LHCb Upgrade Plans

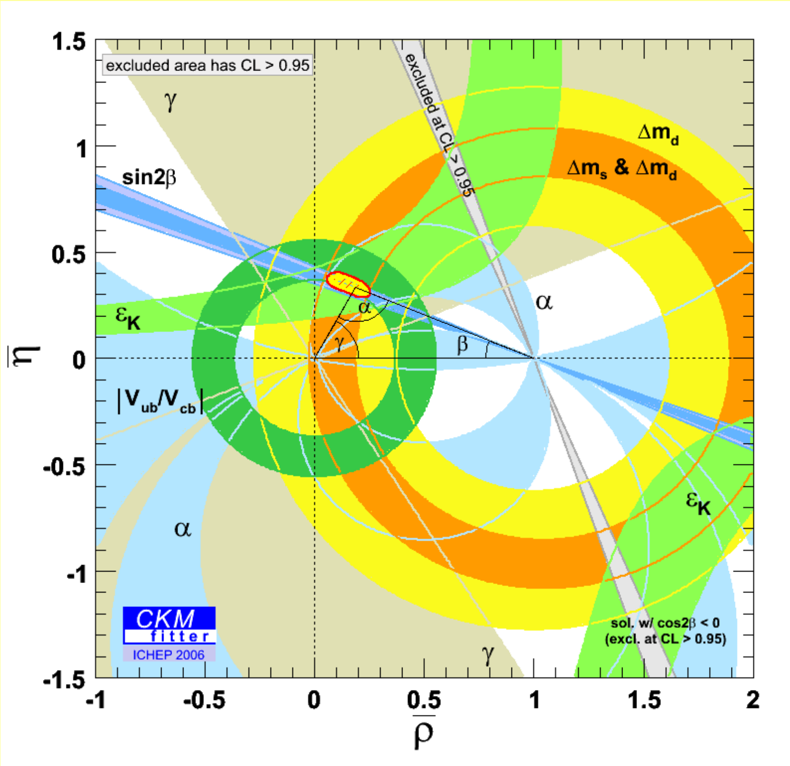
Franz Muheim
University of Edinburgh
on behalf of the LHCb collaboration

- Standard Model and New Physics Sensitivity
- LHCb Experiment
  - Physics Programme the first 5 years
  - Running LHCb at 10 times design luminosity
- Physics Reach with a 100 fb^{-1} data sample
  - CP violation in B_s decays
  - Probe New Physics in hadronic and electroweak penguin decays
  - CKM angle gamma
- LHCb Upgrade Detector and Trigger Plans
  - LHCb Upgrade Detector
  - Vertex detector studies
  - Trigger and Read-out studies
- Conclusions

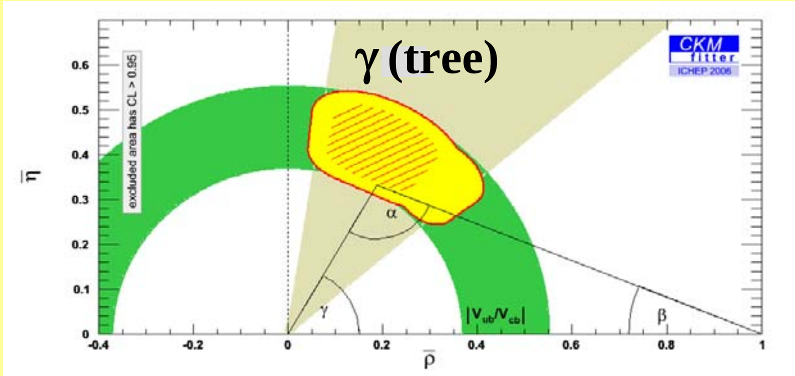
Flavour in the LHC era
CERN Oct 9th 2006

Status of CKM Unitarity Triangles

- **ICHEP2006 Status**
  - including CDF Δm_s measurement



- **Tree diagrams**
  - Not sensitive to New Physics



- **Probe New Physics**
  - by comparing to SM predictions including loops
  - by measuring γ in loop diagrams
  - same for α, β and χ

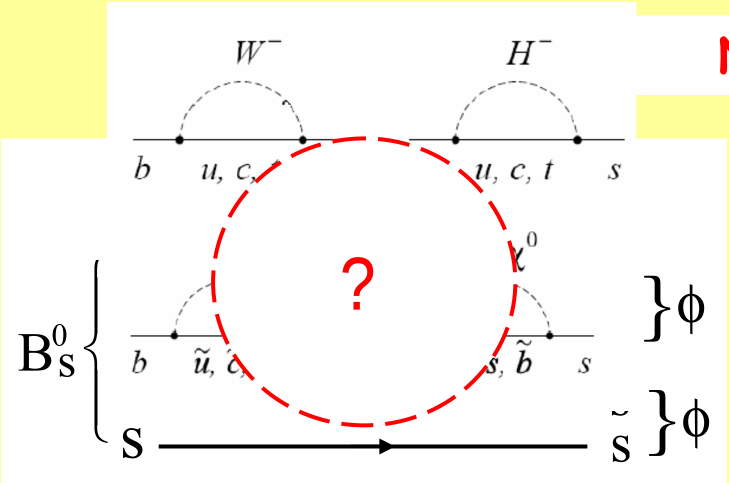
- Standard Model is a very successful theory
- *We are very likely beyond the era of « alternatives» to the CKM picture. NP would appear as «corrections» to the CKM picture* — *Nir*

Probing New Physics in B_s Mesons

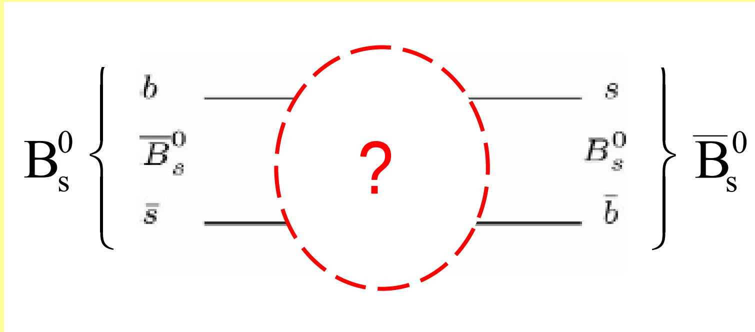
- **Flavour Changing Neutral Currents**
  - NP appears as virtual particles in loop processes
  - leading to observable deviations from SM expectations in flavour physics and CP violation (~~CP~~)
  - New Physics parameterisation in B_s Oscillations

