Future flavour physics at the LHC

Jim Libby (University of Oxford)

Flavour physics with an upgraded LHCb

Jim Libby (University of Oxford)

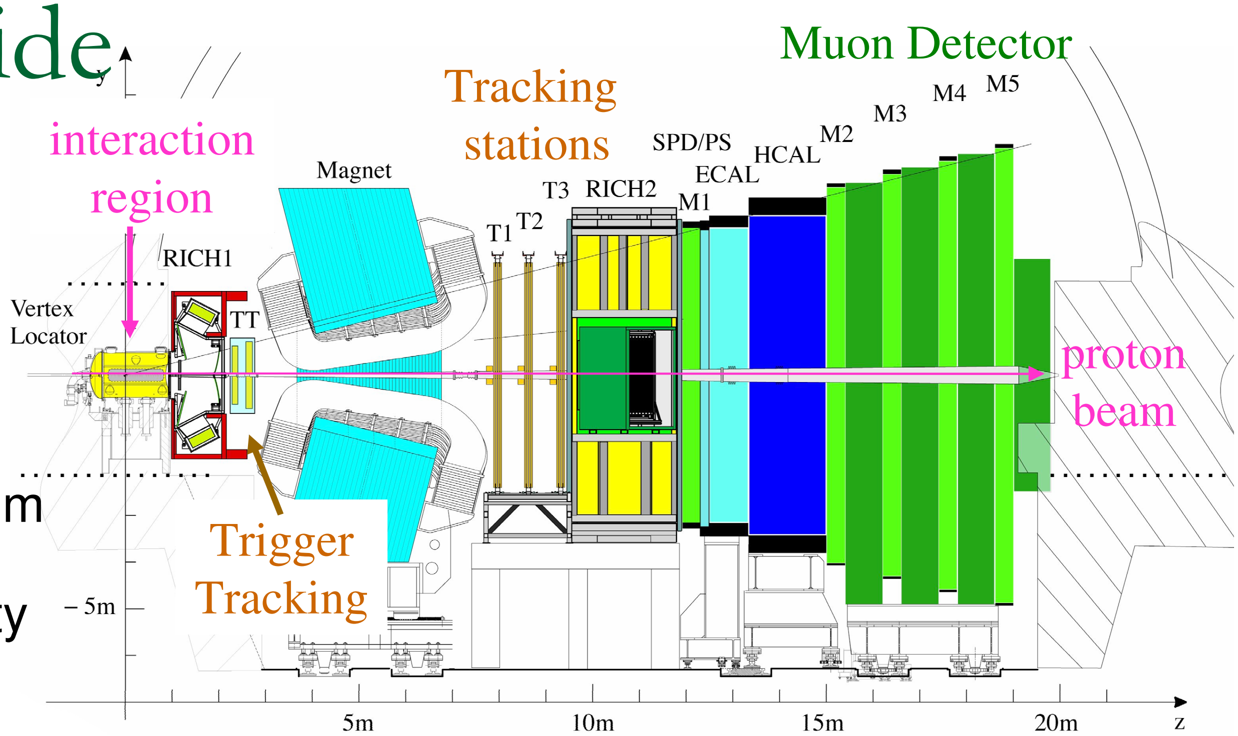
Flavour Physics with an upgraded LHCb

- **LHCb**
  - Reminder of what is planned by 2012/2013
- **SuperLHCb**
  - Luminosity goals
  - Technical requirements and desires
- **The SLHCb physics programme**
  - Unitarity triangle and CPV
  - FCNC decays
  - Charm physics
- **Conclusion**
  - Including comments on time-scale and cost

- Primary sources
  - Hans Dijkstra (FPCP)
  - Sheldon Stone (Flavour in the era of the LHC)
  - Guy Wilkinson (1st LHCb upgrade workshop)

LHCb in a slide

- Forward geometry:
  - 10^{12} bb/2 fb^{-1} produced
  - both B hadrons in acceptance for tagging
  - excellent proper time resolution (40 fs)
- RICHs for hadron ID from 1 to 100 GeV/c
- Instantaneous luminosity $(2\text{-}5)\times10^{32}\ cm^{-2}s^{-1}$
  - Factor 50 to 20 below peak design luminosity for GPDs



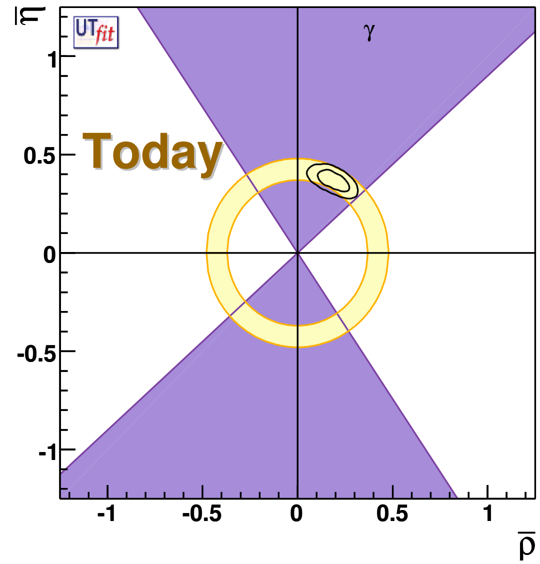
- Level-0: high p_t $l^{\pm}$, hadron or γ hardware trigger 40→1 MHz
  - Effectively 10 → 1 MHz
- Software Higher Level Trigger (HLT):
  - ensure high p_t object associated with large impact parameter tracks
  - inclusive and exclusive selections to reduce storage rate to 2 kHz

