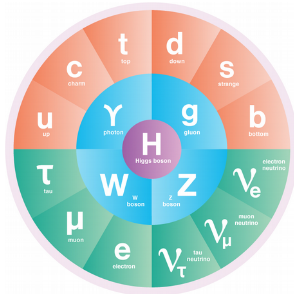
Charmless *b*-hadron decays at LHCb

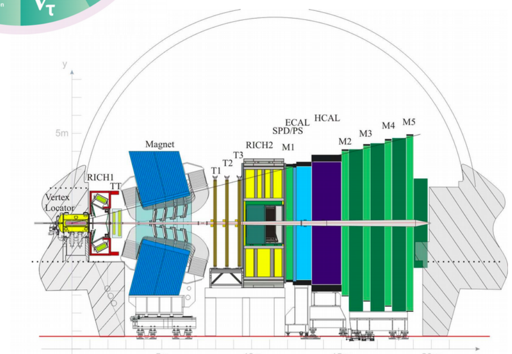
L. Henry
Strasbourg, 07/03/2018

Outline

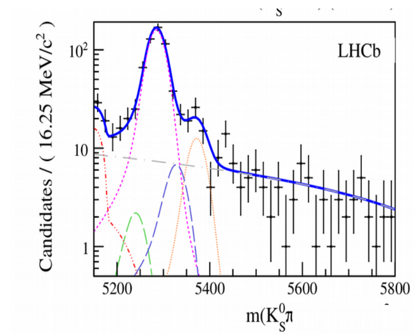
- Introduction



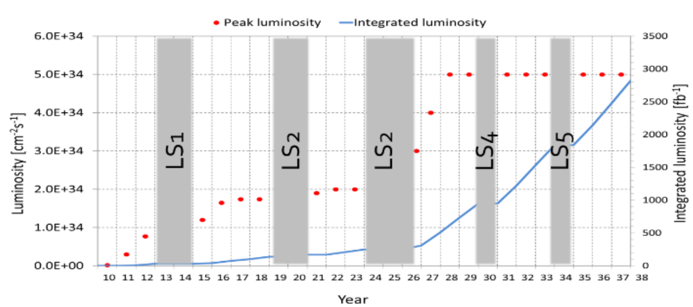
- The LHCb detector

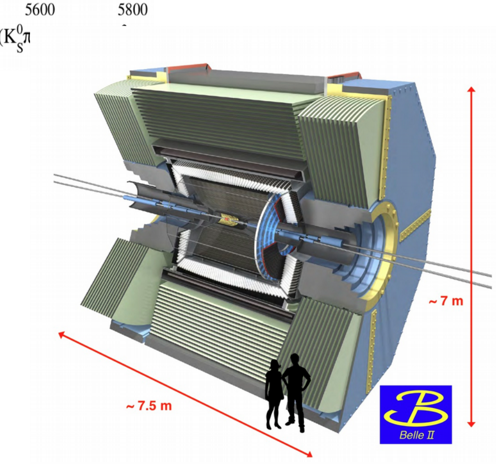


- Charmless b-hadron decays at LHCb



- Prospects



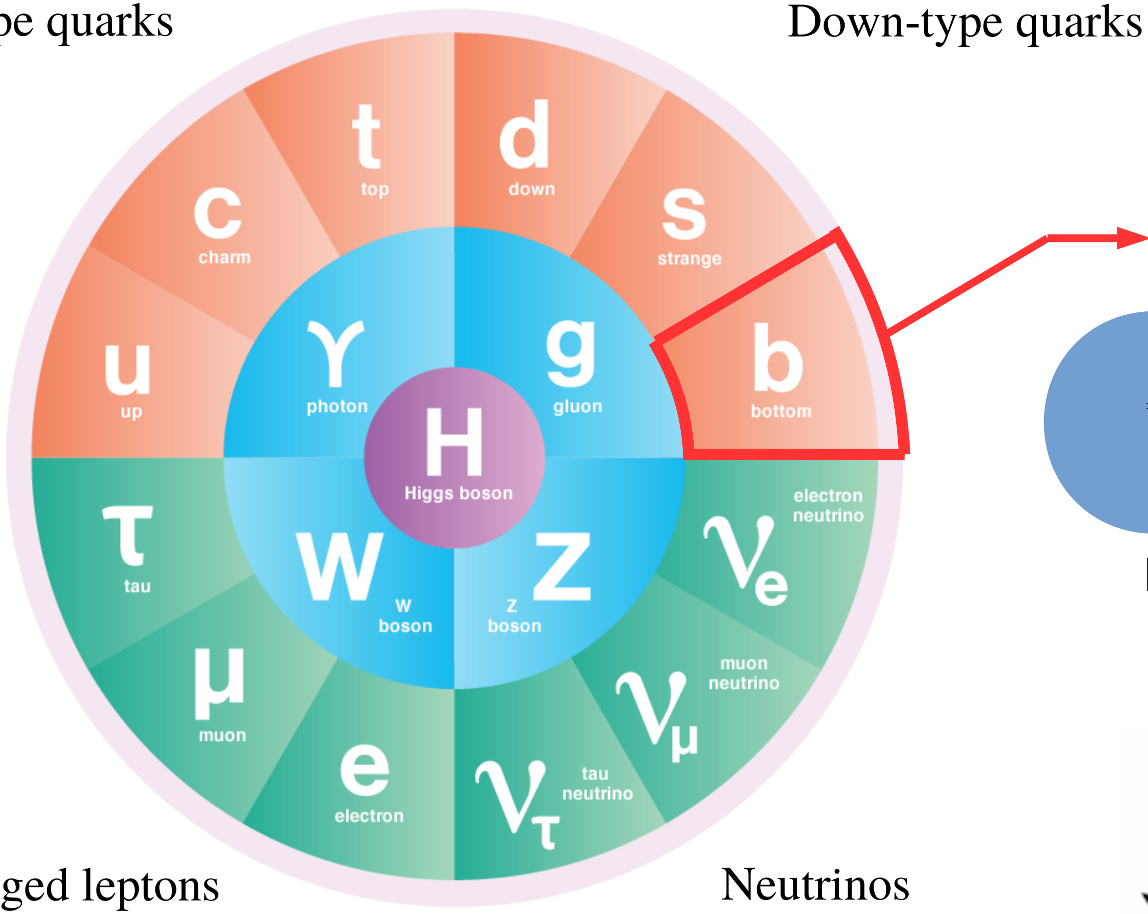


Introduction

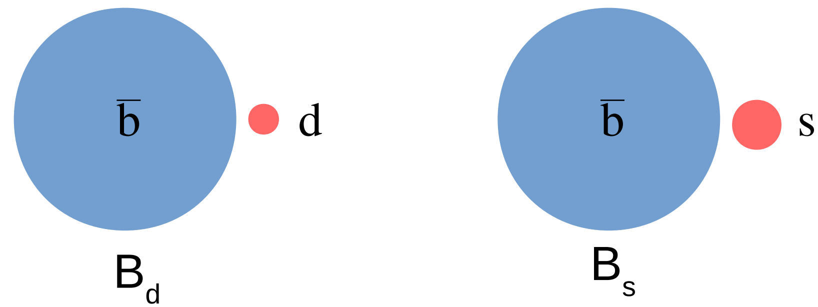
Standard Model and beauty physics

Up-type quarks

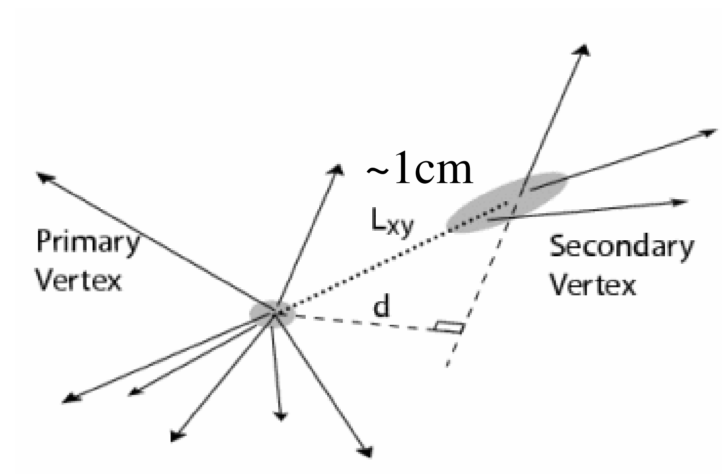
Down-type quarks



Quark “beauty”
m = 4 GeV/c^2



$\tau(B_d, B_s) \sim 10^{-10}$s



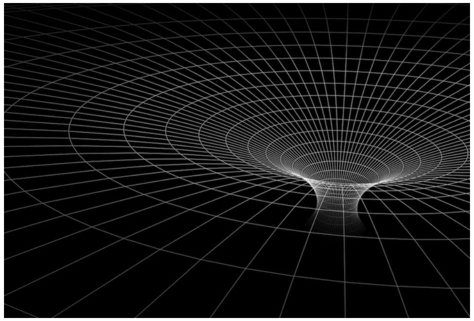
Charged leptons

Neutrinos

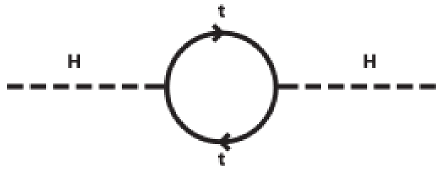
+ antiparticles

Limits of the Standard Model

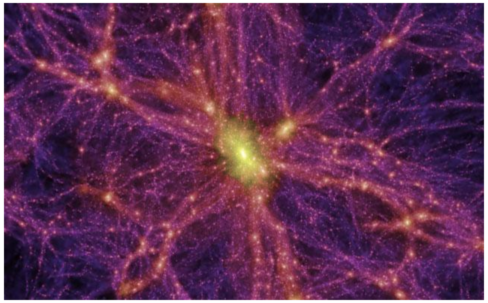
Gravity

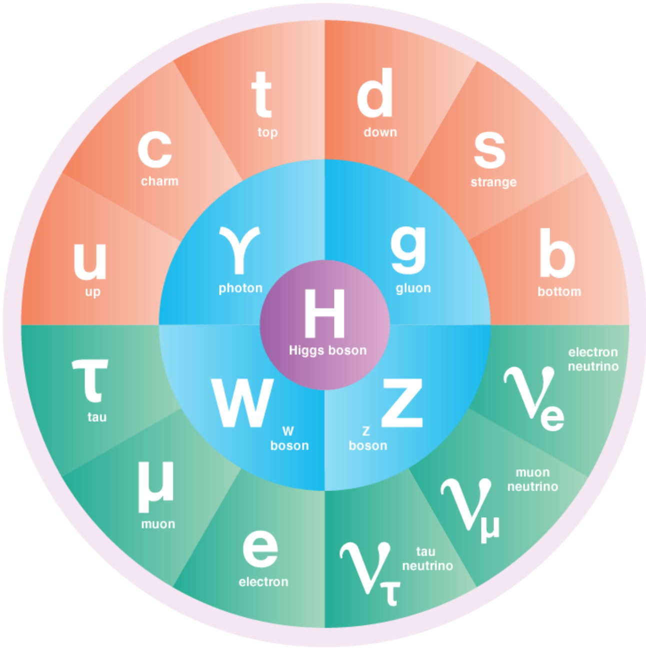


Higgs naturalness

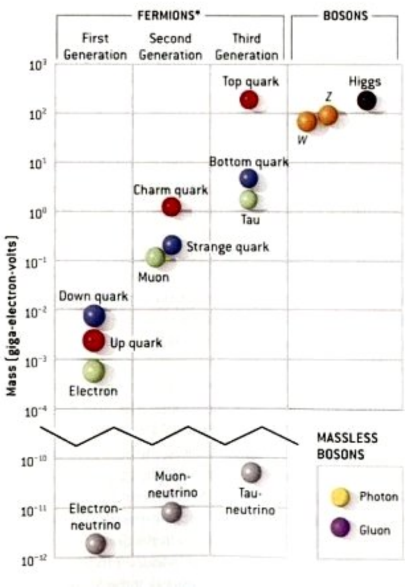


Dark matter candidate





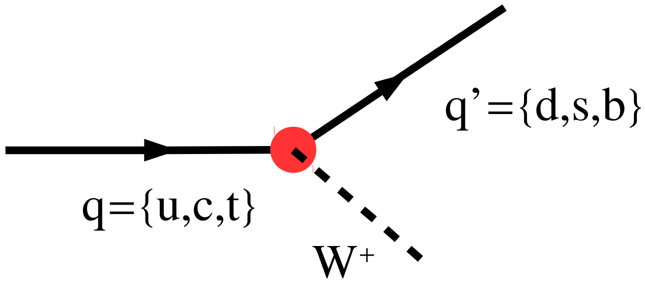
Mass hierarchy



Baryon-antibaryon asymmetry of the Universe.
Sakharov conditions → interaction that violates **C** and **CP** symmetries

The CKM matrix and KM mechanism

- Weak interaction quark eigenstates $q_{u,d} \neq$ flavour eigenstates $Q_{u,d}$



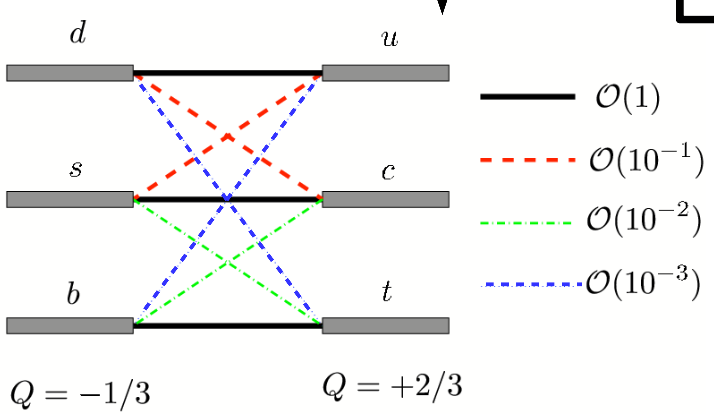
$$q = V_{Uq} Q_u$$

$$q' = V_{Dq'} Q_d$$

Coupling prop. to $V_{Uq}^{T} V_{Dq'} = V^{CKM}_{qq'}$

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

Hierarchical:
Transitions between ≠ families suppressed.
Can be expanded in terms of $\lambda \approx 0.2$.
($\lambda = \sin \theta_c$)