$$\Delta m_q = \left|1 + h_q e^{2i\sigma_q}\right| \Delta m_q^{SM}$$

New Physics



$B_s \rightarrow \phi\phi$ penguin decay



B_s-$\bar{B}_s$ oscillations

- **If New Physics is found at LHC**
  - Probe NP flavour structure with FCNC

LHCb Sensitivities with 2 fb^{-1}

	Channel	Yield	B/S	Precision
γ	$B_s \to D_s^{-+} K^{+-}$	5.4k	< 1.0	$\sigma(\gamma) \sim 14^o$
	$B_d \to \pi^+ \pi^-$	36k	0.46	$\sigma(\gamma) \sim 4^o$
	$B_s \to K^+ K^-$	36k	< 0.06	
	$B_d \to D^0 (K\pi, KK) K^{*0}$	3.4 k, 0.5 k, 0.6 k	<0.3, <1.7, < 1.4	$\sigma(\gamma) \sim 7^o$ - 10^o
	$B^- \to D^0 (K^-\pi^+, K^+\pi^-) K^-$	28k, 0.5k	0.6, 1.5	$\sigma(\gamma) \sim 5^o$ - 15^o
	$B^- \to D^0 (K^+K^-, \pi^+\pi^-) K^-$	4.3 k	1.0	
	$B^- \to D^0 (K_S\pi^+\pi^-) K^-$	1.5 - 5k	< 0.7	$\sigma(\gamma) \sim 8^o$ - 16^o
α	$B_d \to \pi^+ \pi^- \pi^0$	14k	< 0.8	$\sigma(\alpha) \sim 10^o$
	$B \to \rho^+\rho^0, \rho^+\rho^-, \rho^0\rho^0$	9k, 2k, 1k	1, <5, < 4	
β	$B_d \to J/\psi(\mu\mu)K_S$	216k	0.8	$\sigma(\sin 2\beta) \sim 0.022$
Δm_s	$B_s \to D_s^- \pi^+$	120k	0.4	$\sigma(\Delta m_s) \sim 0.01\ ps^{-1}$
ϕ_s	$B_s \to J/\psi(\mu\mu)\phi$	131k	0.12	$\sigma(\phi_s) \sim 0.023$
Rare decays	$B_s \to \mu^+\mu^-$	17	< 5.7	
	$B_d \to K^{*0} \mu^+\mu^-$	4.4 k	< 2.6	$\sigma(C_7^{eff}/C_9^{eff}) \sim 0.13$
	$B_d \to K^{*0} \gamma$	35k	< 0.7	$\sigma(A_{CP}) \sim 0.01$
	$B_s \to \phi \gamma$	9.3 k	< 2.4	
charm	$D^{*+} \to D^0 (K^-\pi^+) \pi^+$	100 M		

Alessio Sarti

Frederic Teubert

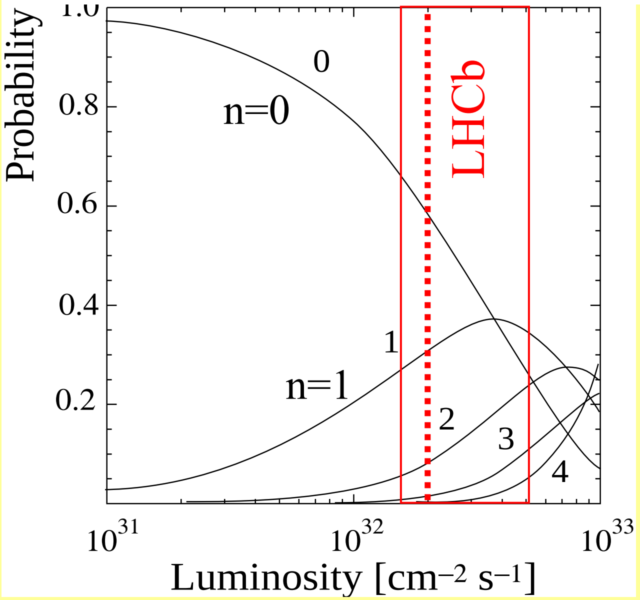
Ulrik Egede

Patrick Spradlin

LHCb – The First Five Years

- **LHCb Operations**
  - Luminosity tuneable by adjusting beam focus
  - Design is to run at $\mathcal{L} \sim 2\times10^{32}$ cm^{-2}s^{-1} detectors up to 5×10^{32} cm^{-2}s^{-1}
  - little pile-up (n = 0.5)
  - less radiation damage
  - Luminosity will be achieved during 1st physics run
- **LHCb Physics Goals**
  - Run five (nominal) years at $\mathcal{L} \sim 2\times10^{32}$ cm^{-2}s^{-1} and collect 6 to 10 fb^{-1}
  - Exploit the B_s system
  - Observation of CP violation in B_s mesons
  - Precision measurements of B_s mass and lifetime difference
  - Reduce error on CKM angle γ by a factor 5
  - Probe New Physics in rare B meson decays with electroweak, radiative and hadronic penguin modes
  - First observation of very rare decay $B_s \to \mu^+\mu^-$

n = # of pp interactions/crossing



Physics Case for LHCb at High Luminosity

- **What's next?**
  - Many LHCb results will be statistically limited
  - New Physics effects are small -> require better precision measurements
  - LHCb is only B-physics experiment approved for running after 2010
  - **Can LHCb exploit the full potential of B physics at hadron colliders?**

- **LHCb Luminosity**
  - Running at $\mathcal{L} \sim 2 \times 10^{32}\ cm^{-2}s^{-1}$ is a LHCb design choice
  - LHC design luminosity is 50 times higher $\mathcal{L} \sim 10^{34}\ cm^{-2}s^{-1}$

- **LHCb Upgrade Plans**
  - Upgrade LHCb detector such that it can operate at 10 times design luminosity of $\mathcal{L} \sim 2 \times 10^{33}\ cm^{-2}s^{-1}$
  - **Run ~5 yrs at $\mathcal{L} \sim 2 \times 10^{33}\ cm^{-2}s^{-1}$**
  - **Collect ~100 fb^{-1} data sample**
  - Multiple interactions per beam crossing increases to n ~ 4
  - Is compatible with possible LHC luminosity upgrade (SLHC)
  - Does not require SLHC
  - Could be implemented ~2013

ϕ_s from $B_s \to J/\psi\phi$

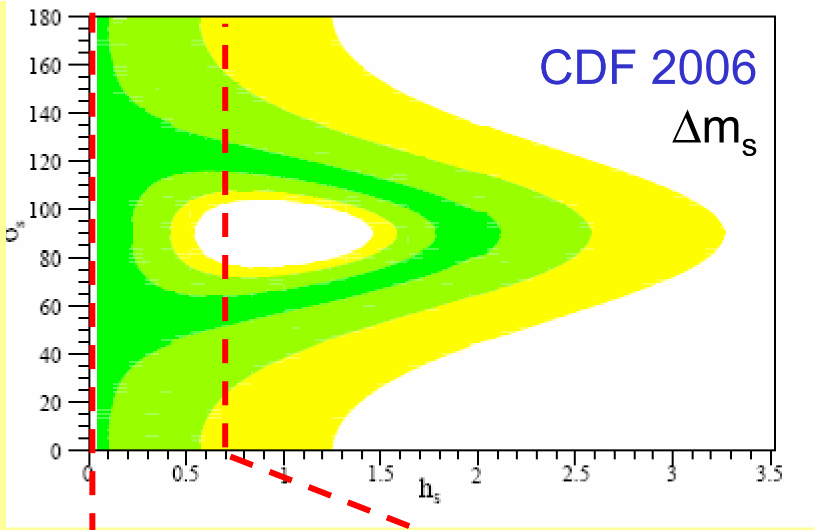
- **CP Violation in B_s mesons**
  - Interference in B_s mixing and decay
  - ~~CP~~ B_s weak mixing phase ϕ_s is very small in SM