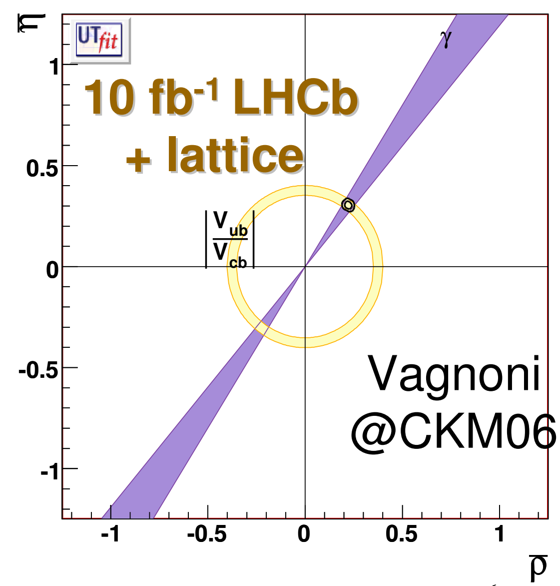
LHCb programme and goals

- **Highlights of the physics programme by 2013 (data set ~10 fb^{-1})**
  - $B_s \to \mu^+\mu^-$ observed
    - BR measured to ~15% if SM
  - B_s mixing phase measured with an uncertainty 0.01 rad
    - Current CKMFitter prediction –0.036±0.003
  - γ measured to a few degrees **(several ways)**
    - $B \to DK$
    - $B_s \to D_s K$
    - $B_{(s)} \to h^+h^-$ exploiting U-spin
  - $B \to K^* \mu^+\mu^-$: 38k events with B/S<0.5
    - angular analyses

The particle physics landscape in 2013

- All measurements listed on previous slide very sensitive to virtual NP effects
- Three tangible scenarios in 2013
  1. NP at GPDs and LHCb
  2. NP at LHCb but not at GPDs
  3. NP at GPDs not at LHCb
     - But maybe a few 2-3σ effects
- **Trivial to motivate upgrade in first two**
- If we can build a powerful case for scenario 3 then we can justify upgrade before we see any NP signature
- There is a scenario 4 (LHC wasteland)
  - No one wants this!
  - However, virtual effects will be the only way to set scale of NP





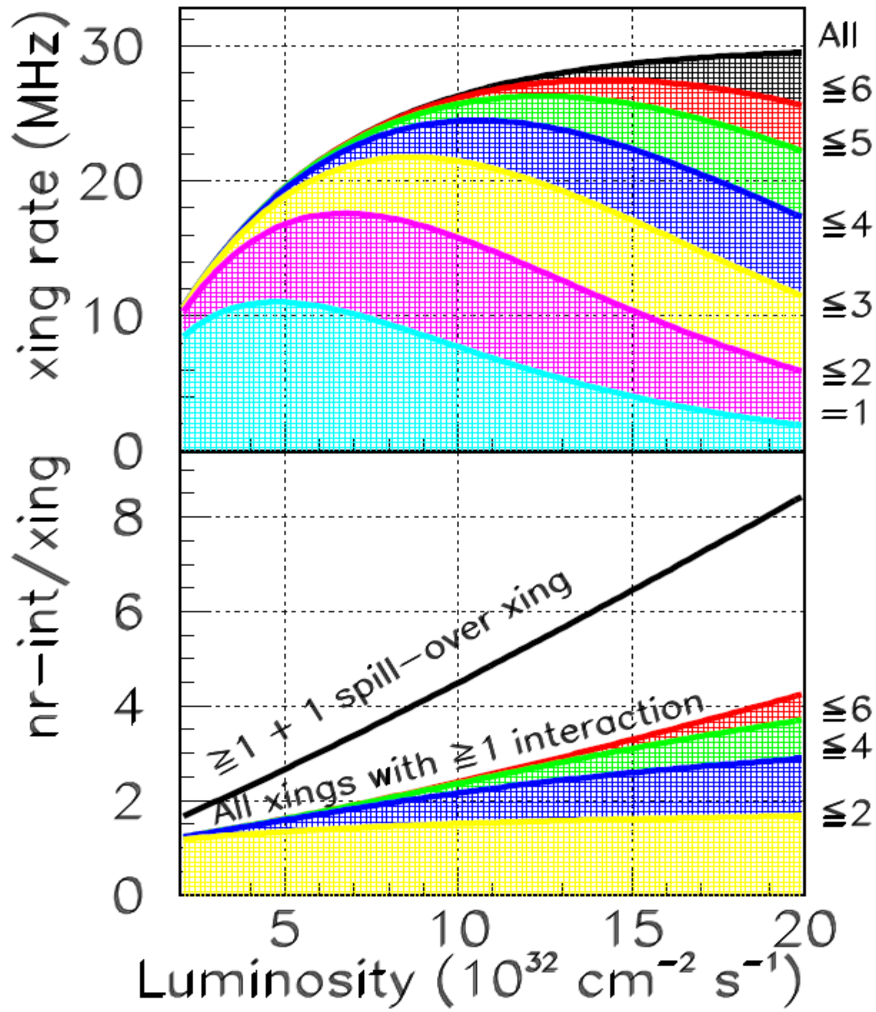
Definition of an upgrade

- Before returning to the importance of such a data set in scenario 3, I will address the technical considerations
- An order of magnitude or more improvement
  - Tevatron a successful example:
    - ~100 pb^{-1} (Run I) to 2000 pb^{-1} and counting (Run II)
    - Improvements to detectors particular silicon and trigger
  - Super Flavour Factory use this standard also:
    - 2 to 75 ab^{-1}
    - Mainly accelerator
- **Sets the scale for SLHCb**
  - **10 to 100 fb^{-1}**
  - **All necessary improvements are in the detector**