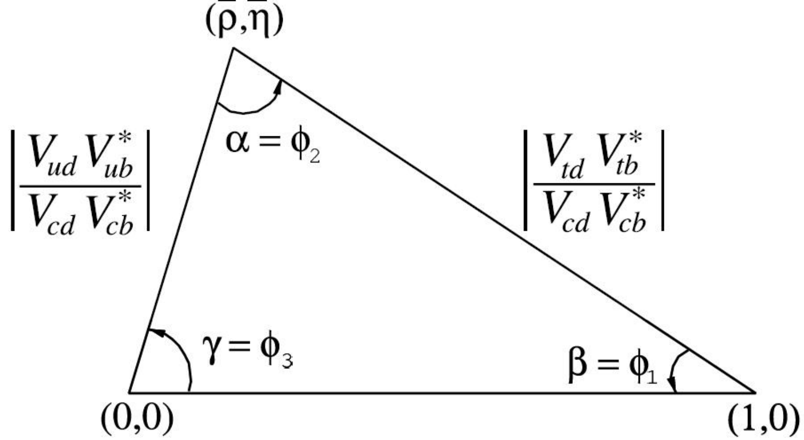


3x3 **unitary** matrix
→ 1 physical (irreducible) phase

Interferences can give rise to CP violation (CPV) by the weak interaction in the quark sector

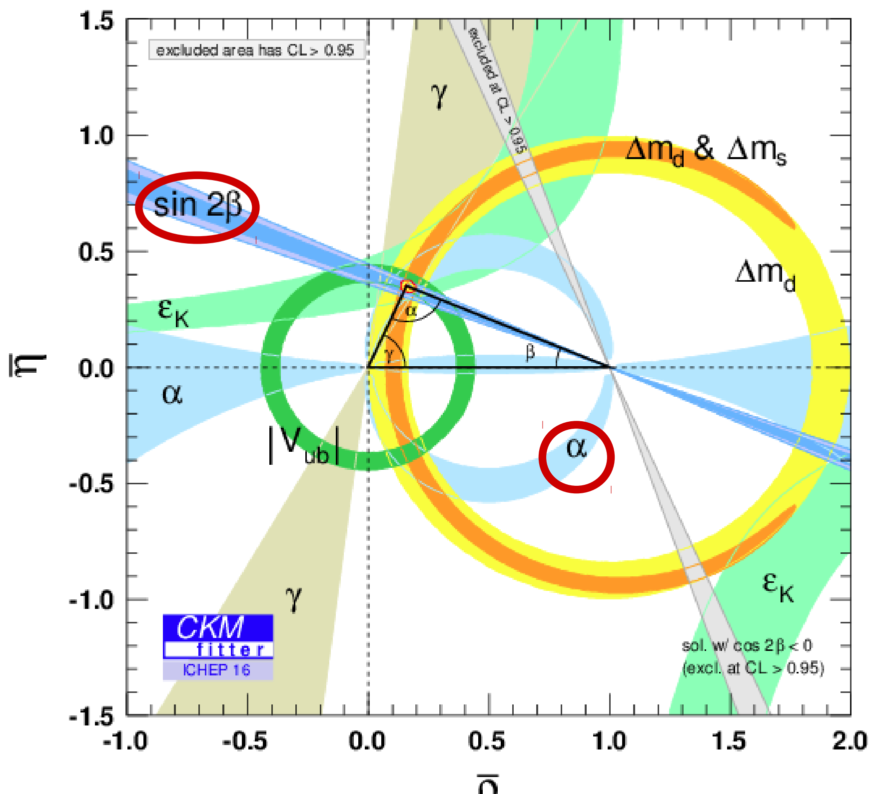
The unitarity triangle

$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0,$$
$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0,$$
$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0,$$
$$V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0,$$
$$V_{td}^* V_{ud} + V_{ts}^* V_{us} + V_{tb}^* V_{ub} = 0,$$
$$V_{td}^* V_{cd} + V_{ts}^* V_{cs} + V_{tb}^* V_{cb} = 0.$$

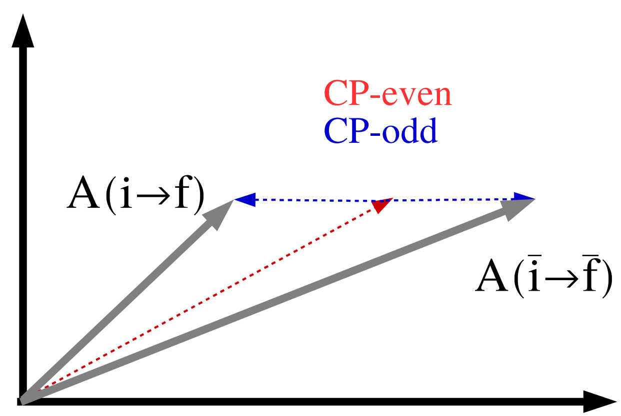


$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$ → $b \to u\bar{u}d$

$$\beta = \arg\left(-\frac{V_{cb}^*V_{cd}}{V_{tb}^*V_{td}}\right)$$ → $b \to c\bar{c}d$ or $b \to q\bar{q}s$

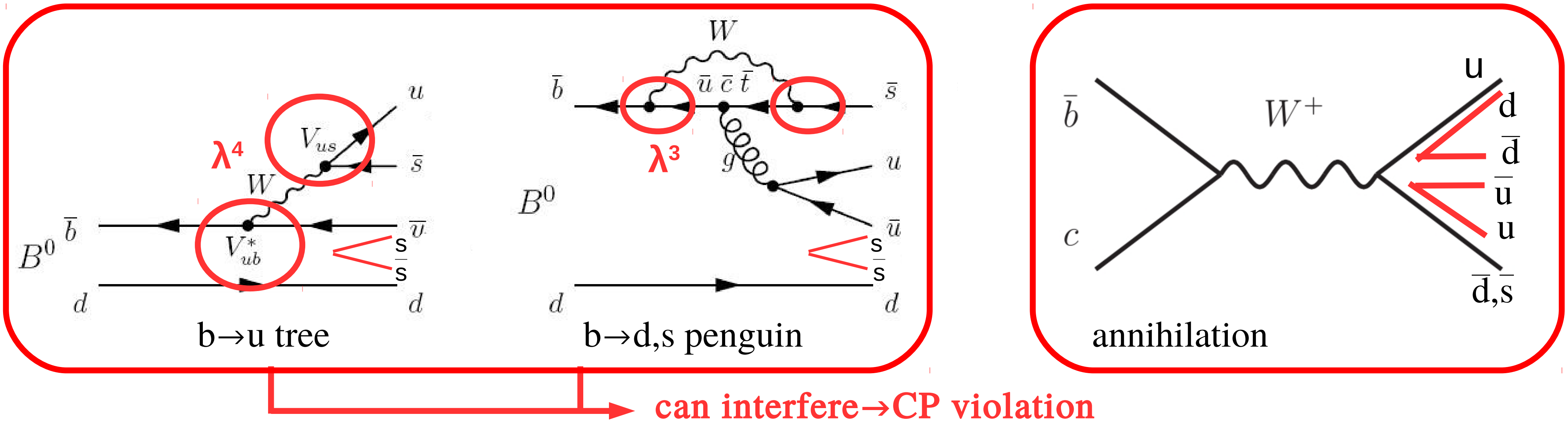


CKMfitter, as of ICHEP 2016



Physics case of charmless hadronic *b*-decays

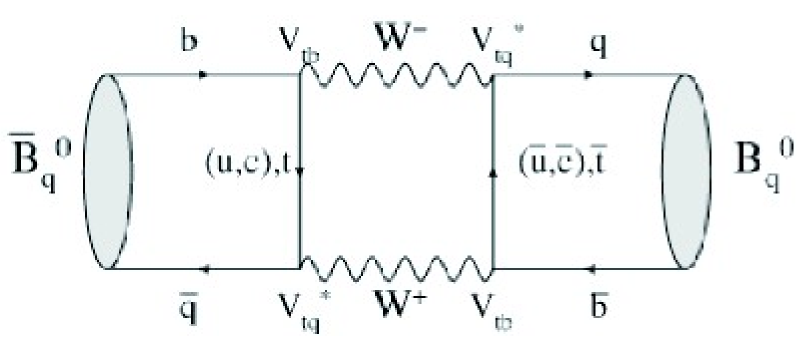
- Charmless *b*-hadron decays proceed through various processes.

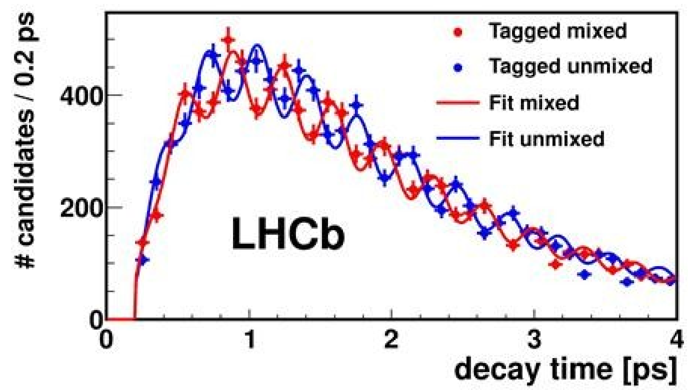


- BSM particles can contribute inside of loops or instead of W^+.
- (n>2)-body decays allow access to phases between quasi two-body decays (Q2B) using amplitude analyses.
- No trigonometric ambiguity!

Charmless decays at LHCb

- Many channels not yet observed
  - Suppressed decays (BR < 10^{-4})
  - Includes decays of B_s, Λ_b, *b*-baryons etc.→not (easily) accessible by *B* factories.
- Hadronic final states (except for $\pi^0 \rightarrow \gamma\gamma$).
- For most channels, CPV accessible only through time-dependent, flavour-tagged analyses.





- For most decays, program in two steps:

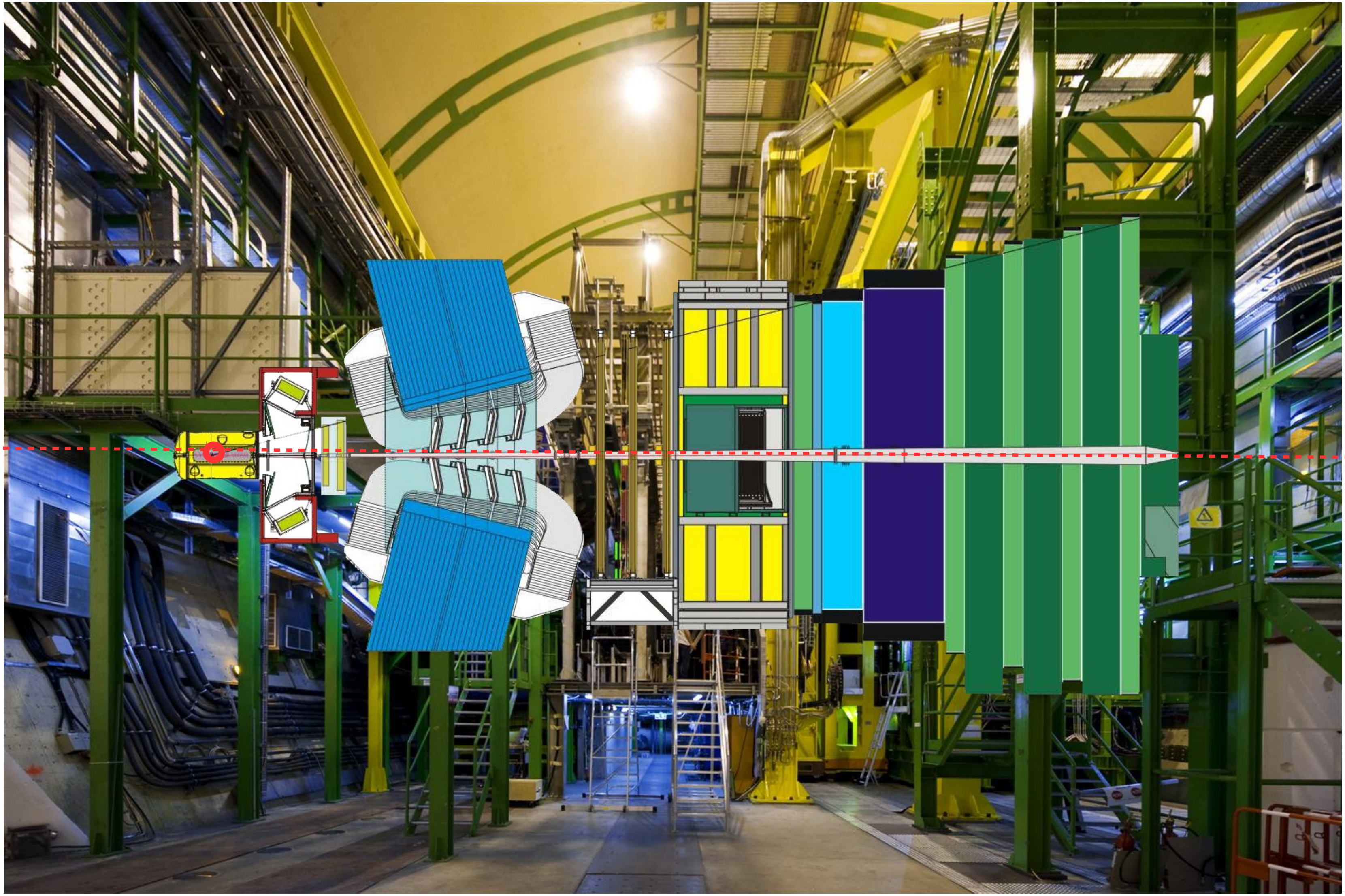
  1. Observe modes for the first time and extract branching fractions.
  2. Perform angular, Dalitz-plot analyses to access physics observables , e.g. **phases, CPV observables**.

