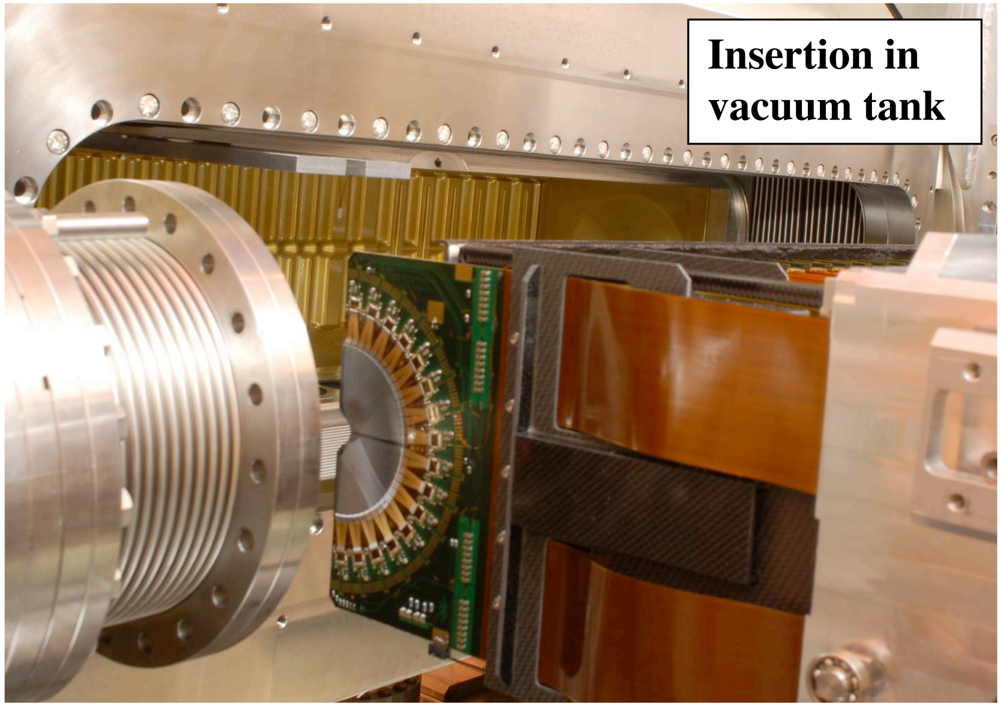
The beast in its cage … (waiting to be tamed)



VELO installation (Oct 30–31, 2007)



VELO half with
21 Silicon stations



Insertion in
vacuum tank

Installed !

Alignment strategy

- ❑ Complete survey of all sub-detectors and structures
- ❑ Hardware position monitoring
  - — info from stepping motors of VELO halves
  - — RASNIK system for large OT structures
  - — laser alignment system for RICH mirrors
- ❑ Software alignment with tracks:
  - — Internal alignment (O(10^3) alignable objects):
    - align VELO, IT, OT, RICH internally
  - — Global alignment (only few dof at each step):
    - Align the IT+OT wrt VELO
    - Align TT (not alignable internally) wrt VELO+IT+OT system
    - Align RICH, ECAL, HCAL, and Muon wrt tracking system

☆ Note: cosmics not adapted
- — Need beam1 halo, beam1-gas interactions, or beam-beam collisions

❶ Align tracking devices **without B field**
- — Use ~1M min bias events (10 min at 2 kHz) + beam halo tracks
- — Select clean tracks
- — If needed, use calo for rough p estimate

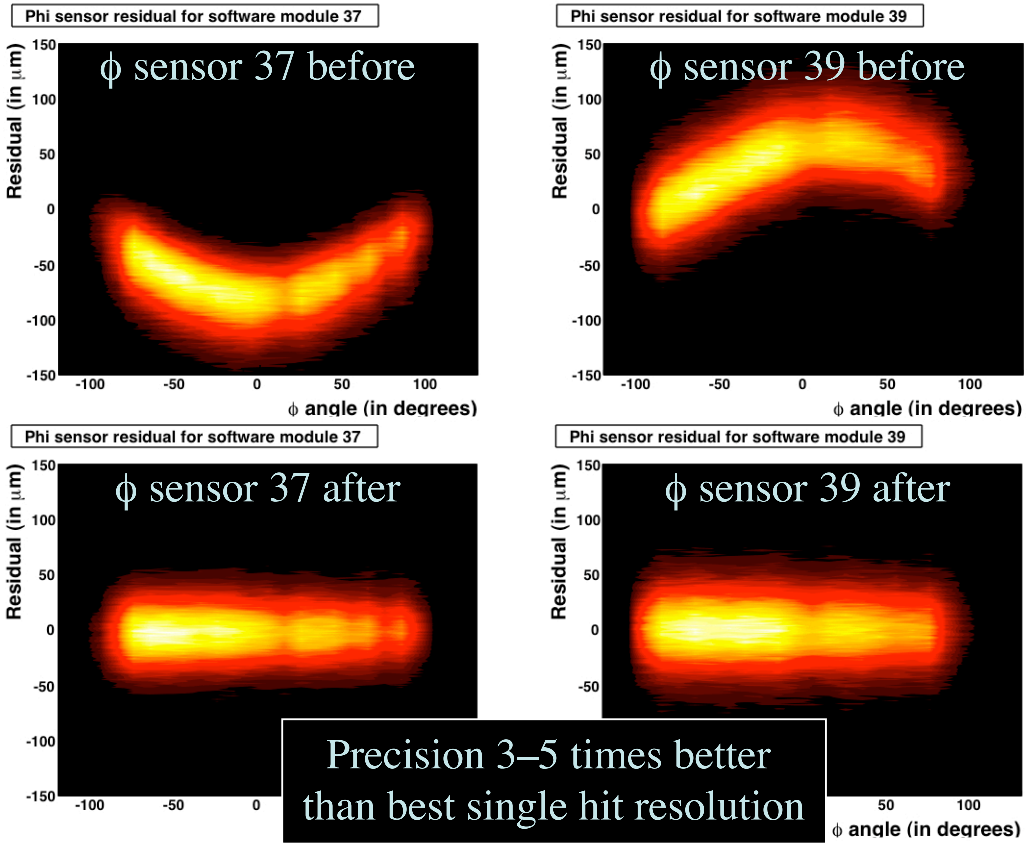
❷ Repeat **with B field**
- — Can apply p cut
- — Get final alignment; consistency check

VELO alignment

- **Internal alignment in a half:**
  - Sensor in a module
    - < 2 μm in x, y
  - Module in a half
    - Expect 1.3 μm in x, y and 0.12 mrad around z using 10^5 tracks (in 5000 min bias events) + 2000 beam halo tracks
- **Relative alignment of VELO halves:**
  - **Closed VELO**: 2 methods
    - "overlap tracks", with hits in both halves
    - reconstructed primary vertexes (PV)
  - **Open VELO**:
    - only PV method (with less stat.)

	x or y transl.	x or y rot.
300 overlap tracks	**12 μm**	**36 μrad**
1500 recons. PVs	**28 μm**	**108 μrad**

