Flavour Physics at LHCb

Michael Schmelling – MPI for Nuclear Physics

e-Mail: Michael.Schmelling@mpi-hd.mpg.de

Overview

- Introduction
- CP-Violation Measurements
- B-Physics with LHCb
- Selected Decay Channels
- Summary

Why B-Physics ? – or – Where is all the Anti-Matter?

naive expectation: equal amounts of matter and anti-matter from the Big Bang, but...

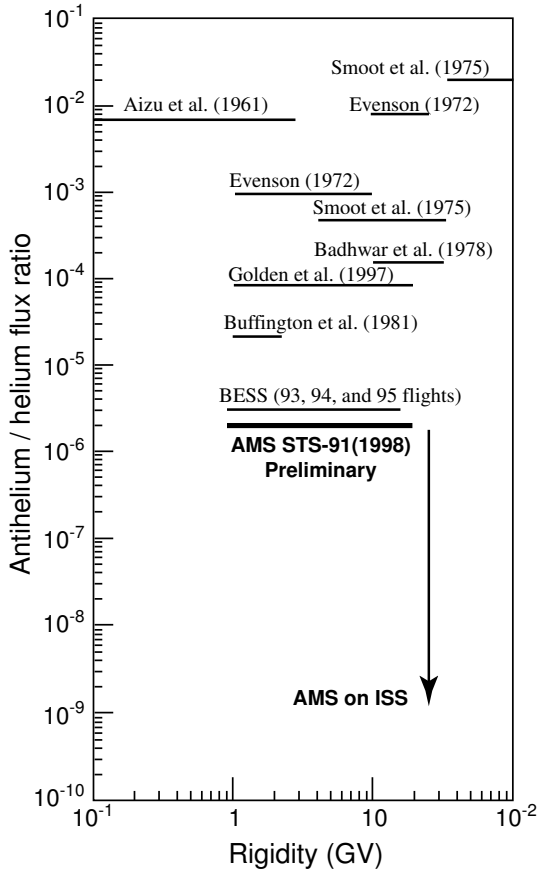
- for example, no annihilation radiation seen in γ-rays from space,
- or search primordial $\overline{\text{He}}$ so far without positive results...

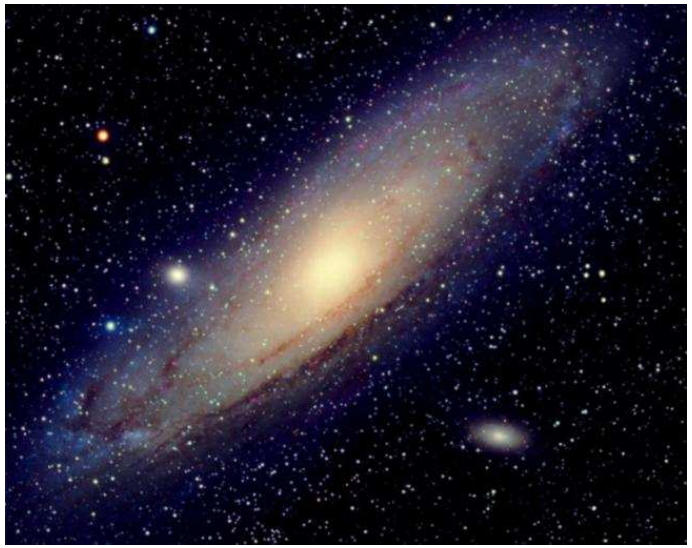
look for:

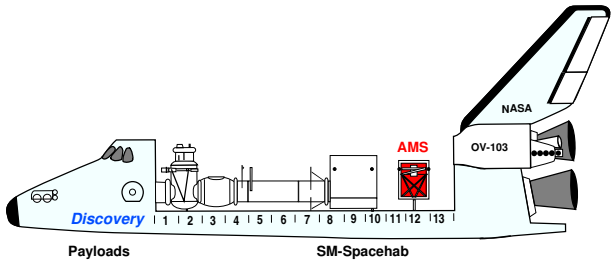
- ➜ cosmic ray $\overline{\text{He}}$
- ➜ go into space
- ➜ AMS experiment

Result:

no $\overline{\text{He}}$ found







Zakharov's Conditions

The necessary conditions to explain the matter dominance of the universe are:

1. C- and CP-violation
2. baryon-number violation
3. thermal non-equilibrium

Standard Model:

- C- and CP-violation exist in CKM-sector
- baryon-number violation via Spalerons and thermal non-equlibrium can be created in a 1st order phase transition during the early universe

Problem:

- SM-Higgs particle is too heavy to generate the 1st order phase transition and the CP-violation in the CKM-sector is too small to explain the matter dominance of the universe
  - ➜ extra sources of CP violation are needed
  - ➜ "New Physics" expected in CP-violation measurements

2. CP-Violation Measurements

CP-Asymmetry A_{CP} for decays into a final state y:

$$A_{CP} = \frac{\Gamma(X \to y) - \Gamma(\overline{X} \to \bar{y})}{\Gamma(X \to y) + \Gamma(\overline{X} \to \bar{y})} \qquad \text{with partial widths} \qquad \Gamma(\cdot) = |a(\cdot)|^2$$

Consider mixing induced CP-violation in decays to a CP-eigenstate $y = y_{CP}$:

$$a(X \to y_{CP}) = a_m(X \to X) \cdot a_d(X \to y_{CP}) + a_m(X \to \overline{X}) \cdot a_d(\overline{X} \to y_{CP})$$

$$a(\overline{X} \to y_{CP}) = a_m(\overline{X} \to \overline{X}) \cdot a_d(\overline{X} \to y_{CP}) + a_m(\overline{X} \to X) \cdot a_d(X \to y_{CP})$$

The contributing amplitudes are:

$$\left.\begin{matrix} a_d(X \to y_{CP}) \\ a_d(\overline{X} \to y_{CP}) \end{matrix}\right\} = A e^{\pm i\omega} \quad \left.\begin{matrix} a_m(X \to X) \\ a_m(\overline{X} \to \overline{X}) \end{matrix}\right\} = \cos\frac{\Delta m t}{2} \quad \left.\begin{matrix} a_m(X \to \overline{X}) \\ a_m(\overline{X} \to X) \end{matrix}\right\} = i \sin\frac{\Delta m t}{2} e^{\pm i\phi}$$

with phase factors

- phase from the decay: ω
- mixing phase: ϕ

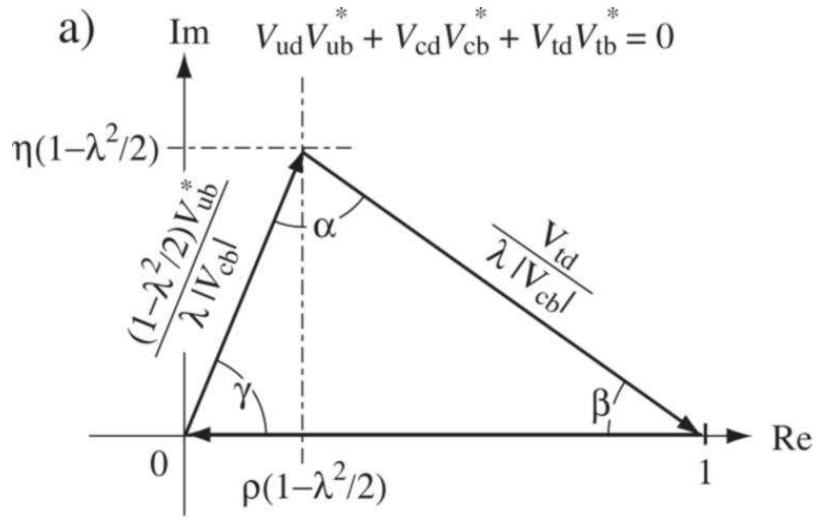
$$\boxed{A_{CP} = -\sin(\Delta m t)\sin(\phi - 2\omega)}$$