LHC and luminosity

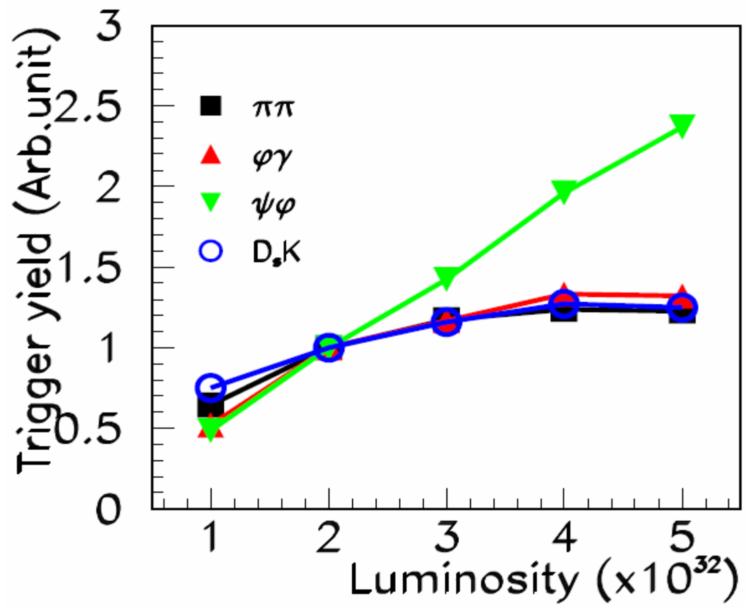
- Peak LHC luminosity 10^{34} cm^{-2}s^{-1}
- LHC operating at 2×10^{32} cm^{-2}s^{-1}
  - 10 MHz of crossings with ≥ 1 int.
- LHC operating at 2×10^{33} cm^{-2}s^{-1}
  - 30 MHz of crossings with ≥ 1 int.
  - Number of int./crossing increased by factor of two
  - **BUT** with spill-over (int. from previous crossing) increased by factor 3
- SLHC peak luminosity 8×10^{34} cm^{-2}s^{-1}
- Not needed by LHCb, but
  - Baseline scheme 25 ns bunches with alternating high (I^H) and low (I_L) current
  - GPDs: $I^H\times I^H$, $I_L\times I_L$, $I^H\times I^H$, $I_L\times I_L$,……
    - Effective 20 MHz crossing rate
  - LHCb: $I^H\times I_L$, $I_L\times I^H$, $I^H\times I_L$, $I_L\times I^H$,…….
    - Select I_L for desired luminosity

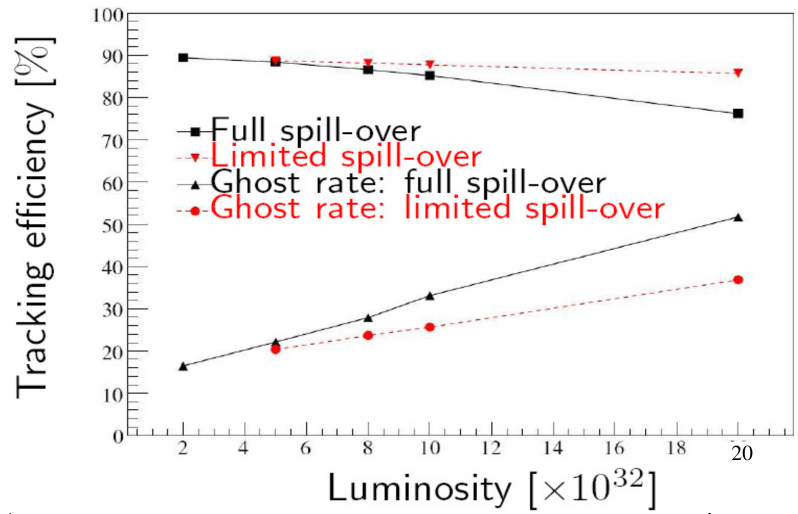
Assumes $\sigma_{visible}$=63 mb



Current LHCb and luminosity

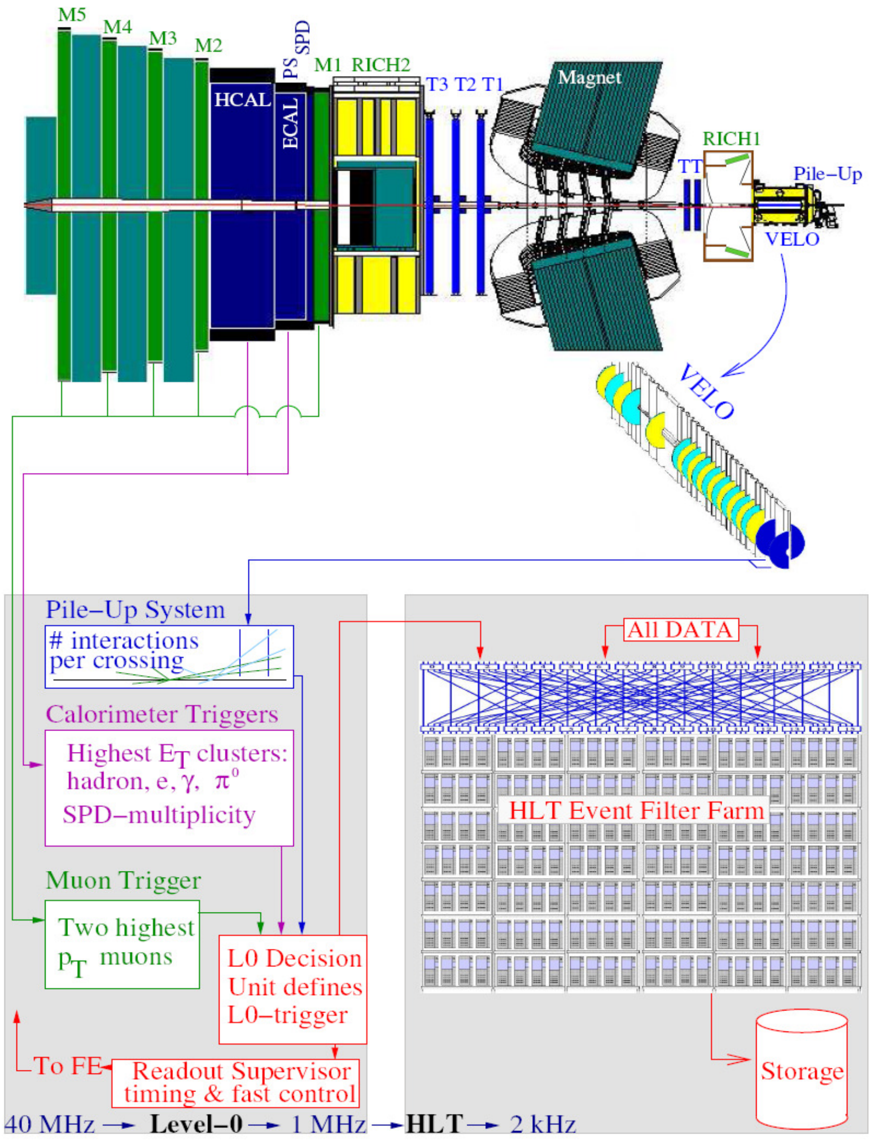
- Current LHCb no gain for hadron modes when lumi goes above $2\times10^{32}\ cm^{-2}s^{-1}$
  - **Limitation from L0 trigger**
- Radiation damage
  - Spec was for less than 20 fb^{-1}
  - Principally affects large η
- Tracking and particle ID:
  - **Straws: significant problems from spill-over above $10^{33}\ cm^{-2}s^{-1}$**
  - Hadron PID and tagging OK to $\sim5\times10^{32}$ but degrades with reduced tracking performance
  - Si tracking fine