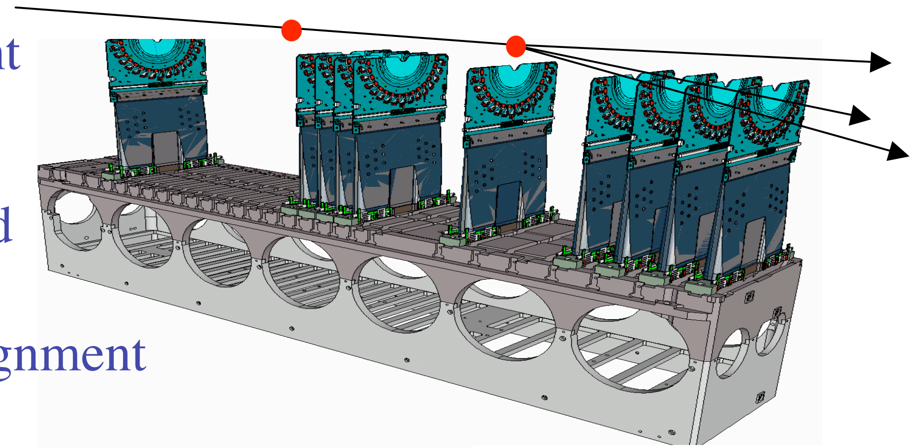
Test beam data: track residuals vs ϕ

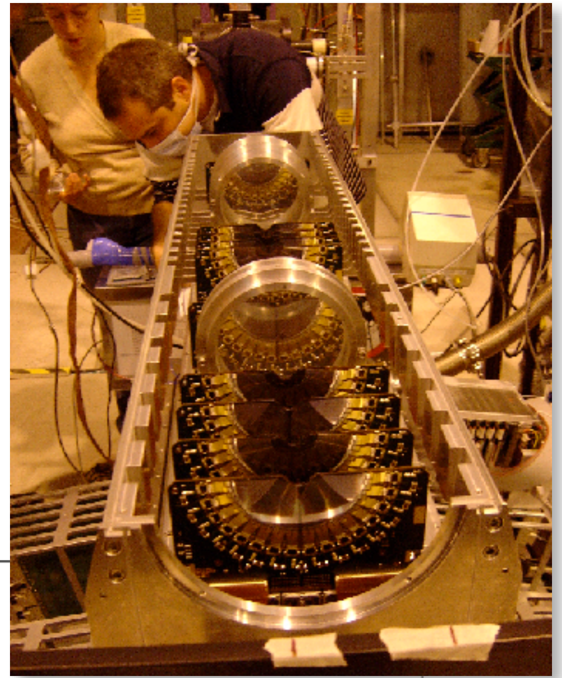


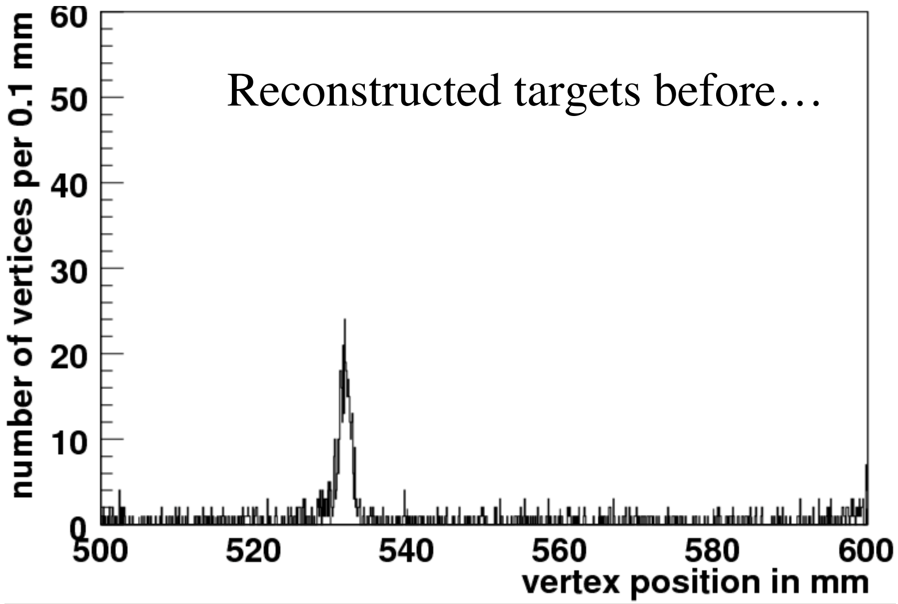
Within requirements, in particular for the trigger

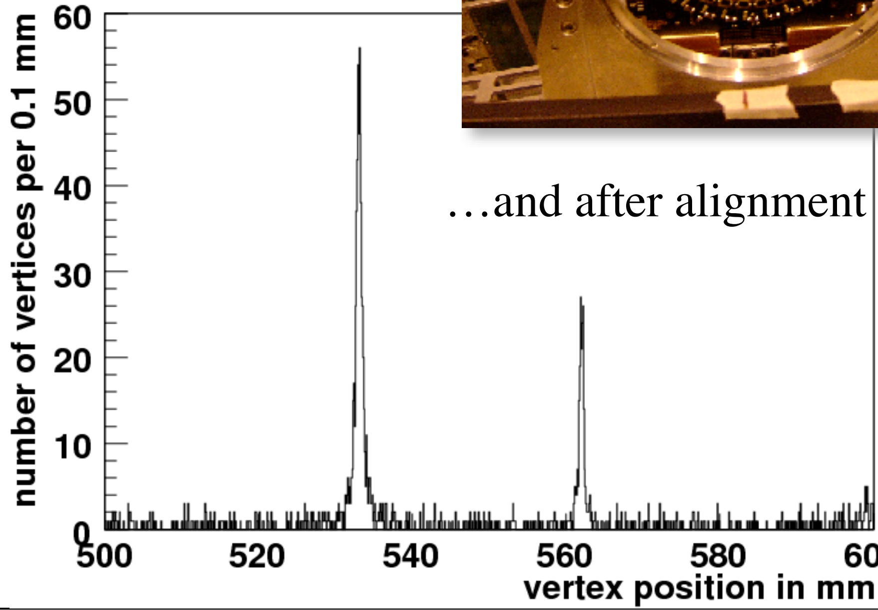
VELO test beam

- Nov 2006 test beam
  - Internal alignment procedure successfully applied and tested
  - Second target resolved after alignment





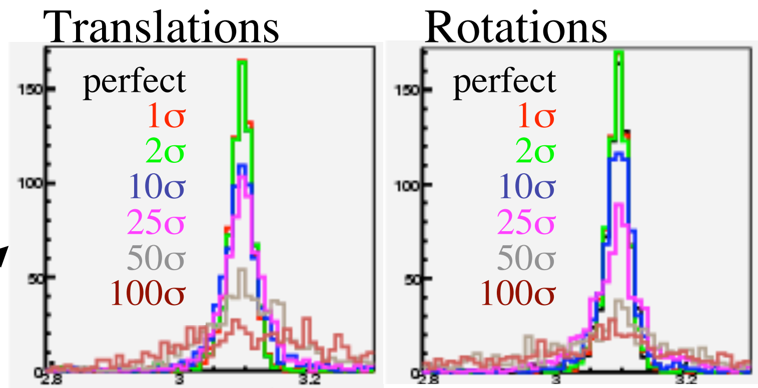




Momentum measurement

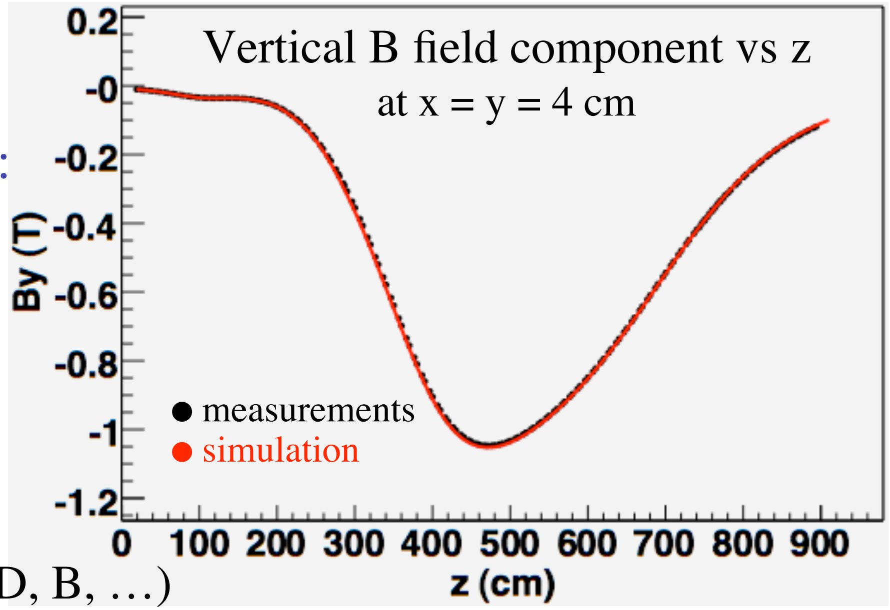
Momentum resolution:

- σ_p/p = **0.35%–0.55%** depending on p
- IT and OT alignment important to avoid degradation:
  - e.g IT box aligned to σ = 5 (50) μm and σ = 0.1 (0.2) mrad in x and y (z)
  - Degradation of 10 MeV/c² J/ψ→μμ mass resolution as a function of IT box misalignment



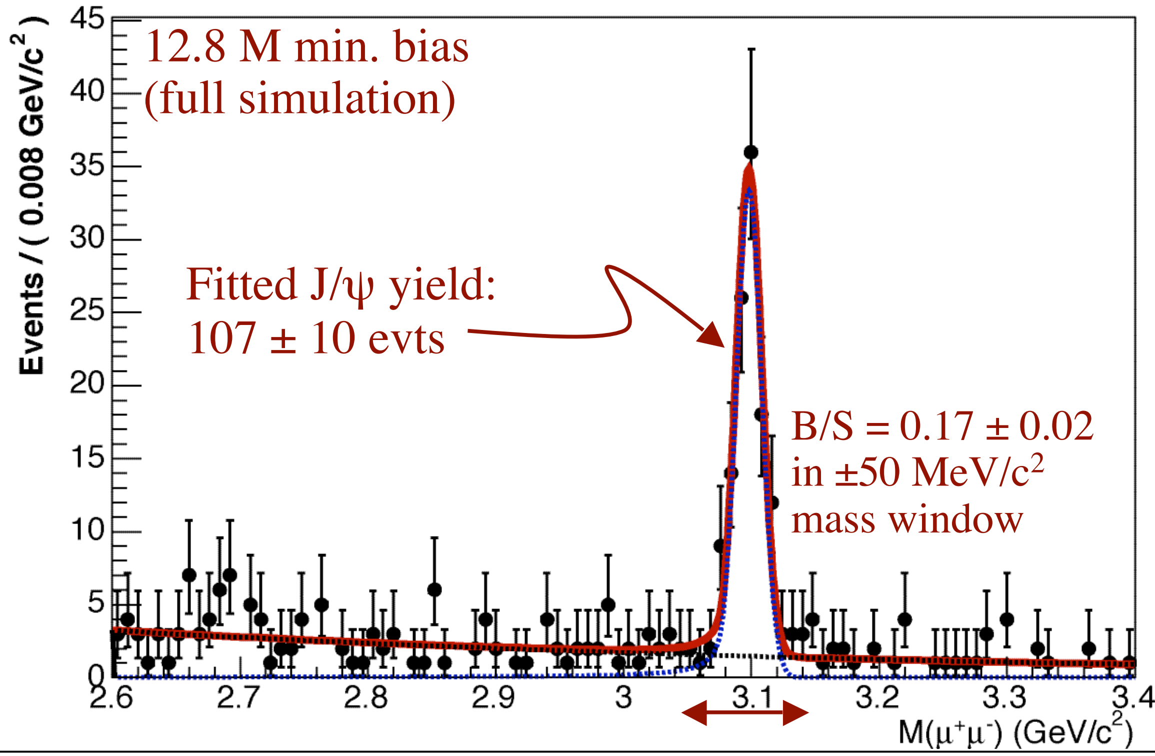
Momentum calibration:

- Full 3D B-field map at startup (both polarities):
  - Parametrized using measurements (Dec 2005) checked against TOSCA simulation
  - Expected rel. precision: few 10^{-3}
- Check/refine with systematic mass studies:
  - Value of J/ψ mass vs momentum, etc …
  - Use also less abundant dimuon mass peaks (ψ(2S), ϒ) and hadronic mass peaks (K_S, ϕ, Λ, D, B, …)



Physics with very early data

- Minimum bias events:
  - e.g. 10^8 events in ~20 hours at 2×10^{28} cm^{-2}s^{-1} with interaction trigger
  - First look at 14 TeV data: everything new !
    - (Ratio of) multiplicities vs η, pT, φ of charged tracks (+/–, π/K/p)
    - Reconstruction and production studies of K_S, Λ, ϕ, D, …
- $J/\psi \to \mu\mu$ events:
  - ~1M $J/\psi \to \mu\mu$ in 1 pb^{-1} (little bit of trigger needed)
    - Fraction of J/ψ from b decays or prompt production vs p_T
    - First exclusive $B \to J/\psi X$ peaks
    - Measurements of bb production cross section, …



Trigger

- Two stages:
  - **L0** = Level 0 (hardware, max. output rate = 1 MHz):
    - Info from pileup system, ECAL, HCAL and MUON: select minimum p_T h, μ, e, γ, π^0
  - **HLT** = High Level Trigger (software, after full readout, ~2 kHz output rate):
    - Several trigger lines: μ, μ+h, h, ECAL, …(start with L0 confirmation)
    - Then inclusive and exclusive selections (full B decay chains)

- Early running scenarios:
  - Start with loose L0
    - Until saturation of output rate at ~ 2×10^{31} cm^{-2}s^{-1}

Lumi	nr-bunches	pp-int/xing	non-empty rate	L0-YES
1.1×10^{29}	* 4	0.15	6 kHz	3 kHz
2.3×10^{30}	* 16	0.76	94 kHz	47 kHz
2.6×10^{31}	936(75 ns)	0.15	1.4 MHz	0.7 MHz
2.0×10^{32}	2622 (25 ns)	0.4	10 MHz	1 MHz

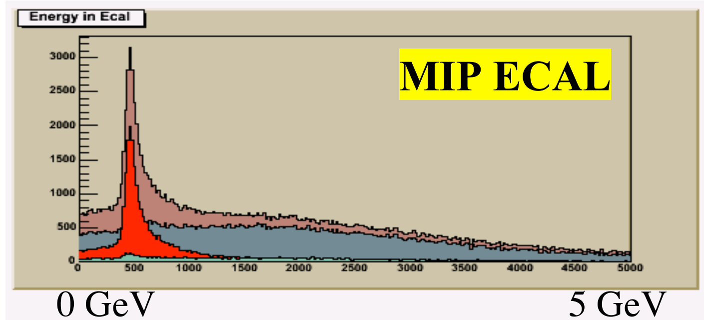
* NB: LHCb will only get collisions with "displaced" bunches

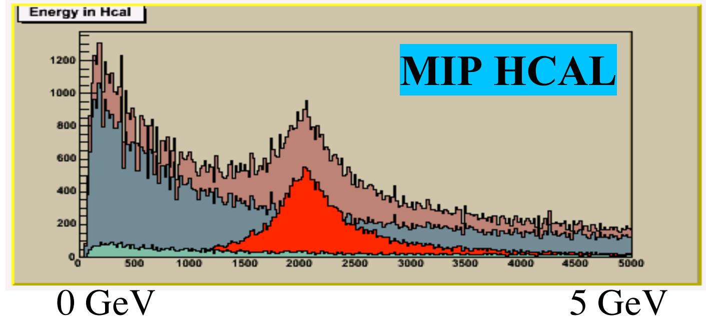
  - No HLT active until ~10^{29} cm^{-2}s^{-1}
    - Check/debug L0 and L0 confirmation
    - Understand/fix crucial distributions (σ(p), $\sigma(p_T)$, σ(IP), …), compare with offline and MC
    - Test/adjust selections, i.e. background rejection and CPU timing
      - no signal needed at this stage, use abundant bkg data (instead of limited MC samples)