Standard Model: All phases arise from CKM Matrix elements

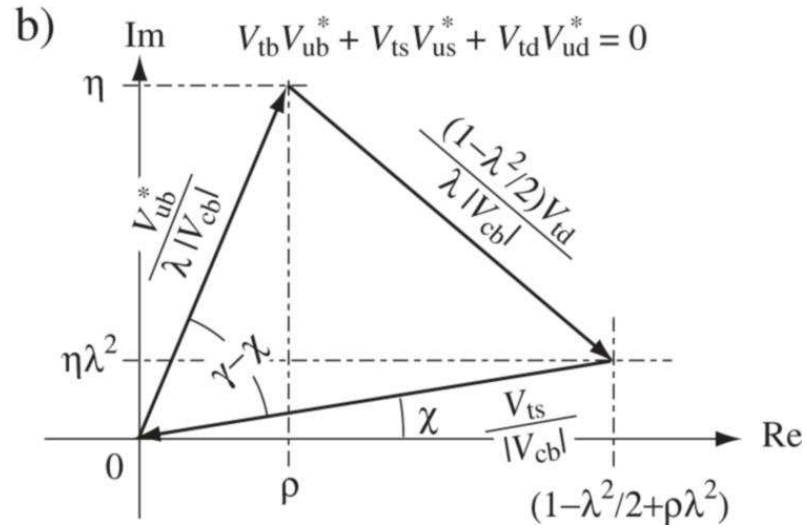
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx$$

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein-parametrization



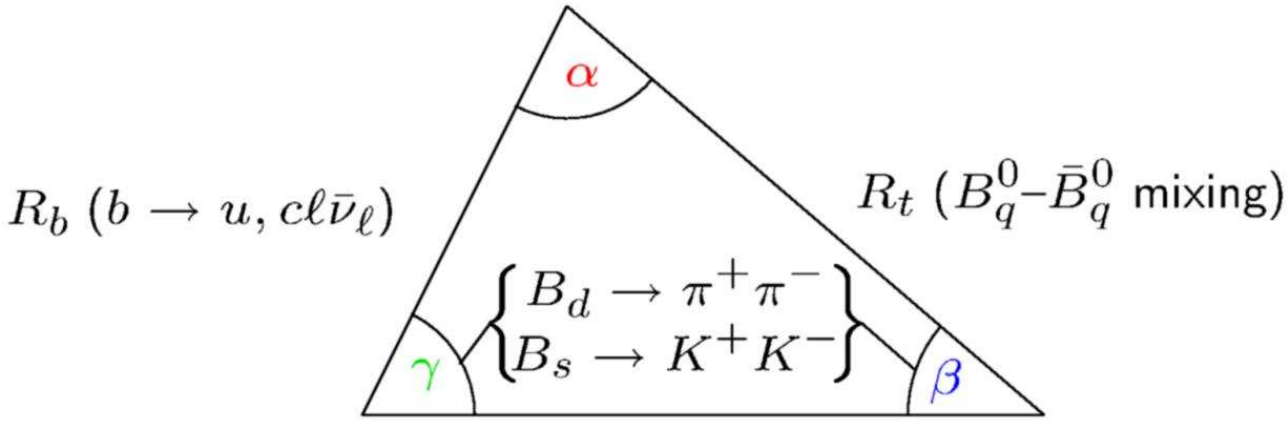
- unitary matrix, i.e. $C_i \cdot C_j^\star = R_i \cdot R_j^\star = \delta_{ij}$, parametrized by 4 free parameters
- qualitative picture determined by $\lambda \approx 0.22$
- unitarity triangles $C_1 \cdot C_3^\star = R_3 \cdot R_1^\star = 0$
  - ➜ $\arg(V_{td}) = -\beta$ (B_d-mixing)
  - ➜ $\arg(V_{ub}) = -\gamma$ ($B_d \to \pi^+\pi^-$ decays)
  - ➜ $\arg(V_{ts}) = \chi + \pi \approx \eta\lambda^2 + \pi$ (B_s-mixing)



note: $V \neq 1$ goes beyond Higgs search in addressing the origin of mass!

Phenomenology of B-decay Channels

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$



$B \to \pi K$ (penguins)

$B_d \to \psi K_S$ ($B_s \to \psi\phi$: $\phi_s \approx 0$)

$B_d \to \phi K_S$ (pure penguin)

$$\left.\begin{array}{l} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{array}\right\} \text{only trees}$$

$$\left.\begin{array}{l} B_d \to D^{(*)\pm}\pi^\mp : \ \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \ \gamma + \phi_s \end{array}\right\} \text{only trees}$$

from R. Fleischer hep-ph/0505018v1

Search for New Physics in B-Decays

- compare measurements which are insensitive to new physics with measurements of the same quantity from a decay channel that is sensitive to new physics
  - ➜ β from $B_d \to J/\psi\ K_s$ - tree level dominates
  - ➜ β from $B_d \to \phi K_s$ - pure penguin
  - ➜ γ from $B_s \to D_s K$ - tree level dominates
  - ➜ γ from $B_d \to \pi K$ - with penguin contribution
- study observables which have a small expectation value in the standard model
  - ➜ CP-asymmetry in $B_s \to J/\psi\ \phi$
  - ➜ transitions sensitive to FCNC, for example
    - ✘ $B \to K^\star \gamma$ i.e. $b \to s\gamma$
    - ✘ $B_d \to K^{0*}\mu^+\mu^-$
    - ✘ rare decays $B_{d,s} \to \mu^+\mu^-$
- compare UT from length and angle measurements

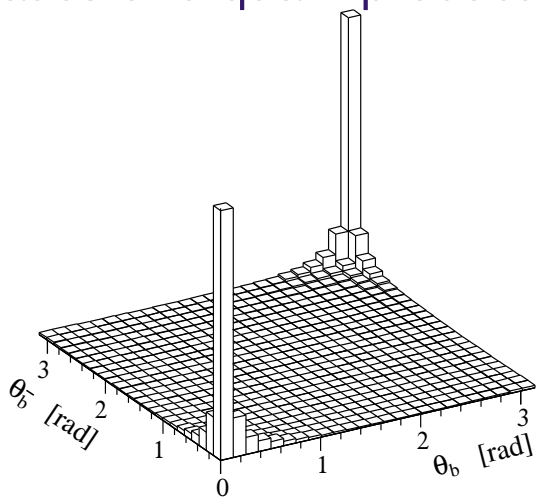
Note:

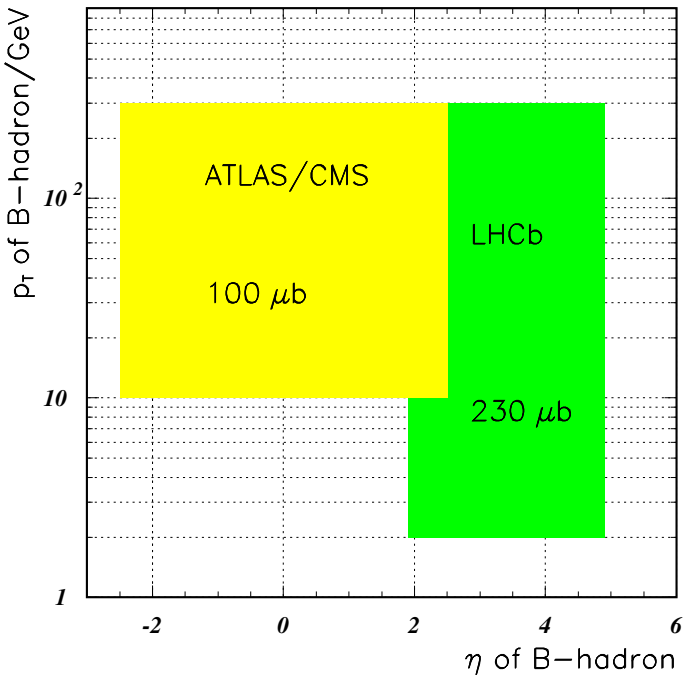
The discussion here focuses on mixing induced CP-violation. In addition also direct CP-violation can be measured, with usually different sensititivity to New physics...

$$A_{CP}(t) \sim A_{dir} \cos(\Delta m t) + A_{mix} \sin(\Delta m t)$$

3. B-Physics with LHCb

Kinematics of b-quark production:





Challenges to the detector:

EFFICIENT TRIGGER FOR NON-LEPTONS

DISTINGUISH π/K

RESOLVE x_s

$B \to D^*\pi, D^*3\pi$
$B \to \rho\pi$

$B \to DK^*$
$B \to K^*\gamma$

$B_s \to D_s\pi$

$B_{d,s} \to D^+_{d,s}D^-_{d,s}$

$B_s \to KK$

$B_s \to D_sK$

$B_s \to K^{*+}K^{*-}$

$B_s \to J/\psi\phi$

$B_s \to J/\psi K_s$

$B \to \rho^+\rho^-$
$B \to K^{*0}\overline{K}^{*0}$

$B \to \pi\pi$
$B \to K\pi$

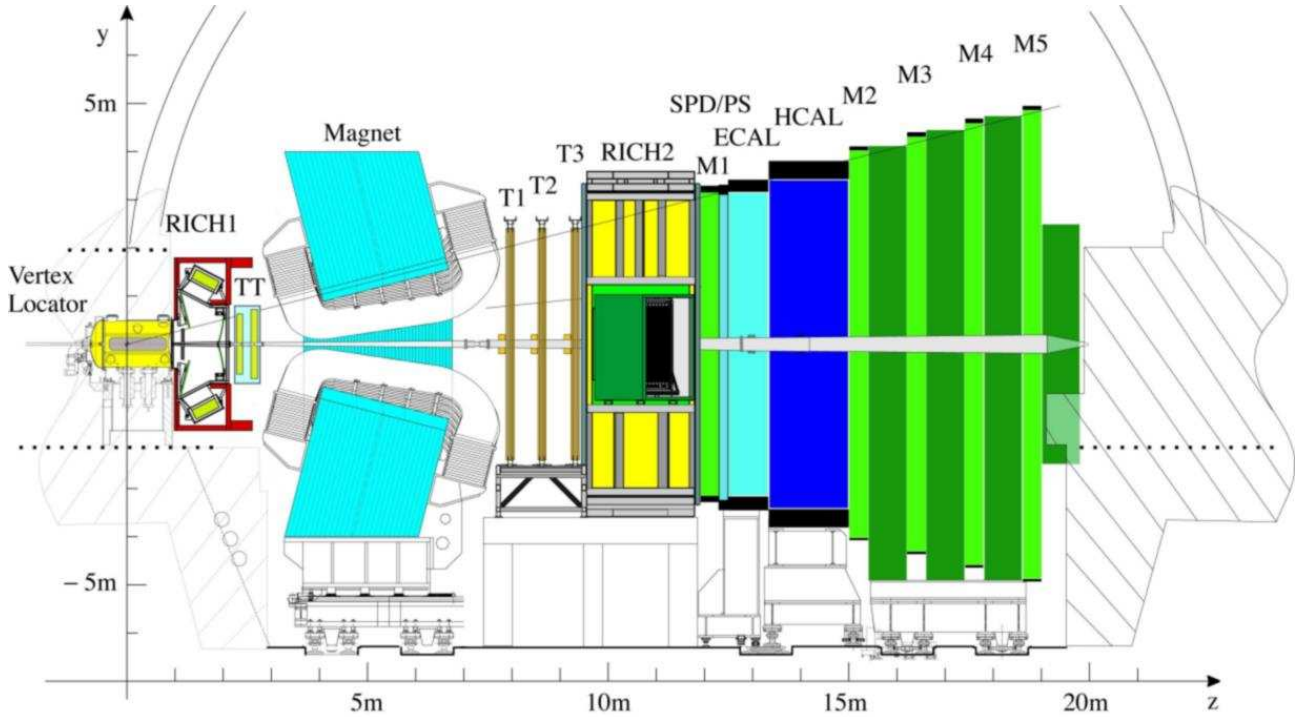
$B_d \to J/\psi K_s$

$B_d \to J/\psi\rho^0$

$B_{s,d} \to \mu^+\mu^- \quad (\mathcal{O}(10^{-9})\,!)$

➜ LHCb: optimized to meet these requirements

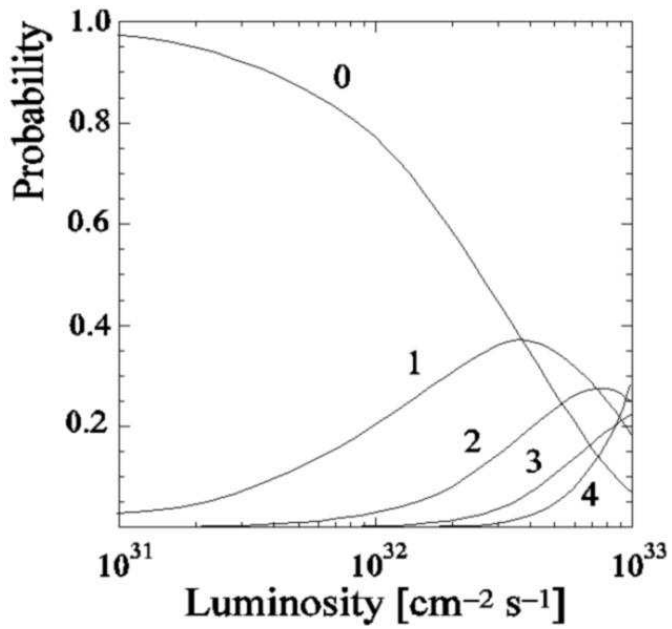
The LHCb Experiment



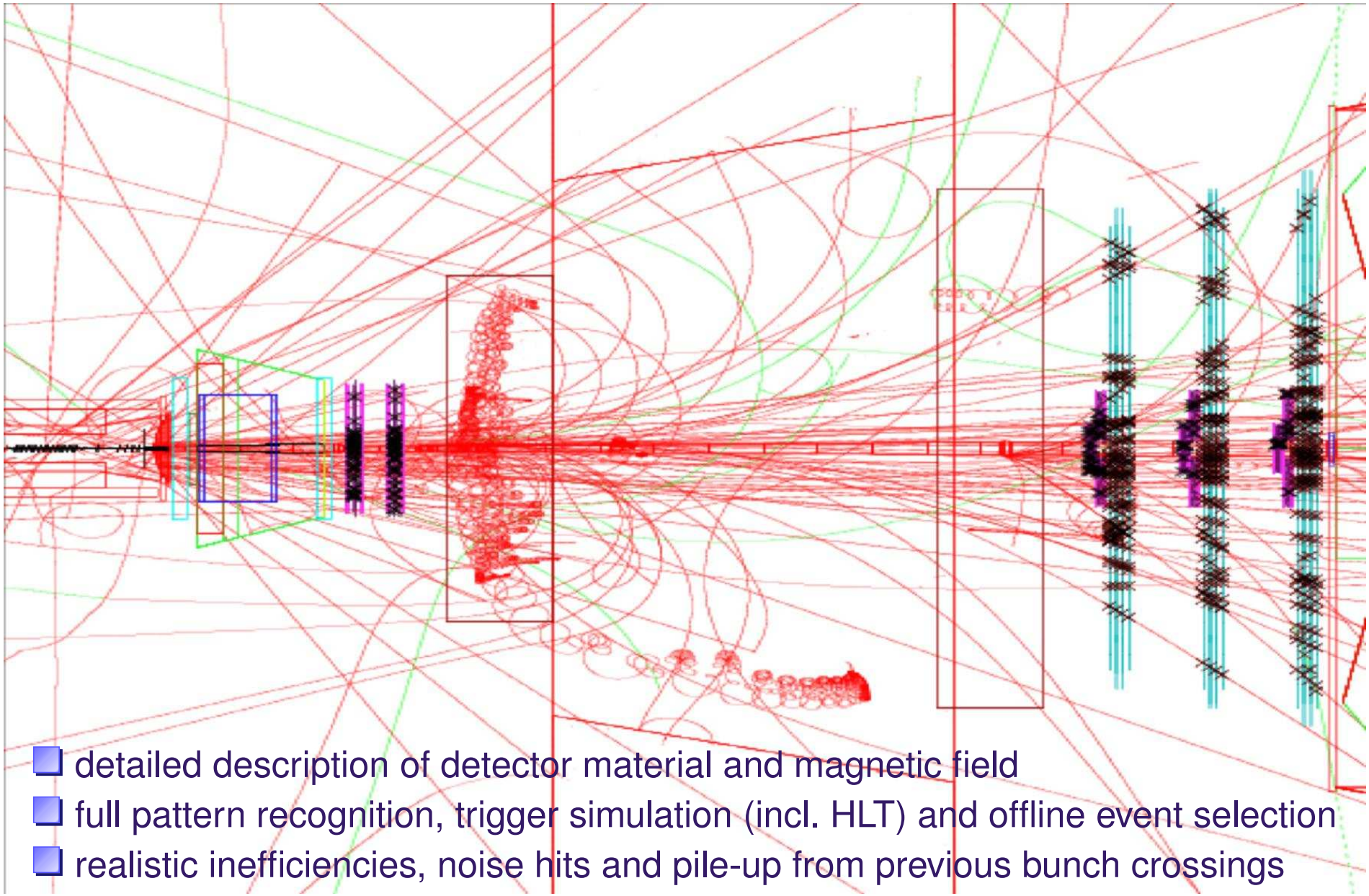
- $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2}s^{-1}, adjustable
- 10^5 b-events/second, $2 \cdot 10^{12}$ b-hadrons/year
- $B^0 : B^{\pm} : B_s : \Lambda_b \approx 0.8 : 0.8 : 0.2 : 0.2$
- lepton and hadron trigger
  - ✘ 200 Hz exclusive B-candidates
  - ✘ 600 Hz high mass Di-muons
  - ✘ 300 Hz D^* candidates
  - ✘ 900 Hz inclusive b-trigger

- ➜ forward spectrometer
- ➜ excellent particle-ID
- ➜ high vertex resolution
- ➜ flexible trigger
  - ✘ 1 MHz readout to HLT
  - ✘ 2 kHz to disk

pp interactions/BX



LHCb Monte Carlo Simulation

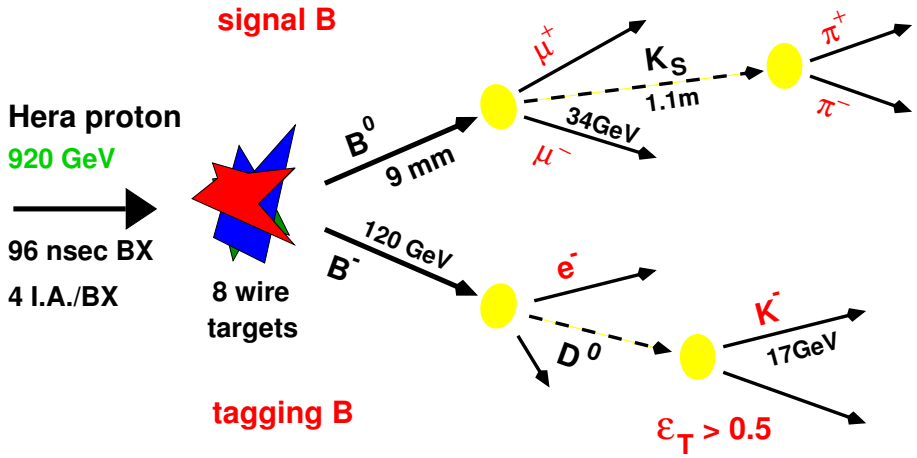


- detailed description of detector material and magnetic field
- full pattern recognition, trigger simulation (incl. HLT) and offline event selection
- realistic inefficiencies, noise hits and pile-up from previous bunch crossings

Flavour Tagging

➜ determination of the initial flavour of a B-meson

- obvious for charged B-mesons
- experimental challenge for neutral B-mesons
  - ➜ opposite side tagging
    - ✘ reconstruct flavour of “idler”-B
  - ➜ same-side tagging
    - ✘ self-tagging B**-decays
    - ✘ fragmentation products



LHCb Flavour tagging performance:

Channel	$\varepsilon_{\rm tag}$ (%)	w (%)	$\varepsilon_{\rm eff}$ (%)
$B^0 \to \pi^+\pi^-$	41.8±0.7	34.9±1.1	3.8±0.5
$B^0 \to K^+\pi^-$	43.2±1.4	33.3±2.1	4.8±1.0
$B^0 \to J/\psi(\mu\mu)K^0_S$	45.1±1.3	36.7±1.9	3.2±0.8
$B^0 \to J/\psi(\mu\mu)K^{*0}$	41.9±0.5	34.3±0.7	4.1±0.3
$B^0_s \to K^+K^-$	49.8±0.5	33.0±0.8	5.8±0.5
$B^0_s \to \pi^+K^-$	49.5±1.8	30.4±2.6	7.6±1.7
$B^0_s \to D^-_s\pi^+$	54.6±1.2	30.0±1.6	8.7±1.2
$B^0_s \to D^\mp_s K^\pm$	54.2±0.6	33.4±0.8	6.0±0.5
$B^0_s \to J/\psi(\mu\mu)\phi$	50.4±0.3	33.4±0.4	5.5±0.3