$$\phi_s = -\arg(V_{ts}^2) = -2\chi \approx -2\lambda^2\eta \approx -0.035$$

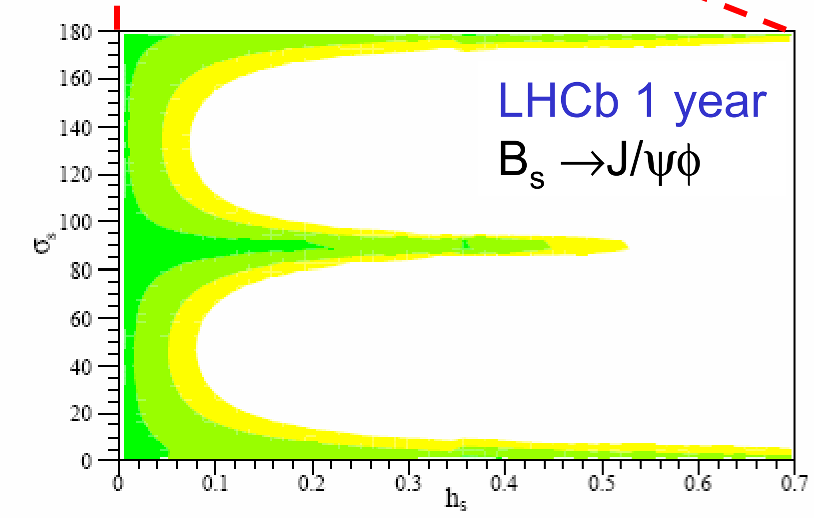
  - $\Rightarrow$ sensitive probe for **New Physics** e.g. stringent NMFV test
  - NP parameterisation

$$\Delta m_q = \left|1 + h_q e^{2i\sigma_q}\right| \Delta m_q^{SM}$$

  - Angular analysis to separate $J/\psi\phi$ 2 CP-even and 1 CP-odd amplitudes
- **ϕ_s Sensitivity**
  - at Δm_s = 20 ps^{-1}
  - Expect 131k $B_s \to J/\psi\phi$ signal events per 2 fb^{-1} (1 year)
  - Expected precision **$\sigma(\sin\phi_s) \sim 0.023$**
  - Small improvement in ϕ_s precision by adding pure CP modes



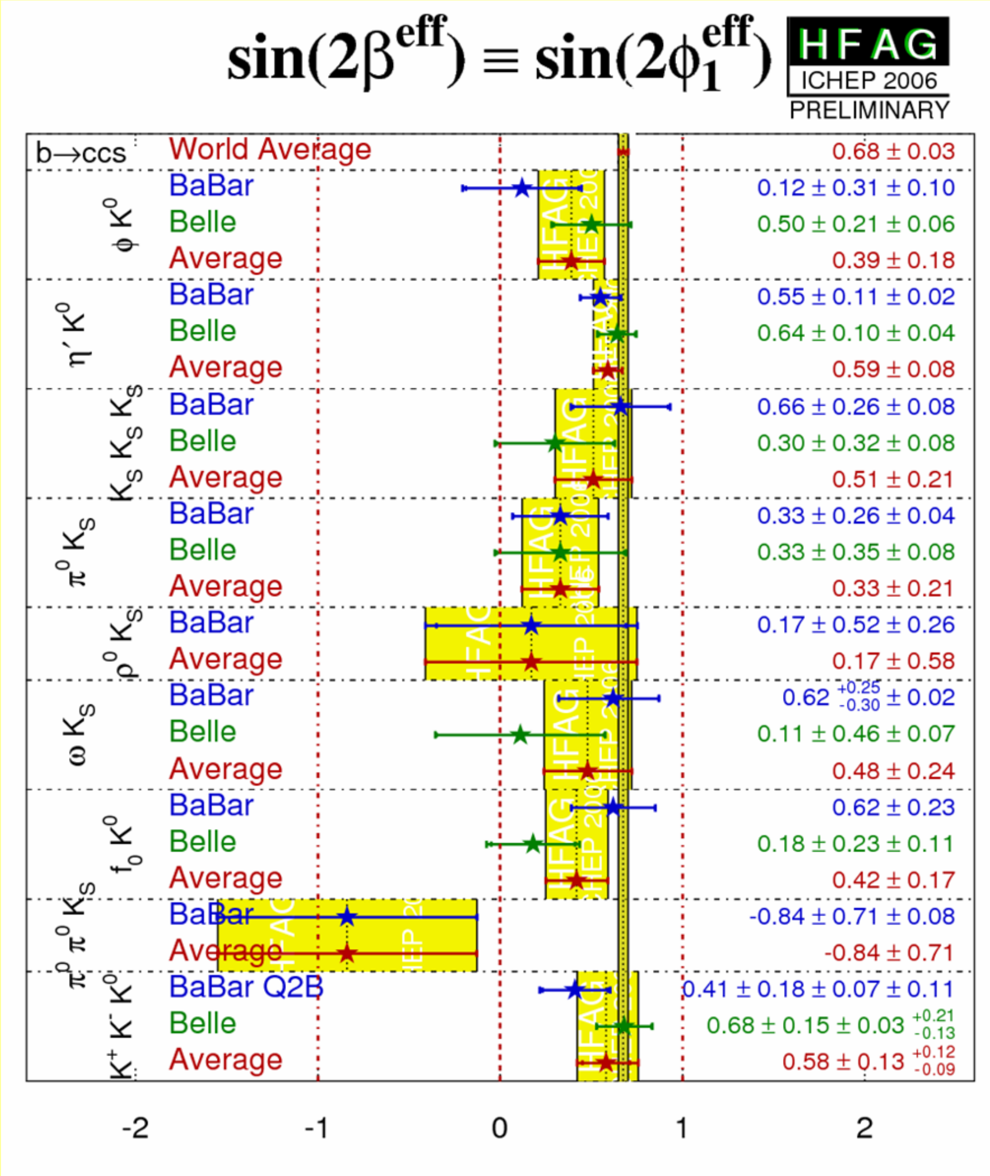
hep-ph/0604112
hep-ph/0509242



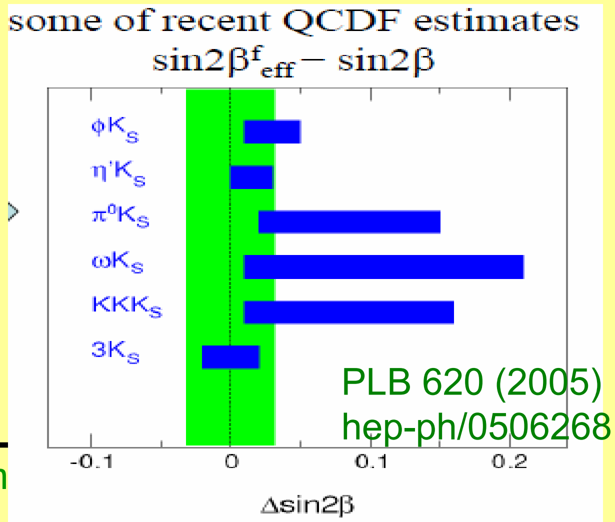
ϕ_s from $B_s \to J/\psi\phi$

- **ϕ_s will be the ultimate SM test**
  - For ~~CP~~ in B mesons
  - Similar to ε' in kaons for direct CP violation
- **ϕ_s Sensitivity**
  - LHCb for 10 fb^{-1} (first 5 years) — $\sigma(\sin \phi_s) \sim 0.010$
  - ~3 σ SM evidence for $\phi_s \approx -0.035$
  - ϕ_s precision statistically limited
  - Theoretically clean
- Historical Aside
  - 1988 NA31 measures ~3 σ from zero — $\varepsilon'/\varepsilon = (3.3 \pm 1.1)\, 10^{-3}$
  - Community approves NA48 & KTEV
- **LHCb Upgrade Sensitivities**
  - Based on 100 fb^{-1} data sample
  - Preliminary estimates by scaling with luminosity
  - Potential trigger efficiency improvements not included
- **$B_s \to J/\psi\phi$ - Key channel for LHCb Upgrade**
  - ϕ_s Sensitivity with 100 fb^{-1} data sample
  - ~10 σ SM measurement with 100 fb^{-1} — $\sigma(\sin \phi_s) \sim 0.003$