The LHCb detector at LHC

The LHCb detector

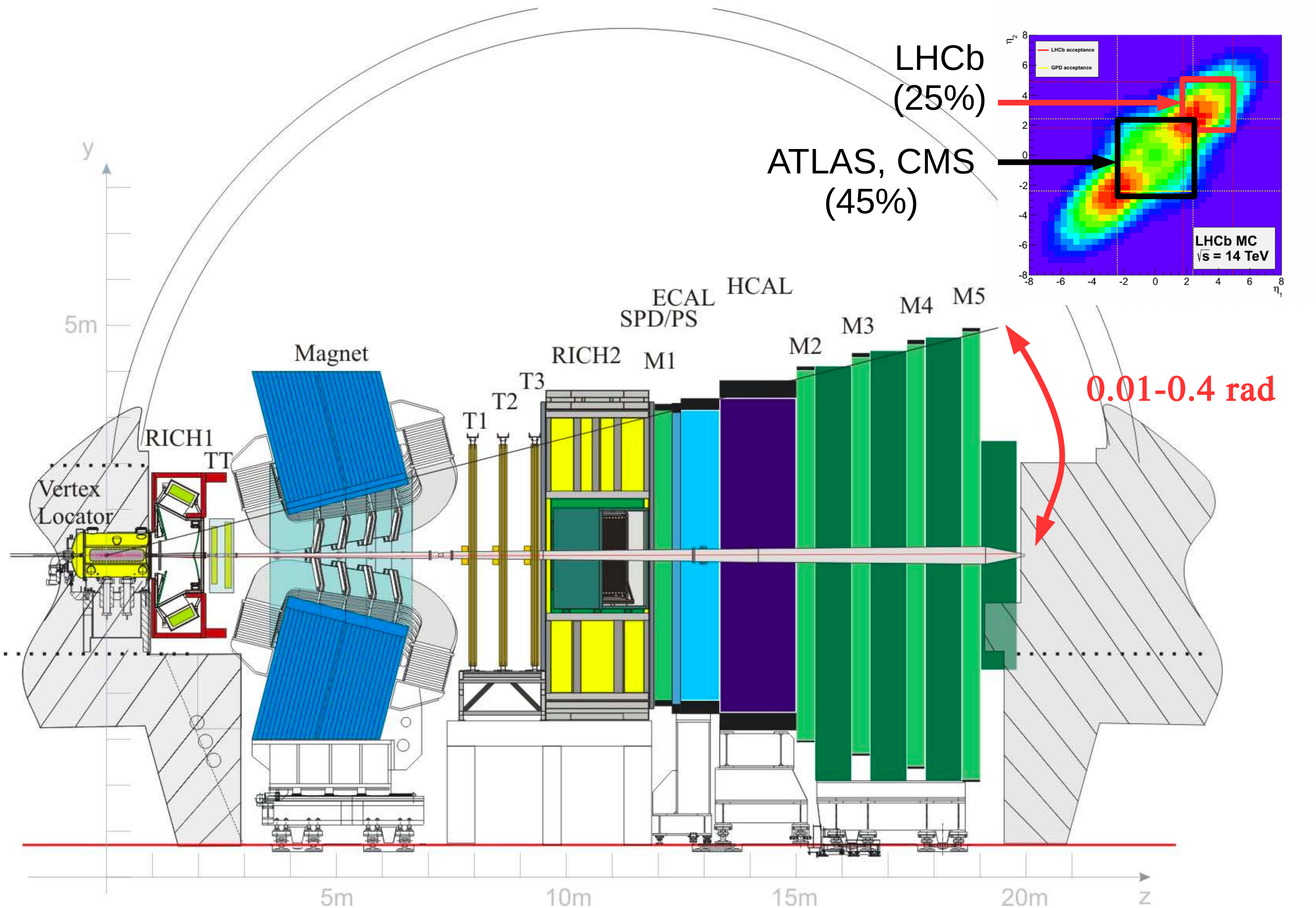
The LHCb detector

Beam pipe



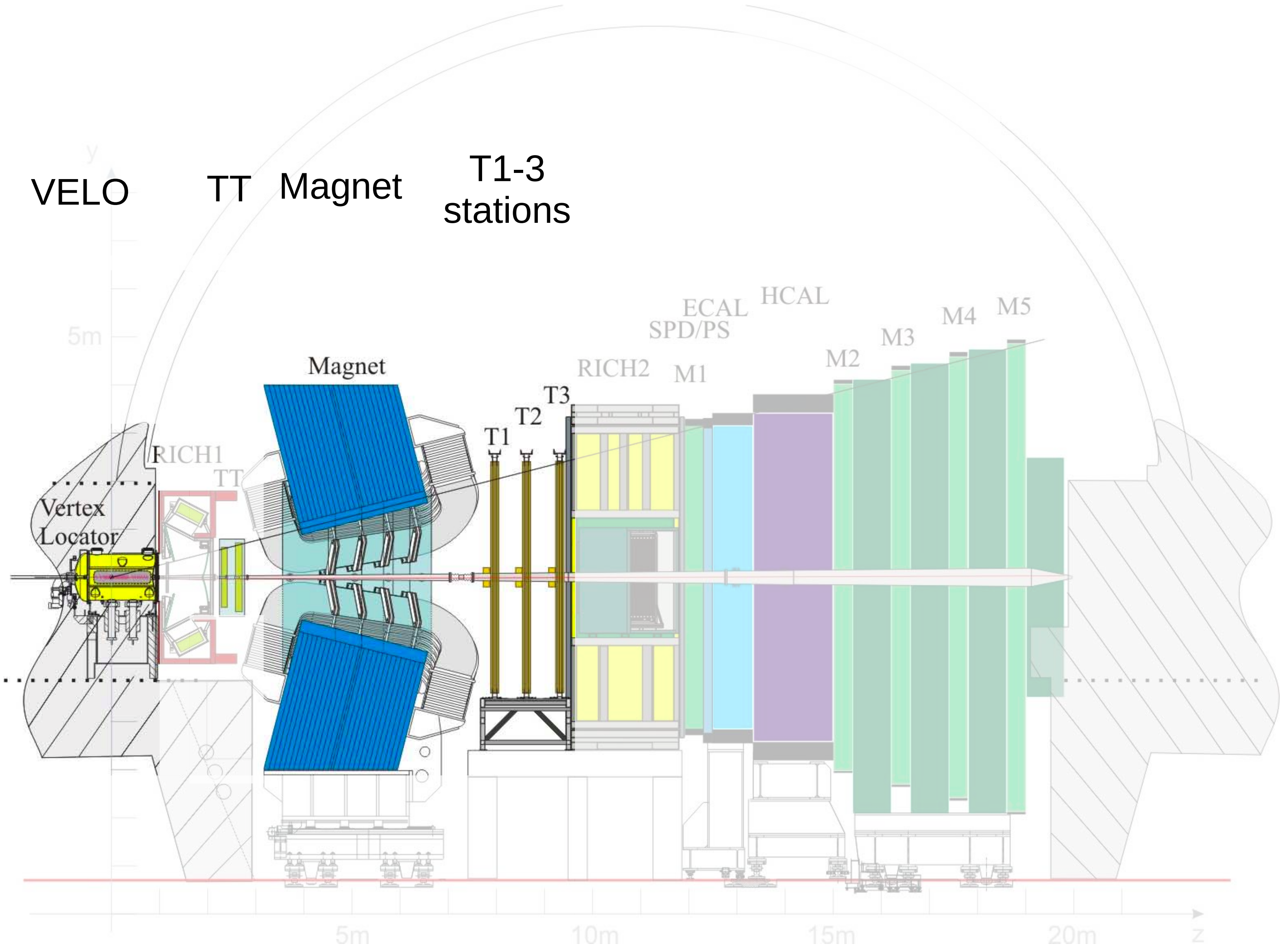
Single-arm forward spectrometer [JINST 3(2008) S08005.]

The LHCb detector: sketch



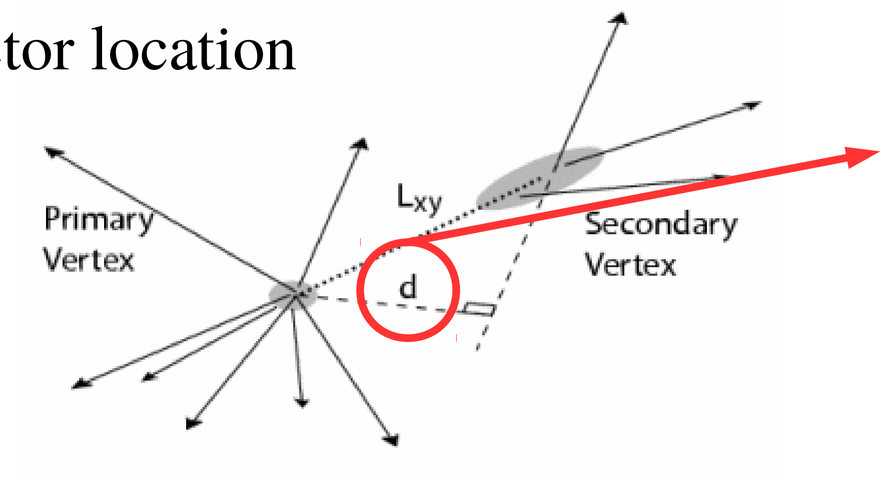
[JINST 3(2008) S08005.]

