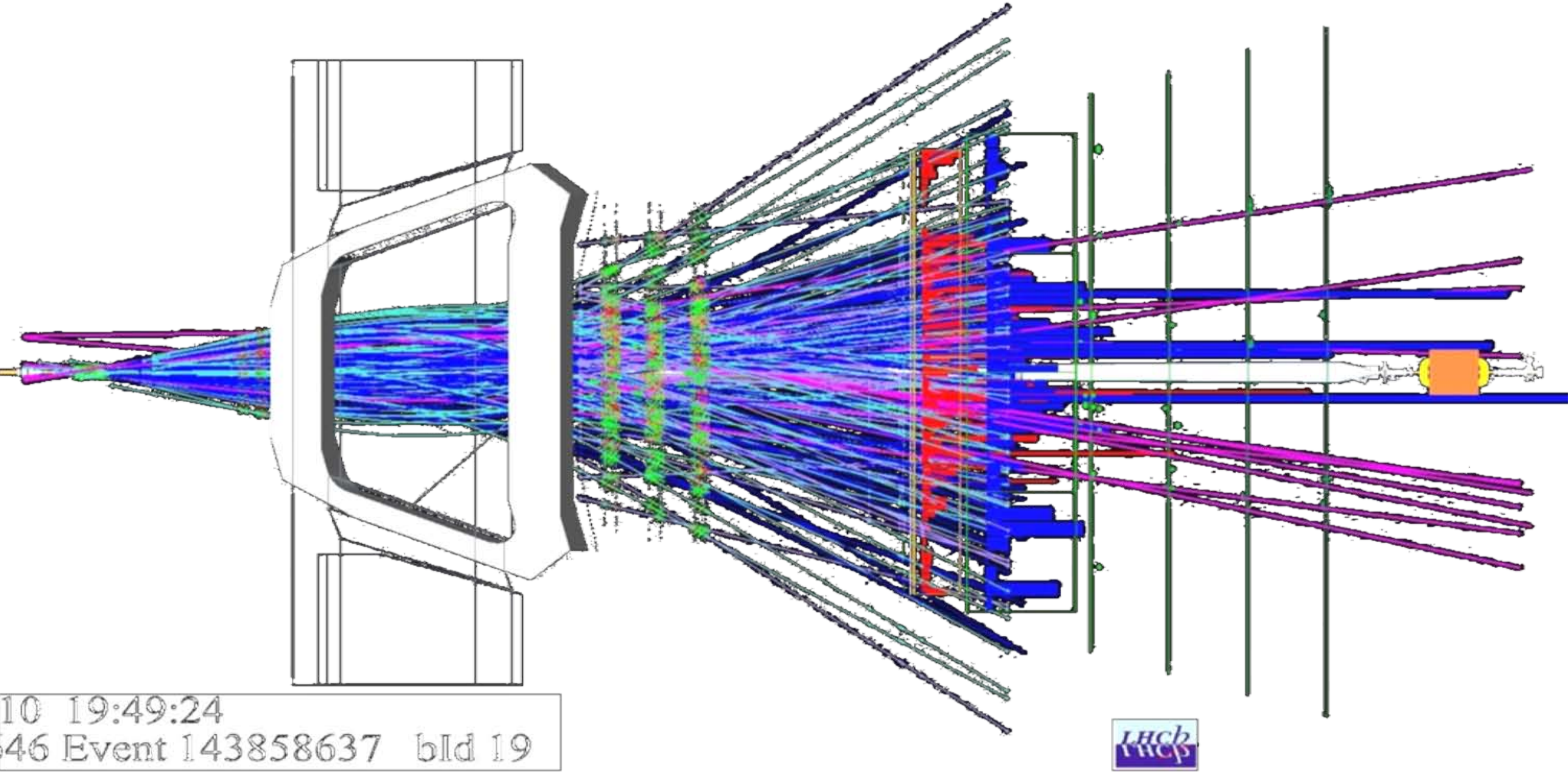
The LHCb Upgrade



On behalf of the LHCb collaboration
Specific thanks to P.Collins, M. Merk, J. Panman and Ch. Parker

Presentation

LHCb performance

LHCb limitations

Upgrade Physics Programme

Upgrade Detector

Referees' view of Physics programme

"Case for flavour physics with 50 fb^{-1} compelling"

At good bookshops near to you

LHCb physics programme: well underway

Excellent trigger and reconstruction performance

Br($B_s \to \mu^+\mu^-$) < 5.6 x 10^{-8} @ 95% C.L.

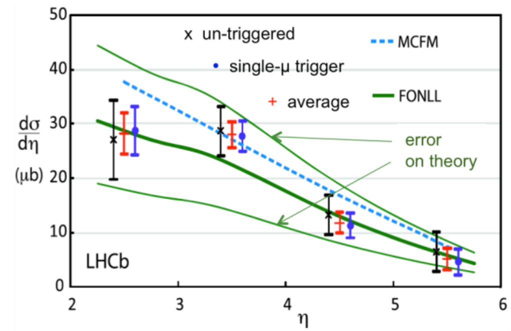
Production cross sections in beauty and charm

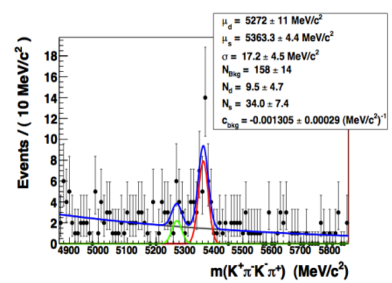
Clean Δm_s measurement at Tevatron precision and with 2x smaller systematic error

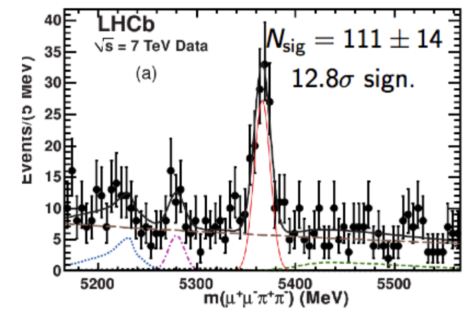
First observations: $B_s \to J/\psi f_0$, $B_s \to D_s K^{*0}$, $B_s \to K^{0*} K^{0*}$ …

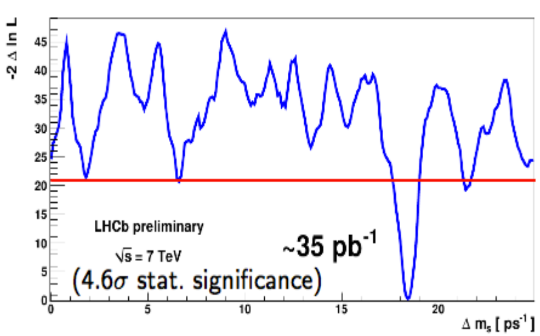
Huge yields in critical channels

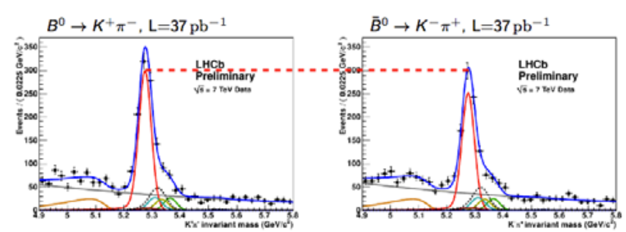
Ingredients in place for core CPV programme