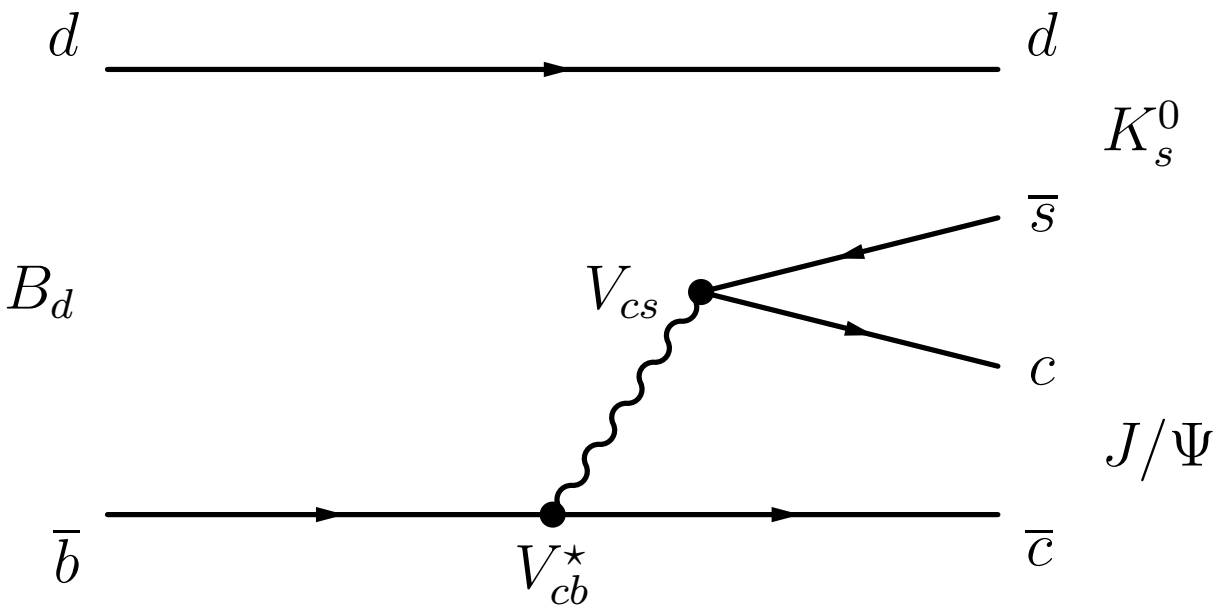
note: effective fraction of perfect tags

$$\varepsilon_{\rm eff} = \varepsilon_{\rm tag}(1-2w)^2$$

with

- ➜ $\varepsilon_{\rm tag}$ tagging efficiency
- ➜ w mistag fraction

The "golden Decay" $B_d \to J/\Psi K_s$

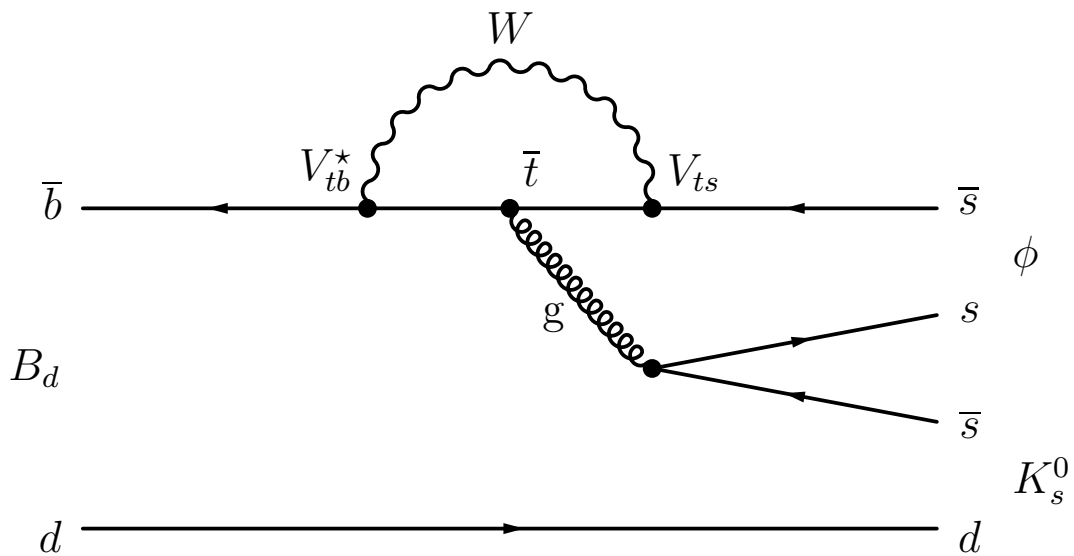


- ➜ "classical" example for mixing induced CP-violation
- ➜ in Wolfenstein-parametrization no phase from decay
- ➜ in Standard-Model measures the B_d-mixing phase
- ➜ dominated by tree level contributions
- ➜ small or no New Physics contributions expected

➜ Measurement of $\sin 2\beta$

The Decay $B^0 \to \phi K_s$

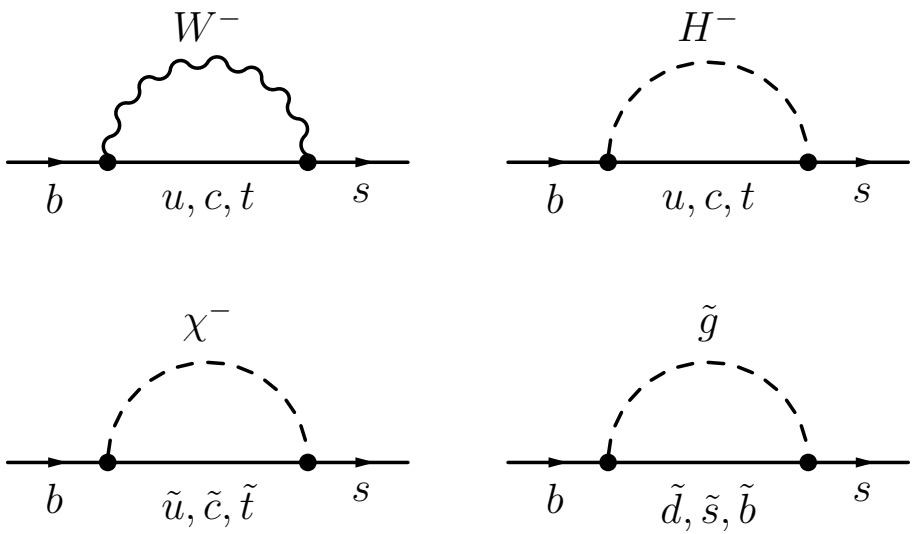
Standard Model: alternative way of measuring $\sin 2\beta$ in a pure penguin mode