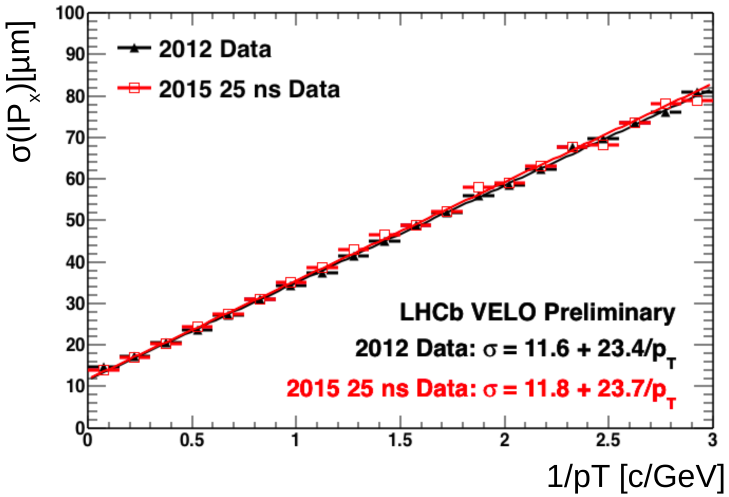
The LHCb detector: tracking subsystems



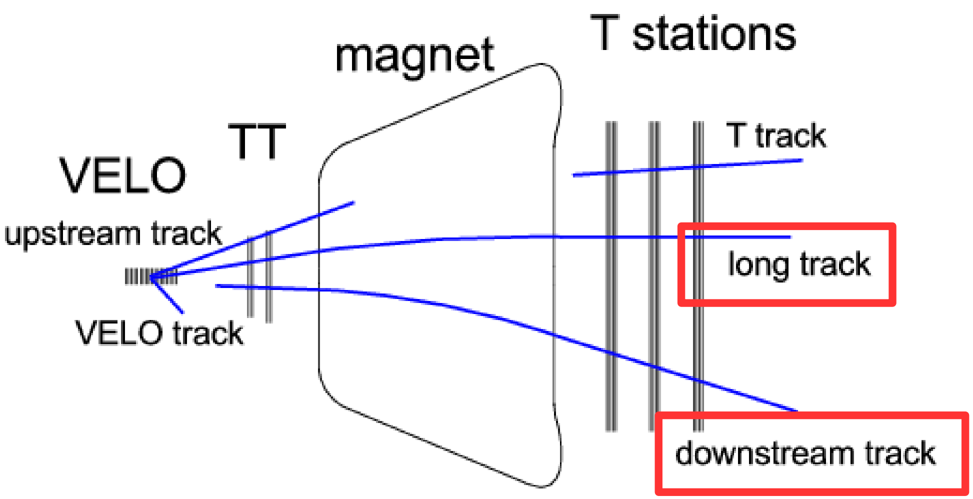
The LHCb detector: tracking subsystems

Vector location





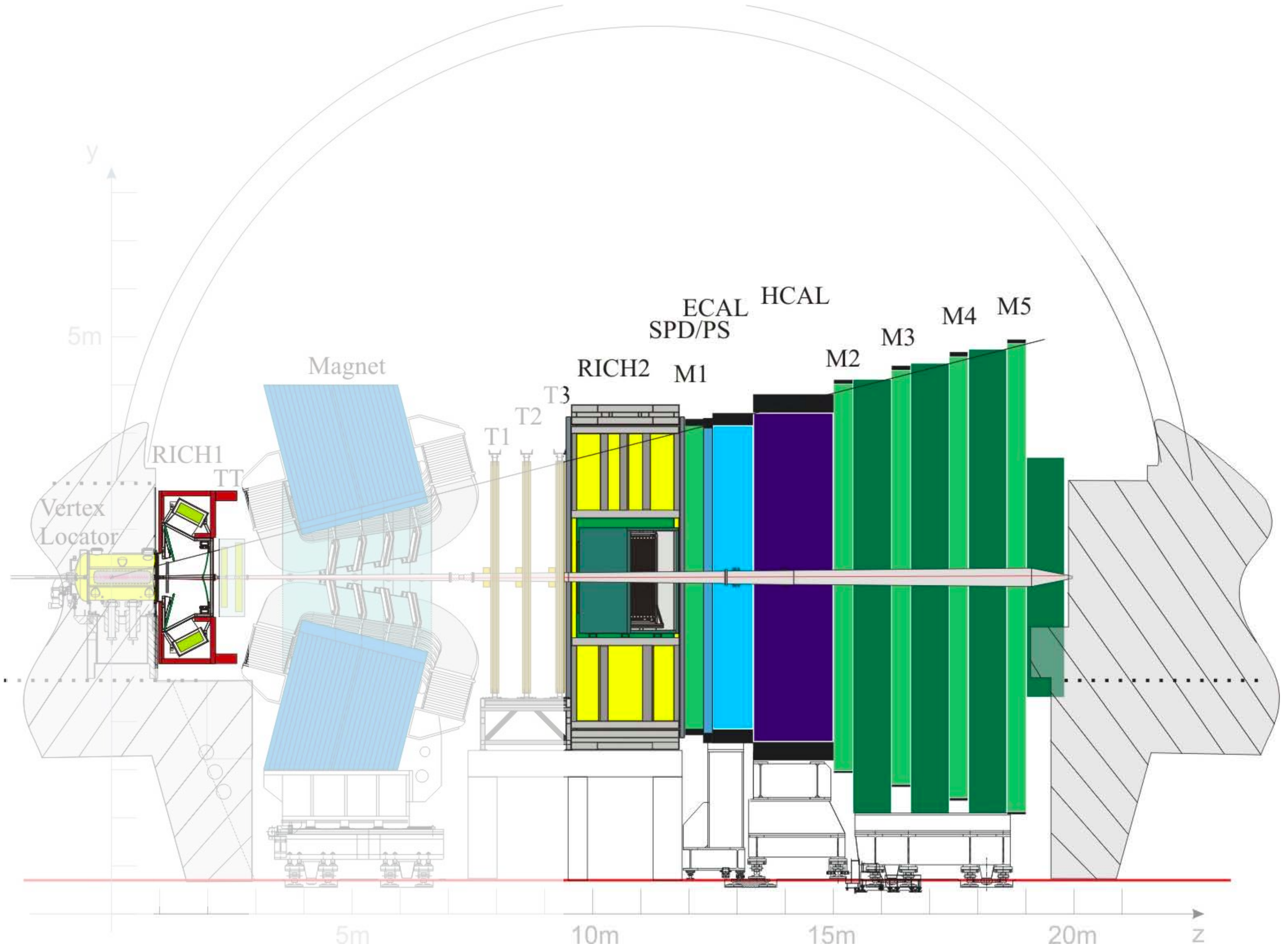
Momentum measurement



LHCb performance paper
arXiv:1412.6352

$\delta p/p \sim 0.5\%$ for Long tracks

The LHCb detector: particle identification



The LHCb detector: particle identification

LHCb performance paper
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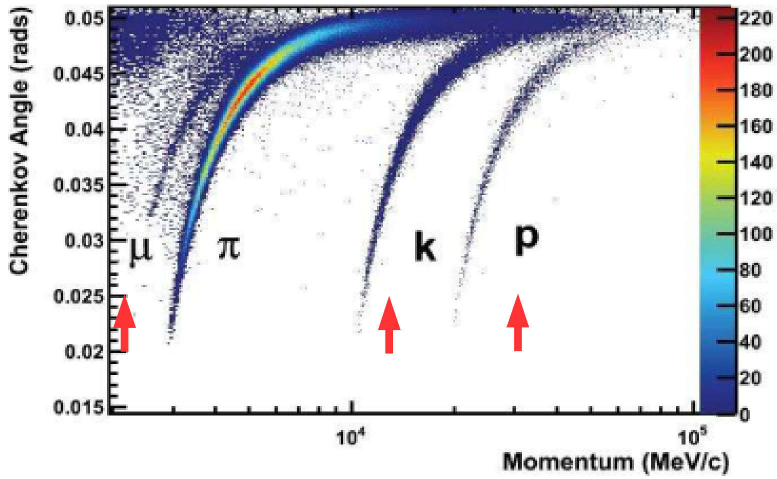
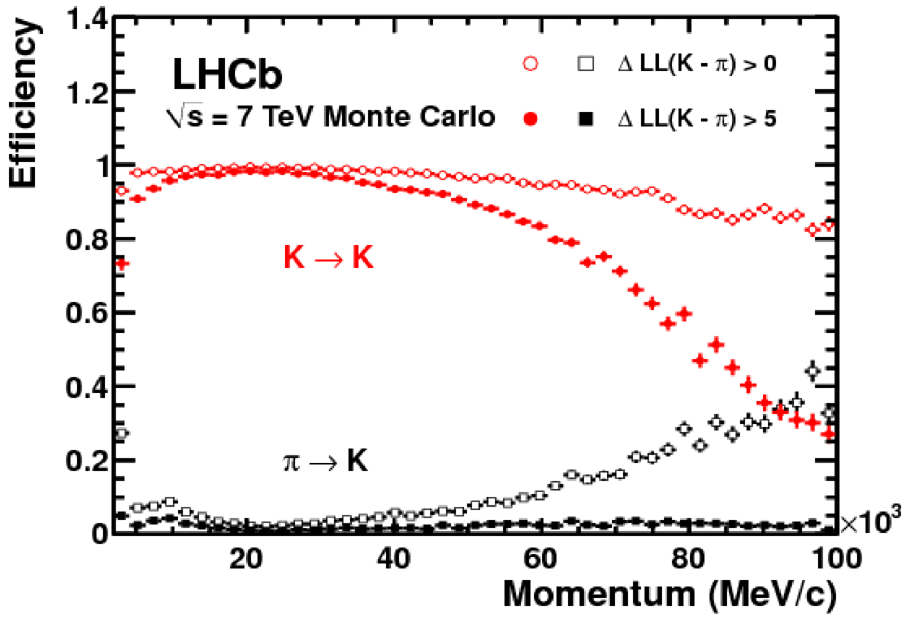


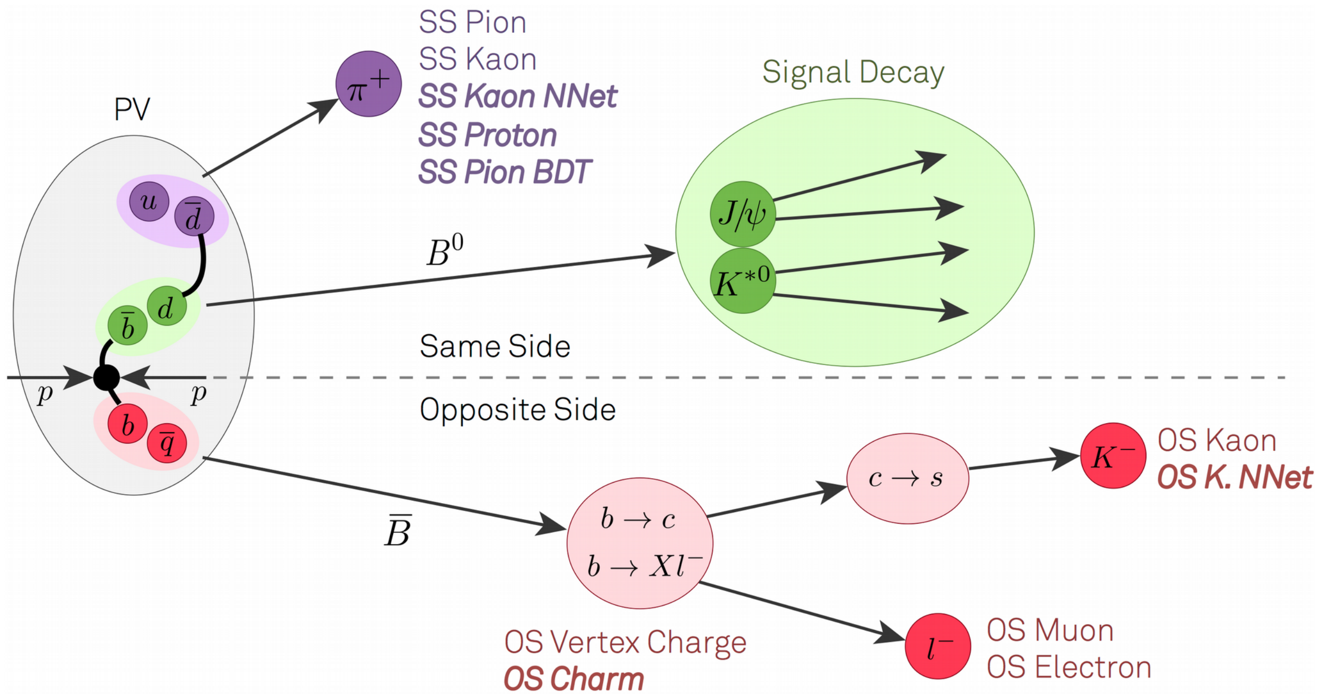
- Fully hadronic final states (except for $\pi^0 \to \gamma\gamma$).

- LHCb particle identification relies on:
  - Cherenkov detectors (RICH);
  - shower development;
  - calorimetry.



The LHCb detector: flavour tagging

- LHC is a hadronic machine → no precise knowledge of the initial state (energy, flavour).
- Tagging: determination of the flavour at production of the meson.



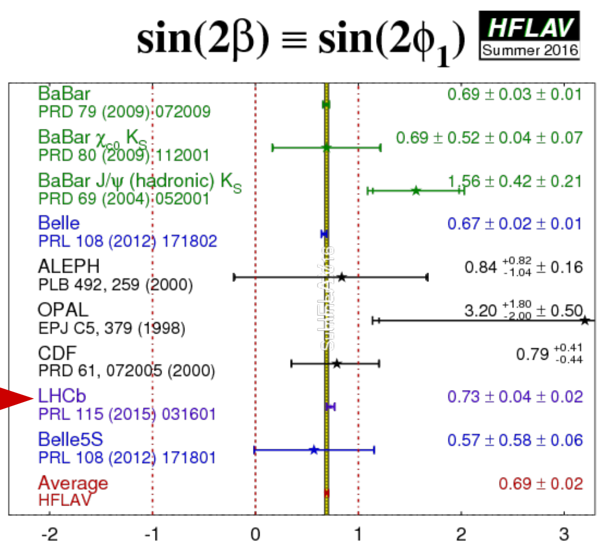
Combined tagging power: 3-8%

Physics analyses

Charmless decays: legacy from B factories

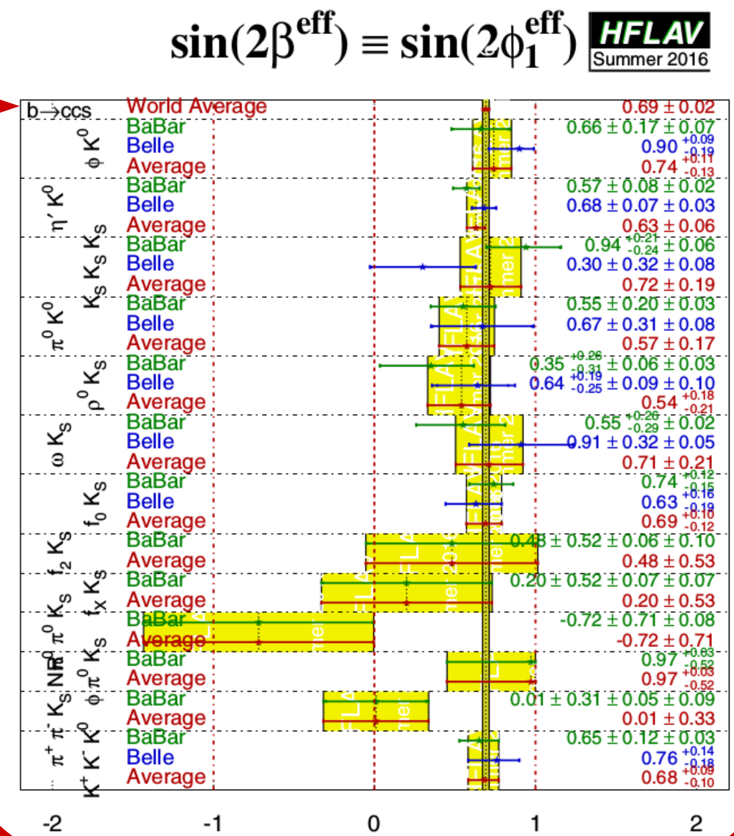
- B-factories have narrowed down the apex of the UT quite impressively.
- Several key modes: $B^0 \to \eta' K^0$, $B^0 \to \phi K^0$...
- In these mode, flavour-tagged, time-dependent analyses performed → large number of CPV observables measured and used to constrain the SM.

$b \to c\bar{c}d$



Eur. Phys. J. C77 (2017) 895

$b \to q\bar{q}s$



Charmless b-decays: LHCb contribution

- Charmless analyses only on Run 1 ($3fb^{-1}$) for the moment.

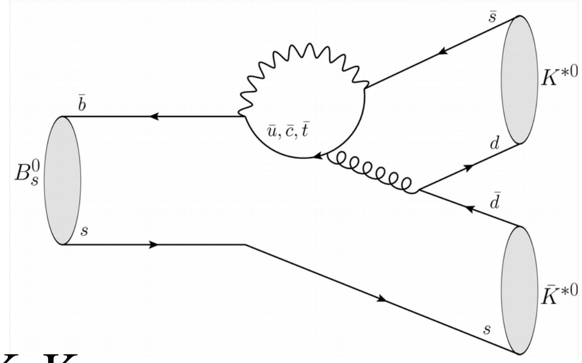
- Already some outstanding results, for instance:
  - First evidence for CPV in $\Lambda_b \to p\pi^+\pi^-\pi^+$.
    - Nature Physics 13, 391-396 (2017)
  - First observation of baryonic B_s decay: $B_s \to p\overline{\Lambda}\pi$.
    - Phys. Rev. Lett. 119, 041802 (2017)
  - First measurement of ϕ_s in $B_s \to \phi\phi$.
    - Phys. Rev. D 90, 052011 (2014)

- … and the results we are going to discuss just next.

- Common pattern: most results are direct CPV and/or new observations.

Measurement of $\phi_s^{d\bar{d}}$ in $B_s \to (K^+\pi^-)(K^-\pi^+)$

- Decay first observed in 2011 by LHCb [PLB 709 (2012) 50], updated in 2012 [JHEP 07 (2015) 166]
- Decay dominated by a gluonic penguin diagram
  - Complementary to measurements in EW penguins.
- Powerful check of the SM.
  - $\Phi_s^{c\bar{c}}$ = -0.021 ± 0.031 rad, measured in for instance $B_s \to J/\Psi K^+K^-$



$$\Gamma \propto \sum e^{-\Gamma_s t}\left[a_{ij}\cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_{ij}\sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_{ij}\cos\left(\Delta m_s t\right) + d_{ij}\sin\left(\Delta m_s t\right)\right]$$

Time-dependent amplitude analysis

First time for tensor components !

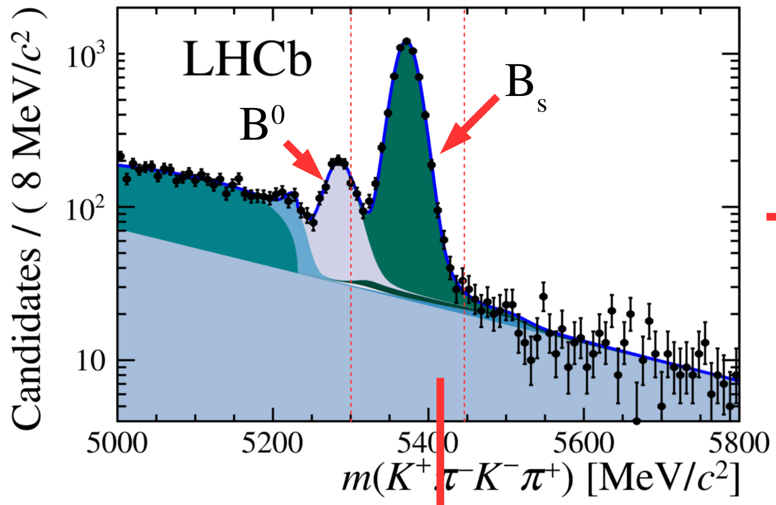
Decay	Mode	j_1	j_2	Allowed values of h	Number of amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	scalar-scalar	0	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\bar{K}^*(892)^0$	scalar-vector	0	1	0	1
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	vector-scalar	1	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\bar{K}_2^*(1430)^0$	scalar-tensor	0	2	0	1
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	tensor-scalar	2	0	0	1
$B_s^0 \to K^*(892)^0\bar{K}^*(892)^0$	vector-vector	1	1	$0, \parallel, \perp$	3
$B_s^0 \to K^*(892)^0\bar{K}_2^*(1430)^0$	vector-tensor	1	2	$0, \parallel, \perp$	3
$B_s^0 \to K_2^*(1430)^0\bar{K}^*(892)^0$	tensor-vector	2	1	$0, \parallel, \perp$	3
$B_s^0 \to K_2^*(1430)^0\bar{K}_2^*(1430)^0$	tensor-tensor	2	2	$0, \parallel_1, \perp_1, \parallel_2, \perp_2$	5