Current trigger limits

- Level-0 largest E_T hadron, e(γ) and μ
- Bottleneck is 1 MHz output rate
  - Thresholds tuned to match this
- At L>10^{33} $cm^{-2}s^{-1}$
  - interactions @ 30 MHz so only 3% can be retained
  - Number of int./crossing 2-4
  - **Leads to E_T threshold >> M_B!**
- Furthermore, desire to improve efficiency for hadrons and photons
  - $\varepsilon_{L0}(B\rightarrow \text{hadronic}) \sim 25\text{-}35\%$
  - $\varepsilon_{L0}(B\rightarrow \gamma X) \sim 30\text{-}40\%$
  - $\varepsilon_{L0}(B\rightarrow \mu\mu X) \sim 60\text{-}70\%$
- Higher Level Trigger
  - Only limitation is CPU and our algorithmic ingenuity
  - (Former) improves with Moore's Law



Hardware path to upgrade

- **Address trigger bottleneck:**
  - Perform whole trigger in CPU farm $\therefore$ **read out 40 MHz**
  - Preliminary studies:
    - Event building at 40 MHz OK with suitable CPU
    - Hadron trigger efficiency can be increased by incorporating vertex and coarse momentum early (c.f. BTeV)
    - **However, all subsystems front-end electronics need to be replaced**
      - New RICH photon detectors
- **Radiation:**
  - Vertex detector replacement already required after ~6 fb^{-1}
    - **Upgrade to rad. hard Si pixels?**
  - Inner region of calorimeter to crystals $\rightarrow$ improved $\sigma(E)/E$
- **Occupancy ×4 in outer tracker**
  - Only two fold without spillover $\rightarrow$ faster gas?
  - Increase inner Si coverage
  - More radical SciFi tracker!
- **Apart from full 40 MHz readout no decisions taken on technologies-there is R&D to be done**

Minimal Flavour Violation

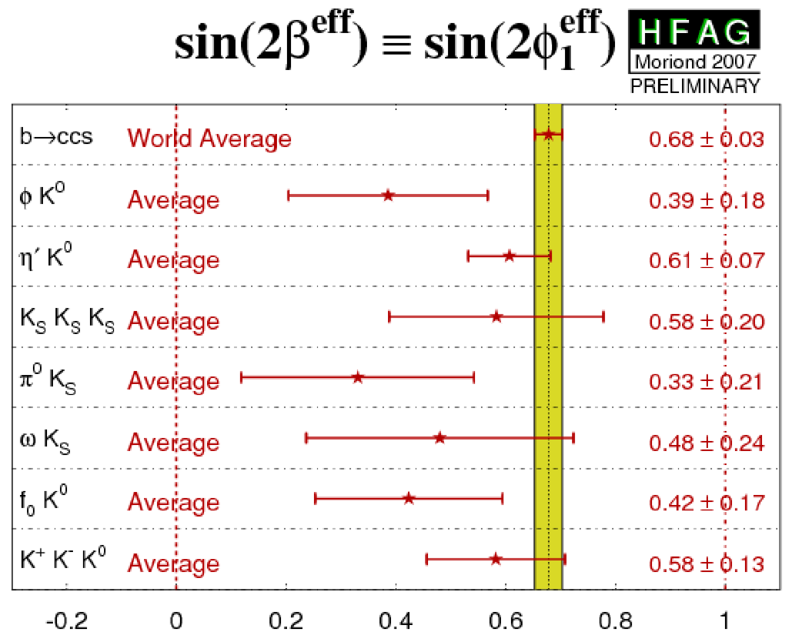
- But before embarking on these technical challenges we must concentrate on whether 100 fb^{-1} data set is motivated in scenario 3:
  - the new physics at GPDs is not influencing the flavour sector
- MFV: CP violation is purely Standard Model
  - no new phases in flavour sector of New Physics
    - test angles to the degree level or better
  - but (small) changes expected in rates and differential distributions of FCNC
    - $b \to s(d)$ transitions
    - $B_s \to \mu\mu$