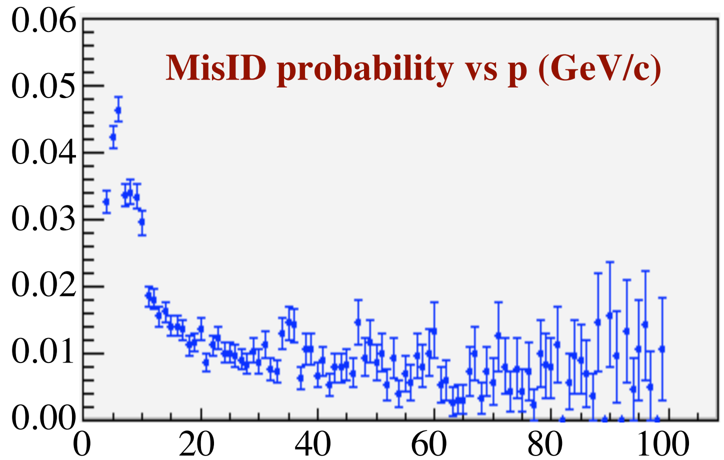
Muon ID calibration

All rates quoted at nominal luminosity

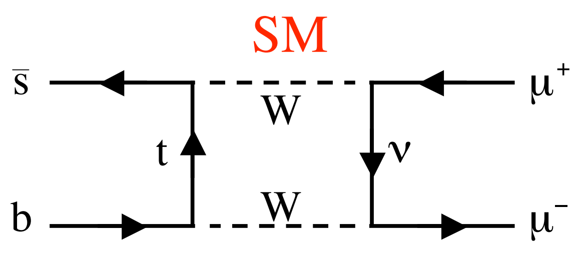
- Muon samples to measure efficiency (> 95%):
  - Generic muons (50 Hz)
    - **Not triggered**
    - MIP in calo, few muon hits (2x nominal window)
    - IP cuts to reduce prompt hadrons
  - Prompt $J/\psi \rightarrow \mu\mu$ (< 2 Hz)
    - 2 generic muons as above, but without IP cut
    - Vertex + mass requirements
  - $J/\psi \rightarrow \mu\mu$ from B (0.3 Hz)
    - 1 triggered muon (with IP cut) + calo MIP
    - Vertex + mass requirements
    - Highest purity (90%)
- Hadron samples to measure muon misID:
  - $D^{*+} \rightarrow D^0(K^-\pi^+)\pi^+$ (16 Hz of hadrons)
    - MisID due to decays in flight (~70%), noise hits in muon chambers (~20%), punch-through (~10%)
  - Hadrons from B $\rightarrow$ hh (0.02 Hz)
    - Useful to determine misID in $B_s \rightarrow \mu\mu$ analysis (same phase-space)