Direct CPV in $B \to K^{\pm}\pi^{\mp}$

LHCb: Initial Highlights – Part 1

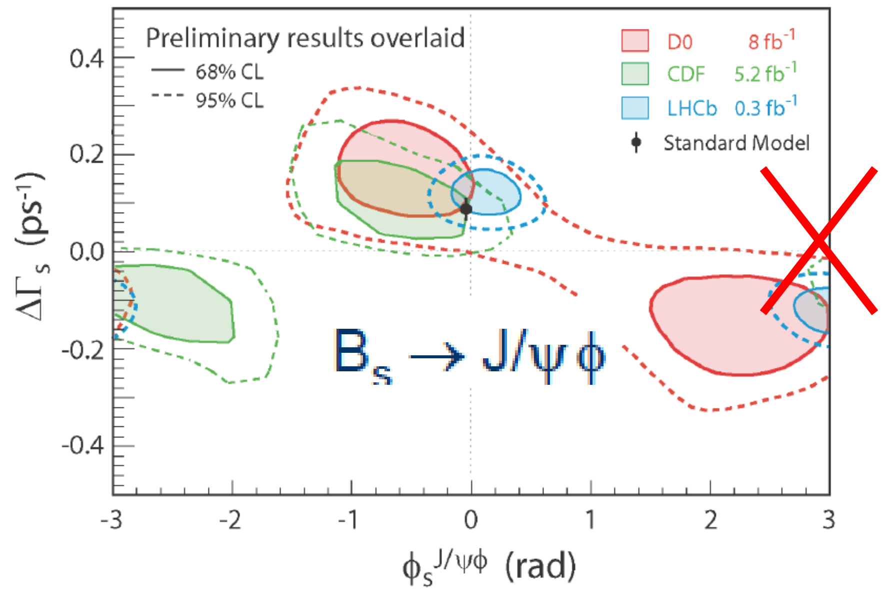
World Best

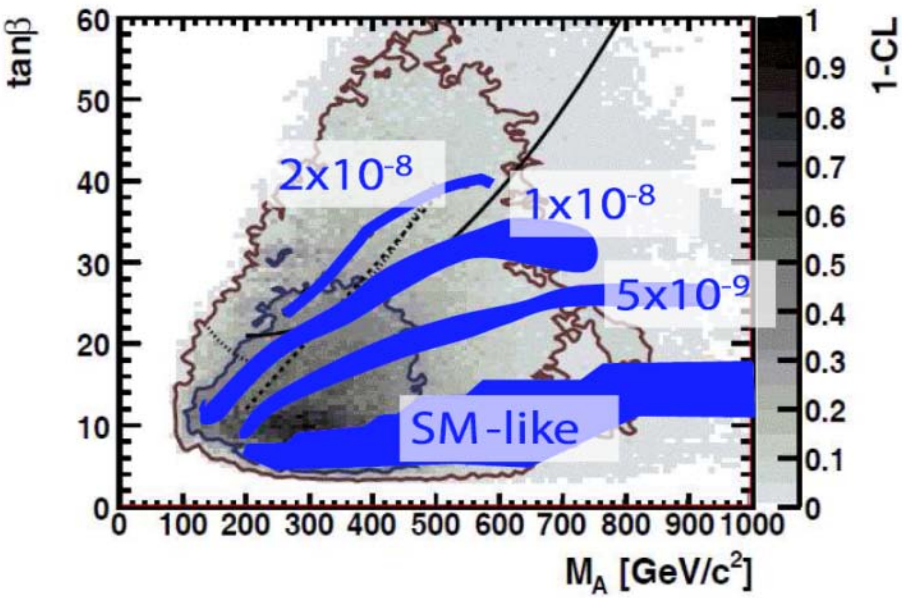
Φ_s: the B_s mixining

-Tagged, time dependent,angular analysis

- Tevatron SM discrepancy resolved

- Ambiguity removed





- $B_s \to \mu^+\mu^-$: constraining SUSY
  - Strongly suppressed in SM
  - Enhanced in MSSM

World Best

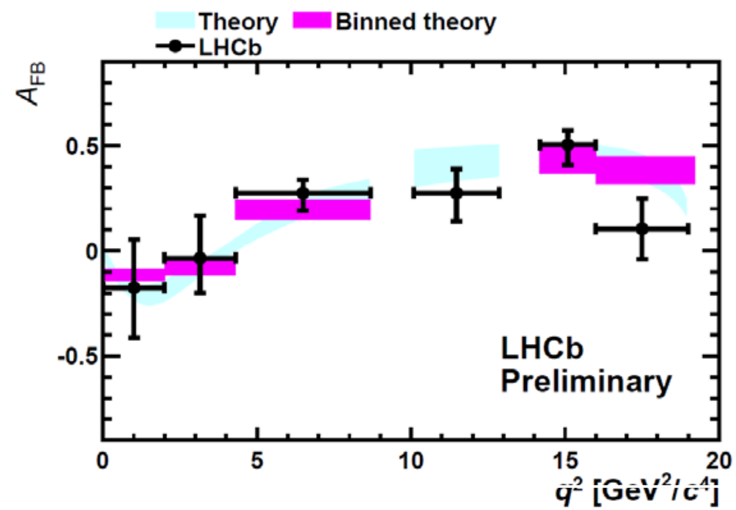
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.4 \times 10^{-8}$$

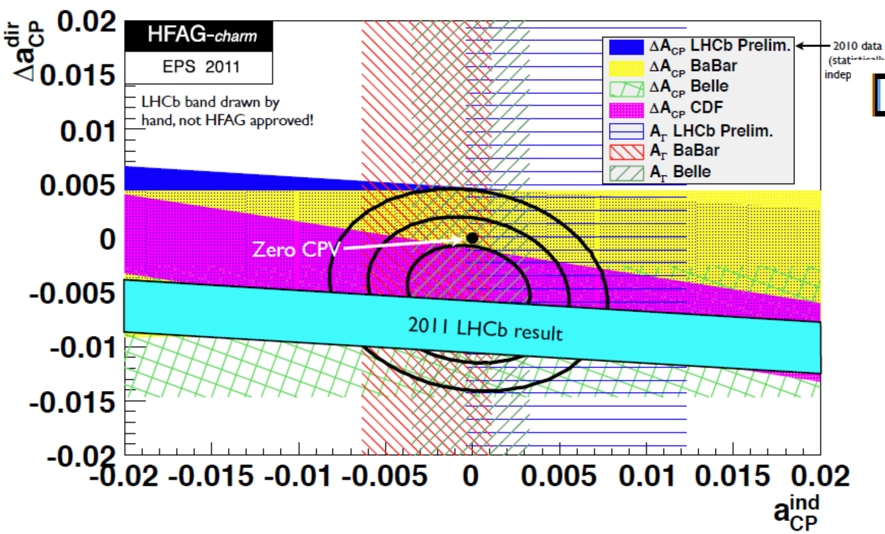
LHCb: Initial Highlights – Part 2

$B^0 \rightarrow K^*\mu^+\mu^-$: NP in loops

World Best

- Rare decays are not so rare now !
- No sign of B-factory / CDF discrepancy





- Charm CP Violation

$D^{*+} \rightarrow D^0(K^+K^-)\pi^+$ and $D^{*+} \rightarrow D^0(\pi^+\pi^-)\pi^+$

FIRST

- First evidence of CP violation in charm sector
- Direct CP Asymmetry
- Also measured y_{CP}, A_Γ

Limited by Detector

But **NOT** Limited by LHC

- Upgrade to extend Physics reach
  - Exploit advances in detector technology
    - Displaced Vertex Trigger, 40MHZ readout
    - Radiation Hard Vertex Detector
  - Better utilise LHC capabilities
- Timescale, 2018
- Collect >50 fb^{-1} data
- Modest cost compared with existing accelerator infrastructure

Independent of LHC upgrade
- HL-LHC not needed
- But compatible With HL-LHC phase

Upgrade: Beyond the Energy Frontier

- Physics Programme

Complementary to ATLAS / CMS direct searches

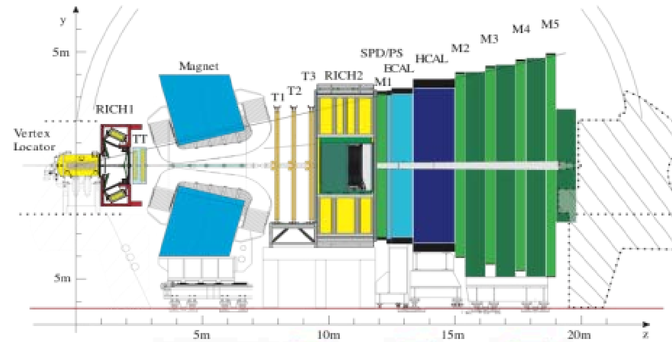
- New particles are discovered
  - LHCb measure flavour couplings through loop diagrams
- No new particles are found
  - LHCb probe NP at multi-TeV energy scale

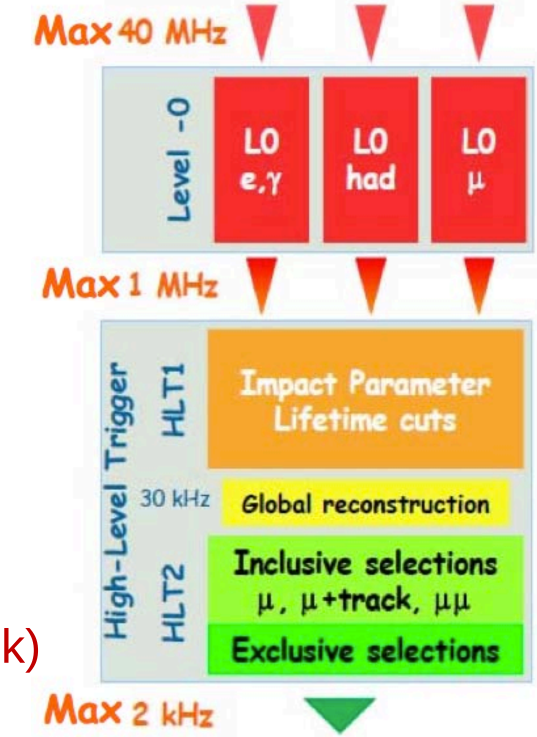
What are the future Prospects for LHCb

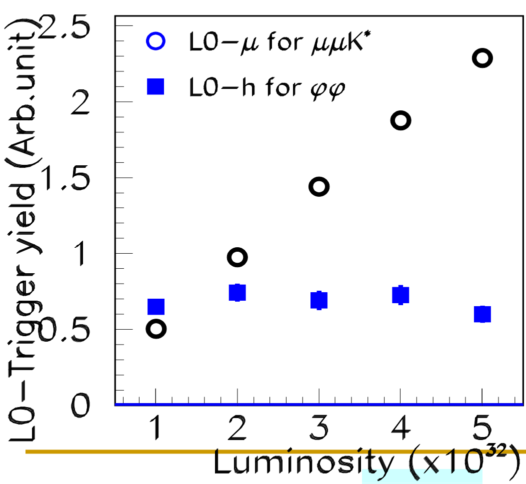
After accumulating ~5 fb^{-1} time to double stats is too low
So, why not just turn up the luminosity?