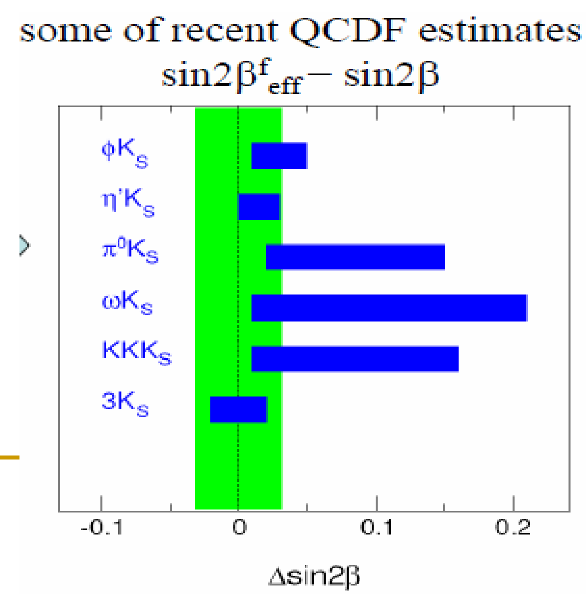
The physics of 100 fb^{-1}

- **Highlights of the physics programme by 2013 (~10 fb^{-1}) revisited**
  - γ measured to a few degrees (several ways)
    - $B \to DK$, $B_s \to D_s K$ and $B_{(s)} \to h^+h^-$ exploiting U-spin
    - **Upgrade:** improvements will lead to 20-fold increase in statistics
    - **Upgrade:** concentrating on theoretically cleanest modes < 1^0 precision should be possible
  - B_s mixing phase measured with an uncertainty 0.01 rad
    - Current CKMFitter prediction –0.036±0.003
    - **Upgrade:** <10% measurement SM
    - **Upgrade:** most systematic uncertainties $\propto$ (Lumi.)$^{-1}$
  - $B \to K^* \mu^+\mu^-$: 38k events with B/S<0.5 to perform angular analyses
    - **Upgrade:** Precision measurement of theoretically clean angular observables
  - $B_s \to \mu^+\mu^-$ observed
    - BR measured to ~15% if SM
    - **Upgrade:** improve precision to systematic (lumi) limitations
    - **Upgrade:** $B_d \to \mu^+\mu^-$?

CPV in gluonic penguin

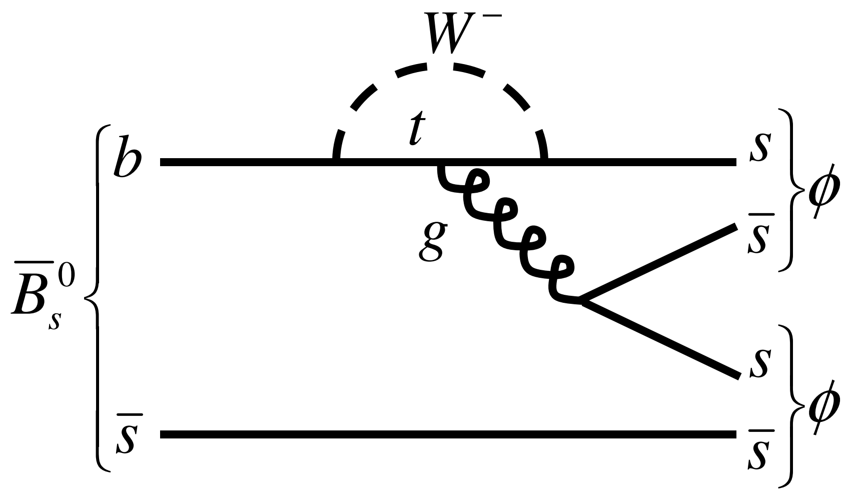
- One of the poster children of a SFF
  - For good reason given the tantalising hints of a discrepancy with sin2β from b→ccs
- Concentrate on the cleanest modes $B_d \to \phi K^0, \eta' K^0$ and $K^0 K^0 K^0$
  - **Average discrepancy 0.10±0.06**
    - No attempt to add theory
  - 5σ with current central value an important goal
- $B_d \to \phi K^0$ most promising at current LHCb
  - Precision at end of LHCb 0.14
  - **End of SLHCb 0.03**
    - assuming $2\times\varepsilon_{trigger}$
    - same as SFF but they have the other important modes…..





$B_s \to \phi\phi$

- B_s analogue of $B_d \to \phi K^0, \eta' K^0$ *etc*
- Dependence on V_{ts} in both the decay and B_s mixing amplitudes leads to the SM CPV being < 1%
  - for example M. Raidal, PRL 89, 231803 (2002)
- $P \to VV$ decay requires full angular analysis to extract CP info
- Simulation studies with background and detector effects
  - 2000 (4000) events/fb^{-1} @ (S)LHCb
  - NP phase sensitivity of 0.042 at current LHCb
  - **SLHCb sensitivity 0.009 (0.5°)**



$$\lambda^{SM}_{\phi\phi} = \frac{q}{p}\frac{\overline{A}_{\phi\phi}}{A_{\phi\phi}} = \underbrace{\frac{V_{tb}V^*_{ts}}{V^*_{tb}V_{ts}}}_{\text{mixing}}\underbrace{\frac{V^*_{tb}V_{ts}}{V_{tb}V^*_{ts}}}_{\text{decay}} = 1$$

Toward a sub-degree error on γ

- Extrapolating to 100 fb^{-1} only consider strategies which are theoretically clean

	LHCb (10 fb^{-1})	Super-LHCb (100 fb^{-1})	SFF (75 ab^{-1})
D_sK	27 k	540k	-
$D(K_s\pi\pi)K$	≤25k	0.5M	80k
$D(K\pi)_{fav}$ K	280k	5.6M	131k

Extrapolations from published B-factory analyses

- $B_s \to D_sK$: statistical scaling leads to **1° uncertainty** for 100 fb^{-1}
- $B \to D(K_s\pi\pi)K$: statistical scaling leads to **1.2 °** for 100 fb^{-1}
  - need to consider model independent method (Bondar & Poluektov) exploiting $\psi'' \to DD$ data with $K\pi\pi$ vs CP and $K\pi\pi$ vs $K\pi\pi$
  - 3° with final CLEO-c statistics BES-III coming soon
  - **Other modes $B \to D(K_sK\pi)K$, $B \to D(K_sKK)K$ and 4-body to be exploited**
- $B \to D(hh)K$: ADS/GLW methods statistics huge but will need global fit including additional information to overconstrain