b →s Transitions in B_d Mesons



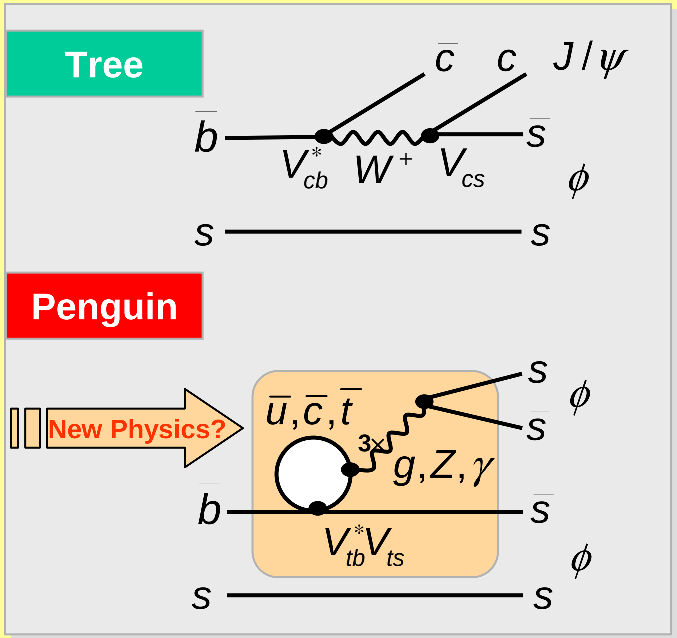
- **Compare sin2β measurements**
  - in $B_d \to \phi K_S$ with $B_d \to J/\psi K_S$
  - Individually, each decay mode in reasonable agreement with SM
  - But all measurements lower than sin2β from
- **Naïve b → s penguin average**
  - $\sin 2\beta_{eff} = 0.52 \pm 0.05$
  - 2.6 σ discrepancy from SM
- **Theory models**
  - Predict to increase $\sin 2\beta_{eff}$ in SM



PLB 620 (2005) 143
hep-ph/0506268

$b \to s$ Transitions in $B_s \to \phi\phi$

- **$B_s \to \phi\phi$ hadronic penguin decay**
  - In SM weak mixing phase ϕ_s is identical in $B_s \to \phi\phi$ and $B_s \to J/\psi\phi$
  - Define $\Delta S(\phi\phi) = \sin\phi_s(\phi\phi) - \sin\phi_s(J/\psi\phi)$
  - Measurement of $\Delta S(\phi\phi) \approx \sin\phi_s(\phi\phi) \neq 0$ is clear **signal** for **New Physics (NMFV)**
- **$\Delta S(\phi\phi)$ Sensitivity**
  - Best $b \to s$ penguin mode for LHCb
  - Expect 1.2 k $B_s \to \phi\phi$ events per 2 fb^{-1}
  - Estimate sensitivity by scaling with $B_s \to J/\psi\phi$
  - $\sigma(\Delta S(\phi\phi)) \sim 0.14$ in 10 fb^{-1}



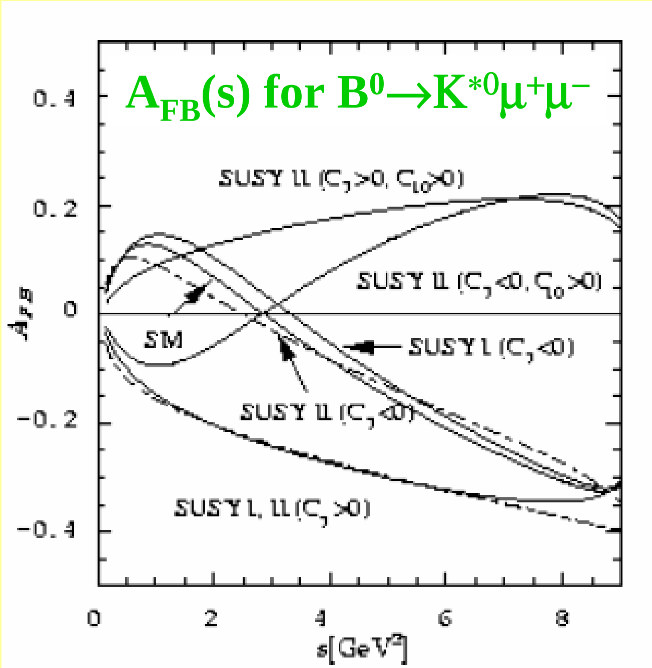
- **Key channel for LHCb Upgrade**
  - $\Delta S(\phi\phi)$ precision statistically limited
  - With 100 fb^{-1} estimate precision $\sigma(\Delta S(\phi\phi)) \sim 0.04$ exciting NP probe
  - Requires **1^{st} level detached vertex trigger** for hadronic decay
    Expect similar precision for $\Delta S(\phi K_S)$ in decay $B_d \to \phi K_S$

γ from $B^0 \to DK^{*0}$, $B^\pm \to DK^\pm$ & $B_s^0 \to D_s^\mp K^\pm$

- **LHCb goals for measuring CKM angle γ**
  - $B^0 \to D^0K^{*0}$, $B^\pm \to D^0K^\pm$
    Two interfering tree processes in neutral or charged B decay
  - Use decays common to D^0 and anti-D^0
    Cabbibo favoured self-conjugate D decays
    e.g. $D^0 \to K_S\pi\pi$, K_SKK, $KK\pi\pi$ Dalitz analysis
    Cabbibo favoured, single & doubly Cabbibo suppressed D decays
    e.g. $D^0 \to K\pi$, KK, $K\pi\pi\pi$ ADS (GLW) method
  - $B_s \to D_s^\mp K^\pm$ - two tree decays ($b \to c$ and $b \to u$) of $O(\lambda^3)$
    Interference via B_s mixing
- **γ Sensitivity**
  - Expected precision for ADS and Dalitz $\sigma(\gamma) \sim 5^\circ$ -15° in 2 fb^{-1}
- **Motivation for LHCb Upgrade**
  - Theoretical error in SM is very small < 1°
  - Large statistics helps to reduce systematic error to similar level
  - With 100 fb^{-1} estimate precision $\sigma(\gamma) \sim 1^\circ$
  - Requires **1^{st} level detached vertex trigger** for hadronic decays

Asymmetry A_{FB} in $B_d \rightarrow K^{*0}\mu^+\mu^-$

- **Forward-backward asymmetry $A_{FB}(s)$**
  - Asymmetry angle - B flight direction wrt μ^+ direction in $\mu^+\mu^-$ rest-frame

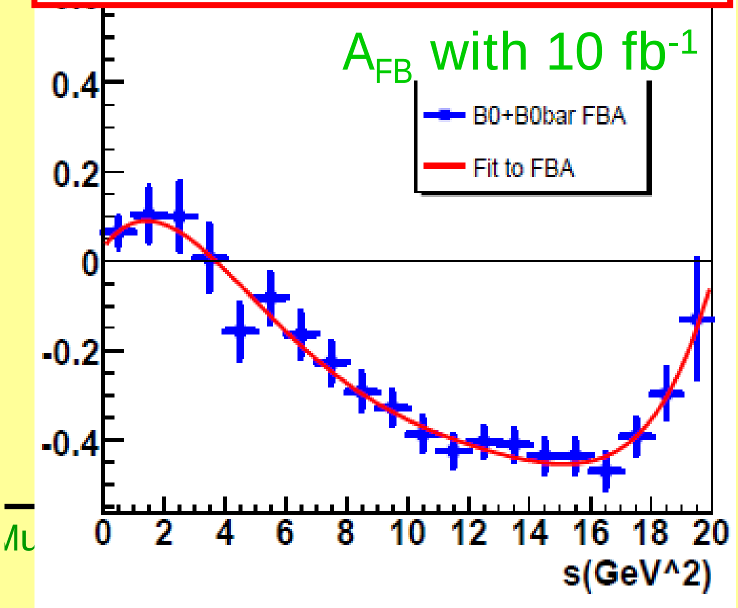


hep-ph/0003238
PRD61, 074024 (2000)