→ **19 amplitudes**

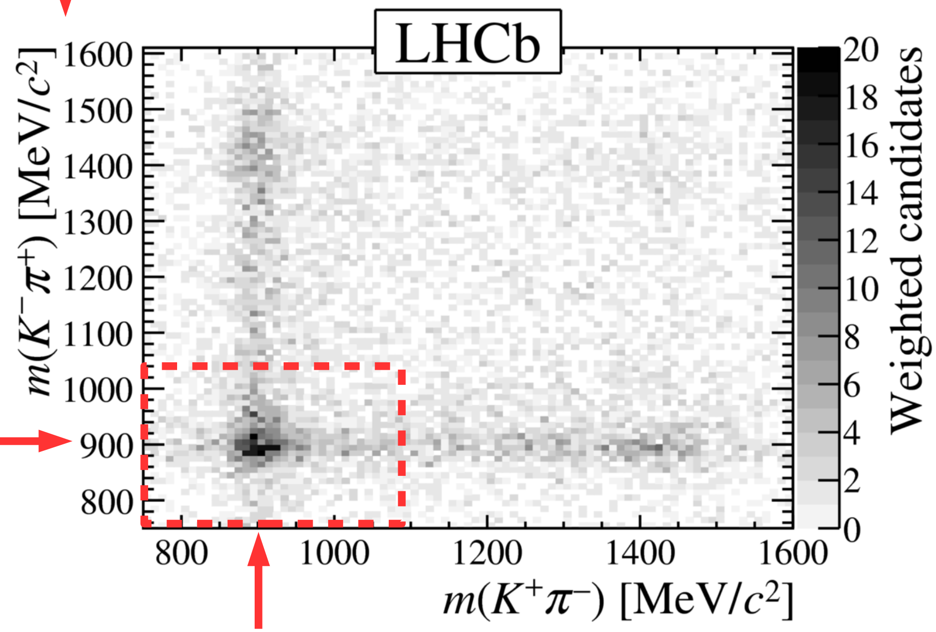
arXiv:1712.08683

Measurement of $\phi_s^{d\bar{d}}$ in $B_s \to (K^+\pi^-)(K^-\pi^+)$

- First things first: yield extraction



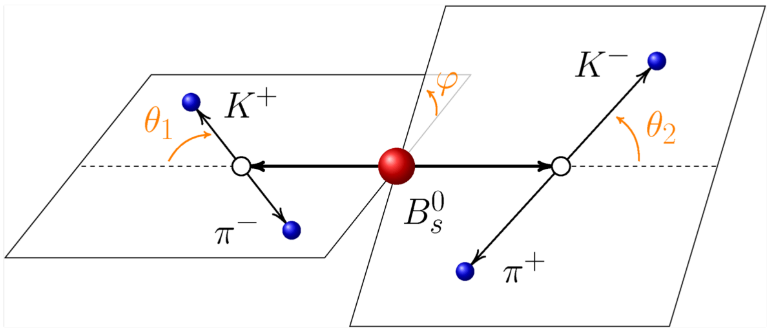
Channel	Yield	Yield in Signal Region
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$	6080 ± 83	6004
$B^0 \to (K^+\pi^-)(K^-\pi^+)$	1013 ± 49	103
$B^0 \to (K^+\pi^-)(K^-K^+)$	281 ± 47	1
$B_s^0 \to (K^+\pi^-)(K^-K^+)$	8 ± 3	4
$B^0 \to (K^+\pi^-)(\pi^-\pi^+)$	57 ± 13	33
$\Lambda_b^0 \to (p\pi^-)(K^-\pi^+)$	44 ± 10	13
Partially reconstructed	2580 ± 151	0
Combinatorial	2810 ± 214	372



arXiv:1712.08683

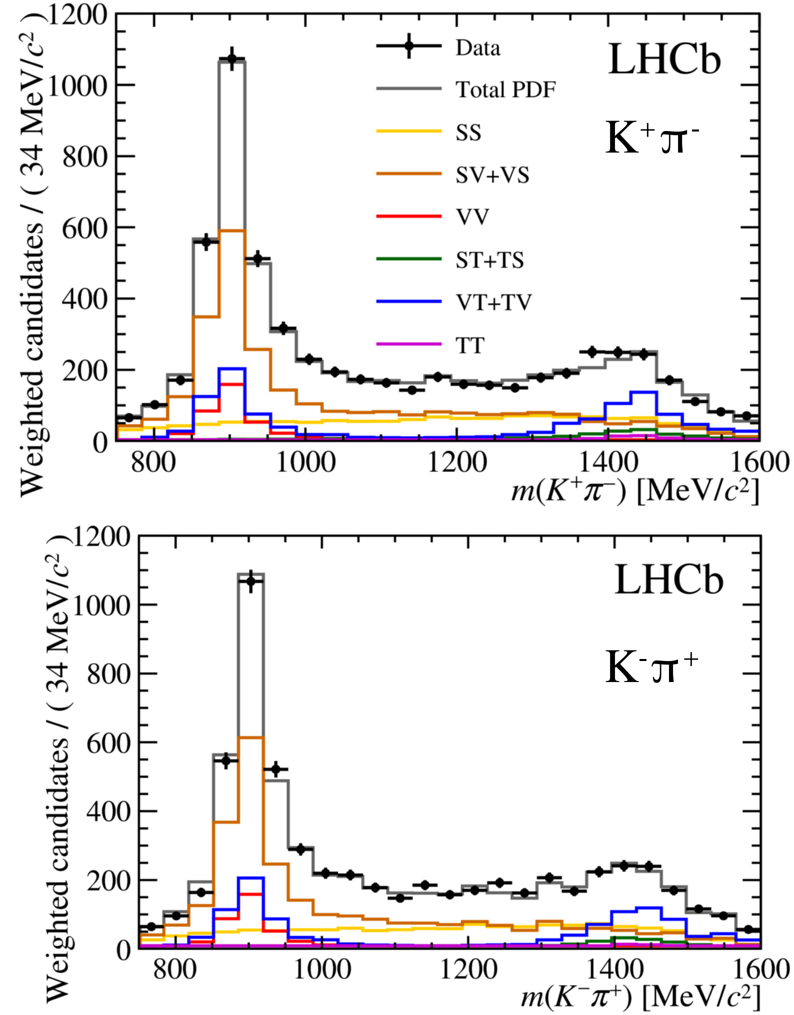
Measurement of $\phi_s^{d\bar{d}}$ in $B_s \to (K^+\pi^-)(K^-\pi^+)$

- Amplitudes depend on masses and angles.



- Tagging power ~ 5%.

Tagging algorithm	ϵ_{tag} [%]	ϵ_{eff} [%]
SS	62.0 ± 0.7	1.63 ± 0.21
OS	37.1 ± 0.7	3.70 ± 0.21
Combination	75.6 ± 0.6	5.15 ± 0.14



$\Phi_s^{d\bar{d}} = -0.10 \pm 0.13$ (stat.) ± 0.14 (syst.)
Consistent with SM prediction and $B_s \to \phi\phi$

arXiv:1712.08683

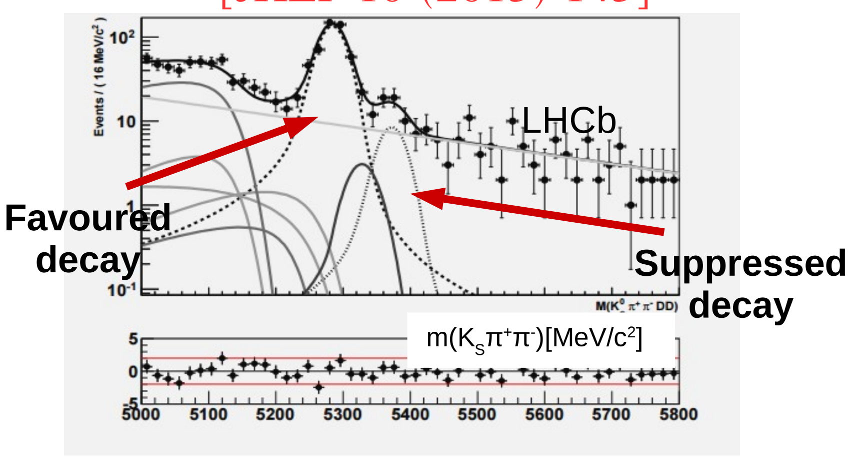
Update of $B_{d,s} \to K_S h^+ h'^-$ branching fractions

- $B_{d,s} \to K_s h^+ h^{-\prime}$, with h, h' = π,K → 8 decays. K_S reconstructed as $\pi^+\pi^-$.

$B_d \to K_S \pi^+\pi^-$	$B_d \to K_S K^+\pi^-$	$B_d \to K_S K^-\pi^+$	$B_d \to K_S K^+ K^-$
$B_s \to K_S \pi^+\pi^-$	$B_s \to K_S K^+\pi^-$	$B_s \to K_S K^-\pi^+$	$B_s \to K_S K^+ K^-$

Green: observed; **Red**: not observed; ▭: favoured decay (see below).

Previous LHCb analysis ($1 fb^{-1}$)
[JHEP 10 (2013) 143]



- Observed $B_s \to K_S \pi^+\pi^-$.
- Confirmed $B_d \to K_S K^\pm \pi^\pm$.
- Observed $B_s \to K_S K^\pm \pi^\pm$.

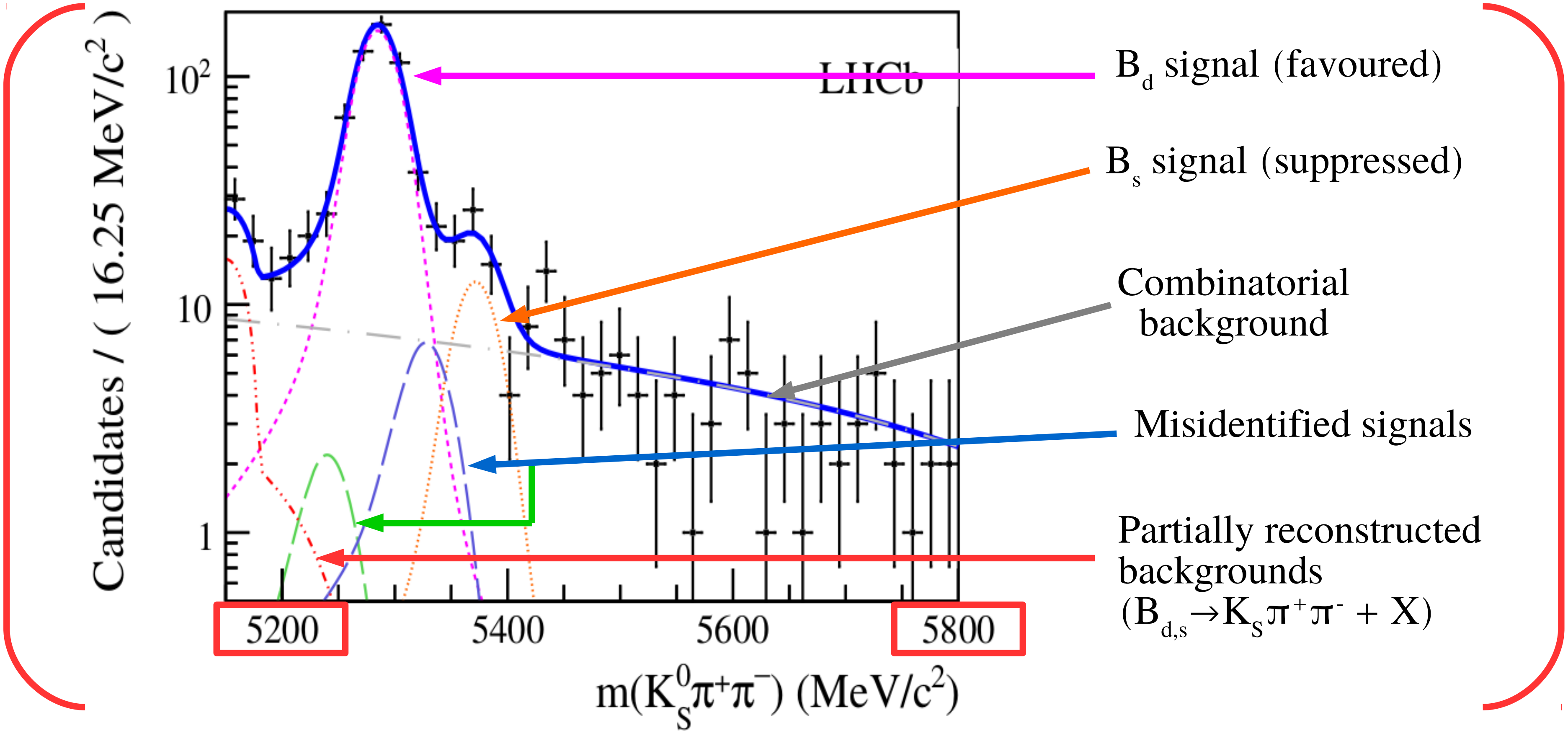
- Goals of the LHCb analysis using $3fb^{-1}$:
  - update measurement of branching fractions;
  - search for $B_s \to K_S K^+ K^-$;
  - prepare Dalitz-plot analyses of all modes.
- Dataset divided into:
  - 4 final states;
  - 2 K_S reconstruction categories;
  - 3 data-taking periods.

  → 24 invariant-mass distributions

J. High Energ. Phys. (2017) 2017: 27

Update of $B_{d,s} \to K_S h^+ h'^-$ branching fractions: Modeling the invariant-mass distributions

24 x



- Shapes taken from Monte-Carlo, except for combinatorial background.
- B_d and B_s masses and widths fit in data.
- Fast Monte-Carlo developed for partially reconstructed backgrounds modeling.
- Gaussian constraints on misidentified signals and partially recontructed backgrounds yields.