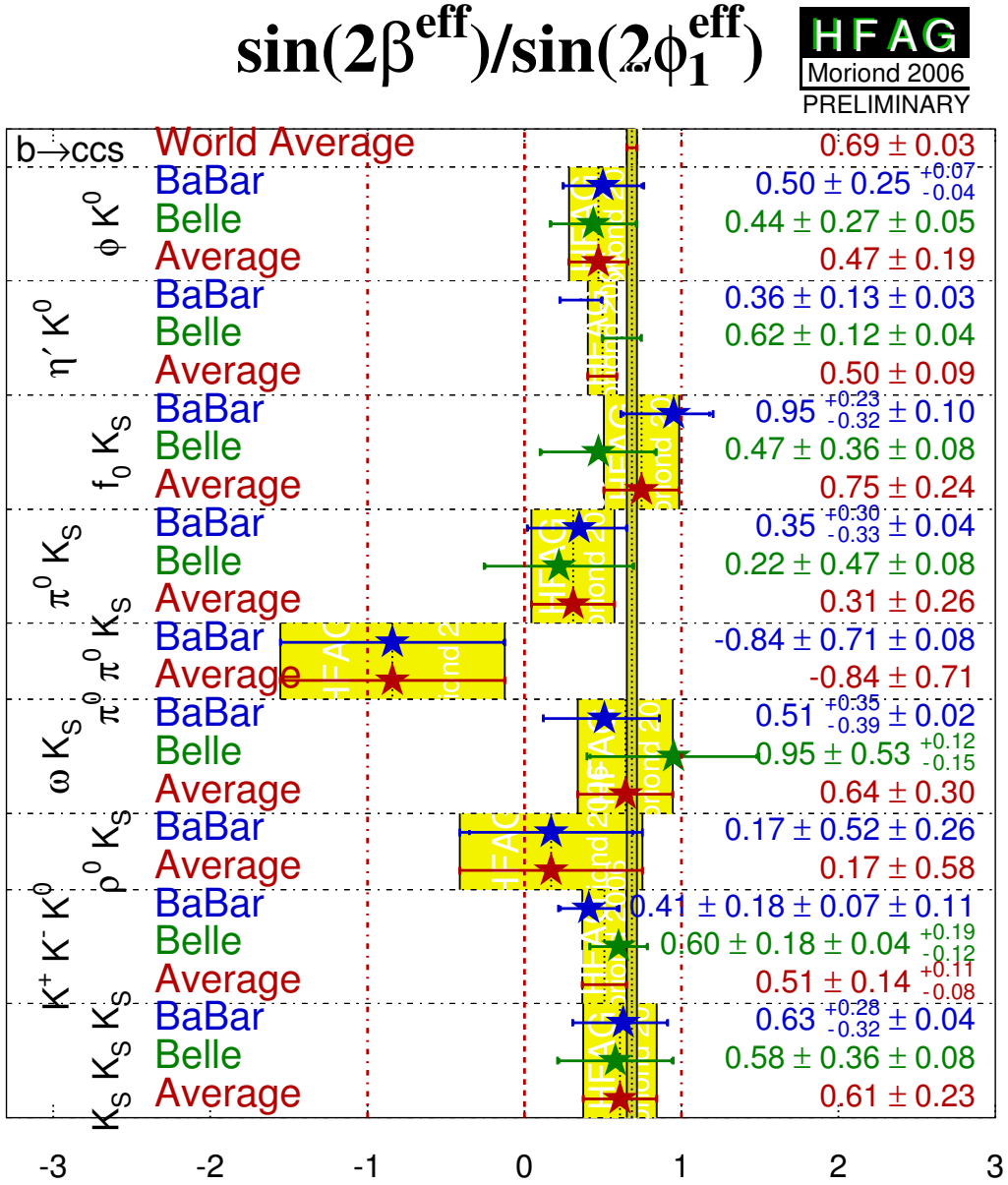
the weak phase from decay is dominated by $\arg(V_{td})$ which is $\mathcal{O}(\lambda^2)$

➜ possible contributions from new physics:

- new heavy bosons with CKM-like couplings
- new contributions to FCNC transitions
  - ✘ would show up elsewhere as well
  - ✘ constrained by other limits



Results from the B-Factories

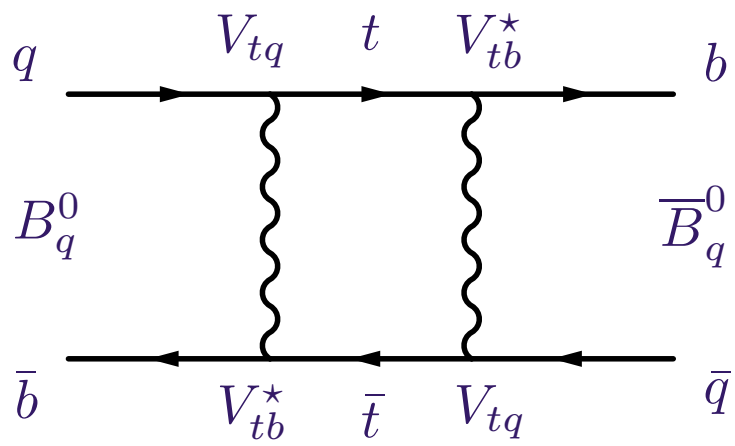


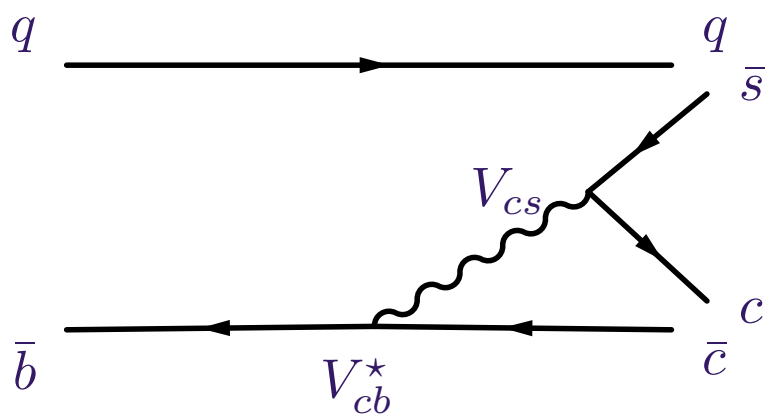
- $n = 16$ measurements
- 14 below $b \to c\bar{c}s$
- consider the probability that from n measurements which fluctuate symmetrically around the $b \to c\bar{c}s$ average, at most $M = 2$ are above:

$$p = 2^{-n} \sum_{k=0}^{M} \binom{n}{k} \approx 0.0021$$

➜ 3-sigma effect . . . stay tuned!