- **Sensitive probe of New Physics**
  - Deviations from SM by SUSY, graviton exchanges, extra dimensions
  - $A_{FB}(s_0) = 0$ - predicted at LO without hadronic uncertainties
  - Zero point s_0 and integral at high s sensitive to Wilson coefficients

- **Expected Signal Yield**
  - 4.4 k events per 2 fb^{-1}
  - Large statistics allows to measure additional transversity amplitudes
  - Sensitive to right-handed currents
- **A_{FB} zero point sensitivity**
  - $s_0 = 4.0 \pm 0.5$ GeV^2 in 10 fb^{-1}
- **LHCb Upgrade Sensitivity**
  - $s_0 = 4.00 \pm 0.16$ GeV^2 in 100 fb^{-1}

  4% error on C_7^{eff}/C_9^{eff}



More Physics with 100 fb^{-1}

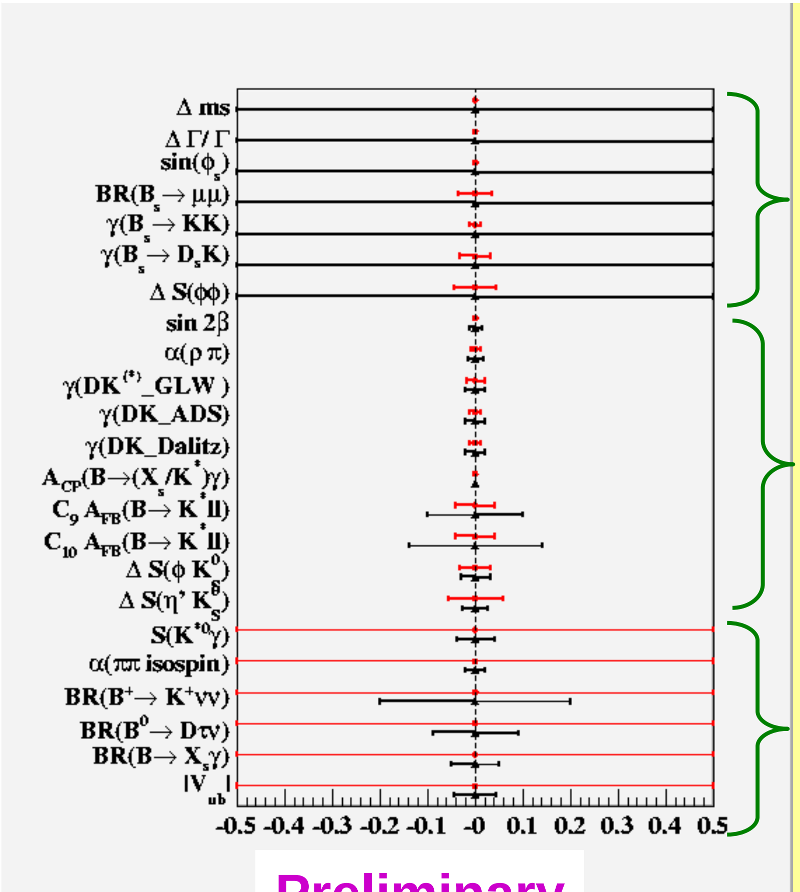
- **What are key measurements?**
  - Selection of four discussed above
  - Importance of different decays could change again with additional data from LHC, Tevatron and B-factories
- **LHCb measurements**
  - Many more are statistics limited
  - can be improved with **LHCb Upgrade**
  - many of these are very sensitive to New Physics
- **Additional LHCb Upgrade measurements**
  - Semileptonic charge asymmetry A_{SL}
  - Very rare decays
    e.g. observation of $B_d \to \mu^+\mu^-$ and precision measurement of $B_s \to \mu^+\mu^-$
  - Electroweak and radiative penguin decays
    e.g. $\Lambda_b \to \Lambda\mu^+\mu^-$
  - Other hadronic penguin decays
    e.g. $B_d \to \phi K_S$ $B_d \to \eta' K_S$
  - CP violation and mixing in charm meson decays
  - Lepton flavour violation in B, charm and tau decays
    e.g. $B^0 \to \mu^+e^-$, $D^0 \to \mu^+e^-$, $\tau^+ \to \mu^+\gamma$, $\tau^+ \to \mu^+\mu^-\mu^+$

Comparison with Super-B factory

Sensitivity Comparison ~2020

LHCb 100 fb^{-1} vs Super-B factory 50 ab^{-1}

SuperB numbers from M Hazumi - Flavour in LHC era workshop



Preliminary

B_s only accessible to LHCb

Common

No IP
Neutrals, ν

LHCb Upgrade Detector and Trigger

LHCb Performance vs Luminosity

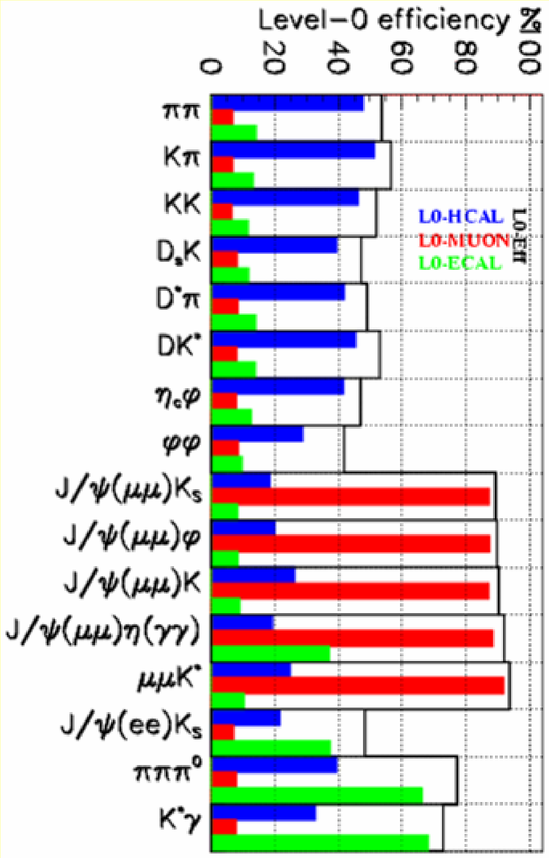
- **LHCb Luminosity**
  - Running at $\mathcal{L} \sim 2 \times 10^{32}\ cm^{-2}s^{-1}$ is default
  - Make use of learning experience in running LHCb
  - Will operate at luminosity up to $\mathcal{L} \sim 5 \times 10^{32}\ cm^{-2}s^{-1}$