Current L0 trigger: High p_T in HCAL, ECAL & muon
Experiment capable of reading out at up to 1 MHz
High level trigger outputs at ~2 kHz

With the information currently available at L0:
Efficiency for hadronic channels flattens out at
L ~ 2-3·10^{32} cm^{-2} s^{-1} (E_T-cut!)







Our current limitation
Is the trigger!

Solution: Increase readout rate to 40 Mhz and improve HLT (see Abraham Gallas' talk)

Outlook for first decade of LHC: 2010-2020

LHC had a very bright startup:

2010: 250 bunches with ca. 2.6 10^{13} ppb

2011: 768 bunches and beyond

Luminosity > 10 10^{32}cm^{2}

Plan to run at 7 TeV for 2011 and 2012+

18 month shutdown in 2013-2014 to repair splices

Next shut down ~ 2018

Installation of Upgraded LHCb

2010-2012+
Ramping up to fewx10^{33} @ 7TeV
Up to 5 fb-1 delivered

Long shutdown
Splice repairs

2015-2016/7
Ramping up to 10^{34}
Up to 100 fb-1 delivered

Injector and LHC
Phase I upgrades

2018-2020/1
Ramping up to 10^{34}
Up to 100 fb-1 delievered per year

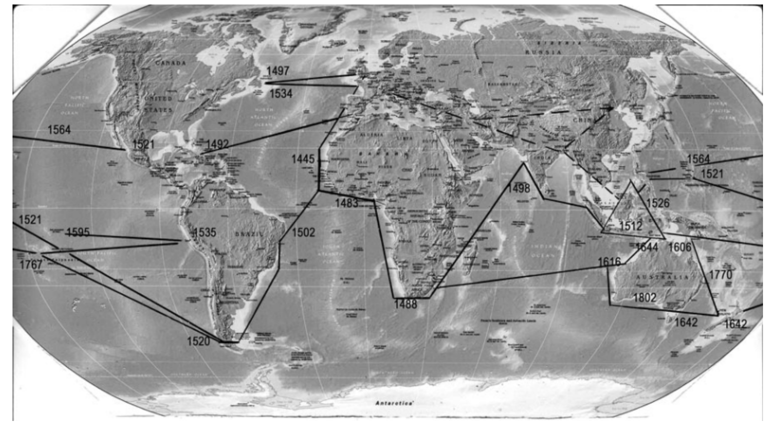
Towards High
Luminosity LHC

5 to 50 fb^{-1} : From Exploration to Detailed Mapping

LHCb: pioneering exploratory measurements

- $B_s \rightarrow \mu^+\mu^-$ down to SM value
- Measurement of $2\beta_s$ to SM value
- $B \rightarrow K^*\mu^+\mu^-$ crossing point
- Measurement of γ to 3^o
- Evidence of non-SM photon polarisation

And together with ATLAS and CMS uncover the cracks in the SM??



LHCb upgrade will provide accurate mapping of the SM parameters in the fermion mass sector , through

- Precise measurement of $B_s \rightarrow \mu^+\mu^-$
- $2\beta_s$ to 20% of SM value
- $B \rightarrow K^*\mu^+\mu^-$ full kinematics

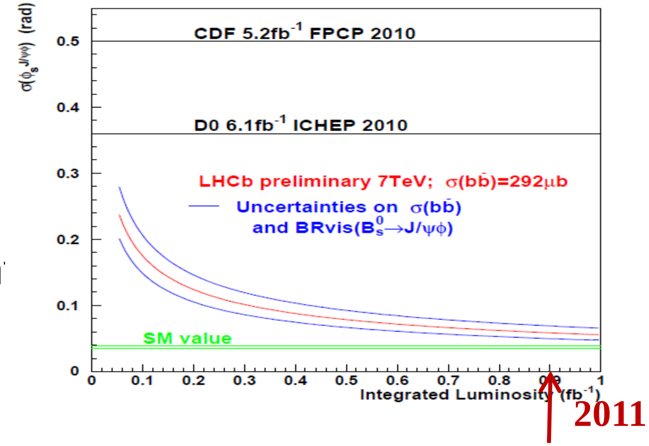
And there's more….

… and open up a new world of exploration at the bounderies of the Standard Model

$B_s \to \phi\phi$, $K^{0*}\bar{K}^{0*}$ penguins
$B_s \to \phi\gamma$
Measure γ to $< 1^o$
Search for $B_d \to \mu^+\mu^-$
Charm CPV search below 10^{-4}
A_{fs} hadronic modes
Physics beyond flavour
etc. etc.

β_s with >> 5 fb^{-1}

NP may or may not be lurking just around the corner
LHCb results show that SM uncertainty can be reached within 5 fb^{-1} and either find or rule out large anomaly

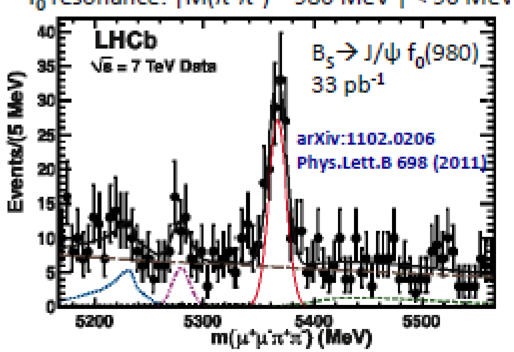


LHCb Upgrade will improve and enrich this measurement to Beyond SM precision $\sigma \sim 0.006$

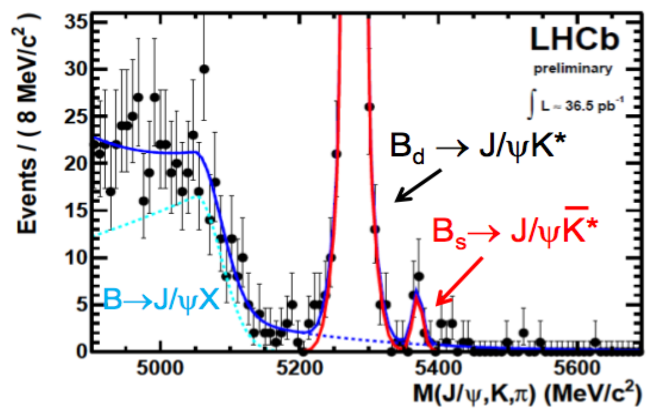
- add pure CP states: $B_s \rightarrow D_s^+ D_s^-$ and $B_s \rightarrow J/\psi\, f_0$
- fit S-wave K^+K^- contributions (5-10%), bias β_s if ignored
- reduce SM uncertainties due to (suppressed) penguin contribution by using $B_s \rightarrow J/\psi\, K^*$ and penguin-free $B_s \rightarrow D^0\, \Phi$ decays

$B_s \rightarrow J/\psi\, f_0$:

f_0 resonance: $|M(\pi^+\pi^-) - 980\text{ MeV}| < 90$ MeV



$B_s \rightarrow J/\psi\, K^*$: LHCb-CONF-2011-025



CP violation in mixing via $A_{fs}(B_s)$

Asymmetry larger than 10^{-4} would be clear NP signal

- <u>D0</u>: $A_{sl}^{b} = -0.00957 \pm 0.00251\ (stat) \pm 0.00146\ (syst) \approx (a_{fs}^{s} + a_{fs}^{d}) / 2$

  [Phys. Rev. D82 (2010) 032001; Phys. Rev. Lett. 105 (2010) 081801]

<u>LHCb</u>: flavour specific <u>semileptonic decays</u>

- measure $A_{fs}(B_s) - A_{fs}(B^0)$ via $B_s \rightarrow D_s^- \mu^+ X$ and $B \rightarrow D^- \mu^+ X$
- ✓ identical final state B^0 and B_s to reduce biases due to detector asymmetry

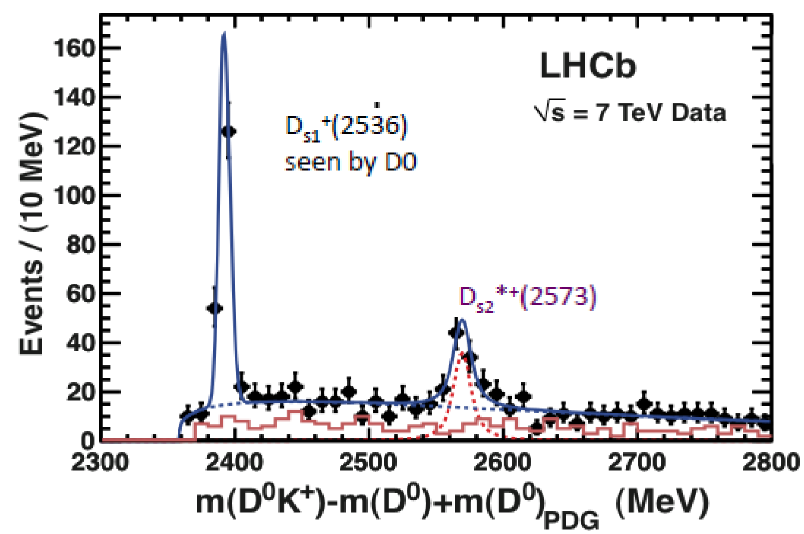
$$A_{fs}(B_s) = \frac{\Gamma(B_s^0\bar{B}_s^0 \to l^- l^- X) - \Gamma(B_s^0\bar{B}_s^0 \to l^+ l^+ X)}{\Gamma(B_s^0\bar{B}_s^0 \to l^- l^- X) + \Gamma(B_s^0\bar{B}_s^0 \to l^+ l^+ X)}$$