The Decay $B_s \to J/\psi\ \phi$

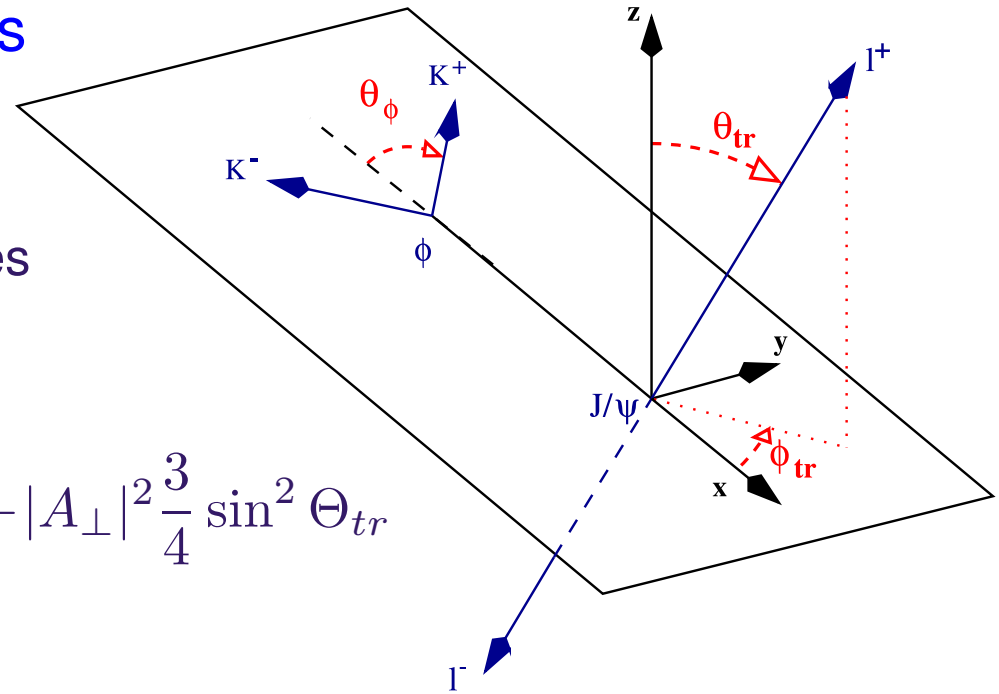




- similar to the "golden decay" $B_d \to J/\psi\ K_s$ with $d \to s$
- theoretically clean measurement, only very small penguin contribution
- only small CP-asymmetry expected in SM: $\phi_s = -\arg V_{ts}^2 \approx -2\eta\lambda^2 \approx -0.04$
- sensitive probe to NP, e.g.
  - ➜ gluinos and squarks in box diagram: $\sin\phi_s \sim 1$ (Ball et al., hep-ph/0311361)
  - ➜ up-type quark singlets: $\sin\phi_s \sim \lambda$ (Aguilar-Saavedra et al., hep-ph/0406151)
- mix of different CP eigenstates because two CP-odd vector mesons in final state
  - ➜ CP-even states from scalar 0 and longitudinal $||$ polarization
  - ➜ CP-odd states from transverse $\perp$ polarization
- study also final states which are CP-eigenstates, e.g.
  - ➜ $B_s \to J/\psi\ \eta$, $B_s \to \eta_c\phi, \ldots$

LHCb Sensitivity for ϕ_s with $2\ fb^{-1}$

➜ dealing with different CP-Eigenstates



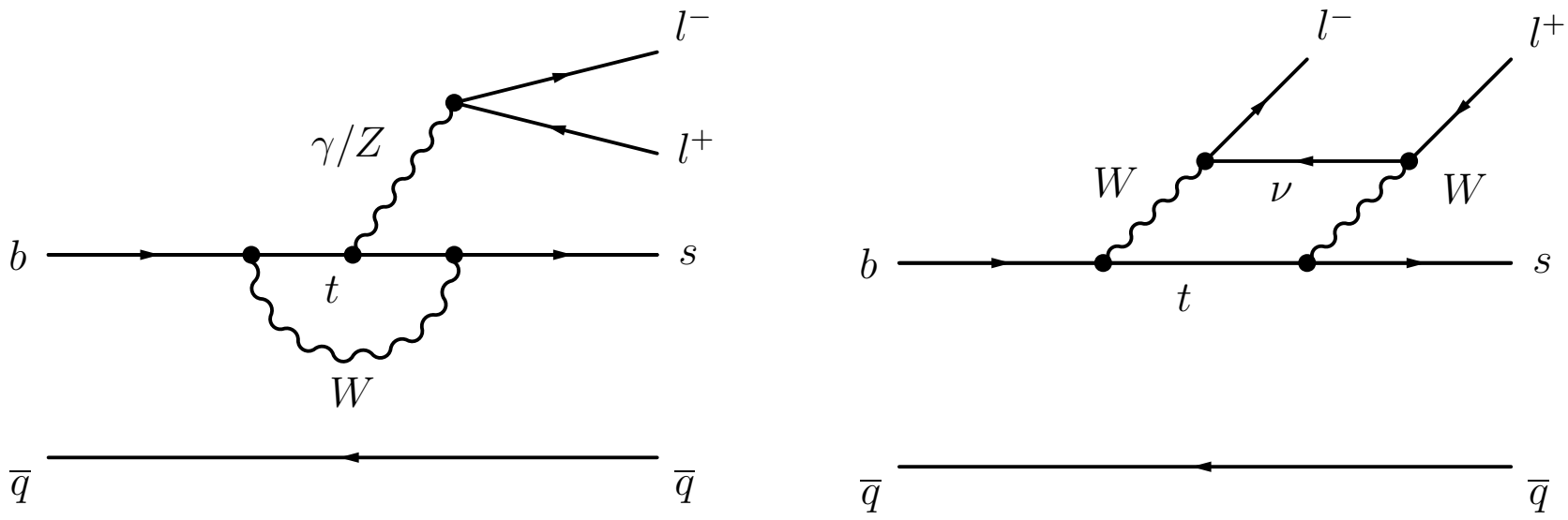
- standard measurement for CP-Eigenstates
- angular analysis for $B_s \to J/\Psi\phi$

$$\frac{d\Gamma}{d\cos\Theta_{tr}} \propto \left[|A_0|^2 + |A_{||}|^2\right]\frac{3}{8}(1+\cos^2\Theta_{tr}) + |A_\perp|^2\frac{3}{4}\sin^2\Theta_{tr}$$

➜ Results (L. Fernandez/J. van Hunen)

Channel	CP-Eigenstate	$\sigma(\phi_s)$[rad]
$B_s \to J/\Psi\phi$	mixed	0.023
$B_s \to D_s D_s$	even	0.133
$B_s \to J/\Psi\eta(\pi^+\pi^-\pi^0)$	even	0.129
$B_s \to J/\Psi\eta(\gamma\gamma)$	even	0.108
$B_s \to \eta_v\phi$	even	0.108
combined		0.021