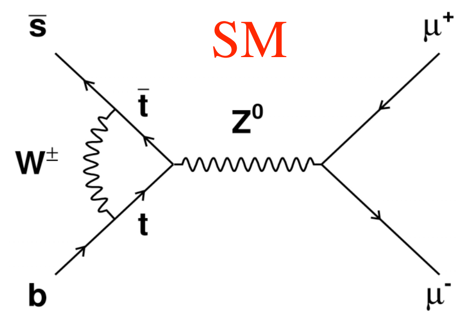


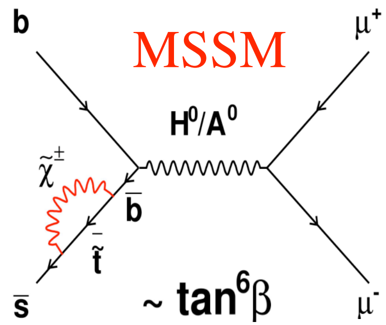




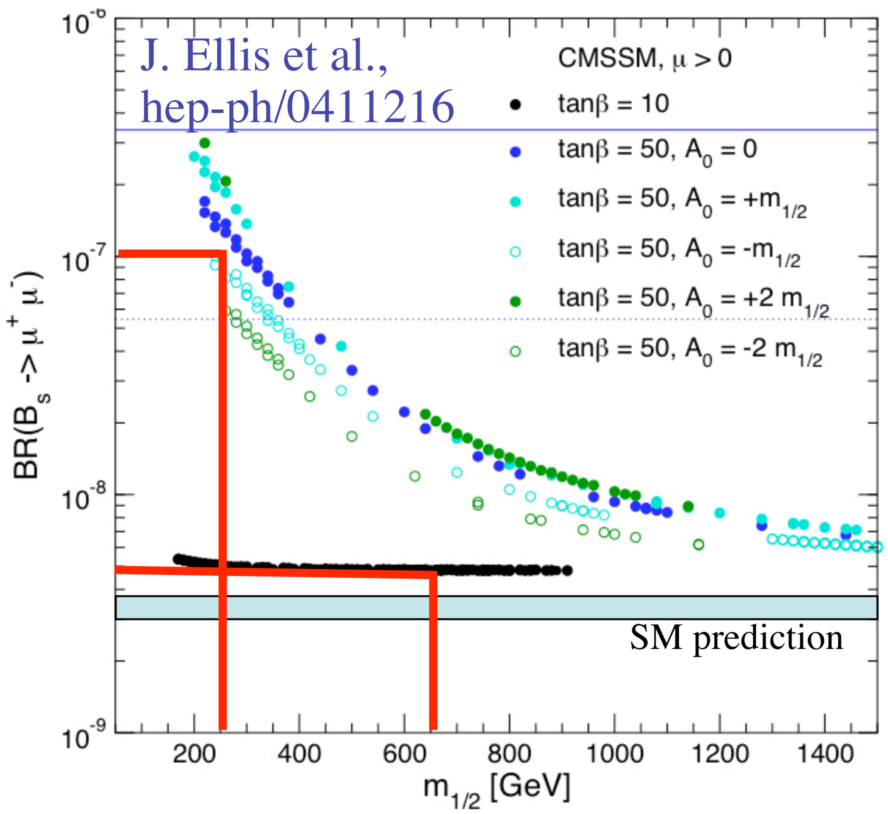
$B_s \to \mu^+\mu^-$





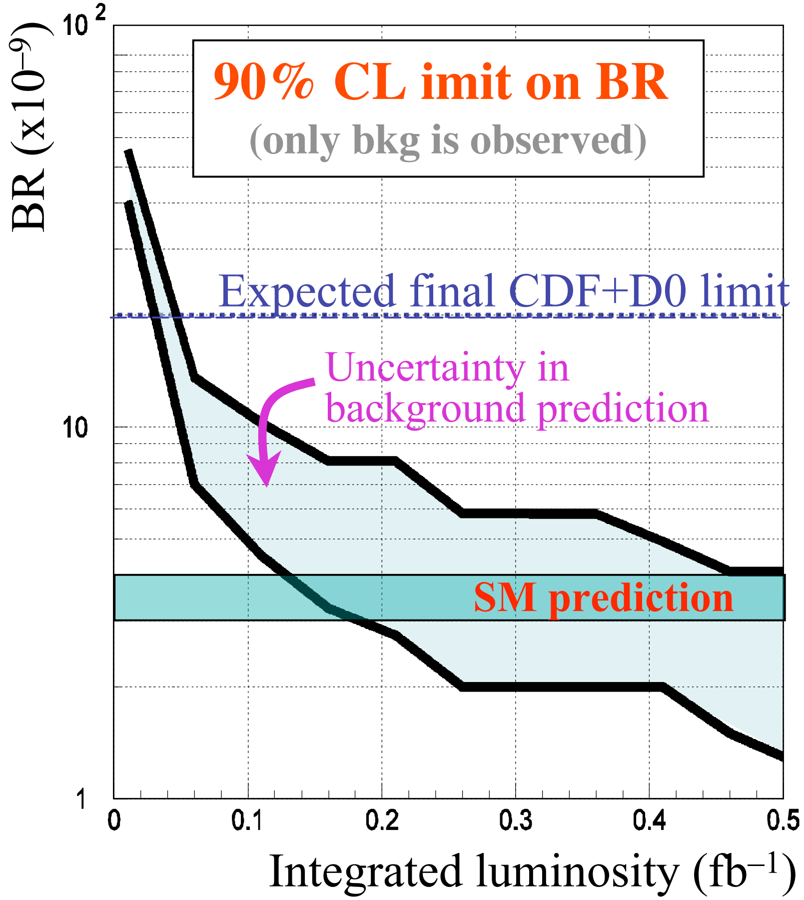


- Very rare loop decay, sensitive to new physics:
  - $BR_{SM} = (3.55\pm0.33)\times10^{-9}$
  - Can be strongly enhanced in SUSY:
    - e.g. current measurement of $g_\mu-2$ suggests gaugino mass between 250 and 650 GeV/c²
      $\Rightarrow$ BR($B_s \to \mu^+\mu^-$) up to 100×10^{-9} within the CMSSM for high tanβ
  - Current 90% CL limits:
    - $47\times10^{-9} = 13\times BR_{SM}$ (CDF, 2 fb^{-1}, prel)
    - $75\times10^{-9} = 21\times BR_{SM}$ (D0, 2 fb^{-1}, prel)



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

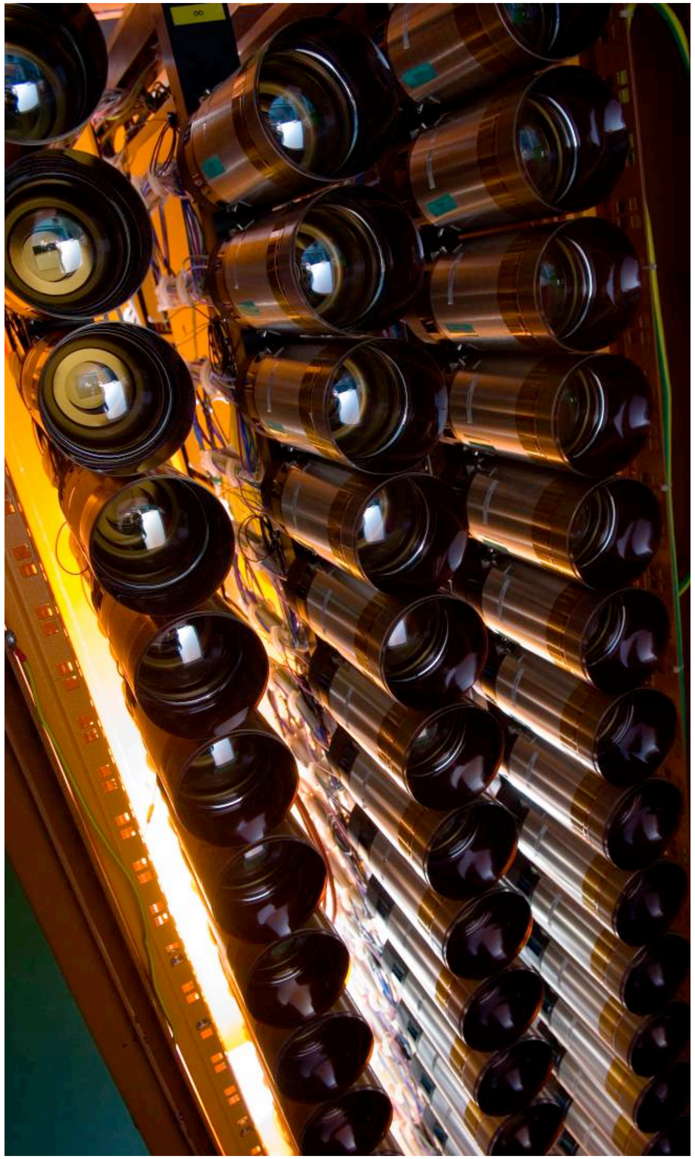
- "Easy" for LHCb to trigger and select
  - Large total efficiency (10%)
  - Main issue is background rejection
    - study based on limited MC statistics
    - largest background is $b\to\mu$, $b\to\mu$
    - specific background dominated by $B_c \to J/\psi(\mu\mu)\mu\nu$
  - Exploit good detector performance:
    - muon ID
    - vertexing (topology)
    - mass resolution (18 MeV/c^2)

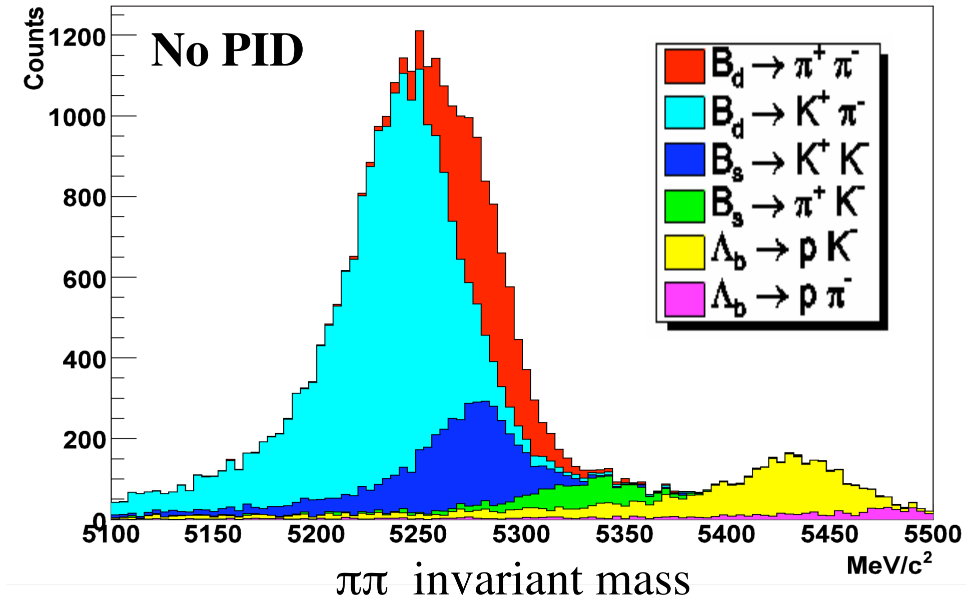


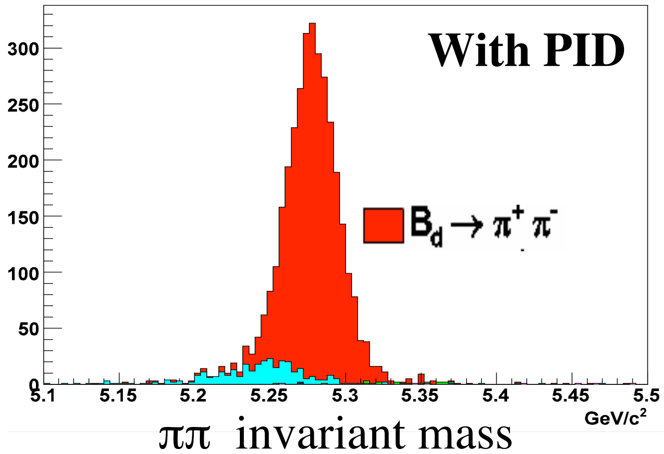
0.05 fb^{-1} ⇒ overtake CDF+D0
0.5 fb^{-1} ⇒ exclude BR values down to SM
2 fb^{-1} ⇒ 3σ evidence of SM signal
6 fb^{-1} ⇒ 5σ observation of SM signal

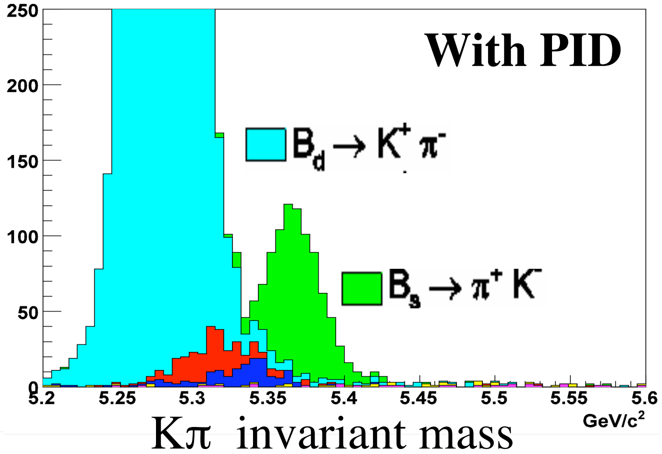
LHCb's best NP discovery potential with the very early data !