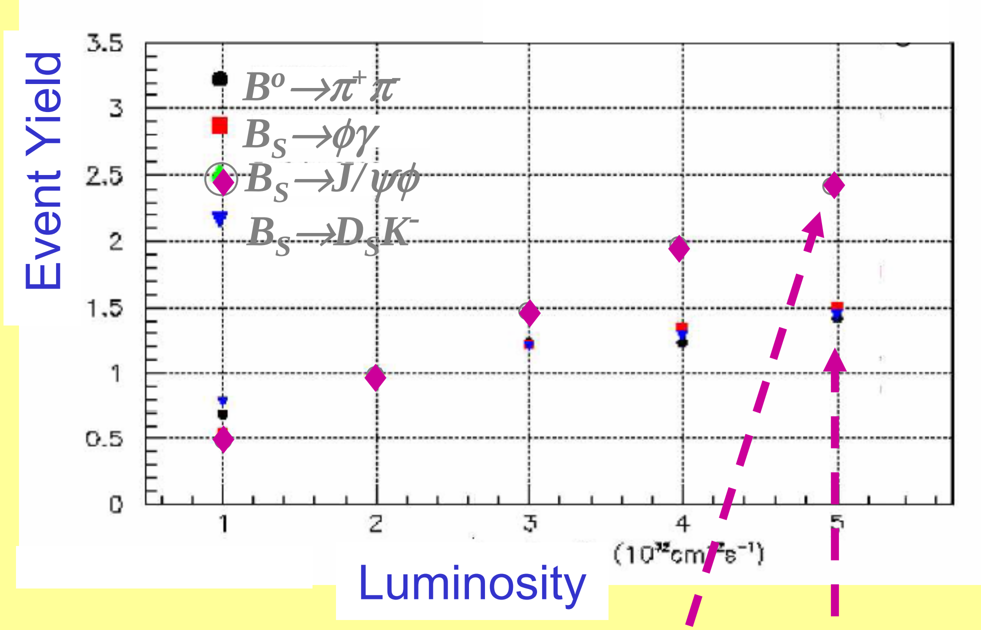
- **LHCb Detectors**
  - Detectors able to cope with $\mathcal{L} \sim 5 \times 10^{32}\ cm^{-2}s^{-1}$
  - Vertex detector sensors require replacing after 6 – 8 fb^{-1} (~3 years)
  - Default replacement – same geometry, similar slightly improved sensors

- **Level-0 Trigger – L0**
  - High p_T - μ, $\mu\mu$, e, γ, hadron + pileup
  - Read-out at 40 MHz 4 μs latency
  - Existing Front-End electronics limits L0 Trigger output to 1.1 MHz

LHCb L0 Trigger

L0 efficiency





- **L0 muon trigger**
  - ~90% efficiency
  - scales with luminosity
- **L0 hadron trigger**
  - ~40% efficient
  - does not scale with luminosity
  - Required for $B_s \to \phi\phi$ and $B^\pm \to D^0K^\pm$

LHCb Upgrade Plans

- **The Big Question**
  - How do we upgrade LHCb detector such that it can operate at 10 times design luminosity of $\mathcal{L} \sim 2 \times 10^{33}\ cm^{-2}s^{-1}$?
  - Physics, Detector and Trigger studies have started
  - Several approaches under investigation

- **Vertex Detector**
  - VELO sensors require replacing with radiation-hard sensors
- **L0 Detached Vertex Trigger**
  - Add Vertex Detector (VELO) and Trigger Tracker (TT) to L0 Trigger
  - Requires 40 MHz readout of VELO and TT
  - Implementation in FPGAs
  - Is Magnetic field in VELO region required?
- **Other LHCb Detectors**
  - need upgrade due to occupancy and/or irradiation
  - Replace inner most region of RICH photo detectors
  - Replace inner most region of ECAL with crystal calorimeter
  - Possibly add other sub-detectors to 40 MHz readout

LHCb Upgrade Plans II

- **Readout full detector at 40 MHz**
  - Requires new readout architecture
  - All trigger decisions in CPU farm
  - All Front-end electronics must be redesigned
  - Increased radiation hardness required
  - Electronics R&D can profit from common LHC development

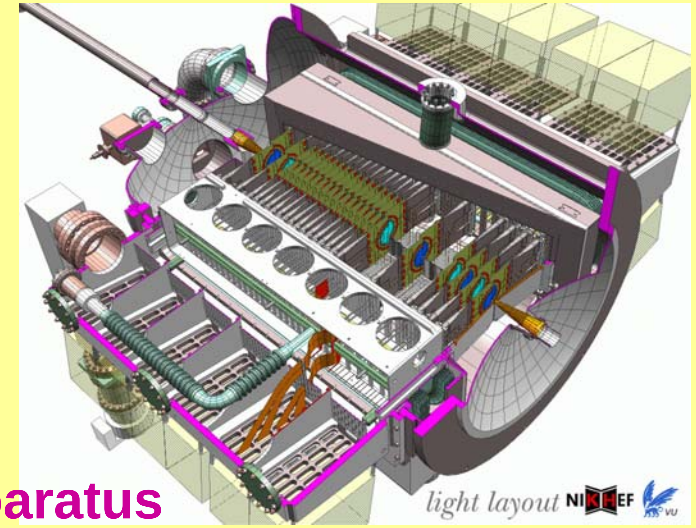
- **Detectors for 40 MHz Readout**
  - VELO sensors require replacing with radiation-hard sensors
  - Silicon tracker sensors (TT and IT) need to be replaced
  - Outer tracker occupancy likely prohibitive
    Increase (decrease) area of Inner/Outer Tracker
  - RICH photo detectors need to be replaced

- **Additional Considerations**
  - for running LHCb at $\mathcal{L} \sim 2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Costs expected to compare favourably with existing infrastructure and complementary approaches