SM: $A_{fs}(B_s) = (2.06 +- 0.57) \times 10^{-5}$ A. Lenz and U. Nierste, JHEP 0706 (2007)

LHCb upgrade:

- measure separately $A_{fs}(B^0)$ and $A_{fs}(B_s)$ with hadronic decays
- flavour specific decay via $B_s \rightarrow D_s^- \pi^+$ with $D_s^- \rightarrow K^+ K^- \pi^-$
- ✓ suppress detector asymmetry with fully charge symmetric final state
- ✓ requires high statistics and flexible trigger with high efficiency for hadronic channels

First Observation of $B_s \rightarrow D_{s2}^{*+} X \mu^- \nu$:



Charmless hadronic B-decays

→ rare penguin decay topologies sensitive to NP

LHCb:

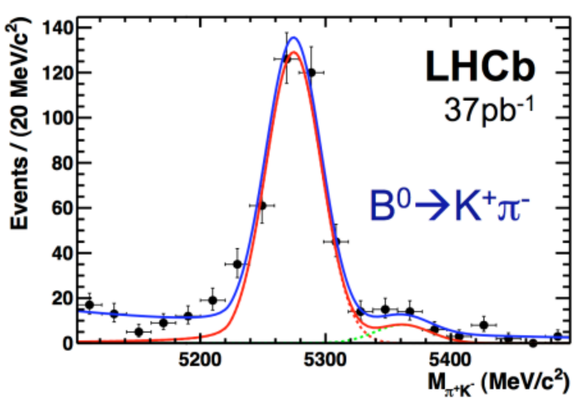
- direct CP violation in B_s and Λ_b
- time dependent CPV in $B_s \rightarrow K^+K^-$
- observe channels $B_s \rightarrow K^{*0}\overline{K}^{*0}$, $B_s \rightarrow \phi\phi$

→ $\sigma(\phi_{CP}) \sim 0.08$ with 5 fb^{-1}

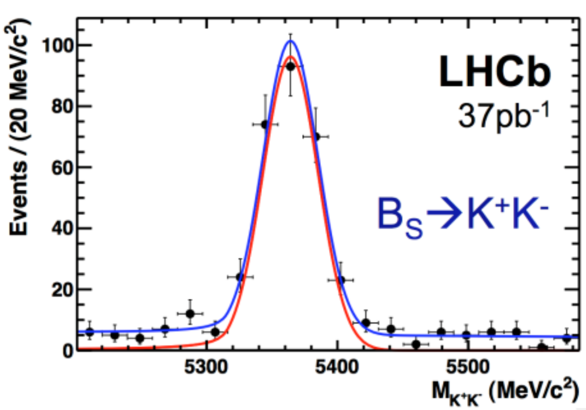
LHCb Upgrade:

- precision time dependent CPV in penguin dominated $B_s \rightarrow \overline{K}^{*0}K^{*0}$, $B_s \rightarrow \phi\phi$: $\sigma \sim 0.02$
  - ✓ SM predicts CP < 2% due to cancellation of mixing and decay phases
  - ✓ control S-wave contributions from non-resonant $B_s \rightarrow \Phi K^+K^-$ and $B_s \rightarrow \Phi f_0$
- CP asymmetry in $B^0 \rightarrow \phi K_s$ with $\sigma \sim 0.03$

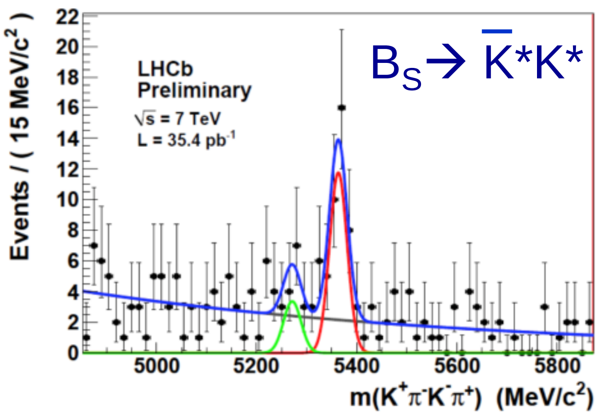
LHCb-CONF-2011-011



LHCb-CONF-2011-011



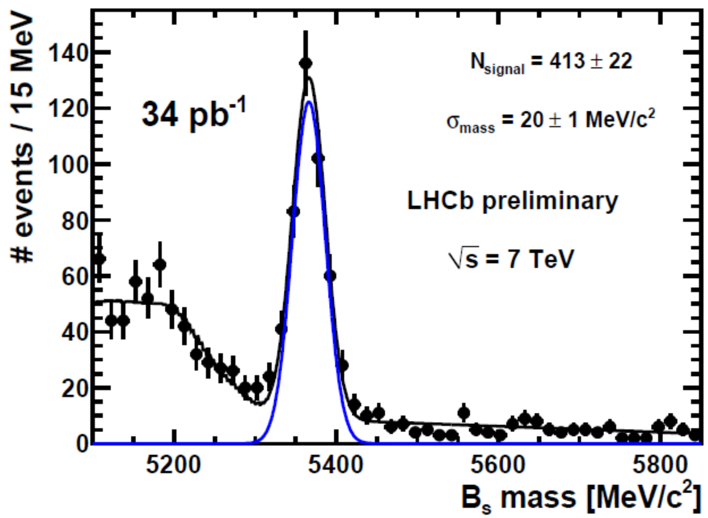
LHCb-CONF-2011-019



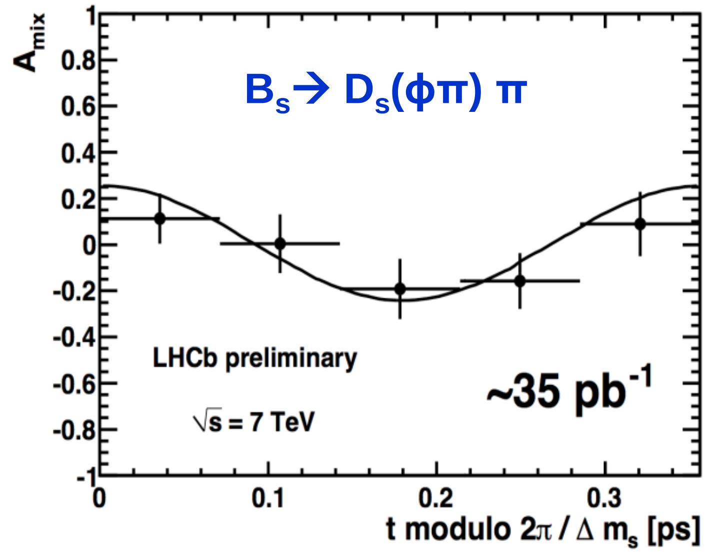
Precision CKM metrology at upgraded LHCb

2010 data give confidence that we can measure γ very well – around 3^o with 5 fb^{-1}
Key LHCb measurements in B->DK modes

$B_s \rightarrow D_s(\phi\pi)\ \pi$



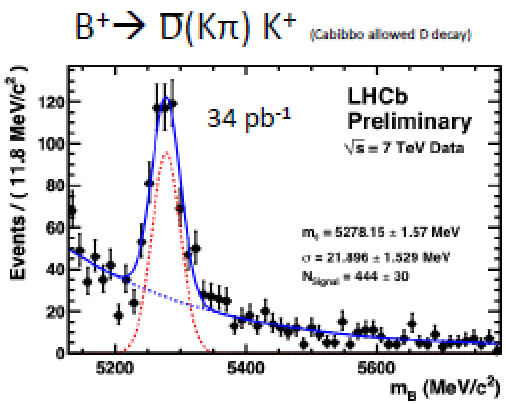
LHCb-CONF-2011-005

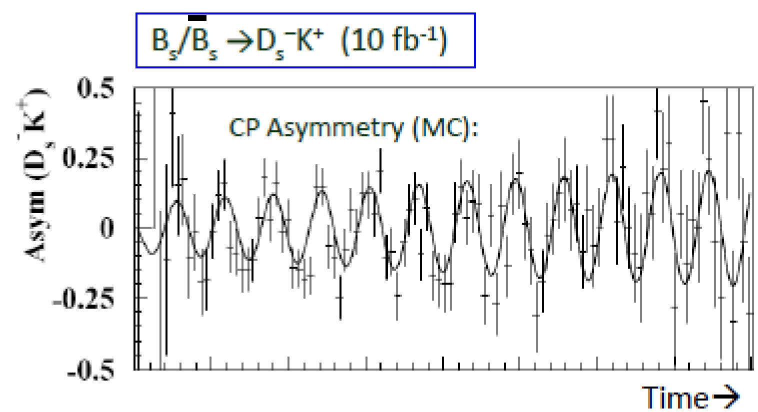


This will be a huge improvement on present status, and will match current error from SM prediction. But as lattice QCD improves so will SM prediction....