Particle ID performance with RICH



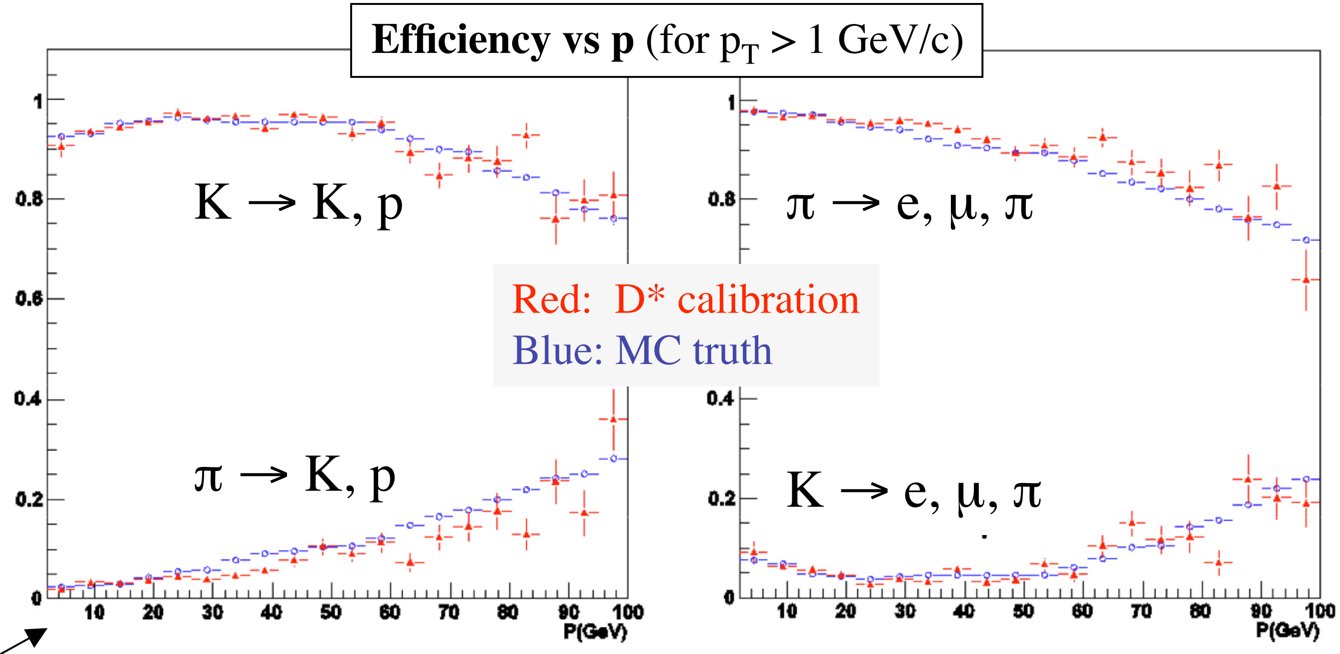


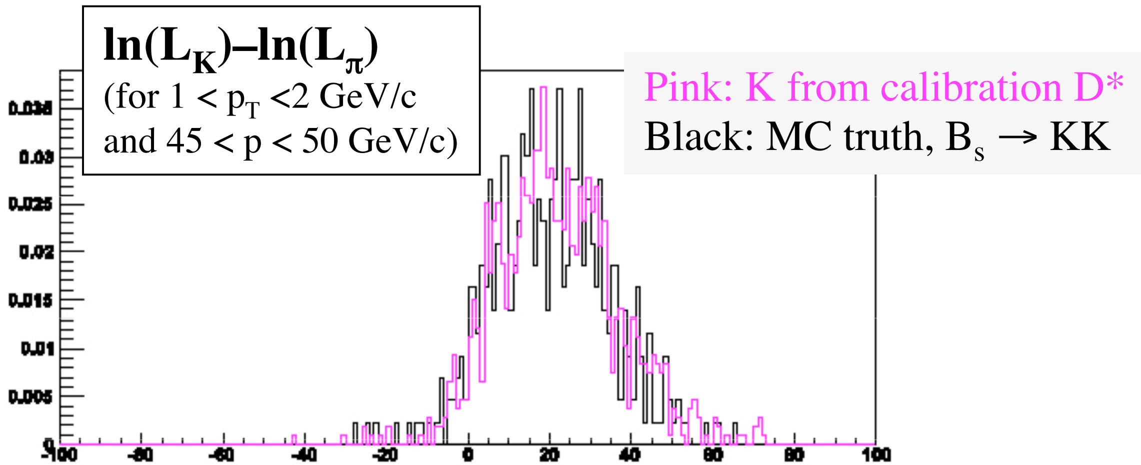




RICH PID calibration

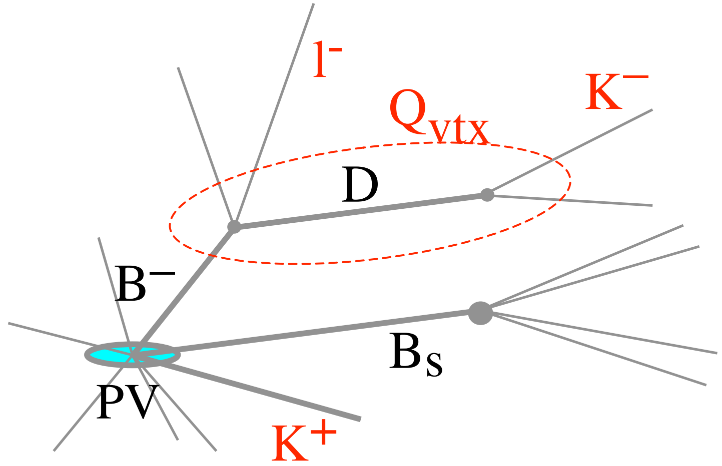
- K/π ID calibration:
  - Use kaons and pions from $D^{*+} \to D^0(K^-\pi^+)\pi^+$ decays, selected without using RICH information:
    - ~ 5 Hz of triggered and selected D* at nominal luminosity
    - Purity 90%
  - With first ~10k events:
    - Rough calibration vs momentum
  - Eventually:
    - Full calibration of PID estimator Δln(L) in bins of p and p_T