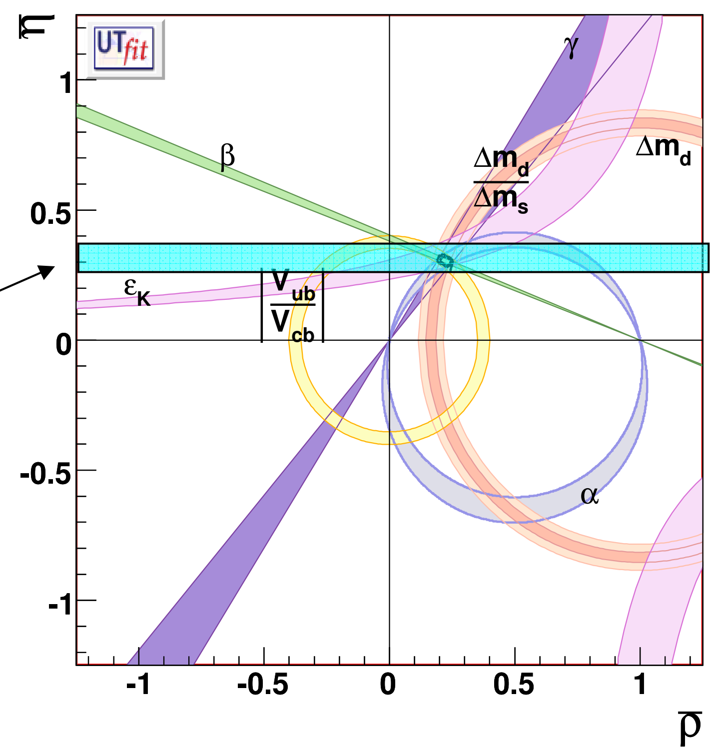
Mixing phases-the systematic frontier

- $\sin 2\beta$ improvement can be made with control channel measurements of penguin pollution and tagging
  - $B_s \rightarrow J/\psi K^0_S$
    - R. Fleischer, Eur. Phys. J. C. 10., 299 (1999)
  - **Push toward 1%/0.2° uncertainty**

(Super-)LHCb	2 fb^{-1}	10 fb^{-1}	100 fb^{-1}
σ (stat)	0.021	0.009	0.003

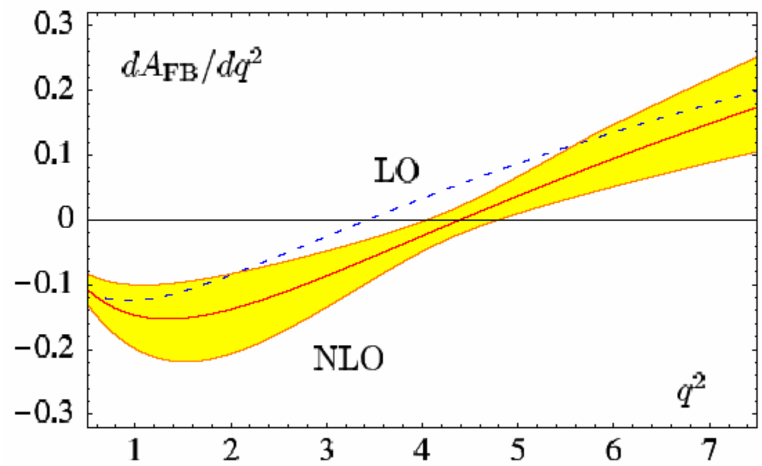
- 8% relative uncertainty on SM-like B_s mixing phase from $B_s \rightarrow J/\psi\phi$ possible at SLHCb
  - Matches current indirect determination
  - Direct proportionality to η leads to interesting constraint on UT
    - // to that from $K_L \rightarrow \pi^0 \nu\nu$
  - Penguin control possible from $B_s \rightarrow J/\psi\rho$

Superposed on LHCb 10 fb^{-1} + lattice

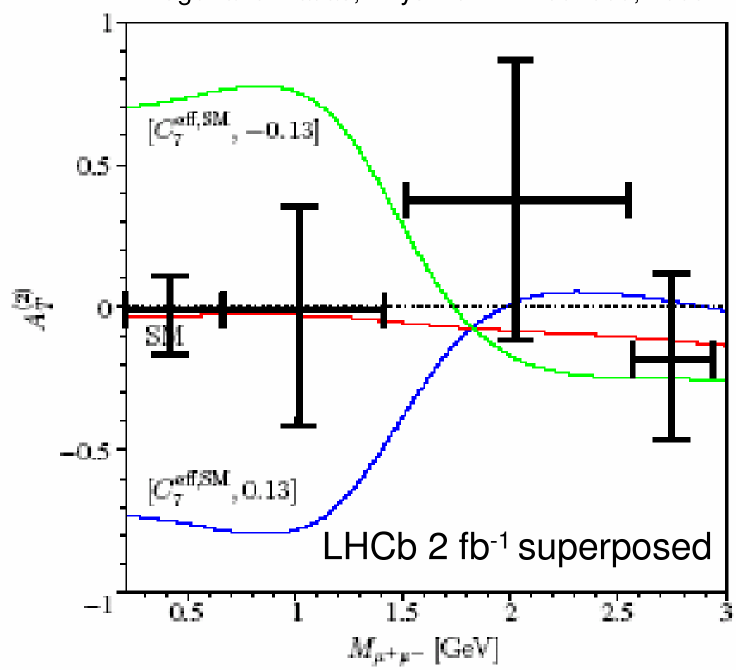


$B \to K^* \mu\mu$

- $A_{FB}(s_0)=0$ is not enough:
  - SLHCb $\sigma_{s0}/s_0=2.1\%$
  - Exclusive NLO theory today $\sigma_{s0}/s_0=9\%$
  - Not unreasonable to expect exclusive error to improve by 2020
- Inclusive reconstruction has lower theory uncertainties ~5%
  - But a truly inclusive measurement (B-beam) at a SFF will not match this
- However, transversity angle asymmetry analysis looks extremely promising
  - Probes chiral structure (c.f. TDCPV $B \to K^* \gamma$)
  - Theoretically clean
  - Will benefit greatly from SLCHb statistics