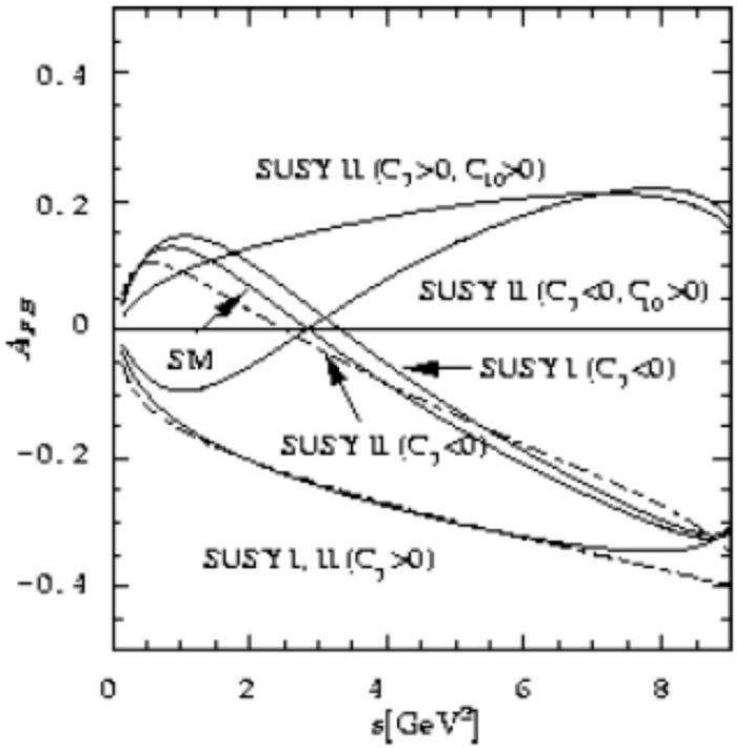
The Decay $B_d \to X\mu^+\mu^-$

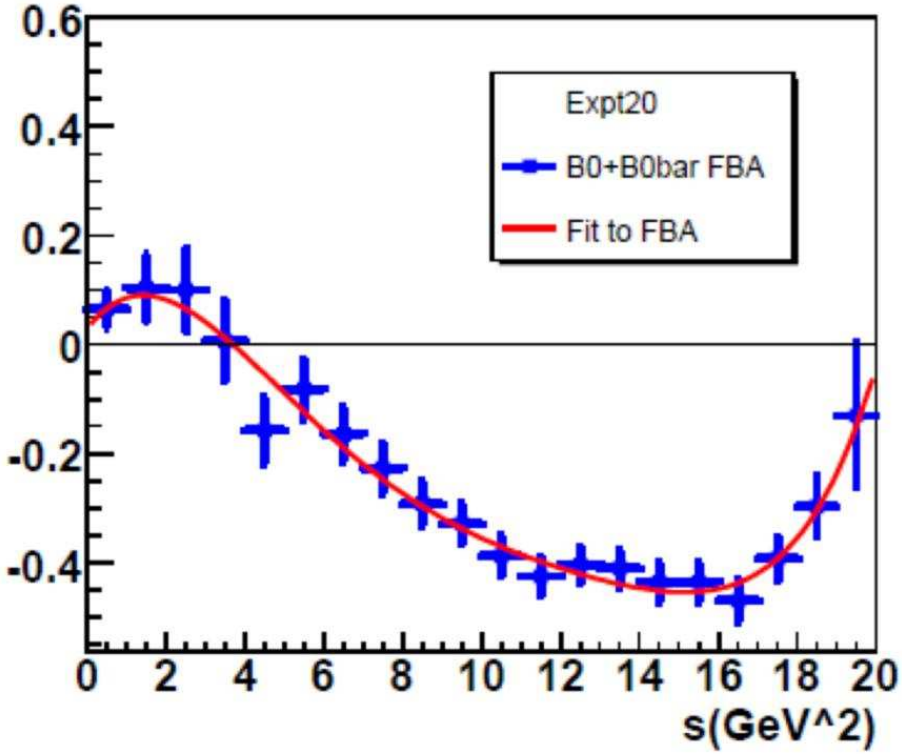


- many possible New Physics contributions
  - ➜ in $bs\gamma$-vertex, which contributes also to $B \to K^*\gamma$ with $A_{CP}^{SM} \leq 0.01$
  - ➜ extra Z-bosons
  - ➜ new particles in box diagrams
- theoretically rather clean prediction for inclusive processes and ratios
- still good accuracy for experimentally accessible exclusive final states
  - ➜ $B_d \to X\mu^+\mu^-$ with $X = K^*, \rho, \phi$

➜ study FB-asymmetry of the muons w.r.t. their common momentum . . .

SM vs SUSY Predictions for $B_d \to K^* \mu^+ \mu^-$





- forward-backward asymmetry
  - ➜ SM predicts zero around $s = 3$ Gev^2
  - ➜ very small hadronic uncertainties
  - ➜ supersymmetry naturally expects no change of sign
- LHCb sensitivity after 5 nominal years
  - ➜ 22k events
  - ➜ zero point $s_0 = 4.0 \pm 0.5$ GeV^2
  - ➜ constraint on $C_7^{\mathtt{eff}}$

note: only continuum is shown – contributions from J/Ψ, Ψ' etc. are suppressed

5. SUMMARY

- B-Physics at LHC is a excellent place to look for new physics
  - ➜ many ways to look for New Physics by overconstraining the SM
    - ✘ SM (tree level) dominated measurements
    - ✘ penguin dominated processes
    - ✘ box diagram dominated decays
  - ➜ comparison of results will reveal New Physics
  - ➜ sensitivity to new particles in quantum corrections up $\mathcal{O}$(TeV)
- LHCb is optimized to exploit the B-Physics potential of LHC
  - ➜ dedicated to study of B-physics and rare decays
  - ➜ full physics potential from day-1 of LHC
  - ➜ precision measurements of couplings
  - ➜ "worst case" will be precision measurements of CKM matrix
    - ✘ historical precedent: Tycho Brahe . . .
- potential for charm physics not yet explored
- thinking has already started towards upgrades . . .

LHCb Sensitivities for 2 fb^{-1}

	Channel	Yield*	B_{bb}/S	Precision
γ	$B_s \to D_s K$	5.4k	<1	$\sigma(\gamma) \approx 14^\circ$
	$B_d \to \pi\pi$	26k	<0.7	
	$B_s \to KK$	37k	0.3	$\sigma(\gamma) \approx 6^\circ$
	$B_d \to D^0(K^-\pi^+)K^{*0}$	0.5k	<0.3	
	$B_d \to D^0(K^+\pi^-)K^{*0}$	2.4k	<2	$\sigma(\gamma) \approx 8^\circ$
	$B_d \to D_{CP}(K^+K^-)K^{*0}$	0.6k	<0.3	
	$B^- \to D^0(K^-\pi^+)K^-$	60k	0.5	
	$B^- \to D^0(K^+\pi^-)K^-$	2k	0.5	$\sigma(\gamma) \approx 5^\circ$
α	$B_d \to \pi^0\pi^-\pi^+$	14k	0.8	$\sigma(\alpha) \approx 10^\circ$
ϕ_s	$B_s \to J/\Psi\Phi$	125k	0.3	
	$B_s \to J/\Psi\eta$	12k	2-3	$\sigma(\phi_s) \approx 2^\circ$
	$B_s \to \eta_c\Phi$	3k	0.7	
Δm_s	$B_s \to D_s\pi$	80k	0.3	Δm_s up to 68 ps^{-1}
β	$B_d \to J/\Psi K_S$	216k	0.8	$\sigma(\sin 2\beta) \approx 0.022$
rare decays	$B_d \to K^*\mu^+\mu^-$	4.4k	<2.6	C_7^{eff}/C_9^{eff} with 13% error
	$B_s \to \mu^+\mu^-$	17	<5.7	NP search
	$B_d \to K^*\gamma$	35k	<0.7	$\sigma(A_{CP}^{dir}) \approx 0.01$