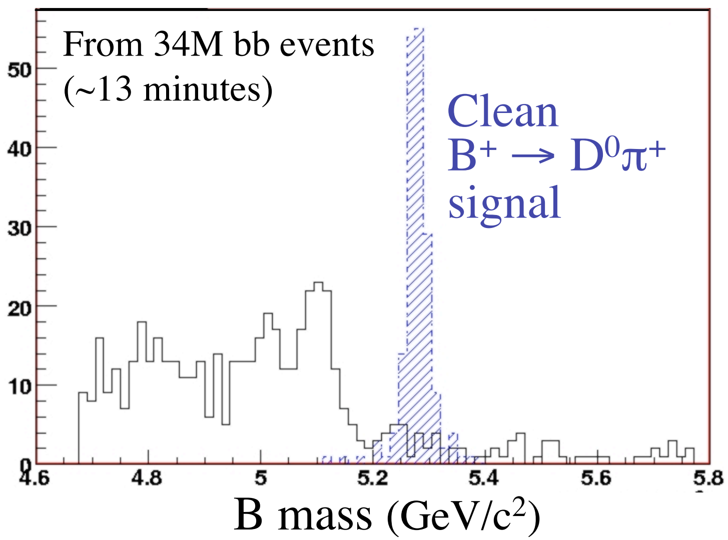


B vs $\overline{\text{B}}$ flavour tagging

- Several tags:
  - Opposite side (OS): electron, muon, kaon, vertex charge
  - Same side (SS): pion (B^0) or kaon (B_s)
    - most powerful tags: SS kaon and OS kaon
  - Expected combined performance on triggered and selected MC events:
    - **$\varepsilon D^2 = \varepsilon(1-2w)^2$ = 4–5% for B^0**
    - **$\varepsilon D^2 = \varepsilon(1-2w)^2$ = 7–9% for B_s**



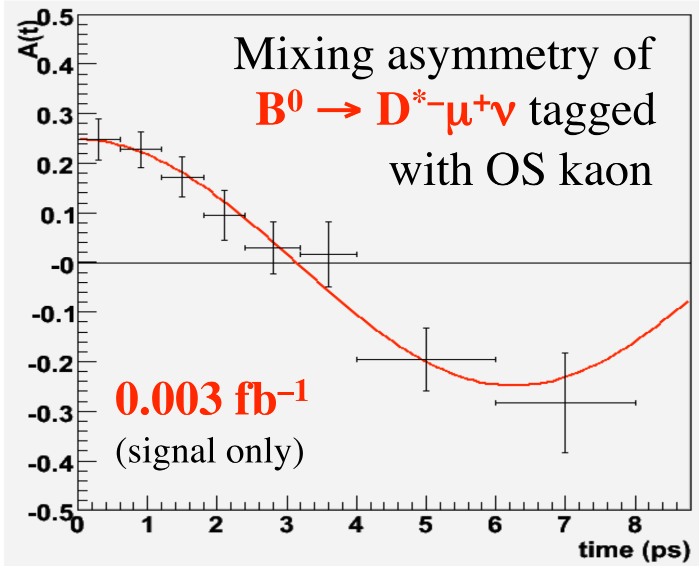
- Using data:
  - Reconstruct and select several control samples
    - High-statistics flavour-specific B decay modes
  - Look at tags one by one:
    - assess performance (mistag rate w)
    - tune tag selection

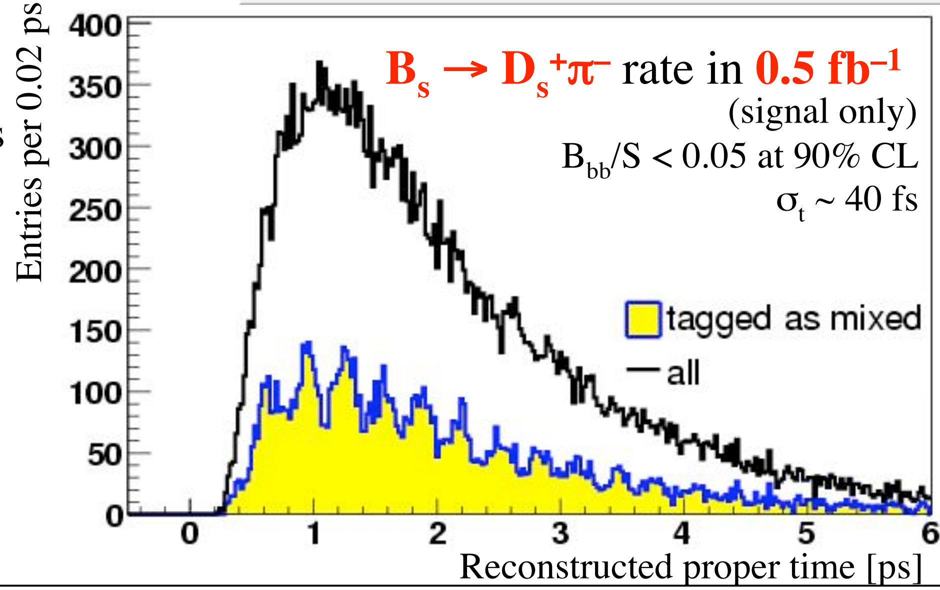


Control channel	0.1 fb^{-1} yield	B_{bb}/S
$B^+ \to J/\psi(\mu\mu)K^+$	85k	0.4
$B^0 \to J/\psi(\mu\mu)K^{*0}$	45k	0.2
$B^+ \to D^0\pi^+$	50k	0.1
$B_s \to D_s^+\pi^-$	7k	0.2
$B^+ \to D^0\mu^+\nu X$	120k	0.8
$B^0 \to D^{*-}\mu^+\nu$	460k	0.3
$B_s \to D_s\mu^+\nu X$	55k	0.4

Control of tagging and proper time

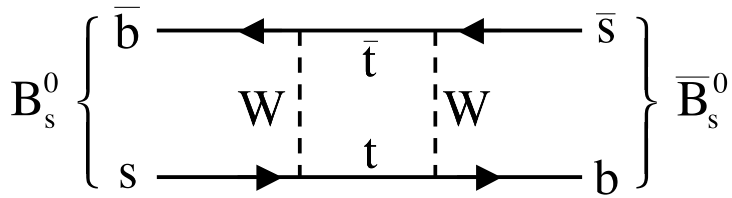
- **Extraction of flavour mistag probabilities:**
  - Opposite-side tags:
    - **$\sigma(w_{OS})/w_{OS}$ ~ 1–2% with 0.1 fb^{-1}**
      - Use B^+ control samples (counting)
      - Use B^0 control samples (fit of time-dependence)
  - Same-side kaon tag:
    - **$\sigma(w_{SS})/w_{SS}$ ~ 6% with 0.1 fb^{-1}**
      - Use B_s control samples (double tagging method, fit of time-dependence)
  - Warning:
    - Tagging can be biased by trigger & selection
    - Can only compare two samples with same bias
- **"Control" physics measurements:**
  - Demonstrate time-dependent CP physics capability on 0.1–0.5 fb^{-1} of data with measurements of well-known observables:
    - Specific b-hadron lifetimes, Δm_d, $\sin(2\beta)$, Δm_s





B_s mixing phase ϕ_s wrt $b \rightarrow c\bar{c}\bar{s}$

- $\phi_s = -2\beta_s$ is the strange counterpart of $\phi_d = 2\beta$
  - ϕ_s very small in SM
    - $\phi_s^{SM} = -\arg(V_{ts}^2) = -2\lambda^2\eta =$ **−0.0368 ± 0.0018**
  - Could be much larger in presence of New Physics



- Golden b→ccs mode is $B_s \rightarrow J/\psi\phi$:
  - Single decay amplitude
  - Angular analysis needed to separate CP-even and CP-odd contributions
- Current experimental situation:
  - No evidence of CP violation found
  - D0 result (1.1 fb^{-1}, ~1k $B_s \rightarrow J/\psi\phi$)
    - $\phi_s = -0.79 \pm 0.56 \, {}^{+0.14}_{-0.01}$ [PRL 98, 121801 (2007)]
- LHCb sensitivity with 0.5 fb^{-1}:

$$\boxed{\sigma_{stat}(\phi_s) = 0.046}$$

~33k $B_s \rightarrow J/\psi(\mu\mu)\phi$ events (before tagging),
$B_{bb}/S = 0.12$, $\sigma_t = 36$ fs