Vertex Detector Upgrade

- Critical for LHCb upgrade physics programme

Radiation Hard Vertex Detector
with
Displaced Vertex Trigger

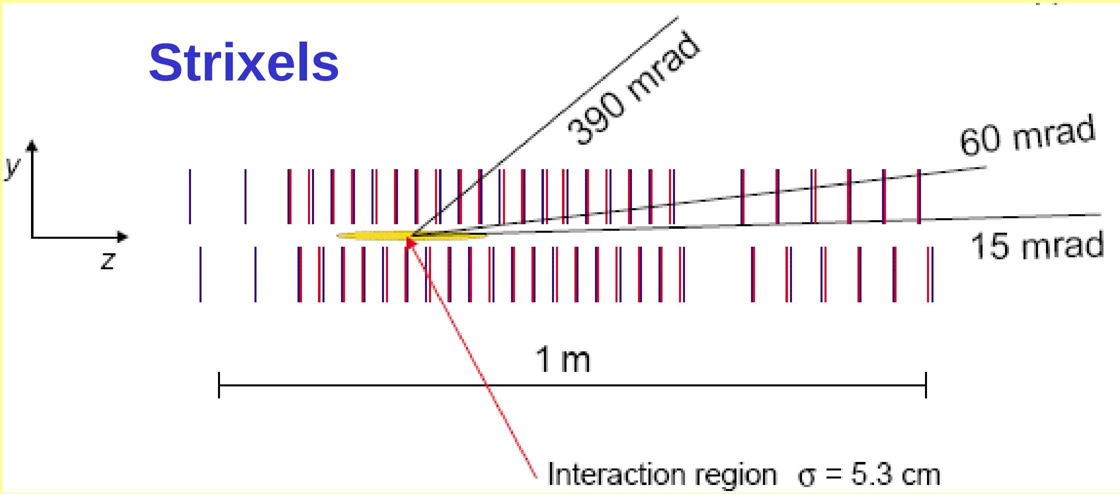


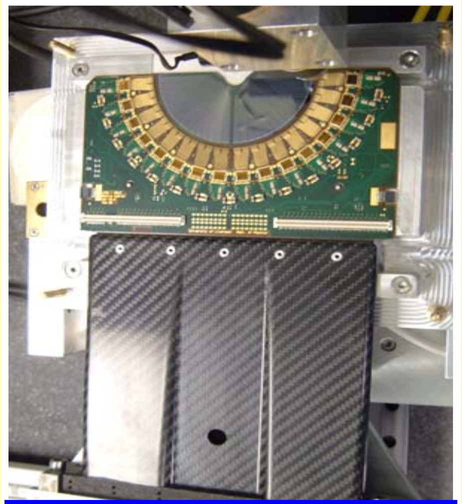
VESPA

VElo Superior Performance Apparatus

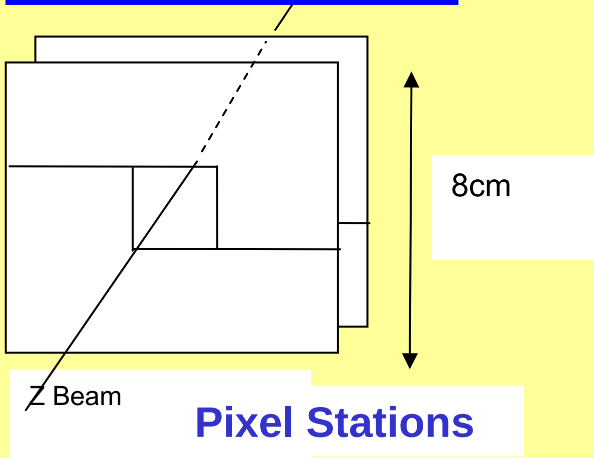
Radiation Hard Vertex Detector

- Vertex Detector for LHCb Upgrade
  - requires high radiation tolerance device
    >10^{15} 1 MeV neutron_{eq} /cm^2
- Geometry - Strixels / Pixels
  - remove RF foil
    3% X_0 before 1st measurement
  - move closer to beam from 8 → 5mm





VELO Module

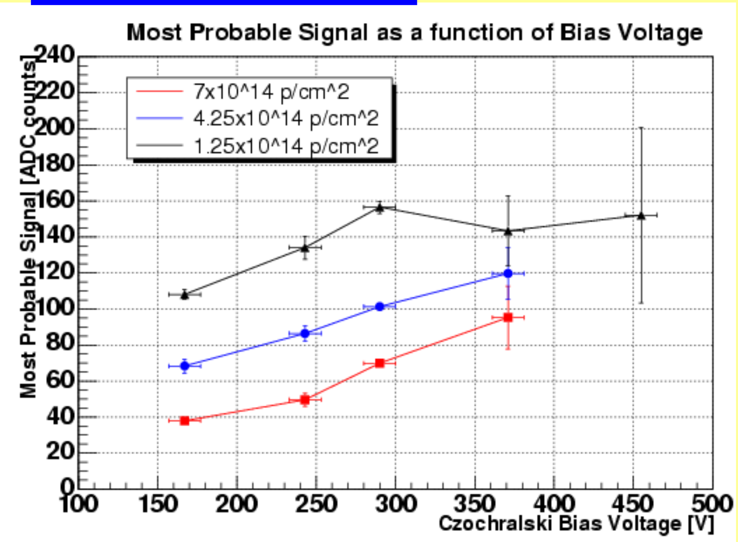


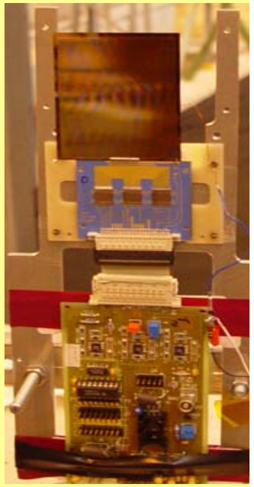
Pixel Stations

Radiation Hard Technologies

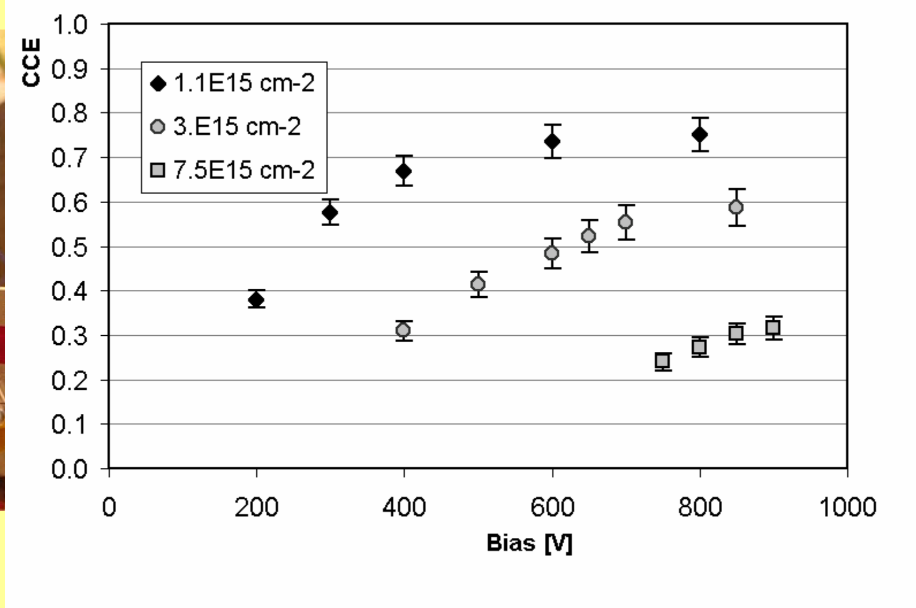
- Active Technology R&D for LHC upgrades
- Applicable to strixels & pixels