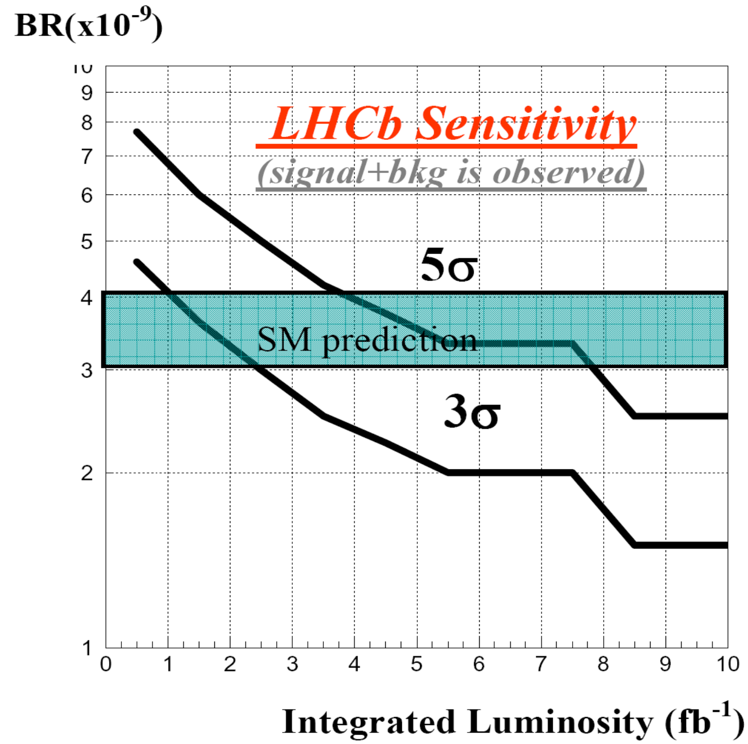


Kruger and Matias, Phys.Rev.D71:094009, 2005



$B_{s(d)} \to \mu\mu$

- **5σ observation expected at current LHCb even if value of BF is SM**
- Theory prediction already at ~10%
- More precise determination at SLHCb would be constraining of NP models with large tanβ
  - c.f. $B \to K^* \mu\mu$ transversity analysis constrains small tanβ
- $B_s \to \mu\mu / B_d \to \mu\mu = 32.4 \pm 1.9$ tightly constrained in SM and MFV
  - one of the magic numbers of CMFV (Buras)
- Matching theory precision is impossible with 100 fb^{-1}
  - But observation possible at SLHCb as long PID can cope with double punch-through background from $B_d \to \pi\pi$
  - Maybe SLHC GPDs???? **Or UltraLHCb!**



Charm physics

If charm mixing has indeed been observed, what next ?

- Precise measurements of $x^{(')}$ and $y^{(')}$
- Search for (***and detailed study***) of CPV in charm – v. promising for NP

Target charm analyses at LHCb and SLHCb **(diverse programme!):**

- Mixing studies in $D^0 \to hh$
- CPV search in partial width differences in $D^0 \to KK$, $\pi\pi$ (SCS)
- CPV search in T-odd moment & amplitude analysis of $D^0 \to KK\pi\pi$ (SCS)
- CPV search in $D^+ \to K^- \pi\pi$ Dalitz (SCS)
- Mixing and CPV in $D^0 \to K_s \pi\pi$ Dalitz
- Mixing and CPV in $D^0 \to K^+ \pi\pi\pi$ (DCS)
- Rare decays, eg. $D^{(0)}_{(s)} \to l^+ l^-$ [(Xu,s)]

Recent detailed simulation studies at LHCb show great promise in $D^0 \to hh$ decays.

- After all selection cuts yield from B decays alone is expected to be 10-20 times (10 fb^{-1}) that of total from B-factories (2 ab^{-1}).

Will benefit from change of trigger strategy at SLHCB

Conclusion

- There is a strong case to continue flavour physics even without clear NP signatures by 2013
  - If MFV is correct can be verified through precise determination of CPV and FCNC in B(D) decays at SLHCb
- Schedule
  - 2010 decision on upgrade instrumentation
  - 2013-2015 upgrade detector during planned SLHC upgrade
  - 2015-2020 gather 100 fb^{-1}
- Cost
  - Current LHCb cost 45 M€
  - Upgrade no detailed costing given lack of instrumentation decisions made
    - Front-end electronics replacement estimate 12 M€
  - Previous cost probably a sensible upper limit