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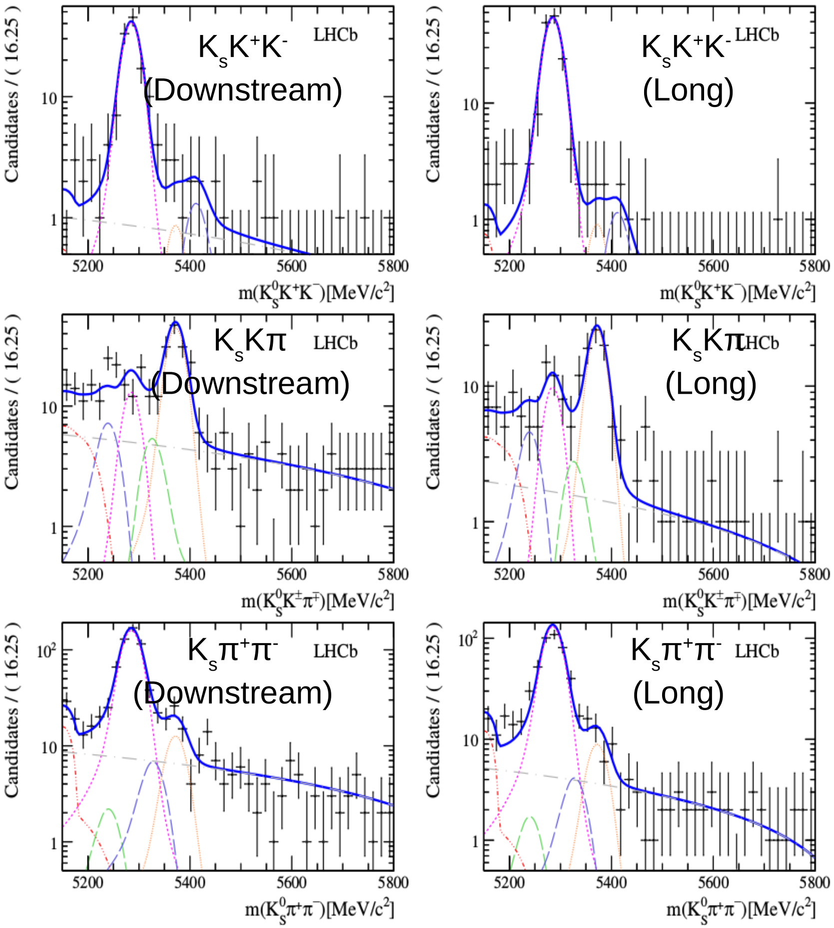
Update of $B_{d,s}\to K_S h^+ h'^-$ branching fractions: Results

[LHCB-PAPER-2017-010]



$$\mathcal{B}(B^0_{d,s}\to K^0_S h^+ h'^-) = \frac{N^{corr}_{B^0_{d,s}\to K^0_S h^+ h'^-}}{\mathcal{L}.\sigma_{pp\to b\bar{b}}.f_{d,s}}$$

$$\frac{\mathcal{B}(B^0_{d,s}\to K^0_S h^+ h'^-)}{\mathcal{B}(B^0\to K^0_S\pi^+\pi^-)} = \frac{f_{d,s}}{f_d}\frac{N^{corr}_{B^0_{d,s}\to K^0_S h^+ h'^-}}{N^{corr}_{B^0\to K^0_S\pi^+\pi^-}}.$$

$$\frac{\mathcal{B}(B^0\to K^0_S K^\pm\pi^\mp)}{\mathcal{B}(B^0\to K^0_S\pi^+\pi^-)} = 0.123\pm0.009\,(\text{stat.})\;\pm0.015\,(\text{syst.})\,,$$

$$\frac{\mathcal{B}(B^0\to K^0_S K^+K^-)}{\mathcal{B}(B^0\to K^0_S\pi^+\pi^-)} = 0.549\pm0.018\,(\text{stat.})\;\pm0.033\,(\text{syst.})\,,$$

$$\frac{\mathcal{B}(B^0_s\to K^0_S\pi^+\pi^-)}{\mathcal{B}(B^0\to K^0_S\pi^+\pi^-)} = 0.191\pm0.027\,(\text{stat.})\;\pm0.031\,(\text{syst.})\;\pm0.011\,(f_s/f_d)\,,$$

$$\frac{\mathcal{B}(B^0_s\to K^0_S K^\pm\pi^\mp)}{\mathcal{B}(B^0\to K^0_S\pi^+\pi^-)} = 1.70\;\pm0.07\;(\text{stat.})\;\pm0.11\;(\text{syst.})\;\pm0.10\;(f_s/f_d)\,,$$

$$\frac{\mathcal{B}(B^0_s\to K^0_S K^+K^-)}{\mathcal{B}(B^0\to K^0_S\pi^+\pi^-)} = 0.026\pm0.011\,(\text{stat.})\;\pm0.007\,(\text{syst.})\;\pm0.002\,(f_s/f_d)\,,$$

Compatible with previous measurements
Dalitz-plot analyses underway.

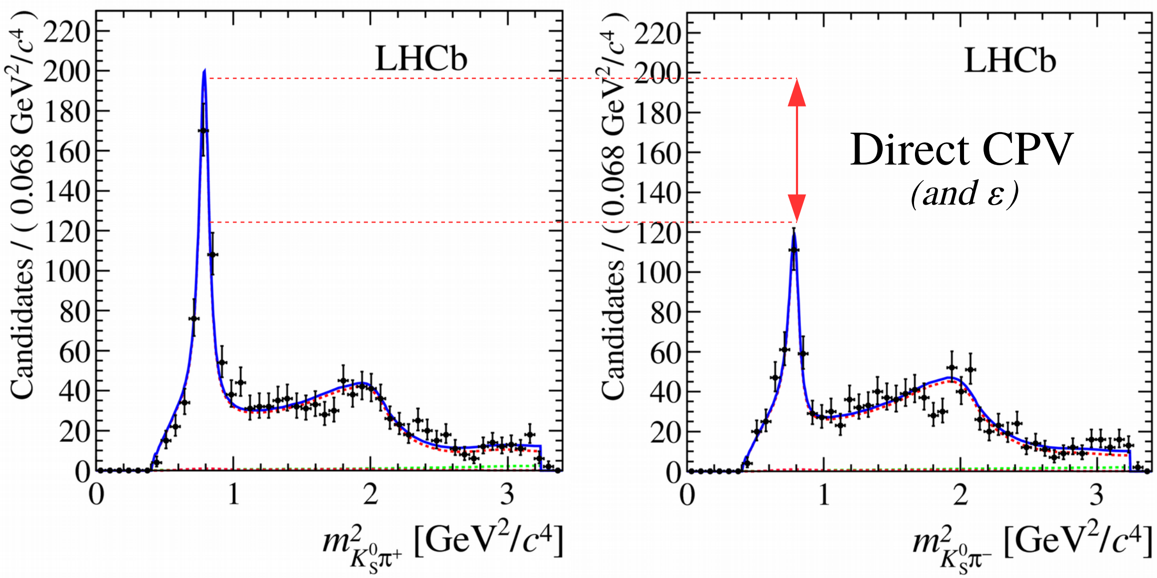
$B_s\to K_S K^+ K^-$: 2.5σ significance.

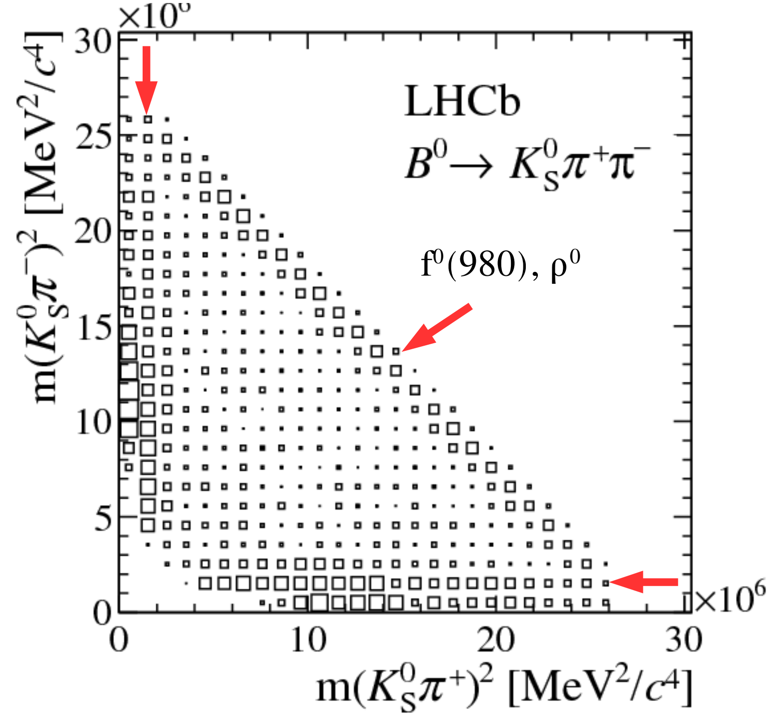
$$\frac{\mathcal{B}(B^0_s\to K^0_S K^+K^-)}{\mathcal{B}(B^0\to K^0_S\pi^+\pi^-)} \in [0.008 - 0.051] \text{ at } 90\% \text{ C.L.}$$

J. High Energ. Phys. (2017) 2017: 27

Amplitude analysis of $B^0 \to K_S \pi^+ \pi^-$: results

- Only a time-dependent, flavour-tagged analysis would provide complete information.
- Direct CPV on flavour-specific resonance available.





Stat. Syst. Model.

$$\begin{aligned}
\mathcal{A}_{CP}(K^*(892)^-\pi^+) &= -0.308 \pm 0.060 \pm 0.011 \pm 0.012\,,\\
\mathcal{A}_{CP}((K\pi)^-_0\pi^+) &= -0.032 \pm 0.047 \pm 0.016 \pm 0.027\,,\\
\mathcal{A}_{CP}(K^*_2(1430)^-\pi^+) &= -0.29 \pm 0.22 \pm 0.09 \pm 0.03\,,\\
\mathcal{A}_{CP}(K^*(1680)^-\pi^+) &= -0.07 \pm 0.13 \pm 0.02 \pm 0.03\,,\\
\mathcal{A}_{CP}(f_0(980)K^0_S) &= 0.28 \pm 0.27 \pm 0.05 \pm 0.14\,,
\end{aligned}$$

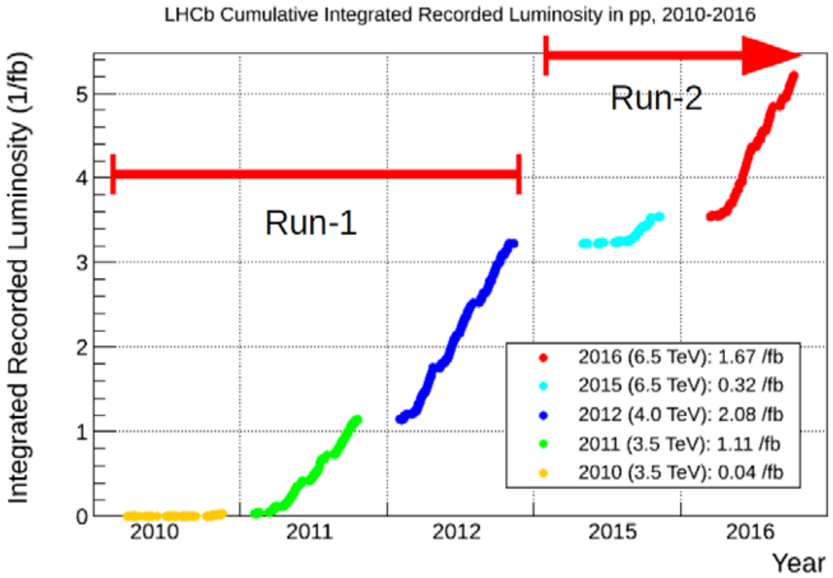
arXiv:1712.09320

First observation of direct CPV in $B^0 \to K^*(892)\pi$ decays

Prospects from Run II and further

Prospects: near and far future of LHCb

- All presented results use only data from Run I of the LHC → $3fb^{-1}$ at centre-of-mass energy of 7 and 8 TeV.
- Run 2 aims at adding 5 fb^{-1} at 13 TeV → more than four times as much data as in Run I.
- Most current charmless analyses are dominated by statistical uncertainties.



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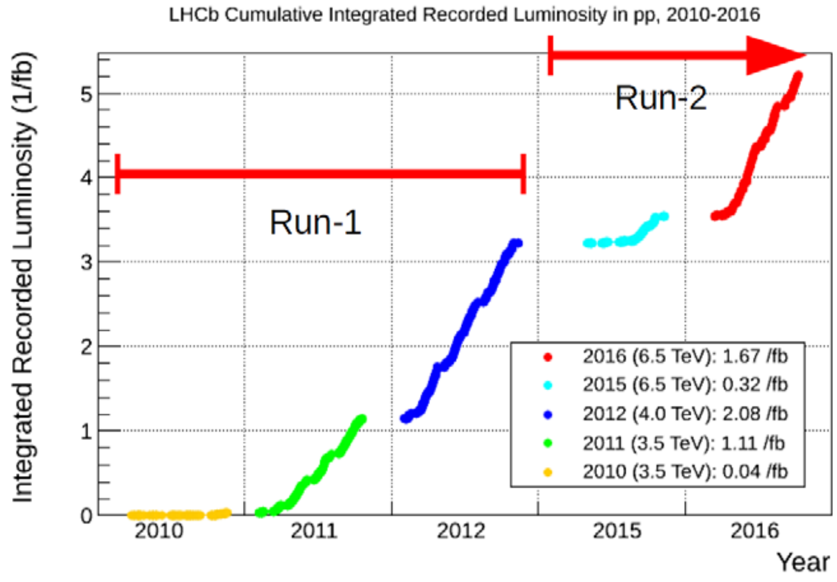
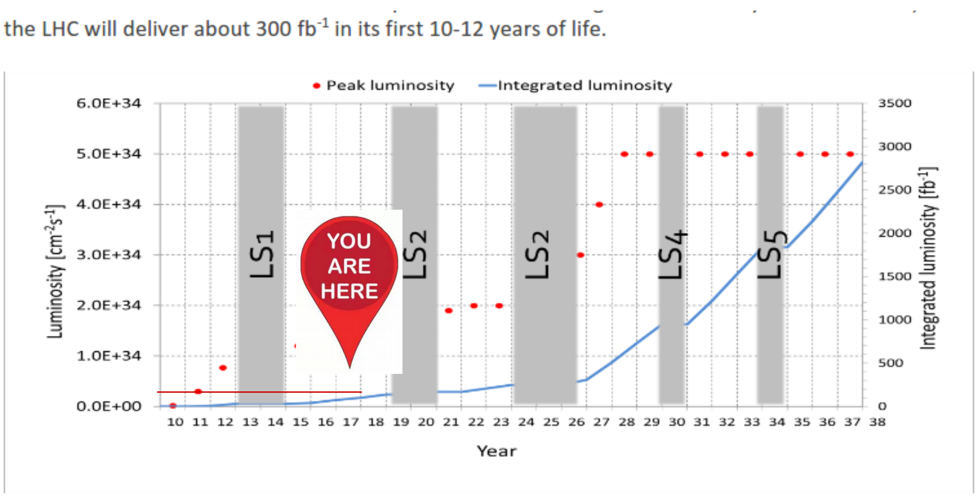


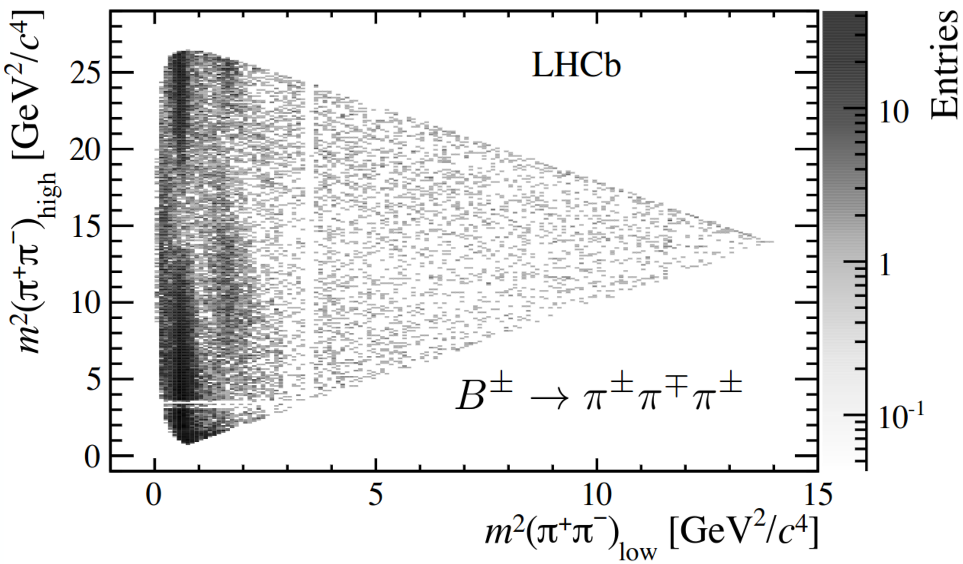
- Run 2 aims at adding 5 fb[-1] at 13 TeV → more than four times as much data as in Run I.
- Most current charmless analyses are dominated by statistical uncertainties.
- Upgrade planned after 2018, including:
  - massive overhaul of the trigger system;
  - complete change of all the tracking subsystem.