Precision CKM metrology at upgraded LHCb

$B^+ \to DK^+$, $B^0 \to DK^{*0}$, $B_s \to D_s^{\pm} K^{\pm}$





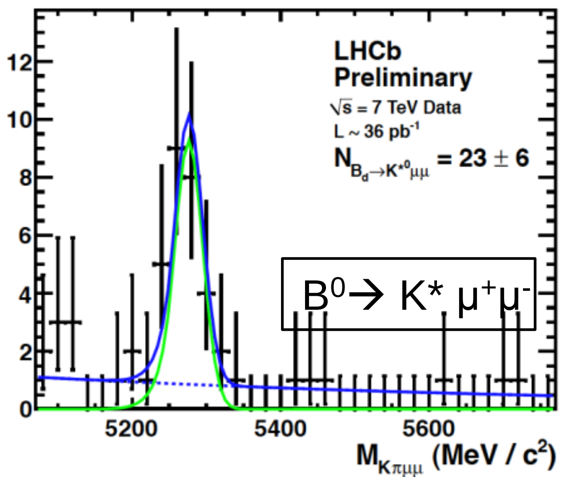
Still need simulated data here …

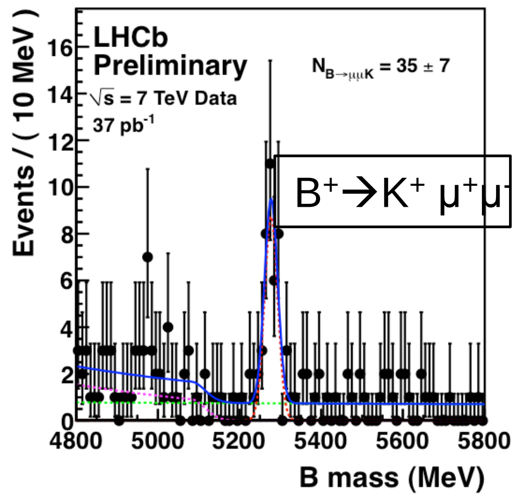
Upgrade, with software trigger, will allow us to reduce uncertainty to 1° or better
Essential to match the indirect constraint on γ which will improve with lattice
Calculations on V_{ub} and $\Delta m_d/\Delta m_s$

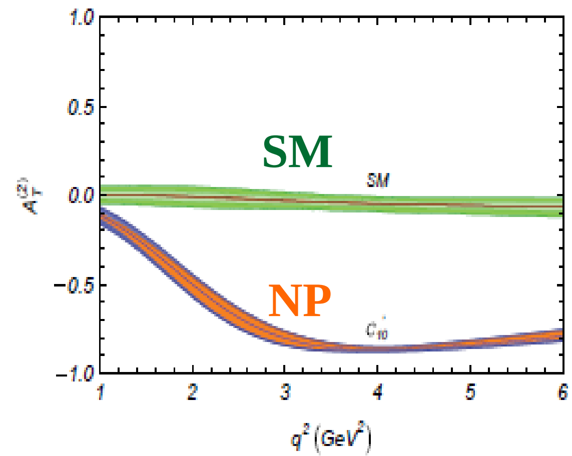
$B_0 \rightarrow K^*\mu^+\mu^-$ and $b \rightarrow s\gamma^{(*)}$

$B_0 \rightarrow K^*\mu^+\mu^-$ and related channels ($B^0 \rightarrow K^*\mu^+\mu^-$, $B^+ \rightarrow K^+\mu^+\mu^-$, $B_s \rightarrow \phi\, \mu^+\mu^-$, $\Lambda_b \rightarrow \Lambda^{(*)}\mu^+\mu^-$) sensitive to NP via angular distribution

Principal task for current experiment is to map out the AFB curve and in particular determine the crossing point

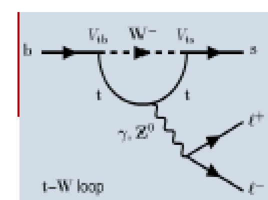






LHCb upgrade: access full range of kinematic observables e.g. transversity asymmetry AT

- $A_T^{(2)}$ is sensitive to new right handed currents
- $BR(B^+ \rightarrow K^+e^+e^-) / BR(B^+ \rightarrow K^+\mu^+\mu^-)$ sensitive to Neutral Higgs Bosons



Photon polarisation in exclusive $b \rightarrow s\gamma^{(*)}$

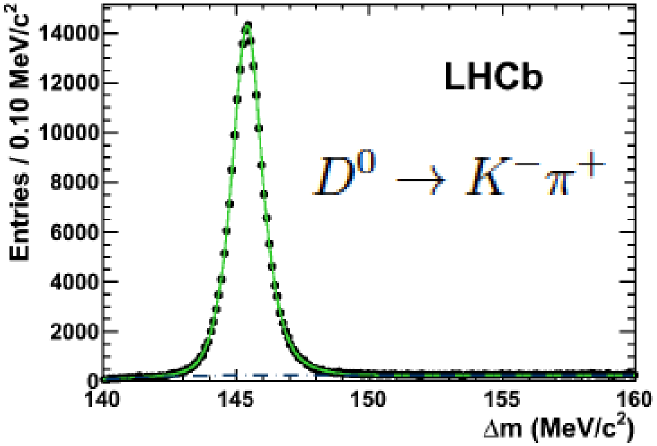
$B_s \rightarrow \Phi\gamma$: stat limited with 5 fb^{-1}. Measure polarisation to % level at upgrade

Similar story for $B^0 \rightarrow K^{*0}e^+e^-$, $B^+ \rightarrow K_1^+(K\pi\pi)\gamma$, $B^+ \rightarrow \Phi K^+\gamma$

Charm

- LHCb is world's foremost charm factory
  - – Evidence direct CP violation (arXiv:1112.0938)
  - – Probing oscillations (y_{CP})
  - – CP violation in mixing* (A_Γ) (arXiv:1112.4698)
    - Upgrade D sample approx 1000 X B factories and time dependent measurements benefit from excellent resolution
  - – Rare decay measurements e.g. $D^0 \to \mu^+\mu^-$
    - where limit currently 10^6 X larger than SM
  - – Dalitz Analyses e.g.

    $D^+ \to K^+K^-\pi^+$
  - – Time dep. CP violation in $D^0 \to K_S^0 h^+ h^-$



* mostly, see arXiv:1111.6515

Lepton Flavour Violation

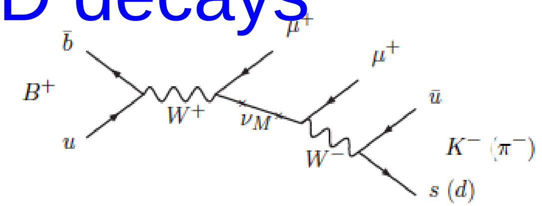
- Neutrino oscillations established

T. Asaka and M. Shaposhnikov, Phys. Lett. **B 620** (2005) 17; T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. **B 631** (2005) 151; F. Bezrukov, D. Gorbunov, JHEP **1005** (2010) 010. [arXiv:0912.0390 [hep-ph]]; A. Roy, M. Shaposhnikov, Phys. Rev. **D82** (2010) 056014. [arXiv:1006.4008 [hep-ph]].

  - but low neutrino mass scale to be understood
  - Heavy Majorana neutrinos in many NP models
    - e.g. νMSM (dark matter, baryon asymmetry)
  - Direct Search: long lived from B& D decays

Search for the lepton number violating decays $B^+ \to \pi^- \mu^+ \mu^+$ and $B^+ \to K^- \mu^+ \mu^+$

(arXiv:1110.0730)



  - Indirect: lepton violating e.g.

$$D_s^\pm \to \pi^\mp \ell^\pm \ell^\pm \text{ or } B^\pm \to \pi^\mp \ell^\pm \ell^\pm$$

Lepton Flavour violating τ-decays

- – Vanishingly small in SM with mixing

- LHC mainly produces τ's from B and D_s decays
  - – LHCb : τ→3μ
    - Phase-1: aim to match B-factories with few years
    - Upgrade: 10^{-9} level

Other upgrade B-physics topics

Other B-physics topics need upgrade for useful measurements to be made

Rare hadronic B decays

- Pure annihilation diagrams $B^+ \rightarrow D^*K^{*0}$ and $B^+ \rightarrow D_s^+\Phi$ could be observed at SM BFs. Unique insights into dynamics of hadronic B decays.
- Isospin violating decays: $B_s \rightarrow \Phi\rho^0$ and $B_s \rightarrow \Phi\pi^0$ – provide clean handle on electroweak Penguins, are observable at SM level, but also sensitive to NP
- Decays like $B^+ \rightarrow K^+K^+\pi^-$, $K^-\pi^+\pi^+$ negligibly small in SM, but not in NP

All benefit from software trigger !