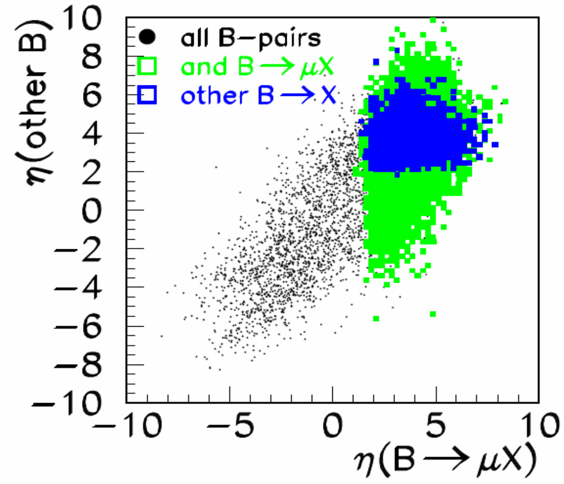
Backup

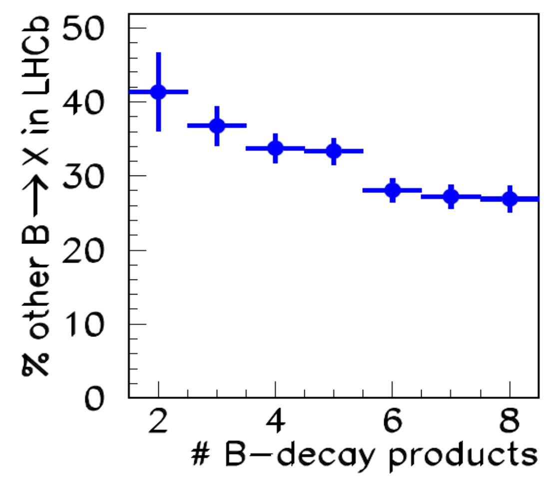
Other physics highlights

- CP violation
  - α from $\rho\pi$ and $\rho\rho$
- FCNC
  - RH currents with $B_s \rightarrow \phi\gamma$
  - $b \rightarrow d\gamma$
  - $b \rightarrow d\mu\mu$
- LFV
  - $B \rightarrow e\mu$
  - $B \rightarrow K^{*} e\mu$
  - $\tau \rightarrow \mu\mu\mu$
- **By no means exhaustive**

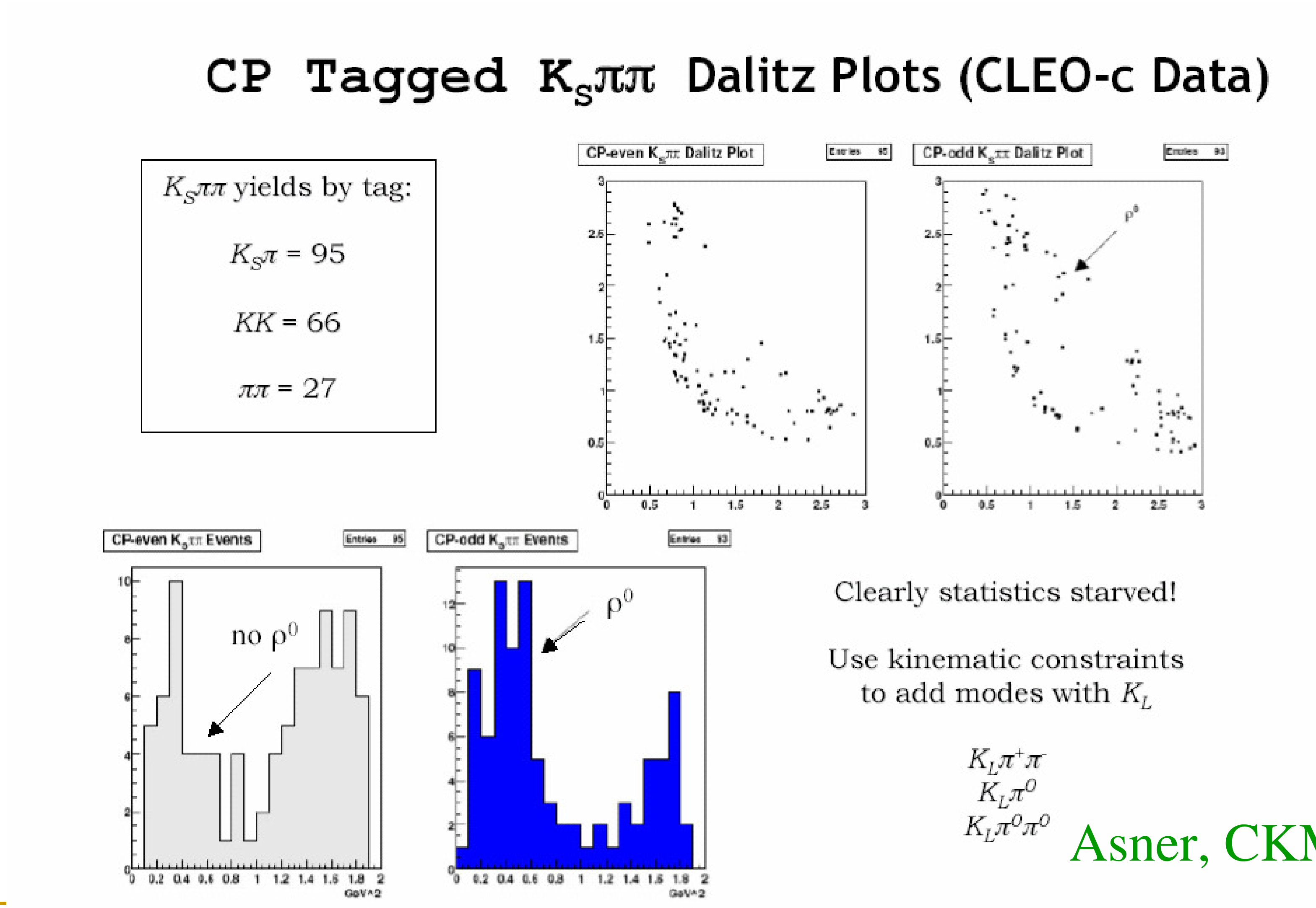
Current HLT trigger performance

- HLT partitioning
  - 200 Hz exclusive B: core modes
  - 600 Hz high mass μμ unbiased in lifetime: B→J/ψX
  - 300 Hz D* for charm physics (CPV) and PID calibration
  - 900 Hz large impact parameter single μ for data mining (untriggable modes)
- Data mining stream
  - 550 Hz true B with tagging $\varepsilon D^2=0.15$
  - ~35% of the other B decays fully contained
  - 1.5 billion fully contained B events/2 fb-1
  - Equivalent to ~1.4 (0.7) ab^{-1} of untagged (tagged) e^+e^-





CP tagged D0 decays at the ψ(3770)



Asner, CKM 2006