- Expected LHC luminosity delivery.
  [2016 J. Phys.: Conf. Ser.706 022002]
- What can be done with that amount of data?

Prospects: three-body charmless decays

- New channels observed → physics programme of charmless decays is expanding.
- Wealth of different channels:
  - Initial hadron: baryon, B^0, B_s, B_c^+
  - Final state: baryonic, V0 particle...
- Work on amplitude analyses already ongoing.
  - Allows to measure many more Q2B branching fractions.
  - Allows to access more physics observables.



Phys. Rev. D 90 (2014) 112004

- In some cases ($B^+ \to 3h$), data already there (>100k events) but need for refined analysis techniques.

Expected "phase transition" in charmless analyses at LHCb from first observations to fully fledged amplitude analyses.

Prospects: near and far future of LHCb

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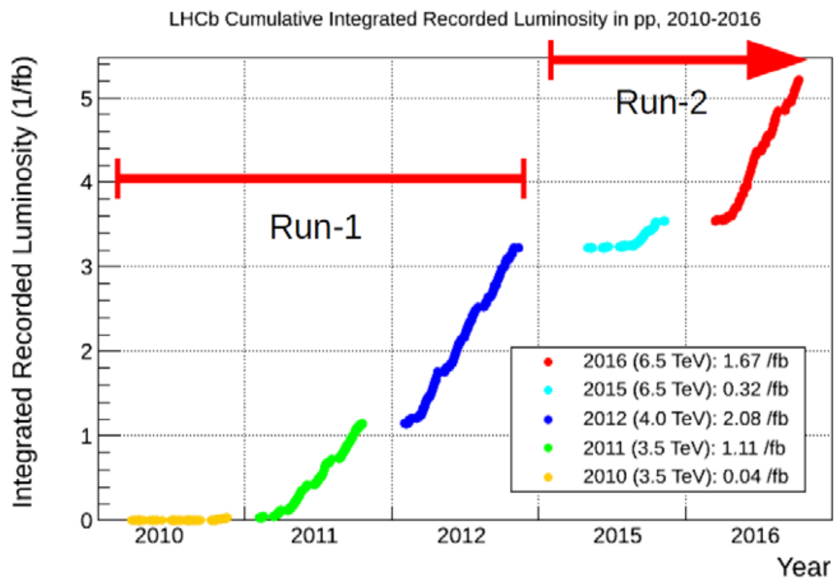

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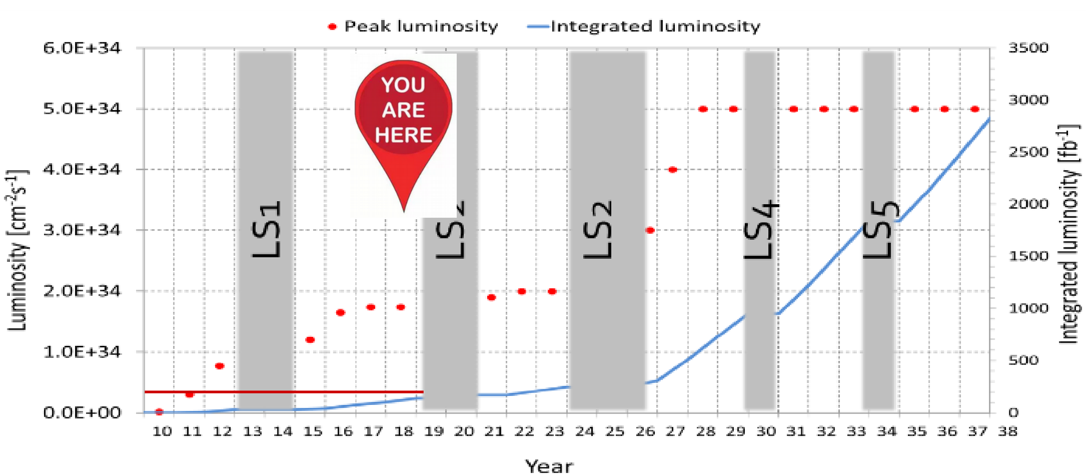
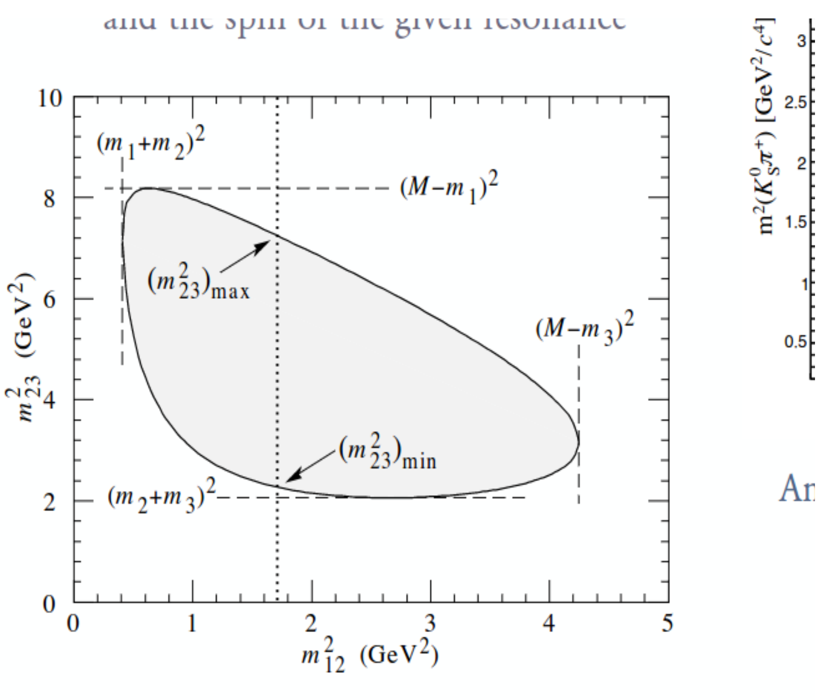
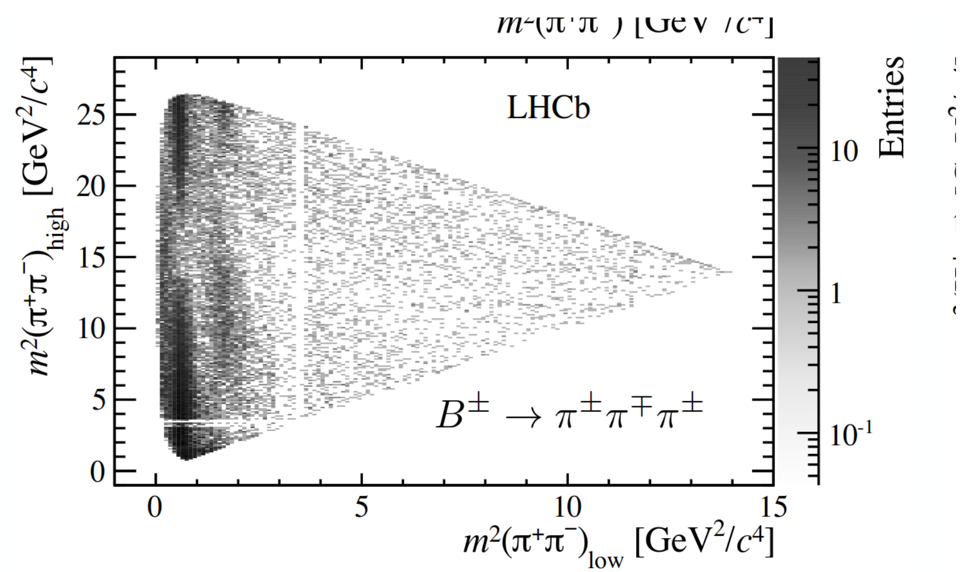


Prospects: a case for new techniques

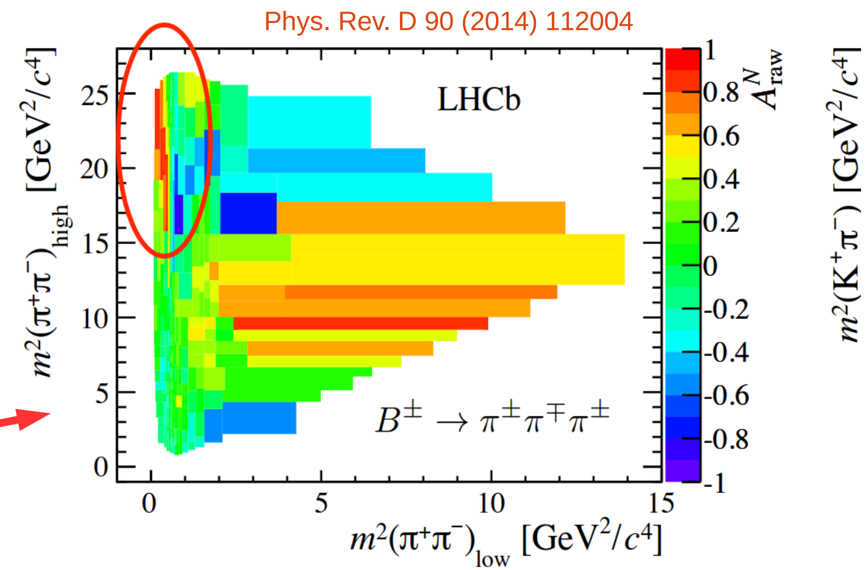
- Direct CP asymmetries in $B^+ \to h^+ h^- h^+$ (favoured) [PRD 90, 112004 (2014)].
- Large efficiencies, "large" BF→>100k events. "Glimpse" into the future.
- Usual technique: Dalitz-plot analysis.





Phase-space is flat on the Dalitz plot
→irregularities signal underlying dynamics

$A^N_{Raw} = [N(B^+)-N(B^-)]/[N(B^+)+N(B^-)]$
Large, localised, direct CP asymmetries.
Require full amplitude analyses.



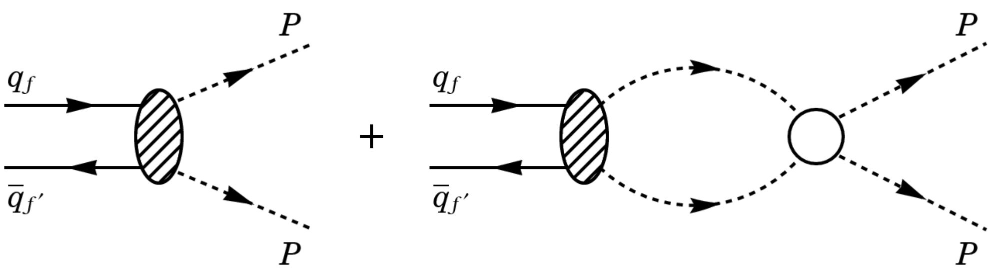
Prospects: a case for new techniques

- Most Dalitz-plot amplitudes use isobar model:

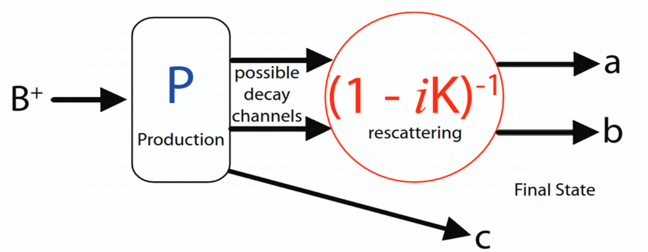
CP violating — Strong dynamics *CP* conserving

$$\mathcal{A}(m_{ij}^2, m_{jk}^2) = \sum_{l=1}^{N} c_l F_l(m_{ij}^2, m_{jk}^2)$$

- Shortcomings:
  - B-meson decays have a large phase space→ nonresonant component not easy to model.
  - Localised, large, direct CP violation can be due to (ππ↔KK) rescattering.



  - There are hints of three-body final-state interactions. Cannot fit into that model.
- Several approaches attempted:

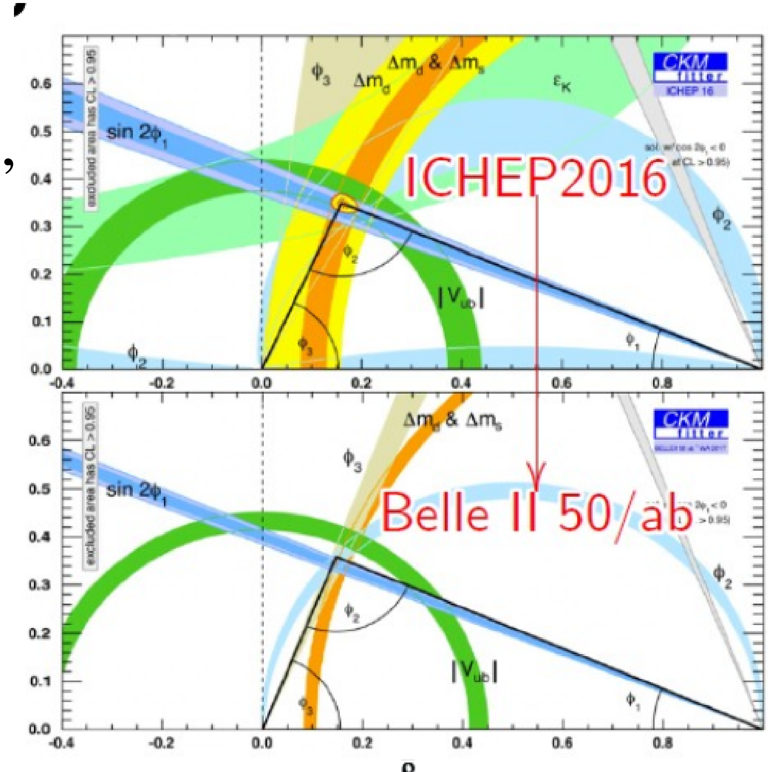


  - adapting the isobar model [arXiv:1506.08332];
  - K-matrix approach;
  - Quasi-model independent (bin the phase space and determine mag/phase in each bin).

Increased datasets will both allow us and force us to develop new and more refined amplitude analysis techniques.

Prospects: Belle 2

- Pros:
  - you know what you order → known energy, better flavour-tagging (37% power).
  - larger efficiency on electrons, K_S mesons, K_L mesons, γ, π^0.
- Cons:
  - you know exactly what you order → fewer initial states (fewer B_s, B_c, *b*-baryons).
  - smaller data samples on fully charged modes.
- Personal summary: Belle has more final states, LHCb has more initial states.
- And charmless? Charmless is most powerful when all related channels are studied together → possible Belle 2 advantage here.
  - e.g. arXiv:1306.5574 (γ extraction using B→KKK and Kππ decays).