$B \rightarrow D^{(*)}\tau\nu$

Similar to B-factory flagship mode $B \rightarrow \tau\nu$, but with more observables

Sensitive to charged Higgs

Branching ratio high, but efficiency low. Distinctive topology would benefit from flexible trigger of upgrade.

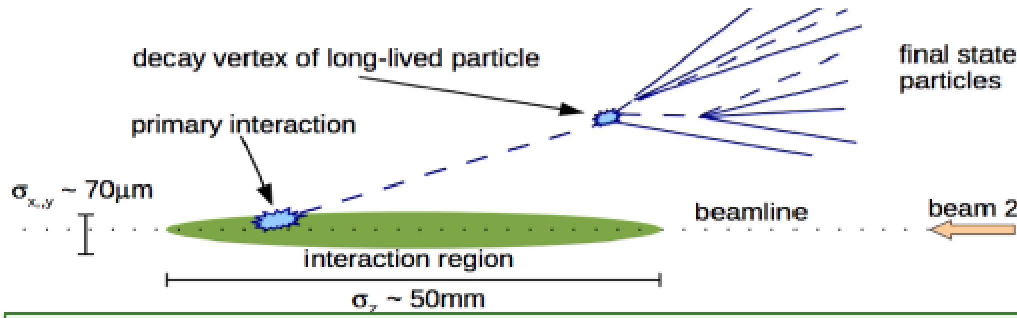
… And other lepton flavour physics

An upgraded LHCb can also illuminate the lepton sector

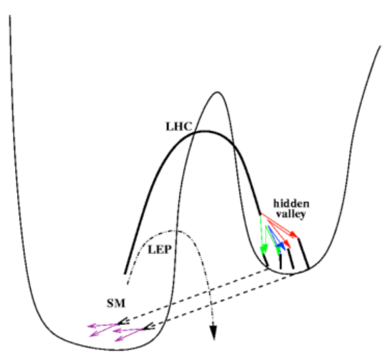
LFV tau decays, e.g. $\tau \rightarrow \mu\mu\mu$

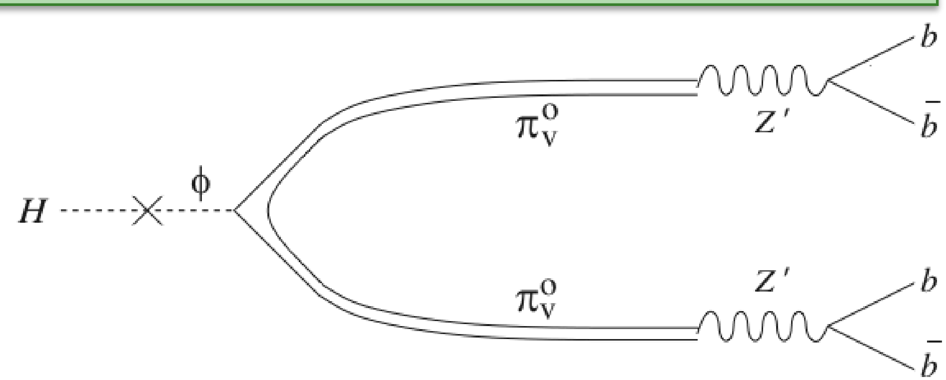
Present detector will probably attain a sensitivity not much better than B-factories (2.1×10^{-8} at 90% CL). Upgrade could improve limit by an order of magnitude.

More Flavour Physics and Beyond Flavour



- Hierarchy problem: why is Higgs mass not at Planck scale?
  - Many models (Susy, Xtra dimensions, Technicolour, Little Higgs) predict new states at TeV scale: Z', 4th generation, leptoquarks, Hidden Valley particles
- Hidden Valley particles carry "v" quantum number and can be low mass
  - Lightest v-particle is a dark matter candidate
  - V-neutral particles might have long lifetime and decay, e.g. to b bbar
  - V flavoured particles could be produced by Higgs





Physics beyond flavour

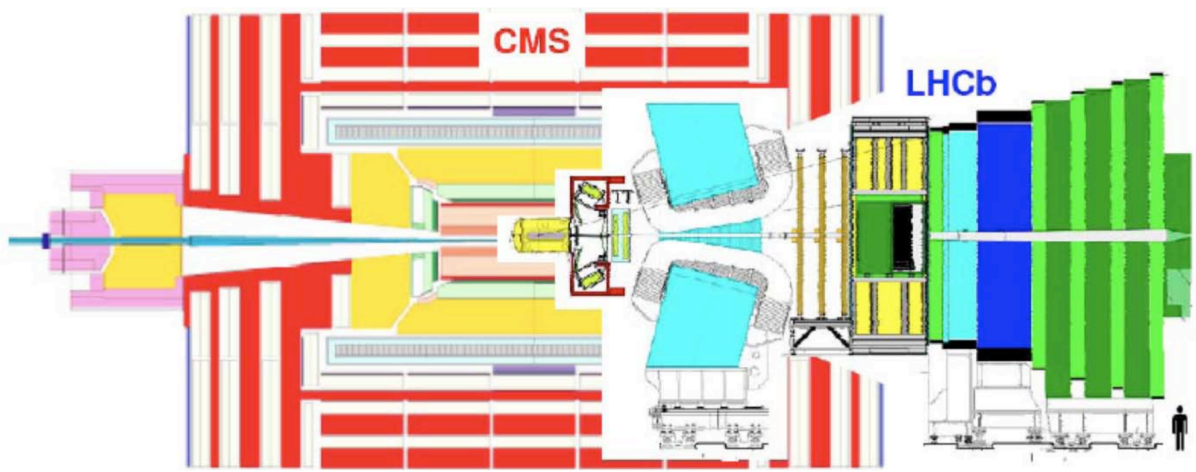
Forward acceptance means that a priori LHCb is complementary to ATLAS and CMS in many important physics topics beyond flavour

This attribute is enhanced by LHCb's unique vertexing and PID capabilities

Further advantages will come from fully flexible trigger & ability to run at high lumi

Some areas where LHCb can contribute:

- EW physics
- Search physics and exotics
- QCD



Electroweak Physics

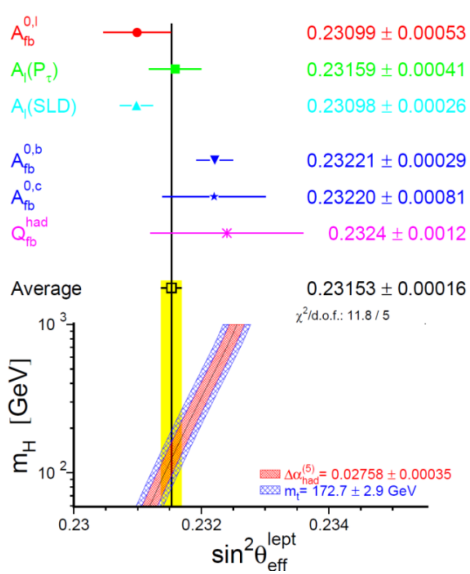
LHCb can contribute up to ILC/CLIC

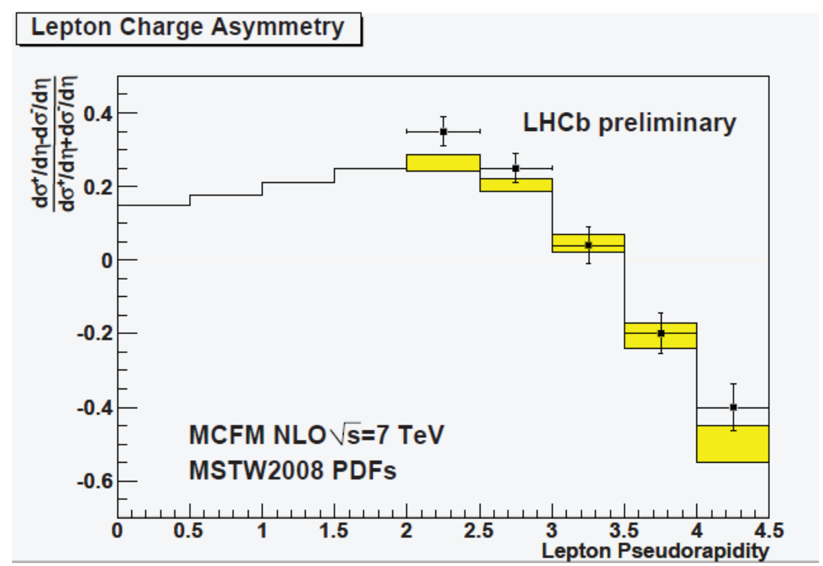
Determine $\sin^2\theta_{eff}^{lept}$ by measuring A_{FB} of leptons in Z decays

Measurement diluted by unknown direction of quark and anti quark – situation eased in forward direction