Czochralski

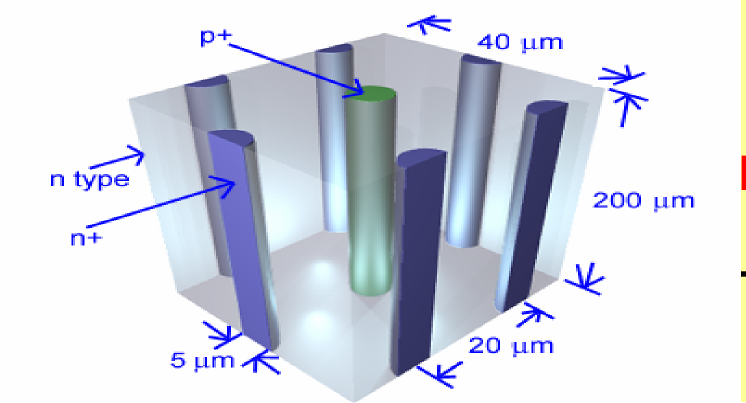




n-on-p

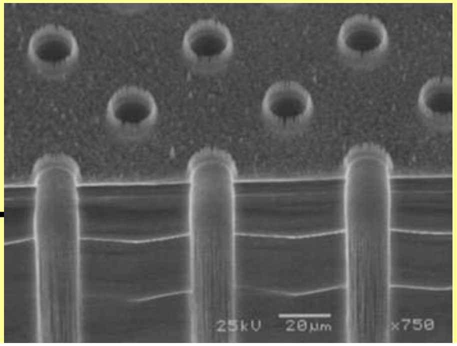


3D



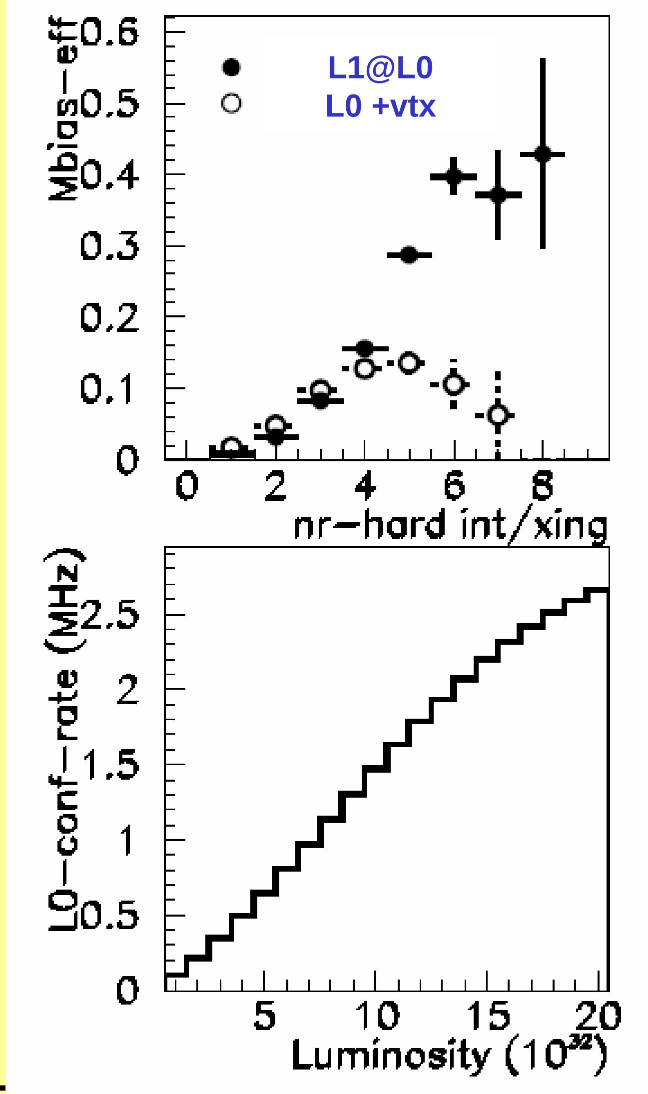
Extreme radiation hard
For 4.5 x 10^{14} 24 GeV p/cm^2
Depletion voltage = 19V

F. Muheim



LHCb Upgrade Trigger Studies

- **Method**
  - Combine L0 with detached vertex trigger
    L0 – hadron $E_T > 3$ GeV
    track with largest $p_T > 2$ GeV
    impact parameter $|IP| > 50$ um
  - Run L1 trigger algorithm at L0
- **Preliminary results**
  - $B_s \to D_s^{\mp} K^{\pm}$ at $L = 6 \times 10^{32}$
  - For L0+vxt Min. bias efficiency does not depend strongly on # of interactions n_r
  - L0 – hadron rate: $r = 0.8$ MHz
    $B_s \to D_s^{\mp} K^{\pm}$ efficiency $\varepsilon = 66\%$
  - Better efficiency than L0 trigger at $L = 2 \times 10^{32}$ (baseline)
    $r = 0.7$ MHz $\varepsilon = 39\%$
  - Yield $B_s \to D_s^{\mp} K^{\pm}$ is 5 times baseline
  - Yield scales linearly with luminosity



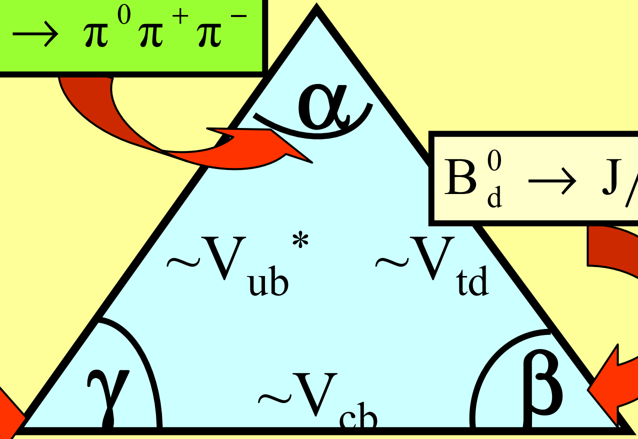
Conclusions

- **Standard Model is very successful**
  - Require precision measurements to probe/establish flavour structure of New Physics
- **Many LHCb results will be statistically limited**
  - LHCb plans to run initially for five years at $\mathcal{L} \sim 2 .. 5 \times 10^{32}\ cm^{-2}s^{-1}$
  - 6 - 10 fb^{-1} data set will not reach full potential of B physics at hadron colliders
- **LHCb Upgrade Plans**
  - Replace VELO with radiation hard vertex detector
  - Add first level detached vertex trigger to LHCb experiment to trigger efficiently on hadronic modes at high luminosities
  - Readout of all LHCb detectors at 40 MHz
  - Requires new front-end electronics, silicon sensors,. RICH photo detectors
  - Run five years at $\mathcal{L} \sim 2 \times 10^{33}\ cm^{-2}s^{-1}$ and collect 100 fb^{-1} data sample
- **LHCb Physics reach with 100 fb^{-1}**
  - Perform ~10σ measurement of SM weak B_s mixing phase ϕ_s = -0.035 in $B_s \to J/\psi\phi$
  - Probe or establish New Physics by measuring ϕ_s in hadronic penguin decay $B_s \to \phi\phi$ with a precision of $\sigma(\Delta S(\phi\phi))$ = 0.040
  - Measure CKM angle γ to a precision of $\sigma(\gamma) \sim 1°$
  - Probe New Physics in rare B meson decays
    Measure Wilson coefficient C_7/C_9 to 4% in electroweak decay $B \to K^{*0}\mu^+\mu^-$
  - Measure $B_d \to \mu^+\mu^-$

Backup Slides

LHCb Physics Programme

$B_d^0 \to \pi^0 \pi^+ \pi^-$

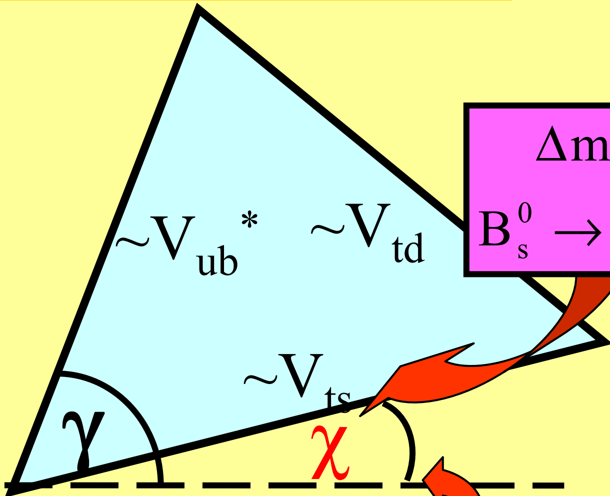


$B_d^0 \to J/\Psi \ K_S^0$

$B_s^0 \to D_s^{\pm} K^{\mp}$ $\gamma - 2\chi$

$B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ β and γ

$B_d^{\pm} \to D^0 K^{\pm}$
$B_d^0 \to D^0 K^{*0}$ } γ



Δm_s
$B_s^0 \to D_S \pi$

$B_s^0 \to J/\Psi \ \Phi, \ J/\Psi \ \eta^{(')}$

B production,
B_c , b-baryon physics
Charm decays
Tau Lepton flavour violation

Rare decays - very sensitive to NP

- Radiative penguin e.g. $B_d \to K^* \gamma$, $B_s \to \Phi \gamma$
- Electroweak penguin e.g. $B_d \to K^{*0} \mu^+\mu^-$
- Gluonic penguin e.g. $B_s \to \Phi\Phi$, $B_d \to \Phi K_s$
- Rare box diagram e.g. $B_s \to \mu^+\mu^-$