Unitarity triangle

Summary and conclusion

Conclusion: the LHCb side

- Charmless hadronic *B* decays offer vast diversity of channels and physics observables, including
  - branching fractions;
  - weak phases ($\beta_{(s),\mathrm{eff}}$, γ) → indirect searches for CPV;
  - strong phases → better understanding of QCD/hadronic interactions.
- **Situation pre-LHCb:** some decays known, some full amplitude analyses performed.
- **Situation post-Run I:** many first observations, especially in new domains (e.g. baryons).
- **Situation Run > II:** many amplitude analyses performed, weak and strong phases measured in those decays.
- But this is not a straight path:
  - transition from counting experiments (branching fractions) to amplitude analyses;
  - need to refine existing tools to face the challenge of handling that much data.

Thank you!

Amplitude analysis of $B^0 \to K_S \pi^+ \pi^-$: the Dalitz plot

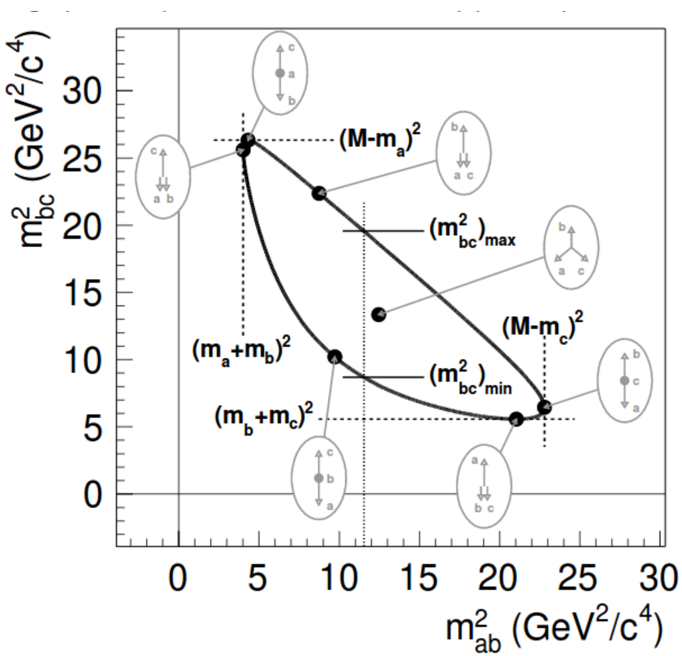
$B_d \to K_s h^+ h'^-$ decay $\to$ 3x4 degrees of freedom (d.o.f)	12
Conservation of momentum	-4
Mass constraints	-3
All particles are pseudoscalars $\to$ isotropic decay	-3

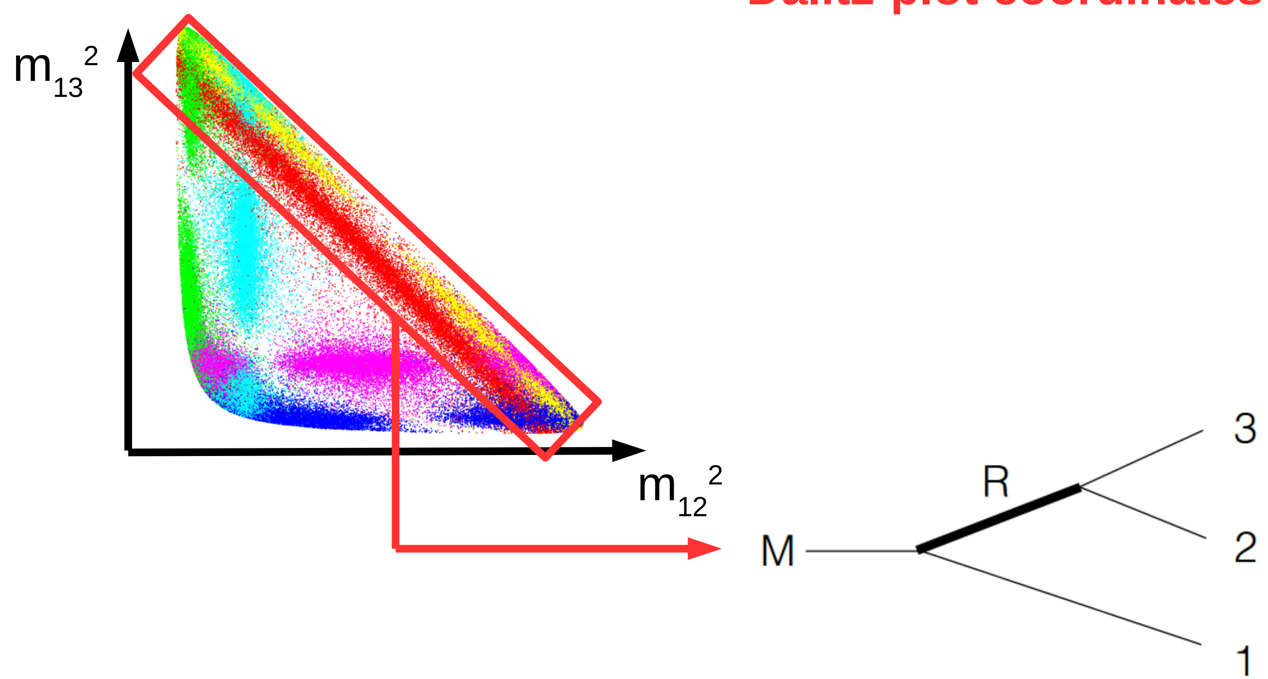
- Decay amplitude can be written

  $\to$ in absence of dynamics, amplitude flat.

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32 M^3} |\mathcal{M}|^2 dm_{12}^2 dm_{13}^2$$

Dalitz-plot coordinates





Few orders of magnitude

- **Luminosity** at LHCb: fb^{-1}.
- **Acceptance**: 0.01-0.4 rad, ~25% of producted bb pairs.
- **bb cross-section** in acceptance: **72 – 154 μb** (7-13 TeV).
  - So ~ 200 billions of pairs in acceptance for Run 1.
- **Charmless branching fraction**: 10^{-4}–10^{-6}.
  - Adding ε(rec) ~ 10^{-3} → typical number of events from hundreds to tens of thousands.
- **Tagging power**: 5% → effective N: from few events to 1000.
- **Daughter energy**: 10-50 GeV/c^2, transverse energy: ~10% of that.
- **Decay-time resolution**: 0.02-0.05 ps, linear with delta(t).
- **Efficiency on a K_S**: depends strongly on decay. For Kshh, factor 20-50.

The isobar approach

- Isobar approach: A_f written as coherent sum of partial amplitudes (isobars). Can be resonant or nonresonant.

$$\overset{(-)}{\mathcal{A}} = \sum_{n}^{N} \overset{(-)}{\mathcal{A}}_n , \qquad \overset{(-)}{\mathcal{A}}_n = \overset{(-)}{a}_n F_n\left(m_{ij}^2, m_{jk}^2\right) ,$$

$$F_n\left(m_{ij}^2, m_{jk}^2\right) = X_L(|\mathbf{p}^*|r')X_L(|\mathbf{q}|r)T_n(L,\mathbf{p},\mathbf{q})R_n(m_{ij}),$$

(L = angular momentum of bachelor and pair)

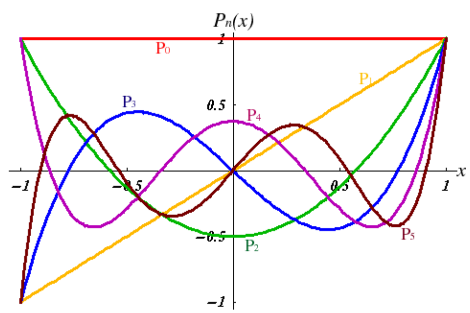
Blatt-Weisskopf barrier factors

$$F_0(x) = 1$$

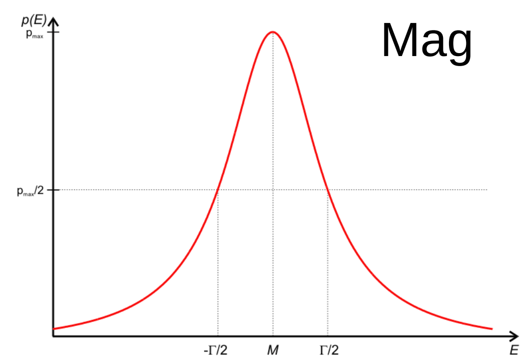
$$F_1(x) = \sqrt{\frac{x}{x+1}}$$

$$F_2(x) = \sqrt{\frac{13x^2}{(x-3)^2+9x}}$$

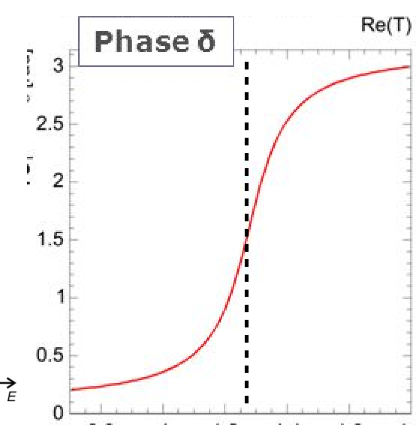
Zemach tensor



Lineshape (Breit-Wigner, Flatte...)



Mag



Prospects

- From L. Silvestrini @ Manchester 2016 (to be taken with a grain of salt).

Parameter	Error				
	Now	50/fb	300/fb	1000/fb	3000/fb
ΔM_d [ps^{-1}]	0.002	0.0005	0.0002	0.0001	0.00006
ΔM_s [ps^{-1}]	0.021	0.005	0.002	0.001	0.0006
$\sin 2\beta$	0.022	0.008	0.0026	0.0018	0.001
γ [°]	6.5	0.9	0.4	0.2	0.09
α [°]	5.5	1	Belle II		
β_s [°]	4	0.26	0.11	0.06	0.034
V_{us}	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$			
V_{cb}	2.7%	1%	Belle II		
V_{ub}	10%	1%	Belle II		
x		$1.5 \cdot 10^{-4}$	$4.5 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$
y		10^{-4}	$3 \cdot 10^{-5}$	$2 \cdot 10^{-5}$	10^{-5}
$\lvert q/p \rvert$		0.01	0.003	0.002	0.001
ϕ [°]		3	0.9	0.6	0.3
A_Γ		$4 \cdot 10^{-5}$	$12 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
$\alpha_s(M_Z)$	0.0005	0.0002			
m_t	760 MeV	250 MeV	theory limited		
m_b	50 MeV	10 MeV			
B_K	1.3%	0.1%			
F_{B_s}	5 MeV	1 MeV			
F_{B_s}/F_{B_d}	1.4%	0.5%			
$F_{B_s}\sqrt{B_{B_s}}$	3.8%	3%			
ξ	2.5%	0.5%			

Prospects (2)

- From B. Golob @ Manchester 2016

	Observables	Belle or LHCb* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 8 fb^{-1}	(2018)	LHCb 50 fb^{-1}
UT angles	$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012 (0.9^\circ)$		0.3°	0.6°	~	0.3°
	α [°]	85 ± 4 (Belle+BaBar)		1			
	γ [°] $(B \to D^{(*)} K^{(*)})$	68 ± 14		1.5	4	!	1
	$2\beta_s (B_s \to J/\psi\phi)$ [rad]	$0.07 \pm 0.09 \pm 0.01^*$			0.025	!	0.009
Gluonic penguins	$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$		0.018	0.2	?	0.04
	$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$		0.011			
	$S(B \to K_S^0 K_S^0 K_S^0)$	$0.30 \pm 0.32 \pm 0.08$		0.033			
	$\beta_s^{eff}(B_s \to \phi\phi)$ [rad]	$-0.17 \pm 0.15 \pm 0.03^*$			0.12	!	0.03
	$\beta_s^{eff}(B_s \to K^{*0} \bar{K}^{*0})$ [rad]	–			0.13		0.03
Direct CP in hadronic Decays	$\mathcal{A}(B \to K^0 \pi^0)$	$-0.05 \pm 0.14 \pm 0.05$		0.04		?	
UT sides	$\lvert V_{cb} \rvert$ incl.	$41.6 \cdot 10^{-3} (1 \pm 2.4\%)$					
	$\lvert V_{cb} \rvert$ excl.	$37.5 \cdot 10^{-3} (1 \pm 3.0\%_{ex.} \pm 2.7\%_{th.})$		1.4%		~	
	$\lvert V_{ub} \rvert$ incl.	$4.47 \cdot 10^{-3} (1 \pm 6.0\%_{ex.} \pm 2.5\%_{th.})$		3.0%		!	
	$\lvert V_{ub} \rvert$ excl. (had. tag.)	$3.52 \cdot 10^{-3} (1 \pm 10.8\%)$		2.4%		!	
Leptonic and Semi-tauonic	$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$96 (1 \pm 26\%)$		5%		~	
	$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7		7%			
	$R(B \to D\tau\nu)$ [Had. tag]	$0.440 (1 \pm 16.5\%)^\dagger$		3.4%		~	
	$R(B \to D^*\tau\nu)^\dagger$ [Had. tag]	$0.332 (1 \pm 9.0\%)^\dagger$		2.1%	...	!	
Radiative	$\mathcal{B}(B \to X_s\gamma)$	$3.45 \cdot 10^{-4} (1 \pm 4.3\% \pm 11.6\%)$		6%			
	$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$		0.5			
	$S(B \to K_S^0 \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$		0.035			
	$2\beta_s^{eff}(B_s \to \phi\gamma)$	–			0.13	!	0.03
	$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$		0.07			
	$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	< 8.7		–			
Electroweak penguins	$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$ $[10^{-6}]$	< 40		30%			
	$\mathcal{B}(B \to K^+\nu\bar{\nu})$ $[10^{-6}]$	< 55		30%			
	C_7/C_9 $(B \to X_s\ell\ell)$	~20%		5%			
	$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	–		–			
	$\mathcal{B}(B_s \to \mu\mu)$ $[10^{-9}]$	$2.9^{+1.1}_{-1.0}{}^*$			0.5	!	0.2

Belle 2 vs LHCb

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2$ TeV) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 13$ TeV) LHC
Production cross-section	1 nb	$\sim 100\ \mu$b	$\sim 500\ \mu$b
Typical $b\bar{b}$ rate	10 Hz	~ 100 kHz	$\lesssim 1$ MHz
Pile-up	0	1.7	1–40
Trigger efficiency	100 %	20–80 %	
B hadron mixture	B^+B^- ($\sim 50\,\%$), $B^0\bar{B}^0$ ($\sim 50\,\%$)	B^+ (40 %), B^0 (40 %), B_s^0 (10 %), Λ_b^0 (10 %), others ($< 1\,\%$)	
B hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
$B\bar{B}$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Effective flavour tagging efficiency	$\sim 30\,\%$	$\lesssim 6\,\%$	

KsKK in a nutshell