LHCb upgrade: 2.5 x better precision than LEP/SLD

LHCb can also contribute to M_W programme by constraining PDFs



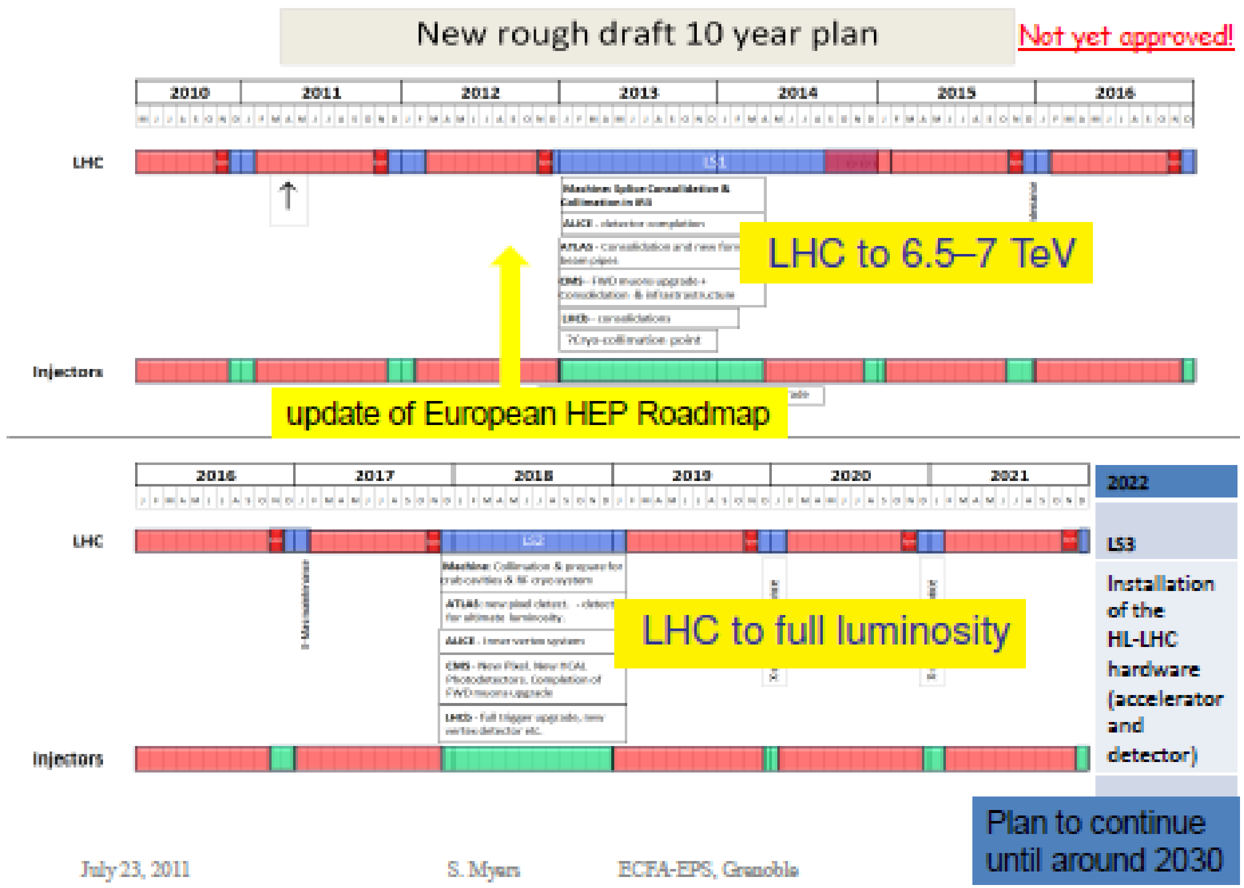


Sensitivities to key quark flavour channels

Type	Observable	Current precision	LHCb ($5\ \text{fb}^{-1}$)	Upgrade ($50\ \text{fb}^{-1}$)	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K_S^0)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s\ (B_s \to J/\psi\phi)$	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\ A_{\text{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20°$	$\sim 4°$	0.9°	negligible
	$\gamma\ (B_s \to D_s K)$	-	$\sim 7°$	1.5°	negligible
	$\beta\ (B^0 \to J/\psi\, K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

LHCb upgrade schedule UNOFFICIAL

LOI submitted to LHCC [CERN-LHCC-2011-001]
Well received – 40 MHz scheme realistic
Aim at TDRs in time for installing in 2018 – new collaborators welcome



LHCb Upgrade Summary

- 40 MHz Readout of all subdetectors
  - Flexible Trigger

  Retain key LHCb advantages:
  - Vertex Resolution
  - Momentum resolution
  - Particle ID

- Installation 2018
- General Purpose Experiment for Forward region:
  - Beauty, Charm, LFV, Electroweak, QCD, Exotica

Backup

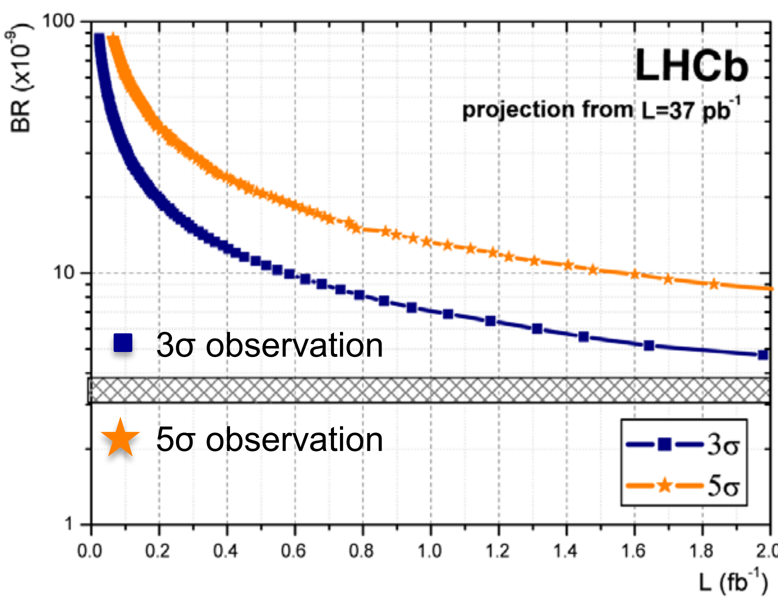
$B_{s,d} \rightarrow \mu^+\mu^-$

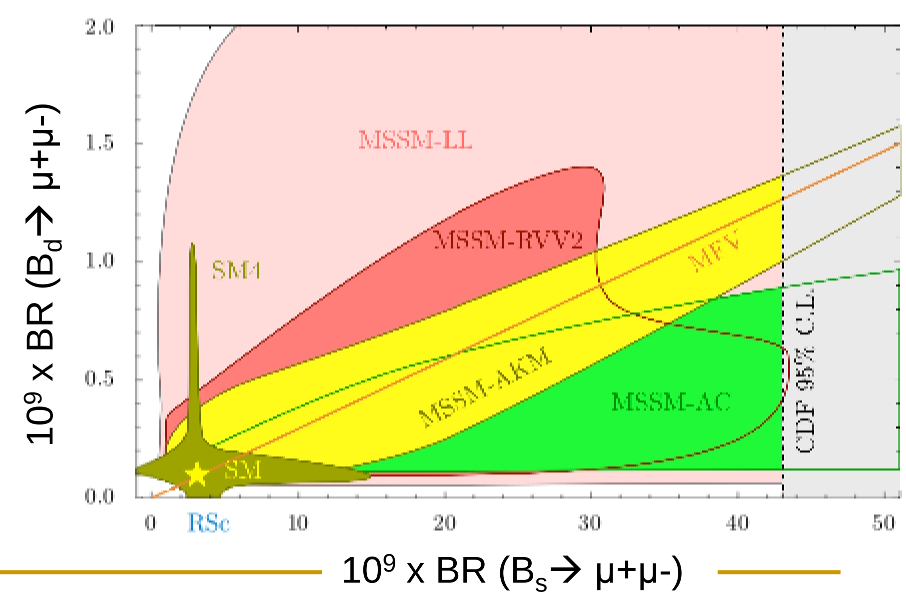
LHCb: exploit statistical power

- sensitivity of current limit in agreement with roadmap: $43 \cdot 10^9$ @ 90% C.L. with 40 pb^{-1}
- expect 5σ observation down to SM value with ~3 fb^{-1} at 14 TeV cms-energy
- fragmentation fraction f_s/f_d measured with semileptonic decays to 10% (stat. limited)

LHCb Upgrade

- SM BR($B_s \rightarrow \mu^+\mu^-$) can be measured to 8% precision @ 50 fb^{-1}
  - ✓ strong constraints for NP models
- measure ratio BR($B_d \rightarrow \mu^+\mu^-$) over BR($B_s \rightarrow \mu^+\mu^-$) to ~35% level (SM uncertainty ~5%)
  - ✓ challenge: low BR $B_d \rightarrow \mu^+\mu^-$ and larger background from B →ππ





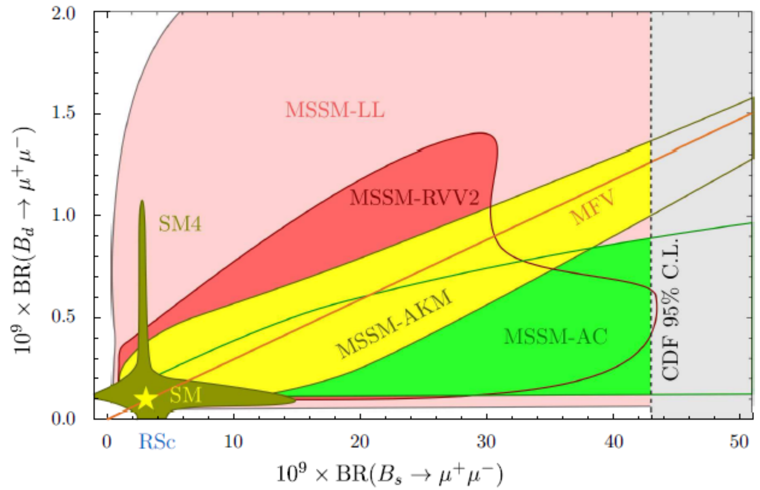
Impact on New Physics Models

LHCb upgrade will provide measurements essential to understand physics landscape that the coming decade will unveil..