Time-dependent CP asymmetry:

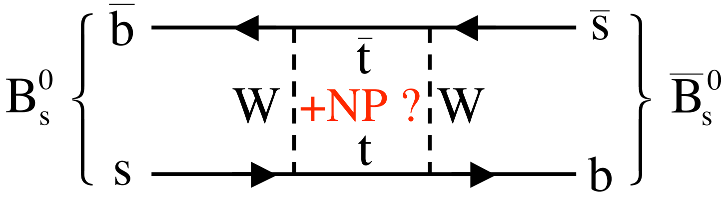
$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}_s^0(t) \rightarrow f\right) - \Gamma\left(B_s^0(t) \rightarrow f\right)}{\Gamma\left(\bar{B}_s^0(t) \rightarrow f\right) + \Gamma\left(B_s^0(t) \rightarrow f\right)}$$

For a final state f with CP eigenvalue η_f:

$$A_{CP}(t) = \frac{-\eta_f \sin\phi_s \sin(\Delta m_s t)}{\cosh\left(\Delta\Gamma_s t/2\right) - \eta_f \cos\phi_s \sinh\left(\Delta\Gamma_s t/2\right)}$$

- Eventually:
  - Add also pure CP modes ($J/\psi\eta^{(\prime)}$, $\eta_c\phi$, D_sD_s)
  - With 10 fb^{-1}, obtain >3σ evidence of CP violation ($\phi_s \neq 0$), even if only SM

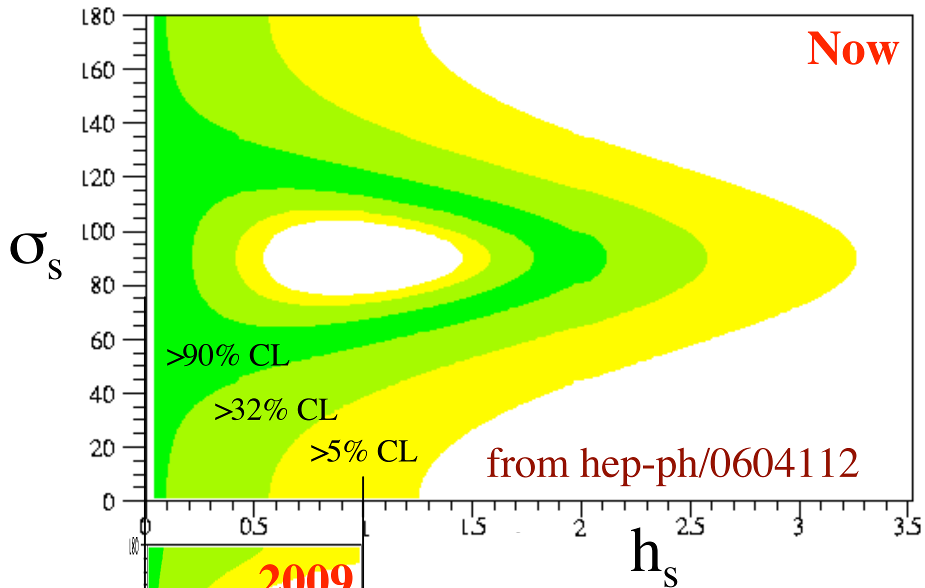
Constraints on New Physics in B_s mixing from ϕ_s measurement

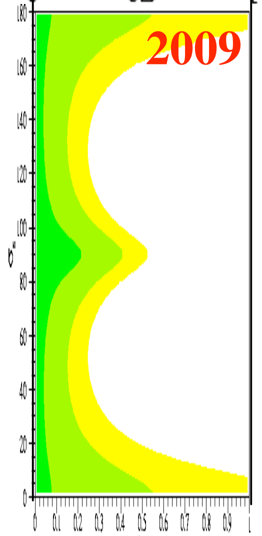


- New Physics in B_s mixing:
  - amplitude M_{12} parametrized with h_s and σ_s:

$$M_{12} = \left(1 + h_s e^{2i\sigma_s}\right) M_{12}^{SM}$$

  - LHCb can exclude already significant region of allowed phase space with the very first data or …





After LHCb measurement of ϕ_s with $\sigma(\phi_s) = \pm\, 0.1$ ($\sim 0.2\ \mathrm{fb}^{-1}$)

courtesy Z. Ligeti

LHCb B physics examples with 0.5 fb^{-1}

Decay mode	0.5 fb^{-1} yield	0.5 fb^{-1} stat. sensitivity	Rough stat. break-even point with competition *
$B_d \to J/\psi(\mu\mu)K_S$	59k	$\sigma(\sin(2\beta)) = 0.04$	2 fb^{-1}
$B_s \to D_s^- \pi^+$	35k	$\sigma(\Delta m_s) = 0.012$ ps^{-1}	0.2 fb^{-1}
$B_s \to D_s^- K^\pm$	1.6k	$\sigma(\gamma) = 21$ deg	–
$B_s \to J/\psi(\mu\mu)\phi$	**33k**	**$\sigma(\phi_s) = 0.046$**	**0.3 fb^{-1}**
$B_d \to \phi K_S$	230	$\sigma(\sin(2\beta_{eff})) = 0.46$	8 fb^{-1}
$B_s \to \phi\phi$	780	$\sigma(\Delta\phi^{NP}) = 0.22$	–
$B^+ \to D(hh)K^\pm$ $B^+ \to D(K_S\pi\pi)K^\pm$	16k 1.3k	$\sigma(\gamma) = 12–14$ deg	0.3 fb^{-1}
$B_d \to \pi^+\pi^-$	8.9k	$\sigma(S, C) = 0.074, 0.086$	1–2 fb^{-1}
$B_s \to K^+K^-$	9.0k	$\sigma(S, C) = 0.088, 0.084$	–
$B_d \to \rho\pi \to \pi^+\pi^-\pi^0$	3.5k	α	2 fb^{-1}
$B_d \to K^{*0}\gamma$	15k	A_{CP}	0.4 fb^{-1}
$B_s \to \phi\gamma$	2.9k	$A_{CP}(t)$	–
$B_d \to K^{*0}\mu^+\mu^-$	1.8k	$\sigma(q^2_0) = 0.9$ GeV^2	0.1 fb^{-1}
$B_s \to \mu^+\mu^-$	**18**	**BR_{SM} at 90%CL**	**0.05 fb^{-1}**

* Assuming naive $1/\sqrt{N}$ scaling of stat. uncertainty of existing results at Tevatron ($\to$ 16 fb^{-1}) or current B factories ($\to$ 1.75 ab^{-1})

— For many measurements based on B_s, or untagged B^0, B^+ decays only few 0.1 fb^{-1} are necessary to produce the world's best results

Conclusion

- **Startup:**
  - First beam (clockwise, please !) and first collisions with LHCb magnet off:
    - **Establish** running procedure, check/adjust **time alignment**
    - **Exercise reconstruction** software on real data, **align detector in space**
  - First collisions with magnet on (+ second polarity, once possible):
    - **Calibrate** momentum, energy, PID, … + check alignment
    - Study crucial distributions (resolutions, …) and **commission trigger**
    - **Exercise computing model** with real data (use of Tier1 centers + Grid analysis)
    - Want/push to get 25ns bunch-spacing and 2×10^{32} $cm^{-2}s^{-1}$ as soon as possible
- **Physics:**
  - Early bread-and-butter measurements (e.g. J/ψ production, σ_{bb}, …)
  - Most "core physics" to be started already with 0.1–0.5 fb^{-1}
  - **Search for new physics starts immediately** with highly promising and competitive results to get out asap, e.g.

$B_s \rightarrow \mu\mu$
ϕ_s with $B_s \rightarrow J/\psi\phi$