Minimal Flavour Violation (MFV) hypothesis

All sources of flavour- and CP-violation in quarks will be same as SM. In this case searches for NP will be fruitless in CPV, but not in rare decays

e.g. In MFV $BR(B_s \to \mu\mu)$ *can* differ from SM but *not* $BR(B_d \to \mu\mu)/BR(B_s \to \mu\mu)$



SM with 4-families (SM4)

Add 2 new quarks (t', b') plus 5 new quark-mixing parameters

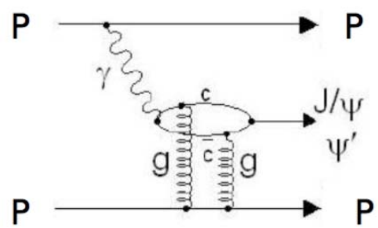
New CPV possibilities that could show up in D^0, B^0 and B_s system

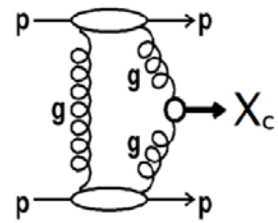
Both proposals can be disproved / strongly constrained with improved flavour data

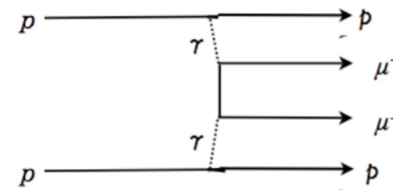
Central Exclusive Production

$pp \to p + X + p$

rapidity gaps

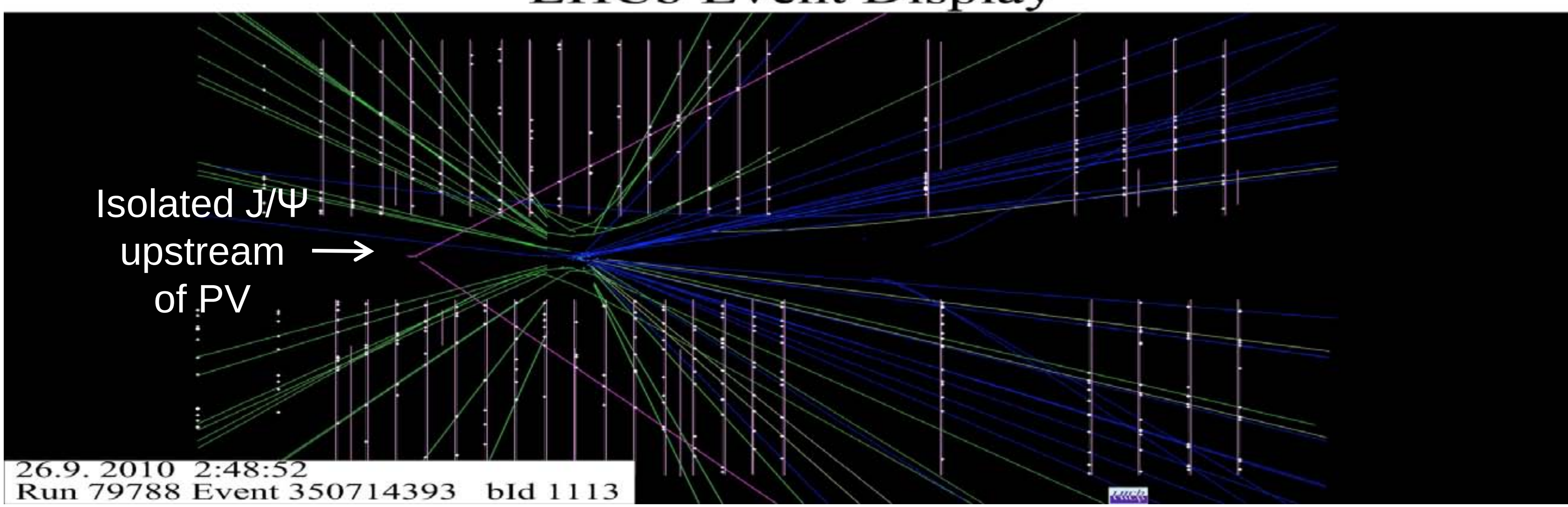




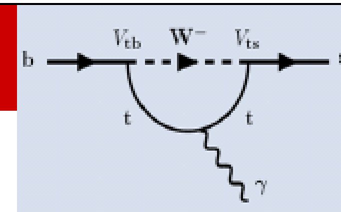


- photon or pomeron exchange
- observe and study exotic particles in clean environment (exclusive χ_c is seen)
- signature: ~ no activity (even in backward silicon planes) apart from signal

LHCb Event Display



$b \rightarrow s\gamma : B_s \rightarrow \phi\gamma$



$$A_{CP}(t) = \frac{\Gamma(\overline{B}_s \to \phi\gamma) - \Gamma(B_s \to \phi\gamma)}{\Gamma(\overline{B}_s \to \phi\gamma) + \Gamma(B_s \to \phi\gamma)} = \frac{A_{dir}\cos\Delta m t + A_{mix}\sin\Delta m t}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_\Delta \sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$

$b \rightarrow \gamma(L) + (m_s/m_b) \times \gamma(R)$

- $B_s \rightarrow \phi\gamma$: Time dependent decay rate
  - SM: photons are predominantly ($O(m_s/m_b)$) left polarized: no interference B_s and $\overline{B}_s$
  - Observed CP violation depends on polarization and weak phase.
    - Sizeable $\Delta\Gamma_s$ allows measurement A_Δ:
  - Phase 1: expect 5500 $B_s \rightarrow \phi\gamma$/year; photon polarisation measurement to 0.10
  - Phase 2: expect 40000 $B_s \rightarrow \phi\gamma$/year; precision to percent level

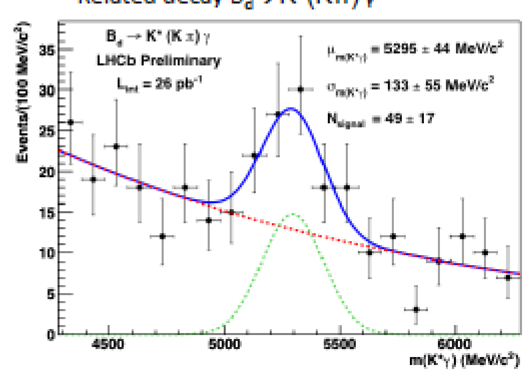
SM:

$A_{dir} \approx 0$, $A_{mix} \approx \sin 2\psi \sin 2\phi_s$, $A_\Delta \approx \cos 2\psi \cos\phi_s$

$\tan\psi = |b \rightarrow s\gamma_R| / |b \rightarrow s\gamma_L|$, $\cos\phi_s \approx 1$

A_Δ measures fraction "wrong" γ polarization

Related decay $B_d \rightarrow K^*(K\pi)\gamma$



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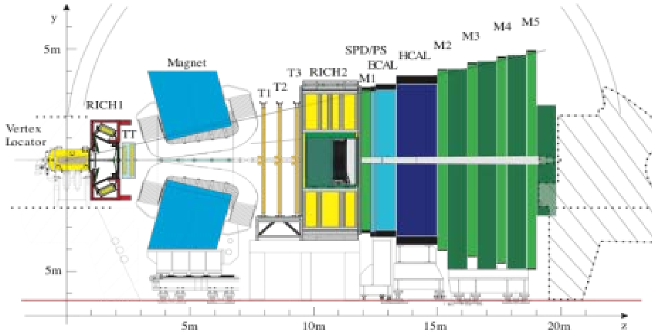
Solution: Upgrade detector to 40MHz readout



Upgrade Trigger fully software based
Runs in stageable Event Filter Farm
Up to **40 MHz input rate and 20 kHz output rate**
Trigger has access to all event information

Run at **5 times LHCb** lumi ($\rightarrow L \sim 10^{33}\ cm^{-2}\ s^{-1}$)
Gain in signal rates **up to factor 9** for hadronic modes

Efficiency	Farm Size = 5 x 2011	Farm Size = 10 x 2011
$B_s \rightarrow \phi\phi$	29%	50%
$B^0 \rightarrow K^*\mu\mu$	75%	85%
$B_s \rightarrow \phi\gamma$	43%	53%

40 MHz

Optional
Low Level Trigger
throttle
1-40 MHz

HLT
Tracking and vertexing
Impact Parameter cuts
Inclusive/Exclusive selections

20 MHz